

Cosmological radiation density with non-standard neutrino physics

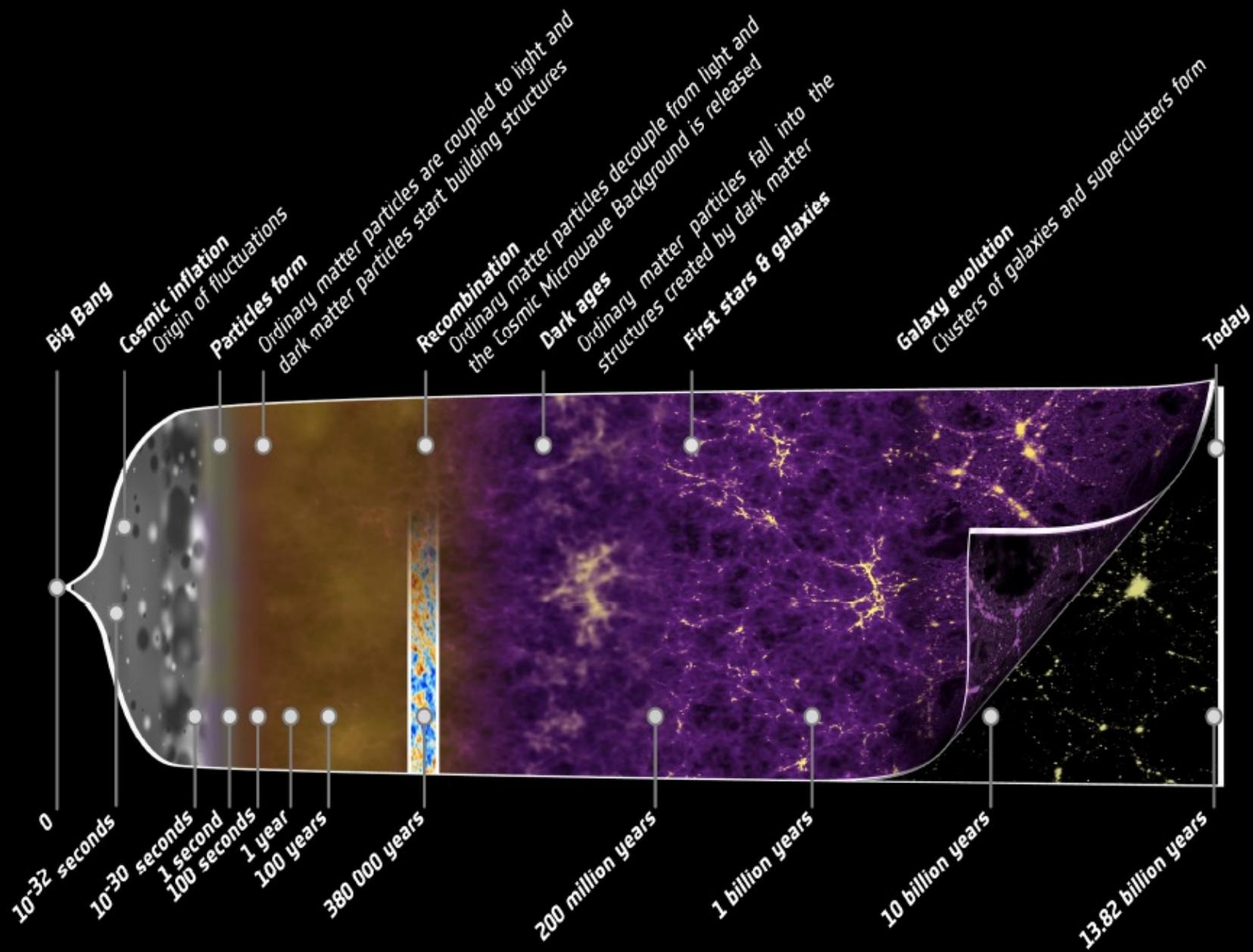


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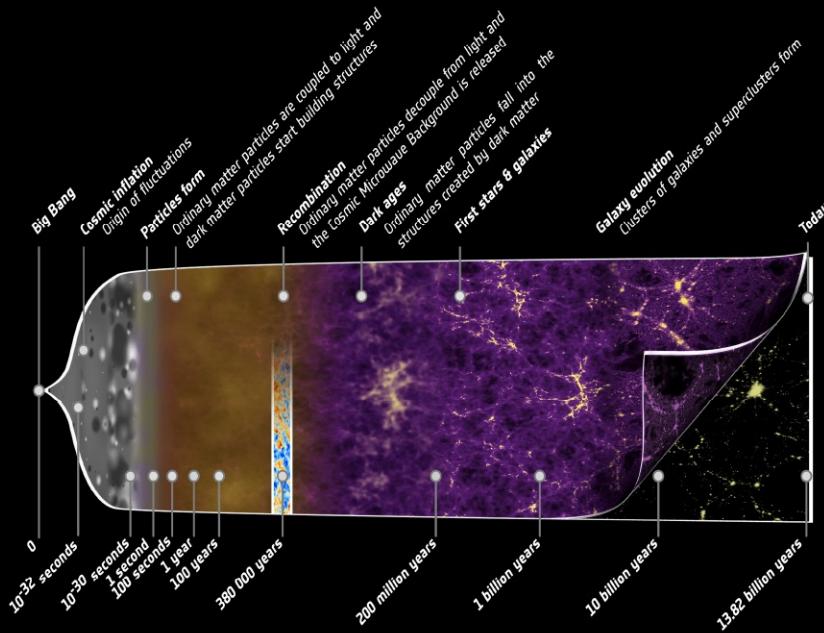


ICHEP 2022
BOLOGNA

Evolution of the universe



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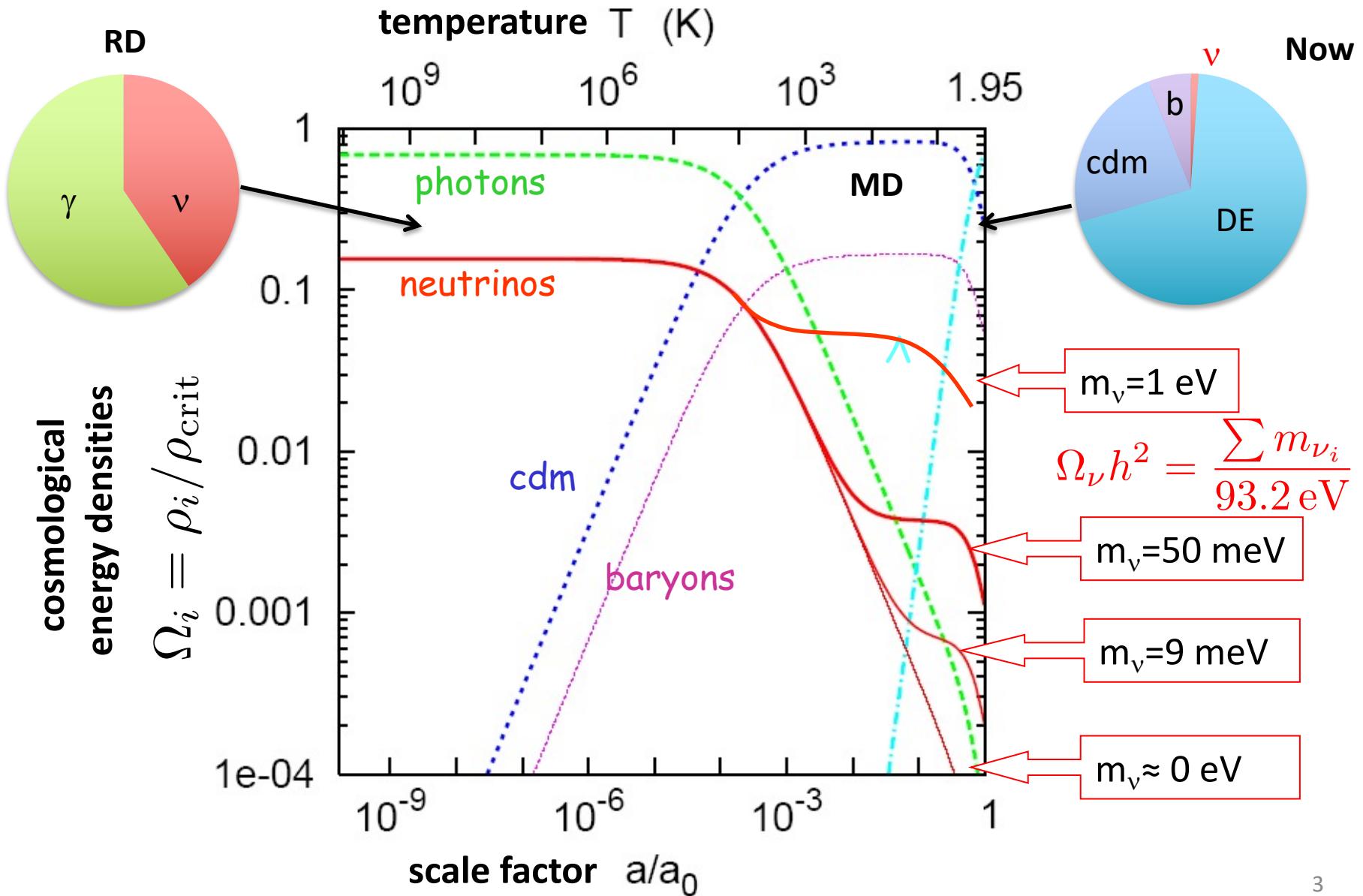
energy density: $\rho(a) = a^{-3(1+w)}$

$$\rho_R \sim a^{-4} \quad , \quad w = 1/3 \quad (\text{Radiation})$$

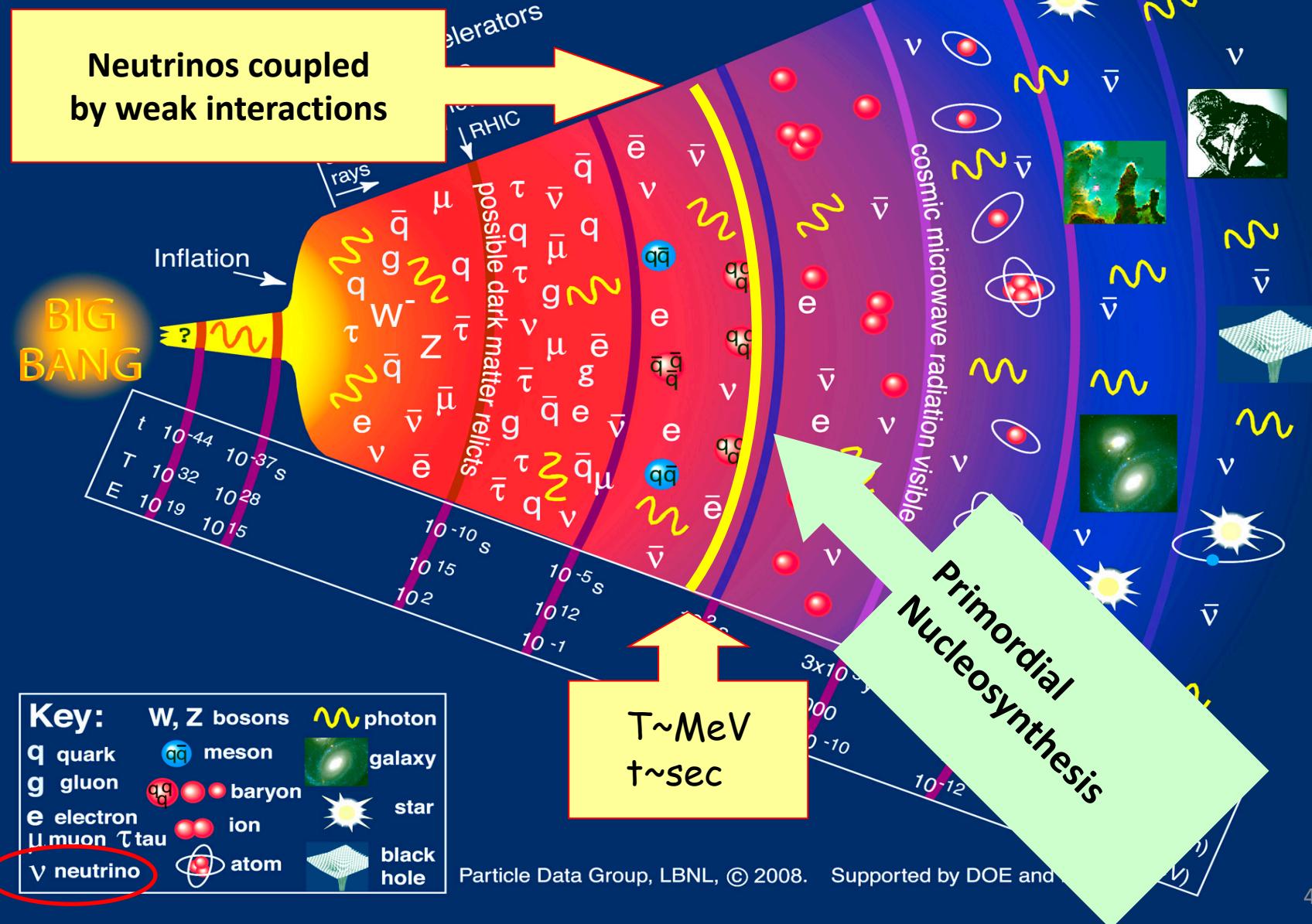
$$\rho_M \sim a^{-3} \quad , \quad w = 0 \quad (\text{Matter})$$

$$\rho_\Lambda \sim \text{const.} \quad , \quad w = -1 \quad (\text{Cosmological constant})$$

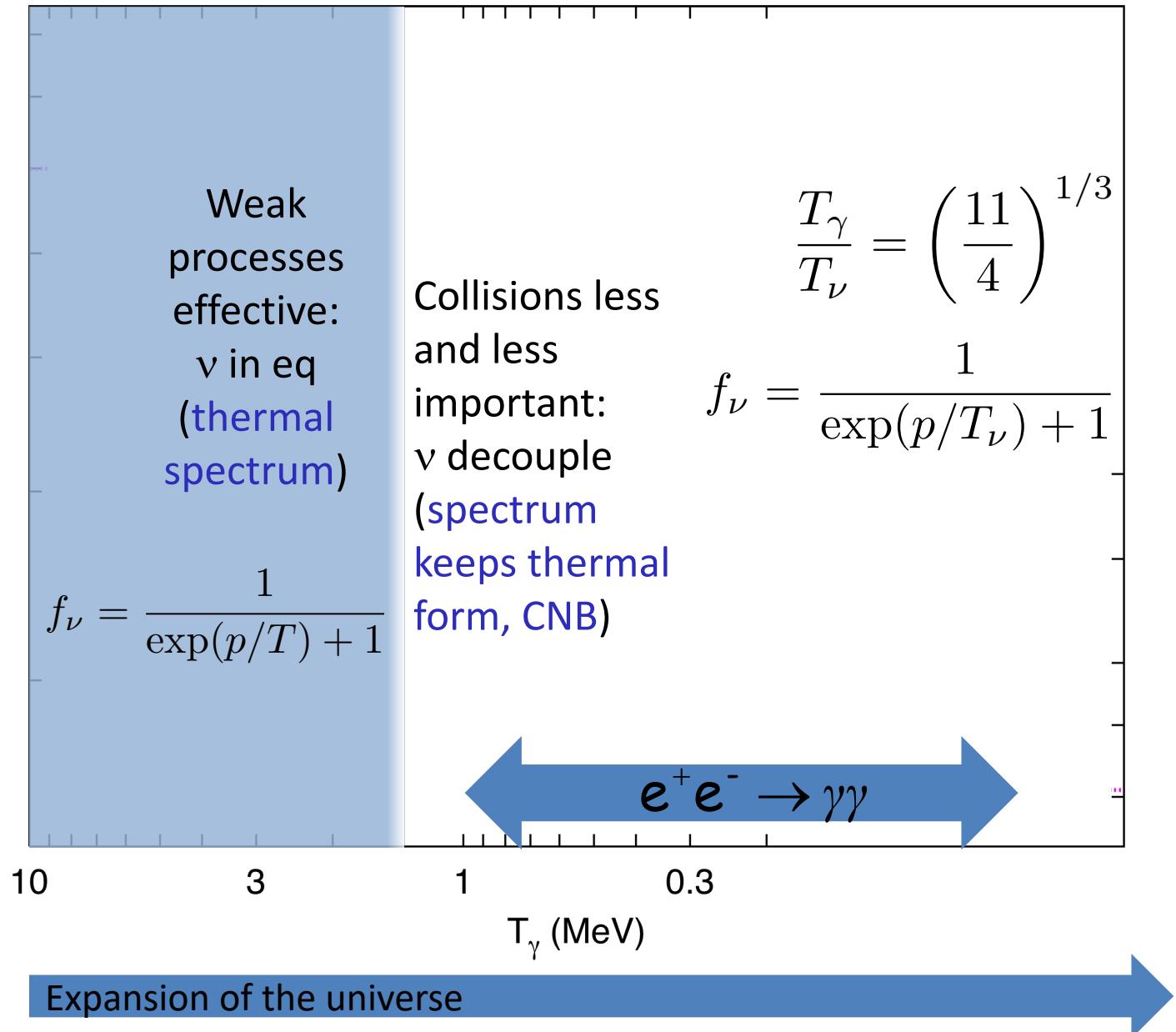
Evolution of the background densities: 1 MeV → now



History of the Universe



Neutrino decoupling and e^\pm annihilation



Relativistic particles in the universe

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

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

Valid for standard neutrinos in the
instantaneous decoupling approximation

Relativistic particles in the universe

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

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

effective number of relativistic neutrino species
(effective number of neutrinos)

N_{eff} is a way to measure the ratio

$$\frac{\rho_\nu + \rho_x}{\rho_\gamma}$$

1960s-1970s : $N_{\text{eff}} = N_\nu$, **extra neutrinos** would enhance the cosmological expansion

>1980s: $N_{\text{eff}} = \text{additional relativistic particles}$

Relativistic particles in the universe

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

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

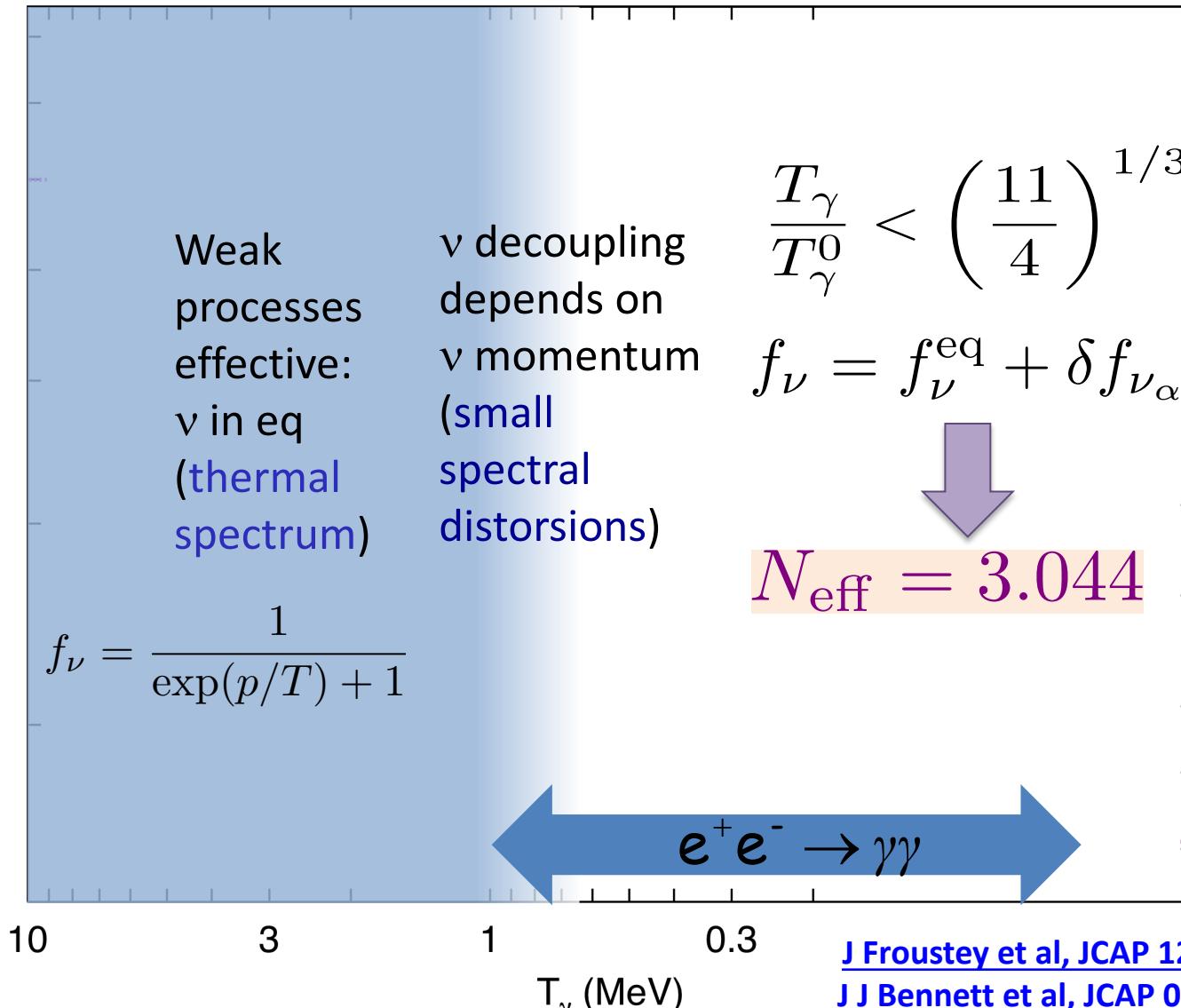
effective number of neutrinos

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

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

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

$N_{\text{eff}} > 3$: standard case



Expansion of the universe

[J Froustey et al, JCAP 12 \(2020\) 015](#)

[J J Bennett et al, JCAP 04 \(2021\) 073](#)

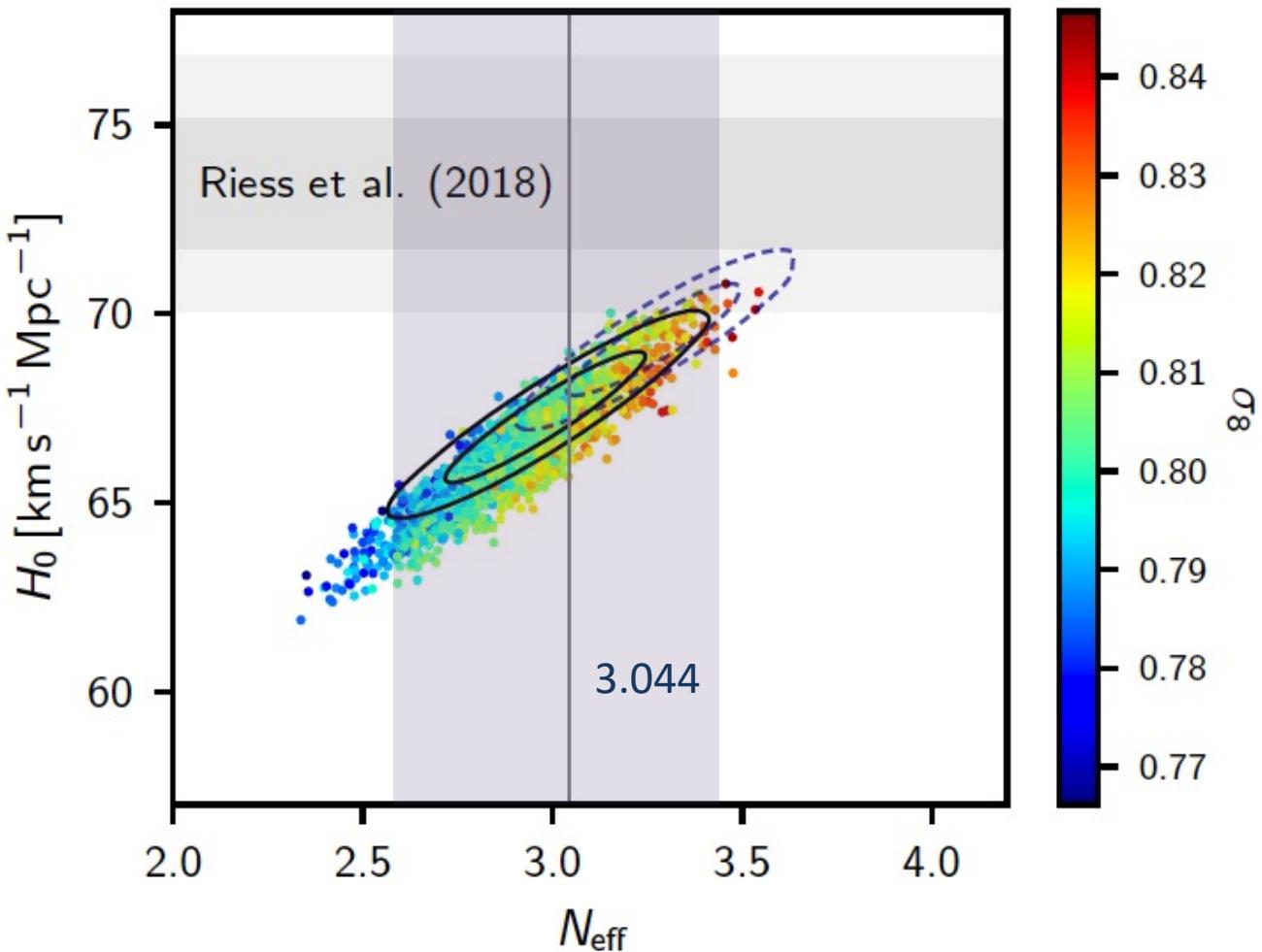
CMB anisotropies + other data

$N_{\text{eff}} \lesssim 17$ (2001) early CMB data

$N_{\text{eff}} = 4.2^{+1.2}_{-1.7}$ (2005) WMAP+...

$N_{\text{eff}} = 2.99^{+0.34}_{-0.33}$ (2018) [Planck](#)

(95%, TT,TE,EE+lowE+lensing+BAO)



N_{eff} with non-standard neutrino-electron interactions

Non-standard neutrino-electron interactions

Non-standard interactions (NSI) between neutrinos and electrons can be parametrised as follows:

$$\mathcal{L}_{\text{NSIe}} = -2\sqrt{2}G_F \sum_{\alpha,\beta} \varepsilon_{\alpha\beta}^X (\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta) (\bar{e} \gamma_\mu P_X e)$$

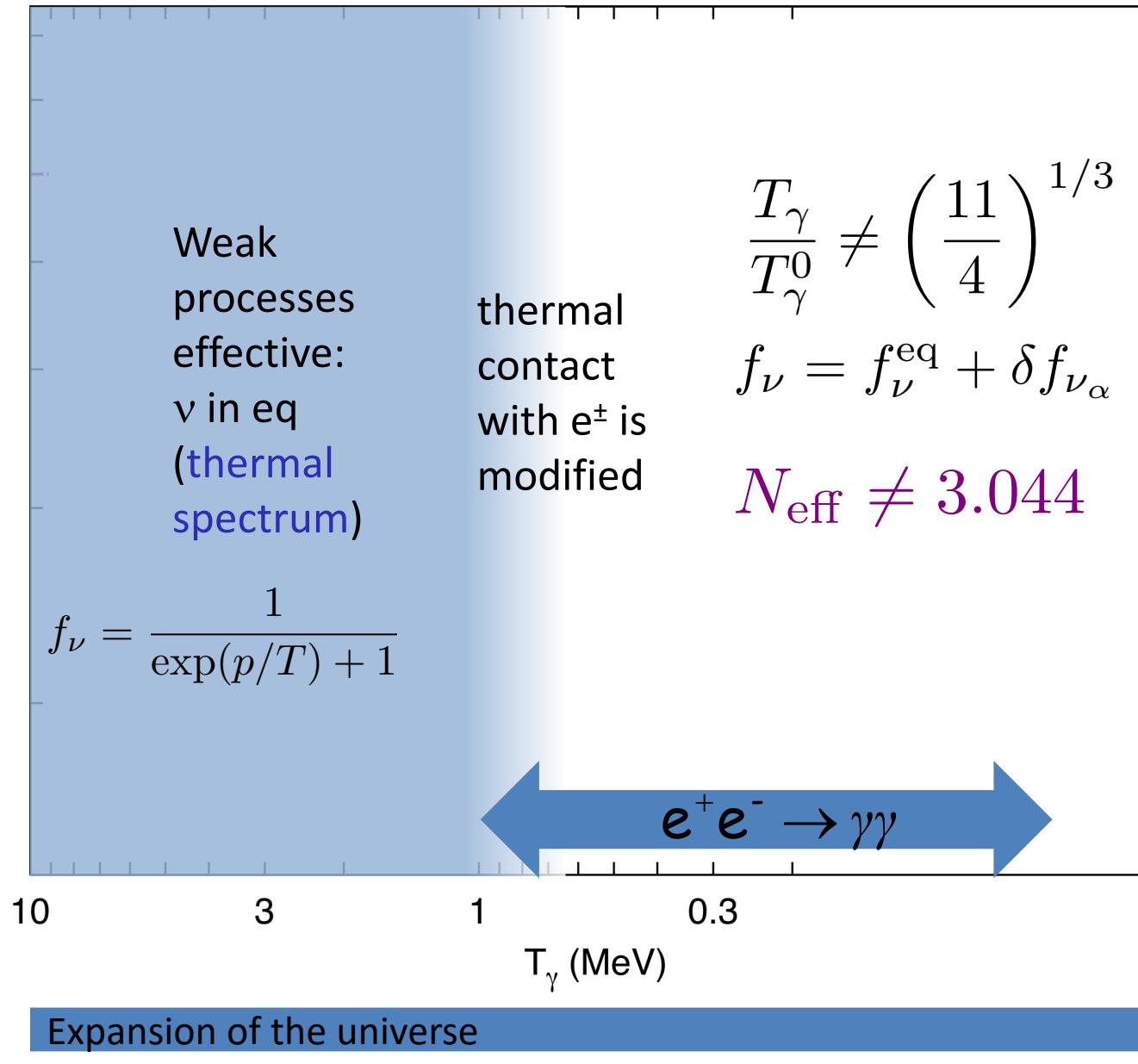
with $X \in \{L, R\}$
 $\alpha, \beta \in \{e, \mu, \tau\}$

Dimensionless coefficients $\varepsilon_{\alpha\beta}^X$ quantify the strength of the interactions with respect to the SM

$\varepsilon_{\alpha\alpha}^X$ **Non-universal NSI**

$\varepsilon_{\alpha\beta}^X$ (with $\alpha \neq \beta$) **Flavour-changing ($\alpha \neq \beta$) NSI**

N_{eff} with non-standard neutrino-electron interactions



Equations for the neutrino density matrix

**diagonal terms
(occupation numbers)**

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

off-diagonal terms

Boltzmann evolution equations (matrix form)

[G Sigl & GG Raffelt NPB 406 \(1993\) 423](#)

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

+ continuity
equation
vacuum osc.
term
matter potential
term
collision integrals
 (αG_F^2)

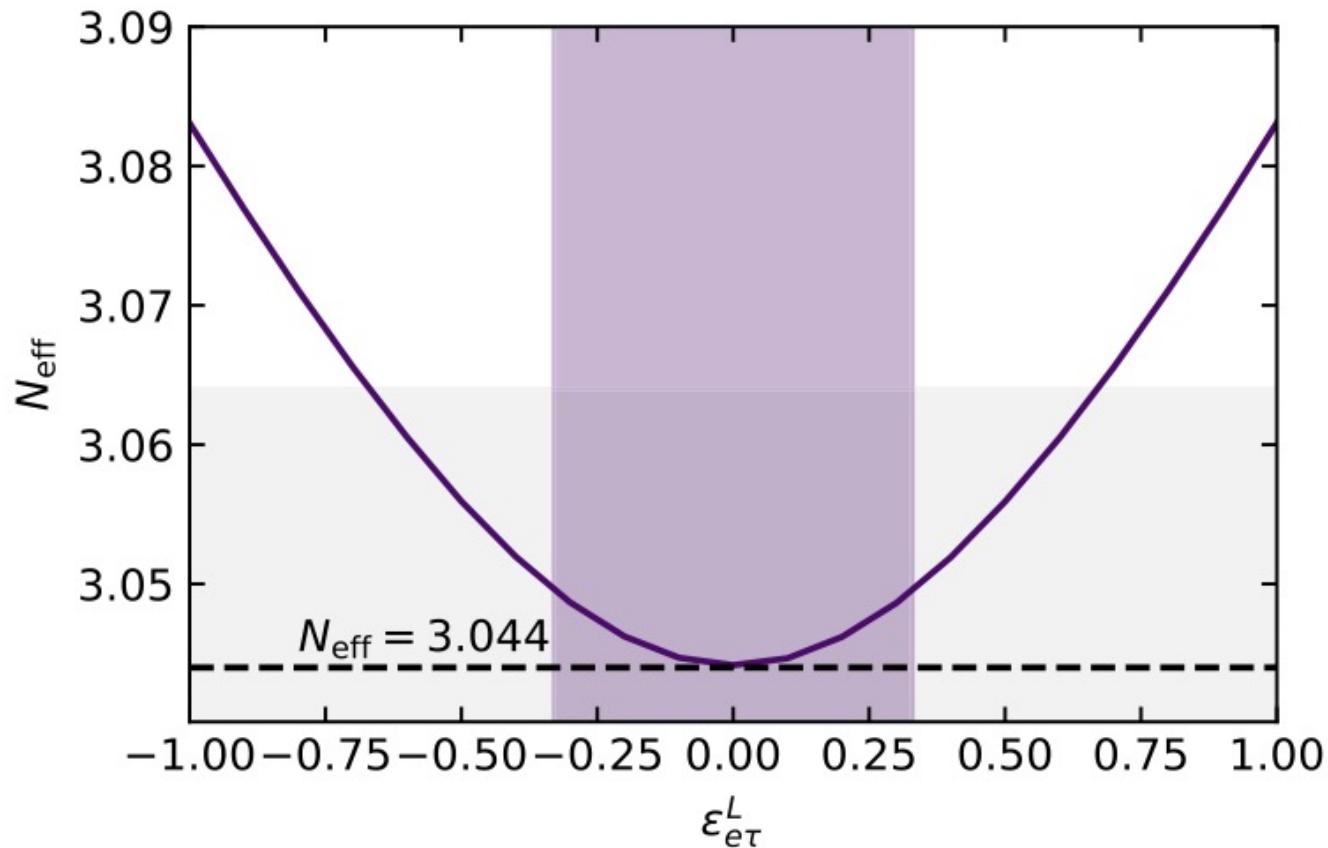
$$\dot{\rho} = -3H(\rho + P)$$

Code: **FORTran-Evolved Primordial Neutrino Oscillations (FortEPiaNO)**

[S Gariazzo, PF de Salas & SP, JCAP 07 \(2019\) 014](#)

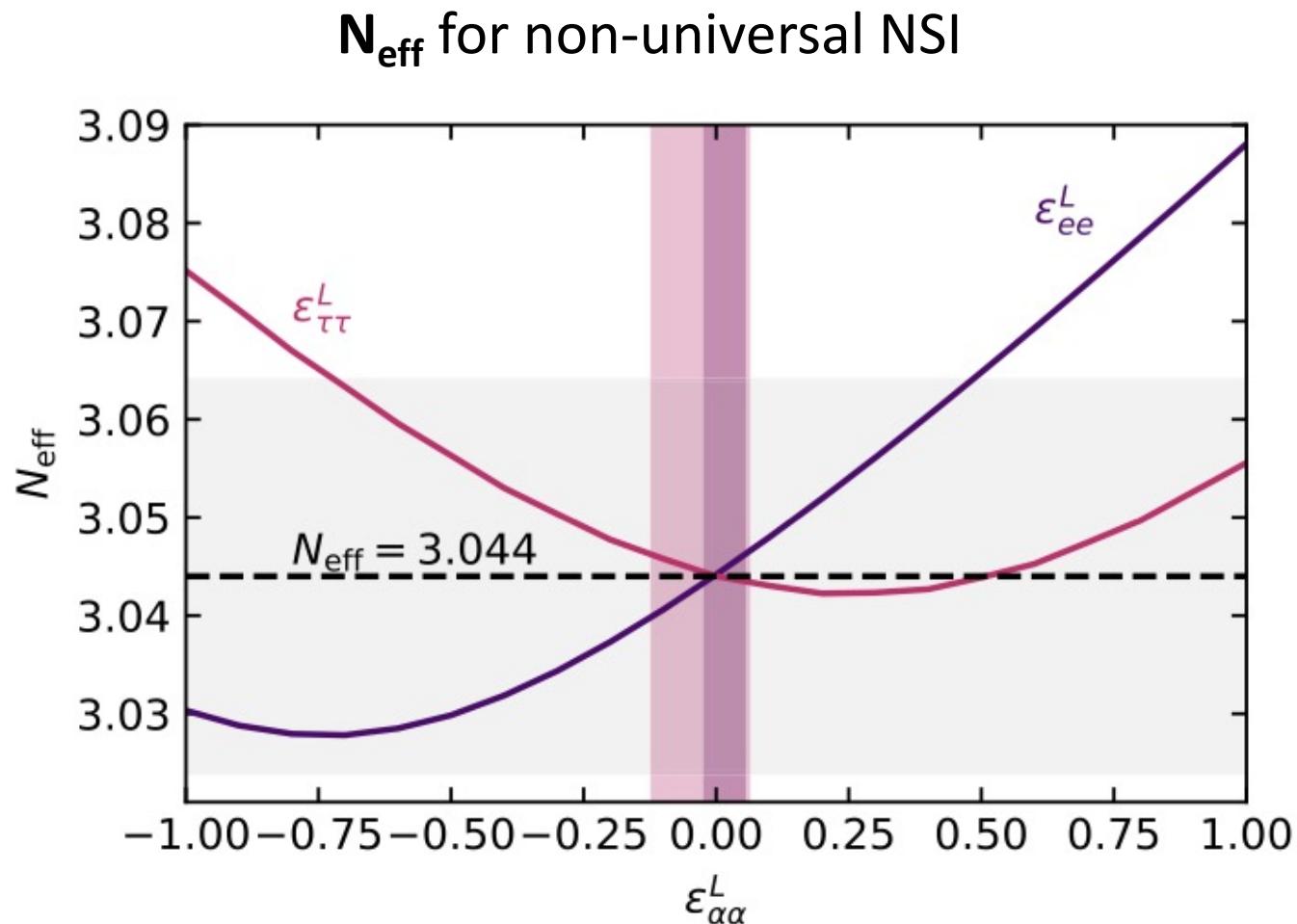
N_{eff} with only one NSI parameter

N_{eff} for flavour-changing NSI



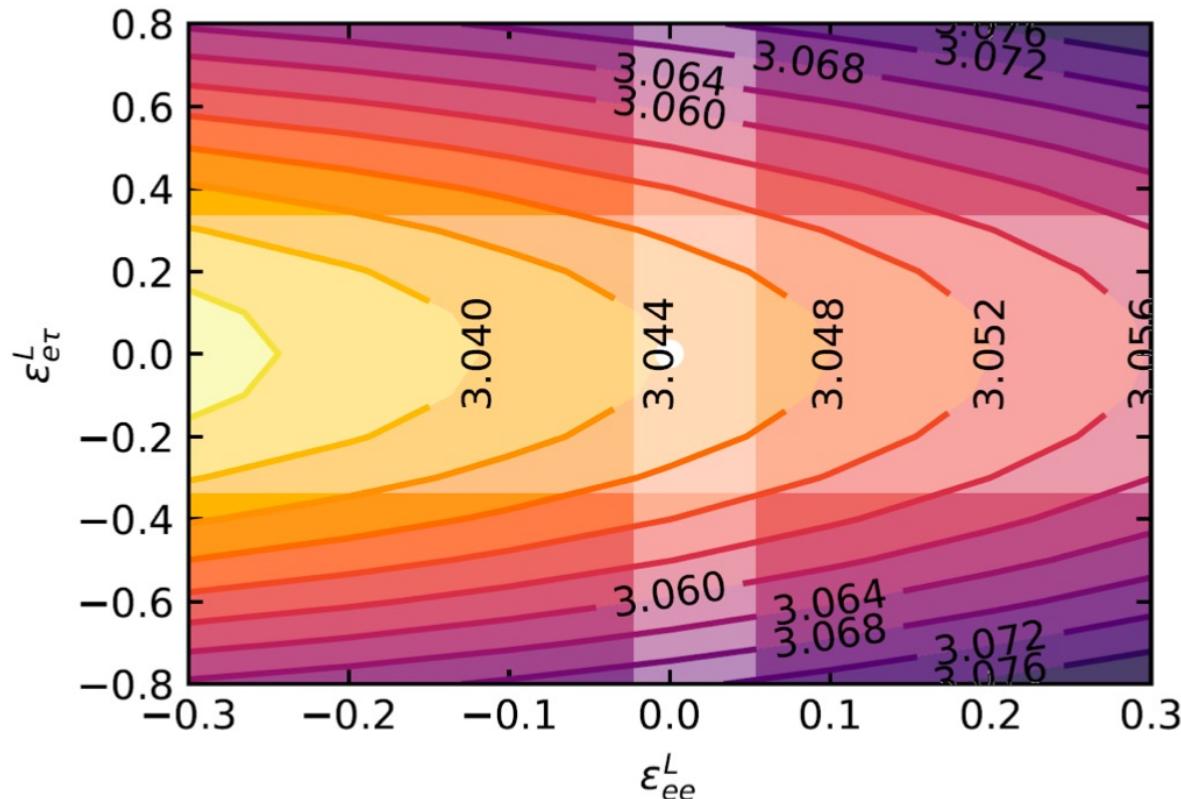
[PF de Salas et al, PLB 820 \(2021\) 136508](#)

N_{eff} with only one NSI parameter



[PF de Salas et al, PLB 820 \(2021\) 136508](#)

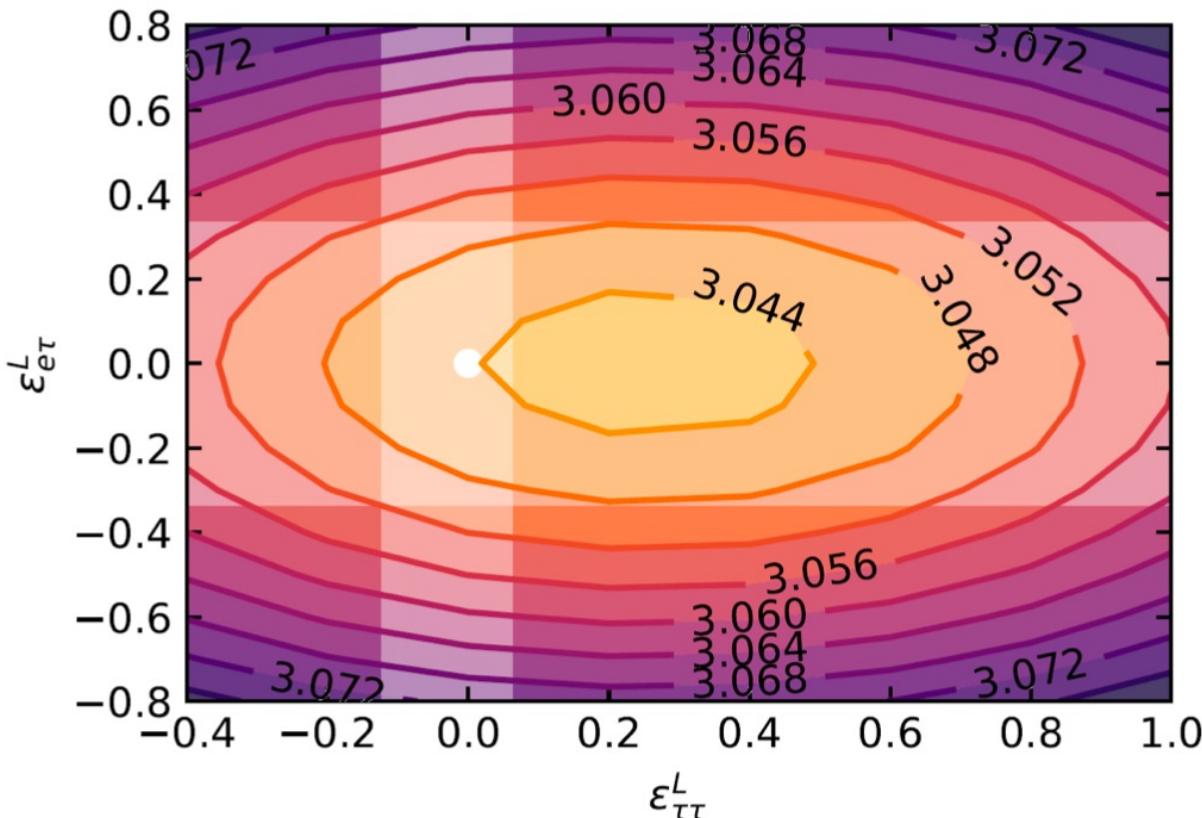
N_{eff} varying 2 NSI parameters



Future sensitivities
on N_{eff} of the order of
0.02 - 0.05

White shaded bands
correspond to terrestrial
bounds on NSI.
(One-parameter only)

N_{eff} varying 2 NSI parameters

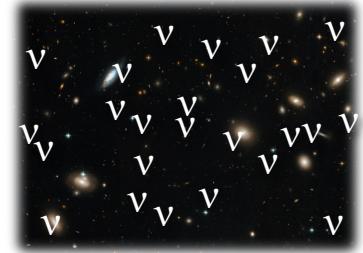


Future sensitivities
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N_{eff}

Conclusions



- ✓ N_{eff} : a parameter that quantifies the ratio of **cosmological energy densities in neutrino-like relics to photons** in the early universe
- ✓ Standard value of N_{eff} slightly different from 3. Last analyses (2020-21) with flavour oscillations and QED effects → $N_{\text{eff}} = 3.044$
- ✓ Presence of **non-standard neutrino-electron interactions** (allowed by laboratory data) could slightly modify $N_{\text{eff}} = 3.04-3.08$