Relic density of neutrinos with primordial asymmetries

SP, T.Pinto & G.Raffelt,
PRL 102 (2009) 241302 [arXiv:0808.3137]

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Picture from Hubble ST

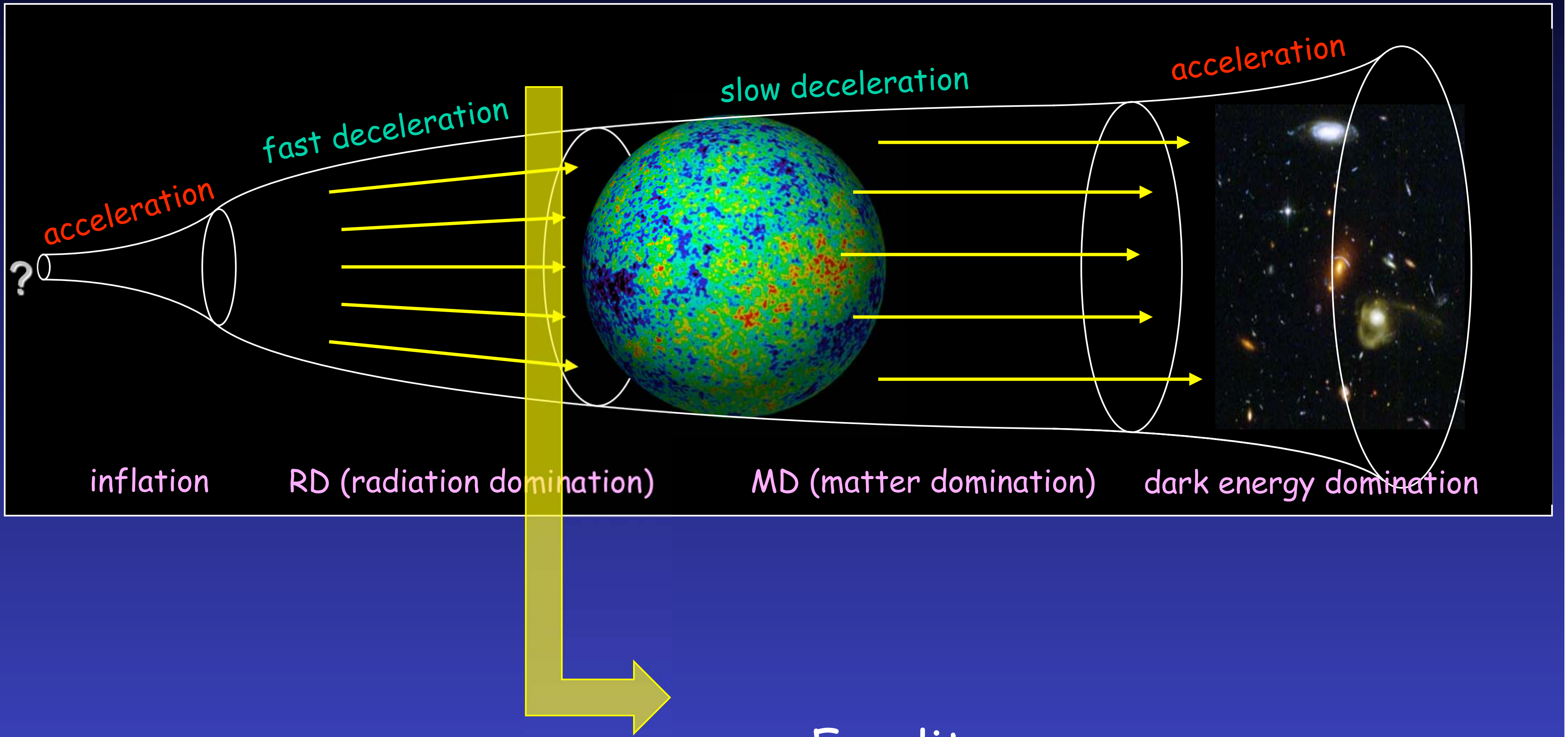
Outline

Introduction: the radiation component of the Universe

Relic neutrino asymmetries and flavour oscillations

Relic density of neutrinos with primordial asymmetries

Evolution of the Universe



a_{eq}: Equality $\rho_r = \rho_m$

Relativistic energy density

At $T \gg m_e$, the radiation content of the Universe is

$$\rho_r = \rho_\gamma + \rho_\nu = \frac{\pi^2}{15} T^4 + 3 \times \frac{7}{8} \times \frac{\pi^2}{15} T^4 = \left[1 + \frac{7}{8} \times 3\right] \rho_\gamma$$

At $T < m_e$, the radiation content of the Universe is

$$\rho_r = \rho_\gamma + \rho_\nu = \frac{\pi^2}{15} T_\gamma^4 + 3 \times \frac{7}{8} \times \frac{\pi^2}{15} T_\nu^4 = \left[1 + \frac{7}{8} \left(\frac{4}{11}\right)^{4/3} 3\right] \rho_\gamma$$

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

$$\frac{T_\nu^4}{T_\gamma^4}$$

Relativistic energy density

At $T<m_e$, the radiation content of the Universe is

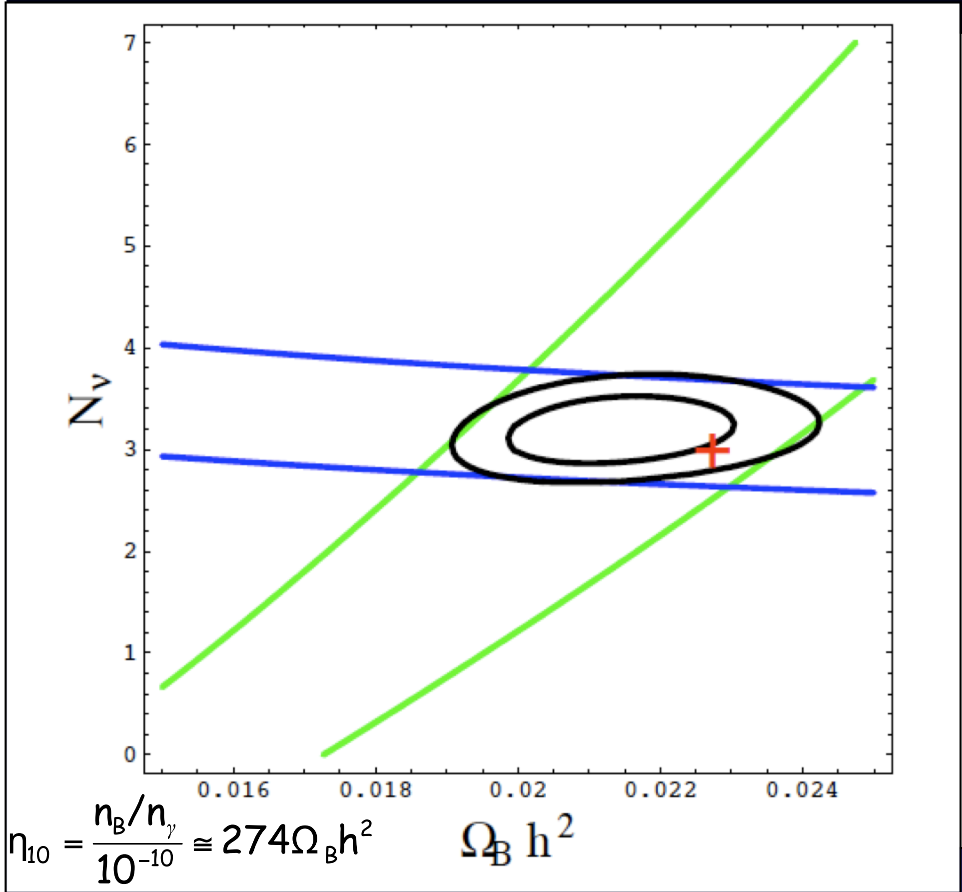
$$\rho_{\rm r} = \rho_\gamma + \rho_\nu + \rho_x = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\right] \rho_\gamma$$

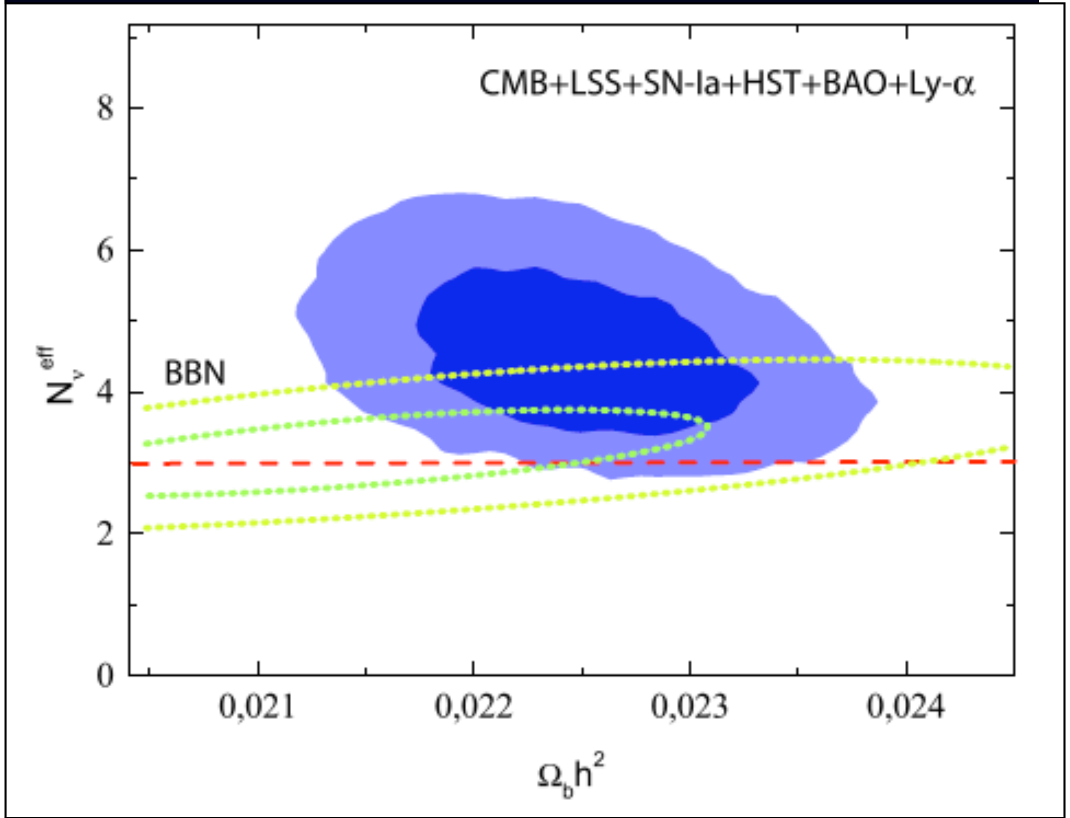
Effective number of relativistic neutrino species

Traditional parametrization of the energy density stored in relativistic particles

# of flavour neutrinos: $N_\nu = 2.984 \pm 0.008$ (LEP data)

allowed ranges for N_{eff}





Bounds from BBN

F. Iocco et al, Phys. Rep. 472 (2009) 1

$$N_{eff} = 3.0 \pm 0.3_{stat} \pm 0.3_{syst}$$

(95% CL)

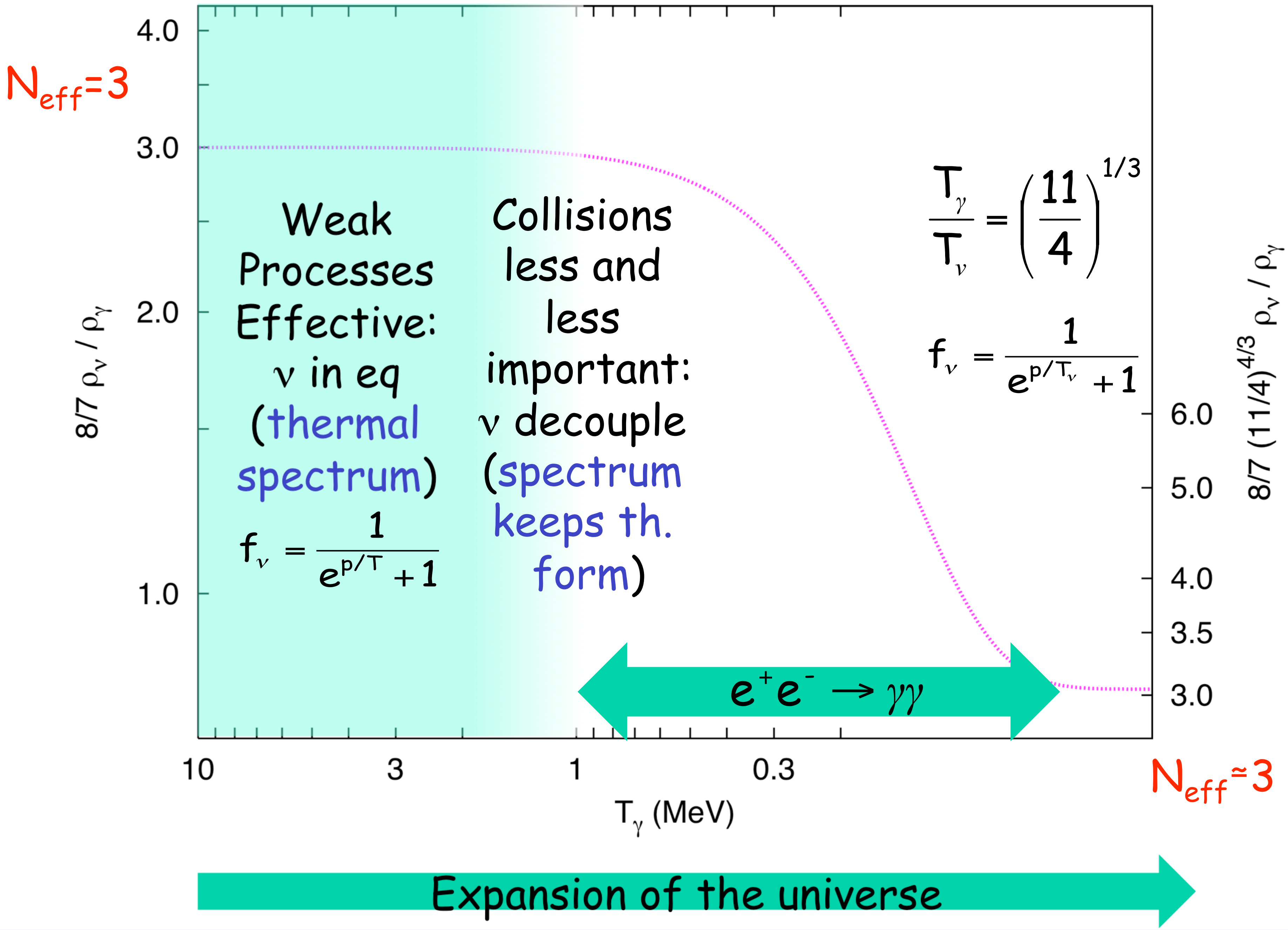
Bounds from non-BBN data

Mangano et al, JCAP 0703 (2007) 006

$$3.0 < N_{eff} < 7.9 \quad \text{(CMB + LSS data)}$$

$$3.1 < N_{eff} < 6.2 \quad \text{(+BAO and Ly-}\alpha\text{)}$$

Evolution of ρ_ν/ρ_γ before and after ν decoupling

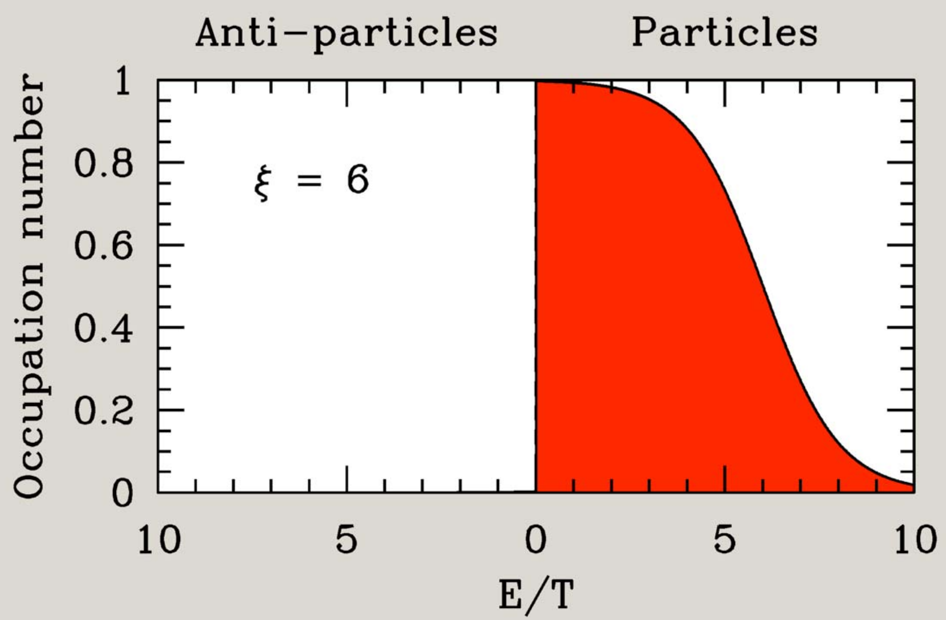


Primordial Neutrino asymmetries

Fermi-Dirac distribution

- Temperature T
- Chemical potential μ
  - $+\mu$ Particles
  - $-\mu$ Anti-particles

$$f_p = \frac{1}{\exp\left(\frac{E-\mu}{T}\right)+1}$$



Degeneracy parameter $\xi = \frac{\mu}{T}$ **Invariant under cosmic expansion**

Number density

$$n_{\nu\bar{\nu}} = \int dE \frac{4\pi}{(2\pi)^3}\left(\frac{E^2}{1+\exp(E/T-\xi)} + \frac{E^2}{1+\exp(E/T+\xi)}\right)$$

$$= \frac{3\zeta_3}{2\pi^2} T_\nu^3 \left[1 + \frac{2\ln(2)}{3\zeta_3}\xi^2 + \frac{1}{72\zeta_3}\xi^4 + \ldots\right]$$

BBN and Neutrino Chemical Potentials

Expansion Rate Effect (all flavors)

Energy density in one neutrino flavor with degeneracy parameter $\xi = \mu/T$

$$\rho_{\nu\bar{\nu}} = \frac{7\pi^2}{120} T_\nu^4 \left[1 + \underbrace{\frac{30}{7}\left(\frac{\xi}{\pi}\right)^2 + \frac{15}{7}\left(\frac{\xi}{\pi}\right)^4}_{\Delta N_{\rm eff}}\right]$$

Beta equilibrium effect for electron flavor

$n + \nu_e \leftrightarrow p + e^-$

Helium abundance essentially fixed by n/p ratio at beta freeze-out

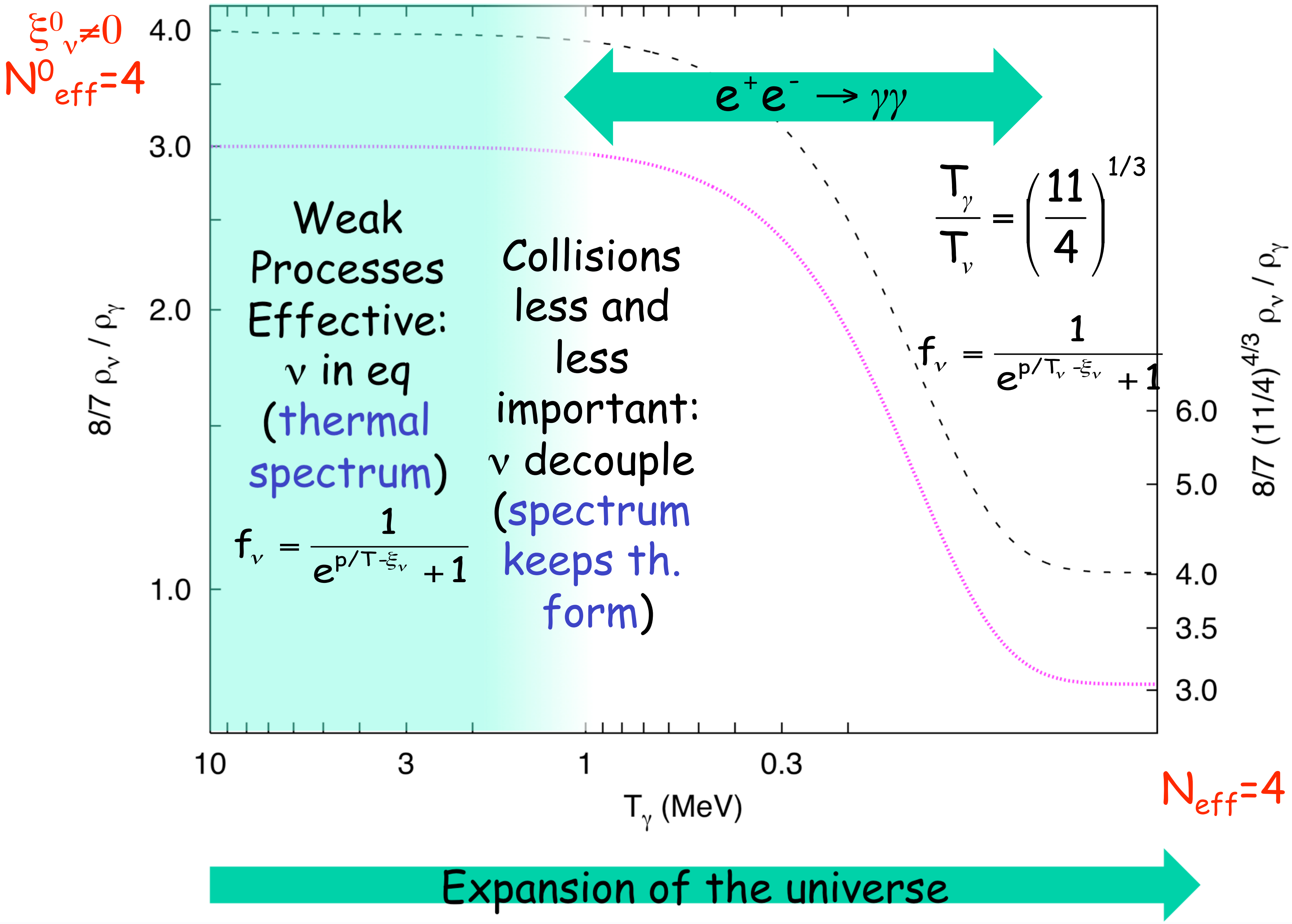
$$\frac{n}{p} = e^{-(m_n - m_p)/T - \xi_{\nu_e}}$$

$|\xi_{\nu_e}| \lesssim 0.07$

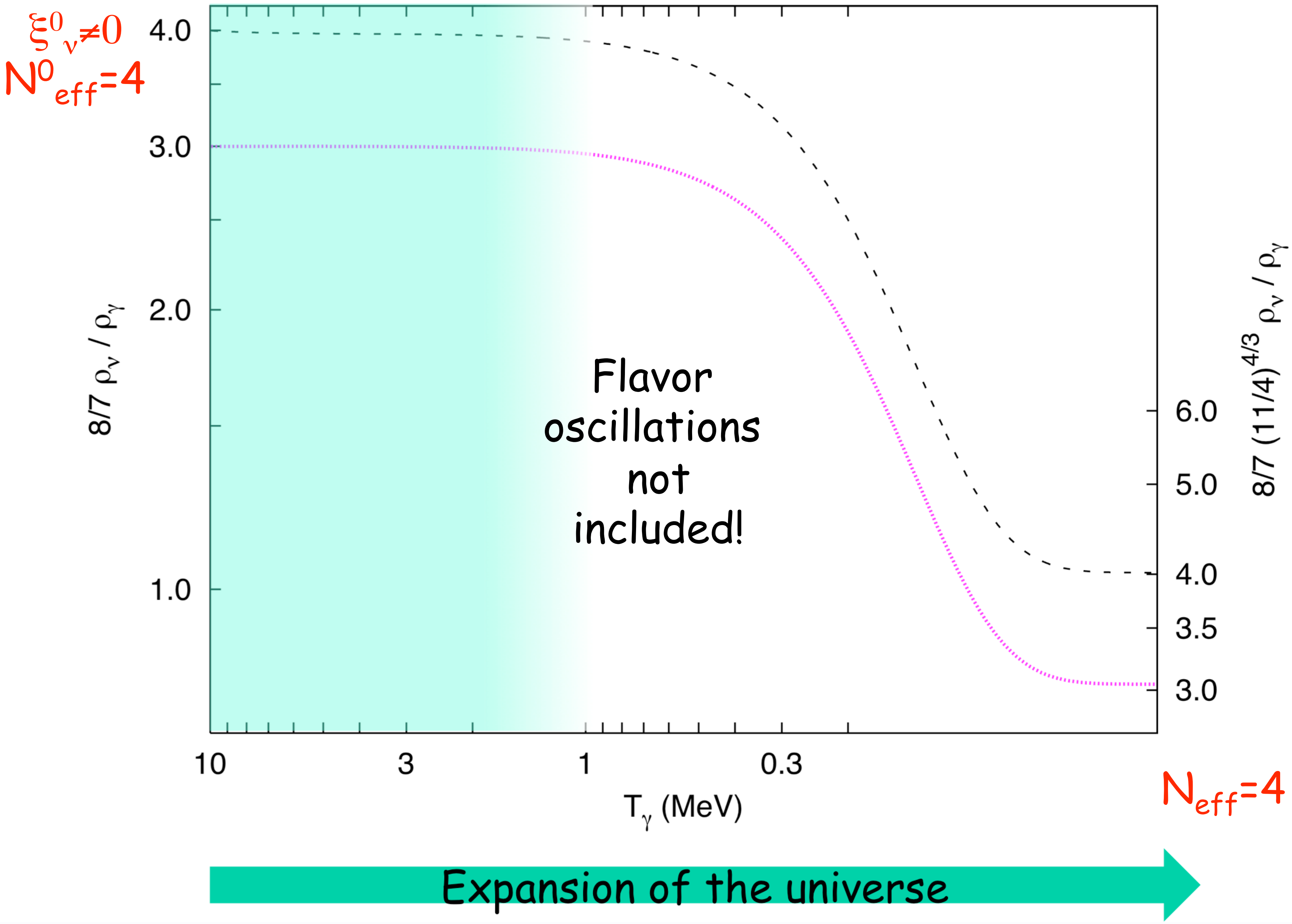
Effect on ^{4}He equivalent to $\Delta N_{\rm eff} \sim -18\, \xi_{\nu_e}$

- ν_e beta effect can compensate expansion-rate effect of $\nu_{\mu,\tau}$
- No significant BBN limit on neutrino number density

Evolution of ρ_ν/ρ_γ with asymmetries ($L_\nu^{tot}=0$)



Evolution of ρ_ν/ρ_γ with asymmetries (L_ν^{tot}=0)



Chemical Potentials and Flavor Oscillations

Flavor mixing (neutrino oscillations)

Flavor lepton numbers not conserved

Only one common neutrino chemical potential

Stringent ξ_{ν_e} limit applies to all flavors

$|\xi_{\nu_{e,\mu,\tau}}| < 0.07$

Extra neutrino density $\Delta N_{eff} < 0.0064$

Cosmic neutrino density close to standard value

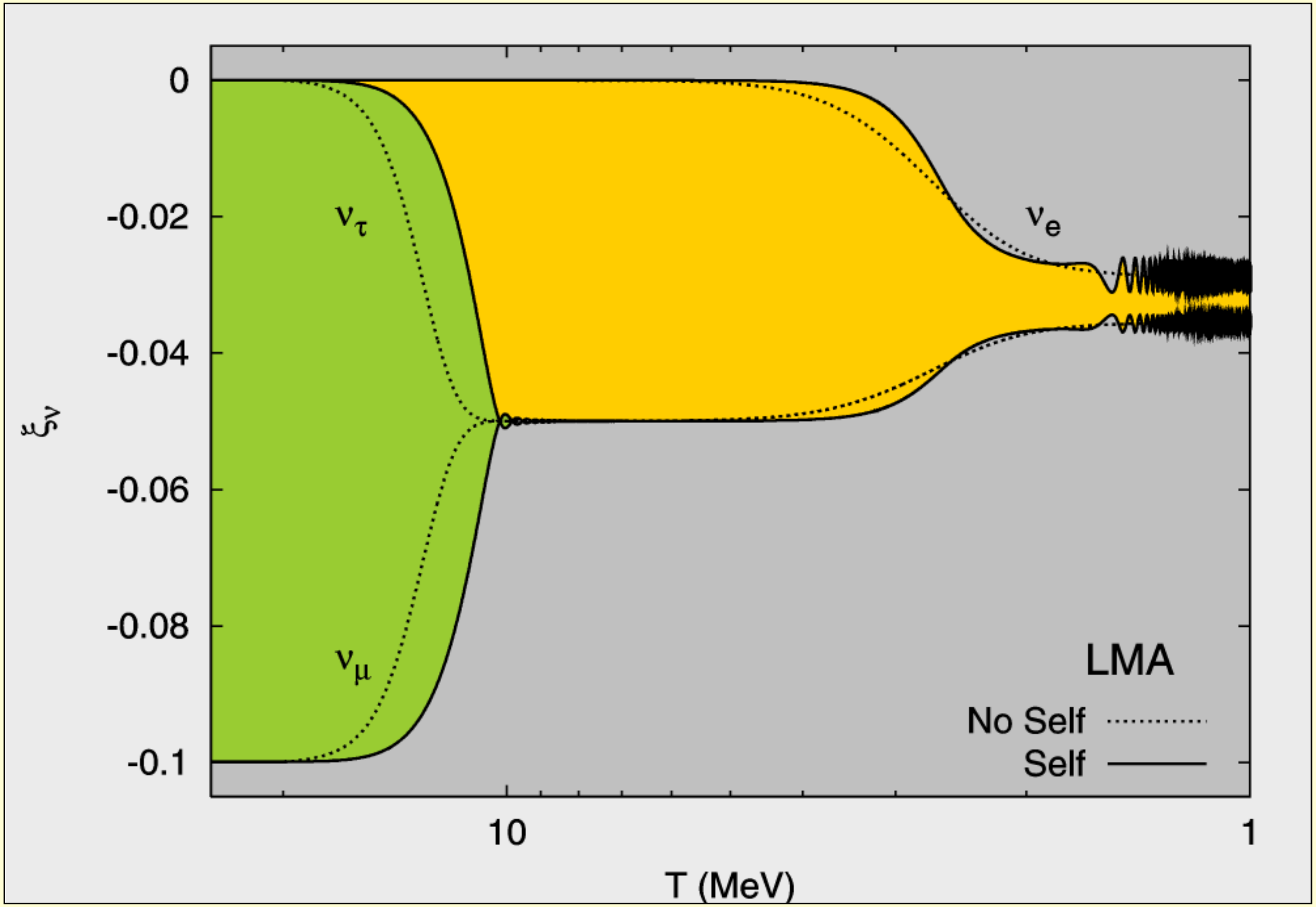
- Oscillations effective before n/p freeze out ?
- YES for solar LMA solution
- Our knowledge of the cosmic neutrino density depends on measured oscillation parameters

- Lunardini & Smirnov, hep-ph/0012056
- Dolgov, Hansen, SP, Petcov, Raffelt & Semikoz, hep-ph/0201287
- Abazajian, Beacom & Bell, astro-ph/0203442
- Wong, hep-ph/0203180

However, important caveats!

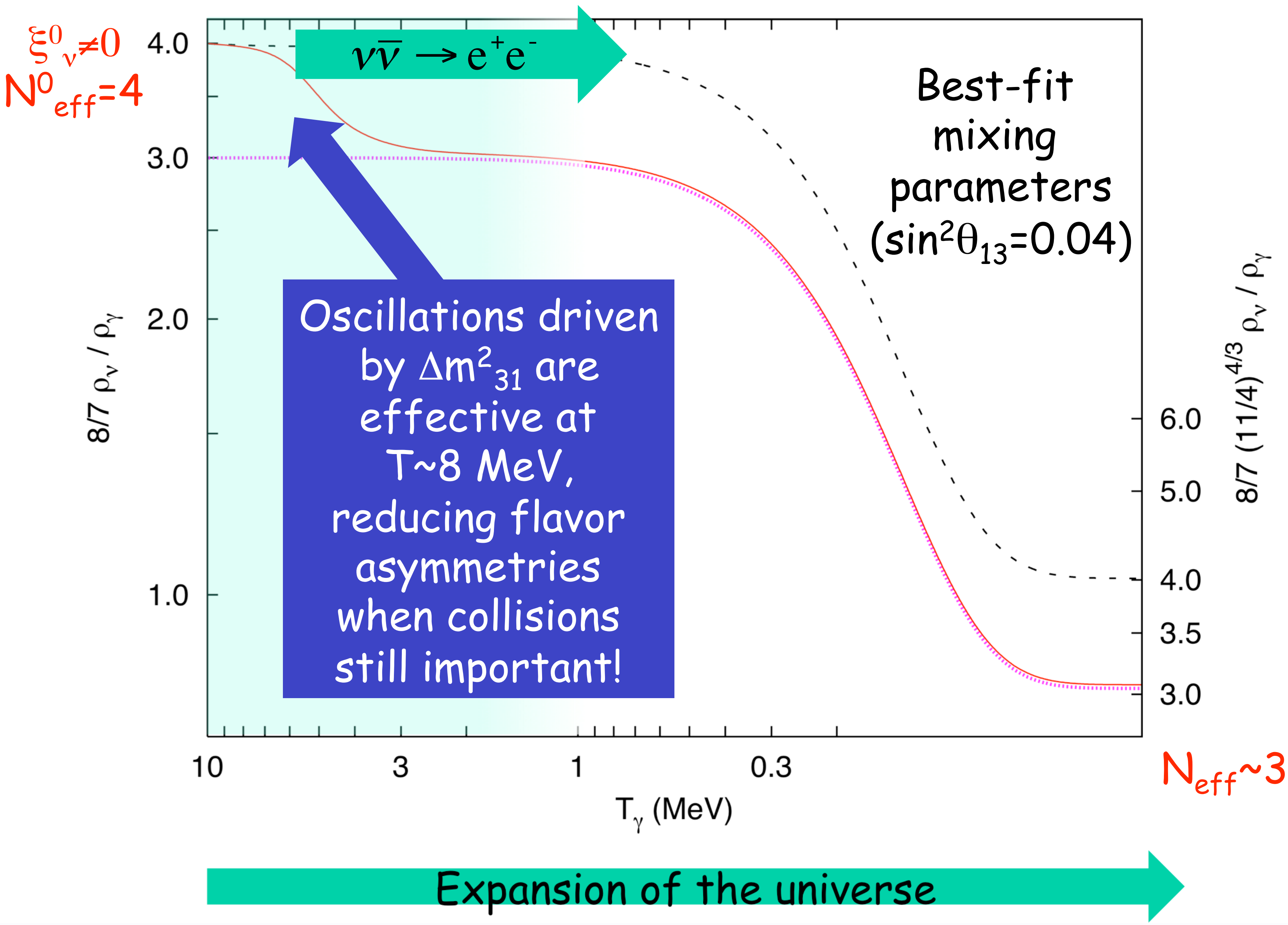
SP, Pinto & Raffelt
PRL 102 (2009) 241302 [arXiv:0808.3137]

Flavor Transformation for LMA Solution

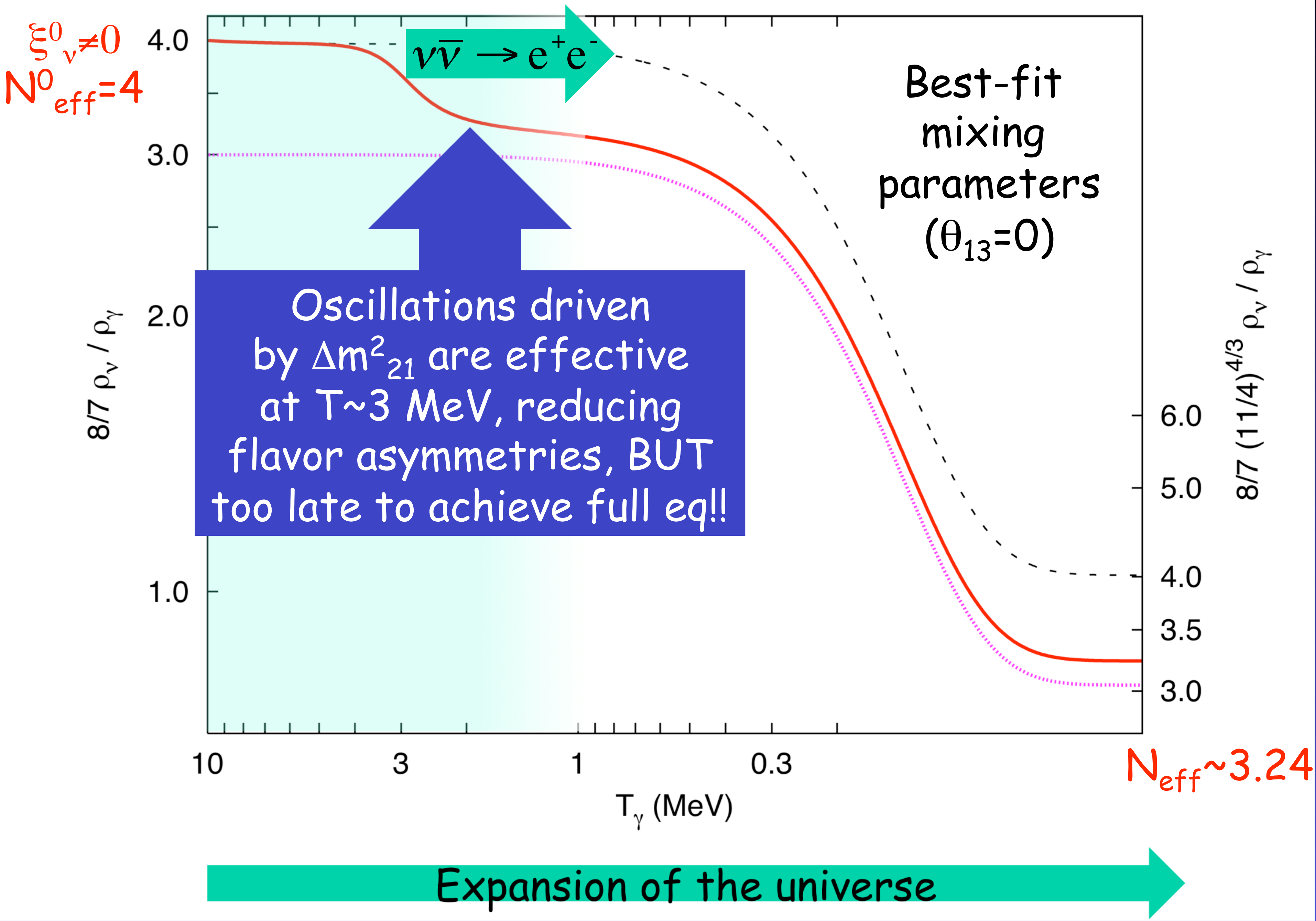


Dolgov, Hansen, SP, Petcov, Raffelt & Semikoz, hep-ph/0201287

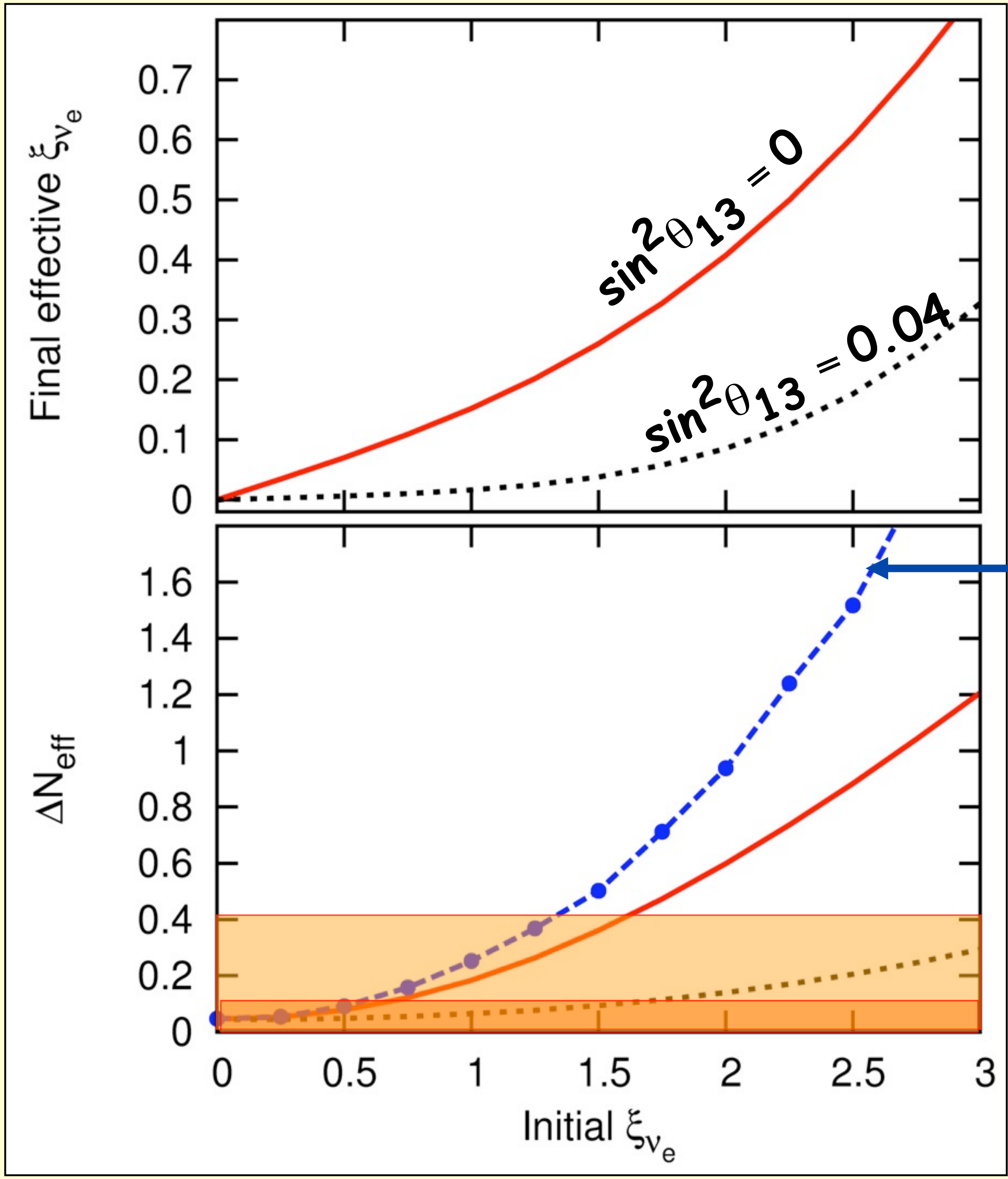
Evolution of ρ_ν/ρ_γ with asymmetries ($L_\nu^{tot}=0$)



Evolution of ρ_ν/ρ_γ with asymmetries ($L_\nu^{tot}=0$)



Final radiation density



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- No global lepton asymmetry
  $n(\nu_e) = n(\bar{\nu}_\mu) + n(\bar{\nu}_\tau)$
- Equilibrium between ν_μ and ν_τ
  $n(\bar{\nu}_\mu) = n(\bar{\nu}_\tau)$

Initial ν_e and ν_μ/ν_τ asymmetries not exactly opposite,but adjusted such that $\xi(\nu_e)$ falls into the allowed BBN range

PLANCK sensitivity: N_{eff}~0.4

Best CMB sensitivity: N_{eff}~0.1

Summary

- **Flavor neutrino oscillations with the measured mixing parameters do not lead to full equilibrium before BBN, in contrast to what is frequently stated**

- **A 13-mixing angle close to the Chooz limit strongly helps to establish equilibrium**

- **The initial densities of ν_e and $\bar{\nu}_\mu$ plus $\bar{\nu}_\tau$ can be adjusted such that at BBN the ν_e asymmetry falls into the allowed range, yet there is a significant excess radiation density**