Neutrino & Cosmology

G. Mangano
INFN Napoli

NNN 2014 Paris 4-6 November 2014

Precision is a matter of prejudice

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 ?

Summary

- 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 ? ✗
- Any relation with dark matter ? ✗✗
- Majorana or Dirac particles ? ✗✗✗

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 N_{eff} gives a higher expansion speed, a shorter age of the universe T at recombination.

Diffusion length ≈ $\sqrt{T}$
Sound horizon ≈ T

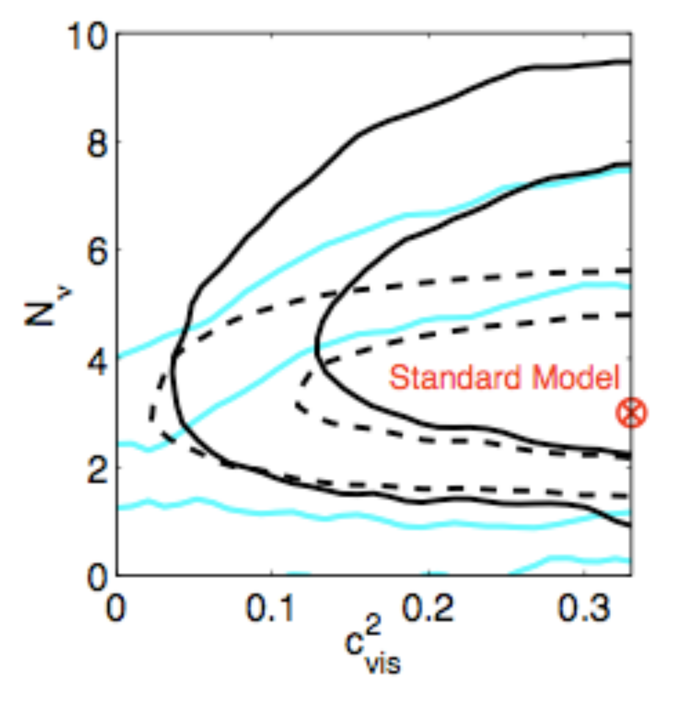
$N_{eff} = 3$ is a good fit (see later)

Are there neutrinos in the universe?

Perturbation effects:

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

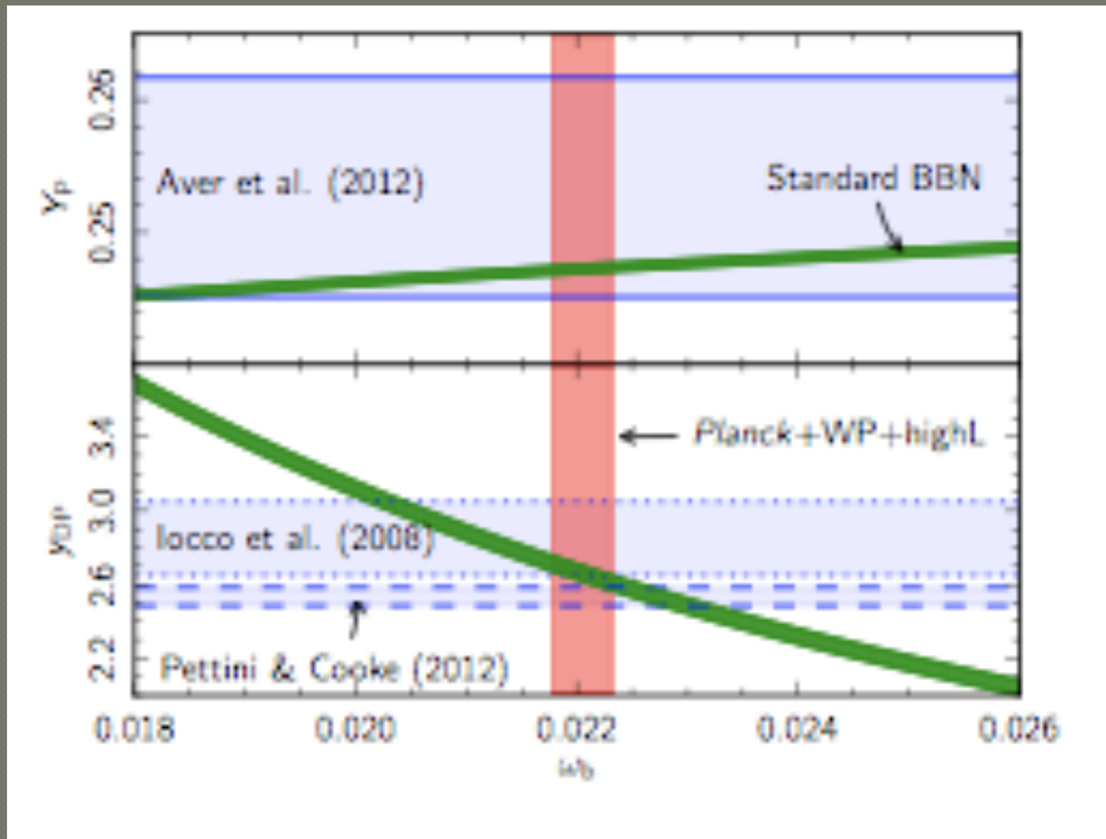
c_{vis} :velocity/metric shear – anisotropic stress relation (Hu 1998)



Troota & Melchiorri 2005

Are there neutrinos in the universe?

CMB and BBN are quite consistent



Ade et al. 2013
(Planck XVI)

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

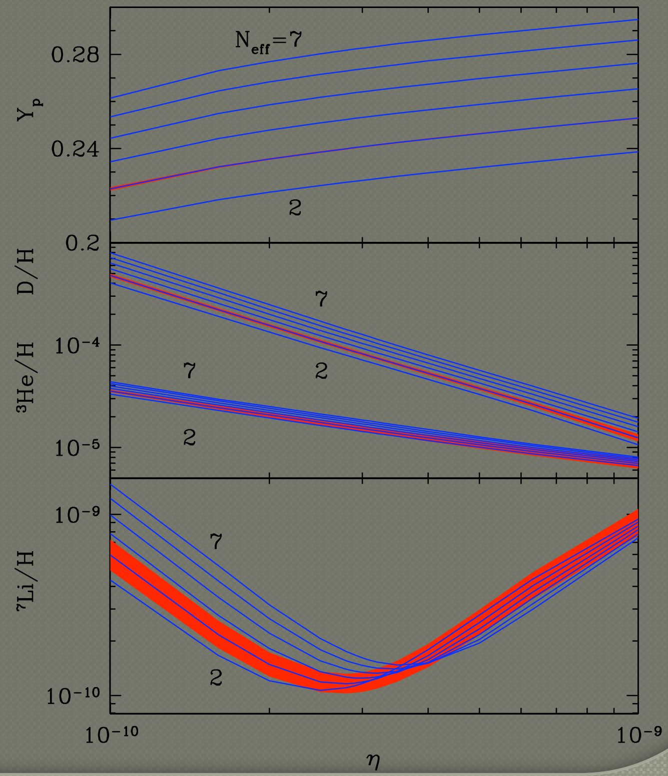
both ^4He mass fraction Y_p and $^2H/H$ are increasing functions of N_{eff}:
change of expansion rate
ν_e distribution crucial in weak rates
baryon density basically fixed by CMB!
(but still $^2H/H$ can varies a lot)

$$\Omega_b h^2 = 0.02207 \pm 0.00027$$

crucial inputs:

experimental values

nuclear rates



Cyburt 2004

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
$Y_p \leq 0.2631 \;\; 95\%$ 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"

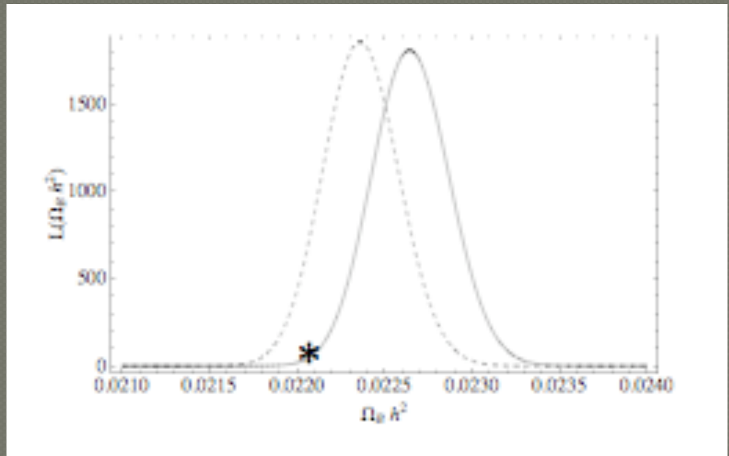
to

"No room for extra neutrinos"

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

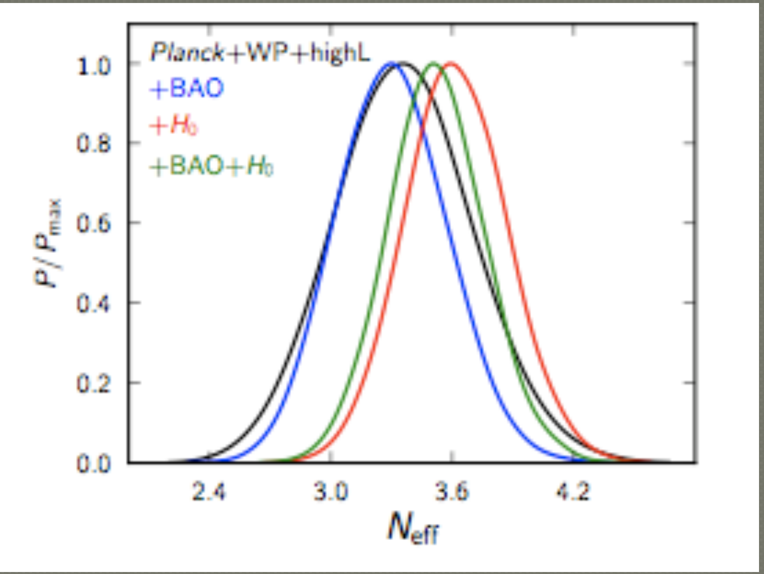
$$^{2}H/H = (2.65 \pm 0.07) \cdot 10^{-5}$$

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

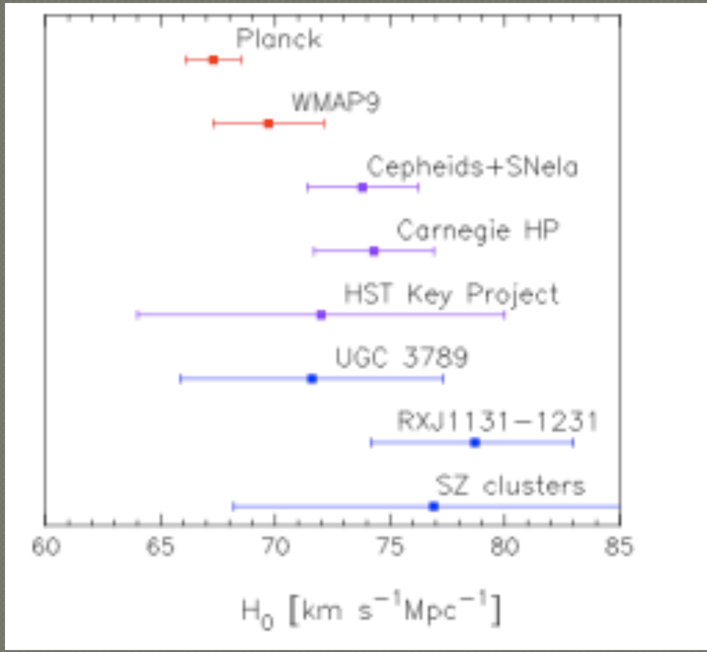


How many of them? (the long tale of N_{eff})

News from Planck: 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)

Neutrino mass: universe better than lab's ?

Mass bounds

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;

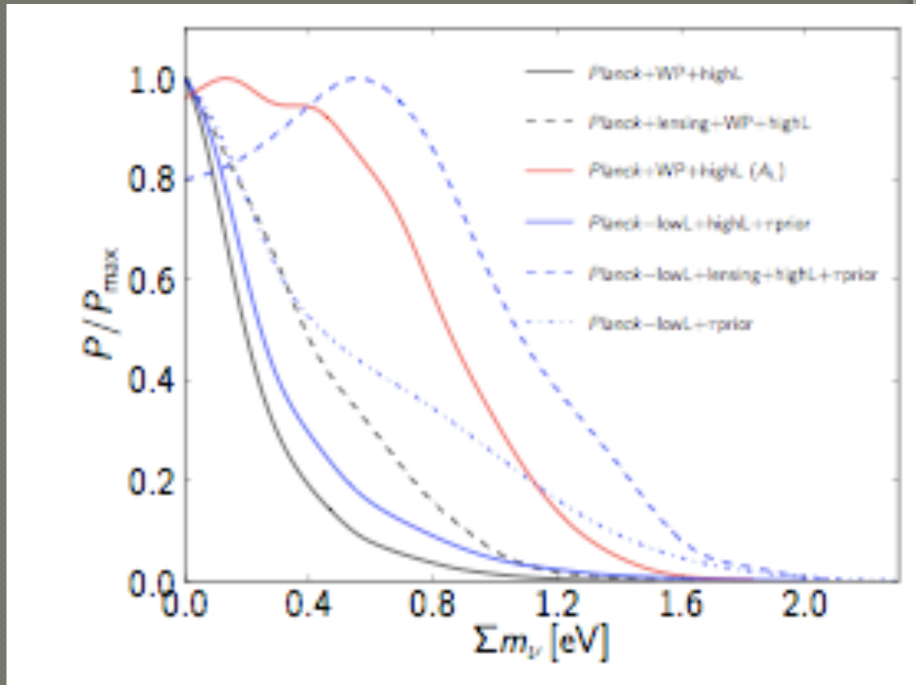
Planck: gravitational lensing. Increasing neutrino mass, increases the expansion rate at $z > 1$ and so suppresses clustering on scales smaller than the horizon size at the nonrelativistic transition (Kaplinghat et al. 2003 ; Lesgourgues et al. 2006). Suppression of the CMB lensing potential.

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 H0)

Including BAO constraint is much tighter:

$\Sigma\ m_\nu < 0.98$ eV (CMB)
$\Sigma\ m_\nu < 0.32$ eV (CMB + BAO)



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

→ f_a slightly distorted
$N_{eff} = 3.046$

Oscillations and neutrino asymmetries

density matrix formalism ρ_{ab}

ρ_{aa} occupation number

ρ_{ab} $a \neq b$ 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

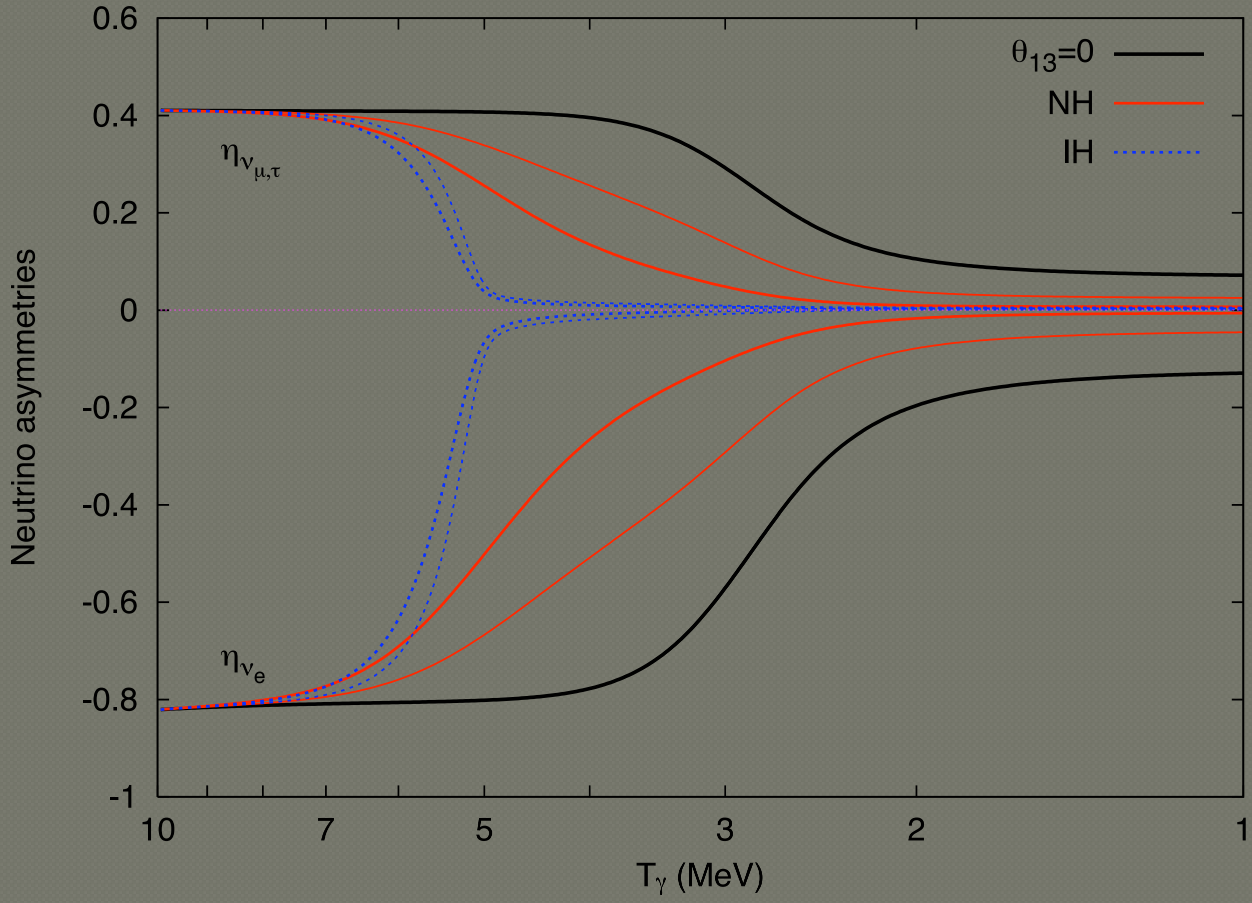
$$\eta_a = \frac{n_a - n_{\bar{a}}}{n_\gamma} = \frac{1}{12\zeta(3)}\left(\pi^2\xi_a + \xi_a^3\right) \approx \eta_B = 6\times 10^{-10}$$

unless leptogenesis takes place well below the EW breaking scale

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

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

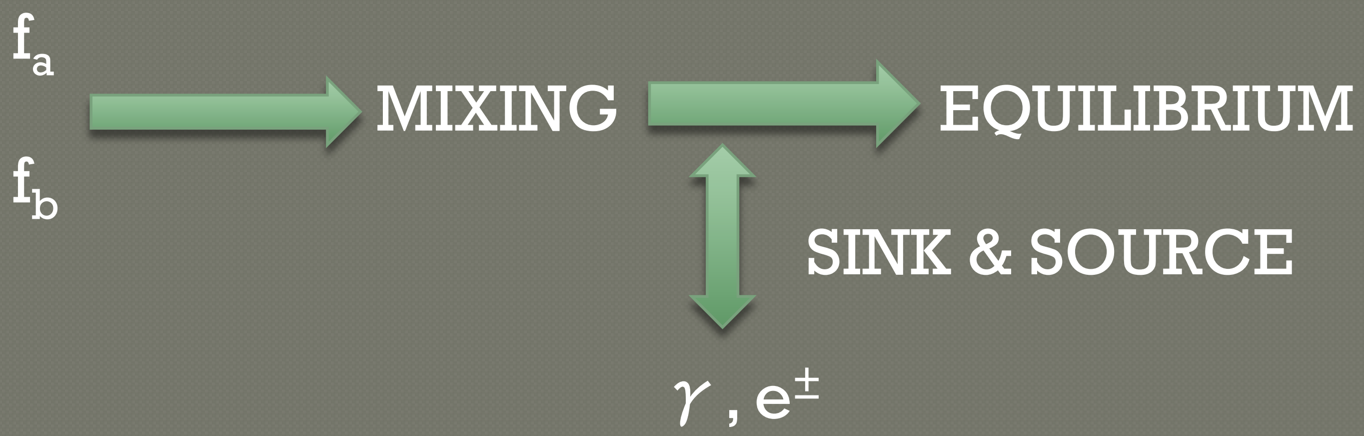
Oscillations and neutrino asymmetries

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

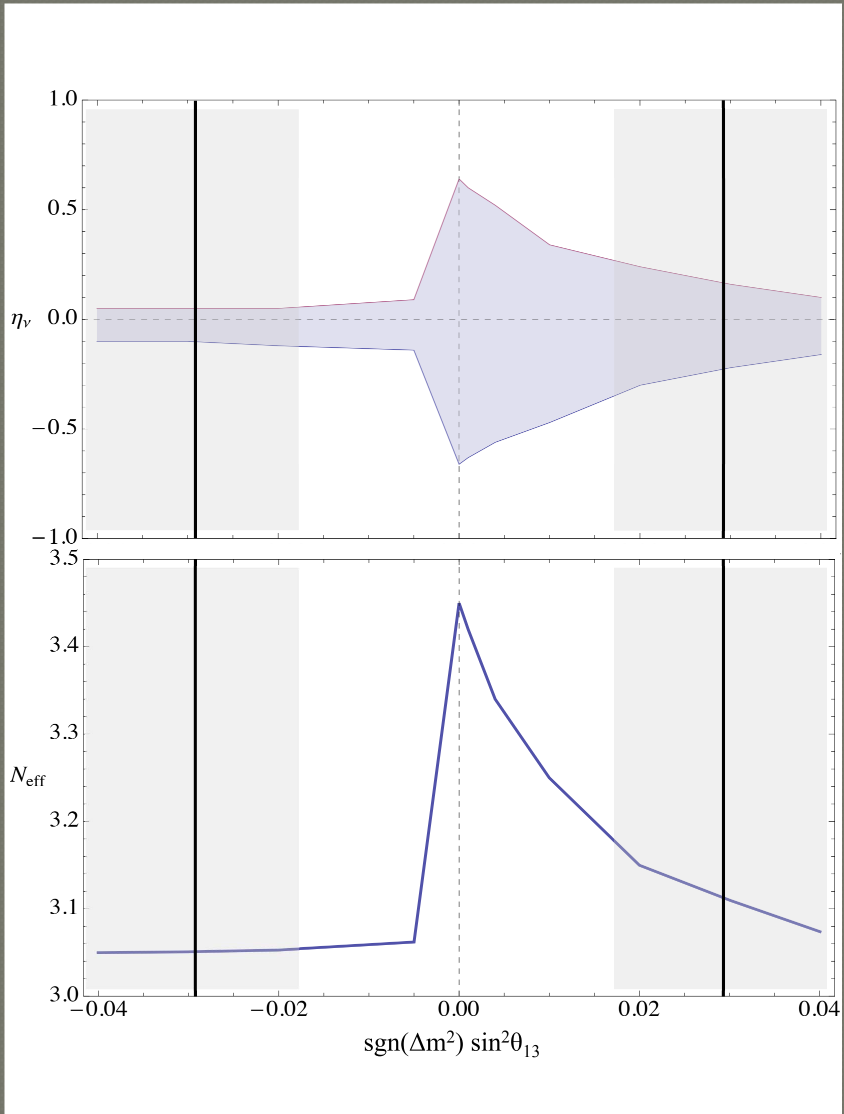
$T_{mix} << T_{dec}$ $$f_a = f_b = \cos^2\theta \frac{1}{e^{p/T-\xi}+1} + \sin^2\theta \frac{1}{e^{p/T+\xi}+1}$$

$N_{eff} > 3$

unless $\xi = 0$



Oscillations and neutrino asymmetries



the bounds:
scanning all asymmetries compatible with BBN

$N_{eff} < 3.2$

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

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

After Planck I results still inconclusive !

Sterile states?

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

LSND, MiniBoone
Reactor anomaly
Gallium anomaly

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

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 (unlikely^2 for Ockam)

Sterile states?

Planck analysis (Planck XVI 2013)

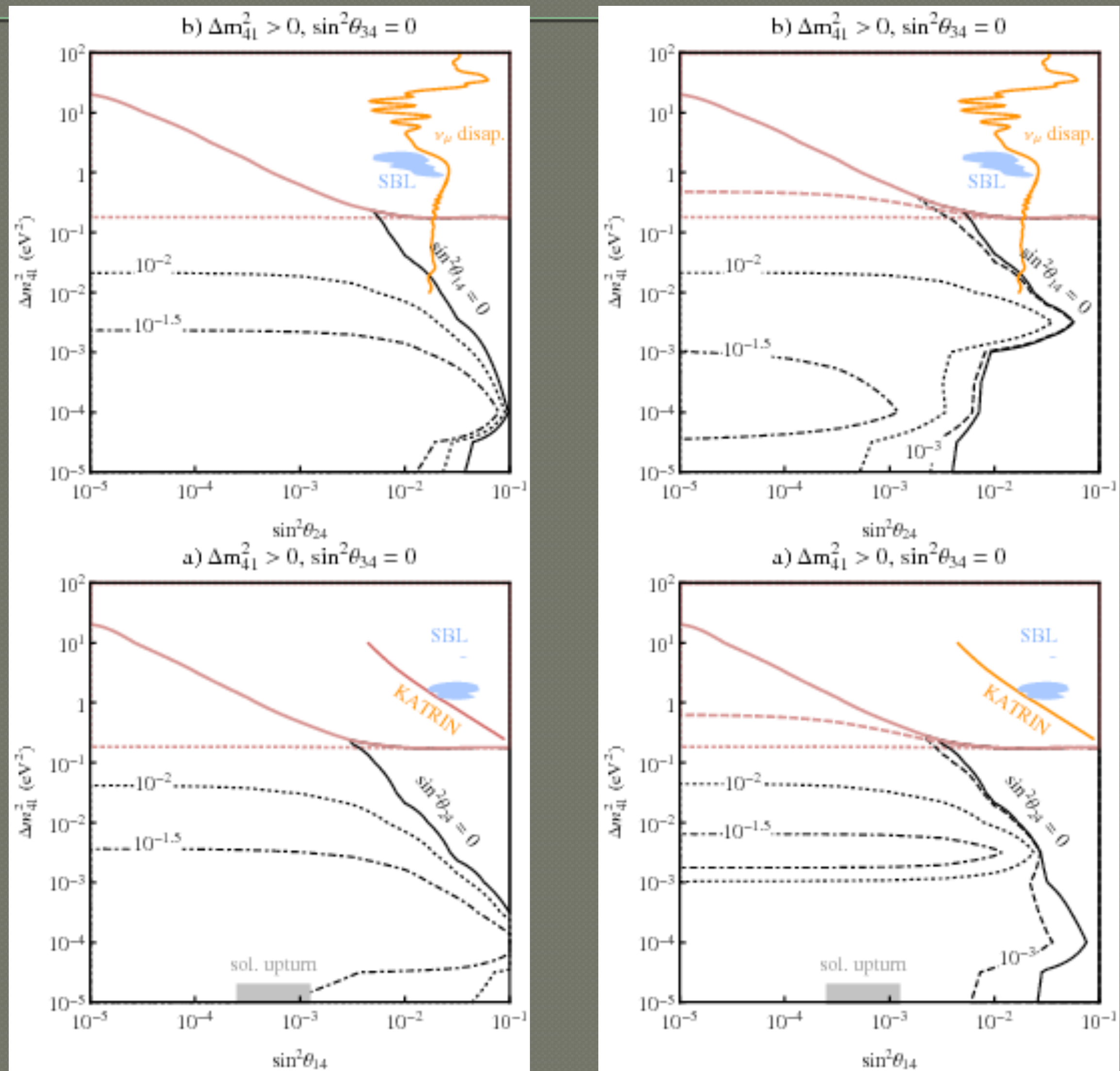
$N_{eff} < 3.91$
$m_s < 0.59$ eV

$N_{eff} < 3.80$
$m_s < 0.42$ eV (including BAO)

Sterile states?

The standard case

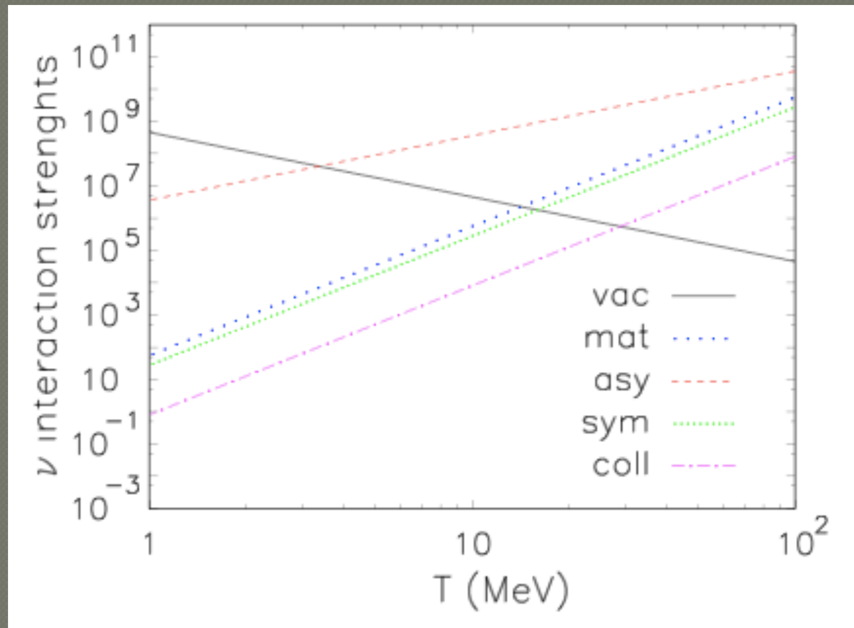
(Mirizzi et al 2013)

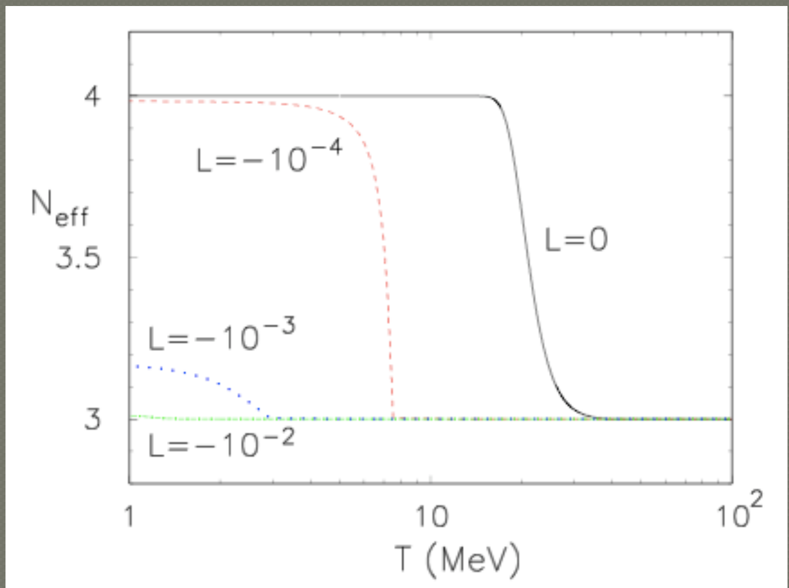


Sterile states?

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

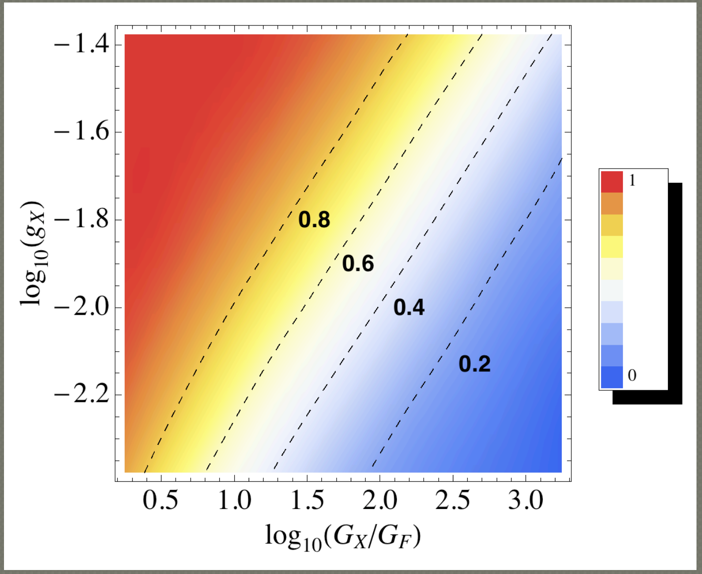
$$V_s = -\sqrt{2} G_X \frac{8\langle p \rangle \rho_s}{3 M_X^2}$$

(Hannestad et al 2013)

G_X larger than Fermi constant.

OK for N_{eff} smaller than 1.

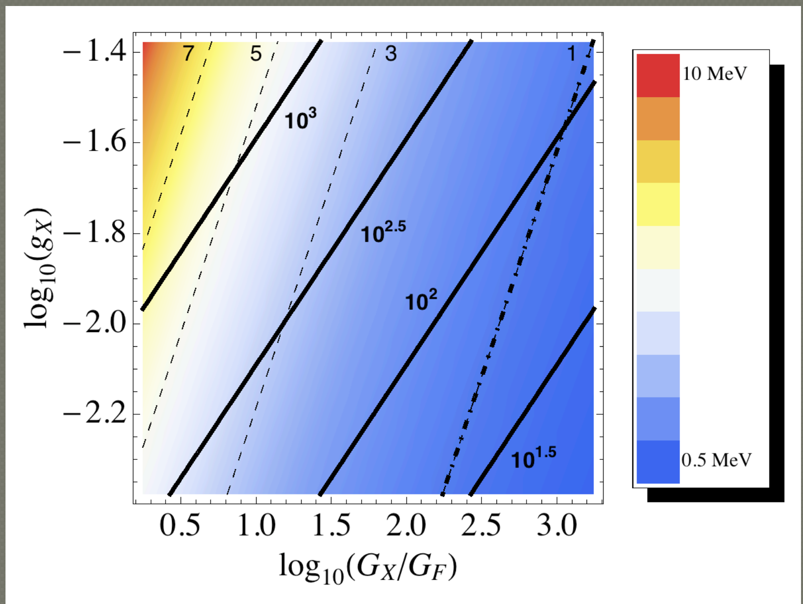
$$G_X = \frac{\sqrt{2} g_X^2}{8 M_X^2}$$

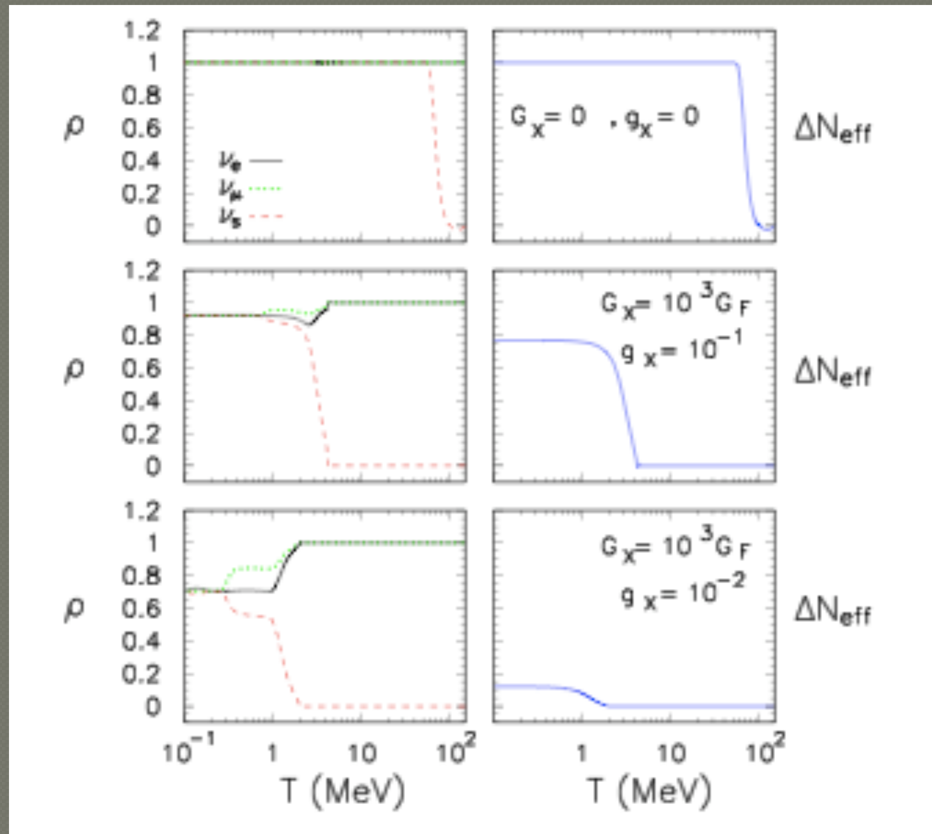


Saviano et al 2014

Sterile states?

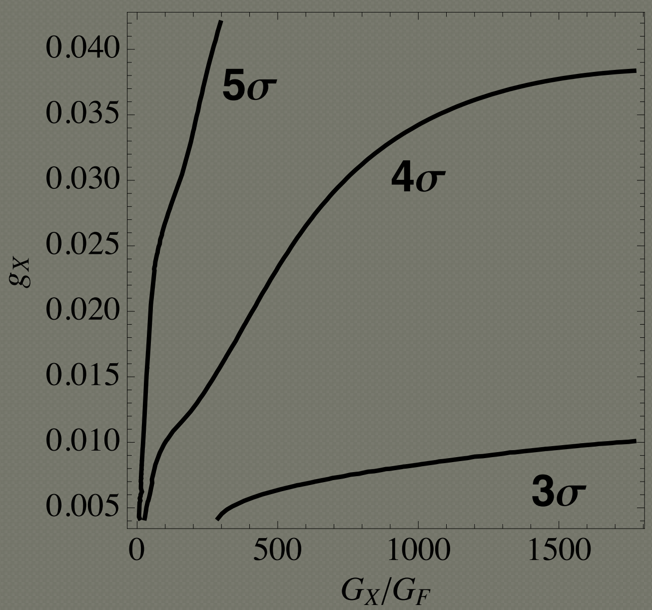
Bounds from BBN ! If resonance takes place at MeV scale the ν_e distribution gets distorted.





Sterile states?

Main constrain from $^2H/H$ (with Planck baryon number). Increasing Ω_b helps but choosing it at 3σ from Planck best fit)



Majorana or Dirac particles ?

Can we distinguish Majorana or Dirac neutrinos from cosmology ?

Relativistic regime: NO ✗
Structure formation: NO ✗
Leptogenesis: YES ✓✓
Direct detection: YES ! (really demanding) ✓

Majorana or Dirac particles ?

Neutrino capture on ^3H (PTOLEMY R&D, Katrin too low ^3H mass)

$\nu_e + {}^3H \rightarrow e + {}^3He$

Weinberg 1962
Cocco et al 2007

- Dirac: only the left-helicity neutrinos & anti-neutrinos cannot be captured.
- Majorana: both left- and right-helicity neutrinos, ➔capture rate doubled

PTOLEMY (100g ^3H) :

4 events yr^{-1} Dirac
8 events yr^{-1} Majorana

Lunardini et al. 2014

Conclusions

What we would like to know about neutrinos ?

- mass ✓
- Majorana or Dirac ✗
- Other neutrinos (sterile, mirror,…) ✓

Cosmological data are precise today (% level)

&

Standard cosmological model is extremely on shape !!

Beware degeneracies …

…and epicycles !!