COSMOLOGY AND THE SECRET LIFE OF STERILE NEUTRINOS

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COSMOLOGY AND THE SECRET LIFE OF STERILE NEUTRINOS

OUTLINE

- STERILE NEUTRINOS
- SBL EVIDENCE OR HINTS
- TROUBLE WITH COSMOLOGY
- A CLOSER LOOK AT THE PRODUCTION MECHANISM
- THE SECRET INTERACTION
- POTENTIAL OTHER CONSEQUENCES

NEUTRINO MIXING IN THE STANDARD PICTURE

FLAVOUR STATES

PROPAGATION STATES

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1(m_1) \\ \nu_2(m_2) \\ \nu_3(m_3) \end{pmatrix}$$

$$U = \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix}$$

$$c_{12} = \cos\theta_{12}$$

$$s_{12} = \sin\theta_{12}$$

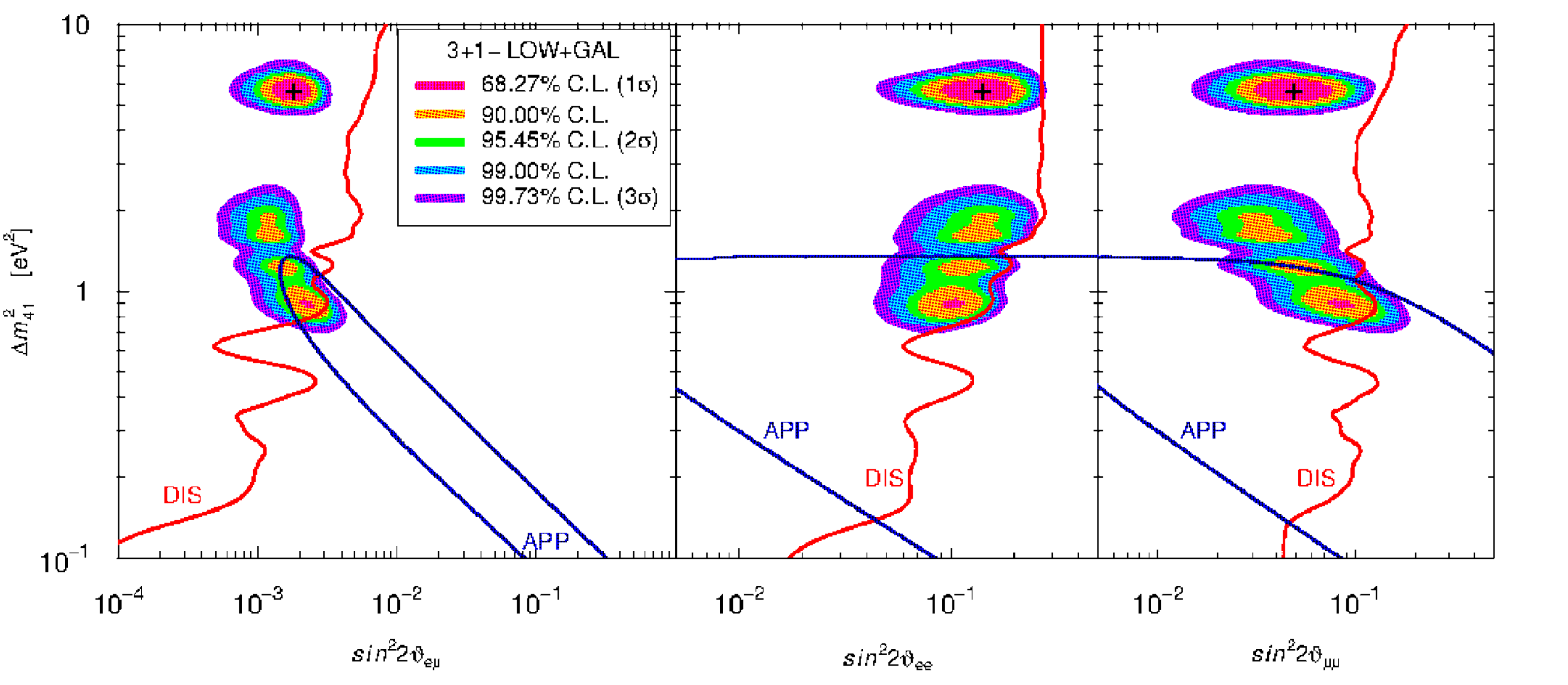
Simplest 3+1 model with sterile neutrino

FLAVOUR STATES →

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = U \begin{pmatrix} \nu_1(m_1) \\ \nu_2(m_2) \\ \nu_3(m_3) \\ \nu_4(m_4) \end{pmatrix}$$

← PROPAGATION STATES

THERE ARE A NUMBER OF HINTS FROM EXPERIMENTS THAT A FOURTH, eV-MASS STERILE STATE MIGHT BE NEEDED:
LSND, MiniBoone, reactor anomaly, Gallium



Giunti & Laveder 2011

NEUTRINO MASS AND ENERGY DENSITY FROM COSMOLOGY

NEUTRINOS AFFECT STRUCTURE FORMATION BECAUSE THEY ARE A SOURCE OF DARK MATTER ($n \sim 100\ \mathrm{cm}^{-3}$)

$$\Omega_\nu h^2 = \frac{\sum m_\nu}{93\,\mathrm{eV}}$$

FROM

$$T_\nu = T_\gamma \left(\frac{4}{11}\right)^{1/3} \approx 2\,\mathrm{K}$$

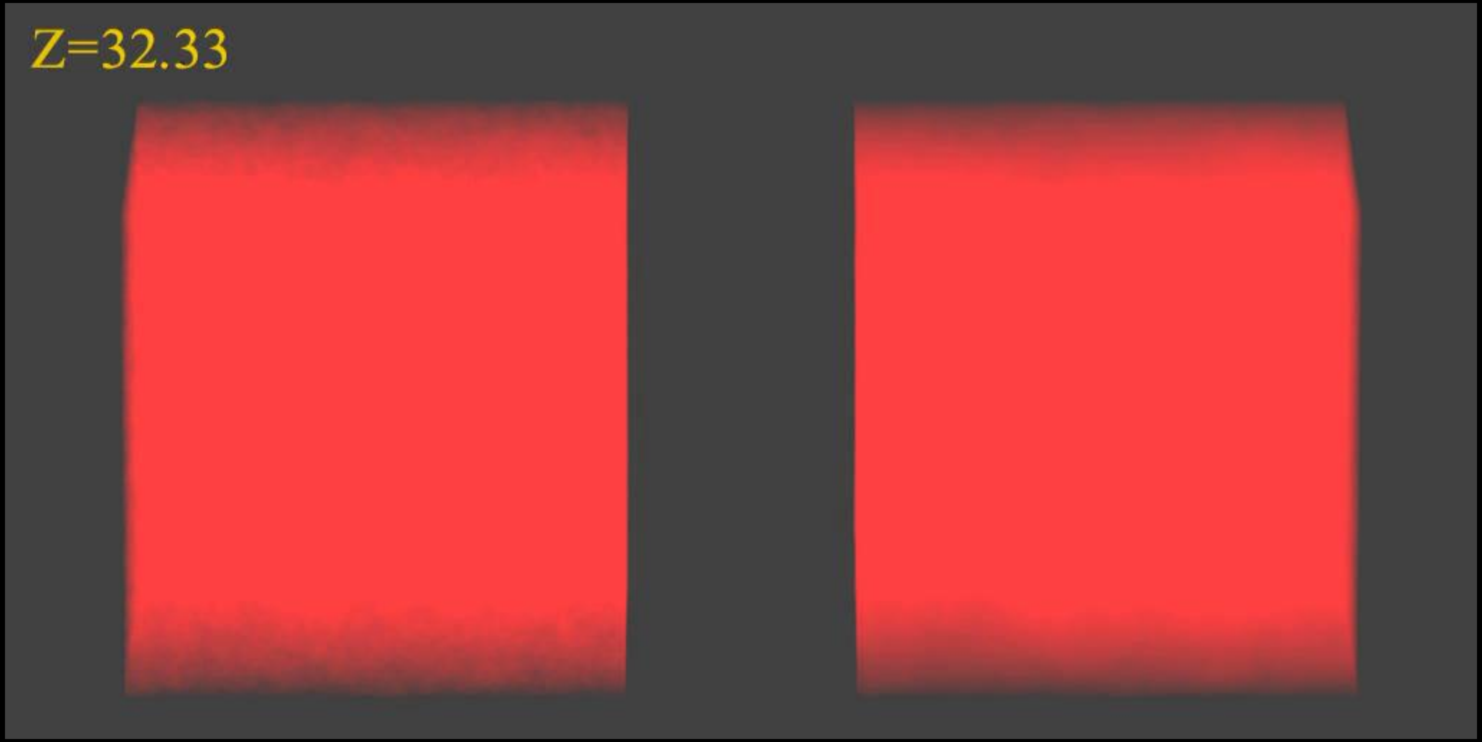
HOWEVER, eV NEUTRINOS ARE DIFFERENT FROM CDM BECAUSE THEY FREE STREAM

$$d_{\mathrm{FS}} \sim 1\,\mathrm{Gpc}\, m_{\mathrm{eV}}^{-1}$$

SCALES SMALLER THAN d_{FS} DAMPED AWAY, LEADS TO SUPPRESSION OF POWER ON SMALL SCALES

N-BODY SIMULATIONS OF ΛCDM WITH AND WITHOUT NEUTRINO MASS (768 Mpc^3) – GADGET 2

256 Mpc

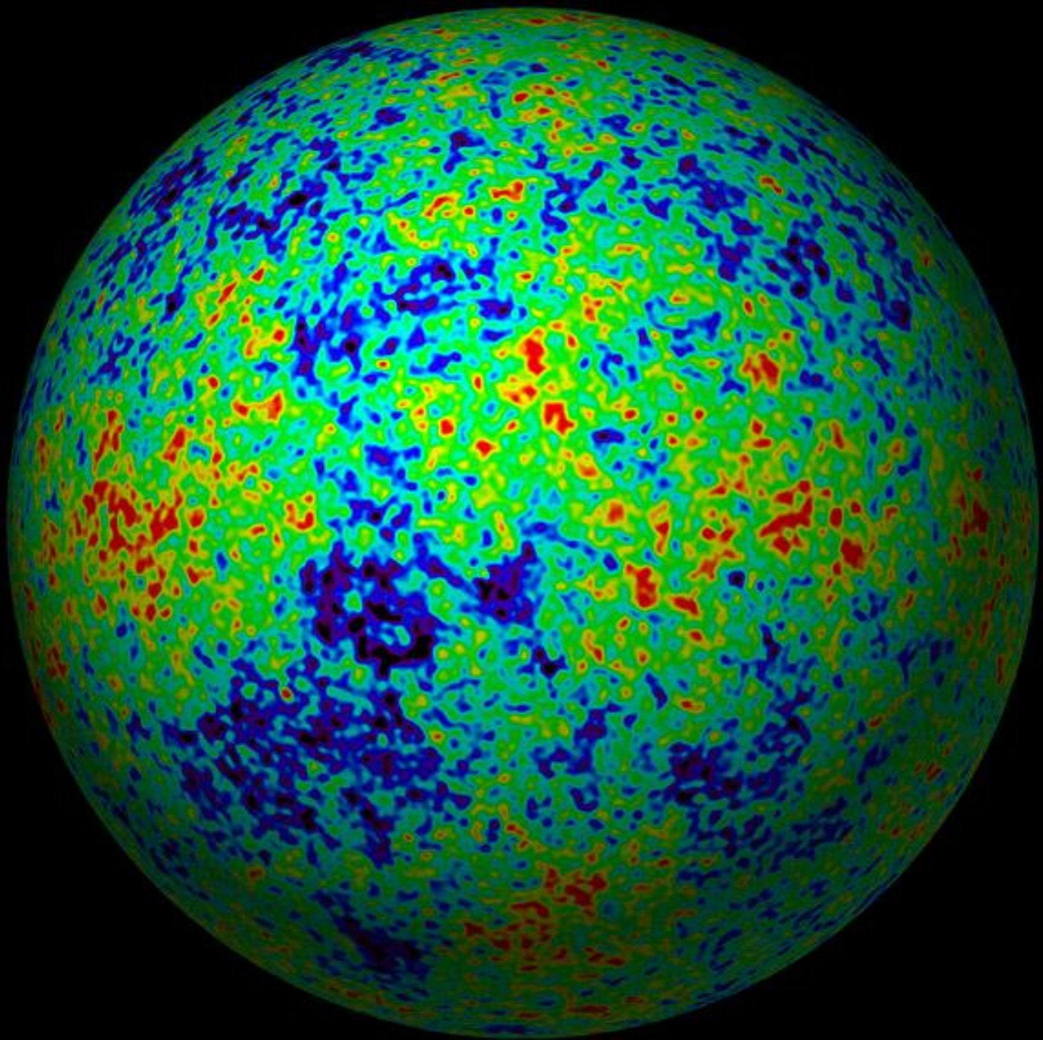


$\sum m_\nu = 0$

$\sum m_\nu = 6.9\,\mathrm{eV}$

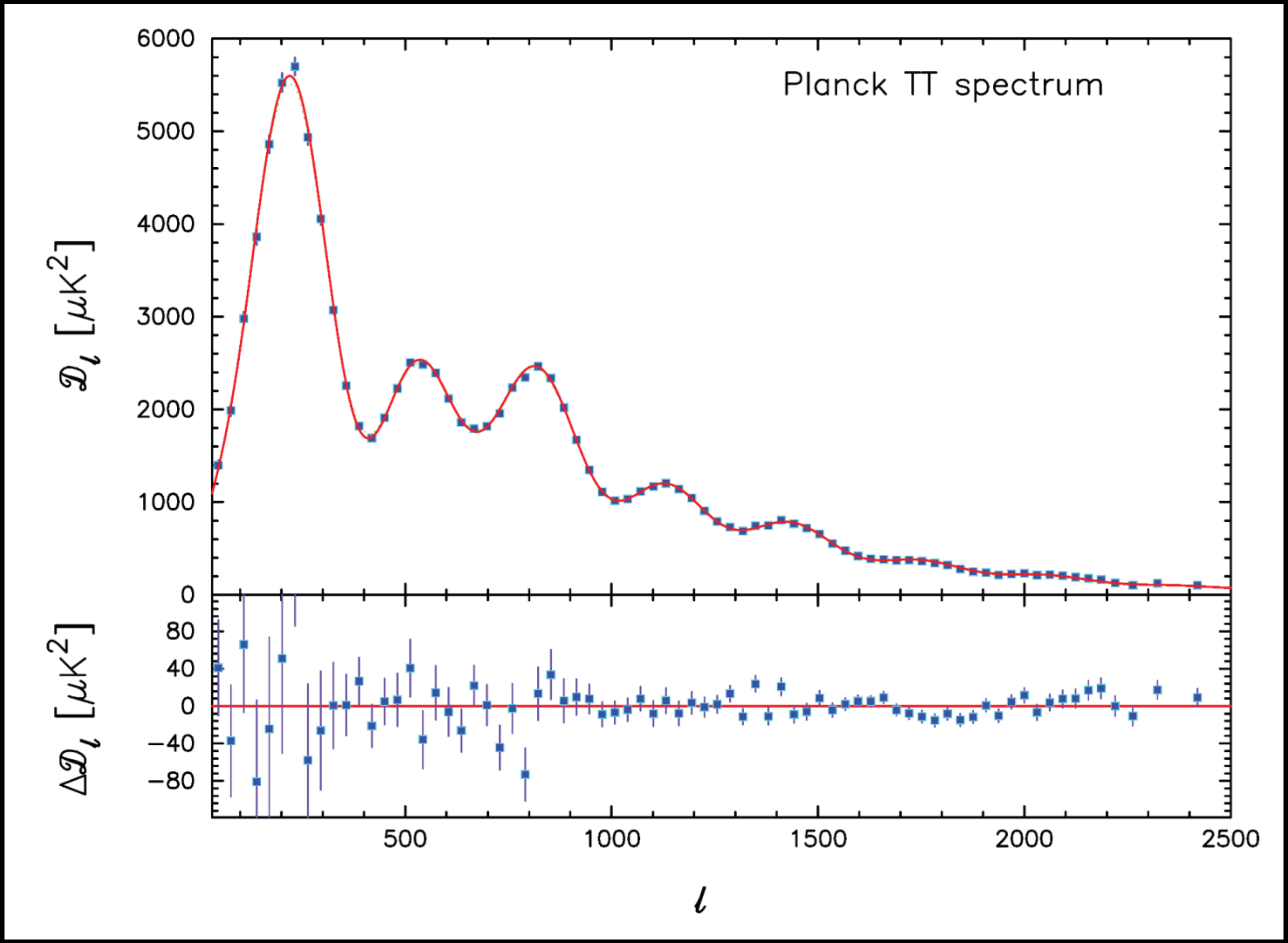
AVAILABLE COSMOLOGICAL DATA

THE COSMIC MICROWAVE BACKGROUND



CMB TEMPERATURE MAP

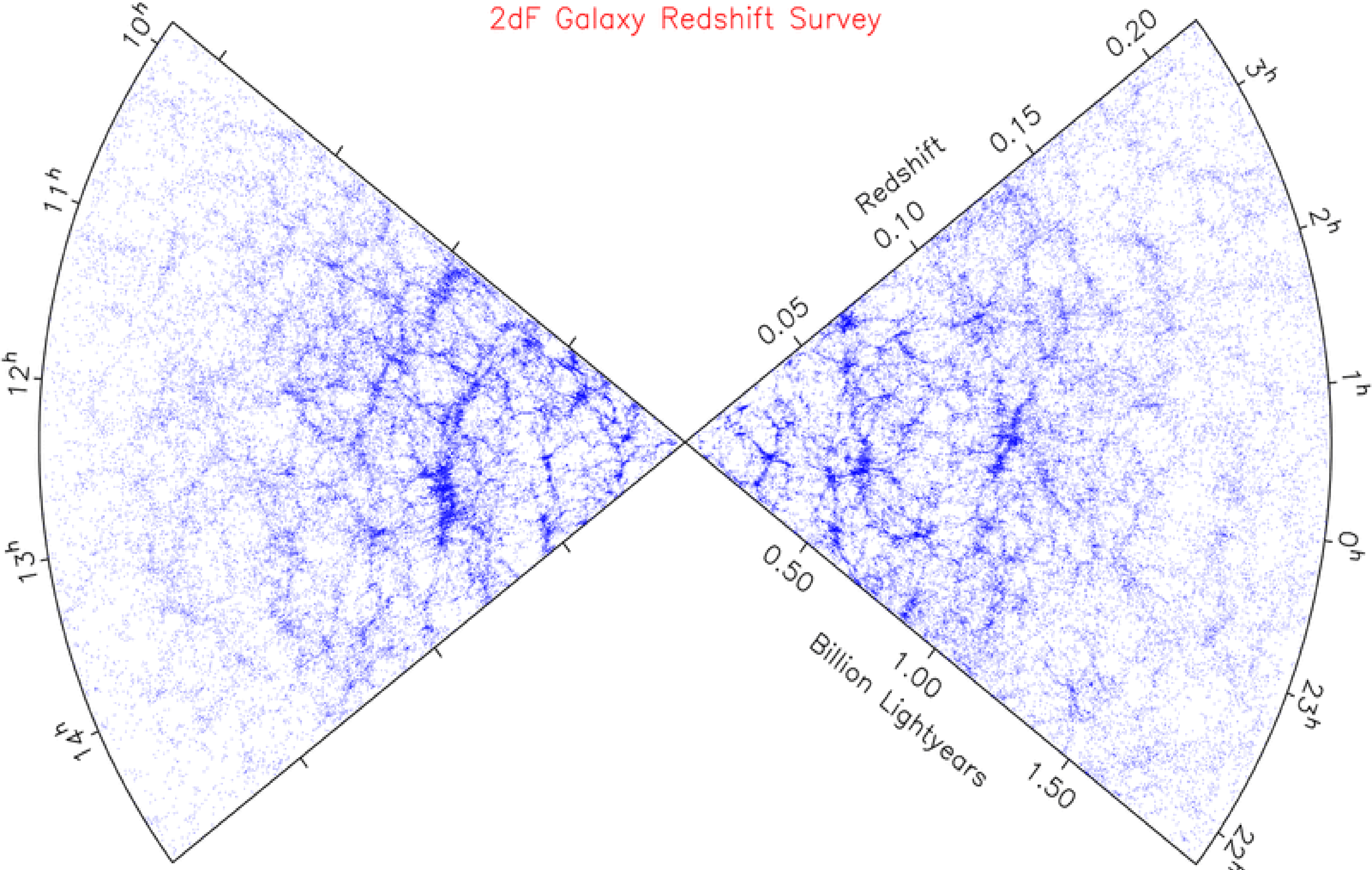
PLANCK TEMPERATURE POWER SPECTRUM



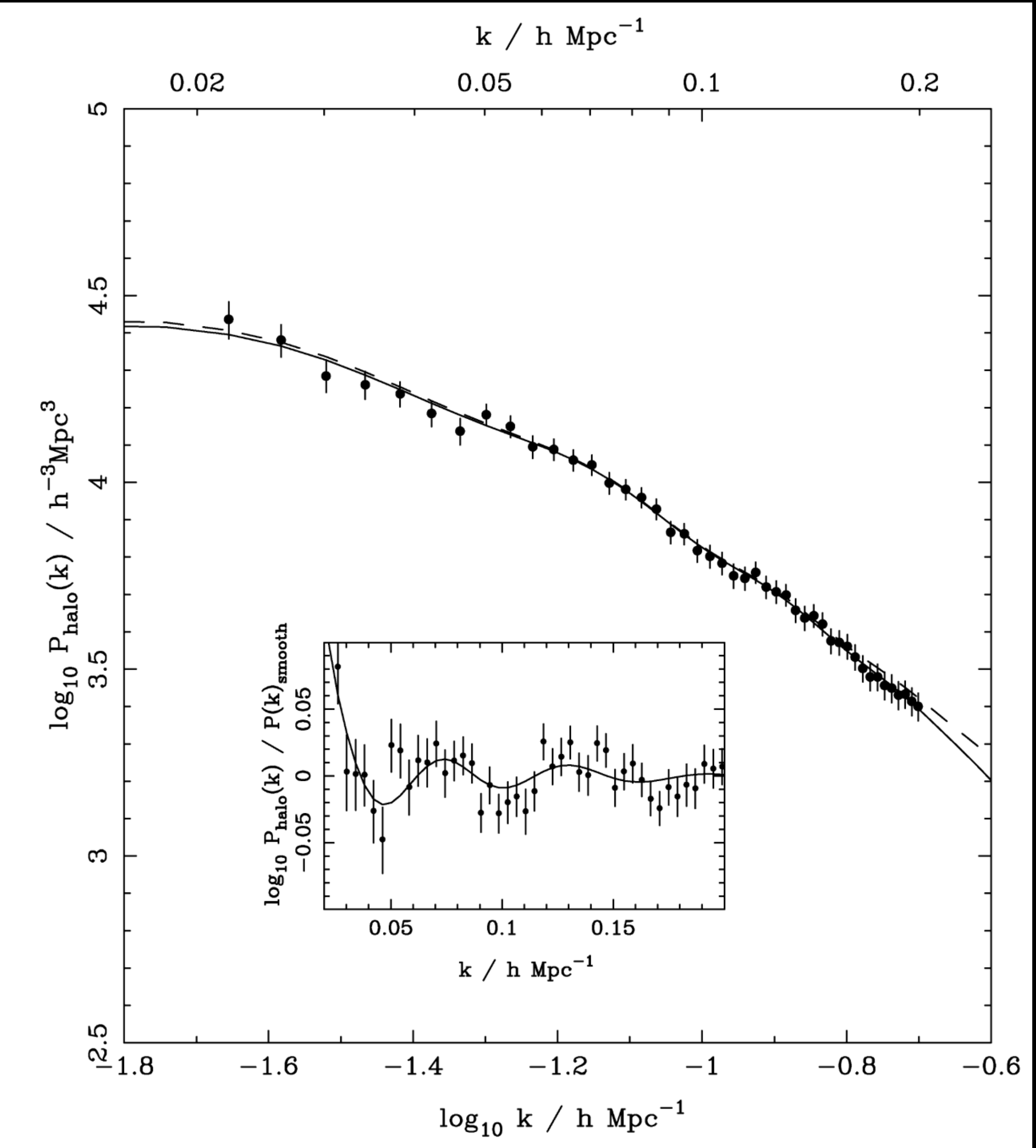
ADE ET AL, ARXIV 1303.5076

ADDITIONAL DATA ON SMALLER SCALES FROM
ATACAMA COSMOLOGY TELESCOPE (Sievers et al. 2013)
SOUTH POLE TELESCOPE (Hou et al. 2012)

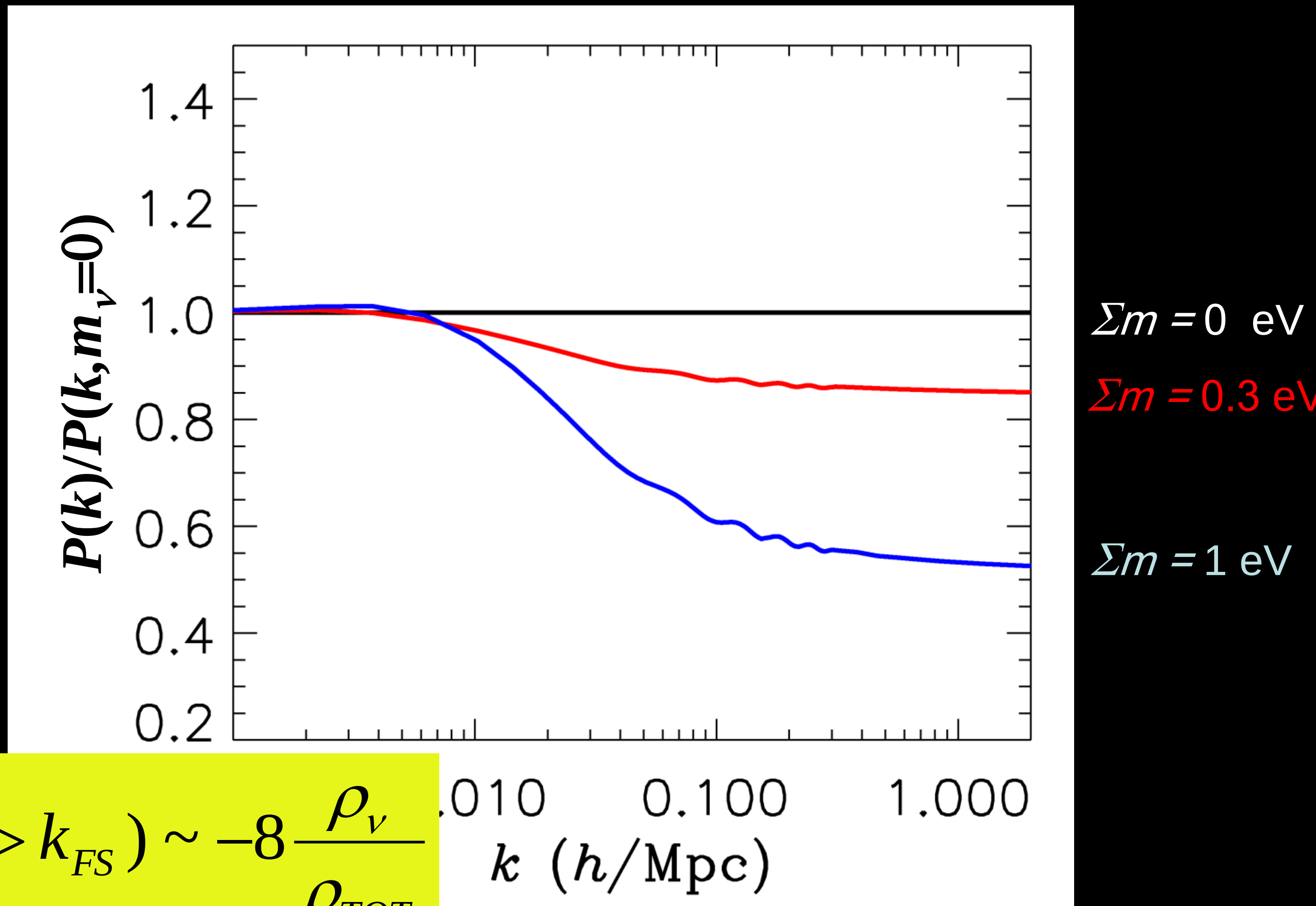
LARGE SCALE STRUCTURE SURVEYS - 2dF AND SDSS



SDSS DR-7
LRG SPECTRUM
(Reid et al '09)



FINITE NEUTRINO MASSES SUPPRESS THE MATTER POWER SPECTRUM ON SCALES SMALLER THAN THE FREE-STREAMING LENGTH



$$\frac{\Delta P}{P_{m=0}}(k >> k_{FS}) \sim -8\frac{\rho_\nu}{\rho_{TOT}}$$

NOW, WHAT ABOUT NEUTRINO PHYSICS?

WHAT IS THE PRESENT BOUND ON THE NEUTRINO MASS?

DEPENDS ON DATA SETS USED AND ALLOWED PARAMETERS

THERE ARE MANY ANALYSES IN THE LITERATURE. THE BOUND APPLIES TO ANY NEUTRINO-LIKE PARTICLE WHICH IS LIGHT

$$\sum m_\nu \leq 1.08\,\mathrm{eV}\ @\ 95\,\mathrm{C.L.}\quad \mathrm{Planck\ only}$$

$$\sum m_\nu \leq 0.32\,\mathrm{eV}\ @\ 95\,\mathrm{C.L.}\quad \mathrm{Planck} + \mathrm{BAO}$$

arXiv:1303.5076 (Planck)

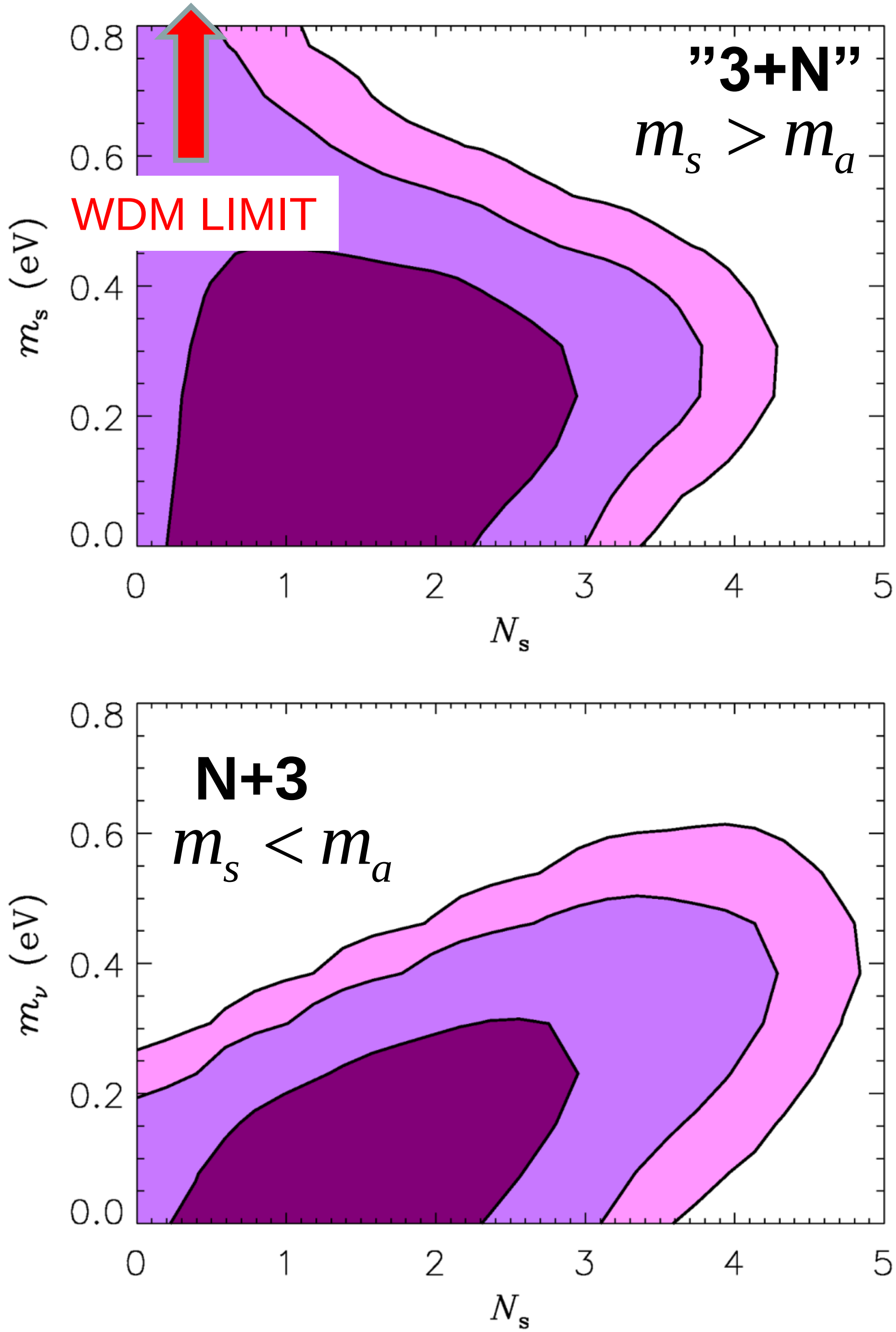
ASSUMING A NUMBER OF ADDITIONAL STERILE STATES OF APPROXIMATELY EQUAL MASS, TWO QUALITATIVELY DIFFERENT HIERARCHIES EMERGE. IN ANALOGY WITH THE STANDARD MODEL NEUTRINO HIERARCHY WE CAN CALL THEM NORMAL AND INVERTED HIERARCHY

3+N (NORMAL) **N+3 (INVERTED)**

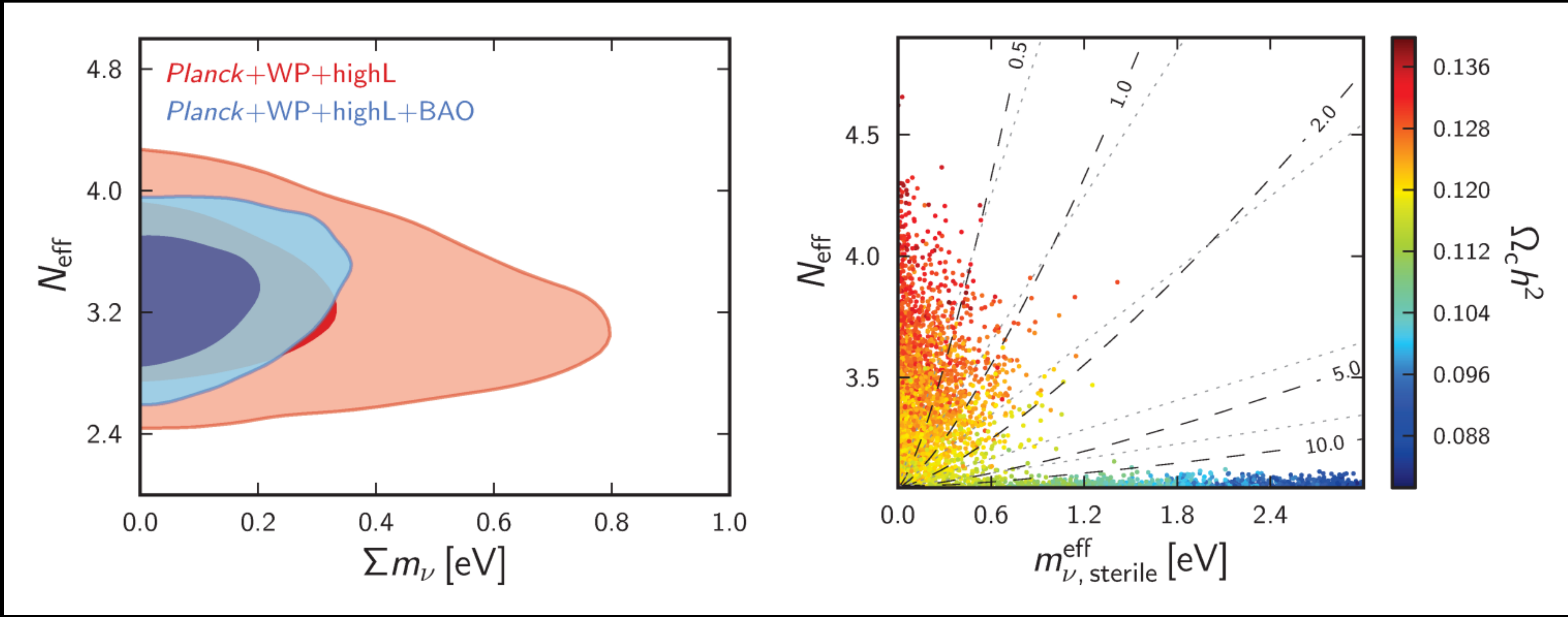
Hamann, STH, Raffelt, Tamborra, Wong, arxiv:1006.5276 (PRL)

$$N_s = \frac{\rho_s}{\rho_{\nu,0}}$$

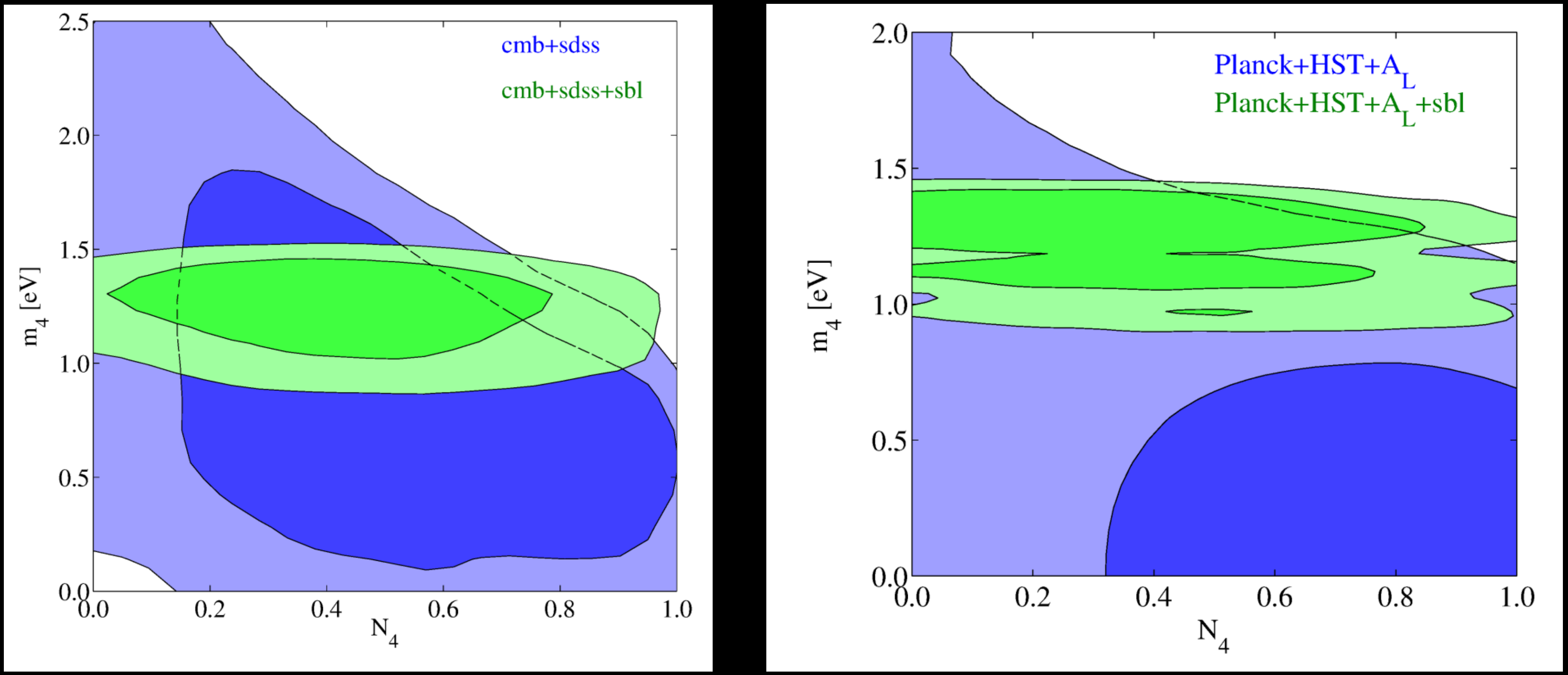
See also
Dodelson et al. 2006
Melchiorri et al. 2009
Acero & Lesgourgues 2009
Hamann et al 2011
Joudaki et al 2012
Motohashi et al. 2012
Archidiacono et al 2012, 2013
and many others



$$N_{eff} = \frac{\rho_s + \rho_a}{\rho_{\nu,0}}$$



ADE ET AL. 2013 (WITHOUT HUBBLE DATA!)



Archidiacono, Fornengo, Giunti, STH, Melchiorri, arXiv:1302.6720 (PRD)

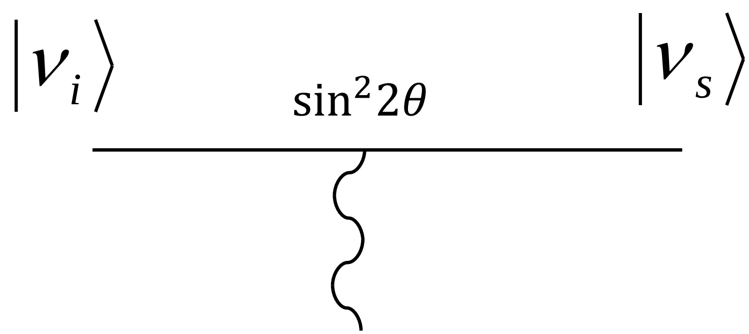
Bottom line: Sterile neutrinos in the mass range preferred by SBL data can be accomodated by cosmology, but ONLY if they are not fully thermalised

Sterile neutrino thermalisation in the early Universe: The simple version

The weak interactions measure sterile content of a mass state and very simplistically the production rate of steriles is given by

$$\Gamma_s \sim \Gamma \sin^2 2\theta$$

where Γ is the total weak interaction rate



More quantitatively we want to follow an equation similar to the usual Boltzmann equation for the single-particle distribution function

We are interested in following the density matrix associated with the mixed active-sterile system and the corresponding system for the anti-particles,

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

P is the polarization vector
P_z describes the active or sterile content
f_0 is the equilibrium Fermi-Dirac distribution

IMPORTANT: We are assuming 1+1 so that we always work with SU(2)

Ordinary vacuum oscillations can be described as a simple precession equation for ***P***

$$\dot{\boldsymbol{P}} = V \times \boldsymbol{P}$$

$$\begin{pmatrix} V_x \\ V_y \\ V_z \end{pmatrix} = \begin{pmatrix} \frac{-dm^2}{2xT} \sin 2\theta \\ 0 \\ \frac{dm^2}{2xT} \sin 2\theta \end{pmatrix} \qquad x = p/T$$

At first order in the interaction forward scattering changes the potential felt by the propagating states

$$\dot{\boldsymbol{P}} = V \times \boldsymbol{P}$$

$$\begin{pmatrix} V_x \\ V_y \\ V_z \end{pmatrix} = \begin{pmatrix} \frac{-dm^2}{2xT} \sin 2\theta \\ 0 \\ \frac{dm^2}{2xT} \sin 2\theta + C G_F T^3 L \end{pmatrix}$$

where *L* is the lepton asymmetry, i.e. the effect cancels out in a CP-symmetric medium

At next order in the interaction there are many separate effects which must be taken into account:

- A change to the potential even in the CP-symmetric case
- Damping of the transverse part of the polarisation vector because of ”measurements” (the quantum zeno effect)
- Production and annihilation of active states from the thermal plasma

Full set of evolution equations to second order:

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

$$P_i^{\pm} = P_i \pm \bar{P}_i \quad , \quad i = 0, x, y, z.$$

$$\begin{aligned} P_a^{\pm} =& P_0^{\pm} + P_z^{\pm} = 2\frac{\rho_{aa}^{\pm}}{f_0}, \\ P_s^{\pm} =& P_0^{\pm} - P_z^{\pm} = 2\frac{\rho_{ss}^{\pm}}{f_0}. \end{aligned}$$

$$\begin{aligned} \dot{P}_a^{\pm} =& V_x P_y^{\pm} + \Gamma\left[2 f_{\rm eq}^{\pm}/f_0 - P_a^{\pm}\right], \\ \dot{P}_s^{\pm} =& - V_x P_y^{\pm}, \\ \dot{P}_x^{\pm} =& - \left(V_0 + V_1\right) P_y^{\pm} - V_L P_y^{\mp} - D P_x^{\pm}, \\ \dot{P}_y^{\pm} =& \left(V_0 + V_1\right) P_x^{\pm} + V_L P_x^{\mp} - \frac{1}{2} V_x \left(P_a^{\pm} - P_s^{\pm}\right) - D P_y^{\pm}. \end{aligned}$$

See e.g. Hannestad, Tamborra, Tram 2012

$$\begin{aligned}
\dot{P}_a^{\pm} =& V_x P_y^{\pm} + \Gamma\left[2f_{\rm eq}^{\pm}/f_0 - P_a^{\pm}\right], \\
\dot{P}_s^{\pm} =& - V_x P_y^{\pm}, \\
\dot{P}_x^{\pm} =& - \left(V_0 + V_1\right) P_y^{\pm} - V_L P_y^{\mp} - D P_x^{\pm}, \\
\dot{P}_y^{\pm} =& \left(V_0 + V_1\right) P_x^{\pm} + V_L P_x^{\mp} - \frac{1}{2} V_x \left(P_a^{\pm} - P_s^{\pm}\right) - D P_y^{\pm}.
\end{aligned}$$

$$\begin{aligned}
V_x =& \frac{\delta m_s^2}{2xT} \sin 2\theta_s, \\
V_0 =& - \frac{\delta m_s^2}{2xT} \cos 2\theta_s, \\
V_1^a =& - \frac{7\pi^2}{45\sqrt{2}} \frac{G_F}{M_Z^2} x T^5 \left[n_{\nu_a} + n_{\bar{\nu}_a}\right] g_a, \\
V_L^a =& \frac{2\sqrt{2}\zeta(3)}{\pi^2} G_F T^3 L_{(a)},
\end{aligned}$$

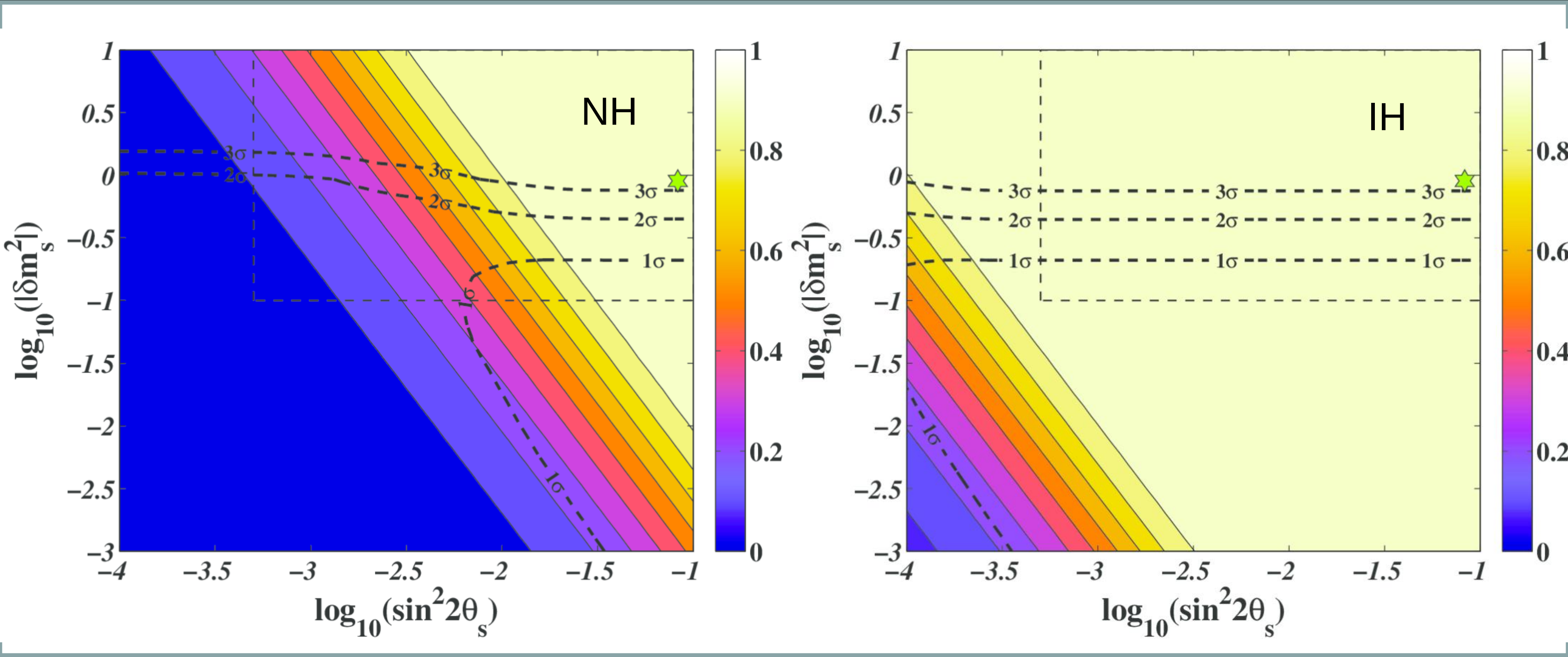
$$D = \frac{1}{2}\Gamma,$$

$$\Gamma = C_a G_F^2 x T^5.$$

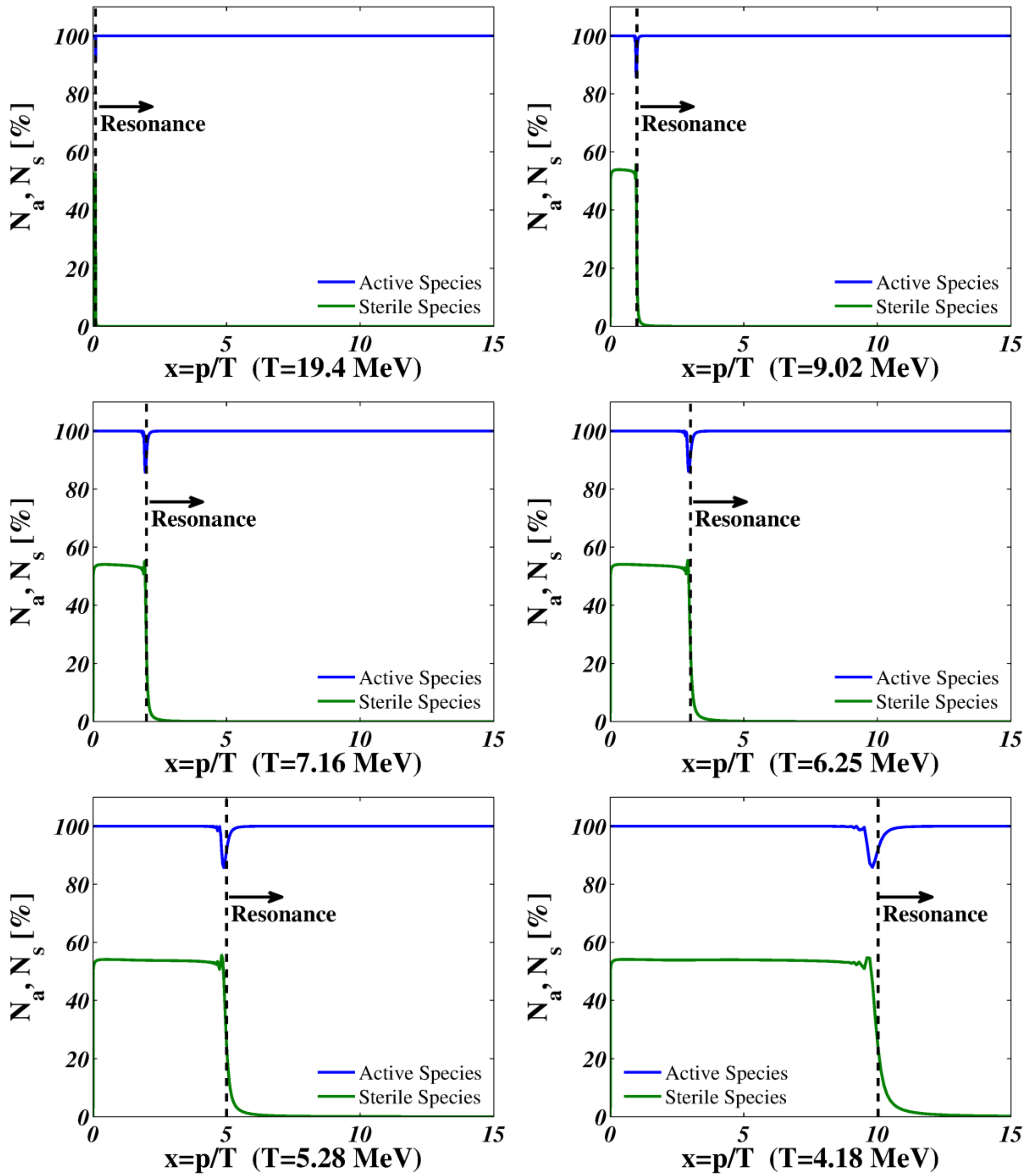
$$x = p/T$$

See e.g. Hannestad, Tamborra, Tram 2012

STERILE NEUTRINO THERMALISATION WITH ZERO LEPTON ASYMMETRY

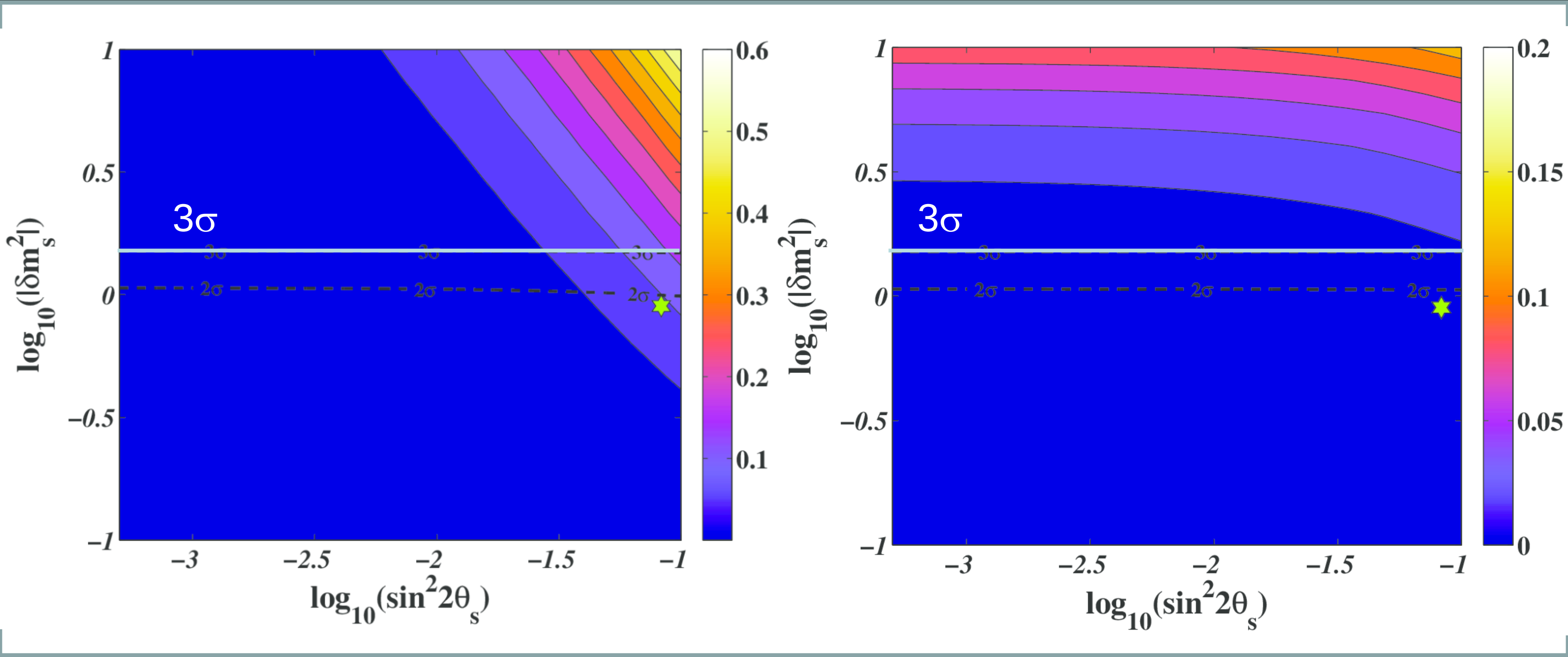


STH, Tamborra, Tram 2012 (arXiv:1204.5861)



Resonance
Active Species
Sterile Species
N_a, N_s [%]
x=p/T (T=19.4 MeV)
x=p/T (T=9.02 MeV)
x=p/T (T=7.16 MeV)
x=p/T (T=6.25 MeV)
x=p/T (T=5.28 MeV)
x=p/T (T=4.18 MeV)

STERILE NEUTRINO THERMALISATION WITH LARGE LEPTON ASYMMETRY



STH, Tamborra, Tram 2012 (arXiv:1204.5861)
(see also Saviano et al. arXiv:1302.1200

The presence of a significant asymmetry can block the production of steriles and make them compatible with cosmology.

However, from a model building perspective the generation of the asymmetry is difficult because it must be done at low energy

Could there be another way of modifying the matter potential?

YES! Non-standard interactions for either active or sterile neutrinos

Interactions must be relatively strong and for active neutrinos they might be excluded.

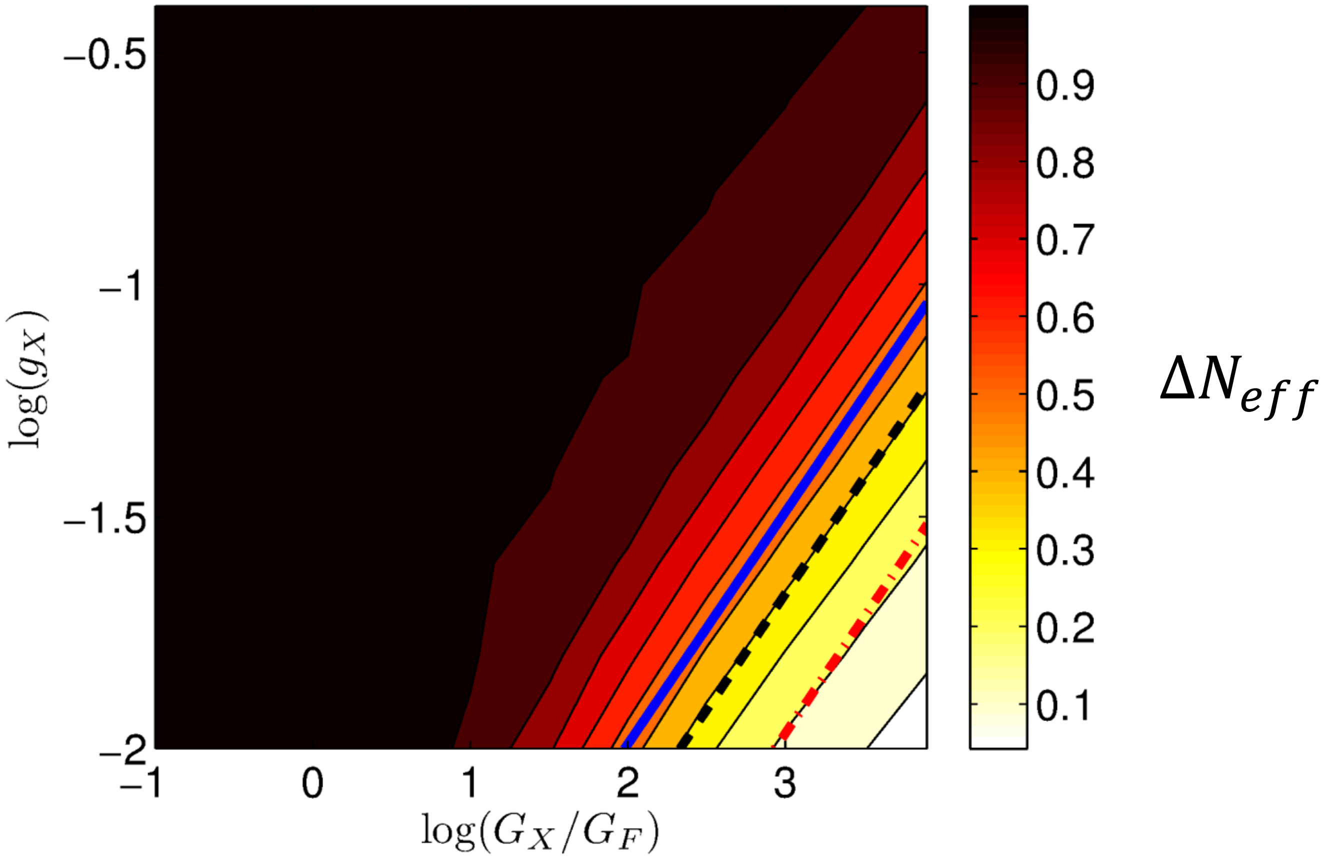
Sterile neutrino self-interactions are possible, and perhaps even natural.

Introduce a new 4-point interaction for sterile neutrinos, controlled by a new coupling constant $G_X = g_X^2/m_X^2$

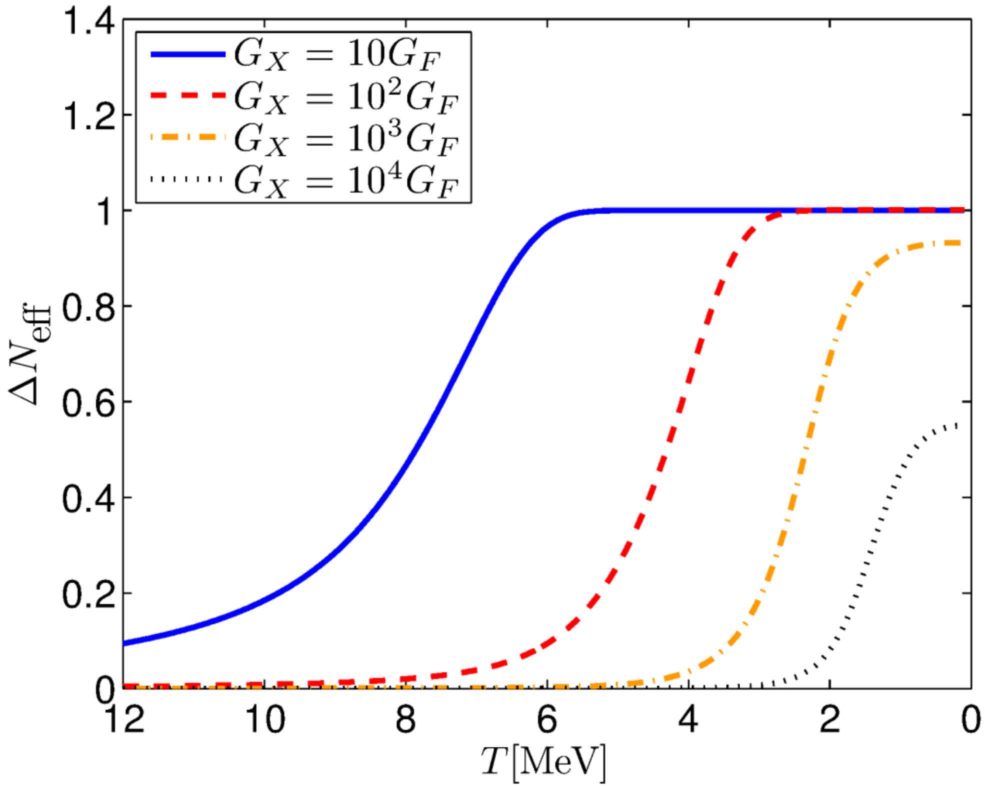
$$\dot{P}_a = V_x P_y + \Gamma_a \left[2\frac{f_0}{f_0} - P_a\right],$$
$$\dot{P}_s = -V_x P_y + \Gamma_s \left[2\frac{f_{\mathrm{eq},s}(T_{\nu_s}, \mu_{\nu_s})}{f_0} - P_s\right],$$
$$\dot{P}_x = -V_z P_y - D P_x,$$
$$\dot{P}_y = V_z P_x - \frac{1}{2} V_x (P_a - P_s) - D P_y.$$

$$V_x = \frac{\delta m_s^2}{2p} \sin 2\theta,$$
$$V_z = V_0 + V_a + V_s,$$
$$V_0 = -\frac{\delta m_s^2}{2p} \cos 2\theta,$$
$$V_a = -\frac{14\pi^2}{45\sqrt{2}} p \left[\frac{G_F}{M_Z^2} T_\gamma^4 n_{\nu_a}\right],$$
$$V_s = +\frac{16 G_X}{3\sqrt{2} M_X^2} p u_{\nu_s}.$$

Hannestad, Hansen, Tram, 2013 (arXiv:1310.5926)
(see also Dasgupta & Kopp 1310.6337)



Hannestad, Hansen, Tram, 2013 (arXiv:1310.5926)



Hannestad, Hansen, Tram, 2013 (arXiv:1310.5926)

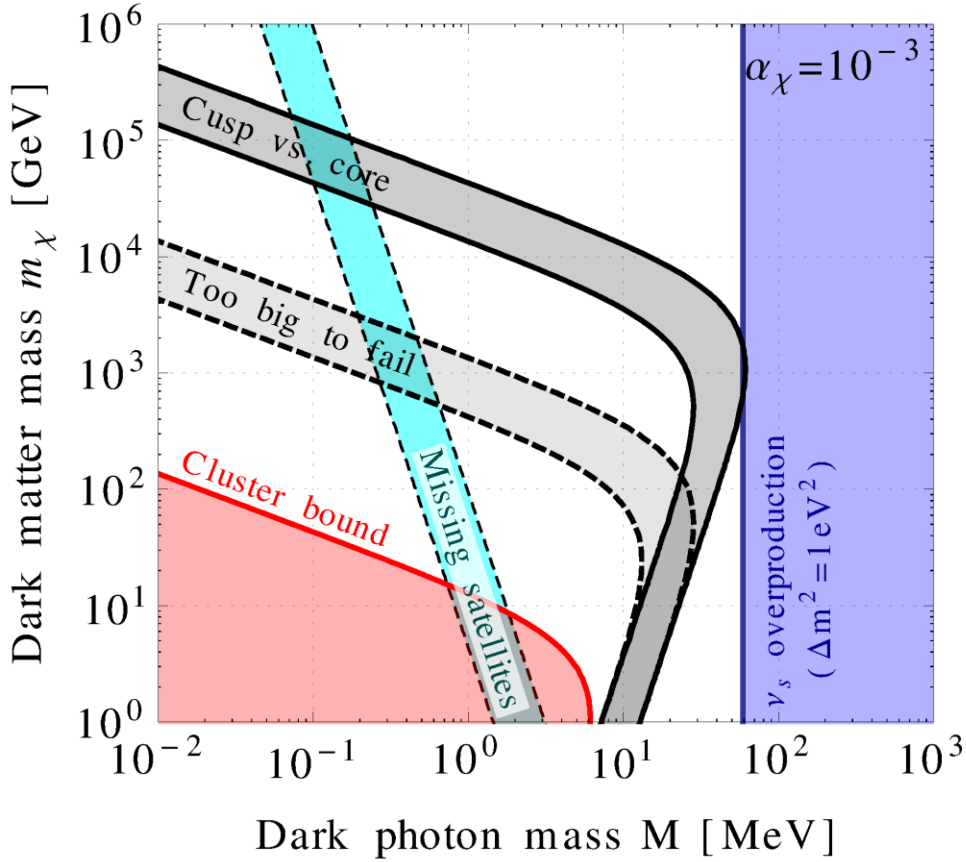
The thermalisation degree depends almost exclusively on m_X^2, not on g
Why?

Remember that

$$\Gamma_s \sim \Gamma \sin^2 2\theta \propto \frac{G_X^2}{V^2} \propto \frac{G_X^2}{G_X^2/m_X^4} \propto m_X^4$$

Hannestad, Hansen, Tram, 2013 (arXiv:1310.5926)

If dark matter couples to the new vector boson it causes self-interactions which have implications for structure formation



Dasgupta & Kopp 1310.6337

CONCLUSIONS

- There are hints at eV scale sterile neutrinos from SBL experiments
- Cosmology is not compatible with this result unless the sterile neutrinos are prevented from thermalising fully in the early Universe
- This can be achieved by coupling the sterile state to a new vector boson with a mass much lower than Z
- There might be interesting implications for dark matter physics