The Neutrino Sky at Very High Energies[☆]

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Abstract

Neutrino astronomy opens a new window for the observation and study of high-energy phenomena in our Universe. The emission of high-energy neutrinos in extragalactic sources or the cosmic environment is intimately related to that of γ-rays and cosmic rays. We will review the various indirect neutrino limits that arise from this cosmic connection and compare this to the present direct limits of neutrino observatories. Specific models of extragalactic TeV to PeV neutrino sources are already testable by large volume neutrino observatories like IceCube. At the EeV energy scale the flux of cosmogenic neutrinos associated with the propagation of ultra-high energy cosmic rays in the cosmic radiation background seems to be the most promising contribution to the diffuse neutrino background. We will discuss its model dependence w.r.t. chemical composition and evolution of the sources and provide simple bolometric scaling relations.

Keywords: extragalactic neutrino sources, cosmogenic neutrinos

1. Introduction

Our Universe shows a remarkable variety of non-thermal activity. Possibly the most mysterious of these phenomena are ultra-high energy (UHE) cosmic rays (CRs) that extend to energies beyond 10^{20} eV following a simple power-law close to E^{-3}. Experimental data on composition and origin of these CRs is unfortunately very limited. Candidate sources of UHE CRs have to fulfill the necessary requirements of an efficient particle acceleration to these extreme energies [1] with an integrated power density of a few 10^{44} erg Mpc^{-3} yr^{-1} above 10^{19} eV. Among the usual suspects are gamma-ray bursts occurring at a rate of a few hundreds per year in the visible Universe and releasing an energy of $\sim 10^{52}$ erg within seconds [2, 3]. Other candidate sources are active galactic nuclei with an average distance of the order of 100 Mpc and extended jets carrying kinetic energies of $\sim 10^{44}$ erg s^{-1} [4] (for reviews see [5, 6]).

The existence of UHE CRs is a strong motivation for neutrino astronomy at very high energies; it seems unavoidable that UHE CRs undergo hadronic interactions with radiation backgrounds and ambient matter prior to their arrival at Earth. Mesons produced in these interactions quickly decay and release a flux of high-energy neutrinos. The resulting neutrinos point back directly to the interaction site and are thus a smoking-gun signal for the CR accelerator. Moreover, they allow the study of very distant accelerators at energies that are not accessible by other messengers due to deflection and energy loss in magnetic fields (CRs/electrons) or absorption in radiation backgrounds (CRs/γ-rays). However, the relation between the CR and neutrino luminosity of candidate sources depends on the particular source environment which is mostly model-dependent, *i.e.* either unknown or uncertain at best. We will summarize in the following various estimates on the neutrino emission of multi-messenger sources.

On the other hand, the prediction of cosmogenic neutrinos produced during the propagation of UHE CRs over cosmological distances does not depend on the specific environmental parameters of the sources; their flux can be directly normalized to the spectrum of UHE CRs observed at the Earth. The prediction is however limited by the uncertainties of these observations, in particular the chemical composition of UHE CRs. If the spectrum is dominated by protons it is feasible that the transition between Galactic and extragalactic CRs appears significantly below the CR ankle at 4×10^{18} eV ("low-crossover" model [7]). The corresponding cosmogenic neutrino flux can then be much larger as it depends on the evolution of the CR source density with redshift. We will discuss in the following simple estimates how the GZK flux scales with CR source models.

In any case, the flux of high-energy neutrinos at Earth is expected to be very faint and their interactions with matter are only very rare (the interaction length of multi-TeV neutrinos is of the order of the Earth's diameter). Neutrino observatories have thus to face the enormous challenge of observing and identifying very rare neutrino interactions in huge detection volumes. Secondary charged particles produced in weak interactions of neutrinos with nuclei can be identified by Cherenkov light emission in optically transparent media. This method has been suc-

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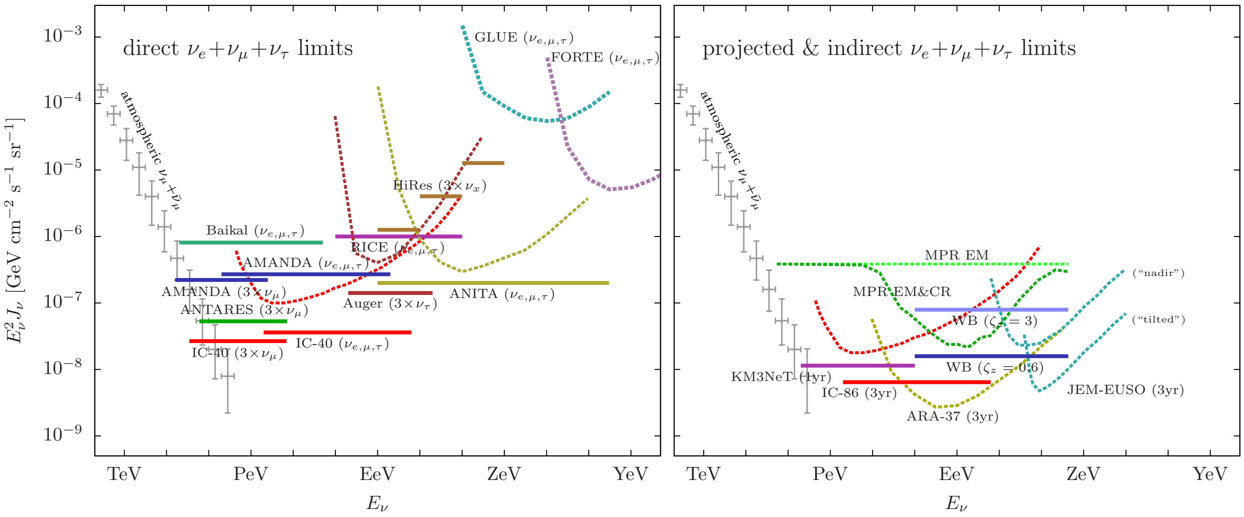

Figure 1: **Left:** Summary of diffuse neutrino limits (see text for references) and the background of atmospheric neutrinos [8]. We show the limits as a sum over all flavors assuming equal contributions of all flavors. **Right:** Projected limits of present and proposed future neutrino observatories as well as indirect limits based on diffuse γ-ray and cosmic ray observations (see main text for description).

cessfully applied in Lake Baikal [9], the Mediterranean (ANTARES [10]) and the Antarctic glacier (AMANDA [11, 12], IceCube [13, 14]). Coherent radio Cherenkov emission has been studied from the regolith of the Moon (GLUE [15]), in the Greenland ice sheet (FORTE [16]), and in Antarctic ice (ANITA [17], RICE [18]). Cosmic ray observatories can also identify neutrinos in CR air showers as deeply penetrating quasi-horizontal events and as electo-magnetic showers from Earth-skimming tau-neutrinos (HiRes [19] and Auger [20]).

Despite the large experimental effort, neutrino observatories have yet to identify the first extragalactic neutrino source and can so far only place upper limits on their fluxes. The left panel of Fig. 1 shows a summary of diffuse neutrino limits from the various experiments mentioned above. In combining these limits we assume that the total neutrino flux arrives at Earth with an equal composition of flavors. This is expected from neutrino production via pion decay in weak magnetic fields and subsequent flavor oscillation over cosmological distances. We will argue in the following that present neutrino limits place already bounds on possible cosmic ray acceleration sites and mechanisms and thus provides indirect information of possible UHE CR scenarios.

2. Multi-Messenger Sources

Hadronic interactions in CR accelerators would lead us to expect a strong correlation between the emitted neutrino and γ-ray flux [21]. Charged pions produced in hadronic interactions decay via $\pi^+ \to \mu^+\nu_\mu \to e^+\nu_e\bar{\nu}_\mu\nu_\mu$ and the charge conjugate process. In this decay each neutrino takes a quarter of the energy of the original pion. In comparison, the neutral pion decays as $\pi^0 \to \gamma\gamma$ into two high energy photons. If energy loss of pions prior to decay is negligible the neutrino energy relates to the γ-ray energy as $E_\nu \simeq E_\gamma/2$ (per neutrino). The total ν and γ emissivity (Q in units of GeV^{-1} s^{-1}) from pion decays in the source can then be related by particle number conservation as

$$Q_{\mathrm{all}\,\nu}(E_\nu) \simeq \frac{3}{2}\frac{\Delta E_\gamma}{\Delta E_\nu} K Q_\gamma(E_\gamma)\,, \tag{1}$$

where the factor K depends on the relative multiplicities of charged and neutral pions, $K = N_{\pi^\pm}/N_{\pi^0}$. There is also one electron from the decay of the muon which contributes as $Q_{\mathrm{all}\,\nu}(E_\nu) \simeq 3Q_e(E_\nu)$.

As long as energy loss of pions before their decay is negligible we can set $\Delta E_\gamma/\Delta E_\nu \simeq 2$. In pp-interactions we have roughly $N_{\pi^+} : N_{\pi^0} : N_{\pi^-} \sim 1 : 1 : 1$ and hence $K \simeq 2$. Resonant $p\gamma$-interactions produce $N_{\pi^+} : N_{\pi^0} : N_{\pi^-} \sim 1 : 2 : 0$ which would imply $K \simeq 1/2$. Direct pion production via $p\gamma \to \pi^+ n$ contributes only 1/5th to the total cross section at the resonance [22]. However, since this is almost exclusively into π^+, the relative abundance of pions from both channels is rather $N_{\pi^+} : N_{\pi^0} : N_{\pi^-} \sim 1.75 : 2 : 0$ and hence $K \simeq 1$. Contributions from off-resonant multi-pion production that might become important for flat photon/proton spectra are expected with an even larger ratio $K \gg 1$. Conservatively, we will take in the following the values $K_{p\gamma} = 1$ and $K_{pp} = 2$ for $p\gamma$ and pp interactions, respectively. For simplicity, we will only consider neutrinos produced in $p\gamma$ interactions in the following, hence $K = 1$.

The neutrino point-source flux $\mathrm{d}F_\nu/\mathrm{d}E$ (GeV^{-1} cm^{-2} s^{-1}) of a source at red-shift z with luminosity Q_ν is given as

$$\frac{\mathrm{d}F_\nu}{\mathrm{d}E}(z, E) = \frac{(1+z)^2}{4\pi d_L^2} Q_\nu((1+z)E)\,. \tag{2}$$

where d_L is the luminosity distance of the source at red-shift z. In a spatially flat universe the luminosity distance depends on the Hubble expansion $H(z)$ as

$$d_L = (1+z)\int\limits_0^z \frac{\mathrm{d}z'}{H(z')}\,. \tag{3}$$

Note that the corresponding γ-ray flux could be predicted by an analogous Eq. (2) and could serve as a normalization for the neutrino emission. However, there are two difficulties. Firstly, the Universe is mostly opaque to extragalactic γ-ray emission due to pair-production with the cosmic radiation background. The absorption length becomes of the order of Mpc at PeV energies. The still observable flux of multi-TeV γ-rays has to be corrected for its absorption in the infra-red to optical background light at different redshifts. Secondly, there are alternative models for TeV γ-ray sources that are dominated by leptonic emission. A generic CR accelerator will also accelerate electrons. Low energy photons, *e.g.* from synchrotron radiation of the electrons in the source magnetic field can be up-scattered to higher energies via inverse-Compton scattering. In any case, the γ-ray emission serves as an upper limit of the possible neutrino production at TeV energies.

3. Cascade Limit

The multi-TeV γ-rays produced in distant extragalactic sources cannot reach Earth unscathed. At these energies γ-rays interact with intergalactic radiation fields, producing e^+e^- pairs. The γ-radiation is recycled to somewhat lower energies by inverse Compton scattering of the electrons and positrons off the same radiation background. These two mechanisms develop electro-magnetic cascades until the center of mass energy of $\gamma\gamma$-scattering drops below the pair production threshold at the order of MeV. For optical photons with energies of the order of eV this occurs at TeV energies. Other processes like synchrotron radiation in inter-galactic magnetic fields, double or triple pair production can also contribute to the cascades spectrum [23]. The net result is a pile up of γ-rays at GeV-TeV energies.

The *cascade limit* of diffuse neutrino fluxes is a consequence of the bolometric energy budget of this process. The inferred energy density ω_γ of the extragalactic diffuse γ-ray background in the GeV-TeV region constitutes an upper limit for the total electro-magnetic energy from pion-production of CR protons. From Eq. (1) with $K=1$ we have

$$\frac{4\pi}{c}\int \mathrm{d}E E J_{\mathrm{all}\,\nu}(E) \simeq \omega_\nu < \frac{3}{5}\omega_\gamma\,. \tag{4}$$

The most recent result from Fermi-LAT translates into an energy density of $\omega_{\mathrm{tot}} \simeq 5.8\times10^{-7}\mathrm{eV/cm}^3$ [24, 25]. Assuming an E^{-2} neutrino spectrum between energies E_- and E_+ a numerical simulation gives a cascade limit of

$$E^2 J^{\mathrm{cas}}_{\mathrm{all}\,\nu}(E) \simeq \frac{3\times10^{-7}}{\log_{10}(E_+/E_-)}\,\mathrm{GeV\,cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}\,. \tag{5}$$

This is only slightly lower than the estimate (4).

Further limitations may arise from energy losses of pions and muons in the source environment prior to decay. The acceleration of relativistic particles in the source requires the presence of magnetic fields. If the loss time of synchrotron radiation is larger than the life-time of pions or muons this will reduce the neutrino flux at the highest energies. If B_T is the field strength of regular magnetic field in units of Tesla intermingling the acceleration region the corresponding neutrino break is $E_{\mathrm{br}} \simeq 3$ PeV/B_T for pions. This effect is particularly important for compact CR accelerators [1].

4. Optically Thin Sources

So far we have not taken into account the emission of CRs from the source. In fact, this is a somewhat problematic part of the acceleration process [26]. The prevailing mechanism of UHE CR sources is 1st order Fermi acceleration of charged particles via diffusion through a shocked plasma ("diffusive shock acceleration"). The accelerated particles are advected downstream of the shock. In the presence of magnetic fields these particles remain trapped in the source until their magnetic confinement is lifted. If cooling processes are significant after the time of acceleration these particles may lose their energy before they are finally emitted.

A possible way out of this dilemma exists in sources that are optically thin to photo-hadronic interactions. Accelerated protons can convert into neutrons via $p\gamma$ interactions in the background radiation. This process becomes resonant, $p\gamma\to\Delta^+\to\pi^+n$, at energies

$$E_p \simeq \frac{m_\Delta^2 - m_p^2}{4\omega\Gamma^2} \simeq \frac{160\mathrm{PeV}}{\omega_{\mathrm{eV}}\Gamma^2} \tag{6}$$

where Γ is the Lorentz factor of the environment and ω_{eV} the photon energy in eV. In the optically thin environment the neutron has the chance of escaping the magnetic region before it decays back to a proton. It is hence feasible that the bulk of UHE CRs consists of protons that are emitted as neutrons from these sources. The charged pion produced in the same interaction decays into neutrinos.

The advantage of this CR emission model is that the neutrino emission becomes highly predictable. We can relate the neutrino and neutron emissivity density of the sources ($\mathcal{Q}$ in units of GeV^{-1} s^{-1} cm^{-3}) by

$$\mathcal{Q}_{\mathrm{all}\,\nu}(E) \simeq 3\frac{4}{\epsilon_\pi}\mathcal{Q}_{\mathrm{CR}}(4E/\epsilon_\pi)\,. \tag{7}$$

Here, $\epsilon_\pi = \langle E_\pi/E_n\rangle$ is the average pion to neutron energy ratio of the interaction $p\gamma\to n\pi^+$ and it is assumed that each of the three neutrinos receives one quarter of the pion's energy.

For the calculation of the UHE CR spectrum we assume that the cosmic source distribution is spatially homogeneous and isotropic. The evolution equations in an expanding Universe can most easily be studied via Boltzmann equations. Their general form can be expressed in terms of the comoving number density $Y_i = n_i/(1+z)^3$ at redshift z for each type of messenger i (CR nucleus, neutrino, *etc.*),

$$\dot{Y}_i = \partial_E(HEY_i) + \partial_E(b_iY_i) - \Gamma_i\,Y_i + \sum_j \int \mathrm{d}E_j\,\gamma_{j\to i}Y_j + \mathcal{L}_i\,. \quad (8)$$

The cosmic expansion is encoded in the Hubble parameter $H(z)$ with present value of $H_0 \sim 70\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$. We assume the usual "concordance model" dominated by a cosmological constant with $\Omega_\Lambda \sim 0.7$ and a (cold) matter component, $\Omega_{\rm m} \sim 0.3$ which gives $H^2(z) = H_0^2\,[\Omega_{\rm m}(1+z)^3 + \Omega_\Lambda]$ [5]. The first and second term in the r.h.s. of Eq. (8) describe continuous energy losses (CEL) due to red-shift and e^+e^- pair production on the cosmic photon backgrounds, respectively. The third and fourth terms describe more general interactions involving particle losses ($i \to$ anything) with interaction rate Γ_i, and particle generation $j \to i$ (see Refs. [27, 28] for further details of the calculation). The last term, $\mathcal{L}_i$, accounts for the CR emission rate per co-moving volume. Cosmic evolution of the CR sources is taken into account by the ansatz $\mathcal{L}_{\rm CR}(z,E) = \mathcal{H}_{\rm GRB}(z)\mathcal{Q}_{\rm CR}(E)$, where $\mathcal{Q}_{\rm CR}(E)$ is the emissivity density today.

The observed spectrum of UHE CRs sets an upper limited on the contribution of protons from optically thin sources. This limit is stronger than the cascade limit for neutrino energies $E_\nu \simeq 10$ PeV and we neglect the γ-constraint for the moment. The CR constraint can be applied in different ways. An integrated limit was derived by *Waxman & Bahcall* (WB) [29] assuming and E^{-2}-emission of protons from optically thin sources. Assuming that charged and neutral pions are produced in equal numbers, they derived the bound

$$E_\nu^2\,J^{\rm WB}_{{\rm all}\,\nu} \simeq \frac{3}{4}\frac{1}{2}\frac{c}{4\pi}\epsilon\xi_z t_H E^2_{\rm CR}\mathcal{Q}_{\rm CR}\,. \quad (9)$$

Here, the factor $\epsilon < 1$ is the total power of (charged and neutral) pions relative to the UHE CRs. The factor ξ_z corrects for a possible cosmological evolution of the sources with emissivity density $E^2_{\rm CR}\mathcal{Q}_{\rm CR} \simeq 10^{44}\,\mathrm{erg\,Mpc^{-3}\,yr^{-1}}$ over the Hubble time $t_H \simeq 14$ Gyr. It can be defined as

$$\xi_z = H_0 \int\limits_0^{z_{\rm max}} \mathrm{d}z \frac{(1+z)^{n-\gamma}}{H(x)}\,. \quad (10)$$

Waxman&Bahcall considered the cases $\xi_z = 0.6$ ("no evolution") to $\xi_z \simeq 3$ ("strong evolution" of quasi-stellar objects (QSO)) and a maximal contribution $\epsilon = 1$. Hence, the total neutrino flux associated with the sources of the highest energy CRs is loosely confined to the range

$$E_\nu^2\,J^{\rm WB}_{{\rm all}\,\nu} \simeq (1.6 - 8.0)\times 10^{-8}\,\mathrm{GeV\,cm^{-2}\,s^{-1}\,sr^{-1}}\,. \quad (11)$$

This range of limits is indicated in the right panel of Fig. 1. Note, that this limit does not only depend on the source evolution, but also on the form of the emission spectrum. More general power-law injection spectra have been studied in [30].

Cosmic ray nuclei will also contribute to the diffuse γ-ray background via Bethe-Heitler (BH) pair production and photo-pion ($\gamma\pi$) interactions in the cosmic radiation background. This contribution will also cascade into the diffuse γ-ray background. The contribution to the cascade energy density can be determined via the comoving energy density of electromagnetic (EM) cascades of electrons, positrons and γ-rays defined as

$$\omega_{\rm cas}(z) \equiv \int \mathrm{d}E\,E\,[Y_\gamma(z,E) + Y_{e^\pm}(z,E)]\,. \quad (12)$$

The production of EM cascades can be considered as a continuous energy loss with coefficient $b_{i,{\rm EM}} = b_{i,{\rm BH}} + b_{i,p\gamma}$. For a nuclei i with charge Z_i and mass number A_i this can be related to the energy loss of protons as $b_{i,{\rm BH}}(E) \simeq Z_i^2 b_{p,{\rm BH}}(E/A_i)$. Instead, photo-pion productions scale with the number of nucleons of the nucleus and can be approximated as $b_{i,\gamma\pi} \simeq A_i b_{p,\gamma\pi}(E/A_i)$. We can derive their evolution equation from Eqs. (8) and (12),

$$\dot{\omega}_{\rm cas} + H\omega_{\rm cas} = \sum_i \int \mathrm{d}E\,b_{i,{\rm EM}}(z,E)Y_i(z,E)\,. \quad (13)$$

The energy density (eV cm^{-3}) of the electromagnetic background observed today is hence given by

$$\omega_{\rm cas} = \sum_i \int \mathrm{d}t \int \mathrm{d}E\,\frac{b_{i,{\rm EM}}(z,E)}{(1+z)}\,Y_i(z,E)\,. \quad (14)$$

Th combined CR and diffuse γ-ray constraint is most esily applied by means of test-spectra $\propto E^{-1}e^{-E/E_+}$, that can be considered as a basis of a general (also broken) power-law flux, e.g. $E^{-\gamma} \propto \int \mathrm{d}E_+ E_+^{-\gamma}E^{-1}e^{-E/E_+}$. This method has first been applied by *Mannheim, Protheroe & Rachen* (MPR) [31]. The limit can then be defined as the maximal envelope of the neutrino spectra consistent with the diffuse γ-ray background and the UHE CR spectrum. Note that this has to be considered as a differential limit in contrast to the WB bound. In the right panel of Fig. 1 we show the result of this maximization process for the γ-ray spectrum only ("MPR EM") and together with CRs ("MPR EM&CR"). For the calculation we assumed the parameters $z_{\rm max} = 1$, $n = 3$ and also introduced a low energy cutoff E_- with $\log_{10}(E_+/E_-) = 1/4$.

5. GZK Neutrinos

Photo-pion production of CR nuclei with the CMB becomes resonant at energies of about 7×10^{11} GeV. This leads to a strong suppression of CR protons beyond an

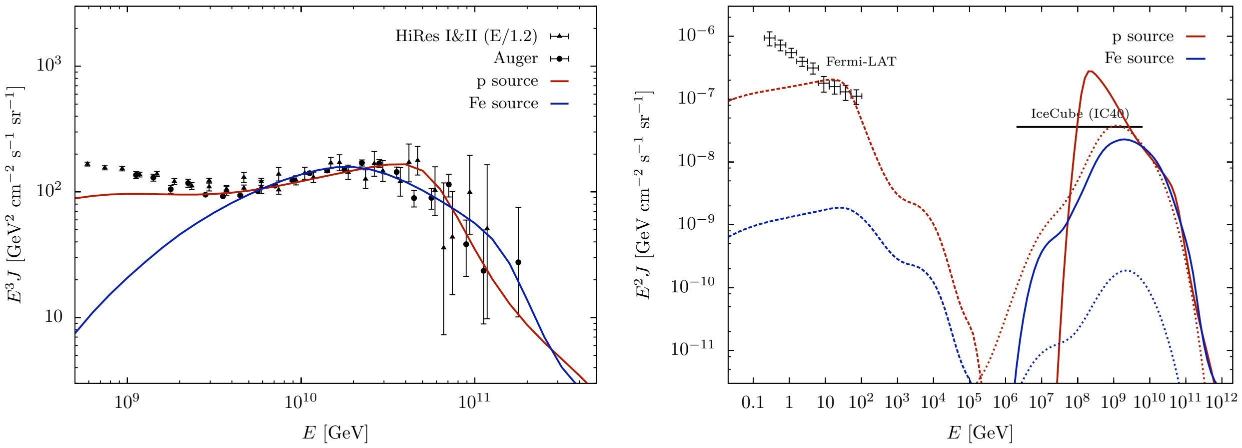

Figure 2: **Left:** Two models of extragalactic CRs assuming a homogenous distribution of protons (red line) and iron (blue line) (from Ref. [28]). The model parameters are discussed in the main text. **Right:** The corresponding spectra of cosmogenic γ-rays (dashed lines) and neutrinos (dotted line) for the two models. The diffuse γ-ray spectrum of the proton model is marginally consistent with the diffuse extragalactic spectrum inferred by Fermi-LAT [32] and the recent diffuse upper neutrino limit of IceCube [13].

energy[1] $E_{\rm GZK} \simeq 5 \times 10^{19}$ eV, which is known as the *Greisen-Zatspin-Kuz'min* (GZK) cutoff [33, 34]. The neutrinos from the decaying pions are called cosmogenic or GZK neutrinos [35].

The flux of GZK neutrinos can be directly normalized to the spectrum of UHE CRs. However, the experimental uncertainties of the absolute CR spectra and the relative contribution of elements translates into large uncertainties in the GZK neutrino predictions. The most optimistic GZK neutrino fluxes arise in models of proton-dominated extragalactic sources with a low-crossover requiring a strong source evolution [24, 25, 36]. Pessimistic models have a large contribution of heavy nuclei, weak evolution and low maximal energies [28, 37–40].

GZK neutrinos from interactions with the CMB follow a broad distribution centered around EeV energies (see Eq. (6)). We can estimate the scaling of the energy density with cosmological parameters similar to the case of EM cascades, see Eqs. (12-14). The energy density (eV cm^{-3}) of the GZK neutrino background observed today is given by

$$\omega_{\rm GZK} = \sum_i \int {\rm d}t \int {\rm d}E\, \frac{b_{i,{\rm GZK}}(z,E)}{(1+z)}\, Y_i(z,E)\,, \qquad (15)$$

where $b_{i,{\rm GZK}}(E) \simeq 0.2E\Gamma_{\gamma\pi}(E/A_i)$ is an approximation of the energy loss of the nuclei into GZK neutrinos [28].

The relative effect of cosmic evolution on the energy density can then be estimated in the following way. The UHE CR interactions with background photons are rapid compared to cosmic time-scales. The energy threshold of these processes scale with redshift z as $A_iE_{\rm th}/(1+z)$ where $E_{\rm th}$ is the (effective) threshold today. We can hence approximate the evolution of the energy density as

$$\dot\omega_{\rm GZK} + H\omega_{\rm GZK} \simeq \eta_{\rm GZK}\mathcal{H}(z)\sum\nolimits_i \int\limits_{A_iE_{\rm th}/(1+z)} {\rm d}E\, E\, \mathcal{Q}_i(E)\,, \quad (16)$$

where $\eta_{\rm GZK}$ denotes the energy fraction of the CR luminosity converted to GZK neutrinos. Assuming a power-law emissivity density $\mathcal{Q}_i(E) \propto E^{-\gamma_i}$ with sufficiently large cutoff $E_{\rm max} \gg E_{\rm th}$ we see that cosmic evolution enhances the GZK flux as

$$\omega_{\rm GZK} \propto \sum_i A_i^{2-\gamma_i} \int_0^{z_{\rm max}} {\rm d}z\, \frac{(1+z)^{n+\gamma_i-4}}{H(z)}\, \frac{E_{\rm th}^2\mathcal{Q}_i(E_{\rm th})}{2-\gamma_i}\,, \qquad (17)$$

where the last term assumes $\gamma_i > 2$.

The relation (17) shows that as long as the maximal energy per nucleon is much larger than $E_{\rm GZK}$ and the injection is $\gamma_i \simeq 2$ the main difference in the energy density of GZK neutrinos comes from the underlying evolution model, not the inclusion of heavy elements. The fact that typical CR models including heavy nuclei produce significantly less GZK neutrinos can be traced back to a low maximal energy per nucleon and/or a weak evolution of CR sources. Note that the latter is an important ingredient of proton-dominated low-crossover models [7], whereas CR models of heavy nuclei including more model degrees of freedom are less predictable w.r.t. the source evolution.

As an illustration we show in Fig. 2 two models of extragalactic CR sources, that have been discussed in Ref. [28]. The first model consists of CR proton sources with a strong evolution ($n = 5$) with a relatively low crossover below the ankle. The injection spectrum uses a power index $\gamma = 2.3$ and assumes exponential cutoffs at $E_- = 10^{18}$ eV and $E_+ = 10^{20.5}$ eV. The spectrum of protons after propagation through the CRB is shown as a red line in the left panel of Fig. 2. The second model assumes a pure injection of iron with the same spectral index $\gamma = 2.3$ but no

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[1] The GZK break or cutoff can be defined here as the proton energy, where the energy loss rate of BH pair production equals the photo-pion energy loss rate.

evolution of the sources ($n = 0$). It assumes the same exponential cutoff at low energies as in the case of the proton model, $E_- = 10^{18}$ eV, and a high energy cutoff at $E_+ = 26 \times 10^{20.5}$ eV, motivated by the rigidity dependence of the maximal energy of CR accelerators, $E_+ \propto Z$. The total spectrum of primary iron and secondary nuclei produced via photo-disintegration is shown as the blue line in the left panel of Fig. 2. Both models reproduce the UHE CR data above the ankle reasonably well. The deficit below the ankle is assumed to be supplemented by a galactic contribution.

The right panel of Fig. 2 shows the diffuse γ-ray spectra (dashed lines) from the all-proton model (red lines) and the all-iron model (blue lines). Whereas the all-iron model has only a negligible contribution to the extragalactic diffuse γ-ray background the proton model saturates the observed background at 10-100 GeV from Fermi-LAT [32]. The cosmogenic neutrino flux (summed over flavors) of these models are shown as dotted lines. The relative contributions from the two models differ by about two orders of magnitude similar to the case of γ-rays. Using Eq. (17) and taking into account the difference in the overall CR normalization ($\mathcal{Q}_{\rm Fe}/\mathcal{Q}_{\rm p} \simeq 0.9$) we derive a relative factor of ~ 82, in good agreement with the calculation. The remaining difference can be attributed to threshold effects from $E_\pm$ that are neglected in the approximation (17).

6. Neutrino Diagnostics of CR Scenarios

One notices that recent direct upper neutrino limits shown in the left panel of Fig. 1 are starting to overtake the indirect limits ("WB" and "MPR") shown in the right panel. Since the indirect limits are model-dependent it is hence possible to infer model constraints from the non-observation of neutrinos. For instance, one can constrain the contribution of neutrons emitted by optically thin sources to the bulk of UHE CRs [27]. Present neutrino limits are also only marginally consistent with cosmogenic neutrinos from proton sources as can be seen by the example shown in Fig. 2. More specific CR source models like GRB fireballs and the emission of PeV neutrinos coincident with the burst are also highly constraint by recent limits from IceCube [41, 42].

In the right panel of Fig. 2 we also show the projected limits of the present and future Cherenkov telescopes IceCube [13] and KM3NeT [43], respectively, the proposed radio Cherenkov array ARA [44] and the space mission JEM-EUSO [45]. The results of these observatories will be signifiant; either by the first detection of extragalactic neutrino sources or by the strong constraint a non-observation places on CR models. In particular, the proposed Askaryan Radio Array [44] will have the potential to test many of the less optimistic models of GZK neutrinos and help to constrain the chemical composition of UHE CRs.

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