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The IceCube low-energy excess: A Dark Matter interpretation

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Summary. — The recent study on the 6 year up-going muon neutrinos by the Ice-Cube Collaboration support the hypothesis of a two-component scenario explaining the diffuse TeV-PeV neutrino flux. Once a hard astrophysical power-law is considered, an excess in the IceCube data is shown in the energy range 10–100 TeV (low-energy excess). By means of a statistical analysis on the neutrino energy spectrum and on the angular distribution of neutrino arrival directions, we characterize a two-component neutrino flux where decaying/annihilating Dark Matter particles provide a contribution to the IceCube observations.

1. – Introduction

The IceCube Neutrino Telescope has observed for the first time a diffuse extraterrestrial neutrino flux in the TeV–PeV energy range, with a deviation from the atmospheric background of about 7σ [1-4]. However, until now the origin of such a diffuse neutrino flux is unclear. Under the reasonable assumption of a correlation with hadronic cosmic rays, one would expect that standard astrophysical sources give rise to a neutrino flux parametrized in terms of a power-law behavior $E_\nu^{-\gamma}$ with γ being the *spectral index* [5-7].

The recent IceCube observations of 6 year up-going muon neutrinos [4] are well explained at high energies ($E_\nu \geq 100 \, \text{TeV}$) by a single hard power-law with $\gamma = 2.13 \pm 0.13$. Such a value is in a 3.3σ tension with the previous analyses that provide a combined best-fit spectral index of 2.50 ± 0.09 [2]. This tension suggests the presence of a second component in the 10–100 TeV energy range. Moreover, such a new component may have a galactic origin since the 6 year up-going muon neutrino data do not point towards the Galactic Center of the Milky Way.

Indeed, once an astrophysical power-law flux with spectral index 2.0 (2.2) is considered for all neutrino flavours([1]), a *low-energy excess* (10–100 TeV) appears in both 2 year

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([1]) In the case of standard astrophysical sources, the flavour ratio at the Earth is $(\nu_e : \nu_\mu : \nu_\tau) = (1 : 1 : 1)$ due to the neutrino oscillations.

MESE [1] and 4 year HESE [3] IceCube data with a local statistical significance of 2.3σ (1.9σ) [8,9]. Assuming that the low-energy excess is not just a statistical fluctuation, we have characterized the properties of a Dark Matter (DM) signal able to explain it.

2. – Two-component neutrino flux

In addition to the atmospheric background, we have proposed the following two-component neutrino flux:

$$(1) \qquad \frac{\mathrm{d}\phi}{\mathrm{d}E_\nu \mathrm{d}\Omega} = \phi_0^{\mathrm{Astro}} \left(\frac{E_\nu}{100\,\mathrm{TeV}} \right)^{-\gamma} + \frac{\mathrm{d}\phi^{\mathrm{DM}}}{\mathrm{d}E_\nu \mathrm{d}\Omega},$$

where the DM neutrino flux takes the form(^{2})

$$(2) \qquad \left.\frac{\mathrm{d}\phi^{\mathrm{DM}}}{\mathrm{d}E_\nu \mathrm{d}\Omega}\right|_{\mathrm{dec.}} = \frac{1}{4\pi\, m_{\mathrm{DM}}\, \tau_{\mathrm{DM}}} \left\{ f_{\mathrm{dec.}}^{\mathrm{G}} \left[\rho_h\left(s,\theta\right), \frac{\mathrm{d}N}{\mathrm{d}E_\nu} \right] + f_{\mathrm{dec.}}^{\mathrm{EG}} \left[\frac{\mathrm{d}N}{\mathrm{d}E_\nu} \right] \right\},$$

$$(3) \qquad \left.\frac{\mathrm{d}\phi^{\mathrm{DM}}}{\mathrm{d}E_\nu \mathrm{d}\Omega}\right|_{\mathrm{ann.}} = \frac{\langle\sigma v\rangle}{8\pi\, m_{\mathrm{DM}}^2} \left\{ f_{\mathrm{ann.}}^{\mathrm{G}} \left[\rho_h\left(s,\theta\right)^2, \frac{\mathrm{d}N}{\mathrm{d}E_\nu} \right] + f_{\mathrm{ann.}}^{\mathrm{EG}} \left[\frac{\mathrm{d}N}{\mathrm{d}E_\nu}, B\left(z\right) \right] \right\},$$

in the decaying (dec.) and annihilating (ann.) cases, respectively. In the above expressions, m_{DM} is the DM mass, whereas τ_{DM} and $\langle\sigma v\rangle$ are the lifetime and the thermally averaged cross-section, respectively. In the brackets, the Galactic component f^{G} depends on the angular coordinate θ measuring the angular distance from the Galactic Center through the DM halo density profile ρ_h [10](^{3}), while the ExtraGalactic one f^{EG} is isotropic. The behaviour of the DM neutrino flux as a function of the energy is instead described by the energy spectrum $\mathrm{d}N/\mathrm{d}E_\nu$ that depends on the particular decaying/annihilating channel considered. Finally, in the case of annihilating DM the ExtraGalactic component also depends on the so-called boost factor $B\left(z\right)$ [10].

In order to infer the properties of the DM neutrino flux explaining the low-energy excess, we have performed two complementary studies: an *angular* analysis and an *energetic* one. The angular analysis is based on comparing the distribution of the arrival directions of IceCube events with the angular distributions expected from a DM signal. Since decaying and annihilating DM fluxes have distinct angular distributions due to the different dependence on the DM halo density profile (see eqs. (2) and (3)), such an angular analysis can discern among the two DM signals. On the other hand, the analysis on the neutrino energy spectrum is sensitive to the decaying/annihilating channel considered since, for instance, the energy spectrum is quite different in the case of leptons or quarks in the final states. Moreover, such an analysis also provides the allowed regions in the parameters spaces m_{DM}-τ_{DM} and m_{DM}-$\langle\sigma v\rangle$ compatible with the IceCube observations.

3. – Results and conclusions

The angular analysis performed on the 4-year HESE data [8] shows that only the case of annihilating DM with a small boost factor is already ruled out, while other

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(^{2}) More details about the expressions of the DM flux can be found in ref. [9].
(^{3}) We consider the Navarro-Frenk-White (NFW) distribution [11] as a benchmark.
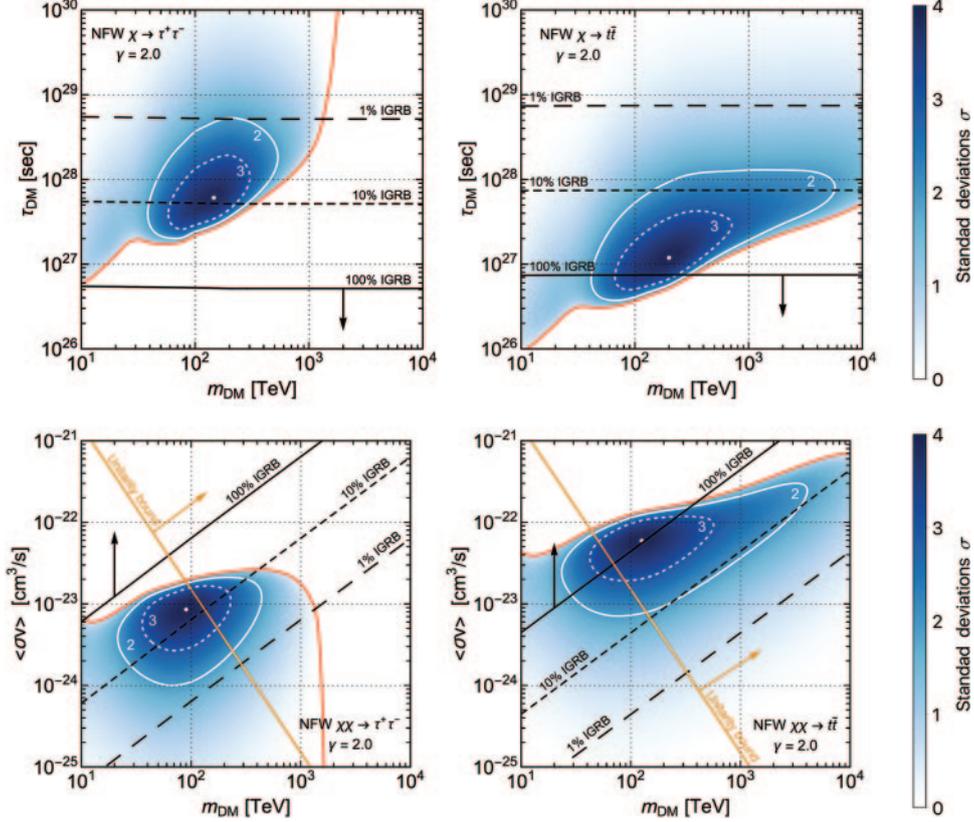
Fig. 1. – Statistical significance of the two-component scenario with respect to the case of a single astrophysical power-law, once a spectral index of 2.0 is considered. The left (right) panels refer to the case of leptonic (hadronic) final-states, whereas the top (bottom) plots correspond to the decaying (annihilating) DM scenario. The plots are taken from ref. [9].

DM scenarios are still allowed by data. Indeed, in order to statistically rule out a DM interpretation of the excess, hundreds of events in the 10–100 TeV energy range are required [8].

The main results of the analysis on the neutrino energy spectrum are reported in fig. 1 (see ref. [9] for more details). The plots show the statistical preference in standard deviations σ (evaluated by means of a likelihood-ratio statistical test) of the IceCube data for the two-components scenario provided in eq. (1). The maximum significance of the DM component (white dot) reaches about 4σ. Moreover, the red lines delimit from above the region in the parameter space that is excluded by the IceCube measurements. The gamma-rays constraints are shown by the black lines, which are related to different DM contributions (1%, 10% and 100%) to the Isotropic diffuse Gamma-Ray Background (IGRB) measured by Fermi-LAT [12]. Finally, the yellow lines bound the region that is not allowed according to the unitarity constraint on the cross-section [13].

It is worth observing that, since it is reasonable to assume that standard astrophysical sources account at least for the 90% of the IGRB spectrum, the neutrino and gamma-ray data favour a decaying DM interpretation of the IceCube low-energy excess over an

annihilating one. Furthermore, leptonic final states (represented by the $\tau^+\tau^-$ channel) are preferred with respect to hadronic ones (represented by the $t\bar{t}$ channel).

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