Sterile Neutrino as Dark Matter candidate from CMB alone

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Abstract
Distortions of CMB temperature and polarization maps caused by gravitational lensing, observable with high angular resolution and sensitivity, can be used to constrain the sterile neutrino mass, $m_s$, from CMB data alone. We forecast $m_s > 1.75$ keV from PLANCK and $m_s > 4.97$ keV from Inflation Probe at 95% CL, by using the CMB weak lensing extraction.

1 Introduction
The confluence of the most recent experimental data of the cosmic microwave background (CMB) anisotropies, large-scale structure (LSS) galaxy surveys, supernovae luminosity distance, Lyman-α forest and Hubble parameter, have lead in specifying the ΛCDM model as the cosmological concordance model [1]. According to this model the Universe is spatially nearly flat with energy densities of $\Omega_{\text{CDM}}=0.27\pm0.07$ in cold dark matter (CDM) particles, $\Omega_b=0.044\pm0.004$ in baryons, $\Omega_\Lambda=0.70\pm0.03$ in dark energy and Hubble constant $H_0=72\pm5$ km s$^{-1}$ Mpc$^{-1}$.

The direct confirmation of this theory was the detection of the acoustic Doppler peaks structure of the CMB angular power spectrum. Further successes are related to the correct prediction of the hierarchical structure formation via gravitational instability, the abundance of clusters at small redshifts, the spatial distribution and the number density of galaxies, the LSS matter power spectrum, the Lyman-α forest amplitude and spectrum.

Despite its successes on large scales, the ΛCDM model produces too much power on small scales. In general, the observed structures have softer cores, lower concentrations and are less clumped than those predicted by the ΛCDM model [2].

A possibility to alleviate the accumulating contradiction between ΛCDM predictions on small scales and observations is to add properties to the dark matter sector, relaxing the hypothesis on dark matter as being cold. Free streaming due to thermal motion of dark matter particles is the simplest known mechanism for smearing out small scale structure. For example, the velocity dispersion of warm dark matter (WDM) particles is sufficient to alleviate some of these problems [3].

Sterile neutrinos are considered the most promising WDM candidates. Lower limits on sterile neutrino mass have been placed from various observational probes [4].

1Throughout the paper the sterile neutrino mass is quoted at 95% CL.
The combination of CMB measurements, LSS and Lyman-α forest power spectra lead to $m_s > 1.7$ keV with a further improvement to $m_s > 3$ keV when high-resolution Lyman-α spectra are considered [4].

The upper limit of sterile neutrino mass is constrained by the limits on its radiative decay from Virgo cluster observations [5] and by the observations of the diffuse X-ray background [5]. The combination of all above constraints allows the range $1.7$ keV $< m_s < 8.2$ keV for the mass of sterile neutrino as dark matter candidate.

A significantly more stringent lower limit constraint, $m_s > 14$ keV, was placed by using the Lyman-α forest power spectrum and high-resolution spectroscopy observations in combination with CMB and galaxy clustering data, excluding sterile neutrino as dark matter candidate [7].

2 Sterile neutrino mass from CMB lensing extraction

Like active neutrinos, sterile neutrinos can not cluster via gravitational instability on scales below the free-streaming scale, with important implications for the growth of density perturbations at late times.

The alteration of the gravitational potential changes the gravitational lensing of the CMB photons. Week lensing introduces a deflection field so that the deflection angle power spectrum $C^{\phi \phi}_l$ and the projected gravitational potential power spectrum $C^{\Phi \Phi}_l$ are related through $C^{dd}_l = l(l+1)C^{\phi \phi}_l$.

We modified the CMB anisotropy code CAMB [8] to compute the lensed CMB temperature and polarization anisotropy power spectra and the projected gravitational potential power spectrum in the presence of a sterile neutrino component. We include in the computation the momentum-dependent sterile neutrino phase-space distribution function [5], its unperturbed and perturbed energy density and pressure, energy flux and shear stress.

The CMB weak lensing map can be reconstructed from the statistical analysis of the CMB temperature and polarization anisotropy maps. To evaluate the ability of the future CMB experiments as PLANCK [9] and the hypothetical Inflation Probe to detect the sterile neutrino mass we employ the quadratic estimator method [10] to compute the expected noise power spectrum from lensing extraction.

The experimental parameters for the CMB projects considered in this work are presented in Table 1. For each experiment we construct the covariance matrix:

$$
\mathbf{C} = \begin{pmatrix}
C_{TT}^l + N_{TT}^l & C_l^{TE} & C_l^{EE} + N_l^{EE} \\
C_l^{TE} & C_l^{EE} + N_l^{EE} & 0 \\
C_l^{dd} + N_l^{dd} & 0 & C_l^{dd} + N_l^{dd}
\end{pmatrix}
$$

where $C_{XX}^l$ with $X = \{T, E\}$ are the power spectra of primary anisotropies, and $N_{XX}^l$ are the corresponding noise power spectra, $C_l^{dd}$ is deflection angle power spectrum, $N_l^{dd}$ the noise power spectrum associated to the lensing extraction.
Figure 1: Left: The CMB temperature and polarization power spectra, $C_{l}^{TT}$ and $C_{l}^{EE}$, and the deflection angle power spectrum, $C_{l}^{dd}$, for the fiducial model. Dashed lines (from top to bottom) are the noise power spectra associated to temperature, polarization and lensing extraction for Planck (blue dashed) and Inflation Probe (red dash-dotted). Right: Constraints on sterile neutrino parameter space potentially obtained by the future Planck and Inflation Probe from CMB weak lensing extraction compared with other experimental constraints (see also the text). The red line represents the constraint on sterile neutrino parameter space from an ideal noise-less experiment.

and $C_{l}^{Td}$ is the power spectrum of the cross-correlation between the temperature and deflection angle.

In the left panel of Figure 1 we present the above power spectra obtained for our fiducial model, the ΛCDM concordance model. We assume adiabatic initial conditions, primordial scalar density perturbations with scalar spectral index $n_s=0.95$ and three active neutrino flavors with a total mass $m_\nu=0.7\text{eV}$.

The right panel of Figure 1 presents the constraints on sterile neutrino parameter space that can be potentially obtained by the future experiments Planck and Inflation Probe from the CMB weak lensing extraction.
Table 1: Experimental characteristics of the CMB experiments considered in this work: $\nu$ is the frequency of the channel, $\theta_b$ is the FWHM, $\sigma_T$ and $\sigma_P$ are the sensitivities per pixel for temperature and polarization maps.

| Experiment         | Frequency(GHz) | FWHM (arc-minutes) | $\sigma_T(\mu K)$ | $\sigma_P(\mu K)$ |
|--------------------|----------------|--------------------|--------------------|--------------------|
| PLANCK             | 100            | 9.5                | 6.8                | 10.9               |
|                    | 143            | 7.1                | 6.0                | 11.4               |
|                    | 217            | 5.0                | 13.1               | 26.7               |
| INFLATION PROBE    | 70             | 6.0                | 0.29               | 0.41               |
|                    | 100            | 4.2                | 0.42               | 0.59               |
|                    | 150            | 2.8                | 0.63               | 0.88               |
|                    | 220            | 1.9                | 0.92               | 1.30               |

3 Conclusions

In this paper we have studied the ability of the future CMB projects to constrain the sterile neutrino as dark matter candidate by using the CMB weak lensing extraction. Weak lensing offers several advantages: it probes a larger range of scales, unlike the Lyman-$\alpha$ forest data and does not involve any light-to-mass bias, unlike the galaxy redshift surveys data.

We found $m_s > 1.75$ keV from PLANCK and $m_s > 4.97$ keV from INFLATION PROBE at 95% CL for sterile neutrino mass from CMB data alone.

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