SHEP Seminars
Southampton University
23st January 2015

ν in cosmology: current bounds and new physics scenarios

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Contents

- ✓ 3ν scenario & Early Universe
    - ✓ Neutrino proprieties from cosmological probes
- ✓ Extended scenario: sterile neutrinos
    - ✓ Formalism and EoM for active-sterile evolution
    - ✓ cosmological bounds after Planck data
    - ✓ new physics scenarios
- ✓ Conclusions

3ν *Scenario*

The Standard Model includes 3 species of massless neutrinos interacting only through the weak interactions.

ν_e ν_μ ν_τ

+ anti-neutrinos

LEP data: $N_\nu = 2.984 \pm 0.008$

(PDG 2012)

3ν Scenario + Oscillations (I)

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In the last two decades, a long series of ν oscillation experiments has established that neutrinos ***are massive and oscillate***.

Indeed the 3-flavour eigenstates (ν_e, ν_μ, ν_τ) produced by charged-current weak interactions oscillate due to he fact that they are quantum superposition of the 3-mass eigenstates (ν_1, ν_2, ν_3) :

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i} |\nu_i\rangle$$

flavour eigenstates

flavour eigenstates

3ν *Scenario + Oscillations* (II)

Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix:

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\beta} & 0 \\ 0 & 0 & e^{i\gamma} \end{pmatrix}$$

$$s_{ij} = \sin\theta_{ij},\ c_{ij} = \cos\theta_{ij}$$

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$$U = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\text{atmospheric sector}} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{solar sector}} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\beta} & 0 \\ 0 & 0 & e^{i\gamma} \end{pmatrix}$$

Parameters well-known from oscillation experiments:

- ✓ mixing angles $\theta_{23} \approx 39^o$, $\theta_{13} \approx 9^o$, $\theta_{12} \approx 34^o$

- ✓ oscillations driven by 2 independent mass squared differences

$$\Delta m^2_{21} = \Delta m^2_{sol} = 7.5 \times 10^{-5}\ eV^2, \quad |\Delta m^2_{31,2}| = |\Delta m^2_{atm}| = 2.4 \times 10^{-3}\ eV^2$$

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atmospheric sector *solar sector*

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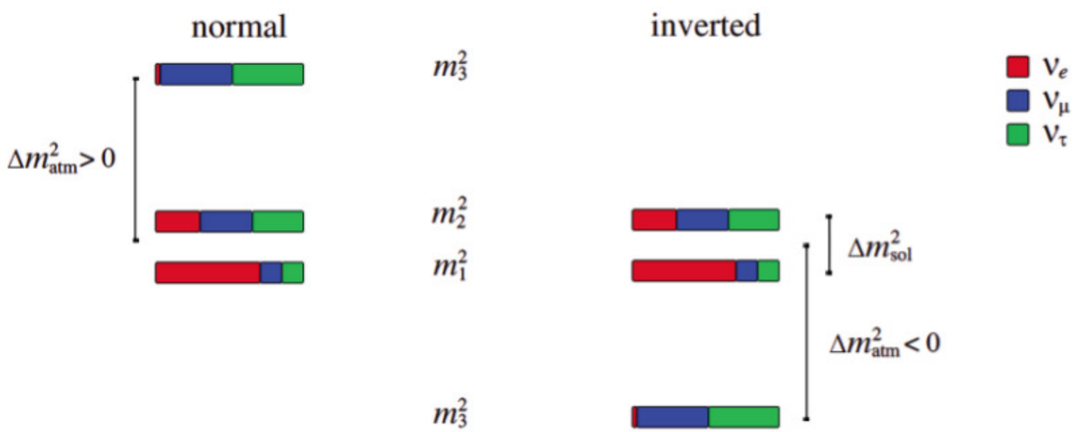
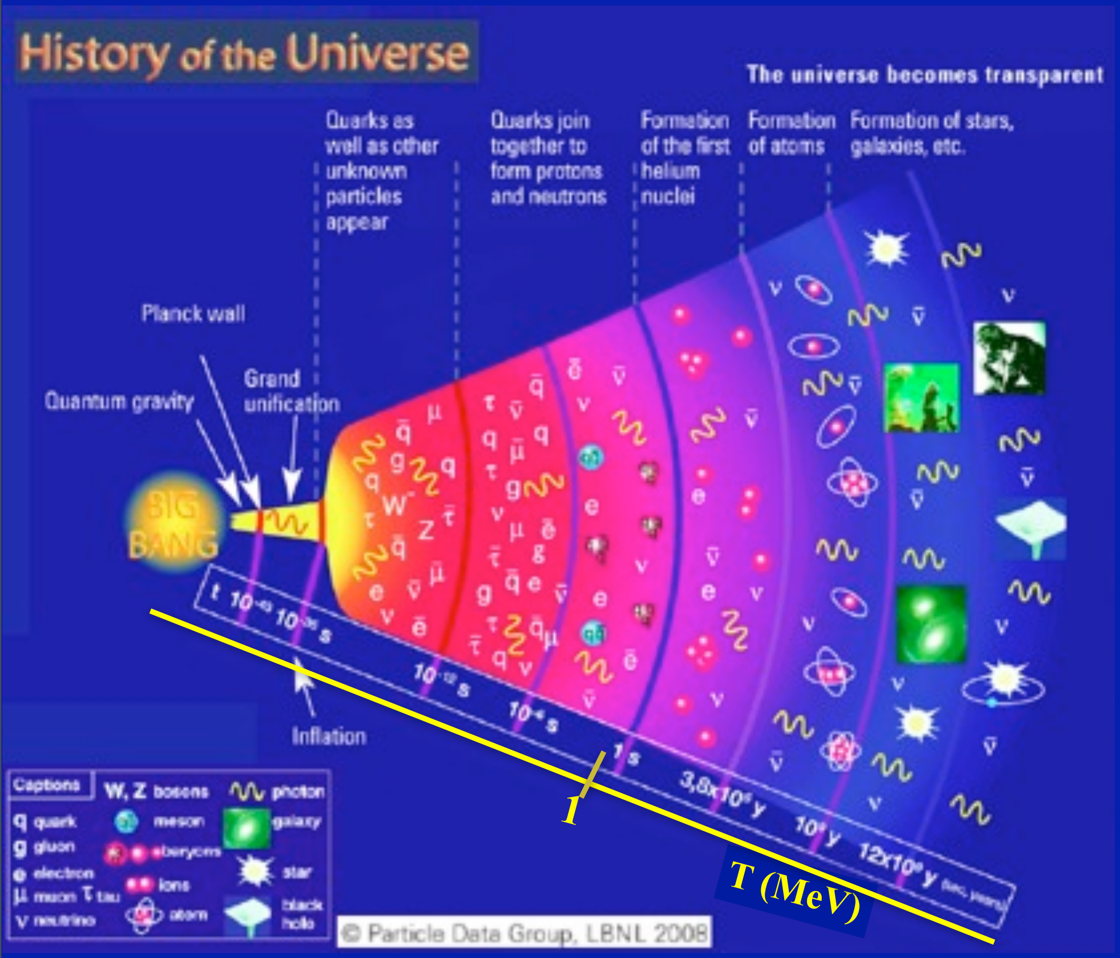
Still unknown: δ_{CP} and the *neutrino hierarchy* (i.e. the sign of Δm^2_{atm}):



ν in the Early Universe (I)



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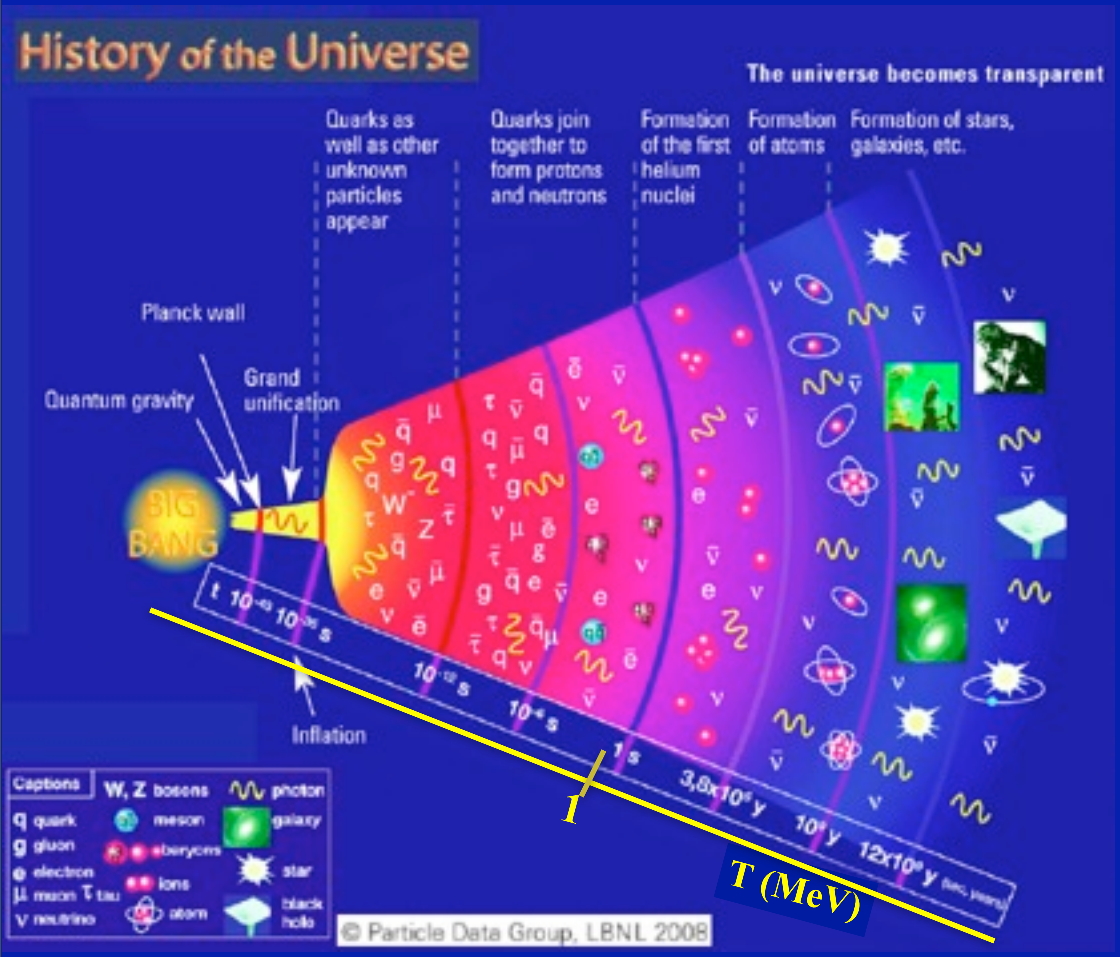

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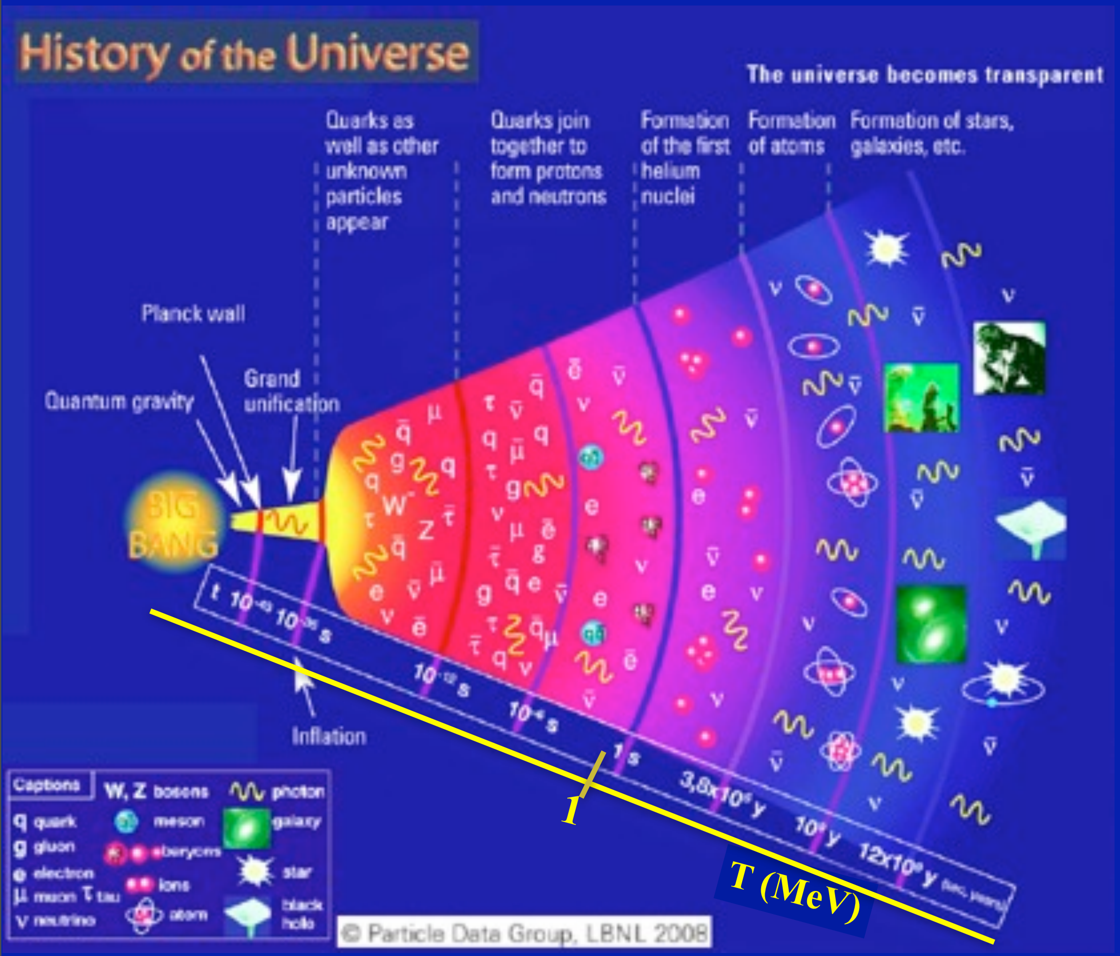

- T >> 1 MeV ⇛ ν's are populated by weak interactions
- $T_d \sim 1$ MeV (1 sec): $\Gamma_{WK}(T_d) = H(T_d)$

↓

ν decoupling by weak interactions with the primordial plasma → CNB

(Cosmic Neutrino Background)

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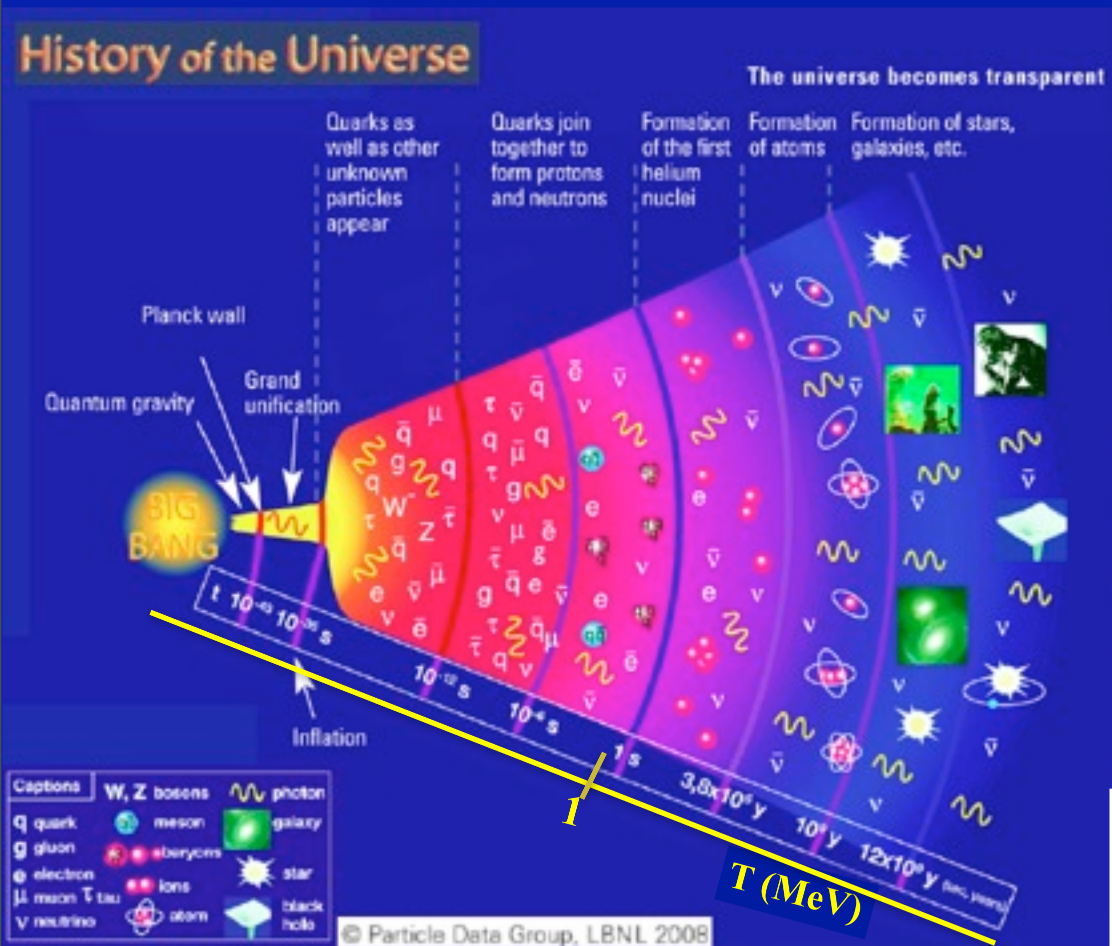

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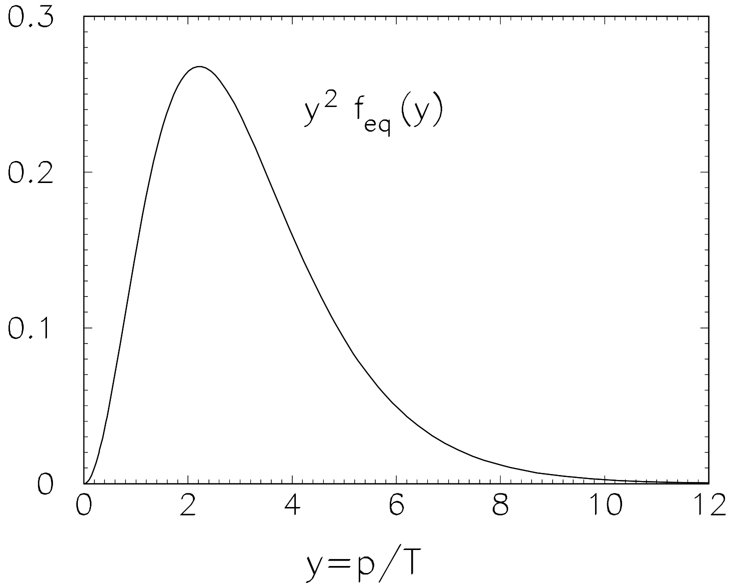
(Cosmic Neutrino Background)

CNB contributes to radiation at early times and to matter at late times

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

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

ν in the Early Universe (II)



Neutrinos mass < 1 eV → still ultra-relativistic at the decoupling

Neutrinos keep **a momentum spectrum with an equilibrium Fermi- Dirac form with temperature T**

$$f_{eq}(p,T) = \frac{1}{e^{p/T}+1}$$

- In the ***standard cosmological scenario***, neutrinos of different flavours are produced with the same energy spectrum (except for small spectral distortions due to a non-instantaneous neutrino decoupling)

no effect from the oscillations among the 3 flavour states in the standard scenario.

- In non-standard scenarios (primordial neutrino asymmetry, sterile neutrinos, low reheating)

→ Oscillations can lead to cosmological consequences, depending on the temperature

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

$\Delta N =$ 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

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

$\frac{n}{p} \to 1/7$ including neutron decays

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

Helium mass fraction

Abundance of light elements predicted as function of:

- ➢ standard scenario: $\omega_b = \Omega_b h^2$
  (equivalently $\eta_B = n_B/n_\gamma$)

- ➢ non-standard: $\omega_b = \Omega_b h^2$
  N_{eff} (>3)
  ξ_ν (chemical potential)

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BBN code: PArthENoPE (Pisanti et al, 2008)
numerical solution of a set of differential equations governing the evolution of each nuclide species

- weak rates (known at 0.1% level)
- neutron lifetime τ_n (=880.1± 1.1 s; *PDG 2012*)
- nuclear rates

ν and Big Bang Nucleosynthesis

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

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

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

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

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.

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

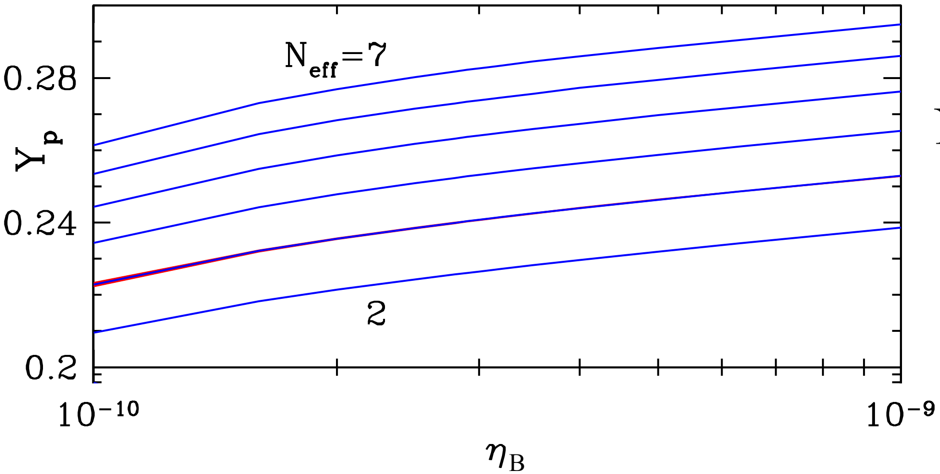
(γ, e, ν, x)

$\hookrightarrow \propto N_{\rm eff}$

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:

No strong indication for $\Delta N_{eff} > 0$ from BBN alone

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

Hamann et al, 2011

Mangano and Serpico. 2012

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

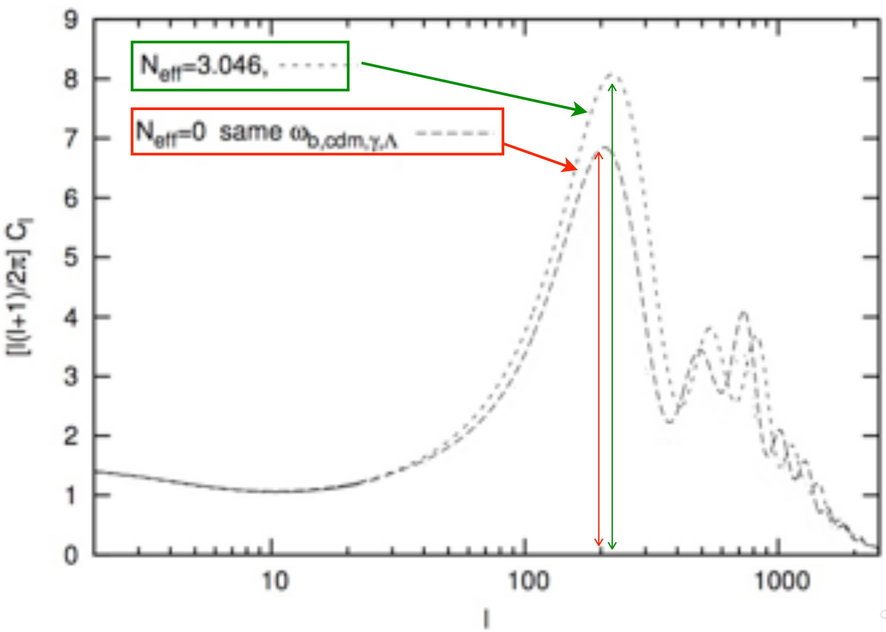
$N_{eff} = 3.28 \pm 0.28$

Cooke, Pettini et al., 2013

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

ν and CMB and LSS

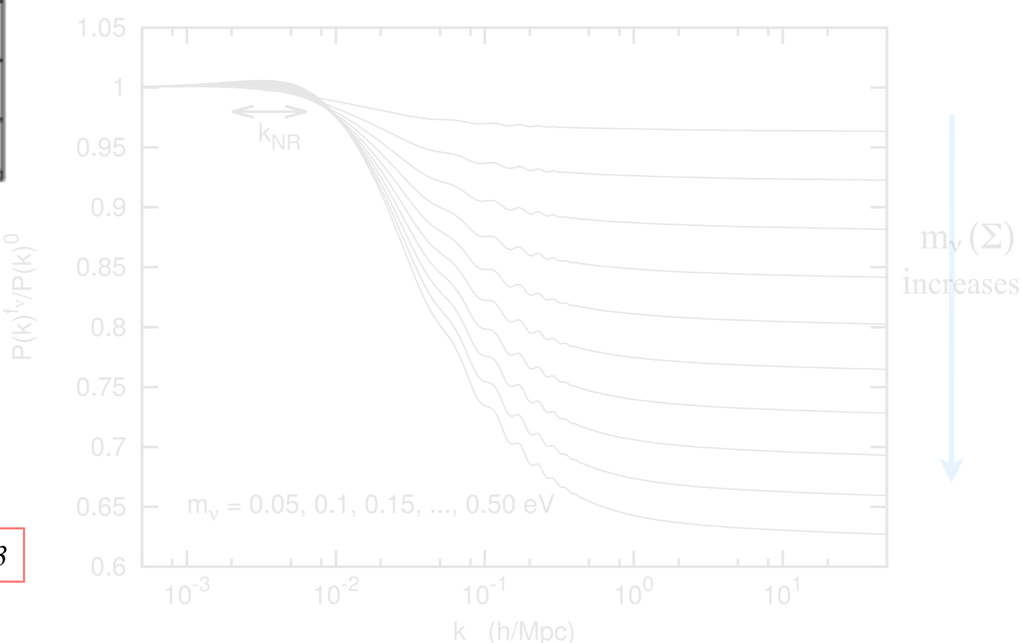
ν's and their masses effect the PS of temperature fluctuations of CMB (T < eV) and the matter PS of the LSS inferred by the galaxy surveys.



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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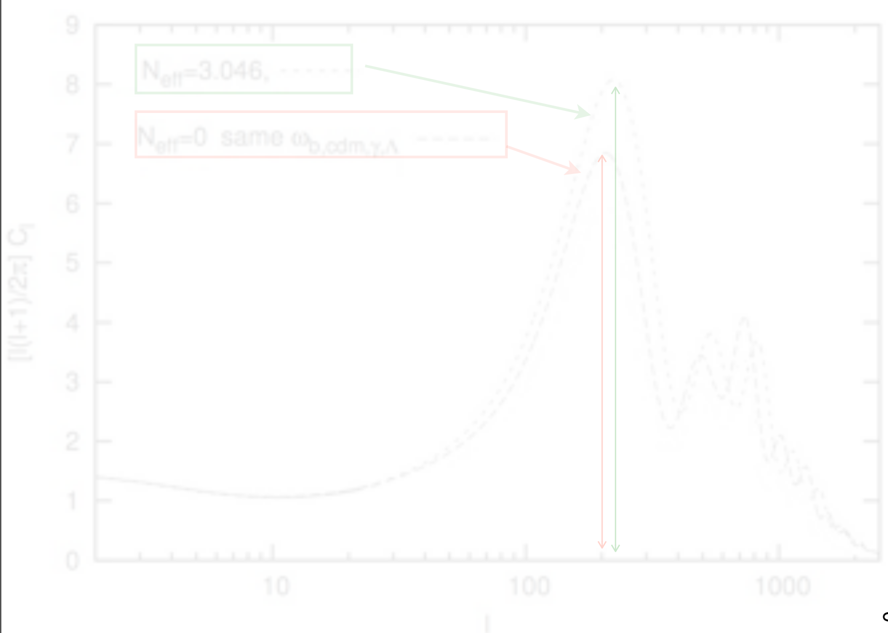
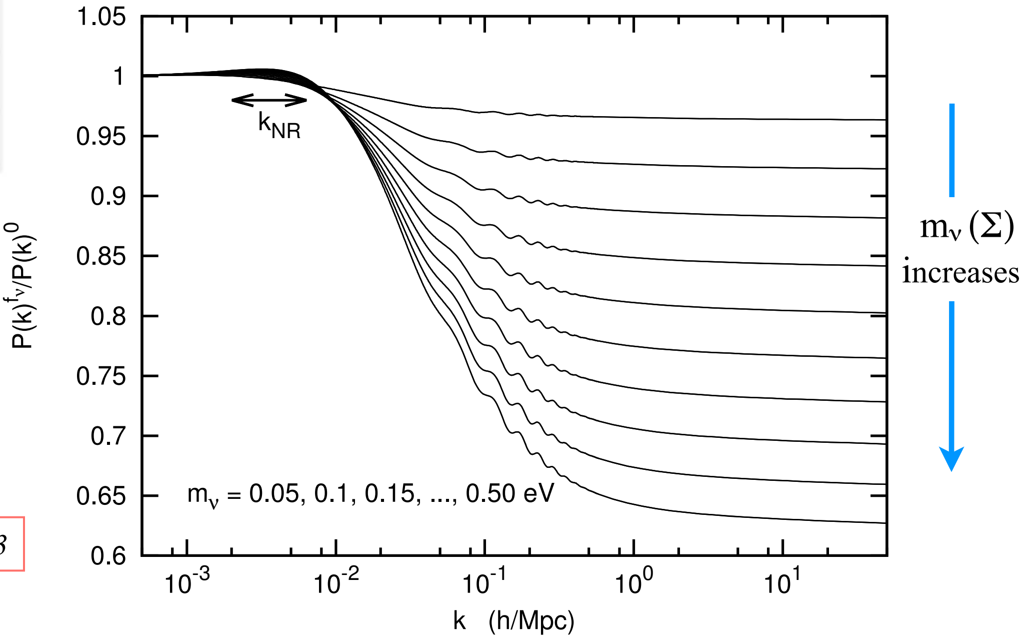


The small-scale matter power spectrum $P(k > k_{nr})$ is reduced in presence of massive ν:

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



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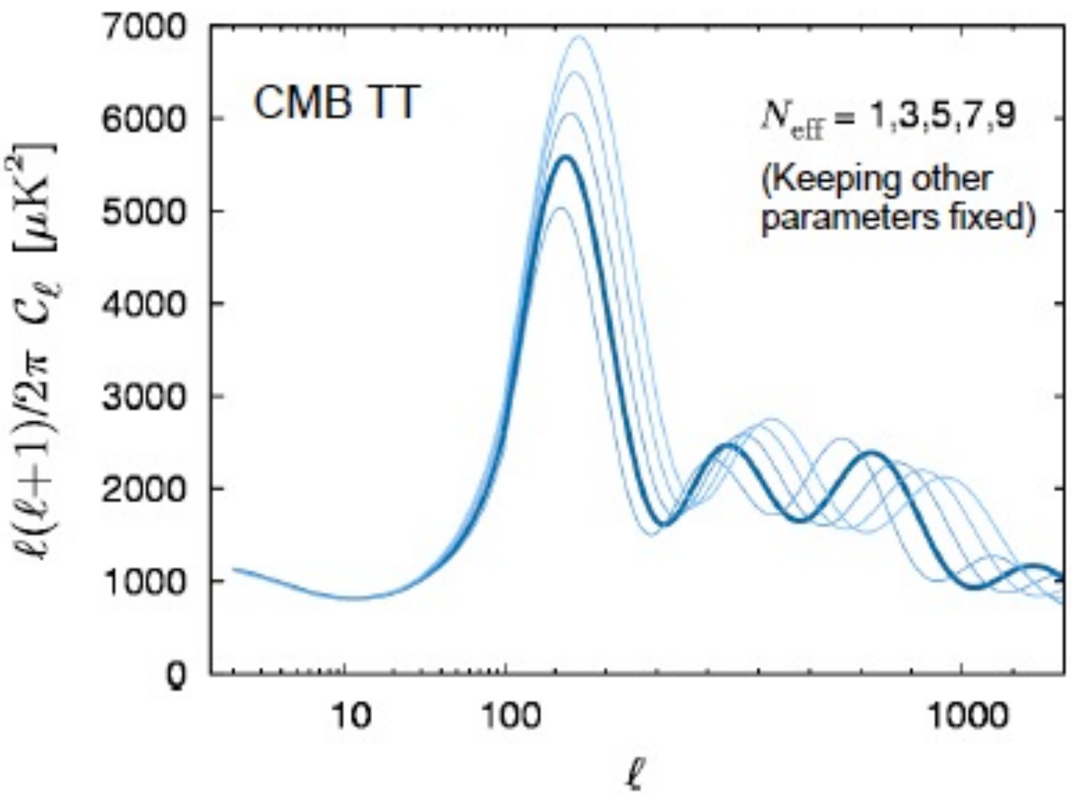
Extra radiation impact on CMB

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

constraints N_{eff} from the CMB Spectrum



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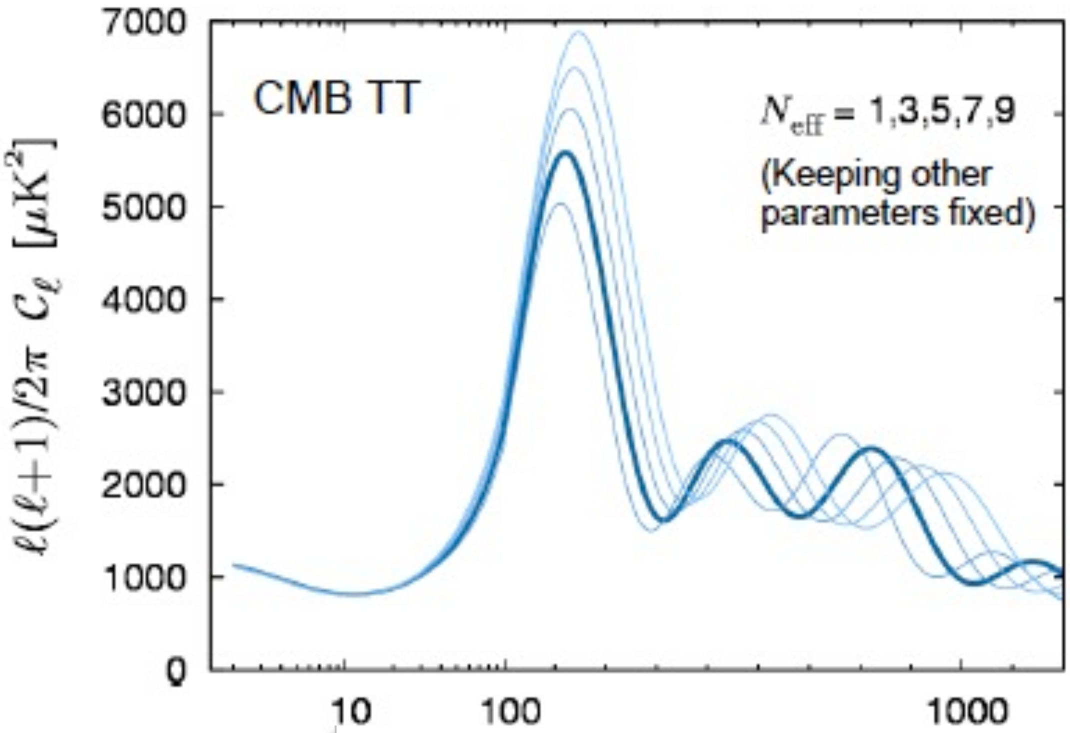


Same data used to measure other cosmological parameters

basic parameters of ΛCDM:

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

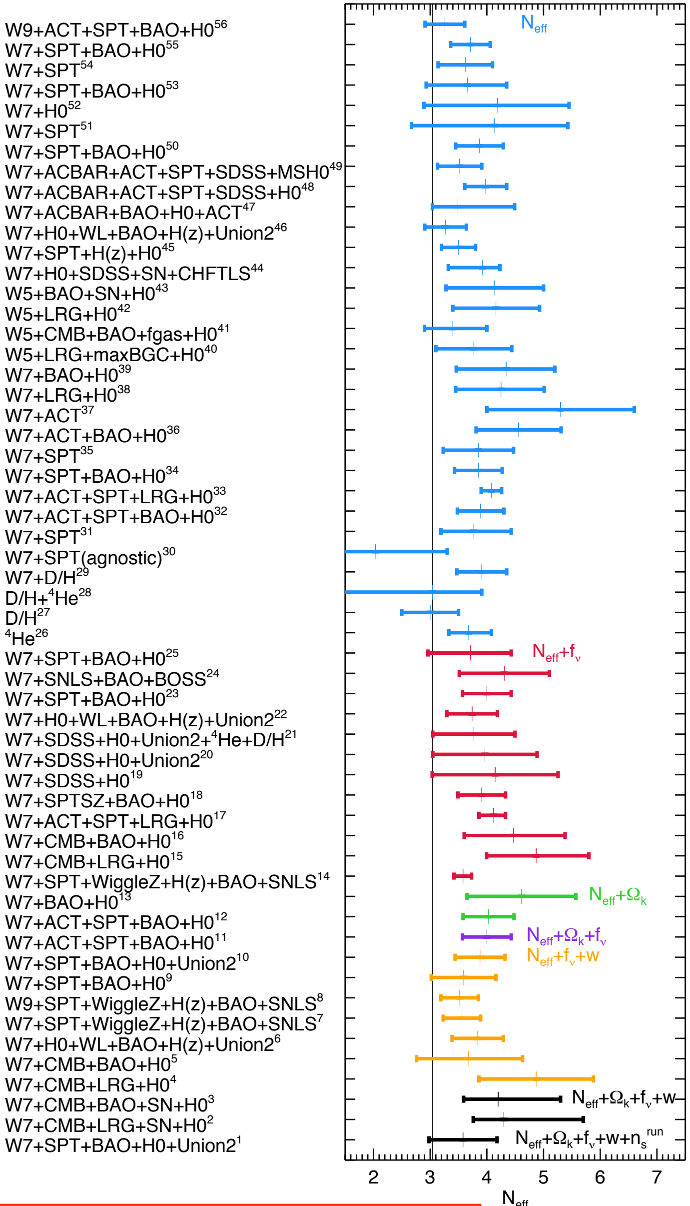
+ derived parameters

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

→ ***degeneracies***

→ *necessary to combine with other cosmological probes*

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



Riemer-Sørensen, Parkinson & Davis, 2013

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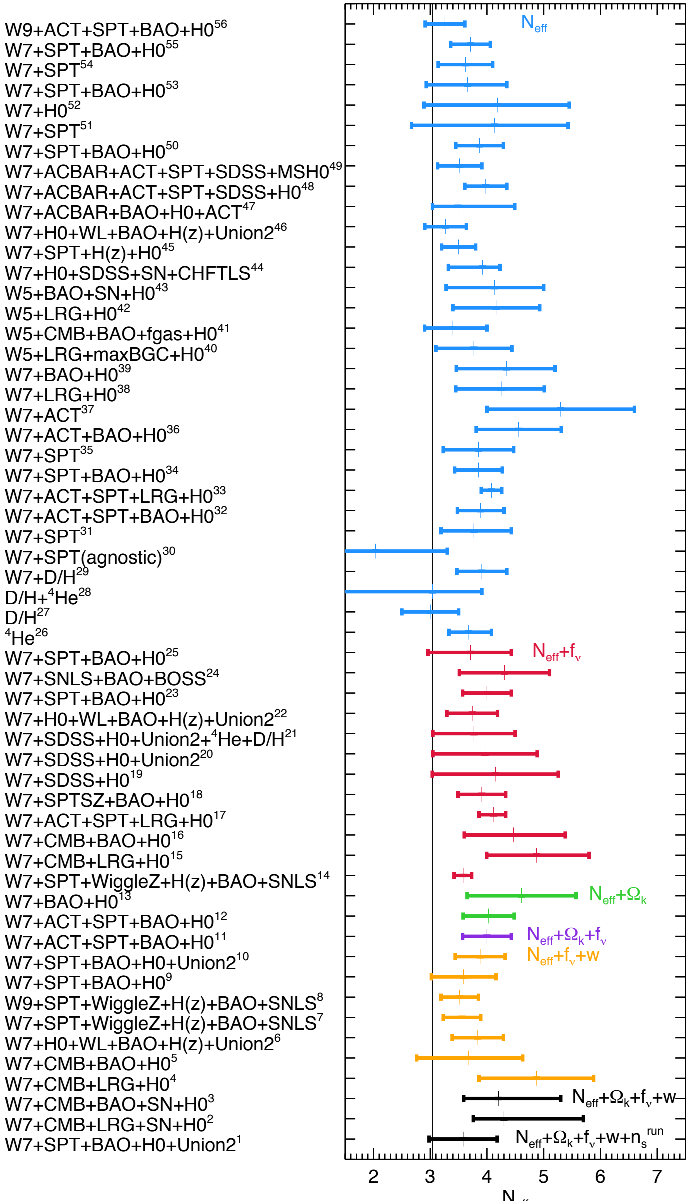

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Summarizing:

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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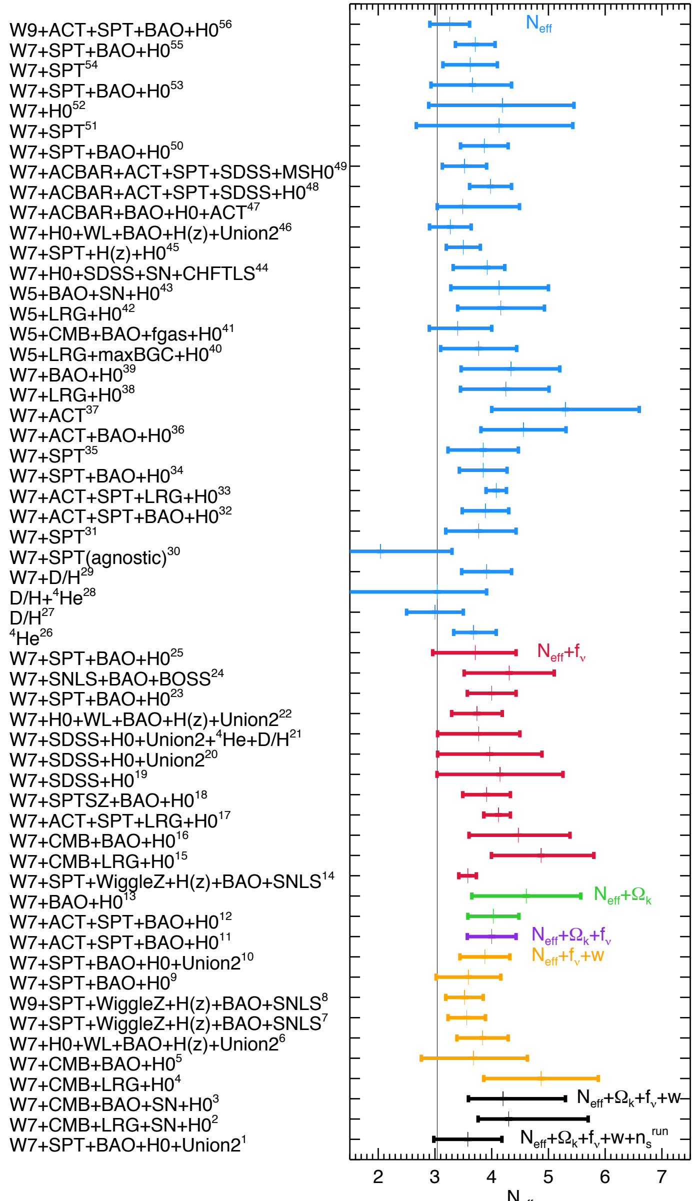

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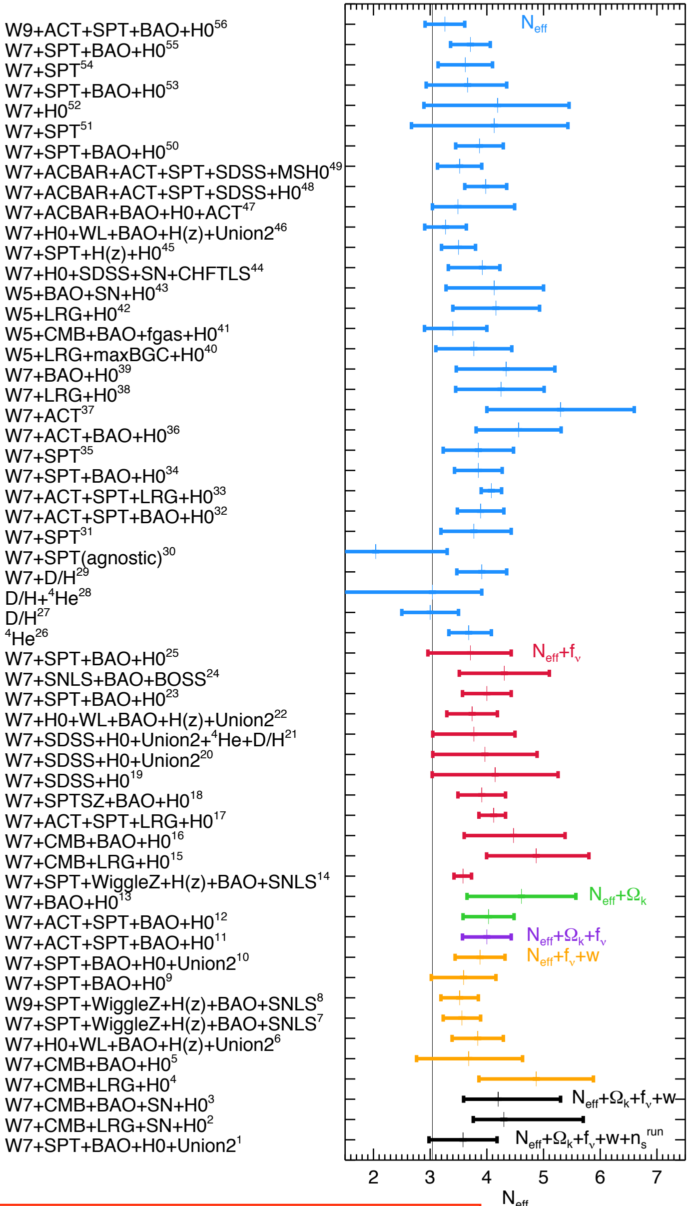

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Hints for extra radiation reduce over the years

Slight preference for N_{eff} >3.046

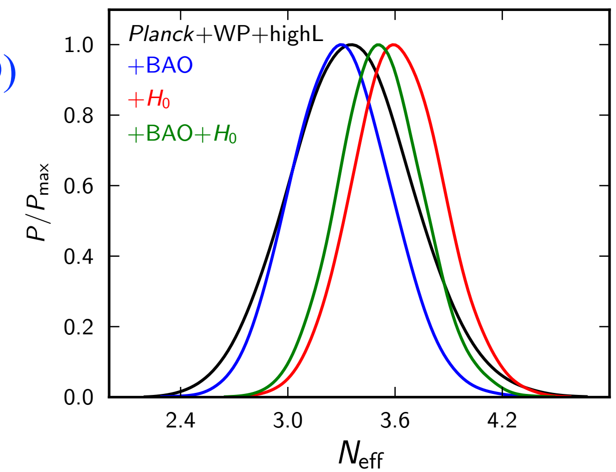
N_{eff} *and* Σm_ν *constraints* **after Planck**

(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*



Planck XVI, 2013

- For 3 degenerate active ν :

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

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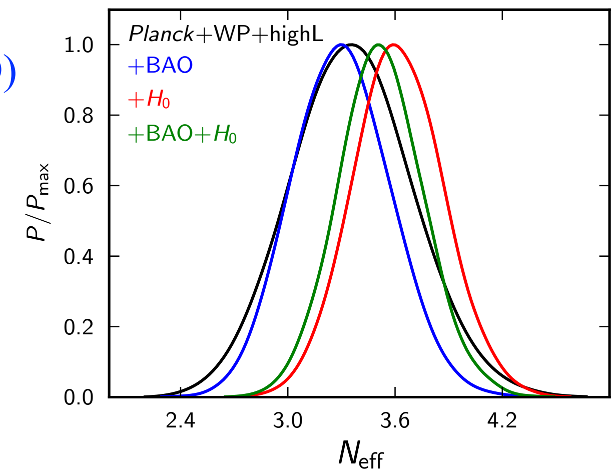

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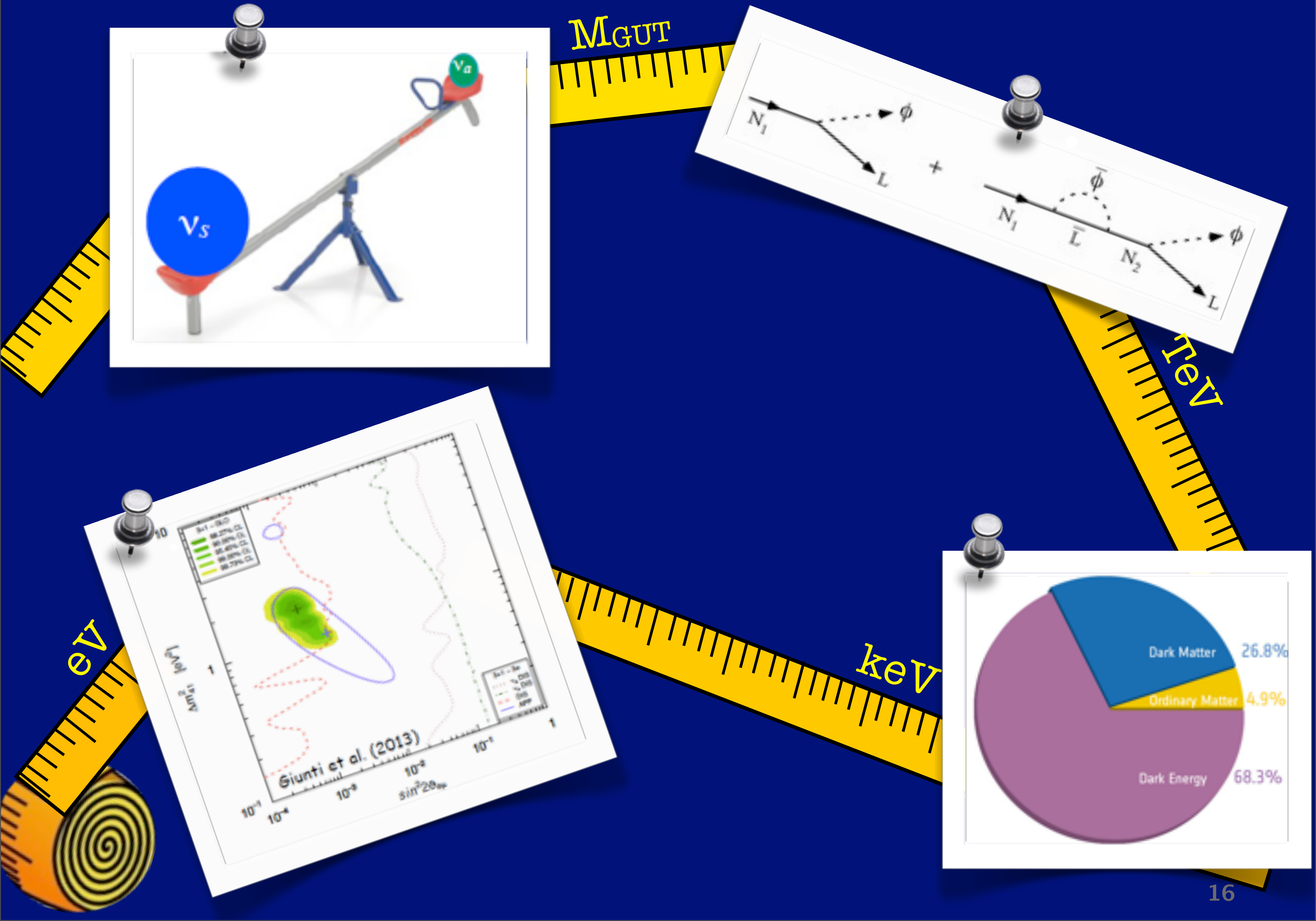
Second release to appear very soon….

only rumors from conference presentations…

Extended scenario:

sterile neutrinos

Sterile Neutrinos



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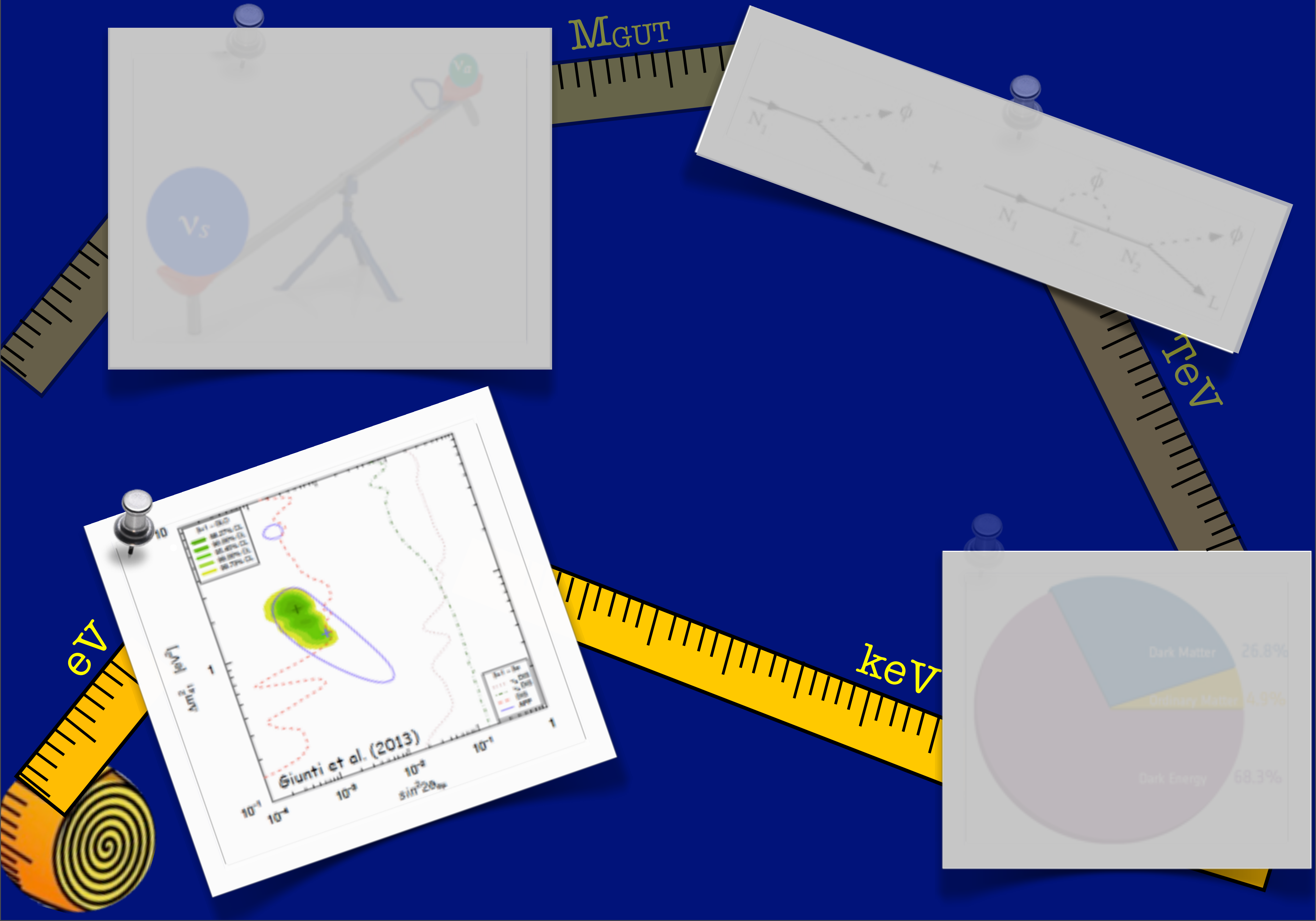
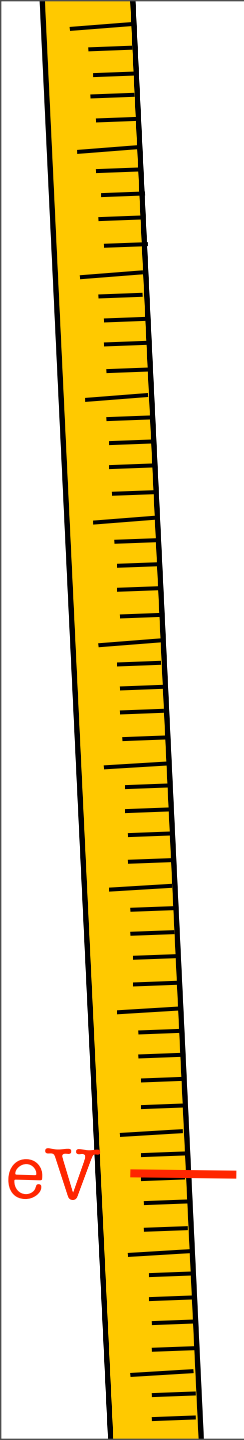


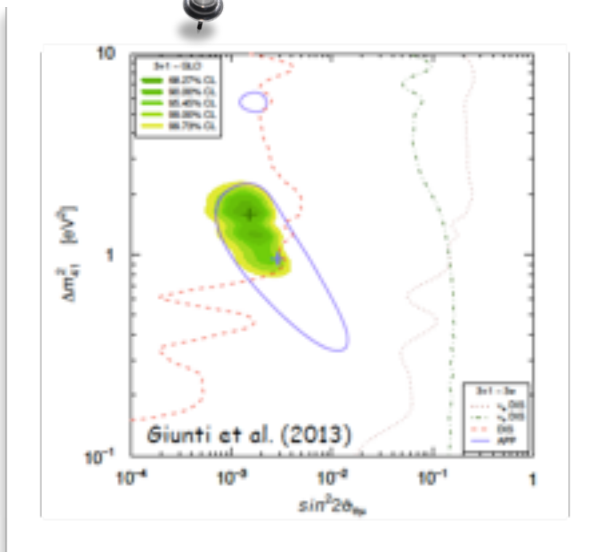
eV Sterile Neutrino



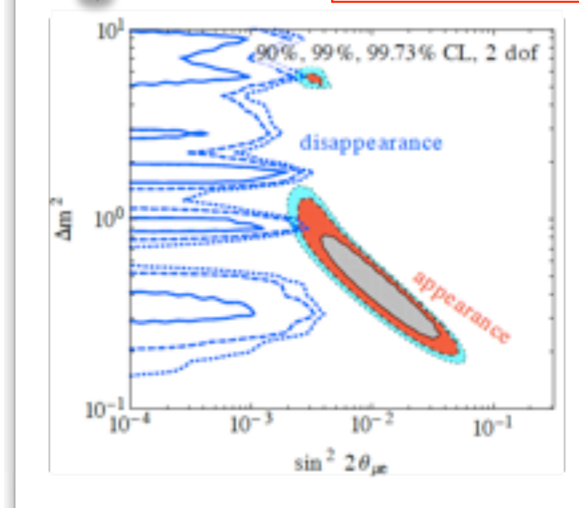
eV Sterile Neutrino

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

- LNSD
- MiniBooNE
- Gallium
- Reactor



J. Kopp et al, 2013



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

3+1, 3+2 schemes

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

eV

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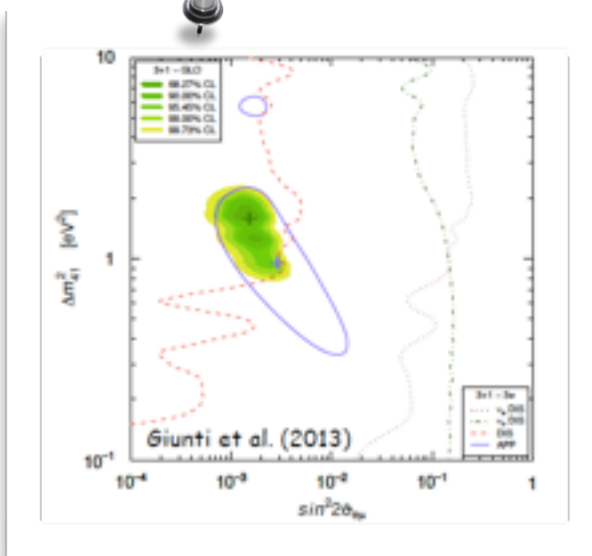

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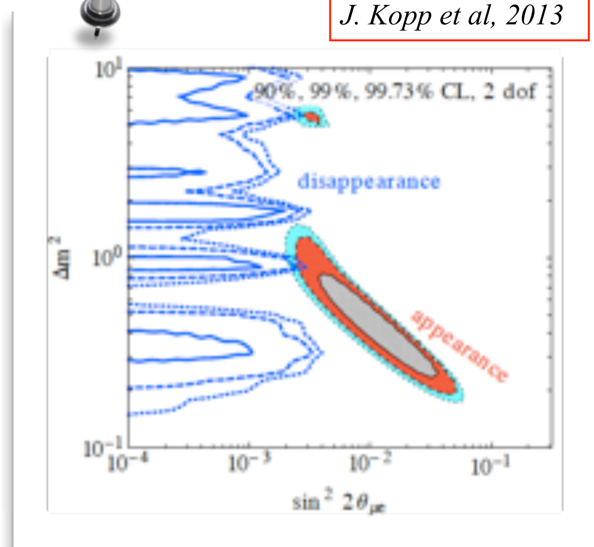

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Are eV ν_s compatible with cosmology?

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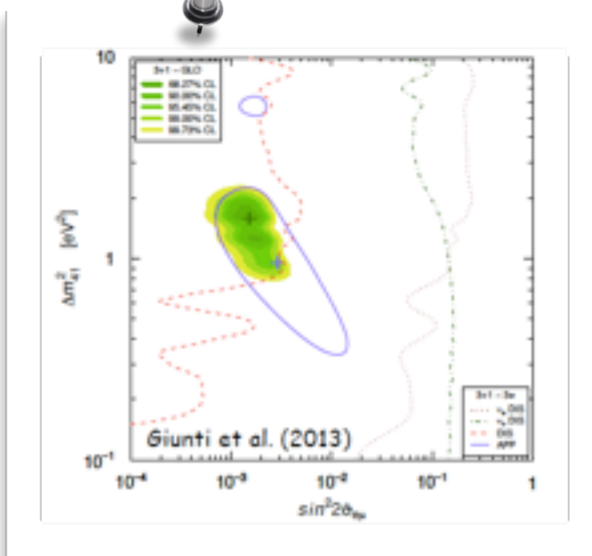

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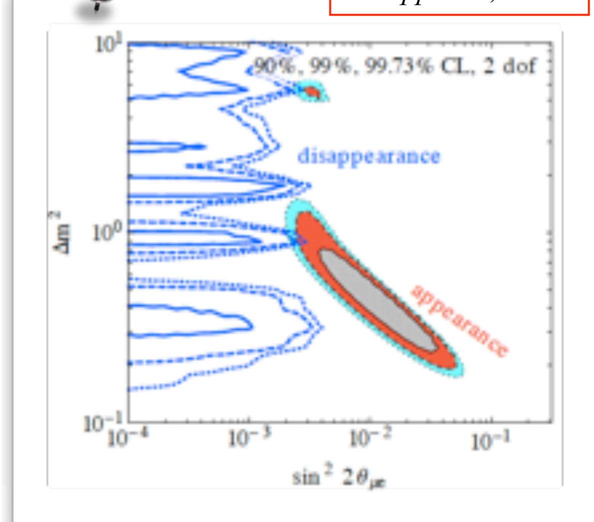

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Are eV ν_s compatible with cosmology?

...is necessary to assess the conditions under which they are produced

Active-sterile flavour evolution

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

Stodolsky , Raffelt and Sigl,1992 ; Sigl and Raffelt 1993;

Effects to take into account for the *ν* propagation:

1. **Interactions with the external background medium**
   - Refractive effects (forward scatterings)
   - Collisions which destroy the coherence of the evolution, influencing the behavior of the mixing

2. **Neutrinos interactions among themselves** (refractive *self-interactions*): the *ν* gas is so dense, that *ν* form a background medium, making the problem a ***non-linear*** phenomenon

Active-sterile flavour evolution

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

Stodolsky , Raffelt and Sigl,1992 ; Sigl and Raffelt 1993;

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particle distribution functions (occupation number) ➜ ***flavour contents***

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ϱ_{ss} → ***sterile abundance***

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encode the phase informations and vanish for zero mixing

Equation for the flavour evolution

Evolution equation:

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

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Vacuum term

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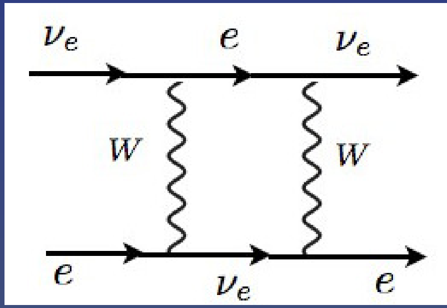
MSW effect with background medium
(refractive effect) $\propto G_F$

→ 2th order term: "symmetric" matter effect

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



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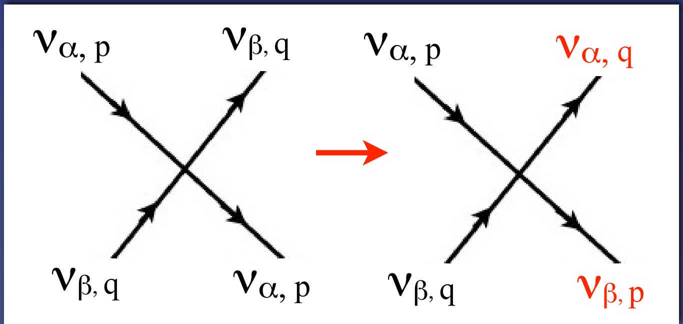
self-interactions of ν with the ν background:

off-diagonal potentials ➠ non-linear EoM



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

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

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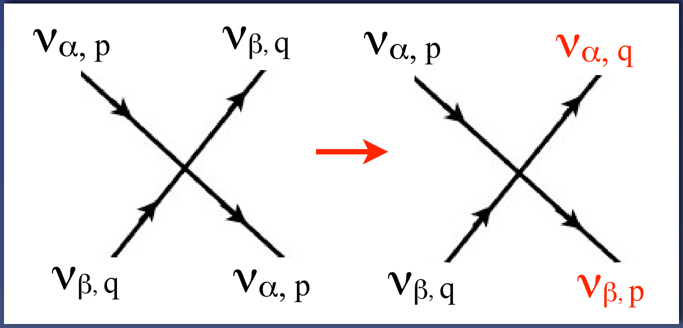

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$C[\varrho]$ Collisional term $\propto G_F^2$

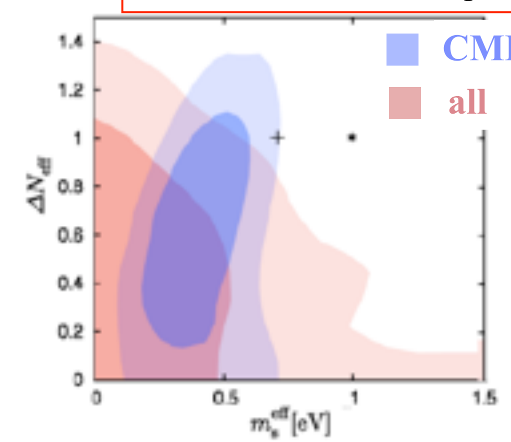
creation, annihilation and all the momentum exchanging processes

Joint constraints on N_{eff} and Σm_ν

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

Planck XVI, 2013

Hamann and Hasenkamp, 2013

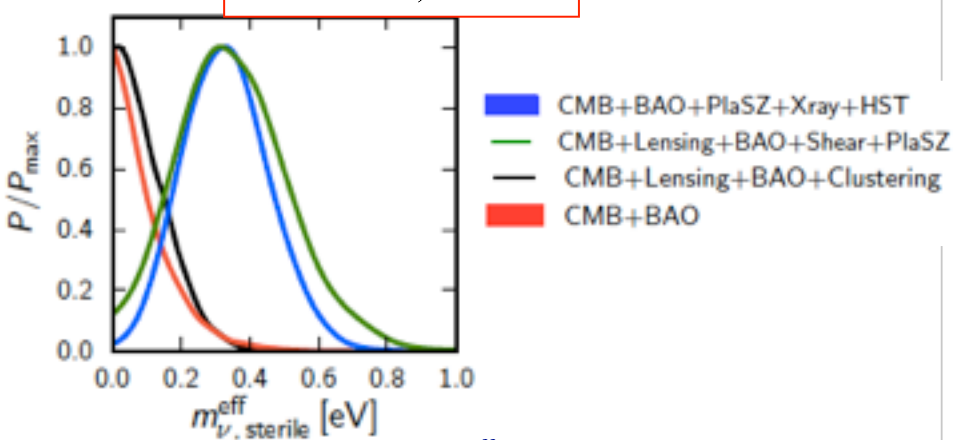


all= CMB+H0+ C+ CFHTLens

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

$m^{eff}_{\nu s} = 0.41$+-0.13 eV (1σ)

L. Verde et al, 2014



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

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

Bounds on active-sterile mixing parameters after Planck

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

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

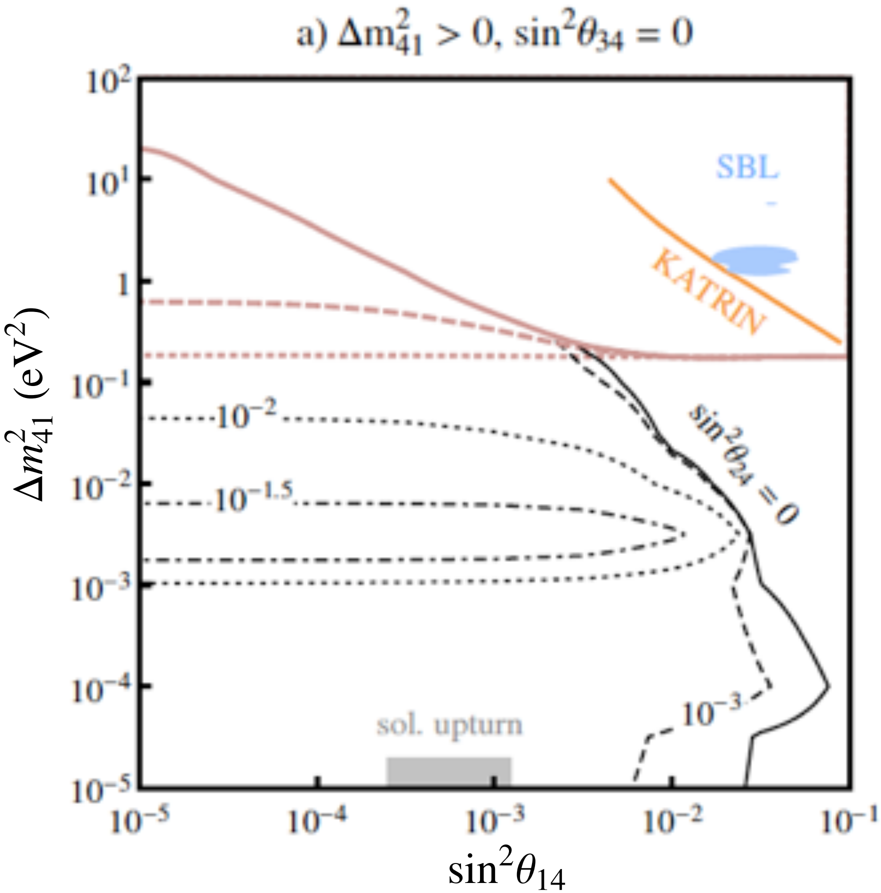
- ✔ sterile mass-square difference $\Delta m^2_{st} = \Delta m^2_{41}$ (+ 2 active) $10^{-5} \leq \Delta m^2_{41}/\mathrm{eV}^2 \leq 10^2$

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

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

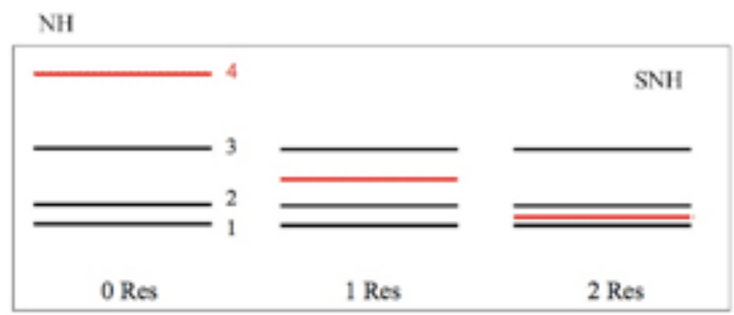
Bounds on active-sterile mixing parameters after Planck

... our results



Mirizzi et al 2013, arXiv1303.5368

- ✓ Normal active hierarchy
- ✓ Normal sterile hierarchy

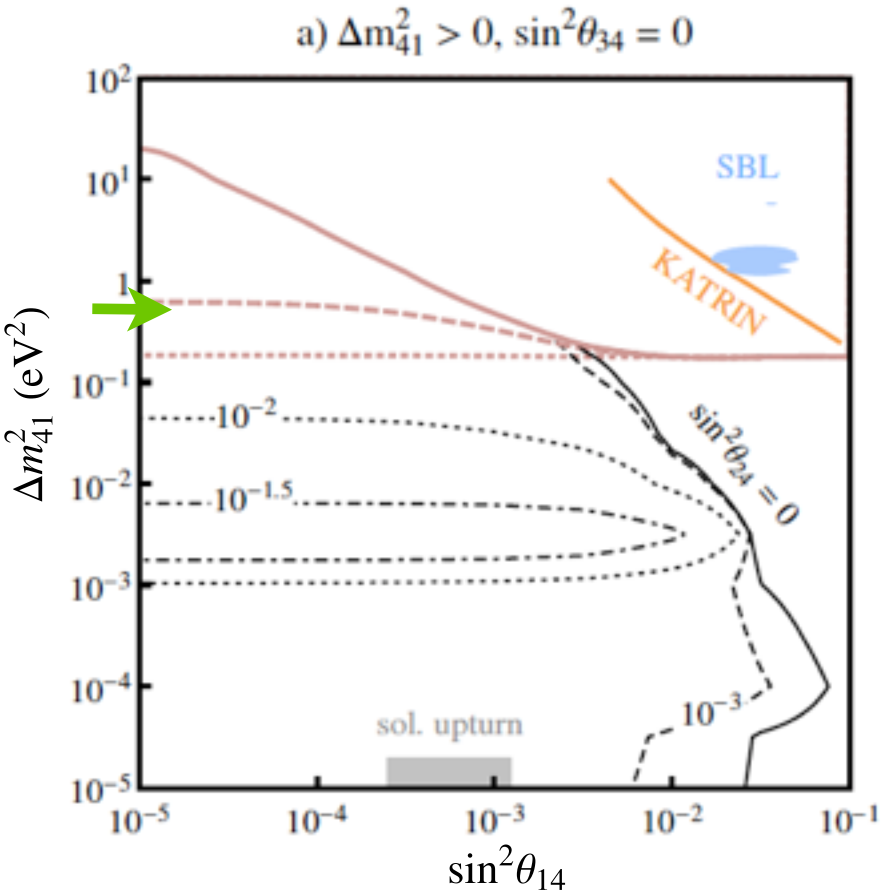


Radiation bounds

- 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.

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



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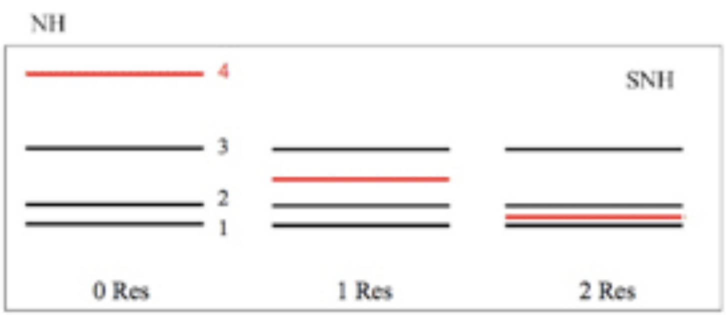

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Note: above m ~ $\mathcal{O}$(1 eV), sterile ν are not relativistic anymore at CMB → **NO radiation constraint**

BUT mass constraints become important

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

Mirizzi et al 2013, arXiv1303.5368

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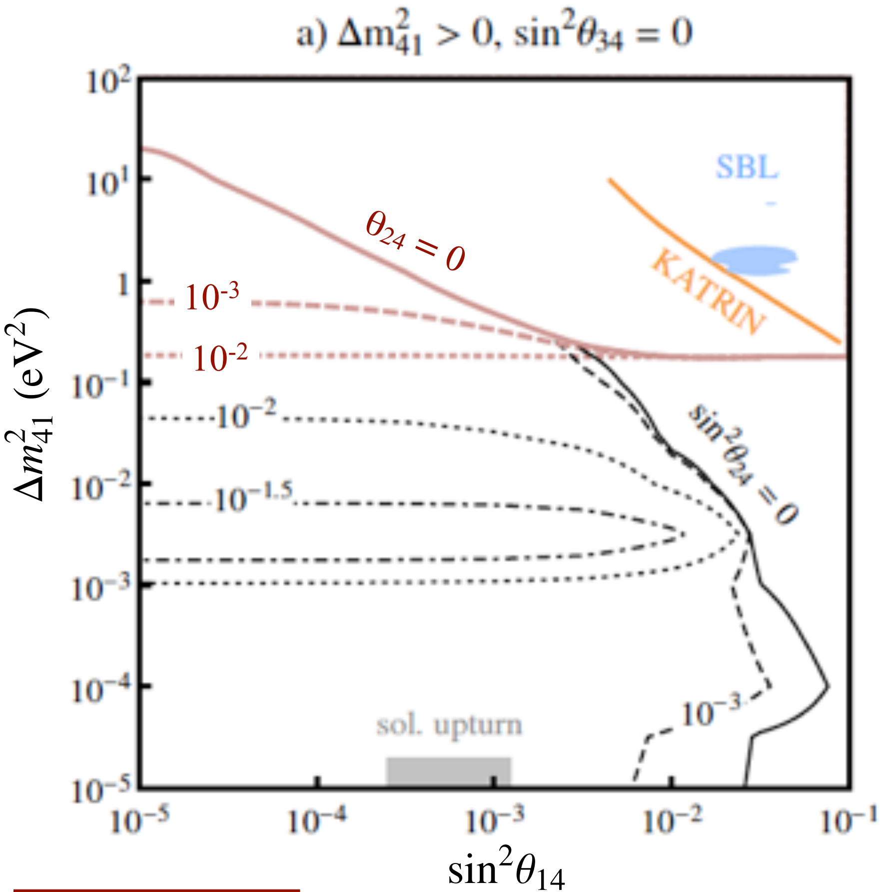

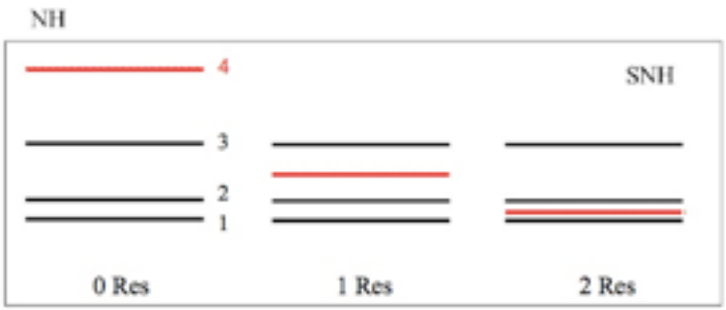

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- Red curves imposing the 95% C.L. Planck constraint $m^{eff}_{\nu s} < 0.42 \Leftrightarrow \Omega_\nu h^2 < 4.5\ 10^{-3}$ on ours

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

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Bounds on active-sterile mixing parameters after Planck

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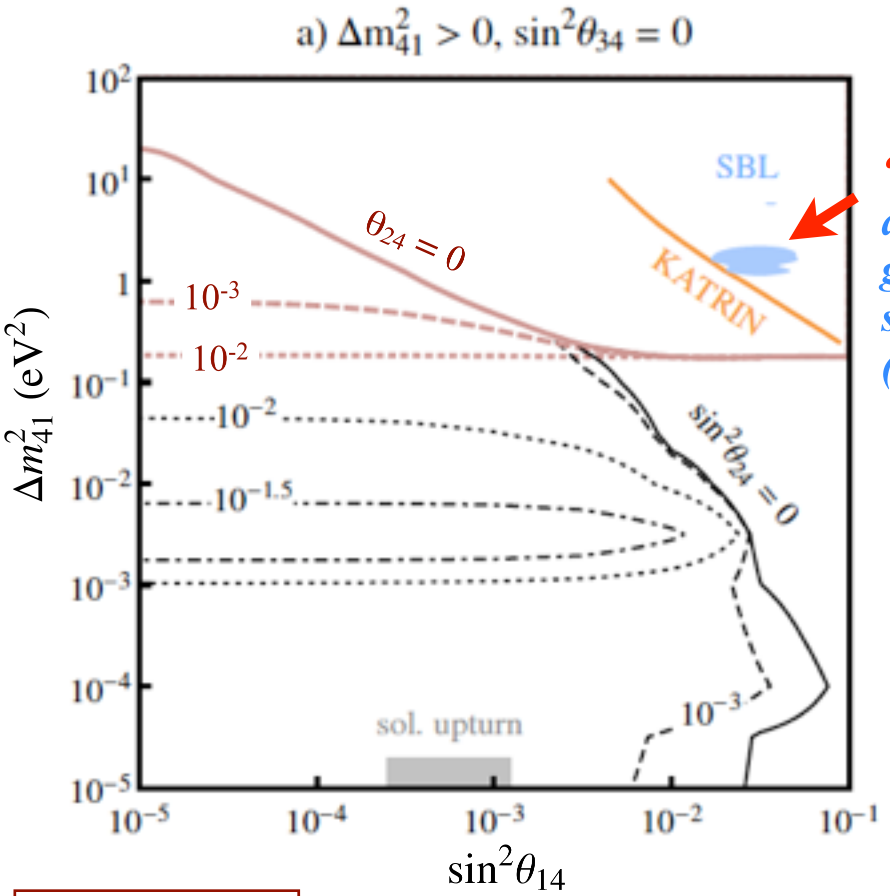

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"eV sterile ν "
allowed region from global analysis of SBL $\sin^2\theta_{24} = 10^{-2}$, 95%C.L. (Giunti et al.)

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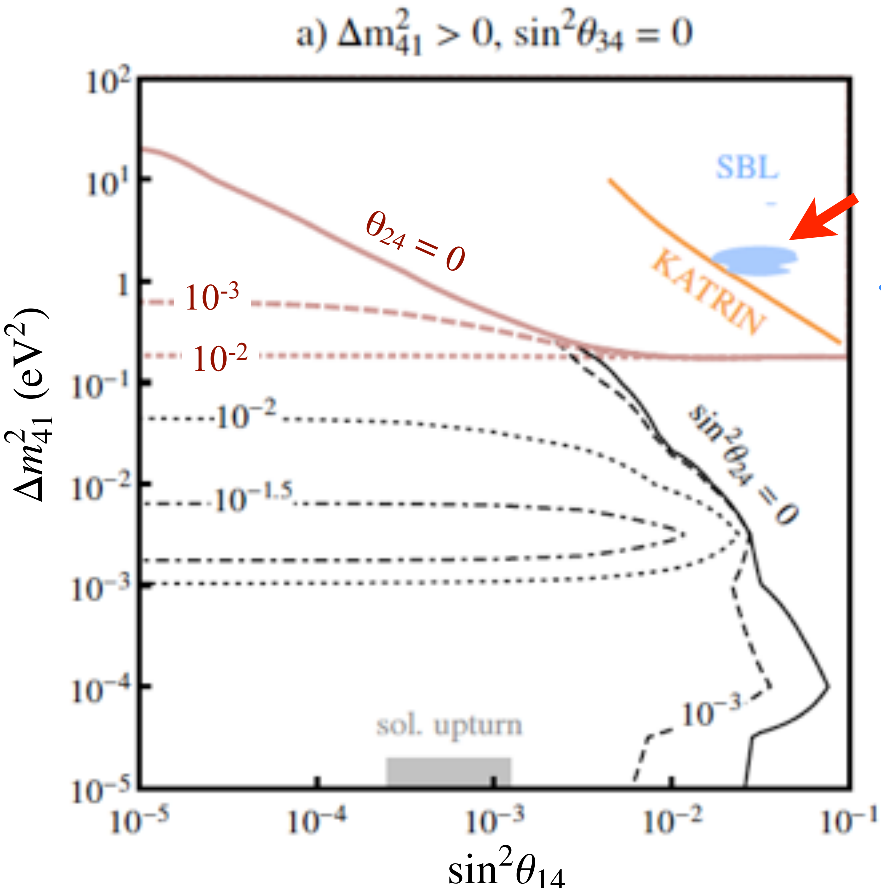

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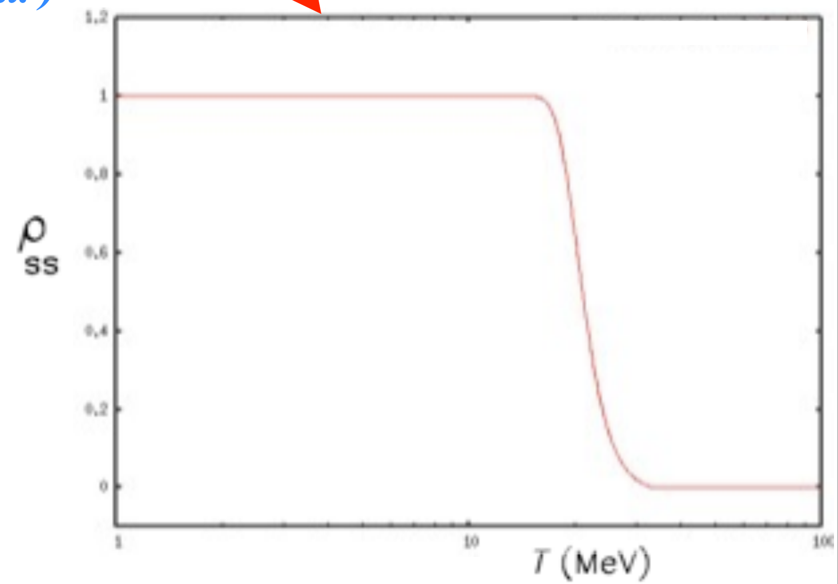

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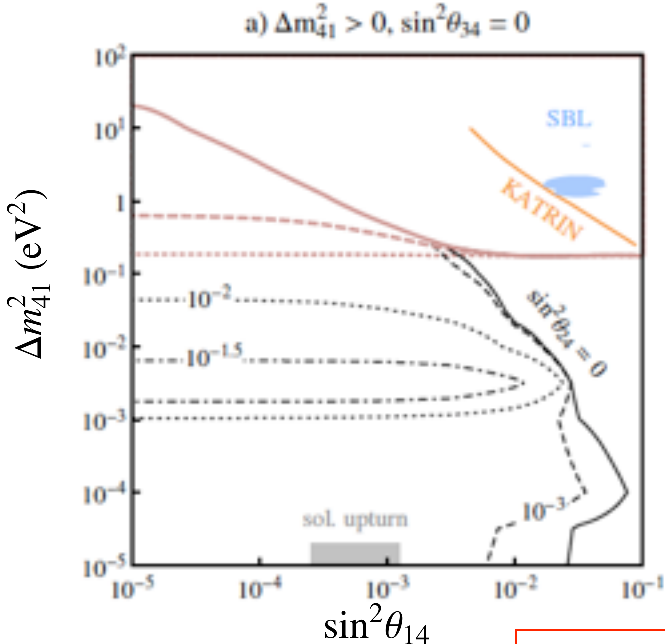
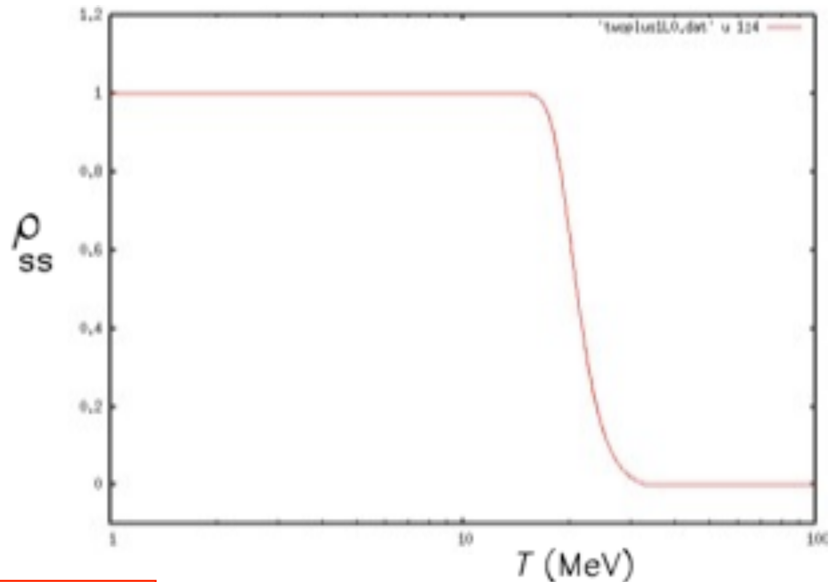




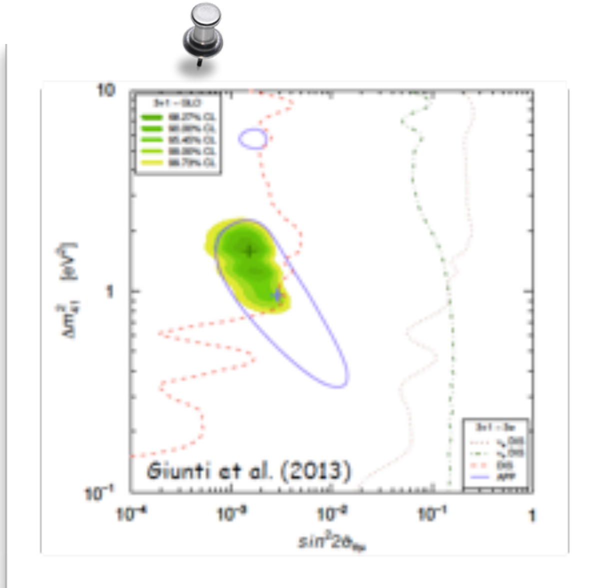
Mirizzi et al 2013, arXiv:1303.5368

- *The sterile neutrino parameter space is severely constrained.*
- ***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*

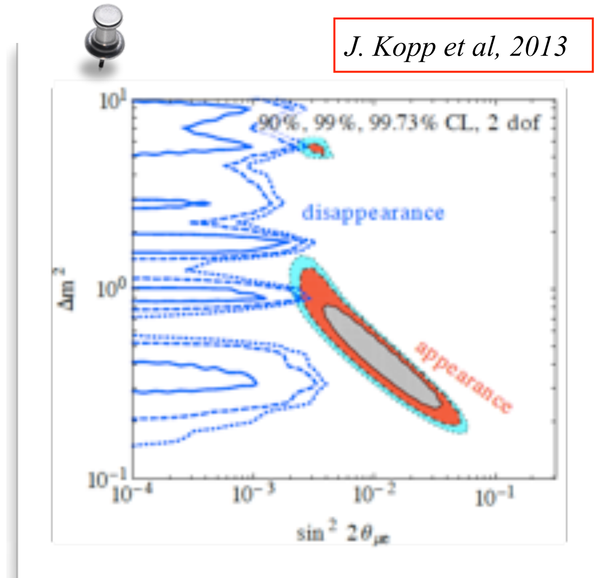
eV Sterile Neutrino

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

- LNSD
- MiniBooNE
- Gallium
- Reactor



J. Kopp et al, 2013



(…sometimes in tension among themselves….)

3+1, 3+2 schemes

eV

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

Are eV ν_s compatible with cosmology? NO

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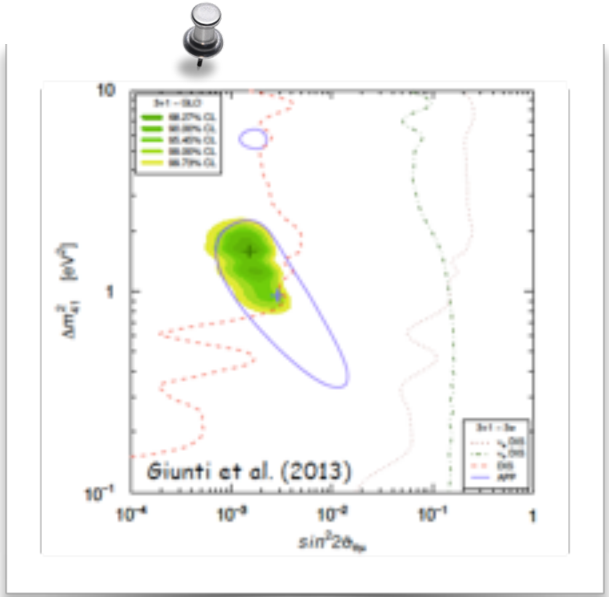

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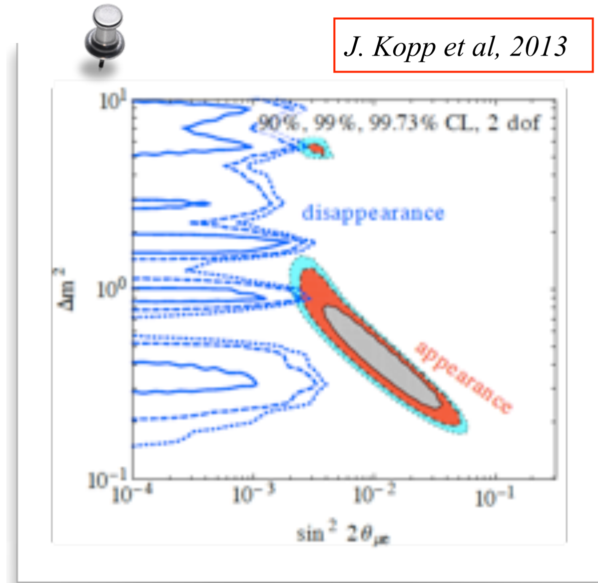

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Does exist an escape route?

A possible solution: suppression of ν_s production

- ***Different mechanisms:***

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

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

   ⚠ Non trivial implication for BNN

   Saviano et al., 2013

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

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

   ⚠ Implications on BBN

   ⚠ Fully unconstrained model

   Hannestad et al., 2013,
   Dasgupta and Kopp 2013,
   Archidiacono et al., 2014

3. **low reheating scenario**

   ✓ sterile abundance depends on reheating temperature

   ⚠ simplified scenarios

   Gelmini, Palomarez-Ruiz, Pascoli, 2004
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Sterile production with primordial neutrino asymmetry

Foot and Volkas, 1995

Introducing $L = \dfrac{n_\nu - n_{\bar{\nu}}}{n_\gamma}$ → *Suppress the thermalization of sterile neutrinos* (ρ_{ss} ↓)
(Effective ν_a-ν_s mixing reduced by large matter term ∝ L)

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

⇩

large L are necessary to reach the suppression

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

Sterile production by neutrino asymmetry

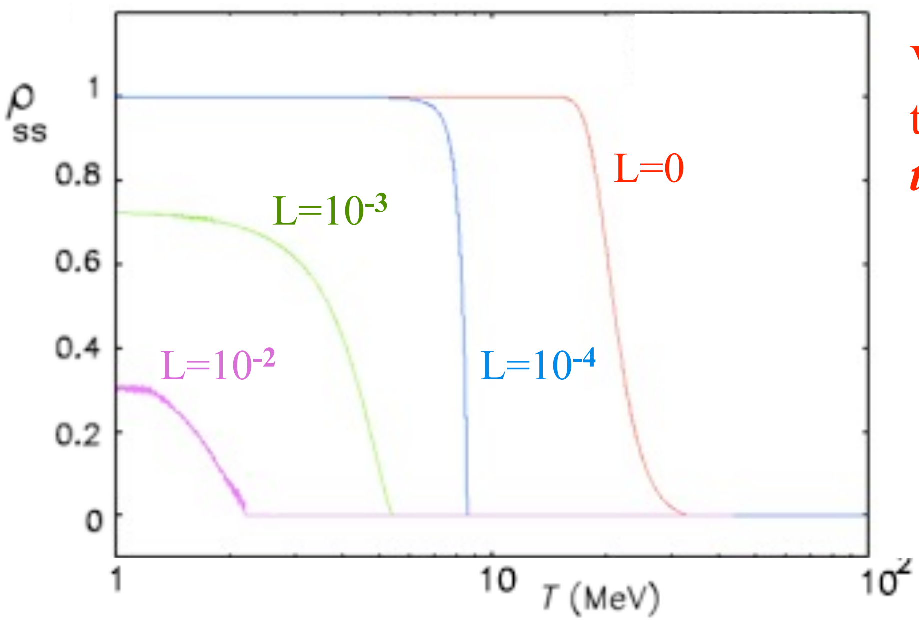
✓ ρ_{ss} and distortions of ν_e spectra as function of the ν ***asymmetry parameter***

→ evaluation of the cosmological consequences

✗ Very challenging task, involving time consuming numerical calculations

→ few representative cases

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



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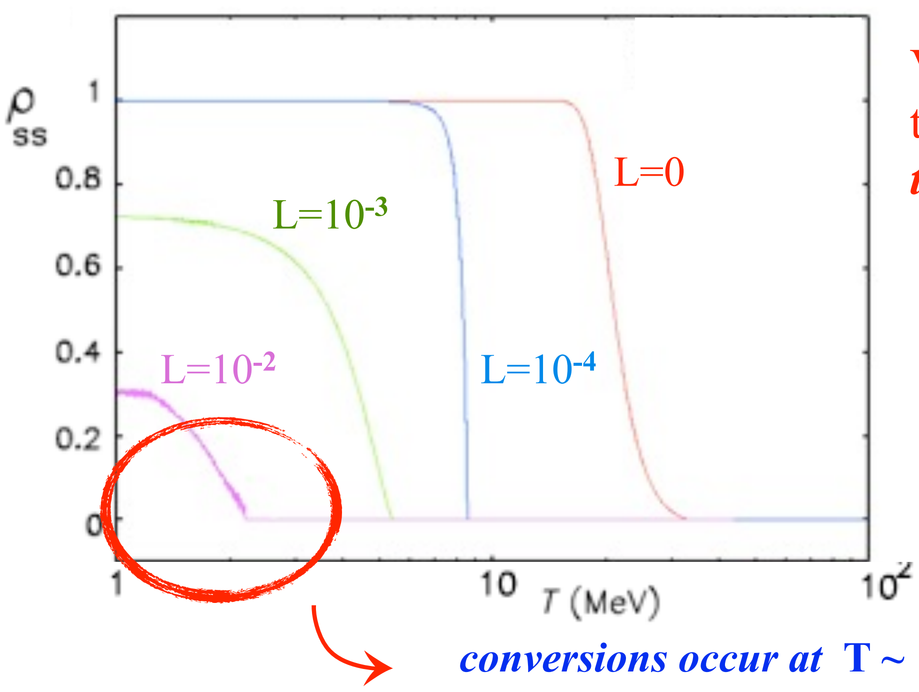
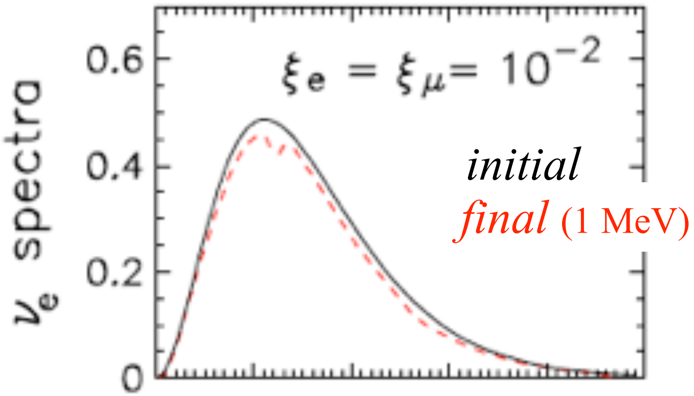


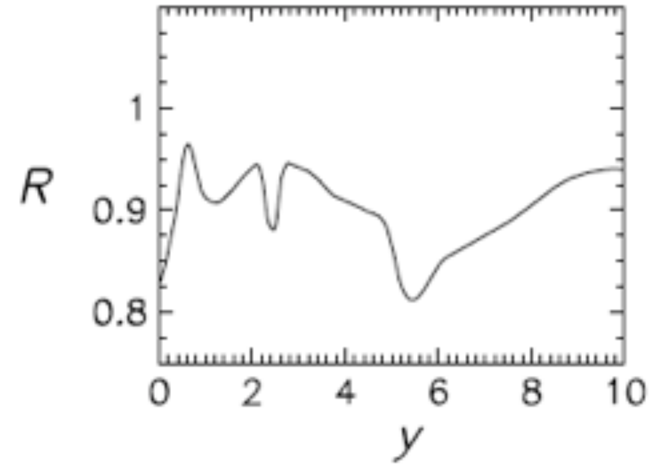
Very large asymmetries are necessary to suppress the sterile neutrino abundances leading to ***non trivial consequences on BBN***

conversions occur at $T \sim T_\nu$ *decoupling*

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

Consequences on BBN





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ν_e spectra distorted → implications on BBN

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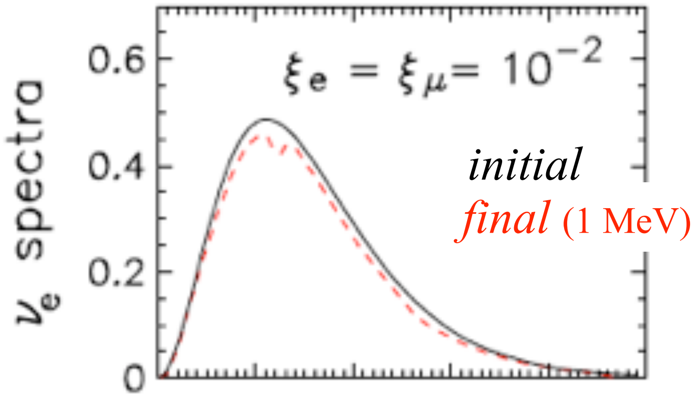

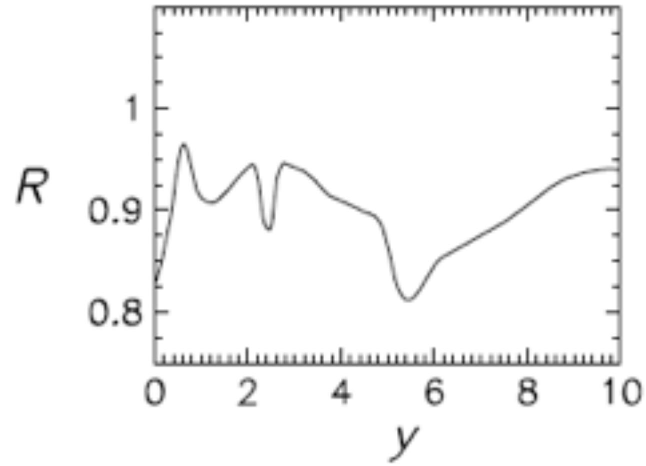

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ν_e spectra distorted → implications on BBN

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

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

Helium mass fraction

Y_p ↑

H^2 ↑

A possible solution: suppression of ν_s production

- ***Different mechanisms:***

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

   ✓ In the presence of large ν−ν asy 10^{-2}) sterile production strongly suppressed. Planck ma be evaded

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

   ⚠ Non trivial implic for BNN

   Saviano et al., 2013

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

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

   ⚠ Possible implications on BBN

   ⚠ Fully unconstrained model

   Hannestad et al., 2013,
   Dasgupta and Kopp 2013,
   Archidiacono et al., 2014

3. **low reheating scenario**

   ✓ sterile abundance depends on reheating temperature

   ⚠ simplified scenarios

   Gelmini, Palomarez-Ruiz, Pascoli, 2004
   Yaguna 2007

Secret interactions for sterile ν_s

Hannestad, Hansen & Tram, 2013

new secret self-interactions among sterile ν mediated by a massive gauge boson X : $M_X << M_W$

➔ *Suppress the thermalization of sterile neutrinos*

(Effective ν_a-ν_s mixing reduced by a large matter term)

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consequences on cosmological bounds at low temperature

- If the new mediator interaction X also couples to Dark Matter →
  → possible attenuation of some of the small scale structure problems ("missing satellites" problem...)

Dasgupta and Kopp, 2013
Bringmann et al, 2013

Active-Sterile flavour evolution

- ν_s - ν_s *interaction strength* $\boldsymbol{G_X = \frac{\sqrt{2}}{8}\frac{g_X^2}{M_X^2}}$ *for T<< M_X*
- *2+1 scenario and single-momentum approximation:* $\varrho_{\mathbf{p}}(T) \to f_{FD}(p)\,\rho(T)$
- *mass and mixing best fit parameters for active and sterile sector*

(from Capozzi et al.) *(from Giunti and coll.)*

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$*$ ν asymmetry L= 0

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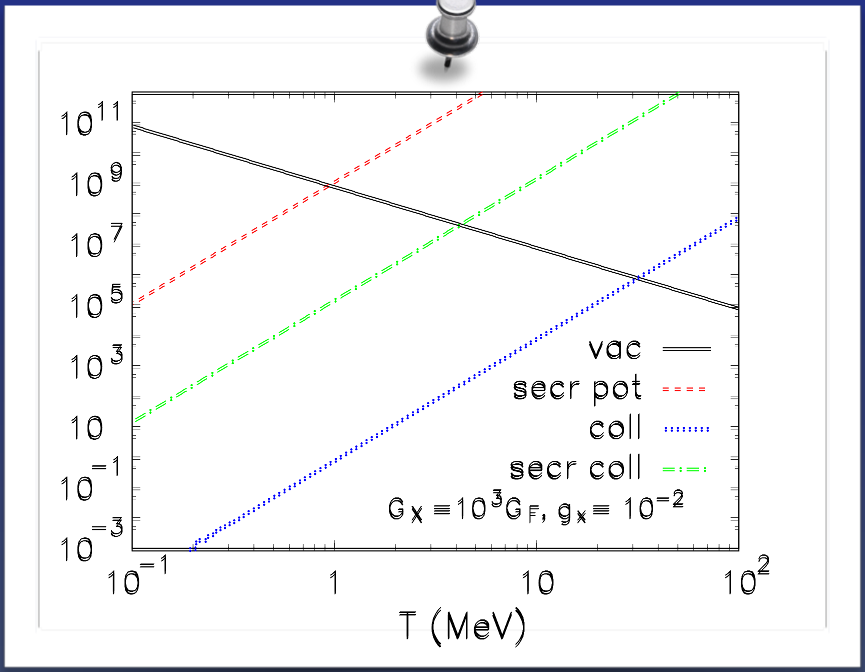
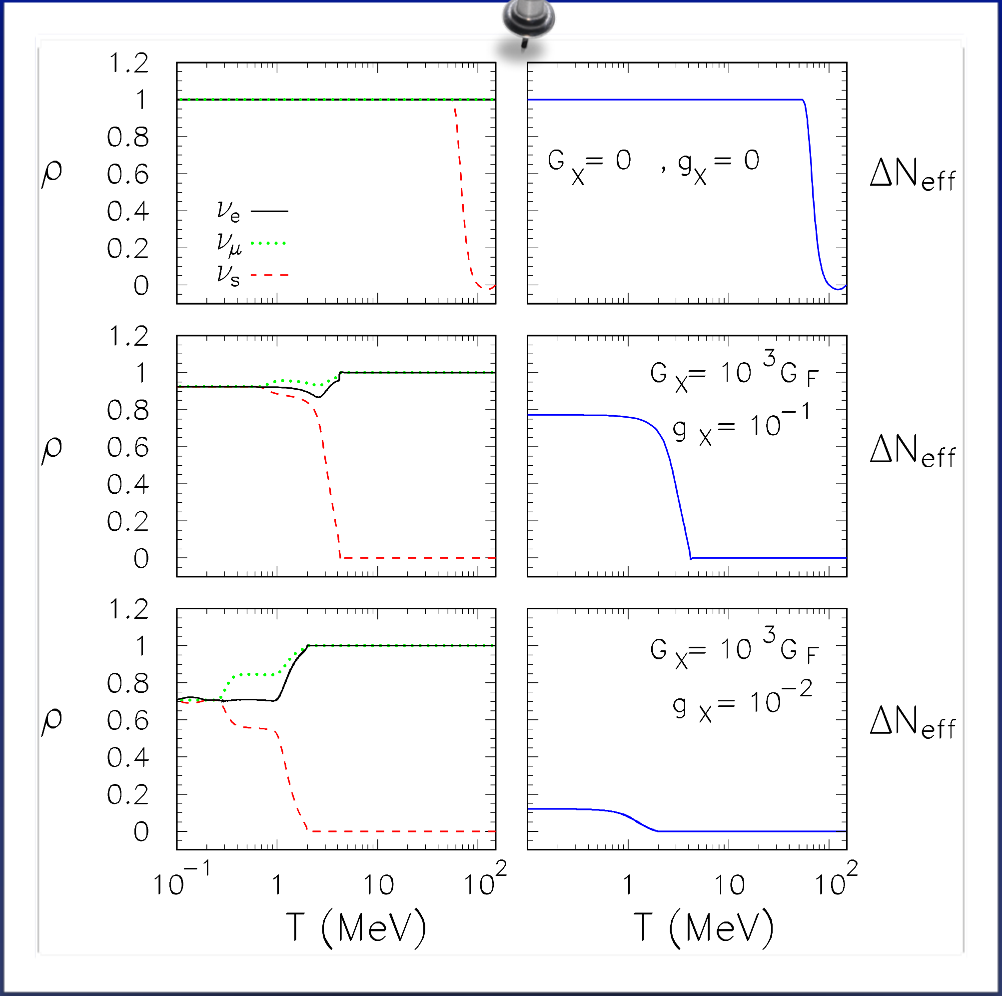


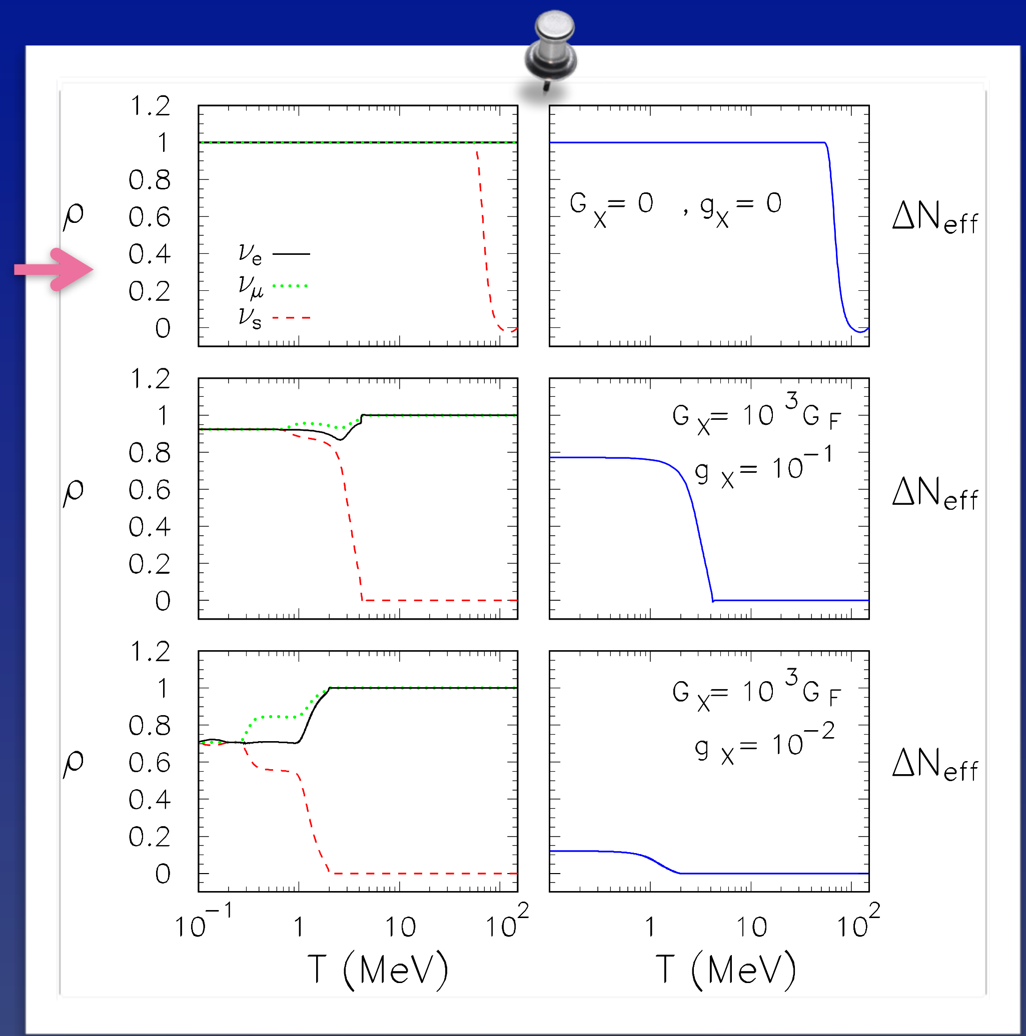
Sterile production by secret interactions



Saviano, Pisanti, Mangano, Mirizzi 2014, ArXiv: *1409.1680*

Sterile production by secret interactions

Standard case: as expected the sterile are copiously produced and thermalize



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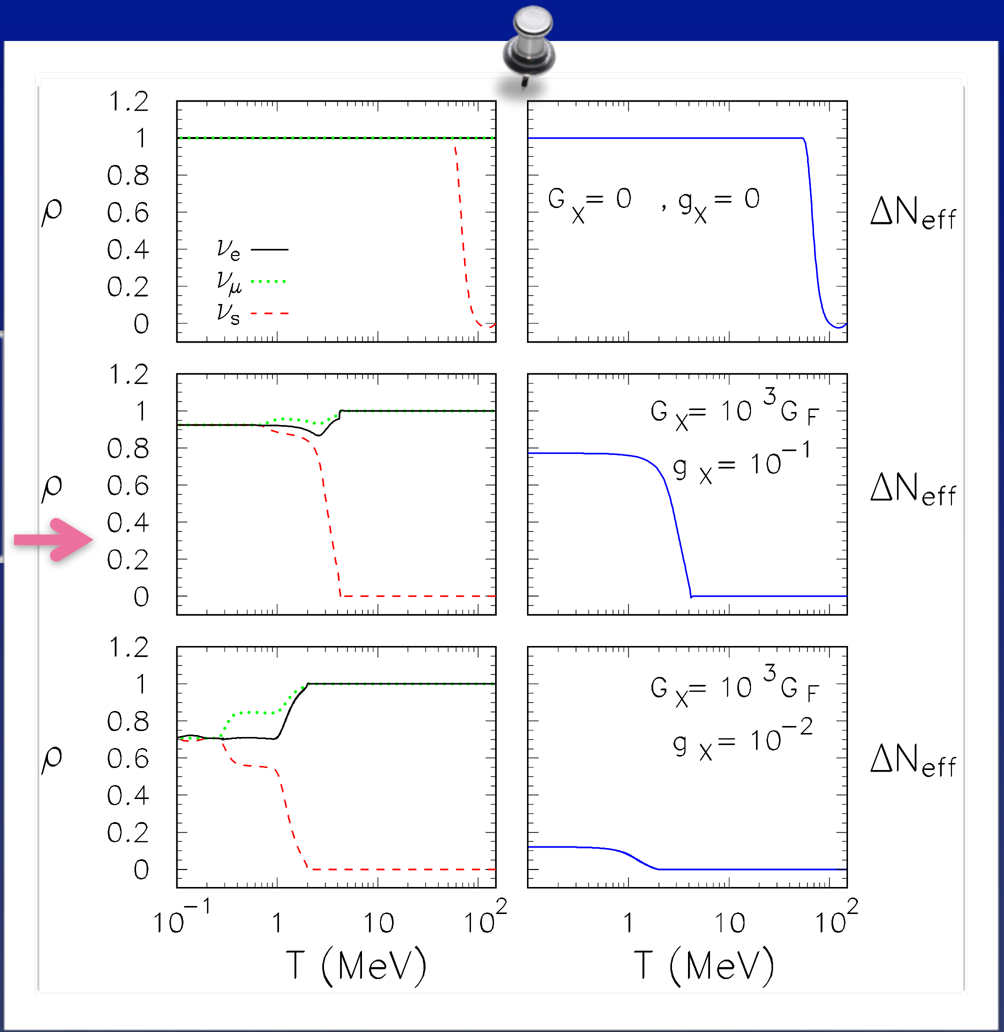

Secret interactions: shift of the conversions at lower T and sterile abundance starts to be reduced

Saviano, Pisanti, Mangano, Mirizzi 2014, ArXiv: *1409.1680*

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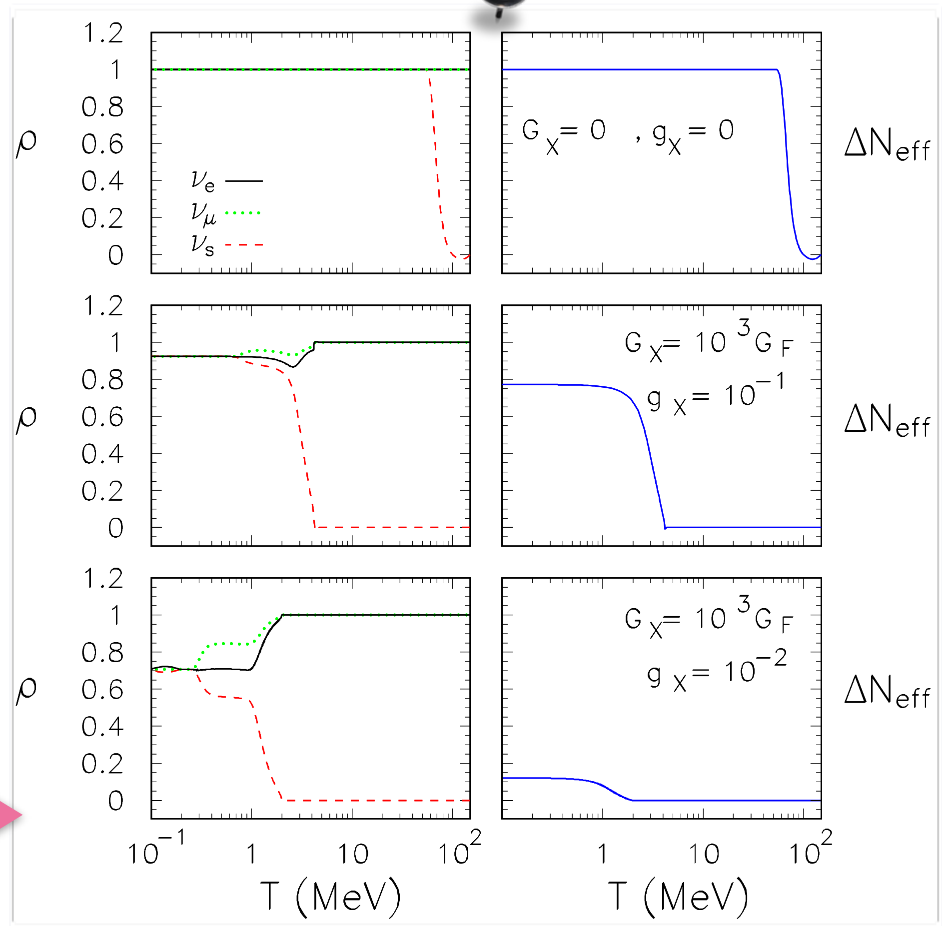


Secret interactions: resonances around 1 MeV, sterile ν suppressed.

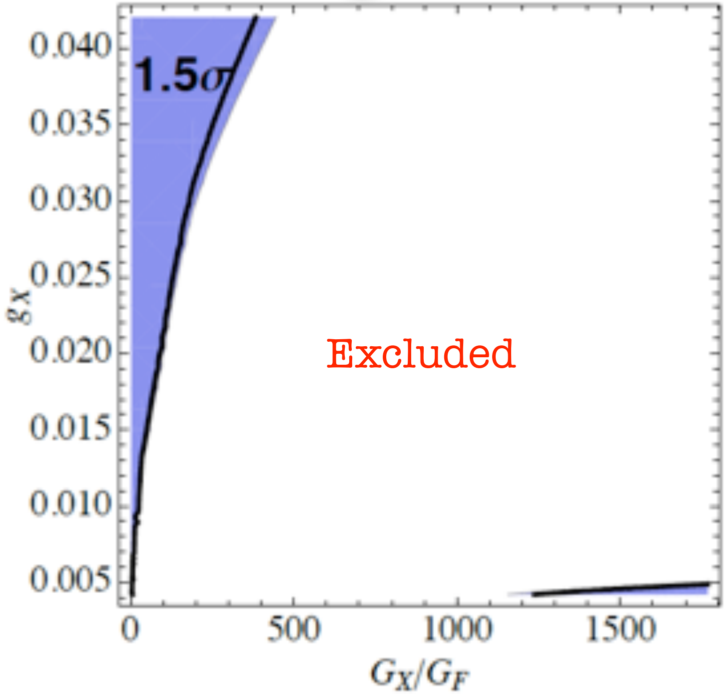
Note that also ν_e and ν_μ the are depleted: crucial for N_{eff} but also for BBN

$\rho_{ee} = 0.7$, $\Delta N_{eff} = 0.18$

Saviano, Pisanti, Mangano, Mirizzi 2014, ArXiv: *1409.1680*

BBN constrains: primordial ^{4}He yield

PArthENoPE code
Pisanti et al, 2012



Planck best fit $\Omega_b h^2 = 0.02207$

95% C.L. Planck range $\Omega_b h^2$

- ΔN reduced but anyway > 0
- $\rho_{ee} < 0$

both conspire to produce a large Y_p

Experimental reference value: $Y_p = 0.2465 \pm 0.0097$ (σ)

E. Aver et al, 2013
Y.I. Izotov et al, 2007

^{4}He analysis dominated by
the experimental error
(theoretical one extremely small)

Saviano, Pisanti, Mangano, Mirizzi 2014, ArXiv: *1409.1680*

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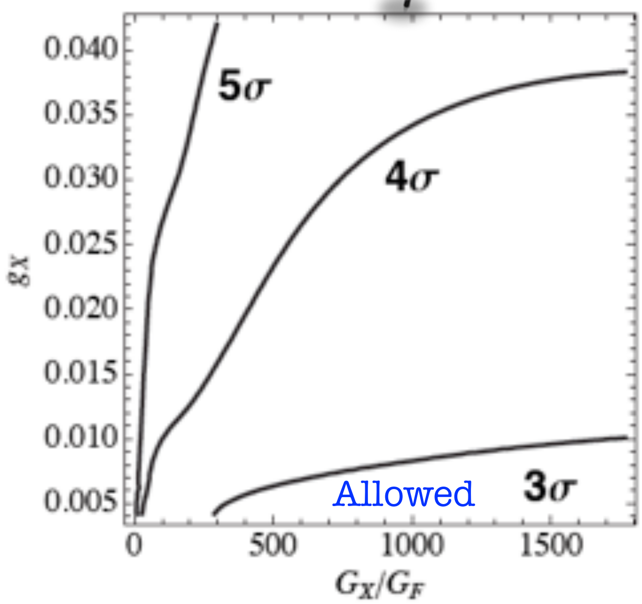

$$\sigma = \sqrt{\sigma_{exp}^2 + \sigma_{th}^2}$$

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Experimental reference value: $^2\mathrm{H/H} = (2.53 \pm \underbrace{0.04) \times 10}_{\sigma_{exp}}{}^{-5}$ *R. Cooke et al, 2013*

Remark: theoretical value affected by an error due mainly to the present uncertainty on the reaction $d(p,\gamma)^3$He ➜ $\sigma_{th} = 0.062 \times 10^{-5}$

Most of the parameter space excluded at 3σ ⬌ mass permitted $M_X \leq 40$ MeV

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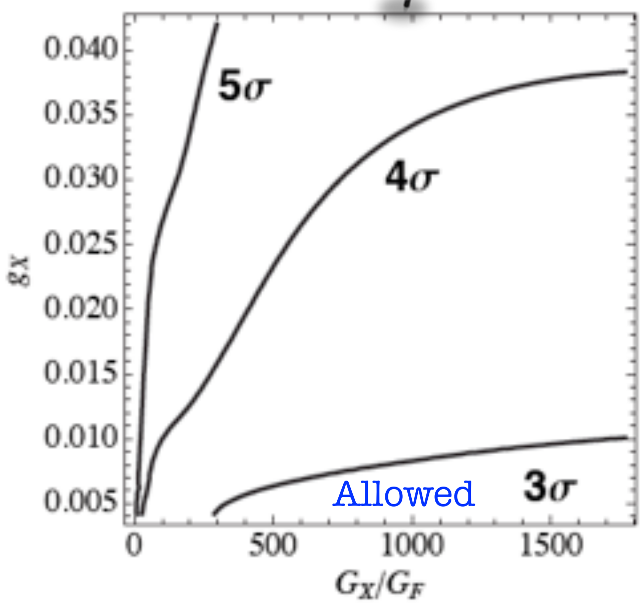

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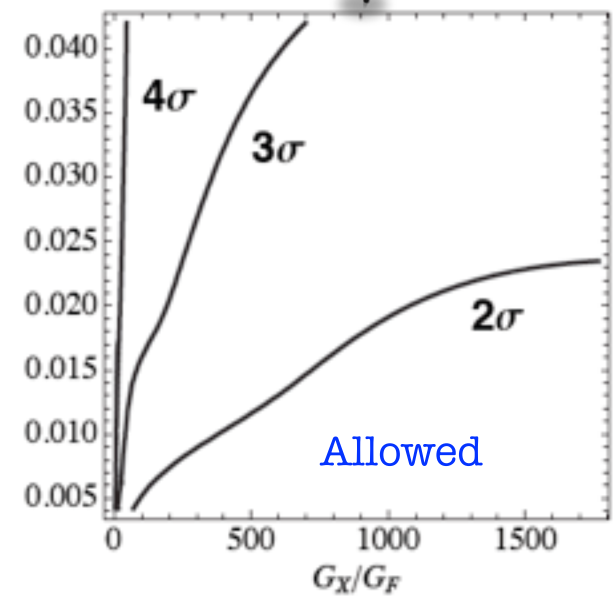

95% C.L. Planck upper range $\Omega_b h^2 < 0.02261$

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Most of the parameter space excluded at 3σ ↔ mass permitted $M_X \leq 40$ MeV

^{2}H constraints weaker for larger values of $\Omega_b h^2$ ↔ mass permitted $M_X \leq 220$ MeV at 3σ

Mass constraints for secret interactions

BBN can put constraints down to a mass $M_X = 40$ MeV...

. . . could we say something for lower masses ??

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lower M_X ↔ very large G_X ($> 10^6\, G_F$) ➔ very strong secret collisional term leading to a quick flavor equilibrium

Scatterig rate: $\Gamma_X \simeq G_X^2 T_\nu^5 \frac{p}{\langle p \rangle} \frac{n_s}{n_a}$

$$(\rho_{ee},\ \rho_{\mu\mu},\ \rho_{\tau\tau},\ \rho_{ss})_{\text{initial}} \longrightarrow (\rho_{ee},\ \rho_{\mu\mu},\ \rho_{\tau\tau},\ \rho_{ss})_{\text{final}}$$

$$(1,\ 1,\ 1,\ 0) \qquad (3/4,\ 3/4,\ 3/4,\ 3/4)$$

Stodolsky, 1987

The flavour evolution leads to a large population of sterile states, in conflict with the cosmological mass bound

Mirizzi,Mangano, Pisanti Saviano, 2014,
ArXiv:1410.1385

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$$m_{st}^{eff} = \rho_{ss}\sqrt{\Delta m_{st}^2} = \frac{3}{4}\sqrt{\Delta m_{st}^2}$$

→ lower value in the 2σ range gives $m_{st}^{eff} \sim 0.8$ eV

for the most parameter space in tension with the cosmological bounds on sterile mass (0.7 eV)

Mirizzi, Mangano, Pisanti Saviano, 2014, ArXiv:1410.1385

Cosmological constraints on secret interactions

Summarising:

✓ Very large M_X → thermalization of ν_s ↔ secret interactions do not have effect

✓ 400 MeV< M_X < 40 MeV → severely constrained by BBN bounds

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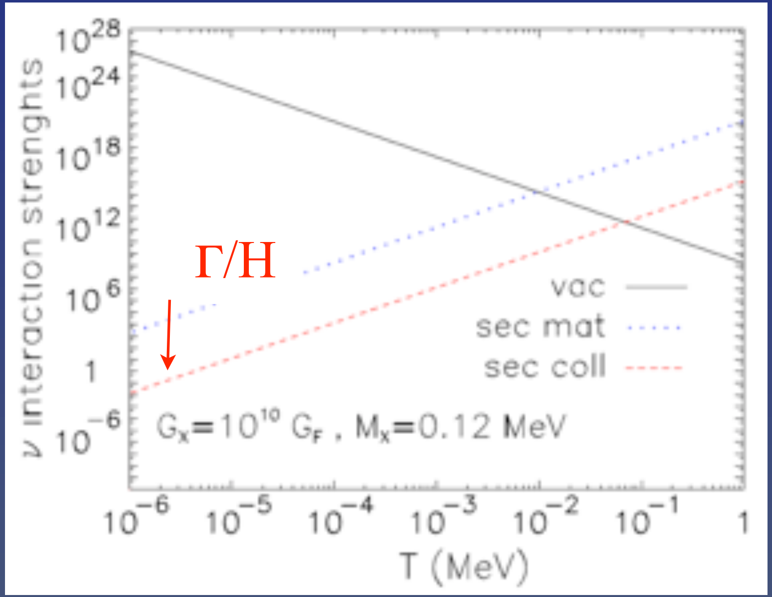

For M_X < 0.1 MeV ➔ ν_s could be still coupled at CMB and LSS epoch ➔ no free-streaming

Present cosmological mass bound obtained considering free-streaming ν

⬇

An appropriated analysis should be performed

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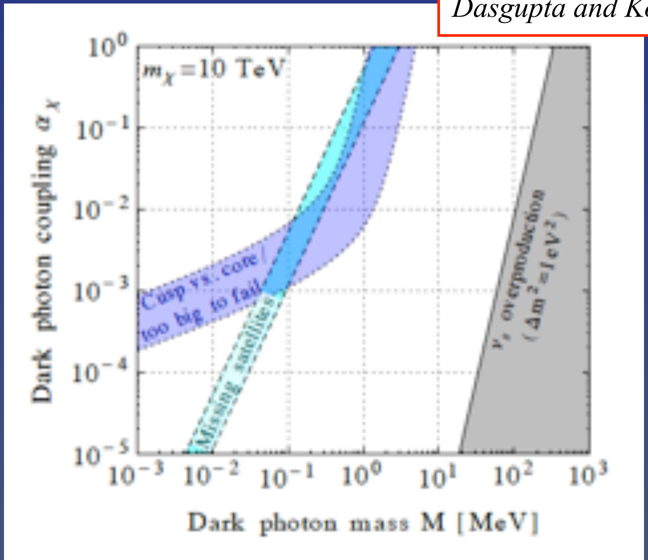

In particular for M_X = 0.1 MeV , secret interactions would play also an interesting role in relation to dark matter and small-scale structures.

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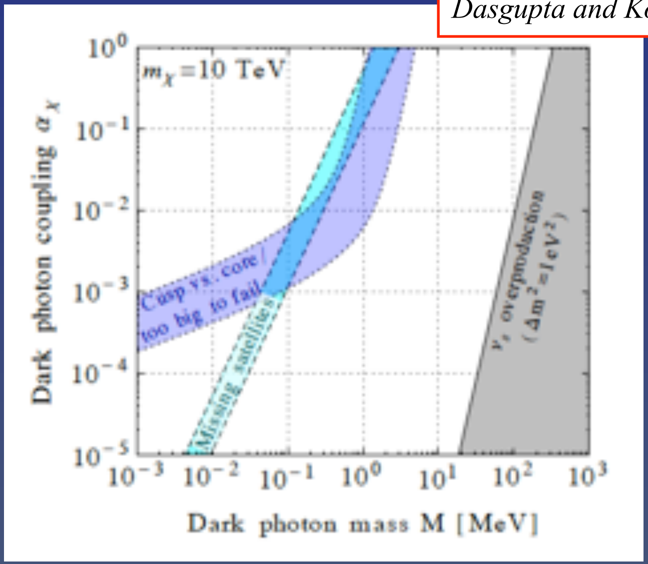

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The game is still open

A surprising feature on Neff

- After the production, ν_s have a "grey-body" spectrum ($\rho_{ss} = 3/4$)....

.... but the collisions and oscillations are still active pushing all neutrinos to a common FD distribution

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Constraint: $n_{\nu\ TOT}$ must be constant

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T_ν is reduced by a factor $(3/4)^{1/3}$,
leading to an effect on the radiation density

$$\epsilon_{\nu,\mathrm{in}} = 3 \times \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} \epsilon_\gamma$$

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$$N_{\text{eff}} \sim 4 \times \left(\frac{3}{4}\right)^{4/3} \sim 2.7$$

Mirizzi,Mangano, Pisanti Saviano, 2014, ArXiv:1410.1385

Conclusions

- neutrino cosmology is entering the precision epoch

  $N_{eff} < 4$ $\Sigma_{m\nu} < 0.23$ eV

- eV sterile ν ***incompatible*** with cosmological bounds:
  too heavy for structure formation
- It is necessary to suppress the sterile production → ***exotic scenarios***
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looking forward new data...

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