# Snowmass2021 - Letter of Interest

# *Sterile neutrinos with non-standard interactions*

**NF Topical Groups:**

- ■ (NF1) Neutrino oscillations
- ■ (NF2) Sterile neutrinos
- ■ (NF3) Beyond the Standard Model
- ■ (NF4) Neutrinos from natural sources
- ■ (NF5) Neutrino properties
- ■ (CF7) Cosmic Probes of Fundamental Physics
- ■ (TF09) Astro-Particle Physics & Cosmology
- ■ (TF11) Theory of neutrino physics

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**Abstract:**

Neutrino oscillation anomalies, hinting at the presence of light sterile neutrinos, are inconsistent with up-to-date cosmological results. If confirmed by forthcoming neutrino oscillation experiments, the presence of these additional light species will be a new open problem in cosmology. The intent of this *Letter of Interest* is to elaborate on this potential tension between particle physics and cosmology, as a motivation to devise new physics in the form of sterile neutrino non-standard interactions. The ultimate goal is to indicate a multi-disciplinary strategy to detect this new hidden sector.

## Science Motivation: SBL experiments vs. cosmology

Short-baseline (SBL) neutrino oscillation experiments have consistently exhibited a number of anomalies[1–5], which might be attributed to the presence of one or more light neutrinos beyond the three predicted by the standard model. Such additional neutrino species are required to be singlets under the standard model interactions, but since they mix with the active neutrinos they can affect neutrino oscillation experiments, and they also have an impact on cosmology.

Precision data from Cosmic Microwave Background (CMB) and large scale structure surveys have already put very tight constraints on the presence of such particles. High redshift CMB measurements from Planck[6] have constrained the number of relativistic degrees of freedom ($N_{\rm eff} = 2.92^{+0.36}_{-0.37}$, 95% c.l., Planck TT,TE,EE+lowE) to be consistent with the standard scenario of three active neutrinos ($N_{\rm eff}^{\rm SM} = 3.045$[7]), leaving no room for extra light species relativistic at decoupling. Moreover, CMB augmented with Baryonic Acoustic Oscillations (BAO)[8–10] have set very tight upper bounds on the sum of neutrino masses ($\sum m_\nu < 0.12$ eV, 95% c.l., Planck TT,TE,EE+lowE+lensing+BAO), which are at odds with the eV scale indicated by SBL anomalies.

However, the cosmological constraints are derived assuming the neutrino momentum distribution predicted by the standard model. This assumption reflects the fact that the mixing angles favored in global fits of SBL anomalies imply full thermalization between active and sterile neutrinos in the early Universe[11;12], i.e. $N_{\rm eff} = 3 + 1$. New physics efficient in the early Universe may prevent such thermalization, inducing a deviation of the sterile neutrino distribution from the Fermi-Dirac.

## Model Overview: sterile neutrinos with non-standard interactions

Non-standard interactions among sterile neutrinos mediated either by a vector boson[13–15] or by a light pseudoscalar ($\phi$)[16] can lead to this partial thermalization. They induce a new matter effect that suppresses the mixing angle and, thus, delays the production of sterile neutrinos in the early Universe ($T \sim 10$ MeV). If the coupling between sterile neutrinos and the mediator is large enough ($g > 10^{-6}$), sterile neutrinos are produced only after active neutrino decoupling ($T \sim 1$ MeV), and their phase space distribution remains non-thermal. Therefore, the contribution of one sterile neutrino to $N_{\rm eff}$ turns out to be much smaller than one.

The low energy phenomenology of the pseudoscalar model[17] can also reconcile eV sterile neutrinos with the sub-eV cosmological neutrino mass bounds. Indeed, once sterile neutrinos go non-relativistic, they annihilate into the light mediator, disappearing from the cosmic neutrino background[18]. As a consequence, the CMB+BAO bound on the neutrino mass sum applies only to the sum of the active neutrino masses, while the eV sterile neutrinos can evade this bound.

At the state-of-the-art, sterile neutrinos with self-interactions mediated by a light pseudoscalar[19;20] are marginally consistent with CMB data: compared to the standard $\Lambda$CDM model, they degrade the fit of Planck temperature and polarization measurements at high multipoles. On the other hand, the pseudoscalar model points to a value of the Hubble constant fully consistent with the local distance measurements[21], solving the $H_0$ problem[22;23]. As for the agreement with the SBL anomalies, the cosmological constraints on the pseudoscalar model still leave room to accommodate light sterile neutrinos provided that their mass is $\lesssim 1$ eV.

## Future directions: a multi-disciplinary approach

The rationale behind neutrino non-standard interactions comes from the interconnection between different fields. Therefore, the existence of such new physics can be scrutinized from different angles:

- **Cosmology.** Forthcoming cosmological survey, both CMB (Simons Observatory[24], CMB-S4[25]) and galaxy (Euclid[26], Vera Rubin Observatory[27]), will increase the sensitivity to $\sum m_\nu$ and $N_{\rm eff}$. The sensitivity to $\sum m_\nu$ will allow a $\gtrsim 3\sigma$ evidence of a non-zero neutrino mass in the minimal normal ordering scenario ($\sum m_\nu = 0.06$ eV)[28]. The precision on the determination of $N_{\rm eff}$ will shed light on the presence of new light particles, such as the mediators of neutrino non-standard interactions. If future cosmological bounds confirm that $N_{\rm eff} = 4$ is excluded, and, at the same time, they indicate a deviation (either positive or negative) from $N_{\rm eff}^{\rm SM} = 3.045$, this will be a compelling evidence for a new hidden sector.

- **Astrophysics.** Future supernovae explosions might improve the constraints on neutrino self-interactions[29] overcoming the current uncertainty due to the modeling of neutrino oscillations inside the supernovae. The constraints are based on the energy loss due to the annihilation of sterile neutrinos into pseudoscalars. Moreover, astrophysical neutrinos scattering off neutrinos from the cosmic background can also induce a detectable signal in the future upgrade of IceCube[30].

- **Experimental Particle Physics.** Future measurements of neutrinoless double-beta decay with the emission of a pseudoscalar, which practically behaves as a Majoron, would be a clear hint of the pseudoscalar model. Additional signatures of the presence of a pseudoscalar would be an increased invisible decay width of the Z-boson due to the process $Z \to \nu_a + \bar{\nu}_4 + \phi$; and small corrections in neutrino oscillations due to scattering between $\nu_4$ and $\phi$. Finally, it should be noted that here the discussion is focussed on non-standard interactions confined to the sterile sector; several additional experimental bounds can indeed constrain non-standard interactions if extended to active neutrinos[31].

Although none of the aforementioned effects alone represents a smoking gun, they demonstrate how the discovery of new physics such as sterile neutrinos with non-standard interactions can be triggered by a multi-field action plan.

### Summary

In the next decade a wide program of neutrino oscillation experiments[32–35] is set to provide the definitive answer about sterile neutrinos. Taken at face value, the existence of additional neutrino species would cause a new cosmological problem, whose solution requires physics beyond the standard model. Non-standard interactions represent an elegant way to accommodate sterile neutrinos in cosmology. In the near future the complementarity of cosmological surveys and astrophysical observations, as well as particle physics experiments, will be essential to proving the presence of this new hidden sector.

## References

[1] C. Athanassopoulos *et al.* [LSND], Phys. Rev. Lett. **77**, 3082-3085 (1996) `http://dx.doi.org/10.1103/PhysRevLett.77.3082` [`http://arxiv.org/abs/arXiv:nucl-ex/9605003` [nucl-ex]].

[2] A. Aguilar-Arevalo *et al.* [LSND], beam," Phys. Rev. D **64**, 112007 (2001) `http://dx.doi.org/10.1103/PhysRevD.64.112007` [`http://arxiv.org/abs/arXiv:hep-ex/0104049` [hep-ex]].

[3] J. N. Abdurashitov *et al.*, Phys. Rev. C **73**, 045805 (2006) `http://dx.doi.org/10.1103/PhysRevC.73.045805` [`http://arxiv.org/abs/arXiv:nucl-ex/0512041` [nucl-ex]].

[4] C. Giunti and M. Laveder, Mod. Phys. Lett. A **22**, 2499-2509 (2007) `http://dx.doi.org/10.1142/S0217732307025455` [`http://arxiv.org/abs/arXiv:hep-ph/0610352` [hep-ph]].

[5] G. Mention, M. Fechner, T. Lasserre, T. A. Mueller, D. Lhuillier, M. Cribier and A. Letourneau, Phys. Rev. D **83**, 073006 (2011) `http://dx.doi.org/10.1103/PhysRevD.83.073006` [`http://arxiv.org/abs/arXiv:1101.2755` [hep-ex]].

[6] N. Aghanim *et al.* [Planck], [`http://arxiv.org/abs/arXiv:1807.06209` [astro-ph.CO]].

[7] P. F. de Salas and S. Pastor, JCAP **1607**, 051 (2016) `http://dx.doi.org/10.1088/1475-7516/2016/07/051` [`http://arxiv.org/abs/arXiv:1606.06986` [hep-ph]].

[8] F. Beutler, C. Blake, M. Colless, D. H. Jones, L. Staveley-Smith, L. Campbell, Q. Parker, W. Saunders and F. Watson, Mon. Not. Roy. Astron. Soc. **416**, 3017-3032 (2011) `http://dx.doi.org/10.1111/j.1365-2966.2011.19250.x` [`http://arxiv.org/abs/arXiv:1106.3366` [astro-ph.CO]].

[9] A. J. Ross, L. Samushia, C. Howlett, W. J. Percival, A. Burden and M. Manera, Mon. Not. Roy. Astron. Soc. **449**, no.1, 835-847 (2015) `http://dx.doi.org/10.1093/mnras/stv154` [`http://arxiv.org/abs/arXiv:1409.3242` [astro-ph.CO]].

[10] S. Alam *et al.* [BOSS], Mon. Not. Roy. Astron. Soc. **470**, no.3, 2617-2652 (2017) `http://dx.doi.org/10.1093/mnras/stx721` [`http://arxiv.org/abs/arXiv:1607.03155` [astro-ph.CO]].

[11] S. Hannestad, I. Tamborra and T. Tram, JCAP **1207**, 025 (2012) `http://dx.doi.org/10.1088/1475-7516/2012/07/025` [`http://arxiv.org/abs/arXiv:1204.5861` [astro-ph.CO]].

[12] S. Gariazzo, P. F. de Salas and S. Pastor, JCAP **07**, 014 (2019) `http://dx.doi.org/10.1088/1475-7516/2019/07/014` [`http://arxiv.org/abs/arXiv:1905.11290` [astro-ph.CO]].

[13] S. Hannestad, R. S. Hansen and T. Tram, Phys. Rev. Lett. **112** (2014) no.3, 031802 `http://dx.doi.org/10.1103/PhysRevLett.112.031802` [`http://arxiv.org/abs/arXiv:1310.5926` [astro-ph.CO]].

[14] B. Dasgupta and J. Kopp, Phys. Rev. Lett. **112** (2014) no.3, 031803 `http://dx.doi.org/10.1103/PhysRevLett.112.031803` [`http://arxiv.org/abs/arXiv:1310.6337` [hep-ph]].

[15] X. Chu, B. Dasgupta, M. Dentler, J. Kopp and N. Saviano, JCAP **11** (2018), 049 `http://dx.doi.org/10.1088/1475-7516/2018/11/049` [`http://arxiv.org/abs/arXiv:1806.10629` [hep-ph]].

[16] M. Archidiacono, S. Hannestad, R. S. Hansen and T. Tram, Phys. Rev. D **91**, no.6, 065021 (2015) `http://dx.doi.org/10.1103/PhysRevD.91.065021` [`http://arxiv.org/abs/arXiv:1404.5915` [astro-ph.CO]].

[17] M. Archidiacono, S. Hannestad, R. S. Hansen and T. Tram, Phys. Rev. D **93**, no.4, 045004 (2016) `http://dx.doi.org/10.1103/PhysRevD.93.045004` [`http://arxiv.org/abs/arXiv:1508.02504` [astro-ph.CO]].

[18] J. F. Beacom, N. F. Bell and S. Dodelson, Phys. Rev. Lett. **93**, 121302 (2004) `http://dx.doi.org/10.1103/PhysRevLett.93.121302` [`http://arxiv.org/abs/arXiv:astro-ph/0404585` [astro-ph]].

[19] M. Archidiacono, S. Gariazzo, C. Giunti, S. Hannestad, R. Hansen, M. Laveder and T. Tram, JCAP **08**, 067 (2016) http://dx.doi.org/10.1088/1475-7516/2016/08/067 [http://arxiv.org/abs/arXiv:1606.07673 [astro-ph.CO]].

[20] M. Archidiacono, S. Gariazzo, C. Giunti, S. Hannestad and T. Tram, [http://arxiv.org/abs/arXiv:2006.12885 [astro-ph.CO]].

[21] A. G. Riess, S. Casertano, W. Yuan, L. M. Macri and D. Scolnic, Astrophys. J. **876**, no.1, 85 (2019) http://dx.doi.org/10.3847/1538-4357/ab1422 [http://arxiv.org/abs/arXiv:1903.07603 [astro-ph.CO]].

[22] C. D. Kreisch, F. Y. Cyr-Racine and O. Dore, Phys. Rev. D **101** (2020) no.12, 123505 http://dx.doi.org/10.1103/PhysRevD.101.123505 [http://arxiv.org/abs/arXiv:1902.00534 [astro-ph.CO]].

[23] N. Blinov and G. Marques-Tavares, [http://arxiv.org/abs/arXiv:2003.08387 [astro-ph.CO]].

[24] P. Ade *et al.* [Simons Observatory], JCAP **02**, 056 (2019) http://dx.doi.org/10.1088/1475-7516/2019/02/056 [http://arxiv.org/abs/arXiv:1808.07445 [astro-ph.CO]].

[25] K. Abazajian *et al.* , Bull. Am. Astron. Soc. **51**, no.7, 209 (2019) http://dx.doi.org/10.2172/1556957 [[http://arxiv.org/abs/arXiv:1908.01062 [astro-ph.IM]].

[26] R. Laureijs *et al.* [EUCLID], [http://arxiv.org/abs/arXiv:1110.3193 [astro-ph.CO]].

[27] P. A. Abell *et al.* [LSST Science and LSST Project], [[http://arxiv.org/abs/arXiv:0912.0201 [astro-ph.IM]].

[28] T. Sprenger, M. Archidiacono, T. Brinckmann, S. Clesse and J. Lesgourgues, JCAP **02**, 047 (2019) http://dx.doi.org/10.1088/1475-7516/2019/02/047 [http://arxiv.org/abs/arXiv:1801.08331 [astro-ph.CO]].

[29] Y. Farzan, Phys. Rev. D **67**, 073015 (2003) http://dx.doi.org/10.1103/PhysRevD.67.073015 [http://arxiv.org/abs/arXiv:hep-ph/0211375 [hep-ph]].

[30] J. F. Cherry, A. Friedland and I. M. Shoemaker, [http://arxiv.org/abs/arXiv:1605.06506 [hep-ph]].

[31] P. S. Bhupal Dev, K. S. Babu, P. B. Denton, P. A. N. Machado, C. A. Arguelles, J. L. Barrow, S. S. Chatterjee, M. C. Chen, A. de Gouvea, B. Dutta, D. Goncalves, T. Han, M. Hostert, S. Jana, K. J. Kelly, S. W. Li, I. Martinez-Soler, P. Mehta, I. Mocioiu, Y. F. Perez-Gonzalez, J. Salvado, I. M. Shoemaker, M. Tammaro, A. Thapa, J. Turner and X. J. Xu, SciPost Phys. Proc. **2** (2019), 001 http://dx.doi.org/10.21468/SciPostPhysProc.2.001 [http://arxiv.org/abs/arXiv:1907.00991 [hep-ph]].

[32] L. Stanco, [http://arxiv.org/abs/arXiv:1604.06769 [hep-ph]].

[33] B. Caccianiga, AIP Conf. Proc. **1666**, no.1, 180002 (2015) http://dx.doi.org/10.1063/1.4915599

[34] D. Lhuillier, AIP Conf. Proc. **1666**, no.1, 180003 (2015) http://dx.doi.org/10.1063/1.4915600

[35] J. Spitz, AIP Conf. Proc. **1666**, no.1, 180004 (2015) `http://dx.doi.org/10.1063/1.4915601`