Cosmological constraints on sterile neutrino Dark Matter production mechanisms

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Abstract. Presently, the constraints on the scalar neutrino DM resonant production (RP) and scalar decay production (SDP) mechanisms are based on the power suppression of the gravitational clustering at small scales, dominated by non-linear effects. These constraints are obtained in the linear theory under the assumption that sterile neutrinos are all of the DM.

In this paper, we analysed the validity of those scenarios through their impact on the acoustic scales, the small scale fluctuations and the low-redshift geometric observables, probes that are prevented from non-linear effects, relaxing the assumption of sterile neutrino DM as being all of the DM.

We complement the reconstructed CMB gravitational lensing potential, that is sensitive to the DM distribution in the universe out to high redshifts with the cosmic shear data that constraints the gravitational potential at lower redshifts than CMB. We also use the most recent low-redshift BAO measurements that are insensitive to the non-linear effects, providing robust geometrical tests.

Significantly, in the RP case we find that the best fit values of sterile neutrino DM mass and mixing angle are in the parameter space of interest for sterile neutrino DM decay interpretation of the 3.5 keV X-ray line with a DM mass fraction that excludes the assumption of sterile neutrinos as being all of the DM. In contrast, we find that SDP as a dominant DM mechanism. Sterile neutrino mass predicted by both RP and SDP are consistent within 0.3σ.

We obtain cosmological constrains that clearly show that the present-day cosmological data does not exclude the existence of sterile neutrino DM, starting to discriminate between different sterile neutrino DM production mechanisms.

Keywords: cosmic microwave background, dark matter, dark energy, cosmological observations
1 Introduction

Cosmic Microwave Background (CMB) measurements from the Planck satellite, alone or in combination with other astrophysical datasets, provide no powerful evidence supporting new physics beyond the standard ΛCDM cosmological model [1–3]. With around 5% of the total energy density of the universe representing the baryonic matter, 21% the Dark Matter (DM) and 74% accounting for the Dark Energy (DE), the ΛCDM model is remarkably successful at reproducing the large-scale structure (LSS) of the universe. In addition, the Planck results show that the signature of neutrino sector is consistent with the ΛCDM model assumptions and that DE is compatible with the Λ cosmological constant. Some tension still exists between the Planck determination of several observables and their values obtained from astrophysical independent probes. The most notable tension concern the smaller value of the Hubble constant, $H_0$, discordant at about 2.5σ level with the value obtained from direct astrophysical measurements [4–6]. Also, Planck determination of $\sigma_8$ (the amplitude of linear power spectrum on scale of $8h^{-1}$ Mpc, $h$ being the reduced Hubble constant, $h = H_0/(100$ km s$^{-1}$ Mpc$^{-1}$) and of matter energy density, $\Omega_m$, are discordant at 2σ level with the corresponding values inferred from cluster data that prefer lower values of these observables [7, 8]. These discrepancies may arise because of biases and calibration errors of direct astrophysical measurements [2, 9] but may also be related to the assumption of the underlying ΛCDM cosmological model [10].

Interpretation of DE in the form of $\Lambda$ is facing challenges such as the cosmological constant problem [11] and the coincidence problem [12]. The first problem refers to the small observed value of $\Lambda$, incompatible with the prediction of the field theory. The second problem regards the fact that there is not a natural explanation why DM and DE energy densities are of the same order of magnitude today. Alternative DE models aiming to alleviate these
problems have been proposed. In these models DE is generally described by a dynamical cosmological fluid associated either to a scalar field [13] or to modifications of gravity [14, 15], although a quantum running of $\Lambda$ could provide a satisfactory evolving DE scenario [16–18].

The nature and composition of DM is still unknown. Attempts involving collision-less DM particles fail to solve the ΛCDM problems at reproducing the cosmological structures at small scales (missing satellite problem [19–21], core-cusp problem [22–24], too-big-to-fail problem [25, 26]), suggesting that DM particles may also exhibit gravitational properties and requiring the extension of the Standard Model (SM) of particle physics [27–29].

The Weakly Interacting Massive Particles (WIMPs) with masses above the electroweak scale are good DM candidates [30]. As WIMPs decouple from the thermal plasma when the Hubble expansion rate becomes larger than their interaction rate (thermal freeze-out) they keep a thermal spectrum. Although well theoretically motivated, currently no conclusive WIMPs experimental evidences have been found (see e.g. [31] and references therein).

Another theoretically well motivated DM candidate is sterile neutrino [32–35]. Arising in the minimal extension of SM, the sterile neutrino with mass in keV range can simultaneously explain the active neutrino oscillations, the DM properties and the matter-antimatter asymmetry of the universe [36, 37]. Detection of a weak X-ray emission line at an energy of $\sim$3.5 keV from clusters and Andromeda galaxy independently reported by XMM-Newton and Chandra satellites [38, 39] initiated a large debate on the possibility that this line is the signature of DM decay [40–42]. If confirmed, this signal could be the signature of decaying sterile neutrino DM with a mass of 7.1 keV [43].

As sterile neutrinos are weakly interacting particles they cannot be produced in the early universe by thermal freeze-out. Instead they could be gradually produced from the thermal plasma by the thermal freeze-in [44] with non-thermal spectrum, the dominant production occurring when the temperature drops below the sterile neutrino mass. Several keV sterile neutrino DM production mechanisms have been proposed.

In the Dodelson-Widrow (DW) scenario [45], keV sterile neutrinos DM are produced by non-resonant oscillations with active neutrinos in presence of negligible leptonic asymmetry. This mechanism is now excluded by the observations of structure formation as it produces too hot sterile neutrino velocity spectra [46, 47].

The keV sterile neutrino DM resonant production (RP) via the conversion of active to sterile neutrinos through Shi-Fuller mechanism [48] in presence of leptonic asymmetry has also been investigated [49–51]. In this scenario, sterile neutrino parameters required to reproduce the X-ray line of $\sim$3.5 keV are consistent with main cosmological parameters inferred from present cosmological measurements [52]. Local Group and high-z galaxy count constraints and successfully solve the missing satellite and too-big-to-fail problems [53–55]. Some tension with Ly-α data still exists (at 2.5 $\sigma$ level) [66]. This tension however, which could be related to some uncertainties in theoretical modelling of the intergalactic medium (IGM) and the associated numerical methods [53, 57], is not strong enough to rule out the RP scenario.

The keV sterile neutrino DM production by particle decays has been also extensively discussed [58–62]. A particularly interesting case is the DM sterile neutrino production by scalar decay (SDP). This process involves a generic scalar singlet with the vacuum expectation value (vev) $< S > $ that could be produced via SM Higgs interactions. Depending on the strength of the Higgs coupling $\lambda_H$, the singlet scalar can be produced like WIMPs via freeze-out [63–65] or like “Feeble Interacting Massive Particles” (FIMPs) via freeze-in [66, 67] mechanisms and must couple with the right-handed neutrino fields through Yukawa interaction, leading to sterile neutrino Majorana masses $m_N = y_k < S > $, where $y_k$ is the Yukawa
coupling strength. Ref. [68] presents a complete treatment of the SDP mechanism for the whole parameter space, giving the general solution on the level of space-phase distribution functions.

Other proposed mechanisms are the production via interactions with the inflaton field [69, 70], production from pion decays [71], Dirac fermions [72] or light vector bosons [73, 74]. The coupled DE models (CDE) in which the DM particles, in addition to the gravitational interaction, have an interaction mediated by the DE scalar field have been also studied. A classification of these models can be found in Ref. [15]. The strength of coupling modifies the shape and amplitude of cosmological perturbations [75], affecting the growth rate of cosmological structures [76]. Moreover, the strength of the coupling is degenerate with the amount of DM energy density, having impact on determination of different cosmological parameters, including the Hubble expansion rate [77] and the equation of state of DE [78].

So far, the constraints on various keV sterile neutrino DM production mechanisms are based on the power suppression of the gravitational clustering at small scales where the non-linear effects are important. These constraints are in general obtained in linear theory under the assumption that sterile neutrinos are all of the DM [66, 79, 80].

The aim of this paper is to place cosmological constraints on the RP and SDP mechanisms through their impact on the acoustic scales, the small scale fluctuations and the low-redshift probes that are prevented from degeneracies and non-linear effects, assuming that sterile neutrino DM is a fraction from all the DM.

The paper is organised as follows: Section 2 summarise the RP and SDP Boltzmann formalisms calculations. Section 3 describes the model parameters and the methods involved in the analysis. Section 4 presents the datasets. Section 5 presents our results and examine the consistency and cosmological implications of sterile neutrino DM production mechanisms. The conclusions are summarised in Section 6.

2 Sterile neutrino DM production mechanisms

In this section we present the sterile neutrino DM production calculations. We compute the evolution of phase space distributions in an homogeneous and isotropic Friedman-Robertson-Walker universe employing the Boltzmann equation:

\[ \dot{L}[f] = C[f], \]  

(2.1)

where \( f \) is the phase space distribution, \( C \) is the collision term which encodes the details of a specific sterile neutrino DM production mechanism and \( L \) is the Liouville operator:

\[ \dot{L} = \frac{\partial}{\partial t} - \mathcal{H}p \frac{\partial}{\partial p}, \]  

(2.2)

where \( p \) is the particle momentum and \( \mathcal{H} \) is the Hubble function. In order to bring Eq. (2.2) into a more convenient form, we perform the following transformation of variables [68]:

\[ t \to r = r(t, p), \]  

\[ p \to \xi = \xi(t, p). \]  

(2.3)

Exploiting the correspondence between temperature \( T \) and time \( t \) and by using the conservation of the comoving entropy, the above transformations can be written in the form (for
\[ r = \frac{m_0}{T}, \]
\[ \xi = \left( \frac{g_s(T_0)}{g_s(T)} \right)^{1/3} \frac{p}{T}, \]  \hspace{1cm} (2.4)

where \( g_s(T) \) is the effective number of relativistic entropy degrees of freedom and we choose \( m_0 = T_0 = m_h \) where \( m_h = 125 \text{ GeV} \) is the Higgs boson mass. In terms of the variables given in Eqs. (2.4), the Liouville operator reads as:
\[ \hat{L} = H r \left( \frac{T g_s'(T)}{3 g_s(T)} + 1 \right)^{-1} \frac{\partial}{\partial r}, \]  \hspace{1cm} (2.5)

and the time-temperature relation is given by:
\[ \frac{dT}{dt} = -HT \left( \frac{T g_s'(T)}{3 g_s(T)} + 1 \right)^{-1}, \]  \hspace{1cm} (2.6)

where \( ' \) denotes the derivative with respect to the temperature \( T \). We used the fitting formulas from Ref. [81] to compute the temperature evolution of the effective number of relativistic entropy degrees of freedom \( g_s(T) \) and its derivative \( g_s'(T) \).

2.1 Sterile neutrino resonant production (RP)

The Boltzmann equation describing the sterile neutrino RP in terms of variables given by Eqs. (2.4) can be written as:
\[ H r \left( \frac{T g_s'(T)}{3 g_s(T)} + 1 \right)^{-1} \frac{\partial}{\partial r} f_{\nu_s}(r, \xi) \simeq \Gamma(\nu_\alpha \rightarrow \nu_s) [f_{\nu_\alpha}(r, \xi) - f_{\nu_s}(r, \xi)]. \]  \hspace{1cm} (2.7)

There is similar equation for antineutrinos \( \bar{\nu}_\alpha \). In the above equation \( f_{\nu_\alpha} (\alpha = e, \mu, \tau) \) is the active neutrino phase space density (PSD), \( f_{\nu_s} \) is the sterile neutrino PSD and \( \Gamma(\nu_\alpha \rightarrow \nu_s) \) is the active-sterile neutrino conversion rate:
\[ \Gamma(\nu_\alpha \rightarrow \nu_s) \approx 0.25 \Gamma_{\nu_\alpha}(\xi) \sin^2 2\theta_M, \]  \hspace{1cm} (2.8)

where \( \Gamma_{\nu_\alpha}(\xi) \) is the collision rate of active neutrinos with thermal plasma and \( \theta_M \) is the effective matter mixing angle encoding information on neutrino weak potential that can be split into a thermal part, \( V^T \), due to the background finite temperature and a lepton asymmetric part, \( V^L \), due to the asymmetries in the lepton number [33, 49]. For temperatures characteristic to the post weak decoupling era (\( T < 3 \text{ MeV} \)) the contribution of the thermal potential is very small and can be neglected. In the presence of a primordial lepton asymmetry \( V^L \) is given by:
\[ V^L = 2\sqrt{2}\zeta(3)\pi^{-2}G_F T^3 L_\alpha. \]  \hspace{1cm} (2.9)

where \( G_F \) is the Fermi constant, \( \zeta(3) \) is the Reimann \( \zeta \) function of 3 and \( L_\nu_\alpha \) is the potential lepton number corresponding to an active neutrino flavour \( \alpha \):
\[ \mathcal{L}_{\nu_\alpha} \equiv 2L_{\nu_\alpha} + \sum_{\beta \neq \alpha} L_{\nu_\beta}, \quad L_{\nu_\beta} = \left( \frac{1}{12\zeta(3)} \right) \left( \frac{T_\nu}{T_\gamma} \right)^3 \left[ \pi^2 \xi_{\nu_\alpha} + \xi_{\nu_\beta} \right] \quad \beta = (e, \mu, \tau) \] (2.10)

In the above equation \( \pm \xi_{\nu_\alpha} \) is \( \nu_\alpha/\bar{\nu}_\alpha \) chemical potential, \( L_{\nu_\beta} \) is the lepton number and \( T_\nu \) is the present temperature of the neutrino background \([T_\nu/T_\gamma = (4/11)^{1/3}]\). The MSW condition for the resonant scaled neutrino momentum \( \xi_{\text{res}} \) is given by:

\[ \xi_{\text{res}} = \left( \frac{g_s(T_0)}{g_s(T)} \right)^{1/3} \left( \frac{T}{T_\gamma} \right)_{\text{res}} \approx \left( \frac{\delta m^2 \cos 2\theta}{4\sqrt{2}\zeta(3)\pi^2 G_F \mathcal{L}_{\nu_\alpha}} \right) \frac{1}{T_\gamma} \] (2.11)

where \( \delta m^2 = m_2^2 - m_1^2 \approx m_2^2 \) is the difference of the squares of sterile neutrino and active neutrino mass eigenvalues, \( T \) is the plasma temperature and \( \theta \) is the vacuum mixing angle. The evolution of the potential lepton number when the resonant active neutrino momentum sweeps from 0 to \( \xi_{\text{res}} \) is then given by:

\[ \mathcal{L}_{\nu_\alpha}(\xi_{\text{res}}) = \mathcal{L}_{\nu_\alpha}^{\text{init}} - \frac{1}{2\zeta(3)} \left( \frac{T_\nu}{T_\gamma} \right)^3 \int_0^{\xi_{\text{res}}} (1 - e^{-\pi \gamma/2}) f_{\nu_\alpha} d\xi , \] (2.12)

where \( f_{\nu_\alpha} \) is the initial neutrino Fermi-Dirac PDS and \( \gamma \) is the dimensionless adiabaticity parameter \([82]\). We simultaneously evolve Eqs. (2.6), (2.7), (2.11) and (2.12) to obtain the active and sterile neutrino PSDs in the expanding universe for the entire range of resonant scaled neutrino momentum.

The sterile neutrino number density \( n_{\nu_\alpha}(r) \) and the sterile neutrino physical energy density \( \Omega_{\nu_\alpha} h^2 \) are then given by:

\[ n_{\nu_\alpha}(r) = \frac{N}{2\pi^2} \frac{g_s(T_0)}{g_s(T)} \frac{m_{\nu_\alpha}}{r} \int_0^{\xi_{\text{res}}} \xi d\xi f_{\nu_\alpha}(\xi, r) , \] (2.13)

\[ \Omega_{\nu_\alpha} h^2 = \frac{s_0}{s(r)} \frac{m_{\nu_\alpha} n_{\nu_\alpha}(r)}{\rho_c/h^2} , \] (2.14)

where \( s(r) \) is the co-moving entropy density, \( s_0=2891.2 \text{ cm}^{-3} \) is the entropy density at the present time and \( \rho_c/h^2=1.054 \times 10^{-2} \text{ MeV cm}^{-3} \) is the critical density in terms of reduced Hubble constant \( h \).

The sterile neutrino RP mechanism is parameterised with respect to the sterile neutrino mass \( m_{\nu_\alpha} \), the matter mixing angle \( \sin^2 2\theta \), and the initial lepton asymmetry of each active neutrino flavour, \( \mathcal{L}_{\nu_\alpha} \). We restrict our computation to three active \( \nu_\alpha/\bar{\nu}_\alpha \) flavours and one sterile neutrino \( \nu_\alpha \) and assume the same initial lepton asymmetry of each \( \nu_\alpha/\bar{\nu}_\alpha \) flavour. The details of this computation can be found in Ref. [52].

Fig. 1 presents in the left panel the dependence of the sterile neutrino final PFDs on the co-moving momentum \( q = p/T \) for different values of \( m_\alpha, \sin^2 2\theta \) and \( \mathcal{L}_{\nu_\alpha} \). The effect of increasing \( \mathcal{L}_{\nu_\alpha} \) when \( m_\alpha \) and \( \sin^2 2\theta \) are fixed is the increase of the averaged co-moving momentum, leading to a larger cutoff scales in the gravitational potential and matter power spectra. The same behaviour is present when \( \sin^2 2\theta \) and \( \mathcal{L}_{\nu_\alpha} \) are fixed and \( m_\alpha \) is increased. A larger value of \( \sin^2 2\theta \) leads to larger sterile neutrino production rates. The resonance occurs in this case at a higher temperature and smaller averaged co-moving momentum. The same behaviours are shown by these models in the right panel from Fig. 1 that presents the evolution with time parameter \( r = m_\alpha/T \) of active and sterile neutrino abundances \( \chi(r) = n(r)/T^3 \), where \( n(r) \) are corresponding number densities.
2.2 Sterile neutrino production by the scalar decay (SDP)

In the case of SDP mechanism, the PDFs evolution of scalar $f_S$ and of sterile neutrino $f_{\nu_s}$ are obtained by solving the coupled Boltzmann equations:

\[
\dot{L}[f_S] = C^S, \quad \dot{L}[f_{\nu_s}] = C^{\nu_s},
\]

where $\dot{L}$ is the Liouville operator given in Eq. (2.5) and $C^S$ and $C^{\nu_s}$ are the scalar and sterile neutrino collision terms encoding the effects of different processes that contribute to their production. In this work we take the leading processes contributing to $C^S$ and $C^{\nu_s}$:

\[
C^S = C^S_{hh \leftrightarrow SS} + C_{S \rightarrow \nu_s \nu_s},
\]

\[
C^{\nu_s} = C^{\nu_s}_{S \rightarrow \nu_s \nu_s}
\]

where: $C^S_{hh \leftrightarrow SS}$ describes the depletion of scalars due to the annihilation into pairs of SM Higgs particles and the reverse process, $C_{S \rightarrow \nu_s \nu_s}$ describes the decay of scalars into pairs of sterile neutrinos and $C^{\nu_s}_{S \rightarrow \nu_s \nu_s}$ describes the creation of sterile neutrinos from the decays of scalars. A detailed discussion regarding the contributions of different processes to the collision terms can be found in Refs. [67, 68].

With these assumptions, the SDP scenario is parametrised with respect to the sterile neutrino mass $m_{\nu_s}$, the scalar mass $M_S$, the strength of the Higgs coupling $\lambda_H$ and of the Yukawa coupling $y_k$. We use the explicit forms of the collision terms given in Ref. [68] and simultaneously evolve Eqs. (2.6) and (2.15) to obtain the scalar and sterile neutrino PSDs in the expanding universe. The sterile neutrino number density and the corresponding physical energy density are then obtained by using Eqs. (2.13) and (2.14).
We fix the scalar mass to $M_S=533$ GeV, the best fit value obtained from our analysis (see below) and present in the left panel of Fig. 2 the dependence of the sterile neutrino final PFDs on the co-moving momentum $q = p/T$ for different values of $\lambda_H$ and $y_k$. The right panel shows the evolution with time parameter $r = m_h/T$ of scalar and sterile neutrino abundances $\chi(r) = n(r)/T^3$. The distributions obtained for the best fit parameters are represented by black lines.

3 Parameterisation and methods

The baseline model is an extension of the standard $\Lambda$CDM model, here after $\Lambda$CDM-ext, described by the following cosmological parameters: the present baryon energy density $\Omega_b h^2$, the present CDM energy density $\Omega_c h^2$, the ratio of the sound horizon to the angular diameter distance at decoupling $\theta_{MC}$, the optical depth at reionisation $\tau$, the amplitude and the spectral index of the primordial power spectrum of curvature perturbations at pivot scale $k = 0.05$ Mpc$^{-1}$, $A_s$ and $n_s$, the total mass of three degenerated active neutrino flavours $m_{\nu}$, and the number of relativistic degrees of freedom, $N_{\text{eff}}$, which parametrise the contributions from any non-interacting relativistic particles. In the SM with three neutrino species $N_{\text{eff}} = 3.046$ due to the non-instantaneous decoupling corrections [83].

The RP mechanism model includes, in addition to the baseline model parameters, the total chemical potential of three degenerated active $\nu/\bar{\nu}$ species, $\pm \zeta_\nu$, and the sterile neutrino DM mass fraction defined as $f_s = \Omega_s/\Omega_{DM}$, where $\Omega_s$ is the sterile neutrino DM energy density.
and $\Omega_{DM}$ is the total DM energy density.

The SDP mechanism model extend the baseline model by the inclusion of the scalar mass, $M_S$, the Yukawa strengths coupling, $y_k$, the Higgs strengths coupling, $\lambda_H$, and the sterile neutrino DM mass fraction, $f_s$.

We modify the baseline Boltzmann code camb\textsuperscript{1} \cite{camb} to allow the calculation of sterile neutrino DM production Boltzmann formalisms presented in the previous section to obtain the lensed CMB anisotropies, the lensing potential and the matter power spectra.

Non-linear corrections: The main signature of the DM production models is expected at the sterile neutrino DM free-streaming scales where the non-linear effects due to the growth of structures are important. We use the halofit model \cite{halofit1, halofit2} implemented in the camb code to account for the non-linear effects in the matter and CMB lensing potential power spectra.

Recombination: The process of recombination determines the size of sound horizon at this epoch, affecting the characteristic angular size of the CMB fluctuations and the diffusion damping scale. We use the recombination history model developed in Ref. \cite{recombination} and further improved for full numerical implementation in the recfast\textsuperscript{2} code \cite{recfast}.

Nucleosynthesis: The model of the big bang nucleosynthesis (BBN) gives the relation between helium mass fraction, $Y_P$, photon-to-baryon ratio, $\rho_\gamma/\rho_b$, and the number of relativistic degrees of freedom, $N_{eff}$. In the case of RP mechanism the leptonic asymmetry increases the radiation energy density parametrised by variation of the number of relativistic degrees of freedom $\Delta N_{eff}$:

$$
\Delta N_{eff}(\zeta_\nu) = 3 \left[ \frac{30}{7} \left( \frac{\zeta_\nu}{\pi} \right)^2 + \frac{15}{7} \left( \frac{\zeta_\nu}{\pi} \right)^4 \right].
$$

The leptonic asymmetry also shifts the beta equilibrium between protons and neutrons with effects on $Y_P$ that decreases with the increase of $\zeta_\nu$. The electron neutrino/antineutrino, $\nu_e/\bar{\nu}_e$, phase-space distributions determine the rates of the neutron and proton interaction at BBN. In the RP model the non-thermal $\nu_e/\bar{\nu}_e$ spectra change these rates and hence the $Y_P$ value over the case with thermal Fermi-Dirac spectrum \cite{bbn1, bbn2}.

We use the PArthENoPE BBN code \cite{parthene} to set the value of $Y_P$. For SDP model we compute the dependence of $Y_P$ on $\Omega_b h^2$ and $N_{eff}$. For the RP model we consider in addition the effects on $Y_P$ of $\zeta_\nu$ and of the changes of neutron and proton interaction rates.

4 Cosmological data

We adapted the the Monte-Carlo Markov Chains code COSMO MC\textsuperscript{3} \cite{cosmomc} for our analysis and use the following data-sets:

The CMB measurements: We use the CMB angular power spectra from PLANCK 2015 release \cite{planck} and the PLANCK likelihood codes \cite{plancklikelihood} corresponding to different multipole ranges: Commander for $2 \leq l \leq 29$, CamSpec $50 \leq l \leq 2500$, LowLike for $2 \leq l \leq 32$ for polarization data and Lensing for $40 \leq l \leq 400$ of lensing data.

As the sterile neutrino DM mechanism affects the DM amount and therefore the strength of gravitational lensing we include in the analysis the PLANCK power spectrum of the reconstructed lensing potential \cite{plancklensing}.

Baryonic acoustic oscillations (BAO): BAO measurements are low-redshift probes insensitive

\begin{footnotesize}
\begin{enumerate}
\item http://camb.info
\item http://www.astro.ubc.ca/people/scott/recfast.html
\item https://cosmologist.info/cosmomc/
\end{enumerate}
\end{footnotesize}
to non-linear effects because their characteristic acoustic scale, of around 147 Mpc, is much larger than the scale of the virialized cosmological structures. Moreover, as BAO features in the matter power spectrum can be observed as a function of both angular and redshift separations [97, 98] these measurements are robust geometrical tests. We include in the analysis the BAO characteristic parameter measurements from Baryon Oscillation Spectroscopic Survey (BOSS) LOWZ at $z_{\text{eff}} = 0.32$ and CMASS at $z_{\text{eff}} = 0.57$ [98], BOSS DR12 at $z_{\text{eff}} = 0.38$, 0.51 and 0.61 [99] and 6dF Galaxy Survey (6dFGS) at $z_{\text{eff}} = 0.1$ [100].

Cosmic shear: Weak lensing of galaxies, or cosmic shear, constrains the gravitational potential at redshifts lower than the CMB lensing. Presently, the cosmic shear measurements are available from several surveys [101–103]. We use the CosmoMC implementation of 1-year Dark Energy Survey (DES) [104] cosmic shear measurements described in Ref. [105].

5 Analysis and results

In this section we present constraints on the parameters of sterile neutrino RP and SDP mechanisms. We also analyse to which extend our data-sets can distinguish between these two mechanisms through their cosmological predictions for the acoustic scales, the small-scale fluctuations and the low-redshift geometric probes. The mean values and the associated errors for all parameters are presented in Table 1.

5.1 Constraints on sterile neutrino DM production parameters

RP case: In Fig. 3 we present the likelihood probability distributions and the joint confidence regions for the RP mechanism parameters. The dominant effect on the sterile neutrino DM resonant production is given by the total $\nu/\bar{\nu}$ chemical potential value, $\zeta_{\nu_{\alpha}}$, that sets the initial lepton number $L_{\nu_{\alpha}}$ which in turn sets the matter mixing angle $\sin^2 2\theta$ to get the sterile neutrino mass fraction $f_{\nu_{s}}/\Omega_{DM}$. Significantly, the best fit values of these parameters lead to $f_{\nu_{s}} = 0.28 \pm 0.3$ (68\% C.L.), indicating that RP is a subdominant mechanism. We find that $m_{s}$ and $\sin^2 2\theta$ values are in the parameter space of interest for sterile neutrino DM decay interpretation of the 3.5 keV X-ray line [43].

SDP case: In Fig. 4 we present the likelihood probability distributions and the joint confidence regions obtained for the SDP mechanism parameters. The dominant effect on SDP mechanism is given by the strength of the Higgs coupling, $\lambda_{H}$, that sets $M_{S}$, and by the strength of Yukawa coupling, $y_{k}$, that sets $m_{s}$, which in their turn set the sterile neutrino DM mass fraction, $f_{s}$. The best fit values of these parameters lead to $f_{s} = 0.86 \pm 0.07$ (68\% C.L.), indicating that SDP is a dominant mechanism. Sterile neutrino mass predicted by RP and SDP mechanisms are consistent within 0.3$\sigma$.

5.2 Cosmological predictions of sterile neutrino DM production mechanisms

5.2.1 Acoustic scales

The characteristic angular size of CMB fluctuations, $\theta_{s} = r_{s}(z)/D_{A}(z)$, is determined by the co-moving sound horizon at recombination, $r_{s}(z)$, and the angular diameter distance at which fluctuations are observed, $D_{A}(z)$. This is a quite robust parameter as its determination is based on observations when CMB fluctuations were entirely in the linear regime and therefore the higher order effects are negligible small.

The transverse BAO angular scale, $\theta_{d} = r_{\text{drag}}(z)/D_{A}(z)$, where $r_{\text{drag}}(z)$ is the comoving sound horizon at the end of the baryonic drag epoch, is the analog of $\theta_{s}$. 

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Figure 3: The marginalised likelihood probability distributions and the joint confidence regions (68% and 95% CL) for RP mechanism parameters colour-coded by the values of the initial lepton number $L_4 = 10^4 L_{\nu_a}$. The dominant effect on the sterile neutrino resonant production is the value of $L_{\nu_a}$ that sets the matter mixing angle, $\sin^2 2\theta$, to get a sterile neutrino mass fraction, $f_\nu$. The best fit values of these parameters lead to $f_\nu = 0.28 \pm 0.3$ (68% C.L.), indicating that RP is a subdominant mechanism. The sterile neutrino DM mass and the mixing angle are in the parameter space of interest for sterile neutrino DM decay interpretation of the 3.5 keV X-ray line [43].

The dependence on the unknown angular diameter distance can be removed by taking the ratio $r_d/r_s = \theta_d/\theta_s$. A tight constraint on the ratio $\theta_d/\theta_s$ implies a tight constraint on the radiation energy density at photon decoupling, usually parametrised by number of relativistic degrees of freedom, $N_{\text{eff}}$. A simple scaling analysis shows that $\Delta(\theta_d/\theta_s) \sim \Delta N_{\text{eff}} [106]$. We find that the values of $N_{\text{eff}}$ obtained in RP and SDP scenarios are consistent with the SM value of $N_{\text{eff}}$ within $1.8\sigma$ and $1.5\sigma$ respectively. Left panel from Fig. 5 shows that RP and SDP mechanisms are consistent within less than $1\sigma$ in the $\theta_d/\theta_s - N_{\text{eff}}$ plane.
Figure 4: The marginalised likelihood probability distributions and the joint confidence regions (68% and 95% CL) for SDP mechanism parameters colour-coded by the scalar mass values $M_S$. The dominant effect on SDP mechanism is given by the strength of the Higgs coupling, $\lambda_H$, that sets $M_S$, and the strength of Yukawa coupling, $y_k$, that sets $m_s$, which in their turn set the sterile neutrino DM mass fraction, $f_s$. The best fit values of these parameters lead to $f_s = 0.86 \pm 0.07$ (68% C.L.), indicating that SDP is a dominant mechanism. Sterile neutrino mass predicted by RP and SDP mechanisms are consistent within 0.3σ.

Motivated by the fact that $\Omega_m h^3$ is a well determined parameter orthogonal to the acoustic scale degeneracy in the flat cosmologies [107, 108], we present in the right panel from Fig. 5 the confidence regions in $\theta_s - \Omega_m h^3$ plane showing that RP and SDP mechanisms are also consistent within less than 1σ.

5.2.2 Small-scale fluctuations
The amplitude of the CMB acoustic Doppler peaks is exponentially suppressed on scales smaller than the Hubble radius at reionization due to the Thomson scattering of the free
Figure 5: The role of the acoustic scale measurements to discriminate the sterile neutrino DM production mechanisms. The contours show the 68% and 95% C.L. **Left:** The confidence regions in $\theta_d/\theta_s - N_{\text{eff}}$ plane showing that RP and SDP mechanisms are consistent within less than 1σ. **Right:** The confidence regions in $\theta_s-\Omega_m h^3$ plane showing that RP and SDP mechanisms are also consistent within less than 1σ.

Electrons produced at this epoch. The amount of this suppression is given by $e^{-2\tau}$, where $\tau$ is the optical depth of the CMB photons. PLANCK high precision measurements of the CMB anisotropy and lensing power spectra at small scales accurately constrain the damped amplitude while the lensing potential reconstruction provides the determination of the amplitude independent on the optical depth [1, 2]. As the CMB lensing power spectrum constraints the matter density fluctuations along the line of sight, the present-day rms matter density power, $\sigma_8$, is also determined. The CMB small-scale power fluctuations directly fixes the combination $\sigma_8 e^{-\tau}$ that is tightly constrained by the data [3]. Also, the weak gravitation lensing of galaxies (cosmic shear) is sensitive to the matter fluctuations at small-scales, providing constraints on the combination $S_8 \equiv \sigma_8(\Omega_m/0.3)^{0.5}$ [104]. A number of studies used the abundance of Sunyaev-Zeldovich selected clusters [109–112] and of X-ray selected clusters [113, 114] to constrain $S_8$. Fig. 6 illustrates the degree of consistency between the sterile neutrino RP and SDP mechanisms and the ACMD-ext model at small-scales. The left panel shows the impact of $\sigma_8 e^{-\tau}$ and $\Omega_m$. The RP and SDP models prefer higher values of $\sigma_8 e^{-\tau}$ that make them distinguishable from ACMD-ext at 1.2σ level. In the right panel of the same figure we show the impact of $S_8 \equiv \sigma_8(\Omega_m/0.3)^{0.5}$ and the Hubble parameter $H_0$. The value of $S_8 = 0.792 \pm 0.024$ (68% C.L.) obtained by DES survey from the combined clustering and lensing measurements [104] is also indicated. We find that $S_8$ values obtained in RP and SDP scenarios are consistent with that determined by DES within 0.6σ and 1.5σ respectively.

5.2.3 Low-redshift geometric probes

We consider the low-redshift geometric probes, BAO and Hubble parameter $H_0$, to constrain different sterile neutrino DM production mechanisms. Detected for the first time in the matter power spectrum by the 2dF Galaxy Redshift Survey [115] and the SDSS redshift survey [116], the BAO observations constrain the comoving size of the sound horizon $r_s(z_{\text{drag}})$ at the end of the drag epoch, $z_{\text{drag}}$, when baryons and photons are completely decoupled.
Figure 6: The degree of consistency between sterile neutrino RP and SDP mechanisms and the ΛCDM-ext model at small-scales. The contours show the 68% and 95% C.L. Left: The impact of $\sigma_8 e^{-\tau}$ and $\Omega_m$. The RP and SDP models prefer higher values of $\sigma_8 e^{-\tau}$ that make them distinguishable from ΛCDM-ext model at more than 1σ. Right: The impact of $S_8 \equiv \sigma_8(\Omega_m/0.3)^{0.5}$ and Hubble parameter $H_0$. The horizontal dashed line and the grey band mark the central value and ±2σ error of $S_8$ value determined by DES survey from the combined clustering and lensing measurements [104].

The BAO surveys measure the acoustic-scale distance ratio:

$$d_z = \frac{r_s(z_{\text{drag}})}{D_V(z_{\text{eff}})}$$ (5.1)

where $z_{\text{eff}}$ is the effective redshift for the population of observed galaxies and $D_V(z_{\text{eff}})$ is a combination of the angular diameter distance $D_A(z)$, Hubble parameter $H(z)$ and the speed of light $c$:

$$D_V(z) = \left[ (1+z)^2 D_A^2(z) \frac{cz}{H(z)} \right]^{1/3}.$$ (5.2)

We evaluate the characteristic BAO parameter (5.2) at $z_{\text{eff}} = 0.57$ reported by the BOSS DR11 survey [97]. Left panel from Fig. 7 presents constraints on our models in $H_0 - r_s/D_V(z_{\text{eff}})$ plane. The horizontal dashed line and the grey bands mark the central value and ±1σ and ±2σ errors of the BOSS measurement while the vertical dashed line and the grey bands do the same for $H_0$ determination from SHOES experiment [117].

On the other hand, the BAO features in the galaxy correlation function can be measured in both line-of-sight and transverse directions, leading to joint constraints on the angular diameter distance and the Hubble parameter at $z_{\text{eff}}$ [97]. Taking the fiducial sound horizon distance at the drag epoch $r_{\text{fid}} = 147.78$ Mpc [99], we compute the constraints on our models in $D_A(z_{\text{eff}})r_{\text{fid}}/r_{\text{drag}} - H_0(z_{\text{eff}})r_{\text{drag}}/r_{\text{fid}}$ plane. The the join confidence regions are presented in the right panel from Fig. 7.

We conclude that present low-redshift geometric probes like BAO and $H_0$ start to discriminate between the sterile neutrino RP and SDP mechanisms. However, the SDP scenario remains consistent with ΛCDM-ext model within less than 1σ.
Figure 7: The role of the low-redshift geometric probes to discriminate between the sterile neutrino DM production mechanisms. The contours show the 68% and 95% C.L.

Left: The impact of Hubble parameter $H_0$ and of the BAO characteristic parameter $r_s/D_V(z_{eff})$. The horizontal dashed line and the grey bands mark the central value and ±1σ and ±2σ errors of the BOSS measurement at $z_{eff} = 0.57$ [97], while the vertical dashed line and the grey bands do the same for $H_0$ determination from SHOES experiment [117].

Right: The role of BAO measurements on line-of-sight and transverse directions, leading to joint constraints of $D_A(z_{eff})/r_{drag}$ and $H_0(z_{eff})r_{drag}$. We take the fiducial sound horizon distance at the drag epoch $r_{fid}=147.78$ Mpc [99].

6 Conclusions

Presently, the constraints on the scalar neutrino DM resonant production (RP) and scalar decay production (SDP) mechanisms are based on the power suppression of the gravitational clustering at small scales, dominated by non-linear effects. These constraints are in general obtained in the linear theory under the assumption that sterile neutrinos are all of the DM.

In this paper, we analysed the validity of those scenarios through their impact on the acoustic scales, the small scale fluctuations and the low-redshift geometric observables, probes that are prevented from non-linear effects, relaxing the assumption of sterile neutrino DM as being all of the DM.

We complement the reconstructed CMB gravitational lensing potential, that is sensitive to the DM distribution in the universe out to high redshifts (preventing from the assumptions on light-to-mass bias and non-linear corrections required only at very small scales) with the cosmic shear data that constraints the gravitational potential at lower redshifts than CMB. We also use the most recent low-redshift BAO measurements that are insensitive to the non-linear effects, providing robust geometrical tests.

Significantly, in the RP case we find that the best fit values of sterile neutrino DM mass and mixing angle are in the parameter space of interest for sterile neutrino DM decay interpretation of the 3.5 keV X-ray line with a DM mass fraction that excludes the assumption of sterile neutrinos as being all of the DM. In contrast, we find that SDP as a dominant DM mechanism. Sterile neutrino mass predicted by both RP and SDP are consistent within 0.3σ. We obtain cosmological constrains that clearly show that the present-day cosmological data does not exclude the existence of sterile neutrino DM, starting to discriminate between different sterile neutrino DM production mechanisms. However, we expect the future BAO and weak lensing surveys, such as EUCLID, to provide much robust constraints.
Table 1: The table shows the mean values and the absolute errors of the main parameters obtained from the fit of ΛCDM-ext, RP and SDP models with the data-sets. The errors are quoted at 68% C.L. The upper limits are quoted at 95%C.L. The first group of parameters are the base cosmological parameters sampled in the Monte-Carlo Markov Chains analysis with uniform priors. The others are derived parameters.

| Parameter | ΛCDM-ext | RP | SDP |
|-----------|----------|----|-----|
| Ω_b h^2  | 0.0275±0.0003 | 0.0221±0.0003 | 0.0220±0.0003 |
| Ω_c h^2  | 0.122±0.004  | 0.118±0.003  | 0.123±0.004  |
| 100θ_{MC} | 1.0412±0.0007 | 1.0404±0.0011 | 1.0410±0.0009 |
| τ        | 0.084±0.015  | 0.069±0.020  | 0.069±0.012  |
| Σ m_ν    | < 0.032     | < 0.021     | < 0.036     |
| N_{eff}  | 3.530±0.271  | 3.216±0.109  | 3.380±0.232  |
| f_s      | 0.281±0.03   | 0.860±0.071  | 0.860±0.071  |
| sin^2 2θ | 2.460±1.750  | 2.460±1.750  | 2.460±1.750  |
| 10^9ζ_{να} | -0.822±2.691 | 533.60±47.21 |
| M_S (GeV) | 533.60±47.21 | 3.780±0.642  | 3.451±1.820  |
| 10^{-9}y_k | 3.780±0.642  | 3.451±1.820  | 3.451±1.820  |
| Ω_m     | 0.294±0.013  | 0.294±0.018  | 0.285±0.011  |
| σ_8      | 0.795±0.021  | 0.818±0.014  | 0.836±0.019  |
| H_0      | 70.512±1.556 | 69.299±1.675 | 71.210±1.433 |
| m_ν (keV) | 6.831±1.630  | 7.882±0.731  | 7.882±0.731  |
| L_4=10^4L_να | -2.081±6.710 | -2.081±6.710 | -2.081±6.710 |
| 100θ_s   | 1.0411±0.0002 | 1.0391±0.0011 | 1.0421±0.0011 |
| 100θ_d   | 0.1622±0.0002 | 0.1619±0.0061 | 0.1632±0.0011 |

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References

[1] Planck Collaboration; P. A. R. Ade et al., Planck 2013 results. XVI.Cosmological Parameters, A & A 571 (2014) 66 [arXiv:1303.5076].
[2] Planck Collaboration; P. A. R. Ade et al., Planck 2015 results. XIII. Cosmological Parameters, A & A 594 (2016) 63 [arXiv:1502.01589].
[3] Planck Collaboration; N. Aghanim et al., Planck 2018 results. VI. Cosmological parameters, (2018) [arXiv:1807.06209].
[4] A. G. Riess et al., A 3% Solution: Determination of the Hubble Constant with the Hubble Space Telescope and Wide Field Camera 3, ApJ 730 (2011) 119 [arXiv:astro-ph/1103.2976].
[5] W. L. Freedman et al., Carnegie Hubble Program: A Mid-Infrared Calibration of the Hubble Constant ApJ 758 24 (2012) [arXiv:astro-ph/1208.3281].

[6] S. H. Suyu, M. W. Auger, S. Hilbert, et al., Two accurate time-delay distances from strong lensing: Implications for cosmology ApJ 766 70 (2013) [arXiv:astro-ph/1208.6010].

[7] A. Vikhlinin, A. V. Kravtsov, R. A. Burenin et al., Chandra Cluster Cosmology Project III: Cosmological Parameter Constraints, ApJ 692 (2009) 1060 [arXiv:astro-ph/0812.2720].

[8] H. Bohringer, G. Chon and C. A. Collins, The extended ROSAT-ESO Flux Limited X-ray Galaxy Cluster Survey (REFLEX II) IV. X-ray Luminosity Function and First Constraints on Cosmological Parameters, A&A 570 (2014) 31 [arXiv:astro-ph/1403.2927].

[9] V. Marra, L. Amendola, I. Sawicki, W. Valkenburg, Cosmic Variance and the Measurement of the Local Hubble Parameter, PRL 110 (2013) 241305 [arXiv:astro-ph/1303.3121].

[10] Z. Berezhiani, A. D. Dolgov, I. I. Tkachev, Reconciling Planck results with low redshift astronomical measurements, Phys. Rev. D92 061303 [arXiv:1505.03644].

[11] S. Weinberg, The cosmological constant problem, Rev. Mod. Phys. 61 1 (1989).

[12] L. P. Chimento, A. S. Jakubi, D. Pavon, and W. Zimdahl, Dark energy, dissipation, and the coincidence problem, Phys. Rev. D67 (2003) 083513 [arXiv:astro-ph/0303145].

[13] B. Ratra and P. J. E. Peebles, Cosmological consequences of a rolling homogeneous scalar field, Phys. Rev. D37 (1998) 3406.

[14] S. Matarrese, C. Baccigalupi and F. Perrotta, Approaching $\Lambda$ without fine-tuning, Phys. Rev. D70 061301 (2004) [arXiv:astro-ph/0403480].

[15] L. Amendola and S. Tsujikawa, Dark Energy: Theory and Observations, edt. Cambridge University Press (2010).

[16] P. J. E. Peebles and B. Ratra, Cosmology with a time-variable cosmological 'constant', ApJ. Lett. 325, L17-L20.

[17] I. L. Shapiro and J. Sola, On the possible running of the cosmological ?constant?, Phys. Lett. B682 105 (2009) [arXiv:astro-ph/0910.4925].

[18] J. Sola, Dark energy: a quantum fossil from the inflationary universe?, J. Phys. A41 164066 (2008) [arXiv:astro-ph/0710.4151].

[19] A. Klypin, A. V. Kravtsov, O. Valenzuela, F. Prada, Where Are the Missing Galactic Satellites?, ApJ 522 (1999) 82 [arXiv:astro-ph/9901240].

[20] M. A. Zwaan, M. J. Meyer, L. Staveley-Smith, The velocity function of gas-rich galaxies, MNRAS 403 (2010) 1969 [arXiv:0912.1754].

[21] E. Papastergis, A. M. Martin, R. Giovanelli, M. P. Haynes, The Velocity Width Function of Galaxies from the 40% ALFALFA Survey: Shedding Light on the Cold Dark Matter Overabundance Problem, ApJ 739 (2011) 38 [arXiv:1106.0710].

[22] P. Salucci, A. Burkert, Dark Matter Scaling Relations, Astrophys. J. 737 (2000) 9 [arXiv:astro-ph/0004397].

[23] G. Gentile, P. Salucci, U. Klein, D. Vergani, P. Kalberla, The cored distribution of dark matter in spiral galaxies, MNRAS 351 (2004) 963 [arXiv:astro-ph/0403154].

[24] R. Kuzio de Naray, T. Kaufmann, Recovering cores and cusps in dark matter haloes using mock velocity field observations, MNRAS 414 (2011) 3617 [arXiv:1012.3471].

[25] M. Boylan-Kolchin, J. S. Bullock, M. Kaplinghat, Too big to fail? The puzzling darkness of massive Milky Way subhaloes, MNRAS 415 (2011) L40 [arXiv:1103.0007].

[26] M. Boylan-Kolchin, J. S. Bullock, M. Kaplinghat, The Milky Way’s bright satellites as an
apparent failure of CDM, MNRAS 422 (2012) 1203 [arXiv:1111.2048].

[27] G. Jungman, M. Kamionkowski, K. Griest, Supersymmetric dark matter, Phys. Rep. 267 (1996) 195 [arXiv:hep-ph/9506380].

[28] G. Bertone, D. Hooper, J. Silk, Particle dark matter: evidence, candidates and constraints, Phys. Rep. 405 (2005) 279 [arXiv:hep-ph/0404175].

[29] J. L. Feng, Dark Matter Candidates from Particle Physics and Methods of Detection, Ann. Rev. Astron. Astrophys. 48 (2010) 495 [arXiv:1003.0004].

[30] P. Gondolo and G. Gelmini, Cosmic abundances of stable particles: Improved analysis, Nucl. Phys. B360 (1991) 1-45.

[31] R. Adhikari, M. Agostini, N. A. Ky, T. Araki et al, JCAP 1701 (2017) 025 [arXiv:1602.04816].

[32] K.N. Abazajian, G.M. Fuller and M. Patel, Sterile neutrino hot, warm and cold dark matter, Phys. Rev. D 64 (2001) 023501 [astro-ph/0101524].

[33] K.N. Abazajian and G.M. Fuller, Bulk QCD thermodynamics and sterile neutrino dark matter, Phys. Rev. D 66 (2002) 023526 [astro-ph/0204293].

[34] A. Boyarsky, O. Ruchayskiy and M. Shaposhnikov, The Role of sterile neutrinos in cosmology and astrophysics, Ann. Rev. Nucl. Part. Sci. 59 (2009) 191 [arXiv:0901.0011].

[35] A. Kusenko, Sterile neutrinos: The Dark side of the light fermions, Phys. Rep. 481 (2009) 1 [arXiv:0906.2968].

[36] T. Asaka, S. Blanchet and M. Shaposhnikov, The MSW dark matter and neutrino masses, Phys. Lett. B 631 (2005) 151 [hep-ph/0503065].

[37] T. Asaka and M. Shaposhnikov, The MSM, dark matter and baryon asymmetry of the universe, Phys. Lett. B 620 (2005) 17 [hep-ph/0505013].

[38] E. Bulbul, M. Markevitch, A.R. Foster, R.K. Smith, M. Loewenstein and S.W. Randall, Detection of An Unidentified Emission Line in the Stacked X-ray spectrum of Galaxy Clusters, ApJ 789 (2014) 13 [arXiv:1402.2301].

[39] A. Boyarsky, O. Ruchayskiy, D. Iakubovskyi and J. Franse, Unidentified Line in X Ray Spectra of the Andromeda Galaxy and Perseus Galaxy Cluster, Phys. Rev. Lett. 113 (2014) 251301 [arXiv:1402.4119].

[40] E. Bulbul, M. Markevitch, A.R. Foster, R.K. Smith, M. Loewenstein and S.W. Randall, Detection of an Unidentified Emission Line in the Stacked X-Ray Spectrum of Galaxy Clusters, Astrophys. J 789, (2014) [arXiv: 1402.2301].

[41] A. Boyarsky, J. Franse, D. Iakubovskyi and O. Ruchayskiy, Comment on the paper “Dark matter searches going bananas: the contribution of Potassium (and Chlorine) to the 3:5 keV line” by T. Jeltema and S. Profumo” [arXiv:1408.4388].

[42] E. Carlson, T. Jeltema and S. Profumo, Where do the 3:5 keV photons come from? A morphological study of the Galactic Center and of Perseus, JCAP 02 (2015) 009 [arXiv:1411.1758].

[43] K.N. Abazajian, G.M. Fuller and M. Patel, Sterile neutrino hot, warm and cold dark matter, Phys. Rev. D 64 (2001) 023501 [astro-ph/0101524].

[44] L. J. Hall, K. Jedamzik, J. March-Russell, S. M. West, Freeze-in production of FIMP dark matter, JHEP 1003 (2010) 080 [arXiv:0911.1120].

[45] S. Dodelson and L.M. Widrow, Sterile-neutrinos as dark matter, Phys. Rev. Lett. 72 (1994) 17 [hep-ph/9303287]

[46] L. Canetti, M. Drewes, T. Frossard, M. Shaposhnikov, Dark matter, baryogenesis and neutrino oscillations from right-handed neutrinos, Phys. Rev. D 87 (2013) 093006 [arXiv:1208.4607].
[47] A. Merle and V. Niro, *Influence of a keV sterile neutrino on neutrinoless double beta decay: How things changed in recent years* Phys. Rev. D 88 (2013) 113004 [arXiv: 1302.2032].

[48] X.-D. Shi and G.M. Fuller, *A New dark matter candidate: Nonthermal sterile neutrinos*, Phys. Rev. Lett. 82 (1999) 2832 [astro-ph/9810076].

[49] K.N. Abazajian, G.M. Fuller and M. Patel, *Sterile neutrino hot, warm and cold dark matter*, Phys. Rev. D 64 (2001) 023501 [astro-ph/0101524].

[50] K.N. Abazajian and G.M. Fuller, *Bulk QCD thermodynamics and sterile neutrino dark matter*, Phys. Rev. D 66 (2002) 023526 [astro-ph/0204293].

[51] M. Laine and M. Shaposhnikov, *Sterile neutrino dark matter as a consequence of MSM-induced lepton asymmetry*, JCAP 06 (2008) 031 [arXiv:0804.4543].

[52] L. A. Popa, D. Tonoiu, *Subdominant Dark Matter sterile neutrino resonant production in the light of Planck*, JCAP 09 (2015) 066 [arXiv:1501.06355].

[53] K.N. Abazajian, *Resonantly Produced 7 keV Sterile Neutrino Dark Matter Models and the Properties of Milky Way Satellites*, Phys. Rev. Lett. 112 (2014) 161303 [arXiv:1403.0954].

[54] S. Horiuchi, B. Bozek, K. N. Abazajian, et al., *Properties of Resonantly Produced Sterile Neutrino Dark Matter Subhalos*, MNRAS 456 (2016) 4346 [arXiv:1512.04548].

[55] M. R. Lovell, S. Bose, A. Boyarsky, et al., *Satellite galaxies in semi-analytic models of galaxy formation with sterile neutrino dark matter*, MNRAS 461 (2016) 60 [arXiv:1511.04078].

[56] A. Merle and A. Schneider, *Production of Sterile Neutrino dark matter and the 3.5 keV line*, Phys. Lett. B 749 (2015) [arXiv:1409.6311].

[57] M. Viel, G. D. Becker, J. S. Bolton, and M. G. Haehnelt, *Warm dark matter as a solution to the small scale crisis: New constraints from high redshift Lyman-a forest data*, Phys. Rev. D 88 (2013) 043502 [arXiv:1306.2314].

[58] W. B. Lin, D. H. Huang, X. Zhang, and R. H. Brandenberger, *Nonthermal Production of Weakly Interacting Massive Particles and the Subgalactic Structure of the Universe*, Phys. Rev. Lett. 86 (2001) 954 [astro-ph/0009003].

[59] J. Hisano, K. Kohri, and M. M. Nojiri, *Neutralino warm dark matter*, Phys. Lett. B 505, (2001) 169 [hep-ph/0011216].

[60] M. Kaplinghat, *Dark matter from early decays*, Phys. Rev. D 72 (2005) 063510 [astro-ph/0507300].

[61] P. Di Bari, S. F. King and A. Merle, *Dark Radiation or Warm Dark Matter from long lived particle decays in the light of Planck*, Phys. Rev. Lett. B 724 (2013) 77 [arXiv:1303.6267].

[62] R. Adhikari, N. A. Ky, T. Akari et al., *A White Paper on keV sterile neutrino Dark Matter JCAP 01* (2017) 025 [arXiv:1602.04816].

[63] K. Petraki and A. Kusenko, *Dark-matter sterile neutrinos in models with a gauge singlet in the Higgs sector*, Phys. Rev. D 77 (2008) 065014 [arXiv:0711.4646].

[64] A. Kusenko, *Sterile neutrinos, dark matter, and the pulsar velocities in models with a Higgs singlet*, Phys. Rev. Lett. 97 (2006) 241301 [hep-ph/0609081].

[65] A. Kusenko, *Sterile neutrinos: The Dark side of the light fermions*, Phys. Rept. 481 (2009) 1 [arXiv:0906.2968].

[66] A. Merle, V. Niro and D. Schmidt, *New Production Mechanism for keV Sterile Neutrino Dark Matter by Decays of Frozen-in Scalars*, JCAP 1403 (2014) 028 [arXiv:1306.3996].

[67] A. Merle and M. Totzauer, *keV Sterile Neutrino Dark Matter from Singlet Scalar Decays: Basic Concepts and Subtle Features*, JCAP 1506 (2015) 011 [1502.01011].
[68] J. König, A. Merle, M. Totzauer, $keV$ sterile neutrino dark matter from singlet scalar decays: the most general case, JCAP 11 (2016) 038 [arXiv:1609.01289].

[69] M. Shaposhnikov and I. Tkachev, The $v_{	ext{MSM}}$ inflation and dark matter, Phys. Lett. B 639 (2006) 414 [hep-ph/0604236].

[70] F.L. Bezrukov and D.S. Gorbunov, Relic Gravity Waves and 7 $keV$ Dark Matter from a GeV scale inflation, Phys. Lett. B 736 (2014) 494 [arXiv:1403.4638].

[71] L. Lello and D. Boyanovsky, Phys. Rev. D91(6), 063502 (2015), 1411.2690.

[72] A. Abada, G. Arcadi, and M. Lucente, JCAP 10 (2014) 001.

[73] D. Boyanovsky, Phys. Rev D78 (2008) 103505 [arXiv:0807.0646].

[74] B. Shuve and I. Yavin, Phys. Rev. D 89 (2014) 113004 [arXiv:1403.2727].

[75] L. Amendola, V. Pettorino, C. Quercellini, and A. Vollmer, Phys. Rev. D 85, 103008 (2012) [arXiv:1111.1404].

[76] G. Caldera-Cabral, R. Maartens, and B. M. Schaefer, The Growth of Structure in Interacting Dark Energy Models, JCAP 0907 (2009) 027 [arXiv:0905.0492].

[77] L. Amendola, G. Camargo Campos, and R. Rosenfeld, Consequences of dark matter-dark energy interaction on cosmological parameters derived from SNIa data, Phys. Rev. D 75 (2007) 083506 [astro-ph/0610806].

[78] G. Izquierdo and D. Pavon, Limits on the parameters of the equation of state for interacting dark energy, Phys. Lett. B 688 (2010) 115 [arXiv:1004.2360].

[79] K.N. Abazajian, Resonantly Produced 7 $keV$ Sterile Neutrino Dark Matter Models and the Properties of Milky Way Satellites, Phys. Rev. Lett. 112 (2014) 161303 [arXiv:1403.0954]

[80] R. Murgia, A. Merle, M. Viel, M. Totzauer, A. Schneider, Non-cold dark matter at small scales: a general approach, JCAP 11 (2017) 046 [arXiv:1704.07838].

[81] O. Wantz and E. P. S. Shellard, Axion Cosmology Revisited, Phys. Rev. D 82 (2010) 123508, [arXiv:0910.1066].

[82] D. Boyanovsky, C. Ho, Sterile neutrino production via active-sterile oscillations: the quantum Zeno effect, JHEP 0707 (2007) 030 [arXiv:hep-ph/0612092].

[83] G. Mangano, G. Miele, S. Pastor, et al., Relic neutrino decoupling including flavour oscillations, Nucl. Phys. B 729 (2005) 221 [arXiv:hep-ph/0506164].

[84] A. Lewis & S. Bridle, Cosmological parameters from CMB and other data: A Monte Carlo approach, 2002, Phys. Rev. D 66 (2002) 103511 [arXiv:astro-ph/0205436]

[85] A. Lewis, A. Challinor and A. Lasenby, Efficient computation of CMB anisotropies in closed FRW models, ApJ 538 (2000) 473 [astro-ph/9911177].

[86] R. E. Smith, J. A. Peacock, A. Jenkins, et al., Stable clustering, the halo model and nonlinear cosmological power spectra MNRAS 341 (2003) 1311, [arXiv:astro-ph/0207664].

[87] R. Takahashi, M. Sato, T. Nishimichi, A. Taruya, M. Oguri, Revising the Halofit Model for the Nonlinear Matter Power Spectrum ApJ 761 152 (2012) [arXiv:1208.2701].

[88] S. Seager, D. D. Sasselov, & D. Scott, A New Calculation of the Recombination Epoch, 1999, ApJ 523 (1999) L1 [arXiv:astro-ph/9909275].

[89] W. Y. Wong, A. Moss, & D. Scott, How well do we understand cosmological recombination? , MNRAS 386 (2008) 1023 [arXiv:0711.1357]

[90] K.N. Abazajian, N.F. Bell, G.M. Fuller and Y.Y.Y. Wong, Cosmological lepton asymmetry, primordial nucleosynthesis and sterile neutrinos, Phys. Rev. D 72 (2005) 063004 [astro-ph/0410175].
C.J. Smith, G.M. Fuller, C.T. Kishimoto and K.N. Abazajian, *Light Element Signatures of Sterile Neutrinos and Cosmological Lepton Numbers*, Phys. Rev. D **74** (2006) 085008 [astro-ph/0605377].

O. Pisanti, A. Cirillo, S. Esposito, et al., *PARthENOPE: Public Algorithm Evaluating the Nucleosynthesis of Primordial Elements*, Comput. Phys. Commun. **178** (2008) 956 [arXiv:0705.0290].

A. Lewis & S. Bridle, *Cosmological parameters from CMB and other data: A Monte Carlo approach*, 2002, *PRD* **66** (2002) 103511 [arXiv:astro-ph/0205436].

Planck Collaboration I; R. Adam et al., *Planck 2015 results. I. Overview of products and results*, A & A, **594** (2016) [arXiv:1502.01582].

Planck Collaboration, P. A. R. Ade et al., *Planck 2013 results. XV. CMB power spectra and likelihood*, A & A **571** (2016) A11 [arXiv:1303.5075].

Planck Collaboration, P. A. R. Ade et al., *Planck 2015 results. XV. Gravitational lensing*, A & A **594** (2016) A15 [arXiv:1502.01591].

L. Anderson et al., *The clustering of galaxies in the SDSS-III Baryon Oscillation Spectroscopic Survey: Baryon Acoustic Oscillations in the Data Release 10 and 11 galaxy samples* MNRAS **441** (2014) 24 [arXiv:1312.4877].

H. Gill-Marin et al., *The clustering of galaxies in the SDSS-III Baryon Oscillation Spectroscopic Survey: BAO measurement from the LOS-dependent power spectrum of DR12 BOSS galaxies* MNRAS **460** (2016) 4210 [arXiv:1509.06373].

S. Alam, et al., *The clustering of galaxies in the completed SDSS-III Baryon Oscillation Spectroscopic Survey: cosmological analysis of the DR12 galaxy sample*, MNRAS **470** (2017) 2617 [arXiv:1607.03155].

F. Beutler et al., *The 6dF Galaxy Survey: Baryon Acoustic Oscillations and the Local Hubble Constant*, MNRAS **416** (2011) 3017 [arXiv:1106.3366].

C. Heymans et al., *CFHTLenS: The Canada-France-Hawaii Telescope Lensing Survey*, MNRAS **427** (2012) 146 [arXiv:1210.0032].

M. J. Lee, J. A. Tyson, S. Hilbert et al., *Cosmic shear results from the Deep Lens Survey - II: Full Cosmological Parameter Constraints from Tomography*, ApJ **824** (2016) 77 [arXiv:1510.03962].

H. Hildebrandt et al., *KiDS-450: Cosmological parameter constraints from tomographic weak gravitational lensing*, MNRAS **465** (2017) 1454 [arXiv:1606.05338].

DES Collaboration, *Dark Energy Survey Year 1 Results: Cosmological Constraints from Galaxy Clustering and Weak Lensing* (2017) [arXiv:1708.01530].

M. A. Troxel, et al., *Dark Energy Survey Year 1 Results: Cosmological Constraints from Cosmic Shear*, Phys. Rev. D **98** (2018) 043528 [arXiv:1708.01538].

E. Grohs, G.M. Fuller, C.T. Kishimoto and M.W. Paris, *Probing neutrino physics with a self-consistent treatment of the weak decoupling, nucleosynthesis and photon decoupling epochs*, JCAP **05** (2015) 017 [arXiv:1502.02718].

W. J. Percival, W. Sutherland, J. A. Peacock et al., *Parameter constraints for flat cosmologies from cosmic microwave background and 2dFGRS power spectra*, MNRAS **337** (2002) 1068 [astro-ph/0206256].

C. Howlett, A. Lewis, A. Hall, A. Challinor, *CMB power spectrum parameter degeneracies in the era of precision cosmology*, JCAP **1204** (2012) 027 [arXiv:1201.3654].

Planck Collaboration XXIV, *Planck 2015 results. XXIV. Cosmology from Sunyaev-Zeldovich cluster counts*, A&A **594** (2016) A24 [arXiv:1502.01597].
[10] C. L. Reichardt et al., *Galaxy Clusters Discovered via the Sunyaev-Zel’dovich Effect in the First 720 Square Degrees of the South Pole Telescope Survey*, *ApJ* 763 (2013) 127 [arXiv:1203.5775].

[11] L. E. Bleem, B. Stalder, T. de Haan et al., *Galaxy Clusters Discovered via the Sunyaev-Zel’dovich Effect in the 2500-Square-Degree SPT-SZ Survey*, *APJs* 216 27 (2015) [arXiv:1409.0850].

[12] K. Andersson et al., *X-Ray Properties of the First Sunyaev-Zel’dovich Effect Selected Galaxy Cluster Sample from the South Pole Telescope*, *ApJ* 738 (2011) 48 [arXiv:1006.3068].

[13] A. B. Mantz, A. von der Linden, S. W. Allen et al., *Weighing the giants - IV. Cosmology and neutrino mass* *MNRAS* 446 (2015) 2205 [arXiv:1407.4516].

[14] G. Schellenberger and T. H. Reiprich, *HICOSMO: cosmology with a complete sample of galaxy clusters ? II. Cosmological results*, *MNRAS* 471 (2017) 1370 [arXiv:1705.05843].

[15] S. Cole, W. J. Percival, A. J. Peacock, et al., *The 2dF Galaxy Redshift Survey: power-spectrum analysis of the final data set and cosmological implications*, *MNRAS* 362 (2005) 505 [arXiv:astro-ph/0501174].

[16] D. J. Eisenstein, I. Zehavi, D. W. Hogg, et al., *Detection of the Baryon Acoustic Peak in the Large-Scale Correlation Function of SDSS Luminous Red Galaxies*, *ApJ* 633 (2005) 560 [arXiv:astro-ph/0501171].

[17] A. G. Riess, L. Macri, S. Casertano, et al., *A 3 % Solution: Determination of the Hubble Constant with the Hubble Space Telescope and Wide Field Camera3*, *ApJ* 730 (2011) 119 [arXiv:1103.2976].