High Energy Neutrinos From Radio Galaxies

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Abstract

The **IceCube** experiment has recently reported the **first observation of high-energy cosmic neutrinos**, however, their origin is still unknown. Here, we investigate the possibility that they originate in radio galaxies. We show that hadronic interactions (pp) in the generally less powerful, more frequent, **FR-I radio galaxies are one of the candidate source classes** being able to accommodate the observation. In contrast, the more powerful, less frequent, class of FR-II radio galaxies has too low of a column depths to explain the signal.

1 The Question

The measurement of 28 high-energy neutrino events with IceCube provides a significance of $\sim 4\,\sigma$ and corresponds to an astrophysical flux of $E^2\,dN/dE = (1.2 \pm 0.4)\cdot 10^{-8}\,\mathrm{GeV}^{-1}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}\mathrm{cm}^{-2}$ [1]. However, the directional information does not suffice to answer the question of their origin. Here, we investigate the hypothesis of radio galaxies being the sources of ultra-high energy cosmic rays (UHECRs).

2 The Neutrino Flux At The Source

Pions are generated in the jets of active galactic nuclei (AGN) by proton-proton interactions via $p\,p \to \pi^{0/\pm}$ and subsequently, neutrinos are produced via the decay of the charged pions. The differential proton number per energy and time interval at the source is given as $j_{\mathrm{p}}(E_{\mathrm{p}}) = A_{\mathrm{p}} \cdot \left((E_{\mathrm{p}} - m_p \cdot c^2)/\mathrm{GeV}\right)^{-p}$, with the normalization constant A_{p}.

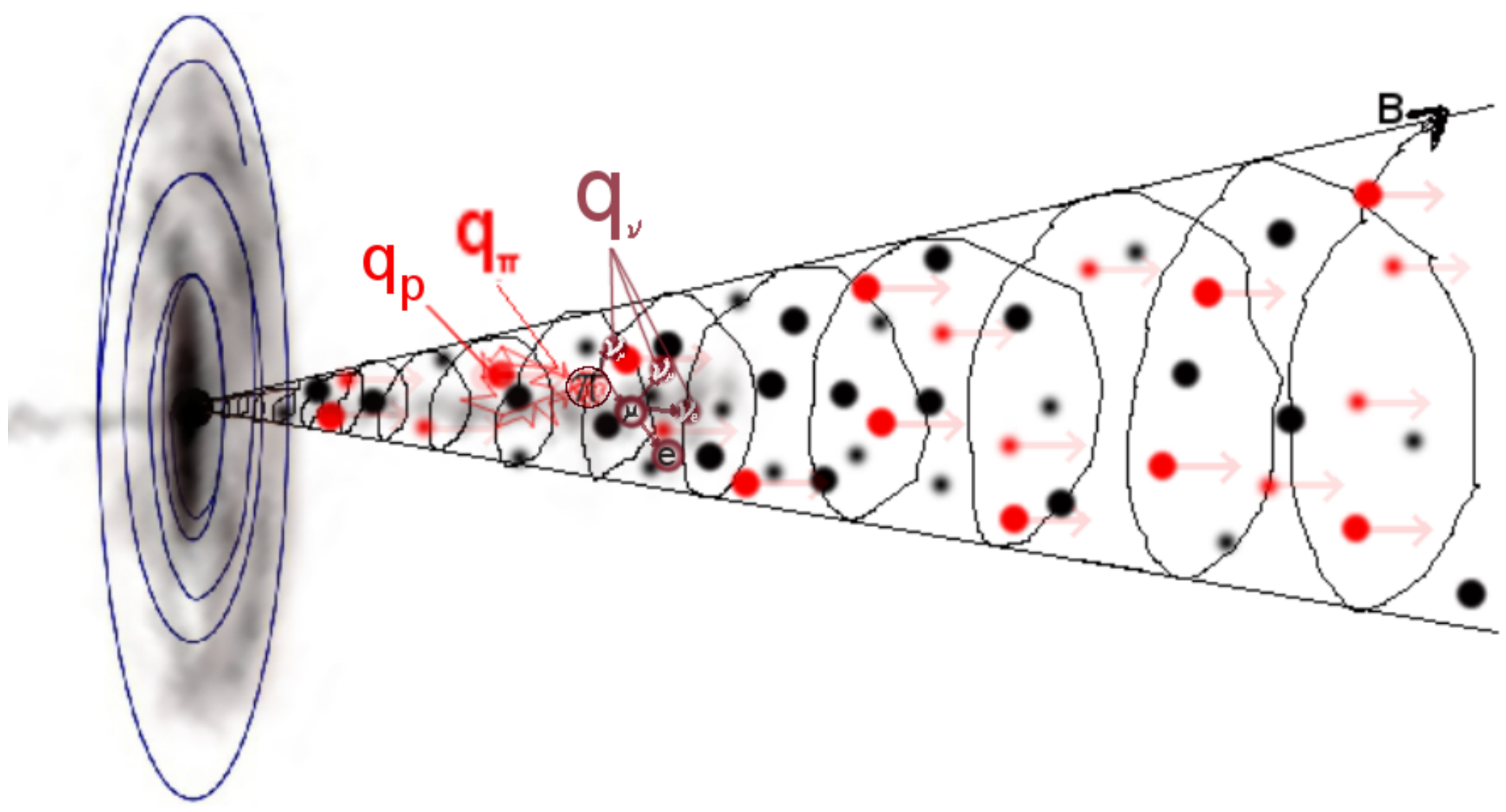

Fig.1: Hadronic pion production scenario in AGN jets.

Consequently, the total neutrino rate at the source is determined (using the delta-functional approach) by

$$\begin{aligned} q_{\nu,\mathrm{tot}}(E_{\nu_i}) &= q^{(1)}_{\nu_\mu} + q^{(2)}_{\nu_\mu} + q_{\nu_e} \simeq 12\, q_\pi(E_\pi = 4 E_{\nu_i}) \\ &\simeq 3\cdot 10^2 \cdot N_H \cdot A_{\mathrm{p}} \cdot \sigma_{\mathrm{pp}} \cdot \left(\frac{24 \cdot E_\nu}{\mathrm{GeV}}\right)^{-\frac{4}{3}p + \frac{2}{3}} , \end{aligned} \qquad (1)$$

where N_H denotes the column density of the interaction region and the cross-section for proton-proton interactions is assumed to be constant $\sigma_{\mathrm{pp}} \simeq 3\cdot 10^{-26}\,\mathrm{cm}^2$.

2.1 Normalization of the Cosmic Ray spectrum

The normalization of the cosmic ray spectrum can be estimated by the radio luminosity of AGN, L, so that

$$L_{\mathrm{p}} \equiv \int j_{\mathrm{p}}(E_{\mathrm{p}}) E_{\mathrm{p}}\, dE_{\mathrm{p}} \approx \frac{\chi \cdot L}{f_e} . \qquad (2)$$

Here, we used the fraction $\chi = L_e/L$ of electron-to-radio luminosity as well as the ratio $f_e = L_e/L_{\mathrm{p}}$ between electron and proton luminosity.
From theoretical considerations (see e.g. [3, 2]), for equal spectral indices of electrons and protons at injection, the latter ratio of the luminosities should be $f_e \approx (m_e/m_p)^{(p-1)/2} \approx 0.02$ for a primary spectral index of $p = 2$.
The radio luminosity L is assumed to result from synchrotron radiation of the electrons, so that the electron-to-radio luminosity ratio χ depends on the magnetic field strength B of the interaction region (see Fig.2).

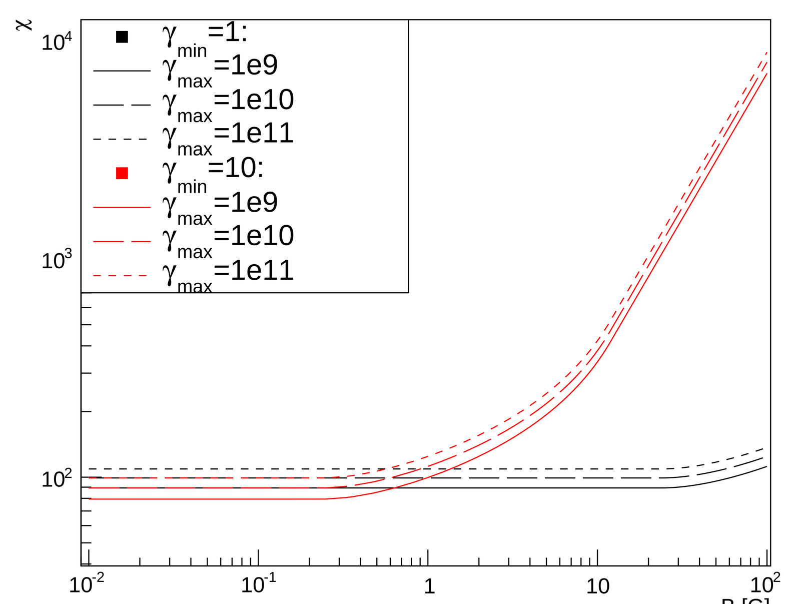

Fig.2: Electron-to-radio luminosity ratio χ plotted against the magnetic field strength B for different minimal and maximal Lorentz factors of the electrons.

3 The Diffuse Neutrino Flux At Earth

The *diffuse neutrino flux at Earth* is determined by

$$\Phi_\nu = \int_L \int_z \frac{q_{\nu,tot}}{4\,\pi\, d_L(z)^2} \cdot \frac{dn_{\mathrm{AGN}}}{dV\, dL} \cdot \frac{dV}{dz}\, dz\, dL\,, \qquad (3)$$

where d_L denotes the luminosity distance, $\mathrm{d}n_{\mathrm{AGN}}/(\mathrm{d}V\,\mathrm{d}L)$ is the radio luminosity function of the AGN (which is in the case of FR-I and FR-II galaxies provided by Willott et al., 2001, [4]) and $\mathrm{d}V/\mathrm{d}z$ is the comoving volume at a fixed redshift z.

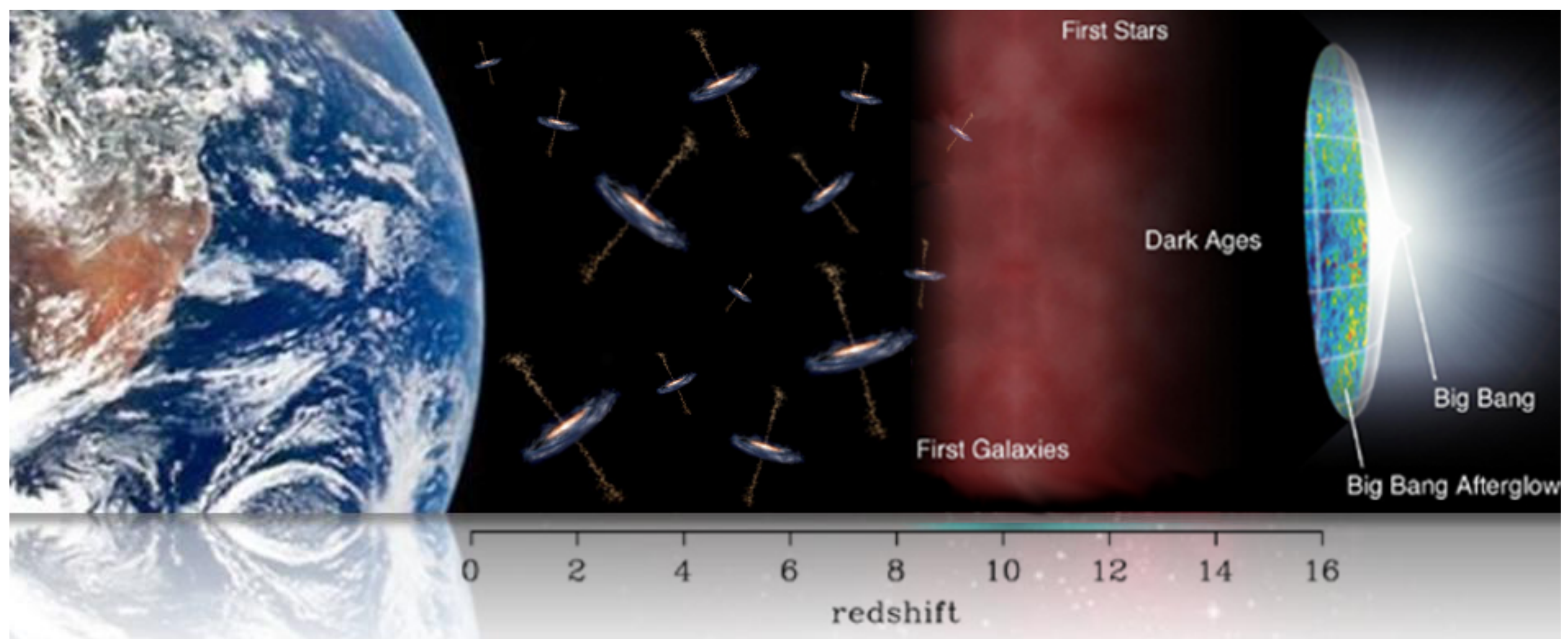

Fig.3: Evolution of the Universe with respect to AGN and its emitted neutrino flux.

If we now consider FR-I and FR-II galaxies, respectively, as responsible for the IceCube excess, the total neutrino flux per flavor must match the observed flux, i.e.

$$\frac{1}{3}\left(\frac{E_{\nu,0}}{\mathrm{GeV}}\right)^2 \Phi_\nu = 1.2\cdot 10^{-8}\,\mathrm{GeV}^{-1}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}\,\mathrm{sr}^{-1}\,. \qquad (4)$$

Comparing Equ. (4) with the theoretical prediction due to Equ. (3), the column density of the interaction region in this scenario is constrained to

$$\begin{aligned} N_{H,FR-I} &\approx 10^{24.57\pm 1.0} \left(\frac{f_e}{0.06}\right)\left(\frac{100}{\chi}\right) \mathrm{cm}^{-2} \\ N_{H,FR-II} &\approx 10^{25.03\pm 1.0} \left(\frac{f_e}{0.06}\right)\left(\frac{100}{\chi}\right) \mathrm{cm}^{-2}\,. \end{aligned} \qquad (5)$$

4 The Answer

Fig. 4 shows, that the lobes of FR-II galaxies can be excluded as a source of the observed IceCube signal due to its far too less particle densities, however, the knots of FR-I galaxies (like the nearby Centaurus A) are a serious candidate.

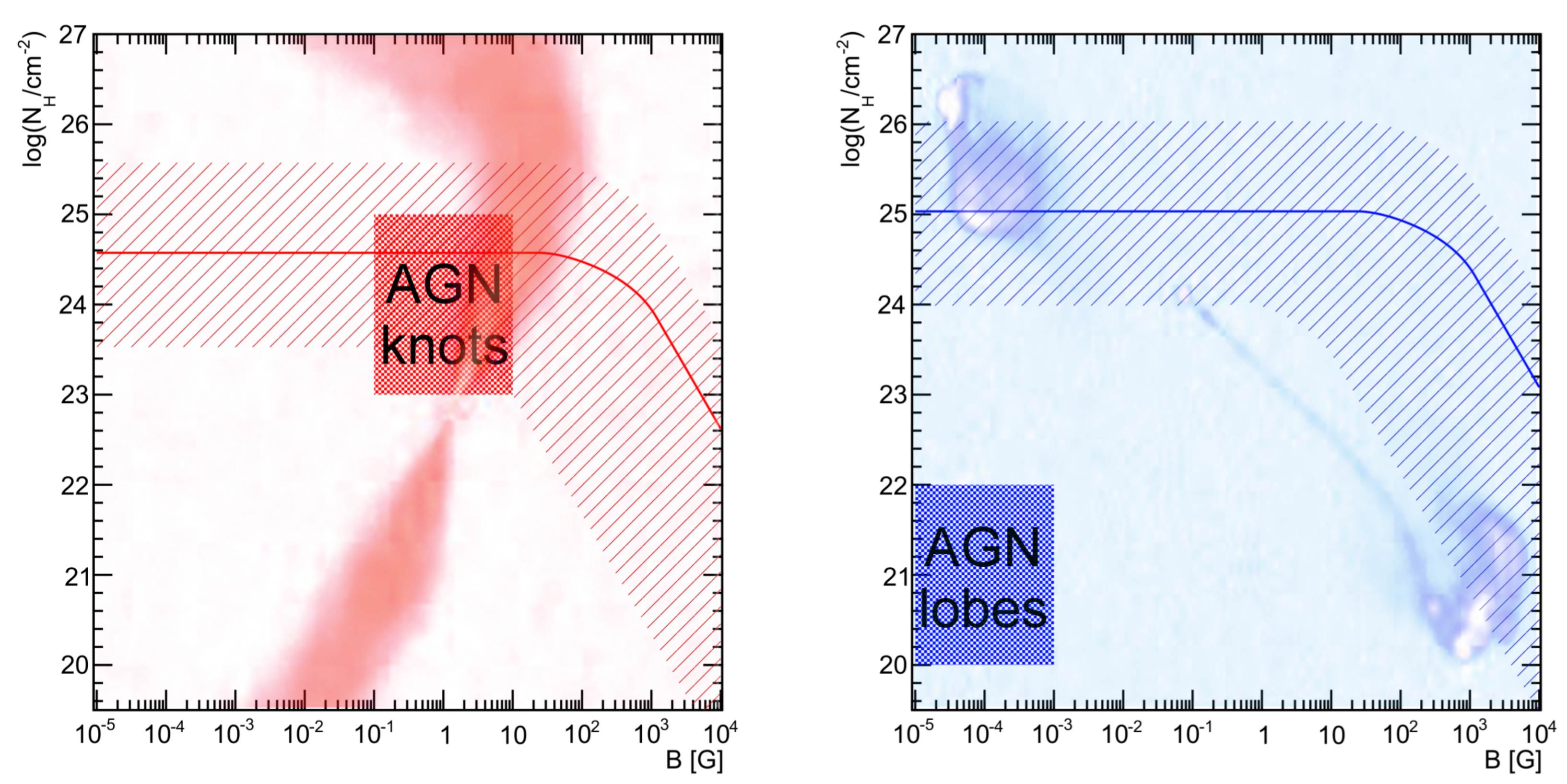

Fig.4: Column density (and its possible error) of FR-I (left) and FR-II (right) galaxies dependent on the magnetic field strength. The square areas mark the allowed parameter space.

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