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# Cosmological neutrino signatures for grand unification scale physics

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## Abstract

Physics beyond the standard model might imply the cosmological production of particles with grand unification scale energies. Nucleons and  $\gamma$ -rays from such processes are candidates for the cosmic rays observed beyond 100 EeV ( $10^{20}$  eV). Using a new particle propagation code, we calculate the neutrino fluxes predicted by such scenarios if consistency with the observed cosmic ray flux and the universal  $\gamma$ -ray background at 1–10 GeV is required. Flux levels detectable by proposed  $\text{km}^3$  scale neutrino observatories are allowed by these constraints. Bounds on or detection of a neutrino flux above  $\sim 1$  EeV would allow neutrino astronomy to probe grand unification scale physics.

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The recent detection of ultra-high energy cosmic rays (UHE CRs) with energies above 100 EeV [1,2] has prompted an intensive discussion in the literature on the nature and origin of these particles [3–5]. At these energies, nucleons and heavy nuclei are subject to photopion production on the cosmic microwave background (CMB) (the Greisen-Zatsepin-Kuzmin effect [6]), and to photodisintegration via the giant dipole resonance [7], respectively, which limits their range to less than about 30 Mpc. Together with the fact that protons above 100 EeV are expected to be deflected by only a few degrees in the galactic and extragalactic magnetic fields [3], this puts severe constraints on models explaining these events by acceleration of charged particles in active galactic nuclei (AGN) or other known astronomical objects.

In a more speculative class of so-called “top-down” (TD) models, predominantly  $\gamma$ -rays, electrons (positrons), and neutrinos are produced directly at UHEs by the cascades initiated by the decay of a supermassive elementary “X” particle associated with some grand unified theory (GUT), rather than being accelerated. The X particles are usually thought to be released from topological defects such as cosmic strings, domain walls and magnetic monopoles left over from GUT phase transitions. Models of this type predict spectra which are considerably harder and extend much further beyond 100 EeV than shock acceleration spectra and therefore appear as a natural alternative to explain the highest energy events observed [8]. The predicted flux level is very model dependent [9], but, in at least some of the scenarios

considered [10], is consistent with the observed UHE CR fluxes.

Several signatures which might distinguish top-down scenarios from more conventional “bottom-up” acceleration models have been suggested in the literature: above  $\simeq 100$  EeV, domination of the UHE CR flux by a hard  $\gamma$ -ray component [11], which potentially produces a “gap” [12] in the UHE CR spectrum, and at lower energies  $\simeq 10$  EeV, a  $\gamma$ -ray to total cosmic ray flux ratio on the order of 10% [13]. Another potentially important signature of TD models is their prediction of a large cosmological neutrino flux [8] which above 100 EeV can dominate by far contributions expected from other sources such as AGN [14]. TD scenarios also predict a substantial  $\gamma$ -ray flux at lower (GeV) energies that is constrained by the observed background levels [15,16,13,17]. In this Letter, we use a new propagation code [18] to establish a relation between the UHE neutrino flux predictions within TD scenarios and the constraints arising from the corresponding  $\gamma$ -ray flux predictions around 1 GeV and above  $\sim 10$  EeV. For  $\text{km}^3$  scale neutrino observatories, prototypes of which are AMANDA, DUMAND, Baikal, and NESTOR [19], we estimate the UHE neutrino event rates predicted by a TD scenario which explains UHE CRs and give the maximum event rates consistent with the  $\gamma$ -ray flux constraints. We also estimate rates for deeply penetrating showers for fluorescence detectors such as the High Resolution Fly’s Eye (HiRes) [20] and the Telescope Array [21], and for horizontal neutrino events that might be observed in the proposed Pierre Auger project [22].

The X particles released from topological defects via physical processes such as collapse or annihilation could have GUT scale masses  $m_X$  up to  $\sim 10^{16}$  GeV. We assume that the X particles quickly decay into leptons and quarks of comparable energy. We take the primary lepton produced in a decay to be an electron with energy  $m_X/2$ . This lepton was not included in prior calculations but can significantly contribute to the  $\gamma$ -ray flux predicted at low energies. The quarks produced in the decays interact strongly and fragment into jets of hadrons typically containing  $10^4$ – $10^5$  mesons and baryons. Given the X particle production rate,  $dn_X/dt$ , the effective production spectrum for particle species  $a$  ( $a = \gamma, N, e^\pm, \nu$ ) via this hadronic channel can be

written as  $\Phi_a(E, t) = (dn_X/dt)(2/m_X)(dN_a/dx)$ , where  $x \equiv 2E/m_X$ , and  $dN_a/dx$  is the relevant effective fragmentation function. For the total hadronic fragmentation function  $dN_h/dx$  we use solutions of the QCD evolution equations in modified leading logarithmic approximation which provide good fits to accelerator data at LEP energies [23]. We assume that about 3% of the total hadronic content consists of nucleons and the rest is produced as pions and distributed equally among the three charge states. The effective production spectra of  $\gamma$ -rays, electrons, and neutrinos are then determined from the pion decay spectra. The X particle production rate is assumed to be spatially uniform and in the matter-dominated era can be parametrized as [8]  $dn_X/dt \propto t^{-4+p}$ , where  $p$  depends on the specific defect scenario. A network of ordinary cosmic strings [24] and annihilation of magnetic monopole-antimonopole pairs [10] are represented by  $p = 1$ , whereas  $p = 2$  corresponds to a constant comoving production rate. As there is considerable uncertainty in the TD model physics, we will not explicitly consider any specific TD scenario. Rather, we parametrize a TD model by the typical X particle mass,  $m_X$ , the X particle production rate at zero redshift,  $(dn_X/dt)(z = 0)$ , and the cosmological evolution of this rate, determined by  $p$ .

The shapes of the UHE nucleon and  $\gamma$ -ray spectra predicted within TD models are “universal” in the sense that they depend only on the physics of X particle decay. This is because at UHEs nucleons and  $\gamma$ -rays have attenuation lengths in the cosmic microwave background (CMB) which are small compared to the Hubble scale. Cosmological evolutionary effects which depend on the specific TD model are therefore negligible. Since the resulting spectra tend to be harder than any other components from acceleration sources, TD mechanisms could contribute to the flux dominantly above  $\simeq 100$  EeV, but negligibly in the range  $10^{14}$  eV–10 EeV.

In contrast to the universality of UHE spectral shapes, the predicted  $\gamma$ -ray flux below  $\sim 10^{14}$  eV (the threshold for pair production of photons on the CMB) and the predicted neutrino flux depend on the total energy release integrated over redshift and thus on the specific TD model. Compared to acceleration scenarios, this energy release can be substantial, especially at high redshifts where conventional sources such as galaxies are not expected to contribute. The produc-

tion of UHE particles in TD scenarios is therefore subject to a variety of constraints of mostly cosmological nature. Electromagnetic (EM) energy injected into the universe above the pair production threshold on the CMB is recycled into a generic cascade spectrum below this threshold on a time scale short compared to the Hubble time. This can have several potentially observable effects [16] such as modified light element abundances due to  ${}^4\text{He}$  photodisintegration [25] and distortions of the CMB. Comparison with observational data already rules out the class of TD scenarios corresponding to  $p = 0$  [16] to which certain superconducting cosmic string models belong [26].

In addition, for a TD scenario to be viable, its predicted spectrum must be consistent with all flux measurements and limits available for energies between  $\simeq 100$  MeV and a few 100 EeV. Observational data on the universal  $\gamma$ -ray background in the 1–10 GeV region [27], to which the generic cascade spectrum would contribute directly, turn out to provide an important constraint. Since the UHE  $\gamma$ -ray flux is especially sensitive to certain astrophysical parameters such as the extragalactic magnetic field (EGMF), a reliable calculation of the predicted spectral shapes requires numerical methods. To this end we recently performed extensive numerical simulations for the propagation of extragalactic nucleons,  $\gamma$ -rays and electrons (positrons) in the energy range  $10^8 \text{ eV} < E < 10^{25} \text{ eV}$ , details of which are given in Refs. [13,18]. The calculations take into account all the relevant interactions with the (redshift dependent) universal low energy photon background in the radio, microwave and optical/infrared regime. For nucleons this includes production of  $e^{+-}$  pairs (for protons) and multiple pions. The  $\gamma$ -rays interact via production of single and double  $e^{+-}$  pairs, and electrons via inverse Compton scattering and triplet pair production. In addition, electrons can suffer significant synchrotron losses in EGMFs. We assume a flat universe, a Hubble constant of  $H_0 = 75 \text{ km sec}^{-1} \text{ Mpc}^{-1}$ , and zero cosmological constant.

Neutrino fluxes within TD scenarios have been calculated before in the literature: Ref. [29] contains a discussion of the (unnormalized) predicted spectral shape and Ref. [30] computes the absolute flux predicted by specific processes such as cusp evaporation on ordinary cosmic strings. Ref. [8] and Ref. [31]

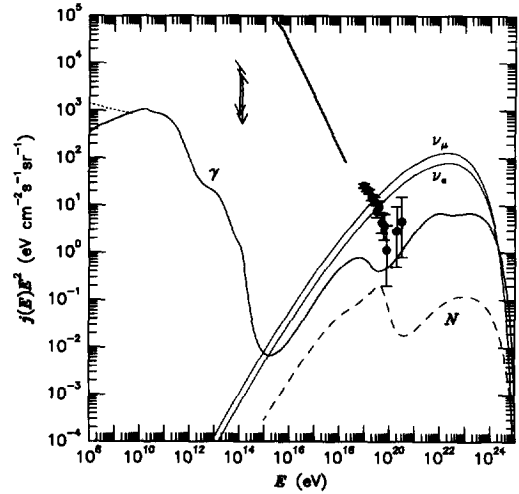


Fig. 1. Predictions for the differential fluxes of  $\gamma$ -rays (solid line), nucleons (dashed line), and  $\nu_\mu$  (or  $\bar{\nu}_\mu$ ),  $\nu_e$  (or  $\bar{\nu}_e$ ) (thin solid lines in decreasing order) by the TD model characterized by  $p = 1$ ,  $m_X = 2 \times 10^{25} \text{ eV}$ , assuming an EGMF of  $10^{-12} \text{ G}$ . Also shown are the combined data from the Fly's Eye [1] and the AGASA [2] experiments above 10 EeV (dots with error bars), piecewise power law fits to the observed charged CR flux (thick solid line) and experimental upper limits on the  $\gamma$ -ray flux at 1–10 GeV from EGRET data [27] (dotted line on left margin). The arrows indicate limits on the  $\gamma$ -ray flux from Ref. [28].

also calculate absolute fluxes within scenarios such as the one discussed above, with Ref. [31] discussing in detail neutrino propagation and experimental issues related to the HiRes and the Telescope Array experiments. However, none of these discussions take into account the cosmological constraints on TD models, in particular from the low energy  $\gamma$ -ray spectrum.

Fig. 1 shows flux predictions from our code for a typical TD scenario for an EGMF of  $10^{-12} \text{ G}$ . In this scenario, the UHE CR events are assumed to be cascade  $\gamma$ -rays produced by the decay of X particles whose decay rate has been normalized accordingly. Although  $\gamma$ -ray primaries might be somewhat disfavored [4], this is consistent with the currently unknown UHE CR composition. The  $\gamma$ -ray and nucleon fluxes shown in Fig. 1 are consistent with observational estimates of the integral flux above 300 EeV [1,2], with a likelihood significance above 50% for  $E \gtrsim 100 \text{ EeV}$ , and with all data at lower energies. Interestingly, the constraints arising from the diffuse  $\gamma$ -ray background observed at 1–10 GeV [27] are somewhat less stringent than earlier analytical

estimates [15,16]. As a consequence, for EGMFs  $\lesssim 10^{-9}$  G TD scenarios with X particle masses as high as  $10^{16}$  GeV can still be viable models of UHE CRs [13]. As in Ref. [8], the accompanying neutrino fluxes which are also shown in Fig. 1 were calculated using the absorption cross section of UHE neutrinos in the thermal neutrino background. The resulting fluxes satisfy present bounds from the Fréjus detector [32] within about five orders of magnitude. With fluxes of this level, neutrinos are unlikely UHE CR candidates because of their low interaction probability in the atmosphere [33].

UHE neutrinos can produce muons in ordinary matter via charged current reactions with nucleons (Ns) [34,35]. The most recent calculation of the corresponding cross section can roughly be parametrized by  $\sigma_{\nu N}(E) \simeq 2.82 \times 10^{-32} \text{ cm}^2 (E/10 \text{ EeV})^{0.402}$  for  $E \gtrsim 1 \text{ PeV}$ , where  $E$  is the neutrino energy [35]. We note that uncertainties of the  $\nu N$  cross sections above 10 EeV from extrapolation of QCD evolution of up to a factor of 10 translate into corresponding uncertainties in the predicted rates. For an (energy dependent) ice or water equivalent acceptance  $A(E)$  (in units of volume times solid angle), one can obtain an approximate expected rate of UHE muons produced by neutrinos with energy  $> E$ ,  $R(E)$ , by multiplying  $A(E)\sigma_{\nu N}(E)n_{\text{H}_2\text{O}}$  with the integral muon neutrino flux  $\simeq E j_{\nu_\mu}$ . Here,  $n_{\text{H}_2\text{O}}$  is the nucleon density in water. The neutrino energy and arrival direction can be reconstructed from the observed muon bremsstrahlung and the track geometry. Alternatively, one could use acoustic detection methods. The backgrounds are in general expected to be small [19,36]. The rate prediction from the model shown in Fig. 1 can be written as

$$R(E) \simeq 6 \times 10^{-3} \left[ \frac{A(E)}{1 \text{ km}^3 \times 2\pi \text{ sr}} \right] \times \left( \frac{E}{10 \text{ EeV}} \right)^{-0.1} \text{ yr}^{-1} \quad (1)$$

around  $E \sim 10 \text{ EeV}$ . Above  $\simeq 100 \text{ EeV}$  the corresponding fluxes would dominate all present model predictions for AGN neutrino fluxes [14] as well as the flux of “cosmogenic” neutrinos produced by interactions of UHE CRs with the universal photon background [37,38,31]. Note that the  $p = 0$  model in Ref. [8] which implies neutrino event rates about three

orders of magnitude higher than Eq. (1) is ruled out because of overproduction of low energy  $\gamma$ -rays [13]. We also note that UHE neutrinos can produce lepton pairs on the thermal neutrino background via the Glashow resonance [39] whose decay products in turn contain secondary neutrinos. As was shown in Ref. [29], for  $m_X \gtrsim 10^{24} \text{ eV}$  this effect, which was not taken into account in our simulation, can increase neutrino fluxes around 100 EeV by factors of a few which makes our estimate Eq. (1) conservatively low. Our flux estimates are further reduced compared to Ref. [31] for similar scenarios by our normalization procedure which assures consistency of predicted  $\gamma$ -ray and nucleon fluxes with observational data at all energies.

For detectors based on the fluorescence technique such as the HiRes [20] and the Telescope Array [21], the sensitivity to UHE neutrinos is often expressed in terms of an effective aperture  $a(E)$  which is related to  $A(E)$  by  $a(E) = A(E)\sigma_{\nu N}(E)n_{\text{H}_2\text{O}}$ . For the cross sections from Ref. [35], the apertures given in Ref. [20] for the HiRes correspond to  $A(E) \simeq 3 \text{ km}^3 \times 2\pi \text{ sr}$  for  $E \gtrsim 10 \text{ EeV}$  for muon neutrinos. The expected acceptance of the proposed Pierre Auger project for horizontal UHE neutrino induced events is  $\simeq 20 \text{ km}^3 \text{ sr}$  at 10 EeV and  $\simeq 200 \text{ km}^3 \text{ sr}$  at  $10^{23} \text{ eV}$  [40]. We conclude that detection of neutrino fluxes predicted by scenarios such as the one shown in Fig. 1 requires running a detector of acceptance  $\gtrsim 100 \text{ km}^3 \times 2\pi \text{ sr}$  over a period of a few years. Again, the backgrounds seem to be negligible [31].

A more model independent estimate for the average event rate  $R(E)$  can be made if the underlying scenario is consistent with observational nucleon and  $\gamma$ -ray fluxes and the bulk of the energy is released above the pair production threshold on the CMB. Let us assume that the ratio of energy injected into the neutrino versus EM channel is a constant  $r$ . As in Fig. 1, cascading effectively reprocesses most of the injected EM energy into low energy photons whose spectrum peaks at  $\simeq 10 \text{ GeV}$  [41]. Since the ratio  $r$  remains roughly unchanged during propagation, the height of the corresponding peak in the neutrino spectrum should roughly be  $r$  times the height of the low-energy  $\gamma$ -ray peak, i.e., we have the condition  $\max_E [E^2 j_{\nu_\mu}(E)] \simeq r \max_E [E^2 j_\gamma(E)]$ . Imposing the observational upper limit on the diffuse  $\gamma$ -ray flux around 10 GeV shown in Fig. 1,  $\max_E [E^2 j_{\nu_\mu}(E)] \lesssim$

$2 \times 10^3 r \text{ eV cm}^{-2} \text{ sec}^{-1} \text{ sr}^{-1}$ , then bounds the average neutrino rate at all energies  $E \gtrsim 1 \text{ PeV}$  to be

$$R(E) \lesssim 0.34 r \left[ \frac{A(E)}{1 \text{ km}^3 \times 2\pi \text{ sr}} \right] \times \left( \frac{E}{10 \text{ EeV}} \right)^{-0.6} \text{ yr}^{-1}. \quad (2)$$

For  $r \lesssim 10^5 (10 \text{ EeV}/E)$  this bound is consistent with the constraint from the Fréjus experiment [32]. In typical TD models such as the one discussed above,  $r \simeq 0.3$ . However, mechanisms with  $r \gg 1$  could induce appreciable event rates above  $\sim 1 \text{ EeV}$  in a  $\text{km}^3$  scale detector. A detection would thus open the exciting possibility to establish an experimental lower limit on  $r$ . We stress that Eq. (2) holds regardless of whether or not the underlying TD mechanism explains the observed UHE CR events.

The transient event rate could be much higher than Eq. (2) in the direction to discrete sources which emit particles in bursts. Corresponding pulses in the UHE nucleon and  $\gamma$ -ray fluxes would only occur for sources nearer than  $\simeq 100 \text{ Mpc}$  and, in case of protons, would be delayed and dispersed by deflection in galactic and extragalactic magnetic fields [42]. The recent observation of a possible correlation of CRs above  $\simeq 40 \text{ EeV}$  by the AGASA experiment [43] might suggest sources which burst on a time scale  $t_b \ll 1 \text{ yr}$ . A burst fluence of  $\simeq r [A(E)/1 \text{ km}^3 \times 2\pi \text{ sr}] (E/10 \text{ EeV})^{-0.6}$  neutrinos within a time  $t_b$  could then be expected. Associated pulses could also be observable in the GeV–TeV  $\gamma$ -ray flux if the EGMF is smaller than  $\simeq 10^{-15} \text{ G}$  in a significant fraction of extragalactic space [44].

In conclusion, by using a new particle propagation code we have given conservative estimates of the UHE neutrino flux above  $1 \text{ EeV}$  which is predicted by a typical TD type scenario of UHE CR origin. We demonstrated that the constraint imposed by requiring that TD scenarios do not overproduce the measured universal  $\gamma$ -ray background at  $1\text{--}10 \text{ GeV}$  implies an upper limit on these neutrino fluxes which only depends on the ratio  $r$  of energy injected into the neutrino versus EM channel, and not on any specific TD scenario or even a possible connection to UHE CRs. For  $r \gtrsim 1$ , neutrino fluxes near this upper limit are potentially detectable by a  $\text{km}^3$  scale neutrino observatory. A detection of the UHE neutrino flux might establish an

experimental lower limit on  $r$  and thus allow important insights into new fundamental physics near the GUT scale. Due to the increase of the  $\nu N$  cross section with energy, neutrino event rates tend to decrease less strongly with energy than UHE CR event rates and the spectral shape and cutoff of the neutrino flux (and thus  $m_X$ ) might be more easily accessible. A non-detection with more stringent upper limits would also be useful since it could eliminate large classes of TD models of UHE CR origin. For example, failing to detect neutrinos above  $\simeq 10 \text{ EeV}$  with an exposure  $A \cdot t$  would rule out scenarios of the type shown in Fig. 1 for  $r \gtrsim (100 \text{ km}^3 2\pi \text{ sr yr}/A \cdot t)$ . Neutrino astronomy might thus be connected to new fundamental physics.

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