inνisibles13
neutrinos, dark matter & dark energy physics

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Neutrino oscillations, N_{eff} and cosmological constraints: role of the sterile ν

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Experimental anomalies & sterile ν interpretation

Some experimental data in tension with the standard 3ν scenario + oscillations

(...and sometimes in tension among themselves....)

Kopp at al., 2013

1. *$\overline{\nu}_e$ appearance signals*

- excess of $\overline{\nu}_e$ originated by initial $\overline{\nu}_\mu$: LSND/ MiniBooNE

A. Aguilar et al., 2001

A. Aguilar et al., 2010

2. *$\overline{\nu}_e$ and ν_e disappearance signals*

- deficit in the ν_e fluxes from nuclear reactors (at short distance)

Mention et al.2011

Mention's talk

- reduced solar $\overline{\nu}_e$ event rate in Gallium experiments

Acero, Giunti and Lavder, 2008

Giunti and Lavder, 2011

Kopp, et al. 2011

All these anomalies, if interpreted as oscillation signals, point towards the possible existence of ***1*** (or more) ***sterile neutrino*** with $\Delta m^2 \sim O\,(\mathrm{eV}^2)$ and $\theta_s \sim O\,(\theta_{13})$

Many analysis have been performed → 3+1, 3+2 schemes

Sterile neutrino : does not have weak interactions and does not contribute to the number of active neutrinos determined by LEP

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 $N_{\rm eff}$

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

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

(+ oscillations)

Mangano et al. 2005

At T~ m_e, e^+e^- pairs annihilate heating photons. Since $\mathbf{T_{dec}(\nu)}$ is close to $\mathbf{m_e}$, neutrinos share a small part of the entropy release

ΔN = 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...

For a recent review on Cosmic Dark radiation and ν see M. Archidiacono et al., 2013

ν and Big Bang Nucleosynthesis

Big Bang Nucleosynthesis (BBN) is the epoch of the Early Universe (T~1- 0.01 MeV) when the primordial abundances of light elements were produced, in particular ^2H, ^3He, ^4He, ^7Li.

When $\Gamma_{n \leftrightarrow p} < H$ ➜ $\frac{n_n}{n_p} = \frac{n}{p} = e^{-\Delta m/T}$ *freezes out* → *fixing the primordial yields*

↳ $1/7$ including neutron decays

$$Y_p = \frac{2n/p}{1+n/p}$$

Helium mass fraction

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Cosmological ν influence the production of primordial light elements in two ways:

1) $\nu_e, \overline{\nu}_e$ participate in the CC weak interactions which rule the $n \longleftrightarrow p$ interconversion

any change in the their energy spectra can shift the n/p ratio freeze out temperature ➪ modification in the primordial yields

$$\nu_e + n \to e^- + p$$
$$\overline{\nu}_e + p \to e^+ + n$$
$$e^- + \overline{\nu}_e + p \to n$$

i.e. $\nu_e - \overline{\nu}_e$ asymmetry (chemical potential ξ_e) → $\frac{n}{p} = e^{(-\Delta m/T - \xi_e)}$

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2) ν_α contribute to the radiation energy density that governs the expansion rate of the Universe before and during BBN epoch and then the *n/p* ratio.

$$H = \frac{\dot{a}}{a} = \sqrt{\frac{8\pi G_N \epsilon_R}{3}}$$

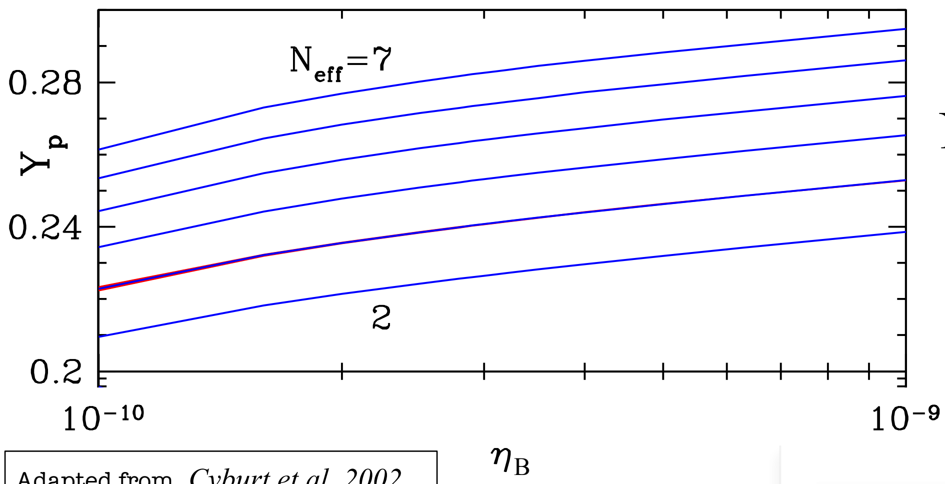
→ (γ, e, ν, x)

↳ $\propto N_{\rm eff}$

Changing the *H* would alter the *n/p* ratio at the onset of BBN and hence the light element abundances

Extra radiation impact on BBN and constraints

Light element abundances are sensitive to extra radiation:



Adapted from *Cyburt et al, 2002*

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

Upper limit on N_{eff} from constrains on primordial yields of D and ^{4}He

Mangano and Serpico. 2012

$\Delta N_{eff} \leq 1$

(at 95% C.L)

Same results from analysis on **sterile neutrino**:

no strong indication for $N_s > 0$ from BBN alone

Hamann et al, 2011

From a measurement of D in a particle astrophysical system:

$N_{eff} = 3.0 \pm 0.5$

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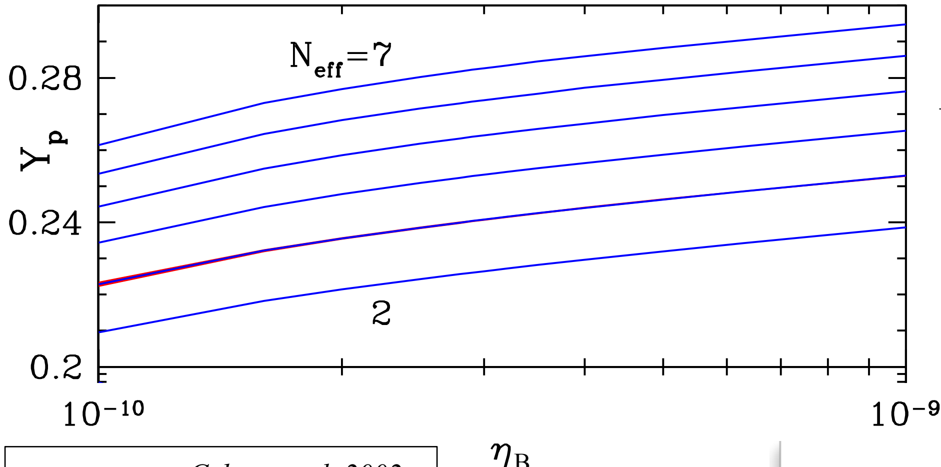

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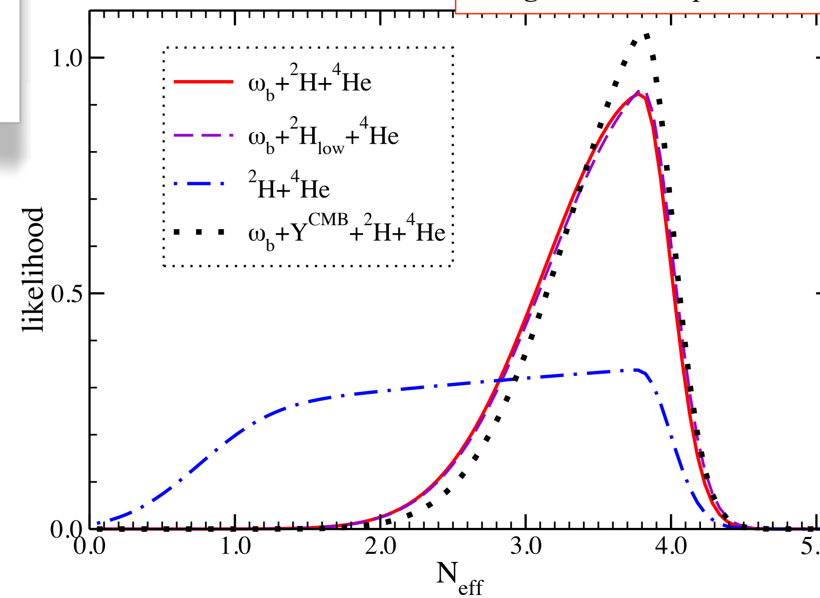

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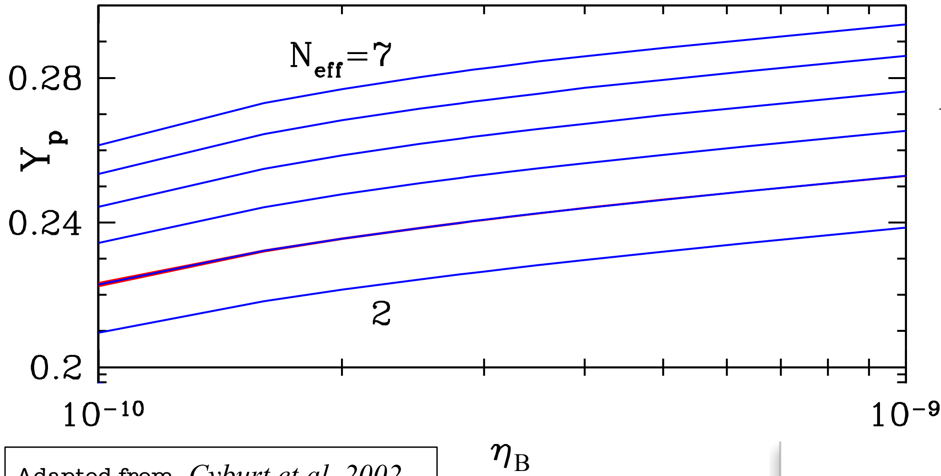

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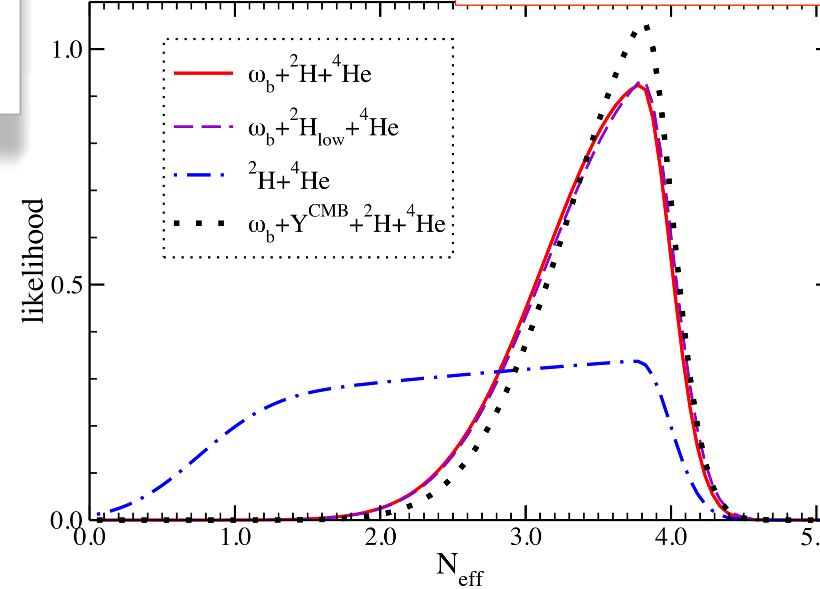

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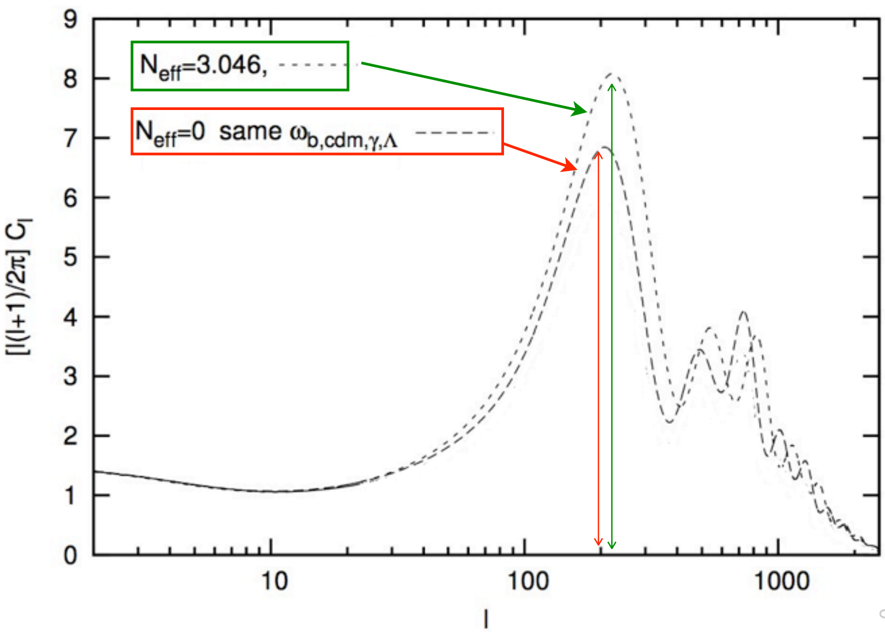
ν and CMB and LSS

ν's and their masses effect the PS of temperature fluctuations of CMB ($T < eV$) and the matter PS of the LSS inferred by the galaxy surveys.

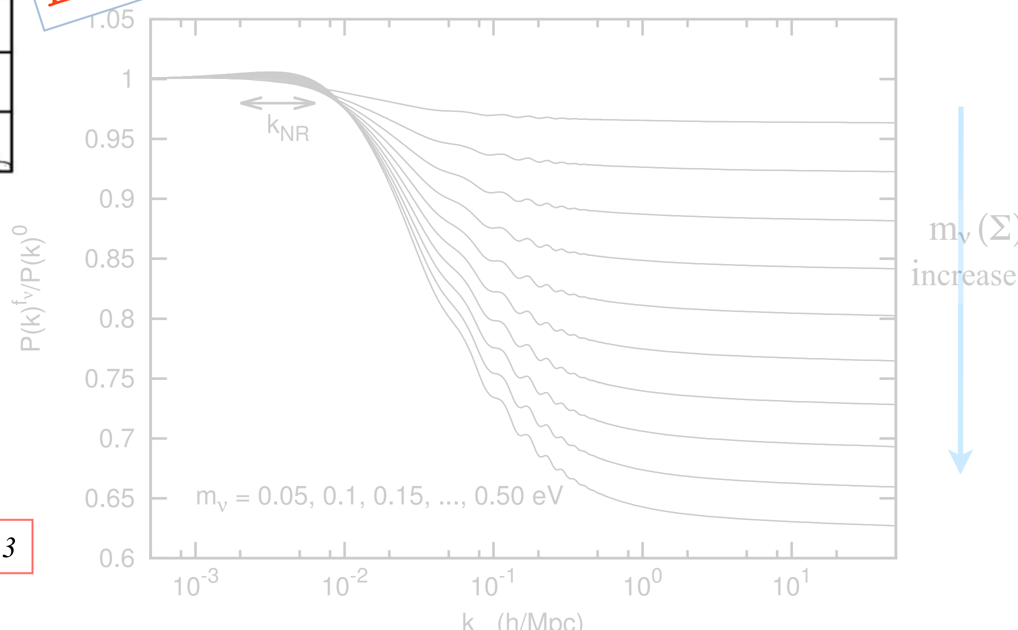


N_{eff} and m_ν affect the time of *matter-radiation equality*

➡ consequences on the amplitude of the first peak and on the peak locations

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

Lesgourgues's talk



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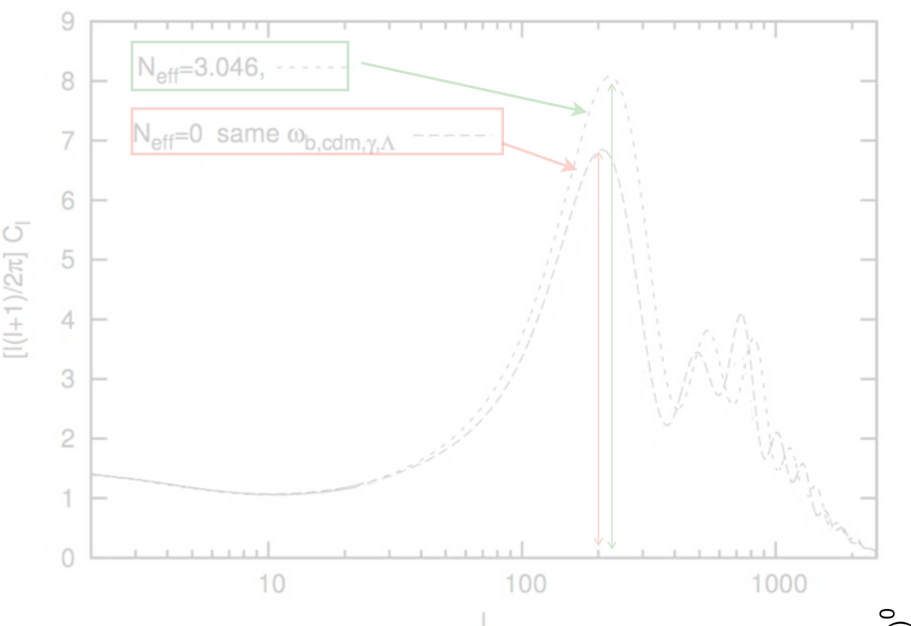
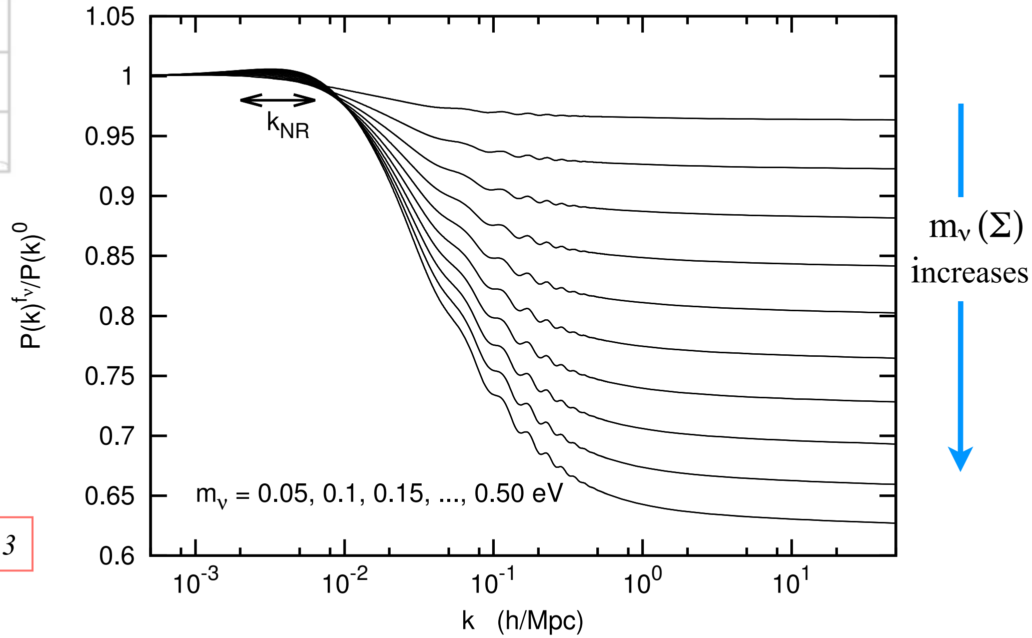


The small-scale matter power spectrum $P(k > k_{nr})$ is reduced in presence of massive ν:

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



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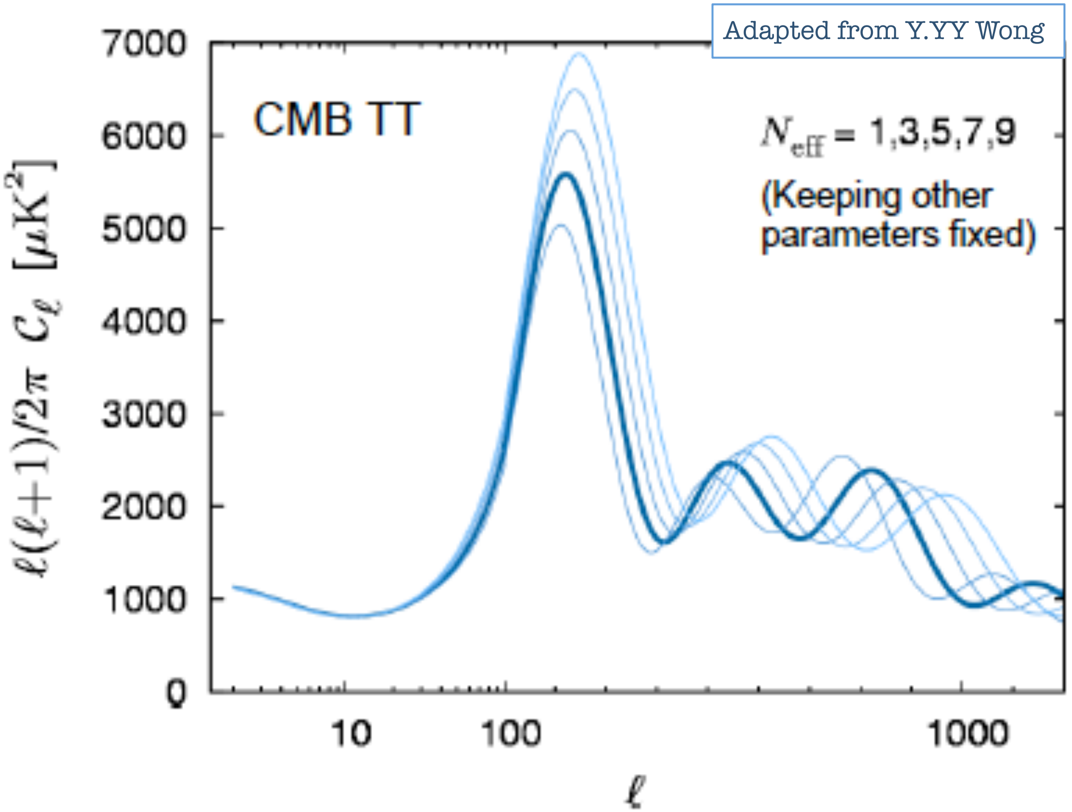
Extra radiation impact on CMB

If additional degrees of freedom are still relativistic at the time of CMB formation, they impact the CMB anisotropies.

Constraints N_{eff} from the CMB Spectrum

(peaks height and position, anisotropic stress (l~ 200), damping tail (l >1000))



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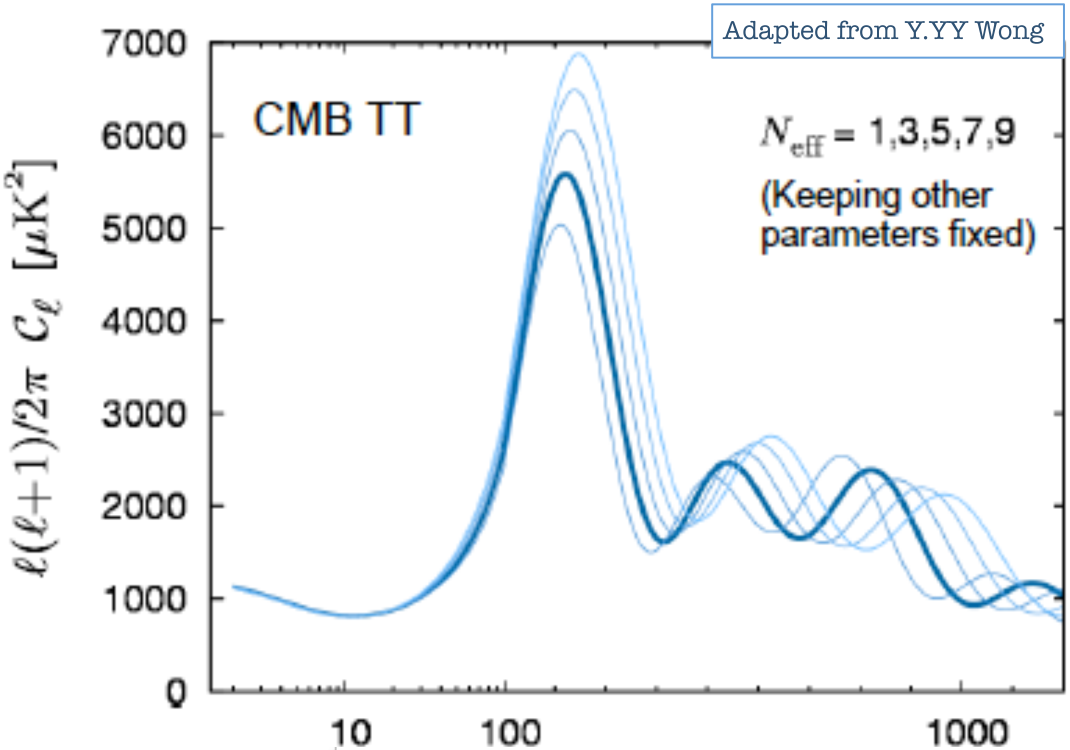


Same data used to measure other cosmological parameters

basic parameters of ΛCDM:

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

+ derived parameters

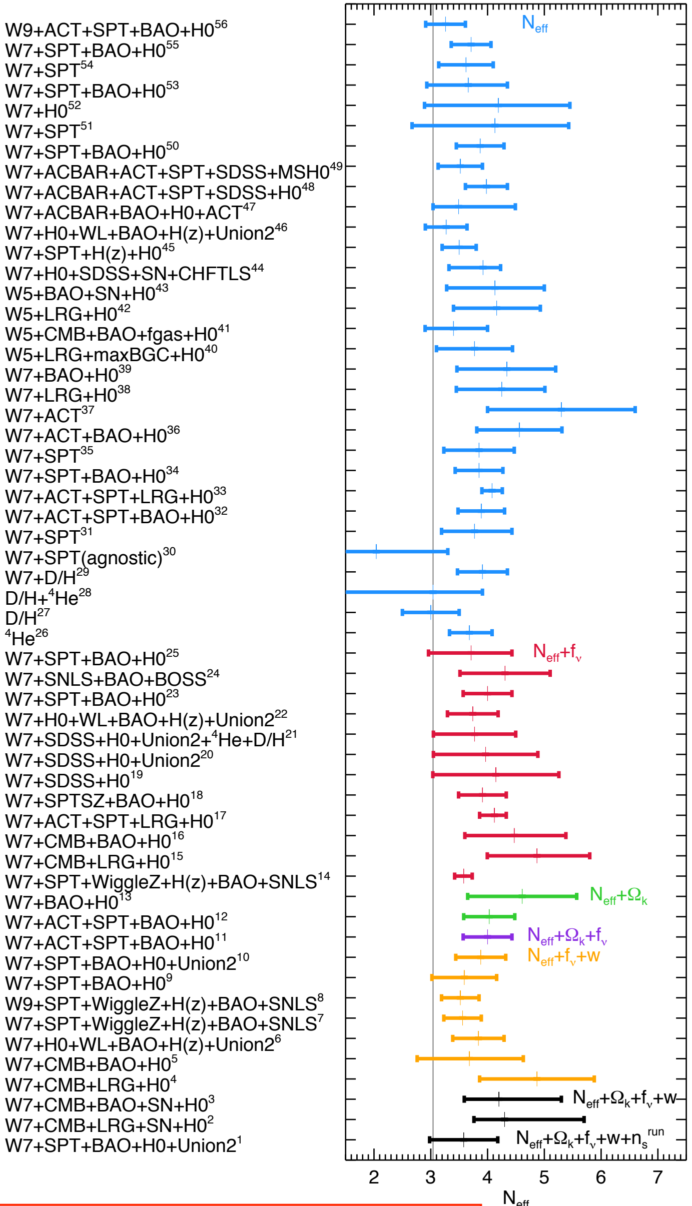
$$(H_0, \Omega_k, \Omega_\Lambda, N_{\rm eff}, \sigma_8, \sum m_\nu,$$

$$z_{re}, Y_p, w, \Omega_m z_{LS} \ldots)$$

→ ***degeneracies***

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

CMB & LSS hints for extra radiation **before Planck**



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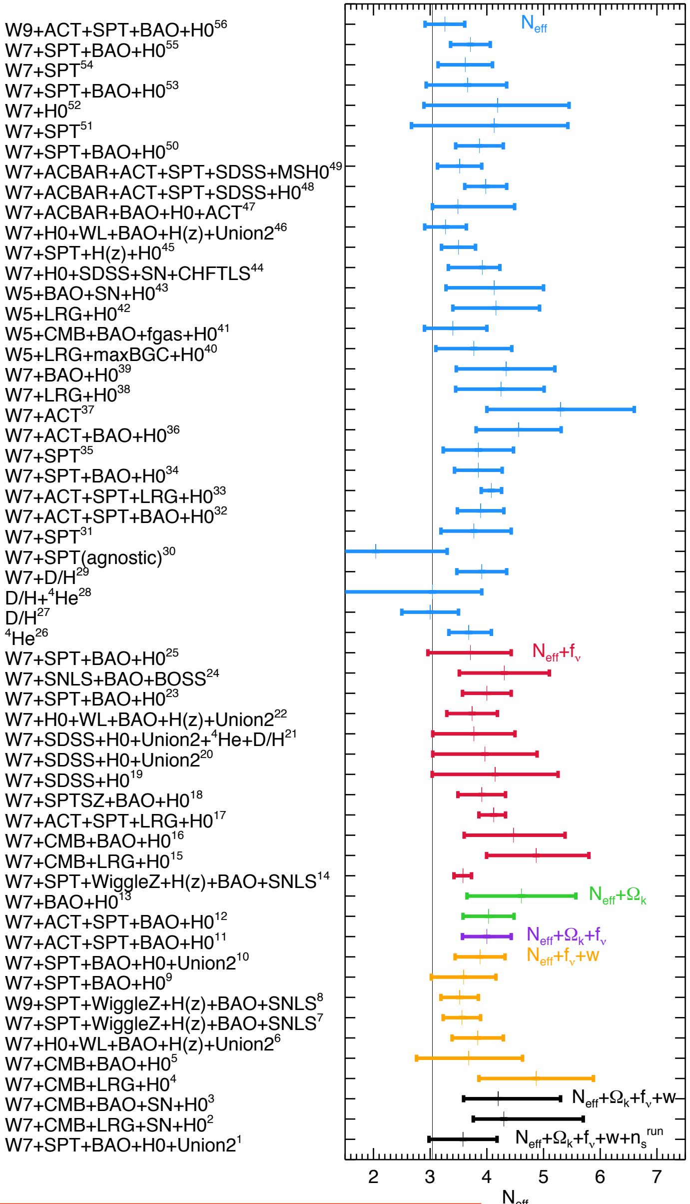

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Summarizing:

CMB (combined)	N_{eff}
WMAP5+ BAO+ H0+SN	4.4 ± 1.5 (68% C.L.)
WMAP7+ BAO+ H0	4.4 ± 0.84 (68% C.L.)
WMAP9+ BAO+ H0+ ACT+ SPT (Y_p fixed)	3.84 ± 0.40 (68% C.L.)

Komatsu et al., 2008,2010

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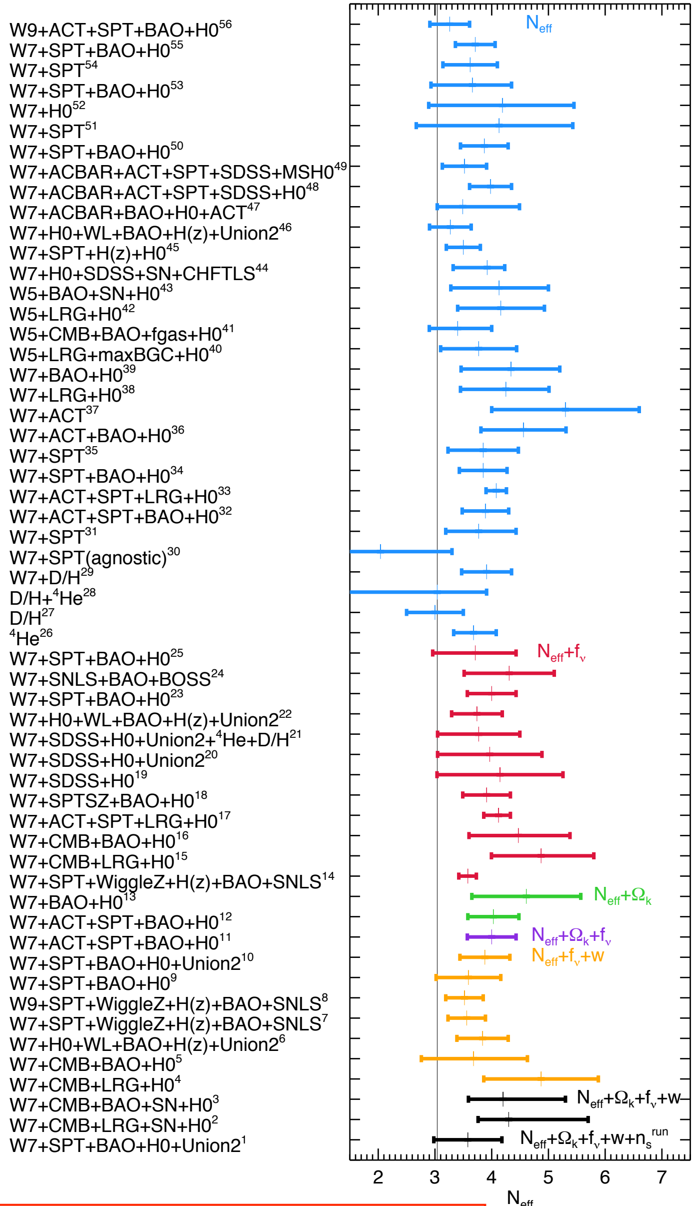

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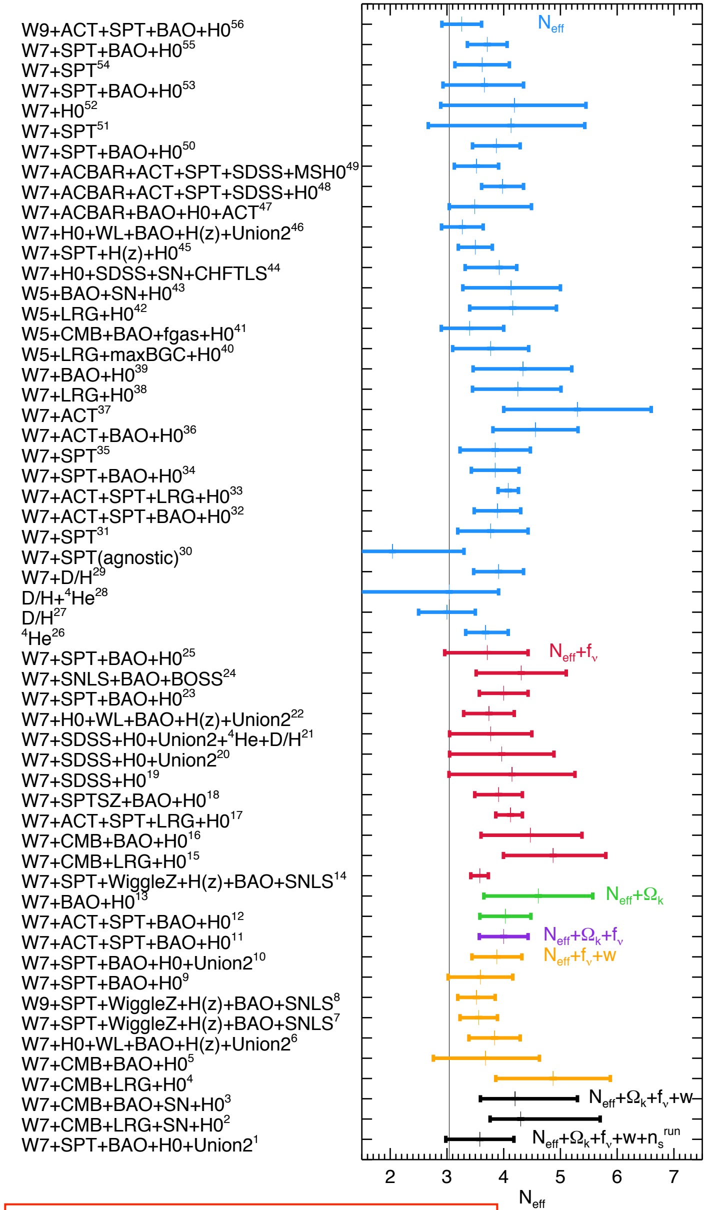

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Hints for extra radiation reduce over the years

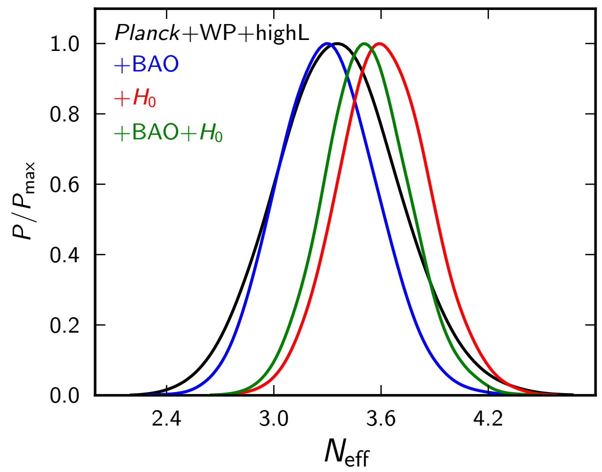
Slight preference for N_{eff} >3.046

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

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

compatible with the standard value at 1-σ

Lesgourgues's talk



Planck XVI, 2013

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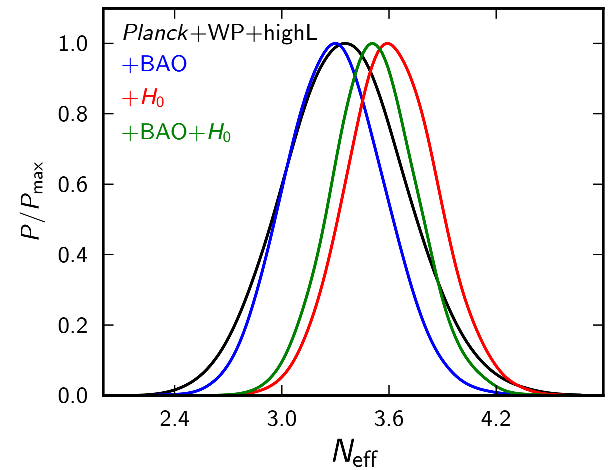

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bounds on ν mass

model	Planck +	mass bound (eV) (95% C.L.)
3 degenerate ν_a	WP+HighL+BAO	$\Sigma m_\nu < 0.23$
Joint analysis N_{eff} & 3 degen ν_a	WP+HighL+BAO	$N_{eff} = 3.32 \pm 0.54$ $\Sigma m_\nu < 0.28$
Joint analysis N_{eff} & 1 mass ν_s	BAO	$N_{eff} < 3.80$ $m^{eff}_{\nu s} < 0.42$

see also E. Giusarma et al. 2013, with clustering data

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

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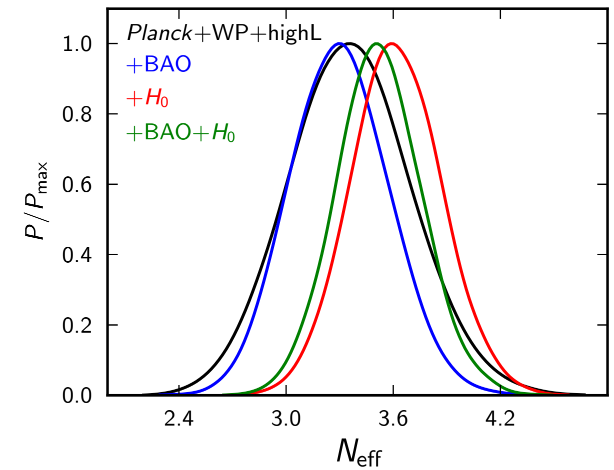

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Active-sterile flavor evolution

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

✳ No primordial sterile neutrinos are present

- Describe the ν ensemble in terms of 4x4 density matrix $\varrho(x,y) = \begin{pmatrix} \varrho_{ee} & \varrho_{e\mu} & \varrho_{e\tau} & \varrho_{es} \\ \varrho_{\mu e} & \varrho_{\mu\mu} & \varrho_{\mu\tau} & \varrho_{\mu s} \\ \varrho_{\tau e} & \varrho_{\tau\mu} & \varrho_{\tau\tau} & \varrho_{\tau s} \\ \varrho_{se} & \varrho_{s\mu} & \varrho_{s\tau} & \varrho_{ss} \end{pmatrix}$

- introduce the dimensionless variables $x \equiv m\ a;\ y \equiv p\ a;\ z \equiv T_\gamma\ a;$

with m = arbitrary mass scale; a= scale factor, a(t) → 1/T

- denote the time derivative $\partial_t \to \partial_t - Hp\,\partial_{\mathbf{p}} = Hx\,\partial_x$, H the Hubble parameter $\overline{H} \equiv \frac{x^2}{m} H$

➢ the EoM become:

$$i\frac{d\varrho}{dx} = +\frac{x^2}{2m^2\,y\,\overline{H}}\,[\mathrm{M}^2,\varrho] + \frac{\sqrt{2}G_F\,m^2}{x^2\,\overline{H}} \times \left[-\frac{8\,y\,m^2}{3\,x^2}\left(\frac{\mathsf{E}_\ell}{m_W^2} - \frac{\mathsf{E}_\nu}{m_Z^2}\right) + \mathsf{N}_\nu,\varrho\right] + \frac{x\,\hat{C}[\varrho(y)]}{m\,\overline{H}}$$

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Vacuum term
with M neutrino mass matrix
$U\,M^2 U^\dagger$

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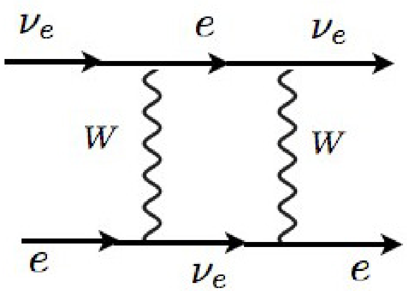
MSW effect with background medium
(refractive effect)

charged lepton asymmetry subleading ($O(10^{-9})$) ➜
➜ 2[th] order term: "symmetric" matter effect
sum of e⁻ - e⁺ energy densities ε
$\mathsf{E}_\ell \equiv \mathrm{diag}(\varepsilon_e, 0, 0, 0)$



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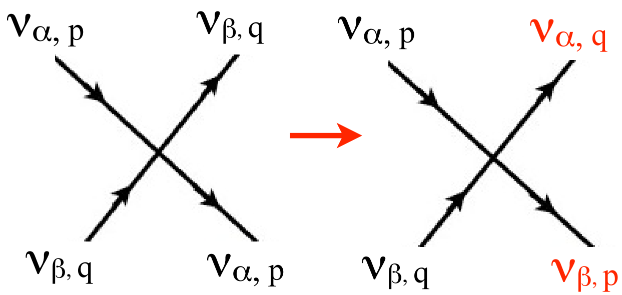
refractive ν–ν term



self-interactions of ν with the ν background:

off-diagonal potentials ➠ non-linear EoM

Sigl and Raffelt 1993;
McKellar & Thomson, 1994
Dolgov et al., 2002.

Active-sterile flavor evolution

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

✳ No primordial sterile neutrinos are present

- Describe the ν ensemble in terms of 4x4 density matrix $\varrho(x,y) = \begin{pmatrix} \varrho_{ee} & \varrho_{e\mu} & \varrho_{e\tau} & \varrho_{es} \\ \varrho_{\mu e} & \varrho_{\mu\mu} & \varrho_{\mu\tau} & \varrho_{\mu s} \\ \varrho_{\tau e} & \varrho_{\tau\mu} & \varrho_{\tau\tau} & \varrho_{\tau s} \\ \varrho_{se} & \varrho_{s\mu} & \varrho_{s\tau} & \varrho_{ss} \end{pmatrix}$

- introduce the dimensionless variables $x \equiv m\ a;\ y \equiv p\ a;\ z \equiv T_\gamma\ a;$

  with m = arbitrary mass scale; a= scale factor, a(t) → 1/T

- denote the time derivative $\partial_t \to \partial_t - Hp\,\partial_{\mathbf{p}} = Hx\,\partial_x$, H the Hubble parameter $\overline{H} \equiv \frac{x^2}{m} H$

➢ the EoM become:

$$i\frac{d\varrho}{dx} = +\frac{x^2}{2m^2\,y\,\overline{H}}\left[\mathsf{M}^2, \varrho\right] + \frac{\sqrt{2}G_F\,m^2}{x^2\,\overline{H}} \times \left[-\frac{8\,y\,m^2}{3\,x^2}\left(\frac{\mathsf{E}_\ell}{m_W^2} - \frac{\mathsf{E}_\nu}{m_Z^2}\right) + \mathsf{N}_\nu, \varrho\right] + \frac{x\,\hat{C}[\varrho(y)]}{m\,\overline{H}}$$

symmetric term

$\propto (\varrho + \overline{\varrho})$

Sigl and Raffelt 1993;
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asymmetric term

$\propto (\varrho - \overline{\varrho}) \leftrightarrow L$

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Collisional term $\propto G_F^2$

creation, annihilation and all the momentum exchanging processes

Sigl and Raffelt 1993;
McKellar & Thomson, 1994
Dolgov et al., 2002.

Bounds on active-sterile mixing parameters after Planck

✔ sterile abundance by flavor evolution of the active-sterile system for 3+1 scenario (to compare with the Planck constraints)

✔ 2 sterile mixing angles (+ 3 active ones) $10^{-5} \leq \sin^2\theta_{i4} \leq 10^{-1}$ (i= 1,2)

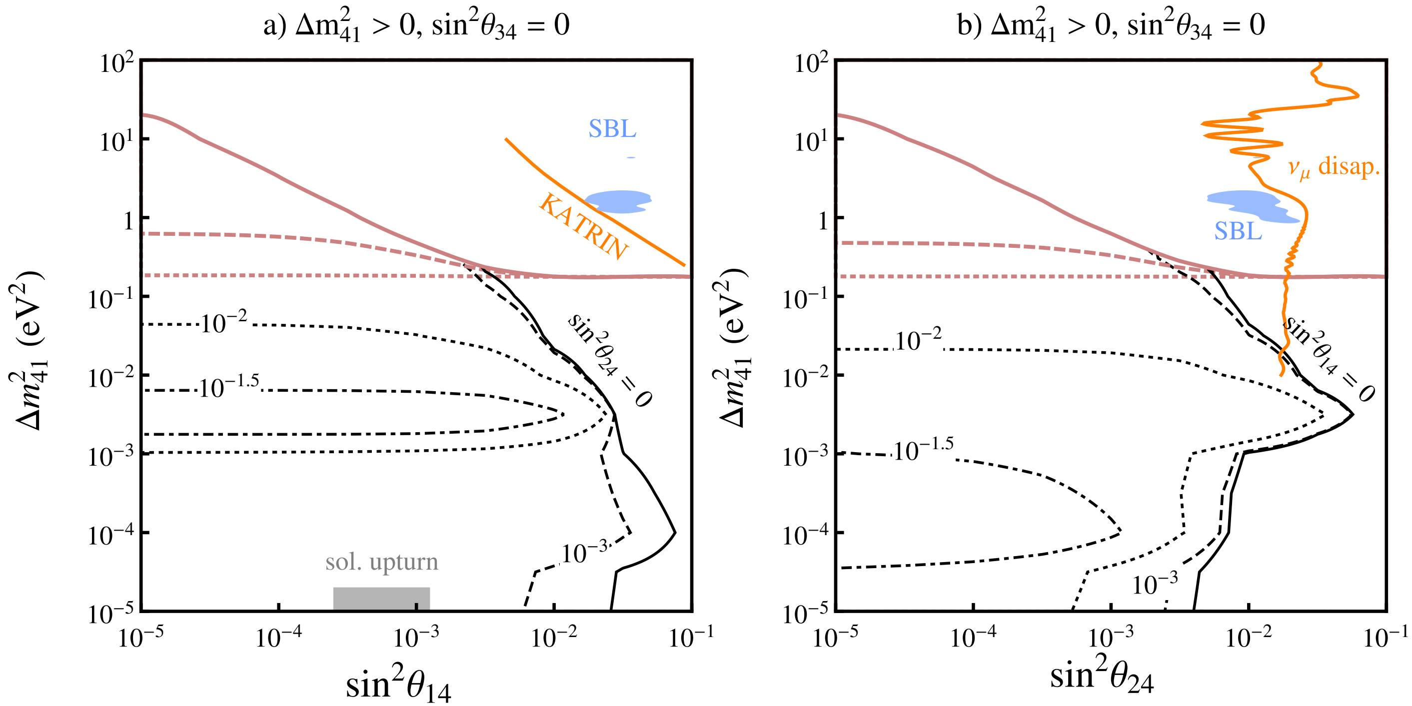
✔ sterile mass-square difference $\Delta m^2_{st} = \Delta m^2_{41}$ (+ 2 active ones) $10^{-5} \leq \Delta m^2_{41}/\text{eV}^2 \leq 10^2$

✔ *average-momentum* approximation (single momentum): $\varrho_{\mathbf{p}}(T) = f_{FD}(p)\rho(T)$ $(\langle p \rangle = 3.15\ T)$

✔ conservative scenario: vanishing primordial neutrino asymmetry

Mirizzi, Mangano, ***N.S****. et al 2013,* arXiv:1303.5368

Bounds on active-sterile mixing parameters after Planck
... our results



Mirizzi et al 2013, arXiv:1303.5368

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

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

Bounds on active-sterile mixing parameters after Planck

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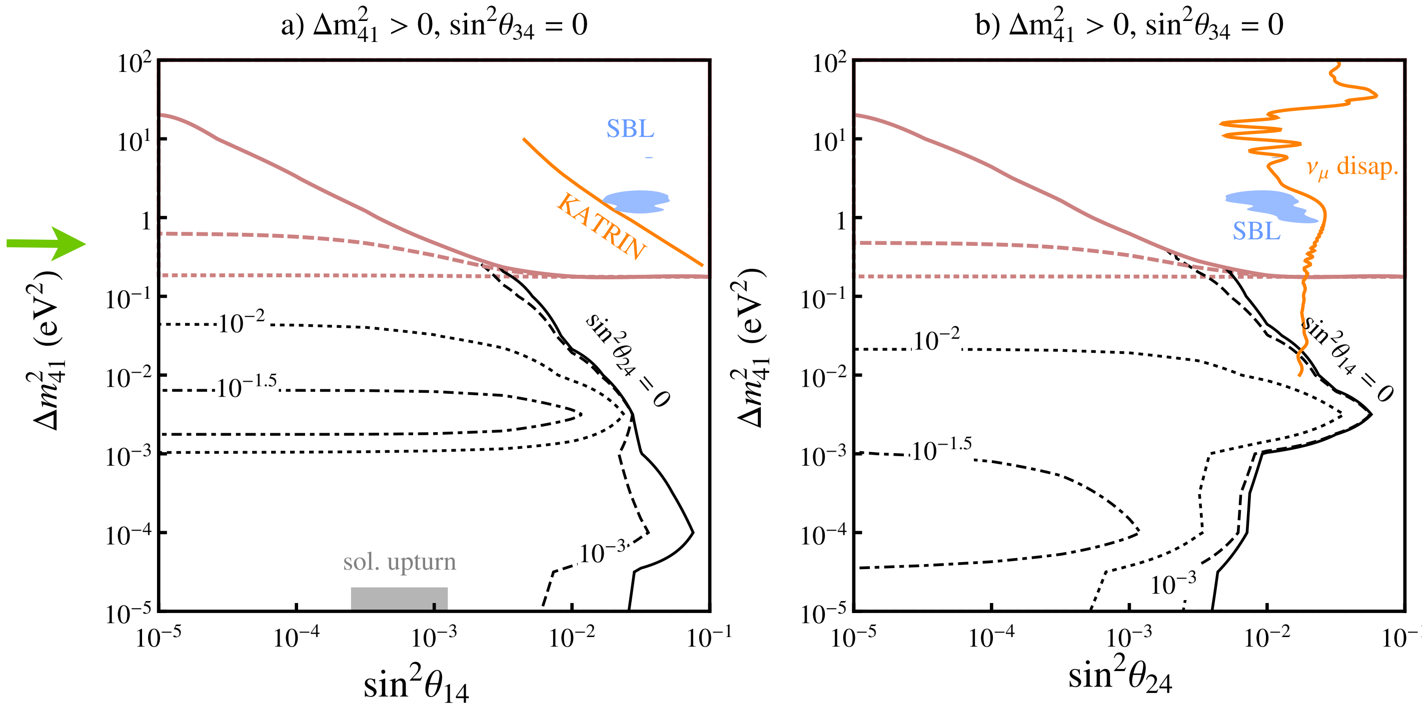

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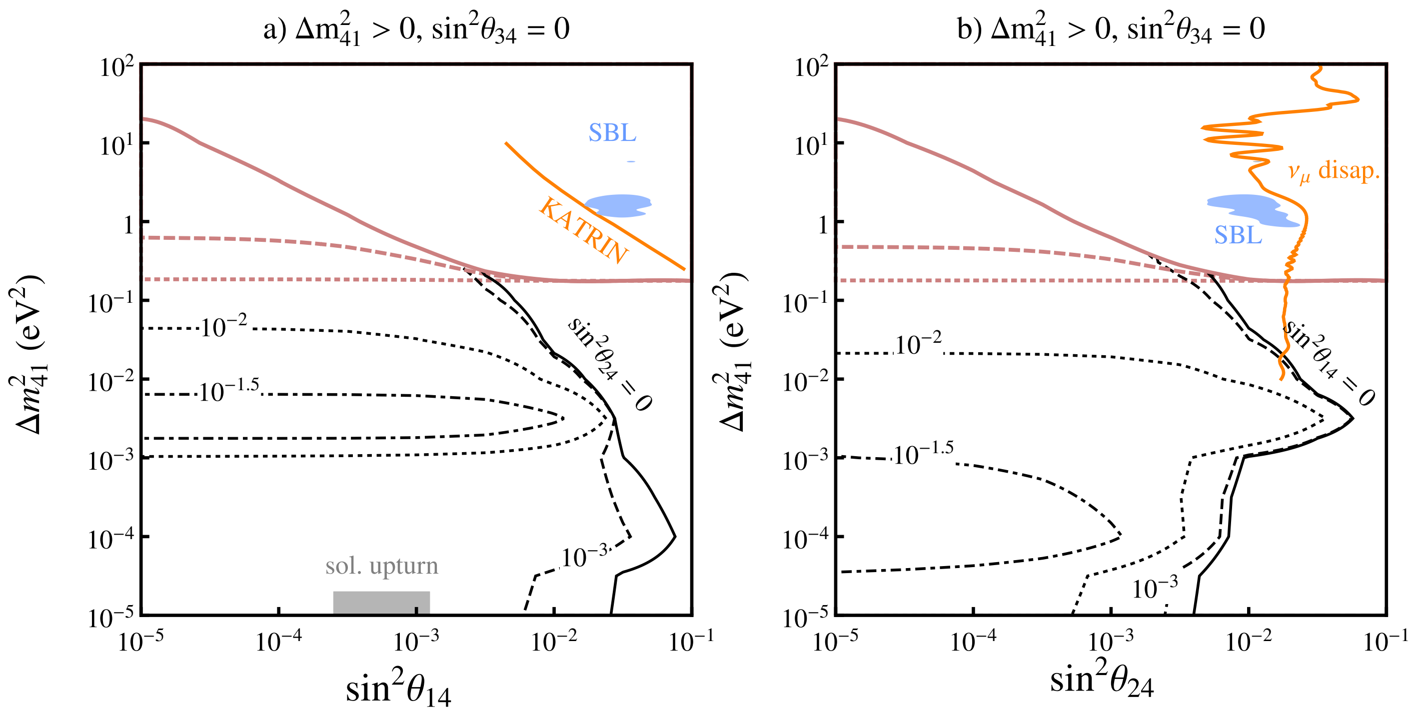
Note: above m ~ $\mathcal{O}$(1 eV), sterile ν are not relativistic anymore at CMB → **NO radiation constraint**

BUT mass constraints become important

Bounds on active-sterile mixing parameters after Planck

... our results



Mirizzi et al 2013, arXiv:1303.5368

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

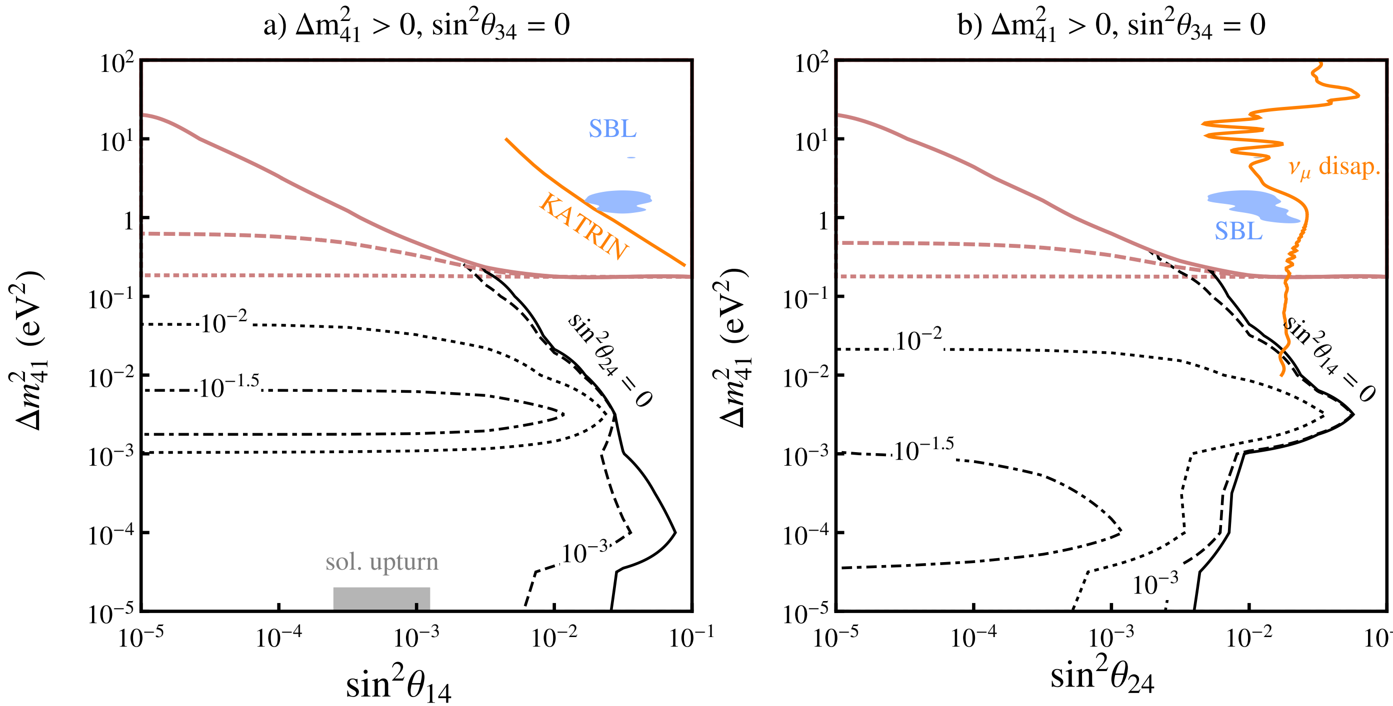
The excluded regions are those on the right or at the exterior of the black contours.

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

The excluded regions are those above the red contours.

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

Bounds on active-sterile mixing parameters after Planck ... our results



Mirizzi et al 2013, arXiv:1303.5368

The sterile neutrino parameter space is severely constrained.
Excluded area from the ***mass bound*** *covers the region accessible by current and future laboratory experiments.*
Remarkably, ***sterile ν with m ~ $\mathcal{O}$(1 eV) strongly disfavoured***

Extra radiation vs laboratory sterile neutrino

The mass and mixing parameters preferred by experimental anomalies $\Delta m^2 \sim O\,(1\ \mathrm{eV}^2)$ and $\theta_s \sim O\,(0.1)$ lead to the production and **thermalization** of ν_s (i.e., $\Delta N = 1, 2$) in the Early Universe via ν_a-ν_s oscillations + ν_a scatterings

Barbieri & Dolgov 1990, 1991
Di Bari, 2002
Melchiorri et al 2009

in the "standard" scenarios, thermalized eV lab-sterile ν are ***incompatible*** with cosmological bounds

– 3+2: Too ***many*** for BBN (3+1 minimally accepted) and for CMB

– 3+1: Too ***heavy*** for LSS/CMB → $m_s < 0.5$ eV (at 95% C.L)

versus lab best-fit $m_s \sim 1$ eV

It is possible to find an escape route to reconcile sterile ν's with cosmology?

A possible answer: primordial neutrino asymmetry

Foot and Volkas, 1995

Introducing $L = \frac{n_\nu - n_{\bar{\nu}}}{n_\gamma}$ → *Suppress the thermalization of sterile neutrinos* (ρ_{ss} ↓)

(Effective ν_a-ν_s mixing reduced by large matter term $\propto L$)

Caveat : L can also generate MSW-like resonant flavor conversions among active and sterile neutrinos enhancing their production

A lot of work has been done in this direction…

Enqvist et al., 1990, 1991,1992; Foot, Thomson & Volkas, 1995;Bell, Volkas & Wong, 1998; Dolgov, Hansen, Pastor & Semikoz, 1999;Di Bari & Foot, 2000; Di Bari, Lipari and lusignoli , 2000;Kirilova & Chizhov, 2000; Di Bari, Foot, Volkas & Wong, 2001; Dolvgov & Villante, 2003; Abazajian, Bell, Fuller, Wong, 2005; Kishimoto, Fuller, Smith, 2006; Chu & Cirelli, 2006; Abazajian & Agrawal, 2008; Hannestad et al, 2012

... very often adopting severe approximations

… looking for the right L

Our approach: beyond most approximations

In order to *properly* determine the sterile neutrino abundance, we follow the flavor evolution of the active-sterile system in presence of different primordial neutrino asymmetries L for *3+1* and *2+1* scenarios in :

✓ **Average (or single) momentum approximation**

✓ **Multi-momentum treatment**

Few remarks:

- L dynamically evolved during the flavor evolution
- Evolution for both neutrino and antineutrino channel
- in **multi-flavor system** all active neutrinos can mix with the sterile, allowing to explore effects not possible in a simplified scenario "1+1".

Best-fit parameters in the active and sterile sectors

Global 3 ν oscillation analysis, in terms of best-fit values

Parameter	Best fit
$\delta m^2/10^{-5}$ eV^2 (NH or IH)	7.54
$\sin^2\theta_{12}/10^{-1}$ (NH or IH)	3.07
$\Delta m^2/10^{-3}$ eV^2 (NH)	2.43
$\Delta m^2/10^{-3}$ eV^2 (IH)	2.42
$\sin^2\theta_{13}/10^{-2}$ (NH)	2.41
$\sin^2\theta_{13}/10^{-2}$ (IH)	2.44
$\sin^2\theta_{23}/10^{-1}$ (NH)	3.86
$\sin^2\theta_{23}/10^{-1}$ (IH)	3.92
δ/π (NH)	1.08
δ/π (IH)	1.09

Fogli et al., 2012

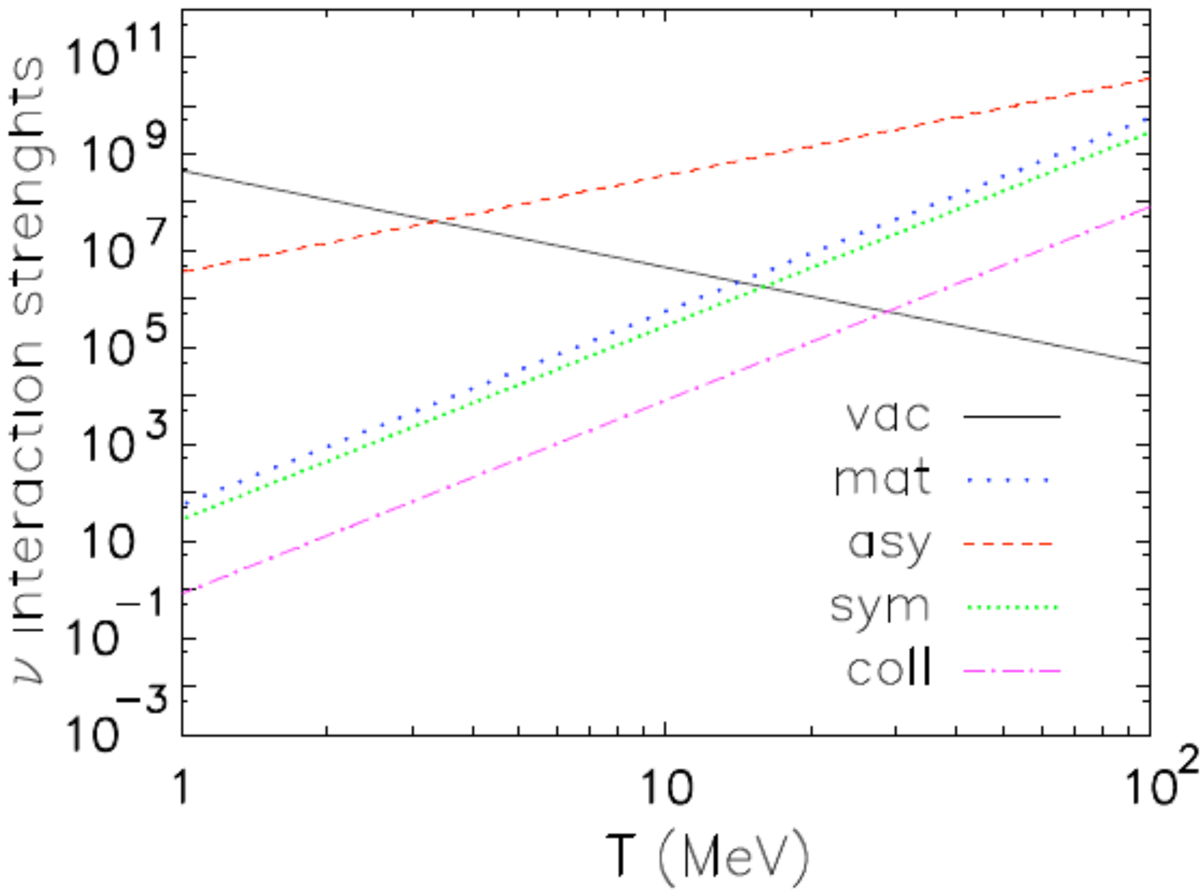
Best-fit values of the mixing parameters in 3+1 fits of short-baseline oscillation data.

	3+1
$\chi^2_{\rm min}$	100.2
NDF	104
GoF	59%
Δm^2_{41} [eV^2]	0.89
$\|U_{e4}\|^2$	0.025
$\|U_{\mu4}\|^2$	0.023
Δm^2_{51} [eV^2]	
$\|U_{e5}\|^2$	
$\|U_{\mu5}\|^2$	
η	
$\Delta\chi^2_{\rm PG}$	24.1
NDF$_{\rm PG}$	2
PGoF	6×10^{-6}

τ-s sector undetermined

Giunti and Laveder, 2011

Strength of the different interactions



*Mirizzi, **N.S.**, Miele, Serpico 2012*
arXiv:1206.1046

$L = -10^{-4}$

(kept constant)

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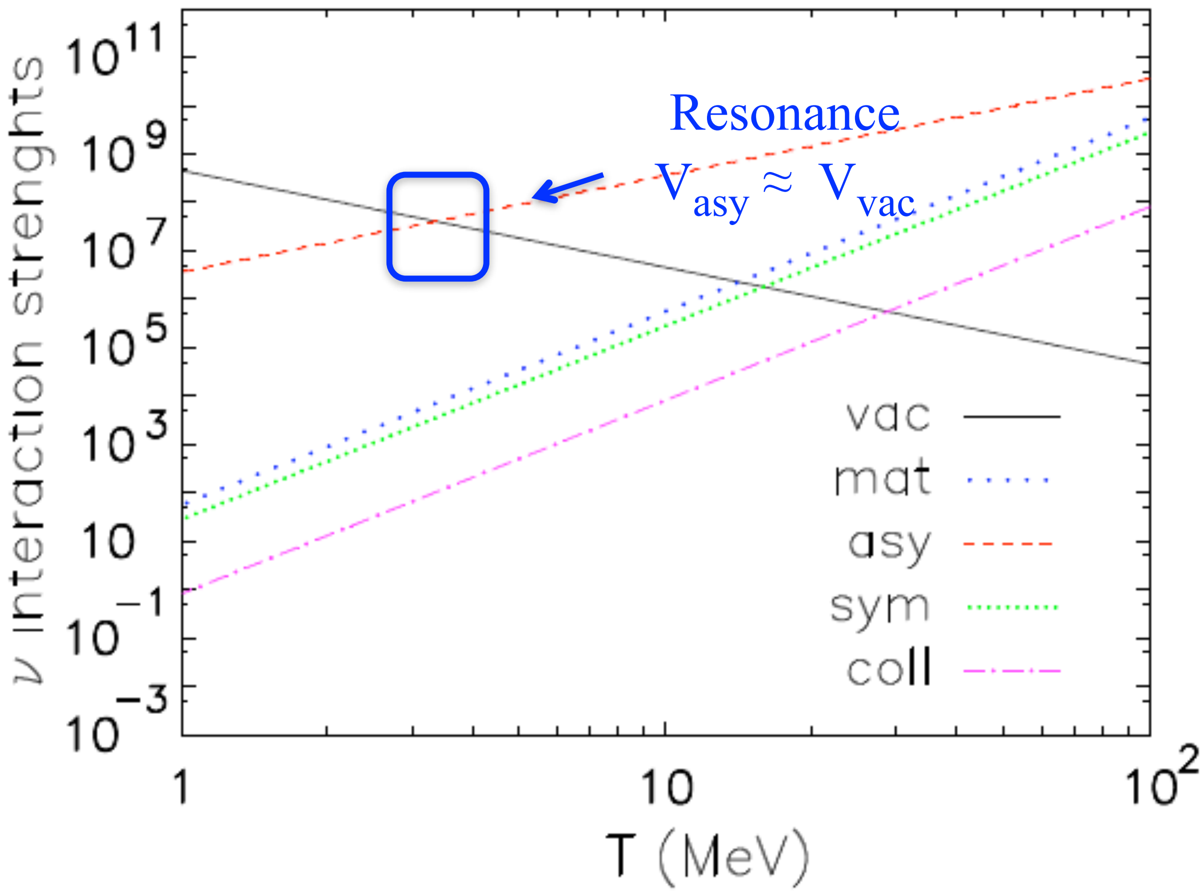

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$L = -10^{-4}$
(kept constant)

MSW effect on ν-ν asymmetric interaction term (V_{asy}) → ***resonant sterile ν production***

- For L < 0 → resonance occurs in the anti– ν channel
- For L > 0 → resonance occurs in the ν channel

Due to it's dynamical nature , L changes sign → resonances in both ν and $\overline{\nu}$ channels

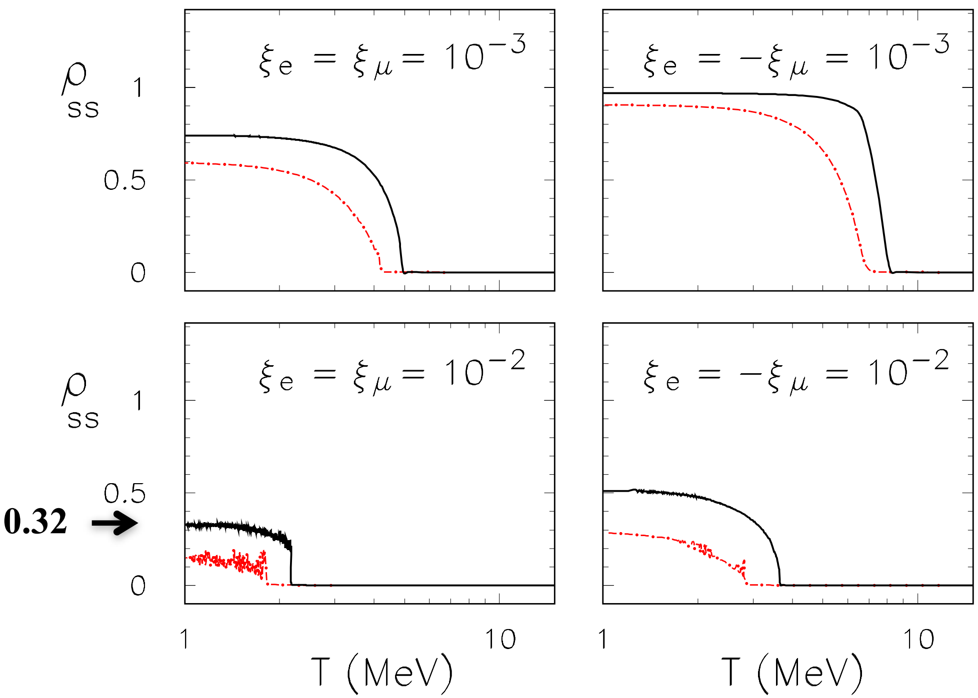
Multi-momentum treatment

✓ Compute N_{eff} and possible 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 ⟶ study in (2+1) scenario and for few representative cases

Saviano et al, 2013; arXiv:1302.1200

Results:



— multi-momentum $\rho_{ss}(x) = \frac{\int dy \; y^2 \varrho_{ss}(x,y)}{\int dy \; y^2 f_{\mathrm{eq}}(y,0)}$

— single-momentum

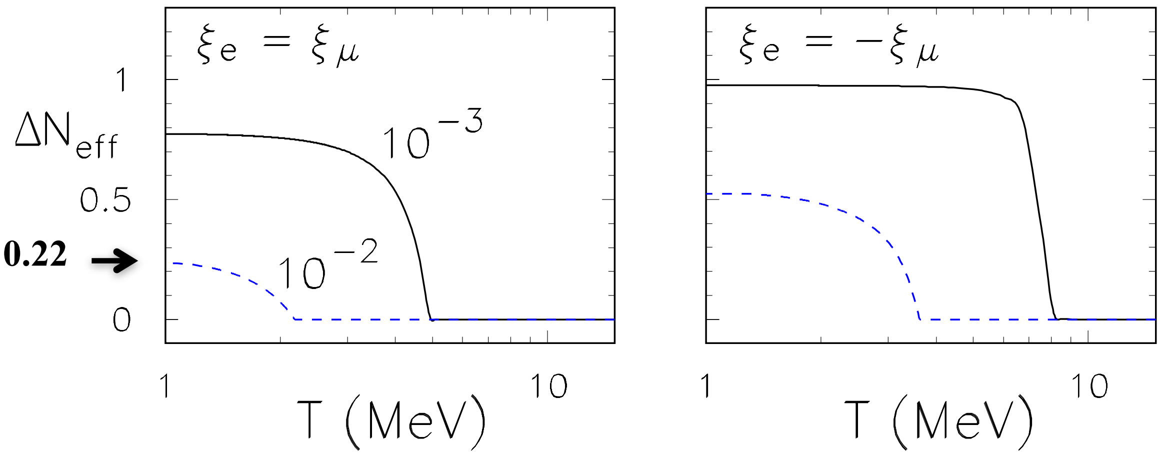
Enhancement of the sterile production with respect to the single-momentum approx.

$$L_\alpha = \frac{1}{12\zeta(3)} \left(\frac{T_\nu}{T_\gamma}\right)^3 (\pi^2 \xi_\alpha + \xi_\alpha^3) \simeq 0.68 \; \xi_\alpha \left(\frac{T_\nu}{T_\gamma}\right)^3$$

N_{eff} *from multi-momentum treatment*

✓ Compute N_{eff} as function of the ν ***asymmetry parameter***

looking at the extra contribution $\Delta N_{\mathrm{eff}} = \frac{60}{7\pi^4}\int dy\; y^3 \mathrm{Tr}[\varrho(x,y)+\bar{\varrho}(x,y)] \;-2$



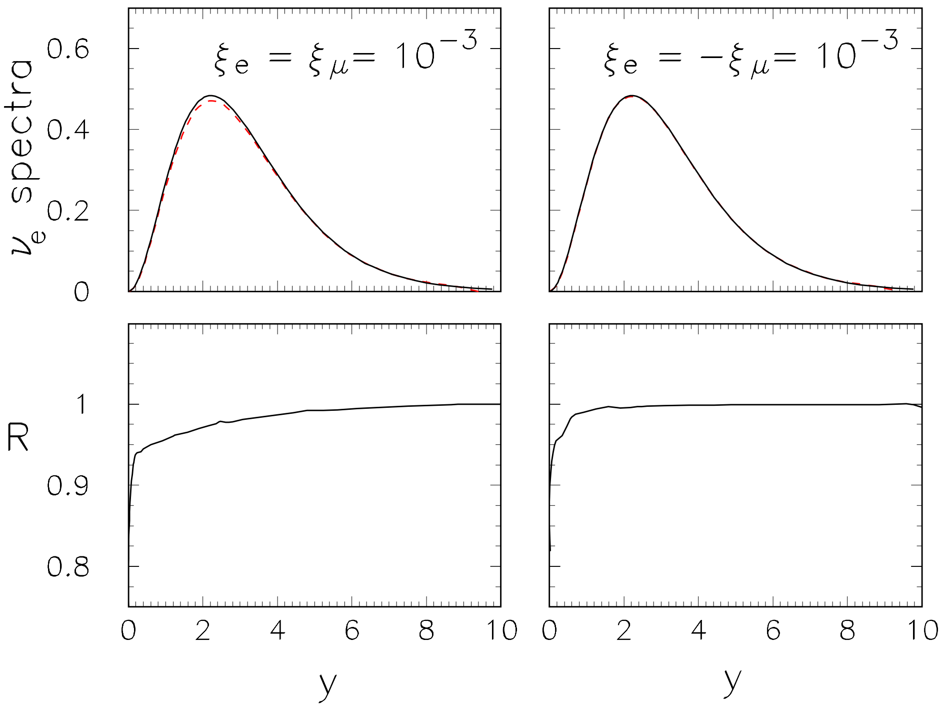
Case	ΔN_{eff}	$\Delta N_{\mathrm{eff}}^{\langle y \rangle}$
$\lvert\xi\rvert \ll 10^{-3}$	1.0	1.0
$\xi_e = -\xi_\mu = 10^{-3}$	0.98	0.89
$\xi_e = \xi_\mu = 10^{-3}$	0.77	0.51
$\xi_e = -\xi_\mu = 10^{-2}$	0.52	0.44
$\xi_e = \xi_\mu = 10^{-2}$	0.22	0.04

Enhancement at most of 0.2 of unity for ΔN with respect to the single-momentum approx.

One needs to consider very large asymmetries in order to significantly suppress the production of sterile neutrinos.

see also *Hannestad, Tamborra and Tram, 2012*

Spectral distortions

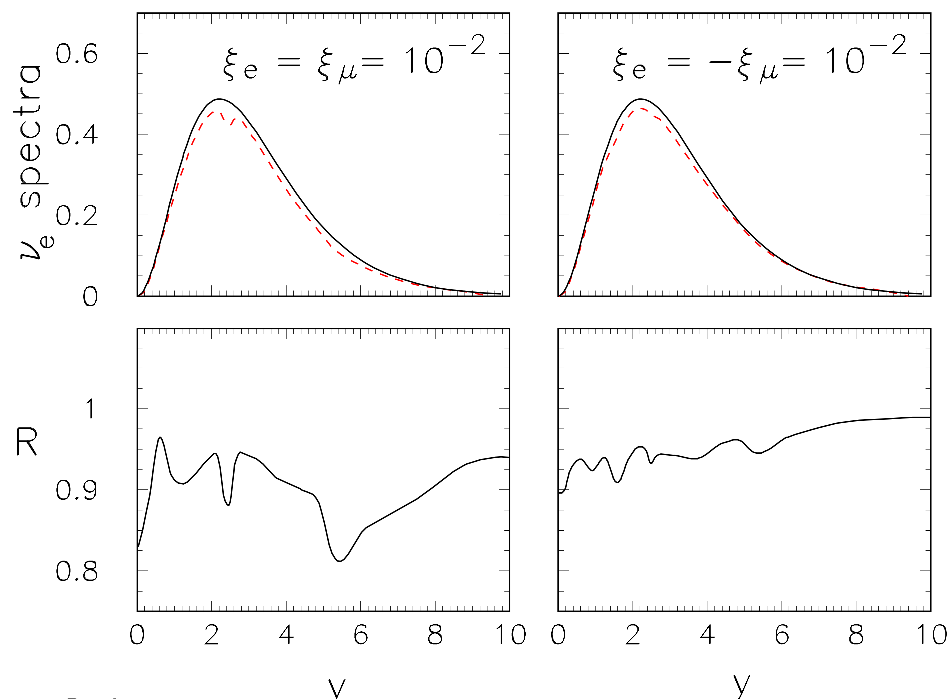


— $y^2 \rho_{ee}(y)$

— $y^2 f_{eq}(y, \xi_e)$

$\xi_\nu = \mu_\nu / T$

$$R = \frac{\varrho_{ee}(y)}{f_{eq}(y, \xi_e)}$$



Sizable distortions (especially for $\xi = 10^{-2}$)

→ consequences on primordial yields

Saviano et al, 2013; arXiv:1302.1200

Non-trivial implications on BBN

Saviano et al, 2013;
arXiv:1302.1200

Case	$\Delta N_{\rm eff}$	$\Delta N_{\rm eff}^{\langle y \rangle}$	Y_p	^{2}H/H ($\times 10^5$)
$\lvert\xi\rvert \ll 10^{-3}$	1.0	1.0	0.259	2.90
$\xi_e = -\xi_\mu = 10^{-3}$	0.98	0.89	0.257	2.87
$\xi_e = \xi_\mu = 10^{-3}$	0.77	0.51	0.256	2.81
$\xi_e = -\xi_\mu = 10^{-2}$	0.52	0.44	0.255	2.74
$\xi_e = \xi_\mu = 10^{-2}$	0.22	0.04	0.251	2.64
$\xi_e = \lvert\xi_\mu\rvert = 10^{-3}$, no ν_s	~ 0	–	0.246	2.56
$\xi_e = \lvert\xi_\mu\rvert = 10^{-2}$, no ν_s	~ 0	–	0.244	2.55
standard BBN	0	0	0.247	2.56

PArthENoPE code. *Pisanti et al, 2008*

$$Y_p = \frac{2(n/p)}{1+n/p}$$

Helium mass fraction

Non-trivial implications on BBN

Saviano et al, 2013;
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Deuterium mainly sensitive to the increase of $N_{\rm eff}$

Helium 4 sensitive both to
- increase of $N_{\rm eff}$
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The effect of the ν_s on BBN due only the increase of $N_{\rm eff}$

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The effect of the ν_s on Y_p due mainly to changes in weak interactions after spectral distortions

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asymmetry + ν_s

Y_p ↑

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Y_p ↓

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asymmetry + ν_s

Y_p ↑

asymmetry

Y_p ↓

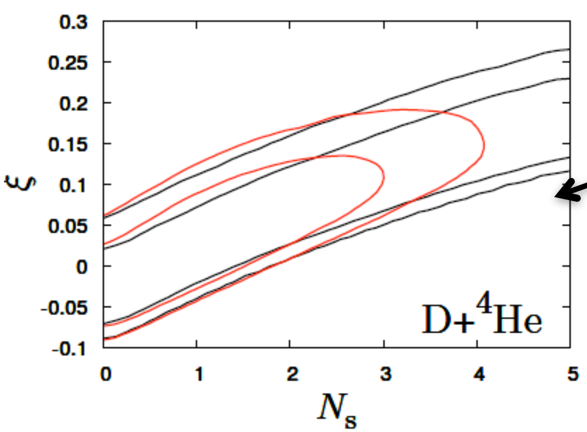
PArthENoPE code. *Pisanti et al, 2012*

Comment 1

- Standard BNN allows at most 1 ν_s for the parameter chosen

Original idea: degenerate BBN (large chemical potential) to accommodate more ν_s

for very large positive ξ, $n/p = \exp\left(-\frac{\Delta m}{T} - \xi\right)$ ↓ ⇨ Y_p ↓



Positive correlation between the increase of ξ and $N_{\rm eff}$

Hamman et al., 2011

Non-trivial implications on BBN

Case	$\Delta N_{\rm eff}$	$\Delta N_{\rm eff}^{\langle y \rangle}$	Y_p	^{2}H/H ($\times 10^5$)
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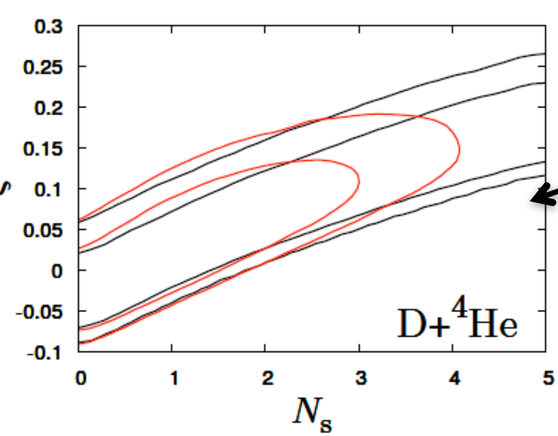

Positive correlation between the increase of ξ and $N_{\rm eff}$

Hamman et al., 2011

not possible

if the ν_s is treated properly

Non-trivial implications on BBN

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asymmetry

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PArthENoPE code. *Pisanti et al, 2012*

Comment 2

The increase of Y_p can be mimicked by both large an low value of $N_{\rm eff}$

Possible inconsistency in the value of $N_{\rm eff}$ as extracted from CMB and form BBN

Conclusions

- ✓ Current precision cosmological data show a very slight preference for extra relativistic degrees of freedom (beyond 3 active neutrinos)… Planck: $N_{\rm eff} = 3.30 \pm 0.54$

- ✓ ν_s interpretation of extra radiation: ***mass and mixing parameters severely constrained***, solving the non-linear EOM for ν_a-ν_s oscillations in a 3+1 scenario.
  - ✓ Laboratory eV sterile neutrinos ***incompatible (> 4-σ)*** with cosmological bounds: *too many and too heavy*

- ✓ A possibility to reconcile cosmological and laboratory data would be the introduction of a neutrino asymmetry ($L \geq 10^{-2}$) to suppress the sterile abundance in the Early Universe.

- ✓ However, $L \sim 10^{-2}$ lead to sizable distortions of ν_e and $\overline{\nu}_e$ spectra that are basic input for BBN weak rates → ***non trivial implication on BBN***

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If lab ν_s would be confirmed → new physics in the particle sector and also radical modification of the standard cosmological model.

Surprises could still emerge from the interplay between cosmology and lab searches of sterile ν

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. $D + p \rightarrow {}^3He + \gamma$
4. $D + D \rightarrow {}^3He + n$
5. $D + D \rightarrow {}^3H + p$
6. ${}^3H + D \rightarrow {}^4He + n$
7. ${}^3H + {}^4He \rightarrow {}^7Li + \gamma$
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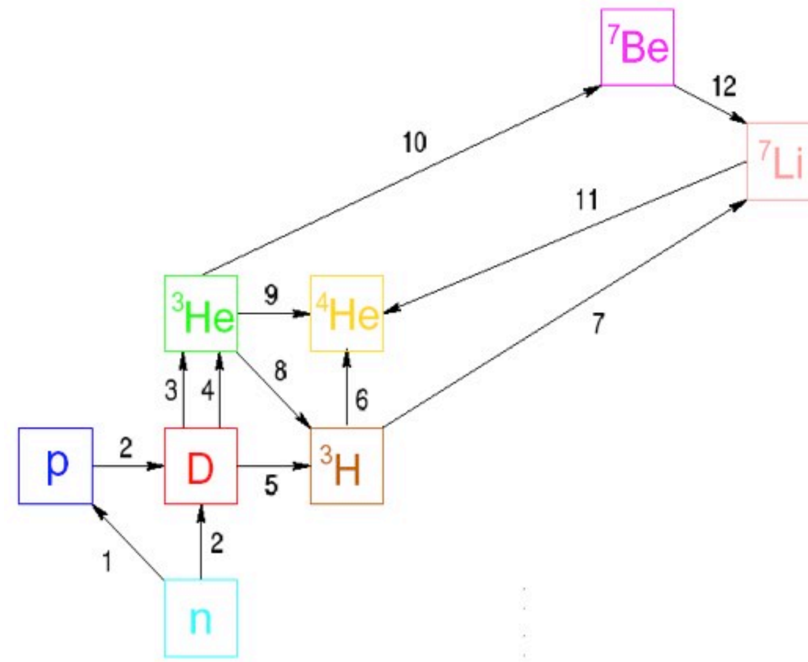
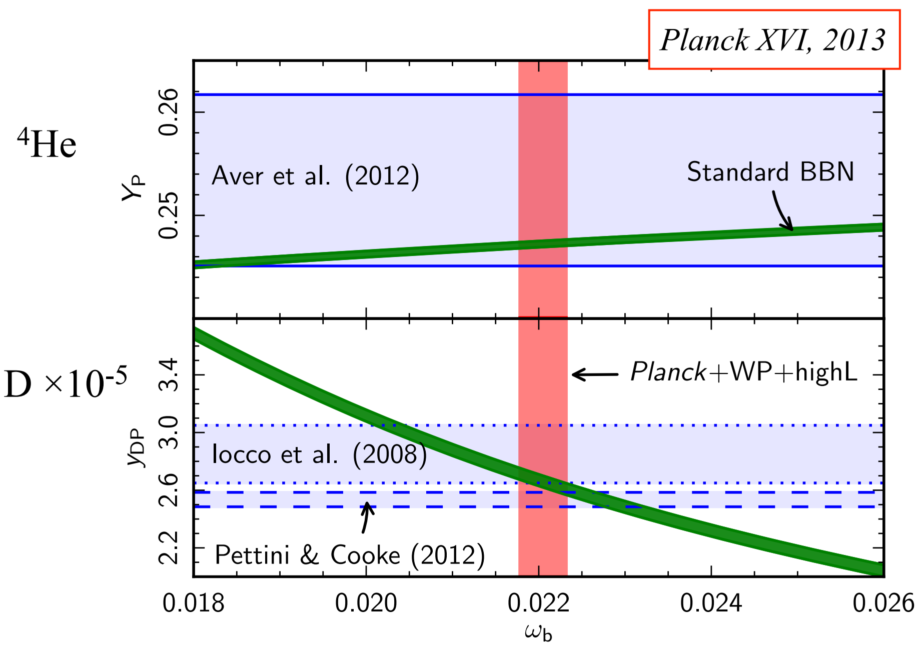
12. ${}^7Be + n \rightarrow {}^7Li + p$





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

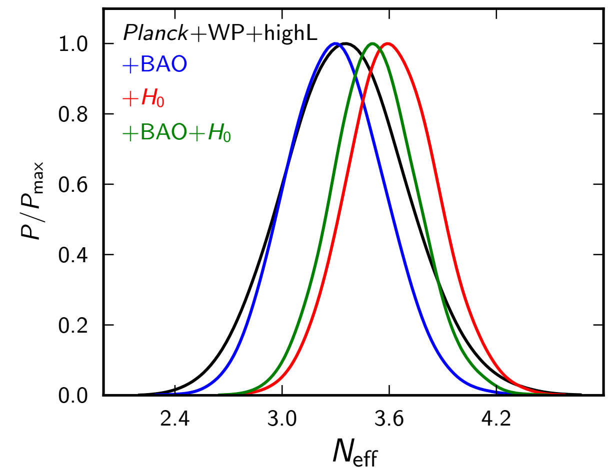
Blue regions: primordial yields from measurements performed in different astrophysical environments

$\omega_b = 0.02207 \pm 0.00027$

$N_{\rm eff}$ *and* Σm_ν *constraints* after Planck

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

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

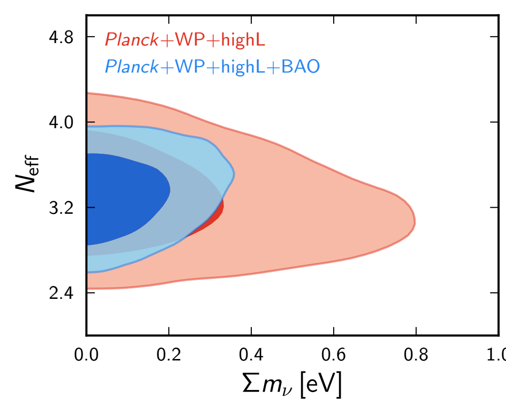


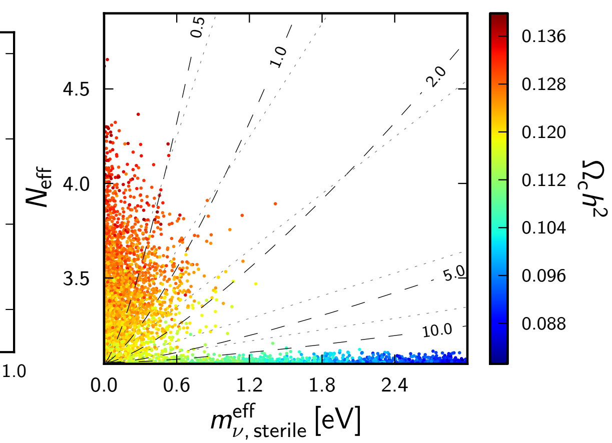
Planck XVI, 2013

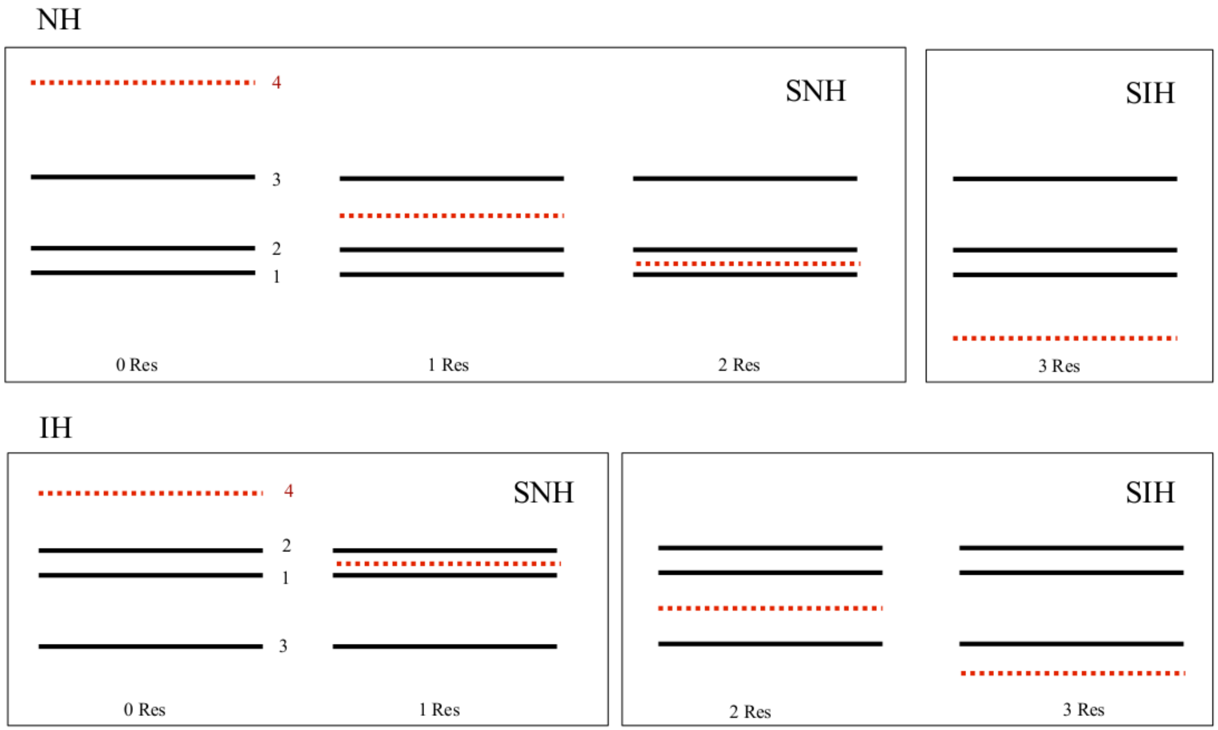
bounds on ν mass

model	Planck +	mass bound (eV) (95% C.L.)
3 degenerate ν_a	WP+HighL +BAO	$\Sigma m_\nu < 0.23$
Joint analysis $N_{\rm eff}$ & 3 degen ν_a	WP+HighL +BAO	$N_{\rm eff} = 3.32 \pm 0.54$ $\Sigma m_\nu < 0.28$
Joint analysis $N_{\rm eff}$ & 1 mass ν_s	BAO	$N_{\rm eff} < 3.80$ $m^{\rm eff}_{\nu s} < 0.42$

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







Scheme of possible resonances

The matter terms can induce MSW-like resonances when they become of the same order of the sterile mass splittings

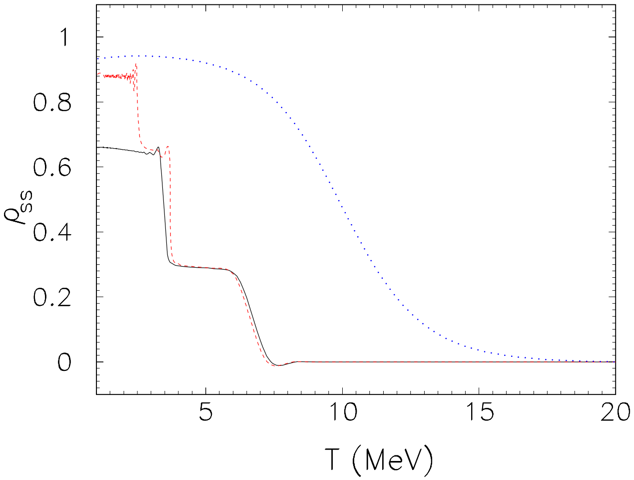
Resonances are associated with the three different active-sterile mass splittings Δm^2_{4i} and with the different θ_{i4} mixing angles.

Evolution of sterile density component ρ_{ss} for 3 sterile mass splitting

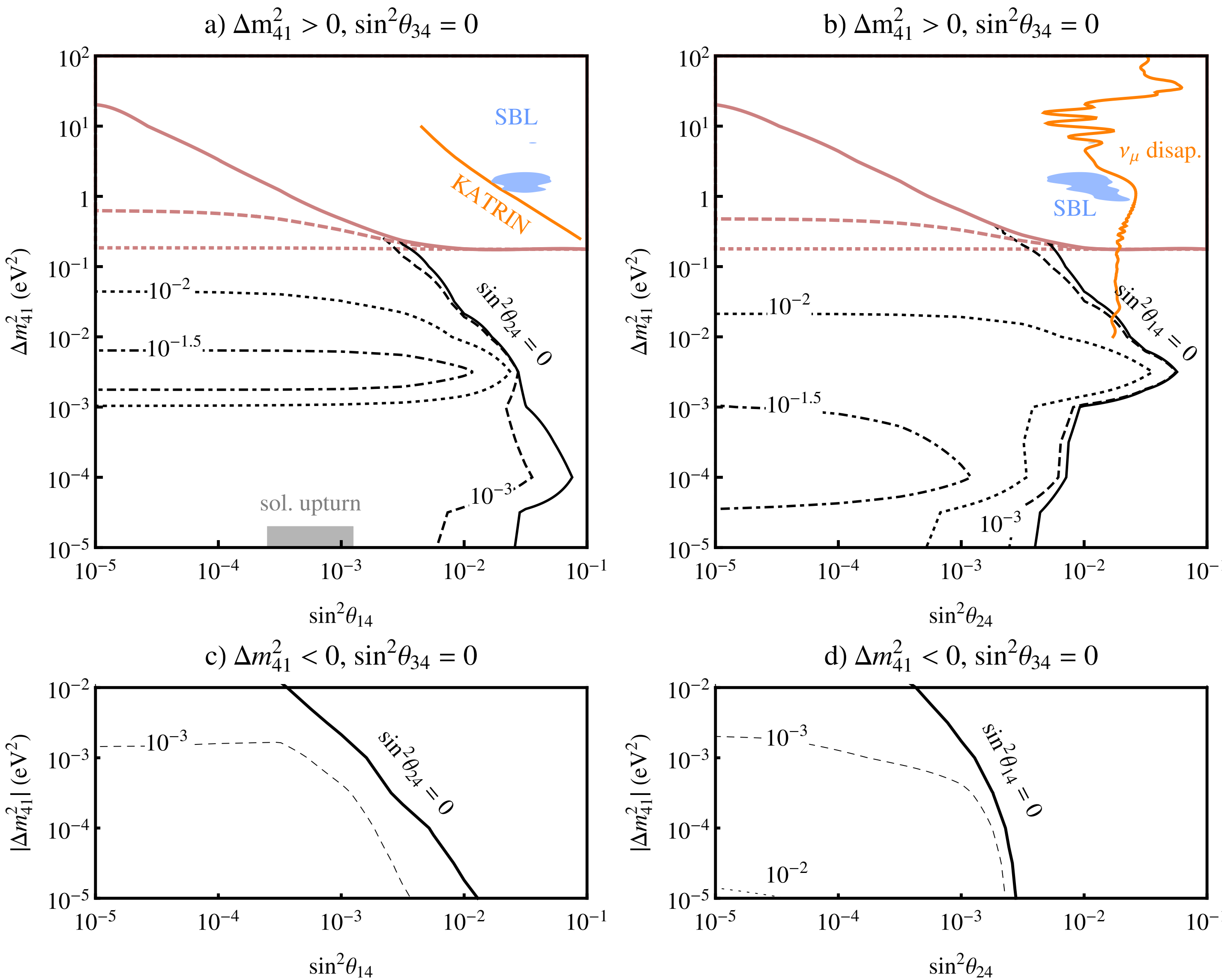
$\Delta m^2_{41} = 10^{-5}$ eV^2

$\Delta m^2_{41} = -10^{-5}$ eV^2

$\Delta m^2_{41} = 5 \times 10^{-2}$ eV^2



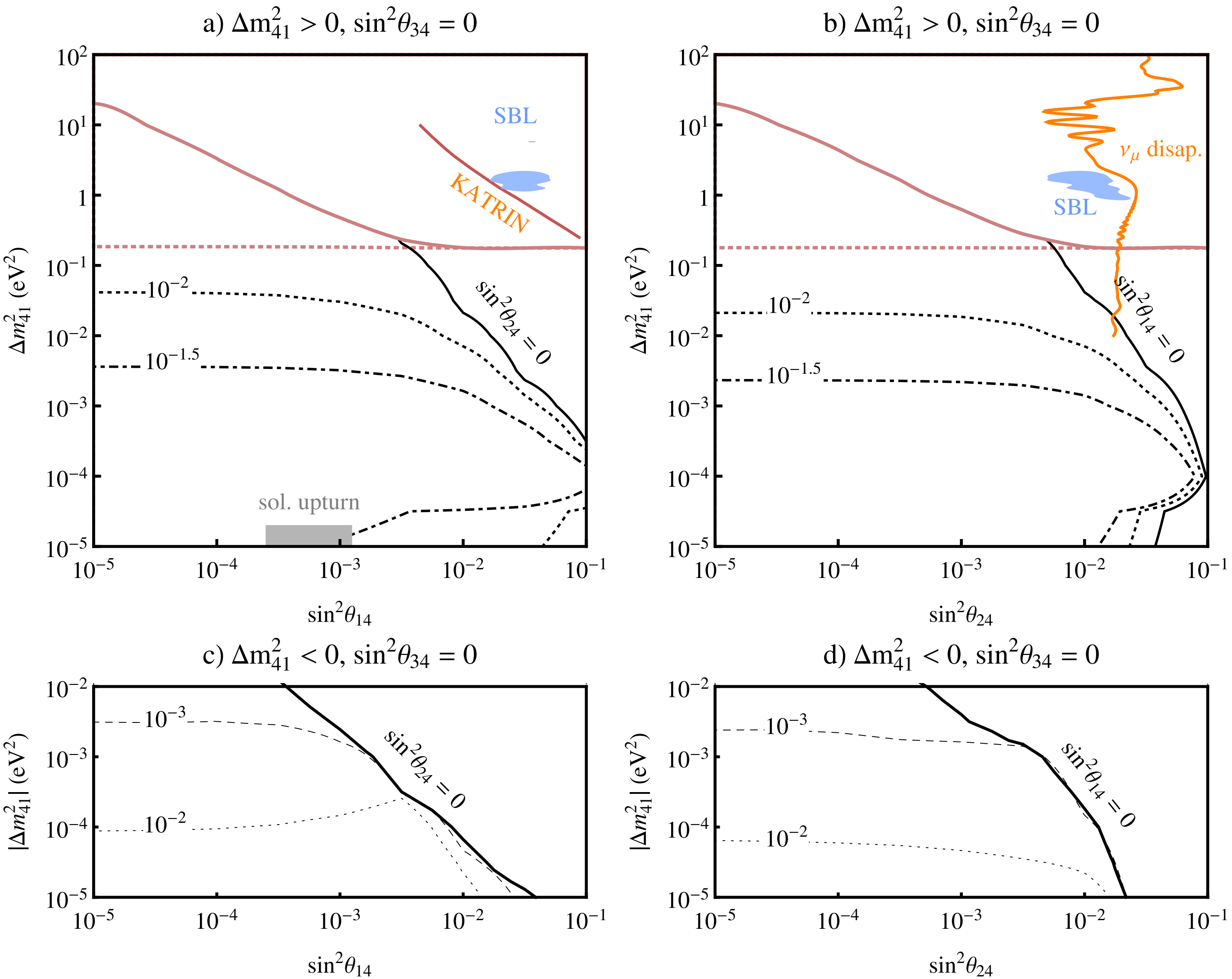
Active NH



Sterile NH

Sterile IH

Active IH

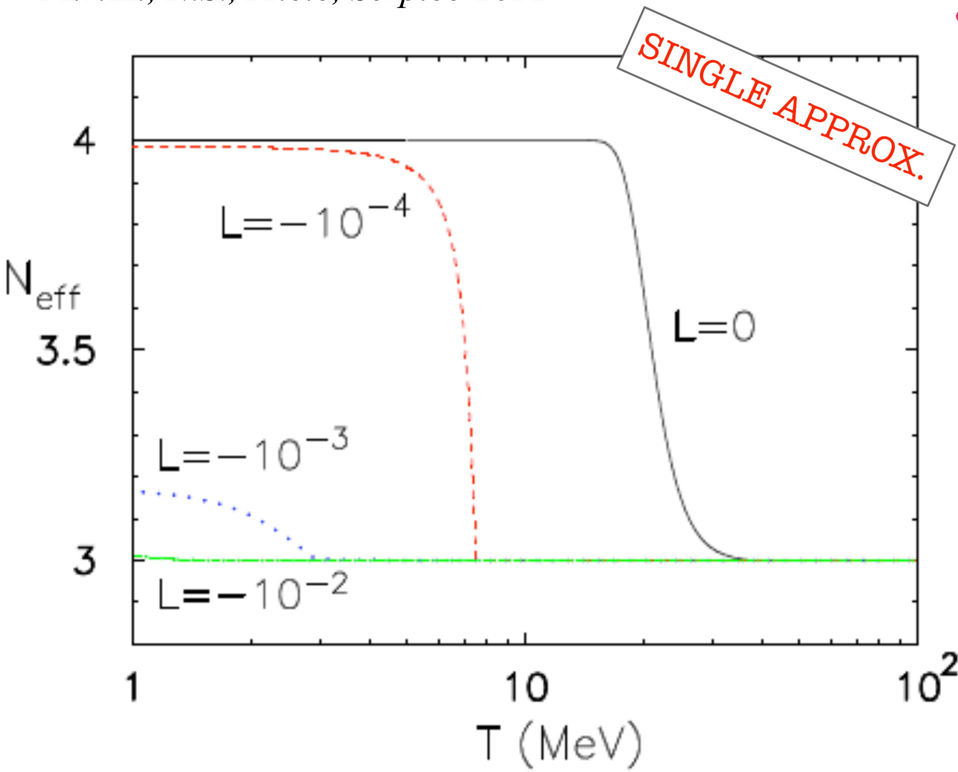


Sterile NH

Sterile IH

Consequences on N_{eff}

Mirizzi, N.S., Miele, Serpico 2012



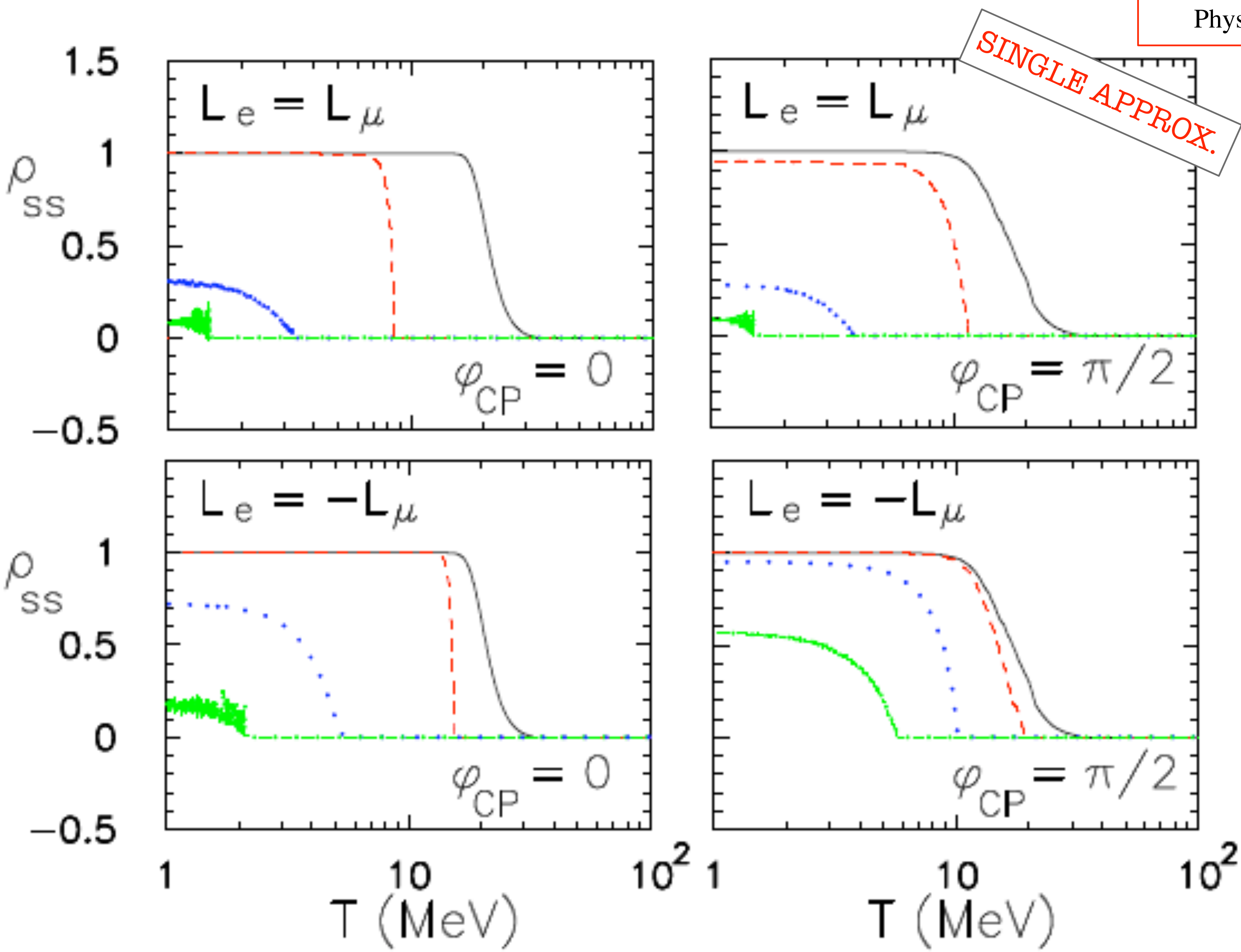
- $|L| \leq 10^{-4}$, ν_s fully populated and the ν_a repopulated by collisions → $N_{eff} \sim 4$
  → tension with cosmological mass bounds (and with BBN data)
- $|L| = 10^{-3}$, ν_s produced close to ν-decoupling ($T_d \sim$2-3 MeV) where ν_a less repopulated → effect on N_{eff} less prominent.
- $L > 10^{-2}$, no repopulation of ν_a
  → negligible effect on N_{eff} even if ν_s slightly produced.

Attention:

The lack of repopulation of ν_e, in presence of very large asymmetries, would produce distorted distributions, which can anticipate the n/p freeze-out and hence modify the ^{4}He yield → **Possible impact on the BBN** (Multi-momentum treatment necessary!)

2 + 1 Scenario

Mirizzi, N.S., Miele, Serpico 2012
Phys. Rev. D 86, 053009



L~10^{-3} conservative limit → Suppression crucially depends on the scenario considered

Asymmetry in the 3 active scenario

- Flavor oscillations (effective before BBN) lead to (approximate) global flavor equilibrium. The restrictive BBN bound on the electron asymmetry applies to all flavors

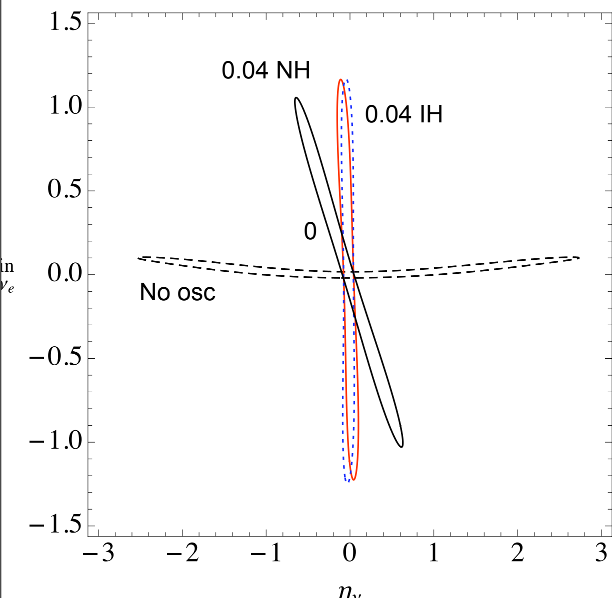
- θ_{13} fixes the onset of flavor oscillations involving ν_e ⟶ crucial to establish the degree of equilibration of flavor ν asymmetries in the Early Universe.

Pastor, Pinto & Raffelt , 2009

Mangano et al., 2011 & 2012

Castorina et al., 2012

- From BBN bound for a range of initial flavor neutrino asymmetries
  → N_{eff} compatible with the standard value $N_{eff} \leq 3.2$

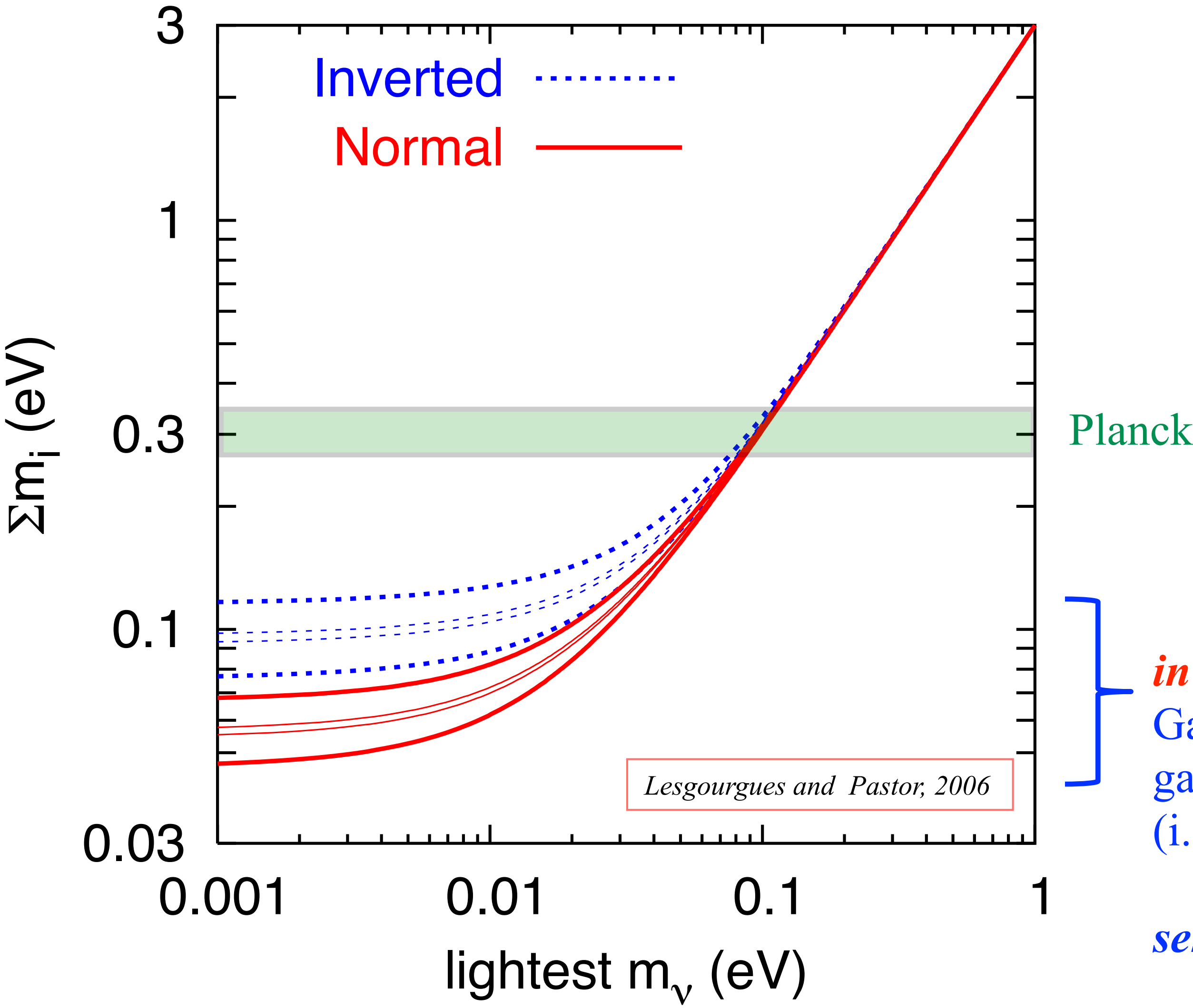


no oscillations:
the value of η_{ν_e} is severely constrained by ^{4}He, while the asymmetry for other flavors could be much larger.

with oscillations:
an initially large $\eta^{in}_{\nu e}$ can be compensated by an asymmetry in the other flavors with opposite sign →bounds applied then to the total asymmetry → ***rotation*** of the allowed region

Note: BBN data still rules and fixes the value of neutrino asymmetry even in presence of CMB and neutrino mass data

Castorina et al., 2012



in future....

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

sensitivity < 0.1

Non-trivial implications on BBN

Saviano et al, 2013;
arXiv:1302.1200

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The effect of the ν_s on Y_p due to the combination of $N_{\rm eff}$ and spectral distortions

PArthENoPE code. *Pisanti et al, 2008*

Deuterium mainly sensitive to the increase of $N_{\rm eff}$

Helium 4 sensitive both to

- increase of $N_{\rm eff}$
- changes in the weak rates due to the spectral distortions