Detection prospects for the Cosmic Neutrino Background using laser interferometers

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Abstract. The cosmic neutrino background is a key prediction of Big Bang cosmology which has not been observed yet. The movement of the earth through this neutrino bath creates a force on a pendulum, as if it were exposed to a cosmic wind. We revise here estimates for the resulting pendulum acceleration and compare it to the theoretical sensitivity of an experimental setup where the pendulum position is measured using current laser interferometer technology as employed in gravitational wave detectors. We discuss how a significant improvement of this setup can be envisaged in a micro gravity environment. The proposed setup could also function as a dark matter detector in the sub-MeV range, which currently eludes direct detection constraints.

Keywords: cosmological neutrinos, neutrino experiments, dark matter experiments

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1 Introduction

The cosmic neutrino background (CNB) is a robust prediction of the standard model of particle physics in standard ΛCDM cosmology. A measurement of this elusive background would confirm or challenge our understanding of these standard models up to an energy scale of about 1 MeV, far beyond the reach of its cousin, the cosmic microwave background (CMB), which over the last decades has provided us with invaluable information covering cosmological energy scales up to about 0.3 eV. Although very abundant in the universe, the weakly interacting nature of the cosmic neutrinos (which makes them so valuable to probe the early universe) makes them inherently hard to detect. Several proposals have been put forward, for some recent overviews, see, e.g., [1, 2], all of them beyond the reach of current technology. The most promising proposal at the moment seems to be the PTOLEMY experiment [3] which aims at detecting the CNB through the inverse beta decay of tritium. However, very recently, the first discovery of gravitational waves by the LIGO/VIRGO collaboration [4] proved the possibility of detecting an even more elusive potential messenger of our cosmic past, namely gravitational waves. In this paper, we investigate the prospects of searching for the CNB with laser interferometer technology, similar to the technology currently developed for gravitational wave detectors. A related proposal was recently put forward for searching for sub-eV dark matter [5].

Let us briefly recall some key features of the CNB. As the temperature decreases in the course of the evolution of the Universe, the weak interactions keeping neutrinos in equilibrium with the thermal bath freeze out (at about $T \sim 1$ MeV) and the CNB decouples from the thermal bath of photons, electrons and positrons. At $T \sim 0.5$ MeV, the production of electrons and positrons freezes out, leading to a reheating of the photon bath sourced by the annihilation of electrons and positrons. Consequently, the CNB temperature $T_\nu$ is predicted to be slightly lower than the observed CMB temperature of $T_0 = 2.735$ K, $T_\nu = (4/11)^{1/3} T_0 \approx 1.95$ K, which corresponds to a thermal energy of $k_B T_\nu \approx 0.16$ meV. The average neutrino number density today is determined by the thermal neutrino abundance at
the time of decoupling, $\bar{n}_\nu = 3/22 n_\gamma \simeq 56\,\text{cm}^{-3}$ per flavour and per chirality.\footnote{Recently, it was also discussed that the CNB might have a non-thermally produced component \cite{bib:6, bib:7} increasing the total neutrino number density by an $\mathcal{O}(1)$ factor. Since the momentum distribution of this non-thermal component is model-dependent, we will not address this possibility here any further.} This average density as well as the momentum distribution may however be altered locally if the neutrinos are heavy enough to cluster to astrophysical gravitational structures such as our galaxy.

The remainder of this paper is organized as follows. In section 2 we review the predicted local density and momentum distribution of the CNB neutrinos. In section 3, after a brief sketch of a possible simple experimental setup, we propose avenues how a significant improvement might be achieved. Then we update and revise theoretical expectations for a mechanical acceleration induced by the CNB wind in section 4. Comparing these values with current interferometer technology as employed by gravitational wave experiments, we conclude that in the simplest setup the sensitivity still falls short by many orders of magnitude using current technology. For comparison we also quote estimates for the solar neutrino wind and a possible dark matter wind. In the latter case, the expected sensitivity is many orders of magnitude below current direct detection bounds for dark matter masses above a few GeV, but could provide competitive bounds for elastic dark matter-nucleon scattering in the sub-MeV range.

2 Neutrino masses and the CNB

Contrary to the photons of the CMB, neutrinos have a (small) mass, rendering the CNB phenomenology more diverse than the more familiar CMB. Current bounds from laboratory experiments require $m_\nu \lesssim 2.8\,\text{eV}/c^2$ \cite{bib:8}, whereas cosmological bounds are pushing down to $\sum m_\nu \lesssim 0.23\,\text{eV}/c^2$ \cite{bib:9}. At the same time, the heaviest eigenstate must be heavier than about $0.05\,\text{eV}/c^2$ to explain neutrino oscillation data \cite{bib:10}. Depending on their mass, CNB neutrinos may be relativistic or non-relativistic and they may cluster gravitationally in the potential wells formed by dark matter. We will assume here that unclustered neutrinos have no average relative velocity with respect to the CMB rest frame as measured by the CMB dipole. Hence, for sufficiently light neutrinos the total neutrino flux on earth is simply the average neutrino density, $2 \cdot \bar{n}_\nu$ per flavour or mass eigenstate, multiplied by the velocity $\beta_\text{CMB}$ $c \approx 369\,\text{km/s}$ of the earth traveling through the CNB rest frame as measured by the CMB dipole. Since the orientation of this dipole is known from the observation of the CMB, so is the direction of the ‘neutrino wind’ on earth. The momentum distribution of these unclustered neutrinos is to good approximation a red-shifted copy of the Fermi-Dirac distribution describing the neutrino bath at decoupling.

However, from neutrino oscillation data we know that at least two neutrino mass eigenstates are non-relativistic, $\sqrt{\left| \Delta m_{31}^2 \right| c^2} \gg \sqrt{\left| \Delta m_{21}^2 \right| c^2} \simeq 8.5 \cdot 10^{-3}\,\text{eV} \gg 3.15\,k_B T_\nu \simeq 5 \cdot 10^{-4}\,\text{eV}$. These non-relativistic neutrinos might gravitationally cluster to large DM structures such as galaxies, clusters and superclusters. Clustering becomes relevant if the intrinsic neutrino velocity drops below the escape velocity of the corresponding astrophysical structure, $v \sim \langle p_\nu \rangle c / E_\nu \sim 3 k_B T_\nu c / m_\nu < v_\text{esc}$. For the Milky Way, the escape velocity is about $v_\text{esc}^{\text{MW}} \simeq 500\,\text{km/s}$ while for our supercluster it is estimated to be $\mathcal{O}(10^3)\,\text{km/s}$. Gravitational clustering will enhance the local neutrino density and modify the momentum distribution. Ref. \cite{bib:11} studied the clustering of neutrinos to the Milky Way and to supercluster structures, finding an enhancement factor of $n_\nu / \bar{n}_\nu = \mathcal{O}(1-100)$, depending on the mass of the neutrinos and the size of the astrophysical structure.
The velocity dispersion of these clustered neutrinos can be estimated from the virial velocity, which for neutrinos bound to the galaxy is about $\beta_{\text{vir}} c \sim 10^{-3} c$ at the position of the earth. Up to an $\mathcal{O}(1)$ factor this agrees with the simulations of ref. [11], which indicate that the momentum distribution is well approximated by a Fermi-Dirac distribution with a cut-off around the escape velocity. In the following we will take the velocity dispersion of clustered neutrinos to be $\beta_{\text{vir}} c$. However, this value might be enhanced by a factor of $\mathcal{O}(1 - 10)$. Note that the direction of the neutrino wind will differ compared to the unbound case. For unbound neutrinos, the neutrino wind is expected at an angle of $\sim 10^\circ$ to the ecliptic plane, for bound neutrinos we expect $\sim 60^\circ$ [12]. In practice the neutrino wind experienced on earth can be a combination of all these possibilities, including relativistic and non-relativistic states as well as (partially) clustered populations.

In addition to the effects described above, gravitational focusing effects within the solar system may induce an annual modulation of the neutrino rate on earth, which is also sensitive to the neutrino mass [12]. It has also been argued that the CNB could be asymmetric (i.e., containing different number densities of neutrinos and anti-neutrinos) in one or more flavours, which could result in an enhancement of the average neutrino density [13]. While Big Bang Nucleosynthesis severely constrains such an asymmetry for electron neutrinos [14–17] the constraints on the muon and tau neutrinos (which would contribute to the extra relativistic degrees of freedom as measured in the CMB) are much weaker [18–20].

In the following we will hence distinguish three cases with increasing absolute neutrino mass scale: relativistic (R), non-relativistic unclustered (NR-NC) and non-relativistic clustered (NR-C) neutrinos. As a reference value we will work with the standard average neutrino density per flavour or mass eigenstate set by $2 \bar{n}_\nu = 112 \text{ cm}^{-3}$.

### 3 The experimental setup

In this section we will first discuss a simple toy setup for the kind of experiment we are considering to estimate the sensitivity which could be achieved in the near future. A comparison with the magnitude of the expected signal, derived in section 4, will reveal that current interferometer technology falls orders of magnitude short of the sensitivity required to detect the CNB. With this in mind, we limit our discussion in this section to a schematic description of the possible experimental setup. In section 3.2 we will outline some potential modifications which might help to drastically increase our expected sensitivity.

#### 3.1 Sketch of the experimental setup

We consider test masses mounted on classical pendulums. The neutrino wind will result in a force on the test masses which leads to an excursion in the direction of the wind, see figure 1. If the force and the excursion $d$ are extremely small and slowly varying (see section 4 for details), we may use the small angle approximation

$$d = l \sin \theta \approx l \frac{\alpha_\nu}{g}, \quad (3.1)$$

where $l$ is the length of the pendulum and $g \approx 980 \text{ cm/s}^2$ is the standard acceleration due to the gravitational field of the earth.

Let us assume that the pendulum fits nicely into an ordinary lab and hence for simplicity we take $l = 100 \text{ cm}$. As a reference value, the current sensitivity of LIGO is $\Delta d = h L \Delta f^{1/2} \approx 1 \cdot 10^{-17} (\Delta f/10 \text{ Hz})^{1/2} \text{ cm}$, with $L = 4 \text{ km}$ denoting the length of the interferometer arms,
Figure 1. Sketch of the experimental setup. The neutrino wind exerts a force on the test mass at the end of the pendulum of length $l$. The resulting excursion, $d$ can be probed by the laser interferometer.

$h \approx 10^{-23}/\sqrt{\text{Hz}}$ denoting the current peak strain sensitivity at $f_0 = 100 \text{ Hz}$ and $\Delta f$ indicating the bandwidth used for the analysis [21]. This translates to a sensitivity for the acceleration of

$$a^\text{now}_{\text{min}} = g \frac{\Delta d}{l} \approx 1 \cdot 10^{-16} \text{ cm/s}^2,$$

(3.2)

where we have set $\Delta f = 10 \text{ Hz}$. The design sensitivity of advanced LIGO is expected to lower this by a factor of 3, with future upgrades expected to improve the current sensitivity by about a factor 10 [21]. For the Einstein telescope with 10 km arm length strain sensitivities of a few times $10^{-25}/\sqrt{\text{Hz}}$ are envisaged [22]. In the future one could thus optimistically estimate a sensitivity of

$$a_{\text{min}} \approx 3 \cdot 10^{-18} \text{ cm/s}^2,$$

(3.3)

for terrestrial experiments. Space based GW interferometers have been designed for lower frequencies $f_0 \sim \text{ few mHz}$, but their expected sensitivity in terms of absolute distance changes is lower ($\Delta d \approx 10^{-11} \text{ cm}$ for LISA [23] for a bandwidth of $\Delta f = 10^{-4} \text{ Hz}$).

Note, that we will assume here for simplicity that the experiment has an optimal orientation with respect to the neutrino wind, i.e., that the movement of the earth rotates the experiment such that within a day, the pendulum interferometer arm is orientated parallel as well as orthogonal to the neutrino wind. The optimal situation is achieved for a neutrino wind orthogonal to the earth’s axis, in which case the pendulum interferometer arm can reach an orientation parallel and anti-parallel to the neutrino wind within a day. In a realistic setup there should also be an additional annual modulation, see [12] for a recent discussion.

It is crucial to note that our above estimates apply for the frequency band of the corresponding detector. In particular, any terrestrial setup will suffer drastically from seismic noise for frequencies below about 1 Hz. On the contrary, the intrinsic frequency of a signal induced by the CNB is set by the earth’s rotation, $1/\text{day} \sim 10^{-5} \text{ Hz}$. It thus seems extremely difficult at best to exploit the remarkable sensitivity of laser interferometers to search for the CNB in an earth based laboratory. A possible way out might be to focus not on the daily variation of he excursion $d$, but on the high frequency component due to individual neutrino
interactions, governed by the rate of neutrinos scattering off the test mass. Optimizing the setup for this measurement requires adjusting the pendulum length as well as the size and material of the test mass.

More concretely, using the expressions derived in section 4, we note that the number of scattering events per unit time, $\Gamma$, depends on the mass of the pendulum $M$ whereas the resulting acceleration $a_{G,F}^2$ to leading order does not,

$$a_{G,F}^2 = R \langle \Delta p \rangle, \quad \Gamma = R M . \quad (3.4)$$

Here $\langle \Delta p \rangle$ denotes the average momentum transfer and $R$ denotes the event rate per second and gram. For example, in the case of non-relativistic non-clustered neutrinos and approximating LIGO’s mirrors as 40 kg pure silicon, we find

$$\Gamma = 86 \text{ Hz} \left( \frac{M}{40 \text{ kg}} \right) \left( \frac{(A-Z)^2/A^2}{0.25} \right) \left( \frac{\rho}{2.34 \text{ g/cm}^3} \right), \quad (3.5)$$

which is right within the LIGO sensitivity band. However, as we will see in the next section, the corresponding acceleration of $a_{G,F}^2 \approx 7.3 \cdot 10^{-32} \text{ cm/s}^2$ for silicon is very far beyond the current reach of LIGO. This acceleration could even drop down to $a_{G,F}^2 \approx 10^{-33} \text{ cm/s}^2$ for light normal hierarchical Majorana neutrinos.

The situation is somewhat more optimistic for DM searches, where the event rate is sensitive to the mass and cross-section of the DM particle. Using the same approximation as above to model LIGO’s mirrors, we find that LIGO’s peak sensitivity of 100 Hz corresponds approximately, e.g., to the following combinations of acceleration, DM mass and cross-section:

$$a_{G,F}^2 \approx 10^{-18} \text{ cm/s}^2, \quad m_X = 10 \text{ GeV}, \quad \sigma_{X-N} = 3 \cdot 10^{-34} \text{ cm}^2, \quad (3.6)$$

$$a_{G,F}^2 \approx 10^{-20} \text{ cm/s}^2, \quad m_X = 0.1 \text{ GeV}, \quad \sigma_{X-N} = 3 \cdot 10^{-36} \text{ cm}^2, \quad (3.7)$$

$$a_{G,F}^2 \approx 10^{-22} \text{ cm/s}^2, \quad m_X = 1 \text{ MeV}, \quad \sigma_{X-N} = 1 \cdot 10^{-40} \text{ cm}^2. \quad (3.8)$$

More details on the dependence of $\Gamma$ and $a_{G,F}^2$ on the DM mass and cross-section are given in section 4.

The numbers found above have to be compared with Cavendish-type torsion balances which try to measure the same kind of acceleration we study here [24, 25]. Recent torsion-balance tests of the weak equivalence principle have sensitivities for differential accelerations of the order of $10^{-13} \text{ cm/s}^2$ [26], and it has been claimed that accelerations down to $10^{-23} \text{ cm/s}^2$ may be reached [24, 25]. In [5] it was argued that assuming an optimal, shot noise limited laser read-out, torsion balance experiments can always do better than a linear displacement experiment as we suggest here. To keep the discussion simple we will imagine a linear setup in the following, keeping in mind that further improvements might be possible with different geometries.

As we will review in section 4, the expected displacements of the pendulum due to the CNB are tiny, far beyond the sensitivity of current and upcoming laser interferometers. We hence do not want to make the discussion unnecessarily complicated with lengthy musings about the exact shape of the modulation or the experimental setup. With all these caveats in mind, we will nevertheless refer to eqs. (3.2) and (3.3) as benchmark values for what might be achieved with this kind of experiment. We do however dedicate the following subsection to some speculation on avenues which might increase the sensitivity by many orders of magnitude.
3.2 Possible avenues for significant improvement

The two distinctive features of the signal are the directional information and the characteristic frequency. Adding a second interferometer orthogonal to the first to get two-dimensional information about the excursion of the pendulum or putting several copies of the experimental setup on different locations on earth would help to discriminate the signal from background.

We further point out that the sensitivity could be significantly improved if the acceleration $g$ is significantly lowered. Implementing such a setup in space inside a rotating satellite with tiny centrifugal forces might sound utopic now, but might be possible in the future. On the International Space Station routinely experiments in micro gravity are performed with a net acceleration of the order of $10^{-6}$ g [27]. Hence, the sensitivity of our setup placed in space could conceivably be increased by six orders of magnitude or more. This could also ameliorate the problem of the required stability over time, since the rotation frequency of a space based experiment could be much faster than the corresponding signal frequency of 1/day on earth. One could also instead imagine to put the pendulum mass in some kind of electromagnetic suspension to compensate earth’s gravity. Cleverly arranged, this might also damp much larger background effects.

We also note the possibility of replacing the pendulum with two or more free falling masses with different total neutrino cross sections - as we will see below dramatically different cross sections can be obtained by varying the target size and material due to an atomic enhancement factor. The free falling test masses would thus drift apart under the influence of the neutrino wind, seemingly violating the equivalence principle. In this context, it is remarkable that LISA Pathfinder has probed the relative acceleration between two free falling (identical) test masses down to $(5.2 \pm 0.1) \cdot 10^{-15} g/\sqrt{Hz}$ for frequencies around 1 mHz [28]. Of course, a measurable effect would require a stability on much longer time scales. A quick estimate shows that a cm - sized lead test mass subject to a constant acceleration of $a = 10^{-27} \text{cm/s}^2$ over one month by the CNB, see section 4.2, would be displaced by $a (30 \text{ days})^2/2 = 3 \cdot 10^{-15} \text{cm}$. A distance which is in principle measurable with current laser technology.

4 Theoretical expectations for the acceleration

The mechanical effect of the cosmic neutrino background has been known already for a long time and we will refer here to the calculations of Duda, Gelmini and Nussinov [29]. The formulas in this section are mostly based on their work, subject to some improvements as we will detail below. We restrict ourselves to the case of Dirac neutrinos which is the more optimistic case for this kind of experiments. For relativistic neutrinos the results for Majorana and Dirac neutrinos are the same while for non-relativistic neutrinos the $G_F$ effect would vanish for clustered neutrinos and the $G_F^2$ effect is suppressed by a factor of $(v_\nu/c)^2 \ll 1$ [29].

4.1 Magnetic torque ($G_F$ effect)

There have been some early proposals to detect cosmic neutrinos using an optical refractive effect [30, 31], which however does not give a net acceleration [13, 32]. But there is another effect linear in Fermi’s constant $G_F$ which was originally proposed by Stodolsky [33], remarkably before the discovery of neutral currents. It is due to the energy splitting of the two spin states of the electrons of the detector material in the bath of cosmic neutrinos. If there is an asymmetry between the densities of neutrinos and anti-neutrinos in the CNB, this results
in a net torque force on the test mass. The acceleration of the test mass of the pendulum reads [29]

\[ a_{G_F} = \frac{N_{AV}}{A m_{AV}} \frac{\Delta E \gamma}{\pi R}, \]

(4.1)

where \( N_{AV}/(A m_{AV}) \) is the number of nuclei in 1 g test material. \( N_{AV} = 6.022 \cdot 10^{23} \) is Avogadro’s constant, \( A \) the number of nucleons in an atom and \( m_{AV} = 1 \) g is introduced here for proper normalization. \( R \) is the radius of the test mass and \( \gamma = M R^2/I \) is a geometrical factor related to the moment of inertia \( I \) of the detector with mass \( M \). Using the expression found in ref. [29] for the induced energy splitting \( \Delta E \) of the electrons we find

\[ a_R G_F = \frac{N_{AV}}{A m_{AV}} \frac{2\sqrt{2}}{\pi} G_F \beta_{\text{CMB}} \gamma \sum_{\alpha=e,\mu,\tau} (n_{\nu_\alpha} - n_{\bar{\nu}_\alpha}) g_A^\alpha, \]

(4.2)

for relativistic neutrinos. For non-relativistic neutrinos this could be at most one order of magnitude larger [29]. Note that this effect only exists in the presence of a lepton asymmetry in the CNB such that the number of neutrinos and anti-neutrinos do not cancel. In the conventions of ref. [29], \( g_e^A = 0.5 = -g_{\mu,\tau}^A \).

The effect is larger for test masses with a small \( A \) and the probe has to be magnetized. This is most easily realized for ferromagnets. The stable, elementary ferromagnet with the smallest atomic number is the iron isotope with \( A = 54 \). Furthermore we assume the test mass to be a massive sphere with a radius of 1 cm (\( \gamma = 0.4 \)) and we find

\[ a_R \approx 4 \cdot 10^{-29} \frac{n_{\bar{\nu}_\mu} - n_{\nu_\mu}}{2 n_\nu} \text{cm/s}^2, \]

(4.3)

where we have for simplicity taken the other two neutrino flavours to be symmetric, \( n_{\bar{\nu}_{\mu,\tau}} = n_{\nu_{e,\mu,\tau}} \). With the expressions above it is straight-forward to derive an estimate for more complicated admixtures of flavours and neutrinos and anti-neutrinos. Unfortunately, our estimate here is many orders of magnitude away from the benchmark sensitivity of \( 3 \cdot 10^{-18} \) cm/s², cf. (3.3).

4.2 Scattering processes \((G_F^2\text{ effect})\)

Next we turn to the force due to the momentum transfer of CNB neutrinos scattering off the target material, first discussed by Opher [30] (for other early works, see, e.g. [31, 34]). Since this force is proportional to \( G_F^2 \), one might expect this effect to be suppressed compared to the magnetic effect discussed above. However, due to the macroscopic wavelength of the low-energy CNB neutrinos, the cross section may be enhanced not only by a nuclear coherence factor \( \sim A^2 \) but also by a coherence factor \( N_c \) from the scattering of multiple nuclei [30, 35, 36], see also [37], such that this effect can be dominant. It also does not require an asymmetry in the CNB. The resulting acceleration of the test mass can be written as [29]

\[ a_{G_F^2} = \Phi_\nu \frac{N_{AV}}{A m_{AV}} N_c \sigma_{\nu-A} \langle \Delta p \rangle, \]

(4.4)

where \( \Phi_\nu = n_\nu p_\nu c^2/E_\nu \) is the neutrino flux with \( E_\nu \) denoting the energy of the CNB neutrinos and \( p_\nu \) the average relative momentum between these neutrinos and the earth. Further, \( N_c \) denotes the coherence enhancement factor, \( \sigma_{\nu-A} \) the neutrino-nucleus cross-section containing the nuclear enhancement factor and \( \langle \Delta p \rangle \) is the average momentum transfer from the scattered neutrinos.
The neutrino cross section at low energies (small recoil energies) is \[38\]
\[
\sigma_{\nu-A} \approx \frac{G_F^2}{4\pi \hbar^4 c^4} (A - Z)^2 E_{\nu}^2,
\]
with \(E_{\nu} \approx m_{\nu} c^2\) for non-relativistic and \(E_{\nu} \approx 3.15 k_B T_{\nu}\) for relativistic neutrinos. In addition, the neutrinos will also scatter off the electrons in the material. For \(E_{\nu} \ll m_{\nu} c^2\) the cross section to one electron is approximately \[39\]
\[
\sigma_{\nu-e} \approx \frac{7 G_F^2}{4\pi \hbar^4 c^4} E_{\nu}^2 \quad \text{and} \quad \sigma_{\nu,\tau - e} = \frac{3}{7} \sigma_{\nu-e},
\]
which is comparable to the nucleus cross section. However, contrary to the nucleus cross section, the electron cross section is sensitive to the flavour composition of the CNB and the effective momentum transfer from the electrons to the macroscopic target will depend on the details of the target material. We will hence omit this contribution in the following, noting however that including this effect may moderately increase the cross section.

The atomic coherence factor \(N_c\) is given by the number of nuclei within the de Broglie wavelength \(\lambda_{\nu} = \frac{2\pi \hbar}{p_{\nu}}\) of the neutrinos \[29\],
\[
N_c = \frac{N_{AV}}{A m_{AV}^2} \rho \lambda_{\nu}^3,
\]
where \(\rho\) denotes the density of the test mass at the end of the pendulum. To maximize the coherence effect the test mass should ideally have the same size as the de Broglie wavelength. Alternatively, one could think of using foam-like \[34\], or laminated materials \[36\] or some embedding of the detector material in a matrix material \[40\]. For CNB neutrinos, the typical de Broglie wavelength is \(O(0.1\,\text{cm})\), leading easily to \(N_c \sim 10^{20}\). So we can rewrite the acceleration as
\[
a_{G_\nu^2} = \frac{2\pi^2 G_F^2}{\hbar c^2} n_{\nu} N_{AV}^2 (A - Z)^2 \rho \langle \Delta p \rangle E_{\nu} \frac{m_{AV}^2}{A^2}.
\]

Now we are left with \(\langle \Delta p \rangle\), which can be categorized roughly into three cases, see the discussion in section 2. The first case are relativistic neutrinos \(m_{\nu} c^2 \ll k_B T_{\nu}\) where
\[
p_{\nu}^{(R)} \simeq 3.15 k_B T_{\nu}/c, \quad \langle \Delta p \rangle_{(R)} \simeq 3.15 \beta_{\nu}^{\text{CMB}} k_B T_{\nu}/c,
\]
with the Boltzmann constant \(k_B = 1.38 \times 10^{-16}\) g cm\(^2\) s\(^{-2}\) K\(^{-1}\) and the speed of light \(c = 2.998 \times 10^{10}\) cm/s. The factor 3.15 arises from the thermal average over the Fermi-Dirac distribution. Here \(\beta_{\nu}^{\text{CMB}}\) denotes the velocity of the earth in the CNB frame. If the earth was at rest in this frame, the neutrinos would arrive uniformly from all directions and the average momentum transfer would vanish. The net effect is thus proportional to the velocity of the earth (the pendulum) moving through the neutrino bath.

Next we consider non-relativistic neutrinos \((m_{\nu} c^2 \gg k_B T_{\nu})\) which can be divided into two sub cases. First, we consider neutrinos which do not cluster gravitationally. Even though they are non-relativistic, their average momentum is thus determined by the CNB temperature,
\[
p_{\nu}^{(\text{NR-NC})} \simeq 3.15 k_B T_{\nu}/c, \quad \langle \Delta p \rangle_{(\text{NR-NC})} \simeq 3.15 \beta_{\nu}^{\text{CMB}} k_B T_{\nu}/c.
\]

Note that in general, the relative momentum should be estimated as
\[
\langle p_{\nu} \rangle_{(\text{NR-NC})} \simeq \max \left\{3.15 k_B T_{\nu}, m_{\nu} \beta_{\nu}^{\text{CMB}} c \right\}.
\]
However, since we are considering non-clustered neutrinos, their velocity must be larger than the escape velocity. Since \( v_{\text{esc}} \gtrsim \beta_{CMB} c \), the former term will always dominate. On the other hand, the rest frame of clustered non-relativistic neutrinos is the frame of the galaxy or (super) cluster. As a reference value for their velocity dispersion we use \( \beta_{\text{vir}} \), which also determines the relative velocity of the earth in this frame, \( v_{\odot} \approx \beta_{\text{vir}} c \).

\[
p_{\nu}^{(\text{NR-C})} \simeq m_{\nu} \beta_{\text{vir}} c, \quad \langle \Delta p \rangle_{\text{(NR-C)}} \simeq m_{\nu} \beta_{\text{vir}} c,
\]

(4.12)

With this we find that the acceleration is given by

\[
a_{G}^{2} = \frac{2 \pi^{2} G_{F}^{2}}{\hbar c^{2}} n_{\nu} \frac{N_{A}^{2}}{A^{2} m_{\nu}^{2} \rho} \begin{cases} 
\beta_{\text{CMB}} c & \text{for (R)}, \\
\frac{m_{\nu} \beta_{\text{CMB}}^{\text{CMB}} c^{3}}{3.15 k_{B} T_{\nu}} & \text{for (NR-NC)}, \\
\frac{c}{\beta_{\text{vir}}} & \text{for (NR-C)}.
\end{cases}
\]

(4.13)

We can now plug in some numbers and compare them to our benchmark sensitivities. As a target we choose lead which has a high density, \( \rho \approx 11.34 \text{ g/cm}^{3} \), with \( A = 208 \) and \( Z = 82 \). In total we then obtain

\[
a_{G}^{2} = \frac{n_{\nu}}{2 n_{\nu}} \begin{cases} 
3 \cdot 10^{-33} \text{ cm/s}^{2} & \text{for (R)}, \\
5 \cdot 10^{-31} (m_{\nu}/0.1 \text{ eV/c}^{2}) \text{ cm/s}^{2} & \text{for (NR-NC)}, \\
2 \cdot 10^{-27} (10^{-3}/\beta_{\text{vir}}) \text{ cm/s}^{2} & \text{for (NR-C)}.
\end{cases}
\]

(4.14)

Here we have normalized the neutrino density to the standard value of \( 2 \bar{n}_{\nu} \). We find here slightly different numbers than ref. [29]. Apart from some improved approximations, the main difference is the expression for \( p_{\nu} \) employed in the (NR-NC) case.

As discussed in section 2, various mechanisms can (moderately) enhance these values. We stress that at least two neutrino generations should be non-relativistic nowadays, and that they are moreover at least partially clustered (at least to the local super cluster) which is the more promising case for a potential discovery. Nevertheless, these rates are many orders of magnitude below the benchmark sensitivities quoted in section 3.1.

For completeness, let us estimate the lower bound on the induced acceleration, taking into account all remaining uncertainties about the CNB. As can be seen from the expressions above, the ‘worst case scenario’ are light (normal ordered) Majorana neutrinos. If the lightest neutrino is massless we find for the other two neutrino masses \( m_{2} \approx 8.5 \cdot 10^{-3} \text{ eV/c}^{2} \) and \( m_{3} \approx 5 \cdot 10^{-2} \text{ eV/c}^{2} \) which is much larger than their kinetic thermal energy \( 3.15 k_{B} T_{\nu} \approx 5 \cdot 10^{-4} \text{ eV} \) such that both of these species can be considered to be non-relativistic. To be more precise their velocities are then \( v_{2} \approx \sqrt{2 E/m_{2}} \approx 0.2 c \) and \( v_{3} \approx \sqrt{2 E/m_{3}} \approx 0.1 c \) which is far above the local escape velocities. Furthermore, the scattering cross section for Majorana neutrinos is suppressed by an additional factor of \( (v/c)^{2} \), see, e.g., [29]. Combining this information we find that the minimal acceleration is of the order

\[
a_{G}^{\text{min}} \approx 8 \cdot 10^{-33} \text{ cm/s}^{2},
\]

(4.15)

where we have summed over all three flavours. This is nearly six orders of magnitude worse than the most optimistic scenario. However, once the neutrino mass scale and ordering is

\[\text{We choose here a material with a high neutron and mass density to increase the induced accelerations. Currently in gravitational wave experiments other lighter materials are preferred to, e.g., reduce thermal noise. For pure silicon, for instance, the acceleration would drop roughly by a factor of seven.}\]
determined the uncertainty on the induced acceleration will shrink significantly. A determination of the Dirac / Majorana nature of neutrinos would furthermore significantly reduce this uncertainty. Vice versa, if neutrino-less double beta decay experiments remain inconclusive, the CNB could one day be a last resort to distinguish these two possibilities.

As we have just seen the scattering effect can indeed be much smaller than the $G_F$ effect, cf. (4.3), which makes it tempting to focus on the latter effect. But this depends on the lepton asymmetries for which there is no such clear theoretical prediction.

4.3 Solar neutrinos and dark matter

In this section we discuss two relevant competing processes which could also result in a pendulum displacement with a similar frequency: solar neutrinos and particle dark matter (DM), see also [29].

The acceleration due to solar neutrinos is given by eq. (4.4) for relativistic neutrinos, taking into account that the maximal momentum transfer of solar neutrinos is simply given by $\langle \Delta p \rangle = E_\nu/c$ (since all solar neutrinos come from the same direction). The de Broglie wavelength of the solar neutrinos is $O(10^{-10})$ cm and hence smaller than the typical atomic distances, implying that there will be no coherent enhancement as for the CNB neutrinos ($N_c = 1$). With the solar neutrino flux $\Phi_{\text{solar-}\nu} = 10^{11}$ cm$^{-2}$ s$^{-1}$, the scattering of $p p$ neutrinos ($E_\nu \simeq 0.3$ MeV) off a lead test mass yields

$$a_{\text{solar-}\nu} \approx 3 \cdot 10^{-26} \text{ cm/s}^2.$$  (4.16)

This acceleration is larger than the CNB wind, however as we discuss in the following section, the event rate is much smaller so that (in an earth based laboratory) the expected signal would be clearly distinguishable. Moreover, in contrast to the CNB signal, this signal will be correlated with the relative position of the sun.

Eq. (4.4) also applies to the acceleration induced by collisions with cold dark matter particles $X$. In this case, the corresponding flux is given by $\Phi_X = n_X \beta_X c$ and the momentum transfer by $\langle \Delta p \rangle_X = m_X \beta_X c$ where $n_X$, $\beta_X c$ and $m_X$ denote the number density, average velocity and mass of the particles $X$. For dark matter masses $m_X \gtrsim 1$ GeV/c$^2$, as expected in the WIMP scenario, the de Broglie wavelength is smaller than $10^{-10}$ cm and we can set $N_c = 1$. Together, for a lead target as considered above this yields

$$a_{\text{DM}} \approx 4 \cdot 10^{-30} \left( \frac{(A-Z)^2}{76A} \right) \left( \frac{\sigma_{X-N}}{10^{-46} \text{ cm}^2} \right) \left( \frac{\rho_{\text{dark(local)}}}{10^{-24} \text{ g/cm}^3} \right) \left( \frac{\beta_X}{10^{-3}} \right)^2 \text{ cm/s}^2,$$  (4.17)

with $\rho_{\text{dark(local)}} = m_X n_X$ the local dark matter density, implying that the benchmark sensitivity of eq. (3.2) corresponds to cross sections in this dark matter range of $\sigma_{X-N} \gtrsim 2 \cdot 10^{-33}$ cm$^2$. In the prototypical WIMP mass range of $\text{GeV/c}^2 < m_X < 100 \text{ GeV/c}^2$, such a cross section is excluded by many orders of magnitude by current direct detection searches, which find $\sigma_{X-N} \lesssim 10^{-46}$ cm$^2$ for spin-independent nucleon-DM interactions for $m_X \approx 40 - 50$ GeV/c$^2$ [41, 42].

Given these strong constraints, sub-GeV DM candidates have recently received a lot of attention, see, e.g., [43] and references therein. In this mass range, the constraints from direct detection become irrelevant and the strongest bounds are derived from cosmology and astrophysical considerations [44]. For example, a thermal dark matter candidate which is lighter than about 10 MeV/c$^2$ would decouple from the Standard Model after the decoupling of the CNB, and hence generically perturb the standard $T_\nu/T_0$-relation - which in turn is
bounded by the $\Delta N_{\text{eff}}$ measurements in the CMB [45, 46]. Further constraints arise from the relic abundances of the elements produced in Big Bang Nucleosynthesis [47–49] and from bounds on CMB distortions [50, 51]. Assuming standard cosmology, these constraints exclude wide mass-ranges of sub-MeV thermal relics [44], subject however to assumptions on, e.g., the annihilation channels, the nature of the mediator fields and the production mechanism.

In contrast, it is interesting to note that the setup we propose here could function as a fairly model-independent direct DM detector. In the sub-MeV mass range, our proposal gains ground in a two-fold way: firstly, the DM number density increases as $1/m_X$ implying that DM acts more like a constant ‘wind’ (as in the CNB case) instead of separate individual events even for lower cross sections. Secondly, and more importantly, the atomic enhancement factor $N_c$ begins to rapidly grow for $m_X \lesssim \text{MeV}/c^2$, reaching $N_c \sim 10^9$ for a lead test mass at $m_X = 3.3\text{keV}/c^2$ (which corresponds to the lower bound on the DM mass from structure formation for a thermal relic [52]). In this mass range our setup with the benchmark sensitivity of eq. (3.2) could thus allow to probe DM - Nucleon cross sections down to $\sigma_{X-N} \approx 10^{-42}\text{cm}^2$.

Note that even lighter DM masses are theoretically viable if the DM particle has a suitable non-thermal history and hence its contribution to washout during structure formation is suppressed. These numbers should be compared with other very recent proposals to directly measure DM in this mass range, see, e.g., refs. [53–61].

A dark matter signal might be disentangled from a CNB signal through the phase of the annual modulation [12]. The fractional modulation for light, unbound neutrinos is expected to peak in fall, whereas the peak for bound particles (such as DM) is expected in spring, see figure 2 of [12]. This is of course only possible if the CNB neutrinos are mainly unclustered. Note that the expected signal from bosonic sub-eV dark matter as discussed in [5] oscillates with a frequency of $m_X/(2\pi\hbar) \sim m_X/(0.05\text{ eV}/c^2) \cdot 10^{13}\text{ Hz}$. For $m_X \gtrsim 10^{-19}\text{ eV}/c^2$ this is much faster than the 1/day frequency of the signals discussed here.

4.4 Cosmic wind vs. cosmic nudges

A question which has not explicitly been addressed in the literature to our knowledge is, if the CNB really acts like a wind or if it is more realistically a series of feeble nudges on the test mass. To understand this issue better let us first have a look at the event rates of CNB neutrinos, focusing for simplicity here only on the $G_F^2$ effect. From

$$R = \frac{aG_F^2}{\langle \Delta p \rangle} = \Phi_\nu \frac{N_{AV}}{A m_{AV}} N_c \sigma_{\nu-A}, \quad \text{(4.18)}$$

we obtain

$$R_{(R)} \approx 1 \cdot 10^{-4} \frac{n_\nu}{2 \bar{n}_\nu} \frac{m_\nu}{g} \text{ s}^{-1}, \quad \text{(4.19)}$$

$$R_{(NR-NC)} \approx 0.02 \frac{n_\nu}{2 \bar{n}_\nu} \frac{m_\nu}{0.1\text{ eV}/c^2} \text{ g}^{-1} \text{ s}^{-1}, \quad \text{(4.20)}$$

$$R_{(NR-C)} \approx 0.4 \frac{n_\nu}{2 \bar{n}_\nu} \frac{0.1\text{ eV}/c^2}{m_\nu} \left( \frac{10^{-3}}{\beta_{\text{vir}}} \right)^2 \text{ g}^{-1} \text{ s}^{-1}, \quad \text{(4.21)}$$

using the above results and with lead as detector material. For a total test mass of about 100 kg (arranged properly to fully exploit the atomic coherence factor) the expected frequency of events is in all three cases larger than the oscillation frequency of the pendulum ($f = 1/(2\pi)\sqrt{g/l} \approx 0.5\text{ Hz}$), and it is indeed justified to speak of a neutrino ‘wind’. Interestingly one could also follow another approach here. It is difficult to keep the interferometers stable.
on the time scale of a day. Instead, one can choose the material, the size of the detector and
the length of the pendulum in such a way that the signal appears as noise in the frequency
band where the detector is most sensitive (i.e., \( R \sim 100 \) Hz for LIGO). The daily/annual
modulation as well as the preferred average direction of the signal would then result in a
fluctuation of the noise which might be easier identified than the very low-frequency signal
discussed above as we also have pointed out already in section 3.1.

Interestingly, the event rate for solar neutrinos is very low

\[ R_{\text{solar}-\nu} \approx 2 \cdot 10^{-9} \text{ g}^{-1} \text{s}^{-1} \]  

(4.22)

which might seem surprising due to the very large flux and the much higher nucleus cross
section. But in this case the missing atomic coherence factor really makes a big difference.
Consequently, solar neutrinos will register in our setup as a series of individual nudges.
Disentangling these from other background events seems challenging but again the directional
information can help.

For WIMP-like cold dark matter the rate is given by

\[ R_{\text{DM}} \approx 8 \cdot 10^{-3} \left( \frac{100 \text{ GeV}/c^2}{m_X} \right) \left( \frac{\sigma_{X-N}}{10^{-33} \text{cm}^2} \right) \left( \frac{\rho_{\text{dark(local)}}}{10^{-24} \text{g/cm}^3} \right) \left( \frac{\beta_X}{10^{-3}} \right) \text{ g}^{-1} \text{s}^{-1}, \]  

(4.23)

normalized to our expected sensitivity for the cross-section for 100 GeV/c^2 dark matter as
discussed above. This rate is extremely small once one inserts the direct detection constraints,
\( \sigma_{X-N} \lesssim 10^{-46} \text{ cm}^2 \), as expected compared to plausible rates in dark matter direct searches.
However, this picture drastically changes considering light dark matter due to the atomic
coherence factor. For \( m_X \lesssim 1 \text{ MeV}/c^2 \),

\[ R_{\text{light DM}} \approx 4 \cdot 10^6 \left( \frac{3.3 \text{ keV}/c^2}{m_X} \right) \left( \frac{\sigma_{X-N}}{10^{-42} \text{ cm}^2} \right) \left( \frac{\rho_{\text{dark(local)}}}{10^{-24} \text{g/cm}^3} \right) \left( \frac{\beta_X}{10^{-3}} \right) \text{ g}^{-1} \text{s}^{-1}, \]  

(4.24)

which is now normalized to our expected sensitivity for the cross-section in this mass region.
Here we find large interaction rates even for the low cross-sections considered, which is again
mainly due to the atomic coherence factor.

5 Summary and conclusions

Two of the most outstanding achievements in cosmology in recent years were the precise
measurement of the Cosmic Microwave Background and the detection of gravitational waves.
These remarkable discoveries raise the appetite for more. In particular, in this paper we
address the question if the impressive laser interferometer technology used in gravitational
wave detectors can be used to hunt for an echo of the Big Bang generated much earlier than
the CMB: the Cosmic Neutrino Background.

Unfortunately, this does not seem to be feasible with the current technology. We have
briefly sketched a setup based on an ordinary pendulum which is deflected by the cosmic
neutrino wind. Using current laser interferometers to determine the position of the pendu-
ulum and assuming a very high stability of the experiment on the time-scale of a day it
might be possible to measure accelerations down to \( 10^{-16} \text{ cm/s}^2 \), which would already be an
improvement compared to current torsion balance experiments. Although this sensitivity is
already extremely remarkable it is still far away from a potential signal. The most optimistic
case for this kind of experiments is when the relic neutrinos are non-relativistic nowadays and cluster in our galaxy. This could lead to accelerations of the order of $10^{-27}$ cm/s$^2$. Eleven orders of magnitude below what we estimated might be ideally achieved with current technology. In addition, the low frequency of the CNB signal poses a further serious challenge. A possibility to address this point is by tuning the setup to the high frequency component of the CNB signal, governed by the neutrino interaction rate with the test mass. However, in summary, these results suggest that a mechanical force might not be the most encouraging way to discover the CNB. More promising for the discovery at the moment seems an experiment where cosmic neutrinos are caught with inverse beta decay giving rise to a characteristic peak in the beta spectrum, see the recent PTOLEMY proposal [3]. Such an experiment nevertheless comes with one big disadvantage: it is not immediately sensitive to the directional dependence of the CNB signal.

In the future, one might still want to consider an experiment along the lines discussed here. In fact, the sensitivity could be tremendously improved by putting the setup in a micro-$g$ environment, which could be achieved either by going to space or by compensating the gravitational force by an electromagnetic force here on earth in a laboratory. Another possibility, motivated by the remarkable results of the recent LISA Pathfinder mission, could be a setup based on free falling test masses in space with different CNB cross sections.

A setup along the lines proposed here could moreover also serve as a dark matter detector for sub-MeV DM particles. In particular in the low mass region of a few keV, remarkable sensitivities to the DM nucleon cross section may be reached even with current technology. For example, for DM particles close to the thermal limit, $m_X = 3.3$ keV/c$^2$, we demonstrate how cross sections down to $\sigma_{X-N} \simeq 10^{-42}$ cm$^2$ could be probed assuming a sufficiently high stability of the experimental setup. Expected developments in interferometer technology and the possibility of micro gravity environments have the potential to significantly improve this number.

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