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Angular power spectrum analysis on current and future high-energy neutrino data

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Abstract. To constrain the contribution of source populations to the observed neutrino sky, we consider isotropic and anisotropic components of the diffuse neutrino data. We simulate through-going muon neutrino events by applying statistical distributions for the fluxes of extragalactic sources and investigate the sensitivities of current (IceCube) and future (IceCube-Gen2 and KM3NeT) experiments. The angular power spectrum is a powerful probe to assess the angular characteristics of neutrino data and we can already constrain rare and bright sources with current IceCube data. In addition, decaying and annihilating very heavy dark matter is a potential neutrino source, as suggested by the observed excess in the High-Energy Starting Event dataset. We apply an angular power spectrum analysis to HESE data for different dark matter models, allowing us to interpret the observed neutrino sky and perform a sensitivity forecast.

1. Introduction

Astrophysical high-energy neutrinos have been detected with IceCube in the last couple of years. The distribution of these neutrino events are isotropic, suggesting towards dominant contributions from extragalactic sources. High-energy neutrinos are expected to be produced within or in the surroundings of cosmic-ray accelerators, and since neutrinos can travel in an unattenuated and undeviated path towards Earth, they can provide insight into acceleration processes, on the origin of high-energy cosmic rays and on the potential discovery of new distant sources. Point-like searches have led to upper limits on the contribution of source classes and on the flux per individual source. However, the origin of individual neutrino events remains unknown. In this work, we present an angular clustering study of current and future up-going muon neutrino events, observed with IceCube, IceCube-Gen2 and KM3NeT, by performing an angular power spectrum (APS) analysis. We aim at constraining source populations by Monte Carlo (MC) method, where we apply statistical distributions to assign a flux to each extragalactic neutrino source, instead of using an equal flux for all sources. We perform the same APS analysis to test a two-component scenario, motivated by an observed tension between two data samples in IceCube.The 10-year observation of through-going (TG) events show a best-fit for the spectral index of $\gamma_{\rm TG} = 2.28$ [1], which is as expected from an extragalactic astrophysical origin. The 7.5-year High-Energy Starting Events (HESE) data-set, observing the full sky, prefers a steeper spectrum with a best-fit index of $\gamma^{\rm HESE} = 2.89$ [2]. We test the hypothesis of an isotropic astrophysical flux, taken from the TG best-fit, with an additional dark matter (DM) signal from decaying or annihilating DM. Assuming an isotropic astrophysical flux only from the HESE best-fit, we set constraints on the level of anisotropy induced by the DM component.

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2. Astrophysical neutrino sky map

The simulated neutrino sky maps consist of extragalactic astrophysical sources as well as atmospheric background events using TG events. We apply statistical distributions for the flux of each source, assuming a broken power-law based on cosmological and observational considerations:

$$\frac{dN_s}{dF} = N_\star \times \begin{cases} \left(\frac{F}{F_\star}\right)^{-2.5}, & F_\star < F, \\ \left(\frac{F}{F_\star}\right)^{-1.5}, & F_0 < F < F_\star\,, \end{cases} \quad (1)$$

where N_s is the total number of neutrino sources, $F_\star$ the characteristic flux at the break, and $N_\star$ the characteristic number of sources at $F_\star$ (see Ref. [3] for further details). The distribution is fixed by relating the observed neutrino intensity, Φ_ν taken from [4], to the mean of the flux distribution, and find the following expression for $F_\star$,

$$F_\star \propto \frac{4\pi\Phi_\nu}{N_\star}\,. \quad (2)$$

We leave the characteristic number of sources $N_\star$ as a free parameter, which indicates the source populations. For instance, bright source classes like BL Lacs have small values for $N_\star$ ($N_\star = 6 \times 10^2$) and are expected to show more clustering of neutrino events than abundant and weak source classes with larger $N_\star$, like starburst galaxies that have $N_\star = 10^7$. The sky map of the neutrino flux is obtained by randomly distributing the total number of sources, and assigning each source a random flux following the source flux distribution. The number of neutrino detections from single sources with flux F is calculated by multiplying the flux by the exposure of the neutrino detector and integrating over the neutrino energy. The expected isotropic and anisotropic features can be used to constrain source populations, since we observe an isotropic neutrino sky, and we perform MC realizations for various $N_\star$–values with IceCube, IceCube-Gen2 and KM3NeT exposure.

3. Angular power spectrum analysis

The anisotropy on the neutrino sky is derived with the angular power spectrum. The neutrino sky maps are expanded into spherical harmonics, and the APS is described by averaging the expansion coefficients, $a_{\ell m}$, as:

$$C_\ell = \frac{1}{2\ell+1}\sum_{m=-\ell}^{\ell} |a_{\ell m}|^2. \quad (3)$$

We consider the following χ^2–distribution, evaluated for each $N_\star$,

$$\chi^2\left(C_\ell\right) = \sum_{\ell\ell'} \left(C_\ell - C_\ell^{\rm mean}\right)\left({\rm Cov}_{\ell\ell'}\right)^{-1}\left({\rm C}_{\ell'} - {\rm C}_{\ell'}^{\rm mean}\right), \quad (4)$$

where $C_\ell^{\rm mean}$ is the mean value at each ℓ, and ${\rm Cov}_{\ell\ell'}$ is the covariance matrix, obtained from the set of simulations in order to test $N_\star$. We quantify the probability of obtaining the same or more extreme values of χ^2 for each $N_\star$ as the p-value, and look for constraints at 95% confidence level (CL), which is equivalent to $p = 0.05$.

4. Results

Figure 1 shows the p-value results with 2-year IceCube observations (left) and 10-year of IceCube-Gen2 (middle) and KM3NeT (right) exposure. The shaded areas represent the 68% and 95% of the MC realizations where we assume an isotropic sky, and the horizontal line shows the exclusion limit with $p = 0.05$. The 2-year of IceCube data consists of only 21 events, however, we find already a lower limit of $N_\star > 82$ at 95% CL, which is well within the 1σ exclusion region using the simulated isotropic sky. With future neutrino data using 10-year of IceCube-Gen2 and KM3NeT exposure, we can set more significant limits on bright sources. In particular, we find an exclusion of bright sources below $N_\star = 10^4$–2×10^5 in the case of IceCube-Gen2 exposure and $N_\star = 10^4$–3×10^4 in the case of KM3NeT exposure. Bright sources like BL Lacs ($N_\star = 6 \times 10^2$) would produce too much anisotropy and we can set stringent constraints on their contribution in future if not observed individually. If we do measure clustering of events in the future, the contribution of less bright sources like starburst galaxies can be constrained as well and the exclusion tendencies will change as can be found in [5]. Comparing the results of IceCube-Gen2 and KM3NeT we find similar exclusion trends, possibly due to the factor 10 larger effective area of IceCube-Gen2 while a factor 10 improved angular resolution of KM3NeT.

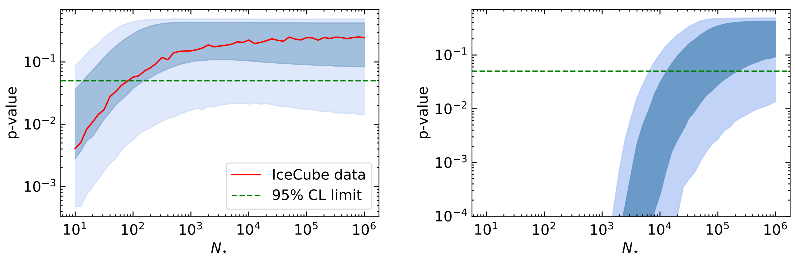

Figure 1. p-value results with 2-years of IceCube observation (left) 10 years of IceCube-Gen2 exposure (middle) and 10 years of KM3NeT exposure (right). The shaded areas represent the 68% and 95% bands of the MC simulations, and the horizontal line shows the exclusion limit.

5. Dark Matter contribution

Another possible neutrino source could be from decaying or annihilating DM, motivated by the tension between the HESE and TG events, and we test this two-component scenario against an extragalactic astrophysical component only as null hypothesis. The two scenarios can be distinguished due to the different expected angular distribution of neutrino events coming from DM, since they correlate with the extended Galactic DM halo. We perfom an angular power spectrum analysis, as described above, for a broad range of lifetime and cross-section values.

Figure 2 presents the result of the analysis, where we show the future sensitivity of neutrino telescopes to decaying (left) and annihilating (right) DM models. The results are for benchmark DM models with channel into tau leptons ($\tau^+\tau^-$), a NFW density profile, and cosmological boost factor taken from Ref. [6], however, we test different DM characteristics in Ref. [7] as well. The current constraints with 6-year of IceCube data is shown by the solid black lines. The bands are obtained by performing the APS analysis of simulated sky maps with different DM masses, and represent the sensitivity for an observed p–value of 0.05 from the median and upper 95% values. Moreover, we show bounds with gamma-ray searches from the galactic halo by HAWC [8] (grey solid lines), global gamma-rays constraints from Ref. [9] (grey dashed lines), and the unitarity constraints on cross-section [10] (black dashed lines). KM3NeT is more sensitive to DM models at the lower DM mass range, however, for DM masses larger than PeV, the sensitivity of IceCube is stronger. IceCube-Gen2 will probe a much bigger parameter space of DM models. It will be sensitive to the present 7.5-year HESE best-fit of the decaying DM component [11], shown with a black stars in the figure. This result relies only on the angular information contained on the neutrino sky maps and thus makes the APS analysis very robust against any potential degeneracies in the neutrino energy spectrum expected from astrophysical sources and DM particles. It is worth observing that for leptophilic channels the current best-fit of the DM component is not yet excluded by gamma-ray constraints.

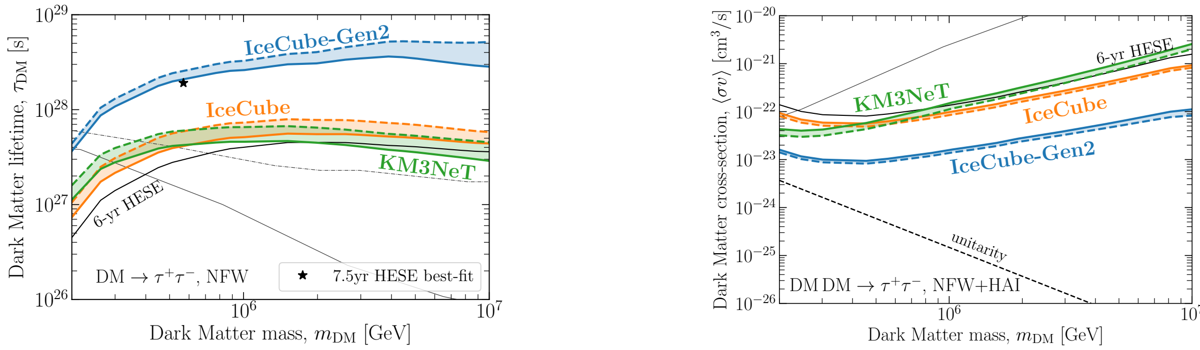

Figure 2. Future sensitivity to decaying (left) and annihilating (right) dark matter models with 10-year of exposures of IceCube, KM3NeT and IceCube-Gen2 experiments. The bands represent the median (dashed lines) and 95% (solid lines) sensitivity from the MC simulations. The gamma-ray constraints are represented by light grey lines: solid with HAWC galactic halo searches [8] and dot-dashed (left panel) from Ref. [9].

6. Conclusions

The angular power spectrum analysis on future neutrino data is a powerful probe to understand what astrophysical sources are dominating the neutrino sky, and in particular to predict what source classes will be observable with future neutrino telescopes. We have derived constraints on source populations through the characteristic number of sources $N_\star$, by analyzing the APS of current and future high-energy neutrino data detectable by IceCube, IceCube-Gen2 and KM3NeT. With 2-year of TG IceCube observations, we find already a constraint of $N_\star > 83$ with 95% CL, excluding the dominant contribution from very bright source populations. We need more data to assess known source classes, and indeed with 10-years of future neutrino data, we expect to significantly constrain BL Lacs and FSRQs if the distribution remains isotropic. If we do observe clustered events in the future, we can also set constraints on weak source classes, which could still be the case with current isotropic measurements. Moreover, with the APS analysis, we can test the two-component interpretation of HESE events, where we test the second component to originate from decaying or annihilating DM. We provide constraints on DM properties deduced from 6-year of IceCube HESE observations as well as future sensitivity to a DM signal after 10-years of observations with IceCube, IceCube-Gen2 and KM3NeT. The result is of paramount importance since it highlights a solid way to distinguish a DM signal from potentially hidden astrophysical sources.

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