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Particle physics solutions to the UHECR puzzle – 2003

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Abstract. The status of solutions to the ultra-high energy cosmic ray (UHECR) puzzle that involve particle physics beyond the standard model is reviewed. Signatures and experimental constraints are discussed for the most promising suggestions like the Z-burst model and topological defects (allowed only as subdominant contributions), supermassive dark matter (no positive evidence in its favor), strongly interacting neutrinos or new primaries (no viable models known), and violation of Lorentz invariance (viable).

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1 Introduction

UHECR protons produced by uniformly distributed astrophysical sources contradict the energy spectrum measured by both the AGASA and HiRes experiments, assuming the small scale clustering of UHECR observed by AGASA is caused by point-like sources [1]. In that case, the small number of sources leads to a sharp exponential GZK cutoff in the UHECR spectrum which is not seen. The status of several solutions to this puzzle that involve particle physics beyond the standard model is here briefly discussed, for a more extensive review see [2].

2 Neutrinos as primaries or messengers

Neutrinos are the only known stable particles that can traverse extragalactic space without attenuation even at energies beyond the GZK cutoff. Either one postulates 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 [3], 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. There are 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 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 measured by EGRET [4] is overproduced. No astrophysical accelerator of this kind is known. (As possible way-out, the authors of [5] 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 transforming around 20% of the initial energy to photons and electrons [6]. 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 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., [7]). For such small masses, the overdensity δ of neutrinos is also small, $\delta \lesssim 10$, on a length scale of 1 Mpc [8]. 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 [9] and GLUE [10] and an improved limit [11] 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 [12]. In Fig. 1, 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

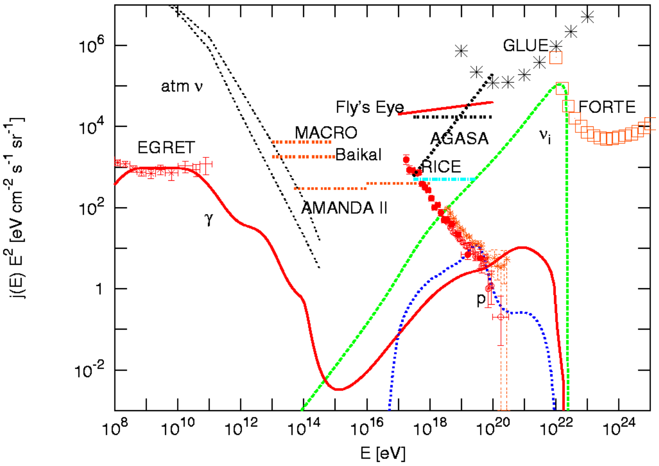

Fig. 1. Expected fluxes in the Z-burst model for an optimal choice of free parameters together with limits for UHE neutrinos fluxes and the new EGRET limit, from [12]

to be $O(\sigma_{\rm tot}) \lesssim 1/M^2 \lesssim 1/m_Z^2$. String theories with large extra dimensions are an exception, because the compactification radius R of the extra dimensions can be large, corresponding to a *small* scale $1/R$ of new physics. Since the weakness of the gravitational interaction is partially compensated by the large number of Kaluza-Klein states and cross sections of reactions mediated by spin 2 particles are increasing rapidly with energy, it has been argued in [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 thus an unitarization procedure has to applied. The unitarized cross section is roughly three orders too small, and also the energy transferred in each interaction is not sufficient to explain the observed properties of EAS [14]. For small enough impact parameters in the neutrino-nucleon collision, black hole production will become important. Using in a simplistic picture a geometric cross section for black hole production, $\sigma_{\rm BH} \sim \pi R_S^2$, where R_S is the corresponding Schwarzschild radius, the cross section has roughly the same size as the one for Kaluza-Klein scattering and is thus also too small.

More recently, [15] 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 [16] found that instanton induced processes keep much heavier suppressed than suggested by [15]. However, it is instructive to ask if strongly interacting neutrinos can mimic extensive air showers initiated by protons in this model at all. At $E = 10^{20}$ eV, the cross section is bounded by $\sigma_{\nu N} \leq 3$ mbarn [17]. 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.

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. These X particles can be either metastable or be emitted by topological defects at the present epoch.

3.1 Topological defects

Topological defects (TD) can be effectively produced in non-thermal phase transitions during the preheating stage. They can naturally produce particles with high enough energies but have problems to produce large enough fluxes 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 nearby by chance. Figure 2 shows the proton, photon and neutrino fluxes choosing optimal parameters in the necklace model, but varying the fraction (0.2, 1, and 1.8) MeV-GeV photons from these sources contribute to the diffuse photon background: the new EGRET limit (in red) allows only a sub-dominant contribution to the UHECR flux from necklaces.

3.2 Superheavy dark matter and its signatures

SHDM was proposed in [18,19] as UHECR source. It constitutes (part of) the CDM and, consequently, its abundance in the galactic halo is enhanced by a factor $\sim 5\times10^4$ above its 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 [18]. SHDM has three clear signatures: 1. No GZK-cutoff, instead a flat spectrum (compared to astrophysical sources) up to $m_X/2$. 2. High neutrino and photon fluxes compared to the proton flux. 3. Galactic anisotropy. 4. If R parity is conserved, the lightest supersymmetric particle as additional UHE primary. Possibly, the observed small-scale clustering gives additional constraints.

1. Spectral shape: The fragmentation spectra of superheavy particles calculated by different methods and different groups agree well [20]. This allows to consider the spectral shape as a signature of this model. The predicted energy spectrum from SHDM decays, $dN/dE \propto E^{-1.9}$, can explain only events at $E \gtrsim (6-8)\times10^{19}$ eV, and most notably the AGASA excess.

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 with only $\sim$ 10% of nucleons. Therefore, a robust prediction of this model is photon dominance with a photon/nucleon ratio of $\gamma/N \simeq 2-3$ at the highest energies.

The muon content of photon induced EAS at $E > 1\times10^{20}$ eV is lower by a factor $5-10$ than in hadronic

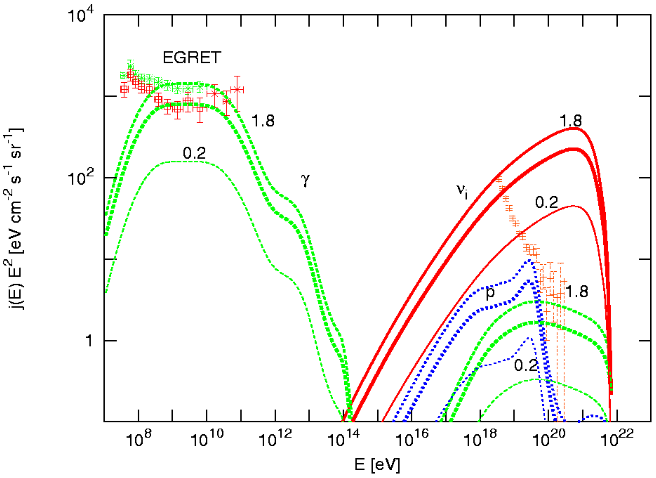

Fig. 2. Fluxes in the necklace model, from [12]

showers [21]. It has been recently measured in a subarray of AGASA [22]. In two of six measured events with $E > 1 \times 10^{20}$ eV, the muon density is almost twice higher than predicted for gamma-induced EAS. The muon content of the remaining 4 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 $0.25 \leq p/\text{tot} \leq 0.33$. This fraction gives a considerable contribution to the probability of observing 4 showers with slightly increased muon content. Not restricting severly the SHDM model, the AGASA events give no evidence in favor of it. Reference [23] re-analyzed the Haverah Park data that above 4×10^{19} eV and found that less than 55% of the UHE primaries can be photons. Since protons from "normal" astrophysical sources dominate the flux up to $(6-8) \times 10^{20}$ eV and the flux is steeply falling with energy, this results does not restrict SHDM models.

3. Galactic anisotropy: The UHECR flux from SHDM should show a galactic anisotropy, because the Sun is not in the centre of the Galaxy [24]. The degree of this anisotropy depends on how strong the CDM is concentrated near the galactic centre – 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. The compatibility of the SHDM hypothesis with the SUGAR data was discussed recently in [25,26].

In [25], 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 ∼ 10% to be consistent with the SHDM model.

4 Conclusions

Strongly interacting neutrinos can neither in the case of large extra dimensions nor of large electroweak instanton cross sections mimic proton showers, while the Z-burst model and topological defects can contribute only a subdominant component to the UHECR flux. There is no positive evidence for SHDM as explanation of UHECR events in its two key-signatures, photons and galactic anisotropy, but the small number of events does not allow to disfavor SHDM strongly. For a discussion of new primaries and violation of Lorentz invariance see 1.

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