Ultra-High Energy Cosmic Rays from Neutrino Emitting Acceleration Sources?

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We demonstrate by numerical flux calculations that neutrino beams producing the observed highest energy cosmic rays by weak interactions with the relic neutrino background require a non-uniform distribution of sources. Such sources have to accelerate protons at least up to 10^{23} eV, have to be opaque to their primary protons, and should emit the secondary photons unavoidably produced together with the neutrinos only in the sub-MeV region to avoid conflict with the diffuse $\gamma-$ray background measured by the EGRET experiment. Even if such a source class exists, the resulting large uncertainties in the parameters involved in this scenario does currently not allow to extract any meaningful information on absolute neutrino masses.

I. INTRODUCTION

In acceleration scenarios ultra high energy cosmic rays (UHECRs) with energies above $10^{18}\,$eV are assumed to be protons accelerated in powerful astrophysical sources. During their propagation, for energies above $\gtrsim$ 50 EeV ($1EeV = 10^{18}eV$) they lose energy by pion production and pair production (protons only) on the cosmic microwave background (CMB). For sources further away than a few dozen Mpc this would predict a break in the cosmic ray flux known as Greisen-Zatsepin-Kuzmin (GZK) cutoff [1], around 50 EeV. This break has not been observed by experiments such as Fly's Eye [2], Haverah Park [3], Yakutsk [4] and AGASA [5], which instead show an extension beyond the expected GZK cutoff and events above 100 EeV. However the new experiment HiRes [6] currently seems to see a cutoff in the monocular data [7]. Taking into account that all old experiments except perhaps AGASA do not have sufficient statistics in the highest energy region to settle the question, the existence of a possible cutoff remains unclear at the moment. The apparent absence of a cutoff especially in the AGASA data has in recent years triggered many theoretical explanations ranging from conventional acceleration in astrophysical sources to models invoking new physics such as the top-down scenarios in which energetic particles are produced in the decay of massive relics from the early Universe [8]. This enigma has also fostered the development of large new detectors of ultra-high energy cosmic rays which will increase very significantly the statistics at the highest energies [9].

In bottom-up scenarios of UHECR origin, in which protons are accelerated in powerful astrophysical objects such as hot spots of radio galaxies and active galactic nuclei [10], one would expect to see the source in the direction of arrival of UHECRs, but above the GZK cutoff in general no suitable candidates have been found within the typical energy loss distance of a few tens of Mpc for the known electromagnetically or strongly interacting particles [11,12]. Even assuming significant deflection by large scale extragalactic magnetic fields requires at least several sources [13] whose locations have not been identified yet.

Moreover, recent observations of small scale clustering by the AGASA experiment [14] suggest that sources of UHECR are point-like [15,16]. This fact together with the lack of nearby sources favors the possibility of sources much further away than 100 Mpc, at redshifts of order unity. An additional motivation for this possibility comes from recently reported possible correlations of the arrival directions of observed UHECR above $\simeq 50\,$EeV with certain classes of sources such as compact radio galaxies [17] or BL Lacertae objects [18]. In the latter case it is still possible that the sources are located at moderate distances $z \simeq 0.1$. In this case photons with extremely high energies $E > 10^{23}$ eV can propagate several hundred Mpc (constantly loosing energy) and can create secondary photons inside the GZK volume [19]. However, this model requires both extreme energies of primary photons and extremely small extra galactic magnetic fields (EGMFs) $B \lesssim 10^{-12}$ G. Moreover, if a correlation with any source at redshift $z > 0.2$ is found, this model will be ruled out.

If sources of the highest energy cosmic rays are indeed at cosmological distances $z \sim 1$, the only known mechanism not involving new physics except for neutrino masses assumes neutrinos as messenger particles: Charged particles accelerated in such sources give rise to a secondary neutrino beam which can propagate essentially unattenuated. If this neutrino beam is sufficiently strong it can produce the observed UHECRs within 100 Mpc by electroweak (EW) interactions with the relic neutrino background [20]. Specifically, if the relic neutrinos have a mass m_ν, Z-bosons, whose decay products can contribute to the UHECR flux, can be resonantly produced by ultra high energy (UHE) neutrinos of energy $E_\nu \simeq M_Z^2/(2m_\nu) \simeq 4.2\times 10^{21}\,\mathrm{eV}\,(\mathrm{eV}/m_\nu)$.

However, this "Z-burst" mechanism is severely constrained by at least two types of observational data: First, there are upper limits on the UHE neutrino flux, based on the non-observation of horizontal air showers by the old Fly's Eye experiment [21] or by the AGASA experiment [22] and from the non-observation of radio pulses that would be emitted from the showers initiated by the UHE neutrinos on the moons rim [23]. Second, even if the sources exclusively emit neutrinos, the EW interactions also produce photons and electrons which initiate an electromagnetic (EM) cascade which transfers the injected energy down to below the pair production threshold for photons on the CMB [8]. The cascade thus gives rise to a diffuse photon flux in the GeV range which is constrained by the flux observed by the EGRET instrument on board the Compton $\gamma-$ray observatory [24]. Reproducing the observed UHECR flux by the Z-burst mechanism under these two constraints has been shown to in general require local relic neutrino over-densities in order to increase the local UHECR flux. These over-densities turn out to be much higher than values 2–3 which would be expected from the over-density in the local supercluster [25].

In order to avoid this difficulty one can suppose that the Z-burst mechanism is responsible only for part of the UHECR flux [26]. In this case, one can reduce both primary neutrino and secondary photon fluxes and obey all existing limits. However, the price for this is to explain only a part of the UHECR events by the Z-burst mechanism and the necessity for a second source mechanism for UHECRs.

Furthermore, Ref. [26] claims that already the present data provides possible evidence for the relic neutrino background and starts to constrain the absolute neutrino mass, a possibility that has recently been discussed in principle in Ref. [29]. This claim is based on tuning many unknown parameters such as the value of the EGMF, the universal radio background (URB) which governs pair production of UHE $\gamma-$rays, and the neutrino source distribution. Also, Ref. [26] did not take into account propagation of UHE photons, instead assuming that all photons are down-scattered into the GeV region. In addition, simply due to the much larger statistics at lower energies, the quality of the fits performed in Ref. [26] is dominated by the low-energy background component. Finally, Ref. [26] assumed that the sources do not emit any $\gamma-$rays, although the $\gamma-$ray energy fluence produced by pion production of accelerated nuclei should be comparable to the produced neutrino fluence, as will be discussed in Sec. III.

In the present paper we show that for all neutrino masses in the range $0.07\mathrm{eV} \leq m_\nu \leq 1\mathrm{eV}$ one can find parameters that fit the UHECR observations with comparable quality. We therefore conclude that, at least at the current state of knowledge, it is impossible to extract evidence for the relic neutrino background or even best fit values for absolute neutrino masses from UHECR data.

We do not consider in the present paper neutrino interaction channels with multiple $W^\pm$ and/or Z^0 production. These channels could be important in case of neutrino masses $m \gtrsim 3$ eV [27], which however are strongly disfavored by considerations on large scale structure formation [28].

By detailed numerical flux calculations we show that a non-uniform source distribution allows the Z-burst mechanism to explain the UHECR flux without substantial relic neutrino over-densities. However, this only works if the sources exclusively emit neutrinos. Because isospin symmetry requires the energy fluence of neutrinos and $\gamma-$rays produced by hadronic charged primary interactions in the source are comparable, this will require the photons to be down-scattered below the GeV range within the source.

II. NEUTRINO SOURCE

We assume in this section that a pure neutrino source model can somehow be constructed and start with this case. In the next section we relax this condition and include other primary particles into consideration.

Our simulations are based on two independent codes that have extensively been compared down to the level of individual interactions. Both of them are implicit transport codes that evolve the spectra of nucleons, $\gamma-$rays, electrons, electron-, muon-, and tau-neutrinos, and their antiparticles along straight lines. Arbitrary injection spectra and redshift distributions can be specified for the sources and all relevant strong, electromagnetic, and weak interactions have been implemented. For details see Refs. [30,31]. Specifically relevant for neutrino interactions in the current problem are both the s-channel production of Z bosons and the t-channel production of W bosons. The decay products of the Z boson were taken from simulations with the [32] Monte Carlo event generator using the tuned parameter set of the OPAL Collaboration [33]. The main ambiguities in propagation concern the unknown rms magnetic field strength B which can influence the predicted $\gamma-$ray spectra via synchrotron cooling of the electrons in the EM cascade, and the strength of the URB which influences pair production by UHE $\gamma-$rays [34]. Photon interactions in the GeV to TeV range are dominated by infrared and optical universal photon backgrounds (IR/O), for which we took the results of Ref. [35]. The resulting photon flux in GeV range in not sensitive to details of the IR/O backgrounds.

Predictions for the nucleon fluxes agree within tens of percents whereas photon fluxes agree only within a factor $\simeq 2$ between the two codes. The latter mostly reflects the ambiguities in photon propagation mentioned above, but has no influence on the conclusions of this paper.

For the present investigation we parameterize the neutrino injection spectra per comoving volume in the following way:

$$\phi_\nu(E,z) = f(1+z)^m \, E^{-q_\nu} \Theta(E^\nu_{\max} - E)$$
$$z_{\min} \le z \le z_{\max} \,, \qquad (1)$$

where f is the normalization that has to be fitted to the data. The free parameters are the spectral index q_ν, the maximal neutrino energy $E^\nu_{\max}$, the minimal and maximal redshifts $z_{\min}$, $z_{\max}$, and the redshift evolution index m. We assume for simplicity that all six neutrino species (three flavors including antiparticles) are completely mixed as suggested by experiments [36] and thus have equal fluxes given by Eq. (1). Finally we chose the Hubble parameter $H_0 = 70$ km s^{-1} Mpc^{-1} and a cosmological constant $\Omega_\Lambda = 0.7$, as favored today.

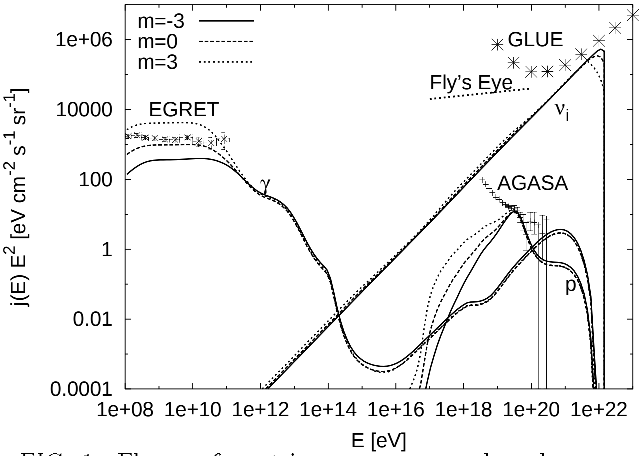

FIG. 1. Fluxes of neutrinos, $\gamma-$rays, and nucleons predicted by the Z-burst mechanism for $m_\nu = 0.5$ eV, assuming sources exclusively emitting neutrinos with fluxes equal for all flavors. We show three cases of the source evolution parameter, $m = -3, 0, 3$ by solid, dashed, and dotted lines, respectively. Values assumed for the other parameters are: $B = 10^{-9}$ G, minimal URB strength, $z_{\min} = 0$, $z_{\max} = 3$, $E^\nu_{\max} = 2 \times 10^{22}$ eV, $q_\nu = 1$. For each case the neutrino flux amplitude f is obtained from minimizing χ^2 for $E_{\min} = 2.5 \times 10^{19}$ eV. Also shown are experimental upper limits on $\gamma-$ray and neutrino fluxes (see text and Ref. [8] for more details).

For a given set of values for all these parameters we find the neutrino flux amplitude f in Eq.(1) obeying all experimental bounds on photon and neutrino fluxes and explaining the UHECR flux at highest energies above some value $E_{\min}$ by the secondary UHE protons and photons by a maximum likelihood fit. The fit quality is characterized by a χ^2 value. Note that there are many different kinds of extragalactic sources which can contribute to the observed UHECR flux with energies below the GZK cutoff $E_{\rm GZK} \simeq 4 \times 10^{19}$ eV. Thus, one should take $E_{\min} \lesssim E_{\rm GZK}$ if one wants to explain all UHECR data above the cutoff by the Z-burst model.

Fig. 1 illustrates how unrealistically high local neutrino background over-density could be avoided by assuming sources that are more abundant at low redshifts. In this figure we show primary neutrino and secondary proton and photon fluxes for the case $m_\nu = 0.5$ eV. The following values have been assumed for the parameters of Eq. (1): spectral index $q_\nu = 1$, maximal neutrino energy $E^\nu_{\max} = 2 \times 10^{22}$ eV, minimal and maximal redshifts $z_{\min} = 0$ and $z_{\max} = 3$. Three cases, corresponding to the redshift evolution index $m = -3, 0, 3$ are plotted as solid, dashed and dotted lines, respectively. A typical value, $B = 10^{-9}$ G, is assumed for the EGMF as well as the minimal strength consistent with observations for the poorly known URB [34]. The latter results in optimistic predictions for the UHE $\gamma-$ray flux. The neutrino flux amplitude was fitted as described above for $E_{\min} = 2.5 \times 10^{19}$ eV. Thus we require that the Z-burst model contributes to 9 bins of non-vanishing flux in the AGASA data. For all three cases in Fig. 1 we obtained $\chi^2(9) \simeq 4$.

As one can see from Fig. 1, the value of the source evolution parameter m mainly affects photons with GeV energies. The value $m = 3$ which was chosen in previous work [25] is similar to evolution of active galaxies. The secondary photon flux for such a source distribution is in conflict with the diffuse GeV photon background observed by the EGRET experiment. The uniform source distribution, $m = 0$, is already in agreement with the EGRET flux, while negative values of the flux, $m = -3$, lead to GeV photon fluxes well below it. The latter case corresponds to sources which are more abundant now than at high redshifts. For example, BL Lacertae objects for which correlations with UHECRs were found in Ref. [18], are distributed in such a way. Note that the choice of unknown EGMF strength B and the URB flux affect only the UHE flux of photons and is not important in the EGRET region which is only sensitive to the total injected EM energy.

Fig. 2 shows results for varying neutrino masses with the unknown parameters B, radio background strength, as well as f, q_ν, $E^\nu_{\max}$, $z_{\min}$, $z_{\max}$, and m chosen such as to produce fits to the UHECR data of comparable quality. We present in Fig. 2 two extreme cases of small $m_\nu = 0.1$ eV and high $m_\nu = 1$ eV neutrino masses. Because parameter space is huge, we fix some parameters to given values ($z_{\min} = 0$, $z_{\max} = 3$, and minimal URB strength) and vary only the evolution parameter m, the EGMF strength B, and the maximum energy $E^\nu_{\max}$ for every given neutrino mass. Again, we determine the neutrino flux amplitude f from minimizing χ^2. For $m_\nu = 0.1$ eV we get $\chi^2(6) = 1.6$, while for $m_\nu = 1$ eV we have $\chi^2(9) = 2.6$, i.e. the fit qualities are comparable. For all intermediate masses we also find similar fit qualities. From this we conclude that no preferred values for the neutrino masses m_ν can be extracted. Instead, for every neutrino mass exists a large parameter region in which the Z-burst model with pure neutrino sources may work.

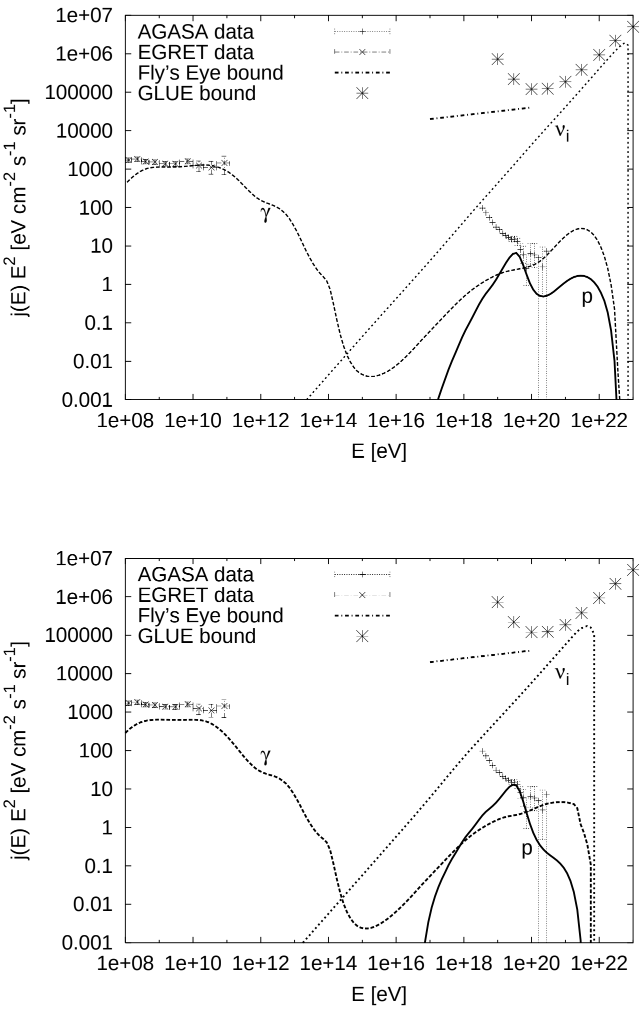

FIG. 2. Dependence of flux predictions in the Z-burst model on neutrino mass. (a) Small neutrino mass $m_\nu = 0.1$ eV, with $m=-3$, $B=5\times10^{-11}G$, $E^\nu_{\rm max}=10^{23}$ eV. (b) Large neutrino mass $m_\nu = 1$ eV, with $m=0$, $B=10^{-12}G$, $E^\nu_{\rm max}=10^{22}$ eV. See also Fig. 1 for explanations.

In Fig. 2a we show the case of small neutrino mass, $m_\nu = 0.1$ eV, with $m=-3$, $B=5\times10^{-11}G$, and $E^\nu_{\rm max}=10^{23}$ eV. For small neutrino masses the resonance energy is large and thus secondary photons and protons are produced at higher energies, apart from the photons produced by t-channel leptons. Due to electromagnetic cascades most of the EM energy ends up in the GeV region and thus the EGRET flux gives the most stringent bound. In particular, for $m_\nu < 0.1$ eV, the parameter space for the Z-burst model shrinks, and even a $m=-3$ distribution of sources is not consistent with the data. However, there is no pronounced cutoff for photons in this case (due to the $\alpha < 1$ power law, see details in Ref. [19]). This allows to explain some fraction of the UHECR events by photons. Finally, the required neutrino flux is higher for small neutrino masses which makes the GLUE experiment bound on the UHE neutrino flux [23] a crucial constraint for the Z-burst model.

In Fig. 2b we present the case of large neutrino mass, $m_\nu = 1$ eV, with $m=0$, $B=10^{-12}G$, and $E^\nu_{\rm max}=10^{22}$ eV. In this case the required flux of neutrinos is somewhat smaller. The available parameter space for the Z-burst mechanism is large and the EGRET bound on the GeV photon flux can be met even for a uniform distribution of sources.

III. PHOTON AND NEUTRINO SOURCE

It is well known that sources capable of accelerating UHECRs produce $\gamma-$rays up to at least $E^\gamma_{\rm max}\sim 100\,{\rm TeV}$ [37]. Since in acceleration scenarios both $\gamma-$rays and neutrinos are produced as secondaries, the power $f_\gamma \sim 1$ radiated in $\gamma-$rays relative to neutrinos has to be of order unity. For the $\gamma-$ray injection spectrum this implies

$$\phi_\gamma(E,z) = 6ff_\gamma\,(1+z)^m\,\frac{g(q_\nu,E^\nu_{\rm max})}{g(q_\gamma,E^\gamma_{\rm max})}\,E^{-q_\gamma}\,\Theta(E^\gamma_{\rm max}-E)$$
$$z_{\rm min}\le z\le z_{\rm max}\,. \qquad (2)$$

Here, q_γ is the $\gamma-$ray spectral index, and $g(q,E_{\rm max})\equiv\int_{E_{\rm min}}^{E_{\rm max}}dE\,E^{1-q}$, where we have introduced some small low energy cut-off $E_{\rm min}$ for convergence.

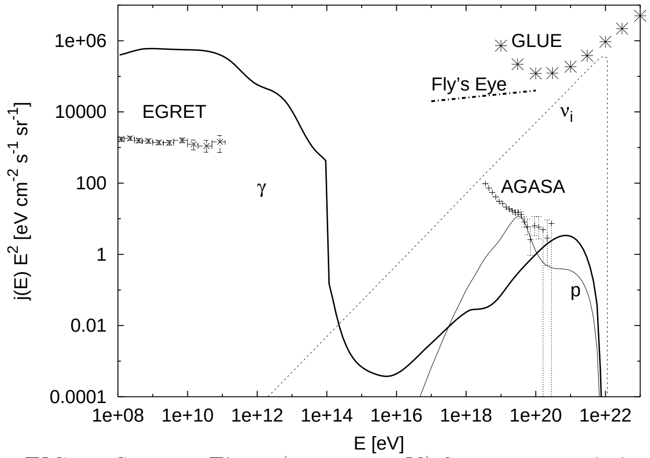

FIG. 3. Same as Fig. 1 ($m_\nu = 0.5$ eV) for sources emitting equal power in neutrinos and $\gamma-$rays, $f_\gamma = 1$ in Eq. (2). The other parameters are chosen as $m=0$, $q_\gamma=2$, $E^\gamma_{\rm max}=100\,{\rm TeV}$.

In this section we consider the more realistic case where the sources also emit $\gamma-$rays with a power comparable to the emitted neutrino power, $f_\gamma = 1$, up to $E^\gamma_{\rm max}=100\,{\rm TeV}$ in Eq. (2). For all other parameters we chose values that minimize the tension with the observational upper limits on the UHE neutrino flux and the diffuse GeV $\gamma-$ray flux. Fig. 3 shows that in this case the

Z-burst scenario cannot be made consistent with observations. A possible solution to this problem is to down-scatter most of the EM energy into the sub-MeV range within the source. Only in this case can the EGRET bound be satisfied. This would requires a very strong photon field up to $\gtrsim$ keV within the source.

Even the scenario in Fig. 3 is still optimistic because it assumes that the source is completely opaque to the primary nucleons. While this may be achieved easier than containment of $\gamma-$rays, for example, by magnetic fields, it is clear from Fig. 3 that even if only a small fraction of the primary nucleons leave the source, the nucleon flux between $\simeq 10^{18}\,\mathrm{eV}$ and $\simeq 10^{19}\,\mathrm{eV}$ would be much higher than observed, in agreement with the conclusions of Ref. [38]. This problem could be avoided if the protons are deflected strongly enough so that they could not reach the Earth. However, this possibility also appears unrealistic as has been discussed in Ref. [39]. This problem can only be solved if the protons are trapped in the source.

Finally we note that the Z-burst mechanism also poses extreme requirements on the acceleration mechanism itself since the primary protons have to be accelerated to energies $E^p_{\max} \sim 10E^\nu_{\max} \gtrsim 4 \times 10^{22}\,\mathrm{eV}\,(\mathrm{eV}/m_\nu)$. In contrast, known mechanisms are usually limited to $E^p_{\max} \lesssim 10^{22}\,\mathrm{eV}$ [40].

Thus, the Z-burst model imposes the following requirements onto the sources: They should emit energy only in neutrinos and in sub-MeV $\gamma-$rays, and should also trap most of the primary protons.

IV. CONCLUSIONS

The Z-burst mechanism where the highest energy cosmic rays are produced by neutrino beams interacting with the relic neutrino background only works with sources exclusively emitting neutrinos in the ultra-high energy regime. In order to avoid conflict with the known diffuse backgrounds of $\gamma-$rays, these sources should emit photons only in the sub-MeV region. In addition, they should trap primary protons in order to avoid an excessive nucleon flux from the source, and should be able to accelerate these protons up to $E^p_{\max} \gtrsim 10^{23}\,\mathrm{eV}\,(\mathrm{eV}/m_\nu)$. None of the astrophysical acceleration models existing in the literature seems to meet this requirement.

Under the assumption that such an extreme source class nevertheless exists we have shown that the Z-burst mechanism can work without unrealistically high local relic neutrino over-densities if the neutrino sources are typically more abundant at present than in the past. Especially neutrino masses $m_\nu \lesssim 0.5\,\mathrm{eV}$ require a non-uniform source distribution $\propto (1+z)^m$ with negative evolution factor, $m < 0$, as is the case with BL Lacertae objects.

The contribution to the UHECR flux from such a speculative extragalactic neutrino source class due to the Z-burst mechanism would exhibit a GZK-cutoff for nucleons and would be dominated by $\gamma-$rays at higher energies. Furthermore, the required UHE neutrino fluxes are close to existing upper limits and should be easily detectable by future experiments such as Auger [41], Euso [42], RICE [43], or by other radio detection techniques [44].

The space of parameters characterizing neutrino sources and their evolution is highly degenerate when fluxes are fit to the observed UHECR fluxes. Since evidence of relic neutrinos and extraction of absolute neutrino masses requires conservative assumptions about these unknown parameters, we conclude that the current state of knowledge does not allow to extract any meaningful information on neutrino masses from UHECR data.

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[42] See http://www.ifcai.pa.cnr.it/Ifcai/euso.html.
[43] For general information see http://kuhep4.phsx.ukans.edu~iceman/index.html.
[44] Proceedings of *First International Workshop on Radio Detection of High-Energy Particles*, Amer. Inst. of Phys., vol. 579 (2001), and at http://www.physics.ucla.edu~moonemp/radhep/workshop.html.