Secret interactions for eV sterile neutrinos and cosmological implications

Ninetta Saviano
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The investigation on Light Sterile Neutrinos has been stimulated by the presence of anomalous results from neutrino oscillation experiments (LNSD, MiniBoone, Gallium, Reactor) see White paper, Abazajian et al., 2012...often in tension among themselves...

Interpretation: 1 (or more) sterile neutrino with $\Delta m^2 \sim O(\text{eV}^2)$ and $\theta_s \sim O(\theta_{13})$
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New bad news are coming from IceCube, Minos, Daya Bay...

Interpretation: 1 (or more) sterile neutrino with $\Delta m^2 \sim O(eV^2)$ and $\theta_s \sim O(\theta_{13})$

Are eV $\nu_s$ compatible with cosmology?
Sensitivity to $N_{\text{eff}}$ and $\nu$ flavour (spectra)

Sensitivity to $N_{\text{eff}}$ and $\nu$ masses
(and to other properties, i.e. neutrino interactions… )
**Radiation Content in the Universe**

At $T < m_e$, the radiation content of the Universe is

$$\varepsilon_R = \varepsilon_\gamma + \varepsilon_\nu + \varepsilon_x$$

The non-e.m. energy density is parameterized by the effective numbers of neutrino species $N_{\text{eff}}$

$$\varepsilon_\nu + \varepsilon_x = \frac{7}{8} \frac{\pi^2}{15} T_\nu^4 N_{\text{eff}} = \frac{7}{8} \frac{\pi^2}{15} T_\nu^4 (N_{\text{eff}}^{\text{SM}} + \Delta N)$$

$$N_{\text{eff}}^{\text{SM}} = 3.046 \quad \text{due to non-instantaneous neutrino decoupling}$$

(+ oscillations)

($N_{\text{eff}}^{\text{SM}} = 3.045$, recent recalculation)

$\Delta N = \text{Extra Radiation: axions and axion-like particles, sterile neutrinos (totally or partially thermalized), neutrinos in very low-energy reheating scenarios, relativistic decay products of heavy particles...}$
Impact on Big Bang Nucleosynthesis

At $T \sim 1 \cdot 0.01$ MeV, production of the primordial abundances of light elements, in particular $^2$H, $^4$He

When $\Gamma_{n \rightarrow p} < H \rightarrow \text{neutron-to-proton ratio freezes out}$

$$\frac{n_n}{n_p} = \frac{n}{p} = e^{-\Delta m/T} \rightarrow 1/7$$
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Sterile $\nu$ influence on BBN:

- contribution to the radiation energy density governing $\text{H}$ before and during BBN

$N_{\text{eff}} \leftrightarrow \text{H} \uparrow \rightarrow \text{early freeze out} \Rightarrow n/p \uparrow \Rightarrow \text{^{4}He} \uparrow, \text{^{2}H} \uparrow$
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BBN constraint on $\Delta N_{\text{eff}}$: NO strong preference

$\Delta N_{\text{eff}} \leq 1$ (95% C.L.)


From new precise measure of D in damped Lyman-\alpha system

$N_{\text{eff}} = 3.28 \pm 0.28$, 1 extra d.o.f. ruled out at 99.3 C.L.

Cooke, Pettini et al., 2013
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oscillating with the active neutrinos, can distort the active spectra which are the basic input for BBN
Impact on CMB and LSS

The small-scale matter power spectrum $P(k > k_{\text{nr}})$ is reduced in presence of massive $\nu$:

- free-streaming neutrinos do not cluster
- slower growth rate of CDM (baryon) perturbations

- $N_{\text{eff}}$ affect the time of matter-radiation equality
- consequences on the amplitude of the first peak and on the peak locations

- Neutrino mass
  - (background and perturbation level, suppression of the lensing...)

- Neutrino Interactions

$\mathbf{degeneracy \ among \ the \ parameters \ \rightarrow \ necessary \ to \ combine \ with \ other \ cosmological \ probes}$

Lesgourgues, Mangano, Miele and Pastor “Neutrino Cosmology”, 2013
Joint constraints on $N_{\text{eff}}$ and $m_{\nu_s}^{\text{eff}}$

<table>
<thead>
<tr>
<th>model</th>
<th>Planck TT +</th>
<th>mass bound (eV) (95% C.L.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Joint analysis $N_{\text{eff}}$ &amp; 1 mass $\nu_s$ (prior $m_{\nu_s}^{\text{ph}} &lt; 10$ eV)</td>
<td>lowP+lensing+BAO</td>
<td>$N_{\text{eff}} &lt; 3.7$</td>
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<tr>
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<td>lowP+lensing+BAO</td>
<td>$N_{\text{eff}} &lt; 3.7$, $m_{\nu_s}^{\text{eff}} &lt; 0.52$</td>
</tr>
</tbody>
</table>

$m_{\nu_s}^{\text{eff}} \equiv (94, 1 \, \Omega_\nu h^2) \text{eV}$

$m_{\nu_s}^{\text{eff}} = \rho_{ss} \, m_{\nu_s}^{\text{ph}}$

Hamann and Hasenkamp, 2013

$\Delta N_{\text{eff}} = 0.61 \pm 0.30$

$m_{\nu_s}^{\text{eff}} = 0.41 \pm 0.13$ eV (68% C.L.)

Planck XIII, 2015

L. Verde et al, 2014

$m_{\nu_s}^{\text{eff}} < 0.3$ eV (95% C.L.)

Less stringent mass bound from combined analysis $\rightarrow m_{\nu_s}^{\text{eff}} < 0.6$ eV
The investigation on Light Sterile Neutrinos has been stimulated by the presence of anomalous results from neutrino oscillation experiments (LNSD, MiniBoone, Gallium, Reactor) see White paper, Abazajian et al., 2012 ...

Interpretation: 1 (or more) sterile neutrino with $\Delta m^2 \sim O(eV^2)$ and $\theta_s \sim O(\theta_{13})$

Are eV $\nu_s$ compatible with cosmology? NO
For the mass and mixing parameters preferred by laboratory sterile ν are copiously produced, reaching 1 extra d.o.f.
Possible solutions...?

• Different mechanisms to suppress the $\nu_s$ abundance:

1. large $\nu - \bar{\nu}$ asymmetries
   In the presence of large $\nu - \bar{\nu}$ asymmetries ($L \sim 10^{-2}$) sterile production strongly suppressed. Mass bound can be evaded.

2. “secret” interactions for sterile neutrinos

3. low reheating scenario
   sterile abundance depends on reheating temperature

• Modification of cosmological models

Inflationary Freedom
Shape of primordial power spectrum of scalar perturbations different from the usual power-law

   Efficacy reduced by more recent paper

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   Sterile abundance depends on reheating temperature.

• **Modification of cosmological models**

  **Inflationary Freedom**
  Shape of primordial power spectrum of scalar perturbations different from the usual power-law

  Efficacy reduced by more recent paper *Di Valentino et al 2016*
Secret interactions for sterile neutrinos

Different authors have assumed the Standard Model (SM) is augmented by one extra species of light (∼ eV) neutrinos $\nu_s$, which do not couple to the SM gauge bosons but experiment a new force

*Hannestad et al., 2013*, *Dasgupta and Kopp 2013, Bringmann et al., 2014*

Such a new interaction can have profound effects on active-sterile neutrino conversion in the early Universe, since sterile $\nu$ feel a new potential that can suppresses active-sterile mixing *(through an effective $\nu_a-\nu_s$ mixing reduced by a large matter term)*

Caveat: they also generate *MSW resonance* and *strong collisional production*, increasing their abundance, with non trivial consequences on the cosmological observables

$\rightarrow$ $\nu$SI constraints from cosmological probes

If the new mediator interaction X also couples to Dark Matter possible attenuation of some of the small scale structure problems (“missing satellites” problem... )
new secret self-interactions among sterile $\nu$ mediated by a massive gauge boson $X$:

$$\nu_s - \nu_s \text{ interaction strength} \quad G_X = \frac{\sqrt{2}}{8} \frac{g_X^2}{M_X^2} \quad \text{for } T < M_X$$

Evolution equation:

$$i \frac{d\rho}{dt} = [\Omega, \rho] + C[\rho]$$

$$\Omega = \Omega_{vac} + \Omega_{mat} + \Omega_{\nu-\nu} + \Omega_{\nu_s-\nu_s}$$

$$C[\rho] = C_{SM} + C_{Secr} \propto G_X^2$$

$$\rho_p = \begin{pmatrix} \rho_{ee} & \rho_{e\mu} & \rho_{e\tau} & \rho_{es} \\ \rho_{\mu e} & \rho_{\mu\mu} & \rho_{\mu\tau} & \rho_{\mu s} \\ \rho_{\tau e} & \rho_{\tau\mu} & \rho_{\tau\tau} & \rho_{\tau s} \\ \rho_{se} & \rho_{s\mu} & \rho_{s\tau} & \rho_{ss} \end{pmatrix}$$
SI in the flavour evolution

new secret self-interactions among sterile $\nu$ mediated by a massive gauge boson $X$:

$$v_s - v_s \text{ interaction strength} \quad G_X = \frac{\sqrt{2}}{8} \frac{g_X^2}{M_X^2} \quad \text{for } T < M_X$$

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Saviano, Pisanti, Mangano, Mirizzi 2014
Constraints for sterile nSI (Vector boson)

- BBN: 40 MeV
- Mass Constraints: 0.1 MeV
- CMB + no free-str.: MX

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BBN constraints for sterile $\nu SI$

After the $\nu$ oscillation in the range of $g_x$ and $G_X$ relevant for BBN, we have both:

$$\Delta N_{\text{eff}} > 0 \quad \text{and} \quad \text{distortions of the active $\nu_e$ spectra}$$

**Deuterium yield**

Experimental reference value:

$$\frac{^2\text{H/\text{H}}}{= (2.53 \pm 0.04) \times 10^{-5}} \quad \text{R. Cooke et al, 2013}$$

Translating in a bound for the mediator mass:

mass permitted: $M_X \leq 40$ MeV

Ninetta Saviano, Pisanti, Mangano, Mirizzi 2014
Mass constraints for sterile $\nu$SI

Constraint on lower $M_X$ $\leftrightarrow$ very large $G_X$ ($> 10^5 \, G_F$)

Very strong secret collisional term leads to a quick flavor equilibrium

\[
\left( \rho_{ee}, \rho_{\mu\mu}, \rho_{\tau\tau}, \rho_{ss} \right)_{\text{initial}} \rightarrow \left( \rho_{ee}, \rho_{\mu\mu}, \rho_{\tau\tau}, \rho_{ss} \right)_{\text{final}}
\]

\[
(1, 1, 1, 0) \rightarrow (3/4, 3/4, 3/4, 3/4)
\]

The flavour evolution leads to a large population of vs, in conflict with the cosmological mass bound

\[
m_{\text{st}}^{\text{eff}} = \rho_{ss} \sqrt{\Delta m_{\text{st}}^2} = \frac{3}{4} \sqrt{\Delta m_{\text{st}}^2}
\]

lower value in the $2\sigma$ range from anomalies gives $m_{\text{eff}}^{\text{st}} \sim 0.8 \, \text{eV}$

in tension with the CMB and LSS conservative bounds on sterile mass ($< 0.6 \, \text{eV}$)

Secret interaction scenario: disfavored $M_X > 0.1 \, \text{MeV}$ ($\sim 10^9 \, G_F$)
A surprising effect on $N_{\text{eff}}$

After the production, $\nu_s$ have a “grey-body” spectrum ($\rho_{ss} = 3/4$)....

.... but the collisions and oscillations are still active pushing all neutrinos to a common FD distribution

Constraint: $n_\nu \text{TOT}$ must be constant

$T_\nu$ is reduced by a factor $(3/4)^{1/3}$, leading to an effect on the radiation density

$$\epsilon_{\nu,\text{fin}} = 4 \times \left(\frac{3}{4}\right)^{4/3} \times \frac{7}{8} \left(\frac{4}{11}\right)^{4/3} \epsilon_\gamma$$

$$N_{\text{eff}} \sim 4 \times \left(\frac{3}{4}\right)^{4/3} \sim 2.7$$

Mirizzi, Mangano, Pisanti Saviano, 2014
We derive our mass bounds, taking into account neutrino scattering via secret interactions and we also take into account the increased density and pressure perturbations in the neutrino fluid, induced by collisions with strength

\[ G_X = \frac{\sqrt{2}}{8} \frac{g_X^2}{M_X^2} \]

For \( M_X \leq 0.1 \text{ MeV} \geq 10^{10} G_F \) \( \rightarrow \) \( \nu_s \) could be still coupled at CMB and LSS epoch \( \rightarrow \) possible no free-streaming.

an appropriated analysis should be performed
CMB constraints for sterile $\nu$SI

Effect of interactions among neutrino species on the evolution of cosmological perturbations:

\[
\hat{L}[\delta f] = \hat{C}[\delta f]
\]

\[
\delta f \equiv f_0 \Psi
\]

\[
\begin{align*}
\dot{\Psi}_{i,0} &= -\frac{4}{3} \frac{q}{\epsilon} \Psi_{i,1} - \frac{2}{3} \dot{h}, \\
\dot{\Psi}_{i,1} &= k^2 \frac{q}{\epsilon} \left( \frac{1}{4} \Psi_{i,0} - \Psi_{i,2} \right), \\
\dot{\Psi}_{i,2} &= \frac{q}{\epsilon} \left( \frac{4}{15} \Psi_{i,1} - \frac{3}{10} k \Psi_{i,3} \right) + \frac{2}{15} \dot{h} + \frac{4}{5} \dot{\eta} - \Gamma_{ij} \Psi_{j,2}, \\
\dot{\Psi}_{i,\ell} &= \frac{k}{2\ell + 1} \frac{q}{\epsilon} \left[ \ell \Psi_{i,(\ell-1)} - (\ell + 1) \Psi_{i,(\ell+1)} \right] - \Gamma_{ij} \Psi_{j,\ell} \quad (\ell \geq 3)
\end{align*}
\]

NOTE: $N_{\text{eff}} = 2.7$

As long as $\Gamma > H$, interacting neutrinos behave as perfect fluid $\rightarrow$ shear and higher moments are exponentially suppressed.

Net effect: density and pressure perturbations are enhanced with respect to the non-interacting case, propagating to the photon fluid, and thus to CMB anisotropies.
CMB constraints for sterile $\nu_{SI}$

Forastieri, Lattanzi, Mangano, Mirizzi, Natoli, Saviano, 2017

<table>
<thead>
<tr>
<th>Parameter</th>
<th>SACDM</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Omega_{b}h^2$</td>
<td>0.02197±0.00021</td>
</tr>
<tr>
<td>$\Omega_{c}h^2$</td>
<td>0.1144±0.0016</td>
</tr>
<tr>
<td>$100\theta_{MC}$</td>
<td>1.04332±0.00063</td>
</tr>
<tr>
<td>$\tau$</td>
<td>0.074 ± 0.018</td>
</tr>
<tr>
<td>$n_s$</td>
<td>0.9392 ± 0.0063</td>
</tr>
<tr>
<td>$\ln(10^{10}A_s)$</td>
<td>3.038 ± 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 ± 0.68</td>
</tr>
</tbody>
</table>
Refined calculations show that all the parameter space seems to be excluded (due also to the X-mediated s-channel process leading to efficient sterile neutrino production)

*Chu et al., in preparation*
**Conclusions**

neutrino cosmology is entering the precision epoch

\[ N_{\text{eff}} \sim 3 \quad \text{m}^{\text{eff}}_{\nu s} < 0.6 \text{ eV} \]

Thermalized eV sterile \( \nu \) **incompatible** with cosmological bounds:

Too many for BBN and CMB and too heavy for structure formation

New exotics scenarios are required (primordial neutrino asymmetry, hidden interactions, inflationary freedom...)

\[ \Rightarrow \text{however the reconciliation with cosmology is not guaranteed and in some cases disfavoured (neutrino asymmetry) and excluded (secret interactions)} \]

Very hard to accommodate sterile neutrino with cosmology

Ninetta Saviano
THANK YOU
Effects of MINOS, IceCube and NEOS

IceCube effect in agreement with
Collin, Arguelles, Conrad, Shaevitz, PRL 117 (2016) 221801
Vacuum term with M neutrino mass matrix
$U M^2 U^\dagger$  

\[ \Omega = \frac{M^2}{2p} + \sqrt{2} G_F \left[ -\frac{8p}{3} \left( \frac{E_\ell}{M_W^2} + \frac{E_\nu}{M_Z^2} \right) \right] + \sqrt{2} G_X \left[ -\frac{8pE_s}{3M_X^2} \right] \]
**Big Bang Nucleosynthesis**

*0.1-0.01 MeV*

Formation of light nuclei starting from D

<table>
<thead>
<tr>
<th>Step</th>
<th>Reaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>( n \rightarrow p + e + \overline{\nu}_e )</td>
</tr>
<tr>
<td>2.</td>
<td>( p + n \rightarrow D + \gamma )</td>
</tr>
<tr>
<td>3.</td>
<td>( D + p \rightarrow ^3\text{He} + \gamma )</td>
</tr>
<tr>
<td>4.</td>
<td>( D + D \rightarrow ^3\text{He} + n )</td>
</tr>
<tr>
<td>5.</td>
<td>( D + D \rightarrow ^3\text{H} + p )</td>
</tr>
<tr>
<td>6.</td>
<td>( ^3\text{H} + D \rightarrow ^4\text{He} + n )</td>
</tr>
<tr>
<td>7.</td>
<td>( ^3\text{H} + ^4\text{He} \rightarrow ^7\text{Li} + \gamma )</td>
</tr>
<tr>
<td>8.</td>
<td>( ^3\text{He} + n \rightarrow ^3\text{H} + p )</td>
</tr>
<tr>
<td>9.</td>
<td>( ^3\text{He} + D \rightarrow ^4\text{He} + p )</td>
</tr>
<tr>
<td>10.</td>
<td>( ^3\text{He} + ^4\text{He} \rightarrow ^7\text{Be} + \gamma )</td>
</tr>
<tr>
<td>11.</td>
<td>( ^7\text{Li} + p \rightarrow ^4\text{He} + ^4\text{He} )</td>
</tr>
<tr>
<td>12.</td>
<td>( ^7\text{Be} + n \rightarrow ^7\text{Li} + p )</td>
</tr>
</tbody>
</table>

Prediction for \(^4\text{He}\) and D in a **standard** BBN obtained by Planck collaboration using **PArthENOPE**

Blue regions: primordial yields from measurements performed in different astrophysical environments

\[ \omega_b = 0.02207 \pm 0.00027 \]
BBN constrains

Experimental reference value: \( ^2\text{H}/\text{H} = (2.53 \pm 0.04) \times 10^{-5} \)

Uncertainty on the reaction \( d(p, \gamma)^3\text{He} \rightarrow \sigma_{\text{th}} = 0.062 \times 10^{-5} \)

\[
\sigma = \sqrt{\sigma_{\text{exp}}^2 + \sigma_{\text{th}}^2}
\]

Experimental reference value: \( Y_p = 0.2551 \pm 0.0022 \)

Most of the parameter space excluded at \( 3\sigma \) \( M_X \geq 40 \text{ MeV} \)

\( ^4\text{He} \) yield

Planck best fit \( \Omega_b h^2 = 0.02207 \)

95\% C.L. Planck range \( \Omega_b h^2 \)

Saviano, Pisanti, Mangano, Mirizzi 2014, ArXiv: 1409.1680

PArthENoPE code
Pisanti et al, 2012
Asymptotic values of $\Delta N_{\text{eff}}$ versus $G_X$ and $g_X$

Resonance temperature in the plane $(G_X, g_X)$
Dashed curves: constant $T_{\text{res}}$ contours
Solid curves: constant $M_X$ contours
Mass constraints for sterile $\nu$SI (vector)

Constraint on lower $M_X \leftrightarrow$ very large $G_X (> 10^5 \, G_F)$

Very strong secret collisional term
leads to a quick flavor equilibrium

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in tension with the CMB and LSS bounds on sterile mass ($< 0.5 \, \text{eV}$)

Secret interaction scenario: disfavored $M_X > 0.1 \, \text{MeV}$ ($\Rightarrow \sim 10^9 \, G_F$)

Planck XVI, 2015, Hamann and Hasenkamp, 2013, Giusarma et al 2016...
CMB constraints for sterile $\nu_{SI}$

<table>
<thead>
<tr>
<th>Description</th>
<th>Parameter Constraints</th>
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<tbody>
<tr>
<td>Standard six-parameter $\Lambda$CDM, $N_{\text{eff}} = 3.046$.</td>
<td>$\Omega_{\text{CDM}} h^2 = 0.12$</td>
</tr>
<tr>
<td>Sterile neutrino extension, $N_{\text{eff}} = 2.7$, $m_s$ free,</td>
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</tr>
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<td>“small” $G_X$ ($\sim 10^8 G_F$).</td>
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<td>$m_s = 1.27 \pm 0.03$ eV (gaussian prior).</td>
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<tr>
<td>$0.93$ eV $\leq m_s \leq 1.43$ eV (flat prior).</td>
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Forastieri, Lattanzi, Mangano, Mirizzi, Natoli, Saviano, 2017
\[\hat{L}[\delta f] = \hat{C}[\delta f]\]

\[\delta f \equiv f_0\Psi\]

\[\hat{C}[\delta f] \simeq \delta f / \tau_c, \quad \tau_c = \langle an\sigma v \rangle^{-1}\]

so-called relaxation time approximation \(\rightarrow\) \(\Gamma = \tau_c^{-1} \sim a G_X^2 T_\nu^5\)

\[\frac{\partial \Psi_i}{\partial \tau} + i \frac{q(\vec{k} \cdot \hat{n})}{\epsilon} \Psi_i + \frac{d \ln f_0}{d \ln q} \left[ \dot{\phi} - i \frac{q(\vec{k} \cdot \hat{n})}{\epsilon} \psi \right] = -\Gamma_{ij} \Psi_j\]

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

\[\Gamma_{ij} = \begin{bmatrix}
\sin^2 \theta_s & 0 & 0 & \sin \theta_s \cos \theta_s \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
\sin \theta_s \cos \theta_s & 0 & 0 & \cos^2 \theta_s
\end{bmatrix}\]

\[(3/2)(\zeta(3)/\pi^2) a G_X^2 T_\nu^5\]
Connection with the DM

If a new force exists, it is plausible that not only (sterile) neutrinos, but also DM particles couple to it

"neutrinoophobic DM" \( \mathcal{L}_{\text{int}} \supset -g_\chi \bar{\chi} \bar{\chi} - g_\nu \bar{\nu} \bar{\nu} \)

This scenario may solve all of the small-scale structure issues mentioned above. Indeed, the efficient scattering of DM would lead to late kinetic decoupling, delaying the formation of the smallest protohalos.

(Barions?)

van den Aarssen, Bringmann and Pfrommer 2012, Dasgupta and Kopp 2013, Bringmann, Hasenkamp, Kersten 2014, Cherry, Friedland, Shoemaker 2014, Archidiacono et al. 2015...
Possible hint (very dependent on the set of data used): in pseudoscalar model, \(10^{-6} \lesssim g_s \lesssim 10^{-5}\) would reconcile eV sterile \(\nu\), \(H_0\), \(\nu\) SI. Also link to the DM small scale problem.

**Archidiacono et al. 2015**
Pseudoscalar model

Sterile neutrino is coupled to a new light pseudoscalar with mass $m_\phi \ll 1\text{eV}$ with $\mathcal{L} \sim g_s \phi \bar{\nu} \gamma_5 \nu$.

Possible hint:

$10^{-6} \lesssim g_s \lesssim 10^{-5}$ would reconcile eV sterile $\nu$, $H_0$

Also connection to the DM small scale problem.

Archidiacono et al. 2015,
Archidiacono et al. 2016
Consequences on BBN

\( \nu_e \) spectra distorted \( \rightarrow \) implications on BBN

Helium 4 sensitive both to:
- Increase of \( N_{\text{eff}} \)
- Changes in the weak rates due to the spectral distortions

Deuterium mainly sensitive to the increase of \( N_{\text{eff}} \)

\[ Y_p = \frac{2(n/p)}{1 + n/p} \]

Helium mass fraction

<table>
<thead>
<tr>
<th>Case</th>
<th>( \Delta N_{\text{eff}} )</th>
<th>( Y_p )</th>
<th>( ^2 \text{H}/\text{H} \times 10^5 )</th>
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</thead>
<tbody>
<tr>
<td>(</td>
<td>\xi</td>
<td>\ll 10^{-3} )</td>
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</tr>
<tr>
<td>( \xi_e = -\xi_\mu = 10^{-3} )</td>
<td>0.98</td>
<td>0.257</td>
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<td>( \xi_e = -\xi_\mu = 10^{-2} )</td>
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<td>0.255</td>
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<tr>
<td>( \xi_e = \xi_\mu = 10^{-2} )</td>
<td>0.22</td>
<td>0.251</td>
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<tr>
<td>( \xi_e =</td>
<td>\xi_\mu</td>
<td>= 10^{-3}, \text{no } \nu_s )</td>
<td>( \sim 0 )</td>
</tr>
<tr>
<td>( \xi_e =</td>
<td>\xi_\mu</td>
<td>= 10^{-2}, \text{no } \nu_s )</td>
<td>( \sim 0 )</td>
</tr>
<tr>
<td>standard BBN</td>
<td>0</td>
<td>0.247</td>
<td>2.56</td>
</tr>
</tbody>
</table>
**Sterile production by neutrino asymmetry**

✓ $\rho_{ss}$ and distortions of $\nu_e$ spectra as function of the $\nu$ asymmetry parameter
  $\Rightarrow$ evaluation of the cosmological consequences

✗ Very challenging task, involving time consuming numerical calculations
  $\Rightarrow$ few representative cases

## Graphs

- **Graph 1**
  - $\rho_{ss}$ vs. $T$ (MeV)
  - $L=10^{-3}$
  - $L=10^{-2}$
  - $L=10^{-4}$
  - Conversions occur at $T \sim T_{\nu}$ decoupling
    $\Rightarrow$ active not repopulated anymore by collisions ($\rho_{ee} < 1$)

- **Graph 2**
  - $\nu_e$ spectra
  - $\xi_e = \xi_\mu = 10^{-2}$

- **Graph 3**
  - $R$ vs. $y$

**Equation**

$L_\alpha \approx 0.68 \xi_\alpha \left(\frac{T_r}{T_\gamma}\right)^3$