Available online at www.sciencedirect.com
SCIENCE @ DIRECT®
ELSEVIER
C. R. Physique 5 (2004) 441–452
COMPTES RENDUS PHYSIQUE

Ultimate energy particles in the Universe/Particules d'énergies ultimes dans l'Univers

Status of particle physics solutions to the UHECR puzzle

Michael Kachelrieß

Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany

Available online 5 May 2004

Presented by Pierre Encrenaz

Abstract

The status of solutions to the ultra-high energy cosmic ray puzzle that involve particle physics beyond the standard model is reviewed. Signatures and experimental constraints are discussed for most proposals such as the Z burst model and topological defects (both allowed only as subdominant contributions), supermassive dark matter (no positive evidence from its key signatures galactic anisotropy and photon dominance), strongly interacting neutrinos or new primaries (no viable models known), and violation of Lorentz invariance (viable). ***To cite this article: M. Kachelrieß, C. R. Physique 5 (2004).***

Résumé

Solutions de l'énigme des rayons cosmiques ultra-énergétiques en physique des particules. Nous présentons une revue des solutions proposées en réponse à l'énigme des rayons cosmiques ultra-énergétiques, faisant intervenir la physique des particules au-delà du Modèle Standard. Nous résumons les signatures et les contraintes expérimentales pour la plupart de ces modèles tels que : la désintégration du Z et les défauts topologiques (tous deux envisageables seulement en tant que modèles sub-dominants), matière noire supermassive (qu'aucune indication, telle l'anisotropie galactique et production dominante de photons, ne favorise), les neutrinos à interaction forte ou des particules nouvelles (pas de modèles viables connus), et la violation de l'invariance de Lorentz (viable). ***Pour citer cet article : M. Kachelrieß, C. R. Physique 5 (2004).***

Keywords: GZK cutoff; UHE neutrinos; Z-burst model; Topological defects; Supermassive Dark Matter; Lorentz invariance violation

Mots-clés : Coupure GZK ; Neutrinos ultra-énergétiques ; Modèle de désintégration du Z ; Défauts topologiques ; Matière Noire supermassive ; Invariance de Lorentz (violation)

1. Introduction

Cosmic Rays are observed in an energy range extending over more than eleven decades, 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 (UHECRs) 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].

1.1. Energy spectrum and propagation effects

The most prominent signature of extragalactic UHECR is the so called Greisen–Zatsepin–Kuzmin (GZK) cutoff [2]: the energy losses of protons increase sharply at $E_{\mathrm{GZK}} \approx 5 \times 10^{19}$ eV, since pion-production on cosmic microwave background

E-mail address: mika@mppmu.mpg.de (M. Kachelrieß).

1631-0705/$ – see front matter © 2004 Published by Elsevier SAS on behalf of Académie des sciences.
doi:10.1016/j.crhy.2004.03.015

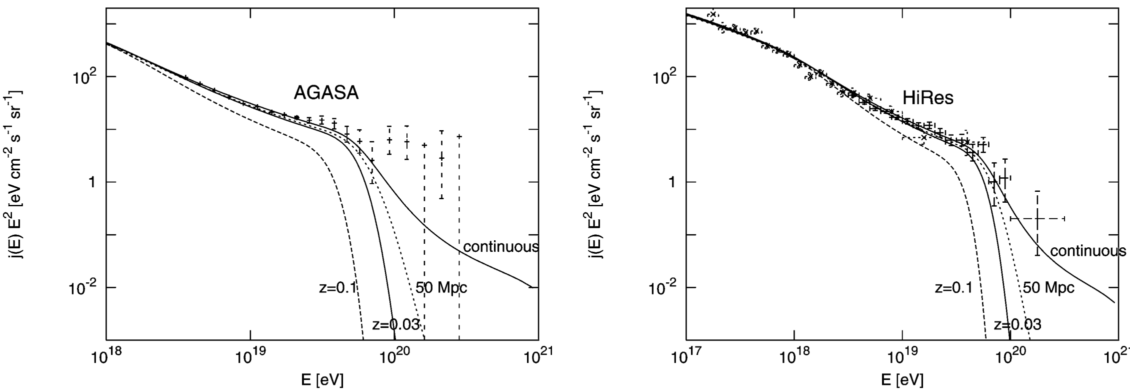


Fig. 1. Energy spectrum multiplied by E^2 with error bars as observed by AGASA (left) and HiRes (right) together with the spectrum expected from uniformly distributed proton sources with generation spectrum $\propto E^{-2.7}$, maximal energy $E_{\max} = 10^{21}$ eV, and minimal distance of the sources as indicated (from [6], with permission of the American Physical Society).

(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 over a few Mpc due to pair-production on the radio background. Thus, the UHECR spectrum should dramatically steepen above E_{GZK} for *any* homogeneous distribution of proton or nuclei sources, for more details see [3]. How pronounced the GZK cutoff is depends not only on the shape and maximal energy of the injection spectrum but also on the total number N_s of sources: the average distance to the nearest sources increases for decreasing N_s, 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 [4] and HiRes [5], are compared to the expectation for uniformly distributed proton sources with different minimal distance to the sources [6]. In particular the flux above $E \gtrsim 10^{20}$ eV depends strongly on the minimal distance used. While the AGASA experiment has detected a significant excess of events above 10^{20} eV compared to the prediction for a continuous source distribution, the flux measured by HiRes is consistent with this assumption. But if there are no sources able to accelerate to the highest energies within less than 50 Mpc, then even the low flux observed by HiRes is difficult to explain.

Another important consequence of the scattering of UHE primaries, especially of photons, on background photons is the cascade or EGRET limit [7]: High energy electrons and photons scattering on CMB photons initiate electromagnetic cascades until their energy is accumulated as gamma radiation in the MeV–GeV region. The observation of this diffuse background by the EGRET experiment [8] limits thereby the injection of UHE particles. Following the new calculation of the Galactic foreground of [9], the limit $\omega_{\mathrm{cas}} \leqslant \omega_{\mathrm{obs}} = 2 \times 10^{-6}$ eV/cm^3 results for any diffuse injection of electromagnetic energy during the history of the Universe. As we will see later, this is a severe constraint for the Z burst and most topological defect models.

1.2. Arrival directions and clustering [10]

No significant enhancement of the arrival directions of the UHECRs above 4×10^{19} eV towards the galactic or supergalactic plane is found; their arrival directions are scattered isotropically on scales larger than 5 degrees. 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 $<1\%$ [11]. Burgett and O'Malley [12] pointed out that clustering in the AGASA data is seen only for $E < 6 \times 10^{19}$ eV, while above this energy the arrival directions are consistent with the expectation for an isotropic distribution. This could be, together with the shape of the AGASA energy spectrum, a hint for a new component in the UHECR flux above $E \gtrsim 6 \times 10^{19}$ eV.

There are two possible interpretations if clustering is confirmed by future experiments. Either the extragalactic magnetic fields are small, UHE protons are propagating nearly undeflected and experiments start to see several events of the same point source, or the extragalactic magnetic fields are close to the upper bound from Faraday rotation measurements. In the latter case, deflections would prevent the identification of few sources nearby and magnetic lensing can be used to explain clustering. Experimentally, the two options can be distinguished by an (auto-) correlation analysis of the arrival directions. Firstly, the shape of the angular autocorrelation function is determined for point sources by the angular resolution function of the experiment, while a broader peak around zero is expected for magnetic lensing. Although the significance of the autocorrelation in the AGASA data is maximal choosing as bin size 2.5°, i.e., the angular resolution of AGASA, the data set is too sparse to disfavour thereby clearly magnetic lensing. Secondly, a correlation analysis of the UHECR arrival directions with possible candidate sources should reveal their true sources if the deflection through magnetic fields is small enough (see below).

Theoretically, the magnitude and structure of extragalactic magnetic fields is rather uncertain. On the one hand, a recent constrained simulation [13] of large-scale structures favors small extragalactic magnetic fields. The deflection of a proton with, e.g., $E = 4 \times 10^{19}$ eV found in [13] is less than 2.5° in 95% (70%) of the sky for a propagation distance of 100 Mpc (500 Mpc). Sigl et al. [14], on the other hand, point out that sources tend to sit in regions of high density and strong magnetic fields, an effect not taken into account in [13]. As a consequence, the deflection angles found in [14] are much larger, implying that source identification may be not possible in their scenario.

The total number N_s of UHECR sources, i.e., including those not detected yet, can be determined by the fraction of clustered events [15]. As N_s decreases, the sources have to become brighter for a fixed UHECR flux and therefore the probability for clustering increases. The analysis given in [16], assuming small magnetic fields, 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.

1.3. Correlations

Tinyakov and Tkachev found a significant, but currently disputed correlation of UHECR arrival directions with BL Lacs [17]. 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 cannot reach us from these distances cannot explain the UHECR data.

The difficulty of accelerating 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 of these 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 $E \gtrsim E_{\mathrm{GZK}}$, 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 [18,19]. 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 [20], UHE neutrinos from distant sources annihilate with relic neutrinos on the Z resonance. The fragmentation products from nearby Z decays, i.e., mainly photons, are supposed to be the primaries responsible for the EAS above the GZK cutoff. For energies of the primary neutrino of $E_0 \sim 4 \times 10^{22}$ eV, the mass of the relic neutrino should be $m_\nu = m_Z^2/(2E_0) \sim 0.1$ eV to scatter resonantly, a value compatible with atmospheric neutrino oscillation data. There are, however, severe constraints on this model.

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 is overproduced. No astrophysical accelerator of this kind is known. Another problem is the extreme luminosity of the astrophysical sources needed in this model [21]: from the required flux of resonant neutrinos $I_\nu(E_0)$ one can estimate the neutrino energy density ω_ν as $\omega_\nu \approx (2.4 - 3.6) \times 10^{-13} m_{\mathrm{eV}}^{-0.5}$ erg/cm^3. The resulting neutrino luminosity of a source, $L_\nu \sim \omega_\nu/(n_s t_0)$, where n_s is the source density and t_0 the age of the Universe, is unacceptably high – $(8 - 12) \times 10^{44}$ erg/s, if the sources are normal galaxies, and $(8 - 12) \times 10^{46}$ erg/s in the case of Seyfert galaxies.

As possible way-out, the authors of [22] 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 corrections to the tree-level process $X \to \bar{\nu}\nu$ give rise to an electroweak cascade

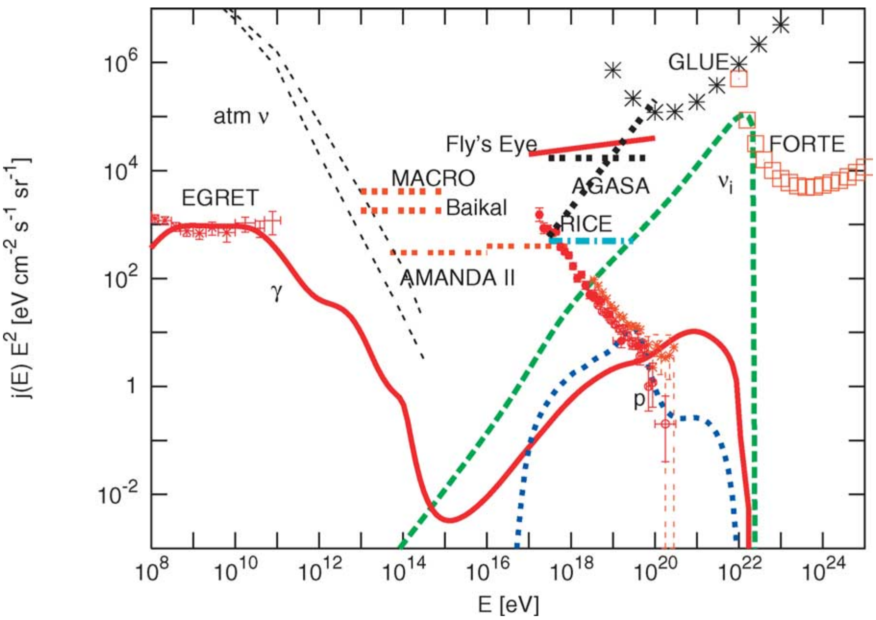


Fig. 2. Expected fluxes in the Z burst model for an optimal choice of free parameters together with various limits for UHE neutrinos fluxes and the new EGRET limit; from [25].

transferring around 20% of the initial energy to photons and electrons [21]. Thus the EGRET limit can be applied also to this variant of the Z burst model.

A combination of the WMAP observations of the CMBR fluctuations and the 2dFGRS 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., Hannestad [23]). For such small masses, the overdensity δ of neutrinos in our Local Group of galaxies is also small, $\delta \lesssim 10$, on a length scale of 1 Mpc [24]. Therefore one expects a rather pronounced GZK cutoff, needs very large neutrino fluxes and has problems with the cascade limit. The latter point can be understood from a simple estimate: the energy density dumped into electromagnetic cascades by the Z burst mechanism during the life-time of the Universe is

$$\omega_{\text{cas}} \sim \frac{1}{2} f_\pi E_0 \dot{n}_Z t_0, \tag{1}$$

where $f_\pi \sim 0.7$ is the branching ratio of Z decays into pions and $\dot{n}_Z$ is the rate of $\bar{\nu}\nu \to Z$ scatterings. The cascade limit, $\omega_{\text{cas}} \leqslant \omega_{\text{obs}}$, translates into a bound on $\dot{n}_Z$, and therefore, on the photon flux

$$I_\gamma(E) = \frac{1}{4\pi} \dot{n}_Z R_\gamma(E) D_\gamma(x)/E_0 \leqslant \frac{\omega_{\text{obs}}}{2\pi f_\pi E_0^2 t_0} R_\gamma(E) D_\gamma(x). \tag{2}$$

Here, $R_\gamma(E)$ is the attenuation length of photons and $D_\gamma(x)$ with $x = 2E/m_Z$ is the differential energy spectrum per Z decay. Estimating $I_\gamma(E)$ at $E' = 10^{20}$ eV and inserting $R_\gamma(E') \sim 10^{25}$ cm and $D(x') \sim 20$ results in the bound $I_\gamma(E') \lesssim 10^{-33}$ sr^{-1} GeV^{-1} cm^{-2} s^{-1}, while the observed UHECR flux is 1–2 orders of magnitude higher.

This discrepancy is weakened assuming, e.g., that the Z burst mechanism started operation only recently and by a more accurate analysis. Semikov and Sigl [25] calculated numerically the expected fluxes in the Z burst model and compared them to the improved limit [9] from EGRET and new experimental limits on the UHE neutrino flux from FORTE [26] and GLUE [27]. Their results are shown in Fig. 2 for $m_\nu = 0.33$ eV, the unrealistic case of an only neutrino emitting source, and an optimal choice of free parameters; 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 $O(\sigma_{\text{tot}}) \lesssim 1/M^2 \lesssim 1/m_Z^2$. String theories with large extra dimensions [28] 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 [19] 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 [29]. For small enough impact parameters in the neutrino-nucleon collision, black hole (BH) production becomes important [30]. 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 that for KK scattering and is thus also too small [31].

More recently, Fodar et al. [32] speculated that the neutrino-nucleon cross section above $E \sim 10^{18}$ eV is enhanced by a factor $\sim 10^5$ by non-perturbative electroweak instanton contributions. The numerical calculations ([33]) found that instanton induced processes are much more heavily suppressed than suggested by [32]. However, it is instructive to ask if strongly interacting neutrinos can mimic at all, in this model, extensive air showers initiated by protons. At $E \leqslant 10^{20}$ eV, the cross section is bounded by $\sigma_{\nu p} \leqslant 3$ mbarn [34]. Thus the difference between $\sigma_{\nu p}$ and $\sigma_{pp}^{\rm inel}$ is still large even at UHE in this model, $\sigma_{pp}^{\rm inel}/\sigma_{\nu p} \sim 40$, but it becomes smaller considering the scattering on air nuclei: while scattering of protons on nuclei with $A > 1$ is already close to the black disc limit ($\sigma_{pA}^{\rm inel} \propto A^{2/3}$), it is reasonable to assume no shadowing, $\sigma_{\nu A} \propto A$, for neutrino-nucleus scattering. Even so, the development of a neutrino induced shower is considerably delayed having its shower maximum around $\geqslant 1400$ g/cm^2. Experiments such as HiRes, or those at the Pierre Auger Observatory, that are able to measure the whole shower development of an EAS in fluorescent light should clearly see this difference.

In summary, experimental and theoretical constraints make it very unlikely that neutrinos can explain – either as messenger particles or as primaries – the observed vertical EAS. Nevertheless, both cases offer exciting possibilities to future experiments: the discovery of the relic neutrino background and, perhaps, a measurement of the absolute neutrino masses via the Z burst mechanism, or the discovery of new contributions to the neutrino-nucleon interaction in horizontal EAS [31,35].

3. Top–down models

A 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 (TDs) [36] such as (superconducting) cosmic strings, monopoles, and hybrid defects can be effectively produced in non-thermal phase transitions during the preheating stage [37]. 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 large enough fluxes of UHE primaries.

Ordinary strings can produce UHE particles, e.g., when string loops self-intersect or when two cusp segments overlap and annihilate. In the latter case, the maximal energy of the produced fragmentation products is not $m_X/2$ but can be much larger due to the high Lorentz factors of the ejected X particles.

Superconducting strings: Cosmic strings can be superconducting in a broad class of particle models. Electric currents can be induced in the string either by a primordial magnetic field that decreases during the expansion of the Universe or when the string moves through galactic fields at present. If the current reaches the vacuum expectation value of the Higgs field breaking the extra U(1), the trapped particles are ejected and can decay.

Monopolium M, a bound-state of a monopole–antimonopole pair, was the first TD proposed as UHECR source [38]. It clusters like Cold Dark Matter (CDM) and is therefore an example for SHDM. The galactic density of monopoles is constrained by the Parker limit: the galactic magnetic field should not be eliminated by the acceleration of monopoles. Reference [39] concluded that the resulting limit on the UHECR flux produced by Monopolium annihilations is 10 orders of magnitude too low.

Cosmic necklaces are hybrid defects consisting of monopoles connected by a string. These defects are produced by the symmetry breaking $G \to H \times U(1) \to H \times Z_2$, where G is semi-simple. In the first phase transition at scale η_m, monopoles are produced. At the second phase transition, at scale $\eta_s < \eta_m$, each monopole gets attached to two strings. The basic parameter for the evolution of necklaces is the ratio $r = m/(\mu d)$ of the monopole mass m and the mass of the string between two monopoles, μd, where $\mu \sim \eta_s^2$ is the mass density of the string and d the distance between two monopoles. Strings lose their energy and contract through gravitational radiation. As a result, all monopoles annihilate in the end producing X particles. Reference [40] argued that for a reasonable range of parameters the model predicts a UHECR flux close to that observed. A numerical study [41] of the evolution of necklaces found that the lifetime of necklaces is generally much shorter than the age of the Universe. An exception is the case $\eta_m \gg \eta_s \sim 100$ GeV [39].

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. Then the flux of UHE particles is either exponentially suppressed or strongly anisotropic if a TD is nearby by chance. An exception is the necklace model where the distance $\sim t_0/\sqrt{r}$ between necklaces can be as small as 10 kpc. Therefore we discuss in the following only this model.

The rate of X particle production by necklaces at time t can be estimated as [40]

$$\dot{n}_X \sim \frac{r^2 \mu}{t^3 M_X} \tag{3}$$

and the resulting cascade energy density is given by

$$\omega_{\text{cas}} = \frac{1}{2} f_\pi r^2 \mu \int_0^{t_0} \frac{\mathrm{d}t}{t^3} \frac{1}{(1+z)^4} = \frac{3}{4} f_\pi r^2 \frac{\mu}{t_0^2}, \tag{4}$$

where $f_\pi \sim 1$ is the fraction of the total energy transferred to the cascade. Using the bound on ω_{cas} and $t_0 = 13.7$ Gyr, the limit $r^2\mu \leqslant 8.9 \times 10^{27}$ GeV^2 follows [42].

In Fig. 4(a), the diffuse fluxes in the necklace model are shown for $r^2\mu = 4.7 \times 10^{27}$ GeV^2, i.e., roughly a factor two below the cascade bound, and $M_X = 1 \times 10^{14}$ GeV. In contrast to earlier calculations using the MLLA (SUSY) QCD fragmentation functions, the flux in the necklace model for UHECR is now below the flux measured by AGASA at $E \geqslant 10^{20}$ eV. This is the consequence of the steeper fragmentation spectra of X particles found in [43,42] and used in the calculation of Fig. 4. Thus UHE particles from necklaces can serve only as an additional component in the observed UHECR flux.

A similar conclusions was reached in [25] based on different assumptions: Fig. 3 shows their 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 continuous 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. In the calculation of [25] the QCD MLLA fragmentation functions were used. Here, the new EGRET limit (lower set of error bars on the left, in red) is essential and allows only a sub-dominant contribution to the UHECR flux from necklaces.

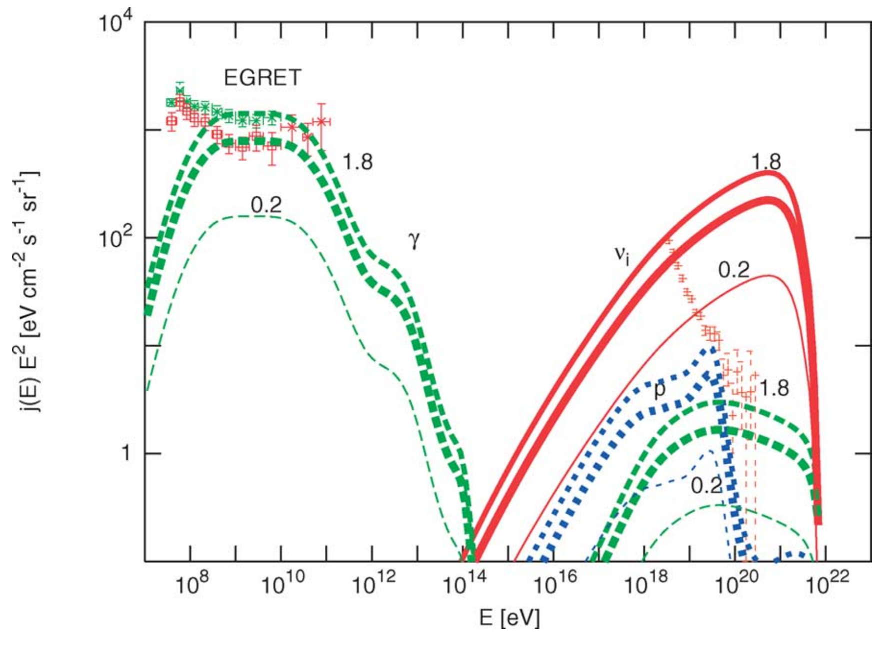
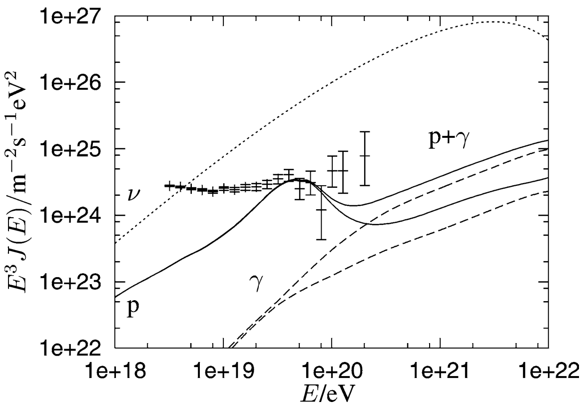
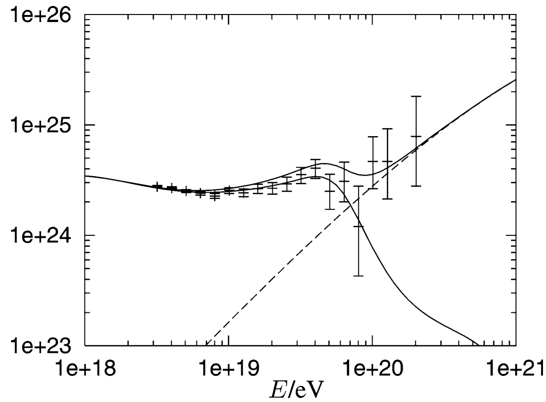


Fig. 3. Proton, photon and neutrino fluxes in a TD model with $M_X = 2 \times 10^{13}$ GeV, evolution $\dot{n}_X \propto t^{-3}$ and continuous distribution of sources. The fraction of the MeV–GeV diffuse photon background MeV–GeV contributed by these sources is chosen as 0.2, 1, and 1.8; from [25].



(a)



(b)

Fig. 4. (a) Diffuse spectra from necklaces together with the AGASA data: photon fluxes are shown for two cases of absorption, the thick continuous curve gives the sum of the proton and the higher photon flux. (b) Comparison of the UHECR flux in the SHDM model with the AGASA data, photons from SHDM decays (dashed line), spectrum of extragalactic protons (thin solid line) in the non-evolutionary model of [53] and the sum of these two spectra shown by the thick curve; both figures from [42].

3.2. Superheavy dark matter

Superheavy metastable relic particles were proposed in [44,45] 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 [44]. 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, $r_X \sim 10^{-11}$. The value of r_X is not predicted in the generic SHDM model, but calculable as soon as a specific particle physics and cosmological model is fixed.

There exist several plausible non-equilibrium production mechanisms. The most promising 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 [46]. In this scenario, the gravitational coupling of the X field to the background metric yields independent of any specific particle physics model the present abundance $\Omega_X h^2 \sim (M_X/10^{13}\mathrm{GeV})^2(10^9\mathrm{GeV}/T_R)$, provided that $M_X \lesssim H_*$. Here, T_R denotes the reheating temperature of the Universe and $H_* \sim 10^{13}$ GeV the effective Hubble parameter at the end of inflation. Thus, SHDM could constitute the main component of CDM for a very interesting set of parameters. 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 $M \sim M_{\mathrm{Pl}}$ and $d \geqslant 7$ is possible. The case of discrete gauged symmetries has been studied in detail in [47]. Another possibility is that the global symmetry is broken only non-perturbatively, either by wormhole [44] or instanton [45] effects. Then an exponential suppression of the decay process is expected and lifetimes $\tau_X \gtrsim t_0$ can be naturally achieved.

An example of a SHDM particle in a semi-realistic particle physics model is the crypton [48]. Cryptons are bound-states 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 through high-dimensional operators. For instance, flipped SU(5) motivated by string theory contains bound-states with mass $\sim 10^{12}$ GeV and $\tau \sim 10^{15}$ yr [49]. Choosing $T_R \sim 10^5$ GeV results in $r_X \sim 10^{-11}$, i.e., the required value to explain the UHECR flux above the GZK cutoff. This example shows clearly that the SHDM model has no generic 'fine-tuning problem'. Other viable candidates suggested by string theory were discussed in [50].

3.3. Signatures of top-down models

Superheavy dark matter has several clear signatures: (i) no GZK cutoff, instead a flat spectrum (compared to astrophysical sources) up to $m_X/2$; (ii) large neutrino and photon fluxes compared to the proton flux; (iii) galactic anisotropy; (iv) if R parity is conserved, the lightest supersymmetric particle (LSP) is an additional UHE primary; (v) small-scale clustering of the UHECR arrival directions gives possibly additional constraints.

3.3.1. Spectral shape

The fragmentation spectra of superheavy particles calculated by different methods and different groups [43,51,42] agree quite well, cf. [42] for a detailed discussion. This allows one to consider the spectral shape as a signature of models with decays or annihilations of superheavy particles. The predicted spectrum in the SHDM model, $\mathrm{d}N/\mathrm{d}E \propto E^{-1.9}$, cannot fit the observed UHECR spectrum at energies $E \leqslant (6\text{–}8) \times 10^{19}$ eV. Thus only events at $E \geqslant (6\text{–}8) \times 10^{19}$ eV, and most notably the AGASA excess at these energies, can be explained in this model. A two-component fit from [42] using protons from uniformly, continuously distributed extragalactic astrophysical sources and photons from SHDM is shown in Fig. 4 together with the experimental data from AGASA.

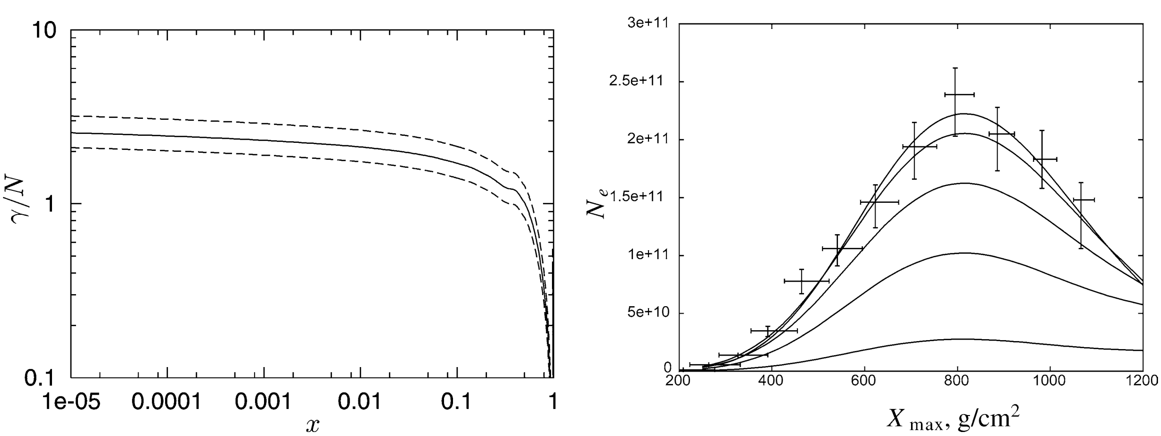
3.3.2. Chemical composition [52]

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 $\gamma/N \simeq 2\text{–}3$, becoming smaller at the largest $x = 2E/M_X$. This ratio is shown in Fig. 5(a) as function of x together with a band illustrating the uncertainty due to the hadronization process [42].

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 [54]. It has been recently measured in a sub-array of AGASA [55]. 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 nucleons in the total flux can be estimated as $0.25 \leqslant N/\mathrm{tot} \leqslant 0.33$. This fraction gives a considerable contribution to the probability of observing four showers with slightly increased muon content. Not restricting severely the SHDM model, the AGASA events give no evidence in favor of it.

Reference [56] 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 $(6\text{–}8) \times 10^{19}$ eV and the flux is steeply falling with energy, this result does not constrain the SHDM model.

The Pierre Auger Observatory [57] 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.



(a) (b)

Fig. 5. (a) Photon/nucleon ratio as function of $x = 2E/M_X$, the band illustrates the uncertainty due to hadronization; from [42]. (b) Comparison of Flye’s Eye highest energy event with the longitudinal shower profile for EAS of energy $E_0 = 3 \times 10^{20}$ eV initiated (from top to down) by protons and by glueballinos with $M_{\tilde{g}} = 2$, 5, 10 and 50 GeV. The shower profiles are shifted so that their $X_{\max}$ agrees with the observed shower maximum; from [66], with permission of the American Physical Society.

3.3.3. Galactic anisotropy

The UHECR flux from SHDM should show a galactic anisotropy [58], because the Sun is not at 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 [59]. The compatibility of the SHDM hypothesis with the SUGAR data was discussed recently in [60,61]. In [60], 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.

3.3.4. 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 [62,63]. 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. 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 [62,64].

3.3.5. Clustering

Clustering of UHECR arrival directions could be explained in the SHDM model by the clumpiness of the DM [65]. 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 clustering is difficult to use at present as an experimental constraint for SHDM. Any analysis should take into account the spectral shape of the UHECR flux predicted in the SHDM model, e.g., by using only events above $E > 6\text{–}8 \times 10^{19}$ eV.

The signatures of TD models are not so clear-cut, especially if TDs contribute only a minor part to the UHECR flux. The high photon/nucleon ratio at generation can be masked by strong absorption of UHE photons, but is still higher than expected from astrophysical sources, cf. Fig 4(a). 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 expected in TD models because TDs emit UHE particles in singular events. Finally, the detection of UHE LSPs is simpler in TD models than for SHDM, because the predicted 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 those 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, as one can see for a composite particle Y like a hadron or magnetic monopole from kinematical considerations [62]; such particles can have large total cross sections with nucleons even when they are heavy, because they contain light constituents as, e.g., gluons. However, the momentum fraction carried by the light constituents goes to zero for $M_Y \to \infty$, and therefore also the energy transferred in soft interactions. Moreover, the relative weight of hard interactions in which a large longitudinal momentum transfer is strongly suppressed by kinematics increases for large M_Y. As a result, heavy hadrons or magnetic monopoles behave as deeply penetrating particles although they have large total cross sections. This behaviour can be seen nicely in Fig. 5(b) where the longitudinal shower profiles for EAS of energy $E_0 = 3 \times 10^{20}$ eV initiated by glueballinos – a bound-state of a gluon and gluino – with mass $M_{\tilde{g}} = 2, 5, 10$ and 50 GeV are compared to the EAS initiated by a proton. In this example, the total cross section decreases only from $\sim$ 100 mbarn ($M_{\tilde{g}} = 2$ GeV) to $\sim$ 90 mbarn ($M_{\tilde{g}} = 50$ GeV), while the energy fraction transferred reduces from $y \sim 0.25$ to 0.02, cf. [66].

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, [66] found that a viable new hadron should have a mass in the range 2 GeV $\lesssim m \lesssim$ 5 GeV. Reference [6] 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 $\sim$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, measurements of electroweak observables at LEPI were used in [67] 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. It is likely that the lightest stable hadron is charged in this case and thus it is implausible 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. Conceptionally different is the possibility that new particles are not produced via a beam-dump, but are either accelerated directly in the source or are produced during the propagation via mixing. A model with an axion-like particle, i.e. a scalar which can mix with a photon in the presence of external magnetic fields, was suggested in [68]. Axion-like particles can be also produced by photons emitted by astrophysical sources via axion-photon oscillations [69]. The main problem of this type of model is the EGRET bound. Bound-states of magnetic monopoles as primaries were proposed in [70]. From the discussion above, it is clear that although their total cross section with nucleons can be large, the energy transfer per interaction is very small. Thus they would behave as deeply penetrating particles and cannot explain the observed EAS.

5. Violation of the 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 dimensionful coupling constant for gravity or if for smaller (wave-) lengths the properties of space-time are changed. If one considers, e.g., the case that $l_{\rm Pl}$ sets a minimum wavelength in a frame-independent way, then 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 $c \to \infty$ from Lorentz transformations. Other schemes in which modifications of Lorentz invariance are expected in a purely four-dimensional frame-work are discrete (e.g., from loop quantum gravity) or noncommutative space-times. Yet another possibility is that in topologically 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 [71]. Finally, Lorentz invariance could be 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 various 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 for different particle species [72]. The two most important consequences are changed dispersion relations [73], 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 [74].

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 [75]. Apart from the extension of the UHECR spectrum beyond $E_{\rm GZK}$, the non-observation of GZK neutrinos would be characteristic for this solution to the UHECR puzzle. Moreover, Dubovsky and Tinyakov [76] suggested, as additional, but model-dependent signature, two sharp transitions in the composition of UHECRs: above a certain threshold energy E_1, neutrons become stable and protons as primaries would be replaced by a neutron/proton mixture. Above a second threshold $E_2 > E_1$, only neutrons would be UHECR primaries. The reason for this mutation of the primary composition is the changed dispersion relation of nucleons that above E_1 prohibits normal beta decay and above $E_2 > E_1$ allows 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 UHECRs 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 also be the case if Lorentz invariance is violated.

The combination of results from low-energy gamma-ray and UHE neutrino experiments already severely constrains TD and Z burst models now. 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.

Lorentz invariance violation should be considered seriously as an explanation for the UHECR puzzle, 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. 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.

Acknowledgements

I am grateful to all my co-authors but in particular to Venya Berezinsky, Sergey Ostapchenko, and Dima Semikoz for fruitful collaborations and many discussions. I would like to thank Andreas Ringwald, Günter Sigl and Peter Tinyakov for helpful comments. This work was supported by the Deutsche Forschungsgemeinschaft within the Emmy-Noether program.

References

[1] M. Ostrowski, Shock acceleration, C. R. Physique (2004) in press;
S. Colgate, H. Lui, Non-Fermi acceleration, C. R. Physique (2004) in press.
[2] K. Greisen, Phys. Rev. Lett. 16 (1966) 748;
G.T. Zatsepin, V.A. Kuzmin, JETP Lett. 4 (1966) 78.
[3] T. Stanev, Propagation of high-energy cosmic rays, C. R. Physique (2004) in press.
[4] M. Takeda, et al., Phys. Rev. Lett. 81 (1998) 1163;
N. Hayashida, et al., Astrophys. J. 522 (1999) 225.
[5] T. Abu-Zayyad, et al., High Resolution Fly's Eye Collaboration, astro-ph/0208243.
[6] M. Kachelrieß, D.V. Semikoz, M.A. Tórtola, Phys. Rev. D 68 (2003) 043005.
[7] V.S. Berezinsky, in: M.A. Markov (Ed.), Proc. of Neutrino-77, vol. 1, 1977, p. 177.
[8] P. Sreekumar, et al., Astrophys. J. 494 (1998) 523.
[9] A.W. Strong, I.V. Moskalenko, O. Reimer, astro-ph/0306345.
[10] R.W. Clay, B.R. Dawson, G.J. Thornton, Directional reconstruction and anisotropy studies, C. R. Physique (2004), in press.
[11] Y. Uchihori, et al., Astropart. Phys. 13 (2000) 151.
[12] W.S. Burgett, M.R. O'Malley, Phys. Rev. D 67 (2003) 092002.
[13] K. Dolag, D. Grasso, V. Springel, I. Tkachev, astro-ph/0310902.
[14] G. Sigl, F. Miniati, T. Enßlin, astro-ph/0401084.
[15] E. Waxman, K.B. Fisher, T. Piran, Astrophys. J. 483 (1997) 1.
[16] S.L. Dubovsky, P.G. Tinyakov, I.I. Tkachev, Phys. Rev. Lett. 85 (2000) 1154;
see also Z. Fodor, S.D. Katz, Phys. Rev. D 63 (2001) 023002;
P. Blasi, D. De Marco, astro-ph/0307067.
[17] P.G. Tinyakov, I.I. Tkachev, JETP Lett. 74 (2001) 445;
P.G. Tinyakov, I.I. Tkachev, astro-ph/0301336;
but see also N.W. Evans, F. Ferrer, S. Sarkar, Phys. Rev. D 67 (2003) 103005;
D.F. Torres, S. Reucroft, O. Reimer, L.A. Anchordoqui, Astrophys. J. 595 (2003) L13.
[18] V.S. Berezinsky, G.T. Zatsepin, Phys. Lett. B 28 (1969) 423;
G. Domokos, S. Nussinov, Phys. Lett. B 187 (1987) 372;
J. Bordes, H. Chan, J. Faridani, J. Pfaudler, S.T. Tsou, Astropart. Phys. 8 (1998) 135.
[19] G. Domokos, S. Kovesi-Domokos, Phys. Rev. Lett. 82 (1998) 1366;
P. Jain, D.W. McKay, S. Panda, J.P. Ralston, Phys. Lett. B 484 (2000) 267.
[20] D. Fargion, B. Mele, A. Salis, Astrophys. J. 517 (1999) 725;
T.J. Weiler, Astropart. Phys. 11 (1999) 303.
[21] V. Berezinsky, M. Kachelrieß, S. Ostapchenko, Phys. Rev. Lett. 89 (2002) 171802.
[22] G. Gelmini, A. Kusenko, Phys. Rev. Lett. 84 (2000) 1378.
[23] S. Hannestad, JCAP 0305 (2003) 004.
[24] S. Singh, C.P. Ma, Phys. Rev. D 67 (2003) 023506.
[25] D.V. Semikoz, G. Sigl, hep-ph/0309328.
[26] N.G. Lehtinen, P.W. Gorham, A.R. Jacobson, R.A. Roussel-Dupre, astro-ph/0309656.
[27] P.W. Gorham, C.L. Hebert, K.M. Liewer, C.J. Naudet, D. Saltzberg, D. Williams, astro-ph/0310232.
[28] N. Arkani-Hamed, S. Dimopoulos, G. Dvali, Phys. Lett. B 429 (1998) 263;
I. Antoniadis, N. Arkani-Hamed, S. Dimopoulos, G. Dvali, Phys. Lett. B 436 (1998) 257.

[29] M. Kachelrieß, M. Plümacher, Phys. Rev. D 62 (2000) 103006, hep-ph/0109184;
G.F. Giudice, R. Rattazzi, J.D. Wells, Nucl. Phys. B 630 (2002) 293.
[30] S. Dimopoulos, G. Landsberg, Phys. Rev. Lett. 87 (2001) 161602;
S.B. Giddings, S. Thomas, Phys. Rev. D 65 (2002) 056010; for recent criticism see V.S. Rychkov, Black hole production in particle collisions and higher curvature gravity, hep-ph/0401116.
[31] J.L. Feng, A.D. Shapere, Phys. Rev. Lett. 88 (2002) 021303.
[32] Z. Fodor, S.D. Katz, A. Ringwald, H. Tu, Phys. Lett. B 561 (2003) 191.
[33] F. Bezrukov, D. Levkov, C. Rebbi, V. Rubakov, P. Tinyakov, Phys. Lett. B 574 (2003) 75.
[34] A. Ringwald, JHEP 0310 (2003) 008.
[35] C. Tyler, A.V. Olinto, G. Sigl, Phys. Rev. D 63 (2001) 055001;
T. Han, D. Hooper, hep-ph/0307120.
[36] A. Vilenkin, E.P.S. Shellard, Cosmic Strings and other Topological Defects, Cambrige University Press, 1994;
M.B. Hindmarsh, T.W.B. Kibble, Rep. Prog. Phys. 58 (1995) 477.
[37] S. Khlebnikov, L. Kofman, A. Linde, I. Tkachev, Phys. Rev. Lett. 81 (1998) 2012;
V.A. Kuzmin, I.I. Tkachev, Phys. Rep. 320 (1999) 199.
[38] C.T. Hill, Nucl. Phys. B 224 (1983) 469.
[39] J.J. Blanco-Pillado, K.D. Olum, Phys. Rev. D 60 (1999) 083001.
[40] V. Berezinsky, A. Vilenkin, Phys. Rev. Lett. 79 (1997) 5202.
[41] X. Siemens, X. Martin, K.D. Olum, Nucl. Phys. B 595 (2001) 402.
[42] R. Aloisio, V. Berezinsky, M. Kachelrieß, hep-ph/0307279, Phys. Rev. D, in press.
[43] V. Berezinsky, M. Kachelrieß, Phys. Rev. D 63 (2001) 034007.
[44] V. Berezinsky, M. Kachelrieß, A. Vilenkin, Phys. Rev. Lett. 79 (1997) 4302.
[45] V.A. Kuzmin, V.A. Rubakov, Phys. Atom. Nucl. 61 (1998) 1028.
[46] D.J. Chung, E.W. Kolb, A. Riotto, Phys. Rev. D 59 (1999) 023501;
V. Kuzmin, I. Tkachev, JETP Lett. 68 (1998) 271.
[47] K. Hamaguchi, Y. Nomura, T. Yanagida, Phys. Rev. D 58 (1998) 103503;
K. Hamaguchi, K.I. Izawa, Y. Nomura, T. Yanagida, Phys. Rev. D 60 (1999) 125009.
[48] J. Ellis, J.L. Lopez, D.V. Nanopoulos, Phys. Lett. B 247 (1990) 257.
[49] K. Benakli, J. Ellis, D.V. Nanopoulos, Phys. Rev. D 59 (1999) 047301.
[50] C. Coriano, A.E. Faraggi, M. Plümacher, Nucl. Phys. B 614 (2001) 233.
[51] S. Sarkar, R. Toldra, Nucl. Phys. B 621 (2002) 495;
C. Barbot, M. Drees, Phys. Lett. B 533 (2002) 107.
[52] A.A. Watson, astro-ph/0312475.
[53] V. Berezinsky, A. Gazizov, S. Grigorieva, astro-ph/0302483.
[54] A.V. Plyasheshnikov, F.A. Aharonian, J. Phys. G 28 (2002) 267.
[55] K. Shinozaki, et al., AGASA collaboration, Astrophys. J. 571 (2002) L117.
[56] M. Ave, et al., Phys. Rev. Lett. 85 (2000) 2244.
[57] D. Zavrtanik, AUGER Collaboration, Nucl. Phys. Proc. Suppl. 85 (2000) 324.
[58] S.L. Dubovsky, P.G. Tinyakov, JETP Lett. 68 (1998) 107.
[59] M.M. Winn, J. Ulrichs, L.S. Peak, C.B. Mccusker, L. Horton, J. Phys. G 12 (1986) 653;
M.M. Winn, J. Ulrichs, L.S. Peak, C.B. Mccusker, L. Horton, J. Phys. G 12 (1986) 675.
[60] M. Kachelrieß, D.V. Semikoz, Phys. Lett. B 577 (2003) 1.
[61] H.B. Kim, P. Tinyakov, astro-ph/0306413.
[62] V. Berezinsky, M. Kachelrieß, Phys. Lett. B 422 (1998) 163.
[63] V. Berezinsky, M. Kachelrieß, Nucl. Phys. Proc. Suppl. A 75 (1999) 377.
[64] C. Barbot, M. Drees, F. Halzen, D. Hooper, Phys. Lett. B 563 (2003) 132.
[65] P. Blasi, R. Sheth, Phys. Lett. B 486 (2000) 233, see also the first work of Ref. [16].
[66] V. Berezinsky, M. Kachelrieß, S. Ostapchenko, Phys. Rev. D 65 (2002) 083004.
[67] P. Janot, Phys. Lett. B 564 (2003) 183.
[68] D.S. Gorbunov, G.G. Raffelt, D.V. Semikoz, Phys. Rev. D 64 (2001) 096005.
[69] C. Csaki, N. Kaloper, M. Peloso, J. Terning, JCAP 0305 (2003) 005.
[70] E. Huguet, P. Peter, Astropart. Phys. 12 (2000) 277.
[71] F.R. Klinkhamer, J. Schimmel, Nucl. Phys. B 639 (2002) 241.
[72] S.R. Coleman, S.L. Glashow, Phys. Rev. D 59 (1999) 116008;
For a complete Lorentz-violating extension of the SM see D. Colladay, V.A. Kostelecky, Phys. Rev. D 58 (1998) 116002.
[73] T.G. Pavlopoulos, Phys. Rev. 159 (1967) 1106.
[74] G. Amelino-Camelia, J.R. Ellis, N.E. Mavromatos, D.V. Nanopoulos, S. Sarkar, Nature 393 (1998) 763.
[75] D.A. Kirzhnits, V.A. Chechin, Yad. Fiz. 15 (1972) 1051;
H. Sato, T. Tati, Prog. Theor. Phys. 47 (1972) 1788.
[76] S.L. Dubovsky, P.G. Tinyakov, Astropart. Phys. 18 (2002) 89.