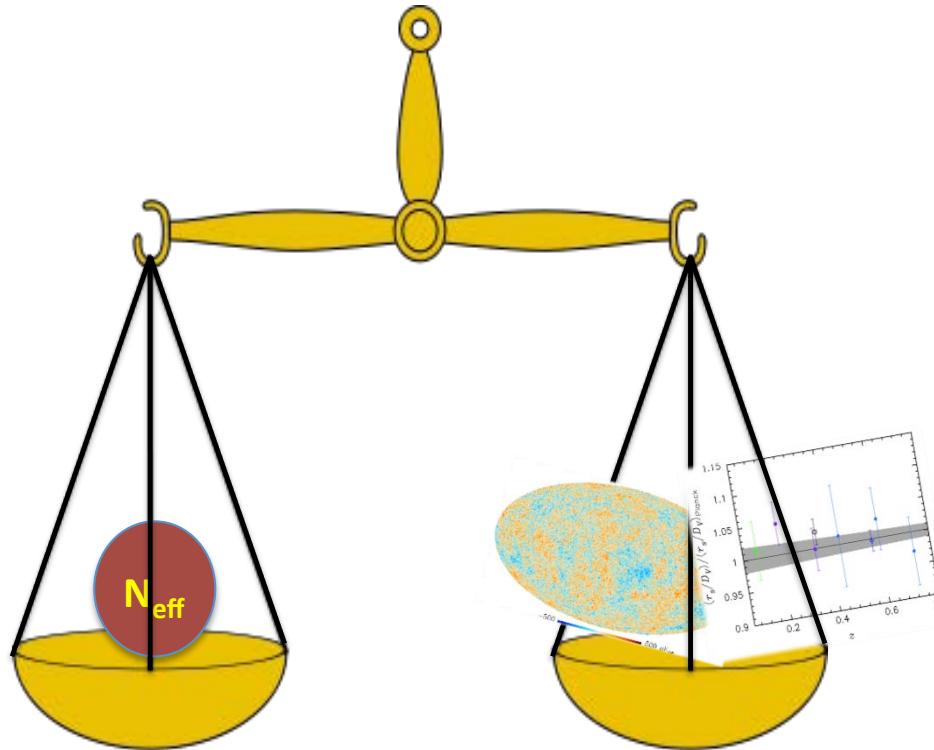


The effective number of neutrinos: standard and non-standard scenarios



**Sergio Pastor
(IFIC Valencia)**

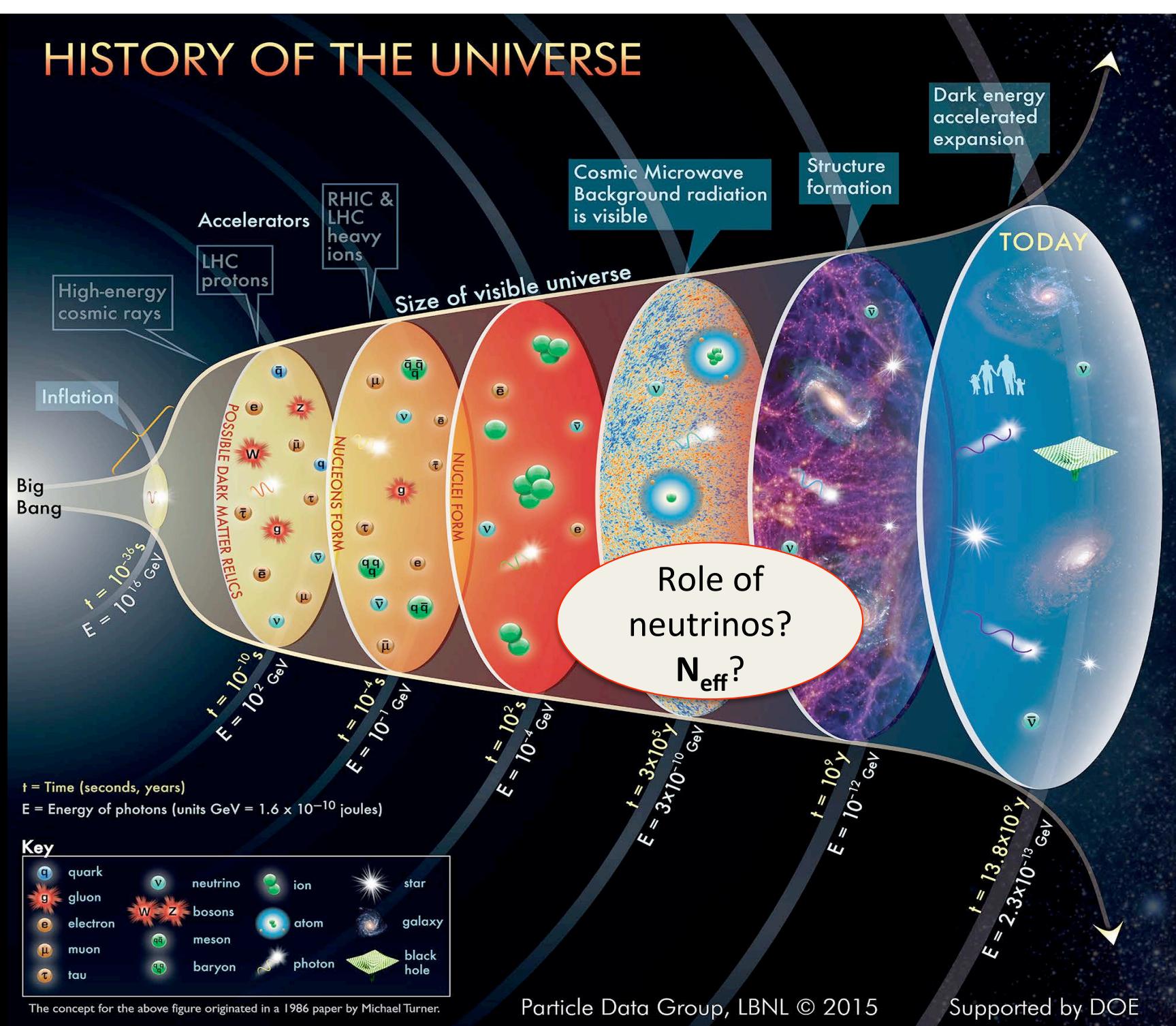
COSMOS meeting on Astroparticle and
Fundamental Physics with the CMB
Ferrara, 26-27 June 2018



UNIVERSITAT
DE VALÈNCIA



HISTORY OF THE UNIVERSE

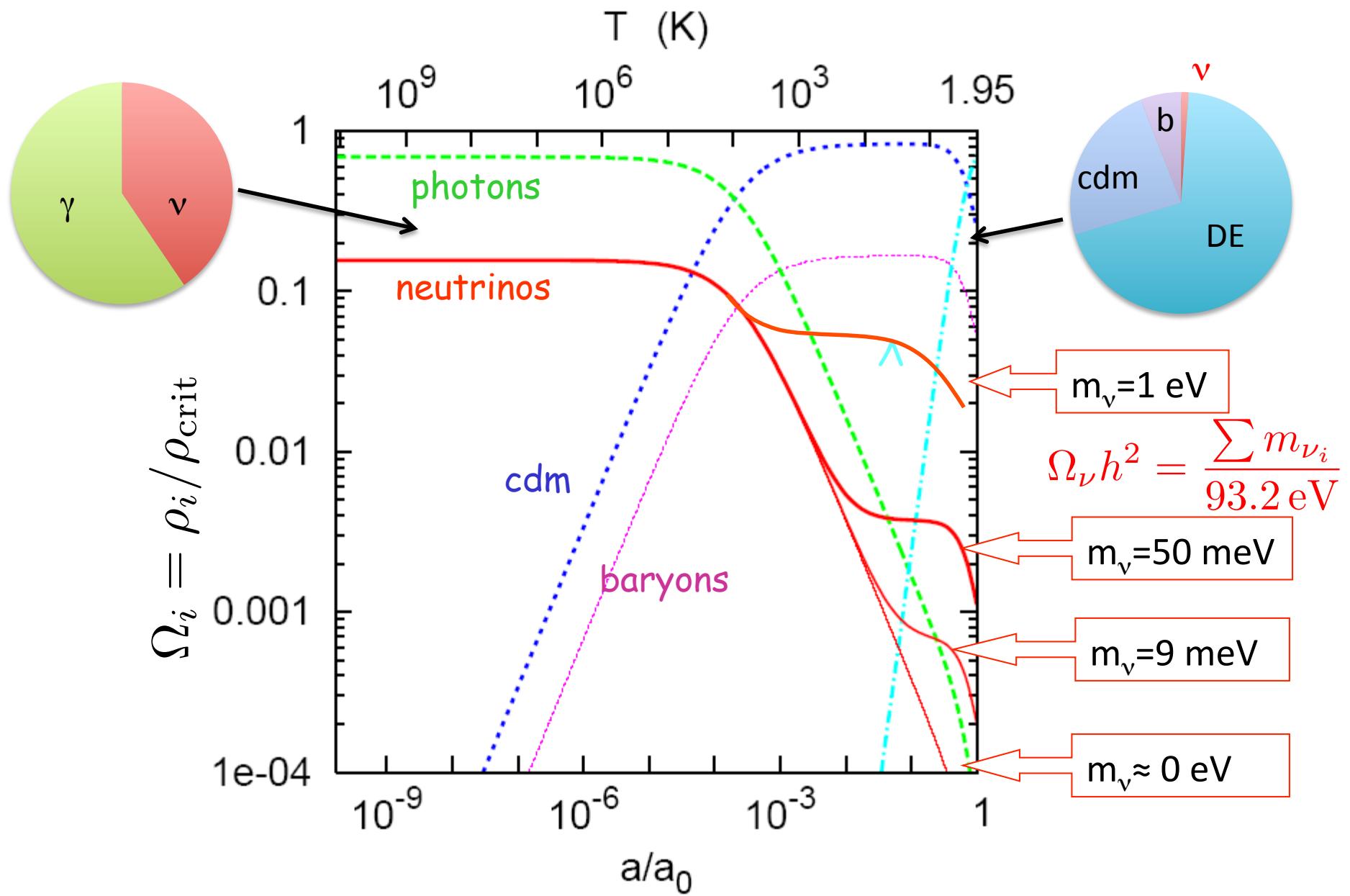


The concept for the above figure originated in a 1986 paper by Michael Turner.

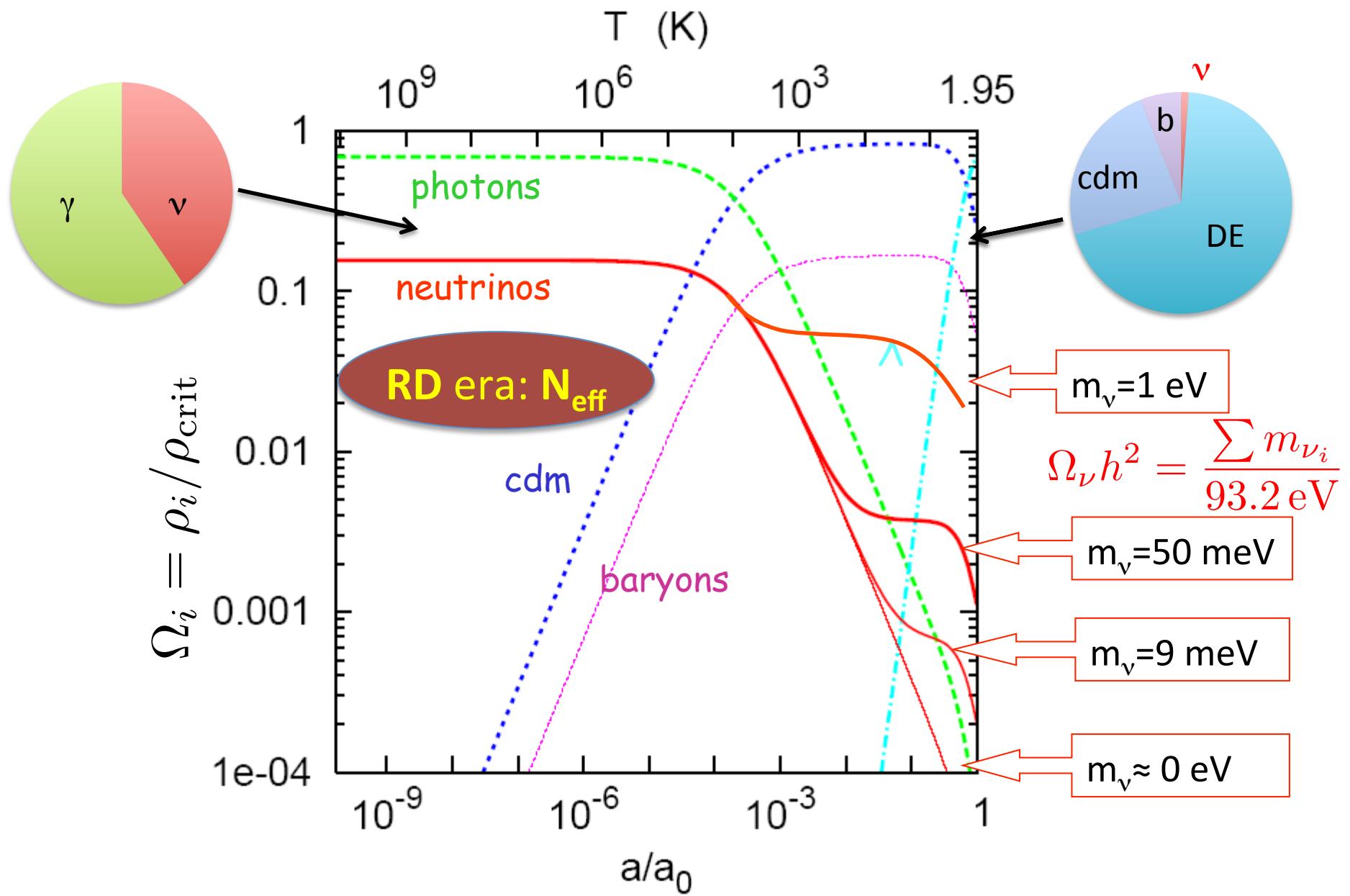
Particle Data Group, LBNL © 2015

Supported by DOE

Cosmological energy densities: 1 MeV → now

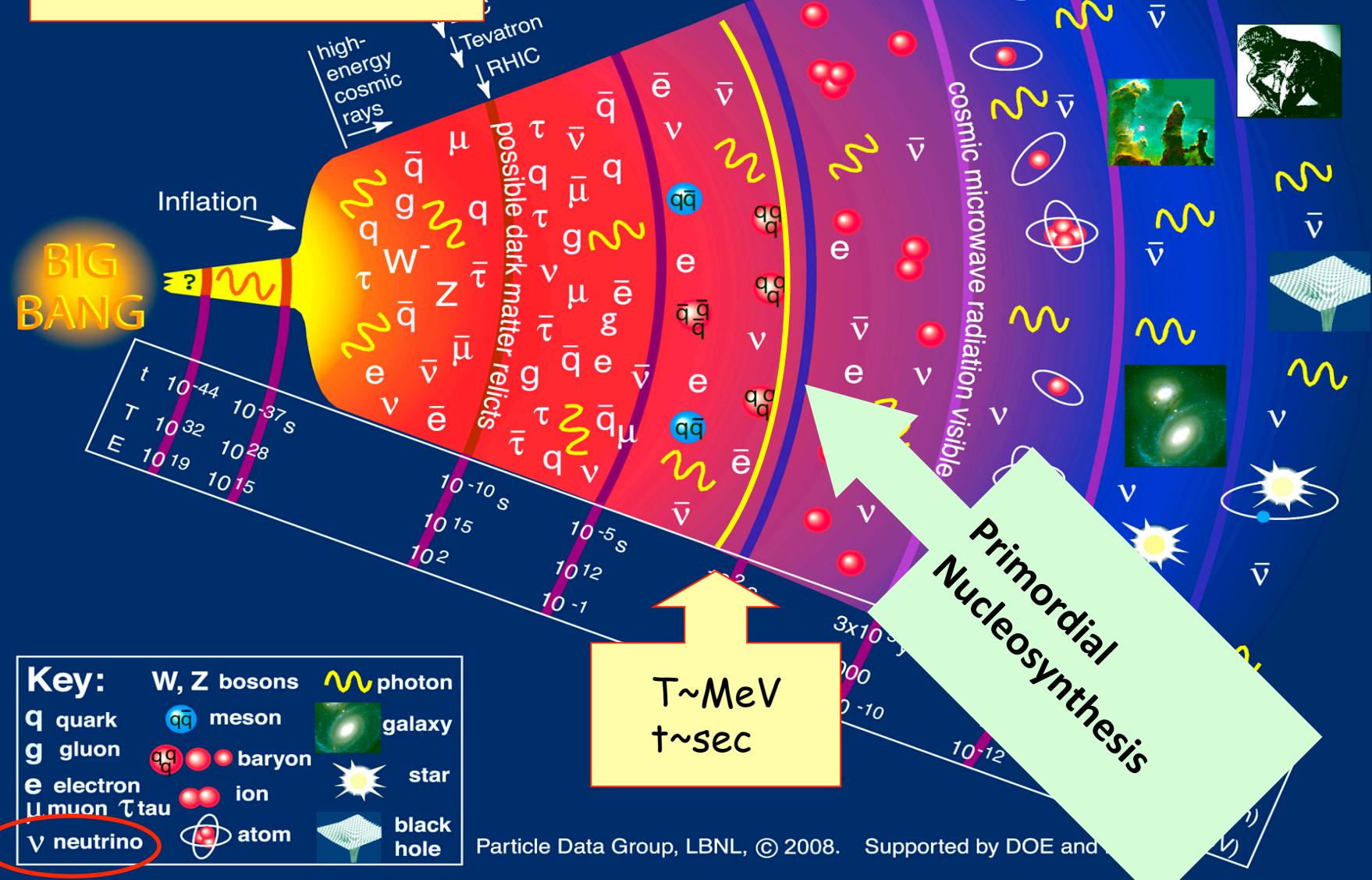


Cosmological energy densities: 1 MeV → now

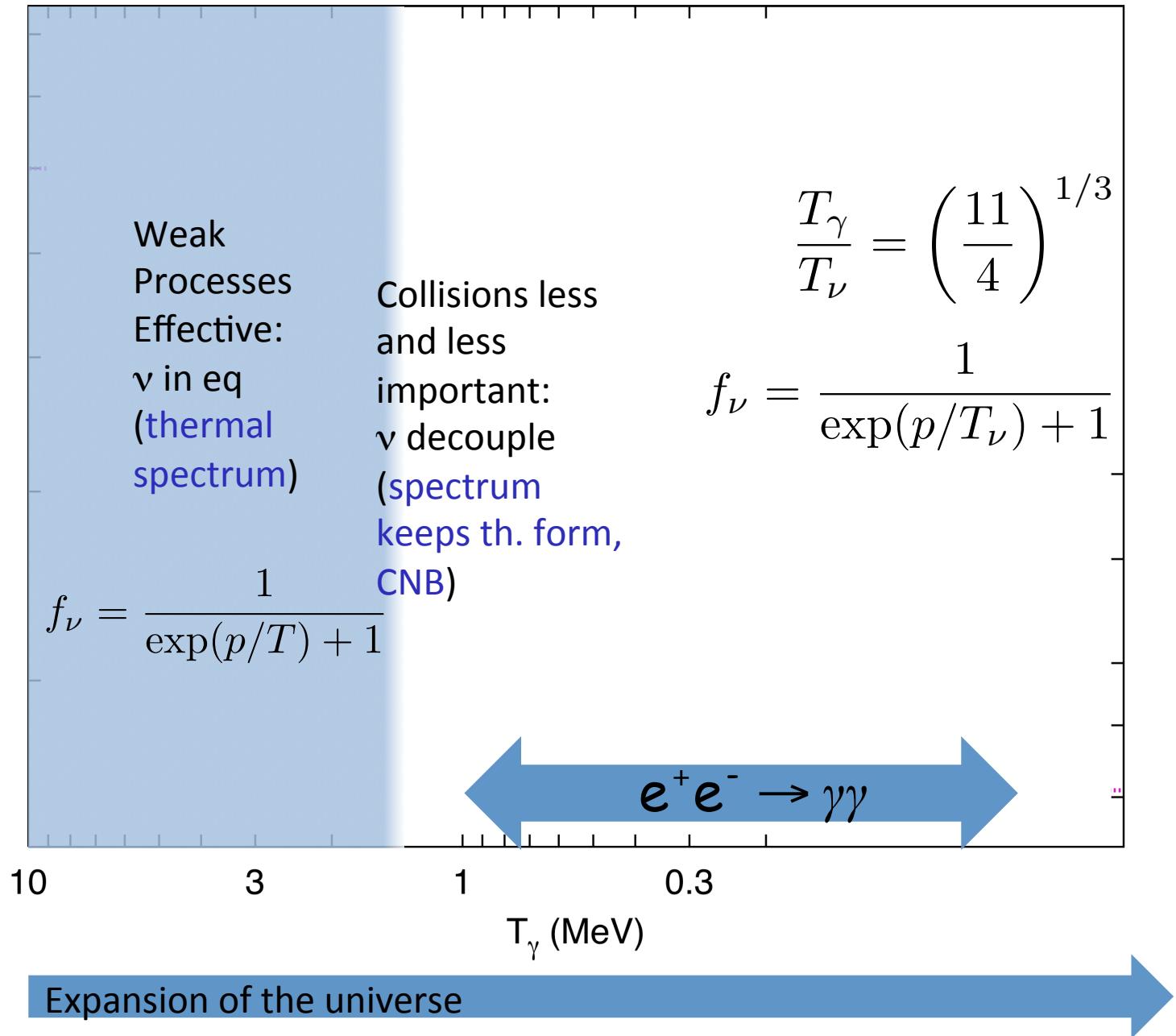


History of the Universe

Neutrinos coupled by weak interactions



Neutrino decoupling and e^\pm annihilation



Relativistic particles in the Universe

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

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

Effective number of relativistic neutrino species

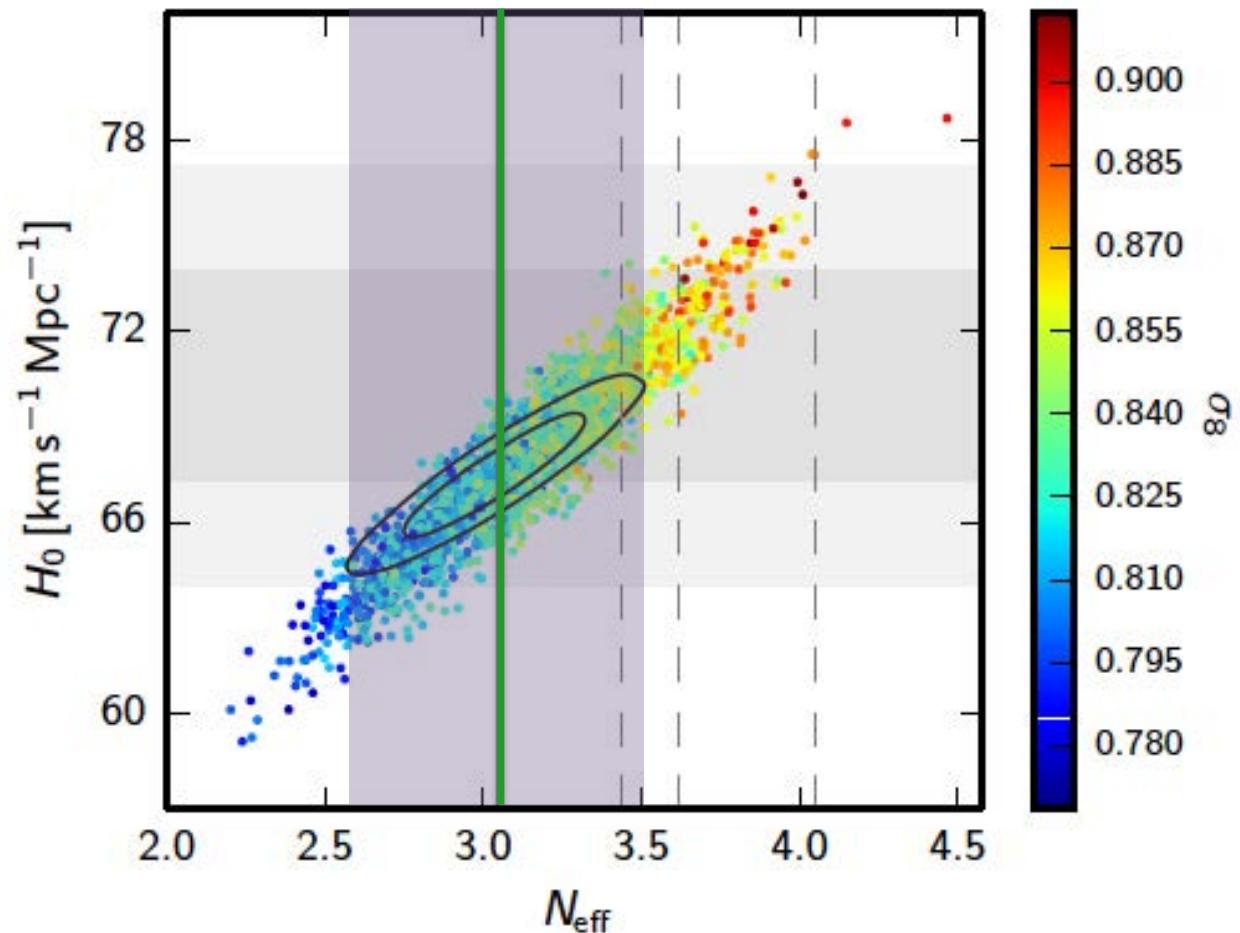
Traditional parametrization of ρ stored in relativistic particles

N_{eff} is a way to measure the ratio $\frac{\rho_\nu + \rho_x}{\rho_\gamma}$

- standard neutrinos only: $N_{\text{eff}} = 3$

Measuring N_{eff}

Indirect detection of
CNB at $10\text{-}17\sigma$



$$N_{\text{eff}} = 3.13 \pm 0.32 \quad \textit{Planck TT+lowP};$$

$$N_{\text{eff}} = 3.15 \pm 0.23 \quad \textit{Planck TT+lowP+BAO};$$

$$N_{\text{eff}} = 2.99 \pm 0.20 \quad \textit{Planck TT, TE, EE+lowP};$$

$$N_{\text{eff}} = 3.04 \pm 0.18 \quad \textit{Planck TT, TE, EE+lowP+BAO}.$$

All 68%CL

Relativistic particles in the Universe

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

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

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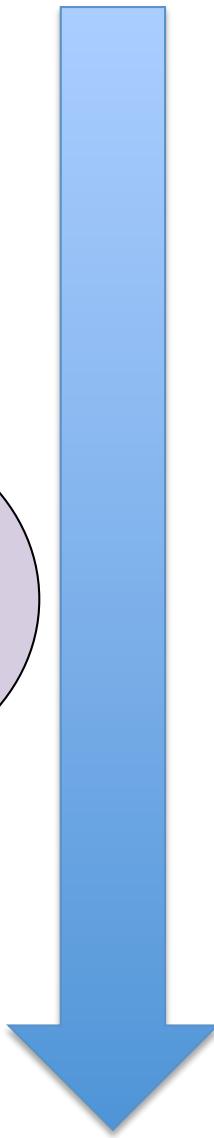
➤ standard neutrinos only: $N_{\text{eff}} = 3$

additional relativistic particles (scalars, pseudoscalars, decay products of heavy particles,...)

non-standard neutrino physics (primordial neutrino asymmetries, totally or partially thermalized **light sterile neutrinos**, non-standard interactions with electrons,...)

$N_{\text{eff}} \neq 3$

$N_{\text{eff}} \neq 3$
from
neutrinos



**Standard case including
neutrino oscillations**

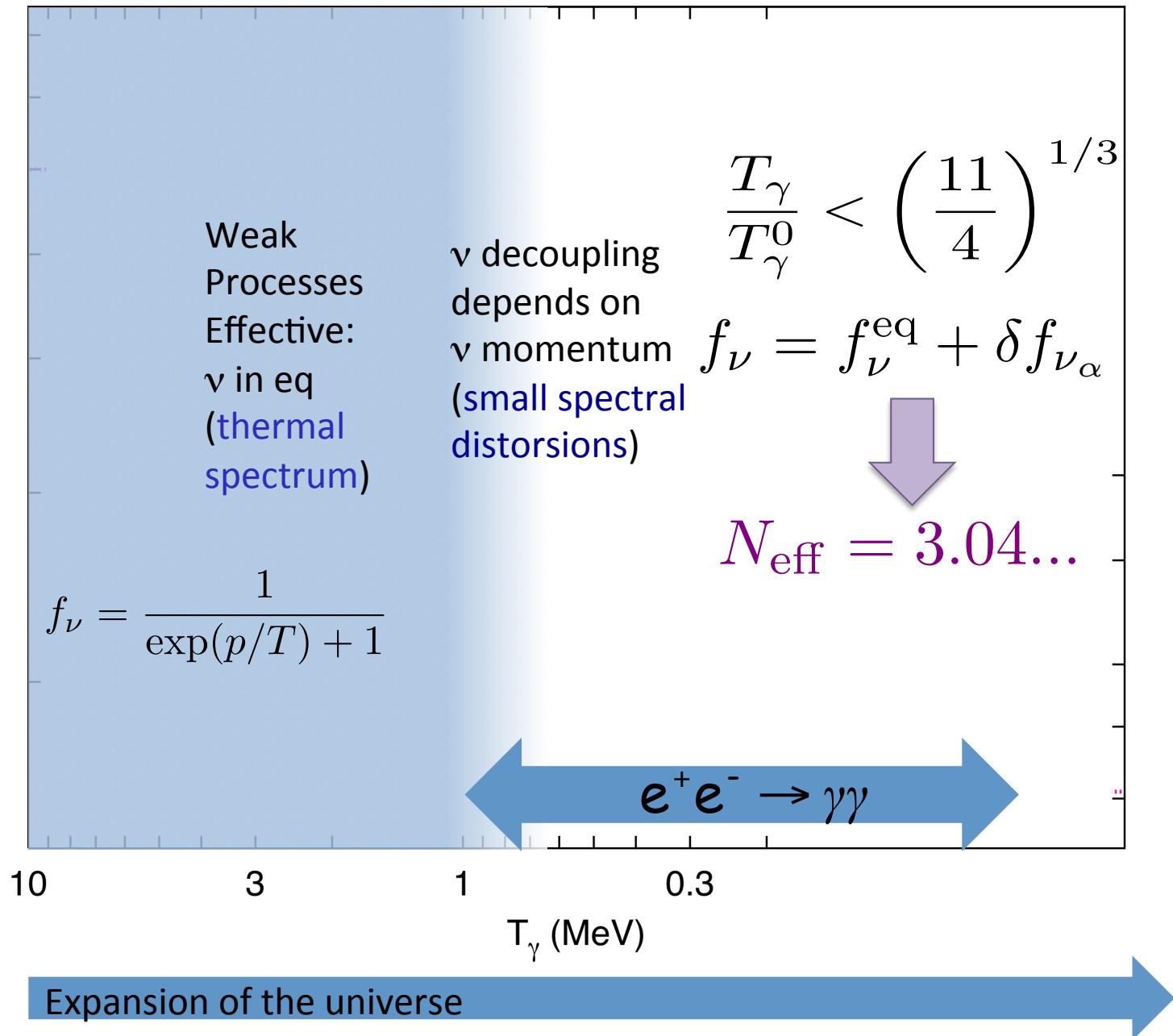
**N_{eff} from non-standard
neutrino-electron interactions**

N_{eff} in very low reheating scenarios

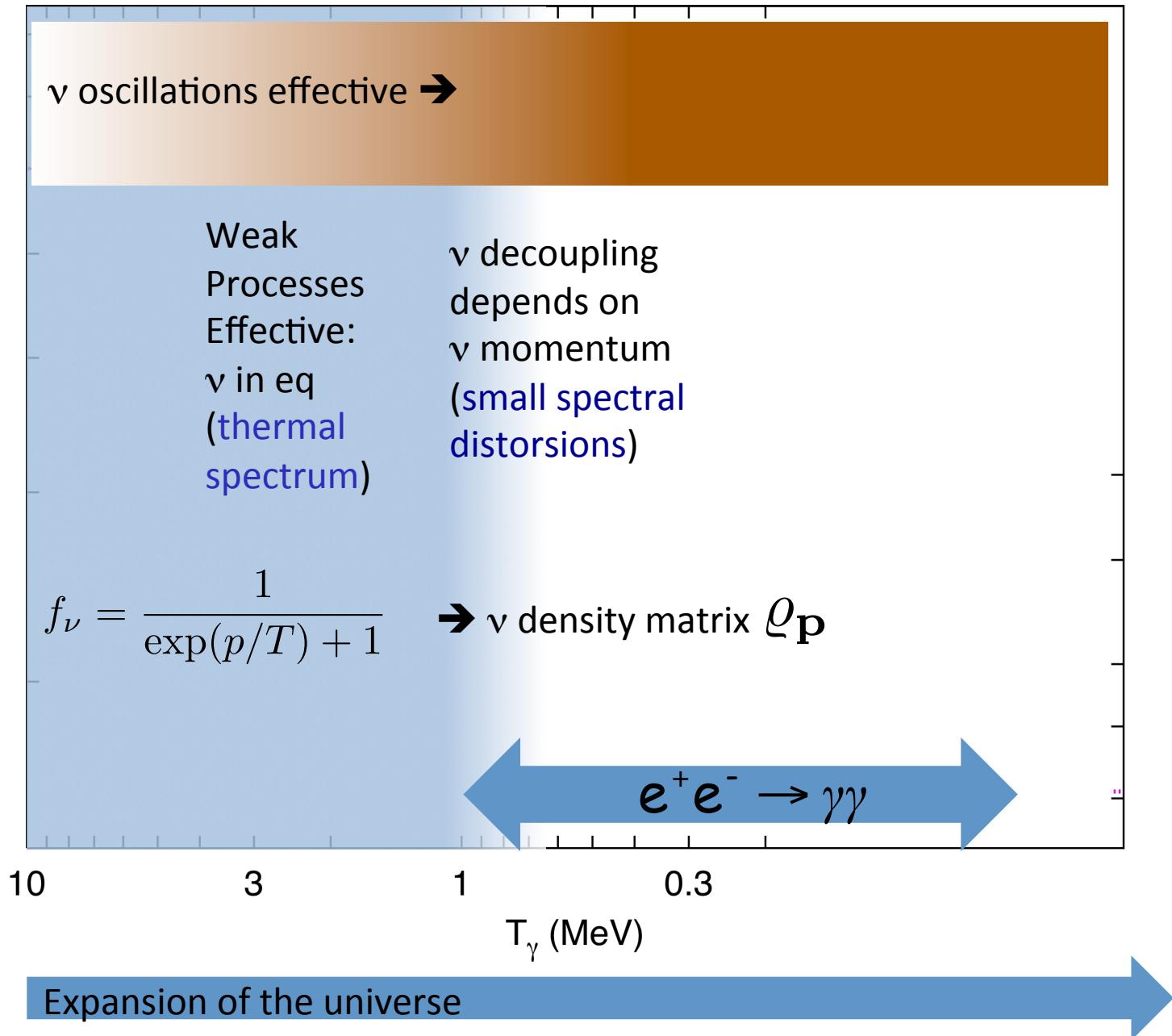
Neutrinos without FD distribution

Standard case

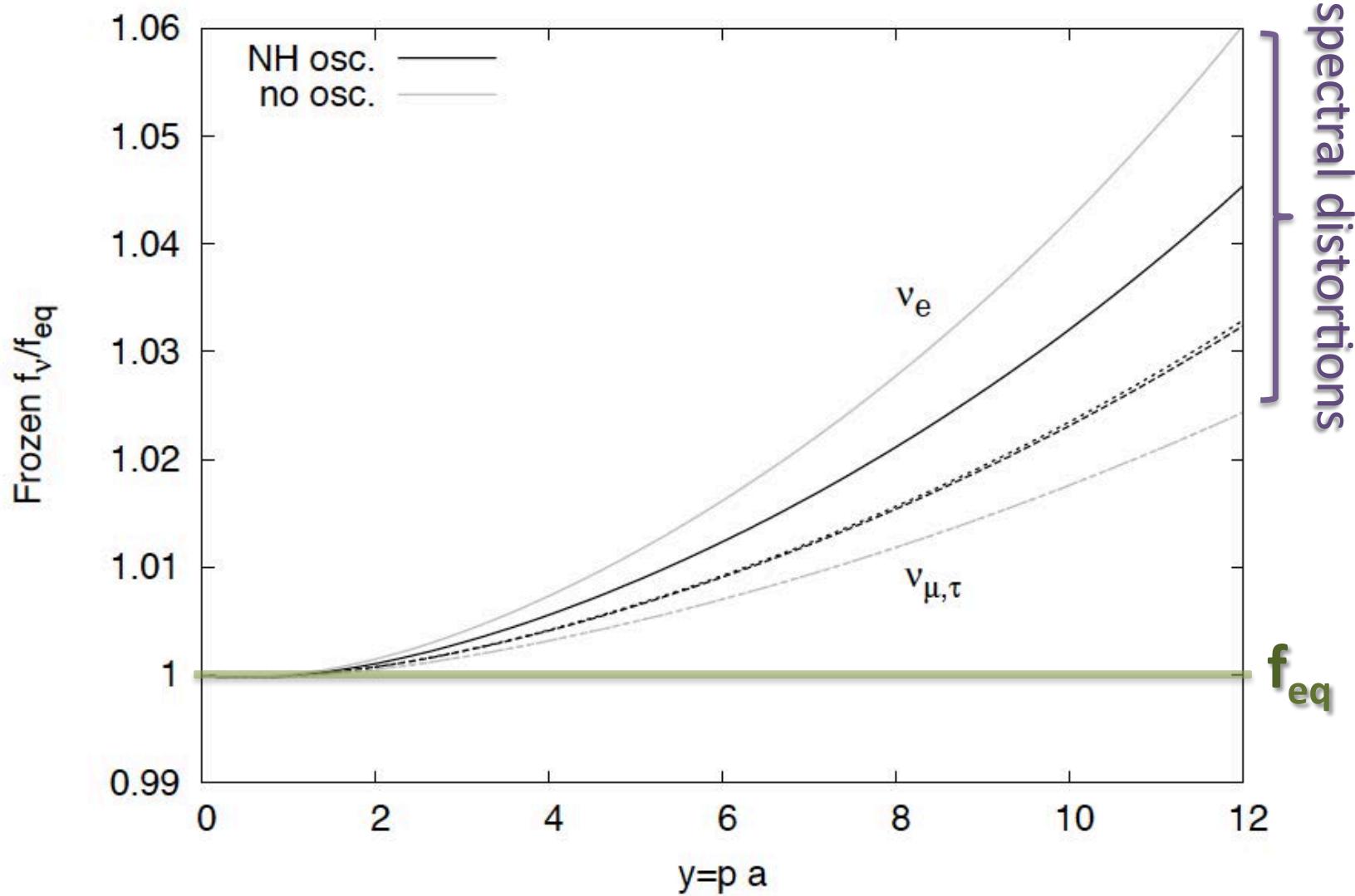
$N_{\text{eff}} > 3$: small neutrino heating



Additional complication: flavour neutrino oscillations



Standard scenario: final distortions



N_{eff} in the standard case

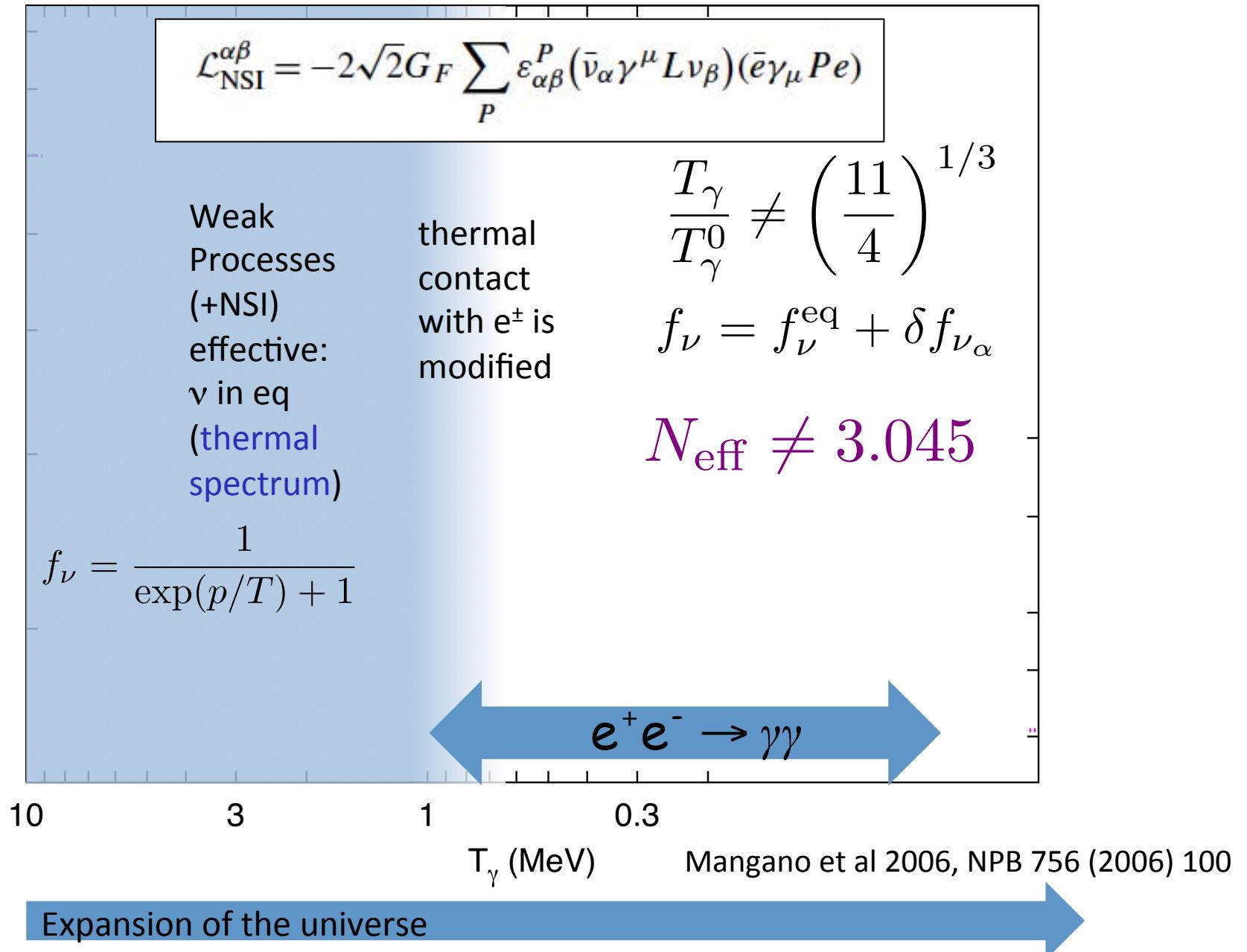
contribution of
distortions to ρ_ν

Case	T_γ/T_γ^0	z_{fin}	$\delta\bar{\rho}_{\nu_e}(\%)$	$\delta\bar{\rho}_{\nu_\mu}(\%)$	$\delta\bar{\rho}_{\nu_\tau}(\%)$	N_{eff}
Instantaneous decoupling	z_0	1.40102	0	0	0	3.000
Inst. dec. (with QED corrections)		1.39975	0	0	0	3.011
No oscillations		1.39784	0.920	0.392	0.392	3.045
Normal hierarchy (NH)		1.39779	0.699	0.511	0.519	3.045
NH (damping terms)		1.39778	0.673	0.529	0.533	3.045
Inverted hierarchy (IH)		1.39779	0.697	0.512	0.520	3.045

$$N_{\text{eff}} = \left(\frac{z_0}{z_{\text{fin}}} \right)^4 (3 + \delta\bar{\rho}_{\nu_e} + \delta\bar{\rho}_{\nu_\mu} + \delta\bar{\rho}_{\nu_\tau})$$

Non-standard scenarios

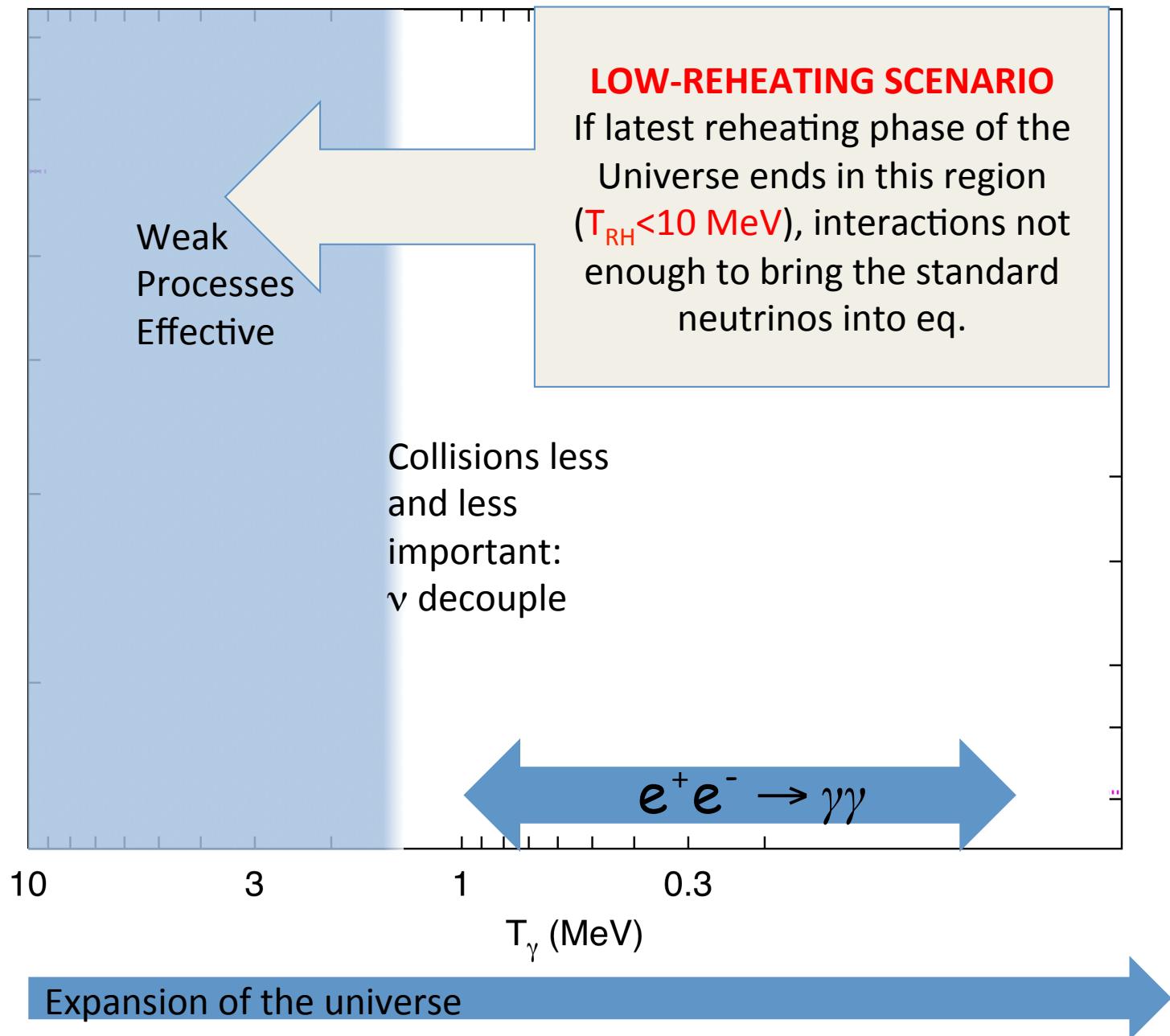
$N_{\text{eff}} \neq 3$: non-standard neutrino-electron interactions



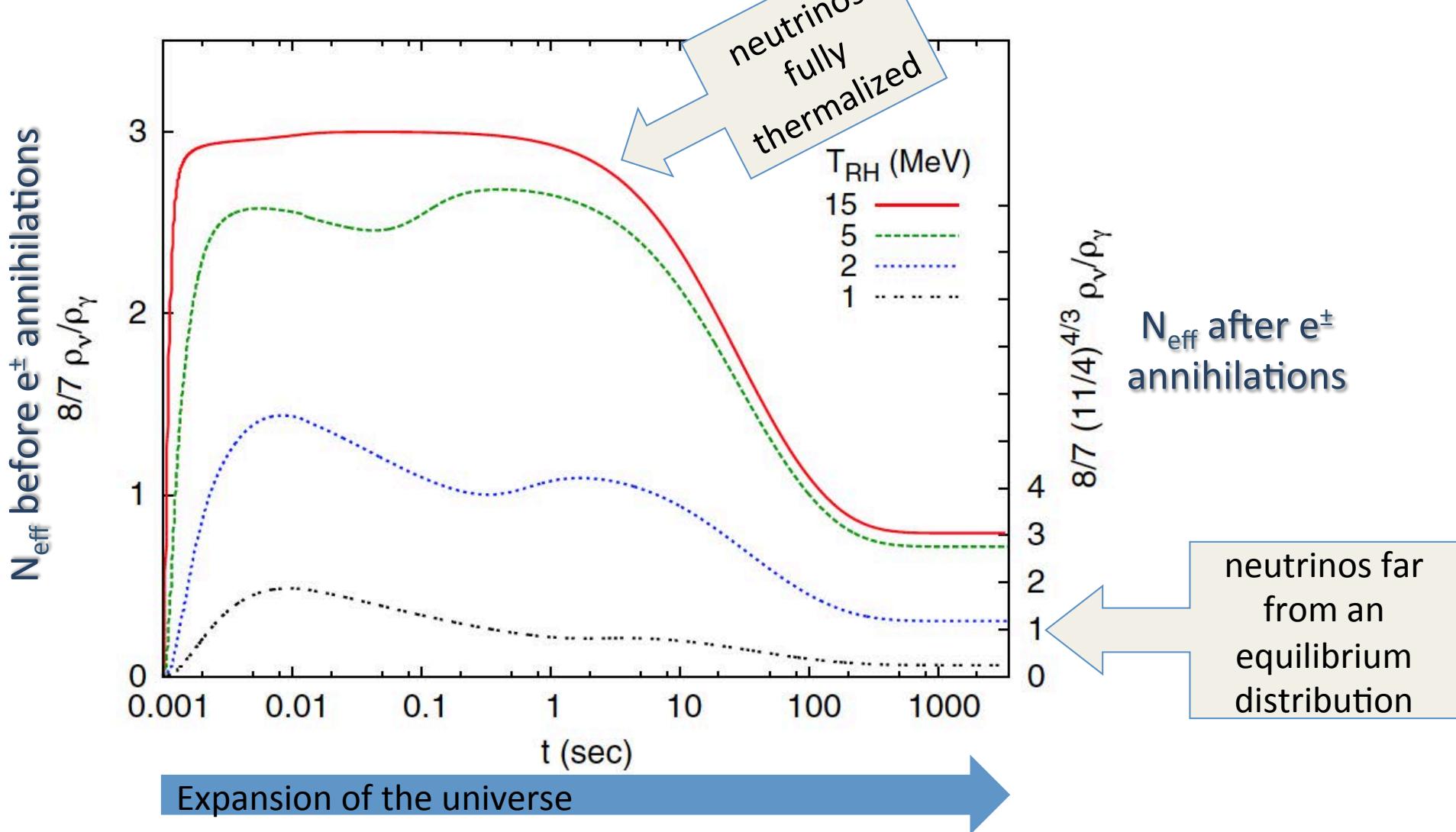
N_{eff} in two NSI cases vs the standard scenario

Case	T_γ/T_γ^0	contribution of distortions to ρ_ν			N_{eff}
		z_{fin}	$\delta\bar{\rho}_{\nu_e}(\%)$	$\delta\bar{\rho}_{\nu_\mu}(\%)$	
Instantaneous decoupling	1.40102	0	0	0	3.000
Inst. dec. (with QED corrections)	1.39975	0	0	0	3.011
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NH (damping terms)	1.39778	0.673	0.529	0.533	3.045
Inverted hierarchy (IH)	1.39779	0.697	0.512	0.520	3.045
NSI ee (NH)	1.39812	0.592	0.460	0.467	3.040
NSI $\tau\tau$ (NH)	1.39708	0.862	0.784	0.812	3.059

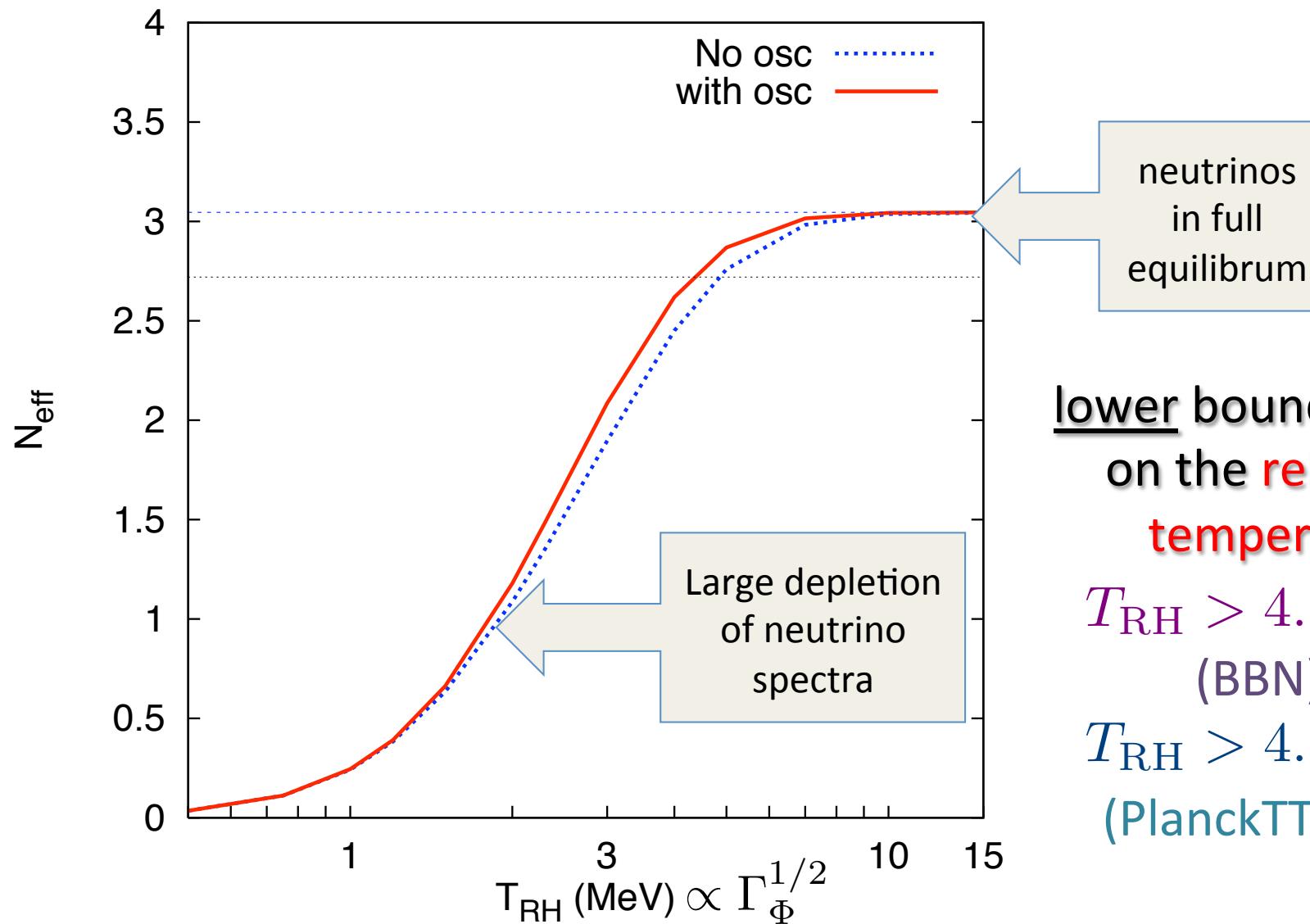
$N_{\text{eff}} < 3 ?$



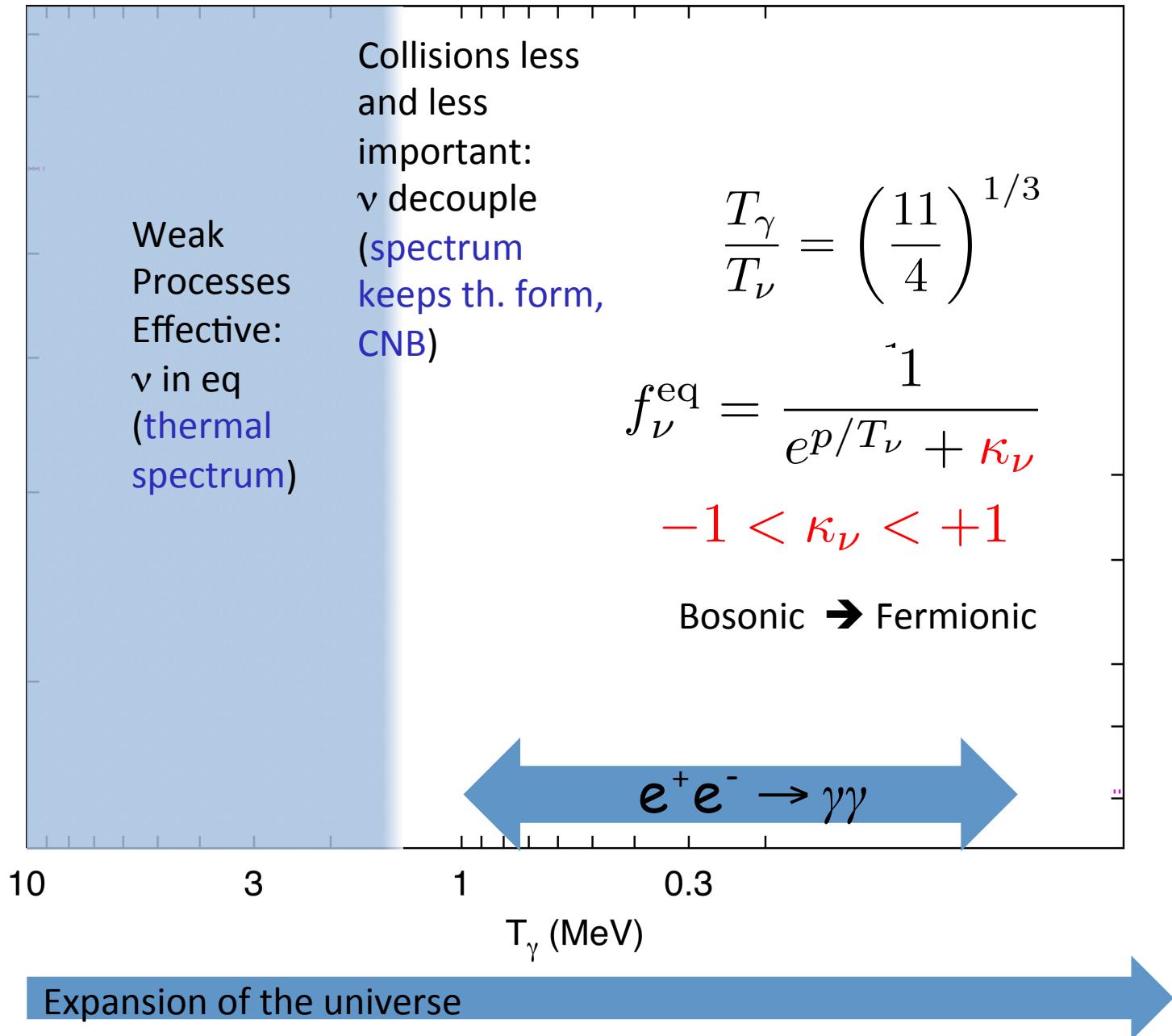
$N_{\text{eff}} < 3$: very low-reheating scenarios



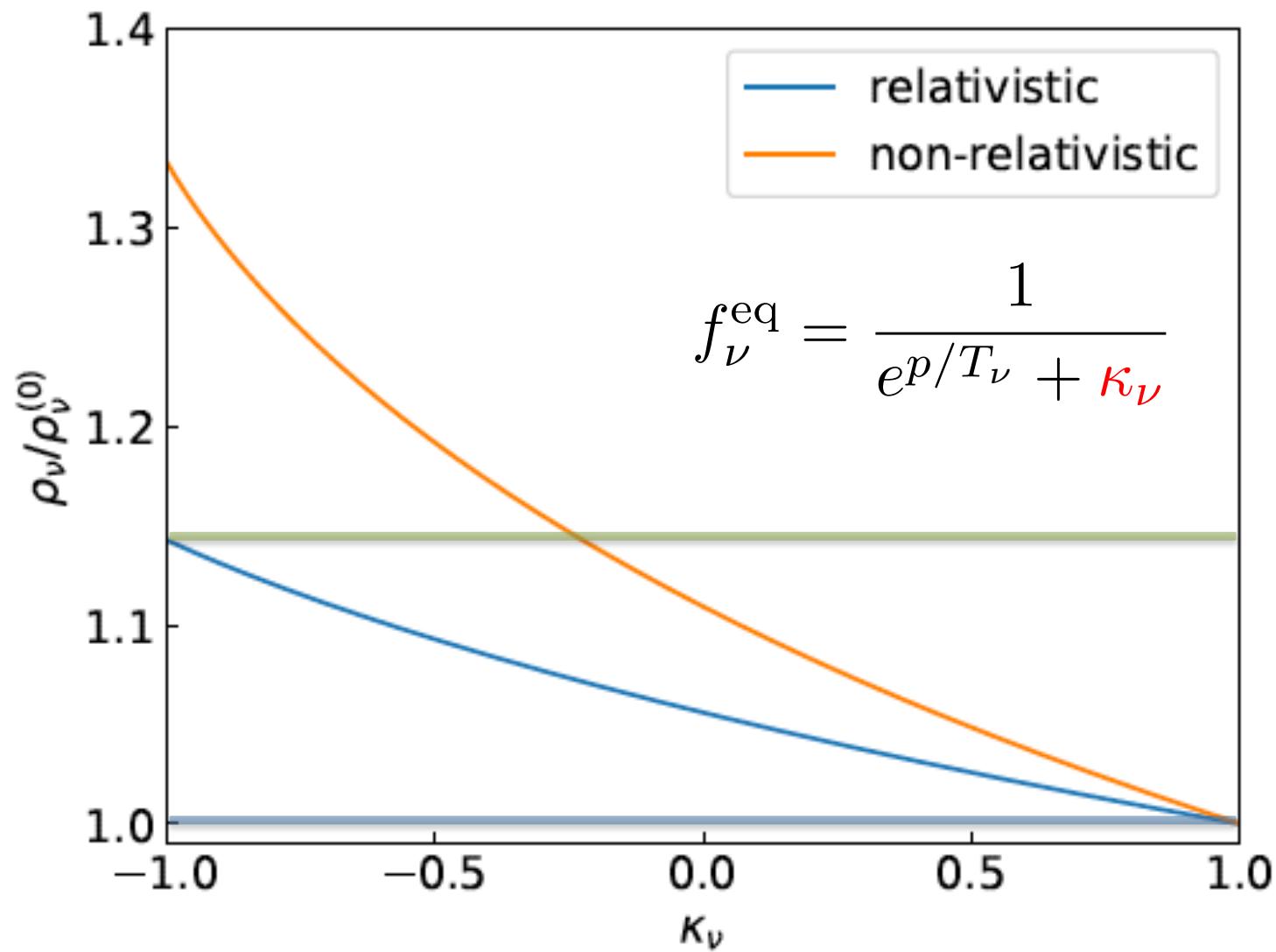
$N_{\text{eff}} < 3$: very low-reheating scenarios



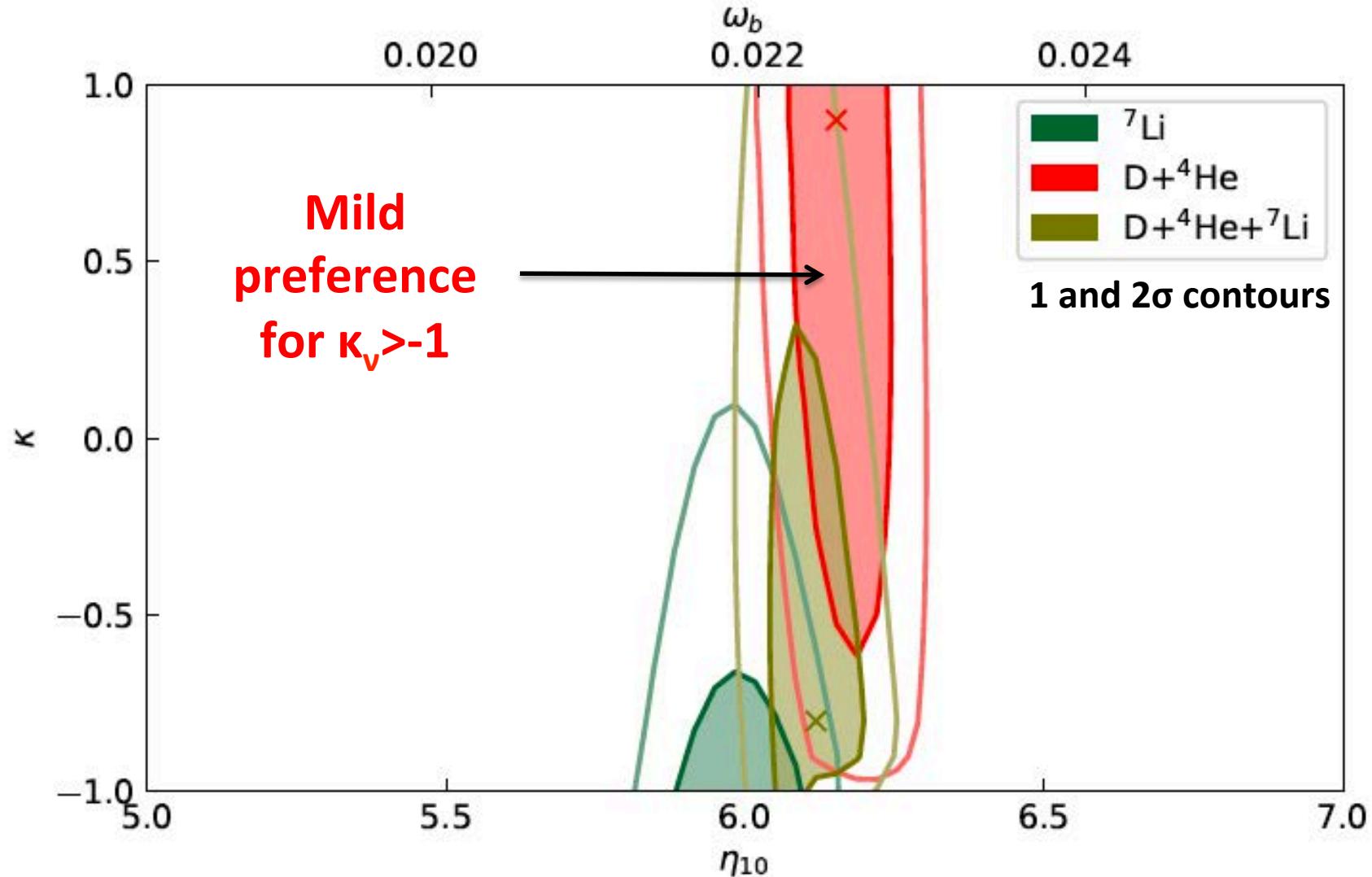
Neutrinos with *wrong* statistics...



Neutrinos with *wrong* statistics...

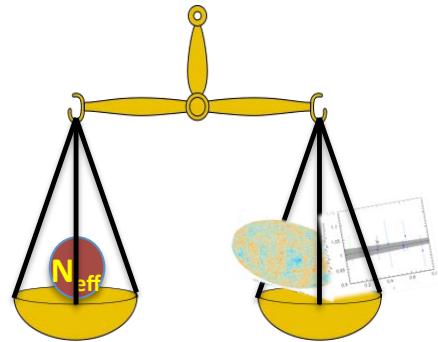


Bounds from BBN + prior on ω_b from CMB

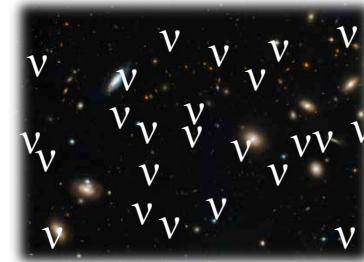


Observation of **2-neutrino double beta decay** will provide better bounds on K_V

Pablo Fernández de Salas et al, JCAP 03 (2018) 050



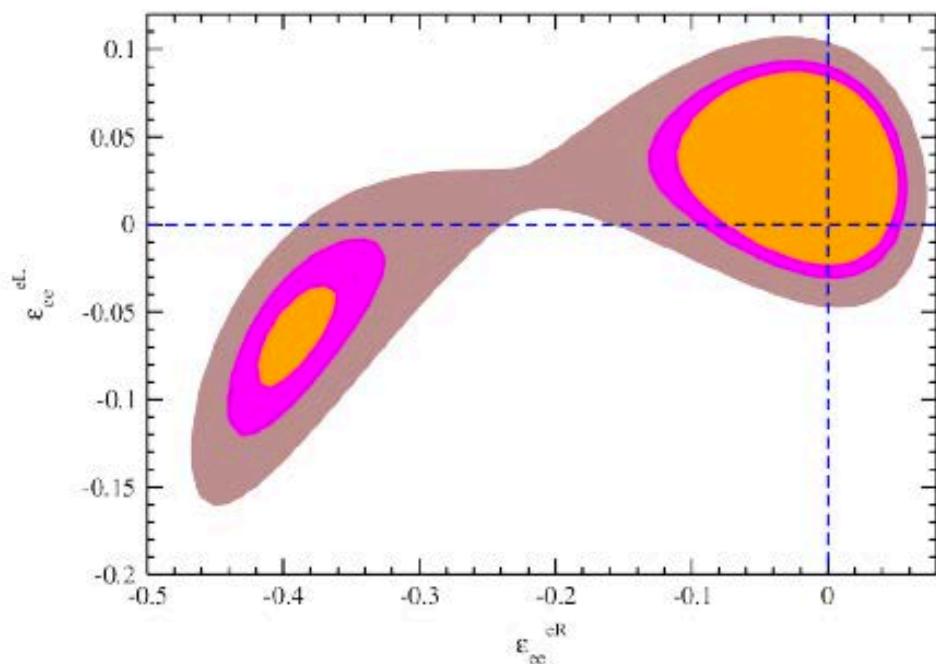
Conclusions



- ✓ Calculation of **N_{eff}** in the standard case (with neutrino oscillations) robust with respect to the inclusion of full off-diagonal collision integrals. **$N_{\text{eff}}=3.045$** , in full agreement with Planck data
- ✓ Presence of **non-standard neutrino-electron interactions** (allowed by laboratory data) could slightly modify **N_{eff} : 3.040-3.059**
- ✓ **N_{eff} below the standard value** difficult to achieve, except *particular cases*. Calculations in a **very low reheating scenario** lead to lower bounds on the reheating temperature: **$T_{\text{RH}} > 4.1\text{-}4.7 \text{ MeV}$** (95% CL)
- ✓ **N_{eff} enhanced** (up to 3.43) if neutrinos **do not follow FD statistics**. Cosmological bounds: only **mild preference for non-bosonic neutrinos**

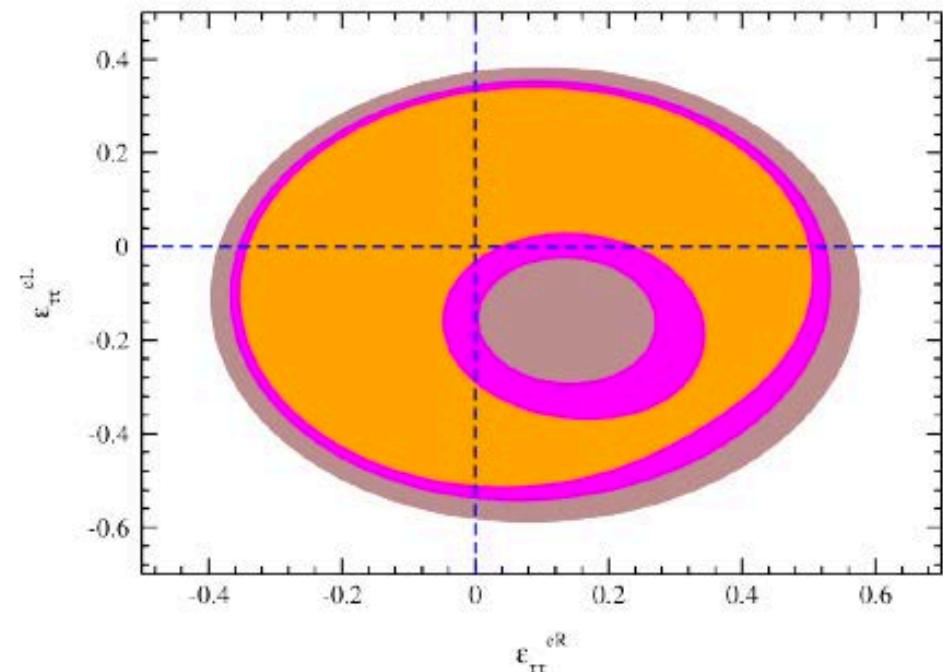
Non-Standard neutrino-electron Interactions

$$\mathcal{L}_{\text{NSI}}^{\alpha\beta} = -2\sqrt{2}G_F \sum_P \epsilon_{\alpha\beta}^P (\bar{\nu}_\alpha \gamma^\mu L \nu_\beta) (\bar{e} \gamma_\mu P e)$$



$$\begin{cases} \epsilon_{ee}^R = -0.42 \\ \epsilon_{ee}^L = -0.09 \end{cases}$$

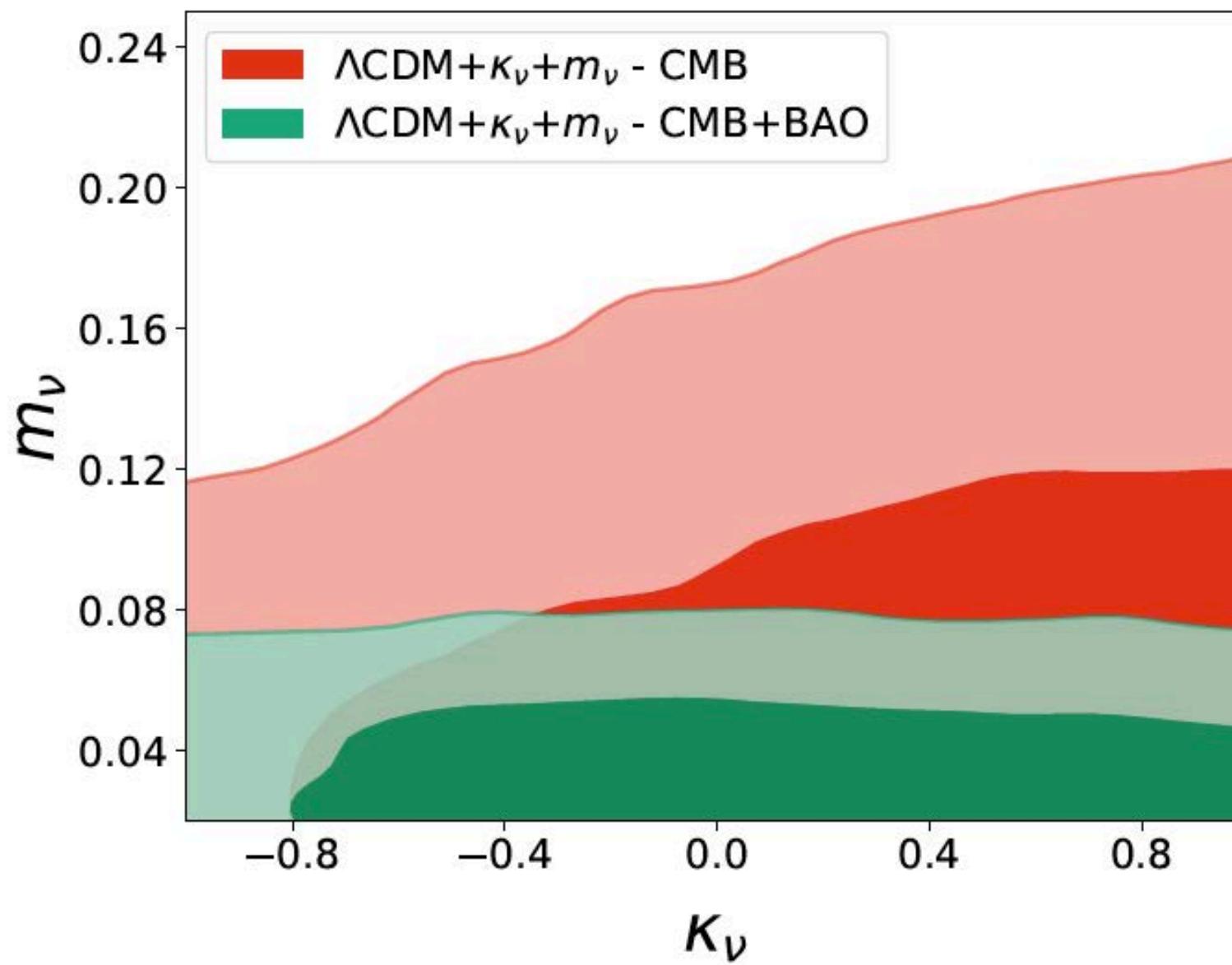
$$\begin{cases} \epsilon_{\tau\tau}^R = 0.37 \\ \epsilon_{\tau\tau}^L = -0.37 \end{cases}$$



$$3.040 \leq N_{\text{eff}} \leq 3.059$$

D.V. Forero & M.M. Guzzo (2011)

Correlations between κ_ν and m_ν



Pablo Fernández de Salas et al, JCAP 03 (2018) 050

Equations for the neutrino density matrix

$$\varrho_p(t) = \begin{pmatrix} \varrho_{ee} & \varrho_{e\mu} & \varrho_{e\tau} \\ \varrho_{\mu e} & \varrho_{\mu\mu} & \varrho_{\mu\tau} \\ \varrho_{\tau e} & \varrho_{\tau\mu} & \varrho_{\tau\tau} \end{pmatrix} = \begin{pmatrix} f_{\nu_e} & a_1 + ia_2 & b_1 + ib_2 \\ a_1 - ia_2 & f_{\nu_\mu} & c_1 + ic_2 \\ b_1 - ib_2 & c_1 - ic_2 & f_{\nu_\tau} \end{pmatrix}$$

diagonal terms
(occupation numbers)

off-diagonal
terms

Boltzmann evolution equations (matrix form)

$$(\partial_t - H p \partial_p) \varrho_p(t) = -i \left[\underbrace{\left(\frac{1}{2p} \mathbb{M}_F - \frac{8\sqrt{2}G_F p}{3m_W^2} \mathbb{E} \right), \varrho_p(t) \right]}_{\text{vacuum osc. term}} + \underbrace{\mathcal{I}[\varrho_p(t)]}_{\text{matter potential term}} \right]$$

**Full collision integrals (diag) +
damping approx ($-D_{\alpha\beta}\varrho_{\alpha\beta}$, off-diag)**

Mangano et al 2005, NPB 729 (2005) 221

Full collision integrals (all)

Pablo Fernández de Salas & SP, JCAP 07 (2016) 051

collision integrals
 $(\propto G_F^2)$

