Snowmass2021 - Letter of Interest

Ultralight dark matter and neutrinos

NF Topical Groups: (check all that apply □/■)

■ (NF1) Neutrino oscillations
■ (NF2) Sterile neutrinos
■ (NF3) Beyond the Standard Model
■ (NF4) Neutrinos from natural sources
■ (NF5) Neutrino properties
■ (TF11) Theory of neutrino physics
■ (NF10) Neutrino detectors
■ (CF2) Dark Matter: Wave-like

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Abstract:
Ultralight bosonic fields with masses much below the eV scale are well-motivated candidates for dark matter. These fields could interact with the SM via the neutrino portal which could result in unique phenomena such as time-variation of neutrino masses and oscillation parameters, which can be probed in various near-future neutrino oscillation experiments. Depending on the mass of the ultralight field and the experimental setup, this could manifest either as a signal time modulation, a distortion in the oscillation probability, or as a fast-varying matter density profile. Such models can also connect black hole physics, early universe cosmology, and neutrino oscillations. A bottom-up, model-independent analysis show that this scenario can be probed in future experiments like DUNE.

The existence of dark matter is unequivocally established by both cosmological and astrophysical observations. However, very little is known about its nature, mass, and interactions. Among the various dark matter candidates, ultralight bosonic fields appear as particularly appealing for two reasons. Firstly, they arise commonly in extensions of the Standard Model as pseudo-Nambu-Goldstone bosons from the spontaneous symmetry breaking of an approximate global symmetry, such as the QCD axion[1–4]. Secondly, they also offer a possible solution to three small-scale cosmological puzzles: cusp-vs-core, missing satellites, and too-big-to-fail problems[5–8].

The DM abundance in this scenario is generated in an interesting, non-thermal mechanism. The idea is that the DM field initially trapped in a false vacuum undergoes a phase transition in the early universe and starts oscillating around its true vacuum. Hubble friction damps these oscillations and the energy density dilutes similarly to the cold dark matter. The surviving oscillations can lead to a curious phenomenon: time variation of what we define as fundamental constants [9–21].

The idea that neutrinos could provide a portal to such ultralight fields is particularly interesting. This is motivated by two facts. Firstly, neutrinos are much lighter than other fermions in the Standard Model, and thus even a small time-dependent VEV could lead to a relatively large impact on neutrino masses and mixing. Secondly since the mechanism of neutrino masses remains unknown, this sector may offer a more natural connection to ultralight physics beyond the Standard Model.

The coupling between an ultralight field and neutrinos would induce a periodic time dependence of neutrinos masses and mixing angles. The time variation on the absolute neutrino mass scale can be parameterized by

$$m_i(t) = [1 + \eta \cos(m_\phi t)]\, m_i^0, \tag{1}$$

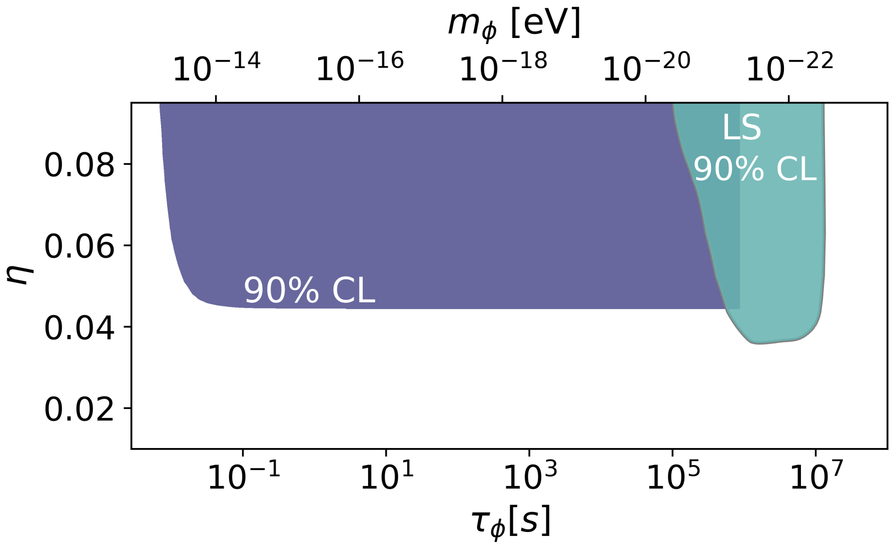

Figure 1: *DUNE sensitivity to the ultralight scalar mass and to the modulation amplitude η. Blue shaded regions correspond to the expected sensitivity using the Lomb Scargle method to search for signal time modulations. The purple shaded region corresponds to the sensitivity to distorted neutrino oscillations. The figure is taken from Ref.*[21].

where m_i^0 is the average value of the mass of neutrino i, m_ϕ is the mass of the scalar field, and η is the modulation amplitude. Consequently, the parameters accessible at neutrino oscillation experiments (mass splittings and mixing angles) could also acquire time dependencies[14;19–30]. Moreover, the frequency of the modulations induced in the mixing angles and mass splittings is set by the mass of the ultralight scalar to which neutrinos are coupled.

Depending on the modulation frequency and its relation with other time scales of the experiment, there are three distinct regimes of phenomenology. Firstly, if the period of modulation is of the same order as the total experiment run time, a time modulation of the oscillation probability will be observed. This is true for both the modulation of mixing angles and mass splittings. Experiments with large statistics and high event rates will be sensitive to time modulation periods much smaller than its lifetime. For instance, searches for modulations in solar neutrino fluxes are sensitive to periods ranging from 10 minutes to 10 years[31–33]. Algorithms like Lomb Scargle periodograms[34–36] are ideally suited to probe this phenomenology.

Secondly, for smaller modulation periods, the rate of change of neutrino oscillation parameters is too fast to be observed as a modulating signal. Nevertheless, the time-averaged oscillation probability could be distorted by such effects and can significantly deviate from the standard neutrino oscillation scenario. The averaging of a modulating mixing angle can be mapped into a different value of the observed mixing. On the other hand, the averaging of mass splittings can lead to distorted neutrino oscillations, or DiNOs for short, thus smearing out the probability similarly to an energy resolution smearing[19]. This regime covers a large range of scalar masses and can be easily searched for in oscillation experiments, as it boils down to a simple novel oscillation effect.

Finally, as the modulating period becomes comparable to the neutrino time of flight, the changes in oscillation parameters need to be treated at the Hamiltonian level and can be modeled by a modified matter effect[20]. This matter potential is time-dependent and it changes as the neutrino propagates towards the detector. When the variations of the matter potential are too fast compared to the neutrino time of flight, they cannot be observed and we recover the standard oscillation phenomenology.

In the case of DUNE, with an estimated lifetime of 7 years and a neutrino time-of-flight of a couple of milliseconds, we can explore almost ten orders of magnitude in m_ϕ [21], ranging from 10^{-14} eV to 10^{-23} eV, as can be seen in Fig. 1.

Many future experiments, armed with state-of-the-art technology and large statistics, are targeting to improve the precision of the measured neutrino oscillation parameters. These experiments can also test a variety of scenarios beyond the SM such as the ultralight field with neutrino portal interactions to the SM. In this letter of interest, we propose to extend their new physics program to include searches for this scenario which would manifest as periodic time modulations in signals or as distorted neutrino oscillations.

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