Astroparticle Physics and the GZK Cutoff

Anargha Mondal (20221042)

Abstract

Over a century after the discovery of cosmic rays (CRs) by Victor Hess established the existence of high energy particles emanating from space, we still have a multitude of questions. The most prominent of the questions are as follows: a) what are the primary sources of these high energy particles, and b) can we place bounds on the spectrum of these particles with our current understanding of the universe. The paper is divided into two broad parts. The first part deals with the former question, while the second part deals with the latter. We also discuss the latest evidence for astrophysical hadronic acceleration and the laborartories that have facilitated for the same. We conclude with a few select topics which exemplify the challenges and promise of the coming decade.

Contents

1 Introduction

One of the main challenges of reviewing astroparticle physics is defining the field itself. Though, of course, there are ideas of what astroparticle physics deals with, and are accepted to be a union of the following broad domains: dark matter, charged cosmic radiation, gamma-ray astronomy, neutrino astrophysics and nuclear astrophysics[2].
It is not clear how early developments in cosmic-ray studies are actually related to the fields of 'particle physics, cosmology and astrophysics' [2], which supposedly form the basis for astroparticle physics. Nonetheless, it is well-accepted that Victor Hess's multiple 'balloon flights' from 1911-1912 confirmed high energy particle showers of super or extra-terrestrial origin [2]. A detailed study requires motivating the nature of these particles, their origins and how they are accelerated to (quite literally) astronomic energy scales and the microphysics of their effect on the inter-stellar environment. We conclude by investigating what these showers can tell us about our understanding of the Universe. The paper is structured as follows: Section 2 details the origin of all the matter and radiation in the universe (in broad strokes). Section 3 details our latest understanding of these high energy phenomena. Section 4 compiles our best attempts at observing these showers and deciphering physics from it. Section 5 briefly talks about other important sources of high energy radiation other than cosmic rays. Section 6 describes the experiments and detectors. Sections 7 discusses the theoretical cutoffs in the high-energy band, living controversies and gives a future outlook for the field.

2 On the Origin of Species

A hot, dense early (0.01-200s old) state of the universe is generally accepted to be the progenitor of all light nuclei, fundamental particles and radiation [1]. The rate of interactions in the primordial plasma was very high, resulting in thermal equilibrium. However, as the Universe expanded (and cooled), this thermal equilibrium was broken and particles decoupled from this primordial soup. All of this mechanism and assumptions are summarised in what is known as a hot Big Bang model of nucleosynthesis.

2.1 After the first three minutes

Big Bang nucleosynthesis began roughly 20 seconds after the Big Bang, when the universe had cooled sufficiently to allow deuterium nuclei to survive disruption by high-energy photons [1]. However, around twenty minutes after the Big Bang, the temperature and density became too low for any significant fusion to occur. At this point, the elemental abundances were nearly fixed, and the only changes were the result of the radioactive decay of the two major unstable products of BBN, tritium and beryllium-7. This state of decoupling light nuclei persisted till about the time the universe was 380,000 years old.

2.2 Recombination makes neutral atoms

At this point, the universe was cold enough (0.3 eV) to decouple the photons from the electrons (coupled by Thomson scattering), which were in turn coupled to protons via Compton scattering. Hence, the radiation field could not immediately ionize neutral hydrogen, and atoms became energetically favored[7]. *Recombination* involves electrons binding to protons to form neutral hydrogen atoms. Because direct recombinations to the ground state (lowest energy) of hydrogen are very inefficient, these hydrogen atoms generally form with the electrons in a high energy state, and the electrons quickly transition to their low energy state by emitting photons. Once photons decoupled from matter, they traveled freely through the universe without interacting with matter and constitute what is observed today as cosmic microwave background radiation (CMB). We shall soon realize that the CMB plays a major role in the physics of cosmic rays.

2.3 Reionization makes charged species

Recombination fills the entire universe with neutral hydrogen, some of which collapse to form stars and proto-galaxies. *Reionization* refers to a change in the intergalactic medium from neutral hydrogen to ions. The neutral hydrogen had been ions at an earlier stage in the history of the universe, thus the conversion back into ions is termed a reionization. The reionization was driven by energetic photons emitted by the first stars and galaxies. In the first stage of reionization, each new star is surrounded by neutral hydrogen. Light emitted by the star ionizes gas immediately around the star. Then light can reach further out to ionize gas. The ions can recombine, competing with the ionization process. The ionized gas will be hot and it will expand, clearing out the region around the star. The sphere of ionized gas expands until the amount of light from the star that can cause ionizations balances the recombination, a process that takes hundreds of millions of years. However, reionization is the primary source of charged particles in the interstellar and circumgalactic gas (IGM, CGM).

3 Cosmic Rays

Cosmic rays (CRs) are a non-thermal population of particles that pervade the Universe. One of the most important findings in early cosmic ray studies was the fact that not all the ionizing particles that had been found were the 'primary' particles of cosmic radiation, but often consisted of their products of decay. When entering the Earth's atmosphere, cosmic rays interact with its atoms, mainly oxygen and nitrogen. The particles that are thus produced are various mesons, like pions or kaons, neutrons or protons. The charged mesons might then decay again into a number of different particles. The produced pions decay like this:

$$\begin{aligned} \pi^0 &\rightarrow \gamma + \gamma, \\ \pi^+ &\rightarrow \mu^+ + \nu_\mu, \\ \pi^- &\rightarrow \mu^- + \bar{\nu}_\mu. \end{aligned} \tag{1}$$

And since the muons are also unstable they decay further:

$$\begin{aligned} \mu^+ &\rightarrow e^+ + \nu_e + \bar{\nu}_\mu, \\ \mu^- &\rightarrow e^- + \bar{\nu}_e + \nu_\mu. \end{aligned} \tag{2}$$

In 1938, Auger and his group were able to show that the radiation at sea level is almost entirely due to the collision or the decay of these particles [2]. In 1939, he proved his hypothesis that the showers were not only produced locally in the lower atmosphere [**?**]. By means of measuring long-distance coincidences at high altitude he demonstrated that there are interactions of primary particles in the high atmosphere. These findings led to the compilation of the *cosmic ray spectrum*, discussed in the next section.

3.1 Phenomenology of the Cosmic Ray Spectrum

What is so special about cosmic rays, compared to other high-energy spectra detections? Not only do these components represent a variety of spatial scales, but their origins are traceable to rather diverse physical processes. These charged particles originate from the charged CGM and IGM that we have discussed in the previous section, but their spectra, acceleration mechanisms, sources and environmental effects require more detailed study.

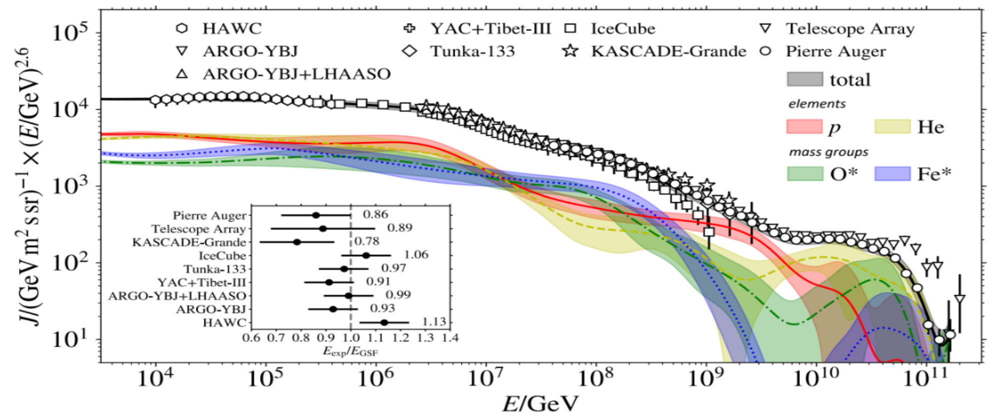

Figure 1: Combined fit of the cosmic-ray energy spectra and its mass composition measured by various experiments [1]

The differential cosmic-ray spectrum (see Fig. 1) is a steeply falling function of energy, roughly in accord with a power-law index -2.7 up to an energy $\sim 4 \times 10^{15}$ eV and then steepening toward higher energy. However, a careful comparison with a single function clearly shows significant deviations at the so-called "knee" at $\sim 4 \times 10^{15}$ eV ($\sim$ 4 PeV) and at the "ankle", near $\sim 5 \times 10^{18}$ eV ($\sim$ 5 EeV) [5]. The cosmic rays of Extremely High Energy (EHE)—those above $\sim 10^{20}$ eV—pose a serious challenge to conventional theories of particle acceleration, so their study is heavily featured in observational campaigns by the current suite of detectors, including the Pierre Auger Observatory. More on this in 4.

It is worthwhile to show why stochastic processes lead to a power law. The reasoning goes as follows: Any stochastic process (like the statistical Fermi acceleration that accelerates cosmic ray primaries [**?**], discussed in more detail in the next section), can be shown to follow the diffusion-loss equation, stated as:

$$\frac{dN}{dt} = D\nabla^2 N - \frac{\partial \phi_E}{\partial E} + \frac{\partial N}{\partial t} \tag{3}$$

where $N \equiv N(E, x, t)$ is the number of particles bound in a volume of the (E, x, t) phase space; ϕ_S and ϕ_E are the spatial and energy fluxes respectively. Now, we invoke certain simplifying assumptions. Assume that the particle leaves the acceleration site immediately after ome characteristic time τ. This allows us to claim N to be indpeendent of x and fix $D = 0$. Also, ϕ_E simplifies to $N\frac{dE}{dt}$. As motivated by [**?**] in his 1949 paper, using energy conservation arguments, it can be shown that:

$$\frac{dE}{dt} = \alpha E \tag{4}$$

where α is a pre-factor depending only on the velocities of the particles. Imposing the equilibrium condition allows us to write a *transfer equation* for N:

$$\alpha N + \alpha E \frac{\partial N}{\partial E} = \frac{N}{\tau} \tag{5}$$

Solving this is trivial,a nd we get:

$$\boxed{N(E) = N_0 E^{-(1+\frac{1}{\alpha\tau})}} \tag{6}$$

which is the famous power-law dependence!

3.2 Sorces of Cosmic Rays

Though we now understand the general aspects of how cosmic rays are energized, major gaps remain throughout the spectrum, with the level of uncertainty tending to increase with energy. The total cosmic-ray energy density measured above Earth's atmosphere is dominated by particles in the range $1 - 10$ GeV. Below $\sim$ 1 GeV, the intensities are correlated with solar activity, so these particles clearly originate with the Sun. At higher energies, however, the cosmic-ray flux is anticorrelated with the strength of the solar wind, whose screening effects therefore point to a cosmic-ray origin outside the solar system.

Conventional wisdom has it that the bulk of the cosmic rays between 1 GeV and the knee are confined to the Galaxy, and are probably produced in supernova remnants. Between the knee and the ankle, the situation is murkier, though the ankle is sometimes interpreted as a crossover from a Galactic to an extragalactic population. Beyond $\sim$ 10 EeV, the cosmic rays are generally expected to have an extragalactic origin due to their isotropy and the fact that galactic magnetic fields would not be able to confine them to the Galaxy.

Let's crunch some numbers to get a better estimate of these showers:

A useful quantity is the cosmic ray replenishment rate, which gives us some insight as to what could be the possible intra-galactic sources. Considering the population is in equilibrium, we arrive at the following expression, from a simple calculation of the density of states with energy E:

$$L_{cr} = \int d^3x dE \frac{4\pi E j_{cr}(E)}{c\tau_{res}} \tag{7}$$

where $j_{cr}(E)$ is the cosmic-ray intensity, which can be read right off of the cosmic ray spectrum, τ_{res} is the acceleration time and is given by $\tau_{res}(E) = \frac{N(E)}{c\rho_{ISM}}$, where ρ_{ISM} is the average density of the interstellar

, and $N(E)$ is the column density of hydrogen. The calculation leads to an estimate $L_{cr} \sim 1.5 \times 10^{41}$ erg s^{-1}. This is of the order of 10% of the total energy output of the galaxy, and is only produced by extremely high energy phenomena such as supernovae.
Another reason for believing that most of the cosmic rays originate within the Galaxy is that if we assume the cosmic-ray density to be the same throughout the universe, then the production of γ-rays from the decay of neutral pions produced in interactions between the cosmic rays and ambient protons exceeds the observed limits. This is not the case within the Galaxy itself, where pion decays actually contribute to the overall γ-ray background, but would clearly be a problem outside the Galaxy. Clearly, energy arguments are the strongest pathway to uncovering cosmic ray physics.
It is worthwhile to consider to discuss other production-mechanisms for cosmic rays, aptly titled the *top-down* and *bottom-up* scenarios. In more widely accepted [9] top-down scenarios, cosmic rays come from the decays of heavier, exotic particles with masses ranging from the typical 100 GeV -1 TeV scale of supersymmetry to the $\frac{1}{r^2}$GeV scale of superheavy particles up to the GUT scale, $M_{GUT} \sim 10^{24}$ eV and beyond - in this last case the GZK cutoff can be avoided, since protons can be produced in the Earth's vicinity. More on the GZK cutoff in 6. The production of protons in particle acceleration processes in sources is instead referred to as the bottom-up scenario. At a scientific conference in 1933, Zwicky and Baade advanced a revolutionary conjecture: massive stars end their lives in explosions which blow them apart; such explosions produce cosmic rays, and leave behind a collapsed star made of densely packed neutrons. Many of the high-energy gamma-ray emitters correspond positionally to SNRs, thus indirectly confirming this conjecture–indeed we are convinced nowadays that most of the accelerators of cosmic rays in our Galaxy are SNRs [9]. Having arrived at this conclusion, it is a great time to review the acceleration and transport mechanisms that drive cosmic ray showers.

4 Cosmic Accelerators

A range of different (but related) acceleration mechanisms have been proposed, including shock acceleration, magnetic reconnection, stochastic acceleration in shear/turbulent sites, magnetospheres, or other alternatives. A clear understanding of these mechanisms, and distinguishing between them, is critical to the study of a wide range of exotic phenomena. Understanding of acceleration represents a fundamental physical problem, with a cross-disciplinary nature that requires key developments in many areas of the field. The sites of such acceleration are usually include active galactic nuclei (AGN), gamma-ray bursts (GRBs), supernova remnants (SNR) and pulsar wind nebula (PWN) and potentially other stellar-remnants. The discussion on these astrophysical objects is beyond the scope of this term paper.

4.1 Theoretical Landscape

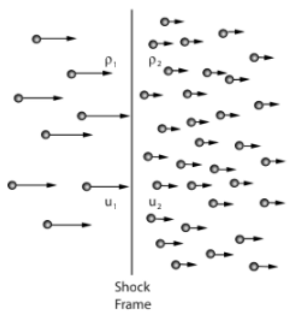

Figure 2: Simplified shock geometry for second-order Fermi acceleration

We can quickly dismiss static electric fields as a candidate for acceleration as they will be quickly neutralised in astrophysical environments. As Fermi showed in his 1949 paper [?], although a combination of stochastic 'head-on' and 'catch-up' collisions of the particles and molecular do indeed result in acceleration (a mechanism now known as Fermi acceleration of the second order), it is not fast enough. But, we shall see that a shock geometry retrieves a first-order dependence of ΔE on the velocities, a mechanism now known as the *Fermi acceleration of first order.* This produces a power-law diffusion, as follows:

$$\boxed{dN(E) = KE^{-5/3}dE} \tag{8}$$

There are other sources of acceleration, like magnetic reconnection, that require a more modern treatment of numerical methods, which are mainly divided into either kinetic/particle or fluid approaches, as well as hybrid methods. However, most of these fluid/hybrid methods are similar in principle: they solve the Vlasov-Fokker-Plank (VFP) equation.

4.2 Cosmic Ray Transport

In the Milky Way, the dominant process in CR transport is diffusion as evidenced by the small anisotropies in CR arrival directions and by certain abundance ratios of nuclear species. This diffusive transport bears some resemblance with heat transport in that it smooths the spatial distribution of CRs. However, in contrast to heat transport, CR diffusion is not due to collisions, but interactions with turbulent magnetic fields. Generally, CRs interact "resonantly" with plasma waves, that is they get affected only by waves with a wavelength similar to the gyroradius of the CR particle. If this condition is satisfied, a CR particle will be deflected by the Lorentz force. Many random deflections lead to a random walk in space, that is diffusion [3].

There is a number of other processes contributing to the transport of charged cosmic rays: momentum losses, i.e. radiative losses for electrons and positrons, ionization and Coulomb losses for nuclei, electrons and positrons; spallation, that is production of (mostly) lighter nuclei by inelastic collisions of heavier ones; and other inelastic collisions, e.g. the production of light mesons. We note that progress in the study of cosmic ray transport is often limited by the nuclear interactions since many cross-sections are poorly known, if at all. The various transport processes are encoded in the cosmic ray transport equation, also referred to as the Parker transport equation in the space physics community. This partial differential equation is supplemented by the boundary condition of free escape on the surface of the (often cylindrical) confinement volume. Only in simplified cases can this equation be solved analytically.

The most instructive case is the 1D approximation where only the direction perpendicular to the Galactic disk is retained. The solution differs for *primaries*, that is species present and accelerated in the cosmic ray sources, and *secondaries*, which are not present in cosmic ray sources, but produced by inelastic collisions of primaries in the gaseous disk of the Galaxy. Diffusion in the Galaxy, characterized by a diffusion coefficient $\kappa(R)$, modifies the source spectrum $q(R)$, resulting in the steady-state spectrum $\psi(R) \propto q(R)/\kappa(R)$. As the production spectrum of secondaries follows the steady-state spectrum of primaries, $q_2(R) \propto \psi_1(R)$, the secondary steady-state spectrum is $\psi_2(R) \propto q_2(R)/\kappa(R) \propto \psi_1(R)/\kappa(R)$. As $\kappa(R)$ grows with R, secondary spectra $\psi_2(R)$ fall more quickly with rigidity than primary spectra $\psi_1(R)$. Unstable secondaries provide additional constraints on the gas density and residence time of cosmic rays. The solution of the transport equation in more realistic setups requires numerical codes [1].

4.3 Cosmic Ray Environment

Low-energy CRs are the only ionizing agents capable of going through large gas column densities and penetrate interstellar clouds. Hence they influence star formation and constitute the first link of a chain of reactions leading to a rich interstellar chemistry. The most crucial reason to study cosmic rays and their astrophysical impacts is to trace back these cumulative effects to study high-energy processes in the universe, and vice-versa, considering the inverse problem to study cosmic ray properties in various energy [3].

Cosmic rays, magnetic fields, and turbulence are in pressure equilibrium in the midplane of the Milky Way, implying that cosmic rays play an important dynamical role in maintaining the ISM energy balance. In fact, if the cosmic ray and magnetic midplane pressures exceed that of the thermal plasma, their buoyancy overcomes magnetic tension and opens up the magnetic field into the halo; this enables cosmic rays to be transported ahead of the thermal plasma along these field lines into the halo. This environmental criterion (called the Hillas criterion) gives us another constraint on the possible sources of cosmic rays. The processes controlling cosmic ray escape from their accelerators depend on the source evolution stage and the surrounding ISM properties. Once they have escaped, cosmic rays can back-react over the surrounding medium of the source. On the other hand, high cosmic ray anisotropies near sources can non-resonantly excite Alfvén modes or drive background ion-cyclotron modes in the comoving cosmic ray frame [1][3]. Besides, the effect of neutrals on higher-order cosmic ray anisotropies is starting to be explored. These instabilities are a local source of magnetic turbulence which increases the cosmic ray scattering rate and decreases their mean free path, so that they are potentially responsible for gamma-ray halos around some pulsars. The generation of magnetic turbulence and this reduced diffusivity around source have multiple consequences: a dynamical feedback over the ISM, explain a part of the cosmic ray grammage, explain detailed features in the cosmic ray spectrum. An essential way to select the correct theory will be to perform dedicated observations of the non-thermal emission around cosmic-ray sources from radio to the multi-TeV domain [1].

5 Beyond Charged Particles

Our discussion on cosmic rays has been largely restricted to the charged component of the showers, as they by themselves constitute an important class of detection events. However, gamma-rays and neutrinos also constitute an important part of cosmic ray showers. We give a quick review of the major features of this part of the spectra.

5.1 γ

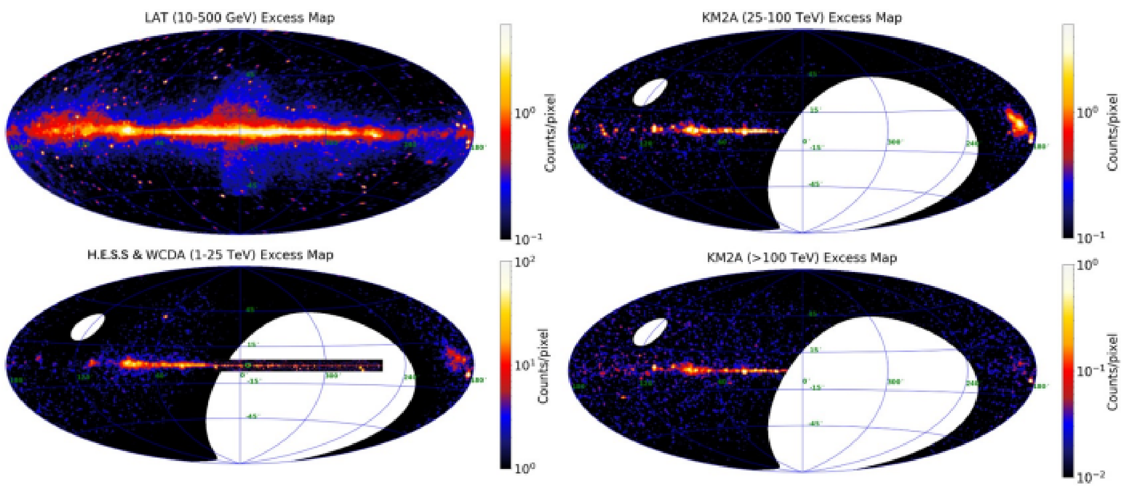

Figure 3: The GeV γ-ray sky maps surveyed by Fermi-LAT, LHAASO and H.E.S.S from 1 GeV to 100 TeV and above.

There is a well-studied flux of cosmic gamma rays (defined here as having energy greater than 1 MeV) present at the top of the atmosphere. Known as the diffuse gamma-ray flux, it has been measured with multiple space and ground-based instruments across a broad range of energy. On top of the diffuse one, many discrete sources have been found with either a steady gamma-ray flux or variability of many types. Three major components are expected in the diffuse spectrum, namely γ-rays from the decay of neutral pions produced via inelastic collisions between energetic cosmic ray nuclei and the interstellar medium (ISM); bremsstrahlung radiation of electrons and positrons in ISM; and inverse Compton scattering of electrons and positrons off the interstellar radiation field. Possible annihilation or decay of dark matter (DM) particles might also give rise to diffuse γ-rays particularly in the densest region of the Galaxy. Therefore, Galactic Diffuse Emission (GDE) serves not only as a very important tool to probe the production, propagation, and interaction of cosmic rays, but also as a route to search for DM in any excess over the expectation, which is based on assumptions of the cosmic-ray spatial distribution, composition, energy spectrum and on the ISM column density along the line-of-sight [1]. The search for DM also depends on the fraction of the contribution by the unresolved dim discrete sources in the GDE. Unfortunately, all of the assumptions have their own large uncertainties at present.
As a neutral component of cosmic rays, γ-rays directly reach the earth from their sources, thus allowing

us to identify the origin of the photons by association with known celestial objects or events. As shown in Figure 4, the source-associated contributions are revealed directly by the bright spots whose sizes are due to the point-spread-function (PSF) of the instruments and the intrinsic spatial extensions of the sources. It is also clearly shown that the sources are divided into two groups: Galactic (e.g., supernova remnants, pulsar wind nebulae, young massive-star clusters, flares, etc) and extragalactic (e.g., Gamma Ray Bursts, Active Galactic Nuclei, etc).

5.2 ν

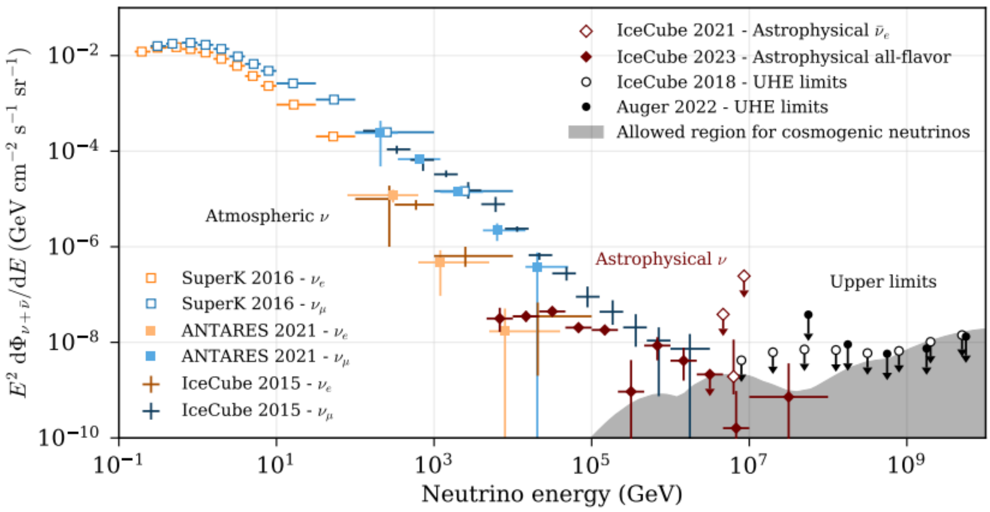

Figure 4: Measured energy spectra of atmospheric and cosmic diffuse neutrino fluxes [1]

In contrast to charged particles, neutrinos are not deflected by electromagnetic fields and thus point back to their origin, making them appealing messengers for astronomical observations [1]. In addition, neutrinos of cosmic origin, or produced in the atmosphere of the Earth, allow us to study particle physics in a kinematic regime not accessible to date to accelerator experiments. In the following, we will consider neutrinos with energies at the GeV energy scale and above.
High-energy neutrinos can be produced in hadronic interactions in a variety of astrophysical objects (astrophysical or cosmic neutrinos), in scattering of extremely energetic protons (p) with the cosmic microwave background (cosmogenic neutrinos) and by cosmic ray interactions in the Earth's atmosphere (atmospheric neutrinos). The main production chain is (A denoting atomic nuclei and X a hadronic system)

$$p(A) + p(A, \gamma) \rightarrow \pi^{\pm} + X \quad \text{with subsequent decays} \quad \pi \rightarrow \mu\nu_\mu \text{ and } \mu \rightarrow e\nu_\mu\nu_e$$

resulting in a ratio $\nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0$ (not distinguishing here between ν and $\bar{\nu}$). If the source density is high, muons can lose most of their energy before decaying, yielding a ratio $0 : 1 : 0$ in the extreme case [1]. If protons were kept in the source region by magnetic fields without interacting, and only neutrons could escape and then decay via $n \rightarrow p + e^- + \bar{\nu}_e$, the ratio would be $1 : 0 : 0$. Over cosmic distances, flavor mixing turns these ratios to $0.30 : 0.36 : 0.34$ for the first source scenario ($1 : 2 : 0$), $0.17 : 0.45 : 0.37$ for the second ($0 : 1 : 0$) and $0.55 : 0.17 : 0.28$ for the third scenario ($1 : 0 : 0$)[1].
Prompt atmospheric neutrinos are produced by the decay of hadrons containing a charm or bottom quark, the production of which is strongly suppressed. Since they are produced early in the air shower and decay before losing energy, however, the energy spectrum of prompt neutrinos is expected to be harder ($E_\nu^{-2.7}$) and to dominate the atmospheric neutrino flux at its highest energies. The corresponding theoretical prediction has large uncertainties related to the cosmic-ray spectrum and mass composition, the model for heavy-flavor production, and the parton distribution functions. At present, experimental measurements only provide upper limits for the prompt flux.
Cosmogenic neutrinos stem from the decay of charged pions generated in interactions of ultra-high-energy cosmic rays with cosmic (a)microwave and (b)infrared background radiation ($p + \gamma \rightarrow n + \pi^+$) and from the (c) decays of neutrons produced in photodisintegration processes. The neutrino flux at EeV energies

is expected to be dominated by (a) and (c). Similar to γ-rays, neutrinos often have (overlapping) astrophysical point sources.

6 Experimental Results

The understanding of cosmic rays is mainly derived from analyzing their energy spectrum, several observables sensitive to their primary nature, and their arrival direction distribution. This is a challenging task mainly due to the small flux, with less than 1 particle per km^2 per year above 30 EeV, but also because the properties of cosmic rays in this energy range can only be inferred indirectly from measurements of the Extensive Air Showers (EAS) whose description relies on extrapolations of particle physics properties at energies several orders of magnitude above those achieved in terrestrial accelerators. Last but not least, since cosmic rays are charged they are deflected by the galactic and intergalactic magnetic fields and their arrival directions at Earth point back only approximately to their actual sourc [1].
In the energy range above 100 PeV the fluorescence technique is used to determine the primary cosmic-ray energy, with the atmosphere where the EAS develops functioning as a calorimeter. In the two state-of-the-art experiments for Ultra High Energy Cosmic Rays (> 1000 PeV) (UHECRs) [?], the Pierre Auger Observatory and the Telescope Array, a sub-sample of events is recorded simultaneously with the fluorescence (FD) and the surface detector (SD) arrays. With the SD, a shower size parameter is measured and calibrated against the energy measured with the FD. This approach provides a more direct method for determining cosmic-ray energy without relying on simulations. Differences in the energy scale between Auger and Telescope Array (TA) remain, however, primarily due to the use of different measurements of the amount fluorescence light emitted per unit of energy deposited, and to the different models for the invisible energy in EAS adopted. When these systematic uncertainties are accounted for, the spectra of the Pierre Auger Observatory and TA have been shown to agree within 5%, except in the energy region near the end of the instep feature and at the suppression[1].

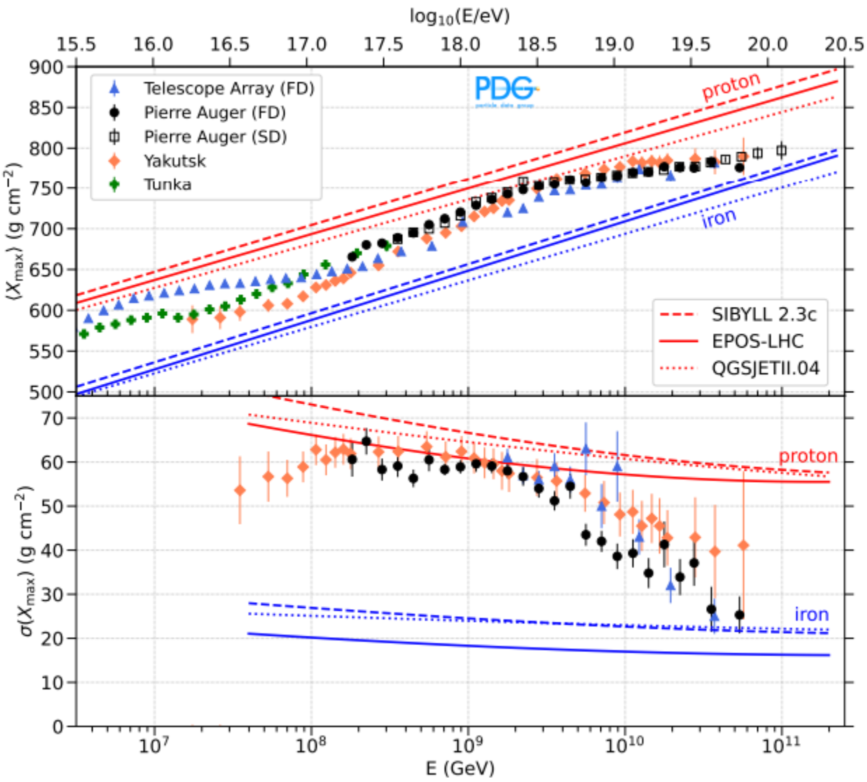

Figure 5: Measurements of hXmaxi (top) and σ(Xmax) (bottom) obtained by the Telescope Array, Pierre Auger Observatory, Yakutsk, and Tunka UHECR detectors, compared to predictions for proton and iron nuclei using the hadronic models SIBYLL2.3c, EPOS-LHC and QGSJET-II.04. Detection techniques: fluorescence (FD), Cherenkov (Yakutsk, Tunka, and TA below ’ 1EeV), and using the surface detector array of the Auger Observatory (SD) [1]

The main observable sensitive to cosmic ray composition is the depth in the atmosphere along shower axis $X_{\max}$) at which the number of particles in the shower is maximum. Observatories capable of detecting Cherenkov and/or fluorescence light induced by the passage of the EAS through the atmosphere, can measure $X_{\max}$ on an event-by-event basis. With sufficient statistics, the distributions of $X_{\max}$ can be determined from which the average value $\langle X_{\max}\rangle$ and its fluctuations $\sigma(X_{\max})$ are obtained. A comparison with the $\langle X_{\max}\rangle$ and $\sigma(X_{\max})$ as predicted in simulations of EAS for different primaries and energies, as well as fits to the $X_{\max}$ distributions lead to the determination of the mean fractions of primary protons, helium, carbon-nitrogen-oxygen and iron in the cosmic-ray flux at Earth. However, the interpretation of any mass-sensitive observable relies on modeling hadronic interactions up to the highest energies where there are no data from terrestrial accelerators, and this introduces a considerable uncertainty in the determination of the mass. Also, due to intrinsic shower-to-shower fluctuations, an event-by-event determination of the mass of the primaries is not currently possible. Despite these limitations, the measurements presented in Fig. 3 alongside the predictions of EAS simulations for proton and iron primaries, reveal a broad trend toward a lighter composition at the knee, within the energy range of a few PeV. This is followed by a gradual rise in the average logarithm of the primary cosmic-ray mass, eventually leading to a heavier composition at around 100 PeV, although notable differences between experiments exist [8]. As the energy increases from 100 PeV up to 2 EeV the measurements point consistently to a predominantly light composition with a large fraction of primary protons. Above that energy, the data from the largest statistical sample of events collected with the FD of the Pierre Auger Observatory indicate that the composition is mixed with the mean mass steadily growing. This observation is further supported by the shower-to-shower fluctuations of $X_{\max}$ also shown in Fig. 3. Though the data of the Telescope Array seem in apparent tension with this picture, they have been shown to be compatible with the results of the Pierre Auger and Yakutsk Observatories [8][11] within the current levels of statistics and understanding of systematic uncertainties. In particular, TA data are compatible with the mixed composition inferred by the Pierre Auger Collaboration.

6.1 The high energy cut-off

Even with our latest instruments, and intensive statistical analysis, a cutoff at around 5×10^{19} eV is observed in the CR spectrum. A theoretical upper limit for the spectrum was predicted by Greisen, Kuz'min and Zatsepin in 1966 based on calculations rooted in special relativity and particle physics. We motivate their resoning in the next section.

7 The GZK Cutoff

7.1 The photon-pion production limit

The very highest energy cosmic rays have such large Lorentz factors that photons of the Cosmic Microwave Background Radiation have very high energies in the rest frame of the cosmic ray and so photo-pion and photo-pair production can take place, which degrade the energy of the cosmic ray. If a proton is bombarded with high energy γ-rays, pions are created, the threshold for his process being $\epsilon_1 = 200$ MeV and the cross-section about 250 microbarns. The reactions involved are

$$\begin{aligned}
&\gamma + p \to n + \pi^+ \\
&\gamma + p \to p + \pi^0 \to p + \gamma + \gamma \\
&\gamma + p \to p + N\pi
\end{aligned}$$

The charged pions then decay creating ultra-high energy muons and muon neutrinos (see Sect. 10.1). These high energy neutrinos could be detected by large ground-based neutrinos detectors. The Cosmic Microwave Background Radiation permeates all space and therefore the cosmic rays cannot escape from it. The average energy of the photons of the background is $\epsilon_0 = 6 \times 10^{-4}$ eV ($\nu = 1.5 \times 10^{11}$ Hz) and therefore, in the rest frame of the cosmic ray, their energies are

$$\epsilon = \epsilon_0 \gamma \left(1 + \frac{v}{c}\cos\theta\right). \quad (15.34)$$

Therefore, the threshold for pion production in the limit $v \to c$, $\cos\theta = 1$ corresponds to an energy $E = 2\gamma_p m_p c^2$ for protons where $\gamma = \epsilon_1/\epsilon_0$, that is $\gamma = 1.7 \times 10^{11}$, or $E = 1.7 \times 10^{20}$ eV. The proper calculation involves integration over the Planck spectrum of the Cosmic Microwave Background Radiation and over all angles. The threshold for the photo-pion production process then decreases to 5×10^{19} eV, well within the range of cosmic ray energies which have been observed in extensive air-showers.
The mean free path for a single scattering is $\lambda = (\sigma_{p\gamma} n_{\rm photon})^{-1}$. Taking $N_{\rm photon} = 5 \times 10^8$ m^{-3} for the Cosmic Microwave Background Radiation and $\sigma_{p\gamma} = 2.5 \times 10^{-32}$ m^{-2}, then $\lambda \approx 10^{23}$ m corresponding to a propagation length of 3 Mpc or a propagation time of 10^{15} years. The energy of the pion created in this process is $\gamma m_\pi c^2$ and therefore the fractional loss of energy of a cosmic ray proton is $\Delta E/E \approx m_\pi/m_p \approx 1/10$. Therefore, the total mean free path for the cosmic ray proton to lose all its energy corresponds to a propagation time of 10^8 years. If cosmic rays of this energy permeated all space and had been present for 10^{10} years, there should be a cut-off in the cosmic ray energy spectrum at about 5×10^{19} eV for protons. If the highest energy cosmic rays are protons, they cannot have originated from further than about 30 Mpc from our Galaxy. These arguments were first discussed by Greisen, Kuz'min and Zatsepin and the cut-off is known as the GZK cut-off. The existence of the cut-off depends upon the value of γ of the cosmic rays and so, if it turned out that the highest energy cosmic rays were iron nuclei rather than protons, the photo-pion production process would not be responsible for the cut-off at 5×10^{19} eV.

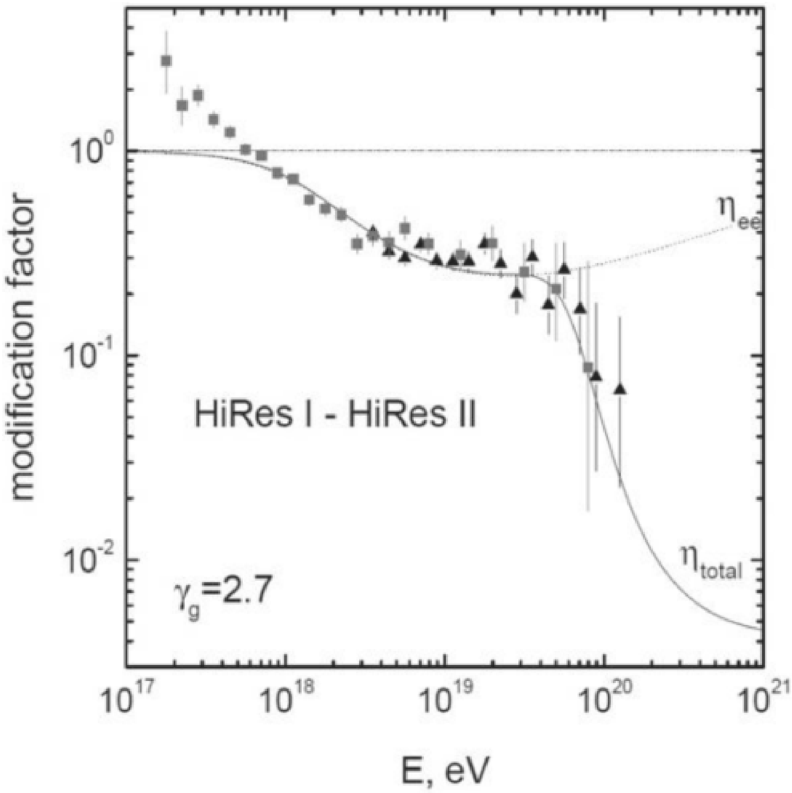

Figure 6: Pair-production dip and GZK cut-off in terms of the modification factor $\eta(E)$ compared with the HiRes observational data. The curves labelled η_{tot} and η_{ee} show the total spectral modification and η_{ee} the spectral modifications due to adiabatic energy losses and pair production [17]

A similar calculation can be carried out for the electron-positron photo-pair production process. The threshold energy for this process is 1.02 MeV, about 200 times less than that for the photo-pion production mechanism. Therefore, the process is important for protons with Lorentz factors $\gamma \geq 10^9$, corresponding to proton energies of about 10^{18} eV. The cross-section for this process in the ultra-relativistic limit is $\sigma_{pair} = 10^{-30} m^2$. Although this cross-section is 40 times larger than that for the production of pions, each photo-pair production event removes only 10^{-3} of the energy of the proton and so the time-scale for the protons to lose all their energy is 25 times longer, that is about 2.5×10^9 years.

Consequently this process is less important for cosmic ray protons of energy 5×10^{19} eV, but it does result in a distortion of the particle spectrum down to energies of about 10^{18} eV.

7.2 Recent Calculations & Controversies

Detailed calculations of the shape of the GKZ cut-off and the photo-pair production loss mechanisms have been carried out by Berezinsky [17] and his colleagues with the results shown in Fig. 6. They present their results in terms of a modification factor $\eta(E)$ which is defined as

$$\eta(E) = J_p(E)/J_p^{unm}(E) \tag{9}$$

where $J_p(E)$ is the spectrum taking account of all the energy losses and $J_p^{unm}(E)$ excludes the above photo-pion and photo-pair processes. The sharp cut-off at about 5×10^{19} eV is the GKZ cut-off. The dotted line shows the 'dip' due to photo-pair production which extends down to about 10^{18} eV. The predictions are compared with the results of the HiRes observations. At energies less than 10^{18} eV, the slope of the observed spectrum increases to $x = 3.1$ and this is interpreted as the spectrum of Galactic cosmic rays. Berezinsky and his colleagues show that the predicted shape of the modification factor $\eta(E)$ seems to have been observed in the HiRes data, implying that the ultra-high energy cosmic rays are extragalactic and must be mainly protons [17].

At the time of writing, there appears to be a discrepancy between the results of the HiRes and Auger projects. The Auger Collaboration find clear evidence that the highest energy cosmic rays are very much heavier than protons, probably iron nuclei. According to Berezinsky and his colleagues, the shape of the Auger energy spectrum also differs from the predicted total spectrum shown in Fig. 6.

If the highest energy particles were nuclei, there would still be a cut-off at energies $E \sim 5 \times 10^{19}$ eV because of photonuclear interactions. This can be demonstrated by an order of magnitude estimate similar to those given above for pions and electrons. As above, the maximum energy of the photon in the centre of momentum frame of reference is $\epsilon = 2\gamma\epsilon_0 = 10^{-3}\gamma$ eV for photons at the peak of the spectrum of the Cosmic Microwave Background Radiation. The binding energy per nucleon for nuclei is of the order of 10 MeV per nucleon and so it is not surprising that there is what is referred to as a giant dipole resonance, which peaks in the γ-ray energy range 10-30 MeV in the nuclear rest frame. The absorption of the photon leads to the excitation of one or two nucleons which are ejected from the nucleus, beginning the disintegration of the nucleus. The necessary value of the Lorentz factor γ to attain this energy in the centre of momentum frame of reference is therefore $\gamma \approx (1-3) \times 10^{10}$ eV. If A is the atomic mass number of the nucleus and E the total energy, the corresponding Lorentz factor is E/Am_nc^2. Therefore, at threshold, photo-disintegration of the nucleus takes place at energies $E > 10^{18}A$ eV. Thus, for the typical atomic mass numbers of cosmic ray nuclei, a photo-disintegration cut-off would also appear about $10^{19} - 10^{20}$ eV. In addition, the path length over which the disintegration of the nuclei would take place is less than that of the photo-pion process.

Stecker and Salaman [14] give an approximate expression for the energy-weighted cross-section for the interaction of heavy nuclei

$$\int_0^\infty \sigma(\epsilon)d\epsilon = 60\frac{NZ}{A} \times 10^{-31}m^2\text{MeV}. \tag{10}$$

Taking the width of the resonance to be of order 5-10 MeV, this cross-section is larger than the photo-pion and electron-pair production cross-sections. The subsequent disintegration of the nucleus has to be followed by Mote Carlo simulations and these have been carried out by Stecker and Salaman. The results of their detailed calculations are shown in Fig. 7 which shows that a cut-off is expected at energies less than 10^{20} eV, even if the highest energy cosmic rays are iron nuclei.

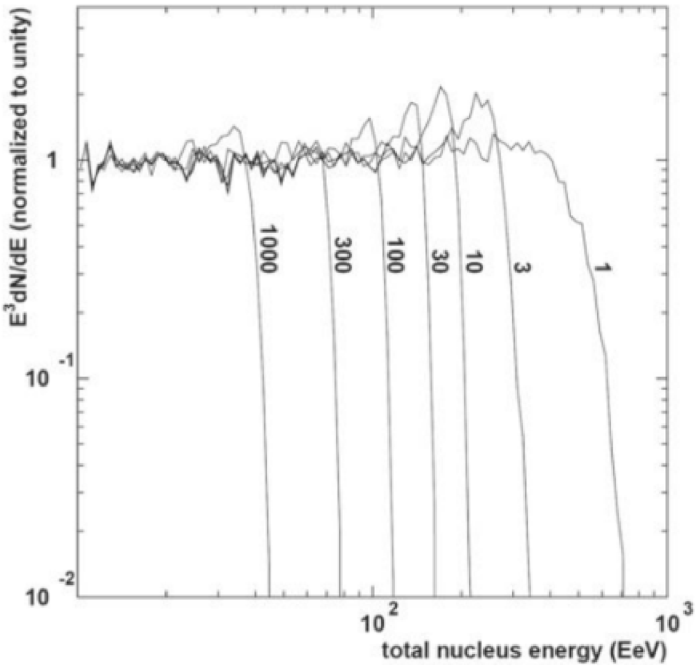

Figure 7: The differential spectra of ultra-high energy cosmic ray iron nuclei (56Fe) after propagating the distance in Mpc indicated on each curve [14]

The situation remains to be resolved. The Auger statistics are now significantly greater than those of the HiRes observations and the value of $RMS(X_{max})$ undoubtedly decreases with increasing energy. The implications are important. If the highest energy cosmic rays are iron nuclei, there would be no ultra high energy neutrinos associated with the decay of the π^+ particles created in the p-p collisions. Berezinsky and his colleagues refer to the latter possibility as the 'disappointing model'. The continuing efforts of the Auger team and the construction of even larger air-shower arrays are the ways forward.

A suppression of the cosmic-ray flux that can be explained with the GZK limit has been confirmed by the latest generation of cosmic-ray observatories. It remains controversial whether the suppression is due to the GZK effect. In July 2007, during the 30th International Cosmic Ray Conference in Mérida, Yucatán, México, the High Resolution Fly's Eye Experiment (HiRes) and the Pierre Auger Observatory (Auger) presented their results on ultra-high-energy cosmic rays (UHECR) [8]. HiRes observed a suppression in the UHECR spectrum at just the right energy, observing only 13 events with an energy above the threshold, while expecting 43 with no suppression. This was interpreted as the first observation of the GZK limit. Auger confirmed the flux suppression, but did not claim it to be the GZK limit. In 2010 and the following years, both the Pierre Auger Observatory and HiRes confirmed again a flux suppression, in case of the Pierre Auger Observatory the effect is statistically significant at the level of 20 standard deviations [13].

However, a number of observations have been made by the largest cosmic-ray experiments Akeno Giant Air Shower Array (AGASA), High Resolution Fly's Eye Cosmic Ray Detector, the Pierre Auger Observatory and Telescope Array Project that appeared to show cosmic rays with energies above the GZK limit [13]. These observations appear to contradict the predictions of special relativity and particle physics as they are presently understood. However, there are a number of possible explanations for these observations that may resolve this inconsistency. The easiest solution is of course, heavier nuclei, although this warrants an investigation of their sources, which are not clear. Similarly, the cosmic rays could have local sources within the GZK horizon, although it is unclear what these sources could be. Finally, the observations could be due to an instrument error or an incorrect interpretation of the experiment, especially wrong energy assignment.

If there are no instrumentation and systematic errors, then a number of theoretical solutions have been proposed. None of them have been concretely shown, but tests on Lorentz Invariance Violation have gained traction over the past decade.

After the flux suppression was established, a heated debate ensued whether cosmic rays that violate the GZK limit are protons. The Pierre Auger Observatory, the world's largest observatory, found with high

statistical significance that ultra-high-energy cosmic rays are not purely protons, but a mixture of elements, which is getting heavier with increasing energy. The Telescope Array Project, a joint effort from members of the HiRes and AGASA collaborations, agrees with the former HiRes result that these cosmic rays look like protons. The claim is based on data with lower statistical significance, however. The area covered by Telescope Array is about one third of the area covered by the Pierre Auger Observatory, and the latter has been running for a longer time.
The controversy was partially resolved in 2017, when a joint working group formed by members of both experiments presented a report at the 35th International Cosmic Ray Conference [1][13]. According to the report, the raw experimental results are not in contradiction with each other. The different interpretations are mainly based on the use of different theoretical models and the fact that Telescope Array has not collected enough events yet to distinguish the pure-proton hypothesis from the mixed-nuclei hypothesis [4].

8 Future Prospects

We come to a close by discussing the future prospects of the field, and how it aims at tackling the unresolved issues, and future directions it can take. Although astroparticle physics has always been a highly interdisciplinary field, traversing the overlaps among cosmology, particle physics and astrophysics, we restrict our discussion largely to the interest of particle physicists [3].
A central challenge for the theory community is to bridge the vast separation of scales—from the microphysics of plasma instabilities to the astrophysical scales of supernova remnants or relativistic jets. There is a significant need to move beyond current computational limits. This includes developing more sophisticated hybrid kinetic/fluid approaches (like MHD-PIC) and running high-resolution, 3D general relativistic magneto-hydrodynamical (GRMHD) simulations [3]. These advanced simulations will be crucial for resolving processes which are believed to be key to particle acceleration.
The origin of ultrahigh energy cosmic rays remains an unsolved, long-standing question. Since current models of relativistic shocks have trouble accelerating particles to the highest observed energies, future investigations will focus on relativistic magnetic reconnection events that can better explain acceleration mechanisms.
The field anticipates a new generation of more sensitive MWL facilities, such as the Cherenkov Telescope Array (CTA), the Square Kilometer Array (SKA), and the next-generation Event Horizon Telescope (EHT). These new instruments will enable some of the first MM variability studies to test and refine models of acceleration physics. A key focus in the coming decade will be to convolve models of individual sources with population synthesis models. This will be essential to predict and test against diffuse fluxes and the overall cosmic-ray distribution measured on Earth [3][1].
Cosmic ray transport is also a field rich with prospects. A future direction is answering fundamental questions about the micro-physics of cosmic ray transport, such as how they interact with and provide feedback to electromagnetic fields. This includes dedicated simulations of cosmic-ray escape.
Progress is currently hampered by a limited knowledge of cross sections for nuclear interactions, particularly for the photodisintegration of nuclei. This highlights a need for new experimental verification of these cross-sections. Astroparticle observations offer a unique window into fundamental physics. Future directions include using cosmic-ray, γ-ray, and neutrino data to search for signals from dark matter (e.g., in the anti-deuteron and anti-helium channels) and to test Beyond-Standard-Model (BSM) physics [3].

9 Summary and Conclusions

In this paper, we reviewed the broad landscape of astroparticle physics with a focus on the origin, acceleration, propagation, and detection of cosmic rays, and the theoretical and observational frameworks associated with the Greisen–Zatsepin–Kuz'min (GZK) limit. Beginning with the thermal history of the Universe, we noted how primordial processes such as Big Bang nucleosynthesis, recombination, and reionization seeded the charged components of the interstellar and circumgalactic medium, thereby providing the backdrop against which cosmic ray physics unfolds. These cosmological epochs not only prepare the medium in which cosmic rays propagate but also furnish the radiation fields—most notably the CMB—that ultimately impose fundamental limits on the highest energies achievable by charged

particles.
We then explored the phenomenology of the cosmic-ray spectrum and argued that its steep power-law behaviour arises naturally from stochastic acceleration mechanisms. The presence of distinct features such as the knee and ankle illustrates the interplay between Galactic and extragalactic components of the spectrum. Theoretical considerations and energetic arguments strongly favour supernova remnants, pulsar wind nebulae, AGNs, and GRBs as major acceleration sites, with diffusive shock acceleration and magnetic reconnection emerging as the dominant mechanisms capable of producing the observed non-thermal spectra. The subsequent transport of these particles through turbulent magnetic fields, and their interaction with the ISM, introduces additional complexity, reflected in anisotropies, spectral features, and environmental feedback processes. Understanding these mechanisms remains a central challenge, given the limited knowledge of key nuclear cross sections and the multiscale nature of the problem.
Beyond charged cosmic rays, we highlighted the complementary roles of high-energy γ-rays and neutrinos as messengers that can bypass magnetic deflection and trace hadronic processes more directly. Their detection has transformed astroparticle physics into a multi-messenger enterprise, allowing stringent tests of particle acceleration models and placing tight bounds on dark matter scenarios. The growing capabilities of detectors such as Fermi-LAT, H.E.S.S., IceCube, and LHAASO have allowed the community to detect PeVatrons and probe environments with unprecedented precision.
A significant focus of this paper was the high-energy suppression observed in the cosmic-ray spectrum. The GZK limit, arising from photo-pion and photo-pair production off the CMB, provides a natural theoretical upper bound for proton energies around 5×10^{19} eV. We reviewed the original argument, recent refinements, and competing interpretations of this suppression. While early results from HiRes appeared consistent with a proton-dominated GZK cutoff, later findings from the Pierre Auger Observatory point toward a mixed or heavier composition at the highest energies. This discrepancy has led to a long-standing debate within the community, with implications for the existence of cosmogenic neutrinos and the identification of potential UHECR sources. Joint analyses between Auger and the Telescope Array have shown that experimental results need not contradict each other; rather, differing interpretations arise from model-dependent assumptions about hadronic interactions at energies far beyond accelerator reach. Despite improved statistics, the question of composition near the cutoff—and hence the interpretation of the cutoff itself—remains open.
Looking ahead, the field is poised for rapid growth. Upcoming observatories and next-generation simulations promise to bridge the scales from microphysical plasma processes to galaxy-scale cosmic-ray environments. Improved modelling of nuclear cross sections, better multi-wavelength and multi-messenger coverage, and deeper theoretical work on acceleration in relativistic reconnection sites will be essential. The resolution of the GZK controversy will likely require a combination of higher-statistics observations, better hadronic models, and an expanded catalogue of UHECR arrival directions anchored by improved magnetic field reconstructions.
In summary, astroparticle physics stands at an exciting juncture. The interplay between theory, simulation, and observation continues to reveal the extraordinary complexity of high-energy processes in the Universe. While significant progress has been made in identifying acceleration sites, understanding spectral features, and constraining propagation physics, many fundamental questions remain open—chief among them the true nature of UHECR composition and the definitive interpretation of the flux suppression near 10^{20} eV. The coming decade, equipped with more sensitive instruments and refined theoretical tools, promises to bring these questions into sharper focus and deepen our understanding of the extreme Universe.

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