How to make the short baseline sterile neutrino compatible with cosmology

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Short baseline hints

Arciadocono et al. (1606.07673)

see also Gariazzo et al. (1507.08204) and Collin, Argüelles, Conrad and Shaevitz (1607.00011)
Cosmological bounds

**Bounds on $N_{\text{eff}}$**

CMB anisotropies and Baryon Acoustic Oscillations (BAO):

D/H from BBN:

$\Delta N_{\text{eff}} < 0.2$

at $2\sigma$.

Cyburt et al. (1505.01076)

Planck (1502.01589)
Cosmological bounds

Bounds on $m_{s,\text{eff}}$

CMB anisotropies:

$$\sum m_\nu < 0.72\text{eV}$$  \text{Planck (1502.01589)}

Mass bound with latest BAO:

$$\sum m_\nu < 0.16\text{eV}.$$  \text{BOSS (1607.03155)}
Sterile neutrino production in the early Universe

Dominant production: Oscillations with active neutrinos due to mixing. (mixing angle $\theta$)

$$P(\nu_a \rightarrow \nu_x) = \sin^2 2\theta \sin^2 \left( \frac{\Delta m^2 L}{4E} \right).$$

Different mechanisms:

- Averaged oscillations: $\rho_{\nu_s}/\rho_{\nu_a} = \frac{1}{2} \sin^2 2\theta$.
- Oscillations + collisions, $\Gamma_{\text{osc}} \gg \Gamma_{\text{coll}}$: $\Gamma_{\text{therm}} \sim \Gamma_{\text{coll}} \frac{1}{2} \sin^2 2\theta$.
- Resonances: Vacuum term canceled by background effect:
  $$V_{\text{bg}} - \frac{\Delta m^2}{4E} \cos 2\theta = 0.$$
Numerical results

- Production if $\Gamma_{\text{therm}} > H$.
- Neutrinos decouple at $\sim 1\text{MeV}$.

Hannestad, RSLH, Tram, Wong (1506.05266)

In matter: $\sin 2\theta_m \propto \frac{\Delta m^2}{V_m} \sin 2\theta \Rightarrow \Gamma_{\text{therm}} \propto (\Delta m^2)^2 \sin^2 2\theta$. 

SBL $\nu_s$ and cosmology, Rasmus Sloth Lundkvist Hansen
Vector mediator

**High mass vector mediator**

New sterile interaction:

\[ G_X = \frac{g_X^2}{M_X^2}. \]

\[ V_s \propto \frac{G_X}{M_X^2} \]

\[ \Gamma_s \propto G_X^2 \]

Thermalisation rate:

\[ \Gamma_{\text{therm}} \propto \Gamma_{\text{coll}} \sin^2 2\theta_m \propto \Gamma_s V_s^{-2} \propto M_X^4 \]

\[ \Delta m^2 = 1\text{eV}, \sin^2 2\theta = 0.05 \]

\[ \log(G_X/G_F) \]

\[ \Delta N_{\text{eff}} \]

Hannestad, RSLH, Tram (1310.5926)

see also Dasgupta and Kopp (1310.6337) and Chu, Dasgupta and Kopp (1505.02795)
Vector mediator

**Low mass vector mediator**

Potential:

\[(T, E \gg M_X)\]

\[V_s = \frac{g^2 T^2}{2E},\]

\[\Gamma_s = \frac{g^4}{M_X^2} n_{\nu_s}\]

Thermalisation rate:

\[\Gamma_{\text{therm}} \propto M_X^{-2}\]

Cherry, Friedland, Shoemaker (1605.06506)

\[\delta m^2 = 3 \text{ eV}^2, \theta_Y = 0.1\]

↑

SBL \(\nu_s\) and cosmology, Rasmus Sloth Lundkvist Hansen
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Thermalisation rate:

\[ \Gamma_{\text{therm}} \propto M_X^{-2} \]
Recall latest BAO: $\sum m_\nu < 0.16\text{eV}$. 

Oscillational recoupling temperature: Cherry, Friedland, Shoemaker (1605.06506) 

For $\Delta N_{\text{eff}} = 0$: $m_{\nu_s}^{\text{eff}} \sim \frac{1}{4} N_{\text{eff}} m_{\nu_s} \gtrsim 0.75\text{eV}$. 

SBL $\nu_s$ and cosmology, Rasmus Sloth Lundkvist Hansen
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Pseudoscalar mediator

**Very low mass mediator**

Pseudoscalar model:  \( \mathcal{L} = ig_\phi \phi \bar{\nu}_4 \gamma_5 \nu_4, \ m_{\nu_4} \ll 1\text{eV}. \)

Supernova bound:  \( g_\phi \lesssim 5 \cdot 10^{-5}. \)

\[
V_s = \frac{g_\phi^2}{8\pi^2 p} \int dp \ p (f_\phi + f_{\nu_4}),
\]

\[
\Gamma_s = \frac{g_\phi^4}{M_\phi^2} n_{\nu_4}, \quad \text{diverge for } M_\phi \to 0.
\]

Plasma effects regulate the divergence:  \( \Gamma_s \sim \frac{g_\phi^4}{T^2} n_{\nu_4}. \)

Notice: No connection between \( \nu_4 \) and \( \nu_{1,2,3} \) once weak SM collisions are frozen out and SM \( \nu \) travel as mass states.
Pseudoscalar mediator

Suppression of $N_{\text{eff}}$

Time line:

$T = 1\text{MeV}$ \quad $V_s > V_{\text{SM}}$ and $\nu_a$ decouple.

$T > 1\text{eV}$ \quad $\langle \nu \sigma_s \rangle n_{\nu_4} > H$

$\Rightarrow$ interacting $\nu_4/\phi$ fluid.

$T \sim m_4$ \quad $\nu_4$ annihilate to $\phi$.

Archidiacono, Hannestad, RSLH, Tram

(1404.5915)
Pseudoscalar mediator

$\nu_4$ annihilation

Archidiacono, Hannestad, RSLH and Tram (1508.02504)
Similar results expected for a vector mediator, but no full freestreaming for $\nu_a$ give some changes.
Adding a 1eV sterile neutrino with $\sim 0.1$ mixing to the Standard Model is in conflict with cosmological observations.

Introducing an interaction only felt by $\nu_s$ can suppress the production.

- $N_{\text{eff}}$ can be suppressed for a wide range of mediator masses.
- Recoupling gives a conflict with the cosmological mass bound.
- A model with a light mediator coupling to $\nu_4$ has no free streaming for $\nu_4$ and avoids the mass bound.
Global fit with ICECUBE

\[ \Delta m^2_{41} / \text{eV}^2 \]

\[ \sin^2 2\theta_{24} \]

Collin, Argüelles, Conrad and Shaevitz (1607.00011)
Large lepton asymmetry ($L$)

Avoid oscillations - make $V_m$ larger

$$V_m = -\frac{7\pi^2 G_F}{45\sqrt{2} M_Z^2} E T^5 n_{\nu_a} + \frac{2\sqrt{2}\zeta(3)}{\pi^2} G_F T^3 L$$

$N_{\text{eff}}(L = 10^{-2})$
**Large lepton asymmetry (L)**

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Baryon asymmetry,

$$\eta \sim 6 \cdot 10^{-10}.$$
Sterile Interactions

The mechanism is not very sensitive to the exact values of $\delta m^2$ and $\sin^2 2\theta$.

\[
\delta m^2 = 1\text{eV}^2, \sin^2(2\theta) = 0.05
\]
How Can $\Delta N_{\text{eff}} > 1$?

The conversion is efficient at the resonance, where $\rho_{ss} < \rho_{aa} \sim f_0$, but not below the resonance where $\rho_{ss} > \rho_{aa}$.

$T = 4.3 \text{MeV}$,
$\Delta N_{\text{eff}} = 1$,
$\delta m^2 = 1 \text{eV}^2$,
$\sin^2 2\theta = 0.05$,
$G_X = G_F$, $g_X = 0.01$
$\Rightarrow M_X = 2.9 \text{GeV}$

Hannestad, RSLH, and Tram (1310.5926)