Particle physics and the UHECR problem

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Abstract: I review the status of solutions to the ultra-high energy cosmic ray puzzle that involve particle physics beyond the standard model and discuss their signatures and experimental constraints.

1. Introduction

Cosmic Rays are observed in a wide energy range, starting from subGeV energies up to 3×10^{20} eV. Apart from the highest energies, these particles are thought to be accelerated in our Galaxy, most probably by supernova remnants. Since the galactic magnetic field cannot confine and isotropize particles with energies higher than $\sim Z \times 10^{19}$ eV but the arrival directions of ultra-high energy cosmic rays (UHECR) are isotropic on large scales, it is natural to think that UHECRs have an extragalactic origin. Moreover, the acceleration of protons or nuclei up to 2–$3{\times}10^{20}$ eV is difficult to explain with the known astrophysical galactic sources [1].

Energy spectrum: The most prominent signature of extragalactic UHECR is the so called Greisen–Zatsepin–Kuzmin (GZK) cutoff [2]: the energy losses of protons sharply increase at $E_{\rm GZK} \approx 5 \times 10^{19}$ eV, since pion-production on cosmic microwave background (CMB) photons, $p + \gamma_{3K} \to \Delta^* \to N + \pi$, reduces their mean free path by more than two orders of magnitude compared to lower energies. Nuclei exhibit an even more pronounced cutoff at a somewhat higher energy, while photons are absorbed on few Mpc due to pair-production on the radio background. Thus, the UHECR spectrum should dramatically steepen above $E_{\rm GZK}$ for *any* homogeneous distribution of proton or nuclei sources, for more details see Ref. [3]. The question how pronounced the GZK cutoff is depends on the total number N_s of sources [4]: As N_s decreases, the average distance to the nearest sources increases and the GZK cutoff becomes thus more pronounced. The spectrum shown usually corresponds to a continuous distribution of sources, i.e. to the limit $N_s \to \infty$, and hence underestimates the GZK suppression. In Fig. 1, the data from the two experiments with the currently largest exposure, AGASA [5] and HiRes [6], are compared to the expectation

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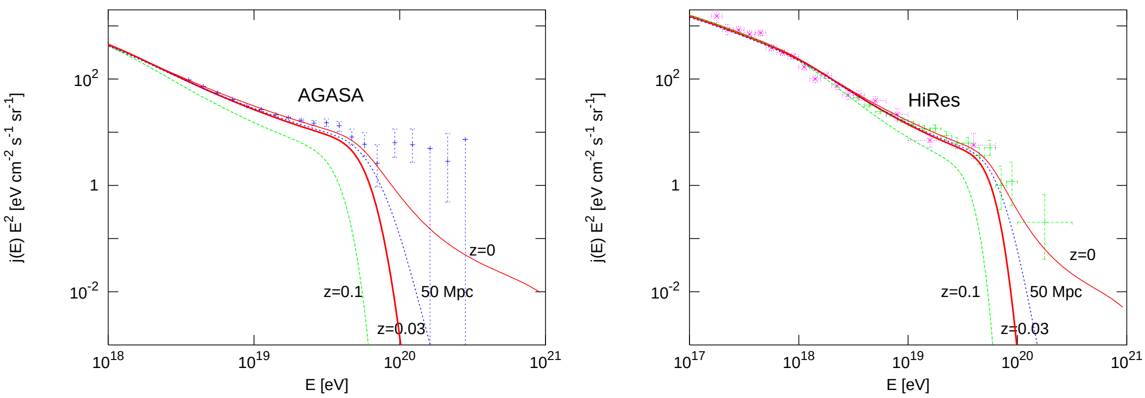

Figure 1: Energy spectrum multiplied by E^2 as observed by AGASA (left) and HiRes (right) together with the spectrum expected from uniformly distributed proton sources with generation spectrum $\propto E^{-2.7}$, maximal energy $E_{\max} = 10^{21}$ eV, and minimal distance of the sources as indicated (from Ref. [4]).

for uniformly distributed proton sources with different minimal distances of the sources. In particular the flux above $E \gtrsim 10^{20}$ eV depends strongly on the used minimal distance of the sources.

Arrival directions and clustering: Constrained simulations of large-scale structure favor small extragalactic magnetic fields. For instance, the deflection of a proton with $E = 4 \times 10^{19}$ eV found in Ref. [7] is less than 2.5° in 95% (70%) of the sky for a propagation distance of 100 Mpc (500 Mpc). Therefore the arrival directions of the UHECRs which are known with several degrees precision should point towards their site of origin. However, no sources of UHECR such as active galactic nuclei (AGN) have been identified within 50 Mpc in the direction of these events. No significant enhancement of the arrival direction of the UHECR above 4×10^{19} eV towards the galactic or supergalactic plane is found, their arrival directions are scattered isotropically on larger scales. However, about 20% of the events are clustered in angular doublets or even triplets; both triplets are found near the supergalactic plane. The chance probability to observe the clustered events in the case of an isotropic distribution of arrival directions was estimated to be < 1% [8]. Since the extragalactic magnetic fields are small, neither magnetic lensing can be used to explain clustering nor strong magnetic fields can prevent the identification of few sources nearby.

The total number N_s of UHECR sources, i.e. including those not detected yet, can be determined by the fraction of clustered events [9]. As N_s decreases, the sources have to become brighter for a fixed UHECR flux and therefore the probability for clustering increases. The analysis of Ref. [10] showed that ~ 400 sources of cosmic rays with $E > 10^{20}$ eV should be inside the GZK volume, compared to ~ 10 GRB sources or ~ 250 AGNs of which only a small fraction is thought to be UHECR sources. However, the statistical uncertainties of this analysis are very large, because of the small number of clustered events observed.

Correlations: Tinyakov and Tkachev found a significant, but currently disputed correlation of UHECR arrival directions with BL Lacs [11]. The BL Lacs which correlate with the UHECRs are located at very large (redshift $z \sim 0.1$) or unknown distances. If it can be shown with an increased data set of UHECRs that this correlation holds at energies $E \gtrsim 6 \times 10^{19}$ eV, then protons that can not reach us from these distances can not explain the UHECR data.

The difficulty to accelerate particles in astrophysical accelerators up to energies $E \gtrsim 10^{20}$ eV, the extension of the UHECR spectrum beyond the GZK cutoff, the missing correlation of the UHECR arrival directions with powerful nearby sources and, more recently, their possible correlation with BL Lacs has prompted many proposals to explain this puzzle that involve particle physics beyond the standard model (SM). In the next sections, the most prominent ones will be discussed and their current status will be reviewed.

2. Neutrinos as primaries or messenger particles

Neutrinos are the only known stable particles that can traverse extragalactic space without attenuation even at energies $E \gtrsim E_{\rm GZK}$, thus avoiding the GZK cutoff. Therefore, it has been speculated that the UHE primaries initiating the observed air showers are not protons, nuclei or photons but neutrinos [12, 13]. However, neutrinos are in the SM deeply penetrating particles producing mainly horizontal not vertical extensive air showers (EAS). Therefore, either one has to postulate new interactions that enhance the UHE neutrino-nucleon cross section by a factor $\sim 10^6$ or neutrinos have to be converted "locally" into hadrons or photons.

2.1 Annihilations on relic neutrinos – Z burst model

In the later scheme [14], UHE neutrinos from distant sources annihilate with relic neutrinos on the Z resonance. The fragmentation products from nearby Z decays are supposed to be the primaries responsible for the EAS above the GZK cutoff. For energies of the primary neutrino of $E_\nu \sim 4 \times 10^{22}$ eV, the mass of the relic neutrino should be $m_\nu = m_Z^2/(2E_\nu) \sim 0.1$ eV which is compatible with neutrino oscillation data. There are, however, severe constraints on this model:

1. Primary protons have to be accelerated to extremely high energies, $E \gtrsim 10^{23}$ eV, in order to produce on a beam-dump in astrophysical sources via $p + \gamma \to$ all or $p + p \to$ all UHE neutrinos as secondaries. The photons which are unavoidably produced in the same reactions have to be hidden inside the source, otherwise the diffuse MeV-GeV photon background—constrained by EGRET observations [15]—is overproduced. No astrophysical accelerator of this kind is known. (As possible way-out, the authors of Ref. [16] combined the Z burst model and superheavy dark matter (SHDM): they suggested that SHDM particles decay exclusively to neutrinos thereby avoiding both the acceleration problem and photon production in astrophysical sources. However, higher-order electroweak corrections to the tree-level process $X \to \bar{\nu}\nu$ give rise to an electroweak cascade transferring around 20% of the initial energy to photons and electrons [17]. Thus the EGRET limit can be applied also to this variant of the Z burst model.)

2. A combination of the WMAP observations of the CMBR fluctuation and the 2dF-GRS galaxy count limits the sum of all neutrino masses as $\sum_i m_{\nu_i} \lesssim 1.0$ eV at 95% CL

(cf., e.g., Ref. [18]). For such small masses, the overdensity δ of neutrinos on our Local Group of galaxies is also small, $\delta \lesssim 10$, on a length scale of 1 Mpc [19]. Therefore one expects a rather pronounced GZK cutoff and needs very large neutrino fluxes.

3. Combining the better limit on the neutrino masses with new experimental limits on the UHE neutrino flux from FORTE [20] and GLUE [21] and an improved limit [22] on the diffuse MeV-GeV photon background from EGRET excludes the Z burst model even for the unrealistic case of an only neutrino emitting source [23]. In Fig. 2, the expected fluxes are shown for $m_\nu = 0.33$ eV; for all other cases, the conflict is more severe.

2.2 Strongly interacting neutrinos

Most models introducing new physics at a scale M to produce large cross sections for UHE neutrinos fail because experiments generally constrain M to be larger than the weak scale, $M \gtrsim m_Z$, and unitarity limits cross sections to be $O(\sigma_{\rm tot}) \lesssim 1/M^2 \lesssim 1/m_Z^2$. String theories with large extra dimensions [24] are different in this respect: If the SM particles are confined to the usual $3+1$-dimensional space and only gravity propagates in the higher dimensions, the compactification radius R of the large extra dimensions can be large, corresponding to a *small* scale $1/R$ of new physics. From a four-dimensional point of view the higher dimensional graviton in these theories appears as an infinite tower of Kaluza-Klein (KK) excitations with mass squared $m_n^2 = n^2/R^2$. Since the weakness of the gravitational interaction is partially compensated by the large number of KK states and cross sections of reactions mediated by spin 2 particles are increasing rapidly with energy, it has been argued in Refs. [13] that neutrinos could initiate the observed vertical showers at the highest energies. However, the naively found growth of $\sigma_{\nu N} \propto s^2$ violates unitarity and an unitarization procedure has to applied. The unitarized cross section is roughly three orders of magnitude too small, and also the energy transferred in each interaction is not sufficient to explain the observed properties of EAS [25]. For small enough impact parameters in the neutrino-nucleon collision, black hole (BH) production becomes important [26]. Using in a simplistic picture a geometric cross section for BH production, $\sigma_{\rm BH} \sim \pi R_S^2$ where R_S is the Schwarzschild radius of a BH with mass equal to the center-of-mass energy of the collision on the parton level, the cross section has roughly the same size as the one for KK scattering and is thus also too small [27].

More recently, Ref. [28] speculated that the neutrino-nucleon cross section above $E \sim 10^{18}$ eV is enhanced by a factor 10^5 by non-perturbative electroweak instanton contributions. The numerical calculations of Ref. [29] found that instanton induced processes keep much heavier suppressed than suggested by [28]. However, it is instructive to ask if strongly interacting neutrinos can mimic at all in this model extensive air showers initiated by protons. At $E \leq 10^{20}$ eV, the cross section is bounded by $\sigma_{\nu N} \leq 3$ mbarn [30]. Thus the first interaction point of a neutrino would be at ≥ 2400 g/cm^2 instead at 40 g/cm^2 for a proton, while the shower maximum would be around ≥ 3200 g/cm^2. The latter value corresponds to a zenith angle of more than 70° and, consequently, the fraction of nearly horizontal showers in this model would be much higher than observed.

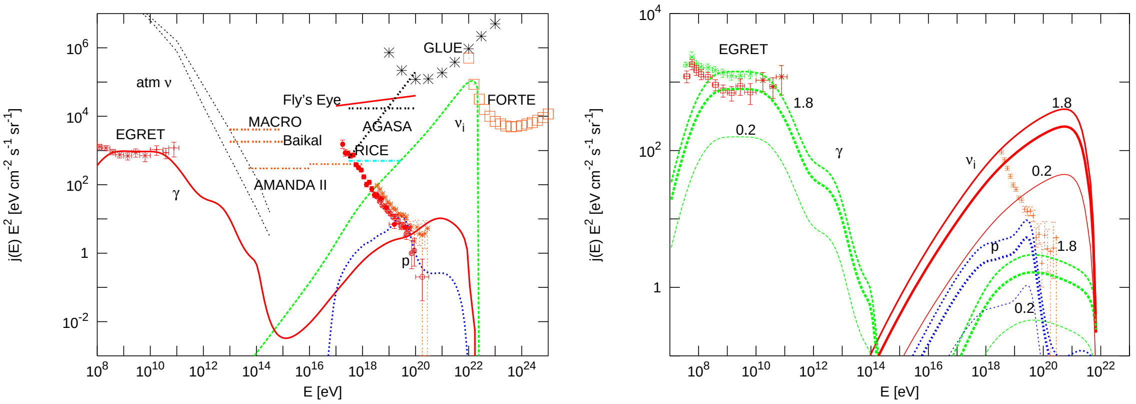

Figure 2: Left panel: Expected fluxes in the Z burst model for an optimal choice of free parameters together with various limits for UHE neutrinos fluxes and the new EGRET limit. Right panel: Proton, photon and neutrino fluxes in a TD model with $M_X = 2 \times 10^{13}$ GeV, evolution $\dot{n}_X \propto t^{-3}$ and continous distribution of sources. The fraction MeV–GeV photons from these sources contribute to the diffuse photon background is choosen as 0.2, 1, and 1.8; both figures from Ref. [23].

3. Top–down models

Top–down model is a generic name for all proposals in which the observed UHECR primaries are produced as decay products of some superheavy particles X with mass $m_X \gtrsim 10^{12}$ GeV. These X particles can be either metastable or be emitted by topological defects at the present epoch.

3.1 Topological defects

Topological defects (TD) [31] such as (superconducting) cosmic strings, monopoles, and hybrid defects can be effectively produced in non-thermal phase transitions during the preheating stage [32]. Therefore the presence of TDs is not in conflict with an inflationary period of the early Universe. They can naturally produce particles with high enough energies but have problems to produce a large enough flux of UHE primaries.

The main observational constraint for topological defect models is the EGRET limit. Another general reason for the low fluxes is the large distance between TDs, which is often comparable to the Hubble radius. Then the flux of UHE particles is either exponentially suppressed or strongly anisotropic if a TD is by chance nearby. An exception is the necklace model where the distance between necklaces can be as small as 10 kpc [33]. Figure 2 shows the proton, photon and neutrino fluxes for a TD model with $M_X = 2 \times 10^{13}$ GeV, injection rate $\dot{n}_X \propto t^{-3}$ (as e.g. in the necklace model) and continous distribution of sources. The fraction MeV–GeV photons from this model contribute to the diffuse photon background is varied between 0.2, 1, and 1.8. Similiar to the case of the Z burst model, the new EGRET limit (in red) allows only a sub-dominant contribution to the UHECR flux from necklaces.

3.2 Superheavy dark matter

Superheavy metastable relic particles (SHDM) were proposed in Refs. [34, 35] as UHECR source. They constitute (part of) the CDM and, consequently, their abundance in the galactic halo is enhanced by a factor $\sim 5 \times 10^4$ above their extragalactic abundance. Therefore, the proton and photon flux is dominated by the halo component and the GZK cutoff is avoided, as was pointed out in Ref. [34]. The quotient $r_X = \Omega_X(t_0/\tau_X)$ of relic abundance Ω_X and lifetime τ_X of the X particle is fixed by the UHECR flux, $r_X \sim 10^{-11}$.

There exist several plausible non-equilibrium production mechanisms. The most promising one is the gravitational production of the X particles by the non-adiabatic change of the scale factor of the Universe at the end of inflation, during the transition from the de-Sitter to the radiation dominated phase [36]. In this scenario, the gravitational coupling of the X-field to the background metric yields the present abundance $\Omega_0 \sim 1$ for $M_X \sim 10^{13}$ GeV, independent of any specific particle physics model. Other mechanisms proposed are thermal production during reheating, production through inflaton decay at the preheating phase, or through the decay of hybrid defects.

The lifetime of the superheavy particle has to be in the range 10^{17} s $\lesssim \tau_X \lesssim 10^{28}$ s, i.e. longer or much longer than the age of the Universe. Therefore it is an obvious question to ask if such an extremely small decay rate can be obtained without fine-tuning. A well-known example of how metastability can be achieved is the proton: in the standard model B–L is a conserved global symmetry, and the proton can decay only via non-renormalizable operators. Similarly, the X particle could be protected by a new global symmetry which is only broken by higher-dimensional operators suppressed by M^d, where for instance $M \sim M_{\rm Pl}$ and $d \geq 7$ is possible. The case of discrete gauged symmetries has been studied in detail in Refs. [37]. Another possibility is that the global symmetry is broken only non-perturbatively, either by wormhole [34] or instanton [35] effects. Then an exponential suppression of the decay process is expected and lifetimes $\tau_X \gg t_0$ can be naturally achieved.

An example of a SHDM particle in a semi-realistic particle physics model is the crypton [38]. Cryptons are boundstates from a strongly interacting hidden sector of string/M theory. Their mass is determined by the non-perturbative dynamics of this sector and, typically, they decay only though high-dimensional operators. For example, flipped SU(5) motivated by string theory contains boundstates with mass $\sim 10^{12}$ GeV and $\tau \sim 10^{15}$ yr [39]. Other viable candidates suggested by string theory were discussed in Ref. [40].

3.3 Signatures of top-down models

Superheavy dark matter has several clear signatures: 1. No GZK cutoff, instead a flat spectrum (compared to astrophysical sources) up to $m_X/2$. 2. Large neutrino and photon fluxes compared to the proton flux. 3. Galactic anisotropy. 4. If R parity is conserved, the lightest supersymmetric particle (LSP) is an additional UHE primary [41]. The observed small-scale clustering of the UHECR arrival directions gives possibly additional constraints.

1. Spectral shape: The fragmentation spectra of superheavy particles calculated by different methods and different groups agree well, for a comparison of different results see [33]. This allows to consider the spectral shape as a signature of models with decays or annihilations of superheavy particles. The predicted spectrum of SHDM, $dN/dE \propto E^{-1.9}$, cannot fit the observed UHECR spectrum at energies $E \leq (6\text{–}8) \times 10^{19}$ eV. Thus only events at $E \gtrsim (6\text{–}8) \times 10^{19}$ eV, and most notably the AGASA excess at these energies,

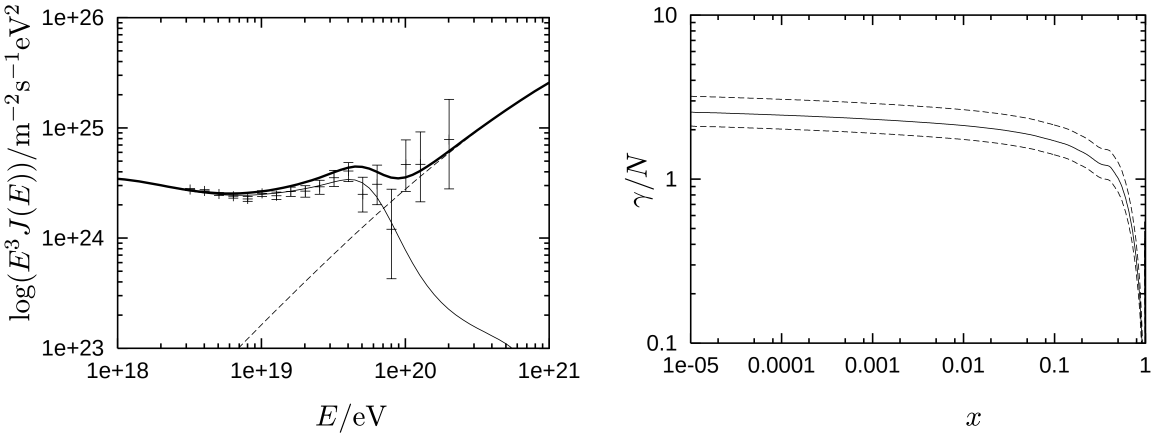

Figure 3: Left panel: Comparison of the UHECR flux in the SHDM model with the AGASA data, photons from SHDM decays (dashed line), spectrum of extragalactic protons in the non-evolutionary model of Ref. [42] and the sum of these two spectra shown by the thick curve. Right panel: Photon/proton ratio as function of x, the band illustrates the uncertainty due to hadronization process; both figures from Ref. [33].

can be explained in this model. A two-component fit from Ref. [33] using protons from uniformly, continuously distributed extragalactic astrophysical sources and photons from SHDM is shown in Fig. 3 together with the experimental data from AGASA. Note that the maximal mass of the X particle is constrained by the non-observation of events above $E > 2\times10^{20}$ eV: requiring that the integral flux above $E > 2\times10^{20}$ eV does not corresponds to more than 3 events in AGASA results in the bound $M_X \lesssim 4 \times 10^{13}$ GeV.

2. Chemical composition: Since at the end of the QCD cascade quarks combine more easily to mesons than to baryons, the main component of the UHE flux are neutrinos and photons from pion decay. Therefore, a robust prediction of this model is photon dominance with a photon/nucleon ratio of $\gamma/N \simeq 2$–3, becoming smaller at the largest $x = 2E/M_X$. This ratio is shown in Fig. 3 as function of x together with a band illustrating the uncertainty due to the hadronization process [33].

The muon content of photon induced EAS at $E > 1 \times 10^{20}$ eV is high, but lower by a factor 5–10 than in hadronic showers [43]. It has been recently measured in a sub-array of AGASA [44]. From eleven events at $E > 1 \times 10^{20}$ eV, the muon density was measured in six. In two of them with energies about 1×10^{20} eV, the muon density is almost twice higher than predicted for gamma-induced EAS. The muon content of the remaining four EAS marginally agrees with that predicted for gamma-induced showers. The contribution of extragalactic protons for these events is negligible, and the fraction of protons in the total flux can be estimated as $0.25 \leq p/\mathrm{tot} \leq 0.33$. This fraction gives a considerable contribution to the probability of observing four showers with slightly increased muon content. Not restricting severly the SHDM model, the AGASA events give no evidence in favor of it.

Reference [45] finds analyzing the Haverah Park data that above 4×10^{19} eV less than 55% of the UHE primaries can be photons. Since protons from "normal" astrophysical sources dominate the flux up to $(6-8) \times 10^{19}$ eV and the flux is steeply falling with energy, this results does not constrain the SHDM models.

AUGER [46] has great potential to distinguish between photon and proton induced EAS through the simultaneous observation of UHECR events in fluorescent light and with water Cherenkov detectors: while for a proton primary both methods should give a consistent determination of the primary energy, the ground array should systematically underestimate the energy of a photon primary. Moreover, the interaction of the photon with the geomagnetic field should induce an anisotropy in the flux.

3. Galactic anisotropy: The UHECR flux from SHDM should show a galactic anisotropy [47], because the Sun is not in the center of the Galaxy. The degree of this anisotropy depends on how strong the CDM is concentrated near the galactic center – a question under debate. Since experiments in the northern hemisphere do not see the Galactic center, they are not very sensitive to a possible anisotropy of arrival directions of UHECR from SHDM. In contrast, the Galactic center was visible for the old Australian SUGAR experiment [48]. The compatibility of the SHDM hypothesis with the SUGAR data was discussed recently in Refs. [49, 50]. In Ref. [49], the expected arrival direction distribution for a two-component energy spectrum of UHECRs consisting of protons from uniformly distributed, astrophysical sources and the fragmentation products of SHDM calculated in SUSY-QCD was compared to the data of the SUGAR experiment using a Kolmogorov-Smirnov test. Depending on the details of the dark-matter profile and of the composition of the two-components in the UHECR spectrum, the arrival directions measured by the SUGAR array have a probability of $\sim$ 5–20% to be consistent with the SHDM model. Also in the case of the galactic anisotropy, we have to wait for a definite answer for the first results of the AUGER experiment.

4. LSP as UHE primary: An experimentally challenging but theoretically very clean signal both for supersymmetry and for top-down models would be the detection of the LSP as an UHE primary [41, 53]. A decaying supermassive X particle initiates a particle cascade consisting mainly of gluons and light quarks but also of gluinos, squarks and even only electroweakly interacting particles for virtualities $Q^2 \gg m_W^2, M_{\rm SUSY}^2$. When Q^2 reaches $M_{\rm SUSY}^2$, the probability for further branching of the supersymmetric particles goes to zero and their decays produce eventually UHE LSPs. Possible signatures of UHE LPSs are a Glashow-like resonance at 10^9 GeV M_e/TeV, where M_e is the selectron mass, and up-going showers for energies where the Earth is opaque to neutrinos [41, 51].

Clustering: The clustering of UHECR arrival direction could be explained in the SHDM model by the clumpiness of the DM [52]. Although a clumpy substructure of CDM is found both in analytical calculations and numerical simulations, it is currently very uncertain how strong CDM is clumped. Therefore the observed clustering is difficult to use as an experimental constraint for SHDM.

The signatures of TD models are not so clear-cut, especially if TD contribute only a minor part to the UHECR flux. The high photon/nucleon ratio at generation can be masked by the strong absorption of UHE photons, but is still higher than expected from astrophysical sources. All TD models predict large fluxes of UHE neutrinos. The GZK cutoff is less pronounced for TDs than for astrophysical sources, because of the flatter generation spectrum of the UHE particles. No clustering is in TD models expected, because TD emit UHE particles in singular events. Finally, the detection of UHE LSPs is simpler in TD models than for SHDM, because the event numbers are higher for the same UHECR flux.

4. New primaries

Any new primary invented to explain the observed UHECR events needs a cross section with nucleons close to the ones typical for hadrons and a large energy transfer in each interaction in order to mimic the observed properties of EAS. This requires a rather light particle with strong or at least electromagnetic interactions. On the other hand, the GZK cutoff for the new primary should be shifted at least to $\gtrsim 10^{20}$ eV. This can be achieved by requiring that the new primary is heavier than a nucleon. Combining these two requirements, Ref. [54] found that a new hadron fulfilling both requirements should have a mass in the range 2 GeV$\lesssim m \lesssim 5$ GeV. Reference [4] discussed the question if such particles can be produced in astrophysical sources without violating bounds like the EGRET limit. The authors concluded the production of a new hadronic primary is only possible in collisions on background photons and for masses smaller than $\lesssim 3$ GeV. Thus there is in principle a mass window around 2–3 GeV where a new hadron could be a viable UHECR primary. But is there any candidate for such a light hadron and a life-time above ~ 1 year, needed to survive its journey?

Until recently, the most discussed possibility of this kind was a gluino as the LSP or next-to-LSP. However, the measurements of electroweak observables at LEPI were used in Ref. [55] to constrain production processes of new particles, and a light gluino with mass below 6.3 GeV was excluded at 95% CL. The only remaining possibility in the minimal supersymmetric SM for a strongly interacting LSP is a light sbottom quark – but it is very unlikely that it remained undetected in (accelerator) experiments, if it is stable.

A similar argumentation can be used against other, non-hadronic primaries. Both the characteristics of EAS and the requirement of efficient production in astrophysical beam-dumps require rather large couplings of any primary to nucleons and photons. Together with the bound on its lifetime, $\gtrsim 1$ year, this makes it rather implausible that such a particle has not been detected yet.

5. Violation of Lorentz invariance

Planck introduced already more than 100 years ago as fundamental length scale $\ell_{\rm Pl} \equiv \sqrt{hG/c^3} \sim 10^{-33}$ cm. Today, it is still an open question if $\ell_{\rm Pl}$ plays just the role of a coupling constant for gravity or if for smaller (wave-) lengths the properties of space-time are changed. If one consider e.g. the case that $l_{\rm Pl}$ sets a minimum wavelength in a frame-independent way, it is clear that special relativity has to be modified: Lorentz symmetry has to be either broken (a preferred inertial system exists) or “deformed.” In the latter case, the usual Lorentz transformations are the limit $l_{\rm Pl} \to 0$ of more general transformations, similar as Galilei transformations are obtained in the limit $c \to 0$ from

Lorentz transformations. Other schemes in which modifications of Lorentz invariance are expected even in a purely four-dimensional frame-work are discrete (e.g. from loop gravity) or noncommutative space-times. Yet another possibility is that in topological non-trivial space-times, as suggested by "space-time foam" à la Wheeler, chiral gauge theories have a CPT anomaly which induces violation of Lorentz invariance [56]. Finally, it could be that Lorentz invariance is violated only from our (3+1)-dimensional point of view, while the underlying higher-dimensional theory respects Lorentz symmetry. In this scheme, the slightly different localization of different SM particles on our (3+1)-dimensional brane would induce modifications of Lorentz invariance.

Lorentz invariance violation can be implemented in an effective way by allowing different maximal velocities c_i for different particle species [57]. The two most important consequences are changed dispersion relations [58], e.g. an energy dependent speed v of (nearly) massless particles like photons and neutrinos, and changed kinematical thresholds in scattering and decay processes. For signals with a very short duration and at cosmological distance like gamma-ray-bursts, the energy dependence of v could result in a detectable shift in the arrival time of specific burst patterns at different frequencies [59].

The change of kinematical thresholds in scattering processes could have a dramatic impact on UHECRs if the threshold of the GZK reaction $p+\gamma_{3K} \to N+\pi$ would be shifted to higher energies. Apart from the extension of the UHECR spectrum beyond $E_{\rm GZK}$, the non-observation of GZK neutrinos would be a characteristic of this solution to the UHECR puzzle. Moreover, Ref. [60] suggested as additional signature two sharp transitions in the composition of UHECRs: Above a certain threshold energy E_1, the neutron becomes stable and protons as primaries would be replaced by a neutron/proton mixture. Above a second threshold $E_2 > E_1$, protons decay and only neutrons would be UHECR primaries. Reason for this mutation of the primary composition are the changed dispersion relations of nucleons that above E_1 prohibit normal beta decay and above $E_2 > E_1$ allow the inverse beta decay $p \to n + e^+ + \nu_e$. This change in the UHECR composition could be detected via a (non-) deflection of the neutron/proton primaries in the galactic magnetic field, if the UHECR correlate with astrophysical sources.

6. Conclusions

Many explanations for the observation of UHECRs beyond the GZK cutoff have been proposed during the last two decades that involve particle physics beyond the standard model. The degree to which they solve the difficulties of the conventional, "bottom-up" scenario is very different: while the Z burst model even aggravates the acceleration problem, top-down models circumvent this issue by construction and, in the particular case of SHDM, predict even no GZK cutoff at all. The latter can be also the case if Lorentz invariance is violated.

The combination of results from low-energy gamma-ray and UHE neutrinos experiments allows already now to severely constrain TD and Z burst models. In the near future, the Pierre Auger Observatory will not only answer the question up to which energies the UHECR energy spectrum extends, but also check conclusively the two key signatures of

SHDM, galactic anisotropy and photon dominance. If there is not a considerable fraction of photon primaries at the highest energies, correlations with sources at cosmological distance can be established, and the spectrum extends well-beyond the GZK cutoff, then Lorentz invariance violation is the leading explanation for the UHECR puzzle. If only the two first conditions are found to be true, but the UHECR spectrum is close to the one measured by HiRes, then bottom-up scenarios are a sufficient explanation for the data.

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