50th Rencontres de Moriond EW 2015

14-21 March 2015

Light sterile ν limits from cosmology

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IPPP, Durham University

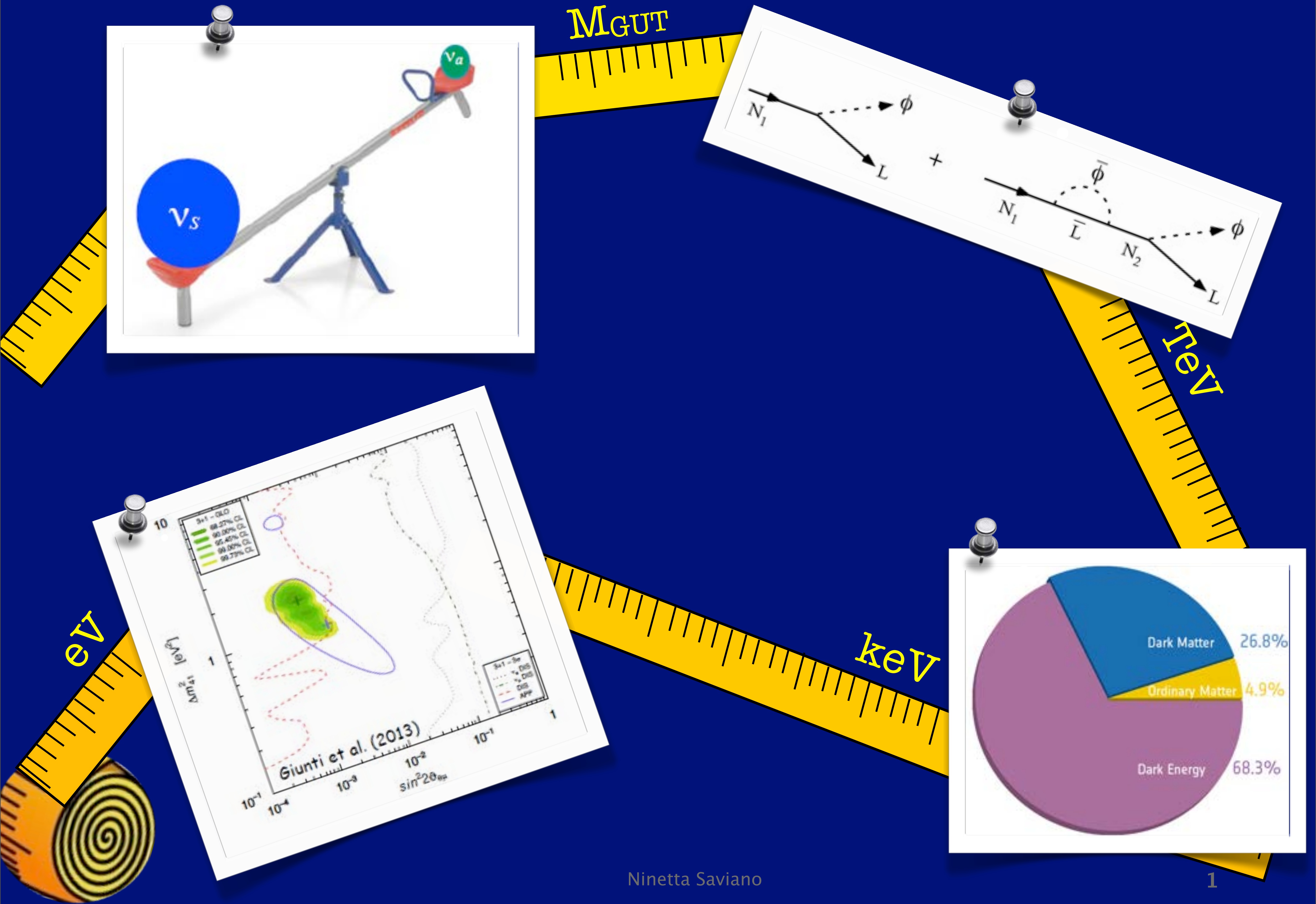
invisibles neutrinos, dark matter & dark energy physics

MARIE CURIE ACTIONS

SEVENTH FRAMEWORK PROGRAMME

IP3 University of Durham

Sterile Neutrinos



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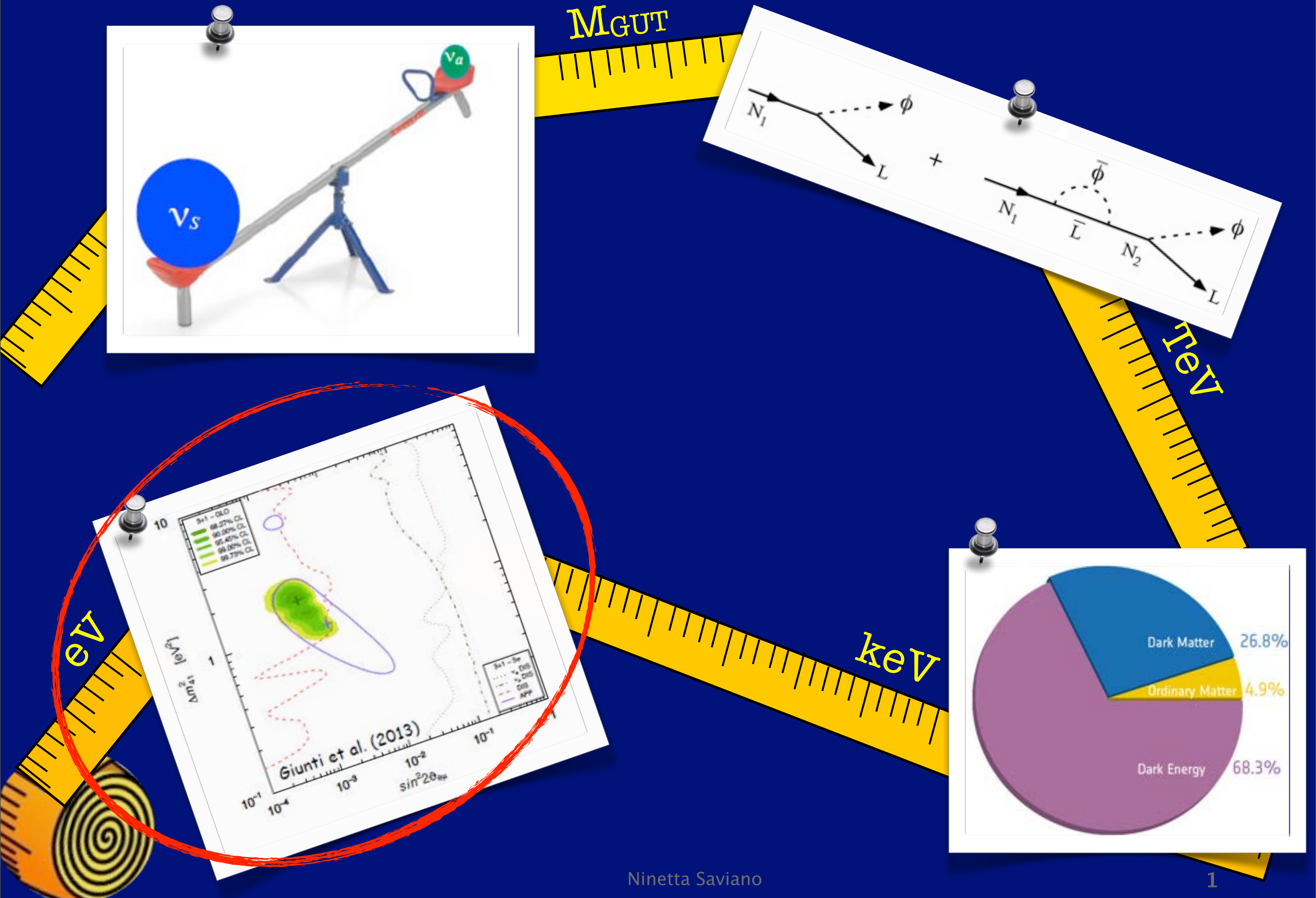
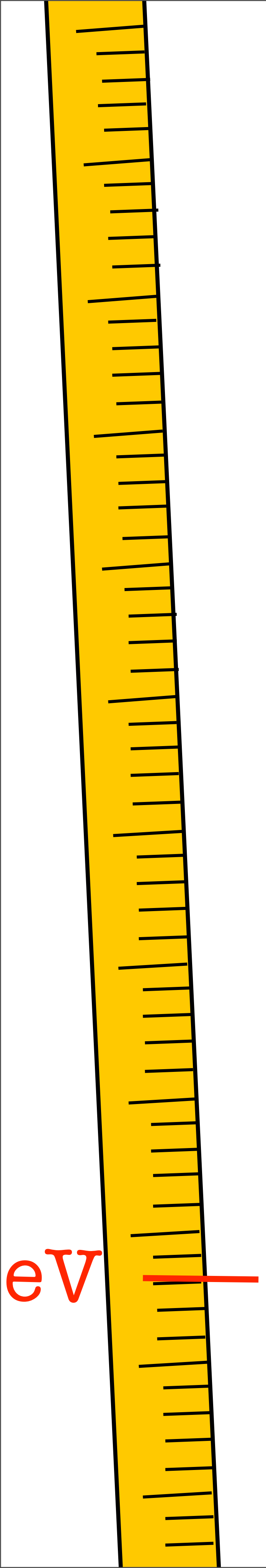


eV Sterile Neutrino

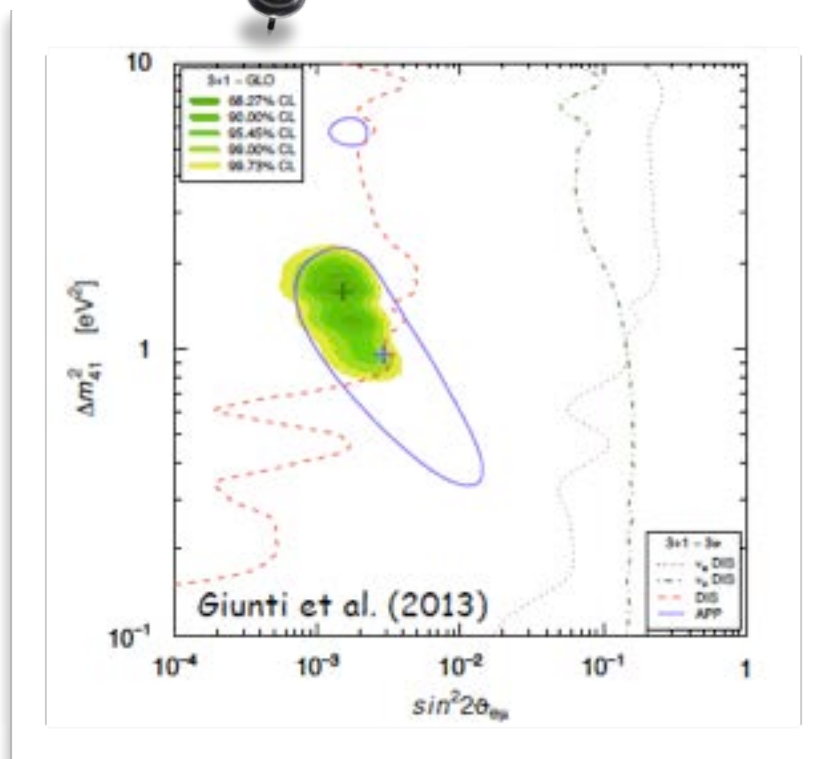


eV Sterile Neutrino

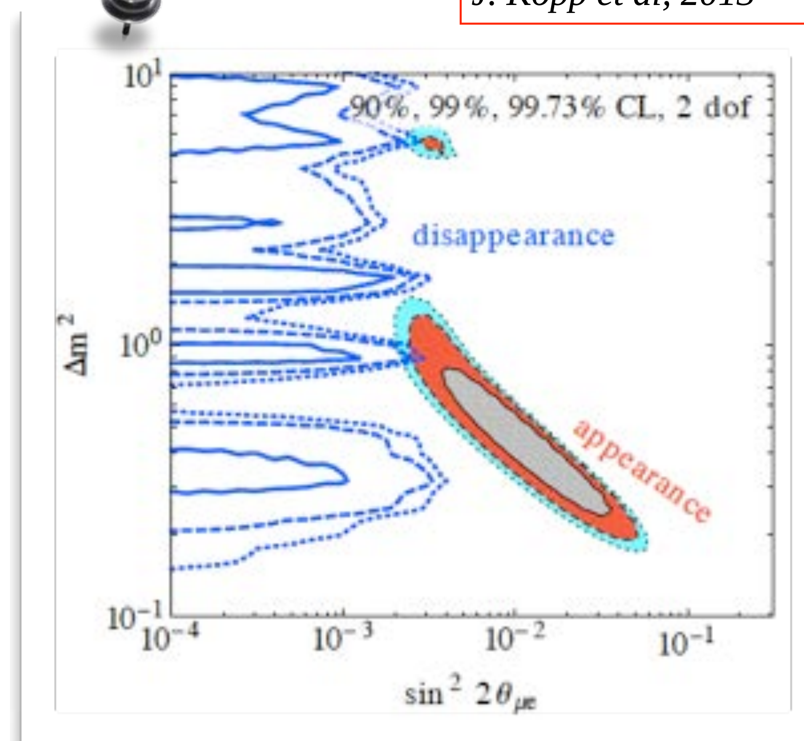
The investigation on Light Sterile Neutrinos has been stimulated by the presence of anomalous results from neutrino oscillation experiments

- **LNSD**
- **MiniBooNE**
- **Gallium**
- **Reactor**

see
White paper, Abazajian et al., 2012,
Palazzo, 2013



J. Kopp et al, 2013



3+1, 3+2 schemes

(…sometimes in tension among themselves….)

eV

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

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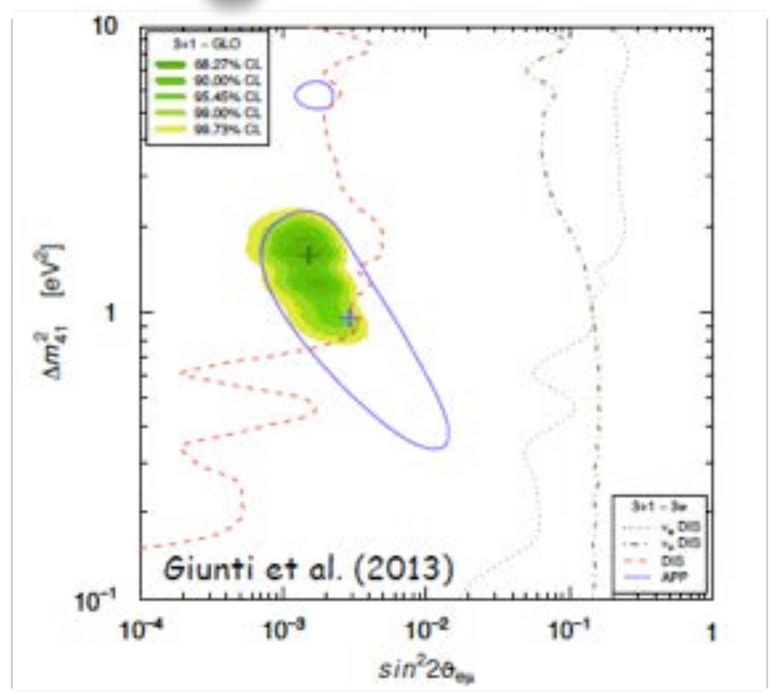

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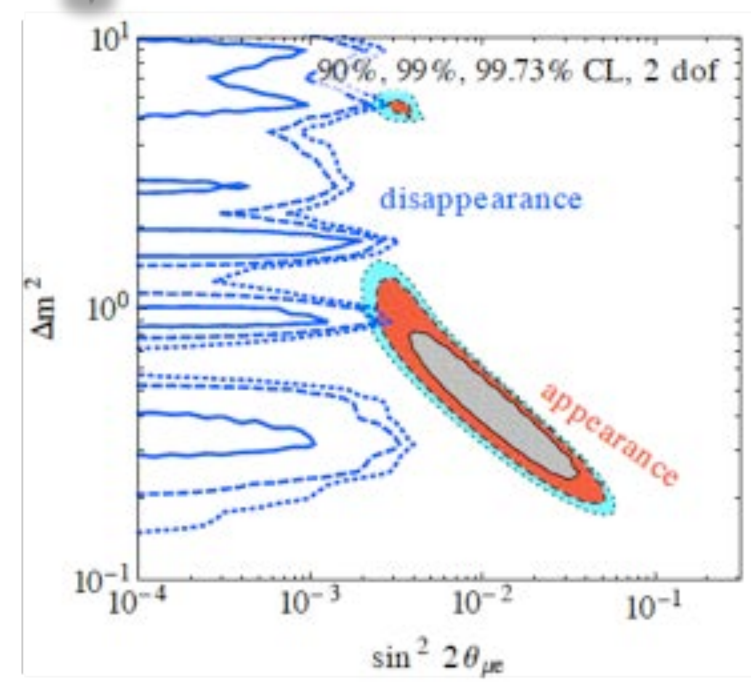

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Are eV ν_s compatible with cosmology?

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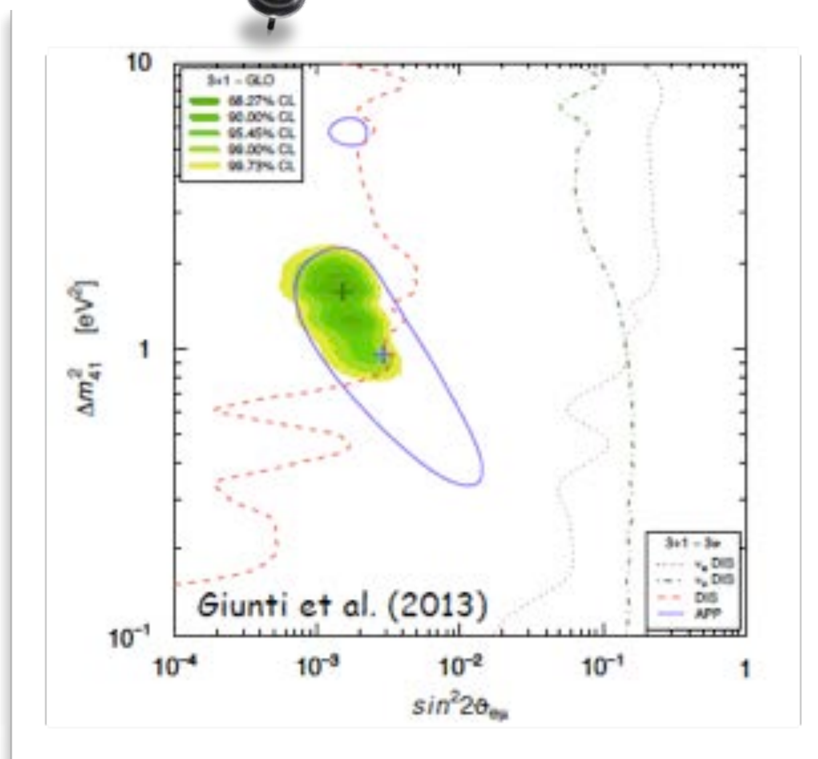

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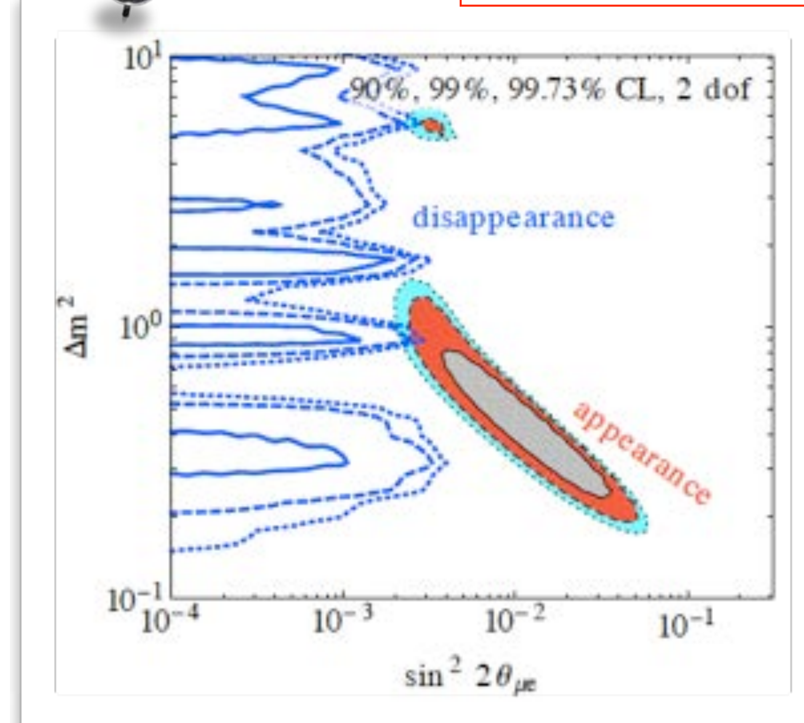

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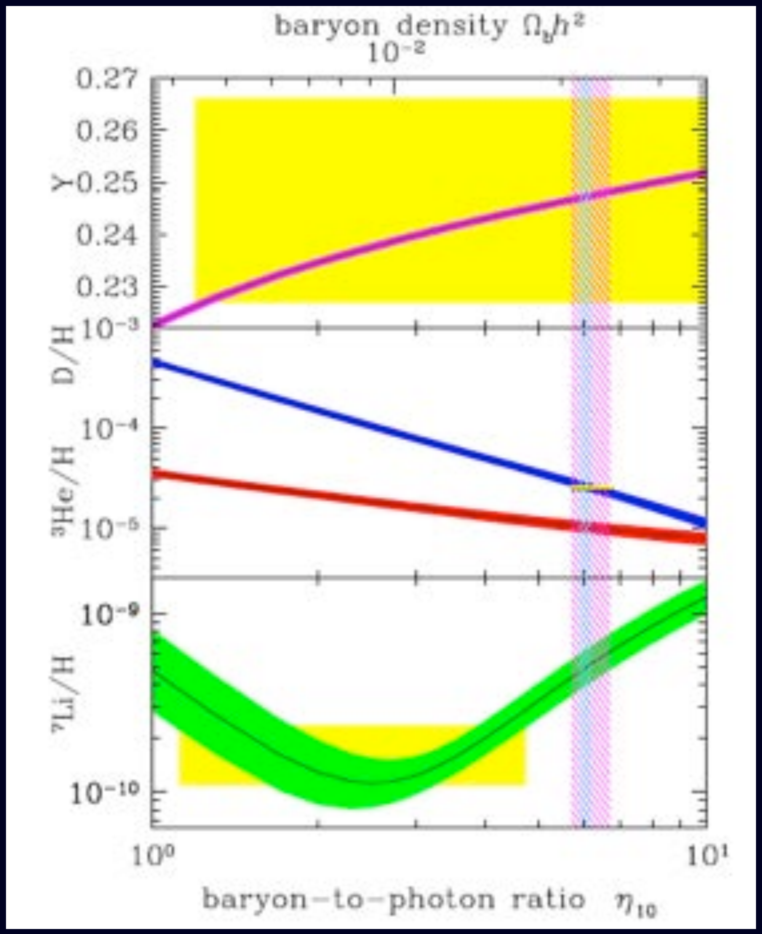
eV — Interpretation: ***1*** (or more) ***sterile neutrino*** with $\Delta m^2 \sim O$ (eV^2) and $\theta_s \sim O$ (θ_{13})

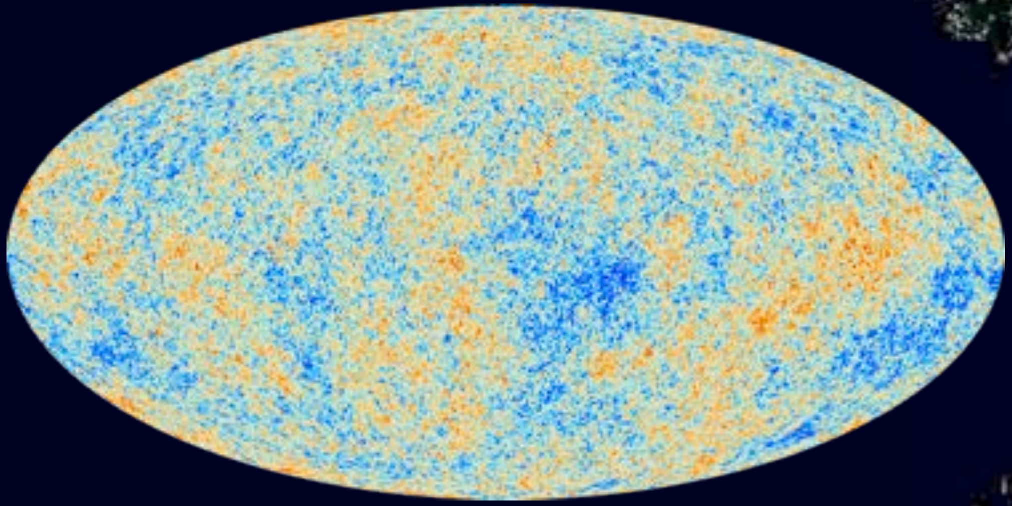
Are eV ν_s compatible with cosmology?

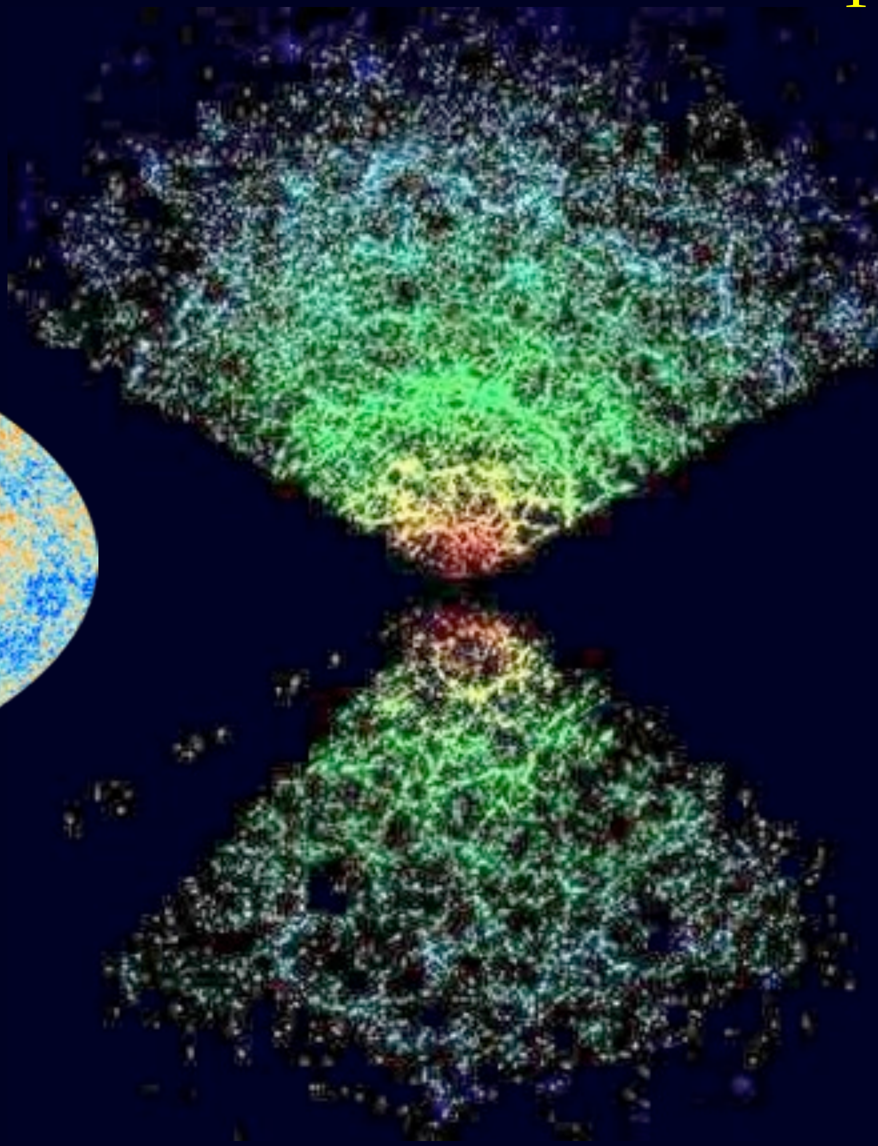
…is necessary to consider the cosmological constraints on extra species and to assess the conditions under which ν_s are produced

Cosmological observations

1 MeV 1 eV T







Sensitivity to N_{eff} and ν flavour

Sensitivity to N_{eff} and ν masses

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_{eff}

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

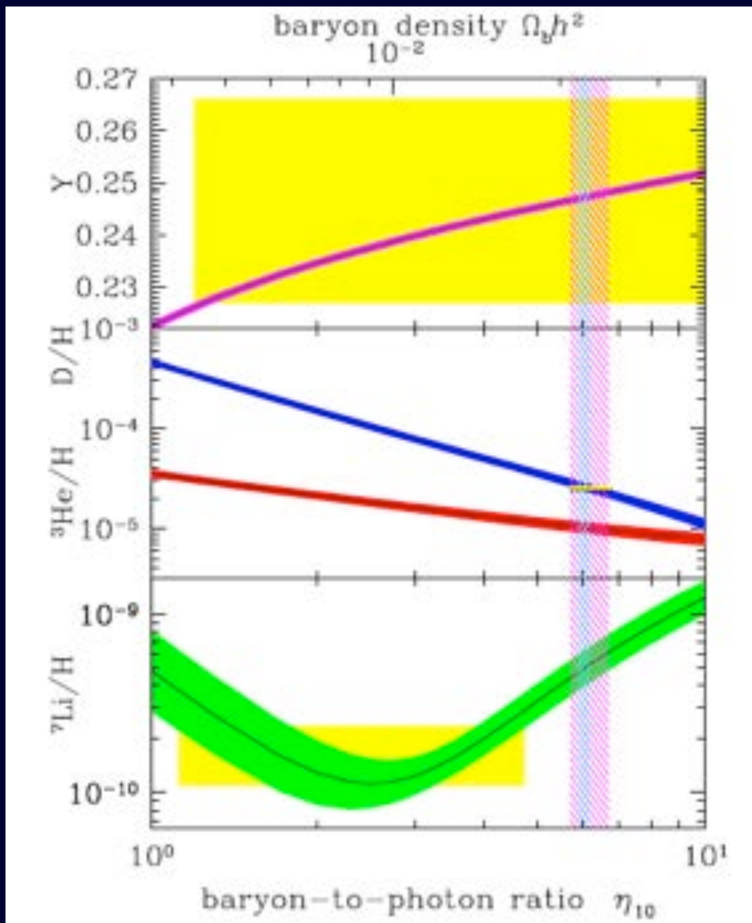
$N_{\text{eff}}^{\text{SM}} = 3.046$ *due to non-instantaneous neutrino decoupling* *Mangano et al. 2005*

(+ 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...

Di Bari et al. 2013, Boehm et al. 2012, Conlon and Marsh, 201,3 Gelmini, Palomarez-Ruiz, Pascoli, 2004

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 $\Gamma_{n\longleftrightarrow p} < H$ ➜ *neutron-to- proton ratio freezes out*

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

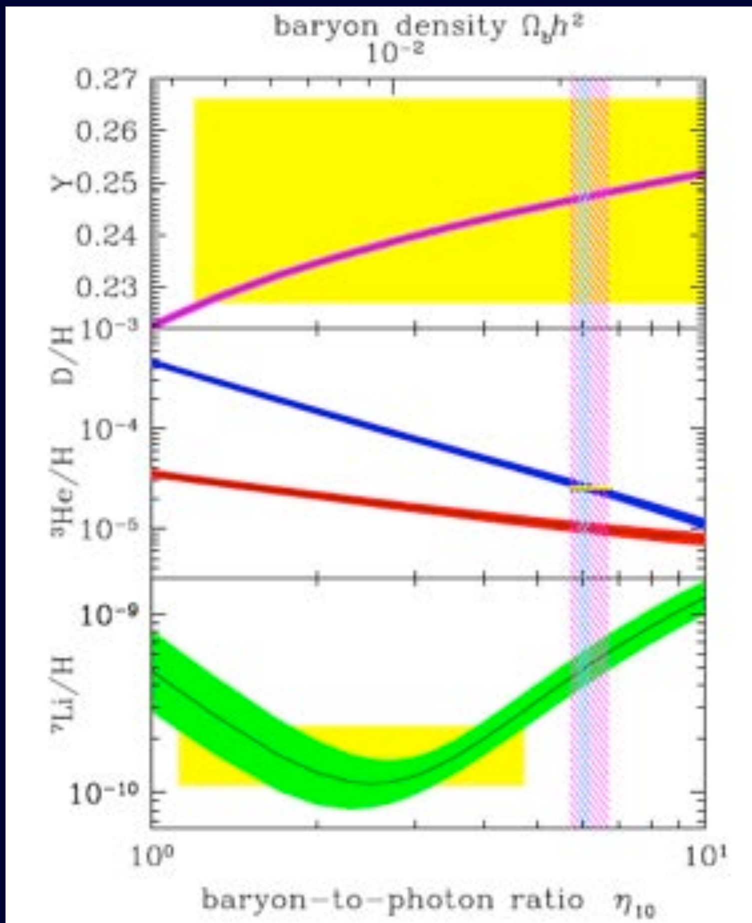
Sterile ν influence on BBN :

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

N_{eff} ↑ ➡ H ↑ ➡ early freeze out ➡ *n/p* ↑ ➡ ^{4}He↑

- oscillating with the active neutrinos, can distort the active spectra which are the basic input for BBN

Impact on Big Bang Nucleosynthesis



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BBN constraint on ΔN_{eff} : **NO strong preference**

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

Hamann et al, 2011

Mangano and Serpico. 2012

From new precise measure of D in damped Lyman-α system

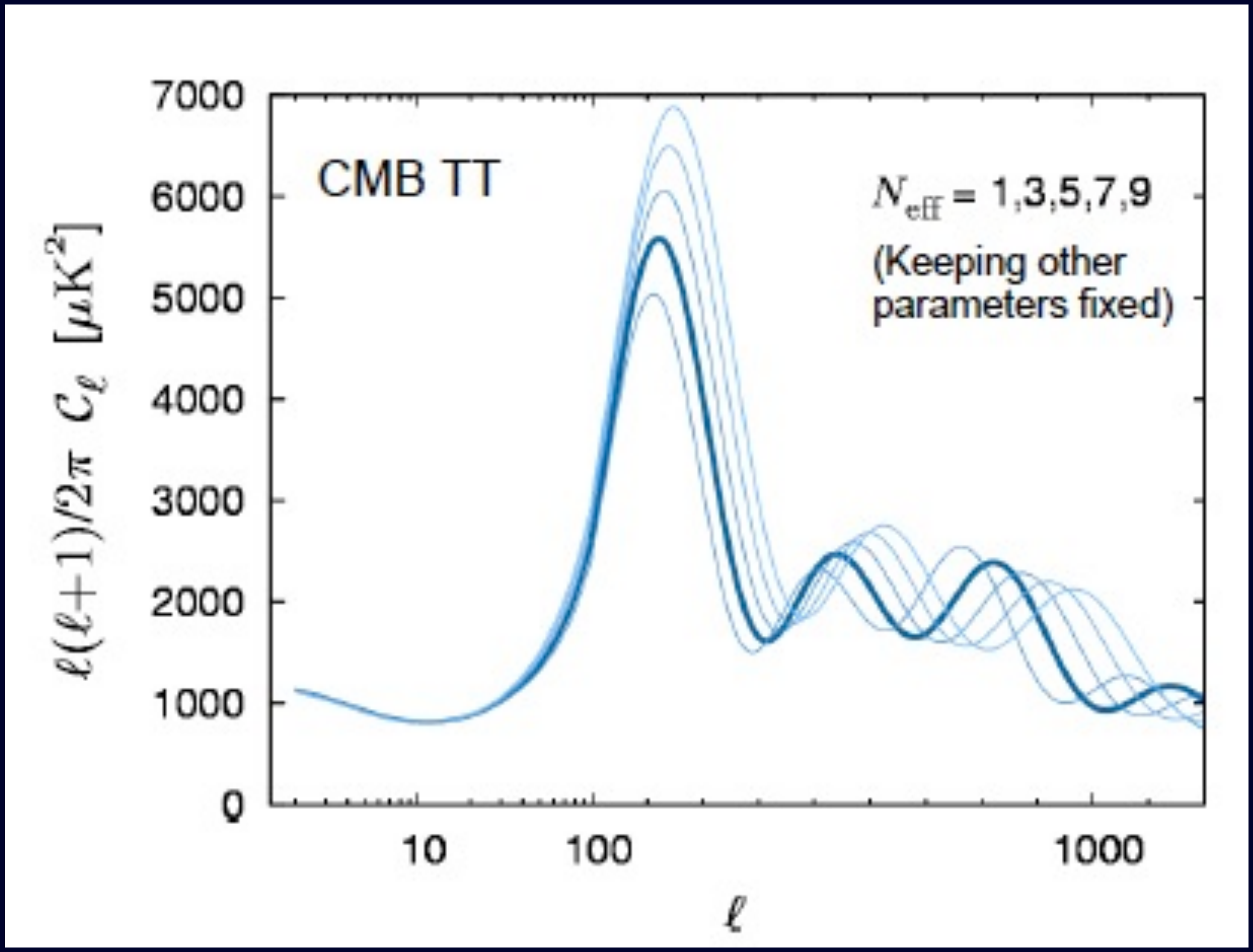
$N_{eff} = 3.28 \pm 0.28$

Cooke, Pettini et al., 2013

1 extra d.o.f. ruled out at 99.3 C.L.

Impact on CMB

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



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

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

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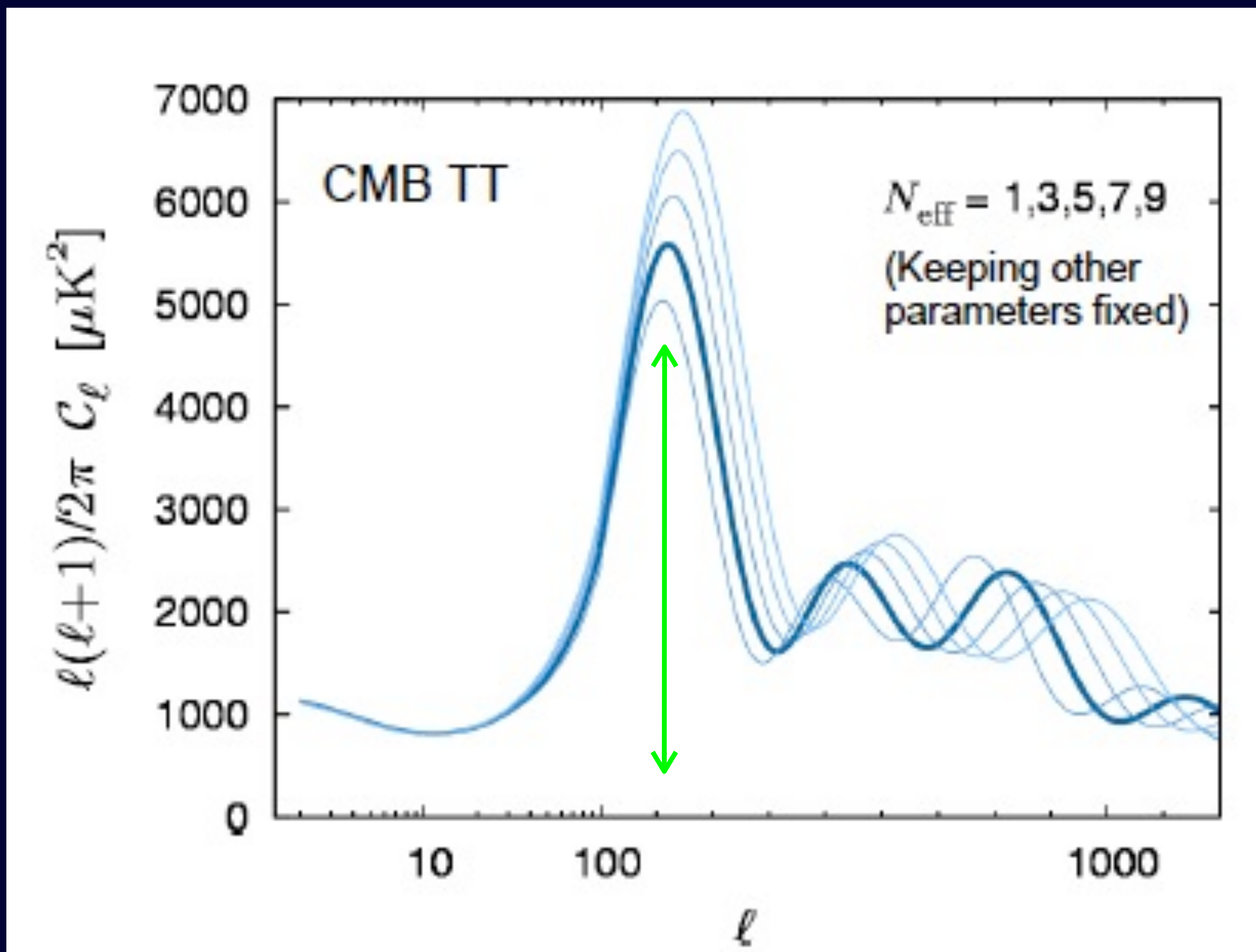

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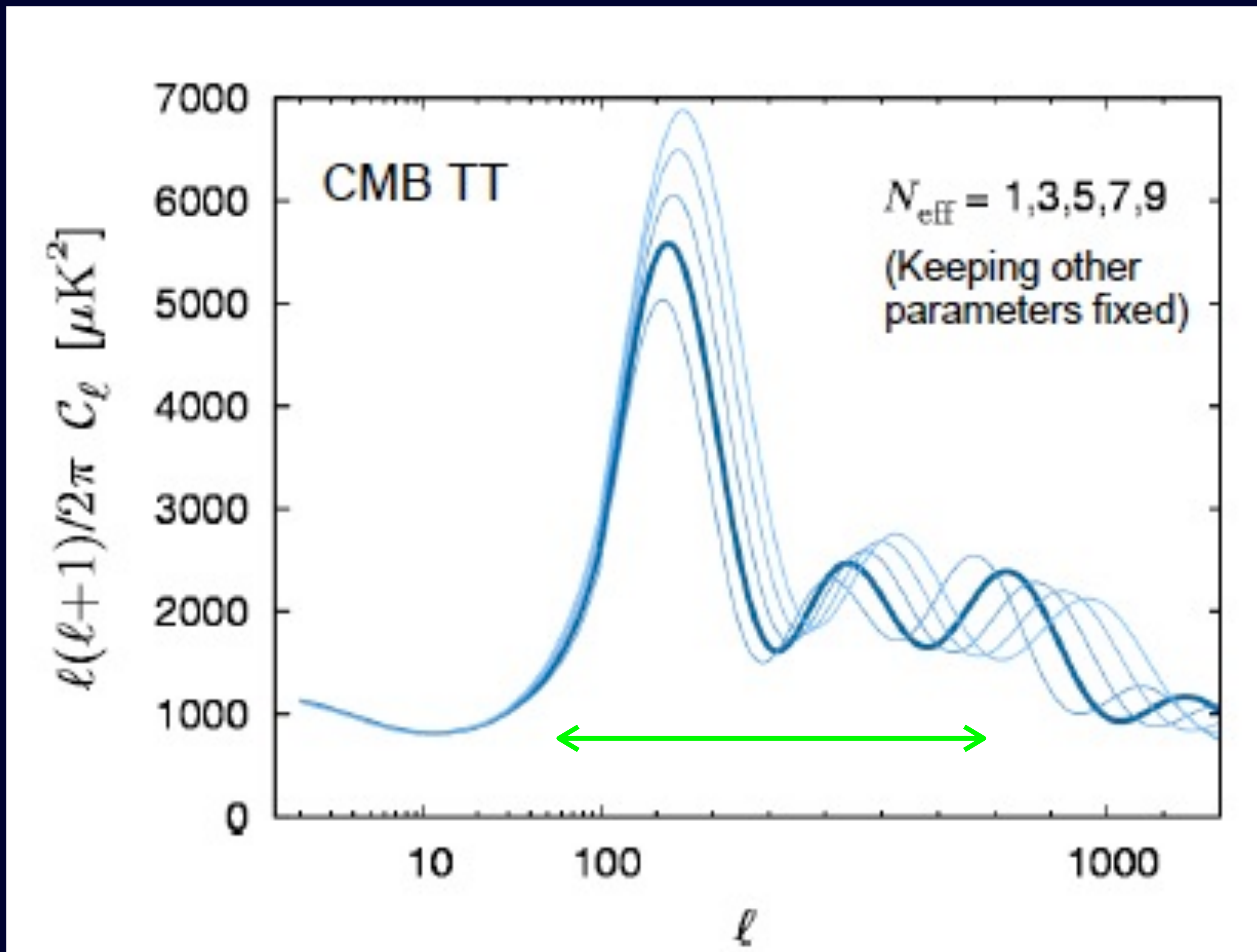

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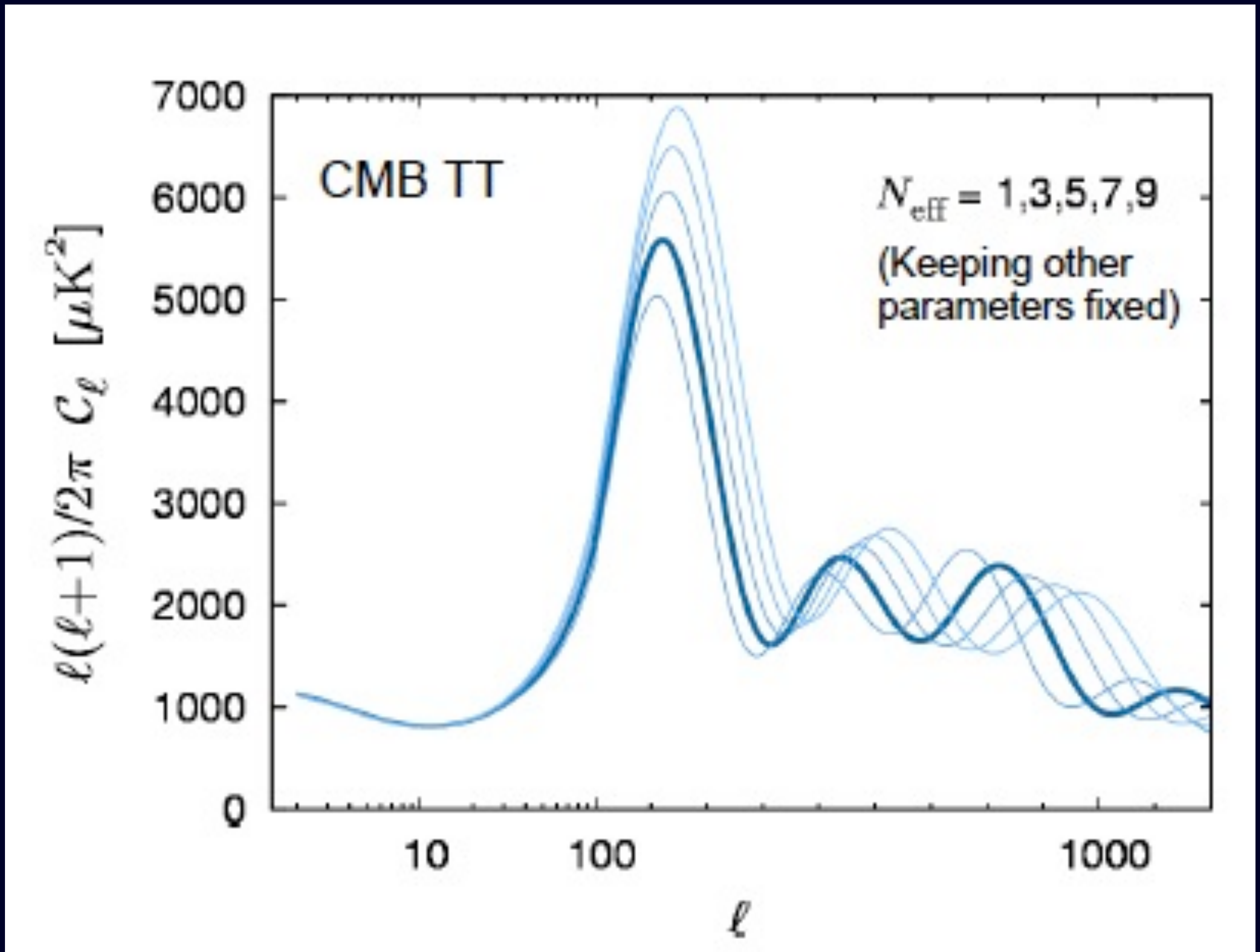

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Same data used to measure other cosmological parameters

basic parameters of ΛCDM:

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

\+ derived parameters

$$(H_0, \Omega_k, \Omega_\Lambda, N_{\rm eff}, \sigma_8, \sum m_\nu, z_{re}, Y_p, w, \Omega_m z_{LS} \ldots)$$

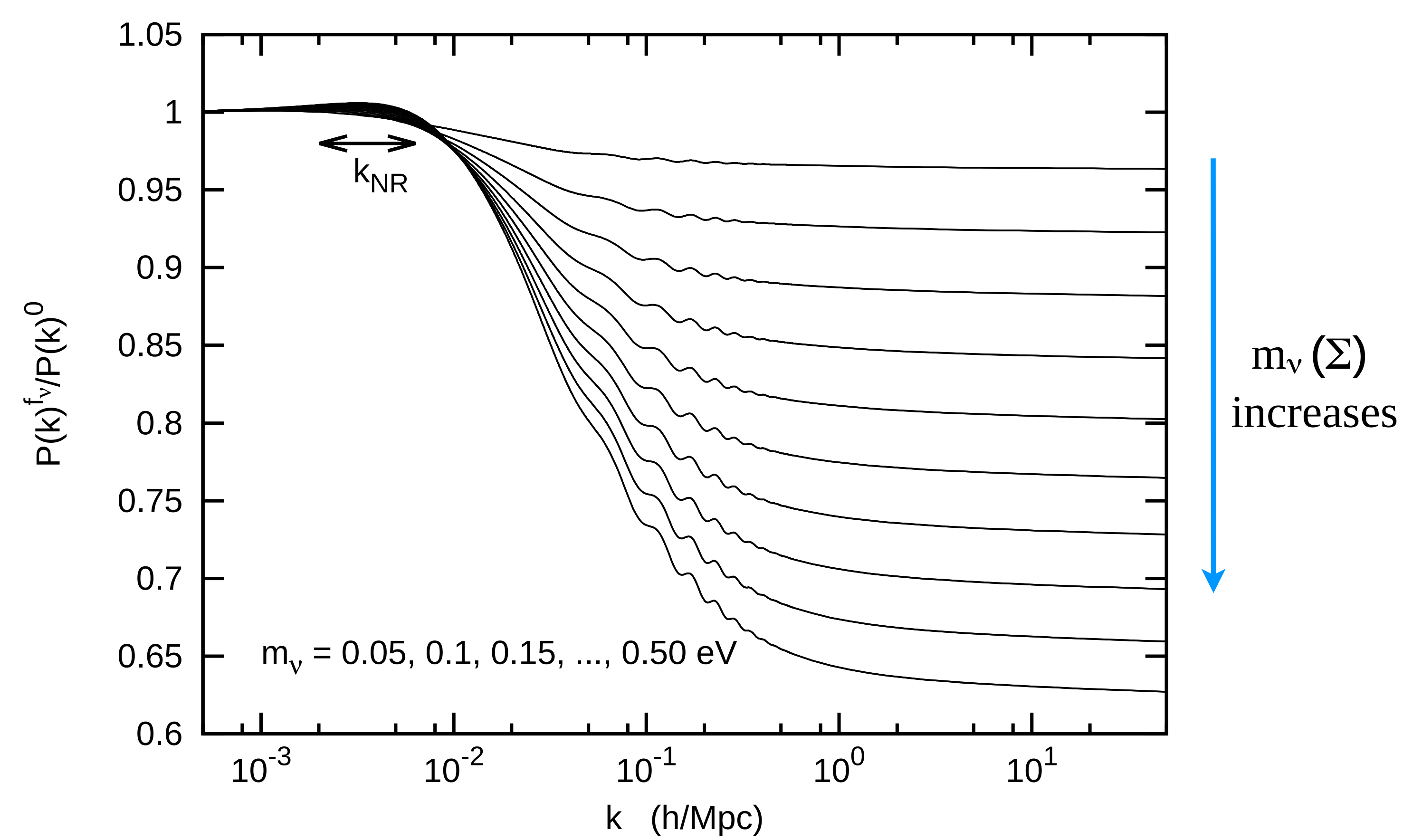
→ ***degeneracies***

→ ***necessary to combine with other cosmological probes***

Impact on the LSS

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

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



Lesgourgues, Mangano, Miele and Pastor "Neutrino Cosmology", 2013

N_{eff} *and* Σm_ν *constraints* **after Planck**

(first release)

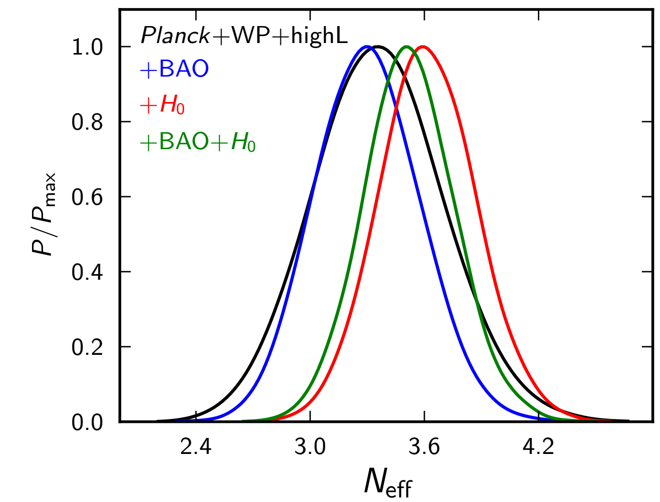
Standard scenario:

✓ $N_{eff} = 3.30 \pm 0.54$ (95 % C.L.; Planck+WP+highL+BAO)

↳ *compatible with the standard value at 1-σ*

✓ For 3 degenerate active ν :

$\Sigma m_\nu < 0.23$ eV (95 % C.L.; Planck+WP+highL+BAO)



Planck XVI, 2013

(second release)

Standard scenario:

✓ the preference for extra radiation is further reduced

$N_{eff} = 3.15 \pm 0.46$ (95 % C.L.; PlanckTT+lowP+BAO)

✓ For 3 degenerate active ν :

$\Sigma m_\nu < 0.21$ eV (95 % C.L.; Planck TT+WP+ lowP+BAO)

Planck XIII, 2015

see Henrot-Versille's talk

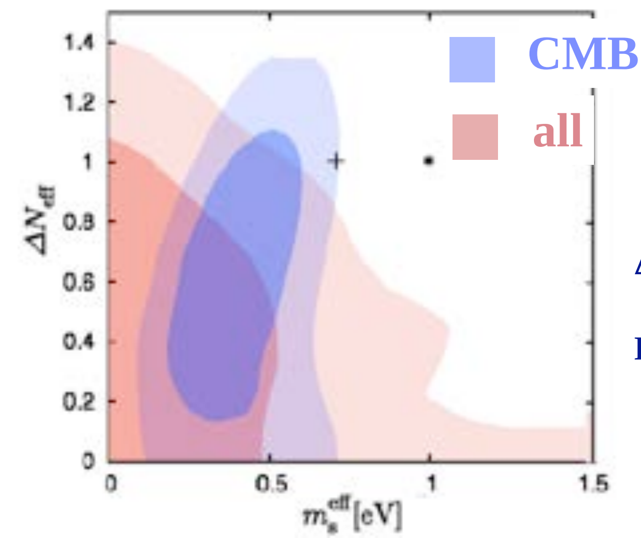
Joint constraints on N_{eff} and $m^{eff}_{\nu s}$

model	Planck +	mass bound (eV) (95% C.L.)
Joint analysis N_{eff} & 1 mass ν_s	WP+HighL+BAO	$N_{eff} < 3.80$ $m^{eff}_{\nu s} < 0.42$

Planck XVI, 2013

$$m^{\rm eff}_{\nu s} \equiv (94,1\ \Omega_\nu h^2)\rm eV$$

Hamann and Hasenkamp, 2013



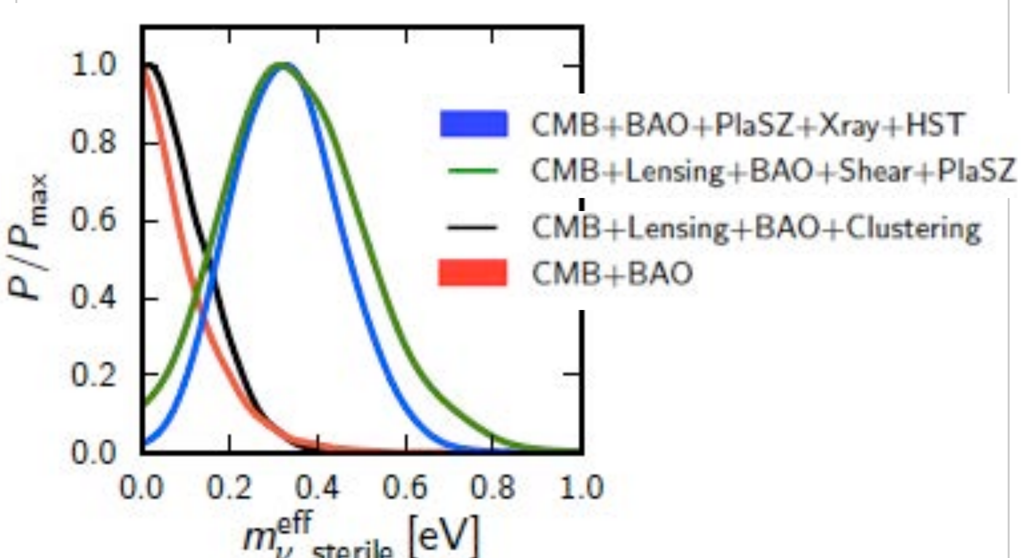
$\Delta N_{eff} = 0.61$ +- 0.30

$m^{eff}_{\nu s} = 0.41$+-0.13 eV

(68% C.L.)

all= CMB+H0+ C+ CFHTLens

L. Verde et al, 2014



$m^{eff}_{\nu s} < 0.3$ eV (95% C.L)

model	Planck TT +	mass bound (eV) (95% C.L.)
Joint analysis N_{eff} & 1 mass ν_s (prior $m_{\nu s}$ <10 eV)	lowP+lensing+BAO	$N_{eff} < 3.7$ $m^{eff}_{\nu s} < 0.52$
Joint analysis N_{eff} & 1 mass ν_s (prior $m_{\nu s}$ <2 eV)	lowP+lensing+BAO	$N_{eff} < 3.7$ $m^{eff}_{\nu s} < 0.38$

Planck XIII, 2014

Active-sterile flavour evolution

Sterile ν are produced in the Early Universe by the mixing with the active species in presence of collisions

Evolution equation:

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

$$\rho_{\mathbf{p}} = \begin{pmatrix} \rho_{ee} & \rho_{e\mu} & \rho_{e\tau} & \rho_{es} \\ \rho_{\mu e} & \rho_{\mu\mu} & \rho_{\mu\tau} & \rho_{\mu s} \\ \rho_{\tau e} & \rho_{\tau\mu} & \rho_{\tau\tau} & \rho_{\tau\tau} \\ \rho_{se} & \rho_{s\mu} & \rho_{s\tau} & \rho_{ss} \end{pmatrix}$$

ν ensemble

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

Vacuum term

MSW effect with background medium *(refractive effect)*

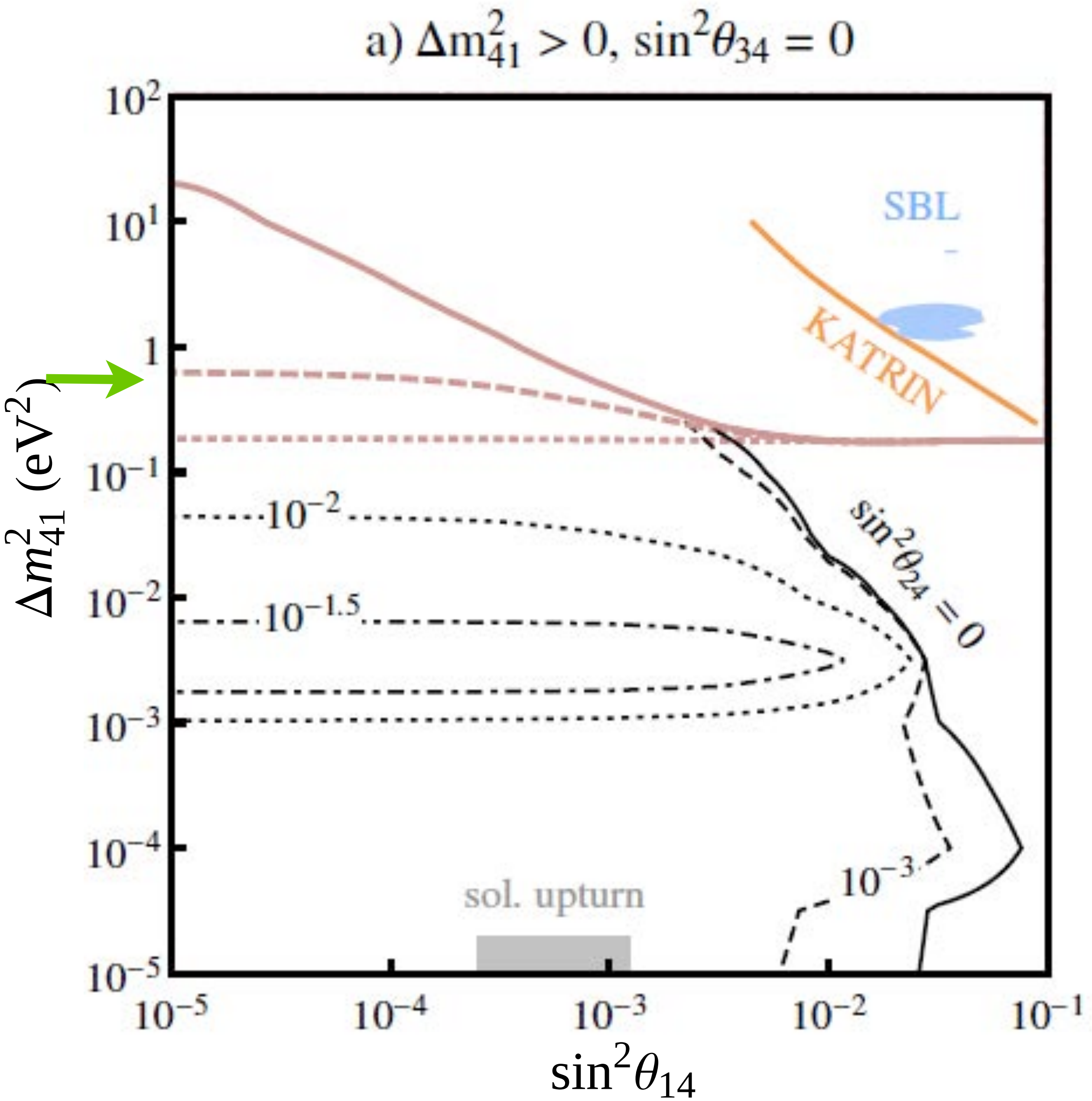
***refractive* ν–ν *self-interactions* term**

$$C[\rho]$$

Collisional term

creation, annihilation and all the momentum exchanging processes

Bounds on active-sterile mixing parameters after Planck



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

Radiation bounds

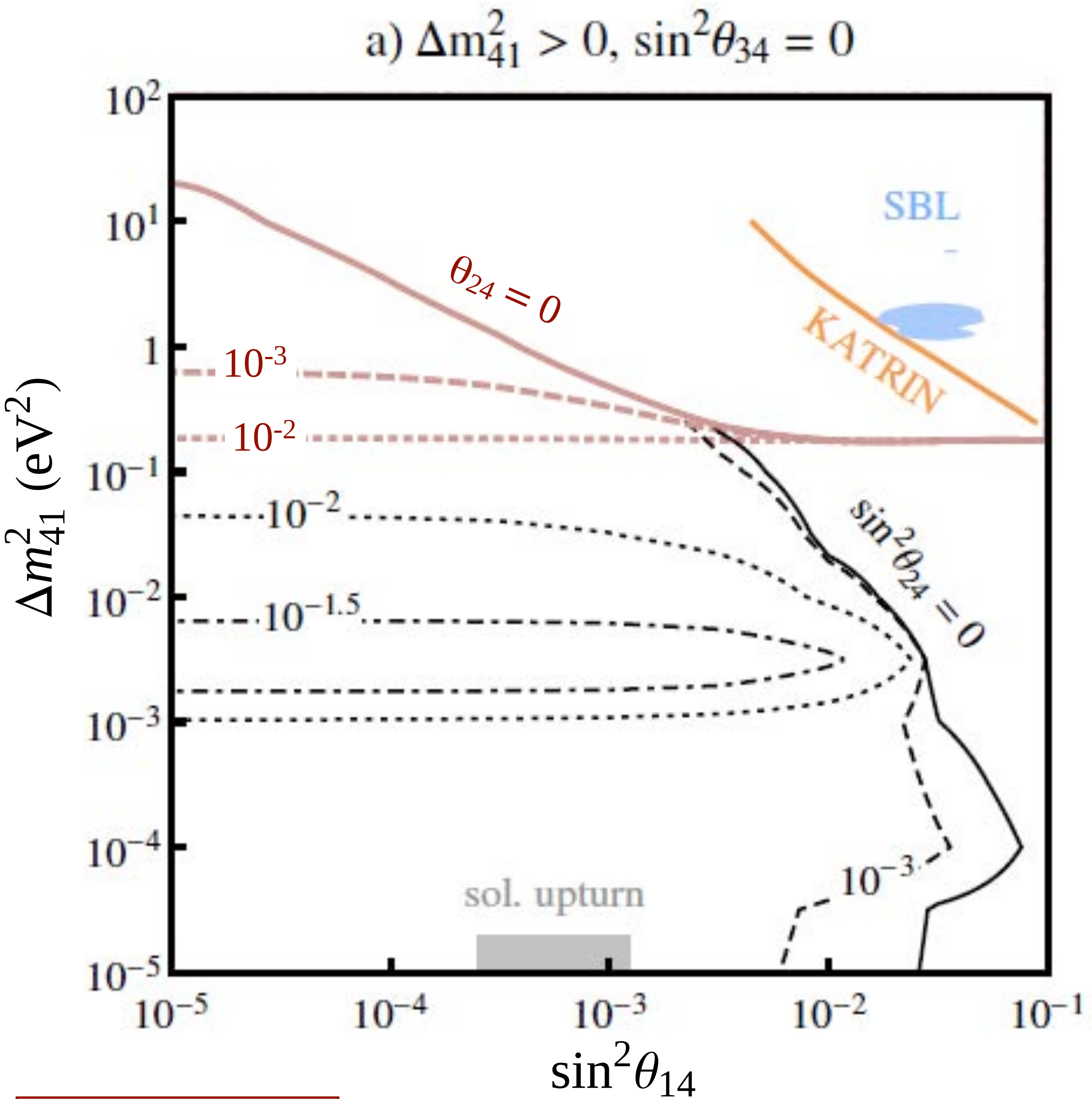
- Black curves imposing the 95% C.L. Planck constraint **$N_{eff} < 3.8$** on computed $N_{\rm eff} = \frac{1}{2} Tr[\rho + \bar{\rho}]$

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

Note: above m ~ $\mathcal{O}$(1 eV), sterile ν are not relativistic anymore at CMB → **NO radiation constraint**

BUT mass constraints become important

Bounds on active-sterile mixing parameters after Planck



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Similar bounds would be obtained with Planck 2015 data

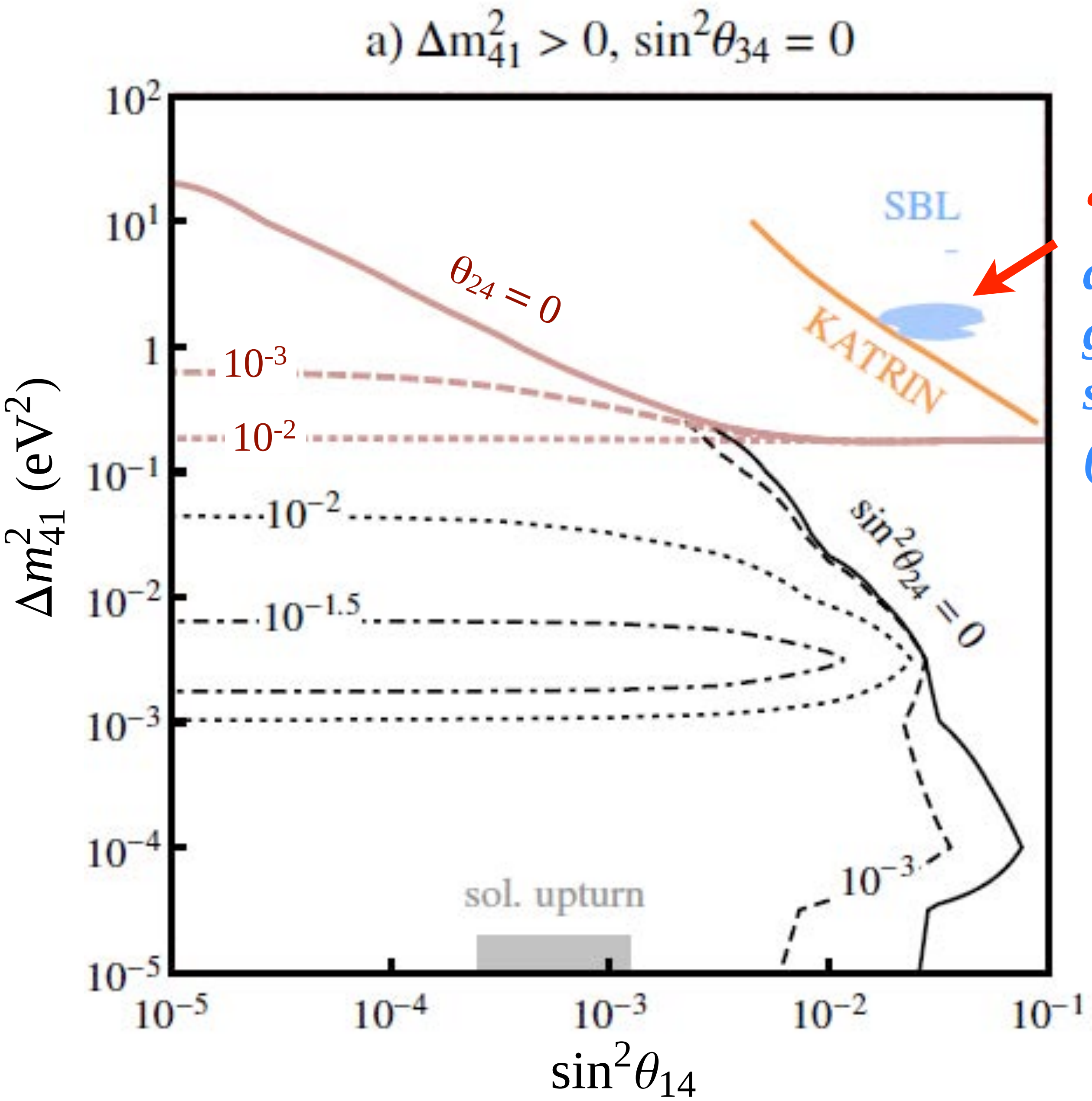
Mass bounds

- Red curves imposing the 95% C.L. Planck constraint $\mathbf{m^{eff}_{\nu s} < 0.42 \Leftrightarrow \Omega_\nu h^2 < 4.5\ 10^{-3}}$ on computed

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

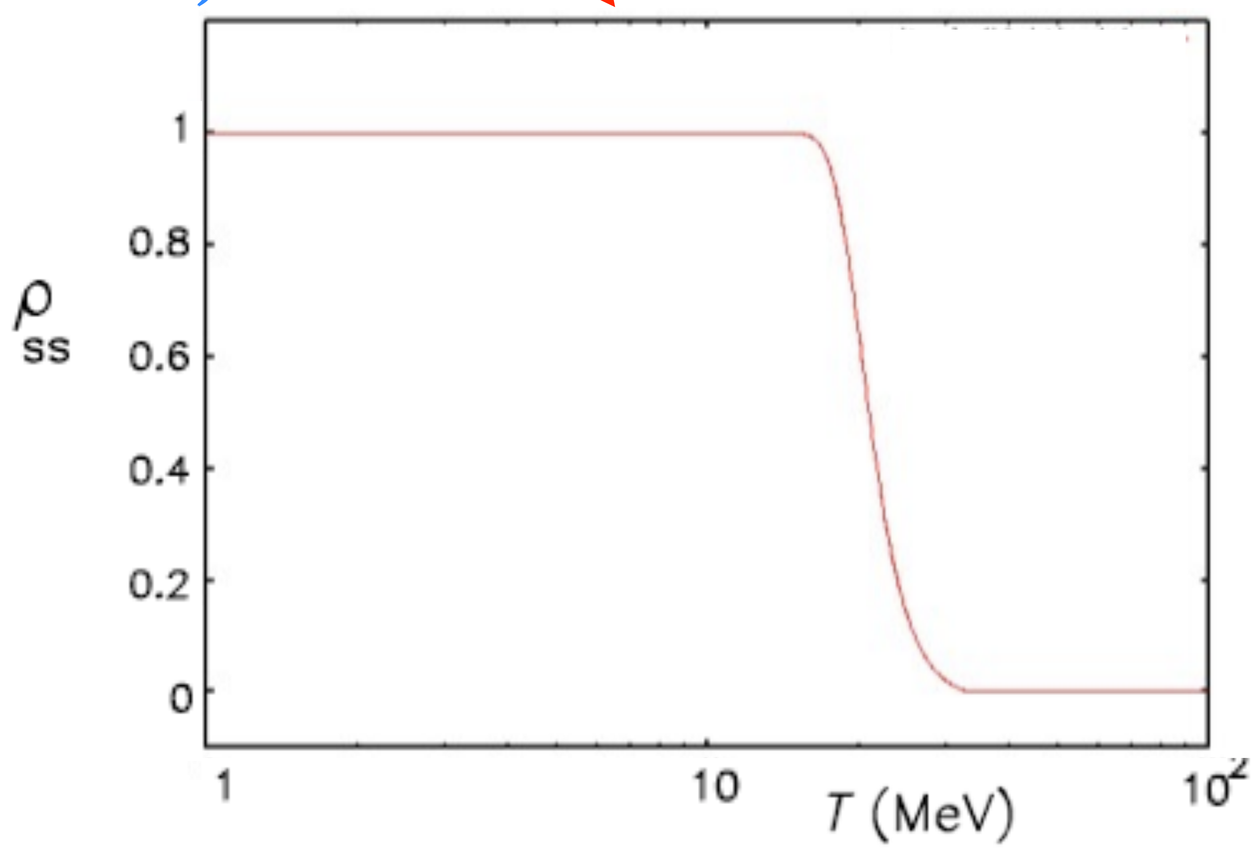
The excluded regions are those above the red contours.

Bounds on active-sterile mixing parameters after Planck



"eV sterile ν "

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



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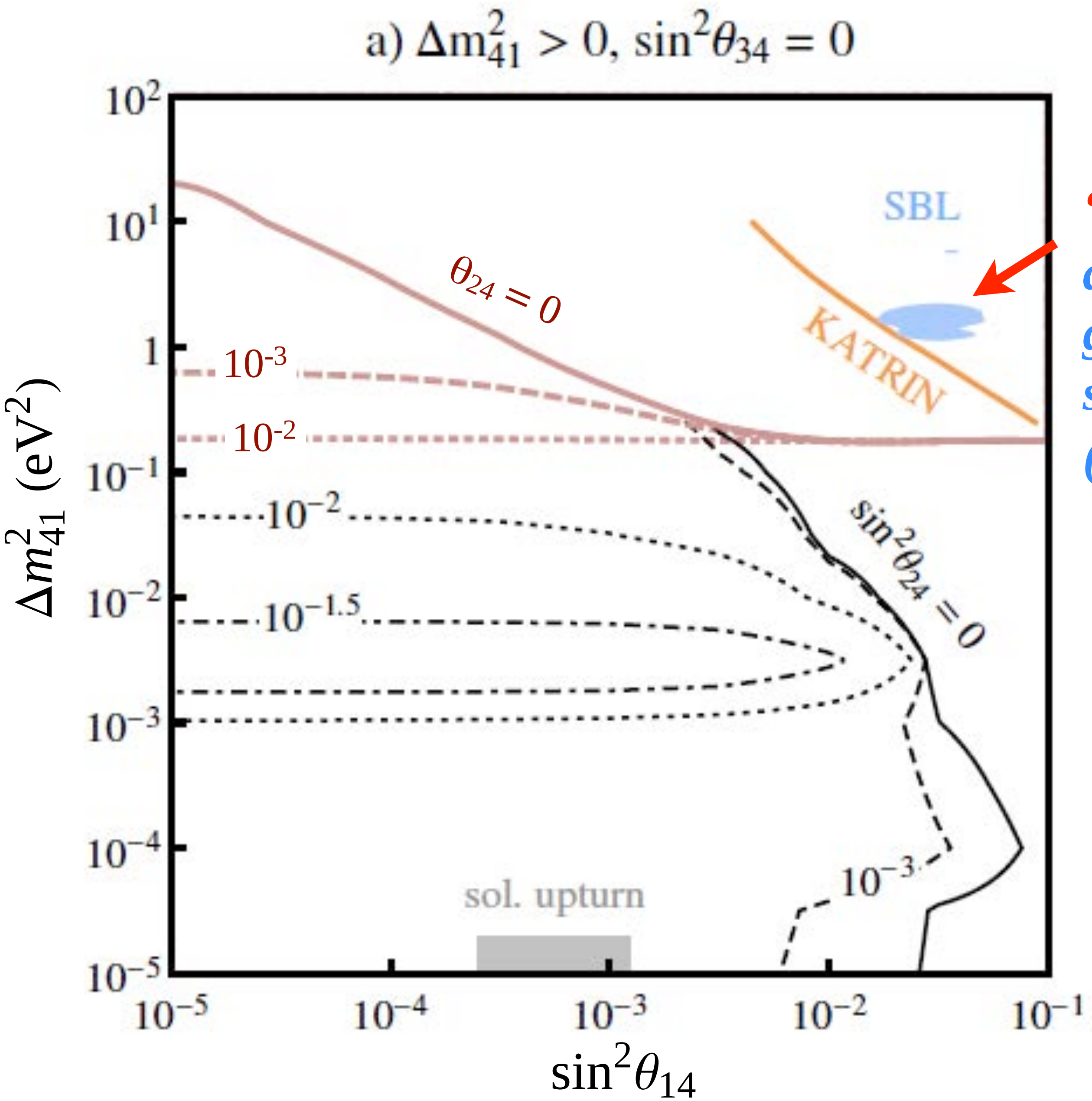

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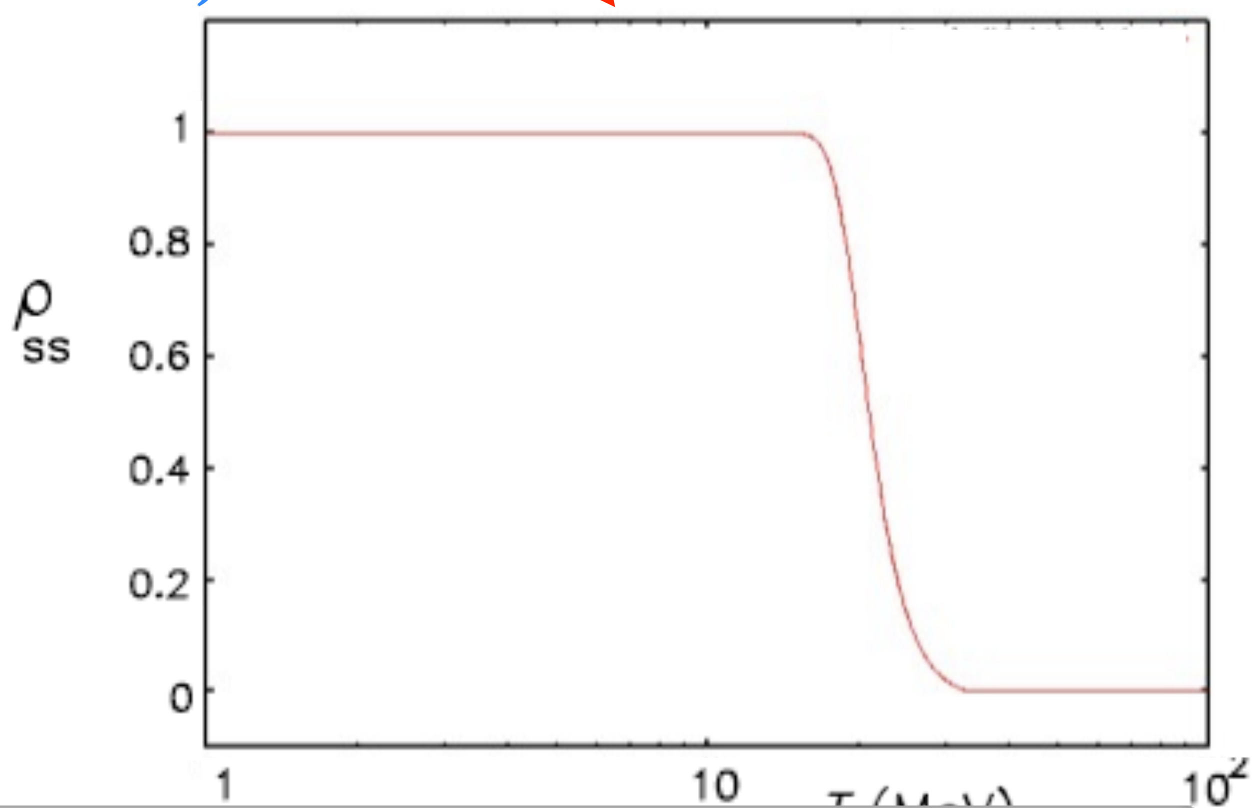

Thermalized sterile ν with **m ~ $\mathcal{O}$(1 eV)** ***strongly disfavored by cosmological constraints***

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

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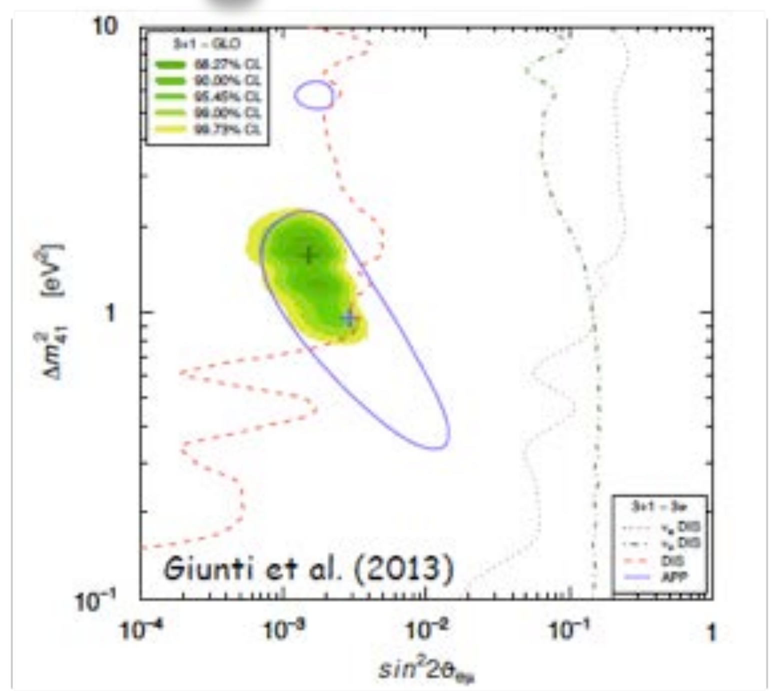
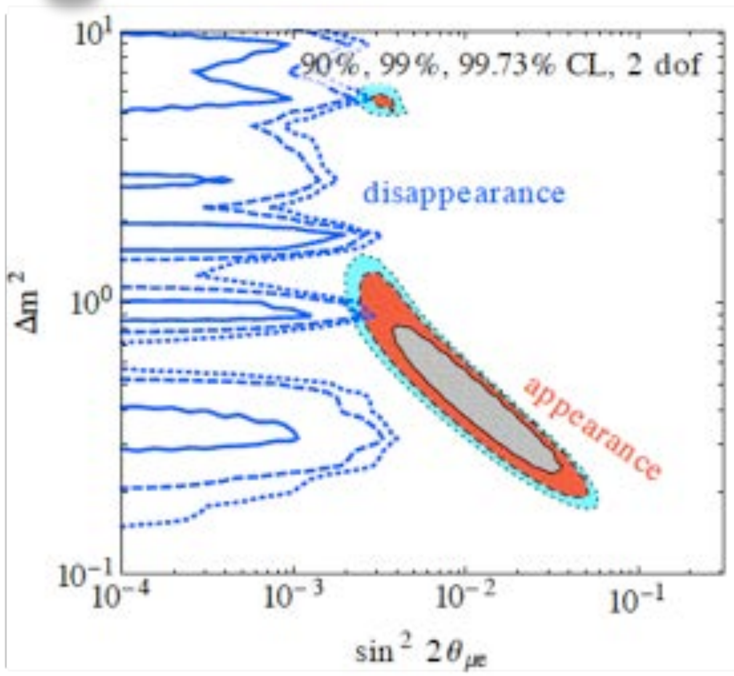


J. Kopp et al, 2013



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Are eV ν_s compatible with cosmology? NO

Possible solutions...?

Different mechanisms to suppress the ν_s abundance:

1. **large $\nu - \bar{\nu}$ asymmetries**

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

⚠ Non trivial implication for BNN

*Mirizzi, **N.S.**, Miele, Serpico 2012*
Saviano et al., 2013
Hannestad, Tamborra and Tram 2012
Chu & Cirelli, 2006
Di Bari et al, 2001

2. **hidden and "secret" interactions for sterile neutrinos**

✓ Sterile ν feel a new potential that suppresses active-sterile mixing

⚠ Scenario strongly constrained by BBN and neutrino mass bounds

Hannestad 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

3. **low reheating scenario**

✓ sterile abundance depends on reheating temperature

⚠ Simplified scenarios

Gelmini, Palomarez-Ruiz, Pascoli, 2004
Yaguna 2007

Modification of cosmological models

Inflationary Freedom

Gariazzo, Giunti Laveder, 2015

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

Conclusions

- neutrino cosmology is entering the precision epoch

$N_{eff} < 4$ $\Sigma m_\nu < 0.23$ eV $m^{eff}_{\nu s} < 0.7$ eV

- Thermalized eV sterile ν ***incompatible*** with cosmological bounds:
too heavy for structure formation

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

➔ ***however the reconciliation with cosmology is not guaranteed and in some cases disfavoured.***

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  ➔ ***however the reconciliation with cosmology is not guaranteed and in some cases disfavoured.***

Open questions:

- ***Will ΔN_{eff} be definitely ruled-out in the future?***
- ***Which are the absolute masses of neutrinos?***
- ***Will the laboratory anomalies be confirmed?***

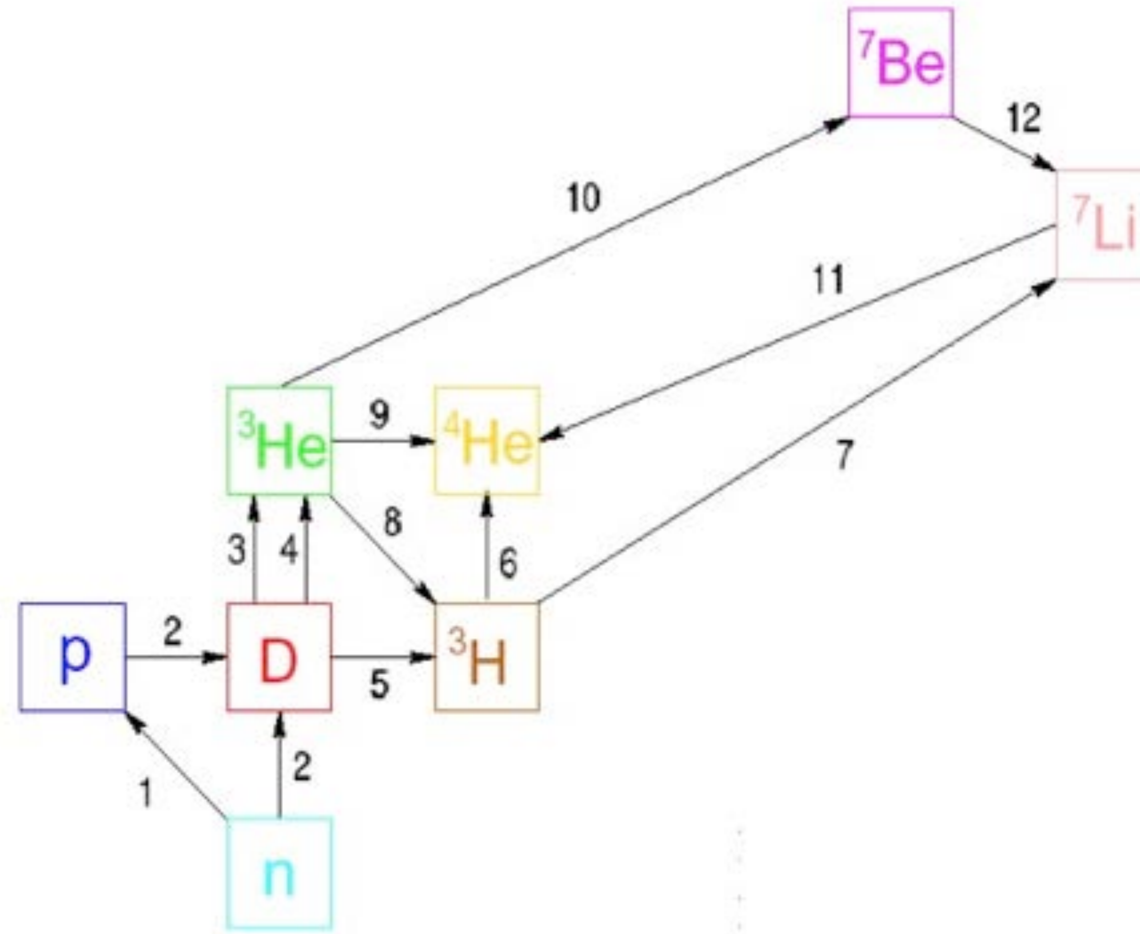
Thank you!

Big Bang Nucleosynthesis (II)

✱ 0.1-0.01 MeV

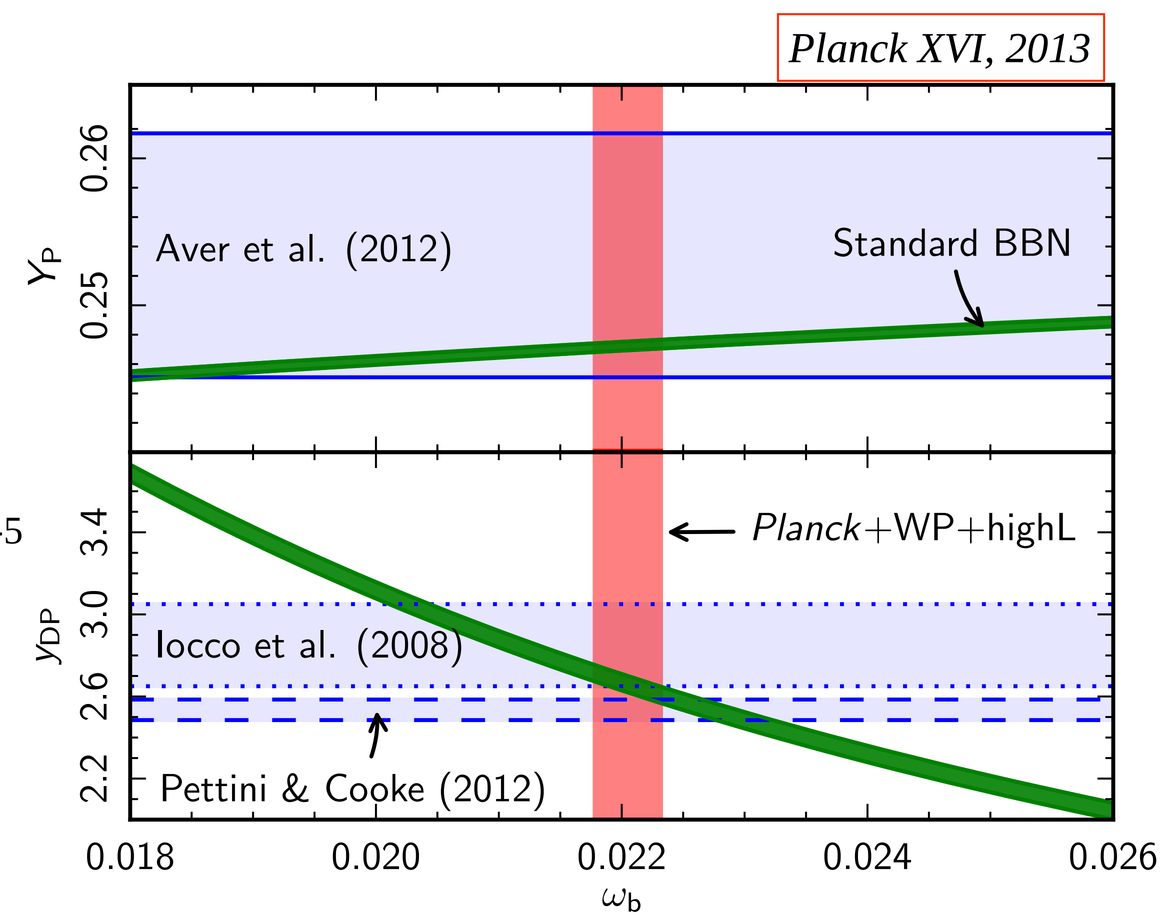
Formation of light nuclei starting from D

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



^{4}He

D ×10^{-5}



Prediction for ^{4}He and D in a **standard** BBN obtained by Planck collaboration using `PArthENoPE`

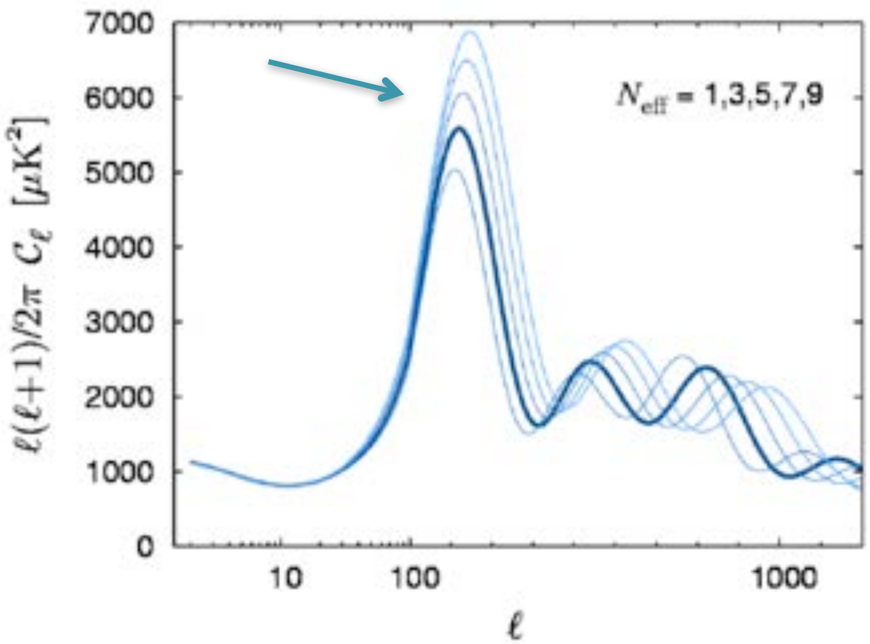
Blue regions: primordial yields from measurements performed in different astrophysical environments

$\omega_b = 0.02207 \pm 0.00027$

Extra radiation impact on CMB...
... and degeneracies

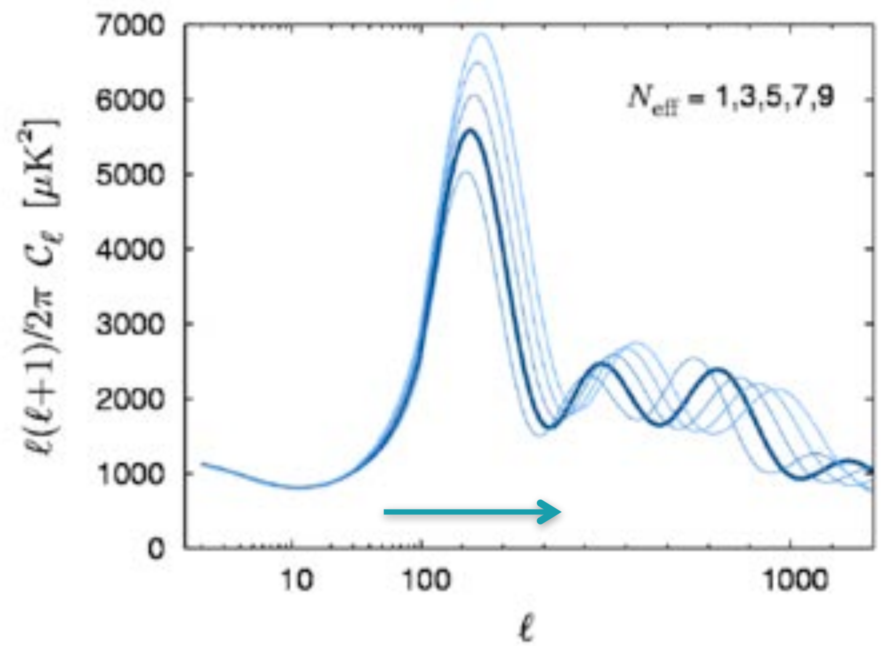
Matter-radiation equality

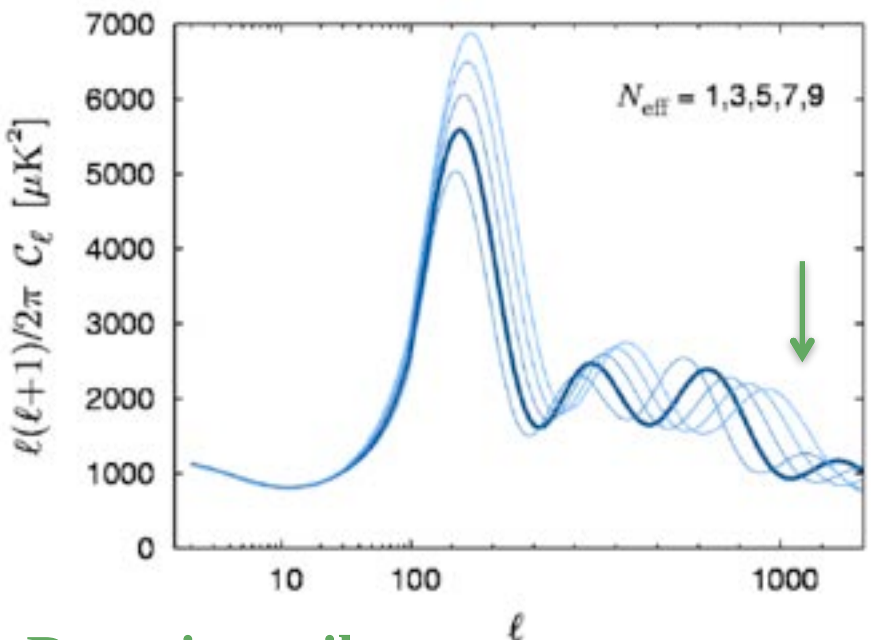
degenerate with Ω_m



Sound horizon/angular positions of the peaks

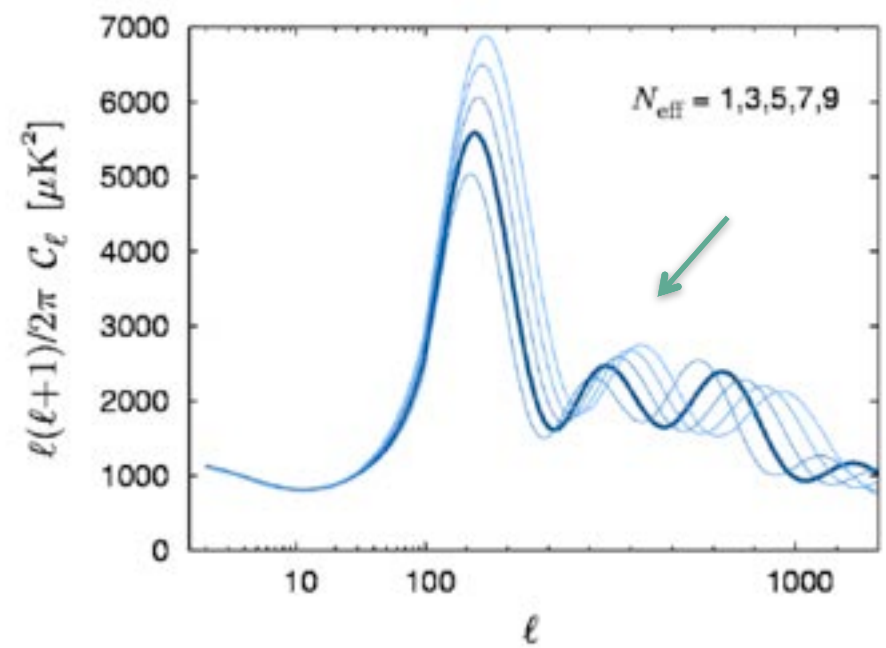
degenerate with H_0 and Ω_m





Damping tail

degenerate with Y_p



Anisotropic stress

(partially) degenerate with A_s and n_s

1. Matter-radiation equality

$$z_{eq} \propto \frac{\omega_m}{\omega_R} \propto \frac{\omega_m}{\omega_\gamma[1 + 0.2271\ N_{\rm eff}]}$$

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

$$\theta_s = \frac{r_s}{D_A}$$

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

depends on the expansion and on sound speed

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

D_A is the angular diameter distance to the Last SS

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

This relation implies that while θ_s constrains the parameter combination $\Omega_m = \omega_m / h^2$ it does not constrain ω_m and h individually

4. Damping tail

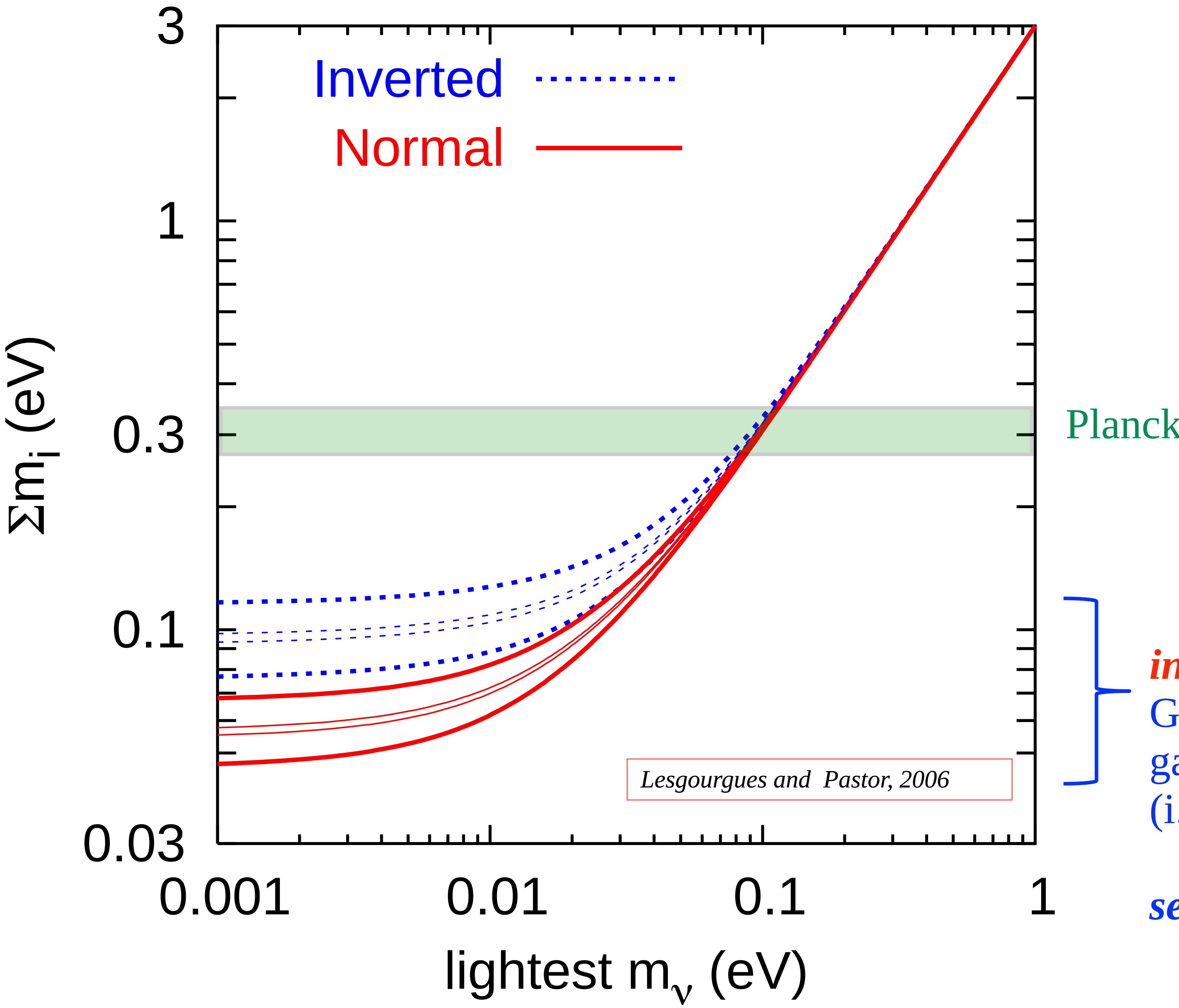
Close to recombination, the tight-coupling approximation breaks down.
Random scattering processes tend to erase perturbations below the photon diffusion length.

The envelope of the secondary peaks at large l depends on the angle $\theta_d = \lambda_d/DA$
where λ_d is the diffusion length .
Increasing the expansion rate will increase λ_d

λ_d which is controlled by the expansion history and recombination history before the decoupling. It depends essentially by free electron n_e ($\propto 1/n_e$).

An enhancing of n_e can compensate the increased expansion rate $\longrightarrow$ less ^4He (less recombination)

$$n_e = (1 - Y_p) n_B$$



in future....
Galaxy distribution, lensing of galaxies, galaxy cluster....
(i.e. Euclid)

sensitivity < 0.1

Equation for the flavour evolution

Evolution equation:

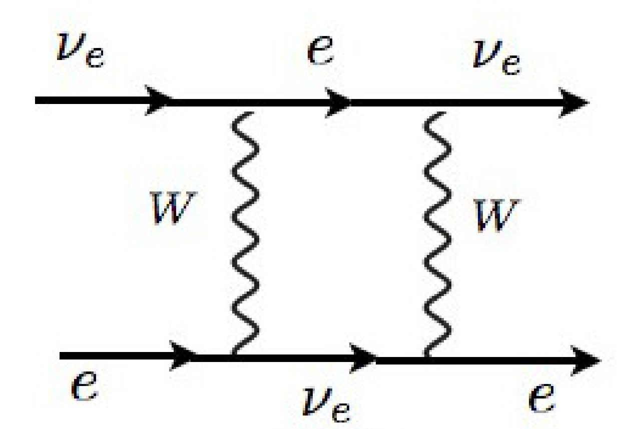
$$\mathrm{i}\,\frac{d\rho}{dt} = [\Omega, \rho] + C[\rho]$$

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

MSW effect with background medium
(refractive effect) $\propto G_F$

➜ 2th order term: "symmetric" matter effect

(charged lepton asymmetry subleading ($O(10^{-9})$))



Equation for the flavour evolution

Evolution equation:

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

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

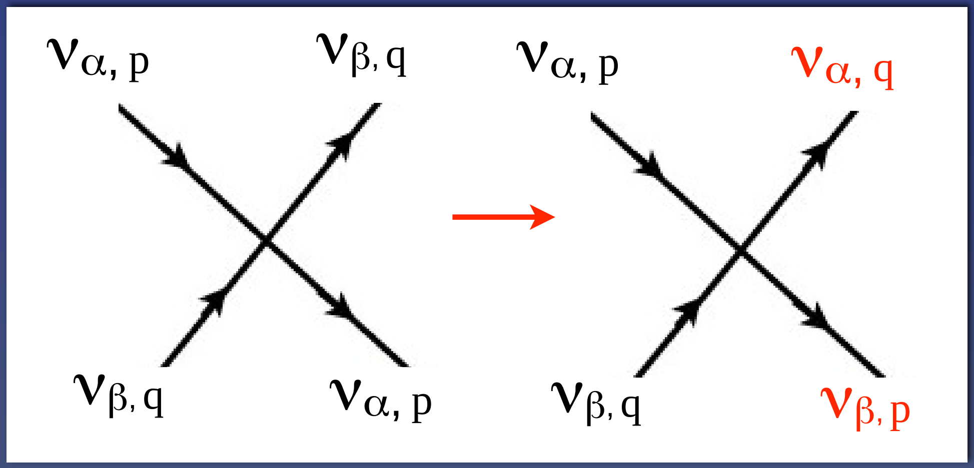
symmetric term $\propto (\varrho + \bar{\varrho})$

asymmetric term $\propto (\varrho - \bar{\varrho})$ = L

refractive ν–ν term $\propto G_F$

self-interactions of ν with the ν background:

off-diagonal potentials ➠ non-linear EoM



The importance of multi-flavour system

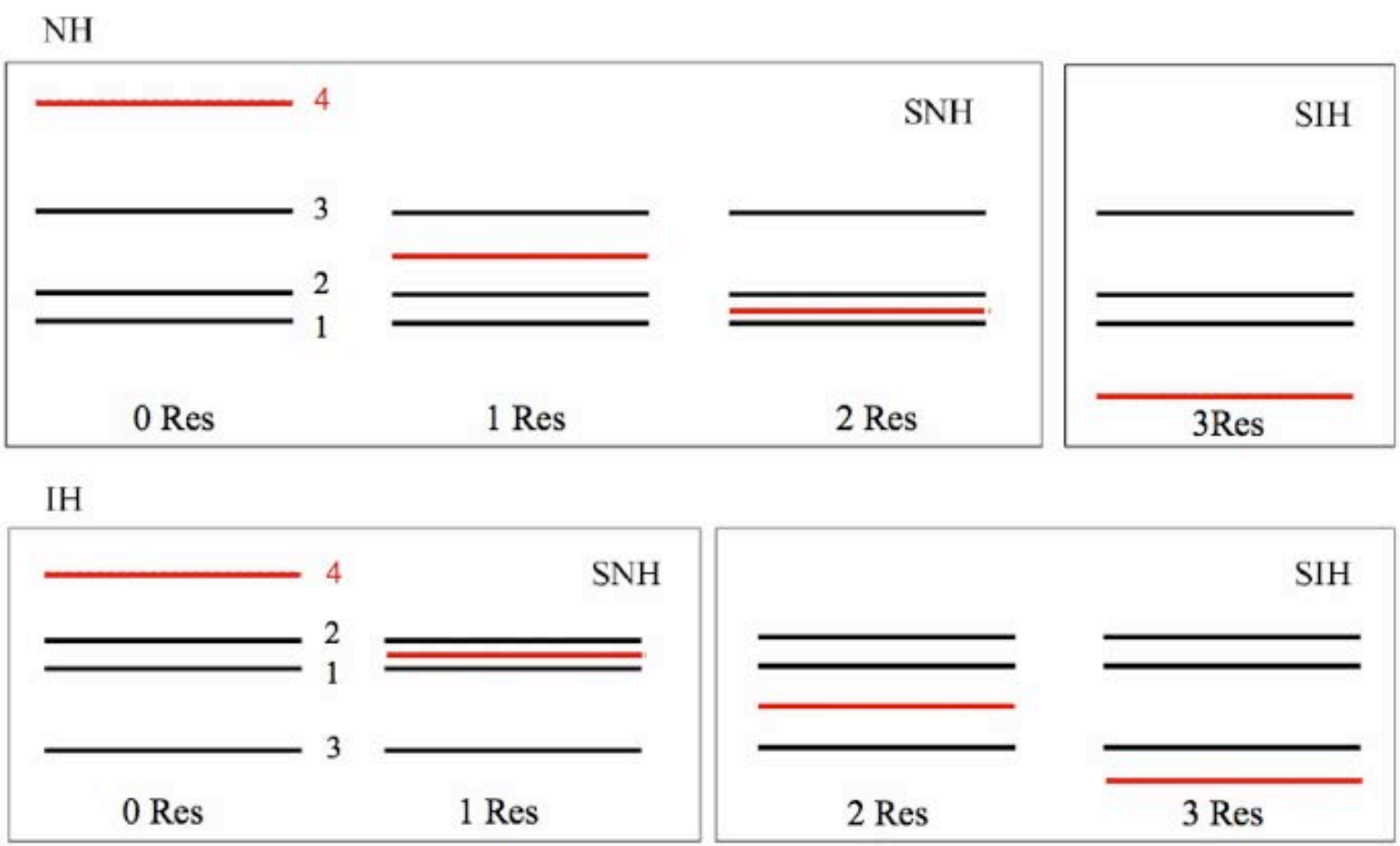
- **More mixing angles:**

Mirizzi et al 2013, arXiv1303.5368

  - 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

Δm^2_{4i} θ_{i4} i=1,2,3

Active	NH, $\Delta m^2_{31} > 0$ IH, $\Delta m^2_{31} < 0$
Sterile	SNH, $\Delta m^2_{41} > 0$ SIH, $\Delta m^2_{41} < 0$

Sterile production by neutrino asymmetry

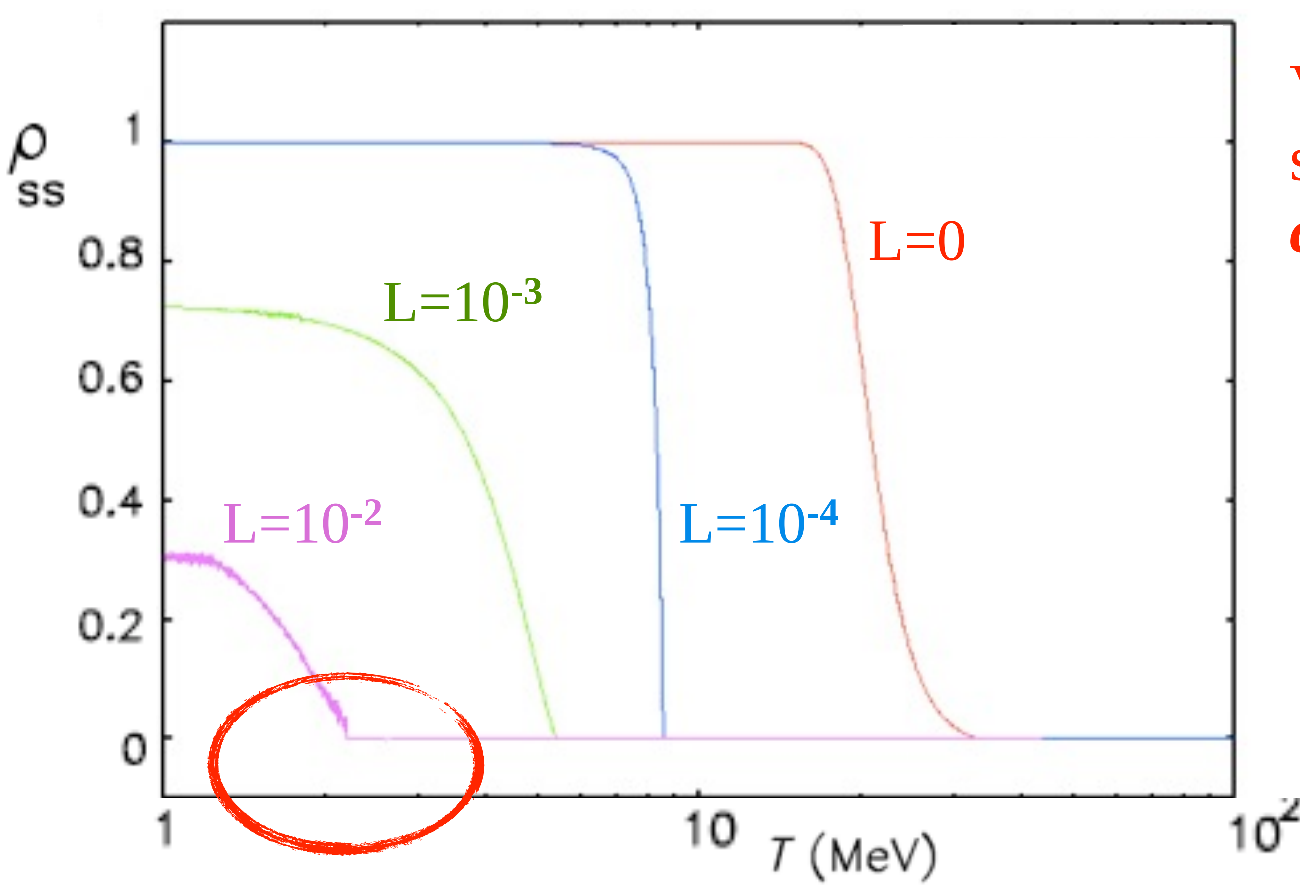
✓ ρ_{ss} and distortions of ν_e spectra as function of the ν ***asymmetry parameter***

→ evaluation of the cosmological consequences

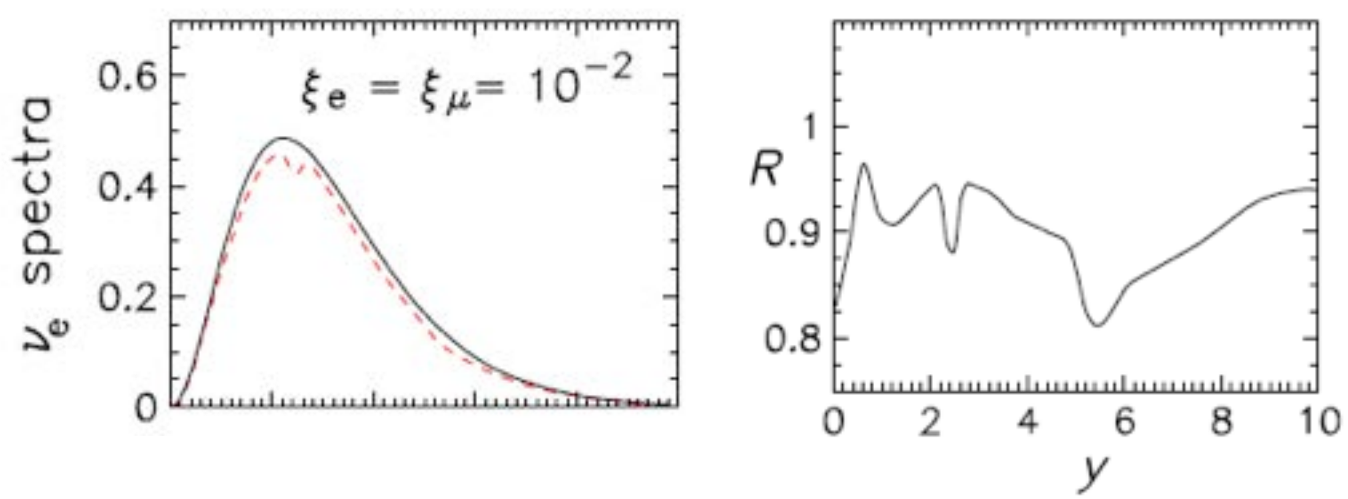
✗ Very challenging task, involving time consuming numerical calculations

→ few representative cases

$$L_\alpha \simeq 0.68\,\xi_\alpha \left(\frac{T_\nu}{T_\gamma}\right)^3$$



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



→ ***conversions occur at T ~ T_ν decoupling***

⇒ active not repopulated anymore by collisions ($\rho_{ee} < 1$)

Active-Sterile flavour evolution

- ν_s - ν_s interaction strength $G_X = \frac{\sqrt{2}}{8}\frac{g_X^2}{M_X^2}$ for $T \ll M_X$

Evolution equation:

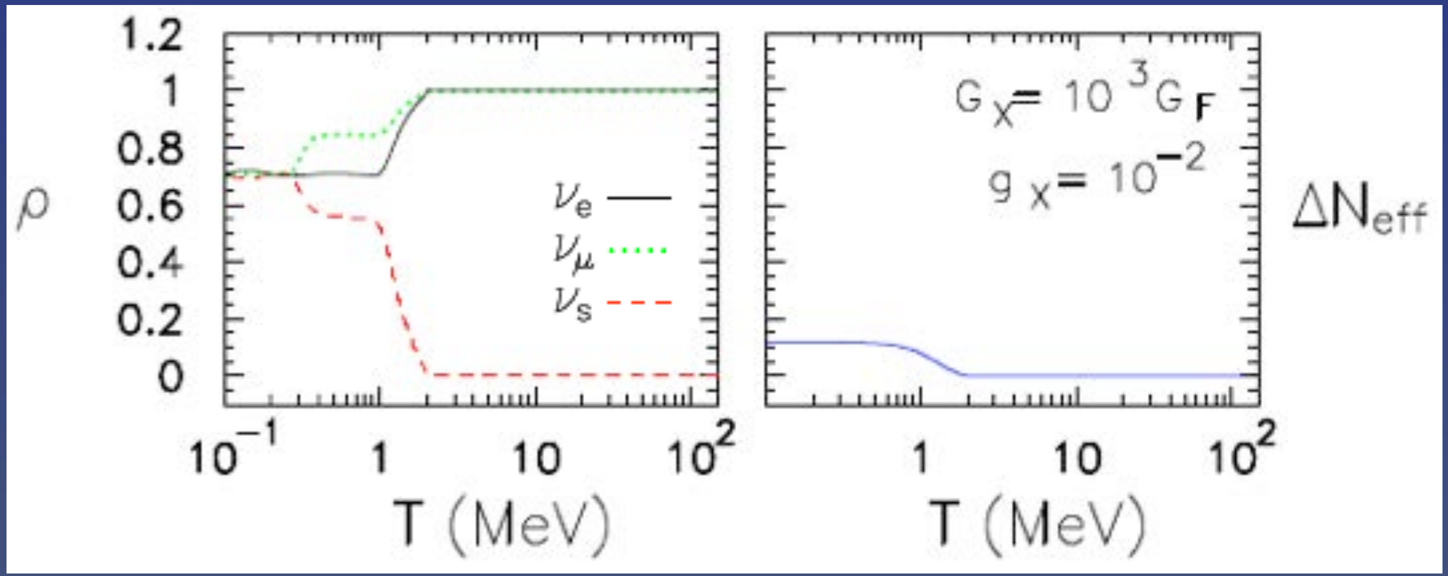
$$i\frac{d\rho}{dt} = [\Omega, \rho] + C[\rho]$$

$$\Omega = \Omega_{\rm vac} + \Omega_{\rm mat} + \Omega_{\nu-\nu} + \Omega^{\rm secr}_{\nu_s-\nu_s}$$

$\Omega_{\rm mat}, \Omega_{\nu-\nu} \propto G_F$; $\Omega^{\rm secr}_{\nu_s-\nu_s} \propto G_X$

$$C = C_{\rm SM} + C_{\rm secr}$$

$C_{\rm SM} \propto G_F^2$; $C_{\rm secr} \propto G_X^2$



primordial ^{2}H yield