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Chapter 1

Introductory Chapter: Ultrahigh-Energy Cosmic Rays

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Additional information is available at the end of the chapter

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1. Introduction

In 1938, Pierre Auger recorded coincidences by particle detectors separated by large distances at ground level. The source was ultrahigh energy cosmic rays (UHECRs) generating in the atmosphere extensive air showers (EAS). The energy of UHECRs reached up to 10^{15} eV [1, 2]. In this time energy of particles produced in laboratories was at the level of 10^{7} eV. In 1962, Linsley at Volcano Ranch recorded an air shower from a cosmic ray with giant energy higher than 10^{20} eV [3]. In 1965, Penzias and Wilson discovered the cosmic microwave background (CMB) radiation. This discovery overshadowed Linsley's experiment, the fantastically huge cosmic ray energy did not receive any attention that it deserved. Just after CMB discovery, **G**reisen, **Z**atsepin, and **K**uzmin (GZK) [4, 5] predicted that photo-pion production by the CMB photons reduces the path length for protons of UHECRs. In the rest frame of proton, the CMB is a beam of very energetic photons. The GZK threshold is the cosmic ray energy at which a Lorentz-boosted CMB photon has energy equal to the pion rest energy. The Planck distribution of CMB photons causes pion photo-production energy loss for protons with energies above approximately 7×10^{19} eV. The effect predicts that the spectrum from distributed homogeneous sources in the universe is suppressed above the GZK threshold at least one order of magnitude compared to the flux without the GZK effect.

If one assumes that the sources accelerate nuclei to a maximum energy above the energy threshold for photo-disintegration on CMB photons, the light elements could then be fragments of heavier nuclei that disintegrated during propagation. Candidate air shower primary particles all suffer severe propagation losses that should produce an effective cut-off at $\leq 10^{20}$ eV in experiments so far, assuming only that high-energy cosmic rays are normal particles that are produced in sources throughout the universe.

At the moment, the UHECRs remain a puzzle. Reliable conclusions from measurements of the energy spectrum, composition, and anisotropy and the proposed models cannot be obtained without a significant improvement in the observations.

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The statistics of registered events with energy about 10^{20} eV is definitely insufficient due to extremely low flux estimated less than 0.5 event per km^2 per century per steradian. So that only detectors of a huge size will be able to observe a sufficient number of events, which may be a fundament of a new physics.

Cosmic rays are high-speed particles traveling throughout our Galaxy, including the Solar System. Some of these particles originate from the Sun, but most come from sources outside the Solar System and are known as galactic cosmic rays (GCRs). The origin of the highest energy cosmic rays is expected to be extragalactic. Simple considerations about the confinement of particles in the Galaxy and Galactic halo strongly suggest that most of the highest-energy CR must have an extragalactic origin (unless their charge is unexpectedly large, which is also not favored by the observations). CR particles arriving at the top of the Earth's atmosphere are called primaries; their collisions with atmospheric nuclei give rise to secondaries.

Several experiments have been investigating ultrahigh-energy cosmic rays with energies reported beyond 10^{20}, but their origin is still unknown. For the current physics, astronomy and cosmology, it is a great challenge. In the 1990s, the largest experiments, AGASA and HiRes (both located in the Northern hemisphere), reported a discrepancy in the energy spectrum and clustering of cosmic ray arrival directions near the GZK energy threshold. This fact showed clearly that we require much more accurate and large-scale experiments to investigate this question without any doubts.

At 10^{15} eV, GCRs consist mostly of protons (nuclei of hydrogen atoms) and alpha particles (helium nuclei). The remainders are electrons and nuclei of heavier atoms. The composition changes with energy. At present, we believe that UHECRs consist mostly of charged nuclei. Gamma rays have been observed with energies as high as ~10^{12} eV. EAS generated by photons would be almost purely electromagnetic.

Because most cosmic ray primaries are strongly influenced by the solar magnetic field, most of those detected near the Earth have kinetic energies in excess of about 0.1 GeV. The number of particles decreases dramatically with increasing energy, but individual particles with the estimated energies above 10^{20} eV have also been recorded.

Due to magnetic fields, primary GCRs that are deflected in the space and arrive at the top of the Earth's atmosphere are nearly uniform from all directions. Thus, identification of UHECR sources based on arrival directions must be excluded. We have to deduce by other ways like, that is, the charge spectrum compared to spectroscopy data of stars and interstellar regions. The abundances of different elements have been well studied for particles with energies from roughly 100 MeV to several hundreds of GeV.

UHECRs are observed in an energy range from 10^9 eV to above 10^{20} eV. Over this range, the flux of cosmic rays appears to follow an approximate single power law ~$E^{-2.7}$, with sharper steepness ~$E^{-3.0}$ between so-called knee and ankle (see **Figure 1**) corresponding to 10^{15} eV and 10^{18} eV, respectively.

Cosmic rays with energies above ~10^{19} eV, known as ultra-high energy cosmic rays (UHECRs) are microscopic particles with a macroscopic amount of energy about a joule or more. The existence of such energetic particles, the mechanism of the acceleration to such extreme energies, the regions of their creation and the composition remains still a mystery.

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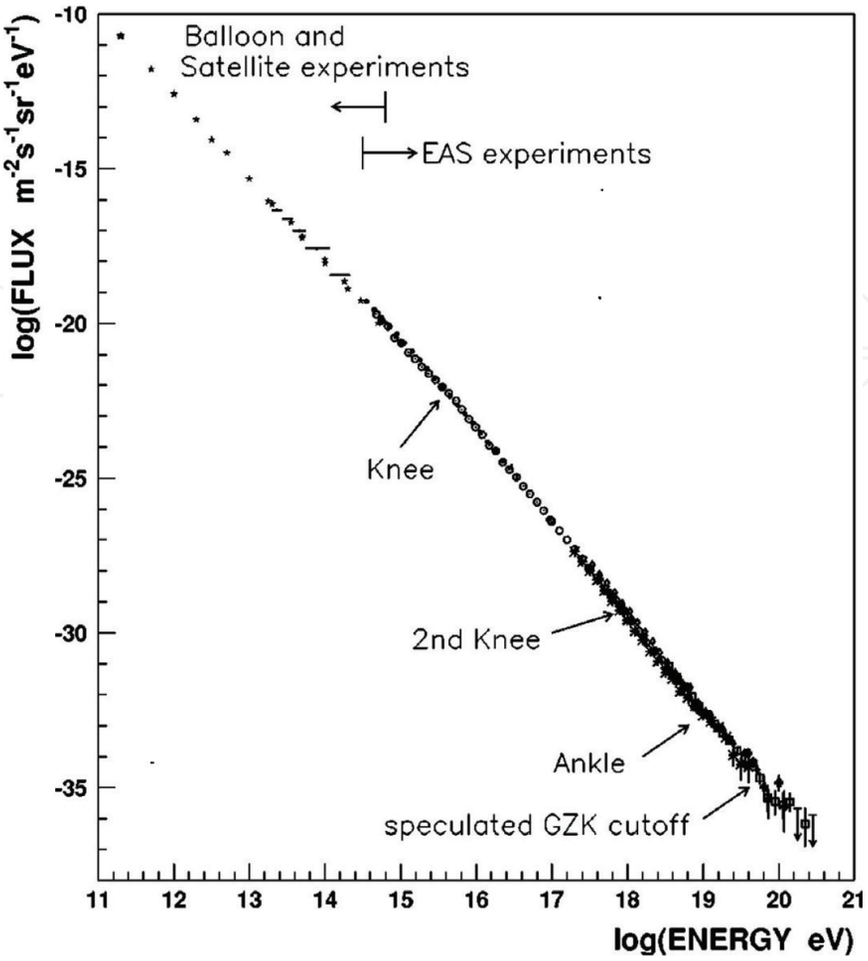


Figure 1. Observed energy spectrum of primary cosmic rays. The spectrum is expressed by a power law from 10^{11} to 10^{20} eV with a slight change of slopes around $10^{15.5}$ eV (knee), $10^{17.8}$ eV (second knee), and 10^{19} eV (ankle) [6].

The acceleration mechanism is still not clear and the study requires very careful measurements of the energy spectrum of UHECR to compare to the predictions from different acceleration models. Arrival directions of UHECRs are the second topic requiring a careful attention, and the third is both small- and large-scale anisotropies in their distribution. The fourth: the composition is one of the most difficult measurements because UHECRs cannot be detected directly using conventional particle detectors. Consequently, the composition as well as energy spectrum and arrival directions must be inferred from auxiliary measurements.

2. Extensive air showers

The cosmic rays with energies greater than 10^{14} eV have been investigated by using the Earth's atmosphere itself as part of the detection equipment. The interaction between high-energy cosmic rays and the air produces avalanches of secondary particles.

The process begins with the collision of the primary cosmic ray with a nucleus near the top of the atmosphere. This first collision produces typically several tens of secondary particles (depending on initial energy), mainly pions. The charged pions, as relatively long-lived,

collide with another nucleus. The subsequent collisions are similar in nature to the primary collision. This process then leads to a cascade of particles, known as hadronic shower.

About 33% of pions, created in collisions, are neutral. They are very short-lived and decay very fast into a pair of photons before a next interaction with nuclei in the atmosphere. Next, photons interacting with the nuclei in the air create electron-positron pairs, which thus produce bremsstrahlung photons. This cascading process forms an electromagnetic avalanche. The hadronic shower itself permanently produces neutral pions and thus is developing secondary electromagnetic cascades along its path.

With an EAS development into the atmosphere, the number of generated particles successively increases (**Figure 2**). However, the process of multiplication is continued until the average energy of the shower particles is insufficient to produce more particles in subsequent collisions. Some part of energy is also leaking to the atmosphere due to ionization processes. Finally, the number of the particles traveling in the shower starts to decrease. This point of the EAS development is known as shower maximum. Beyond the maximum, the shower particles are gradually absorbed with an attenuation length of ~200 g/cm^2. The depth of shower maximum ($\boldsymbol{X_{max}}$) is a function of energy. With a value of about 500 g/cm^2 at 10^{15} eV, the average X_{max} for showers increases by 60–70 g/cm^2 for every decade of energy [7]. The measured value of X_{max} can also be used to estimate the composition of the primary cosmic ray. Hadronic interaction length in air for protons is about 70 g/cm^2, and shorter for heavier nuclei. This means EAS are generated by heavier elements higher in the atmosphere.

More muons and fewer electromagnetic particles are produced by heavy primary particles rather than do lighter primaries, of the same primary energy. Iron and proton showers can be distinguished using surface detector data alone through the ratio of muons to electromagnetic particles, as well as through the arrival time distribution of particles in the shower front.

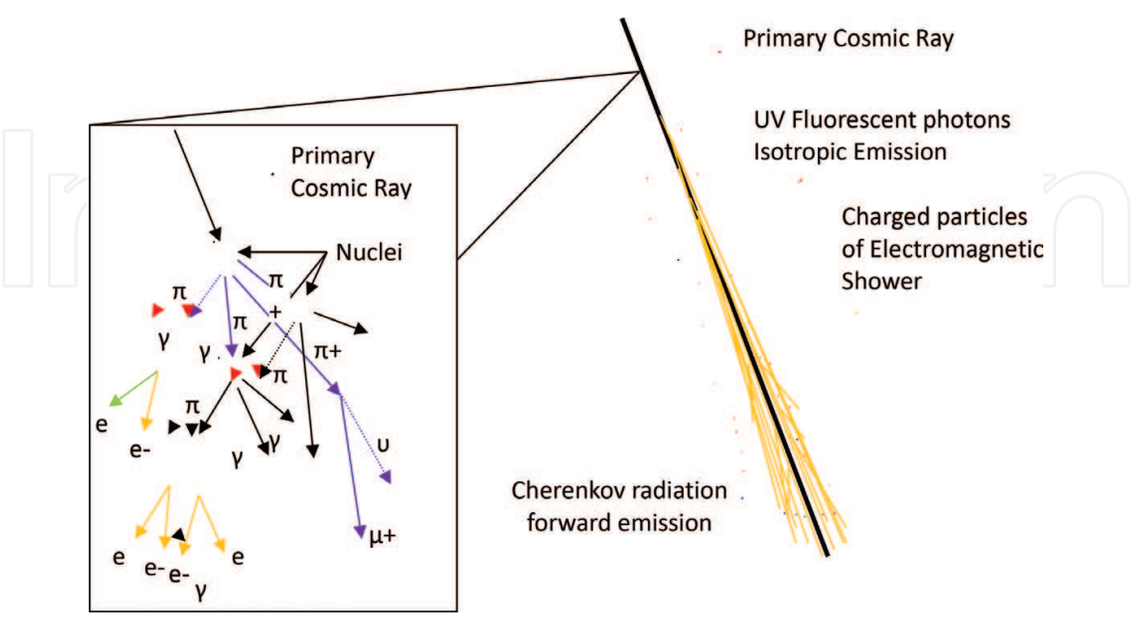


Figure 2. The schematic of the hadronic and electromagnetic components generation in the EAS development.

Particles scatter from the region of the shower axis throughout their development. The shower core effectively acts as a moving point source of both fluorescence photons and particles, which make their way to detectors far from the core. The shower front itself is slightly curved, resembling a cone. Particles far from the core will arrive behind the shower plane due to simple geometry. Electromagnetic component diffuses away from the shower axis throughout the shower development. It is wider in comparison to the hadronic one. Thus, far from the core particles are spread in time, with the time spread roughly proportional to the distance from the axis. This time spread helps to distinguish distant large showers from nearby small showers, and is thus useful in triggering the surface array. The time spread becomes greater as the depth of shower maximum increases.

Fluctuations in shower development distinguish detected signals. One of the most important sources of fluctuations is the depth and characteristics of the first few interactions. Fluctuations in later interactions are averaged over a large number of particles and are not important.

3. The GZK cut-off

We do not know the composition of the UHECRs. However, the set of stable particles as candidates for the UHECRs, which can trespass cosmological distances saving their energy, is quite limited: heavy or light atomic nuclei, photons and neutrinos. No any standard, electromagnetic mechanism can be responsible for photons and neutrinos (as neutral) acceleration. They can only be a product of the interaction of a still higher energy-charged particle. Therefore, in the framework of conventional astrophysics, we believe that light and heavy nuclei are probably the best candidates for the UHECR.

There is experimental evidence that the Universe was created some ~14 billion years ago from some singularity in a giant explosion known as the "Big Bang." Perhaps the most conclusive evidence for the Big Bang is the existence of the isotropic, with Planck distribution T = 2.73 K radiation permeating the entire Universe known as the **c**osmic **m**icrowave **b**ackground (CMB). Shortly after the CMB discovery, Greisen and independently Zatsepin and Kuzmin predicted that at very high energies, the universe should become opaque to light or heavy nuclei due to the following reactions:

$$\begin{aligned} p + \gamma_{CMB} &\rightarrow N + \pi \qquad E_p \geq 1.1 \times 10^{20}\ \text{eV} \\ p + \gamma_{CMB} &\rightarrow \Delta \rightarrow N + \pi \quad E_N \geq 2.5 \times 10^{20}\ \text{eV}, \end{aligned} \tag{1}$$

where E_N is the energy of nucleon being disintegrated.

The energy budget in the center-mass-frame, for an average CMB energy 6.34×10^{-4} eV and protons with energy above 110 EeV, is sufficient for pion-production, during inelastic collisions with CMB photons.

Since in each such inelastic collision, protons leave a large part of their energy (of the order of 13% on average), their energy goes below 10 EeV (EeV = 10^{18} eV) after a few tens of Mpc.

As an example, if the largest energy cosmic ray ever detected 320 EeV (it is more than 50 J) were a proton produced with an initial energy of 10 ZeV (ZeV = 10^{21} eV), the distance of its source should be less than 50 Mpc (**Figure 3**). The same effect is expected for heavy nuclei. Nucleons will be stripped off from the nucleus due to inelastic collisions with most of all infrared background and also with CMB. Thus, the highest energy cosmic rays cannot originate at distances larger than a few tens of Mpc.

3.1. "Bottom-up" production

In order to accelerate charge particles to energies above 10^{20} eV, extremely powerful electromagnetic fields should exist. However, we did not register any stable region with so large potential, which could assure such an extremely energy in a single shot process. One of the earliest theories on the acceleration of cosmic rays proposed was the second order Fermi mechanism [9], where plasma clouds can be treated as a magnetic mirror. A particle trespassing a cloud from the front can be kicked back, like a tennis ball hit by a racket, with energy larger than its initial value. In this way, particles gain energy over many collisions. However, this mechanism is also too slow and too inefficient to account for the observed UHECR.

A more efficient and faster process is acceleration by crossing shock fronts generated in explosive phenomena (first-order Fermi mechanism - $\Delta E > 0$) [10, 11]. However that approach meets difficulties. Let us consider some hypothetical cosmic accelerator. The energy of accelerating

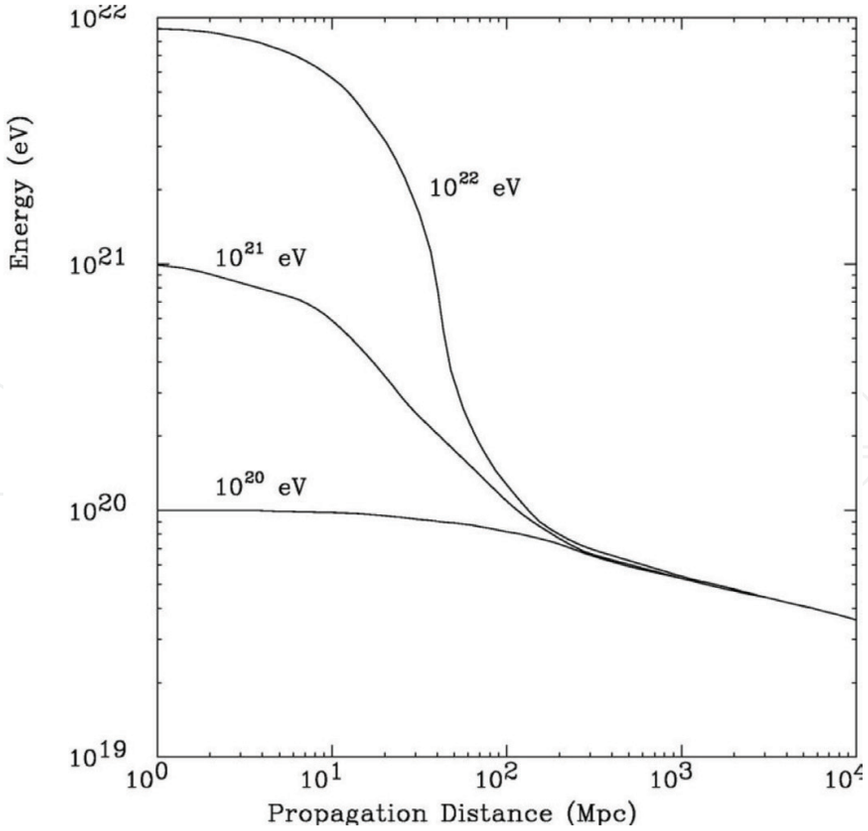


Figure 3. Energy degradation for nucleons as a function of distance to the observer for three different injection energies [8].

particles depends on the value and the size of the magnetic field and is limited by the Larmor radius related to their confinement. If the Larmor radius of the particle exceeds the size of the "accelerator," then the particles escape from it. Candidates of astrophysical object, which possesses such a large BR factor, are given on the Hillas plot [12].

$$E_{max} = qBRc \tag{2}$$

where E_{max} is the maximal energy of particles confined in the magnetic field (J), q is the electric charge (C), B is the induction of the magnetic field (T), R is the radius of the confined trajectory (m), and c is the speed of light (m/s).

Many theories and models propose either sophisticated explanations or require some new physics. One of the models explores ultra-relativistic shock acceleration such as in hot spots of powerful radio galaxies and gamma-ray bursts (GRB) [13]. In the first case, relativistic jets are produced perpendicular to the accretion disk around a supermassive black hole in the central part of an active galactic nucleus. The shock on a jet, several hundred kpc from the central engine, due to collision with the intergalactic medium is considered as being able to accelerate particles up to the highest energies. This hypothesis, however, requires some additional assumptions. Such powerful galaxies are rather rare objects and should be clearly visible in the 50 Mpc distance.

The second model corresponds to the UHECR another astrophysical puzzle: the gamma-ray bursts. The emission of huge amounts of energies (typically a nonnegligible fraction of the mass energy of the Sun) is observed over a very short time (minutes), as gamma rays but with, in some cases, X-ray and optical contributions. Their distribution is cosmological and uniform. GRB happen relatively frequently: 2–3 per day. However, their distribution within the "GZK sphere" rather does not agree with the UHECRs observations. Other objects are also proposed as potential sources of UHECRs, such as rapidly rotating compact objects (young black holes, neutron stars or "magnetars"), which possibly are the sources of the most intense magnetic fields in the universe. The 10^{21} eV energies in such systems are rather difficult to reach.

3.2. "Top-down" production

If we have difficulties to imagine reliable mechanism accelerating particles from low to high energies, let us inverse the situation. Many theories propose top-down mechanism, decay of super-heavy, super-symmetric or Grand Unified Theories (GUT) particles [14]. The only problem is a justification of their existence or their surviving after the Big Bang. They could have survived up to now by some yet unknown mechanism (a very weakly violated quantum number, particles trapped inside huge potential walls called topological defects and released via spontaneous symmetry breaking mechanism). Their decay into a huge number of secondary particles (mainly pions) by hadronization of quark-antiquark pairs could produce the ZeV energies we expect, however they would decay mainly into photons (decays of neutral pions) and neutrinos (decays of charged pions). The current flux limits rule out or strongly disfavor that top-down models can account for a significant part of the observed UHECR

flux. The bounds are reliable as the photon flux limits depend only on the simulation of electromagnetic showers and, hence, are very robust against assumptions on hadronic interactions at very high energy [15]. The photon flux limits have further far-reaching consequences by providing important constraints on theories of quantum gravity involving violation of Lorentz invariance (LIV) [16–19]. And, observing a single photon shower at ultra-high energy would imply very strong limits on another set of parameters of LIV theories [20, 21].

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References

[1] Auger P et al. Etude d'un appareil a grand pouvoir de resolution pour rayons cosmiques. Comptes Rendus. 1938;**206**:1721

[2] Auger P. Extensive Cosmic-Ray Showers. Reviews of Modern Physics. 1939;**11**:288

[3] Linsley J. Evidence for a primary cosmic-ray particle with energy 10^{20} eV. Physical Review Letters. 1963;**10**:146

[4] Zatsepin GT, Kuźmin VA. Upper limit of the spectrum of cosmic rays. JETP Letters. 1966;**4**:78

[5] Greisen K. End to the cosmic-ray spectrum? Physical Review Letters. 1966;**16**:748

[6] Nagano M, Watson AA. Observations and implications of the ultrahigh-energy cosmic rays. Reviews of Modern Physics. 2000;**72**:689

[7] Fomin YA et al. Proc. 20th ICRC, vol. 6; Moscow: USSR; 1987. p. 110

[8] Cronin JW. Summary of the workshop. Nuclear Physics. 1992;**213**:2130. 28B (Proc. Supp.)

[9] Fermi E. On the Origin of the Cosmic Radiation. Physics Review. 1949;**75**:1169

[10] Krymsky GF. A regular mechanism for the acceleration of charged particles on the front of a shock wave. Doklady Akademii Nauk SSSR. 1977;**234**:1306

[11] Blandford RD, Ostriker JP. Particle acceleration by astrophysical shocks. The Astrophysical Journal. 1978;**221**:L29

[12] Hillas AM. The Origin of Ultra-High-Energy Cosmic Rays. Annual Review of Astronomy and Astrophysics. 1984;**22**:425

[13] Meszaros P. Theories of Gamma-Ray Bursts. Astro-ph/0111170

[14] Sigl G. Particle and Astrophysics Aspects of UHECR. Astro-ph/0008364

[15] Risse M, Homola P. Search for ultra-high energy photons using air showers. Modern Physics Letters A. 2007;**A22**:749 astro-ph/0702632

[16] Galaverni M, Sigl G. Lorentz Violation and Ultrahigh-Energy Photons. Physics Review. 2008;**D78**:063003. arXiv:0807.1210

[17] Galaverni M, Sigl G. Lorentz Violation for Photons and Ultra-High Energy Cosmic Rays. Physical Review Letters. 2008;**100**:021102 arXiv:0708.1737. 2015

[18] Liberati S, Maccione L. Quantum gravity phenomenology: achievements and challenges. Journal of Physics Conference Series. 2011;**314**:012007 arXiv:1105.6234

[19] Horvat R, Kekez D, Trampetic J. Spacetime noncommutativity and ultra-high energy cosmic ray experiments. Physics Review. 2011;**D83**:065013 arXiv:1005.3209

[20] Klinkhamer F. Potential sensitivities to Lorentz violation from nonbirefringent modified Maxwell theory of Auger, HESS, and CTA. Physics Review. 2010;**D82**:105024 arXiv:1008.1967

[21] Girelli F, Hinterleitner F, Major S. Loop Quantum Gravity Phenomenology: Linking Loops to Observational Physics. SIGMA. 2012;**8**:098 arXiv:1210.1485

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