Probing Physics and Astrophysics at Extreme Energies with Ultra High Energy Cosmic Radiation

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Abstract. The highest energy cosmic rays observed possess macroscopic energies and their origin is likely to be associated with the most energetic processes in the Universe. Their existence triggered a flurry of theoretical explanations ranging from conventional shock acceleration to particle physics beyond the Standard Model and processes taking place at the earliest moments of our Universe. Furthermore, many new experimental activities promise a strong increase of statistics at the highest energies and a combination with $\gamma-$ray and neutrino astrophysics will put strong constraints on these theoretical models. We give an overview of theoretical developments with a focus on neutrino fluxes and cross sections, an issue that may be of particular relevance for the radio detection method.

INTRODUCTION

Over the last few years, several giant air showers have been detected confirming the arrival of cosmic rays (CRs) with energies up to a few hundred EeV (1 EeV $\equiv 10^{18}$ eV) [1–4]. The existence of such extremely high energy cosmic rays (EHECRs) pose a serious challenge for conventional theories of CR origin based on acceleration of charged particles in powerful astrophysical objects. The question of the origin of these EHECRs is, therefore, currently a subject of much intense debate and discussions as well as experimental efforts; see Ref. [5] for recent brief reviews, and Ref. [6] for a detailed review.

The problems encountered in trying to explain EHECRs in terms of "bottom-up" acceleration mechanisms have been well-documented in a number of studies; see, e.g., Refs. [7–9]. It is hard to accelerate protons and heavy nuclei up to such energies even in the most powerful astrophysical objects such as radio galaxies and active galactic nuclei. Also, nucleons above $\simeq 70$ EeV lose energy drastically due to photo-pion production on the cosmic microwave background (CMB) — the Greisen-Zatsepin-Kuzmin (GZK) effect [10] — which limits the distance to possible sources to less than $\simeq 100$ Mpc [8]. Heavy nuclei are photodisintegrated in the CMB within a few Mpc [11]. There are no obvious astronomical sources within $\simeq 100$ Mpc of the Earth [12,8].

There are, of course, ways to avoid the distance restriction imposed by the GZK effect, provided the problem of energetics is somehow solved separately and provided one allows new physics beyond the Standard Model of particle physics; we shall discuss those suggestions in the last part of this paper.

In contrast, in the "top-down" scenarios, which will be discussed in the next section, the problem of energetics is trivially solved. Here, the EHECR particles are the decay products of some supermassive "X" particles of mass $m_X \gg 10^{20}$ eV, and have energies all the way up to $\sim m_X$. Thus, no acceleration mechanism is needed. The massive X particles could be metastable relics of the early Universe with lifetimes of the order the current age of the Universe or could be released from topological defects that were produced in the early Universe during symmetry-breaking phase transitions envisaged in Grand Unified Theories (GUTs). If the X particles themselves or their sources cluster similar to dark matter, the dominant observable EHECR contribution would come from the Galactic Halo and absorption would be negligible.

The main problem of non-astrophysical solutions of the EHECR problem in general is that they are highly model dependent. On the other hand, it is precisely because of this reason that these scenarios are also attractive — they bring in ideas of new physics beyond the Standard Model of particle physics (such as Grand Unification and new interactions beyond the reach of terrestrial accelerators) as well as ideas of early Universe cosmology (such as topological defects and/or massive particle production in inflation) into the realms of EHECRs where these ideas have the potential to be tested by future EHECR experiments. We discuss these scenarios here because they often lead to significant neutrino fluxes extending up to extreme energies $\gtrsim 10^{21}$ eV, where new techniques such as radio detection could play an important role.

The physics and astrophysics of EHECRs are intimately linked with the emerging field of neutrino astronomy (for reviews see Refs. [13,14]) as well as with the already established field of $\gamma-$ray astronomy (for reviews see, e.g., Ref. [15]). Indeed, all scenarios of EHECR origin, including the top-down models, are severely constrained by neutrino and $\gamma-$ray observations and limits. In turn, this linkage has important consequences for theoretical predictions of fluxes of extragalactic neutrinos above a TeV or so whose detection is a major goal of next-generation neutrino telescopes: If these neutrinos are produced as secondaries of protons accelerated in astrophysical sources and if these protons are not absorbed in the sources, but rather contribute to the EHECR flux observed, then the energy content in the neutrino flux can not be higher than the one in EHECRs, leading to the so called Waxman Bahcall bound [16]. If one of these assumptions does not apply, such as for acceleration sources that are opaque to nucleons or in the TD scenarios where X particle decays produce much fewer nucleons than $\gamma-$rays and neutrinos, the Waxman Bahcall bound does not apply, but the neutrino flux is still constrained by the observed diffuse $\gamma-$ray flux in the GeV range. This is because isospin symmetry in the production of charged and neutral pions leads to a comparable amount of energy in $\gamma-$rays and neutrinos produced.

RELICS FROM THE EARLY UNIVERSE

The apparent difficulties of bottom-up acceleration scenarios discussed earlier motivated the proposal of the "top-down" scenarios, where EHECRs, instead of being accelerated, are the decay products of certain sufficiently massive "X" particles produced by physical processes in the early Universe. Furthermore, particle accelerator experiments and the mathematical structure of the Standard Model of the weak, electromagnetic and strong interactions suggest that these forces should be unified at energies of about 2×10^{16} GeV, 4-5 orders of magnitude above the highest energies observed in CRs. The relevant GUTs predict the existence of X particles with mass m_X around the GUT scale of $\simeq 2 \times 10^{16}$ GeV. If their lifetime is comparable or larger than the age of the Universe, they would be dark matter candidates and their decays could contribute to EHECR fluxes today, with an anisotropy pattern that reflects the expected dark matter distribution. These models avoid the GZK cutoff because the EHECR flux is dominated by particle decays in the halo of our galaxy. However, in order to reproduce the observed EHECR flux, they require strong fine tuning between the density in units of the critical density, Ω_X, and lifetime, t_X, of the X particle, $\Omega_X \sim 10^{-11}(t_X/10^{10}\,\mathrm{yr})$. Details of these scenarios have been discussed in Ref. [17] However, in many GUTs supermassive particles are expected to have extremely small lifetimes and thus have to be produced continuously if their decays are to give rise to EHECRs. This can only occur by emission from topological defects which are relics of cosmological phase transitions that could have occurred in the early Universe at temperatures close to the GUT scale. Phase transitions in general are associated with a breakdown of a group of symmetries down to a subgroup which is indicated by an order parameter taking on a non-vanishing value. Topological defects occur between regions that are causally disconnected, such that the orientation of the order parameter cannot be communicated between these regions and thus will adopt different values. Examples are cosmic strings, magnetic monopoles, and domain walls. The defects are topologically stable, but in the case of GUTs time dependent motion can lead to the emission of GUT scale X particles.

One of the prime cosmological motivations to postulate inflation, a phase of exponential expansion in the early Universe [18], was to dilute excessive production of "dangerous relics" such as topological defects and superheavy stable particles. However, right after inflation, when the Universe reheats, phase transitions can occur and such relics can be produced in cosmologically interesting abundances, and with a mass scale roughly given by the inflationary scale. The mass scale is fixed by the CMB anisotropies to $\sim 10^{13}$ GeV [19], and it is not far above the highest energies observed in CRs, thus motivating a connection between these primordial relics and EHECRs which in turn may provide a probe of the early Universe.

Within GUTs the X particles typically decay into jets of particles whose spectra can be estimated within the Standard Model. Before reaching Earth, the injected spectra are reprocessed by interactions with the low energy photon backgrounds such as the CMB, and magnetic fields present in the Universe (see Ref. [6,20] for details). The "visible" spectrum of nucleons and $\gamma-$rays expected in top-down scenarios (see Fig. 1) shows that the observed flux is reproduced above 3×10^{19} eV; at lower energies where the Universe is transparent to nucleons, bottom-up mechanisms could explain the spectrum. The X particle sources are not necessarily expected to be associated with astrophysical objects, but their distribution has to be sufficiently continuous to be consistent with observed EHECR angular distribu-

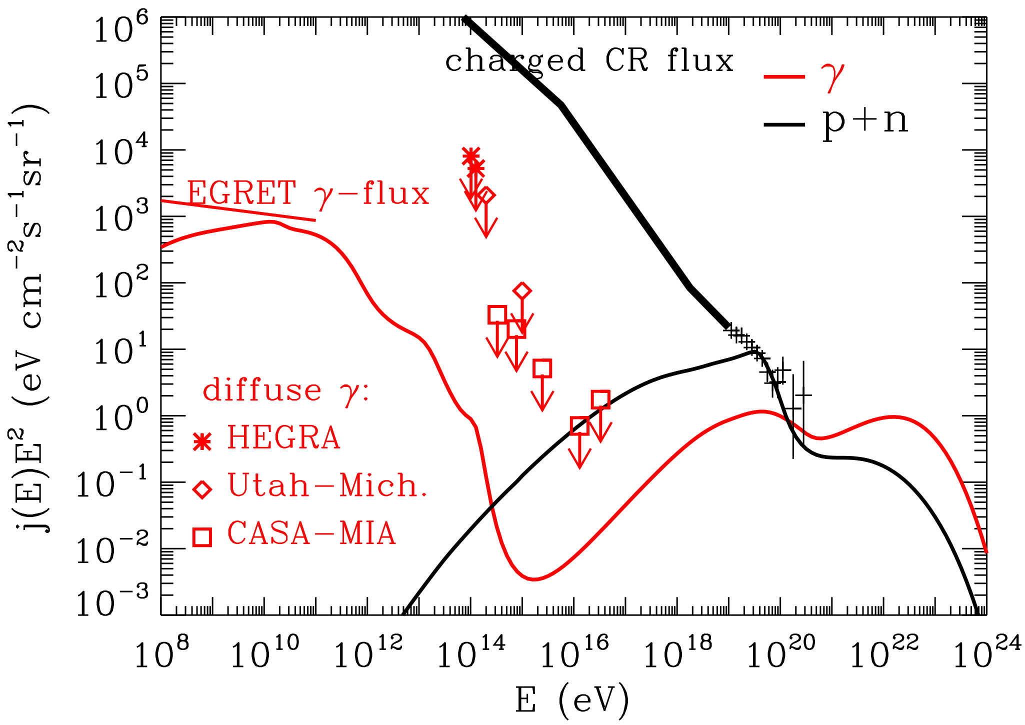

FIGURE 1. The "visible" spectra of nucleons and $\gamma-$rays for a top-down model involving the decay into two quarks of non-relativistic X particles of mass 10^{16} GeV, released from homogeneously distributed topological defects, assuming that quarks fragment into 10% nucleons and 90% pions with a spectrum given by a supersymmetric extension of the QCD fragmentation function. Also assumed was an intermediate estimate for the strength of the universal radio background and a large scale magnetic field $\lesssim 10^{-11}$ g (for details see Refs. [6,20]). One-sigma error bars show combined data from the Haverah Park [1], the Fly's Eye [2], and the AGASA [3] experiments above 10^{19} eV. Also shown are piecewise power law fits to the observed charged CR flux below 10^{19} eV, the measurement of the diffuse γ-ray flux between 30 MeV and 100 GeV by the EGRET instrument [21], as well as upper limits on the diffuse $\gamma-$ray flux from various experiments at higher energies (see Ref. [6] for more details).

tions.

The most characteristic features of top-down models are visible in Figs. 1 and 2: Electromagnetic cascades induced by interactions of the injected particles with the low energy photon backgrounds lead to a contribution to the diffuse $\gamma-$ray flux between 30 MeV and 100 GeV which is close to the flux measured by the EGRET detector flown on board the Compton $\gamma-$ray Observatory satellite [21]. The energy content in these $\gamma-$rays is comparable to the one in the ultra-high energy neutrino flux which should be detectable with next generation experiments

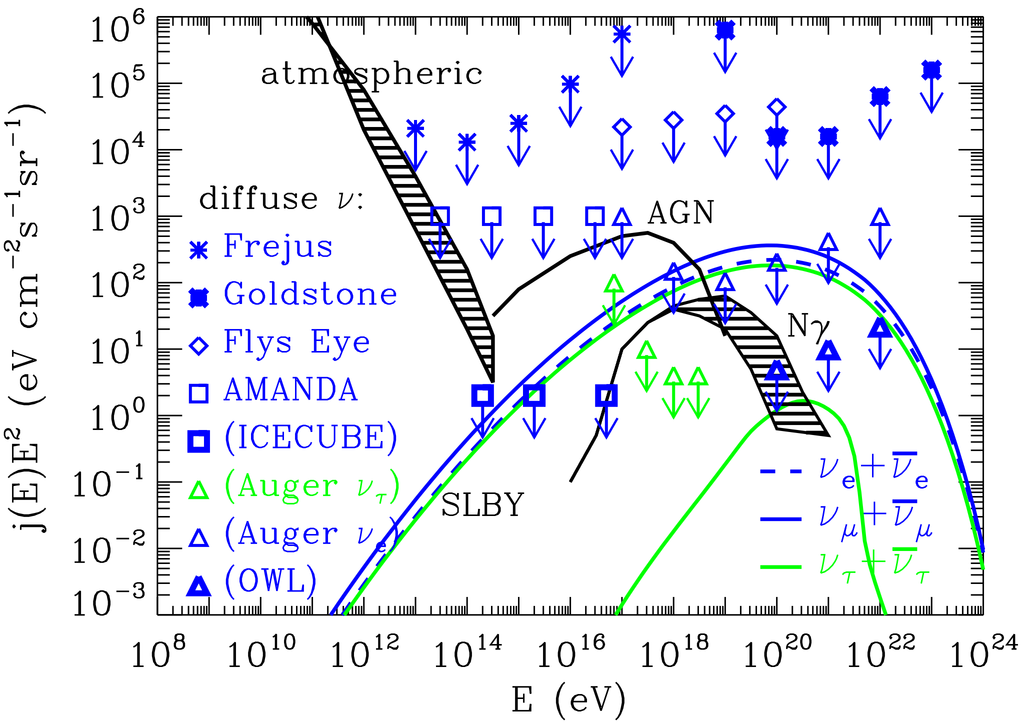

FIGURE 2. Neutrino fluxes for the top-down model of Fig. 1 (marked "SLBY"). Shown are experimental neutrino flux limits from the Frejus underground detector [22], the Fly's Eye experiment [23], the Goldstone radio telescope [24], and the Antarctic Muon and Neutrino Detector Array (AMANDA) neutrino telescope [25], as well as projected neutrino flux sensitivities of ICECUBE, the planned kilometer scale extension of AMANDA [26], the Pierre Auger Project [27] (for electron and tau neutrinos separately) and the proposed space based OWL [28] concept. For comparison also shown are the atmospheric neutrino background (hatched region marked "atmospheric"), and neutrino flux predictions for a model of AGN optically thick to nucleons ("AGN"), and for EHECR interactions with the CMB [29] ("$N\gamma$", dashed range indicating typical uncertainties for moderate source evolution). The top-down fluxes are shown for electron-, muon, and tau-neutrinos separately, assuming no (lower ν_τ-curve) and maximal $\nu_\mu-\nu_\tau$ mixing (upper ν_τ-curve, which would then equal the ν_μ-flux), respectively.

(see Fig. 2). The neutrino flux is hardly influenced by subsequent interactions, and thus directly represents the decay spectrum. In bottom-up scenarios neutrinos can only be produced as secondaries and for sources transparent to the primary nucleons, the neutrino flux is constrained by the Waxman-Bahcall bound [16] which does not apply to top-down scenarios where consequently the neutrino flux can be higher (see Fig. 2). This can also serve as a discriminator between the top-down and bottom-up concepts. Finally, top-down models predict a significant $\gamma-$ray component above $\sim 10^{20}\,$eV, whereas nucleons would dominate at lower energies. This will be a strong discriminator as experiments will improve constraints on EHECR composition which currently favor nucleons [30].

Besides some uncertainties in the shape and chemical composition of the spectrum, possibly the most significant shortcoming of top-down scenarios is their lack of prediction of the absolute flux normalization. At least, the moderate rate of 10 decays per year in a spherical volume with radius equal to the Earth-Sun distance, the rate necessary to explain the EHECR flux, is not in a remote corner of parameter space for most scenarios. Dimensional and scaling arguments imply that topological defects release X particles with an average rate at cosmic time t of

$$\dot{n}_X(t) = \kappa\, m_X^p\, t^{-4+p}\,, \tag{1}$$

where the dimensionless parameters κ and p depend on the specific top-down scenario [6]. For example, hybrid defects involving cosmic strings have $p = 1$ and normalization of predicted spectra both at EGRET energies and around $10^{20}\,$eV (see Fig. 1), leads to $\kappa m_X \sim 10^{13} - 10^{14}\,$GeV. For $\kappa \sim 1$, the resulting mass scale is again close to the inflation and GUT scales.

NEW PRIMARY PARTICLES AND NEW INTERACTIONS

A possible way around the problem of missing counterparts within acceleration scenarios is to propose primary particles whose range is not limited by interactions with the CMB. Within the Standard Model the only candidate is the neutrino, whereas in supersymmetric extensions of the Standard Model, new neutral hadronic bound states of light gluinos with quarks and gluons, so-called R-hadrons that are heavier than nucleons, and therefore have a higher GZK threshold, have been suggested [31].

In both the neutrino and new massive neutral hadron scenario the particle propagating over extragalactic distances would have to be produced as a secondary in interactions of a primary proton that is accelerated in a powerful AGN which can, in contrast to the case of EAS induced by nucleons, nuclei, or $\gamma-$rays, be located at high redshift. Consequently, these scenarios predict a correlation between primary arrival directions and high redshift sources. In fact, possible evidence for an angular correlation of the five highest energy events with compact radio quasars at redshifts between 0.3 and 2.2 was recently reported [32]. A new analysis with the somewhat larger data set now available does not support significant correlations [33]. This is currently disputed since another group claims to have found a correlation on the 99.9% confidence level [34]. Only a few more events could confirm or rule out the correlation hypothesis. Note that these scenarios would require the primary proton to be accelerated up to $\gtrsim 10^{21}$ eV, demanding a very powerful astrophysical accelerator. On the other hand, a few dozen such exceptional accelerators in the visible Universe may suffice.

New Neutrino Interactions

For the remainder we will focus on neutrinos as primary candidates since they have the advantage of being well established particles. However, within the Standard Model their interaction cross section with nucleons, whose charged current part can be parametrized by [35]

$$\sigma_{\nu N}^{SM}(E) \simeq 2.36 \times 10^{-32}(E/10^{19}\,\mathrm{eV})^{0.363}\,\mathrm{cm}^2 \quad (10^{16}\,\mathrm{eV} \lesssim E \lesssim 10^{21}\,\mathrm{eV})\,, \qquad (2)$$

falls short by about five orders of magnitude to produce ordinary air showers. However, it has been suggested that the neutrino-nucleon cross section, $\sigma_{\nu N}$, can be enhanced by new physics beyond the electroweak scale in the center of mass (CM) frame, or above about a PeV in the nucleon rest frame. Neutrino induced air showers may therefore rather directly probe new physics beyond the electroweak scale.

Several possibilities have been discussed in the literature for which unitarity bounds need not be violated. We focus here on the possibility of a large increase in the number of degrees of freedom above the electroweak scale [36]. A specific implementation of this idea is given in theories with n additional large compact dimensions and a quantum gravity scale $M_{4+n} \sim$TeV that has recently received much attention in the literature [37] because it provides an alternative solution (i.e., without supersymmetry) to the hierarchy problem in grand unifications of gauge interactions. The cross sections within such scenarios have not been calculated from first principles yet. Within the field theory approximation which should hold for squared CM energies $s \lesssim M_{4+n}^2$, the spin 2 character of the graviton predicts $\sigma_g \sim s^2/M_{4+n}^6$ [38] For $s \gg M_{4+n}^2$, several arguments based on unitarity within field theory have been put forward. Ref. [38] suggested

$$\sigma_g \simeq \frac{4\pi s}{M_{4+n}^4} \simeq 10^{-27}\left(\frac{M_{4+n}}{\mathrm{TeV}}\right)^{-4}\left(\frac{E}{10^{20}\,\mathrm{eV}}\right)\,\mathrm{cm}^2\,, \qquad (3)$$

where in the last expression we specified to a neutrino of energy E hitting a nucleon at rest. A more detailed calculation taking into account scattering on individual partons leads to similar orders of magnitude [39]. Note that a neutrino would typically start to interact in the atmosphere for $\sigma_{\nu N} \gtrsim 10^{-27}\,\mathrm{cm}^2$, i.e. in the case of Eq. (3) for $E \gtrsim 10^{20}$ eV, assuming $M_{4+n} \simeq 1$ TeV. The neutrino therefore becomes a primary candidate for the observed EHECR events. However, since in a neutral current interaction the neutrino transfers only about 10% of its energy to the shower, the cross section probably has to be at least a few $10^{-26}\,\mathrm{cm}^2$ to be consistent with observed showers which start within the first $50\,\mathrm{g\,cm}^{-2}$ of the atmosphere [40,41]. A specific signature of this scenario would be the absence of any events above the energy where σ_g grows beyond $\simeq 10^{-27}\,\mathrm{cm}^2$ in neutrino telescopes based on ice or water as detector medium [14], and a hardening of the spectrum above this energy in atmospheric detectors such as the Pierre Auger Project [42] and the proposed space based AirWatch type detectors [28,43,44]. Furthermore, according to Eq. (3), the average atmospheric column depth of the first interaction point of neutrino induced EAS in this scenario is predicted to depend linearly on energy. This should be easy to distinguish from the logarithmic scaling expected for nucleons, nuclei, and $\gamma-$rays. To test such scalings one can, for example, take advantage of the fact that the atmosphere provides a detector medium whose column depth increases from $\sim 1000\,\mathrm{g/cm}^2$ towards the zenith to $\sim 36000\,\mathrm{g/cm}^2$ towards horizontal arrival directions. This probes cross sections in the range $\sim 10^{-29} - 10^{-27}\,\mathrm{cm}^2$. Due to the increased column depth water/ice detectors would probe cross sections in the range $\sim 10^{-31} - 10^{-29}\,\mathrm{cm}^2$ [45].

Within string theory, individual amplitudes are expected to be suppressed exponentially above the string scale M_s which for simplicity we assume here to be comparable to M_{4+n}. This can be interpreted as a result of the finite spatial extension of the string states. In this case, the neutrino nucleon cross section would be dominated by interactions with the partons carrying a momentum fraction $x \sim M_s^2/s$, leading to [40]

$$
\begin{aligned}
\sigma_{\nu N} &\simeq \frac{4\pi}{M_s^2}\ln(s/M_s^2)(s/M_s^2)^{0.363} \\
&\simeq 6\times 10^{-29}\left(\frac{M_s}{\mathrm{TeV}}\right)^{-4.726}\left(\frac{E}{10^{20}\,\mathrm{eV}}\right)^{0.363} \\
&\quad\times\left[1+0.08\ln\left(\frac{E}{10^{20}\,\mathrm{eV}}\right)-0.16\ln\left(\frac{M_s}{\mathrm{TeV}}\right)\right]^2\ \mathrm{cm}^2
\end{aligned}
\tag{4}
$$

This is probably too small to make neutrinos primary candidates for the highest energy showers observed, given the fact that complementary constraints from accelerator experiments result in $M_s \gtrsim 1$ TeV [46]. On the other hand, in the total cross section amplitude suppression may be compensated by an exponential growth of the level density [36]. It is currently unclear and it may be model dependent which effect dominates. Thus, an experimental detection of the signatures discussed in this section could lead to constraints on some string-inspired models of extra dimensions.

We note in passing that extra dimensions can have other astrophysical ramifications such as energy loss in stellar environments due to emission of real gravitons into the bulk. The strongest resulting lower limits on M_{4+n} come from the consideration of cooling of the cores of hot supernovae and read $M_6 \gtrsim 50\,\mathrm{TeV}$, $M_7 \gtrsim 4\,\mathrm{TeV}$, $M_8 \gtrsim 1\,\mathrm{TeV}$, and $M_{11} \gtrsim 0.05\,\mathrm{TeV}$ for $n = 2, 3, 4, 7$, respectively [47]. In addition, implications of extra dimensions for early Universe physics and inflation are increasingly studied in the literature, but much work is left to be done on the intersection of these research domains.

Independent of theoretical arguments, the EHECR data can be used to put constraints on cross sections satisfying $\sigma_{\nu N}(E \gtrsim 10^{19}\,\mathrm{eV}) \lesssim 10^{-27}\,\mathrm{cm}^2$. Particles with such cross sections would give rise to horizontal air showers. The Fly's Eye experiment established an upper limit on horizontal air showers [23]. The non-observation of the neutrino flux expected from pions produced by EHECRs interacting with the CMB the results in the limit [45]

$$\begin{aligned}
\sigma_{\nu N}(10^{17}\,\mathrm{eV}) &\lesssim 1 \times 10^{-29}/\bar{y}^{1/2}\,\mathrm{cm}^2 \\
\sigma_{\nu N}(10^{18}\,\mathrm{eV}) &\lesssim 8 \times 10^{-30}/\bar{y}^{1/2}\,\mathrm{cm}^2 \\
\sigma_{\nu N}(10^{19}\,\mathrm{eV}) &\lesssim 5 \times 10^{-29}/\bar{y}^{1/2}\,\mathrm{cm}^2\,,
\end{aligned} \tag{5}$$

where $\bar{y}$ is the average energy fraction of the neutrino deposited into the shower ($\bar{y} = 1$ for charged current reactions and $\bar{y} \simeq 0.1$ for neutral current reactions). Neutrino fluxes predicted in various scenarios are shown in Fig. 1. The projected sensitivity of future experiments such as the Pierre Auger Observatories and the AirWatch type satellite projects indicate that the cross section limits Eq. (5) could be improved by up to four orders of magnitude, corresponding to one order of magnitude in M_s or M_{4+n}. The radio detection technique could also provide an important contribution to test such cross sections beyond The Standard Model.

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