# Neutron β-decay as the origin of IceCube's PeV (anti)neutrinos

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Motivated by the indications of a possible deficit of muon tracks in the first three-year equivalent data set of IceCube we investigate the possibility that the astrophysical (anti)neutrino flux (in the PeV energy range) could originate from β-decay of relativistic neutrons. We show that to accommodate IceCube observations it is necessary that only about 1% to 10% of the emitted cosmic rays in the energy decade $10^{8.5} \lesssim E_{\rm CR}/{\rm GeV} \lesssim 10^{9.5}$, yielding antineutrinos on Earth ($10^{5.5} \lesssim E_{\bar{\nu}}/{\rm GeV} \lesssim 10^{6.5}$), are observed. Such a strong suppression can be explained assuming magnetic shielding of the secondary protons which diffuse in extragalactic magnetic fields of strength $10 \lesssim B/{\rm nG} \lesssim 100$ and coherence length $\lesssim$Mpc.

## I. INTRODUCTION

Very recently, the IceCube Collaboration famously announced the discovery of extraterrestrial neutrinos, including 3 events with well-measured energies around $10^6$ GeV, but notably no events have been observed above about $10^{6.4}$ GeV [1]. At $E_{\bar{\nu}} = 10^{6.8}$ GeV, one expects to observe a dramatic increase in the event rate for $\bar{\nu}_e$ in ice due to the "Glashow resonance" in which $\bar{\nu}_e + e^- \rightarrow W^- \rightarrow$ shower greatly increases the interaction cross section [2]. Indeed, the detection effective area for $\bar{\nu}_e$ at the resonant energy is about 12 times that of off-resonance ($\nu_e, \nu_\mu, \nu_\tau,$ $\bar{\nu}_\mu, \bar{\nu}_\tau$) events. This implies that the falling power law of the incident neutrino spectrum ($\propto E_\nu^{-\Gamma}$) is effectively canceled and that resonant $\bar{\nu}_e$ events could have been seen [3].

Various candidate source models have been proposed to explain the IceCube energy spectrum [4]. In these models neutrinos originate dominantly in the decay of pions, kaons, and secondary muons produced by (photo)hadronic interactions. Consequently, the expectation for the relative fluxes of each neutrino flavor at production in the cosmic sources, $(\alpha_{e,S}: \alpha_{\mu,S}: \alpha_{\tau,S})$, is nearly $(1:2:0)_S$. After neutrino oscillations decohere over the astronomical propagation distances the flavor conversion is properly described by the mean oscillation probability. As a result, the flux of "pionic" cosmic neutrinos should arrive at Earth with democratic flavor ratios, $(\alpha_{e,\oplus}: \alpha_{\mu,\oplus}: \alpha_{\tau,\oplus}) \approx (1:1:1)_\oplus$. If this were the case, then only $1/6$ of the total neutrino flux would be subject to the enhancement at the Glashow resonance. This relaxes the physical significance of the apparent cutoff. The obvious question to ask is whether the flavor ratio $(1:1:1)_\oplus$ is supported by the data.

The IceCube event topologies have been classified as muon tracks and showers. The full 988-day sample contains 37 veto-passing events (9 tracks and 28 showers) with deposited energies in the range $10^{4.7} \lesssim E_\nu/{\rm GeV} \lesssim 10^{6.3}$. Taken at face value the $9:28$ track-to-shower ratio appears consistent with the canonical $(1:1:1)_\oplus$. However, this is not the case when the atmospheric muon and neutrino backgrounds are properly accounted for. The expected background from atmospheric muons is $8.4 \pm 4.2$ and that from atmospheric neutrinos is $6.6^{+5.9}_{-1.6}$ [1]. Altogether, the background expectation for tracks is about 12 events, suggesting that the cosmic component overwhelmingly produces showers inside the detector. For an unbroken power law energy spectrum with $\Gamma = 2$, a recent statistical analysis indicates that the $(1:1:1)_\oplus$ ratio is disfavored at the 92% C.L. [5].[1] The constraint is lessened by the softer spectra favored by the most recent IceCube data [7]; for a spectrum $\propto E_\nu^{-2.3}$, the $(1:1:1)_\oplus$ flavor ratio is disfavored at 86% C.L. [5].

It has been suggested that the possible deficit of muon tracks (as well as the apparent energy gap between $10^{5.5} \lesssim E_\nu/{\rm GeV} \lesssim 10^{6.0}$ [1]) is due to some nonstandard physics which favors Earthly ratios nearly $(1:0:0)_\oplus$, e.g., neutrino decay [8], *CPT* violation [9], pseudo-Dirac neutrinos [10], enhancement of neutrino-quark scattering by a leptoquark that couples to the τ-flavor and light quarks [11], sterile neutrino altered dispersion relations due to shortcuts in extra dimensions [12], and exotic very-soft interactions of cosmogenic neutrinos [13]. In this note we provide a more mundane explanation, in which a $(3:1:1)_\oplus$ flux of antineutrinos originates via neutron β-decay [14]. The typical energy for the $\bar{\nu}_e$ in the lab is that of the parent neutron times $Q/m_n \sim 10^{-3}$ (the $Q$-value for β-decay is $m_n - m_p - m_e = 0.78$ MeV). Therefore, to produce PeV antineutrinos we require a flux of EeV neutrons. Herein we show that to accommodate IceCube observations it is necessary that only about 1% to 10% of the emitted cosmic rays in the energy decade $10^{8.5} \lesssim E_{\rm CR}/{\rm GeV} \lesssim 10^{9.5}$, yielding antineutrinos on Earth ($10^{5.5} \lesssim E_{\bar{\nu}}/{\rm GeV} \lesssim 10^{6.5}$), are observed. Such a strong suppression can be explained assuming magnetic shielding of the secondary protons which diffuse in extragalactic magnetic fields of strength $10 \lesssim B/{\rm nG} \lesssim 100$ and coherence length $\lesssim$Mpc. Before proceeding, we explore the required assumptions on parameters characterizing the neutron-emitting sources (NES).

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[1]See, however, [6].

## II. MODEL ASSUMPTIONS

We assume that the production of neutrons and photons by cosmic ray accelerators is a consequence of photodisintegration of high-energy nuclei, followed by immediate photoemission from the excited daughter nuclei. By far the largest contribution to the photoexcitation cross section comes from the giant dipole resonance (GDR) at $\epsilon_\gamma^{\text{GDR}} \sim$ 10–30 MeV in the nuclear rest frame. The ambient photon energy required to excite the GDR is therefore $\epsilon_\gamma = \epsilon_\gamma^{\text{GDR}}/\gamma_A$, where $\gamma_A = E_A/m_A$ is the boost factor of the nucleus (of mass number $A$ and charge $Ze$) in the lab. The GDR decays by the statistical emission of a single nucleon, leaving an excited daughter nucleus. The probability for emission of two (or more) nucleons is smaller by an order of magnitude. The excited daughter nuclei typically deexcite by emitting one or more photons of energies $\epsilon_\gamma^{\text{dxn}} \sim$ 1–5 MeV in the nuclear rest frame. The lab-frame energy of the $\gamma$-ray is then $E_\gamma = \gamma_A \epsilon_\gamma^{\text{dxn}}$. To produce neutrons in the energy range of interest we require a thermal photon background in the far infrared, $\epsilon_\gamma \sim 10\,\text{meV}$.

There are two channels other than photodisintegration that might contribute to $\gamma$-ray and neutrino production. These are photohadronic ($A - \gamma$) and pure hadronic ($A - p$) interactions. In both cases, $\gamma$-rays (neutrinos) are produced after $\pi^0$ ($\pi^+$ and $\pi^-$) decays; neutrinos carry on average $\sim 1/16$ of the initial cosmic ray energy per nucleon. To avoid overproduction of neutrinos in the EeV energy range we assume that collisions of the relativistic nuclei with the cold ambient interstellar medium are strongly suppressed, due to an extremely low gas density. Photomeson production has a very high energy threshold, being only relevant for very high energetic beams or in very hot photon environments. Even in these extreme cases, the fact that this reaction turns on at so high energies implies that the photons and neutrinos from decaying pions are produced at very high energies too. The energy threshold for GDR excitation is more than one order of magnitude below the threshold for photopion production, $\epsilon_\gamma^{\pi,\text{th}} \sim 150$ MeV. Therefore, in the energy decade of interest ($10^{8.5}$ GeV $\lesssim E_n = E_A/A \lesssim 10^{9.5}$ GeV) our choice of source parameters automatically suppresses photomeson production.

Though all cosmic ray experiments point to a dominance of protons below the "ankle" of the cosmic ray spectrum (that is $E_{\text{CR}} \lesssim 10^{9.6}$ GeV), there is a significant disagreement in interpretation of depth of shower maximum measurements above this energy, with HiRes [15] and TA [16] preferring nearly pure protons and Auger [17] preferring a transition to heavies. To remain consistent with the nonobservation of events at the Glashow resonance, the contribution to the cosmic ray flux from NES cannot extend beyond $10^{9.6}$ GeV. This maximum energy is not inconsistent with the maximum observed energies if one assumes ultrahigh-energy cosmic rays are heavy nuclei; e.g., for iron nuclei $E_n^{\text{max}} \sim 10^{11}/56$ GeV. In the scenario envisaged here neutron emission from nuclei photodisintegration

dominates the spectrum below the ankle. The steeply falling neutron spectrum is overtaken by the harder proton spectrum above about $10^{9.5}$ GeV, where the escape of charged particles becomes efficient. These overlapping spectra could then carve the ankle into the spectrum. The spectrum above the ankle exhibits a progressive transition to heavy nuclei, as $E_A/Z$ reaches the proton escape energy. If, on the other hand, the observed spectrum is dominated by protons above the ankle, we should then assume that there are two different types of sources contributing below and above the ankle [18]. This in turn provides a simple interpretation of the break in the spectrum; namely, a new population of sources emerges which dominates the more steeply falling NES population.

## III. FLUX OF ANTINEUTRINOS AND CONSTRAINTS FROM GAMMA RAYS

We turn to the calculation. Compared to cosmic distances, the decay of even the boosted neutron may be taken as nearly instantaneous. Therefore, the basic formula that relates the neutron flux at the sources to the antineutrino flux observed at Earth ($dF_{\bar{\nu}}/dE_{\bar{\nu}}$) is [14]

$$\frac{dF_{\bar{\nu}}(E_{\bar{\nu}})}{dE_{\bar{\nu}}} = \frac{1}{4\pi H_0} \int dE_n \mathcal{Q}_n(E_n) \int_0^Q d\epsilon_{\bar{\nu}} \frac{dP(\epsilon_{\bar{\nu}})}{d\epsilon_{\bar{\nu}}} \times \int_{-1}^1 \frac{d\cos\bar{\theta}_{\bar{\nu}}}{2} \delta\left[E_{\bar{\nu}} - \frac{E_n \epsilon_{\bar{\nu}}(1 + \cos\bar{\theta}_{\bar{\nu}})}{m_n}\right], \quad (1)$$

where $E_{\bar{\nu}}$ and $E_n$ are the antineutrino and neutron energies in the lab, $\bar{\theta}_{\bar{\nu}}$ is the antineutrino angle with respect to the direction of the neutron momentum in the neutron rest frame, and $\epsilon_{\bar{\nu}}$ is the antineutrino energy in the neutron rest frame. The last three variables are not observed by a laboratory neutrino detector, and so are integrated over. The observable $E_{\bar{\nu}}$ is held fixed. The delta function relates the neutrino energy in the lab to the three integration variables, $E_{\bar{\nu}} = \gamma_n(\epsilon_{\bar{\nu}} + \beta\epsilon_{\bar{\nu}}\cos\bar{\theta}_{\bar{\nu}}) = E_n\epsilon_{\bar{\nu}}(1 + \cos\bar{\theta}_{\bar{\nu}})/m_n$, where $\gamma_n$ is the Lorentz factor and as usual $\beta \approx 1$ is the particle's velocity in units of $c$. Here, $\mathcal{Q}_n(E_n)$ is the neutron emissivity, defined as the mean number of particles emitted per comoving volume per unit time per unit energy as measured at the source. In general, the emissivity may evolve and so depend on time or redshift, but we will ignore this here. We sum the sources out to the edge of the Universe at distance $H_0^{-1}$ (note that an $r^2$ in the volume sum is compensated by the usual $1/r^2$ falloff of flux per source). Finally, $dP/d\epsilon_{\bar{\nu}}$ is the normalized probability that the decaying neutron produces a $\bar{\nu}_e$ with energy $\epsilon_{\bar{\nu}}$ in the neutron rest frame. Note that the maximum $\bar{\nu}_e$ energy in the neutron rest frame is very nearly $Q$ and the minimum $\bar{\nu}_e$ energy is zero in the massless limit. For the decay of unpolarized neutrons, there is no angular dependence in $dP/d\epsilon_{\bar{\nu}}$.

Performing the $\cos\bar{\theta}_{\bar{\nu}}$ integration in (1) over the delta-function constraint leads to

$$\frac{dF_{\bar{\nu}}}{dE_{\bar{\nu}}}(E_{\bar{\nu}}) = \frac{m_n}{8\pi H_0} \int_{E_n^{\min}} \frac{dE_n}{E_n} \mathcal{Q}_n(E_n) \int_{\epsilon_{\bar{\nu}}^{\min}}^{Q} \frac{d\epsilon_{\bar{\nu}}}{\epsilon_{\bar{\nu}}} \frac{dP}{d\epsilon_{\bar{\nu}}}(\epsilon_{\bar{\nu}}), \quad (2)$$

with $\epsilon_{\bar{\nu}}^{\min} = \frac{E_{\bar{\nu}} m_n}{2E_n}$, and $E_n^{\min} = \frac{E_{\bar{\nu}} m_n}{2Q}$. An approximate answer is available if we take the $\beta$-decay as a $1 \to 2$ process of $\delta m_N \to e^- + \bar{\nu}_e$, in which the antineutrino is produced monoenergetically in the rest frame, with $\epsilon_{\bar{\nu}} = \epsilon_0 \simeq \delta m_N (1 - m_e^2 / \delta^2 m_N)/2 \simeq 0.55 \, \text{MeV}$, where $\delta m_N \simeq 1.30 \, \text{MeV}$ is the neutron-proton mass difference. Setting the beta-decay neutrino energy $\epsilon_{\bar{\nu}}$ equal to its mean value $\equiv \epsilon_0$, we have $\frac{dP}{d\epsilon_{\bar{\nu}}}(\epsilon_{\bar{\nu}}) = \delta(\epsilon_{\bar{\nu}} - \epsilon_0)$. In the lab, the ratio of the maximum $\bar{\nu}_e$ energy to the neutron energy is $2\epsilon_0/m_n \sim 10^{-3}$, and so the boosted $\bar{\nu}_e$'s have a spectrum with $E_{\bar{\nu}} \in (0, 10^{-3} E_n)$. When the delta function is substituted into (2), we obtain

$$\frac{dF_{\bar{\nu}}}{dE_{\bar{\nu}}}(E_{\bar{\nu}}) = \frac{m_n}{8\pi\epsilon_0 H_0} \int_{E_n^{\min}}^{E_n^{\max}} \frac{dE_n}{E_n} \mathcal{Q}_n(E_n), \quad (3)$$

where $E_n^{\min} = \max\{E_{\text{th}}^{\text{GDR}}, \frac{m_n E_{\bar{\nu}}}{2\epsilon_0}\}$, and $E_{\text{th}}^{\text{GDR}} \sim 10^{8.5} \, \text{GeV}$ is the neutron energy from a photodisintegrated nucleus at threshold.[2]

Next we must relate $\mathcal{Q}_n$ to an observable. Establishing a connection between the secondary flux of protons $dF_{\text{CR}}/dE_{\text{CR}}$ and the neutron emissivity is really simple because the $\beta$-protons, with energies $10^{8.5} \lesssim E_{\text{CR}}/\text{GeV} \lesssim 10^{9.5}$, travel undeterred through the universal radiation backgrounds permeating the Universe. However, it is possible that some protons are shielded by the intergalactic magnetic field. This will restrict the number of contributing sources to the cosmic ray spectrum. Including here energy redshifting by $1 + z$, we obtain

$$\frac{dF_{\text{CR}}(E_{\text{CR}})}{dE_{\text{CR}}} = \frac{f}{H_0} \int_0^{z_{\max}} dz \mathcal{Q}_n(1 + z, E_n), \quad (4)$$

where $f$ is a suppression factor defined as the ratio of the observed flux to the one that would be obtained for a continuous source distribution without magnetic shielding.

The two observables in (3) and (4), $\beta$-antineutrino and proton spectra at Earth, are related by the common source. The relation is made explicit by assuming a functional form for $\mathcal{Q}_n(E_n)$. If we assume a power law with index $\Gamma$, as shown in [19] the integrals are easily done. For $10^{5.5} \lesssim E_{\bar{\nu}}/\text{GeV} \lesssim 10^{6.5}$, we obtain

$$\frac{dF_{\bar{\nu}}(E_{\bar{\nu}})}{dE_{\bar{\nu}}} \approx \frac{10^3}{f} \left(\frac{E_{\text{th}}^{\text{GDR}}}{E_n^{\max}}\right)^{\Gamma} \left[\left(\frac{E_{\bar{\nu}}^{\max}}{E_{\bar{\nu}}}\right)^{\Gamma} - 1\right] \frac{dF_{\text{CR}}(E_{\text{th}}^{\text{GDR}})}{dE_{\text{CR}}}, \quad (5)$$

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[2]It is implicit that GDR-superscripted variables have an $A$-dependence. This could influence the shape of the cosmic ray spectrum around $10^{8.5}$ GeV, where a spectral feature called the "second knee" has been reported.

where

$$E_{\bar{\nu}}^{\max} = \frac{2\epsilon_0}{m_n} E_n^{\max} \sim 10^{6.5} \left(\frac{E_n^{\max}}{10^{9.5} \, \text{GeV}}\right) \text{GeV}. \quad (6)$$

On the other hand, for $E_{\bar{\nu}} \lesssim 2\epsilon_0 E_{\text{th}}^{\text{GDR}}/m_n$, the $\bar{\nu}_e$ spectrum is flat

$$\frac{dF_{\bar{\nu}}(E_{\bar{\nu}})}{dE_{\bar{\nu}}} \approx \frac{10^{-3}}{f} \frac{dF_{\text{CR}}(E_{\text{th}}^{\text{GDR}})}{dE_{\text{CR}}}, \quad (7)$$

because all the free neutrons have sufficient energy, $E_n \gtrsim 10^{8.5}$ GeV, to contribute equally to all the $\bar{\nu}_e$ energy bins below $E_{\text{th}}^{\text{GDR}}$.

Taking $\Gamma \simeq 2$ as a reasonable example (5) yields

$$\left.\frac{E_{\bar{\nu}}^2 dF_{\bar{\nu}}(E_{\bar{\nu}})}{dE_{\bar{\nu}}}\right|_{10^{5.5} \text{ GeV}} \approx \frac{10^{-3}}{f} (E_{\text{th}}^{\text{GDR}})^2 \frac{dF_{\text{CR}}(E_{\text{th}}^{\text{GDR}})}{dE_{\text{CR}}}. \quad (8)$$

Substituting the observational value [20],

$$(E_{\text{th}}^{\text{GDR}})^2 \frac{dF_{\text{CR}}(E_{\text{th}}^{\text{GDR}})}{dE_{\text{CR}}} \approx 9 \times 10^{-7} \, \text{GeV} \, \text{m}^{-2} \, \text{s}^{-1} \, \text{sr}^{-1}, \quad (9)$$

into (8) and comparing it with the energy square weighted flux reported by the IceCube Collaboration, $\mathcal{O}(10^{-8} \, \text{GeV} \, \text{m}^{-2} \, \text{s}^{-1} \, \text{sr}^{-1})$ [1], we require $f \sim 0.1$ to accommodate our proposal.

The propagation of cosmic ray protons in the extragalactic magnetic field would be diffusive if the distance from the source(s) to Earth is much larger than the scattering length. Depending on the magnetic field strength and diffusion length, a significant fraction of the "emitted" protons can have trajectory lengths comparable to the Hubble radius $H_0^{-1}$. However, if the average separation between the sources ($d_s \sim n_s^{-1/3}$) in a uniform distribution is much smaller than the characteristic propagation length scales due to diffusion and energy loss, the observed cosmic ray flux will be the same as that obtained for a continuous distribution of sources in the absence of magnetic field effects [21]. On the other hand, the flux of protons would be suppressed if (i) particles are unable to reach Earth from faraway sources and (ii) particles take a much longer time to arrive from the nearby sources than they would following rectilinear propagation. It is therefore important to study in detail the suppression effect on the closest sources.

Following [22] we assume diffusion in a random $B$-field with maximum coherent length $l_c$. This assumption yields two different propagation regimes depending on the relation between the Larmor radius $r_L \simeq 1.1(E_{\text{CR}}/\text{EeV}) \times (B/\text{nG})^{-1}$ Mpc and the coherence length. The transition energy between these two regimes, $E_*$, is determined by the condition $r_L(E_*) = l_c$, yielding $E_\star \simeq 10^9 (B/\text{nG}) \times (l_c/\text{Mpc})$ GeV. For $\Gamma = 2$, the suppression factor can be approximated by
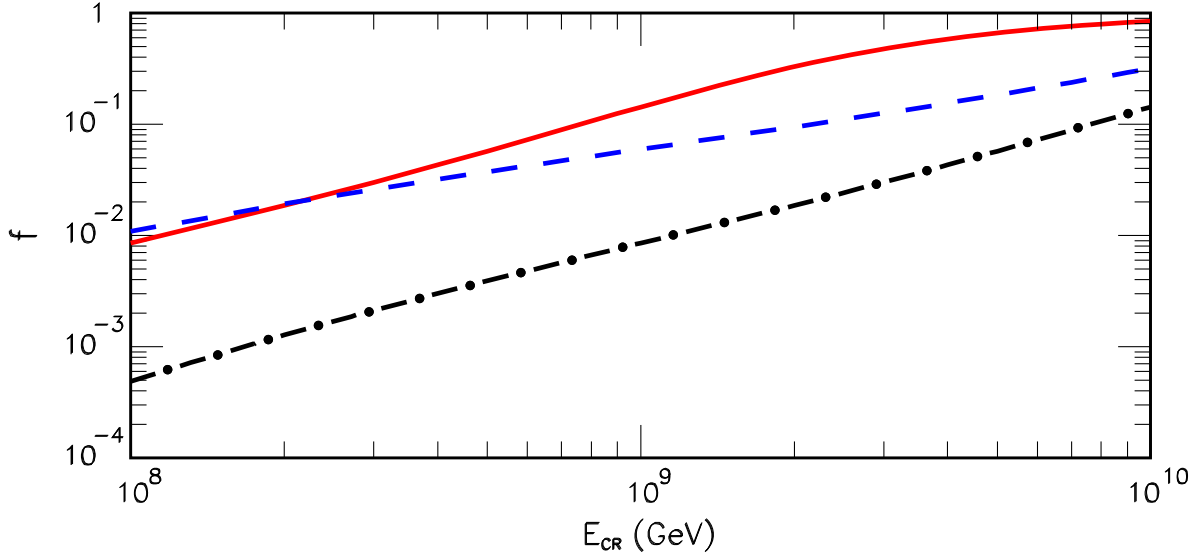
FIG. 1 (color online). The suppression factor for various values of the source density and magnetic field strength ($n_s$/Mpc$^3$, $B$/nG): solid line ($10^{-6}$, 10), dashed line ($10^{-6.5}$, 100), dot-dashed line ($10^{-6}$, 100). In all cases we have taken $l_c = 1$ Mpc.

$$f(E_{\mathrm{CR}}) \sim \exp\left[-\left(\frac{ad_s}{\sqrt{H_0^{-1}l_c}}\right)^\alpha \frac{1}{(E_{\mathrm{CR}}/E_*)^\alpha + b(E_{\mathrm{CR}}/E_*)^\beta}\right],$$

(10)

where $\alpha = 1.43$, $\beta = 0.19$, $a = 0.2$, $b = 0.09$, and $\sqrt{H_0^{-1}l_c} \simeq 65$ Mpc $\sqrt{l_c/\text{Mpc}}$ [23]. In Fig. 1 we show three illustrative examples for which the required range of the value of $f$ can be easily entertained. The approximation in (10) assumes the magnetic field power to be distributed homogeneously in space. For inhomogeneous extragalactic magnetic fields, the parameters in (10) vary significantly depending on the strength of magnetic fields in the voids of the large scale structure distribution, which is subject to large uncertainties [24]. We note that further suppression of the cosmic ray flux can be obtained if some neutrons decay inside the source, resulting in protons which remain trapped until attaining the escape energy.

Next, we estimate the $\gamma$-ray flux produced when the photodissociated nuclear fragments deexcite. These $\gamma$-rays create chains of electromagnetic cascades on the microwave and infrared backgrounds, resulting in a transfer of the initial energy into the so-called *Fermi-LAT* region, which is bounded by observation [25] to not exceed $\omega_{\mathrm{cas}} \sim 5.8 \times 10^{-7}$ eV/cm$^3$ [26]. Fortunately, we can finesse the details of the calculation by arguing in analogy to the work already done. The photodisintegration chain produces one $\beta$-decay antineutrino with energy of order 0.55 MeV in the nuclear rest frame, for each neutron produced [27]. Multiplying this result by 2 to include photodisintegration to protons in addition to neutrons correctly weights the number of steps in the chain. Each step produces on average one photon with energy $\sim 3$ MeV in the nuclear rest frame. In comparison, about 12 times more energy is deposited into photons. Including the factor of 12 relating

$\omega_\gamma$ to $\omega_{\bar{\nu}_e}$, we find from (8) that the photodisintegration/ deexcitation energy emitted in $\gamma$-rays, $\omega_\gamma \sim 1.1 \times 10^{-7}$eV/cm$^3$, is below the *Fermi-LAT* bound.[3]

The analysis described here is subject to several caveats. We have ignored effects of energy redshifting of the neutrino and possible source evolution. A more careful analysis would yield in (1) an additional factor: $H_0 \int dz H^{-1}(z) \mathcal{Q}_n(z)/\mathcal{Q}_n(0)$.[4] We have assumed that not only the nuclei undergoing acceleration remained magnetically trapped in the source, but also the secondary protons released in the photodisintegration process. This may decrease $f$ by a factor of about 2. It is also worth stressing that the picture outlined above is driven by the canonical Fermi index of $\Gamma \simeq 2$. For $\Gamma = 2.2$, $f$ is reduced by a factor of 5 and for $\Gamma = 2.3$, $f$ is reduced by almost one order of magnitude. Given the current level of uncertainties on the source evolution and the magnetic horizon, shifting our assumed spectral index from $\Gamma \simeq 2$ to $\Gamma \simeq 2.3$ will have little impact on the arguments concerning energetics explored herein. In the future, improved measurements all around will require a considerably more elaborate analysis, including detailed numerical simulations.

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[3]$\omega_\nu$ is just the area under the $E_{\bar{\nu}}^2 dF_{\bar{\nu}}/dE_{\bar{\nu}}$ versus $\ln E_{\bar{\nu}}$ curve [26].

[4]A rough estimate can be obtained from the following considerations. The redshift from sources at $z = 1$ will reduce the energy of protons and neutrinos by about 50% and at $z = 2$ by about 30%. If one includes $e^+e^-$ production the energy of the protons will be reduced by about 5% at $z = 1$; see Fig. 3 of [28]. Given that protons lose energy during propagation scattering off the radiation fields while neutrinos do not, the value of $f$ should in fact be somewhat larger than computed in the analysis presented here. Additionally calculating $f$ precisely requires knowledge of the source evolution.

In closing, we note that $E_{\text{th}}^{\text{GDR}}$ can be shifted to lower energies by considering a thermal photon background in the near infrared, $\epsilon_\gamma \sim 1$ eV. Since the cosmic ray spectrum $\propto E_{\text{CR}}^{-3.1}$ is softer than the neutrino spectrum $\propto E_\nu^{-2.46\pm0.12}$ [7], the source energetics discussed herein would also easily accommodate the recently proposed *two-component* flux model [29], in which a steeply falling flux of electron antineutrinos populates the "low-energy" range of the cosmic neutrino spectrum observed by IceCube, and is overtaken at "high energy" by a population of neutrinos produced through pion decay with a harder spectrum.

## IV. CONCLUSIONS

We have presented a model that can accommodate the apparent deficit of muon tracks in IceCube data without the need of invoking unknown physics. The model seems unnaturally fine-tuned as it would be more likely for neutrinos to originate from pion decay; in particular, the energetics requirement would be more easy to satisfy. However, nature is often more subtle than we might like and all options should be considered. In particular, if the significance of the muon deficit increases as IceCube collects more data the model presented here will gather plausibility.

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