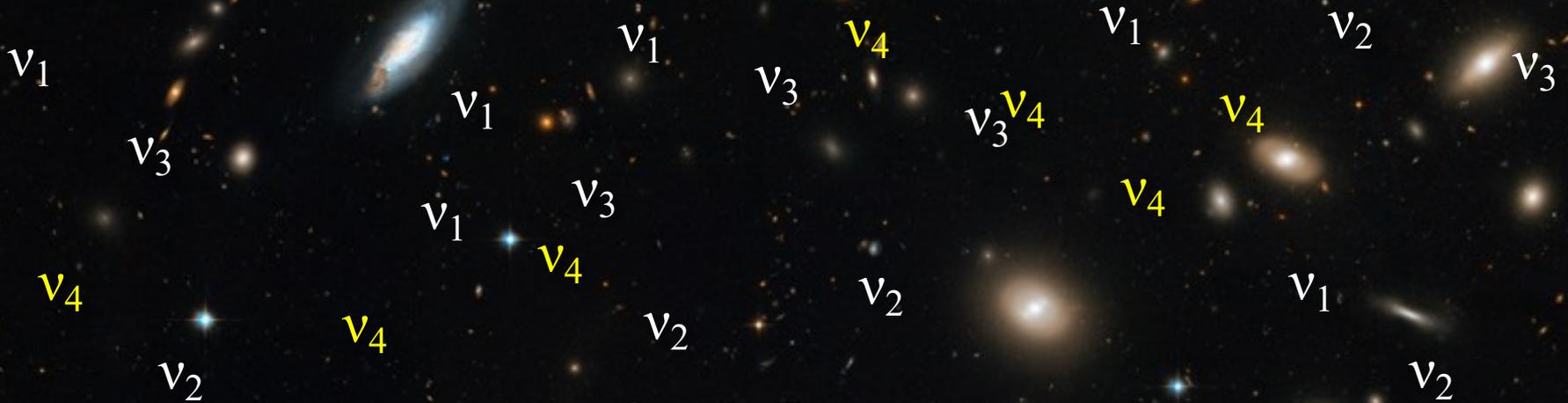


Bounds on 3+1 active-sterile neutrino oscillations in very low reheating scenarios

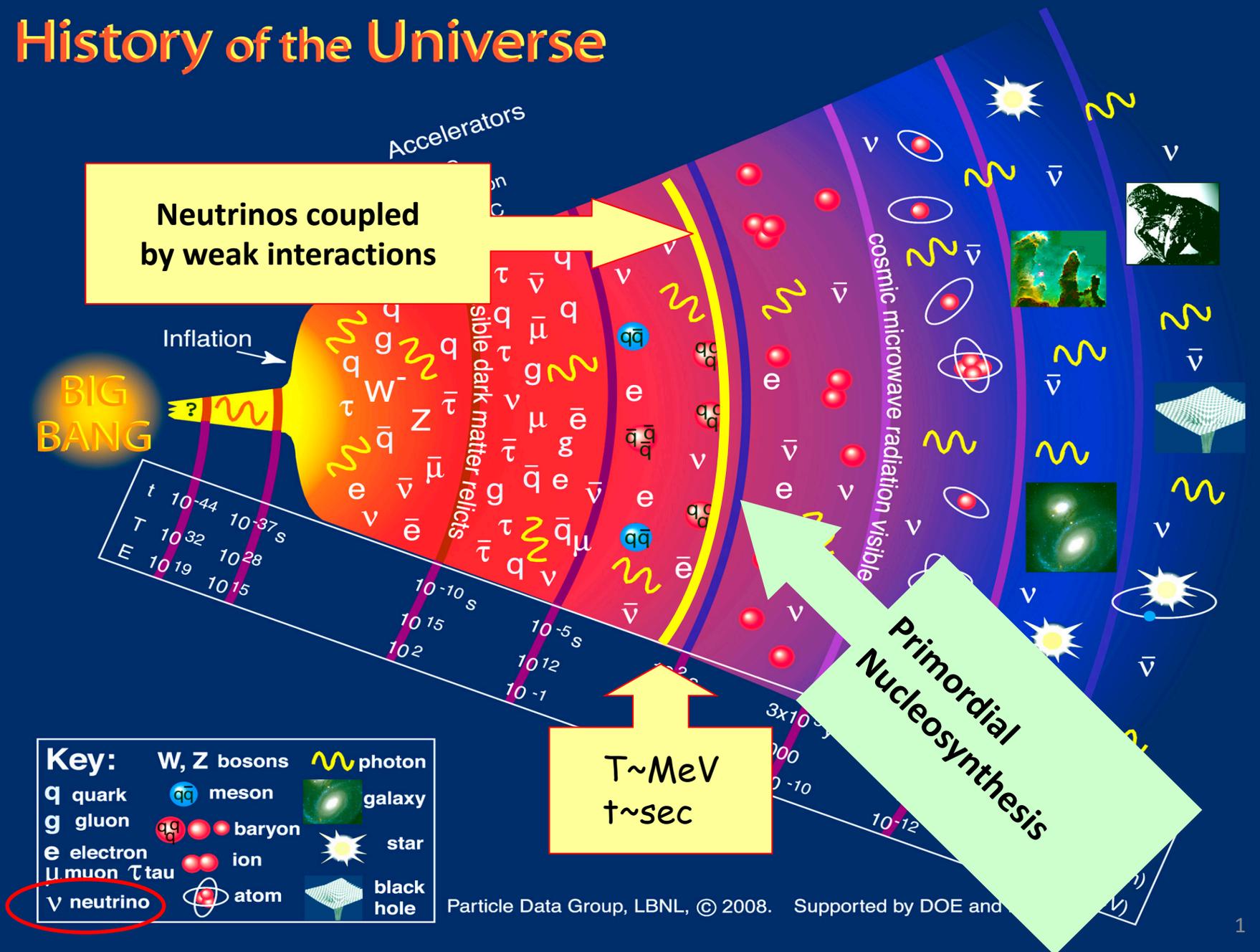


Sergio Pastor
(IFIC Valencia)

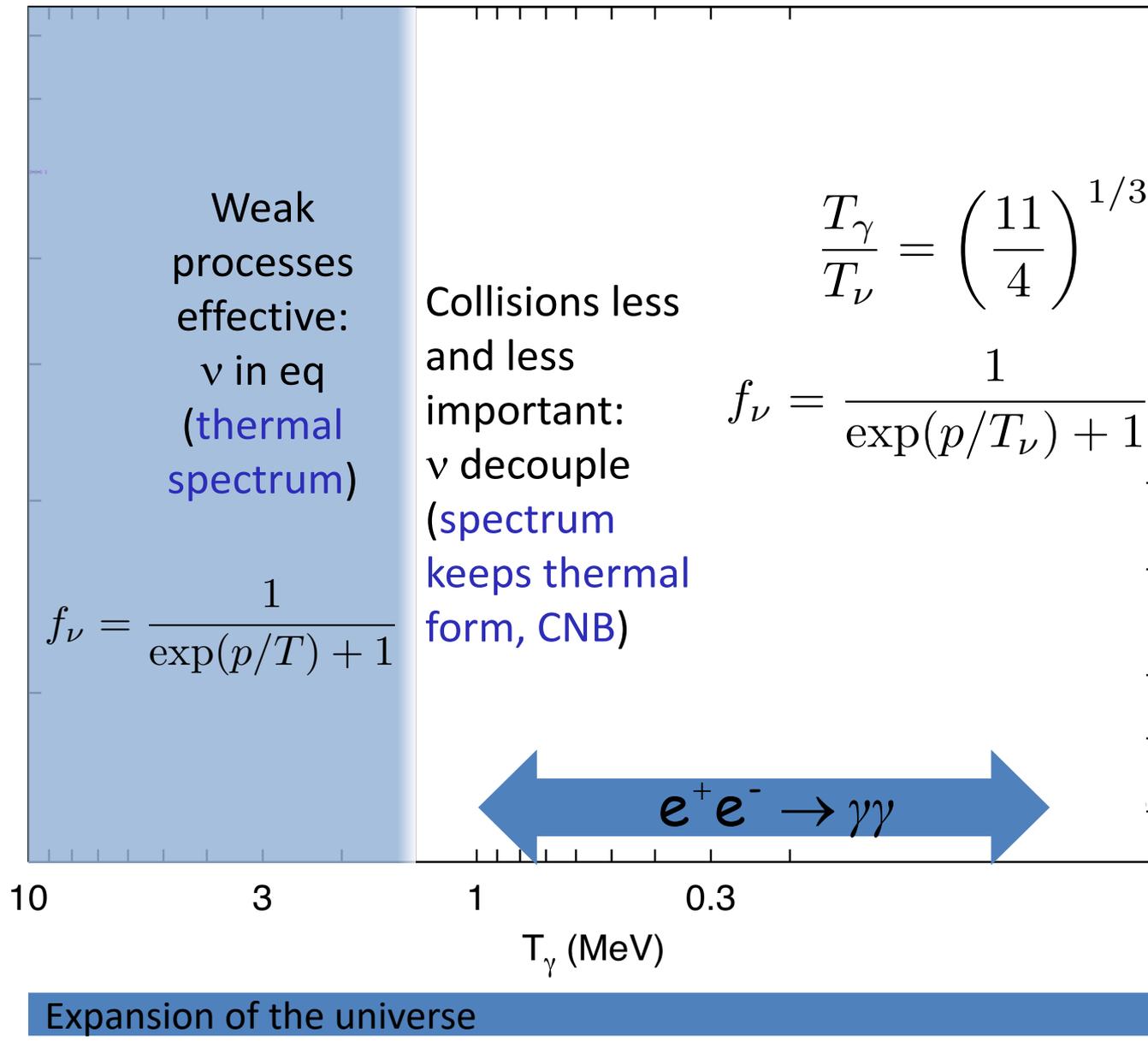
work in preparation with T Brinckmann, PF de Salas,
M Fernández Navarro, S Gariazzo, M Lattanzi & O Pisanti



History of the Universe



Neutrino decoupling and e^\pm annihilation



Relativistic particles in the universe

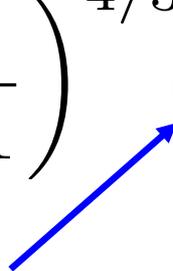
At $T < m_e$, the radiation content of the Universe is

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

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)

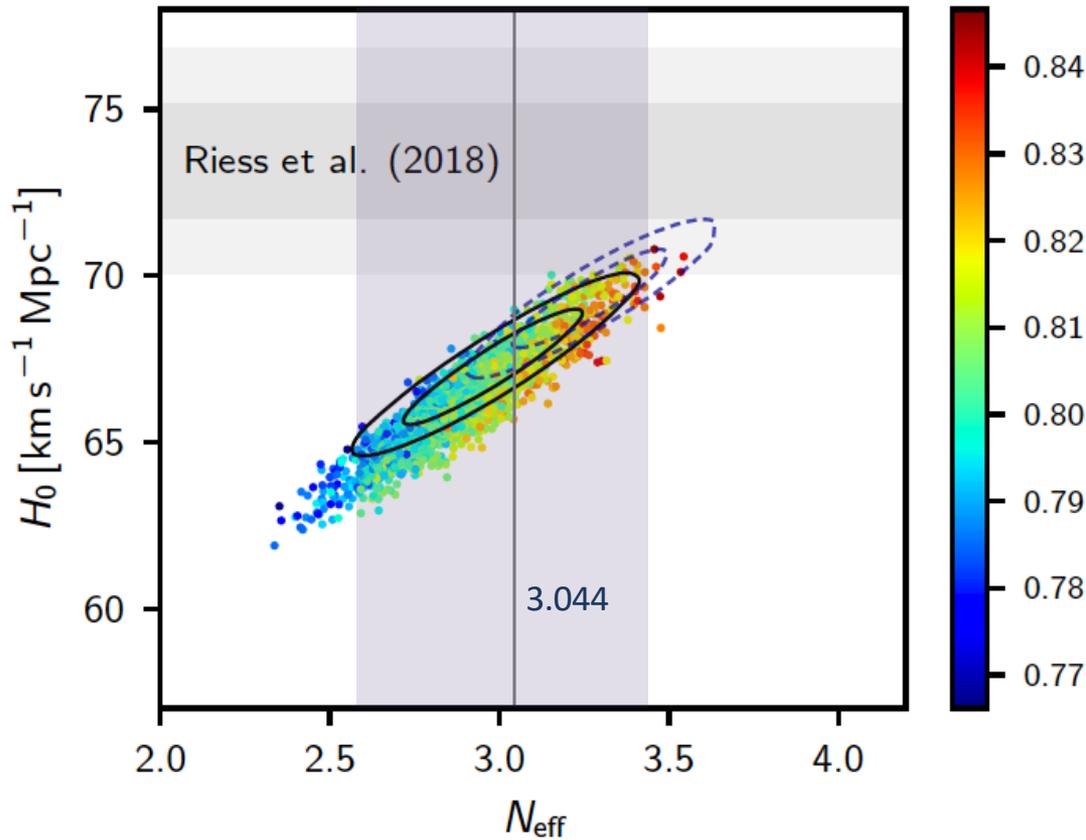
N_{eff} is a way to measure the ratio $\frac{\rho_{\nu} + \rho_x}{\rho_{\gamma}}$

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

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

M Lattanzi's plenary talk

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)

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_{eff} with active-sterile neutrino oscillations

Neutrino mixing and oscillations: 3 flavours

flavour neutrinos ν_α

$$\nu_\alpha = \sum_{k=1}^3 U_{\alpha k} \nu_k \quad (\alpha = e, \mu, \tau)$$

massive neutrinos ν_i

$U_{\alpha k}$ described by 3 mixing angles θ_{12} , θ_{13} , θ_{23} and one CP phase δ

Current knowledge of 3 active ν mixing: de Salas et al, JHEP 02 (2021) 071 & update

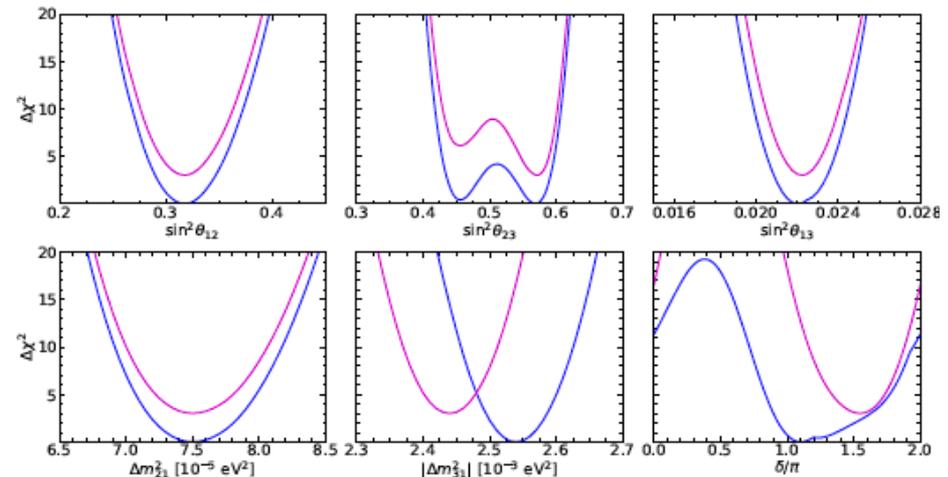
NO/NH: Normal Ordering/Hierarchy, $m_1 < m_2 < m_3$

IO/IH: Inverted O/H, $m_3 < m_1 < m_2$

$$\begin{aligned} \Delta m_{21}^2 &= (7.50^{+0.22}_{-0.20}) \cdot 10^{-5} \text{ eV}^2 \\ |\Delta m_{31}^2| &= (2.54 \pm 0.03) \cdot 10^{-3} \text{ eV}^2 \text{ (NO)} \\ &= (2.44 \pm 0.03) \cdot 10^{-3} \text{ eV}^2 \text{ (IO)} \end{aligned}$$

$$\begin{aligned} 10 \sin^2(\theta_{12}) &= 3.18 \pm 0.16 \\ 10^2 \sin^2(\theta_{13}) &= 2.200^{+0.069}_{-0.062} \text{ (NO)} \\ &= 2.225^{+0.064}_{-0.070} \text{ (IO)} \\ 10 \sin^2(\theta_{23}) &= 4.55 \pm 0.13 \cup 5.71 \pm 0.12 \text{ (NO)} \\ &= 5.71^{+0.14}_{-0.17} \text{ (IO)} \end{aligned}$$

$$\begin{aligned} \delta/\pi &= 1.10^{+0.27}_{-0.12} \text{ (NO)} \\ &= 1.54 \pm 0.14 \text{ (IO)} \end{aligned}$$



mass ordering
still unknown

δ still unknown

See also <http://globalfit.astroparticles.es>

Mixing of four neutrino states?

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

L Wen's plenary talk

4 flavour neutrinos, 4 massive neutrinos

4x4 mixing matrix

$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

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

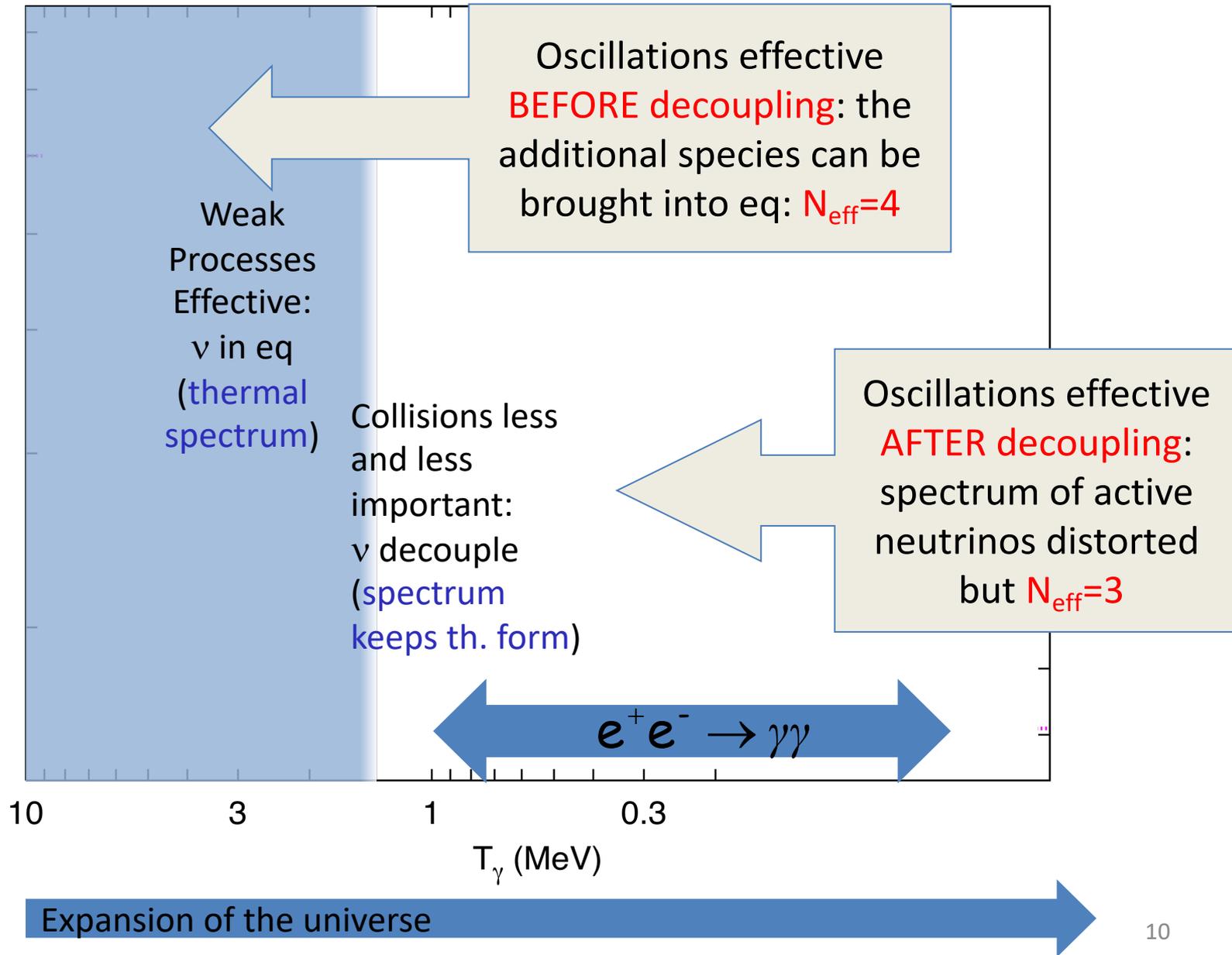
$$|U_{e4}|^2 = \sin^2 \theta_{14},$$

$$|U_{\mu4}|^2 = \cos^2 \theta_{14} \sin^2 \theta_{24},$$

$$|U_{\tau4}|^2 = \cos^2 \theta_{14} \cos^2 \theta_{24} \sin^2 \theta_{34},$$

$$|U_{s4}|^2 = \cos^2 \theta_{14} \cos^2 \theta_{24} \cos^2 \theta_{34}.$$

N_{eff} & active-sterile neutrino oscillations



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)

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

$$\mathbb{M}_F = U \mathbb{M} U^\dagger$$

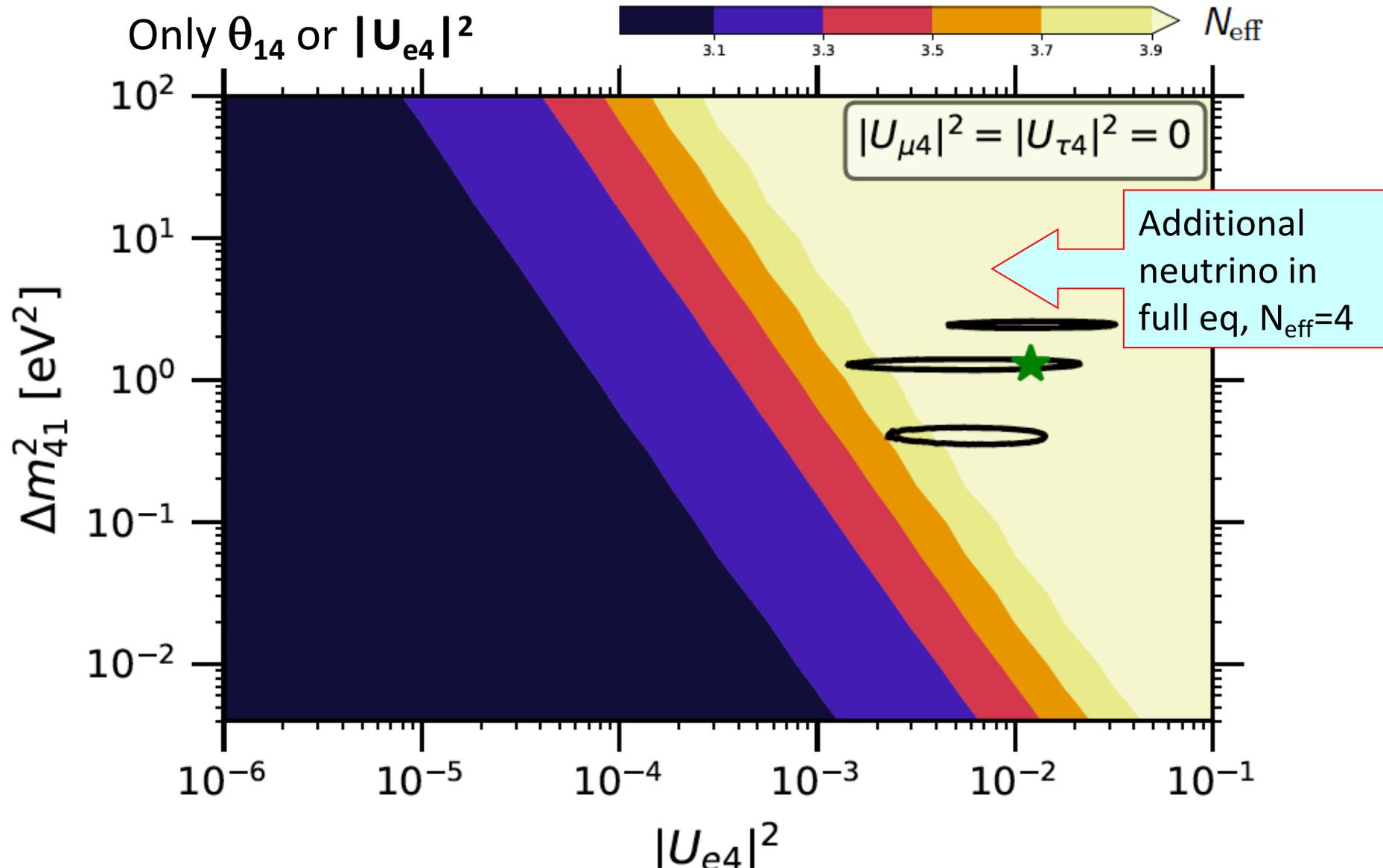
$$\mathbb{M} = \text{diag}(m_1^2, m_2^2, m_3^2, m_4^2)$$

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

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

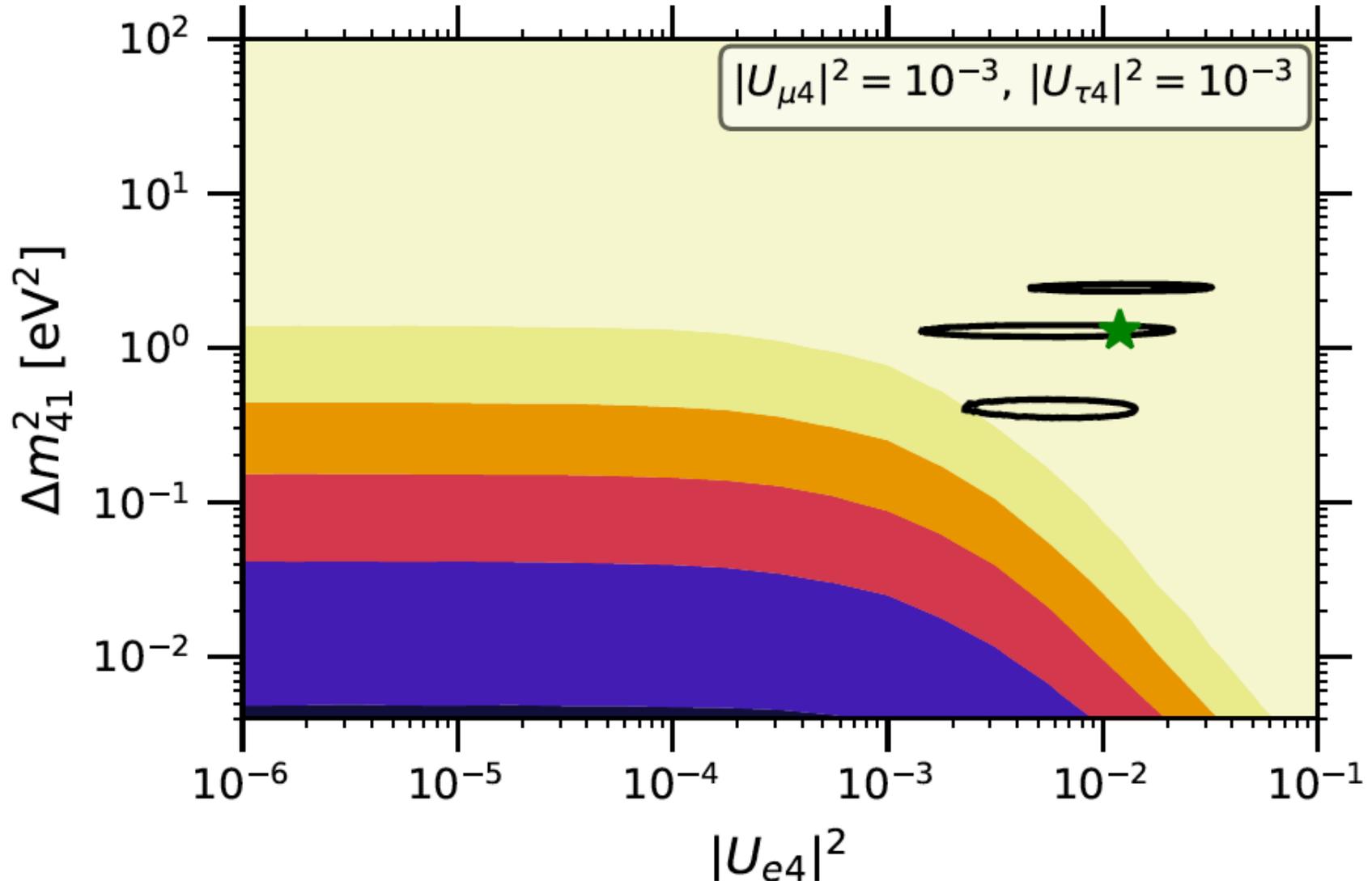
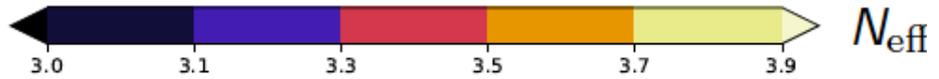
Code: **FORTran-Evolved Primordial Neutrino Oscillations (FortEPiNO)**

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



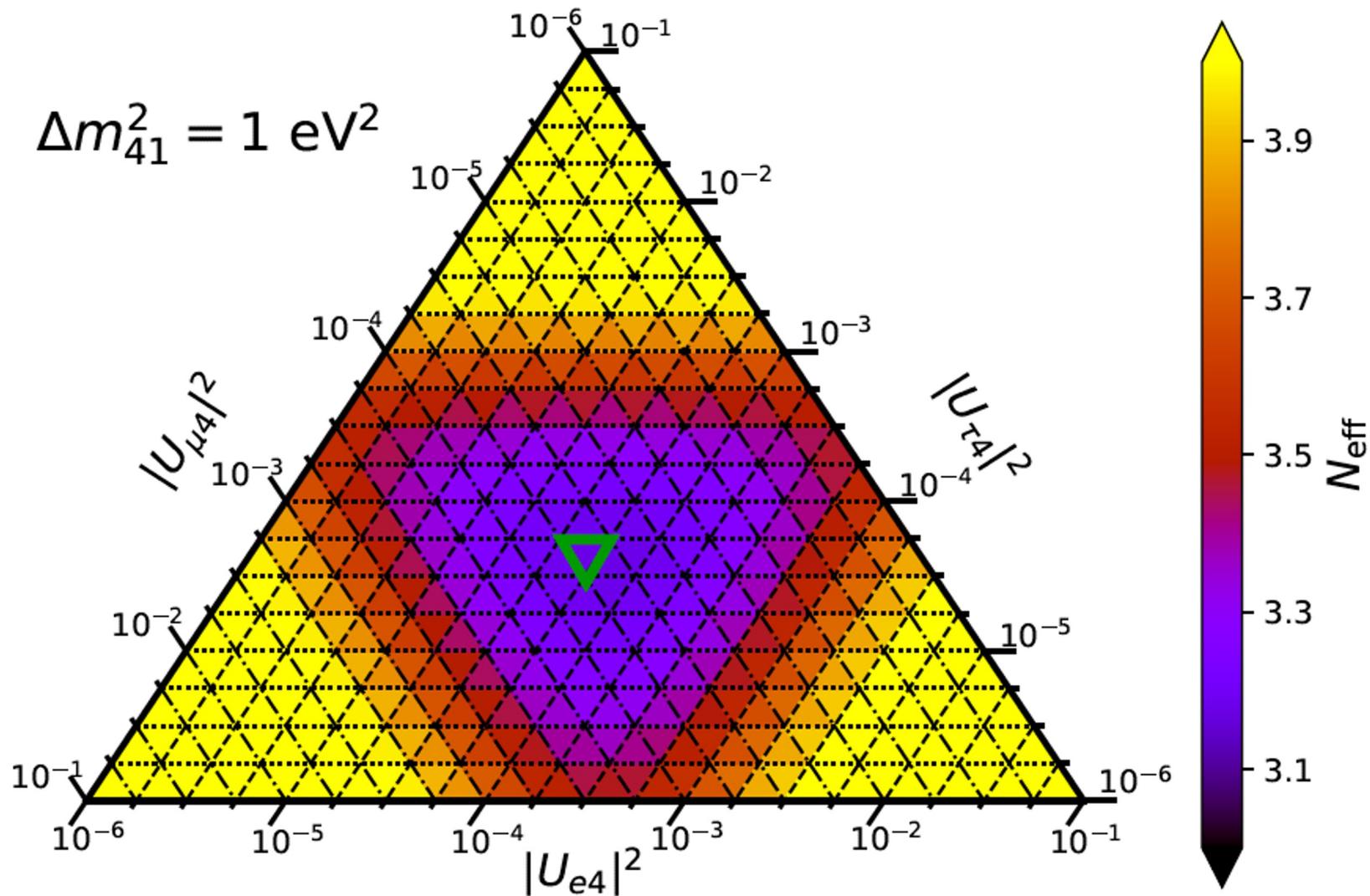
Results: final value of N_{eff} and sterile mixing parameters

We can vary more than one angle:



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!):



How to reconcile 3+1 oscillations with $N_{\text{eff}} < 4$

We would need

- a mechanism to suppress oscillations and full thermalization of ν_s
- to compensate $\Delta N_{\text{eff}} = 1$ with additional mechanisms in Cosmology

Some ideas (an incomplete list!):

- large lepton asymmetry [Foot et al., 1995; Mirizzi et al., 2012; many more]
- new neutrino interactions [Bento et al., 2001; Dasgupta et al., 2014; Hannestad et al., 2014; Saviano et al., 2014; Archidiacono et al. 2016; many more]
- entropy production after neutrino decoupling [Ho et al., 2013]
- very low reheating temperature [Gelmini et al., 2004; Smirnov et al., 2006]
- time varying dark energy components [Giusarma et al., 2012]
- larger expansion rate at the time of ν_s production [Rehagen et al., 2014]



recent analysis with 1+1 active-sterile oscillations:

[T Hasegawa et al, JCAP 08 \(2020\) 015](#)

Very low-reheating scenarios

Cosmological scenarios with low-reheating temperature

Reheating: phase ending inflation

during inflation, the inflaton (non-rel. scalar) dominates the energy density

during reheating: inflaton decays into standard model particles

⇒ photons, electrons, ... are populated directly

radiation domination begins after reheating

neutrinos are populated by weak interactions with electrons!

if reheating occurs too late, neutrinos are not generated and $N_{\text{eff}} < 3$

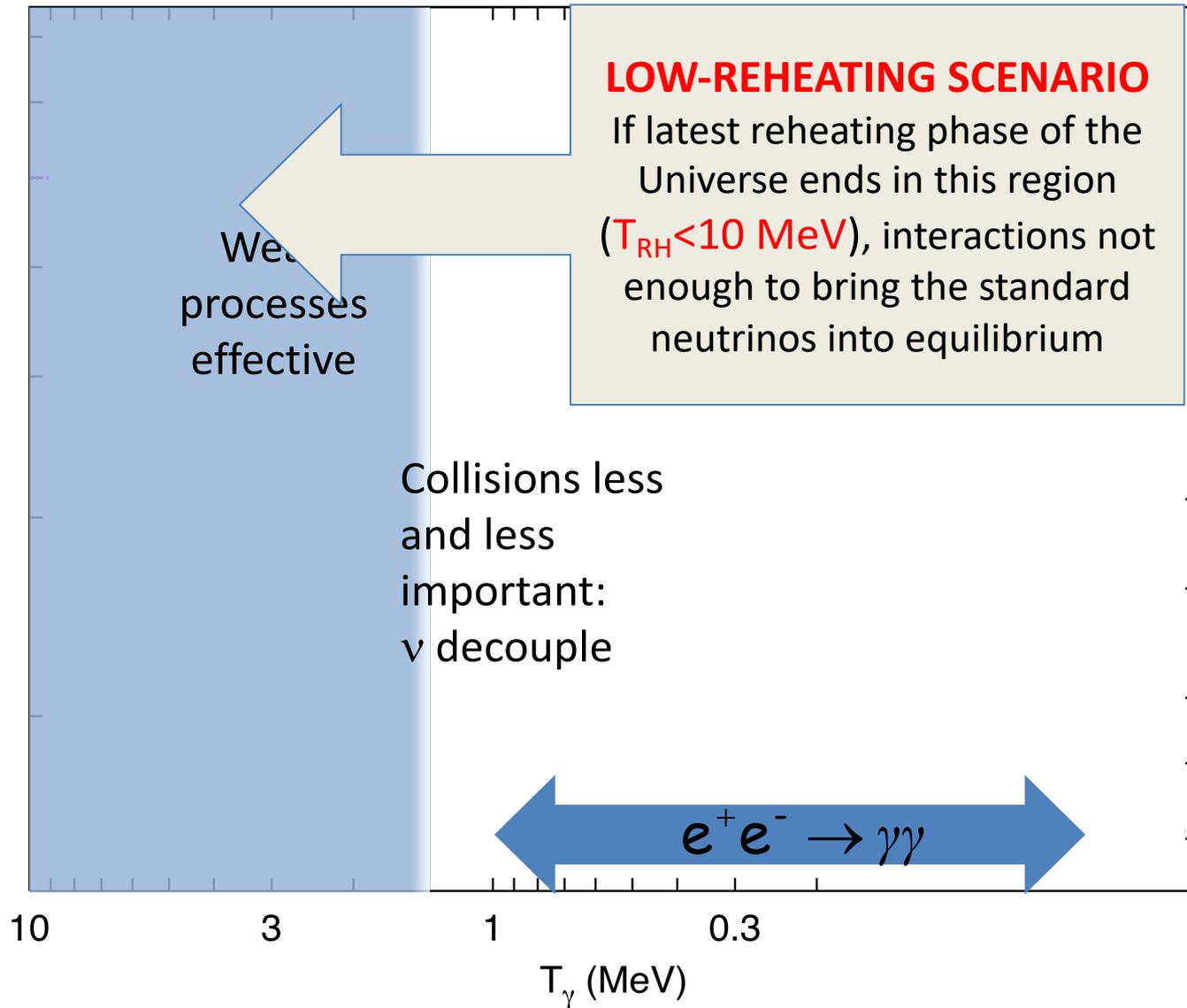
Low reheating temperature: when reheating occurs at $T_{\text{rh}} \lesssim 20$ MeV

notice: if $T_{\text{rh}} \lesssim 3$ MeV, BBN is broken!

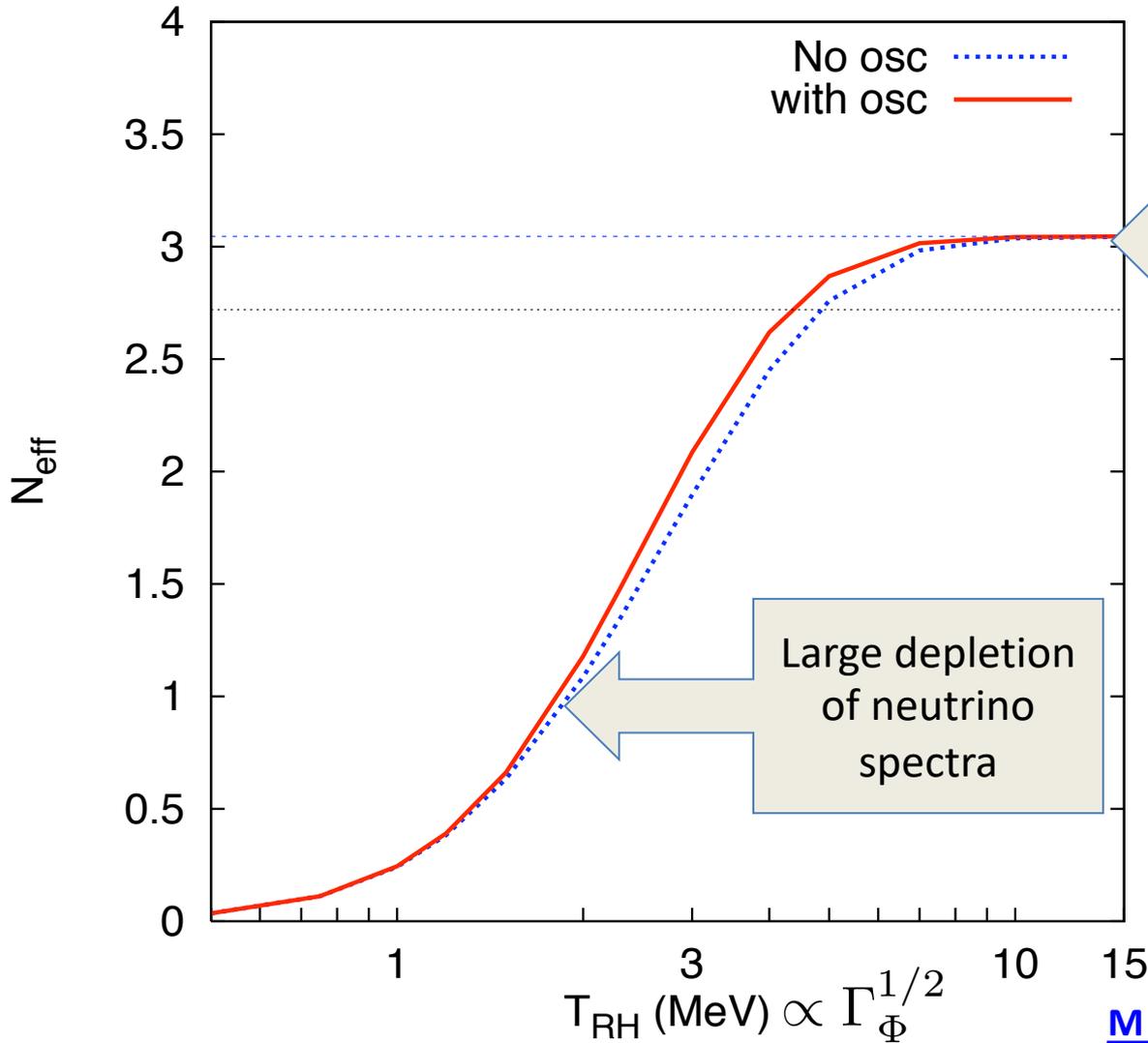
3 neutrino oscillations start to be affected when $T_{\text{rh}} \lesssim 8$ MeV

what about sterile neutrinos?

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



3ν in very low-reheating scenarios



lower bound (95%CL)
on the **reheating**
temperature

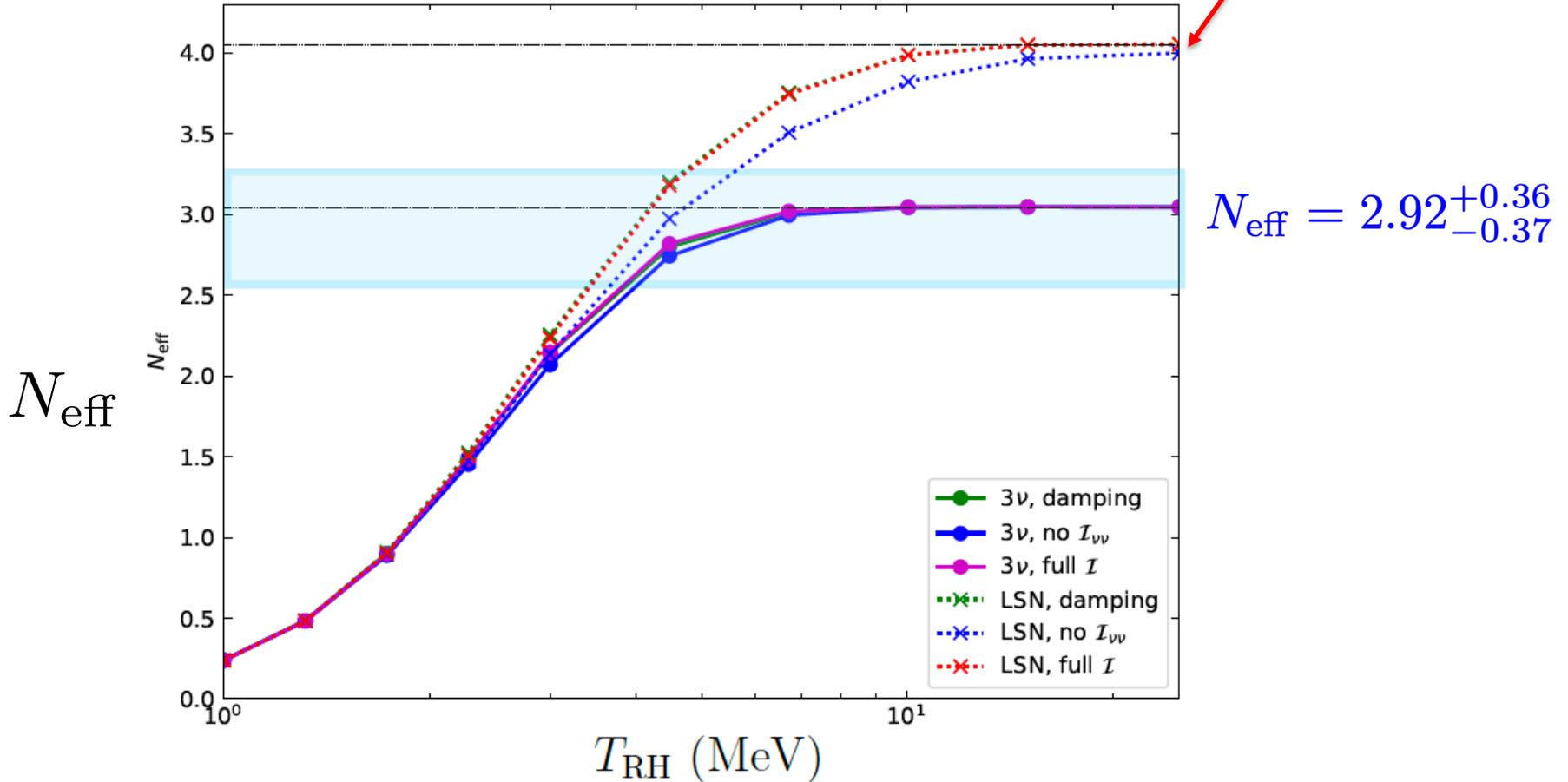
$$T_{\text{RH}} > 4.1 \text{ MeV} \quad (\text{BBN})$$

$$T_{\text{RH}} > 4.7 \text{ MeV} \quad (\text{PlanckTT+ lowP})$$

[M Lattanzi et al, PRD 92 \(2015\) 123534](#)

3+1 case in very low-reheating scenarios

N_{eff} as a function of T_{rh} (3 or 3+1 neutrinos):

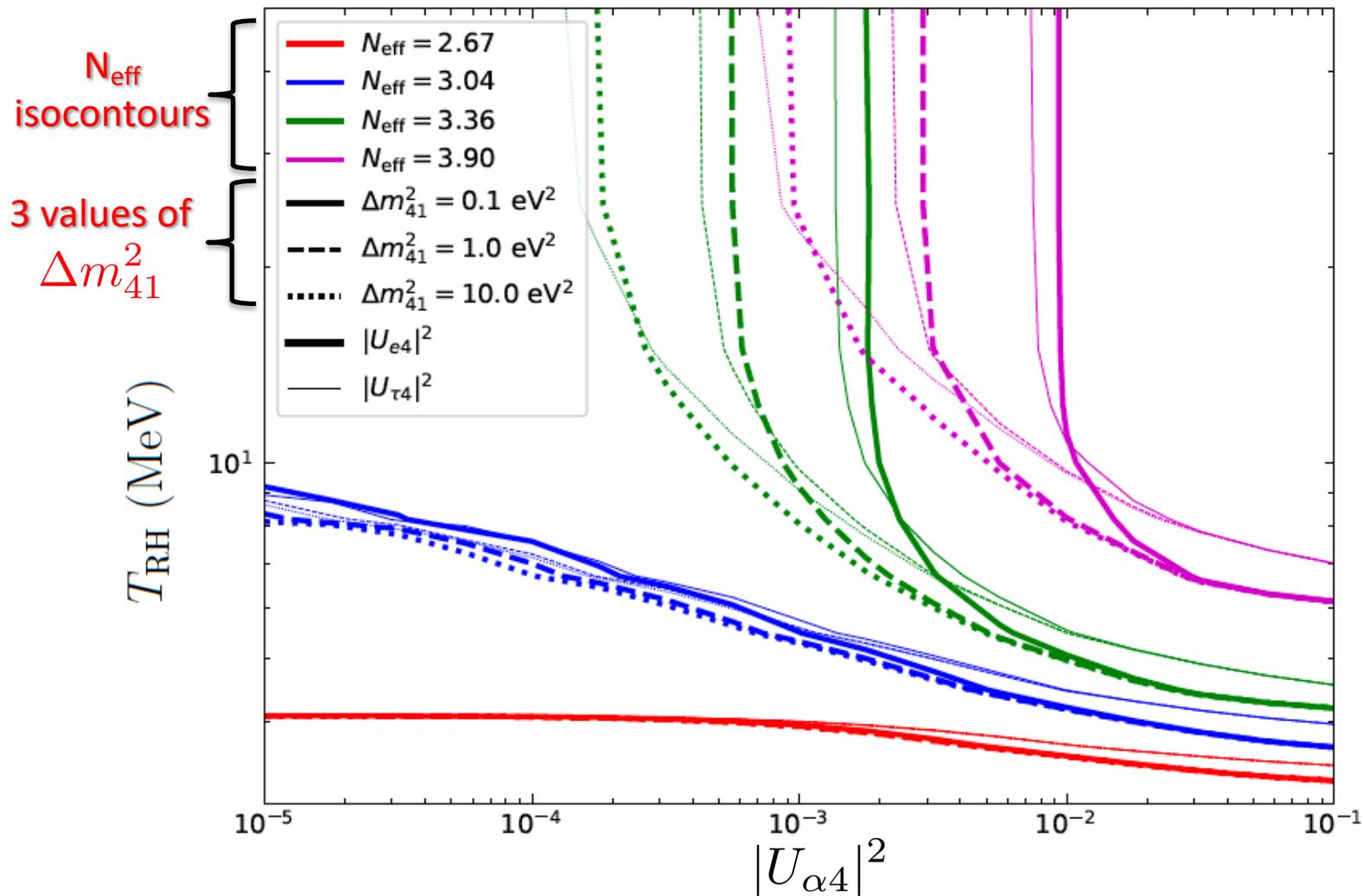


3+1 benchmark case: $\Delta m_{41}^2 = 1 \text{ eV}^2$, $|U_{\tau 4}|^2 = 0.01$, $|U_{e4}|^2 = |U_{\mu 4}|^2 = 0$

T Brinckmann et al, in preparation

N_{eff} with varying mixing angle / mass splitting

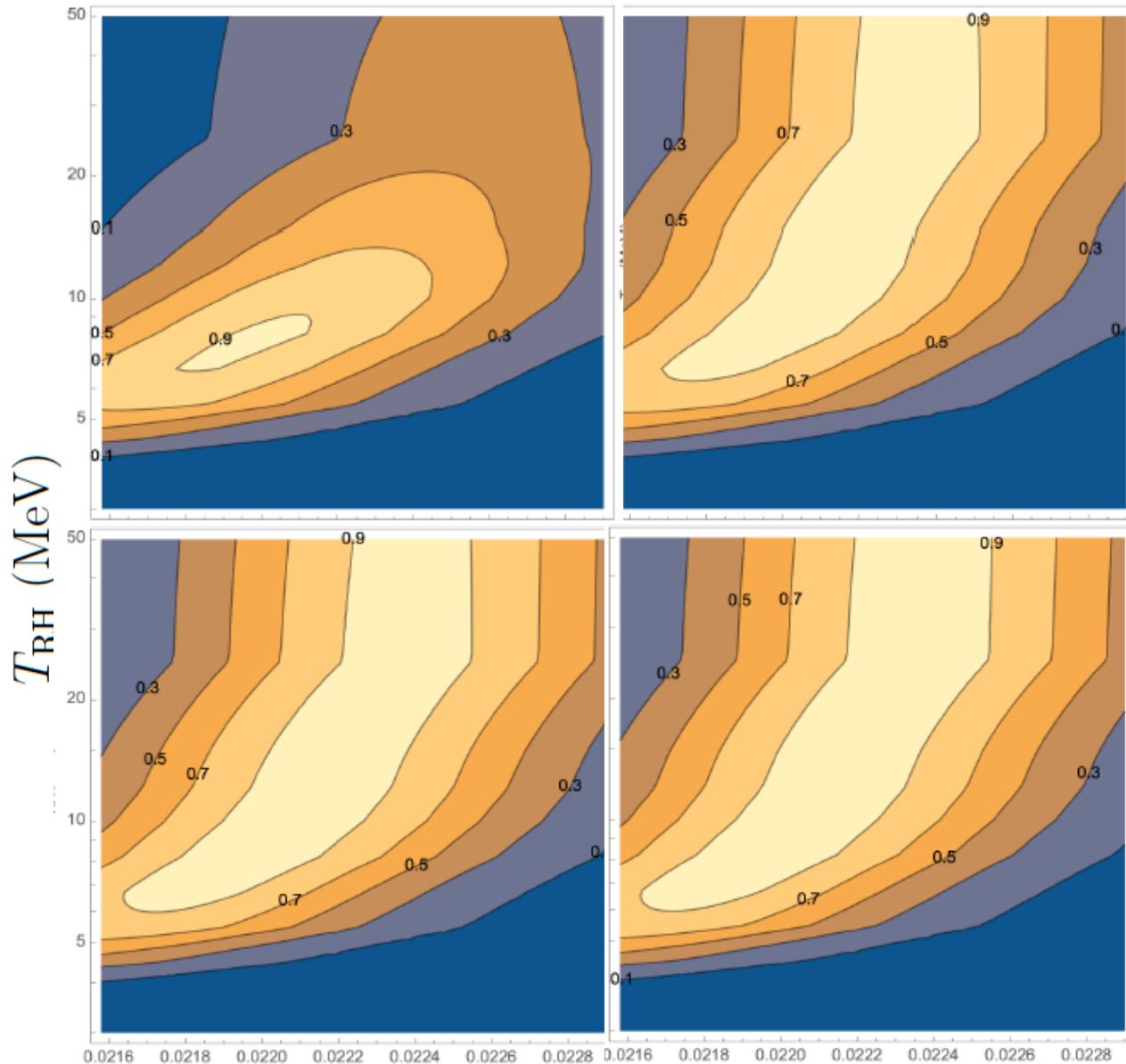
for low T_{rh} , mixing parameters are irrelevant
for higher Δm_{41}^2 , T_{rh} has more impact



T Brinckmann et al, in preparation

$$\Delta m_{41}^2 = 10 \text{ eV}^2$$

$$\Delta m_{41}^2 = 0.1 \text{ eV}^2$$



$$|U_{e4}|^2 = 10^{-4}$$

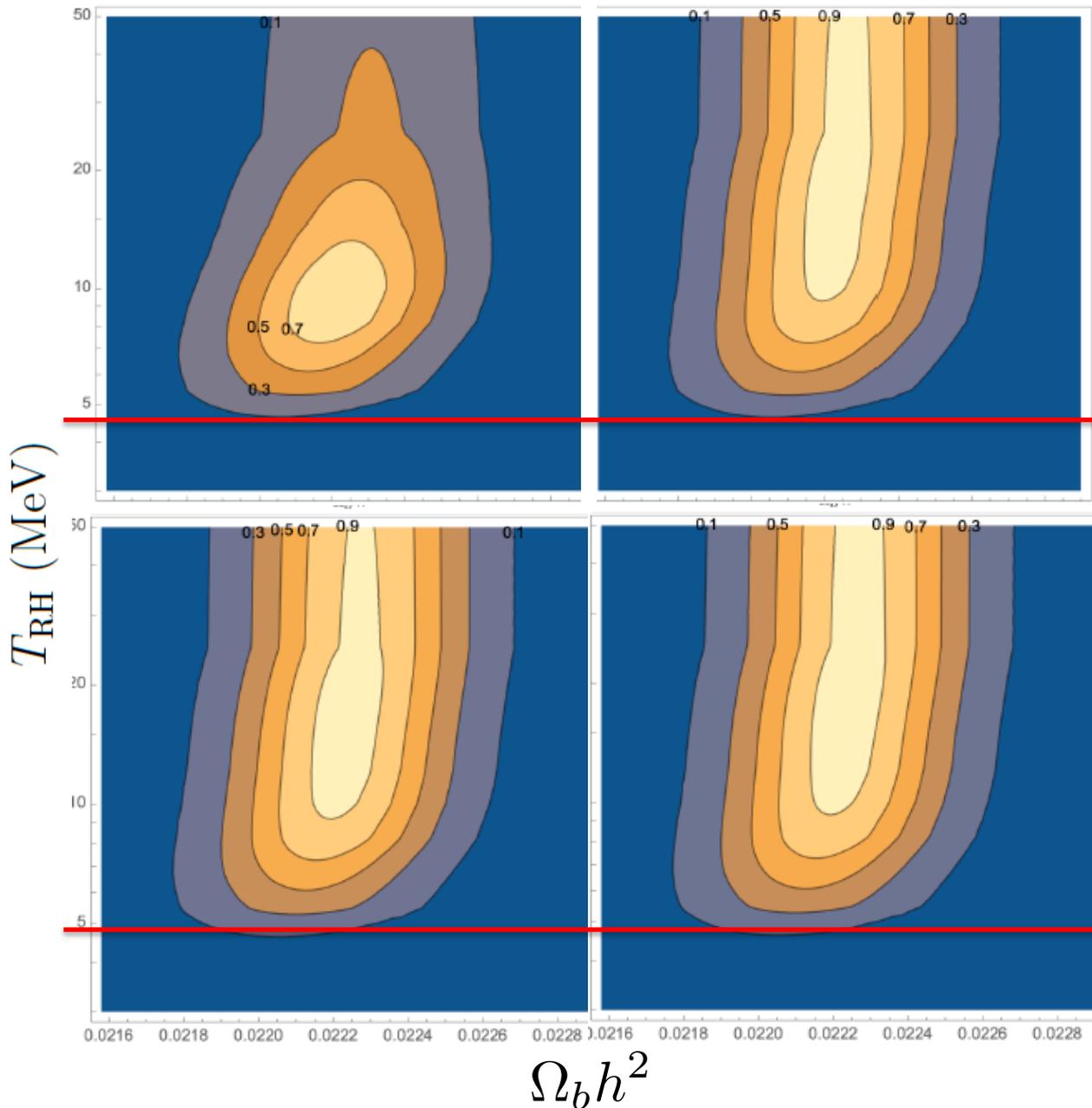
BBN (D+He) only

$$|U_{e4}|^2 = 10^{-5}$$

$$\Omega_b h^2$$

$$\Delta m_{41}^2 = 10 \text{ eV}^2$$

$$\Delta m_{41}^2 = 0.1 \text{ eV}^2$$



$$|U_{e4}|^2 = 10^{-4}$$

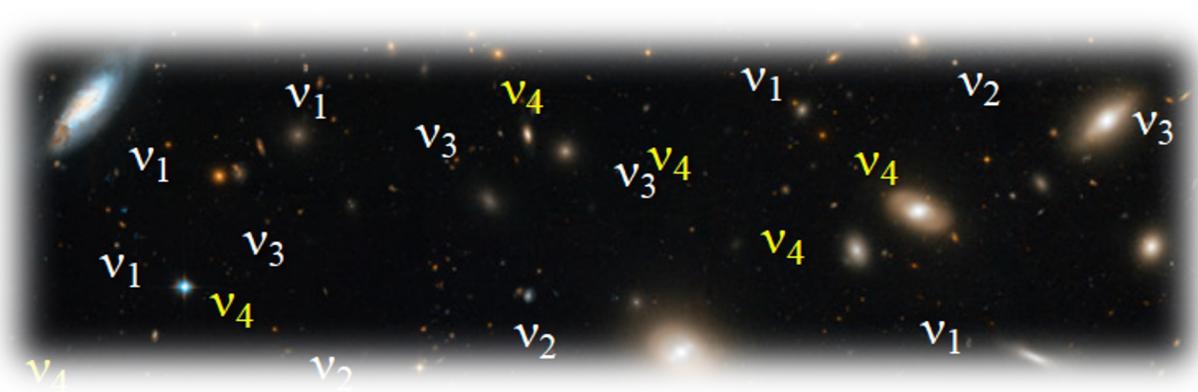
BBN + Planck18 prior

$$|U_{e4}|^2 = 10^{-5}$$

lower bound on the
reheating temperature

$$T_{\text{RH}} \gtrsim 4 \text{ MeV}$$

Conclusions



- ✓ 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} , $m_{\nu, \text{eff}}$)
- ✓ We solved the **momentum-dependent kinetic equations** in the early Universe in the **3+1 neutrino scheme**, including for the first time all neutrino mixings (three active-sterile: θ_{14} , θ_{24} , θ_{34})
- ✓ The **tension** with the cosmological measurement of N_{eff} can be alleviated **in very low reheating scenarios**. The **lower bound on T_{RH}** is almost **independent of the existence of active-sterile mixing**