Closed kinematics

$\Theta_{13}$ and $\nu$ 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.

\[ f_a = f_b \text{ no observable effects} \]

\[ f_a \neq f_b \text{ possible observable effects} \]
- dynamics of oscillations
- oscillations and $\nu$ decoupling:
  - the role of $\theta_{13}$
  - how large $N_{\text{eff}}$ can be?
  - how large $\xi_a$ can be?
  - $N_{\text{eff}}$ and $\xi_a$ not the same parameter!
- $N_{\text{eff}}$ and Planck results
- $\xi_a$ from CMB
Early times:

\[
f_a = \frac{1}{e^{p/T - \xi_a} + 1} \quad f_{\bar{a}} = \frac{1}{e^{p/T + \xi_a} + 1}
\]

Kinetic and chemical equilibrium

MeV scale (set by $G_F$ and $\Delta m^2$ ‘s):
- freezing of weak interaction processes
- $\nu$ distributions mixed up, depending on mixing angles

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

$N_{\text{eff}} = 3.046$
Following oscillations

density matrix formalism

$\rho_{aa}$ occupation number

$\rho_{ab}$ $a \neq b$ mixing

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

$\Omega_{vac}$ vacuum oscillations: $M^2/2p$

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

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

Neutrino oscillation and potential terms (eV)

$\Delta m^2$
$
\delta m^2$
$e^\pm$
$\mu^\pm$
$1 \text{ eV}^2$

$T \ (\text{MeV})$

$\eta_v=10^{-2}$

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Two limiting cases:

$T_{\text{mix}} \gg T_{\text{dec}}$ \quad f_a \text{ mix and interactions lead to equilibrium}

$T_{\text{mix}} \ll T_{\text{dec}}$ \quad \text{non thermal distributions unless } f_a = f_b

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

\[ f_{a,b} \Rightarrow \cos^2 \theta f_a + \sin^2 \theta f_b \Rightarrow f^{eq} \]
Lepton asymmetries expected quite small in (standard) leptogenesis

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

unless leptogenesis takes place well below the EW breaking scale

\[ \exp\left(-\frac{M_W(T)}{g^2 T}\right) \ll 1 \]

(or sphalerons ineffective)

Consider now \( \xi_a = - \xi_b \) (motivation later on)
\[ T_{\text{mix}} >> T_{\text{dec}} \]

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

\[ N_{\text{eff}} = 3.046 \]

\[ T_{\text{mix}} << T_{\text{dec}} \]

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

\[ N_{\text{eff}} > 3 \]

unless  \( \xi = 0 \)
The value of $\theta_{13}$ is crucial (and to a minor extent the mass hierarchy)

Pastor et al 2011
GM et al 2012
BBN is the most robust test of cosmology at early times. Only one parameter in the standard case $\Omega_B h^2$ or $\eta_B$. 

Cyburt 2004
Barring extra relativistic species (as sterile neutrinos)

\[ N_{\text{eff}} \approx 3 \quad \text{standard picture, } \nu \text{ with equilibrium } f_a \]

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

\[ N_{\text{eff}} > 3 \quad \text{effective (time depending) } T_a \text{ and } \xi_a \]

(\text{the first two moments are enough})

\(^4\text{He mass fraction } Y_p \text{ (and } ^2\text{H/H}) \text{ quite sensitive to neutrino asymmetries:} \]

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

Kang and Steigman 1992

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Exploiting BBN

Parameters:
- total asymmetry $\eta_{\nu}$
- initial $\nu_e$ asymmetry $\eta_{\nu_e}^{\text{in}}$

Pastor et al 2011
GM et al 2012
Exploiting BBN

From asymmetries to $N_{\text{eff}}$:

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

\[ N_{\text{eff}} < 3.2 \]

\[ -0.2 \ (-0.1) \leq \eta_{\nu} \leq 0.15 \ (0.05) \]
Planck first results expected early 2013
More complete results in 2014

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

$\Delta N_{\text{eff}} \approx 0.2$
The role of Planck

- $N_{\text{eff}} \leq 3.2$  still compatible with slightly degenerate neutrinos
- $N_{\text{eff}} \geq 3.2$  some extra “dark” radiation required or highly non-thermal neutrino distribution, or both
What can we further learn from CMB alone? A further handle on the value of $\xi_a$?

The role of $\xi_a$ for CMB anisotropies is encoded in $N_{\text{eff}}$.

Recent analyses uses $Y_p(\omega_B, N_{\text{eff}})$ from BBN (if compatible!)
Presently, bounds on $\xi_a$ are dominated by $Y_p$. 

Castorina et al 2012
CMB gravitational lensing (future) experiments such as COreE have excellent sensitivities to neutrino masses and $N_{\text{eff}}$

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...
NEUTRINO COSMOLOGY

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available early 2013