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Multi-Messenger Probes of the Cosmic Ray Origin

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The identification of the sources of high-energy cosmic rays is an on-going challenge in astronomy. The direct observation of individual sources is almost impossible due to the strong magnetic deflection and absorption of cosmic rays as they propagate through Galactic and extragalactic space. High-energy gamma-rays and neutrinos that are produced by cosmic ray interactions with gas or radiation can be powerful probes in this search. The recent observation of an astrophysical flux of TeV-PeV neutrinos has added an important new piece to the puzzle. We will highlight multi-messenger probes of cosmic rays and the implications of recent neutrino observations.

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1. Introduction

One of the most puzzling phenomena in Nature is the existence of cosmic rays (CRs). These particles can reach enormous energy in excess of about 1 EeV, so-called ultra-high energy (UHE) CRs, which are observed via extended air showers that are initiated in collisions with atoms in the atmosphere. The precise mechanism that can produce these energetic particles in the first place are not entirely understood. One of the leading mechanism of CR acceleration is diffuse shock acceleration (DSA) via astrophysical shocks which predicts CR spectra following a power-law $E^{-\gamma}$ with, typically, $\gamma \simeq 2.0-2.2$. In fact, the observed CR spectrum follows a broken power-law $E^{-\gamma}$ that spans over many orders of magnitude [1]. The observed spectral index $\gamma \simeq 2.7-3.3$ is softer than expected from DSA and reflects energy dependent propagation effects. Some prominent spectral features are the CR *knee* at 3-4 PeV ($\gamma \simeq 2.7 \to \gamma \simeq 3.0$), the *2nd knee* at 100-200 PeV ($\gamma \simeq 3.0 \to \gamma \simeq 3.3$) and the *ankle* at 4-6 EeV ($\gamma \simeq 3.3 \to \gamma \simeq 2.7$). These features are thought to be related to transitions between different source populations or CR propagation effects.

Charged particles are deflected in Galactic and extragalactic fields. This poses a challenge for the direct identification of sources via auto-correlation or cross-correlation studies of CR arrival directions. Only UHE CRs have a sufficiently high rigidity to preserve some information of the initial CR source distribution, but all searches so far have been inconclusive[2, 3, 4]. However, the large-scale isotropy of the arrival direction of UHE CRs is consistent with an extragalactic population of sources. In fact, a classical estimate [5] of the necessary conditions of UHE CR sources based on the confinement of particles in cosmic accelerators indicate that acceleration up to the extreme energies would be challenging for Galactic sources, *e.g.* supernova remnants. Candidate sources of extra-galactic UHE CRs include active galaxies, gamma-ray bursts or galaxy clusters, see *e.g.* [6].

High-energy cosmic rays are not only subject to magnetic deflections but also interactions with cosmic radiation backgrounds as they propagate over large cosmic distances. In particular, resonant interactions of CR protons with the photons of the cosmic microwave background (CMB) at an energy of about $E_{\rm GZK} \simeq 50$ EeV limits the CR propagation distance to about 200 Mpc and predicts a cutoff-like feature in the spectrum, known as the *Greisen-Zatsepin-Kuzmin* (GZK) cutoff [7, 8]. The spectra of heavier CR nuclei are also expected to show a similar feature at this energy due to photo-disintegration via the formation of the giant dipole resonance. Indeed, CR observations have identified a break at the CR spectrum close to $E_{\rm GZK}$ with high statistical significance [9, 10].

Unfortunately, the precise experimental determination of the spectrum and mass composition of UHE CRs is limited due to the low event statistics and high systematic uncertainties of hadronic interaction models [11, 12]. Within statistical and systematic uncertainties the spectrum of UHE CRs can be fit by various source spectra and mass compositions. We will discuss in the following how cosmic messengers that are associated with the interaction of CRs in their sources or during propagation can help to identify the CR origin and emission model. A prominent role plays the neutrino, which is considered a *smoking-gun* signal of hadronic interactions. It is an ideal cosmic messenger since it is neither absorbed nor deflected as it propagates through the Universe. A guaranteed contribution the the cosmic flux of neutrinos is the *cosmogenic* or GZK neutrino flux associated with the propagation of UHE CRs. We will discuss in the following how present upper limits of this neutrino flux help us to constrain UHE CR models.

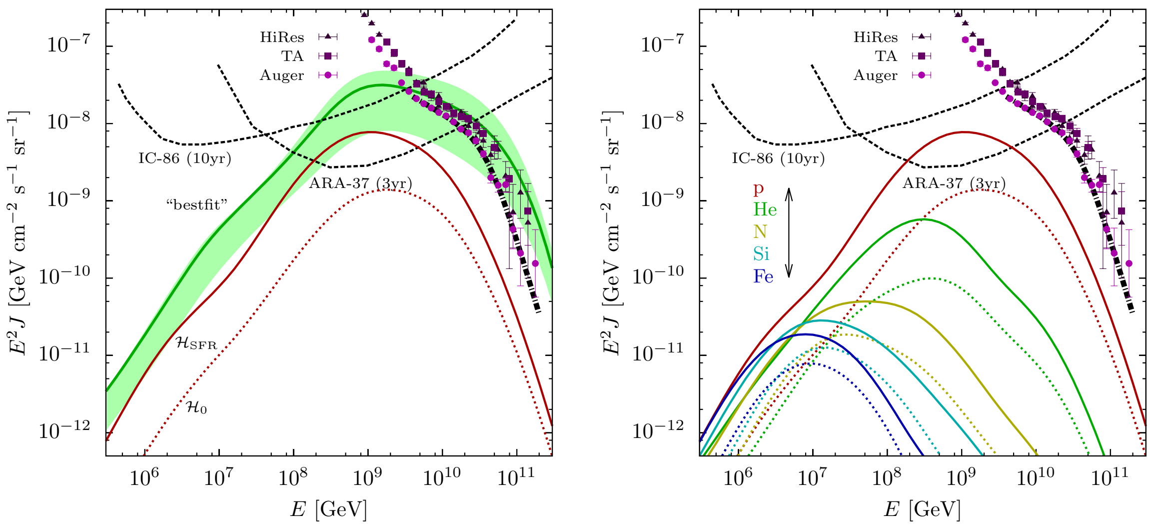

Figure 1: Left panel: Minimal flux of cosmogenic neutrinos assuming dominance of protons above 4 EeV (from Ref. [15]). We show the results without source evolution (dotted) and assuming source evolution according to the star formation rate (solid). Also shown are the projected sensitivities of IceCube (10 years) and the ARA-37 (3 years) as dashed lines. The thick dashed-dotted line shows the approximation of the Auger spectrum above the ankle. For comparison, we also show the bestfit cosmogenic neutrino flux (green solid line) from Ref. [16] ($E_{\rm min} = 10^{18.5}$ eV) including the 99% C.L. (green shaded area) obtained by a fit to the HiRes spectrum. **Right panel:** Minimal flux of cosmogenic neutrinos assuming dominance of protons, helium, nitrogen, silicon or iron in UHE CRs above 4 EeV (from Ref. [15]). We show the results without source evolution (dotted) and assuming source evolution according to the star formation rate (solid).

Interestingly, the IceCube observation has recently identified a flux of high-energy neutrinos in the TeV-PeV energy range [13, 14]. If this flux is generated via the production and decay of pions, it corresponds to the presence of CRs with energies beyond a few ten PeV. This energy scale lies between the CR *knee* and *ankle* which is expected to be the transition region between Galactic and extragalactic CRs. An identification of these neutrinos sources would therefore help to identify this poorly understood part of the CR spectrum.

Gamma-rays are another important messenger that can identify the sources of cosmic rays. Unfortunately, for hadronic PeV gamma-rays associated with the IceCube observation the propagation distance is limited to only 10 kpc, corresponding to the distance between the solar system and the Galactic Center. Therefore, a direct observation is only possible from the local Universe and can help to distinguish Galactic from extragalactic scenarios. However, an indirect observation of the hadronic PeV gamma ray emission is still possible. The combination of pair production and inverse-Compton scattering of electrons and positrons with CMB photons drive electromagnetic cascades that convert the initial radiation into sub-TeV gamma-rays. Since this is a calorimetric process the observed isotropic gamma-ray background provides an upper limit on the hadronic emission of astrophysical sources. We will discuss implications for UHE CRs and CRs corresponding to the IceCube observation.

2. Cosmogenic Neutrinos

The strong photo-hadronic interactions with cosmic radiation backgrounds that are responsible for the GZK feature in the spectrum of UHE CRs are also the main source of high-energy cosmogenic neutrinos [17]. Mesons (mostly pions) produced in these interactions decay via $\pi^+ \to \mu^+ + \nu_\mu$ and $\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$ and the charged conjugate processes. The precise flux of neutrinos depends on the source spectrum, composition and evolution of sources. Cosmogenic neutrinos produced via CMB interactions have typically a peak contribution around a few EeV. In general, lighter compositions and larger maximal energies with hard spectra ($\gamma \simeq 2$) predict higher cosmogenic neutrino fluxes since the pion production threshold scales with atomic mass number. Since the UHE CR spectrum at the highest energies can only receive contributions from local sources ($r \lesssim 200$ Mpc) a strong redshift evolution of the sources with an increased contribution to neutrinos is also feasible. In fact, the "dip"-model [18, 19, 20] explains the CR ankle via the Bethe-Heitler energy loss dip of UHE CR protons and predicts a particularly strong contribution to cosmogenic neutrinos.

In the left panel of Fig. 1 we show an example [15] of the expected cosmogenic neutrino flux from UHE CR models dominated by protons and accounting for the possibility that the evolution of sources follows the star-formation rate (SFR) (solid red) in comparison to no evolution (dotted red). This calculation can be considered as a minimal contribution of proton-dominated models in the sense that the cosmogenic neutrino production is only based on the Auger spectrum above 4 EeV indicated by the black dashed-dotted line. As indicated in the plot, the proposed Askaryan Radio Array (ARA) [21] in the 37 station configuration ("ARA-37") can the sensitivity to this minimal flux of evolving sources after three years of observation. The green line and shaded area in the left panel of Fig. 1 shows the best-fit and 99% confidence level (CL), respectively, of the cosmogenic neutrino flux from Ref. [16] obtained by a fit to the HiRes spectrum assuming a lower CR cutoff at $E_{\rm min} = 10^{18.5}$ eV. This prediction is in reach of the IceCube observatory ("IC-86") within ten years of observation. In fact, recent results of the IceCube collaboration [22] already constrain more optimistic cosmogenic neutrino predictions of pure-proton models.

However, if the UHE CR spectrum is dominated by heavy nuclei as indicated by CR observations by the Auger Collaboration the resonant interaction of CR nucleons with the CMB is shifted to higher CR energies, $(A/56) \times 3$ ZeV, where A is the atomic mass number. For the extreme case of iron this would shift the required CR energies to a level which is beyond the observed CR spectrum and GZK neutrino predictions are therefore not supported by CR data. Due to this increased threshold of GZK neutrino production of heavy nuclei additional cosmic radiation backgrounds with higher photon energies can become a more important target. The extragalactic background light (EBL) in the infrared, optical and ultra-violet are included in most GZK neutrino predictions including heavy nuclei [23, 24, 25, 26, 27, 28, 29, 30, 31]. In general these EBL neutrino predictions shift the peak neutrino production to the 1-10 PeV range but at an absolute level that is beyond present experimental sensitivities. As in the case of the proton dominated model the cosmogenic neutrino prediction depends also on maximal energies and evolution of models.

It is also possible to estimate a minimal, *i.e.* guaranteed contribution of cosmogenic neutrinos from models involving heavy nuclei [15]. The idea here is that instead of parametrizing the neutrino flux in terms of the *initial* chemical composition at the source (an information that gets rapidly

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washed out by GDR cascades) one can instead estimate the neutrino contribution form the *observed* composition. Note that photo-disintegration (approximately) conserves the Lorentz boost of the secondary nuclei and therefore the energy per nucleon. The relevant quantity for the production of cosmogenic neutrinos is therefore the UHE CR nucleon spectrum which can be estimated from the inferred chemical composition of UHE CR data. The contribution to cosmogenic neutrinos is (mostly) independent of the question if the observed nucleus was itself emitted from a distant source or if it was part of a heavier nucleus at an earlier stage of its propagation, as long as the propagation distance is the same [15]. A minimal contribution can then be estimated by fitting the observed CR nucleon spectrum as if it was dominated by proton. The results are shown in the right plot of Fig. 1. Clearly, this figure indidates that cosmogenic neutrino fluxes of models dominated by heavy nuclei are not in reach of present observatories.

3. Astrophysical Neutrinos

The IceCube Collaboration has recently observed a flux of astrophysical neutrinos in the TeV-PeV energy range []. This flux has been observed as high-energy starting events (HESE), *i.e.* as events with Cherenkov light deposition within a virtual veto consisting of an outer layer of optical modules. The event topologies are classified as either *cascade* or *track* events, depending on the presence of an outgoing muon track. The overall significance after three years of observation is 5.7σ and the corresponding best-fit per-flavor E^{-2} flux of events with deposited energies of 60 TeV is

$$E_\nu^2 J^{\rm IC}_{\nu_\alpha} \simeq (0.95 \pm 0.3)\times 10^{-8}{\rm GeV s^{-1} cm^2 sr^{-1}}\,. \tag{3.1}$$

Assuming that the PeV neutrino flux is due to pion-production of CR interactions with gas (pp) or radiation ($p\gamma$), we can identify the corresponding CR nucleon energy as about 20-30 PeV. This corresponds to a CR source population with an energy that extends above the CR *knee*, but not necessarily beyond the CR *ankle*. Therefore, from energetics it is not entirely clear if the source population is Galactic or extragalactic and both scenarios have been invoked to explain the emission.

Possible Galactic source candidates of the IceCube observation are unidentified Galactic PeV sources [32, 33] or microquasars [34], pulsar wind nebulae [35], the *Fermi Bubbles* [36, 37, 38, 39], an extended Galactic Halo [40] or Sagittarius A* [41]. A possible association with a hard diffuse Galactic γ-ray emission [42, 43] has also been considered. Extragalactic sources candidates include galaxies with intense star formation [44, 45, 46, 47, 48, 49], cores of active galactic nuclei (AGN) [50, 51, 52], low-luminosity AGN [41, 53], blazars [54, 35, 55], low-power GRBs [56, 57, 58], cannonball GRBs [59], intergalactic shocks [60], and active galaxies embedded in structured regions [61, 62, 45]. More exotic scenarios have suggested a contribution of neutrino emission from decaying heavy dark matter [63, 64, 65, 66, 67, 68, 69].

Galactic neutrino emission is in general expected to be visible by a correlation of the neutrino arrival direction with Galactic structure, in contrast to the isotropic emission of extragalactic sources. However, this *smoking-gun* feature might be obscured in the HESE data due to source extension, large uncertainties in the arrival direction of cascades (larger than 10 degrees) and limited event statistics (36 events in three years). However, various Galactic emission scenarios are already constraint by the HESE data itself [70]: diffuse Galactic emission to $\lesssim 50\%$, quasi-diffuse emission of neutrino sources to $\lesssim 65\%$, extended diffuse emission from the *Fermi Bubbles* to $\lesssim 25\%$ or unidentified TeV γ-ray sources to $\lesssim 25\%$. Interestingly, the contribution of dark matter decay with a very wide and smooth Galactic distribution is presently unconstrained.

For extragalactic source scenarios one might wonder if the individual limits of neutrino emission from point-like extragalactic sources is consistent with the observation of a combined neutrino flux. This depends on the density ρ or density rate $\dot{\rho}$ of source emission in the Universe: the fewer the sources or bursts during the observation time the stronger the individual emission contributing to the overall emission (3.1). One can estimate that the IceCube observatory should already have identified sparse continuously emitting sources with a local densities of $\rho_0 \lesssim 10^{-6}$ Mpc^{-3} as well as transient sources with local density rates $\dot{\rho}_0 \lesssim 10^{-5}$ Mpc^{-3}yr^{-1} via the association of events with catalogues of nearby sources [71]. Indeed, the upper limits of the combined neutrino emission from blazars [72] or gamma-ray bursts [73] are already constraining their contribution to the IceCube flux (3.1).

Interestingly, the overall energy density of the observed neutrino flux is close to a theoretical limit for neutrino production in the sources of ultra-high energy (UHE) CRs [74]. The neutrino and CR nucleon (N) emission rates Q (in units of GeV^{-1}s^{-1}) can be related to the neutrino emission via the pion production efficiency $f_\pi < 1$ as

$$\frac{1}{3}\sum_\alpha E_\nu^2 Q_{\nu_\alpha}(E_\nu) \simeq \frac{1}{4}\frac{f_\pi K_\pi}{1+K_\pi} E_N^2 Q_N(E_N) \tag{3.2}$$

where $E_\nu \simeq 0.05 E_N$. The factor K_π denotes the ratio of charged to neutral pions produced in the CR interaction with, approximately, $K_\pi \simeq 2$ for pp and $K_\pi \simeq 1$ for $p\gamma$ scenarios. Assuming the dominance of protons in UHE CRs one can estimate the proton emission rate for an E^{-2} flux as $E_p^2 Q_p(E_p) \simeq (1-2)\times 10^{44}\,\mathrm{erg\,Mpc^{-3}\,yr^{-1}}$ [15]. From this, the diffuse neutrino flux can be estimated as

$$E_\nu^2 J_\nu(E_\nu) \simeq \frac{\xi_z f_\pi K_\pi}{1+K_\pi}(2-4)\times 10^{-8}\,\mathrm{GeV\,cm^{-2}\,s^{-1}\,sr}\,, \tag{3.3}$$

were ξ_z is a factor accounting for source redshift evolution ($\xi_z \simeq 0.5$ for no evolution and $\xi_z \simeq 2.4$ for evolution following the star formation rate). Since the pion production efficiency is always smaller then unity, the limit $f_\pi = 1$ corresponds to a theoretical upper limit on neutrino production, the *Waxman-Bahcall* (WB) bound [74].

Neutrino fluxes close to this limit would require very efficient CR production with optical thickness $\tau_{p\gamma/pp} \gg 1$, such that $f_\pi \simeq 1$, *i.e.* CR reservoirs [75] such as starburst galaxies [44, 76] or clusters of galaxies [61, 62, 77]. It has been argued that the energy density of Galactic CRs requires a similar energy density. This coincidence together with the saturation of the WB bound has let to speculations that Galactic and extragalactic CRs might be produced in the same transient sources [75].

4. Hadronic γ-rays

The production of high-energy neutrinos via charged pion production of CRs is associated with

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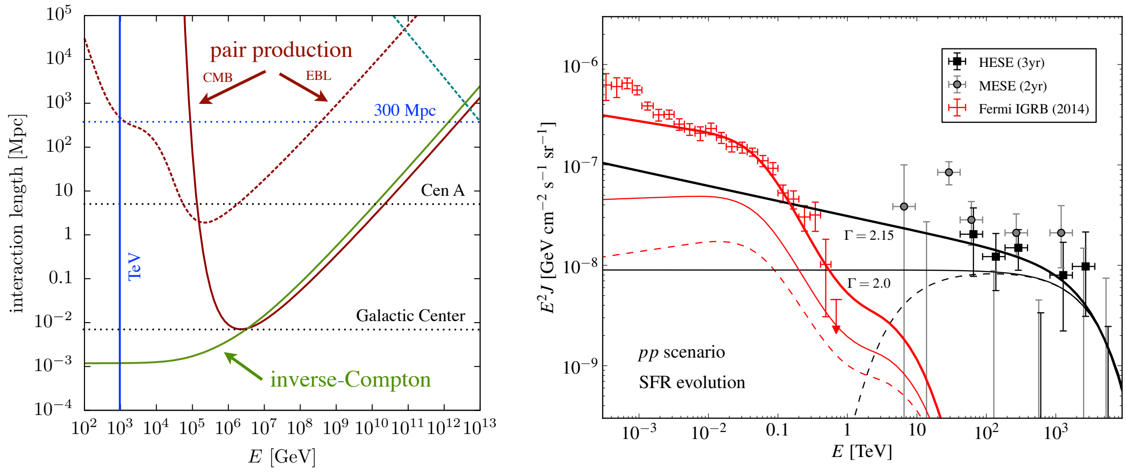

Figure 2: Left Panel: The interaction length of pair production and inverse-Compton scattering of photons with the CMB and EBL. Typical distance scales like the Galactic Center and the close-by radio galaxy Cen A are indicated. **Right Panel:** Isotropic γ-ray background (IGRB) inferred by *Fermi* [82] compared to the diffuse per-flavor neutrino flux observed by IceCube[83, 84] (updated plot of Ref. [37]). The black lines show possible neutrino models consistent with the IceCube data. The red lines are the corresponding γ-rays of pp scenarios reprocessed in the cosmic radiation background. The thick and thin solid lines show a power-law emission with $\Gamma = 2.15$ and $\Gamma = 2$, respectively, with an exponential cutoff around PeV. The dashed lines show an emission that is peaked in the 10TeV-PeV and only contributes in the γ-ray emission via cascades photons.

hadronic γ-rays from the production and decay of neutral pion. The production rates are related as

$$\frac{1}{3}\sum_{\alpha} E_\nu^2 Q_{\nu_\alpha}(E_\nu) \simeq \frac{K_\pi}{4} E_\gamma^2 Q_\gamma(E_\gamma)\,, \tag{4.1}$$

which depend again on the relative charged-to-neutral pion rate K_π. For sources that are dominated by CR-gas interactions (pp sources), this intrinsic neutrino and γ-ray spectra are expected to follow the initial power-law spectrum of CRs. However, the high-energy γ-rays of extragalactic sources will interact with cosmic radiation backgrounds, in particular the cosmic microwave background. The energy dependent interaction and energy loss length in the CMB and EBL [78] is shown in the right panel of Fig. 2. Pair production and subsequent inverse-Compton scattering of the high energy electrons will lead to electromagnetic cascades. As a result, the initial energy density of hadronic γ-ray will be shifted into the sub-TeV γ-ray band, where they supplement the direct emission of the source. The observed γ-ray background in this energy region provides therefore a general upper limit on the diffuse hadronic emission [79], which also applies to the production of cosmogenic neutrinos produced via the GZK interaction [80, 81, 16, 30].

The right panel of Figure 2 shows three pp emission scenarios that follow the diffuse neutrino observation in the TeV-PeV energy range. The black and red lines show the neutrino and γ-ray spectra after accounting for cosmic evolution and cascading in cosmic radiation backgrounds. The thick solid line shows the case of an emission following $E^{-2.15}$ with an exponential cutoff around PeV. This scenario is marginally consistent with the inferred isotropic diffuse γ-ray background

(IGRB) by *Fermi* [82]. The emission at sub-TeV energies is dominated by the direct photons of the sources.

For harder emission ($\Gamma = 2.0$, thin lines) the cascaded spectrum is still a significant contribution to the IGRB. The effect of cascades γ-rays is clearly visible as a bump in the GeV-TeV energy range. For illustration we also show the effect of a low energy cutoff in the intrinsic γ-ray and neutrino spectra (dashed lines). As we already emphasized, this emission spectrum is not expected for a *pp* scenario. However, the observed γ-ray spectrum is in this case dominated by secondary cascaded photons. The contribution to the *Fermi* IGRB between 100 GeV to 1 TeV is still at the level of 10%.

In general, this shows that the diffuse γ-ray contribution to the *Fermi* IGRB is large for *pp* scenarios soft emission spectra ($\Gamma \gtrsim 2.2$) are inconsistent with the data [45]. On the other hand, $p\gamma$ scenarios will most likely contribute to the *leptonic* emission of sources via reprocessed γ-rays. In this case, the hadronic counterparts of the IceCube observation can be identified in the source emission itself, but the energy range will depend on the particular source type.

Note, that over Galactic distances the corresponding emission of hadronic TeV-PeV γ-rays are not completely attenuated by radiation backgrounds, *cf.* the left plot of Fig. 2. In particular the observation of PeV γ-rays with an attenuation length of about 10 kpc via pair production in the CMB would be a *smoking-gun* for Galactic production [85, 37].

5. Conclusions

High-energy gamma-rays and neutrinos are powerful probes of the sources of CRs. Cosmic neutrinos in the 10 TeV to 10 EeV energy range play a special role in multi-messenger studies since these are the only (pointing) probes of the high-energy Universe: extragalactic gamma-rays above 10 TeV are absorbed by pair production and CRs below 10 EeV are expected to be isotropized in extragalactic magnetic fields. Cosmic neutrinos are the *smoking-gun* signal of CR interactions throughout the Universe and the recent observation of a flux of astrophysical TeV-PeV neutrinos by the IceCube Collaboration has added an important new piece of the CR puzzle. Interestingly, the observed energy densities of cosmic neutrinos, gamma-rays and UHE CRs are at a comparable level and could indicate that the high-energy Universe is dominated by hadronic interactions. These are promising prospects for future multi-messenger studies and the identification of extragalactic CR sources.

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