Multiple angles on the sterile neutrino – a combined view of cosmological and oscillation limits

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Abstract. The possible existence of sterile neutrinos is an important unresolved question for both particle physics and cosmology. Data sensitive to a sterile neutrino is coming from both particle physics experiments and from astrophysical measurements of the Cosmic Microwave Background. In this study, we address the question whether these two contrasting data sets provide complementary information about sterile neutrinos. We focus on the muon disappearance oscillation channel, taking data from the MINOS, ICECUBE and Planck experiments, converting the limits into particle physics and cosmological parameter spaces, to illustrate the different regions of parameter space where the data sets have the best sensitivity. For the first time, we combine the data sets into a single analysis to illustrate how the limits on the parameters of the sterile-neutrino model are strengthened. We investigate how data from a future accelerator neutrino experiment (SBN) will be able to further constrain this picture.

1. Introduction
In recent decades, there have been hints of the existence of a sterile neutrino observed by the neutrino oscillation experiments LSND [1] and MiniBooNE [2]. However, constraints on the sterile neutrino come from multiple sources, including the temperature fluctuations of the cosmic microwave background (CMB) (the cosmological constraints), and from other neutrino oscillation experiments (oscillation constraints). In this work (presented in Ref. [3]), we show how the cosmological constraints and the oscillation constraints appear and complement each other in each other’s parameter space.

2. Datasets
For the cosmological constraints, we use the published results of Planck [4] for the temperature fluctuation in the CMB. The presence of additional radiative degrees of freedom (parametrised by the effective number of additional degrees and their effective mass \(\Delta N_{\text{eff}}, m_{\text{eff}}\)) leads to different universe expansion characteristics, and imprints on the power spectrum of the CMB temperature fluctuations.

For the oscillation constraints, we consider the muon-neutrino disappearance results of MINOS [5], ICECUBE [6], and the sensitivity of the short-baseline program at Fermilab SBN [7] in the muon-disappearance channel. A sterile neutrino would produce additional disappearance of the muon neutrino spectrum in these experiments, with the magnitude and frequency of the additional disappearance governed by the sterile mixing parameters \(\sin^2 2\theta_{24}, \Delta m_{24}^2\) (the subscripts 24 and 41 are dropped in the remainder of this text).
3. Converting between the parameter spaces

The conversion between the oscillation and the cosmological parameter space is made by utilising the LASAGNA toolkit [8] which solves the quantum kinetic equations governing the thermalisation of the sterile neutrino in the early universe [9].

For each point in the oscillation parameter space ($\sin^22\theta, \Delta m^2$), we use LASAGNA to calculate the value of $\Delta N_{\text{eff}}$. The value of $m_{\text{eff}}$ is obtained from the equation

$$m_{\text{eff}} = (\Delta N_{\text{eff}})^{3/4} m_4.$$

This calculation automatically provides the reverse mapping from the cosmological parameter space ($\Delta N_{\text{eff}}, m_{\text{eff}}$) to the oscillation space.

![Image of conversion maps](image)

**Figure 1.** Top: conversion map between the oscillation parameter space to $\Delta N_{\text{eff}}$ (left) and $m_{\text{eff}}$ (right). Overlaid are the 95% CL limits from MINOS and ICECUBE, and the projected sensitivity of SBN. Bottom: conversion map between the cosmological parameter space to $\sin^22\theta$ (left) and $\Delta m^2$ (right). Overlaid is the 95% CL limit from Planck.

The four mappings that we produce between the two parameter spaces are shown in Figure 1.

4. Results

Figure 2 shows the results of converting the experiments’ limits into the complementary parameter space. The left panel shows the cosmological parameter space. The MINOS and ICECUBE measured limits have been translated into this space, along with the projected sensitivity of the SBN program in the muon disappearance channel. MINOS and ICECUBE
Figure 2. Left: the oscillation 95% CL limits translated into the cosmological parameter space. Right: the Planck 95% CL limit translated into the oscillation parameter space. The shaded regions are excluded by the limits.

both have exclusion regions complementary to the Planck limit, with MINOS providing stronger constraints at low values of $m_{\text{eff}}$ and high values of $\Delta N_{\text{eff}}$.

The right panel of Figure 2 shows the oscillation parameter space, with the Planck limit translated into this space. This limit is competitive with the limits measured by MINOS and ICECUBE. MINOS however is more constraining at low values of $\Delta m^2$ due to its long baseline and range of neutrino energies studied.

The SBN muon disappearance sensitivities are not competitive with Planck; however the primary focus of the SBN program is to study electron neutrino appearance, which has not been considered in this study.

We also consider the constraint from Planck if there is an initial large lepton asymmetry (with $L = 10^2$ on the high-end of theoretical model predictions) as an initial condition to the thermalisation evaluation. In this case, due to a suppression of thermalisation, the final value of $\Delta N_{\text{eff}}$ is lower for the same sterile neutrino mass and mixing, and the Planck limit becomes weaker when translated into the oscillation parameter space.

Certain assumptions have been made in this work, such as setting the number of sterile neutrinos to be 1, with mixing only with one active neutrino $\nu_2$, and approximating the active neutrinos as massless for the cosmological evaluation. The effect of relaxing these assumptions will be studied in the future.

References
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