Light sterile neutrino thermalisation in 3+1 and low reheating scenarios

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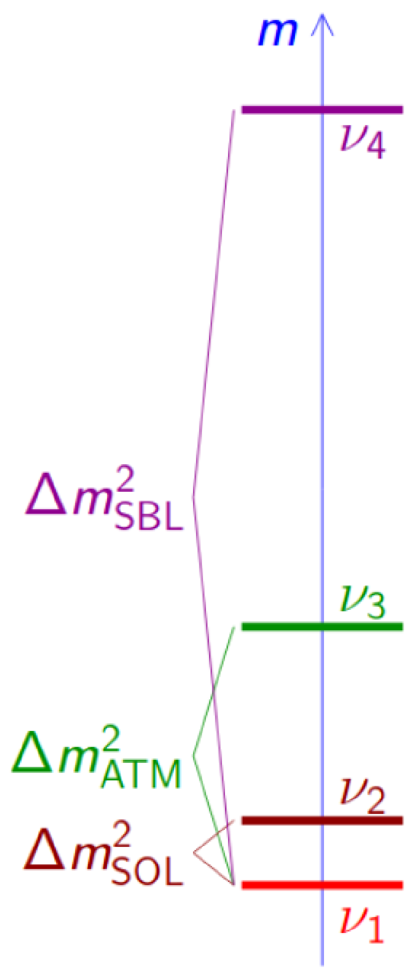
eV-scale sterile neutrino

3+1 model

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

$$|U_{e4}|^2 = \sin^2\theta_{14}$$
$$|U_{\mu4}|^2 = \cos^2\theta_{14}\sin^2\theta_{24}$$
$$|U_{\tau4}|^2 = \cos^2\theta_{14}\cos^2\theta_{24}\sin^2\theta_{34}$$
$$|U_{s4}|^2 = \cos^2\theta_{14}\cos^2\theta_{24}\cos^2\theta_{34}$$

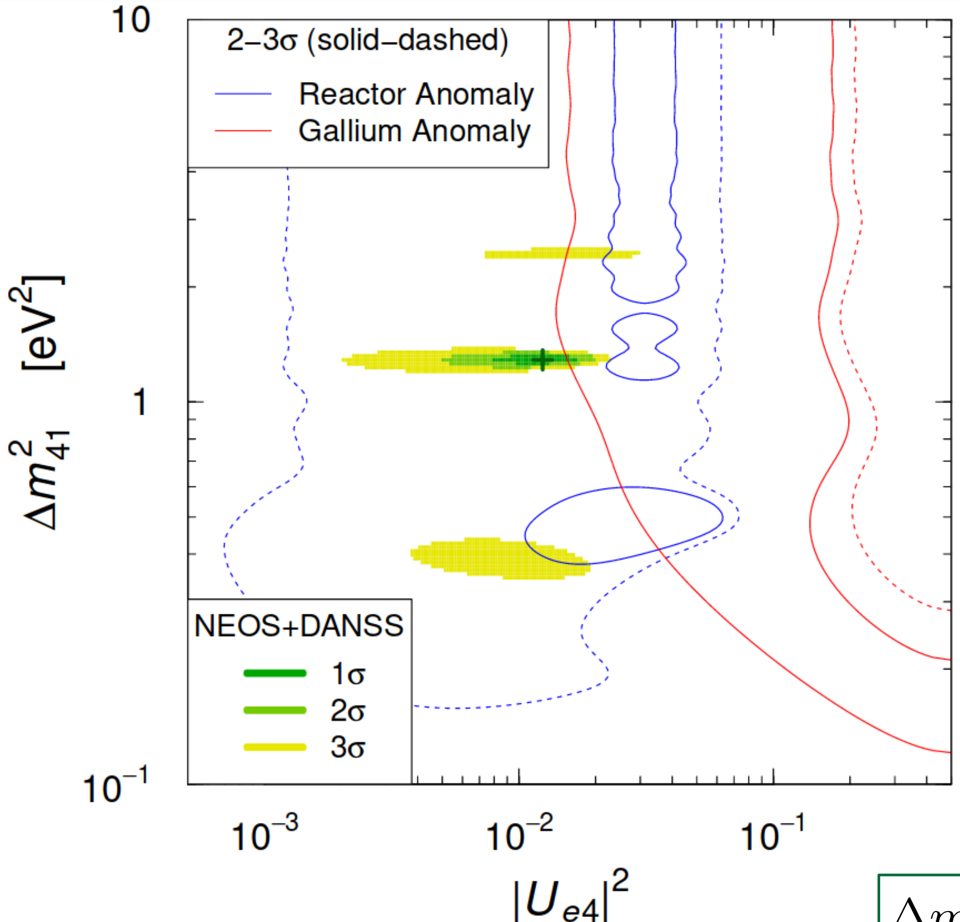


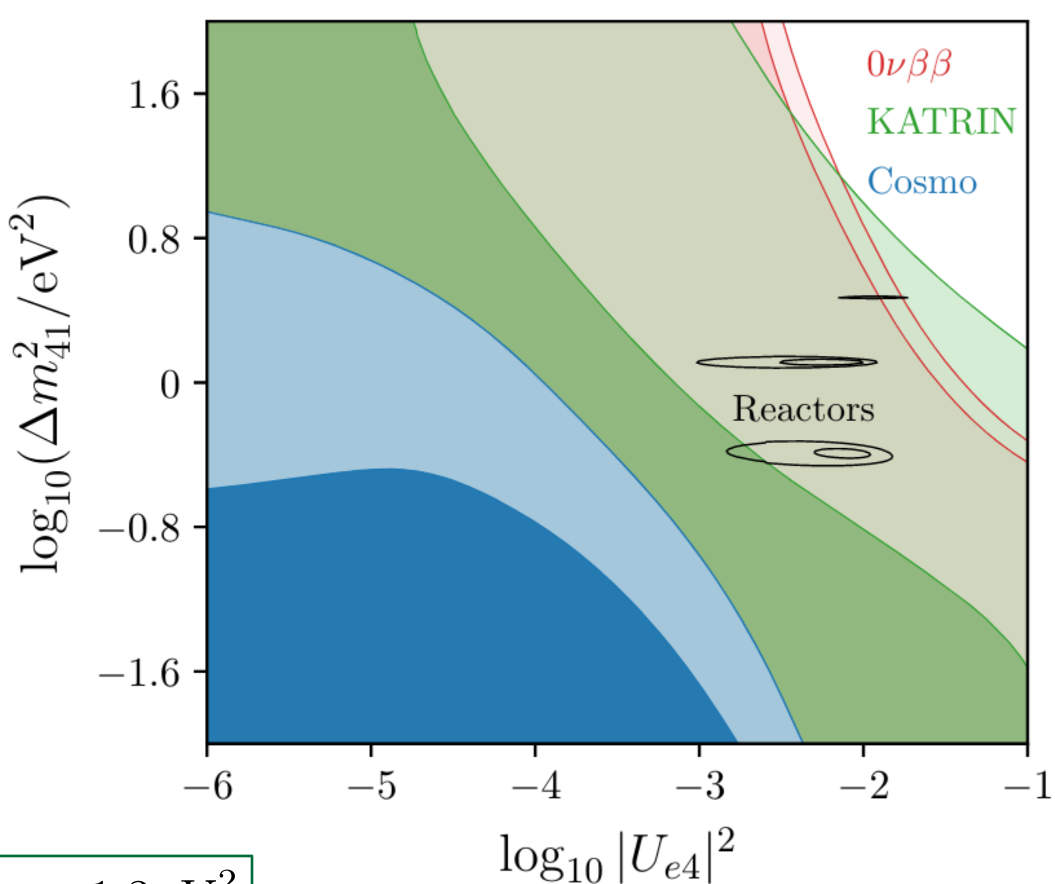
$3_{NO}+1$

C. Giunti and T. Lasserre, arXiv:1901.08330

eV-scale sterile neutrino

3+1 model





S. Gariazzo et al., PLB 782 (2018) 13

See also M. Dentler et al., JHEP 08 (2018) 010

$$\Delta m^2_{41} \simeq 1.3\,\mathrm{eV}^2$$
$$|U_{e4}|^2 \simeq 0.01$$

S. Hagstotz, PFdS et al. arXiv:2003.02289

eV-scale sterile neutrino

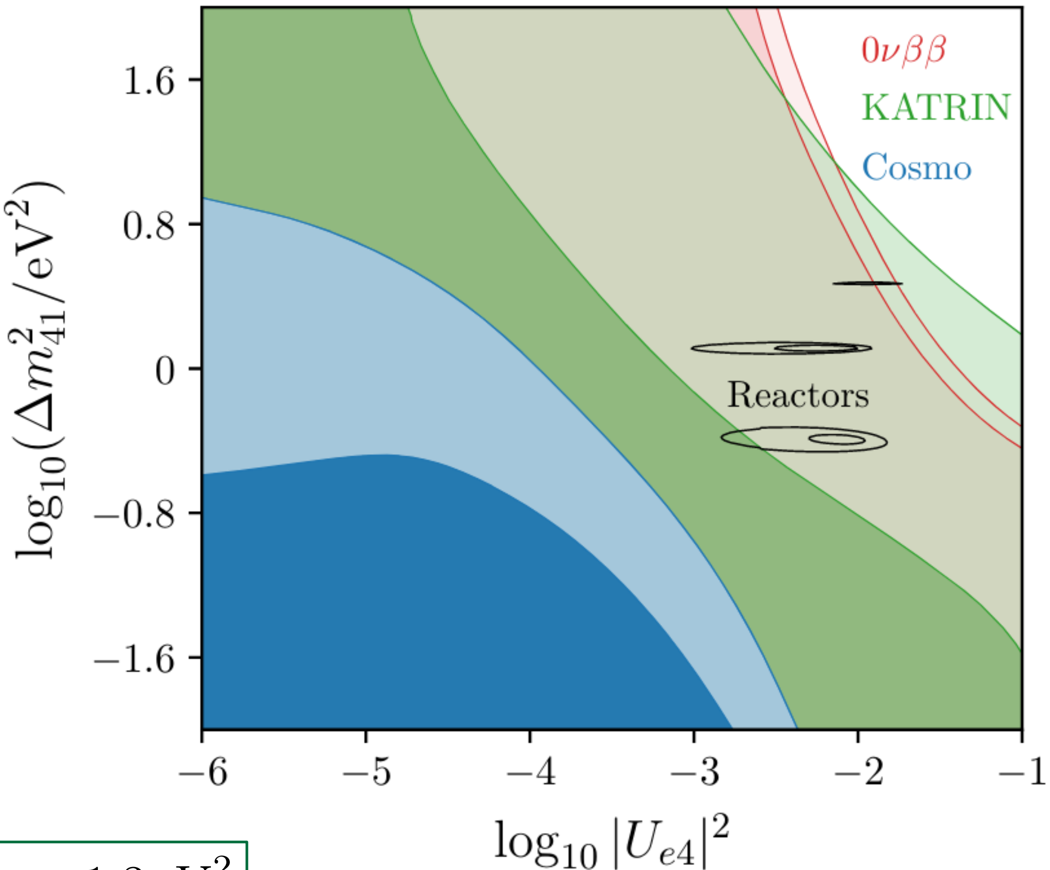
3+1 model

Tension with cosmology:

- sterile neutrino would be **fully thermalised** for the parameter space that could explain SBL anomalies.

Thermalisation of ν_s reduced in **low-reheating scenarios**

G. Gelmini et al., PRL 93 (2004) 081302



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$$|U_{e4}|^2 \simeq 0.01$$

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Effective number of neutrinos

$N_{\rm eff}$ accounts for any contribution to radiation other than photons

$$\rho_{\rm r} = \rho_\gamma + \rho_\nu + \rho_x$$

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

Planck 2018, 95% CL [arXiv:1807.06209]

$$N_{\rm eff} = 3.00^{+0.57}_{-0.53} \quad \rm TT + lowE$$

$$N_{\rm eff} = 2.92^{+0.36}_{-0.37} \quad \rm TT, TE, EE + lowE$$

$$N_{\rm eff} = 2.89^{+0.36}_{-0.38} \quad \rm TT, TE, EE + lowE + lensing$$

$$N_{\rm eff} = 2.99^{+0.34}_{-0.33} \quad \rm TT, TE, EE + lowE + lensing + BAO$$

Standard scenario: only neutrinos $N_{\rm eff}$ = 3.045

[PFdS & S. Pastor, JCAP 07 (2016) 051, arXiv:1606.06986]

Standard value of N_{eff}

To appear soon!

Key aspects of the update:

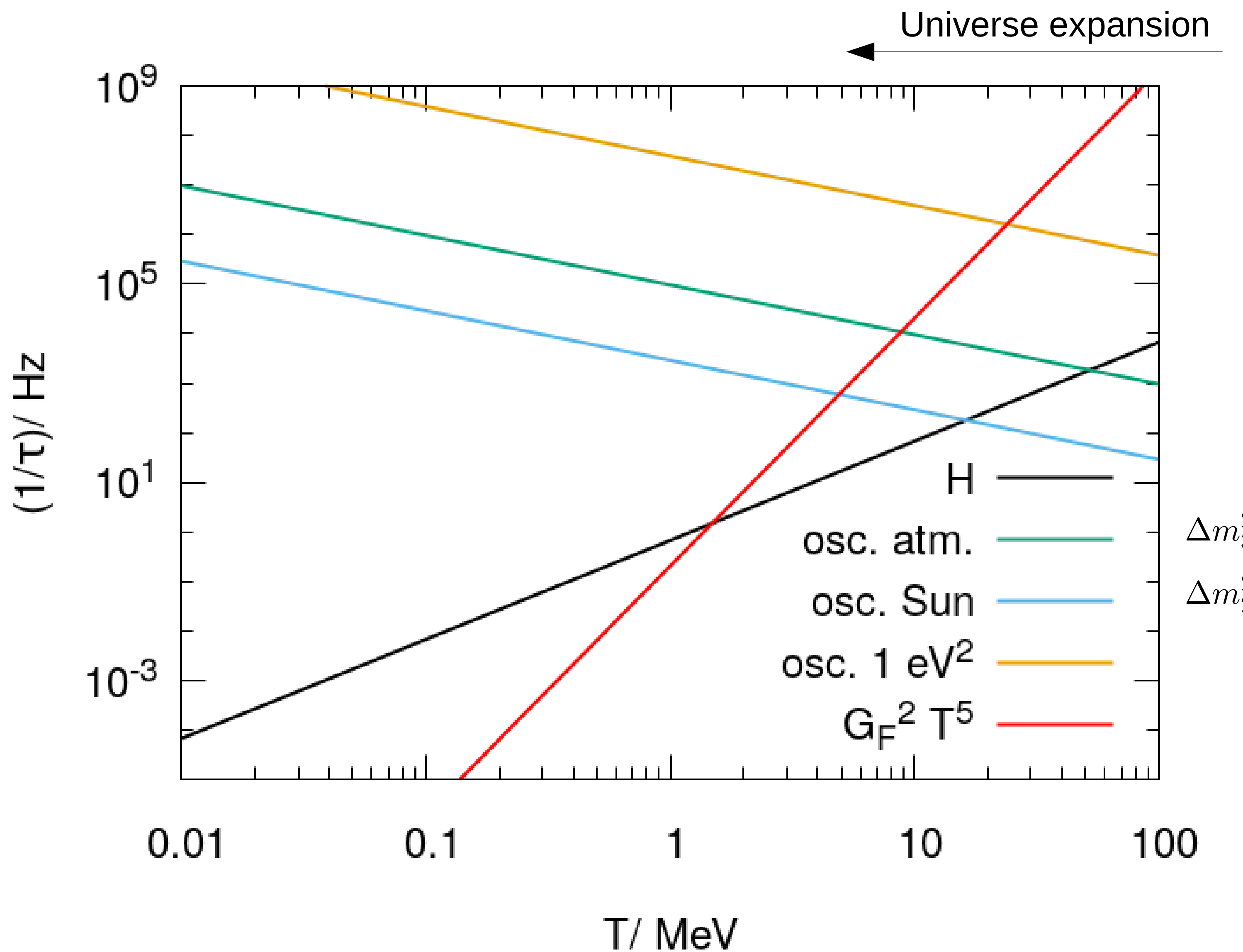
- Subdominant QED finite-temperature corrections $\mathcal{O}(e^3)$
  [J.J. Bennett, G. Buldgen, M. Drewes, and Y. Y. Y. Wong, arXiv:1911.04504]
- Complete neutrino-neutrino integrals – including off-diagonal entries!
- Thorough assessment of uncertainties
- **FortEPiaNO** [S. Gariazzo, PFdS, S. Pastor, arXiv1905.11290]

$$N_{\rm eff} = 3.043\mathrm{X} \pm 0.000\mathrm{E}$$

[J.J. Bennett, G. Buldgen, PFdS, M. Drewes, S. Gariazzo, S. Pastor, and Y.Y.Y. Wong]

To appear soon!

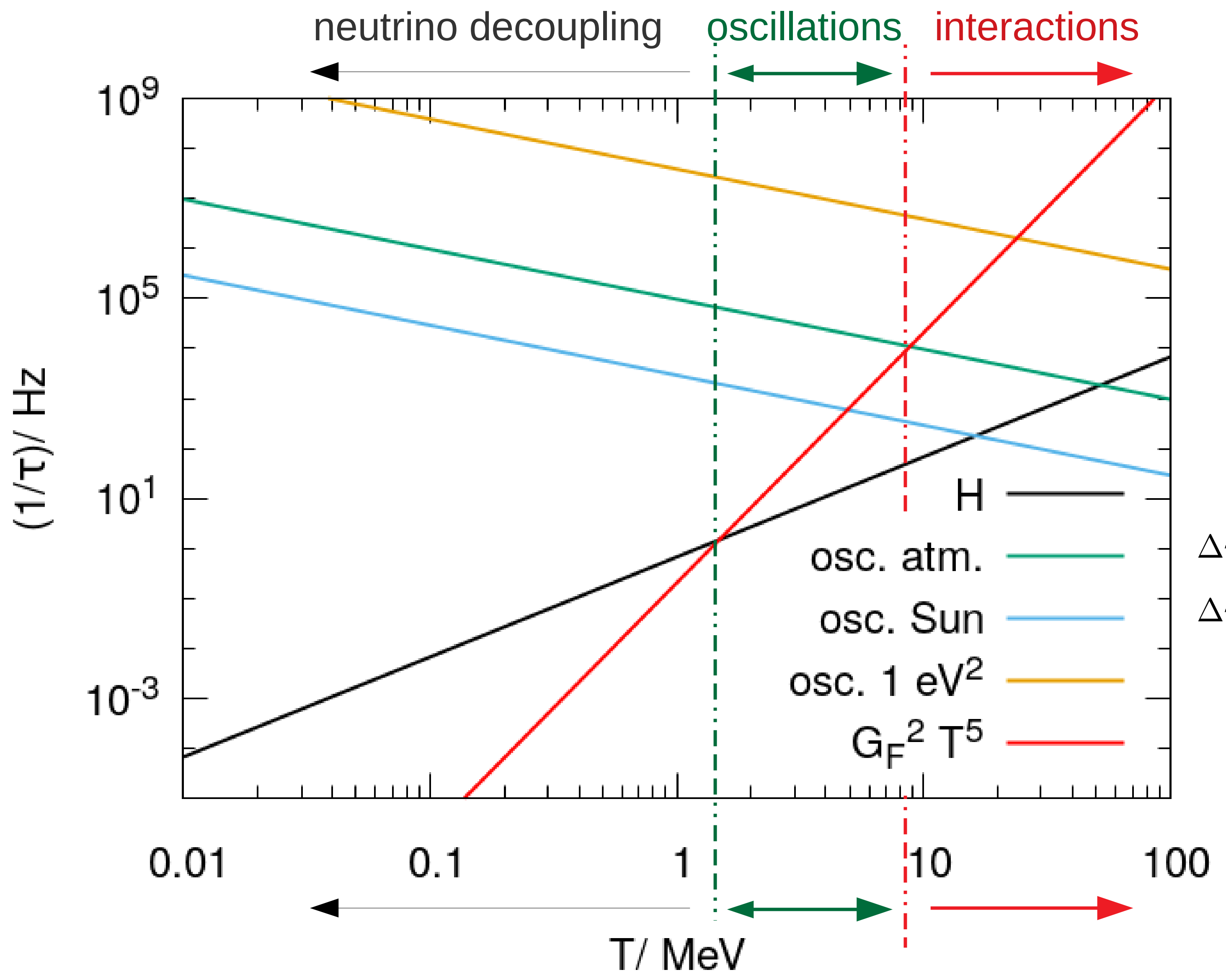
Interactions + oscillations + expanding Universe



$\Delta m^2_{31} \sim 2.5 \cdot 10^{-3}\,\mathrm{eV}^2$

$\Delta m^2_{21} \sim 7.5 \cdot 10^{-5}\,\mathrm{eV}^2$

Interactions + oscillations + expanding Universe



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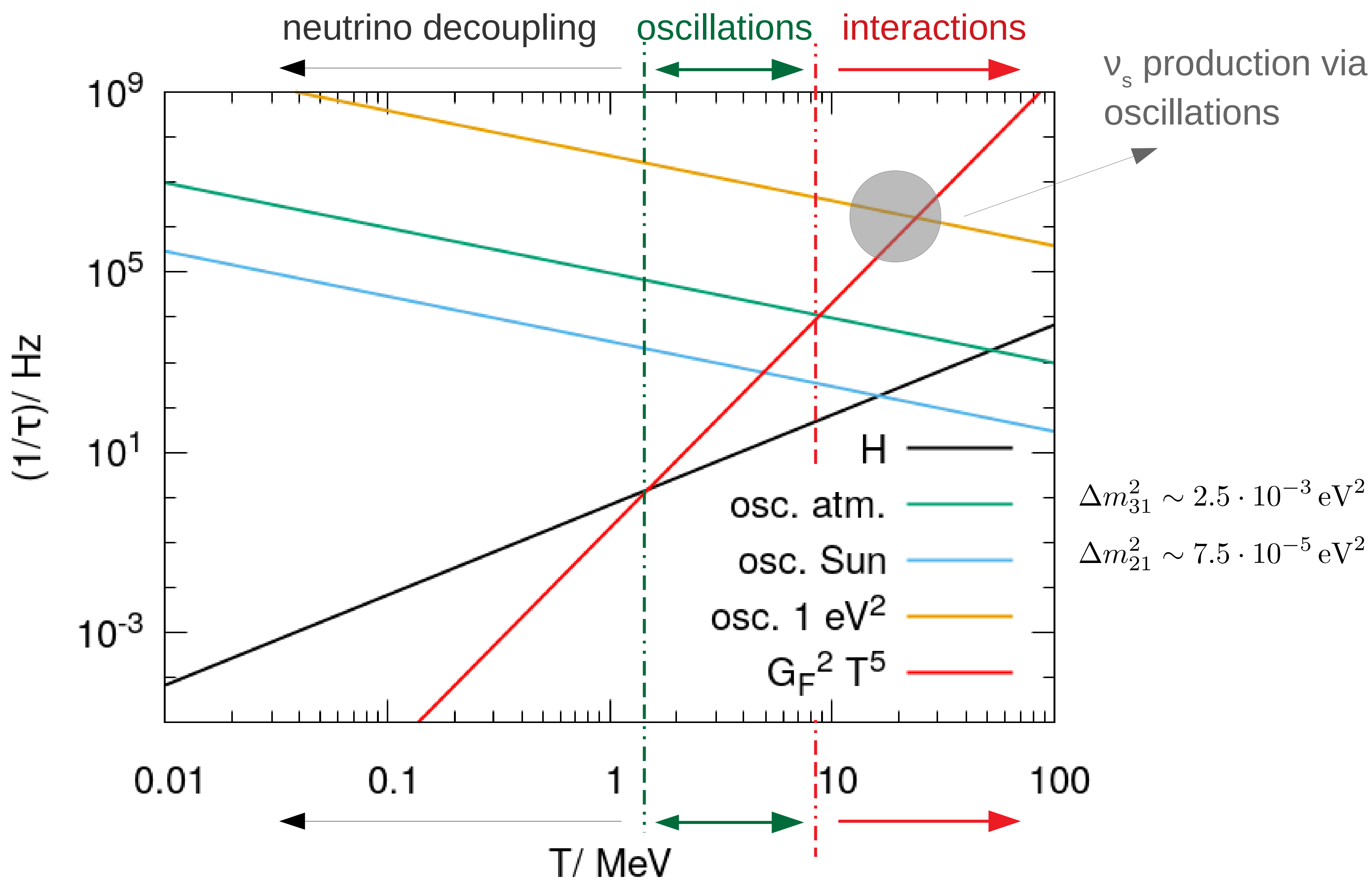
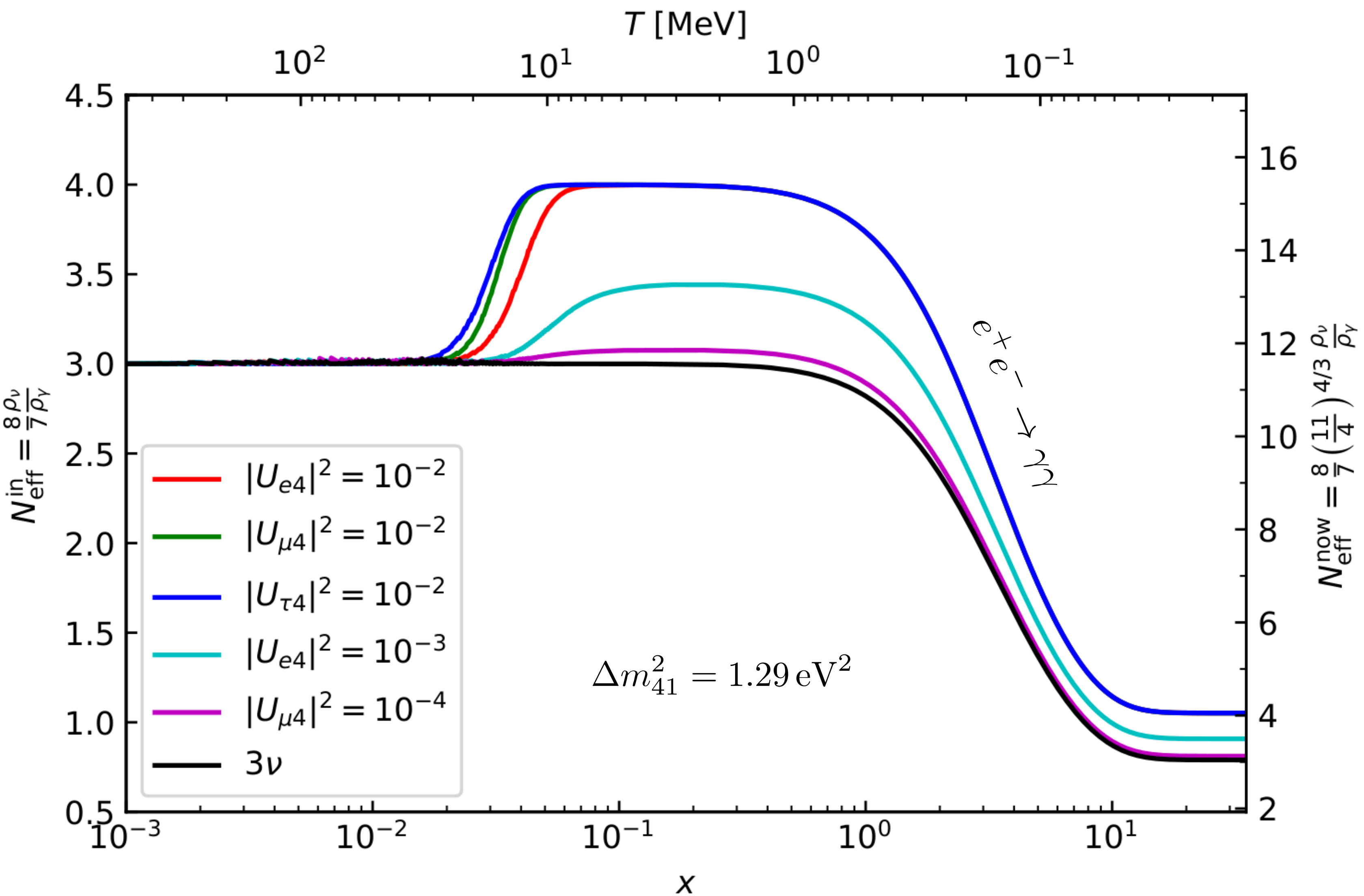


$\Delta m^2_{31} \sim 2.5 \cdot 10^{-3}\,\mathrm{eV}^2$

$\Delta m^2_{21} \sim 7.5 \cdot 10^{-5}\,\mathrm{eV}^2$

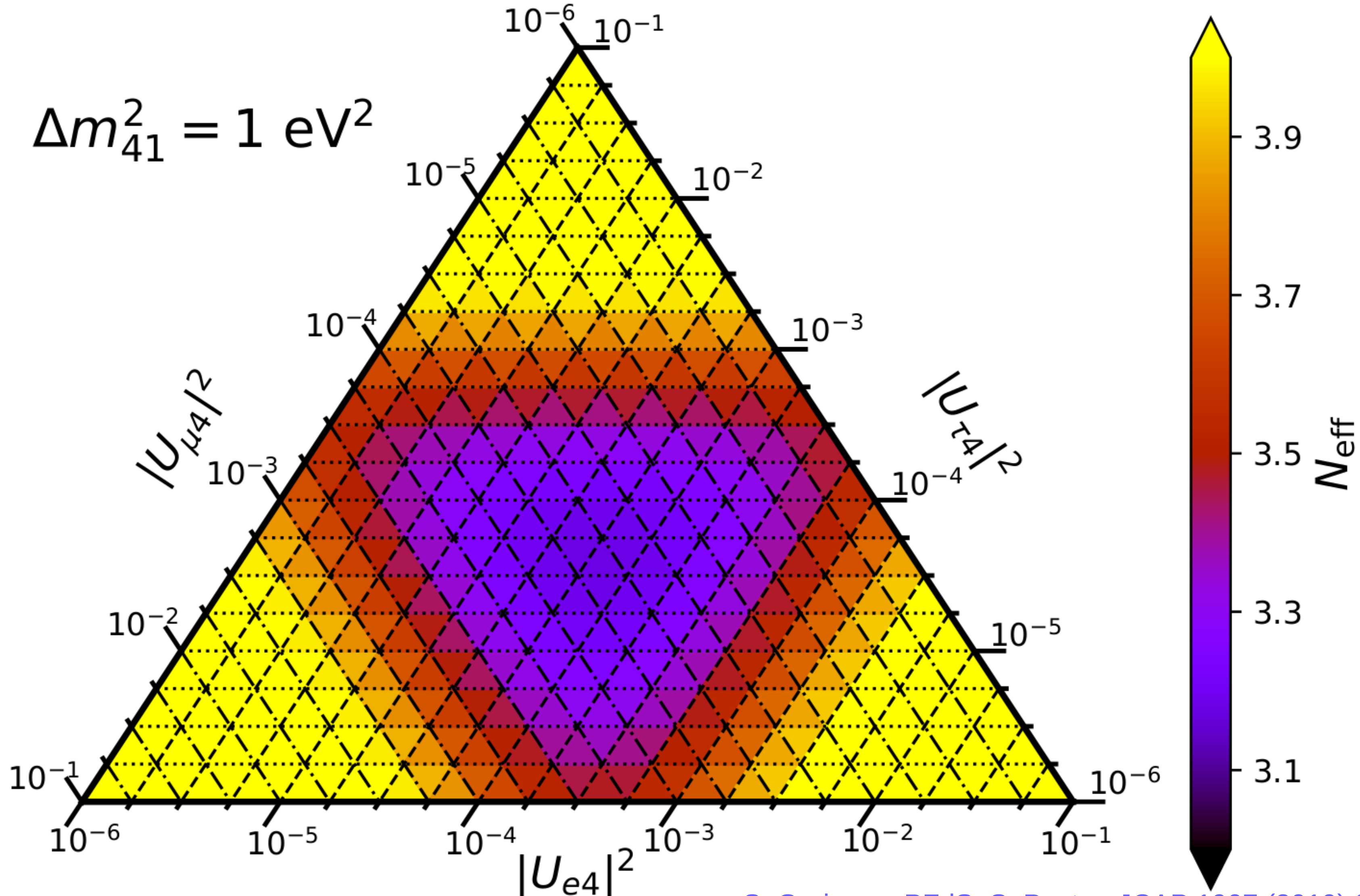
N_{eff} in presence of a sterile



$3 \lesssim N_{eff} \lesssim 4$ depending on the mixing angle and Δm^2_{41}

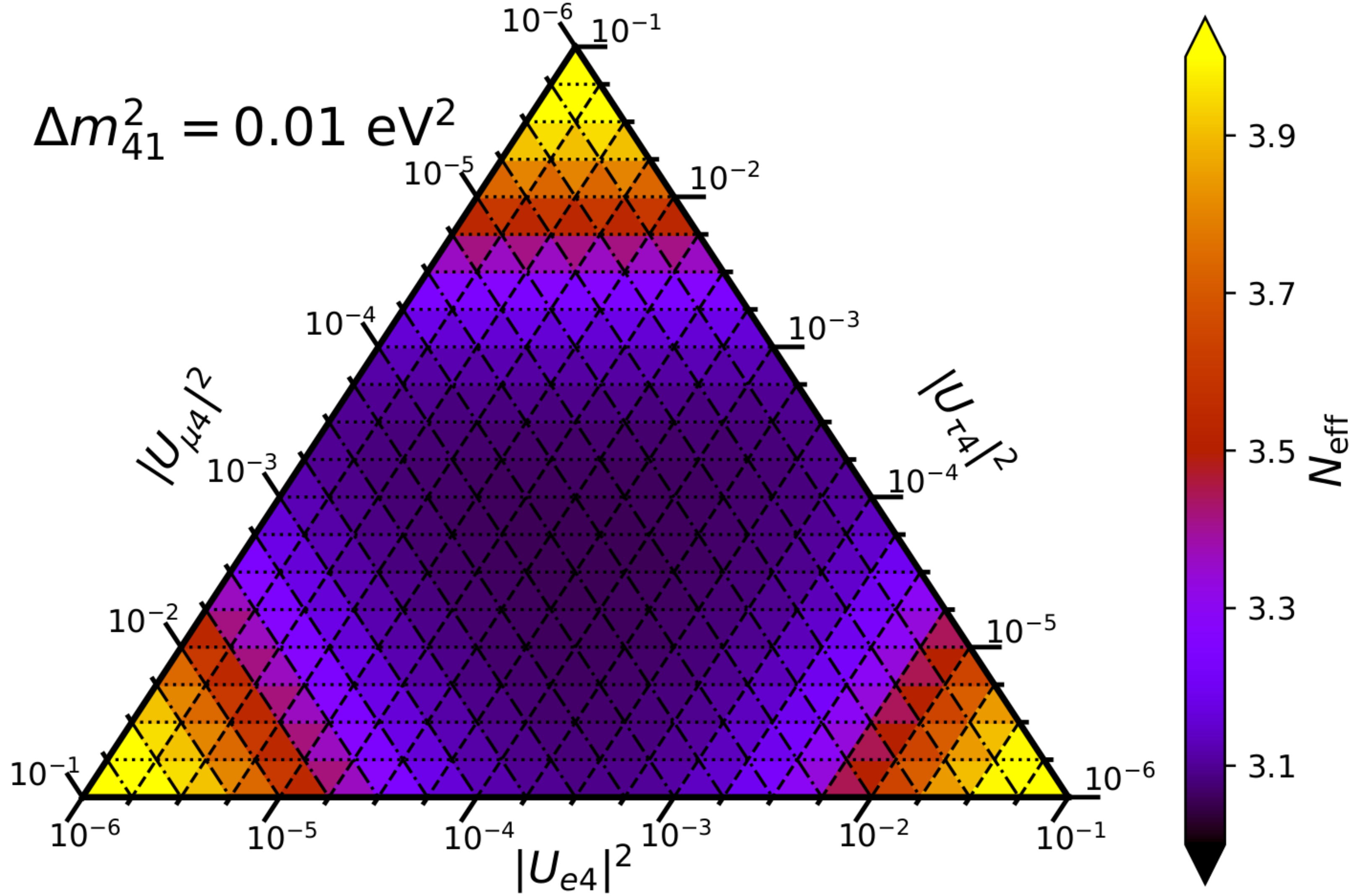
S. Gariazzo, PFdS, S. Pastor, JCAP 1907 (2019) 014

N_{eff} tri-angle planes



S. Gariazzo, PFdS, S. Pastor, JCAP 1907 (2019) 014

N_{eff} tri-angle planes



S. Gariazzo, PFdS, S. Pastor, JCAP 1907 (2019) 014

Low-reheating scenarios

- Last radiation-dominated era arises from the decaying of a massive particle ϕ

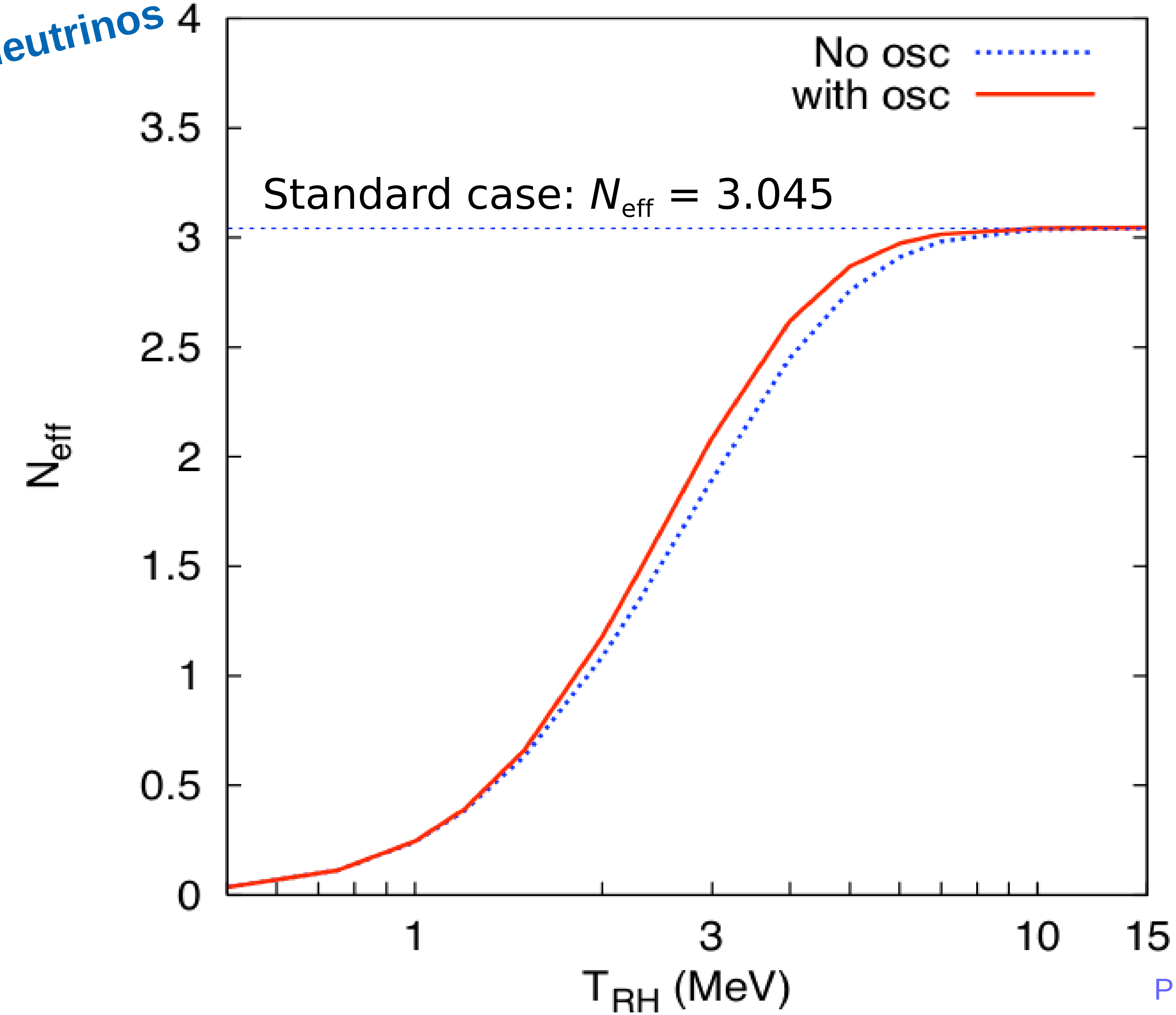
$$\Gamma_\phi = 3H(T_{\rm RH})$$

- We assume that **ϕ decays into relativistic particles** other than neutrinos
- Neutrinos will be populated via weak interactions with charged leptons

- For $T_{\rm RH}$ ~ MeV, neutrinos might not completely thermalise

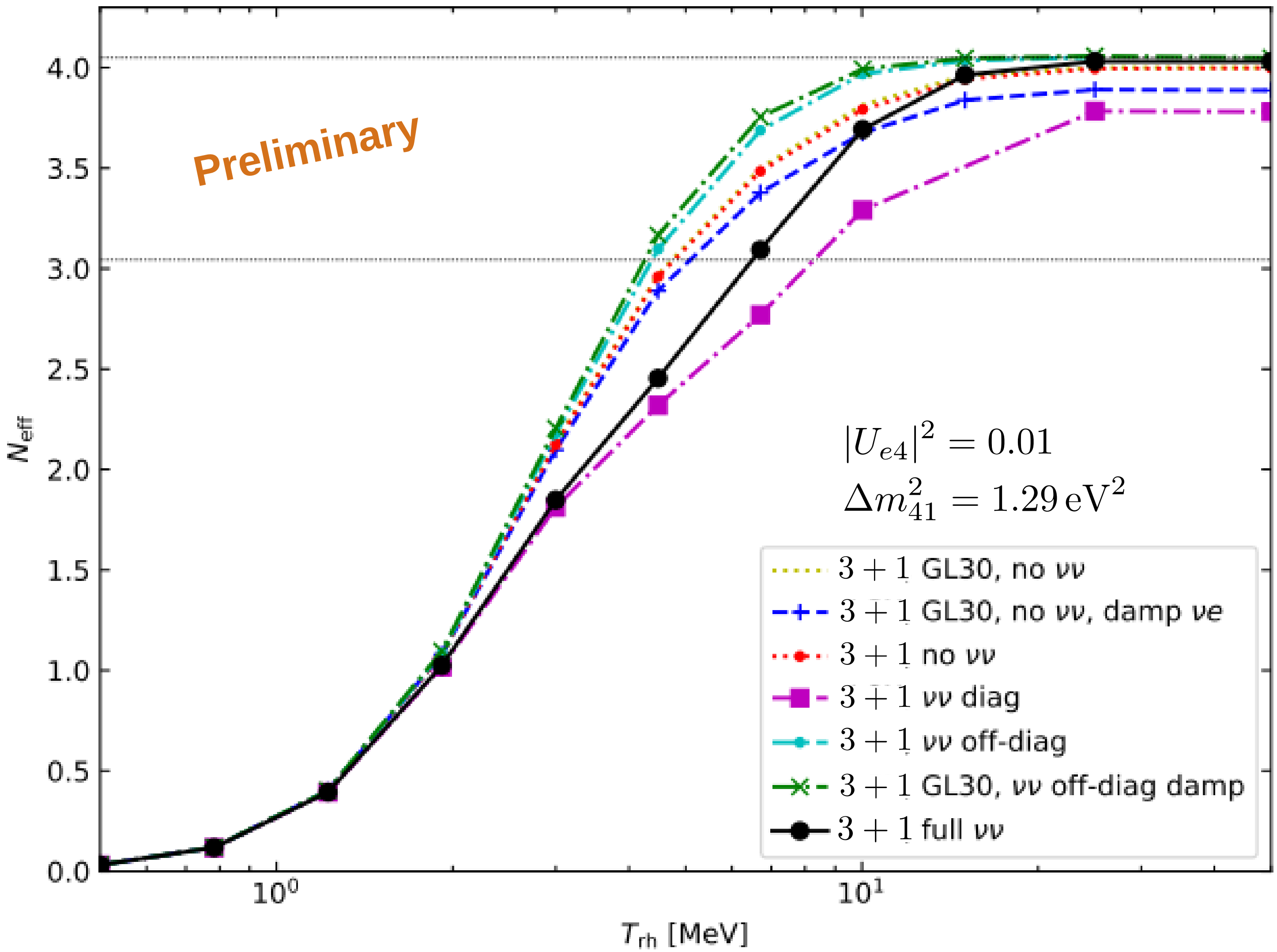
N_{eff} in low-reheating scenarios

Standard neutrinos



PFdS et al, PRD 92 (2015)

N_{eff} in low-reheating scenarios



PFdS, M. Fernández Navarro, S. Gariazzo, M. Lattanzi, S. Pastor, and O. Pisanti, In progress

Conclusions

- A **~1 eV sterile neutrino** might be needed to solve (at least some) **oscillation anomalies**

- The presence of a ~1 eV sterile neutrino **adds up to $\Delta N_{\mathrm{eff}} \simeq 1$**

- We have solved the **momentum-dependent kinetic equations** of neutrino thermalisation in the **3+1 scenario**

  FortEPiaNO

  [S. Gariazzo, PFdS, S. Pastor, JCAP 1907 (2019) 014]

- **For the first time** we include **all neutrino mixing angles** in the 3+1 scheme

- **Low-reheating scenarios** could **alleviate tension with cosmology**

Supplementary slides

Neutrino decoupling and e^+e^- annihilations

Standard neutrinos

Instantaneous decoupling approximation

$$T = T_\gamma = T_\nu$$

$$f_\nu = \frac{1}{\exp\left(p/T\right) + 1}$$

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

$$f_\nu = \frac{1}{\exp\left(p/T_\nu\right) + 1}$$

10 MeV

1 MeV

nucleosynthesis

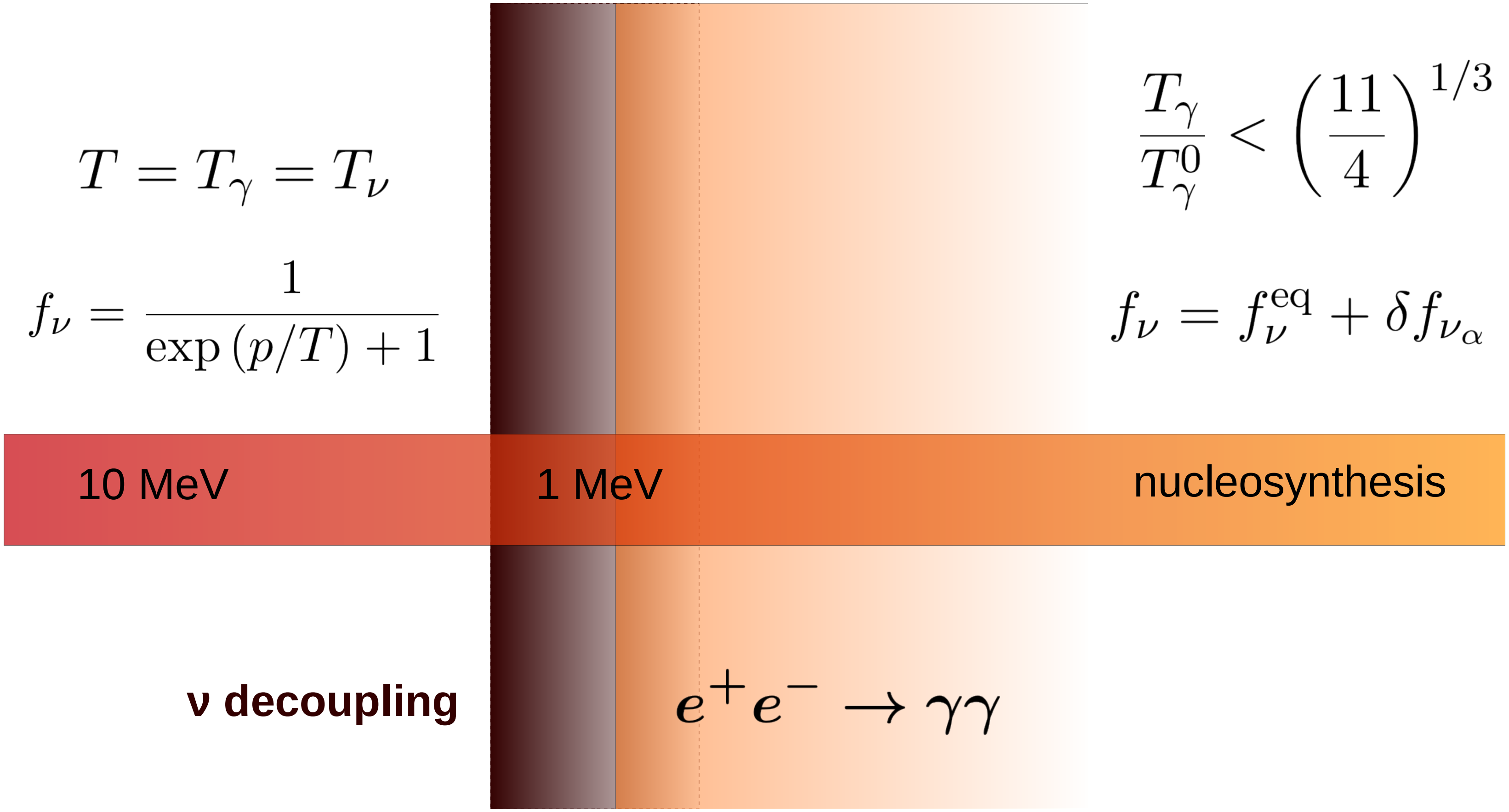
ν decoupling

$$e^+e^- \to \gamma\gamma$$

Beyond instantaneous decoupling approximation

Standard neutrinos

ν decoupling depends on momentum (small spectral distortions)



$$T = T_\gamma = T_\nu$$

$$f_\nu = \frac{1}{\exp{(p/T)} + 1}$$

$$\frac{T_\gamma}{T_\gamma^0} < \left(\frac{11}{4}\right)^{1/3}$$

$$f_\nu = f_\nu^{\rm eq} + \delta f_{\nu_\alpha}$$

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

Computing neutrino decoupling

Density matrix formalism

$$\varrho_p = \begin{pmatrix} \varrho_{ee} & \varrho_{e\mu} & \varrho_{e\tau} & \varrho_{es} \\ \varrho_{\mu e} & \varrho_{\mu\mu} & \varrho_{\mu\tau} & \varrho_{\mu s} \\ \varrho_{\tau e} & \varrho_{\tau\mu} & \varrho_{\tau\tau} & \varrho_{\tau s} \\ \varrho_{se} & \varrho_{s\mu} & \varrho_{s\tau} & \varrho_{ss} \end{pmatrix}$$

Fluid equation

$$\frac{\mathrm{d}\rho}{\mathrm{d}t} = -3H\left(\rho + P\right)$$

Diagonal terms: occupation numbers

off-diagonal terms: non-zero when oscillations are present

Solve Boltzmann equations with Icoll ≠ 0

Vacuum

Matter

$$\left(\partial_t - Hp\partial_p\right)\varrho_p = -i\frac{1}{2p}\left[\left(\mathbb{M}_F - 2p\frac{8\sqrt{2}G_F p}{3m_W^2}\rho_{e\underline{\underline{\varepsilon}}}\right), \varrho_p\right] + I_{\mathrm{coll}}\left[\varrho_p\right]$$

Expanding Universe

Oscillations

Interactions

Computing neutrino decoupling

Collision integrals

- Reduce analytically the integrals from 9 to 2 dimensions
- Solve numerically with a grid on the incoming neutrino momentum
- Code: **FORTran-Evolved PrimordIAl Neutrino Oscillations**

FortEPiaNO

[S. Gariazzo, PFdS, S. Pastor, JCAP 1907 (2019) 014]

Solve Boltzmann equations with $I_{coll} \neq 0$

Vacuum — Matter

$$(\partial_t - Hp\partial_p)\,\varrho_p = -i\frac{1}{2p}\left[\left(\mathbb{M}_F - 2p\frac{8\sqrt{2}G_F p}{3m_W^2}\rho_{e\underline{\underline{\mathcal{E}}}}\right), \varrho_p\right] + I_{\rm coll}\left[\varrho_p\right]$$

Expanding Universe — Oscillations — Interactions

Comoving variables

$x = m_e R$ $\quad y = pR$ $\quad z = T_\gamma R$

scale factor $R = 1/T_\nu$

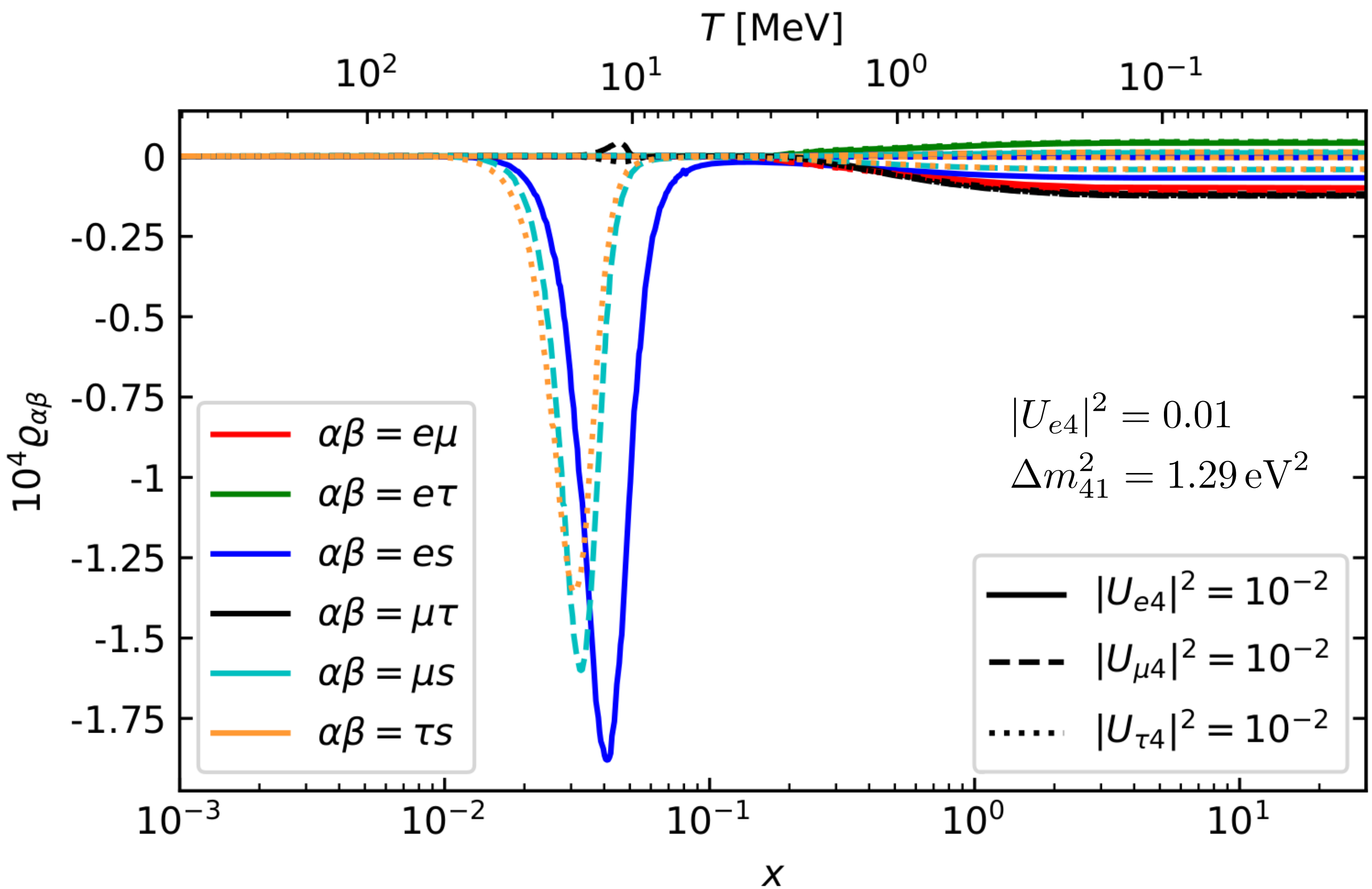
Sterile population depends on mixing angle

Sterile population depends on mixing angle

Reason:
Oscillation is suppressed in presence of large matter effects

Order of relevance

$$\theta_{34}\ \theta_{24}\ \theta_{14}$$



S. Gariazzo, PFdS, S. Pastor, JCAP 1907 (2019) 014

Implications of low-reheating scenarios

Primordial Nucleosynthesis

- **A modification in ρ_ν implies a modification in the Hubble expansion rate**
  - Slower expansion rate → n/p freezes out **later** → **less** light nuclei

$$\rho_R = \left(1 + N_{\rm eff}\,\frac{7}{8}\left(\frac{4}{11}\right)^{4/3}\right)\rho_\gamma$$

No oscillation dependent

- **A deviation in f_{ν_e} changes the neutron-proton (n/p) chemical equilibrium**
  - Slower $\Gamma_{n\to p}$ rate → n/p freezes out **earlier** → **more** light nuclei

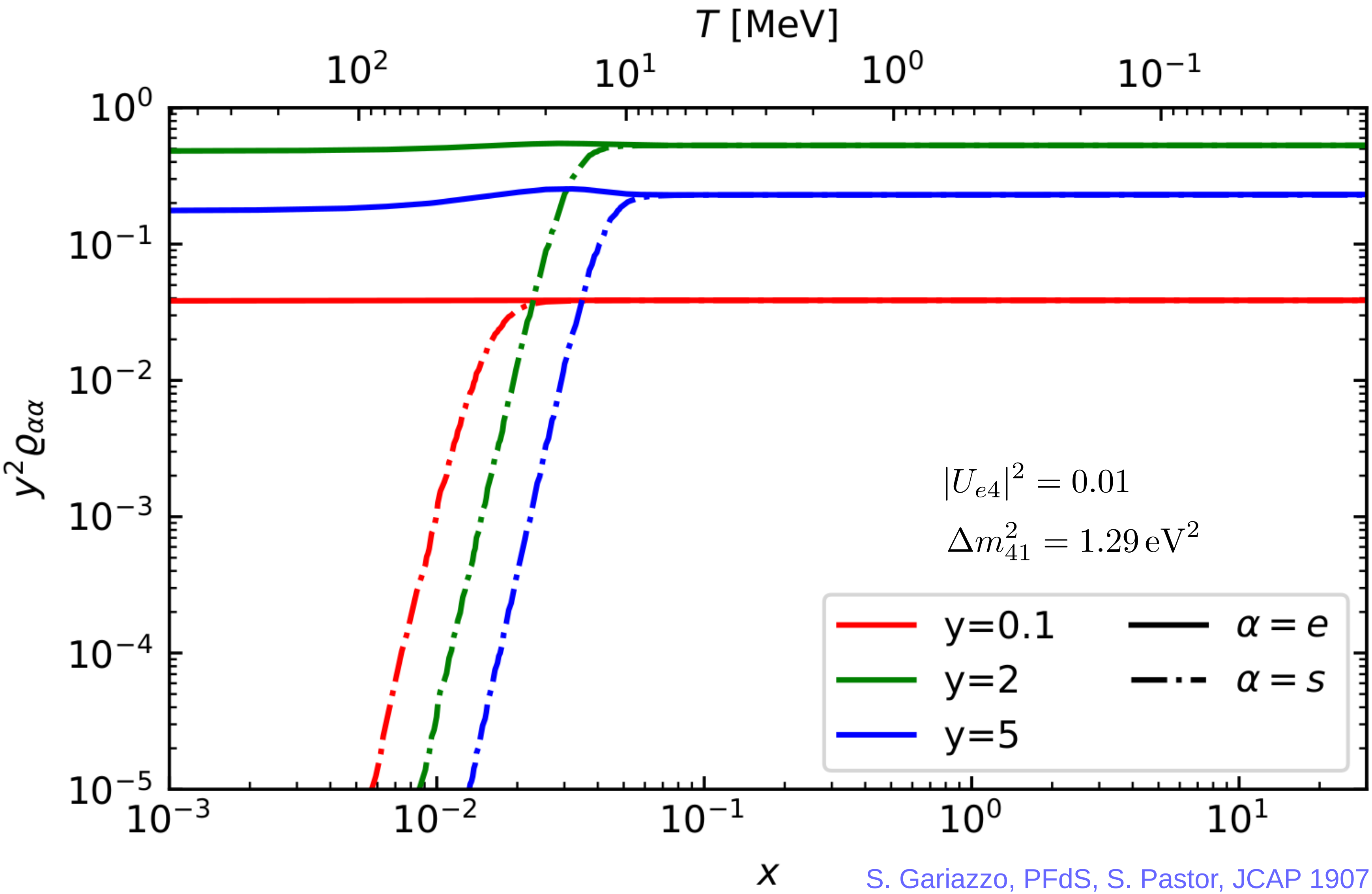
$$n \leftrightarrows p + e^- + \bar\nu_e$$

$$\nu_e + n \leftrightarrows p + e^-$$

$$e^+ + n \leftrightarrows p + \bar\nu_e$$

Oscillation dependent

Larger energies are populated later



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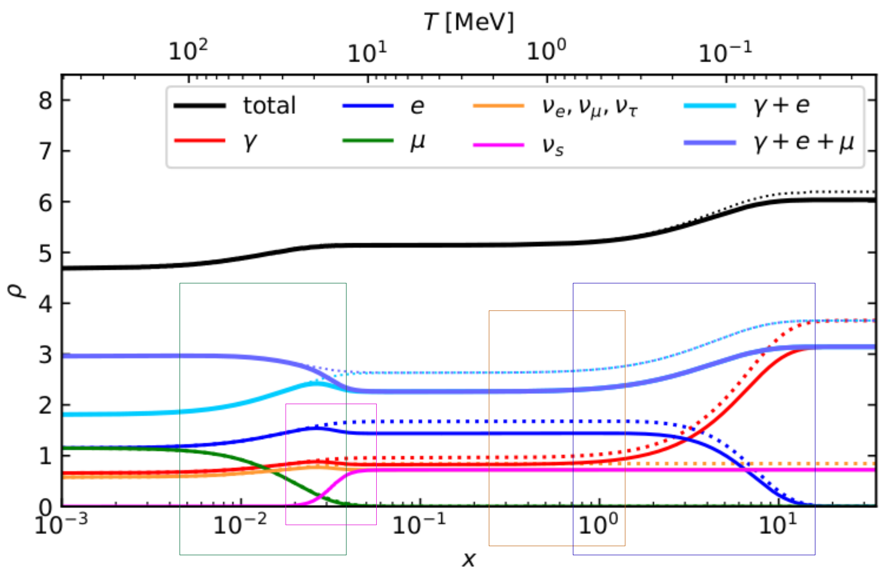
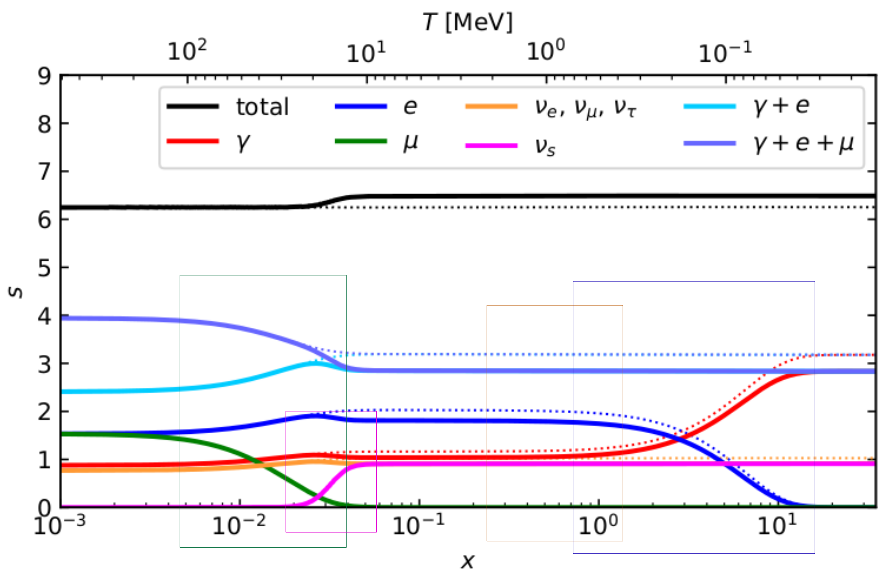
Comoving energy and entropy density evolution





- **Chain of processes in neutrino thermalization**

(*g* = relativistic degrees of freedom)

$$\mu^\pm + \overset{(-)}{\nu}_{e,\mu,\tau} + e^\pm + \gamma \quad \rightarrow \quad g_1 = \frac{57}{4}$$

$\mu^\pm$ annihilation

$$\overset{(-)}{\nu}_{e,\mu,\tau} + e^\pm + \gamma \quad \rightarrow \quad g_2 = \frac{43}{4}$$

ν_s populated via oscillations

$$\overset{(-)}{\nu}_s + \overset{(-)}{\nu}_{e,\mu,\tau} + e^\pm + \gamma \quad \rightarrow \quad g_3 = \frac{50}{4}$$

ν decoupling

$$e^\pm + \gamma \quad \rightarrow \quad g_4 = \frac{22}{4}$$

$e^\pm$ annihilation

$$|U_{e4}|^2 = 0.01$$

$$\Delta m^2_{41} = 1.29\,\mathrm{eV}^2$$

$$\gamma \quad \rightarrow \quad g_5 = \frac{8}{4}$$

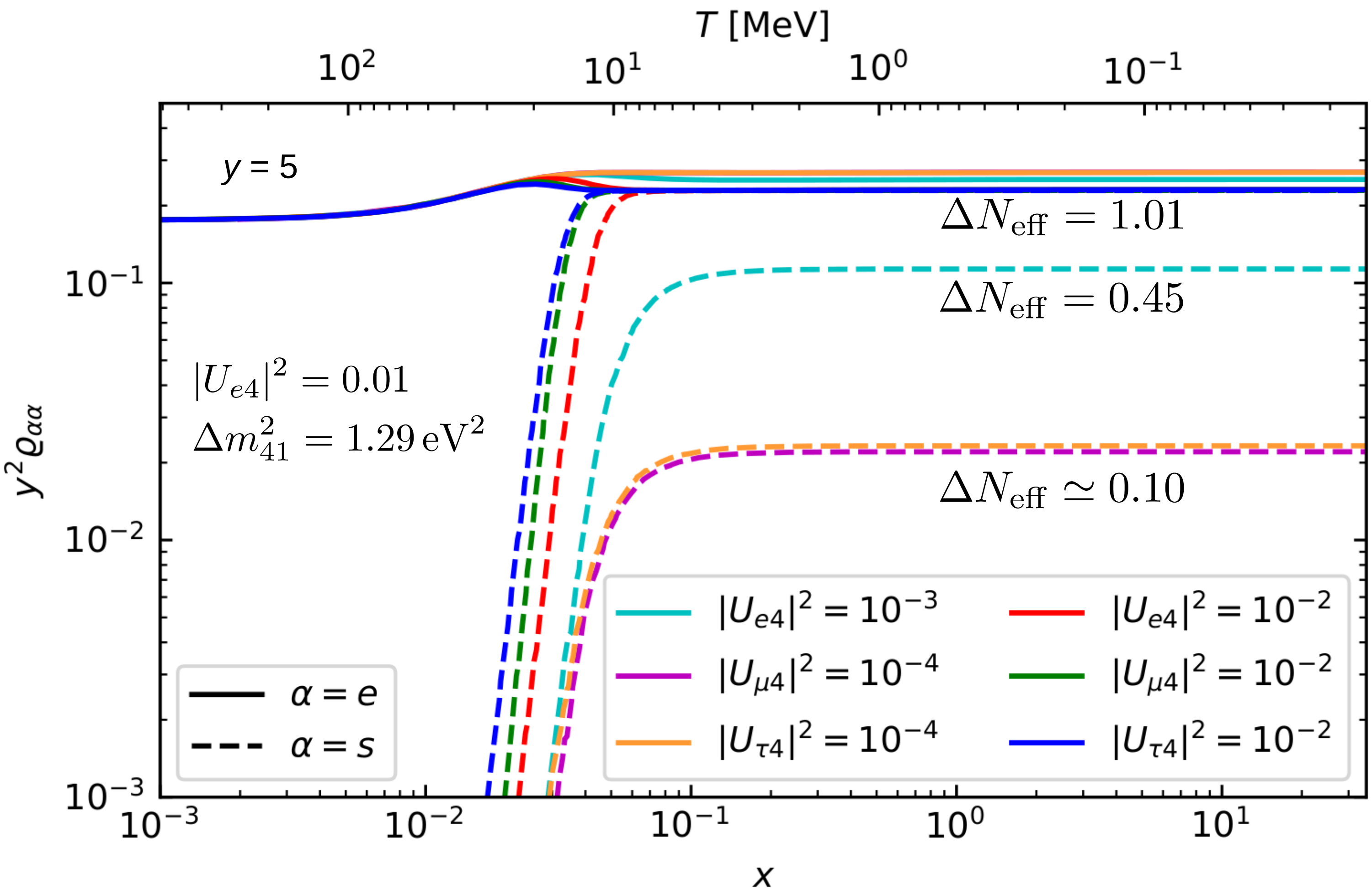
Sterile population depends on mixing angle

Sterile population depends on mixing angle

Reason: Oscillation is suppressed in presence of large matter effects

Order of relevance

$$\theta_{34} \; \theta_{24} \; \theta_{14}$$

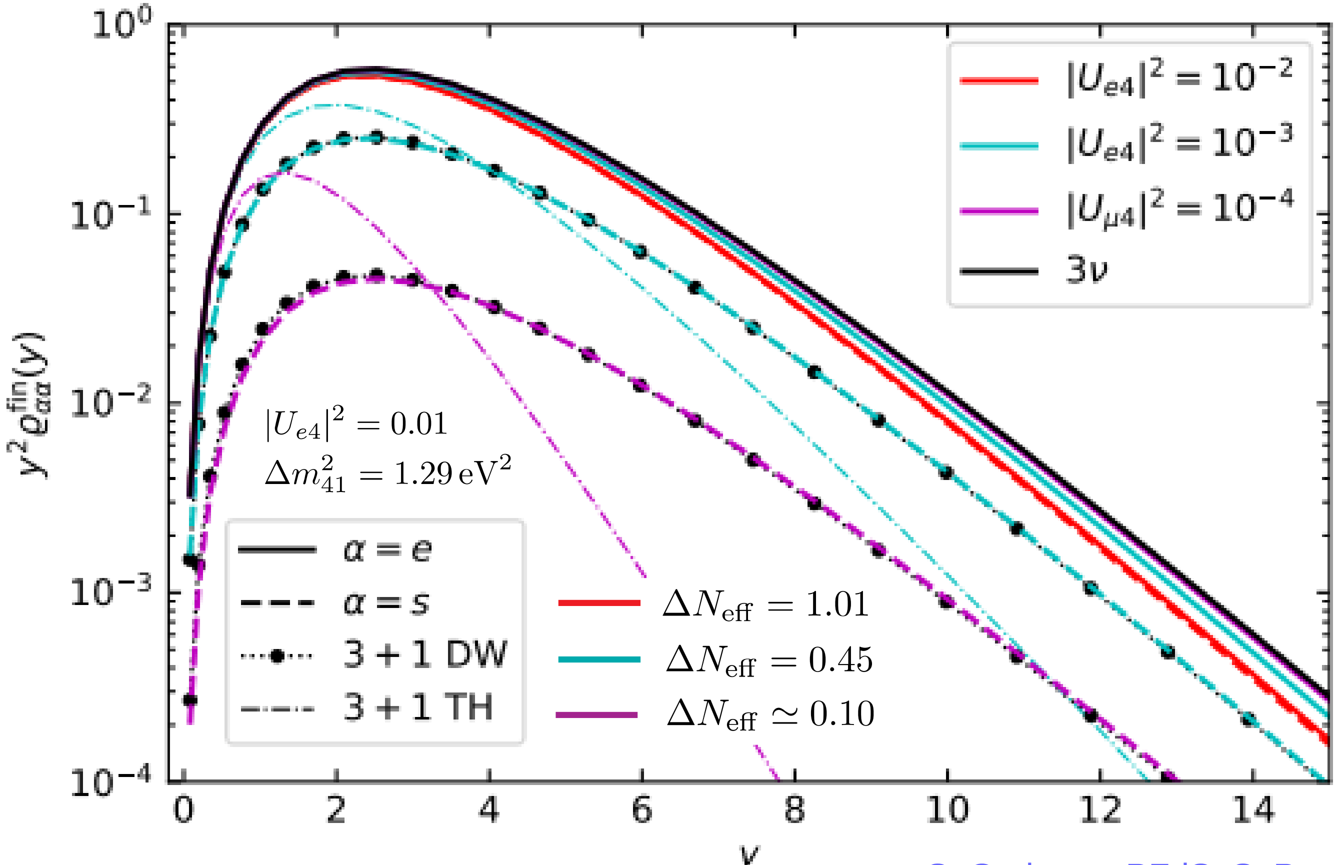


S. Gariazzo, PFdS, S. Pastor, JCAP 1907 (2019) 014

Frozen f_ν distortions

Dodelson-Widrow approximation $f(y) = \Delta N_{\rm eff}\,[\exp(y/w)+1]^{-1}$ [Dodelson & Widrow, 1993]

Thermal approximation $f(y) = [\exp(y/w_s)+1]^{-1}$ $w_s \equiv T_s a = \Delta N_{\rm eff}^{1/4} w$



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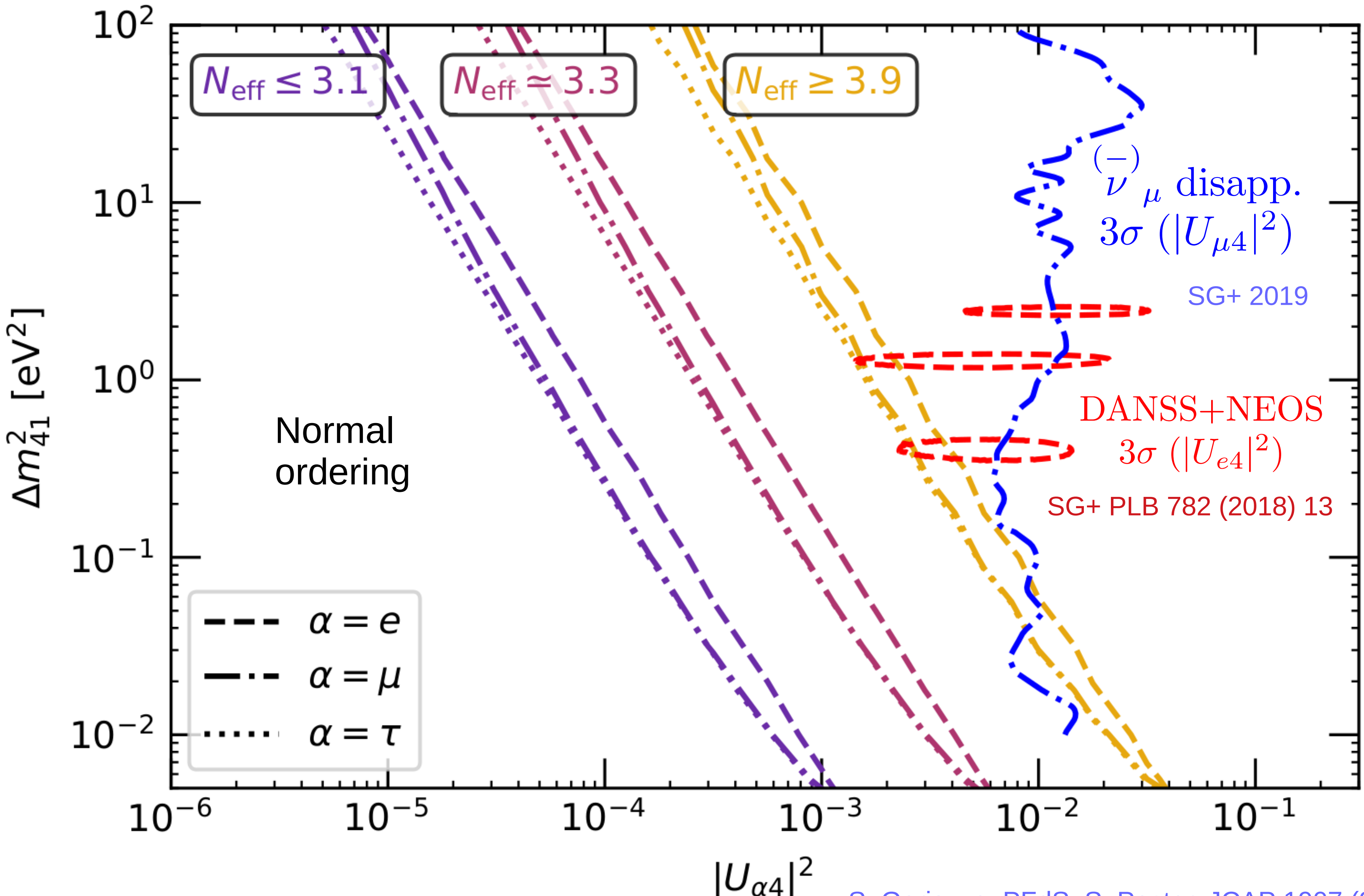
N_{eff} mass-angle planes: $|U_{\alpha 4}|^2$



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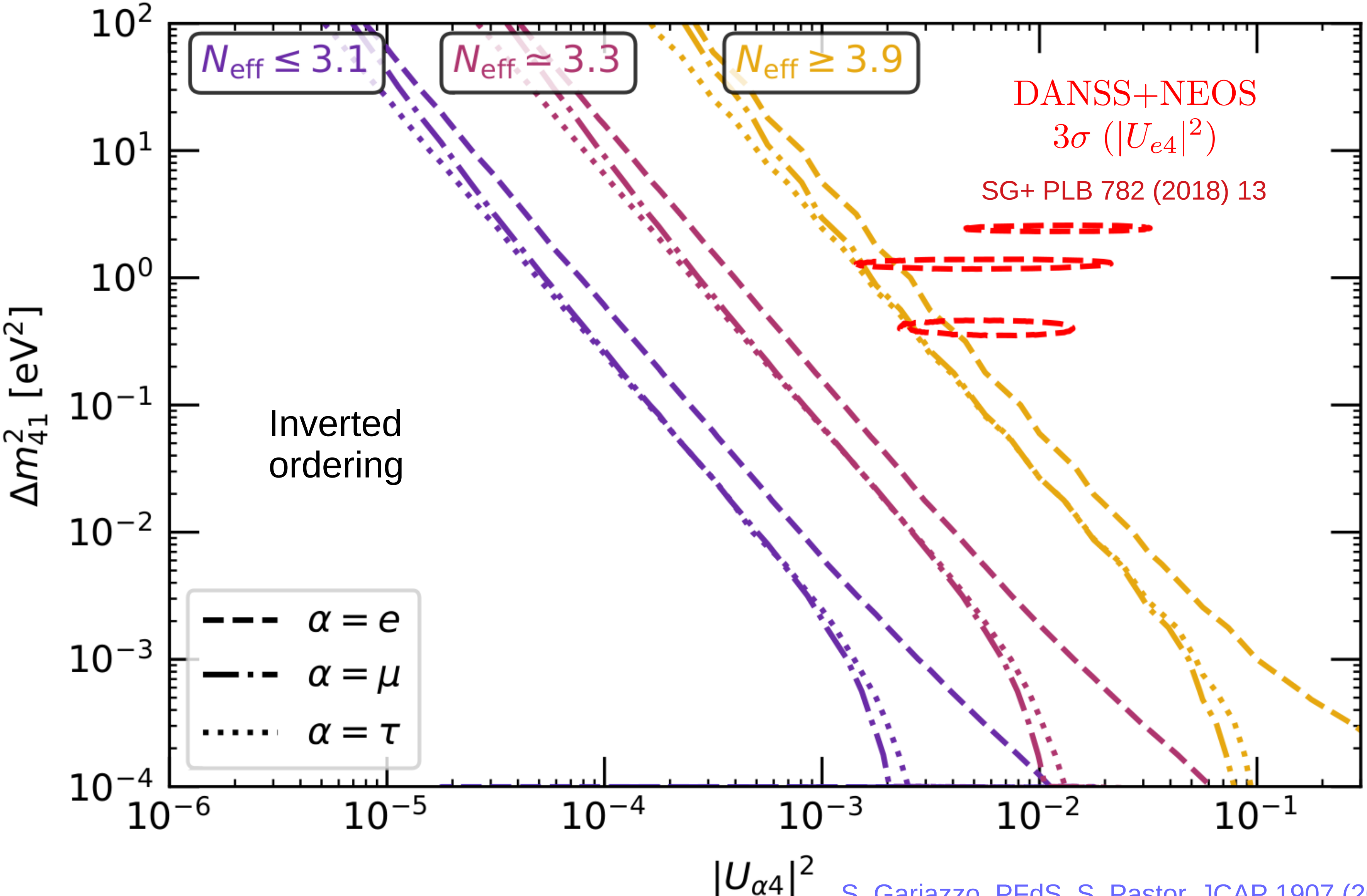
N_{eff} mass-angle planes: $|U_{\alpha4}|^2$



S. Gariazzo, PFdS, S. Pastor, JCAP 1907 (2019) 014

Computing neutrino decoupling

Vacuum oscillations

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

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

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

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

Solve Boltzmann equations with Icoll ≠ 0

Vacuum — Matter

$$(\partial_t - Hp\partial_p)\,\varrho_p = -i\frac{1}{2p}\left[\left(\mathbb{M}_F - 2p\frac{8\sqrt{2}G_F p}{3m_W^2}\rho_{e\underline{\underline{\mathcal{E}}}}\right), \varrho_p\right] + I_{\mathrm{coll}}\left[\varrho_p\right]$$

Expanding Universe — ← Oscillations → — Interactions

Computing neutrino decoupling

Oscillation matter effects

$$\underline{\underline{\epsilon}} = \mathbb{E}_l + \mathbb{E}_\nu$$

$$\mathbb{E}_l = \mathrm{diag}\left(\rho_e, \rho_\mu, 0, 0\right)$$

$$\mathbb{E}_\nu = S_a \left(\int \mathrm{d}y \, y^3 \varrho \right) S_a \qquad S_a = \mathrm{diag}\left(1, 1, 1, 0\right)$$

Solve Boltzmann equations with $I_{coll} \neq 0$

$$\left(\partial_t - Hp\partial_p\right) \varrho_p = -i \frac{1}{2p} \left[\left(\mathbb{M}_F - 2p \frac{8\sqrt{2} G_F p}{3 m_W^2} \rho_e \underline{\underline{\varepsilon}} \right), \varrho_p \right] + I_{\mathrm{coll}} \left[\varrho_p \right]$$

Vacuum — Matter

Expanding Universe — Oscillations — Interactions

Equations in comoving variables

Comoving variables

scale factor $R = 1/T_\nu$

$$x = m_e R \qquad y = pR \qquad z = T_\gamma R$$

Fluid equation

$$\frac{\mathrm{d}z}{\mathrm{d}x} = \frac{\sum_{l=e,\mu}\left(\frac{r_l^2}{r}J(r_l)\right) + G_1(r) - \frac{1}{2\pi^2 z^3}\int_0^\infty \mathrm{d}y\, y^3 \sum_{\alpha=e}^{s}\frac{\mathrm{d}\varrho_{\alpha\alpha}}{\mathrm{d}x}}{\sum_{l=e,\mu}\left(r_l^2 J(r_l) + Y(r_l)\right) + G_2(r) + \frac{2\pi^2}{15}}$$

$$r_l = r\, m_l/m_e$$
$$r = x/z$$

Boltzmann equation

$$\frac{\mathrm{d}\varrho}{\mathrm{d}x} = \sqrt{\frac{3m_\mathrm{P}^2}{8\pi\rho}}\left\{-i\frac{x^2}{m_e^3}\left[\frac{\mathbb{M}_\mathrm{F}}{2y} - \frac{8\sqrt{2}G_\mathrm{F}\,y\,m_e^6}{3x^6}\left(\frac{\mathbb{E}_l}{m_W^2} + \frac{\mathbb{E}_\nu}{m_Z^2}\right), \varrho\right] + \frac{m_e^3}{x^4}\mathcal{I}(\varrho)\right\}$$

For more information see S. Gariazzo, PFdS, S. Pastor, JCAP 1907 (2019) 014

Treatment of collision integrals

Example: annihilation process

$$\mathcal{I}_{\nu\bar{\nu}\to e^- e^+} = \frac{1}{2}\frac{2^5 G_\mathrm{F}^2}{2|\vec{p}_1|}\int \frac{d^3\vec{p}_2}{(2\pi)^3 2|\vec{p}_2|}\frac{d^3\vec{p}_3}{(2\pi)^3 2E_3}\frac{d^3\vec{p}_4}{(2\pi)^3 2E_4}(2\pi)^4\delta^{(4)}(p_1+p_2-p_3-p_4)$$
$$\times\Big\{4(p_1\cdot p_4)(p_2\cdot p_3)F_\mathrm{ann}^{LL}(\nu^{(1)},\bar{\nu}^{(2)},e^{(3)},\bar{e}^{(4)})$$
$$+4(p_1\cdot p_3)(p_2\cdot p_4)F_\mathrm{ann}^{RR}(\nu^{(1)},\bar{\nu}^{(2)},e^{(3)},\bar{e}^{(4)})$$
$$+2(p_1\cdot p_2)m_e^2\left(F_\mathrm{ann}^{RL}(\nu^{(1)},\bar{\nu}^{(2)},e^{(3)},\bar{e}^{(4)})+F_\mathrm{ann}^{LR}(\nu^{(1)},\bar{\nu}^{(2)},e^{(3)},\bar{e}^{(4)})\right)\Big\}\,,$$

$$F_\mathrm{ann}^{ab}(\nu^{(1)},\bar{\nu}^{(2)},e^{(3)},\bar{e}^{(4)}) = f_3\bar{f}_4\left(G^a(1-\bar{\varrho}_2)G^b(1-\varrho_1)+(1-\varrho_1)G^b(1-\bar{\varrho}_2)G^a\right)$$
$$-\,(1-f_3)(1-\bar{f}_4)\left(\varrho_1 G^b\bar{\varrho}_2 G^a + G^a\bar{\varrho}_2 G^b\varrho_1\right)\,.$$

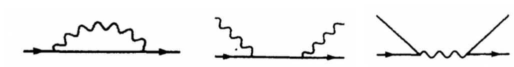
$$G^L = \mathrm{diag}\,(g_L,\tilde{g}_L,\tilde{g}_L)\,,\qquad G^R = \mathrm{diag}\,(g_R,g_R,g_R)\,,$$

G. Sigl and G. Raffelt, NPB 406 (1993) 423

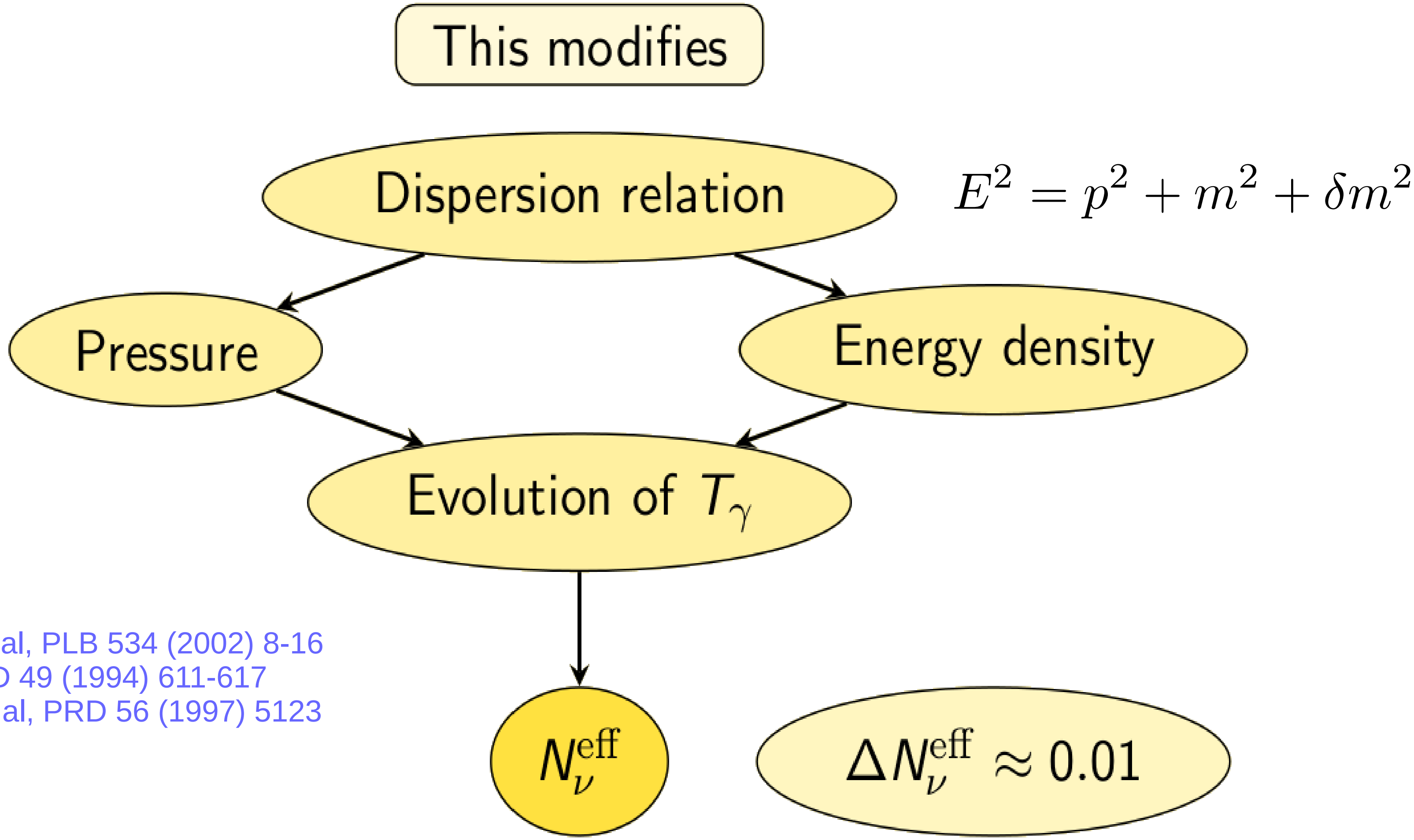
PFdS and S. Pastor JCAP 07 (2016) 051

Finite temperature QED corrections

- Particles are in a thermal bath with a temperature T



- Photons and electrons acquire an additional effective mass



G. Mangano et al, PLB 534 (2002) 8-16
A. Heckler, PRD 49 (1994) 611-617
N. Fornengo et al, PRD 56 (1997) 5123

Neutrino decoupling not complete when $e^{\pm}$ annihilate

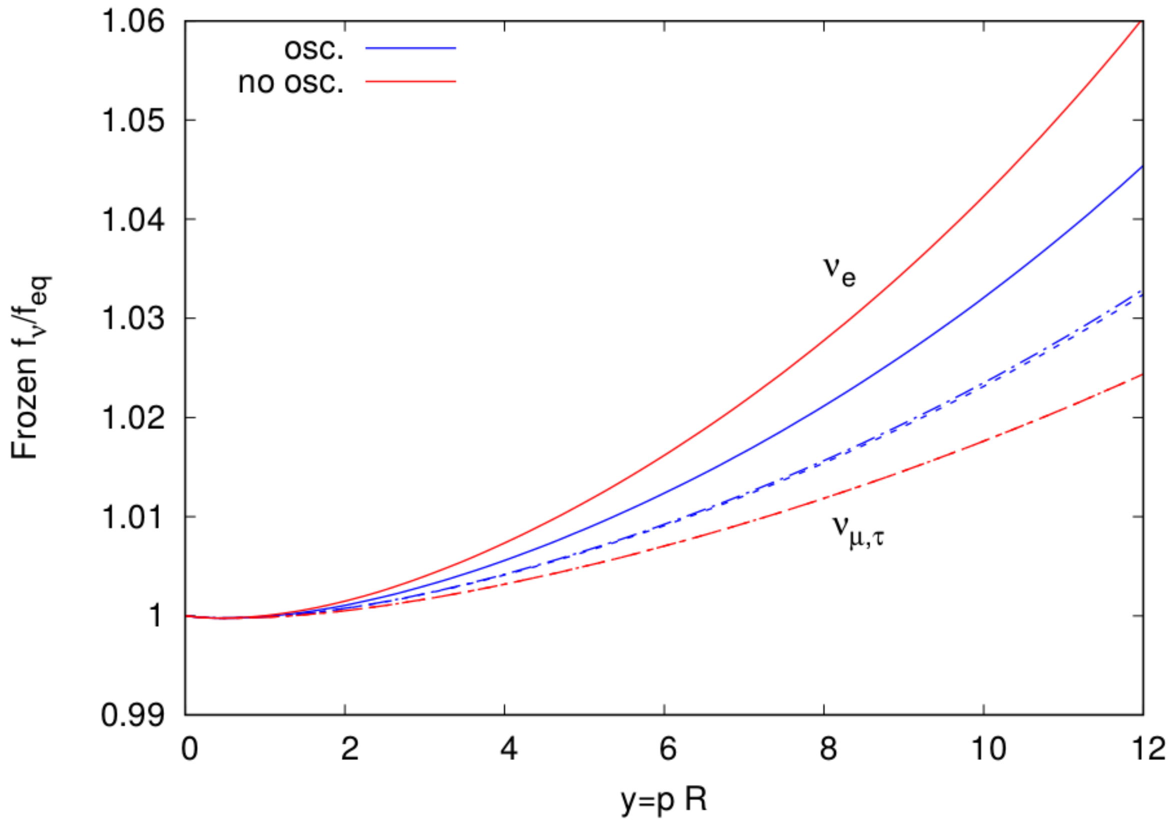
→ **Deviation of f_ν from equilibrium**

Main source of deviation

- Interactions with e^- and e^+

Also important

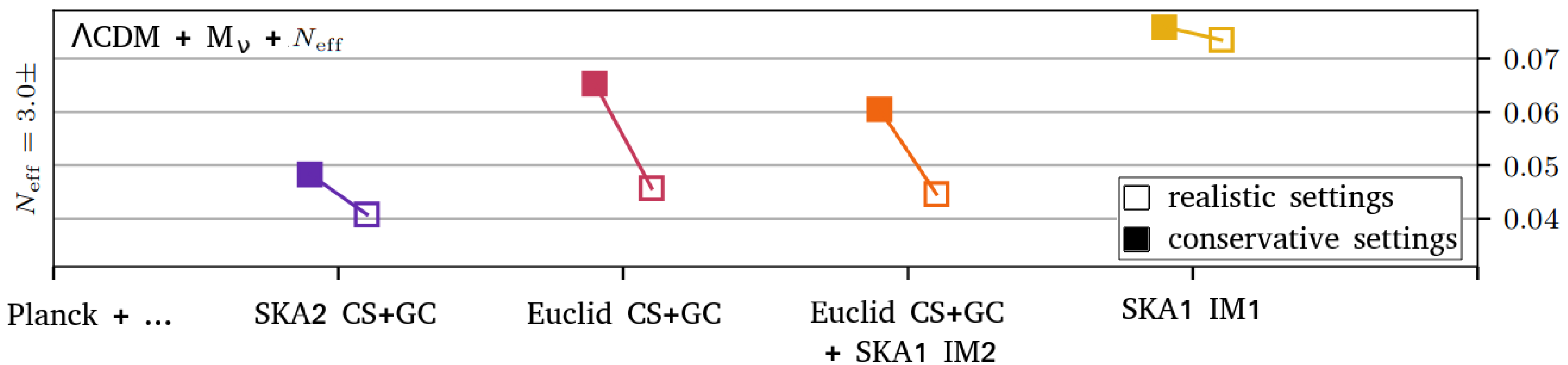
- Neutrino oscillations
- Neutrino self-interactions



PFdS and S. Pastor JCAP 07 (2016) 051

N_{eff} forecasts

[arXiv:1801.08331]



Simons Observatory forecast

[arXiv:1808.07445]