Θ_{13} and ν asymmetries in the early universe or "A tale of two numbers"

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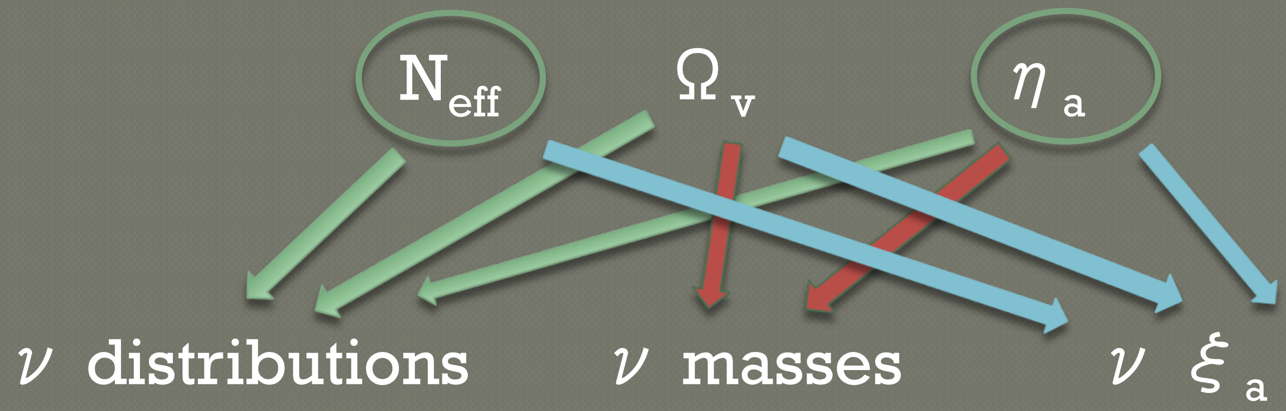
NOW 2012

Dedicated to Milla Baldo Ceolin

Flavour oscillations mix neutrino distributions at the MeV energy scale.

$f_a = f_b$ no observable effects

$f_a \neq f_b$ possible observable effects



Summary

- dynamics of oscillations
- oscillations and ν decoupling: the role of θ_{13}
  - how large N_{eff} can be ?
  - how large ξ_a can be ?
  - N_{eff} and ξ_a not the same parameter!
- N_{eff} and Planck results
- ξ_a from CMB

Following oscillations

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

$N_{eff} = 3.046$

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

Following oscillations

density matrix formalism

ρ_{ab}

ρ_{aa} occupation number

ρ_{ab} a≠b mixing

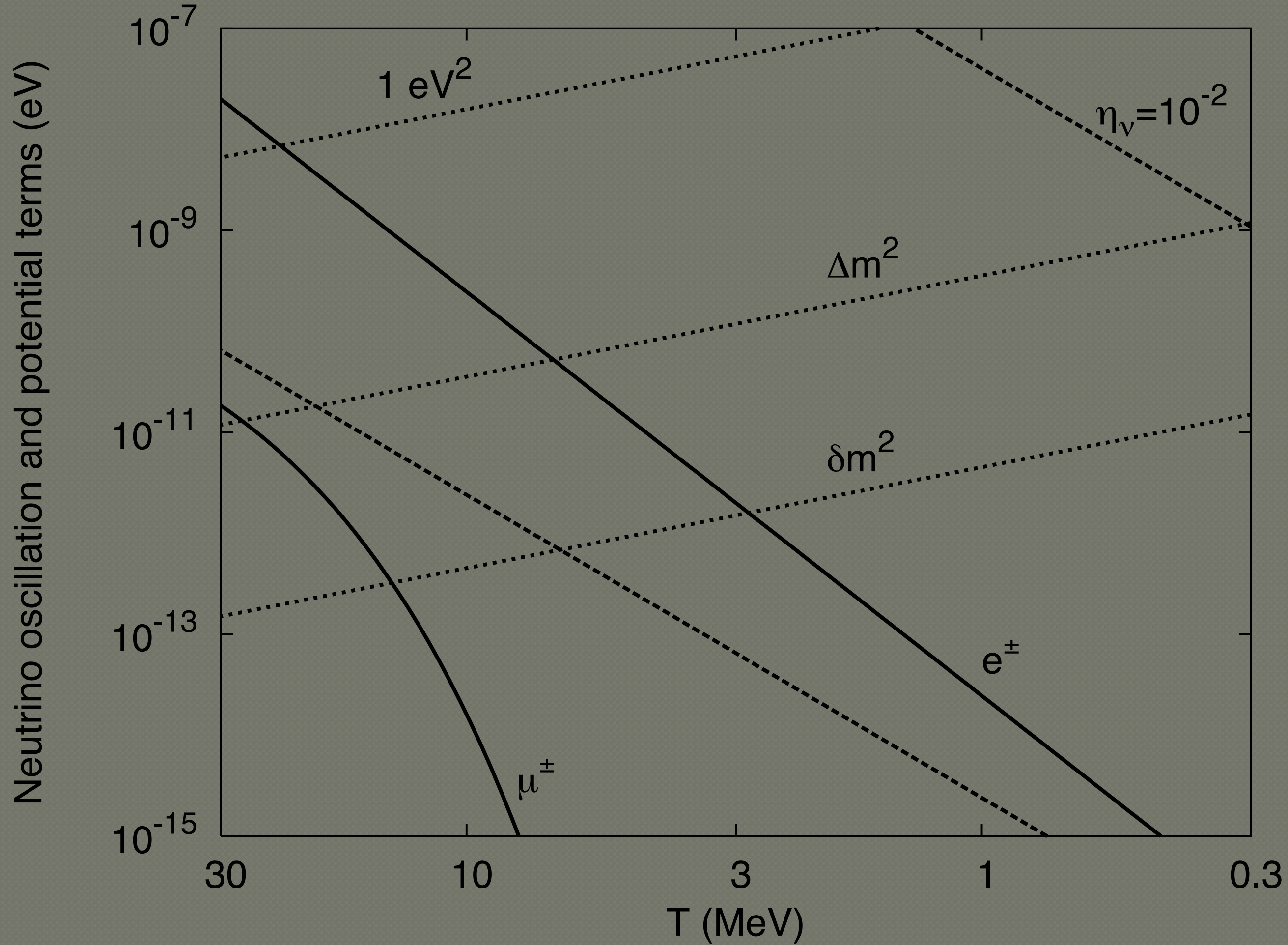
$$\frac{d}{dt}\rho = \frac{1}{i}\left[\Omega_{vac} + \Omega_{matter}, \rho\right] + C$$

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)

Following oscillations



Oscillations vs interactions

Two limiting cases:

$T_{mix} >> T_{dec}$ — f_a mix and interactions lead to equilibrium

$$f_a, f_b \Rightarrow \cos^2\theta f_a + \sin^2\theta f_b \Rightarrow f^{eq}$$

$T_{mix} << T_{dec}$ — non thermal distributions unless $f_a = f_b$

$T_{mix} \approx T_{dec}$ — to be solved numerically

A relevant example: ξ_a

Lepton asymmetries expected quite small in (standard) leptogenesis

$$\eta_a = \frac{n_a - n_{\bar{a}}}{n_\gamma} = \frac{1}{12\zeta(3)}\left(\pi^2\xi_a + \xi_a^3\right) \approx \eta_B = 6\times10^{-10}$$

unless leptogenesis takes place well below the EW breaking scale

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

(or sphalerons ineffective)

Consider now $\xi_a = -\xi_b$ (motivation later on)

A relevant example: ξ_a

$T_{mix} >> T_{dec}$

$$f_a = f_b = \frac{1}{e^{p/T}+1}$$

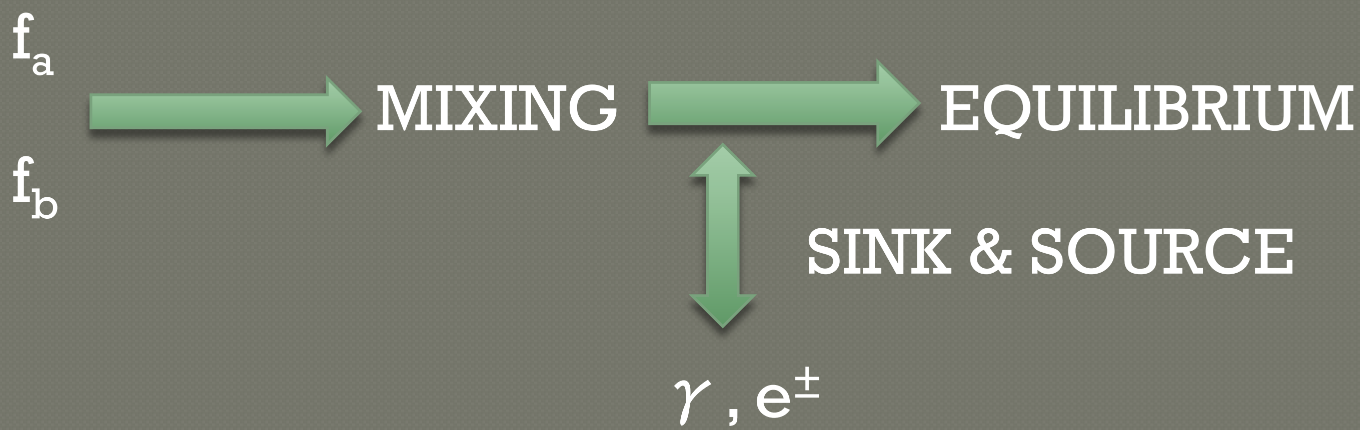
$N_{eff} = 3.046$

$T_{mix} << T_{dec}$

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

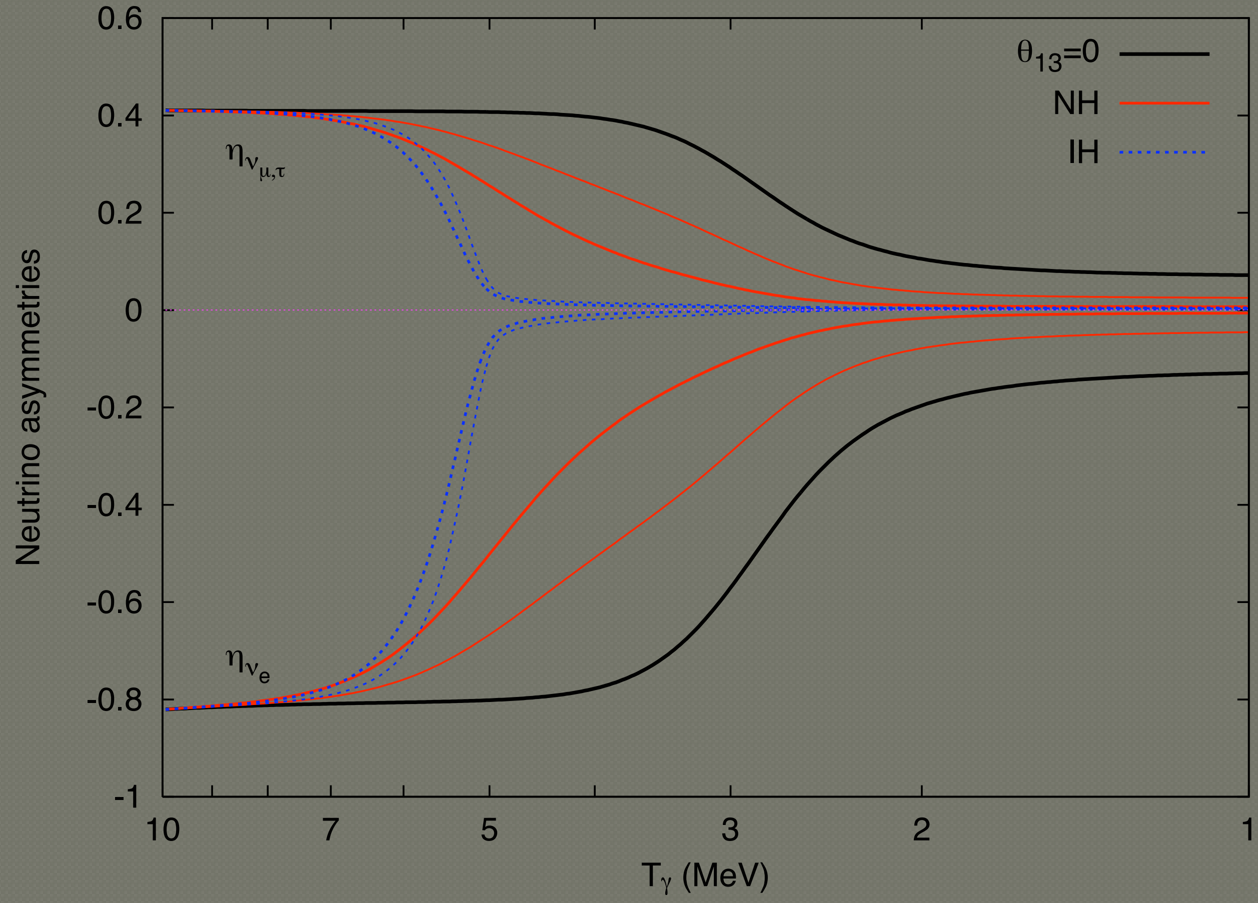
$N_{eff} > 3$

unless $\xi = 0$



A relevant example: ξ_a

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



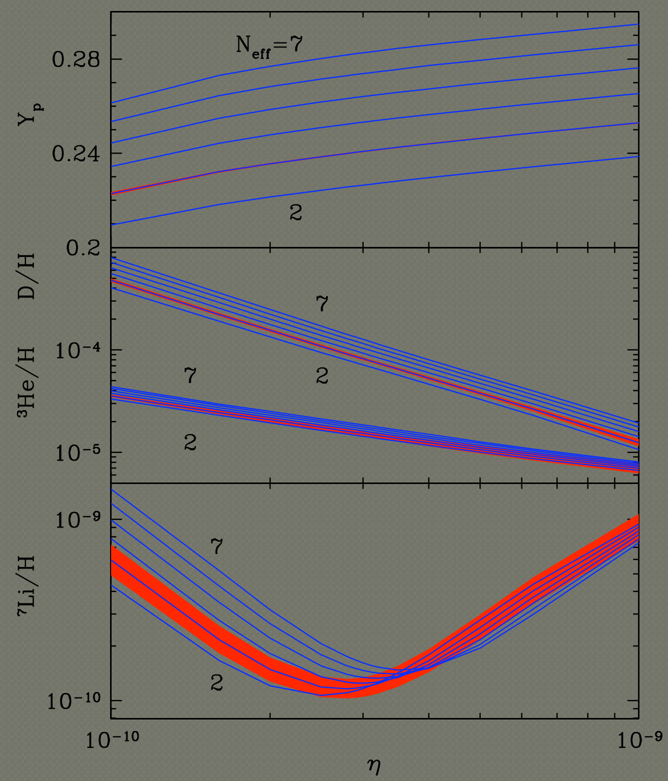
Pastor et al 2011
GM et al 2012

Exploiting BBN

BBN is the most robust test of cosmology at early times.

Only one parameter in the standard case

$\Omega_B h^2$ or η_B



Cyburt 2004

Exploiting BBN

Barring extra relativistic species (as sterile neutrinos)

$N_{eff} \approx 3$ standard picture, ν with equilibrium f_a

$$N_{eff} = 3 + \sum_a \left(\frac{30\xi_a^2}{7\pi^2} + \frac{30\xi_a^4}{7\pi^4} \right)$$

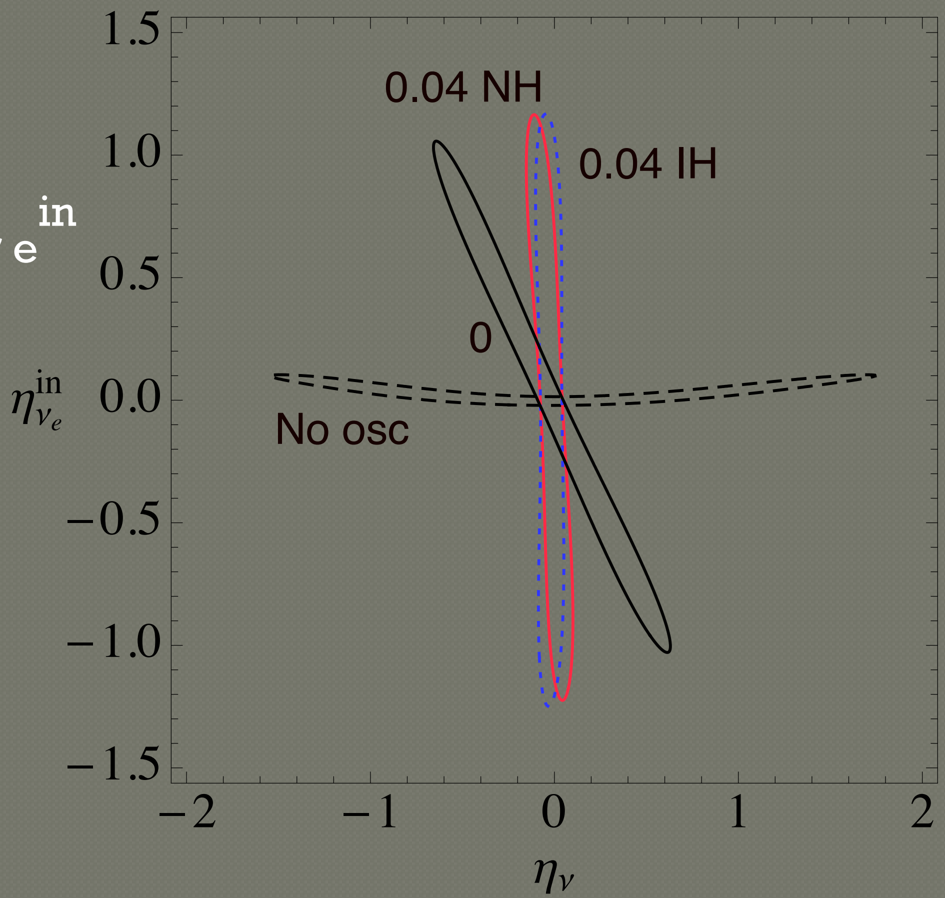
$N_{eff} > 3$ effective (time depending) T_a and ξ_a
(the first two moments are enough)

^{4}He mass fraction Y_p (and ^{2}H/H) quite sensitive to neutrino asymmetries: Kang and Steigman 1992

- $N_{eff} > 3$ speeds up expansion, an earlier n/p freeze out temperature T_{fr}
- $n + \nu_e \Leftrightarrow p + e^-$ $$n/p = \exp\left(-\Delta m / T_{fr}(N_{eff}) - \xi_e\right)$$

Exploiting BBN

Parameters:
total asymmetry η_ν
initial ν_e asymmetry $\eta_{\nu e}^{in}$



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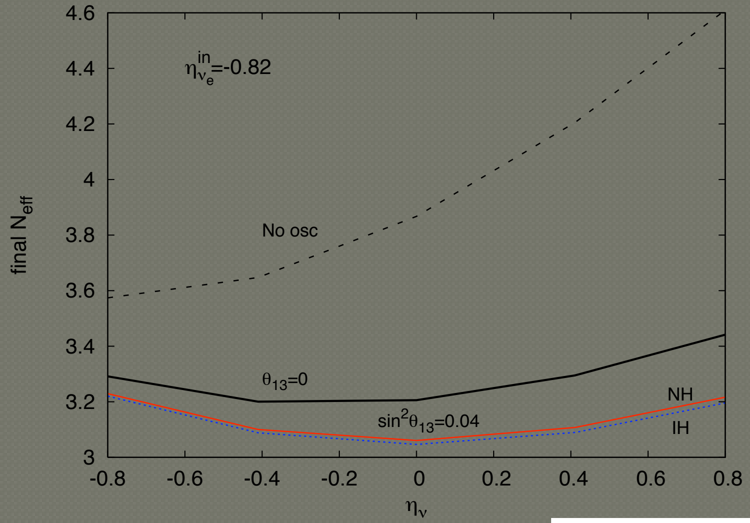
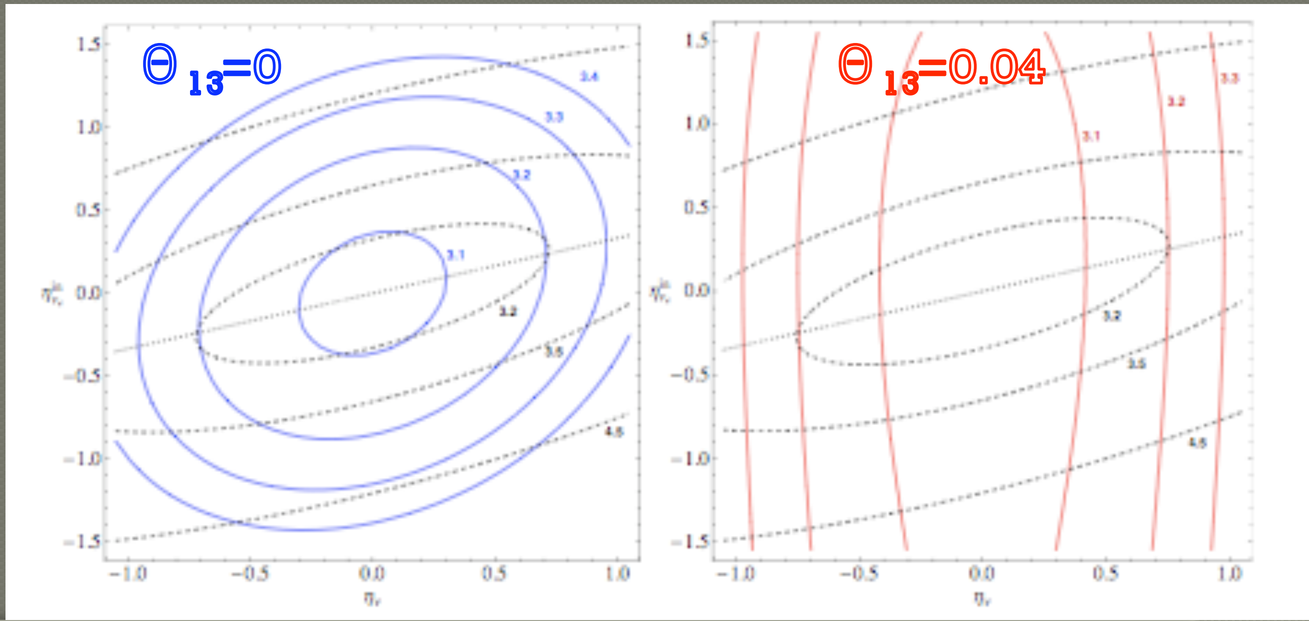
Exploiting BBN

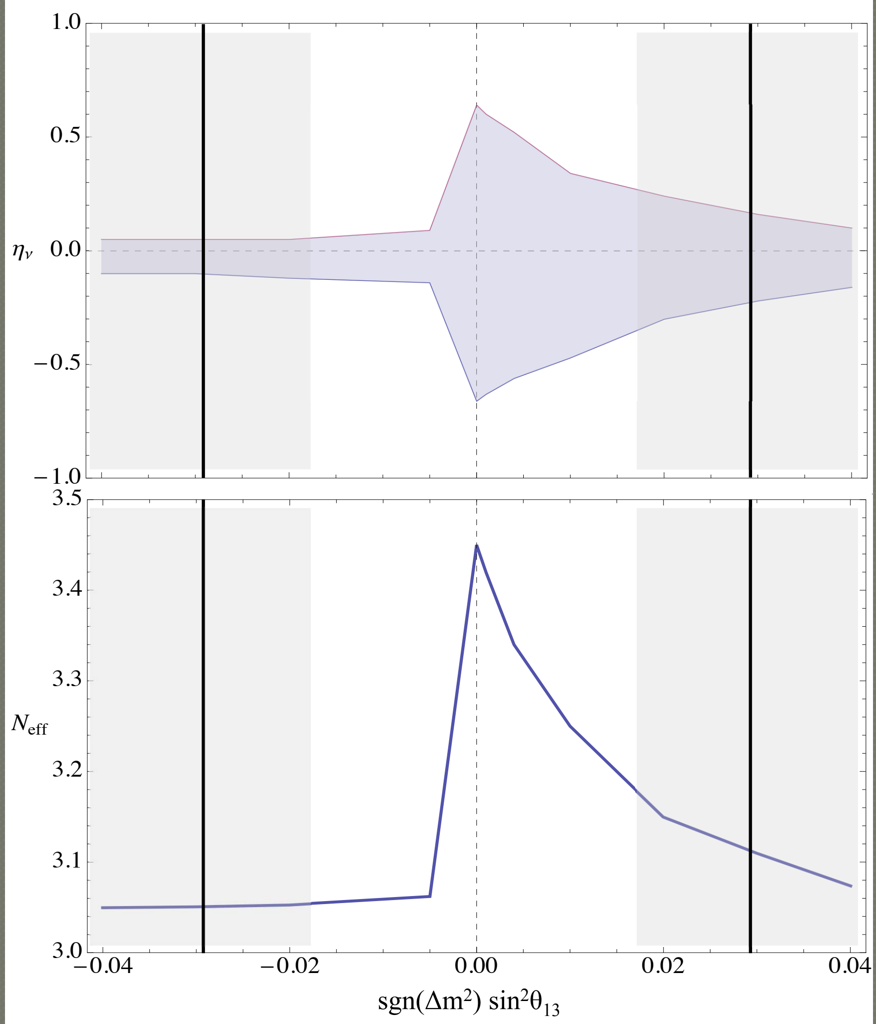


From asymmetries to N_{eff} :

for given initial asymmetries the final neutrino distributions are computed numerically solving Boltzmann equations



Exploiting BBN



the bounds:
scanning all possible asymmetries compatible with BBN

$N_{eff} < 3.2$

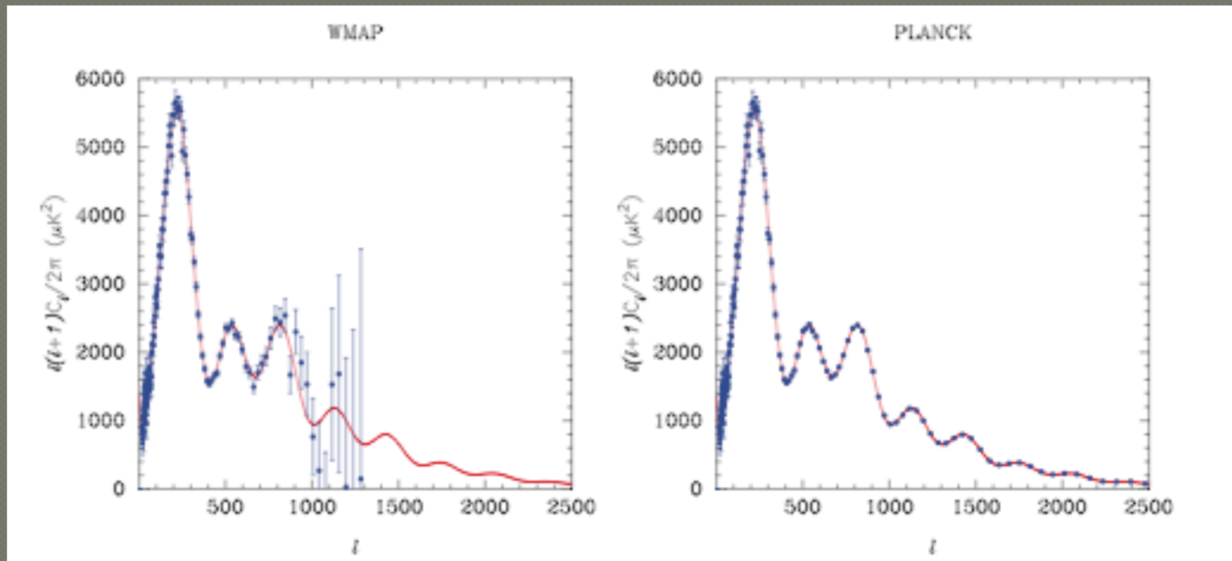
$-0.2\ (-0.1) \leq \eta_\nu \leq 0.15\ (0.05)$

The role of Planck

Planck first results expected early 2013
More complete results in 2014

Very sensitive to N_{eff} (ISW+ damping tail)

$\Delta N_{eff} \approx 0.2$



The role of Planck

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

ξ_a from CMB

What can we further learn from CMB alone ?
A further handle on the value of ξ_a?

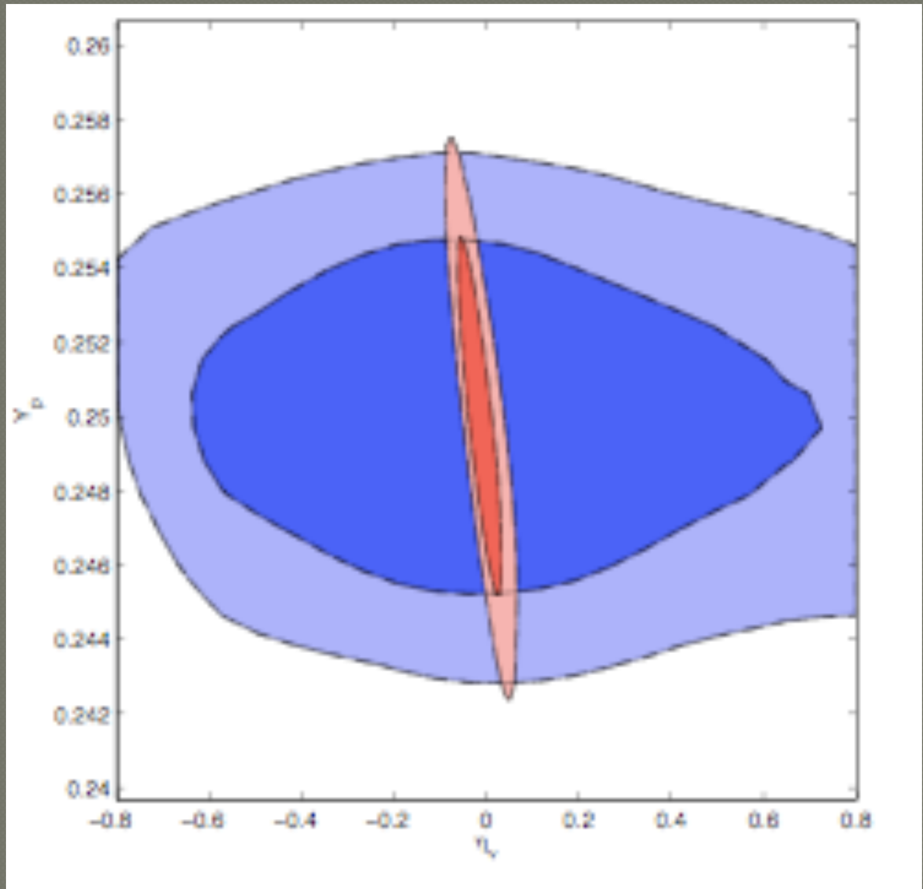
The role of ξ_a for CMB anisotropies is encoded in N_{eff}

Recent analyses uses $Y_p(\omega_B, N_{eff})$ from BBN (if compatible!)

ξ_a from CMB

Presently, bounds on ξ_a are dominated by Y_p

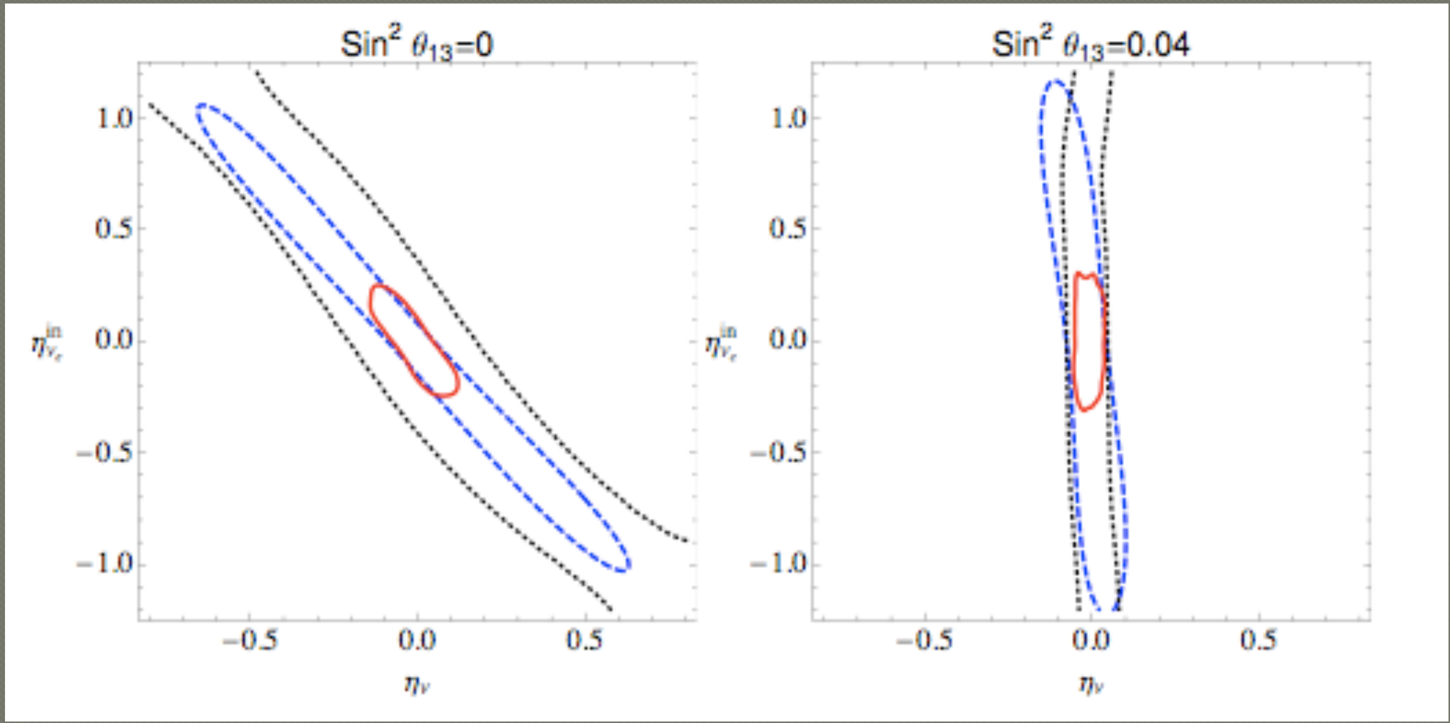
Castorina et al 2012



ξ_a from CMB

CMB gravitational lensing (future) experiments such as **COrE** have excellent sensitivities to neutrino masses and N_{eff}

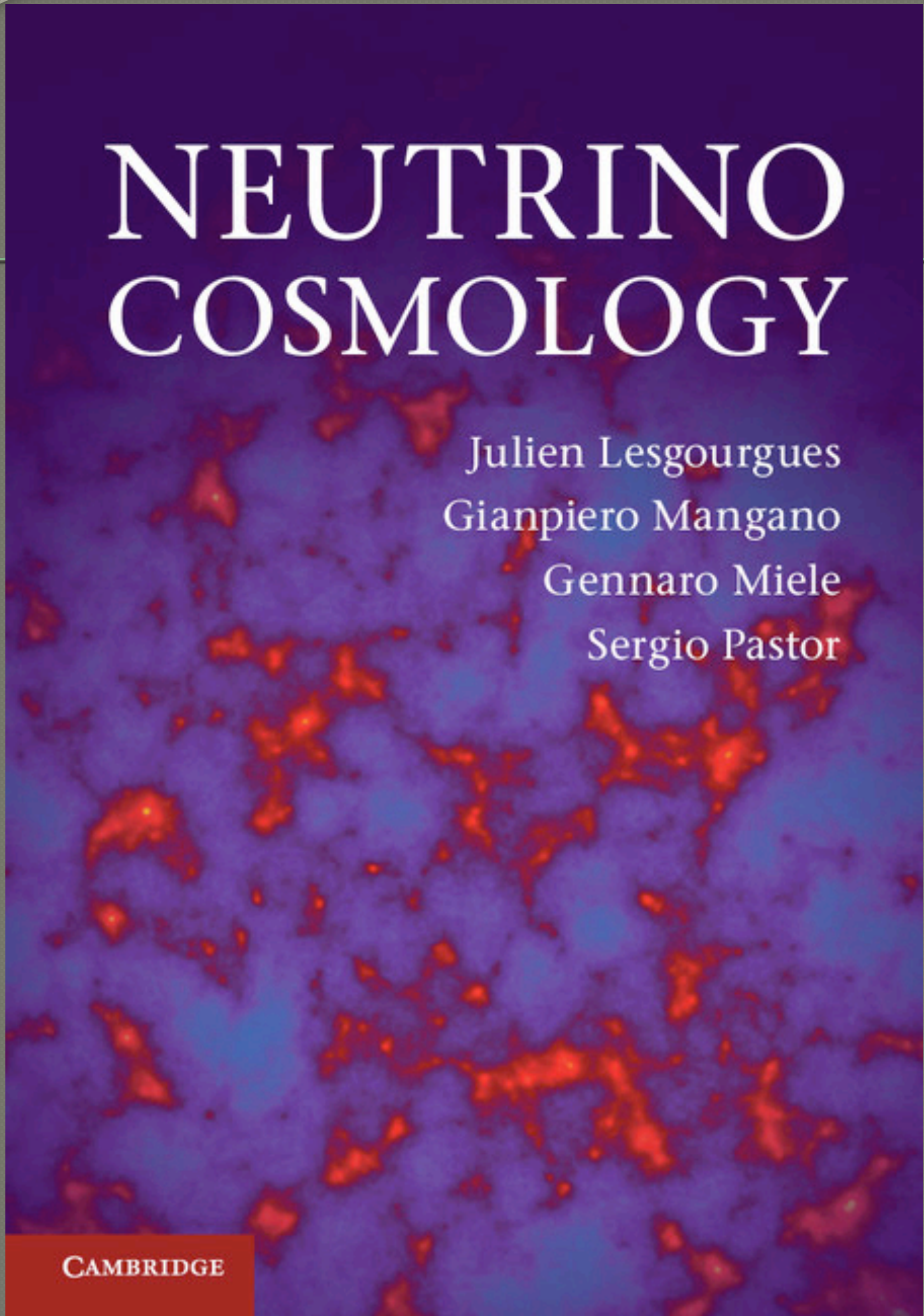
Castorina et al 2012



Conclusions

- Possible hints for extra radiation and neutrino chemical potentials are among the cosmology cadeau for theoretical physicists studying theories beyond the SM
- Flavour mixing combined with the decoupling of neutrinos at the MeV scale lead to non trivial phenomenology based on possible distortions of the neutrino background distribution
- Planck results combined with BBN will tell us something quite soon
- We will see then…

if interested in neutrino cosmology



available early 2013