Reevaluation of the Prospect of Observing Neutrinos from Galactic Sources in the Light of Recent Results in Gamma Ray and Neutrino Astronomy

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Abstract

In light of the recent IceCube evidence for a flux of extraterrestrial neutrinos, we revisit the prospect of observing the sources of the Galactic cosmic rays. In particular, we update the predictions for the neutrino flux expected from sources in the nearby star-forming region in Cygnus taking into account recent TeV gamma ray measurements of their spectra. We consider the three Milagro sources: MGRO J2019+37, MGRO J1908+06 and MGRO J2031+41 and calculate the attainable confidence level limits and statistical significance as a function of the exposure time. We also evaluate the prospects for a kilometer-scale detector in the Mediterranean to observe and elucidate the origin of the cosmic neutrino flux measured by IceCube.

Key words: High energy neutrinos; Neutrino astronomy; High-energy cosmic-ray physics and astrophysics

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1 Introduction

If supernova remnants are indeed the sources of the highest energy Galactic cosmic rays [1], the IceCube neutrino detector is expected to detect a flux of neutrinos accompanying the observed cosmic ray flux. Fermi has recently established the presence of pions in two supernova remnants thus unambiguously indicating the acceleration of cosmic rays [2]. However, their energies do not reach the PeV range and therefore the “PeVatrons” that are the sources of the cosmic rays in the “knee” region of the spectrum, and above, remain unidentified. Generic PeVatrons produce pionic gamma rays whose spectrum extends to several hundred TeV without a cutoff. Their predicted flux should be within reach of the present generation of ground-based gamma ray telescopes but has not been identified so far.

The highest energy survey of the Galactic plane to date has been performed by the Milagro detector. In particular, the survey in the 10 TeV band has revealed a subset of sources located within nearby star-forming regions in Cygnus and in the vicinity of Galactic latitude \( l = 40 \) degrees. Subsequently, directional air Cherenkov telescopes were pointed at some of the sources [3,4], revealing them as PeVatron candidates with gamma-ray fluxes following an \( E^{-2} \) energy spectrum that extends to tens of TeV without evidence for a cutoff. Interestingly, some of the sources cannot be readily associated with known supernova remnants, or with any non-thermal sources observed at other wavelengths. These are likely to be molecular clouds illuminated by the cosmic-ray beam accelerated in young remnants located within about 100 pc. Indeed one expects that multi-PeV cosmic rays are accelerated only over a short time period when the shock velocity is high, i.e., between free expansion and the beginning of its dissipation in the interstellar medium. The high-energy particles can produce photons and neutrinos over much longer periods when they diffuse through the interstellar medium to interact with nearby molecular clouds [5]. An association of molecular clouds and supernova remnants is expected in star-forming regions. Note that any confusion between pionic with synchrotron photons is unlikely to be a problem in this case.

Assuming that the Milagro sources are indeed cosmic-ray accelerators, the equality of the production of pions of all three charges dictates the relation between pionic gamma rays and neutrinos and basically predicts the production of a \( \nu_\mu + \bar{\nu}_\mu \) pair for every two gamma rays seen by Milagro. The calculation can be performed in more detail with approximately the same outcome [6,7]. For average values of the source parameters it was anticipated that the completed IceCube detector should confirm sources in the Milagro sky map as sites of cosmic-ray acceleration at the 3\( \sigma \) level in less than one year and at the 5\( \sigma \) level in three years. This assumes that the source extends to 300 TeV, i.e. approximately 10% of the energy of the cosmic rays near the knee in the
spectrum. There are intrinsic ambiguities of an astrophysical nature in this estimate that may reduce or extend the time required for a 5σ observation [7], most prominently the exact location where the sources run out of energy. Also, the extended nature of some of the Milagro sources represents a challenge for IceCube observations that are optimized for point sources. For other previous analyses of galactic sources of high-energy neutrinos at IceCube, we refer also to Refs. [8] and [9].

IceCube searches have revealed positive fluctuations from these sources in the 8 years of AMANDA data and in 4 out of 5 years of data collected with the partially deployed IceCube detector. On the other hand, the first extraterrestrial neutrino flux observed [10] by IceCube consists of 28 events (more below) with no event originating from the nearby star-forming region in Cygnus. This fact, together with the availability of new information from gamma ray telescopes, has motivated us to revisit the calculation of the neutrino flux in Ref. [7] for some of the sources. In particular we will update the information on MGRO J2019+37, MGRO J1908+06 and MGRO J2031+41 [11,12], 3 of the 6 sources used in the IceCube stacking analysis based on references [7,6,13].

Note that recently a lot of work has been done to try to explain the IceCube results in terms of point sources. For example, in Ref. [14] the authors discuss the possibility to explain the IceCube data, and in particular an hot spot of 7 shower events, with 24 TeV unidentified sources of our Galaxy. Among the sources considered, there are also the two Milagro sources, MGRO J1908+06 and MGRO J2031+41, assumed to be Galactic hypernova remnant. Note that MGRO J2019+37 is, instead, identified as pulsar wind nebulae (PWN). The conclusion of the analysis is that only 3.8 of the IceCube events may originate from the TeV unidentified sources, conclusion obtained by comparing the spatial distribution of the IceCube events and the one from the unidentified sources. In Ref. [14], instead, numerous Galactic sources are examined and for them the shower event rates and muon event rates are calculated. For example, Vela Jr. (RX J0852.0+4622) is a southern-sky source, that could be observed as muon tracks by an km$^3$ Northern hemisphere detector and through cascade events by the IceCube detector. Using both the muon tracks and cascades, it could be possible to better identify the specific source, pinning down its characteristics. In particular both the location (through muon events) and the source spectrum (through cascade events) could be reconstructed with precision.

We want to stress, however, that the three Milagro sources that we are going to consider in this paper will give as main channel in IceCube muon tracks, since they are located in the Northern hemisphere. For this reason, this is the main event signal that we are going to calculate. We won’t consider shower events in a Northern hemisphere detector for these three Milagro sources. Our main scope is to consider the muon tracks and analyzing the possibility that these sources could be detected or not in less than 10 years at IceCube. However, we
will instead consider a Northern hemisphere detector under the hypothesis of testing an hot spot recently revealed by IceCube, as described in the following.

As mentioned above, recently, IceCube has presented the first evidence for an extraterrestrial flux of very high-energy neutrinos, some with PeV energies. IceCube has thus become the latest entry in an extensive and diverse collection of instruments attempting to pinpoint the still enigmatic sources of cosmic rays. Analyzing data collected between May 2010 and May 2012, 28 neutrino events were identified with in-detector deposited energies between 30 and 1200 TeV. Among the 28 events, 21 are showers whose energies are measured to better than 15% but whose directions are determined to 10–15 degrees only. None show evidence for a muon track accompanying the neutrino. If of atmospheric origin, the neutrinos should be accompanied by muons produced in the air shower in which they originate. For example, the probability that a PeV atmospheric neutrino interacting in IceCube is unaccompanied by a muon is of order 0.1%. The remaining seven events are muon tracks. With the present statistics, these are difficult to separate from the competing atmospheric background. Fitting the data to a superposition of an extraterrestrial neutrino flux on an atmospheric background yields a cosmic neutrino flux of

\[ E_\nu dN_\nu / dE_\nu = 3.6 \times 10^{-11} \text{ TeV cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \]  

(1)

Of those 28 events, a hot spot of 7 shower events is evident at RA=281 degrees and dec=23 degrees close to the Galactic center although its significance is only 8% according to the test statistic defined in the blind analysis of the IceCube data. On the other hand, the highest energy event does reconstruct to within 1 degree of the Galactic center and, assuming an isotropic distribution, only 0.7 events are expected in the area of the sky covered by the seven showers. We will speculate that PeVatrons producing cosmic rays in the $10^{15} - 10^{17}$ energy range are the origin of these neutrinos. It is not unreasonable to expect that PeVatrons cluster in the direction of the Galactic center corresponding to the largest concentration of mass along the line of sight. The star-forming region near the Galactic center itself is likely to be distant to be observed individually. We will investigate the opportunities for a kilometer-scale detector in the Northern hemisphere to elucidate the origin of the IceCube flux by observing muon neutrinos which allow for sub-degree angular reconstruction.

In Sec. 2 we update the gamma ray spectra from the three Milagro sources: MGRO J2019+37, MGRO J1908+06 and MGRO J2031+41 and the calculation of the associated neutrino event rates in IceCube. In Sec. 3 we study the attainable confidence level limits and statistical significance which Icecube can set as a function of the exposure time considering different values of the source parameters. We also estimate the prospects for a kilometer-scale detector in the Mediterranean to observe and elucidate the origin of the cosmic neutrino
flux measured by IceCube. We briefly summarize our conclusions in Sec. 4.

2 Point sources

2.1 Neutrino flux

We start by updating the information on 3 of the 6 MILAGRO sources considered in past IceCube analyses. The parameters in Table 1 refer to the parametrization reported in Refs. [11,12], where the $\gamma$-ray flux in the TeV energy range is parametrized in terms of a spectral slope $\alpha_\gamma$, an energy $E_{\text{cut},\gamma}$ where the accelerator cuts off, and a normalization $k_\gamma$ as

$$
\frac{dN_\gamma(E_\gamma)}{dE_\gamma} = k_\gamma \left( \frac{E_\gamma}{\text{TeV}} \right)^{-\alpha_\gamma} \exp \left( -\frac{E_\gamma}{E_{\text{cut},\gamma}} \right),
$$

for a power law with cut-off fit and with

$$
k_\gamma \equiv \frac{K}{(E_{\text{norm}}/\text{TeV})^{-\alpha_\gamma}},
$$

where $E_{\text{norm}}$ is the energy in TeV at which the flux is normalized, i.e. for $E \equiv E_{\text{norm}}$, the value of the flux $dN_\gamma/dE_\gamma$ would be equivalent to $K$, in the absence of an energy cut-off. For sources without a cut-off the parametrization used is the one in Eq. (2) simply setting $E_{\text{cut},\gamma} \to \infty$.

The neutrino fluxes associated with pionic gamma rays emitted by a source is directly determined by particle physics; approximately one $\nu_\mu + \bar{\nu}_\mu$ pair should accompany every 2 gamma rays. The exact relation between the gamma ray and neutrino fluxes has been described in detail in Ref.[16,17]. Their starting point, however, is a parametrization of the gamma-ray flux slightly different from the one in Eq. (2), namely

$$
\frac{dN_\gamma(E_\gamma)}{dE_\gamma} = k_\gamma \left( \frac{E_\gamma}{\text{TeV}} \right)^{-\alpha_\gamma} \exp \left( -\sqrt{\frac{E_\gamma}{E_{\text{cut},\gamma}}} \right),
$$

Next, following the approximate relations given in Ref.[16,17] we can write the corresponding neutrino flux at the Earth after oscillations as

$$
\frac{dN_{\nu_{\mu} + \bar{\nu}_\mu}(E_\nu)}{dE_\nu} = k_\nu \left( \frac{E_\nu}{\text{TeV}} \right)^{-\alpha_\nu} \exp \left( -\sqrt{\frac{E_\nu}{E_{\text{cut},\nu}}} \right),
$$

with
\[ \begin{align*}
    k_\nu &= (0.694 - 0.16 \alpha_\gamma) \kappa_\gamma, \\
    \alpha_\nu &= \alpha_\gamma, \\
    E_{\text{cut,}\nu} &= 0.59 E_{\text{cut,}\gamma}.
\end{align*} \tag{6} \]

We will use Eq. (5) and Eq. (6) for the calculation of the neutrino flux from the different sources and to quantitatively evaluate the response of Icecube. Following Ref. [7] we will simulate the detection at the level of the secondary muons. This allows us to use the direct measurement of the muon energy to better characterize the expected signal.

Before describing in details the calculation of the muon events, we here want to comment on the difference between the parametrization of \( \gamma \)-ray that we use, Eq. (5), and the one used in the literature, Eq. (4). Indeed, we don’t use a MonteCarlo simulation in our analysis to relate the gamma ray and neutrino fluxes, thus, we have to rely on the analytical approximation, described just above, that is based on a specific parametrization of the gamma ray flux. This could constitute a possible limitation of this kind of analytical study, but in the following we will describe how we have overcome this point. For each sources, we chose the parameters \( K, \alpha_\gamma \) and \( E_{\text{cut,}\gamma} \) in such a way to cover all the experimental data available. In particular, we have considered different scenarios when choosing the parametrization to use. With increasing \( \alpha_\gamma \), we have spanned the low-energy spectra of each sources from lower to higher values of the spectra. On the other hand, with increasing \( \alpha_\gamma \), the spectra will go from an harder to a softer spectra at high energies. Moreover, in choosing the different values of \( E_{\text{cut,}\gamma} \), we have considered, for the first two sources and the lowest values of \( \alpha_\gamma \), one scenario in which the spectrum is within the high energy Milagro 1\( \sigma \) region up to roughly 35 TeV, and two other conservative scenarios in which the Milagro results at high energy could be relaxed and an harder spectrum is allowed. However, for these latter two cases, we have required that the spectrum is within the Milagro 1\( \sigma \) band up to 20 TeV.

In Fig. 1 the flux of \( \gamma \)-rays are presented using our parametrization of Eq. (4). The values of \( K, \alpha_\gamma \) and \( E_{\text{cut,}\gamma} \) are the one reported in Table 2. The green dashed, solid green and red dashed lines refer to the values of \( E_{\text{cut,}\gamma} \) as reported in Table 2 from smallest to biggest values. For the three sources, we reported in the plots the respective experimental data, that we will describe in details in the following. The continuous orange line is the best fit to the Milagro data, while the shaded orange area represents the 1\( \sigma \) band [12]. With blue lines, we report also the previous flux measurements by Milagro at 20 TeV and 35 TeV [18,19]. For these two measurements only statistical errors are presented. For an estimation of the systematic errors, we refer to [18,19]. For MGRO J2019+37, the 90% CL upper limits from ARGO-YBJ [20] are shown with black dots. We have also reported with a black star, the CASA-MIA bound at 100 TeV, as inferred in Ref. [21]. Note that the parametrization that we
considered for $\alpha_\gamma = 2.2$ and $E_{\text{cut},\gamma}=45$ TeV is similar to the parametrization used in Ref. [21].

For MGRO J1908+06, the dotted area shows the ARGO-YBJ 1σ band [11], while the solid orange line and the shaded orange area show the best fit and the 1σ band by Milagro [22]. The blue points are the previous flux measurements reported by Milagro [18,19]. We have scanned with the different $\alpha_\gamma$ the different limiting cases of compatibility with the ARGO-YBJ 1σ band. We show in purple the data by HESS [23], that are systematically lower than the other data. The discrepancy between these two different data sets is between 2σ and 3σ [22]. This could be, in principle, due also to statistical fluctuation. However, we want to point out that the source MGRO J1908+06 is not point-like and, for this reason, the Milagro detector, that has a worse angular resolution respect to HESS, observes a much higher flux. The HESS detector, indeed, would just detect the flux from the source core. Moreover, the HESS collaboration finds a spectrum with no evidence of a cut off, but their energy reach is limited to < 20 TeV. Note, finally, that any loss in sensitivity because this source is near the horizon is taken into account in our calculation by the effective area.

For MGRO J2031+41, the power law model is shown in orange and the power law model with cut-off is shown in yellow [12]. The dotted area shows the ARGO-YBJ 1σ band [11], while the blue points are the previous flux measurements reported by Milagro [18,19]. Note that, we didn’t report the measurements by MAGIC [4] and HEGRA [24]. These measurements are mutually consistent, but they disagree with the best fit and 1σ region obtained by Milagro [12], considering both a power-law and a power-law with energy cut-off. In particular, at low energies, the flux measured by air Cherenkov telescopes (ACTs) is much smaller than the flux measured by Milagro (it accounts for just the 3% of the Milagro flux) and is much harder than the power law best-fit given by Milagro. As described in details in Ref. [12], the discrepancy between the experimental data at low energies could be explained by different reasons. First of all, the angular regions considered by the experiments are different, since the angular resolution of ACTs experiments is better than the one of Milagro. For this reason, the Milagro detector measures photons coming from a larger region around the actual position of the source respect to the ACTs measurements. Note, however, that the flux at 0.6 TeV was measured also by Whipple, see Ref. [25] for more details, and this measurements agrees well with the extrapolation of the Milagro result at lower energies. The same is true for ARGO-YBJ, which has an angular resolution similar to Milagro. Second, the way the background is computed is also different. Indeed, the source MGRO J2032+41 has an extension slightly larger than the HEGRA and MAGIC angular resolution and is surrounded by an extended emission. Therefore, Milagro, Whipple and ARGO-YBJ are not able to disentangle the extended emission from the central source and observe a higher flux, while
| Source            | $K$ [TeV$^{-1}$ cm$^{-2}$ s$^{-1}$] | $E_{\text{norm},i}$ [TeV] | $\alpha_{\gamma,i}$ | $E_{\text{cut},\gamma,i}$ [TeV] |
|-------------------|-----------------------------------|--------------------------|---------------------|-------------------------------|
| MGRO J2019+37     | $7^{+5}_{-2} \times 10^{-14}$     | 10                       | 2.0$^{+0.5}_{-1.0}$ | 29$^{+50}_{-16}$             |
| MGRO J1908+06     | $6.1^{+4.4}_{-1.4} \times 10^{-13}$ | 4                        | 2.54$^{+0.36}_{-0.36}$ | -                            |
| MGRO J2031+41(a)  | $2.1^{+0.6}_{-0.3} \times 10^{-14}$ | 10                       | 3.22$^{+0.23}_{-0.18}$ | -                            |
| MGRO J2031+41(b)  | $5^{+157}_{-3} \times 10^{-14}$   | 10                       | 2.7$^{+0.7}_{-3.3}$  | 21$^{+\infty}_{-18}$        |

Table 1

Best-fit values for MGRO J2019+37, MGRO J1908+06 and MGRO J2031+41, as reported in Refs. [11,12] from the ARGO-YBJ and the Milagro experiments. For the MGRO J2031+41 source, we report the values for a power law fit (a) and a power law with cut-off fit (b).

MAGIC and HEGRA consider the extended emission as a background. Note that with the different values of $\alpha_{\gamma}$ that we considered in this paper, we have spectra more in agreement with the ARGO-YBJ data and spectra which follow more the Milagro spectrum. According to Ref. [14] the Milagro spectrum for this source yields neutrino predictions lower by roughly a factor of two respect to the ARGO-YBJ.

We moreover want here to comment on some recent results by Fermi. In particular, the pulsar PSR J1907+0602 was detected to be within the extension of the Milagro source MGRO J1908+06 [26]. Thus, this TeV source can be considered as the pulsar wind nebula of PSR J1907+0602. In particular, using Fermi data, 2$\sigma$ upper limits on the source flux between $10^{-1}$ and $10^2$ GeV were found, see Fig. 4 of Ref. [26]. We decided not to introduce these data explicitly in the analysis, because since these data span different energy scales, it might be difficult to find a common parametrization, considering our Eq. (4). Since we are going to consider only muons with energies above $10^3$ GeV, we decided to find parametrizations that could describe the high energy part of the $\gamma$-ray fluxes and eventually also the energy cut-off reported by Milagro. Note also that other Fermi data for the Cygnus region, have been used recently in the Ref. [27]. In particular, the authors found that considering a 4 degrees radius region, the two sources MGRO J2019+37 and MGRO J2019+41 are within the Fermi field of view and the sum of the Milagro 1$\sigma$ region for the two sources can be considered in agreement with the Fermi data at low energies, see Fig. 4 of [27] for more details.

2.2 Events

The number of events detected by IceCube from a source at zenith angle $\theta_Z$ can be written as [28,7]
Fig. 1. Flux of $\gamma$-rays using our parametrization of Eq. (4). The source flux has been normalized to the values of $K$ reported in Table 2. The green dashed, solid green and red dashed lines refer to the values of $E_{\text{cut},\gamma}$ as reported in Table 2 from smallest to biggest values. For MGRO J2019+37, the continuous orange line is the best fit to the Milagro data, while the shaded orange area represents the $1\sigma$ band. With blue lines, we report also the previous flux measurements by Milagro (only statistical errors are reported) at 20 TeV and 35 TeV [18,19]. The 90% CL upper limits from ARGO-YBJ are shown in black [20], while the inferred CASA-MIA bound of [21] is reported with a black star. For MGRO J1908+06, we show in purple the data by HESS [23] and in blue the previous flux measurements by Milagro [18,19]. The dotted area shows the ARGO-YBJ 1$\sigma$ band [11], while the solid orange line and the shaded orange area show the best fit and the 1$\sigma$ band by Milagro [22]. For MGRO J2031+41, the power law model is shown in orange and the power law model with cut-off is shown in yellow [12]. The previous flux measurements by Milagro are shown in blue [18,19]. Note that for MGRO J2031+41, we didn’t report the measurements by MAGIC [4], HEGRA [24] and Whipple [25], see text for more details.
The differential deep inelastic cross section \( \frac{d\sigma}{dE_{\mu}^{\text{fin}}} \) is calculated as

\[
N_{\text{ev}} = t \times N_T \int dE_{\nu} dE_{\mu}^{0} dE_{\mu}^{\text{fin}} \left[ \frac{dN_{\nu}(E_{\nu})}{dE_{\nu}} \times \text{Att}_{\nu}(E_{\nu}, \theta_Z) \times \frac{d\sigma_{\nu}(E_{\nu}, E_{\mu}^{0})}{dE_{\mu}^{0}} \right] + \frac{dN_{\bar{\nu}}(E_{\bar{\nu}})}{dE_{\bar{\nu}}} \times \text{Att}_{\bar{\nu}}(E_{\bar{\nu}}, \theta_Z) \times \frac{d\sigma_{\bar{\nu}}(E_{\bar{\nu}}, E_{\mu}^{0})}{dE_{\mu}^{0}} \right] 
\times RR(E_{\mu}^{0}, E_{\mu}^{\text{fin}}) \times A^{\text{eff}}_{\mu}(E_{\mu}^{\text{fin}}, \theta_Z),
\]

where we have summed over neutrinos and antineutrinos contributions. The neutrinos from the astrophysical sources or the atmospheric background interact with a cross section \( \frac{d\sigma_{\nu}(E_{\nu}, E_{\mu}^{0})}{dE_{\mu}^{0}} \) to yield a secondary muon of energy \( E_{\mu}^{0} \). For the differential deep inelastic cross section \( d\sigma_{\nu}(E_{\nu}, E_{\mu}^{0})/dE_{\mu}^{0} \), we use the full

\[
\begin{align*}
\text{Fig. 2. Number of events for the three Milagro sources with different values of } \alpha_{\gamma}. \\
\text{The green dashed, solid green and red dashed lines refer to the values of } E_{\text{cut, } \gamma} \\
as reported in Table 2 from smallest to biggest values. The source fluxes have been normalized as reported in Table 2. The black lines represent the atmospheric neutrino background, integrated over a solid angle equal to } \Omega = \pi(1.6 \sigma)^2, \text{ with } \sigma = 0.9^\circ \text{ for MGRO J2019+37 and } 0.6^\circ \text{ for MGRO J1908+06 and } 1.2^\circ \text{ for MGRO J2031+41. A correction for the size of the source has been introduced (factor 72%).}
\end{align*}
\]
Table 2

| Source         | K [TeV$^{-1}$ cm$^{-2}$ s$^{-1}$] | $E_{\text{norm}}$ [TeV] | $\alpha_{\gamma,i}$ | $E_{\text{cut,}\gamma,i}$ [TeV] |
|----------------|-----------------------------------|-------------------------|----------------------|-------------------------------|
| MGRO J2019+37  | 7 $\times$ 10$^{-14}$             | 10                      | 1.8, 2.0, 2.2        | 15, 30, 45                    |
| MGRO J1908+06  | 1.5 $\times$ 10$^{-13}$           | 10                      | 1.9, 2.1, 2.3        | 15, 30, 45                    |
| MGRO J2031+41  | 3 $\times$ 10$^{-14}$             | 10                      | 2.6, 2.8, 3.0        | 30, 100, 300                  |

Values of K, $E_{\text{norm}}$, $\alpha_{\gamma,i}$ and $E_{\text{cut,}\gamma,i}$ that we used in our analysis. We refer to Eq. (4) and Eq. (3) for the definition of the variables.

expression (without any average inelasticity approximation) obtained with the CT10 NNLO PDFs [29] with $\alpha_s = 0.118$. For $x \leq 10^{-5}$ the PDF’s are extrapolated using the double-log-approximation [30] following Refs. [31,32,33]. The muon propagation is taken into account by $RR(E^0_\mu, E^\text{fin}_\mu)$, that describes the probability of a muon produced with initial energy $E^0_\mu$ arriving at the detector with energy $E^\text{fin}_\mu$ after taking into account energy losses due to ionization, bremsstrahlung, $e^+e^-$ pair production and nuclear interactions [34]. We have used the continuous approximation for the energy loss. $N_T$ is the target density of the material surrounding the detector, while $Att_{\nu(\bar{\nu})}(E_\nu, \theta_Z)$ is a factor which accounts for the attenuation of the flux due to neutrino (antineutrino) propagation in the Earth:

$$Att_{\nu(\bar{\nu})}(E_\nu, \theta_Z) = \exp[-X(\theta_Z)(\sigma_{\text{NC}}(E) + \sigma_{\text{CC}}(E))]$$

where $X(\theta_Z)$ is the column density of the Earth assuming the matter density profile of the Preliminary Reference Earth Model [33]. Finally the detector performance is described by its effective area for detecting muons $A^\text{eff}_\mu(E^\text{fin}_\mu, \theta_Z)$ and the exposure time $t$. For the functional form of the effective area we use the one reported in Ref. [7].

We use the Honda flux [36] to calculate the background of atmospheric neutrinos at the zenith angle corresponding to the source. We extrapolate this flux to higher energies to match the one from Volkova [37], that is known to describe the AMANDA data in the energy range of interest here. At high energy, the contribution of prompt neutrinos from charm decay cannot be neglected. We consider in this paper the model of Thunman et al (TIG) [38]. We integrate the atmospheric background over a solid angle $\Omega = \pi(1.6\sigma)^2$ around the direction of the source. The angle $\sigma$ combines the effects of the angular resolution of the detector and the size of the source. For the size of the sources $\sigma_{\text{ext}}$, we refer to Table 3 while the angular resolution of IceCube $\sigma_{\text{IC}}$ at these high energies is around 0.5°. The angle $\sigma$ is then given by $\sqrt{\sigma_{\text{ext}}^2 + \sigma_{\text{IC}}^2}$. Assuming gaussianity, roughly 72% of the flux of the source is contained within this angular bin [39]. We will bin the events in the measured muon energy $E^\text{fin}_\mu$ assuming an energy resolution of 15% in $\log(E^\text{fin}_\mu)$ for $E^\text{fin}_\mu \geq 1$ TeV.

In Fig. 2 we report the number of events for the sources MGRO J2019+37,
Table 3
Position of the sources in right ascension and declination and extensions of the sources [12,23].

| Source            | R.A. [hh mm ss] | Dec. [dd mm ss] | $\sigma_{ext}$ |
|-------------------|-----------------|-----------------|-----------------|
| MGRO J2019+37     | 20 18 35.03     | +36 50 00.0     | 0.75°           |
| MGRO J1908+06     | 19 07 54        | +06 16 07       | 0.34°           |
| MGRO J2031+41     | 20 29 38.4      | +41 11 24       | 1.10°           |

MGRO J1908+06, MGRO J2031+41 and for the respective atmospheric background as a function of the measured muon energy. As described in the following section, we will use these spectra for the calculation of the confidence level at which a source could be excluded in the event of no observation of any signal events, as well as the statistical significance at which a source could be detected in the event of a positive observation, depending on the specific values of $\alpha_\gamma$ and $E_{cut,\gamma}$.

3 Results

3.1 Milagro sources

As mentioned before the first extraterrestrial neutrino flux observed [10] by IceCube consists of 28 events with no event originating from nearby the Milagro sources. If this continues to be the case in the following years of operation, IceCube will be able to impose a bound on the probability of these sources to be galactic PeVatrons. We refer to this probability as the Confidence Level of exclusion of a given source. Conversely if this is not the case and neutrinos are observed from the source direction in the amount expected by the estimates presented in the previous section IceCube will be able to establish the source as a galactic PeVatron with some probability. We refer to this as the Statistical Significance of discovery. We quantify these two statistical tests for the three Milagro sources as a function of the detector exposure and for a range of values of the source parameters $\alpha_\gamma$ and $E_{cut,\gamma}$ as we describe next.

To estimate the Confidence Level of exclusion of a given source we use as observable the total number of events with $E_{\mu}^{fin} \geq 1$ TeV without binning in energy. Generically, for the small statistics expected, the use of the total number of events yields a better rejection power than the use of the energy spectrum. We also studied the dependence of the Confidence Level of exclusion on the minimum $E_{\mu}^{fin}$ and found that as long as $E_{\mu}^{fin}$ was not so large that the number of expected background events became very small the Confidence
Level of exclusion (C.L. from now on) did not change much.

Following standard techniques [40,41,42,43], we define C.L. as

$$\text{C.L.} = \frac{P_{(s+b)}}{1 - P_{b}}$$  \hspace{1cm} (9)

where $P_{(s+b)}$ and $P_{b}$ are the p-values for the signal plus background and background only hypothesis of the data. Note that the denominator is present to avoid penalizing models to which one has little or no sensitivity. If C.L. $\leq \alpha$, a specific source is excluded with $(1 - \alpha)$ confidence level.

To obtain $P_{(s+b)}$ and $P_{b}$ we first generate a large sample of event numbers that are Poisson distributed around the total expected number of background events and estimate what one could expect the “data” of IceCube to be in the absence of any signal, $N_{D}$, as their median. Knowing the theoretical expectations, for signal plus background, $Y_{(s+b)}$, and background only, $Y_{b}$, we construct the data likelihood for signal plus background, $L_{(s+b),D}$, and background only, $L_{b,D}$.

We then generate a large number of experimental results $N_{\text{exp}}$, that are Poisson distributed around the expected total number of signal plus background (background only) events for which we can compute the corresponding likelihoods of signal+background $L_{(s+b),J}$ (background only, $L_{b,J}$) with $J = 1 \ldots N_{\text{exp}}$ and count the number of results, $N_{\text{pos}}(s + b)$ ($N_{\text{pos}}(b)$) for which $-2 \ln L_{(s+b),J} > -2 \ln L_{(s+b),D}$ ($-2 \ln L_{b,J} > -2 \ln L_{b,D}$) so

$$P_{s+b} = \frac{N_{\text{pos}}(s + b)}{N_{\text{exp}}}, \quad 1 - P_{b} = \frac{N_{\text{pos}}(b)}{N_{\text{exp}}}.$$  \hspace{1cm} (10)

The results for the expected C.L. are presented in Fig. 3 for the three sources considered in the paper and for the different values of $\alpha_{\gamma}$ and $E_{\text{cut},\gamma}$, as reported in Table 2. We find that the parameters of the sources MGRO J2019+37 and MGRO J2031+41 will be difficult to constrain at 95% C.L. in less than 10 years. Instead, for MGRO J1908+06, in roughly 4 (7) years the values $\alpha_{\gamma} = 1.9$ and $E_{\text{cut},\gamma} = 45$ TeV could be excluded at 95% (99%) confidence level. Considering $\alpha_{\gamma} = 2.1$ and $E_{\text{cut},\gamma} = 45$ TeV, an exclusion at 95% (99%) confidence level is possible in 6 (10) years, while for $\alpha_{\gamma} = 2.3$ and $E_{\text{cut},\gamma} = 45$ TeV, roughly 8 years are necessary for an exclusion at 95% confidence level. For a lower value of $E_{\text{cut},\gamma}$ of 30 TeV, an exclusion at 95% (99%) confidence level is possible in 7 (10) years for $\alpha_{\gamma} = 1.9$, in 8 years for $\alpha_{\gamma} = 2.1$ and in 10 years for $\alpha_{\gamma} = 2.3$.

Conversely when estimating the Statistical Significance of discovery we find higher sensitivity to the signal when using the full spectral information of expected signal and background events. We compute the statistical significance
Fig. 3. Confidence level at which a source could be excluded as a function of time. For each source, we have considered different values of $\alpha_\gamma$. The green dashed, solid green and red dashed lines refer to the values of $E_{\text{cut,}\gamma}$ as reported in Table 2, from smallest to biggest values. The observed spectra are obtained as the median of random generated values around the background.

of observing a signal as the background-only p-value, considering the analytic expression reported in Ref. [42]:

$$p_{\text{value}} = \frac{1}{2} \left[ 1 - \text{erf} \left( \sqrt{\frac{q_{0}^{\text{obs}}}{2}} \right) \right],$$  \hspace{1cm} (11)$$

where $q_{0}^{\text{obs}}$ is defined as

$$q_{0}^{\text{obs}} \equiv -2 \ln \mathcal{L}_{b,D} = 2 \sum_{i} \left( Y_{b,i} - N_{D,i} + N_{D,i} \ln \left( \frac{N_{D,i}}{Y_{b,i}} \right) \right),$$  \hspace{1cm} (12)$$

with $i$ running over the different energy bins. In this case $N_{D,i}$ is the estimated experimental data in bin $i$ – generated as the median of a large sample of event numbers that are Poisson distributed around the expectation of signal plus background $-, Y_{b,i}$ is the theoretical expectation for the background hypothesis.
The results for the statistical significance are reported in Fig. 4. From the figure we read that the sources MGRO J2019+37 and MGRO J2031+41 will be difficult to detect at $3\sigma$ level in less than 10 years, considering the parameters $\alpha_\gamma$ and $E_{\text{cut,}\gamma}$, as reported in Table 2. The source MGRO J1908+06, instead, could be detected at $3\sigma$ in roughly 7 years for $\alpha_\gamma = 1.9$ and $E_{\text{cut,}\gamma} = 45$ TeV and in 9 years for $\alpha_\gamma = 2.1$. Recently, the authors of Ref. [27] found that the IceCube detector would be able to detect the sources MGRO J2019+37 and MGRO J2031+41 of the Cygnus region only after 20 years of exposure. This is consistent with the results of our study. Moreover, a recent analysis done by the IceCube collaboration, with 3 years data, has revealed no detection for the sources MGRO J2019+37 and MGRO J1908+06 [44]. This is consistent with our findings, since in 3 years, it is not possible to discovery these sources at $3\sigma$ level, see Fig. 4.
Table 4

| Source            | # of yrs for C.L. @ 95% | # of yrs for p-value @ 3σ |
|-------------------|-------------------------|---------------------------|
| MGRO J2019+37     | $\alpha_\gamma = \{1.8, 2.0, 2.2\} \rightarrow$ | $\alpha_\gamma = \{1.8, 2.0, 2.2\} \rightarrow$ |
|                   | # of yrs: $\{>10, >10, >10\}$ | # of yrs: $\{>10, >10, >10\}$ |
| MGRO J1908+06     | $\alpha_\gamma = \{1.9, 2.1, 2.3\} \rightarrow$ | $\alpha_\gamma = \{1.9, 2.1, 2.3\} \rightarrow$ |
|                   | # of yrs: $\{4, 6, 8\}$ | # of yrs: $\{7, 9, >10\}$ |
| MGRO J2031+41     | $\alpha_\gamma = \{2.6, 2.8, 3.0\} \rightarrow$ | $\alpha_\gamma = \{2.6, 2.8, 3.0\} \rightarrow$ |
|                   | # of yrs: $\{>10, >10, >10\}$ | # of yrs: $\{>10, >10, >10\}$ |

Results on the C.L. and p-value for the three different sources that could be obtained in less than ten years. We have considered $E_{\text{cut},\gamma}=45$ TeV for the first and second source and $E_{\text{cut},\gamma}=300$ TeV for the third source.

### 3.2 IceCube evidence for cosmic neutrinos: are (some of) the neutrinos of Galactic origin?

If cosmic accelerators are the origin of the extraterrestrial flux of neutrinos recently observed by IceCube [10], then the neutrinos have most likely been produced in proton-photon or proton-proton interactions with radiation or gas, either at the acceleration site or along the path traveled by cosmic rays to Earth. The fraction of energy transferred to pions is about 20% (50%) for $p\gamma$ ($pp$), respectively, and each of the three neutrinos from the decay chain $\pi^+ \rightarrow \mu^+\nu_\mu$ and $\mu^+ \rightarrow e^+\nu_e\bar{\nu}_\mu$ carries on average one quarter of the pion energy. Hence, the cosmic rays producing the excess neutrinos have energies of tens of PeV, well above the knee in the spectrum. It is tantalizingly close to the energy of 100 PeV [15,16] where the spectrum displays a rich structure, sometimes referred to as the “iron knee.” While these cosmic rays are commonly categorized as Galactic, with the transition to the extragalactic population at the ankle in the spectrum at $3 \sim 4$ EeV, one cannot rule out a subdominant contribution of PeV neutrinos of extragalactic origin. IceCube neutrinos may give us information on the much-debated transition energy.

The acceptance of the starting event analysis producing the first evidence for an extraterrestrial neutrino flux is such that the signal consist mostly of electron and tau neutrinos originating in the Southern hemisphere. While their energy can be reconstructed to 15%, their direction is only measured to $10 \sim 15$ degrees. In contrast, a detector in the Mediterranean views the Southern hemisphere through the Earth and therefore has sensitivity to muon neutrinos that can be reconstructed with sub-degree precision. For illustration, an IceCube detector cloned and positioned in the Mediterranean would observe
a diffuse flux of 71 muon-neutrinos$^1$ per year with energy in excess of 45 TeV for muon neutrino flux of:

$$E^2 \nu dN_{\nu_{\mu}+\bar{\nu}_{\mu}} = 1.2 \times 10^{-11} \text{ TeV cm}^{-2}\text{ s}^{-1}\text{ sr}^{-1}. \quad (13)$$

We here assumed a 1:1:1 distribution of flavors which is consistent with observation. Above 45 TeV, observed event rates should be dominated by the flux of the source, providing a sky map with little background. In the left panel of Fig. 5 we report the number of muon events as a function of the muon energy for the diffuse flux of Eq. (13) and the respective atmospheric background.

As mentioned in the introduction a cluster of seven events is observed close to the center of the Galaxy. If these events are originated from a point source, the corresponding flux would be

$$E^2 \nu dN_{\nu_{\mu}+\bar{\nu}_{\mu}} = 6 \times 10^{-11} \text{ TeV cm}^{-2}\text{ s}^{-1}, \quad (14)$$

corresponding to roughly 41 events per year above 45 TeV in neutrino energy. This number is not corrected for the fact that the center of the Galaxy is only visible 68% of the time for a Mediterranean detector. We introduced this correction in the corresponding figure, see the right panel of Fig. 5. Note that the flux is simply estimated by multiplying the diffuse flux in Eq. (13) by $4\pi \times 7/17.4$ where we correct for the fact that 7 events out of 17.4 (we subtract the 10.6 of background estimation to the measured 28 events) are clustered around the Galactic Center and that both samples consist mainly of shower events. Note that the point source flux of Eq. (14) is compatible with the all-flavor flux reported in Eq.(2) of Ref. [47], calculated for a 0.06 sr solid angle surrounding the Galactic Center.

Both the diffuse and point source signals would be statistically significant within one year. The operating Antares detector is a factor of 40 smaller than the IceCube detector, and therefore the IceCube excess only produces signals at the one-event level per year. Larger event samples, especially of well-reconstructed muon neutrinos, are likely to be the key to a conclusive identification of the origin of the IceCube extraterrestrial flux. If the flux observed in IceCube turns out to be isotropic, IceCube itself will observe the same muon neutrino signals from the Northern hemisphere.

If, on the other hand, any of the IceCube events do originate from a Galactic point source, IceCube itself should be able to observe the accompanying PeV gamma rays. The distance to the center of the Galaxy corresponds to a

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$^1$ This is likely to be an overestimate because the effective area for a diffuse analysis, which typically requires stronger cuts on the data, is smaller than the point source area used here. In the case of IceCube this correction is close to a factor of two.
Fig. 5. Left panel: Events for the diffuse flux of Eq. (13) as a function of the muon energy. We report the number of events for an IceCube-size detector in the north hemisphere (red-dashed line) together with the respective atmospheric background (black-dashed). The sum of the events from the diffuse flux and from the atmospheric background is reported with a blue line. Right panel: Events from Galactic Center source as a function of the neutrino energy. We report the number of events and the background for an IceCube-size detector in the north hemisphere (red-dashed line) and for Antares (green-solid line), together with the respective atmospheric background: black-dashed for IceCube and black-solid for Antares. For the atmospheric background we have integrated over a steradian $\Omega = \pi (1.6 \sigma)^2$, with $\sigma = 0.4^\circ$. Note that the number of events for the Galactic Center source and the background events are corrected for the fact that the center of the Galaxy is only visible 68% of the time for a Mediterranean detector.

single interaction length for a PeV photon propagating in the microwave background. PeV photons are detected as muon-poor showers triggered by IceTop leaving no muons in IceCube. The level of point-source flux per neutrino flavor corresponding to one out of the 28 events is given by

$$E_\nu^2 dN_\nu = 4\pi \frac{1}{28} \times 1.2 \times 10^{-11} \text{ cm}^{-2} \text{ s}^{-1} \text{ TeV}$$

$$\simeq 5.4 \times 10^{-12} \text{ cm}^{-2} \text{ s}^{-1} \text{ TeV},$$

(15)

with the corresponding pionic photon flux a factor of 2 larger, assuming $pp$ interactions; see above. This is a flux of $\sim 10^{-17} \text{ cm}^{-2} \text{ s}^{-1} \text{ TeV}^{-1}$ at 1 PeV, well within the gamma-ray sensitivity of the completed IceCube detector; see Fig. 15 in [48]. In fact, the highest fluctuation in a gamma-ray map obtained with one year of data collected with the detector when it was half complete is in the direction of one of the PeV neutrino events [49].
4 Summary

Recently, the IceCube detector reported evidence for extraterrestrial neutrinos, at very high-energies. Among the data collected between May 2010 and May 2012, 28 neutrino events were detected with energies between 20 and 1200 TeV, while from a background estimation roughly 10.6 events were expected. None of these events seems to originate from the nearby star-forming region in Cygnus, posing the question of whether the observed gamma-ray sources in this region are indeed the postulated PeVatrons originating the galactic cosmic rays.

In view of these results and taking into account recent TeV gamma ray measurements of the spectra of some of the sources, we have updated the calculation of the neutrino expected from Milagro sources MGRO J2019+37, MGRO J1908+06 and MGRO J2031+41. 3 of the 6 sources used in the IceCube stacking analysis based on references [7,6,13]. We have then estimated the confidence level with which IceCube could rule out these sources as galactic PeVatrons, should the results continue being negative in the following years of operation, or the statistical significance with which it can discover neutrinos from these sources if they are indeed galactic PeVatrons.

In particular, we find that the parameters of the sources MGRO J2019+37 and MGRO J2031+41 will be difficult to constrain at 95% C.L. in less than 10 years. For MGRO J1908+06, instead, in roughly 4 years the values $\alpha_\gamma = 1.9$ and $E_{\text{cut,}\gamma} = 45$ TeV could be excluded at 95% confidence level. Increasing the value of $\alpha_\gamma$ to 2.1, an exclusion is possible in 6 years, while for $\alpha_\gamma = 2.3$ roughly 8 years are necessary. Considering the statistic significance, instead, we found that the sources MGRO J2019+37 and MGRO J2031+41 will be difficult to detect at 3$\sigma$ level in less than 10 years, considering the parameters $\alpha_\gamma$ and $E_{\text{cut,}\gamma}$ of our analysis. The source MGRO J1908+06 could be detected at 3$\sigma$ in roughly 7 year for $\alpha_\gamma = 1.9$ and $E_{\text{cut,}\gamma} = 45$ TeV and in 9 years for $\alpha_\gamma = 2.1$.

Moreover, among the 28 events, a hot spot of 7 shower events is evident at a position close to the Galactic Center. We studied the possibility of detecting the point-source flux associated to this hot spot by a kilometer-scale detector in the Northern hemisphere and by the Antares detector.

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