CNB essentials 3: Neutrinos and BBN; neutrino oscillations in the early Universe

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ASTROPARTICLES
Astroparticles and High Energy Physics Group

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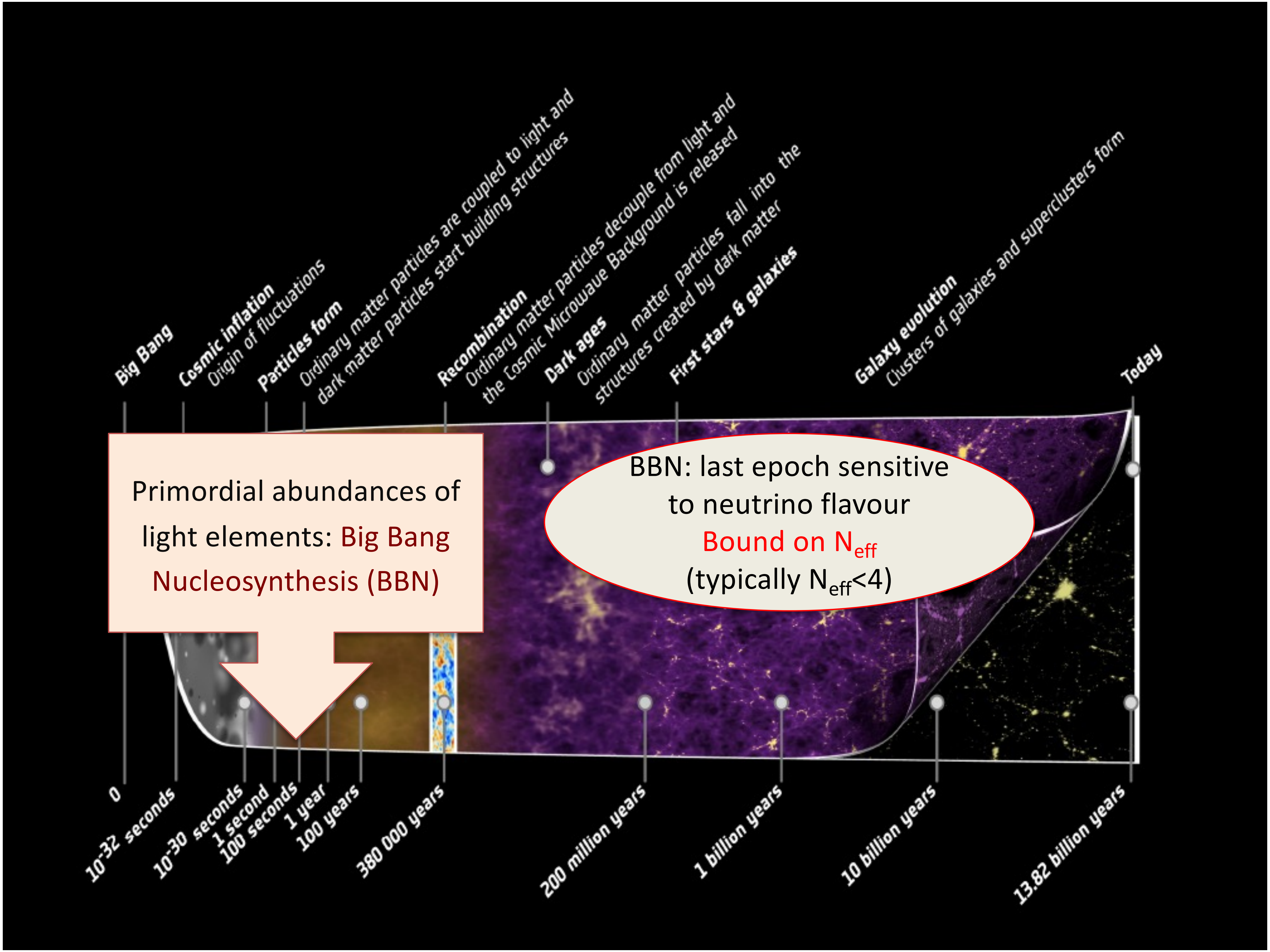
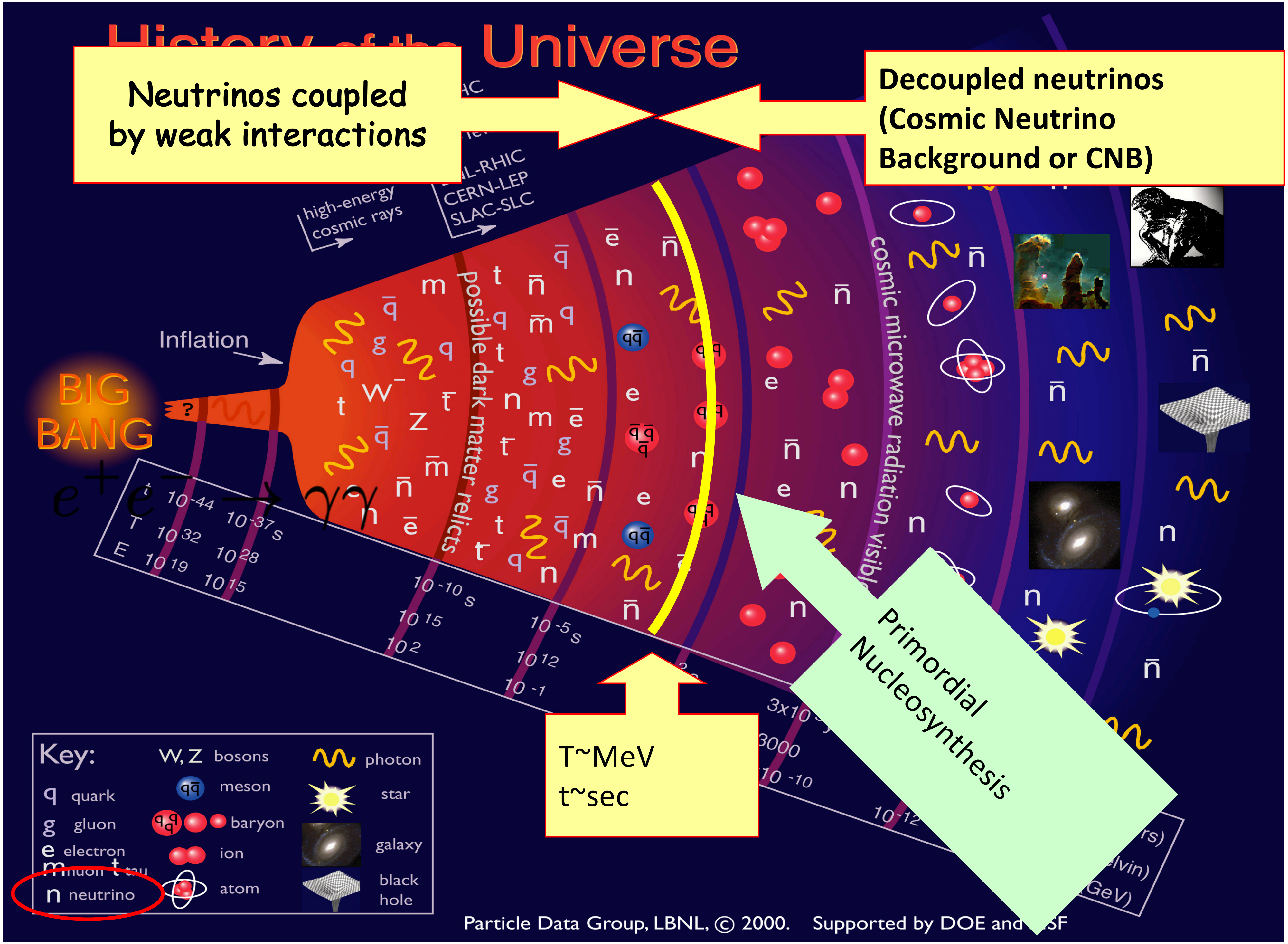
Outline

Neutrinos and Primordial Nucleosynthesis

Neutrino oscillations in the Early Universe

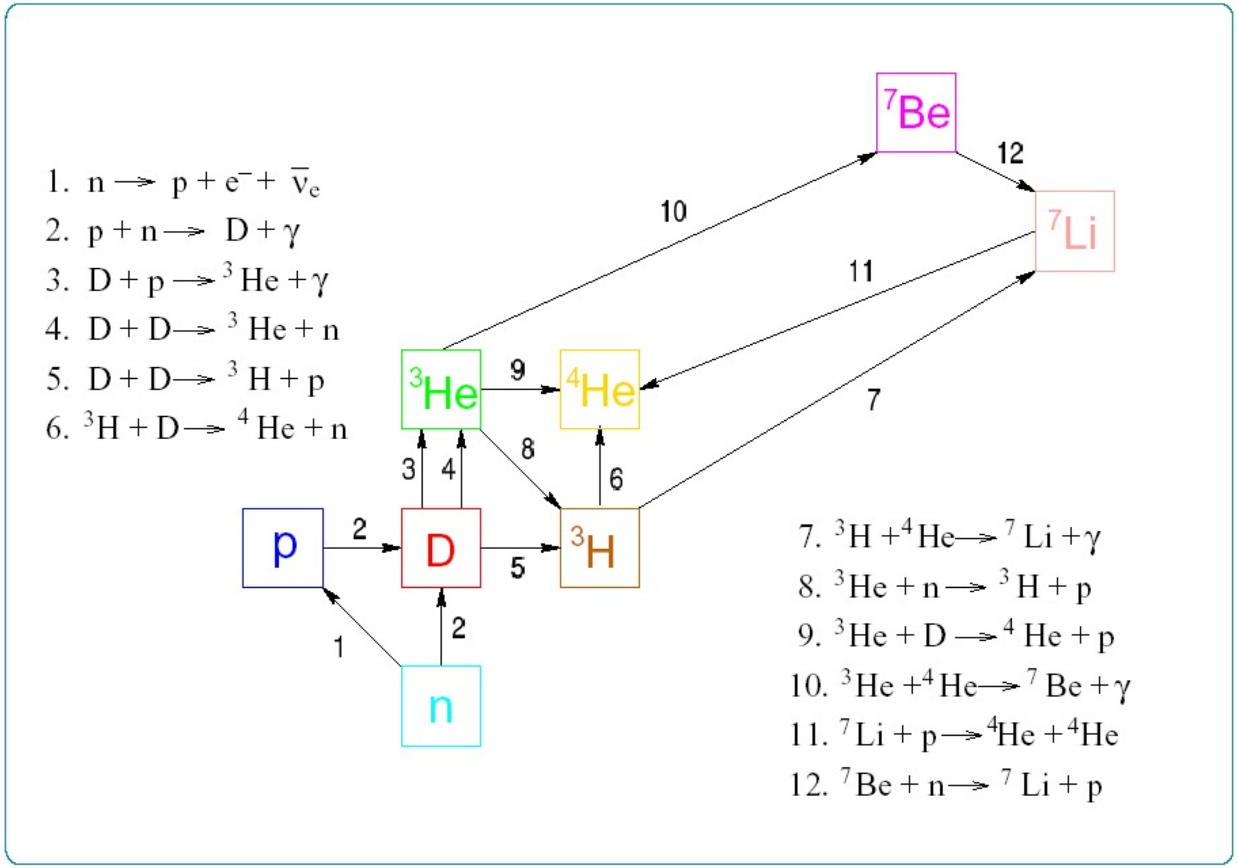
Neutrinos and Primordial Nucleosynthesis


Big Bang
Cosmic inflation
Origin of fluctuations
Particles form
Ordinary matter particles are coupled to light and dark matter particles start building structures
Recombination
Ordinary matter particles decouple from light and the Cosmic Microwave Background is released
Dark ages
Ordinary matter particles fall into the structures created by dark matter
First stars & galaxies
Galaxy evolution
Clusters of galaxies and superclusters form
Today
0
10^{-32} seconds
10^{-30} seconds
1 second
100 seconds
1 year
100 years
380 000 years
200 million years
1 billion years
10 billion years
13.82 billion years
Primordial abundances of light elements: Big Bang Nucleosynthesis (BBN)
BBN: last epoch sensitive to neutrino flavour
Bound on N_{eff}
(typically N_{eff}<4)



History of the Universe
Neutrinos coupled by weak interactions
Decoupled neutrinos (Cosmic Neutrino Background or CNB)
high-energy cosmic rays
BNL-RHIC
CERN-LEP
SLAC-SLC
Inflation
BIG BANG
$e^+e^- \to \gamma\gamma$
possible dark matter relics
cosmic microwave radiation visible
T~MeV
t~sec
Primordial Nucleosynthesis
Key:
q quark
g gluon
e electron
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000.

BBN: Creation of light elements



Produced elements: D, ^{3}He, ^{4}He, ^{7}Li and small abundances of others

Theoretical inputs:

- τ_n, the neutron lifetime;
- G_N, the Newton gravitational constant;
- η, the baryon to photon number density ratio;
- the nuclear rates.

$$\eta_{10} = \frac{n_B/n_\gamma}{10^{-10}} \simeq 274\,\Omega_B h^2$$

BBN: Creation of light elements

Range of temperatures: from 0.8 to 0.01 MeV

$$t \simeq 0{,}74 \left(\frac{\text{MeV}}{T}\right)^2 \ \text{sec}$$

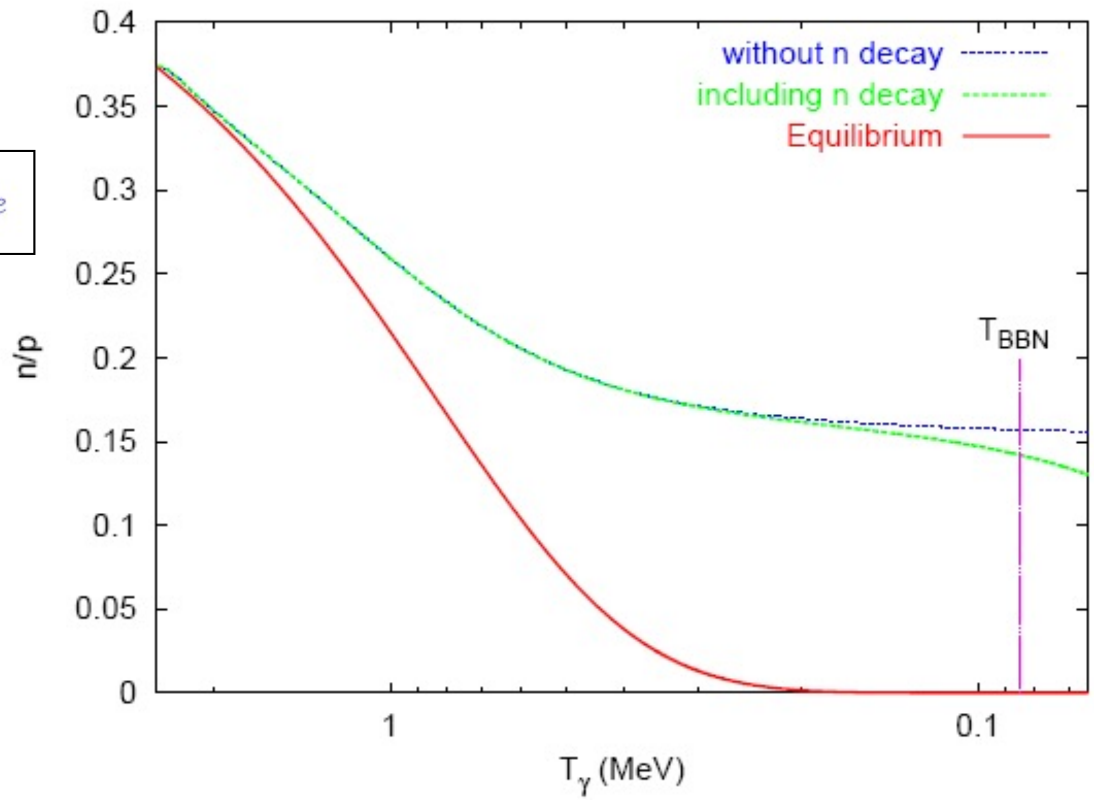
Phase I: 0.8-0.1 MeV

n-p reactions

$$\nu_e + n \longleftrightarrow p + e^- \qquad e^+ + n \longleftrightarrow p + \bar{\nu}_e$$

n/p freezing and neutron decay

$$n \longleftrightarrow p + e^- + \bar{\nu}_e$$

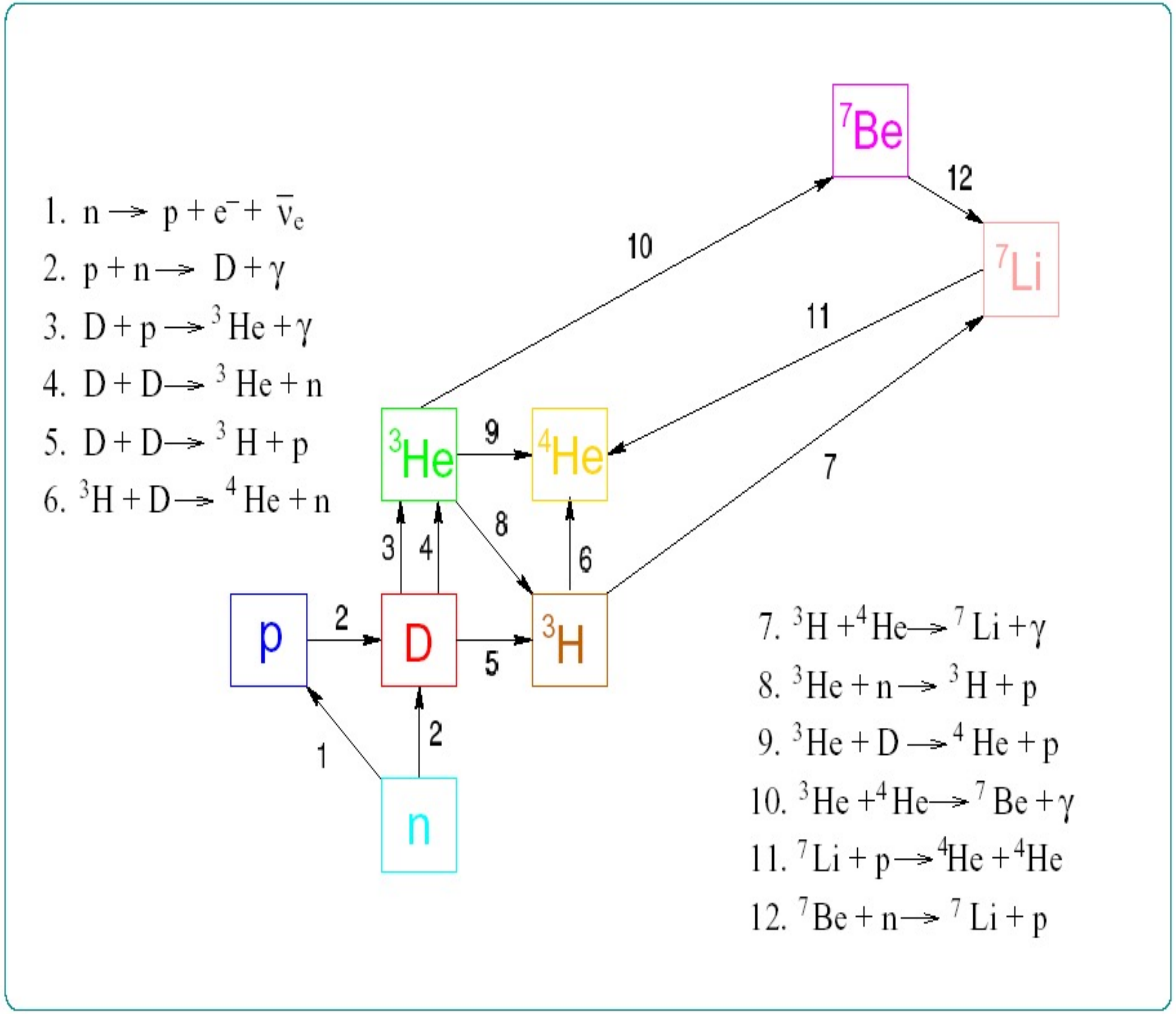


$$\left(\frac{n}{p}\right)_{eq} \simeq \exp\left(-\frac{m_n - m_p}{T_\gamma}\right) = \exp\left(-\frac{1{,}293 \ \text{MeV}}{T_\gamma}\right)$$

BBN: Creation of light elements

Phase II: 0.1-0.01 MeV
Formation of light nuclei starting from D

Photodesintegration prevents earlier formation for temperatures closer to nuclear binding energies



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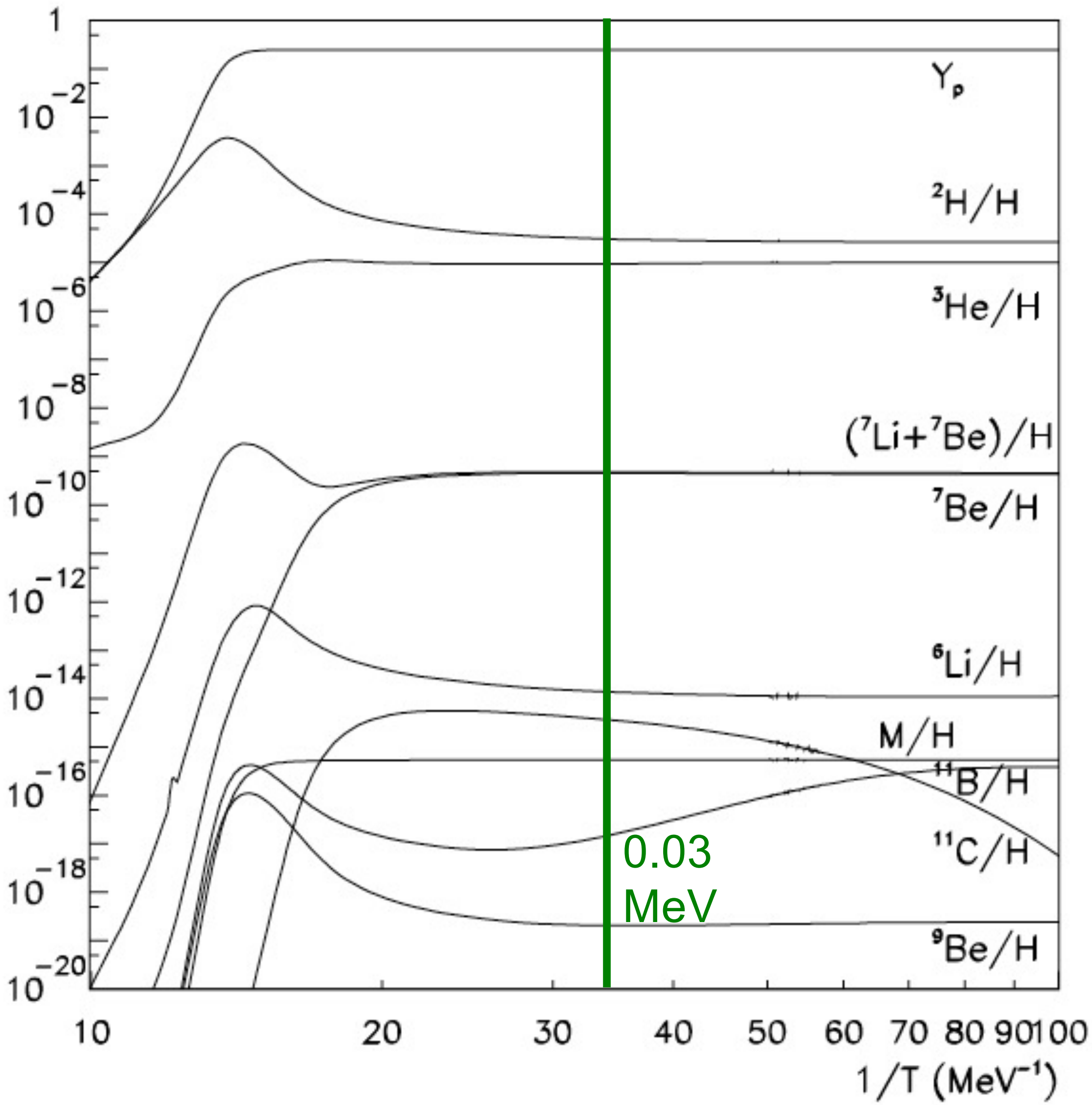

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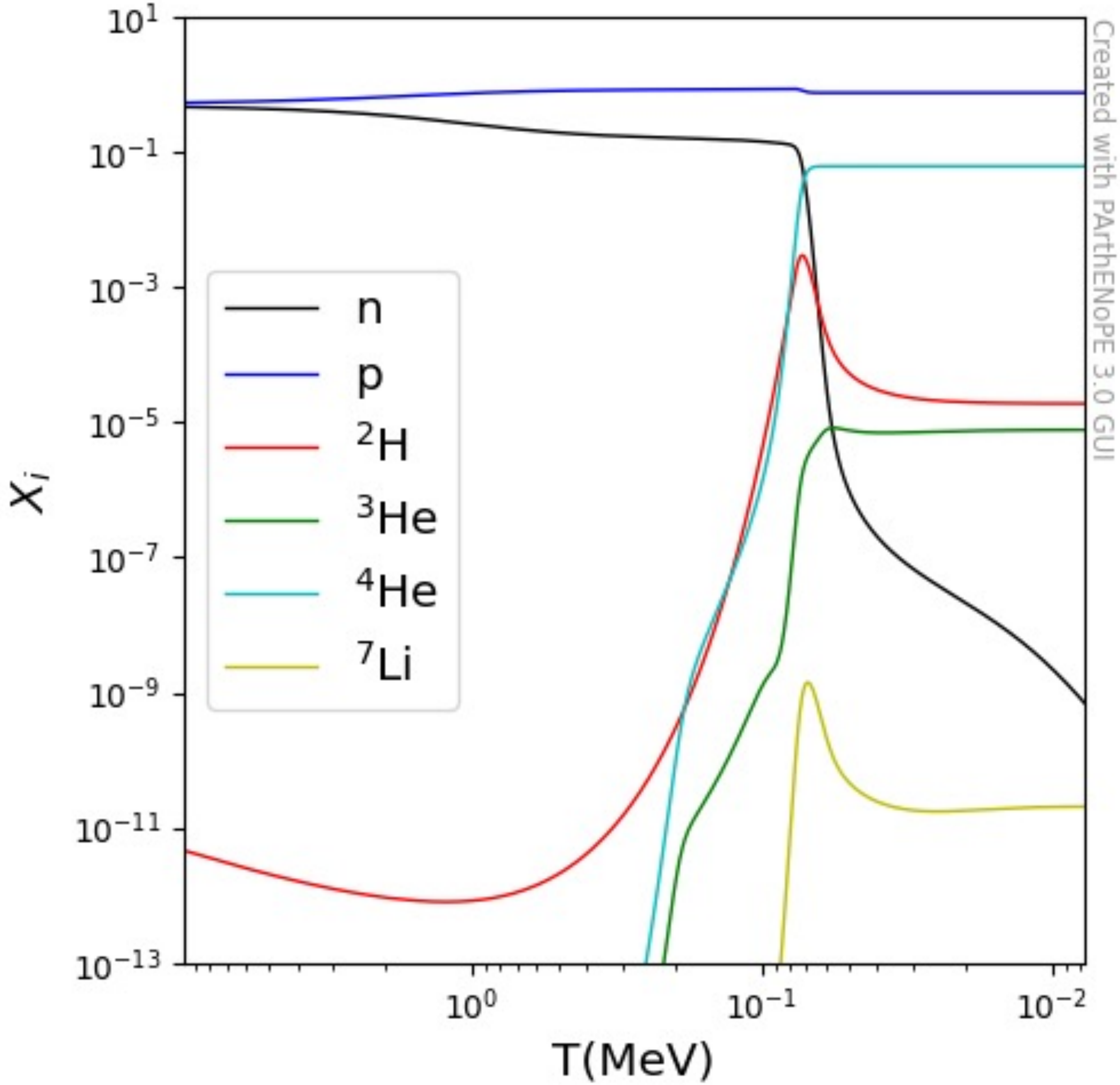


BBN: Measurement of Primordial abundances

Difficult task**: search in astrophysical systems with chemical evolution as small as possible**

Deuterium: destroyed in stars. Any observed abundance of D is a *lower* limit to the primordial abundance. Data from high-z, low metallicity QSO absorption line systems

Helium-3: produced and destroyed in stars (complicated evolution)
Data from solar system and galaxies, but not used in BBN analysis

Helium-4: primordial abundance increased by H burning in stars.
Data from low metallicity, extragalatic HII regions

Lithium-7: destroyed in stars, produced in cosmic ray reactions.
Data from oldest, most metal-poor stars in the Galaxy

Inferred Primordial abundances

Difficult task**: search in astrophysical systems with chemical evolution as small as possible**

^{4}He observed in extragalactic HII regions:

$$Y_P = 0.245 \pm 0.003$$

^{2}H observed in quasar absorption systems (and ISM):

$$D/H|_P = (2.543 \pm 0.027) \times 10^{-5}$$

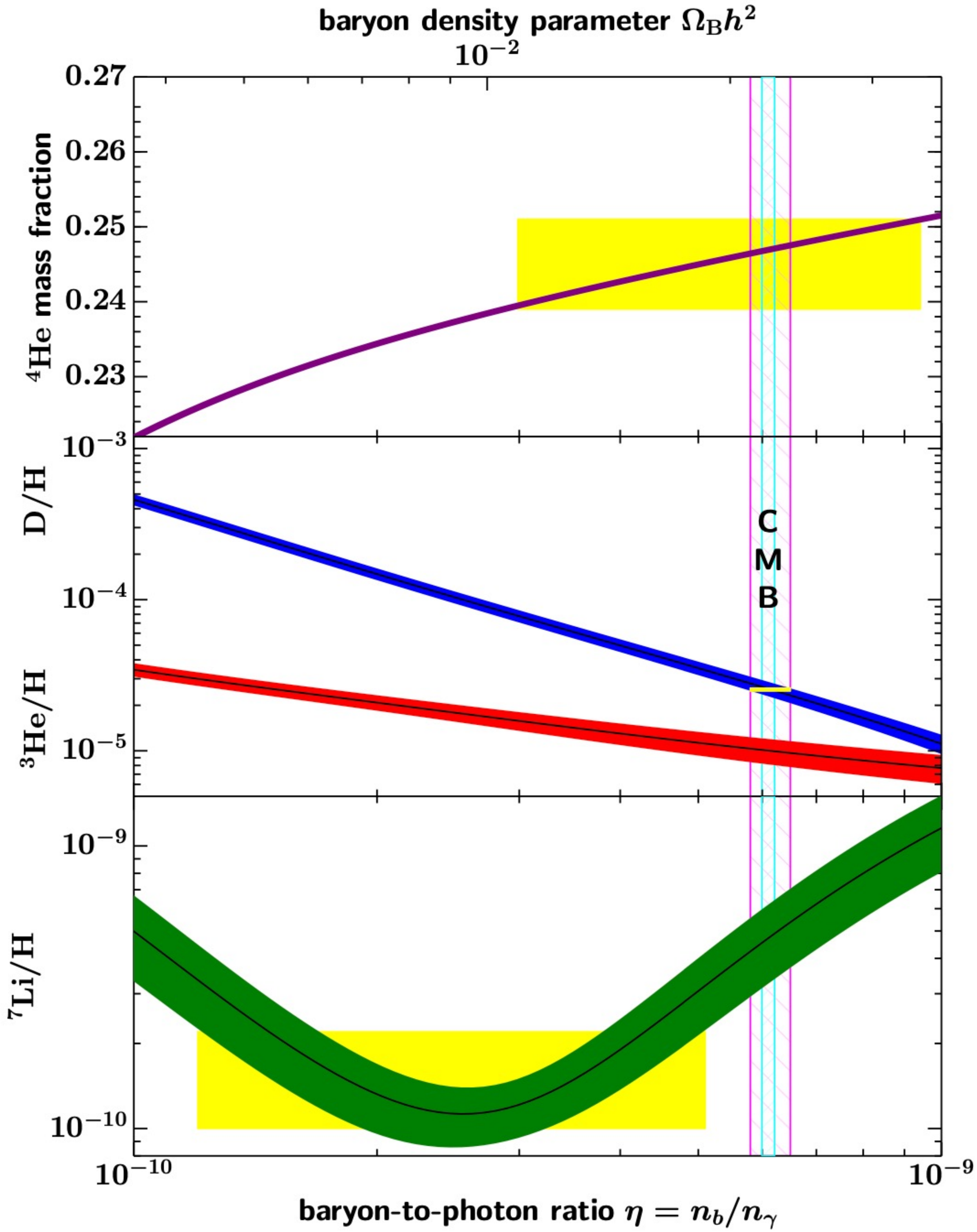
^{7}Li observed in atmospheres of dwarf halo stars:

$$Li/H|_P = (1.6 \pm 0.3) \times 10^{-10}$$

(^{3}He can be both created & destroyed in stars … so primordial abundance *cannot* be reliably estimated)

S. Sarkar, Latest Advances in the Physics of BBN and Neutrino Decoupling 2021

BBN: Predictions vs Observations



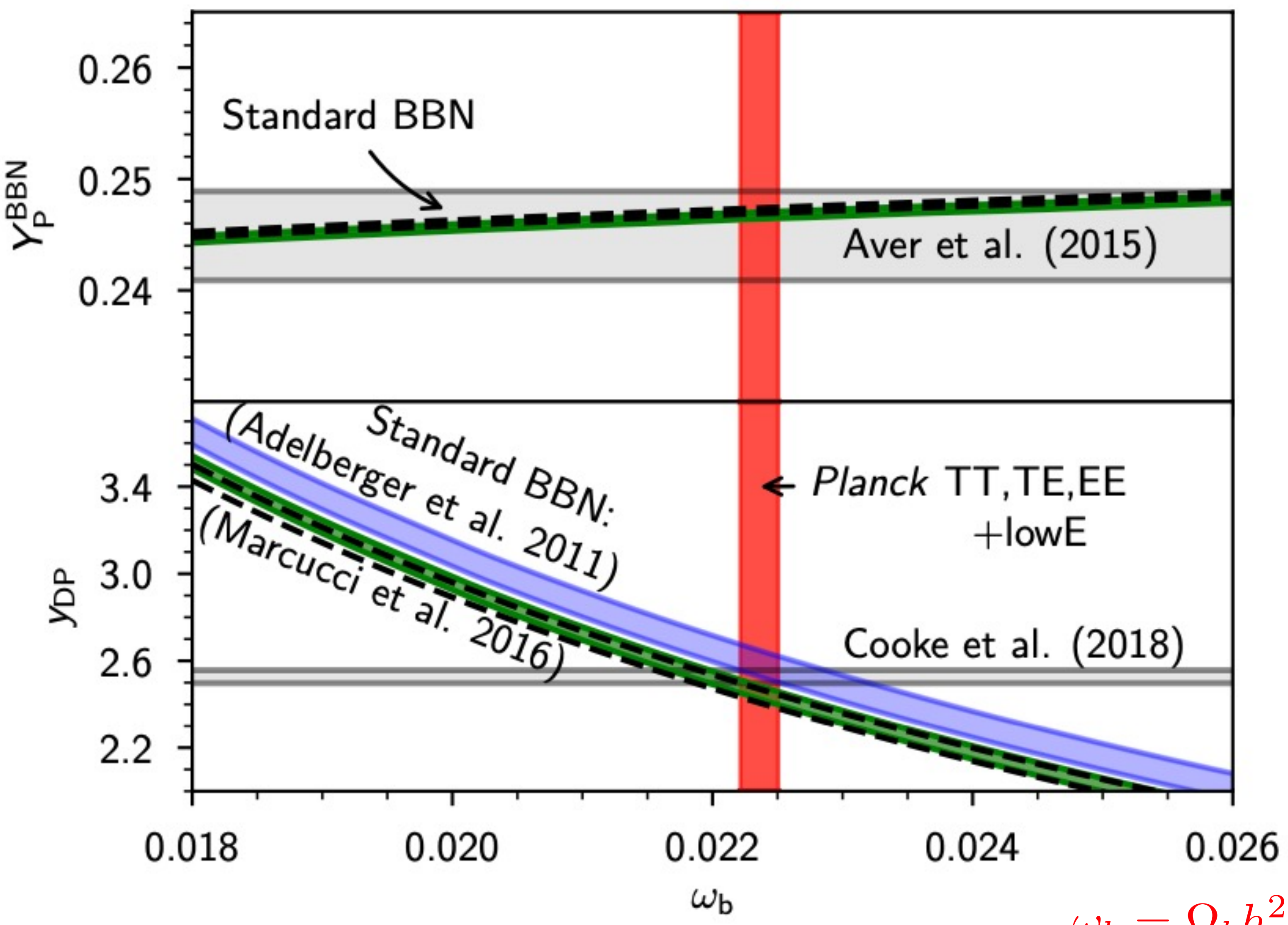
$$\eta_{10} = \frac{n_B/n_\gamma}{10^{-10}} \simeq 274\,\Omega_B h^2$$

Fields, Molaro & Sarkar, PDG 2020

BBN: Predictions vs Observations

^{4}He

D



$\omega_b = \Omega_b h^2$

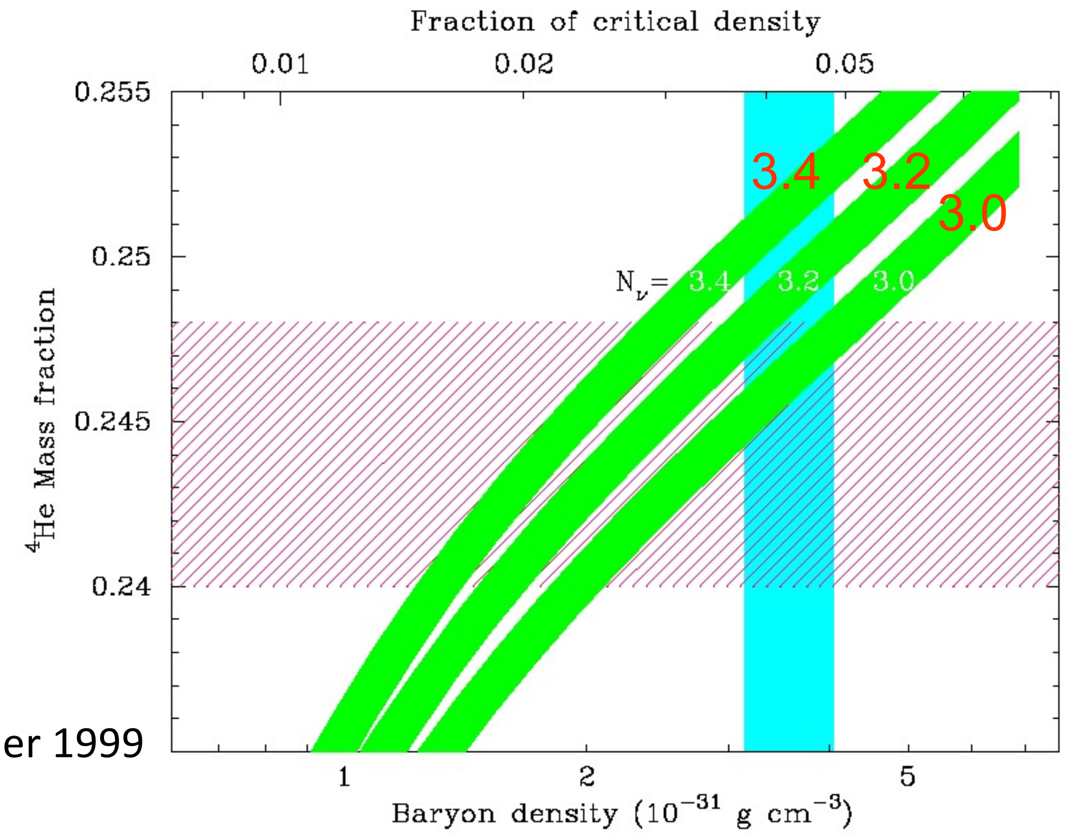
Planck Coll, A&A **641** (2020) A6

Effect of neutrinos on BBN

1. **N_{eff}** fixes the **expansion rate** during BBN

$$H = \sqrt{\frac{8\pi\rho}{3M_p^2}}$$

$\rho(N_{eff}) > \rho_0 \rightarrow \uparrow {}^4He$

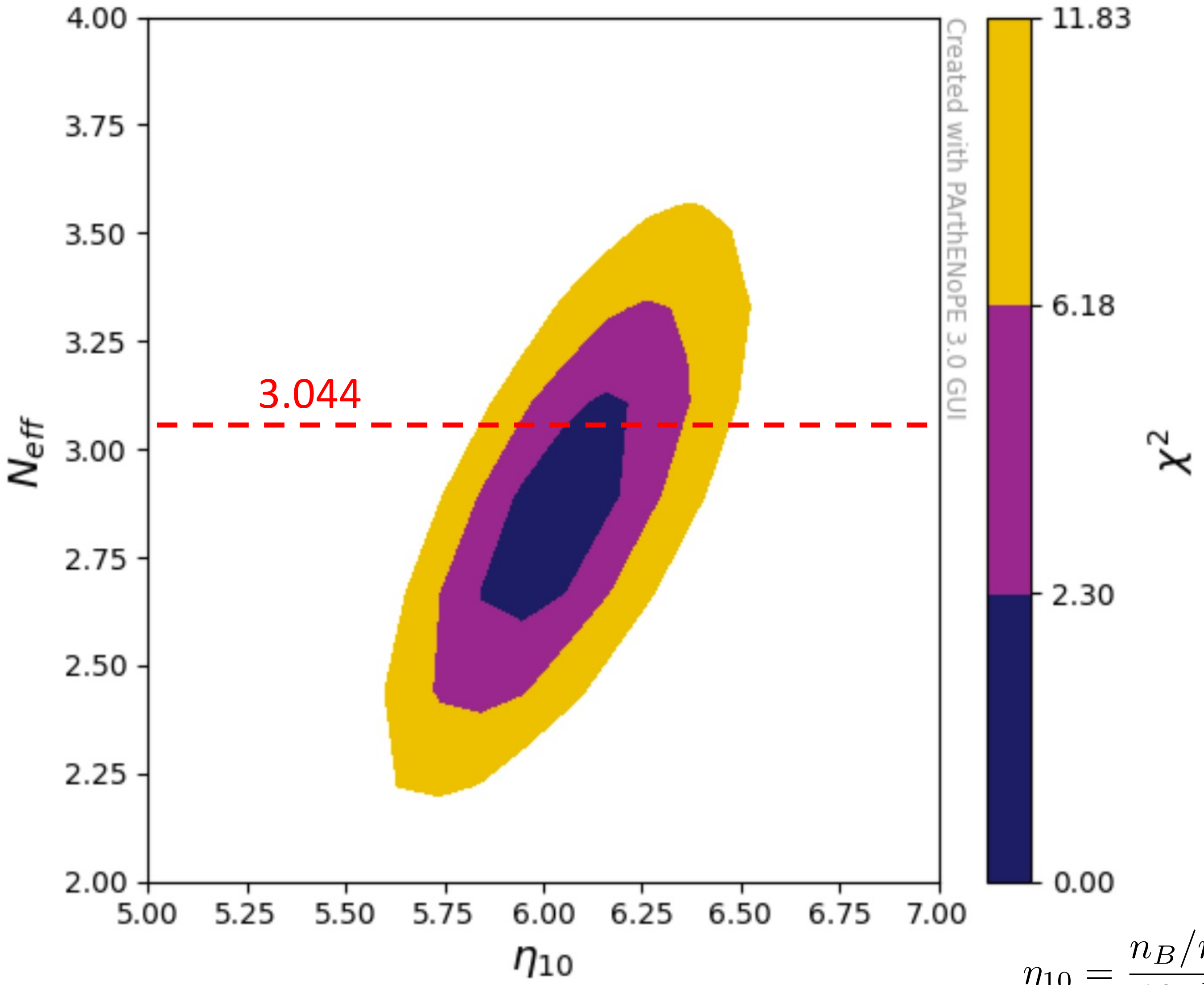


Burles, Nollett & Turner 1999

2. Direct effect of **electron** neutrinos and antineutrinos on the **n-p reactions**

$$\nu_e + n \leftrightarrow p + e^- \qquad e^+ + n \leftrightarrow p + \bar{\nu}_e$$

BBN: allowed ranges for N_{eff}

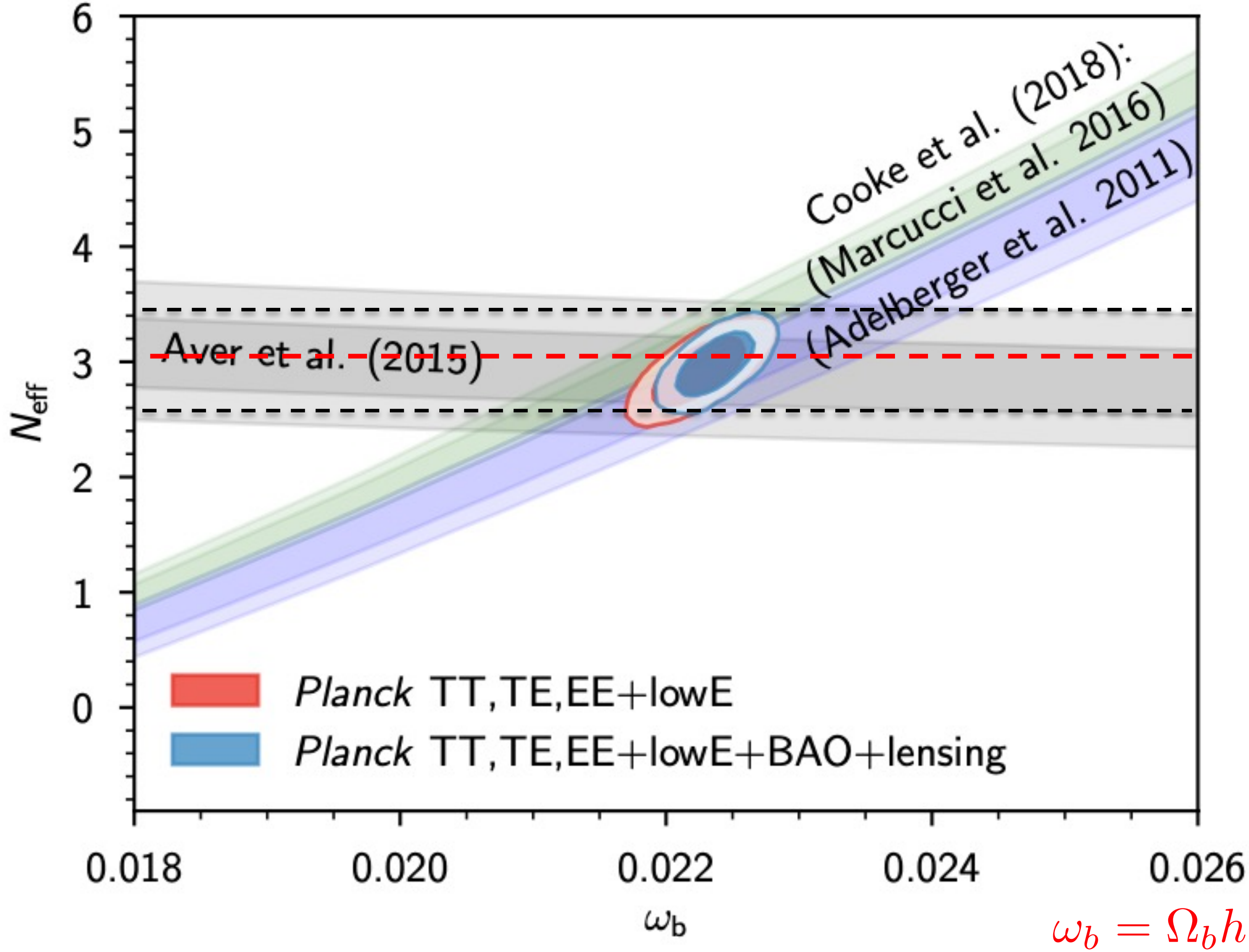


$$\eta_{10} = \frac{n_B/n_\gamma}{10^{-10}} \simeq 274\,\Omega_B h^2$$

^{4}He and D bounds

PArthENoPE BBN code, S Gariazzo et al, arXiv:2103.05027

BBN: allowed ranges for N_{eff}



$$\omega_b = \Omega_b h^2$$

Planck Coll, A&A **641** (2020) A6

Neutrino oscillations in the Early Universe

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

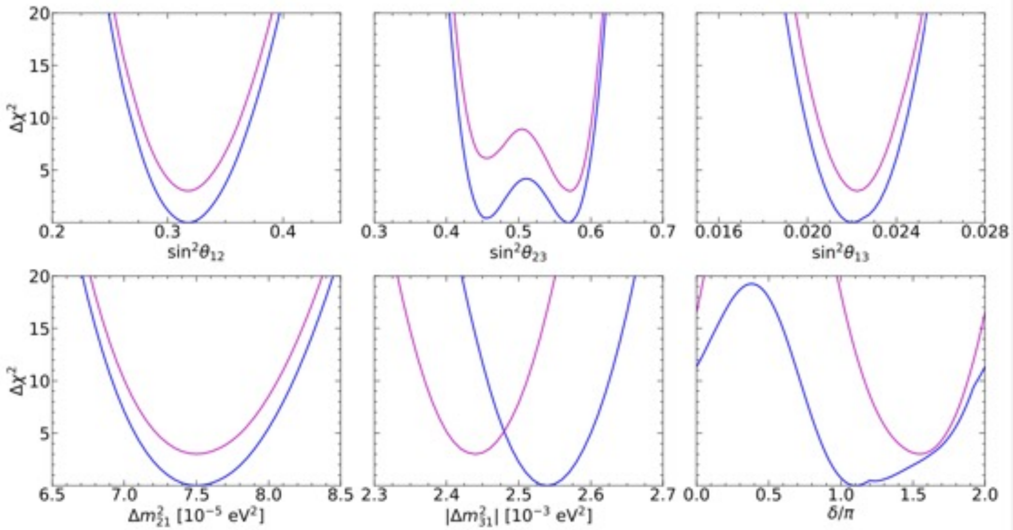
Current knowledge of the 3 active ν mixing: [JHEP 02 (2021) update]

NO/NH: Normal Ordering/Hierarchy, $m_1 < m_2 < m_3$ IO/IH: Inverted O/H, $m_3 < m_1 < m_2$

$$\Delta m^2_{21} = (7.50^{+0.22}_{-0.20}) \cdot 10^{-5}\ \mathrm{eV}^2$$
$$|\Delta m^2_{31}| = (2.54 \pm 0.03) \cdot 10^{-3}\ \mathrm{eV}^2\ (\mathrm{NO})$$
$$= (2.44 \pm 0.03) \cdot 10^{-3}\ \mathrm{eV}^2\ (\mathrm{IO})$$

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

$$\delta/\pi = 1.10^{+0.27}_{-0.12}\ (\mathrm{NO})$$
$$= 1.54 \pm 0.14\ (\mathrm{IO})$$



mass ordering still unknown

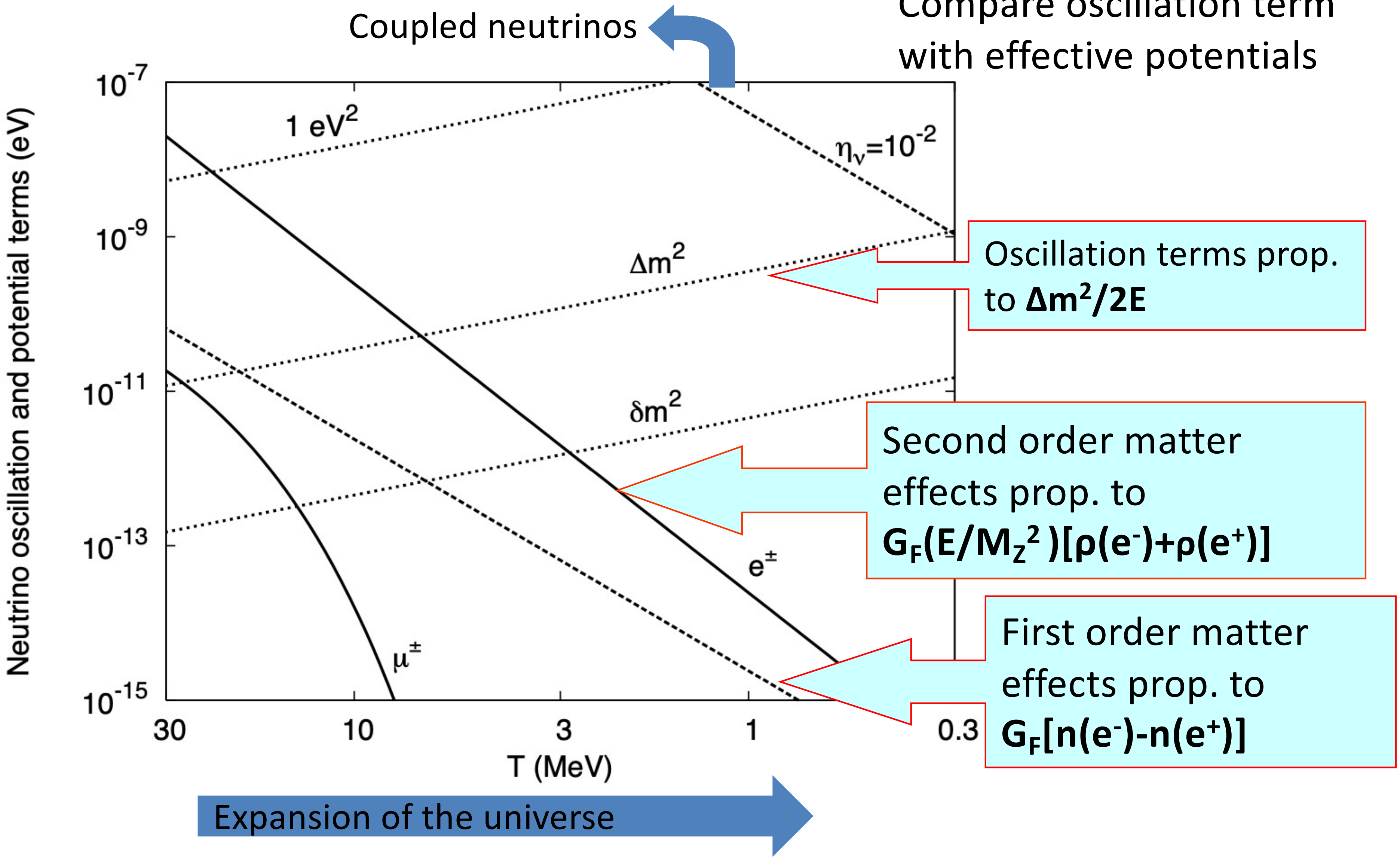
δ still unknown

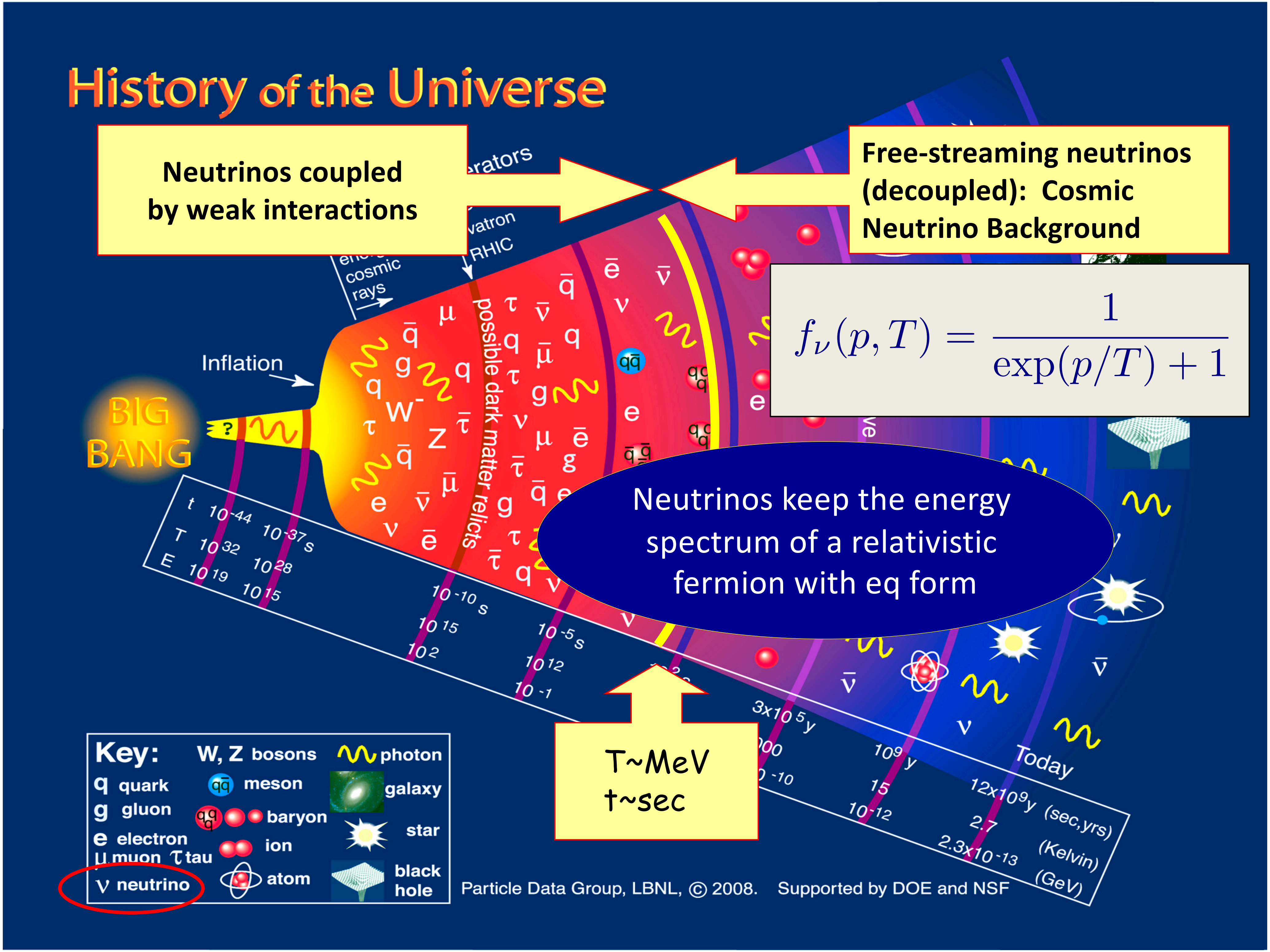
See also **http://globalfit.astroparticles.es**

Neutrino oscillations in the Early Universe

Neutrino oscillations are effective when medium effects get small enough

Compare oscillation term with effective potentials





Neutrinos coupled by weak interactions

Free-streaming neutrinos (decoupled): Cosmic Neutrino Background

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

Neutrinos keep the energy spectrum of a relativistic fermion with eq form

T~MeV
t~sec

Flavour neutrino oscillations in the Early Universe

Standard case: all neutrino flavours equally populated

→ oscillations are effective below a few MeV, but have no effect (except for mixing the small distortions δf_ν)

Cosmology is insensitive to neutrino flavour after decoupling!

Non-zero neutrino asymmetries: flavour oscillations lead to (approximate) global flavour equilibrium

↓

the restrictive BBN bound on the $\nu_e \bar{\nu}_e$ asymmetry applies to all flavors, but fine-tuned initial asymmetries always allow for a large surviving neutrino excess radiation that may show up in precision cosmological data (**value depends on θ_{13}**)

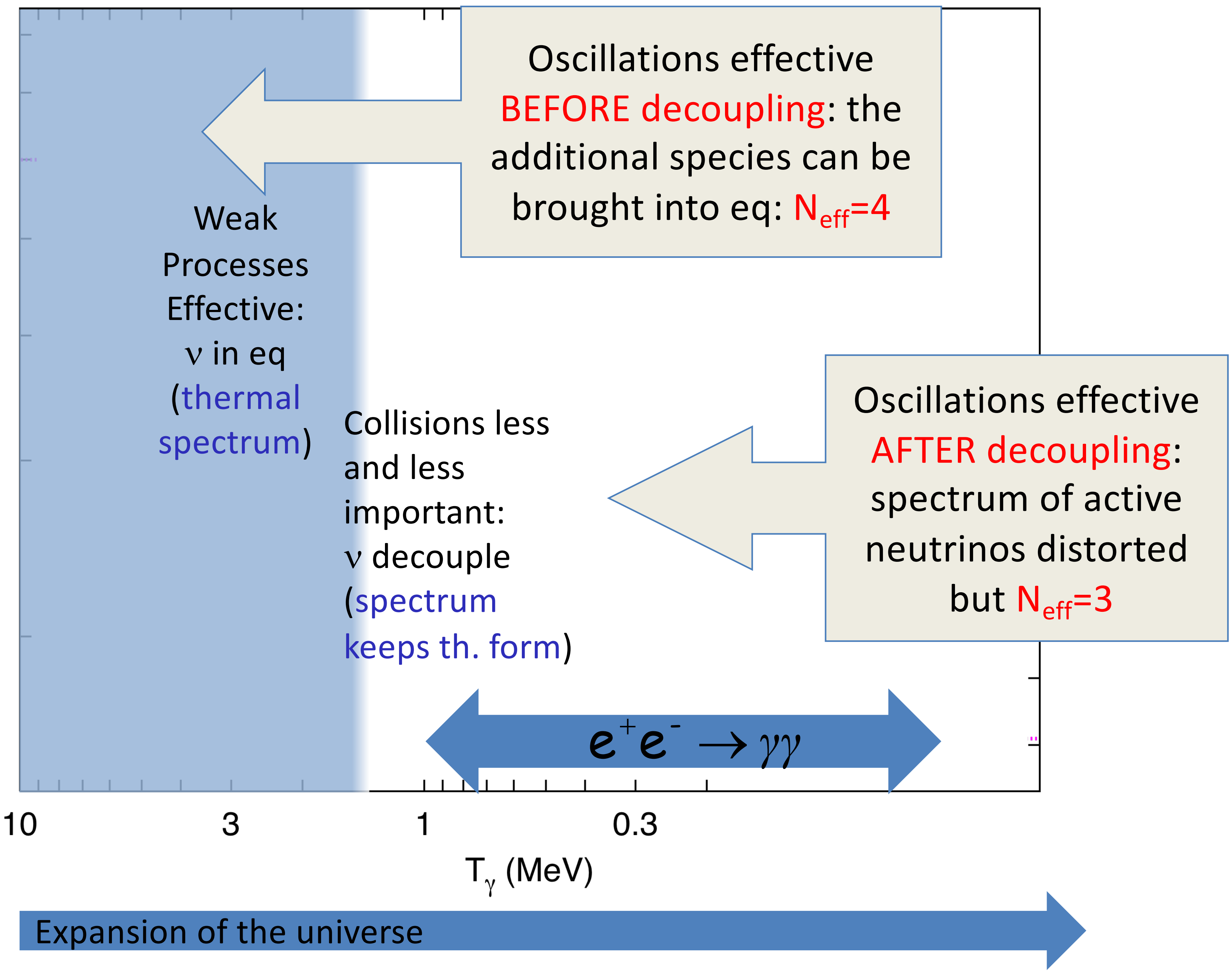
Active-sterile neutrino oscillations

What if additional, light *sterile* neutrino species are mixed with the flavour neutrinos?

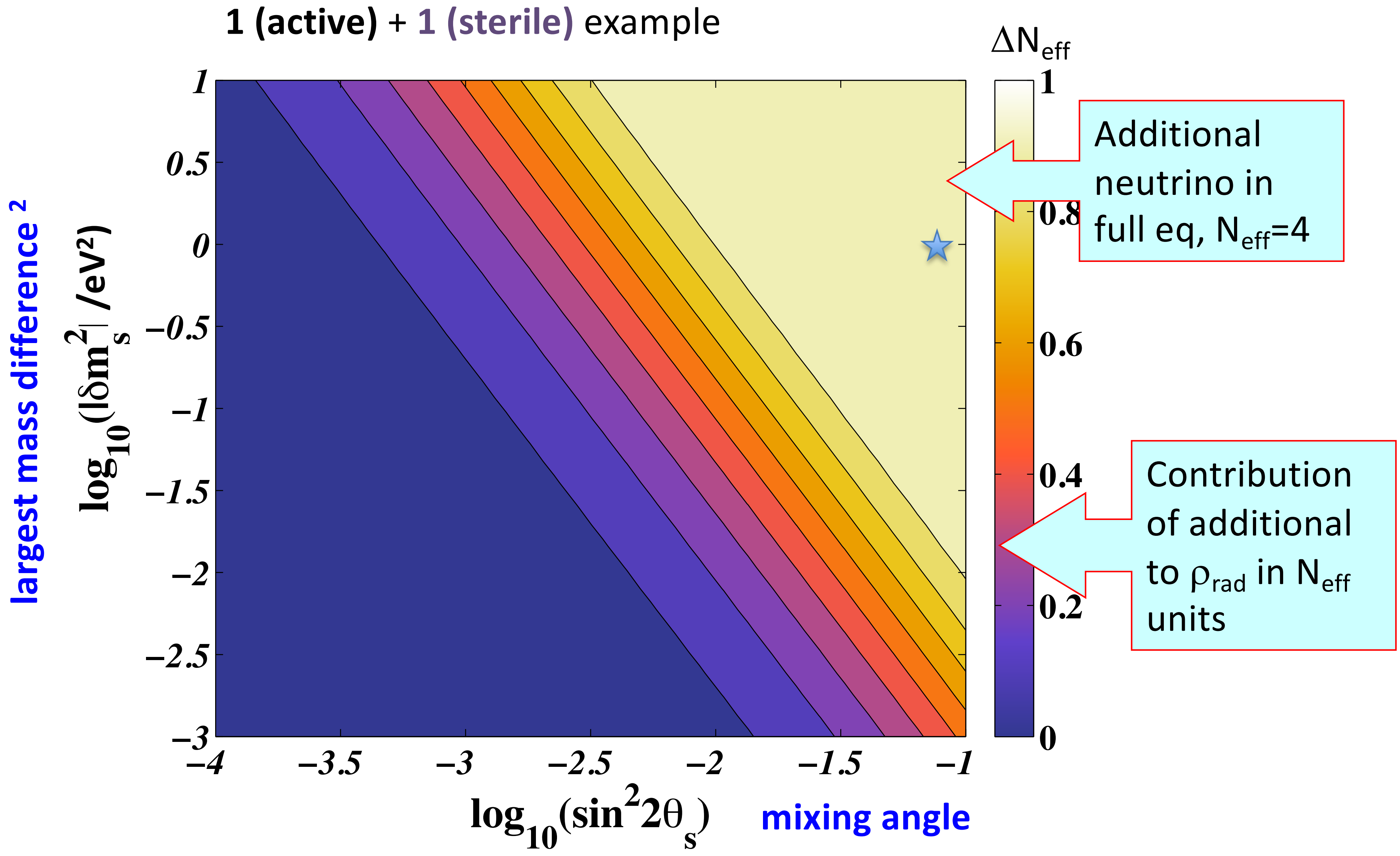
♣ If oscillations are effective before decoupling: the additional species can be brought into equilibrium: $\mathbf{N_{eff}=4}$

♣ If oscillations are effective after decoupling: $\mathbf{N_{eff}=3}$ but the spectrum of active neutrinos is **distorted** (direct effect of ν_e and anti-ν_e on BBN)

N_{eff} & Active-sterile neutrino oscillations



N_{eff} & Active-sterile neutrino oscillations



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

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)

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

vacuum osc. term

matter potential term

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

+ continuity equation

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

comoving coordinates: $a = 1/T \quad x \equiv m_e\, a$

$y \equiv p\, a \quad z \equiv T_\gamma\, a \quad w \equiv T_\nu\, a$

S Gariazzo, PF de Salas & SP, JCAP 07 (2019) 014 [arXiv:1905.11290]

Equations for the neutrino density matrix

Boltzmann evolution equations (matrix form)

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

vacuum osc. term — matter potential term — collision integrals ($\alpha\ G_F^2$)

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

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

$$U = R^{34} R^{24} R^{14} R^{23} R^{13} R^{12} \quad \text{e.g.} \quad R^{14} = \begin{pmatrix} \cos\theta_{14} & 0 & 0 & \sin\theta_{14} \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ -\sin\theta_{14} & 0 & 0 & \cos\theta_{14} \end{pmatrix}$$

Equations for the neutrino density matrix

Boltzmann evolution equations (matrix form)

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

vacuum osc. term — matter potential term — collision integrals ($\alpha\ G_F^2$)

$$\mathbb{E}_\ell = \mathrm{diag}(\rho_e, \rho_\mu, 0, 0) \qquad \mathbb{E}_\nu = S_a \left(\int dy y^3 \varrho \right) S_a \quad \text{with } S_a = \mathrm{diag}(1,1,1,0)$$

lepton densities — neutrino densities — (only for active neutrinos)

take into account matter effects in oscillations

Equations for the neutrino density matrix

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 ($\alpha\ G_F^2$)

$\mathcal{I}(\varrho)$ collision integrals

take into account neutrino-electron scattering and pair annihilation

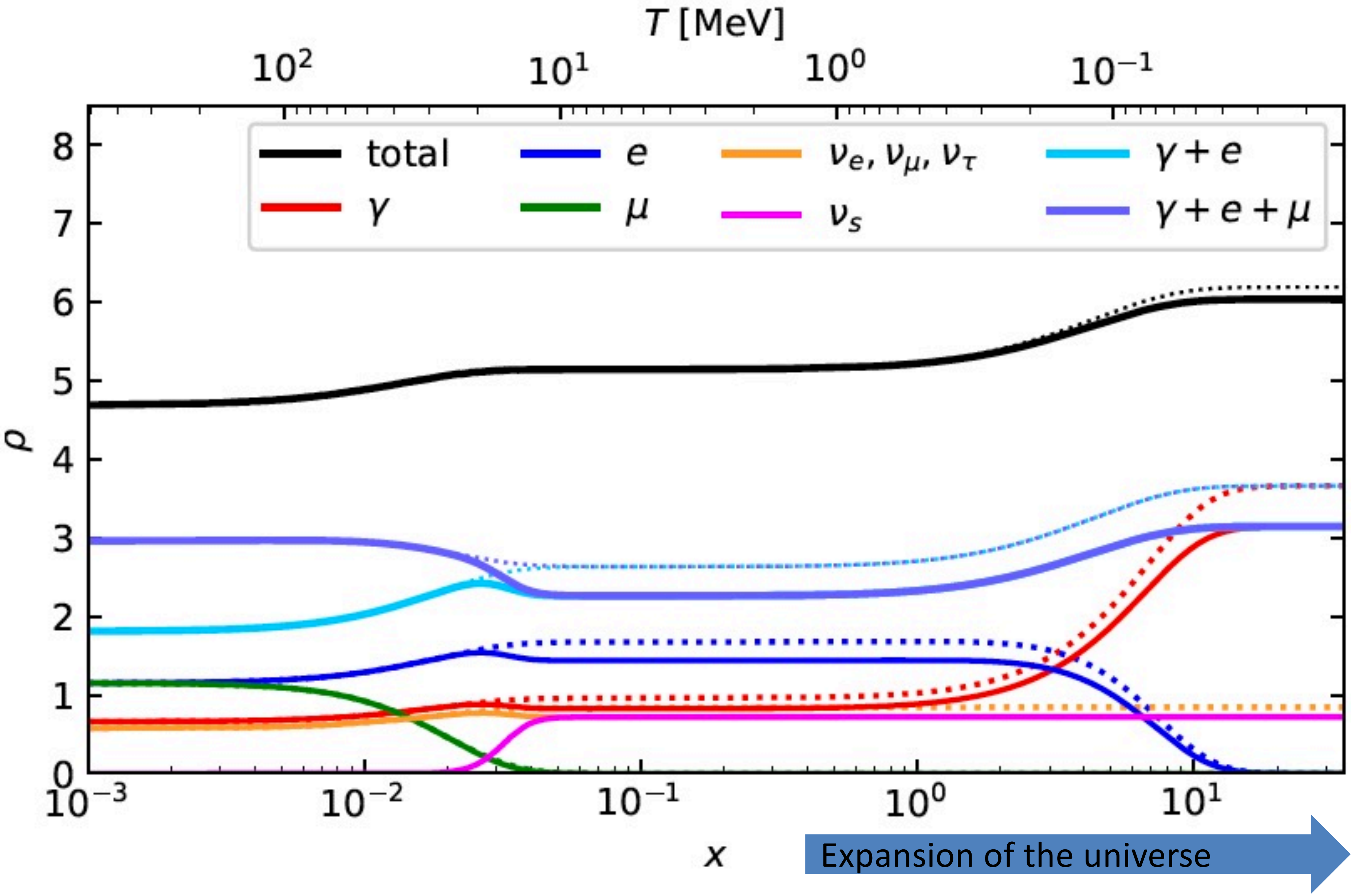
2D integrals over the momentum, take most of the computation time

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

S Gariazzo, PF de Salas & SP, JCAP 07 (2019) 014 [arXiv:1905.11290]

Results: evolution of energy densities (comoving)

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



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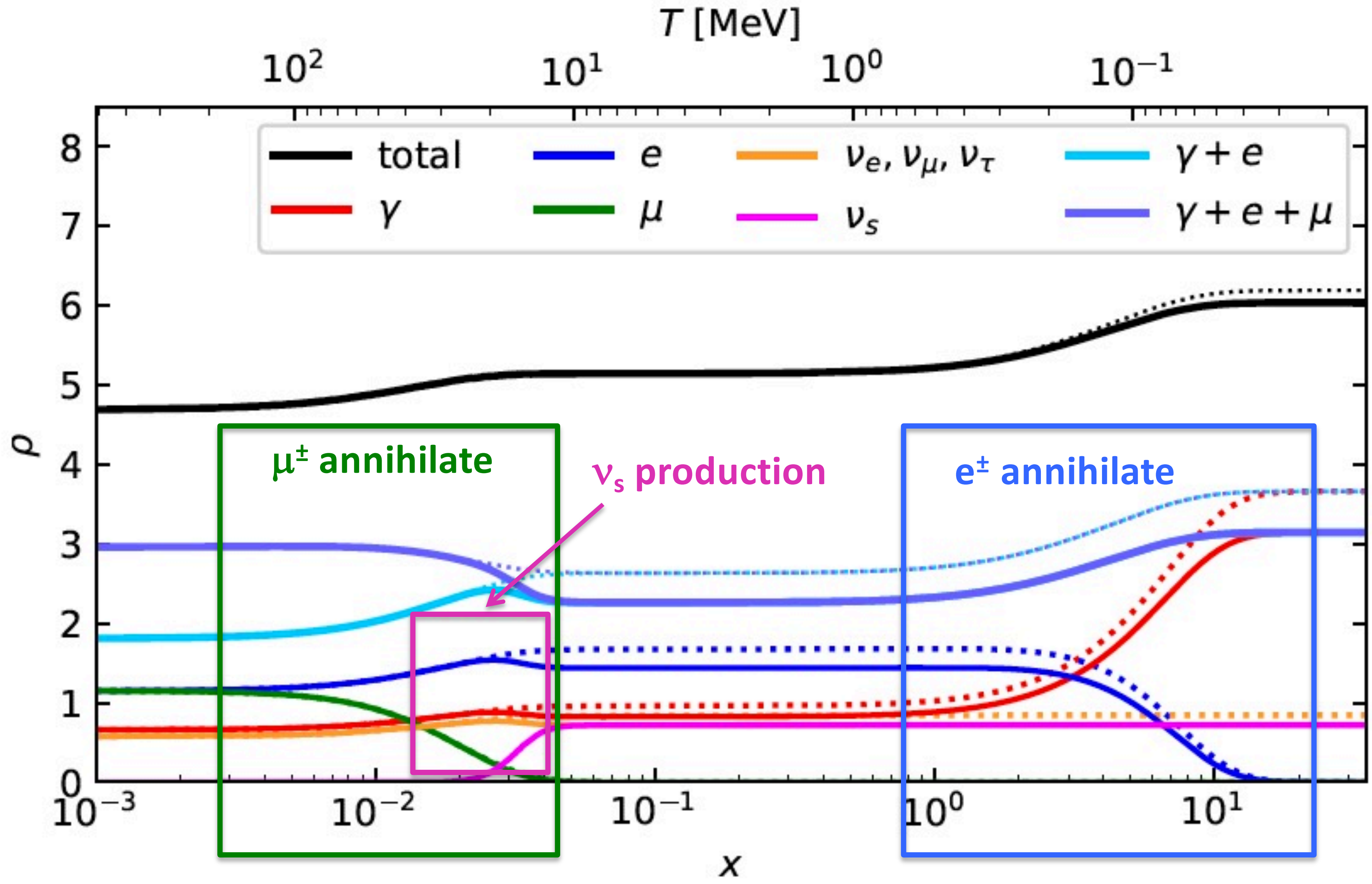
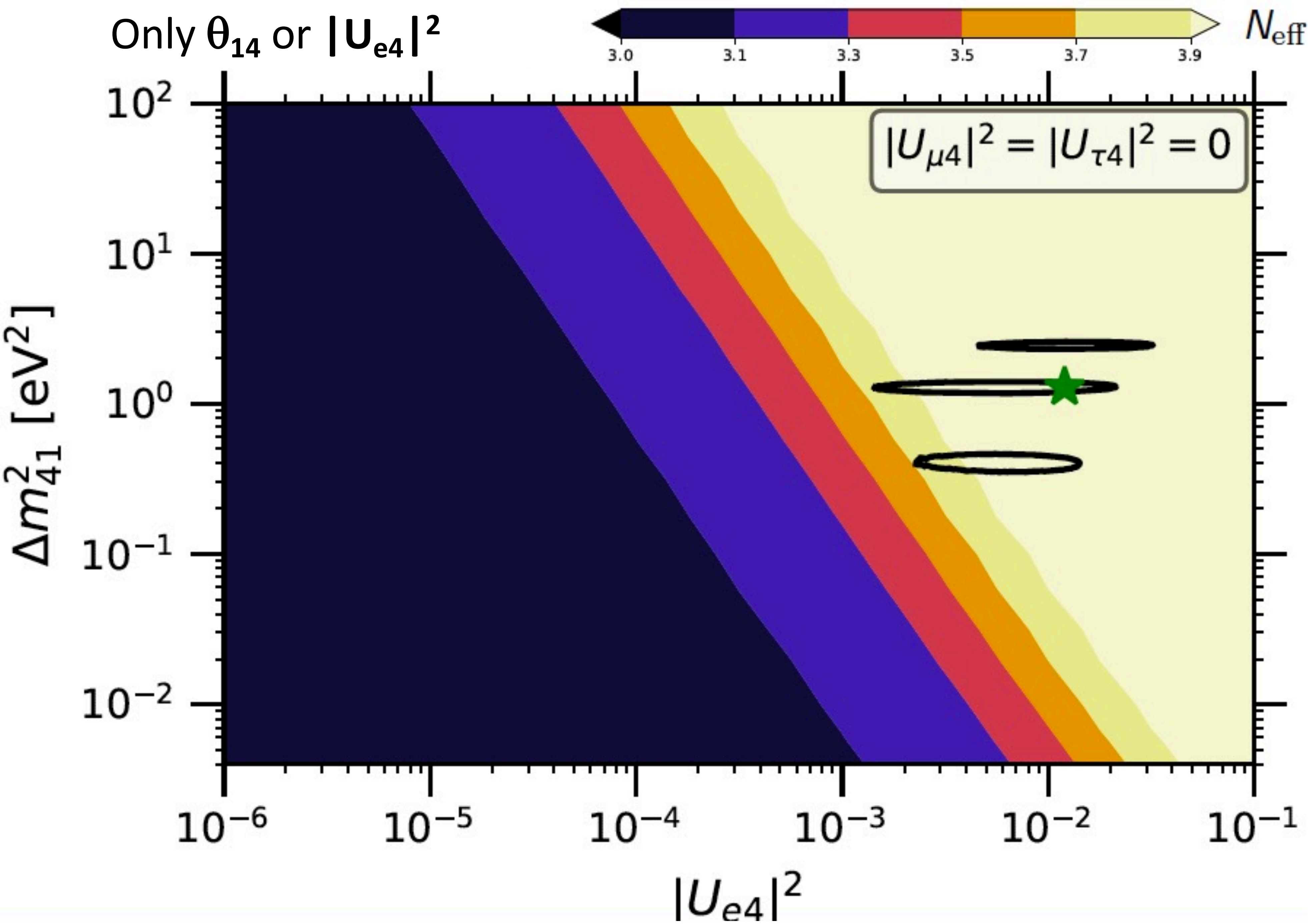


Results: final value of N_{eff} and sterile mixing parameters



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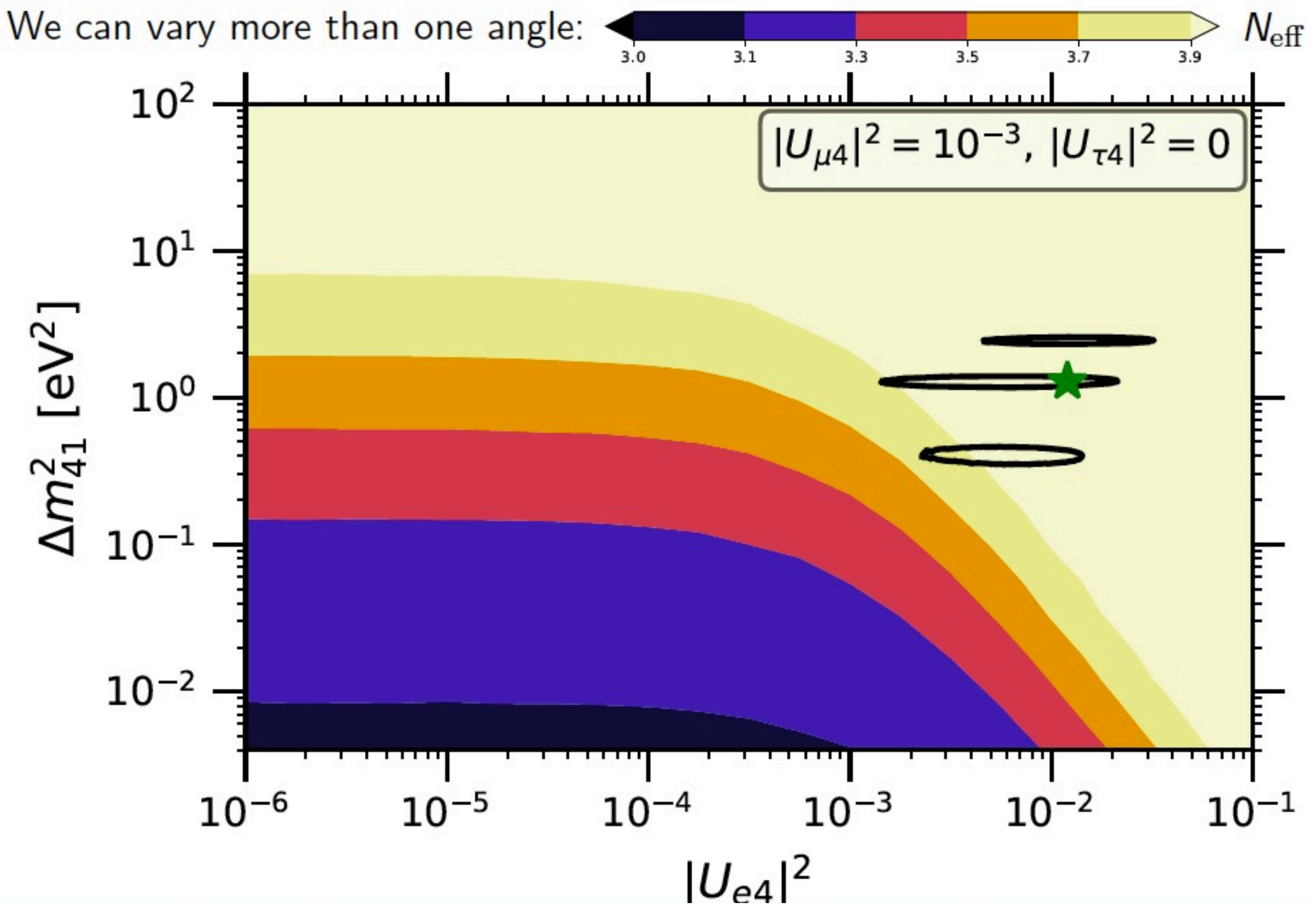

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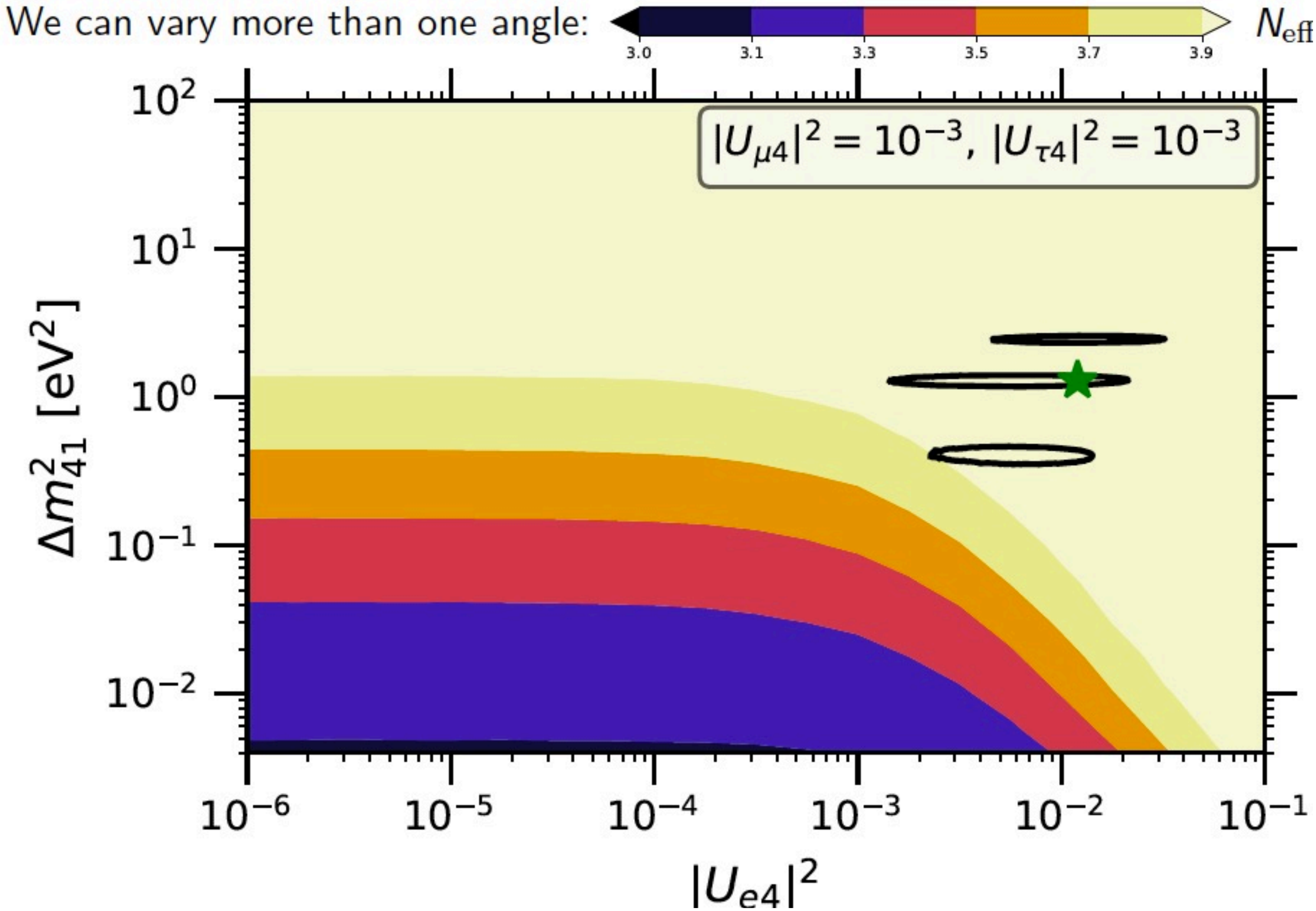
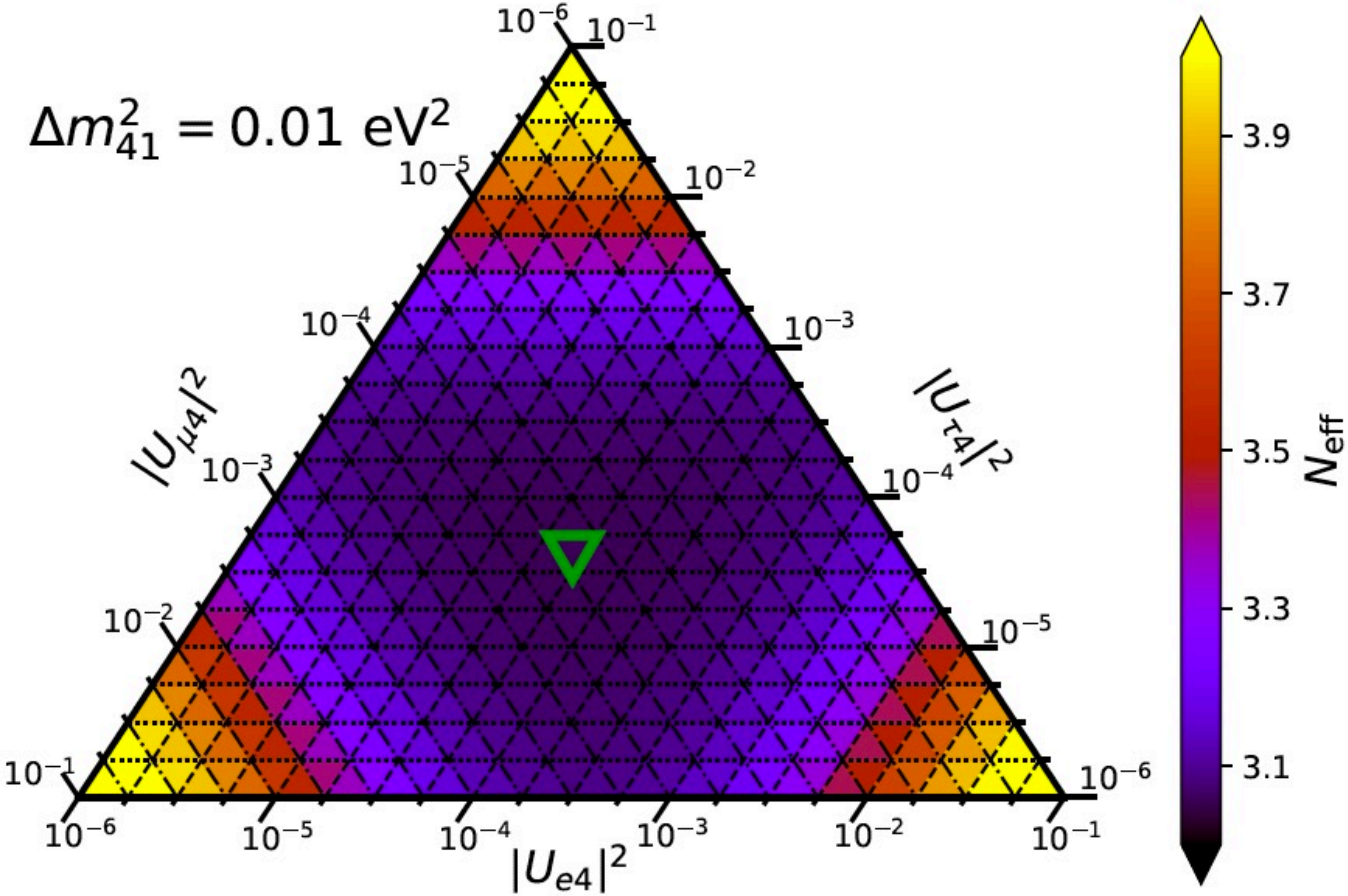


Results: final value of N_{eff} and sterile mixing parameters

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



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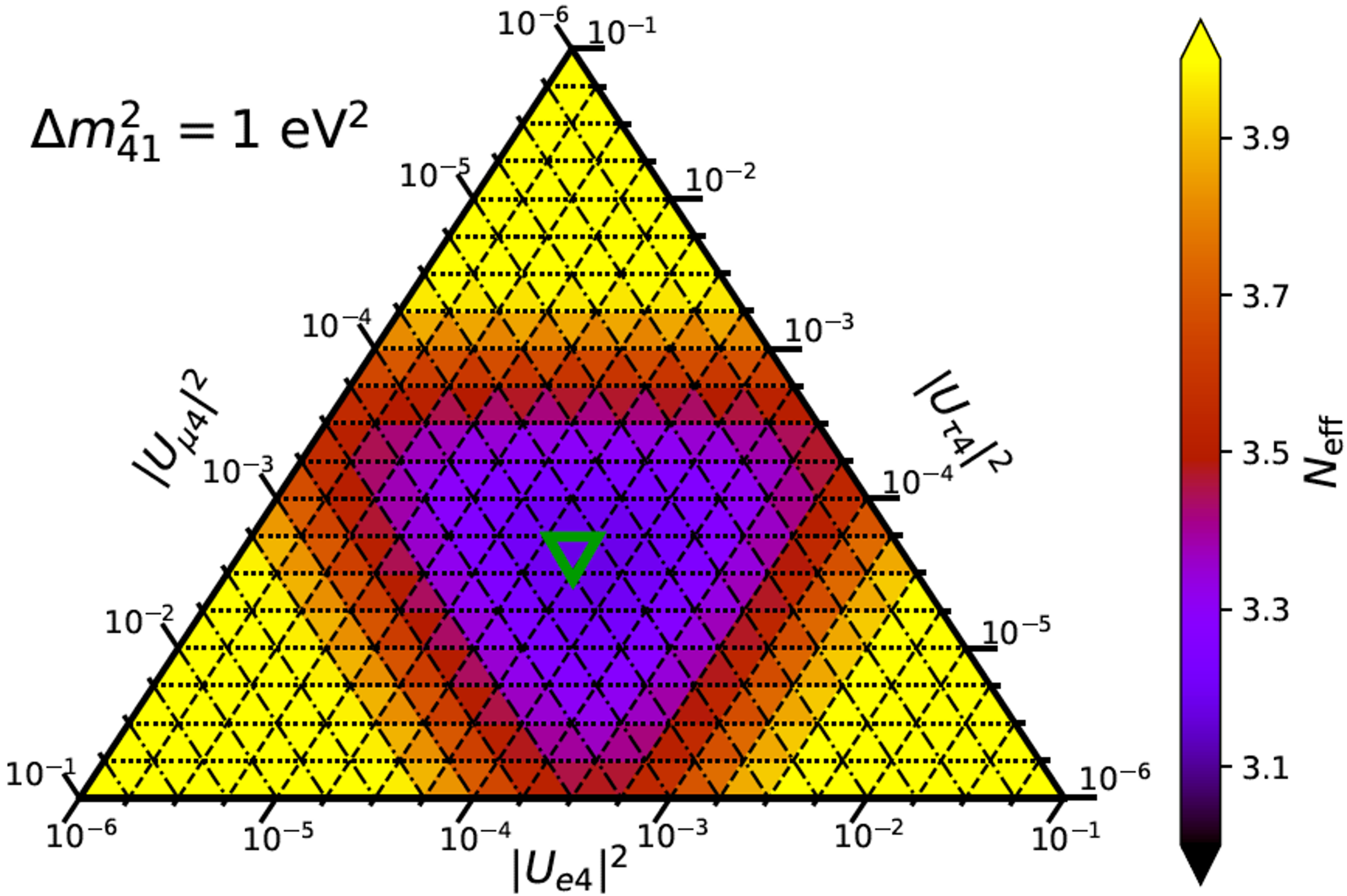

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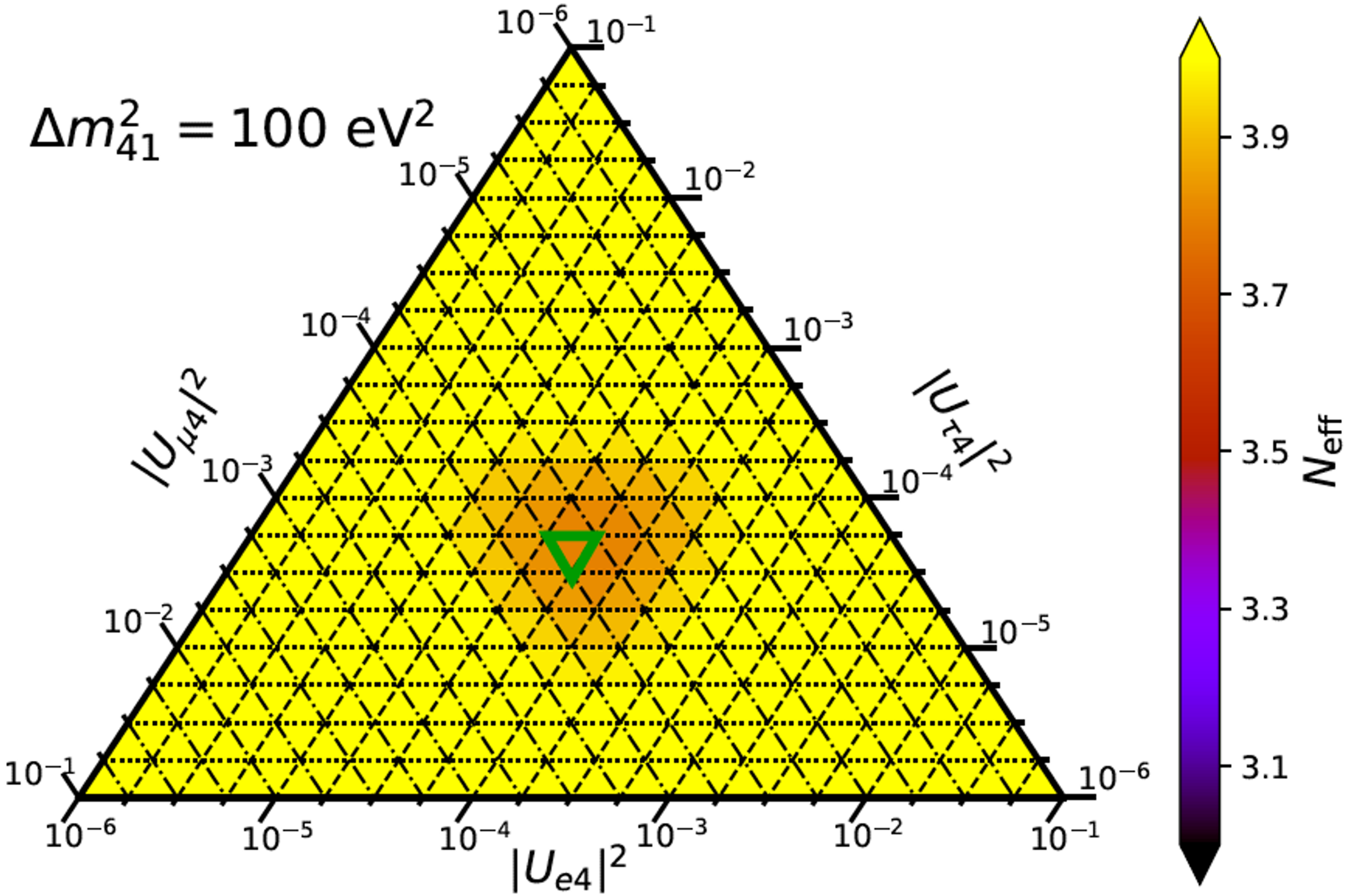

End