A hot spot in the neutrino flux created by cosmic rays from the Cygnus loop

M. Bouyahiaoui¹, M. Kachelrieß², and D. V. Semikoz¹,³,⁴

¹APC, Université Paris Diderot, CNRS/IN2P3, CEA/IRFU, Observatoire de Paris, Sorbonne Paris Cité, 119 75205 Paris, France
²Institutt for fysikk, NTNU, Trondheim, Norway
³JINR RAS, 60th October Anniversary prospect 7a, Moscow, Russia and
⁴National Research Nuclear University MEPhI, Kashirskoe highway 31, 115409 Moscow, Russia

An analysis of 7.5 years of data in the high-energy starting event sample has been recently published by the IceCube collaboration. The hottest spot in a search for neutrino sources was found far above the Galactic plane and is thus, at first sight, difficult to reconcile with a Galactic origin. In this work, we calculate the cosmic ray (CR) density around nearby, young supernova remnants assuming anisotropic diffusion. Combining the obtained CR densities with the matter distribution deduced from extinction maps, we find two prominent hot spots: One of them is close to the most significant point in the IceCube search for point sources, with an intensity corresponding to two neutrino events.

I. INTRODUCTION

Neutrinos are a unique tool to study dense environments and the non-thermal universe [1–3]. High-energy neutrinos may be produced together with photons in hadronic interactions of cosmic rays (CR) close to their sources or during propagation. Since they travel undisturbed, being neither absorbed as high-energy photons nor deflected in magnetic fields as charged particles, they are an ideal tracer of sites where the product of CR and target density is high. Such places can be either the CR sources themselves or dense gas clouds close to the sources. Therefore high-energy neutrino observatories have the potential to identify the yet unknown sources of CRs— and this capability has been one of the key motivation for their construction.

The currently largest of these high-energy neutrino telescopes, the IceCube observatory, has succeeded to establish the existence of a surprisingly large flux of extraterrestrial high-energy neutrinos [4]. In Ref. [5], the IceCube collaboration has reanalyzed 7.5 years of data using neutrinos which interaction vertices are contained inside the fiducial volume of the detector. The energy spectrum of these “HESE” neutrinos is compatible with an unbroken power law \( dN/dE \propto E^{-\alpha} \) with a spectral index of \( \alpha = 2.87^{+0.20}_{-0.19} \). Such a steep spectrum challenges most extragalactic source models. In particular, it excludes transparent extragalactic sources, since the accompanying photons would overshoot the bounds on the diffuse background of extragalactic gamma-rays [6, 7].

A guaranteed contribution to the astrophysical neutrino flux are secondary neutrinos produced in interactions of Galactic “sea” CRs with gas [8, 9]. However, the magnitude of this flux is, even using optimistic parameters, well below the one observed [10, 11]. Moreover, the arrival directions of the astrophysical neutrinos show not the correlation with the Galactic plane expected in this scenario. Therefore, several alternatives which predict a close to isotropic Galactic neutrino flux were suggested: Such neutrinos may originate from a large Galactic halo, formed either by CRs [12, 13] or heavy dark matter particles [14–16], or from the Fermi bubbles [17, 18]. Alternatively, a significant contribution to the Galactic neutrino flux may be rather local, produced by CRs interactions at the boundary the Local Bubble [19, 20].

Studies of specific Galactic neutrino sources have mostly been based on the gamma-ray–neutrino connection: Since the production spectra of gamma-rays and neutrinos in hadronic interactions are correlated, estimates and strict upper bounds on the neutrino flux can be deduced from gamma-ray observations for specific CR sources, see e.g. Ref. [21]. In the case of young CR sources, the finite, energy-dependent distance CRs diffuse may lead, however, to a low-energy cutoff in the secondary spectrum. Therefore gamma-ray observations which are typically limited to energies \( \mathcal{O}(\text{TeV}) \) restrict only weakly the neutrino flux from such sources at \( \mathcal{O}(100\text{ TeV}) \). As result, the brightest spots in the Galactic neutrino sky may be gas clouds immersed into the CR overdensities close—but not close enough to be visible in TeV gamma-rays—to nearby young CR sources [10].

In this work, we study if the nearest Galactic CR accelerators may be visible as neutrino sources. We calculate the CR density around nearby, young supernova remnants (SNR), assuming anisotropic diffusion as suggested in Refs. [22–24]. The faster diffusion of CRs along magnetic field lines implies that gas clouds can give an important contribution to the secondary neutrino flux at larger distances than in the case of isotropic diffusion, if their perpendicular distance to the magnetic field line through the CR source is small. In addition, the slow diffusion perpendicular to the magnetic field enhances the CR density close to magnetic field lines connected to the CR sources. We extract the local matter distribution acting as target for neutrino production from extinction maps derived in Refs. [25, 26]. Combining then this matter map with the calculated CR densities, we find two prominent hot spots: One, produced by CRs from Vela is absent in the IceCube HESE sample. The other one, produced by CRs from the Cygnus Loop supernova remnant (SNR) is close to the most significant point in the IceCube search for point sources. We estimate the nu-
trino intensity of this hot spot and find it compatible with two observed events with energy above 60 TeV.

II. LOCAL COSMIC RAY SOURCES

We use as potential CR sources SNRs which are younger than 30 kyr and located closer than 1 kpc from the Sun. Table I summarizes the available information\(^1\) on these sources. For the calculation of the CR density around these SNRs, we use the same approach as in Refs. [20, 27]: We approximate the Galactic magnetic field by the Jansson-Farrar model [28, 29], with a reduced turbulent field as suggested in Refs. [22–24]. Moreover, we modify this model as described in Ref. [20] to take into account the Local Bubble.

| Source        | Name          | \(\tau/\text{kyr}\) | \(d/\text{kpc}\) |
|---------------|---------------|----------------------|------------------|
| G065.3+05.7   | –             | 20                   | 0.8              |
| G074.0-08.5   | Cygnus Loop   | 15                   | 0.75             |
| G106.3+02.7   | Boomrang      | 10                   | 0.8              |
| G114.3+00.3   | –             | 7.7                  | 0.7              |
| G160.9+02.6   | HB9           | 5.5                  | 0.8              |
| G263.9-03.3   | Vela          | 11                   | 0.29             |
| G266.2-01.2   | Vela Jr       | 3.8                  | 0.75             |
| G330.0+15.0   | Lupus Loop    | 23                   | 0.33             |
| G347.3-00.5   | –             | 1.6                  | 1                |
| B1737-30      | –             | 20.6                 | 0.4              |

TABLE I: Cosmic ray sources considered with average values for their age \(\tau\) and distance \(d\) from the Sun.

No detailed model for the time-dependent escape spectrum of accelerated CRs exist. Since we are interested only in CRs with the highest energies which are accelerated before the transition to the Taylor-Sedov phase, we can however assume that these CRs escaped at a time much smaller than the age \(\tau\) of the source. Moreover, we employ the same injection spectrum for all sources for which we choose motivated by the results of Ref. [20] a broken power law in rigidity \(R = E/ (Ze)\) with a break at \(R_{\text{br}} = 2 \times 10^{15} \text{V}\) and an exponential cut-off at \(R_{\text{max}} = 8 \times 10^{15} \text{V}\),

\[
\frac{dN_i}{dR} = \begin{cases} N_i R^{-2.2}, & \text{if } R < R_{\text{br}} \\ \tilde{N}_i R^{-3.1} \exp(-R/R_{\text{max}}), & \text{if } R \geq R_{\text{br}}. \end{cases}
\]

We inject 5,000 protons per energy at the position of each source and propagate them for the time \(\tau\) in our magnetic field model. Then we calculate the CR density \(n(E)\) in each cell of size (6 pc)\(^3\). The energy injected in CRs by each source is chosen as \(3.5 \times 10^{50} \text{erg}\) in protons and \(2.6 \times 10^{50} \text{erg}\) in helium, respectively, which is compatible with the expectation that \(\approx 50-60\%\) of the explosion energy are transferred into relativistic particles in the case of efficient CR accelerators [30–32].

III. LOCAL MATTER DENSITY FROM DUST MAPS

While dust contributes only a small mass fraction to the interstellar medium (ISM), it efficiently absorbs and scatters photons with wavelengths in the visible and ultraviolet range. Therefore the distribution of dust can be used as a tracer of, e.g., gas which serves CRs as target for secondary neutrino and gamma-ray production.

Most efforts to build 3D maps of Galactic dust have been concentrated on charting dust on large scales. For instance, Ref. [33] mapped three quarters of the sky, while Ref. [34] constructed a map extending out to 3 kpc with 25 pc resolution. These maps succeeded modeling Galactic dust on large scales, but they failed to recover features on small scales because of their missing resolution. In contrast, the authors of Refs. [25, 26] concentrated their study on the closer neighborhood of the Sun, building a dust map for a \(740^2 \times 540 \text{pc}^3\) cube with a superior resolution of 1 pc. Using Gaia, 2MASS, PANSTARRS, and ALLWISE data, they deduced the G band extinction of five million stars with known parallaxes. Their results for the 3D distribution of dust are publicly available as a grid containing the e-folds of extinction per cell.

The extinction due to dust is proportional to the hydrogen column density along the grid cell as [35]

\[
N_H = 2.87 \times 10^{21} \text{ cm}^{-2} A_V/\text{mag}.
\]

Using moreover \(A_G/A_V = 0.789\) as the selective extinction in the GAIA G band from Ref. [36], we obtain

\[
N_H = 3.63 \times 10^{21} \text{ cm}^{-2} A_G/\text{mag}.
\]

In addition, we account for helium which contributes 9.1% to the number density of the ISM.

In order to check the completeness of this map, we calculate the resulting average surface density \(\Sigma\). Summing over the \(z\) coordinate, and multiplying by a factor 1.4 to account for helium and heavier elements, we obtain \(\Sigma = 10.4 M_\odot/\text{pc}^2\). The comparison with the estimate \(\Sigma = 13 M_\odot/\text{pc}^2\) for the local surface density from Ref. [37] indicates that the map includes \(\approx 80\%\) of the total gas.

Combining the obtained matter map with the CR densities and integrating along the line-of-sight,

\[
\Xi^{A, A'}(E, l, b) = \int_0^\infty ds n_{\text{gas}}^{A'}(x) I^{A'}_{\text{CR}}(E, x),
\]

where \(I^{A}_{\text{CR}}(E)\) is the CR intensity of nuclei with mass number \(A\). The intensity of nuclei is connected to their

\(^1\) Data extracted from http://snrcat.physics.umanitoba.ca/SNTable.php.
diffusion number density as \( I_{\nu}^{\text{ICR}}(E) = c/(4\pi) n_{\nu}^{\text{ICR}}(E) \).

We find in \( \Xi \) the two prominent hot spots visible in Fig. 1: The extended region produced by CRs from Vela interacting with gas in the wall of the Local Bubble is absent in the IceCube HESE sample. The other, smaller one produced by CRs from the SNR G074.0-08.5 in the Cygnus Loop is close in position with the hottest spot visible in the IceCube HESE data. As shown in Fig. 1 of this Appendix, CRs propagate along a magnetic field line away from the Galactic plane until they reach a region of increased gas density close to the boundary of the Local Bubble where the interaction probability \( \propto \Xi(E, l, b) \) has a maximum.

**IV. NEUTRINO INTENSITY**

We concentrate now on the neutrinos produced by CRs from SNR G074.0-08.5 in the Cygnus Loop. In this section, we report the results of our numerical calculations which we compare in the appendix with analytical estimates. Because of the rather large uncertainty in the distance to this SNR, \( d = (0.5 - 1) \) kpc, we consider two cases, choosing as the distance the average (\( d = 0.75 \) kpc) and the minimal value (\( d = 0.5 \) kpc) of this range, respectively. The intensity \( I_\nu(E, l, b) \) of neutrinos with energy \( E \) emitted along the line-of-sight with direction \( (l, b) \) is given by

\[
I_\nu(E, l, b) = \sum_{A,A'} \int_{E}^{\infty} dE' \Xi^{A,A'}(E', l, b) \frac{d\sigma^{AA'\rightarrow\nu}(E', E)}{dE}.
\]

(5)

We include both for the target gas and the CRs the contribution of protons and helium nuclei, \( A, A' = \{ p, \text{He} \} \). The neutrino production cross sections are evaluated with \texttt{AAfrag} [38]. In Fig. 2, we show the resulting neutrino intensity \( I_\nu \) for the energy \( E = 10^5 \) TeV in equatorial coordinates, i.e. as function of right ascension \( \alpha \) and declination \( \delta \) for \( d = 0.5 \) kpc. For the larger source distance, \( d = 0.75 \) kpc, the hot spot in the neutrino intensity shrinks slightly in size, while its position is nearly unchanged. The maximum of \( I_\nu(E, \alpha, \delta) \) corresponds to \( \approx 400 \) times the isotropic neutrino intensity measured by IceCube. In the case of the larger source distance, \( d = 0.75 \) kpc, the neutrino intensity is reduced by one third.

We define the equivalent isotropic intensity of a specific source as

\[
\langle I_\nu(E) \rangle \equiv \frac{1}{4\pi} \int d\Omega w(E) I_\nu(E, l, b)
\]

(6)

with the weight \( w(E) \) set to one. Since the observed neutrino intensity \( I_\nu(\alpha, \delta) \) is approximately isotropic, the ratio \( \langle I_\nu(E) \rangle / I_\nu(\alpha, \delta) \) corresponds to the fraction of neutrino events with energy \( E \) from a given source observed by an experiment with uniform exposure. In Fig. 3, we show the isotropic neutrino intensity \( \langle I_\nu(E) \rangle \) produced by CRs from the Cygnus Loop together with Ice Cube data from Ref. [39]. Note that the neutrino flux is dominated by the contribution from helium primaries which have a larger interaction probability and dominate above \( E \approx 10^{14} \) eV the CR injection spectrum defined in Eq. (1). Additionally, we compare the intensity of photons to the sensitivity of the LHASSO experiment estimated in Ref. [40].

For a specific experiment like IceCube, we have to account for the declination dependence of the effective area \( A_{\text{eff}}(E, \delta) \). For the HESE data set, we use the the effective area \( A_{\text{eff}}(E) \) from Ref. [5] and deduce the declination dependence from Ref. [41], see App. B for details. Since the extension of the hot spot is small, we can neglect the declination dependence of the weight, setting \( w = A_{\text{eff}}(E, \delta) / A_{\text{eff}}(E) \approx 1 \) with \( \delta \approx 0^\circ \) for the hot spot of IceCube.

We estimate the number of expected neutrino events...
The simplest explanation for its absence is that Vela is not a PeVatron: A low value of the maximal acceleration energy $E_{\text{max}}$ would reduce the number of CRs which can reach the high density regions close to the boundary of the Local Bubble. Moreover, the production of neutrinos is strongly suppressed above $E_{\text{max}}/20$. Alternatively, our magnetic field model fails close to the Local Bubble: CRs may be spread over a larger solid angle, if the ratio of the turbulent to regular field strength is larger, or the local field lines deviate from the direction in the Jansson-Farrar model.

Third, we comment on the prospects for the detection of gamma-rays which are produced in association with neutrinos in the hot spot. Since the predicted gamma-ray emission from the hot spot is not point-like but rather extended, its detection is challenging and depends strongly on the rejection capability of hadron in the considered gamma-ray experiment. HAWC can detect a diffuse gamma-ray flux on a level comparable to the over-all diffuse neutrino flux measured by IceCube shown, but is not sensitive enough to detect the expected gamma-ray flux from the hot spot shown in Fig. 3. In contrast, the more sensitive LHAASO experiment [42] should be able to detect the photon flux from the hot spot in the energy range $E \sim 100$ TeV within few years.

One should not confuse the Cygnus superbubble which is located in Galactic plane [43, 44] with the Cygnus Loop SNR, considered here. In the case of sources located in the Cygnus superbubble, one expects secondary gamma-rays and neutrinos in the same region. In contrast, the neutrinos and gamma-ray emission considered here is produced after CRs streaming away from the Galactic disk hit gas clouds close to the boundary of the Local Bubble.

Finally, let us comment on the recent detection of 0.1–1 PeV diffuse gamma-rays reported by the Tibet ASgamma collaboration [45]. In their event sample, all gamma rays with energies above 398 TeV were separated by more than $0.5^\circ$ from known TeV sources. In the scenario of anisotropic CR diffusion discussed here, such a separation arises rather naturally. This measurement combined with Fermi LAT data at TeV energies indicate also that the photon flux in the outer Galaxy is rather hard, $1/E^{2.5}$ [46].

VI. CONCLUSIONS

We have proposed in this work that CRs from the SNR G074.0-08.5 in the Cygnus Loop interacting with gas close to the boundary of the Local Bubble lead to an hot spot in the neutrino flux. Anisotropic diffusion of CRs is a necessary ingredient of this proposals, leading to enhanced CR densities along magnetic field lines connected to CR sources. The position of this hot spot is compatible with the most significant point in the IceCube search for point sources, and the neutrino intensity estimated by us corresponds to two events with energy...
above 60 TeV. The corresponding photon fluxes should be detectable by LHASSO within few years, providing a clear signature for a Galactic origin of the hot spot in the neutrino flux observed by IceCube.

Acknowledgments

We would like to thank Austin Schneider for comments on the IceCube exposure, and Torsten Enßlin and especially Raimer Leike for advice on the use of their extinction maps. The work of D.S. was supported in part by the Ministry of Science and Higher Education of the Russian Federation under the contract 075-15-2020-778 in the framework of the program “Large Scientific Projects” within the national project “Science”.

Appendix A: Comparison with analytical estimates

1. Cosmic ray density

For our analytical estimates, we assume that the Cygnus Loop SNR (G074.0-08.5) injected instantaneously $6 \times 10^{50}$ erg in CRs, following a power law with $Q(E) = Q_0 (E/E_0)^{-\alpha}$ and $\alpha \approx 2.2$ for the injection spectrum. To be definite, we split the total energy between protons and helium nuclei as $4:3$. Choosing the lowest injection energy of protons as the normalization energy, $E_0 = 1$ GeV, it follows then $Q_p = E_p/(5E_0^2) \approx 4.3 \times 10^{52}$/GeV. Similarly, it follows $Q_{He} = 4E_{He}/(15E_0^2) \approx Q_p$ for the normalization of the helium flux above the minimal injection energy $4$ GeV.

The diffusion approximation can be applied once CRs have reached distances from the source that are larger than a few times the coherence length of the turbulent magnetic field [47, 48], which is around $\tau_{\text{coh}} \approx \text{few tens of pc}$ close to the disk. At a given energy, the functional behavior of the observed CR flux from a single source at the distance $L$ and with the age $\tau$ can be divided into three regimes: For $2D\tau \ll L^2$, the diffuse flux is exponentially suppressed, while for intermediate times it is given by

$$I(E) \approx \frac{c}{4\pi} \frac{Q(E)}{V(t)}.$$  \hspace{1cm} (A1)

Here, $V(t) = 4\pi L_\perp^2 L_{\parallel}/3$ is the volume of the ellipsoid with major axis $L_{\parallel} = (2D_{\parallel} t)^{1/2}$ and minor axis $L_{\perp} = (2D_{\perp} t)^{1/2}$. When the diffusion front reaches the edge of the Galactic CR halo, CRs start to escape and the slope of the CR intensity steepens.

For the numerical values of the diffusion coefficients in the case of anisotropic diffusion, we read from Fig. 4 from Ref. [24] with $\eta = 0.25$ and $D_{\text{iso}} \approx 1 \times 10^{30}$ cm$^2$/s valid at the reference energy $E_*= 10^{14}$ eV that $D_{\parallel} \approx 5D_{\text{iso}}$, while $D_{\perp} \approx D_{\text{iso}}/500$. Hence CRs with energy $E_*$ fill an ellipsoid with major axis $L_{\parallel} \approx 700$ pc and minor axis $L_{\perp} \approx 14$ pc. The CR intensity of protons inside this ellipsoid can be estimated with $V \approx 1.7 \times 10^{61}$ cm$^3$ as $E_* I(E_*) \approx 6 \times 10^{-6} / (\text{cm}^2 \text{s sr}).$

In Fig. 4, we show for comparison the cells satisfying the condition $I(E) > 0.01 I_{\text{max}}(E)$ at $E = 10^{14}$ eV in our numerical simulations together with the position of the hot spot and of the Cygnus Loop SNR. One can see that the CRs fill a tube with diameter $50$ pc, what agrees quite well with the expectation $\sim 6 \times 2D_{\perp} \tau \approx 80$ pc for $I(E) = 0.01 I_{\text{max}}(E)$. Moreover, the distance between the hot spot and the Cygnus Loop SNR is around $630$ pc and the CR tube extends until it touches the Local Bubble. Note also this diameter is much larger than the extension of a SNR at the age of few hundred years; thus our assumption of a point-like injection is justified.

2. Neutrino production

In order to obtain an estimate for the equivalent isotropic neutrino intensity, we define first the volume $V$ of the neutrino emitting region by the condition

$$n_{\text{gas}}(x) I_{\text{CR}}(E_*, x) > 0.01 \max_{x \in \text{box}} \{n_{\text{gas}}(x) I_{\text{CR}}(E_*, x)\}$$  \hspace{1cm} (A2)
at a given energy $E_*$. Then we introduce in \cite{1}
\begin{equation}
I_\nu(E) = \frac{e}{4\pi} \sum_{A,A'} \int_{E}^{E_{A\to A'}} \frac{d\sigma_{A\to A'}^{\nu}(E',E)}{dE} \int d^3x \frac{n_{A}(E',x) n_{A'}^{gas}(x)}{4\pi d^2},
\end{equation}
for the isotropic neutrino intensity due to $pp$ interactions. We can estimate the contribution of helium projectiles and targets at energies $E_\nu \lesssim 10^{13}$ eV setting $I_\nu(E) \approx I_\nu(E)$ valid for primary energies $\lesssim 10^{14}$ eV. With $\sigma_{inel}^{pp} \approx 48$ mbarn, $\sigma_{inel}^{He} \approx 148$ mbarn, $\sigma_{inel}^{HeHe} \approx 137$ mbarn and $\sigma_{inel}^{HeHe} \approx 324$ mbarn, it follows
\begin{equation}
I^{tot}_{\nu} \approx 0.9(\sigma_{inel}^{pp} + \sigma_{inel}^{He}) + 0.1(\sigma_{inel}^{He} + \sigma_{inel}^{HeHe}) \approx 4.
\end{equation}
Thus our estimate agrees again well the numerical value shown in Fig. 3.

\textbf{Appendix B: Exposure}

We subtract in the Supplemental Fig. 5 of Ref. \cite{5} the line signal+background from the background to obtain the signal $S(\delta)$ as function of the declination $\delta$. Then we calculate with $x = \sin \delta$
\begin{equation}
S_{av} = \frac{1}{2} \int_{-1}^{1} dx \frac{S(\delta)}{S_{av}}.
\end{equation}
The weight $w$ of a source with declination $\delta$ follows then as $w = S(\delta)/S_{av}$.

[1] G. G. Raffelt, Ann. Rev. Nucl. Part. Sci. \textbf{49}, 163 (1999), hep-ph/9903472.
[2] T. K. Gaisser, F. Halzen, and T. Stanev, Phys. Rept. \textbf{258}, 173 (1995), [Erratum: Phys. Rept.271,355(1996)], hep-ph/9410384.
[3] M. Kachelrieß and D. V. Semikoz, Prog. Part. Nucl. Phys. \textbf{109}, 103710 (2019), 1904.08160.
[4] M. G. Aartsen et al. (IceCube), Astrophys. J. \textbf{833}, 3 (2016), 1607.08006.
[5] R. Abbasi et al. (IceCube) (2020), 2011.03545.
[6] V. Berezinsky, A. Gazizov, M. Kachelrieß, and S. Ostapchenko, Phys. Lett. \textbf{B695}, 13 (2011), 1003.1496.
[7] K. Murase, M. Ahlers, and B. C. Lacki, Phys. Rev. \textbf{D88}, 121301 (2013), 1306.3417.
[8] V. S. Berezinsky and A. Yu. Smirnov, Astrophys. Space Sci. \textbf{32}, 461 (1975).
[9] V. S. Berezinsky, T. K. Gaisser, F. Halzen, and T. Stanev, Astropart. Phys. \textbf{1}, 281 (1993).
[10] M. Kachelrieß and S. Ostapchenko, Phys. Rev. \textbf{D90}, 083002 (2014), 1405.3797.
[11] D. Gaggero, D. Grasso, A. Marinelli, A. Urbano, and M. Valli, Astrophys. J. \textbf{815}, L25 (2015), 1504.00227.
[12] A. M. Taylor, S. Gabici, and F. Aharonian, Phys. Rev. \textbf{D89}, 103003 (2014), 1403.3206.
[13] P. Blasi and E. Amato, Phys. Rev. Lett. \textbf{122}, 051101 (2019), 1901.03609.
[14] V. Berezinsky, M. Kachelrieß, and A. Vilenkin, Phys. Rev. Lett. \textbf{79}, 4302 (2016), astro-ph/9708217.
[15] B. Feldstein, A. Kusenko, S. Matsumoto, and T. T. Yanagida, Phys. Rev. \textbf{D88}, 015004 (2013), 1303.7320.
[16] A. Esmaili and P. D. Serpico, JCAP \textbf{1311}, 054 (2013), 1308.1105.
[17] R. M. Crocker and F. Aharonian, Phys. Rev. Lett. \textbf{106}, 101102 (2011), 1008.2658.
[18] C. Lunardini and S. Razzaque, Phys. Rev. Lett. \textbf{108}, 221102 (2012), 1112.4799.
[19] K. J. Anderssen, M. Kachelrieß, and D. V. Semikoz, Astrophys. J. \textbf{861}, L19 (2018), 1712.03153.
[20] M. Bouyahiaoui, M. Kachelrieß, and D. V. Semikoz, Phys. Rev. D \textbf{101}, 123023 (2020), 2001.00768.
[21] F. L. Villante and F. Vissani, Phys. Rev. D \textbf{78}, 103007 (2008), 0807.4151.
[22] G. Giacinti, M. Kachelrieß, and D. V. Semikoz, Phys. Rev. \textbf{D90}, 041302 (2014), 1403.3380.
[23] G. Giacinti, M. Kachelrieß, and D. V. Semikoz, Phys. Rev. \textbf{D91}, 083009 (2015), 1502.01608.
[24] G. Giacinti, M. Kachelrieß, and D. V. Semikoz, JCAP 1807, 051 (2018), 1710.08205.
[25] R. H. Leike and T. A. Enßlin, Astron. Astrophys. 631, A32 (2019).
[26] R. H. Leike, M. Glatzle, and T. A. Enßlin, Astron. Astrophys. 639, A138 (2020).
[27] M. Bouyahiaoui, M. Kachelrieß, and D. V. Semikoz, JCAP 1901, 046 (2019), 1812.03522.
[28] R. Jansson and G. R. Farrar, Astrophys.J. 761, L11 (2012), 1210.7820.
[29] R. Jansson and G. R. Farrar, Astrophys.J. 757, 14 (2012), 1204.3662.
[30] A. R. Bell and S. G. Lucek, Mon. Not. Roy. Astron. Soc. 321, 433 (2001).
[31] D. C. Ellison, A. Decourchelle, and J. Ballet, Astron. Astrophys. 413, 189 (2004), astro-ph/0308308.
[32] A. R. Bell, Mon. Not. Roy. Astron. Soc. 353, 550 (2004).
[33] G. M. Green, E. Schlafly, C. Zucker, J. S. Speagle, and D. Finkbeiner, Astrophys. J. 887, 93 (2019), 1905.02734.
[34] R. Lallement, L. Capitanio, L. Ruiz-Dern, C. Danielski, C. Babusiaux, L. Vergely, M. Elyajouri, F. Arenou, and N. Leclerc, Astron. Astrophys. 616, A132 (2018).
[35] D. R. Foight, T. Güver, F. Özel, and P. O. Slane, Astrophys. J. 826, 66 (2016), 1504.07274.
[36] S. Wang and X. Chen, Astrophys. J. 877, 116 (2019), 1904.04575.
[37] C. Flynn, J. Holmberg, L. Portinari, B. Fuchs, and H. Jahreiss, Mon. Not. Roy. Astron. Soc. 372, 1149 (2006), astro-ph/0608193.
[38] M. Kachelrieß, I. V. Moskalenko, and S. Ostapchenko, Comput. Phys. Commun. 245, 106846 (2019), 1904.05129.
[39] M. G. Aartsen et al. (IceCube), Astrophys. J. 849, 67 (2017), 1707.03416.
[40] A. Neronov and D. Semikoz, Phys. Rev. D 102, 043025 (2020), 2001.11881.
[41] M. G. Aartsen et al. (IceCube), Phys. Rev. Lett. 113, 101101 (2014), 1405.5303.
[42] X. Bai et al. (2019), 1905.02773.
[43] A. U. Abeysekara et al. (2021), 2103.06820.
[44] D. D. Dzhappuev et al. (2021), 2105.07242.
[45] M. Amenomori et al. (Tibet ASgamma), Phys. Rev. Lett. 126, 141101 (2021), 2104.05181.
[46] S. Koldobskiy, A. Neronov, and D. Semikoz (2021), 2105.00959.
[47] G. Giacinti, M. Kachelrieß, and D. V. Semikoz, Phys. Rev. Lett. 108, 261101 (2012), 1204.1271.
[48] G. Giacinti, M. Kachelrieß, and D. V. Semikoz, Phys. Rev. D88, 023010 (2013), 1306.3209.