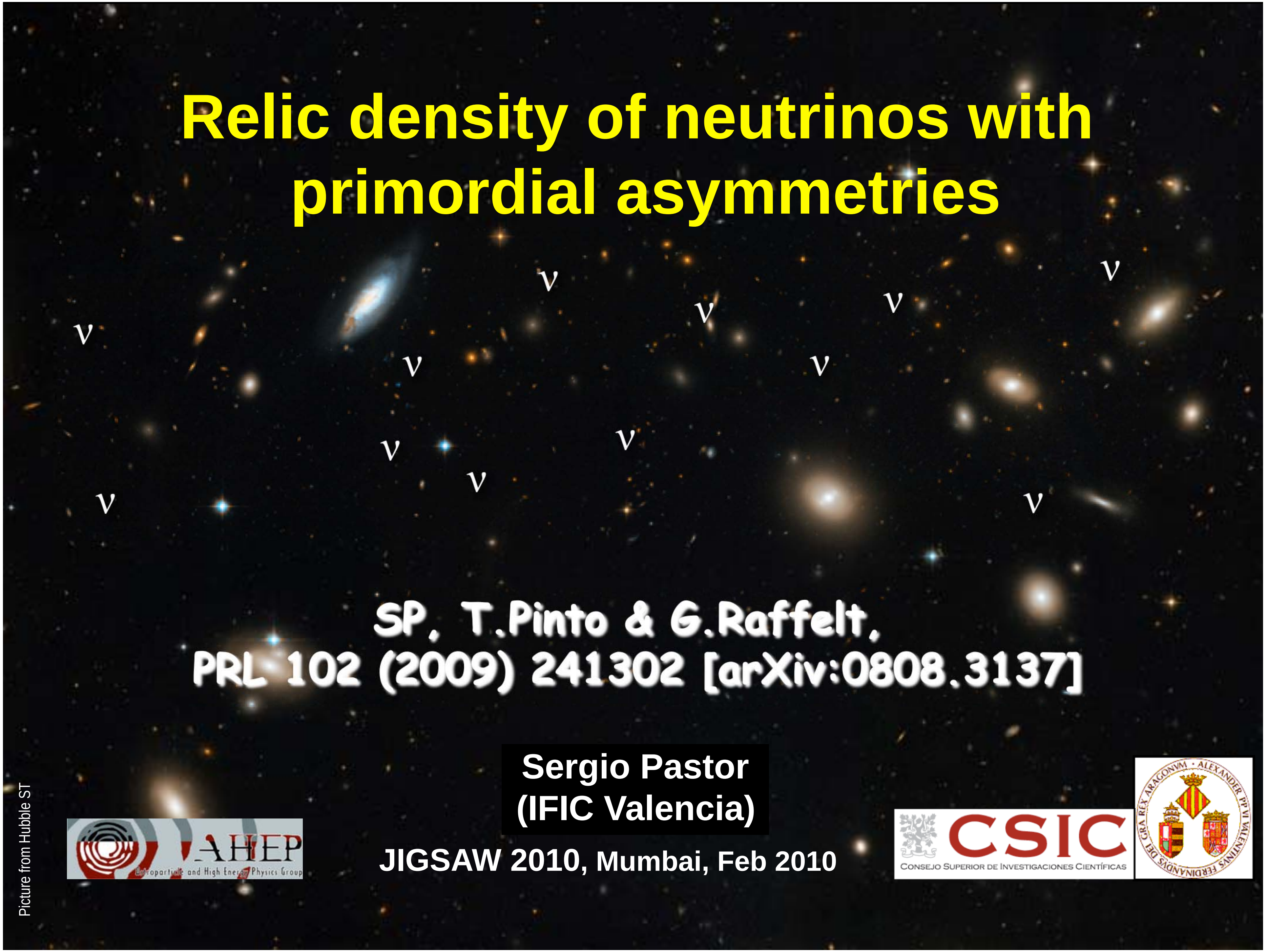
Relic density of neutrinos with primordial asymmetries



Picture from Hubble ST

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

Sergio Pastor
(IFIC Valencia)

JIGSAW 2010, Mumbai, Feb 2010

AHEP Astroparticle and High Energy Physics Group

CSIC Consejo Superior de Investigaciones Científicas

Outline

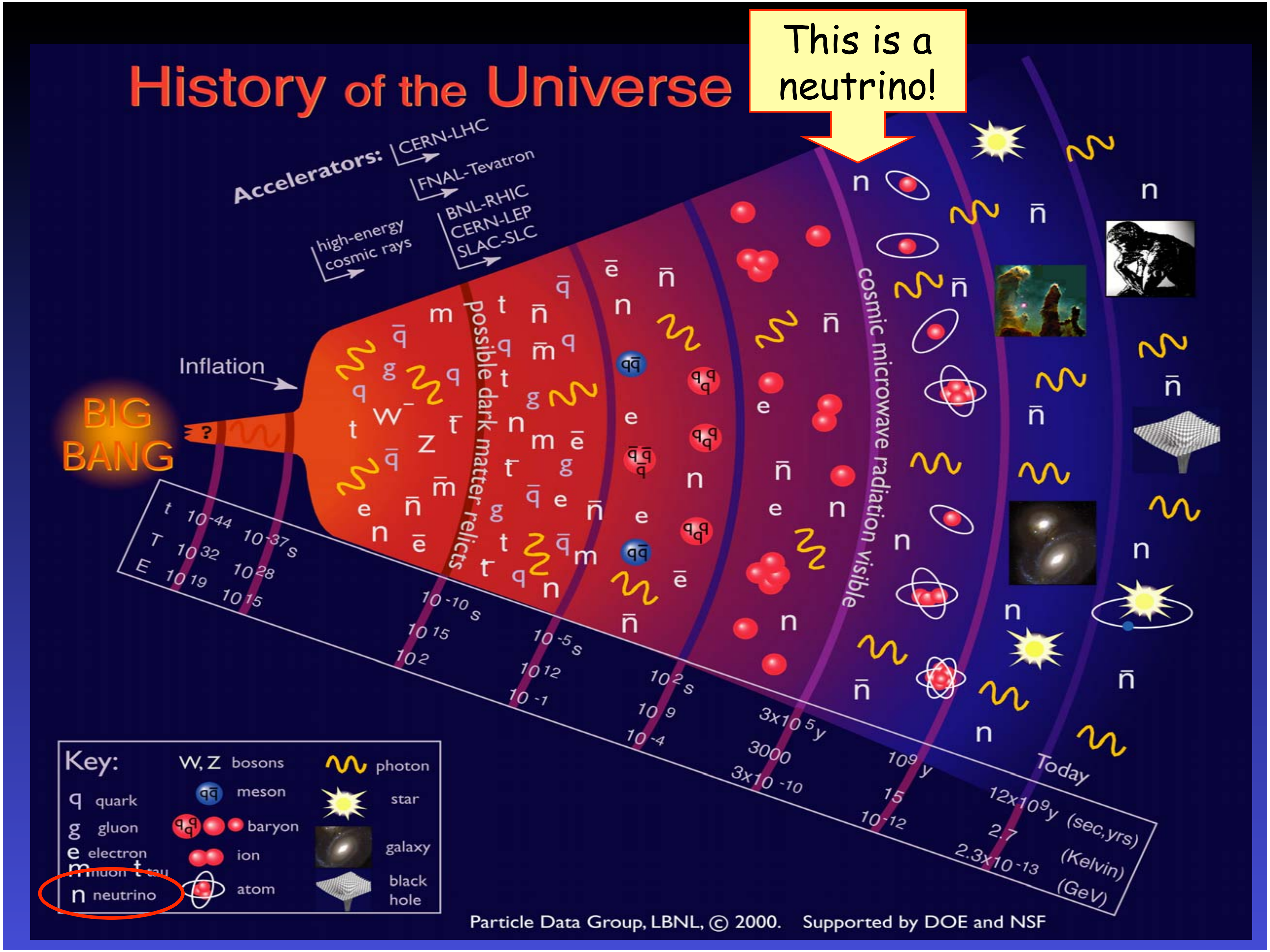
Introduction: the Cosmic Neutrino Background

The radiation component of the Universe

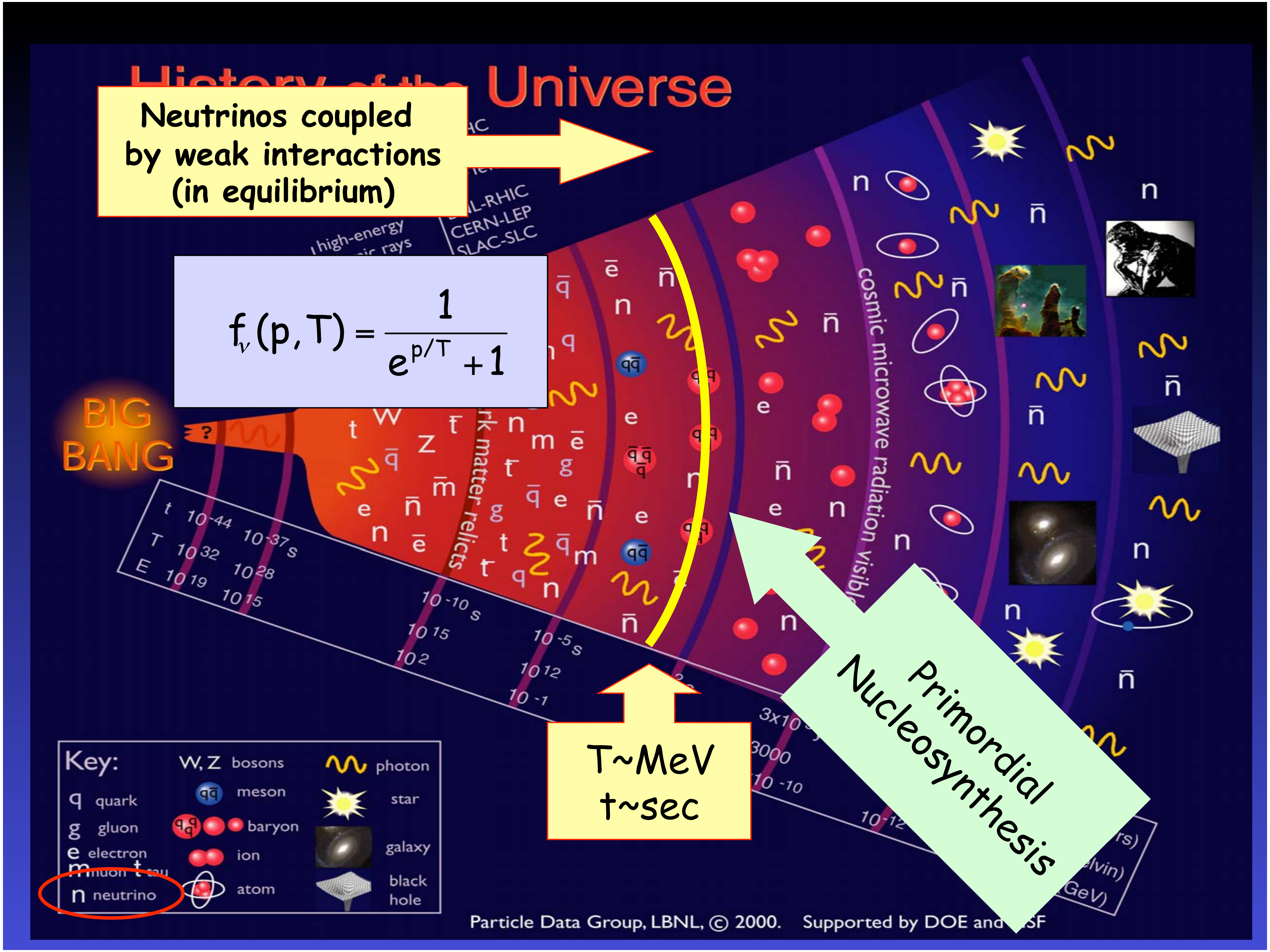
Relic neutrino asymmetries and flavour oscillations

Relic density of neutrinos with primordial asymmetries

Introduction: the Cosmic Neutrino Background



History of the Universe
This is a neutrino!
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
t 10-44 10-37 s
T 10 32 10 28
E 10 19 10 15
10 -10 s
10 15
10 2
10 -5 s
10 12
10 -1
10 2 s
10 9
10 -4
3x10 5 y
3000
3x10 -10
10 9 y
15
10 -12
Today
12x10 9 y (sec,yrs)
2.7 (Kelvin)
2.3x10 -13 (GeV)
Key:
q quark
g gluon
e electron
m muon t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF


Universe
Neutrinos coupled by weak interactions (in equilibrium)
$$f_\nu(p,T) = \frac{1}{e^{p/T}+1}$$
BIG BANG
CERN-LEP
SLAC-SLC
cosmic microwave radiation
dark matter relicts
T~MeV
t~sec
Primordial Nucleosynthesis
Key:
q quark
g gluon
e electron
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000.

Neutrinos in Equilibrium

$1\ \text{MeV} \leq T \leq m_\mu$

$T_\nu = T_e = T_\gamma$

$\nu_\alpha \nu_\beta \leftrightarrow \nu_\alpha \nu_\beta$

$\nu_\alpha \bar{\nu}_\beta \leftrightarrow \nu_\alpha \bar{\nu}_\beta$

$\nu_\alpha e^- \leftrightarrow \nu_\alpha e^-$

$\nu_\alpha \bar{\nu}_\alpha \leftrightarrow e^+ e^-$

$$\mathcal{L}_{\rm SM} = -2\sqrt{2} G_F \left\{ (\bar{\nu}_e \gamma^\mu L \nu_e)(\bar{e}\gamma_\mu L e) + \sum_{P,\alpha} g_P (\bar{\nu}_\alpha \gamma^\mu L \nu_\alpha)(\bar{e}\gamma_\mu P e) \right\}$$

$P = L,\ R = (1 \mp \gamma_5)/2$

$g_L = -\frac{1}{2} + \sin^2\theta_W$ and $g_R = \sin^2\theta_W$

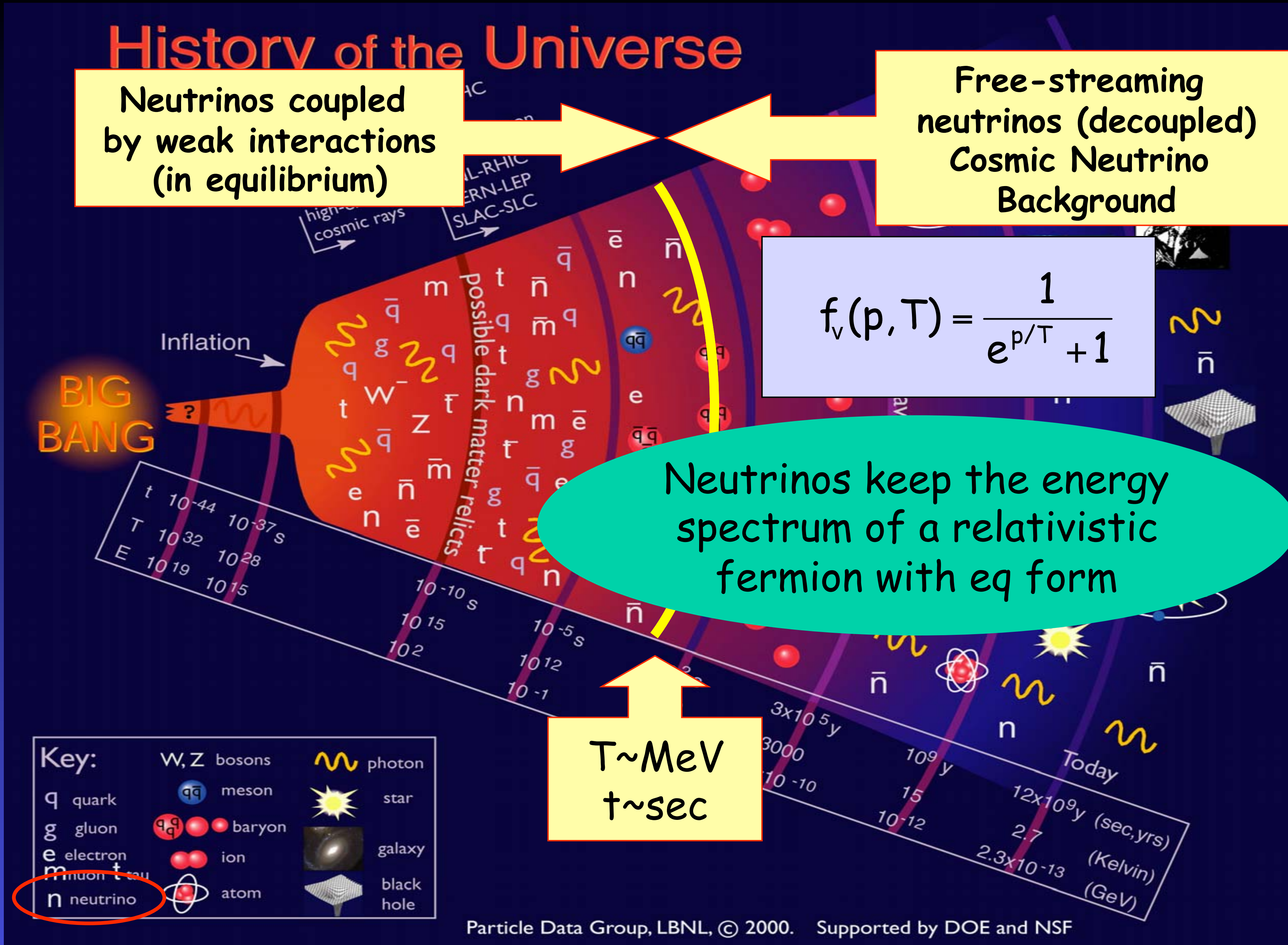
Neutrino decoupling

As the Universe expands, particle densities are diluted and temperatures fall. Weak interactions become ineffective to keep neutrinos in good thermal contact with the e.m. plasma

Rough, but quite accurate estimate of the decoupling temperature

Rate of weak processes ~ Hubble expansion rate

$$\Gamma_w \approx \sigma_w |\mathrm{v}| n \,,\; H^2 = \frac{8\pi\rho_R}{3M_p^2} \rightarrow G_F^2 T^5 \approx \sqrt{\frac{8\pi\rho_R}{3M_p^2}} \rightarrow T_{dec}^{\nu} \approx 1\; MeV$$



Neutrinos coupled by weak interactions (in equilibrium)

Free-streaming neutrinos (decoupled) Cosmic Neutrino Background

$$f_\nu(p,T) = \frac{1}{e^{p/T}+1}$$

Neutrinos keep the energy spectrum of a relativistic fermion with eq form

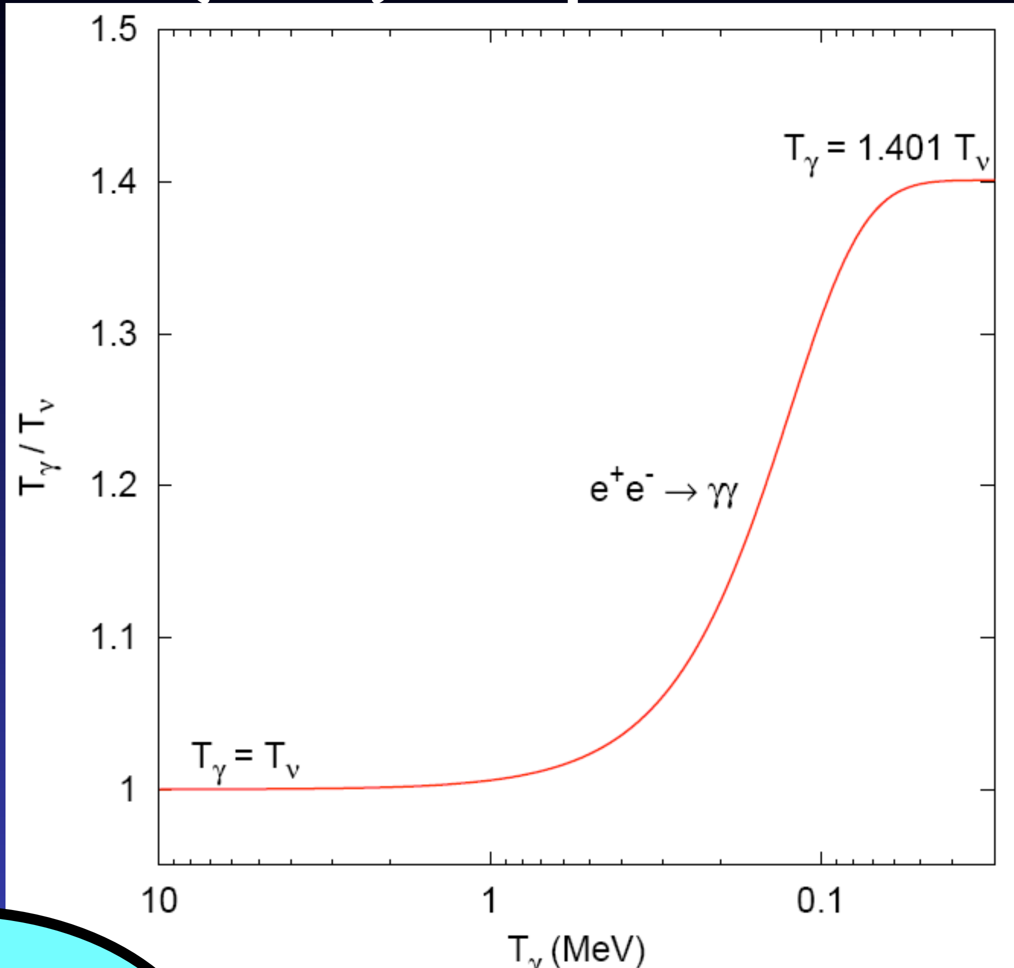
T~MeV
t~sec

Neutrino and Photon (CMB) temperatures

At $T \sim m_e$, electron-positron pairs annihilate

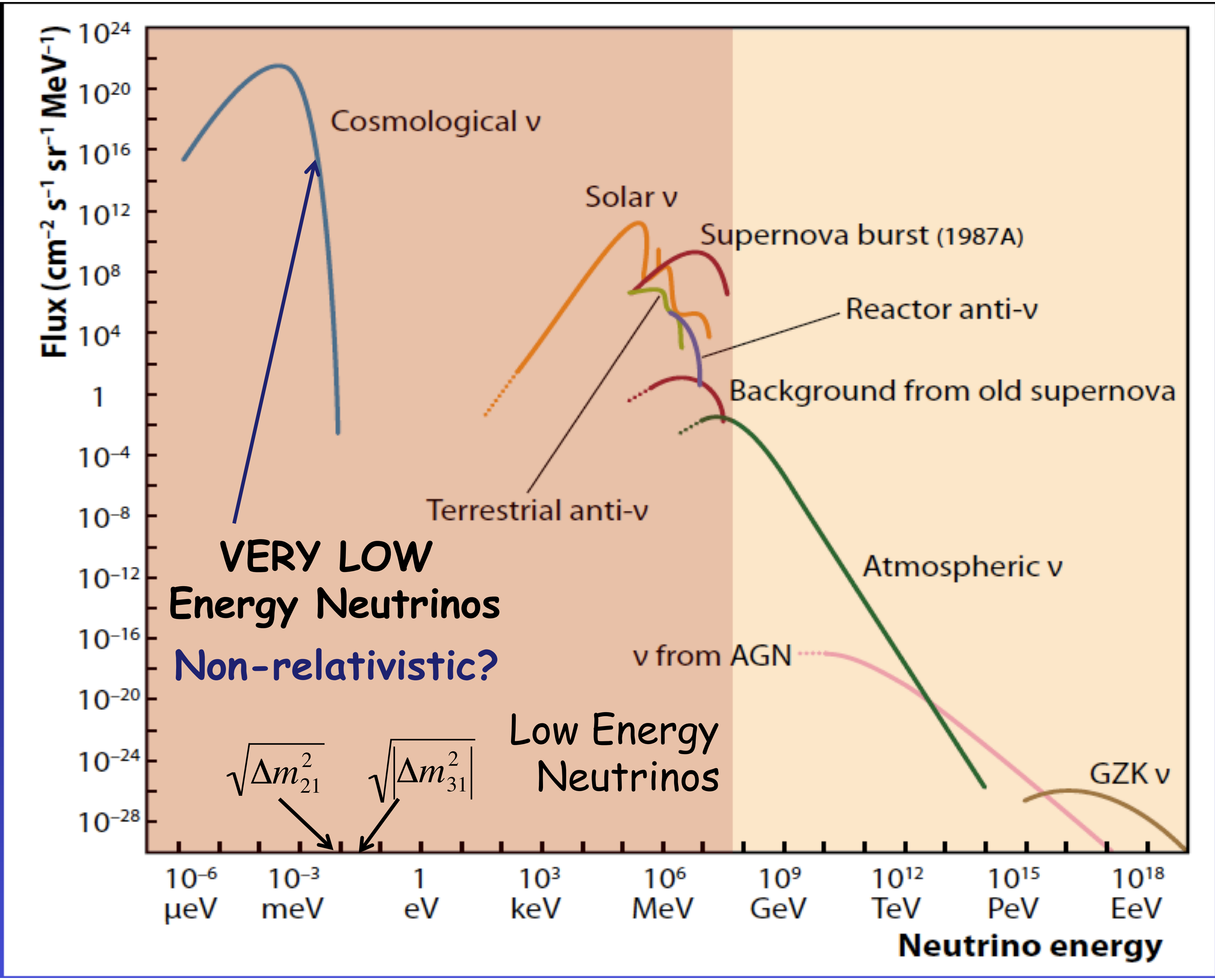
$$e^+ e^- \rightarrow \gamma\gamma$$

heating photons but not the decoupled neutrinos



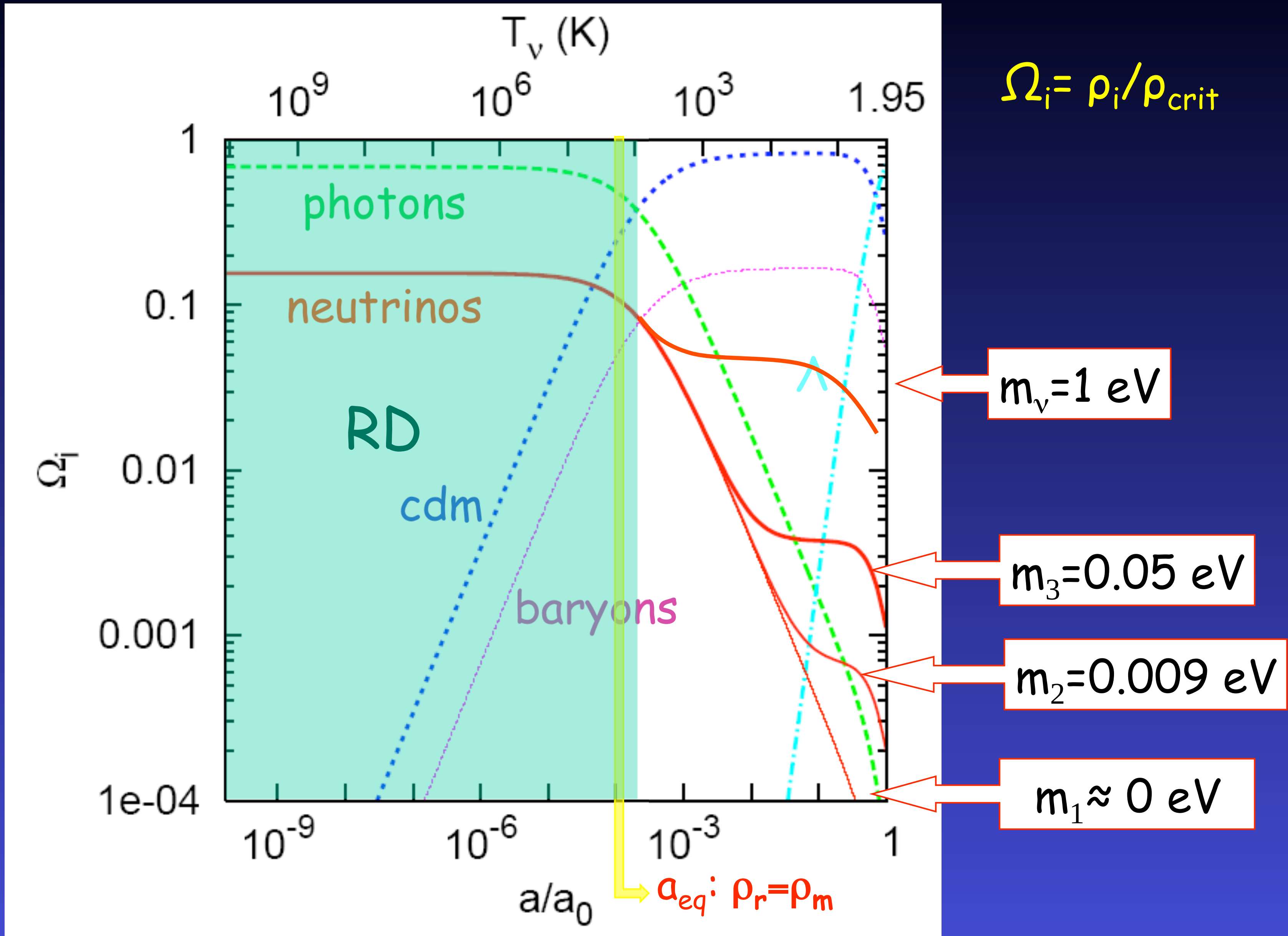
$$\frac{T_\gamma}{T_\nu} = \left(\frac{11}{4}\right)^{1/3}$$

$$f_\nu(p,T) = \frac{1}{e^{p/T_\nu} + 1}$$

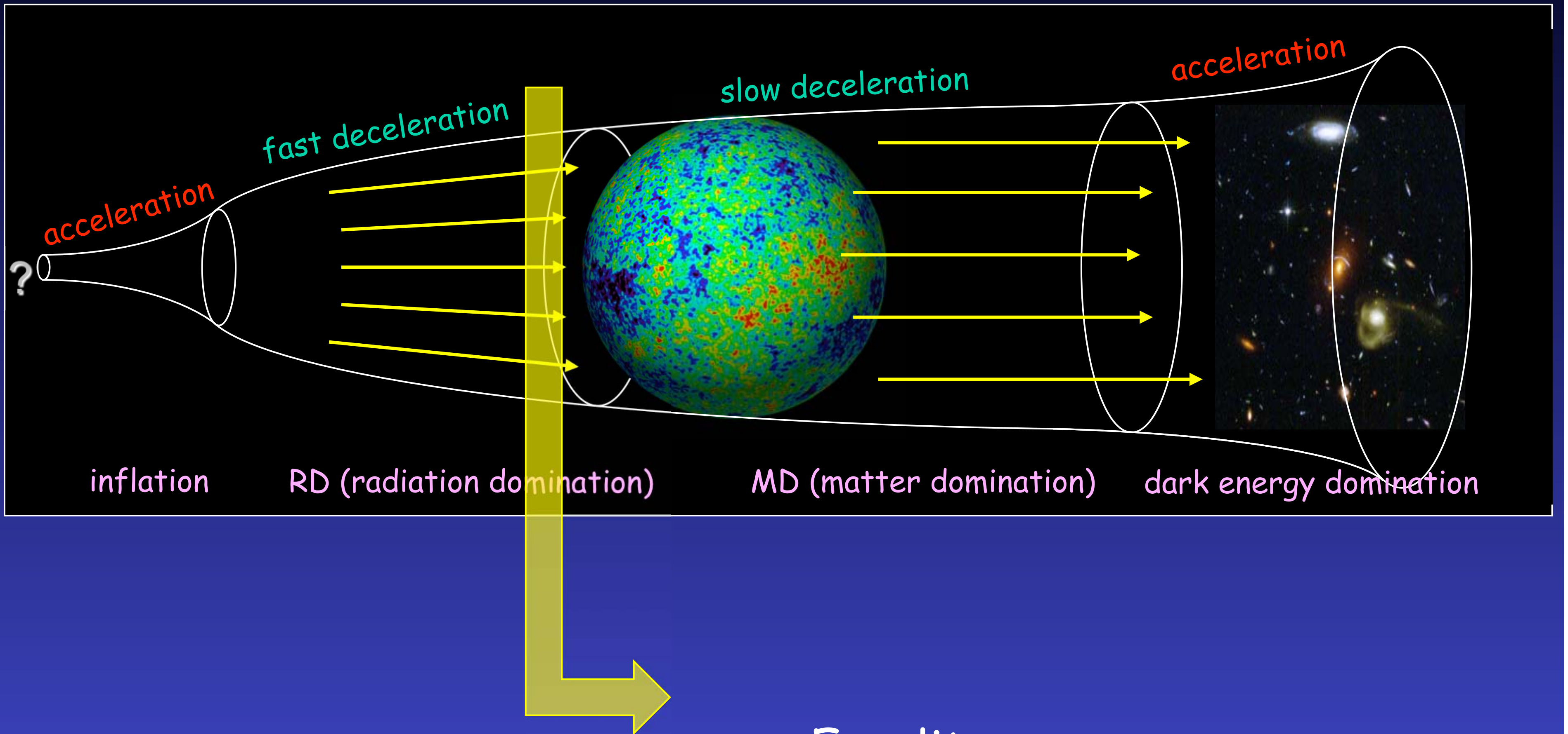


Flux (cm^{-2} s^{-1} sr^{-1} MeV^{-1})
10^{24}
10^{20}
10^{16}
10^{12}
10^{8}
10^{4}
1
10^{-4}
10^{-8}
10^{-12}
10^{-16}
10^{-20}
10^{-24}
10^{-28}
Cosmological ν
Solar ν
Supernova burst (1987A)
Reactor anti-ν
Background from old supernova
Terrestrial anti-ν
Atmospheric ν
ν from AGN
GZK ν
VERY LOW
Energy Neutrinos
Non-relativistic?
Low Energy
Neutrinos
$\sqrt{\Delta m^2_{21}}$
$\sqrt{|\Delta m^2_{31}|}$
10^{-6} μeV
10^{-3} meV
1 eV
10^{3} keV
10^{6} MeV
10^{9} GeV
10^{12} TeV
10^{15} PeV
10^{18} EeV
Neutrino energy

Evolution of the background densities: 1 MeV → now



Evolution of the Universe



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

The radiation content of the Universe (N_{eff})

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

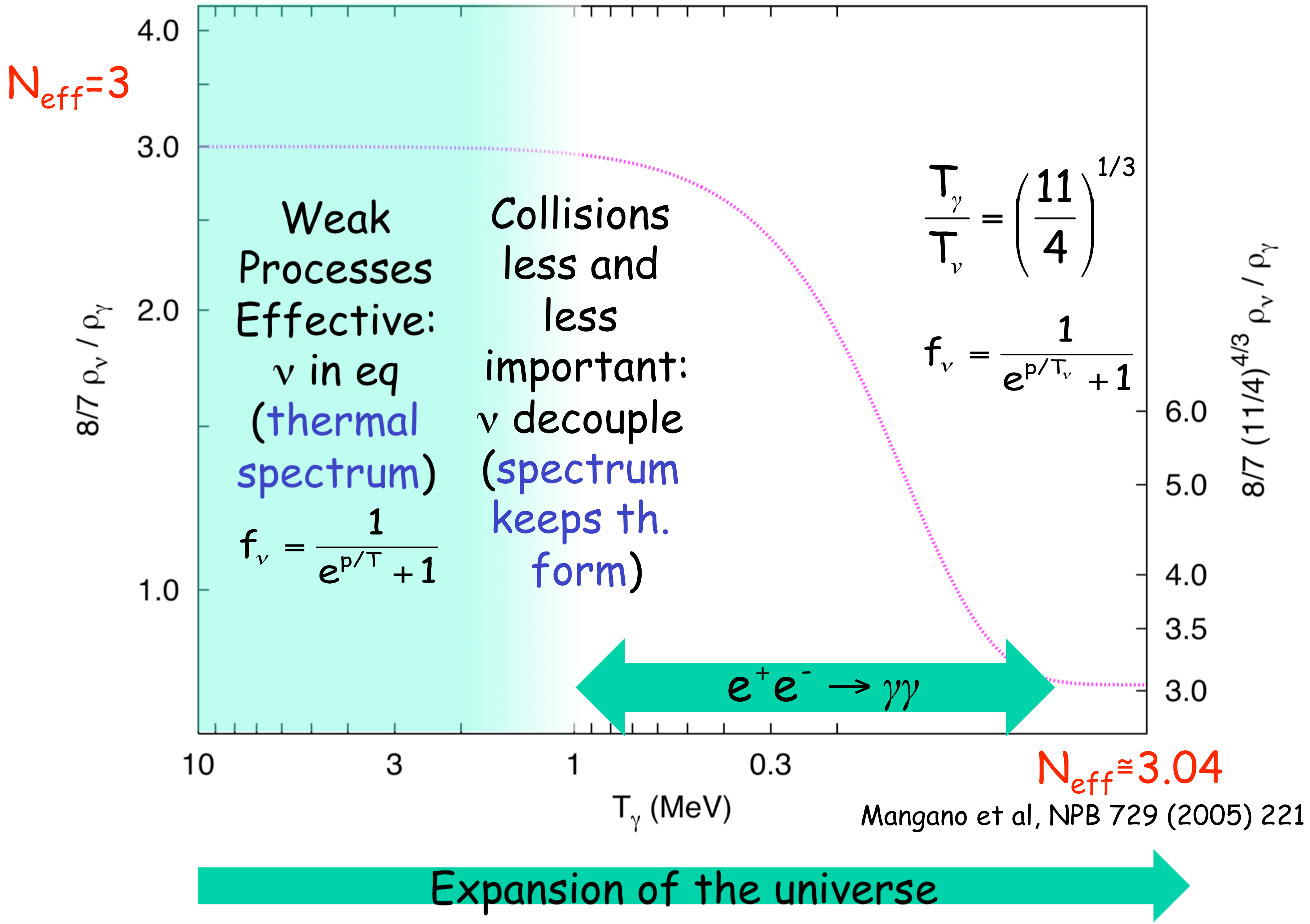
$$\rho_r = \rho_\gamma + \rho_\nu + \rho_x = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\right]\rho_\gamma$$

Effective number of relativistic neutrino species

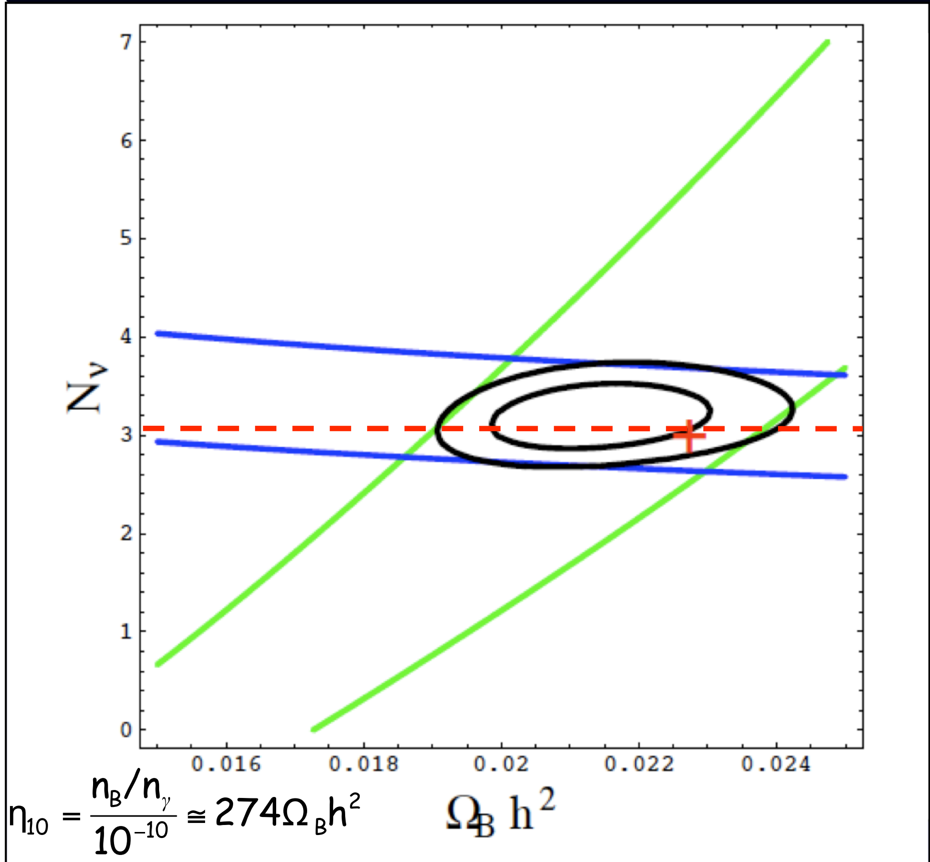
Traditional parametrization of the energy density stored in relativistic particles

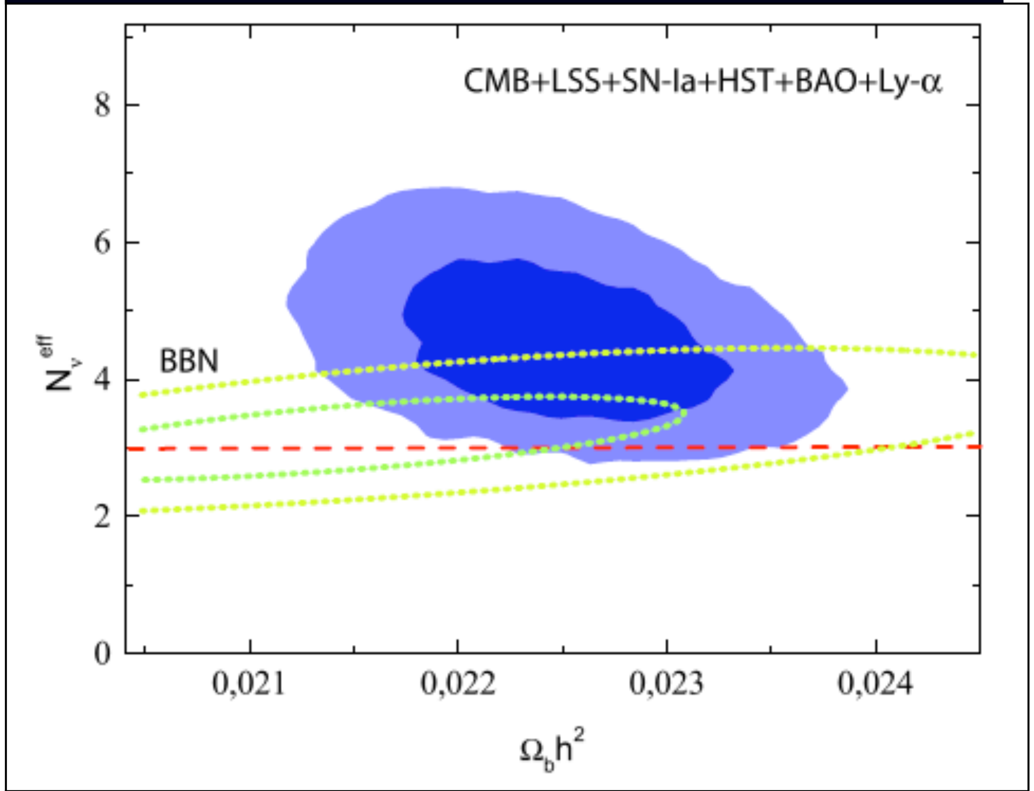
# of flavour neutrinos: $N_\nu = 2.984 \pm 0.008$ (LEP data)

Evolution of ρ_ν/ρ_γ before and after ν decoupling



allowed ranges for N_{eff}





from BBN data

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

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

(95% CL)

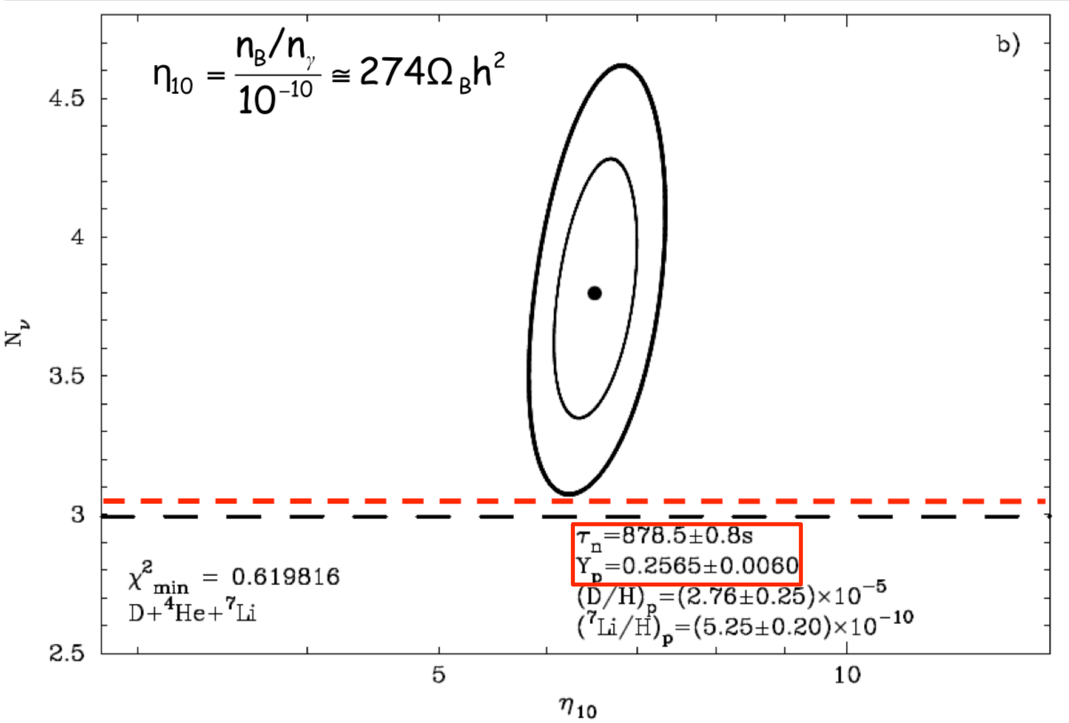
from non-BBN data

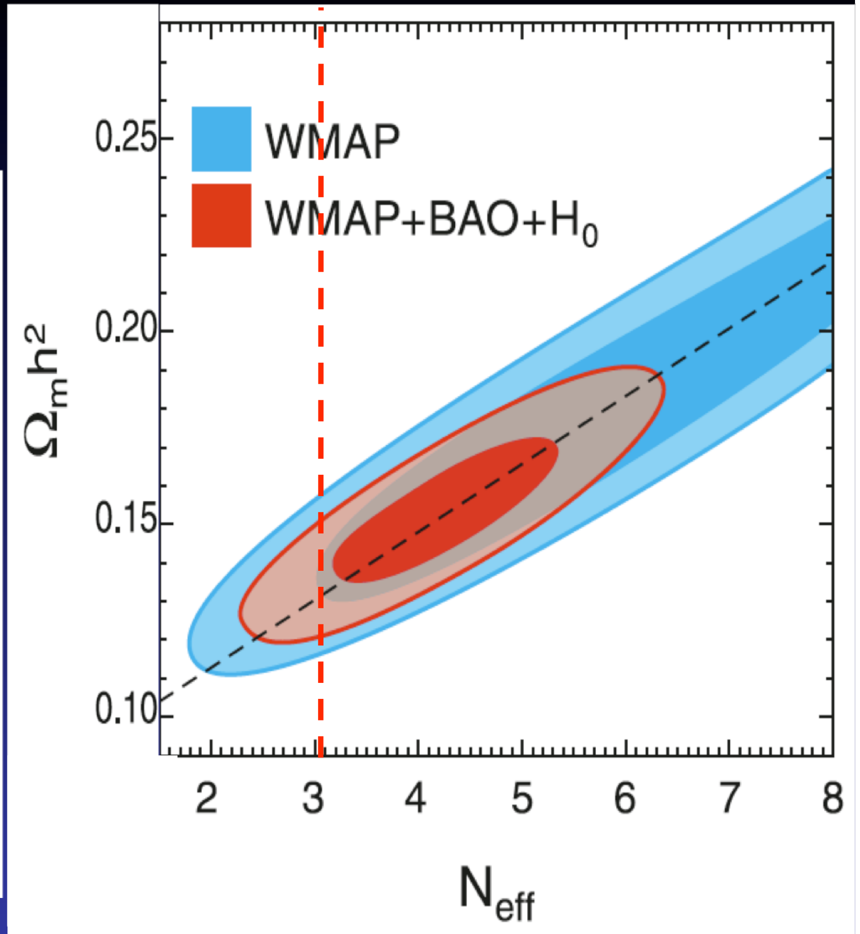
Mangano et al, JCAP 0703 (2007) 006

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

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

allowed ranges for N_{eff}





Recent ^{4}He data

Izotov & Thuan, ApJ 710 (2010) L67
[arXiv:1001.4440]

$$N_{eff} = 3.80^{+0.80}_{-0.70}$$

(95% CL)

from non-BBN data

WMAP [7-year], arXiv:1001.4538

$2.7 < N_{eff} < 6.2$ (WMAP+BAO+H_0)

Extra relativistic particles

• Extra radiation can be:

scalars, pseudoscalars, sterile neutrinos (totally or partially thermalized, bulk), neutrinos in very low-energy reheating scenarios, relativistic decay products of heavy particles…

• Particular case: relic neutrino asymmetries

Constraints from BBN and from CMB+LSS

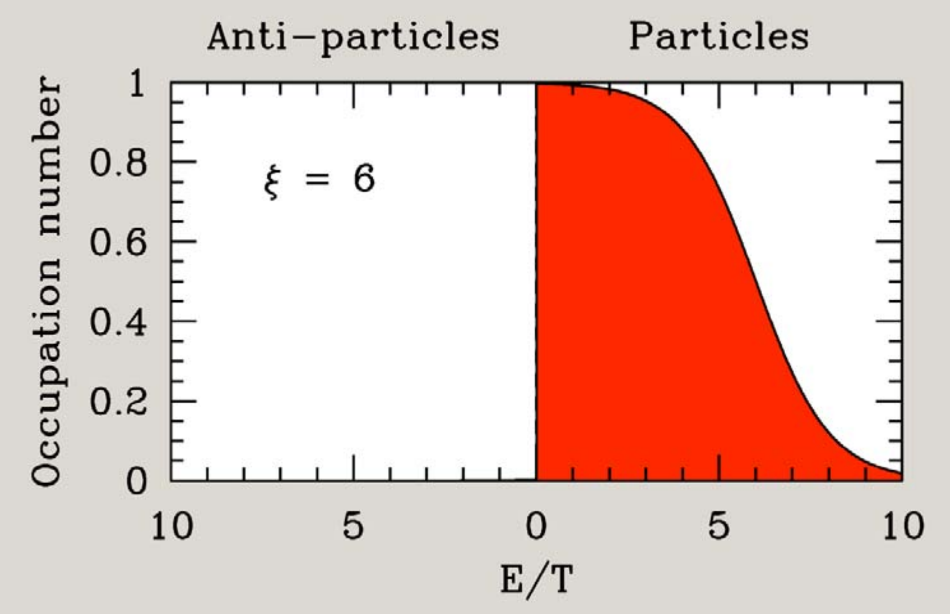
Relic neutrino asymmetries and flavour oscillations

Primordial Neutrino asymmetries

Fermi-Dirac distribution
- Temperature T
- Chemical potential μ

    +μ Particles
    −μ Anti-particles

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



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

Number asymmetry

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

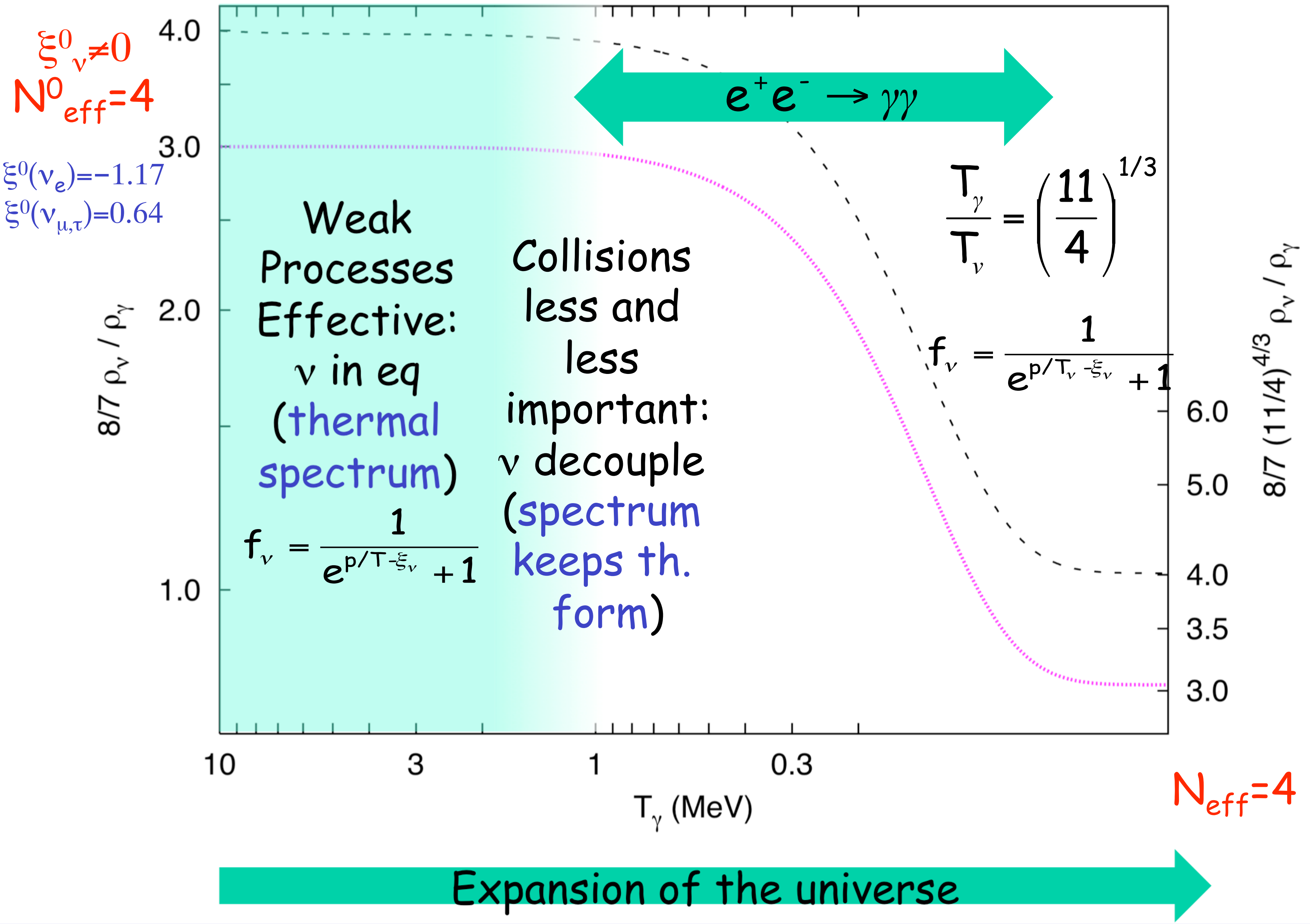
$$= \frac{1}{6\pi^2} T_\nu^3 \left[\xi^3 + \pi^2 \xi\right]$$

BBN and Neutrino Chemical Potentials

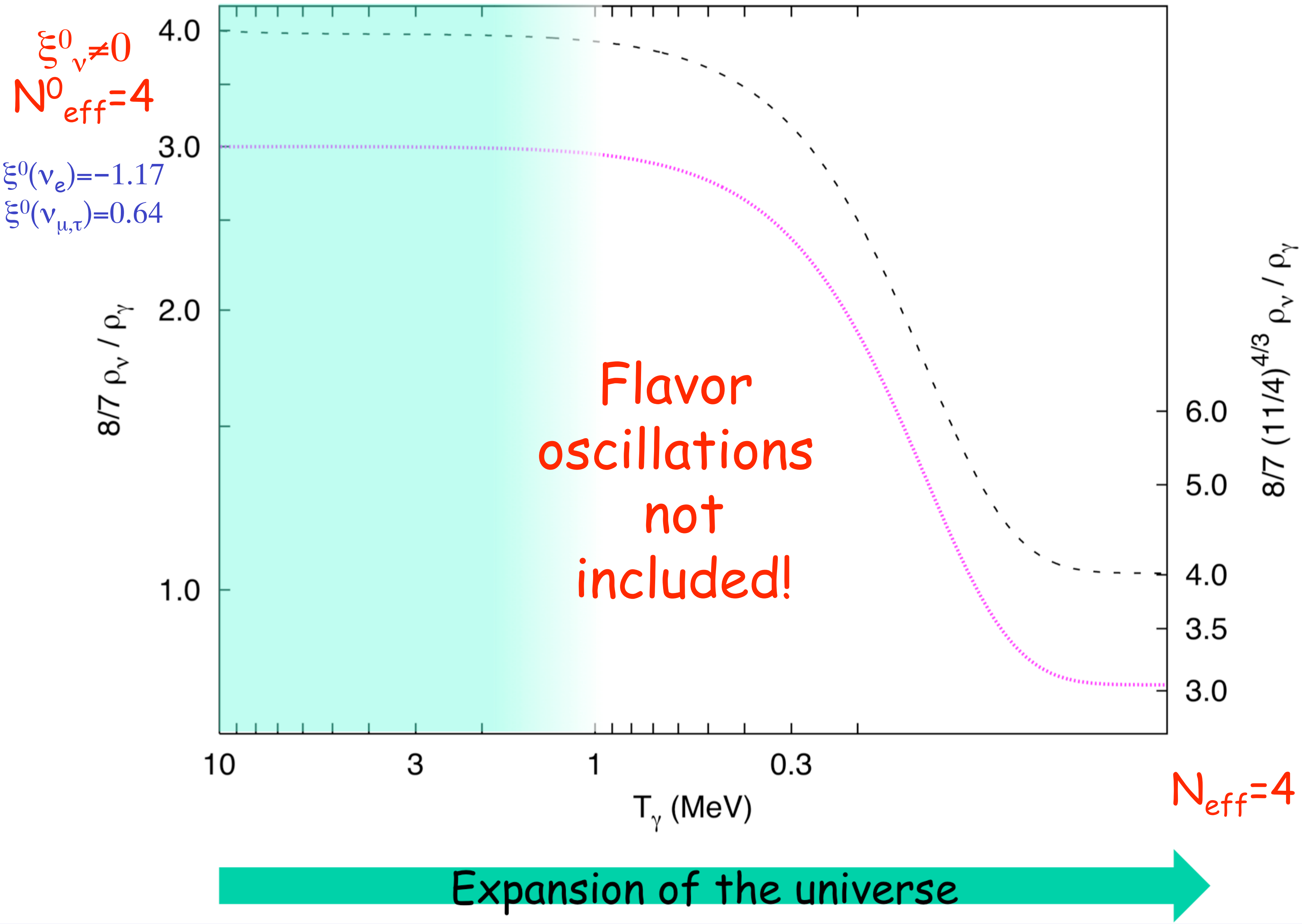
Expansion Rate Effect (all flavors)	Energy density in one neutrino flavor with degeneracy parameter $\xi = \mu/T$ $$\rho_{\nu\bar\nu} = \frac{7\pi^2}{120} T_\nu^4 \Bigg[1 + \underbrace{\frac{30}{7}\left(\frac{\xi}{\pi}\right)^2 + \frac{15}{7}\left(\frac{\xi}{\pi}\right)^4}_{\Delta N_{\rm eff}} \Bigg]$$
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 ($L_\nu^{tot}=0$)



Neutrino oscillations in the Early Universe

Neutrino evolution equations

- Equations of motion in terms of the matrices of density for (anti)neutrinos

$$i\partial_t \varrho_{\mathbf{p}} = [\mathsf{H}_{\mathbf{p}}, \varrho_{\mathbf{p}}]$$

and similar for $\bar{\varrho}_{\mathbf{q}}$ with $\Omega_{\mathbf{p}} \to -\Omega_{\mathbf{p}}$

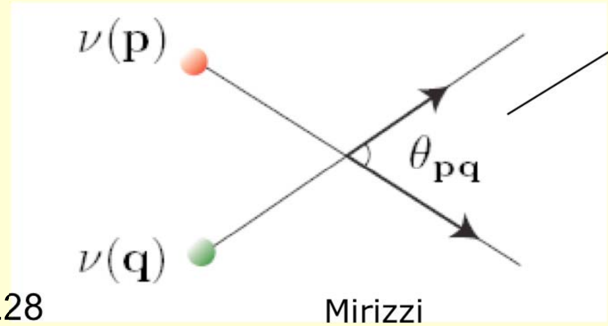
$$\mathsf{H}_{\mathbf{p}} = \Omega_{\mathbf{p}} + \mathsf{V} + \sqrt{2}\, G_{\mathrm{F}} \int \frac{\mathrm{d}^3\mathbf{q}}{(2\pi)^3} \left(\varrho_{\mathbf{q}} - \bar{\varrho}_{\mathbf{q}}\right) \left(1 - \mathbf{v}_{\mathbf{q}} \cdot \mathbf{v}_{\mathbf{p}}\right)$$

Matrix of vacuum oscillation frequencies

$$\Omega_{\mathbf{p}} = \mathsf{M}^2 / 2|\mathbf{p}|$$

MSW Matter effect, **DIAGONAL** in the weak-interaction basis

Neutrino-neutrino refraction term, **NON-DIAGONAL** in the weak-interaction basis



Cross section interaction

$$\propto \sqrt{2} G_F n_\nu (1 - \cos\vartheta_{pq})$$

Pantaleone, PLB 287 (1992) 128

Neutrino evolution equations

- Equations of motion in terms of the matrices of density for (anti)neutrinos

$$\mathrm{i}\partial_t \varrho_{\mathbf{p}} = [\mathsf{H}_{\mathbf{p}}, \varrho_{\mathbf{p}}]$$

and similar for $\bar{\varrho}_{\mathbf{q}}$ with $\Omega_{\mathbf{p}} \to -\Omega_{\mathbf{p}}$

$$\mathsf{H}_{\mathbf{p}} = \Omega_{\mathbf{p}} + \mathsf{V} + \sqrt{2}\, G_{\mathrm{F}} \int \frac{\mathrm{d}^3\mathbf{q}}{(2\pi)^3} \left(\varrho_{\mathbf{q}} - \bar{\varrho}_{\mathbf{q}}\right) \left(1 - \mathbf{v}_{\mathbf{q}} \cdot \mathbf{v}_{\mathbf{p}}\right)$$

Matrix of vacuum oscillation frequencies

$$\Omega_{\mathbf{p}} = \mathsf{M}^2/2|\mathbf{p}|$$

MSW Matter effect, **DIAGONAL** in the weak-interaction basis

Neutrino-neutrino refraction term, **NON-DIAGONAL** in the weak-interaction basis

$$i\dot{\varrho}_{\mathbf{p}} = [\Omega_{\mathbf{p}}, \varrho_{\mathbf{p}}] + C(\varrho_{\mathbf{p}}, \bar{\varrho}_{\mathbf{p}})$$

Early Universe: add collision terms

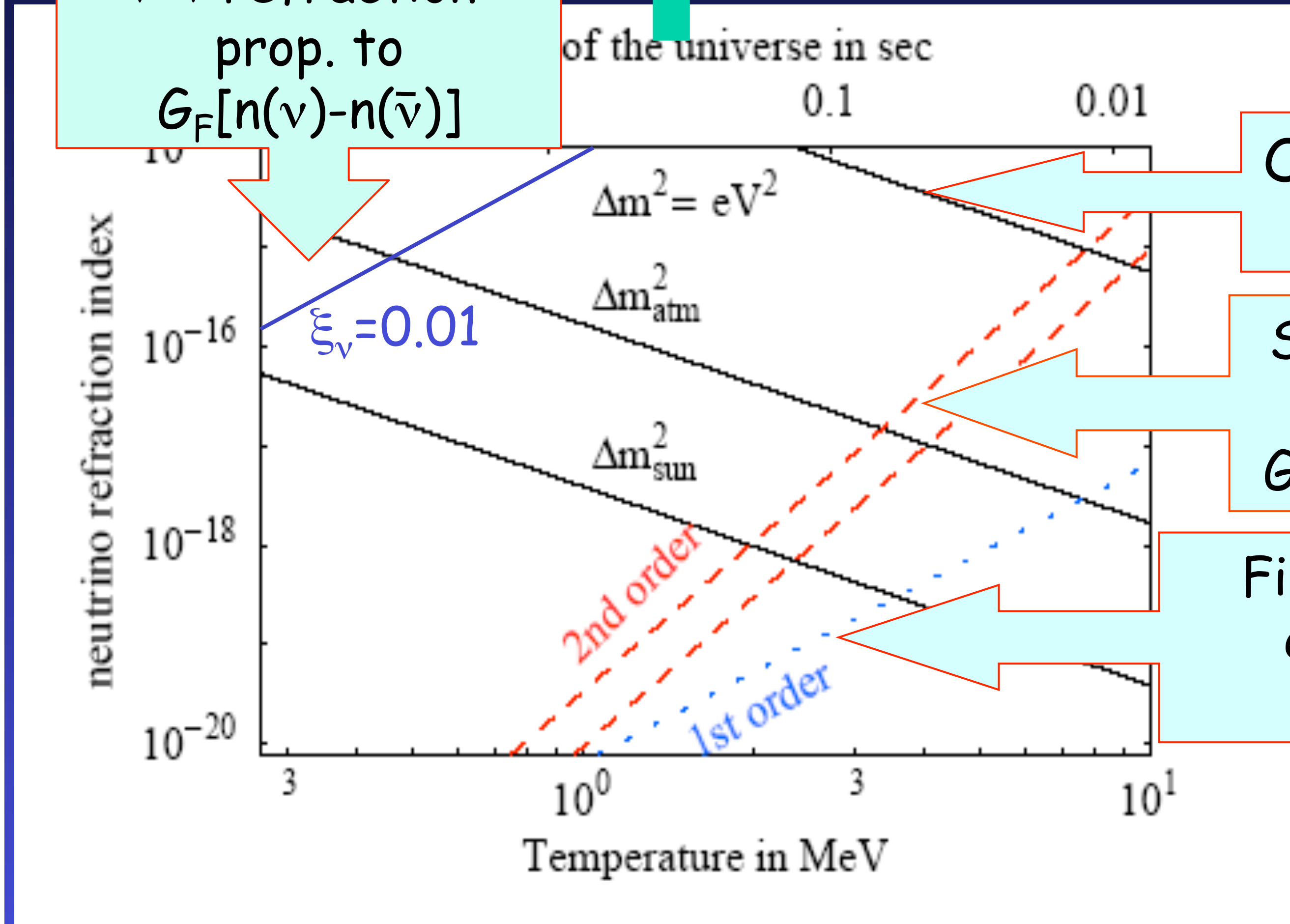
Neutrino oscillations in the Early Universe

Neutrino oscillations are effective when medium effects get small enough

$\nu-\nu$ refraction prop. to $G_F[n(\nu)-n(\bar{\nu})]$

Coupled neutrinos

Compare oscillation term with effective potentials



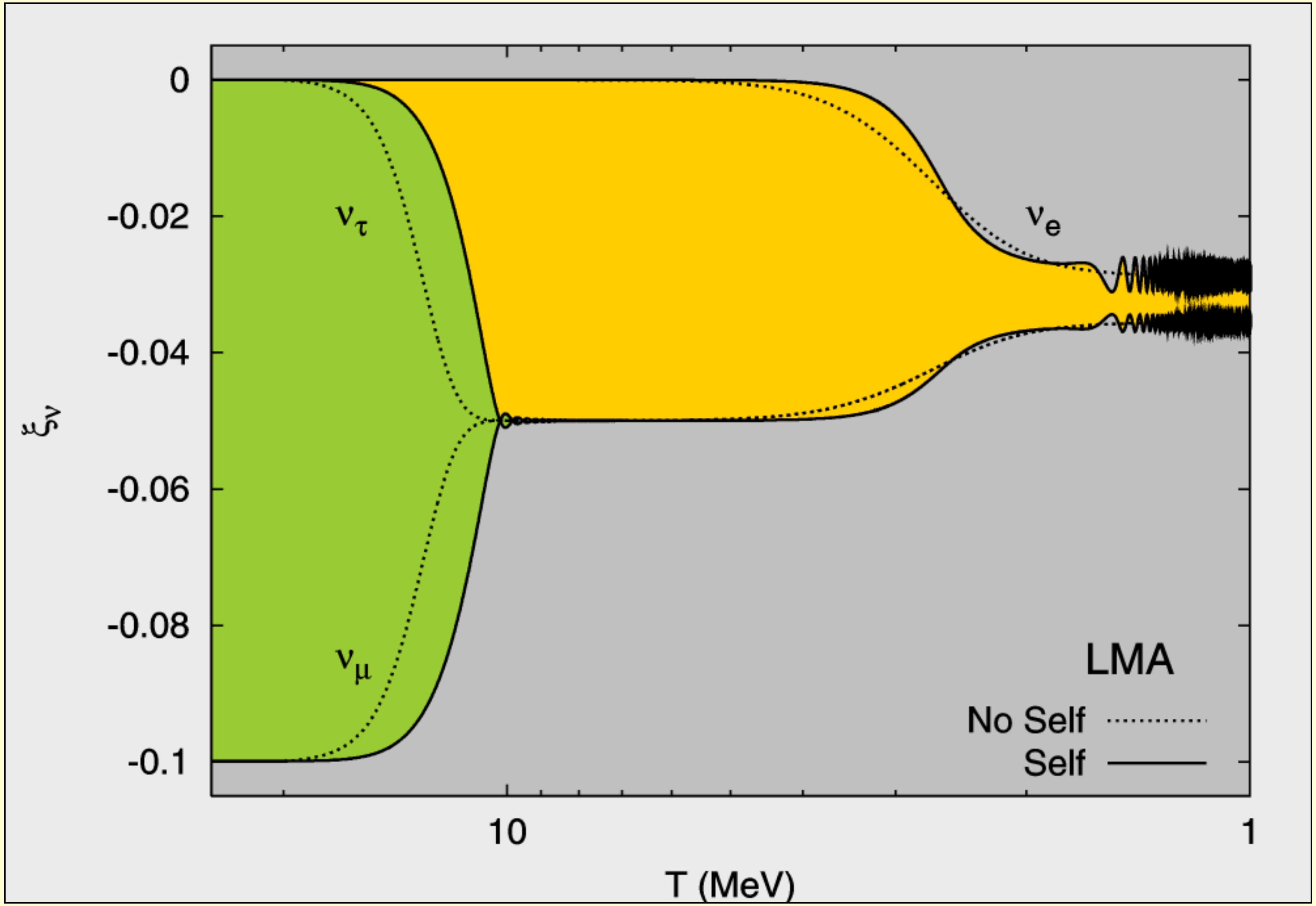
Oscillation term prop. to $\Delta m^2/2E$

Second order matter effects prop. to $G_F(E/M_Z^2)[\rho(e^-)+\rho(e^+)]$

First order matter effects prop. to $G_F[n(e^-)-n(e^+)]$

Strumia & Vissani, hep-ph/0606054

Flavor Transformation for LMA Solution



Dolgov et al, NPB 632 (2002) 363 [hep-ph/0201287]

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

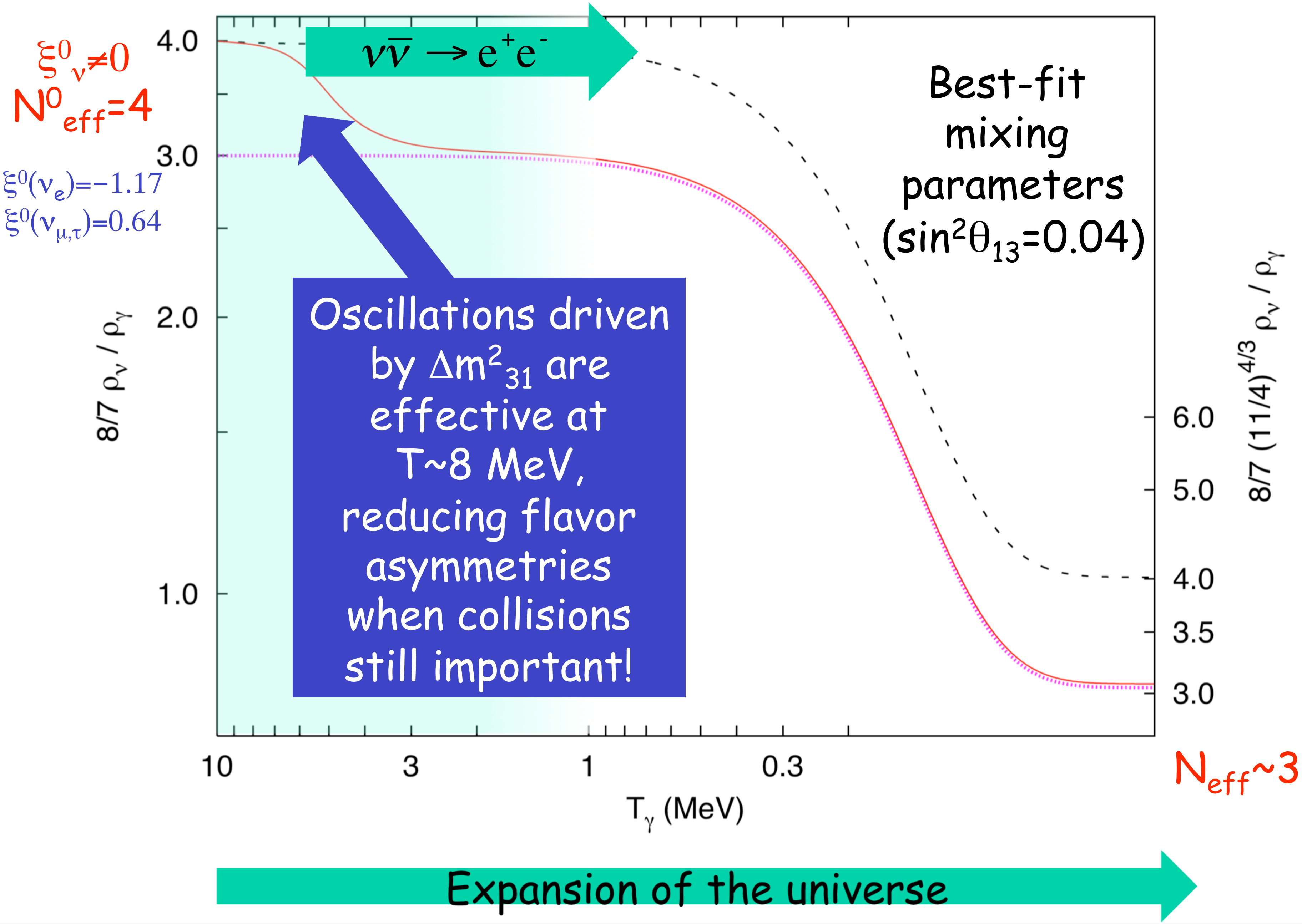
- Oscillations effective before n/p freeze out ?
- YES for solar LMA solution
- Our knowledge of the cosmic neutrino density depends on measured oscillation parameters

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

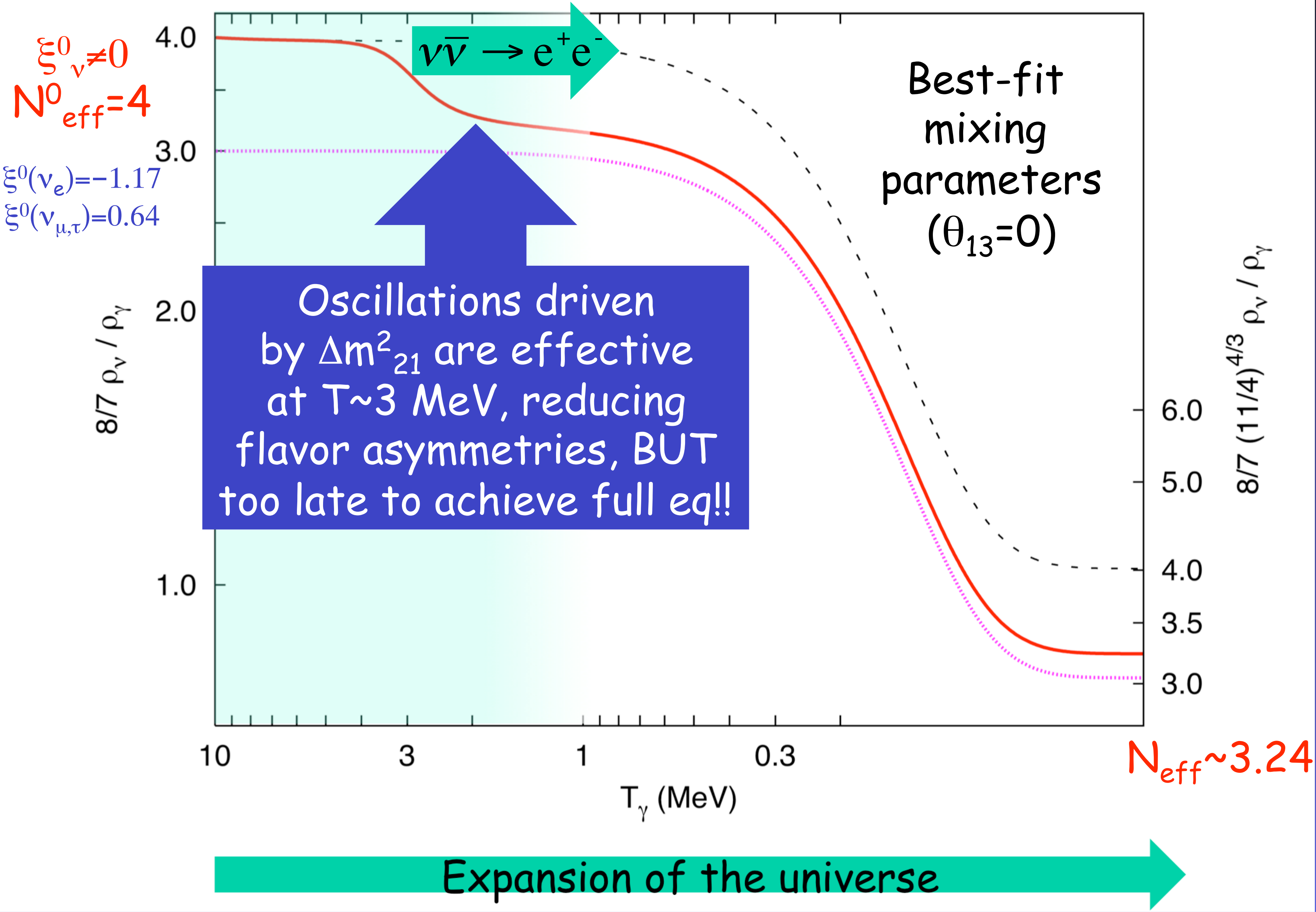
However, important caveats!

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

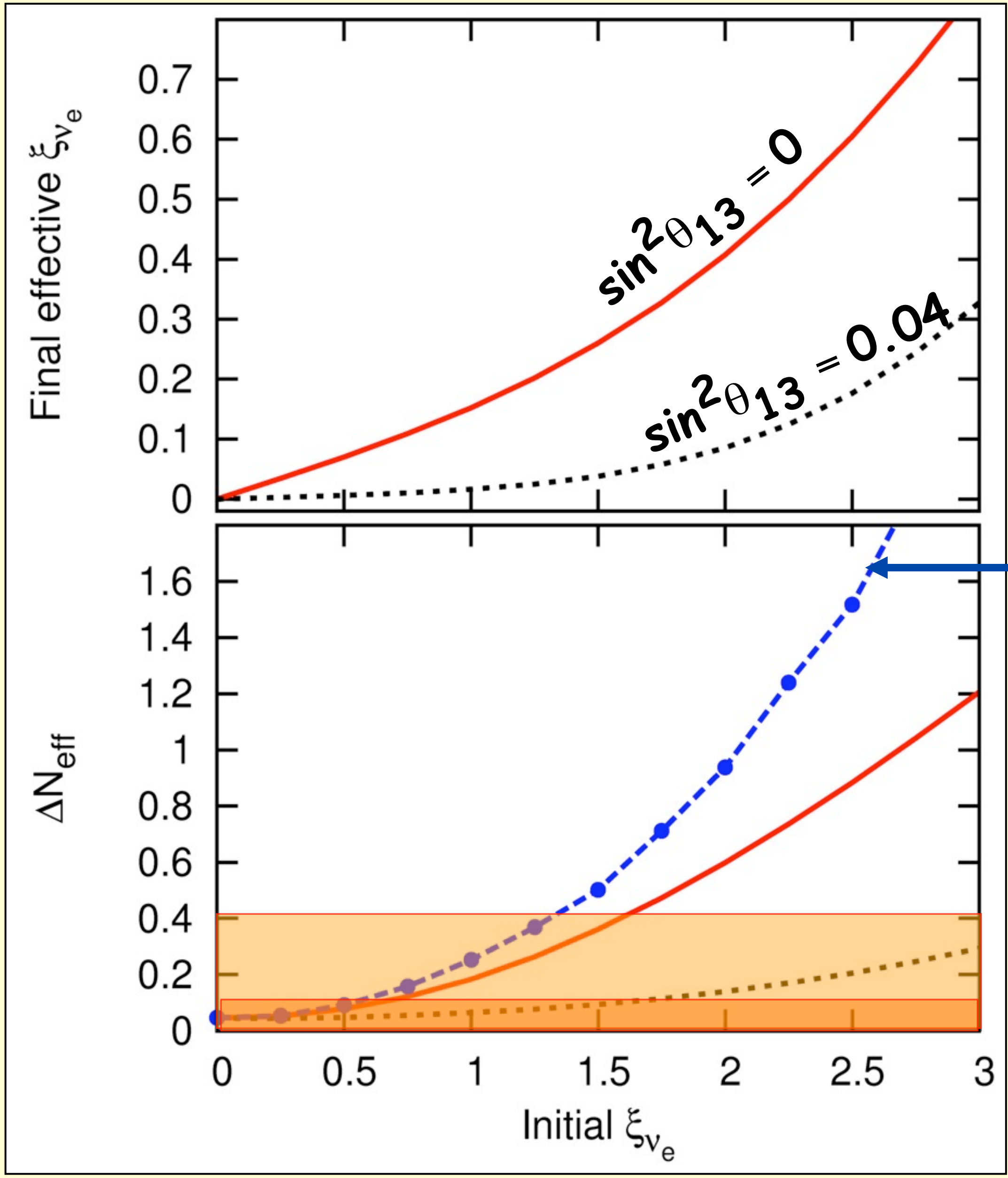
Evolution of ρ_ν/ρ_γ with asymmetries ($L_\nu^{tot}=0$)



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



Final radiation density



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

- 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

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The End