Alexander von Humboldt
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MAX-PLANCK-GESELLSCHAFT

# Light Sterile Neutrinos as Dark Radiation Candidates


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Rencontres de Moriond, EW Interactions and Unified Theories
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# Roadmap

Oscillation experiment anomalies ⇒ sterile neutrinos $[\delta m_s^2 \sim \mathcal{O}(\mathrm{eV}^2)]$

Dark radiation hints ⇒ light sterile neutrinos

| | sub-eV mass | eV mass |
|---|---|---|
| fully thermalized sterile neutrinos |  |  |
| hot dark matter bounds |  |  |
| agreement with terrestrial anomalies |  |  |

Is full-thermalization assumption justified? Could thermalization be prevented?

# Experimental Hints for Sterile Neutrinos

# Experimental hints for sterile neutrinos

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

**- Appearance signals:**

★ LSND anomaly [A. Aguilar et al., PRD 64, 112007 (2001)]

ICARUS “LSND-like anomaly” [M. Antonello et al., arXiv: 1209.0122]

★ MiniBooNE data [A.A.Aguilar-Arevalo et al., arXiv: 1207.4809]

**- Disappearance signals:**

★ 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), Giunti et al. PRD 86, 113014 (2012)]

Sterile neutrinos with mass up to $\delta m_s^2 \sim \mathcal{O}(\mathrm{eV}^2)$ explain quite well these anomalies.*

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

# Cosmological Hints for Sterile Neutrinos

# Radiation content of the universe

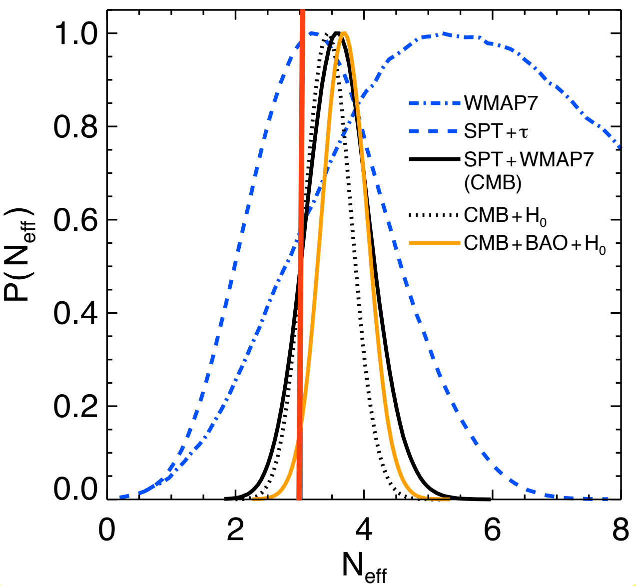
The radiation content of the universe expressed in terms of $N_{\rm eff}$ (any relativistic d.o.f.).

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

standard value $N_{\rm eff} = 3.046$

## Recent results:

WMAP-9+eCMB+BAO+H0 find $N_{\rm eff} = 3.84 \pm 0.4$




Several recent analysis point towards $N_{\rm eff} > 3$.*

BBN: higher $^4He$ abundance ⇨ additional radiation**

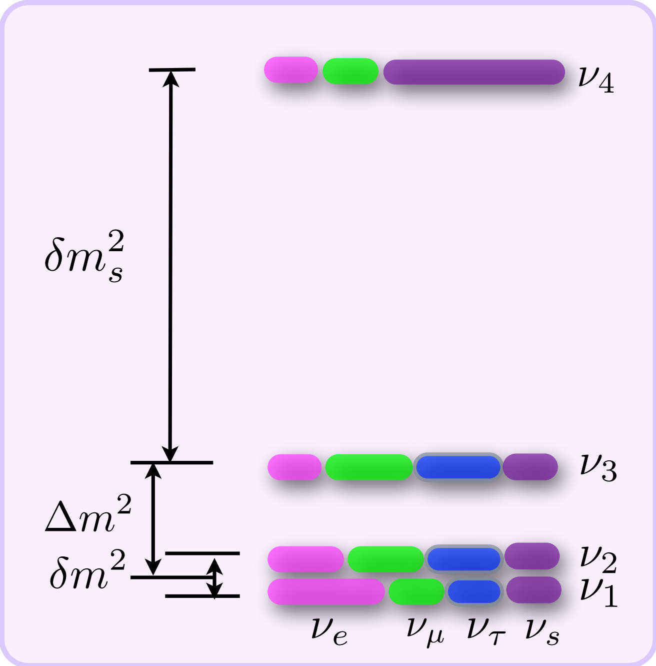
* Z. Hou et al., arXiv: 1212.6267, J. Hamann, JCAP 1203 (2012) 021, Smith et al., PRD 85 (2012) 023001, Archidiacono et al., PRD 84 (2011) 123008. ** Y.I. Izotov and T.X. Thuan, Astrophys. J. 710 (2010) L67.

# How is the radiation excess explained?

**Main radiation components:** Three active neutrino families, photons.

**Extra-radiation components:** Light sterile neutrinos [other candidates allowed]

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




**Allowed scenarios**

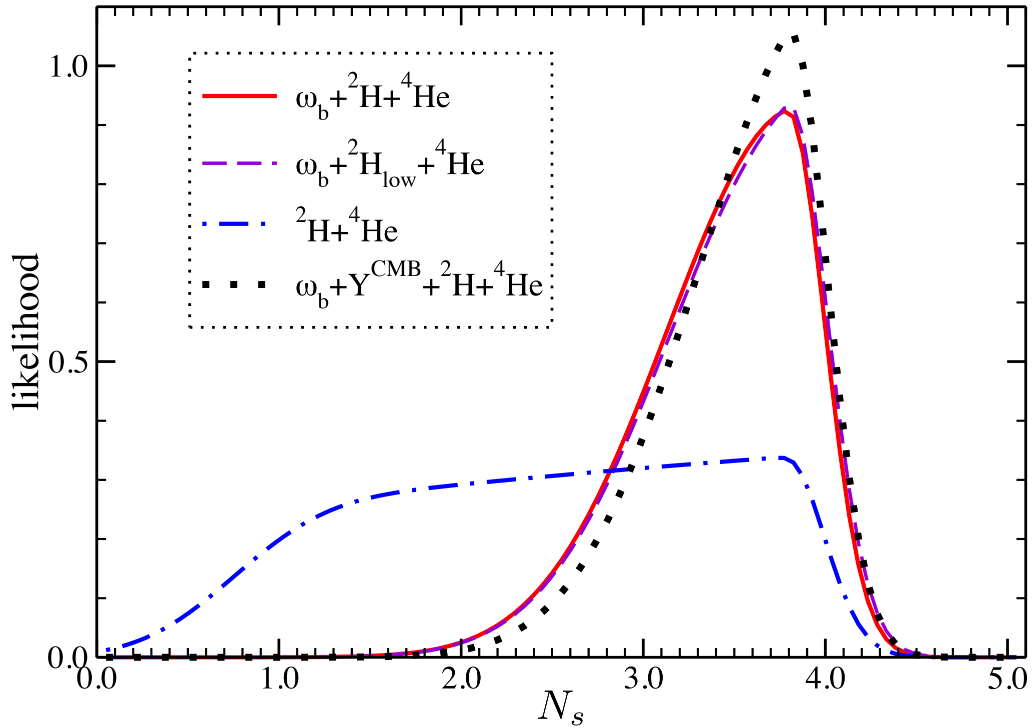
**normal hierarchy (NH):** $\delta m_s^2 > 0$

**inverted hierarchy (IH):** $\delta m_s^2 < 0$

Caveat: Structure formation data strongly disfavor the IH scenario with sterile masses above 0.2-0.3 eV.

# Big Bang Nucleosynthesis bounds

Assuming **fully thermalized** sterile states, BBN constraints the sterile family number $N_s$.




**BBN**: $^4He$ prefers $N_s > 0$, but it may be difficult to accommodate $N_s = 2$! *

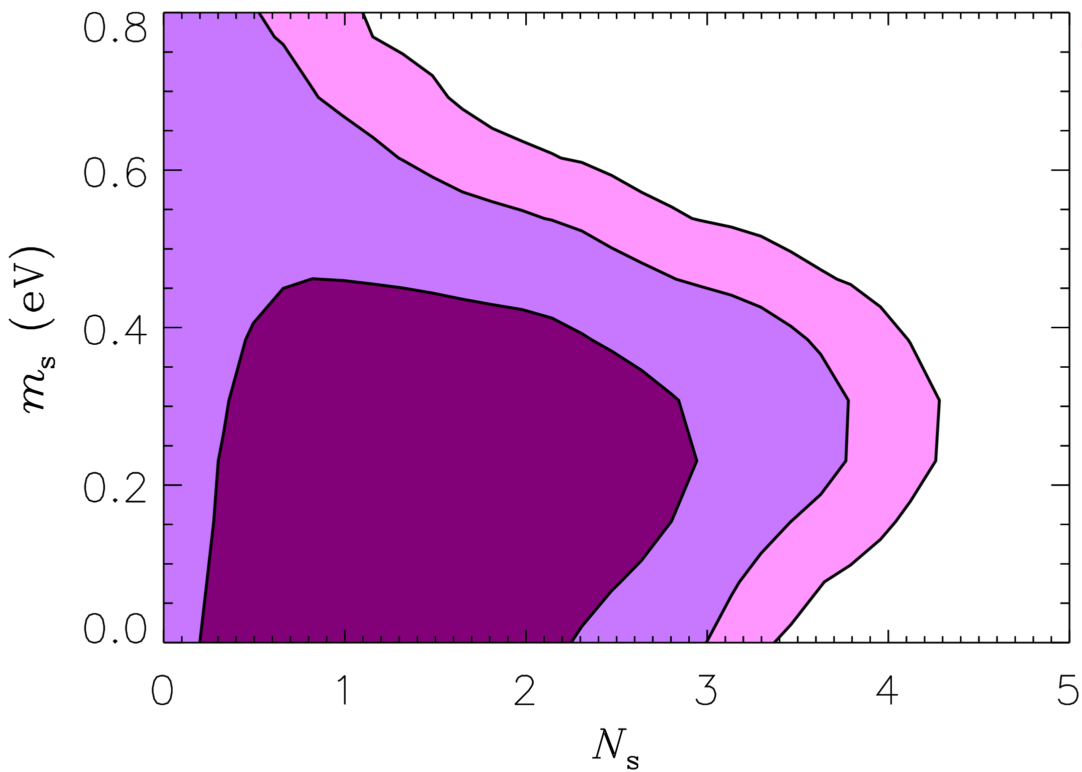
* J. Hamann et al., PRL 105, 181301 (2010). J. Hamann et al., JCAP 1109 (2011) 034.
G. Mangano and P. Serpico, Phys. Lett. B 701 (2011) 296.

# Cosmological bounds: sub-eV masses

$\Lambda CDM$ model

$\underline{3 + N_s \text{ scheme}}$ [CMB+LSS fit]

$m_\nu = 0$ + sterile neutrinos with mass $m_s$



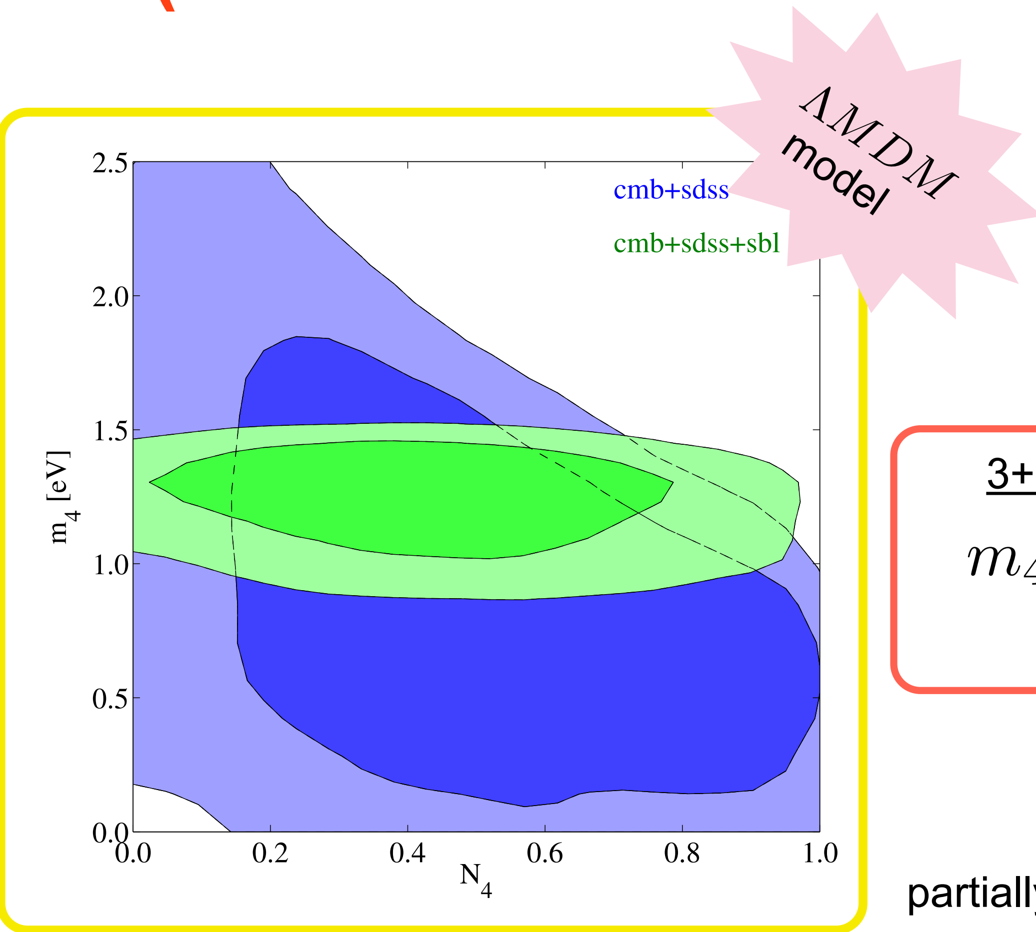

$m_s \gtrsim 1$ eV is viable only if additional ingredients are included (too much hot dark matter).**


* 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.

# Combined bounds: eV-masses (short-baseline + cosmological data)



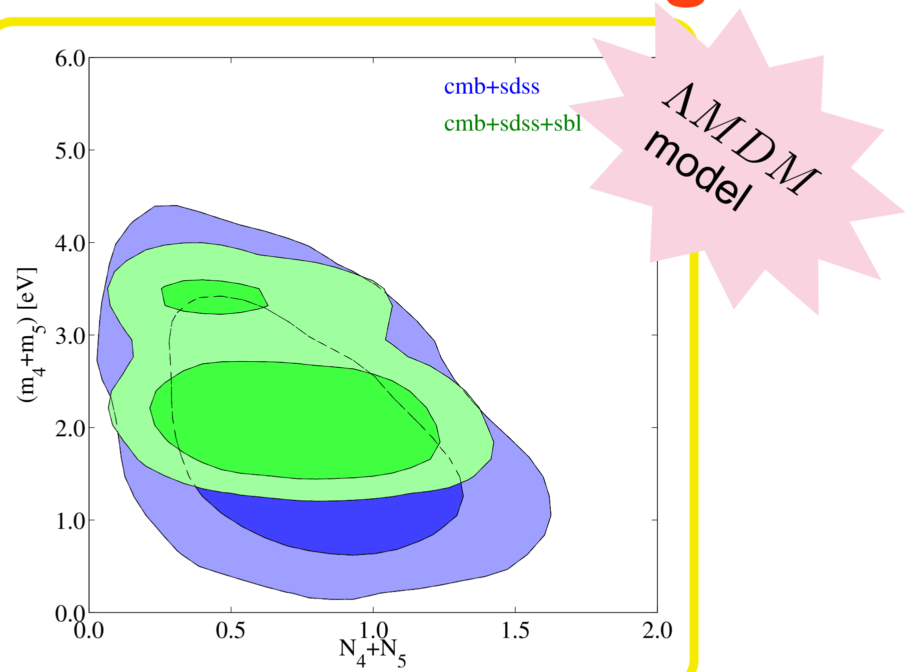

3+1 scheme [SBL + (CMB+LSS) fit]

$$m_4 = 1.23 \pm 0.13 \text{ eV } (1\sigma)$$
$$N_4 < 0.83 \, (2\ \sigma)$$

partially thermalized state $N_i = \dfrac{n_i}{n_{\rm therm}}$

* M. Archidiacono et al., arXiv: 1302.6720.
See also: M. Archidiacono et al. PRD 86 (2012) 065028, S. Joudaki, K. Abazajian, M. Kaplinghat, arXiv: 1208.4354.

# Combined bounds: eV-masses (short-baseline + cosmological data)




<u>3+2 scheme</u> [SBL + (CMB+LSS) fit]

$$N_4 < 0.85 \qquad (2\ \sigma)$$
$$N_5 < 0.62$$
$$m_4 = 0.95 \pm 0.3\ \mathrm{eV} \qquad (1\sigma)$$
$$m_5 = 1.59 \pm 0.49\ \mathrm{eV}$$

<u>3+2 scheme</u> (reduced analysis) [SBL + (CMB+LSS) fit]

$$m_4 + m_5 = 2.33 \pm 0.61\ \mathrm{eV} \qquad (1\sigma)$$
$$N_4 + N_5 = 0.69 \pm 0.29$$

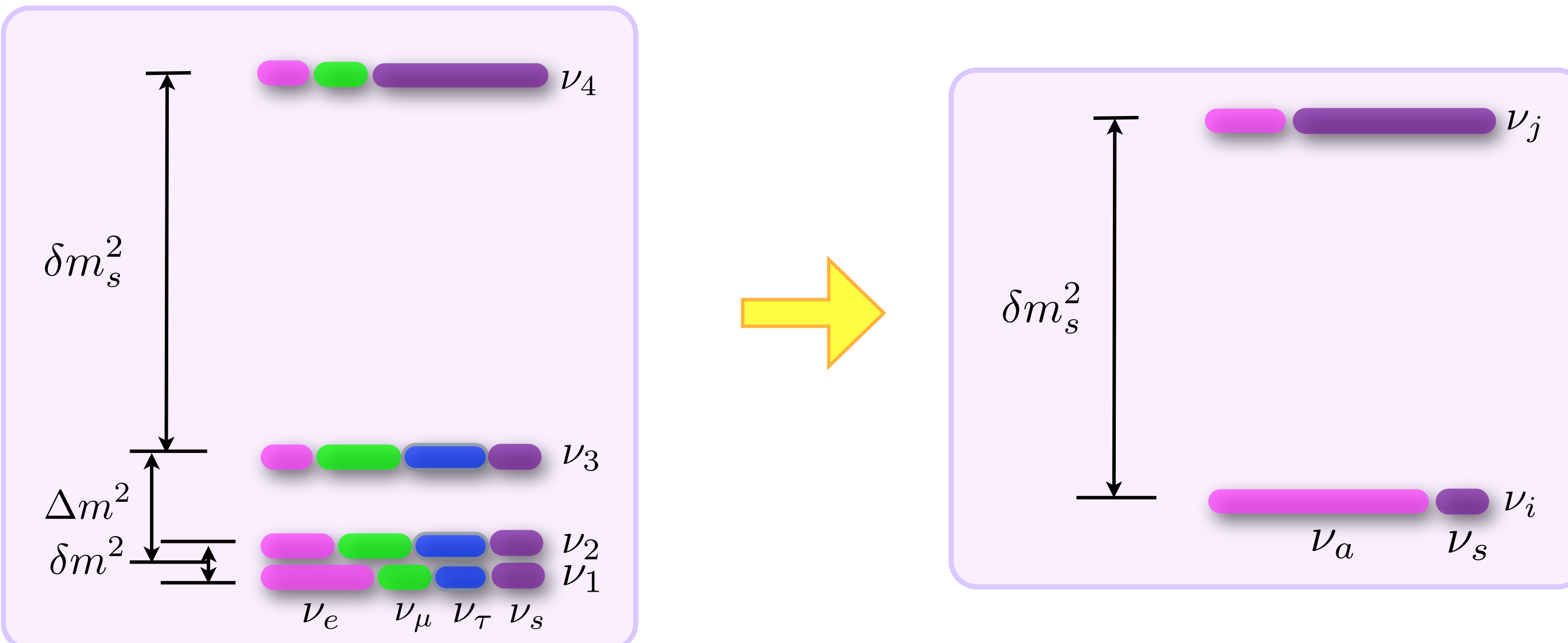
* M. Archidiacono et al., arXiv: 1302.6720.
See also: M. Archidiacono et al. PRD 86 (2012) 065028, S. Joudaki, K. Abazajian, M. Kaplinghat, arXiv: 1208.4354.

# Are sterile neutrinos fully thermalized?

# Thermalization of sterile neutrinos

- ★ BBN constraints assume fully thermalized sterile neutrinos.
- ★ Cosmo and SBL data agree assuming not fully thermalized sterile neutrinos.
- ★ If Planck does not find excess of radiation, how do terrestrial anomalies fit with cosmology?

Let's assume for simplicity* **(1 active + 1 sterile) scheme**:




and adopt the density matrix formalism

$$\rho = \begin{bmatrix} \nu_a & \nu_a - \nu_s \\ \nu_a - \nu_s & \nu_s \end{bmatrix}$$

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

# Thermalization of sterile neutrinos

The density matrix associated with each momentum is written in terms of the Bloch vectors

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

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 $\nu_a$**

**scattering rate**

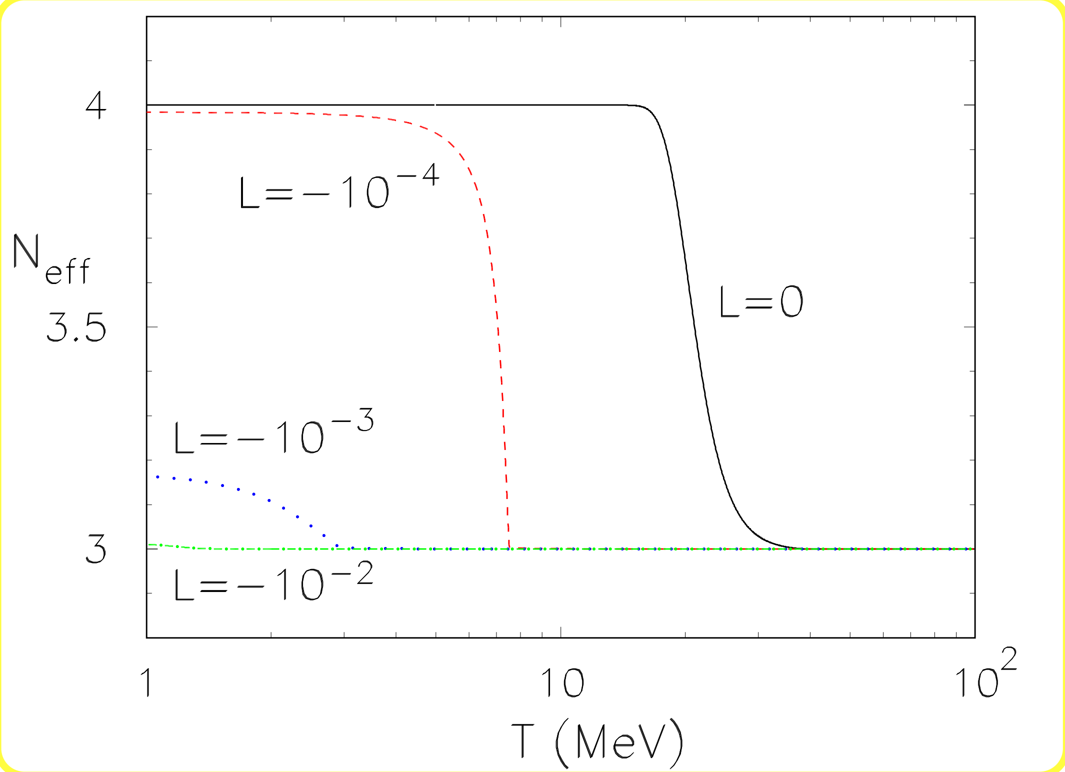
** G. Sigl and G.G. Raffelt, Nucl. Phys. B 406, 423 (1993).

# Thermalization: Asymmetry dependence

effective $\nu_a - \nu_s$ mixing angle reduced by large matter term $\propto L^{(a)} = \dfrac{n_{\nu_a} - n_{\bar{\nu}_a}}{n_\gamma}$

Increasing $L^{(a)}$ → less adiabatic conversion → position of the resonance shifts

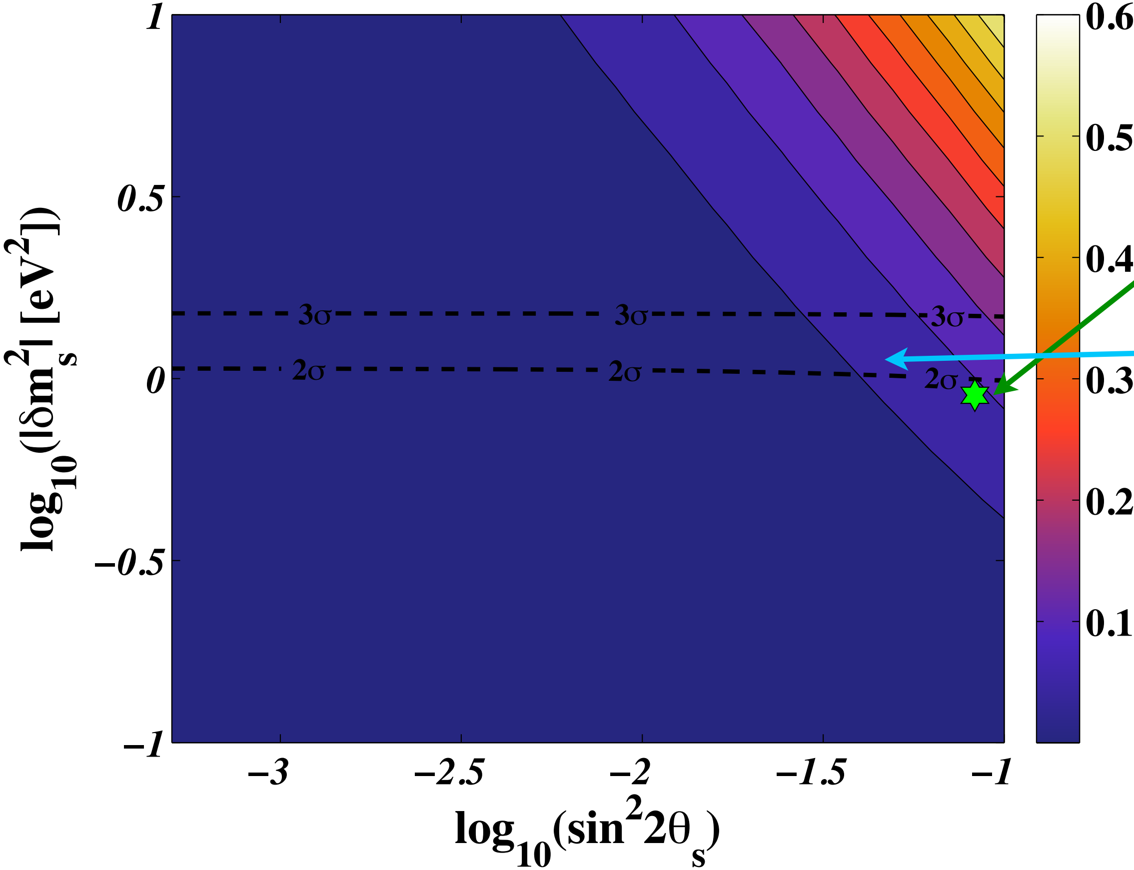
towards lower $T$ → production of sterile thermalized states less efficient*




* Enqvist et al. (1990, 1991, 1992), Foot, Thomson and Volkas (1995), Bell, Volkas and Wong (1998), ...
See also Mirizzi et al., PRD 86 (2012) 053009.

# Thermalization of sterile neutrinos ($L^{(a)} = 10^{-2}$)

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




## normal hierarchy

**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****

**Partial or no-thermalization** occurs for O(eV) mass sterile neutrinos at $T \simeq 1\ \mathrm{MeV}$, supposing large initial leptonic asymmetry.


* S. Hannestad, I. Tamborra, and T. Tram, JCAP 07 (2012) 025.
** J. Hamann et al., PRL 105, 181301 (2010). ***C. Giunti and M. Laveder, PLB 706, 200 (2011).
See also N. Saviano et al., arXiv: 1302.1200.

# Conclusions

★ Cosmological data favor excess of radiation in the universe.
Low-mass sterile neutrinos are one natural possibility.

★ One/two sub-eV/eV sterile states allowed from cosmology (CMB+LSS).
BBN allows one fully thermalized sterile state.

★ Assuming partial thermalization, agreement between cosmology and short-baseline data for both 3+1 and 3+2 schemes.

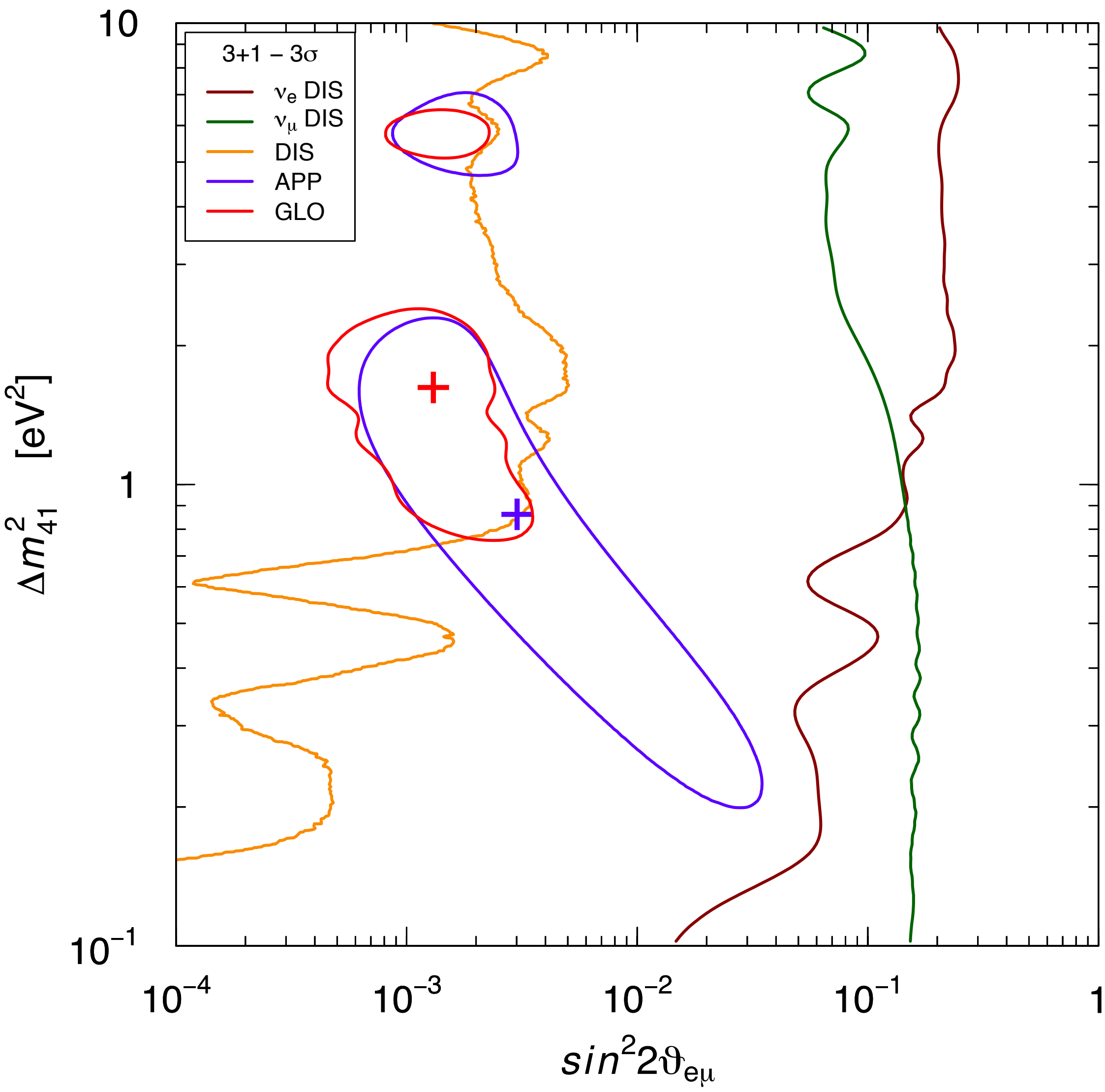
★ Large initial leptonic asymmetry prevents thermalization of sterile states.

★ Planck will provide very precise constraints ($\Delta N_{\rm eff} = \pm 0.26$ or better).

Thank you for your attention!

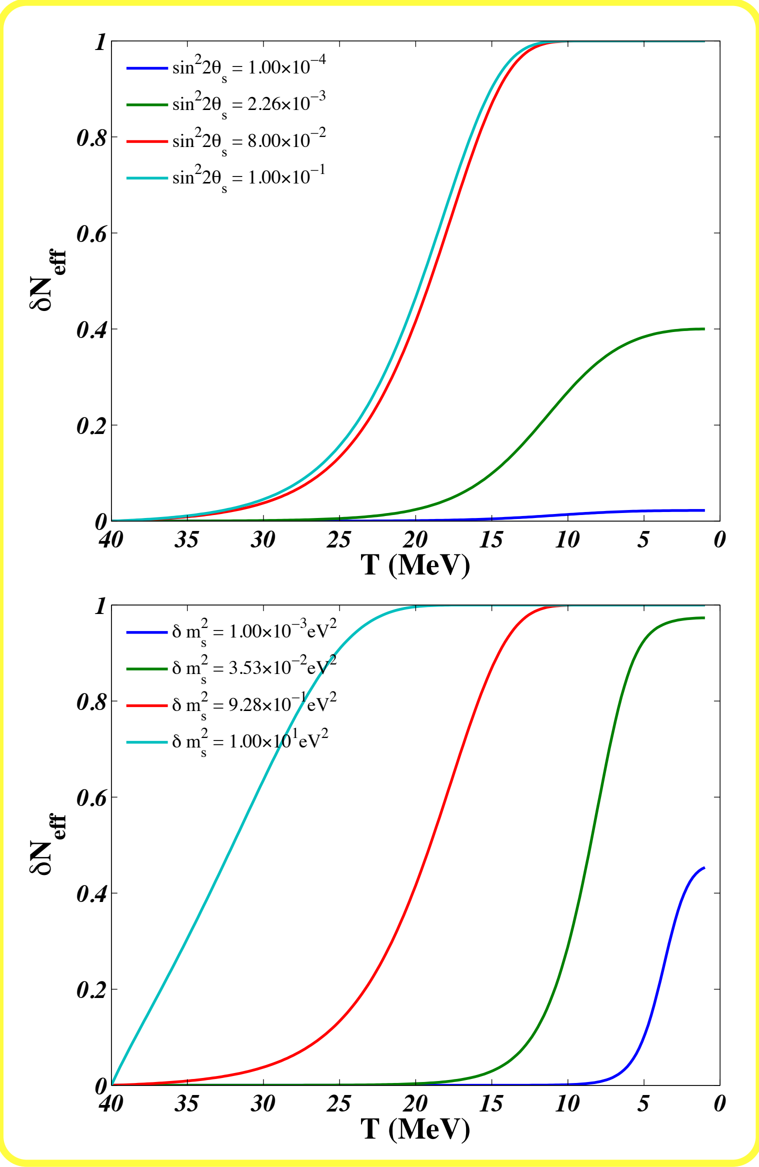
# Back-up slides

# Experimental bounds for sterile neutrinos




* M. Archidiacono et al., arXiv: 1302.6720.

# Thermalization: Mixing dependence



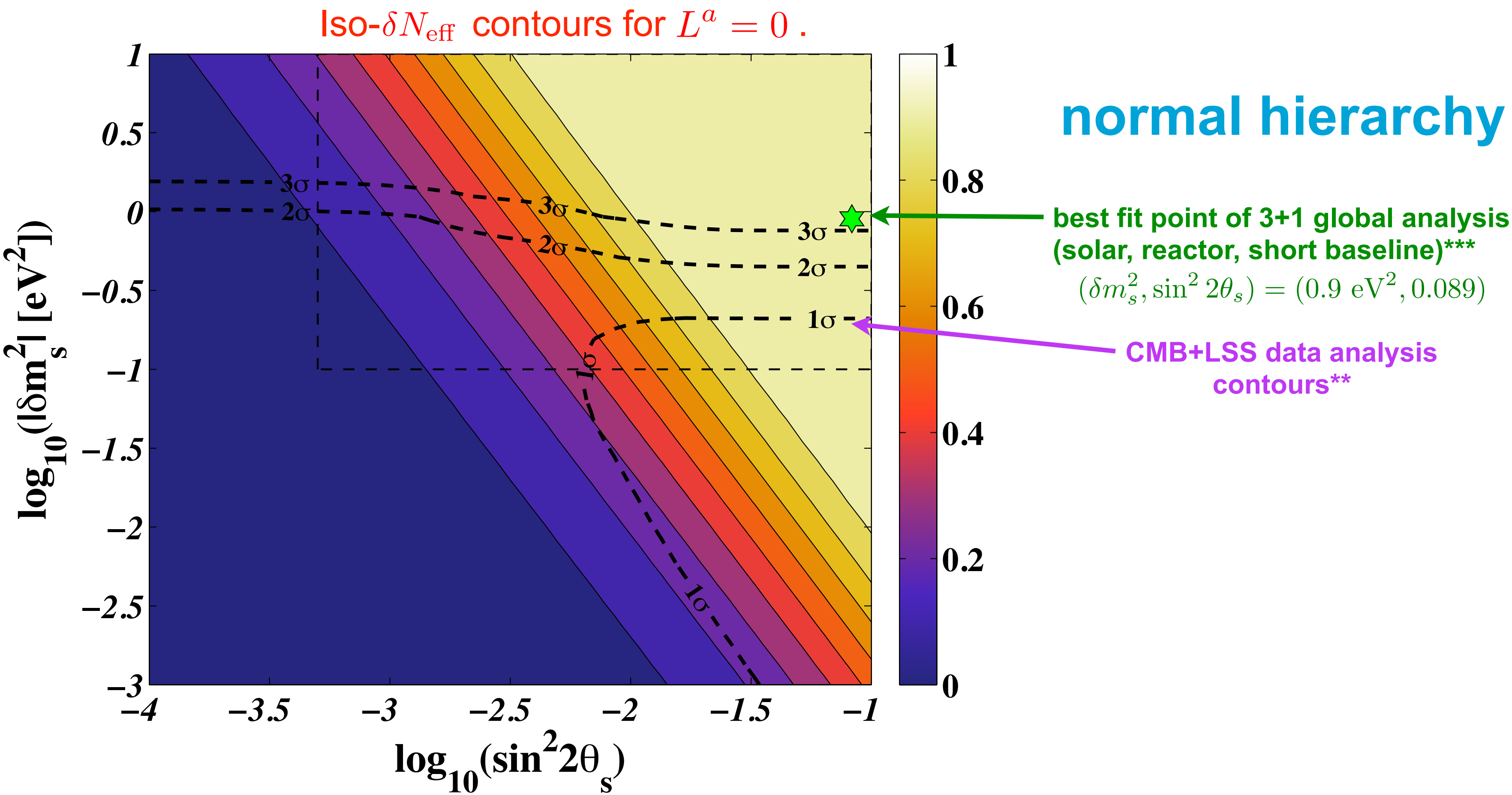

Thermalization begins at higher T and it is more efficient ($L^{(a)} = 0$)

**large mixing angles**

**large mass differences**

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

# Thermalization of sterile neutrinos ($L^{(a)} = 0$)



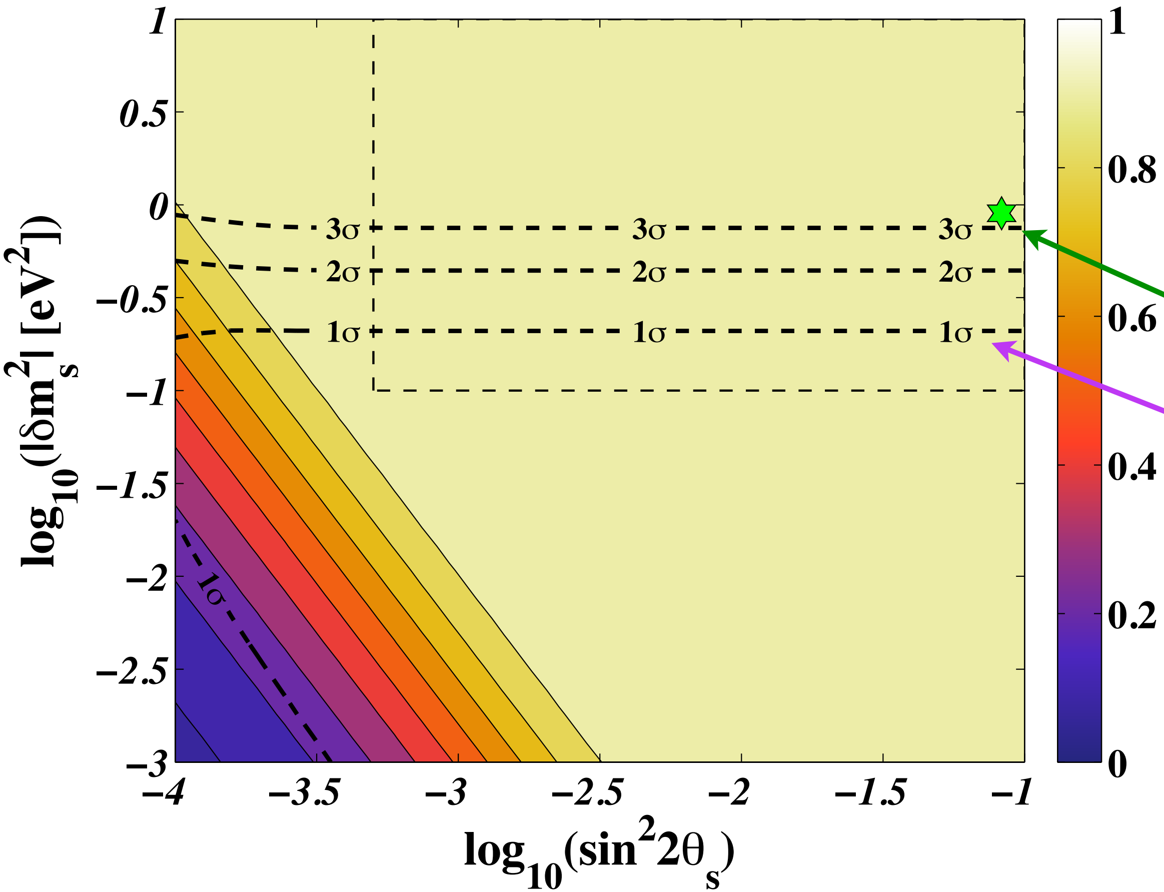

Sterile neutrinos with ~O(eV) mass are **thermalized** for null leptonic asymmetries a $T \simeq 1$ MeV.

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

** J. Hamann et al., PRL 105, 181301 (2010). ***C. Giunti and M. Laveder, PLB 706, 200 (2011).
See also N. Saviano et al., arXiv: 1302.1200.

# Thermalization of sterile neutrinos ($L^{(a)} = 0$)

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




**inverted hierarchy**

**best fit point of 3+1 global analysis (solar, reactor, short baseline)*****

$(\delta m_s^2, \sin^2 2\theta_s) = (0.9\ \mathrm{eV}^2, 0.089)$

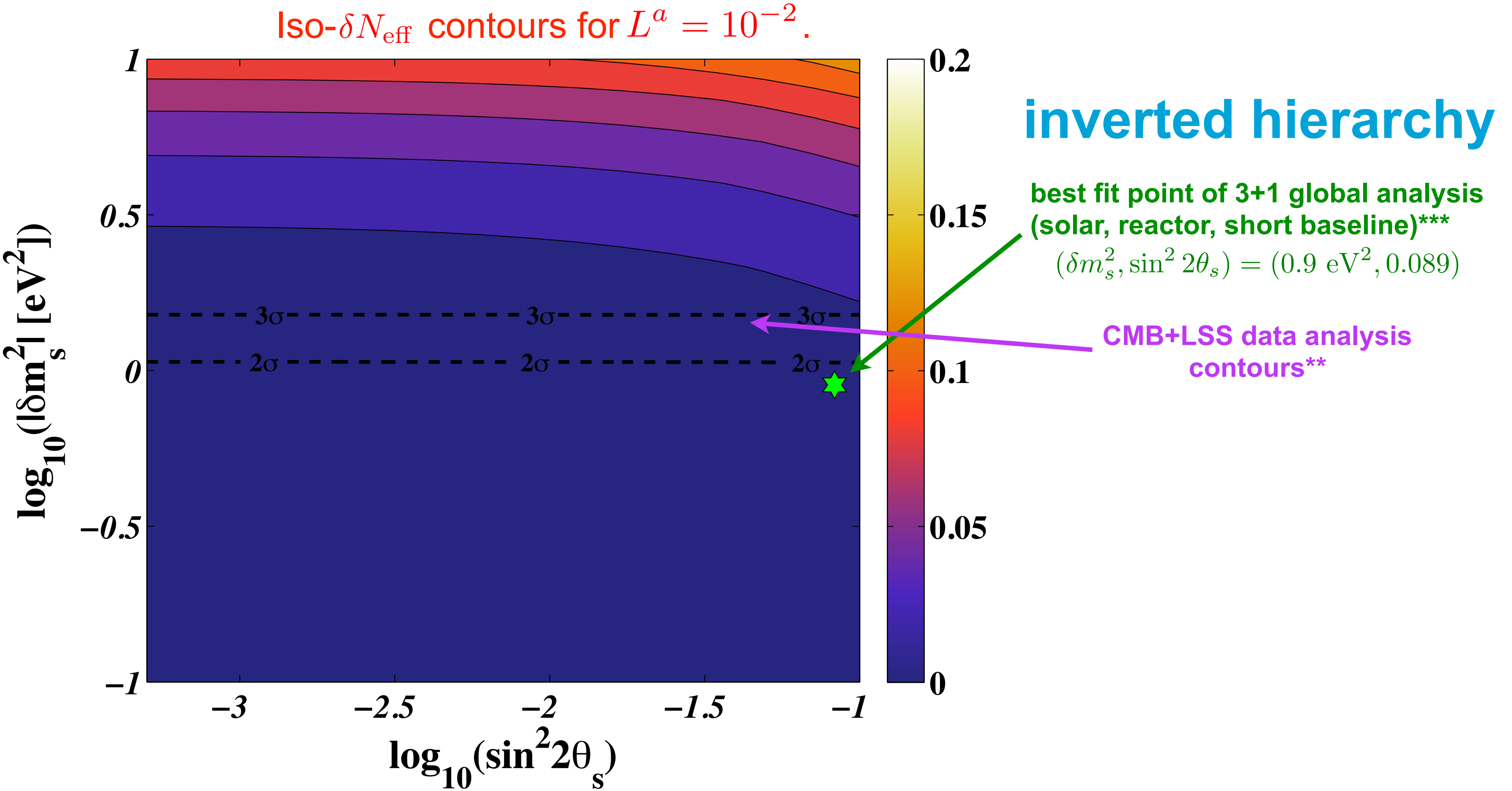
**CMB+LSS data analysis contours****

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


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

** J. Hamann et al., PRL 105, 181301 (2010). ***C. Giunti and M. Laveder, PLB 706, 200 (2011).
See also N. Saviano et al., arXiv: 1302.1200.

# Thermalization of sterile neutrinos ($L^{(a)} = 10^{-2}$)




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

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

** J. Hamann et al., PRL 105, 181301 (2010). ***C. Giunti and M. Laveder, PLB 706, 200 (2011).
See also N. Saviano et al., arXiv: 1302.1200.

# SPT & ACT

| | W9+SPT | W9+SPT + HST | W9+SPT +BAO | W9+SPT +SNLS3 | W9+SPT +BAO+HST | W9+SPT +BAO+SNLS3 |
|---|---|---|---|---|---|---|
| $N_{\rm eff}$ | $3.66 \pm 0.61$ | $4.08 \pm 0.54$ | $3.76 \pm 0.67$ | $4.04 \pm 0.68$ | $4.21 \pm 0.46$ | $3.87 \pm 0.68$ |
| $\sum m_\nu$ (eV) | $1.35 \pm 0.55$ | $0.48 \pm 0.33$ | $0.56 \pm 0.22$ | $< 0.91$ | $0.56 \pm 0.23$ | $0.50 \pm 0.21$ |

TABLE III: Mean values and errors(or 95% CL bounds) on $N_{\rm eff}$ and $\sum m_\nu$ (in eV) in a standard cosmology with $N_{\rm eff}$ massive neutrinos for the different combinations of data sets in the case of considering SPT high multipole data.

| | W9+ACT | W9+ACT + HST | W9+ACT +BAO | W9+ACT +SNLS3 | W9+ACT +BAO+HST | W9+ACT +BAO+SNLS3 |
|---|---|---|---|---|---|---|
| $N_{\rm eff}$ | $2.64 \pm 0.51$ | $3.20 \pm 0.38$ | $2.63 \pm 0.48$ | $2.75 \pm 0.44$ | $3.44 \pm 037$ | $2.78 \pm 0.46$ |
| $\sum m_\nu$ (eV) | $< 0.95$ | $< 0.39$ | $< 0.55$ | $< 0.44$ | $< 0.50$ | $< 0.53$ |

TABLE V: Mean values and errors on $N_{\rm eff}$ and 95% CL upper bounds on $\sum m_\nu$ (in eV) in a standard cosmology with $N_{\rm eff}$ massive neutrinos for the different combinations of data sets in the case of considering ACT high multipole data.

* M. Archidiacono et al., arXiv: 1303.0143.