Sterile Neutrinos in the Early Universe

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Neutrino Oscillation Workshop 2012
Conca Specchiulla
September 14, 2012

Outline

★ Hints for light sterile neutrinos

★ Sterile neutrinos as candidates for the dark radiation

★ Thermalization of sterile neutrinos in the early universe

★ Conclusions and perspectives

This talk is based on a project in collaboration with S. Hannestad and T. Tram [JCAP 1207 (2012) 025].

Experimental hints for sterile neutrinos

Observations at odds with standard 3-neutrino interpretation of global oscillation data:

- ★ LSND anomaly [A. Aguilar et al., PRD 64, 112007 (2001)]
- ★ MiniBooNE data [A.A.Aguilar-Arevalo et al., PRL 102, 101802 (2009)]
- ★ Short-baseline disappearance data (Bugey, ROVNO, ILL)
- ★ Reactor anomaly [Mention et al. PRD 83, 073006 (2011), Huber, PRC 84, 024617 (2011)]
- ★ Gallium anomaly [Giunti, Laveder, PRC 83, 065504 (2011)]
- ★ ICARUS search for the “LSND anomaly” [M. Antonello et al., arXiv: 1209.0122]

Light sterile neutrinos explain quite well these anomalies.*

[See talks by C. Giunti, C. Rubbia, L. Stanco]

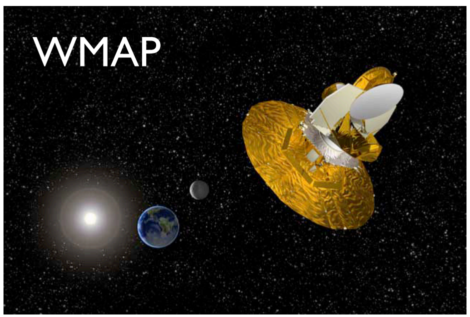
* See the white paper on sterile neutrinos for more details: K.N. Abazajian et al., arXiv: 1204.5379.

Radiation content of the universe

The radiation content of the universe is expressed in terms of a parameter ($N_{\rm eff}$) representing any relativistic degree of freedom.

The standard value is $N_{\rm eff} = 3.046$, and it is associated to 3 neutrino families.
It exceeds 3 because e^+e^- annihilation provides neutrino heating.

Recent results:

★ 

WMAP-7 (Wilkinson Microwave Anisotropy probe)+ LSS (Large Scale Structure) found

$$\boxed{N_{\rm eff} = 4.34^{+0.86}_{-0.88}}$$

★ A similar study including SDSS data release 7 (Sloan Digital Sky Survey) found

$$\boxed{N_{\rm eff} = 4.78^{+1.86}_{-1.79}}$$

★ Recent analysis point towards $N_{\rm eff} > 3$.* [See talk by A. Melchiorri]

* J. Hamann, JCAP 1203 (2012) 021, Smith et al., PRD 85 (2012) 023001, Archidiacono et al., PRD 84 (2011) 123008.

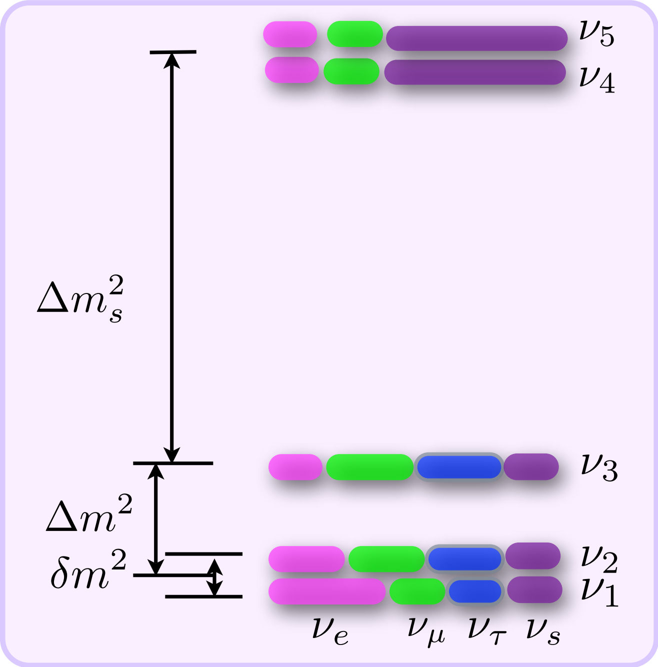
How is the radiation excess explained?

Main radiation components:

★ three different light active neutrino families
★ photons

Extra-Radiation components:

Viable candidates for the excess of radiation, often called “dark radiation,” are sterile neutrinos. However other possible candidates might be considered.



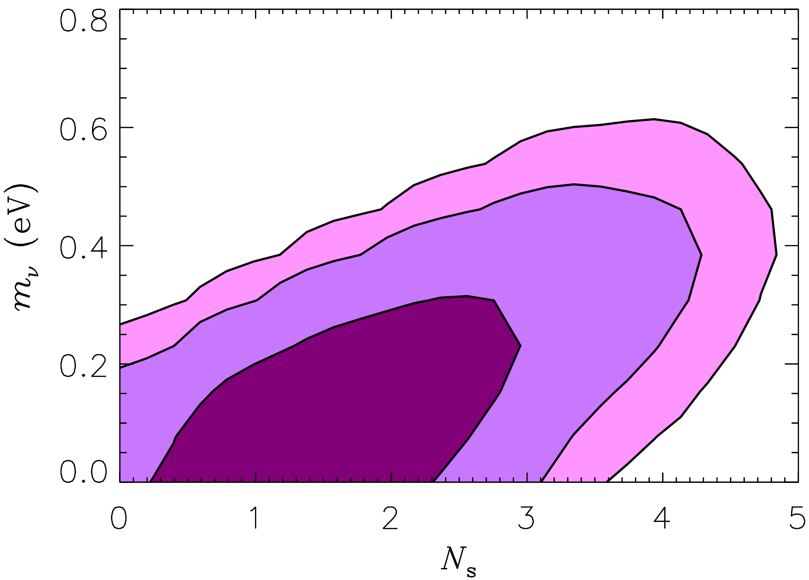
Assuming the existence of light sterile neutrinos, they can mix with the active ones.

Sterile neutrinos can be thermally excited by the interplay of oscillations and collisions.

Cosmological bounds on sterile neutrinos

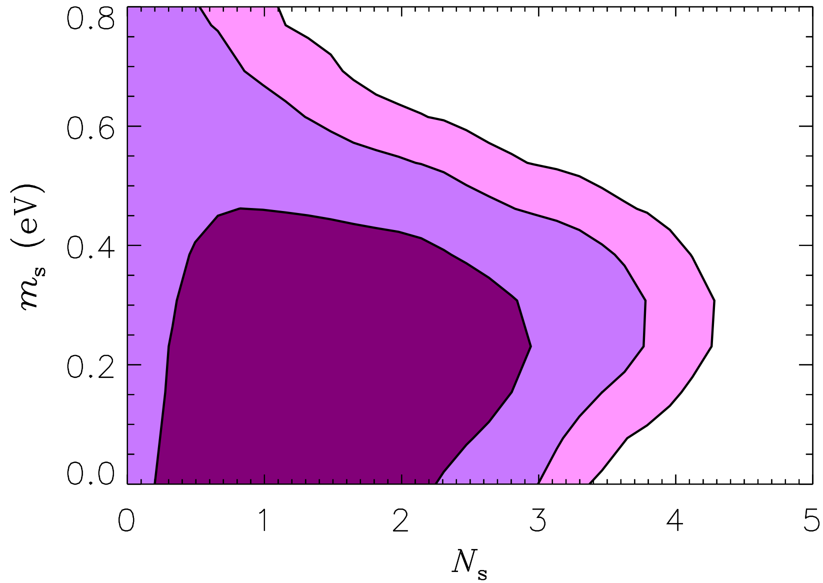
$N_s + 3$ scheme [fit CMB+LSS]

In this scenario, $m_s = 0$ and 3.046 species of ordinary neutrinos have a common mass m_ν .



$3 + N_s$ scheme [fit CMB+LSS]

In this scenario, $m_\nu = 0$ and 2 species of sterile neutrinos have a common mass m_s.



In the $3 + N_s$ scenario, 2D marginalized probability at $N_s < 1$ has a long and narrow tail towards larger m_s, the fewer sterile states there are, the larger the mass they are allowed to possess.
However, $m_s \gtrsim 1$ eV is cosmologically viable only if additional ingredients are included since otherwise the sterile states would contribute too much hot dark matter.**

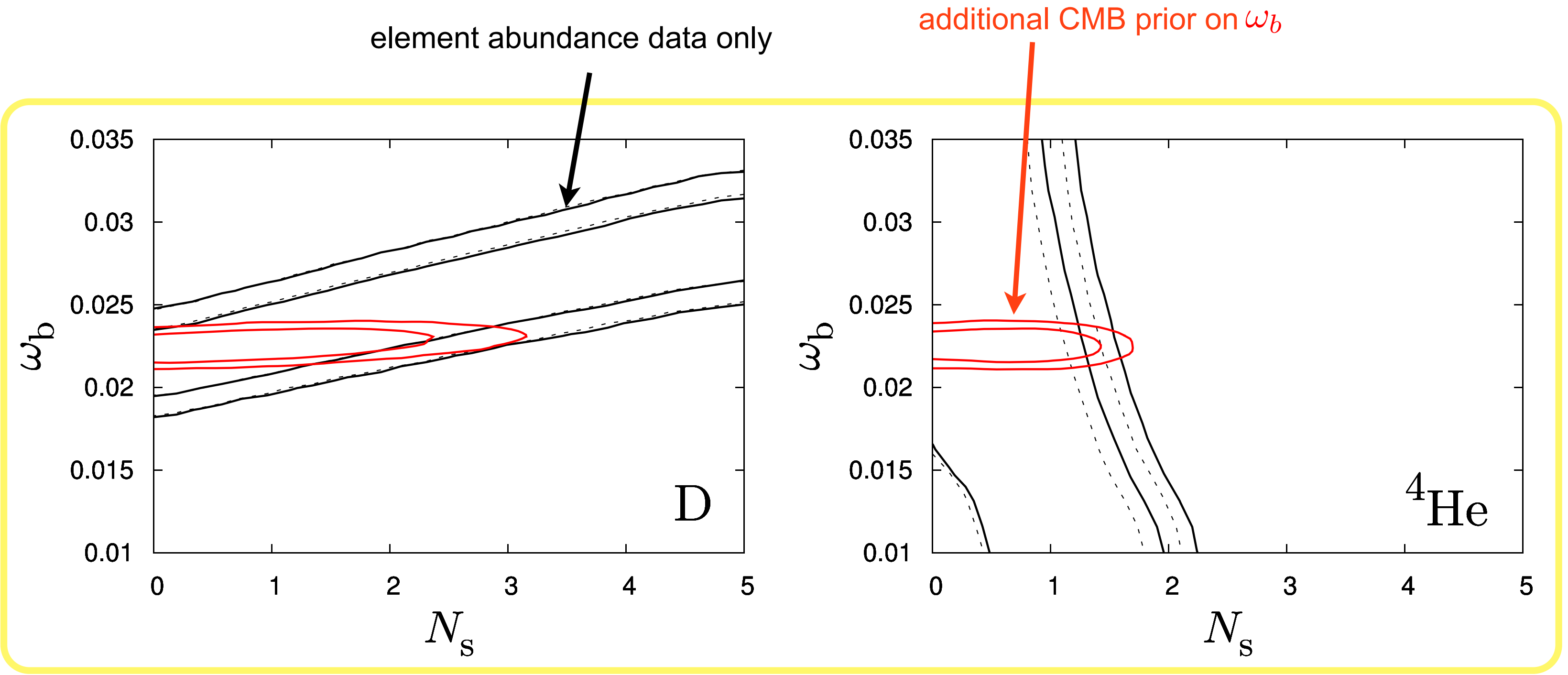
* J. Hamann, S. Hannestad, G.G. Raffelt, I. Tamborra, and Y.Y.Y. Wong, PRL 105, 181301 (2010).

**J. Hamann et al., JCAP 1109 (2011) 034.

See also E. Giusarma et al., PRD 83, 115023 (2011), S. Joudaki, K. Abazajian, M. Kaplinghat, arXiv: 1208.4354.

Big Bang Nucleosynthesis Bounds

Concerning BBN: both ^4He and D prefer $N_s > 0$, but it may be difficult to accommodate $N_s = 2$.*



Bounds on dark radiation from BBN point towards a more constrained value for N_s than what is implied by CMB+LSS data.

* J. Hamann et al., PRL 105, 181301 (2010). J. Hamann et al., JCAP 1109 (2011) 034.
See also G. Mangano and P. Serpico, Phys. Lett. B 701 (2011) 296.

Thermalization of Sterile Neutrinos

Big Bang Nucleosynthesis constraints assume sterile neutrinos are thermalized at the BBN epoch. Is this assumption justified?
To study their thermalization, we* assume (1 active+1 sterile) scheme and adopt the density matrix formalism. The matrix associated with each momentum bin can be decomposed in terms of the Bloch vector components

$$\rho = \frac{1}{2} f_0 (P_0 + \mathbf{P} \cdot \sigma) \,, \qquad \overline{\rho} = \frac{1}{2} f_0 (\overline{P}_0 + \overline{\mathbf{P}} \cdot \sigma)$$

The neutrino kinetic equations for each mode are (with $d_t = \partial_t - Hp\partial_p$)**

$$\mathbf{V} = \mathbf{V}(\delta m_s^2, \theta_s, L^{(a)}, p, T)$$

damping term
(loss of quantum coherence)

$$\boxed{\begin{aligned} \dot{\mathbf{P}} &= \mathbf{V} \times \mathbf{P} - D(P_x \mathbf{x} + P_y \mathbf{y}) + \dot{P}_0 \mathbf{z} \\ \dot{P}_0 &= \Gamma \left[\frac{f_{\rm eq}}{f_0} - \frac{1}{2}(P_0 + P_z) \right] \end{aligned}}$$

processes that deplete or enhance the abundance of ν_a

scattering rate

[See talk by N. Saviano]

* S. Hannestad, I. Tamborra, and T. Tram, JCAP 07 (2012) 025.

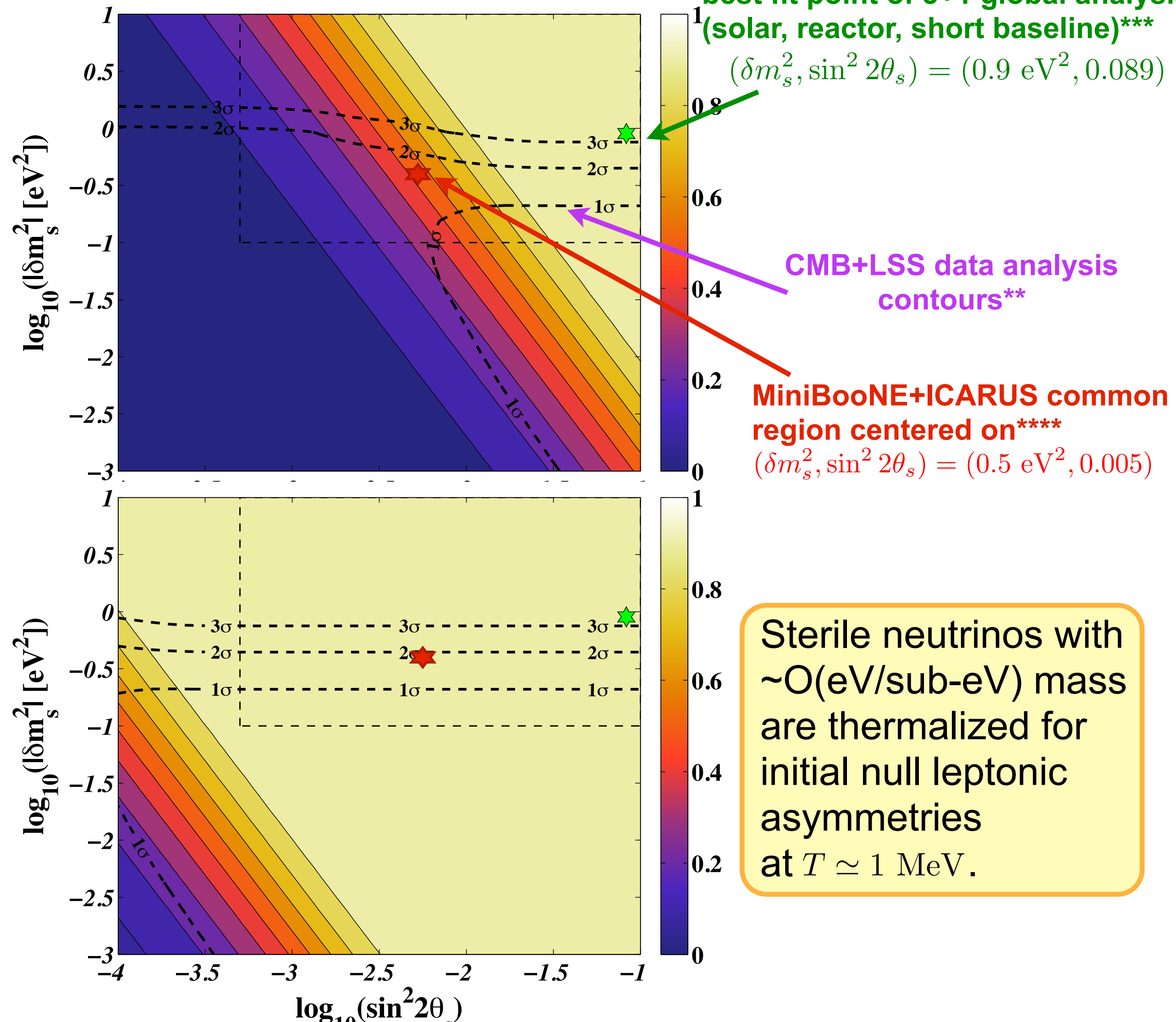
** G. Sigl and G.G. Raffelt, Nucl. Phys. B 406, 423 (1993).

Thermalization of Sterile Neutrinos

Iso-$\delta N_{\rm eff}$ contours for $L^a = 0$.

normal hierarchy
1 + 1 scheme

inverted hierarchy
1 + 1 scheme



Sterile neutrinos with ~O(eV/sub-eV) mass are thermalized for initial null leptonic asymmetries at $T \simeq 1$ MeV.

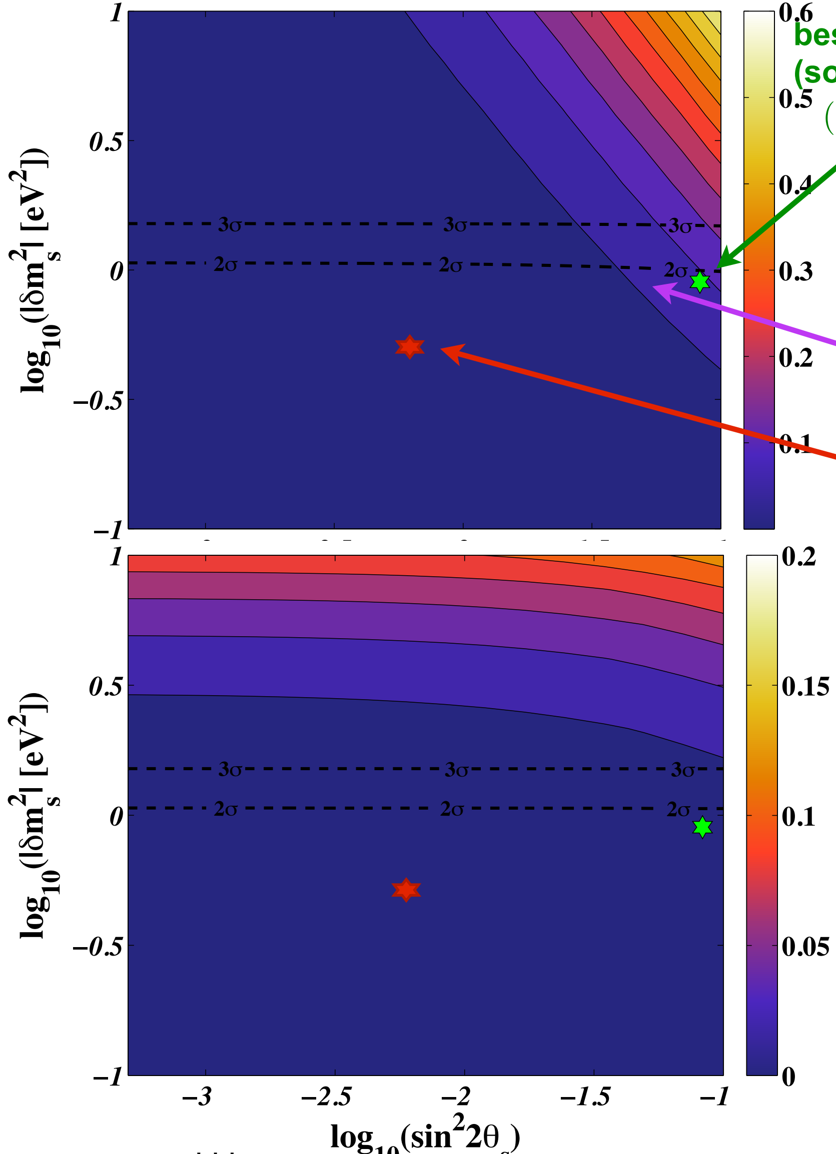
** J. Hamann et al., PRL 105, 181301 (2010). ***C. Giunti and M. Laveder, PLB 706, 200 (2011).
**** M. Antonello et al., arXiv: 1209.0122.

Thermalization of Sterile Neutrinos

Iso-$\delta N_{\rm eff}$ contours for $L^a = 10^{-2}$.

normal hierarchy
1 + 1 scheme

inverted hierarchy
1 + 1 scheme



best fit point of 3+1 global analysis (solar, reactor, short baseline)***
$(\delta m_s^2, \sin^2 2\theta_s) = (0.9\ \mathrm{eV}^2, 0.089)$

CMB+LSS data analysis contours**

MiniBooNE+ICARUS common region centered on****
$(\delta m_s^2, \sin^2 2\theta_s) = (0.5\ \mathrm{eV}^2, 0.005)$

Partial or no-thermalization occurs for sterile neutrinos with ~O(eV/sub-eV) mass and large initial leptonic asymmetries at $T \simeq 1$ MeV.

** J. Hamann et al., PRL 105, 181301 (2010). ***C. Giunti and M. Laveder, PLB 706, 200 (2011).
**** M. Antonello et al., arXiv: 1209.0122.

Conclusions and perspectives

★ Cosmological data favor extra-radiation in the universe beyond photons and neutrinos. Low-mass sterile neutrinos are one natural possibility, introduced also to explain the LSND/MiniBooNE+reactor anomalies.

★ One/two sterile states are allowed from cosmology (CMB+LSS), BBN is more constraining (one thermalized sterile state allowed).

★ Small/null initial leptonic asymmetry: one eV (sub-eV) mass sterile family is thermalized at the BBN epoch. Tension between cosmology and reactor data.

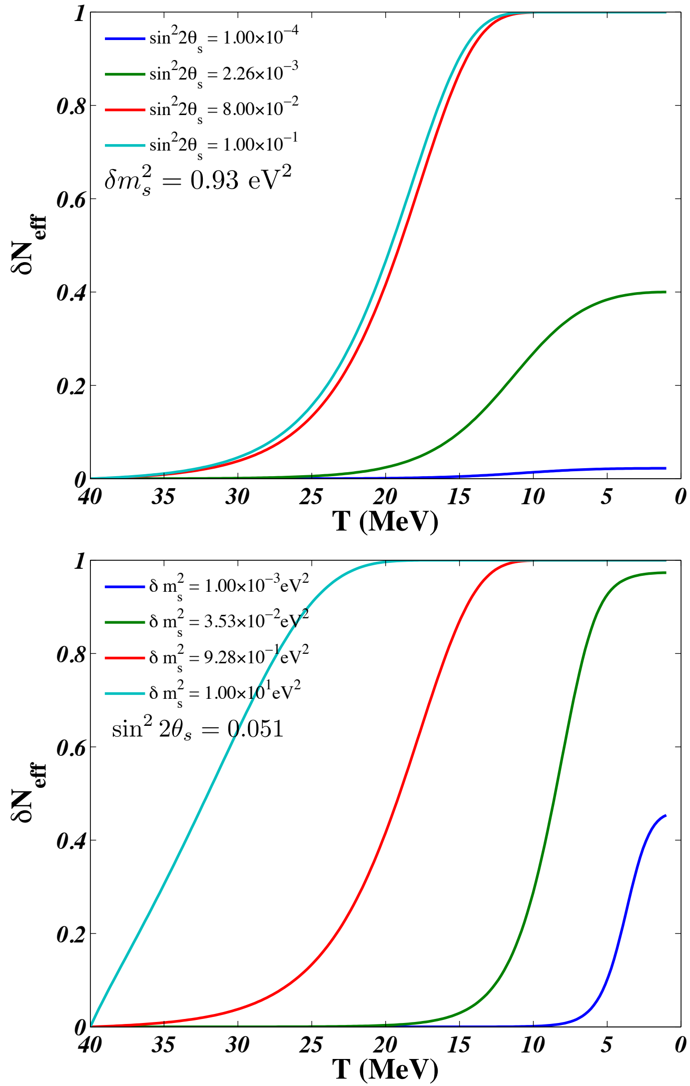
★ Large initial leptonic asymmetry: eV (sub-eV) sterile neutrinos are partially or not thermalized at the BBN epoch.
eV sterile states compatible with CMB+LSS constraints. Agreement between cosmology and reactor anomalies.

★ The Planck results will give us more precise constraints.

Thank you for your attention!

Back-up slides

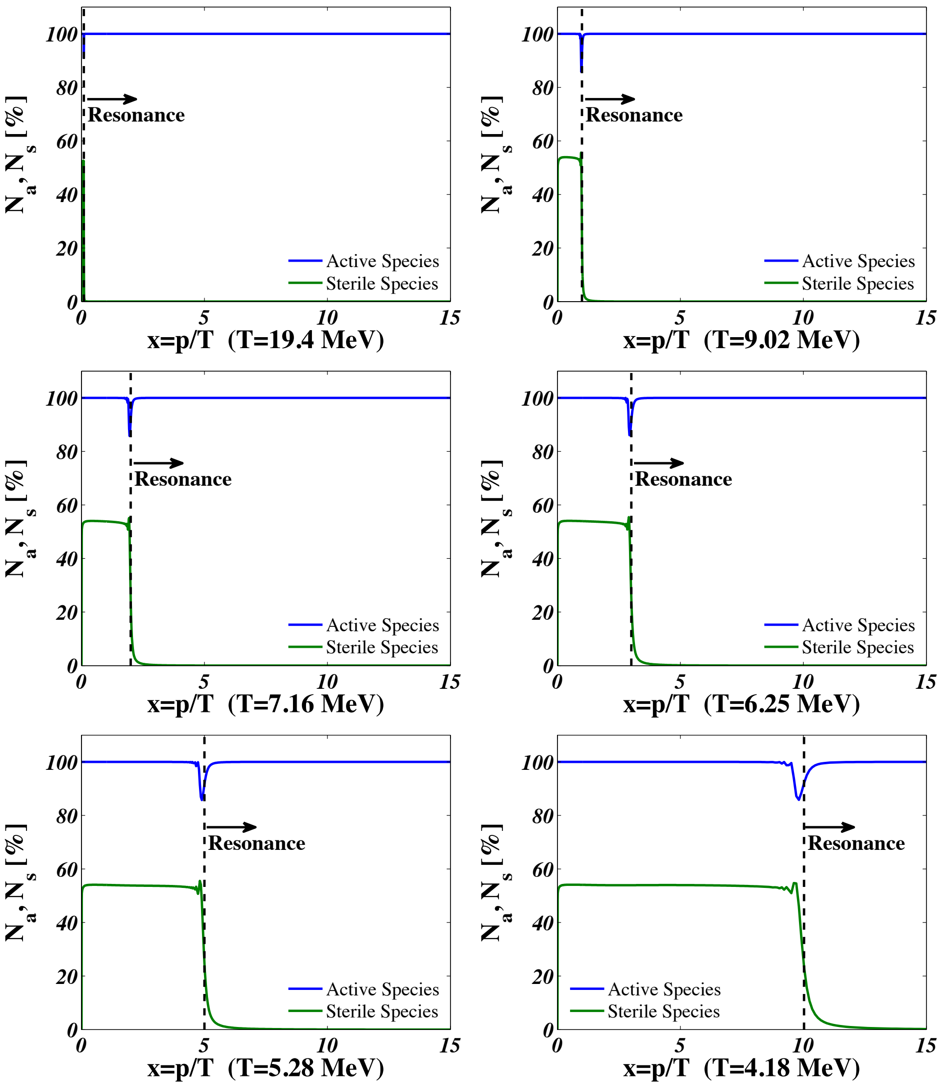
Thermalization dependence from mixing



Thermalization begins earlier and is more efficient for larger mass differences and larger mixing angles (L=0)

* S. Hannestad, I. Tamborra, and T. Tram, JCAP 07 (2012) 025.

Thermalization cartoon

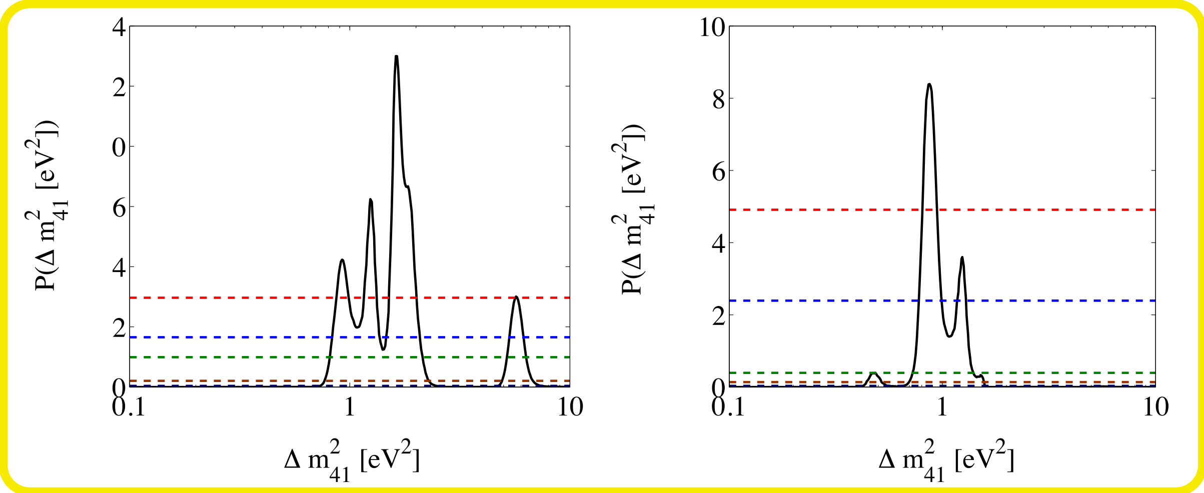


$$(\delta m_s^2, \sin^2\theta_s) = (-3.3\ \mathrm{eV}^2, 6\times10^{-4})$$

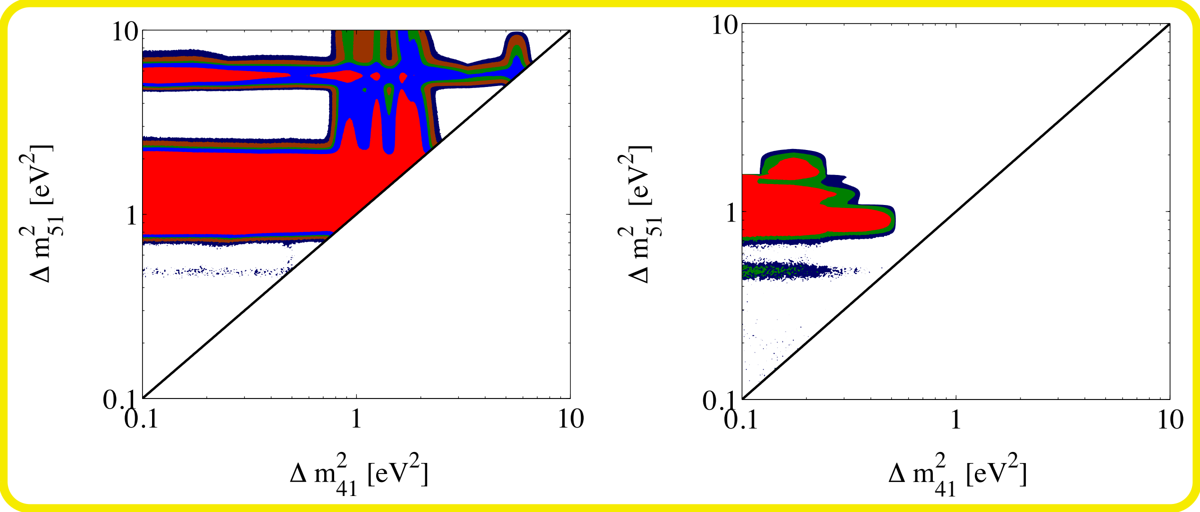
$$L^a = 0$$

* S. Hannestad, I. Tamborra, and T. Tram, JCAP 07 (2012) 025.

Combined analysis of short-baseline + cosmological data



3+1 scheme
[fit SBL + (CMB+LSS)]
$0.85 \text{ eV} < m_4 < 1.18 \text{ eV}$



3+2 scheme
[fit SBL + (CMB+LSS)]
$m_4 < 0.7 \text{ eV}$
$0.67 \text{ eV} < m_5 < 1.35 \text{ eV}$

[See talk by C. Giunti]

* M. Archidiacono et al., arXiv: 1207.6515. See also: S. Joudaki, K. Abazajian, M. Kaplinghat, arXiv: 1208.4354.