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IceCube and high-energy neutrinos

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Summary. — The recent IceCube observation of the first high-energy neutrinos has received the Physics World award for the Breakthrough of the Year 2013. In the light of this important discovery, we revisit the possibility of observing, at the IceCube detector, three Milagro sources: MGRO J2019+37, MGRO J1908+06 and MGRO J2031+41. Moreover, we present a discussion on the possible galactic origin of some of the IceCube events and we comment on the possibility that the high-energy neutrinos detected might come from a Dark Matter decay. Finally, we comment on other important consequences of this discovery, like bounds on Lorentz-invariance violation and on secret neutrino interactions.

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1. – Introduction

Neutrinos are particles that rarely interact with matter and that are unaffected by magnetic fields. For this reason, they can provide information on the physics of particle acceleration and on some of the most energetic and distant phenomena in the Universe. In particular, they can shed light on the origin of cosmic-rays (CR), since, through their detection, it is possible to discriminate between leptonic and hadronic particle acceleration scenarios. In the leptonic scenario, indeed, gamma-rays are produced through processes like bremsstrahlung and inverse Compton scattering, while in the hadronic scenario they are produced from the decay of neutral pions. In the latter case, also neutrinos are produced from the decay of charged pions. Thus, neutrino telescopes can unambiguously probe the hadronic particle acceleration scenario.

There are different possible sources of CR, among these supernovae remnant (SNR) are the most accredited ones for the galactic CR, *i.e.* up to an energy of around PeV (the so-called "knee"), and gamma ray bursts and active galactic nuclei for the extragalactic CR, *i.e.* for energies above roughly EeV (the so-called "ankle"). SNR were firstly proposed in the 1934 by Baade and Zwicky, but only in February 2013 the Fermi satellite has provided evidence that they are acceleration sources of CR protons. They have, indeed, revealed gamma-rays of two SNR, IC 443 and W44, with characteristic pion-decay features [1]. However, the sources of CR around the “knee” region of the spectrum, and above, remain unidentified.

Recently, the IceCube collaboration has presented the first evidence for an extraterrestrial flux of very high-energy neutrinos, with a total of 37 neutrino candidate events, and with three of them at PeV energies [2-4]. For a summary of the IceCube results and of the astrophysical implication, see also ref. [5].

On the other hand, the highest energy survey (TeV energy) in gamma-rays of the Galactic plane has been performed, up to now, by the Milagro detector. This has revealed sources located within the star-forming region of Cygnus and in the vicinity of Galactic latitude $l = 40$ degrees. For three of the Milagro sources: MGRO J2019+37, MGRO J1908+06 and MGRO J2031+41 [6, 7], we present the confidence level at which some of the parameters can be constrained as a function of the IceCube exposure time and which is the respective p-value for the discovery of neutrinos from these sources (and thus for the confirmation that the sources act as CR accelerators). Moreover, we comment on the possibility that some of the IceCube events are of galactic origin, in particular, considering the possibility of detecting some of the IceCube events through a detector located in the Northern hemisphere.

Using the recent IceCube data, different considerations can be drawn, of which we will review some of the most important ones. For example, it is possible to put constraints on Lorentz-invariance violation (LIV) and on secret neutrino interactions, that would produce neutrino-neutrino elastic scattering at a larger rate than the standard weak interactions. Also the possibility that the events come from Dark Matter (DM) decay has been analyzed in the literature.

In sect. 2, we summarize the recent IceCube results, while in sect. 3 we analyze the possibility of detecting neutrinos from three Milagro sources with the IceCube detector. Moreover, we study also the possible galactic origin of some of the detected neutrinos. In sect. 4, we present different considerations and conclusions that can be derived using the IceCube events, in particular on DM properties (under the hypothesis that the neutrinos come from DM decay), on LIV and on neutrino secret interactions. Our summary is presented in sect. 5.

2. – IceCube results

Using the data collected from May 2010 and May 2013, the IceCube detector has revealed 37 neutrino candidate events between roughly 30 TeV and 2 PeV, while the expected background of CR muon events is about 8.4 ± 4.2 and the one of atmospheric neutrinos of $6.6^{+5.9}_{-1.6}$. An atmospheric explanation of the events is thus excluded at 5.7σ [4].

Among the total number of events, two of them are almost certainly penetrating CR muons background. Of the remaining 35 events, 7 are track events, while the rest are shower events.

The per-flavour best-fit flux for astrophysical neutrino and anti-neutrino is obtained for [4]

$$E^2\phi(E) = (0.95 \pm 0.3) \times 10^{-11}\,\text{TeV cm}^{-2}\,\text{s}^{-1}\,\text{sr}^{-1}. \tag{1}$$

The events are compatible with a (1:1:1) flavour distribution and with an isotropic flux. The strongest clustering is near the Galactic Center, with a significance of about 7% [4].

Table I. – *Results on the CL and p-value for three Milagro sources that could be obtained in less than ten years. We have considered* $E_{cut,\gamma} = 45\,\mathrm{TeV}$ *for the first and second source and* $E_{cut,\gamma} = 300\,\mathrm{TeV}$ *for the third source.*

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

3. – Milagro sources and possible galactic origin of some of the IceCube events

Following the previous works of refs. [8-10], we have calculated the possibility of constraining or detecting three Milagro sources, MGRO J2019+37, MGRO J1908+06 and MGRO J2031+41, at the IceCube detector. For other previous analyses of the Milagro sources at IceCube and of other galactic sources of high-energy neutrinos, like RX J1713.7-3946, Vela Junior and Fermi Bubble, see also refs. [11, 12].

In table I our results [13] are presented. We find that the parameters of the MGRO J2019+37 and MGRO J2031+41 are difficult to constrain in less than 10 years (at 95% CL). For MGRO J1908+06, instead, in roughly 4 (6) years the values $\alpha_\gamma = 1.9$ (2.1) and $E_{cut,\gamma} = 45\,\mathrm{TeV}$ could be excluded at 95% CL, while for $\alpha_\gamma = 2.3$ roughly 8 years are necessary. Considering the statistic significance, instead, we found that MGRO J2019+37 and MGRO J2031+41 are difficult to detect at 3σ level in less than 10 years. The source MGRO J1908+06 could be detected at 3σ in roughly 7 (9) years for $\alpha_\gamma = 1.9$ (2.1) and $E_{cut,\gamma} = 45\,\mathrm{TeV}$.

The IceCube events consist mainly of electron and tau neutrinos originated from the Southern hemisphere. The direction for these events can be determined with an angular resolution of the order of $10°$–$15°$. A detector in the Northern hemisphere, instead, observes the southern sky mainly through track events, which can be reconstructed with sub-degree angular resolution. An IceCube-size detector in the Mediterranean see would detect a diffuse flux of *71 muon neutrinos in one year* with $E_\nu \gtrsim 45\,\mathrm{TeV}$ [13] for a flux of muon neutrinos equal to the best-fit reported in ref. [3], that is based on two-years IceCube data and that is compatible with the one in eq. (1).

A cluster of 7 events is observed closed to the Galactic Center. If these events were originated from a point source, the associated flux will give roughly *41 events in one year* with $E_\nu \gtrsim 45\,\mathrm{TeV}$ [13] for an IceCube-size detector in the Mediterranean (note that, however, the Galactic Center is visible only 68% of the time for a detector in the Mediterranean). Since the Antares detector is roughly a factor 40 smaller than IceCube, only *one event in one year is expected* [13]. Driven by this study, the Antares Collaboration has recently analyzed the region close to the Galactic Center and has excluded the possibility that these events come from a single-point source [14].

Since the release of the IceCube results, a lot of work has been done to try to explain the events in terms of point sources. For example, in ref. [15] the authors considered 24 TeV unidentified sources of our Galaxy, among which also MGRO J1908+06 and MGRO J2031+41, to try to explain the IceCube data. They found that only a maximum of 3.8 of the detected events may originate from these TeV unidentified sources. In ref. [16], instead, the authors question if some of the IceCube neutrinos could have a galactic origin, considering both the Fermi bubble region and a broader halo region. For the first case, only few of the detected neutrinos could be explained, see also ref. [17], while for the second case, a really extended halo might explain the IceCube data. The origin of these neutrinos is still to be firmly established, and a greater statistic is needed.

4. – Different considerations on the IceCube results

The IceCube events have been also interpreted as possible signals arising from DM decay. In ref. [18], the authors considered two benchmark decays: an hard channel, $DM \to \nu_e \bar{\nu}_e$, and a soft channel, $DM \to q\bar{q}$. They found that a DM with mass of 3.2 PeV, a lifetime of $\tau = 2 \times 10^{27}$ s and a branching ratio of $b_H = 0.12$ into neutrinos gives a good fit to the data. In general, the DM interpretation requires a rapid drop of the events above an energy equal to half of the DM mass. Moreover, a sub-PeV dip in the energy spectrum can be obtained, depending on the exact final state channels. In ref. [19], the interpretation of the events as DM has been carried on considering both the case for fermionic and scalar DM. In the first case, the best-fit found is $m_\chi \sim 2.2$ PeV and $\tau_\chi = 3.5 \times 10^{29}$ s, while in the second case $m_\chi \sim 5$ PeV and $\tau_\chi \sim 9.2 \times 10^{28}$ s (4.6×10^{29} s) for the decay channel into $2h$ ($\tau^- + \tau^+$).

Using the IceCube events it is also possible to put limits on neutrinos Lorentz invariance violation. Indeed, superluminal extragalactic neutrinos would lose energies via bremssthralung of electron-positron pairs ($\nu \to \nu e^+ e^-$). Using the PeV-energy IceCube events, the authors of ref. [20] found very strong limits on LIV: $\delta = (v^2 - 1) < \mathcal{O}(10^{-18})$, that corresponds to a Quantum-Gravity scale of $M_{QG} \geq 10^5 M_{\rm Pl}$ ($M_{QG} \geq 10^{-4} M_{\rm Pl}$) for a linear (quadratic) LIV term and for models with $\delta > 0$.

It was also checked in ref. [21] that cosmogenic neutrinos, produced by the interactions of protons with photons of the Cosmic Microwave Background, cannot explain the high energy neutrino events revealed by IceCube. Moreover, also the interpretation of the IceCube events as cosmogenic $\bar{\nu}_e$ interacting in the detector via the Glashow resonance was analyzed in the literature. The authors of ref. [22] found that this explanation of the high-energy events is, in general, not satisfactory, unless new physics is invoked, like the neutrino decay or the violation of Lorentz invariance. A general discussion on the photohadronic origin of neutrinos of energy around TeV-PeV observed at IceCube has been presented in ref. [23], where it was found that sources with a high magnetic field are necessary to explain the data.

The high-energy neutrinos detected by IceCube can be used to put limits on the interaction of neutrinos with the cosmic neutrino background, *i.e.* on possible new physics involved in neutrino-neutrino elastic scattering. It was found in refs. [24, 25], that the coupling must be $g < 0.03$ for a mediator with mass $m_X \lesssim 2$ MeV, $g/m_X < 5\,\mathrm{GeV}^{-1}$ for $m_X \gtrsim 20$ MeV and $g/m_X < 0.07\,\mathrm{GeV}^{-1}$ in an intermediate regime.

5. – Summary

Recently, the IceCube detector reported evidence for extraterrestrial neutrinos with very high-energies. Among the data collected between May 2010 and May 2013, 37 possible neutrino events have been detected with energies between 30 and 2000 TeV. This amounts to a 5.7σ excess over the expected background.

In the light of these results, we presented the possibility of detecting at IceCube the Milagro sources in the star-forming region of Cygnus. This would be essential to verify if they can indeed act as PeV galactic CR sources. We also discussed the number of events expected from the point-source flux associated to the cluster of events close to the Galactic Center. We presented the estimation for a kilometer-scale detector in the Northern hemisphere and for the Antares detector. The latter, has recently excluded the possibility that the events clustered close to the Galactic Center come from a single point source. Moreover, considering the Fermi bubbles, only few events detected by IceCube could be explained, unless an extended halo is taken into account.

We have then presented possible constraints that could be set, using the high-energy neutrino events, on DM properties, on LIV and on secret interactions in neutrino-neutrino elastic scattering.

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