NEUTRINO CLUSTERING IN THE MILKY WAY

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Abstract. The Cosmic Neutrino Background is a prediction of the standard cosmological model, but it has been never observed directly. In the experiments with the aim of detecting relic CNB neutrinos, currently under development, the expected event rate depends on the local density of relic neutrinos. Since massive neutrinos can be attracted by the gravitational potential of our galaxy and cluster around it, a local overdensity of cosmic neutrinos should exist. Considering the minimal masses guaranteed by neutrino oscillations, we review the computation of the local density of relic neutrinos and we present realistic prospects for a PTOLEMY-like experiment.

1 Introduction

The standard cosmological model predicts the existence of a relic population of neutrinos produced in the early Universe, which is usually referred to as the Cosmic Neutrino Background (CνB). These neutrinos have nowadays a distribution very close to a Fermi-Dirac with an effective temperature of about 1.9 K, or 0.17 meV. This is small enough to say that at least two neutrinos over three are non-relativistic today, since neutrino oscillation experiments tell us that the second lightest neutrino must have a mass of at least \( \sim 8 \text{ meV} \) [1].

Despite being the second most copious species in the Universe after the photons of the Cosmic Microwave Background, with a mean number density of \( \sim 330 \text{ cm}^{-3} \), relic neutrinos are extremely difficult to detect, due to their very small energy. The most interesting method that we can exploit for their direct detection is the mechanism of neutrino capture (NC) in \( \beta \)-decaying nuclei, acting through the process \( \nu + n \rightarrow p + e^- \) [2]. The interaction of a relic neutrino with a detector atom forces the production of an electron that has an energy above the endpoint of the standard \( \beta \)-decay by twice the neutrino mass: this can be visible in the experiment if the energy resolution is sufficient to distinguish the peak due to NC from the standard \( \beta \)-decay events (see e.g. [3]).

The PTOLEMY experiment [4], currently under development, aims at detecting relic neutrinos with a mass above \( \sim 150 \text{ meV} \), as the expected energy resolution of \( \sim 100 \text{ meV} \) allows. The event rate from NC in the PTOLEMY detector, built with 100 g of atomic tritium, is expected to be of order ten per year, if the mean number density of the CνB is considered.

Even if neutrinos are very light, however, they are expected to cluster around our galaxy, thanks to the gravitational potential of the matter which forms it. An increased local number density of relic neutrinos would correspond to an

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increased event rate in the detector. In the following we will show the results on
the neutrino clustering in the Milky Way (MW), published in ref. [5], which are
based on the $N$-one-body simulation technique firstly presented in [6], and the
corresponding prospects for the event rate in a PTOLEMY-like experiment.

2 $N$-one-body simulations and the Milky Way

We compute the clustering of relic neutrinos in the MW using the $N$-one-body
technique [6], which consists in independently evolving the trajectories of a high
number $N$ of neutrinos of mass $m_{\nu}$ in the gravitational potential of the MW,
from some early time until today, sampling all the possible initial conditions
(neutrino position and momentum). We assume initial homogeneity and spherical
symmetry. The final positions of these test particles are then employed to
reconstruct the relic neutrino distribution in the MW today. The ratio between
the local number density at Earth, $n(m_{\nu})$, and the mean number density, $n_0$,
gives the clustering factor $f_c(m_{\nu}) = n(m_{\nu})/n_0$, which enters the calculation of
the event rate (see next section). In order to compute the neutrino trajectories,
we must adopt a description for the MW content and its time evolution. We
use results from the literature to describe the profiles and the evolution of the
MW content (dark matter, baryons) as follows.

For the dark matter, we assume two possible descriptions for the halo: the
Navarro-Frenk-White (NFW) and the Einasto (EIN) profiles, whose parametriza-
tions are detailed in ref. [5]. The parameters which enter the NFW and EIN
profiles are determined using the astrophysical data from ref. [7] on the dark
matter density. The time dependence of the profiles is computed using the
standard evolution of the universe assuming the ΛCDM model, the evolution
of virial quantities and the results of N-body simulations as given in ref. [8].

The baryon content of the MW is described using the profiles for the five com-
ponents proposed in ref. [9]: stars, warm and cold dust, atomic and molecular
hydrogen gas. The time evolution of the total baryon profile is approximated
as a global renormalization constant, which we obtain from N-body simulations
of MW-sized objects [10]. For more details, we refer to ref. [5].

3 Clustering factors and PTOLEMY prospects

We firstly show the results obtained considering neutrinos with nearly minimal
masses. Assuming that the heaviest mass eigenstate has a mass of $\sim 60 \text{ meV}$,
we run our $N$-one-body simulation and reconstruct the profile of the neutrino
halo using different assumptions on the MW content, as shown in figure [1],
where we plot the results obtained using the NFW (EIN) dark matter profiles
in the left (right) panel, alone and in combination with the MW baryons. We
can see comparing the two plots that the local neutrino density can be up to
20\% larger than the mean neutrino density. The most relevant source of error is represented by the MW structure, since the results can significantly change when different dark matter or baryon distributions are considered.

The rate of relic neutrino events expected in a PTOLEMY-like experiment can be computed using \[^3\]:

\[
\Gamma_{\text{CMB}} = \sum_{i=1}^{3} |U_{\ell i}|^2 f_c(m_i) \left[ n_{i,0}(\nu_{\ell R}) + n_{i,0}(\nu_{\ell L}) \right] N_T \bar{\sigma},
\]

where $U_{\ell i}$ is the matrix element that encodes the mixing between the neutrino mass eigenstate $i$ and the electron neutrino flavour, $n_{i,0}(\nu_{\ell R(L)})$ is the mean number density of right (left) helical neutrinos, $N_T$ is the number of hydrogen nuclei in the detector and $\bar{\sigma} \simeq 3.834 \times 10^{-45} \text{cm}^{-2}$. Since it contains the mixing matrix elements, eq. (1) tells us that the event rate depends on the neutrino mass ordering, when clustered neutrinos are considered. In the case of normal mass ordering, for which the mixing between the electron neutrino and the heaviest mass eigenstate is the smallest, the enhanced local neutrino density has no impact on the expected event rate. On the other hand, if the ordering is inverted, the situation is opposite: the $U_{\ell 1}$ and $U_{\ell 2}$ terms are large and the increase in the event rate is directly proportional to the clustering factor.

The planned resolution for PTOLEMY, unfortunately, will not allow a detection of 60 meV neutrinos. For this reason we have also analysed the case of neutrinos with a mass of 150 meV, that should be the minimum mass detectable by the experiment. Considering this larger value of $m_\nu$, neutrinos are practically degenerate in mass and the event rate is not influenced by the mass ordering. We get a clustering factor between 1.7 and 2.9, as depicted in fig. 2, which corresponds to an increase of the event rate by the same factor. A precise determination of the event rate at PTOLEMY, in this case, would allow us to put constraints on the structure of our galaxy.

Figure 1: Profiles of the neutrino halo in the MW, for a neutrino with a mass of 60 meV and different parametrizations of the MW contents. From ref. [5].
Figure 2: The same as figure 1 but for a neutrino mass of 150 meV. From ref. [5].

Acknowledgements

Work supported by the Spanish grants FPA2014-58183-P and SEV-2014-0398 (MINECO), and by the PROMETEOII/2014/084 (Generalitat Valenciana).

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