The Status and future of ground-based TeV gamma-ray astronomy
A White Paper prepared for the
Division of Astrophysics of the American Physical Society

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1.1 Executive Summary

High-energy γ-ray astrophysics studies the most energetic processes in the Universe. It explores cosmic objects such as supermassive black holes and exploding stars which produce extreme conditions that cannot be created in experiments on Earth. The latest generation of γ-ray instruments has discovered objects that emit the bulk of their power in the form of high-energy γ-rays. High-speed imaging technology, with gigahertz frame rates allow us to detect individual cosmic γ-ray photons produced under the most violent and extreme conditions. Gamma-ray astronomy has unique capabilities to reveal the nature of the elusive dark matter that dominates the matter contents of the Universe.

Motivated by the recent advances of TeV γ-ray astronomy, the Division of Astrophysics of the American Physical Society (APS) charged the editorial board of this White Paper to summarize the status and future of ground-based γ-ray astronomy. The APS requested a review of the science accomplishments and potential of the field. Furthermore, the charge called for a description of a clear path beyond the immediate future to assure the continued success of this field. The editorial board solicited input from all sectors of the astroparticle physics community through six open working groups, targeted international meetings, and emails distributed through the APS and the High-Energy Astrophysics Division of the American Astronomical Society. The board also enlisted senior advisers that represent ground-based and satellite-based γ-ray astronomy, particle physics, and the international community of astroparticle physicists.

This section summarizes the findings and recommendations of the White Paper team. It also gives a brief introduction to the science topics that can be addressed with TeV γ-ray astronomy. The interested reader is referred to the detailed discussions in the reports of the working groups and to excellent review papers about the status and accomplishments of TeV γ-ray astronomy by Hinton[1], and by Aharonian et al.[2]. Appendix A lists the authors of the White Paper, the make-up of the working groups, and the meetings organized by the White Paper team. Appendix B reproduces the APS charge.

1.1.1 Summary of Findings

(F1) The current generation of instruments has demonstrated that TeV γ-ray astronomy is a rich field of research. TeV γ-ray astronomy saw its first major success in the year 1989 with the firm detection of a cosmic source of TeV γ-ray emission, the Crab Nebula, with the Whipple 10-m Cherenkov telescope. To date, advances in instrumentation and analysis techniques have established TeV γ-ray astronomy as one of the most exciting new windows into the Universe. The H.E.S.S., MAGIC, and VERITAS experiments have shown us a glimpse of the discovery potential of this new type of astrophysics. The Milagro and Tibet experiments have explored an alternative experimental technique that permits a full survey of the sky. Due to the increased sensitivity of these instruments, the number of known TeV γ-ray sources has increased by an order of magnitude (from $\sim$10 to $\sim$100) in the past 3 years. Known source classes include the remnants of supernova explosions, neutron stars, supermassive black holes, and possibly groups of massive stars. Many new TeV sources and source classes have been discovered. Several of them have heretofore unobserved substructures resolved by TeV γ-ray telescopes, indicating isolated regions in which energy is transferred to high-energy particles. Several sources show brightness variations clearly resolved in the TeV data; the previously known sources Mrk 421 and PKS 2155-304, both of which involve a supermassive black hole, have been observed to vary on timescales as short as 2 minutes, indicating that the emission regions may be comparable in size to the event horizon of the parent black hole, and revealing the inner

[1] Hinton, J., 2007, http://arxiv.org/abs/0712.3352

[2] Aharonian, F., Buckley, J., Kifune, T., Sinnis, G., 2008, Reports on Progress in Physics, 71, 9, http://stacks.iop.org/0034-4885/71/096901

workings of these powerful systems. The very short variability timescales are also facilitating studies of quantum gravity through the search for violations of Lorentz invariance. Among the most important discoveries is the fact that there are many mysterious unidentified TeV objects that have no currently known counterpart at any other wavelength.

(F2) Primary scientific drivers of ground-based γ-ray astronomy:

- High-energy particles are an ubiquitous but insufficiently studied component of cosmic plasmas. TeV γ-ray astronomy makes it possible to study the acceleration and propagation of these high-energy particles in a wide range of different environments, from the remnants of exploding stars to the formation of the largest gravitationally bound structures in the Universe.

- The combination of γ-ray observations, accelerator experiments, and direct detection experiments may lead to one of the most spectacular discoveries of the 21$^{\text{st}}$ century: The unambiguous identification of the mysterious dark matter that holds together the cosmic entities in which we live: Galaxies and galaxy clusters.

- Supermassive black holes reside at the centers of most galaxies. A black hole that is well-fed with infalling gas will produce collimated outflows, or jets, of gigantic proportions, reaching out beyond the bounds of its host galaxy. TeV γ-ray astronomy offers the possibility to study the formation of jets and to obtain key insights into how black holes grow, thus revealing the cosmic history of supermassive black holes and their influence on the cosmological evolution. The strong beams of γ-rays from these sources can be used to probe the extragalactic infrared background radiation and thus to constrain the star-formation history of the Universe.

(F3) A large-scale ground-based γ-ray observatory would substantially increase the scientific return from a number of present and future ground-based and space-based observatories including (but not limited to) the Low-Frequency Array (LOFAR) and the Square-Kilometer Array (SKA) at radio wavelengths, the Large Synoptic Survey Telescope (LSST), the Fermi Gamma-Ray Space Telescope, the neutrino experiments IceCube and ANITA, and the gravitational wave experiments LIGO and LISA.

(F4) The experimental techniques for the ground-based detection of γ-rays, Imaging Atmospheric Cherenkov Telescopes (IACTs) and Water Cherenkov Arrays (WCAs), were pioneered in the United States and have achieved a state of high maturity. The U.S.-led Fermi satellite was successfully launched in June 2008, but no follow-up experiment is on the horizon. In view of the long lead times of new initiatives, it is mandatory to now start designing and constructing a major ground-based γ-ray observatory.

(F5) TeV γ-ray experiments are very broad in the scientific problems that they can address, and therefore a substantial increase in their sensitivity will provide answers to many different questions. A next-generation experiment could improve on the sensitivity by a factor of 5-10, and could make measurements of the γ-ray sky in unprecedented detail. Technical reasons make sensitive measurements at very low and very large energies difficult, i.e. expensive to achieve, and therefore the 30 GeV to 100 TeV energy range appears the optimal energy band in which the advances in sensitivity should be accomplished. The Fermi satellite experiment will conduct very sensitive studies in the energy band below 50 GeV, and while overlap with Fermi is desirable, there is diminishing return in making GeV γ-ray measurements with TeV γ-ray experimental techniques.

(F6) The IACT and WCA techniques complement each other. IACTs achieve unprecedented instantaneous sensitivity over a small field of view, as well as excellent angular and energy resolution for detailed studies of cosmic objects.

With a large field of view, WCAs can alert the IACTs about the brightest transient phenomena. Furthermore, WCA arrays achieve a high sensitivity for steady extended sources and at >10 TeV energies.

(F7) VHE γ-ray astronomy was pioneered in the U.S., as was the imaging technique which has lead to the success of the current suite of experiments. Due to a lack of sufficient funding and an aggressive effort in other nations, this leadership position is being challenged. However, novel ideas and unique expertise still reside within the U.S. (wide field-of-view optical systems, novel low-cost low-weight mirror technologies, advanced camera design and electronics, and intelligent array triggers) and with sufficient funding the U.S. can regain its leadership position in this area of research. In addition, the U.S. is still the leader in the WCA technique; however, other nations are now beginning to invest in this area and we must provide sufficient funding here to retain our leadership position.

1.1.2 Recommendations

(R1) The IACT and WCA techniques have achieved a high state of maturity that allows high-fidelity extrapolations in cost and performance. A next-generation experiment at an installation cost of $120M could achieve a factor of 5-10 better sensitivity than current experiments. This level of investment is warranted by the guaranteed rich astrophysics return and the exciting potential for more fundamental discoveries in a number of key areas.

(R2) While U.S. groups pioneered ground-based γ-ray astronomy, in the last few years the position of the U.S. has been challenged as European funding agencies were quicker to recognize the potential of the field. To maintain a worldwide leadership role, it is imperative that appropriately funded R&D and design studies for the next-generation experiment start immediately.

(R3) The space born γ-ray observatory Fermi is poised to revolutionize the field of γ-ray astronomy. However, owing to Fermi's limited angular and energy resolutions and rather small collection area, many results will need follow-up observations with a ground based experiment. The Large Hadron Collider (LHC) might find the first evidence for dark matter particles. The design of the next-generation γ-ray experiment (especially the energy band for which it will be optimized) will depend on the science results from Fermi and the LHC. Therefore, the decision on the final design of the experiment should be made two to three years from now. The construction of the full experiment should start 4 to 5 years from now.

(R4) In parallel to work on technology R&D, the U.S. groups should work on establishing a site on which a large-scale experiment can be built during the coming decade. The site should allow for step-wise enlargement; therefore, sufficient space and a long-term lease agreement are mandatory. Procuring a site should be pursued as early as possible to avoid the delays that affected VERITAS and the Heinrich-Hertz SMT on Mt. Graham. To maximize the science return of the experiment, a site should be chosen that allows one to observe the Galactic Center.

(R5) The next generation ground based gamma-ray instrument should be an international project. The U.S. groups should continue and intensify the collaboration with the European and Japanese groups. The U.S. groups have already formed joint scientific and technical working groups. This process should be continued. The merits of distributed and largely independent experiments with telescopes deployed at two or three sites should carefully be compared with the merits of building a single large experiment supported by a world wide collaboration.

(R6) To maximize the return of the investments, broader impact strategies need to be considered along with the development of the scientific and technical aspects of the next-generation experiment. In particular, the U.S. groups should take the lead in efforts to incorporate broader impacts from the beginning of the development phase. These efforts should include:

- Developing observatory and data access policies that encourage full participation of the astroparticle, astronomy, and particle physics communities. One component of the experiment should be a vigorous guest-investigator program and strong multi-wavelength partnerships. In contrast to existing P.I.-type instruments like VERITAS, Milagro, or H.E.S.S., a next-generation detector should be an observatory, so any scientist can apply for observing time and receive support for analyzing the data. The instrument teams should be charged with, and a budget allocated by the funding agencies for, the development and maintenance of the appropriate tools and support systems for researchers outside of the experiment collaboration.

- Many of the most difficult challenges facing our nation in the areas of nuclear nonproliferation, nuclear terrorism, and the identification and reaction to conventional terrorists attacks require technological advances in the areas of ultra-fast low-light imaging systems and event classification and response in real time in the presence of an enormous data volume. These needs are common to the next generation of VHE instruments. The community should work with the appropriate government agencies to ensure that the technology developed can be utilized to find solutions for these critical national needs.

- Building the future generation of scientists and engineers through involving undergraduate and potentially high-aptitude high-school students in all phases of development.

- Partnering with science centers and planetaria to engage the public in the exciting science opened up by TeV γ-ray astronomy, and also to raise the level of science appreciation within the general population.

1.2 Ground based γ-ray astronomy - historical milestones

Our atmosphere absorbs energetic γ-rays. However, at sufficiently high γ-ray energies, it becomes possible to detect radiation from secondary particles produced by the primary γ-rays in the atmosphere with detectors stationed on the ground. In the following, a summary of the major discoveries made with ground based γ-ray experiments is given.

1987: Detection of the first cosmic source of TeV γ-rays, the Crab Nebula (Whipple 10m).
The technique of imaging air showers produced by γ-rays in Earth's atmosphere with fast pixelated cameras permitted the classification of γ-ray like and cosmic ray-like events. The suppression of cosmic ray initiated air showers allowed the Whipple collaboration to detect the Crab Nebula in TeV γ rays. Powered by the strongly magnetized wind of the Crab pulsar, the Crab Nebula now serves as the standard candle of TeV astronomy. Sixty-five cosmic sources of TeV γ-rays have been observed to date.

1992: Detection of the first extragalactic source of TeV γ-rays, the active galactic nucleus Mrk 421 (Whipple 10m).
Active galactic nuclei harbor black holes of about a billion solar masses that eject plasma at approximately the speed of light. In these collimated plasma outflows, called jets, particles are efficiently accelerated and radiate a significant fraction of their energy in the form of γ-rays. Relativistic aberrations make active galactic nuclei that have a jet pointed towards the observer prominent γ-ray sources.

1992: First constraints on the intensity of the Diffuse Extragalactic Infrared Background based on energy spectrum of Mrk 421 (Whipple 10m).
TeV γ-rays produce electron-positron pairs in collisions with extragalactic infrared and optical light. Observed as energy-dependent extinction, this effect permits a measurement of the intensity of the Extragalactic Infrared Background which traces the star-formation history of the Universe.

1996: Discovery of extremely fast γ-ray flux

variability from the active galactic nucleus Mrk 421 (Whipple 10m).
Significant brightness fluctuations can only be produced in an emission region of limited extent. Although the jets of active galactic nuclei are often larger than their host galaxies, the variable γ-ray emission comes from a portion of the jet not bigger than the solar system.

1996: Discovery of Mrk 421 X-ray/TeV-gammaray flux correlation (ASTRO-E, Whipple 10 m).
The correlations indicate that the processes leading to X-ray and TeV γ-ray emission are related. They give important clues to the nature of the radiating particles and the radiation processes.

1997: Discovery of extreme flares of the active galactic nucleus Mrk 501 with X-ray emission up to 100 keV (BeppoSAX) and TeV γ-ray emission up to 16 TeV (HEGRA).
Active galactic nuclei not only change their brightness, but also their spectrum. Correlated measurements of these variations in X-rays and TeV γ-rays allow us to observe the acceleration of the radiating particles nearly in realtime.

2003/2006: Detection of γ-rays from the Radio Galaxy M87 (HEGRA), and discovery of day-scale flux variability (H.E.S.S.).
M 87 is a relatively nearby active galactic nucleus whose jet is not directed to us. Measuring TeV γ-rays and fast γ-ray brightness fluctuations give fundamental clues on particle acceleration and radiation processes in an object that can be spatially resolved in many wavebands, thus revealing the geometrical structure, and for which relativistic corrections are not as severe and difficult to estimate as in system, that have a jet pointed toward us.

2003: Discovery of the first unidentified TeV γ-ray source TeV J2032+4130 (HEGRA).
This source of TeV γ-rays is the first dark accelerator, of which a few dozens have been found to date. The question of which objects are bright in high-energy γ-rays, but relatively dim in all other wavebands, is a fascinating one.

2004: Discovery of γ-rays from the Galactic Center (CANGAROO, Whipple 10m, H.E.S.S.).
The Galactic Center is a region of particular interest because γ-rays can be used to probe the three-million solar-mass black hole residing there, the elusive dark matter presumed to be concentrated in that region, and many other systems. Spectral measurements suggest that the bright emission seen is not produced by dark matter.

2004: First spatially and spectroscopically resolved TeV γ-ray image of the Supernova remnant RX J1713.7-3946 (H.E.S.S.).
The remnants of supernova explosions have long been suspected to be the main sites of particle acceleration in the Galaxy. Advances in imaging now permit us to measure TeV γ-ray energy spectra and their changes across the remnants, thus deciphering the distribution of radiating particles with unprecedented detail.

2005: Scan of the inner region of the Galactic plane reveals a large population of sources, including Pulsar Wind Nebulae and a considerable number of unidentified sources (H.E.S.S.).
A survey of the inner Galaxy proved what researchers have suspected for many years: the Galaxy is filled with a variety of objects that accelerate particles to very high energies and shine prominently in TeV γ-rays. The Galaxy is much more than the stars it contains.

2005: Discovery of the periodic emission from the X-ray binary LS 5039 (H.E.S.S.).
A compact companion, perhaps a black hole, is exposed to the strong stellar 'wind' and the intense light radiated by a massive blue star. The interaction of the compact object with the stellar wind accelerates particles. However, the star light can absorb the γ-rays produced by the high-energy particles, thus leading to a complex modulation pattern of the γ-ray emission. This discovery opens the way to a better understanding of the dynamics of such binary systems.

2005: First detection of super-TeV γ-rays from the Galactic Plane (Milagro).
The Galaxy is permeated with energetic particles called cosmic rays, whose origin is one of the fundamental problems in modern physics. Measurements of a diffuse glow of γ-rays that cosmic rays produce at very high energies give invaluable insight into the properties of cosmic rays far from the solar system.

2006: Discovery of diffuse TeV γ-ray emission from the Galactic Center region (H.E.S.S.).
The bright diffuse emission is evidence for episodic states of high activity in the Galactic Center region during which extreme amounts of energy are transferred to energetic particles, possibly by the massive black hole that resides at the Galactic center. The separation of this diffuse emission from compact sources of γ-rays gives testimony of the imaging capabilities of modern Atmospheric Cherenkov telescopes.

2007/2008: Discovery of 3 min flux variability from 10^9 solar mass black hole systems Mrk 501 (MAGIC) and PKS 2155-304 (H.E.S.S.).
The extremely short variability timescale indicates that the γ-rays come from a region not bigger than the black hole that is the central part of an active galactic nucleus.

2007: Discovery of degree-size unidentified sources of super-TeV γ-rays in the Galactic Plane (Milagro).
The γ-ray sky at energies above 10 TeV shows bright extended features that are likely associated with localized sources. Those features are too large to be caused by the wind of a pulsar, and too powerful to be identified with the remnant of a Supernova explosion, suggesting they may be sites in which many Supernovae exploded and pulsars were born.

2008: Discovery that TeV γ-rays from M 87 most likely come from the compact core rather than the outer jet (VERITAS).
Correlations between X-ray and TeV γ-ray emission from the nearby active galactic nucleus M 87 indicate that the powerful TeV γ-ray emission comes from the central core around the supermassive black hole rather than from various active regions further out in the jet. M 87 is one of the very few active galactic nuclei for which the jet can be resolved and directly imaged in high-energy emission.

2008: Discovery of pulsed γ-ray emission above 20 GeV from the Crab Nebula (MAGIC).
40 years after their discovery, pulsars and their radiation mechanisms are a very active field of research. Precision measurements of the high-energy end of the spectrum of pulsed γ-ray emission provide fundamental insights into the structure of pulsar magnetospheres and the main energy transfer processes at work.

1.3 Scientific overview

1.3.1 High-Energy Particles

The Universe is filled with energetic particles, electrons and fully-ionized atoms, traveling through space very close to the speed of light. Their origin is one of the fundamental unsolved problems in modern astrophysics. We know that our Galaxy contains astrophysical systems capable of accelerating particles to energies beyond the reach of any accelerator built by humans. Candidates for particle accelerators are shocks formed in cosmic plasmas when a star explodes, when a rapidly spinning neutron star expels electromagnetic energy, or when a black hole spews out matter at nearly the speed of light. What drives these accelerators is a major question in physics and understanding these accelerators has broad implications.

The charged energetic particles constitute a very tenuous medium; each particle carries extreme energy, but the particles themselves are very few. However, in our Galaxy high-energy particles carry on average as much energy per unit volume as the gas, the magnetic field between stars, and as star light. The processes that determine their energy and spatial distribution are different from those that shape ordinary gases on Earth, because they rely almost entirely on electric and magnetic fields. Most gases on Earth are "thermal": the energy of the gas is distributed approximately equally among the atoms or molecules of the gas. In contrast, matter in the Universe is often far from equilibrium. In the dilute plasmas that fill most interstellar and intergalactic space, nature chooses to endow a small number of particles with an extreme amount of energy. We witness a fundamental self-organization that, through interactions between particles and electromagnetic fields, arranges the atoms and available energy in three components: a cool or warm gas that carries the bulk of the mass, energetic particles with a wide range of energies, and the turbulent electromagnetic fields that link the two.

Why does nature produce energetic particles? What is the fate of the turbulent magnetic field? Do interactions of high-energy particles generate the magnetic field that permeates large structures in the Universe such as clusters of galaxies?

To address those questions, we need to measure the properties of energetic particles in detail. The energetic particles can be observed through high-energy γ-rays, electromagnetic radiation with very high-energy. Because γ-rays carry so much energy, they must be produced by particles with even more energy, and in particular TeV-γ-ray radiation is a key diagnostic of highly energetic particles. By emitting TeV γ-ray emission, the high-energy particles give us information about some of the most extreme physical environments and the most violent processes in the Universe that cannot be obtained in any other way.

1.3.2 Radiation processes and the sky in high-energy γ-rays

The γ-ray sky is very different from the sky that we see with our own eyes: the Sun is dark, and a bright glow of γ-rays produced by cosmic rays (as energetic particles in the Milky Way Galaxy are called) fills a large fraction of the visible sky. Some structures associated with the remnants of exploded stars cover a few square degrees of the night sky; others may be the annihilation sites of the most mysterious particles that make up dark matter. Embedded in that extended, diffuse emission are compact or point-like sources, some of which can be surprisingly variable: a large fraction of compact TeV γ-ray sources show bright flares on time scales of minutes to days. In most cases these flares are powered by matter falling into black holes.

Energetic particles such as cosmic rays are ionized, comprising, as individual particles, atomic nuclei and the electrons that we would usually find in the shells of atoms. They belong to different families of particles: electrons, together with the elusive neutrinos, are leptons, whereas the protons and neutrons in atomic nuclei are hadrons. The interactions and, in particular, the radiation processes of electrons are different from those of nuclei because of their mass difference. Electrons radiate efficiently when they accelerate or decelerate quickly. Interacting with dense plasmas, electrons emit Bremsstrahlung radiation; synchrotron radiation is emitted by electrons that spiral around magnetic field lines; electrons can transfer a large fraction of their energy to photons in "inverse Compton" processes, when they scatter off low energy photons. We understand the characteristics of these radiation processes, and so by measuring the radiation spectrum from a source we can infer the energy distribution of the radiating particles, provided the emission process is known.

From most astronomical objects synchrotron radiation of electrons is typically observed from the radio band up to X-rays. Inverse Compton emission generally extends from the X-ray band up to very high-energy γ-rays. Correlated measurements of X-ray and TeV γ-rays thus provide us with two views of the same radiating electrons, differing only by the process through which the electrons radiate, thus providing a measure of the number of radiating electrons and the strength of the magnetic field and the radiation environment. A detector of high-energy γ-rays should, therefore, have the capability to measure the radiation spectrum with fine energy resolution over a wide range of wavelengths.

Even though the emission processes described above are inefficient for atomic nuclei on account of their large mass, nuclei can radiate through collisions with ordinary gas by creating unstable particles, about a third of which are neutral pions (π^0) that directly decay into two high-energy gamma rays. The intensity of emission is proportional to the abundance of interaction partners, gas in the case of the radiating nuclei and infrared or other radiation in the case of electrons that undergo inverse Compton scattering. Very often we know the distribution of gas from independent measurements, or we know the strength of the ambient radiation because it is dominated by the cosmological microwave background, and so the spatial distribution of TeV γ-ray emission holds clues to the nature of the radiating par-

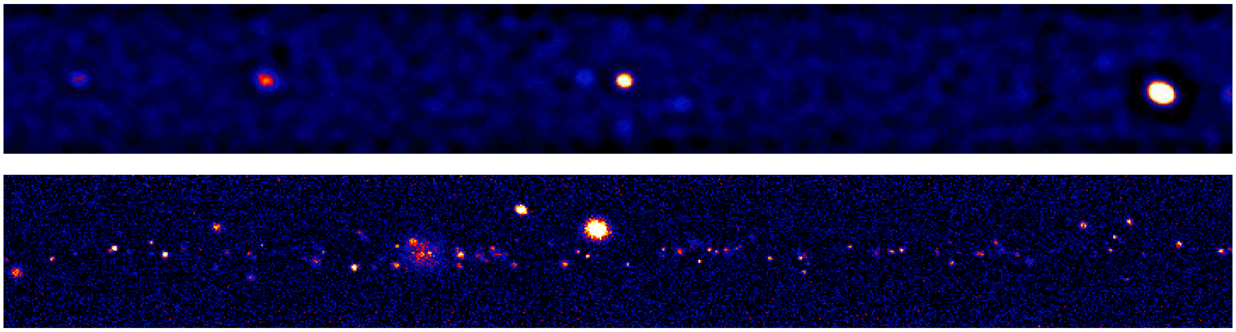

Figure 1: Simulation of a sky survey conducted with a future atmospheric Cherenkov telescope. The top panel gives a map of the inner Galaxy as actually measured with H.E.S.S. during its sky survey. The bottom panel shows a simulated sky map that would be observed with a future atmospheric Cherenkov telescope ten times as sensitive as are H.E.S.S., MAGIC, or VERITAS.

ticles. An excellent angular resolution is thus a key ingredient for a future γ-ray experiment.

Many sources in the Universe emit at a constant level, but not all. If a source significantly changes its brightness within a certain time, the size of the emission region cannot exceed the distance traveled by light in that time (A correction factor of known character must be applied to this relation, if the emission region moves with a velocity close to the speed of light). Suppose a source flares for a minute: One would estimate it is smaller than about 20 million kilometers across, or about one eighth of the distance between sun and Earth, yet the objects may outshine an entire galaxy. The current generation of TeV γ-ray telescopes has detected flux variability from active galactic nuclei down to timescales as short as about 2 minutes, and there has been no lower limit in the distribution of variability timescales. Future telescopes with 10-fold improved sensitivity will be capable of probing timescales less than 10 seconds. In studying such systems we are investigating the most extreme and violent conditions and processes in the Universe.

Brightness variations within a short time require that the radiating particles be produced rapidly and that they lose their energy swiftly, so the source can fade again. In most cases the dominant means of energy loss of energetic particles is radiation, which leads to a characteristic time evolution of the emission spectrum. Variability, in particular when observed at different wavelengths, therefore carries important information about the size of and the physical conditions in astronomical sources. A detector of high-energy γ- rays should therefore have the sensitivity to detect sources within a short time, so their brightness variations can be followed.

Both the spectrum and the variability of high-energy emission are shaped by the efficacy and the energy dependence of the processes that accelerate the radiating electrons or nucleons to high energies. These particles are constantly deflected by fluctuating magnetic fields, but magnetic fields alone can't change their energy. What is required are fluctuating magnetic fields or plasmas, dilute ionized gases in which the magnetic field is embedded, that move relative to each other. More than fifty years ago the eminent Italian physicist Enrico Fermi classified processes of that nature: If the motions of the magnetic-field irregularities are random, we speak of 2nd-order Fermi, or stochastic, acceleration. If the motions of the magnetic-field irregularities change systematically and abruptly, as in a shock front, the associated acceleration process is called 1st-order Fermi, or shock, acceleration.

Historically, scientists have often been too conservative in their predictions of what nature can do. A substantial increase in measurement capability has often led to the discovery of new phenomena or new classes of sources. Likewise for known variable sources, the active phases have been notoriously difficult to predict. To find the unexpected, or to seize the opportunities offered by a source awakening from dormancy, a detector should have a rather large (5°-10° diameter) field of view.

1.3.3 Diffuse emission and the nature and distribution of dark matter

The study of diffuse Galactic γ-ray emission is important for a number of reasons. It provides direct information on the energy distribution of cosmic rays in various locations in the Galaxy, which is needed to understand the origin and interactions of cosmic rays, in particular to separate the characteristics of the production of cosmic rays from those of their propagation. Also, this emission must be understood to properly analyze extended γ-ray sources and to derive self-consistent limits on the amount of dark matter in the Galaxy.

Physicists have assumed for a long time that the matter surrounding us, atoms made of nuclei and electrons, is representative of all the matter in the Universe. In the 1930's, Fritz Zwicky found that additional dark matter beyond the luminous matter is required to explain the existence of galaxies. In the 1970's, Vera Rubin measured the motion of spiral galaxies like our Milky Way and also found strong evidence that non-luminous matter holds the galaxies together. The picture that has emerged is that we live in an highly non-representative concentrate of ordinary matter that accumulated at the center of massive structures of dark matter, so-called dark-matter halos. Although the Universe contains five times as much dark matter as normal matter, we do not yet know what dark matter is.

Ground based γ-ray observations promise to lead to the detection of annihilation γ-rays from accumulations of dark matter particles at the center of dwarf galaxies, at the center of the Milky Way, or in so-called mini-halos that populate the Milky Way. Recent results of particle physics suggest that the very early Universe was filled with massive particles, only the lightest of which survived to constitute dark matter. Those particles would interact with other particles only very rarely, but on those rare occasions would produce high-energy γ-rays that can be observed with the next generation of γ-ray detectors. Depending on the mass of the dark matter particles and the particulars of their decay or annihilation, a γ-ray signal is expected in either the GeV band, to be observed with the Fermi telescope, or beyond 30 GeV, where the next generation of ground-based γ-ray instruments can detect them. The γ-ray measurements could reveal the total mass of dark matter and its distribution in the Milky Way and other galaxies, and thus give unique information about the nature of dark matter that is complementary to the results from laboratory experiments.

1.3.4 Powerful particle accelerators in our Milky Way Galaxy: supernova remnants, pulsars, and stellar-mass black holes

It appears that efficient acceleration of cosmic rays proceeds in systems with outflow phenomena, in which a fraction of the energy can be transferred to cosmic rays. Some of those systems are shell-type supernova remnants (SNR), in which material from the exploded star slams into the ambient gas, forming a shock front. In fact, SNRs have long been suspected as production sites of Galactic cosmic rays because of their total energy output and rate. SNRs in the Galaxy change slowly, so we can compare their appearance in high-energy γ-rays to that in other wavebands such as X-rays, which allows us to determine their spatial structure. The remnants are large enough that they can be resolved in gamma rays, so we have an opportunity to perform spatially-resolved studies in systems with known geometry. The question of cosmic-ray acceleration in SNRs includes aspects of the generation, interaction, and damping of magnetic turbulence in non-equilibrium plasmas. The physics of the coupled system of turbulence, energetic particles, and colliding plasma flows can best be studied in young SNRs, for which X-ray and γ-ray observations indicate very efficient particle acceleration and the existence of a strong turbulent magnetic field. The amplification of magnetic fields in shocks is of particular interest because it may play an important role in the generation of magnetic fields in the Universe.

Compact objects in the Galaxy can also accelerate particles to very high energies. Among the remnants of massive stars are pulsars, highly magnetized remnants of stars crushed to densities greater than atomic nuclei. Pulsar masses are approximately equal to that of the Sun, but their diameters are typically on the order of 10 miles. They are rapidly spinning and produce a beam of radiation like a lighthouse. At the same time, they emit a wind of relativistic particles that moves almost at the speed of light. Gamma rays can be very efficiently produced in those winds, and the entire system is generally referred to as a pulsar-wind nebula (PWN). They provide unique laboratories for the study of relativistic shocks because the properties of the pulsar wind are constrained by our knowledge of the pulsar and because the details of the interaction of the relativistic wind can be imaged in the X-ray, optical, and radio bands. Relativistic shock acceleration may be key to many astrophysical sources, such as active galactic nuclei and Gamma-Ray Bursts. PWNe are, perhaps, the best laboratory to understand the detailed dynamics of such shocks.

When a stellar mass black hole or a pulsar is bound to a companion star, it seems to be able to form tightly collimated plasma beams or jets; TeV γ-rays have been observed from those jets. In fact, TeV emission provides a unique probe of the highest-energy particles in a jet, allowing us to address key questions: Are jets made up of normal ions, or a mixture of matter and antimatter? What is the total energy carried by jets? What accelerates particles in jets? Energetic particles often dominate the energy budget of the jet and the accurate measurement of their spectrum and acceleration time is essential for addressing these questions, which, in turn, are fundamental to our understanding of the physics of jets and their formation.

1.3.5 Extragalactic sources of TeV γ-rays

The Big Bang resulted in a remarkably homogeneous Universe. For the last 13.7 billion years, the history of the Universe has been one of matter clumping together under the influence of gravity. We now think that small clumps formed first and made stars. Later, larger clumps formed, resulting first in galaxies made of billions of stars, and subsequently in galaxy clusters, comprising up to several thousand galaxies. As these large structures grow and draw in matter, large shocks form in which incoming material is heated and cosmic rays are accelerated. Large structures like galaxy clusters thus consist of several components: a dark matter halo that holds the cluster together, the individual galaxies visible with optical telescopes, hot plasma that radiates X-rays, and finally cosmic rays that are expected to carry a substantial fraction of the available energy. This energetically important component has evaded detection so far. A next-generation, ground-based γ-ray observatory has an excellent chance to discover γ-ray emission from this component and to deliver detailed information about its spatial and spectral properties. Such an experiment could thus make a substantial contribution to our understanding of the energy and pressure composition of the plasma in the largest structures in the Universe.

High-energy particles, or cosmic rays, also play an important role in other galaxies. Massive stars produce strong plasma winds and, towards the end of their life, spectacular supernova explosions that violently expel plasma into space. The stellar winds and the supernova outflows are both thought to be efficient cosmic ray accelerators. A next-generation γ-ray observatory will allow us to detect γ-rays from these cosmic rays in a large number of nearby galaxies, and to study the relationship between star formation and cosmic ray acceleration in very different galactic environments. The γ-ray studies will thus revolutionize our understanding of the role of stellar feedback in the formation and evolution of stars and plasma in galaxies.

The deaths of some stars are thought to be responsible for some of the most violent explosions in the Universe, Gamma Ray Bursts. These events may lead to the acceleration of the highest-energy cosmic rays through multiple shocks driven at highly relativistic speeds in their collimated plasma outflows (jets), and they are thought to produce significant TeV γ-ray emission, which has eluded detection thus far. By detecting this emission from gamma-ray bursts and measuring its properties, we would make great strides towards understanding the extreme nature and environments of γ-ray bursts, particularly the local opacity and the bulk Lorentz factor. It could also contribute to our understanding of the decades-old problem of the origin of ultra-high-energy cosmic rays, as well as permit Lorentz-invariance violation studies, γ-ray burst progenitor studies, and thus star formation history studies. An observation of violations of Lorentz invariance would be a major step towards a quantum theory of gravity, which is the only fundamental interaction in nature for which a quantum description has not been successfully formulated to date.

We know that other galaxies harbor supermassive black holes with a mass between a million and a few billion solar masses that are part of what astronomers call active galactic nuclei (AGN). These black holes offer physicists a unique opportunity to test Einstein's theory of the nature of space, time, and the gravitational force. Recent radio and X-ray observations indicate that black holes may play an important role in galaxies and galaxy clusters by regulating the rate of star formation. TeV γ-ray astronomy affords the possibility to study the environment of supermassive black holes, and the processes by which the black holes grow.

The jets from supermassive black holes are laboratories to study turbulence and particle acceleration in the most extreme setting; the flow velocity is much higher than in supernova remnants, and the energy content vastly exceeds that of galactic compact objects. The main questions astrophysicists ask are similar to those relevant for jets of galactic solar-mass black holes, but the parameters are different. Studying the same issue with galactic black holes and with AGN can be likened to probing the same physical behavior with two laboratory experiments that use different techniques, thus offering complementary views that give a better and more complete picture. Better measurements of the spectrum of the highest-energy particles in a jet and its rapid changes, using more refined TeV γ-ray observations and X-ray studies in parallel, are by far the best approach to addressing how nature organizes energy and matter in these most violent conditions.

TeV γ-rays from extragalactic sources also carry information about the infrared light between galaxies: High-energy γ-rays can be absorbed upon collision with infrared and optical light, thus modifying the γ-ray spectra of sources in a way that has a characteristic dependence on their distance. The absorption also depends on the total intensity of optical and infrared light ever emitted by stars. In this way, TeV γ-ray observations constrain the early history of star and galaxy formation in the Universe.

1.4 Technology and the path toward a future observatory

High-energy γ-rays can be observed from the ground by either imaging the Cherenkov light produced by the secondary particles once the γ-ray interacts high in the atmosphere or, using Extended Air Shower (EAS) arrays, by directly detecting the shower particles (electrons, muons and photons) that reach the ground. The former method employs imaging atmospheric Cherenkov telescopes (IACTs). Modern IACT experiments like VERITAS, MAGIC, and H.E.S.S. detect point sources with a TeV γ-ray flux of 1% of the flux from the Crab Nebula. EAS arrays such as Milagro have complementary capabilities to IACTs. While their instantaneous sensitivity is currently a factor of $\sim$150 lower than that of IACTs, their field of view is over 200 times larger and their duty factor is close to 100% as compared to 10% for IACTs. EAS observatories are, therefore, suited to performing unbiased surveys to search for new or transient sources.

It is possible to improve the sensitivity of both techniques by another order of magnitude at a total cost only one order of magnitude higher than that of the present instruments; that is, installation costs of the order of \$ 100M. At the core of designing a next-generation ground-based γ-ray detector is the requirement to improve the integral flux sensitivity in the 50 GeV to 50 TeV regime where the techniques are proven to give excellent performance. At lower energies (below 50 GeV) and at much higher energies (50-200 TeV) there is great discovery potential, but new technical approaches must be explored. For particle-detector (EAS) arrays, the technical roadmap is relatively well-defined. Simulations indicate that by moving to a higher altitude, enlarging the detection area, and optically isolating the detector modules, the proposed High Altitude Water Cherenkov (HAWC) experiment can achieve a sensitivity factor of 10-15 better than that of Milagro. The joint US-Mexico collaboration estimates the total cost of HAWC below \$10M.

In considering the design of future IACT arrays, the development is likely to follow several different (although complementary) branches, with the aim of covering a broad energy range from 10 GeV up to 100 TeV. Achieving an order of magnitude sensitivity improvement in the 200 GeV to 10 TeV regime will require an experiment with an effective area of $\sim$1 km^2 and a large number ($\sim$50) of telescopes. The design, construction, and operation of a large-scale ground based γ-ray experiment also brings new challenges: Efficiently mass-producing telescopes, simplifying the process of checking out and calibrating the telescopes, and minimizing the maintenance required to keep the telescopes fully operational. The design of a future IACT array can be based on the well-studied performance of the existing VERITAS, MAGIC, and H.E.S.S. instruments, for which preliminary studies indicate that the sensitivity improves faster than the square root of the number of telescopes, as would be expected for a large number of telescopes operated as independent detectors. Various technological advances substantially reduce the cost per telescope; e.g., the availability of high-quantum-efficiency photodetectors, the development of fast, integrated, application-specific integrated circuits (ASICs) for the front-end electronics, the use of optimized mechanical and optical designs, and the development of novel mirror technology. Also, the costs of the current experiments were largely driven by the one-time engineering that will form a lower percentage of the project cost for a larger experiment.

Such a next-generation IACT instrument could be designed and built on a time scale of $\sim$5 years. We would recommend a 3-year R&D program to provide a better understanding of the design options, cost uncertainties and reliability. This time scale also makes it possible to adapt the design of the experiment to new science opportunities opened up by discoveries of the Fermi and LHC experiments. We also encourage the community to pursue technologies which could have a large impact on cost, operation, and scientific capability. The R&D program should include the following design studies:

- Based on Monte Carlo simulations, the strengths and weaknesses of different array configurations need to be fully explored. Two specific issues that should be studied further are (i) the impact of the pixel size on the energy threshold, background-rejection capability and angular resolution of the telescopes, and (ii) the impact of the altitude at which the instrument is operated.

- The development and evaluation of different camera options, with emphasis on achieving a higher quantum efficiency of the photodetectors, and a modular design of the camera to reduce assembly and maintenance costs.

- The development of ASIC-based front-end-electronics to further minimize the power and price of the readout per pixel.

- A next-generation experiment should offer the flexibility to operate in different configurations, so that specific telescope combinations can be used to achieve certain science objectives. Such a system requires the development of a flexible trigger system. Furthermore, the R&D should explore possibilities to combine the trigger signals of closely spaced telescopes to synthesize a single telescope of larger aperture.

- The telescope design has to be optimized to allow for mass production and to minimize the maintenance costs.

- The telescopes should largely run in robotic operation mode to enable a small crew to operate the entire system.

The R&D should coincide with the establishment of a suitable experimental site and the build-up of basic infrastructure. Ideally, the site should offer an easily accessible area exceeding 1 km^2. For an IACT array, an altitude between 2 km and 3.5 km will give the best tradeoff between low energy thresholds, excellent high-energy sensitivity, and ease of construction and operation. EAS arrays should be located at higher altitudes to facilitate the direct detection of shower particles.

Beyond the immediate future, alternative optical designs should be explored in greater detail. Such designs have the potential to combine excellent off-axis point-spread functions, large field-of-views, and isochronicity with significantly reduced camera size. Key issues that need to be addressed are the cost and reliability of suitable mirror elements, the procedure of adjusting the mirrors, and the price increase arising from the required mechanical precision and stability of the support structure, the more complex mirror assembly, and primary/secondary obscuration. The reduced camera size would permit using integrated photodetectors such as multi-channel plates and Geiger-mode Si detectors, that are independently developed by the industry. The superior performance, low price, and extreme reliability of both alternative optics and integrated photodetectors must be demonstrated in the next years, before these technologies can form the design baseline of a future IACT array.

The U.S. teams have pioneered the field of ground based γ-ray astronomy during the last 50 years. The U.S. community has formed the AGIS collaboration (Advanced Gamma ray Imaging System) to optimize the design of a future γ-ray detector. A similar effort is currently under consideration in Europe by the CTA (Cherenkov Telescope Array) group, and the Japanese/Australian groups building CANGAROO are also exploring avenues for future progress. Given the scope of a next-generation experiment, the close collaboration of the US teams with the European and Japanese/Australian groups should be continued and intensified. If funded appropriately, the US teams are in an excellent position to lead the field to new heights.

1.5 Synergies with other wavebands and particle astronomy missions

TeV γ-rays are the high energy cousins to photons at lower energies. The closest in energy are GeV photons and are detected with satellite telescopes such as Fermi and AGILE. Together, the ground-based and satellite detectors span 6 orders of magnitude in energy (0.1 GeV to 100 TeV) for probing particle acceleration and emission processes in cosmic accelerators, allowing one to apply the most rigorous tests of theoretical models .

Another relative in the family of fundamental particles is the neutrino. Measurable neutrino fluxes are expected to accompany gamma-ray emission when observing astrophysical objects that harbor an acceleration site of cosmic-ray protons and nuclei. The IceCube detector at the south pole and soon the Antares experiment in the Mediterranean sea will provide information about the hadronic components in cosmic accelerators. Neutrino telescopes, together with the ground-based TeV γ-ray telescopes, could trace, identify and carefully inspect potential sites where the highest energy cosmic rays (UHE short for Ultra High Energy) have their origin. For example, AGNs were identified as TeV γ-ray emitters, providing a possible connection to UHE cosmic ray acceleration.

The direct identification of the sources of cosmic rays is being pursued with the AUGER experiment, which is the largest air shower array capable of detecting weak fluxes of UHE cosmic rays. In fact, evidence for the correlation of the arrival direction of UHE cosmic rays with AGNs was reported recently. These findings give even more urgency to searching for these cosmic Zevatrons, identifying their nature and understanding their production mechanism. The use of different messenger particles such as Neutrinos (IceCube), GeV to TeV γ-rays (satellite and ground-based γ-ray detectors) and UHE cosmic rays (AUGER) are indispensable in understanding the origin of the highest energy radiations in the Universe.

The leptonic component is becoming visible in photons via synchrotron radiation and inverse Compton scattering and is also a big contributor to high energy radiation, sometimes considered an unwelcome background for understanding cosmic-ray sources. Identifying and understanding its role in different types of cosmic accelerators requires the collaboration of radio, optical, X-ray telescopes and γ-ray telescopes. This is also essential in separating out the leptonic and hadronic cosmic ray production in astrophysical objects.

TeV γ-ray instruments have a key role as they provide an important link between X-ray telescopes (Chandra, Swift, RXTE, BeppoSAX, Suzaku, etc.) and cosmic-ray and neutrino telescopes. TeV telescopes bridge the energy gap between the lower energy photon emissions and the highest energy cosmic rays, and are sensitive to radiation of leptonic and hadronic origin, thus holding a key to understanding the energy budget in different types of cosmic accelerators.

2 Galactic diffuse emission, supernova remnants, and the origin of cosmic rays

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2.1 Why are they important?

The origin of Galactic cosmic rays and the mechanisms of their acceleration are among the most challenging problems in astroparticle physics and also among the oldest. Cosmic rays are energetically important in our understanding of the interstellar medium (ISM) because they contain at least as much energy as the other phases of the ISM. They also provide, along with interstellar dust, the only sample of ordinary matter from outside the heliosphere. Yet, the origin of cosmic rays in the Galaxy remains uncertain more than 90 years after their discovery by Victor Hess in 1912 (for a recent review, see [1]). Improving our knowledge of the interaction between highly energetic particles and the other elements of the ISM could help understand other systems, such as active galactic nuclei (AGN) that produce strong outflows with highly energetic particles.

High-energy gamma rays are a unique probe of cosmic rays. Observations in the TeV band are a sensitive probe of the highest energy physical processes occurring in a variety of astronomical objects, and they allow us to measure the properties of energetic particles anywhere in the Universe, such as their number, composition, and spectrum. From such measurements we know already that our Galaxy contains astrophysical systems capable of accelerating particles to energies beyond the reach of any accelerator built by humans. What drives these accelerators is a major question in physics and understanding these accelerators has broad implications, but more sensitive gamma-ray detectors are needed to address these questions. Among the many types of Galactic gamma-ray sources, observations of high-energy emission from shell-type supernova remnants (SNR) are particularly beneficial because:

- The acceleration of relativistic charged particles is one of the main unsolved, yet fundamental, problems in modern astrophysics. Only in the case of SNRs do we have an opportunity to perform spatially resolved studies in systems with known geometry, and the plasma physics deduced from these observations will help us to understand other systems where rapid particle acceleration is believed to occur and where observations as detailed as those of SNRs are not possible.

- The acceleration of particles relies on interactions between energetic particles and magnetic turbulence, so the question of cosmic-ray acceleration is, in fact, one of the generation, interaction, and damping of turbulence in a non-equilibrium plasma. The physics of the coupled system of turbulence, energetic particles, and colliding plasma flows can be ideally studied in young SNRs, for which observations in X-rays [2] and TeV-scale gamma rays [3] indicate a very efficient particle acceleration to at least 100 TeV and the existence of a turbulent magnetic field that is much stronger than a typical shock-compressed interstellar magnetic field. The amplification of magnetic fields by streaming energetic particles is of particular interest because it may play an important role in the generation of cosmological magnetic fields.

- SNR are the most likely candidate for the sources of cosmic rays, either as isolated systems or acting collectively in groups in so-called superbubbles, although to date we do not have conclusive evidence that they produce cosmic-ray ions in addition to electrons. An understanding of particle acceleration in SNR may solve the century-old question of the origin of cosmic rays.

- SNR are a major source of heat and turbulence in the interstellar medium of galaxies, and thus have an impact on the evolution of the galactic ecosystems. In particular, when new insights are extended to shocks from other sources, e.g. the winds of massive stars, they will help in advancing our understanding of the energy balance and evolution of the interstellar medium in galaxies.
- The evolution and interaction of turbulence and cosmic rays determines how the cosmic rays will eventually be released by the SNR, which has an impact on the amplitude and frequency of variations of the cosmic-ray flux near Earth and at other locations in the Galaxy [4].

The study of diffuse Galactic gamma-ray emission is important for a number of reasons.

- It provides direct information on the cosmic-ray spectrum in various locations in the Galaxy, which is needed to understand the origin of cosmic rays near and beyond the knee.
- It must be understood to properly analyze extended gamma-ray sources, in particular in terms of possible spatial variations of its spectrum resulting from non-stationary cosmic ray transport.
- It will enable us to analyze the gamma-ray spectra of supernova remnants self-consistently in the light of their function as possible sources of Galactic cosmic rays.
- It allows us to derive self-consistent limits on the amount of dark matter in the Galaxy by determining both the cosmic ray propagation and radiation properties and the gamma-ray emissivities of dark matter for a variety of spatial distributions.

2.2 What do we know already?

2.2.1 Supernova remnants

Cosmic rays consist of both electrons and hadrons. However, the hadrons dominate the energy budget, and the acceleration of hadrons is the key issue in understanding the origin of cosmic rays. The energy density in local cosmic rays, when extrapolated to the whole Galaxy, implies the existence of powerful accelerators in the Galaxy. Supernova remnants (SNRs) have long been thought to be those accelerators [5], but there is no definitive proof that hadrons are accelerated in SNRs. The classical argument that shocks in shell-type SNRs accelerate cosmic rays is that supernova explosions are one of the few Galactic phenomena capable of satisfying the energy budget of cosmic-ray nuclei, although even supernovae must have a high efficiency ($\sim$10%-20%) for converting the kinetic energy of the SNR explosions to particles [6]. However, these arguments are indirect. Other source classes may exist that have not been considered to date, and one may ask what role is played by the many sources seen in the TeV-band that do not have an obvious counterpart in other wavebands [50]. In any case, observations of TeV photons from SNRs offer the most promising direct way to confirm whether or not SNRs are, in fact, the main sources of CR ions below 10^{15} eV.

Even though very early measurements showed that the fluxes of TeV emission from SNRs are lower than originally predicted if SNRs really do accelerate the bulk of Galactic cosmic rays [33], later observations with H.E.S.S. established shell-type SNRs such as RX J1713-3946 [28] and RX J0852.0-4622 [35] as TeV-band gamma-ray sources. The maturity of high-energy gamma-ray astrophysics is best illustrated by the ability of current atmospheric Cherenkov detectors such as H.E.S.S., MAGIC, and VERITAS to resolve sources and to map the brightness distribution in TeV-band gamma rays. Figure 2 shows such a gamma-ray map and the TeV-band spectrum of RX J1713-3946. The interpretation of these TeV observations is complicated because two compet-

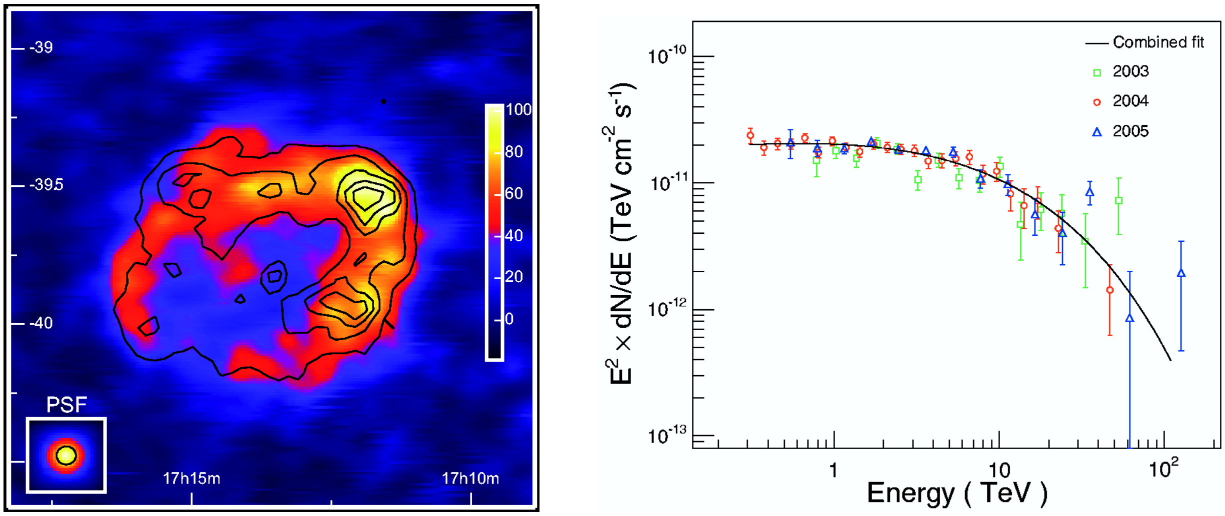

Figure 2: The left panel shows an image of the acceptance-corrected gamma-ray excess rate in the TeV band as observed with H.E.S.S. from the SNR RX J1713-3946 [28]. The insert labeled PSF indicates how a point source would appear in this image. Overlaid are black contour lines that indicate the X-ray intensity at 1-3 keV. Note the similarity between the X-ray and TeV-band images. The right panel shows the TeV-band spectrum for the entire remnant broken down for three different observing seasons.

ing radiation processes, pion-decay photons from ion-ion interactions and Inverse-Compton (IC) emission from TeV electrons scattering off the cosmic microwave background and the ambient galactic radiation, can produce similar fluxes in the GeV-TeV energy range. In the hadronic scenario neutrinos would be produced through the decay of charged pions. If even a few neutrinos are detected from a source at high enough energies, where the atmospheric neutrino background is minimal, then this alone could decisively indicate the hadronic mechanism [36].

SNRs do accelerate *electrons*. As has long been known from radio observations, GeV-scale electrons are accelerated in SNRs, and now compelling evidence for acceleration of electrons at the forward shocks of SNRs comes from observations of non-thermal X-rays from several shell-type SNRs. The X-ray emission is synchrotron radiation from electrons accelerated to TeV energies. In the case of SN 1006, the electrons must have energies of at least 100 TeV [2], see Fig. 3. These electrons must be accelerated in situ because such energetic electrons cannot travel far from their origin before they are attenuated by energy losses due to synchrotron radiation. The same electrons should produce TeV emission via inverse-Compton scattering. The intensity and spectrum of the emission are determined by the electron density, maximum electron energy, and local magnetic field. Combining radio, X-ray, and TeV data can provide a measurement of the magnetic field strength in the vicinity of the shock. This important parameter is not provided by X-ray spectroscopy alone, because the photon cut-off energy is insensitive to the magnetic field strength if it is generated by the competition of strong synchrotron cooling and gyroresonant acceleration of electrons.

An important clue to the nature of the parent particles comes from correlation studies with X-rays in the 2–10 keV band. For the two prominent SNRs, RX J1713.7-3946 and RX J0852.0-4622, one finds a spatial correlation down to angular scales of $\sim 0.1°$, between the X-ray emission and the TeV-band gamma-ray emission, with correlation factors in excess of 70%. This correlation suggests a common emission origin. The non-thermal X-ray emission is known to have structure on scales $\lesssim 0.01°$, and it is the limited angular resolution and sensitivity of the current TeV observatories that prevents a correlation analysis on the physically more relevant small scales. Nevertheless, if the TeV gamma-

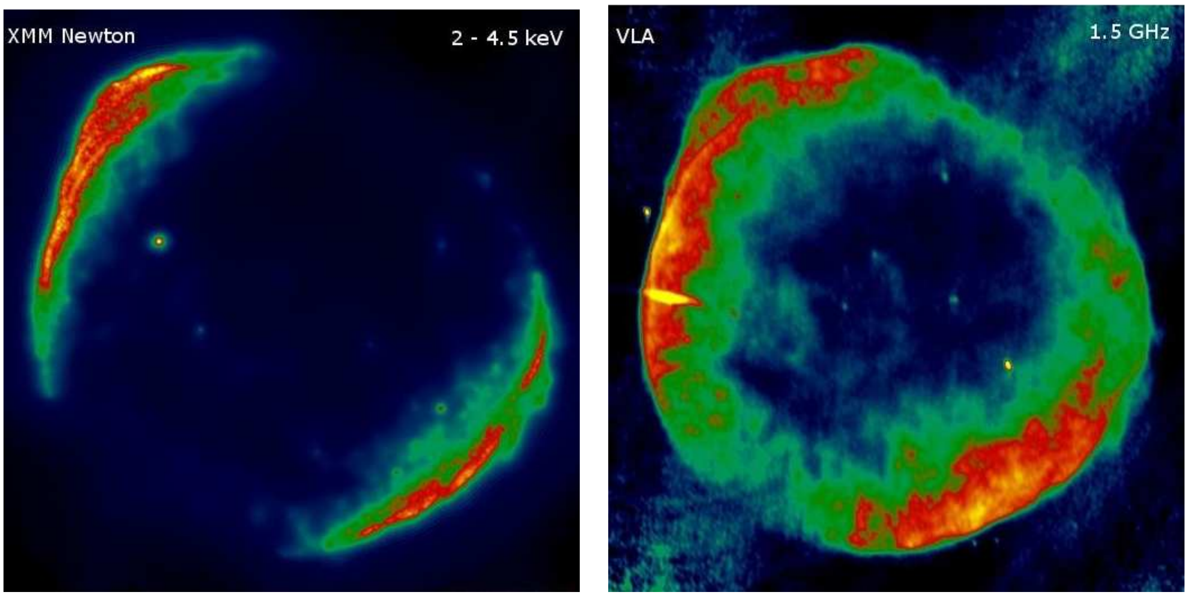

Figure 3: X-ray and radio images of SN 1006 [52]. Hard X-rays (left) are mainly produced by very high-energy electrons ($\sim$ 100 TeV) emitting synchrotron radiation. Radio emission (right) is produced by electrons with energies in the GeV range emitting synchrotron radiation. Imaging TeV observations will enable us to map the inverse-Compton emission from high-energy electrons and make a measurement of the magnetic field strength in the vicinity of the shock. Such mapping is also essential for distinguishing TeV photons produced by electronic versus hadronic cosmic rays. The angular size of the image is 35 arcmin. (Image courtesy of CEA/DSM/DAPNIA/SAp and ESA.)

ray emission was of leptonic origin as suggested by the spatial correlation, the spectra in X-rays and gamma rays should also be similar. As hadronic gamma-ray production requires interaction of the cosmic-ray nucleons with target nuclei, this emission will be stronger for those SNRs located near or interacting with dense gas, such as molecular clouds. The TeV emission should be brightest in those regions of the SNRs where the target density is highest.

In situ observations in the heliosphere show that collisionless shocks can accelerate particles. The process of particle acceleration at SNR shocks is intrinsically efficient [11]. Thus, the shocks should be strongly modified, because the energetic particles have a smaller adiabatic index and a much larger mean free path for scattering than does the quasi-thermal plasma. In addition, the particles at the highest energy escape, thus making energy losses significant and increasing the shock compression ratio [12]. A fundamental consequence of particle acceleration at cosmic-ray modified shocks is that the particle spectrum is no longer a power law, but a concave spectrum, as hard as $N(p) \propto p^{-1.5}$ at high momenta [13, 14]. Gamma-ray observations in the GeV-TeV band appear to be the best means to measure the particle spectra and thus probe the acceleration processes in detail.

Particle confinement near the shock is supported by self-generated magnetic turbulence ahead of and behind the shock that quasi-elastically scatters the energetic charged particles and thus makes their propagation diffusive. The amplitude of the turbulence determines the scattering frequency, and thus the acceleration rate [15]. The instabilities by which cosmic rays drive turbulence in the upstream region were long thought to be weak enough so that quasilinear approximations were realistic, i.e. $\delta B/B < 1$, but recent research suggests that the process by which streaming cosmic rays excite MHD turbulence is different from that usually supposed, if the cosmic-ray acceleration is efficient. The amplitude of the turbulent magnetic field may actually exceed that of the homogeneous, large-scale field [20, 21]. More recent studies [22] suggest that ahead of the shock nonresonant, nearly purely growing modes of short wavelength may be more efficiently excited than resonant plasma waves.

The observation of narrow synchrotron X-ray filaments indicates that the magnetic field must be very strong at the particle acceleration sites [9, 10], thus supporting the notion of magnetic-field amplification by cosmic rays. Those strong magnetic fields will decay as the plasma convects away from the forward shocks of SNRs, and it is an open question how far the regions of high magnetic field strength extend [23, 19]. The magnetic-field generation in shocks is also a candidate process for the creation of primordial magnetic fields in the cosmological context [16, 17, 18]. TeV-band gamma-ray observations, together with high-resolution X-ray studies, are the key to understanding the generation of magnetic fields by energetic particles.

If the acceleration efficiency is kept constant, a strong magnetic field would reduce the TeV-band gamma-ray emission arising from IC scattering of energetic electrons relative to their synchrotron X-ray emission, thus arguing against an IC origin of observable TeV-band emission. Yet it would make the expected IC spectrum similar to that of the hadronic pion-decay gamma rays [24, 25], because strong energy losses and evolution would produce a spectral change in the electron spectrum, as shown in Fig. 4, and would also tie the spatial distribution of the gamma-ray emissivities even closer to that of the synchrotron X-rays. It is therefore mandatory to combine sensitive spectral gamma-ray measurements with a better angular resolution, so as to avoid confusion and to effect discrimination between the hadronic and leptonic origin of the gamma rays.

On the other hand, the pion-decay spectra in the GeV-TeV region, predicted by nonlinear particle acceleration models (e.g., [26]), depend on uncertain parameters such as the ambient density and also somewhat on the strength of the interstellar magnetic field. RX J1713-3946, the brightest shell-type SNR in the TeV band, harbors very little gas [27], thus making less likely a pion-decay origin of the observed TeV-band emission. A robust discriminator, however, is the maximum photon energy. Since large magnetic fields produce severe radiation losses for electrons, there is a strong correlation between the ratio of maximum energy from ion-ion collisions to the maximum energy from IC and the magnetic field strength. The shape of the gamma-ray spectrum above $\sim$100 GeV also contains clues to the efficiency of the underlying acceleration process, and some SNRs, e.g., RX J1713-3946 (see Fig. 2), clearly show gamma-ray spectra too soft to be the result of efficient acceleration of cosmic-ray nucleons to the knee at 3 PeV [54], where the spectrum of Galactic cosmic rays starts to deviate from a simple power-law form.

Since the massive stars of type O and B that explode as supernovae are predominantly formed in so-called OB associations, most SNRs [37, 38, 39] reside in superbubbles [40, 41], giant structures formed by the collective effect of stellar winds and supernovae. Cosmic rays accelerated in superbubbles may achieve a higher particle energy than those produced in isolated SNRs, possibly on account of stochastic acceleration processes in the magnetic turbulence induced by the powerful multiple interacting supersonic stellar winds [47, 48]. The winds from superbubbles, therefore, are a possible alternative cosmic-ray source class, and some aspects of the isotopic composition of Galactic cosmic rays support their origin in superbubbles [45], although the composition of the bulk of the cosmic rays is that of the well-mixed interstellar medium [42], which somewhat limits the role superbubbles can play as the main sources of Galactic cosmic rays. Even though a stellar cluster may have already been seen in TeV-band gamma rays [49], it is very difficult to arrive at firm theoretical estimates and interpretations for superbubbles because of their generally poorly known geometry and history, even though some of them are associated with shell-like structures of atomic hydrogen [46]. There is the possibility of detecting the presence of high-energy heavy nuclei through their interaction with the intense stellar radiation in clusters of massive stars. Nuclei with energies of a few PeV (10^{15} eV) will disintegrate upon collision with the starlight, and the sub-

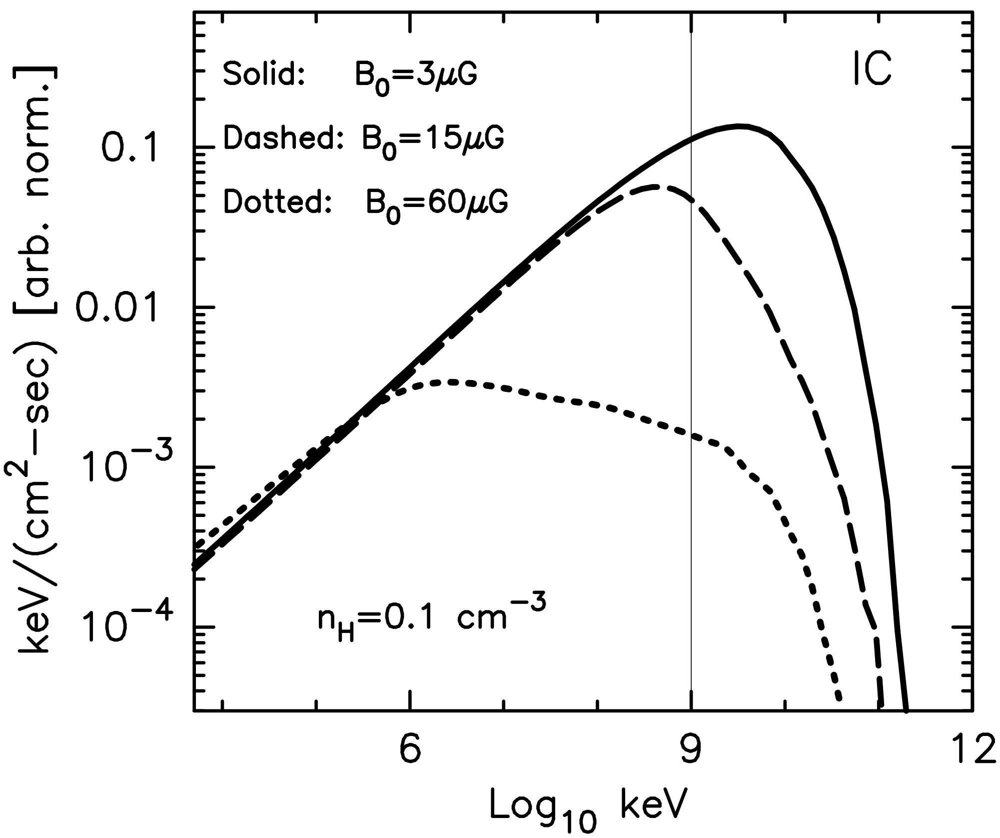

Figure 4: Expected GeV-TeV band gamma-ray emission from Inverse-Compton scattering of the microwave background on highly relativistic electrons, according to recent model calculations [25]. Shown are three spectra for different values of the magnetic field strength upstream of the SNR forward shock. For a high field strength strong radiative losses and evolution make the IC spectrum significantly softer above about 10 GeV, so it becomes similar to the expected gamma-ray spectrum produced by energetic hadrons. The thin vertical line marks 1 TeV photon energy.

sequent de-excitation of the nuclear fragments gives rise to characteristic gamma-ray emission with a distinct peak in power at about 10 TeV gamma-ray energy [44].

Superbubbles in the Galaxy are typically several degrees in size (eg. the X-ray emitting Cygnus superbubble is $\tilde{1}5\ ^{\circ}$ across), and therefore low surface brightness, confusion, and varying absorption complicates their analysis in the radio, optical, and X-ray bands, so Galactic superbubbles may be incompletely cataloged [43]. The Large Magellanic Cloud (LMC) is likely a better location to study superbubbles on account of its distance (roughly 6 times the distance to the Galactic Center) and low foreground absorption. Numerous superbubbles have been found in the LMC [7], which are typically 10 arcminutes in apparent size, similar to Galactic SNRs. Nonthermal X-rays were observed from the outer shell of the superbubble 30 Dor C [8] with a spectrum very similar to the nonthermal X-ray seen from Galactic SNRs like SN 1006, but with a luminosity about a factor of ten higher and an angular size of only a few minutes of arc, which partially compensates for the larger distance. The overall appearance of superbubbles can, therefore, be likened to that of young SNRs, with one exception: the superbubbles are probably much older, so they can maintain efficient particle acceleration for $\sim 10^5$ years, in contrast to the $\sim 10^3$ years after which shell-type SNRs turn into the decelerating (Sedov) phase and gradually lose their ability to efficiently accelerate particles.

The TeV-band to keV-band nonthermal flux ratio of SNRs varies from object to object; that ratio is at least a factor of 20 lower for SN 1006 and Cas A than for RX J1713-3946. However, for superbubbles the flux ratio may actually be significantly higher than for isolated SNRs on account of the typical age of the objects, because the X-ray emitting electrons are severely loss-limited, whereas for gamma-ray-emitting ions that may not be the case. A relatively conservative TeV-band flux estimate can be made by taking the measured flux of nonthermal X-rays and the flux ratio, as for RX J1713-3946. With this, one would expect TeV-band gamma-ray emission from 30 Dor C at a level of a few milliCrab (1 Crab refers to the flux measured from the Crab Nebula: the standard candle in high-energy astrophysics), which is a factor 5-10 below the sensitivity threshold of present-generation imaging Cherenkov telescopes. Galactic superbubbles may be much brighter, with about 1 Crab, but likely a few degrees in size, thus rendering their detection and physical analysis equally difficult.

A future sensitive gamma-ray instrument is needed to perform studies on a whole class of SNRs to finally understand the acceleration and interactions of both energetic nucleons and electrons. It would also investigate in detail the new and exciting topic of magnetic field amplification. Therefore, an advanced gamma-ray facility can, in conjunction with current X-ray telescopes, provide detailed information on the division of the energy budget in shocked SNR environs; namely, how the global energetics is apportioned between cosmic ray electrons, ions and magnetic field turbulence. This is a principal goal that will elucidate our understanding of plasma shocks, generation of magnetic turbulence and cosmic ray acceleration in the cosmos.

2.2.2 Diffuse galactic emission

In contrast to the case of SNRs, most of our knowledge of diffuse galactic gamma-ray emission was obtained with survey-type instrumentation that combines a very large field-of-view with moderate angular resolution of about one degree. Detectors like the Milagro instrument, that used the water-Cherenkov technique to measure gamma rays around 10 TeV energy, or the satellite experiment EGRET, a pair-production instrument sensitive to GeV gamma rays that operated in the Nineties, fall into this category. Survey instruments can provide good sensitivity to large-scale structures, but often suffer from confusion because the small-scale distribution of the signal cannot be determined, and so point sources and extended emission cannot be reliably separated. On the other hand, atmospheric Cherenkov telescopes such as H.E.S.S., MAGIC, and VERITAS offer a high angular resolution, so the angular structure of compact sources can be properly determined; but they generally have a small field-of-view and a reduced sensitivity for structures larger than a few degrees. The different characteristics of survey instruments and high-resolution cameras are evident in the scientific results of existing experiments.

EGRET has produced an all-sky map of the gamma-ray sky up to 10 GeV; at these energies inverse Compton (IC) scattering is still a major component of diffuse emission, possibly even dominant. NASA's next-generation experiment, Fermi, will clarify the nature of excess emission seen with EGRET at a few GeV, dubbed the GeV excess [30], produce an allsky map of GeV-scale diffuse gamma-ray emission, and also extend the coverage to 100 GeV. While at 1 GeV the statistical accuracy will be very high, with more than a hundred detected gamma rays per year and angular resolution element, the angular resolution as measured through angle around the true photon direction for 68% containment still exceeds 0.5 degrees, so confusion will be an issue. At higher energies, around 30 GeV, the angular resolution is better than 0.1°, but we can expect only about one detected photon per 0.1° resolution element through the 5-year mission, so the angular resolution cannot be fully exploited. Fermi will provide invaluable spectral information on the diffuse Galactic gamma-ray emission in the GeV band with degree-scale angular resolution, but TeV-band measurements will produce complementary images and spectra with very high angular resolution for selected regions of the sky that will be particularly useful

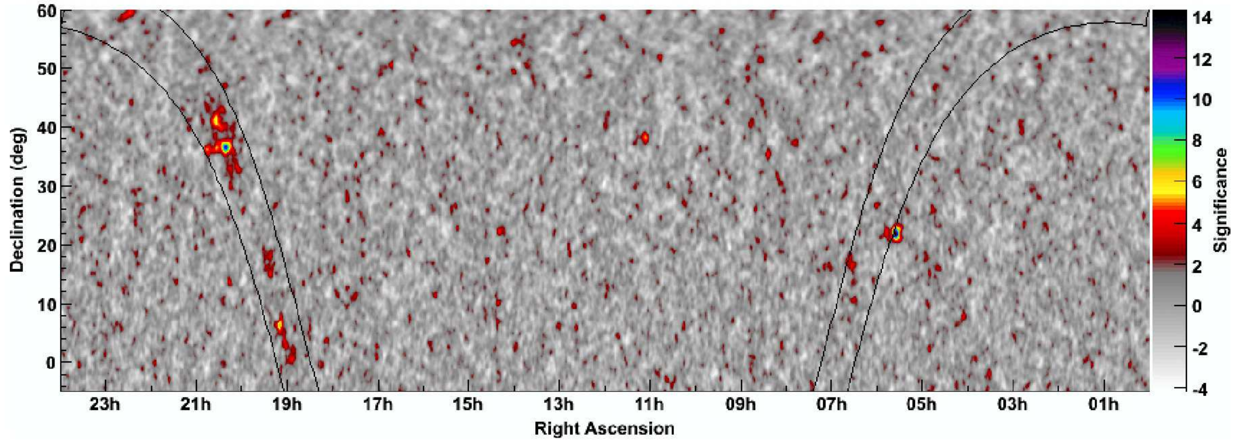

Figure 5: A sky map from 5 years of Milagro data taking [29]. Clearly detected in this plot are the Crab Nebula and the Galactic ridge. The brightest portion of the inner Galaxy is the Cygnus region and we have strong evidence for an extended source embedded within the larger diffuse emission region. The additional structure observed at lower Galactic latitudes has not yet been analyzed in detail and we cannot comment on the significance of any apparent features.

where imaging with Fermi suffers from confusion. GeV- and TeV-band observations can be combined to extract the information required to understand the propagation of energetic particles in the Galaxy.

The IC contribution to the diffuse Galactic gamma-ray emission can be large and not easy to separate from that of pion-decay. The separation of the diffuse gamma-ray signal into the contributions of cosmic-ray ions and those of electrons is desirable, because the propagation properties of the two particle populations is different. Also, measurements of the isotopic composition of cosmic rays near earth with appropriate particle detectors such as, e.g., PAMELA [31] allows us to additionally constrain the propagation history of cosmic-ray ions, although it appears very difficult to both fit the EGRET data and the locally measured spectra of cosmic-ray ions and electrons [32].

For gamma rays with energy above 10 TeV, the electron energies have to be at least a few tens of TeV, but in view of the rapid energy losses it is probable that the electrons do not have the time to propagate away from their acceleration sites; hence, IC is of much less importance for the diffuse emission at those very high energies. An all-sky map above 10 TeV would provide a 'clean' view of the distribution and spectrum of cosmic-ray hadrons over the whole Galaxy. Such a skymap could provide the key to the origin of cosmic-ray hadrons, in particular when it could be combined with information on the intensity of neutrinos.

A measurement of the intensity of diffuse emission at TeV energies would be extremely valuable, provided one is able to separate truly diffuse emission from individual sources such as pulsar-wind nebulae. To date, the Milagro collaboration reports evidence of TeV-scale gamma-ray emission from the Galactic plane, in particular the Cygnus region (see Figure 5). The intensity measured with Milagro at 12 TeV is 70 Crab/sr (about 0.02 Crab/deg^2) and thus extremely sensitive to the point source content. For comparison, the intensity of the 14 new sources detected during the H.E.S.S. survey of the inner Galaxy [50], if they were unresolved, would be 17 Crab/sr above 200 GeV. Assuming the measured spectrum extends to 12 TeV, the equivalent intensity of the 14 H.E.S.S. sources at 12 TeV, which is more relevant for a comparison with the Milagro result, would be 140 Crab/sr, i.e. twice the intensity observed with Milagro. The source density in the region observed with Milagro is probably smaller, but there are also sources not seen with H.E.S.S. or known prior to the survey, and therefore a significant fraction of the Milagro result will be due to unresolved sources, and confusion is a substantial problem.

The H.E.S.S. collaboration has published a map and the spectrum of diffuse emission from the inner degree of the Galaxy, after subtracting two dominating point sources (see Figure 6). In a fit of the observed spectrum as $dN/dE \propto E^{-\gamma}$, the spectral index is $\gamma = 2.3 \pm 0.08$, much harder than expected and measured anywhere else, as cosmic ray ions with a spectrum as directly measured at earth should produce a gamma-ray spectrum with $\gamma \simeq 2.7$. The measured intensity corresponds to 590 Crab/sr at a TeV and is about the highest one may expect anywhere in the Galaxy based on the intensity distribution of GeV-band gamma rays.

2.3 What measurements are needed?

2.3.1 Supernova remnants

With multi-waveband data, it is possible to provide quantitative constraints on the particle acceleration mechanism. Because the maximum IC power output from these objects is expected to be in the TeV region, TeV observations provide information unavailable via any other means. High-resolution maps and accurate spectra of the TeV emission, when compared with data from other wavebands, will permit estimation of the magnetic field and the maximum energy of the accelerated particles. Comparison of the maps from various wavelengths will increase our understanding of the diffusion and lifetimes of the highly energetic electrons.

We stress the importance of GeV-band gamma-ray data that will be shortly provided by Fermi. However, the sensitivity of Fermi at 10–100 GeV is limited: if we extrapolate the TeV-band spectrum of RX J1713-3946 (see Fig. 2) to lower energies as $dN/dE \propto E^{-2}$, or a flat line in the figure, then we expect Fermi to detect two photons per year with energy above 100 GeV from the entire SNR. Above 10 GeV, Fermi would find 20 photons per year, so even after five years, a Fermi gamma-ray excess map would have much lower statistical accuracy than the existing H.E.S.S. map; the single-photon resolution is also worse. At energies below 10 GeV, the number of Fermi-detected photons increases, but the angular resolution deteriorates. Fermi will perform important studies of shell-type SNRs, but TeV-band measurements will provide complementary and, in many cases, richer images and spectra.

A key for any future VHE observatory will be to unambiguously disentangle the emission from electronic versus hadronic cosmic rays. Spectral studies may help arriving at a discrimination between gamma rays from electrons and those produced by hadrons, but they are not sufficient. TeV gamma rays from IC scattering of the microwave background should have a spectral shape that reflects that of synchrotron X-rays below approximately 1 keV, where the discrimination of synchrotron emission and thermal radiation of ordinary hot gas is often difficult and requires a very good angular resolution.

On the other hand, TeV gamma rays of hadronic origin reflect the spectrum of energetic nuclei at about 1–100 TeV energy. If the SNR in question accelerates hadronic cosmic rays to energies beyond the knee at 3 PeV, then we should see a continuation of the gamma-ray emission up to 100 TeV and beyond, which would be a good indication of a hadronic origin of gamma rays (see also Fig. 7). It will therefore be important to maintain a sensitivity up to and beyond 100 TeV. We also note an obvious relation to neutrino astrophysics: all gamma-ray sources at the Crab flux level that do not cut off below 100 TeV energy should be observable with neutrino detectors [36], if the gamma-ray emission arises from interactions of energetic nuclei. In the near term, only IceCube at the South Pole will be large enough to observe Galactic neutrino sources such as SNRs. Since it must look through Earth, it is very important that it be paired with sensitive gamma-ray instruments in the Northern hemisphere. The H.E.S.S. experiment and its possible successor, CTA, planned for the same site in Namibia, can observe many Southern gamma-ray sources, but they won't be paired with an adequately sensitive km^3-scale Mediterranean neutrino detector until much later. The US-led VERITAS experiment currently observes sources

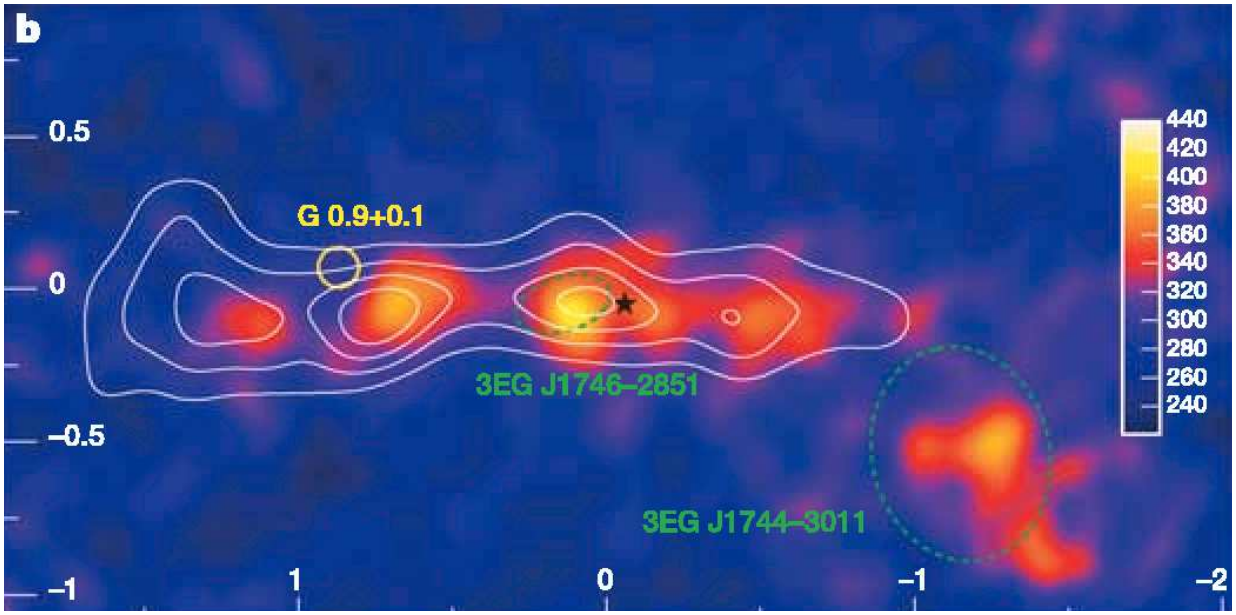

Figure 6: H.E.S.S. gamma-ray count map after subtraction of two bright point sources. The white contour lines indicate the column density of molecular gas traced by CS line emission.

in the Northern sky. A more sensitive successor could optimally exploit the scientific opportunities that lie in the synergies with IceCube. An additional future survey-type instrument could search for very extended sources and serve as a pathfinder for high-angular-resolution observations with the atmospheric Cherenkov telescopes.

High-resolution imaging of the TeV emission, combined with good spectral information is, therefore, required. TeV emission from hadronic interactions should trace the distribution of target material, while TeV emission from electrons should be well correlated with non-thermal X-ray emission (see Figs. 2). Because a significant fraction of the non-thermal X-ray intensity is organized in thin filaments, arcminute-scale resolution in the TeV band combined with the appropriate sensitivity would permit a clear separation of hadronic and leptonic emission, and would allow a direct measurement of the magnetic field strength at the forward shock of SNR, and hence a clean assessment of the efficacy of magnetic-field amplification by energetic particles. The required angular resolution is, therefore, a factor 3–5 better than what is currently achieved with H.E.S.S. and VERITAS. The sensitivity needed to derive well-defined spectra with angular resolution below 0.1° is about a factor of 10 higher than that afforded by the current generation of atmospheric Čherenkov telescopes. This is also the sensitivity likely needed to detect TeV-band gamma rays from superbubbles.

Non-detection of hadronically produced gamma rays would require either a very steep source spectrum, inconsistent with that needed to produce the local spectrum, or a greatly reduced cosmic-ray intensity, inconsistent with the energy budget for cosmic rays. Either of these possibilities would lead to serious revisions in our understanding of the origin of cosmic rays. Detection of TeV photons from hadronic cosmic rays would immediately constrain the spectrum and total energy budget of the cosmic rays, and would provide invaluable constraints on the relative acceleration efficiency of electrons and protons or other ions in shocks. This may help resolve the hundred-year-old question of the origin of cosmic rays, and will yield important information on shock physics that can be used in other shock systems. If hadronic cosmic rays are accelerated in shocks produced by the winds from OB associations, the TeV photons produced by those cosmic rays should, again,

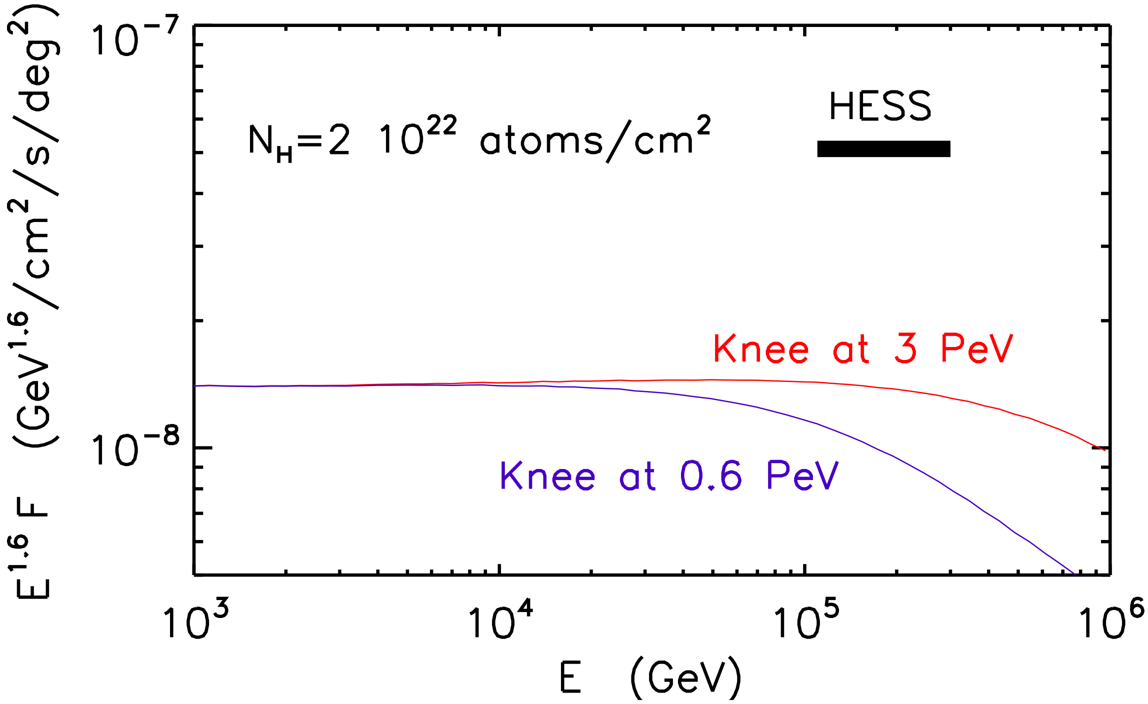

Figure 7: Shown as red line is the intensity of diffuse Galactic gamma rays, multiplied with $E^{1.6}$, for a standard cosmic-ray spectrum with the knee at 3 PeV and one of the Orion molecular clouds. If near some molecular gas complex the knee was at 0.6 PeV, the spectrum of diffuse gamma rays from that region would follow the blue line. Observing a location dependence of the knee energy would provide important clues on the nature of the knee, as do similar measurement for individual sources of cosmic rays (e.g. [54]). The black bar indicates an estimate of the current H.E.S.S. sensitivity in the 100–300 TeV band, based on published spectra of RX J1713-3946. An increase by a factor 10 in sensitivity around 200 TeV would be needed to discriminate the blue and the red curve.

trace the distribution of target material. The angular resolution requirements are similar to those discussed for supernova remnants.

2.3.2 Diffuse galactic emission

Currently most pressing questions are the following: Are cosmic rays above the knee at 3 PeV, where the spectrum of local cosmic rays considerably steepens, really Galactic in origin? What is the origin of the knee? Is the knee a source property, in which case we should see a corresponding spectral feature in the gamma-ray spectra of cosmic-ray sources, or the result of propagation, so we should observe a knee that is potentially dependent on location, because the propagation properties depend on position in the Galaxy?

Another series of questions concerns cosmic-ray electrons, whose source power is significant, but whose spectrum above 1 TeV is essentially unknown. What is the distribution of cosmic-ray electrons at energies beyond 1 TeV? Measuring electron spectra inside and outside their sources carries direct information on the particle acceleration rate, and thus on the nature of the acceleration process, as well as on the propagation properties of cosmic rays up to the knee.

Via their gamma-ray emission, we would therefore wish to independently measure

- the spectrum and flux of cosmic nuclei, which are expected to produce a gamma-ray signal that largely correlates with the density of interstellar gas. The expected intensity on a half-degree scale in, e.g., the Cygnus region is 60 Crab/sr (0.02 Crab/deg^2) in the 100 GeV–1 TeV band, and 40 Crab/sr (0.013 Crab/deg^2) above 1 TeV. Note that gamma rays with energy higher than about 100 TeV map the cosmic-ray nuclei spectrum around the knee, so an increase by at least a factor 10 in sensitivity and a good energy resolution up to and beyond 100 TeV is required to potentially prove a location dependence of the knee (see also Fig. 7). At these energies, pair production with ambient radiation can attenuate the gamma-ray signals as they travel across the Galaxy, but observations of relatively nearby complexes of molecular clouds would ensure that absorption in the Galaxy is negligible and that the intensity measurement can be made by integration over typically a square-degree in solid angle. One should note that a high angular resolution is nevertheless needed for those measurements, both to account for point-source contributions and to verify the spatial correlation of the signal with the distribution of atomic molecular gas, which is known on scales $\lesssim 0.1°$.

- the spectrum and flux of cosmic electrons, which will produce a patchy and spectrally variable gamma-ray signal that does not correlate with the gas density but may have structure on a 1–3 ° scale. The intensity is impossible to estimate without insight into the nature of the EGRET GeV excess, but may be stronger than the hadronic emission in the 100 GeV–1 TeV band.

- the point-source content of the gamma-ray signal to properly separate sources from truly diffuse emission.

None of these measurements requires a very low energy threshold, though one would wish to not have a large gap to the energy range accessible with Fermi, which will make reliable measurements up to about 50 GeV gamma-ray energy. The measurement of hadronic and, in particular, leptonic gamma rays chiefly requires advances in both the effective area and, in particular, the background rejection of future observatories. The field-of-view, in which sensitive gamma-ray observations are taken, is of minor importance, as long at it is at least 4 ° in diameter. This requirement arises from the necessity to independently determine a reliable gamma-ray zero level, which is best done by having the gamma-ray-sensitive field-of-view cover both the source, e.g. an SNR or a molecular cloud complex, and empty regions surrounding it for background measurements.

As a byproduct, one would also be interested in measuring the direct Čerenkov light of local cosmic rays, which provides unique information on the cosmic-ray composition in the PeV energy range. Although cosmic rays form the primary background for ground-based gamma-ray detectors, this background can be used to make a unique measurement of cosmic ray composition. Recently, the H.E.S.S. collaboration has measured the direct Čherenkov light of local cosmic rays [56], which provides unique information on the cosmic-ray composition in the PeV energy range [55]. This method is more direct than that used in extensive air shower experiments because it avoids the dependence on hadronic simulations in identifying the primary particle type. Also, the main air showers display strong statistical fluctuations in their evolution, thus making the observation of direct Čherenkov light a much more precise measurement. The current atmospheric Čherenkov arrays like H.E.S.S. or VERITAS lack the angular and timing resolution to fully exploit this method, and a future instrument with 0.01-degree image pixel resolution and nanosecond time resolution could further improve the determination of the cosmic-ray composition at high energies.

2.4 What is the required instrument performance?

For the study of SNR the two key instrument parameters are angular resolution and a sufficiently high count rate to effectively exploit the angular resolution. The required angular resolution can be estimated from the known angular sizes of the non-thermal X-ray filaments and of the dense molecular clouds and shock regions. For the closer SNRs, the typical angular resolution required is about one arcminute. A key point is that a sufficient number of gamma rays must be detected to make effective use of the angular resolution. The detection rate can be increased relative to current instruments either by increasing the effective area or by reducing the energy threshold. The goal should be to image several SNRs with arcminute-level resolution with a minimum of 150 events in each image bin, so reliable spectra can be reconstructed.

To maximize the scientific return for Galactic sources, a future instrument should be located at sufficiently southern latitude to give good coverage of a large fraction of the Galactic plane extending to the inner Galaxy. At the same time it is desirable that a large overlap is maintained with the coverage of neutrino experiments such as IceCube, which makes a Southern location less advantageous.

To achieve scientifically significant observations of the diffuse Galactic gamma-ray emission with the next-generation instrument, the angular resolution is important, but does not need to be as good as for observations of SNR. Mainly one needs to model and subtract individual sources. A good angular resolution is also needed to find intensity that correlates with the gas distribution.

It is mandatory to achieve a very high sensitivity for extended emission. Given that a number of emission components have to be fitted in parallel and that, at least for the diffuse emission, the data are background-dominated, a strongly improved background rejection is required to achieve the desired sensitivity. A large aperture alone appears insufficient, as it is necessary to achieve both large event numbers and a very low background contamination level.

The instrument requirements can thus be summarized as follows:

- an angular resolution of $\leq 0.02^\circ$ at 1 TeV.
- for the bright parts of SNRs at least 150 gamma rays in each image bin for a reasonable observing time.
- a sensitivity for extended emission that is significantly better than 10 Crab/sr above a TeV and better than 15 Crab/sr below a TeV.
- maintain a high sensitivity up to and possibly beyond 100 TeV.
- a good energy resolution of $\delta E/E \lesssim 15\%$ at all energies.
- a gamma-ray sensitive field-of-view of at least 4 $^\circ$ in diameter. Bigger is better, but tens of degrees are not needed.

3 Galactic compact objects

Group membership:

P. Kaaret, A. A. Abdo, J. Arons, M. Baring, W. Cui, B. Dingus, J. Finley, S. Funk, S. Heinz, B. Gaensler, A. Harding, E. Hays, J. Holder, D. Kieda, A. Konopelko, S. LeBohec, A. Levinson, I. Moskalenko, R. Mukherjee, R. Ong, M. Pohl, K. Ragan, P. Slane, A. Smith, D. Torres

3.1 Introduction

Our Galaxy contains astrophysical systems capable of accelerating particles to energies in excess of several tens of TeV, energies beyond the reach of any accelerator built by humans. What drives these accelerators is a major question in astrophysics and understanding these accelerators has broad implications. TeV emission is a key diagnostic of highly energetic particles. Simply put, emission of a TeV photon requires a charged particle at an energy of a TeV or greater. Observations in the TeV band are a sensitive probe of the highest energy physical processes occurring in a variety of Galactic objects. Galactic TeV emitters also represent the sources for which we can obtain the most detailed information on the acceleration and diffusion of high-energy particles and are, thus, our best laboratories for understanding the mechanisms of astrophysical ultra-relativistic accelerators.

Recent results from the new generation of TeV observations, primarily H.E.S.S., have revealed a large population of Galactic sources; see Fig. 8 which shows the known TeV sources in Galactic coordinates. Galactic sources now comprise a majority of the known TeV emitters with object classes ranging from supernova remnants to X-ray binaries to stellar associations to the unknown. Future TeV observations with a more sensitive telescope array will lead to the discovery of many more TeV emitting objects and significantly advance our understanding of the acceleration of the highest energy particles in the Galaxy.

3.2 Pulsar wind nebulae

Pulsar wind nebulae (PWNe) are powered by relativistic particles accelerated in the termination shock of the relativistic wind from a rotation-powered pulsar. The basic physical picture is that the rotating magnetic field of the pulsar drives a relativistic wind. A termination shock forms where the internal pressure of the nebula balances the wind ram pressure. At the shock, particles are thermalized and re-accelerated to Lorentz factors exceeding 10^6. The energy in the Poynting flux is transferred, in part, to particles. The high energy particles then diffuse through the nebula, partially confined by nebular magnetic fields, and cool as they age due to synchrotron losses, producing radio to X-ray emission, and inverse-Compton losses, producing gamma-ray emission.

Studies of PWNe address several central questions in high-energy astrophysics, the most important of which is the mechanism of particle acceleration in relativistic shocks. PWNe provide a unique laboratory for the study of relativistic shocks because the properties of the pulsar wind are constrained by our knowledge of the pulsar and because the details of the interaction of the relativistic wind can be imaged in the X-ray, optical, and radio bands. Relativistic shock acceleration is key to many astrophysical TeV sources, and PWNe are, perhaps, the best laboratory to understand the detailed dynamics of such shocks. Studies of pulsar-powered nebulae also target a number of crucial areas of pulsar astrophysics, including the precise mechanism by which the pulsar spin-down energy is dissipated, the ratio of magnetic to particle energy in the pulsar wind, the electrodynamics of the magnetosphere, and the distribution of young pulsars within the Milky Way.

Observations of TeV emission are essential to resolve these questions. Measurement of the spectrum from the keV into the TeV range allows one to constrain the maximum particle energy, the particle injection rate, and the strength of the nebular magnetic field. Observation of TeV emission from a significant set of pulsar-powered nebulae would allow us to study how the pul-

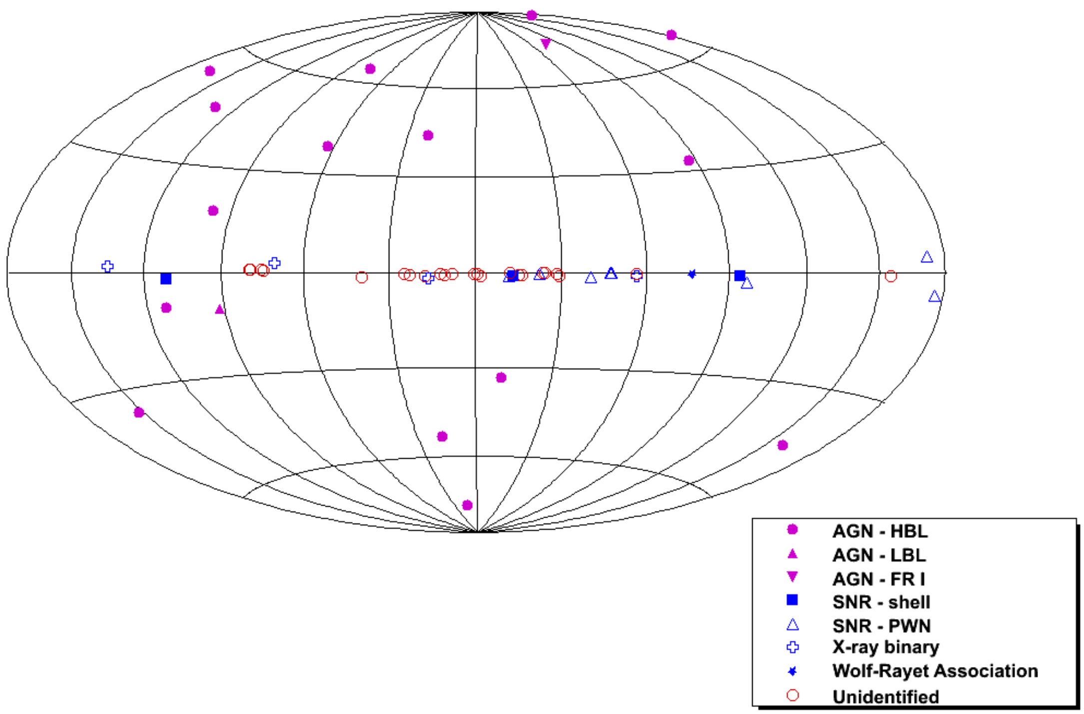

Figure 8: Known TeV emitting objects plotted in Galactic coordinates. The center of the Milky Way is at the center of the ellipse. The Galactic plane is the horizontal midplane. The symbols and colors indicate the source type. Figure courtesy of Dr. E. Hays.

sar wind varies with pulsar properties such as spin-down power and age. Detection and identification of new nebulae may also lead to the discovery of new young pulsars, particularly those lying in dense or obscured parts of the Galaxy where radio searches are ineffective because of dispersion.

PWNe have proven to be prolific TeV emitters. The Crab nebula was the first TeV source to be discovered. H.E.S.S. has recently detected a number of other Galactic sources, several of which are confirmed to be, and many more thought to be, PWNe [57]. Significantly, H.E.S.S. has discovered new PWNe that were not previously detected at other wavelengths. Furthermore, the high resolution capabilities of H.E.S.S. have allowed imaging of the first TeV jet in the PWN of PSR1509-58 [58], which is also the first astrophysical jet resolved at gamma-ray energies. Comparison of the gamma-ray jet with the one detected by Chandra in X-rays, which is less extended and has a flatter spectral index, shows that the evolution of emitting particles in the jet is consistent with synchrotron cooling. In addition, TeV imaging has provided a clearer picture of PWNe such as PSR B1823-13 and Vela X [59] that are offset from the position of the pulsar, an effect which may be due to the pressure of the reverse shock [60].

3.2.1 Measurements needed

Broadband modeling of PWNe The broadband spectrum of a PWN provides constraints on the integrated energy injected by the pulsar as well as the effects of adiabatic expansion and the evolution of the magnetic field. The spectrum consists of two components: 1) synchrotron emission extending from the radio into the X-ray and, in some cases, the

MeV band, and 2) inverse-Compton emission producing GeV and TeV photons. Emission in the TeV band originates primarily from inverse-Compton scattering of ambient soft photons with energetic electrons in the nebula. The ratio of TeV luminosity to pulsar spin-down power varies strongly between different PWN and understanding the cause of this effect will advance our understanding of the physics of PWNe.

All PWNe show spectra that are steeper in the X-ray band than in the radio band, but the nature of the spectral changes between these bands is not well understood. Synchrotron losses result in a spectral break at a frequency that depends on the age and magnetic field strength, while other spectral features can be produced by a significant change in the pulsar input at some epoch, by spectral features inherent in the injection spectrum, and by interactions of the PWN with the reverse shock from its associated supernova remnant. TeV observations provide an independent means to probe the electron energy distribution. Addition of TeV data breaks many of the degeneracies present in analysis of synchrotron emission alone and allows independent estimates of the electron energy distribution and the nebular magnetic field. TeV observations are essential to understand the PWN electron energy distribution and its evolution.

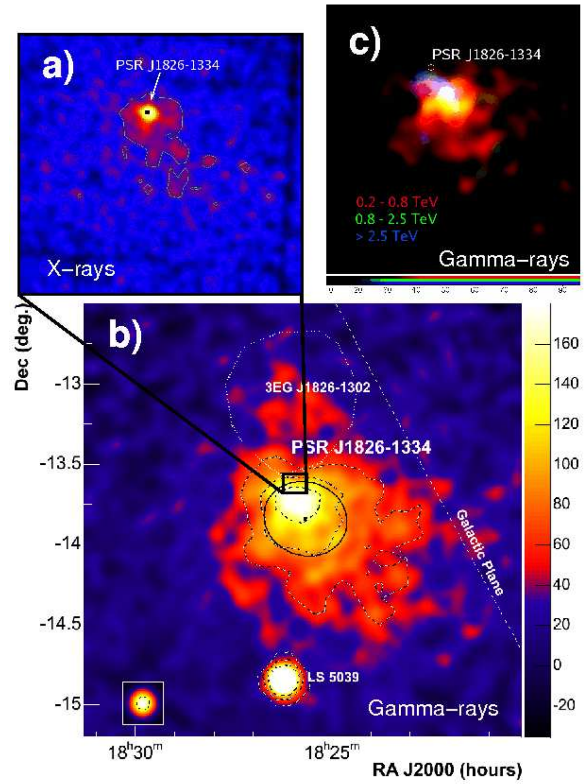

Figure 9: H.E.S.S. map of TeV emission from H.E.S.S. J1825-137 (b), X-ray image of the central part of the field showing the PWN G18.0–0.7 (a), three color image of the TeV emission showing that the nebula is the most compact at the highest energies (c). From [65].

Highly Extended PWNe Several of the recently-discovered H.E.S.S. sources appear to be PWNe, due to the presence of young radio pulsars nearby, but have unexpected morphologies. Examples include H.E.S.S. J1804-216 [61], H.E.S.S. J1825-137 [62], and H.E.S.S. J1718-385 [63]. There are two issues that require considerable further study for these sources. First, the young pulsars suggested as the engines for these nebulae are distinctly separated from the TeV centroids. The most common explanation is that the supernova remnants in which these PWNe formed (most of which are not observed, to date) are sufficiently evolved that the reverse shocks have disturbed the PWNe, as appears to be the case in Vela X, which is also observed as an extended TeV source offset from its pulsar [64]. This requires an asymmetric interaction with the reverse shock, which can occur if the SNR expands into a highly non-uniform medium, and there are suggestions that these systems may indeed be evolving in the vicinity of molecular clouds. In this scenario, the reverse shock encounters one side of the PWNe first, and the disruption leaves a relic nebula of particles that is concentrated primarily on one side of the pulsar. More sensitive TeV observations are required to produce higher fidelity maps of these nebulae, and to search for evidence of a steepening of the spectrum with distance from the pulsar.

A second and more vexing question centers on the very large sizes of these PWNe. These sources are observed to be extended on scales as large as 1° [64], significantly larger than their extent in X-rays. One possible explanation for this is that the extent of the synchrotron radiation observed in the X-ray band is confined to the region inside the magnetic bubble of particles that is sweeping up the ambient ejecta, while the IC emission is produced wherever energetic particles encounter ambient photons. If the diffusion length of these energetic particles is extremely large, they can escape the synchrotron-emitting volume, but still produce TeV gamma rays. Because these sources are relatively faint, high-quality maps of this extended emission do not yet exist. Higher sensitivity, along with somewhat improved angular resolution, are crucial for probing more deeply into the structure of these nebulae.

Jets/Magnetization X-ray observations with Chandra and XMM-Newton have revealed jet structures in a large number of PWNe. Models for the formation of these jets indicate that some fraction of the equatorial wind from the pulsar can be redirected from its radial outflow and collimated by hoop stresses from the inner magnetic field. The formation of these jets is highly dependent upon the ratio of the Poynting flux to the particle energy density in the wind. H.E.S.S. observations of PSR B1509-58 reveal an extended TeV jet aligned with the known X-ray jet. New TeV observations of similar jets should provide insight into the Poynting fraction and the physics of jet formation.

Discovery Space The recently-discovered H.E.S.S. sources that appear to be previously unknown PWNe highlight the potential for uncovering a large number of PWNe in TeV surveys. For cases where the nebula magnetic field is low, thus reducing the synchrotron emissivity, the IC emission could be the primary observable signature. An increase in sensitivity will be important to enhance the discovery space, and cameras with a large field of view would enable large surveys to be conducted. Given that some of the H.E.S.S. sources in this class are extended, improved angular resolution also holds promise both for identifying the sources as PWNe and for investigating the structure of these systems.

3.3 Pulsed emission from neutron stars

The electrodynamics of pulsars can be probed more directly via observation of their pulsed emission. The high timing accuracy achievable with pulsars has led to Nobel prize winning discoveries, but the mechanism which produces the pulsed emission, from the radio to gamma rays, is not well understood. TeV observations may provide key insights.

A key question that has pervaded pulsar paradigms over the last two decades is where is the locale of the high-energy non-thermal magnetospheric emission? Two competing models have been put forward for gamma-ray pulsars: (1) polar cap scenarios, where the particle acceleration occurs near the neutron star surface, and (2) the outer gap picture, where this acceleration arises out near the light cylinder. Data have not yet discriminated between these scenarios, and our understanding of pulsar magnetopheres has stalled because of this. For energetic young pulsars like the Crab and Vela, TeV telescopes/arrays would offer the greatest impact if the outer gap model is operable. For millisecond pulsars, TeV telescopes should provide valuable insight regardless of the emission locale. Indeed, the answer to the question may differ according to which subset of pulsars is examined.

Knowing the location of their radiative dissipation will permit the identification of the pertinent physical processes involved and open up the possibility for probing the acceleration mechanism. This could then enable refinement of pulsar electrodynamics studies, a difficult field that is currently predominantly tackled via MHD and plasma simulations. Should polar cap environs prevail as the site for acceleration, then there is a distinct possibility that pulsar observations could provide the first tests of quantum electrodynamics in strong magnetic fields. An additional issue is to determine whether there are profound differences in emission locales between normal pulsars and their millisecond counterparts. High-energy gamma-ray observations are central to distinguishing between these competing models and accordingly propelling various aspects of our knowledge of pulsar electrodynamics.

Detection of pulsed emission at TeV energies has so far been elusive. The observation of high-energy cutoffs below 10 GeV in the pulsed emission spectra of several normal pulsars with high magnetic fields by EGRET [66] has made the prospects of detecting emission at energies above 100 GeV very unlikely. Indeed, such cutoffs are predicted from magnetic pair production in polar cap models [67] and from radiation reaction limits in outer gap models [68]. However, outer gap models predict that a separate component produced by inverse Compton scattering should be detectable at TeV energies, while polar cap models do not expect such a contribution. This provides a key opportunity for distinguishing between these competing pictures. Yet, the outer gap scenario has suffered through a sequence of non-detections (e.g. see [69] for Whipple limits on the Crab's pulsed signal) in focused observations by TeV telescopes, progressively pushing the pulsed flux predictions down. In a recent addition to this litany, MAGIC has obtained constraining flux limits at 70 GeV and above to PSR B1951+32 [70], implying turnovers below around 35 GeV in the curvature/synchrotron component, thereby mandating a revision of the latest outer gap predictions of inverse Compton TeV fluxes [71].

This result highlights the importance of lowering the threshold of ground-based ACT arrays. Such saliency is even more palpable for the study of millisecond pulsars (MSPs). Polar cap model predictions can give turnovers in the 30-70 GeV range for MSPs [72], though outer gap turnovers for MSPs are actually at lower energies due to significant primary electron cooling by curvature radiation reaction. While possessing much lower magnetic fields than normal energetic young pulsars, millisecond pulsars can be expected to be as luminous in some portion of the gamma-ray band because their rapid periods imply large spin-down power. Hence, future sub-TeV observations of MSPs should significantly advance our understanding of these objects.

3.3.1 Measurements needed

What is clearly needed to advance the pulsar field is a lower detection threshold and better flux sensitivity in the sub-TeV band. The goal of lower thresholds is obviously to tap the potential of large fluxes from the curvature/synchrotron component. At the same time, greater sensitivity can provide count rates that enable pulse-profile determination at the EGRET level or better, which can then probe emission region geometry. Pulse-phase spectroscopy is a necessary and realizable goal that will enable both model discrimination and subsequent refinement. Since the current generation ACTs cannot quite reach thresholds below 70 GeV, and since the model predictions are very dependent on emission and viewing geometry, it seems that detection of very high-energy emission from millisecond and young pulsars will be unlikely for the current instruments and will require new telescopes. Hence, goals in the field are to both lower the threshold to the 30-50 GeV band, and improve the flux sensitivity by a factor of ten.

3.4 Relativistic Jets from Binaries

One of the most exciting recent discoveries in high-energy astrophysics is the detection of TeV emission from binaries systems containing a compact object, either a neutron star or black hole (see Fig. 10). TeV emission requires particles at TeV or higher energies and promises to give unique insights into the acceleration of ultrarelativistic particles in X-ray binaries. The TeV emission is found to be strongly time varying. Hence, multiwavelength (TeV, GeV, X-ray, optical, and radio) light curves will strongly constrain models of high-energy particle acceleration and interaction within these systems.

Key questions that will be addressed by TeV observations include:

• What is the composition of ultra-relativistic jets? Even though ultra-relativistic jets are ubiquitous features of compact objects, occurring in systems ranging from supermassive black holes to neutron stars, the basic question of whether

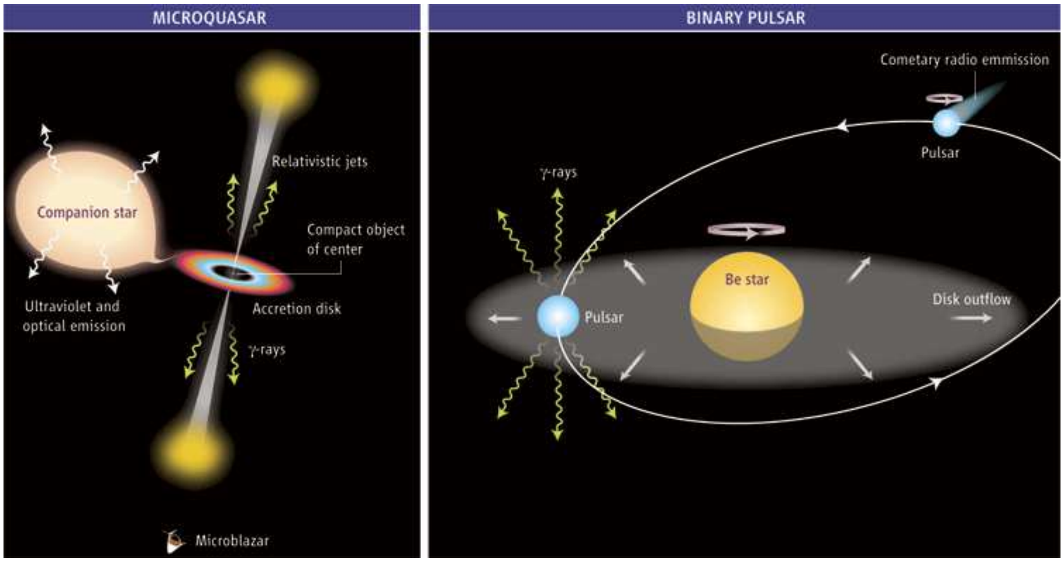

Figure 10: The two types of binaries systems producing TeV emission. The left image shows a microquasar powered by accretion onto a compact object, neutron star or black hole. The right image shows a rotation-powered pulsar (neutron star) in a binary where the relativistic wind from the pulsar leads to the production of TeV photons. From [73].

the jets are electron-positron or have a significant hadronic component remains unanswered for almost all objects. The only case with a clear signature of the composition is SS 433, in which X-ray line emission reveals the presence of iron nuclei. However, even for SS 433, the matter may be entrained from the companion star wind. This question is fundamental in understanding the physics of jet production. Measurement of the time variation of the TeV/GeV/X-ray spectrum from TeV emitting binaries has the potential to resolve this question.

- What is the total energy carried by jets? TeV emission provides a unique probe of the highest energy particles in a jet. These particles often dominate the total energy of the jet and their accurate measurement is essential in understanding the energetics of jets.
- What accelerates particles in jets? Measuring the acceleration time and the spectrum of the highest energy particles in a jet is critical for addressing this question.

3.4.1 Current Status

The first evidence that binary systems containing stellar-mass compact objects could accelerate particles to TeV energies came from observations of X-ray synchrotron radiation from the large-scale jets of XTE J1550-564 [74, 75]. The detection of deceleration in these jets suggests that the high-energy particles are accelerated by shocks formed by the collision of the jet with the interstellar medium. The acceleration is likely powered by the bulk motion of the jets. More recently, three TeV-emitting compact-object binaries have been found at high confidence. One, PSR B1259-63 contains a young, rotation-powered pulsar [76]. The nature of the other two systems, LS 5039 and LS I 61 303 [77] is less clear. A lower significance signal (3.2σ after trials) has been reported from the black hole X-ray binary Cyg X-1 [78].

PSR B1259-63 consists of a young, highly energetic pulsar in a highly eccentric, 4.3 year orbit around a luminous Be star. At periastron the pulsar passes within about 1 A.U. of its companion star. Radio and hard X-ray emission, interpreted as synchrotron radiation, from the source suggest that electrons are accelerated to relativistic energies, mostly likely by shocks produced by interaction of the pulsar wind with the outflow from the Be star [79]. However, the electron energy and magnetic field strength cannot be determined independently from the X-ray and radio data and alternative interpretations of the X-ray emission are possible. H.E.S.S. detected TeV emission from PSR B1259-63 [76]. TeV emission was detected over observations within about 80 days of periastron passage and provides unambiguous evidence for the acceleration of particles to TeV energies.

LS I +61 303, a high mass X-ray binary system located at ∼2 kpc distance which has been a source of interest for many years due to its periodic outbursts in radio and X-ray correlated with the ∼26.5 day orbital cycle and its coincidence with a COS-B and EGRET GeV gamma-ray source [80, 81, 82]. MAGIC found variable TeV emission from this source [77]. The nature of the compact object in LS I +61 303 is not well established. The identification of LS I +61 303 as a microquasar occurred in 2001 [83] when what appeared to be relativistic, precessing radio jets were discovered extending roughly 200 AU from the center of the source. However, recent repeated VLBI imaging of the binary shows what appears to be the cometary tail of a pulsar wind interacting with the wind from the companion star. This suggests that the binary is really a pairing of a neutron star and a Be main sequence star [84]. The (much) shorter orbital period of LS I +61 303, as compared to PSR B1259-63, makes the system much more accessible for observations. Also, the detection of LS I +61 303 at GeV energies will enable constraints on the modeling which are not possible for PSR B1259-63.

H.E.S.S. has detected TeV emission from the high-mass X-ray binary LS 5039 [85]. The TeV spectral shape varies with orbital phase. LS 5039/RX J1826.2-1450 is a high-mass X-ray binary. Radio jets from LS 5039 have been resolved using the Very Long Baseline Array [86, 87]. This suggests that the compact object is accreting. Optical measurement of the binary orbit also suggests a black hole, although the measurements do not strongly exclude a neutron star [80].

3.4.2 Measurements needed

It should be possible to determine the correct emission mechanism for the TeV emission in both neutron-star and black hole binaries via simultaneous multiwavelength (radio, X-ray, GeV, TeV) observations of the time variable emission. Important in this regard will be measuring how the various emission components vary with orbital phase. The key here is adequate cadence, which requires good sensitivity even for short observations. Understanding the correct emission mechanism will place the interpretation of the TeV observations on a firm footing and allow one to use them to make strong inferences about the jet energetics and the populations of relativistic particles in the jets. If the TeV emission from a given system can be shown to arise from interactions of relativistic protons with a stellar wind, then this would show that the jet contains hadrons. This would provide a major advance in our understanding of the physics of jets.

If the jets do have a significant hadronic component, then they are potential neutrino sources. The calculated neutrino flux levels, assuming a hadronic origin for the observed TeV emission, are detectable with neutrino observatories now coming on line, such as ICECUBE [88]. The detection of neutrinos from a compact object binary would be very exciting in opening up the field of neutrino astronomy and would be definitive proof of a hadronic jet.

Detailed light curves will also allow us to extract information about the interaction of the pulsar wind or black hole jet with the outflow from the stellar companion. This is a very exciting possibility which will provide a direct confrontation of magnetohydrodynamical simulations with observation and significantly advance our understanding of time-dependent relativistic shocks. The knowledge gained will be important for essentially all aspects of high-energy astrophysics. If the broad-band spectrum of PSR B1259-63 is modeled assuming that the TeV photons are produced by inverse-Compton interactions of photons from the companion star with the same population of accelerated electrons producing the synchrotron emission, then the TeV data break the degeneracy between electron energy and magnetic field and allow the magnetic field to be estimated to be ~ 1 G. This estimate is similar to the values predicted by magnetohydrodynamical simulations of the pulsar wind. Future more sensitive observation would enable measurement of the time evolution of the magnetic field.

The detection of TeV emission from a black hole binary, perhaps already accomplished, would have important implications. Acceleration of particles to TeV energies is required to produce the TeV emission. It is unlikely that such acceleration occurs in the accretion disk or corona; the particle acceleration likely occurs in the jet. The same is not true about X-ray or hard X-ray emission. This is significant ambiguity about whether any X-ray/hard X-ray spectral component can be attributed to the jet, and the strong X-ray flux from the accretion disk complicates isolation of any jet emission. This makes TeV emission a unique probe of the properties of jet and observation of TeV gamma rays from the jets of accreting stellar-mass black holes should lead to important information about the jet production mechanism.

There are two possible mechanisms for the generation of the TeV emission. Electrons accelerated to very high energies may inverse-Compton scatter photons emitted from the O6.5V companion star. However, the radiation density from the O star companion at the position of the compact object is very high and the radiative time scale is ~ 300 s. Very rapid acceleration would be required for the electrons to reach the high energies required in the face of such rapid energy loss. Instead, the TeV emission may arise from the interactions of protons accelerated in a jet with the stellar wind.

Even with the ambiguity between an electron versus proton mechanism for the TeV emission, the luminosity in the TeV band indicates an extremely powerful outflow. For very efficient, $\sim 10\%$, conversion of bulk motion into VHE radiation, the jet power must be comparable to X-ray luminosity. For more typical acceleration efficiencies at the level of a few percent, the energy in the outflow would be several times the X-ray luminosity. The result has major implications for our understanding of accretion flows near black holes. The balance between accretion luminosity and jet power is currently a major question in the study of microquasars, but estimation of the total jet kinetic energy from the observed radio luminosity is uncertain [89]. Recently, a radio/optical ring was discovered around the long-known black hole candidate Cyg X-1 [90]. The ring is powered by a compact jet and acts as a calorimeter allowing the total jet kinetic energy to be determined (the energy radiated by the jet is negligible). The jet power is between 7% and 100% of the X-ray luminosity of the system. This implies that the jet is a significant component of the overall energy budget of the accretion flow. It is remarkable that a similar inference can be made directly from the observed TeV luminosity of LS 5039. This suggests that additional TeV sources of black hole jet sources will be important in understanding the balance between accretion luminosity and jet power and the fundamental role of jet production in accretion dynamics.

A future TeV instrument with improved sensitivity would enable observation of sources at lower luminosities than those currently known. An important current question in the study of Galactic black hole is how the ratio of jet power to X-ray luminosity varies as a function of accretion rate. The observed relation between X-ray and radio flux for black holes producing compact jets [91] has been interpreted as evidence that the jet dominates the accretion flow at low accretion rates [89]. Sensitive TeV observations should enable us to directly probe this relation; the strategy would be to observe a black hole transient in the X-ray and TeV bands as it decays back to quiescent after an outburst. This would provide important information on the nature of the accretion flow at low luminosities which would impact the question of whether the low quiescent luminosities of black holes are valid evidence for the existence of event horizons and also the effect of (nearly) quiescent supermassive black holes (such as Sgr A*) on the nuclei of galaxies.

3.5 Required instrument performance

For the study of PWNe, the performance drivers are improved sensitivity, angular resolution, and extension of the spectral coverage up to 100 TeV. In order to detect large populations of fainter sources, improved sensitivity in the band around 1 TeV is essential. The properties of PWNe and the resident pulsars vary significantly and a large sample of sources is needed to fully understand these objects and it is essential to use them as probes of pulsar astrophysics. Improved angular resolution, with sufficient counting statistics to make effective use of the resolution, is needed to accurately map the TeV emission. Radio and X-ray maps are available with arcseconds precision which cannot be matched in the TeV band. However, angular resolution sufficient to produce multiple pixel maps of the TeV emission is adequate to map the distribution of high-energy particles as needed to understand their diffusion within PWNe. Extension of the spectral coverage up to 100 TeV would enable us to measure the spectral break and determine the highest energies to which particles are accelerated. This would provide fundamental information on the physics of the acceleration process.

Since many pulsar spectra cut off below 10 GeV, extension of the energy range down to the lowest energies possible is important for the study of pulsed emission. Detection of the pulsed emission from a significant number of pulsars will likely require sensitivity below 50 GeV. However, a search for the inverse Compton component predicted in outer gap models to lie at TeV energies will provide important constraints on models.

For the study of binaries, both neutron star and black hole, sensitivity is the main driver in order to detect additional sources and to study known objects with high time resolution. A factor of ten increase in sensitivity in the 'canonical' TeV band (0.2-5 TeV) should significantly increase the number of binaries which are detected in the TeV band, permitting studies of how TeV emission correlates with binary properties; i.e., spin-down power, orbital separation, and companion star type. This will provide insights into the mechanism which produces the TeV photons.

Increased sensitivity is essential to study binaries at faster cadence. All of the binary sources are variable and the differing time evolution at different wavebands will likely be the key to understanding the dynamics of particle acceleration and TeV photon production in these systems. In addition, the ability to monitor a given source on a daily basis for long periods is essential to allow studies of the dependence of the TeV flux on orbital phase. To search for jet emission from quiescent black holes, a flux sensitivity $10^{-14}\,\mathrm{erg\,s^{-1}}$ in the 0.25-4 TeV band is required.

4 Dark matter searches with a future VHE gamma-ray observatory

Group membership:

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4.1 Introduction

In the last decade, a standard cosmological picture of the universe (the ΛCDM cosmology) has emerged, including a detailed breakdown of the main constituents of the energy-density of the universe. This theoretical framework is now on a firm empirical footing, given the remarkable agreement of a diverse set of astrophysical data [92, 93]. In the ΛCDM paradigm, the universe is spatially flat and its energy budget is balanced with ∼4% baryonic matter, ∼26% cold dark matter (CDM) and roughly 70% dark energy.

While the dark matter has not been directly detected in laboratory experiments, the gravitational effects of dark matter have been observed in the Universe on all spatial scales, ranging from the inner kiloparsecs of galaxies out to the Hubble radius. The Dark Matter (DM) paradigm was first introduced by Zwicky [95] in the 1930s to explain the anomalous velocity dispersion in galaxy clusters.

In 1973, Cowsik and McClelland [96] proposed that weakly-interacting massive neutrinos could provide the missing dark matter needed to explain the virial mass discrepancy in the Coma cluster. However, since neutrinos would be relativistic at the time of decoupling, they would have a large free-streaming length. While neutrino dark matter would provide an explanation for structure on the scale of clusters, this idea could not explain the early formation of compact halos that appear to have seeded the growth of smaller structures, such as galaxies.

This observation motivated the concept of cold dark matter (CDM) consisting of weakly interacting massive particles (WIMPs) with rest energy on the order of 100 GeV that were nonrelativistic (cold) at the time of decoupling. CDM would first form very small, dense structures that coalesced into progressively larger objects (galactic substructure, galaxies, then galaxy clusters and superclusters) in a bottom-up scenario known as hierarchical structure formation. A plethora of diverse observations suggests the presence of this mysterious matter: gravitational lensing, the rotation curves of galaxies, measurements of the cosmic microwave background (CMB), and maps of the large-scale structure of galaxies.

Measurements of the CMB have been the key to pinning down the cosmological parameters; the angular distribution of temperature variations in the CMB depends on the power spectrum of fluctuations produced in the inflationary epoch and subsequent acoustic oscillations that resulted from the interplay of gravitational collapse and radiation pressure. These acoustic peaks contain information about the curvature and expansion history of the universe, as well as the relative contributions of baryonic matter, dark matter and dark energy. Combined with measurements of the large-scale distribution of galaxies, as mapped by the Sloan Digital Sky Survey (SDSS) and the 2dF Galaxy Redshift survey, these data can be well described by models based on single field inflation.

Observations of galactic clusters continue to be of central importance in understanding the dark matter problem. Recent compelling evidence for the existence of particle dark matter comes from the analysis of a unique cluster merger event 1E0657-558 [97]. Chandra observations reveal that the distribution of the X-ray emitting plasma, the dominant component of the visible baryonic matter, appears to be spatially segregated from the gravitational mass (revealed by weak lensing data). This result provides strong evidence in favor of a weakly-interacting-particle dark matter, while contradicting other explanations, such as modified gravity.

The primordial abundances of different particle species in the Universe are determined by as-

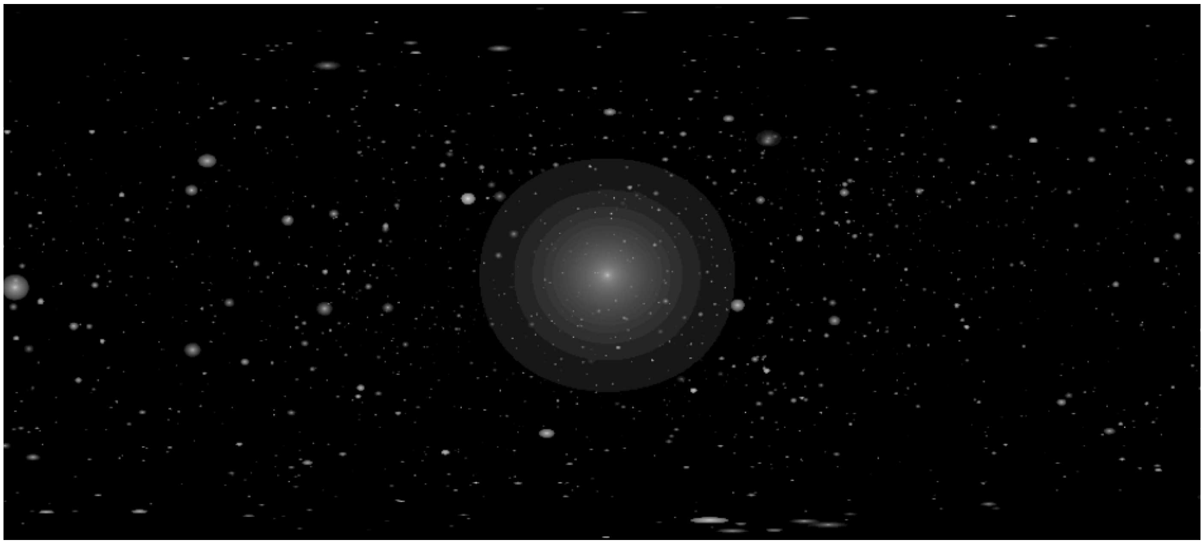

Figure 11: Simulated appearance of the gamma-ray sky from neutralino annihilation in the galactic halo plotted as the intensity in galactic coordinates [94]. The galactic center appears as the bright object at the center of the field of view. If the sensitivity of a future ACT experiment were high enough, a number of the other galactic substructures visible in this figure could be detected with a ground-based gamma-ray experiment.

suming that dark matter particles and all other particle species are in thermal equilibrium until the expansion rate of the Universe dilutes their individual reaction rates. Under this assumption (which provides stunningly accurate estimates of the abundance of light elements and standard-model particles), particles that interact weakly fall out of equilibrium sooner, escaping Boltzmann suppression as the temperature drops, and hence have larger relic abundances in the current universe. While a weakly-interacting thermal relic provides an appealing and well-constrained candidate for the dark matter, nonthermal relics such as axions or gravitinos, resulting from the decay of other relics, can also provide contributions to the total matter density or even provide the dominant component of the dark matter.

Just as there is an unseen component of the universe required by astrophysical observations, there are compelling theoretical arguments for the existence of new particle degrees of freedom in the TeV to Planck scale energy range. In particle physics, a solution to the so-called hierarchy problem (the question of why the expected mass of the Higgs particle is so low) requires new physics. An example is provided by supersymmetry, a symmetry in nature between Fermions and bosons, where the supersymmetric partners of standard model particles lead to cancellations in the radiative corrections to the Higgs mass. The hierarchy problem in particle physics motivates the existence of new particle degrees of freedom in the mass range of 100 GeV to TeV scale. It is a remarkable coincidence that if dark matter is composed of a weakly interacting elementary particle with an approximate mass of this order (i.e., on the scale of the weak gauge bosons $\sim$ 100 GeV), one could naturally produce the required cosmological density through thermal decoupling of the DM component. To make a viable candidate for the dark matter, one more ingredient is required; the decay of such a particle must be forbidden by some conserved quantity associated with an, as yet, undiscovered symmetry of Nature so that the lifetime of the particle is longer than the Hubble time.

In supersymmetry, if one postulates a conserved quantity arising from some new symmetry (R-parity), the lightest supersymmetric particle (LSP) is stable and would provide a natural candidate for the dark matter. In fact, R-parity conservation is introduced into supersymmetry not to solve the dark matter problem, but rather to ensure the stability of the proton. In many regions of supersymmetric parameter space, the LSP is the neutralino, a Majorana particle (its own antiparticle) that is the lightest super-symmetric partner to the electroweak and Higgs bosons.

For a subset of the supersymmetric parameter space, these particles could be within the reach of experimental testing at the Large Hadron Collider (LHC) (if the rest mass is below about 500 GeV) [98] or current or future direct detection experiments XENON-I,II [99], GENIUS [101, 100] ZEPLIN-II,III,IV [102], SuperCDMS[103], and EDELWEISS-I,II[105] (if the nuclear recoil cross-section is sufficiently large). While it is possible that the LHC will provide evidence for supersymmetry, or that future direct detection experiments will detect a clear signature of nuclear-recoil events produced by dark matter in the local halo, *gamma-ray observations provide the only avenue for measuring the dark matter halo profiles and illuminating the role of dark matter in structure formation.*

Neutralinos could also be observed through other indirect astrophysical experiments searching for by-products of the annihilation of the lightest supersymmetric particle, such as positrons, low-energy antiprotons, and high-energy neutrinos. Since positrons and antiprotons are charged particles, their propagation in the galaxy suffers scattering off of the irregular inter-stellar magnetic field and hides their origin. Electrons with energy above $\sim$10 GeV suffer severe energy losses due to synchrotron and inverse-Compton radiation, limiting their range to much less than the distance between Earth and the galactic center. However, cosmic-ray observations could provide evidence for local galactic substructure through characteristic distortions in the energy spectra of these particles. Detection of electrons from dark matter annihilation thus depend critically on large uncertainties in the clumpiness of the local halo. Neutrinos would not suffer these difficulties and, like photons, would point back to their sources. But given the very low detection cross section compared with gamma-rays, the effective area for a $\sim$km^3 neutrino experiment is many orders of magnitude smaller than for a typical ground-based gamma-ray experiment. While detection of neutrinos directly from discrete sources (e.g., the Galactic center) would be difficult for the current generation of neutrino detectors there is a reasonable prospect for detection of neutrinos from WIMPs s in the local halo that are captured by interactions with the earth or sun where they might have sufficient density to give an observable neutrino signal. Compared with all other detection techniques (direct and indirect), γ-ray measurements of dark-matter are unique in going beyond a detection of the local halo to providing a measurement of the actual distribution of dark matter on the sky. Such measurements are needed to understand the nature of the dominant gravitational component of our own Galaxy, and the role of dark matter in the formation of structure in the Universe.

In other regions of supersymmetric parameter space, the dark matter particle could be in the form of a heavy scalar like the sneutrino, or Rarita-Schwinger particles like the gravitino. In general, for gravitino models, R-parity need not be conserved and gravitinos could decay very slowly (with a lifetime on the order of the age of the universe) but could still be visible in gamma-rays [106]. Supersymmetry is not the only extension to the standard model of particle physics that provides a dark matter candidate, and there is no guarantee that even if supersymmetry is discovered it will provide a new particle that solves the dark matter problem. Other extensions of the standard model involving TeV-scale extra dimensions, include new particles in the form of Kaluza-Klein partners of ordinary standard-model particles. The lightest Kaluza-Klein particle (LKP) could be stable and hence provide a candidate for the dark matter if one invokes an absolute symmetry (KK parity conservation) resulting from momentum conservation along the extra dimension. The mass of the lightest Kaluza-Klein particle (e.g, the $B^{(1)}$ particle corresponding to the first excitation of the weak hypercharge boson) is related to the physical length scale of the extra dimension and could be on the TeV-scale (but not much smaller) and provide a viable CDM candidate. The $B^{(1)}$ is expected to annihilate mainly to quarks or charged leptons accompanied by an internal bremsstrahlung photon by the process $B^{(1)} + B^{(1)} \to l^+ + l^- + \gamma$ [107]. The high energy of the LKP ($\gtrsim$1 TeV), and very-hard spectrum gamma-ray production make ground-based gamma-ray and high-energy cosmic-ray electron measurements promising avenues for discovery.

As an interesting aside, TeV-scale extra dimensions may also manifest themselves in a dispersion in the propagation velocity of light in extragalactic space [108]. Observations of the shortest flares, at the highest energies from the most distant objects can place tight constraints on theories with large extra dimensions. Such constraints have already been produced by TeV measurements [109] and could be dramatically improved with a future higher-sensitivity gamma-ray instrument, capable of detecting shorter flares from distant AGNs and GRBs. Thus, ground-based TeV gamma-ray astronomy probes TeV-scale particle physics both by providing a possible avenue for detection of a Kaluza-Klein particle and by constraining the the TeV^{-1}-scale structure of space-time from gamma-ray propagation effects.

A new class of theories (the so-called "little Higgs" or LH models) has been proposed to extend the standard model to the TeV scale and offer an explanation for the lightness of the Higgs. The LH models predict a light (possibly composite) Higgs boson as well as other TeV-scale particles that could provide candidates for the dark matter in the ~100 GeV or $\gtrsim$500 GeV mass range [110]. However, only a small subset of the LH models have weak-scale masses and interactions together with a symmetry principle that protects the stability of the particle on a lifetime comparable to the age of the universe. In fact, for the composite Higgs, the particles (like their analog, the neutral pion) could decay with relatively short lifetimes. Still, this class of models (like other new physics at the TeV scale) could provide a viable dark matter candidate with an observable gamma-ray signature.

The recent discoveries of neutrino mass from measurements of atmospheric and solar neutrinos may also have a bearing on the prospects for gamma-ray detection of dark-matter. While the primordial density of light standard-model (SM) neutrinos ν_e, ν_μ and ν_τ will provide a very small hot-dark-matter contribution to the energy budget of the universe, they are ruled out as candidates for the CDM component needed to explain structure formation. However, a new heavy neutrino (or the superpartner thereof) may provide a viable candidate for the CDM. Krauss, Nasri and Trodden [111] proposed that a right-handed neutrino with TeV mass could play a role in giving masses to otherwise massless standard model neutrinos through high-order loop corrections. This model is a version of the Zee model [112] that has been successfully applied to results on solar and atmospheric neutrino observations to explain the observed parameters of the mass and mixing matrix. A discrete Z_2 symmetry, and the fact that the right-handed Majorana neutrino N_R is typically lighter than the charged scalars in the theory, make the massive neutrino stable, and a natural dark matter candidate [113]. Direct annihilation to a

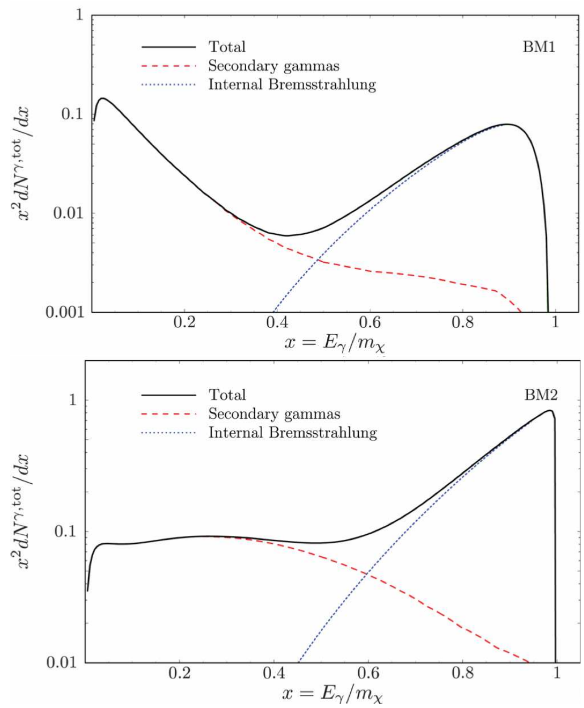

Figure 12: Continuum emission from neutralino annihilation from mSUGRA models.

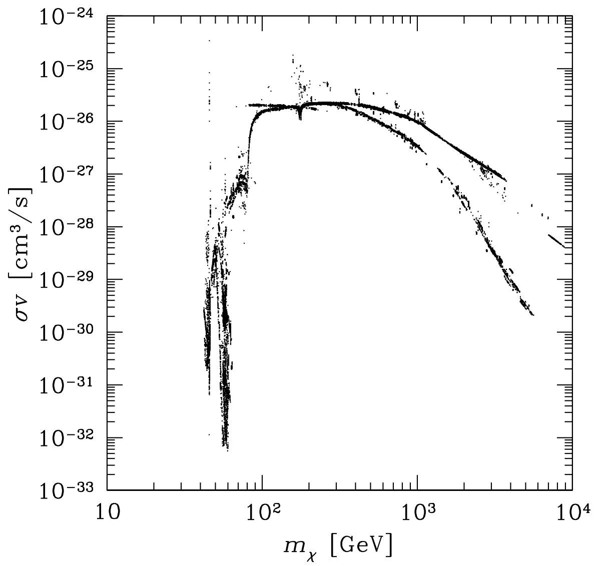

Figure 13: Scatter plot of neutralino annihilation cross section versus neutralino mass for supersymmetric models that satisfy accelerator and WMAP constraints. A typical cross-section (assumed in our estimates) is $\sigma v \approx 2 \times 10^{-26}\mathrm{cm}^3\mathrm{s}^{-1}$.

gamma-ray line $N_R N_R \rightarrow \gamma\gamma$ with a cross-section $\langle \sigma_{N_R N_R \rightarrow \gamma\gamma} v \rangle \approx 10^{-29}\mathrm{cm}^3\mathrm{s}^{-1}$ is at the limit of detectability and direct annihilation to charged leptons is also expected to give a very small cross-section. However, [113] have shown that internal bremsstrahlung can give rise to an observable gamma-ray continuum from decays to two leptons and a gamma-ray $N_R N_R \rightarrow l^+ l^- \gamma$. The three-body final state gives rise to a very hard spectrum that peaks near the N_R mass, then drops precipitously. Unlike direct annihilation to leptons, this non-helicity-suppressed process can have a large cross-section, with an annihilation rate a factor of α/π (where α is the fine structure constant) times the annihilation rate at freeze-out (with cross section $\langle \sigma v \rangle \approx 3 \times 10^{-26}\mathrm{cm}^3\mathrm{s}^{-1}$), and orders of magnitude lager than the helicity-suppressed two-body $N_R N_R \rightarrow l^+ + l^-$ rate typically considered in the past [113].

Recently, Bringmann, Bergström and Edsjö [114] have pointed out that internal-bremsstrahlung process could also play a role in neutralino annihilation, and in some cases result in a large enhancement in the continuum gamma-ray signal for certain model parameters. Fig. 4.1 shows the continuum emission from neutralino annihilation from mSUGRA models with particularly pronounced IB features, that could be observed in the gamma-ray spectrum. There are a number of different particle physics and astrophysical scenarios that can lead to the production of an observable gamma-ray signal with a spectral form that contains distinct features that can be connected, with high accuracy, to the underlying particle physics.

In what follows, we focus on predictions for the neutralino. While we show detailed results for the specific case of SUSY models and the neutralino, for any theory with a new weakly interacting thermal relic (e.g., the LKP) the model parameter space is tightly constrained by the observed relic abundance and hence the results for the overall gamma-ray signal level are fairly generic for any WIMP candidate. In the case of neutralino dark matter, the cross-sections for annihilation have been studied in detail by a number of groups. Fig. 13 shows the cross-section calculated for a range of parameters in supersymmetric parameter space as a function of mass. Only points that satisfy accelerator constraints and are compatible with a relic abundance matching the WMAP CMB measurements are shown. At high energies, the neutralino is either almost purely a Higgsino (for mSUGRA) or Wino (for anomaly-mediated SUSY breaking) resulting in the relatively narrow bands. Thus, the annihilation cross-section predictions for gamma-ray production from higher energy (∼100 GeV–TeV) candidates are well constrained, with the particle-physics uncertainty contributing ∼ one order of magnitude to the range of the predicted gamma-ray fluxes.

We elaborate further on the potential of γ-ray experiments to play a pivotal role in identifying the dark matter particle and in particular, how a next-generation γ-ray experiment can in fact provide information on the actual formation of structure in the Universe.

4.2 Dark Matter Annihilation into γ-rays, and the uncertainties in the predicted flux

For any of the scenarios that have been considered, the dark-matter particle must be neutral and does not couple directly to photons, however most annihilation channels ultimately lead to the production of photons through a number of indirect processes. While the total cross-section for gamma-ray production is constrained by the measured relic abundance of dark matter, the shape of the gamma-ray spectrum is sensitive to the details of the specific particle-physics scenario. Summarizing the previous discussion, dark matter annihilation may yield photons in three ways: (1) by the direct annihilation into a two-photon final state (or a $Z^0\gamma$ or $H\gamma$ final state) giving a nearly monoenergetic line, (2) through the annihilation into an intermediate state (e.g. a quark-antiquark pair), that subsequently decays and hadronizes, yielding photons through the decay of neutral pions and giving rise to a broad featureless continuum spectrum or (3) through internal-bremsstrahlung into a three-particle state, e.g. $\chi\chi \rightarrow W^+W^-\gamma$ yielding gamma-rays with a very hard spectrum and sharp cutoff. The cross section for the direct annihilation into two photons, or a photon and Z^0 are loop-suppressed and can be at least 2 orders of magnitude less than the processes that lead to the continuum emission. However, for some cases of interest (e.g., a massive Higgsino) the annihilation line can be substantially enhanced. Also, in the next-to-minimal supersymmetric standard model (NMSSM) with an extended Higgs sector, one-loop amplitudes for NMSSM neutralino pair annihilation to two photons and two gluons, extra diagrams with a light CP-odd Higgs boson exchange can strongly enhance the cross-section for the annihilation line. Such models have the added feature of providing a mechanism for electroweak baryogenesis [115]. By combining Fermi measurements of the continuum, with higher energy constraints from ground-based ACT measurements, one can obtain constraints on the line to continuum ratio that could provide an important means of discriminating between different extensions to minimal supersymmetry or other dark matter scenarios

In general, the flux of γ-rays from a high-density annihilating region can be written as

$$\frac{dN_\gamma}{dAdt} = L\mathcal{P} \tag{1}$$

where,

$$L = \frac{1}{4\pi}\int_{\rm LOS} \rho^2(r)dl \tag{2}$$

contains the dependence to the distribution of dark matter, and

$$\mathcal{P} = \int_{E_{th}}^{M_\chi} \sum_i \frac{\langle\sigma v\rangle_i}{M_\chi^2}\frac{dN_{\gamma,i}}{dE}\,dE \tag{3}$$

is the particle physics function that contains the detailed physical properties of the dark matter particle. The sum over the index i represents the sum over the different photon production mechanisms. (In Eq. 2, M_χ is the neutralino mass, l is the line-of-sight distance while r is the radial distance from the center of the halo distribution. Note that this definition of L is similar to the definition of the J-factor used elsewhere in the literature (e.g., [121])

Given the fact that supersymmetry has not been detected yet, the uncertainty in the value of $\mathcal{P}$ is rather large. Sampling of the available supersymmetric parameter space reveals that the uncertainty in cross sections can be as large as 5 orders of magnitude if one covers the entire mass range down that extends over several orders of magnitude (see Fig. 13), but collapses considerably for $M_\chi \gtrsim$100 GeV. For supersymmetric dark matter, $\mathcal{P}$ can take a *maximum* value of approximately $\mathcal{P} \approx 10^{-28}\,\mathrm{cm^3s^{-1}GeV^{-2}}$ when $M_\chi \approx 46\,\mathrm{GeV}$, $\sigma v = 5\times10^{-26}\,\mathrm{cm^3s^{-1}}$ and $E_{\rm th} = 5\,\mathrm{GeV}$ (with a more typical value of $\approx 2\times10^{-26}\,\mathrm{cm^3s^{-1}}$ at energies between 100 GeV and 1 TeV . On the other hand, for a threshold energy of $E_{\rm th} = 50\,\mathrm{GeV}$ and a particle mass of $M_\chi \approx 200\,\mathrm{GeV}$, the value is $\mathcal{P} \approx 10^{-31}\,\mathrm{cm^3s^{-1}GeV^{-2}}$.

It is important to emphasize that even though the actual value of $\mathcal{P}$ from supersymmetry can be orders of magnitude smaller, in theories with universal extra dimensions, both the cross section into a photon final state and the mass of the particle can actually be higher than this value.

The quantity L, on the other hand, contains all the information about the spatial distribution of dark matter. Specifically, L is proportional to the line of sight (LOS) integration of the square of the dark matter density. Dissipationless N-body simulations suggest the density profiles of dark matter halos can be described by the functional form

$$\rho(\tilde{r}) = \frac{\rho_s}{\tilde{r}^{\gamma}(1+\tilde{r})^{\delta-\gamma}} \quad (4)$$

where $\tilde{r} = r/r_s$ (e.g., [116, 117]).

The quantities ρ_s and r_s are the characteristic density and radius respectively, while γ sets the inner, and δ the outer slope of the distribution. Recent simulations suggest that $\delta \approx 3$, while the value of γ has a range of values, roughly $0.7 \leq \gamma \leq 1.2$ down to $\sim 0.1\%$ of the virial radius of the halo [118, 119]. A change in the value of the inner slope γ between the values of 0.7 and 1.2 for a fixed halo mass results in a change in the value of L that is roughly 6 times smaller or higher respectively [120]. The values of ρ_s and r_s for a dark matter halo of a given mass are obtained if one specifies the virial mass and concentration parameter. In general ρ_s (or the concentration parameter) depends solely on the redshift of collapse, while r_s depends on both the mass of the object as well as the redshift of collapse. In many previous studies the "fiducial" halo profile is that of Navaro, Frenck and White (NFW; [116]) derived from an empirical fit to the halo profile determined by N-body simulations and corresponding to Eq. 4 with $\delta = 3$ and $\gamma = 1$.

The main difficulty in estimating the value of L for a dark matter halo is due to the unknown density profiles in the regions from which the majority of the annihilation flux is emitted. Experimental data on the inner kiloparsec of our Galactic (or extragalactic) halos is sparse and theoretical understanding of these density profiles is limited by our lack of knowledge about the initial violent relaxation in dark matter halos, and the complicated physics behind the evolutionary compression of DM during the condensation of baryons in galactic cores. Both processes still lack a complete theoretical understanding. The uncertainty in the first is due to the unknown spectrum of density fluctuations at small spatial scales and difficulties of predicting their evolution in high resolution numerical simulations. The uncertainty in the second is due to the complexity of the gravitational interaction of the dark matter with the dissipative baryonic matter on small scales and in regions of high density. Experimentally, measurements of rotation curves and stellar velocity dispersion are limited by finite angular resolution and geometric projection effects. While progress is being made on both theoretical and experimental fronts, large uncertainties remain.

4.3 Targets for Gamma-Ray Detection

The Galactic center has been considered the most promising target for the detection of dark matter annihilation, with a flux more than an order of magnitude larger than any potential galactic source (e.g., [121]). The detection of γ-rays from the region of Galactic Center by the Whipple and H.E.S.S. collaborations [122, 123] can, in principle, include a contribution from annihilating dark matter [124]. While the flux and spectra of the Whipple and HESS detections are in agreement, the Cangaroo-II group reported the detection of high-energy gamma-ray emission from the GC region [188], with a considerably softer spectrum that now appears to be a transient effect (due to a variable source, or spurious detection) in view of the latest, detailed HESS results.

In Ref. [125] the possibility of interpreting the GR data from the GC in terms of WIMP pair annihilations was analyzed in full generality. Examples of fits to the HESS data with a Kaluza-Klein (KK) $B^{(1)}$ DM particle, with WIMPs annihilating into W^+W^- in 100% of the cases and with the best possible combination of final states, namely $\sim 30\%$ into $b\bar{b}$ and $\sim 70\%$ into $\tau^+\tau^-$ are shown in fig. 14. Those options give a χ^2 per degree of freedom of around 1.8, 2.7 and

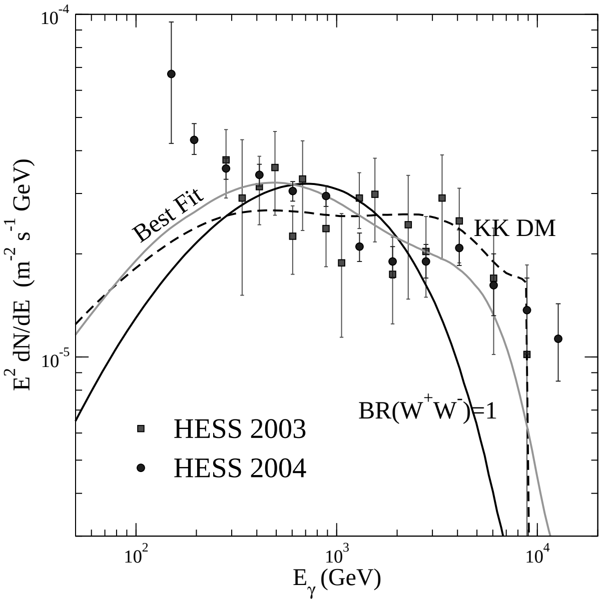

Figure 14: The HESS 2003 (grey squares) and HESS 2004 (filled circles) data on the flux of GR from the GC, and the best fit to those data with a KK $B^{(1)}$ pair-annihilating lightest KK particle (dashed line), with a WIMP annihilating into a W^+W^- pair (black solid line), and with the best WIMP spectral function fit (light grey line).

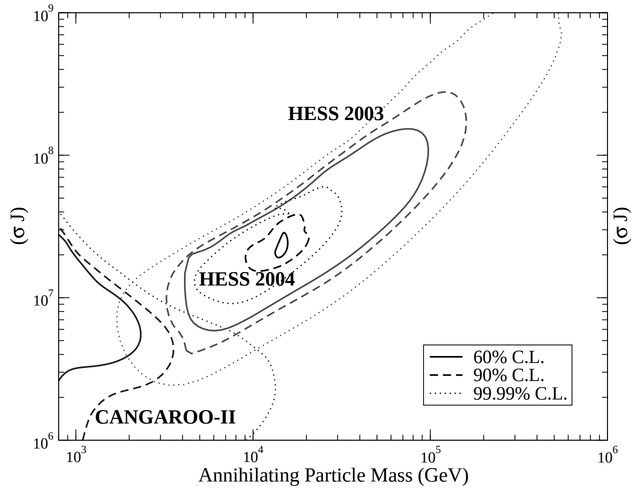

Figure 15: Iso-confidence-level contours of "*best spectral functions*" fits to the Cangaroo-II and to the 2003 and 2004 HESS data, in the plane defined by the annihilating particle mass and by the quantity (σJ).

1: only the best-fit model is found to be statistically viable.

Using the Galactic-center data and assuming that the observed gamma-ray emission arises from dark-matter annihilation, Profumo [125] derived confidence intervals for the product of the total annihilation cross-section σ and the J-factor (characterizing the astrophysical uncertainty from the halo density profile) versus the neutralino mass m_χ. Iso-confidence-level contours in the $(m_\chi, (\sigma J))$ plane are shown in fig. 15. From the figure, it is clear that a dark-matter origin for the emission requires a DM mass range between 10-20 TeV. Further, a value of $(\sigma J) \approx 10^7$ implies either a very large astrophysical boost factor ($\approx 10^3$ larger than what expected for a NFW DM profile), or a similar enhancement in the CDM relic abundance compared with the expectations for thermal freeze-out

Ref. [125] showed that some supersymmetric models can accommodate large enough pair annihilation cross sections and masses to both give a good fit to the HESS data and thermally produce the right DM abundance even though, from a particle physics point of view, these are not the most natural models. An example is a minimal anomaly-mediated SUSY breaking scenario with non-universal Higgs masses. For some choices of model parameters, such a dark matter particle could even be directly detected at ton-sized direct detection experiments, even though the lightest neutralino mass is in the several TeV range [125].

However, the interpretation is particularly complicated since the center of our own Milky Way galaxy has a relatively low mass-to-light ratio and is dominated by matter in the form of a central massive black hole and a number of other young massive stars, supernova remnants and compact stellar remnants. Moreover, the lack of any feature in the power-law spectrum measured b HESS, and the extent of this spectrum up to energies above 10 TeV makes a dark-matter interpretation difficult.

A way of dealing with this background is to exclude the galactic center source seen by HESS, and instead look at an annulus about the Galactic center position [126, 127]. Even though the background grows in proportion to the solid angle of the annular region (and the sensitivity degrades as the square-root of this solid angle) for a sufficiently shallow halo profile, the signal-to-noise ratio for detection continues to grow out to large angles. Moreover, any component of diffuse contaminating background falls off more steeply as a function of latitude than the annihilation of the smooth component of the dark matter halo. This result may even be enhanced by the presence of other bound high density structures within the inner parts of the Milky Way [128].

We make a conservative estimate of the signal from an annulus centered on the galactic center. For this calculation, we assume that the Milky Way halo has a profile as given by Navaro, Frenck and White [116] (NFW profile) with a scale radius of $r_s = 21.7$ kpc and a central density of $\rho_s = 5.38\,M_\odot\,\mathrm{kpc}^{-3}$ from Fornengo et al. [129]. To be somewhat more conservative, in light of more recent N-body simulations that show a flattening of the inner halo profile, we assume a 10 pc constant density core. The minimum angle for the annular region is set by the assumed PSF for a future instrument. We assume that the flux from the point source at the GC (or from the diluted contribution from the galactic ridge emission) will fall below 10% of the GC value, 0.2 deg from the position of Sgr A*. The optimum angular radius for the outer bound on the annulus is 12 deg (see [127] for details), somewhat beyond the largest field of view envisioned for a future imaging ACT (with a more realistic value of 6-8 deg). As shown in Fig. 16, Fermi might also have adequate sensitivity and angular resolution to detect the continuum emission and separate this from the other point sources. If the neutralino mass is large enough (above several TeV) and one chooses favorable parameters for the annihilation cross-section and density, EAS detectors have the large field-of-view required to observe such extended sources as well as other regions of emission along the galactic plane. However, these detectors lack the good angular and energy resolution to separate this emission from other point sources and would require follow-up observations by more sensitive instruments such as imaging ACT arrays. For the IACT sensitivity, we assume that we have an instrument with effective area of 1 km^2, an exposure of 200 hrs, and that the background comes from cosmic-ray electrons, cosmic-ray atmospheric showers, and diffuse gamma-rays following the method given in Ref. [121]. For the diffuse gamma-ray spectrum, we take the EGRET diffuse flux, and assume that it continues with a relatively hard $\sim E^{-2.5}$ spectrum up to TeV energies. We also assume that the largest practical angular radius of the annular region is 2 deg, a reasonable value for a moderately wide-field-of view future instrument. The simulated spectrum is calculated for a typical annihilation cross section of $\langle\sigma v\rangle = 2\times10^{-26}\mathrm{cm}^3\mathrm{s}^{-1}$ and for an arbitrary set of branching ratios corresponding to 50% $\tau\bar{\tau}$, 50% $b\bar{b}$ and a line-to-continuum ratio of 6×10^{-3}. Assuming a 15% energy resolution, we obtain the simulated spectrum shown in Fig. 16. This demonstrates that a future instrument could observe a spectral signature of dark matter annihilation in the region around the GC, above the residual astrophysical backgrounds. To search for gamma-ray emission from dark-matter annihilation in the Galactic center region, the requirements for the future instrument include: a large effective area ($\sim$1 km^2), a moderately large field of view ($\gtrsim 7^\circ$ diameter), a good energy resolution ($\lesssim$ 15%), a low energy threshold ($\lesssim$ 50 GeV), excellent angular resolution to exclude contributions from astrophysical point-sources ($<\sim 0.1^\circ$) and a location at low geographic latitude (preferably in the southern hemisphere) for small-zenith-angle low-threshold measurements of the GC region.

However, given the large backgrounds in our own galaxy, the observation of a wider class of astrophysical targets is desirable. A future km^2 ACT array should, for the first time, have the sensitivity required to detect extragalactic sources such as Dwarf galaxies, without resorting to very optimistic assumptions about the halo distribution. The VERITAS collaboration previously undertook such an observing program with the Whipple 10m telescope and reported upper limits for several extragalactic targets (M33, Ursa Minor & Draco dwarf galaxies, M15) [130, 131, 132]. The HESS group published limits on the Sagittarius dwarf galaxy and the resulting constraints on the halo models [133]. However, more sensitivity is required to detect a more generic annihilation flux from such sources.

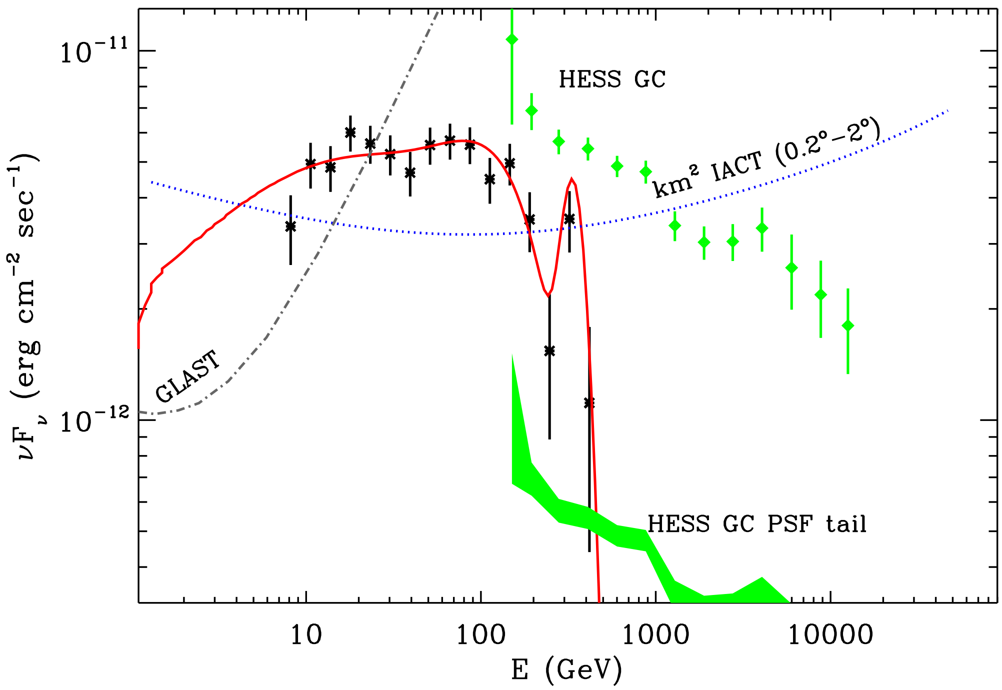

Figure 16: Gamma-ray spectrum from dark matter annihilation in an annulus between 0.2° and 2° about the Galactic center assuming an NFW halo with a central density of $\rho_s = 5.4 \times 10^6\, M_\odot/\mathrm{kpc}^3$ and a scale radius of $r_s = 21.7\,\mathrm{kpc}$. We show the HESS spectrum of the point source near the GC, and 10% of this value assumed to bleed into the annulus from the tails of the gamma-ray point-spread-function. Here we assume a 200 hour exposure of a a km^2 IACT instrument. The reduced sensitivity, compared with that for a point source, comes from integrating the hadronic, electron, and diffuse gamma-ray background over the relatively large solid angle of the annulus.

4.3.1 Dwarf Spheroidals

Dwarf spheroidal (dSph) systems are ideal dark matter laboratories because astrophysical backgrounds and baryon-dark matter interactions are expected not to play a major role in the distribution of dark matter. Furthermore, the mass–to–light ratio in dSphs can be very large, up to a few hundred, showing that they are largely dark-matter dominated systems. Numerous theoretical studies point to the potential for detecting dark matter annihilation in dwarf spheroidal galaxies or galaxies in the local group based on rough assumptions of the distribution of dark matter [125, 134, 135, 137, 138]. However, with the advent of more data on the stellar content of dSphs, it has recently been possible to perform a likelihood analysis on the potential dark matter profiles that these systems could posses. Under the assumption that dSphs are in equilibrium, the radial component of the stellar velocity dispersion is linked to the gravitational potential of the system through the Jeans equation. This approach (utilized in [136, 120, 139]) has the significant advantage that observational data dictate the distribution of dark matter with a minimum number of theoretical assumptions. The main results of these studies are that dSphs are very good systems for the search for dark matter annihilation, because most of the uncertainties in the distribution of dark matter can be well quantified and understood. In addition, dSphs are expected to be relatively free of intrinsic γ-ray emission from other astrophysical sources, thus eliminating contaminating background that may hinder the interpretation of any observation. Assuming a scenario for supersymmetric dark matter where $M_\chi = 200\,\mathrm{GeV}$, $E_{\mathrm{th}} = 50\,\mathrm{GeV}$ and

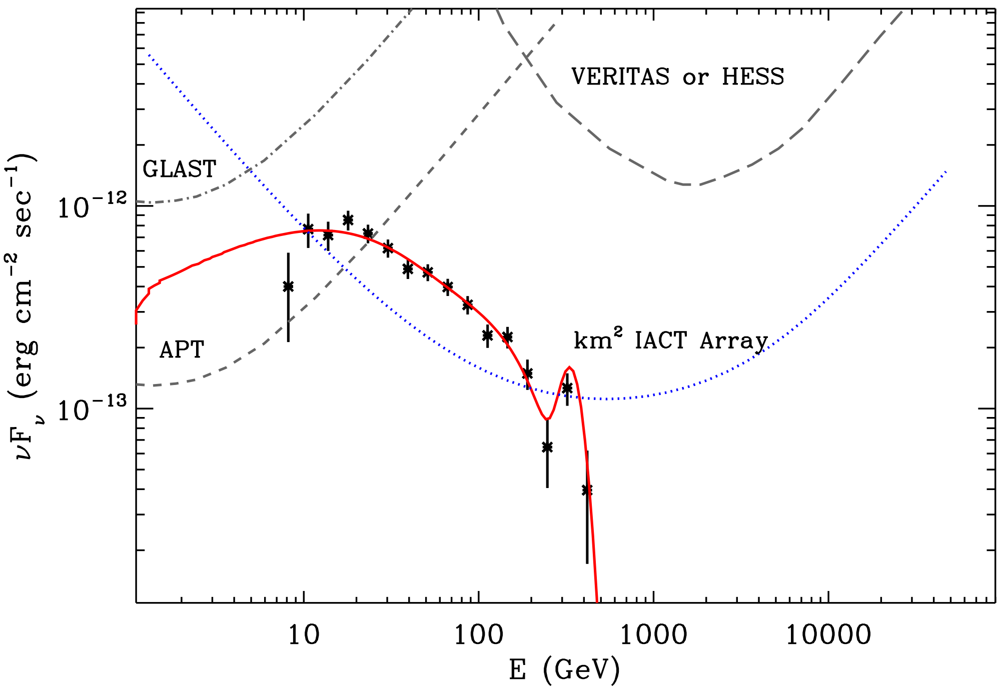

Figure 17: Predicted gamma-ray signal from the dwarf spheroidal galaxy Ursa Minor for neutralino mass of 330 GeV, branching into $\tau^+\tau-$ 20% of the time, and into $b\bar{b}$ 80% of the time and with a line to continuum ratio of $2{\times}10^{-3}$. We assume a typical annihilation cross-section of $2\times10^{-26}\mathrm{cm}^3\mathrm{s}^{-1}$ the halo values from Strigari et al. [139] with $r_s = 0.86\,\mathrm{kpc}$ and central density $\rho_s = 7.9\times10^7\ M_\odot/\mathrm{kpc}^3$. We also assume a modest boost factor of $b = 3$ from halo substructure. We assume an ideal instrument with an effective area of 1 km^2 and sensitivity limited only by the electron background, diffuse gamma-ray background (assuming an $\sim E^{-2.5}$ spectrum connecting to the EGRET points) and cosmic-ray background (10 times lower than current instruments). For this idealized IACT array, we do not include the effect of a threshold due to night-sky-background, and assume an energy resolution of 15%. The data points are simulated given the signal-to-noise expected for the theoretical model compared with our anticipated instrument sensitivity.

$\mathcal{P} \approx 10^{-31}\,\mathrm{cm}^3\mathrm{s}^{-1}\mathrm{GeV}^{-2}$, the maximum expected fluxes from 9 dSphs studied in [120, 139] can be as large as 10^{-12} photons cm^{-2} s^{-1} (for Willman 1). Observing γ-rays from dark matter annihilation in dwarf spheroidals is of fundamental importance for 2 reasons: First and foremost, these observations can lead to an identification of the dark matter, especially if line emission or other distinct features in the continuum are detected and second, they will provide information on the actual spatial distribution of dark matter halos in these important objects. If there is a weakly interacting thermal relic, then γ-ray telescopes can tell us something about non-linear structure formation, a task unattainable by any other experimental methods.

Fig. 17 shows an example of one possible spectrum that might be measured for Ursa Minor given conservative assumptions including: a typical annihilation cross-section, a halo distribution constrained by stellar velocity measurements (from Strigari et al. [139]) and a modest boost factor of $b = 3$ at the low end of the expected range for such halos. This prediction demonstrates that detection from Dwarf galaxies is most likely out of reach of the current generation of IACT experiments (HESS and VERITAS) or proposed EAS experiments, but may be within reach of a future km^{2}IACT instrument, if the point-source sensitivity is improved by an order of magnitude, the energy resolution is good enough to resolve the spectral features (better than 15%) and the energy threshold can be pushed well below 100 GeV.

With the advent of the Sloan Digital Sky Survey (SDSS), the number of known dSph satellites of the local group has roughly doubled during the last decade [140]. Since the survey is concentrated around the north Galactic pole, it is quite likely that there are many more dSph satellites waiting to be discovered. For an isotropic distribution, and assuming that SDDS has found all the satellites in its field of view, we would expect ~ 50 dwarfs in all. Since simulation data suggests that dwarf satellites lie preferentially along the major axis of the host galaxy, the number of Milky-Way dwarf satellites could be well above this estimate. With more dwarf galaxies, and increasingly detailed studies of stellar velocities in these objects, this class of sources holds great promise for constraints on dark matter halos and indirect detection of dark matter. Since many of these discoveries are very new, detailed astronomical measurements are still required to resolve the role of dark matter in individual sources. For example, for the new object Willman I, some have argued that this is a globular cluster while others have made the case that despite it's relatively small mass, this is a dark-matter dominated object and not a globular cluster [141]. Other studies challenge the inferences about the dark matter dominance in dSphs attributing the rise in rotation velocities in the outer parts of dSphs to tidal effects rather than the gravitational potential [142]. Future progress in this blossoming area of astronomy could provide important additional guidance for a more focused survey on the most promising sources using pointed observations with very deep exposures.

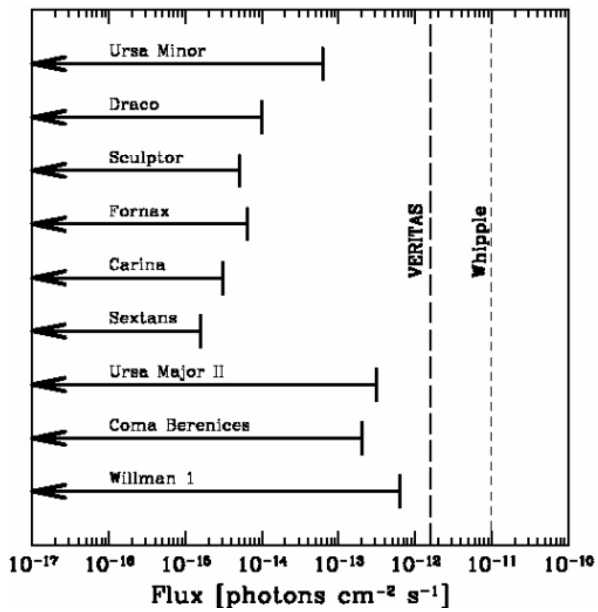

Figure 18: Prospects for detecting the most prominent Dwarf-galaxy targets for dark matter annihilation. Upper-limit bars show the range of theoretical predictions [189] with fluxes dropping below the level of detectability as one traverses the full range of parameter space including the neutralino mass, cross-section and halo distribution. The plot includes dark-matter dominated dwarf spheroidal systems in the Milky Way halo, including promising sources located at high galactic latitude and with virtually no known intrinsic γ ray emission from astrophysical sources. The thin-dashed line represents the sensitivity of Whipple, while the long-dashed line depicts the sensitivity of VERITAS.

4.3.2 Local group galaxies

Local group galaxies offer attractive targets for the search of γ-rays form dark matter annihilation for many of the same reasons dSph galaxies do: they are relatively small systems, with relatively high mass-to-light ratios (except M31). Relative to dSphs, the influence of baryons in the central regions is higher, especially if a black hole is present (such as M32). Nevertheless, their relative proximity and size make them viable targets that should be explored. Recently, Wood et al. (2007) [132] used the Whipple 10m telescope and placed bounds on the annihilation cross section of neutralinos assuming a distribution of dark matter in the halos of M32 and M33 that resembles dark matter halos seen in N-body simulations. While these observations with Whipple and now with VERITAS and HESS provide interesting limits on some of the more extreme astrophysical or particle physics scenario, more sensitive observations are needed if one makes more conservative estimates. Even with an order of magnitude increase in sensitivity over the current generation experiments, it is still possible that Dwarf or local-group galaxies will evade detection with the next generation detector without some enhancement in the central halo (e.g. a cusp steepened by the stellar population or a large boost factor). Given this uncertainty the best strategy for detecting dark matter from Dwarf galaxies, or local group galaxies is to observe an ensemble of sources, taking advantage of the source-to-source variance in the halo profile until better constraints are available from new astronomical measurements (e.g., stellar velocity dispersion or rotation curves).

4.3.3 Detecting the Milky Way Substructure

A generic prediction of the hierarchical structure formation scenario in cold dark matter (CDM) cosmologies is the presence of rich substructure; bound dark matter halos within larger, host halos. Small dark matter halos form earlier, and therefore have higher characteristic densities. This makes some of these subhalos able to withstand tidal disruption as they sink in the potential well of their host halo due to dynamical friction. Unfortunately, even though this is a natural outcome of CDM, there is no clear explanation as to why the Milky Way appears to contain a factor of 10-100 *fewer* subhalos than it should, based on CDM predictions [144, 145]. Several solutions to this problem have been suggested, such as changing the properties of the dark matter particle (e.g., [146, 147, 148]), modifying the spectrum of density fluctuations that seed structure growth (e.g., [149, 150]), or invoking astrophysical feedback processes that prevent baryonic infall and cooling (e.g., [151, 152, 153]). The most direct experimental way to probe the presence of otherwise dark substructure in the Milky Way is through γ-ray observations. Theoretical studies [154], as well as numerical simulations of a Milky Way-size halo [128], predict that given the probability of an otherwise completely dark subhalo nearby, the expected flux in γ-rays can be as large as $\sim 10^{-13}$ cm^{-2} s^{-1}.

4.3.4 Detecting Microhalos

The *smallest* dark matter halos formed are set by the RMS dark matter particle velocities at kinetic decoupling, the energy scale at which momentum–changing interactions cease to be effective [155, 156, 157, 158, 159, 160, 161, 162]. For supersymmetric dark matter this cutoff scale fives a mass range for *microhalos* of around $10^{-13} \leq [M/M_\odot] \leq 10^{-2}$, depending on the value of the kinetic decoupling temperature which is set by the supersymmetric parameters. While the survival of microhalos in the Solar neighborhood is still under debate, there are indications that some fraction ($\sim 20\%$) may still be present. In this case, microhalos could even be detected via the proper motion of their γ-ray signal [163, 164]. Microhalos that exhibit proper motion must be close enough that their proper motion is above a detection threshold set by the angular resolution and length of time over which the source can be monitored(given by the lifetime of the observatory). Microhalos must be abundant enough so that at least one is within the volume set by this proper motion requirement. The expected flux from a microhalo that may exhibit detectable proper motion [164] is $\sim 10^{-15}$ cm^{-2} s^{-1}. Such objects are most likely to be detected by very wide-field instruments like Fermi. Follow-up measurements with IACT arrays would be required to determine the characteristics of the spectrum and angular extent of these sources at higher energies.

4.3.5 Spikes around Supermassive and Intermediate-Mass Black Holes

There are other potential dark matter sources in our own Galaxy that may be formed by a gravitational interplay of dark halos and baryonic matter. In particular, it is possible that a number of intermediate-mass black holes (IMBHs) with cuspy halos, might exist in our own galaxy. The effect of the formation of a central object on the surrounding distribution of matter has been investigated in Refs. [165, 166, 167, 168] and for the first time in the framework of DM annihilations in Ref. [169]. It was shown that the *adi-*

abatic growth of a massive object at the center of a power-law distribution of DM, with index γ, induces a redistribution of matter into a new power-law (dubbed "spike") with index

$$\gamma_{sp} = (9 - 2\gamma)/(4 - \gamma) \quad . \tag{5}$$

This formula is valid over a region of size $R_{sp} \approx 0.2\, r_{BH}$, where r_{BH} is the radius of gravitational influence of the black hole, defined implicitly as $M(< r_{BH}) = M_{BH}$, where $M(< r)$ denotes the mass of the DM distribution within a sphere of radius r, and where M_{BH} is the mass of the Black Hole [170]. The process of adiabatic growth is, in particular, valid for the SMBH at the galactic center. A critical assessment of the formation *and survival* of the central spike, over cosmological timescales, is presented in Refs. [171, 172] and references therein. Adiabatic spikes are rather fragile structures, that require fine-tuned conditions to form at the center of galactic halos [173], and that can be easily destroyed by dynamical processes such as major mergers [174] and gravitational scattering off stars [175, 171].

However Intermediate Mass BHs, with mass $10^2 < M/\mathrm{M}_\odot < 10^6$, are not affected by these destructive processes. Scenarios that seek to explain the observed population and evolutionary history of supermassive-black-holes actually result in the prediction of a large population of wandering IMBHs, with a number in our own Galaxy. They may form in rare, overdense regions at high redshift, $z \sim 20$, as remnants of Population III stars, and have a characteristic mass-scale of a few $10^2\,\mathrm{M}_\odot$ [176, 177, 178, 179, 180]. Alternatively, IMBHs may form directly out of cold gas in early-forming halos and are typified by a larger mass scale of order $10^5\,\mathrm{M}_\odot$ [181]. We show in Fig. 4.3.5 the number of objects that can be detected as a function of the detector sensitivity. The spiky halos around galactic intermediate-mass black holes could provide a large enhancement in the gamma-ray signal that could be effectively detected by all-sky low-threshold instruments such as Fermi then followed-up by ground-based measurements. Over most of the allowed parameter space, Fermi would detect the onset of the continuum spectrum but would lack the sensitivity to measure the detailed spectral shape above hundreds of GeV. Ground-based measurements with good point-source sensitivity, and good energy resolution (10-15%) would be necessary to follow-up these detections to measure the spectral cutoff and other features of the annihilation spectrum needed to clearly identify a dark-matter origin for the gamma-ray signal.

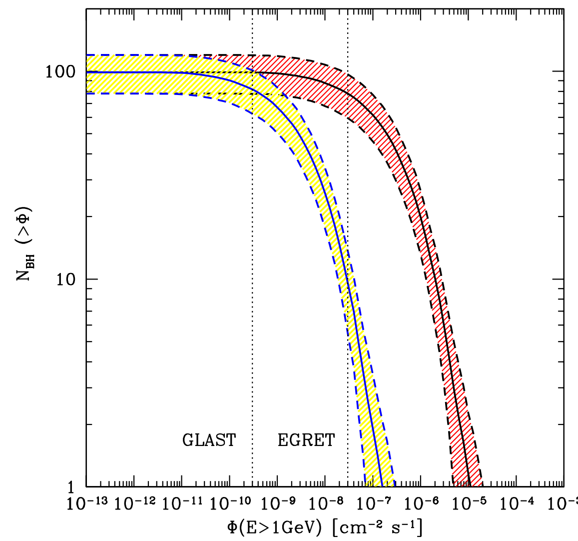

Figure 19: IMBHs integrated luminosity function, i.e. number of IMBHs that can be detected from experiments with point source sensitivity Φ (above 1 GeV), as a function of Φ. We show for comparison the 5σ point source sensitivity above 1 GeV of EGRET and Fermi (GLAST) in 1 year. From Ref. [177].

High energy gamma-ray astronomy can also indirectly provide information about the formation history of IMBHs through a very different avenue, i.e., infrared absorption measurements of gamma-rays from distant AGN. For example, the early population-III stars that may seed the growth of IMBHs are likely to be massive (100 $M_\odot$) stars that form in dark matter clumps of mass $\sim 10^6 M_\odot$. These short lived stars would result in a large contribution to the total amount of visible and UV light in the early (large-redshift) universe, that contribute to the present-day diffuse infrared background. Present observations by Whipple, HEGRA, MAGIC and HESS already provide constraints on the contribution from population-III stars. Gamma-ray astronomy has the unique potential to provide important constraints on the history of structure formation in the universe through observations of the annihilation signal from dark-matter halos on a range of mass scales (including IMBH halos) in addition to probing the history of star formation through measurements of the diffuse infrared background radiation.

4.3.6 Globular clusters

Globular clusters are relatively low mass-to-light ratio bound systems in the Milky Way that are dominated by a dense stellar core. The presence of dark matter in the core of a collapsed globular cluster is questionable because it is expected that 2-body stellar interactions will deplete dark matter from the region. On the other hand, if there is any dark matter left-over from the core-collapse relaxation process, it is possible that the dense stellar core would adiabatically steepen the distribution of dark matter, thus making some dense globular clusters potential targets for dark matter detection. Wood et al. (2007) [132] observed the relatively close M15 globular cluster with the Whipple 10m telescope, and placed upper bounds on the cross section for dark matter annihilation.

4.4 Complementarity of γ-Ray Searches with Other Methods for Dark Matter Searches

Both Fermi and the LHC are expected to become operational in 2008. What guidance will these instruments provide for a future ground-based experiment? The ATLAS and CMS experiments at the Large Hadron Collider (LHC) are designed to directly discover new supersymmetric particles in the range of a few ~ 100 GeV/c^2 and will start collecting data in the very near future. The LHC alone will not, under even the most optimistic circumstances, provide all of the answers about the nature of dark matter. In general, a combination of laboratory (LHC, ILC) detection and astrophysical observations or direct detection experiments will be required to pin down all of the supersymmetric parameters and to make the complete case that a new particle observed in the laboratory really constitutes the dark matter. Due to the fact that the continuum gamma-ray signal depends directly on the total annihilation cross-section, there are relatively tight constraints on the gamma-ray production cross-section from the cosmological constraints on the relic abundance. For direct detection, on the other hand, the nuclear recoil cross-section is only indirectly related to the total annihilation cross-section and thus there are a number of perfectly viable model parameters that fall many orders of magnitude below any direct detection experiment that may be built in the foreseeable future. Thus gamma-ray astronomy is unique in that the detection cross-section is closely related to the total annihilation cross section that determines the relic abundance. A given theoretical scenario of SUSY breaking at low energies, e.g. mSUGRA, SplitSUSY, non-universal SUGRA, MSSM-25, AMSB, etc., reduces the available parameter phase space. Therefore, it is natural to expect that, for some set of the parameters, the neutralino might be detected by all experimental techniques, while in other cases only a single method has sufficient sensitivity to make a detection [182]. Only a combination of accelerator, direct, and indirect searches would cover the supersymmetric parameter space [183]. For example, the mass range of neutralinos in the MSSM is currently constrained by accelerator searches to be above a few GeV [184, 185] and by the unitarity limit on the thermal relic to be below ~ 100 TeV [186] (a narrower region would result if specific theoretical assumptions are made, e.g. mSUGRA).

For the LHC to see the lightest stable SUSY particle, it must first produce a gluino from which the neutralino is produced. This limits the reach of the LHC up to neutralino masses of $m_\chi \approx 300$GeV, well below the upper end of the allowed mass range. Direct detection of WIMP-nucleon recoil is most sensitive in the 60 to 600 GeV regime. Indirect observations of self-annihilating neutralinos through $\gamma-$rays with energies lower than $\sim$ 100 GeV will best be accomplished by Fermi, while VERITAS and the other ground-based $\gamma-$ ray observatories will play critical role in searches for neutralinos with mass larger than $\sim$ 100 GeV.

While direct detection and accelerator searches have an exciting discovery potential, it should be emphasized that there is a large region of parameter space for which gamma-ray instruments could provide the only detection for cases where the nuclear recoil cross-section falls below the threshold of any planned direct detection experiment, or the mass is out of range of the LHC or even the ILC. Any comprehensive scientific roadmap that puts the discovery of dark matter as its priority must include support for a future, high-sensitivity ground-based gamma-ray experiment in addition to accelerator and direct searches

But the next 5-10 years of DM research may provide us with a large amount of experimental results coming from LHC, direct DM searches [99, 101, 100, 102, 103, 105] and indirect observations of astrophysical γ-rays. Current gamma-ray experiments such as AGILE, Fermi, VERITAS, HESS and MAGIC will continue making observations of astrophysical sources that may support very high density dark matter spikes and may, with luck, provide a first detection of dark matter. The wide field-of-view Fermi instrument could provide serendipitous detections of otherwise dark, dark matter halos, and search for the unique dark matter annihilation signal in the isotropic cosmological background. EAS experiments will provide evidence about the diffuse galactic background at the highest energies, helping to understand backgrounds for dark matter searches and even offering the potential for discovery of some unforeseen very high mass, nonthermal relic that form the dark matter. All of these results will guide the dark matter research which can be conducted by a future ground-based observatory needed to study the dark matter halos, and would affect strongly the design parameters of such an observatory.

To briefly summarize the interplay between the LHC, Fermi and a future ground-based gamma-ray instrument, it is necessary to consider several different regimes for the mass of a putative dark matter particle:

- *Case I:* If $m_\chi \sim 100\,\mathrm{GeV}$ and the LHC sees the LSP, Fermi will probably provide the most sensitive measurements of the continuum radiation and will be needed to demonstrate that a supersymmetric particle constitutes the dark matter [189]. Ground-based measurements will be needed to constrain the line-to-continuum ratio to better determine the supersymmetric parameters or to obtain adequate photon statistics (limited by the $\sim$m^2 effective area of Fermi) to obtain the smoking gun signature of annihilation by observing line emission.

- *Case II:* If $100\,\mathrm{GeV} < m_\chi < 300\,\mathrm{GeV}$, the LHC could still see the neutralino, but both the line and continuum emission could be better detected with a a low-threshold (i.e., 20-40 GeV threshold) ground-based experiment than with Fermi, if the source location is known. Again these gamma-ray measurements are still required to demonstrate that a supersymmetric particle constitutes astrophysical halos, and to further measure supersymmetric parameters [94].

- *Case III:* If $m_\chi > 300\,\mathrm{GeV}$ future direct-detection experiments and ground-based gamma-ray experiments may be able to detect the neutralinos. Only ground-based instruments will be able to determine the halo parameters, and will provide additional constraints on SUSY parameter space somewhat orthogonal to the constraints provided by the determination of the direct detection cross-sections. For a sizeable fraction of parameter space, nuclear recoil cross-sections may be too small for direct detection but the total annihilation cross section could still be large enough for a gamma-ray detection. Detection at very high energies would be particularly important for non-SUSY dark matter candidates such as the lightest Kaluza-Klein partner, where current constraints put the likely mass range above the TeV scale. Since TeV-scale neutralinos are likely to be either pure Higgsino or pure Wino particles, particle-physics uncertainties are expected to be smaller in this VHE energy regime.

4.5 Conclusions

A next-generation γ-ray telescope has the unique ability to make the connection from particles detected in the laboratory to the dark matter that dominates the density of matter in the universe, and to provide important constraints that help to identify the nature of the dark matter particle. The main findings of our study about the potential impact of gamma-ray measurements on the dark-matter problem and the requirements for a future instrument are summarized below:

- Compared with all other detection techniques (direct and indirect), γ-ray measurements of dark-matter are unique in going beyond a detection of the local halo to providing a measurement of the actual distribution of dark matter on the sky. Such measurements are needed to understand the nature of the dominant gravitational component of our own Galaxy, and the role of dark matter in the formation of structure in the Universe.

- There are a number of different particle physics and astrophysical scenarios that can lead to the production of a gamma-ray signal with large variations in the total flux and spectral shape. The spectral form of the gamma-ray emission will be universal, and contains distinct features that can be connected, with high accuracy, to the underlying particle physics.

- The annihilation cross-section for gamma-ray production from higher energy (TeV) candidates are well constrained by measurements of the relic abundance of dark matter, with the particle-physics uncertainty contributing $\sim$ one order of magnitude to the range of the predicted gamma-ray fluxes.

- The Galactic center is predicted to be the strongest source of gamma-rays from dark matter annihilation but contains large astrophysical backgrounds. To search for gamma-ray emission from dark-matter annihilation in the Galactic center region, the requirements for the future instrument include: extremely good angular resolution to reject background from other point sources, a moderately large field of view ($\gtrsim 7°$ diameter), a good energy resolution ($\lesssim 15\%$), a low energy threshold $\lesssim 50$ GeV, and location at a southern hemisphere site.

- Observations of local-group dwarf galaxies may provide the cleanest laboratory for dark-matter searches, since these dark-matter dominated objects are expected to lack other astrophysical backgrounds. For these observations, a very large effective area and excellent point-source sensitivity down to $\lesssim$50 GeV is required. Energy resolution better than 15-20% is required to determine the spectral shape. Currently, the best strategy for detecting dark matter from dwarf galaxies, globular clusters or local group galaxies is to observe an ensemble of sources, taking advantage of the source-to-source variance in the halo profile that may lead to large enhancements in the signal from some sources, although improvements in constraints on the dark-matter density profile from future detailed astronomical measurements (e.g., from stellar velocity dispersion) will allow for a refinement of the list of most promising targets.

- Observations of halo-substructure could provide important new constraints on CDM structure formation, providing information on the mass of the first building blocks of structure, and on the kinetic decoupling temperature. The most direct experimental way to probe the presence of otherwise dark halo substructure in the Milky Way is through γ-ray observations. Space-based low-threshold all-sky measurements will be most effective for identifying candidate objects, but ground-based measurements will be required to determine the detailed spectral shape (cutoff, line-to-continuum ratio) needed to identify the dark matter candidate.

- The spiky halos around galactic intermediate-mass black holes could provide a large enhancement in the gamma-ray signal that could be effectively detected by all-sky low-threshold instruments such as Fermi or a future space-based instrument, then followed-up by ground-based measurements. Over most of the allowed parameter space, Fermi would detect the onset of the continuum spectrum but would lack the sensitivity to measure the detailed spectral shape above hundreds of GeV. Ground-based measurements with good point-source sensitivity, and good energy resolution (10-15%) would be necessary to follow-up these detections to measure the spectral cutoff and other features of the annihilation spectrum needed to clearly identify a dark-matter origin of the gamma-ray signal.

- While a space-based instrument or future IACT arrays are probably the only means of providing the large effective area, low threshold, energy and angular resolution for detailed measurements of gamma-rays from dark matter annihilation, future EAS experiments like HAWC can also play a useful role. Future EAS experiments, with their wide field of view and long exposure time, also have the potential for serendipitous discovery of some corners of parameter space, in particular for nonthermal relics and mass close to the unitarity limit. The good sensitivity of EAS experiments can provide important measurements of diffuse, hard-spectra galactic backgrounds.

- Gamma-ray astronomy has the unique potential to provide important constraints on the history of structure formation in the universe through dark-matter observations of dark-matter halos on a range of mass scales (including IMBH halos) in addition to probing the history of star formation through measurements of the diffuse infrared background radiation.

- In general, a combination of laboratory (LHC, ILC) detection and astrophysical observations or direct detection experiments will be required to pin down all of the supersymmetric parameters and to make the complete case that a new particle observed in the laboratory really constitutes the dark matter.

- Gamma-ray astronomy is unique in that the detection cross-section is closely related to the total annihilation cross section that determines the relic abundance.

  In closing, we reiterate that a comprehensive plan for uncovering the nature of dark matter must include gamma-ray measurements. With an order of magnitude improvement in sensitivity and reduction in energy threshold, a future IACT array should have adequate sensitivity to probe much of the most generic parameter space for a number of sources including Galactic substructure, Dwarf galaxies and other extragalactic objects.

5 Extragalactic VHE astrophysics

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5.1 Introduction

A next-generation gamma-ray experiment will make extragalactic discoveries of profound importance. Topics to which gamma-ray observations can make unique contributions are the following: (i) the environment and growth of Supermassive Black Holes; (ii) the acceleration of cosmic rays in other galaxies; (iii) the largest particle accelerators in the Universe, including radio galaxies, galaxy clusters, and large scale structure formation shocks; (iv) study of the integrated electromagnetic luminosity of the Universe and intergalactic magnetic field strengths through processes including pair creation of TeV gamma rays interacting with infrared photons from the Extragalactic Background Light (EBL).

The following sections will describe the science opportunities in these four areas. Gamma-ray bursts and extragalactic searches for dark matter annihilation gamma rays are discussed in separate sections.

5.2 Gamma-ray observations of supermassive black holes

Supermassive black holes (SMBH) have masses between a million and several billion solar masses and exist at the centers of galaxies. Some SMBHs, called Active Galactic Nuclei (AGN) are strong emitters of electromagnetic radiation. Observations with the *EGRET Energetic Gamma-Ray Experiment Telescope* on board of the Compton Gamma-Ray Observatory (CGRO) revealed that a certain class of AGN known as blazars are powerful and variable emitters, not just at radio through optical wavelengths, but also at $\geq$100 MeV gamma-ray energies [194]. EGRET largely detected quasars, the most powerful blazars in the Universe. Observations with ground-based Cherenkov telescopes showed that blazars emit even at TeV energies [195]. In the meantime, more than twenty blazars have now been identified as sources of >200 GeV gamma rays with redshifts ranging from 0.031 (Mrk 421) [195] to 0.536 (3C 279) [259] [3]. Most TeV bright sources are BL Lac type objects, the low power counterparts of the quasars detected by EGRET. The MeV to TeV gamma-ray emission from blazars is commonly thought to originate from highly relativistic collimated outflows (jets) from mass accreting SMBHs that point at the observer [192, 193]. The only gamma-ray emitting AGN detected to date that are not blazars are the radio galaxies Centaurus A [190] and M87 [191]. The observation of blazars in the gamma-ray band has had a major impact on our understanding of these sources. The observation of rapid flux variability on time scales of minutes together with high gamma-ray and optical fluxes [200, 253] implies that the accreting black hole gives rise to an extremely relativistic jet-outflow with a bulk Lorentz factor exceeding 10, most likely even in the range between 10 and 50 [254, 255]. Gamma-ray observations thus enable us to study plasma which moves with $\geq$99.98% of the speed of light. Simultaneous broadband multiwavelength observations of blazars have revealed a pronounced correlation of the X-ray and TeV gamma-ray fluxes [201, 202, 205, 196]. The X-ray/TeV flux correlation (see Fig. 20) suggests that the emitting particles are electrons radiating synchrotron emission in the radio to X-ray band and inverse Compton emission in the gamma-ray band.

Blazars are expected to be the most copious extragalactic sources detected by ground-based IACT arrays like VERITAS and by the satel-

[3] Up-to-date lists of TeV γ-ray sources can be found at the web-sites: http: //tevcat.uchicago.edu and http: //www.mpp.mpg.de/ ~rwagner/sources/.

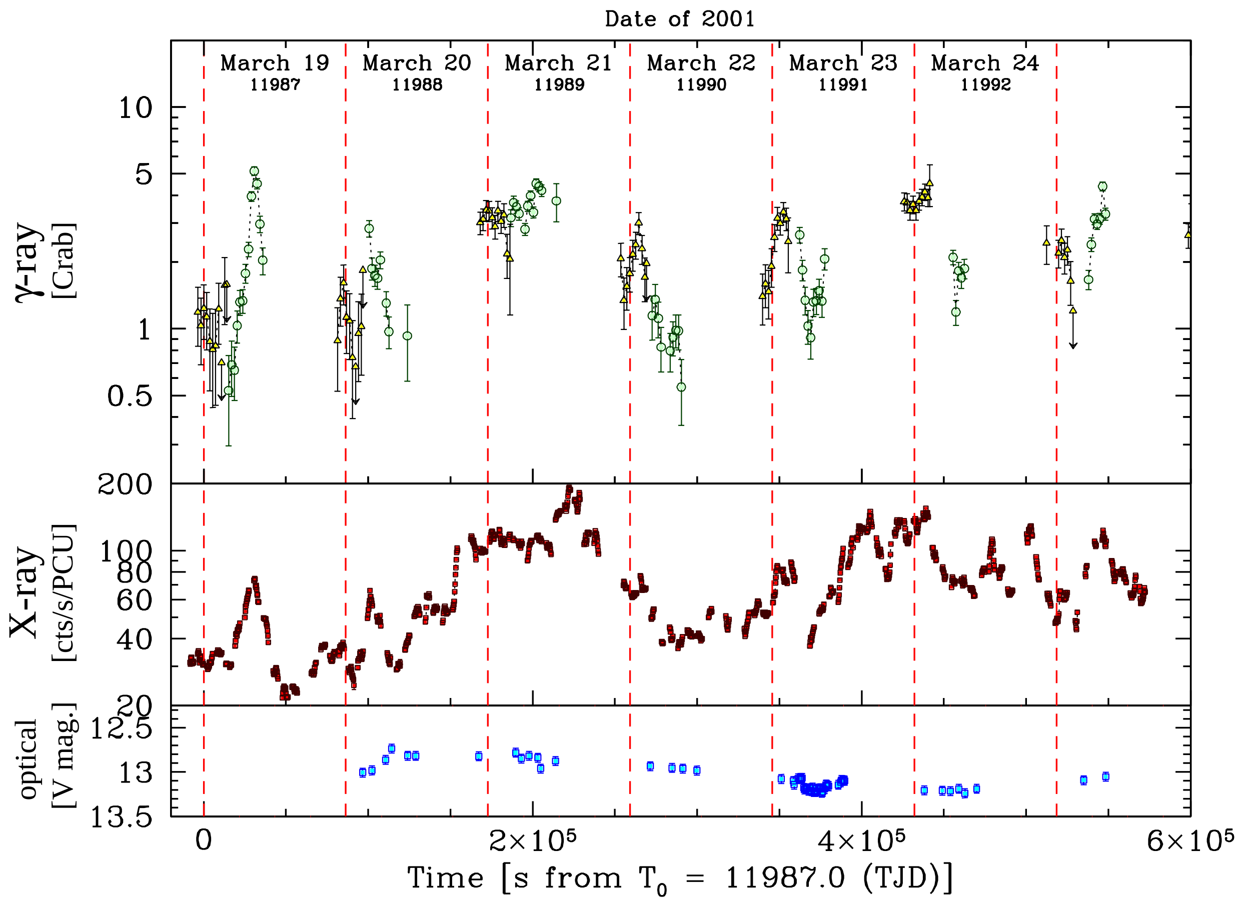

Figure 20: Results from 2001 Rossi X-ray Timing Explorer (RXTE) 2-4 keV X-ray and Whipple (full symbols) and HEGRA (open symbols) gamma-ray observations of Mrk 421 in the year 2001 [196]. The X-ray/gamma-ray fluxes seem to be correlated. However, the interpretation of the data is hampered by the sparse coverage at TeV gamma rays.

lite borne gamma-ray telescope Fermi. For extremely strong sources, IACT arrays will be able to track GeV/TeV fluxes on time scales of seconds and GeV/TeV energy spectra on time scales of a few minutes. Resolving the spectral variability during individual strong flares in the X-ray and gamma-ray bands should lead to the unambiguous identification of the emission mechanism. The present generation of IACTs will be able to track spectral variations only for a very small number of sources and only during extreme flares. The next-generation gamma-ray experiments will be able to do such studies for a large number of sources on a routine basis. Sampling the temporal variation of broadband energy spectra from a few tens of GeV to several TeV will allow us to use blazars as precision laboratories to study particle acceleration and turbulence in astrophysical plasmas, and to determine the physical parameters describing a range of different AGN. The observations of blazars hold the promise to reveal details about the inner workings of AGN jets. Obtaining realistic estimates of the power in the jet, and the jet medium will furthermore constrain the origin of the jet and the nature of the accretion flow.

Recently, spectracular results have been obtained by combining monitoring VLBA, X-ray and TeV γ-ray observations. This combination has the potential to pinpoint the origin of the high energy emission based on the high resolution radio images, and thus to directly confirm or to refute models of jet formation. For example, radio VLBA, optical polarimetry, X-ray and TeV γ-ray observations of the source BL Lac seem to indicate that a plasma blob first detected with the VLBA subsequently produces an X-ray, an optical and a γ-ray flare [257]. A swing of the optical polarization seems to bolster the case for a helical magnetic field as predicted by magnetic models of jet formation and acceleration. Presently such observations are extremely difficult as the current instruments can detect sources like M 87, BL Lac, W Com only in long observations or during extreme flares. Next-generation γ-ray instruments will allow us to study the correlation of fast TeV flares and radio features on a routine basis.

In addition to ground-based radio to optical coverage, several new opportunities might open up within the next decade. The Space Interferometry Mission (SIM) will be able to image emerging plasma blobs with sub milli-arcsec angular resolution [203]. The center may be located with an accuracy of a few micro-arcsec. For a nearby blazar at z=0.03, 1 milli-arcsec corresponds to a projected distance of 0.6 pc. The SIM observations could thus image the blobs that give rise to the flares detected in the gamma-ray regime. Joint X-ray/radio interferometry observations already give some tentative evidence for the emergence of radio blobs correlated with X-ray flares. If a Black Hole Finder Probe like the Energetic X-ray Imaging Space Telescope (EXIST) [204] will be launched, it would provide reliable all-sky, broad-bandwidth (0.5-600 keV), and high-sensitivity X-ray coverage for all blazars in the sky. EXIST's full-sky sensitivity would be 2×10^{-12} ergs cm^{-2} s^{-1} for 1 month of integration. For bright sources, EXIST could measure not only flux variations but also the polarization of hard X-rays. Opportunities arising from neutrino coverage will be described below.

At the time of writing this white paper, the Fermi gamma-ray telescope is in the process of detecting a few thousand blazars. The source sample will make it possible to study the redshift dependent luminosity function of blazars, although the identification of sources with optical counterparts may be difficult for the weaker sources of the sample, owing to Fermi's limited angular resolution. Another important task for the next-generation instrument will be to improve on the Fermi localization accuracies, and thus to identify a large number of the weaker Fermi sources.

Independent constraints on the jet power, kinematics, and emission processes can be derived from GeV-TeV observations of the large scale (up to hundreds of kpc) jets recently detected by Chandra. Although such large scale jets will not be spatially resolved, the fact that the gamma-ray emission from the quasar core is highly variable permits us to set upper limits to the steady GeV-TeV large scale jet emission [206]. In the case of the relatively nearby 3C 273, for example, the electrons that produce the large scale jet IR emission will also produce a flat GeV component. The fact that this emission is weaker than the EGRET upper limit constrains the Doppler factor of the large scale jets to less than 12, a value that can be pushed down to 5 with Fermi observations. Such low values of delta have implications on the nature of the large scale jet X-ray emission observed by Chandra. In particular, they disfavor models in which the X-ray emission is inverse Compton scattering of the cosmic microwave background (CMB), because the jet power required increases beyond the so-called Eddington luminosity, thought by many to be the maximum luminosity that can be channeled continuously in a jet. A synchrotron interpretation for the X-ray emission, requiring significantly less jet power, postulates a population of multi-TeV electrons that will unavoidably up-scatter the CMB to TeV energies. The existing 3C 273 shallow HESS upper limit constrains the synchrotron interpretation to Doppler factors less than 10. Combining deep TeV observations with a next-generation experiment with Fermi observations holds the promise of confirming or refuting the synchrotron interpretation and constraining the jet power.

Whereas the X-ray/gamma-ray correlation favors leptonic models with electrons as the emitters of the observed gamma-ray emission, hadronic models are not ruled out. In the latter case, the high-energy component is synchrotron emission, either from extremely high-energy (EHE) protons [219, 220, 221], or from secondary e^+/e^- resulting from synchrotron and pair-creation cascades initiated by EHE protons [222] or high-energy electrons or photons [223, 224, 225, 226]. If blazars indeed accelerate UHE protons, it might even be possible to correlate their TeV gamma-ray emission with their flux of high-energy neutrinos detected by the IceCube detector [227]. The high sensitivity of a next-generation ground-based experiment would be ideally suited to perform such multi-messenger studies.

Although most observations can be explained with the emission of high-energy particles that are accelerated in the jets of AGN , the observations do not exclude that the emitting particles are accelerated closer to the black hole. If the magnetic field in the black hole magnetosphere has a poloidal net component on the order of $B_{100} = 100$ G, both the spinning black hole [208] and the accretion disk [209, 207] will produce strong electric fields that could accelerate particles to energies of 2×10^{19} B_{100} eV. High-energy protons could emit TeV photons as curvature radiation [210], and high-energy electrons as Inverse Compton emission [211]. Such models could be vindicated by the detection of energy spectra, which are inconsistent with originating from shock accelerated particles. An example for the latter would be very hard energy spectra which require high minimum Lorentz factors of accelerated particles.

The improved data from next-generation gamma-ray experiments can be compared with improved numerical results. The latter have recently made very substantial progress. General Relativistic Magnetohydrodyamic codes are now able to test magnetic models of jet formation and acceleration (see the review by [258]). The Relativistic-Particle-in-Cell technique opens up the possibility of greatly improving our understanding a wide range of issues including jet bulk acceleration, electromagnetic energy transport in jets, and particle acceleration in shocks and in magnetic reconnection while incorporating the different radiation processes [215, 216, 217, 218].

Blazar observations would benefit from an increased sensitivity in the 100 GeV to 10 TeV energy range to discover weaker sources and to sample the energy spectra of strong sources on short time scales. A low energy threshold in the 10-40 GeV range would be beneficial to avoid the effect of intergalactic absorption that will be described further below. Increased sensitivity at high energies would be useful for measuring the energy spectra of a few nearby sources like M 87, Mrk 421, and Mrk 501 at energies $\gg$10 TeV and to constrain the effect of intergalactic absorption in the wavelength range above 10 microns. The interpretation of blazar data would benefit from dense temporal sampling of the light curves. Such sampling could be achieved with gamma-ray experiments located at different longitudes around the globe.

5.3 Cosmic rays from star-forming galaxies

More than 60% of the photons detected by EGRET during its lifetime were produced as a result of interactions between cosmic rays (CRs) and galactic interstellar gas and dust. This diffuse radiation represents approximately 90% of the MeV-GeV gamma-ray luminosity of the Milky Way [228]. Recently H.E.S.S. reported the detection of diffuse radiation at TeV energies from the region of dense molecular clouds in the innermost 200 pc around the Galactic Center [229], confirming the theoretical expectation that hadronic CRs could produce VHE radiation in their interaction with atomic or molecular targets, through the secondary decay of π°'s. Only one extragalactic source of diffuse GeV radiation was found by EGRET: the Large Magellanic Cloud, located at the distance of ~ 55 kpc [230]. A simple re-scaling argument suggests that a putative galaxy with Milky-Way-like gamma-ray luminosity, located at the distance of 1 Mpc, would have a flux of approximately 2.5×10^{-8} cm^{-2} s^{-1} ($>$ 100MeV), well below the detection limit of EGRET and $\sim 2\times10^{-4}$ of the Crab Nebula flux ($>$ 1 TeV), well below the sensitivity of VERITAS and H.E.S.S. Thus, a next-generation gamma-ray observatory with sensitivity at least an order of magnitude better than VERITAS would allow the mapping of GeV-PeV cosmic rays in normal local group galaxies, such as M31, and study diffuse radiation from more distant extragalactic objects if their gamma-ray luminosity is enhanced by a factor of ten or more over that of the Milky Way.

Nearby starburst galaxies (SBG's), such as NGC253, M82, IC342, M51 exhibit regions of strongly enhanced star formation and supernova (SN) explosions, associated with gas clouds which are a factor of $10^2 - 10^5$ more dense than the average Milky Way gas density of ~ 1 proton per cm^3. This creates nearly ideal conditions for the emission of intense, diffuse VHE radiation, assuming that efficient hadronic CR production takes place in the sites of the SNR's (i.e. that the galactic CR origin paradigm is valid) and in colliding OB stellar winds [231]. In addition, leptonic gamma-ray production through inverse-Compton scattering of high density photons produced by OB associations may become effective in star forming regions [232]. Multiple attempts to detect SBGs have been undertaken by the first generation ground-based gamma-ray observatories. At TeV energies, M82, IC342, M81, and NGC3079 were observed by the Whipple 10 m telescope [233], while M82 and NGC253 were observed by HEGRA. However, none of these objects were detected. A controversial detection of NGC 253 by the CANGAROO collaboration in 2002 [235] was ruled out by H.E.S.S. observations [236]. The theoretical predictions of TeV radiation from starburst galaxies have not yet been confirmed by observations and these objects will be intensively studied by the current generation instruments during the next several years. The optimistic theoretical considerations suggest that a few SBG's located at distances less than ~ 10 Mpc may be discovered. Should this prediction be confirmed, a next-generation gamma-ray observatory with sensitivity at least an order of magnitude better than VERITAS will potentially discover thousands of such objects within the ~ 100 Mpc visibility range. This will enable the use of SBG's as laboratories for the detailed study of the SNR CR acceleration paradigm and VHE phenomena associated with star formation, including quenching effects due to evacuation of the gas from star forming regions by SNR shocks and UV pressure from OB stars.

If accelerated CR's are confined in the regions of high gas or photon density long enough that the escape time due to diffusion through the magnetic field exceeds the interaction time, then the diffuse gamma-ray flux cannot be further enhanced by an increased density of target material, and instead an increased SN rate is needed. Ultra Luminous InfraRed Galaxies (ULIRGs), which have SN rates on the scale of a few per year (compared to the Milky Way rate of ~ 1 per century) and which also have very large amounts of molecular material, are candidates for VHE emission [237]. Although located at distances between ten and a hundred times farther than the most promising SBG's, the ULIRG's Arp220, IRAS17208, and NGC6240 may be within the range of being detected by Fermi, VERITAS and H.E.S.S. [238]. Next-generation gamma-ray instruments might be able to detect the most luminous objects of this type even if they are located at ~ 1 Gpc distances. Initial studies of the population of ULIRGs indicate that these objects underwent significant evolution through the history of the Universe and that at the moderate redshift ($z < 1$) the abundance of ULIRGs increases. Any estimate of the number of ULIRGs that may be detected is subject to large uncertainties due to both the unknown typical gamma-ray luminosity of these objects and their luminosity evolution. However, if theoretical predictions for Arp220 are representative for objects of this type, then simple extrapolation suggests $> 10^2$ may be detectable.

The scientific drivers to study ULIRG's are similar to those of SBGs and may include research of galaxy gamma-ray emissivity as a function of target gas density, supernova rate, confining magnetic field, etc. In addition, research of ULIRGs may offer a unique possibility to observe VHE characteristics of star formation in the context of the recent history of the Universe ($z < 1$) since ULIRGs might be detectable to much further distances. Other, more speculative, avenues of research may also be available. A growing amount of evidence suggests that AGN feedback mechanism connects episodes of intense starbursts in the galaxies with the accretion activity of central black holes. One can wonder then if a new insight into this phenomena can be offered by observation of VHE counterparts of these processes detected from dozens of ULIRGs in the range from 0.1-1 Gpc.

5.4 The largest particle accelerators in the Universe: radio galaxies, galaxy clusters, and large scale structure formation shocks

The possibility of observing diffuse GeV and TeV radiation from even more distant, rich galaxy clusters (GCs) has widely been discussed in the literature. As the Universe evolves, and structure forms on increasingly larger scales, the gravitational energy of matter is converted into random kinetic energy of cosmic gas. In galaxy clusters, collisionless structure formation shocks, triggered by accretion of matter or mergers, are thought to be the main agents responsible for heating the inter-cluster medium (ICM) to temperatures of ~ 10 keV. Through these processes a fraction of gravitational energy is converted into the kinetic energy of non-thermal particles: protons and electrons. Galactic winds [239] and re-acceleration of mildly relativistic particles injected into the ICM by powerful cluster members [240] may accelerate additional particles to non-thermal energies. Cosmic ray protons can escape clusters diffusively only on time scales much longer than the Hubble time. Therefore, they accumulate over the entire formation history [239] and interact with the intercluster thermal plasma to produce VHE gamma radiation. Theoretical predictions for the detection of such systems in gamma rays by VERITAS and H.E.S.S. include clusters in the range from $z = 0.01$ to $z = 0.25$ (see Fig. 21) [231, 241, 242]. Objects of this category were observed with Whipple [243] and H.E.S.S. [244] but were not detected. Multiple attempts to find gamma-ray signals from GCs in EGRET data also failed. Nevertheless, a large theoretical interest [246, 247, 248] motivates further observations of the particularly promising candidates, such as the Coma and Perseus clusters by VERITAS and H.E.S.S.. If nearby representatives of the GC class are detected, a next-generation gamma-ray observatory with sensitivity increased by a factor of 10 would be able to obtain spatially resolved energy spectra from the close, high-mass systems, and should be able to obtain flux estimates and energy spectra of several dozen additional clusters. The detection of gamma-ray emission from galaxy clusters would make it possible to study acceleration mechanisms on large scales (> 10 kpc). It would permit measurement of the energy density of non-thermal particles and investigation of whether they affect the process of star formation in GCs, since their equation of state and cooling behavior differs from that of the thermal medium. If cosmic ray protons indeed contribute noticeably to the pressure of the ICM, measurements of their energy density would allow for improved estimates of the cluster mass based on X-ray data, and thus improve estimates of the universal baryon fraction. Based on population studies of the gamma-ray fluxes from GCs, one could explore the correlation of gamma-ray luminosity and spectrum with cluster mass, temperature, and redshift. If such correlations are found, one could imagine using GCs as steady "standard candles" to measure the diffuse infrared and visible radiation of the Universe through pair-production attenuation of gamma rays. From a theoretical point of view the spectral properties of gamma-ray fluxes from GCs might be better understood than the intrinsic properties of blazars.

The anticipated discovery of extragalactic sources by VERITAS and H.E.S.S. will put theoretical predictions discussed here on firmer ground, at least for the number of sources that the next generation ground-based observatory may detect. Over the next five years, Fermi will make major contributions to this area of studies. If the origin of gamma radiation in these sources is hadronic, Fermi should be able to detect most of the SBGs, ULIRGs, and GCs, which could potentially be detected by VERITAS and H.E.S.S. Under some scenarios, in which gamma rays are

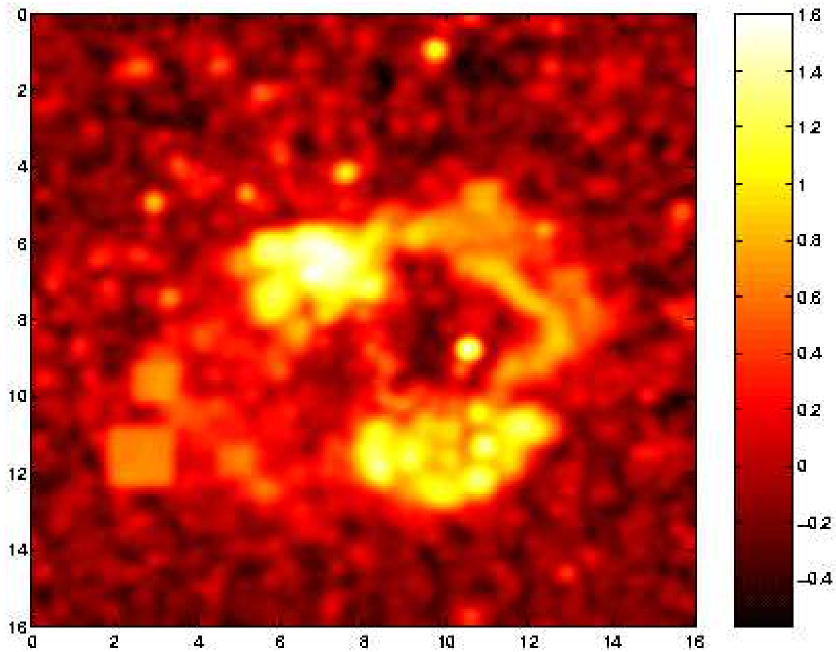

Figure 21: Results from a cosmological simulation showing how the > 10 GeV gamma-ray emission from a nearby rhich galaxy cluster could look like when mapped with a gamma-ray telescope with 0.2° angular resolution. The image covers a 16° × 16° region (color scale: $\log(J/\bar{J})$ for an average >10 GeV flux of $\bar{J} = 8.2\times10^{-9}$ cm^{-2} sec^{-1} sr^{-1}) (from [241])

produced via leptonic mechanisms, a fraction of sources may escape Fermi detection (M82 might be such example), yet may still be detectable with VERITAS and H.E.S.S. Future theoretical effort will be required to guide observations of these objects. In general, benefiting from the full sky coverage of Fermi, a program to identify the Fermi sources using the narrow field of view ACT observatories of the present day will be possible, and it is likely that diffuse gamma-ray extragalactic sources will be discovered. Fermi will measure the galactic and extragalactic gamma-ray backgrounds with unprecedented accuracy and will likely resolve the main contributing populations of sources in the energy domain below a few GeV. The task of determining the contribution from the diffuse gamma-ray sources to the extragalactic background in the range above a few GeV to $\sim$ 100 GeV will be best accomplished by the next generation ground-based instrument, capable of detecting a large number of sources rather than a few. Most of these sources are anticipated to be weak, so they will require deep observations.

Large scale structure formation shocks could accelerate protons and high-energy electrons out of the intergalactic plasma. Especially in the relatively strong shocks expected on the outskirts of clusters and on the perimeters of filaments, PeV electrons may be accelerated in substantial numbers. CMB photons Compton scattered by electrons of those energies extend into the TeV gamma-ray spectrum. The energy carried by the scattered photons cools the electrons rapidly enough that their range is limited to regions close to the accelerating shocks. However, simulations have predicted that the flux of TeV gamma rays from these shocks can be close to detection limits by the current generation of ground-based gamma-ray telescopes [249]. If true, this will be one of the very few ways in which these shocks can be identified, since very low thermal gas densities make their X-ray detection virtually impossible. Since, despite the low gas densities involved, these shocks are thought to be a dominant means of heating cluster gas, their study is vital to testing current models of cosmic structure formation.

The origin of ultra-high-energy cosmic rays (UHECRs, $E \gtrsim 10^{16}$ eV) is one of the major unsolved problems in contemporary astrophysics. Recently, the Auger collaboration reported tentative evidence for a correlation of the arrival directions of UHECRs with the positions of nearby Active Galactic Nuclei. Gamma-ray observations may be ideally suited to study the accel-

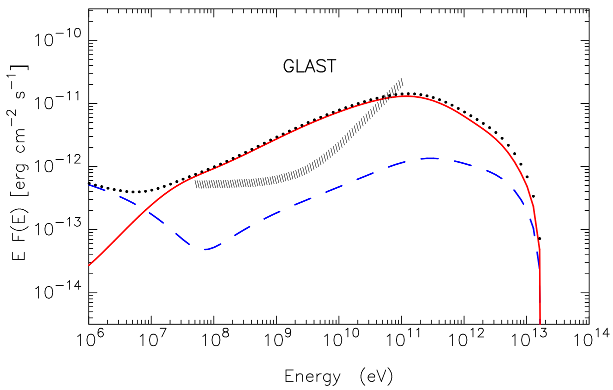

Figure 22: Fluxes from the electromagnetic cascade initiated in Cyg A by UHECRs assuming the total injection power of secondary UHE electrons and gamma rays injected at $\leq 1\,\mathrm{Mpc}$ distances about 10^{45} erg/s. The solid and dashed lines show the synchrotron and Compton fluxes, respectively.

eration process, as the UHECRs must produce gamma rays through various processes. The UHECRs may be accelerated far away from the black hole where the kpc jet is slowed down and dissipates energy. If they are accelerated very close to the black hole at $\sim$pc distances, the high-energy particle beam is expected to convert into a neutron beam through photo-hadronic interactions [467]. On a length scale $l \sim 100\,(E_n/10^{19}\,\mathrm{eV})\,\mathrm{kpc}$ the neutron beam would convert back into a proton beam through beta decays.

The interaction of UHECR with photons from the Cosmic Microwave Background (CMB) creates secondary gamma rays and electrons/positrons. Depending on the strength of the intergalactic magnetic field (B_{IGMF}), a next-generation ground-based gamma-ray experiment could detect GeV/TeV gamma rays from synchrotron emission of first generation electrons/positrons ($B_{\mathrm{IGMF}} \geq 10^{-9}$ G), or inverse Compton radiation from an electromagnetic cascade ($B_{\mathrm{IGMF}} \leq 10^{-9}$ G) [251]. Figure 22 shows gamma-ray fluxes expected from the electromagnetic cascade initiated in the CMBR and $B = 3\,\mu G$ environment of Cyg A by injecting 10^{45} erg/s of secondary electrons and/or gamma rays from GZK protons. For the distance to Cyg A of $\simeq 240\,\mathrm{Mpc}$ the assumed radial size of the cluster $R <\sim 1\,Mpc$ corresponds to an extended source, or halo, of angular size $<\sim$ 14 arcmin. Although the absorption in EBL at TeV energy is significant, the source should be detectable with a next-generation experiment because the source spectrum is very hard owing to synchrotron emission of UHE electrons. The detection of such emission could give information about the $\gg$TeV luminosity of these sources, about the intensity and spectrum of the EBL, and about the strength of the IGMF. A few aspects will be discussed further below.

A next-generation experiment might also be able to detect gamma-ray haloes with diameters of a few Mpc around superclusters of galaxies. Such haloes could be powered by all the sources in the supercluster that accelerate UHECRs. The size of the halo in these cases will be defined by the combination of gyroradius of the UHE electrons and their cooling path (synchrotron and Compton in Klein-Nishina regime). The spectral and spatial distibutions of such halos will contain crucial information about the EBL and intergalactic magnetic fields.

5.5 Extragalactic radiation fields and extragalactic magnetic fields

Very high-energy gamma-ray beams traveling over extragalactic distances are a unique laboratory for studying properties of photons, to constrain theories that describe spacetime at the Planck scale and for testing radiation fields of cosmological origin. The potential for probing the cosmic infrared background with TeV photons was first pointed out by Gould and Schréder [260] and was revived by Stecker, de Jager & Salamon [199], inspired by the detection of extragalactic TeV gamma-ray sources in the nineties. High-energy gamma rays traveling cosmological distances are attenuated en route to Earth by $\gamma + \gamma \rightarrow e^+ + e^-$ interactions with photons from the extragalactic background light. While the Universe is transparent for gamma-ray astronomy with energies below 10 GeV, photons with higher energy are absorbed by diffuse soft photons of wavelengths short enough for pair production. Photons from the EBL in the 0.1 to 20 micron wavelength range render the Universe opaque in TeV gamma rays, similarly to the cosmic microwave background that constitutes a barrier for 100 TeV photons. The transition region from an observational window turning opaque with increasing gamma-ray energy provides the opportunity for deriving observational constraints to the intervening radiation field. Whereas the cosmic microwave background is accessible via direct measurements, the cosmic infrared background (CIB) has been elusive and remains extremely difficult to discern by direct measurements. Energy spectra of extragalactic gamma-ray emitters between 10 GeV to 100 TeV allow us to extract information about the diffuse radiative background using spectroscopic measurements. Non-thermal gamma-ray emission spectra often extend over several orders of magnitude in energy and the high-energy absorption features expected from pair production can be adequately resolved with the typical energy resolution of 10% to 20% achievable with atmospheric Cherenkov telescopes.

The EBL, spanning the UV to far-infrared wavelength region, consists of the cumulative energy releases in the Universe since the epoch of recombination (see [261] for a review). The EBL spectrum comprises of two distinct components. The first, peaking at optical to near-infrared wavelengths (0.5-2 μm), consists of primary redshifted stellar radiation that escaped the galactic environment either directly or after scattering by dust. In a dust-free Universe, the SED of this component can be simply determined from knowledge of the spectrum of the emitting sources and the cosmic history of their energy release. In a dusty Universe, the total EBL intensity is preserved, but the energy is redistributed over a broader spectrum, generating a second component consisting of primary stellar radiation that was absorbed and reradiated by dust at infrared (IR) wavelengths. This thermal emission component peaks at wavelengths around 100 to 140 μm. The EBL spectrum exhibits a minimum at mid-IR wavelengths (10 - 30 μm), reflecting the decreasing intensity of the stellar contribution at the Rayleigh-Jeans part of the spectrum, and the paucity of very hot dust that can radiate at these wavelengths.

All energy or particle releases associated with the birth, evolution, and death of stars can ultimately be related to or constrained by the intensity or spectral energy distribution (SED) of the EBL. The energy output from AGN represent a major non-nuclear contribution to the radiative energy budget of the EBL. Most of the radiative output of the AGN emerges at X-ray, UV, and optical wavelengths. However, a significant fraction of the AGN output can be absorbed by dust in the torus surrounding the accreting black hole, and reradiated at IR wavelengths. In addition to the radiative output from star forming galaxies and AGN, the EBL may also harbor the radiative imprint of a variety of "exotic" objects including Population III stars, decaying particles, and primordial massive objects. EBL measurements can be used to constrain the contributions of such exotic components.

Direct detection and measurements of the EBL are hindered by the fact that it has no distinctive spectral signature, by the presence of strong foreground emission from the interplanetary (zodiacal) dust cloud, and from the stars and interstellar medium of the Galaxy. Results obtained from TeV gamma-ray observations will complement the results from a number of NASA missions, i.e. Spitzer, Herschel, the Wide-Field Infrared Survey Explorer (WISE), and the James Webb Space Telescope (JWST). In order to derive the EBL density and spectrum via gamma-ray absorption, ideally one would use an astrophysical standard candle of gamma rays to measure the absorption component imprinted onto the observed spectrum. In contrast, extragalactic TeV gamma-ray sources detected to date are highly variable AGN. Their gamma-ray emission models are not unanimously agreed upon, making it impossible to predict the intrinsic source spectrum. Therefore, complementary methods are required for a convincing detection of EBL attenuation. Various approaches have been explored to constrain/measure the EBL intensity [199, 262, 263, 264, 265, 266], ranging from searching for cutoffs, the assumption of plausible theoretical source models, the possibility of using contemporaneous X-ray to TeV measurements combined with emission models and the concept of simultaneous constraints from direct IR measurements/limits combined with TeV data via exclusion of unphysical gamma-ray spectra. All of these techniques are useful; however, none has so far provided an unequivocal result independent of assumed source spectra.

The next-generation gamma-ray experiments will allow us to use the flux and spectral variability of blazars [267, 268, 269] to separate variable source phenomena from external persistent spectral features associated with absorption of the gamma-ray beam by the EBL. Redshift dependent studies are required to distinguish possible absorption by radiation fields nearby the source from extragalactic absorption. The most prominent feature of blazars is their occasional brightness (sometimes $>$ 10 Crab) yielding a wealth of photon statistics. Those flares are to date the most promising tests of the EBL density based on absorption. To constrain the EBL between the UV/optical all the way to the far IR a statistical sample of gamma-ray sources, and a broader energy coverage with properly matched sensitivity are required.

Since the cross-section for the absorption of a given gamma-ray energy is maximized at a specific target photon wavelength (e.g., a 1 TeV gamma-ray encounters a 0.7 eV soft photon with maximum cross-section), there is a natural division of EBL studies with gamma rays into three regions: the UV to optical light, the near- to mid-IR and the mid- to far-IR portion of the EBL are the most effective absorbers for $\approx$ 10 - 100 GeV, the $\approx$ 0.1 TeV to 10 TeV and the $\approx$ 10 - 100 TeV regime, correspondingly.

In the search for evidence of EBL absorption in blazar spectra it is important to give consideration to the shape of the EBL spectrum showing a near IR peak, a mid IR valley and a far IR peak; absorption could imprint different features onto the observed blazar spectra. For example, a cutoff from the rapid increase of the opacity with gamma-ray energy and redshift is expected to be most pronounced in an energy spectral regime that corresponds to a rising EBL density; e.g., as is found between 0.1 - 2 micron. This corresponds to gamma ray energies of 10 GeV - 100 GeV. A survey with an instrument with sensitivity in the 10 GeV to several 100s of GeV could measure a cutoff over a wide range of redshifts and constrain the UV/optical IR part of the EBL. Fermi, together with existing ground-based telescopes, is promising in yielding first indications or maybe first conclusive results for a detection of the EBL absorption feature. However, an instrument with a large collection area over the given energy range by using the ground-based gamma-ray detection technique would allow stringent tests via spectral variability measurements.

Similarly, a substantial rise in the opacity with gamma-ray energy is expected in the energy regime above 20 TeV, stemming from the far IR peak. A corresponding cutoff should occur in the 20-50 TeV regime. Prospective candidate objects are Mrk 421, Mrk 501 or 1ES1959+650, as they provide episodes of high gamma-ray fluxes, allowing a search for a cutoff with ground-based instruments that have substantially enlarged collection areas in 10 - 100 TeV regime. Sensitivity for detection of a cutoff in this energy regime requires IACTs with a collection area in excess of 1km^2.

Finally, a promising and important regime for ground-based telescopes to contribute to EBL constraints lies in the near and the mid IR (0.5 - 5 micron). The peak in the near IR and the slope of decline in the mid IR could lead to unique spectral imprints onto blazar spectra around 1-2 TeV, assuming sufficient instrumental sensitivity. A steep decline could lead to a decrease in opacity, whereas a minimal decline could result in steepening of the slope of the source spectrum. If this feature is sufficiently pronounced and/or the sensitivity of the instrument is sufficient, it could be a powerful method in unambiguously deriving the level of absorption and discerning the relative near to mid IR density. The location of the near IR peak and, consequently, the corresponding change in absorption, is expected to occur around 1.5 TeV, which requires excellent sensitivity between 100 GeV and 10 TeV. The discovery of a signature for EBL absorption at a characteristic energy would be extremely valuable in establishing the level of absorption in the near to mid IR regime. The origin of any signature could be tested using spectral variations in blazar spectra and discerning a stable component.

A powerful tool for studying the redshift dependence of the EBL intensity are pair haloes [270]. For suitable IGMF strengths, such haloes will form around powerful emitters of >100 TeV gamma rays or UHECRs, e.g. AGN and galaxy clusters. If the intergalactic magnetic field (IGMF) is not too strong, the high-energy radiation will initiate intergalactic electromagnetic pair production and inverse Compton cascades. For an intergalactic magnetic field (IGMF) in the range between 10^{-12} G and 10^{-9} G the electrons and positrons can isotropize and can result in a spherical halo glowing predominantly in the 100 GeV – 1 TeV energy range. These haloes should have large extent with radial sizes > 1 Mpc. The size of a 100 GeV halo surrounding an extragalactic source at a distance of 1 Gpc could be less than 3° and be detectable with a next-generation IACT experiment. The measurement of the angular diameter of such a halo gives a direct estimate of the local EBL intensity at the redshift of the pair halo. Detection of several haloes would thus allow us to obtain unique information about the total amount of IR light produced by the galaxy populations at different redshifts.

For a rather weak IGMF between $\sim 10^{-16}$ G and $\sim 10^{-24}$ G, pair creation/inverse Compton cascades may create a GeV/TeV "echo" of a TeV GRB or AGN flare [449]. The IGMF may be dominated by a primordial component from quantum fluctuations during the inflationary epoch of the Universe, or from later contributions by Population III stars, AGN, or normal galaxies. The time delay between the prompt and delayed emission depends on the deflection of the electrons by the IGMF, and afford the unique possibility to measure the IGMF in the above mentioned interval of field strengths.

6 Gamma-ray bursts

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6.1 Introduction

High energy astrophysics is a young and relatively undeveloped field, which owns much of the unexplored "discovery space" in contemporary astronomy. The edge of this discovery space has recently been illuminated by the current generation of very high energy (VHE) telescopes, which have discovered a diverse catalog of more than seventy VHE sources. At this time, gamma ray bursts (GRBs) have eluded attempts to detect them with VHE telescopes (although some tentative, low-significance detections have been reported). However, theoretical predictions place them near the sensitivity limits of current instruments. The time is therefore at hand to increase VHE telescope sensitivity, thus facilitating the detection of these extreme and mysterious objects.

Much has been learned since the discovery of GRBs in the late 1960s. There are at least two classes of GRB, most conveniently referred to as "long" and "short," based on the duration and spectral hardness of their prompt sub-MeV emission. The distribution of the types and star formation rates of the host galaxies suggests different progenitors for these two classes. The exact nature of the progenitors nevertheless remains unknown, although it is widely believed that long GRBs come from the deaths of massive rotating stars and short GRBs result from compact object mergers. The unambiguous solution to this mystery is critical to astrophysics since it has fundamental importance to several topics, including stellar formation history and ultra high energy cosmic ray acceleration. A detection of VHE emission from GRBs would severely constrain the physical parameters surrounding the particle acceleration from GRBs and the energy injected into the particle acceleration sites, and would therefore constrain the properties of the GRB progenitors themselves. These same observations would constrain models for cosmic ray acceleration.

One of the big questions regarding GRBs is whether the jets are dominated by ultrarelativistic protons, that interact with either the radiation field or the background plasma, or are dominated by e^+e^- pairs. The combination of Fermi and current generation VHE telescopes such as HESS, MAGIC and VERITAS will contribute to progress on these questions in the near term, but more sensitive observations will likely be needed.

The same shocks which are thought to accelerate electrons responsible for non-thermal γ-rays in GRBs should also accelerate protons. Both the internal and the external reverse shocks are expected to be mildly relativistic, and are expected to lead to relativistic protons. The maximum proton energies achievable in GRB shocks are estimated to be $\sim 10^{20}$ eV, comparable to the highest energies of the mysterious ultra high energy cosmic rays measured with large ground arrays. The accelerated protons can interact with the fireball photons, leading to pions, followed by high-energy gamma rays, muons, and neutrinos. Photopion production is enhanced in conditions of high internal photon target density, whereas if the density of (higher-energy) photons is too large, the fireball is optically thick to gamma-rays, even in a purely leptonic outflow. High-energy gamma-ray studies of GRBs provide a direct probe of the shock proton acceleration as well as of the photon density.

6.1.1 Status of theory on emission models

Gamma-ray burst νF_ν spectra have a peak at photon energies ranging from a few keV to several MeV, and the spectra are nonthermal. From EGRET data, it is clear that the spectra extend to at least several GeV [283, 284, 285, 286], and there is a possible detection in the TeV range by

Milagrito [287, 288]. These non-thermal spectra imply that a significant fraction of the explosion energy is first converted into another form of energy before being dissipated and converted to nonthermal radiation. The most widely accepted interpretation is the conversion of the explosion energy into kinetic energy of a relativistic flow [289, 290, 291]. At a second stage, the kinetic energy is converted into radiation via internal collisions (internal shock model) resulting from variability in the ejection from the progenitor [292, 293] or an external collision (external shock model) with the surrounding medium [294, 295, 296]. The collisions produce shock waves, which enhance and are believed to create magnetic fields, as well as to accelerate electrons to high energies [297, 298, 299, 300, 301]. In the standard theoretical model, the initial burst of emission described above (prompt emission) is followed by afterglow emission, discussed below, from an external shock that moves through the circumburst environment.

Flux variability in GRBs is seen on timescales as short as milliseconds and can occur at late times. This rapid variability can be easily explained in the internal shock model, which makes it the most widely used model. It can also be explained in the context of the external shock model either if one assumes variations in the strength of the magnetic field or in the energy transfer to the non-thermal electrons [302], or by collisions of the outflow with small, high density clouds in the surrounding medium [295, 296].

An alternative way of producing the emission involves conversion of the explosion energy into magnetic energy [303, 304, 305], which produces a flow that is Poynting-flux dominated. The emission is produced following dissipation of the magnetic energy via reconnection of the magnetic field lines [306, 307, 308, 309]. An apparent advantage of this model over the internal or external shock model is that the conversion of energy to radiation is much more efficient (see [310, 311] on the efficiency problem in the internal shocks model). The microphysics of the reconnection process in this model, like the microphysics determining the fraction of energy in relativistic electrons and in the magnetic field in the internal and external shock scenarios, is not yet fully understood.

VHE observations probe the extremes of the efficiency of energy conversion for each of these models and simultaneously probe the environment where the emission originated.

The dissipation of kinetic and/or magnetic energy leads to the emission of radiation. The leading emission mechanism employed to interpret the GRB prompt emission in the keV-MeV region of the spectral energy distribution is nonthermal synchrotron radiation [312, 313, 314]. An order of magnitude estimate of the maximum observed energy of photons produced by synchrotron emission was derived in [315]: Assuming that the electrons are Fermi accelerated in the shock waves, the maximum Lorentz factor of the accelerated electrons $\gamma_{\max}$ is found by equating the particle acceleration time and the synchrotron cooling time, yielding $\gamma_{\max} = 10^5/\sqrt{B/10^6}$, where B is the magnetic field strength in gauss. For relativistic motion with bulk Lorentz factor Γ at redshift z, synchrotron emission from electrons with $\gamma_{\max}$ peaks in the observer's frame at energy $70\,(\Gamma/315)(1+z)^{-1}$ GeV, which is independent of the magnetic field. Thus, synchrotron emission can produce photons with energies up to, and possibly exceeding, $\sim$100 GeV.

Many of the observed GRB spectra were found to be consistent with the synchrotron emission interpretation [316, 317, 318]. However, a significant fraction of the observed spectra were found to be too hard (spectral photon index harder than 2/3 at low energies) to be accounted for by this model [319, 320, 321, 322, 323]. This motivated studies of magnetic field tangling on very short spatial scales [324], anisotropies in the electron pitch angle distributions [325, 326], reprocessing of radiation by an optically thick cloud heated by the impinging gamma rays [327] or by synchrotron self absorption [328], and the contribution of a photospheric (thermal) component [329, 330, 331]. A thermal component that accompanies the first stages of the overall nonthermal emission and decays after a few seconds was consistent with some observations [332, 333]. Besides explaining the hard spectra observed in some of the GRBs seen by the Burst and Transient Source Experiment (BATSE), the thermal component provides seed photons that can be Compton scattered by relativistic electrons, resulting in a potential VHE gamma ray emission signature that can be tested.

A natural emission mechanism that can contribute to emission at high energies ($\gtrsim$MeV) is inverse-Compton (IC) scattering. The seed photons for the scattering can be synchrotron photons emitted by the same electrons, namely synchrotron self-Compton (SSC) emission [334, 335, 336, 337, 338, 339, 340, 341], although in some situations this generates MeV-band peaks broader than those observed [342]. The seed photons can also be thermal emission originating from the photosphere [343, 344], an accretion disk [345], an accompanying supernova remnant [346, 347], or supernova emissions in two-step collapse scenarios [348]. Compton scattering of photons can produce emission up to observed energies $15\,(\gamma_{\max}/10^5)\,(\Gamma/315)(1+z)^{-1}$ TeV, well into the VHE regime.

The shapes of the Comptonized emission spectra in GRBs depend on the spectra of the seed photons and the energy and pitch-angle distributions of the electrons. A thermal population of electrons can inverse-Compton scatter seed thermal photons [349] or photons at energies below the synchrotron self-absorption frequency to produce the observed peak at sub-MeV energies [350]. Since the electrons cool by the IC process, a variety of spectra can be obtained [315, 344]. Comptonization can produce a dominant high-energy component [351] that can explain hard high-energy spectral components, such as that observed in GRB 941017 [286, 352, 353]. Prolonged higher energy emission could potentially be observed with a sensitive VHE gamma ray instrument.

The maximum observed photon energy from GRBs is limited by the annihilation of gamma rays with target photons, both extragalactic IR background and photons local to the GRB, to produce electron-positron pairs. This limit is sensitive to the uncertain value of the bulk motion Lorentz factor as well as to the spectrum at low energies, and is typically in the sub-TeV regime. Generally, escape of high-energy photons requires large Lorentz factors. In fact, observations of GeV photons have been used to constrain the minimum Lorentz factor of the bulk motion of the flow [354, 355, 356, 357, 358, 359], and spectral coverage up to TeV energies could further constrain the Lorentz factor [360, 361, 362]. If the Lorentz factor can be determined independently, e.g. from afterglow modeling, then the annihilation signature can be used to diagnose the gamma-ray emission region [363].

The evidence for acceleration of leptons in GRB blast waves is based on fitting lepton synchrotron spectra models to GRB spectra. This consistency of leptonic models with observed spectra still allows the possibility of hadronic components in these bursts, and perhaps more importantly, GRBs with higher energy emission have not been explored for such hadronic components due to the lack of sensitive instruments in the GeV/TeV energy range. The crucially important high-energy emission components, represented by only 5 EGRET spark chamber bursts, a handful of BATSE and EGRET/TASC GRBs, and a marginal significance Milagrito TeV detection, were statistically inadequate to look for correlations between high-energy and keV/MeV emission that can be attributed to a particular process. Indeed, the prolonged high-energy components in GRB 940217 and the "superbowl" burst, GRB 930131, and the anomalous gamma-ray emission component in GRB 941017, behave quite differently than the measured low-energy gamma-ray light curves. Therefore, it is quite plausible that hadronic emission components are found in the high energy spectra of GRBs.

Several theoretical mechanisms exist for hadronic VHE emission components. Accelerated protons can emit synchrotron radiation in the GeV–TeV energy band [364, 365, 366]. The power emitted by a particle is $\propto \gamma^2/m^2$, where γ is the Lorentz factor of the particle and m is its mass. Given the larger mass of the proton, to achieve the same output luminosity, the protons have $\sim$1836 times higher mean Lorentz factor, the acceleration mechanism must convert

~ 3 million times more energy to protons than electrons and the peak of the proton emission would be at $\gtrsim 2000$ times higher energy than the peak energy of photons emitted by the electrons. Alternatively, high-energy baryons can produce energetic pions, via photomeson interactions with the low energy photons, creating high-energy photons and neutrinos following the pion decay [365, 367, 368, 369, 370, 371]. This process could be the primary source of ultra high energy (UHE) neutrinos. Correlations between gamma-ray opacity, bulk Lorentz factor, and neutrino production will test whether GRBs are UHE cosmic ray sources [372]. If the neutrino production is too weak to be detected, then the former two measurements can be obtained independently with sensitive GeV-TeV γ-ray telescopes and combined to test for UHE cosmic ray production. Finally, proton-proton or proton-neutron collisions may also be a source of pions [292, 373, 374, 375, 376], and in addition, if there are neutrons in the flow, then the neutron β-decay has a drag effect on the protons, which may produce another source of radiation [377]. Each of these cases has a VHE spectral shape and intensity that can be studied coupled with the emission measured at lower energies and with neutrino measurements.

Afterglow emission is explained in synchrotron-shock models by the same processes that occur during the prompt phase. The key difference is that the afterglow emission originates from large radii, $\gtrsim 10^{17}$ cm, as opposed to the much smaller radius of the flow during the prompt emission phase, $\simeq 10^{12} - 10^{14}$ cm for internal shocks, and $\simeq 10^{14} - 10^{16}$ cm for external shocks. As a result, the density of the blast-wave shell material is smaller during the afterglow emission phase than in the prompt phase, and some of the radiative mechanisms, e.g. thermal collision processes, may become less important.

Breaks in the observed lightcurves, abrupt changes in the power law slope, are attributed to a variety of phenomena, such as refreshed shocks originating from late time central engine activity [378, 379], aspherical variations in the energy [380], or variations in the external density [381, 382]. Blast wave energy escaping in the form of UHE neutrals and cosmic rays can also produce a rapid decay in the X-ray light curve [296]. In addition, interaction of the blast wave with the wind termination shock of the progenitor may be the source of a jump in the lightcurve [383, 384, 385], although this bump may not be present at a significant level [386]. High-energy gamma-ray observations may show whether new photohadronic emission mechanisms are required, or if the breaks do not require new radiation mechanisms for explanation (see, e.g., [387, 388]).

6.1.2 GRB Progenitors

We still do not know the exact progenitors of GRBs, and it is therefore difficult, if not impossible, to understand the cause of these cosmic explosions. These GRB sources involve emission of energies that can exceed 10^{50} ergs. The seat of this activity is extraordinarily compact, as indicated by rapid variability of the radiation flux on time scales as short as milliseconds. It is unlikely that mass can be converted into energy with better than a few (up to ten) percent efficiency; therefore, the more powerful short GRB sources must "process" upwards of $10^{-3}M_{\odot}$ through a region which is not much larger than the size of a neutron star (NS) or a stellar mass black hole (BH). No other entity can convert mass to energy with such a high efficiency, or within such a small volume. The leading contender for the production of the longer class of GRBs — supported by observations of supernovae associated with several bursts — is the catastrophic collapse of massive, rapidly rotating stars. The current preferred model for short bursts, the merger of binary systems of compact objects, such as double neutron star systems (e.g. Hulse-Taylor pulsar systems) is less well established. A fundamental problem posed by GRB sources is how to generate over 10^{50} erg in the burst nucleus and channel it into collimated relativistic plasma jets.

The progenitors of GRBs are essentially masked by the resulting fireball, which reveals little more than the basic energetics and microphysical parameters of relativistic shocks. Although long and short bursts most likely have different progenitors, the observed radiation is very similar. Progress in understanding the progenitors can come from determining the burst environment, the kinetic energy and Lorentz factor of the ejecta, the duration of the central engine activity, and the redshift distribution. VHE gamma-ray observations can play a supporting role in this work. To the extent that we understand GRB emission across the electromagnetic spectrum, we can look for the imprint of the burst environment or absorption by the extragalactic background light on the spectrum as an indirect probe of the environment and distance, respectively. VHE emission may also prove to be crucial to the energy budget of many bursts, thus constraining the progenitor.

6.2 High-energy observations of gamma-ray bursts

Some of the most significant advances in GRB research have come from GRB correlative observations at longer wavelengths. Data on correlative observations at shorter wavelengths are sparse but tantalizing and inherently very important. One definitive observation of the prompt or afterglow emission could significantly influence our understanding of the processes at work in GRB emission and its aftermath. Although many authors have predicted its existence, the predictions are near or below the sensitivity of current instruments, and there has been no definitive detection of VHE emission from a GRB either during the prompt phase or at any time during the multi-component afterglow.

For the observation of photons of energies above 300 GeV, only ground-based telescopes are available. These ground-based telescopes fall into two broad categories, air shower arrays and imaging atmospheric Cherenkov telescopes (IACTs). The air shower arrays, which have wide fields of view that are suitable for GRB searches, are relatively insensitive. There are several reports from these instruments of possible TeV emission: emission >16 TeV from GRB 920925c [389], an indication of 10 TeV emission in a stacked analysis of 57 bursts [390], and an excess gamma-ray signal during the prompt phase of GRB 970417a [287]. In all of these cases however, the statistical significance of the detection is not high enough to be conclusive. In addition to searching the Milagro data for VHE counterparts for over 100 satellite-triggered GRBs since 2000 [391, 392, 393], the Milagro Collaboration conducted a search for VHE transients of 40 seconds to 3 hours duration in the northern sky [394]; no evidence for VHE emission was found from these searches.

IACTs have better flux sensitivity and energy resolution than air shower arrays, but are limited by their small fields of view (3–5°) and low duty cycle (∼10%). In the BATSE [395] era (1991–2000), attempts at GRB monitoring were limited by slew times and uncertainty in the GRB source position [396]. More recently, VHE upper limits from 20% to 62% of the Crab flux at late times ($\gtrsim$4 hours) were obtained with Whipple Telescope for seven GRBs in 2002-2004 [397]. The MAGIC Collaboration took observations of GRB 050713a beginning 40 seconds after the prompt emission but saw no evidence for VHE emission [398]. Follow-up GRB observations have been made on many more GRBs by the MAGIC Collaboration [399] but no detections have been made [400, 401]. Upper limits of 2–7% of the Crab flux on the VHE emission following three GRBs have also been obtained with VERITAS [402].

One of the main obstacles for VHE observations of GRBs is the distance scale. Pair production interactions of gamma rays with the infrared photons of the extragalactic background light attenuate the gamma-ray signal, limiting the distance over which VHE gamma rays can propagate. The MAGIC Collaboration has reported the detection of 3C279, at redshift of 0.536 [403]. This represents a large increase in distance to the furthest detected VHE source, revealing more of the universe to be visible to VHE astronomers than was previously thought.

6.3 High Energy Emission Predictions for Long Bursts

As described earlier, long duration GRBs are generally believed to be associated with core collapses of massive rotating stars [404, 405], which lead to particle acceleration by relativistic internal shocks in jets. The isotropic-equivalent gamma-ray luminosity can vary from 10^{47} erg s^{-1} all the way to 10^{53} erg s^{-1}. They are distributed in a wide redshift range (from 0.0085 for GRB 980425 [406] to 6.29 for GRB 050904 [407], with a mean redshift of 2.3–2.7 for Swift bursts, e.g. [408, 409]). The low redshift long GRBs ($z \lesssim 0.1$, e.g. GRB 060218, $z = 0.033$ [410]) are typically sub-luminous with luminosities of $10^{47} - 10^{49}$ erg s^{-1} and spectral peaks at lower energies, so they are less likely detected at high energy. However, one nearby, "normal" long GRB has been detected (GRB 030329, $z = 0.168$), which has large fluences in both its prompt gamma-ray emission and afterglow.

6.3.1 Prompt emission

The leading model of the GRB prompt emission is the internal shock model [293], and we begin by discussing prompt emission in that context. The relative importance of the leptonic vs. hadronic components for high energy photon emission depends on the unknown shock equipartition parameters, usually denoted as ϵ_e, ϵ_B and ϵ_p for the energy fractions carried by electrons, magnetic fields, and protons, respectively. Since electrons are much more efficient emitters than protons, the leptonic emission components usually dominate unless ϵ_e is very small. Figure 23a displays the broadband spectrum of a long GRB within the internal shock model for a particular choice of parameters [411]. Since the phenomenological shock microphysics is poorly known, modelers usually introduce ϵ_e, ϵ_B, ϵ_p as free parameters. For ϵ_e's not too small ($\gtrsim 10^{-3}$), the high energy spectrum is dominated by the electron IC component, as in Fig. 23a. For smaller ϵ_e's (e.g. $\epsilon_e = 10^{-3}$), on the other hand, the hadronic components become at least comparable to the leptonic component above ~100 GeV, and the π^0-decay component dominates the spectrum above ~10 TeV.

A bright GRB, 080319B, with a plethora of multiwavelength observations has recently allowed very detailed spectral modelling as a function of time, and it has shown that an additional high energy component may play an important role. For GRB 080319B, the bright optical flash suggests a synchroton origin for the optical emission and SSC production of the ~500 keV gamma-rays [412]. The intensity of these gamma rays would be sufficient to produce a second-order IC peak around 10–100 GeV.

Due to the high photon number density in the emission region of GRBs, high energy photons have an optical depth for photon-photon pair production greater than unity above a critical energy, producing a sharp spectral cutoff, which depends on the unknown bulk Lorentz factor of the fireball and the variability time scale of the central engine, which sets the size of the emission region. Of course, the shape of time-integrated spectra will also be modified (probably to power laws rolling over to steeper power laws) due to averaging of evolving instantaneous spectra [413]. For the nominal bulk Lorentz factor $\Gamma = 400$ (as suggested by recent afterglow observations, e.g. [414]) and for a typical variability time scale $t_v = 0.01$ s, the cut off energy is about several tens of GeV. Below 10 GeV, the spectrum is mostly dominated by the electron synchrotron emission, so that with the observed high energy spectrum alone, usually there is no clean differentiation of the leptonic vs. hadronic origin of the high energy gamma-rays. Such an issue may however be addressed by collecting both prompt and afterglow data. Since a small ϵ_e is needed for a hadronic-component-dominated high energy emission, these fireballs must have a very low efficiency for radiation, $\lesssim \epsilon_e$, and most of the energy will be carried by the afterglow. As a result, a moderate-to-high radiative efficiency would suggest a leptonic origin of high energy photons, while a GRB with an extremely low radiative efficiency but an extended high energy emission component would be consistent with (but not a proof for) the hadronic origin. If the

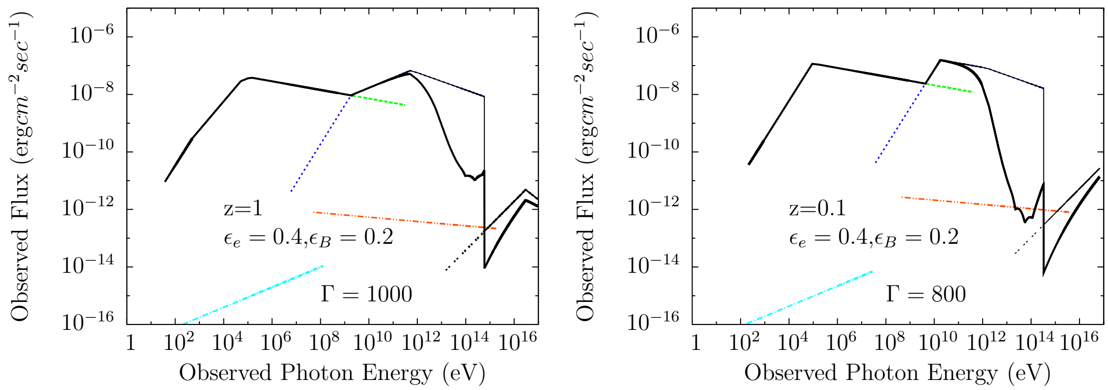

Figure 23: Broad-band spectrum of the GRB prompt emission within the internal shock model (from [411]). (a) A long GRB with the observed sub-MeV luminosity of $\sim 10^{51}$ erg s^{-1}, is modeled for parameters as given in the figure. The solid black lines represent the final spectrum before (thin line) and after (thick line) including the effect of internal optical depths. The long dashed green line (mostly hidden) is the electron synchrotron component; the short-dashed blue line is the electron IC component; the double short-dashed black curve on the right side is the π^0 decay component; the triple short-dashed dashed line represents the synchrotron radiation produced by e$^\pm$ from $\pi^\pm$ decays; the dash-dotted (light blue) line represents the proton synchrotron component. (b) The analogous spectrum of a bright short GRB with 10^{51} erg isotropic-equivalent energy release.

fireball has a much larger Lorentz factor ($\gtrsim 800$), the spectral cutoff energy is higher, as in Fig. 23. This would allow a larger spectral space to diagnose the origin of the GRB high energy emission and would place the cutoff energies in the spectral region that can only be addressed by VHE telescopes. At even higher energies, the fireball again becomes transparent to gamma rays [359], so that under ideal conditions, the $\sim$ PeV component due to π^0 decay can escape the fireball. Emission above one TeV escaping from GRBs would suffer additional external attenuation by the cosmic infrared background (CIB) and the cosmic microwave background (CMB), thus limiting VHE observations of GRBs to lower redshifts (e.g. z$\lesssim$0.5–1).

The external shock origin of prompt emission is less favored by the Swift observations, which show a rapidly falling light curve following the prompt emission before the emergence of a more slowly decaying component attributed to the external shock. A small fraction of bursts lack the initial steep component, in which case the prompt emission may result from an external shock. Photons up to TeV energies are expected in the external shock scenario [418], and the internal pair cut-off energy should be very high, more favorable to detection at VHE energies, because of the less compact emission region.

The "cannonball model" of GRBs [415], in which the prompt GRB emission is produced by IC scattering from blobs of relativistic material ("cannonballs"), can also be used to explain the keV/MeV prompt emission, but it does not predict significant VHE emission during the prompt phase. Sensitive VHE observations would provide a strong constraint to differentiate between these models. The cannonball model could still produce delayed VHE emission during the deceleration phase, in much the same way as the fireball model: as a consequence of IC scattering from relativistic electrons accelerated by the ejecta associated with the burst [416].

6.3.2 Deceleration phase

A GRB fireball would be significantly decelerated by the circumburst medium starting from a distance of $10^{16} - 10^{17}$ cm from the central engine, at which point a pair of shocks propagate into the circumburst medium and the ejecta, respectively. Both shocks contain a similar amount of energy. Electrons from either shock region would Compton scatter the soft seed synchrotron photons from both regions to produce high energy photons [334, 352, 353, 417, 418, 419, 420].

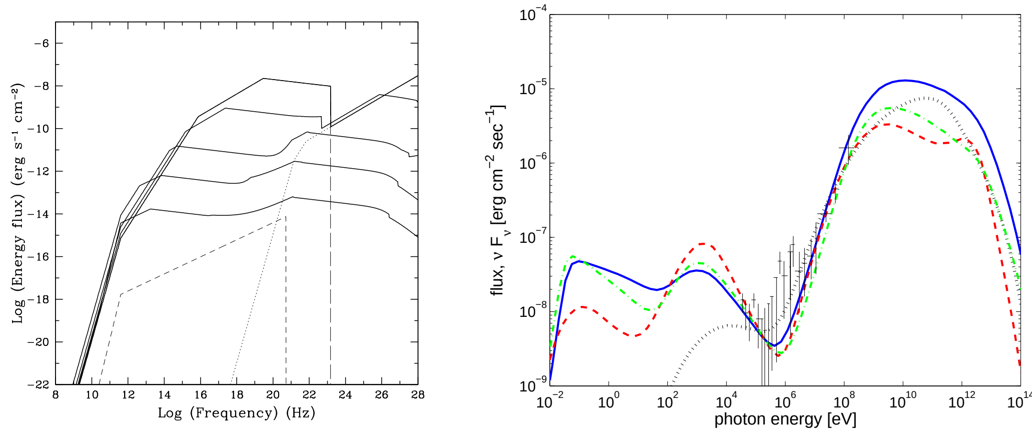

Figure 24: (a) The SSC emission from the forward shock region in the deceleration phase. Temporal evolution of the theoretical models for synchrotron and SSC components for $\epsilon_e = 0.5$, $\epsilon_B = 0.01$; solid curves from top to bottom are at onset, 1 min, 1 hour, 1 day, 1 month. The contributions to the emission at onset are shown as long-dashed (electron-synchrotron), short-dashed (proton-synchrotron) and dotted (electron IC) curves [417]. (b) Fit to the prompt emission data of GRB 941017 using the IC model of Ref. [353].

Compared with the internal shock radius, the deceleration radius corresponds to a low "compactness" so that high energy photons more readily escape from the source. Figure 24(a) presents the theoretical forward shock high energy emission components as a function of time for the regime of IC dominance (from [417]). It is evident that during the first several minutes of the deceleration time, the high energy emission could extend to beyond $\sim$ 10 TeV. Detection of this emission by ground-based VHE detectors, for sources close enough to have little absorption by the IR background, would be an important test of this paradigm.

Various IC processes have been considered to interpret the distinct high energy component detected in GRB 941017 [286, 352]. For preferable parameters, the IC emission of forward shock electrons off the self-absorbed reverse shock emission can interpret the observed spectrum (Fig. 24b, [353]).

6.3.3 Steep decay

Swift observations revealed new features of the GRB afterglow. A canonical X-ray lightcurve generally consists of five components [422, 423]: a steep decay component (with decay index ~ -3 or steeper), a shallow decay component (with decay index ~ -0.5 but with a wide variation), a normal decay component (with decay index ~ -1.2), a putative post-jet-break component seen in a small group of GRBs at later times, and multiple X-ray flares with sharp rise and decay occurring in nearly half GRBs. Not all five components appear in every GRB, and the detailed afterglow measurements of GRB 080319B [412] present some challenges to the standard picture we describe here. The steep decay component [424] is generally interpreted as the tail of the prompt gamma-ray emission [422, 423, 425]. Within this interpretation, the steep decay phase corresponds to significant reduction of high energy flux as well. On the other hand, Ref. [296] suggests that the steep decay is the phase when the blastwave undergoes a strong discharge of its hadronic energy. Within such a scenario, strong high energy emission of hadronic origin is expected. Detection/non-detection of strong high energy emission during the X-ray steep decay phase would greatly constrain the origin of the steep decay phase.

6.3.4 Shallow decay

The shallow decay phase following the steep decay phase is still not well understood [426, 427, 428]. The standard interpretation is that the external forward shock is continuously refreshed by late energy injection, either from a long-term central engine, or from slower shells ejected in the prompt phase [422, 423, 429, 430]. Other options include delay of transfer of the fireball energy to the medium [431], a line of sight outside the region of prominent afterglow emission [432], a two-component jet model [433], and time varying shock micro-physics parameters [433, 434, 435].

Since the pre-Swift knowledge of the afterglow kinetic energy comes from the late afterglow observations, the existence of the shallow decay phase suggests that the previously estimated external SSC emission strength is overestimated during the early afterglow. A modified SSC model including the energy injection effect indeed gives less significant SSC flux [436, 437]. The SSC component nonetheless is still detectable by Fermi and higher energy detectors for some choices of parameters. Hence, detections or limits from VHE observations constrain those parameters. If, however, the shallow decay phase is not the result of a smaller energy in the afterglow shock at early times, compared to later times, but instead due to a lower efficiency in producing the X-ray luminosity, the luminosity at higher photon energies could still be high, and perhaps comparable to (or even in excess of) pre-Swift expectations. Furthermore, the different explanations for the flat decay phase predict different high-energy emission, so the latter could help distinguish between the various models. For example, in the energy injection scenario, the reverse shock is highly relativistic for a continuous long-lived relativistic wind from the central source, but only mildly relativistic for an outflow that was ejected during the prompt GRB with a wide range of Lorentz factors and that gradually catches up with the afterglow shock. The different expectations for the high-energy emission in these two cases may be tested against future observations.

6.3.5 High-energy photons associated with X-ray flares

X-ray flares have been detected during the early afterglows in a significant fraction of gamma-ray bursts (e.g. [438, 439, 440]). The amplitude of an X-ray flare with respect to the background afterglow flux can be up to a factor of $\sim$500 and the fluence can approximately equal the prompt emission fluence (e.g. GRB 050502B [438, 441]). The rapid rise and decay behavior of some flares suggests that they are caused by internal dissipation of energy due to late central engine activity [422, 438, 441, 442]. There are two likely processes that can produce very high energy (VHE) photons. One process is that the inner flare photons, when passing through the forward shocks, would interact with the shocked electrons and get boosted to higher energies. Another process is the SSC scattering within the X-ray flare region [437, 443].

Figure 25 shows an example of IC scattering of flare photons by the afterglow electrons for a flare of duration δt superimposed upon an underlying power law X-ray afterglow around time $t_f = 1000\,\mathrm{s}$ after the burst, as observed in GRB 050502B. The duration of the IC emission is lengthened by the angular spreading effect and the anisotropic scattering effect as well [437, 443]. Using the calculation of [443], for typical parameters as given in the caption, νF_ν at 1 TeV reaches about 4×10^{-11} erg cm^{-2} s^{-1}, with a total duration of about 2000 s.

The peak energy of the SSC scattering within the X-ray flare region lies at tens of MeV [443] to a few hundreds of MeV [437]. The flares may come from internal dissipation processes similar to the prompt emission, so their dissipation radius may be much smaller than that of the afterglow external shock. A smaller dissipation radius causes strong internal absorption to very high energy photons. For a flare with luminosity $L_x \sim 10^{48}$ erg s^{-1} and duration $\delta t = 100$ s, the VHE photons can escape only if the dissipation radius is larger than $\sim 10^{16}$ cm. So in general, even for a strong X-ray flare occurring at small dissipation radius, the SSC emission at TeV energies should be lower than the IC component above.

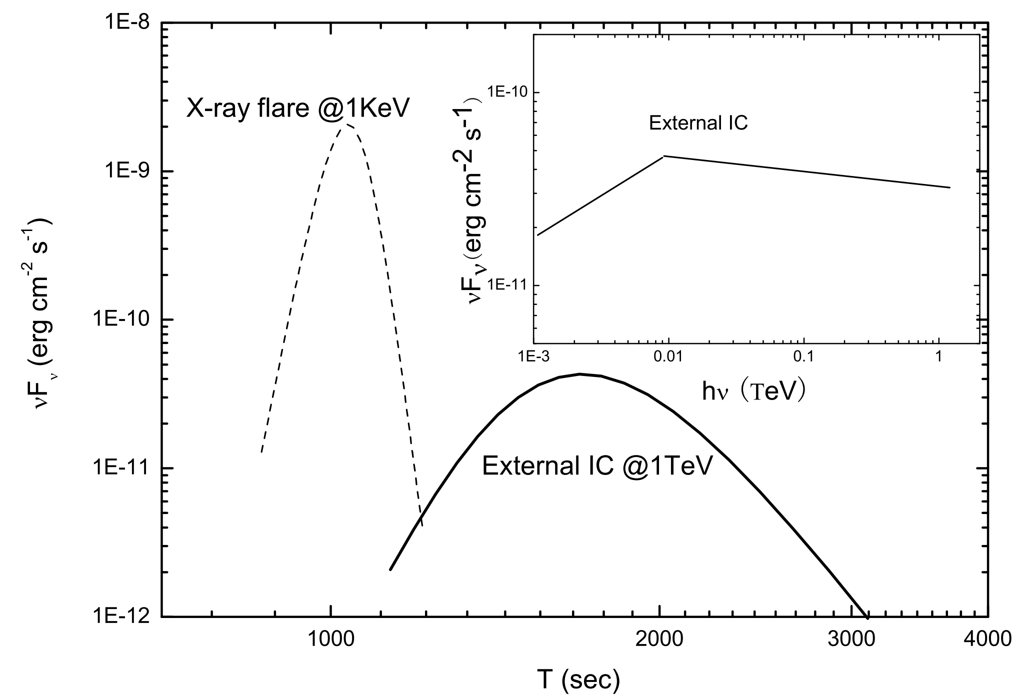

Figure 25: The expected light curves (main figure) and spectral energy distribution (insert figure) of IC scattering of X-ray flare photons by forward shock electrons. The flux is calculated according to [443], based on the following parameters: 10^{53} erg blast wave energy, electron energy distribution index 2.2, electron equipartition factor $\epsilon_e = 0.1$, 1 keV peak energy of the X-ray flare, $10^{28.5}$ cm source distance and that the flare has $\delta t/t_f = 0.3$.

6.3.6 High-energy photons from external reprocessing

Very high energy photons above 100 GeV produced by GRBs at cosmological distances are subject to photon-photon attenuation by the CIB (e.g. [444, 445]) and CMB. The attenuation of E TeV photons by the CIB would produce secondary electron-positron pairs with a Lorentz factor of $\gamma_e \simeq 10^6 E$, which in turn IC scatter off CMB photons to produce MeV–GeV emission [359, 446, 447, 448]. This emission is delayed relative to the primary photons by two mechanisms: one is the opening angles of the scattering processes, producing a deviation from the direction of the original TeV photons by an angle $1/\gamma_e$; the other is the deflection of the secondary pairs in the intergalactic magnetic field [449]. Only if the intergalactic magnetic field is less than $\sim 10^{-16}$ G would the delayed secondary gamma-rays still be beamed from the same direction as the GRB.

6.4 High Energy Emission Predictions for Short Bursts

Recent observational breakthroughs [450, 451, 452, 453, 454] suggest that at least some short GRBs are nearby low-luminosity GRBs that are associated with old stellar populations and likely to be compact star mergers. The X-ray afterglows of short duration GRBs are typically much fainter than those of long GRBs, which is consistent with having a smaller total energy budget and a lower density environment as expected from the compact star merger scenarios. Observations suggest that except being fainter, the afterglows of short GRBs are not distinctly different from those of long GRBs. The long duration GRB 060614 has a short, hard emission episode followed by extended softer emission. It is a nearby GRB, but has no supernova association, suggesting that 060614-like GRBs are more energetic versions of short GRBs [455, 456].

The radiation physics of short GRBs is believed to be similar to that of long GRBs. As a result, all the processes discussed above for long GRBs are relevant to short GRBs as well. The predicted prompt emission spectrum of a bright short GRB is presented in Fig. 23b [411]. Figure 23b is calculated for a comparatively bright, 1-second burst at redshift 0.1 with isotropic-equivalent luminosity 10^{51} erg s^{-1}. Fig. 23b suggests that the high energy component of such a burst is barely detectable by Fermi. Due to internal optical depth, the spectrum is cut off beyond about 100 GeV. VHE observations can constrain the bulk Lorentz factor, since VHE emission can be achievable if the bulk Lorentz factor is even larger (e.g. 1000 or above).

No evidence of strong reverse shock emission from short GRBs exists. For the forward shock, the flux is typically nearly 100 times fainter than that of long GRBs. This is a combination of low isotropic energy and presumably a low ambient density. The SSC component in the forward shock region still leads to GeV-TeV emission, but the flux is scaled down by the same factor as the low energy afterglows. Multiple late-time X-ray flares have been detected for some short GRBs (e.g. GRB 070724 and GRB 050724), with at least some properties similar to the flares in long GRBs, so that the emission mechanisms discussed above for long GRB flares may also apply, scaled down accordingly. In general, short GRBs may be less prominent emitters of high energy photons than long GRBs, mainly due to their low fluence observed in both prompt emission and afterglows. A potential higher bulk Lorentz factor on the other hand facilitates the escaping of 100 GeV or even TeV photons from the internal emission region. Furthermore, a few short GRBs are detected at redshifts lower than 0.3, and the average short GRB redshift is much lower than that of long GRBs. This is favorable for TeV detection since the CIB absorption is greatly reduced at these redshifts.

6.5 Supernova-associated gamma-ray bursts

Nearby GRBs have been associated with spectroscopically identified supernovae, *e.g.*, GRB 980425/SN 1998bw, GRB 031203/SN 2003lw, GRB 060218/SN 1006aj, and GRB 030329/SN 2003lw. The processes discussed in the section on high-energy emission from long GRBs can all apply in these bursts, and with their close distances, VHE emission from these sources would not be significantly attenuated by the CIB. These bursts have low luminosity, but the internal absorption by soft prompt emission photons may therefore be lower, so that VHE photons originating from the internal shock are more likely to escape without significant absorption, compensating for the overall low flux. In addition, if there is a highly relativistic jet component associated with the supernovae, supernova shock breakout photons would be scattered to high energies by the shock-accelerated electrons in the forward shocks [457]. The strong thermal X-ray emission from GRB 060218 may be such a relativistic supernova shock breakout [410, 458]. It has been shown [457] that if the wind mass loss rate from the progenitor star is low, the $\gamma\gamma$ absorption cutoff energy at early times can be larger than $\sim$100 GeV, so VHE emission could be detected from these nearby SN-GRBs.

6.6 Ultra High Energy Cosmic Rays and GRBs

The origin of the UHE cosmic rays (UHECR) is an important unsolved problem. The idea that they originate from long duration GRBs is argued for a number of reasons. First, the power required for the cosmic rays above the "ankle" ($\sim 10^{19}$ eV) is within one or two orders of magnitude equal to the hard X-ray/γ-ray power of BATSE GRBs, assumed to be at average redshift unity [459, 460, 461]. Second, GRBs form powerful relativistic flows, providing extreme sites for particle acceleration consistent with the known physical limitations, e.g. size, required to achieve ultra high energy. Third, GRBs are expected to be associated with star-forming galaxies, so numerous UHECR sources would be found within the $\sim$ 100 Mpc GZK radius, thus avoiding the situation that there is no persistent powerful source within this radius. And, finally, various features in the medium- and high-energy γ-ray spectra of GRBs may be attributed to hadronic emission processes.

The required Lorentz factors of UHECRs, $\gtrsim 10^{10}$, exceed by orders of magnitude the baryon-loading parameter $\eta \gtrsim 100$ thought typical of GRB outflows. Thus the UHECRs must be accelerated by processes in the relativistic flows. The best-studied mechanism is Fermi acceleration at shocks, including external shocks when the GRB blast wave interacts with the surrounding medium, and internal shocks formed in an intermittent relativistic wind.

Protons and ions with nuclear charge Z are expected to be accelerated at shocks, just like electrons. The maximum energy in the internal shock model [459] or in the case of an external shock in a uniform density medium [462, 463] are both of order a few Z 10^{20} eV for typical expected burst parameters. Thus GRBs can accelerate UHECRs. The ultrarelativstic protons/ions in the GRB jet and blast wave can interact with ambient soft photons if the corresponding opacity is of the order of unity or higher, to form escaping neutral radiations (neutrons, γ-rays, and neutrinos). They may also interact with other baryons via inelastic nuclear production processes, again producing neutrals. So VHE gamma rays are a natural consequence of UHECR acceleration in GRBs. While leptonic models explain keV–MeV data as synchrotron or Compton radiation from accelerated primary electrons, and GeV–TeV emission from inverse-Compton scattering, a hadronic emission component at GeV–TeV energies can also be present.

Neutrons are coupled to the jet protons by elastic p-n nuclear scattering and, depending on injection conditions in the GRB, can decouple from the protons during the expansion phase. As a result, the neutrons and protons travel with different speeds and will undergo inelastic p-n collisions, leading to π-decay radiation, resulting in tens of GeV photons [375, 376]. The decoupling leads to subsequent interactions of the proton and neutron-decay shells, which may reduce the shell Lorentz factor by heating [377]. The n-p decoupling occurs in short GRBs for values of the baryon-loading parameter $\eta \sim 300$ [464]. The relative Lorentz factor between the proton and neutron components may be larger than in long duration GRBs, leading to energetic ($\sim$50 GeV) photon emission. Applying this model to several short GRBs in the field of view of Milagro [465] gives fluxes of a few 10^{-7} cm^{-2} s^{-1} for typical bursts, suggesting that a detector of large effective area, $\gtrsim 10^7$ cm^2, at low threshold energy is needed to detect these photons. For the possibly nearby ($z = 0.001$) GRB 051103, the flux could be as large as $\sim 10^{-3}$ cm^{-2} s^{-1}.

Nuclei accelerated in the GRB jet and blast wave to ultra high energies can make γ-rays through the synchrotron process; photopair production, which converts the target photon into an electron-positron pair with about the same Lorentz factor as the ultrarelativistic nucleus; and photopion production, which makes pions that decay into electrons and positrons, photons, and neutrinos. The target photons for the latter two processes are usually considered to be the ambient synchrotron and synchrotron self-Compton photons formed by leptons accelerated at the forward and reverse shocks of internal and external shocks. If the pion-decay muons decay before radiating much energy [466], the secondary leptons, γ-rays, and neutrinos each carry about 5% of the primary energy.

About one-half of the time, neutrons are formed in a photopion reaction. If the neutron does not undergo another photopion reaction before escaping the blast wave, it becomes free to travel until it decays. Neutrons in the neutral beam [467], collimated by the bulk relativistic motion of the GRB blast wave shell, travel $\approx (E_n/10^{20}$ eV) Mpc before decaying. A neutron decays into neutrinos and electrons with $\approx 0.1\%$ of the energy of the primary. Ultrarelativistic neutrons can also form secondary pions after interacting with other soft photons in the GRB enviroment. The resulting decay electrons form a hyper-relativistic synchrotron spectrum, which is proposed as the explanation for the anomalous γ-ray emission signatures seen in GRB 941017 [468].

The electromagnetic secondaries generate an electromagnetic cascade when the optical depth is sufficiently large. The photon number index of the escaping γ-rays formed by multiple generations of Compton and synchrotron radiation is generally between $-3/2$ and -2 below an exponential cutoff energy, which could reach to GeV or, depending on parameter choices, TeV energies [369, 467].

Gamma-ray observations of GRBs will help distinguish between leptonic and hadronic emissions. VHE γ-ray emission from GRBs can be modeled by synchro-Compton processes of shock-accelerated electrons [315, 335, 336, 340, 418], or by photohadronic interactions of UHECRs and subsequent cascade emission [365, 469, 470], or by a combined leptonic/hadronic model. The clear distinction between the two models from γ-ray observation will not be easy. The fact that the VHE γ-rays are attenuated both at their production sites and in the CIB restricts measurements to energies below 150 GeV ($z \sim 1$) or 5 TeV ($z \lesssim 0.2$). Distinctive features of hadronic models are:

- Photohadronic interactions and subsequent electromagnetic γ-ray producing cascades develop over a long time scale due to slower energy loss-rate by protons than electrons. The GeV-TeV light curves arising from hadronic mechanisms then would be longer than those expected from purely leptonic processes [365], facilitating detection with pointed instruments.

- Cascade γ rays will be harder than a -2 spectrum below an exponential cutoff energy, and photohadronic processes can make hard, ~ -1 spectra from anisotropic photohadronic-induced cascades, used to explain GRB 941017 [286, 468]. A "two zone" leptonic synchro-Compton mechanism can, however, also explain the same observations [352, 353, 417, 471], with low energy emission from the prompt phase and high energy emission from a very early afterglow.

- Another temporal signature of hadronic models is delayed emission from UHECR cascades in the CIB/CMB [472] or $\gtrsim$PeV energy γ-rays, from π^0 decay, which may escape the GRB fireball [359]. However, $\gtrsim$TeV photons created by leptonic synchro-Compton mechanism in external forward shocks may imitate the same time delay by cascading in the background fields [448].

- Quasi-monoenergetic π^0 decay γ-rays from n-p decoupling, which are emitted from the jet photosphere prior to the GRB, is a promising hadronic signature [375, 376, 464], though it requires that the GRB jet should contain abundant free neutrons as well as a large baryon load.

Detection of high-energy neutrino emissions would conclusively demonstrate cosmic ray acceleration in GRBs, but non-detection would not conclusively rule out GRBs as a source of UHECRs, since the ν production level even for optimistic parameters is small.

6.7 Tests of Lorentz Invariance with Bursts

Due to quantum gravity effects, it is possible that the speed of light is energy dependent and that $\Delta c/c$ scales either linearly or quadratically with $\Delta E/E_{QG}$, where E_{QG} could be assumed to be at or below the Planck energy, E_P [473, 474, 475]. Recent detections of flaring from the blazar Mrk 501, using the MAGIC IACT, have used this effect to constrain the quantum gravity scale for linear variations to $\gtrsim 0.1E_P$ [476]. This same technique could be applied to GRBs, which have fast variability, if they were detected in the TeV range and if the intrinsic chromatic variations were known. However, there may be intrinsic limitations to some approaches [477]. By improving the sensitivity and the energy range with a future telescope array, the current limit could be more tightly constrained, particularly if it were combined with an instrument such as Fermi at lower energies, thus increasing the energy lever arm.

6.8 Detection Strategies for VHE Gamma-Ray Burst Emission

Ground-based observations of TeV emission from gamma ray bursts are difficult. The frac-

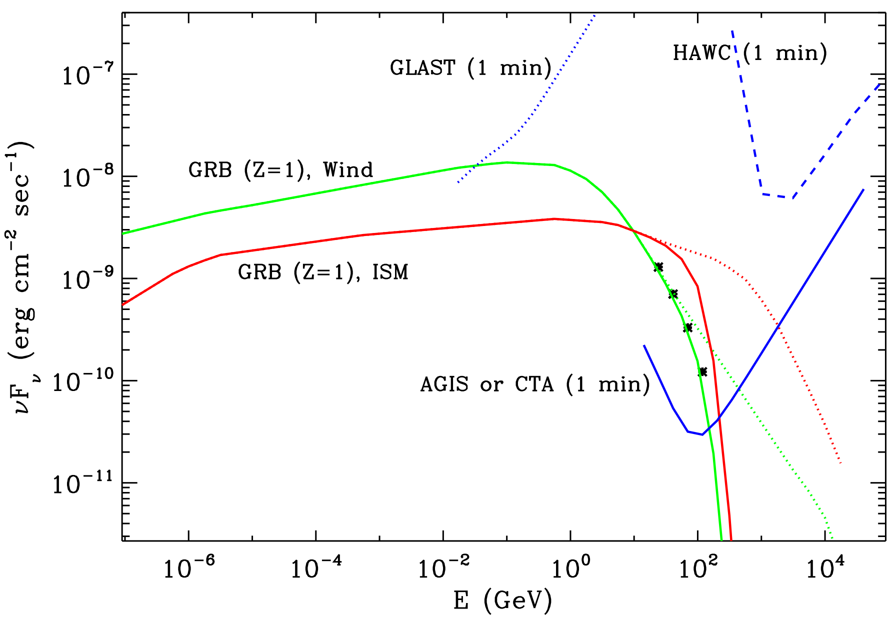

Figure 26: A plot of the predicted gamma-ray spectrum from a GRB at a redshift of z=1 adapted from Pe'er and Waxman [478], reduced by a factor of 10 to illustrate the sensitivity even to weaker bursts. The green and red curves show the calculation for a wind environment and an ISM-like environment. The dotted curves give the source spectrum, while the solid curves include the effects of intergalactic absorption using a model from Franceschini et al. [479]. The blue curves show the differential sensitivity curves for Fermi (GLAST; dotted), a km^2 IACT array like AGIS or CTA (solid) and the HAWC air shower array (dashed). For the AGIS/CTA curve we show the differential sensitivity for 0.25 decade bins, while for the HAWC instrument we assume 0.5 decade bins. The sensitivity curve is based on a 5 sigma detection and at least 25 detected photons. Black points and error bars (not visible) are simulated independent spectral points that could be obtained with AGIS/CTA.

tion of GRBs close enough to elude attenuation at TeV energies by the CIB is small. Only ∼10% of long bursts are within z<0.5, the redshift of the most distant detected VHE source, 3C 279 [403]. Short bursts are more nearby with over 50% detected within z<0.5, but the prompt emission has ended prior to satellite notifications of the burst location.

Therefore, wide field of view detectors with high duty cycle operations would be ideal to observe the prompt emission from gamma-ray bursts. Imaging atmospheric Cherenkov telescopes (IACT) can be made to cover large sections of the sky by either having many mirrors each pointing in a separate direction or by employing secondary optics to expand the field of view of each mirror. However, the duty factor is still ∼10% due to solar, lunar, and weather constraints. IACTs could also be made with fast slewing mounts to allow them to slew to most GRBs within ∼20 seconds, thus allowing them to observe some GRBs before the end of the prompt phase. Alternatively, extensive air shower detectors intrinsically have a field of view of ∼2 sr and operate with ∼95% duty factor. These observatories, especially if located at very high altitudes, can detect gamma rays down to 100 GeV, but at these low energies they lack good energy resolution and have a point spread function of ∼1 degree. The traditionally less sensitive extensive air shower detectors may have difficulty achieving the required prompt emission sensitivity on short timescales ($> 5\sigma$ detection of 10^{-9} erg s^{-1} cm^{-2} in $\lesssim 20$ sec integration). The combined observations of both of these types of detectors would yield the most complete picture of the prompt high energy emission. The expected performance of the two techniques relative to a particular prompt GRB emission model is shown in Figure 26.

The detector strategy for extended emission associated with traditional afterglows or with late-time flares from GRBs is far simpler than the strategy for early prompt emission. The high sensitivity and low energy threshold of an IACT array are the best way to capture photons from this emission at times greater than $\sim$1 min, particularly if fast slewing is included in the design.

6.9 Synergy with other instruments

While GRB triggers are possible from wide angle VHE instruments, a space-based GRB detector will be needed. Swift, Fermi, or future wide field of view X-ray monitors such as EXIST or JANUS must provide lower energy observations. GRBs with observations by both Fermi and VHE telescopes will be particularly exciting and may probe high Lorentz factors. Neutrino telescopes such as IceCube, UHECR telescopes such as Auger, and next generation VHE observatories can supplement one another in the search for UHECRs from GRBs, since neutrinos are expected along with VHE gamma rays. Detection of gravitational waves from GRB progenitors with instruments such as LIGO have the potential to reveal the engine powering the GRB fireball. Correlated observations between gravitational wave observatories and VHE gamma-ray instruments will then be important for understanding which type(s) of engine can power VHE emission.

Correlated observations between TeV gamma-ray detectors and neutrino detectors have the potential for significant reduction in background for the participants. If TeV gamma sources are observed, observers will know where and when to look for neutrinos (and vice versa [480], though the advantage in that direction is less significant). For example, searches for GRB neutrinos have used the known time and location to reduce the background by a factor of nearly 10^5 compared to an annual all-sky diffuse search [481]. Beyond decreasing background, correlated observations also have the potential to increase the expected signal rate. If the spectrum of high-energy gamma rays is known, then constraints on the expected neutrino spectrum can also be introduced, allowing the signal-to-noise ratio of neutrino searches to be significantly improved [482]. In the case of the AMANDA GRB neutrino search, which is based on a specific theoretical neutrino spectrum, the expected signal collection efficiency is nearly 20 times higher than the less constrained search for diffuse UHE neutrinos. With combined photon and neutrino observational efforts, there is a much better chance of eventual neutrino detection of sources such as GRBs (and AGN).

6.10 Conclusions

Gamma-ray bursts undoubtedly involve a population of high-energy particles responsible for the emission detected from all bursts (by definition) at energies up to of order 1 MeV, and for a few bursts so far observable by EGRET, up to a few GeV. Gamma-ray bursts may in fact be the source of the highest energy particles in the universe. In virtually all models, this high-energy population can also produce VHE gamma-rays, although in many cases the burst environment would be optically thick to their escape. The search for and study of VHE emission from GRB therefore tests theories about the nature of these high energy particles (Are they electrons or protons? What is their spectrum?) and their environment (What are the density and bulk Lorentz factors of the material? What are the radiation fields? What is the distance of the emission site from the central source?). In addition, sensitive VHE measurements would aid in assessing the the total calorimetric radiation output from bursts. Knowledge of the VHE gamma-ray properties of bursts will therefore help complete the picture of these most powerful known accelerators.

An example of the insight that can be gleaned from VHE data is that leptonic synchrotron/SSC models can be tested, and model parameters extracted, by correlating the peak energy of X-ray/soft γ-ray emission with GeV–TeV data. For long lived GRBs, the spectral properties of late-time flaring in the X-ray band can be compared to the measurements in the VHE band, where associated emission is expected. Of clear interest is whether there are distinctly evolving high-energy γ-ray spectral components, whether at MeV, GeV or TeV energies, unaccompanied by the associated lower-energy component expected in leptonic synchro-Compton models. Emission of this sort is most easily explained in models involving proton acceleration. As a final example, the escape of VHE photons from the burst fireball provides a tracer of the minimum Doppler boost and bulk Lorentz motion of the emission region along the line of site, since the inferred opacity of the emission region declines with increasing boost.

There are observational challenges for detecting VHE emission during the initial prompt phase of the burst. The short duration of emission leaves little time (tens of seconds) for repointing an instrument, and the opacity of the compact fireball is at its highest. For the majority of bursts having redshift $\gtrsim$0.5, the absorption of gamma rays during all phases of the burst by collisions with the extragalactic background light reduces the detectable emission, more severely with increasing gamma-ray energy. With sufficient sensitivity, an all-sky instrument is the most desirable for studying the prompt phase, in order to measure the largest sample of bursts and to catch them at the earliest times. As discussed in the report of the Technology Working Group, the techniques used to implement all-sky compared to pointed VHE instruments result in a trade-off of energy threshold and instantaneous sensitivity for field of view. More than an order of magnitude improvement in sensitivity to GRBs is envisioned for the next-generation instruments of both types, giving both approaches a role in future studies of GRB prompt emission.

The detection of VHE afterglow emission, delayed prompt emission from large radii, and/or late X-ray flare-associated emission simply requires a sensitive instrument with only moderate slew speed. It is likely that an instrument with significant sensitivity improvements over the current generation of IACTs will detect GRB-related VHE emission from one or all of these mechanisms which do not suffer from high internal absorption, thus making great strides towards understanding the extreme nature and environments of GRBs and their ability to accelerate particles.

In conclusion, large steps in understanding GRBs have frequently resulted from particular new characteristics measured for the first time in a single burst. New instruments improving sensitivity to very-high-energy gamma-rays by an order or magnitude or more compared to existing observations have the promise to make just such a breakthrough in the VHE band.

7 Technology working group

Group membership:

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7.1 Introduction and Overview

High-energy gamma rays can be observed from the ground by detecting secondary particles of the atmospheric cascades initiated by the interaction of the gamma-ray with the atmosphere. Imaging atmospheric Cherenkov telescopes (IACTs) detect broadband spectrum Cherenkov photons ($\lambda > 300$ nm), which are produced by electrons and positrons of the cascade and reach the ground level without significant attenuation. The technique utilizes large mirrors to focus Cherenkov photons onto a finely pixelated camera operating with an exposure of a few nanoseconds, and provides low energy threshold and excellent calorimetric capabilities. The IACTs can only operate during clear moonless and, more recently, partially-moonlit nights. Alternatively, the extended air shower (EAS) arrays, which directly detect particles of the atmospheric cascade (electrons, photons, muons, etc.) can be operated continuously but require considerably larger energy of the gamma rays necessary for extensive air showers to reach the ground level.

The field of TeV gamma-ray astronomy was born in the years 1986 to 1988 with the first indisputable detection of a cosmic source of TeV gamma rays with the Whipple 10 m IACT, the Crab Nebula [483]. Modern IACT observatories such as VERITAS [484, 485], MAGIC [486, 487], and H.E.S.S. [488, 489] can detect point sources with a flux sensitivity of 1% of the Crab Nebula corresponding to a limiting νF_ν-flux of $\sim 5 \times 10^{-13}$ ergs cm^{-2} s^{-1} at 1 TeV. The improvement of sensitivity by two orders of magnitude during the last two decades has been made possible due to critical advances in IACT technology and significantly increased funding for ground-based gamma-ray astronomy. The high point-source flux sensitivity of IACT observatories is a result of their large gamma-ray collecting area ($\sim 10^5$ m^2), relatively high angular resolution ($\sim$ 5 arcminutes), wide energy coverage (from $<$ 100 GeV to $>$ 10 TeV), and unique means to reject cosmic ray background ($>$ 99.999% at 1 TeV). The limitations of the IACT technique are the small duty cycle ($\sim$ 10%), and narrow field of view ($\sim 4\,$deg; 3.8×10^{-3} sr for present-day IACTs).

Large EAS arrays provide complementary technology for observations of very high-energy gamma rays. Whereas their instantaneous sensitivity is currently a factor $\sim$ 150 less sensitive than that of IACT observatories, their large field of view ($\sim 90\,$deg; 1.8 sr) and nearly 100% duty cycle makes these observatories particularly suited to conduct all-sky surveys and detect emission from extended astrophysical sources (larger than $\sim 1\,$deg, e.g. plane of the Galaxy). Milagro [490], the first ground-based gamma-ray observatory which utilized EAS technology to discover extended sources [491], has surveyed 2π sr of the sky at 20 TeV for point sources to a sensitivity of 3×10^{-12} ergs cm^{-2} s^{-1}. Due to the wide field of view coverage of the sky and uninterrupted operation, the EAS technique also has the potential for detection of Very High Energy (VHE) transient phenomena. The current limitations of EAS technique are high-energy threshold ($\sim$ 10 TeV), low angular resolution ($\sim$ 30 arcminutes), and limited capability to reject cosmic-ray background and measure energy.

The primary technical goal for the construction of the next generation of observatories is to achieve an improvement of sensitivity by a factor of α at the cost increase less than a factor of α^2, the increase that would be required if the observatory were constructed by simply cloning present day instrumentation [4]. The history of ground-based gamma-ray astronomy over the last two decades has shown twice an improvement in the sensitivity of the observatories by a

[4]Background dominated regime of observatory operation is assumed

factor of ten while the cost has increased each time only by a factor of ten [492].

The construction of a large array of IACTs covering an area of ~ 1 km^2 will enable ground-based γ-ray astronomy to achieve another order of magnitude improvement in sensitivity. This next step will be facilitated by several technology improvements. First, large arrays of IACTs should have the capability to operate over a broad energy range with significantly improved angular resolution and background rejection as compared to the present day small arrays of telescopes, such as VERITAS or H.E.S.S.. Second, the capability of using subarrays to fine tune the energy range to smaller intervals will allow for considerable reduction of aperture of individual telescopes and overall cost of the array while maintaining the collecting area at lower energies equal to the smaller array of very large aperture IACTs. Finally, the cost per telescope can be significantly reduced due to the advancements in technology, particularly the development of low cost electronics, novel telescope optics designs, replication methods for fabrication of mirrors, and high efficiency photo-detectors, and due to the distribution of initial significant non-recurring costs over a larger number of telescopes.

In the case of EAS arrays, the breakthrough characterized by the improvement of sensitivity faster than the inverse square root of the array footprint area is possible due to mainly two factors. First, next generation EAS array must be constructed at a high elevation (> 4000 m) to increase the number of particles in a shower by being closer to the altitude where the shower has the maximum number of particles. Thus, a lower energy threshold is possible and energy resolution is improved. Second, the size of the EAS array needs to be increased in order to more fully contain the lateral distribution of the EAS. A larger array improves the angular resolution of the gamma-ray showers and also dramatically improves the cosmic ray background rejections. The lateral distribution of muons in a cosmic ray shower is very broad, and identification of a muon outside the shower core is key to rejecting the cosmic ray background.

The science motivations for the next generation ground-based gamma-ray observatories are outlined in this document. There are clear cost, reliability, maintenance, engineering, and management challenges associated with construction and operation of a future ground-based astronomical facility of the order $\sim$100M dollar scale. Detailed technical implementation of a future observatory will benefit from current and future R&D efforts that will provide better understanding of the uncertainties in evaluation of the cost impact of improved and novel photon detector technologies and from the current incomplete simulation design studies of the large optimization space of parameters of the observatory. In the remainder of this section, we outline a broadly defined technical roadmap for the design and construction of future instrumentation which could be realized within the next decade. We start with a status of the field, identify the key future observatory design decisions, technical drivers, describe the current state of the art technologies, and finally outline a plan for defining the full technology approach.

7.2 Status of ground-based gamma-ray observatories

Status of Ground-Based Gamma-ray Observatories

At present, there are four major IACT and three EAS observatories worldwide conducting routine astronomical observations, four of which are shown in Fig 27. Main parameters of these instruments are the following:

VERITAS is a four-telescope array of IACTs located at the Fred Lawrence Whipple Observatory in Southern Arizona (1268 m a.s.l.). Each telescope is a 12 m diameter Davies-Cotton (DC) reflector (f/1.0) and a high resolution 3.5deg field of view camera assembled from 499 individual photo multiplier tubes (PMTs) with an angular size of 0.15 deg. The telescope spacing varies from 35 m to 109 m. VERITAS was commissioned to scientific operation in April 2007.

Figure 27: The images show four major ground-based gamma-ray observatories currently in operation: VERITAS, MAGIC, H.E.S.S. , and MILAGRO. A future ground-based gamma-ray project can build on the success of these instruments.

The H.E.S.S. array consists of four 13 m DC IACTs (f/1.2) in the Khomas Highlands of Namibia (1800 m a.s.l.). The 5 deg field of view cameras of the telescopes contain 960 PMTs, each subtending 0.16deg angle. The current telescopes are arranged on the corners of a square with 120m sides. H.E.S.S. has been operational since December 2003. The collaboration is currently in the process of upgrading the experiment (H.E.S.S. -II) by adding a central large (28 m diameter) telescope to the array to lower the trigger threshold for a subset of the events to 20 GeV and will also improve the sensitivity of the array above 100 GeV.

MAGIC is a single 17 m diameter parabolic reflector (f/1.0) located in the Canary Island La Palma (2200 m a.s.l.). It has been in operation since the end of 2003. The 3.5 deg non-homogenous camera of the telescope is made of 576 PMTs of two angular sizes 0.1deg (396 pixels) and 0.2deg (180 pixels). The MAGIC observatory is currently being upgraded to MAGIC-II with a second 17-m reflector being constructed 85 m from the first telescope. The addition of this second telescope will improve background rejection and increase energy resolution.

CANGAROO-III consists of an array of four 10 m IACTs (f/0.8) located in Woomera, South Australia (160 m a.s.l.) [493]. The telescope camera is equipped with an array of 552 PMTs subtending an angle of 0.2deg each. The telescopes are arranged on the corners of a diamond with sides of 100 m.

Milagro is an EAS water Cherenkov detector located near Los Alamos, New Mexico (2650 m a.s.l.). Milagro consists of a central pond detector with an area of 60 x 80m^2 at the surface and has sloping sides that lead to a 30 x 50 m^2 bottom at a depth of 8 m. It is filled with 5 million gallons of purified water and is covered by a light-tight high-density polypropylene line. Milagro consists of two layers of upward pointing 8" PMTs. The tank is surrounded with an array of water tanks. The central pond detector has been operational since 2000. The array of water tanks was completed in 2004.

The AS-γ and ARGO arrays are located at the YangBaJing high-altitude laboratory in Tibet, China. AS-γ, an array of plastic scintillator detectors, has been operational since the mid 1990s. ARGO consists of a large continuous array of Resistive Plate Counters (RPCs) and will become operational in 2007 [494].

The current generation of ground based instruments has been joined in mid-2008 by the space-borne **Fermi Gamma-ray Space Telescope** (formerly GLAST). Fermi comprises two instruments, the Large Area Telescope (LAT) [495] and the Fermi Gamma-ray Burst Monitor (GBM) [496]. The LAT covers the gamma-ray energy band of 20 MeV - 300 GeV with some spectral overlap with IACTs. The present generation of IACTs match the νF_ν-sensitivity of Fermi. Next-generation ground-based observatories with one order of magnitude higher sensitivity and significantly improved angular resolution would be ideally suited to conduct detailed studies of the Fermi sources.

7.3 Design Considerations for a Next-Generation Gamma-Ray Detector

At the core of the design of a large scale ground-based gamma-ray observatory is the requirement to improve the integral flux sensitivity by an order of magnitude over instruments employed today in the 50 GeV-20 TeV regime where the techniques are proven to give excellent performance. At lower energies (below 50 GeV) and at much higher energies (50-200 TeV) there is great discovery potential, but new technical approaches must be explored and the scientific benefit is in some cases less certain. For particle-detector (EAS) arrays, it is possible to simultaneously improve energy threshold and effective area by increasing the elevation, and the technical road-map is relatively well-defined. In considering the design of future IACT arrays, the development path allows for complementary branches to more fully maximize the greatest sensitivity for a broad energy range from 10 GeV up to 100 TeV. Table 1 summarizes specific issues of the detection technique and scientific objectives for four broad energy regimes (adapted from [497, 498]).

7.4 Future IACT Arrays

The scientific goals to be addressed with a future IACT array require a flux sensitivity at least a factor of ten better than present-day observatories, and an operational energy range which extends preferably into the sub-100 GeV domain in order to open up the γ-ray horizon to observations of cosmologically distant sources. These requirements can be achieved by an array with a collecting area of ~ 1 km^2 (see Fig 1).

The intrinsic properties of a ~ 1 km^2 IACT array could bring a major breakthrough for VHE gamma-ray astronomy since it combines several key advantages over existing 4-telescope arrays:

- A collection area that is 20 times larger than that of existing arrays. Comparison of the collection area of a ~ 1 km^2 array with the characteristic size of the Cherenkov light pool ($\sim 5 \times 10^4$ m^2) suggests that the array should be populated with 50-100 IACTs.

- Fully contained events for which the shower core falls well within the geometrical dimensions of the array, thus giving better angular reconstruction and much improved background rejection. The performance of a typical IACT array in the energy regime below a few TeV is limited by the cosmic-ray background. The sensitivity of a future observatory could be further enhanced through improvements of its angular resolution and background rejection capabilities. It is known that the angular resolution of the present-day arrays of IACTs, which typically have four telescopes, is not limited by the physics of atmospheric cascades, but by the pixelation of their cameras and by the number of telescopes simultaneously observing a γ-ray event [500, 499, 501].

- Low energy threshold compared to existing small arrays, since contained events provide sampling of the inner light pool where the Cherenkov light density is highest. Lower

Table 1: Gamma-ray energy regimes, scientific highlights and technical challenges.

Regime	Energy Range	Primary Science Drivers	Requirements/Limitations
multi-GeV:	$\leq$50 GeV	extragalactic sources (AGN, GRBs) at cosmological distances ($z > 1$), Microquasars, Pulsars	very large aperture or dense arrays of IACTs, preferably high altitude operation & high quantum efficiency detectors required; angular resolution and energy resolution will be limited by shower fluctuations, cosmic-ray background rejection utilizing currently available technologies is inefficient.
sub-TeV:	50 GeV – 200 GeV	extragalactic sources at intermediate redshifts($z < 1$), search for dark matter, Galaxy Clusters, Pair Halos, Fermi sources	very-large-aperture telescopes or dense arrays of mid-size telescopes and high light detection efficiency required; limited but improving with energy cosmic-ray background rejection based on imaging analysis. For gamma-ray bursts, high altitude EAS array.
TeV:	200 GeV – 10 TeV	nearby galaxies (dwarf, starburst), nearby AGN, detailed morphology of extended galactic sources (SNRs, GMCs, PWNe)	large arrays of IACTs: best energy flux sensitivity, best angular and energy resolutions, best cosmic-ray hadron background rejection, new backgrounds from cosmic-ray electrons may ultimately limit sensitivity in some regions of the energy interval. At the highest energy end, an irreducible background may be due to single-pion sub-showers. EAS arrays for mapping Galactic diffuse emission, AGN flares, and sensitivity to extended sources.
sub-PeV:	$\geq$10 TeV	Cosmic Ray PeVatrons (SNRs, PWNe, GC, ...), origin of galactic cosmic rays	requires very large (10 km^2 scale) detection areas; large arrays of IACTs equipped with very wide ($\geq 6^\circ$) FoV cameras and separated with distance of several hundred meters may provide adequate technology. Background rejection is excellent and sensitivity is γ-ray count limited. Single-pion sub-showers is ultimate background limiting sensitivity for very deep observations. Regime of best performance of present EAS arrays; large EAS arrays ($\geq 10^5 m^2$).

energy thresholds (below 100 GeV) generally require larger aperture ($>$ 15 m) telescopes; however, a $\sim$ 1 km^2 IACT has an intrinsic advantage to lower the energy threshold due to the detection of fully contained events.

- A wider field of view and the ability to operate the array as a survey instrument.

In order to maximize the scientific capabilities of a $\sim$ 1 km^2 array with respect to angular resolution, background suppression, energy threshold and field of view, it is necessary to study a range of options including the design of the individual telescopes and the array footprint. Furthermore, it is necessary to determine the most cost effective/appropriate technology available. The reliability of the individual telescopes is also a key consideration to minimize operating costs.

The history of the development of instrumentation for ground-based γ-ray astronomy has shown that a significant investment into the design and construction of new instruments ($\sim$ 10 times the cost of previously existing ACTs)

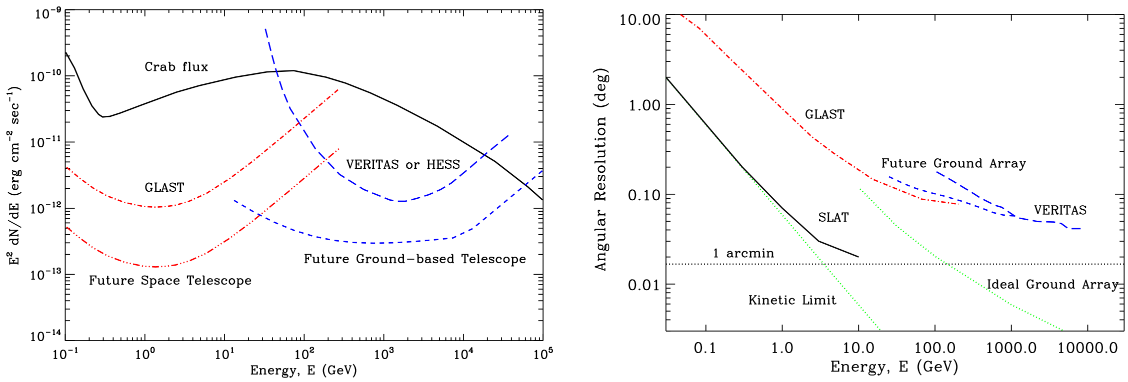

Figure 28: *Left:* Differential sensitivities calculated for present and future gamma-ray experiments. For the future IACT array, an area of $\sim$1 km^2, no night-sky-background, a perfect point spread function [502], and an order of magnitude improvement in cosmic-ray rejection compared with current instruments has been assumed. All sensitivities are 5 sigma detections in quarter decade energy intervals (chosen to be larger than the expected full-width energy resolution). *Right* Angular resolution for Fermi (GLAST) [504], VERITAS [503] and for ideal future space-borne and ground based [499] gamma-ray detectors.

has yielded significant increases in sensitivity. For example, the construction of high resolution cameras in the 1980s assembled from hundreds of individual PMTs and fast electronics made the "imaging" technique possible. This advancement improved the sensitivity of the observatories by a factor of 10 through the striking increase of angular resolution and cosmic-ray background rejection, and ultimately led to a detection of the first TeV source [483]. Another factor of ten investment into the development of small arrays of mid-sized IACTs (12 m) demonstrated the benefits of "stereoscopic" imaging and made possible the H.E.S.S. and VERITAS observatories. The sensitivity of these instruments improved by a factor of 10 due to the increase of angular resolution and CR background discrimination, despite their only relatively modest increase in the γ-ray collecting area compared to the previous-generation Whipple 10 m telescope.

The next logical step in the evolution of the IACT technique is the $\sim$ 1 km^2 array concept. Technological developments such as novel multi-pixel high-quantum-efficiency photodetectors (MAPMTs, SiPMs, APDs, CMOS sensors, etc.) or PMTs with significantly improved QE, new telescope optical design(s), and modular low-cost electronics based on ASICs (Application-Specific Integrated Circuits) and intelligent trigger systems based on FPGAs (Field Programmable Gate Arrays) hold the promise to (i) significantly reduce the price per telescope, and (ii) considerably improve the reliability and versatility of IACTs.

The improvement in sensitivity with a $\sim$ 1 km^2 array is in part achieved by increasing the number of telescopes. Simple scaling suggests that a factor of 10^1 improvement in sensitivity requires a factor of 10^2 increase in the number of telescopes and observatory cost. However, this is not the case for the $\sim$ 1 km^2 IACT array concept, since the $\sim$ 1 km^2 concept inherently provides a better event reconstruction so that the sensitivity improves far beyond simple scaling arguments. For the current generation of small arrays, the shower core mostly falls outside the physical array dimensions. A $\sim$ 1 km^2 array could, for the first time, fully constrain the air shower based on many view points from the ground. This leads to several substantial improvements and can be understood by considering the Cherenkov light density distribution at the ground.

The Cherenkov light pool from an atmospheric cascade consists of three distinct regions: an inner region ($r < 120$ m) in which the photon density is roughly constant, an intermediate region where density of the Cherenkov photons declines as a power law (120 m $< r <$ 300 m) and an outer region where the density declines exponentially. A small array (VERITAS, HESS) samples the majority of cascades in the intermediate and outer regions of the light pool. A ~ 1 km^2 array samples for its mostly contained events, the inner, intermediate and outer region of the light pool and allows a much larger number of telescopes to participate in the event reconstruction with several important consequences:

- First of all, at the trigger level this results in a lower energy threshold since there are always telescopes that fall into the inner region where the light density is highest. For example, the 12 m reflectors of the VERITAS array sample a majority of 100 GeV γ rays at distances of ~ 160 m and collect ~ 105 PEs per event. The same median number of photons would be collected by 9.3 m reflectors, if the atmospheric cascades were sampled within a distance of ~ 120 m. A ~ 1 km^2 array of IACTs with fully contained events could operate effectively at energies below 100 GeV despite having a telescope aperture smaller than that of VERITAS [500, 506]. Reducing the telescope size translates into a reduction of cost per telescope and total cost for a future observatory.

- The second factor which significantly affects the sensitivity and cost of future IACT arrays is the angular resolution for γ-rays. Due to the small footprint of the VERITAS and H.E.S.S. observatories, the majority of events above ~ 100 GeV are sampled outside the boundaries of the array, limiting the accuracy to which the core of atmospheric cascade can be triangulated. Even higher resolution pixels will not help to improve the angular resolution below ~ 9 arc-minutes [502] for small arrays. However, contained events in a ~ 1 km^2 array of IACTs provide a nearly ideal reconstruction based on simultaneous observations of the shower from all directions while sampling multiple core distances. Simulations of idealized (infinite) large arrays of IACTs equipped with cameras composed from pixels of different angular sizes suggest that the angular resolution of the reconstructed arrival direction of γ-rays improves with finer pixelation up to the point at which the typical angular scale, determined by the transverse size of the shower core is reached [501]. Figure 28 shows the angular resolution that can be achieved (few minutes of arc) with an ideal "infinite" array of IACTs when instrumental effects are neglected [499].

- The third factor improving the sensitivity of ~ 1 km^2 arrays of IACTs comes through enhanced background discrimination. For atmospheric cascades contained within the array footprint, it is possible to determine both the depth of the shower maximum and the cascade energy relatively accurately, thereby enabling better separation of hadronic and electromagnetic cascades. Multiple viewpoints from the ground at different core distances also allow the detection of fluctuations in light density and further improve background rejection. Additional improvements extending to energies below 200 GeV may be possible by picking up muons from hadronic cascades, a technique that is used in air shower arrays. A "muon veto" signal present in the images obtained of a large array could improve the technique even further. Another method to reject cosmic-ray background at the lowest energies and low light levels [505] is based on the parallactic displacement of images. The images viewed from multiple viewpoints at the ground show significant fluctuations in lateral displacements for hadronic showers and simulations indicate appreciable γ/hadron separation capabilities in a regime where faint Cherenkov light images can no longer be resolved for the calculation of standard image parameters. This technique could become effective close to the trigger threshold of large arrays.

In summary, the concept of "large IACT arrays" provides strongly improved sensitivity at mid-energies, ~ 1 TeV, not only due to increased collecting area, but also due to enhanced angular resolution and CR background rejection. It also presents a cost-effective solution for increasing the collecting area of the observatory at lower energies.

For energies above > 10 TeV, the collecting area of the ~ 1 km^2 IACT array will be approximately two times larger than its geometrical area due to events impacting beyond the perimeter of the array. It must be noted that in this energy regime the observatory is no longer background limited and therefore its sensitivity scales inversely proportional to the collecting area and exposure.

Clearly, versatility is another virtue of a "large IACT array". If the astrophysics goal is to only measure the high-energy part of the spectrum (> 10 TeV) of a given source, e.g. the Crab Nebulae or Galactic Center, only $1/10^{\mathrm{th}}$ of the observatory telescopes, spaced on the grid of ~ 300 m, would be required to participate in the study to gain a required sensitivity, while at the same time other observation programs could be conducted. The flexibility of a large array also allows operation in a sky survey mode to detect transient galactic or extragalactic sources [500]. In this mode of operation a large field of view would be synthesized by partially overlapping the fields of view of individual telescopes. Survey observations, in which collecting area has been traded for wide solid-angle coverage, could then be followed up by more sensitive "narrow-field" of view for detailed source studies.

Although the design considerations outlined above are relevant for any "large IACT array", realistic implementations of this concept could vary. An alternative approach to the array, consisting of identical telescopes, is being developed, based on an extrapolation from small arrays, H.E.S.S. and VERITAS, and is known as the hybrid array concept. In this approach the limitation of the cost of the future observatory is addressed through a design with multiple types of IACTs, each addressing a different energy range. For example, a central core composed of a few very large aperture telescopes (~ 20 m) equipped with fine pixel cameras (or very high spatial density mid-size reflectors [506]), provides for the low energy response of the array. A significantly larger, ~ 1 km^2, ring area around the array core is populated with VERITAS class telescopes (> 12 m) to ensure improved collecting area and performance at mid-energies, ~ 1 TeV. Finally, a third ring surrounds the 1 km^2 array with a very spread-out array of inexpensive, small (2 m aperture), wide-field IACTs outfitted with coarsely pixelated cameras ($0.25°$), which would cover areas up to 10 km^2. On the order of 100 telescopes with 300 m spacing might be required to gain the desired response at the highest energies (> 10 TeV) [507].

The hybrid array concept with a central region of several large aperture telescopes is motivated by significant changes in the distribution of Cherenkov photons at energies considerably smaller than ~ 100 GeV. At very low energies, ~ 10 GeV, the Cherenkov light is distributed over a relatively large area, but with lower overall density. Therefore, large aperture telescopes arranged in an array with significant separation between them may provide a cost effective solution to improve the low energy response.

Independently from exact implementation of the IACT array layout, the sensitivity of future ground-based observatories could be improved through the increase of both camera pixelation and the number of telescopes. The low energy sensitivity will also be affected by the telescope aperture. Therefore, a trade-off optimization of these factors should also be performed under a constraint of constant cost of the observatory. For example, if the camera dominates the overall cost of the IACT significantly, then a reduction of camera pixelation and increase of the number of telescopes is suggested for optimizing cost. If the telescope optical and positioning systems dominate the cost, then reducing the number of telescopes and improving their angular resolution is preferential for achieving the highest sensitivity. The cost per pixel and of the indivisual telescopes of a given apearture are the most critical parameters required for future observatory design decisions.

Through the design and construction of

H.E.S.S., VERITAS, and MAGIC, considerable experience has been gained in understanding the cost and technical challenges of constructing prime focus, Davies-Cotton (DC) and parabolic reflectors and assembling cameras from hundreds of individual PMTs. The relatively inexpensive, DC telescope design has been used in ground-based γ-ray astronomy for almost fifty years successfully and provides an excellent baseline option for a future observatory. For example, the HESS 13 m aperture telescopes have an optical pointspread function of better than 0.05 deg. FWHM over a 4 degree field of view and pixel size of 0.15 deg., demonstrating that this telescope design could in principle accommodate a few arc minute camera resolution. To reach significantly better angular resolution in conjunction with wider field of view systems, alternative designs are being considered.

An alternative telescope design that could be used in future IACT array is based on the Schwarzschild-Couder (SC) optical system (see Fig. 30) [509], which consists of two mirrors configured to correct spherical and coma aberrations, and minimize astigmatism. For a given light-collecting area, the SC optical system has considerably shorter focal length than the DC optical system, and is compatible with small-sized, integrated photo-sensors, such as Multi Anode PMTs (MAPMTs) and possibly Silicon PMs (SiPMs). Although the SC telescope optical system, based on aspheric mirrors, is more expensive than that of a DC design of similar aperture and angular resolution, it offers a reduction in the costs of focal plane instrumentation using pixels that are physically substantially smaller. In addition, the SC telescope offers a wide, unvignetted, 6 degree field-of-view, unprecedented for ACTs, which can be further extended up to 12 degrees, if necessary, when a modest degradation of imaging and loss of light-collecting area can be tolerated. Unlike a DC telescope, the two-mirror aplanatic SC design does not introduce wavefront distortions, allowing the use of fast $>$ GHz electronics to exploit the very short intrinsic time scale of Cherenkov light pulses ($<$3 nsec). The Schwarzschild telescope design was proposed in 1905 [510], but the construction of an SC telescope only became technologically possible recently due to fundamental advances in the process of fabricating aspheric mirrors utilizing replication processes such as glass slumping, electroforming, etc. It is evident that the SC design requires novel technologies and is scientifically attractive. Prototyping and a demonstration of its performance and cost are required to fully explore its potential and scientific capabilities.

To summarize, "large" IACT array concept provides the means to achieve the required factor of 10 sensitivity improvement over existing instruments. Significant simulations and design studies are required to make an informed decision on the exact array implementation, such as deciding between uniform or graded arrays. Two telescope designs, DC & SC, offer a possibility for the largest collecting area, largest aperture, and highest angular resolution IACT array options. Studies of the tradeoff of performance costs and robustness of operation are necessary for design conclusions.

7.5 Future EAS Observatory

The success of EAS observatories in gamma-ray astronomy is relatively recent, with the first detection of new sources within the last couple of years [491], as compared to the over 20 year history of successes with IACTs. However, EAS observatories have unique and complementary capabilities to the IACTs. The strengths of the technique lie in the ability to perform unbiased all-sky surveys (not simply of limited regions such as the Galactic plane), to measure spectra up to the highest energies, to detect extended sources and very extended regions of diffuse emission such as the Galactic plane, and to monitor the sky for the brightest transient emission from active galaxies and gamma-ray bursts and search for unknown transient phenomena.

The instantaneous field of view of an EAS detector is $\approx$2 sr and is limited by the increasing depth of the atmosphere that must be traversed by the extensive air shower at larger zenith angles. However, for higher energy gamma rays, the showers are closer to shower maximum and

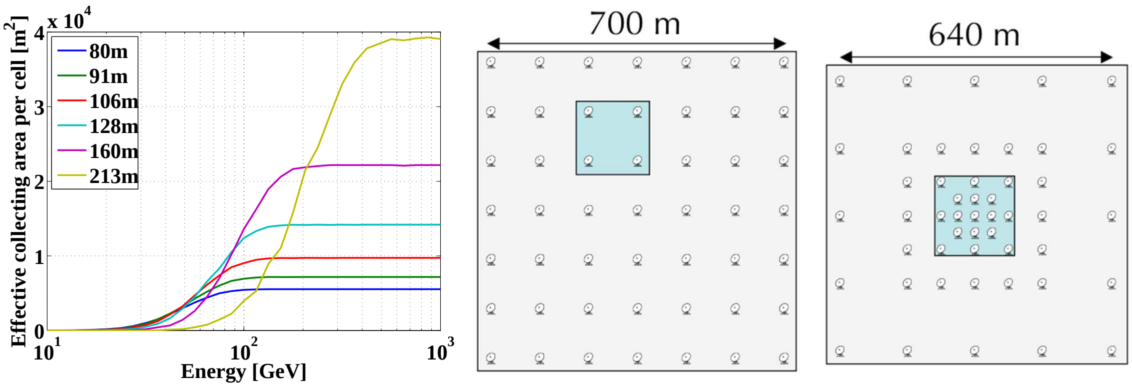

Figure 29: *Left:* Effective area vs. energy for a single cell for different telescope spacings; for a very large array with a fixed number of telescopes, the total effective area will be proportional to this number. *Center,Right:* Two possible array configurations showing a uniform array and one where the central cluster of telescopes is more densely packed to achieve a balance between the desires for low threshold and large effective are at higher energies.

have more particles; thus the resolution improves. As the Earth rotates, all sources that pass within ≈45 degrees of the detector's zenith are observed for up to 6 hours. For a source with a Crab-like spectrum, the flux sensitivity of an EAS detector varies by less than 30% for all sources located within $\approx 2\pi$ sr.

The angular resolution, energy resolution, and γ-hadron separation capabilities of EAS technique are limited by the fact that the detectors sample the particles in the tail of the shower development well past the shower maximum. The angular resolution improves at higher energies ($>$ 10 TeV), and the best single-photon angular resolution achieved to date is $0.35°$ which was achieved with the highest energy observations of Milagro. Placing an extensive shower detector at a higher elevation will allow the particles to be detected closer to the shower maximum. For example, an observatory at 4100m above sea level detects 5-6 times as many particles for the same energy primary as an observatory at 2650m (the elevation of Milagro).

Also, increasing the size of a detector will increase the collection area and thus the sensitivity. As both signal and background are increased, the relative sensitivity would scale proportional to Area$^{0.5}$ if there were no other improvements. However, the effectiveness of the gamma-hadron cuts improves drastically with detector size, because the lateral shower distribution is more thoroughly sampled. The background hadron induced showers can be efficiently rejected through the identification of muons, hadrons and secondary electromagnetic cores. But the large transverse momentum of hadronic interactions spreads the shower secondaries over a much larger area on the ground than the gamma-ray initiated showers. Detailed simulations using Corsika to simulate the air showers and GEANT4 to simulate a water Cherenkov observatory show that most background hadronic showers can be rejected by identifying large energy deposits separated from the shower core[511]. Simulations of larger versions of such a detector demonstrate that sensitivity scales as Area$^{0.8}$ at least up to 300m x 300m.

The high-energy sensitivity of all gamma-ray detectors is limited by the total exposure because the flux of gamma rays decreases with energy. An EAS detector has a very large exposure from observing every source every day. For example, a detector of area $2 \times 10^4 \mathrm{m}^2$ after 5 years will have over 1 km$^2\times$ 100 hours of exposure. And as the energy increases, EAS observatories become background free because the lateral distribution of muons, hadrons and secondary cores in hadronic showers is better sampled.

The low energy response of EAS detectors is very different from IACTs, again because only

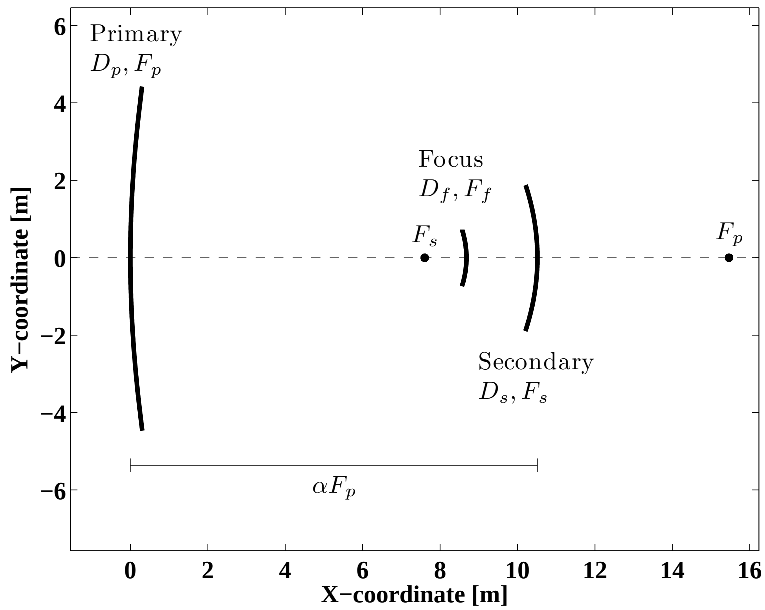

Figure 30: A future Cherenkov telescope array may use conventional Davies-Cotton or parabolic optical reflectors similar to the ones used by VERITAS, MAGIC, and H.E.S.S., or may use novel Schwarzschild-Couder optical designs that combine wide field of views with excellent point spread functions and a reduction of the plate-scale, and thus of the camera size, weight, and costs. The image shows the cross-section of an exemplary Schwarzschild-Couder design (from [509]).

the tail of the longitudinal distribution of the shower is observed. Past shower maximum, the number of particles in the shower decreases with each radiation length. However, the probability of a primary penetrating several radiation lengths prior to first interaction in the atmosphere decreases exponentially with radiation length. These two facts, as well as the number of particles at shower maximum is proportional to the primary energy, imply the effective area increases with energy E as $E^{2.6}$ until a threshold energy where the shower can be detected if the primary interacts within the first radiation length in the atmosphere. Therefore, EAS detectors can have an effective area up to 100 m^2 at the low energies of $\sim$ 100 GeV. This area is considerably larger than Fermi's of $\sim$ 1 m^2, and is sufficient to observe bright, extragalactic sources such as active galactic nuclei and possibly gamma-ray bursts. The wide field of view of EAS observatories is required to obtain long term monitoring of these transient sources and EAS observatories search their data in real time for these transient events to send notifications within a few seconds to IACTs and observers at other wavelengths.

The HAWC (High Altitude Water Cherenkov) observatory is a next logical step in the development of EAS observatories[512]. It will be located in Mexico at Sierra Negra at an altitude of 4100 m and will have 10-15 times the sensitivity of Milagro. The (HAWC) observatory will re-use the existing photomultiplier tubes from Milagro in an approximately square array of 900 large water tanks. The tanks will be made of plastic similar to the Auger tanks, but will be larger, with a diameter of 5 m and 4.3 m tall. An 8" diameter PMT would be placed at the bottom of each tank and look up into the water volume under ≈4 m of water. The array would enclose 22,500 m^2 with ≈75% active area. Thus, unlike Milagro, the same layer of PMTs would be used to both reconstruct the direction of the primary gamma ray and to discriminate against the cosmic-ray background. The optical isolation of each PMT in a separate tank allows a single layer to accomplish both objectives. A single tank has been tested in conjunction with Milagro and its performance agrees with Monte Carlo simulation predictions. The optical isolation also improves the background discrimination (especially at the trigger level), and the angular and energy resolution of the detector.

The performance of HAWC is shown in Figure 31 and is compared to Milagro. These detailed calculations use the same Monte Carlo simulations that accurateley predict the performance of Milagro. The top panel shows the large increase in the effective area at lower energies as expected from the increase in altitude from 2600m to 4100m. At higher energies the geometric area of HAWC is similar to the geometric area of Milagro with its outrigger tanks. However, the improved sampling of the showers over this area with the continuous array of HAWC tanks results in improved angular resolution and a major increase in background rejection efficiency. Therefore, the combined sensitivity improvement for a Crab-like source is a factor of 10-15 times better than Milagro. This implies that the Crab can be detected in one day as compared to three months with Milagro.

The water Cherenkov EAS detector can be extrapolated to enclose even larger areas and the sensitivity of such a detector is relatively straight forward to calculate. Earlier work in this area discussed an array enclosing 100,000 m^2, with two layers of PMTs [513, 514]. Recent work indicates that a single deep layer (as in the HAWC design) will perform as well as the previous two-layer design. For example, a detector with an active detection area 100,000 m^2 (HAWC100), located at 5200 m above sea level, would have an effective area at 100 GeV of $\sim$10,000 m^2 for showers from zenith. The low-energy response allows for the detection of gamma-ray bursts at larger redshifts than current instruments ($z \sim 1$ for HAWC compared to $z \sim 0.3$ for Milagro if, at the source, the TeV fluence is equal to the keV fluence). While current instruments, such as Milagro, indicate that the typical TeV fluence from a GRB is less than the keV fluence, instruments such as HAWC100 and HAWC would be sensitive to a TeV fluence 2-3 orders of magnitude smaller than the keV fluence of the brightest gamma-ray bursts.

7.6 Technology Roadmap

The recent successes of TeV γ-ray astronomy both in terms of scientific accomplishments and in terms of instrument performance have generated considerable interest in next-generation instruments. Part of the excitement originates from the fact that an order of magnitude sensitivity improvement seems to be in reach and at acceptable costs for making use of existing technologies. New technologies could result in even better sensitivity improvements. A roadmap for IACT instruments over the next 3 years should focus on design studies to understand the tradeoffs between performance, costs, reliability of operation of IACT arrays, and on carrying out prototyping and the required research and development. It is anticipated that, at the end of this R&D phase, a full proposal for construction of an observatory would be submitted. A next generation instrument could be built on a time scale of $\sim$5 years to then be operated for between 5 years (experiment-style operation) and several decades (observatory-style operation). For IACT instruments, the following R&D should be performed:

- Monte Carlo simulations of performance of large IACT arrays to optimize array configuration parameters such as array type (hybrid or homogeneous), array layout, aperture(s) of the telescope(s), and pixilation of the cameras, with a fixed cost constraint. Effects of these parameters on energy threshold, angular resolution, and sensitivity of the observatory should be fully understood, together with associated cost implications.

- The conservative Davies-Cotton telescope design with $f - \frac{F}{D} \sim 1$ should be considered as a baseline option for the future observatory. However, limitations of this design and benefits and cost impact of alternative options should be investigated. These alternatives include large focal length Davies-Cotton or parabolic prime-focus reflectors

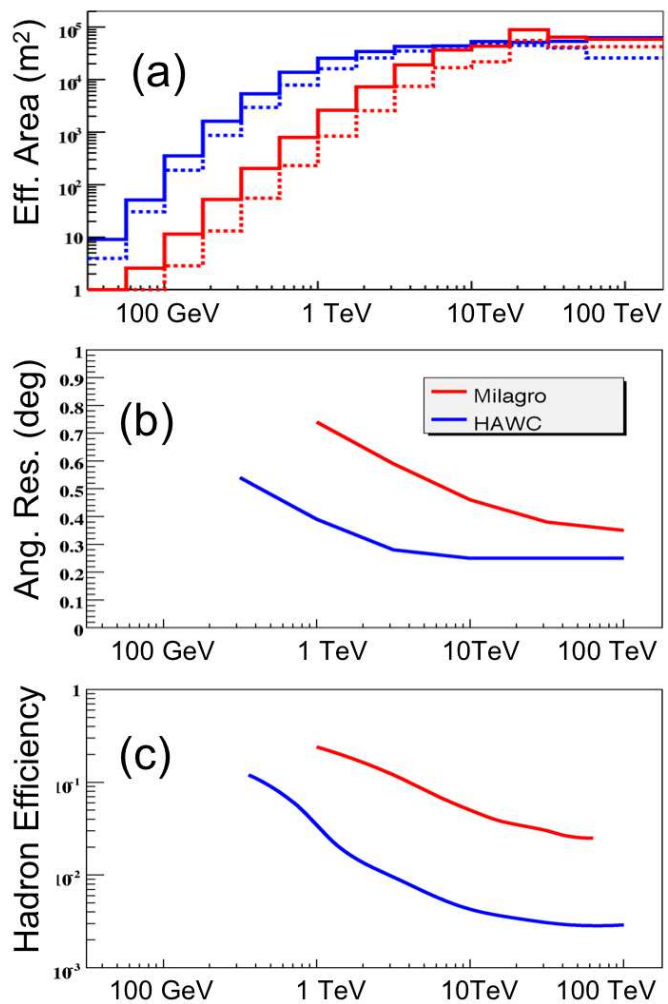

Figure 31: : The sensitivity of HAWC and Milagro versus primary gamma-ray energy. Panel (a) shows the effective area, (b) the angular resolution, and (c) the efficiency with the hadronic background showers are rejected when half of the gamma-ray events are accepted.

with $f \sim 2$ and aplanatic two-mirror optical systems, such as Schwarzschild-Couder and Ritchey-Chrétien telescopes. The latter designs have the potential to combine significantly improved off-axis point spread functions, large field-of-views, and isochronicity with reduced plate scales and consequently reduced costs of focal plane instrumentation. Prototyping of elements of the optical system of SC or RC telescopes is required to assess cost, reliability and performance improvement. Mechanical engineering feasibility studies of large focal length prime focus telescopes and two-mirror telescopes should be conducted.

- The development and evaluation of different camera options should be continued. Of particular interest are alternative photodetectors (photomultiplier tubes with ultra high quantum efficiency, multi-anode photomultipliers, multi channel plates, Si photomultipliers, Geiger mode Si detectors, and hybrid photodetectors with semiconductor photocathodes such as GaAsP or InGaN) and a modular design of the camera which reduces the assembly and maintenance costs. Compatibility of these options with different telescope designs and reliability of operation and cost impact should be evaluated.

- The development of ASIC-based front-end-electronics should be continued to further minimize the power and price of the readout per pixel.

- A next-generation experiment should offer the flexibility to operate in different configurations, so that specific telescope combinations can be used to achieve certain science objectives. Such a system requires the development of a flexible trigger system. Furthermore, the R&D should explore the possibility of combining the trigger signals of closely spaced telescopes to synthesize a single telescope of larger aperture. A smart trigger could be used to reduce various backgrounds based on parallactic displacements of Cherenkov light images [505].

- The telescope design has to be optimized to allow for mass production and to minimize the maintenance costs.

- The telescopes should largely run in robotic operation mode to enable a small crew to operate the entire system. The reliability of operation of large IACT arrays should be specifically researched, including tests of instrumentation failure rates and weathering to evaluate required maintenance costs.

A roadmap for EAS array over the next 5 years (HAWC) is well defined by the benefits of moving the experiment to high altitudes and enlarging the detection area. The cost of this path is $<$ \$10M USD. A site in Mexico has been identified and is a few km from the Large Millimeter Telescope; it is a 2 hour drive from the international airport in Puebla, and has existing infrastructure of roads, electricity, and internet. The HAWC project will be a joint US and Mexican collaboration with scientists from Milagro, Auger, and other astronomical and high-energy physics projects.

The R&D for IACT could be finalized on a time scale of between 3 (IACTs). The R&D should go hand in hand with the establishment of a suitable experimental site and the build-up of basic infrastructure. Ideally, the site should offer an easily accessible area exceeding 1 km^2. For an IACT array, an altitude between 2 km and 3.5 km will give the best tradeoff between low energy thresholds, excellent high-energy sensitivity, and ease of construction and operation.

The U.S. teams have pioneered the field of ground based γ-ray astronomy during the last 50 years. The U.S. community has formed the "AGIS" collaboration (Advanced Gamma ray Imaging System) to optimize the design of a future γ-ray detector. A similar effort is currently under consideration in Europe by the CTA (Cherenkov Telescope Array) group, and the Japanese/Australian groups building CANGAROO are also exploring avenues for future progress. Given the scope of a next-generation experiment, the close collaboration of the US teams with the European and Japanese/Australian groups should be continued and intensified. If funded appropriately, the US teams are in an excellent position to lead the field to new heights.

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Appendices

A Glossary

A.1 Astronomical and Physics Terms

30 Dor C - 30 Dor C is a *superbubble* in the *Large Magellanic Cloud* coinciding with an *OB association*. The detection of non-thermal radio emission indicates the presence of relativistic electrons.

AGN - An Active galactic nucleus is a compact region at the center of a galaxy that has a much higher than normal luminosity over most of the electromagnetic spectrum ranging from the radio, infrared, optical, ultra-violet, X-ray and high energy to very high energy *VHE* gamma-ray energies. Active galactic nuclei (AGN) often show a pair of *relativistic jets* that are powered by accretion onto a *supermassive black hole* the size of our solar system. These large scale jets are prospective sites for particle acceleration since they often reveal relativistic phenomena (see also *blazars*).

Blazar - Blazars are *AGN* that have their *jet* axis closely aligned with the observer's line of sight. Consequently, *relativistic Doppler boosting* of emission regions moving along the *jet* axis causes blazars to appear extremely bright and to exhibit rapid flux variations.

Bremsstrahlung - The radiation that is emitted by the deceleration of an electron in the electric field of an atomic nucleus.

Cosmic rays - Cosmic rays are energetic particles, mostly protons and helium nuclei that impinge on the Earth's atmosphere. Although cosmic rays were discovered in 1912 by Victor Hess, their origin is still unknown. Their vast energy range (10^9- 10^{20} eV) suggests that cosmic rays are produced in astrophysical environments of vastly different size scales and magnetic field strengths. Currently favored sites are parsec (pc) scale *supernova remnants* with the potential to accelerate atomic nuclei to a few PeV and kpc scale *jets* associated with *AGN* that might achieve energies in the 10^{20} eV (*EHE*) regime.

Crab Nebula - The Crab Nebula is a *supernova remnant* with a *pulsar wind nebula* that dates back to a *supernova* that occurred in 1054 AD. Due to its strong and steady emission of *synchrotron radiation* from the nebula, the Crab is used as a standard candle in X-ray and gamma-ray astronomy and source fluxes are often given in units of 1 Crab.

Cygnus region - The Cygnus region is a prominent bright feature in the galactic sky map across many wavelengths with gamma-ray emission extending up to several TeV. The presence of *supernova remnants*, *OB associations* and *Wolf-Rayet stars* makes it a very promising site for relativistic particle acceleration in our galaxy.

Dark matter - Approximately 80% of the matter in the universe is made from Dark matter which is a hypothetical form of matter of unknown composition that does not emit or interact with light at a level that is directly observable. Only less than 20% of the matter in the universe appears luminous through the emission of light and is made from baryonic matter such as protons and nuclei. The existence of dark matter is concluded from its gravitational effects on light and the dynamics of individual galaxies and *galaxy clusters*.

Dwarf galaxies - A dwarf galaxy is a small galaxy composed of up to several billion stars, a small number compared to our own *Milky Way* galaxy with 200-400 billion stars.

EBL - Extragalactic background light describes the diffuse background radiation with wavelengths between 0.1 micron and 1000 micron. The EBL is produced by all cumulative radiative energy releases after the epoch of recombination and constitutes the second most important radiative energy density permeating the universe after the *cosmic microwave background*.

EHE - Extremely high energy stands for 10^{18} eV and is used for describing the energy scale of the highest energy *cosmic rays*.

Galactic Center - The Galactic Center refers to the center of the Milky Way galaxy that contains a *supermassive black hole* accreting mass from stars, dust and gas.

Galaxy cluster - Galaxies occur in groups, the larger groups with 50 to 1000 galaxies are called galaxy clusters, the space in between galaxies is filled with a hot gas, the *intracluster medium* (ICM).

Gamma-ray burst - Gamma-ray bursts (GRBs) are flashes of gamma-rays originating in random places in space and are the most luminous events since the big bang.

Heliosphere - The heliosphere is a bubble in the *interstellar medium* produced by the solar wind and surrounds the sun out to a radial distance of $\approx$ 100 astronomical units (1 AU = distance between Earth and Sun).

Intracluster medium - The intracluster medium (ICM) permeates the space between galaxies in a *galaxy cluster* and typically has a temperature of $10^7 - 10^8$ K and is detected in X-rays from thermal *bremsstrahlung* and atomic line emission.

Inverse Compton scattering - Inverse Compton scattering is the process in which a photon gains energy from the interaction with a relativistic electron.

Interstellar medium - The interstellar medium (ISM) consists of a dilute mixture of mostly hydrogen and helium gas (together about 99% by mass), 1% dust grains, cosmic rays and a magnetic field that permeates the interstellar space between stars in a galaxy.

LMC - The Large Magellanic Cloud (LMC) is a nearby satellite galaxy of the Milky Way and resides at a distance of 50 kpc. It contains just about 1/10 of the Milky Way's mass.

Microquasar - Microquasars share important similarities with *quasars*: strong and variable radio emission, a pair of radio *jets* and a compact region surrounded by an accretion disk. Microquasars are found in stellar binary systems and may be powered by accretion of mass from a companion star onto a compact object, either a neutron star or a black hole. Microquasars play an important role in the study of *relativistic jets* since they are miniature versions of *quasars*.

Milky Way Galaxy - Our solar system belongs to the Milky Way Galaxy that consists of over 200-400 billion stars, mostly distributed in a disk of a few hundred light years thick and a radial extension of 100,000 light years across.

Millisecond pulsars - Millisecond pulsars are extremely rapid spinning neutron stars with rotation periods of 1 - 10 milliseconds. These are extreme rotation periods even for *pulsars*, and could arise from angular momentum transfer via accretion. Millisecond pulsars are found in X-ray binary star systems with a massive companion star consistent with the idea that they have evolved from regular *pulsars* and were spun up by accretion.

Molecular cloud - A molecular cloud is an interstellar cloud containing hydrogen gas with a density and temperature cool enough to allow the formation of H_2 molecules. Since H_2 is difficult to detect, the presence of carbon monoxide (CO) is often used as a proxy for tracing H_2 since the ratio between CO luminosity and the mass in H_2 is thought to be constant.

Neutrino - A subatomic particle with little mass that interacts only weakly making it difficult to detect. Neutrinos are generated in reactors, inside the Sun, in a *supernova* and in *cosmic-ray* interactions therefore probing a variety of astrophysical phenomena. Their study is particularly useful for studying processes in dense and hidden environments of astrophysical sources.

OB associations - The term OB association describes star forming regions comprised of 10 to 100 massive stars, mostly O and B (very hot) stars.

Parsec - Distance unit often used in astronomy where 1 parsec corresponds to 3.26 light years.

Periastron - Periastron describes the closest approach of a star orbiting the center of attraction in a binary system.

Pions - In particle physics, pion is the collective name for three subatomic particles: a neutral, a negatively and a positively charged particle. Pions are the lightest mesons and play an important role in explaining low-energy properties of the strong nuclear force.

PeV - 1 petaelectronvolt corresponds to an energy of 10^{15} eV.

Pulsar - Pulsars are highly magnetized rapidly rotating neutron stars which emit a beam of detectable electromagnetic radiation in the form of radio waves. The beam can only be observed when it is directed towards the observer's line of sight.

PWN - A Pulsar wind nebula is a *synchrotron radiation* emitting nebula powered by the relativistic wind of an energetic pulsar. The most prominent example is the *Crab nebula*.

Quasar - Quasars are extremely bright radio sources located at the centers of very distant active galaxies. Historically, quasars were detected as radio sources initially without optical counterpart, hence their name (QUASi-stellAR radio source). It is generally agreed upon that a quasar is a halo of matter surrounding a supermassive black hole at the center of an active galaxy. Quasars have been detected out a redshift of 6.43, corresponding to a distance of 8.5 Gpc.

Relativistic Doppler boosting - Relativistic Doppler boosting refers to the increase in luminosity for a light source moving at relativistic speed towards the observer, whereas a reduction in luminosity is seen for a light source moving in opposite direction. *Blazars* are therefore extremely bright as one of their jets is directed towards the observer.

Relativistic jets - Relativistic jets are narrow, pencil-beam structures of plasma that move at relativistic speeds from the centers of active galactic nuclei (*AGN*). Mildly relativistic jets are also observed in galactic objects such as *microquasars*. The large scale jets in *AGN* often reach several thousand *parsec* in scale and are prime candidates for producing the highest energy cosmic rays.

SS 433 - SS 433 is an X-ray binary system (13.1 day orbital period) with either a neutron star a black hole as the compact object. Strong evidence for two mildly (0.26 c) *relativistic jets* is given by varying Doppler-shifted emission lines.

Starburst galaxies - Starburst galaxies exhibit star formation rates hundreds of times larger than in our own galaxy. Such high star formation rates are attributed to a collision with another galaxy.

Supermassive black holes - Supermassive black holes have masses ranging from a hundred thousand up to several tens of billions of solar masses. Most if not all galaxies appear to harbor a supermassive black hole at their center.

Superbubble - Superbubbles are regions in interstellar space that contain hot gas of 10^6 Kelvin most likely produced by multiple *supernovae* and stellar winds.

Supernova - A star that can no longer support its own weight collapses. This occurs in stars that accrete matter from a companion star or in stars that run out of fuels for nuclear fusion. As a result it throws off its outer layer causing a bright burst of electromagnetic radiation that can outshine an entire galaxy.

Supernova remnants (SNR) - A supernova remnant is the result of the gigantic explosion of a star, a *supernova*. The remnant is shaped by an expanding shock wave that consists of ejected material sweeping up interstellar gas leading to the acceleration of charged particles along the way.

Synchrotron radiation - Synchrotron radiation is electromagnetic radiation, similar to cyclotron radiation, but generated by the acceleration of ultrarelativistic (i.e., moving near the speed of light) charged particles through magnetic fields.

UHE - Ultra high energy refers to *cosmic ray* particle energies between 10^{14} eV to 10^{20} eV.

Ultraluminous infrared galaxies - Ultraluminous infrared galaxies (ULIRG) are galaxies that emit most of their energy output at far-infrared wavelengths with luminosities exceeding more than 10^{12} solar luminosities. This indicates that they contain a large amount of dust.

X-ray binary - X-ray binary star systems are powerful X-ray sources. The X-ray emission results from accretion from a companion star onto a compact object.

VHE - Very high energy refers to the gamma-ray energy region of 10^{10} eV to 10^{14} eV and is generally covered by ground based gamma-ray observatories.

Wolf-Rayet stars - Wolf-Rayet stars are evolved, massive stars (over 20 solar masses), and are losing their mass rapidly by means of a very strong stellar wind, with speeds up to 2000 km/s.

A.2 Abbreviations & Acronyms

AGIS - Advanced Gamma-ray Imaging System is a concept of a large future array of imaging atmospheric Cherenkov telescopes *(IACTs)* with a collection area of 1 km^2 and is currently pursued by U.S. scientists. A similar effort (*CTA*) is being studied by groups in Europe.

ANITA - The ANtarctic Impulsive Transient Antenna is a balloon-borne neutrino detector circling Antartica, looking for radio evidence of particle showers generated from extremely high-energy neutrinos interacting with the Antartic ice sheet.

CGRO - The Compton Gamma-Ray Observatory was launched in 1990 and is the second of NASA's four great observatories. This observatory consisted of four instruments (EGRET, Comptel, OSSE and BATSE) and provided sensitivity in the gamma-ray regime between 20 keV and 30 GeV.

CTA - Cherenkov Telescope Array (CTA) is pursued by European scientists, is similar to *AGIS* and aims to build a 1 km^2 array of imaging atmospheric Cherenkov telescopes.

Chandra - X-ray observatory that was launched in 1999 and is one of NASA's great observatories.

EXIST - Energetic X-ray Imaging Space Telescope would provide an all-sky survey at energies between 0.5-600 keV.

EGRET - The Energetic Gamma-Ray Experiment Telescope was operated on the Compton Gamma-Ray Observatory satellite in the 1990s and was sensitive to 20 MeV - 30 GeV.

Fermi/GLAST - Gamma-ray Large Area Space Telescope, a 20 MeV - 300 GeV pair conversion telescope to be launched in early 2008. GLAST will also have a burst monitor on board that is sensitive between 8 keV and 25 MeV.

HAWC - The High Altitude Water Cherenkov observatory is a proposed wide field of view gamma-ray experiment over an energy range of approx 700 GeV - 50 TeV.

H.E.S.S. - High Energy Stereoscopic System, an array of four imaging atmospheric Cherenkov telescope (see also *IACT*) systems in Namibia and has been operating since 2003.

IACT - Imaging Atmospheric Cherenkov Telescopes use a technique to detect gamma-rays with ground based telescopes which was pioneered by the Whipple collaboration. The technique is based on measurements of the secondary particle cascade (air shower) from a gamma-ray primary in the atmosphere. The air shower is detected by recording Cherenkov light images of the shower.

IceCube - The high energy neutrino telescope using a 1 km^3 of the ice at the south pole.

LHC - Large Hadron Collider experiment at CERN.

LIGO - The Laser Interferometer Gravitational-wave Observatory, consisting of two 4-km laser interferometers to detect gravitational waves.

LISA - The Laser Interferometer Space Antenna.

LOFAR - The LOw Frequency Array, a joint Dutch-U.S. initiative to study radio wavelengths longer than 2 m.

LSST - The Large-aperture Synoptic Survey Telescope, a 6.5 m class optical telescope.

MAGIC - Major Atmospheric Gamma-ray Imaging Cerenkov telescope, a 17 m diameter imaging atmospheric Cherenkov telescope on the island of La Palma to detect sub-TeV - 10 TeV gamma radiation.

Milagro - A water Cherenkov detector for the detection of very high energy gamma-rays.

Milagrito - A prototype water Cherenkov detector for the detection of very high energy gamma-rays that ultimately became the Milagro observatory.

PAMELA - The Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics, is the first satellite dedicated to detecting cosmic rays and also antimatter from space, in the form of positrons and antiprotons. PAMELA pursues a long-term monitoring of the solar modulation of cosmic rays and measurement of energetic particles from the Sun.

SIM - The Space Interferometry Mission to be launched in 2011 will provide accurate distance measurements using parallax out to distances of 250 kpc.

Swift - The Swift gamma-ray burst (*GRB*) mission is a multi-wavelength observatory dedicated to the study of *GRBs*. Its three instruments can observe a *GRB* at gamma-ray, X-ray, ultraviolet and optical wavebands. It also provides burst notification within a few seconds time allowing both ground-based and other space-based telescopes around the world the opportunity to observe the burst's afterglow.

VERITAS - The Very Energetic Radiation Imaging Telescope Array System is an array of four imaging atmospheric Cherenkov telescopes (*IACTs*) located in southern Arizona and has been operating since spring of 2007.

WCA - Water Cherenkov Array, a technique to detect gamma-rays from ground, was pioneered by the Milagro collaboration.

Whipple 10 m gamma-ray telescope - The Whipple 10 m gamma-ray telescope is the pioneering instrument that was used to develop the imaging atmospheric Cherenkov technique and is located in southern Arizona at Whipple Observatory.

B Charge from APS

UNIVERSITY *of* NEW HAMPSHIRE

September 27, 2006

Martin Pohl
Department of Physics and Astronomy
Iowa State University
Ames, IA 50011

Dear Colleagues,

The Division of Astrophysics of the American Physical Society invites you to prepare a review or white paper on the status and future of ground based TeV gamma-ray astronomy. With the upcoming commissioning of VERITAS and the success of HESS and others in this emerging field, a review of the science accomplishments and potential would be welcome. Furthermore, given the long lead time for designing, developing and deploying new instruments, we need a clear path for proceeding beyond the near term.

Understanding that this is a significant task, we would ask you to do the following:

- Consider yourselves the editorial board for this white paper. This entails being ultimately responsible for the drafting, formatting and distribution of the report.

- Recruit, as necessary, a very small number of other people to augment you as an editorial board. These people might be important players in TeV gamma-ray astronomy or astrophysics who might lend their expertise and stature to the preparation of the report. Please ensure that a spectrum of researchers is represented on the board to promote objectivity and avoid the appearance of advocacy.

- Delegate, as necessary, to willing and knowledgeable people in the field the collection and synthesis of information necessary for drafting this report. These people would likely draft sections of the report that you would, in turn, edit and merge with other sections.

There is little time to prepare this report for release at the April 2007 APS meeting, however, it would fitting if this report could be released at the April 2008 meeting. If is available a sufficient time before the April 08 meeting, we should consider releasing it by other means for the benefit of the community.

Space Science Center
Institute for the Study of Earth, Oceans, and Space (EOS) Morse Hall 39 College Road Durham, New Hampshire 03824-3525

We suggest that as soon as possible you begin soliciting financial support from interested agencies, institutions and parties. The costs for travel and production of the report will not be trivial.

Although, I am in no position to offer financial support from the DAP you are free to ask for such support, but as members you know the limitations of our resources and the difficulty of maintaining them.

The Executive Committee appreciates your investment of time and energy into the future directions of this important field. If we, the Executive Committee, can be of help, please feel free to ask.

On Behalf of the DAP Executive Committee,
Sincerely Yours,

Jim

James Ryan
Chair

cc: DAP Executive Committee
V. Vassiliev
H. Krawczynski
B. Dingus

C Letter to community (via e-mail)

Dear Colleague,

In recent years, ground-based gamma-ray observatories have made a number of important astrophysical discoveries which have attracted the attention of the wider scientific community. The high discovery rate is expected to increase during the forthcoming years, as the VERITAS observatory and the upgraded MAGIC and HESS observatories commence scientific observations and the space-based gamma-ray telescope, GLAST, is launched. The continuation of these achievements into the next decade will require a new generation of observatories. In view of the long lead time for developing and installing new instruments, the Division of Astrophysics of the American Physical Society has requested the preparation of a White Paper (WP) on the status and future of ground-based gamma-ray astronomy to define the science goals of the future observatory, to determine the performance specifications, and to identify the areas of necessary technology development. The prime focus of the WP will be on the astrophysical problems which can be addressed at energies above 10 GeV. No particular experiment or technology will be endorsed by the WP; instead it will enumerate available space and ground-based technological alternatives. On behalf of the working groups, we would like to invite both US and international scientists from the entire spectrum of astrophysics to contribute to the concepts and ideas presented in the White Paper.

The work on the WP is organized through six science working groups (SWGs) and a technology working group (TWG). We would like to invite you to contribute your expertise and time to our efforts on (fill in specific working group). We anticipate that in the final version, the WP will consist of a brief Executive summary designed for non- scientists, an extended summary written for physicists, and it will also include detailed "Appendices" written by each working group for specialists in the appropriate fields of astrophysics or technology. While the Executive and extended summaries will be compiled by the WP editorial board, the Appendices will be written by the members of the SWGs and TWG. All contributing scientists will be authors of the WP, and the paper will be endorsed by them.

The approximate timeline for writing the WP is as follows. A first brief public meeting to discuss the White Paper will be held on Feb 8, 2007, the last day of the GLAST symposium at Stanford University, California. Information about this splinter meeting is available at: `http://cherenkov.physics.iastate.edu/wp/glast.html`. We invite contributions from all interested scientists. The format of the presentations can be further discussed with the organizers of the WP SWGs and TWG, which are listed below. We expect that the first drafts of the Appendices will be completed by the working groups in late March, 2007. A special session devoted to the White Paper will be organized at the meeting of the American Physical Society, April 14-17, 2007 in Jacksonville, FL. The revised versions of the working group reports (the Appendices) are expected to be produced in early May, 2007. We plan to have a designated one day meeting on the WP during the workshop, "Ground Based Gamma Ray Astronomy: Towards the Future," May 13-14, 2007 in Chicago, IL `http://www.hep.anl.gov/byrum/next-iact/index.html`. The final version of the Appendices is expected in early July. We plan to complete WP in late fall 2007.

Further information about the White Paper, the science and technology working groups, and the associated meetings can be found at the web-site:

`http://cherenkov.physics.iastate.edu/wp/`

To directly contact a current working group organizer, send an e-mail to:

Henric Krawczynski *krawcz@wuphys.wustl.edu* (Extragalactic Astrophysics),
Eric Perlman *perlman@jca.umbc.edu* (10 GeV Sky Survey sub-group),
Phil Kaaret *philip-kaaret@uiowa.edu* (Galactic compact objects),
Martin Pohl *mkp@iastate.edu* (SNR and cosmic rays),
Jim Buckley *buckley@wuphys.wustl.edu* (Dark matter),
Abe Falcone *afalcone@astro.psu.edu* or
David Williams *daw@scipp.ucsc.edu* (Gamma-ray bursts),
Karen Byrum *byrum@hep.anl.gov* (Technology).

For additional information please contact a member of the editorial board:

Brenda Dingus *dingus@lanl.gov*
Francis Halzen *halzen@pheno.physics.wisc.edu*
Werner Hofmann *Werner.Hofmann@mpi-hd.mpg.de*
Henric Krawczynski *krawcz@wuphys.wustl.edu*
Martin Pohl *mkp@iastate.edu*
Steven Ritz *Steven.M.Ritz@nasa.gov*
Vladimir Vassiliev *vvv@astro.ucla.edu*
Trevor Weekes *weekes@egret.sao.arizona.edu*

We understand that you have many commitments and appreciate any investment of time and expertise you could provide to this endeavor. We would be grateful for your reply to this invitation during the next week.

Sincerely,

D Agenda for Malibu meeting[5]

October 20, Thursday: Science (Mays' landing)

Please arrive to Mays' Landing no earlier than 8:30AM. Parking is strictly limited, carpooling (at least two participants per car) is a must. Meeting begins at 9:00AM. Coffee will be available from 8:45 to 9:00
Chairperson: Vladimir Vassiliev

1. Recent progress in ground-based gamma-ray astronomy and the goals of this meeting. (Simon Swordy) 10 min
2. Overview of Particle Astrophysics in the U.S. (roadmaps, future missions, funding). (Rene Ong) 20 min
3. High energy astrophysics after the GLAST mission (5 years of operation) (Julie McEnery) 25 min

Coffee Break (30 min)

4. Development of ideas in ground based gamma-ray astronomy, status of the field, and scientific expectations from HESS, VERITAS, MAGIC, CANGAROO. (Trevor Weekes) 20 min
5. Scientific expectations from MILAGRO and motivations for a 2 pi sr, 95detector (Brenda Dingus) 20 min
6. Discussion: Politics, etc. (Rene Ong) 40 min

LUNCH

7. Very high energy extragalactic transient sources: AGNEBL. (Henric Krawczynski) 20 min
8. Very high energy extragalactic transient sources: GRBs. (David Williams) 20 min
9. Galactic science in the 1 GeV -1 TeV domain (Martin Pohl) 20 min

Coffee Break (30 min)

10. Galactic science in the 1-100 TeV domain. (Stephan LeBohec) 10 min
11. Astroparticle physics: Dark Matter, Annihilation of cosmological defects, exotic particles (James Buckley) 15 min
12. Astroparticle physics: Non-standard model, broken symmetries, PBH searches, etc. (Frank Krennrich) 15 min
13. Brief outline of a few science ideas for VHE observations (Paolo Coppi) 15 min
14. Discussion: Scientific justification of future observatory and required performance characteristics (solid angle, energy domain, etc.) (Gus Sinnis) 1 hour

Meeting ends at 4:45PM.

DINNER - 6:30pm, The Sunset Restaurant (`http://www.thesunsetrestaurant.com`)

[5] `http://gamma1.astro.ucla.edu/future_cherenkov`

October 21, Friday: Technical design options for a future observatory (Mays' landing)

Please arrive to Mays' Landing no earlier than 8:30AM. Parking is strictly limited, so carpooling is a must. Meeting begins at 9:00AM. Coffee will be available from 8:45 to 9:00.
Chairperson: Simon Swordy

1. Concept(s) for very low energy observations (<10 GeV) (John Finley for Alexander Konopelko) 20 min
2. High energy transient observatory (HE-ASTRO 1km^2 array) (Stephen Fegan) 20 min
3. Small Telescope Arrays (STAR) (Henric Krawczynski) 20 min

Coffee Break (15 min)

4. Optimization of High Altitude Water Cherenkov (HAWC) detector (Gus Sinnis) 20 min
5. Design, sensitivity, and cost of miniHAWC (Andrew Smith) 20 min
6. Strategies associated with observations at >10 TeV regime (Stephan LeBohec) 10 min
7. Increasing the collection area for Cherenkov telescopes at high energies (Jamie Holder) 10 min
8. Effect of the FoV of IACTs on the sensitivity for point and extended sources (David Kieda) 10 min
9. Discussion: Design evaluation criteria. (Simon Swordy) 50 min

LUNCH

Chairperson: Karen Byrum

10. Considerations of beyond-CANGAROO projects (Takanori Yoshikoshi) 10 min
11. Summary of thoughts from HESS & MAGIC members (Vladimir Vassiliev) 10 min
12. Wide field of view Cherenkov Telescopes: Cassegrain Cherenkov telescopes (James Buckley) 15 min
13. Wide FoV: Initial design considerations (Vladimir Vassiliev) 15 min
14. High Elevation Sites in Mexico (Alberto Carraminana) 15 min
15. Site Considerations (Stephen Fegan) 15 min

Coffee Break (15 min)

Technology development:

16. Intelligent trigger concepts: Scientific motivations (Frank Krennrich) 15min
17. Photodetectors and electronic readout options (James Buckley) 15 min

18. Digital Asic (Gary Drake) 15 min
19. HE-ASTRO: focal plane instrument and trigger concept (Vladimir Vassiliev) 15 min
20. Triggering and data acquisition (high data rates regime) (Jim Linnemann) 15 min
21. Discussion: What systems should be pursued with further R&D? (Karen Byrum) 1+ hour

Meeting ends at 4:45PM.

October 22, Saturday: Organizational issues, R&D plans (UCLA)
Meeting begins at 9:00AM

Depending on the number of contributions, part of the agenda of this day may be moved to the evening of the previous day.

1. Discussion (tasks, responsibilities, goals) & Organization of working groups (science, detectors, simulations, ...)
2. Upcoming funding opportunities (Potential proposals)
3. Future conferences

E Agenda for Santa Fe meeting[6]

Thursday, May 11, 2006

9:00 - 9:10	Welcome	Gus Sinnis
9:10 - 9:20	Science Section of the White Paper	Brenda Dingus
9:20 - 9:50	Extragalactic Sources Working Group	Henric Krawczynski
9:50 - 10:20	Particle Acceleration in TeV Gamma-Ray Sources	Siming Liu
10:20 - 10:35		Paolo Coppi
10:35 - 11:00	Break	
11:00 - 11:30	Gamma Ray Bursts	Abe Falcone
11:30 - 12:00	Milagro Detection of the Cygnus Region	Aous Abdo
12:00 - 12:45	Lunch	
12:45 - 1:15	Galactic Diffuse Working Group	Martin Pohl
1:15 - 1:45	Dark Matter & Gamma-Ray All-Sky Surveys	Savvas Koushiappas
1:45 - 2:15	Dark Matter and Other Particle Physics Working Group	Jim Buckley
2:15 - 2:45	Break	
2:45 - 3:15	Galactic Sources	Phil Kaaret
3:15 - 3:45	Physics Motivations	Martin Pohl
3:45 - 4:15	Extending GLAST Science Simulations to TeV	Julie McEnery
4:15 - 5:30	Science Working Groups Meet Separately	
6:00	Banquet	

Friday, May 12, 2006

8:30 - 8:50	ACT Overview: Technology Drivers and Design Metrics	Jim Buckley
8:50 - 9:05	Mirror Design	John Finley
9:05 - 9:20	Digitizers	Gary Drake
9:20 - 9:35	Photodetectors	Gary Drake
9:35 - 9:50	Trigger Electronics	Frank Krennrich
9:50 - 10:05	DAQ Electronics	Scott Wakely
10:05 - 10:20	Mobile ACTs	Henric Krawczynski
10:20 - 10:35	LANL CMOS Camera Development	Kris Kwiatkowski
10:35 - 11:00	Break	
11:00 - 11:15	VERITAS Update	Trevor Weekes
11:15 - 11:30	TRICE	Karen Byrum
11:30 - 12:00	miniHAWC	Andy Smith
12:00 - 12:15	Mexico Sites	Alberto Carraminana
12:15 - 12:30	Utah Sites	Dave Kieda
12:30 - 1:30	Lunch	
1:30 - 2:00	<100 GeV ACTs	Alex Konopelko
2:00 - 2:10	Experimental Approaches to the High Energy End of γ-Ray Source Spectra	Stephan LeBohec
2:10 - 2:20	ACTs and Intensity Interferometry	Stephan LeBohec
2:20 - 2:35	HE-ASTRO	Stephan Fegan
	STAR	Abe Falcone
2:35 - 3:05	HESS & Beyond	German Hermann
3:05 - 3:30	Break	
3:30 - 4:00	Summary & Comparison of Future Projects	Frank Krennrich
4:00 - 5:00	White Paper Discussion	Jim Ryan

Saturday, May 13, 2006

Tour of Milagro Site in the morning

[6] `http://www.lanl.gov/orgs/p/g_a_d/p-23/gammaworkshop/`

F Agenda for Chicago meeting[7]

Future in Gamma-ray Astronomy Meeting
May 13 & 14, 2007 at the Wyndham Hotel in downtown Chicago

	Sun. Morning Session: 9:00 am - 12:30 pm	
08:15-09:00	Continental Breakfast	
09:00-09:10	Welcome and Introduction	Scott Wakely
09:10-09:40	Current Status and Near Future	Trevor Weekes
09:40-10:00	White Paper Status and Timeline	Vladimir Vassiliev
10:00-10:30	Coffee Break	
10:30-10:50	Extragalactic Talk	Markos Georganopoulos
10:50-11:10	Extragalactic Talk	Charles Dermer
11:10-11:30	Extragalactic Discussion	Led by Henric Krawczynski
11:30-12:00	Gal. Compacts Talk	Roger Romani
12:00-12:20	Gal Compacts Discussion	Led by Phil Kaaret
12:20-12:30	Group Photo	
12:30-14:00	Lunch (provided)	
	Sun. Afternoon Session: 14:00 pm - 18:30 pm	
14:00-14:20	SNR/CR Talk	Patrick Slane
14:20-14:40	SNR/CR Talk	Igor Moskalenko
14:40-15:00	SNR/CR Discussion	Led by Martin Pohl
15:00-15:20	Dark Matter Talk	Tim Tait
15:20-15:40	Dark Matter Talk	Savvas Koushiappas
15:40-16:00	Dark Matter Discussion	Led by Jim Buckley
16:00-16:30	Coffee Break	
16:30-16:50	GRB Talk	Shri Kulkarni
16:50-17:10	GRB Talk	Neil Gehrels
17:10-17:30	GRB Discussion	Led by David Williams
17:30-18:30	Spare/Extra Time	
	Dinner: 7:00pm	
	Mon. Morning Session: 9:00 am - 12:30 pm	
08:15-09:00	Continental Breakfast	
09:00-09:30	Summary & Status of Tech. Section of the WP	Frank Krennrich
09:30-09:50	Status of CTA focusing on the science	Agnieszka Jacholkowska
09:50-10:10	Status of CTA focusing on possible instrument studies	German Hermann
10:10-11:00	Coffee Break & Poster Viewing & Mingling	
11:00-11:15	Interesting sites for Cherenkov telescopes in Argentina	Adrian Rovero
11:15-11:30	Mexican proposal for hosting Cherenkov detectors	Alberto Carraminana
11:30-11:50	The ILC detector R&D Model	Harry Weerts
11:50-12:05	Update on Decadel Survey	Brenda Dingus
12:05-13:30	Lunch (provided)	
	Afternoon Session: 13:30 pm - 18:30 pm - Chair: Dave Kieda	
13:30-14:00	Future Directions: Steps towards the future	Martin Pohl
14:00-14:30	R&D Proposal	Jim Buckley
14:30-15:00	Continuation of discussion of Next Steps	Dave Kieda
	Establishing a new CollaborationTeam	
15:00-15:30	Coffee Break	
15:30-17:30	Break into smaller working groups and identify tasksaction items.	

[7] `http://www.hep.anl.gov/byrum/next-iact/agenda.html`

G Agenda for SLAC meeting[8]

Day 1

8:00 Breakfast

Welcome and overview session:

8:30 Welcome note (R. Blandford - KIPAC)
8:40 Current status of the field and future directions (W. Hofmann - MPI-K Heidelberg)
9:10 Summary of the White Paper (H. Krawczynski - Washington University)
9:40 Discussion
10:00 Coffee Break

Science Session:

10:40 Galactic talk - Top 10 Science Questions (S. Funk, KIPAC)
11:10 Extragalactic talk - Top 10 Science Questions (P. Coppi Yale)
11:40 New physics talk - Top 10 Science Questions (L. Bergstrom - Stockholm University)
12:10 The connection to GLAST (O. Reimer - Stanford University)
12:40 Lunch break

Projects session:

14:30 HAWC (B. Dingus - Los Alamos National Lab)
15:00 AGIS (J. Buckley - Washington University)
15:30 CTA (M.Martinez IFAE Barcelona)
16:00 Status of the Japanese Gamma-ray Community (T. Tanimori - Kyoto University).
16:30 Other ideas for Gamma-ray instruments (S. LeBohec - University of Utah)
17:00 Coffee Break
17:30 Technical challenges and parameters for a future design (S. Swordy - University of Chicago)
18:00 Wrap up and social event

Day 2: Technical Session

8:30 Breakfast
9:00 Wide field of view instruments and secondary optics (V. Vassiliev - UCLA)
9:25 Monte Carlo Studies for CTA (K. Bernloehr MPIK Heidelberg)
9:50 Monte Carlo Studies for a future instrument (S. Fegan - UCLA)
10:15 Coffee Break
10:45 Survey instrument (G. Sinnis - Los Alamos National Lab)
11:10 Backend electronics and readout (H. Tajima SLAC)
11:35 Triggering etc. (F. Krenrich - Iowa State University)
12:00 Current and future Photodetectors for AGIS (Bob Wagner ANL)
12:25 Photodetectors in gamma-astronomy (M. Teshima MPIP Munich)
12:50 Lunch Break
14:00 Future of Space-based Gamma-Astronomy (N. Gehrels - NASA/GSFC)
AGIS Session (3pm-6pm) devoted to AGIS collaboration and future R&D proposals
15:00 Opening comments (V. Vassiliev)
15:30 Short presentations (1 transparency) of visions for the future instrument (discussion moderated by J. Buckley)
16:00 General discussion of AGIS collaboration issues: International collaboration, schedule for collaboration meetings, timescale for proposals, possible site (north versus south).
16:30 Presentation on optimization of design parameters for an array of IACTs (S. Bugaev)
16:40 The Low Energy Array of A Major Future VHE Gamma-Ray Experiment (A. Konopelko)
16:50 Discussion of cost of different cameraapproaches (H. Tajima)
17:05 Coffee Break
17:20 Discussion of mechanical design and fabrication, schedule (B. Wagner and V. Gaurino)
17:40 Presentation on the SPM site

Future Gamma-Ray Observatories
APS White Paper Meeting
Thurs. 8 Feb 2007 in McGaw Hall 1:30-5:00

Bring a 1-viewgraph idea to share or just come and listen. Everyone is welcome and encouraged to participate now or in the future.

Organizing Committee:
Brenda Dingus, Henric Krawczynski, Martin Pohl, Vladimir Vassiliev
Additional Members of Editorial Board:
Francis Halzen, Werner Hofmann, Steve Ritz, Trevor Weekes

8 Feb 2007 AGENDA:
1:30-1:45 Motivation & Organization
1:45-2:10 Extragalactic Working Group
2:10-2:35 Gamma Ray Burst Working Group
2:35-3:00 Dark Matter Working Group
3:00-3:15 Break
3:15-3:40 Galactic Compact Sources Working Group
3:40-4:05 Galactic Diffuse Working Group
4:05-4:30 Technology Working Group
4:30-5:00 General Discussion

H Agenda and record of white paper teleconference meetings

Conference call on Jun 09, 2006
- Discussion of organizational structure
- Nomination of Working Group chairs
- Milestones and deadlines.

Conference call on Jun 15, 2006
- Web page discussion
- Description of draft letter to the community describing the white paper
- Preliminary organization for a fall whitepaper meeting in St. Louis

Conference call on Aug 22, 2006
- Discussion of external participation on organizing committee
- Update from working groups.
- Plans for one-day workshop at the GLAST symposium

Conference call on Sep 13, 2006
- Update from working groups; working group reports posted on our web site.
- Action items discussed for GLAST symposium
- Jim Ryan announces APS-DAP plans to officially invite us to produce a white paper.

Conference call on Oct 12, 2006
- Detailed update from working groups.
- Formalize plans for whitepaper workshop at GLAST symposium.

Conference call on Nov 01, 2006
- Election of external organizing committee members
- Update from working groups
- Outline plans for reaching out to a broader community for support

Conference call on Nov 08, 2006
- Discussion on members for editorial board

Conference call on Nov 15, 2006
- Discussion of gamma-ray astrophysics session at April 2007 APS
- Initial planning for a Chicago Spring meeting
- Working group discussions

Conference call on Nov 22, 2006
- Expansion of the editorial board
- Working group updates
- Webpage update
- Organization of GLAST symposium talks

Conference call on Nov 29, 2006
- Working group updates and planning for GLAST symposium

Conference call on Dec 04, 2007
- Working group update

Conference call on Jan 11, 2007
- Update on submissions of White Paper abstracts to APS
- Discussion of template of invitation e-mail to broader community

Conference call on Mar 19, 2007
- Update on progress of working groups

Conference call on Apr 23, 2007
- Working group updates.
- Discussion following APS meeting

Conference call on Aug 28, 2007
- Working group updates
- Discussion of summary sections

Conference call on Oct 29, 2007
- Remaining White Paper contributions

Conference call on Dec 04, 2007
- Discussion of White Paper working group contributions.

I Membership

Editors	Affiliation
Brenda Dingus	Los Alamos National Laboratory
Henric Krawczynski	Washington University (St.Louis)
Martin Pohl	Iowa State University
Vladimir Vassiliev	University of California Los Angeles

Senior Advisors	Affiliation
Francis Halzen	University of Wisconsin, Madison
Werner Hofmann	Max-Planck-Institut für Kernphysik (Heidelberg)
Steven Ritz	NASA Goddard Space Flight Center
Trevor Weekes	The Harvard Smithsonian Center for Astrophysics

Group Chairs	Affiliation	Group
Jim Buckley	Washington University (St.Louis)	DM
Karen Byrum	Argonne National Laboratory	Tech
Abe Falcone	Penn State	GRB
Phil Kaaret	The University of Iowa	GCO
Henric Krawczynski	Washington University (St.Louis)	EG
Martin Pohl	Iowa State University	SNR
David Williams	University of California, Santa Cruz	GRB

Secretarial staff	Affiliation
Alan Hulsebus	Iowa State University
Iris D. Peper	Washington University (St.Louis)

Group Members	Affiliation	Group
Armen Atoyan	Montreal University	EG
Ahmad Abdo	Michigan State University	SNR, GCO
Jonathan Arons	University of California, Berkeley	GCO
Armen Atoyan	Universite de Montreal	EG, SNR
Edward Baltz	Kavli Institute for Particle Astrophysics and Cosmology	DM
Matthew Baring	Rice University	SNR, GCO, GRB
John Beacom	Ohio State University	SNR
Matthias Beilicke	Washington University (St. Louis)	EG
Gianfranco Bertone	Institut d'Astrophysique de Paris	DM
Roger Blandford	Kavli Institute for Particle Astrophysics and Cosmology, Stanford Linear Accelerator Center	EG, SNR, GRB
Markus Böttcher	Ohio University	EG
Jim Buckley	Washington University (St. Louis)	DM, Tech, GRB
Slava Bugayov	Washington University (St. Louis)	Tech

Yousaf Butt	The Harvard Smithsonian Center for Astrophysics	SNR
Andrei Bykov	Ioffe Physico-Technical Institute, St. Petersburg	SNR
Karen Byrum	Argonne National Laboratory	DM, Tech
Alberto Carraminana	Instituto Nacional de Astrofísica, Óptica y Electrónica	EG
Valerie Connaughton	National Space Science and Technology Center	GRB
Paolo Coppi	Yale University	EG, GRB
Wei Cui	Purdue University	GCO
Charles Dermer	U.S. Naval Research Laboratory	EG, GRB
Brenda Dingus	Los Alamos National Laboratory	DM, EG, GCO, GRB, Tech
Gary Drake	Argonne National Laboratory	Tech
Eli Dwek	Goddard Space Flight Center	EG
Don Ellison	North Carolina State University	SNR
Abe Falcone	Pennsylvania State University	EG, GRB
Steve Fegan	University of California, Los Angeles	DM, Tech
Francesc Ferrer	Case Western Reserve University	DM
John Finley	Purdue University	EG, GCO, Tech
Chris Fryer	Los Alamos National Laboratory	GRB
Stefan Funk	Kavli Institute for Particle Astrophysics and Cosmology, Stanford Linear Accelerator Center	EG, GCO, Tech
Bryan Gaensler	The University of Sydney, Austrailia	GCO
Neil Gehrels	NASA Goddard Space Flight Center	GRB
Markos Georganopoulos	NASA Goddard Space Flight Center	EG
Paolo Gondolo	The University of Utah	DM
Jonathan Granot	Stanford Linear Accelerator Center	GRB
Jeter Hall	Fermi National Accelerator Laboratory	DM
Francis Halzen	University of Wisconsin, Madison	SNR
Alice Harding	NASA Goddard Space Flight Center	GCO
Elizabeth Hays	NASA Goddard Space Flight Center	GCO, SNR, Tech
Sebastian Heinz	University of Wisconsin, Madison	GCO
Jamie Holder	University of Delaware	EG, GCO, Tech
Dan Hooper	Fermi National Accelerator Laboratory	DM
Deirdre Horan	Argonne National Laboratory	DM, EG, GRB, Tech
Brian Humensky	The University of Chicago	SNR
Tom Jones	University of Minnesota	EG, SNR
Ira Jung	Washington University (St. Louis)	EG
Philip Kaaret	The University of Iowa	EG, GCO, SNR
Jonathan Katz	Washington University (St. Louis)	EG, GRB
Dave Kieda	The University of Utah	SNR, GCO
Alexander Konopelko	Purdue University	Tech
Savvas Koushiappas	Brown University	DM
Henric Krawczynski	Washington University (St. Louis)	DM, EG, Tech
Frank Krennrich	Iowa State University	EG, Tech
Kyler Kuehn	Center for Cosmology and Astroparticle Physics	GRB
Stephan LeBohec	The University of Utah	DM, EG, GCO, SNR, Tech
Amir Levinson	Tel Aviv University, Israel	GCO

Julie McEnery	NASA Goddard Space Flight Center	EG
Peter Mészáros	Pennsylvania State University	GRB, SNRB
Igor Moskalenko	Stanford Linear Accelerator Center	SNR
Reshmi Mukherjee	Columbia University	EG, GCO
Jay Norris	NASA Goddard Space Flight Center	GRB
Pablo Saz Parkinson	University of California, Santa Cruz	GRB
Rene Ong	University of California, Los Angeles	EG, GCO
Asaf Pe'er	University of Amsterdam & Space Telescope Science Institute	GRB
Eric Perlman	Flordia Institute of Technology	EG
Martin Pohl	Iowa State University	DM, EG, GCO, SNR
Stefano Profumo	University of California, Santa Cruz	DM
Ken Ragan	McGill University	GCO
Enrico Ramierez-Ruiz	University of California, Santa Cruz	GRB
Soeb Razzaque	Pennsylvania State University	GRB
Steven Ritz	NASA Goddard Space Flight Center	EG
James Ryan	University of New Hampshire	EG
Joe Silk	Oxford University	DM
Gus Sinnis	Los Alamos National Laboratory	EG, Tech
Patrick Slane	Harvard-Smithsonian Center for Astrophysics	SNR, GCO
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Vladimir Vassiliev	University of California, Los Angeles	DM, EG, Tech
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Group Legend

DM	Dark Matter
EG	Extragalactic Very-High-Energy Astrophysics
GCO	Galactic Compact Objects
GRB	Gamma-Ray Bursts
SNR	Supernova Remnants
Tech	Technology