Light sterile $\nu$ limits
from cosmology

Ninetta Saviano
IPPP, Durham University
Sterile Neutrinos

$M_{GUT}$

$TeV$

$kVeV$

Ninetta Saviano
Sterile Neutrinos

$M_{\text{GUT}}$

$\text{TeV}$

$\text{keV}$

Ninetta Saviano

$\nu_s$ $\nu_\alpha$

$\phi$ $\phi$

$N_1$ $L$

$N_2$ $L$

$\sim 10^{-6} \text{~g}_e$

$\sim 5 \times 10^{-25} \text{~g}_e$

Giunti et al. (2013)

$5 \times 10^{-20}$

$10^{-3}$

$10^{-1}$

$10^1$

$10^2$

$10^3$

$10^4$

$10^5$

$10^6$

$\Delta m_{\nu, i}$
eV Sterile Neutrino

Ninetta Saviano
The investigation on Light Sterile Neutrinos has been stimulated by the presence of anomalous results from neutrino oscillation experiments. 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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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?

Ninetta Saviano
The investigation on Light Sterile Neutrinos has been stimulated by the presence of anomalous results from neutrino oscillation experiments. See White paper, Abazajian et al., 2012, Palazzo, 2013.

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

Are eV $\nu_s$ compatible with cosmology? 

...is necessary to consider the cosmological constraints on extra species and to assess the conditions under which $\nu_s$ are produced.
Cosmological observations

Sensitivity to $N_{\text{eff}}$ and $\nu$ flavour

Sensitivity to $N_{\text{eff}}$ and $\nu$ masses

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

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

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

($+\text{ oscillations}$)

$\Delta N$ = 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...

*Mangano et al. 2005*

Impact on Big Bang Nucleosynthesis

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

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

$$\frac{n_n}{n_p} = \frac{n}{p} = e^{-\Delta m/T} \rightarrow 1/7$$

Sterile $\nu$ influence on BBN:

- contribution to the radiation energy density governing H before and during BBN

$N_{\text{eff}} \uparrow \Rightarrow H \uparrow \Rightarrow \text{early freeze out} \Rightarrow n/p \uparrow \Rightarrow ^4\text{He}$

- oscillating with the active neutrinos, can distort the active spectra which are the basic input for BBN
At T ~ 1 - 0.01 MeV production of the primordial abundances of light elements, in particular $^2$H, $^4$He.

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

$$\frac{n_n}{n_p} = \frac{n}{p} = e^{-\Delta m/T} \rightarrow 1/7$$

**BBN constraint on $\Delta N_{\text{eff}}$:** NO strong preference

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

Hamann et al, 2011  Mangano and Serpico, 2012

From new precise measure of D in damped Lyman-α 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
If sterile neutrinos are still relativistic at the CMB epoch, they impact the CMB spectrum $N_{\text{eff}}$ and $m_\nu$ affect the time of matter-radiation equality $\Rightarrow$ consequences on the amplitude of the first peak and on the peak locations

$$1 + z_{eq} = \frac{\omega_m}{\omega_\gamma} \frac{1}{1 + 0.227N_{\text{eff}}}$$
Impact on CMB

If sterile neutrinos are still relativistic at the CMB epoch, they impact the CMB spectrum

\( N_{\text{eff}} \) and \( m_\nu \) affect the time of matter-radiation equality \( \Rightarrow \) consequences on the amplitude of the first peak and on the peak locations

\[
1 + z_{eq} = \frac{\omega_m}{\omega_\gamma} \frac{1}{1 + 0.227N_{\text{eff}}}
\]
Impact on CMB

If sterile neutrinos are still relativistic at the CMB epoch, they impact the CMB spectrum. 

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

$$1 + z_{\text{eq}} = \frac{\omega_m}{\omega_\gamma} \left( \frac{1}{1 + 0.227N_{\text{eff}}} \right)$$
Impact on CMB

If sterile neutrinos are still relativistic at the CMB epoch, they impact the CMB spectrum

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

\[
1 + z_{eq} = \frac{\omega_m}{\omega_\gamma} \frac{1}{1 + 0.227 N_{\text{eff}}}
\]

Same data used to measure other cosmological parameters

basic parameters of $\Lambda$CDM:

\[
(\Omega_b h^2, \Omega_c h^2, 100\theta_{MC}, n_s, A_s, \tau)
\]

+ derived parameters

\[
(H_0, \Omega_k, \Omega_\Lambda, N_{\text{eff}}, \sigma_8, \sum m_\nu,
\quad z_{re}, Y_p, w, \Omega_m \zeta_{LS}, \ldots)
\]

$\Rightarrow$ degeneracies
Impact on the LSS

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

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

✓ $N_{\text{eff}} = 3.30 \pm 0.54$ (95% C.L.; Planck+WP+highL+BAO) 
  $\Rightarrow$ compatible with the standard value at 1-σ

✓ For 3 degenerate active $\nu$:
  $\Sigma m_{\nu} < 0.23$ eV (95% C.L.; Planck+WP+highL+BAO)

see Henrot-Versille’s talk
Joint constraints on $N_{\text{eff}}$ and $m_{\nu_s}^{\text{eff}}$

<table>
<thead>
<tr>
<th>model</th>
<th>Planck</th>
<th>mass bound (eV) (95% C.L.)</th>
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<tbody>
<tr>
<td>Joint analysis $N_{\text{eff}}$ &amp; 1 mass $\nu_s$</td>
<td>WP+HighL+BAO</td>
<td>$N_{\text{eff}} &lt; 3.80$</td>
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<td>$m_{\nu_s}^{\text{eff}} &lt; 0.42$</td>
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<td>$m_{\nu_s}^{\text{eff}} = (94, 1 \Omega_{\nu} h^2)eV$</td>
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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.)

L. Verde et al, 2014

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

Planck XVI, 2013

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<td>Joint analysis $N_{\text{eff}}$ &amp; 1 mass $\nu_s$ (prior $m_{\nu_s} &lt; 10$ eV)</td>
<td>lowP+lensing+BAO</td>
<td>$N_{\text{eff}} &lt; 3.7$</td>
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<td></td>
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<td>$m_{\nu_s}^{\text{eff}} &lt; 0.52$</td>
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<td>$m_{\nu_s}^{\text{eff}} &lt; 0.38$</td>
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<td>$N_{\text{eff}} &lt; 3.7$</td>
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Active-sterile flavour evolution

Sterile $\nu$ are produced in the Early Universe by the mixing with the active species in presence of collisions

Evolution equation:

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

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

Vacuum term

MSW effect with background medium (refractive effect)

Collisional term

creation, annihilation and all the momentum exchanging processes
**Bounds on active-sterile mixing parameters after Planck**

- **a)** $\Delta m^2_{41} > 0$, $\sin^2 \theta_{34} = 0$

![Graph showing $\Delta m^2_{41}$ vs $\sin^2 \theta_{14}$](Image)

**Radiation bounds**

- Black curves imposing the 95% C.L. Planck constraint $N_{\text{eff}} < 3.8$ on computed $N_{\text{eff}} = \frac{1}{2} Tr[\rho + \bar{\rho}]$

The excluded regions are those on the right or at the exterior of the black contours.

**Note:** above $m \sim O(1$ eV), sterile $\nu$ are not relativistic anymore at CMB $\rightarrow$ **NO radiation constraint**

**BUT** mass constraints become important

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**Mirizzi, Mangano, N.S et al 2013**

- See also:
  - Hannestad, Tamborra and Tram 2012
  - Cirelli, Marandella, Strumia, Vissani, 2004
  - Archidiacono et al., 2013

Similar bounds would be obtained with Planck 2015 data
**Bounds on active-sterile mixing parameters after Planck**

**Mass bounds**

- Red curves imposing the 95% C.L. Planck constraint $m_{\text{eff}}^{\nu_5} < 0.42 \Leftrightarrow \Omega_\nu h^2 < 4.5 \times 10^{-3}$ on computed

\[
\Omega_\nu h^2 = \frac{1}{2} \frac{\sqrt{\Delta m_{41}^2 (\rho_{ss} + \bar{\rho}_{ss})}}{94.1 \text{ eV}}
\]

The excluded regions are those above the red contours.

---

**3+1 Scenario**

**Mirizzi, Mangano, N.S et al 2013**

See also:

- Hannestad, Tamborra and Tram 2012
- Cirelli, Marandella, Strumia, Vissani, 2004
- Archidiacono et al., 2013

Similar bounds would be obtained with Planck 2015 data.
Bounds on active-sterile mixing parameters after Planck

\[ \Delta m_{41}^2 > 0, \sin^2 \theta_{34} = 0 \]

\[ \sin^2 \theta_{24} = 0 \]

\[ \sin^2 \theta_{24} = 0 \]

sol. upturn

“eV sterile \( \nu \)”
allowed region from global analysis of SBL
\( \sin^2 \theta_{24} = 10^{-2}, \) 95\%C.L.
(Giunti et al.)

Ninetta Saviano
**Bounds on active-sterile mixing parameters after Planck**

In particular, in Panel b) the change in the slope in the exclusion plot is at a smaller value with respect to Fig. 3. Concerning the bound from different values of $\sin^2 \theta_{24}$ to $\sin^2 \theta_{41}$, much larger than the active mass splittings, it is independent on the mass hierarchy and so it is the same as in Fig. 3. The mixing angles are larger than the corresponding ones in the upper panels. (Upper panels) and SIH (lower panels) cases from FIG. 3: Active normal mass hierarchy NH. Exclusion plots for the active-sterile neutrino mixing parameter space for SNH.

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**Thermalized sterile $\nu$ with $m \sim \mathcal{O}(1 \text{ eV})$ strongly disfavored by cosmological constraints**

- **3+1**: Too heavy for LSS/CMB
- **3+2**: Too heavy for LSS/CMB and too many for BBN/CMB

---

"eV sterile $\nu$" allowed region from global analysis of SBL $\sin^2 \theta_{24} = 10^{-2}, 95\% \text{C.L.}$ (Giunti et al.)
The investigation on Light Sterile Neutrinos has been stimulated by the presence of anomalous results from neutrino oscillation experiments.

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

Are eV $\nu_s$ compatible with cosmology? NO
**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 (\(~10^{-2}\)) sterile production strongly suppressed. Mass bound can be evaded
   - ![Non trivial implication for BNN](image)

2. **hidden and “secret” interactions for sterile neutrinos**
   - Sterile $\nu$ feel a new potential that suppresses active-sterile mixing
   - ![Scenario strongly constrained by BBN and neutrino mass bounds](image)

3. **low reheating scenario**
   - Sterile abundance depends on reheating temperature
   - ![Simplified scenarios](image)

**Modification of cosmological models**

**Inflationary Freedom**

- Shape of primordial power spectrum of scalar perturbations different from the usual power-law
  - ![Modification of cosmological models](image)

---

**References**

- Mirizzi, N.S., Miele, Serpico 2012
- Hannestad, Tamborra and Tram 2012
- Chu & Cirelli, 2006
- Di Bari et al, 2001
- Hnannestad et al., 2013
- Dasgupta and Kopp 2013
- Bringmann et al., 2013
- Archidiacono et al., 2014
- Saviano et al., 2014
- Mirizzi, Mangano, Pisanti, N.S. 2014
- Cherry et al, 2014
- Tang, 2014
- Gelmini, Palomarez-Ruiz, Pascoli, 2004
- Yaguna 2007
- Gariazzo, Giunti Laveder, 2015
Thermalized eV sterile $\nu$ incompatible with cosmological bounds: too heavy for structure formation.

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

$N_{\text{eff}} < 4$  $\Sigma_{m\nu} < 0.23$ eV  $m^{\text{eff}}_{\nu_s} < 0.7$ eV

Conclusions

$N_{\text{eff}} < 4$  $\Sigma_{m\nu} < 0.23$ eV  $m^{\text{eff}}_{\nu_s} < 0.7$ eV

Thermalized eV sterile $\nu$ is incompatible with cosmological bounds: too heavy for structure formation.

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

$\Rightarrow$ **however the reconciliation with cosmology is not guaranteed and in some cases disfavoured.**

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Thermalized eV sterile $\nu$ incompatible with cosmological bounds: too heavy for structure formation.

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

$\Rightarrow$ however the reconciliation with cosmology is not guaranteed and in some cases disfavoured.

**Conclusions**

- Will $\Delta N_{\text{eff}}$ be definitely ruled-out in the future?
- Which are the absolute masses of neutrinos?
- Will the laboratory anomalies be confirmed?

Open questions:
Thank you!
**Big Bang Nucleosynthesis (II)**

0.1-0.01 MeV

Formation of light nuclei starting from D

1. $n \rightarrow p + e^- + \bar{\nu}_e$
2. $p + n \rightarrow D + \gamma$
3. $D + p \rightarrow ^3\text{He} + \gamma$
4. $D + D \rightarrow ^3\text{He} + n$
5. $D + D \rightarrow ^4\text{He} + p$
6. $^3\text{He} + D \rightarrow ^4\text{He} + n$
7. $^3\text{He} + ^4\text{He} \rightarrow ^7\text{Li} + \gamma$
8. $^3\text{He} + n \rightarrow ^3\text{H} + p$
9. $^3\text{He} + D \rightarrow ^4\text{He} + p$
10. $^3\text{He} + ^4\text{He} \rightarrow ^7\text{Be} + \gamma$
11. $^7\text{Li} + p \rightarrow ^4\text{He} + ^4\text{He}$
12. $^7\text{Be} + n \rightarrow ^7\text{Li} + p$

**Planck XVI, 2013**

<table>
<thead>
<tr>
<th>$\omega_b$</th>
<th>$Y_p$</th>
<th>$Y_{\text{DP}}$</th>
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<tr>
<td>0.018</td>
<td>0.26</td>
<td>2.2</td>
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<tr>
<td>0.020</td>
<td>0.25</td>
<td>2.6</td>
</tr>
<tr>
<td>0.022</td>
<td>0.24</td>
<td>3.0</td>
</tr>
<tr>
<td>0.024</td>
<td>0.23</td>
<td>3.4</td>
</tr>
<tr>
<td>0.026</td>
<td>0.22</td>
<td>3.4</td>
</tr>
</tbody>
</table>

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

$\omega_b = 0.02207 \pm 0.00027$
Extra radiation impact on CMB...

... and degeneracies

Matter-radiation equality
degenerate with $\Omega_m$

Damping tail
degenerate with $Y_p$

Sound horizon/angular positions of the peaks
degenerate with $H_0$ and $\Omega_m$

Anisotropic stress
(partially) degenerate with $A_s$ and $n_s$
The equality redshift is one of the direct observables from the temperature power spectrum. The CMB data constrain $z_{eq}$ mainly from the ratio of the first peak to the third peak. Measuring $z_{eq}$ essentially fixes the ratio of the energy density in matter to the energy density in radiation.

2. Sound horizon and location peaks

The sound horizon affects the angular position of the acoustic peaks via

$$r_s = \int_0^{\tau_*} d\tau' c_s(\tau')$$

depends on the expansion and on sound speed

$$c_s \propto \frac{\bar{\varepsilon}_\gamma}{\bar{\varepsilon}_B}$$

$$\theta_s \propto \frac{\Omega_m^{-1/2}}{\int_{a_s}^1 \frac{da}{a^2 \sqrt{\Omega_m a^{-3} + (1-\Omega_m)}}}$$

This relation implies that while $\theta_s$ constrains the parameter combination $\Omega_m=\omega_m / h^2$ it does not constrain $\omega_m$ and $h$ individually.
4. Damping tail

Close to recombination, the tight-coupling approximation breaks down. Random scattering processes tend to erase perturbations below the photon diffusion length.

The envelope of the secondary peaks at large \( l \) depends on the angle \( \theta_d = \frac{\lambda_d}{DA} \)
where \( \lambda_d \) is the diffusion length.
Increasing the expansion rate will increase \( \lambda_d \)

\( \lambda_d \) which is controlled by the expansion history and recombination history before the decoupling. It depends essentially by free electron \( n_e \) (\( \propto \frac{1}{n_e} \)).

An enhancing of \( n_e \) can compensate the increased expansion rate  

\[ n_e = (1 - Y_p) n_B \]
Oscillation experiments can measure the differences of squared neutrino masses \( \Delta m_{21}^{2} = m_{2}^{2} - m_{1}^{2} \) and \( \Delta m_{31}^{2} = m_{3}^{2} - m_{1}^{2} \), the relevant ones for solar and atmospheric neutrinos, respectively. As a reference, we take the following 3σ ranges of mixing parameters from an update of ref. [13],

\[
\Delta m_{21}^{2} = (7.9 \pm 1.0 - 0.8) \times 10^{-5} \text{eV}^2
\]

\[
\Delta m_{31}^{2} = (2.2 \pm 1.1 - 0.8) \times 10^{-3} \text{eV}^2
\]

\[
\theta_{12} = 0.30 \pm 0.10 - 0.06 \text{ rad}
\]

\[
\theta_{23} = 0.50 \pm 0.18 - 0.16 \text{ rad}
\]

Unfortunately, oscillation experiments are insensitive to the absolute scale of neutrino masses, since the knowledge of \( \Delta m_{21}^{2} > 0 \) and \( |\Delta m_{31}^{2}| \) leads to the two possible schemes shown in Fig. 1, but leaves one neutrino mass unconstrained (see e.g. the discussion in the reviews [14,15,16,17]). These two schemes are known as normal (NH) and inverted (IH) hierarchies, characterized by the sign of \( \Delta m_{31}^{2} \), positive and negative, respectively. For small values of the lightest neutrino mass \( m_{0} \), i.e. \( m_{1} \) (\( m_{3} \)) for NH (IH), the mass state follows a hierarchical scenario, while for mass states much larger than the differences all neutrinos share in practice the same mass and then we say that they are degenerate. In general, the relation between the individual masses and the total neutrino mass can be found numerically, as shown in Fig. 2.
Equation for the flavour evolution

Evolution equation:

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

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

MSW effect with background medium

(refractive effect) $\propto G_F$

$\rightarrow$ 2$^\text{th}$ order term: “symmetric” matter effect

(charged lepton asymmetry subleading ($O(10^{-9})$))
Equation for the flavour evolution

Evolution equation:

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

\[ \Omega = \Omega_{vac} + \Omega_{mat} + \Omega_{\nu-\nu} \]

Refraction term of \( \nu \) with the \( \nu \) background:

- **Self-interaction terms**
  - In extreme environments, such as the SN and the Early Universe, the density of the neutrinos can be high that the neutrinos themselves form a background medium for their propagation [59]. The neutrino-neutrino interactions, \( G_F \), make an additional contribution to the refractive energy shift. In particular, in addition to the diagonal refractive index, there will be present also "off-diagonal refractive potentials" given by the zero-momentum transfer processes in which neutrinos flavor exchange. The amplitudes contributing to these processes are shown in the panel (c), (d), (e), (f) of the Fig. 2.1.

**Self-conservation**

**Leading order NC interactions and non-linear EoM**
The importance of multi-flavour system

- **More mixing angles:**
  - oscillation mechanism shared between different flavours ➔ effects not possible in the simple “1+1” scenario

- **More resonances with the matter term, affecting the sterile neutrino production**
  - When the matter term becomes of the same order of the neutrino mass-squared splitting, induce MSW-like resonances between the active and sterile states

In the sterile sector:

- **resonances associated with**
  - $\Delta m^2_{4i}$
  - $\theta_{i4}$ for $i=1,2,3$

- **Active**
  - $\Delta m^2_{31} > 0$ for NH
  - $\Delta m^2_{31} < 0$ for IH

- **Sterile**
  - $\Delta m^2_{41} > 0$ for SNH
  - $\Delta m^2_{41} < 0$ for SIH
Sterile production by neutrino asymmetry

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

✗ Very challenging task, involving time consuming numerical calculations
→ few representative cases

Very large asymmetries are necessary to suppress the sterile neutrino abundances leading to non trivial consequences on BBN

$\mathcal{L}_0 \approx 0.68 \xi_\alpha \left( \frac{T_\nu}{T_\gamma} \right)^3$

![Graph showing $\rho_{ss}$ vs. $T$ for different $L$ values](image)

conversions occur at $T \sim T_\nu$ decoupling
⇒ active not repopulated anymore by collisions ($\rho_{ee} < 1$)
Active-Sterile flavour evolution

\( \nu_s - \nu_s \) interaction strength \( G_X = \frac{\sqrt{2}}{8} \frac{g_X^2}{M_X^2} \) for \( T \ll M_X \)

Evolution equation:

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

\[
\Omega = \Omega_{\text{vac}} + \Omega_{\text{mat}} + \Omega_{\nu-\nu} + \Omega_{\nu_s-\nu_s}^\text{secr}
\]

\[
C = C_{\text{SM}} + C_{\text{secr}}
\]

\( \propto G_F \)

\( \propto G_X^2 \)

\( \propto G_X^2 \)

\( \propto G_F \)

Primordial \( ^2 \)H yield

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

\( \sigma = \sqrt{\sigma_{\exp}^2 + \sigma_{\text{th}}^2} \)

PARthENoPE code

Pisanti et al., 2012