High-Energy Neutrino Emissivity from Galaxy Cross-Correlations

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Take-away message

The sources of high energy neutrinos remain unknown. If these sources follow the large-scale structure (LSS), the neutrino-galaxy angular cross-correlation is non-zero [1,2]. If detected, the cross-correlation would allow us to (a) obtain information about the neutrino emissivity and (b) determine how neutrino sources correlate with the LSS via the linear bias. In the future this technique will provide valuable information to distinguish between neutrino source classes.

IceCube and Neutrino Data Set

IceCube is a high energy neutrino experiment located in Antarctica. We use the **public 10-year all-sky IceCube dataset** [3], from which we make the following selection:

- To avoid atmospheric muons we only use events with **declination > -5°**.
- Because the fraction of astrophysical neutrinos increases with the energy, we focus on the highest energies **above 1 TeV**.

Modelling Auto- and Cross-Correlations

The galaxy auto-correlation can be expressed as:

$$C_\ell^{GG} = b_g^2 \int \frac{d\chi}{\chi^2} [q_g(\chi)]^2 P(k/\chi, z)$$

Where q_g is the galaxy radial kernel and b_g the galaxy bias, which we can obtain from the auto-correlation. Similarly, the neutrino-galaxy cross-correlation is:

$$C_\ell^{I_N G} = b_g \, b_\nu \int \frac{d\chi}{\chi^2} q_g(\chi) \frac{\dot{n}_\nu(z)}{4\pi(1+z)^{1-\beta}} P(k/\chi, z)$$
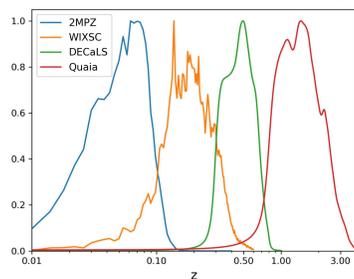
Where we have assumed that neutrinos sources emit with a power law of spectral index β. Here both the **neutrino bias and the average comoving neutrino number density rate** $\dot{n}_\nu(z)$ are unknowns.

Since atmospheric neutrinos do not correlate with galaxies, only the astrophysical ones will contribute to the cross-correlation. In order to compare the theory cross-correlation with the data, we need to apply an effective beam obtained directly from the beamed neutrino map auto-correlation $C_\ell^{\bar{\nu}\bar{\nu}}$ as [2]: $B_\ell^{\text{eff}} := \frac{C_\ell^{\bar{\nu}\bar{\nu}}}{C_\ell^{\nu\nu}}$

Tomographic approach

The Tomographic approach consists in dividing our galaxy sample into different redshift bins and combine the results for improved statistics.

In order to do that, we use the surveys **2MPZ, WIXSC, DECaLS and Quaia.** The galaxies from each catalogue are selected from separate photometric redshift bins. After source matching with spectroscopic information, the redshift distribution of our samples is the following.

We can then use each catalogue as one redshift bin for the tomographic approach. For more details on them, see [5].
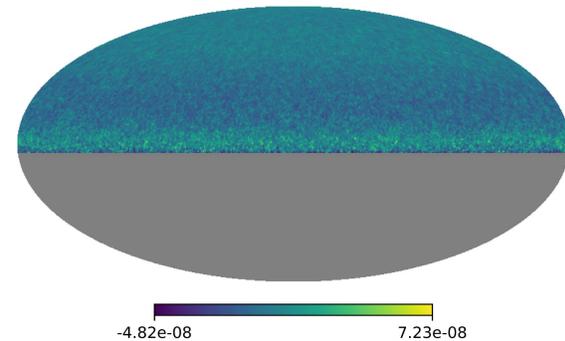
References

[1] Ke Fang, Arka Banerjee, Eric Charles, Yuuki Omori "A Cross-Correlation Study of High-energy Neutrinos and Tracers of Large-Scale Structure"

[2] Aaron Ouellette, Gilbert Holder "Cross-correlating IceCube neutrinos with a large set of galaxy samples around redshift z ~ 1"

[3] IceCube Collaboration "IceCube Data for Neutrino Point-Source Searches Years 2008-2018"

[4] David Alonso, Javier Sanchez, Anže Slosar "A unified pseudo-C_ℓ framework"

[5] David Alonso, Mehraveh Nikjoo, Arianna I. Renzini, Emilio Bellini and Pedro G. Ferreira "Tomographic constraints on the production rate of gravitational waves from astrophysical sources"

Neutrino Map

To generate the map we weight each event with its inverse effective area. We then apply a gaussian beam to each event, taking into account its angular resolution. The dataset is composed of 10 seasons that are weighted according to their average effective area.

In order to retain the physical information about the magnitude of the comoving neutrino emissivity, we **do not divide by the monopole and do not work with overdensity maps**. Instead, to mitigate contaminations caused by the smooth distribution of atmospheric neutrinos, we subtract the map's monopole and dipole. This is a key difference with previous studies [1,2].

Event Neutrino Map [$\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$]

-4.82e-08   7.23e-08

Parametrization and Likelihood

In order to make predictions for the neutrino emissivity at different redshifts we need to specify the neutrino radial kernel. We consider 2 cases:

- $\dot{n}_\nu(z) = N(1+z)^a$; with negative α (power-law model).
- $\dot{n}_\nu(z) = N(1+z)^2 e^{-z^2}$; which peaks at z = 1 [2] (peak model).

Note that the normalization constant **N and the neutrino bias are completely degenerate** in the expression for the cross-correlation, so together they form one single parameter. The other free parameter, only for the power-law case, is the slope α.

To handle the spherical harmonic expansion with a masked sky, we use Namaster [4]. In order to determine the unknown parameters p we minimise the likelihood:
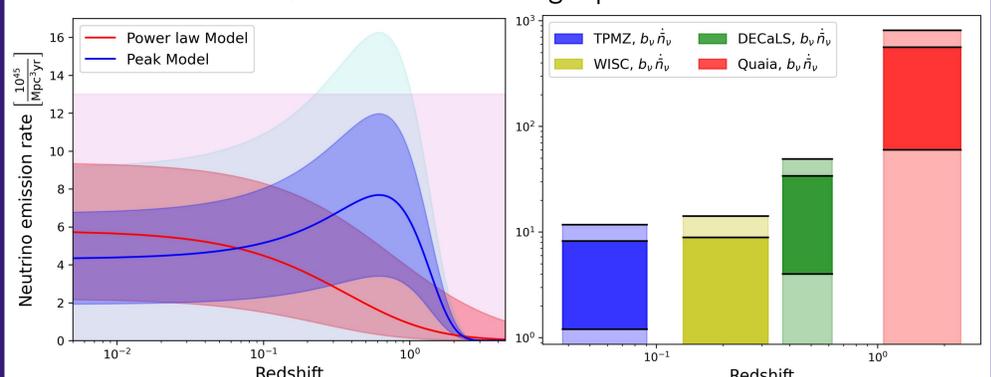
$$\mathcal{L}(p) := -\frac{1}{2} \sum_G \left(\mathbf{X}^{D,G} - \mathbf{X}^{M,G}(p) \right) \mathcal{M}^{G-1} \left(\mathbf{X}^{D,G} - \mathbf{X}^{M,G}(p) \right)$$

Where **X** is the cross-correlation vector (Data and Model), M the corresponding covariance matrix (obtained through Namaster), G the galaxy catalogues.

Results

Here we show the 1σ and 2σ contours obtained for for the two neutrino kernels on the left panel.

Alternatively, the tomographic approach also **allows us to give constraints based on individual catalogues**. Assuming that each redshift bin is sufficiently small, we take the neutrino number density rate as a constant and give constraints for each catalogue individually. These constraints (also at the 1σ and 2σ levels) are shown on the right panel.