Light sterile neutrinos with pseudoscalar interactions in cosmology

Based on [JCAP 08 (2016) 067]

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Neutrino Oscillations

Analogous to CKM mixing for quarks:

\[ \nu_\alpha = \sum_{k=1}^{3} U_{\alpha k} \nu_k \quad (\alpha = e, \mu, \tau) \]

\(\nu_\alpha\) flavour eigenstates, \(U_{\alpha k}\) PMNS mixing matrix, \(\nu_k\) mass eigenstates.

Current knowledge of the 3 active \(\nu\) mixing: [PDG - Olive et al. (2015)]

\(\Delta m^2_{ji} = m^2_j - m^2_i\), \(\theta_{ij}\) mixing angles

NO: Normal Ordering, \(m_1 < m_2 < m_3\)

IO: Inverted Ordering, \(m_3 < m_1 < m_2\)

\[
\begin{align*}
\Delta m^2_{SOL} &= (7.53 \pm 0.18) \cdot 10^{-5} \text{ eV}^2 \\
\Delta m^2_{ATM} &= (2.44 \pm 0.06) \cdot 10^{-3} \text{ eV}^2 (\text{NO}) \\
&= (2.49 \pm 0.06) \cdot 10^{-3} \text{ eV}^2 (\text{IO}) \\
\sin^2(2\theta_{12}) &= 0.846 \pm 0.021 \\
\sin^2(2\theta_{23}) &= 0.999^{+0.001}_{-0.018} (\text{NO}) - 1.000^{+0.000}_{-0.017} (\text{IO}) \\
\sin^2(2\theta_{13}) &= 0.085 \pm 0.005
\end{align*}
\]

CP violating phase \(\delta_{\text{CP}}\) still unknown. Hint: \(\delta_{\text{CP}} = -\pi/2?\) [T2K Collaboration, 2015]

See various talks in next days
Short Baseline (SBL) anomaly

Problem: anomalies in SBL experiments ⇒ \{ errors in flux calculations? deviations from 3-ν description? \}

A short review:

**LSND** search for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$, with $L/E = 0.4 \div 1.5$ m/MeV. Observed a $3.8\sigma$ excess of $\bar{\nu}_e$ events [Aguilar et al., 2001]

**Reactor** re-evaluation of the expected anti-neutrino flux ⇒ disappearance of $\bar{\nu}_e$ events compared to predictions ($\sim 3\sigma$) with $L < 100$ m [Azabajan et al, 2012]

**Gallium** calibration of GALLEX and SAGE Gallium solar neutrino experiments give a $2.7\sigma$ anomaly (disappearance of $\nu_e$) [Giunti, Laveder, 2011]

**MiniBooNE** (inconclusive) search for $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$, with $L/E = 0.2 \div 2.6$ m/MeV. No $\nu_e$ excess detected, but $\bar{\nu}_e$ excess observed at $2.8\sigma$ [MiniBooNE Collaboration, 2013]

Possible explanation:

Additional squared mass difference

$$\Delta m^2_{SBL} \simeq 1 \text{ eV}^2$$

See various talks in next days
\section*{3+1 Neutrino Model}

SBL anomalies $\Rightarrow \Delta m_{SBL}^2 \simeq 1 \text{ eV}^2$

$\Downarrow$

Existence of an additional neutrino degree of freedom, mass around 1 eV, no weak interaction $\Rightarrow$ light, sterile neutrino ($LS\nu$)

$\Downarrow$

3 active ($m_i \ll 1 \text{ eV}$) + 1 sterile ($m_s \simeq 1 \text{ eV}$) \(\nu\) scenario

We must update our mixing paradigm:

$$\nu_\alpha = \sum_{k=1}^{3+1} U_{\alpha k} \nu_k \quad (\alpha = e, \mu, \tau, s)$$

\(\nu_s\) is mainly \(\nu_4\):

$$m_s \simeq m_4 \simeq \sqrt{\Delta m_{41}^2} \simeq \sqrt{\Delta m_{SBL}^2}$$

\textbf{Active \(\nu\):}

$$\sum m_{\nu,\text{active}} \simeq 0$$

\textbf{Sterile \(\nu\):}

$$0.82 \leq m_s^2 / \text{eV}^2 \leq 2.19 \quad (3\sigma)$$

[SG et al., 2016]
(Relativistic) $LS\nu$ in cosmology: $\Delta N_{\text{eff}}$

**Radiation energy density $\rho_r$ in the early Universe:**

$$\rho_r = \left[1 + \frac{7}{8} \left(\frac{4}{11}\right)^{4/3} N_{\text{eff}}\right] \rho_\gamma = [1 + 0.2271N_{\text{eff}}] \rho_\gamma$$

$\rho_\gamma$ photon energy density, $7/8$ is for fermions, $(4/11)^{4/3}$ due to photon reheating after neutrino decoupling

- $N_{\text{eff}} \rightarrow$ all the radiation contribution not given by photons
- $N_{\text{eff}} \simeq 1$ correspond to a single family of active neutrino, in equilibrium in the early Universe
- Active neutrinos: $N_{\text{eff}} = 3.046$ [Mangano et al., 2005] due to not instantaneous decoupling for the neutrinos
- $+ \text{ Non Standard Interactions: } 3.040 < N_{\text{eff}} < 3.059$ [de Salas et al., 2016]
- additional $LS\nu$ contributes with $\Delta N_{\text{eff}} = N_{\text{eff}} - 3.046$:

$$\Delta N_{\text{eff}} = \frac{\rho_{s}^{\text{rel}}}{\rho_\nu} = \left[\frac{7}{8} \frac{\pi^2}{15} T_\nu^4\right]^{-1} \frac{1}{\pi^2} \int dp \, p^3 f_s(p)$$

[Acero et al., 2009]

$\rho_\nu$ energy density for one active neutrino species, $\rho_{s}^{\text{rel}}$ energy density of $LS\nu$ when relativistic, $p$ neutrino momentum, $f_s(p)$ momentum distribution, $T_\nu = (4/11)^{1/3} T_\gamma$
**LS$\nu$ thermalization**

Using SBL best-fit parameters for the LS$\nu$ ($\Delta m_{41}^2$, $\theta_s$):

[Hannestad et al., JCAP 1207 (2012) 025]  
[Mirizzi et al., PRD 86 (2012) 053009]

(Colors coding $\Delta N_{\text{eff}}$)  

(L: lepton asymmetry)

Unless $L \gtrsim O(10^{-3})$, $\Delta N_{\text{eff}} \approx 1$

See also: [Saviano et al., PRD 87 (2013) 073006], [Hannestad et al., JCAP 08 (2015) 019]
(Non-relativistic) LS$\nu$ in cosmology: $m^\text{eff}_s$ and $m_s$

$m_s \simeq 1 \text{ eV} \rightarrow \nu_s$ is non-relativistic today ($T_\nu \propto 10^{-4} \text{ eV}$)

LS$\nu$ density parameter today:

$$\omega_s = \Omega_s h^2 = \frac{\rho_s}{\rho_c} h^2 = \frac{h^2 m_s}{\rho_c \pi^2} \int dp \ p^2 f_s(p)$$  [Acero et al., 2009]

$\rho_s$ energy density of non-relativistic LS$\nu$, $\rho_c$ critical density and $h$ reduced Hubble parameter

Alternatively:

$$m^\text{eff}_s = 94.1 \text{ eV} \ \omega_s$$  [Planck 2013 Results, XVI]

The factor (94.1 eV) is the same for the active neutrinos:

$$\omega_{\nu, \text{active}} = \sum_{\text{active}} m_\nu / (94.1 \text{ eV})$$

If $f_s(p) = f_{\text{active}}(p)$, $m^\text{eff}_s \equiv m_s$

Thermal production $\Rightarrow f_s(p) = \frac{1}{ep/T_s + 1} \Rightarrow m^\text{eff}_s = \Delta N_{\text{eff}}^{3/4} m_s$
**LSν constraints from cosmology**

**CMB+local:** [Planck Collaboration, 2015]

\[
\begin{align*}
N_{\text{eff}} < 3.7 & \quad (\text{TT+lensing+BAO}) \\
m_s^{\text{eff}} < 0.52 \text{ eV} & \quad [m_s < 5 \text{ eV}]
\end{align*}
\]

**BBN constraints:** \(N_{\text{eff}} = 2.90 \pm 0.22 \) (BBN+\(Y_p\)) [Peimbert et al., 2016]

**Summary:** \(\Delta N_{\text{eff}} = 1\) from LS\(\nu\) incompatible with \(m_s \simeq 1\) eV!

TT=Planck 2015 TT + lowTEB

All the constraints are at 2\(\sigma\) CL
Hubble parameter today:
\[ v = H_0 d, \text{ with } H_0 = H(z = 0) \]

Local measurements: \( H(z = 0) \), local and independent on evolution (model independent, but systematics?)

CMB measurements (probe \( z \simeq 1100 \)): \( H_0 \) from the cosmological evolution (model dependent, well controlled systematics)

Using HST Cepheids:
- [Efstathiou 2013]: \( H_0 = 72.5 \pm 2.5 \text{ Km s}^{-1} \text{ Mpc}^{-1} \)
- [Riess et al., 2016]: \( H_0 = 73.02 \pm 1.79 \text{ Km s}^{-1} \text{ Mpc}^{-1} \) (most recent)

(\( \Lambda \)CDM model - CMB data only)
- [Planck 2013]: \( H_0 = 67.3 \pm 1.2 \text{ Km s}^{-1} \text{ Mpc}^{-1} \)
- [Planck 2015]: \( H_0 = 67.27 \pm 0.66 \text{ Km s}^{-1} \text{ Mpc}^{-1} \)
Tensions on the matter perturbations at small scales

Assuming $\Lambda$CDM model:

- $\sigma_8$: rms fluctuation in total matter (baryons + CDM + neutrinos) in $8h^{-1}\text{ Mpc}$ spheres, today;
- $\Omega_m$: total matter density today divided by the critical density

CFHTLenS weak lensing data alone

[Heymans et al., 2013] (68% CL):

$$\sigma_8(\Omega_m/0.27)^{0.46\pm0.02} = 0.774 \pm 0.04$$

CMB results

[Planck 2013] (68% CL):

$$2\sigma \text{ discrepancy!} = 0.89 \pm 0.03$$

Planck SZ Cluster Counts

[Planck 2013 Results XX] (68% CL):

$$\sigma_8(\Omega_m/0.27)^{0.3} = 0.764 \pm 0.025$$

CMB results

[Planck 2013] (68% CL):

$$3\sigma \text{ discrepancy!} = 0.87 \pm 0.02$$

Qualitatively similar results from SPT clusters, Chandra Cluster Cosmology Project.

Alert!

- is the nonlinear evolution well known?
  see e.g. [Planck 2015 Results, papers XIII and XIV]

- are we taking into account all the astrophysical systematics?
  [Joudaki et al., 2016] [Kitching et al., 2016]
Adding a new interaction

Prevent LS$\nu$ thermalization?

new (hidden) interaction!

e.g.: new broken $U(1)$ symmetry

Coupling confined to sterile sector

pseudoscalar mediator $\phi$

Lagrangian: $\mathcal{L} \sim g_s \phi \bar{\nu}_4 \gamma_5 \nu_4$

$\nu_4$ annihilation into $\phi$ at late times (to avoid mass bounds)

coupling $g_s$ large enough to prevent full $\nu_s$ thermalization

$10^{-6} \lesssim g_s \lesssim 10^{-5}$ is fine

$\phi$ must avoid mass bounds itself

$m_\phi \lesssim 0.1$ eV

matter effect induced by $\phi$

no $\nu_s$ production until after $\nu_a$ decoupling

incomplete thermalization, $N_{\text{eff}} \lesssim 4$

[Archidiacono et al., PRD 91 (2015) 065021]

S. Gariazzo
"Light sterile neutrinos with pseudoscalar interactions in cosmology"
Constraints on the pseudoscalar interaction?

Particle physics constraints on the pseudoscalar?

IceCube constraints on secret interactions?
[Ioka et al., 2014] [Cherry et al., 2014] [Ng et al., 2014] [Cherry et al., 2016]

$\phi$ coupled to $\nu_4$ + IceCube flux made of active flavor neutrinos

very small mixing with $\nu_4$ and interaction rate with $\phi$
[cross section $\propto g_s^2 / s$]

SN energy loss
[Farzan, 2003]

$g_s \lesssim 10^{-4}$

don’t apply

don’t apply

fifth force constraints?
pseudoscalar is spin coupling, but unpolarized medium

don’t apply

IceCube constraints on secret interactions?

S. Gariazzo  “Light sterile neutrinos with pseudoscalar interactions in cosmology”  NOW 2016 - 5/9/16 11/16
Results - I

Standard LS$\nu$ model:
$\Lambda$CDM$ + N_{\text{eff}} + m_s$
($\Lambda$CDM params + free $N_{\text{eff}}$ and $m_s$)

Pseudoscalar model (PSE):
$N_{\text{eff}} = 3.046 + N_{\text{fluid}}$
$N_{\text{fluid}}$: $\nu_s + \phi$ contributions

- Problems with $\Delta N_{\text{eff}} = 1$? solved (incomplete thermalization due to suppression of active-sterile oscillations in primordial plasma);
- mass bounds avoided
  $\Rightarrow$ large $m_s$ allowed and preference for $m_s \simeq 4$ eV;
- high values of $H_0$ predicted by cosmology
  $\Rightarrow$ more compatible with local measurements.

S. Gariazzo “Light sterile neutrinos with pseudoscalar interactions in cosmology” NOW 2016 - 5/9/16
Results - II

- **PSE**: posterior on $m_s$ wider
- preference for high **SBL** peaks? (agreement with recent results by [IceCube, 2016] and [MINOS, 2016])

- **PSE**: very close to **Riess2016** results (better than $\Lambda$CDM+$N_{\text{eff}}+m_s$)
- $\Lambda$CDM+$1\nu_s$: even higher $H_0$, but from $\Delta N_{\text{eff}}=1$ and $m_s \approx 0$. 

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[Archidiacono, SG et al., JCAP 08 (2016) 067]
What about the $\sigma_8$ tension (matter perturbations at small scales)?

**$\Lambda$CDM model:**

- smaller $\Omega_m$ today. Good?
- Also higher $\sigma_8 \Rightarrow$ no improvement! The tension remains.
- due to higher $H_0$, not to reduced matter fluctuations.

**Pseudoscalar model:**
Joint Results

Cosmological results as a prior in SBL analysis:

Cosmological constraints are too much permissive!

- Regions at $\Delta m_{41}^2 \simeq 6$ eV$^2$ (slightly) enlarged
- (small) new region at $\Delta m_{41}^2 \simeq 8.5$ eV$^2$ appears ($3\sigma$ CL only)
- Towards [IceCube, 2016] and [MINOS, 2016] hints for $\Delta m_{41}^2 \gtrsim 1$ eV?

[Archidiacono, SG et al., JCAP 08 (2016) 067]
Conclusions

- light $\nu_s$ ($m_s \simeq 1$ eV) from SBL analysis?
- full thermalization incompatible with cosmological measurements $\times$ (given mass and mixing angles from SBL oscillations)
- $H_0$ and $\sigma_8$ problems?
- New interaction mediated by a pseudoscalar $\phi$:
  - hidden in the sterile sector, no fifth force constraints $\checkmark$
  - light pseudoscalar to avoid mass bounds after $\nu_s$ annihilation $\checkmark$
  - avoid full $\nu_s$ thermalization in the early Universe ($10^{-6} \lesssim g_s \lesssim 10^{-5}$) $\checkmark$
  - matter effect induced by $\phi$ allows $N_{\text{eff}} \lesssim 4$ $\checkmark$
- Results:
  - preference for large $m_s$ $\checkmark$
    - Towards IceCube and MINOS recent results?
  - preference for $H_0$ compatible with local measurements $\checkmark$
  - no solution to matter fluctuations at small scales $\times$

Thank you for the attention
$\Delta N_{\text{eff}}$ and pseudoscalar interaction

[Archidiacono et al., PRD 91 (2015) 065021]

obtained with $\sin^2(2\theta_s) = 0.05$, $m_s = 1$ eV