Neutrino flavour conversion in the early Universe

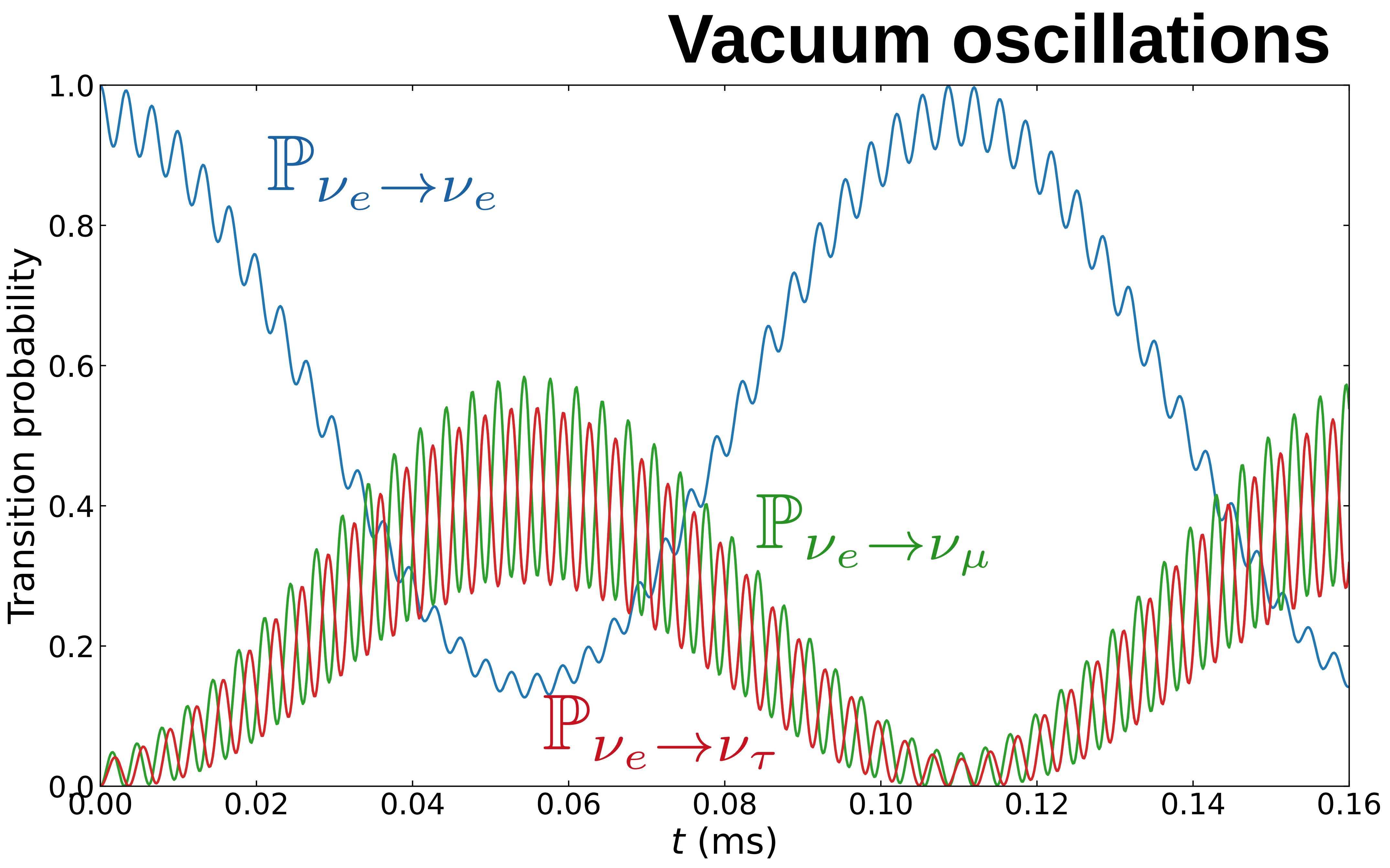
Julien Froustey

Severo Ochoa Postdoctoral Fellow,
IFIC, Valencia

Neutrino flavour oscillations

ACTIVE-ACTIVE

Well established and understood



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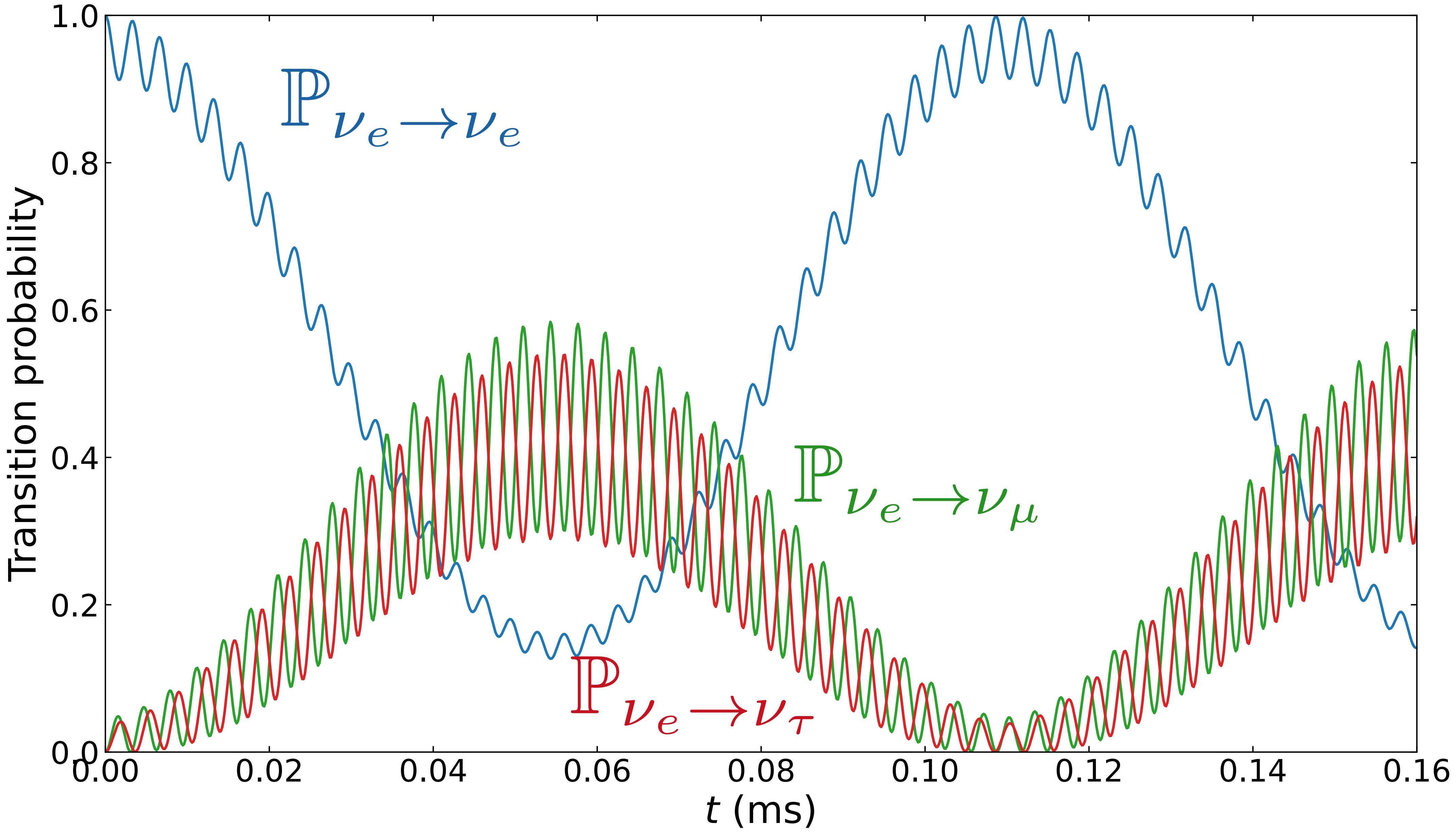
Vacuum oscillations



+ Matter effects (MSW, …)

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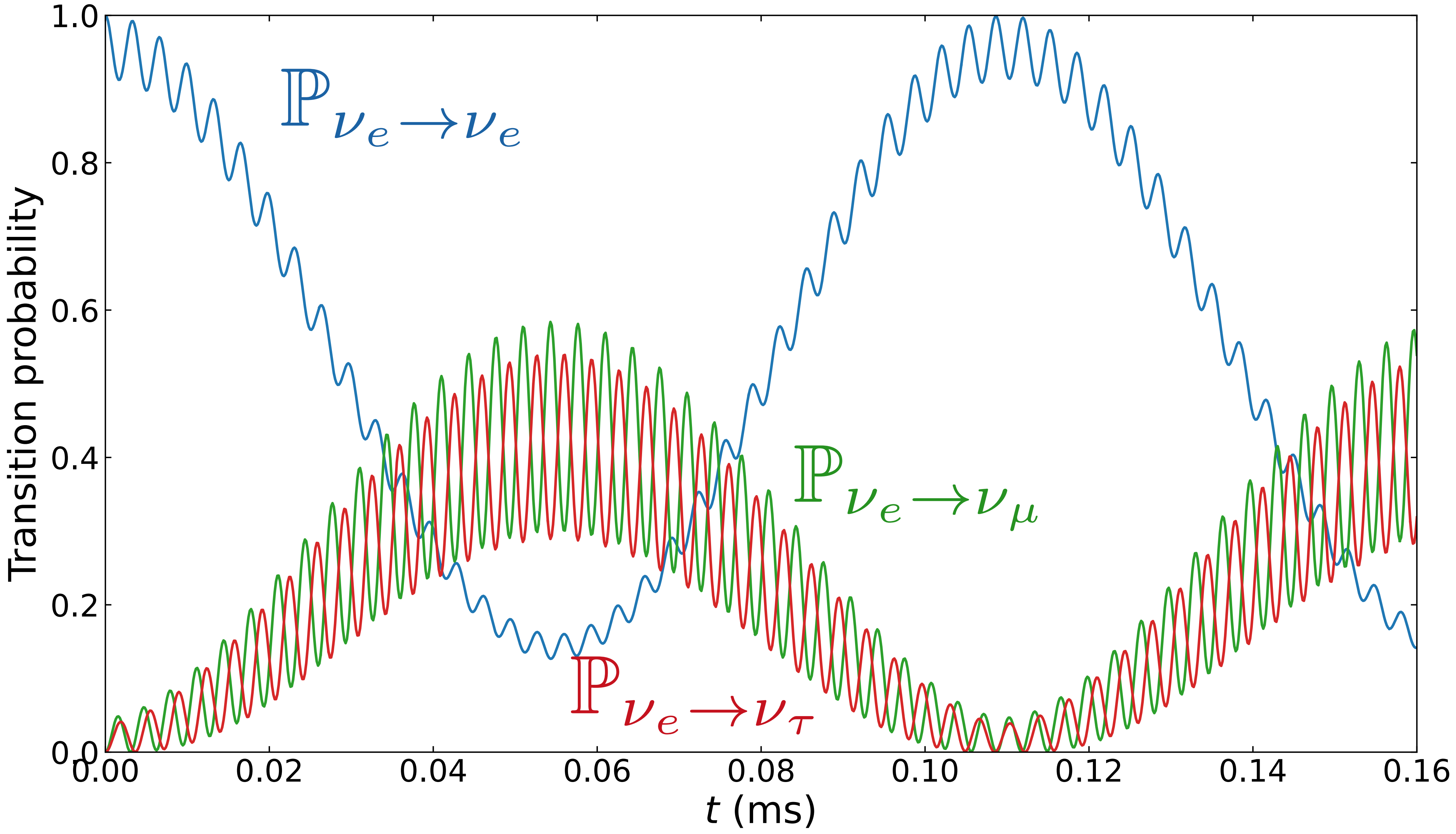

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ACTIVE-STERILE

Suggested / Constrained / …

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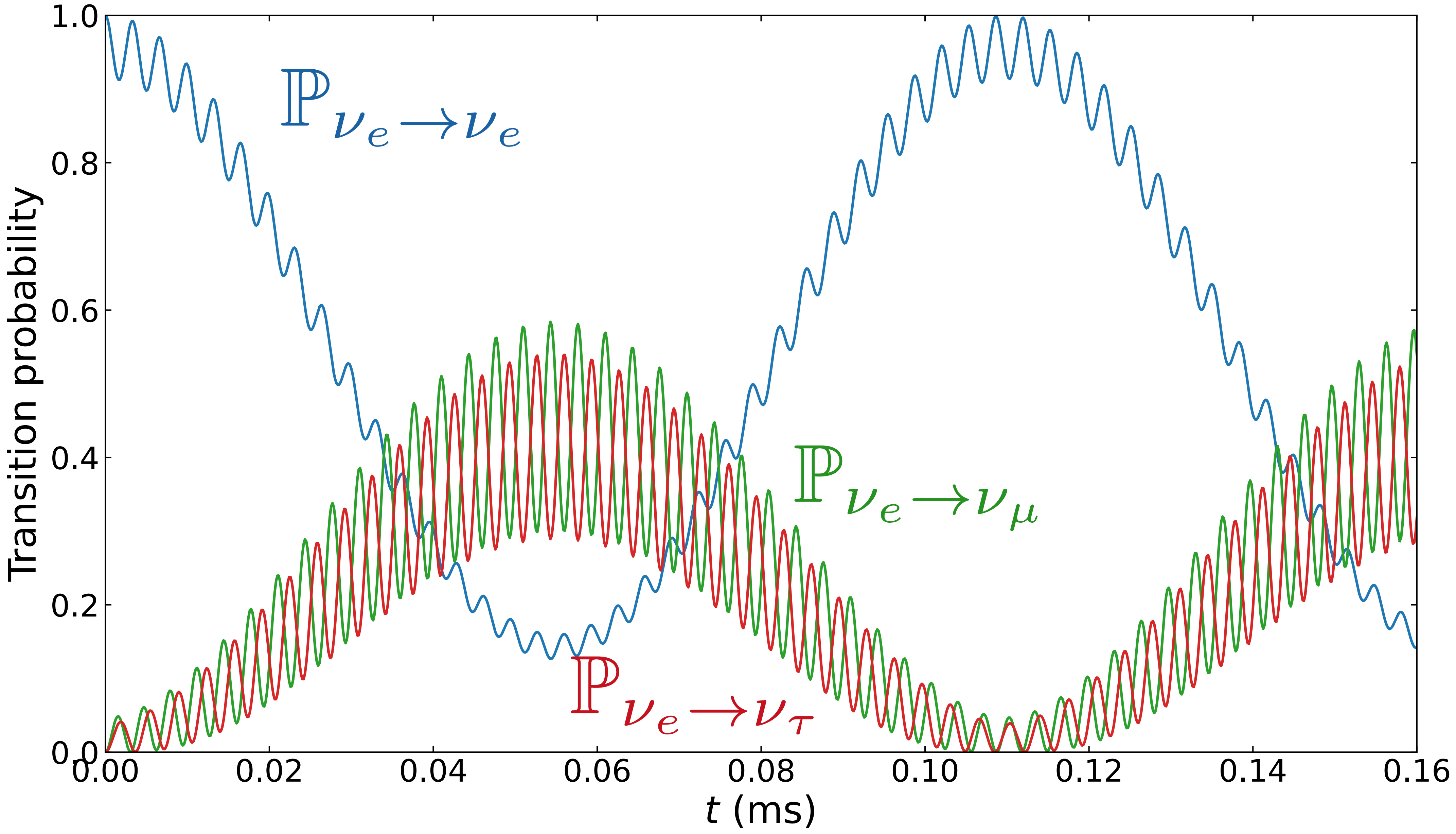

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↓

Effects on cosmological observables

Neutrino flavour oscillations

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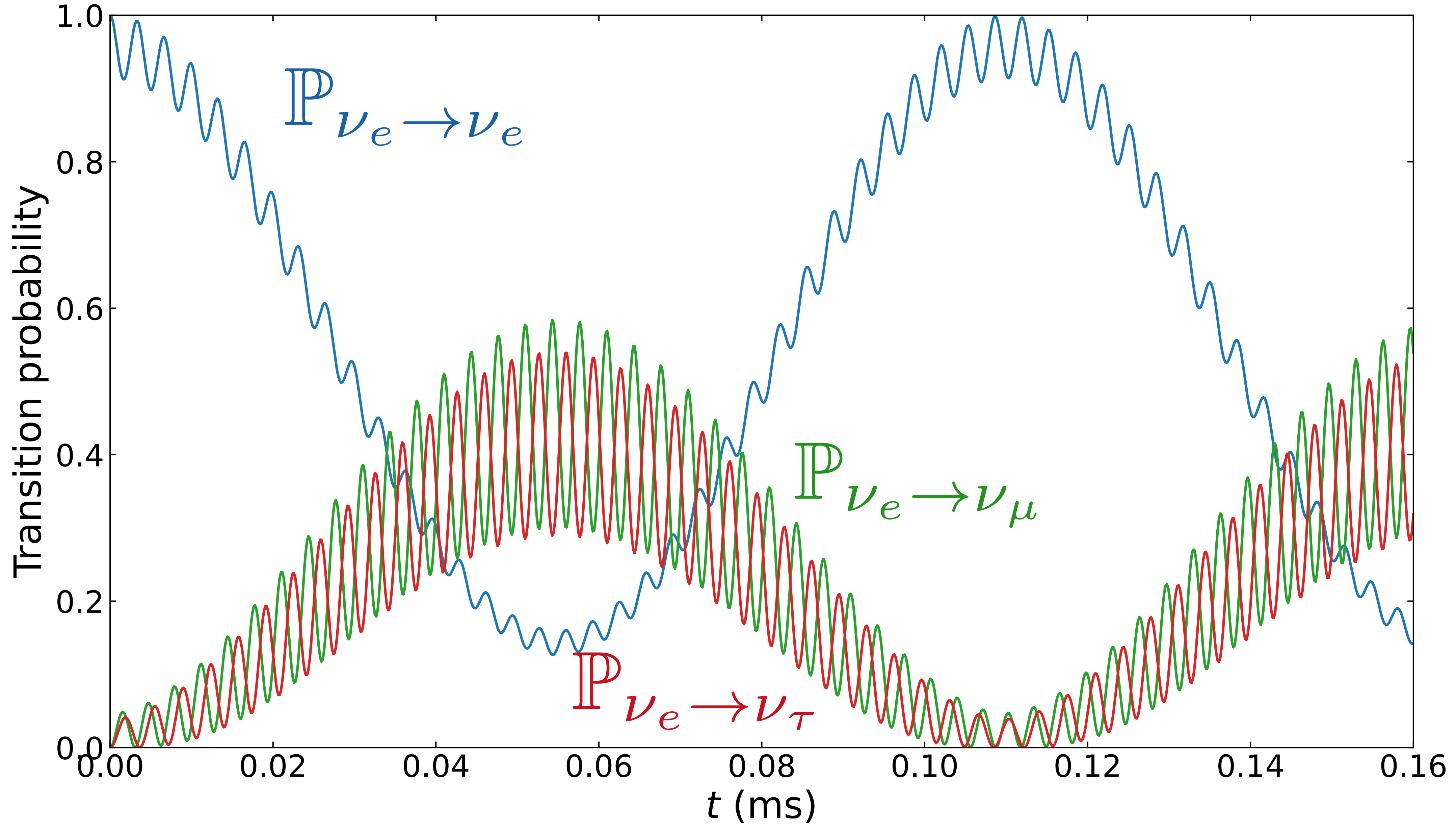

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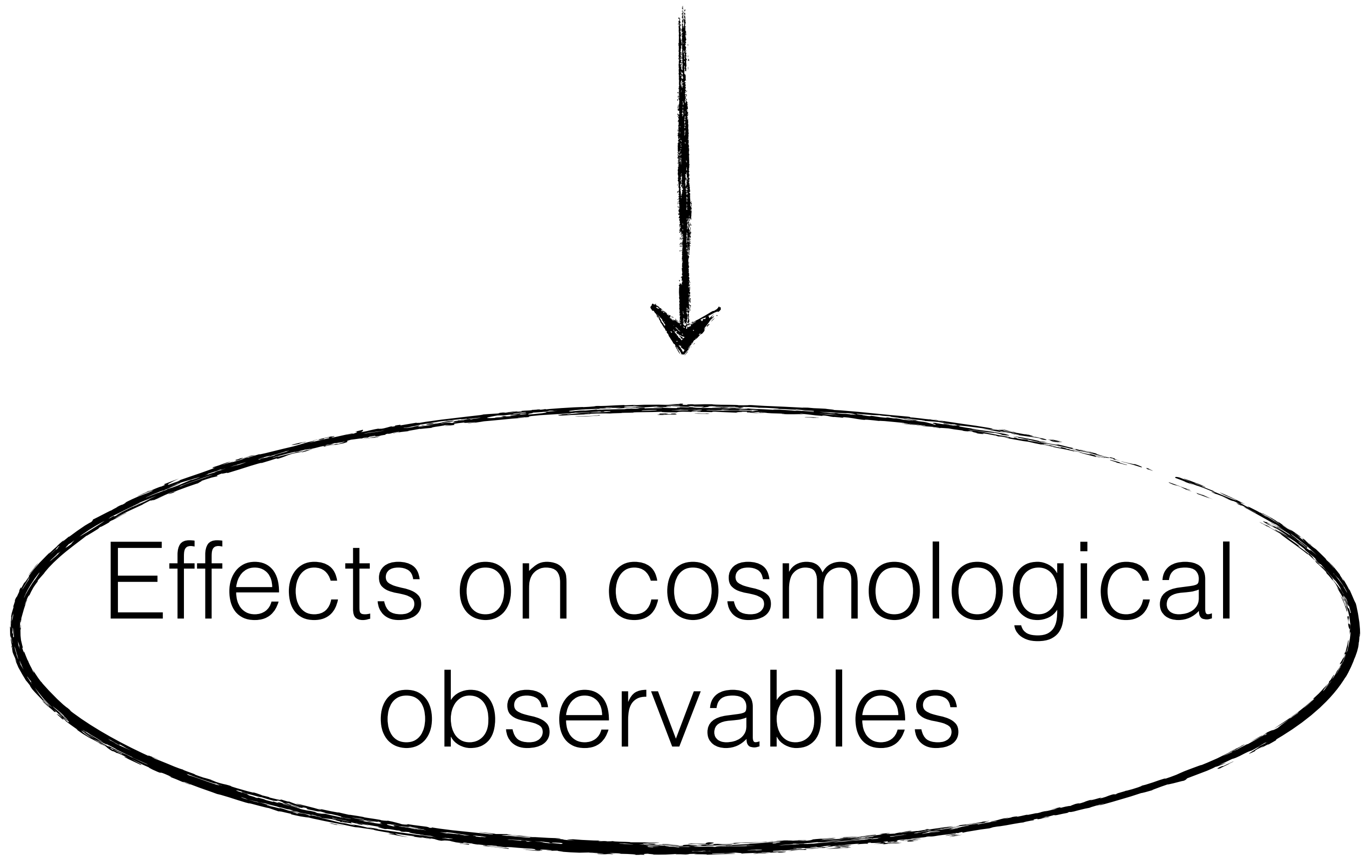
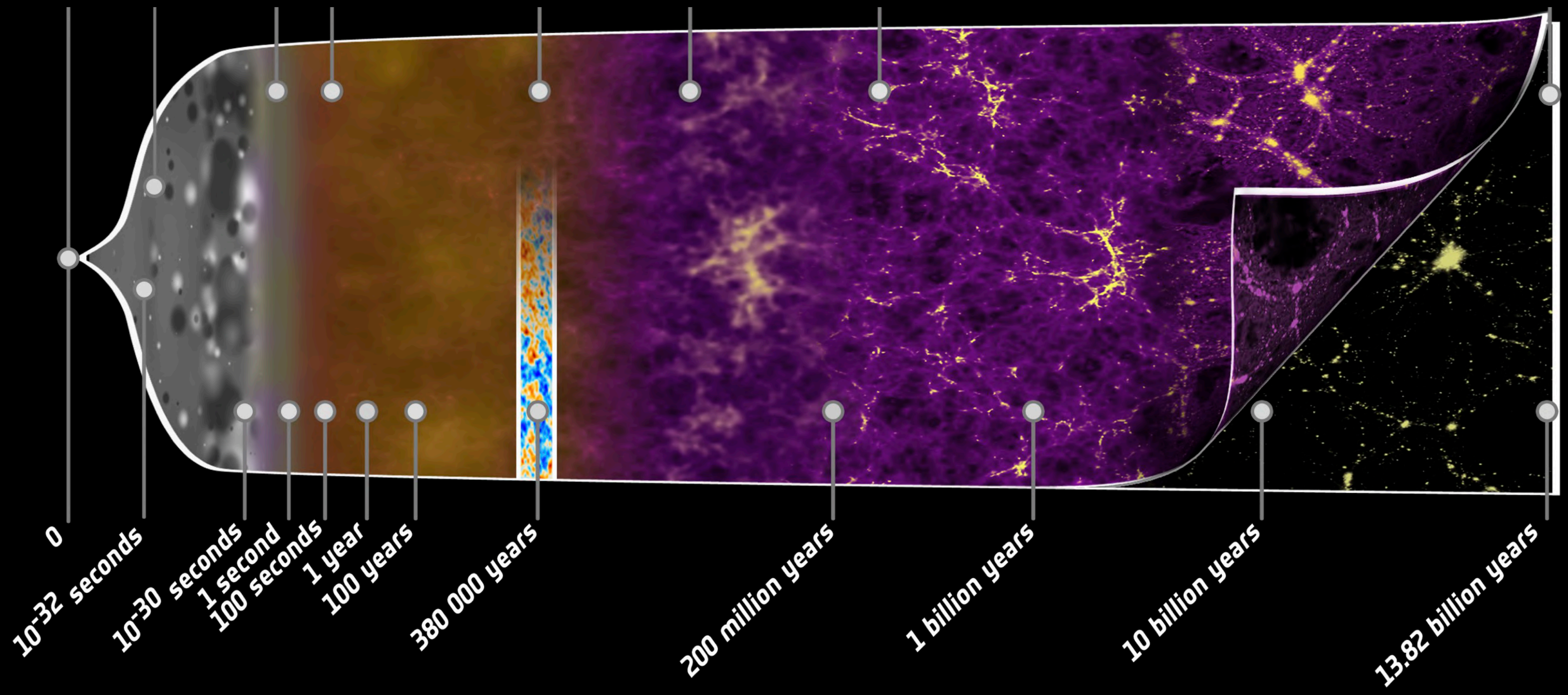


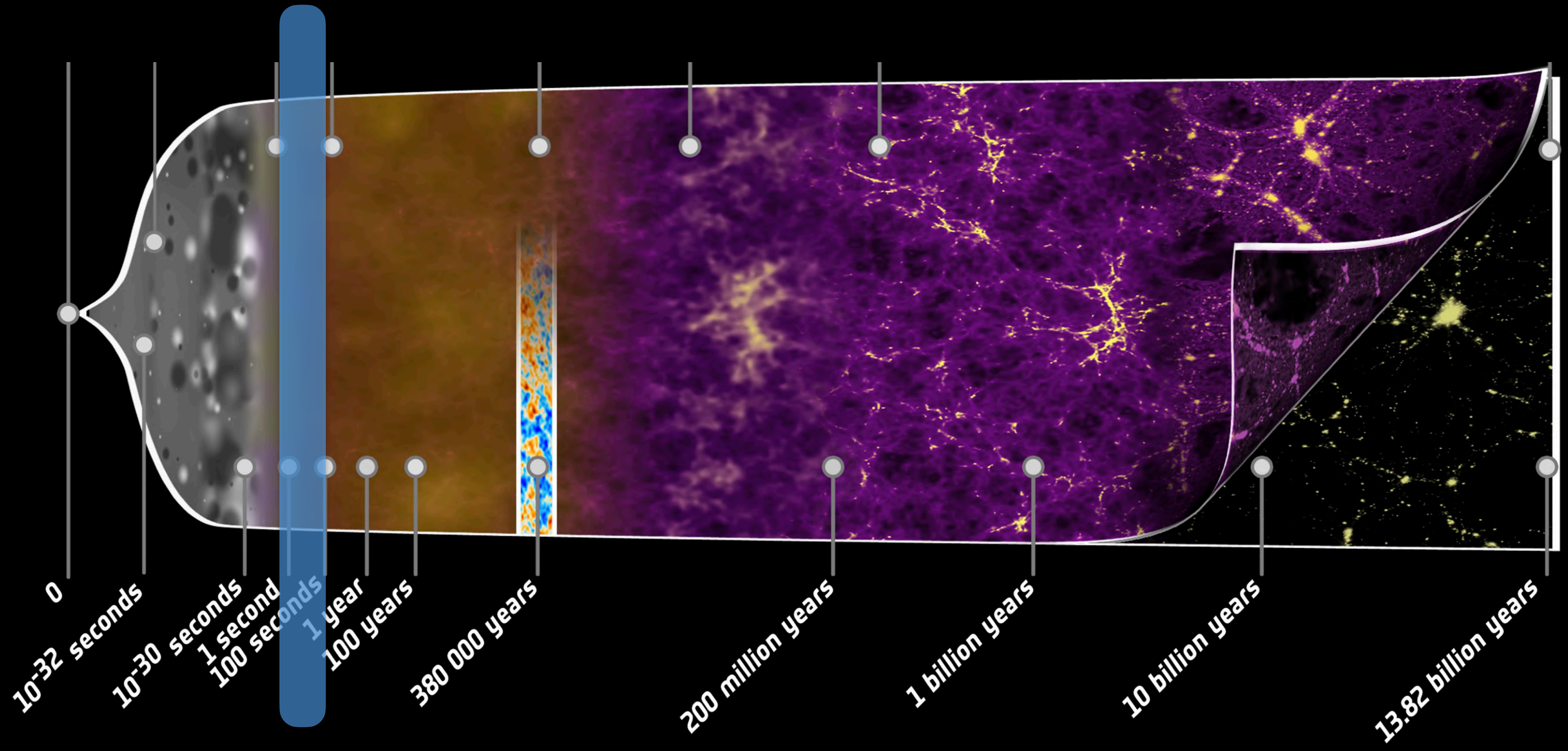
Example: **sterile neutrino dark matter**


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

Credits: ESA

Formation of the

Cosmic Neutrino Background



$$k_B T \sim 1\,\text{MeV} \sim 10^{10}\,\text{K}$$

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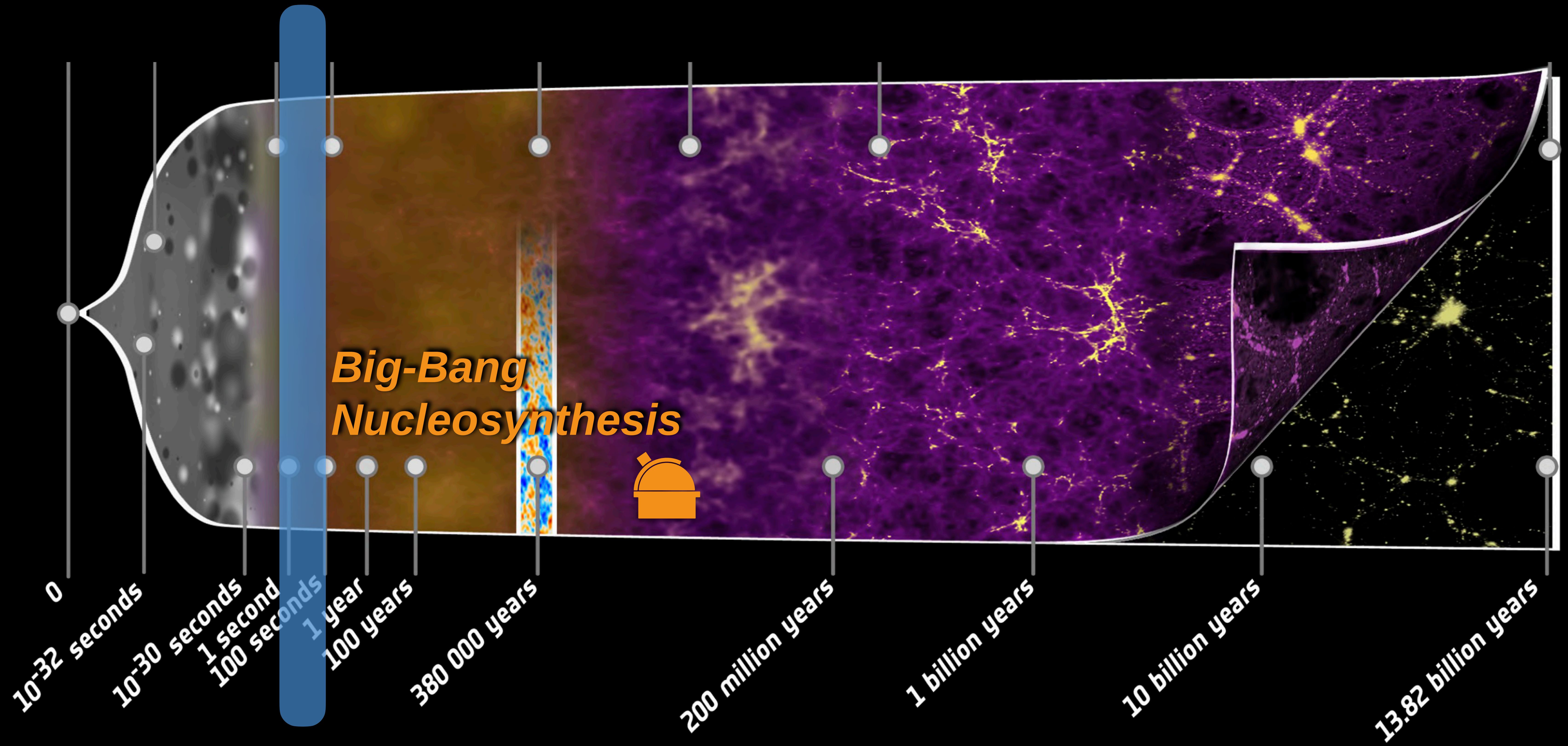

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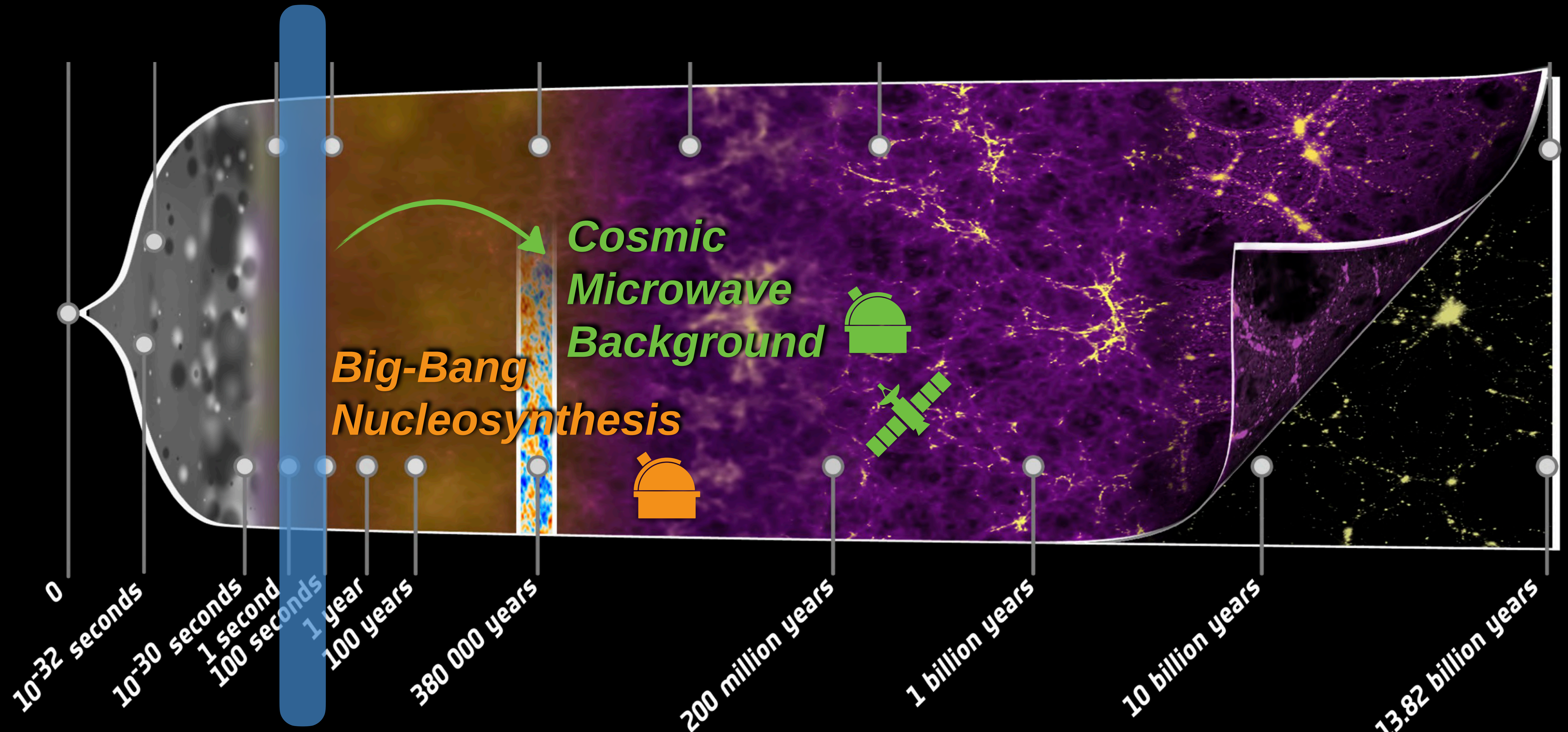

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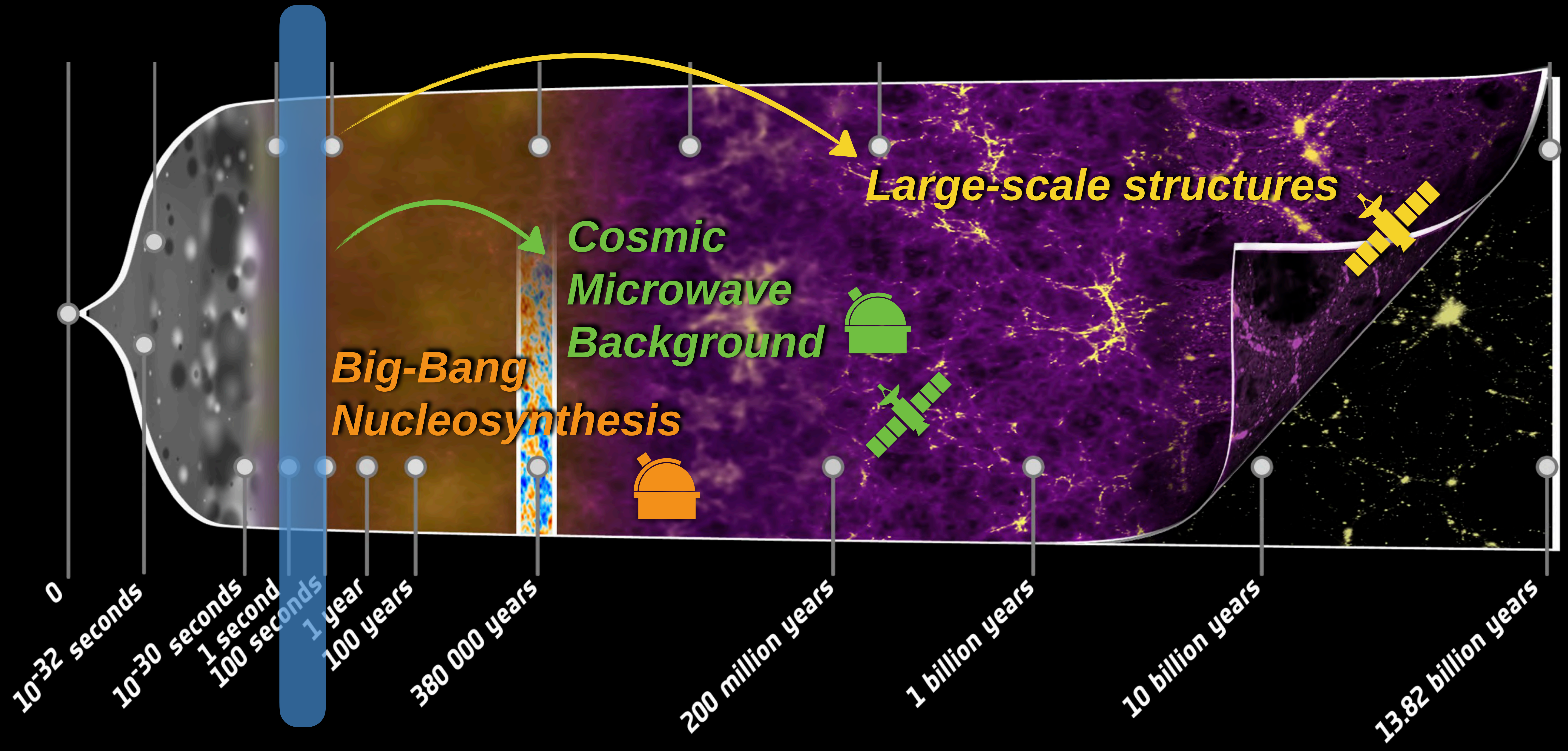

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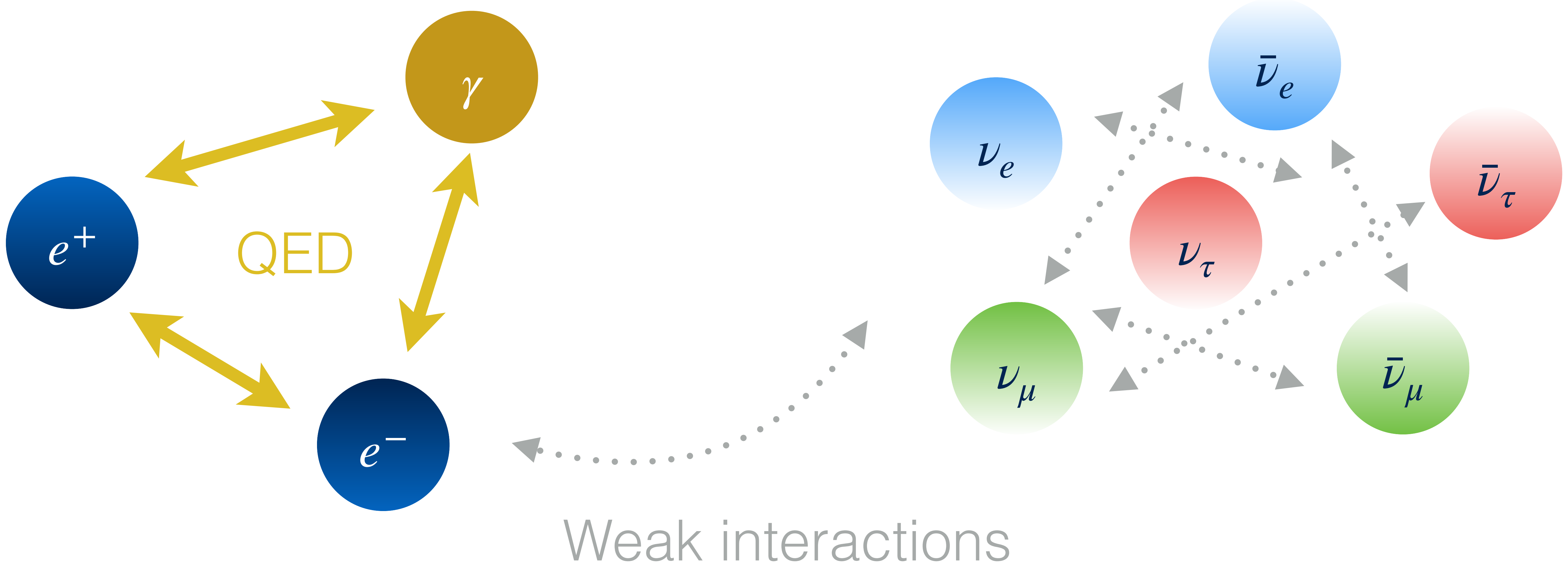
Neutrinos in the MeV age

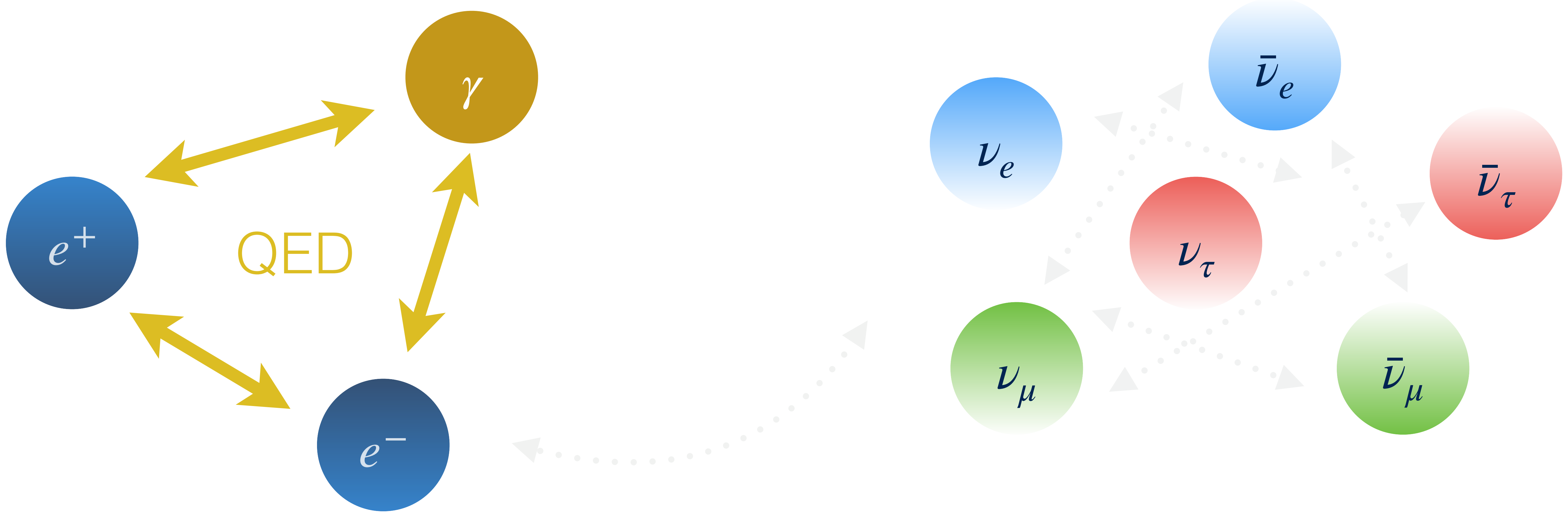


Neutrinos in the MeV age

NEUTRINO DECOUPLING

$$\frac{\text{collision rate}}{\text{expansion rate}} \qquad \frac{\Gamma}{H} \simeq \frac{G_F^2 T^5}{\sqrt{g_*}T^2/M_{\rm Pl}}$$

$$\Gamma/H = 1 \longleftrightarrow \quad T_{\rm dec} \simeq 1\,\mathrm{MeV}$$



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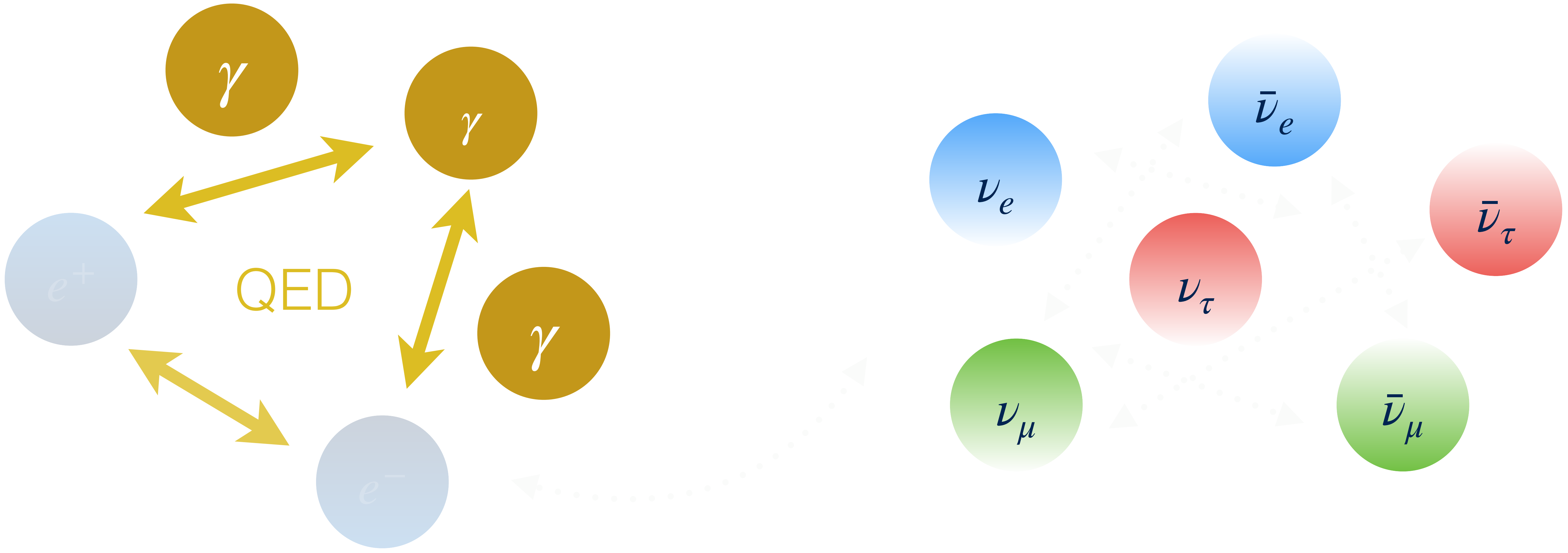

ELECTRON-POSITRON ANNIHILATIONS

→ entropy release

$$T_{e^\pm} = 0.511\,\text{MeV}$$

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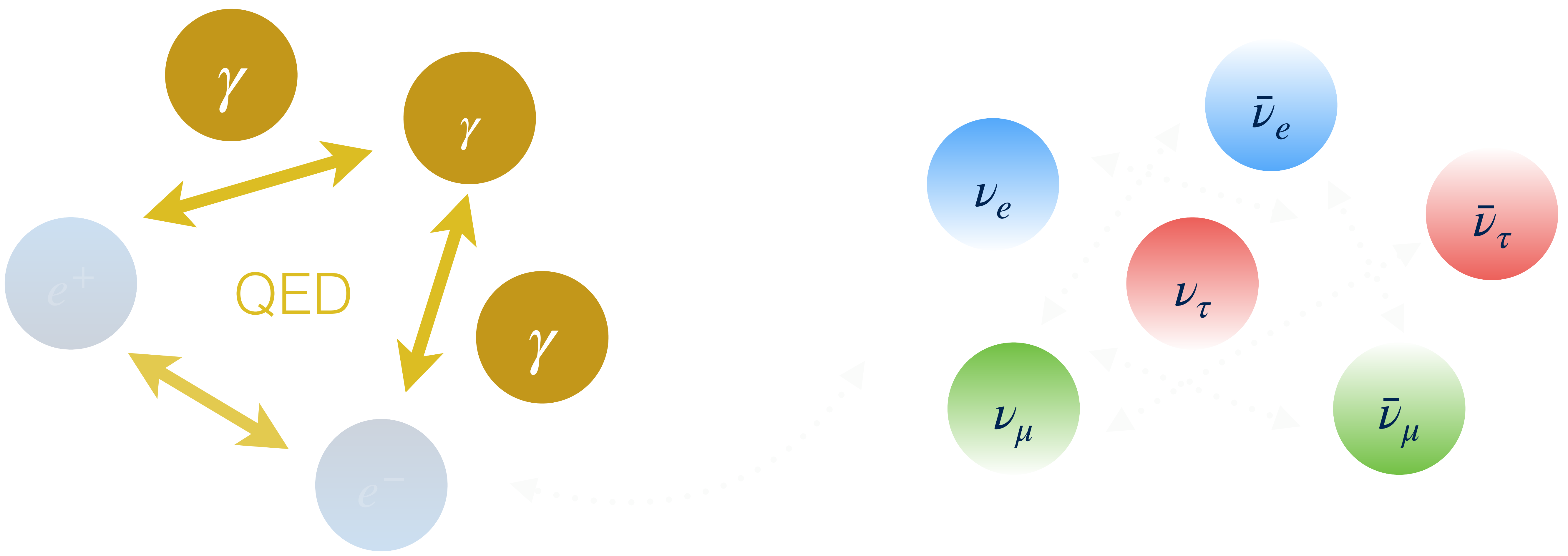

Neutrino oscillations

$$\Omega_{\rm vac} = \frac{\Delta m^2}{2E}$$

$$\Omega_{\rm matt} = \frac{\sqrt{2} G_F}{m_W^2} E \left[\rho_{e^\pm} + P_{e^\pm}\right] = \frac{7\pi^2}{45} \frac{\sqrt{2} G_F}{m_W^2} E\, T^4$$

MSW transition for $\Omega_{\rm vac} = \Omega_{\rm matt}$

$$T_{\rm MSW} \in [12\,\mathrm{MeV},\ 2.8\,\mathrm{MeV}]$$

Electron-positron annihilations

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Describing neutrino evolution

- We need to follow the evolution of neutrino distribution functions, including a lot of physics:
  - Expansion of the Universe
  - Weak interactions of neutrinos
  - Thermodynamics of the electromagnetic plasma
  - Neutrino oscillations

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$$\begin{pmatrix} f_{\nu_e} & & \\ & f_{\nu_\mu} & \\ & & f_{\nu_\tau} \end{pmatrix} \longrightarrow \varrho = \begin{pmatrix} \varrho_{ee} & \varrho_{e\mu} & \varrho_{e\tau} \\ \varrho^*_{e\mu} & \varrho_{\mu\mu} & \varrho_{\mu\tau} \\ \varrho^*_{e\tau} & \varrho^*_{\mu\tau} & \varrho_{\tau\tau} \end{pmatrix}$$

$$\frac{\partial \varrho}{\partial t} - Hp\frac{\partial \varrho}{\partial p} = -\mathrm{i}\left[\mathcal{H}_{\rm vac} + \mathcal{H}_{\rm mat} + \mathcal{H}_{\nu\nu}, \varrho\right] + \mathcal{C}$$

G. Mangano *et al.* [astro-ph/0111408]
A.D. Dolgov *et al.* [hep-ph/0201287]
S. Pastor, T. Pinto and G. Raffelt [0808.3137]
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Liouville term **Oscillations** **Collisions**

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Neutrino transport in the early Universe

- Calculation of **standard neutrino decoupling**

JF, C. Pitrou, M.C. Volpe [2008.01074]
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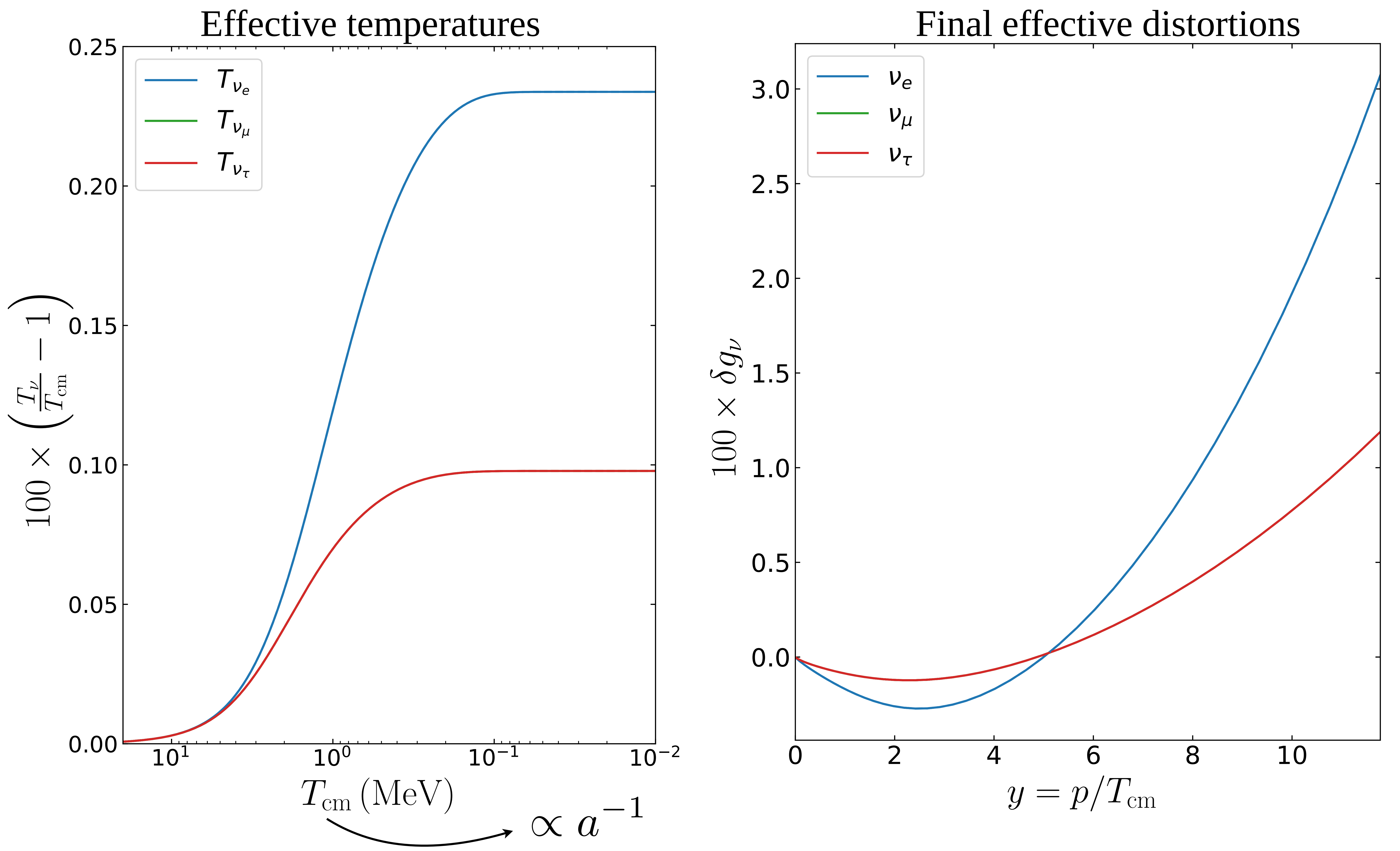

NO FLAVOUR OSCILLATIONS

Parametrization

$$f_{\nu_\alpha}(p,t) = \frac{1 + \delta g_{\nu_\alpha}(p,t)}{e^{p/T_{\nu_\alpha}} + 1}$$

$$\rho_{\nu_\alpha} \equiv \frac{7}{8}\frac{\pi^2}{30} T_{\nu_\alpha}^4$$

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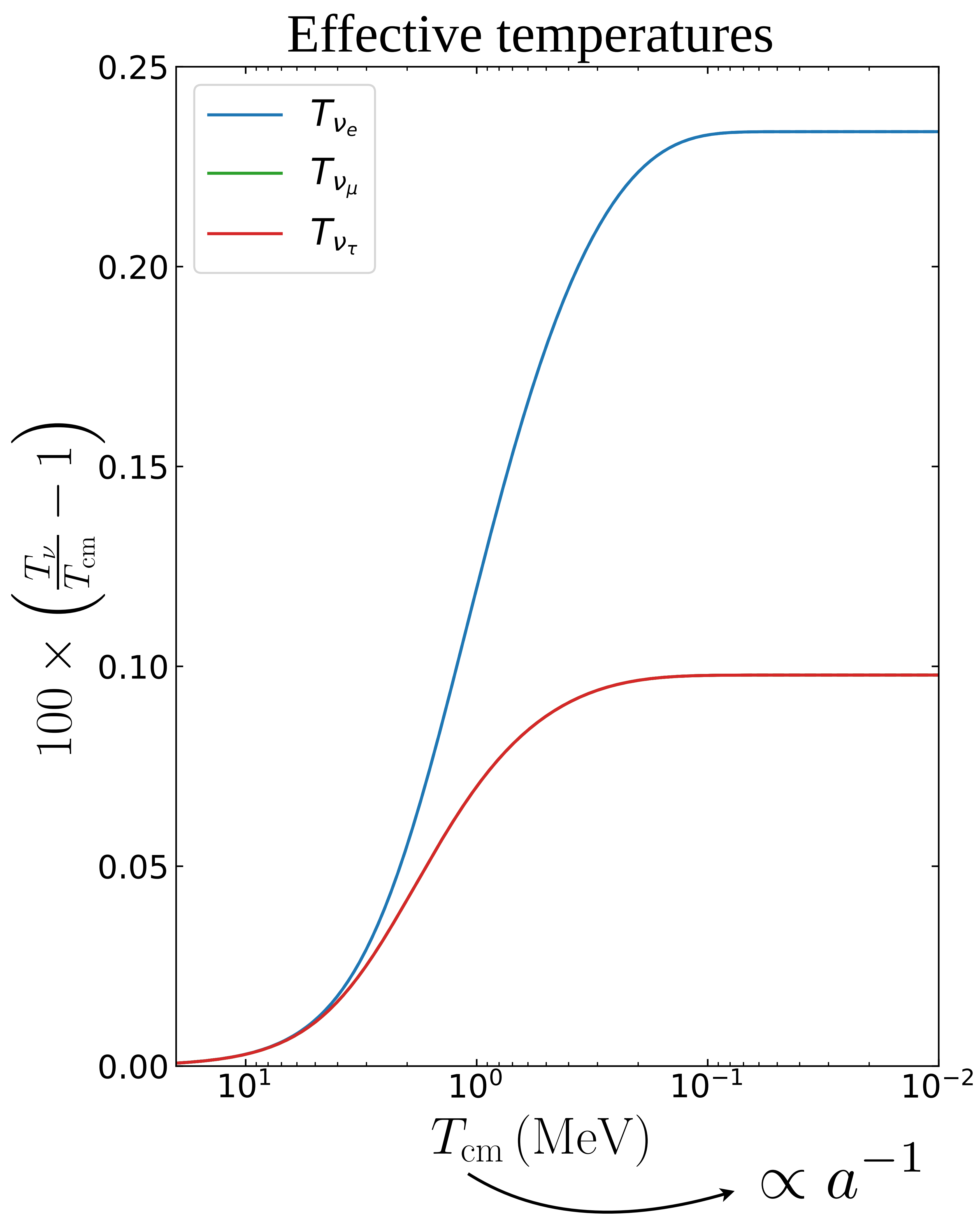

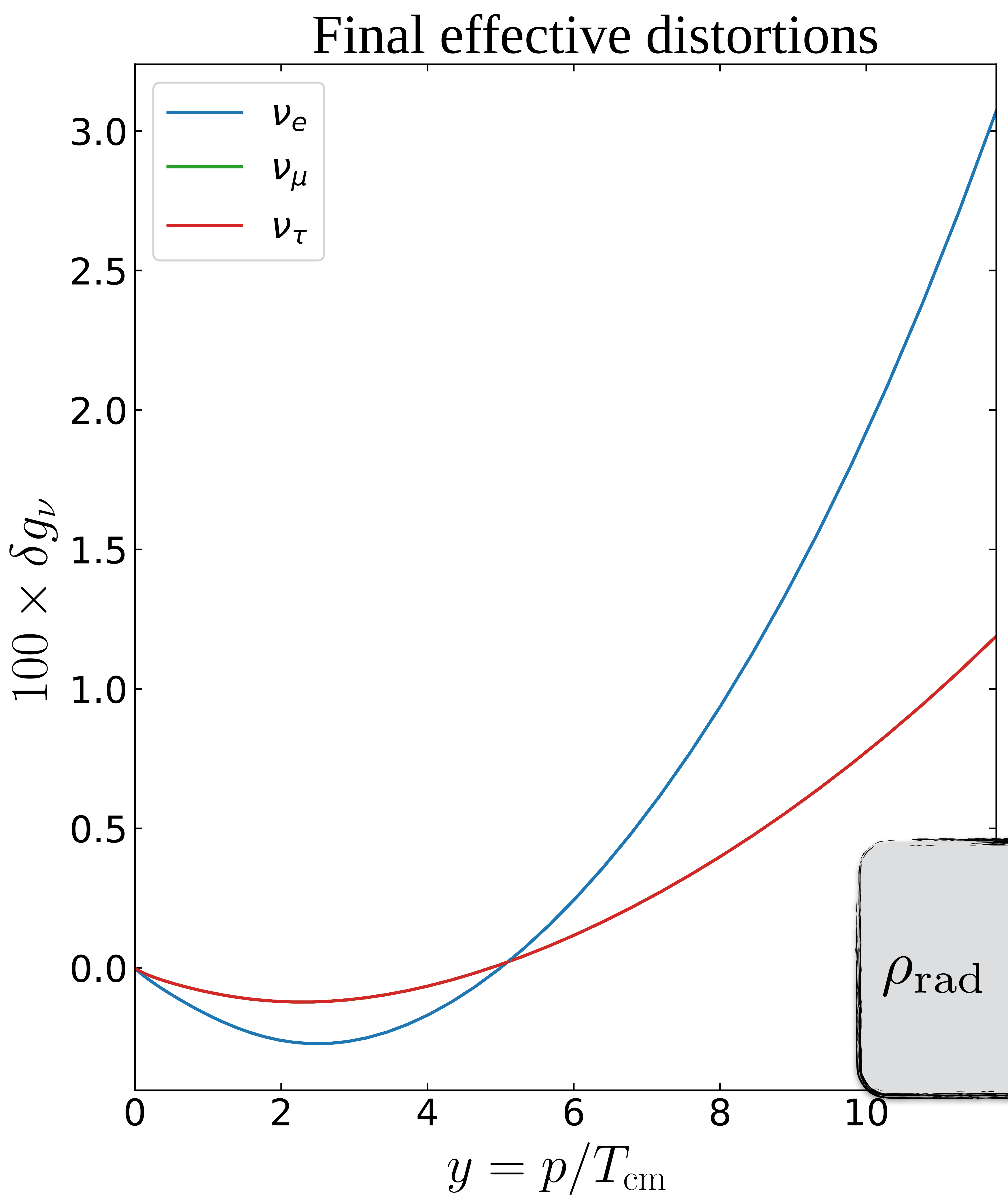

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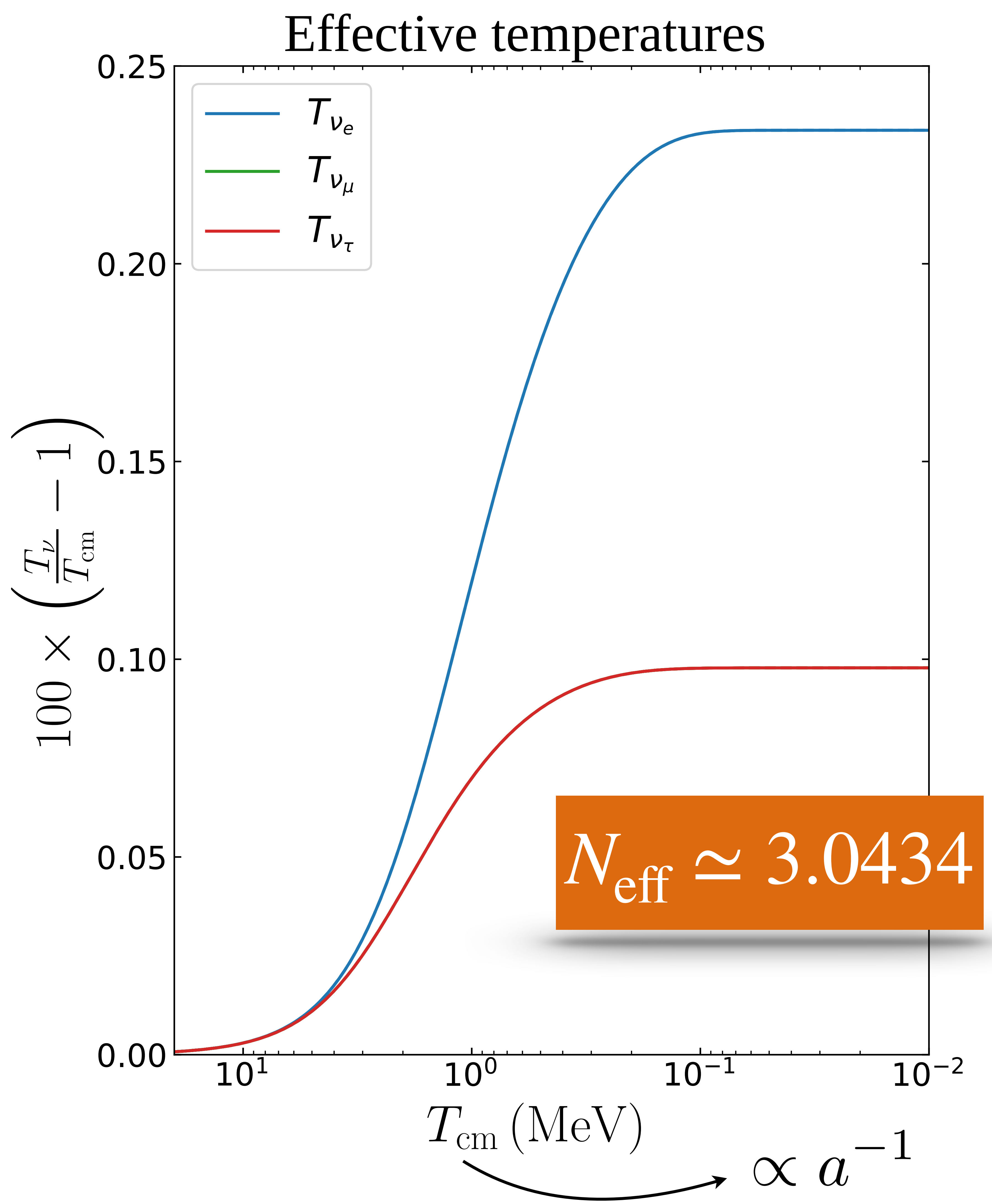
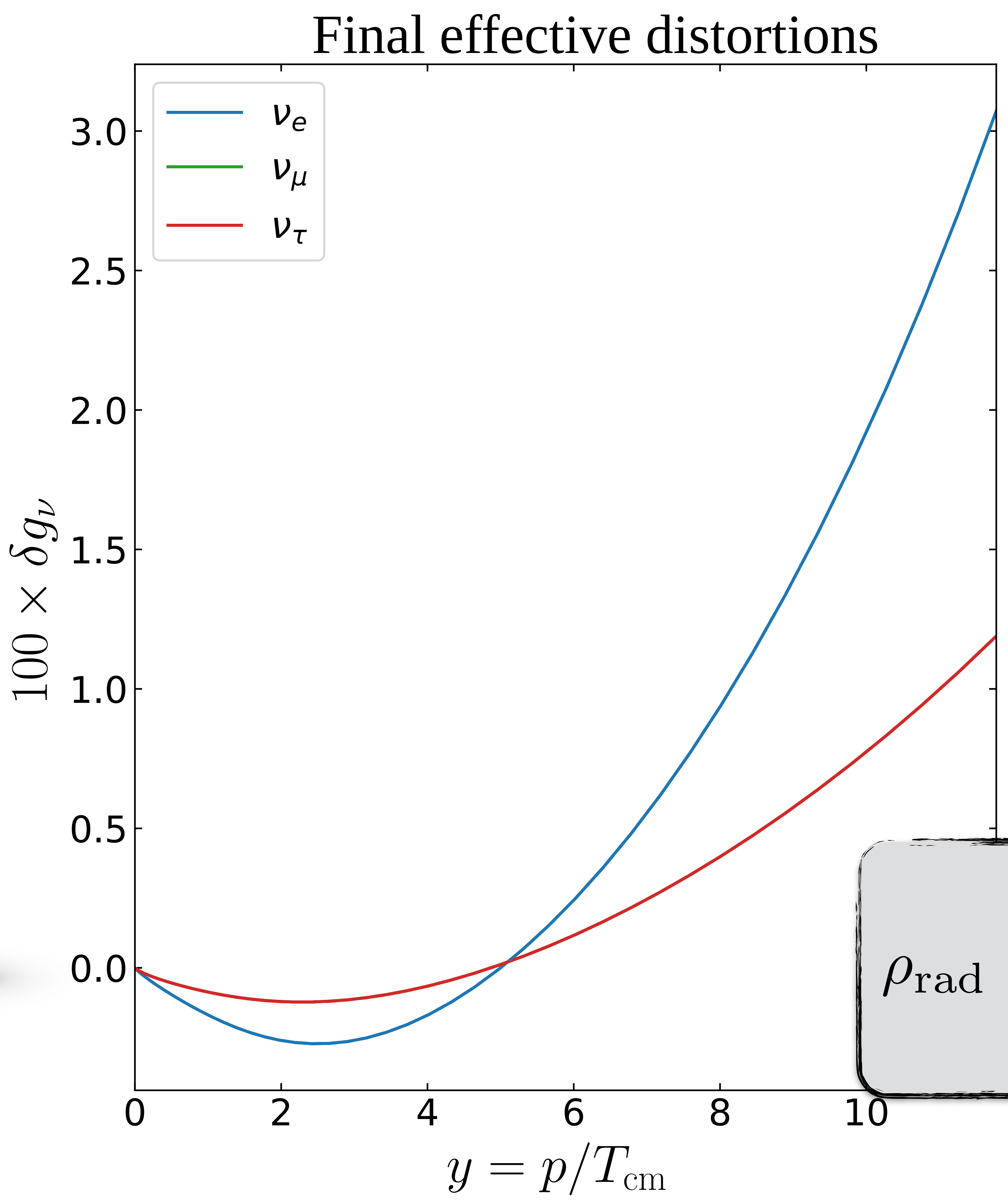


$N_{\rm eff} \simeq 3.0434$



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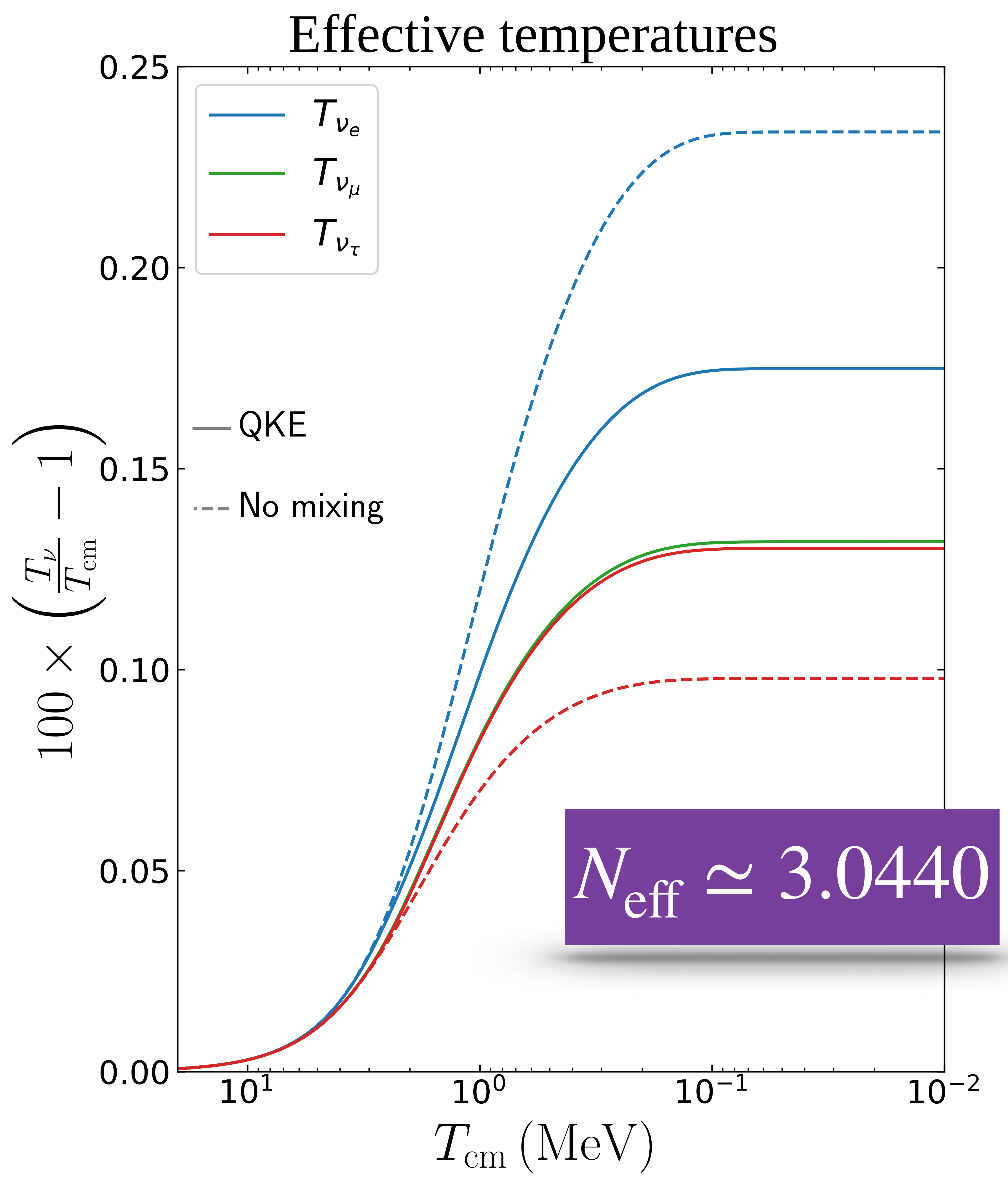
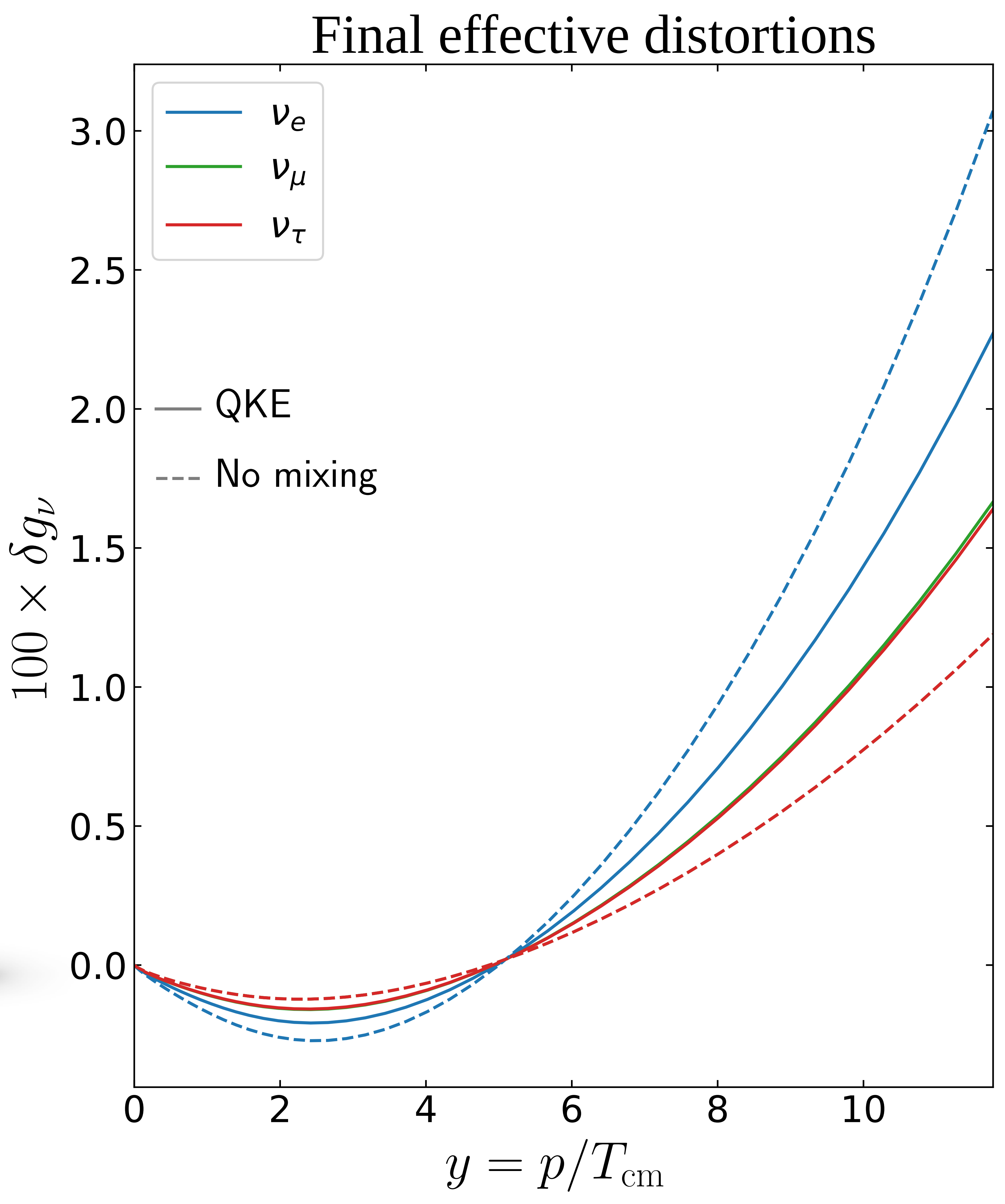


$N_{eff} \simeq 3.0440$



WITH FLAVOUR OSCILLATIONS

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Neutrino transport in the early Universe

- Calculation of **standard neutrino decoupling**: $N_{\text{eff}} = 3.044$

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  → *Very small effect of flavour oscillations*

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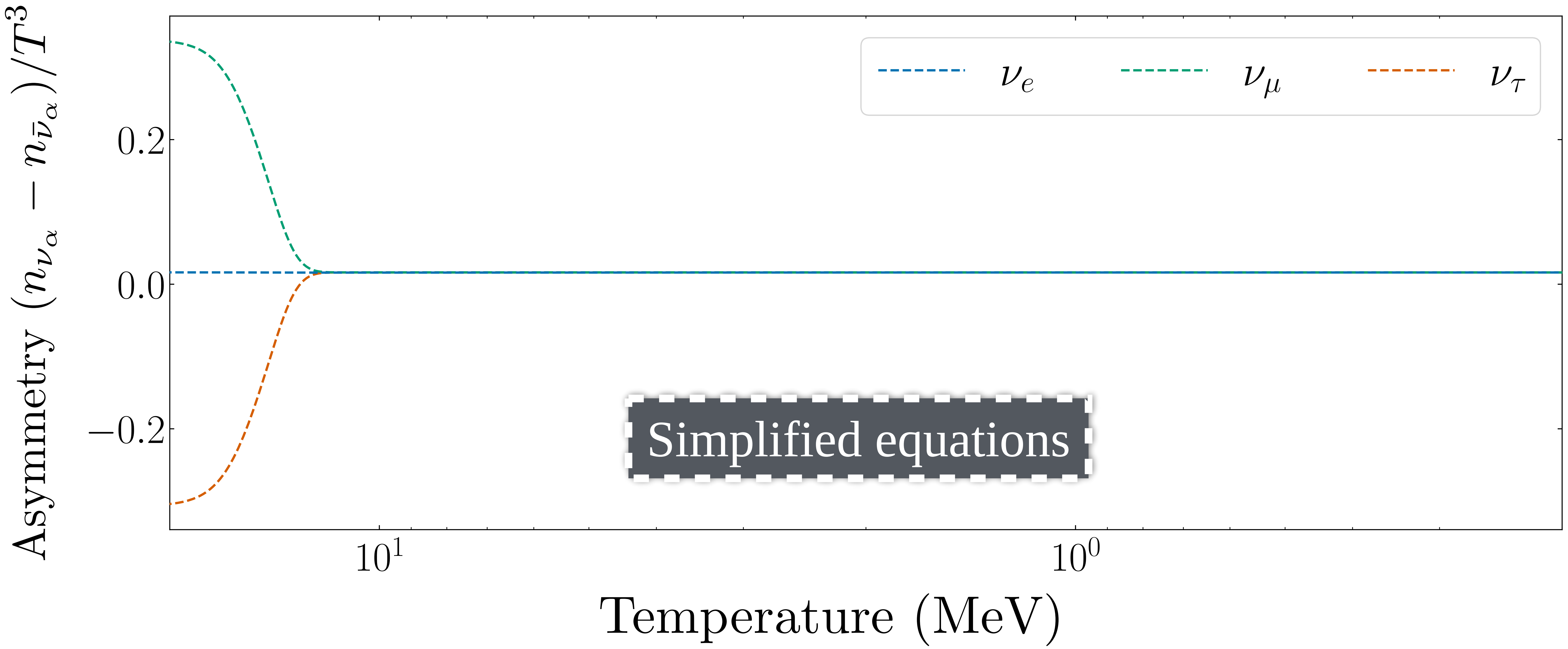
- Extension to the case of **nonzero neutrino/antineutrino asymmetries**

$$\eta_\alpha \equiv \frac{n_{\nu_\alpha} - n_{\bar{\nu}_\alpha}}{T^3} \propto \frac{\mu_\alpha}{T} \neq 0$$



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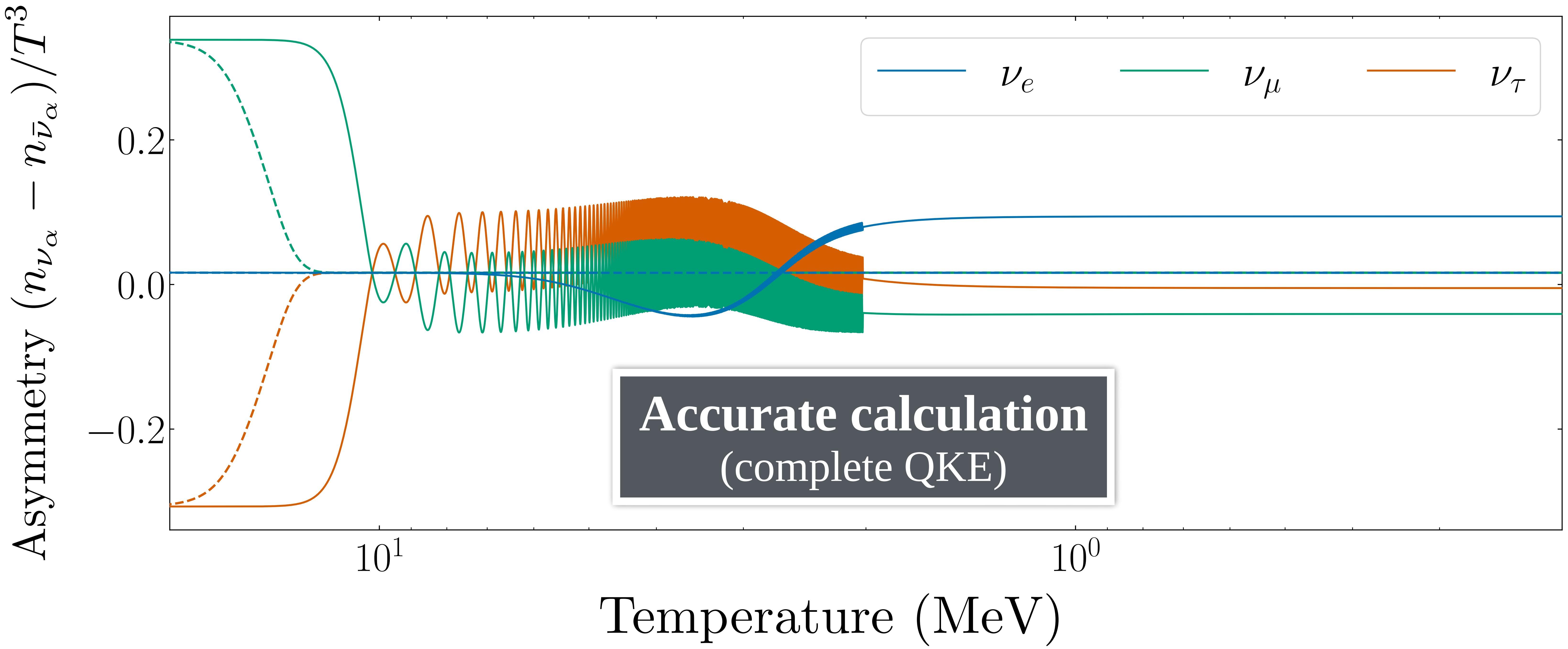

JF, C. Pitrou [2110.11889]
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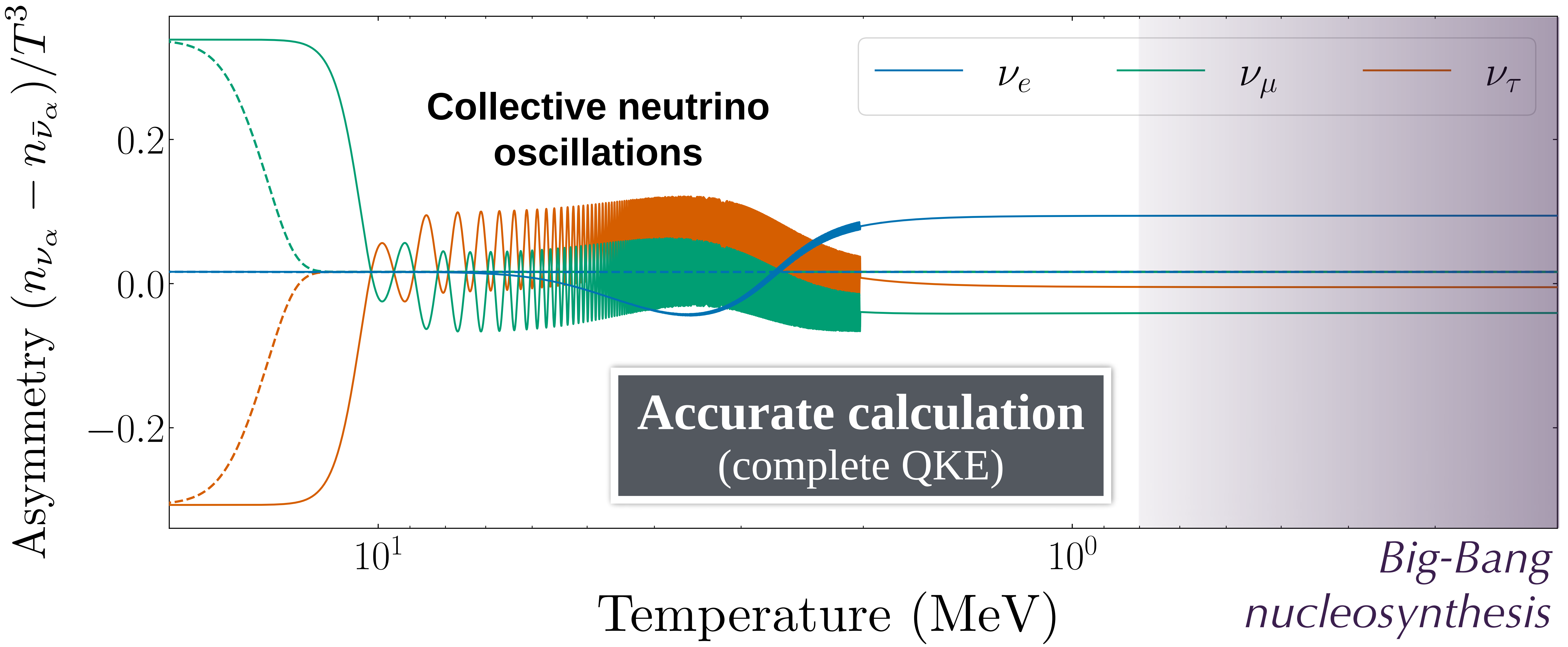

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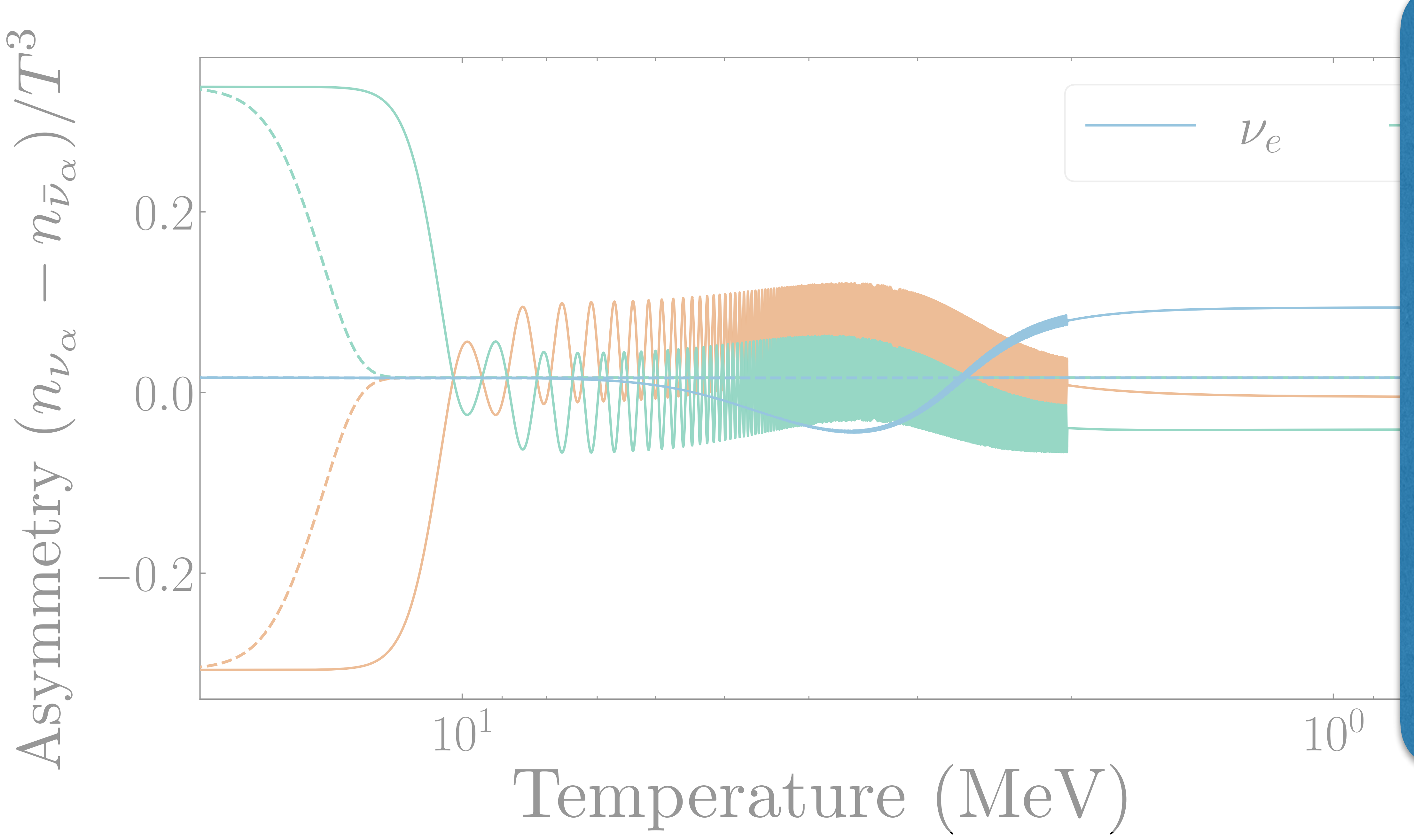
[Normal mass ordering]

Constraining primordial neutrino asymmetries



Asymmetries at the BBN epoch

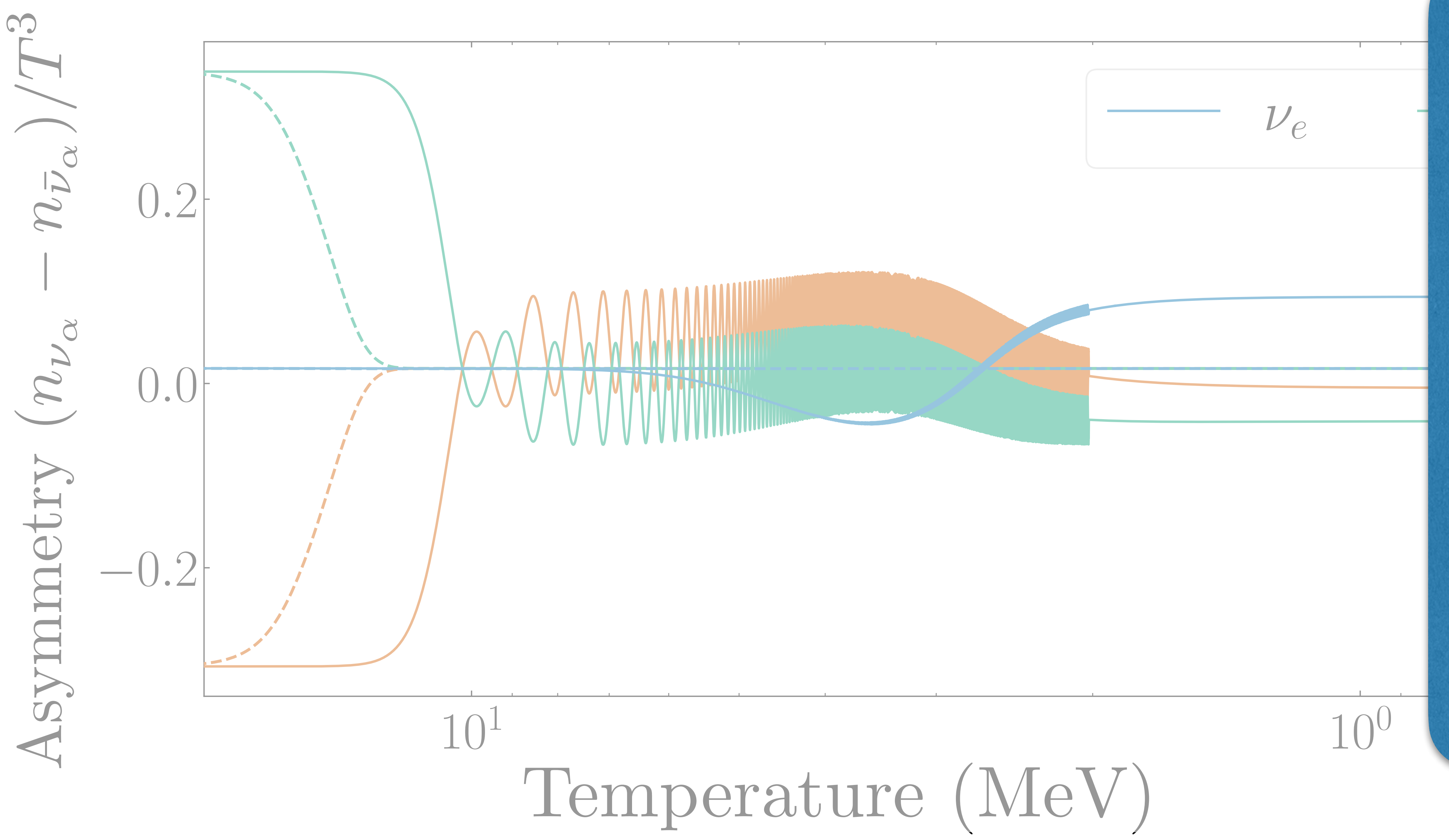
Constraining primordial neutrino asymmetries

Effects of asymmetries:

$$\eta_\alpha \equiv \frac{n_{\nu_\alpha} - n_{\bar{\nu}_\alpha}}{T^3}$$

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

$$\Delta N_{\text{eff}} \propto \sum_{\alpha=e,\mu,\tau} \eta_\alpha^2$$



Asymmetries at the BBN epoch

N_{eff}

(Anti)neutrino distributions

⇩

[BBN code PRIMAT]

⇩

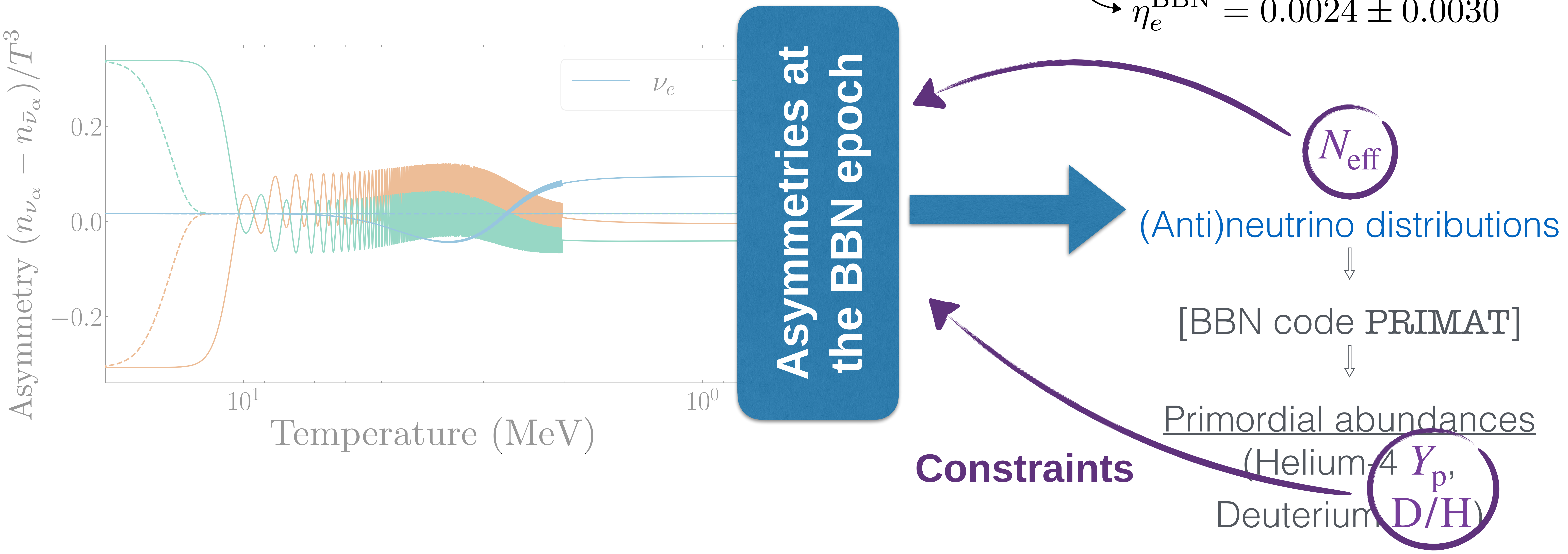
Primordial abundances

(Helium-4 Y_p, Deuterium D/H)

Constraining primordial neutrino asymmetries

Oldengott & Schwarz [1706.01705],
Burns *et al.* [2206.00693],
Escudero *et al.* [2208.03201],
…

$$\eta_e^{\mathrm{BBN}} = 0.0024 \pm 0.0030$$



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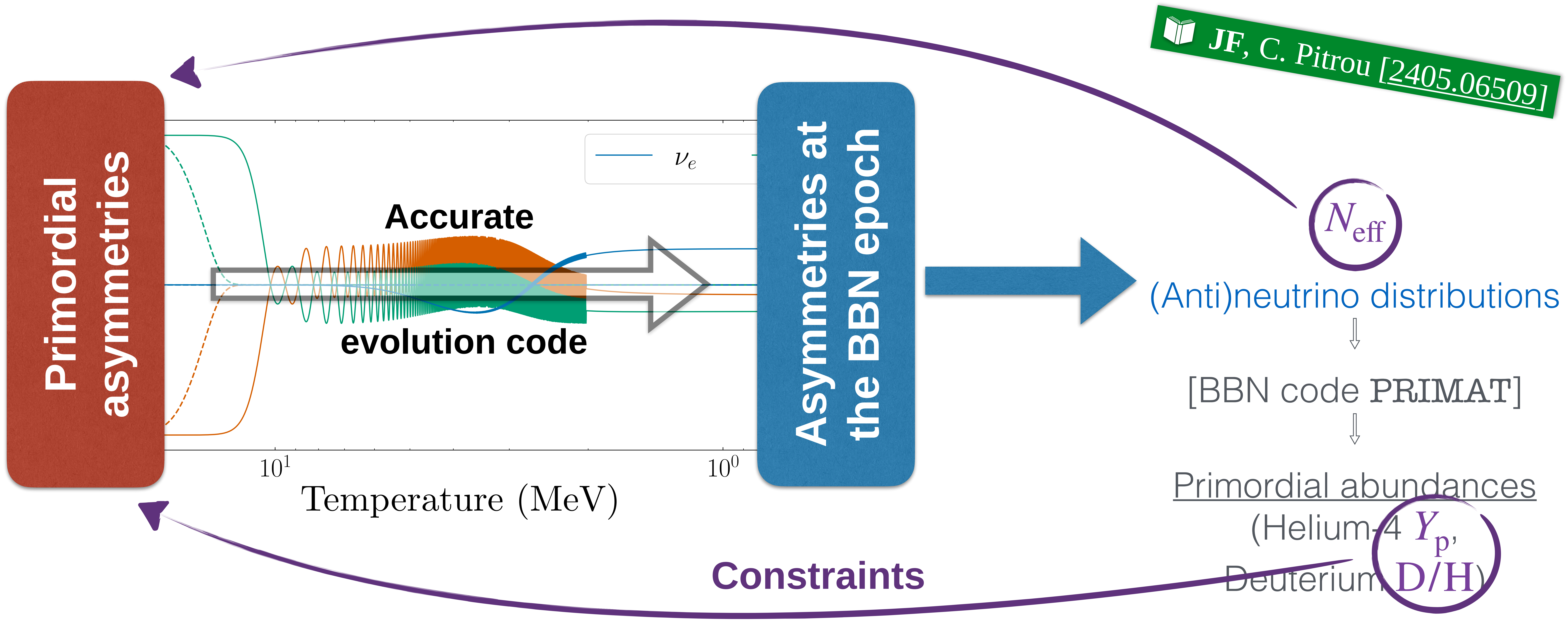

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JF, C. Pitrou
[2405.06509]

- **Large lepton asymmetries are allowed**, with a complicated landscape due to the dynamics of flavor oscillations.

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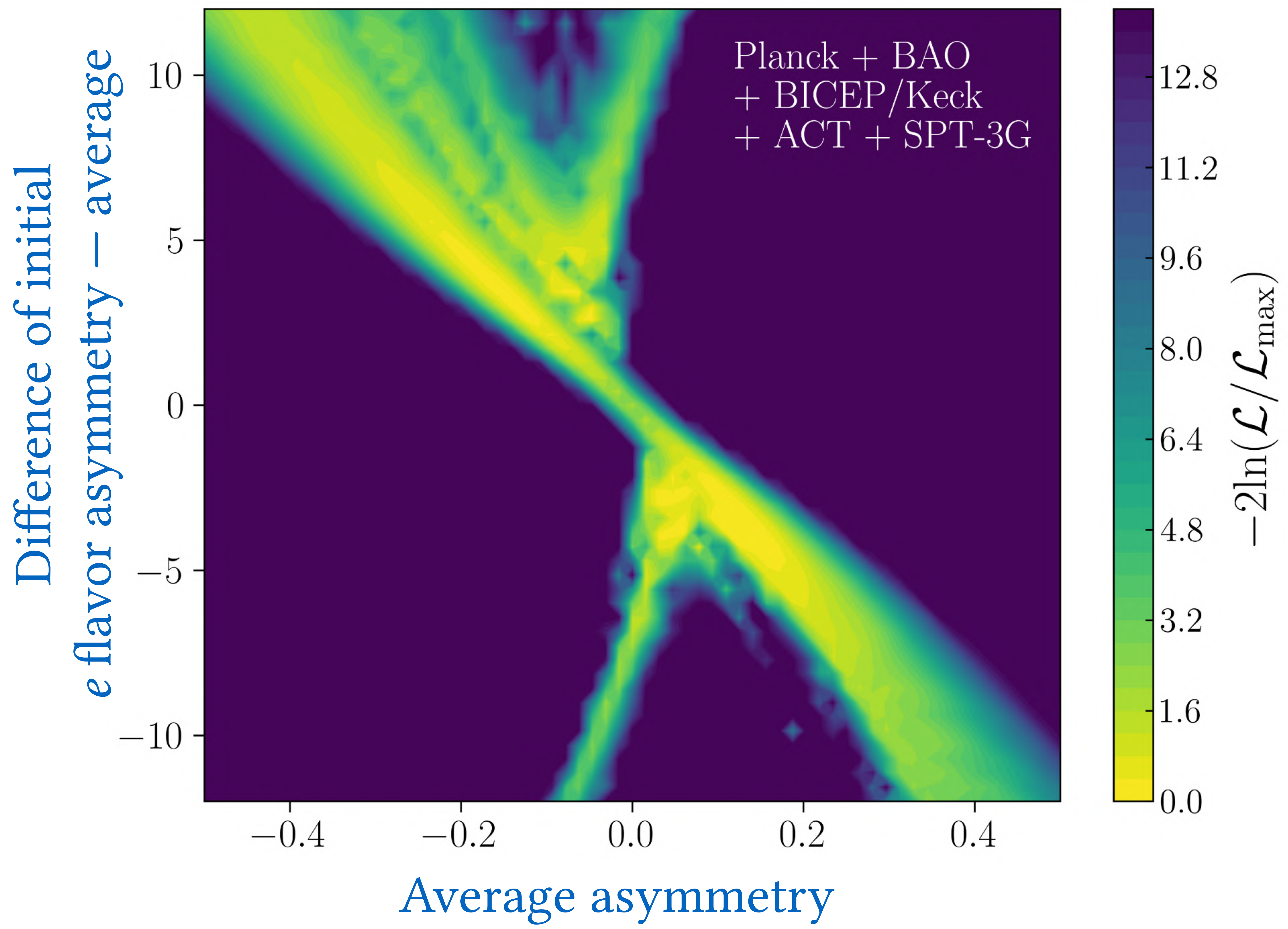

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See M. Fernández Navarro's talk

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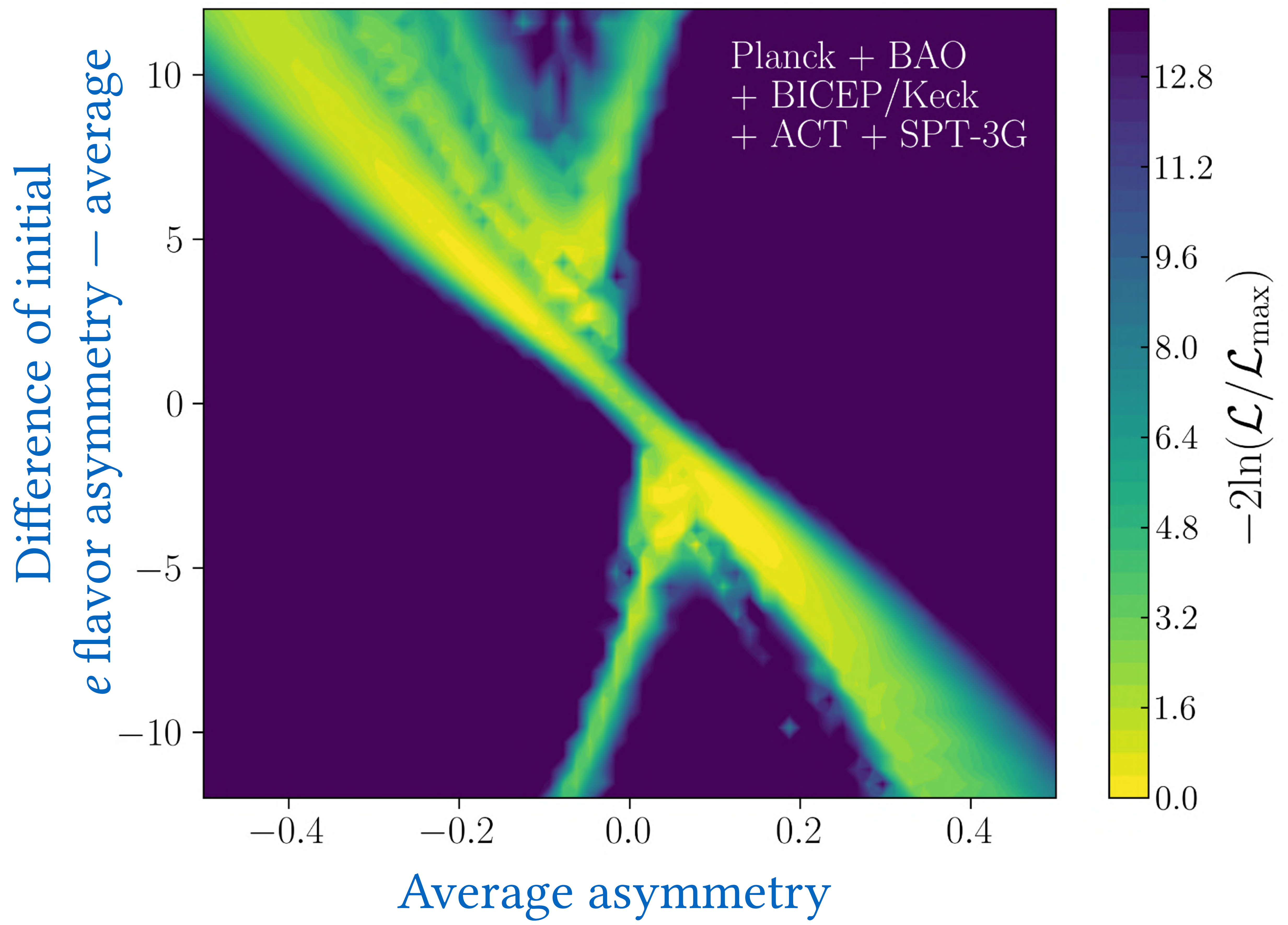

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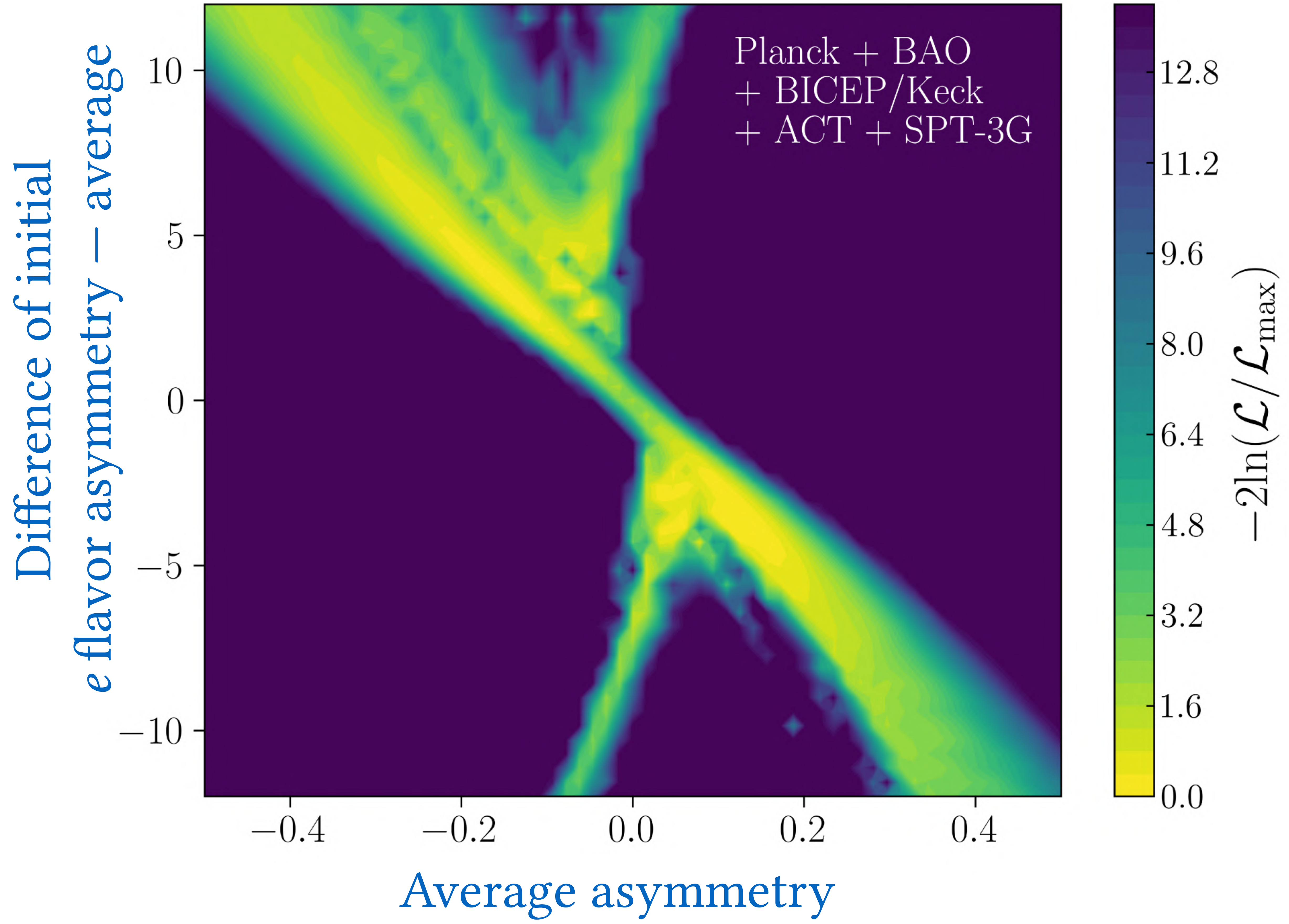


See M. Fernández Navarro's talk

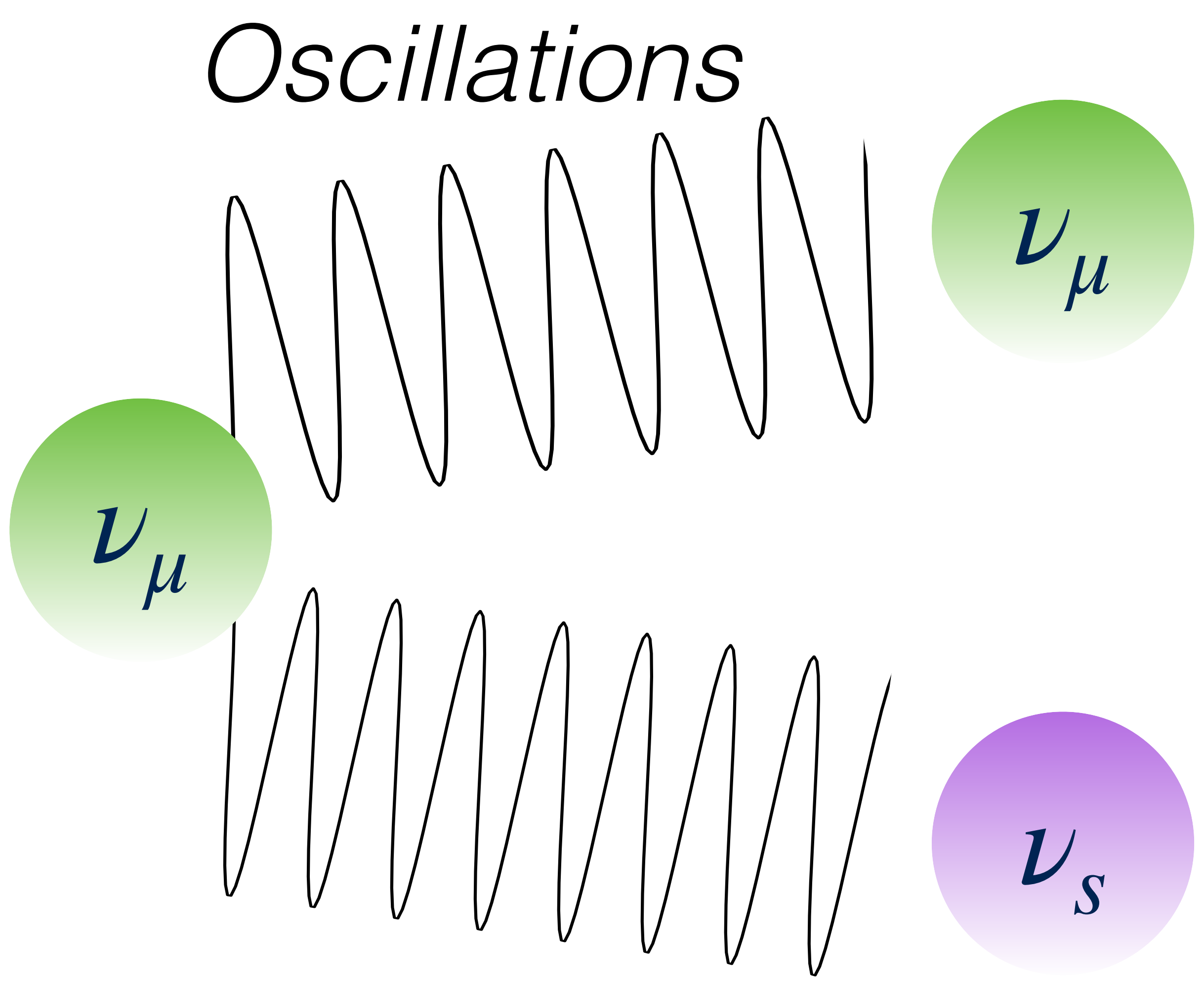
- Large lepton numbers are needed for some nonstandard scenarios, e.g., the **resonant production of sterile neutrino dark matter** (*Shi-Fuller* mechanism).

D. Gorbunov, D. Kalashnikov and G. Krugan [2502.17374]
C. Vogel, H. Escudero, **JF** and K. Abazajian [2507.18752]
K. Akita, K. Hamaguchi and M. Ovchynnikov [2507.20659]

Sterile neutrino dark matter production

ν_μ

Sterile neutrino dark matter production



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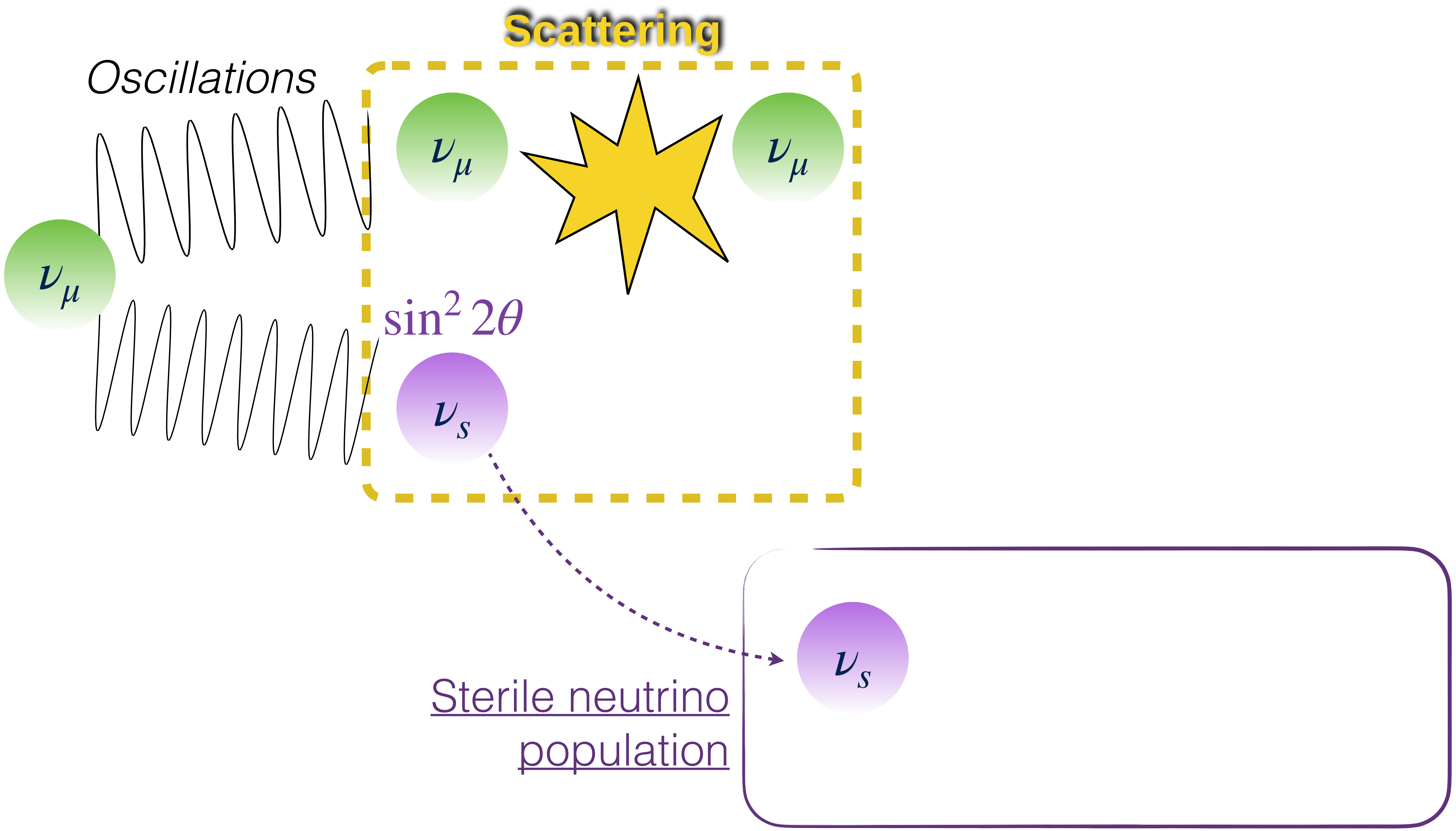

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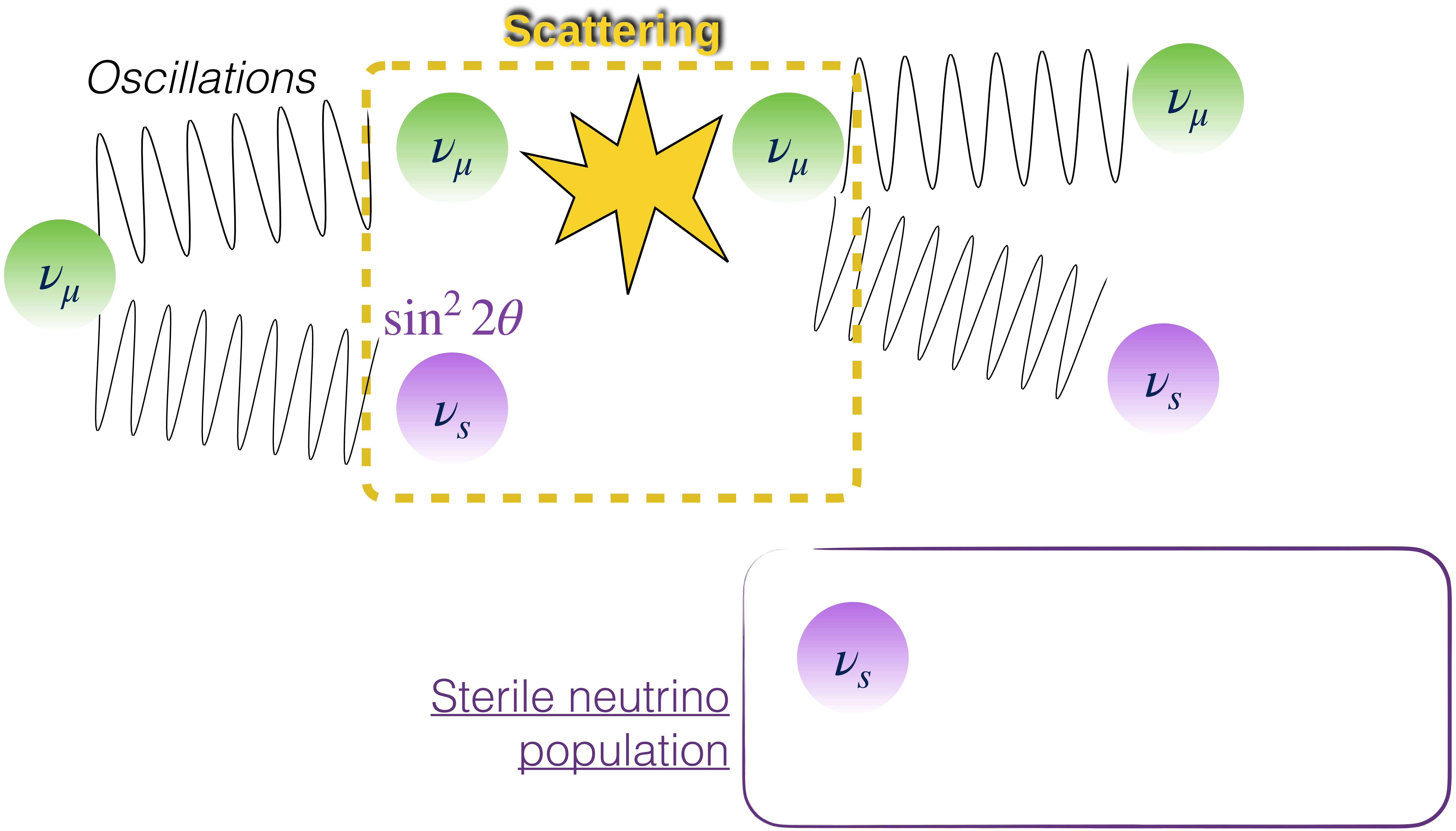

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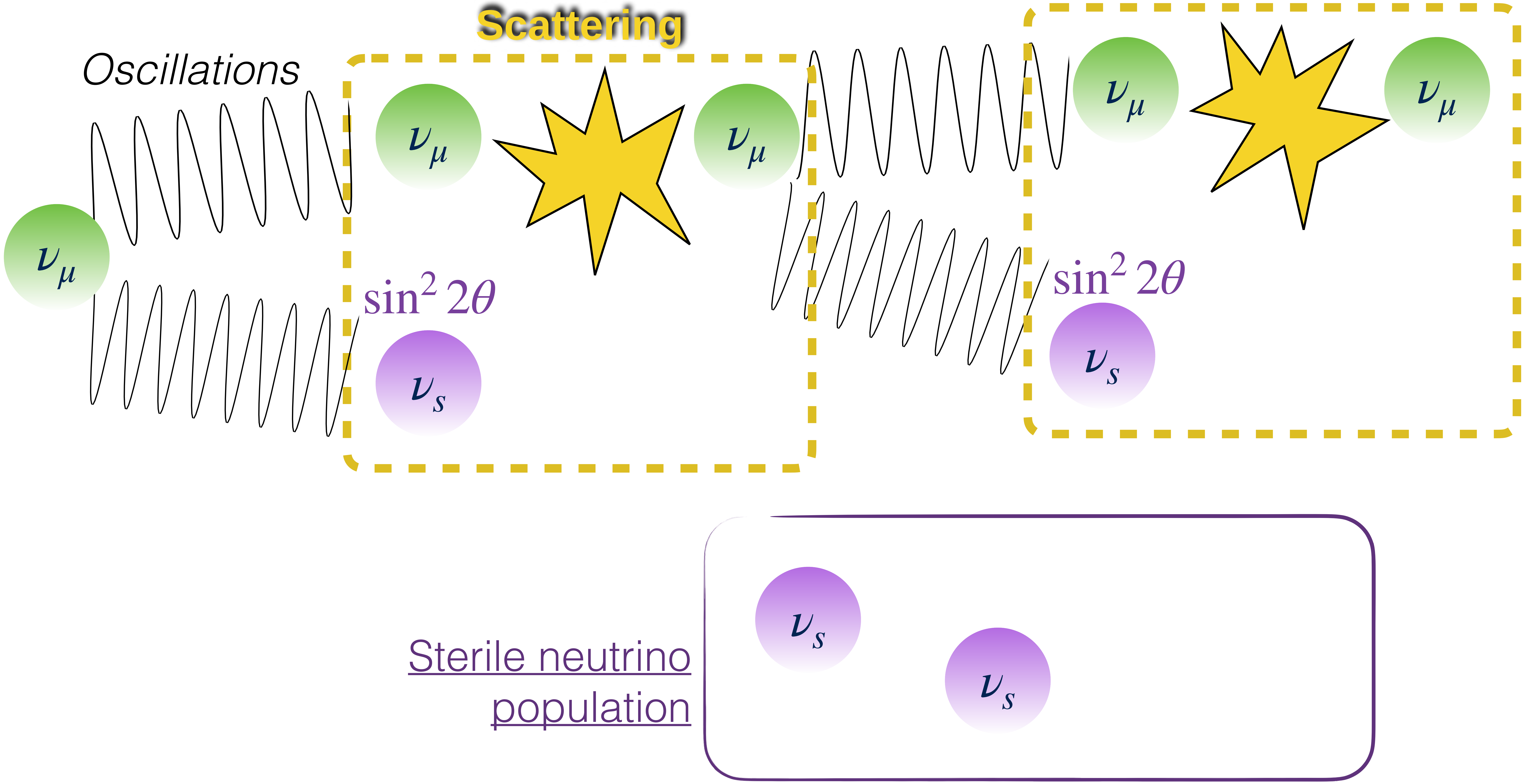


Sterile neutrino dark matter production

Sterile neutrino dark matter production

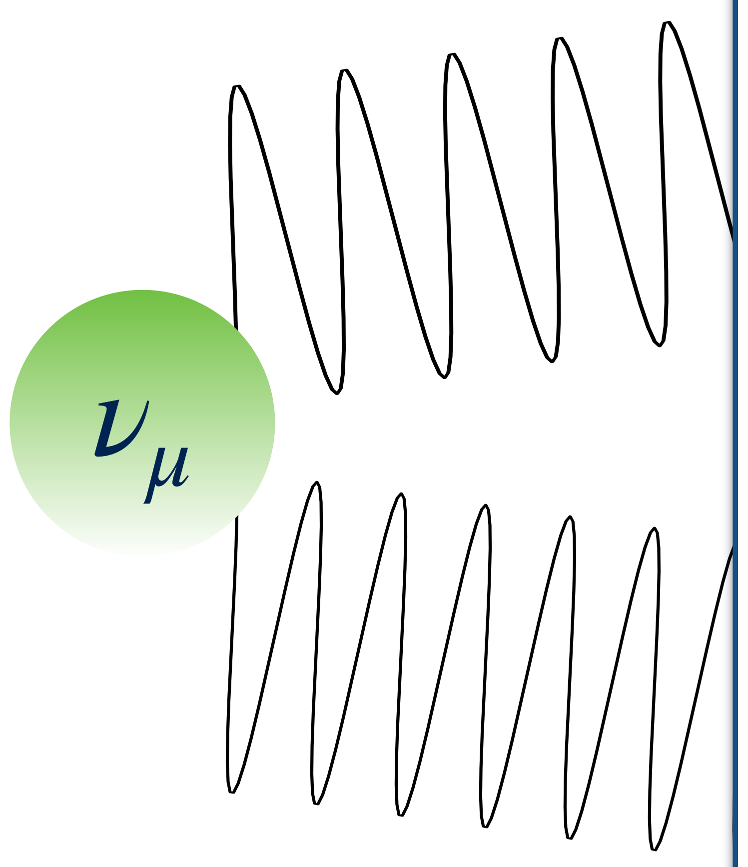
DODELSON-WIDROW MECHANISM

"Scattering-induced decoherence"

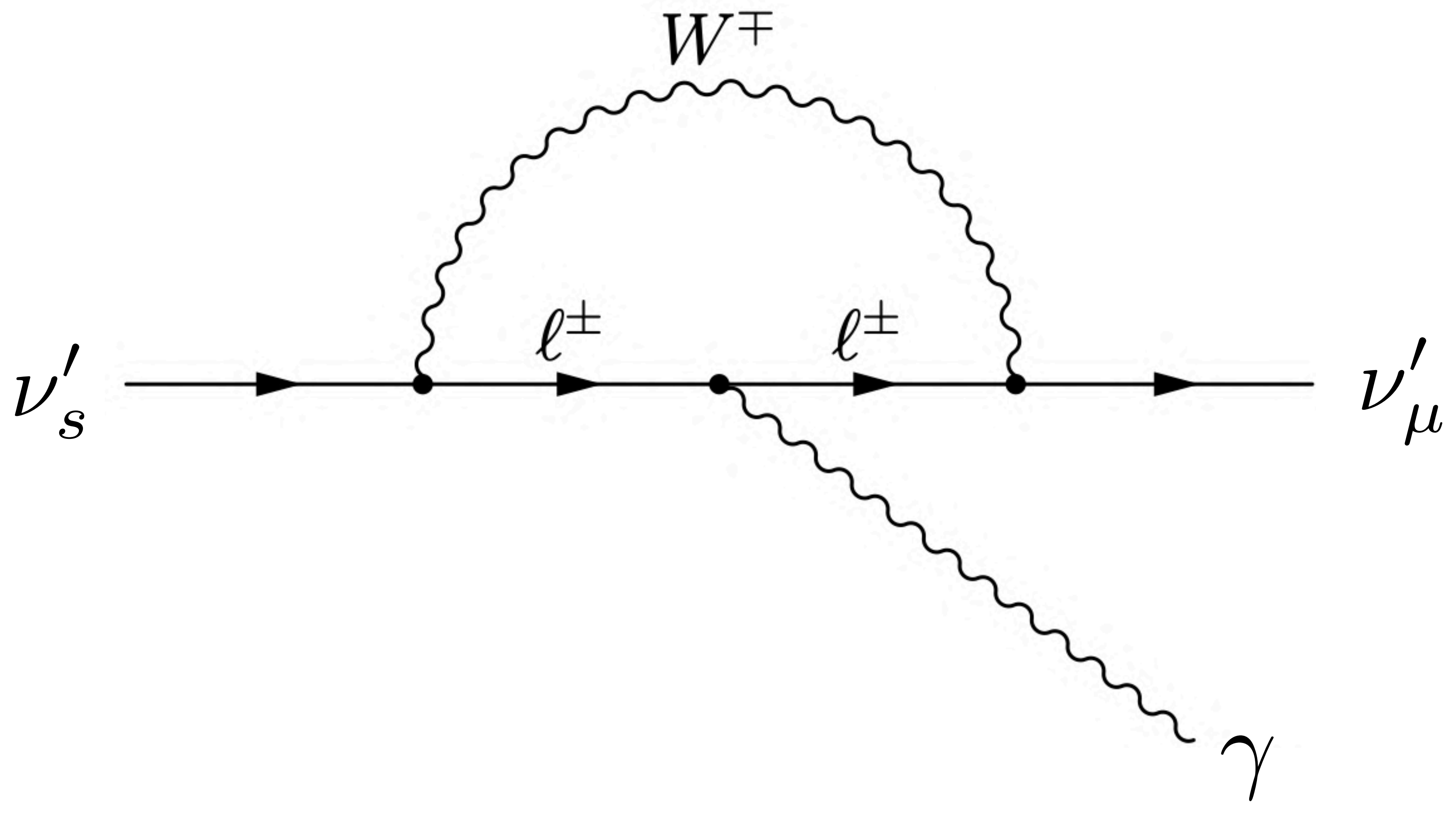
Dodelson & Widrow,
Phys. Rev. Lett. **72**, 17 (1994)

Sterile neutrino dark matter production

Oscillations



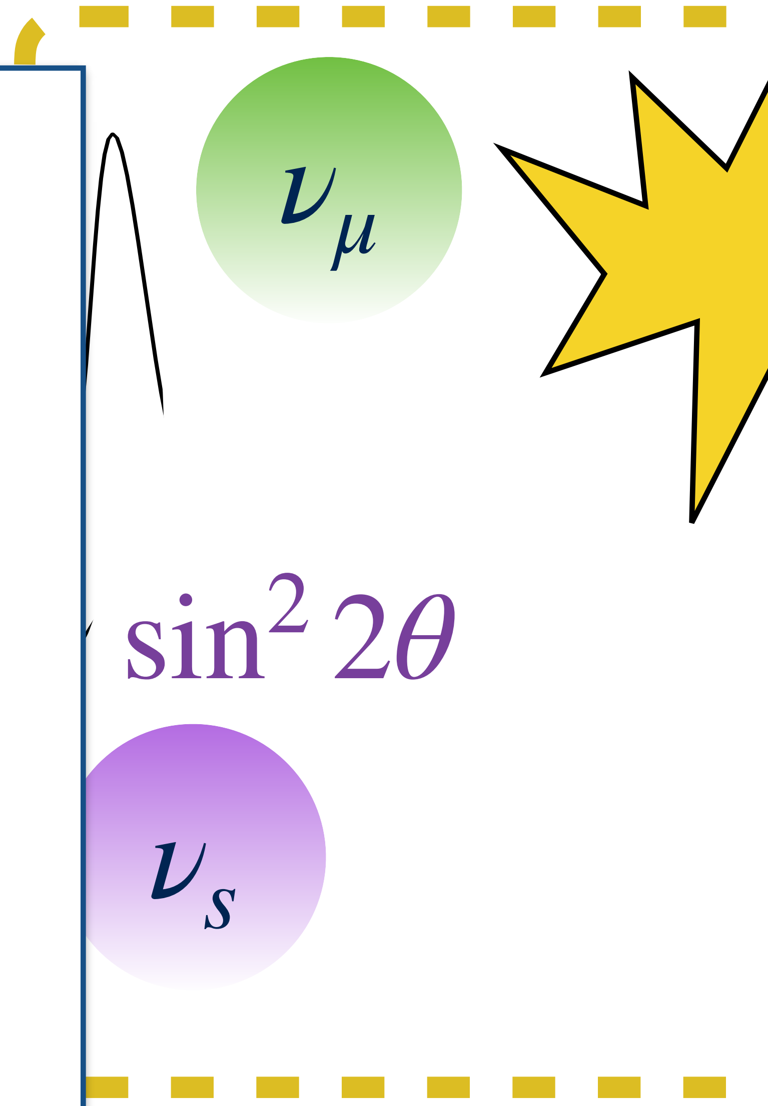
Radiative decay

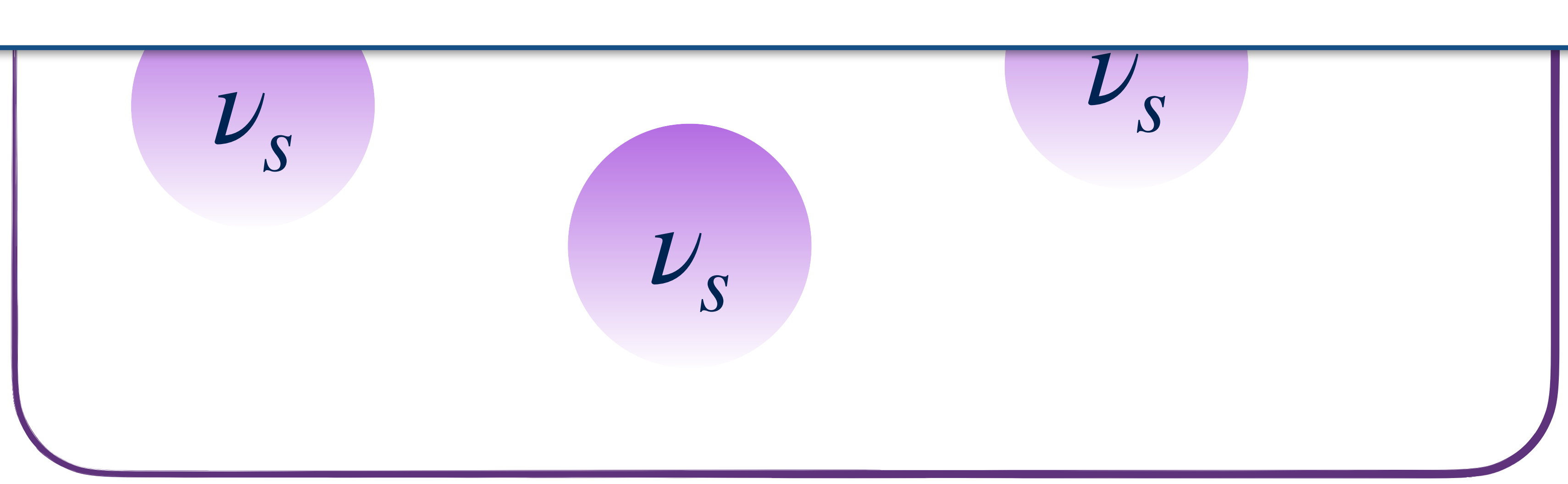


$$\Gamma_{\text{decay}} \propto m_s^5 \sin^2 2\theta$$

$$E_\gamma = \frac{m_s}{2}$$

→ **X-ray line**





Sterile neutrino population

$\propto \sin^2(2\theta)$

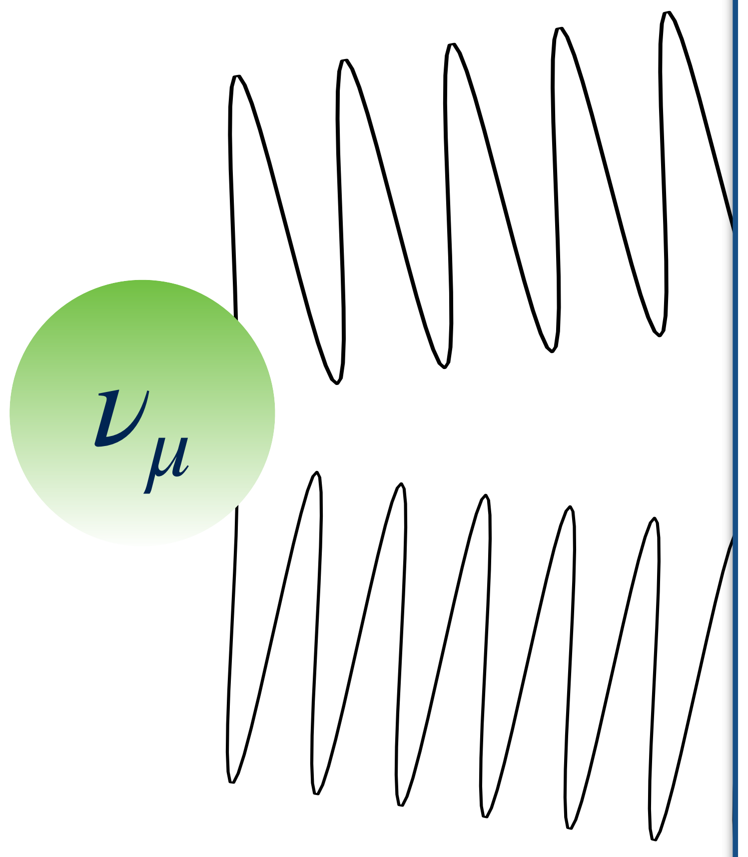
WIDROW MECHANISM

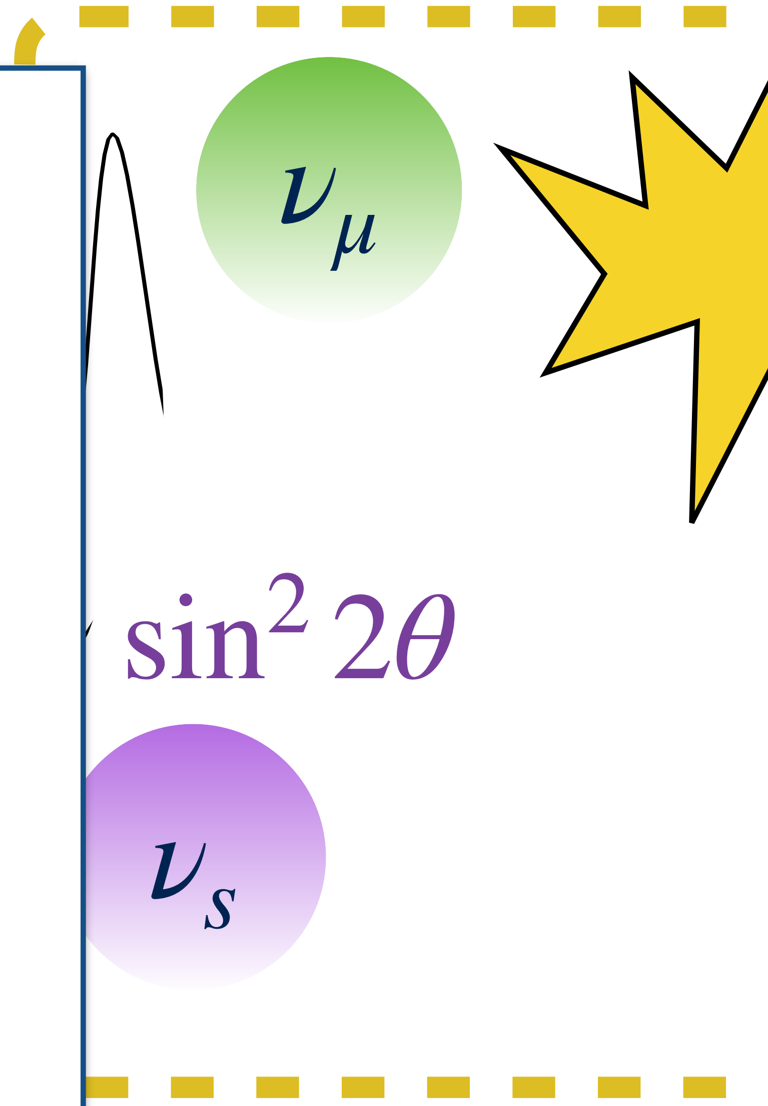
"Scattering-induced decoherence"

Dodelson & Widrow, *Phys. Rev. Lett.* **72**, 17 (1994)

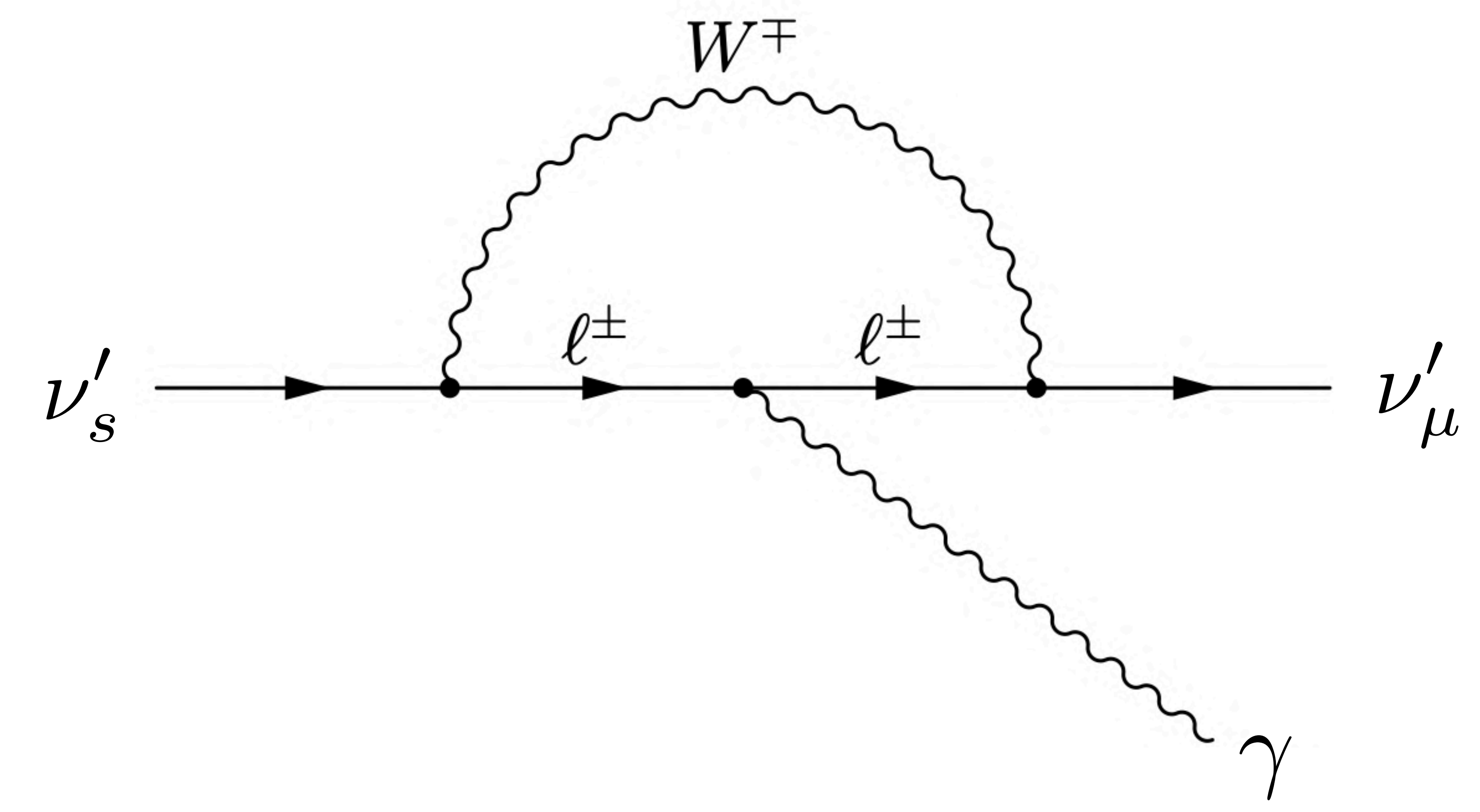
Sterile neutrino dark matter production

Oscillations





Radiative decay

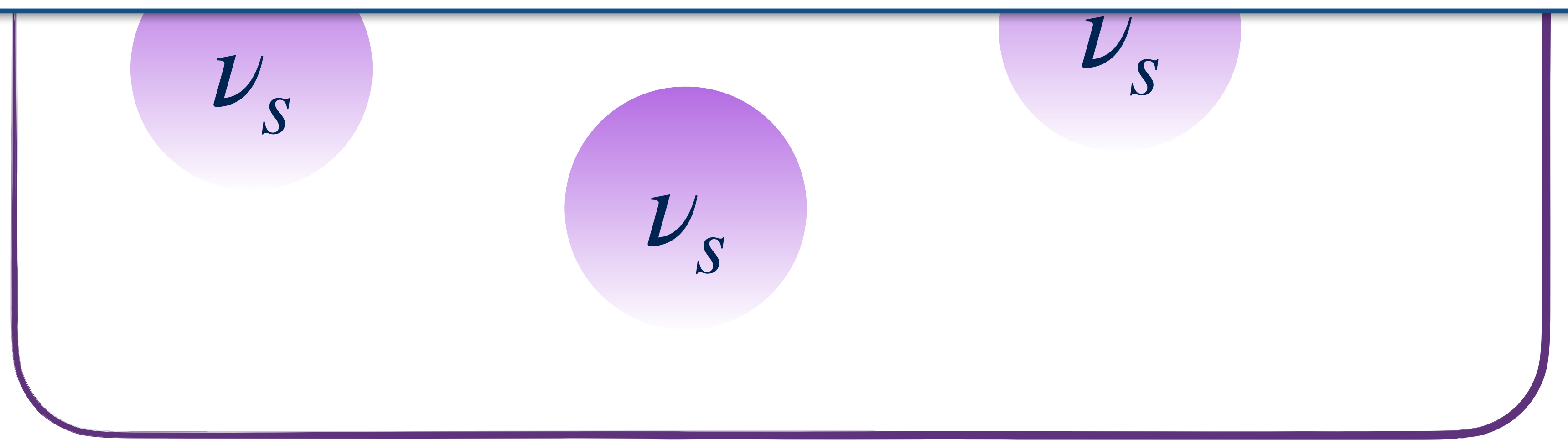


$$\Gamma_{\text{decay}} \propto m_s^5 \sin^2 2\theta$$

$$E_\gamma = \frac{m_s}{2}$$ → **X-ray line**

Sterile neutrino population

$\propto \sin^2(2\theta)$



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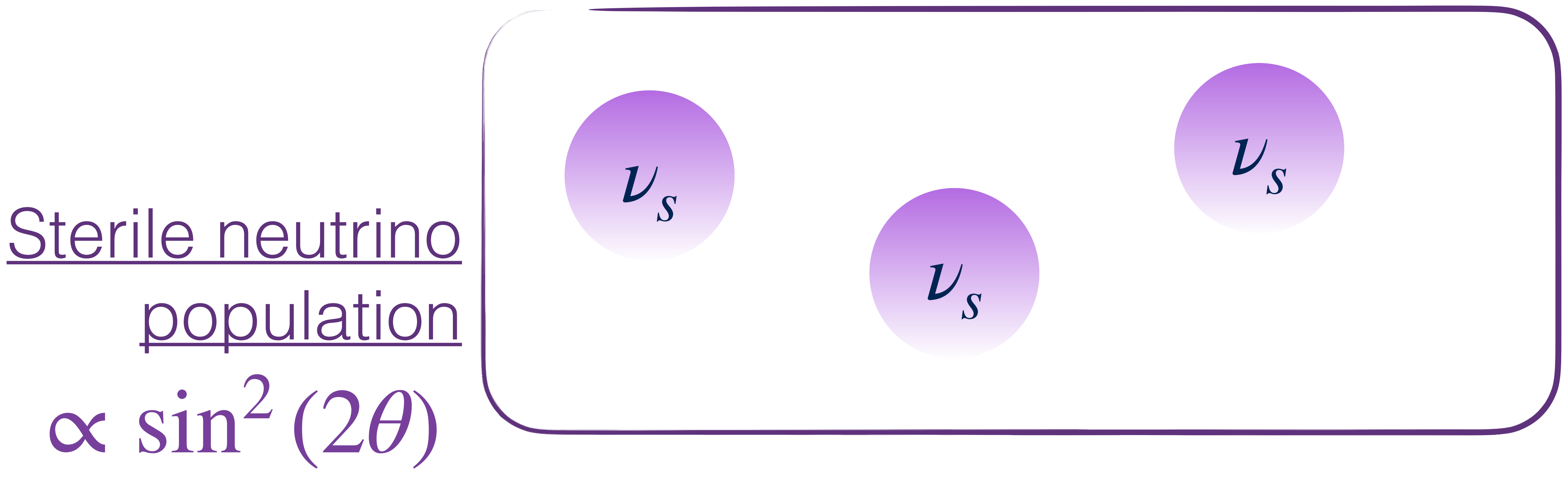

DODELSON-WIDROW MECHANISM

"Scattering-induced decoherence"

Dodelson & Widrow, *Phys. Rev. Lett.* **72**, 17 (1994)

Sterile neutrino dark matter production

$\propto \sin^2(2\theta_{\rm eff}) \gg \sin^2(2\theta)$

SHI-FULLER MECHANISM

"Resonant production"

Shi & Fuller,
Phys. Rev. Lett. **82**, 2832 (1999)

Constraints on SF sterile neutrino dark matter

C. Vogel *et al.* [2507.18752]

Mass m_s

Mixing angle θ

Initial lepton number

$$L = L_\mu = \frac{n_{\nu_\mu} - n_{\bar{\nu}_\mu}}{n_\gamma} \simeq 4\eta_\mu$$

`sterile-dm`

Venumadhav *et al.* [1507.06655]

$L(T)$

Phase-space distributions

$[\Omega_{\rm DM} h^2](T)$

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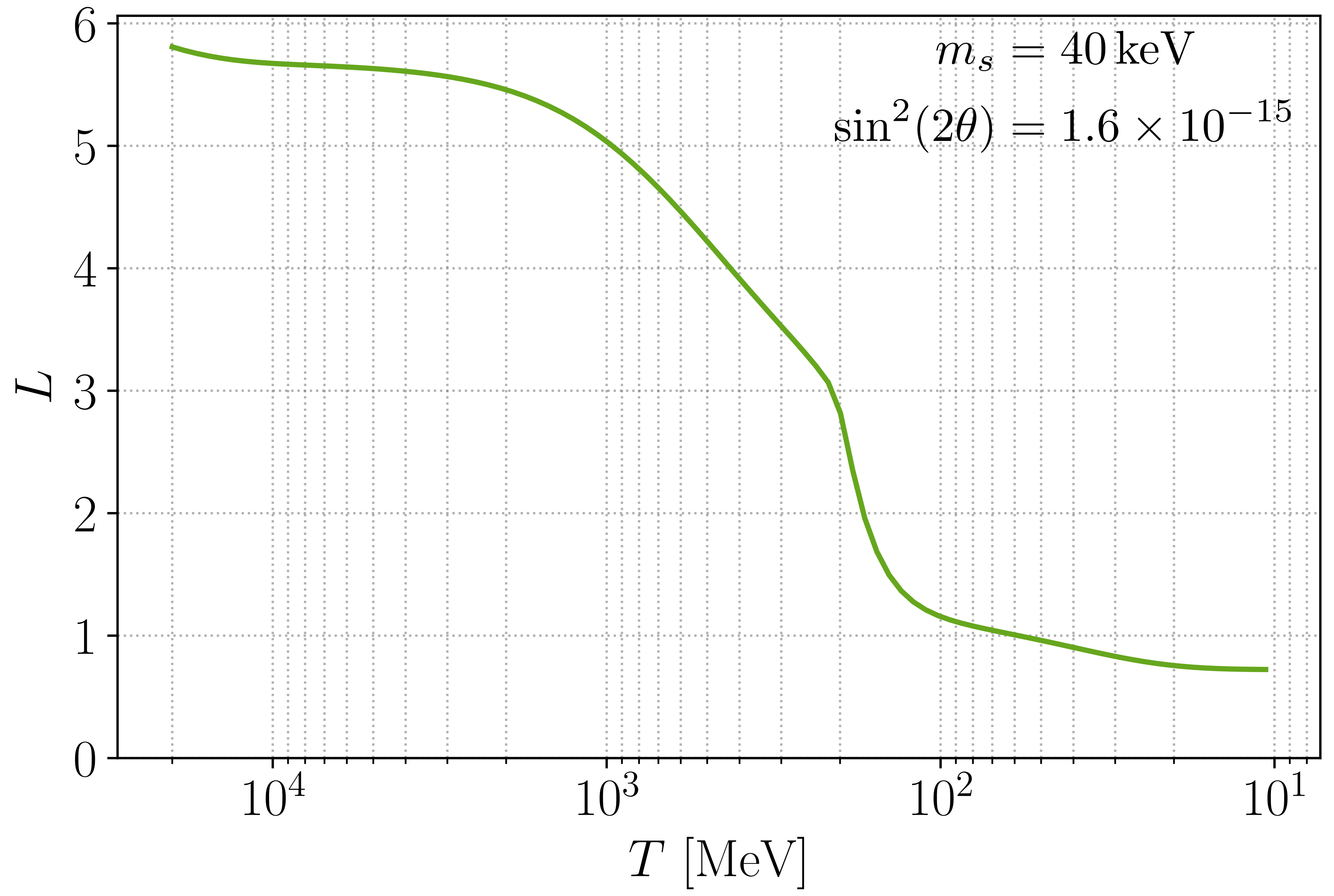

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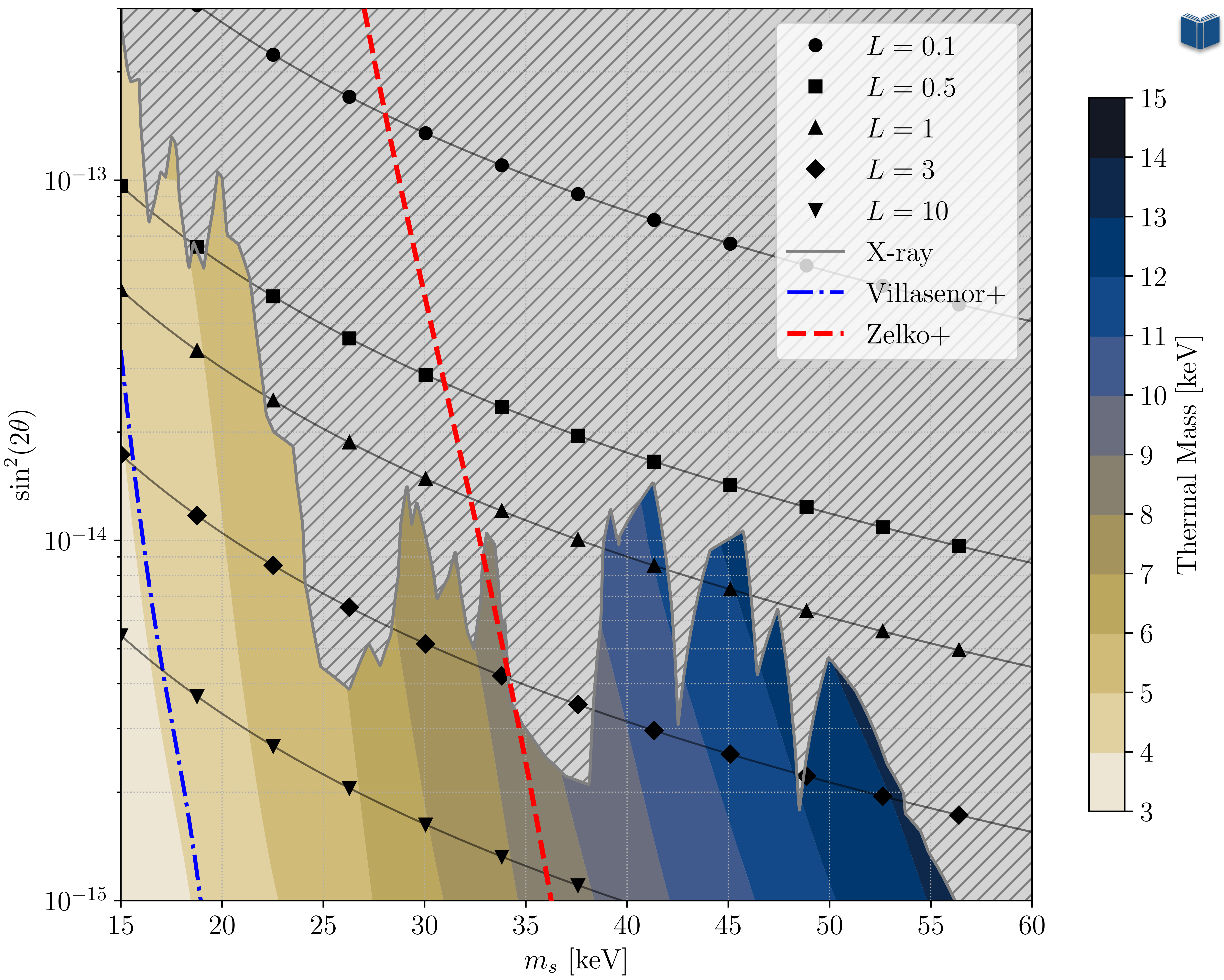

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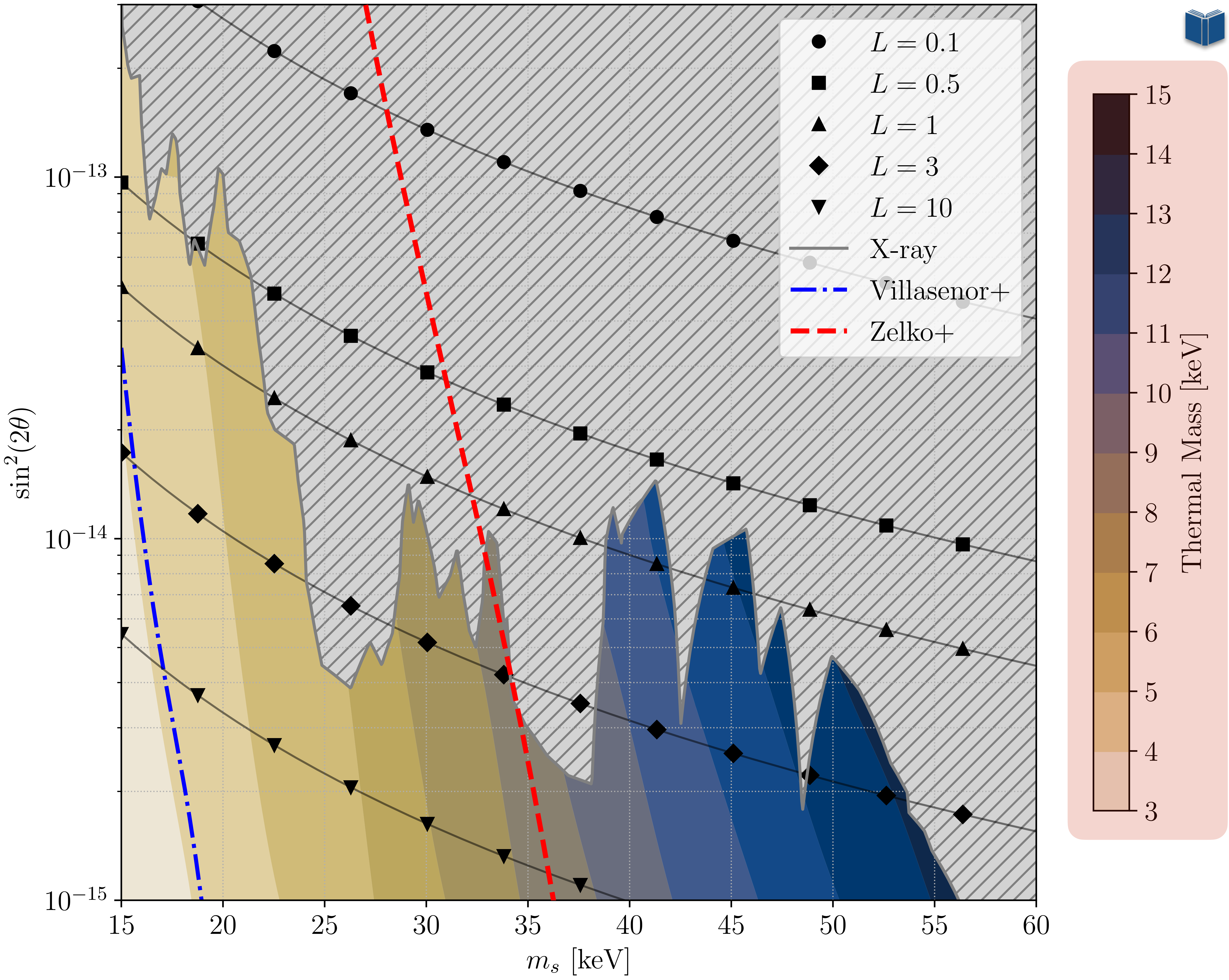

Equivalent thermal warm dark matter mass, for structure formation constraints

Summary

Neutrino flavour mixing is a key ingredient of neutrino evolution in the early Universe *in nonstandard cases*.

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Constraints on primordial asymmetries…

- We combined a full quantum kinetic transport code for neutrinos with a BBN network to connect primordial asymmetries to cosmological observables.
- Larger than previously thought *primordial* neutrino asymmetries are allowed.
- Asymmetries are mixed, but **not perfectly equilibrated** in general

⟶ complicated landscape of allowed asymmetries

JF, C. Pitrou [2110.11889]
JF, C. Pitrou [2405.06509]

V. Domcke *et al.* [2502.14960, 2510.02438]

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… and sterile neutrino dark matter models

- This (re-)opens the parameter space for **resonant production of sterile neutrino dark matter** via the *Shi-Fuller mechanism*.
- Importance of future X-ray observatories in the ~ 20 keV range!
- Limitations of the sterile neutrino production code for very large lepton numbers: future study!

C. Vogel *et al.* [2507.18752]
K. Akita *et al.* [2507.20659]

Quantum Kinetic Equation

Classical distribution functions

$$\begin{pmatrix} f_{\nu_e} & & \\ & f_{\nu_\mu} & \\ & & f_{\nu_\tau} \end{pmatrix} \longrightarrow \varrho = \begin{pmatrix} \varrho_{ee} & \varrho_{e\mu} & \varrho_{e\tau} \\ \varrho^*_{e\mu} & \varrho_{\mu\mu} & \varrho_{\mu\tau} \\ \varrho^*_{e\tau} & \varrho^*_{\mu\tau} & \varrho_{\tau\tau} \end{pmatrix}$$

Density matrix

Generalization of Boltzmann's equation for quantum transport

$$i\left[\frac{\partial}{\partial t} - Hp\frac{\partial}{\partial p}\right]\varrho(p,t) = \left[U\frac{\mathbb{M}^2}{2p}U^\dagger, \varrho\right] - 2\sqrt{2}G_F p\left[\frac{\mathbb{E}_{\rm lep}+\mathbb{P}_{\rm lep}}{m_W^2}, \varrho\right] + \sqrt{2}G_F\left[\mathbb{N}_\nu - \mathbb{N}_{\bar\nu}, \varrho\right] + i\,\mathcal{C}(\varrho,\bar\varrho)$$

Vacuum

Self-interactions
(effective potential due to the $\nu, \bar\nu$ background)

$$\mathbb{E}_{\rm lep} + \mathbb{P}_{\rm lep} = \begin{pmatrix} \rho_{e^\pm} + P_{e^\pm} & 0 & 0 \\ 0 & \rho_{\mu^\pm} + P_{\mu^\pm} & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

Lepton mean-field
(effective potential due to the charged lepton background)

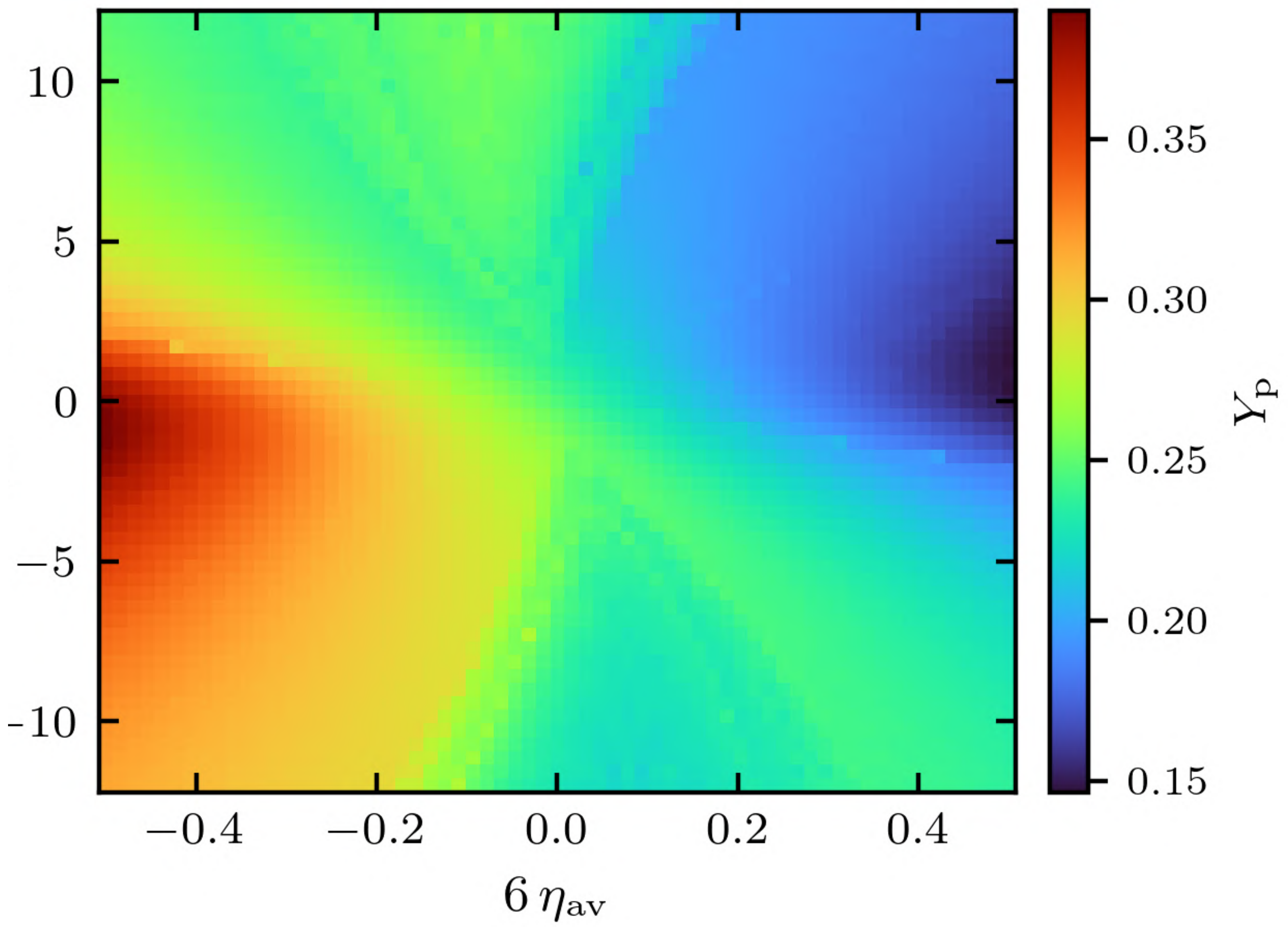
Collisions

$$\mathcal{C} = \mathcal{C}^{[\nu e^- \to \nu e^-]} + \mathcal{C}^{[\nu e^+ \to \nu e^+]} + \mathcal{C}^{[\nu\bar\nu \to e^- e^+]} + \mathcal{C}^{[\nu\nu]}$$

Output of neutrino + BBN calculation

$\eta_\mu = \eta_\tau$

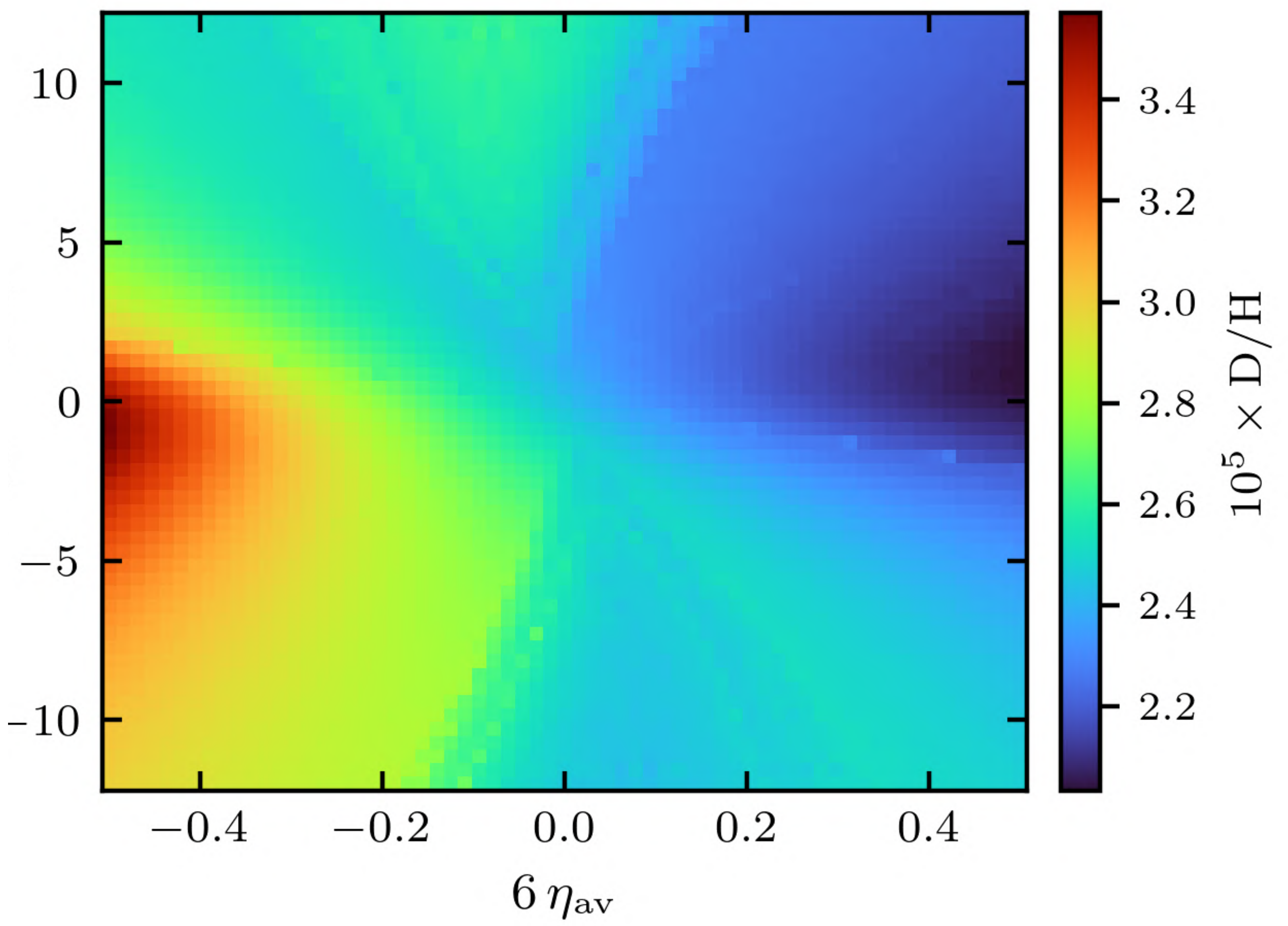
Helium-4 abundance



Difference of initial *e* flavor asymmetry − average

Average asymmetry

Deuterium abundance



Difference of initial *e* flavor asymmetry − average

Average asymmetry

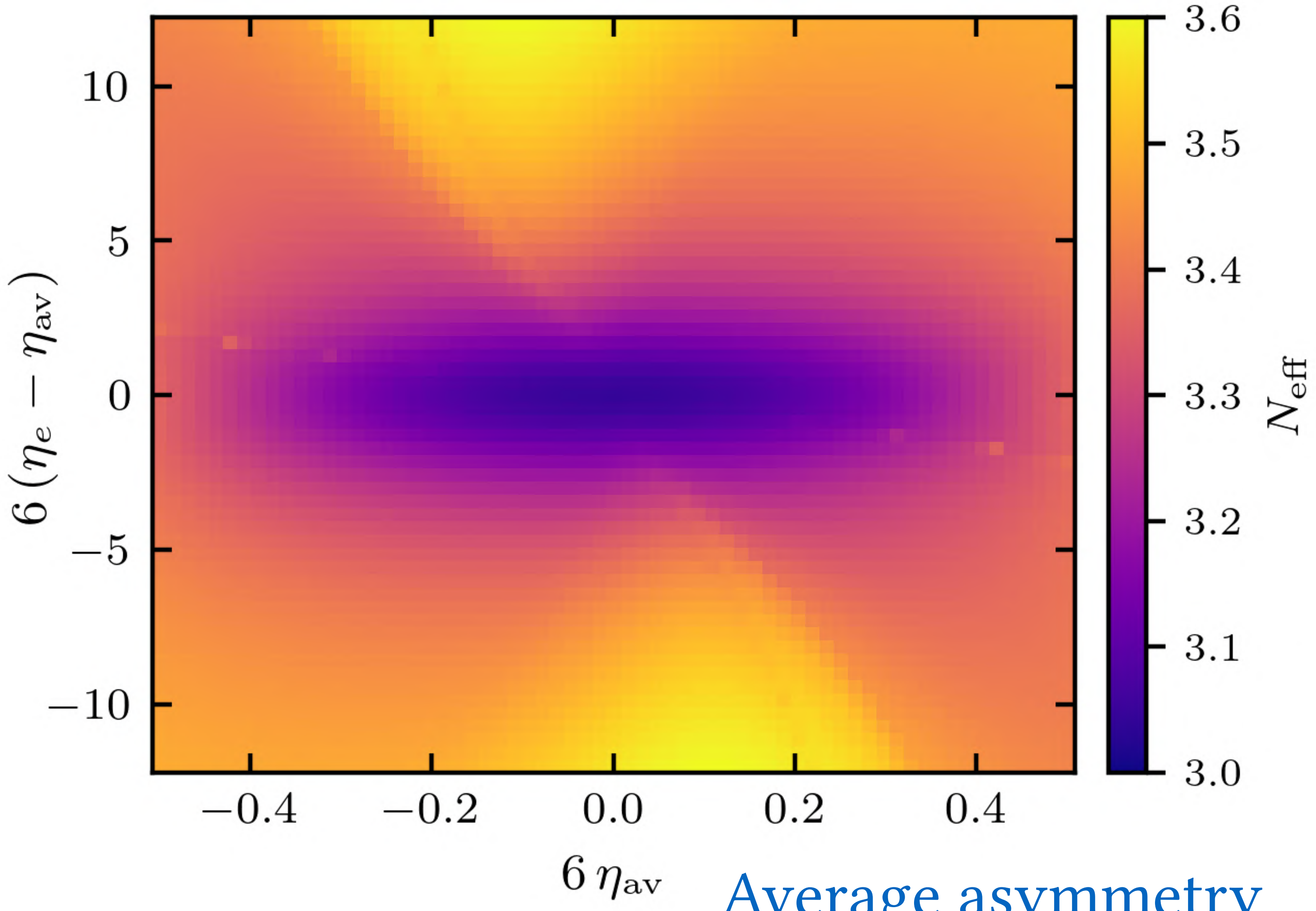
Spectroscopic measurements

$Y_{\rm p} = 0.2453 \pm 0.0034$

$\mathrm{D/H} = (2.53 \pm 0.03) \times 10^{-5}$

Aver *et al.* [2010.04180]
Cooke *et al.* [1710.11129]
Kislitsyn *et al.* [2401.12797]

Effective number of relativistic d.o.f.



Difference of initial *e* flavor asymmetry − average

Average asymmetry

CMB + BAO (< 2024)

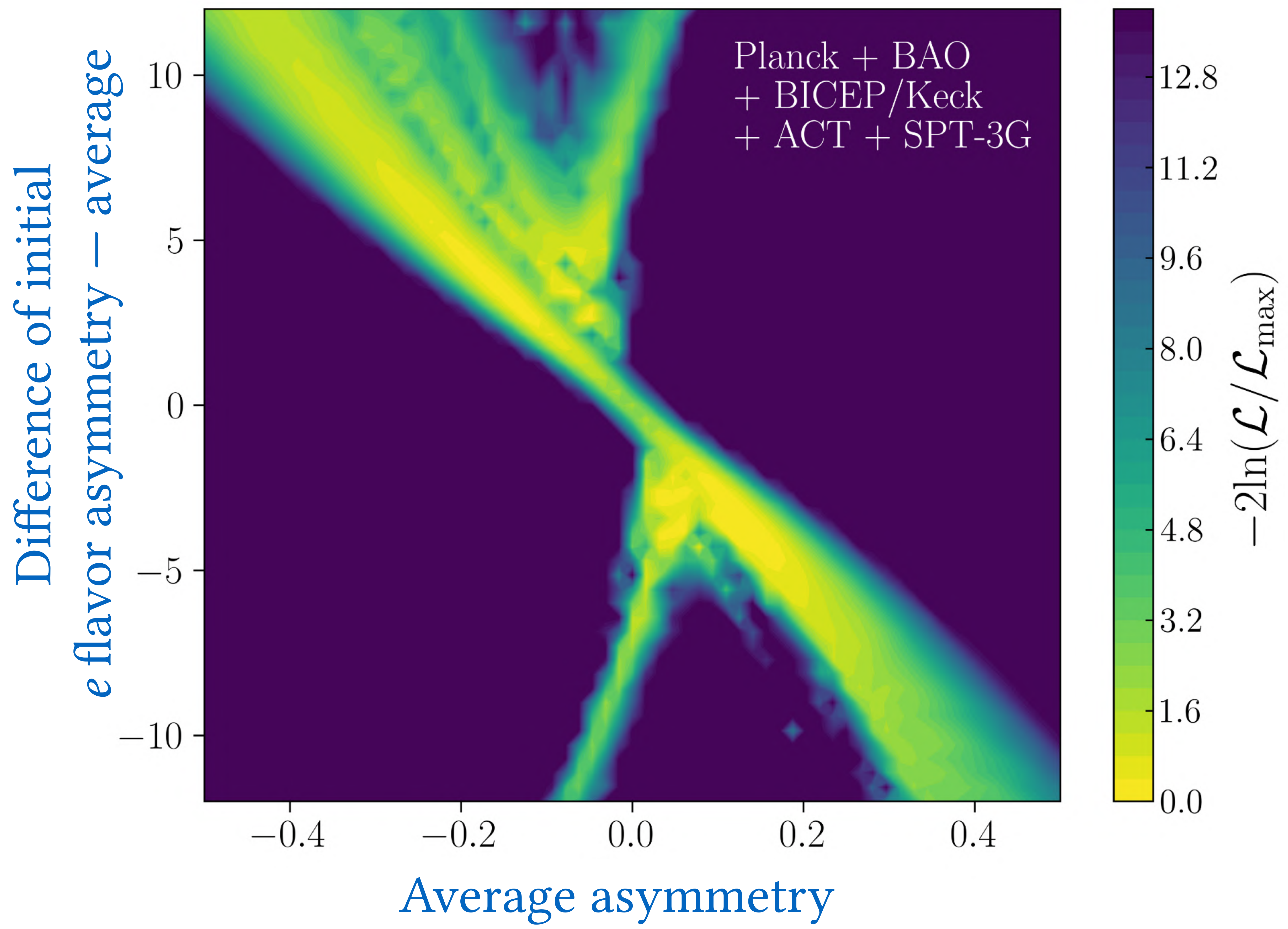
$N_{\rm eff} = 2.99 \pm 0.24 \quad (68\,\%)$

Constraining primordial neutrino asymmetries

JF, C. Pitrou
[2405.06509]

- **Large lepton asymmetries are allowed**, with a complicated landscape due to the dynamics of flavor oscillations.

[Normal mass ordering]



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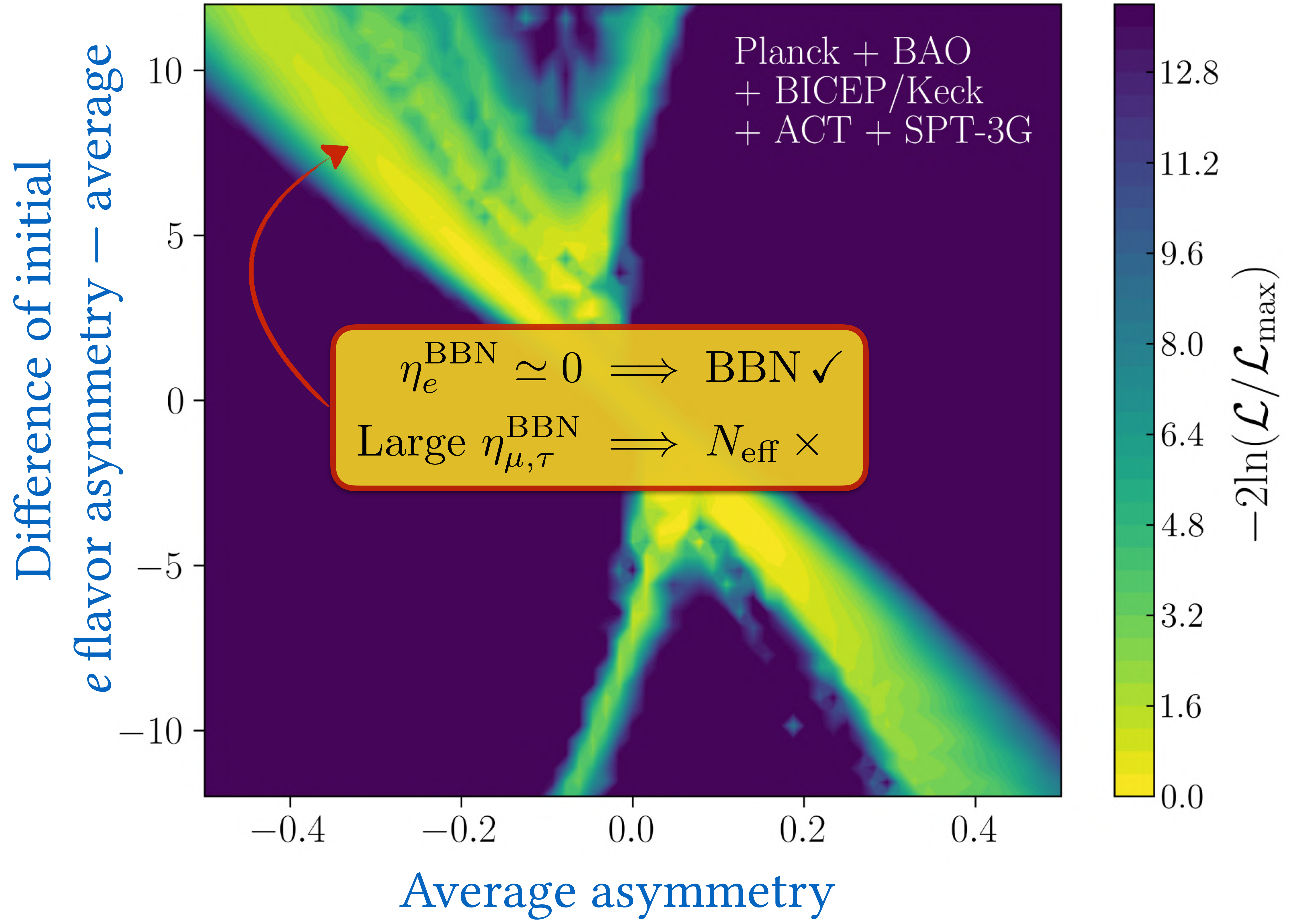

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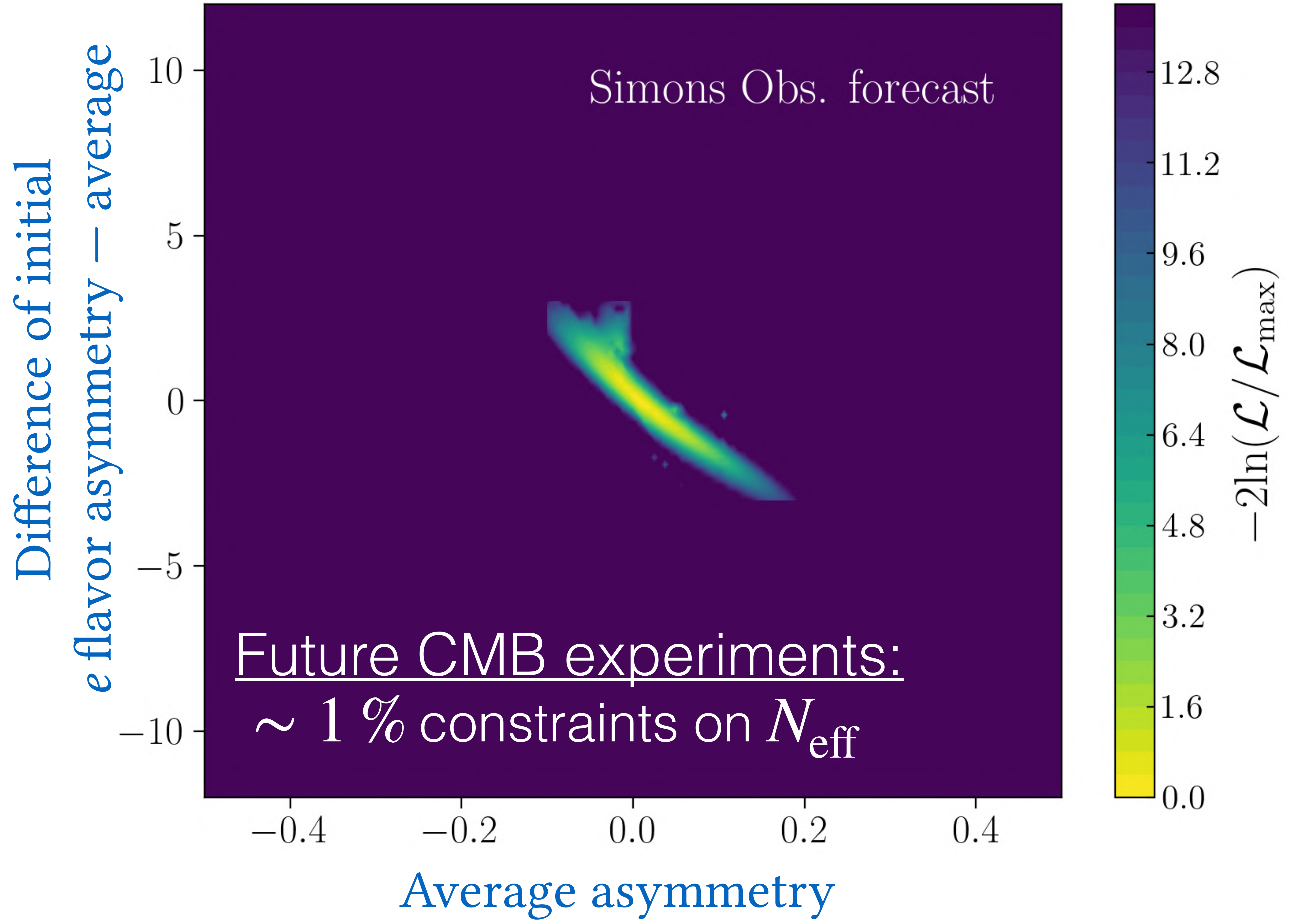

Connection with thermal warm dark matter

Transfer function $T(k) = \sqrt{\frac{P(k)}{P_{\Lambda\mathrm{CDM}}(k)}}$