A Galactic Halo Origin of the Neutrinos Detected by IceCube

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Recent IceCube results suggest that the first detection of very high energy astrophysical neutrinos have been accomplished. We consider these results at face value in a Galactic origin context. Emission scenarios from both the Fermi bubble and broader halo region are considered. We motivate that such an intensity of diffuse neutrino emission could be Galactic in origin if it is produced from an outflow into the halo region. This scenario requires cosmic ray transport within the outflow environment to be different to that inferred locally within the disk and that activity in the central part of the Galaxy accelerates cosmic rays to trans-"knee" energies before they escape into an outflow. The presence of a large reservoir of gas in a very extended halo around the Galaxy, recently inferred from X–ray observations, implies that relatively modest acceleration power of 10^{39} erg s^{-1} in PeV energy cosmic rays may be sufficient to explain the observed neutrino flux. Such a luminosity is compatible with that required to explain the observed intensity of CR around the "knee".

I. INTRODUCTION

The IceCube collaboration has recently reported the detection of 28 neutrinos with energies in excess of $\approx$ 30 TeV, on an expected background of $10.6^{+5.0}_{-3.6}$ events. A purely atmospheric origin for the detected events has thus been rejected at the 4 σ level [1, 2]. Data have been accumulated from some 662 days of observation of the full sky. Furthermore, although limited in statistics, the neutrino distribution indicates a very extended if not isotropic distribution of arrival directions of these neutrinos [2, 3].

Such an excess of events corresponds to a diffuse energy flux of neutrinos in the energy interval 0.1-1 PeV, for all three flavours, at the level:

$$E_\nu^2 \frac{dN}{dE_\nu} \approx 30 \text{ eV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}, \quad (1)$$

with a spectral slope which is estimated to be close to flat (i.e. $\alpha \approx 2$ for $dN/dE_\nu \propto E_\nu^{-\alpha}$) in this representation.

The origin of the neutrinos detected by IceCube presently remains unknown. Both Galactic [3–5] and extragalactic [6, 7] scenarios of their production have been proposed, with a tendency to disfavor Galactic models other than those involving a connection with the Fermi bubble structures. These structures, whose existence were only recently disclosed both in γ-rays and radio [8, 9], extend well outside the Galactic plane region and may well house a significant population of cosmic ray (CR) particles.

Generally, two classes of scenarios can be envisaged in an attempt to explain the apparently isotropic neutrino flux detected by IceCube. The observed flux level (Eq. 1) might either result from the superposition of discrete sources or be truly diffuse on some scale. Indeed, insight into the problems facing the origin of this emission may be obtained through the consideration specifically of one of these scenarios.

Assuming that some fraction of the neutrino flux recently observed is not actually diffuse on the largest scales, originating instead from the Galactic plane region, an indication of the expected neutrino detection rate can be derived from the γ-ray emission flux from this region, some $\Omega_{\rm d} \sim 0.1$ sr in size. The level of very high energy γ-rays allowed from the Galactic plane, as was considered in [10], the MILAGRO observations [11] which partially covered this region provide a basis for determining its multi-TeV gamma-ray brightness. Using these observations to determine the corresponding neutrino flux brightness from the Galactic plane, the expected detection rate of neutrinos from the region can be determined. Specifically, the MILAGRO observations from this region, whose median photon energy was estimated to be 15 TeV, motivate a photon energy flux at the level,

$$E_\gamma F_\gamma^{\rm d} = \Omega_{\rm d} E_\gamma^2 \frac{dN}{dE_\gamma} \approx 70 \text{ eV cm}^{-2} \text{ s}^{-1}. \quad (2)$$

For the highly optimistic scenario in which the spectrum of parent protons continues with an E^{-2} spectral shape up to a cutoff energy of 30 PeV, the corresponding neutrino detection rate expected from the Galactic plane region is obtained by convolving the parent CR flux with the IceCube effective area. For the effective area, we adopt a monotonic function of the form

$$A^\nu_{\rm eff} \approx A_0 \left(\frac{E}{\rm TeV}\right)^\gamma e^{-(E_b/E)} \text{ m}^2. \quad (3)$$

with A_0 =1, 0.9, 0.4, γ =0.4, 0.4, 0.5, and E_b =117 TeV, 155 TeV, 170 TeV for ν_e, ν_μ, and ν_τ, respectively. This parameterisation is found to fit well, within an accuracy of $\sim$ 20%, the published all–sky effective area for the three different neutrino species shown in fig. 7 of [2]. Thus, overall, a total of $\sim$1 event per year is predicted from the Galactic plane region, with >30 TeV energy neutrinos dominating the contribution to this rate.

This result clearly demonstrates the inability for this bright diffuse source to account for the level of flux apparently observed in neutrinos at multi-TeV energies (see also [12]). It should be noted that the numbers obtained above are a factor of $\sim$2 smaller than those obtained in [13] for the Galactic center region, for which an $E^{-2.3}$ power-law scaling from the 100 GeV fluxes, at the level 3500 eV cm^{-2} s^{-1} sr^{-1} observed by Fermi [14], were adopted.

More generally, as shown in [10, 15], the following simple but nevertheless robust rule–of–the–thumb can be used: a neutrino flux at the level corresponding in γ-rays to 1 Crab (i.e. $F_\nu(> 1\ \mathrm{TeV}) > 10^{-11}\nu\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$) would yield a detection rate of about 1 neutrino per flavor per year in a detector whose size is one cubic kilometer. For typical spectra of astrophysical sources, the count rate is dominated by $\approx$ 10 TeV neutrinos, and decreases at larger energies. This implies that a quite large number of discrete neutrino sources with fluxes at the Crab level (or, equivalently, an unreasonably large number of significantly weaker sources) are required to explain IceCube data. If neutrinos are produced through inelastic proton–proton interactions, a γ-ray flux of the same order of magnitude is also expected from such sources. Thus, the scarce number of very high energy γ-ray sources detected by current instruments at the Crab flux level seems to rule out this possibility. In the same context, a detailed investigation has been recently performed to assess the possible contribution to the neutrino flux from unidentified TeV sources in our Galaxy [16] and the results from this study are in line with the simple considerations made above.

A possible way out is to invoke the existence of a population of heavily absorbed γ-ray sources in the Galaxy. The most effective absorption mechanism for γ-rays in astrophysical environments is pair–production in a soft photon field. The presence of an intense radiation field would dramatically suppress the γ-ray flux from a source, while leaving the neutrino flux unaffected. Naturally, such a scenario may only be played out in compact objects like binary systems [17] or hypernovae, which have also been considered as candidate neutrino sources [16].

Finally, regardless of whether the source of the emission is generated through CR interactions within their actual sources or via their interactions with atomic and molecular gas material in the disk, the arrival directions of the neutrinos produced are expected to originate from the Galactic plane region. Though present observations are consistent with a broader than disk distribution for the arriving neutrinos, only through an improvement in statistics can a deeper probe of the underlying flux distribution be made.

Do the above considerations exclude a Galactic origin of the reported flux of PeV neutrinos? No. In this paper we argue that a Galactic origin of these neutrinos remains a viable option if one assumes that they are produced in the Galactic halo. This model assumes that the neutrinos result from PeV CR interactions, after their escape from the Galactic disk, with the diffuse ambient gas of non-negligible density present, giving rise to a quasi-isotropic neutrino flux at the level detected by IceCube. In section II, a comparison is made of the relative neutrino emission rates from the Galactic plane and halo regions, under the constant CR intensity assumption. In section III we address the timescales involved for both CR escape from the Galaxy and their energy loss times, which collectively dictate the efficiency with which power is converted from CR to neutrinos. In section IV, non-uniform CR intensity scenarios in which CR within Galactic outflows power diffuse neutrino flux emission are put forward. In section V, we consider the prospects for testing such scenarios using the associated electromagnetic emission expected to accompany that output in neutrinos. We summarise out conclusions in section VI.

II. DIFFUSE PLANE/HALO EMISSION RATIO

We here discuss the case in which the observed neutrino flux is truly diffuse and originates from the interactions between CR and ambient gas in the Galaxy. The intensity dN/dE_{CR} of the CR responsible for the production of the high energy neutrinos is assumed to be constant throughout the whole Galaxy (disk plus halo). Such a setup can be considered as a zeroth order approximation for the possible configuration on which further considerations will be based. Under such circumstances, the expected number of neutrinos N_ν detected by a given telescope in a time Δt, from a region subtending a solid angle $\Delta\Omega$, and within an energy interval ΔE_ν can be written as:

$$N_\nu \ \propto \ \sigma_{pp} \ \frac{dN}{dE_{\mathrm{CR}}} \ N_H \ \Delta\Omega \ \Delta E_\nu \ \Delta t \tag{4}$$

where σ_{pp} is the relevant cross section and $N_H = n_p L$ is the gas column density along the line of sight. Here, L is the length of the line of sight characterized by a typical interstellar hydrogen density n_p and, as an order of magnitude estimate, in the following discussion it will be considered equal to the size of the considered system.

Typical values for the gas density and the size of the disk are $n_p^d = 1\ n_{p,0}^d\ \mathrm{cm}^{-3}$ and $L^d = 10\ L_1^d$ kpc, which give a column density of $N_H^d = 3\times10^{22} n_{p,0}^d L_1^d\ \mathrm{cm}^{-2}$, while for the halo the following reference values are adopted, $n_p^h = 10^{-3}\ n_{p,-3}^h\ \mathrm{cm}^{-3}$ and $L^h = 10\ L_1^h$ kpc which gives a column density equal to $N_H^h = 3\times 10^{19} n_{p,-3}^h L_1^h\ \mathrm{cm}^{-2}$. Following [10] we consider an extension for the disk in Galactic longitude and latitude of $-40^\circ < l < 40^\circ$ and $-2^\circ < b < 2^\circ$, respectively, whose corresponding solid angle is then $\Delta\Omega^d \approx 0.1$ sr, while for the Galactic halo we adopt an optimistic value of $\Delta\Omega^h = 2\pi$ sr. By using Eq. 4 it is now possible to compute the ratio between the number of neutrinos detected from the halo and those detected from the disk of the Galaxy. This reads:

$$\frac{N_\nu^h}{N_\nu^d} = \left(\frac{n_p^h}{n_p^d}\right)\left(\frac{L^h}{L^d}\right)\left(\frac{\Delta\Omega^h}{\Delta\Omega^d}\right) \quad (5)$$

$$\approx 0.05\left(\frac{n_{p,-3}^h}{n_{p,0}^d}\right)\left(\frac{L_1^h}{L_1^d}\right)\left(\frac{\Delta\Omega^d}{0.1}\right)^{-1} .$$

It follows that under the constant CR intensity assumption, the diffuse neutrino flux is dominated by the neutrinos coming from the Galactic disk, unless the Galaxy has a very extended halo (i.e. $L_1^h \ll L_1^d$). The recent claim for the detection of a huge reservoir of ionized gas in a ≈ 100 kpc region around the Milky Way [26] might give support to the latter scenario. Given that the neutrino emission from the Galactic disk might hardly explain the IceCube data (see [10] and the discussion in Sec. I), it seems more plausible to consider an extended Galactic halo as the site of production of the observed neutrinos.

To summarize, the simple considerations made above under the constant CR flux intensity approximation motivate that the Galactic halo can potentially be an important source of Galactic neutrinos. For this case, some natural candidate production sites are the Galactic halo itself (if sufficiently extended) and the Fermi Bubbles, which are giant structures, subtending $\Omega_{\rm FB} \sim 0.8$ sr, detected in GeV gamma rays that extend for several tens of kiloparsecs away from the Galactic disk.

In the following sections, we consider further the possibility that the arriving neutrino flux consists of large scale diffuse emission. For this scenario, we determine the required CR luminosity levels needed to support a flux at the level recently measured.

III. SOURCE LUMINOSITY REQUIREMENTS

The secondary neutrino and parent CR luminosities are related by

$$L_\nu = f L_{\rm CR}, \quad (6)$$

where L_ν and $L_{\rm CR}$ are the neutrino and CR luminosities and f the efficiency of energy transfer between the CR and neutrino populations. Such an efficiency relates to the fractional energy passed into the neutrino population through inelastic proton–proton interactions, K_ν, the energy loss time, t_{pp}, and the escape time $t_{\rm esc}$,

$$f = K_\nu(1 - e^{-\frac{t_{\rm esc}}{t_{pp}}}). \quad (7)$$

$$t_{pp} = 4 \times 10^9 \left(\frac{10^{-2}\ {\rm cm}^{-3}}{n_p}\right)\ {\rm yrs}, \quad (8)$$

and

$$t_{\rm esc} = 3 \times 10^9 \left(\frac{R}{100\ {\rm kpc}}\right)^2 \left(\frac{10^{30}\ {\rm cm}^2\ {\rm s}^{-1}}{D}\right)\ {\rm yrs} \quad (9)$$

where D is the energy dependent CR diffusion coefficient. Eq. 9 implicitly assumes that the transport of CRs proceeds in the diffusive regime. If, on the other hand, an advective flow of velocity $u_{\rm adv}$ dominates over diffusion, a more appropriate expression is

$$t_{\rm esc} = 3 \times 10^9 \left(\frac{R}{100\ {\rm kpc}}\right)\left(\frac{30\ {\rm km\ s}^{-1}}{u_{\rm adv}}\right) {\rm yrs}, \quad (10)$$

in which case the escape time is expected to be independent of the particle energy.

Thus, for a given size region R, the underlying CR luminosity required to support the inferred neutrino luminosity may be determined. In the following sections we will specifically consider whether different scenarios for a Galactic outflow emission origin are able to explain the observed flux.

Before proceeding, however, it is helpful to highlight the following general point about CR interactions with Galactic material. Following Eq. 8, for interaction times on the size of the Hubble scale, the number density of target material required is $n_p \approx 10^{-3}\ {\rm cm}^{-3}$. Similarly, setting the escape time from the Galactic halo, given in Eq. 9, to this scale requires a diffusion coefficient within the halo of $D \approx 10^{29}\ {\rm cm}^2{\rm s}^{-1}$. Thus provided that the diffuse halo region is sufficiently turbulent (ie. $\delta B/B \sim 1$) so as to support a diffusion coefficient at this level for CR up to a given energy, the Galaxy can be expected to operate as a calorimeter for these particles. Note that the diffusion coefficient of $\approx 10^{29}\ {\rm cm}^2{\rm s}^{-1}$ quoted above corresponds to the Bohm diffusion coefficient of ≈ 10 PeV particles in a highly turbulent magnetic field of few microGauss with a coherence length greater than a few pc. Such a set-up also requires that advective escape is sufficiently slow so as not to provide shorter escape times.

We next consider specific Galactic origin scenarios in order to determine the expected level of neutrino emission from these regions given what we have already learnt from them through investigations of them in γ-rays. For the description of the γ-ray yields following pp interactions and their energy distribution, the [18] parameterisation is adopted.

IV. GALACTIC OUTFLOW EMISSION

If diffuse on larger angular scales than the Galactic plane, the detection of surprisingly bright neutrino emission at PeV energies can have important implications with regards their Galactic ejection and escape at multi-PeV energies. Indeed, in the following section we consider a departure from the constant intensity assumption for CR throughout the Galaxy, with Galactic activity from/near the central region, either the central blackhole itself [19] or that from a nearby central starburst region [20], powering fast CR acceleration and advection into the Galactic halo region. It is worth highlighting that CR which enter an advective flow are not expected to return to the disk region, and therefore, with regards spallation constraints on their propagation time, can be considered to have effectively escaped [21].

Fermi Bubbles: recent ejection from the Galactic center in the last few Myr into the Fermi bubble region may have deposited a fresh population of CR which have not had time to diffusively escape from the region. Such a scenario apparently fits in with recent dynamic modelling of the Fermi bubble structures [22].

With constraints on the possible multi-TeV γ-ray flux from this region being placed by extrapolations from Fermi satellite measurements, an optimistic estimate of the number of neutrinos expected from the Fermi bubble regions may be obtained.

Adopting an energy flux of 100 GeV γ-rays from the Fermi bubble regions at a level of $E_\gamma^2 \frac{dN}{dE_\gamma} \approx$ 300 eV cm^{-2} s^{-1} sr^{-1}, and accounting for their larger angular size with $\Omega_{\rm FB}/\Omega_{\rm d} \approx 8$, the results for the Galactic plane region can be scaled up by a factor of 4 to obtain the expected rates from these regions. Thus, as shown in fig. 1, potentially a rate of 6 events per year would be expected to arrive from these regions at energies $>$ 30 TeV, in agreement with similar calculations by others [5, 23].

Using the above result, an optimistic estimation for the neutrino luminosity from the Fermi bubble regions is, $L_\nu = 3 \times 10^{36}$ erg s^{-1}. However, the long pp cooling time in the region well outside the Galactic plane, for which we adopt $n_p = 10^{-2}$ cm^{-3}, and large scale height of 10 kpc, result in an energy transfer efficiency of CR power into neutrinos, with $t_{\rm esc}/t_{pp} = (3{\times}10^7)/(4{\times}10^9) =$ 0.008. Thus, overall, a proton luminosity with a value of $L_p \approx 10^{39}$ erg s^{-1} is required. Such a luminosity, though large, is comparable to that required by hadronic origin scenarios used to explain the existence of Fermi Bubble regions at GeV energies [24]. Furthermore, should the CR be sufficiently fresh so as not yet to have diffusively probed their new environment, the CR spectrum would not have steepened through diffusive escape of the higher energy particles. Shorter residence times within the Fermi bubbles, of course, would increase the value of the required CR luminosity determined above.

This result, however, follows for the highly optimistic scenario for which the CR flux takes an E^{-2} spectral shape over four and a half decades in energy, from $\sim$1 TeV up to a cutoff energy of 30 PeV.

Galactic Halo: beyond the Fermi bubbles, the diffuse γ-ray background [25] sits at a level of only a factor of a few lower than the Fermi bubble emission flux, and appears isotropic. The origin of this emission remains unclear. Furthermore, a dominant component of Fermi bubble emission beyond the observed boundaries, with a weaker observed brightness, would be swamped by this background.

With regards a target for pp collisions within the halo, recent new observational evidence now suggests that the "missing baryons problem" may be solved by the presence of a dominant component of baryons in the halo [26]. These baryons sit within the Galactic virial radius ($\sim$ 200 kpc) and may provide an important target for Galactic CR in the halo. Assuming 10^{11} $M_\odot$ of baryonic material exists within the halo and is contained within 100 kpc, a mean density of $\bar{n}_p = 10^{-3}$ cm^{-3} is expected.

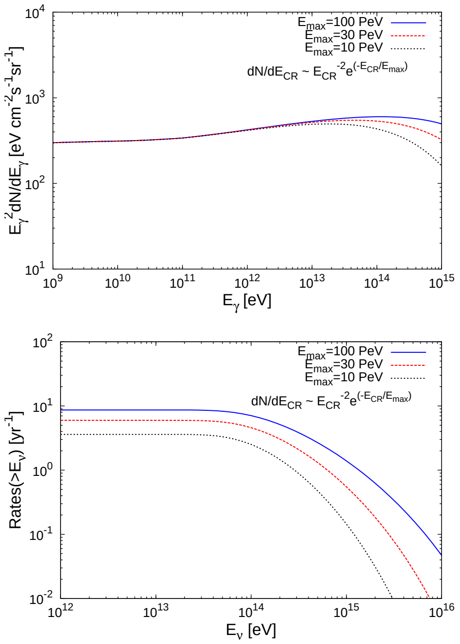

FIG. 1: TOP: The γ-ray energy flux for a scenario in which the Fermi bubble flux is explained by a CR population with shape $dN/dE \propto E^{-2}e^{-E/E_{\rm max}}$, with $E_{\rm max}$ =10, 30 PeV, and 100 PeV respectively. BOTTOM: The corresponding neutrino detection rate expected from the Fermi bubble region by IceCube.

With the level of the diffuse flux being dictated by the target material distribution, we adopt a profile of the form

$$r\frac{dN}{dr} \propto \left(\frac{1.0}{1.0 + (r/r_0)}\right)^\beta . \qquad (11)$$

This expression takes a similar functional form to the MB model in [27].

The observed brightness from CR interactions with such a distribution is dictated by the column depth of material along different lines of sight convolved with the radial distribution of the CR. Thus, adopting an r^{-1} CR distribution for the region $r < r_0$, a flat surface brightness would be expected for the case of a conical outflow, with the decrease in CR flux being compensated by the increase in column depth with distance (ie. r) from the Galactic center. Beyond r_0, the observed brightness would be expected to decrease. With regards the total emission from shells for this set-up, however, this would be expected to increase for shells out to r_0, with emission from larger shell radii plateauing due to the emitting volume growing with r^2. It should therefore be borne in mind that the Fermi bubbles may be only the tip of an iceberg whose true size has yet to be revealed due to the current limits in sensitivity. Indeed, recent analysis suggesting an energy dependence of the bubble morphology

[28] lends credence to the idea that the present bubble boundaries are dictated by instrument sensitivity.

Assuming that the origin of the full observed neutrino flux comes from a region with average distance $d_s \approx 100$ kpc away, the observed energy flux translates into a source luminosity of

$$L_\nu = 4\pi d_s^2 E_\nu F_\nu = 8 \times 10^{38} \ \ \text{erg s}^{-1}. \qquad (12)$$

Furthermore, provided that $t_{pp} < t_{\rm esc}$, the target can act as an energy dump and the observed neutrino flux spectral shape will reflect that output by the source. Thus, for $K_\nu \approx 0.5$, a comparable level efficiency factor is also expected, and the corresponding CR luminosity required to power the system is $L_{\rm CR} \approx 10^{39}$ erg s^{-1}. This value is comparable to estimations of the CR source power required to support the CR population between the "knee" and "ankle" regions [29]. Indeed, the suggestion of a single source of this magnitude powering the CR population above the "knee" was made previously in [30].

Alternatively, the flatness in the energy flux of the observed neutrinos could reflect a weakly or energy independent escape at multi-PeV energies from the halo. The associated corresponding decrease in energy transfer efficiency would of course require a larger underlying CR luminosity to support the observed flux than for the case considered above. However, with recent evidence indicating a significant budget of underlying power exists for particle acceleration within outflows from the Galactic center [31], an increase of more than an order of magnitude beyond this estimated luminosity could still be considered acceptable.

V. FUTURE DETECTION

For the case in which some component of the reported neutrino flux originates from the Galactic plane region, the future prospects for determining the validity of such a model are promising. Observations of the Galactic plane in the near future by the HAWC γ-ray detector will be able to probe the multi-TeV brightness of a large fraction of Galactic plane region. Such observations will therefore determine whether the Galactic plane flux does indeed sit at a level of $\sim$ 700 eV cm^{-2} s^{-1} sr^{-1}, as motivated by MILAGRO observations of the Cygnus and inner Galactic plane region. Furthermore, the angular distribution of future IceCube events provides the most obvious discerning power for such an origin.

For the large-scale diffuse halo scenario, however, the situation is less clear. At an energy of ~1 PeV, the diffuse CR energy flux sits at a level of, $E_{\rm CR}^2 dN/dE_{\rm CR} \approx 2 \times 10^5$ eV cm^{-2} s^{-1}sr^{-1}. Assuming that the γ-ray flux associated with the diffuse neutrino flux is diffuse on the largest scales, it is expected to be at a level of $E_\gamma^2 dN/dE_\gamma \approx 30$ eV cm^{-2} s^{-1}sr^{-1}, the photon fraction level of diffuse high energy radiation at PeV energies is therefore $\gamma/p \sim 10^{-4}$. At lower energies, this ratio decreases even further due to the rapid growth in the CR energy flux. The search for the presence of a γ-ray component in CR air-shower experiments via their muon-poor signature presently places a constraint on a diffuse PeV γ-ray flux approximately at this level [32, 33]. Future searches for this component by IceTop and IceCube collectively are expected to allow a more sensitive probe of this component [34].

With regards dedicated γ-ray observatories, in the near future the HAWC detector will provide a promising probe for the diffuse scenario, with a capability to detect Crab level diffuse fluxes ($F_\gamma(> 1 \text{ TeV}) > 10^{-11}\gamma$ cm^{-2} s^{-1}) from regions less than ~15° in size [35]. Cherenkov telescope experiments such as HESS also have the possibility to probe a diffuse background component through their studies of electromagnetic air showers [36]. Though unable to discern between electrons and photons, at multi-TeV energies, the cooling times of the electrons are extremely short, which severely limits their diffusive propagation distance. For this reason, at multi-TeV energies, electrons from nearby sources are not expected to be detected at Earth, and thus the electromagnetic showers seen by HESS are most likely photons. With regards a detection of diffuse fluxes, at energies beyond ~20 TeV, the presence of a diffuse electromagnetic background at the level detected by IceCube should be within reach. Although the fluxes at such energies may not be feasibly detected with present generation instruments, next generation instruments such as CTA may well offer sufficiently sensitivity. In this same vein of next generation instruments, LHAASO [37] also hold great potential for probing diffuse Galactic scenarios even further. Thus, presently, several promising methods exist for discerning the origin of the neutrinos, providing complementary additional information for future arrival directions studies.

On the other hand, with the halo scenario predicting a potentially very broad angular distribution in the arriving neutrino flux, the determination of its origin through angular distribution studies for this scenario will be challenging. Furthermore, with PeV γ-rays being born into the Galactic halo region under the above scenario, pair production interactions with the omnipresent 2.7 K CMB radiation fields is inevitable. Along with the electrons produced through charged pion decay, these electrons will preferentially cool via synchrotron emission provided the magnetic fields present within the halo are $> \mu$G in strength. The energy of this synchrotron emission being $E_\gamma \approx 50 \ (E_e/\text{PeV})^2 (B/\mu\text{G})$ keV. The prospects for detecting this diffuse emission from our own Galaxy are not so promising, providing only a subdominant component of the total diffuse X-ray background, whose make-up is thought to be dominated by faint extragalactic point-like sources [38].

The possibility of detecting such synchrotron halos around other nearby galaxies, the existence of which are motivated by radio observations [39], are more interesting. Adopting a fiducial distance 3 Mpc and a luminosity in PeV electrons of 10^{37} erg s^{-1}, the synchrotron energy flux expected from such a Galaxy would be $E_\gamma F_\gamma \approx 10^{-14} \left(\frac{L_e}{10^{37}\ \mathrm{erg\ s^{-1}}}\right)\left(\frac{3\ \mathrm{Mpc}}{D_s}\right)^2$ erg cm^{-2} s^{-1}. with an angular extension of $\theta \approx 0.1/3 \approx 1^\circ$. Thus, for the case in which CR in nearby galactic halos have significantly enhanced intensities above those present locally in the Milky Way, the detection of synchrotron halos by new sensitive X-ray instruments such as NuSTAR [40] and ASTRO-H [41] hold great potential. In fact, more powerful galaxies some 30 Mpc away, with larger expected surface brightness, such as Arp 220, are particularly strongly motivated for such studies. Phenomenological predictions of this emission are essentially similar to those of pair halos expected to exist around AGN, with higher energy electrons being produced and cooling through synchrotron emission closer to the source region than lower energy electrons. As a result, a softening of the spectrum is expected with increasing distance from the source.

VI. CONCLUSION

An investigation of possible Galactic origin scenarios to explain the observation of multi-TeV to PeV neutrinos reported by IceCube is carried out. On dimensional grounds, the Galactic halo is motivated to be a potentially significant source of high energy neutrinos provided that sufficient target material exists out at these large radii.

Consideration of constraints from diffuse γ-ray flux measurements from the Fermi bubble region by the Fermi satellite, even with extreme extrapolations into the multi-TeV domain, are demonstrated to yield an insufficient neutrino flux to account for the excess of neutrinos observed. An origin of the emission from the more extended Galactic halo region, however, cannot be ruled out and may have a physical basis if the neutrino emission is connected to an advected CR population. Such a scenario would justify the violation of the uniform CR hypothesis usually adopted.

Future detection of either diffuse γ-rays from the Galactic halo or synchrotron halos present around our or neighbouring galaxies are suggested as a means of testing such a Galactic halo hypothesis.

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