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Local density of relic neutrinos with minimal mass

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1. Introduction

The standard cosmological model predicts the existence of a relic population of neutrinos produced in the early Universe, known as the Cosmic Neutrino Background (CνB). Its existence is indirectly established by present data, in particular the most recent analyses of the power spectrum of Cosmic Microwave Background (CMB) anisotropies and other cosmological observables [1]. However, the direct detection of the CνB is extremely difficult due to the very small energy of these neutrinos and the feebleness of the weak interaction.

The present evidence for flavour neutrino oscillations (see e.g. [2]) guarantees that at least two of the three neutrino masses ($m_{1,2,3}$) are not zero, which in turn means that at least two of the neutrino mass eigenstates that form the CνB are non-relativistic today, because their mass is larger than their effective temperature $T_\nu^0 \simeq 1.6 \times 10^{-4}$ eV. This represents the only known situation in which neutrinos behave as non-relativistic particles.

Since the time of the first proposal by Weinberg [3], several techniques have been studied to detect the relic neutrinos, but the task is still very challenging. Given the present tiny values of the neutrino energy, the most promising approach is to consider an interaction process with no energy threshold. In particular, the case of neutrino capture (NC) on β-decaying nuclei, through the process $\nu_e + n \to p + e^-$, has been considered (see e.g. [4, 5]). A neutrino capture by a nucleus A that can spontaneously β-decay stimulates the emission of an electron with an energy above the β-decay endpoint. Therefore, CνB interactions in the detector would be responsible for an energy peak at $2m_\nu$ above the β-decay endpoint. A detection of relic neutrinos could be achieved if the energy resolution Δ is smaller than the neutrino mass, a very challenging requirement.

Among the available beta-decaying nuclei, tritium is considered as the best candidate. A dedicated experimental effort based on neutrino capture by tritium was proposed recently: the Princeton Tritium Observatory for Light, Early-universe, Massive-neutrino Yield (PTOLEMY) [6]. Its phenomenology and potential for CνB detection has been studied in detail in ref. [5]. Unfortunately, the designed energy resolution of PTOLEMY, $\Delta \simeq 150$ meV, is too large for CνB detection if the heaviest neutrino state has the minimal mass guaranteed by flavour oscillations, of the order of $m_\nu \simeq 50$ meV [2]. However, the experiment could be sensitive to larger masses $m_\nu > 150$ meV, that are disfavoured but not completely ruled out by the current cosmological limits on the sum of neutrino masses.

A calculation of the expected event rate for a PTOLEMY-like experiment must take into account the overdensity of neutrinos in the Earth's galactic region. This was estimated by Ringwald & Wong [7], assuming neutrino masses above 150 meV. We have recently [8] used the so-called "N-one-body" technique described in ref. [7] to improve the calculation of relic neutrino clustering in the local environment. We have considered lighter neutrino masses, closer to values allowed by the recent cosmological bounds on the total neutrino mass, in order to obtain more realistic estimates for a PTOLEMY-like experiment. In addition, we also improve the treatment of the matter distribution in our local region of the Milky Way (MW), using the results of recent estimates and N-body simulations of MW-like objects for both the dark matter (DM) and baryons densities.

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 [7], which consists in independently evolving the trajectories of a high number N of neutrinos of mass m_ν 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 near the Earth, $n(m_\nu)$, and the mean cosmological 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 (DM, 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 [8]. The parameters of the NFW and EIN profiles are determined using the astrophysical data from [9] on the DM 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 [10]. The baryon content of the MW is described using the profiles for the five components proposed in ref. [11]: 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 [12].

3. Clustering factors and PTOLEMY prospects

We first show the results for neutrinos with nearly minimal masses (∼60 meV). With our N-one-body simulation the profile of the neutrino halo can be reconstructed using different assumptions on the MW content, as shown in figure 1, where we include the results obtained using the NFW (EIN) dark matter profiles in the upper (lower) panel, alone and including the MW baryons. One can see that the local neutrino density could be up to 20% larger than their mean cosmological density. The most relevant source of error is represented by the matter distribution in the MW, since the results can significantly change when different dark matter or baryon profiles are considered.

The rate of relic neutrino events expected in a PTOLEMY-like experiment is [5],

$$\Gamma_{\mathrm{C}\nu\mathrm{B}} = \sum_{i=1}^{3} |U_{ei}|^2 \, f_c(m_i) \, [n_{i,0}(\nu_{h_R}) + n_{i,0}(\nu_{h_L})] \, N_T \, \bar{\sigma} \, , \tag{1}$$

where U_{ei} is the matrix element that encodes the mixing between the neutrino mass eigenstate i and the electron neutrino flavour, $n_{i,0}(\nu_{h_{R(L)}})$ is the mean number density of right (left) helical neutrinos, N_T is the number of hydrogen nuclei in the detector and $\bar{\sigma} \simeq 3.834 \times 10^{-45}$ 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

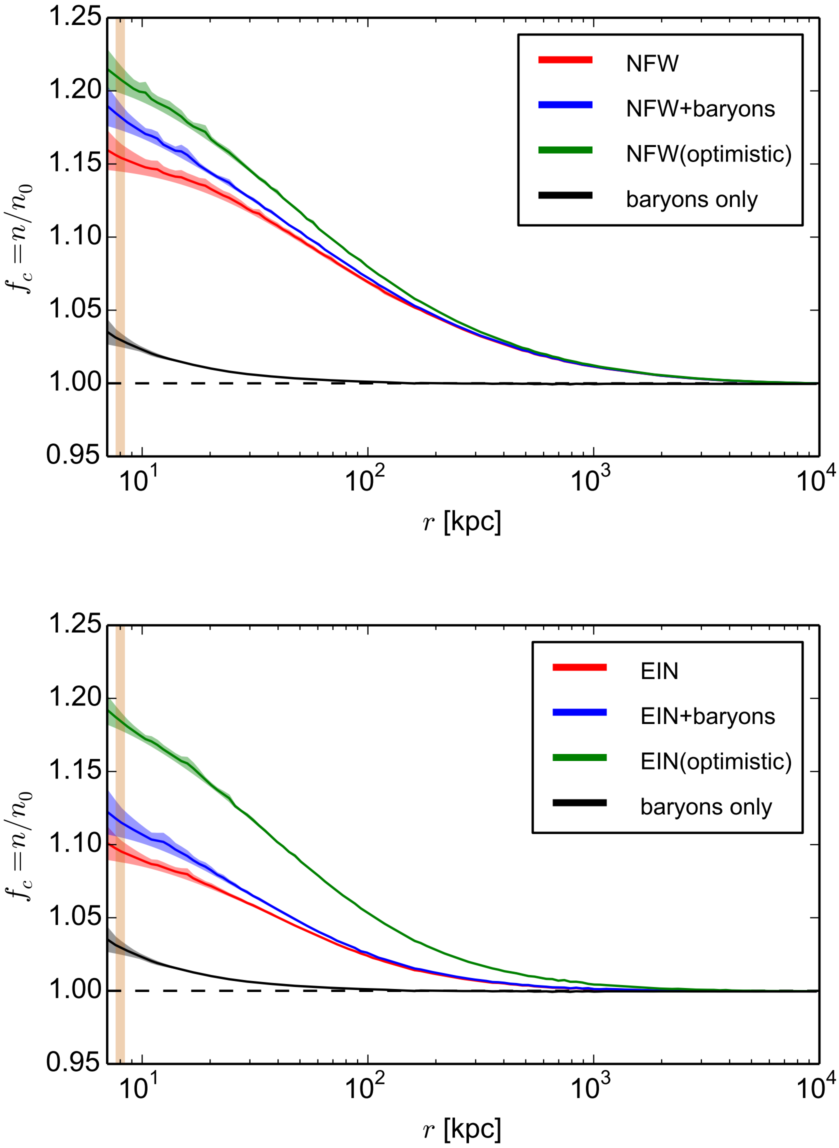

Figure 1. Profiles of the neutrino halo in our galaxy, for a mass of 60 meV and different parametrizations of the MW matter distribution [8]. The vertical band represents the Earth position.

ordering, for which the mixing between the electron neutrino and the heaviest mass eigenstate is the smallest, the enhanced local neutrino density has little impact on the expected event rate. On the other hand, if the ordering is inverted, the situation is opposite: the U_{e1} and U_{e2} terms are large and the increase in the event rate is directly proportional to the clustering factor.

The planned energy 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_ν, neutrinos are practically degenerate in mass and the event rate is not influenced by the mass ordering. We get a clustering factor of the order of $2-3$, as depicted in

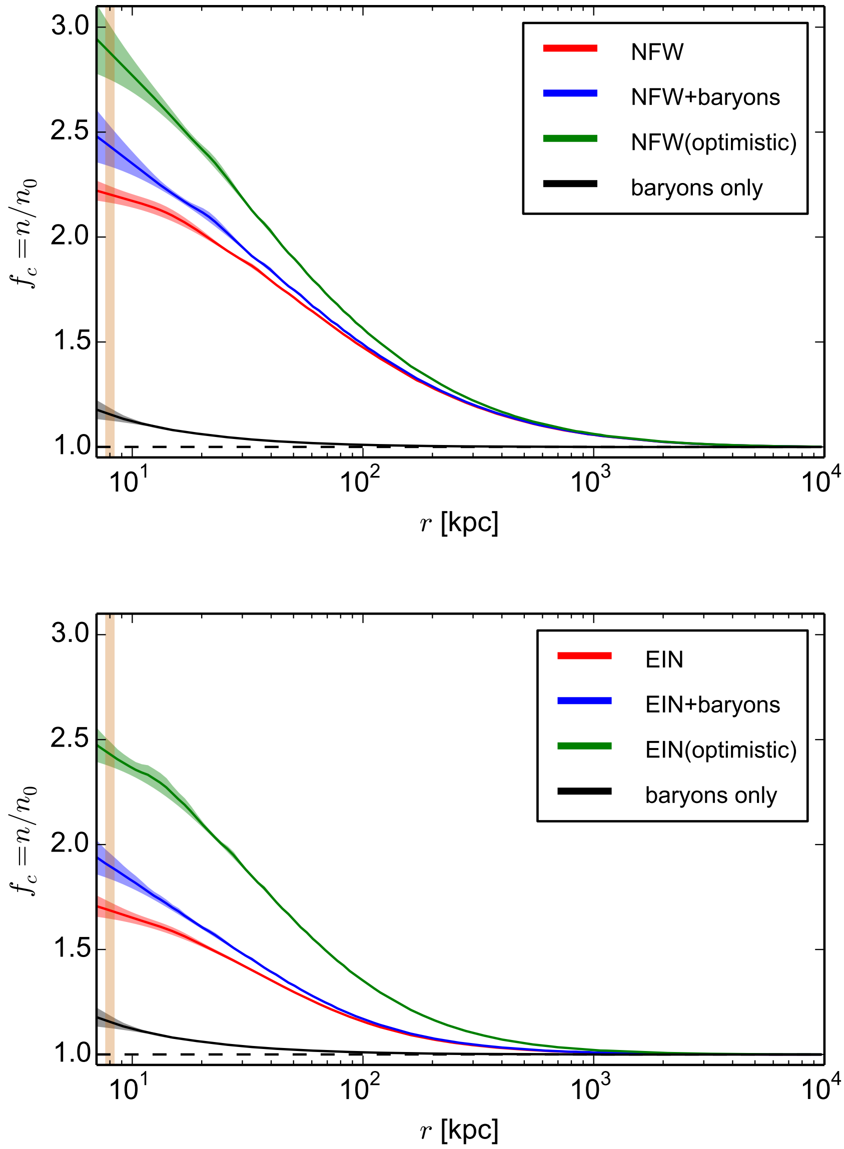

Figure 2. Same as figure 1, but for a neutrino mass of 150 meV [8].

fig. 2, which corresponds to an increase of the event rate by the same factor.

On the other hand, significant overdensities could be reached if neutrino masses were larger than 1 eV, a case that is not possible for standard, active neutrinos. If a fourth massive state exists, introduced in order to provide an explanation to the short-baseline neutrino oscillation anomalies and mostly sterile, we find that gravitational clustering would lead to large enhancement factors. For instance, of order $140 - 210$ for a 1.3 eV neutrino mass [8].

For each case, the corresponding increase in the event rate at a PTOLEMY-like experiment can be calculated [8]. Its value depends on the nature of neutrinos (Dirac or Majorana), as well as on their mass ordering.

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