Constraints on secret interactions among sterile neutrinos from Planck 2015 data
Based on JCAP_046P_0417

Francesco Forastieri

Department of Physics and Earth Science, University of Ferrara and INFN Ferrara

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Work in collaboration with M.Lattanzi, P.Natoli, N.Saviano, A.Mirizzi, G.Mangano
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 $N_{\text{eff}}$ in the $\Lambda$CDM model for three active neutrino families is:

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

$$N_{\text{eff}} = 3.13 \pm 0.32 \ (\text{Planck} \ TT + \text{lowP})$$

$$N_{\text{eff}} = 2.99 \pm 0.20 \ (\text{Planck} \ TT, \ TE, \ EE + \text{lowP})$$
Short Baseline (SBL) anomalies

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

\[ (-) \nu_e \rightarrow (-) \nu_e \quad (\nu_\mu \rightarrow \nu_e) \quad (\nu_\mu \rightarrow \nu_\mu) \]

[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 $N_{\text{eff}}$ depending on the model assumed:

a) Thermal distribution of sterile $\nu_s$

b) Dodelson-Widrow (depending on a scale factor $\chi_s$)

Cosmologically speaking we parametrize phenomenologically in this way:

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

(1)

Extra degrees of freedom

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

mass of the sterile

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

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

\[ \mathcal{L}_{\text{int}} = g_X \bar{\nu}_s \gamma_\mu (1 - \gamma^5) \nu_s X^\mu \]

It behaves like the standard Weak interaction:

\[ \sigma_X = G_X^2 T^2_\nu, \quad \Gamma_X = G_X^2 T^5_\nu \]

compared with the Hubble expansion rate:

\[ \frac{\Gamma_X}{H} \propto T^{7/2} \text{ [MD]} \] (2)

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

Color legend corresponds to $\Delta N_{\text{eff}}$.
Solid, dashed, and dot-dashed lines are $M_X = 300\text{ MeV}$, $200\text{ MeV}$ and $100\text{ MeV}$ respectively.
Large coupling constant \((G_X \sim 10^4 - 10^5 \ G_F) \) → copious production of sterile neutrinos by the scattering → quick flavor equilibration.

\[ \nu_s \simeq \sin \theta_s \nu_1 + \cos \theta_s \nu_4 \]

The scattering process \(\nu_s\) Fermi-Dirac distribution → push towards oscillations between sterile and active states through a mixing angle \(\theta_s\).

\[ \rho^\text{in}_\nu = 3 \cdot \frac{7}{8} \left( \frac{4}{11} \right)^{\frac{4}{3}} \rho_\gamma , \]

\[ \rho^\text{fin}_\nu = 4 \cdot \left( \frac{3}{4} \right)^{\frac{4}{3}} \frac{7}{8} \left( \frac{4}{11} \right)^{\frac{4}{3}} \rho_\gamma , \]

Entropy conservation

\[ N_{\text{eff}} = 4 \cdot \left( \frac{3}{4} \right)^{\frac{4}{3}} \sim 2.7 . \]

\(2\sigma\) within Planck 2015 constraints.
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 $\sum m_\nu = 0.06\text{eV}$, and 1 sterile neutrino.

<table>
<thead>
<tr>
<th>Model</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Lambda$CDM</td>
<td>Standard six-parameter $\Lambda$CDM, $N_{\text{eff}} = 3.046$.</td>
</tr>
<tr>
<td>$S\Lambda$CDM_GX0</td>
<td>Sterile neutrino extension, $N_{\text{eff}} = 2.7$, $m_s$ free, “small” $G_X \sim 10^8 G_F$.</td>
</tr>
<tr>
<td>$S\Lambda$CDM</td>
<td>Sterile neutrino extension, $N_{\text{eff}} = 2.7$, $m_s$ and $G_X$ free.</td>
</tr>
<tr>
<td>$S\Lambda$CDM_Narrow</td>
<td>Sterile neutrino extension, $N_{\text{eff}} = 2.7$, $G_X$ free, $m_s = 1.27 \pm 0.03\text{eV}$ (gaussian prior).</td>
</tr>
<tr>
<td>$S\Lambda$CDM_Broad</td>
<td>Sterile neutrino extension, $N_{\text{eff}} = 2.7$, $G_X$ free, $0.93\text{eV} \leq m_s \leq 1.43\text{eV}$ (flat prior).</td>
</tr>
</tbody>
</table>

In $S\Lambda$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:

\[
\Gamma_{ij} \sim [\theta_{ij}] a G_X^2 T_\nu^5
\]

This suppresses the shear and increases the pressure in the Boltzmann hierarchy.
Most relevant parameters for the considered models (PlanckTT):

<table>
<thead>
<tr>
<th>Parameter</th>
<th>ΛCDM</th>
<th>SACDM_GX0</th>
<th>SACDM</th>
<th>SACDM_Broad</th>
<th>SACDM_Narrow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ω_b h^2</td>
<td>0.02222 ± 0.00023</td>
<td>0.02177 ± 0.00024</td>
<td>0.02172 ± 0.00025</td>
<td>0.02167 ± 0.00025</td>
<td>0.02166±0.00024</td>
</tr>
<tr>
<td>Ω_c h^2</td>
<td>0.1197 ± 0.0021</td>
<td>0.1167 ± 0.0022</td>
<td>0.1171 ± 0.0023</td>
<td>0.1165 ± 0.0022</td>
<td>0.1160 ± 0.0021</td>
</tr>
<tr>
<td>100θ_MC</td>
<td>1.04085 ± 0.00047</td>
<td>1.04103 ± 0.00050</td>
<td>1.04323+0.00091−0.00073</td>
<td>1.04319 ± 0.00074</td>
<td>1.04307+0.0010−0.00077</td>
</tr>
<tr>
<td>τ</td>
<td>0.078 ± 0.019</td>
<td>0.070 ± 0.018</td>
<td>0.065 ± 0.018</td>
<td>0.067 ± 0.018</td>
<td>0.066 ± 0.018</td>
</tr>
<tr>
<td>n_s</td>
<td>0.9655 ± 0.0061</td>
<td>0.9448 ± 0.0070</td>
<td>0.9284 ± 0.0088</td>
<td>0.9191+0.0076−0.0078</td>
<td>0.9161+0.0081−0.0072</td>
</tr>
<tr>
<td>ln(10^{10} A_s)</td>
<td>3.089 ± 0.036</td>
<td>3.063 ± 0.035</td>
<td>3.023 ± 0.038</td>
<td>3.027 ± 0.037</td>
<td>3.028 ± 0.036</td>
</tr>
<tr>
<td>G_X / G_F</td>
<td>–</td>
<td>10^8</td>
<td>&lt; 2.8 × 10^{10}</td>
<td>&lt; 2.9 × 10^{10}</td>
<td>&lt; 4.0 × 10^{10}</td>
</tr>
<tr>
<td>m_s</td>
<td>–</td>
<td>&lt; 0.82</td>
<td>&lt; 0.82</td>
<td>[0.93, 1.30]</td>
<td>1.27 ± 0.028</td>
</tr>
<tr>
<td>H_0</td>
<td>67.31 ± 0.95</td>
<td>62.2^{+2.0}_{-1.7}</td>
<td>62.6^{+1.8}_{-1.8}</td>
<td>59.56 ± 0.88</td>
<td>58.91^{+0.82}_{-0.79}</td>
</tr>
</tbody>
</table>

Goodness of fit:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>ΛCDM</th>
<th>SACDM_GX0</th>
<th>SACDM</th>
<th>SACDM_Broad</th>
<th>SACDM_Narrow</th>
</tr>
</thead>
<tbody>
<tr>
<td>χ^2_{min}</td>
<td>11265.1</td>
<td>11272.8</td>
<td>11269.0</td>
<td>11275.2</td>
<td>11277.6</td>
</tr>
</tbody>
</table>
Constrained parameters for $S\Lambda\text{CDM}$ (PlanckTT+BAO)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$S\Lambda\text{CDM}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Omega_b h^2$</td>
<td>$0.02197 \pm 0.00021$</td>
</tr>
<tr>
<td>$\Omega_c h^2$</td>
<td>$0.1144^{+0.0016}_{-0.0015}$</td>
</tr>
<tr>
<td>$100\theta_{MC}$</td>
<td>$1.04332^{+0.00090}_{-0.00063}$</td>
</tr>
<tr>
<td>$\tau$</td>
<td>$0.074 \pm 0.018$</td>
</tr>
<tr>
<td>$n_s$</td>
<td>$0.9392 \pm 0.0063$</td>
</tr>
<tr>
<td>$\ln(10^{10} A_s)$</td>
<td>$3.038 \pm 0.036$</td>
</tr>
<tr>
<td>$G_X / G_F$</td>
<td>$&lt; 1.97 \times 10^{10}$</td>
</tr>
<tr>
<td>$m_s$</td>
<td>$&lt; 0.29$</td>
</tr>
<tr>
<td>$H_0$</td>
<td>$65.26 \pm 0.68$</td>
</tr>
</tbody>
</table>
The red star at $G_X = 1.5 \times 10^{10} G_F$ and $m_s = 1 \text{ eV}$ is representative of the strongly self-interacting scenario described in [X. Chu, et. al 2015].
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 $N_{\text{eff}}$ due to the thermalization of the sterile eigenstate.

- The goodness of fit of the model considered, obtained using CMB data, is worse than the $\Lambda$CDM 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 $\Lambda$CDM value.

- Using different data the $\alpha_s - M_X$ parameter space is extremely reduced. No space for sterile Fermi-like interacting neutrinos.
Thank you
The interaction is implemented in the Boltzmann hierarchy, the scattering rate becomes:

\[
\Gamma_{ij} = (3/2)(\zeta(3)/\pi^2) \ G_X^2 \begin{pmatrix}
\sin^2 \theta_s & 0 & 0 & \sin \theta_s \cos \theta_s \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
\sin \theta_s \cos \theta_s & 0 & 0 & \cos^2 \theta_s \\
\end{pmatrix} \ T^5_\nu
\]

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

\[
\dot{\Psi}_{i,0} = -\frac{qk}{\epsilon} \Psi_{i,1} + \frac{1}{6} h \frac{d \ln f_0}{d \ln q}, \\
\dot{\Psi}_{i,1} = \frac{qk}{3 \epsilon} (\Psi_{i,0} - 2 \Psi_{i,2}), \\
\dot{\Psi}_{i,2} = \frac{qk}{5 \epsilon} (2 \Psi_{i,1} - 3 \Psi_{i,3}) - \left( \frac{1}{15} h + \frac{2}{5} \eta \right) \frac{d \ln f_0}{d \ln q} - \Gamma_{ij} \Psi_{j,2}, \\
\dot{\Psi}_{i,\ell} = \frac{qk}{(2\ell + 1) \epsilon} \left[ \ell \Psi_{i,(\ell-1)} - (\ell + 1) \Psi_{i,(\ell+1)} \right] - \Gamma_{ij} \Psi_{j,\ell} \quad (\ell \geq 3),
\]
At early times the interaction is very strong $\rightarrow$ tight coupling approximation:

\[
\begin{align*}
\dot{\psi}_0 &= -\frac{4}{3} q \frac{\psi_1}{\epsilon} - \frac{2}{3} \dot{h}, \\
\dot{\psi}_1 &= k^2 \frac{q}{\epsilon} \left( \frac{1}{4} \psi_0 - \psi_2 \right), \\
\psi_2 &= -\Gamma_x^{-1} \left[ \frac{2}{5} k \frac{q}{\epsilon} \psi_1 + \frac{2}{15} \dot{h} + \frac{4}{5} \dot{\eta} \right]
\end{align*}
\]