IFAE, 9-11 April 2013

Neutrinos in Cosmology after Planck

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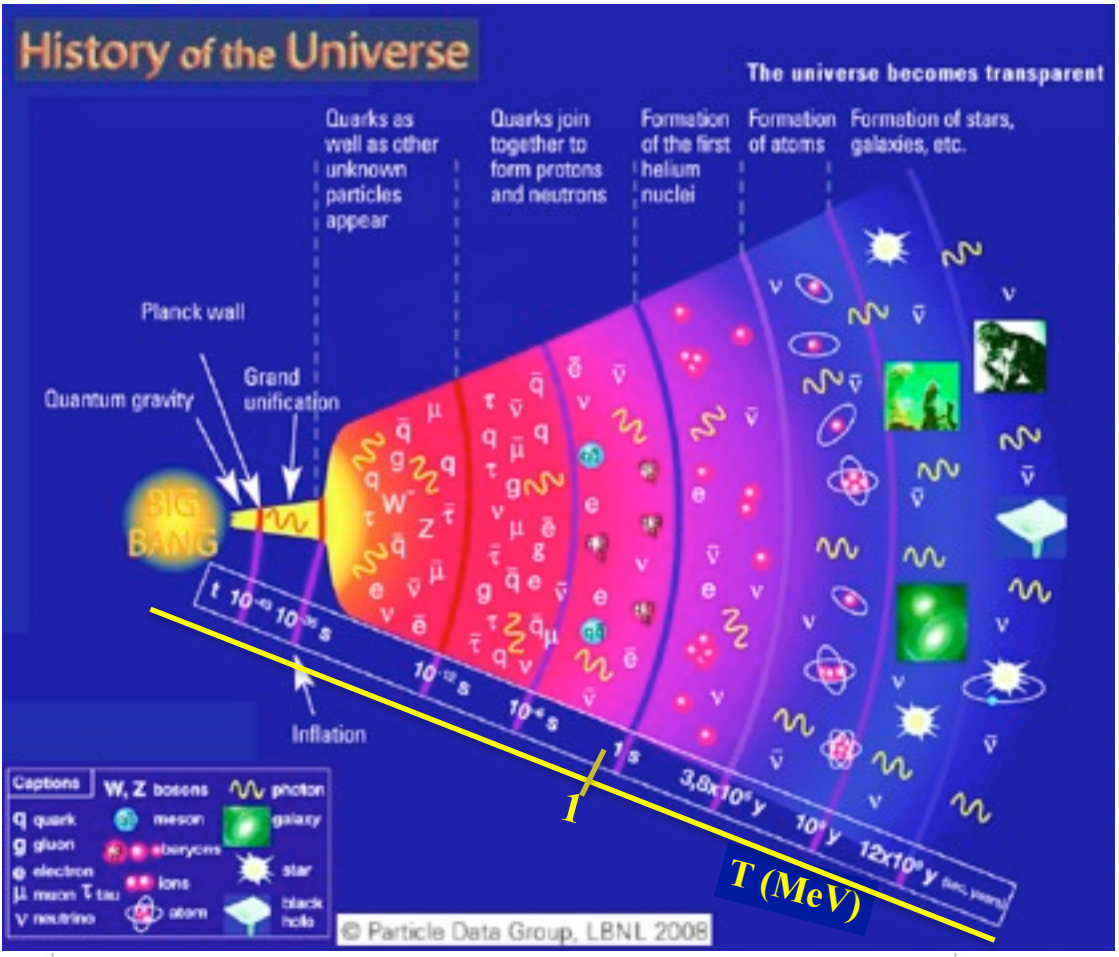
ν in the Early Universe



- $T \gg 1$ MeV ⇛ ν's are populated (and reach a thermal distribution) by weak interactions

- $T_d \sim 1$ MeV (1 sec): $\Gamma_{WK}(T_d) = H(T_d)$

ν decoupling by weak interactions with the primordial plasma → CNB (Cosmic Neutrino Background)

Relic ν are very abundant, not detected yet but established by cosmological observables at different epochs:
the CNB contributes to radiation at early times and to matter at late times

BBN	CMB	LSS
T~ 0.8 MeV	T < eV	
ν flavor sensitivity	ν mass sensitivity	
N_{eff}	N_{eff}	

- Thermal distribution: $T_\nu = 1.95$ K
- Number density ($\nu + \bar{\nu}$): 112 cm^{-3}/*flavor*
- Mean kinetic energy: << meV
- Energy density (m >T): $\Omega_\nu h^2 = \frac{\sum_i m_i}{94.1 \text{ eV}}$

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 $N_{\rm eff}$

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

$N_{\rm eff}^{\rm SM} = 3.046$ *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

$\Delta N =$ 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...

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 ^{2}H, ^{3}He, ^{4}He, ^{7}Li.

When $\Gamma_{n\leftrightarrow p} < H$ ➜ *neutron-to- proton ratio* $\frac{n_n}{n_p} = \frac{n}{p} = e^{-\Delta m/T}$ *freezes out*

$1/7$ including neutron decays

This ratio fixes the primordial yields, especially the ^{4}He abundance characterized by $\boxed{Y_p = \frac{2n/p}{1+n/p}}$

Helium mass fraction

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Cosmological ν influence the production of primordial light elements:

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

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

changes in the their energy spectra shift the T_{FO} ➪ modification in the primordial yields

i.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 H before and during BBN

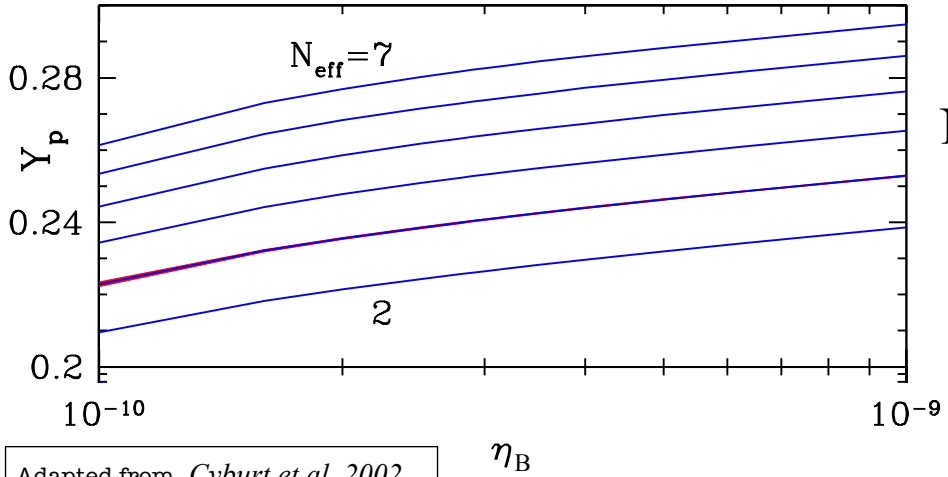
$$H = \frac{\dot{a}}{a} = \sqrt{\frac{8\pi G_N \epsilon_R}{3}}$$

$\propto N_{\rm eff}$

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*

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

Upper limit on N_{eff} from constrains on primordial yields of D and ^{4}He: $\Delta N_{eff} \leq 1$ (at 95% C.L)

Mangano and Serpico. 2012

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

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

Hamann et al, 2011

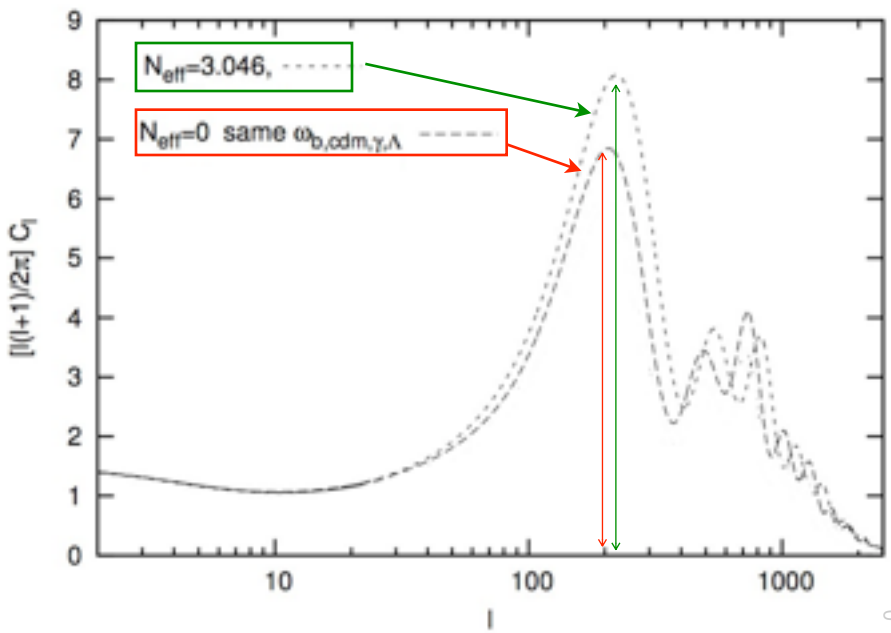
From a measurement of D in a particle astrophysical system:

$N_{eff} = 3.0 \pm 0.5$

Pettini and Cooke, 2013

ν and CMB and LSS

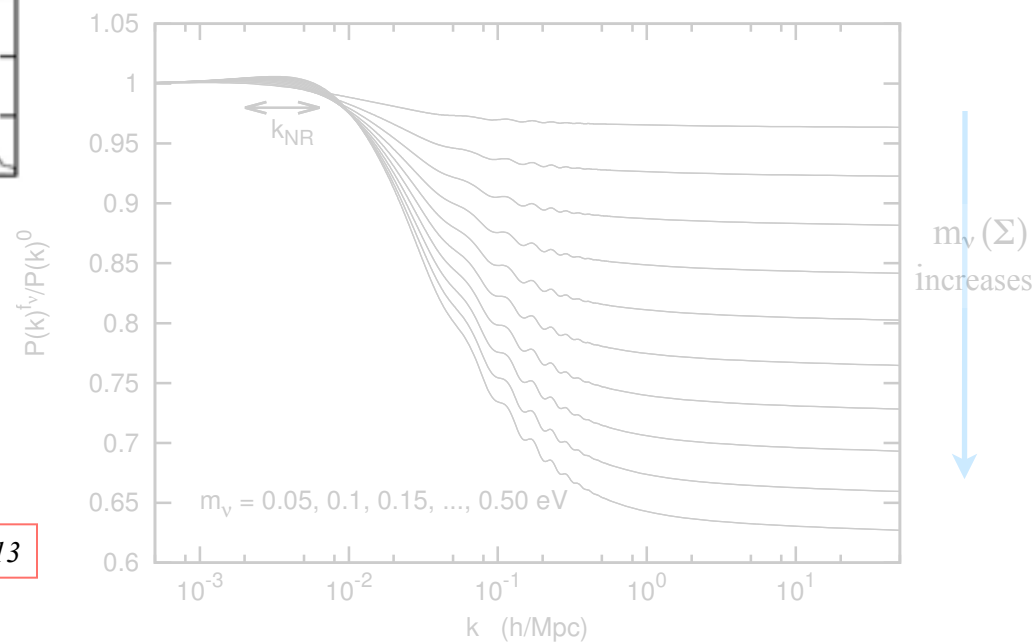
ν's and their masses effect the PS of temperature fluctuations of CMB (T < eV) and the matter PS of the LSS inferred by the galaxy surveys.



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

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



Taken from

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

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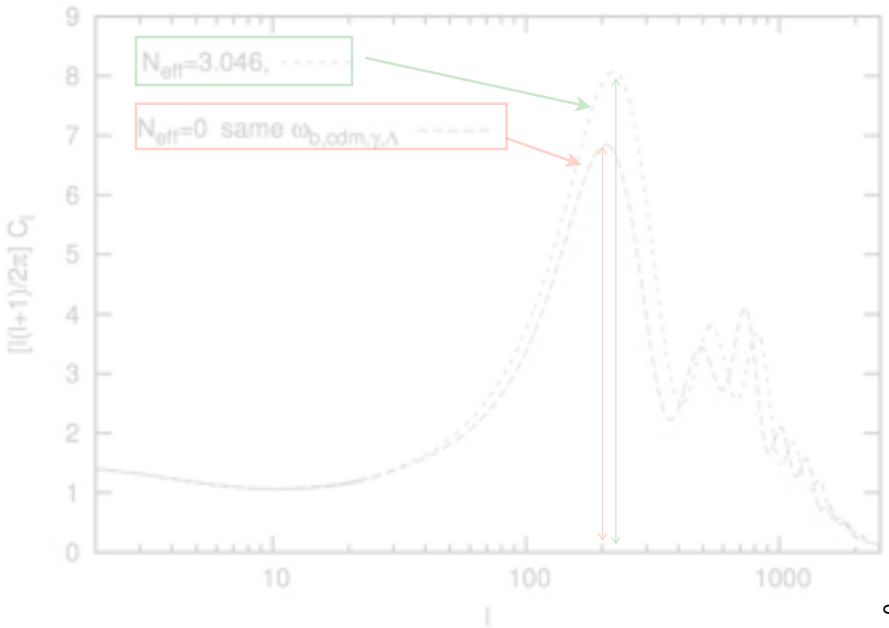
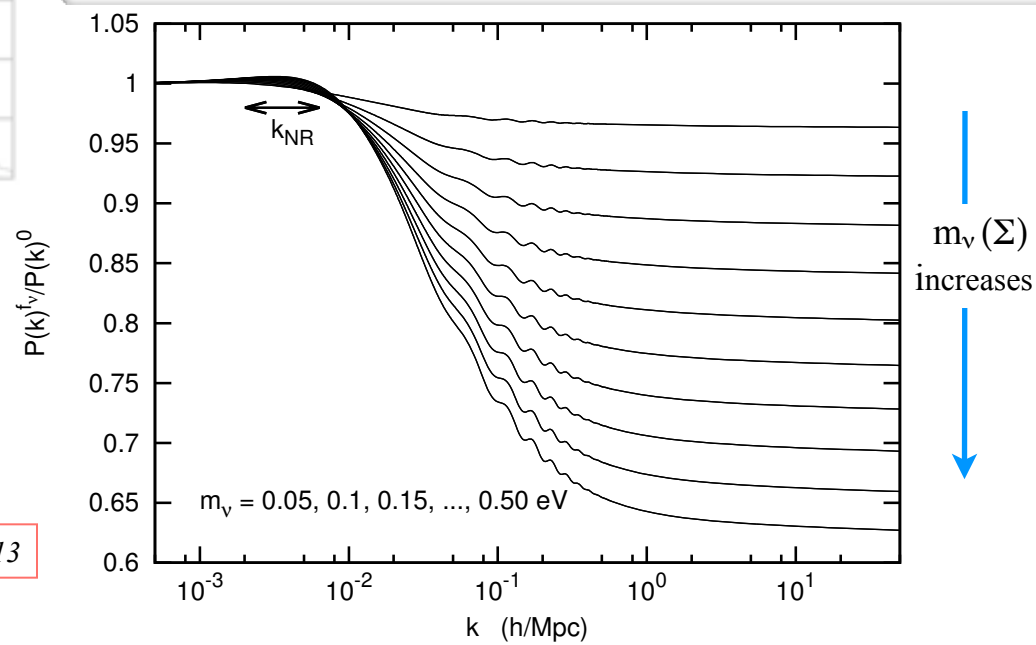


The small-scale matter power spectrum $P(k > k_{nr})$ is reduced in presence of massive ν:

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



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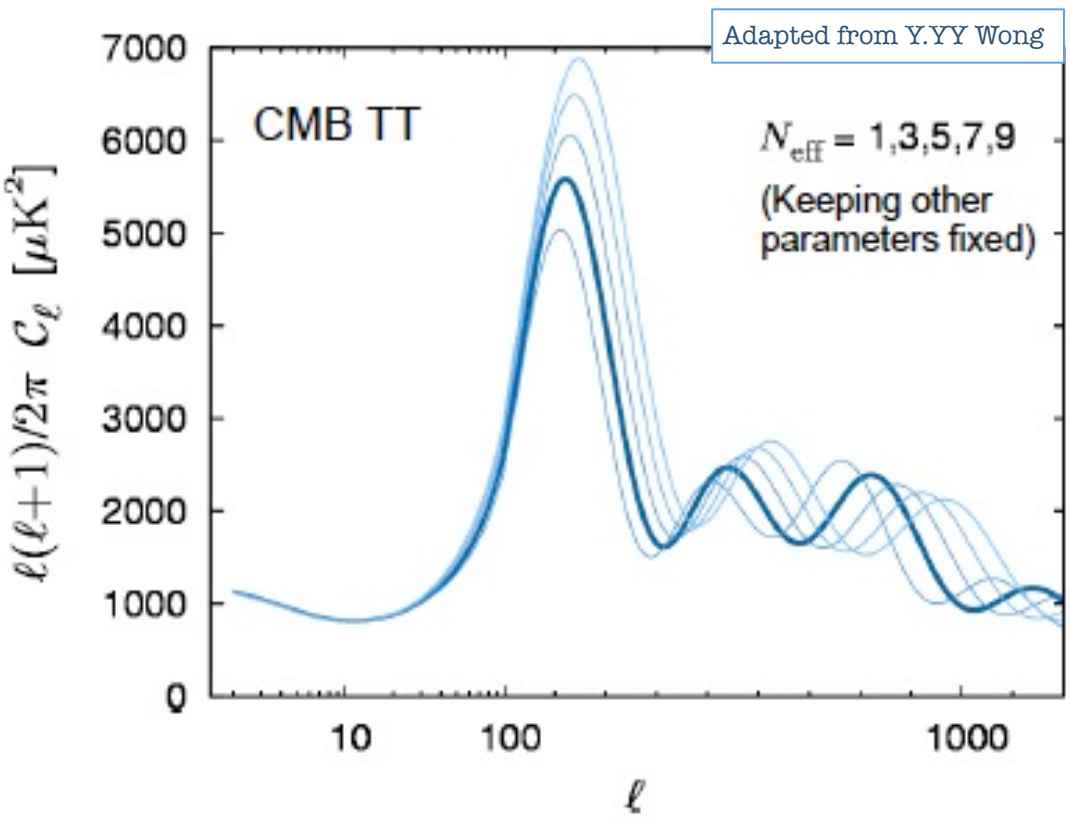
Extra radiation impact on CMB

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

constraints $N_{\rm eff}$ from the CMB Spectrum



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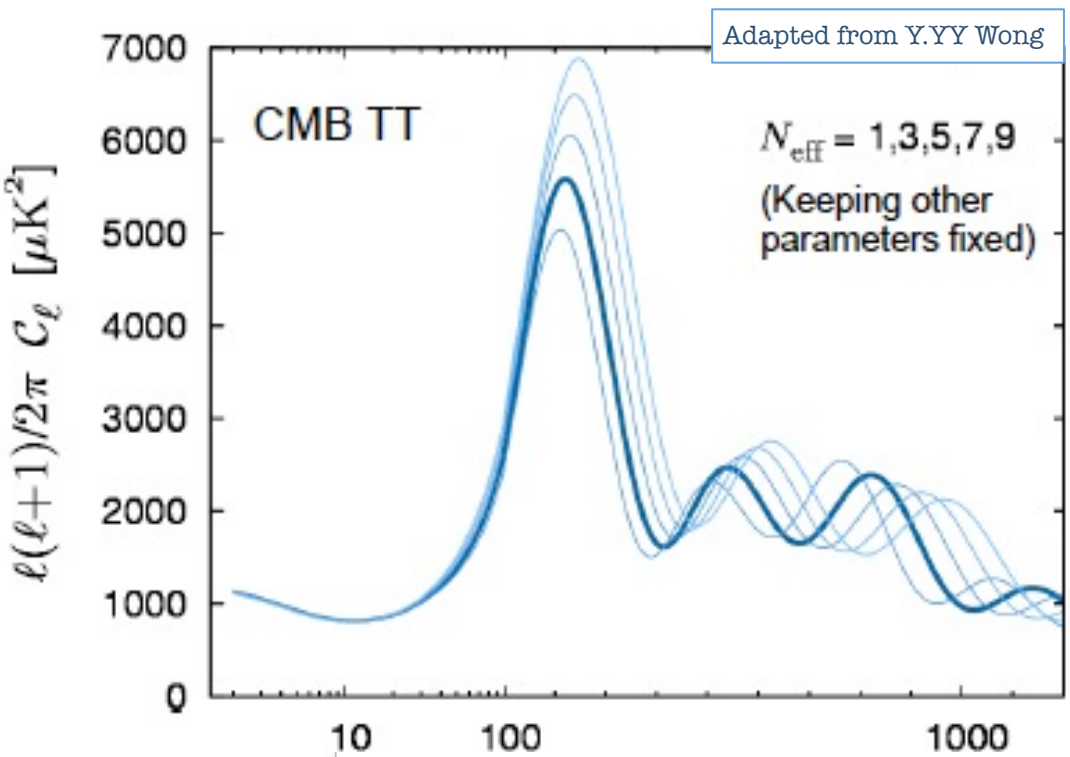


Same data used to measure other cosmological parameters

basic parameters of ΛCDM:

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

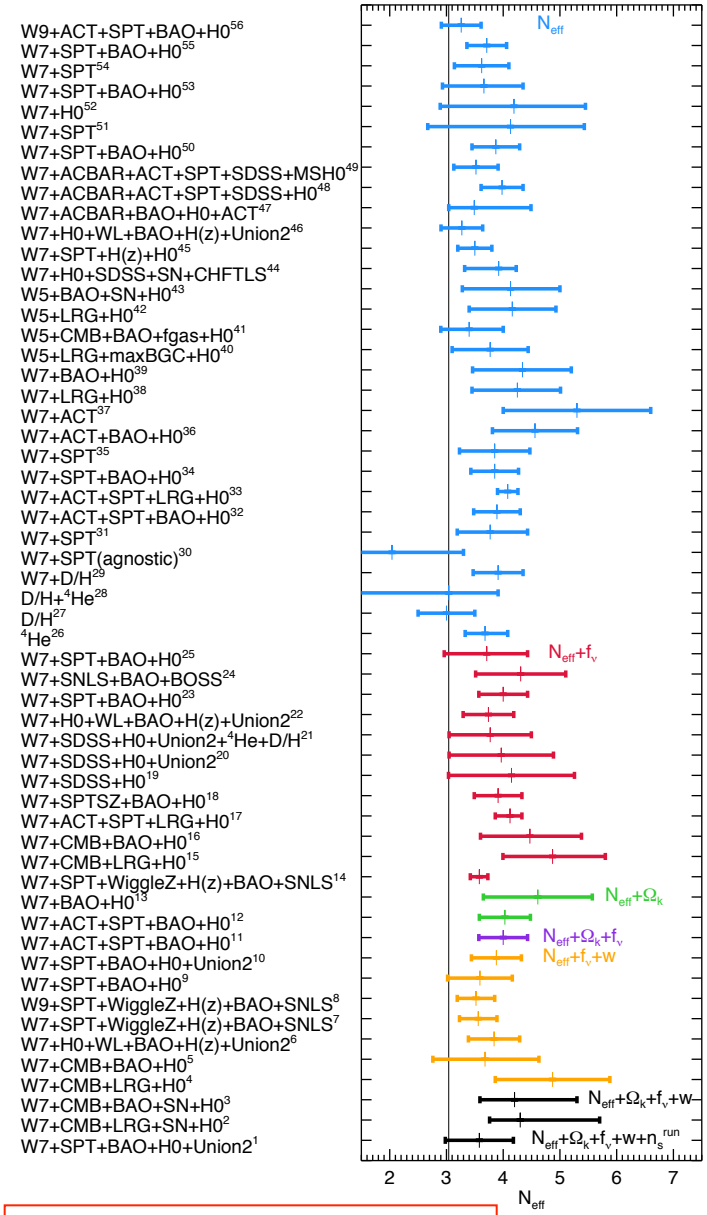
+ derived parameters

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

→ ***degeneracies***

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

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



Riemer-Sørensen, Parkinson & Davis, 2013

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

G. Hinshaw, et al.2013

J.L.Sievers et al. 2013

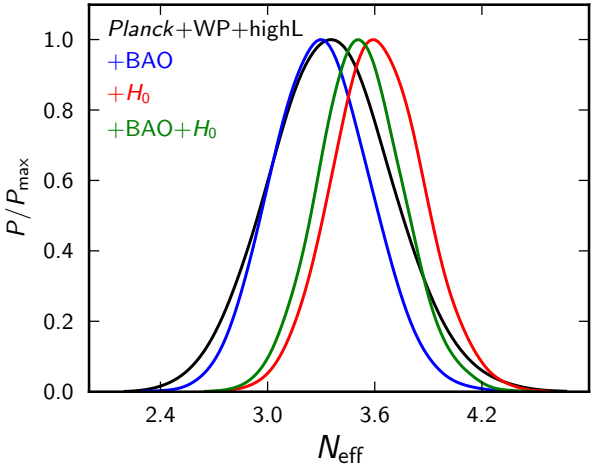
Hints for extra radiation reduce over the years

Slight preference for N_{eff} >3.046

$N_{\rm eff}$ *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

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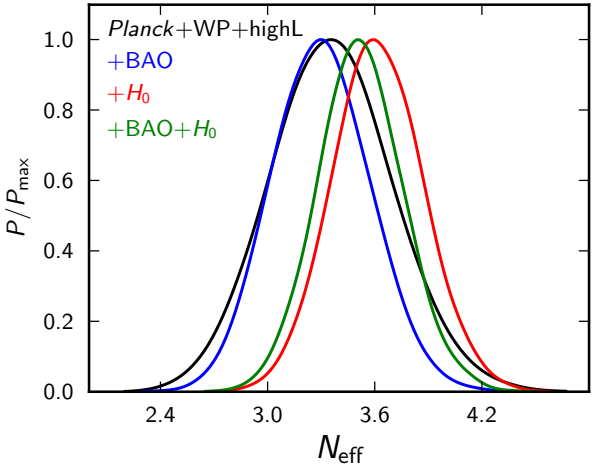

Planck XVI, 2013

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	$N_{\rm eff} < 3.80$ $m^{\rm eff}_{\nu s} < 0.42$

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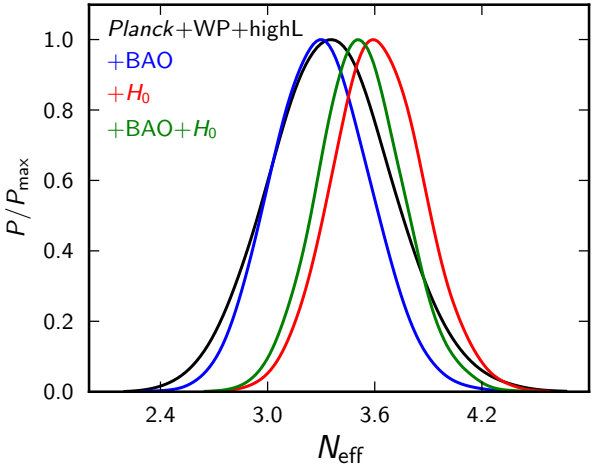

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Light sterile neutrino interpretation of extra radiation

Experimental anomalies & sterile ν interpretation

Some experimental data in tension with the standard 3ν scenario:

(…and sometimes in tension among themselves….)

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

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

A. Aguilar et al., 2001

A. Aguilar et al., 2010

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

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

Mention et al.2011

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

Acero, Giunti and Lavder, 2008

Giunti and Lavder, 2011

Kopp, et al. 2011

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

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

Kopp at al., 2013
Giunti et al., 2013

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

Active-sterile flavor evolution

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

✳ No primordial sterile neutrino is present

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

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  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 $\boxed{\overline{H} \equiv \frac{x^2}{m} H}$

➢ the EoM become:

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

Sigl and Raffelt 1993;
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MSW effect with background medium
(refractive effect)

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

➜ 2th order term: "symmetric" matter effect

sum of e^- - e^+ energy densities ε

$\mathsf{E}_\ell \equiv \mathrm{diag}(\varepsilon_e, 0, 0, 0)$

Sigl and Raffelt 1993;
McKellar & Thomson, 1994
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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;
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symmetric term

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

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

asymmetric term

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

Sigl and Raffelt 1993;
McKellar & Thomson, 1994
Dolgov et al., 2002.
Dolgov and Villante, 2003

Active-sterile flavor evolution

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

✳ No primordial sterile neutrino is 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 $\boxed{\overline{H} \equiv \frac{x^2}{m} H}$

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Collisional term ∝ G_F^2

creation, annihilation and all the momentum exchanging processes

Sigl and Raffelt 1993;
McKellar & Thomson, 1994
Dolgov et al., 2002.
Dolgov and Villante, 2003

Bounds on active-sterile mixing parameters after Planck

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

see also Cirelli, Marandella, Strumia and Vissani, 2004

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

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

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

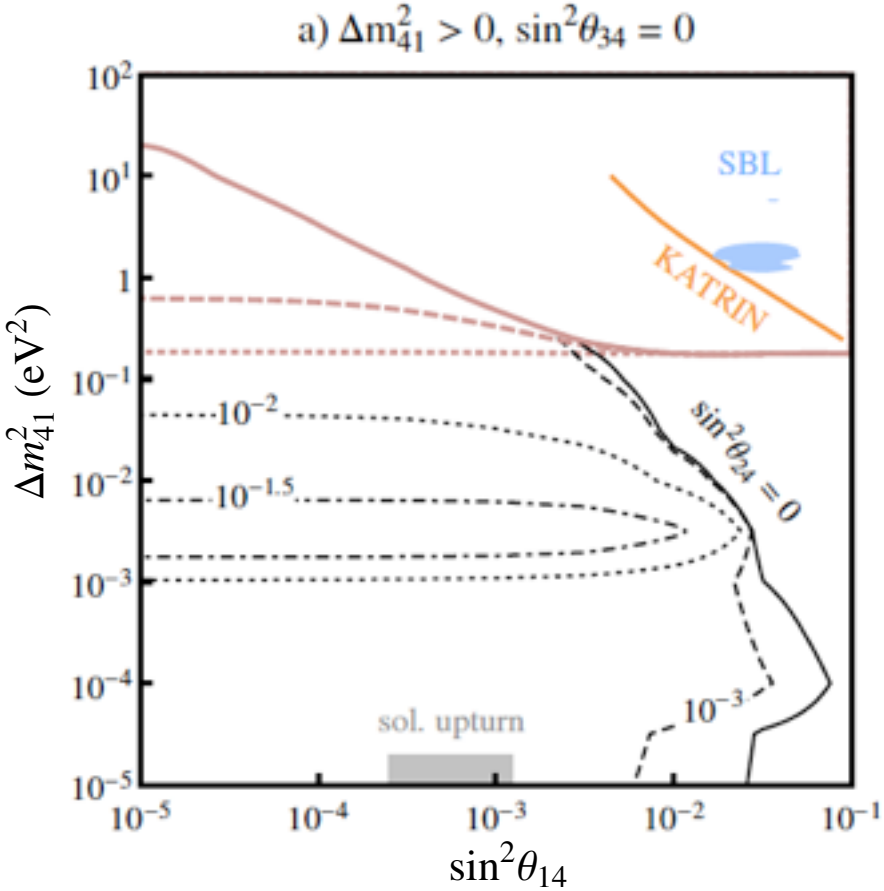
✔ conservative scenario: vanishing primordial neutrino asymmetry

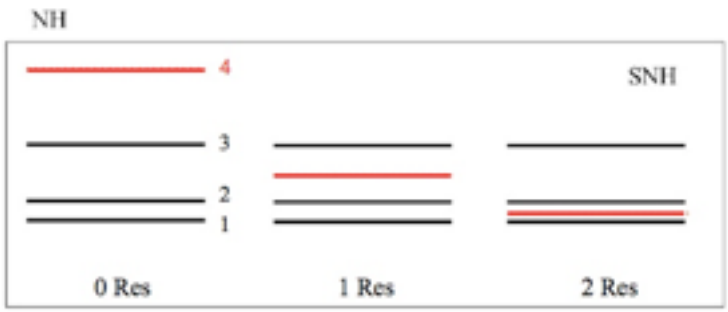
*Mirizzi, Mangano, **N.S**. et al 2013,* arXiv:1303.5368

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

Mirizzi et al 2013, arXiv1303.5368

- ✓ Normal active hierarchy
- ✓ Normal sterile hierarchy





Radiation bounds

- 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.

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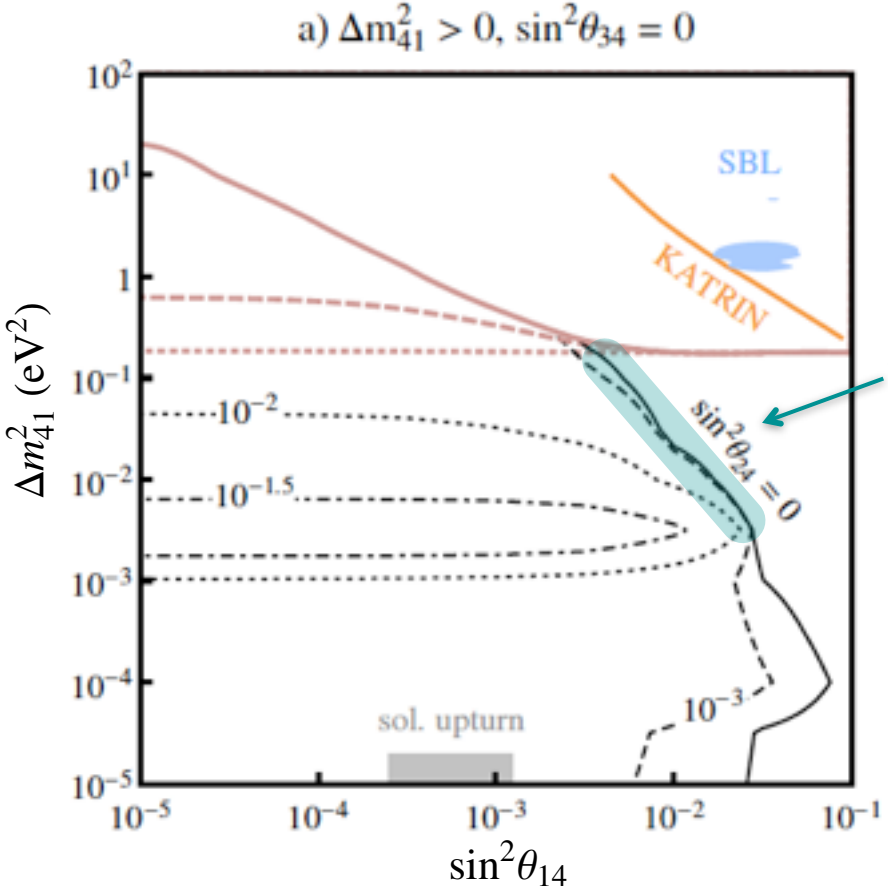
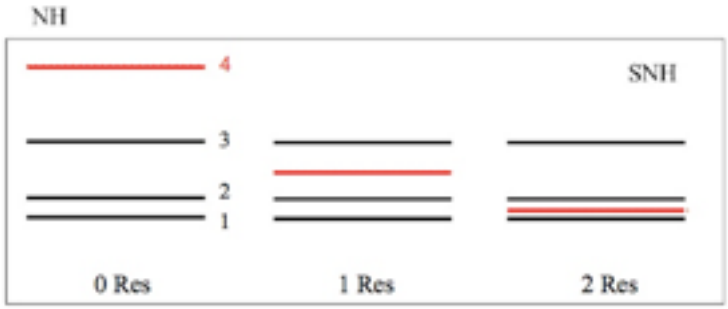


simple behavior for $\theta_{24} \simeq 0$ and for large sterile mass

see also Hannestad, Tamborra and Tram 2012



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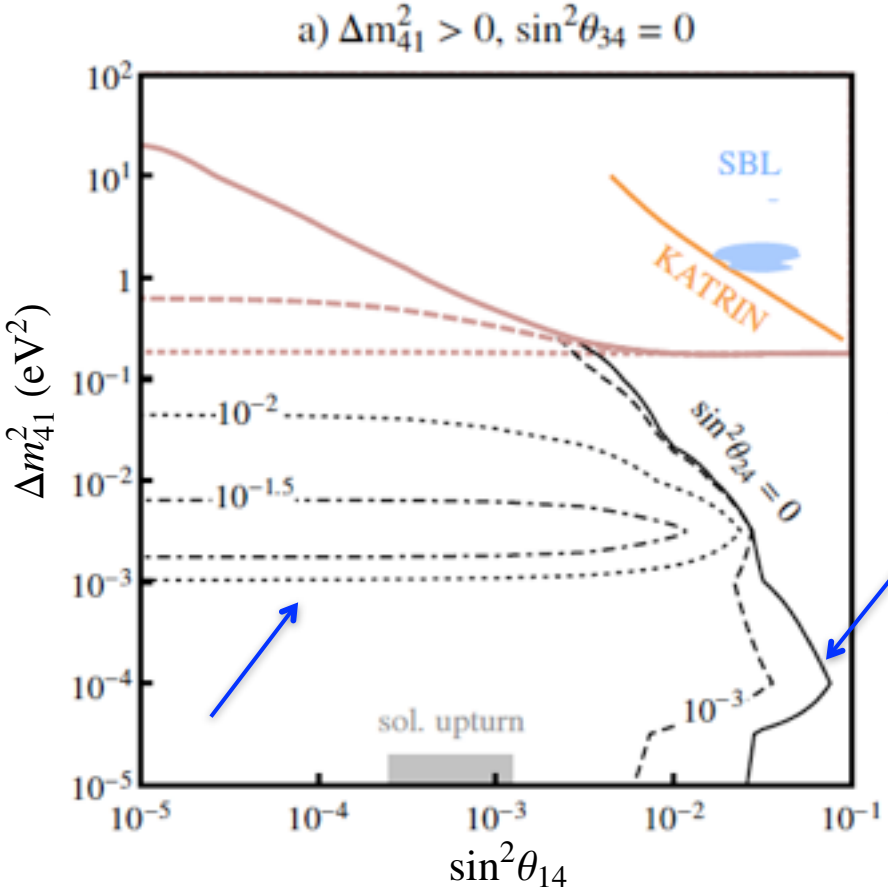
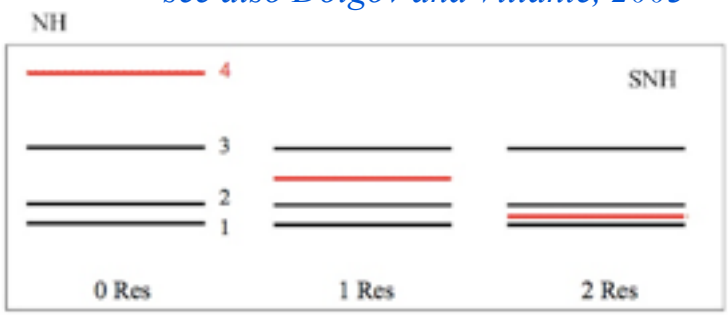


complex behavior for small sterile mass due to resonances and for $\theta_{24} > 0$

see also Dolgov and Villante, 2003



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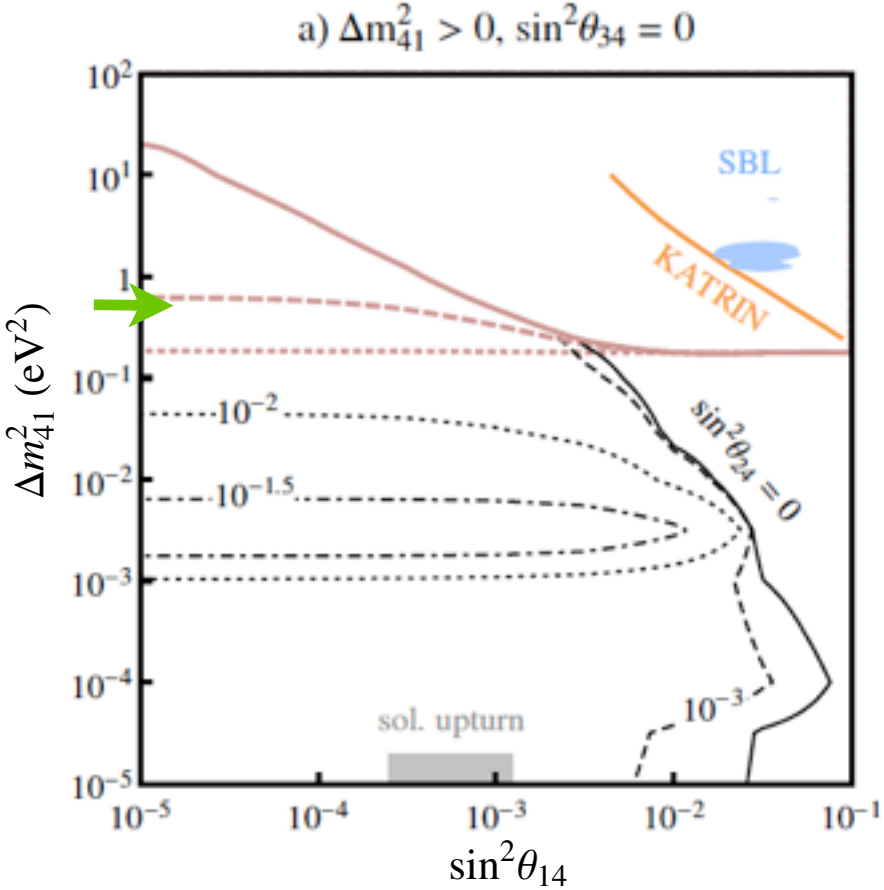

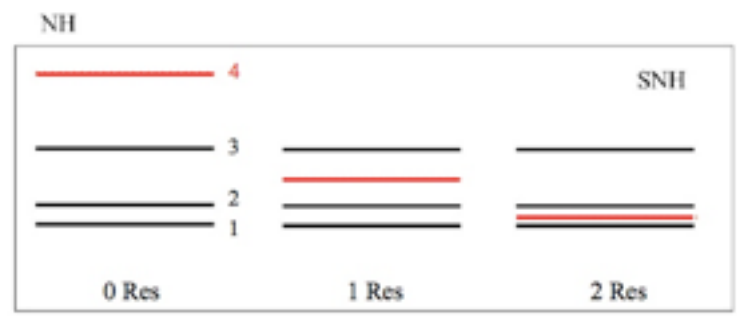

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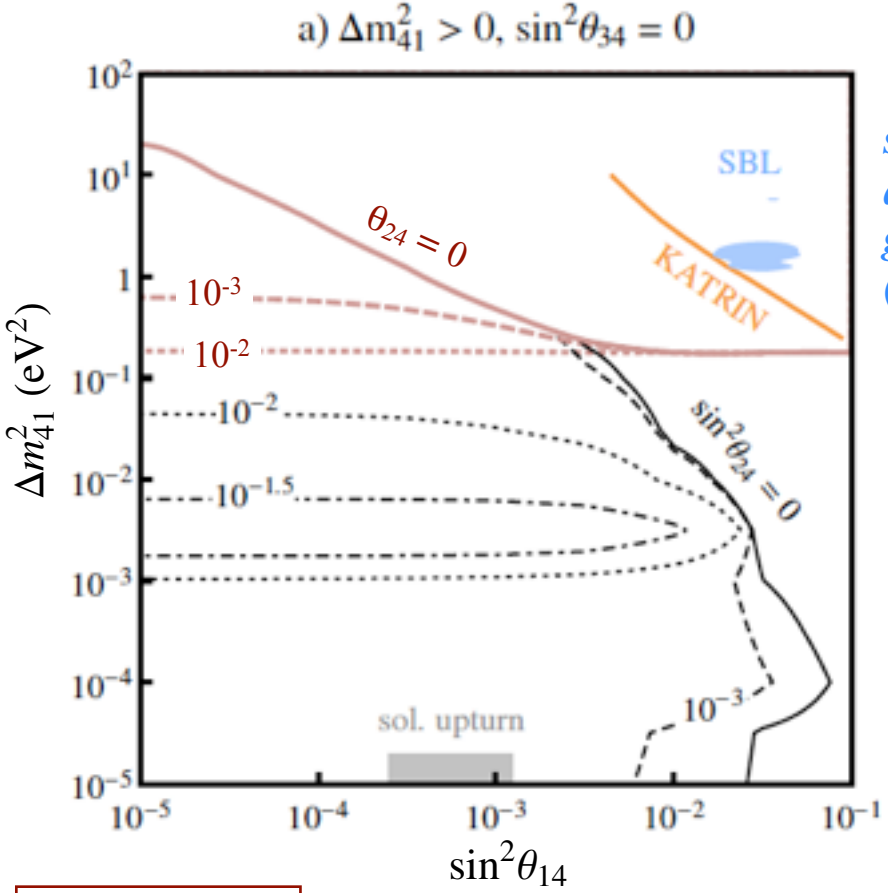
The excluded regions are those on the right or at the exterior of the black contours.

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 ... our results

Mirizzi et al 2013, arXiv1303.5368



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

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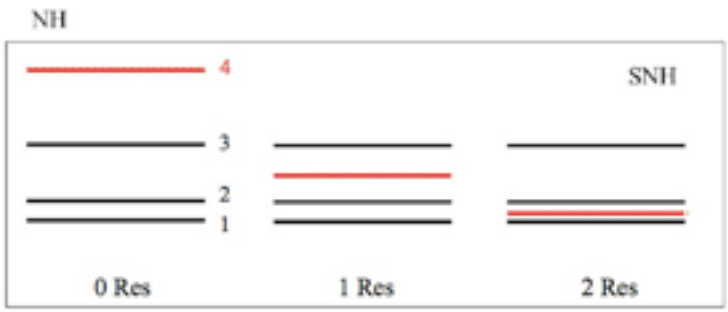
- ✓ Normal sterile hierarchy



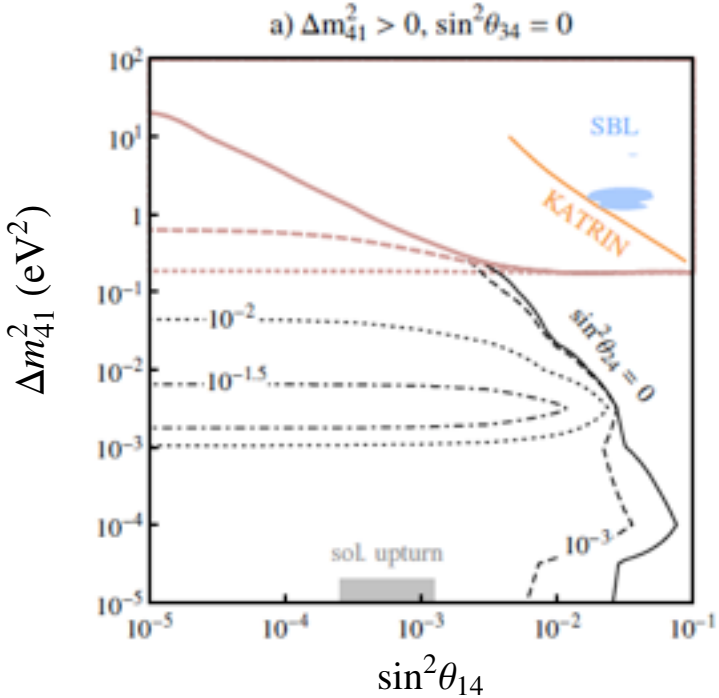
Mass bounds

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

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

The excluded regions are those above the red contours.

Bounds on active-sterile mixing: CONCLUSIONS



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.*
- ***Sterile ν with*** **m** ~ $\mathcal{O}$**(1 eV)** ***strongly disfavored***

Bounds on active-sterile mixing: an escape route?

- ***Suppression of the sterile production***

Bounds on active-sterile mixing: an escape route?

Suppression of the sterile production

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

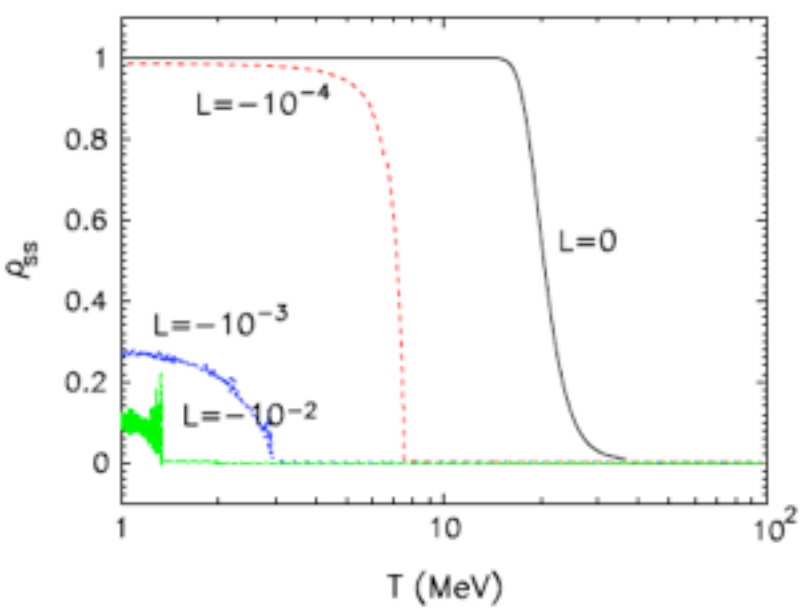
✓ In the presence of large $\nu-\nu$ asymmetries ($L\sim10^{-2}$) sterile production strongly suppressed. Planck mass bound can be evaded

Chu & Cirelli, 2006

⚠ Non trivial implication for BNN

*Mirizzi, **N.S.**, Miele, Serpico 2012*

Saviano et al., 2013



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

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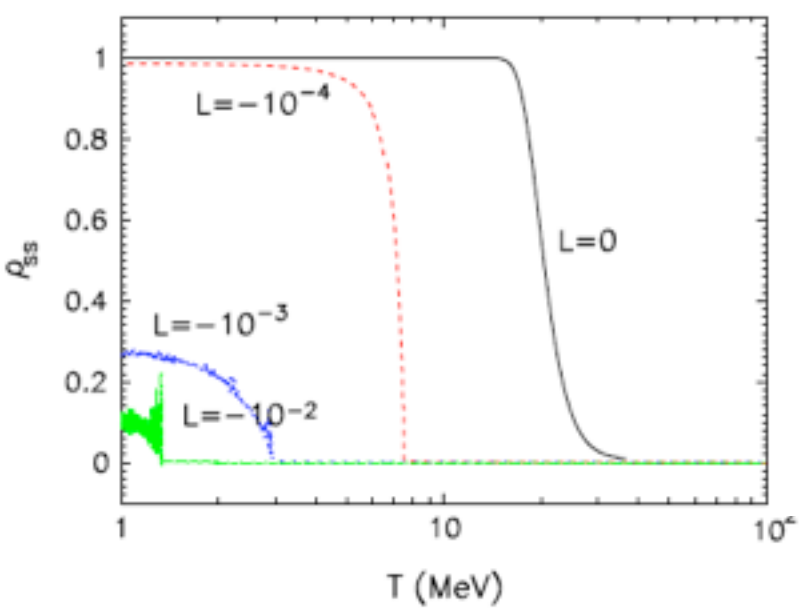
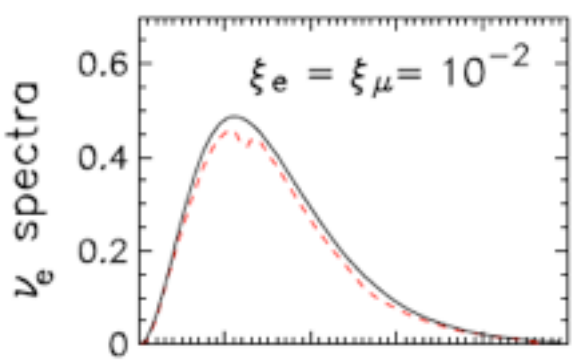
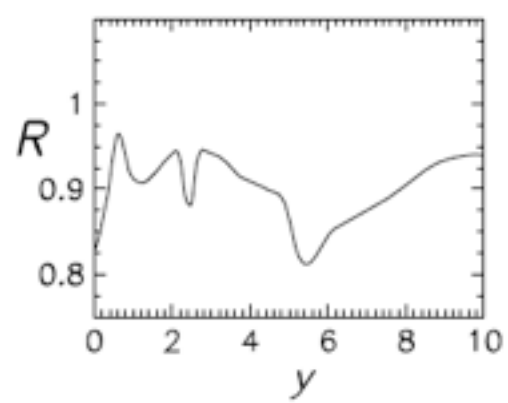






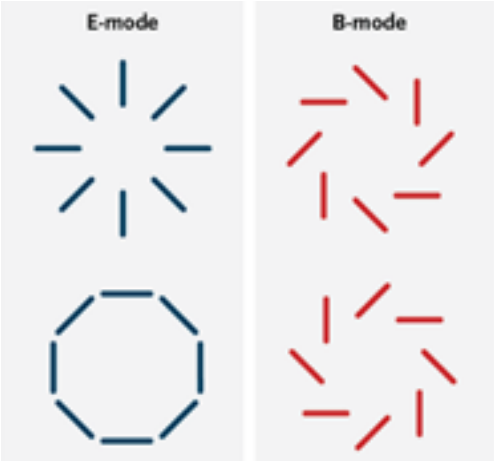
IFAE, 9-11 April 2013

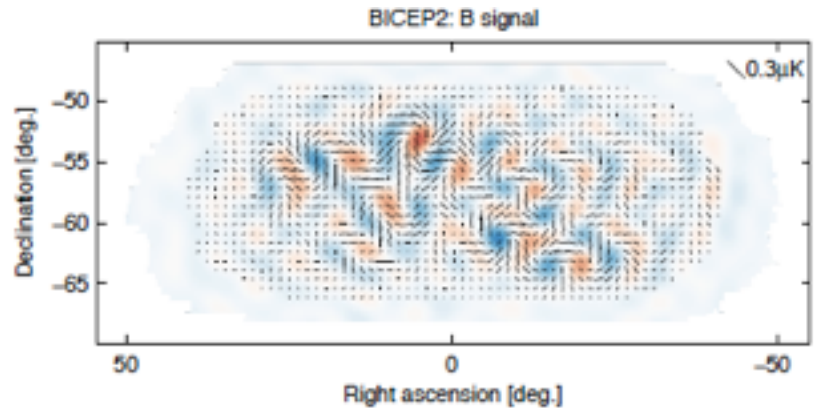
Neutrinos in Cosmology
~~after Planck~~
after Planck and BICEP 2

Ninetta Saviano

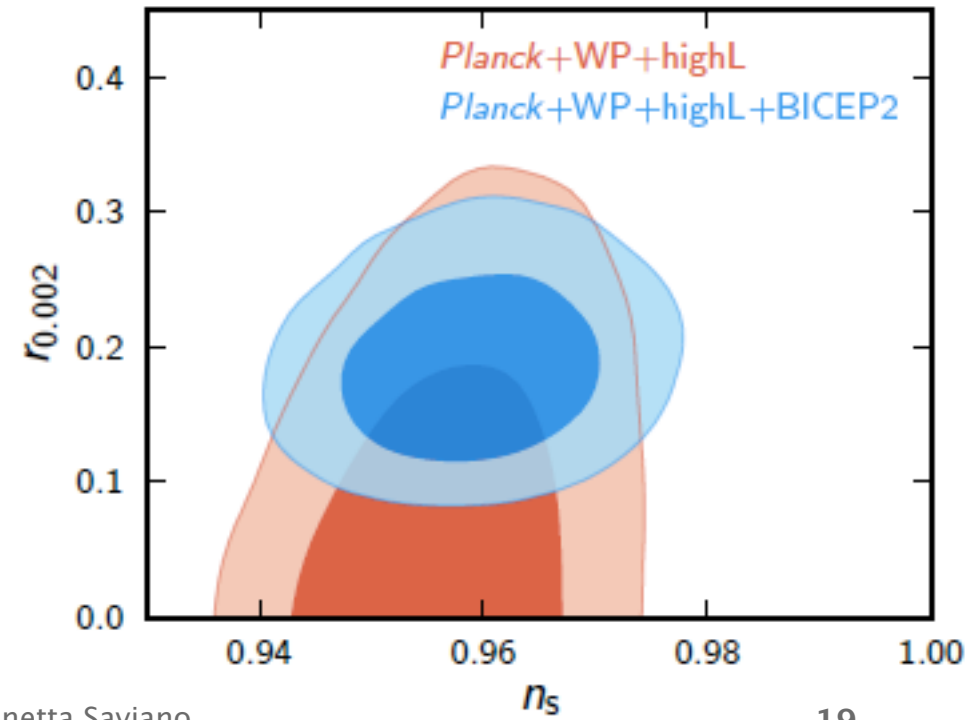
IPPP, Department of Physics, Durham University

B-mode by BICEP2





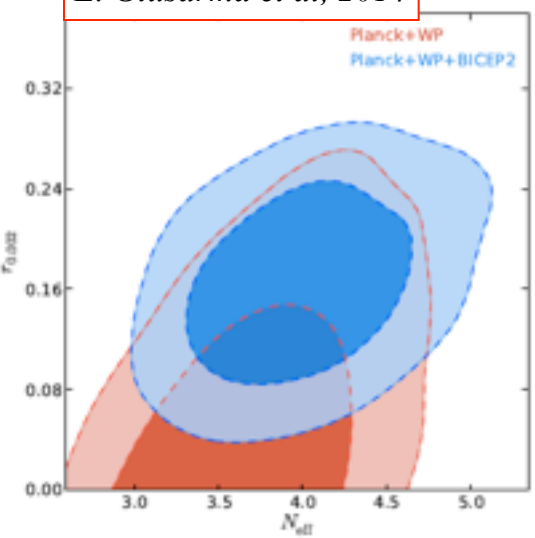
Detection at about 5.9 σ for B-mode polarization on large angular scales, compatible with the presence of a tensor component with amplitude
$r_{0.002}$ = 0. 2+-0.06 at 68 % c.l.



Special Edition

New possibility for sterile neutrinos?

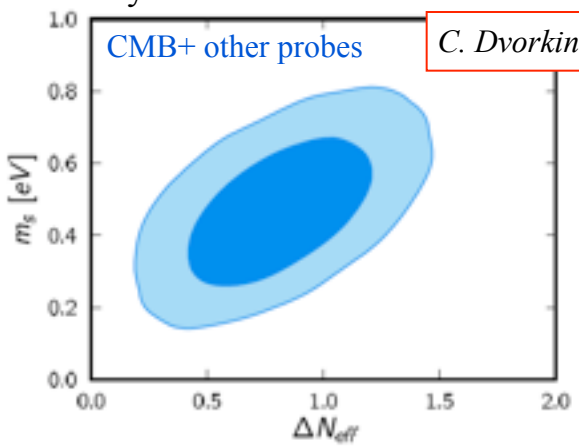
E. Giusarma et al, 2014



N_{eff} = 4.00 +- 0.41 (68% C.L.)
(Only CMB data)
Extra radiation seems to mitigate the tension among Planck and BICEP2 results

Neutrinos help reconcile Planck measurements with both Early and Local Universe

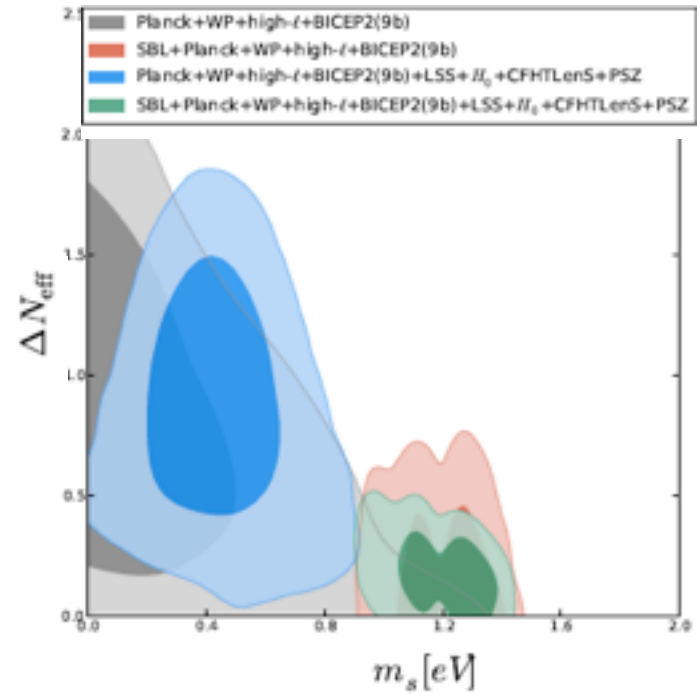
C. Dvorkin et al, 2014



$m^{eff}_{\nu s}$ = 0.47+-0.13 eV

N_{eff} = 0.81 +- 0.25

M. Archidiacono et al, 2014



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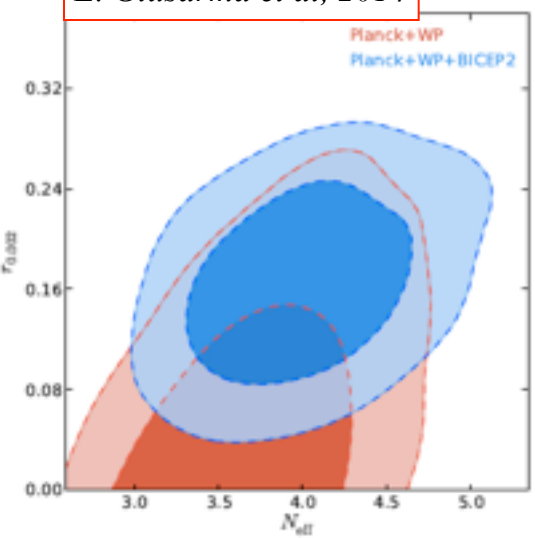

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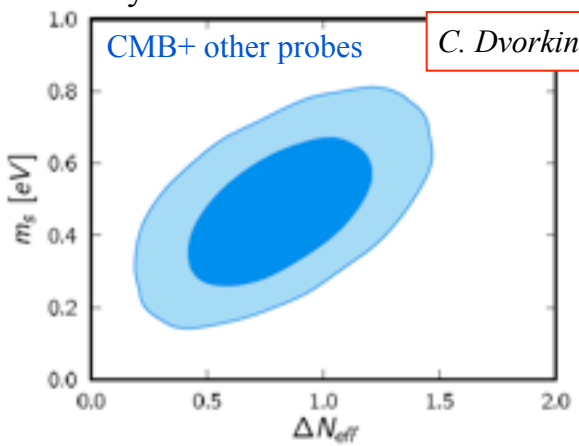

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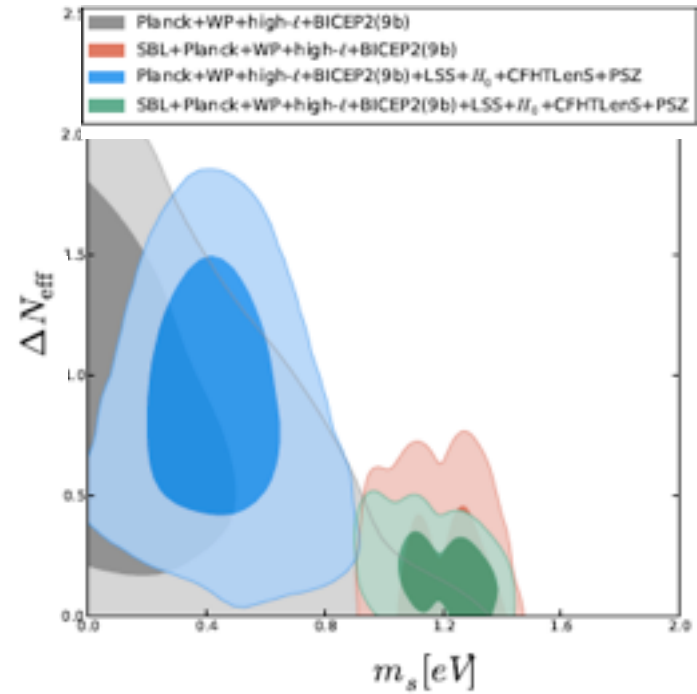


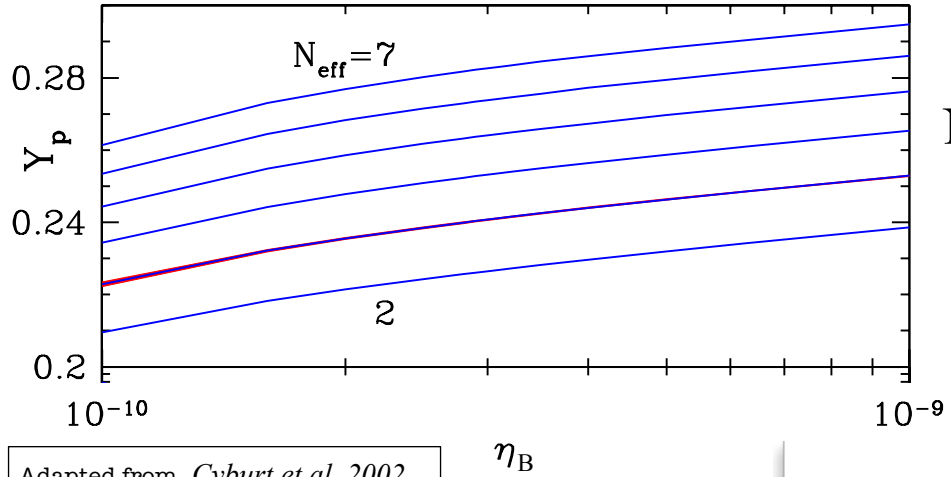
Caution: whatever N_{eff}, fully thermalized eV sterile neutrinos are too heavy for the LSS

A serious theoretical consideration for possible candidates is necessary


Grazie

Extra radiation impact on BBN and constraints

Light element abundances are sensitive to extra radiation:



Adapted from *Cyburt et al, 2002*

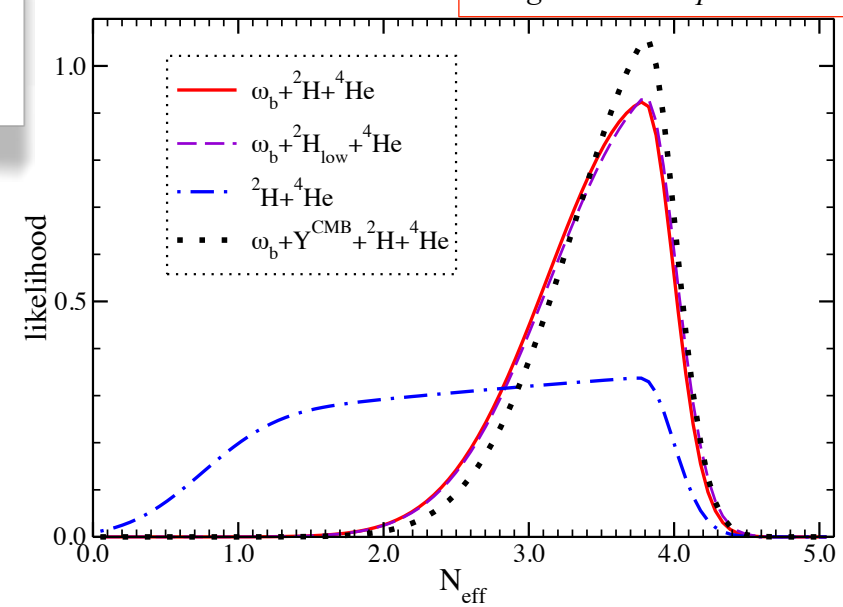
N_{eff} ↑ ⇒ H ↑ ⇒ early freeze out (T_d ↑) ⇒ n/p ↑ ⇒ ^{4}He ↑

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

$\Delta N_{eff} \leq 1$

(at 95% C.L)

Mangano and Serpico. 2012



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 single astrophysical system:

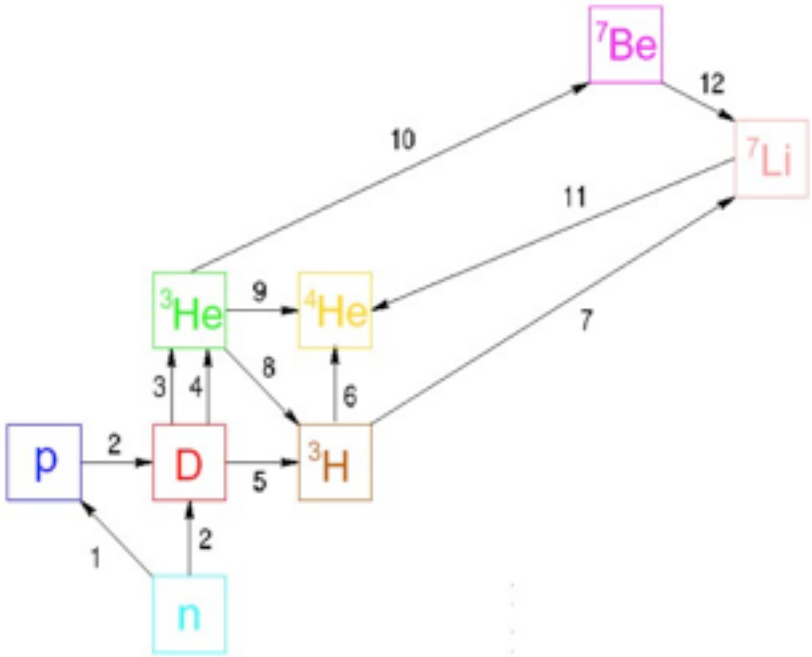
$N_{eff} = 3.0 \pm 0.5$

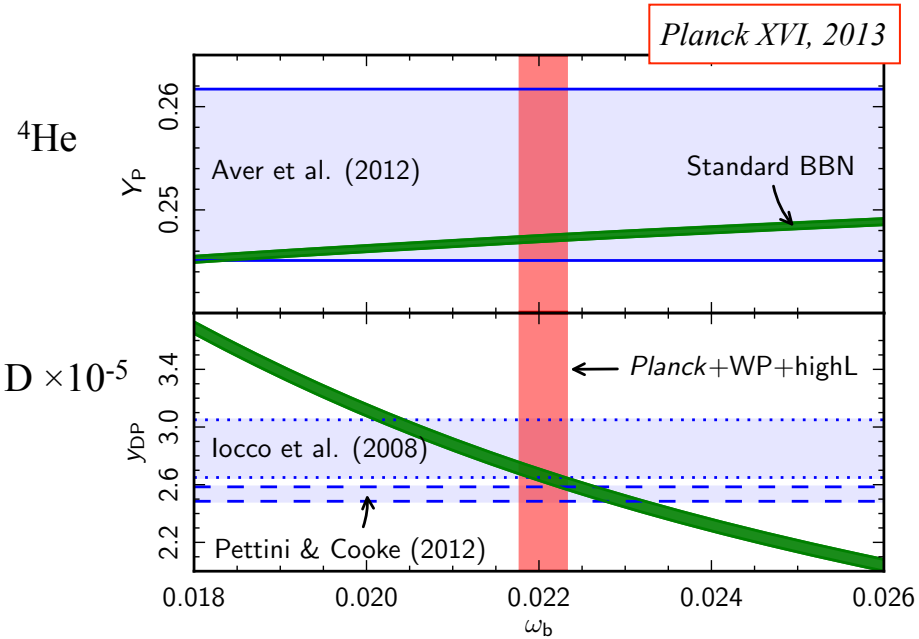
Pettini and Cooke, 2012

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. ${}^3H + {}^4He \rightarrow {}^7Li + \gamma$
8. ${}^3He + n \rightarrow {}^3H + p$
9. ${}^3He + D \rightarrow {}^4He + p$
10. ${}^3He + {}^4He \rightarrow {}^7Be + \gamma$
11. ${}^7Li + p \rightarrow {}^4He + {}^4He$
12. ${}^7Be + n \rightarrow {}^7Li + p$





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

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

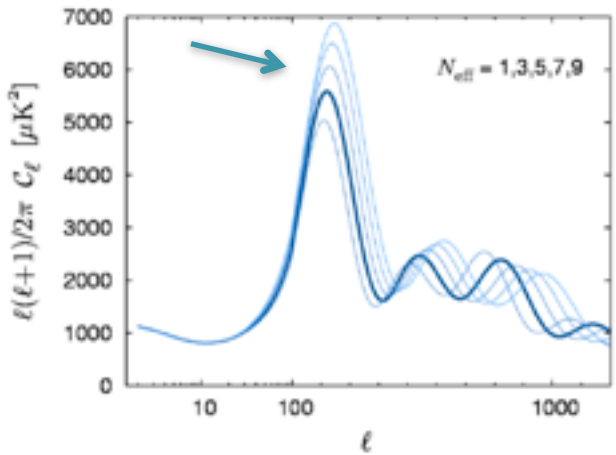
$\omega_b = 0.02207 \pm 0.00027$

Extra radiation impact on CMB...

... and degeneracies

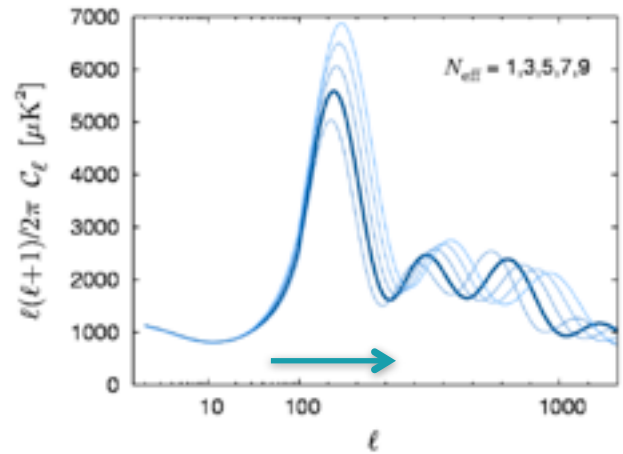
Matter-radiation equality

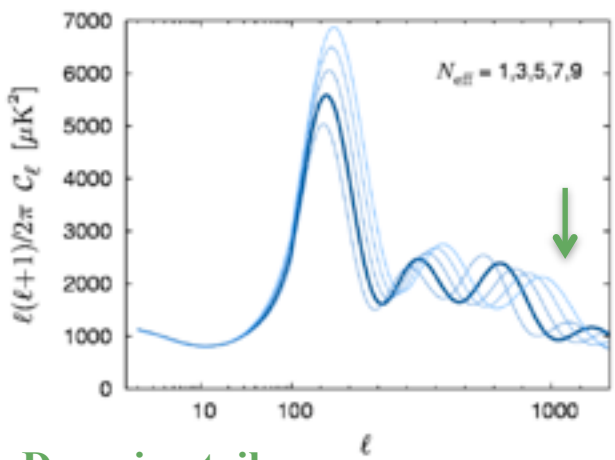
degenerate with Ω_m



Sound horizon/angular positions of the peaks

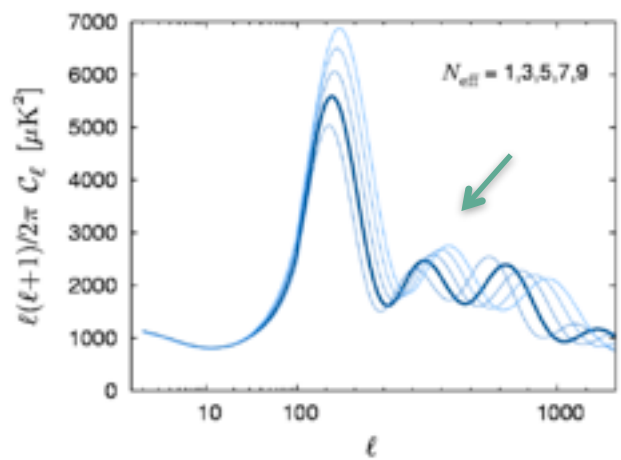
degenerate with H_0 and Ω_m





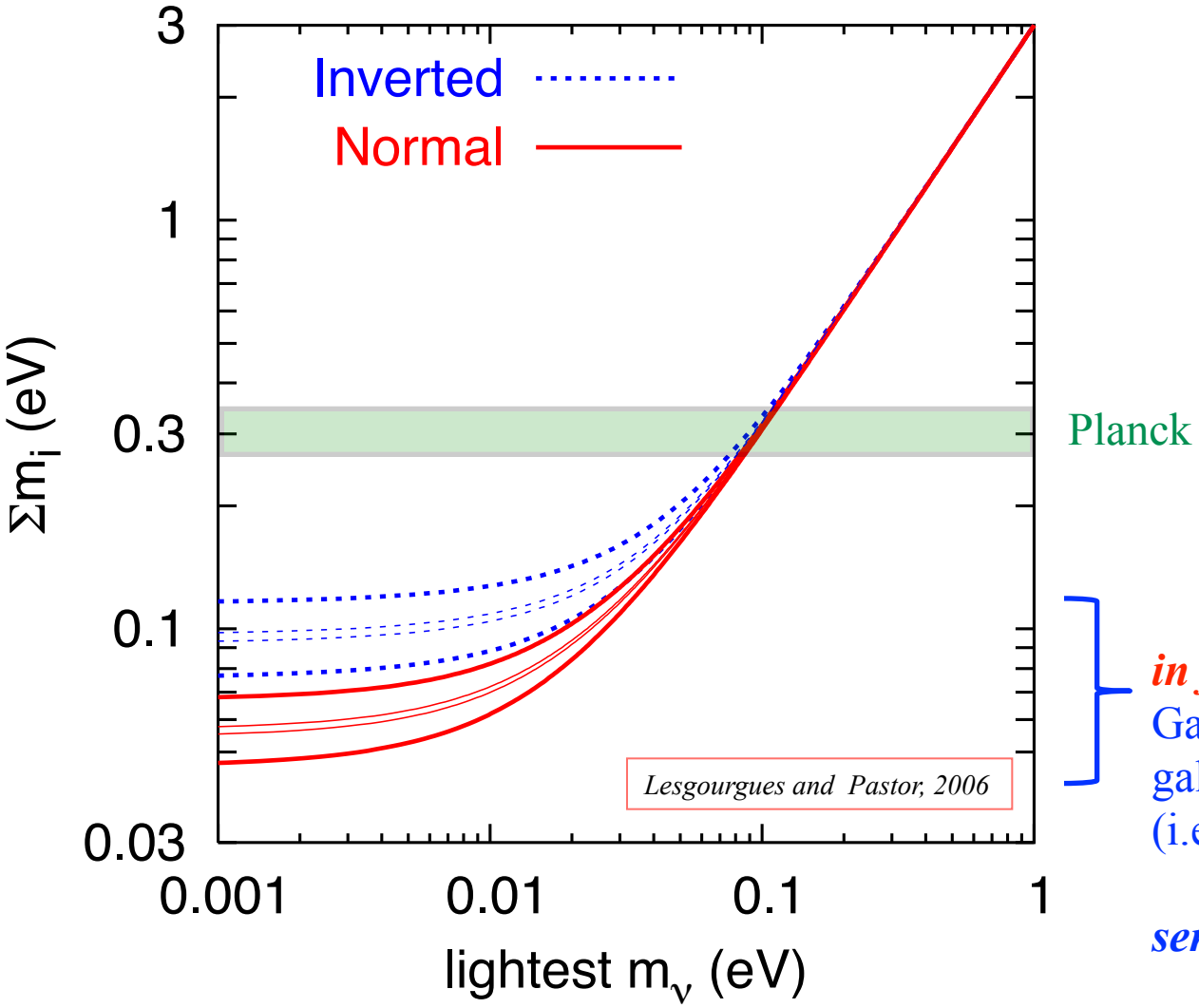
Damping tail

degenerate with Y_p



Anisotropic stress

(partially) degenerate with A_s and n_s



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

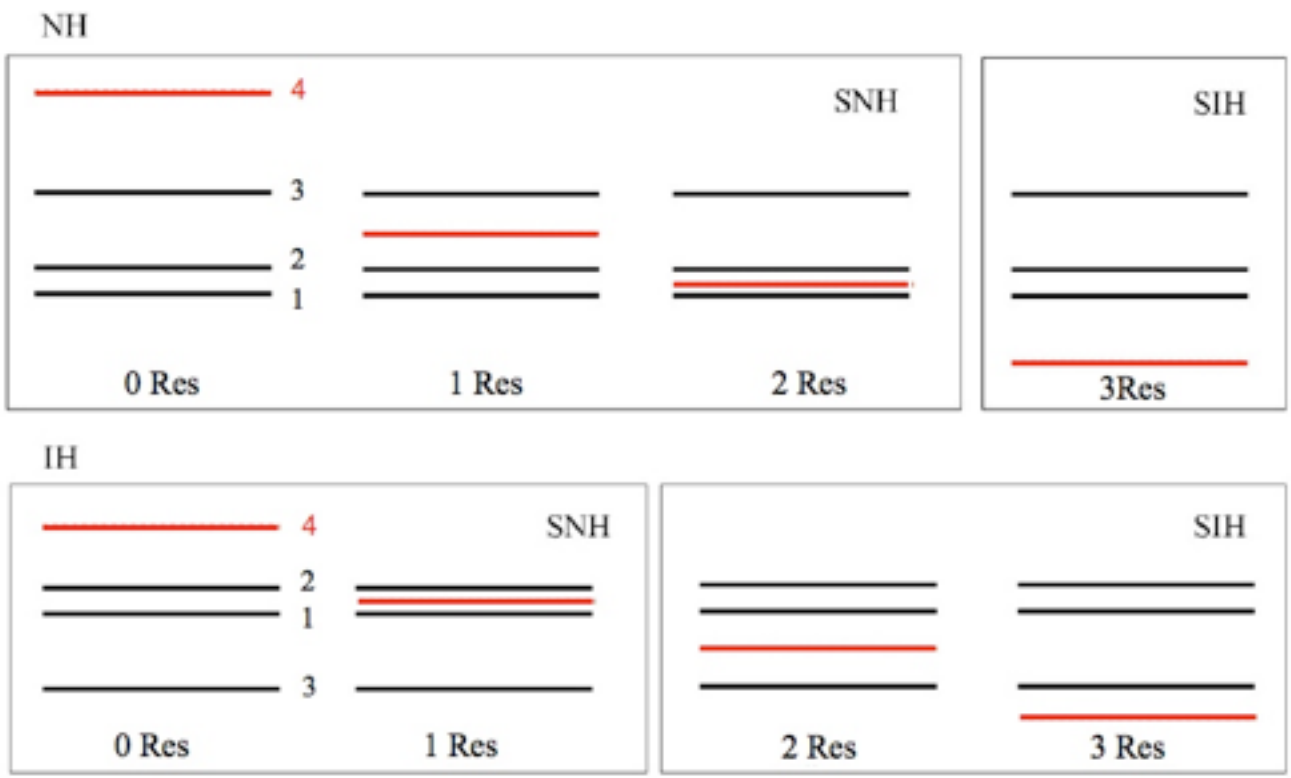
sensitivity < 0.1

Why is the multi-flavour system important ?

Mirizzi et al 2013, arXiv1303.5368

- **More mixing angles:**
  - 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

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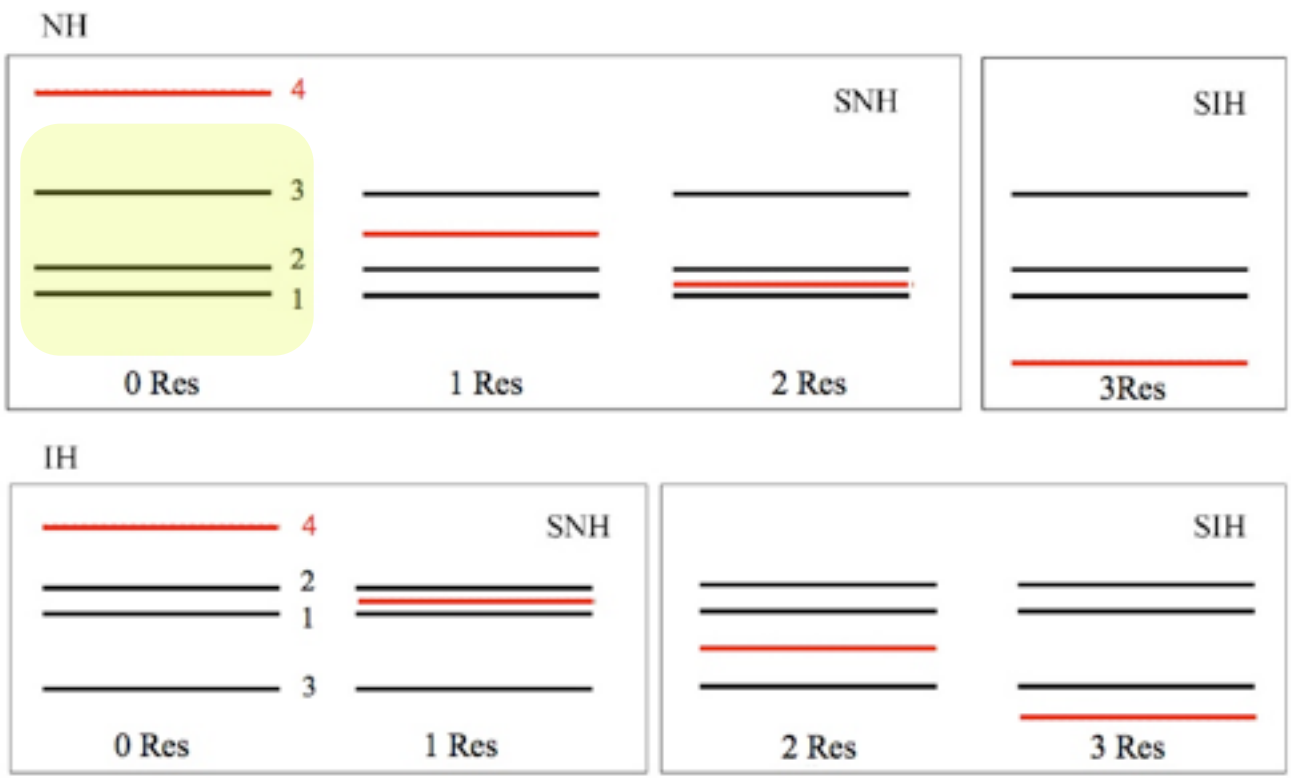

In the sterile sector:

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

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Mirizzi et al 2013, arXiv1303.5368

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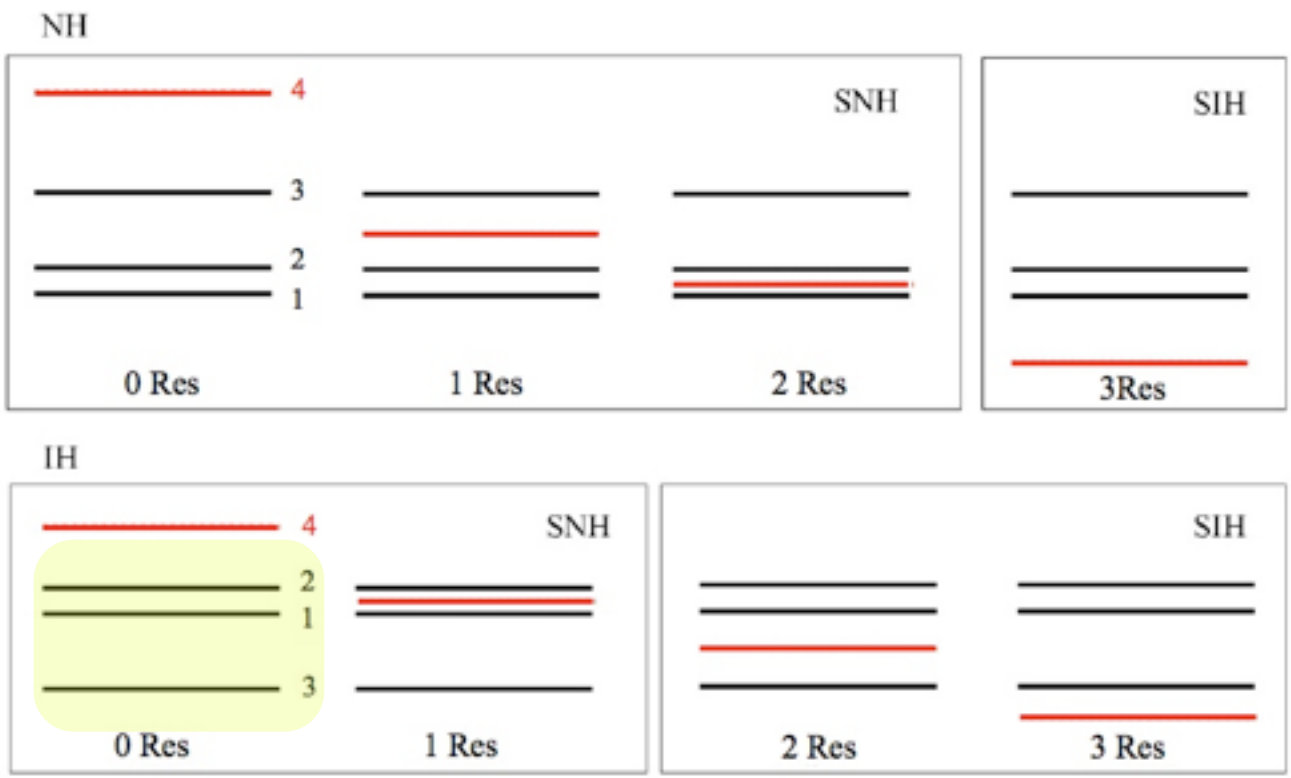
  - oscillation mechanism shared between different flavours ➜ effects not possible in the simple "1+1" scenario

- **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, $\Delta m^2_{31} < 0$

Why is the multi-flavour system important ?

Mirizzi et al 2013, arXiv1303.5368

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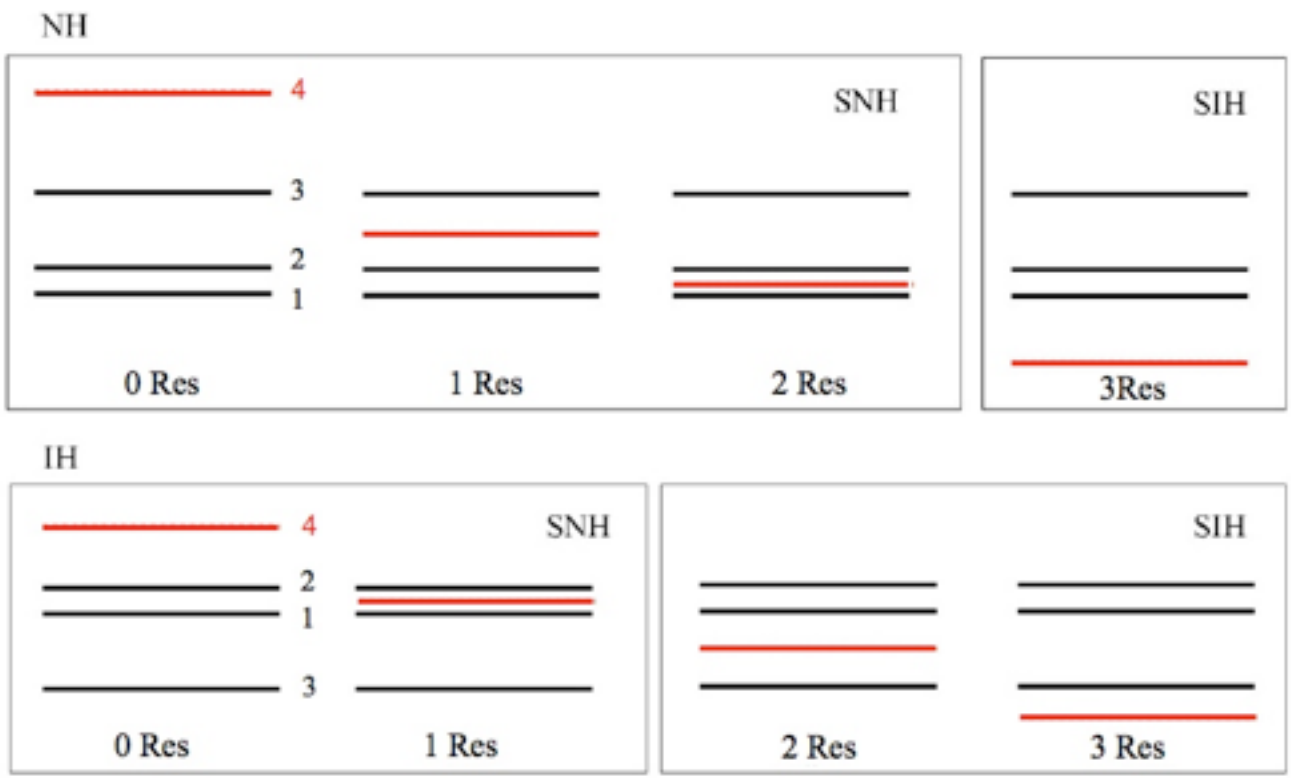


In the sterile sector:

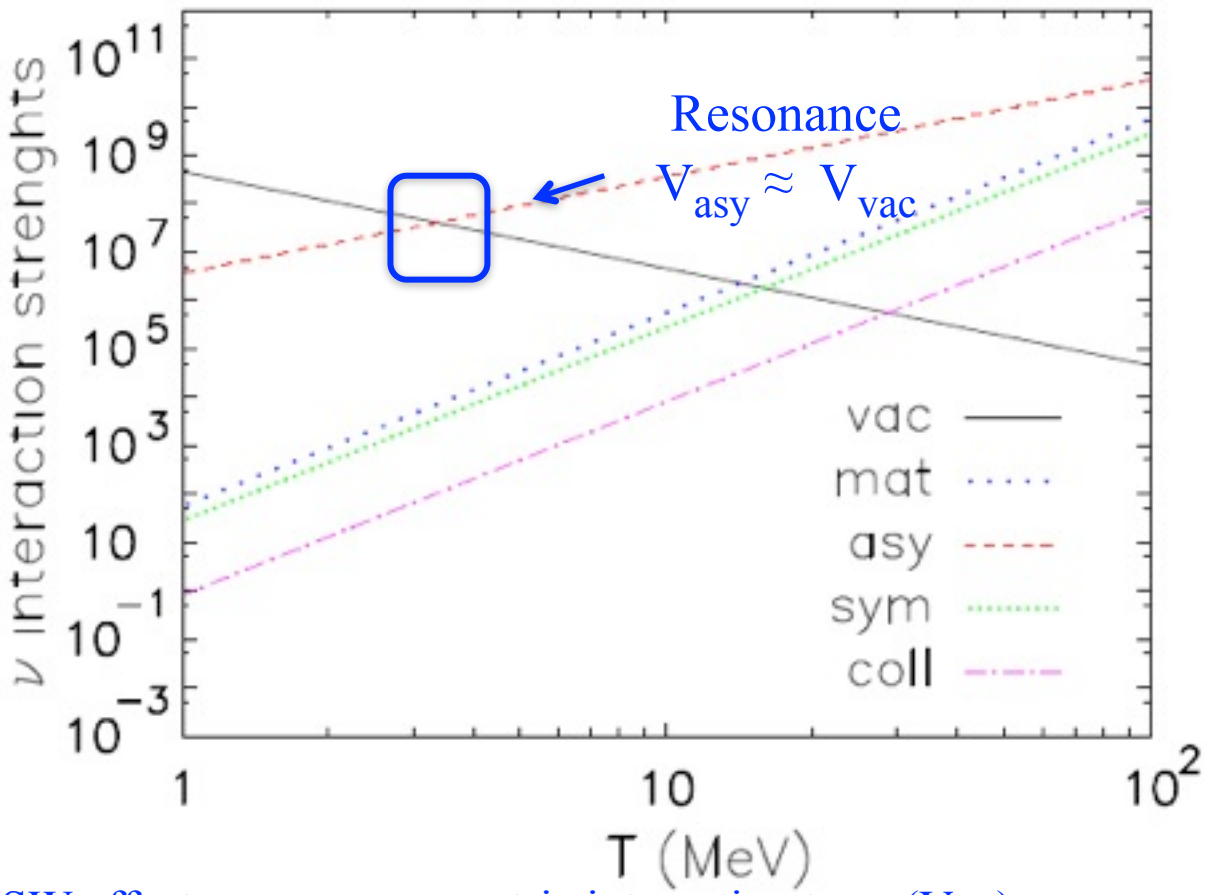
resonances associated with

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, $\Delta m^2_{41} < 0$

Strength of the different interactions

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



$L = -10^{-4}$

(kept constant)

MSW effect on ν-ν asymmetric interaction term (V_{asy})

- 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 $\bar{\nu}$ channels

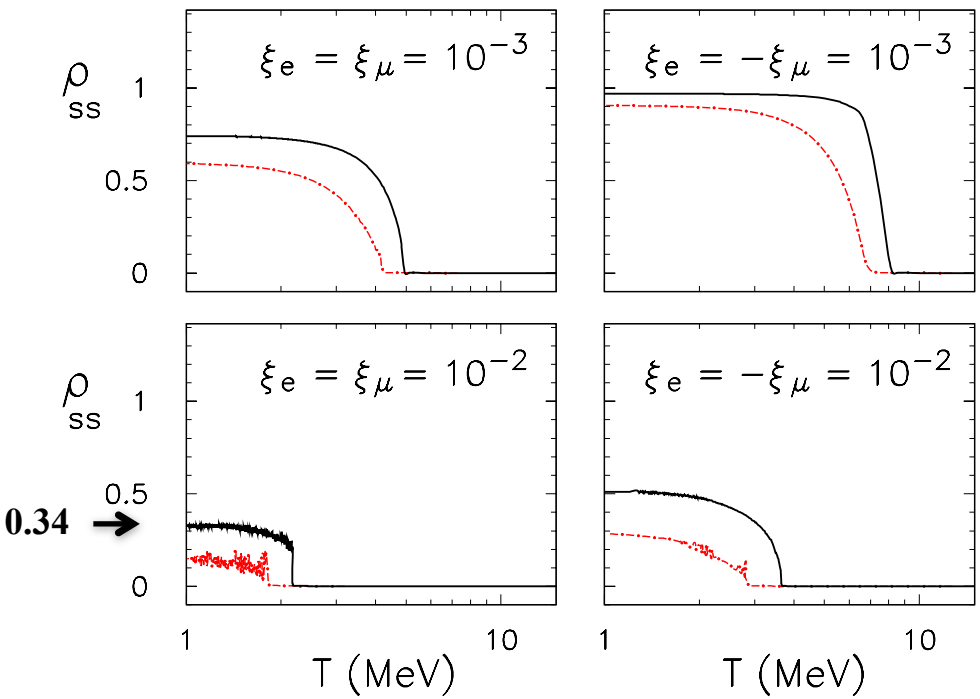
Multi-momentum treatment

✓ 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

Results:

Saviano et al, 2013



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

— single-momentum

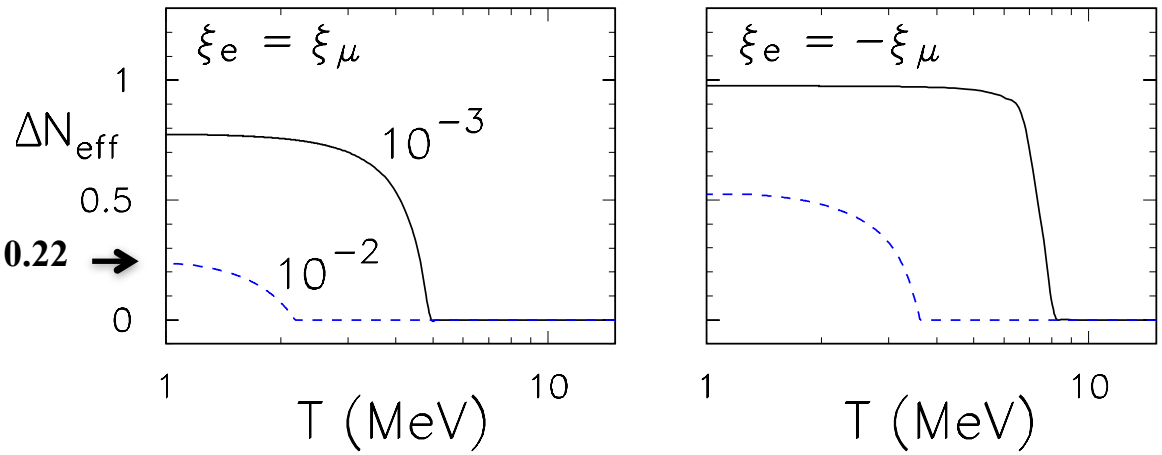
Enhancement of the sterile production with respect to the single-momentum approx.

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

$N_{\rm eff}$ *from multi-momentum treatment*

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

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



Case	$\Delta N_{\rm eff}$	$\Delta N_{\rm eff}^{\langle y \rangle}$
$\lvert\xi\rvert \ll 10^{-3}$	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.

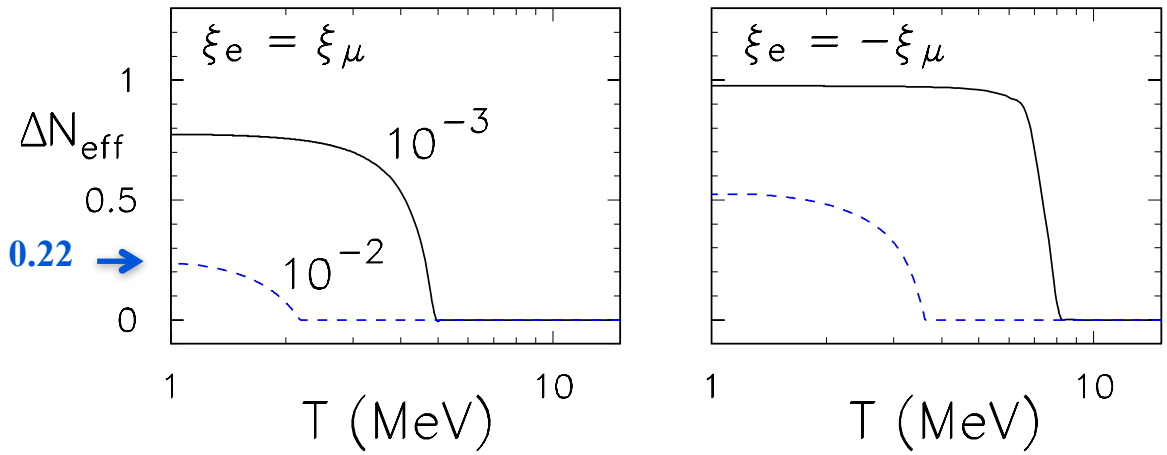
One needs to consider very large asymmetries in order to significantly suppress the production of sterile neutrinos.

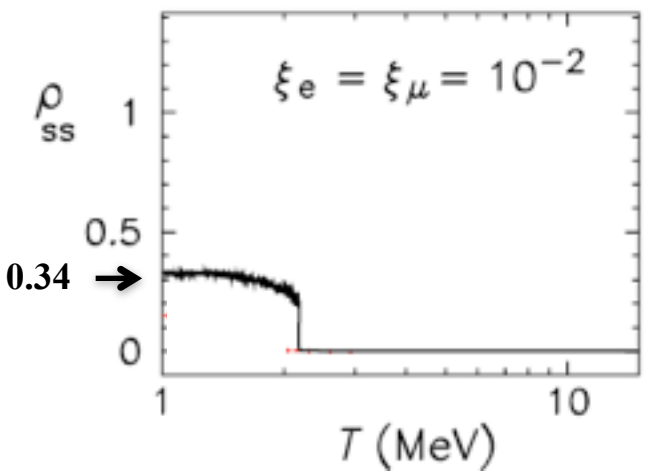
see also *Hannestad, Tamborra and Tram, 2012*

$N_{\rm eff}$ *from multi-momentum treatment*

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

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

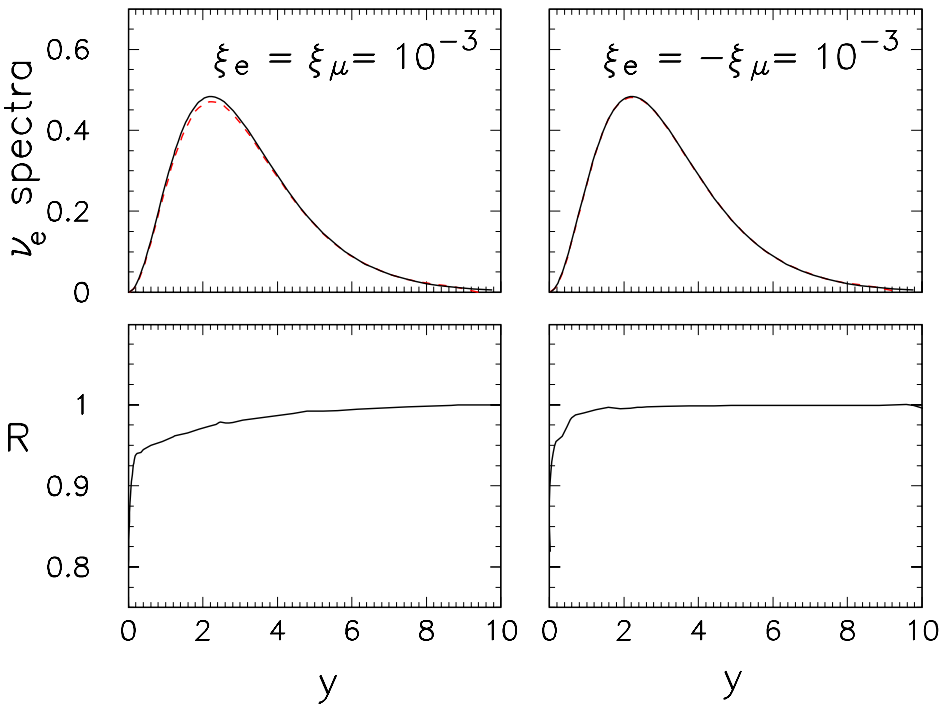




Clear indication that active are depleted since they are not fully repopulated by collisions near the temperature of neutrino decoupling

possible distortion in the active neutrino spectra

Spectral distortions at T = 1 MeV

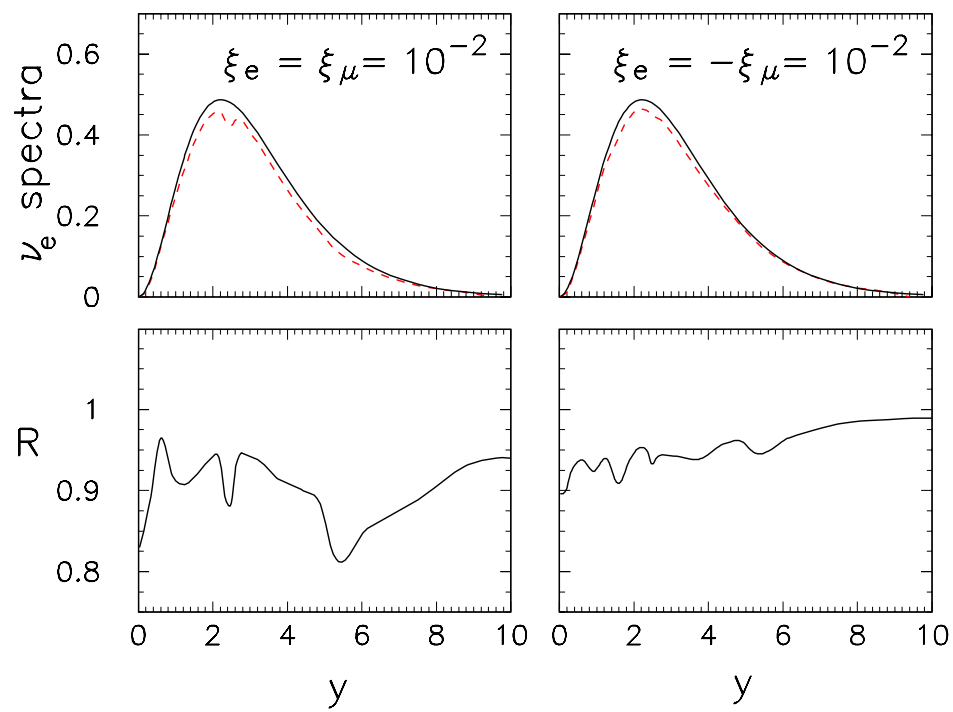


— $y^2 \rho_{ee}(y)$

— $y^2 f_{eq}(y, \xi_e)$

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

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



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

→ consequences on primordial yields

Saviano et al, 2013

Non-trivial implications on BBN

Saviano et al, 2013

Case	$\Delta N_{\rm eff}$		Y_p	^{2}H/H ($\times 10^5$)
$\lvert\xi\rvert \ll 10^{-3}$	1.0		0.259	2.90
$\xi_e = -\xi_\mu = 10^{-3}$	0.98		0.257	2.87
$\xi_e = \xi_\mu = 10^{-3}$	0.77		0.256	2.81
$\xi_e = -\xi_\mu = 10^{-2}$	0.52		0.255	2.74
$\xi_e = \xi_\mu = 10^{-2}$	0.22		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		0.247	2.56

asymmetry + ν_s

Y_p ↑

asymmetry

Y_p ↓

PArthENoPE code.

Pisanti et al, 2012