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A Case for Radio Galaxies as the Sources of IceCube's Astrophysical Neutrino Flux

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Abstract. We present an argument that radio galaxies (active galaxies with mis-aligned jets) are likely to be the primary sources of the high-energy astrophysical neutrinos observed by IceCube. In particular, if the gamma-ray emission observed from radio galaxies is generated through the interactions of cosmic-ray protons with gas, these interactions can also produce a population of neutrinos with a flux and spectral shape similar to that measured by IceCube. We present a simple physical model in which high-energy cosmic rays are confined within the volumes of radio galaxies, where they interact with gas to generate the observed diffuse fluxes of neutrinos and gamma rays. In addition to simultaneously accounting for the observations of Fermi and IceCube, radio galaxies in this model also represent an attractive class of sources for the highest energy cosmic rays.

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1 Introduction

In 2013, the IceCube Collaboration published the first detection of high-energy astrophysical neutrinos [1]. Subsequent analyses [2–5] have found IceCube's events to follow an approximate power-law spectrum extending from tens of TeV to a few PeV, and with flavor ratios consistent with those predicted from pion decay [6]. Although a variety of astrophysical sources for TeV-PeV neutrinos have been proposed over the years (for reviews, see Refs. [7, 8]), many of these source classes now appear to be disfavored. Perhaps most notably, gamma-ray bursts had long been considered to be among the most promising sources for the ultra-high energy cosmic rays [9–11] and a likely source of high-energy neutrinos [12–14]. The lack of any detected correlations in time between IceCube's events and observed gamma-ray bursts has all but ruled out this possibility, however [15]. Furthermore, a joint analysis of IceCube's events with data from the Fermi Gamma-Ray Space Telescope has lead to the conclusion that less than 20% of IceCube's flux can originate from blazars [16] (see also Ref. [17]). Similarly, a recent analysis has demonstrated that star-forming galaxies can generate no more than 28% of IceCube's observed spectrum [18].

In light of these and other constraints, radio galaxies (active galaxies with jets that are not aligned along the line-of-sight) now appear to be, perhaps, the most promising class of sources for IceCube's observed neutrino flux [19–21]. In contrast to blazars, which are generally thought to be the subset of active galaxies whose jets are directed within approximately 14° of Earth [22], radio galaxies appear individually less luminous, but are much more numerous. Radio galaxies are further classified according to their morphological characteristics as either Fanaroff-Riley Type I or Type II galaxies, which are generally interpreted as the misaligned counterparts of BL Lacs and flat spectrum radio quasars, respectively.

In a recent study [23], it was demonstrated that the isotropic gamma-ray background (IGRB) measured by the Fermi Gamma-Ray Space Telescope [24] is dominated by emission from unresolved radio galaxies, along with a smaller but non-negligible contribution from blazars [25–29] (possibly among other sources, including star-forming galaxies [30, 31], galaxy clusters [32], millisecond pulsars [33, 34], propagating ultra-high energy cosmic rays [35, 36], and/or annihilating dark matter particles [37–40])[1]. This result was made possible by utilizing an empirical correlation that had been previously identified between the radio and

[1] Previous work has shown that a large fraction of the total extragalactic gamma-ray background is dominated by emission from blazars, in particular at energies above ∼50 GeV [41]. We emphasize that the results of Ref. [23] are not in conflict with this finding, as the IGRB makes up only about half of the total extragalactic background at these energies [24].

gamma-ray luminosities of this class of sources [42, 43]. More quantitatively, Ref. [23] concluded that unresolved radio galaxies account for $83.3^{+27.4}_{-10.1}\%$ of the $E_\gamma > 1$ GeV photons that make up Fermi's IGRB. This result is consistent with the findings of other recent work [38–40, 44–47], including analyses based on cross-correlations of the IGRB with multi-wavelength data [48–51].

The realization that radio galaxies dominate the IGRB has important implications for IceCube and their observed flux of high-energy astrophysical neutrinos. In this paper, we demonstrate that if the gamma-ray emission observed from radio galaxies is generated through the interactions of cosmic-ray protons with gas, then one should expect these sources to also produce a spectrum of neutrinos that is qualitatively similar to that observed by IceCube. Given the large fraction of the IGRB that originates directly from these sources, we argue that any diffuse contribution from electromagnetic cascades must be suppressed, for example by very-high energy photon scattering taking place within or near the radio galaxies themselves, or through non-negligible synchrotron losses. Although scenarios in which IceCube's neutrinos are produced within the jets or lobes of active galactic nuclei (AGN) are possible, we instead consider a simple model in which high-energy cosmic rays are confined within the volumes of radio galaxies, where they interact with gas to generate the observed neutrino and gamma-ray fluxes (similar to earlier work within the context of starburst galaxies [52] and galaxy clusters [53]). This model predicts a cut-off in the neutrino spectrum at energies above approximately $E_\nu \sim$ 1-100 PeV, resulting from the transition between Kolmogorov diffusion and effective free-streaming. If we extrapolate the spectrum of cosmic rays that are accelerated by radio galaxies from $\sim 10^8$ GeV to $\sim 10^{11}$ GeV, we find that these sources can also generate the observed flux and spectrum of the ultra-high energy cosmic rays. It is possible that cosmic rays and/or neutrinos could be detected from individual radio galaxies in the future, making the most nearby and luminous examples of such sources (including Centaurus A, Centaurus B, and M 87) particularly promising targets of study.

2 Gamma Rays and Neutrinos From Radio Galaxies

The sum of the emission from all unresolved radio galaxies leads to a gamma-ray flux that is given by:

$$\frac{dF_\gamma}{dE_\gamma\, d\Omega} = \int dz \frac{d^2V}{dz\, d\Omega} \int \frac{dF_\gamma}{dE_\gamma} \frac{dL_\gamma}{L_\gamma \log(10)} \rho_\gamma(L_\gamma, z)(1 - \omega(F_\gamma(L_\gamma, z))) \exp(-\tau_\gamma(E_\gamma, z)),$$

where $d^2V/dz\, d\Omega$ is the co-moving volume element, and dF_γ/dE_γ is the spectrum of gamma-rays from a radio galaxy of luminosity L_γ and located at redshift z. The function ω represents Fermi's point source detection efficiency [54], which accounts for the fact that resolved radio galaxies do not contribute to the diffuse gamma-ray background[2]. The attenuation of the gamma-ray spectrum from scattering with the extragalactic background light is characterized by the optical depth, $\tau_\gamma(E_\gamma, z)$, for which we adopt the model of Ref. [55].

In a recent study [23], we refined the empirical correlation between the radio and gamma-ray emission detected from radio galaxies (see also Refs. [42, 43]) and combined this information with the measured radio luminosity function and redshift distribution [56] to determine the gamma-ray luminosity function of radio galaxies, $\rho_\gamma(L_\gamma, z)$, and ultimately the total contribution from all unresolved radio galaxies to the diffuse gamma-ray background. In doing

[2] In the case of radio galaxies, this calculation depends very little on the precise form of ω, as only a very small fraction of the total gamma-ray flux originates from above or near threshold sources.

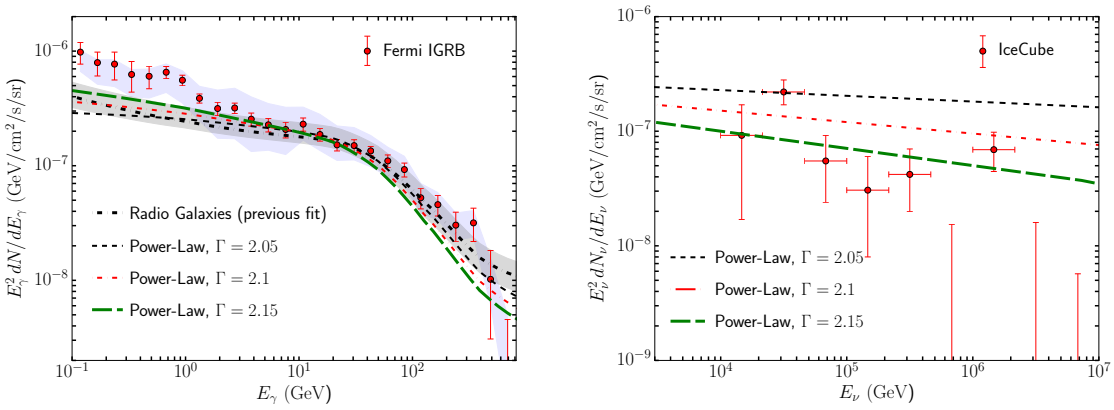

Figure 1. Left Frame: The contribution to the diffuse gamma-ray background from unresolved radio galaxies, as determined previously [23] (solid black and surrounding grey band), and compared to power-law spectra (prior to attenuation) with three values of the spectral index (dashed black, solid red, long-dashed green). We also show the measurement of the isotropic gamma-ray background (IGRB) as reported by the Fermi Collaboration [24]. The error bars in this figure include both the statistical uncertainty and the systematic uncertainties associated with the effective area and cosmic ray background subtraction, while the light blue shaded band reflects the systematic uncertainties associated with the modeling of the Galactic foreground emission. Right Frame: The (all-flavor) neutrino spectrum from the same radio galaxy models shown in the left frame, assuming that 1) the gamma-ray emission is generated through proton-proton collisions, and 2) the spectrum of this emission can be extrapolated to the energy range measured by IceCube. The fact that these extrapolated models are able to approximately accommodate the diffuse neutrino flux reported by the IceCube Collaboration [2] is suggestive of a scenario in which high-energy protons in radio galaxies are responsible for both the majority of the observed isotropic gamma-ray background and the diffuse high-energy neutrino flux.

so, we found that this class of sources dominates the unresolved extragalactic gamma-ray flux, accounting for $83.3^{+27.4}_{-10.1}\%$ of the isotropic gamma-ray background (IGRB) observed by Fermi [24] above 1 GeV.

At this time, it is not entirely clear whether the gamma-ray emission observed from radio galaxies results from hadronic (pion production) or leptonic (inverse Compton) processes. If hadronic processes are responsible, however, then high-energy neutrinos will accompany the observed gamma-rays. In this section, we will focus on models in which gamma rays and neutrinos are generated through the interactions of cosmic-ray protons with gas, and the subsequent decays of charged and neutral pions ($\pi^+ \to e^+\nu_e\nu_\mu\bar{\nu}_\mu$, $\pi^- \to e^-\bar{\nu}_e\nu_\mu\bar{\nu}_\mu$, $\pi^0 \to \gamma\gamma$). The spectra of these gamma rays and neutrinos are generally predicted to have a common shape (prior to attenuation), and with relative fluxes given by $F_\nu/F_\gamma = 2 \times (3/4) = 3/2$, where the factors of 2 and 3/4 result from the ratio of charged-to-neutral pions that are produced in such interactions and from the fact that three of the four decay products of a charged pion are neutrinos.

In the left frame of Fig. 1, we show the contribution to the diffuse gamma-ray background from unresolved radio galaxies as determined in Ref. [23] and compare this to Fermi's measurement of the IGRB [24]. In Ref. [23], the total gamma-ray spectrum from radio galaxies (prior to attenuation) was calculated as a weighted sum of power-laws. For simplicity (and to facilitate a more straightforward extrapolation), we will instead consider spectra that are described by a single power-law. In the left frame of Fig. 1, we find that a power-law in-

dex of $\Gamma \simeq 2.1$ provides a reasonable match to that obtained in Ref. [23], especially in the energy range best measured by Fermi ($\sim$0.7-10 GeV). In each case, we have accounted for gamma-ray attenuation using the infrared background model described in Ref. [55].

In the right frame of Fig. 1, we show the (all-flavor) neutrino spectrum for the same three power-law models, normalized as in the left frame, and assuming that the power-law spectra extend to the energy range measured by IceCube. When these extrapolated spectra are compared to the results reported by the IceCube Collaboration [2] (see also Refs. [1, 3–5]), we find reasonable agreement. This result is suggestive, and provides support for scenarios in which high-energy protons in active galaxies are responsible for both Fermi's observed isotropic gamma-ray background and IceCube's high-energy neutrino flux.

Radio galaxies not only produce gamma rays directly, but also through the electromagnetic cascades that result from the scattering of very-high energy photons with radiation. The intensity of any diffuse cascade emission is significantly limited by the results of Ref. [23], however, which allow for only a relatively small fraction of the IGRB to originate from cosmologically induced cascades. The predicted intensity of the cascade contribution depends on the redshift distribution of the very-high energy gamma-ray sources, and on the maximum energy to which their (unattenuated) spectrum extends. If the neutrino and gamma-ray spectra injected from radio galaxies does in fact extend up to $\sim$PeV energies or above, one might expect the resulting cascade emission to constitute a significant fraction of the IGRB [57–60], in possible conflict with the findings of Ref. [23].

In Fig. 2, we plot the contributions to the IGRB from radio galaxies and from the corresponding cascade emission (for details regarding the cascade calculation, see Refs. [61–65]), for three values of the spectral index and for two choices of the maximum gamma-ray energy, $E_{\rm cut}$. Even for the minimum value of $E_{\rm cut} = 10$ TeV,[3] the contribution from electromagnetic cascades is in some tension with Ref. [23], although concordance may be possible if $\Gamma \gtrsim 2.15$. This tension is made significantly worse, however, if the gamma-ray spectrum from these sources extends to $E_{\rm cut} \sim$ PeV, as would be required to accommodate IceCube's measured neutrino spectrum (see Fig. 3).

This tension can be relieved, however, if a non-neglibile fraction of the high photons initiating electromagnetic cascades do so within or nearby the location of their parent radio galaxy. If this is the case, much of the cascade emission will point in the direction of the source radio galaxy, and will thus simply be included as part of the emission that we label in Fig. 2 as being from "unresolved radio galaxies" (as opposed to that from "cascade emission"). Photons with an energy of $\sim$1 PeV or more are predicted to scatter with radiation before escaping a galaxy, even in the case of Milky Way-like systems [72–74]. In active galaxies, with higher densities of infrared radiation, such interactions will be more efficient, plausibly leading to the scattering of most of the gamma-rays with $E_\gamma \gtrsim 10$ TeV. We also mention that synchrotron cooling could reduce the energy in some electromagnetic cascades, suppressing the total amount of energy in diffuse gamma-rays (for a discussion of synchrotron and inverse Compton energy losses, see Ref. [75]).

With this in mind, we plot in the upper two frames of Fig. 4 the gamma-ray spectrum from unresolved radio galaxies and from their corresponding cascade emission, in scenarios in which 50% or 25% of the total cascade energy goes into diffuse gamma rays (those not directed at their source). In both cases, we have taken $E_{\rm cut}$ =4 PeV, enabling these sources to generate the neutrino spectrum observed by IceCube (as shown in the lower frame of

[3] As a number of radio galaxies have been observed by ground-based gamma-ray telescopes at energies of $\sim$10 TeV (see, for example, Refs. [66–71]) we take this to be the minimum acceptable value of $E_{\rm cut}$.

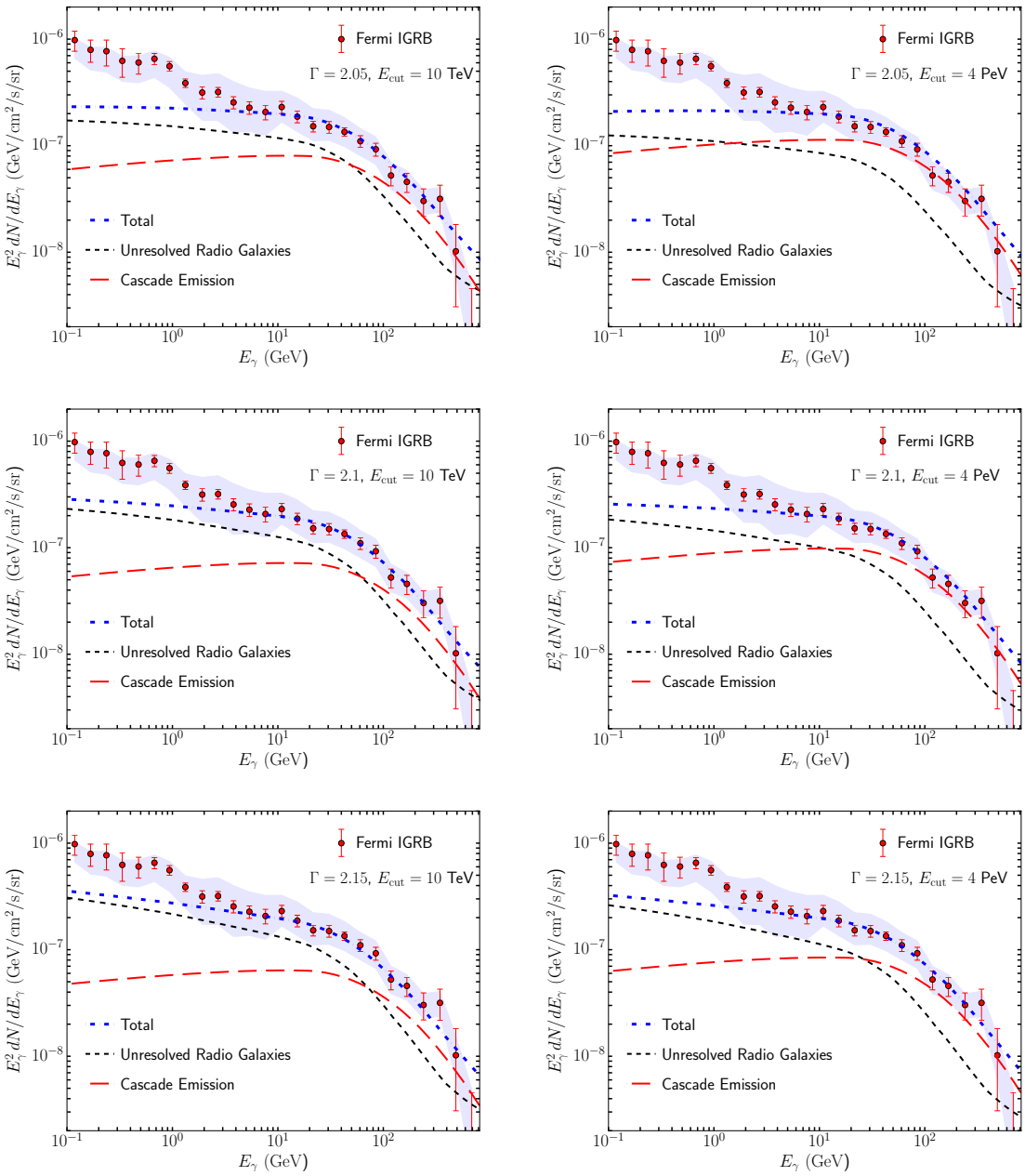

Figure 2. The contribution to the diffuse gamma-ray background from unresolved radio galaxies, and from the emission generated in the electromagnetic cascades initiated by very-high energy photons. We show results for three choices of the spectral index, and for two choices of the cut-off energy in the initial (unattenuated) gamma-ray spectrum, $E_{\rm cut}$. The total flux in each frame is normalized to the measured intensity of the IGRB. Here, we assume that 100% of the total energy in electromagnetic cascades goes into the production of diffuse gamma rays ($f_{\rm cas} = 1$).

this figure). From this comparison, we conclude that Fermi's IGRB and IceCube's diffuse neutrino spectrum can be simultaneously generated by radio galaxies in scenarios in which a significant fraction of the electromagnetic cascades are initiated in or nearby their source galaxy ($f_{\rm cas} \sim 0.1 - 0.5$).

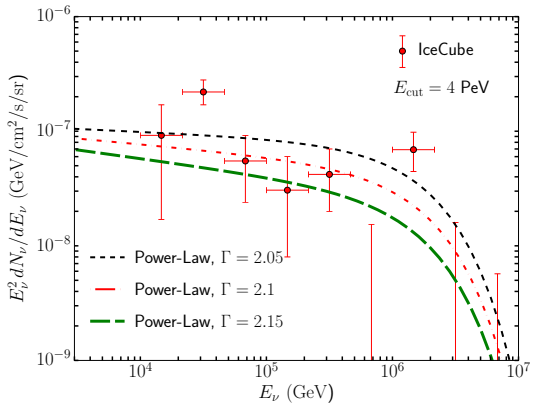

Figure 3. The (all-flavor) neutrino spectra for the models shown in Fig. 2, for the case of $E_{\rm cut} = 4$ PeV and $f_{\rm cas} = 1$.

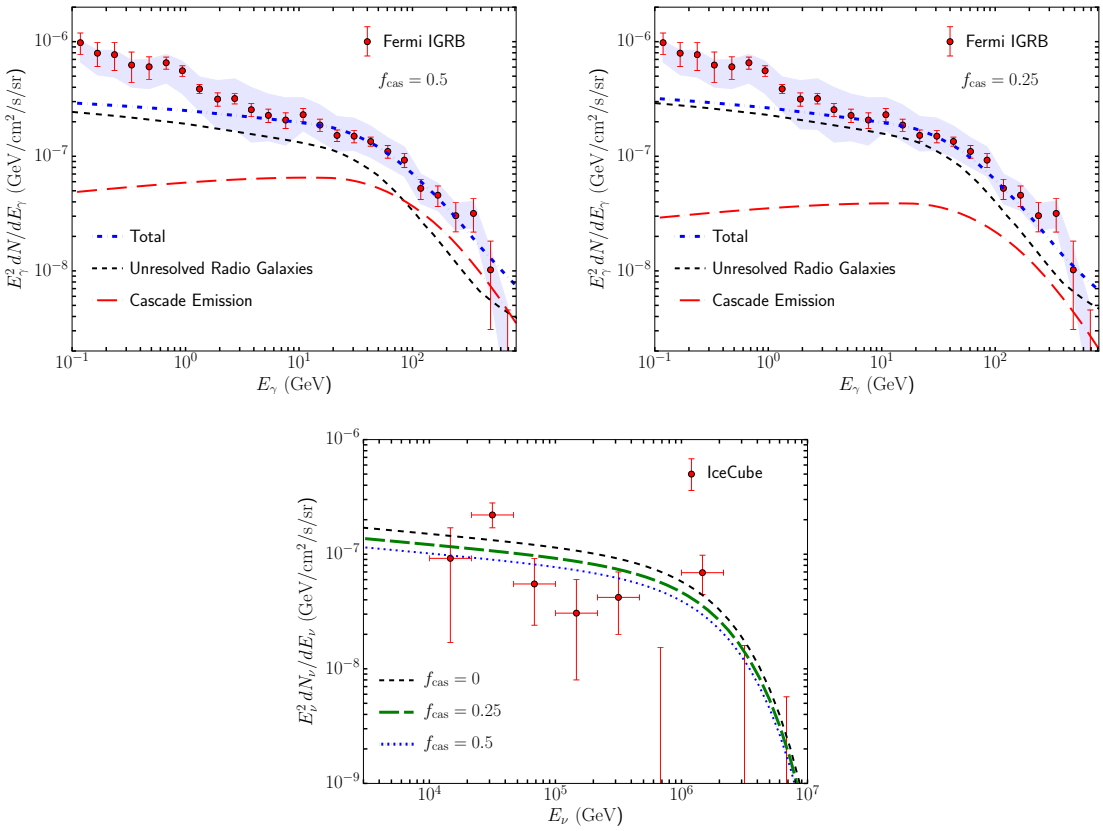

Figure 4. Upper frames: As in Fig. 2, but assuming that 50% or 25% of the total energy in electromagnetic cascades goes into diffuse gamma rays ($f_{\rm cas} = 0.5$, 0.25). In each case, we have taken $\Gamma = 2.1$ and $E_{\rm cut} = 4$ PeV. Lower Frame: The (all-flavor) neutrino spectra for the same range of models, with three values of $f_{\rm cas}$. Fermi's IGRB (including the fraction that originates directly from radio galaxies [23]) and IceCube's diffuse neutrino spectrum can be simultaneously accommodated in this class of scenarios.

3 Toward a Physical Model for Cosmic Ray Diffusion and Scattering in Radio Galaxies

Active galaxies have long been considered to be one of the most promising classes of sources for the highest energy cosmic rays, with magnetic fields and geometries that make them potentially capable of accelerating protons and/or nuclei up to the highest observed energies [76]. While within the jet of an active galactic nuclei (AGN), cosmic rays may or may not efficiently scatter with radiation fields, depending on the spectrum and energy density of the target photons (for additional discussion, see Ref. [21]). Interactions between cosmic rays and gas are generally not expected to be important within AGN jets (for exceptions, see the models described in Refs. [19, 77]). Thus, as long as the radiation fields are not overly dense, we expect most of the cosmic rays accelerated in these environments to escape into the surrounding galaxy.

After leaving the jet, high-energy protons will diffuse through the volume of their parent galaxy (or galaxy cluster), moving under the influence of the magnetic fields in a way that resembles a random walk. Over a time, t, a typical particle will be displaced by a distance of $d_{\rm dif} \sim 2\sqrt{D(E_p)t}$, where $D(E_p)$ is the energy dependent diffusion coefficient. Adopting a Kolmogorov spectrum of magnetic inhomogeneities, the diffusion coefficient takes the following form:

$$\begin{aligned} D(E_p) &= \frac{1}{3} c\, l_c \left(\frac{r_L}{l_c}\right)^{1/3} \\ &\approx 1.5 \times 10^{30}\,{\rm cm}^2/{\rm s} \left(\frac{E_p}{\rm PeV}\right)^{1/3} \left(\frac{l_c}{\rm kpc}\right)^{2/3} \left(\frac{\mu{\rm G}}{B}\right)^{1/3}, \end{aligned} \tag{3.1}$$

where l_c is the coherence length of the magnetic field and r_L is the Larmor radius of the propagating cosmic ray. We note that for $l_c^2/B \simeq {\rm kpc}^2/\mu{\rm G}$, this diffusion coefficient matches the value measured for GeV-TeV cosmic rays in the Milky Way [78, 79]. The expression given in Eq. 3.1 is expected to be valid only in the limit of $r_L \ll l_c$, corresponding to $E_p \ll 0.9\,{\rm EeV} \times (l_c/{\rm kpc})(B/\mu{\rm G})$ [80]. At energies around or above this value, the diffusion coefficient increases rapidly, enabling cosmic rays to effectively free-stream out of their parent galaxy. We thus anticipate that the spectrum of cosmic rays confined within such a galaxy will undergo a sharp cutoff at an energy on the order of $E_p^{\rm max} \sim 0.1-1\,{\rm EeV} \times (l_c/{\rm kpc})(B/\mu{\rm G})$.

From the above diffusion coefficient, we can estimate the length of time that a typical cosmic ray-proton will remain confined within the volume of its parent galaxy:

$$\begin{aligned} t_{\rm esc} &\sim \frac{d_{\rm dif}^2}{2D(E_p)} \\ &\sim 7.9 \times 10^{13}\,{\rm s} \times \left(\frac{d_{\rm dif}}{10\,{\rm kpc}}\right)^2 \left(\frac{\rm PeV}{E_p}\right)^{1/3} \left(\frac{\rm kpc}{l_c}\right)^{2/3} \left(\frac{B}{\mu{\rm G}}\right)^{1/3}. \end{aligned} \tag{3.2}$$

Over this period of time, the probability that a given proton will scatter with the ambient gas is $P(E_p) = 1 - e^{-\tau_{pp}(E_p)}$, where the optical depth is given by:

$$\begin{aligned} \tau_{pp}(E_p) &= \sigma_{pp}(E_p)\, c\, t_{\rm esc}\, n_{\rm gas} \\ &\approx 0.054 \times \left(\frac{n_{\rm gas}}{0.3\,{\rm cm}^{-3}}\right) \left(\frac{d_{\rm dif}}{10\,{\rm kpc}}\right)^2 \left(\frac{\rm PeV}{E_p}\right)^{1/3} \left(\frac{\rm kpc}{l_c}\right)^{2/3} \left(\frac{B}{\mu{\rm G}}\right)^{1/3}. \end{aligned} \tag{3.3}$$

Here, $n_{\rm gas}$ represents the average number density of target nucleons within the volume of the diffusion region. From this equation, we learn that for $E_p \gtrsim 10^2$ GeV, τ is less than one, and the probability of scattering can be approximated by $P(E_p) \simeq \tau_{pp}(E_p) \propto E_p^{-1/3}$.

In the energy range of interest, the average number of pions produced in a proton-proton collision scales as $N_\pi \propto E_p^{1/4}$, while the average fraction of energy carried by a given pion scales as $\langle E_\pi \rangle / E_p \propto E_p^{-1/4}$ [19, 81].[4] The neutrinos and gamma rays generated in the decays of these pions are further reduced in energy by factors of 4 and 2, respectively, following from the number of particles in their decays. If we consider a power-law spectrum of protons, $dN_p/dE_p = A_p E_p^{-\Gamma_p}$, it follows that the resulting neutrinos and gamma-rays will take on power-law spectra with an index of $\Gamma_{\nu,\gamma} = -(4/3)\Gamma_p + (2/3)$ [19].

Together, this leads to the following spectra for neutrinos and gamma rays:

$$\frac{dN_\gamma}{dE_\gamma} \approx A_\gamma \times \left(\frac{n_{\rm gas}}{0.3\,{\rm cm}^{-3}}\right)\left(\frac{d_{\rm dif}}{10\,{\rm kpc}}\right)^2 \left(\frac{\rm kpc}{l_c}\right)^{2/3} \left(\frac{B}{\mu{\rm G}}\right)^{1/3} \left(\frac{E_\gamma}{\rm GeV}\right)^{-\frac{4}{3}\Gamma_p + \frac{1}{3}}, \tag{3.4}$$

and

$$\frac{dN_\nu}{dE_\nu} \approx A_\gamma \times \frac{3}{2} \times \left(\frac{n_{\rm gas}}{0.3\,{\rm cm}^{-3}}\right)\left(\frac{d_{\rm dif}}{10\,{\rm kpc}}\right)^2 \left(\frac{\rm kpc}{l_c}\right)^{2/3} \left(\frac{B}{\mu{\rm G}}\right)^{1/3} \left(\frac{E_\nu}{\rm GeV}\right)^{-\frac{4}{3}\Gamma_p + \frac{1}{3}},$$

where A_γ is related to A_p by $\int A_p E_p^{-\Gamma_p+1} \tau_{pp}(E_p) dE_p = (5/3) \int A_\gamma E_\gamma^{(-4/3)\Gamma_p + (4/3)} dE_\gamma$. These power-laws are expected to extend up to energies of $E_\gamma \sim (8-80)\,{\rm PeV} \times (l_c/{\rm kpc})(\mu{\rm G}/B)$ and $E_\nu \sim (4-40)\,{\rm PeV} \times (l_c/{\rm kpc})(\mu{\rm G}/B)$, above which $r_L \gtrsim l_c$ and protons diffuse with $D \propto E_p^2$, leading to a steepening of the resulting gamma-ray and neutrino spectra by an additional power of $E_{\gamma,\nu}^{-5/3}$ [80]. We note that the spectral cut-off predicted in this scenario is distinct from that found for the model described in Ref. [19], where it was argued that the detection of such a feature would disfavor radio galaxies as the sources of IceCube's neutrinos.

To accommodate the required spectral index for gamma rays and neutrinos, $\Gamma_\gamma \simeq 2.1$ (see Sec. 2), Eq. 3.4 indicates that protons must be injected into their parent galaxies with an index of $\Gamma_p \simeq 1.8$. This value is within the range favored to explain the observed ultra-high energy cosmic ray spectrum, as is the measured redshift distribution of radio galaxies [35, 83, 84].

In light of these features, radio galaxies appear to be excellent candidates for the sources of the ultra-high energy cosmic rays. The famous calculation by Waxman and Bahcall can be used to relate the fluxes of ultra-high energy cosmic rays and neutrinos (for the case of proton-proton collisions and an E^{-2} spectral shape) [85, 86]:

$$\begin{aligned}[E_\nu^2 \Phi_\nu]_{\rm WB} &\approx \xi_Z\, \tau_{pp}\, t_H \frac{c}{8\pi}\, E_{\rm CR}^2 \frac{d\dot{N}_{\rm CR}}{d\dot{E}_{\rm CR}} \\ &\approx 8.0 \times 10^{-8}\,{\rm GeV\,cm^{-2}\,s^{-1}\,sr^{-1}} \times \left(\frac{\xi_Z}{4.8}\right)\left(\frac{\tau_{pp}}{0.054}\right). \end{aligned} \tag{3.5}$$

In this expression, ξ_Z is a factor which accounts for redshift dependent source evolution. For the observed redshift distribution of FR-I type radio galaxies [56], we calculate $\xi_Z \simeq 4.8$. t_H is the Hubble time and $E_{\rm CR}^2 d\dot{N}_{\rm CR}/d\dot{E}_{\rm CR} \approx 10^{44}$ erg Mpc^{-3} yr^{-1} is the (local) injection rate

[4] For useful parameterizations of the neutrino and gamma-ray spectra from proton-proton collisions, based on fits to accelerator data, we direct the reader to Ref. [82].

of ultra-high energy ($> 10^{19}$ eV) cosmic ray sources. For the optical depth given in Eq. 3.3, we find excellent agreement with IceCube's measured flux. In other words, if we were to simply extrapolate the cosmic ray spectrum from radio galaxies from energies of $\sim 10^{17}$ eV (as required to generate IceCube's observed flux) to $\sim 10^{20}$ eV, this spectrum would provide a reasonable match to that of the ultra-high energy cosmic rays.

4 Discussion and Conclusions

At this point in time, it has become possible to make some rather far-reaching and model-independent statements regarding the origin of IceCube's neutrino flux. Of particular importance is Fermi's measurement of the isotropic gamma-ray background (IGRB), which significantly restricts the range of scenarios that could potentially be responsible for the observed neutrinos. For a wide range of spectral shapes, source distributions, and interactions (γp, pp), it has been shown that models capable of generating the spectrum measured by IceCube also generate a diffuse flux of gamma rays that approximately saturates or exceeds that observed by Fermi. And although this conclusion can be mitigated, to some extent, by considering sources that are not entirely transparent to very-high energy gamma rays [59] (as we did in Sec. 2, by considering in-galaxy pair production), this argument appears to favor a common origin for both IceCube's neutrino flux and the majority of the IGRB.

This connection is particularly powerful in light of the recent results of Ref. [23], which found that the IGRB is dominated by emission from unresolved radio galaxies. We have argued in this paper that radio galaxies – active galaxies with mis-aligned jets – are likely to also be the primary source of the astrophysical neutrinos observed by IceCube. We have presented a simple physical model in which cosmic rays are confined by magnetic fields within radio galaxies for timescales of $t_{\rm esc} \sim 2.5\,{\rm Myr} \times ({\rm PeV}/E_p)^{1/3}$, during which they scatter with gas to generate the observed diffuse fluxes of gamma rays and neutrinos. For cosmic rays accelerated by AGN with a spectral index of $\Gamma_p \simeq 1.8$, we can simultaneously accommodate the characteristics of Fermi and IceCube's observations, while also providing an attractive class of sources for the ultra-high energy cosmic rays.

Smoking gun signals that would confirm the class of scenarios discussed here include the detection of neutrinos or ultra-high energy cosmic rays from indivdual, likely nearby, radio galaxies. From this perspective, the radio galaxy Centaurus A (Cen A) is particularly interesting. At a distance of 3.8 Mpc, Cen A is the nearest radio galaxy, as well as the brightest at GeV energies (see Table 1 of Ref. [23]). Furthermore, in 2010, the Auger Collaboration reported a modest excess of events above 55 EeV from directions within $\sim 20^\circ$ of Cen A [87, 88]. Given the estimated 4% chance probability of such an excess appearing randomly, however, further data will be required to confirm the authenticity of this signal.

Cen A is also a promising source for detection with future high-energy neutrino telescopes [17]. The gamma-ray flux from Cen A represents approximately 0.1% of the total IGRB, and if we assume that the neutrino flux from Cen A is also equal to 0.1% of IceCube's total astrophysical flux, we estimate that this source should generate a neutrino flux of $\sim 1.3 \times 10^{-9}$ GeV cm^{-2} s^{-1}, which is a factor of $\sim$20 below the upper limits currently placed by the IceCube Collaboration [89]. Radio galaxies located in the northern hemisphere (including Cen B, NGC 6251, NGC 2484, 3C 264 and M 87) also represent promising targets for future point source searches with IceCube.

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References

[1] IceCube collaboration, M. G. Aartsen et al., *First observation of PeV-energy neutrinos with IceCube*, *Phys. Rev. Lett.* **111** (2013) 021103, [1304.5356].

[2] IceCube collaboration, M. G. Aartsen et al., *A combined maximum-likelihood analysis of the high-energy astrophysical neutrino flux measured with IceCube*, *Astrophys. J.* **809** (2015) 98, [1507.03991].

[3] IceCube collaboration, M. G. Aartsen et al., *Evidence for Astrophysical Muon Neutrinos from the Northern Sky with IceCube*, *Phys. Rev. Lett.* **115** (2015) 081102, [1507.04005].

[4] IceCube collaboration, M. G. Aartsen et al., *Observation of High-Energy Astrophysical Neutrinos in Three Years of IceCube Data*, *Phys. Rev. Lett.* **113** (2014) 101101, [1405.5303].

[5] IceCube collaboration, M. G. Aartsen et al., *Evidence for High-Energy Extraterrestrial Neutrinos at the IceCube Detector*, *Science* **342** (2013) 1242856, [1311.5238].

[6] IceCube collaboration, M. G. Aartsen et al., *Flavor Ratio of Astrophysical Neutrinos above 35 TeV in IceCube*, *Phys. Rev. Lett.* **114** (2015) 171102, [1502.03376].

[7] J. K. Becker, *High-energy neutrinos in the context of multimessenger physics*, *Phys. Rept.* **458** (2008) 173–246, [0710.1557].

[8] F. Halzen and D. Hooper, *High-energy neutrino astronomy: The Cosmic ray connection*, *Rept. Prog. Phys.* **65** (2002) 1025–1078, [astro-ph/0204527].

[9] E. Waxman, *Cosmological gamma-ray bursts and the highest energy cosmic rays*, *Phys. Rev. Lett.* **75** (1995) 386–389, [astro-ph/9505082].

[10] M. Vietri, *On the acceleration of ultrahigh-energy cosmic rays in gamma-ray bursts*, *Astrophys. J.* **453** (1995) 883–889, [astro-ph/9506081].

[11] M. Milgrom and V. Usov, *Possible association of ultrahigh-energy cosmic ray events with strong gamma-ray bursts*, *Astrophys. J.* **449** (1995) L37, [astro-ph/9505009].

[12] E. Waxman and J. N. Bahcall, *High-energy neutrinos from cosmological gamma-ray burst fireballs*, *Phys. Rev. Lett.* **78** (1997) 2292–2295, [astro-ph/9701231].

[13] J. P. Rachen and P. Meszaros, *Cosmic rays and neutrinos from gamma-ray bursts*, *AIP Conf. Proc.* **428** (1997) 776, [astro-ph/9811266].

[14] D. Guetta, D. Hooper, J. Alvarez-Muniz, F. Halzen and E. Reuveni, *Neutrinos from individual gamma-ray bursts in the BATSE catalog*, *Astropart. Phys.* **20** (2004) 429–455, [astro-ph/0302524].

[15] IceCube collaboration, R. Abbasi et al., *An absence of neutrinos associated with cosmic-ray acceleration in γ-ray bursts*, *Nature* **484** (2012) 351–353, [1204.4219].

[16] IceCube collaboration, T. Glsenkamp, *Analysis of the cumulative neutrino flux from Fermi-LAT blazar populations using 3 years of IceCube data*, in *5th Roma International Conference on Astro-Particle physics (RICAP 14) Noto, Sicily, Italy, September 30-October 3, 2014*, 2015. 1502.03104.

[17] M. Ahlers and F. Halzen, *Pinpointing Extragalactic Neutrino Sources in Light of Recent IceCube Observations*, *Phys. Rev.* **D90** (2014) 043005, [1406.2160].

[18] K. Bechtol, M. Ahlers, M. Di Mauro, M. Ajello and J. Vandenbroucke, *Evidence against star-forming galaxies as the dominant source of IceCube neutrinos*, 1511.00688.

[19] J. Becker Tjus, B. Eichmann, F. Halzen, A. Kheirandish and S. Saba, *High-energy neutrinos from radio galaxies*, *Phys. Rev.* **D89** (2014) 123005, [1406.0506].

[20] G. Giacinti, M. Kachelrie, O. Kalashev, A. Neronov and D. Semikoz, *Unified model for cosmic rays above 10^{17} eV and the diffuse gamma-ray and neutrino backgrounds*, *Phys. Rev.* **D92** (2015) 083016, [1507.07534].

[21] K. Murase, *Active Galactic Nuclei as High-Energy Neutrino Sources*, 1511.01590.

[22] C. M. Urry and P. Padovani, *Unified schemes for radio-loud active galactic nuclei*, *Publ. Astron. Soc. Pac.* **107** (1995) 803, [astro-ph/9506063].

[23] D. Hooper, T. Linden and A. Lopez, *Radio Galaxies Dominate the High-Energy Diffuse Gamma-Ray Background*, 1604.08505.

[24] Fermi-LAT collaboration, M. Ackermann et al., *The spectrum of isotropic diffuse gamma-ray emission between 100 MeV and 820 GeV*, *Astrophys. J.* **799** (2015) 86, [1410.3696].

[25] A. Cuoco, E. Komatsu and J. M. Siegal-Gaskins, *Joint anisotropy and source count constraints on the contribution of blazars to the diffuse gamma-ray background*, *Phys. Rev.* **D86** (2012) 063004, [1202.5309].

[26] J. P. Harding and K. N. Abazajian, *Models of the Contribution of Blazars to the Anisotropy of the Extragalactic Diffuse Gamma-ray Background*, *JCAP* **1211** (2012) 026, [1206.4734].

[27] M. Ajello et al., *The Luminosity Function of Fermi-detected Flat-Spectrum Radio Quasars*, *Astrophys. J.* **751** (2012) 108, [1110.3787].

[28] M. Ajello et al., *The Cosmic Evolution of Fermi BL Lacertae Objects*, *Astrophys. J.* **780** (2014) 73, [1310.0006].

[29] F. W. Stecker and T. M. Venters, *Components of the Extragalactic Gamma Ray Background*, *Astrophys. J.* **736** (2011) 40, [1012.3678].

[30] I. Tamborra, S. Ando and K. Murase, *Star-forming galaxies as the origin of diffuse high-energy backgrounds: Gamma-ray and neutrino connections, and implications for starburst history*, *JCAP* **1409** (2014) 043, [1404.1189].

[31] Fermi-LAT collaboration, M. Ackermann et al., *GeV Observations of Star-forming Galaxies with Fermi LAT*, *Astrophys. J.* **755** (2012) 164, [1206.1346].

[32] F. Zandanel, I. Tamborra, S. Gabici and S. Ando, *High-energy gamma-ray and neutrino backgrounds from clusters of galaxies and radio constraints*, *Astron. Astrophys.* **578** (2015) A32, [1410.8697].

[33] F. Calore, M. Di Mauro, F. Donato and F. Donato, *Diffuse gamma-ray emission from galactic pulsars*, *Astrophys. J.* **796** (2014) 1, [1406.2706].

[34] D. Hooper, I. Cholis, T. Linden, J. Siegal-Gaskins and T. Slatyer, *Pulsars Cannot Account for the Inner Galaxy's GeV Excess*, *Phys. Rev.* **D88** (2013) 083009, [1305.0830].

[35] A. M. Taylor, M. Ahlers and D. Hooper, *Indications of Negative Evolution for the Sources of the Highest Energy Cosmic Rays*, *Phys. Rev.* **D92** (2015) 063011, [1505.06090].

[36] M. Ahlers and J. Salvado, *Cosmogenic gamma-rays and the composition of cosmic rays*, *Phys. Rev.* **D84** (2011) 085019, [1105.5113].

[37] Fermi-LAT collaboration, M. Ackermann et al., *Limits on Dark Matter Annihilation Signals from the Fermi LAT 4-year Measurement of the Isotropic Gamma-Ray Background*, *JCAP* **1509** (2015) 008, [1501.05464].

[38] M. Di Mauro and F. Donato, *Composition of the Fermi-LAT isotropic gamma-ray background intensity: Emission from extragalactic point sources and dark matter annihilations*, *Phys. Rev.* **D91** (2015) 123001, [1501.05316].

[39] M. Ajello et al., *The Origin of the Extragalactic Gamma-Ray Background and Implications for Dark-Matter Annihilation*, *Astrophys. J.* **800** (2015) L27, [1501.05301].

[40] I. Cholis, D. Hooper and S. D. McDermott, *Dissecting the Gamma-Ray Background in Search of Dark Matter*, *JCAP* **1402** (2014) 014, [1312.0608].

[41] Fermi-LAT collaboration, M. Ackermann et al., *Resolving the Extragalactic γ-Ray Background above 50 GeV with the Fermi Large Area Telescope*, *Phys. Rev. Lett.* **116** (2016) 151105, [1511.00693].

[42] Y. Inoue, *Contribution of the Gamma-ray Loud Radio Galaxies Core Emissions to the Cosmic MeV and GeV Gamma-Ray Background Radiation*, *Astrophys. J.* **733** (2011) 66, [1103.3946].

[43] M. Di Mauro, F. Calore, F. Donato, M. Ajello and L. Latronico, *Diffuse γ-ray emission from misaligned active galactic nuclei*, *Astrophys. J.* **780** (2014) 161, [1304.0908].

[44] M. Fornasa and M. A. Snchez-Conde, *The nature of the Diffuse Gamma-Ray Background*, *Phys. Rept.* **598** (2015) 1–58, [1502.02866].

[45] Fermi-LAT collaboration, M. Di Mauro, *The origin of the Fermi-LAT γ-ray background*, in *14th Marcel Grossmann Meeting on Recent Developments in Theoretical and Experimental General Relativity, Astrophysics, and Relativistic Field Theories (MG14) Rome, Italy, July 12-18, 2015*, 2016. 1601.04323.

[46] M. Cavadini, R. Salvaterra and F. Haardt, *A New model for the extragalactic γ-ray background*, 1105.4613.

[47] J. M. Siegal-Gaskins, *Separating astrophysical sources from indirect dark matter signals*, in *Sackler Colloquium: Dark Matter Universe: On the Threshhold of Discovery Irvine, USA, October 18-20, 2012*, 2013. 1308.2228. DOI.

[48] J.-Q. Xia, A. Cuoco, E. Branchini and M. Viel, *Tomography of the Fermi-lat γ-ray Diffuse Extragalactic Signal via Cross Correlations With Galaxy Catalogs*, *Astrophys. J. Suppl.* **217** (2015) 15, [1503.05918].

[49] A. Cuoco, J.-Q. Xia, M. Regis, E. Branchini, N. Fornengo and M. Viel, *Dark Matter Searches in the Gamma-ray Extragalactic Background via Cross-correlations With Galaxy Catalogs*, *Astrophys. J. Suppl.* **221** (2015) 29, [1506.01030].

[50] M. Shirasaki, S. Horiuchi and N. Yoshida, *Cross-Correlation of Cosmic Shear and Extragalactic Gamma-ray Background: Constraints on the Dark Matter Annihilation Cross-Section*, *Phys. Rev.* **D90** (2014) 063502, [1404.5503].

[51] M. Shirasaki, S. Horiuchi and N. Yoshida, *Cross-Correlation of the Extragalactic Gamma-ray Background with Luminous Red Galaxies*, *Phys. Rev.* **D92** (2015) 123540, [1511.07092].

[52] A. Loeb and E. Waxman, *The Cumulative background of high energy neutrinos from starburst galaxies*, *JCAP* **0605** (2006) 003, [astro-ph/0601695].

[53] V. S. Berezinsky, P. Blasi and V. S. Ptuskin, *Clusters of Galaxies as a Storage Room for Cosmic Rays*, *Astrophys. J.* **487** (1997) 529–535, [astro-ph/9609048].

[54] Fermi-LAT collaboration, *The Fermi-LAT high-latitude Survey: Source Count Distributions and the Origin of the Extragalactic Diffuse Background*, *Astrophys. J.* **720** (2010) 435–453, [1003.0895].

[55] J. D. Finke, S. Razzaque and C. D. Dermer, *Modeling the Extragalactic Background Light from Stars and Dust*, ApJ **712** (Mar., 2010) 238–249, [0905.1115].

[56] C. J. Willott, S. Rawlings, K. M. Blundell, M. Lacy and S. A. Eales, *The radio luminosity function from the low-frequency 3crr, 6ce & 7crs complete samples*, *Mon. Not. Roy. Astron. Soc.* **322** (2001) 536–552, [astro-ph/0010419].

[57] K. Murase, M. Ahlers and B. C. Lacki, *Testing the Hadronuclear Origin of PeV Neutrinos*

Observed with IceCube, *Phys. Rev.* **D88** (2013) 121301, [1306.3417].

[58] X.-C. Chang, R.-Y. Liu and X.-Y. Wang, *How far are the sources of IceCube neutrinos? Constraints from the diffuse TeV gamma-ray background*, 1602.06625.

[59] K. Murase, D. Guetta and M. Ahlers, *Hidden Cosmic-Ray Accelerators as an Origin of TeV-PeV Cosmic Neutrinos*, *Phys. Rev. Lett.* **116** (2016) 071101, [1509.00805].

[60] O. E. Kalashev and S. V. Troitsky, *IceCube astrophysical neutrinos without a spectral cutoff and 10^{15} 10^{17} eV cosmic gamma radiation*, *JETP Lett.* **100** (2015) 761–765, [1410.2600].

[61] K. Murase, *High-Energy Emission Induced by Ultra-high-Energy Photons as a Probe of Ultra-high-Energy Cosmic-Ray Accelerators Embedded in the Cosmic Web*, *Astrophys. J.* **745** (2012) L16, [1111.0936].

[62] K. Murase and J. F. Beacom, *Constraining Very Heavy Dark Matter Using Diffuse Backgrounds of Neutrinos and Cascaded Gamma Rays*, *JCAP* **1210** (2012) 043, [1206.2595].

[63] K. Murase, C. D. Dermer, H. Takami and G. Migliori, *Blazars as Ultra-High-Energy Cosmic-Ray Sources: Implications for TeV Gamma-Ray Observations*, *Astrophys. J.* **749** (2012) 63, [1107.5576].

[64] K. Murase, J. F. Beacom and H. Takami, *Gamma-Ray and Neutrino Backgrounds as Probes of the High-Energy Universe: Hints of Cascades, General Constraints, and Implications for TeV Searches*, *JCAP* **1208** (2012) 030, [1205.5755].

[65] V. Berezinsky and O. Kalashev, *High energy electromagnetic cascades in extragalactic space: physics and features*, 1603.03989.

[66] V. A. Acciari et al., *Observation of gamma-ray emission from the galaxy M87 above 250 GeV with VERITAS*, *Astrophys. J.* **679** (2008) 397, [0802.1951].

[67] HESS collaboration, M. Dyrda, A. Wierzcholska, O. Hervet, R. Moderski, M. Janiak, M. Ostrowski et al., *Discovery of VHE gamma-rays from the radio galaxy PKS 0625-354 with H.E.S.S*, in *Proceedings, 34th International Cosmic Ray Conference (ICRC 2015)*, 2015. 1509.06851.

[68] VERTIAS, HESS, MAGIC collaboration, V. A. Acciari et al., *Radio Imaging of the Very-High-Energy Gamma-Ray Emission Region in the Central Engine of a Radio Galaxy*, *Science* **325** (2009) 444–448, [0908.0511].

[69] VERITAS collaboration, N. Galante, *VERITAS Observations of Radio Galaxies*, 0912.3850.

[70] MAGIC collaboration, J. Aleksi et al., *Contemporaneous observations of the radio galaxy NGC 1275 from radio to very high energy γ-rays*, *Astron. Astrophys.* **564** (2014) A5, [1310.8500].

[71] MAGIC collaboration, J. Aleksic et al., *MAGIC observations of the giant radio galaxy M87 in a low-emission state between 2005 and 2007*, *Astron. Astrophys.* **544** (2012) A96, [1207.2147].

[72] J.-L. Zhang, X.-J. Bi and H.-B. Hu, *VHE gamma-ray absorption by galactic interstellar radiation field*, *Astron. Astrophys.* **449** (2006) 641, [astro-ph/0508236].

[73] I. V. Moskalenko, T. A. Porter and A. W. Strong, *Attenuation of vhe gamma rays by the milky way interstellar radiation field*, *Astrophys. J.* **640** (2006) L155–L158, [astro-ph/0511149].

[74] N. Gupta, *PeV Gamma Rays from Interactions of Ultra High Energy Cosmic Rays in the Milky Way*, *Astropart. Phys.* **35** (2012) 503–507, [1110.5257].

[75] S. Lee, *On the propagation of extragalactic high-energy cosmic and gamma-rays*, *Phys. Rev.* **D58** (1998) 043004, [astro-ph/9604098].

[76] A. M. Hillas, *The Origin of Ultrahigh-Energy Cosmic Rays*, *Ann. Rev. Astron. Astrophys.* **22** (1984) 425–444.

[77] S. S. Kimura, K. Murase and K. Toma, *Neutrino and Cosmic-Ray Emission and Cumulative*

Background from Radiatively Inefficient Accretion Flows in Low-Luminosity Active Galactic Nuclei, *Astrophys. J.* **806** (2015) 159, [1411.3588].

[78] M. Simet and D. Hooper, *Astrophysical Uncertainties in the Cosmic Ray Electron and Positron Spectrum From Annihilating Dark Matter*, *JCAP* **0908** (2009) 003, [0904.2398].

[79] R. Trotta, G. Johannesson, I. V. Moskalenko, T. A. Porter, R. R. de Austri and A. W. Strong, *Constraints on cosmic-ray propagation models from a global Bayesian analysis*, *Astrophys. J.* **729** (2011) 106, [1011.0037].

[80] R. Aloisio and V. Berezinsky, *Diffusive propagation of UHECR and the propagation theorem*, *Astrophys. J.* **612** (2004) 900–913, [astro-ph/0403095].

[81] K. Mannheim and R. Schlickeiser, *Interactions of cosmic ray nuclei*, A&A **286** (June, 1994) , [astro-ph/9402042].

[82] T. Kamae, N. Karlsson, T. Mizuno, T. Abe and T. Koi, *Parameterization of Gamma, e+/- and Neutrino Spectra Produced by p-p Interaction in Astronomical Environment*, *Astrophys. J.* **647** (2006) 692–708, [astro-ph/0605581].

[83] A. M. Taylor, *UHECR Composition Models*, *Astropart. Phys.* **54** (2014) 48–53, [1401.0199].

[84] A. M. Taylor, M. Ahlers and F. A. Aharonian, *The need for a local source of UHE CR nuclei*, *Phys. Rev.* **D84** (2011) 105007, [1107.2055].

[85] J. N. Bahcall and E. Waxman, *High-energy astrophysical neutrinos: The Upper bound is robust*, *Phys. Rev.* **D64** (2001) 023002, [hep-ph/9902383].

[86] E. Waxman and J. N. Bahcall, *High-energy neutrinos from astrophysical sources: An Upper bound*, *Phys. Rev.* **D59** (1999) 023002, [hep-ph/9807282].

[87] Pierre Auger collaboration, P. Abreu et al., *Update on the correlation of the highest energy cosmic rays with nearby extragalactic matter*, *Astropart. Phys.* **34** (2010) 314–326, [1009.1855].

[88] R.-Y. Liu, X.-Y. Wang, W. Wang and A. M. Taylor, *On the excess of ultra-high energy cosmic rays in the direction of Centaurus A*, *Astrophys. J.* **755** (2012) 139, [1206.3907].

[89] IceCube collaboration, M. G. Aartsen et al., *Search for Time-independent Neutrino Emission from Astrophysical Sources with 3 yr of IceCube Data*, *Astrophys. J.* **779** (2013) 132, [1307.6669].