

Pseudoscalar - sterile neutrino interactions: reconciling the cosmos with neutrino oscillations

Maria Archidiacono^a, Stefano Gariazzo^{b,c}, Carlo Giunti^c, Steen Hannestad^d, Rasmus Hansen^e, Marco Laveder^f, Thomas Tram^g

^aInstitute for Theoretical Particle Physics and Cosmology (TTK), RWTH Aachen University, D-52056 Aachen, Germany.

^bDepartment of Physics, University of Torino, Via P. Giuria 1, I-10125 Torino, Italy

^cINFN, Sezione di Torino, Via P. Giuria 1, I-10125 Torino, Italy

^dDepartment of Physics and Astronomy, Aarhus University, 8000 Aarhus C, Denmark

^eMax-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany

^fDipartimento di Fisica e Astronomia “G. Galilei”, Università di Padova, and INFN, Sezione di Padova, Via F. Marzolo 8, I-35131 Padova, Italy

^gInstitute of Gravitation and Cosmology, University of Portsmouth, Dennis Sciama Building, Burnaby Road, Portsmouth, PO1 3FX, United Kingdom

E-mail: archidiacono@physik.rwth-aachen.de, gariazzo@to.infn.it, giunti@to.infn.it, steen@aias.au.dk, rasmus@mpi-hd.mpg.de, laveder@pd.infn.it, thomas.tram@port.ac.uk

Abstract. The Short BaseLine (SBL) neutrino oscillation anomalies hint at the presence of a sterile neutrino with a mass of around 1 eV. However, such a neutrino is incompatible with cosmological data, in particular observations of the Cosmic Microwave Background (CMB) anisotropies. However, this conclusion can change by invoking new physics. One possibility is to introduce a secret interaction in the sterile neutrino sector mediated by a light pseudoscalar. In this pseudoscalar model, CMB data prefer a sterile neutrino mass that is fully compatible with the mass ranges suggested by SBL anomalies. In addition, this model predicts a value of the Hubble parameter which is completely consistent with local measurements.

Contents

1	Introduction	1
2	Short-baseline neutrino oscillations	2
3	Cosmology and light sterile neutrinos	4
3.1	Standard light sterile neutrinos	4
3.2	The pseudoscalar model	6
3.3	Light sterile neutrinos in the pseudoscalar model	8
4	Joint analyses	10
4.1	SBL results as a prior in the cosmological analysis	11
4.2	Cosmology as a prior in the SBL analysis	12
5	Conclusions	13

1 Introduction

One of the long-standing open issues of modern physics is the tension between cosmological constraints on the effective number of relativistic degrees of freedom N_{eff} and on the neutrino mass sum and the hints for sterile neutrinos from oscillation experiment [1–4]. Indeed, precise measurements of the primordial abundances at the time of Big Bang Nucleosynthesis rule out a fourth sterile neutrino with high significance [5, 6]. Moreover, the tension with Planck Cosmic Microwave Background (CMB) data [7] is twofold: on the one hand CMB data are fully consistent with the standard cosmological value of N_{eff} ($N_{\text{eff}} = 3.04 \pm 0.18$, Planck TT, TE, EE + lowP + BAO), on the other constraints on the neutrino mass sum are tight ($\Sigma m_\nu < 0.17$ eV at 95% c.l., Planck TT, TE, EE + lowP + BAO). Invoking the tension between CMB and either local measurements of the Hubble constant H_0 [8] or the lensing measurements of the clumpiness of the local Universe (i.e. $\sigma_8 (\Omega_m/\Omega_{m0})^\gamma$) does not represent an escape route. Concerning the latter discrepancy, the situation is still unclear. The latest results from the Dark Energy Survey [9] alleviated the tension found by CFHTLenS [10], while the recently published intermediate results of KiDS [11] find a 2.3σ tension with Planck, in the Λ CDM model. Indeed the joint analysis performed by Planck in the context of an extended cosmological model simultaneously constraining N_{eff} and m_s ¹, namely Λ CDM + N_{eff} + m_s model, shows that the global $\Delta\chi^2$ does not improve significantly, and the N_{eff} and m_s constraints remain far away from the oscillation preferred regions, considering that $\Delta m^2 \sim 1$ eV and that the large mixing angle would lead to $N_{\text{eff}} \sim 4$ [12]. The only way to reconcile eV sterile neutrinos in cosmology is by delaying their production and, thus, suppressing their thermalisation in the early Universe [12, 13]. Thus, this highly debated tension between cosmology and neutrino oscillations may point to physics beyond the standard model.

In this paper we show how eV sterile neutrinos, highly disfavoured in the standard thermalised case, can be naturally accommodated within the pseudoscalar interaction model.

¹More precisely the constraint is on the so-called effective sterile neutrino mass, which for additional thermally distributed degrees of freedom N_s is related to the physical mass through $m_s^{\text{eff}} = (N_s)^{3/4} m_s$.

The paper is organised as follows: in section 2 we report the latest global-fit of laboratory experiments; in section 3 we derive cosmological constraints on light sterile neutrinos in both the standard and the pseudoscalar model; in section 4 we present the results of the combined analyses of cosmological and oscillation data, within the context of the pseudoscalar model; finally section 5 summarises our findings.

2 Short-baseline neutrino oscillations

There are three anomalies found in short-baseline neutrino oscillation experiments which cannot be explained in the standard framework of three-neutrino mixing (see the recent reviews in refs. [3, 4]):

1. The measurement of $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ transitions in the LSND short-baseline neutrino oscillation experiment [14, 15].
2. The short-baseline disappearance of ν_e [16–19] measured in the Gallium radioactive source experiments GALLEX [20] and SAGE [21].
3. The deficit of the rate of $\bar{\nu}_e$ events [22] observed in several short-baseline reactor neutrino experiments in comparison with that expected from the calculation of the reactor neutrino fluxes [1, 23, 24].

These anomalies can be explained by neutrino oscillations if, besides the standard three massive neutrinos ν_1, ν_2, ν_3 which are mainly mixed with the three standard active neutrinos ν_e, ν_μ, ν_τ , there is at least one new massive neutrino ν_4 which is mostly sterile and has a mass at the eV scale. In this so-called 3+1 neutrino mixing scheme, the new massive neutrino generates a new short-baseline squared-mass difference

$$\Delta m_{\text{SBL}}^2 = \Delta m_{41}^2 \simeq \Delta m_{42}^2 \simeq \Delta m_{43}^2 \gtrsim 1 \text{ eV}^2, \quad (2.1)$$

with $\Delta m_{kj}^2 \equiv m_k^2 - m_j^2$, which is much larger than the standard solar squared-mass difference $\Delta m_{\text{SOL}}^2 = \Delta m_{21}^2 \simeq 7.5 \times 10^{-5} \text{ eV}^2$ and the standard atmospheric squared-mass difference $\Delta m_{\text{ATM}}^2 = |\Delta m_{31}^2| \simeq |\Delta m_{32}^2| \simeq 2.3 \times 10^{-3} \text{ eV}^2$ (see refs. [25–27]).

The short-baseline anomalies are also compatible with a 1+3 neutrino mixing scheme in which the squared-mass differences in Eq. (2.1) have opposite sign, but cosmological data exclude the existence of three standard massive neutrinos at the eV scale [7]. Taking into account that the current cosmological limit on the sum of the masses of the three standard neutrinos is well below the eV scale and the experimental bounds on neutrinoless double- β decay², which imply that the scale of the masses of the three standard neutrinos is much smaller than 1 eV [30], we consider the 3+1 scheme with $m_1, m_2, m_3 \ll m_4$. In this case the approximation $m_4^2 \simeq \Delta m_{41}^2 = \Delta m_{\text{SBL}}^2$ allows us to compare and combine the results of the analysis of cosmological data, which is sensitive to m_4 , and the results of the analysis of the data of short-baseline neutrino oscillation experiments. Following a common convention, in the rest of the paper we will often denote m_4 as m_s , since ν_4 is mostly sterile.

We have performed a Bayesian global fit to the short-baseline neutrino oscillation data considered in ref. [3]. In the framework of 3+1 neutrino mixing, the effective probability of

² Assuming that massive neutrinos are Majorana particles (see refs. [28, 29]).

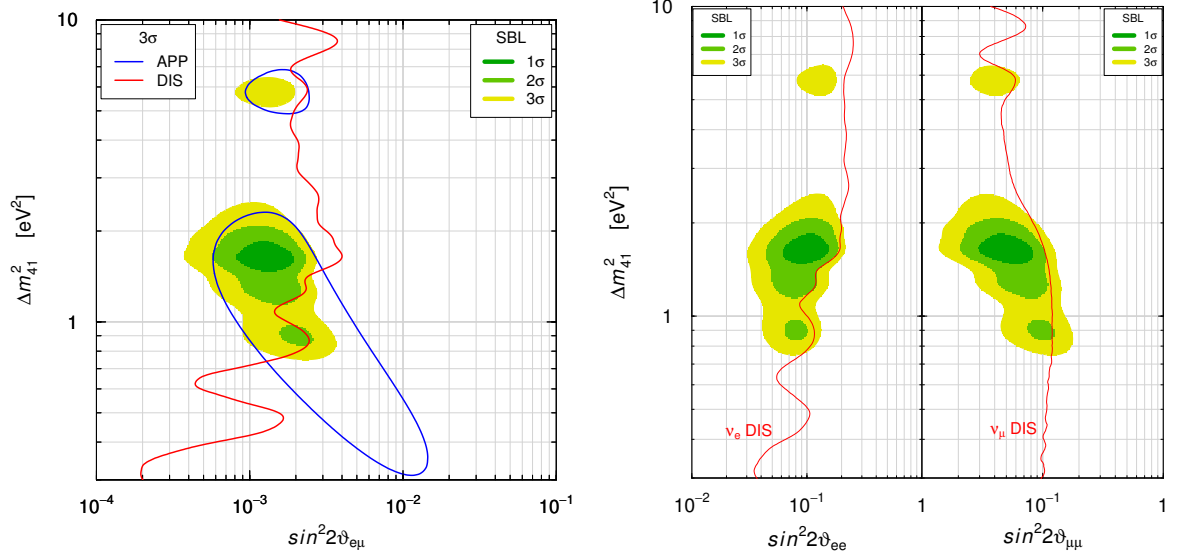


Figure 1: Regions in the planes of the effective amplitudes $\sin^2 2\vartheta_{e\mu}$, $\sin^2 2\vartheta_{ee}$ and $\sin^2 2\vartheta_{\mu\mu}$ versus Δm_{41}^2 which are allowed by the Bayesian global fit of short-baseline (SBL) neutrino oscillation data. Also shown are the 3σ bounds obtained from the separate fits of appearance (APP; the regions inside the two blue contours are allowed) and disappearance (DIS; the regions on the left of the red lines are allowed) data. 1σ , 2σ and 3σ correspond, respectively, to 68.27%, 95.45% and 99.73% posterior probability.

$\nu_\alpha \rightarrow \nu_\beta$ and $\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta$ transitions in short-baseline experiments is given by [31]

$$P_{\nu_\alpha \rightarrow \nu_\beta} = P_{\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta} = \delta_{\alpha\beta} - 4|U_{\alpha 4}|^2 (\delta_{\alpha\beta} - |U_{\beta 4}|^2) \sin^2 \left(\frac{\Delta m_{41}^2 L}{4E_\nu} \right), \quad (2.2)$$

where U is the 4×4 mixing matrix in the mixing relation of the left-handed neutrino fields:

$$\nu_{\alpha L} = \sum_{k=1}^4 U_{\alpha k} \nu_{kL} \quad (\alpha = e, \mu, \tau, s). \quad (2.3)$$

We considered the following short-baseline data sets:

- $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ transitions, with amplitude $\sin^2 2\vartheta_{e\mu} = 4|U_{e4}|^2 |U_{\mu 4}|^2$,
- ν_e and $\bar{\nu}_e$ disappearance, with amplitude $\sin^2 2\vartheta_{ee} = 4|U_{e4}|^2 (1 - |U_{e4}|^2)$,
- ν_μ and $\bar{\nu}_\mu$ disappearance³, with amplitude $\sin^2 2\vartheta_{\mu\mu} = 4|U_{\mu 4}|^2 (1 - |U_{\mu 4}|^2)$.

Although there are three effective angles which determine the oscillations, ϑ_{ee} , $\vartheta_{\mu\mu}$ and $\vartheta_{e\mu}$, their values depend only on the absolute values of two elements of the mixing matrix, U_{e4} and $U_{\mu 4}$.

The results of the Bayesian global fit of short-baseline neutrino oscillation data is shown in figure 1, where we have plotted the allowed regions in the planes of the effective amplitudes

³ We did not consider the recent results of the IceCube [32] and MINOS [33] experiments, which constrain $\sin^2 2\vartheta_{\mu\mu}$ for $\Delta m_{41}^2 \lesssim 1 \text{ eV}^2$, because we do not have sufficient information for the data analysis.

$\sin^2 2\vartheta_{e\mu}$, $\sin^2 2\vartheta_{ee}$ and $\sin^2 2\vartheta_{\mu\mu}$ versus Δm_{41}^2 . These allowed regions can be compared with those in figure 4 of ref. [3], which have been obtained with a χ^2 analysis. One can see that the Bayesian allowed regions are slightly larger than the χ^2 -allowed regions and there is a Bayesian region allowed at 3σ at $\Delta m_{41}^2 \approx 6 \text{ eV}^2$ which does not appear in the χ^2 analysis. Figure 1 shows also the 3σ bounds obtained from the separate fits of appearance and disappearance data. From the left panel one can see that there is an appearance-disappearance tension (see ref. [3]) and the large- $\sin^2 2\vartheta_{e\mu}$ part of the region allowed by the appearance data is excluded by the disappearance data.

3 Cosmology and light sterile neutrinos

3.1 Standard light sterile neutrinos

Cosmology can constrain the properties of the additional neutrino [34], through its contribution to the effective number of relativistic species N_{eff} and its mass $m_s \simeq m_4$ (see section 2). Several analyses in this direction were performed in the past, see e.g. refs. [3, 7, 35–42]. Here we update the cosmological constraints on neutrino related parameters using the most recent cosmological data. The cosmological model is described by the following set of parameters:

$$\{\omega_b, \omega_{\text{cdm}}, \theta, \tau, n_s, A_s, N_{\text{eff}}, m_s\} \quad (3.1)$$

where $\omega_{\text{cdm}} \equiv \Omega_{\text{cdm}} h^2$ and $\omega_b \equiv \Omega_b h^2$ are the present-day physical CDM and baryon densities respectively, θ is the size of the sound horizon at recombination, τ is the optical depth to reionisation, and A_s and n_s denote respectively the amplitude and spectral index of the initial power spectrum of the scalar fluctuations. The N_{eff} parameter encodes the contribution of the active and sterile neutrinos to the radiation energy density in the early Universe: $N_{\text{eff}} = 3.046 + \Delta N_{\text{eff}}$, where ΔN_{eff} accounts for the sterile neutrino degrees of freedom and 3.046 is the standard contribution of the active neutrinos [43].

We consider two distinct models for the standard sterile neutrino. In the first one we consider an extension of the Λ CDM model where we introduce a sterile neutrino with mass m_s contributing with ΔN_{eff} to the value of N_{eff} . Both ΔN_{eff} and m_s are allowed to vary and we will refer to this model as “ Λ CDM + N_{eff} + m_s ”. In the second one we will allow the mass to vary, but we will assume that the sterile neutrino is fully thermalised, i.e. $\Delta N_{\text{eff}} = 1$. This model is motivated by the SBL constraints on the mixing angles which would lead to $\Delta N_{\text{eff}} \simeq 1$ [12] for a wide range of m_s . We will denote this model by “ Λ CDM+ $1\nu_s$ ”.

We sample the parameter space (3.1) using the Markov Chain Monte Carlo sampler CosmoMC [44] and data from both the CMB and local measurements. We use the Planck 2015 data release [45] for the CMB data and include low multipole polarisation and high multipole temperature auto-correlation data as our base-line dataset (denoted by “TT” for the sake of brevity) and, in addition, in combination with high ℓ E-mode polarisation auto-correlation and temperature cross correlation (TTTEEE). Local Universe probes include the prior on the Hubble constant from direct measurements, $H_0 = 73.00 \pm 1.75 \text{ Km s}^{-1} \text{ Mpc}^{-1}$ [8] (HST) and Baryonic Acoustic Oscillations (BAO) from a list of different experiments, that probe different redshifts: 6dFGS [46], SDSS-MGS [47], and from the LOWZ [48] and CMASS [49] DR11 results from the SDSS BOSS experiment.

The cosmological constraints on the neutrino properties in the Λ CDM + N_{eff} + m_s model are summarised in figure 2, where we plot the 2D marginalised constraints in the m_s – ΔN_{eff} plane as obtained from some selected combinations of cosmological data. The points

Parameter	TT	TT+HST	TT+BAO	TT+HST+BAO	TTTEEE
H_0 [km/s/Mpc]	$68.0^{+1.0}_{-1.5}$	$70.7^{+1.7}_{-2.0}$	$68.3^{+0.6}_{-1.0}$	$69.8^{+1.2}_{-1.5}$	$67.0^{+0.7}_{-0.8}$
N_{eff}	< 3.53	< 3.88	< 3.49	< 3.84	< 3.36

Table 1: Constraints on H_0 and N_{eff} in the $\Lambda\text{CDM} + N_{\text{eff}} + m_s$ model. Marginalised constraints are given at 1σ , while upper bounds are given at 2σ .

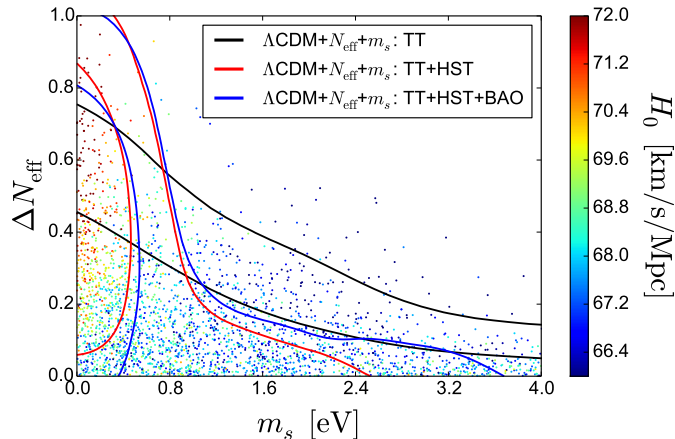


Figure 2: Marginalised constraints in the $m_s - \Delta N_{\text{eff}}$ plane, obtained from the analyses of the cosmological data in the context of the $\Lambda\text{CDM} + N_{\text{eff}} + m_s$ model, at 1σ and 2σ confidence level. The excluded regions are on the right of each line. The points obtained with the TT dataset are colour-coded by their H_0 value.

are colour-coded by their H_0 value. The results are in full agreement with those presented by the Planck collaboration [7, 38], even if the parameterization they adopt involves the effective mass m_s^{eff} instead of the sterile neutrino physical mass m_s . We can easily see that a sterile neutrino with $m_s \simeq 1$ eV and contributing with $\Delta N_{\text{eff}} \simeq 1$ is strongly disfavoured by all the data combinations. As stated in ref. [8], the possibility to increase N_{eff} improves the compatibility between the cosmological estimates and the local measurement of H_0 , but this is true only for a sterile neutrino much lighter than 1 eV. As we can see in table 1, indeed, the marginalised constraints on H_0 obtained from the $\Lambda\text{CDM} + N_{\text{eff}} + m_s$ model are slightly more compatible with the local value determined by HST, but the tension remains strong.

We will now consider the SBL motivated model $\Lambda\text{CDM} + 1\nu_s$ where $\Delta N_{\text{eff}} = 1$. In this case the high value of N_{eff} prevents large values of m_s , and the SBL preferred region is excluded at more than 2σ in the most favorable case. Indeed the 95% C.L. upper bounds obtained are: $m_s < 0.66$ eV for CMB (TT) alone, $m_s < 0.55$ eV including the prior on the Hubble parameter (TT+HST), and $m_s < 0.53$ eV using the most complete data combination that we adopt here (TT+HST+BAO). Given that the $m_s \simeq 1$ eV neutrino is firmly excluded, we do not make a combined fit of the cosmological and SBL data with a fixed $\Delta N_{\text{eff}} = 1$. If the existence of the sterile neutrino is confirmed by future experiments like SOX [50], we will be forced to introduce some new physics. In the next section we will show that the

pseudoscalar model is a natural candidate in this case.

3.2 The pseudoscalar model

Refs. [51, 52] have shown that hidden neutrino interactions, confined in the sterile sector and mediated by a light < 0.1 eV pseudoscalar of a new U(1) broken symmetry can solve the tension and reconcile eV sterile neutrinos with cosmology. The model is described by the Lagrangian

$$\mathcal{L} \sim g_s \phi \bar{\nu}_4 \gamma_5 \nu_4, \quad (3.2)$$

where g_s is the coupling and ϕ is the pseudoscalar. The phenomenological success of the model relies on two things. First, ν_4 must annihilate into ϕ at late time to avoid the mass bound from large scale structure. For this to work ϕ must not only be lighter than the fourth mass eigenstate but also light enough to avoid the mass bound itself. Thus we consider $m_\phi \lesssim 0.1$ eV as an upper bound. Second, the coupling g_s should be large enough to prevent full thermalisation of the sterile neutrino. Numerical studies [51] show that the transition from full to zero thermalisation happens in the interval $10^{-6} \lesssim g_s \lesssim 10^{-5}$, so we will assume g_s to be in that range.

The secret coupling has to be confined in the sterile sector so that its effect on active neutrinos is Yukawa suppressed: the Universe does not end up being a “neutrinoless” Universe [53] and active neutrinos remain free-streaming, as indicated by current data [54, 55].

The coupling of the mediator is not constrained by fifth force experiments, because the pseudoscalar couples only to the spin and the medium is globally unpoarised. The IceCube constraints on secret interactions discussed in refs. [56–59] do not apply either, because the secret interaction concerns only the massive neutrino ν_4 . If the astrophysical PeV neutrinos detected by IceCube [60] were produced as active flavor neutrinos they had only a small component of ν_4 and only this small component can in principle be depleted through the secret interaction by scattering on the pseudoscalar ϕ (the ν_4 background annihilates away as soon as the temperature drops below the ν_4 mass). However, the cross section for this interaction is exceedingly small since $\sigma \sim g_s^4/s$, where $s = 2ET_\phi$ and E is the energy of the astrophysical neutrino.

The only non-cosmological bound on the pseudoscalar coupling to neutrinos is related to the supernova energy loss argument of ref. [61] which implies $g_s \lesssim 10^{-4}$. Finally the new mediator might also couple to dark matter χ and the induced $\chi - \nu_s$ scattering⁴ can provide a solution to the small scale structure problems of Λ CDM (see refs. [63–65]).

Since pair production only brings the mediator ϕ into thermal equilibrium at very late times ($T \ll \text{MeV}$) for the values of g_s considered here there should essentially be no pre-existing population of these particles. Of course ϕ could potentially be produced by direct inflaton decay in the very early universe. However, such a population would have been strongly diluted by subsequent entropy production and thus completely negligible.

When neutrinos start oscillating, the MSW-like potential induced by the new interactions with $g_s \gtrsim 10^{-6}$ suppresses the sterile neutrino production until after the collisional decoupling of active neutrinos ($T \sim 1$ MeV): when sterile neutrinos are later produced through oscillations with the active neutrinos, the latter are not able to thermalise with the plasma. This partial thermalisation can also be achieved by means of a large lepton asymmetry [12, 13] or secret interactions mediated by a massive vector boson [64, 66–70].

⁴The same effect can arise from dark matter scattering off of a different dark radiation component rather than sterile neutrinos, such as dark photons or dark gluons [62].

Here it should be noted that [59] pointed out that scatterings mediated by the pseudoscalar can in principle be important for thermalising sterile neutrinos. The reason is that the scattering rate diverges as $1/p^2$ for small momentum transfer as long as $p > m$, where m is the mass of the mediator⁵. However, even though the momentum transfer becomes small, the interaction still provides a flavour measurement and thus contributes to the thermalisation of the fourth mass state. For a model like the one presented here this at first sight leads to a gigantic increase in the thermalisation rate because the mediator mass is very small. However, the divergence only occurs in vacuum. In a medium which is charge neutral (i.e. not spin polarised in the case of a pseudoscalar interaction), Debye screening regulates the divergence through an effective screening mass, m_D . While a quantitative calculation of the screening mass is very involved, we note that the usual Debye mass from QED is $\sim eT$. In comparison, the screening mass is order T in a nuclear medium with interactions through pion exchange (see e.g. [71]). None of these two examples are exactly equivalent to a gas of sterile neutrinos and pseudoscalars, but they should give a lower and upper estimate for the screening mass. Compared to QED, the screening will be more efficient since the pseudoscalar potential falls off as $1/r^3$ rather than $1/r^2$. On the other hand, the composite nature of the mesons plays an important role for their screening mass, and in the pseudoscalar model we might not expect the screening to be as efficient. With a screening mass around T , the rate of flavour measurement through scattering becomes comparable to the one from annihilation/pair-production which is $\sim n_{\nu_s} g^4 / T^2$ and completely negligible compared to the standard model flavour measurement rate because of the tiny value of g^4 . On the other hand, if the screening mass lies closer to the QED value of gT , the scattering processes dominate and this could lead to additional thermalisation. Since a full calculation of the screening mass is beyond the scope of this paper and we expect the results only to be modified moderately, we adopt the agnostic view that it will just be another process contributing to N_{eff} .

The value of T should represent the temperature of the fourth mass state, i.e. it only becomes important once thermalisation begins in earnest. This means that the divergence of the scattering rate can in principle be important, but only provided that the effective temperature of the fourth mass state is very small. Consequently, the thermalisation through scattering is self-regulating and most likely switches off long before complete thermalisation occurs. The most reasonable expectation is thus that there is little or no sterile neutrino thermalisation at high temperature.

However, the crucial point of the pseudoscalar model is related to its late time phenomenology: indeed, the collisional term is inversely proportional to the temperature, so it becomes relevant (i.e. $\Gamma_{\text{coll}} > H_{\text{Hubble rate}}$) at late times. Provided that $g_s \gtrsim 10^{-6}$, as required by the early Universe constraints, the pseudoscalar - sterile neutrino re-coupling occurs before the non-relativistic transition, which, for a 1 eV neutrino, is around the time of photon decoupling. The sterile neutrino annihilation will transfer energy to the pseudoscalar, so the temperature of the fluid will decrease less rapidly than for standard neutrinos ($T \propto a^{-1}$) and the contribution of the fluid to the energy density of relativistic species will be larger than the one of a standard active neutrino. The tightly coupled fluid will not affect structure formation in the same way as free-streaming neutrinos and the matter power spectrum does not deviate significantly from the prediction of a pure Λ CDM model. The residual difference in the matter power spectrum is not induced by the sterile neutrino mass, but instead by the increase in N_{eff} , i.e. by the increase of the energy density of relativistic species, due to the

⁵The model studied in [59] is based on a vector mediator. However, the infrared divergence does not depend on this and also occurs in models with scalar or pseudoscalar mediators.

Data	χ^2_{tot}	χ^2_{CMB}	χ^2_{HST}	χ^2_{BAO}	Model
TT	11260.5	11260.5	--	--	P
	11262.6	11262.6	--	--	Λ
TT+HST	11260.2	11260.2	0.0	--	P
	11272.1	11265.6	6.5	--	Λ
TT+BAO	11267.6	11263.2	--	4.4	P
	11270.5	11265.6	--	4.9	Λ
TT+HST+BAO	11269.1	11262.8	1.4	4.9	P
	11276.5	11265.6	6.5	4.9	Λ
TTTEEE	12930.5	12930.5	--	--	P
	12932.2	12932.2	--	--	Λ

Table 2: Best-fit χ^2 for various models (Λ stands for Λ CDM and P for pseudoscalar model) and various data set combinations, as explained in the main text. The obtained values of χ^2 are typically within $\Delta\chi^2 \sim 1$ of the true global best-fit value.

presence of the additional neutrino and pseudoscalar degrees of freedom.

3.3 Light sterile neutrinos in the pseudoscalar model

We implemented the phenomenology of the pseudoscalar-sterile neutrino fluid in the Boltzmann solver CAMB [72] and we then fit the theoretical model to various cosmological data as in section 3.1. The parameter space is the same as (3.1), but now the physical interpretation of N_{eff} is different. We now have $N_{\text{eff}} = 3.046 + N_{\text{fluid}}$, where N_{fluid} encodes the sterile neutrinos and pseudoscalar degrees of freedom, which, by the time of photon decoupling, are collisional and not free-streaming. Notice that the active neutrinos are kept fixed to the standard cosmological value 3.046: the reason is that the pseudoscalar coupling is diagonal in mass basis, therefore the Standard Model neutrino mass eigenstates never recouple to the pseudoscalar after they decouple from the thermal bath at $T \sim 1$ MeV.

We point out that this consideration about the active states leads to a parametrisation which is somewhat different from the one we used in [52], where we assumed flavour equilibration between the sterile and the active sector after neutrino decoupling. However, this flavour equilibration only occurs when the Standard Model mass eigenstates are also partially affected by interactions with pseudoscalars as the two plasmas will otherwise be fully disconnected.

As in section 3.1, m_s is the sterile neutrino mass which in the pseudoscalar model determines the time when sterile neutrinos annihilate into pseudoscalars. In table 2 we have listed the best-fit χ^2 of the pseudoscalar model compared to the Λ CDM model for various data combinations. The preference for the pseudoscalar model is clearly strong, and even without including HST measurements it provides a better fit than the Λ CDM model. This is in contrast to models with a free N_{eff} , where the χ^2_{HST} gets better at the expenses of a worse χ^2_{CMB} . In other words, the CMB χ^2 is not affected by the inclusion of the prior on H_0 . The reason is that the pseudoscalar model naturally predicts a value of H_0 consistent with local measurements (see table 3 and figure 3 left panel).

Parameter	TT	TT+HST	TT+BAO	TT+HST+BAO	TTTEEE
H_0 [km/s/Mpc]	$71.4^{+1.8}_{-3.0}$	72.4 ± 2.5	69.8 ± 1.4	71.1 ± 1.2	70.9 ± 1.8
N_{eff}	< 3.94	3.53 ± 0.18	< 3.67	3.49 ± 0.18	< 3.69

Table 3: Constraints on H_0 and N_{eff} in the pseudoscalar model. Marginalised constraints are given at 1σ , while upper bounds are given at 2σ . Data-set combinations are the same as in table 2.

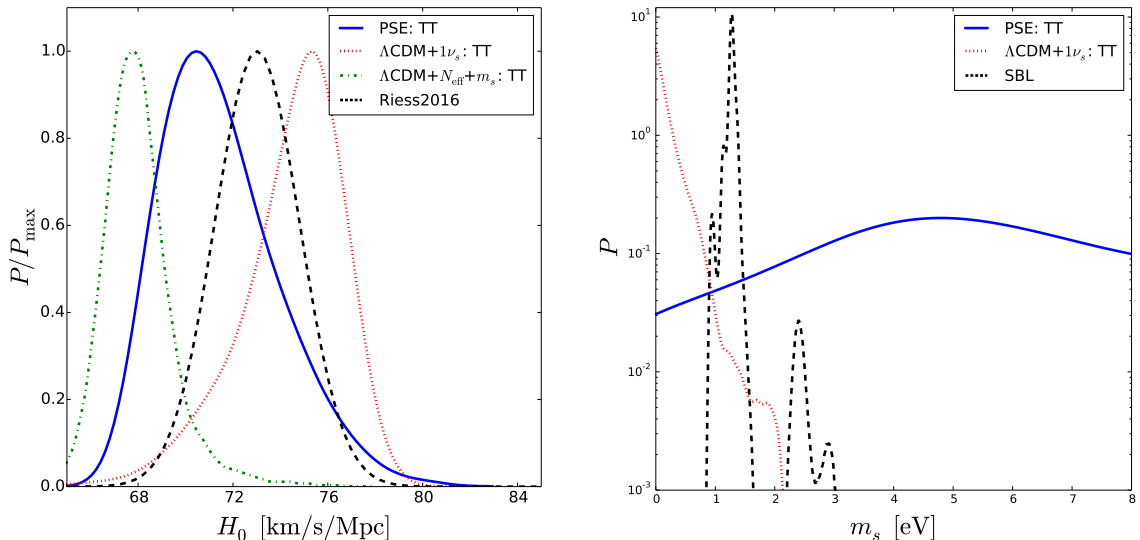


Figure 3: Comparison of the one-dimensional marginalised posterior distribution of the H_0 (left panel) and m_s (right panel) parameters as obtained from the analyses of the TT data in the $\Lambda\text{CDM}+1\nu_s$ model and in the pseudoscalar model. In the left panel, we also report the local measure $H_0 = 73.00 \pm 1.75 \text{ Km s}^{-1} \text{ Mpc}^{-1}$ [8] and the constraints obtained in the $\Lambda\text{CDM} + N_{\text{eff}} + m_s$ model (see table 1). In the panel on the right, the posteriors are in logarithmic scale and are normalized such that they integrate to one. We also show the posterior for m_s obtained in the SBL analysis described in section 2. It is visible the secondary peak at $m_s \simeq 2.4$, corresponding to the regions at $\Delta m_{41}^2 \simeq 6$ in figure 1.

Marginalised constraints on H_0 and N_{eff} are shown in table 3. Including the H_0 prior leads to an evidence for a non-zero component of the pseudoscalar-sterile neutrino fluid at more than 2.5σ (3.1σ for TT+HST). The constraints on N_{eff} are roughly the same in the pseudoscalar model as in the $\Lambda\text{CDM} + N_{\text{eff}} + m_s$ model, but the difference in χ^2 -values are $\Delta\chi^2 \sim -5$, i.e. there is a preference for additional degrees of freedom that are collisional/interacting rather than free-streaming.

At the same time, the fact that the sterile neutrinos annihilate into a massless pseudoscalar allows the bounds on m_s to be less constraining. In the right panel of figure 3 we present a comparison of the constraints obtained from SBL analyses (black dashed line), from the $\Lambda\text{CDM}+1\nu_s$ model discussed in section 3.1 (red dotted) and from the pseudoscalar model

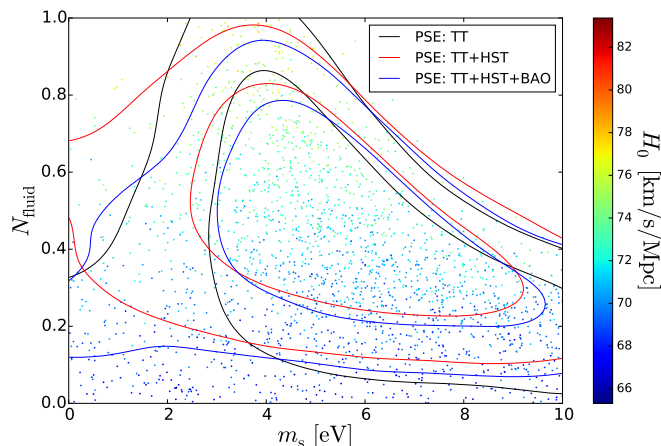


Figure 4: Marginalised 1 and 2σ contours in the plane m_s – N_{fluid} for the pseudoscalar model. The points inside the contours are coloured according to the value of H_0 obtained by fitting only TT data.

(PSE, blue solid). As we can see, in the pseudoscalar model the preferred mass is around $m_s \simeq 5$ eV and the posterior is wide enough to be compatible with 1 eV. For this reason, a combined fit of cosmological and SBL data is possible. Indeed, we will present the results of the joint analyses in section 4. We also notice that in the pseudoscalar model m_s and N_{fluid} are uncorrelated (see figure 4); however, the allowed range of masses is larger when sterile neutrinos are partially thermalized.

Figure 5 shows that the consistency of the pseudoscalar model with the CFHTLenS weak lensing measurements is the same as in a pure Λ CDM model. Indeed, weak gravitational lensing mainly probes a combination of $(H_0, \Omega_m, \sigma_8)$ on small scales. Due to its peculiar late time phenomenology, the pseudoscalar model is consistent with local Universe measurements of H_0 and, at the same time, it does not induce any significant deviation of Ω_m – σ_8 from the prediction of the Λ CDM model. The preferred marginalised regions, however, slightly move in the direction of reconciling the cosmological predictions with the local determinations.

4 Joint analyses

In the following we will present the results of the combination of the analyses of short-baseline neutrino oscillation data and of cosmological data in the pseudoscalar model with two approaches:

- In section 4.1 we will analyse the cosmological data using as a prior the marginal posterior probability for $m_s = \sqrt{\Delta m_{41}^2}$ obtained from the short-baseline analysis. This approach will allow us to get information on the cosmological parameters taking into account the short-baseline data.
- In section 4.2 we will analyse the short-baseline neutrino oscillation data using as a prior the marginal posterior probability for $\sqrt{\Delta m_{41}^2} = m_s$ obtained from the analysis of cosmological data. This approach will allow us to get information on the neutrino mixing parameters.

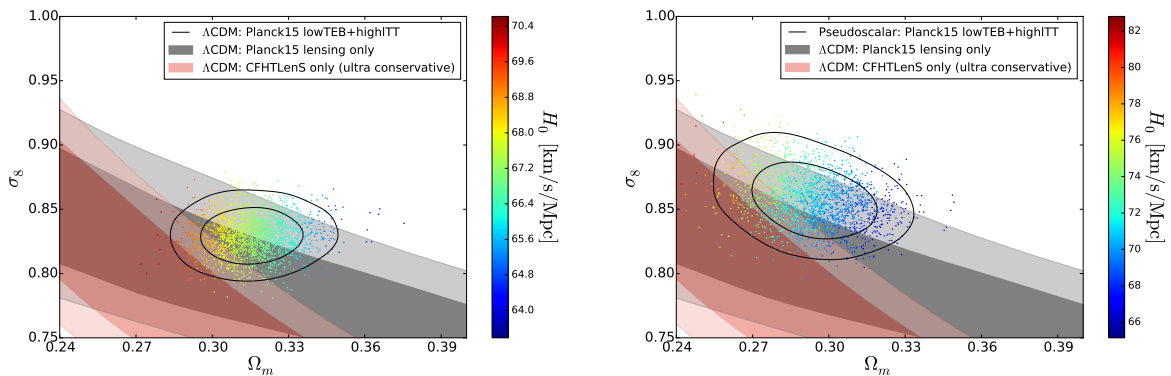


Figure 5: Marginalised 1 and 2σ contours in the plane σ_8 - Ω_m of the Λ CDM model (left panel) and of the pseudoscalar model (right panel). The points inside the contours are coloured according to the value of H_0 (see the scale on the right hand side of each plot). The red and gray shaded areas show the constraints from Planck CMB lensing [73] and from CFHTLenS weak lensing data [74], respectively.

Parameter	SBL+TT	SBL+TT+HST	SBL+TT+BAO	SBL+TT+HST+BAO
H_0 [km/s/Mpc]	$70.9^{+1.6}_{-3.3}$	72.2 ± 1.7	$69.19^{+0.83}_{-1.4}$	$70.6^{+1.1}_{-1.4}$
N_{eff}	< 3.97	3.51 ± 0.20	< 3.57	$3.43^{+0.18}_{-0.22}$
m_s [eV]	$1.272^{+0.052}_{-0.038}$	$1.274^{+0.050}_{-0.038}$	$1.270^{+0.055}_{-0.035}$	$1.270^{+0.055}_{-0.035}$

Table 4: Constraints on H_0 , N_{eff} and m_s in the pseudoscalar model for various cosmological data-set in combination with the SBL prior. marginalised constraints are given at 1σ , while upper bounds are given at 2σ . Data-set combinations are the same as in table 2.

4.1 SBL results as a prior in the cosmological analysis

As we have seen in section 3.3, the pseudoscalar model on one hand provides a good fit to the cosmological data and on the other hand leads to cosmological results consistent with a light sterile neutrino. Therefore, it is timely to perform a combined analysis of cosmological data together with oscillation data in the framework of the pseudoscalar model. In order to do so we have followed the procedure described in section 3.3 and we add an extra χ^2 obtained by fitting the cosmological sterile neutrino mass m_s to the SBL prior described in section 2. As expected $\Delta\chi^2 \lesssim 1$, since the cosmological posterior on m_s is broad and extends up to the oscillation preferred values of the sterile neutrino mass. Table 4 reports the constraints on H_0 , N_{eff} and m_s . Given the consistency between oscillation and cosmological results, the constraints do not deviate significantly from the ones listed in table 3 and the value of the Hubble constant is still in agreement with local Universe measurements. The main effect of adding the SBL prior is that the sterile neutrino mass is singled out around the oscillation best-fit, as shown in figure 6.

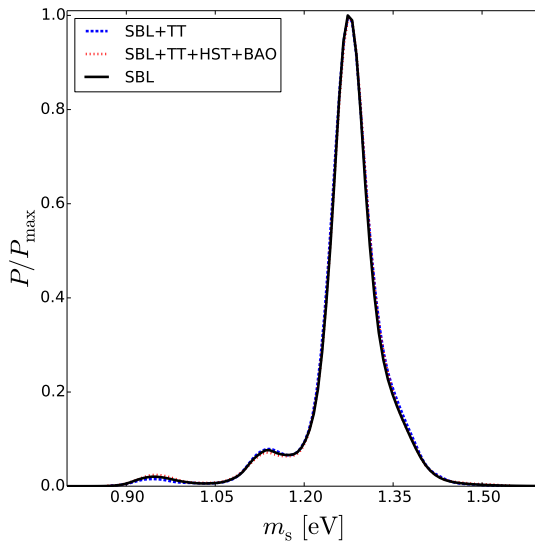


Figure 6: One-dimensional marginalised posterior distribution on the cosmological parameters m_s obtained in the pseudoscalar model by including the SBL prior.

4.2 Cosmology as a prior in the SBL analysis

It is interesting to investigate what are the implications of the analysis of the cosmological data in the pseudoscalar model for the mixing parameters relevant for short-baseline neutrino oscillations. We performed this study by considering the posterior on m_s obtained from the analysis of cosmological data as a prior on $\sqrt{\Delta m_{41}^2} = m_s$ in a Bayesian global analysis of short-baseline neutrino oscillation data. The results for the allowed regions in the $\sin^2 2\vartheta_{e\mu} - \Delta m_{41}^2$, $\sin^2 2\vartheta_{ee} - \Delta m_{41}^2$ and $\sin^2 2\vartheta_{\mu\mu} - \Delta m_{41}^2$ planes are shown in figure 7, where we considered the TT, TT+HST, TT+BAO and TT+HST+BAO data sets.

From figure 7, one can see that taking into account the cosmological data in the pseudoscalar model has little effect on the values of the mixing parameters that are favored by short-baseline data. This is due to the compatibility of cosmological and short-baseline data in the 3+1 pseudoscalar model already discussed in section 3.3 and to the wide cosmological posteriors for m_s in the right panel of figure 3.

The main small effect of cosmological data that one can notice comparing the filled regions and the contour lines in figure 7 is the increase of the Bayesian region allowed at 3σ at $\Delta m_{41}^2 \approx 6 \text{ eV}^2$ and the emergence of a new Bayesian region allowed at 3σ at $\Delta m_{41}^2 \approx 8 - 9 \text{ eV}^2$ in the fits which include the HST data. These effects are due to the preference for relatively large values of m_s obtained in the analyses of cosmological data and to the absence of strong constraints from ν_e ($\bar{\nu}_e$) and ν_μ ($\bar{\nu}_\mu$) disappearance short-baseline experiments at those values of Δm_{41}^2 . The indication in favor of values of Δm_{41}^2 larger than about 1 eV^2 is consistent with the recent constraints on short-baseline ν_μ ($\bar{\nu}_\mu$) disappearance with $\Delta m_{41}^2 \lesssim 1 \text{ eV}^2$ obtained in the IceCube [32] and MINOS [33] experiments.

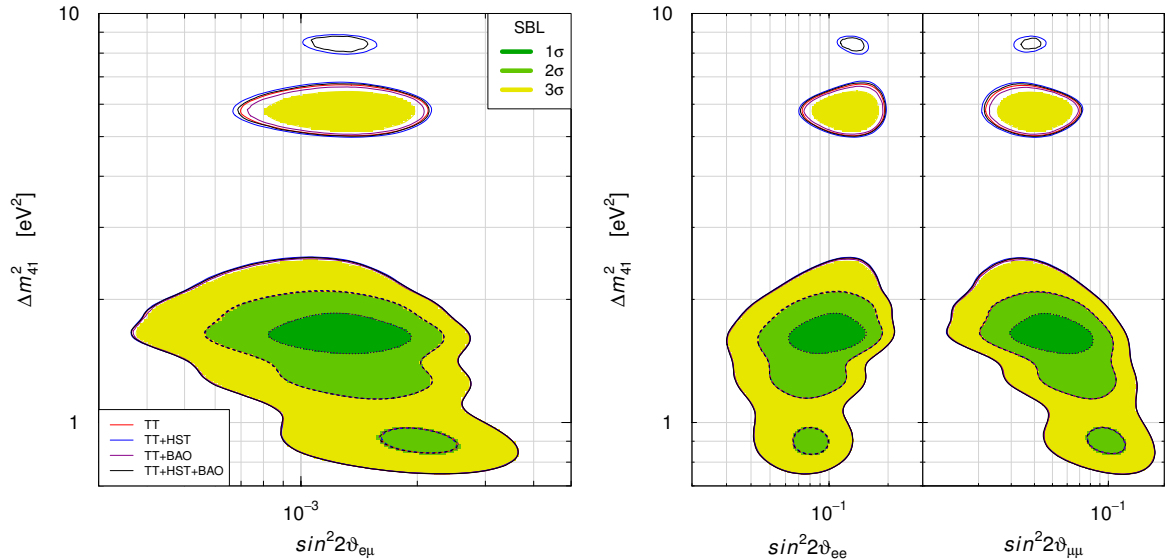


Figure 7: The coloured regions show the constraints in the planes of the effective amplitudes $\sin^2 2\vartheta_{e\mu}$, $\sin^2 2\vartheta_{ee}$ and $\sin^2 2\vartheta_{\mu\mu}$ versus Δm_{41}^2 which are allowed by the Bayesian global fit of short-baseline neutrino oscillation data, as in figure 1. The dotted, dashed and solid coloured curves enclose the regions allowed, respectively, at 1σ , 2σ and 3σ in the combined analyses with different priors on Δm_{41}^2 obtained from the analysis of cosmological data in the pseudoscalar model using the TT, TT+HST, TT+BAO and TT+HST+BAO data sets (see section 4.2). A difference of the contours is visible only for the large- Δm_{41}^2 regions.

5 Conclusions

We have performed an updated analysis of light sterile neutrinos in the context of cosmology. A fourth, mainly sterile mass state with the mass and mixing needed to fit short baseline data is inevitably thermalised in the early Universe and its effect on structure formation and the CMB makes it extremely disfavoured by current data. The fact that the presence of additional massless or massive neutrinos is disfavoured remains true even in extended cosmological models with significantly more parameters than the standard Λ CDM model [75]. However, if sterile neutrinos are charged under a new, non-standard interaction this picture can change dramatically.

Here we investigated how the model first suggested in [51] can alleviate the tension. The model is based on an interaction mediated by a light pseudoscalar particle, coupled only to the fourth neutrino mass eigenstate. This model has a phenomenology which is very different from the standard picture. First, the new interaction induces a large matter potential which can suppress equilibration of the additional mass state until after active neutrino decoupling. Second, the interaction becomes very strong at late times and leads to a strongly coupled fluid of neutrinos and pseudoscalars. This suppresses the anisotropic stress and surprisingly provides an excellent fit to all current data. Very interestingly the model also predicts a value of the Hubble parameter much higher than the one obtained in the Λ CDM model and completely compatible with the locally measured value.

We found an excellent agreement of the cosmological posterior for the sterile neutrino mass m_s with the squared-mass difference $\Delta m_{41}^2 \simeq m_s^2$ obtained from the analysis of short-

baseline neutrino oscillation data. The combined fit indicates a preference for values of Δm_{41}^2 larger than about 1 eV^2 , in agreement with the constraints obtained recently in the IceCube [32] and MINOS [33] experiments.

The question of the existence of the light sterile neutrino indicated by the reactor, Gallium and LSND anomalies will be answered in a definitive way in the next few years through a wide program of many new neutrino oscillation experiments which will investigate the short-baseline disappearance of ν_e ($\bar{\nu}_e$) produced in nuclear reactors and radioactive sources and the short-baseline $\nu_\mu \rightarrow \nu_e$ ($\bar{\nu}_\mu \rightarrow \bar{\nu}_e$) transitions and ν_μ ($\bar{\nu}_\mu$) disappearance of accelerator neutrinos (see the reviews in refs. [3, 76–82]). Moreover, in the near future the Euclid satellite will pin down the neutrino mass sum and the number of effective relativistic degrees of freedom [83]: if Σm_ν is confirmed to be close to the minimum value of either the normal or inverted active neutrino hierarchy and, at the same time, there is an evidence for a value of N_{eff} slightly larger than the standard 3.046, it will be a clear hint for physics beyond the standard model and beyond the standard picture of three massive neutrinos. In other words, if, on one hand, neutrino experiments will confirm the existence of $\sim \text{eV}$ sterile neutrinos, and, on the other hand, precision cosmology will rule out additional neutrino-like species, though, indicating a deviation from $N_{\text{eff}} = 3.046$, the search for a new hidden sector, with new interactions and new particles, will be essential. In this scenario the pseudoscalar model would provide the simplest and most natural way of reconciling laboratory experiments with cosmological observations.

Note Added

After the completion of this work the phenomenology of light sterile neutrinos was discussed at the Neutrino 2016 Conference. The Daya Bay and RENO Collaborations presented new upper limits on $\sin^2 2\vartheta_{ee}$ for $3 \times 10^{-4} \lesssim \Delta m_{41}^2 \lesssim 0.3 \text{ eV}^2$, which do not constrain the allowed region in Figs. 1 and 7. The MINOS Collaboration confirmed the upper limits on $\sin^2 2\vartheta_{\mu\mu}$ for $3 \times 10^{-3} \lesssim \Delta m_{41}^2 \lesssim 100 \text{ eV}^2$ presented in ref. [33], that we discussed above. The Daya Bay and MINOS results have been published too, respectively, in ref. [84] and ref. [85]. Moreover, the two collaborations presented a joint analysis of their data and of the data of the Bugey-3 experiment [86] in order to constrain $\sin^2 2\vartheta_{e\mu}$ for $3 \times 10^{-4} \lesssim \Delta m_{41}^2 \lesssim 100 \text{ eV}^2$. The results of this analysis, also published in ref. [87], are not relevant for our global fits, because the data of Bugey-3 experiment are already taken into account together with those of other reactor neutrino experiments (see ref. [3]).

At the Neutrino 2016 Conference there was also a presentation of the IceCube [32] constraints on $\sin^2 2\vartheta_{\mu\mu}$ for $\Delta m_{41}^2 \lesssim 1 \text{ eV}^2$ discussed above. These constraints have been taken into account in a global fit of short-baseline neutrino oscillation data in ref. [88], confirming the indication in favor of values of Δm_{41}^2 larger than about 1 eV^2 discussed in this paper.

Acknowledgments

S.G., C.G. and M.L. are supported by the research Grant *Theoretical Astroparticle Physics* number 2012CPPYP7 under the Program PRIN 2012 funded by the Ministero dell’Istruzione, Università e della Ricerca (MIUR). R.H. acknowledges support from the Alexander von Humboldt Foundation. S.H. acknowledges support from the Villum Foundation.

References

- [1] K. N. Abazajian et al., *Light Sterile Neutrinos: A White Paper*, [1204.5379](#).
- [2] J. Kopp, P. A. N. Machado, M. Maltoni and T. Schwetz, *Sterile Neutrino Oscillations: The Global Picture*, *JHEP* **05** (2013) 050, [[1303.3011](#)].
- [3] S. Gariazzo, C. Giunti, M. Laveder, Y. F. Li and E. M. Zavanin, *Light sterile neutrinos*, *J. Phys.* **G43** (2016) 033001, [[1507.08204](#)].
- [4] M. C. Gonzalez-Garcia, M. Maltoni and T. Schwetz, *Global Analyses of Neutrino Oscillation Experiments*, [1512.06856](#).
- [5] R. Cooke, M. Pettini, R. A. Jorgenson, M. T. Murphy and C. C. Steidel, *Precision measures of the primordial abundance of deuterium*, *Astrophys. J.* **781** (2014) 31, [[1308.3240](#)].
- [6] R. H. Cyburt, B. D. Fields, K. A. Olive and T.-H. Yeh, *Big Bang Nucleosynthesis: 2015*, *Rev. Mod. Phys.* **88** (2016) 015004, [[1505.01076](#)].
- [7] P. A. R. Ade et al., *Planck 2015 results. XIII. Cosmological parameters*, [1502.01589](#).
- [8] A. G. Riess et al., *A 2.4% Determination of the Local Value of the Hubble Constant*, [1604.01424](#).
- [9] J. Kwan et al., *Cosmology from large scale galaxy clustering and galaxy-galaxy lensing with Dark Energy Survey Science Verification data*, [1604.07871](#).
- [10] M. Kilbinger et al., *CFHTLenS: Combined probe cosmological model comparison using 2D weak gravitational lensing*, *Mon. Not. Roy. Astron. Soc.* **430** (2013) 2200–2220, [[1212.3338](#)].
- [11] H. Hildebrandt et al., *KiDS-450: Cosmological parameter constraints from tomographic weak gravitational lensing*, [1606.05338](#).
- [12] S. Hannestad, I. Tamborra and T. Tram, *Thermalisation of light sterile neutrinos in the early universe*, *JCAP* **1207** (2012) 025, [[1204.5861](#)].
- [13] N. Saviano, A. Mirizzi, O. Pisanti, P. D. Serpico, G. Mangano and G. Miele, *Multi-momentum and multi-flavour active-sterile neutrino oscillations in the early universe: role of neutrino asymmetries and effects on nucleosynthesis*, *Phys. Rev.* **D87** (2013) 073006, [[1302.1200](#)].
- [14] LSND collaboration, C. Athanassopoulos et al., *Candidate events in a search for anti-muon-neutrino \rightarrow anti-electron-neutrino oscillations*, *Phys. Rev. Lett.* **75** (1995) 2650–2653, [[nucl-ex/9504002](#)].
- [15] LSND collaboration, A. Aguilar-Arevalo et al., *Evidence for neutrino oscillations from the observation of anti-neutrino(electron) appearance in a anti-neutrino(muon) beam*, *Phys. Rev.* **D64** (2001) 112007, [[hep-ex/0104049](#)].
- [16] M. Laveder, *Unbound neutrino roadmaps*, *Nucl. Phys. Proc. Suppl.* **168** (2007) 344–346.
- [17] C. Giunti and M. Laveder, *Short-Baseline Active-Sterile Neutrino Oscillations?*, *Mod. Phys. Lett.* **A22** (2007) 2499–2509, [[hep-ph/0610352](#)].
- [18] C. Giunti and M. Laveder, *Statistical Significance of the Gallium Anomaly*, *Phys. Rev.* **C83** (2011) 065504, [[1006.3244](#)].
- [19] C. Giunti, M. Laveder, Y. F. Li, Q. Y. Liu and H. W. Long, *Update of Short-Baseline Electron Neutrino and Antineutrino Disappearance*, *Phys. Rev.* **D86** (2012) 113014, [[1210.5715](#)].
- [20] F. Kaether, W. Hampel, G. Heusser, J. Kiko and T. Kirsten, *Reanalysis of the GALLEX solar neutrino flux and source experiments*, *Phys. Lett.* **B685** (2010) 47–54, [[1001.2731](#)].
- [21] SAGE collaboration, J. N. Abdurashitov et al., *Measurement of the solar neutrino capture rate with gallium metal. III: Results for the 2002–2007 data-taking period*, *Phys. Rev.* **C80** (2009) 015807, [[0901.2200](#)].

- [22] G. Mention, M. Fechner, T. Lasserre, T. A. Mueller, D. Lhuillier, M. Cribier et al., *The Reactor Antineutrino Anomaly*, *Phys. Rev.* **D83** (2011) 073006, [[1101.2755](#)].
- [23] T. A. Mueller et al., *Improved Predictions of Reactor Antineutrino Spectra*, *Phys. Rev.* **C83** (2011) 054615, [[1101.2663](#)].
- [24] P. Huber, *On the determination of anti-neutrino spectra from nuclear reactors*, *Phys. Rev.* **C84** (2011) 024617, [[1106.0687](#)].
- [25] D. V. Forero, M. Tortola and J. W. F. Valle, *Neutrino oscillations refitted*, *Phys. Rev.* **D90** (2014) 093006, [[1405.7540](#)].
- [26] M. C. Gonzalez-Garcia, M. Maltoni and T. Schwetz, *Updated fit to three neutrino mixing: status of leptonic CP violation*, *JHEP* **11** (Sept., 2014) 052, [[1409.5439](#)].
- [27] F. Capozzi, E. Lisi, A. Marrone, D. Montanino and A. Palazzo, *Neutrino masses and mixings: Status of known and unknown 3ν parameters*, 2016. [1601.07777](#).
- [28] S. M. Bilenky and C. Giunti, *Neutrinoless Double-Beta Decay: a Probe of Physics Beyond the Standard Model*, *Int. J. Mod. Phys.* **A30** (Nov., 2015) 1530001, [[1411.4791](#)].
- [29] S. Dell’Oro, S. Marcocci, M. Viel and F. Vissani, *Neutrinoless double beta decay: 2015 review*, [1601.07512](#).
- [30] KAMLAND-ZEN collaboration, *Search for Majorana Neutrinos near the Inverted Mass Hierarchy region with KamLAND-Zen*, [1605.02889](#).
- [31] S. M. Bilenky, C. Giunti and W. Grimus, *Neutrino mass spectrum from the results of neutrino oscillation experiments*, *Eur. Phys. J.* **C1** (1998) 247–253, [[hep-ph/9607372](#)].
- [32] THE ICECUBE collaboration, *Searches for Sterile Neutrinos with the IceCube Detector*, [1605.01990](#).
- [33] A. Timmons, *Searching for Sterile Neutrinos with MINOS*, 2016. [1605.04544](#).
- [34] J. Lesgourgues and S. Pastor, *Neutrino cosmology and Planck*, *New J. Phys.* **16** (2014) 065002, [[1404.1740](#)].
- [35] M. Archidiacono, N. Fornengo, C. Giunti and A. Melchiorri, *Testing $3+1$ and $3+2$ neutrino mass models with cosmology and short baseline experiments*, *Phys. Rev.* **D86** (2012) 065028, [[1207.6515](#)].
- [36] M. Archidiacono, N. Fornengo, C. Giunti, S. Hannestad and A. Melchiorri, *Sterile neutrinos: Cosmology versus short-baseline experiments*, *Phys. Rev.* **D87** (2013) 125034, [[1302.6720](#)].
- [37] J. R. Kristiansen, Ø. Elgarøy, C. Giunti and M. Laveder, *Cosmology with sterile neutrino masses from oscillation experiments*, [1303.4654](#).
- [38] P. A. R. Ade et al., *Planck 2013 results. XVI. Cosmological parameters*, *Astron. Astrophys.* **571** (Nov., 2014) A16, [[1303.5076](#)].
- [39] J. Hamann and J. Hasenkamp, *A new life for sterile neutrinos: resolving inconsistencies using hot dark matter*, *JCAP* **1310** (2013) 044, [[1308.3255](#)].
- [40] S. Gariazzo, C. Giunti and M. Laveder, *Light Sterile Neutrinos in Cosmology and Short-Baseline Oscillation Experiments*, *JHEP* **11** (2013) 211, [[1309.3192](#)].
- [41] M. Archidiacono, N. Fornengo, S. Gariazzo, C. Giunti, S. Hannestad and M. Laveder, *Light sterile neutrinos after BICEP-2*, *JCAP* **1406** (2014) 031, [[1404.1794](#)].
- [42] J. Bergström, M. C. Gonzalez-Garcia, V. Niro and J. Salvado, *Statistical tests of sterile neutrinos using cosmology and short-baseline data*, *JHEP* **10** (2014) 104, [[1407.3806](#)].
- [43] G. Mangano, G. Miele, S. Pastor, T. Pinto, O. Pisanti and P. D. Serpico, *Relic neutrino decoupling including flavor oscillations*, *Nucl. Phys.* **B729** (2005) 221–234, [[hep-ph/0506164](#)].

- [44] A. Lewis and S. Bridle, *Cosmological parameters from CMB and other data: A Monte Carlo approach*, *Phys. Rev.* **D66** (2002) 103511, [[astro-ph/0205436](#)].
- [45] N. Aghanim et al., *Planck 2015 results. XI. CMB power spectra, likelihoods, and robustness of parameters*, *Submitted to: Astron. Astrophys.* (July, 2015) , [[1507.02704](#)].
- [46] F. Beutler, C. Blake, M. Colless, D. H. Jones, L. Staveley-Smith, L. Campbell et al., *The 6dF Galaxy Survey: Baryon Acoustic Oscillations and the Local Hubble Constant*, *Mon. Not. Roy. Astron. Soc.* **416** (2011) 3017–3032, [[1106.3366](#)].
- [47] A. J. Ross, L. Samushia, C. Howlett, W. J. Percival, A. Burden and M. Manera, *The clustering of the SDSS DR7 main Galaxy sample – I. A 4 per cent distance measure at $z = 0.15$* , *Mon. Not. Roy. Astron. Soc.* **449** (2015) 835–847, [[1409.3242](#)].
- [48] L. Anderson et al., *The clustering of galaxies in the SDSS-III Baryon Oscillation Spectroscopic Survey: Baryon Acoustic Oscillations in the Data Release 9 Spectroscopic Galaxy Sample*, *Mon. Not. Roy. Astron. Soc.* **427** (2013) 3435–3467, [[1203.6594](#)].
- [49] BOSS collaboration, L. Anderson et al., *The clustering of galaxies in the SDSS-III Baryon Oscillation Spectroscopic Survey: baryon acoustic oscillations in the Data Releases 10 and 11 Galaxy samples*, *Mon. Not. Roy. Astron. Soc.* **441** (2014) 24–62, [[1312.4877](#)].
- [50] BOREXINO collaboration, G. Bellini et al., *SOX: Short distance neutrino Oscillations with BoreXino*, *JHEP* **08** (2013) 038, [[1304.7721](#)].
- [51] M. Archidiacono, S. Hannestad, R. S. Hansen and T. Tram, *Cosmology with self-interacting sterile neutrinos and dark matter - A pseudoscalar model*, *Phys. Rev.* **D91** (2015) 065021, [[1404.5915](#)].
- [52] M. Archidiacono, S. Hannestad, R. S. Hansen and T. Tram, *Sterile neutrinos with pseudoscalar self-interactions and cosmology*, *Phys. Rev.* **D93** (2016) 045004, [[1508.02504](#)].
- [53] J. F. Beacom, N. F. Bell and S. Dodelson, *Neutrinoless universe*, *Phys. Rev. Lett.* **93** (2004) 121302, [[astro-ph/0404585](#)].
- [54] F.-Y. Cyr-Racine and K. Sigurdson, *Limits on Neutrino-Neutrino Scattering in the Early Universe*, *Phys. Rev.* **D90** (2014) 123533, [[1306.1536](#)].
- [55] M. Archidiacono and S. Hannestad, *Updated constraints on non-standard neutrino interactions from Planck*, *JCAP* **1407** (2014) 046, [[1311.3873](#)].
- [56] K. Ioka and K. Murase, *IceCube PeVEeV neutrinos and secret interactions of neutrinos*, *PTEP* **2014** (2014) 061E01, [[1404.2279](#)].
- [57] J. F. Cherry, A. Friedland and I. M. Shoemaker, *Neutrino Portal Dark Matter: From Dwarf Galaxies to IceCube*, [1411.1071](#).
- [58] K. C. Y. Ng and J. F. Beacom, *Cosmic neutrino cascades from secret neutrino interactions*, *Phys. Rev.* **D90** (2014) 065035, [[1404.2288](#)].
- [59] J. F. Cherry, A. Friedland and I. M. Shoemaker, *Short-baseline neutrino oscillations, Planck, and IceCube*, [1605.06506](#).
- [60] ICECUBE collaboration, M. G. Aartsen et al., *Observation of High-Energy Astrophysical Neutrinos in Three Years of IceCube Data*, *Phys. Rev. Lett.* **113** (2014) 101101, [[1405.5303](#)].
- [61] Y. Farzan, *Bounds on the coupling of the Majoron to light neutrinos from supernova cooling*, *Phys. Rev.* **D67** (2003) 073015, [[hep-ph/0211375](#)].
- [62] J. Lesgourgues, G. Marques-Tavares and M. Schmaltz, *Evidence for dark matter interactions in cosmological precision data?*, *JCAP* **1602** (July, 2016) 037, [[1507.04351](#)].
- [63] T. Bringmann, J. Hasenkamp and J. Kersten, *Tight bonds between sterile neutrinos and dark matter*, *JCAP* **1407** (2014) 042, [[1312.4947](#)].

- [64] B. Dasgupta and J. Kopp, *Cosmologically Safe eV-Scale Sterile Neutrinos and Improved Dark Matter Structure*, *Phys. Rev. Lett.* **112** (2014) 031803, [[1310.6337](#)].
- [65] X. Chu and B. Dasgupta, *Dark Radiation Alleviates Problems with Dark Matter Halos*, *Phys. Rev. Lett.* **113** (2014) 161301, [[1404.6127](#)].
- [66] S. Hannestad, R. S. Hansen and T. Tram, *How Self-Interactions can Reconcile Sterile Neutrinos with Cosmology*, *Phys. Rev. Lett.* **112** (2014) 031802, [[1310.5926](#)].
- [67] A. Mirizzi, G. Mangano, O. Pisanti and N. Saviano, *Collisional production of sterile neutrinos via secret interactions and cosmological implications*, *Phys. Rev.* **D91** (Oct., 2015) 025019, [[1410.1385](#)].
- [68] N. Saviano, O. Pisanti, G. Mangano and A. Mirizzi, *Unveiling secret interactions among sterile neutrinos with big-bang nucleosynthesis*, *Phys. Rev.* **D90** (2014) 113009, [[1409.1680](#)].
- [69] F. Forastieri, M. Lattanzi and P. Natoli, *Constraints on secret neutrino interactions after Planck*, [1504.04999](#).
- [70] X. Chu, B. Dasgupta and J. Kopp, *Sterile neutrinos with secret interactions—lasting friendship with cosmology*, *JCAP* **1510** (2015) 011, [[1505.02795](#)].
- [71] W. Florkowski and B. L. Friman, *Spatial dependence of the finite temperature meson correlation function*, *Z. Phys.* **A347** (1994) 271–276.
- [72] A. Lewis, A. Challinor and A. Lasenby, *Efficient computation of CMB anisotropies in closed FRW models*, *Astrophys. J.* **538** (2000) 473–476, [[astro-ph/9911177](#)].
- [73] P. A. R. Ade et al., *Planck 2015 results. XV. Gravitational lensing*, [1502.01591](#).
- [74] C. Heymans et al., *CFHTLenS tomographic weak lensing cosmological parameter constraints: Mitigating the impact of intrinsic galaxy alignments*, *Mon. Not. Roy. Astron. Soc.* **432** (2013) 2433, [[1303.1808](#)].
- [75] E. Di Valentino, A. Melchiorri and J. Silk, *Reconciling Planck with the local value of H_0 in extended parameter space*, [1606.00634](#).
- [76] T. Lasserre, *(sub)eV Sterile Neutrinos: experimental aspects*, *Nucl. Part. Phys. Proc.* **265-266** (2015) 281–287.
- [77] D. Lhuillier, *Future short-baseline sterile neutrino searches with reactors*, *AIP Conf. Proc.* **1666** (2015) 180003.
- [78] B. Caccianiga, *Future short baseline neutrino searches with nuclear decays*, *AIP Conf. Proc.* **1666** (2015) 180002.
- [79] J. Spitz, *Future short-baseline sterile neutrino searches with accelerators*, *AIP Conf. Proc.* **1666** (2015) 180004.
- [80] C. Giunti, *Light Sterile Neutrinos*, 2015. [1512.04758](#).
- [81] L. Stanco, *Search for Sterile Neutrinos at Long and Short Baselines*, 2016. [1604.06769](#).
- [82] A. Fava, *Experimental investigation of the thriving mystery of sterile neutrinos*, *Rev. Phys.* **1** (2016) 52–59.
- [83] S. Hannestad, J. Hamann and Y. Y. Y. Wong, *Current and future constraints on neutrino physics from cosmology*, *J. Phys. Conf. Ser.* **485** (2014) 012008.
- [84] F. P. An et al., *Improved Search for a Light Sterile Neutrino with the Full Configuration of the Daya Bay Experiment*, [1607.01174](#).
- [85] P. Adamson et al., *A search for sterile neutrinos mixing with muon neutrinos in MINOS*, [1607.01176](#).
- [86] BUGEY collaboration, B. Achkar et al., *Search for neutrino oscillations at 15-meters*,

40-meters, and 95-meters from a nuclear power reactor at bugey, *Nucl. Phys.* **B434** (1995) 503–534.

- [87] MINOS, DAYA BAY collaboration, P. Adamson et al., *Limits on Active to Sterile Neutrino Oscillations from Disappearance Searches in the MINOS, Daya Bay, and Bugey-3 Experiments*, Submitted to: *Phys. Rev. Lett.* (2016) , [[1607.01177](#)].
- [88] G. H. Collin, C. A. Argelles, J. M. Conrad and M. H. Shaevitz, *First Constraints on the Complete Neutrino Mixing Matrix with a Sterile Neutrino*, [1607.00011](#).