Constraints on secret interactions among sterile neutrinos from Planck 2015 data

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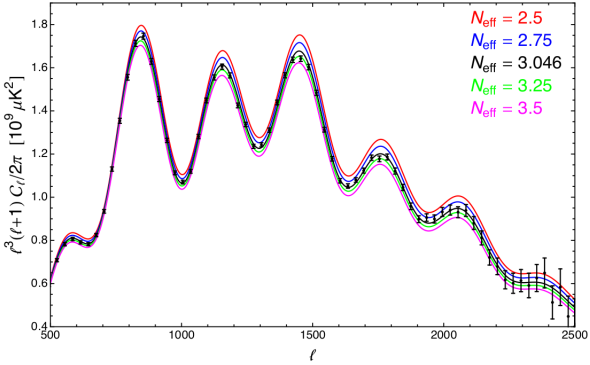
Summary

- Standard neutrino cosmology
- SBL anomalies
- Sterile neutrinos
- Non-standard interactions
- Sterile neutrinos with non-standard interactions
- Results
- Conclusions

Standard neutrino cosmology

- The theoretical value for $N_{\rm eff}$ in the ΛCDM model for three active neutrino families is:

$$N_{\rm eff} = 3.046$$

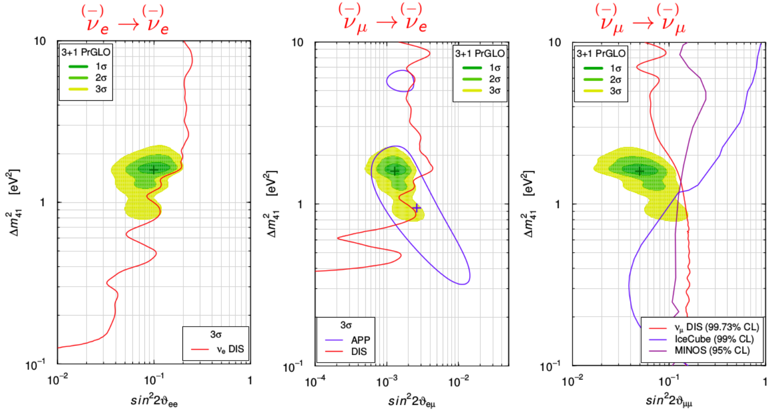


[credits: M.Lattanzi]

$$N_{\rm eff} = 3.13 \pm 0.32\,(Planck TT + lowP)$$
$$N_{\rm eff} = 2.99 \pm 0.20\,(Planck TT, TE, EE + lowP)$$

Short Baseline (SBL) anomalies

Short baseline laboratory experiments (SBL) show anomalies that can be fitted by light sterile neutrinos. (Gallium, MiniBooNE, Reactor, LSND)
light $\rightarrow\ m_{\nu s} \sim O(\mathrm{eV})$



[Gariazzo, CG, Laveder, Li, Zavanin, JPG 43 (2016) 033001]

Sterile neutrinos

The immediate interpretation is a light sterile neutrino, however the introduction of an extra component impacts on N_{eff} depending on the model assumed:

a) Thermal distribution of sterile νs
b) Dodelson-Widrow (depending on a scale factor χ_s)

Cosmologically speaking we parametrize phenomenologically in this way:

$$\rho_\nu + \rho_x = \frac{7}{8}\frac{\pi^2}{15} T_\nu^4 \left(N_{eff}^{SM} + \Delta N_{eff} \right) \quad (1)$$

Extra degrees of freedom

$$\Delta N_{eff} = \begin{cases} \left(\frac{T_s}{T_\nu}\right)^4 & [a] \\ \chi_s & [b] \end{cases}$$

mass of the sterile

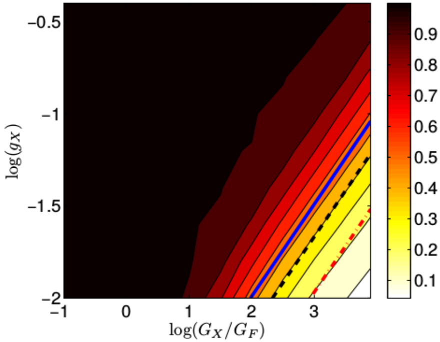
$$m_s = \begin{cases} m_s^{eff} \left(\frac{T_s}{T_\nu}\right)^3 = m_s^{eff} \Delta_{Neff}^{\frac{3}{4}} & [a] \\ \frac{m_s^{eff}}{\chi_s} = \frac{m_s^{eff}}{\Delta_{Neff}} & [b] \end{cases}$$

Compatible with the prediction of the SM, this excludes a possible extra thermalized neutrino (sterile or active) at 3 and 5σ

Sterile neutrinos having non-standard interactions

[Hannestad et al., 2013]

Introducing a new secret interaction between sterile neutrinos mediated by a massive boson having $M_X < M_{W\pm}$ can suppress the thermalization.



$$\mathcal{L}_{\rm int} = g_X \bar{\nu}_s \gamma_\mu \left(1-\gamma^5\right) \nu_s X^\mu$$

It behaves like the standard Weak interaction:

$$\sigma_x = G_X^2 T_\nu^2 , \qquad \Gamma_X = G_X^2 T_\nu^5$$

compared with the Hubble expansion rate:

$$\frac{\Gamma_X}{H} \propto T^{\frac{7}{2}} \,[\mathrm{MD}] \qquad (2)$$

If $G_X > G_F$, neutrino-neutrino collisions stay in equilibrium longer than weak interactions.

Color legend corresponds to ΔN_{eff}.
Solid, dashed, and dot-dashed lines are $M_X = 300\,\mathrm{MeV}$, $200\,\mathrm{MeV}$ and $100\,\mathrm{MeV}$ respectively.

[A.Mirizzi et al. 2016]

Large coupling constant ($G_X \sim 10^4 - 10^5\ G_F$) $\rightarrow$ copious production of sterile neutrinos by the scattering $\rightarrow$ quick flavor equilibration.

$$\nu_s \simeq \sin\theta_s \nu_1 + \cos\theta_s \nu_4$$

The scattering process $\rightarrow$ νs Fermi-Dirac distribution $\rightarrow$ push towards oscillations between sterile and active states through a mixing angle θ_s.

$$\rho_\nu^{in} = 3 \cdot \frac{7}{8} \left(\frac{4}{11}\right)^{\frac{4}{3}} \rho_\gamma \,,$$

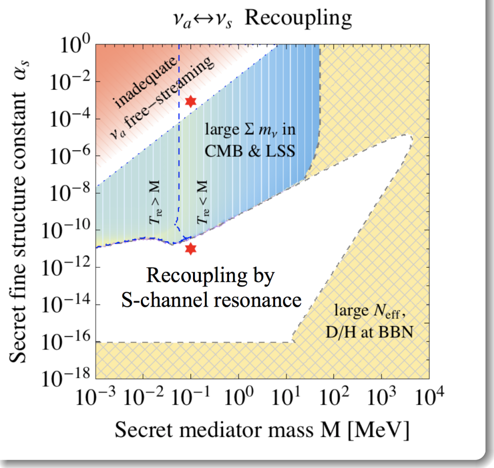
$$\rho_\nu^{fin} = 4 \cdot \left(\frac{3}{4}\right)^{\frac{4}{3}} \frac{7}{8} \left(\frac{4}{11}\right)^{\frac{4}{3}} \rho_\gamma \,,$$

Entropy conservation

$$N_{eff} = 4 \cdot \left(\frac{3}{4}\right)^{\frac{4}{3}} \sim 2.7 \,.$$

2σ within Planck 2015 constraints.

[X. Chu 2015]



2D plane $\alpha_s - M_X$ for sterile neutrinos interactions. (LSS, CMB (mass), BBN, free streaming)

Here $\alpha_s \sim g_X^2/4\pi$

Red star are the best-fits (small and large values of G_X)

The white regions are allowed by current constraints.

Working with the CMB

Method and data

Datasets

Planck 2015 cosmological data. (PlanckTT)

- Third-generation CMB ESA satellite
- Angular resolution form $30'$ to $5'$ and sensitivity $\Delta T/T \sim 2 \cdot 10^{-6}$

Baryon Acoustic Oscillation (BAO) data. (PlanckTT+BAO)

- Geometrical information from the BAO results from the 6dF Galaxy Survey, BOSS DR11 LOWZ, CMASS samples and the Main Galaxy Sample of the Sloan Digital Sky Survey.

Investigating the parameters space (PS)

- 3 active massive neutrinos having $\sum_\nu m_\nu = 0.06\mathrm{eV}$, and 1 sterile neutrino.

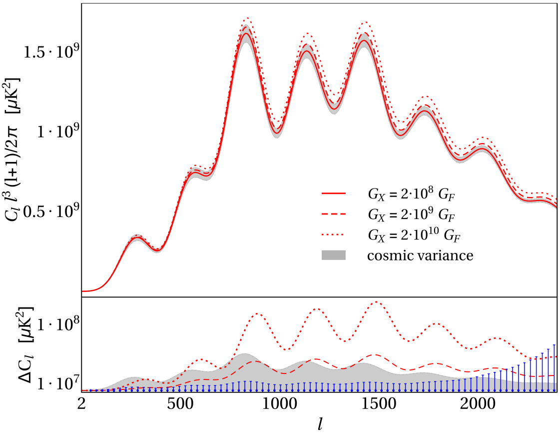
$\Lambda\mathrm{CDM}$	Standard six-parameter $\Lambda\mathrm{CDM}$, $N_{\mathrm{eff}} = 3.046$.
$\mathrm{S}\Lambda\mathrm{CDM\_GX0}$	Sterile neutrino extension, $N_{\mathrm{eff}} = 2.7$, m_s free, "small" G_X ($\sim 10^8 G_F$).
$\mathrm{S}\Lambda\mathrm{CDM}$	Sterile neutrino extension, $N_{\mathrm{eff}} = 2.7$, m_s and G_X free.
$\mathrm{S}\Lambda\mathrm{CDM\_Narrow}$	Sterile neutrino extension, $N_{\mathrm{eff}} = 2.7$, G_X free, $m_s = 1.27 \pm 0.03\,\mathrm{eV}$ (gaussian prior).
$\mathrm{S}\Lambda\mathrm{CDM\_Broad}$	Sterile neutrino extension, $N_{\mathrm{eff}} = 2.7$, G_X free, $0.93\ \mathrm{eV} \leq m_s \leq 1.43\ \mathrm{eV}$ (flat prior).

In $\mathrm{S}\Lambda\mathrm{CDM}$ models $\theta_s = 0.1$

Effects on the CMB Anisotropies Power Spectrum

We use CAMB and CosmoMC.
Introducing a collisional term in the Boltzmann equation.

$$\frac{\partial \Psi_i}{\partial \tau} + i\frac{q(\vec{k}\cdot\hat{n})}{\epsilon}\Psi_i + \frac{d\ln f_0}{d\ln q}\left[\dot{\eta} - \frac{\dot{h}+6\dot{\eta}}{2}\left(\hat{k}\cdot\hat{n}\right)^2\right] = -\Gamma_{ij}\Psi_j\,,$$



We will use the relaxation time approximation:

$$\Gamma_{ij} \sim [\theta_{ij}]aG_X^2\,T_\nu^5$$

This suppresses the shear and increases the pressure in the Boltzman hierarchy.

Most relevant parameters for the considered models (PlanckTT):

Parameter	ΛCDM	SΛCDM_GX0	SΛCDM	SΛCDM_Broad	SΛCDM_Narrow
$\Omega_b h^2$	0.02222 ± 0.00023	0.02177 ± 0.00024	0.02172 ± 0.00025	0.02167 ± 0.00025	$0.02166^{+0.00024}_{-0.00024}$
$\Omega_c h^2$	0.1197 ± 0.0021	0.1167 ± 0.0022	0.1171 ± 0.0023	0.1165 ± 0.0022	0.1160 ± 0.0021
$100\theta_{MC}$	1.04085 ± 0.00047	1.04103 ± 0.00050	$1.04323^{+0.00091}_{-0.00073}$	1.04319 ± 0.00074	$1.04307^{+0.0010}_{-0.00077}$
τ	0.078 ± 0.019	0.070 ± 0.018	0.065 ± 0.018	0.067 ± 0.018	0.066 ± 0.018
n_s	0.9655 ± 0.0061	0.9448 ± 0.0070	0.9284 ± 0.0088	$0.9191^{+0.0076}_{-0.0078}$	$0.9161^{+0.0081}_{-0.0072}$
$\ln(10^{10} A_s)$	3.089 ± 0.036	3.063 ± 0.035	3.023 ± 0.038	3.027 ± 0.037	3.028 ± 0.036
G_X/G_F	–	10^8	$< 2.8 \times 10^{10}$	$< 2.9 \times 10^{10}$	$< 4.0 \times 10^{10}$
m_s	–	< 0.82	< 0.82	$[0.93, 1.30]$	1.27 ± 0.028
H_0	67.31 ± 0.95	$62.2^{+2.0}_{-1.7}$	$62.6^{+1.8}_{-1.8}$	59.56 ± 0.88	$58.91^{+0.82}_{-0.79}$

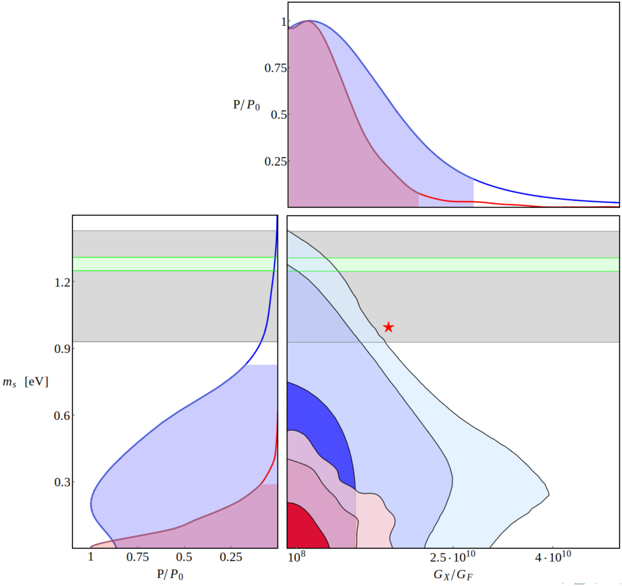
Goodness of fit:

Parameter	ΛCDM	SΛCDM_GX0	SΛCDM	SΛCDM_Broad	SΛCDM_Narrow
$\chi^2_{\min}$	11265.1	11272.8	11269.0	11275.2	11277.6

Constrained parameters for SΛCDM (PlanckTT+BAO)

Parameter	SΛCDM
$\Omega_b h^2$	0.02197 ± 0.00021
$\Omega_c h^2$	$0.1144^{+0.0016}_{-0.0015}$
$100\theta_{MC}$	$1.04332^{+0.00090}_{-0.00063}$
τ	0.074 ± 0.018
n_s	0.9392 ± 0.0063
$\ln(10^{10} A_s)$	3.038 ± 0.036
G_X / G_F	$< 1.97 \times 10^{10}$
m_s	< 0.29
H_0	65.26 ± 0.68

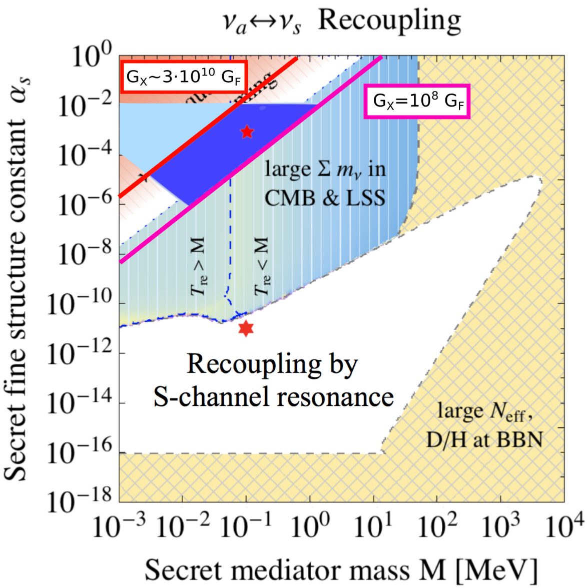
Results (Constraints)



(PlanckTT)
(PlanckTT+BAO)

Broad
Narrow

The red star at $G_X = 1.5 \times 10^{10} G_F$ and $m_s = 1$ eV is representative of the strongly self-interacting scenario described in [X. Chu, et. al 2015]



$\nu_a \leftrightarrow \nu_s$ Recoupling
$G_X \sim 3\cdot10^{10}$ G_F
$G_X = 10^8$ G_F
large $\Sigma\, m_\nu$ in
CMB & LSS
$T_{re} > M$
$T_{re} < M$
Recoupling by
S-channel resonance
large N_{eff},
D/H at BBN
Secret fine structure constant α_s
Secret mediator mass M [MeV]
10^0
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-18}
10^{-3} 10^{-2} 10^{-1} 10^0 10^1 10^2 10^3 10^4

Conclusions

- We have tested neutrino SBL anomalies with CMB data considering the existence of a Fermi-like non-standard neutrino interaction in order to avoid the increase in N_{eff} due to the thermalization of the sterile eigenstate.
- The goodness of fit of the model considered, obtained using CMB data, is worse than the ΛCDM one.
- Imposing the sterile mass suggested by SBL it enlarge the $H0$ tension with the HST measurement and introduce a $4-5\sigma$ shift also in the n_s parameter with respect the standard ΛCDM value.
- Using different data the $\alpha_s - M_X$ parameter space is extremely reduced. No space for sterile Fermi-like interacting neutrinos.

Thank you

Backup Slides

The interaction is implemented in the Boltzmann hierarchy, the scattering rate becomes:

$$\Gamma_{ij} = (3/2)(\zeta(3)/\pi^2)\ G_X^2 \begin{pmatrix} sin^2\theta_s & 0 & 0 & sin\theta_s\, cos\theta_s \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ sin\theta_s\, cos\theta_s & 0 & 0 & cos^2\theta_s \end{pmatrix} T_\nu^5 \tag{3}$$

Allowing scattering processes inside the sterile sector and mixing between the first and the fourth massive eigenstates.

$$\dot{\Psi}_{i,0} = -\frac{qk}{\epsilon}\Psi_{i,1} + \frac{1}{6}\dot{h}\frac{d\ln f_0}{d\ln q}\,,$$

$$\dot{\Psi}_{i,1} = \frac{qk}{3\epsilon}\left(\Psi_{i,0} - 2\Psi_{i,2}\right)\,,$$

$$\dot{\Psi}_{i,2} = \frac{qk}{5\epsilon}\left(2\Psi_{i,1} - 3\Psi_{i,3}\right) - \left(\frac{1}{15}\dot{h} + \frac{2}{5}\dot{\eta}\right)\frac{d\ln f_0}{d\ln q} - \Gamma_{ij}\Psi_{j,2}\,,$$

$$\dot{\Psi}_{i,\ell} = \frac{qk}{(2\ell+1)\epsilon}\left[\ell\Psi_{i,(\ell-1)} - (\ell+1)\Psi_{i,(\ell+1)}\right] - \Gamma_{ij}\Psi_{j,\ell} \quad (\ell \geq 3)\,,$$

At early times the interaction is very strong → tight coupling approximation:

$$\dot{\Psi}_0 = -\frac{4}{3}\frac{q}{\epsilon}\Psi_1 - \frac{2}{3}\dot{h},$$
$$\dot{\Psi}_1 = k^2\frac{q}{\epsilon}\left(\frac{1}{4}\Psi_0 - \Psi_2\right),$$
$$\Psi_2 = -\Gamma_x^{-1}\left[\frac{2}{5}k\frac{q}{\epsilon}\Psi_1 + \frac{2}{15}\dot{h} + \frac{4}{5}\dot{\eta}\right]$$