Neutrinos Associated With Cosmic Rays of Top-Down Origin

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Abstract

Top-down models of cosmic rays produce more neutrinos than photons and more photons than protons. In these models, we reevaluate the fluxes of neutrinos associated with the highest energy cosmic rays in light of mounting evidence that they are protons and not gamma rays. While proton dominance at EeV energies can possibly be achieved by efficient absorption of the dominant high-energy photon flux on universal and galactic photon and magnetic background fields, we show that the associated neutrino flux is inevitably increased to a level where it should be within reach of operating experiments such as AMANDA II, RICE and AGASA. In future neutrino telescopes, tens to a hundred, rather than a few neutrinos per kilometer squared per year, may be detected above 1 PeV.

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I. INTRODUCTION

The discovery of cosmic rays with energy exceeding the GZK cutoff \(^{[1]}\) presents an interesting challenge to astrophysics, particle physics, or both \(^{[2, 3]}\). Numerous scenarios have been proposed to solve the problem. These include exotic particles \(^{[4]}\), neutrinos with QCD scale cross sections \(^{[5]}\), semi-local astrophysical sources \(^{[6]}\) and top-down models \(^{[7]}\).

Top-down models can be motivated by a variety of arguments. For example, the recent measurements of the cosmic microwave background and of supernova redshifts have dramatically confirmed that our universe contains a large fraction of cold dark matter \(^{[8]}\). A top-down model in which annihilating or decaying superheavy relic particles produce the highest energy cosmic rays could potentially solve both of these problems \(^{[9, 10]}\). Topological defects could also solve the ultra-high energy cosmic ray problem in a similar way \(^{[7]}\). In this paper, we reevaluate the implications of generic top-down models producing parton jets of \(10^{21}\) or \(10^{25}\) eV that fragment into the observed super GZK cosmic rays.

Established particle physics implies that such ultra high-energy jets fragment predominantly into pions and kaons, with a small admixture of protons \(^{[11]}\). The mesons will eventually decay into photons or electrons plus neutrinos. A typical QCD jet therefore produces more photons than protons. This is true in particular at relatively low values of \(x = E_{\text{particle}}/E_{\text{jet}}\), but even at large \(x\) the photon flux is at least as large as the proton flux in a jet. This seems to be in disagreement with mounting evidence that the highest energy cosmic rays are not photons \(^{[12]}\). The observed shower profile of the original Fly’s Eye event, with energy exceeding \(10^{20}\) eV, fits the assumption of a primary proton, or, possibly, that of a nucleus. The shower profile information is sufficient to conclude that the event is unlikely to be of photon origin. The same conclusion is reached for the Yakutsk event that is characterized by a large number of secondary muons, inconsistent with a purely electromagnetic cascade initiated by a gamma ray. A recent reanalysis of Haverah Park data further reinforces this conclusion \(^{[13]}\). In light of this information, it seems likely that protons, and not gamma rays, dominate the highest energy cosmic ray spectrum. This does not necessarily rule out superheavy particles as the source of the highest energy cosmic rays. The uncertainties associated with the cascading of the jets in the universal and galactic radio backgrounds and with the strength of intergalactic magnetic fields leave open the possibility that ultra high-energy photons may be depleted from the cosmic ray spectrum near \(10^{20}\)
eV, leaving a dominant proton component at GZK energies [14, 15]. With this in mind, we will choose to normalize the proton spectrum from top-down scenarios to the observed ultra high-energy cosmic ray flux.

Neutrinos are produced more numerously than protons and travel much greater distances. The main point of this paper is to point out that this “renormalization” of the observed cosmic ray flux to protons generically predicts observable neutrino signals in operating experiments such as AMANDA II, RICE and AGASA. Top-down models, if not revealed, will be severely constrained by high-energy neutrino observations in the near future.

II. NUCLEONS FROM ULTRA-HIGH ENERGY JETS

The assumption that nucleons from the decay (or annihilation) of very massive $X$ particles are the source of the highest energy cosmic rays normalizes the decay or annihilation rate of their sources, once the shape of the spectrum of the produced nucleons is known. One needs mass $M_X \geq 10^{21}$ eV in order to explain the observed UHECR events. The presence of such very massive particles strongly indicates the existence of superparticles with masses at or below the TeV scale, since otherwise it would be difficult to keep the weak energy scale ten or more orders of magnitude below $M_X$ in the presence of quantum corrections. Moreover, we know that all gauge interactions are of comparable strength at energies near $M_X$. These two facts together imply that the evolution of a jet with energy $\geq 10^{21}$ eV shows some new features not present in jets produced at current particle collider experiments.

First of all, primary $X$ decays are likely to produce approximately equal numbers of particles and superparticles, since $M_X$ is much larger than the scale $M_{\text{SUSY}} \leq 1$ TeV of typical superparticle masses. Even if the primary $X$ decay only produces ordinary particles, superparticles will be produced in the subsequent shower evolution. Note also that (at least at high energies) electroweak interactions should be included when modeling the parton shower. Both effects taken together imply that the jet will include many massive particles – superparticles, electroweak gauge and Higgs bosons, and also top quarks. The decays of these massive particles increase the overall particle multiplicity of the jet, and also produce quite energetic neutrinos, charged leptons and lightest supersymmetric particles (LSP). Eventually the quarks and gluons in the jet will hadronize into baryons and mesons, many of which will in turn decay.
We model these jets at the point of their origin using the program described in Ref. [16]. This program allows us to calculate spectra for different $X$ decay modes. It then follows the supersymmetric parton cascade down to virtuality (or inverse time) of the order of $M_{\text{SUSY}}$, including all gauge interactions as well as third generation Yukawa interactions. At $M_{\text{SUSY}}$ all massive particles are decoupled from the parton shower, and decay. Supersymmetric cascade decays are fully taken into account; the results presented below have been obtained using the same spectrum of superparticles as in ref. [16]. At virtualities below $M_{\text{SUSY}}$ only ordinary QCD interactions contribute significantly to the development at the jet; $b$ and $c$ quarks are decoupled at their respective masses, hadronize, and decay. At a virtuality near 1 GeV the light quarks and gluons hadronize, with a meson to baryon ratio of roughly thirty to one (five to one) at small (large) $x$. All baryons will eventually decay into protons, while the mesons (mostly pions) decay into photons, electrons [17] and neutrinos (plus their antiparticles). The heavier charged leptons (muons and taus) also decay. The final output of the code is the spectra of seven types of particles which are sufficiently long–lived to reach the Earth: protons, electrons, photons, three flavors of neutrinos, and LSPs. We assume that $X$ decays are CP–symmetric, i.e. we assume equal fluxes of particles and antiparticles of a given species.

The calculation of Ref. [16] was based on conventional one–loop evolution equations for the relevant fragmentation functions. These may not be reliable in the region of very small $x$. We wish to calculate neutrino fluxes at energies down to $\sim 10^{15}$ eV (1 PeV), which corresponds to $x \sim 10^{-6}$ ($10^{-10}$) for $M_X = 10^{21}$ ($10^{25}$) eV. At these very small $x$ values color coherence effects are expected to suppress the shower evolution [18]. We try to estimate the size of these effects by matching our spectra computed using conventional evolution equations to the so–called asymptotic MLLA spectra; details of this procedure will be described elsewhere [19]. The effect of this modification on the neutrino event rate is relatively modest for primary jet energy near $10^{21}$ eV, but becomes significant at $10^{25}$ eV. However, even at this higher energy the proton flux, which we only need at $x \geq 10^{-5}$, is not affected significantly.

This calculation gives us the shape of the spectra of the stable particles at source. The spectra on Earth might differ significantly due to propagation effects. As stated in the introduction, we will assume that (almost) all UHE photons get absorbed. This is actually expected to be true for a homogeneous source distribution. However, according to current estimates of the strengths of the magnetic fields and of the radio wave background in (the
FIG. 1: The ultra high-energy cosmic ray flux predicted for the decay of superheavy particles with mass $M_X = 2 \cdot 10^{21}$ eV is compared to the HIRES (darker) and AGASA (lighter) cosmic ray data. The distribution of jets used includes an overdensity factor of $10^5$ within 20 kpc of the galaxy. Spectra are shown for quark+antiquark (solid), quark+squark (dot-dash), $SU(2)$ doublet lepton+slepton (dots) and 5 quark+5 squark (dashes) initial states. Dark lines are from top-down origin alone whereas lighter lines are top-down plus an homogeneous extragalactic contribution as predicted in Ref. [14]. Note that all observed super GZK events can be explained by this mechanism.

halo of) our own galaxy most UHE photons produced in the halo of our galaxy are expected to reach the Earth. As stated in the Introduction, this seems to be in conflict with observation. We will therefore assume that the interaction length of UHE photons in our galaxy has been greatly over–estimated, and explore the consequences of this assumption for neutrino signals.

As well known, (anti)protons lose energy when traveling through the intergalactic medium, mostly through scattering off photons of the ubiquitous cosmic microwave background (CMB). We calculate the observed spectrum of protons taking into account scattering off the CMB at the $\Delta-$resonance and scattering by $e^+e^-$ pair production; energy losses
FIG. 2: As in figure 1, but using particles of mass $M_X = 2 \cdot 10^{25}$ eV.

through the Hubble expansion of the Universe are also included [14, 20]. Note that the photo-

toproduction of charged pions contributes to the observed neutrino flux on Earth. In order to solve the ultra high-energy cosmic ray problem, the (anti)proton flux must accommodate the events above the GZK cutoff. Observations indicate on the order of a few times $10^{-27}$ events $\text{m}^{-2}\text{s}^{-1}\text{sr}^{-1}\text{GeV}^{-1}$ in the energy range above the GZK cutoff ($5 \times 10^{19}$ eV to $2 \times 10^{20}$ eV)[2, 3].

The formalism of a generic top-down scenario is sufficiently flexible to explain the data from either the HIRES [3] or AGASA [2] experiments. Figure 1 compares HIRES and AGASA data to the proton spectrum predicted for a galactic distribution of decaying particles with mass $M_X = 2 \cdot 10^{21}$ eV. The drop near a few times $10^{19}$ eV is a manifestation of the GZK cutoff. Note, however, that there are sufficient semi-local events to explain all observed super GZK events. Similarly, figure 2 compares HIRES and AGASA data to the spectrum predicted for $M_X = 2 \cdot 10^{25}$ eV, rather than $2 \cdot 10^{21}$ eV, decaying particles for the same distribution. Although HIRES and AGASA data differ at face value, especially above the GZK cutoff, top-down scenarios can accommodate all events observed above the GZK
cutoff in either experiment.

If the cosmic ray sources are not distributed with a large overdensity in the galaxy, the resulting cosmic ray and neutrino spectrum will be modified. For example, using a homogeneous distribution, the GZK cutoff will again be manifest and the observed cosmic ray spectrum will be difficult to explain. A galactic overdensity of $10^3$ to $10^4$ or more seems necessary to fit the data. The figure 1 shows a $10^5$ overdensity, which is the overall overdensity of matter in our galaxy at the location of the Sun. Note that for less extreme overdensities, the average distance at which a proton is produced will be larger. This implies larger energy losses, and hence a reduced proton flux on Earth for a given number of sources. Conversely, if we fix the proton flux to the observed flux of UHECR events, models with lower overdensity require more sources. Since neutrino fluxes are not degraded by propagation through the intergalactic medium, the number of neutrinos increases proportionally to the number of sources, with additional contributions to the neutrino flux coming from pion production on the CMB background. Thus, the neutrino event rates and spectrum shown in the figures reflect the most conservative choice of distributions. The table shows results for both homogeneous and galactic distributions.

III. NEUTRINOS FROM ULTRA HIGH-ENERGY JETS

As discussed earlier, the program computing the proton flux at source also gives the neutrino flux at source. Neutrinos, not being limited by scattering, travel up to the age of the universe at the speed of light ($\sim 3000$ Mpc in an Euclidean approximation). The only nontrivial effect of neutrino propagation is due to oscillations. In our case the propagation distance of neutrinos amounts to many oscillation lengths, if oscillation parameters are fixed by the currently most plausible solutions of the atmospheric and solar neutrino deficits [21]. As a result, the UHE neutrino flux on Earth is the same for all three flavors, and amounts to the average of the fluxes of the three neutrinos flavors at source.

The predicted neutrino flux is shown in figures 3 and 4. At $E_\nu \ll E_{\text{jet}}$ the main contribution comes from $\pi^\pm \rightarrow \mu^\pm \nu_\mu \rightarrow e^\pm \nu_e \nu_\mu$ decays, but at larger $E_\nu$ there can be significant contributions from the decays of heavy (s)particles. The peak in the dotted curves at $E_\nu = E_{\text{jet}}$ results from our assumption that in this scenario $X$ decays directly into first or second generation $SU(2)$ doublet (s)leptons, which implies that 50% of all $X$ decays give rise
to a primary neutrino; in this case the ratio of neutrino and proton fluxes has a maximum at high energy. On the other hand, if primary $X$ decays are purely hadronic, the neutrino flux at the largest energy is only slightly above the proton flux at that energy. The reason is that neutrinos from meson decays only carry a fraction of the energy of the meson, so a five to one meson to proton ratio at large $x$ leads to a nearly one to one neutrino to proton ratio. We see that the neutrino flux at the highest energy depends quite strongly on how the $X$ particles decay; there is also some dependence on the parameters of the SUSY model [16, 19]. For given proton flux the neutrino flux at smaller $x$ is much less model dependent. At very small $x$ a new uncertainty appears due to coherence effects. These have so far only been studied in a pure QCD parton shower; our treatment of these effects is therefore of necessity rather crude.

![Predicted Neutrino Flux](image)

**FIG. 3:** The neutrino plus anti-neutrino flux corresponding to the cosmic ray spectra of figure 1 from the decay of superheavy particles with mass $M_X = 2 \cdot 10^{21}$ eV. Spectra are shown for quark-antiquark (solid), quark-squark (dot-dash), lepton-slepton (dots) and 5 quark-5 squark (dashes) initial states.
IV. EVENT RATES IN HIGH-ENERGY NEUTRINO TELESCOPES AND AIR SHOWER EXPERIMENTS

We will discuss two classes of experiments capable of observing high energy cosmic neutrinos: neutrino telescopes and air shower experiments.

Optical Cerenkov neutrino telescopes such as the operating AMANDA II and next generation IceCube are designed to observe muon tracks from charged current interactions as well as showers which occur in the detector. The probability of detecting a neutrino passing through the detector from its muon track is given by

$$P_{\nu \rightarrow \mu}(E_{\nu}, \theta_{\text{zenith}}) = \sigma_{\nu N}(E_{\nu}) n_{\text{H}_2\text{O}} R_{\mu}(E_{\mu}, \theta_{\text{zenith}})$$

where $n_{\text{H}_2\text{O}}$ is the number density of nucleons in the detector medium (water or ice), and the muon range $R_{\mu}(E_{\mu}, \theta_{\text{zenith}})$ is the average distance traveled by a muon of energy $E_{\mu}$ before falling below some threshold energy (we have used 100 TeV). This quantity depends on the zenith angle of the incoming neutrino because for a detector depth of $\sim 2$ km, only
quasi-horizontal or upgoing events can benefit from longer muon ranges. At the energies we
are most concerned with, the majority of muon events will be quasi-horizontal. The number
of muon events observed is then given by
\[ N_{\text{events}} = \int dE_\nu \, d\Omega \frac{d\phi_\nu}{dE_\nu} P_{\nu \rightarrow \mu}(E_\nu, \theta_{\text{zenith}}) A_{\text{eff}} \, T, \]  
where \( T \) is the time observed and \( A_{\text{eff}} \) is the effective area of the detector: one twentieth
square kilometers for AMANDA II and one square kilometer for IceCube.

AMANDA II and IceCube can also observe showers generated in charged or neutral
current interactions within the detector volume. The event rate from showers is not enhanced
by long muon ranges, but can be generated by all three flavors of neutrinos and with greater
cross section (neutral + charged current). We use a shower energy threshold of 100 TeV.
The energy threshold imposed effectively removes any background events from atmospheric
neutrino events. For a review of Optical Cerenkov neutrino telescopes see Ref.\[22\].

The operating radio Cerenkov experiment, RICE, is capable of observing showers generated in charged current electron neutrino events. RICE’s effective volume increases with
energy. At 100 TeV, RICE has an effective volume less than one hundredth of a cubic kilo-
meter. By 10 PeV, however, it increases to about ten cubic kilometers \[23\]. Again, we use
a hard 100 TeV shower threshold.

Air shower experiments can also observe very high energy cosmic neutrinos. We con-
sider AGASA, the largest ground array currently in operation \[24\], and the next generation
AUGER array \[25\].

To determine that an air shower was initiated by a neutrino, rather than a proton or
other cosmic ray, we require a slant depth greater than 4000 g/cm². This corresponds to
a zenith angle very near 75 degrees. Therefore, only quasi-horizontal air shower events can
be identified as neutrinos. Additionally, unlike showers generated in the upper atmosphere,
deeply penetrating showers provide both muon and electromagnetic shower components
which help them be differentiated from showers with hadronic primaries. The probability of
detecting and identifying a neutrino initiated air shower is described in terms of the array’s
acceptance, \( A \), in units of volume times water equivalent steradians (we sr). The detector’s
acceptance increases with energy. For AGASA, the acceptance is about 0.01 km³ we st at 10⁷
GeV but increases to 1.0 km³ we st at 10¹⁰ GeV and above. For AUGER, the acceptance is
about 0.1 km³ we st at 10⁷ GeV, 10.0 km³ we st at 10⁹ GeV and 50.0 km³ we st at 10¹² GeV.
The number of events observed is then

\[ N_{\text{events}} = \int dE_\nu d\Omega n_{\text{H}_2\text{O}} \frac{d\phi_\nu}{dE_\nu} \sigma_{\nu N}(E_\nu) A(E_\nu) T, \]  

(3)

where \( T \) is again the time observed, \( n_{\text{H}_2\text{O}} \) is the number density of nucleons in water and \( A(E_\nu) \) is the detector’s acceptance. AGASA presently has about five years of effective running time between 1995 and 2000 analyzed. A useful treatment of air shower event rates from neutrinos can be found in Ref. [26].

|                  | AMANDA II | AGASA | RICE | IceCube | AUGER |
|------------------|-----------|-------|------|---------|-------|
| \( q\bar{q}, 10^{21} \text{ eV, Galactic} \) | 0.39      | 0.056 | 11.5 | 12.2    | 1.5   |
| \( q\bar{q}, 10^{21} \text{ eV, Galactic} \) | 0.36      | 0.052 | 10.7 | 11.4    | 1.4   |
| \( 5 \times q\bar{q}, 10^{21} \text{ eV, Galactic} \) | 1.4       | 0.11  | 33.7 | 44.6    | 3.1   |
| \( l\bar{l}, 10^{21} \text{ eV, Galactic} \) | 0.96      | 0.20  | 24.5 | 29.8    | 7.0   |
| \( q\bar{q}, 10^{25} \text{ eV, Galactic} \) | 0.041     | 0.019 | 1.1  | 1.2     | 0.60  |
| \( q\bar{q}, 10^{25} \text{ eV, Galactic} \) | 0.039     | 0.018 | 1.0  | 1.1     | 0.56  |
| \( 5 \times q\bar{q}, 10^{25} \text{ eV, Galactic} \) | 0.039     | 0.016 | 1.1  | 1.1     | 0.50  |
| \( l\bar{l}, 10^{25} \text{ eV, Galactic} \) | 0.047     | 0.022 | 1.3  | 1.4     | 0.69  |
| \( q\bar{q}, \text{ no MLLA, } 10^{25} \text{ eV, Galactic} \) | 0.27      | 0.041 | 7.0  | 8.9     | 1.2   |
| \( q\bar{q}, 10^{21} \text{ eV, Homogeneous} \) | 3.5       | 0.50  | 103.8| 110.3   | 13.2  |
| \( q\bar{q}, 10^{21} \text{ eV, Homogeneous} \) | 3.2       | 0.47  | 95.9 | 102.2   | 12.3  |
| \( 5 \times q\bar{q}, 10^{21} \text{ eV, Homogeneous} \) | 6.9       | 0.57  | 168.3| 223.2   | 15.4  |
| \( l\bar{l}, 10^{21} \text{ eV, Homogeneous} \) | 4.8       | 1.0   | 122.5| 149.2   | 35.0  |
| \( q\bar{q}, 10^{25} \text{ eV, Homogeneous} \) | 0.62      | 0.28  | 16.5 | 18.0    | 9.0   |
| \( q\bar{q}, 10^{25} \text{ eV, Homogeneous} \) | 0.58      | 0.27  | 15.5 | 16.9    | 8.5   |
| \( 5 \times q\bar{q}, 10^{25} \text{ eV, Homogeneous} \) | 0.58      | 0.25  | 17.0 | 17.1    | 7.5   |
| \( l\bar{l}, 10^{25} \text{ eV, Homogeneous} \) | 0.71      | 0.33  | 18.9 | 20.7    | 10.3  |
| \( q\bar{q}, \text{ no MLLA, } 10^{25} \text{ eV, Homogeneous} \) | 4.1       | 0.61  | 104.6| 133.2   | 17.9  |

**Table 1:** Neutrino events per year in top-down scenarios for several operating and next generation experiments. For AMANDA II and IceCube, 100 TeV shower and muon energy thresholds were imposed. Events are only calculated up to \( 10^{12} \text{ GeV} \) as discussed in the text.

Table 1 shows the event rates expected for a variety of models, and for several experiments.
AMANDA-II, with an effective area of \( \sim 50,000 \) square meters can place the strongest limits on high energy neutrino flux presently. Furthermore, AGASA, with five years of effective observing time, has similar sensitivity. RICE, just beginning to release results, will be capable of raising the level to which top-down scenarios can be tested, perhaps being capable of testing all 16 models shown in the table. Even if no events are observed with operating experiments, next generation experiments, especially IceCube, will be able to test all models with adequate sensitivity.

Event rates shown in table 1 include only events below \( 10^{12} \) GeV. Above this energy, uncertainties in the neutrino-nucleon cross sections and in detector performance make such calculations difficult and unreliable. Our most reasonable extrapolations into this energy range indicate about a 20\% enhancement to the event rate if all energies are considered for \( 10^{25} \) eV jets. There is no effect for the \( 10^{21} \) eV jet case.

High-energy neutrino event rates have been calculated in Ref. [27] for a similar model. Their calculation used the model of reference [28] which normalized the ultra high-energy cosmic ray flux to the photons and protons generated in superheavy particle decay rather than the proton flux alone. For this reason, their results show only two events per year in a square kilometer neutrino telescope, a smaller rate than we predict for most models. Another recent estimate of neutrino fluxes on Earth in top–down models [29] finds broadly similar results as our’s. However, there the ‘MLLA’ form for the fragmentation functions was used for all energies, which (incorrectly) predicts nearly energy–independent ratios of neutrino, photon and proton fluxes.

V. CONCLUSIONS

If a top-down scenario, such as the decay or the annihilation of superheavy relics, is the source of the highest energy cosmic rays, then a high-energy neutrino flux should accompany the observed cosmic ray flux. This neutrino flux will be much higher than the flux of nucleons due to the much greater mean free path of neutrinos and greater multiplicity of neutrinos produced in high-energy hadronic jets.

The high-energy neutrino flux generated in such a scenario can be calculated by normalizing the flux of appropriate particles to the ultra–high energy cosmic ray flux. With mounting evidence that the highest energy cosmic rays are protons or nuclei and not photons, we have
assumed that the ultra high-energy photons are degraded by the universal and/or galactic radio background, leaving protons to dominate the highest energy cosmic ray flux. The neutrino flux must then be normalized to the proton flux resulting in significantly improved prospects for its detection.

A word about the uncertainties in our calculation might be in order. First of all, the uncertainty of the measured UHECR flux, and in particular the discrepancy between the HIRES and AGASA results, leads to an overall uncertainty of a factor of $2 - 3$. On the theoretical side, the main uncertainty probably comes from the calculation of the particle spectra at “small” energies, where currently not very well understood coherence effects can play a role. This effect is bigger for higher primary jet energy, and can change the event rate by up to a factor of about 7 (see table). Relaxing our assumption that all UHE photons are absorbed would lead to a corresponding reduction of the fitted source density, and hence of the neutrino flux. In this context it is worth mentioning that in the scenario which seems to fit the data best, with primary jet energy near $10^{21}$ eV and a galactic source overdensity of about $10^5$ (see Fig. 1 and ref. [30]), including the photon flux fully would only reduce the predicted event rate by a factor of two to three, since in this case the flux of $10^{20}$ eV photons at source is only slightly larger than the corresponding proton flux. This would still give a neutrino flux in easy striking range of km$^2$ scale detectors.

This paper shows that the neutrino flux accompanying the highest energy cosmic rays in top-down scenarios is of order of the limits placed by operating experiments such as AMANDA II, RICE and AGASA. Further data from these experiments, or next generation experiments IceCube and AUGER, can test the viability of top-down scenarios which generate the highest energy cosmic rays. If a signal is found soon, future high statistics experiments should be able to map out the neutrino spectrum, thereby allowing us direct experimental access to physics at energy scales many orders of magnitude beyond the scope of any conceivable particle collider on Earth.

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