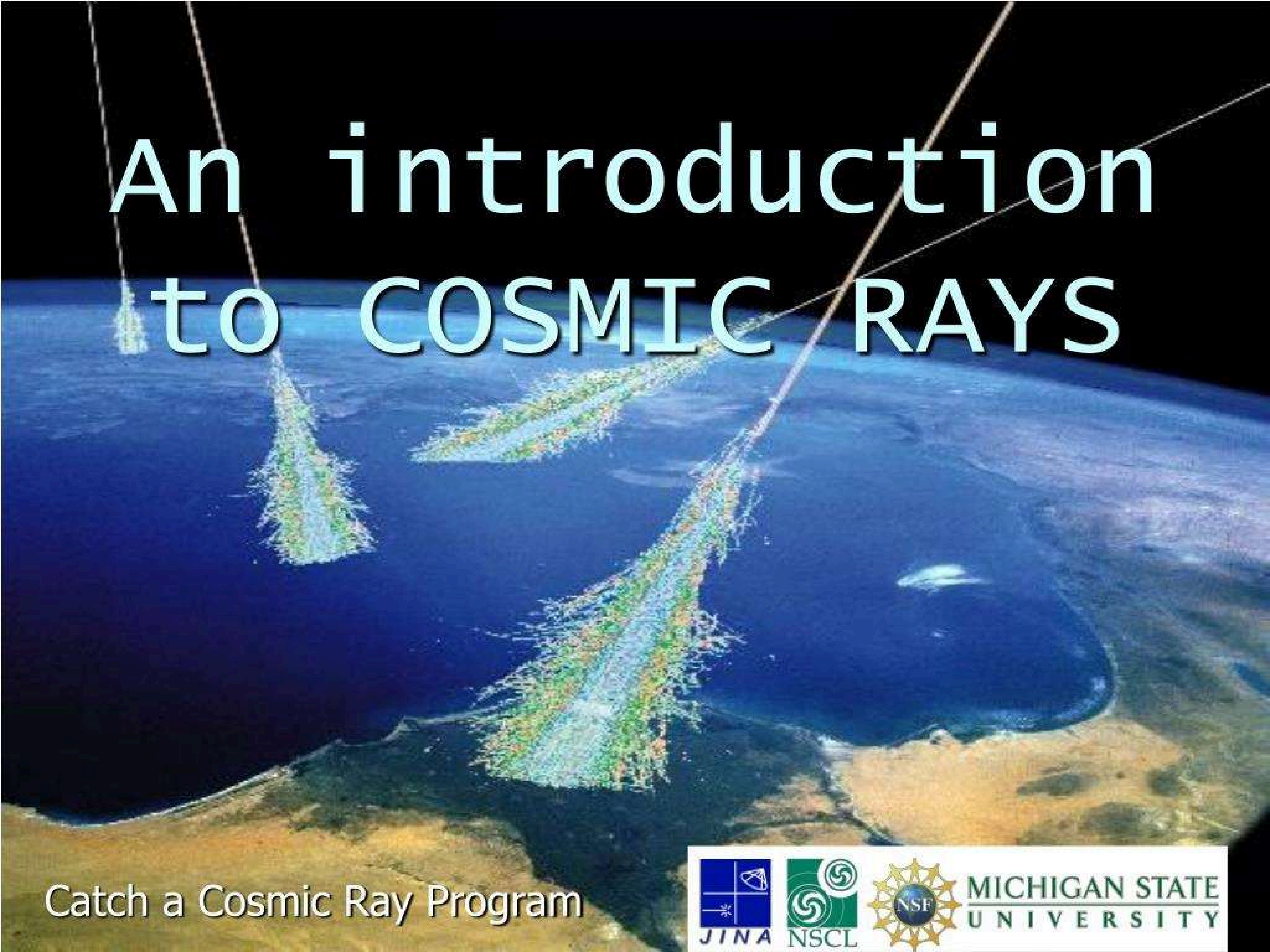
Summer Project'25

Astral Trails

SESSION 4

An introduction to COSMIC RAYS



Catch a Cosmic Ray Program

COSMIC RAYS:

Messages from exploding stars and even more powerful objects

- What are cosmic rays?
- How do we detect them?
- What can we learn from them?
- Where do they come from?

History of Cosmic Rays: 1785-1902

- <u>1785 Charles Coulomb</u>
  - Discovered that charged body in the air becomes discharged→ "there are ions in the atmosphere"

- <u>1902 Rutherford, McLennan, Burton</u>
  - Discovered that penetrating radiation passes through the atmosphere

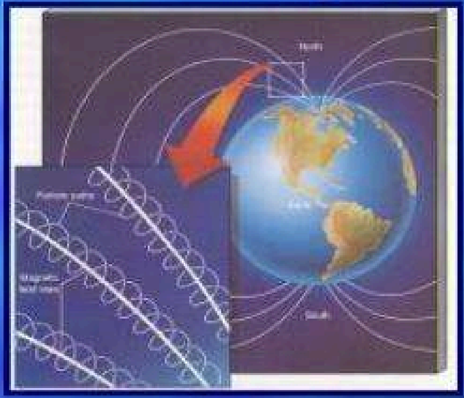
History of Cosmic Rays: 1912

- 1912 Victor Hess
  - Investigated *sources* of radiation – took balloon up to 5000 meters
    - Found radiation increased after 2500 meters
    - This could be attributed to the fact that there was less atmosphere above to shield him from radiation
    - Thus he discovered that radiation is coming from space ... "*cosmic* radiation"
  - Won Nobel Prize in 1936

Hess after his flight, which he took without breathing apparatus in very cold and thin air!

History of Cosmic Rays: 1933-1937

- 1933 Sir Arthur Compton
  - Radiation intensity depends on magnetic latitude

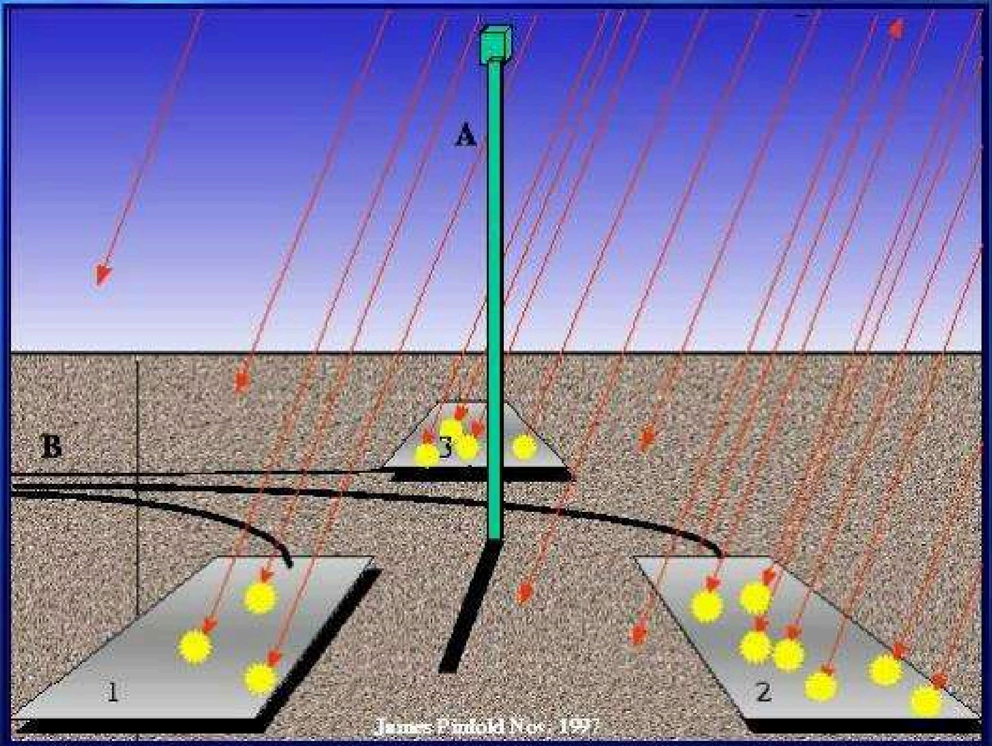


http://www.sciencebulletins.amnh.org
search: Earth's magnetic shield

- 1937 Street and Stevenson
  - Discovery of the muon particle in cosmic rays (207 x heavier than an electron)

History of Cosmic Rays: 1938

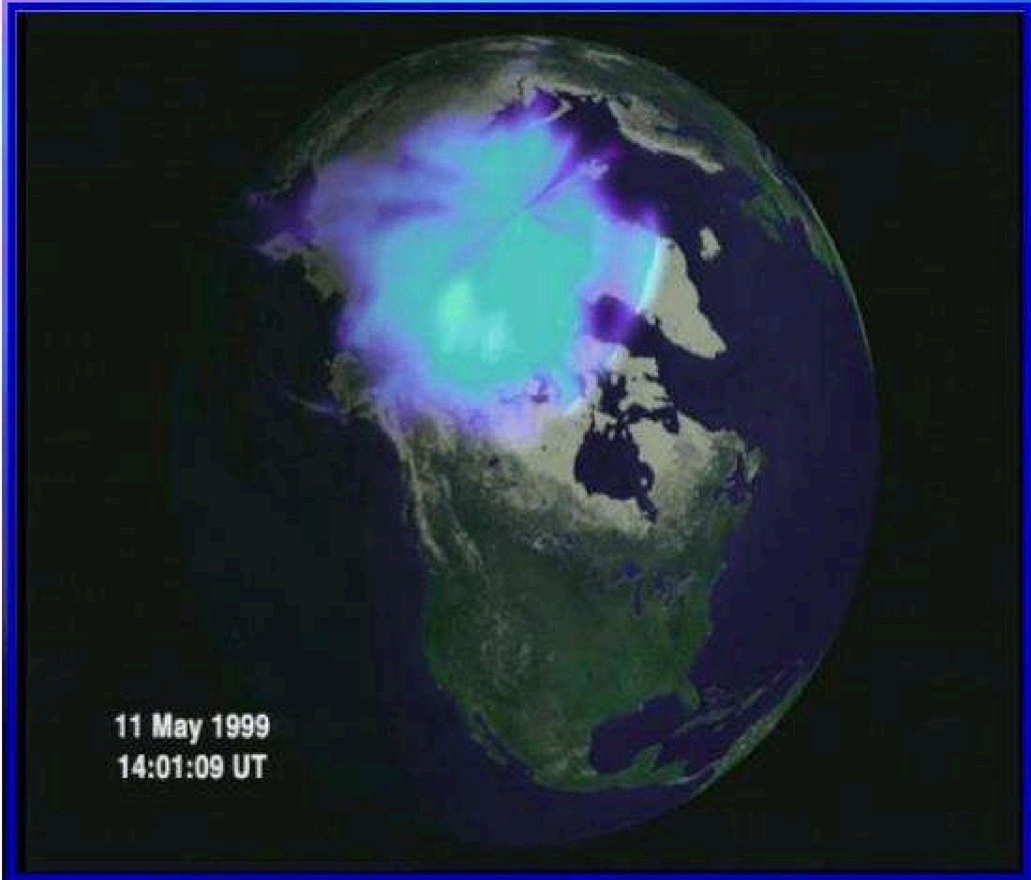
- Pierre Auger and Roland Maze
  - Rays in detectors separated by 20m (later 200m) arrive simultaneously
  - This is known as coincidence



History of Cosmic Rays: 1982

- Sekido and Elliot
  - Gave the first correct explanation of what Cosmic Rays are: ionized atoms (nuclei) from space hitting the atmosphere

In summary:

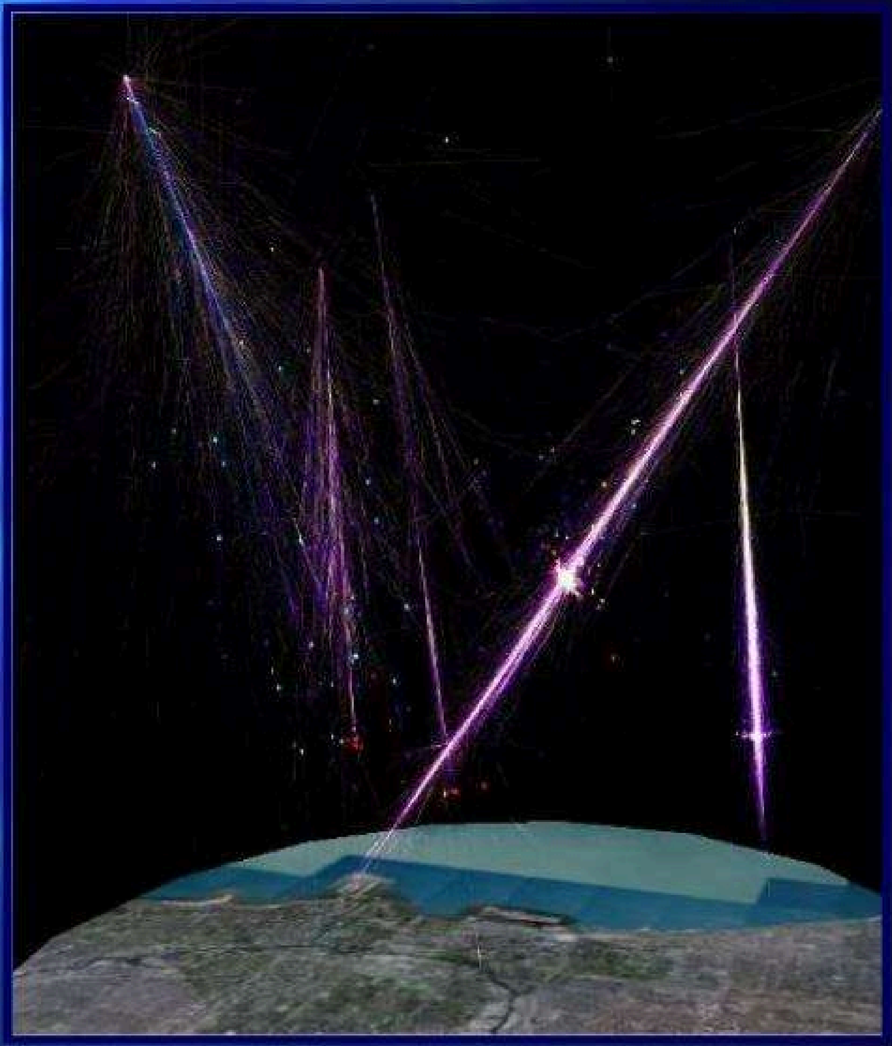


- Centuries ago, scientists became aware of radiation in the air, more than there should be on Earth
- Hess figured out that radiation was coming from space since radiation increased with altitude
- Others discovered that cosmic rays were charged particles called "ions", since our magnetic field steers them to the poles

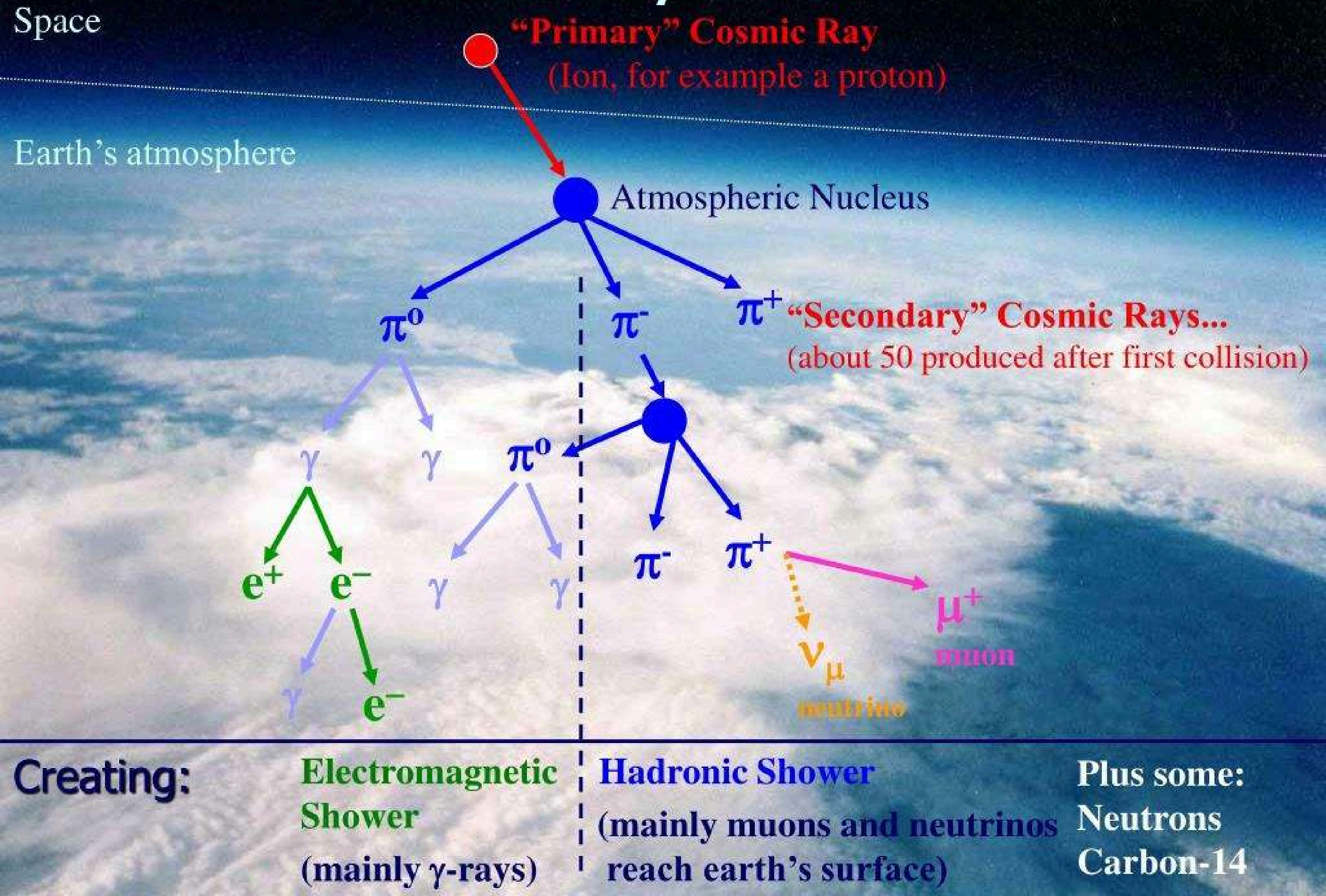
What are cosmic rays?

What are cosmic rays (CRs)?

- As it turns out, these charged particles are atomic nuclei zooming through space
  - Called "primary" CRs
  - Mostly protons or α (He) nuclei (other elements too, in much shorter supply)
  - There are more coming in at lower than higher energies
- When these hit another nucleus in the atmosphere and stop, *more* particles are knocked downward, causing a cascading effect called a "shower"
  - Particles in the shower are called "secondary" CRs

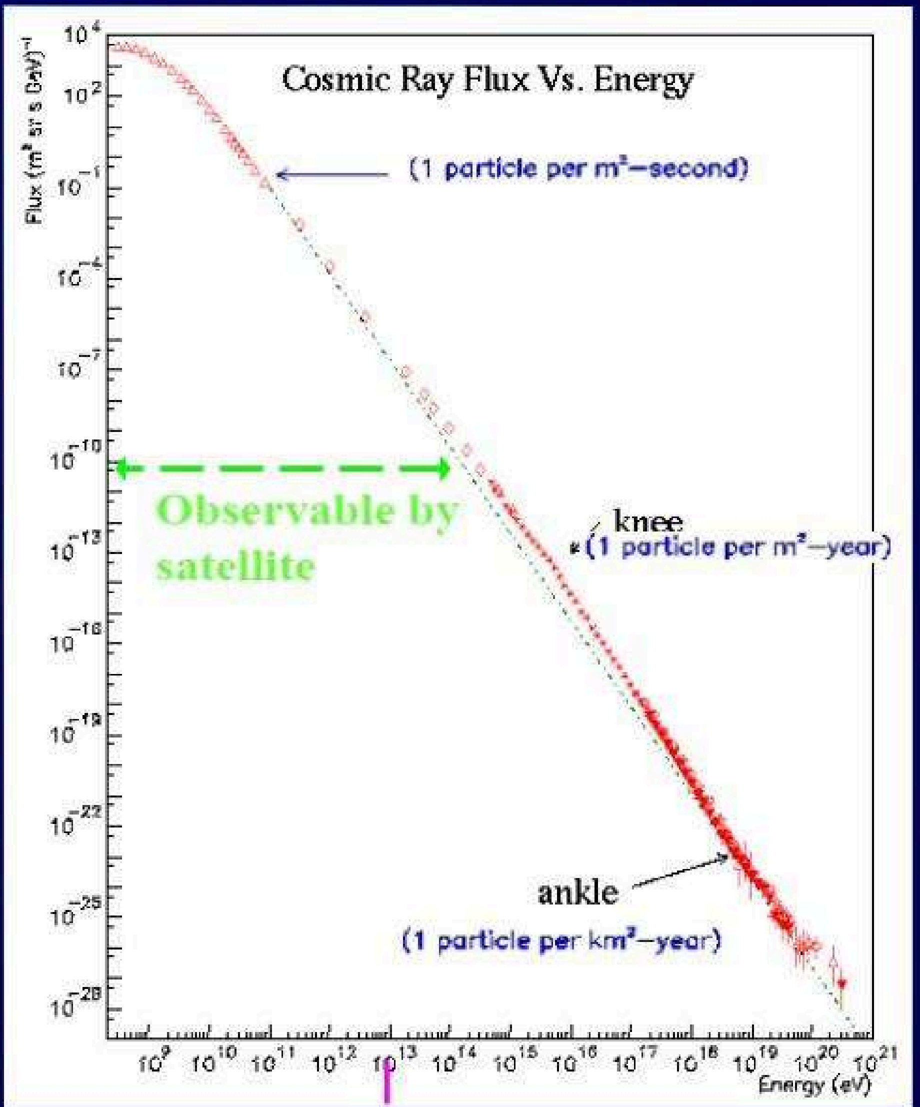


Cosmic Ray "Showers"



Primary Cosmic Rays

- Mostly H/He
- Other elements too (in much shorter supply)
- Lower-energy CRs are common, while high-energy CRs are rare



Man made accelerators

<u>Just a reminder:</u>

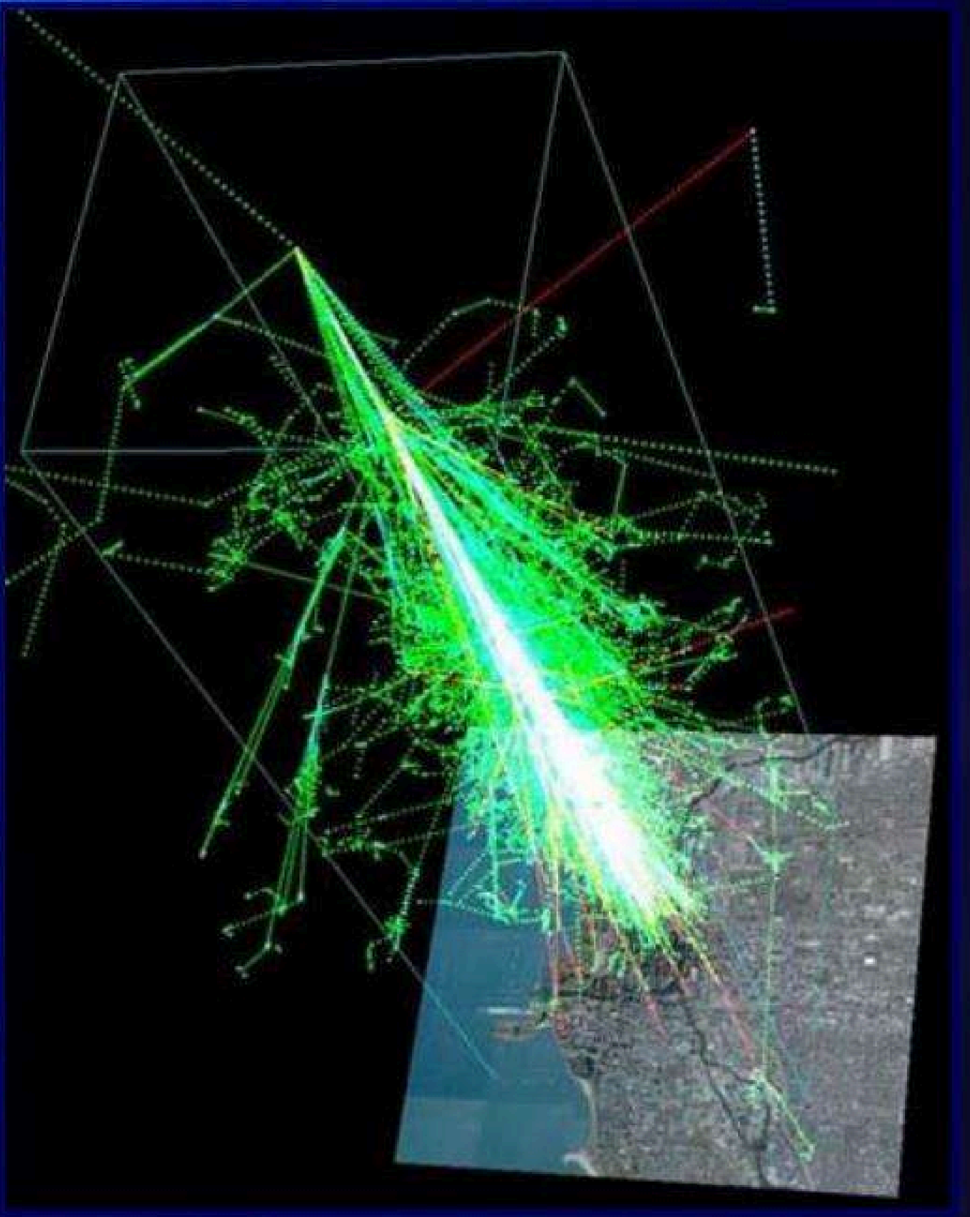
<u>Flux</u> – number of arriving particles per (unit area x unit time)

<u>eV</u> – (very small) unit of energy

- **one volt times the charge of a single electron**
- **1 eV = 1.609 x 10^{-19} joules**

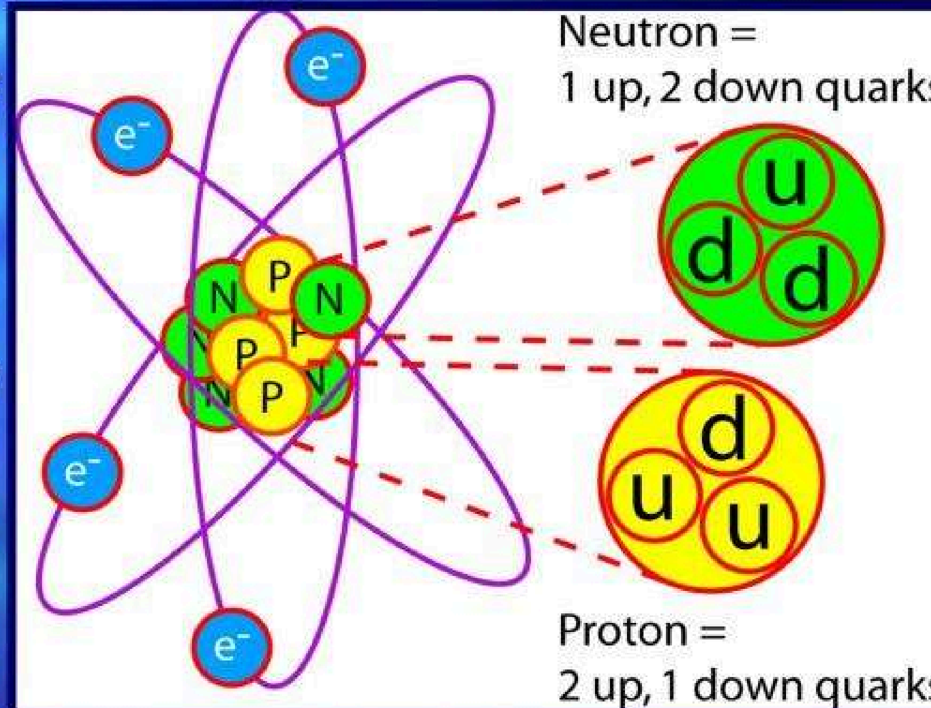
Secondary Cosmic Rays

- "Shower particles"
  - Electromagnetic (electrons, gamma rays)
  - Pions, muons
- Can travel faster than the speed of light in air (they are still slower than the speed of light in vacuum)
- 150 muons are striking every square meter of the Earth every second
  - You are bombarded with these particles every day!
  - Not all shower particles reach the ground… the atmosphere blocks some



Ordinary matter is made of atoms

- The protons and neutrons can be thought of being made up of quarks (in reality they contain also gluons and many more quarks)
  - Pions are also made up of quarks
    - They are produced as secondary CRs



Pion	
$\pi^+ = ud$	26 ns lifetime – decay into μ^+, υ_μ
$\pi^- = du$	26 ns lifetime – decay into μ^-, υ_μ
$\pi^0 = uu + dd$	1×10^{-17} s lifetime – decay into $\gamma\gamma$

- Muons are produced when pions decay...
- They are the secondary cosmic rays that reach the Earth's surface. We look for them to detect that a primary cosmic ray has reached Earth's atmosphere

How can we detect cosmic rays?

To "catch" a cosmic ray, detectors are spread out over a large area in hopes that a cosmic ray will hit that area.

How do we detect cosmic rays?

- To detect primaries, observatories are put in space
  - Good: it studies the original cosmic ray w/o interference from the atmosphere
  - Bad: it is an expensive detector that is too small to "catch" a lot of CRs

- To detect secondary showers, observatories are put on the ground
  - Good: they are cheaper, bigger, and detect a lot more!
  - Bad: it takes some work to figure out what the primary is like. But it can be done to some extent!
  - Can either detect the particles, or look for the light as those particles bounce off the air and create fluorescence

When it comes to CR detectors… BIGGER = BETTER

- They catch more cosmic rays overall
- Detect more of the ones that are rare! Ultra-high-energy cosmic rays (UHECRs) with more than 10^{18} eV are found only one per square km per century!
- Big area can detect larger shower → from higher-energy CRs

- The West Desert provides an ideal location for fluorescence observations.
  - An altitude of ~4,500 feet where the nearest population centers are more than 30 miles away
  - Light pollution is mostly blocked by the surrounding mountains.
- For 347 days per year, the visibility is better than 10 miles.

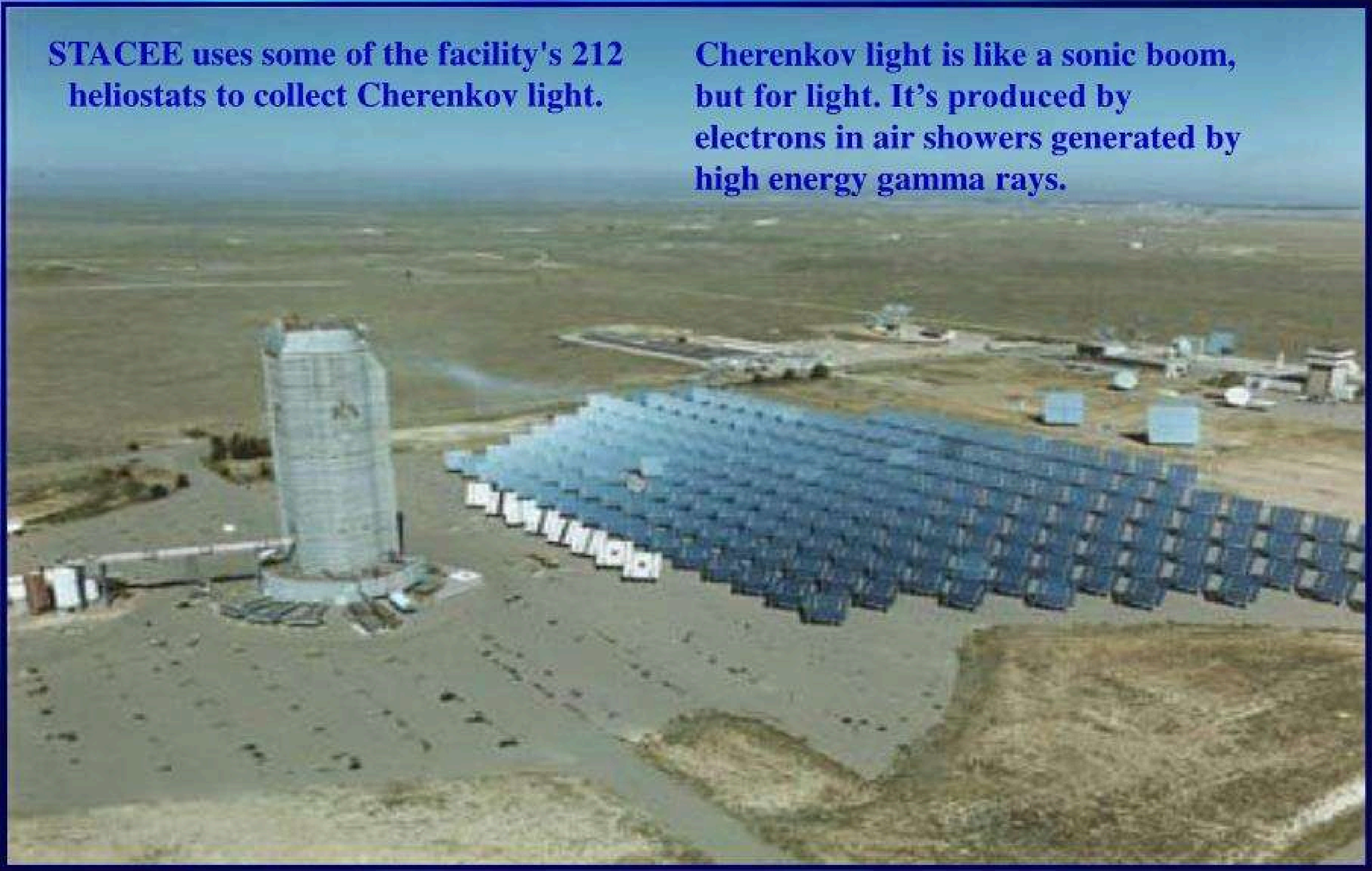
Particle detector arrays

- Casa Mia, Utah (pictured below):

1089 detectors spaced 15 meters apart

Large observatories

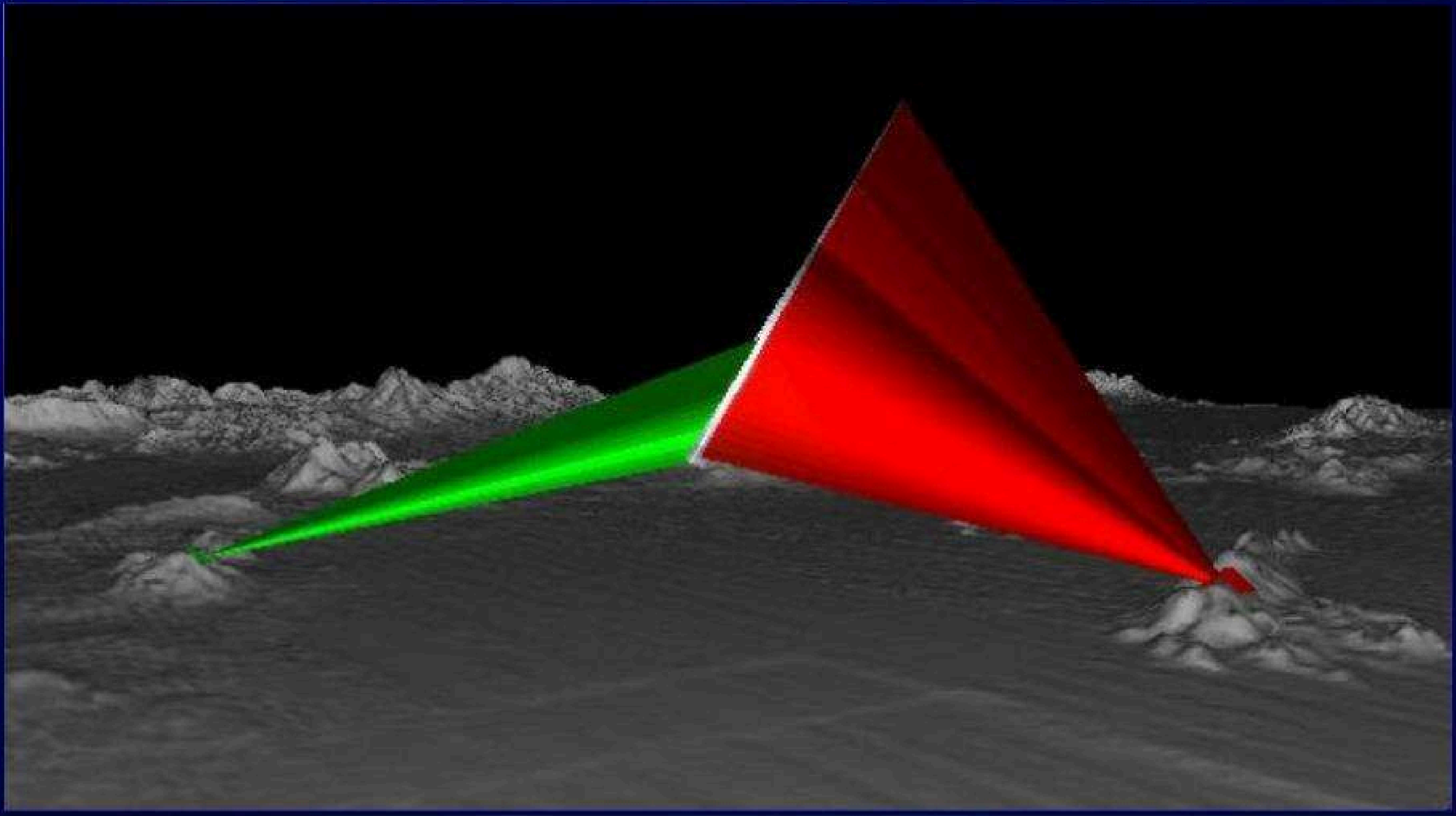
STACEE: Albuquerque, New Mexico



Air scintillation detector

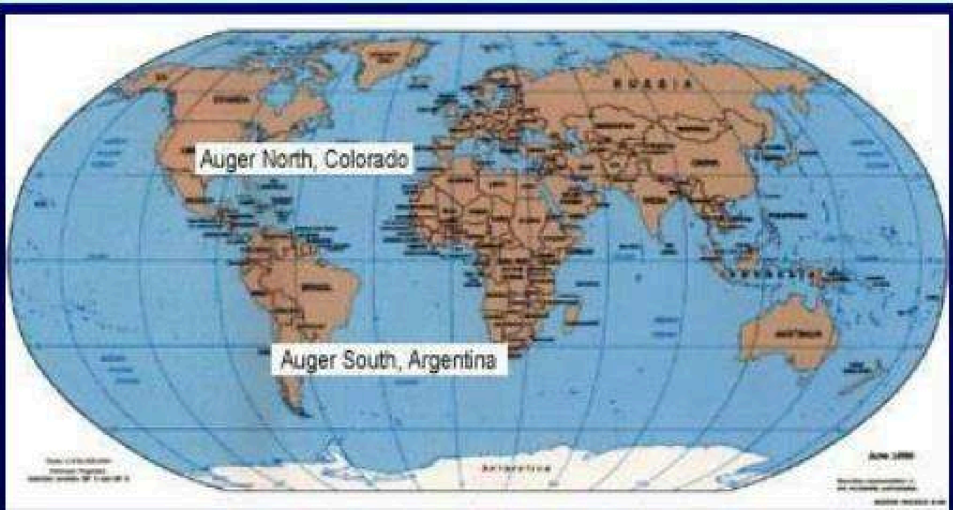
- 1981 – 1992: Fly's Eye, Utah
- 1999 - present: HiRes, same site

▪2 detector systems for stereo view ▪42 and 22 mirrors a 2m diameter	▪Each mirror reflects light into 256 photomultipliers ▪Sees showers up to 20-30 km high



Pierre Auger Project

- The Pierre Auger Observatory will have two sites, one in the northern hemisphere and the other in the south, allowing scientists to view ultra high energy cosmic rays (UHECRs) over the entire sky
- The first is currently under construction in the southern hemisphere (Argentina) and a second one is planned for North America.
- It will comprise 1600 surface detectors covering an area roughly the size of Rhode Island (3000 square kilometers)

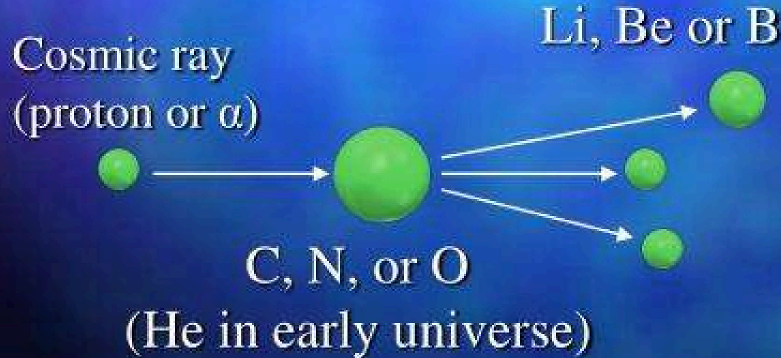


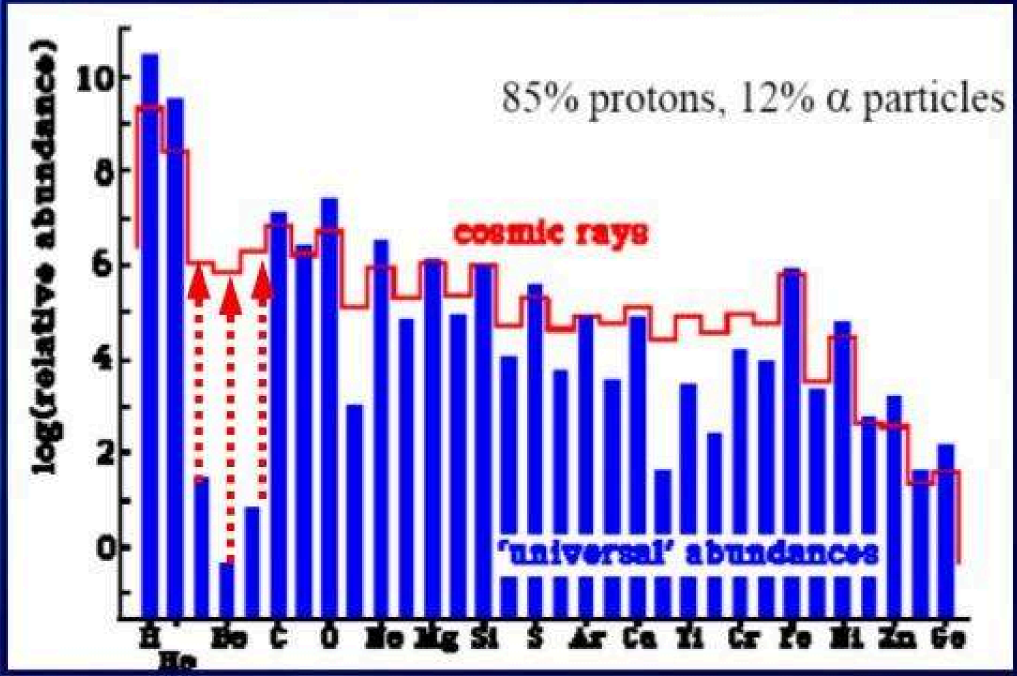
What can we learn from Cosmic Rays?

- *What elements are in the universe*
- *Where they come from*
- *How they are produced*

What the elements are in the universe

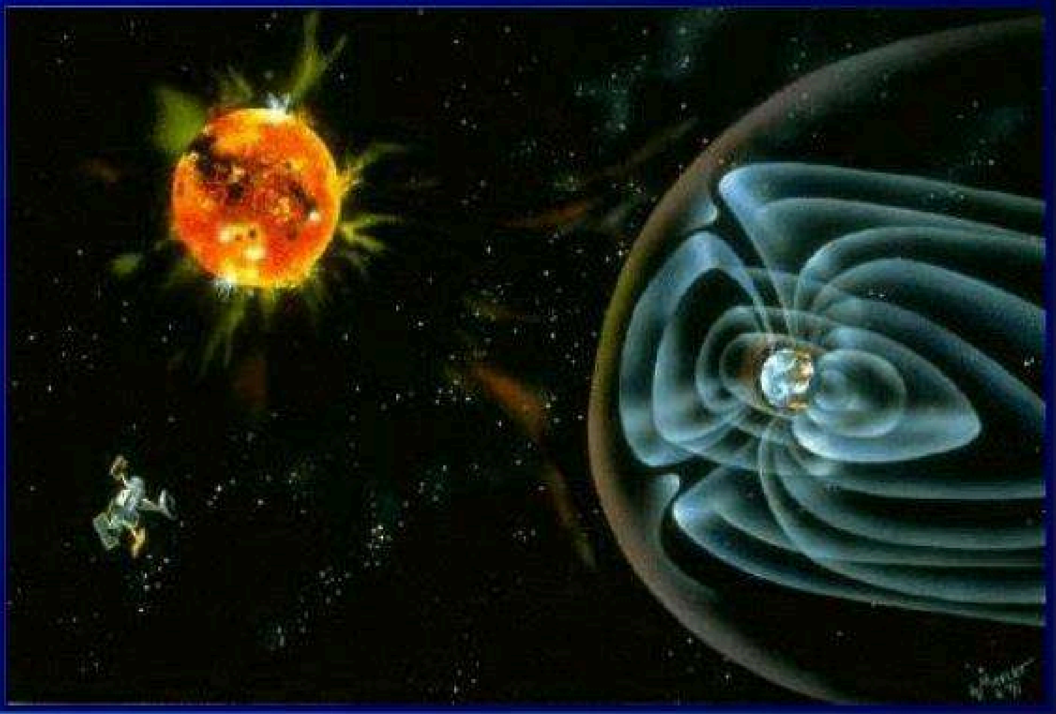
- There are more cosmic rays of certain elements than there should be
  - Due to collisions with other atoms somewhere in space!
  - These collisions are a major source of lithium, beryllium and boron in the universe





Where do cosmic rays come from?

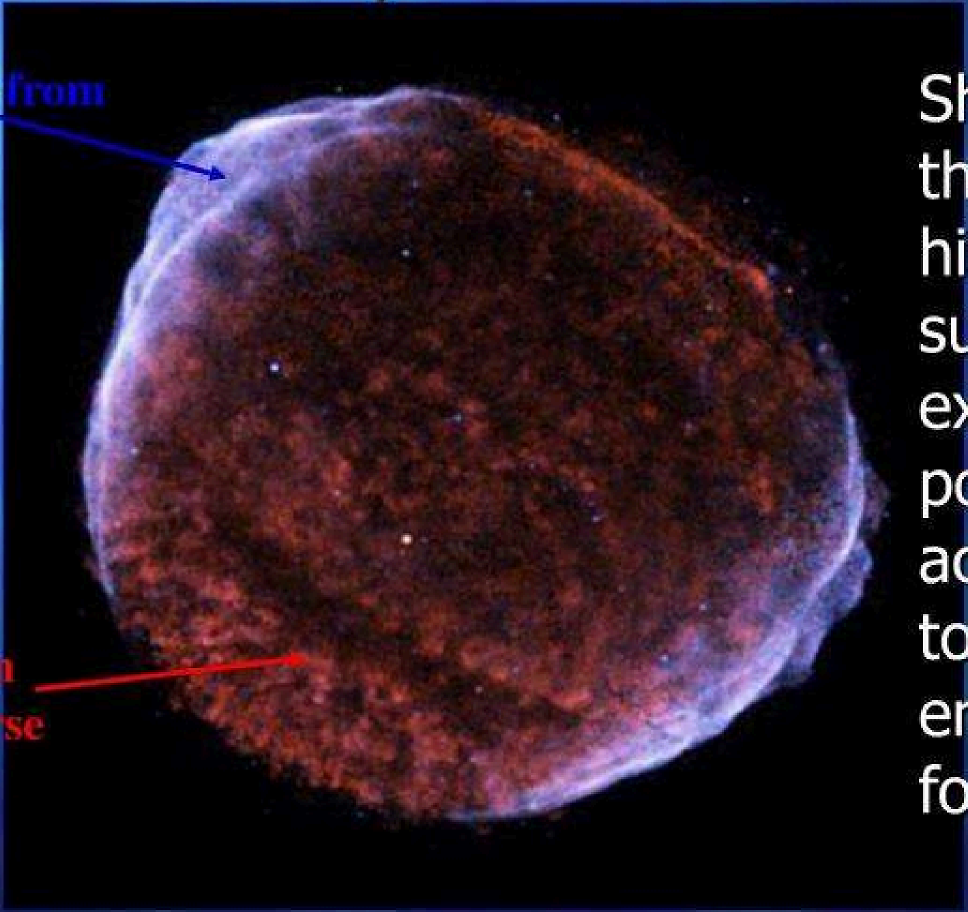
- Stars produce low-energy CRs
  - e.g., "Solar wind" ejects protons, α and other particles
- Supernovae produce medium-energy CRs



- But what could possibly make cosmic rays with $E > 10^{18}$ eV (UHECRs)?

Supernovas: a source of UHECRs?

X-ray image by Chandra of Supernova 1006



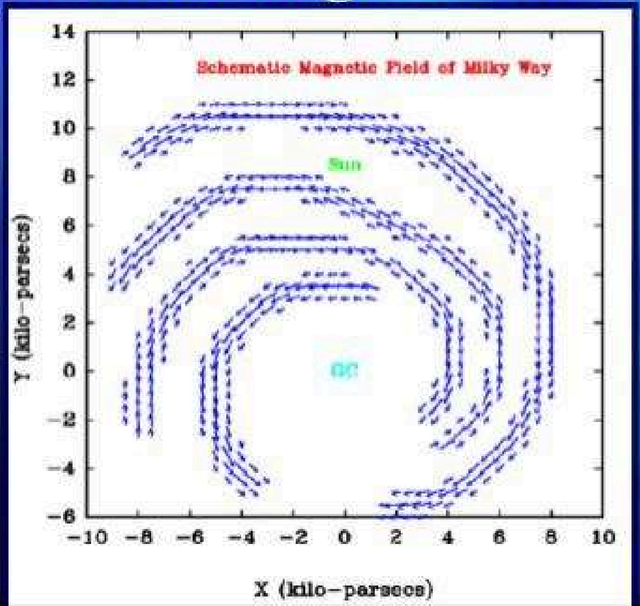
Shockwave from the supernova hits gas surrounding the explosion, possibly accelerating CRs to 10^{15} eV. Not enough energy for UHECRs!

Where do cosmic rays come from?

Problem: Sources of cosmic rays with $E < 10^{18}$ eV cannot be determined because of their deflection in the galactic magnetic field.

Solution (?): But UHECRs (with $E > 10^{18}$ eV) are *much less deflected* (travel straighter) and their direction should point towards their origin

Galactic magnetic field



M83 spiral galaxy

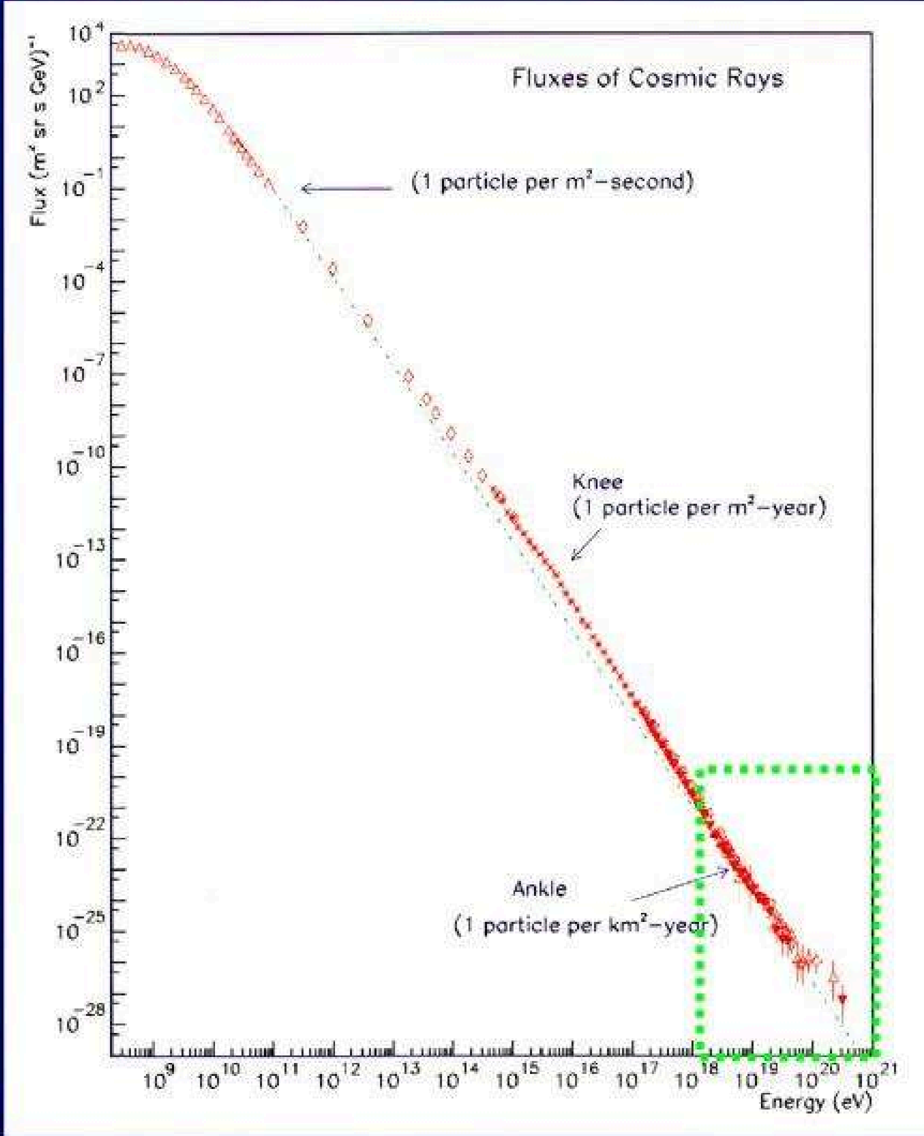
Unfortunately, UHECRs are rare.

Ultra High Energy Cosmic Rays:

- greater than ~10^{18} eV
  - **One** UHECR has enough energy to send a **baseball (140g) flying at 27m/s (60mph)**!

UHECR detection:

- Problem: very few UHECRs, big detectors are needed
- There have been 40 events with energies greater than 4 x 10^{18} eV (Auger has detected more now…)
  - 7 events greater than 10^{20} eV
  - Record: 3×10^{20} eV by Fly's Eye, Oct. 15^{th} 1991



Ultra High Energy Cosmic Rays: The Mystery

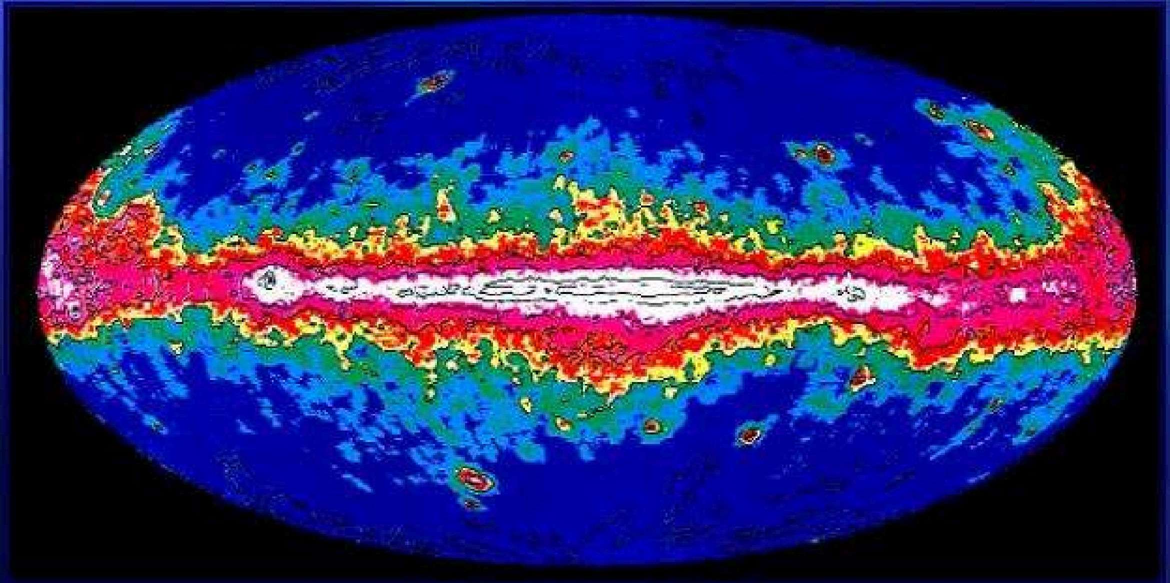
- The UHECRs we have detected appear to come from all directions, so they probably come from far away (only sources nearby are galaxies in few directions)
  - Problem: UHECRs should lose energy when they travel
    - Cosmic microwave background radiation should slow them down or destroy them
    - GZK cutoff – an upper limit on the energy from distant sources
  - …*but* we've detected UHECRs that have much more energy than they should have after coming from far away!
- Another problem: *we don't know* of any object in the cosmos that would accelerate particles to such high energies (means: no working models)

Potential sources of UHECRs?

- Colliding galaxies
- Super-magnetized spinning neutron stars
- Giant black holes spinning rapidly
- Gamma ray bursts
- Something we haven't seen yet?

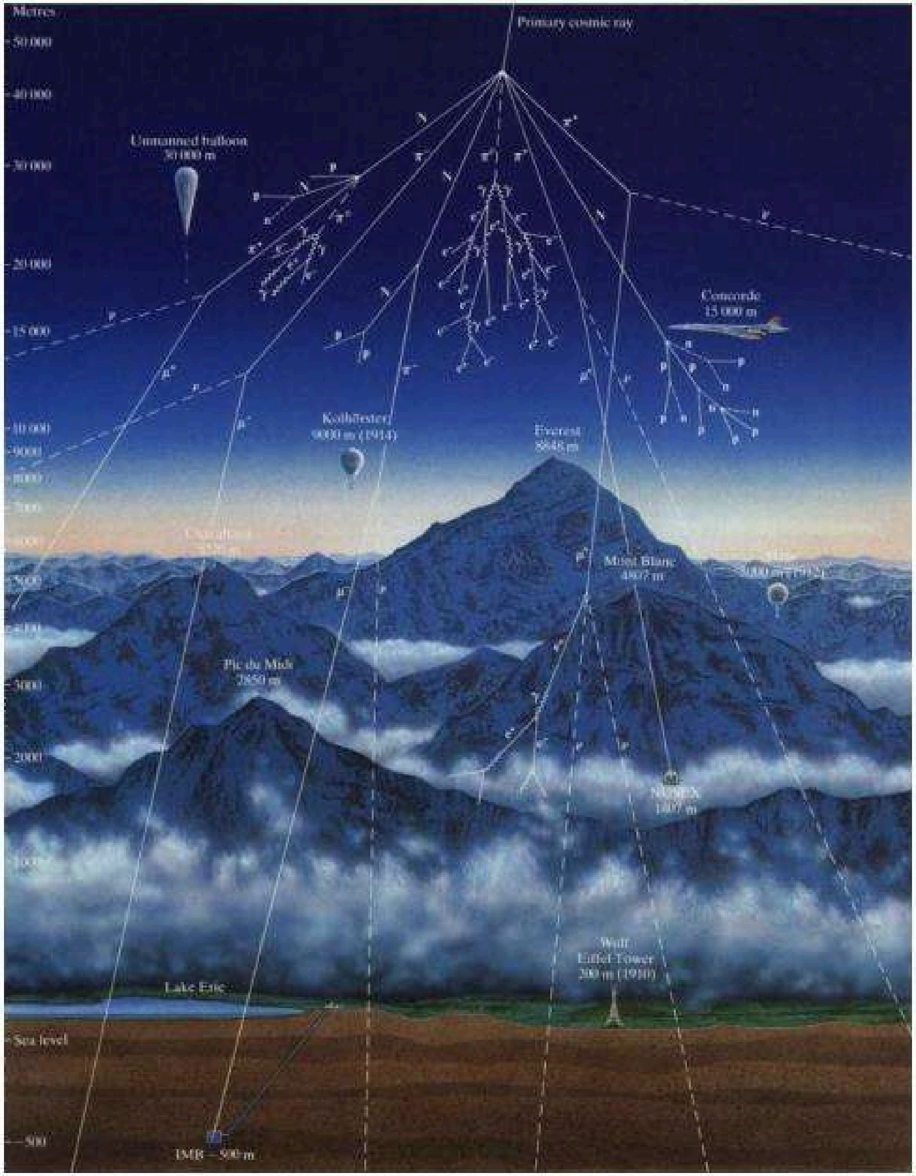
The Future of Cosmic Ray Research

- We will continue trying to explain how and where UHECRs are produced
- We will build bigger detectors on the ground and launch more into space



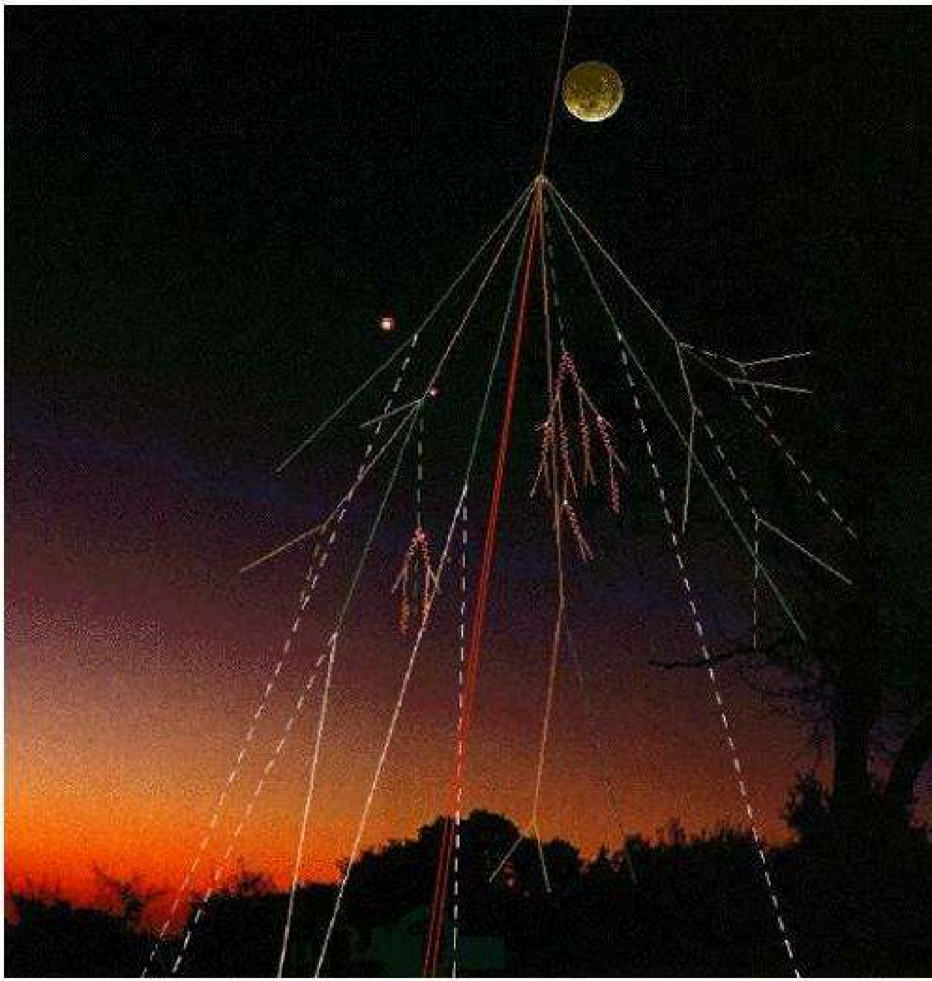
A composite image showing cosmic ray distribution in the sky

Cosmic Rays


Metres
50 000
40 000
30 000
20 000
15 000
10 000
9000
8000
7000
5000
3000
2000
Sea level
500
Primary cosmic ray
Unmanned balloon
30 000 m
Concorde
15 000 m
Kolhörster
9000 m (1914)
Everest
8848 m
Mont Blanc
4807 m
Pic du Midi
2850 m
Wulf
Eiffel Tower
300 m (1910)
Lake Erie
IMB – 500 m

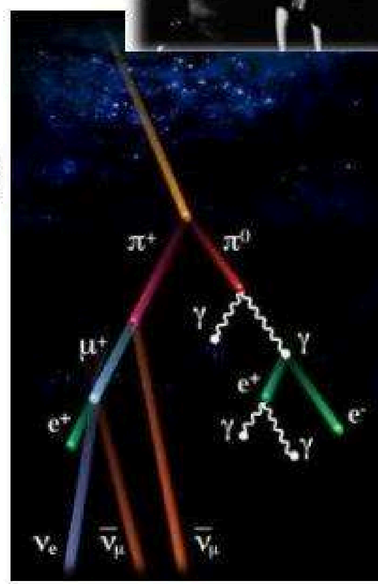
What is a cosmic Ray?

- A cosmic ray is a high-speed particle
  - Could be an electron
  - Could be an atomic nucleus like hydrogen or helium stripped of its electrons
- These particles travel throughout the Milky Way galaxy
  - Some come from the sun
  - Some from outside the solar system
- Cosmic rays are the source of the highest energy particles known!



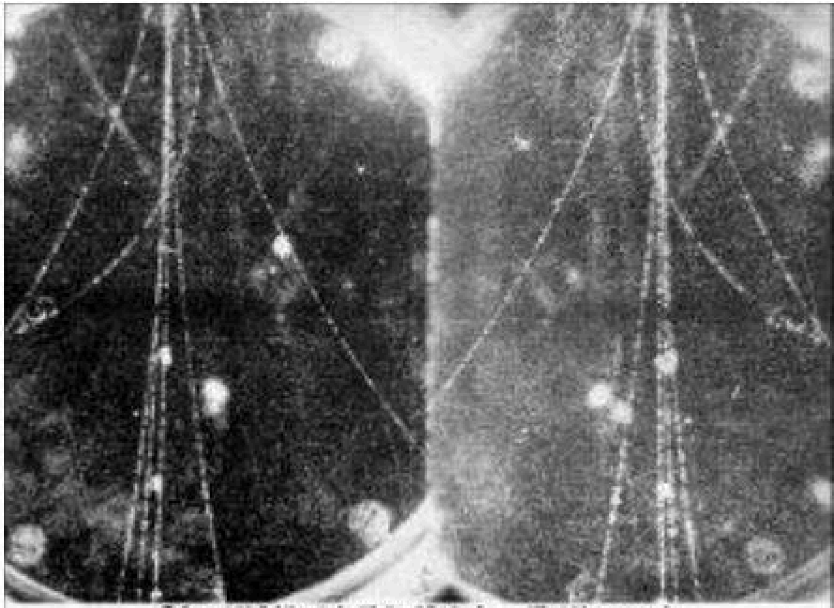
The Discovery of Cosmic Rays

- At the beginning of the 20th century, scientists thought there was too much radioactivity than could be accounted for naturally. Where was it coming from?
  - Victor Hess decided to test the idea that the additional radiation came from outer space. In 1912, one way to do this was by BALLOON!
  - He got to about 18,000 feet (without oxygen) He noticed that the radiation steadily increased.
    - COSMIC RAYS!



The Discovery of Antimatter!

- In 1932 Carl Anderson studied cosmic rays using a "cloud chamber".
- Charged particles produced in cosmic rays would enter the chamber and leave "tracks". The tracks would bend in circles because the chamber was placed in a strong magnetic field
  - Positive particles bend one way
  - Negative particles bend the other way
- He found equal numbers of positive and negative particles
  - Maybe the negative particles were electrons? (YES!)
  - Maybe the positive particles were protons? (NO!)
- By studying how much energy the positive particles lost, he figured out that they had the same mass as the electrons!
  - Positive electrons!
  - Antimatter!
  - Nobel Prize!

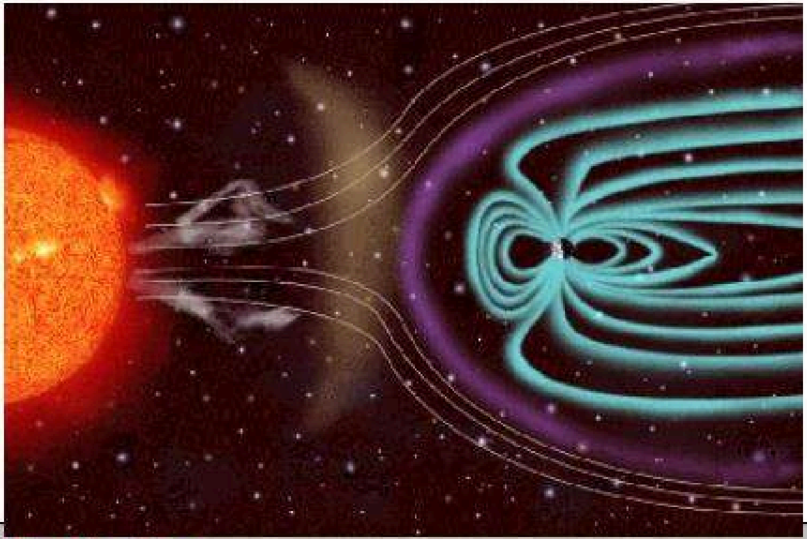


What are cosmic rays made of?

- What are Cosmic Rays? The term "Cosmic Rays" refers to elementary particles, nuclei, and electro-magnetic radiation of extra-terrestrial origin. These may include exotic, short-lived particles such as muons, pi-mesons or lambda baryons.
- In the energy range of 10^{12}-10^{15} eV, cosmic rays arriving at the edge of the Earth's atmosphere have been measured to consist of:
- ~50% protons
  ~25% alpha particles (helium nuclei)
  ~13% C/N/O nuclei
  <1% electrons
  <0.1% gammas

Solar Wind

- The sun produces a constant stream of particles (mostly electrons and protons) called the solar wind
  - In fact, 1 million tons of particles come from the Sun every second! This stream of particles is called the solar wind
- Solar wind shapes the Earth's magnetosphere, and magnetic storms are illustrated here as approaching Earth. These storms, which occur frequently, can disrupt communications and navigational equipment, damage satellites and even cause blackouts. The magnetic cloud of plasma can extend to 30 million miles or 50 million km wide by the time it reaches Earth.
- The solar wind is very thin. Near the Earth, the plasma is only about 6 particles per cubic centimeter (compared to ~10^{19} molecules/cm^3 at sea level due to the atmosphere



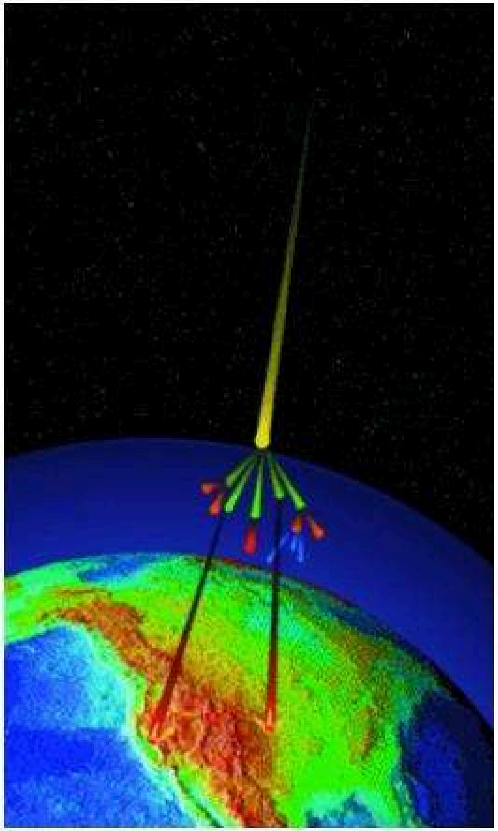
The white lines represent the solar wind; the purple line is the bow shock line; and the blue lines surrounding Earth represent its protective magnetosphere.

Low Energy Cosmic Rays

- The sun is a source of cosmic rays: the solar wind consists of protons and electrons ejected from the sun's corona and from solar flares. Almost all these solar cosmic rays, however, have a very low energy and except for a minute fraction they are all deflected by the earth's magnetic field and absorbed in the atmosphere. They have enough energy to ionize the various gasses in the upper atmosphere, which then causes beautiful displays known as the *Aurora*. More specifically, in the northern hemisphere it is called the *Aurora Borealis*, also known as *Northern Lights*, while in the southern hemisphere it is called *Aurora Australis*.
- http://www2.slac.stanford.edu/vvc/cosmicrays/crsun.html

Cosmic Rays at the Earth Surface

- A proton from outer space (yellow) hits the upper atmosphere, and produces a *shower* of other particles (green). Some of these particles (mostly pions) decay into muons (red). Only a small fraction of the muons reaches the earth's surface, because most decay in flight. Therefore, at higher altitudes there are more muons, because fewer have decayed. At sea level, one muon goes through an area the size of your fingernail about every minute!

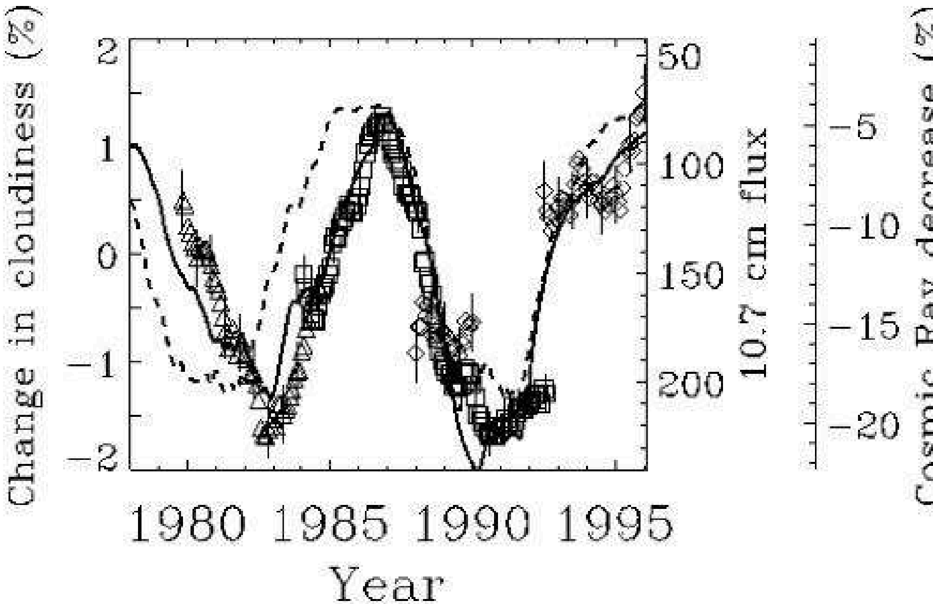


Cosmic Rays and Relativity

- In these high-energy collisions many secondary particles are produced, including lots of high-energy particles called pions . Pions decay rapidly but some may first interact and make even more (somewhat lower energy pions.
- A high-energy (charged) pion decay makes a high-energy muon and two (unseen) neutrinos . Muons have two properties that allow them to reach the earth's surface:
  - Muons decay relatively slowly compared to pions (but the muon lifetime is onl 2 microseconds!)
  - Muons penetrate large amounts of material without interacting.
  - Muons, unlike pions, have no strong interaction properties and unlike electron they are too massive to be significantly deflected by atomic electric fields that they encounter.
- But how do the muons make it to earth? A muon would travel 0.66 km on average before decaying. As cosmic ray muons are created at about 60 km, this implies that almost no muons should reach sea level.
- But a significant fraction do reach sea level. Special Relativity explains how muons with total energy 3 GeV (as detected at sea level) can travel about 20 km on average before decaying.

Effect of Cosmic Rays on Weather!

- Dashed: Solar flux
- Solid: Cosmic rays detected by CLIMAX
- Triangles and Squares: total cloud cover for the Southern Hemisphere over oceans
- Diamonds: data from geostationary satellites over oceans with the tropics excluded.

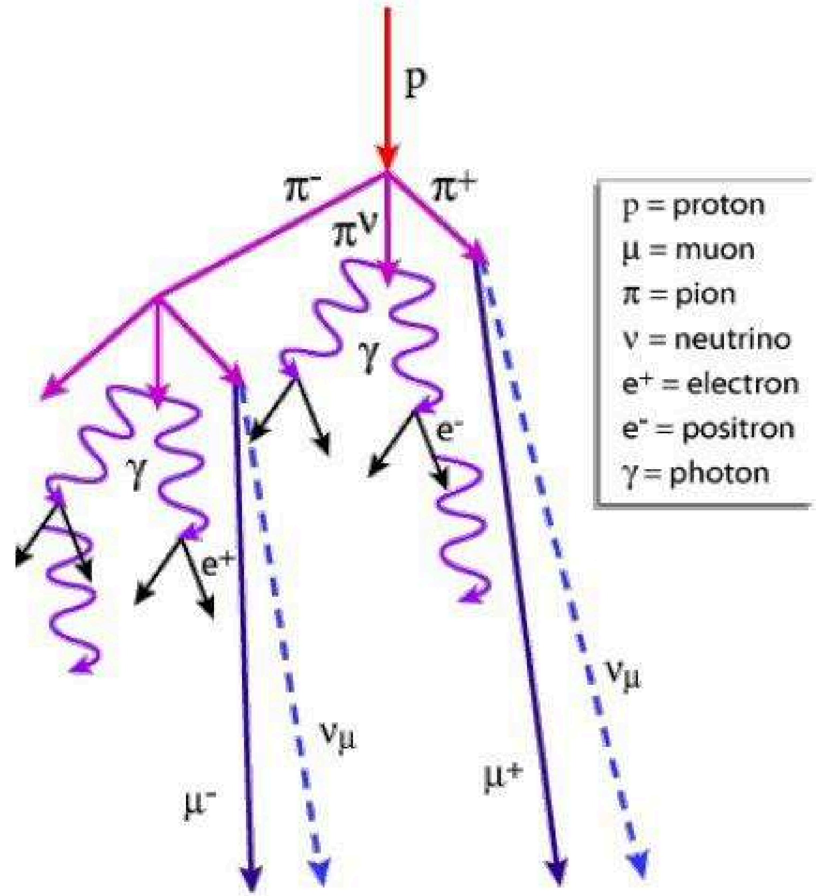


Cosmic rays and the weather

- While low-energy cosmic rays such as the solar wind cause ionization in the upper atmosphere, muons cause most of the ionization in the lower atmosphere. When a muon ionizes a gas molecule, it strips away an electron, making that molecule into a positive ion. The electron is soon captured, either by another gas molecule turning it into a negative ion, or it may find an already ionized positive ion and neutralize it (this is called recombination). There is a balance between ionization and recombination, and so there is a fairly constant density of positive and negative ions in the atmosphere. But there is a difference between the types of molecules that become negative ions and the ones that are positive. On average, the negative ions are more "mobile" than the positive ones, and this results in the fact that there is an electric field in atmosphere. On a normal quiet day, this electric field is about 100 Volts per meter. When a thunder shower forms, there is an as yet not completely understood mechanism that tends to lift the negative ions up while pushing the positive ones down. This changes the electric field strength to tens of thousands of Volts/meter. When the field strength becomes to high, a discharge occurs: lightning. Clearly, without ionization, thunder and lightning would not happen, so cosmic rays have a direct influence on the types of weather we can have on earth

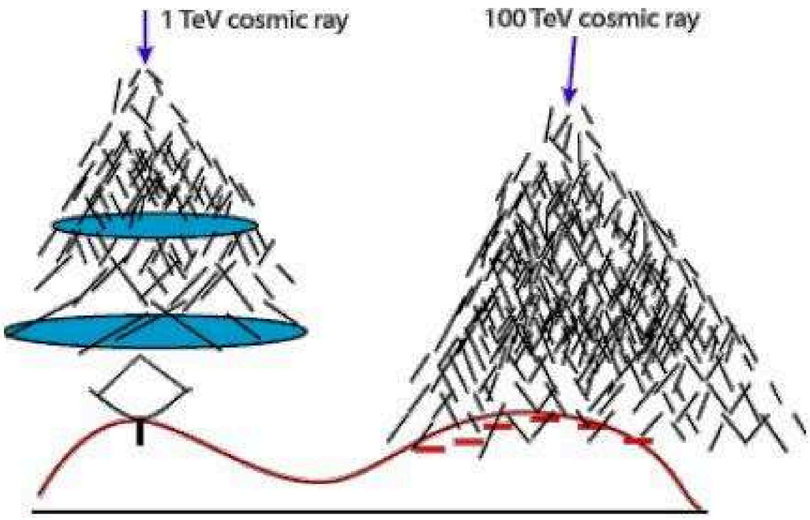
An Air Show Caused by a Cosmic Ray

- When a high-energy cosmic ray enters the atmosphere it loses its energy via interactions with the nuclei that make up the air. At high energies these interactions create particles. These new particles go on to create more particles, etc. This multiplication process is known as a particle cascade. This process continues until the average energy per particle drops below about 80 MeV (million electron-volts). At this point the interactions lead to the absorption of particles and the cascade begins to die. This altitude is known as shower maximum. The particle cascade looks like a pancake of relativistic particles traveling through the atmosphere at the speed of light. Though the number of particles in the pancake may be decreasing, the size of the pancake always grows as the interactions cause the particles to diffuse away from each other. When the pancake reaches the ground it is roughly 100 meters across and 1-2 meters thick. If the primary cosmic ray was a photon the pancake will contain electrons, positrons, and gamma rays. If the primary cosmic ray was a nucleus the pancake will also contain muons, neutrinos, and hadrons (protons, neutrons, and pions). The number of particles left in the pancake depends upon the energy of the primary cosmic ray, the observation altitude, and fluctuations in the development of the shower. This particle pancake is known as an extensive air shower (or simply an air shower).



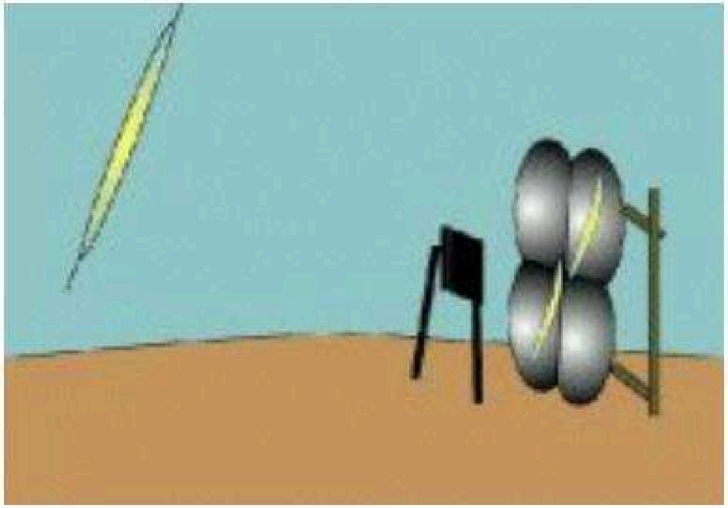
Detecting Cosmic Rays

- **Detecting an Extensive Air Shower**
- This leads to two different methods that can be used to detect the passage of an extensive air shower: one can look for the particles in the pancake directly, or one can look for the Cherenkov light generated by the particles in the atmosphere. The figure below illustrates both techniques.
-
- **On the left is an air Cherenkov telescope (ACT).** These are large mirrors that focus the Cherenkov light generated by the air shower onto an array of PMTs, which form an image of the air shower. Properties of the image are used to distinguish between air showers generated by gamma-ray primaries and nuclear primaries. Though very few particles may survive to the ground, the Cherenkov light will reach the ground. Thus, air Cherenkov telescopes can detect lower energy cosmic rays than extensive air shower arrays. However, since they are optical instruments they can only operate on clear moonless nights and they can only view a small piece of the sky at a time.
- **On the right is an extensive air shower array (EAS array).** An EAS array has traditionally been composed of a sparse array of plastic scintillators. The scintillators detect the passage of charged particles that travel through them. They are very inefficient detectors of the gamma rays in the EAS. Since gamma rays outnumber electrons and positrons by a ratio of roughly 4:1 and the scintillator covers less then 1% of the total area of the array, traditional EAS arrays have rather high energy thresholds. Unlike ACTs EAS arrays can operate under all conditions, night or day, and can view the entire overhead sky continuously. By using buried counters they can detect the muons in air showers generated by cosmic-ray nuclei. However, this method of distinguishing between gamma rays and nuclear cosmic rays is not as efficient as the imaging method used by ACTs.



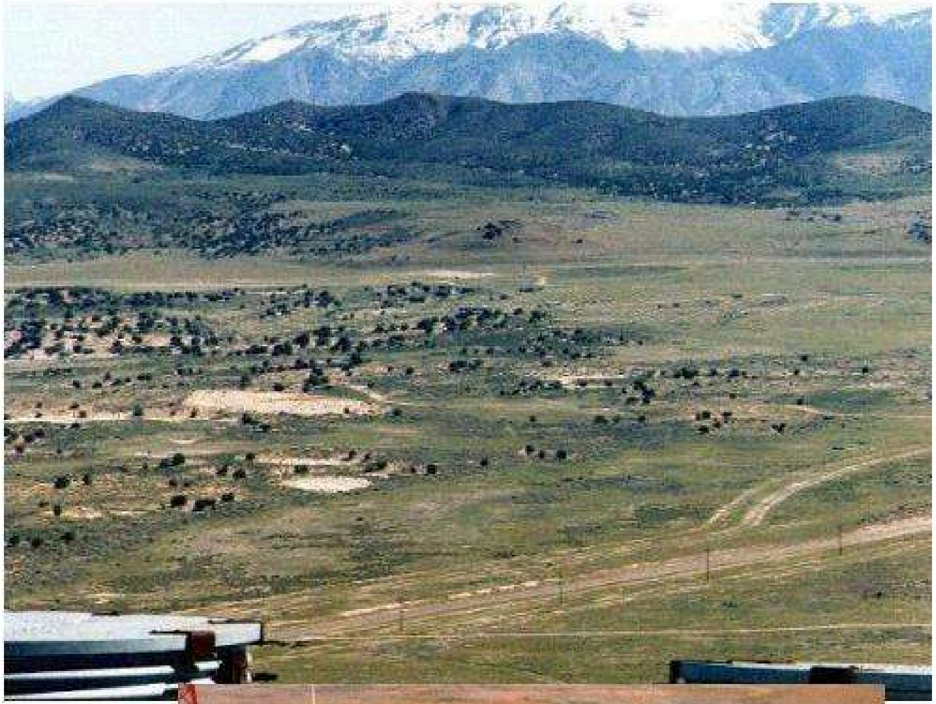
Air Fluorescence

- The passage of charged particles in an extensive air shower through the atmosphere results in the ionizationand excitation of the gas molecules (mostly nitrogen). Some of this excitation energy is emitted in the form of visible and UV radiation. This is luminescence , but is referred to as air Fluorescence
- This figure shows a schematic of a fluorescence air shower detector. The scintillation light is collected using a lens or a mirror and imaged on to a camera located at the focal plane. The camera pixelizes the image and records the time of arrival of light along with the amount of light collected at each pixel element. This technique can be made to work on clear, moonless nights, using very fast camera elements to record light flashes of a few microseconds in duration.

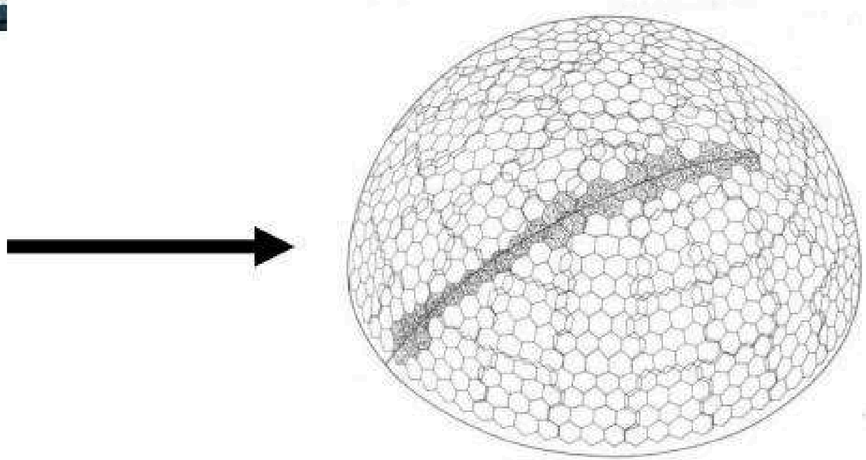


Many charged particles are expelled from a nuclear explosion, and these particles will also produce scintillation light as they pass through air. The amount of light collected can then be use to estimate the total energy released from the device.

The Fly's Eye(s)

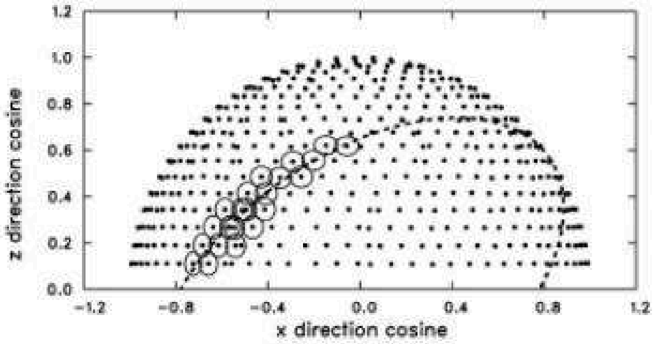


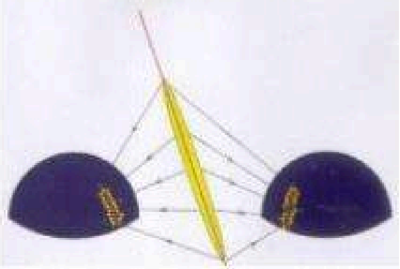
located in the West Desert of Utah, within the United States Army Dugway Proving Ground (DPG). The detectors sit atop Little Granite Mountain. Dugway is located 160 km southwest of Salt Lake City.



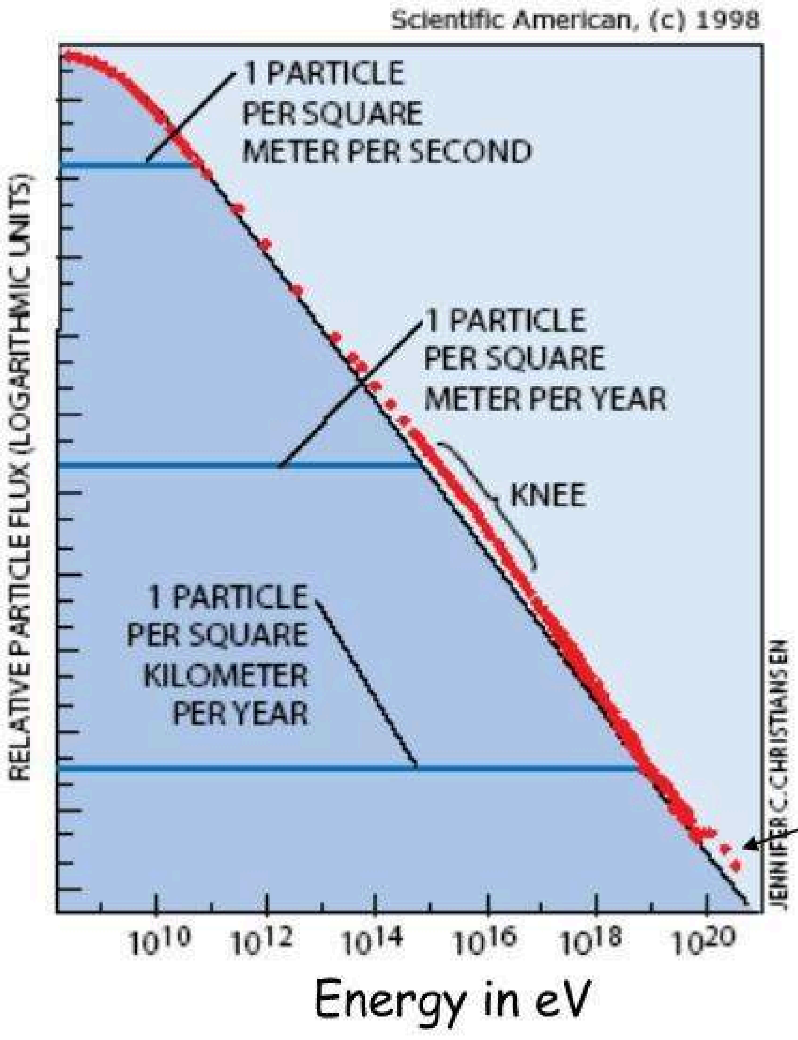
The Highest Energy Particle Ever Recorded

- In November of 1991, The FE1 detector at HiRes observed an air shower with an energy of 3.2×10^{20} eV. This corresponds to ~50 joules or ~12 calories, or roughly the kinetic energy of a well-pitched baseball. As of the year 2000, this remains the highest energy particle ever recorded from any source. A display of the event is shown below, where the *x*- and *z*-direction cosines of the hit pixels are circled.



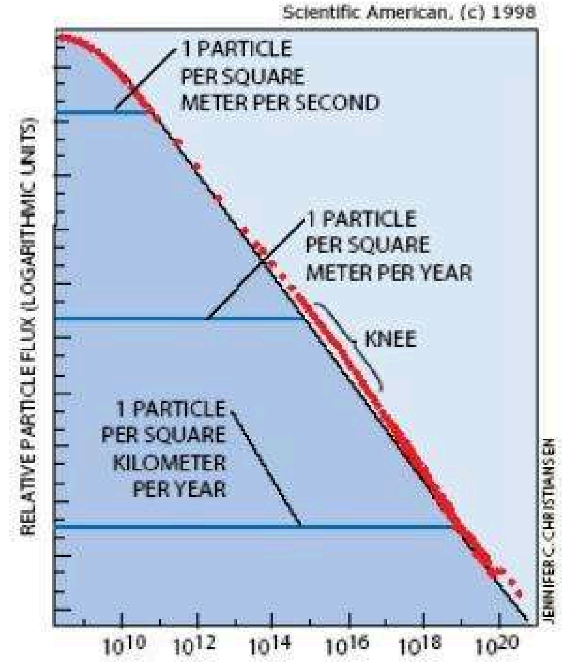


The Energy Spectrum of Cosmic Rays



Very High Energy Cosmic Rays

- We expect the cosmic ray spectrum to end around 6·1019 eV. This cutoff, first predicted by Greisen (1966) and Zatsepin and Kuz'min (1966) and named the GZK-cutoff, is expected due to the interaction of cosmic ray particles with the 2.7°K cosmic microwave background radiation. The collision of 10^20 eV protons with 10-3 eV photons produces center of mass energies above 100 MeV, which is above the threshold for photo pion production. Subsequently, any proton or nucleus with a travel distance from its origin to the Earth of more than around 50 Mpc suffers severe energy losses, and independent of the original energy will end up with an energy below the GZK cutoff energy.
- The AGASA cosmic ray experiment has found that the spectrum seems to continue beyond this energy without evidence for a cutoff. This leaves us with a two-fold problem: while it is already difficult to explain how ``traditional'' astrophysical sources can accelerate protons to energies above 10^20 eV, the expected energy losses due to interaction with the microwave background require the sources to be relatively nearby, at a distance of 50 Mpc at most.
- The situation is complicated by the fact that the deflection of protons in Galactic and intergalactic magnetic fields is less than a few degrees at these distances, so cosmic rays should point back to their origin. The distribution, however, seems uniform and shows no strong correlation with the matter distribution in the nearby universe.



Scales of Energy

- Scientists measure the energies of fast-moving particles like those in cosmic rays and particle accelerators in units called electron volts, abbreviated eV. An electron volt is the amount of energy that one electron gains when it is accelerated by an electrical potential of one volt. (A flashlight battery has about 1.5 volts.) Electrons in a television set are accelerated by the picture tube to an energy of about 50,000 electron volts. When they strike the screen, they make it glow.
- The most powerful man-made particle accelerator, Fermilab's Tevatron, can accelerate protons to nearly one trillion electron volts. The highest-energy cosmic ray particle ever observed had an energy 300 million times higher than the protons at the Tevatron. Scientific notation, shown below, saves writing out the many zeros required for such large numbers.

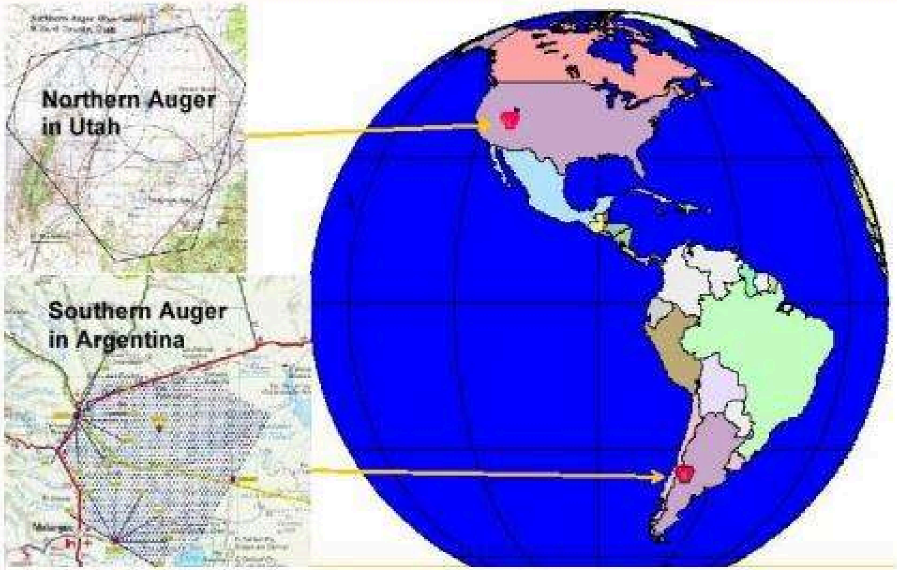
Questions regarding cosmic rays

- What is responsible for accelerating particles to the highest energies we observe?
- What are the high energy cosmic rays? Protons? Something else like Iron?
- Where are these cosmic rays coming from? Somewhere nearby?

Pierre Auger

- That we know anything about such extraordinary particles is because of searches that were started for the origin of much lower energy cosmic rays many years ago. In 1938, the French scientist, Pierre Auger, discovered serendipitously that showers of particles, secondaries created in the atmosphere by an incoming cosmic ray, were spread out over distances of 300 m at ground level. The energy of the initiating particles was estimated to be about 10^15 eV. The particles making up the showers travel through the atmosphere at the velocity of light and are confined to a relatively thin disc, rather like a giant dinner plate. By measuring the relative arrival times of the shower disc at detectors placed on a widely spaced grid, the direction of the incoming primaries can be found to about one degree, so cosmic ray astronomy can be contemplated. A shower produced by a cosmic ray of 10^20 eV contains about 10^11 particles at ground level spread out over an area of about 20 km2.

The Pierre Auger Observatory

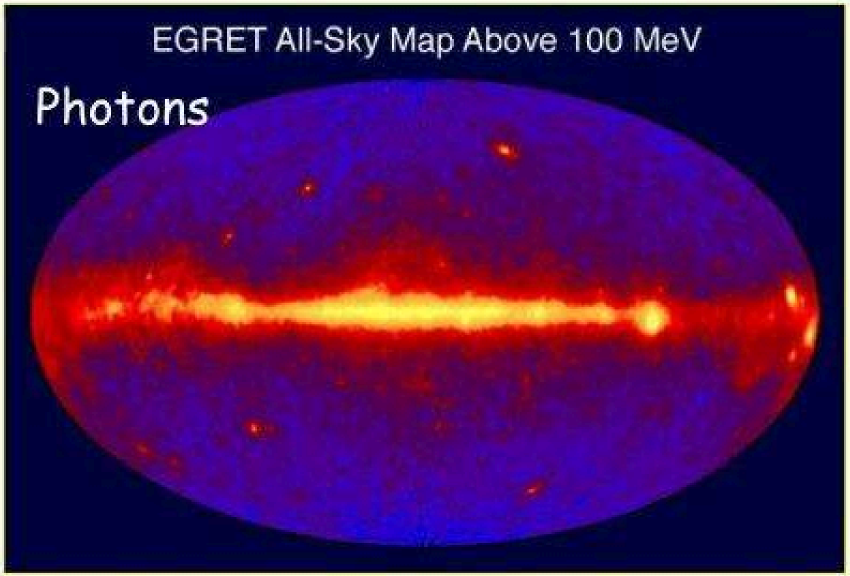


- Mendoza Province, Argentina
- 1600 water Cherenkov detectors 1.5 km grid
- 4 fluorescence eyes -total of 30 telescopes each with $30^{\circ} \times 30^{\circ}$ FOV

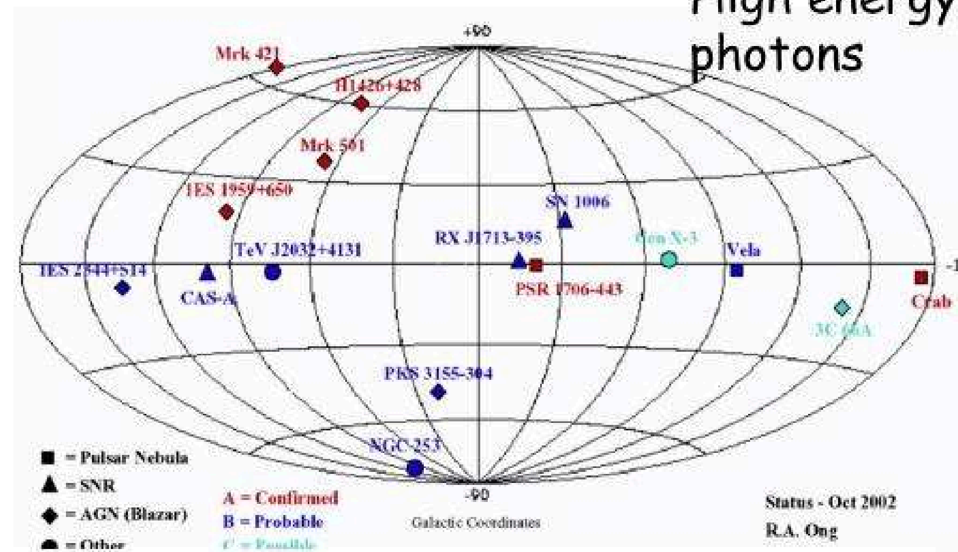
The Pierre Auger Observatory

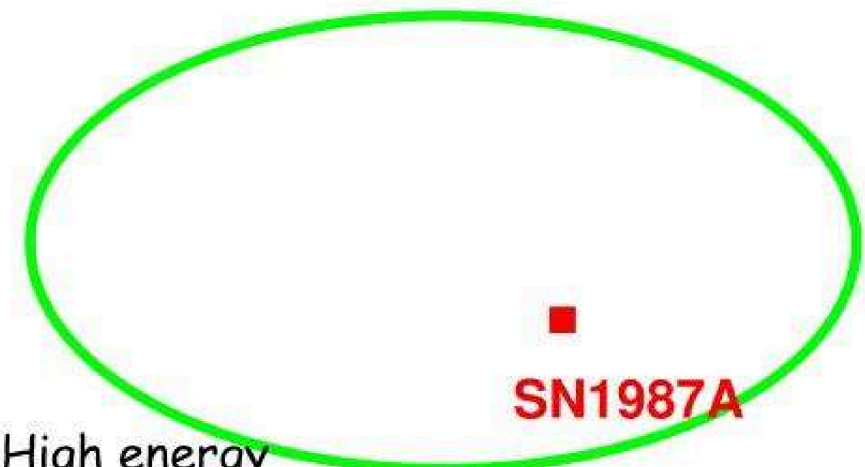
- Auger will detect the shower in two ways. Twenty four hours a day, an array of over 1600 particle detectors will measure shower particles as they hit the ground, which will allow a reconstruction of the shower providing measures of the original cosmic ray's energy, arrival direction, and mass. During clear, moonless nights, the showers will be viewed as they traverse the atmosphere. The passage of the showers will cause the atmosphere to fluoresce, and the faint UV light is detected by arrays of large mirrors equipped with fast photomultiplier image arrays.

Goal: Mapping the Sky

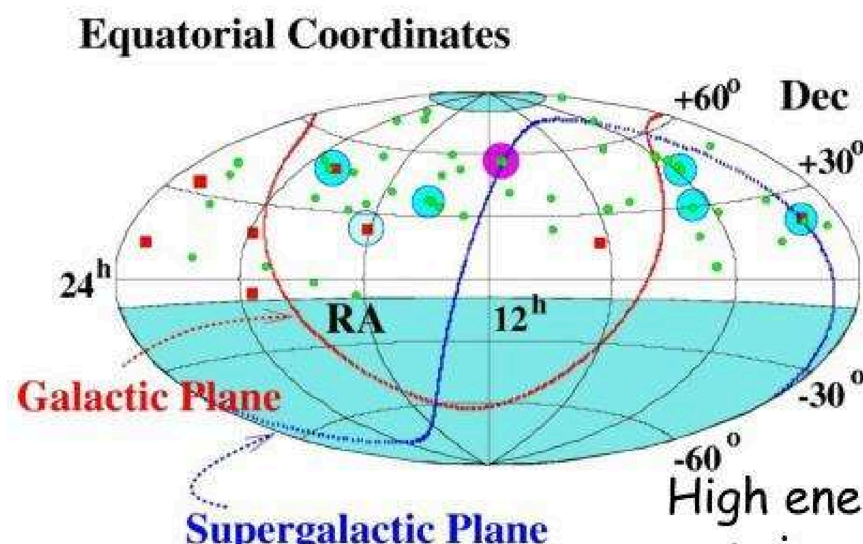


High energy photons





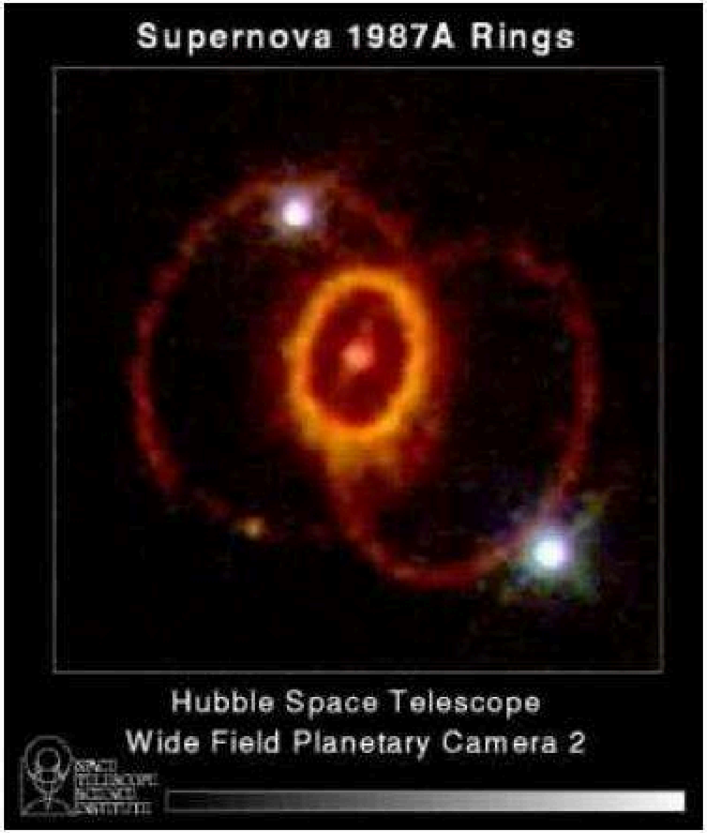
High energy neutrinos



High energy cosmic rays

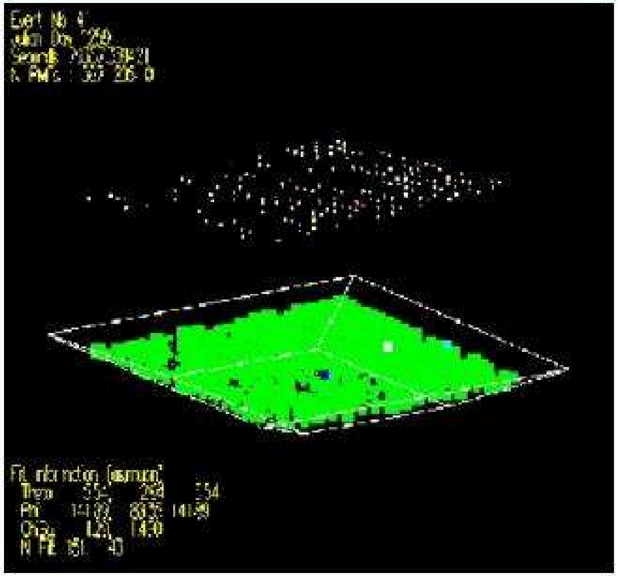
A possible acceleration method

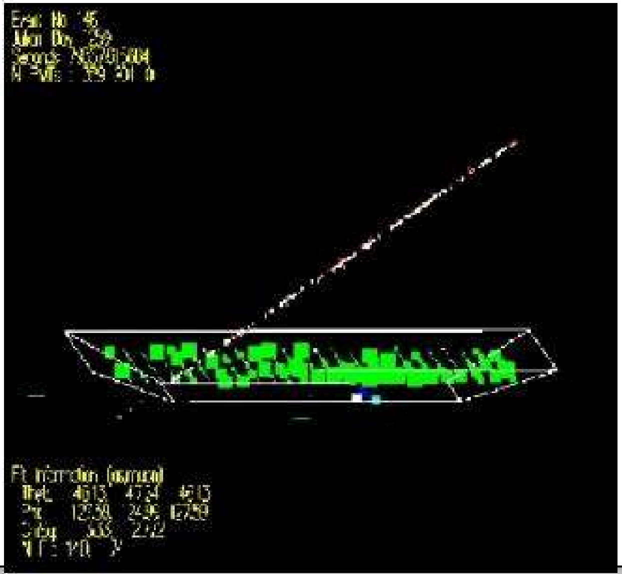
- It is thought that the two large red rings are painted in the sky by two jets of high-energy particles created by the interaction of the supernovae and it's companion, which is an object that could be either a neutron star or black hole. The black hole (if that is what it is) spins around its axis and this axis of rotation itself rotates, or precesses, tracing out a cone. The jets are created from matter from the supernovae remnant falling towards the black hole. This matter is heated and shot back into space along the two directions of the rotation axis. These jets then interact with clouds of gas that were emitted from the star long before it became a supernovae and now form a more or less spherical shell around it. The two red rings we see are the intersections of the cone swept out by the axis with this shell as viewed from earth.



Milagro

- A visualization of an actual event as seen by Milagro. The green boxes in the pond represent the amount of light received by each PMT. The white dots hovering above the pond are the individual PMT arrival times fit to a plane. This plane is a measurement of the front edge of the pancake of relativistic particles discussed on the pages describing the detection of cosmic rays.





Cosmic Rays Acceleration

- Cosmic Ray Energies and Acceleration: The energy of cosmic rays is usually measured in units of MeV, for mega-electron volts, or GeV, for giga-electron volts. (One electron volt is the energy gained when an electron is accelerated through a potential difference of 1 volt). Most galactic cosmic rays have energies between 100 MeV (corresponding to a velocity for protons of 43% of the speed of light) and 10 GeV (corresponding to 99.6% of the speed of light). The number of cosmic rays with energies beyond 1 GeV decreases by about a factor of 50 for every factor of 10 increase in energy. Over a wide energy range the number of particles per m2 per steradian per second with energy greater than E (measured in GeV) is given approximately by N(>E) = k(E + 1)-a, where k ~ 5000 per m2 per steradian per second and a ~1.6. The highest energy cosmic rays measured to date have had more than 1020 eV, equivalent to the kinetic energy of a baseball traveling at approximately 100 mph!
- It is believed that most galactic cosmic rays derive their energy from supernova explosions, which occur approximately once every 50 years in our Galaxy. To maintain the observed intensity of cosmic rays over millions of years requires that a few percent of the more than 1051 ergs released in a typical supernova explosion be converted to cosmic rays. There is considerable evidence that cosmic rays are accelerated as the shock waves from these explosions travel through the surrounding interstellar gas. The energy contributed to the Galaxy by cosmic rays (about 1 eV per cm3) is about equal to that contained in galactic magnetic fields, and in the thermal energy of the gas that pervades the space between the stars.

Cosmic Ray Composition

- Cosmic Ray Composition: Cosmic rays include essentially all of the elements in the periodic table; about 89% of the nuclei are hydrogen (protons), 10% helium, and about 1% heavier elements. The common heavier elements (such as carbon, oxygen, magnesium, silicon, and iron) are present in about the same relative abundances as in the solar system, but there are important differences in elemental and isotopic composition that provide information on the origin and history of galactic cosmic rays. For example there is a significant overabundance of the rare elements Li, Be, and B produced when heavier cosmic rays such as carbon, nitrogen, and oxygen fragment into lighter nuclei during collisions with the interstellar gas. The isotope 22Ne is also overabundant, showing that the nucleosynthesis of cosmic rays and solar system material have differed. Electrons constitute about 1% of galactic cosmic rays. It is not known why electrons are apparently less efficiently accelerated than nuclei.

Cosmic Rays in the Galaxy

- : Because cosmic rays are electrically charged they are deflected by magnetic fields, and their directions have been randomized, making it impossible to tell where they originated. However, cosmic rays in other regions of the Galaxy can be traced by the electromagnetic radiation they produce. Supernova remnants such as the Crab Nebula are known to be a source of cosmic rays from the radio synchrotron radiation emitted by cosmic ray electrons spiraling in the magnetic fields of the remnant. In addition, observations of high energy (10 MeV - 1000 MeV) gamma rays resulting from cosmic ray collisions with interstellar gas show that most cosmic rays are confined to the disk of the Galaxy, presumably by its magnetic field. Similar collisions of cosmic ray nuclei produce lighter nuclear fragments, including radioactive isotopes such as 10Be, which has a half-life of 1.6 million years. The measured amount of 10Be in cosmic rays implies that, on average, cosmic rays spend about 10 million years in the Galaxy before escaping into inter-galactic space.

Cosmic Rays in the Solar System

- : Just as cosmic rays are deflected by the magnetic fields in interstellar space, they are also affected by the interplanetary magnetic field embedded in the solar wind (the plasma of ions and electrons blowing from the solar corona at about 400 km/sec), and therefore have difficulty reaching the inner solar system. Spacecraft venturing out towards the boundary of the solar system they have found that the intensity of galactic comic rays increases with distance from the Sun. As solar activity varies over the 11 year solar cycle the intensity of cosmic rays at Earth also varies, in anti-correlation with the sunspot number.
- The Sun is also a sporadic source of cosmic ray nuclei and electrons that are accelerated by shock waves traveling through the corona, and by magnetic energy released in solar flares. During such occurrences the intensity of energetic particles in space can increase by a factor of 102to 106 for hours to days. Such solar particle events are much more frequent during the active phase of the solar cycle. The maximum energy reached in solar particle events is typically 10 to 100 MeV, occasionally reaching 1 GeV (roughly once a year) to 10 GeV (roughly once a decade). Solar energetic particles can be used to measure the elemental and isotopic composition of the Sun, thereby complementing spectroscopic studies of solar material.
- A third component of cosmic rays, comprised of only those elements that are difficult to ionize, including He, N, O, Ne, and Ar, was given the name "anomalous cosmic rays" because of its unusual composition. Anomalous cosmic rays originate from electrically-neutral interstellar particles that have entered the solar system unaffected by the magnetic field of the solar wind, been ionized, and then accelerated at the shock wave formed when the solar wind slows as a result of plowing into the interstellar gas, presently thought to occur somewhere between 75 and 100 AU from the Sun (one AU is the distance from the Sun to the Earth). Thus, it is possible that the Voyager 1 spacecraft, which should reach 100 AU by 2007, will have the opportunity to observe an example of cosmic ray acceleration directly.