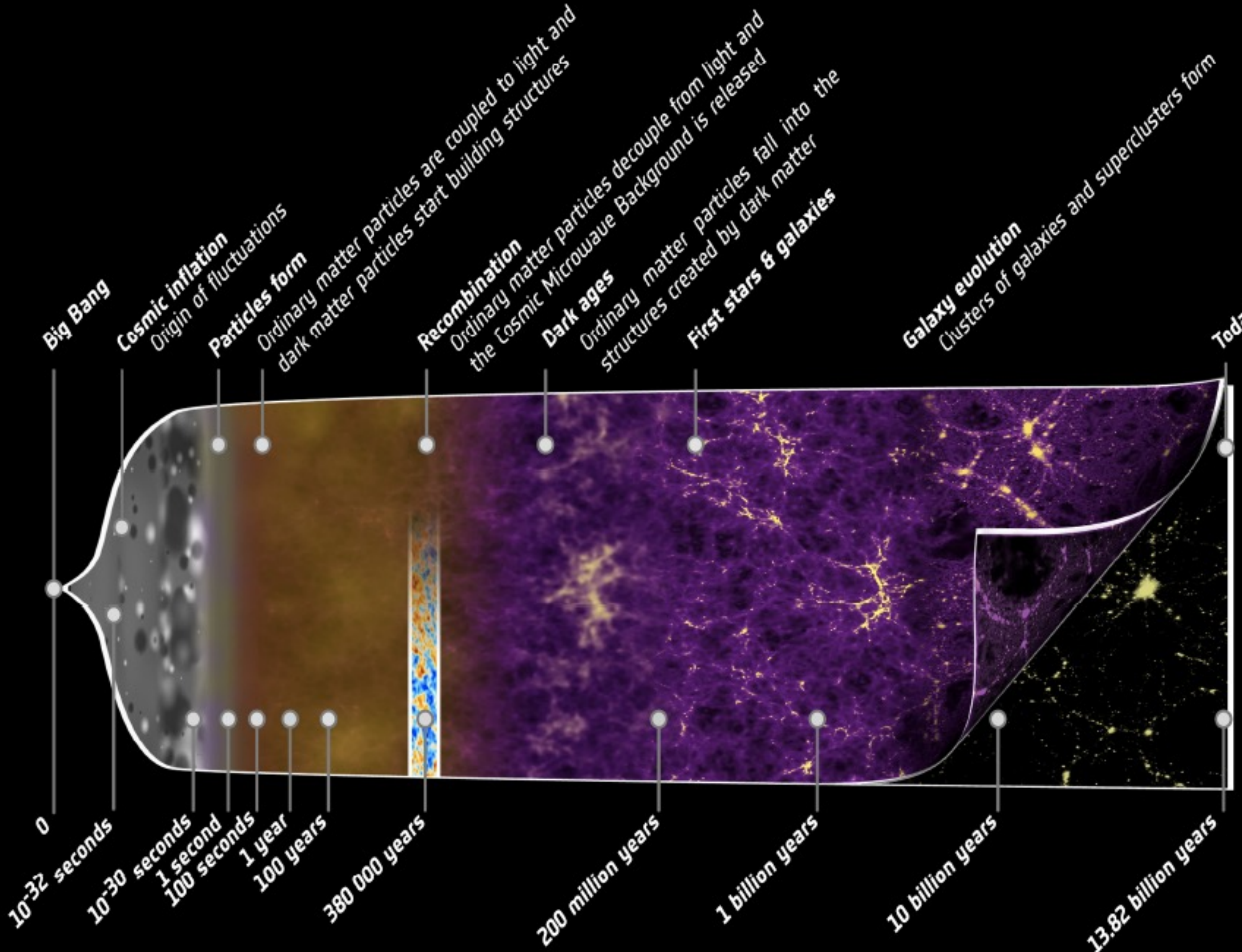
The effective number of neutrinos in non-standard scenarios

↑ neutrino

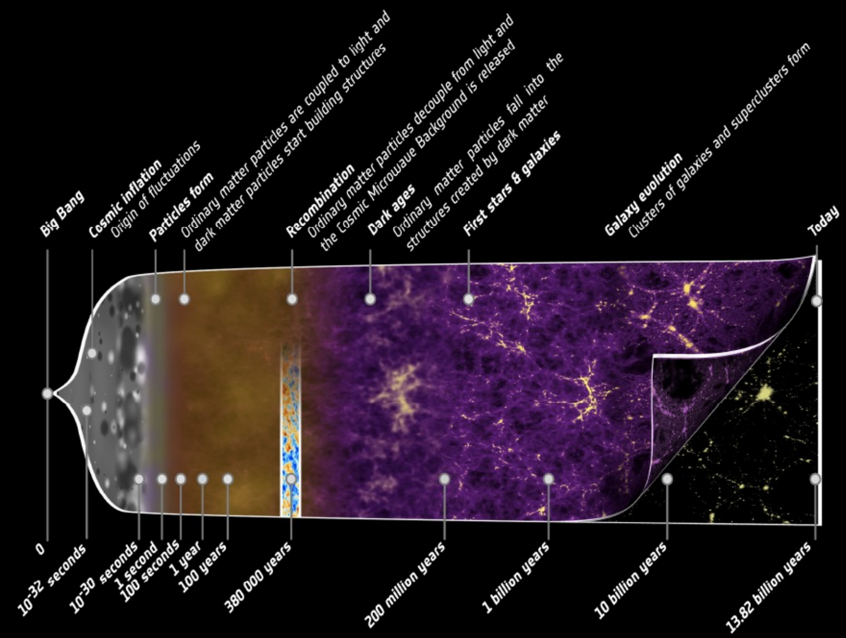
Sergio Pastor
(IFIC Valencia)

Neutrino frontiers
Focus week
GGI (2 July 2024)

Evolution of the universe



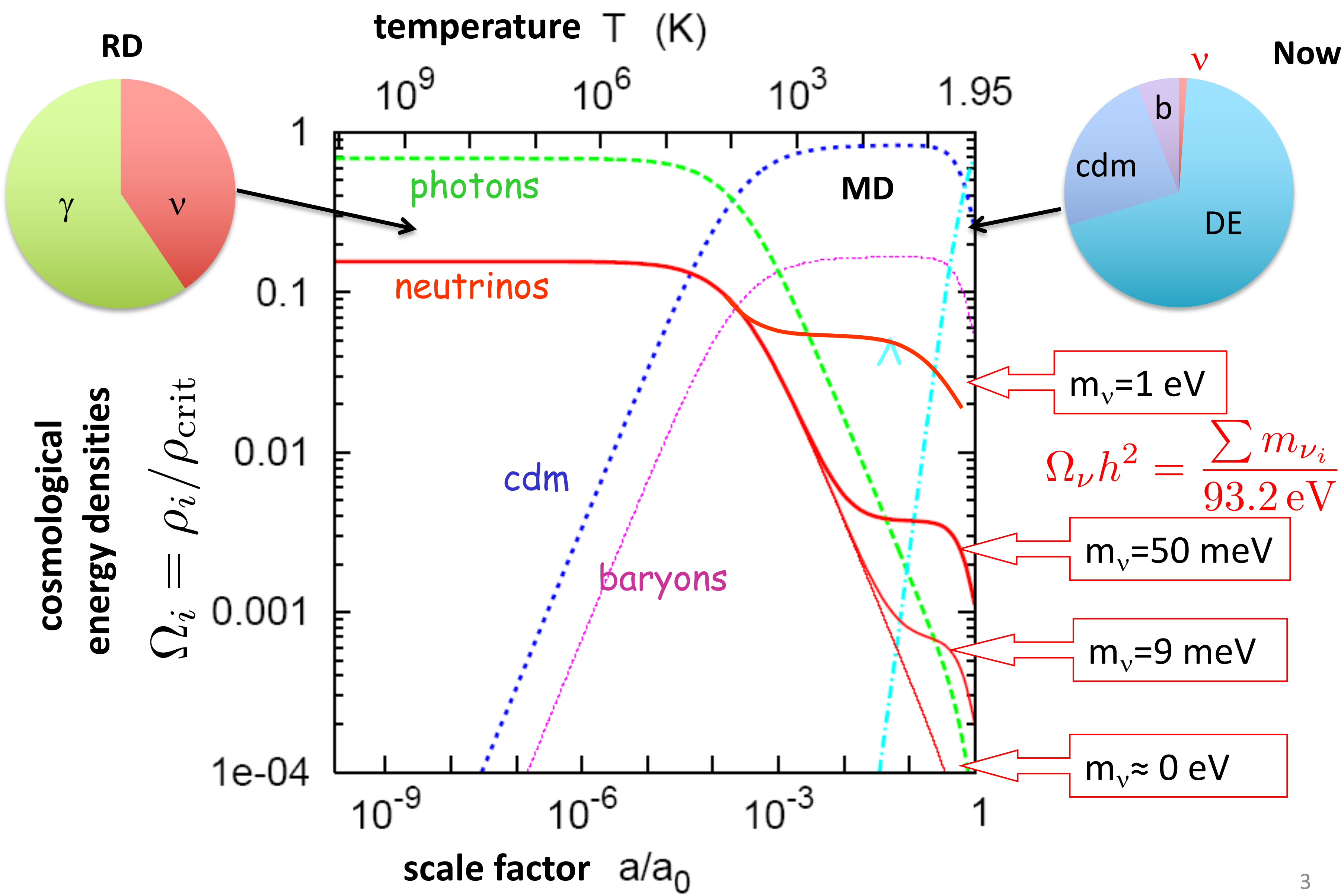
Evolution of the universe



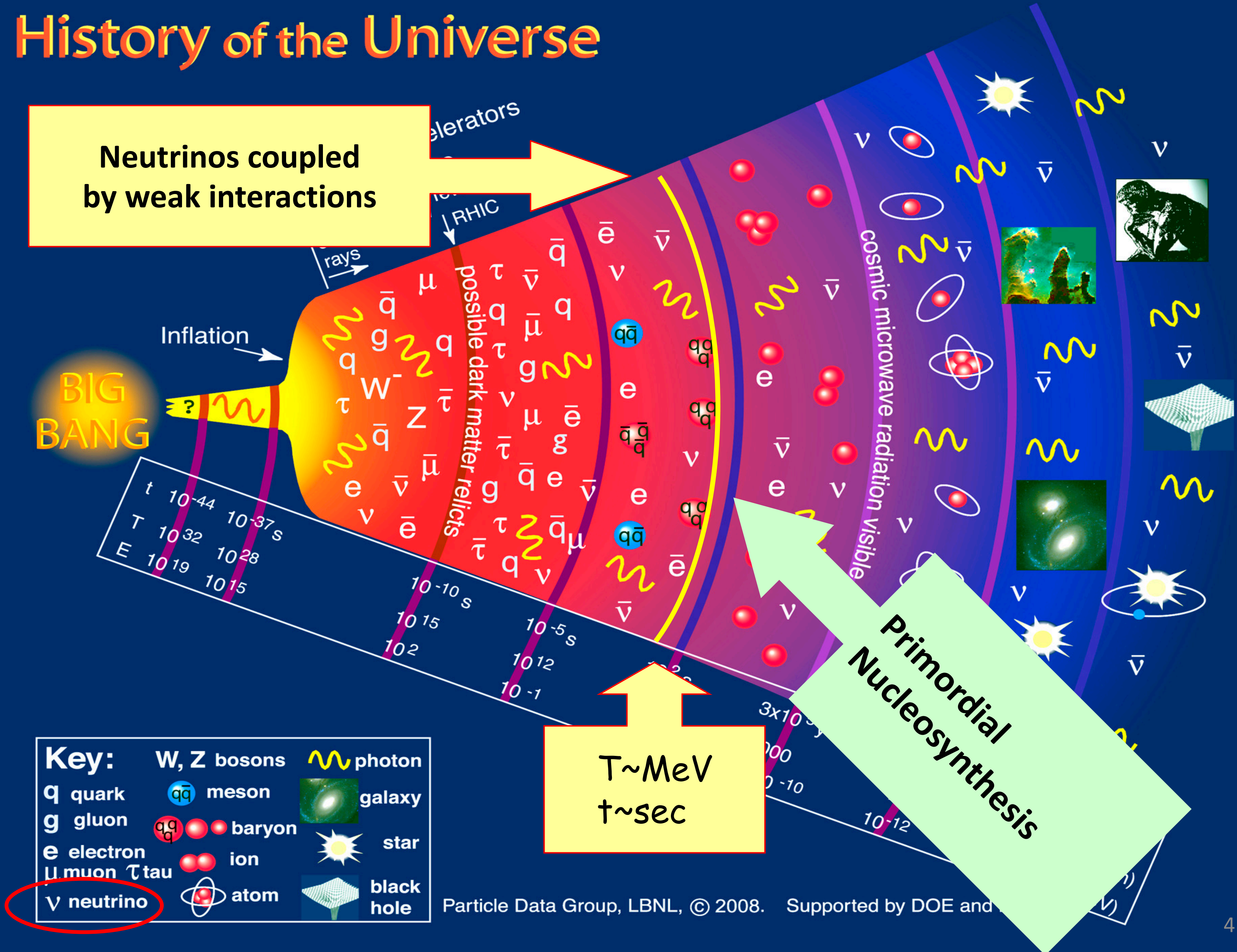
energy density: $\rho(a) = a^{-3(1+w)}$

$$\rho_R \sim a^{-4} \quad , \qquad w = 1/3 \qquad \text{(Radiation)}$$
$$\rho_M \sim a^{-3} \quad , \qquad w = 0 \qquad \text{(Matter)}$$
$$\rho_\Lambda \sim \text{const.} \quad , \qquad w = -1 \qquad \text{(Cosmological constant)}$$

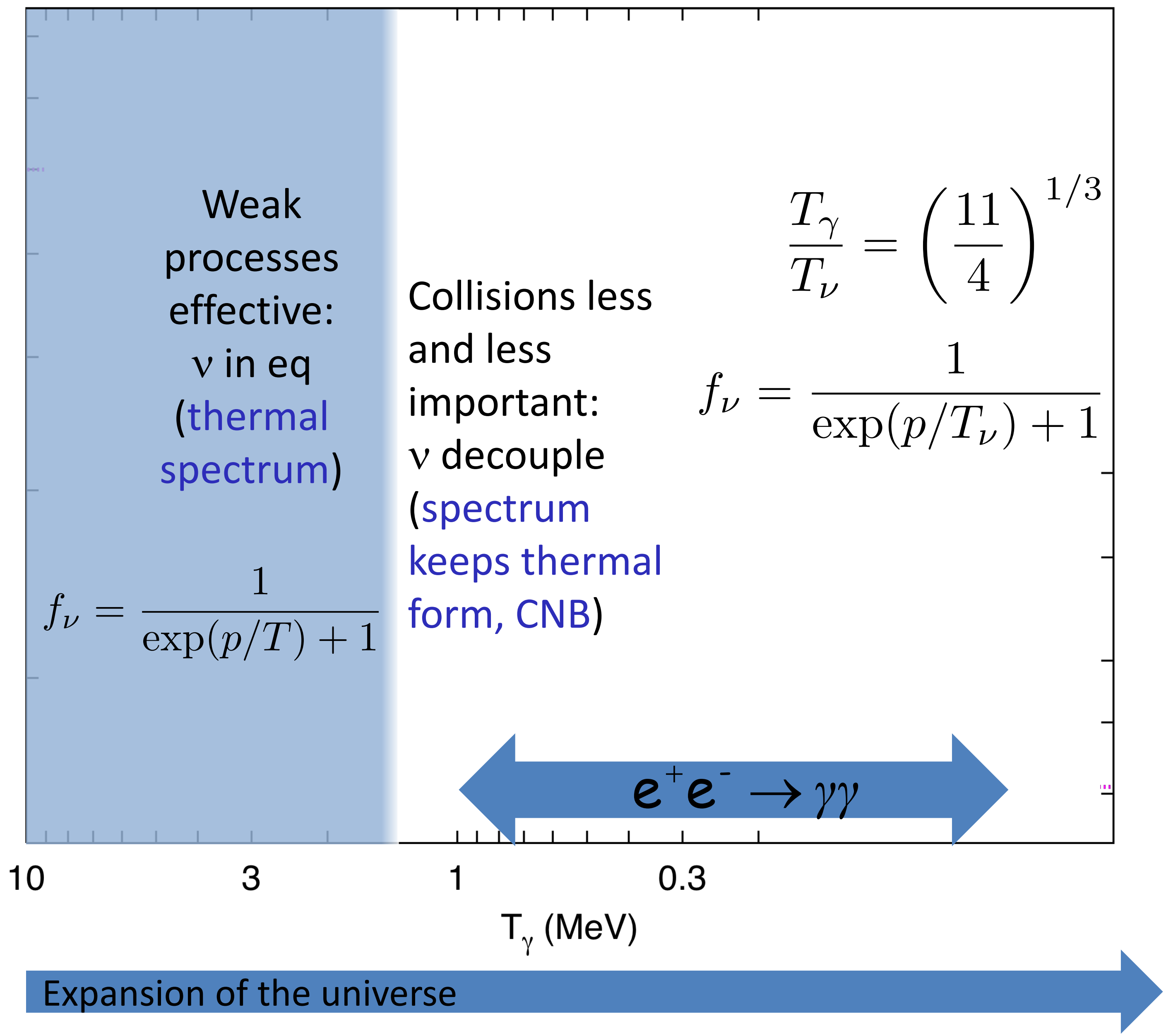
Evolution of the background densities: 1 MeV → now



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

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

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

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

effective number of relativistic neutrino species

(effective number of neutrinos)

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

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

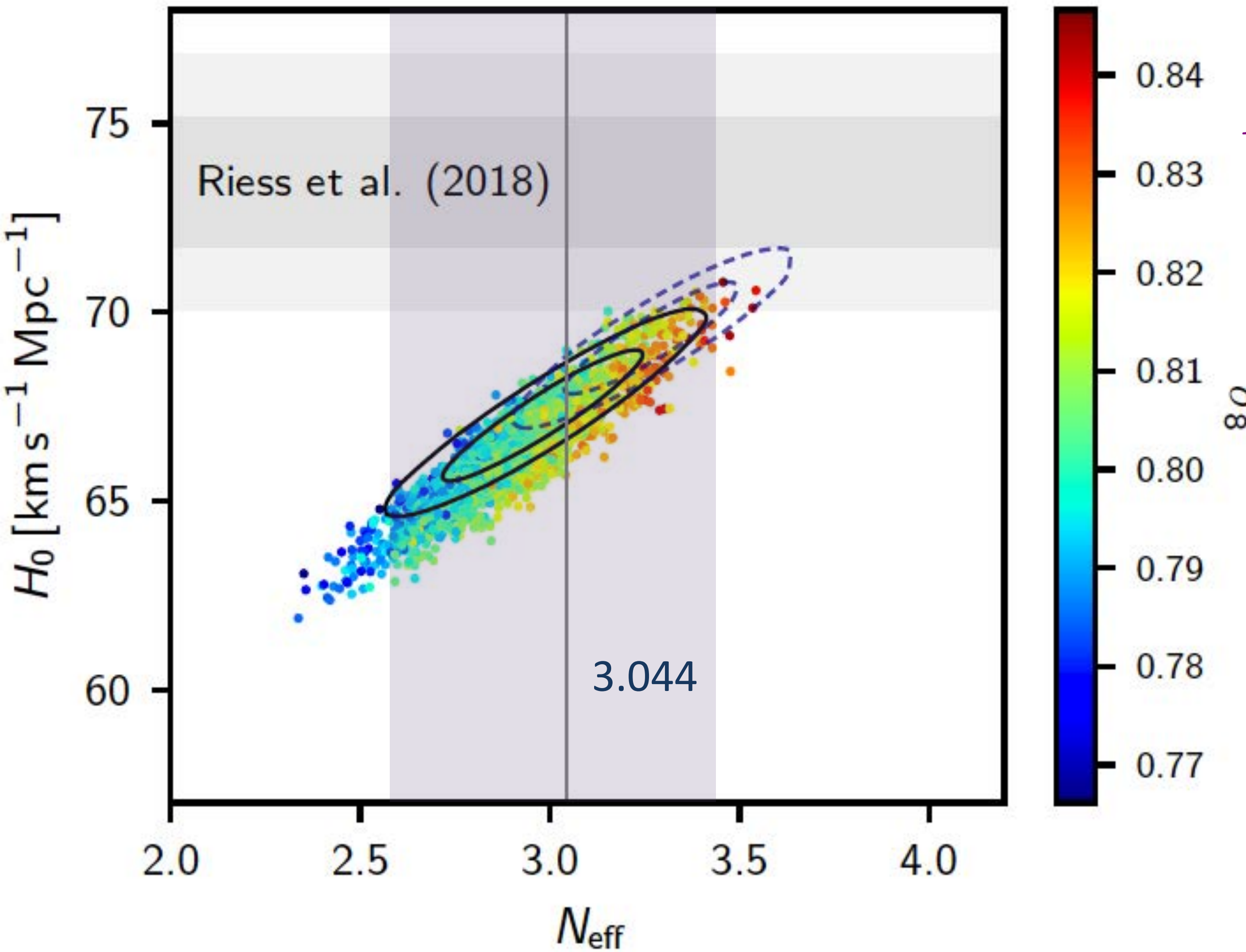
>1980s: N_{eff} = **additional relativistic particles**

CMB anisotropies + other data

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

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

$N_{\rm eff} = 2.99^{+0.34}_{-0.33}$ (2018) Planck
(95%, TT,TE,EE+lowE+lensing+BAO)



$N_{\rm eff} = 3.10 \pm 0.17$ (68%)

(2024) CMB+DESI

Relativistic particles in the universe

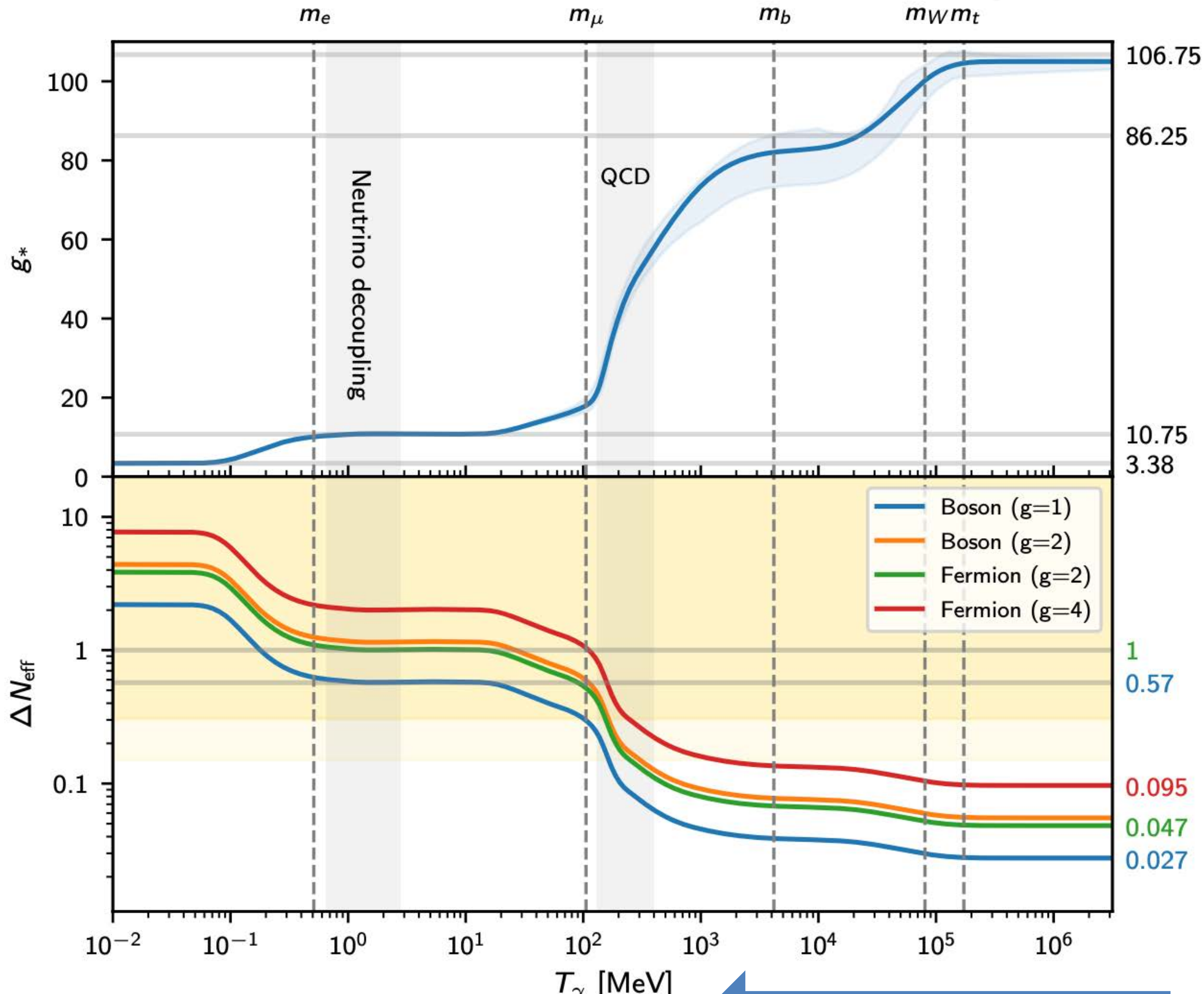
At $T<m_e$, the radiation content of the Universe is

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

effective number of neutrinos

$N_{\rm eff} \neq 3$ → **additional relativistic particles** (scalars, pseudoscalars, decay products of heavy particles,…)

Constraints on additional relativistic particles



Future sensitivities on N_{eff}

[Planck coll., Astron & Astrophys 641 (2020) A6]

Expansion of the universe

Relativistic particles in the universe

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

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

effective number of neutrinos

$N_{\rm eff} \neq 3$

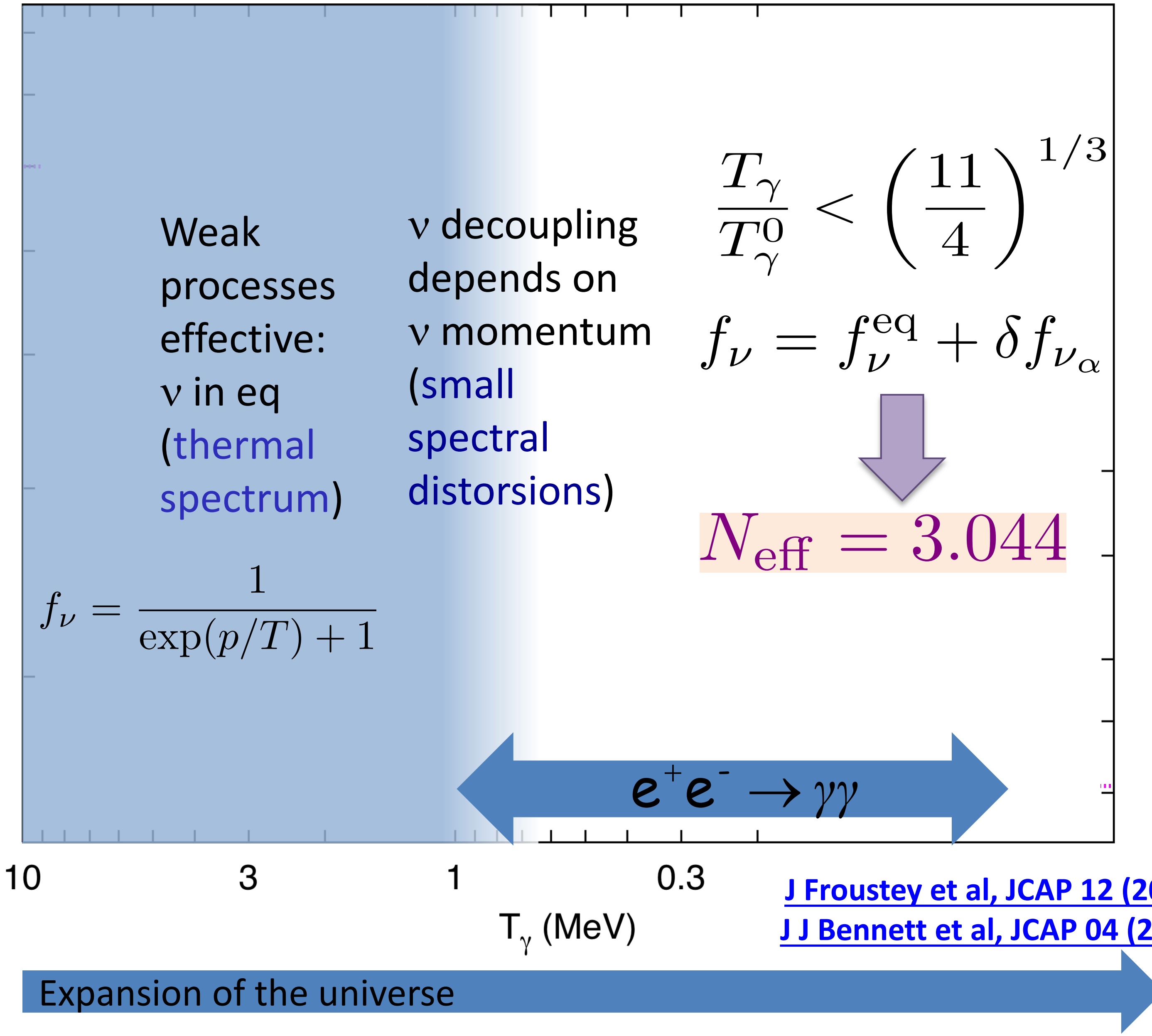
- **additional relativistic particles** (scalars, pseudoscalars, decay products of heavy particles,…)

J Froustey & C Pitrou, arXiv:2405.06509

- **non-standard neutrino physics** (primordial neutrino asymmetries, totally or partially thermalised **light sterile neutrinos**, **non-standard interactions with electrons**, non-unitary 3-neutrino mixing…)

S Gariazzo et al, JCAP 03 (2023) 046

$N_{eff} > 3$: standard case



J Froustey et al, JCAP 12 (2020) 015

J J Bennett et al, JCAP 04 (2021) 073

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

Non-standard neutrino-electron interactions

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

$$\mathcal{L}_{SM} = -2\sqrt{2}G_F \left[(\overline{\nu}_e \gamma^\mu P_L e)(\overline{e}\gamma_\mu P_L \nu_e) + \sum_{X,\alpha} g_X (\overline{\nu}_\alpha \gamma^\mu P_L \nu_\alpha)(\overline{e}\gamma_\mu P_X e) \right]$$

$$\mathcal{L}_{NSIe} = -2\sqrt{2}G_F \sum_{\alpha,\beta} \varepsilon^X_{\alpha\beta} (\overline{\nu}_\alpha \gamma^\mu P_L \nu_\beta)(\overline{e}\gamma_\mu P_X e)\,.$$

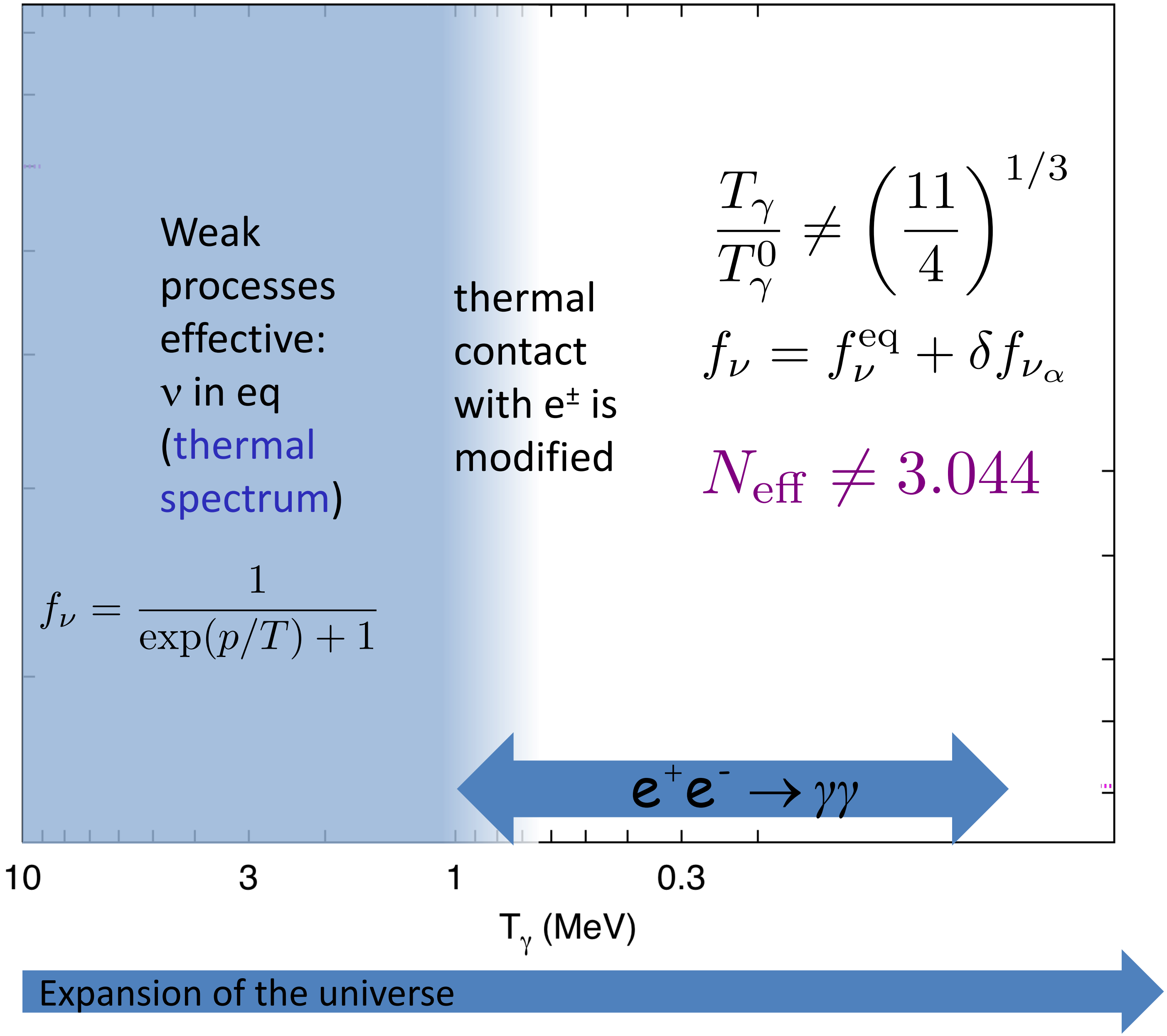
with $X \in \{L, R\}$
$\alpha, \beta \in \{e, \mu, \tau\}$

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

$\varepsilon^X_{\alpha\alpha}$ Non-universal NSI

$\varepsilon^X_{\alpha\beta}(\text{with } \alpha \neq \beta)$ Flavour-changing ($\alpha \neq \beta$) NSI

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



Equations for the neutrino density matrix

diagonal terms (occupation numbers)

off-diagonal terms

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

Boltzmann evolution equations (matrix form)

G Sigl & GG Raffelt NPB 406 (1993) 423

$$(\partial_t - H p \, \partial_p) \, \varrho_p(t) = -i \left[\left(\frac{1}{2p} \mathbb{M}_\mathrm{F} - \frac{8\sqrt{2} G_\mathrm{F} p}{3 m_\mathrm{W}^2} \mathbb{E} \right), \varrho_p(t) \right] + \mathcal{I}[\varrho_p(t)]$$

vacuum osc. term

matter potential term

collision integrals (α G_F^2)

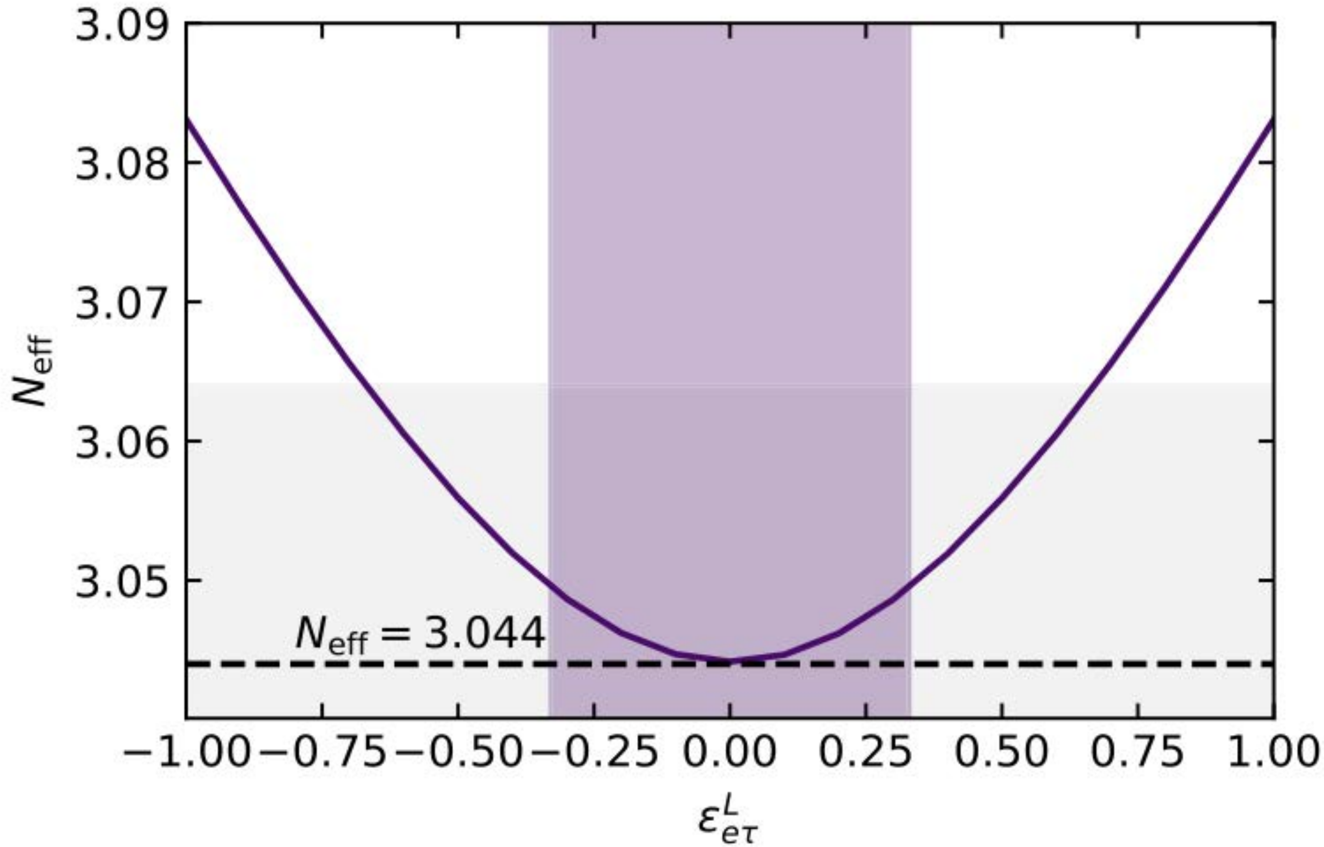
+ continuity equation

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

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

N_{eff} with only one NSI parameter

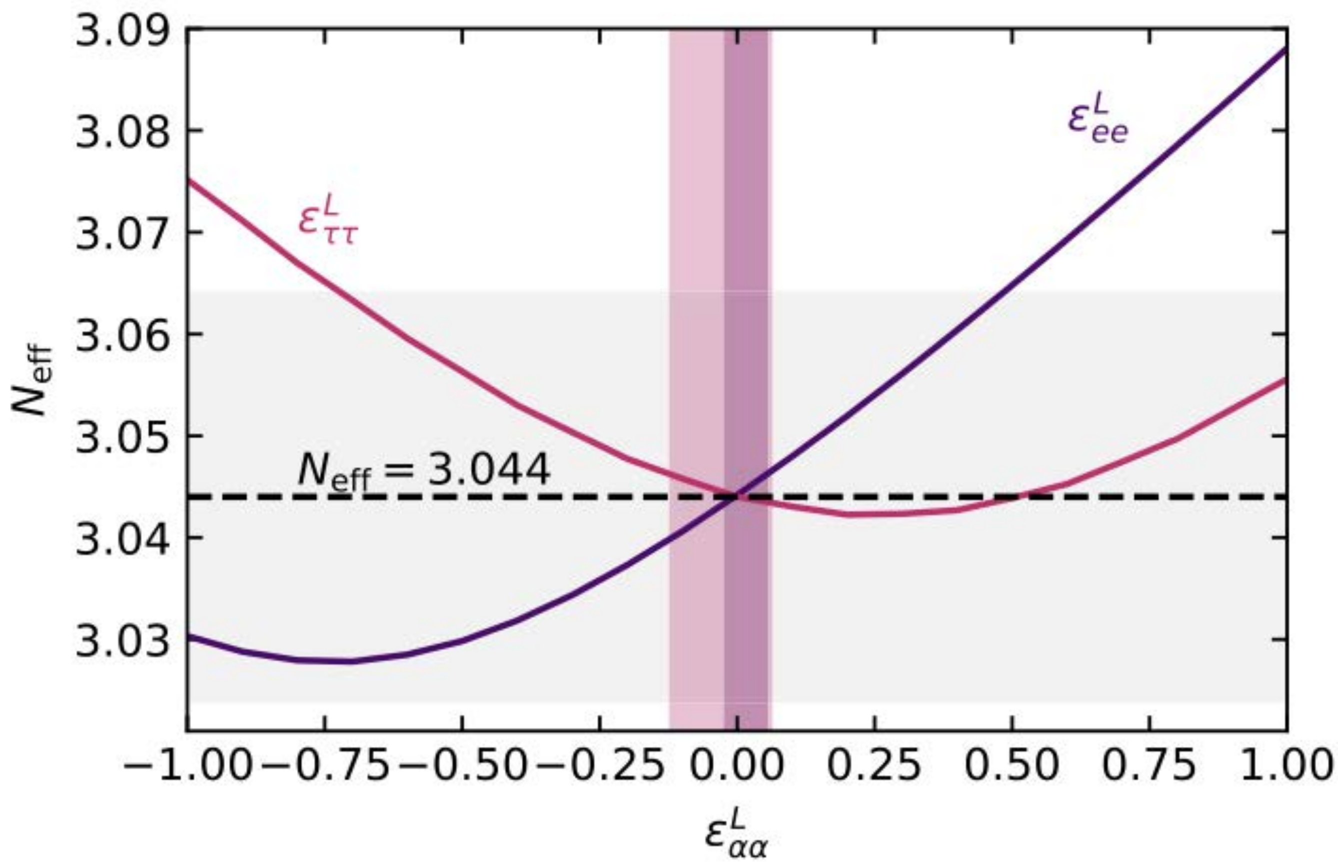
N_{eff} for flavour-changing NSI



PF de Salas et al, PLB **820** (2021) 136508

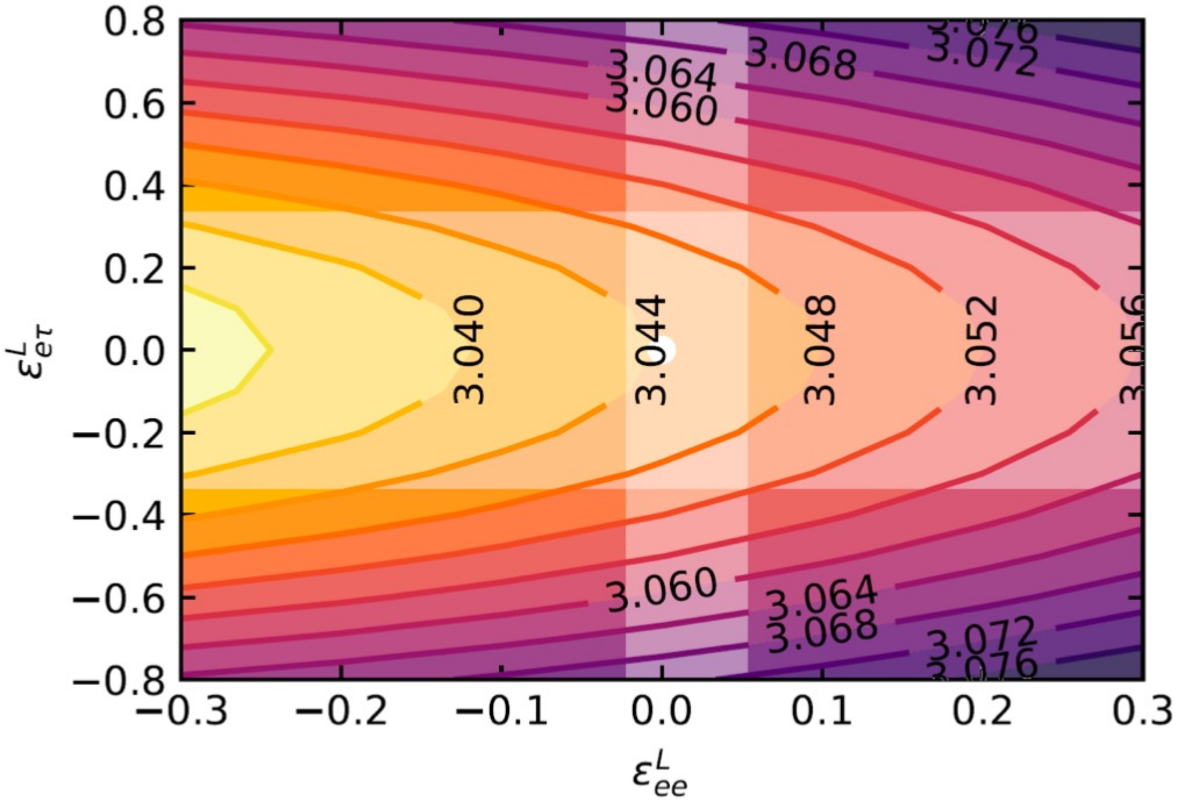
N_{eff} with only one NSI parameter

N_{eff} for non-universal NSI



PF de Salas et al, PLB **820** (2021) 136508

N_{eff} varying 2 NSI parameters

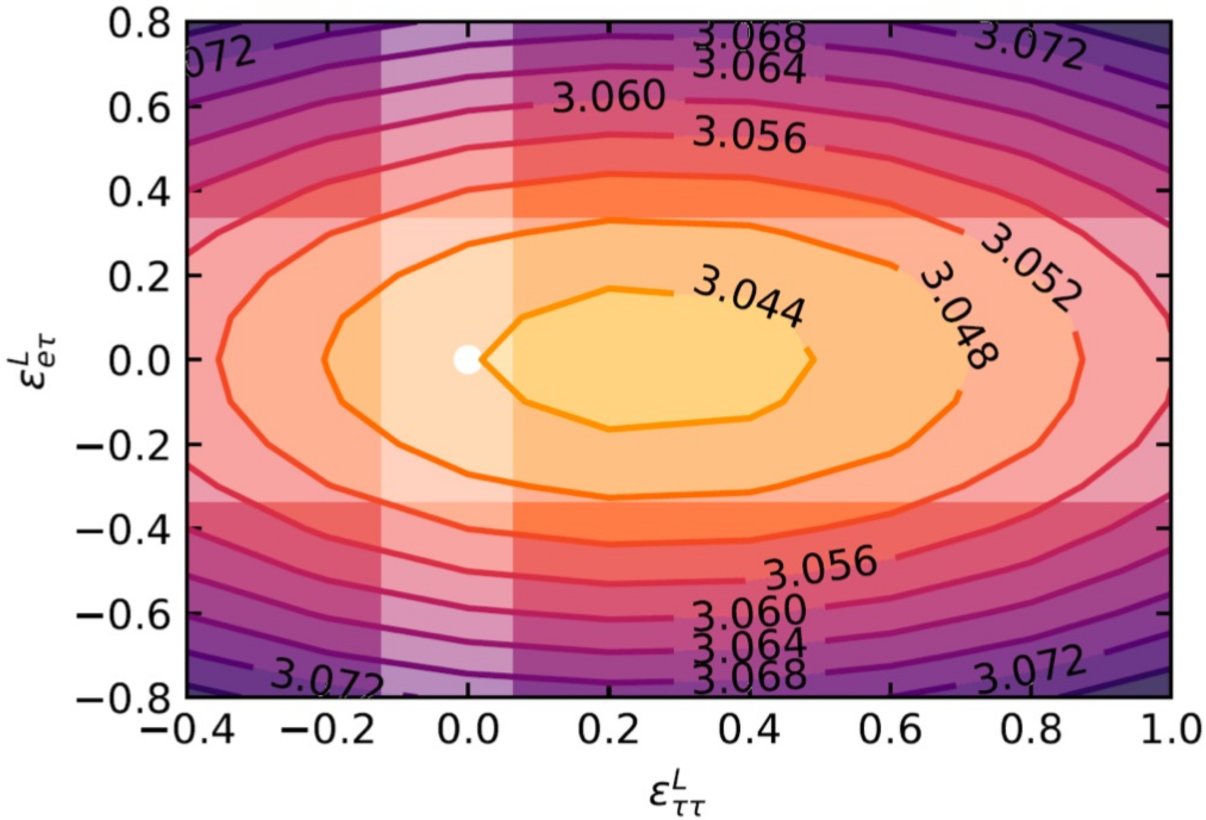


Future sensitivities on N_{eff} of the order of 0.02 - 0.05

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

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)

PF de Salas et al, PLB **820** (2021) 136508

N_{eff} with active-sterile neutrino oscillations

Mixing of four neutrino states?

Additional neutrino (sterile) **states** introduced in order to explain some anomalies in experimental data

4 flavour neutrinos, **4** massive neutrinos

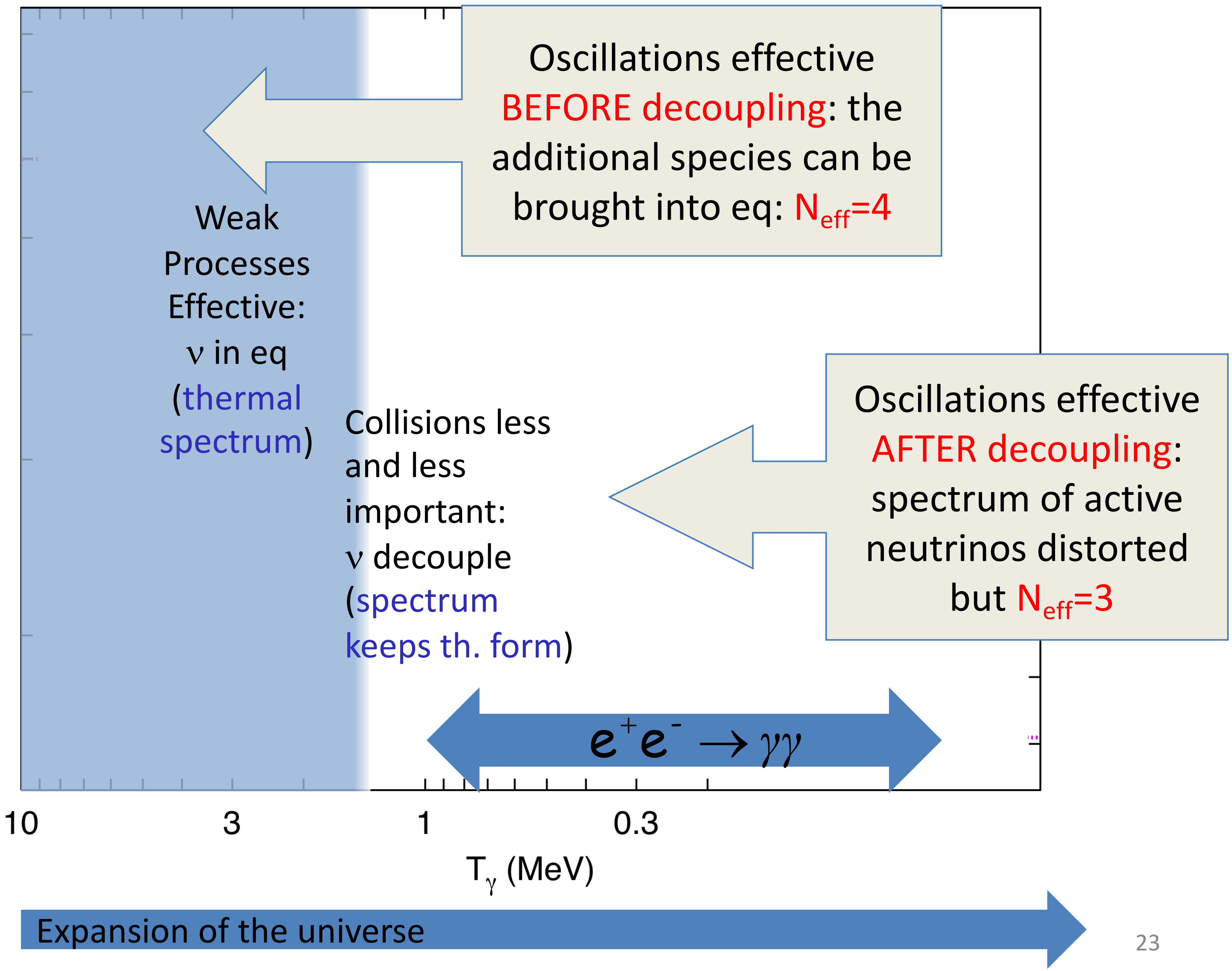
4x4 mixing matrix

$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s_1 1} & U_{s_1 2} & U_{s_1 3} & U_{s_1 4} \end{pmatrix}$$

We consider **3 (active)** + **1 (sterile)**, a perturbation of the 3-neutrino case

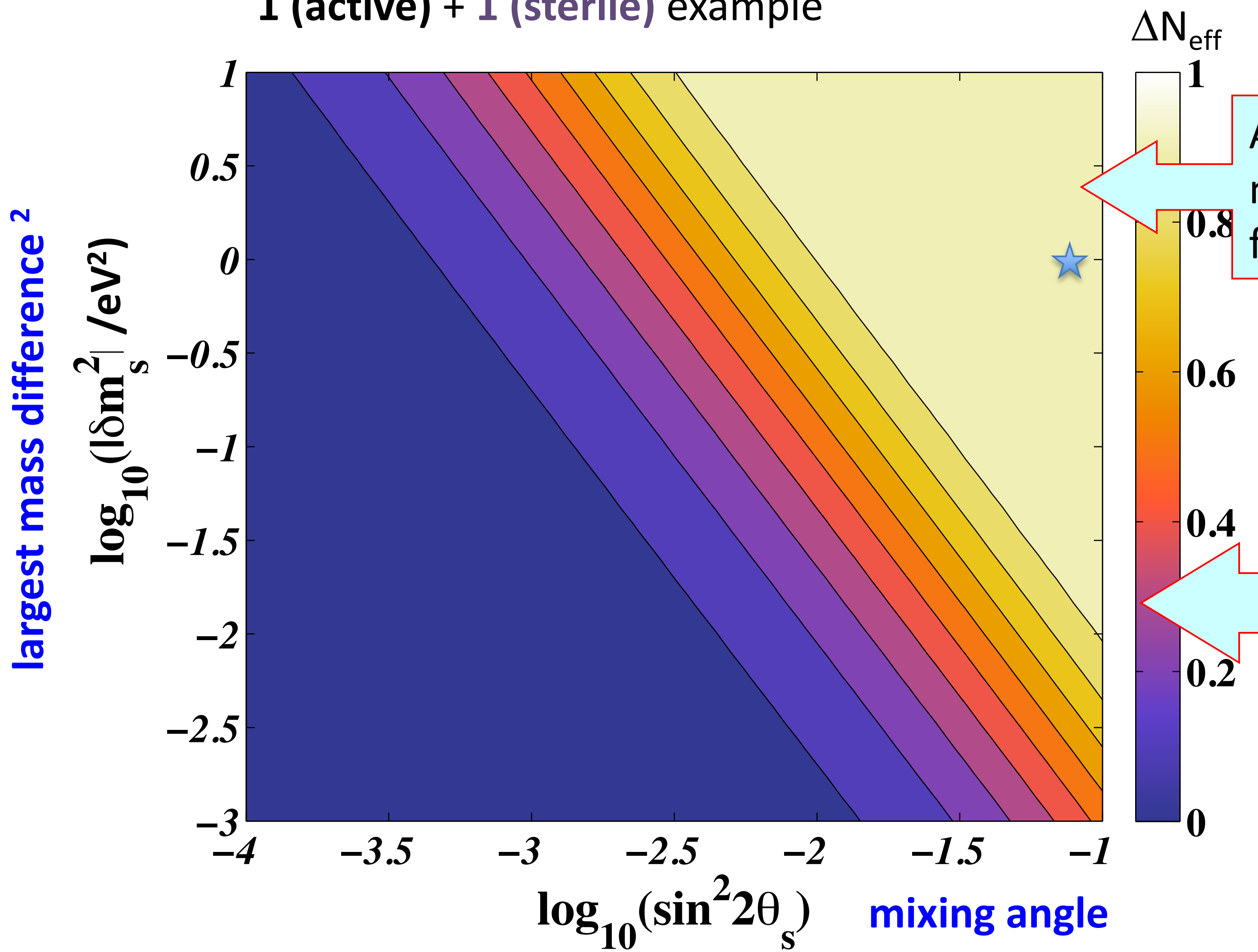
$$\begin{aligned} |U_{e4}|^2 &= \sin^2\theta_{14}, \\ |U_{\mu 4}|^2 &= \cos^2\theta_{14}\sin^2\theta_{24}, \\ |U_{\tau 4}|^2 &= \cos^2\theta_{14}\cos^2\theta_{24}\sin^2\theta_{34}, \\ |U_{s4}|^2 &= \cos^2\theta_{14}\cos^2\theta_{24}\cos^2\theta_{34}. \end{aligned}$$

N_{eff} & active-sterile neutrino oscillations



N_{eff} & active-sterile neutrino oscillations

1 (active) + **1 (sterile)** example



Additional neutrino in full eq, N_{eff}=4

Contribution of additional to ρ_{rad} in N_{eff} units

Hannestad, Tamborra & Tram, JCAP 07 (2012) 025

3+1 case: equations for the neutrino density matrix

$$\varrho(p,t) = \begin{pmatrix} \varrho_{ee} & \varrho_{e\mu} & \varrho_{e\tau} & \varrho_{es} \\ \varrho_{\mu e} & \varrho_{\mu\mu} & \varrho_{\mu\tau} & \varrho_{\mu s} \\ \varrho_{\tau e} & \varrho_{\tau\mu} & \varrho_{\tau\tau} & \varrho_{\tau s} \\ \varrho_{se} & \varrho_{s\mu} & \varrho_{s\tau} & \varrho_{ss} \end{pmatrix}$$

diagonal terms (occupation numbers)

off-diagonal terms

Boltzmann evolution equations (matrix form)

$$(\partial_t - H p\, \partial_p)\, \varrho_p(t) = -i \left[\left(\frac{1}{2p}\mathbb{M}_\mathrm{F} - \frac{8\sqrt{2}G_\mathrm{F} p}{3m_\mathrm{W}^2}\mathbb{E} \right), \varrho_p(t) \right] + \mathcal{I}\left[\varrho_p(t)\right]$$

vacuum osc. term

matter potential term

collision integrals ($\alpha\ G_F^2$)

$$\mathbb{M}_\mathrm{F} = U \mathbb{M} U^\dagger$$

$$\mathbb{M} = \mathrm{diag}(m_1^2, m_2^2, m_3^2, m_4^2)$$

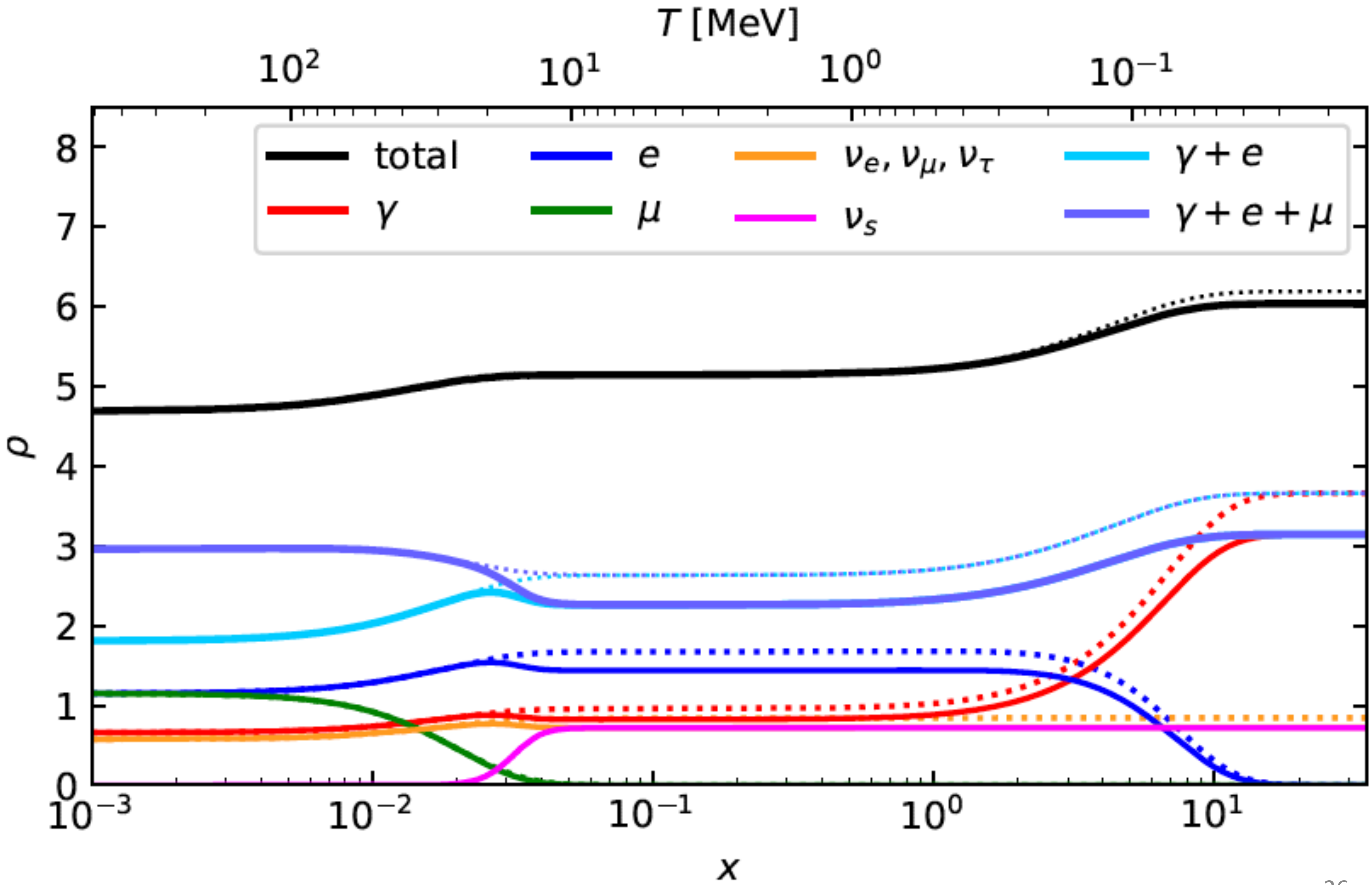
$$U = R^{34} R^{24} R^{14} R^{23} R^{13} R^{12}$$

e.g. $$R^{14} = \begin{pmatrix} \cos\theta_{14} & 0 & 0 & \sin\theta_{14} \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ -\sin\theta_{14} & 0 & 0 & \cos\theta_{14} \end{pmatrix}$$

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

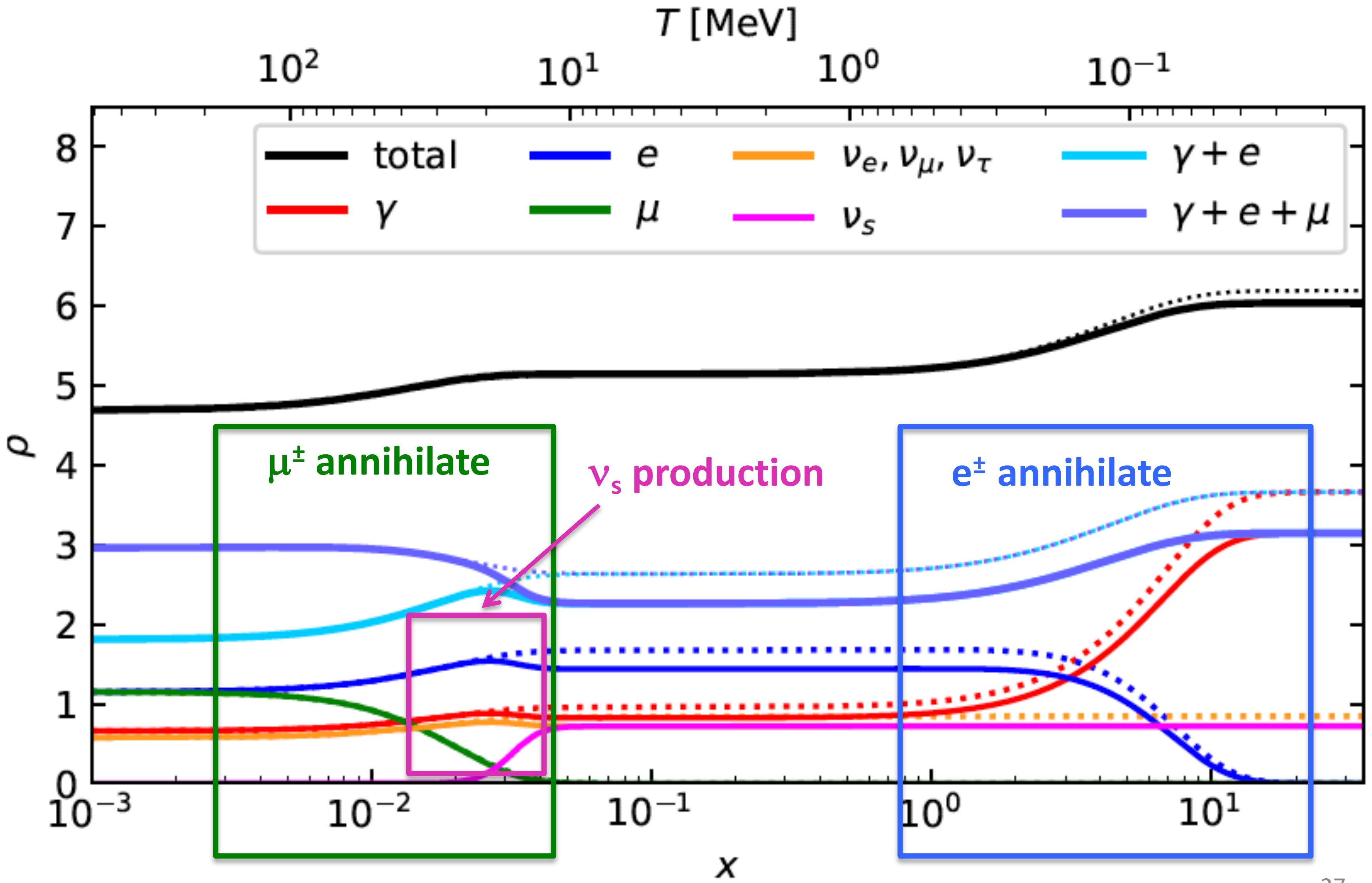
Results: evolution of energy densities (comoving)

dashed: 3ν, solid: $|U_{e4}|^2 = 10^{-2}$, $|U_{\mu4}|^2 = |U_{\tau4}|^2 = 0$. $\Delta m^2_{41} = 1.29$ eV^2



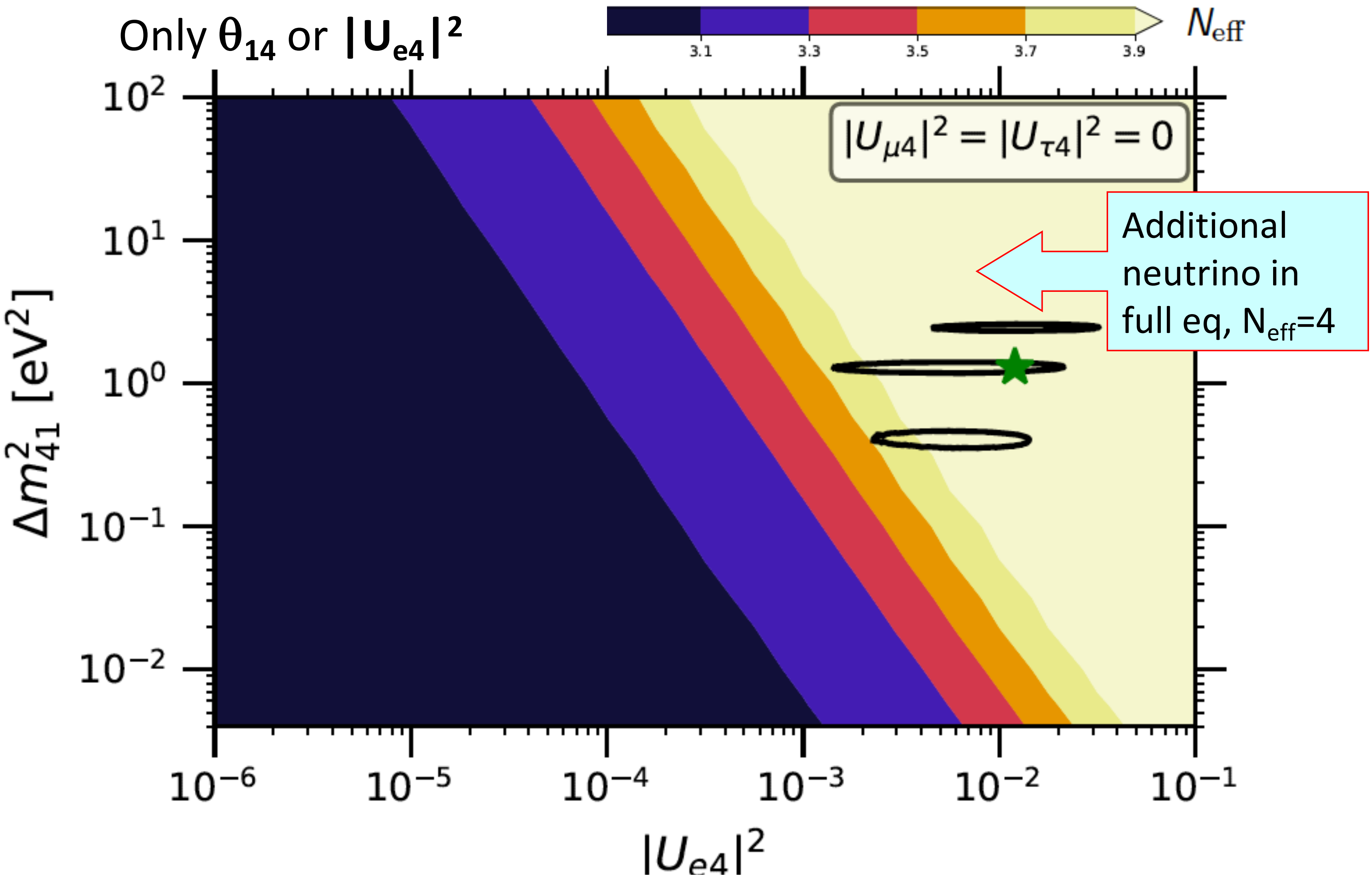
Results: evolution of energy densities (comoving)

dashed: 3ν, solid: $|U_{e4}|^2 = 10^{-2}$, $|U_{\mu 4}|^2 = |U_{\tau 4}|^2 = 0$. $\Delta m_{41}^2 = 1.29$ eV^2



Results: final value of N_{eff} and sterile mixing parameters

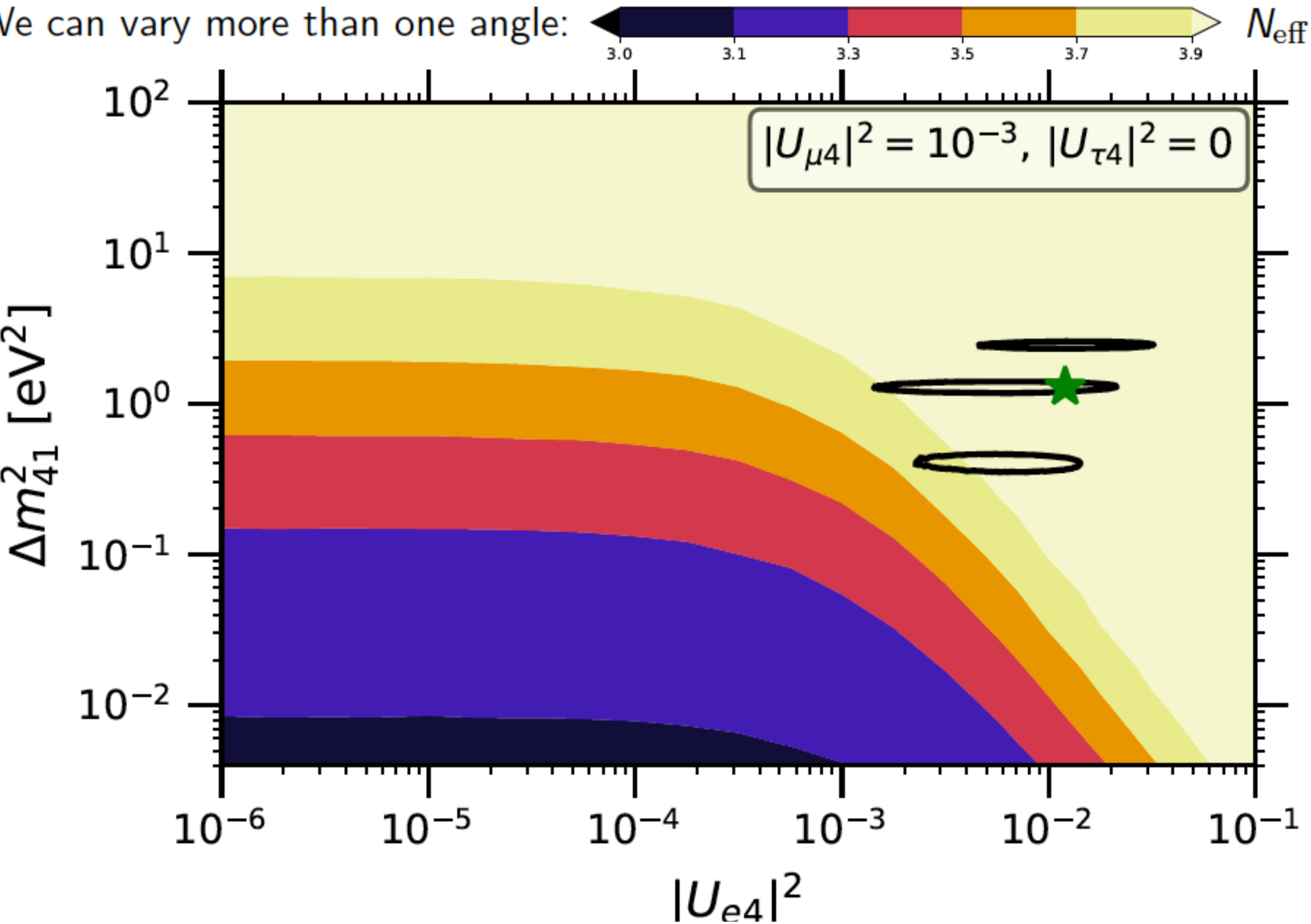
Only θ_{14} or $|U_{e4}|^2$



S Gariazzo, PF de Salas & SP JCAP 07 (2019) 014

Results: final value of N_{eff} and sterile mixing parameters

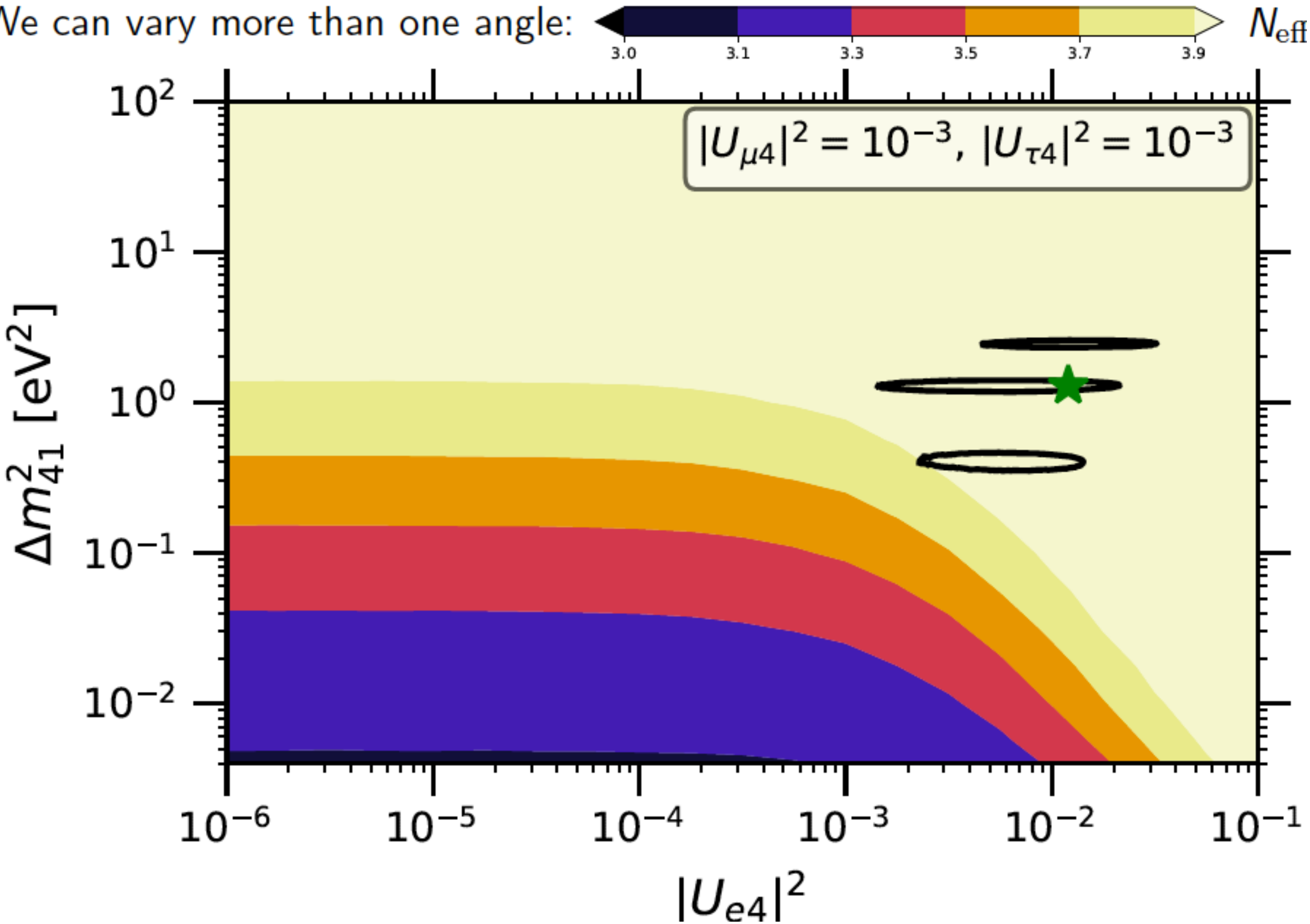
We can vary more than one angle:



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

Results: final value of N_{eff} and sterile mixing parameters

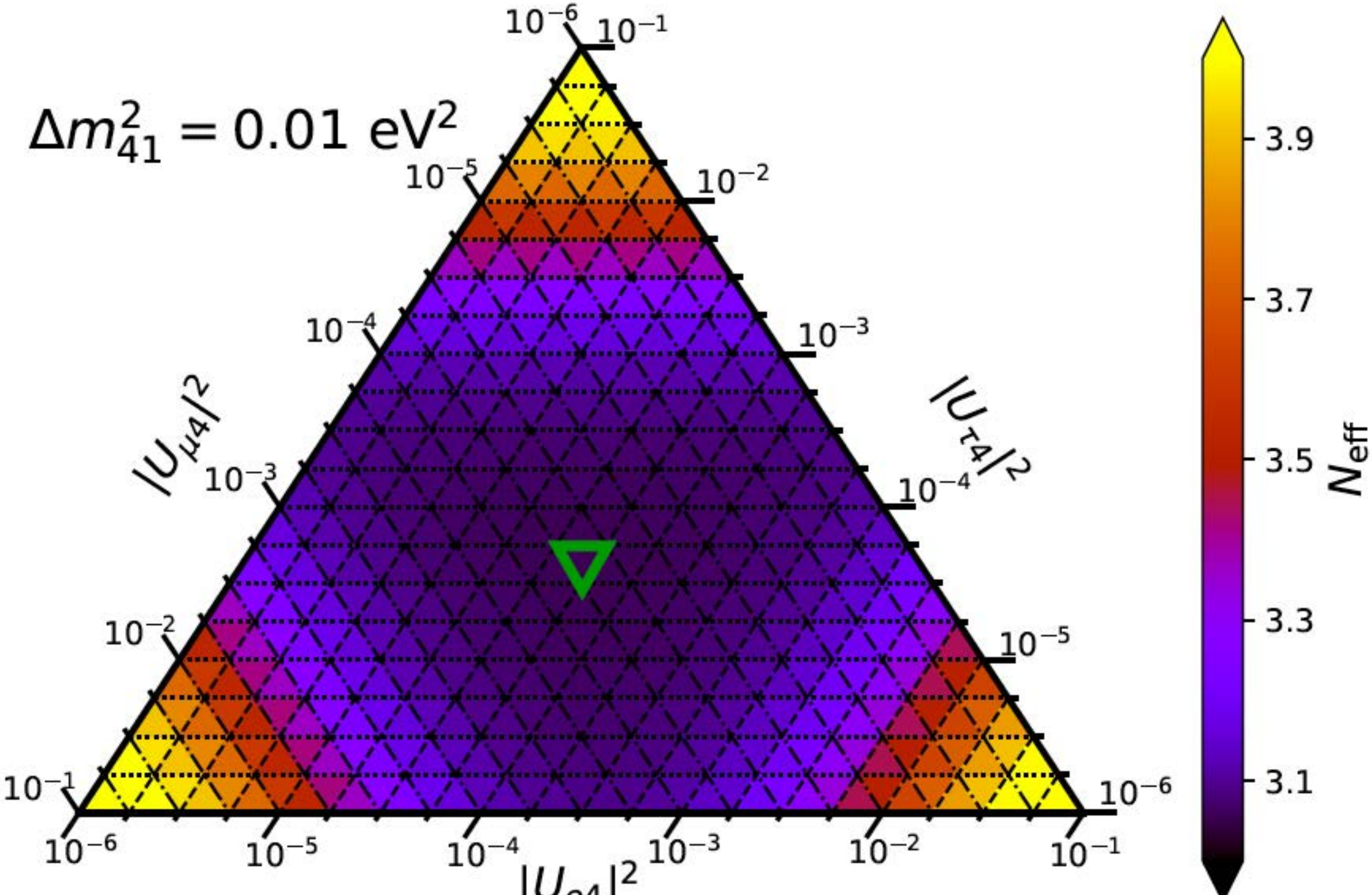
We can vary more than one angle:



S Gariazzo, PF de Salas & SP JCAP 07 (2019) 014

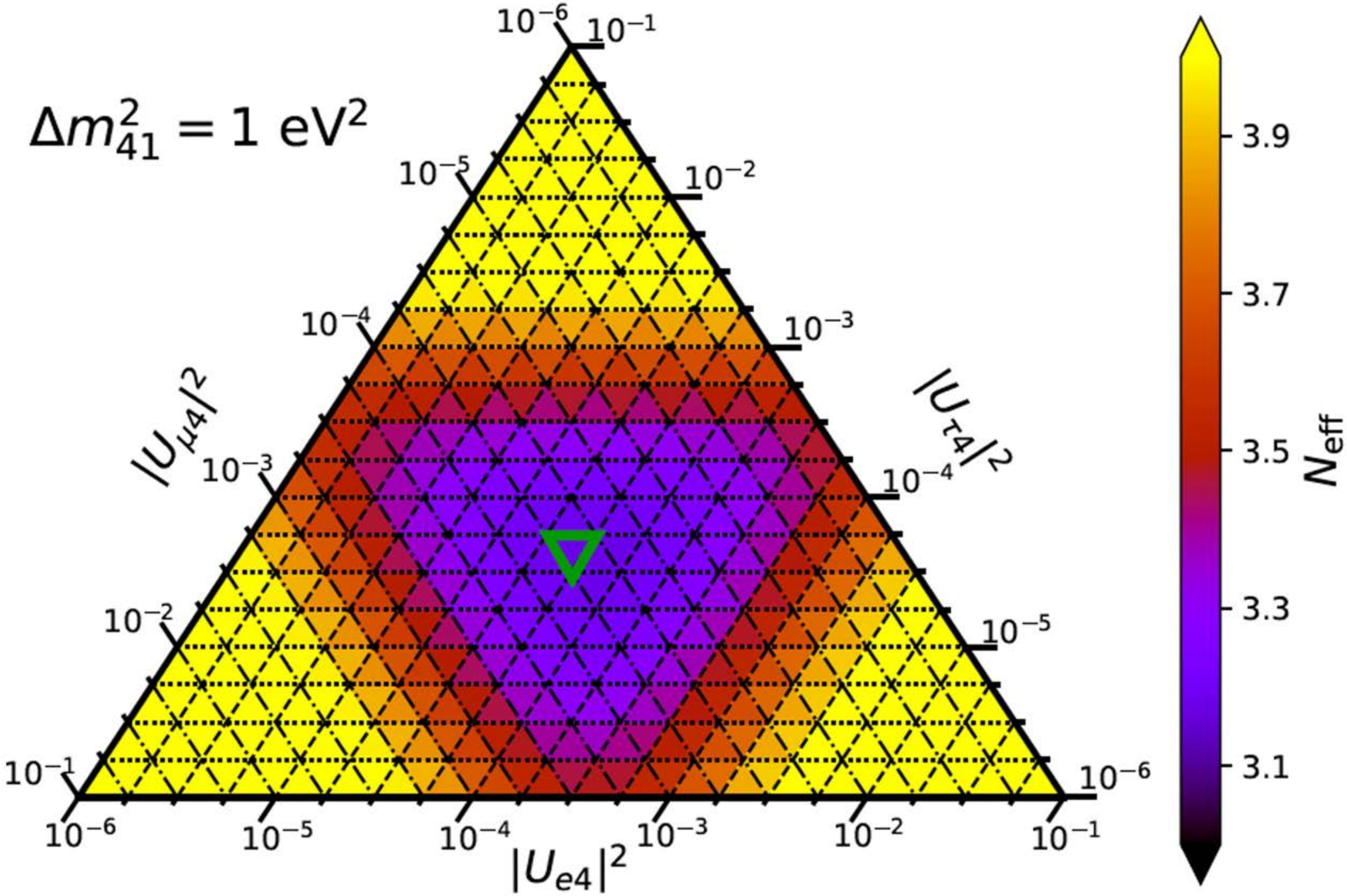
Results: final value of N_{eff} and sterile mixing parameters

Sort of ternary plot (sum of $|U_{\alpha 4}|^2$ does not add up to 1!):



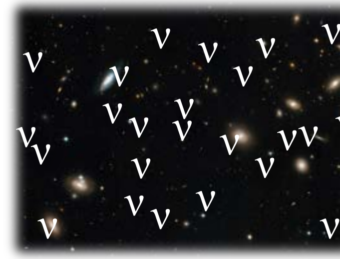
Results: final value of N_{eff} and sterile mixing parameters

Sort of ternary plot (sum of $|U_{\alpha 4}|^2$ does not add up to 1!):



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

✓ Presence of **non-standard neutrino-electron interactions** (allowed by laboratory data) could slightly modify **N_{eff} = 3.04-3.08**

✓If a fourth (sterile) neutrino state exists in order to explain the anomalies in oscillation measurements, it would have important implications for the cosmological scenario (**N_{eff}, $m_{\nu,eff}$**)