Neutrino Cosmology
after
Planck 2015

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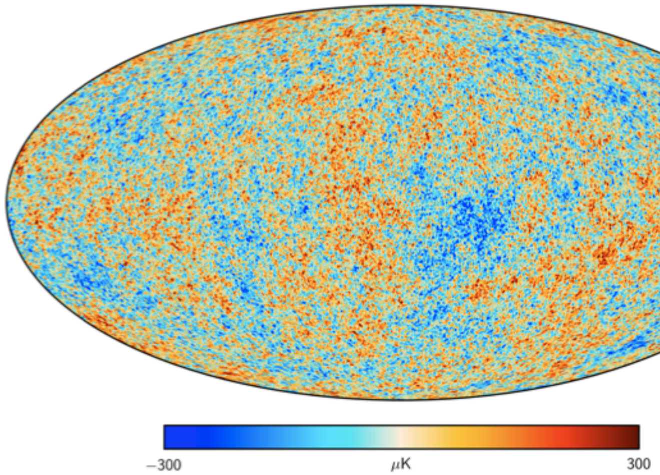
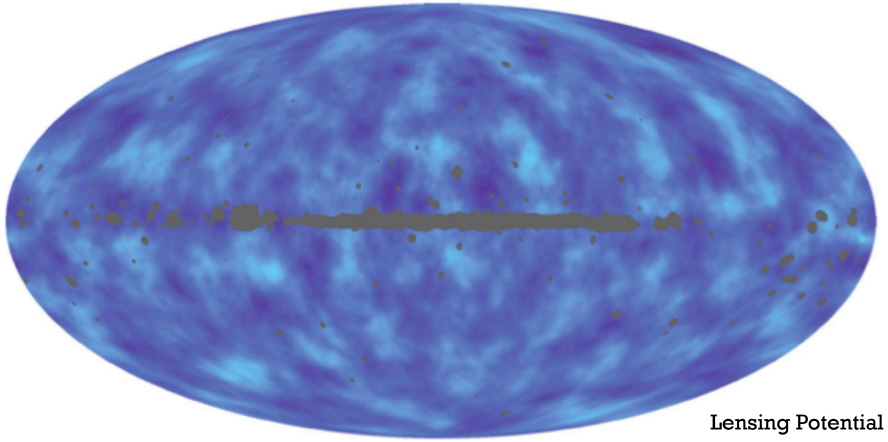
Summary

- Planck 2015
- Neutrino properties from cosmology: overview
- Neutrino properties from cosmology: details
    - Are there neutrinos in the universe?
    - How many of them? (the long tale of N_{eff})
    - Neutrino mass: universe better than lab’s ?
    - Oscillations and neutrino asymmetries
- Sterile states ?

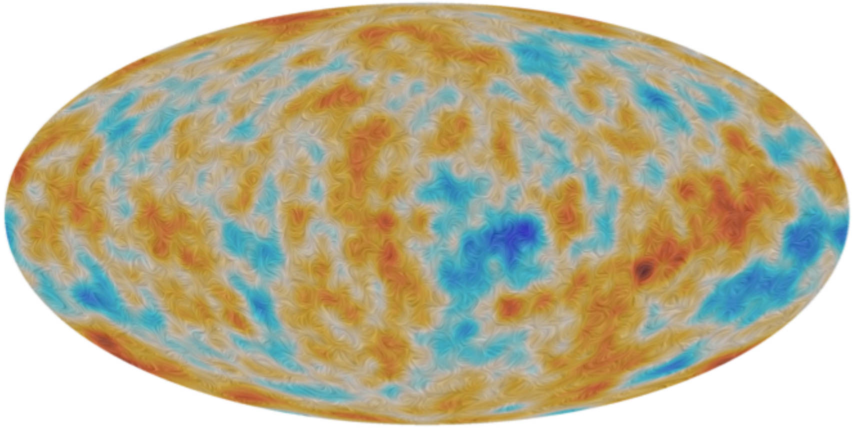
Planck 2015



Temperature

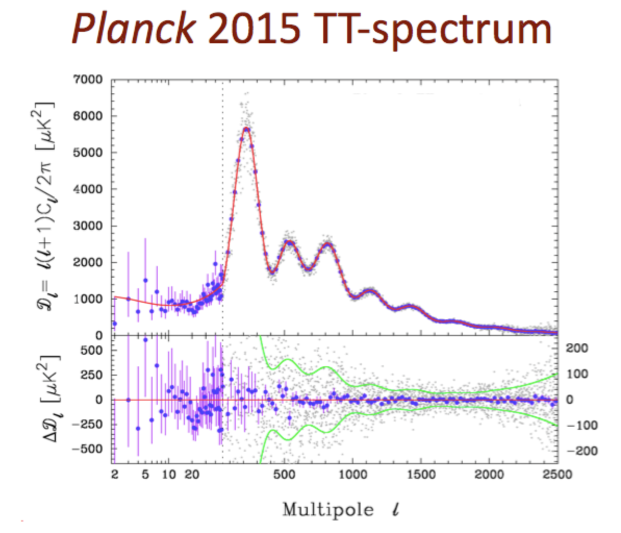


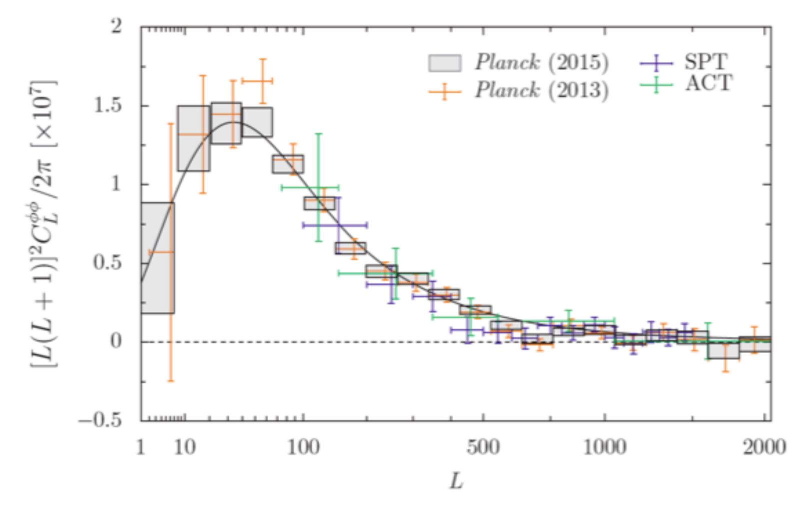
Lensing Potential

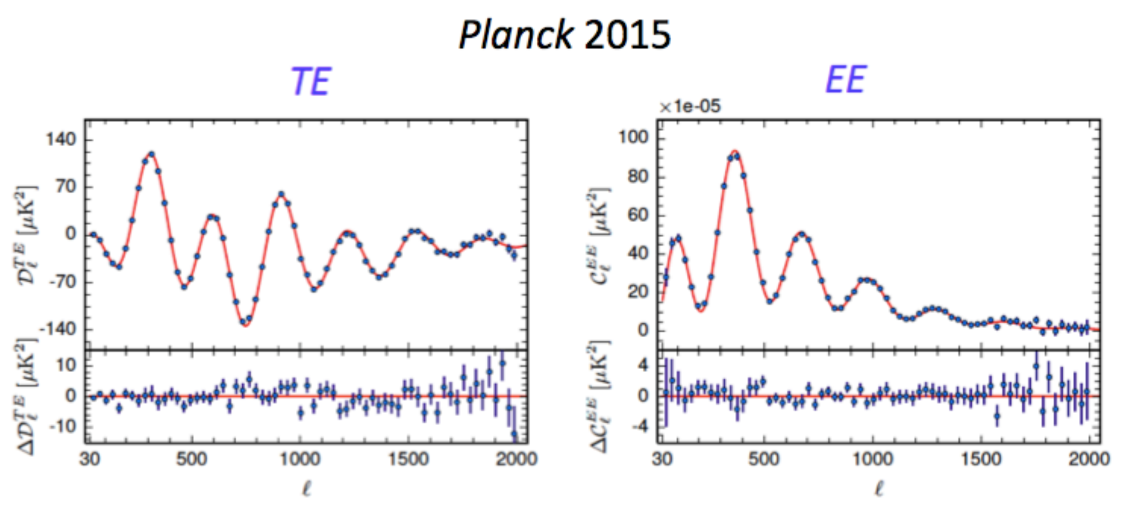


Polarization

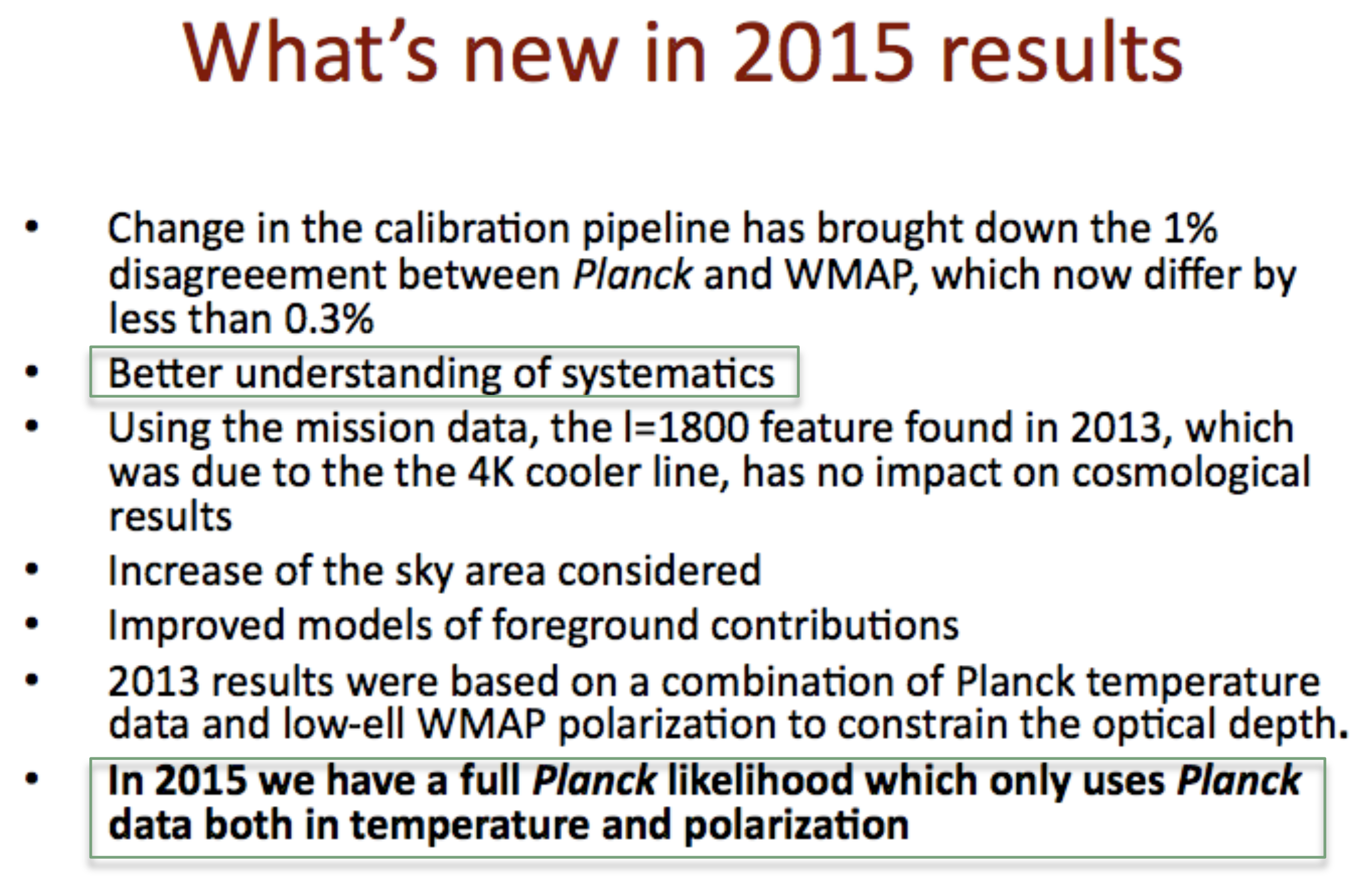
Planck 2015


Planck 2015 TT-spectrum




Planck 2015

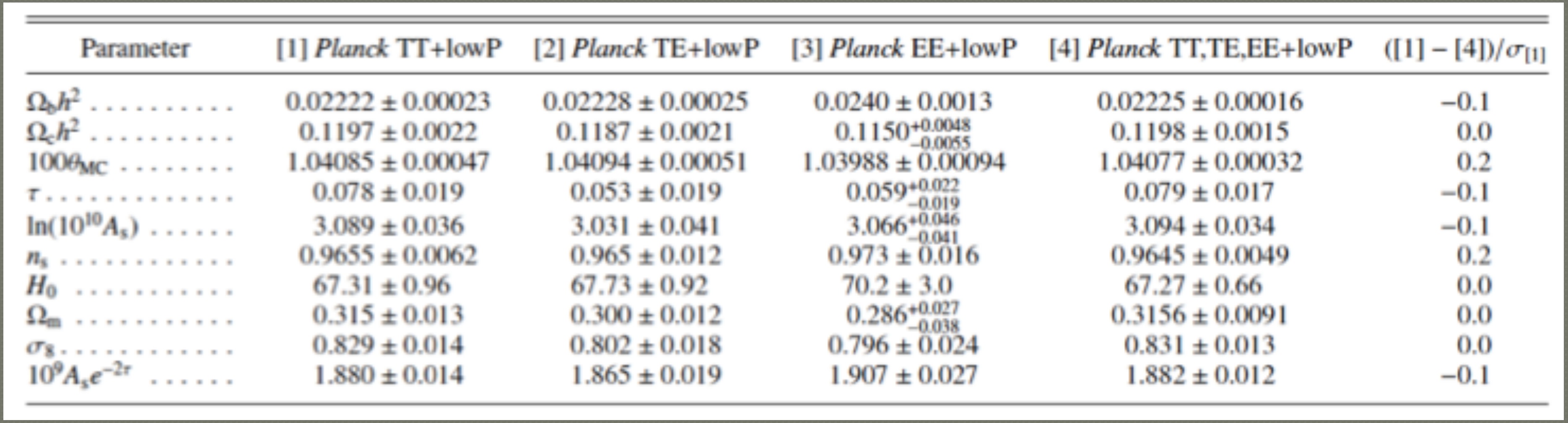
Planck 2015



What’s new in 2015 results

- Change in the calibration pipeline has brought down the 1% disagreeement between *Planck* and WMAP, which now differ by less than 0.3%
- Better understanding of systematics
- Using the mission data, the $l=1800$ feature found in 2013, which was due to the the 4K cooler line, has no impact on cosmological results
- Increase of the sky area considered
- Improved models of foreground contributions
- 2013 results were based on a combination of Planck temperature data and low-ell WMAP polarization to constrain the optical depth.
- **In 2015 we have a full *Planck* likelihood which only uses *Planck* data both in temperature and polarization**

Planck 2015



Parameter	[1] *Planck* TT+lowP	[2] *Planck* TE+lowP	[3] *Planck* EE+lowP	[4] *Planck* TT,TE,EE+lowP	$([1]-[4])/\sigma_{[1]}$
$\Omega_b h^2$	0.02222 ± 0.00023	0.02228 ± 0.00025	0.0240 ± 0.0013	0.02225 ± 0.00016	-0.1
$\Omega_c h^2$	0.1197 ± 0.0022	0.1187 ± 0.0021	$0.1150^{+0.0048}_{-0.0055}$	0.1198 ± 0.0015	0.0
$100\theta_{MC}$	1.04085 ± 0.00047	1.04094 ± 0.00051	1.03988 ± 0.00094	1.04077 ± 0.00032	0.2
τ	0.078 ± 0.019	0.053 ± 0.019	$0.059^{+0.022}_{-0.019}$	0.079 ± 0.017	-0.1
$\ln(10^{10}A_s)$	3.089 ± 0.036	3.031 ± 0.041	$3.066^{+0.046}_{-0.041}$	3.094 ± 0.034	-0.1
n_s	0.9655 ± 0.0062	0.965 ± 0.012	0.973 ± 0.016	0.9645 ± 0.0049	0.2
H_0	67.31 ± 0.96	67.73 ± 0.92	70.2 ± 3.0	67.27 ± 0.66	0.0
Ω_m	0.315 ± 0.013	0.300 ± 0.012	$0.286^{+0.027}_{-0.038}$	0.3156 ± 0.0091	0.0
σ_8	0.829 ± 0.014	0.802 ± 0.018	0.796 ± 0.024	0.831 ± 0.013	0.0
$10^9 A_s e^{-2\tau}$	1.880 ± 0.014	1.865 ± 0.019	1.907 ± 0.027	1.882 ± 0.012	-0.1

Planck 2015 results, XIII

Λ CDM model is an excellent fit of data

Planck 2015

What's new in 2015 results for neutrinos:

better determination of N_{eff}
tighter mass scale bound
strong evidence of free streaming ν's
concordance with BBN
less room for light (eV) sterile states

Neutrino properties from cosmology: overview

Neutrinos impact expansion history:

High T regime (> MeV):
weak + gravitational effects (BBN)
observables: phase space density (in particular ν_e distribution), non standard interactions, chemical potentials, number of species (active, sterile)

Intermediate T regime (eV):
gravitational effects including perturbations (CMB)
observables: phase space density, non standard interactions, mass scale

Neutrino properties from cosmology: overview

Low T regime (< eV):
gravitational effects including perturbations (LSS)
observables: phase space density, non standard interactions, mass scale

Not in this seminar:

Extremely high T regime (above EW scale):
Majorana vs. Dirac, see-saw mechanism, high scale physics (Leptogenesis)

Extremely low T regime (today): mass scale, local density (Cosmic Neutrino Background (CNB) direct detection)

Neutrino properties from cosmology: details

Are there neutrinos in the universe?

BBN and CMB probe the light particle content at different epochs: both require relativistic species in addition to photons

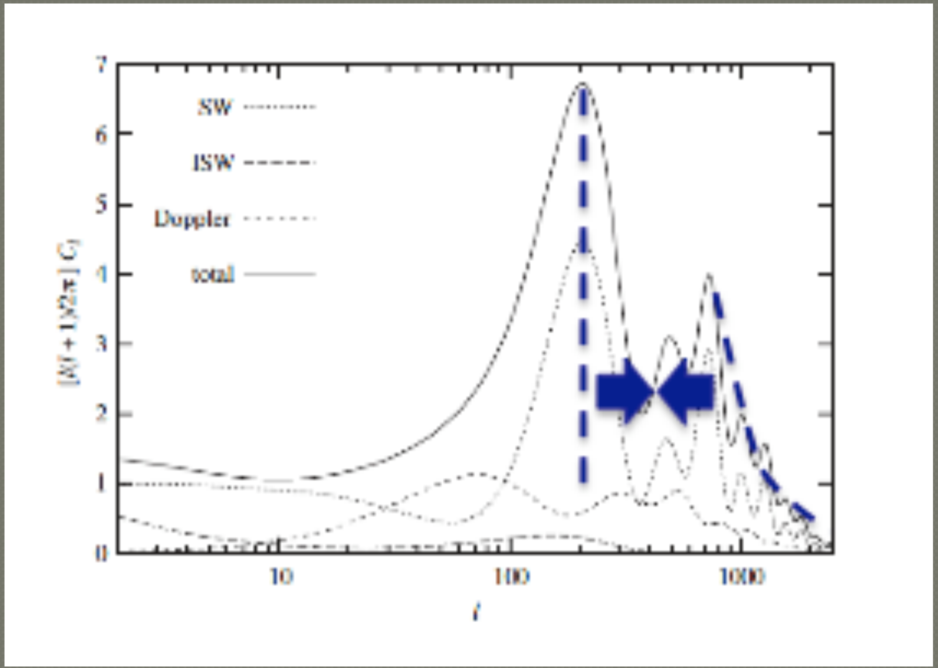
$$\rho_R = \rho_\gamma \left(1 + \frac{7}{8} \left(\frac{4}{11} \right)^{4/3} N_{eff} \right)$$

For BBN: N_{eff} = 3 is a good fit (see later)
BBN requires electron neutrinos!

Are there neutrinos in the universe?

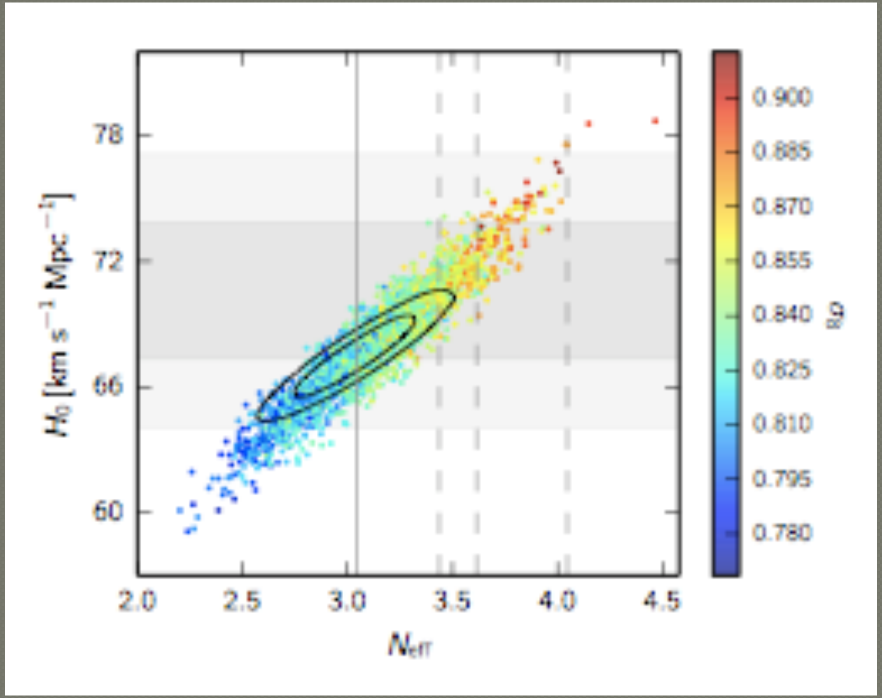
CMB
fixing the angular scale of acoustic peaks and
z_{eq} , a larger amount of dark radiation (and a larger H_0)
gives a higher expansion speed, a shorter age of the
universe T at recombination.

Diffusion length ≈ √T
Sound horizon ≈ T



J. Lesgourgues, Planck 2014, Ferrara

Are there neutrinos in the universe?



Planck 2015 results, XIII

$N_{\rm eff} > 0$ at 10 σ

Are there neutrinos in the universe?

BBN needs a radiation dominated expansion: radiation but not necessarily neutrinos. N_{eff} blind to the specific nature of relativistic species.

BBN needs ν_e: neutrons and protons kept in chemical equilibrium via CC processes. For n≈p the primordial ^{4}He mass fraction would be

$$Y_p = 4\,(n/2)/(n+p) \approx 1$$

Data say $Y_p \approx 0.25$

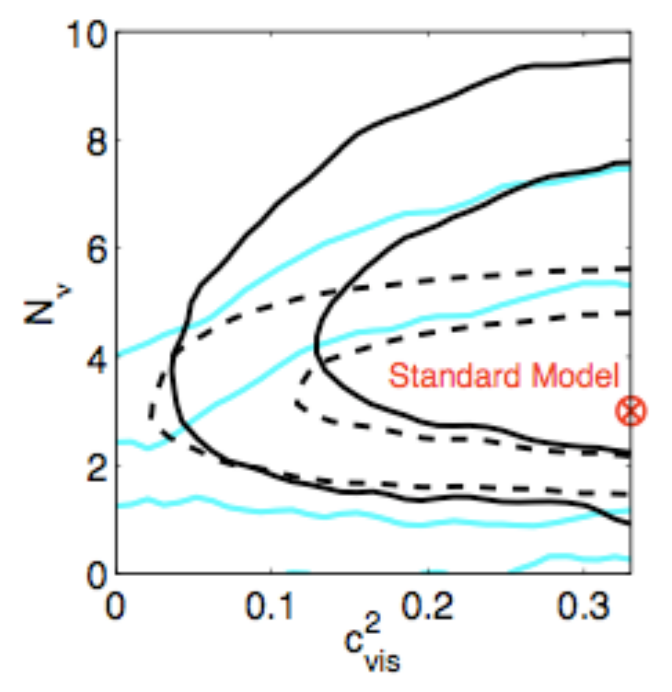
From flavour oscillations: BBN needs the same amount of the three active species!

Are there neutrinos in the universe?

Perturbation effects:

- gravitational feedback of neutrino free streaming damping
- anisotropic stress contributions

c_{vis} :velocity/metric shear – anisotropic stress relation (Hu 1998)



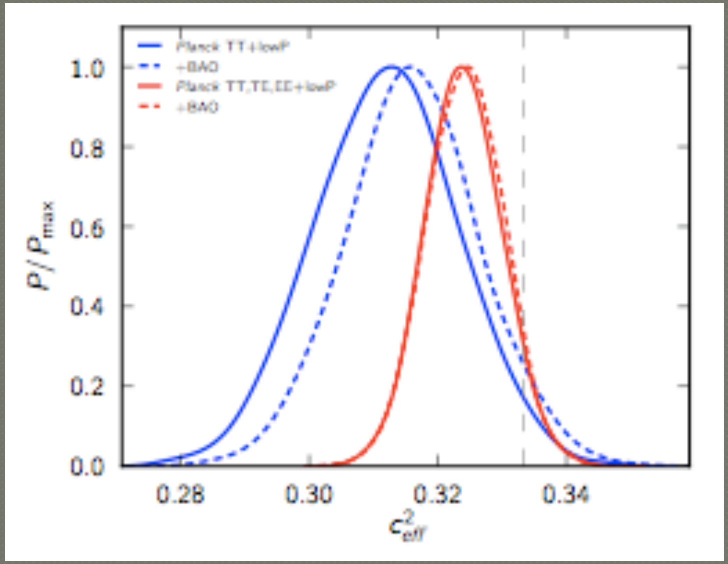
Trotta & Melchiorri 2005

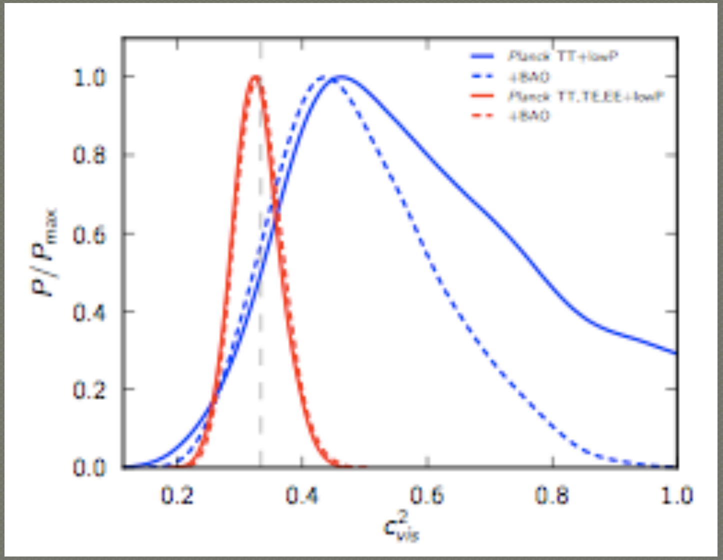
Are there neutrinos in the universe?

Neutrino perturbations in terms of two phenomenological parameters:

$$\delta P = c_{\text{eff}}^2 \, \delta \rho \quad (1/3)$$

$$c_{\text{vis}}^2 \quad (1/3)$$





Planck 2015 results, XIII

How many of them? (the long tale of N_{eff})

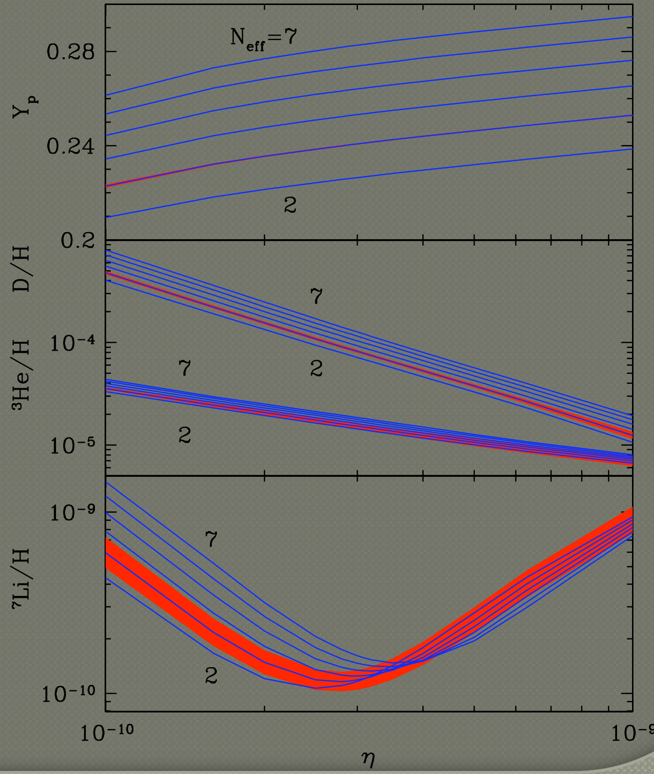
both ^{4}He mass fraction Y_p and ^{2}H/H are increasing functions of N_{eff}:
change of expansion rate
ν_e distribution crucial in weak rates
baryon density fixed by CMB!
(but still ^{2}H/H can varies a lot)

$$\Omega_b h^2 = 0.02225 \pm 0.00016$$

crucial inputs:

experimental values

nuclear rates



Cyburt 2004

$\eta \approx 10^{-10}\, 274\ \Omega_b h^2$

How many of them? (the long tale of N_{eff})

^{4}He still affected by a remarkable systematic uncertainty
Recent re-analysis

$Y_p = 0.2565 \pm 0.0010(stat) \pm 0.0050(syst)$	Izotov & Thuan 2010
$Y_p = 0.2561 \pm 0.0108$	Aver et al. 2010
$Y_p = 0.2573 \pm 0.033$	Aver etl. 2012
$Y_p = 0.2465 \pm 0.0097$	Aver et al. 2013
$Y_p \leq 0.2631 \quad 95\% \text{ C.L.}$	Mangano & Serpico 2011

^{2}H/H is presently quite well determined, thanks to new very metal poor system measurements (Cooke et al. 2013)

$$^2H/H = (2.53 \pm 0.04) \cdot 10^{-5}$$

How many of them? (the long tale of N_{eff})

Several claims, spanning from
"Evidence for extra neutrinos"

to

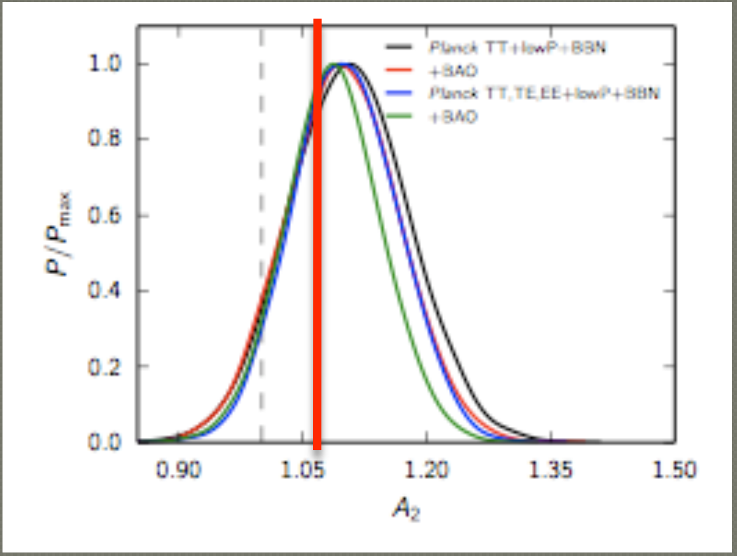
"No room for extra neutrinos"

Conservative estimate: $N_{eff} < 4$ (still !)
Degeneracies! One example: for Planck baryon density a higher deuterium

$$^{2}H/H = (2.65 \pm 0.07) \cdot 10^{-5}$$

N_{eff} smaller than 3 (2.7)? Maybe, or a larger S-factor for $d(p,\gamma)^3He$, as in the theoretical estimate of Marcucci et al. (2005)

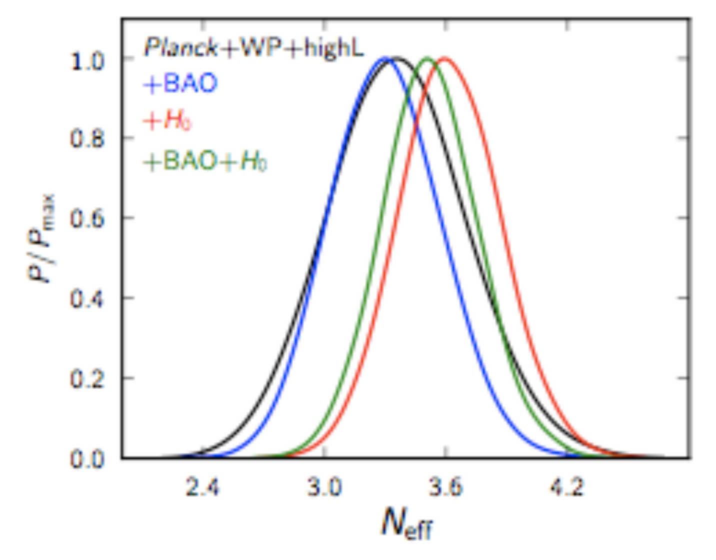
Di Valentino et al (2014): $\text{rate}/\text{rate}_{exp} = A_2$

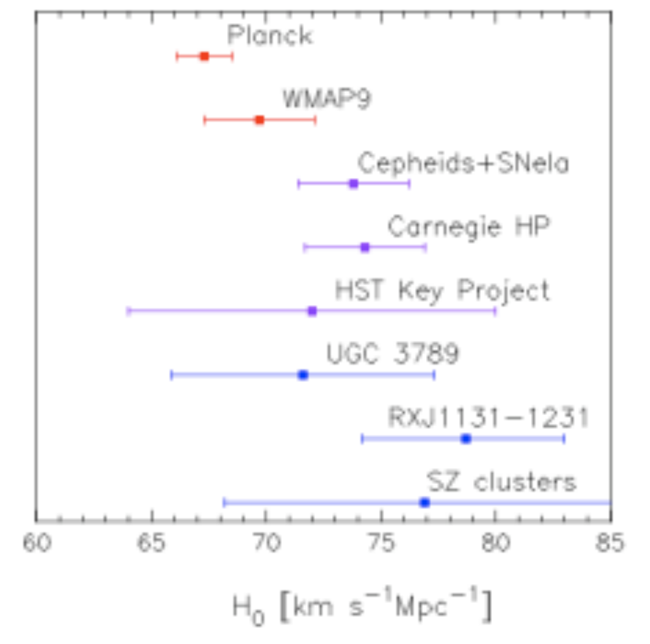


Planck 2015 results, XIII

How many of them? (the long tale of N_{eff})

Planck 2013 : a narrower 95 % C.L. range for N_{eff}, but still inconclusive. H_0 problem:





3.4±0.7

3.3±0.5

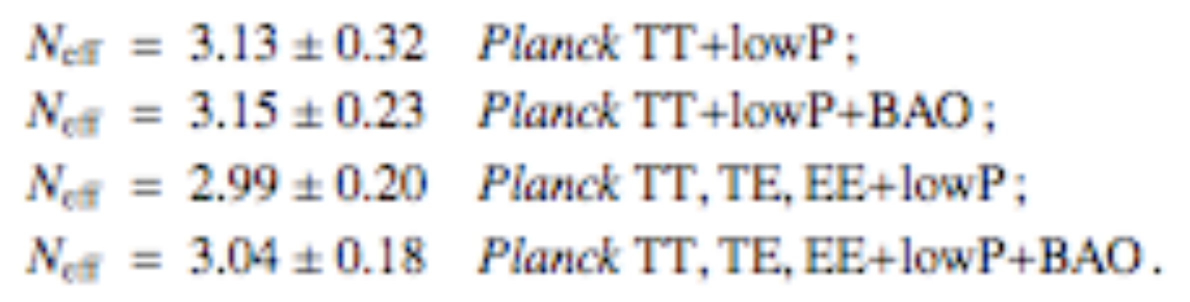
3.6±0.5

3.5±0.5

Ade et al. 2013
(Planck XVI)

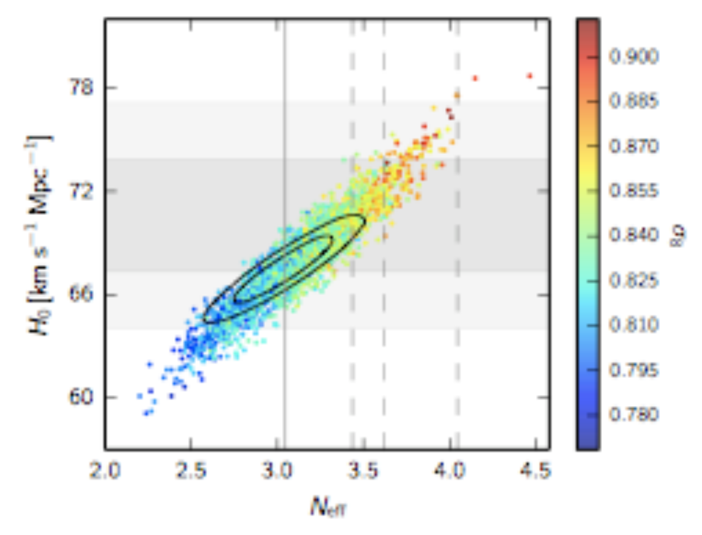
How many of them? (the long tale of N_{eff})

Planck 2015 :



$$N_{\rm eff} = 3.13 \pm 0.32 \quad Planck\ \mathrm{TT{+}lowP}\,;$$
$$N_{\rm eff} = 3.15 \pm 0.23 \quad Planck\ \mathrm{TT{+}lowP{+}BAO}\,;$$
$$N_{\rm eff} = 2.99 \pm 0.20 \quad Planck\ \mathrm{TT, TE, EE{+}lowP}\,;$$
$$N_{\rm eff} = 3.04 \pm 0.18 \quad Planck\ \mathrm{TT, TE, EE{+}lowP{+}BAO}\,.$$

In good agreemnt with Standard expectation (3.046)

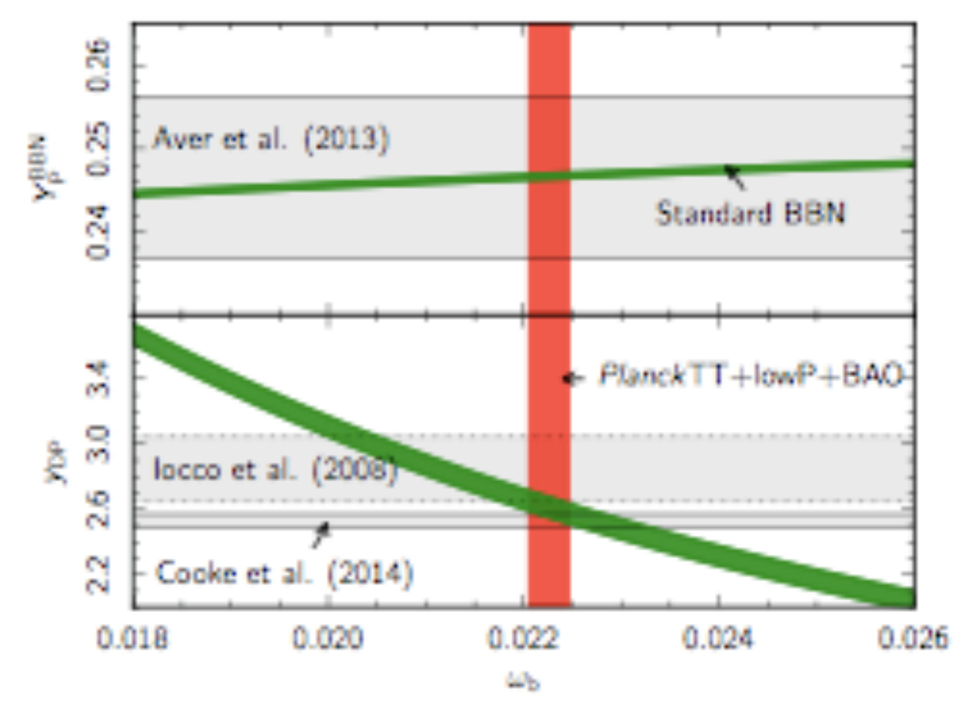


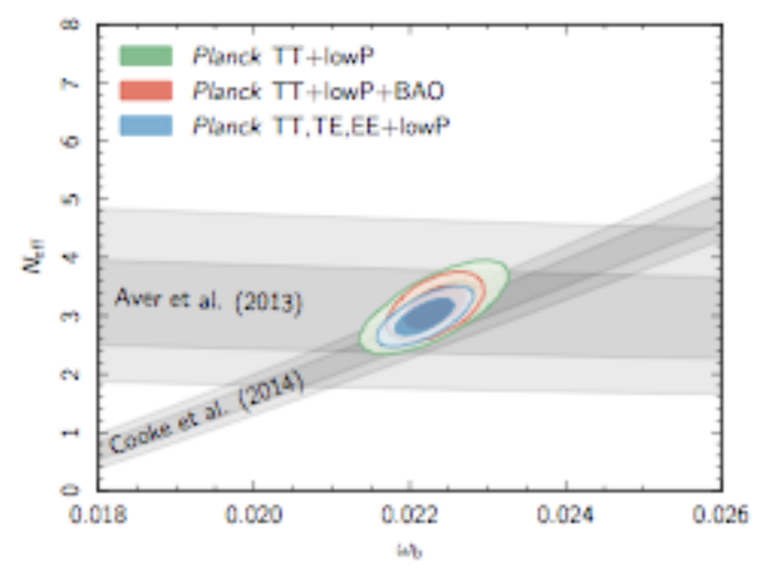
GM et al 2004

Caveat: discrepancy with SNIa value of H_0 at 2.2 σ level

How many of them? (the long tale of N_{eff})

CMB and BBN are quite consistent





N_{eff}=3.046

N_{eff} free

Planck 2015 results, XIII
Pisanti et al 2008 (PArthENoPE)

Neutrino mass: universe better than lab's ?

Laboratory is still missing! 2 eV for ν_e

Katrin wil tell us more (when?)

Cosmology blind to neutrino mass till recent times.

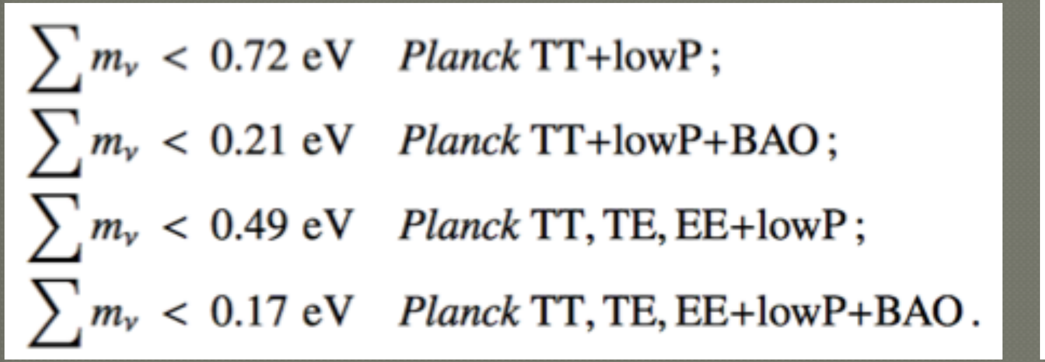
CMB:
For the expected mass range the main effect is around the first acoustic peak due to the early integrated Sachs-Wolfe (ISW) effect;

Planck: gravitational lensing. Increasing neutrino mass, increases the expansion rate at $z > 1$ and so suppresses clustering on scales smaller than the horizon size at the nonrelativistic transition (Kaplinghat et al. 2003 ; Lesgourgues et al. 2006). Suppression of the CMB lensing potential.

Neutrino mass: universe better than lab's ?

Total neutrino mass also affects the angular-diameter distance to last scattering, and can be constrained through the angular scale of the first acoustic peak. Degenerate with Ω_Λ (and so the derived H_0)

Including BAO constraint is much tighter:

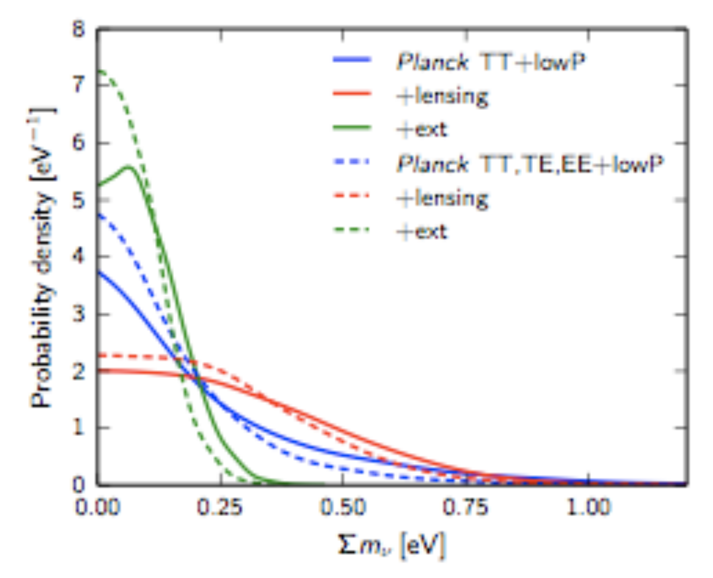


$$\sum m_\nu < 0.72\ \mathrm{eV} \quad \textit{Planck}\ \mathrm{TT{+}lowP}\,;$$

$$\sum m_\nu < 0.21\ \mathrm{eV} \quad \textit{Planck}\ \mathrm{TT{+}lowP{+}BAO}\,;$$

$$\sum m_\nu < 0.49\ \mathrm{eV} \quad \textit{Planck}\ \mathrm{TT, TE, EE{+}lowP}\,;$$

$$\sum m_\nu < 0.17\ \mathrm{eV} \quad \textit{Planck}\ \mathrm{TT, TE, EE{+}lowP{+}BAO}\,.$$



Planck 2015 results, XIII

Oscillations and neutrino asymmetries

Early times:

$$f_a = \frac{1}{e^{p/T - \xi_a} + 1} \qquad f_{\bar{a}} = \frac{1}{e^{p/T + \xi_a} + 1}$$

Kinetic and chemical equilibrium

MeV scale (set by G_F and Δm^2 ‘s) :

• freezing of weak interaction processes

• ν distributions mixed up, depending on mixing angles

Oscillations and neutrino asymmetries

density matrix formalism ρ_{ab}

ρ_{aa} occupation number

ρ_{ab} a≠b mixing

$$\frac{d}{dt}\rho = \frac{1}{i}\left[\Omega_{vac} + \Omega_{matter}, \rho\right] + C$$

Ω_{vac} vacuum oscillations: $M^2/2p$

Ω_{matter} matter term: $2^{1/2} G_F \, \Delta n_i + 8 \, 2^{1/2} G_F \, p \, T_0{}^0/3M^2{}_{W,Z}$

C: collisional integral (loss of coherence and distribution re-shuffling)

Stodolski 1987
Raffelt ad Sigl 1993
…….

Oscillations and neutrino asymmetries

When oscillations matter:

Lepton asymmetries expected quite small in (standard) leptogenesis

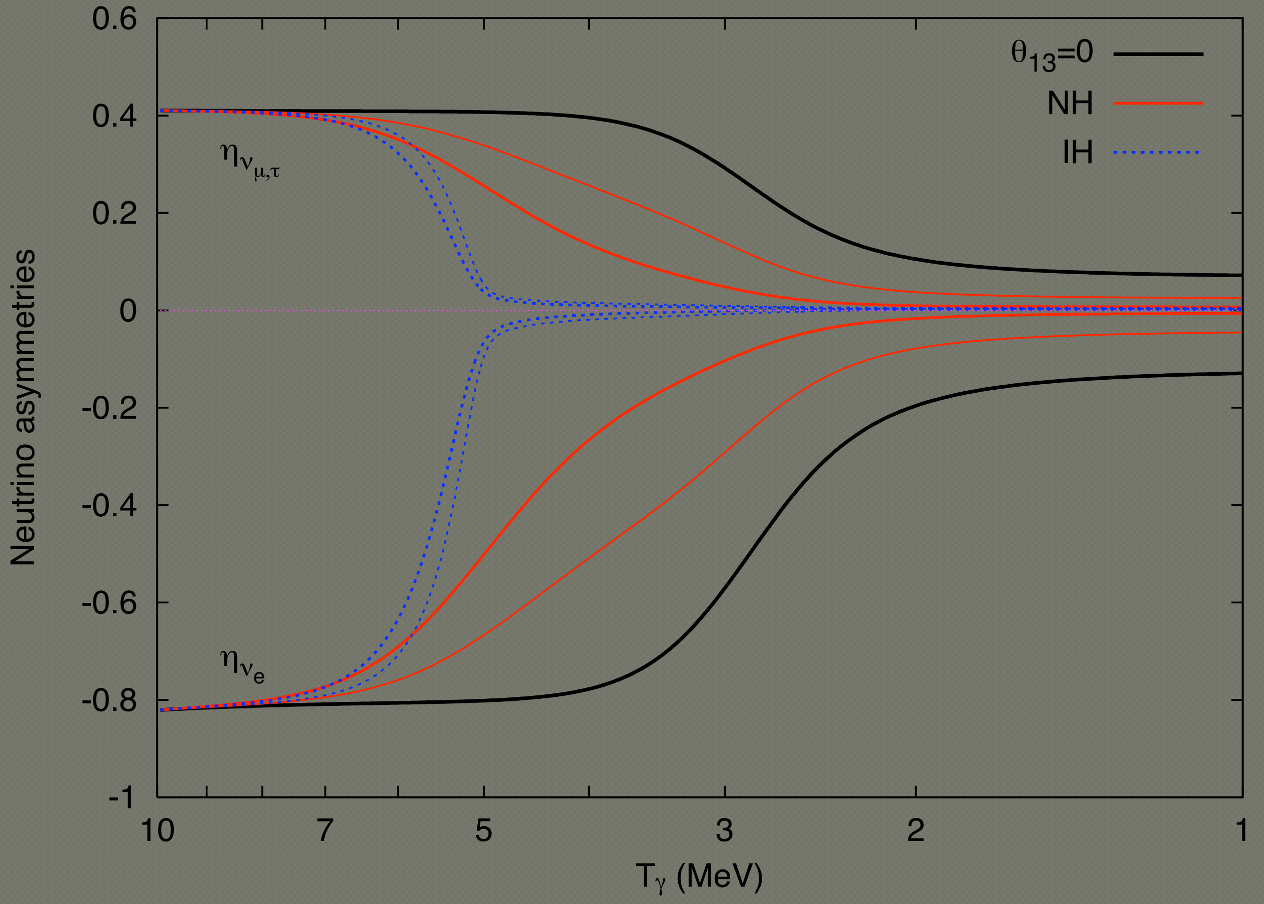
$$\eta_a = \frac{n_a - n_{\bar{a}}}{n_\gamma} = \frac{1}{12\zeta(3)}\left(\pi^2 \xi_a + \xi_a^3\right) \approx \eta_B = 6 \times 10^{-10}$$

unless leptogenesis takes place well below the EW breaking scale

$$\exp\left(-M_W(T)/g^2 T\right) << 1$$

Oscillations and neutrino asymmetries

The value of θ_{13} is crucial (and to a minor extent the mass hierarchy)



Pastor et al 2011
GM et al 2012

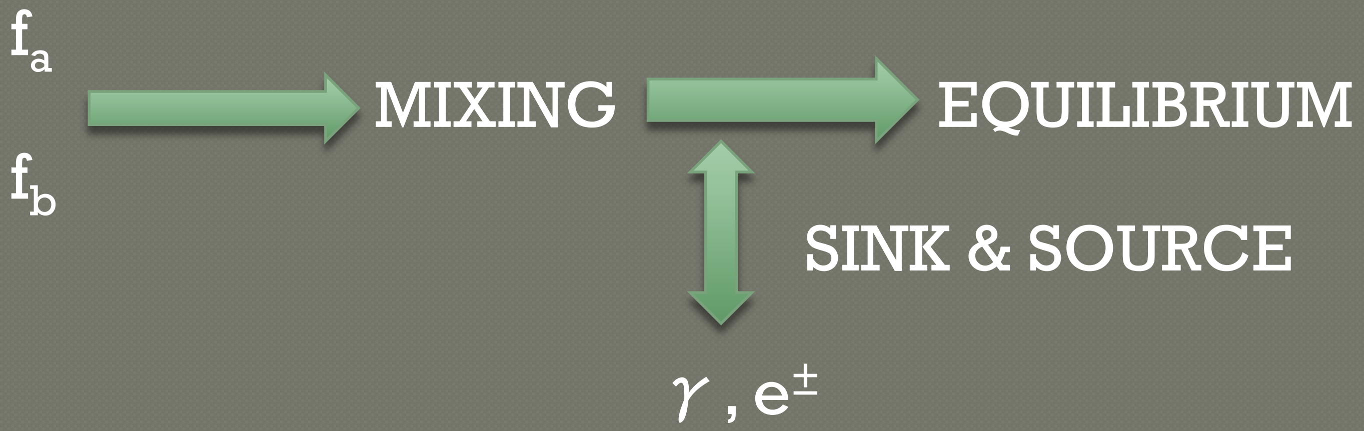
Oscillations and neutrino asymmetries

$T_{\mathrm{mix}} >> T_{\mathrm{dec}}$ $$f_a = f_b = \frac{1}{e^{p/T}+1}$$ $N_{\mathrm{eff}} = 3.046$

$T_{\mathrm{mix}} << T_{\mathrm{dec}}$ $$f_a = f_b = \cos^2\theta \frac{1}{e^{p/T-\xi}+1} + \sin^2\theta \frac{1}{e^{p/T+\xi}+1}$$

$N_{\mathrm{eff}} > 3$

unless $\xi = 0$



f_a

f_b

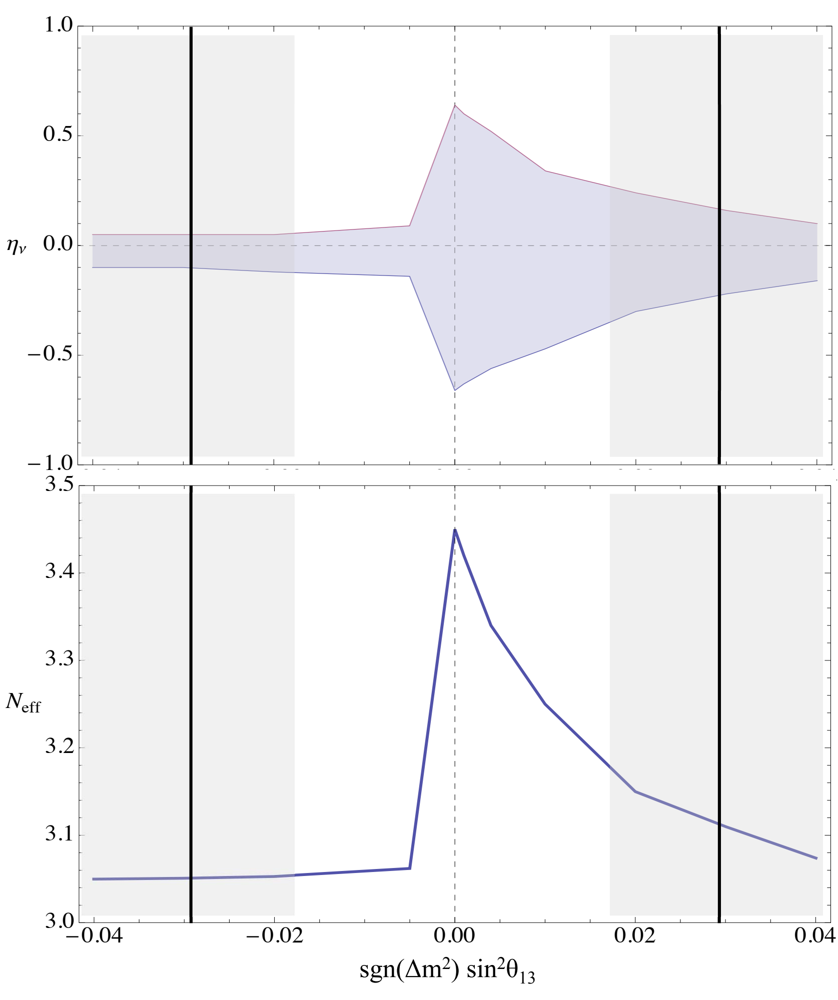
MIXING

EQUILIBRIUM

SINK & SOURCE

γ , $e^{\pm}$

Oscillations and neutrino asymmetries



the bounds:
scanning all asymmetries
compatible with BBN

$N_{\rm eff} < 3.2$

$-0.2\ (-0.1) \le \eta_\nu \le 0.15\ (0.05)$

GM et al 2012

Oscillations and neutrino asymmetries

- $N_{eff} \leq 3.2$ still compatible with slightly degenerate neutrinos
- $N_{eff} \geq 3.2$ some extra “dark” radiation required or higly non-thermal neutrino distribution, or both

Planck 2015: a (large) neutrino asymmetry is still viable and can saturate the N_{eff} (68 % C.L.) upper bound

Sterile states?

Hints for sterile neutrino states from long(short) standing anomalies

LSND, MiniBoone
Reactor anomaly
Gallium anomaly

$m_\nu \approx \mathrm{eV}, \quad \sin^2 \theta_{as} \approx 10^{-2}$

With standard assumptions too many sterile neutrinos in the early universe, produced via oscillations

Sterile states?

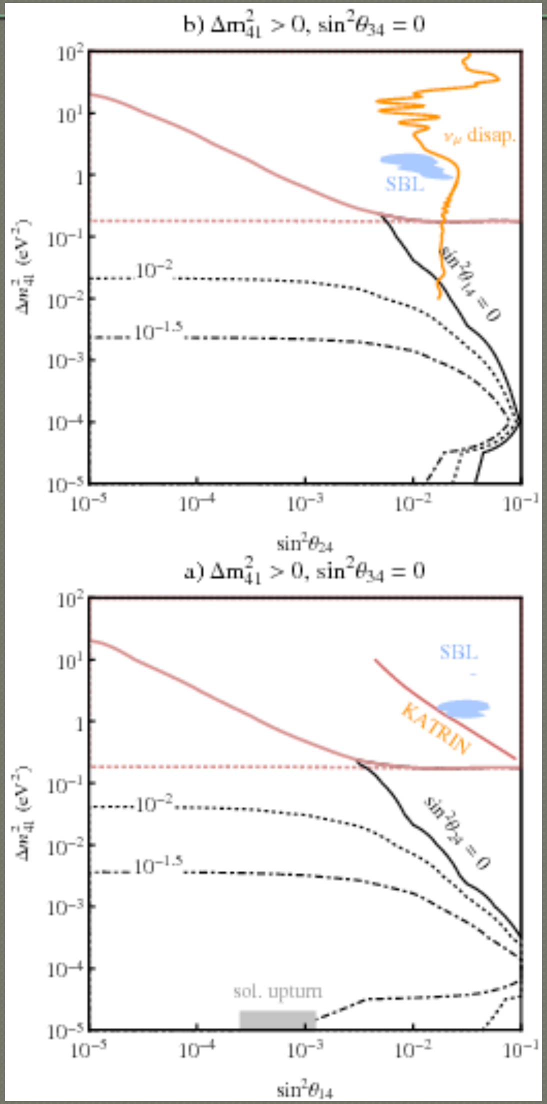
Unless there is a fine tuning, the typical outcome is either too few or too many (and too heavy !)

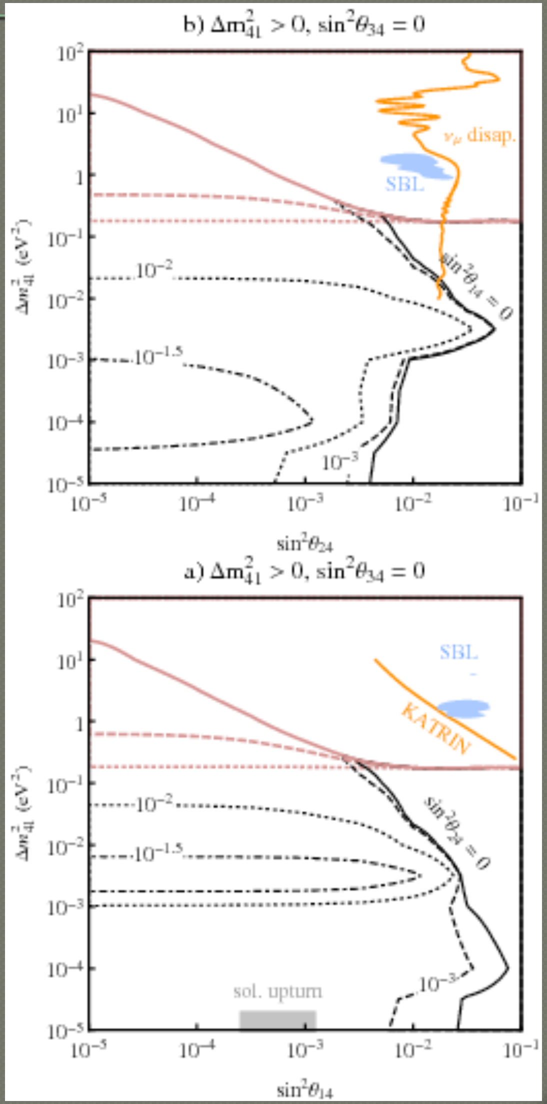
1. The standard case
2. Large lepton asymmetries
3. “secret” “sterile” interactions

Sterile states?

The standard case

(Mirizzi et al 2013)





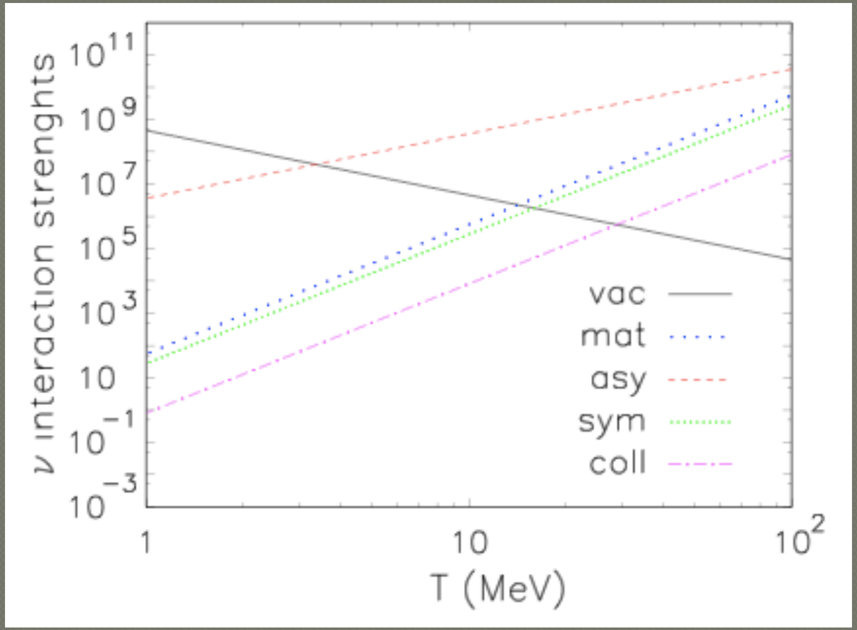
New Planck analysis
(Planck XIII 2015)

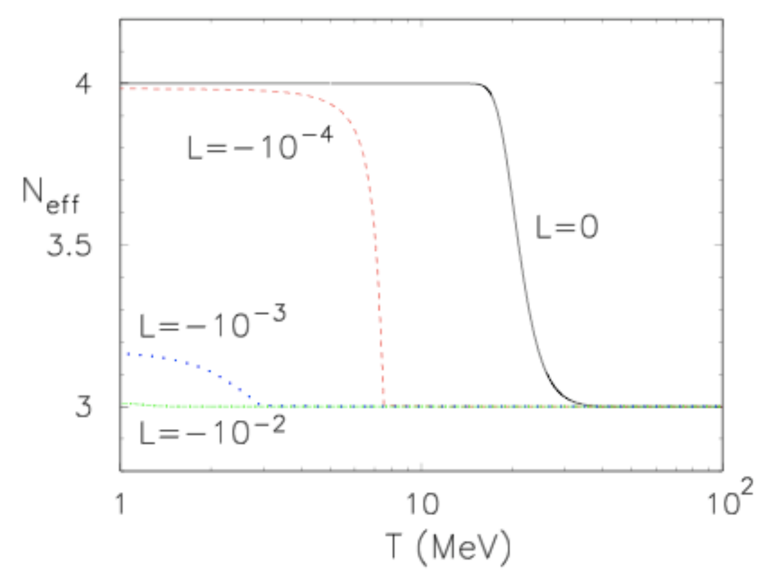
$N_{eff} < 3.7$
$m_s < 0.38$ eV

Sterile states?

Lepton asymmetry suppresses sterile production

$V = \sqrt{2}\, G_F\, L_\nu$





$L_\nu = 10^{-4}$

Mirizzi et al. 2012

Sterile states?

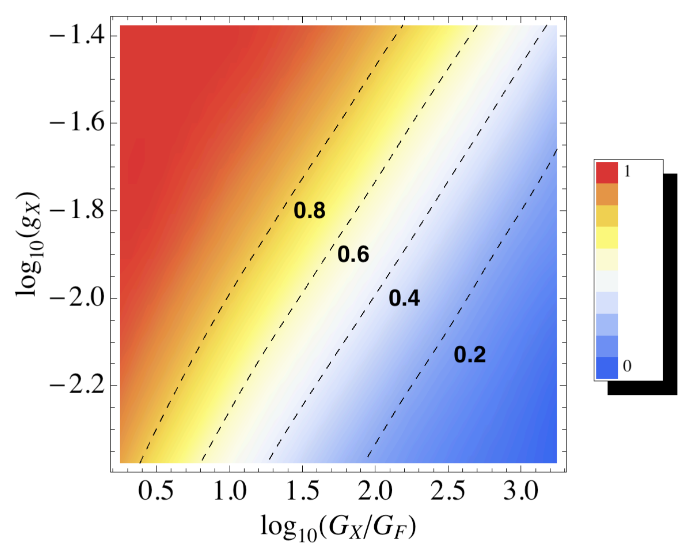
Large sterile self-interactions suppress sterile production due to large potential

$$V_s = -\sqrt{2} G_X \frac{8\langle p \rangle \rho_s}{3 M_X^2}$$

(Hannestad et al 2013)

G_X larger than Fermi constant. OK for N_{eff} smaller than 1.

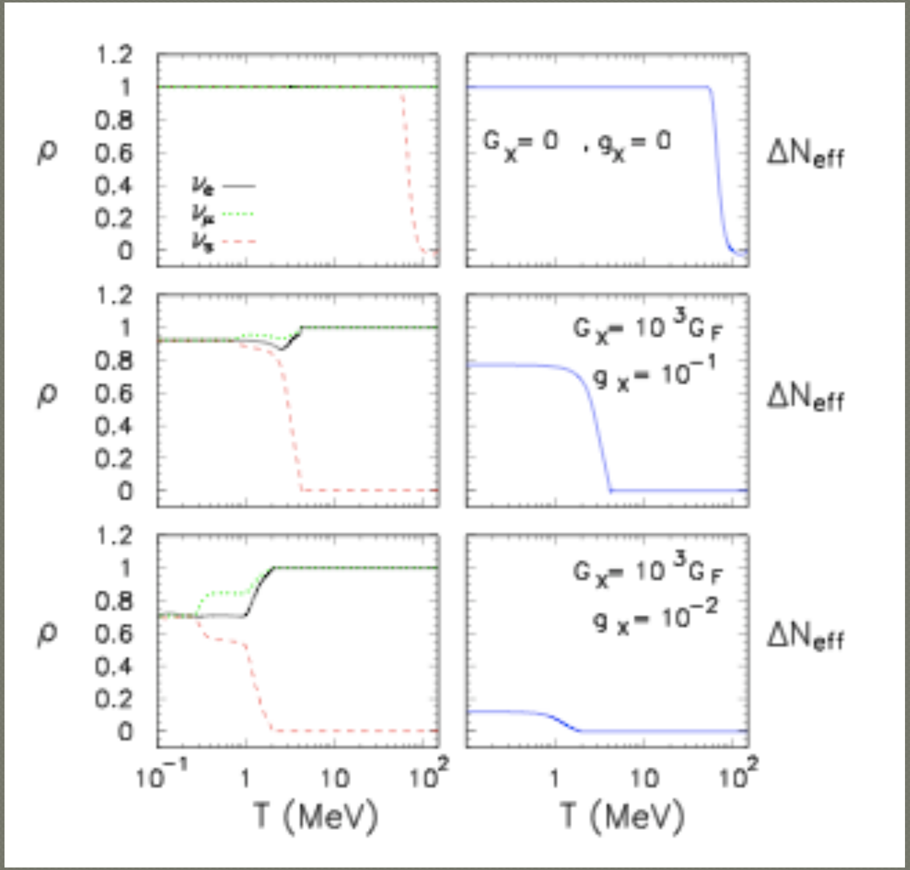
$$G_X = \frac{\sqrt{2} g_X^2}{8 M_X^2}$$



Saviano et al 2014

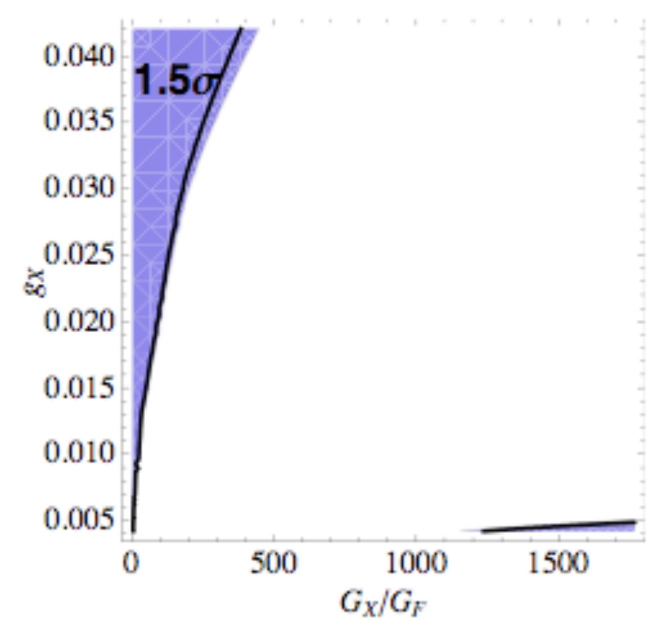
Sterile states?

BBN sensitive to ν_e distribution

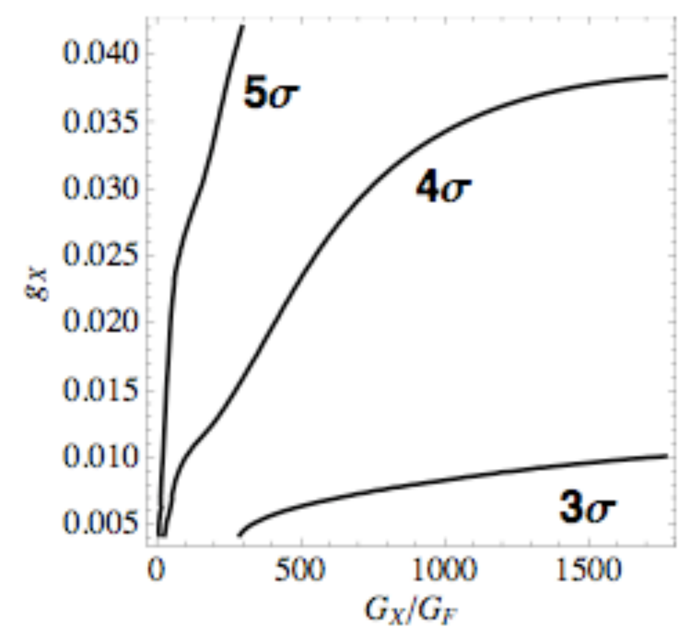


Saviano et al 2014

Sterile states?



Y_p

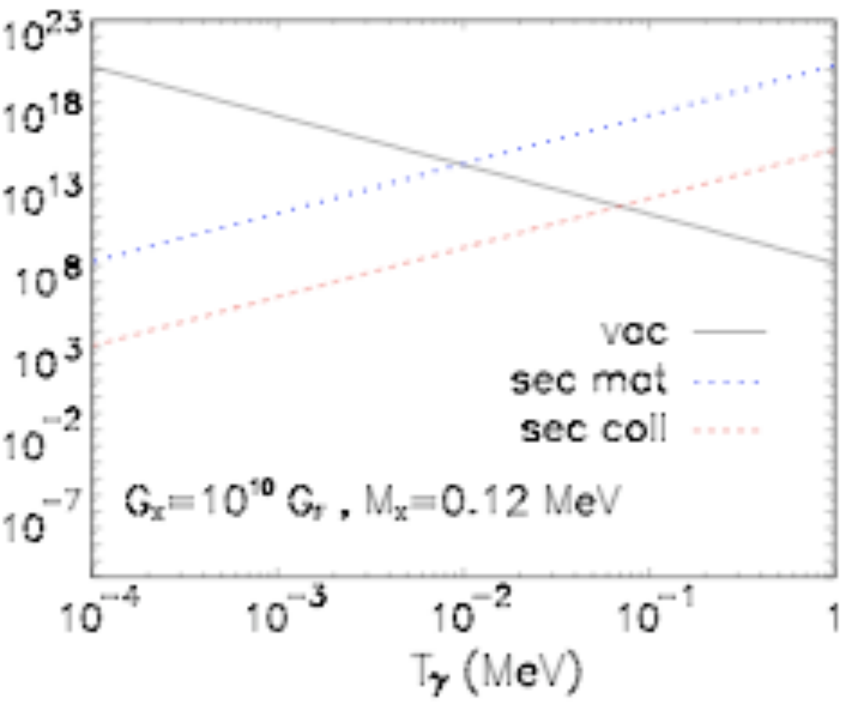


$^2H/H$

Saviano et al 2014

Sterile states?

Can we evade BBN constraints?



Mirizzi et al 2014

Large couplings suppresses sterile production well after BBN

But eventually sterile states are excited: $n_{\text{sterile}} \approx n_{\text{active}}$

Entropy conservation: $N_{\text{eff}} \approx 2.7$

Two regimes:

Sterile become collisionless before non relativistic: mass bound applies

Sterile become collisionless after non relativistic: mass bound does not apply

Conclusions

We know a lot about neutrino properties from lab experiments.

We would like to know more exploiting their impact on cosmological and astrophysical observables.

Precision Cosmology: precise observations which fit the standard model extremely well.

But: as soon as we move away from our comfortable standard?

Robust vs weak predictions:
which is the case for neutrino properties ?