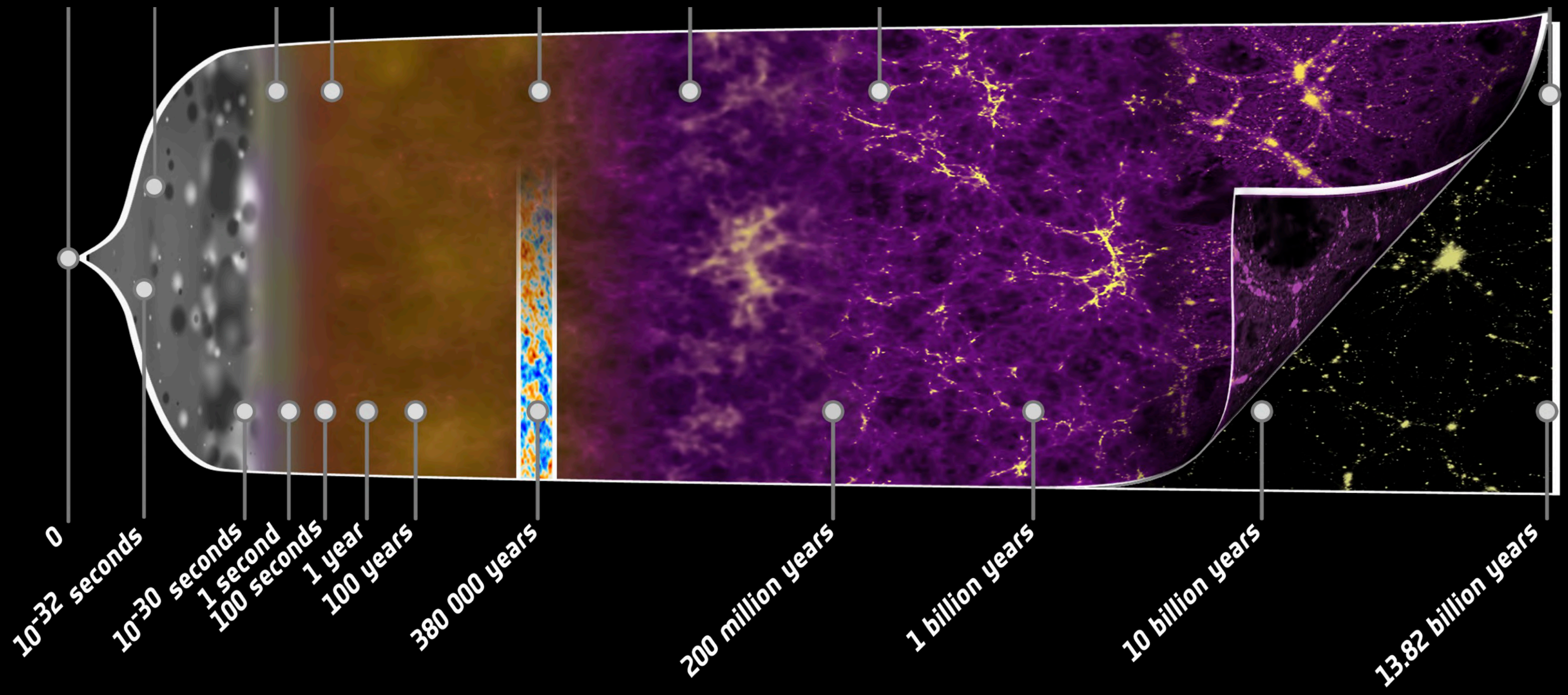
Primordial lepton asymmetries:
constraints and consequences

Julien Froustey

Severo Ochoa Postdoctoral Fellow,
IFIC (CSIC-UV), Valencia

Particle Physics in the Early Universe

14/09/2026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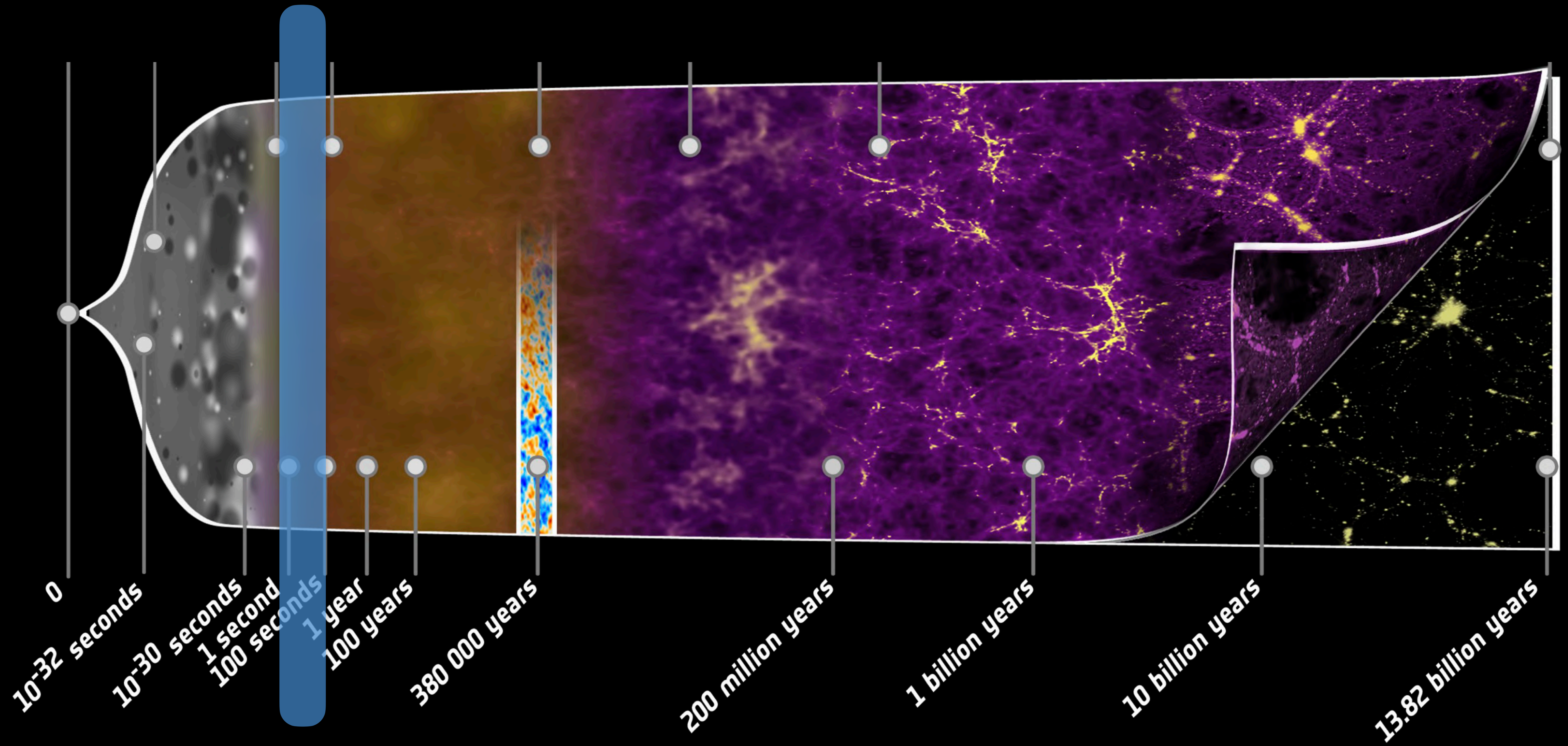
10^{-32} seconds
10^{-30} seconds
1 second
100 seconds
1 year
100 years
380 000 years
200 million years
1 billion years
10 billion years
13.82 billion years

Credits: ESA

Formation of the

Cosmic Neutrino Background



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

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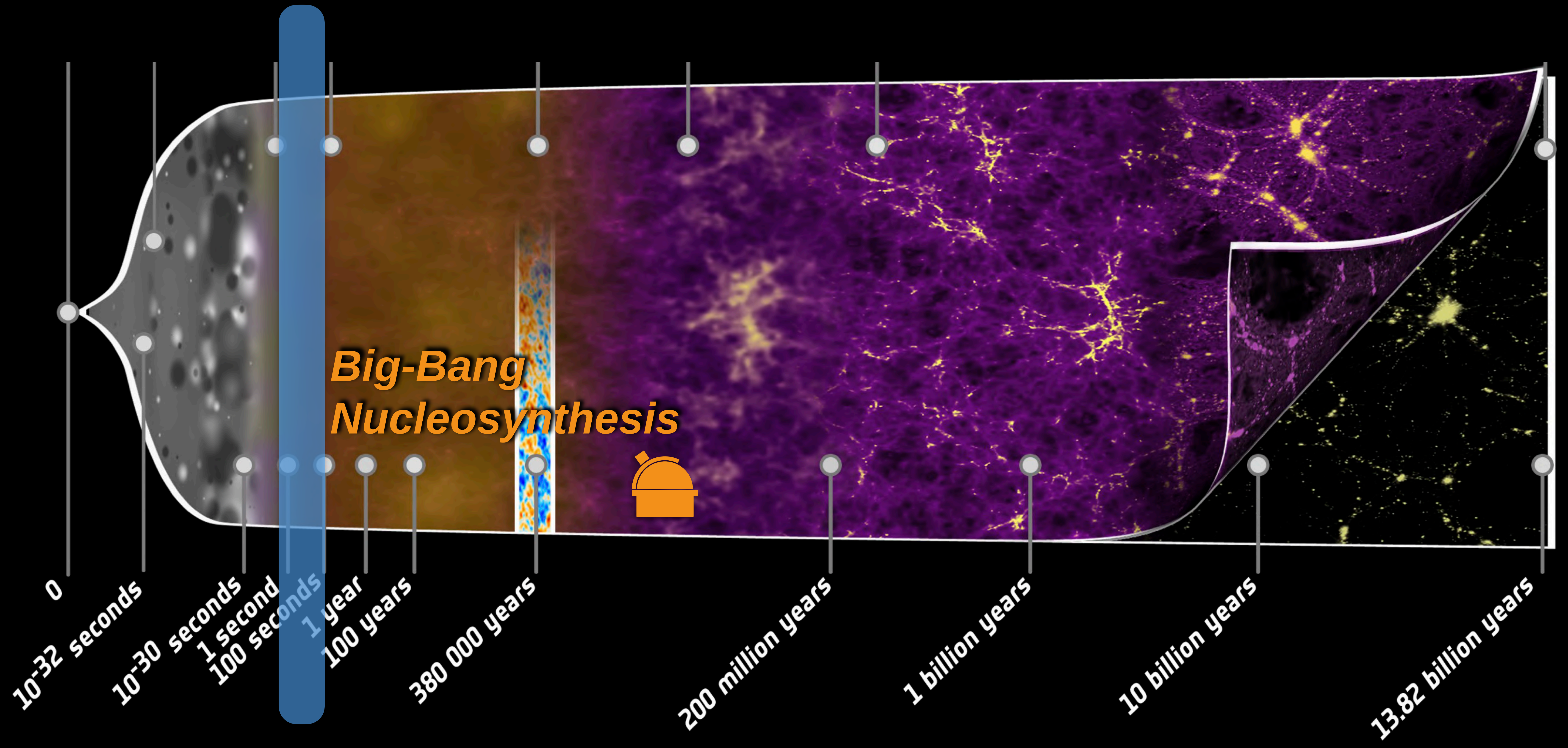

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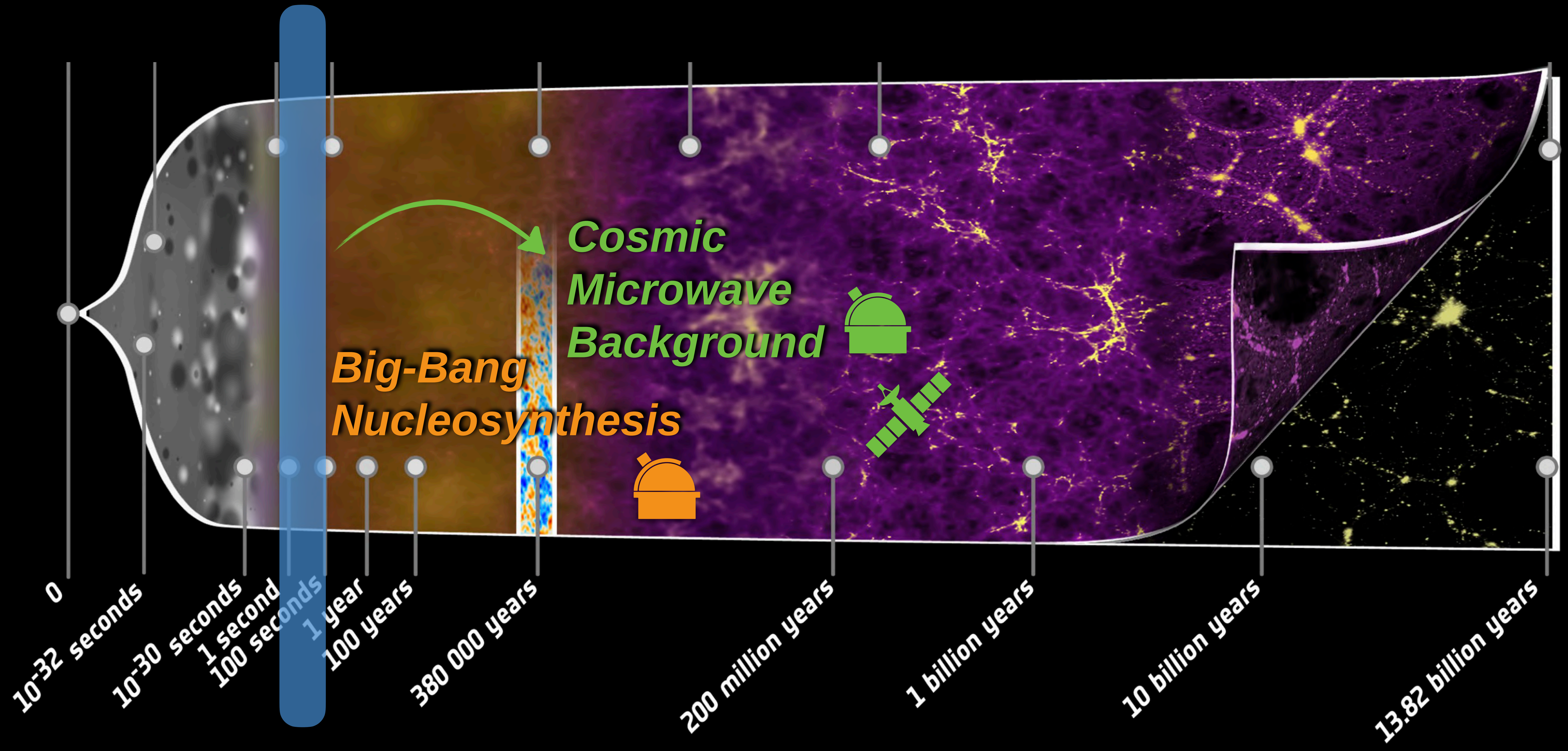

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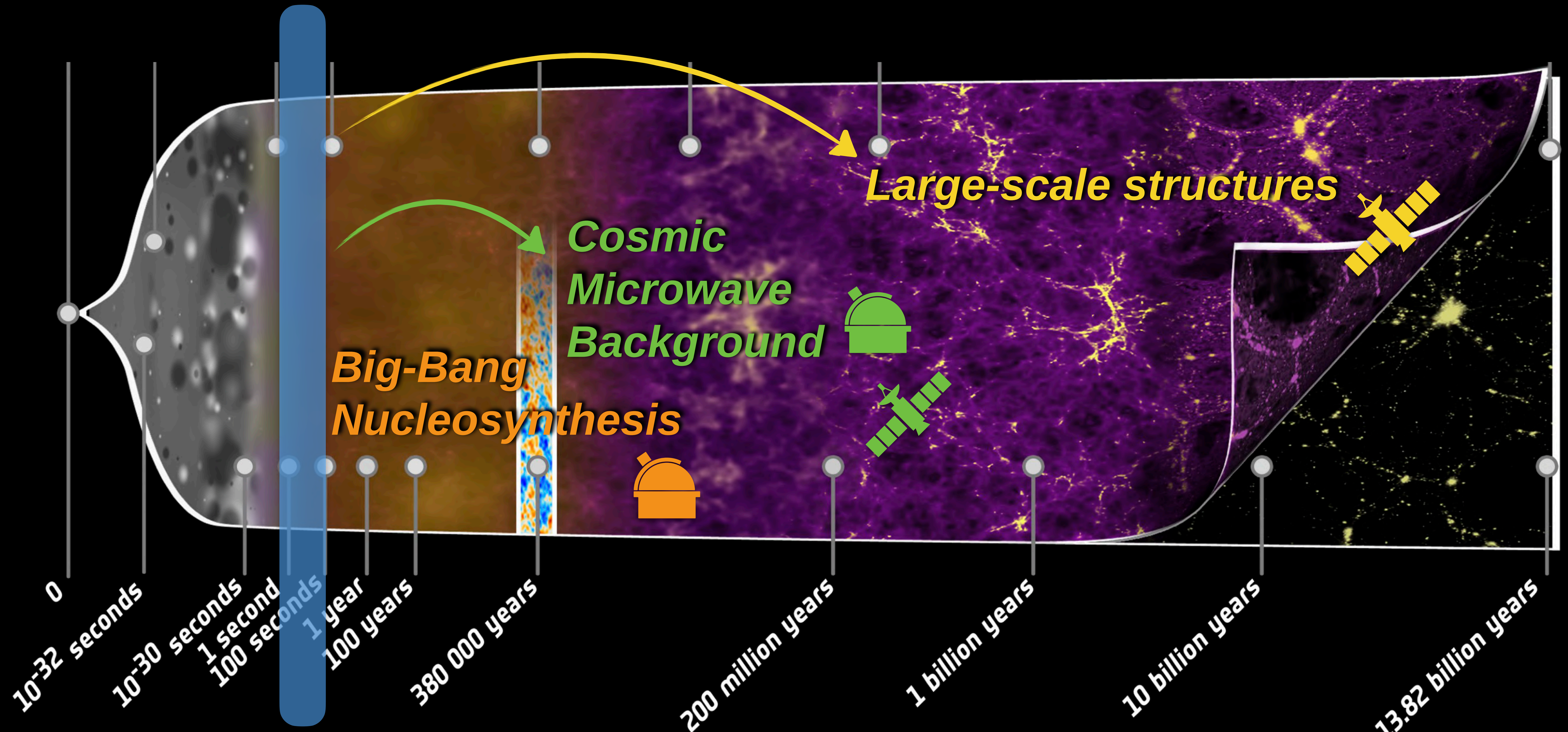

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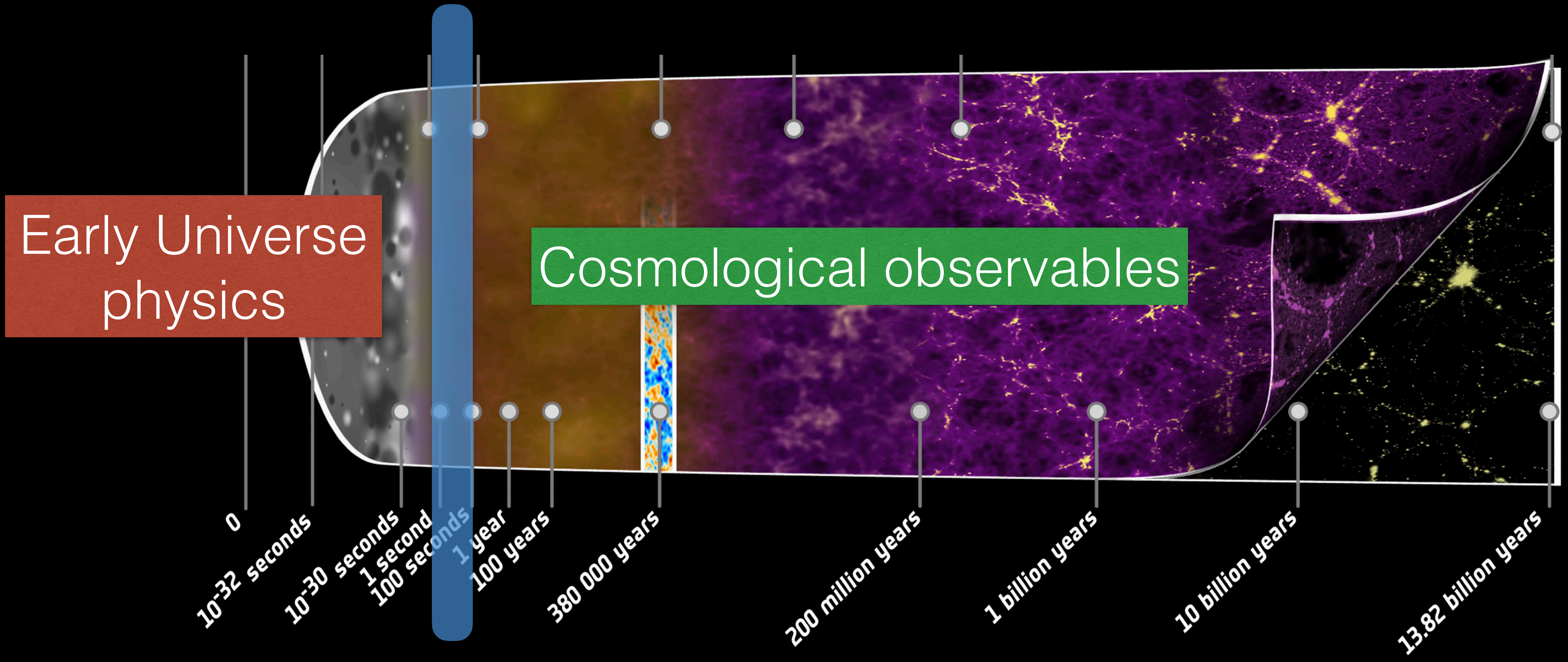

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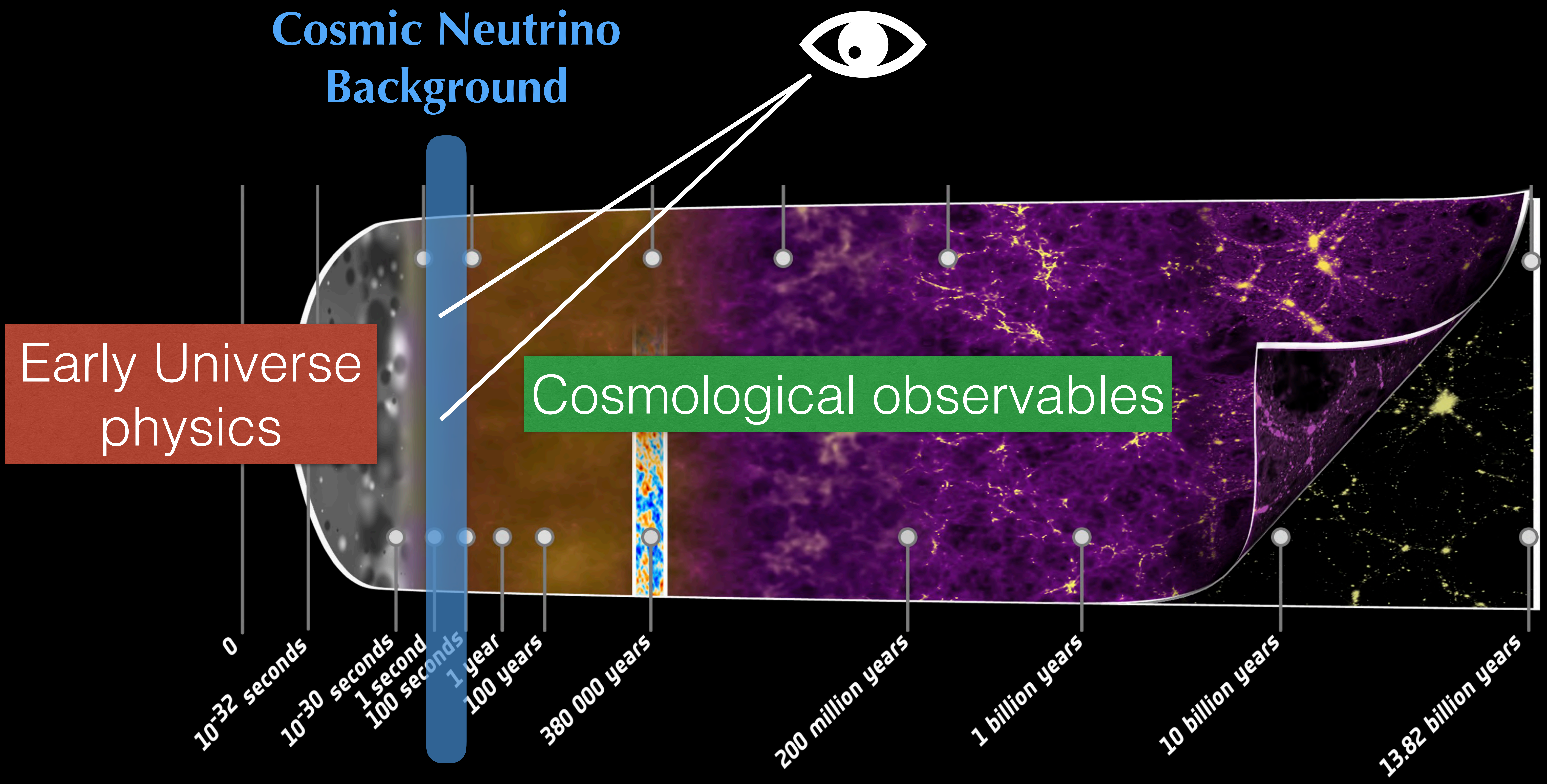

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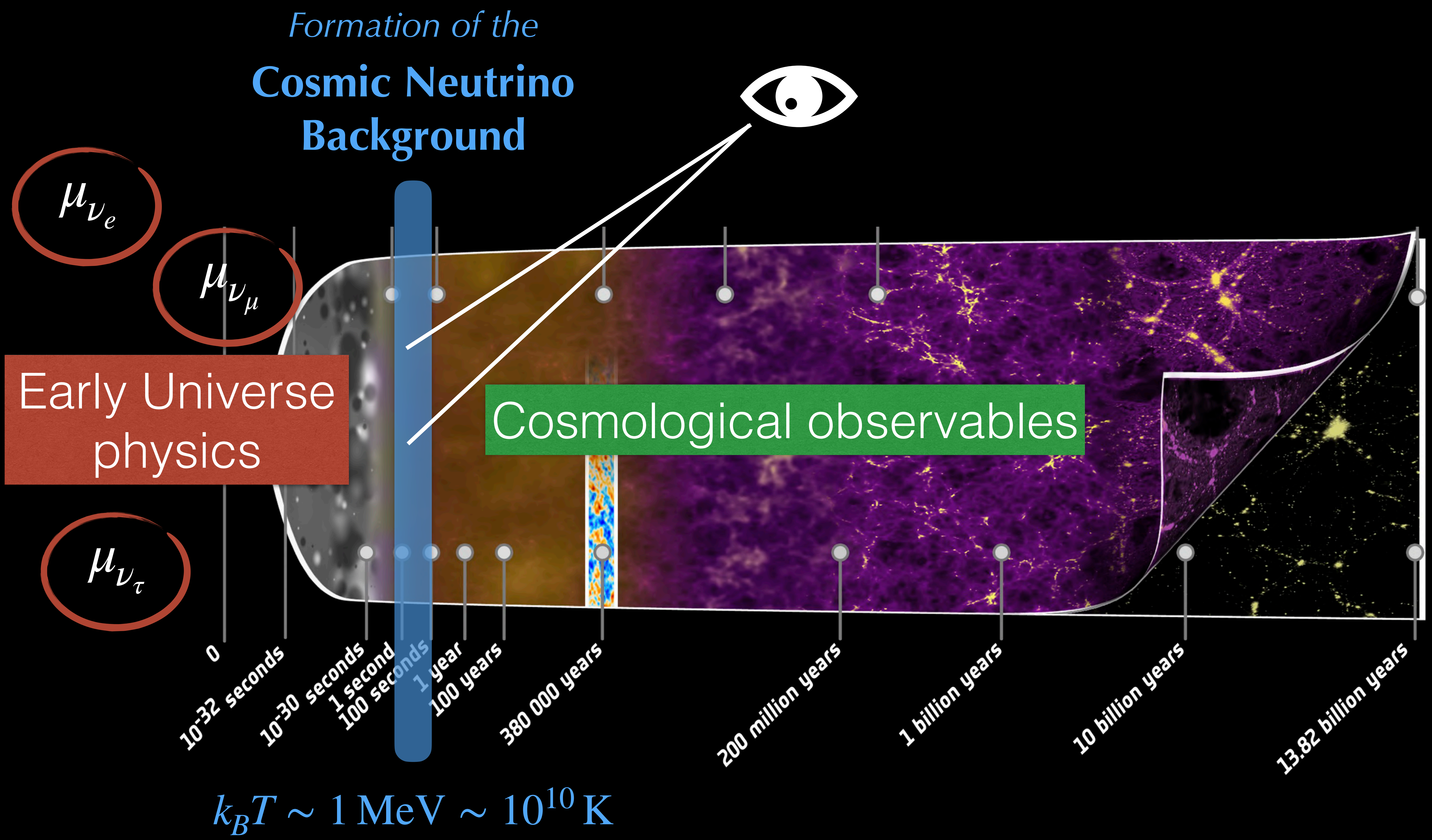

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μ_{ν_e}
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Outline

1. Primordial asymmetry evolution and constraints

   JF, C. Pitrou, *JCAP* **03**, 065 (2022) [2110.11889]
   JF, C. Pitrou, *Phys. Rev. D* **110**, 103551 (2024) [2405.06509]

2. Large lepton number and sterile neutrino dark matter

   C. Vogel, H. Escudero, K. Abazajian and **JF**, *Phys. Rev. D* **112**, 123508 (2025) [2507.18752]

3. Lepton asymmetries and primordial black hole formation

   M. Gonin, **JF**, A. Escrivà, A. Magaraggia, G. Hasinger and F. Kühnel, [2608.22240]

1. Primordial asymmetry evolution and constraints

Based on:

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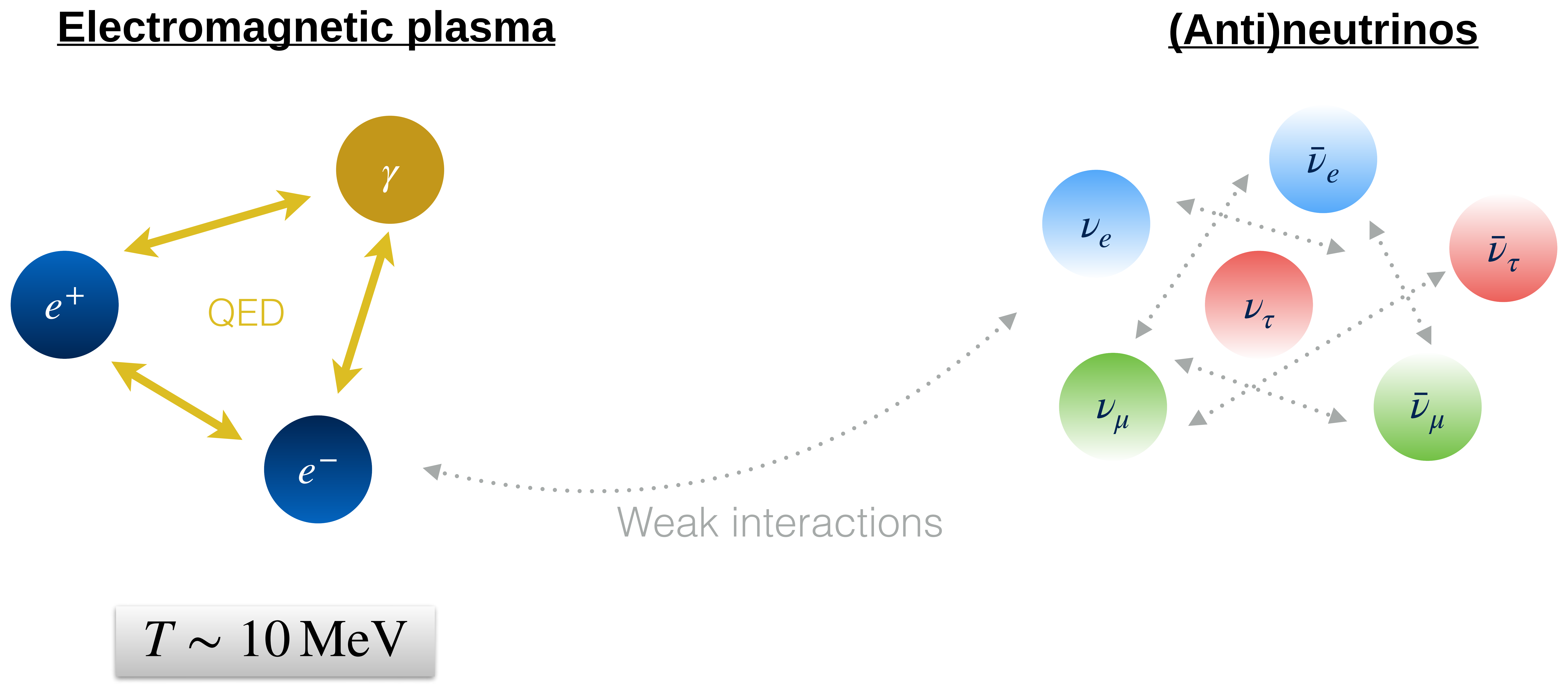
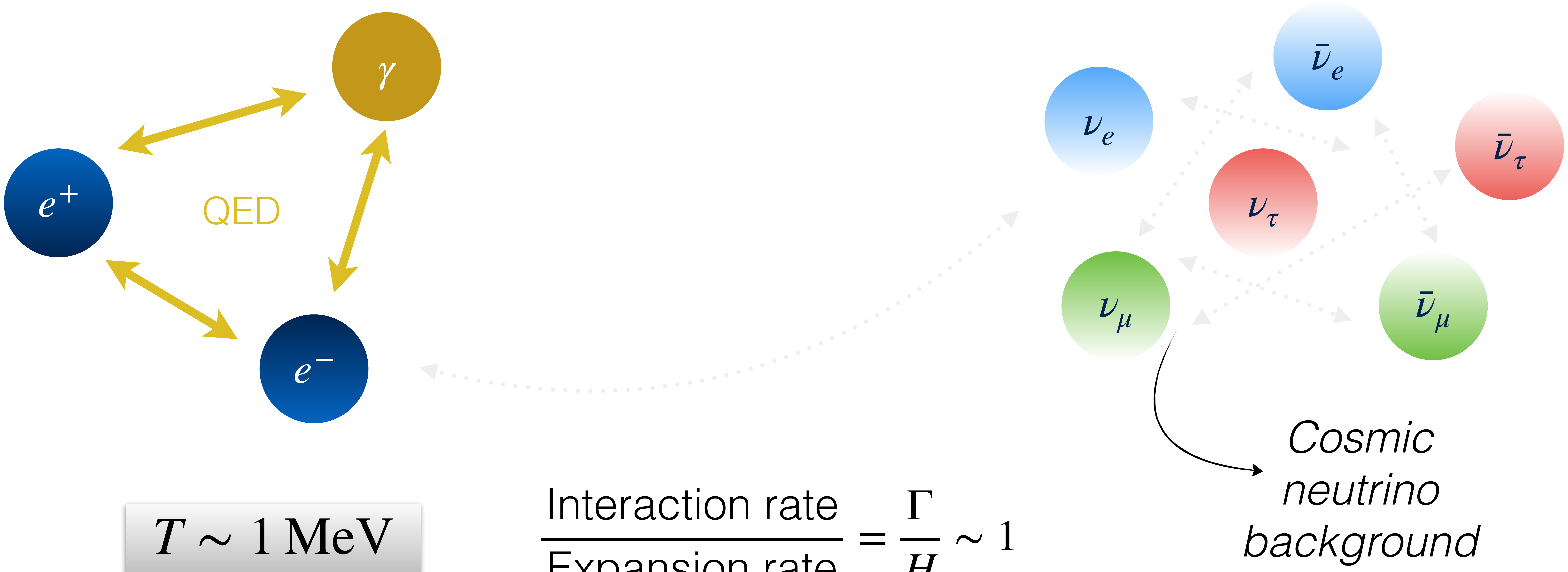
Standard neutrino decoupling



Standard neutrino decoupling

Electromagnetic plasma

(Anti)neutrinos



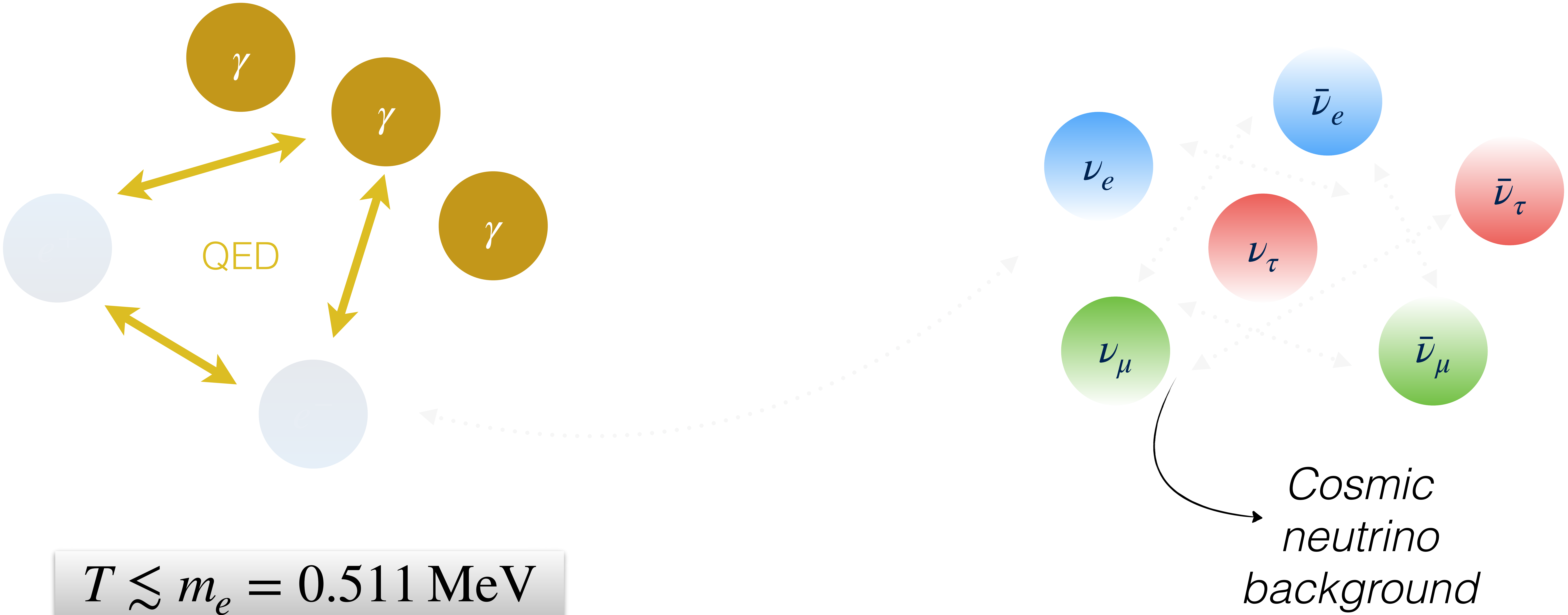
$T \sim 1\,\mathrm{MeV}$

$$\frac{\text{Interaction rate}}{\text{Expansion rate}} = \frac{\Gamma}{H} \sim 1$$

Neutrino decoupling

Standard neutrino decoupling

Electromagnetic plasma | **(Anti)neutrinos**



$$T \lesssim m_e = 0.511\,\mathrm{MeV}$$

Entropy transfer to photons $\Longrightarrow$ $$\frac{T_\gamma}{T_\nu} \simeq \left(\frac{11}{4}\right)^{1/3} \simeq 1.40$$

Neutrinos and cosmological observables

Effective number of relativistic species

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

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Primordial abundances

Neutron/proton ratio

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

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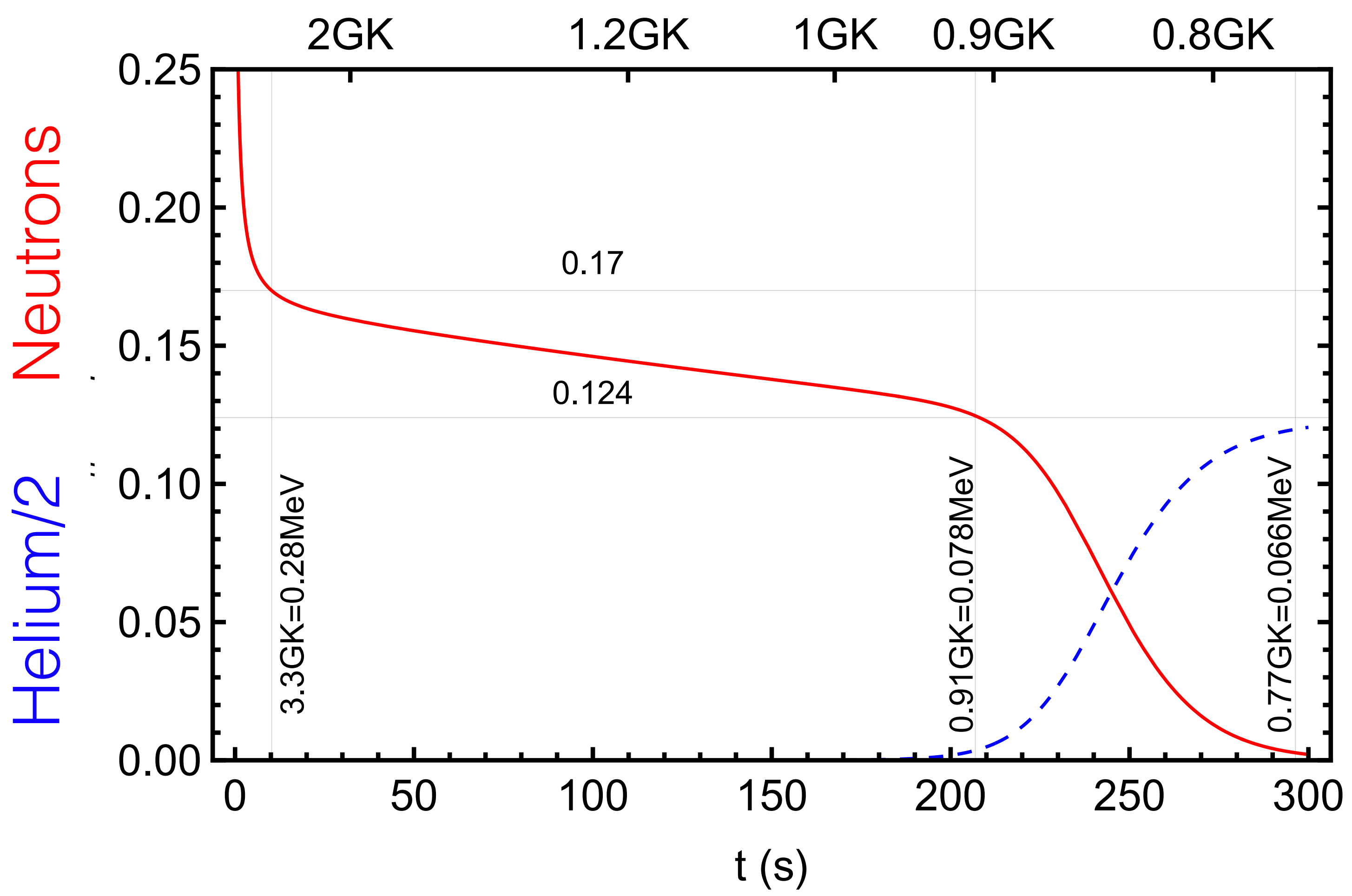

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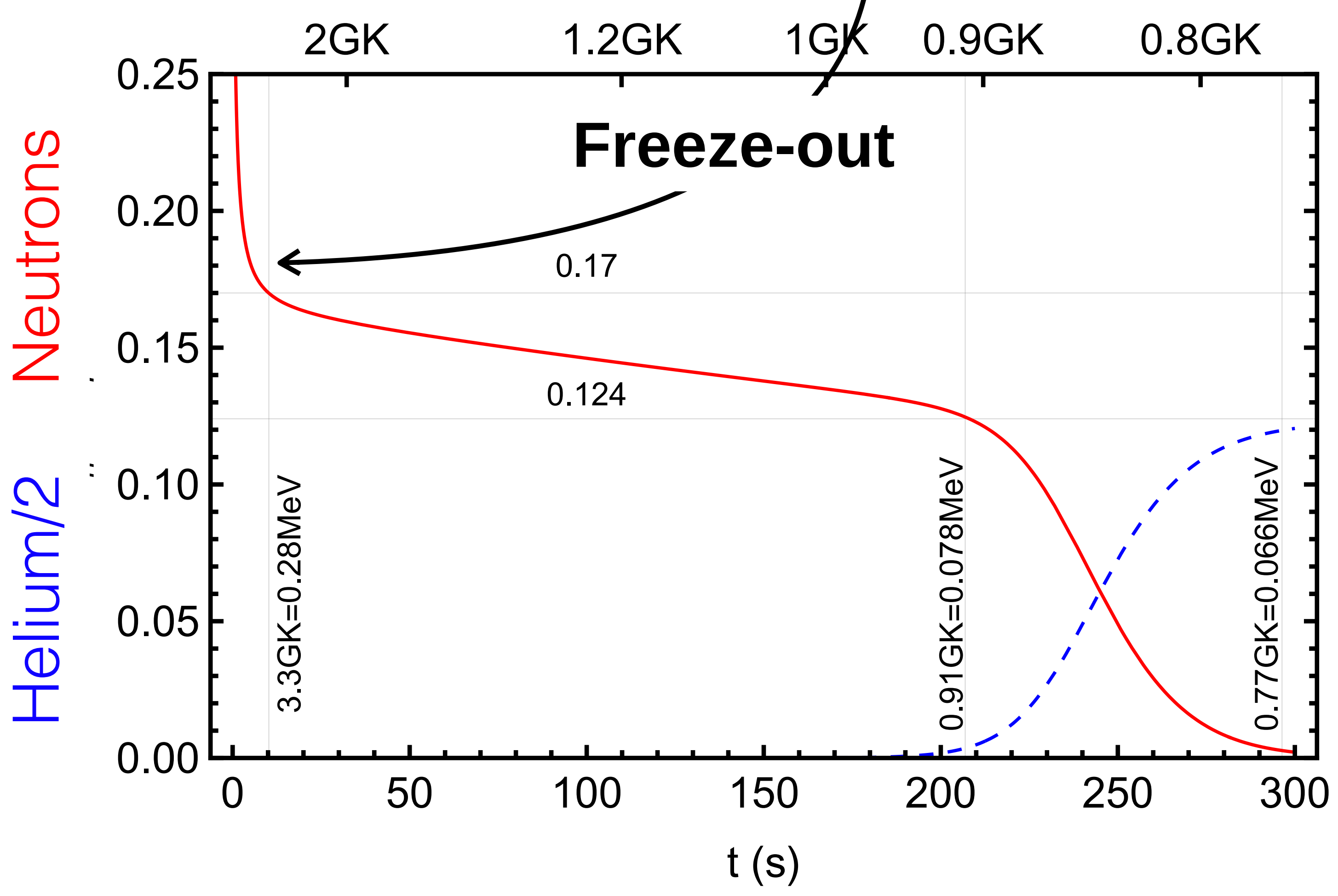

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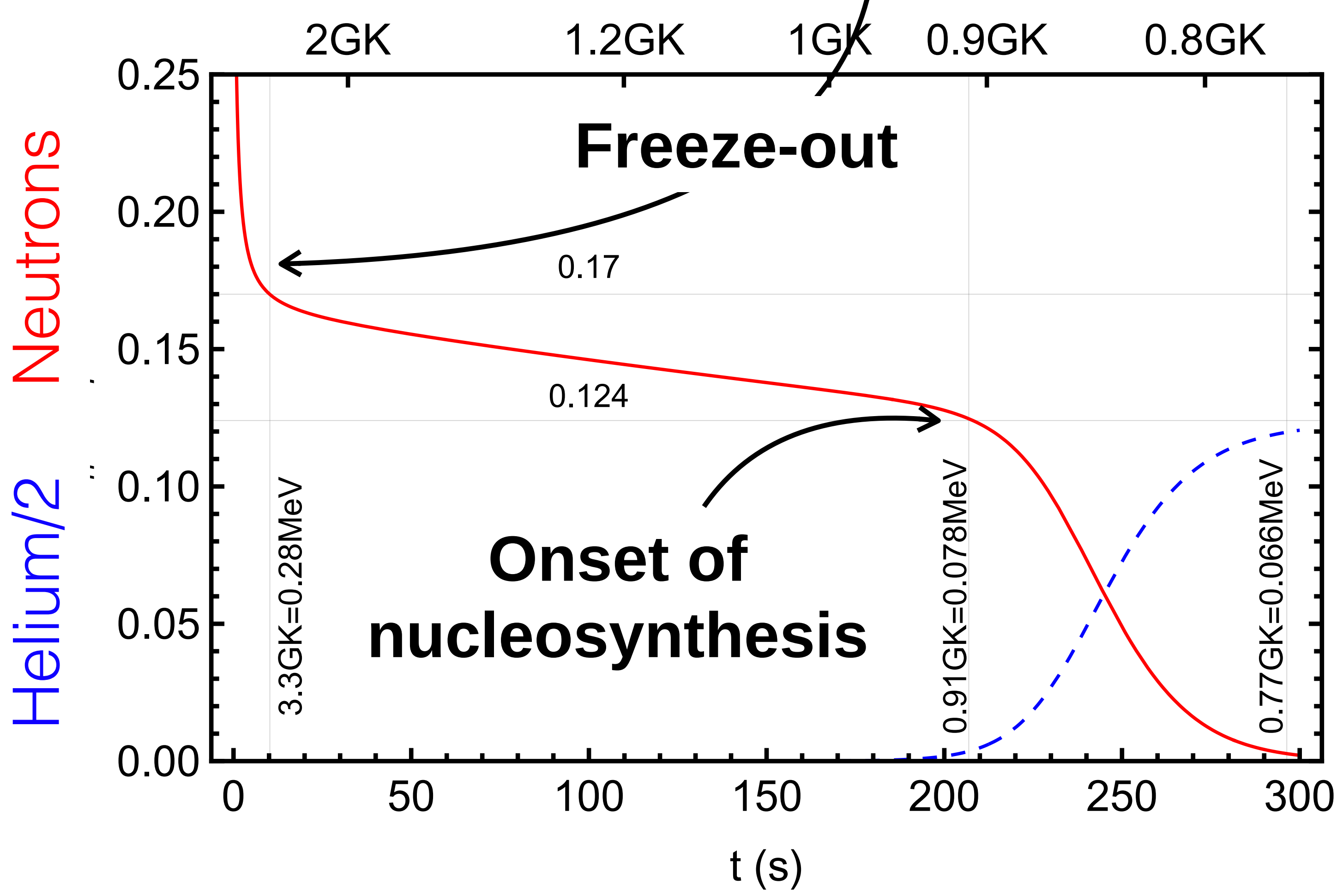

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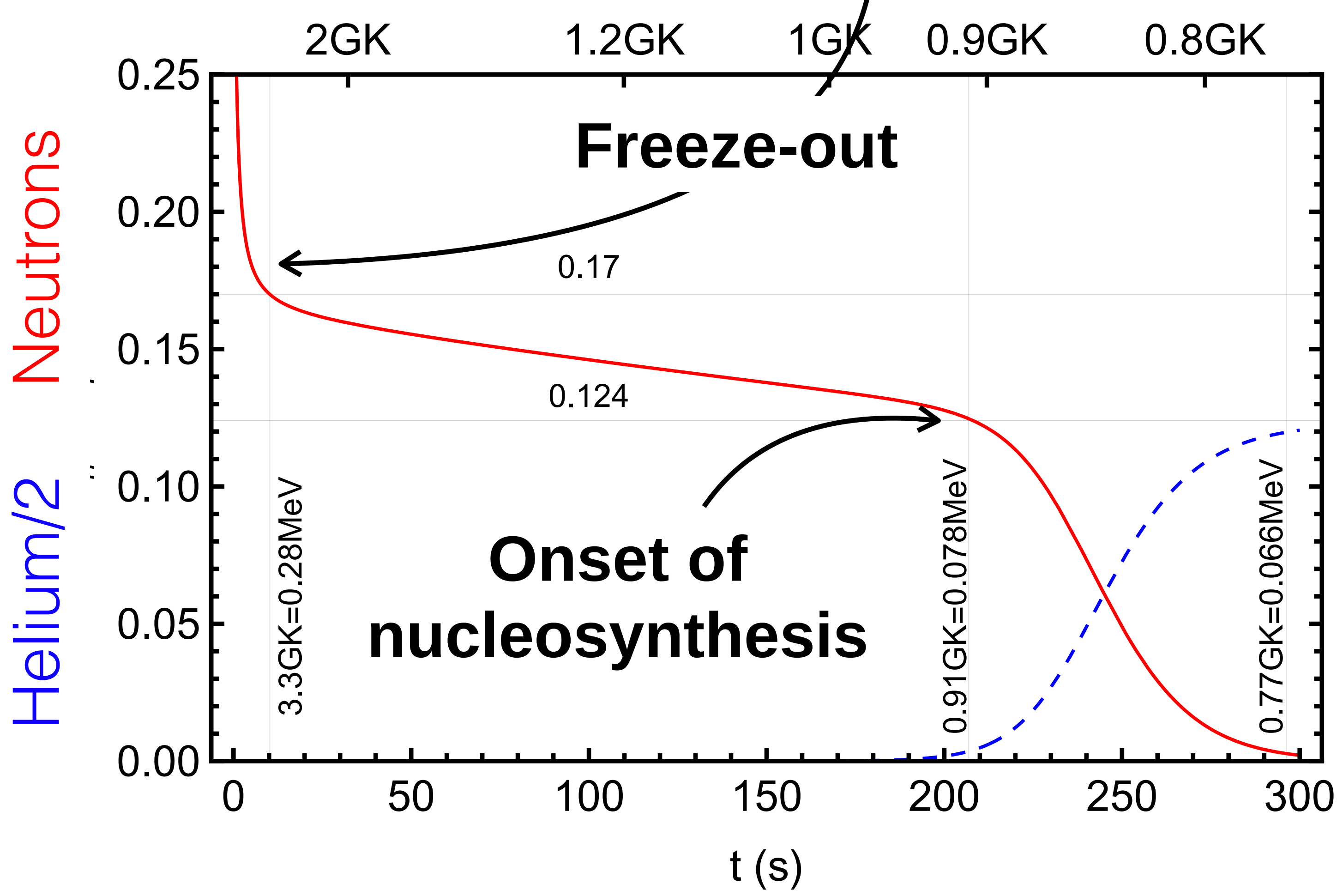

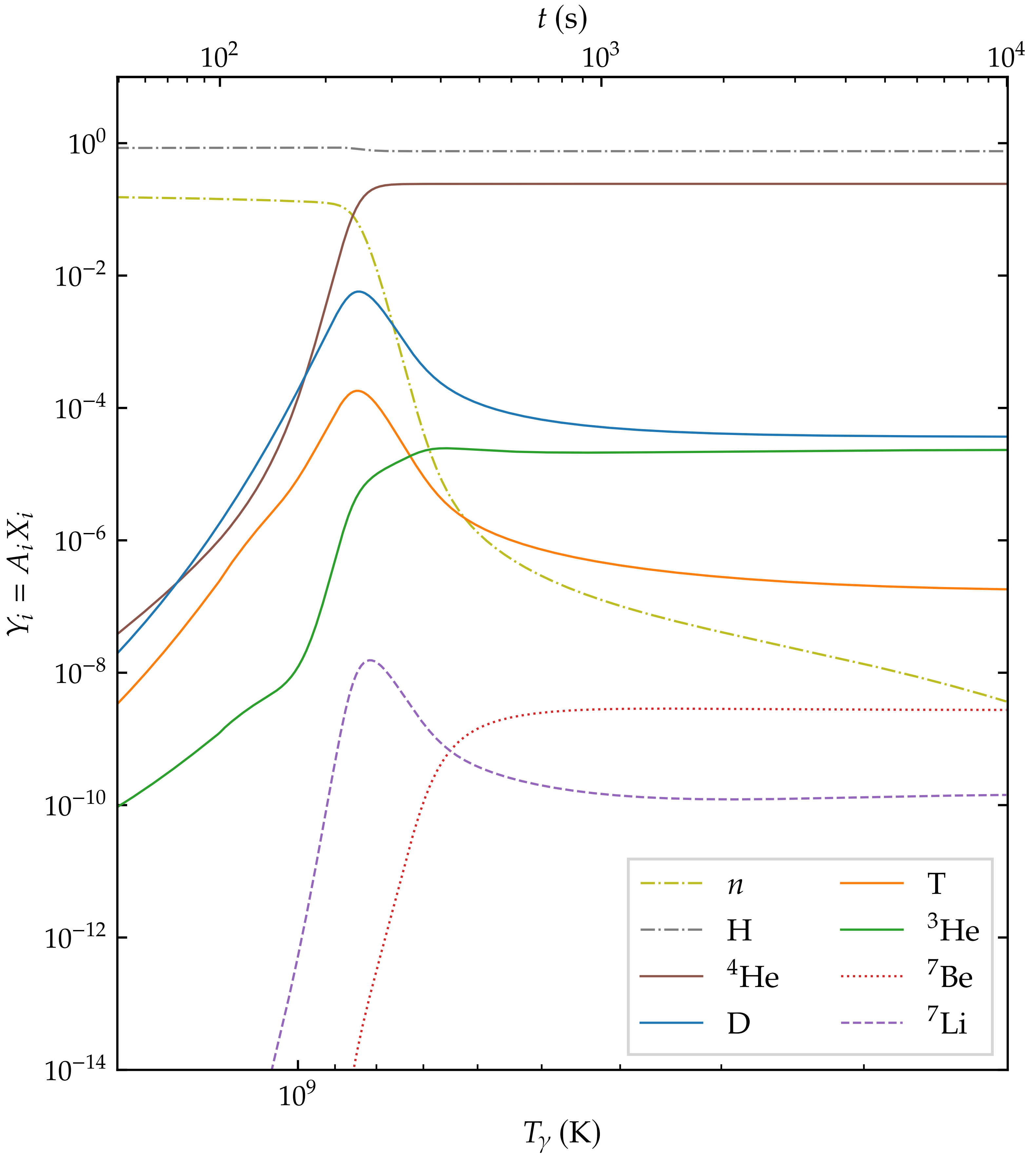

$$Y_{\text{p}} = \frac{4n_{[^4\text{He}]}}{n_b}$$

$$\text{D/H} = \frac{n_{[^2\text{H}]}}{n_{[^1\text{H}]}}$$

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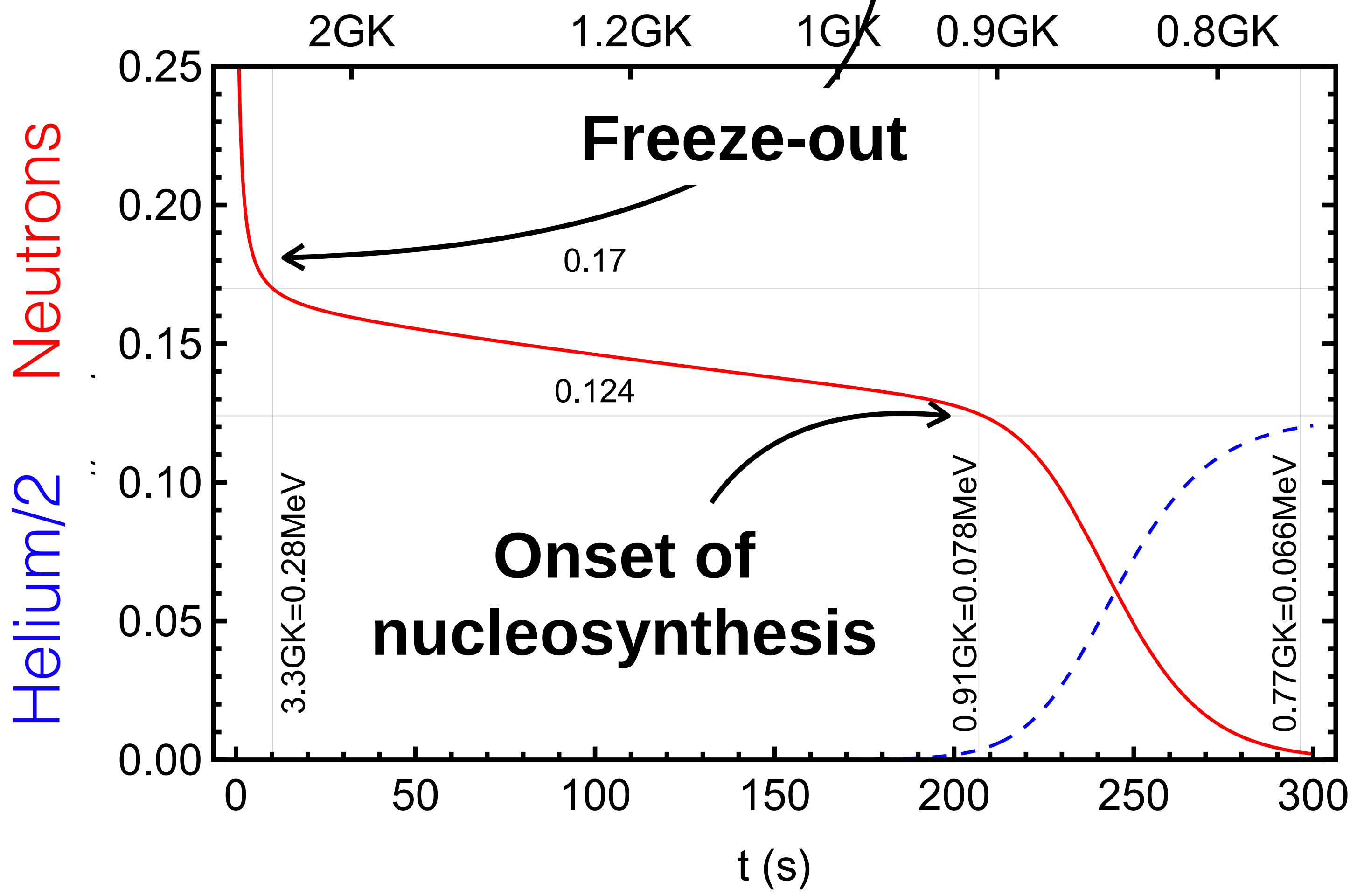

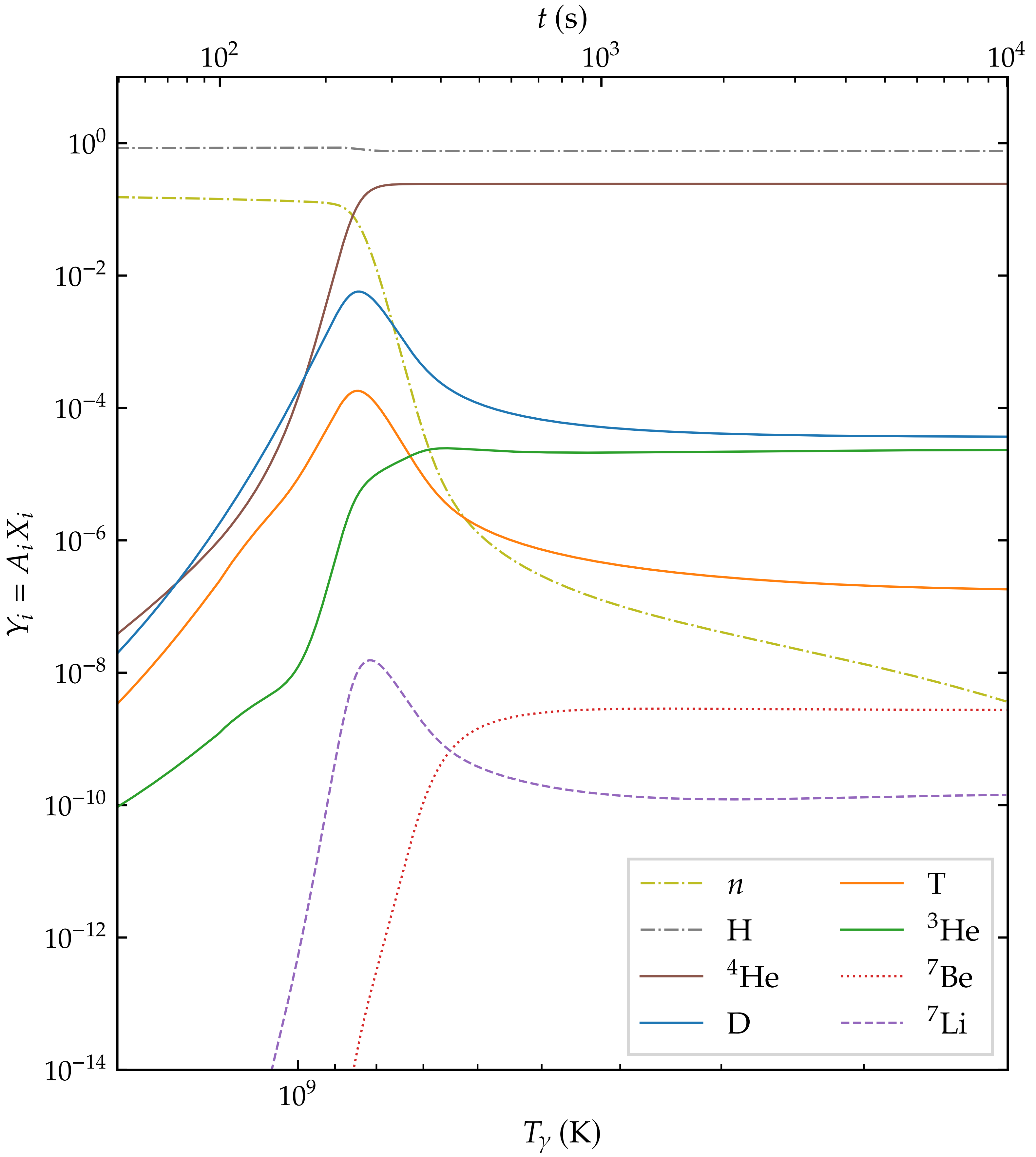

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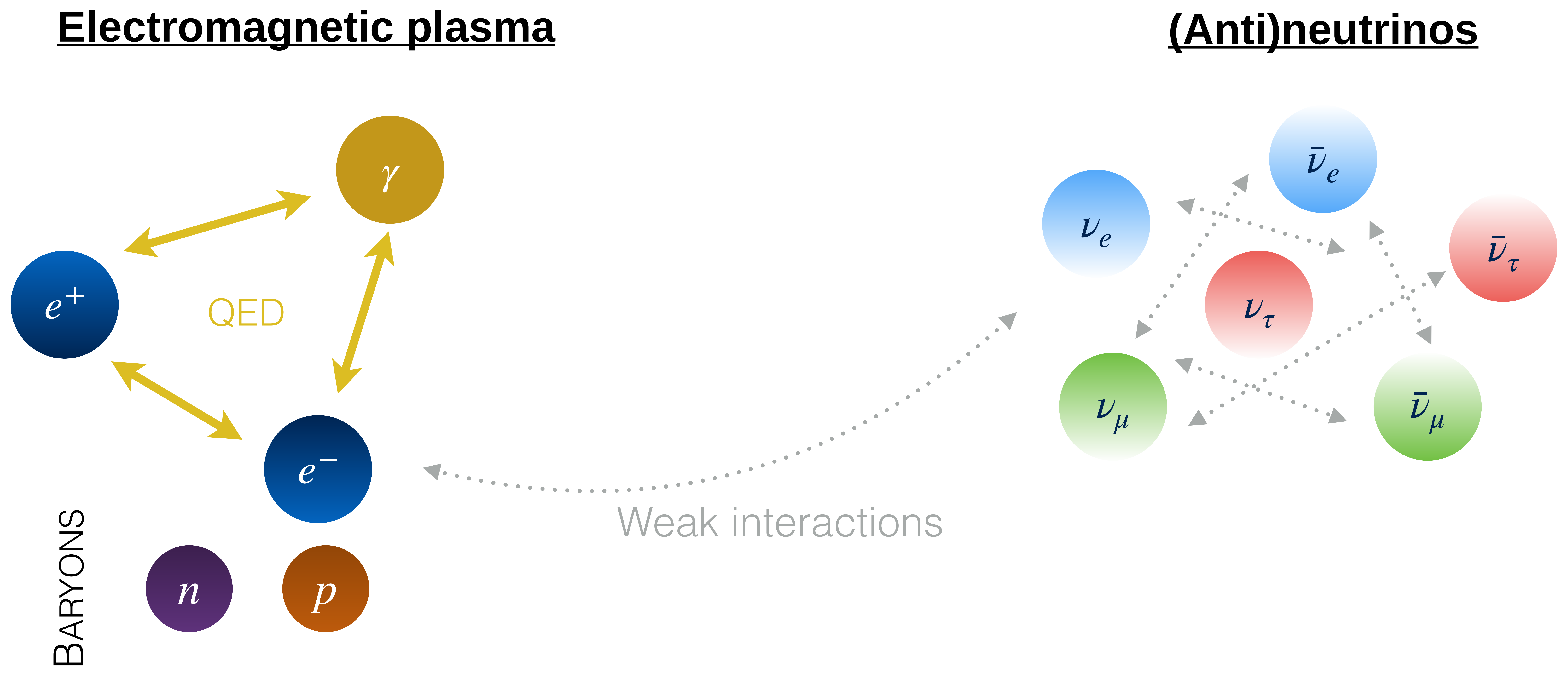
Asymmetries in the Universe at $T \sim 10\,\mathrm{MeV}$



$$\eta_b = \frac{n_b}{n_\gamma} \sim 10^{-9}$$

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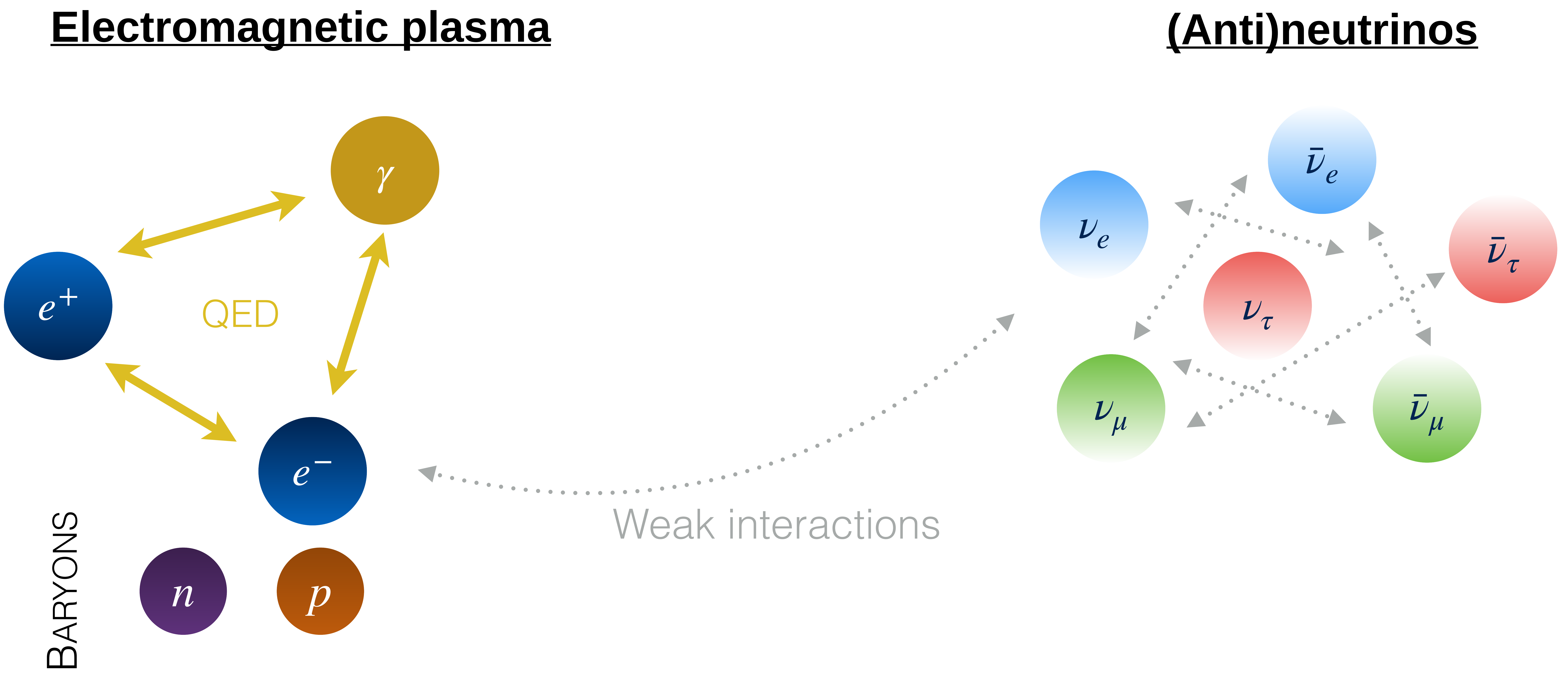
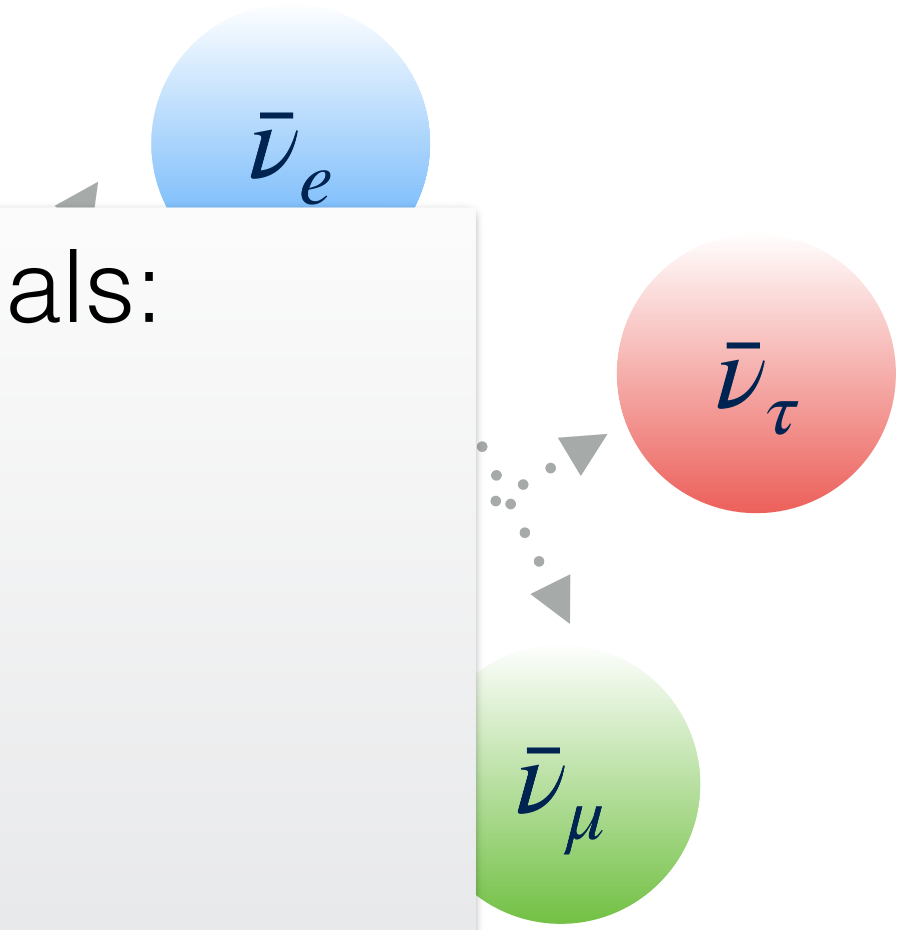


$$\eta_b = \frac{n_b}{n_\gamma} \sim 10^{-9} \xrightarrow{\text{charge neutrality}} \frac{n_{e^-} - n_{e^+}}{n_\gamma} = \eta_b \ll 1$$

Asymmetries in the Universe at $T \sim 10\,\mathrm{MeV}$

Electromagnetic plasma | **(Anti)neutrinos**



For neutrinos however, possibly large chemical potentials:

$$f^{(\mathrm{eq})}_{\nu_\alpha}(p) = \frac{1}{e^{(p-\mu_\alpha)/T}+1} \qquad \bar{\mu}_\alpha = -\mu_\alpha$$

"**Asymmetry**"

$$\eta_\alpha \equiv \frac{n_{\nu_\alpha} - n_{\bar{\nu}_\alpha}}{T^3} = \frac{1}{6}\left[\xi_\alpha + \frac{\xi_\alpha^3}{\pi^2}\right] \quad \text{where} \quad \xi_\alpha = \frac{\mu_\alpha}{T}$$

BARYONS

charge neutrality

$$\eta_b = \frac{n_b}{n_\gamma} \sim 10^{-9} \longrightarrow \frac{n_{e^-} - n_{e^+}}{n_\gamma} = \eta_b \ll 1$$

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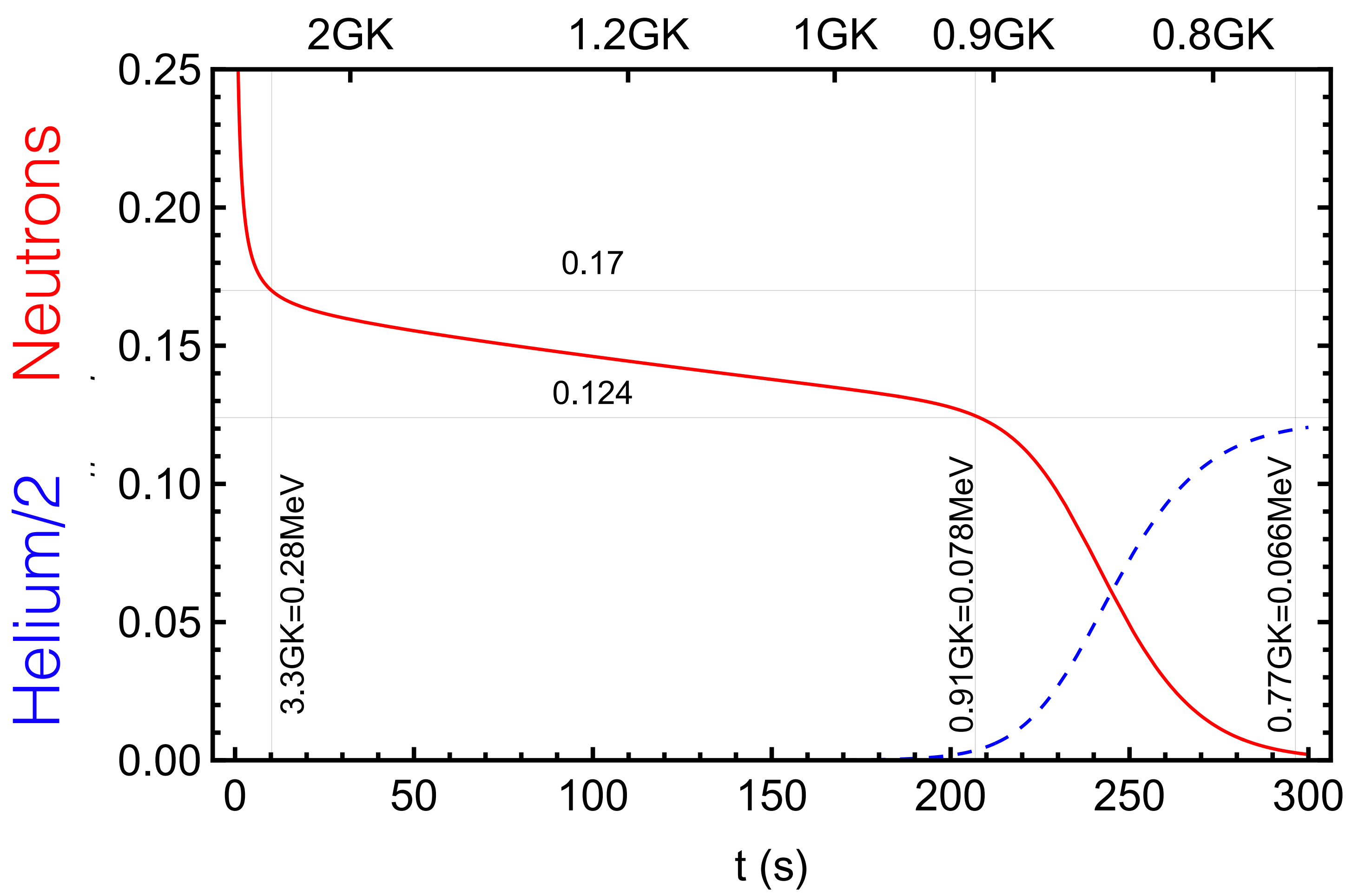

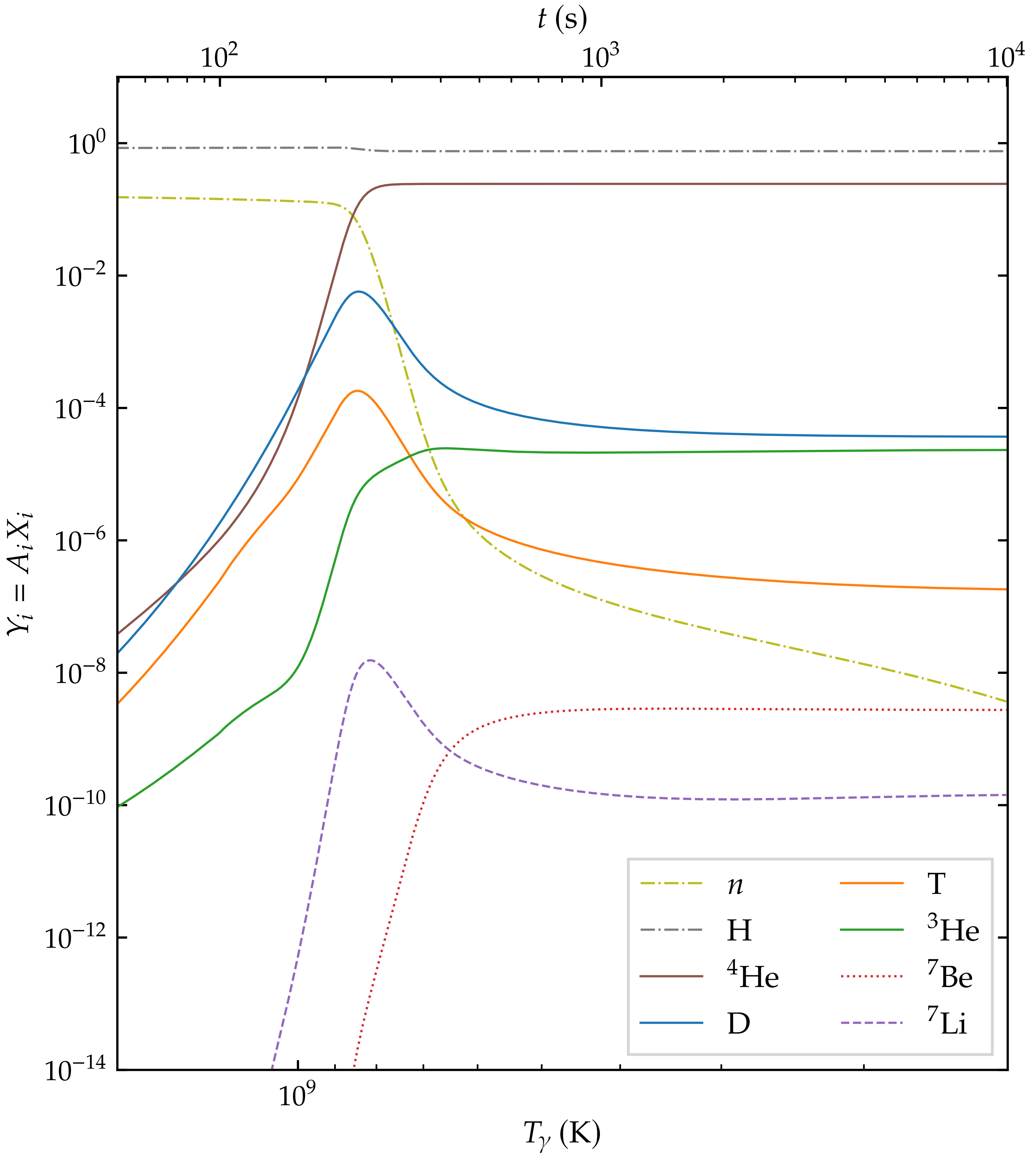

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$$\Delta N_{\rm eff} = \sum_{\alpha=e,\mu,\tau}\left[\frac{30}{7}\left(\frac{\xi_\alpha}{\pi}\right)^2 + \frac{15}{7}\left(\frac{\xi_\alpha}{\pi}\right)^4\right]$$

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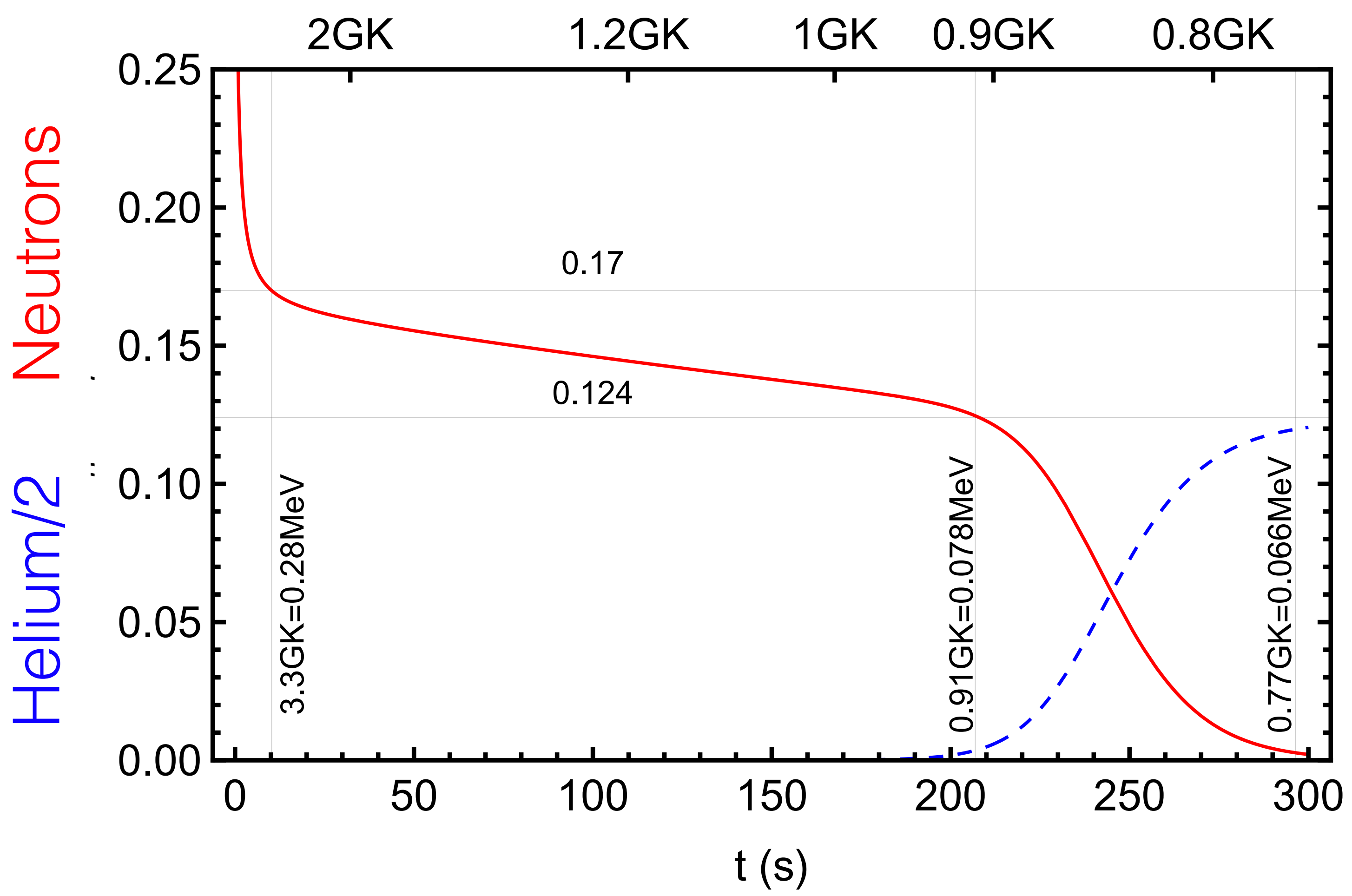

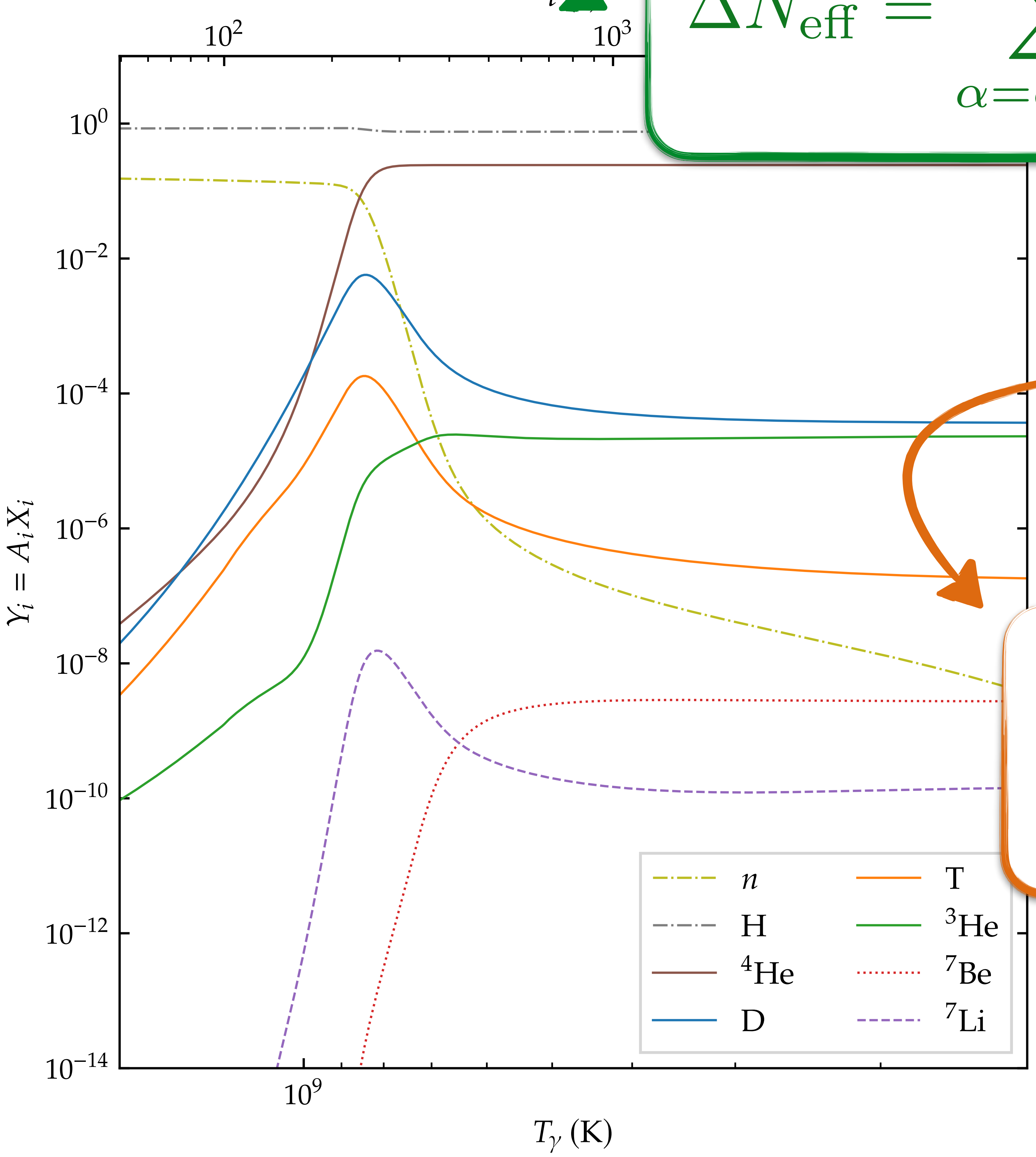

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Pitrou et al. (2018)

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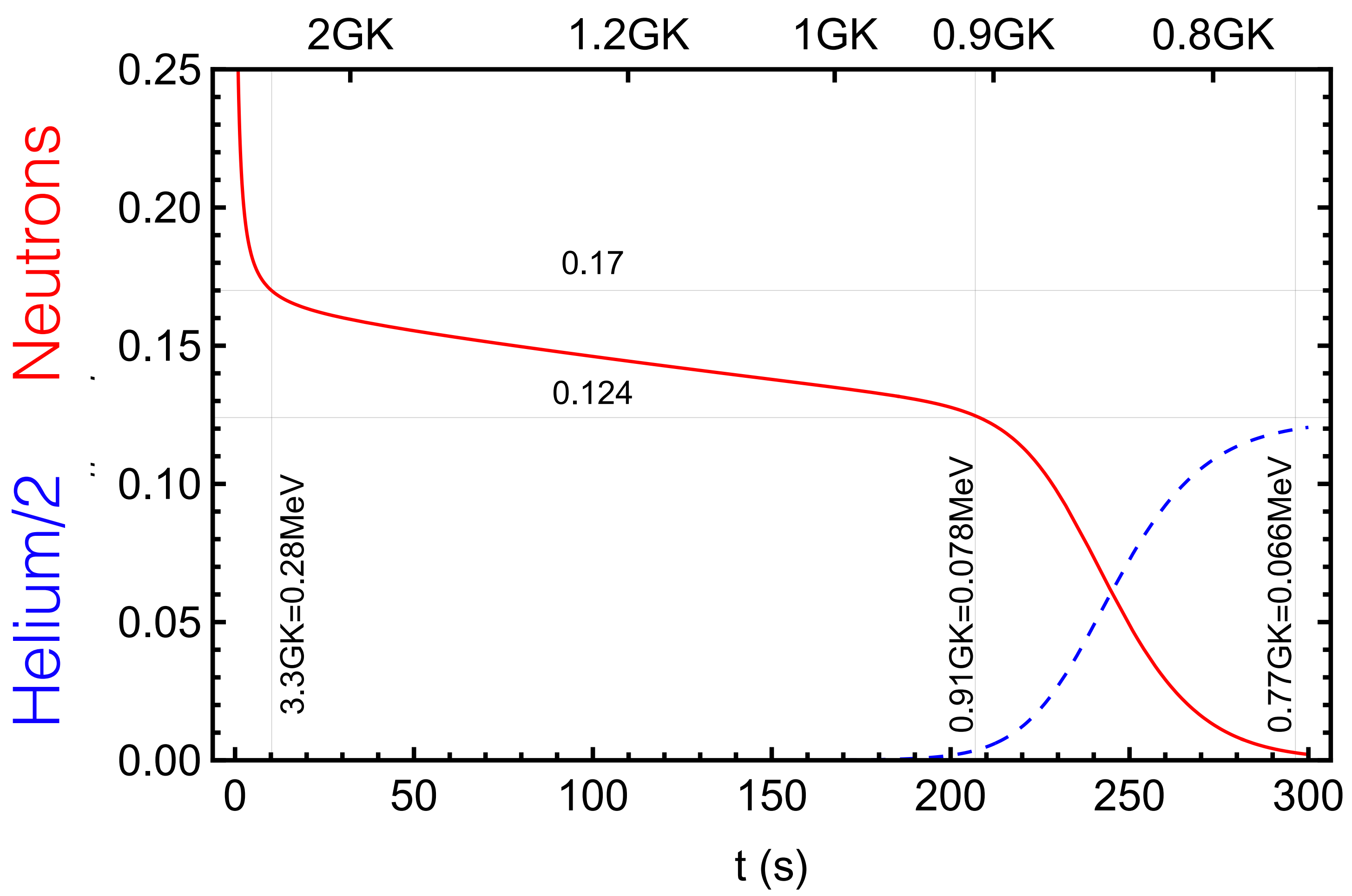

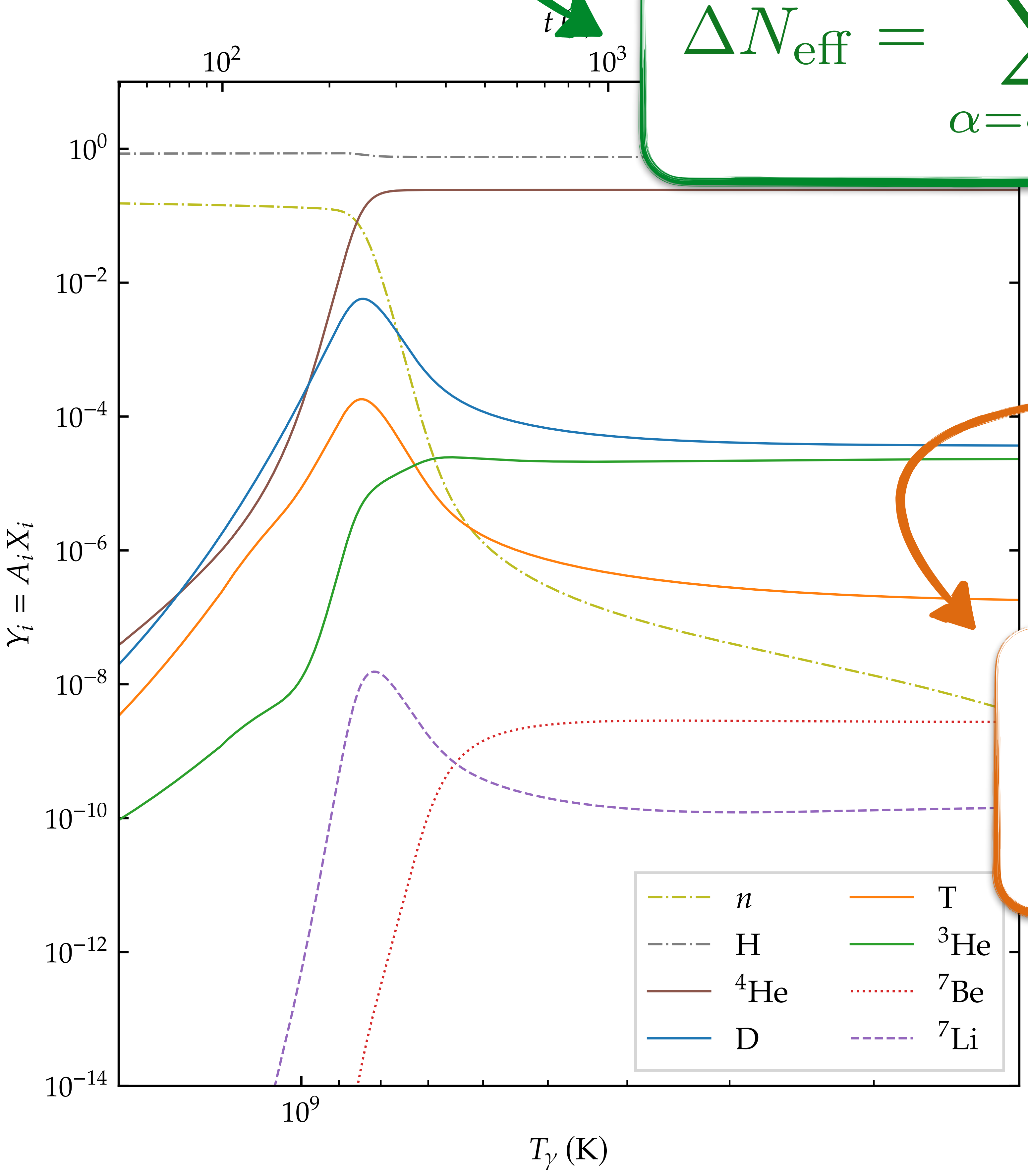

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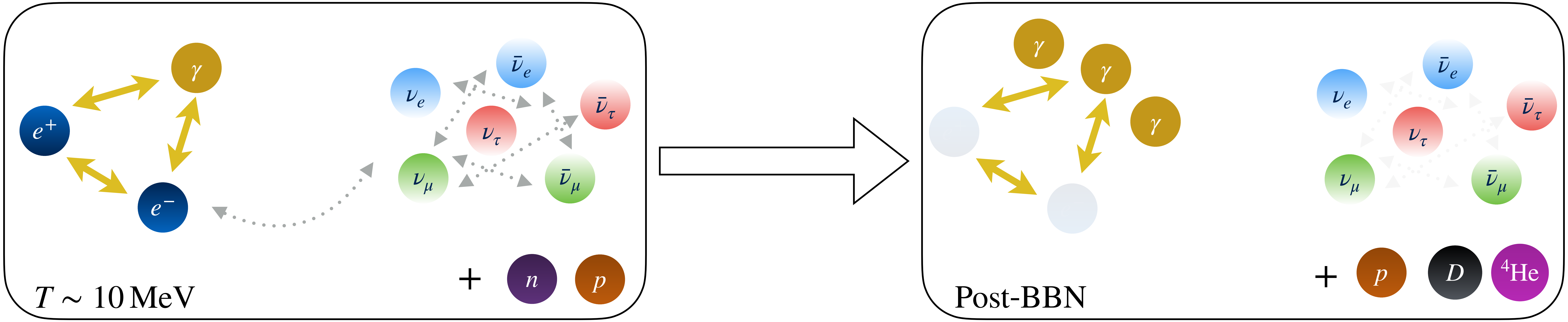
! ξ_α values at BBN

Describing neutrino evolution



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  - Expansion of the Universe
  - Weak interactions of neutrinos
  - Thermodynamics of the electromagnetic plasma

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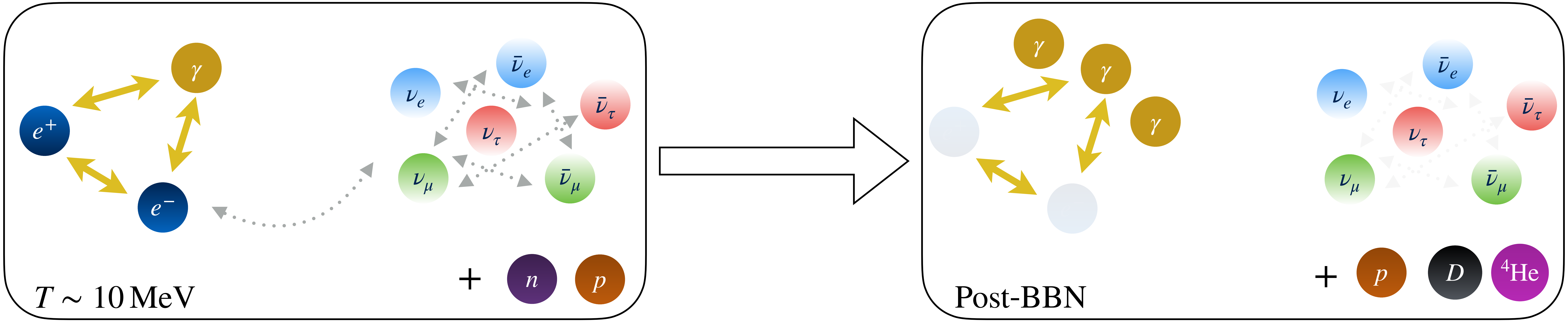

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  - Expansion of the Universe
  - Weak interactions of neutrinos
  - Thermodynamics of the electromagnetic plasma
  - **Neutrino oscillations**

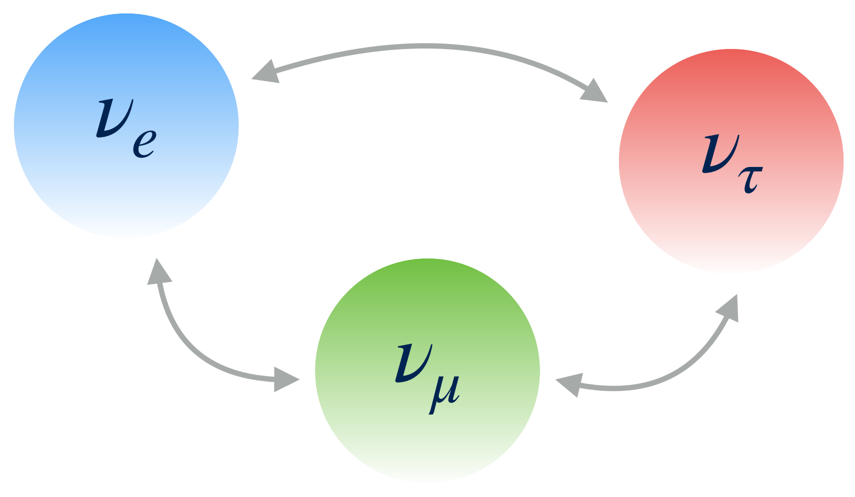
Neutrino flavor oscillations

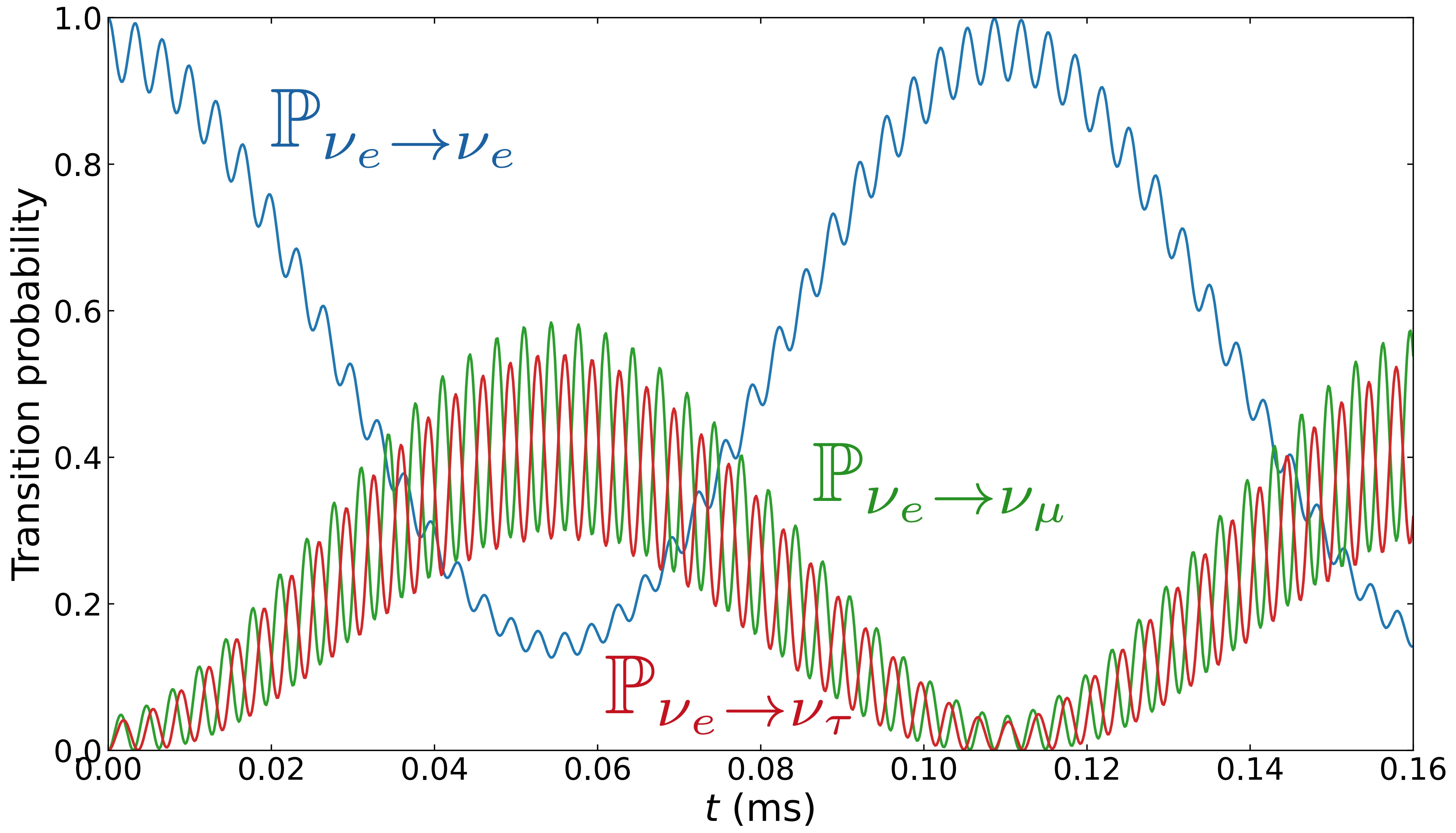
- Standard Model: 3 species of massless neutrinos ν_L
- Experimental evidence in the second half of the 20th century
  $\rightarrow$ massive neutrinos

Flavor states $\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$ Mass states

PMNS mixing matrix

$\Longrightarrow$ neutrino oscillations





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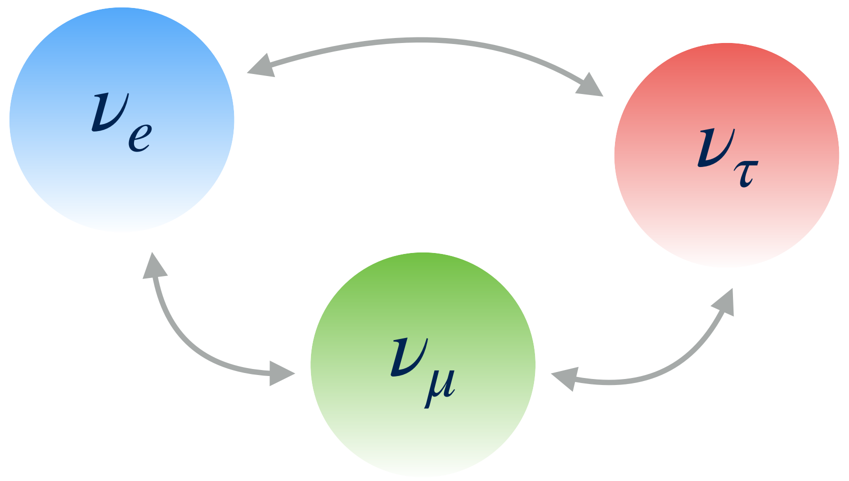
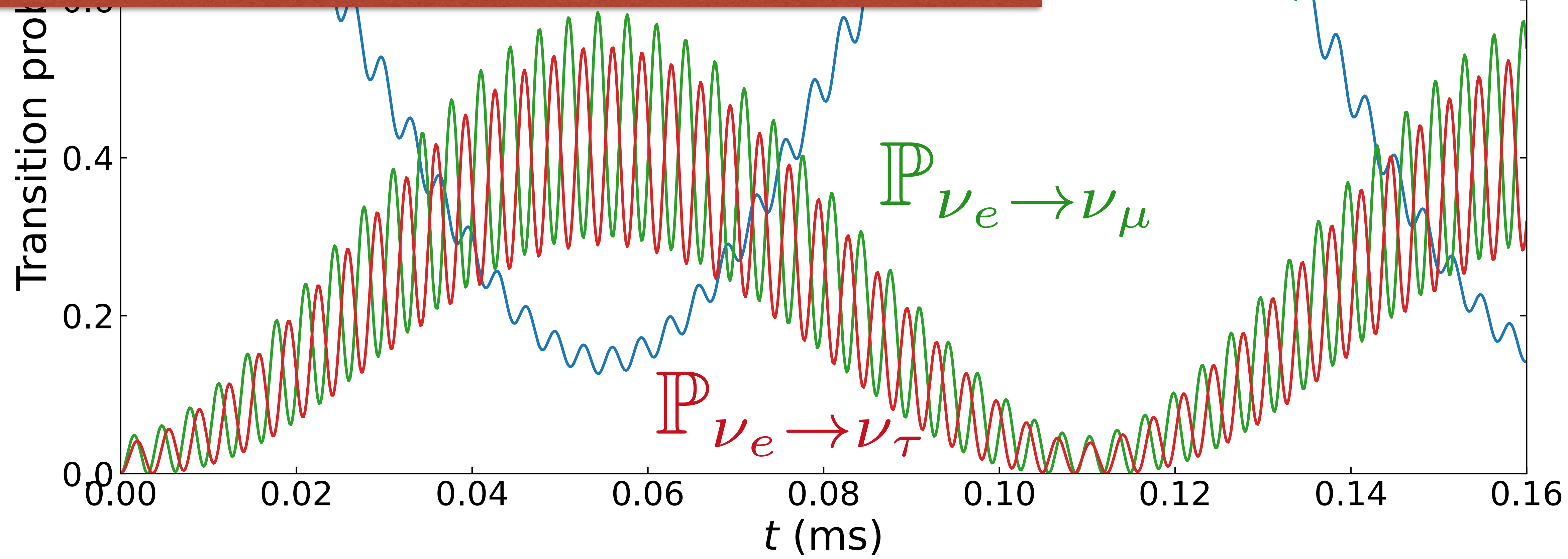
Flavor st … s states

Additional complexity in dense environments:

- Mean-field potential due to **interactions with matter**
- Mean-field potential due to neutrino **self-interactions** (makes the problem non-linear, gives rise to *collective oscillations*)

$\Longrightarrow$ neutrino oscillati





Classical and quantum transport

- Classical neutrino transport:

Boltzmann's equation

Distribution function

Collision term

$$\left(\frac{\partial}{\partial t} - Hp\frac{\partial}{\partial p}\right) f_{\nu_\alpha} = C_{\nu_\alpha}$$

$f_{\nu_\alpha}(\vec{x}, \vec{p}, t)\, \mathrm{d}^3\vec{x}\, \mathrm{d}^3\vec{p}$

Number of neutrinos of flavor α at position $\vec{x}$ with momentum $\vec{p}$

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- Quantum neutrino transport:

One-body density matrix

$$\varrho = \begin{pmatrix} \varrho_{ee} & \varrho_{e\mu} & \varrho_{e\tau} \\ \varrho^*_{e\mu} & \varrho_{\mu\mu} & \varrho_{\mu\tau} \\ \varrho^*_{e\tau} & \varrho^*_{\mu\tau} & \varrho_{\tau\tau} \end{pmatrix} = \begin{pmatrix} \text{Distrib. function of } \nu_e & & \text{Flavor coherences} \\ & \text{Distrib. function of } \nu_\mu & \\ \text{Flavor coherences} & & \text{Distrib. function of } \nu_\tau \end{pmatrix}$$

Quantum Kinetic Equation

$$\left(\frac{\partial}{\partial t} - Hp\frac{\partial}{\partial p}\right) \varrho = -i\left[\mathcal{H},\varrho\right] + \mathcal{C}$$

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Collisions

Vacuum term + mean-field potentials

$$\mathcal{H}_{\nu\nu} \propto \int (\varrho - \bar{\varrho})$$

Neutrino transport in the early Universe

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

JF, C. Pitrou, M.C. Volpe [2008.01074]
J. Bennett *et al.* [2012.02726]

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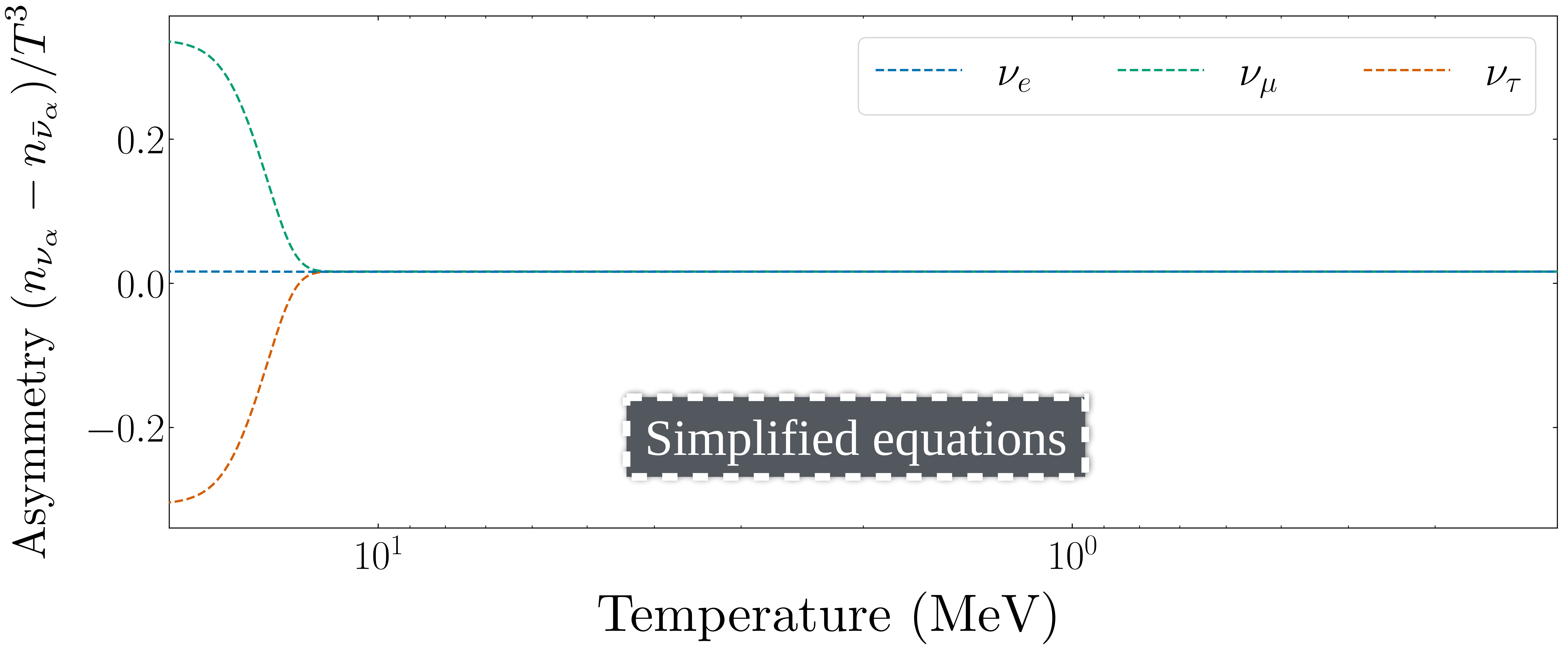
- Extension to the case of **nonzero neutrino/antineutrino asymmetries**

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



Neutrino transport in the early Universe

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

JF, C. Pitrou, M.C. Volpe [2008.01074]
J. Bennett *et al.* [2012.02726]

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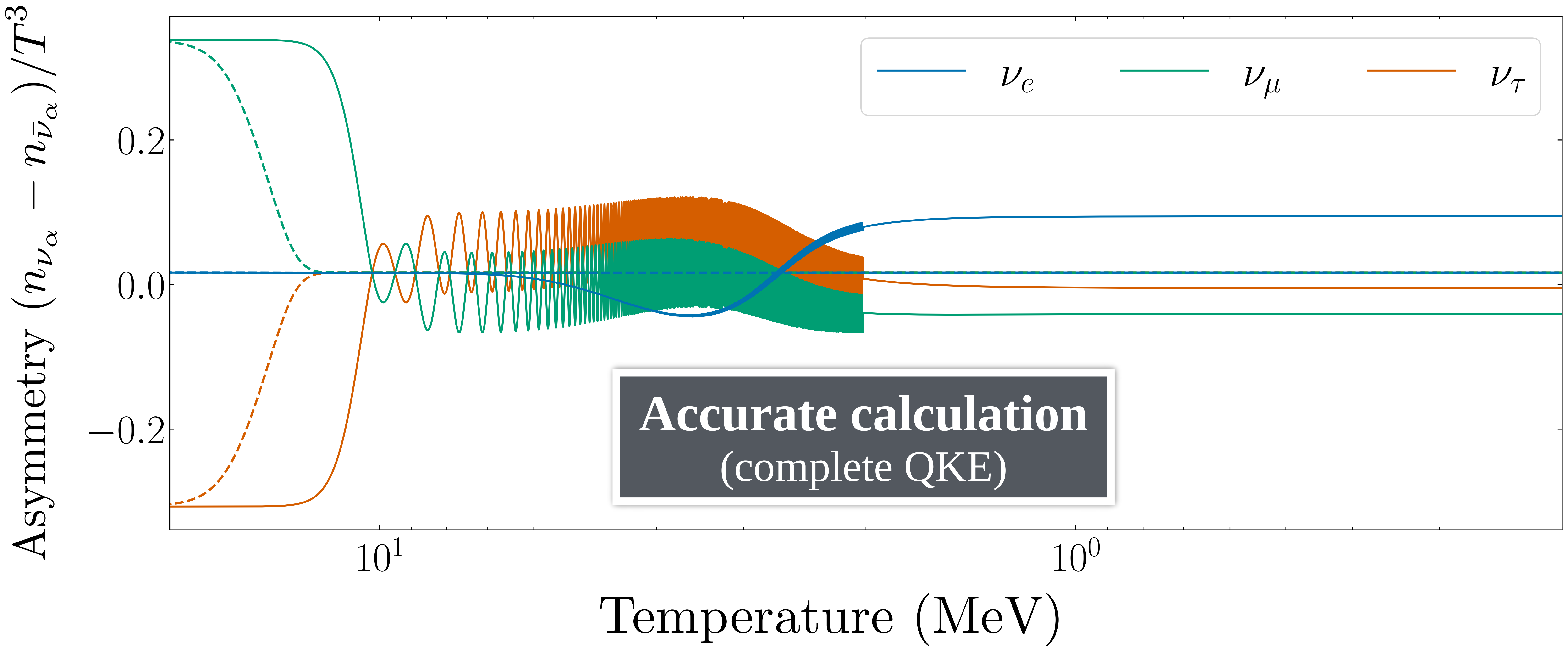

JF, C. Pitrou [2110.11889]
JF, C. Pitrou [2405.06509]

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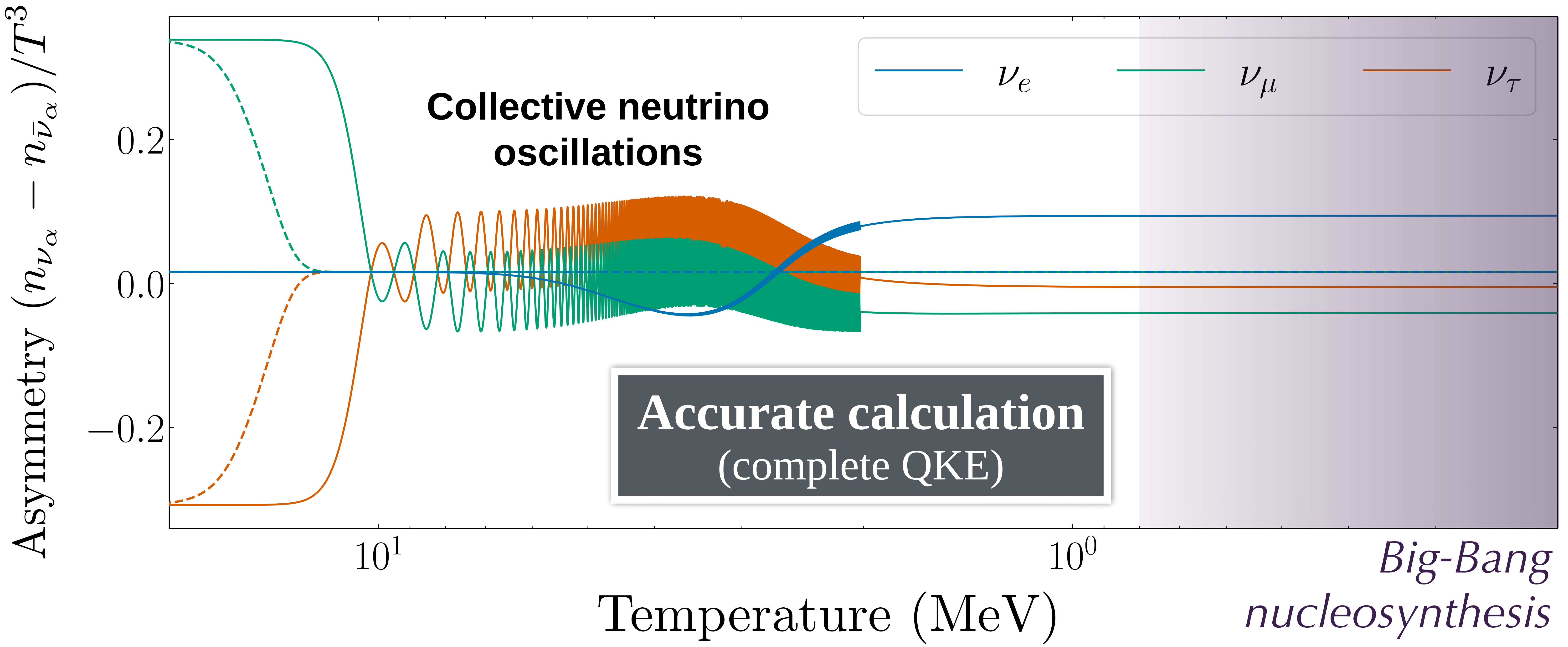
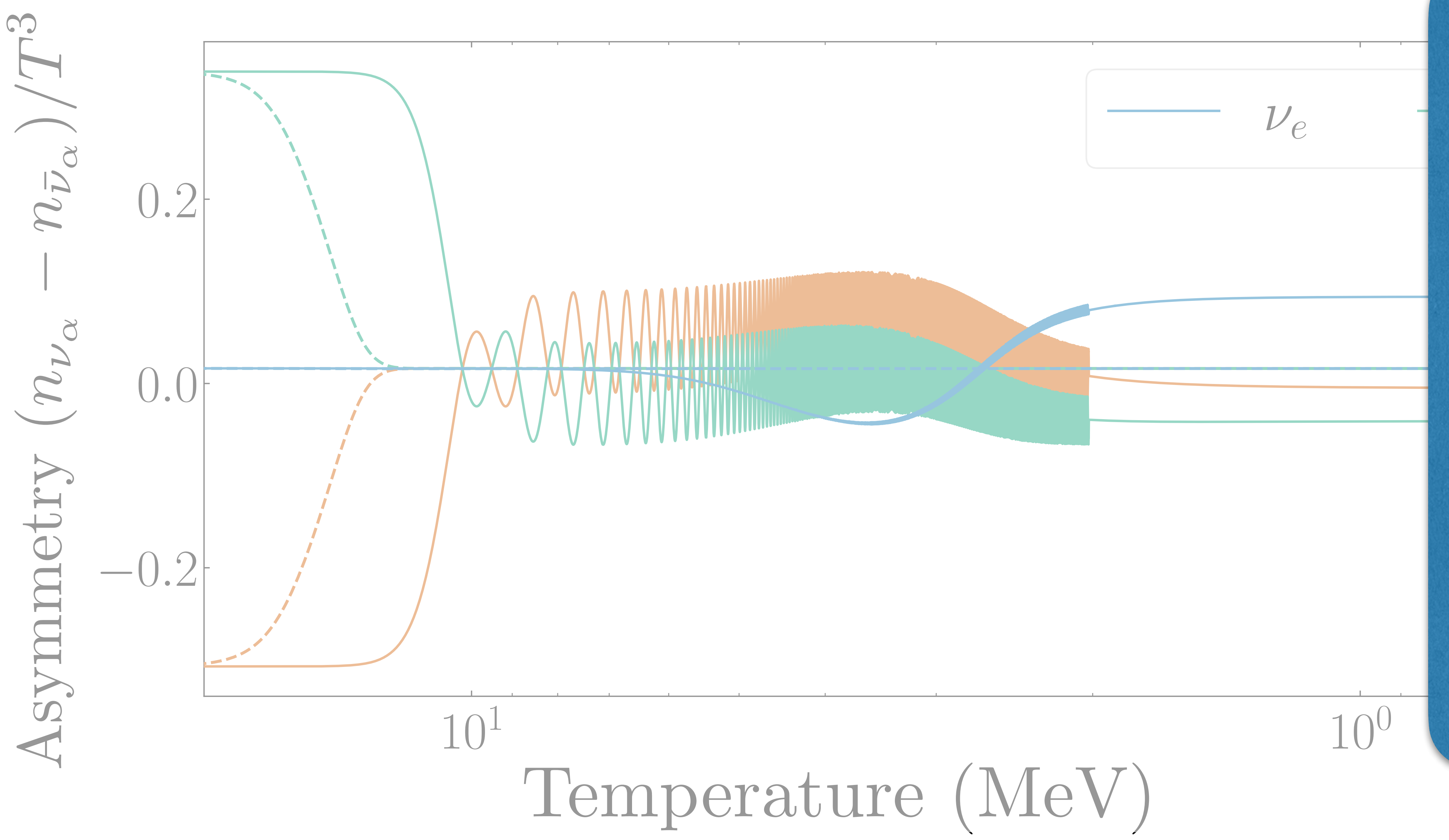


Constraining primordial neutrino asymmetries



Asymmetries at the BBN epoch

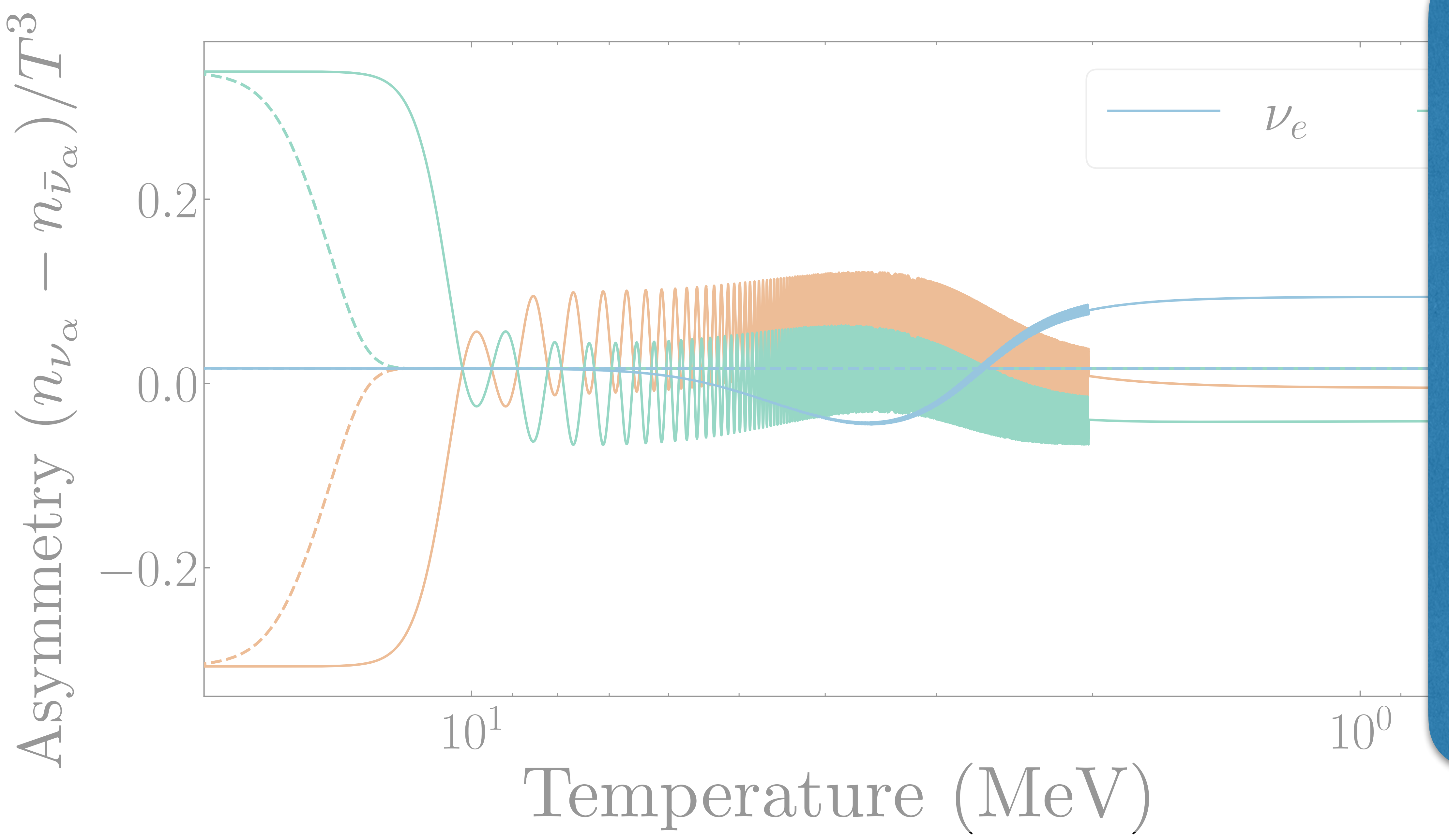
Constraining primordial neutrino asymmetries

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]

⇩

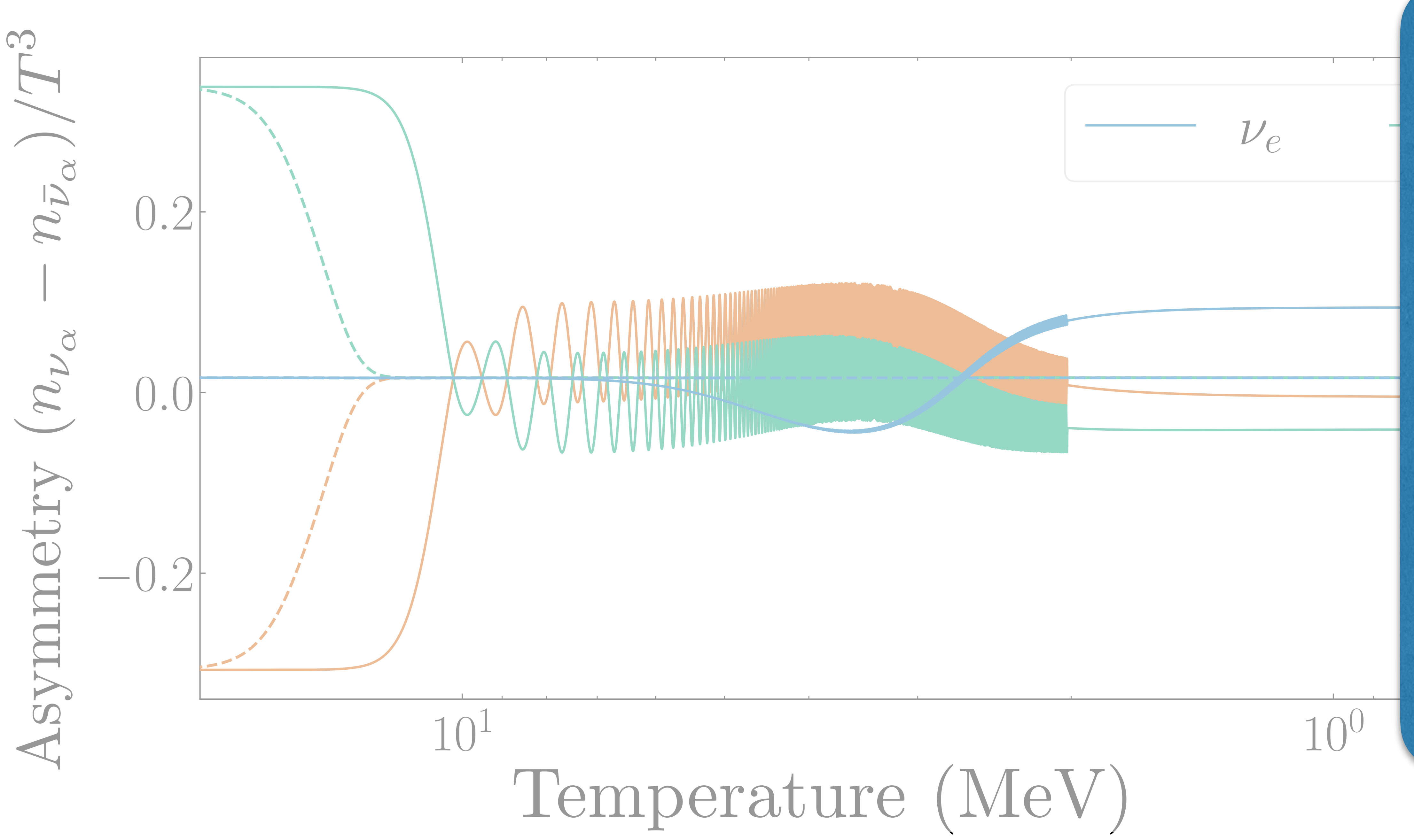
Primordial abundances

(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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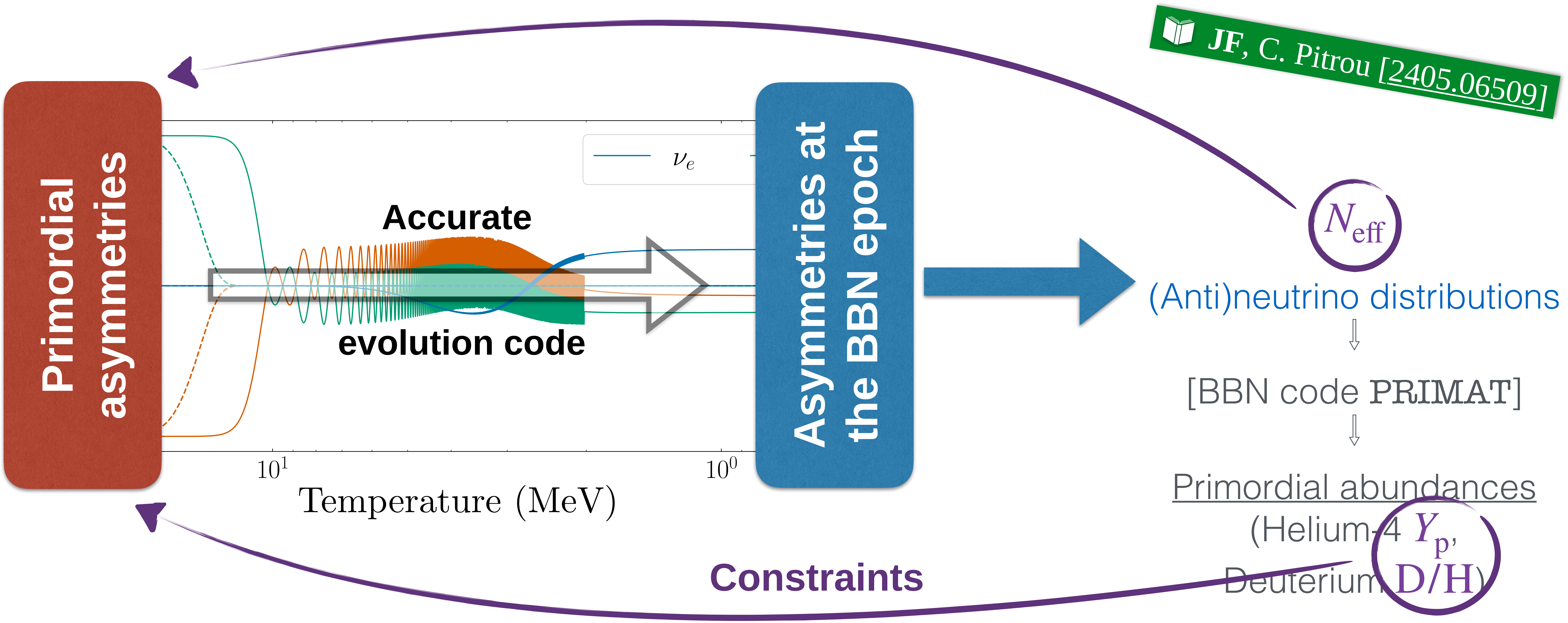
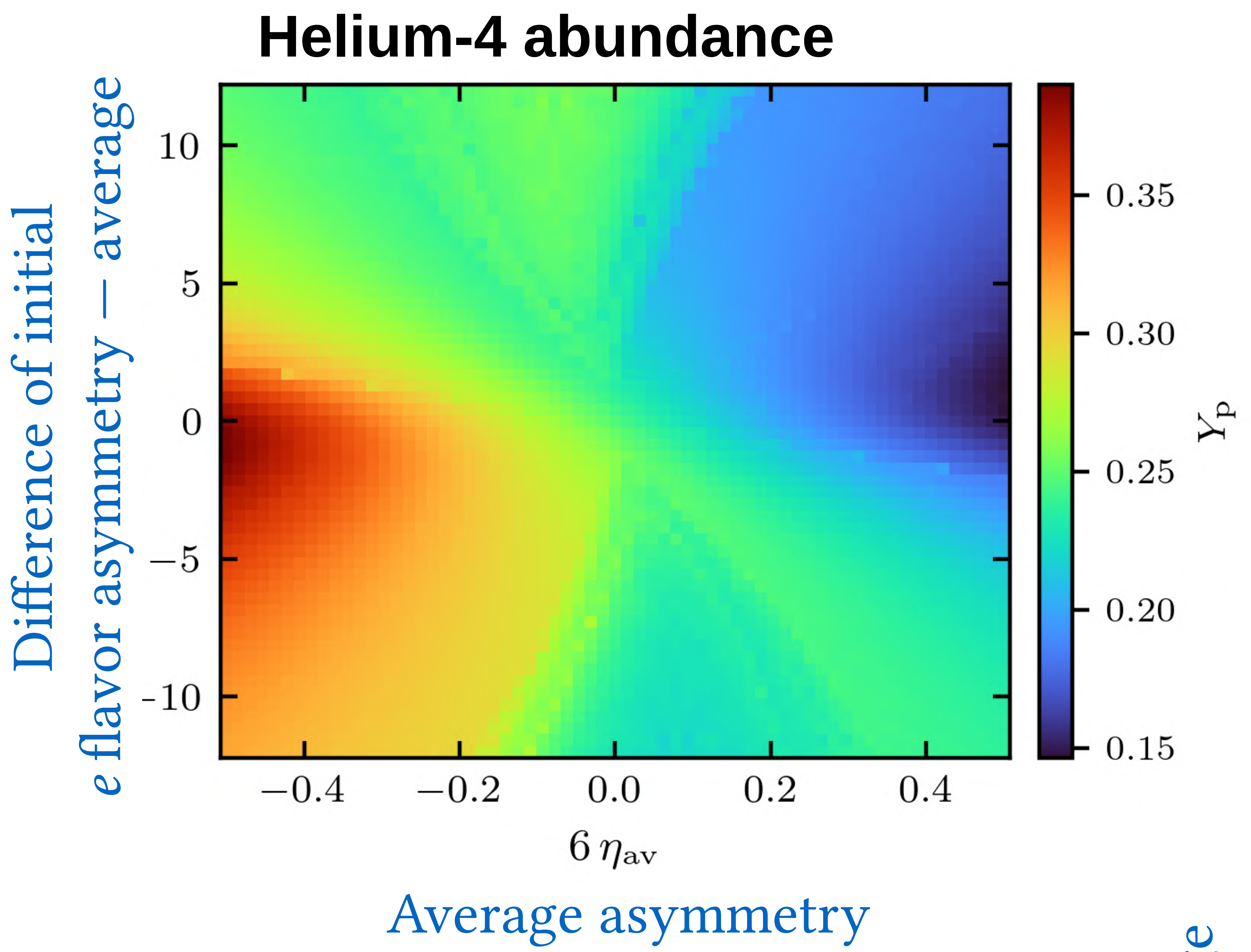
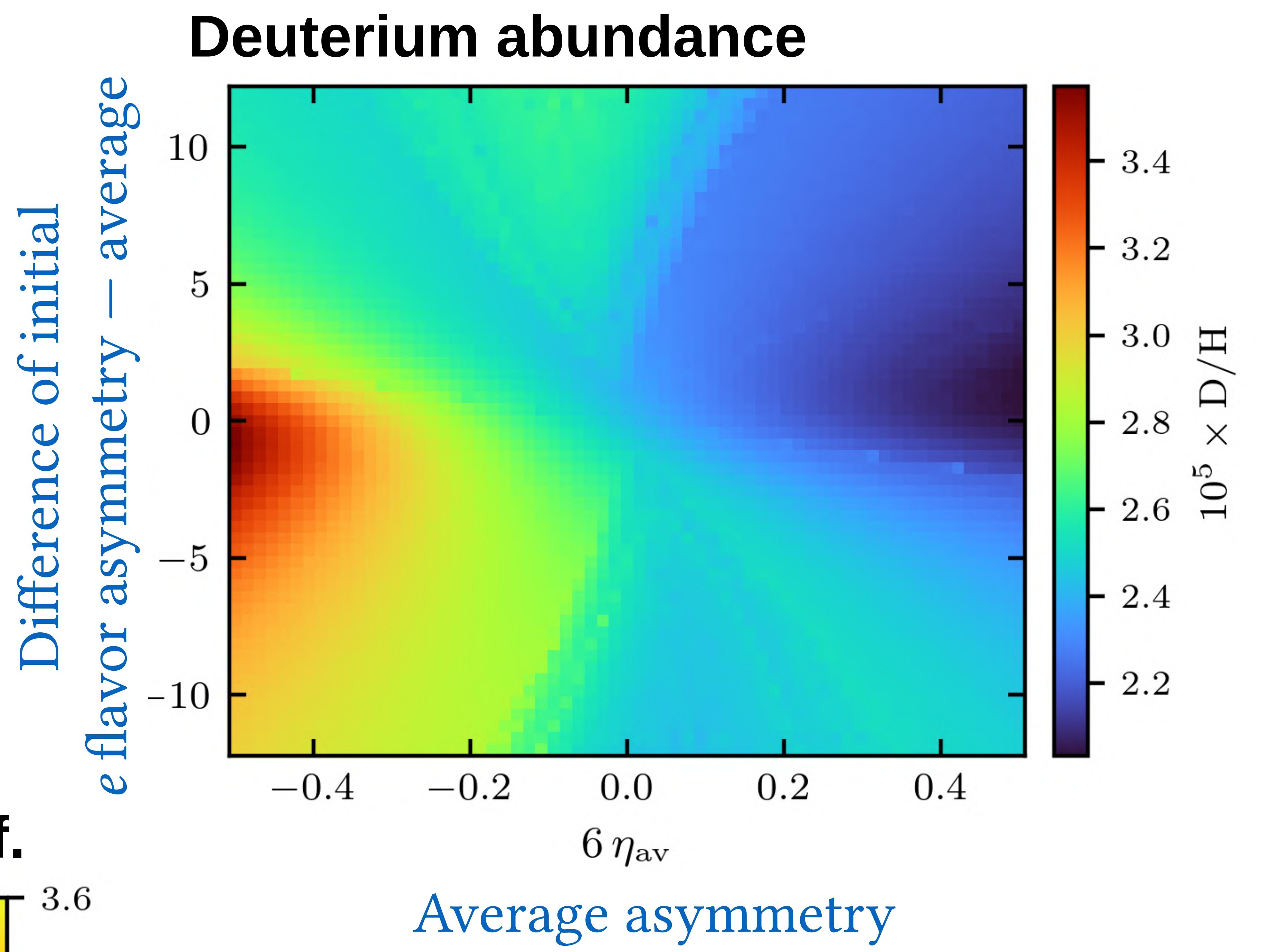
Constraining primordial neutrino asymmetries

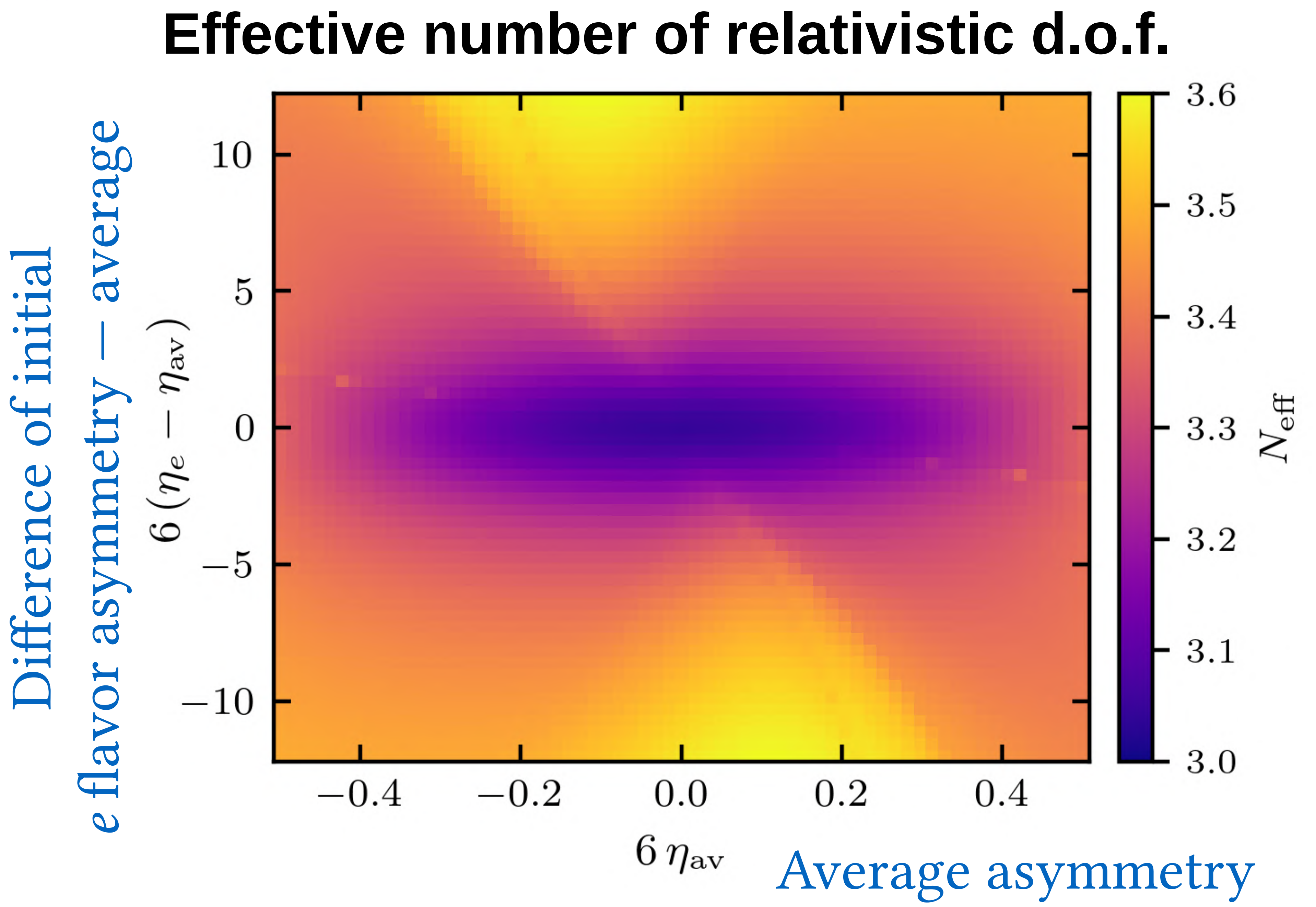


Output of neutrino + BBN calculation

$\eta_\mu = \eta_\tau$







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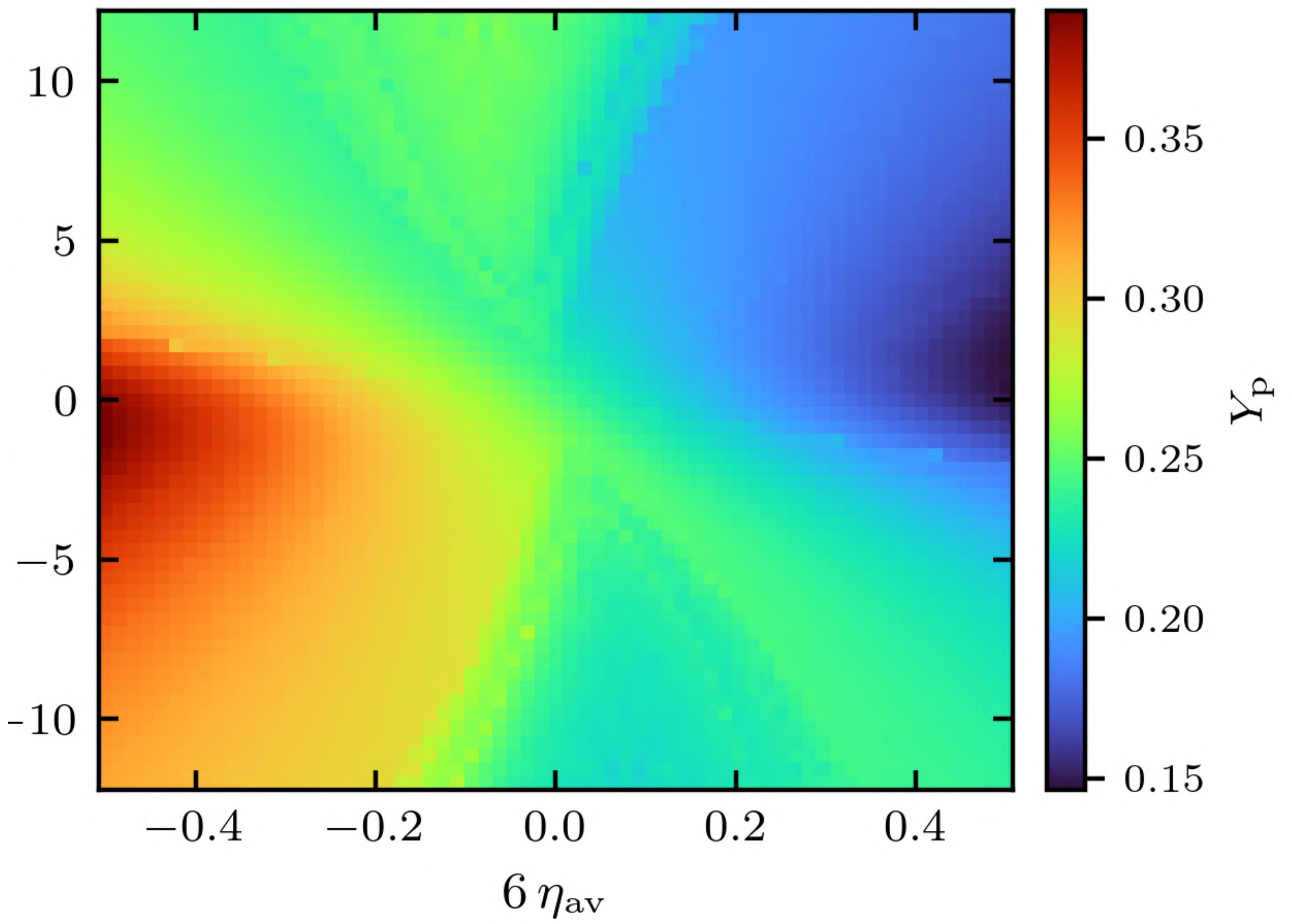
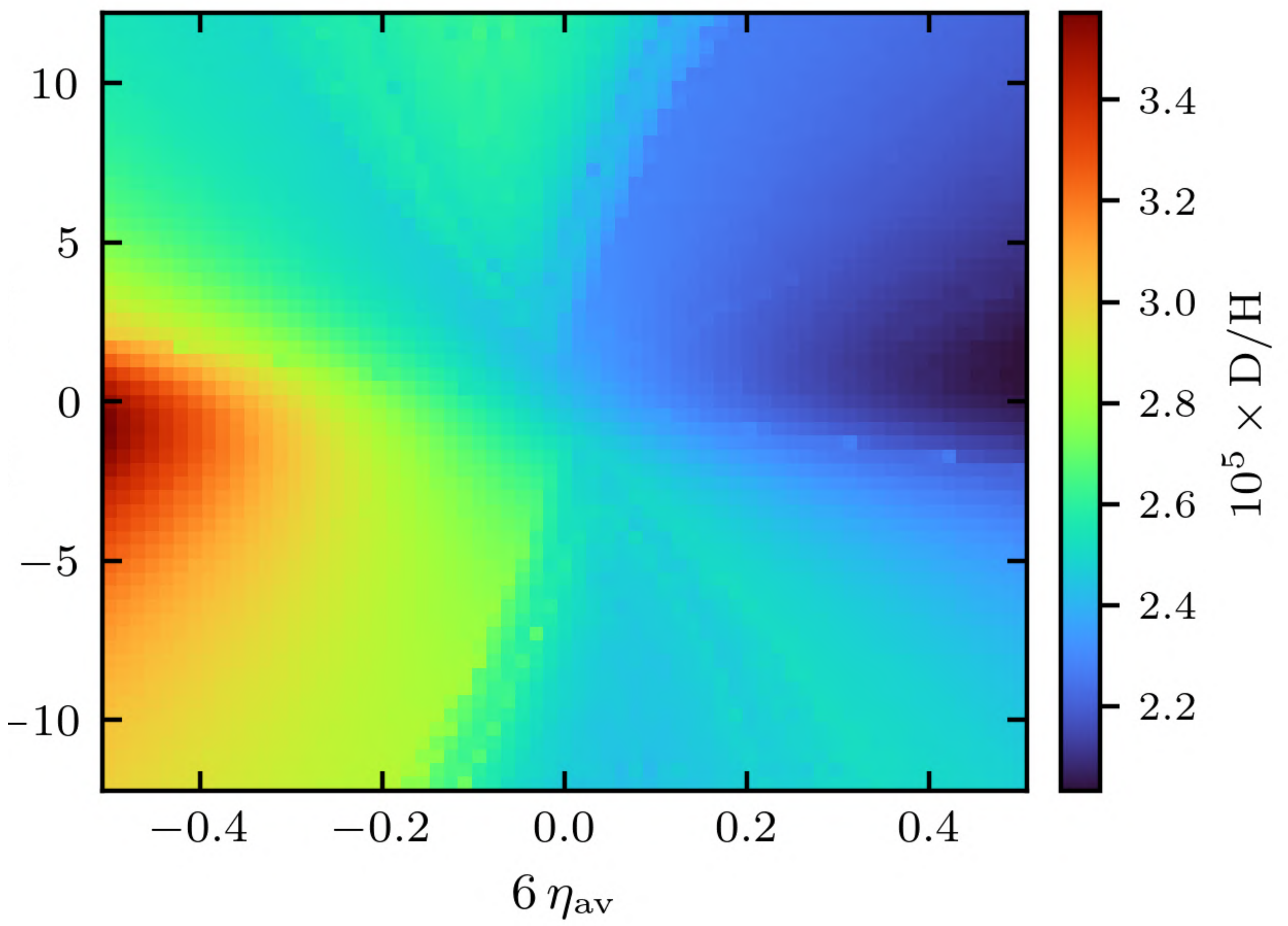
Helium-4 abundance



Difference of initial *e* flavor asymmetry − average

Average asymmetry

Deuterium abundance



Difference of initial *e* flavor asymmetry − average

Average asymmetry

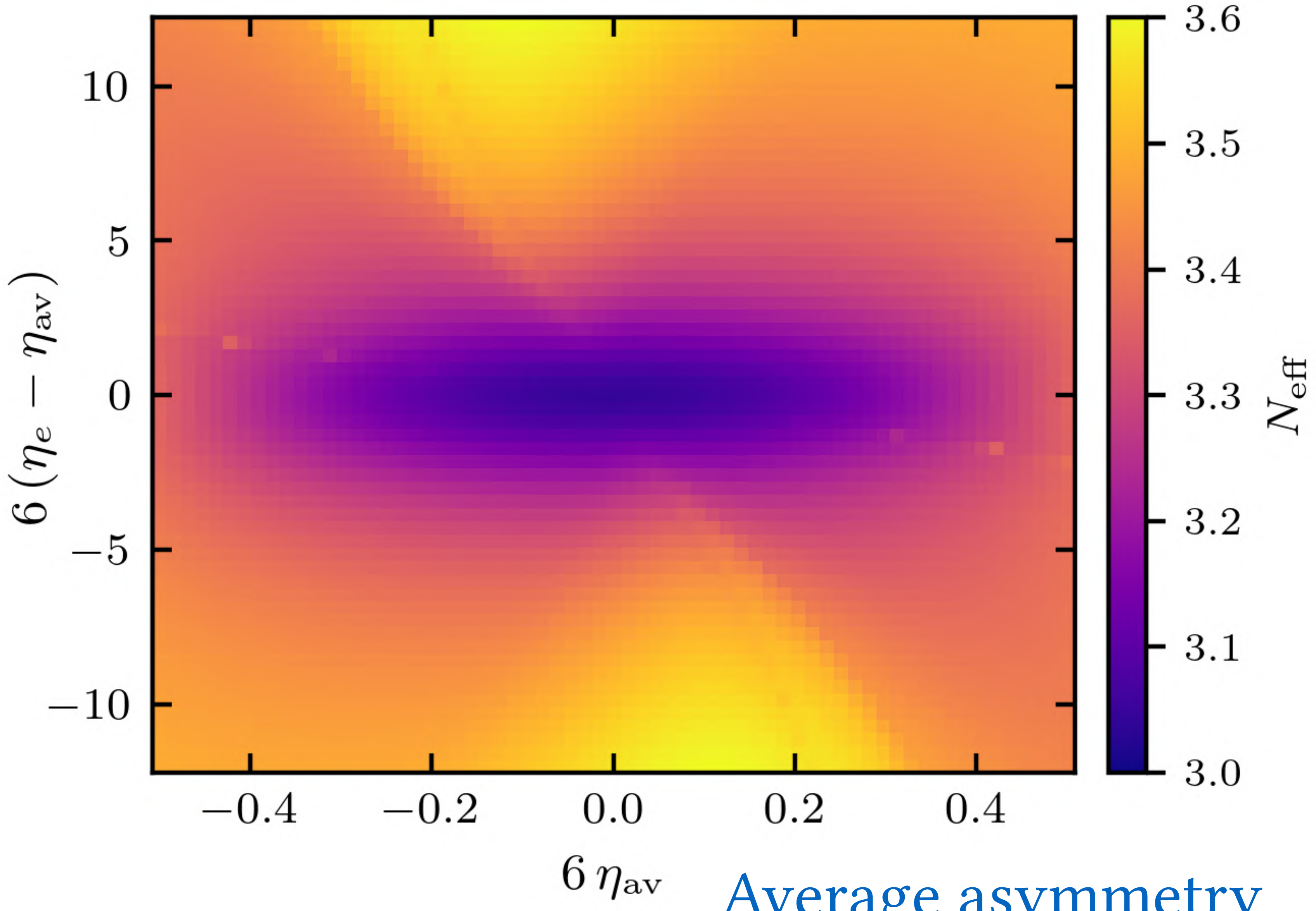
Spectroscopic measurements

$Y_p = 0.2453 \pm 0.0034$

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

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)

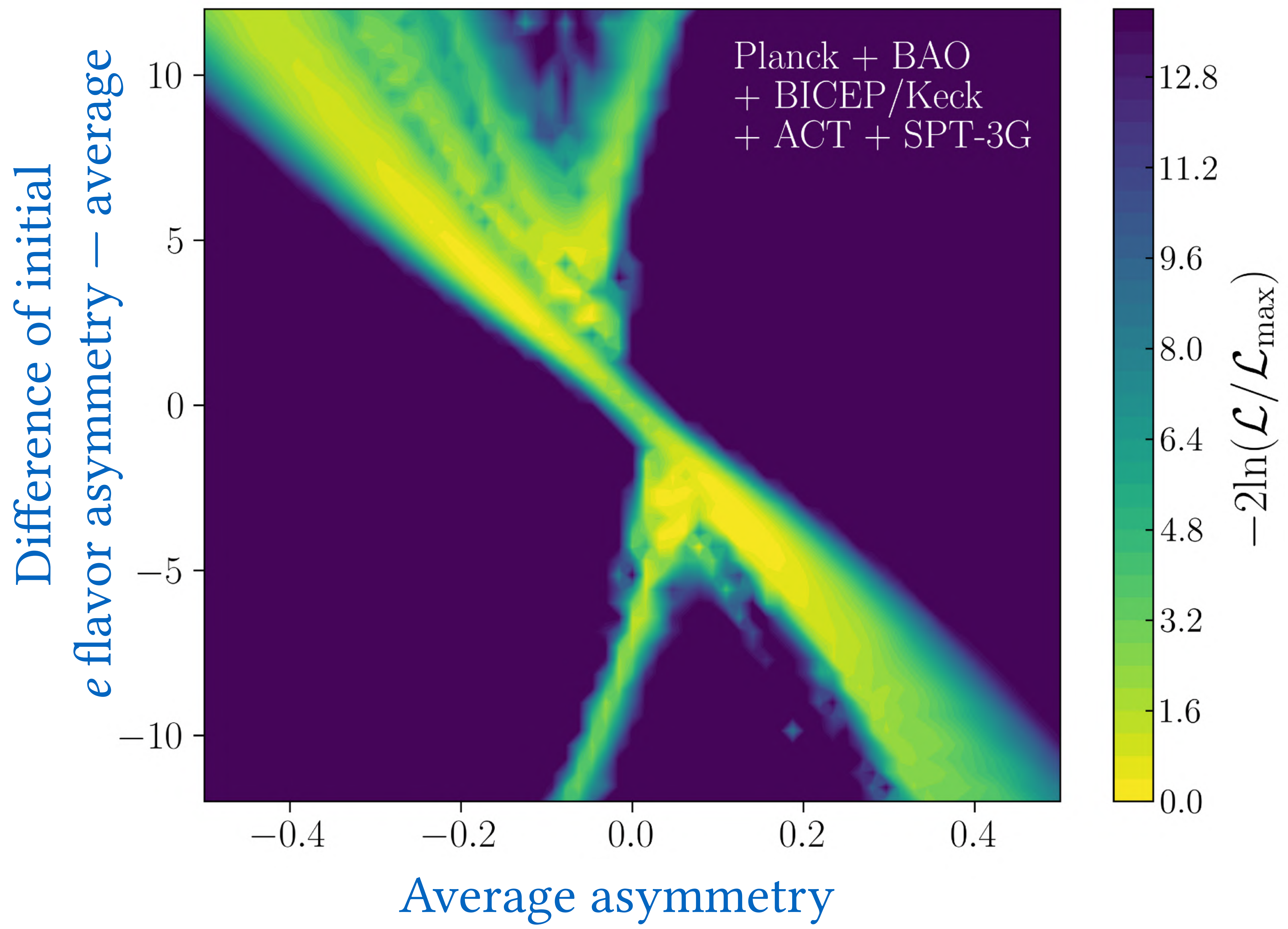
$N_{\mathrm{eff}} = 2.99 \pm 0.24 \quad (68\,\%)$

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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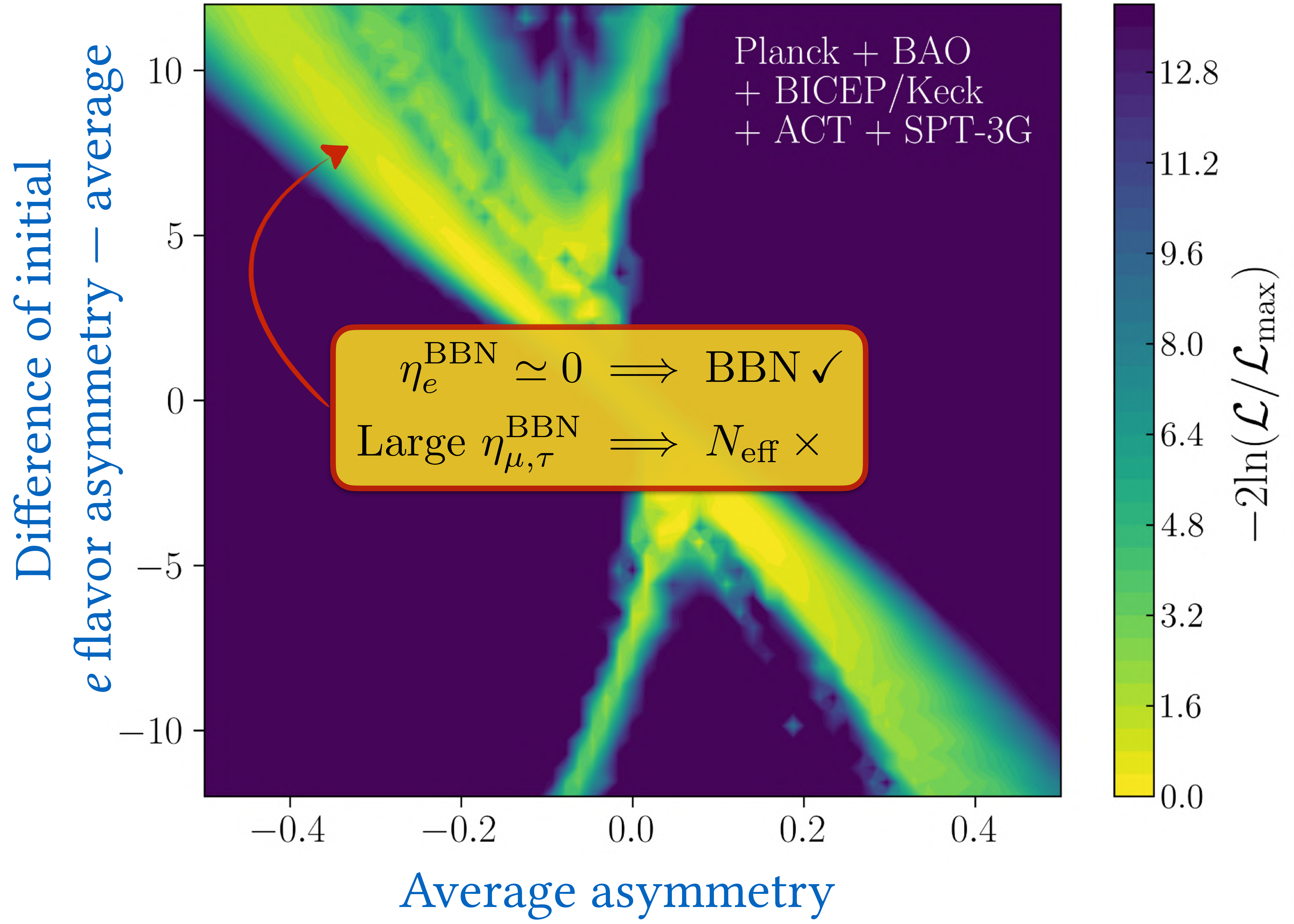

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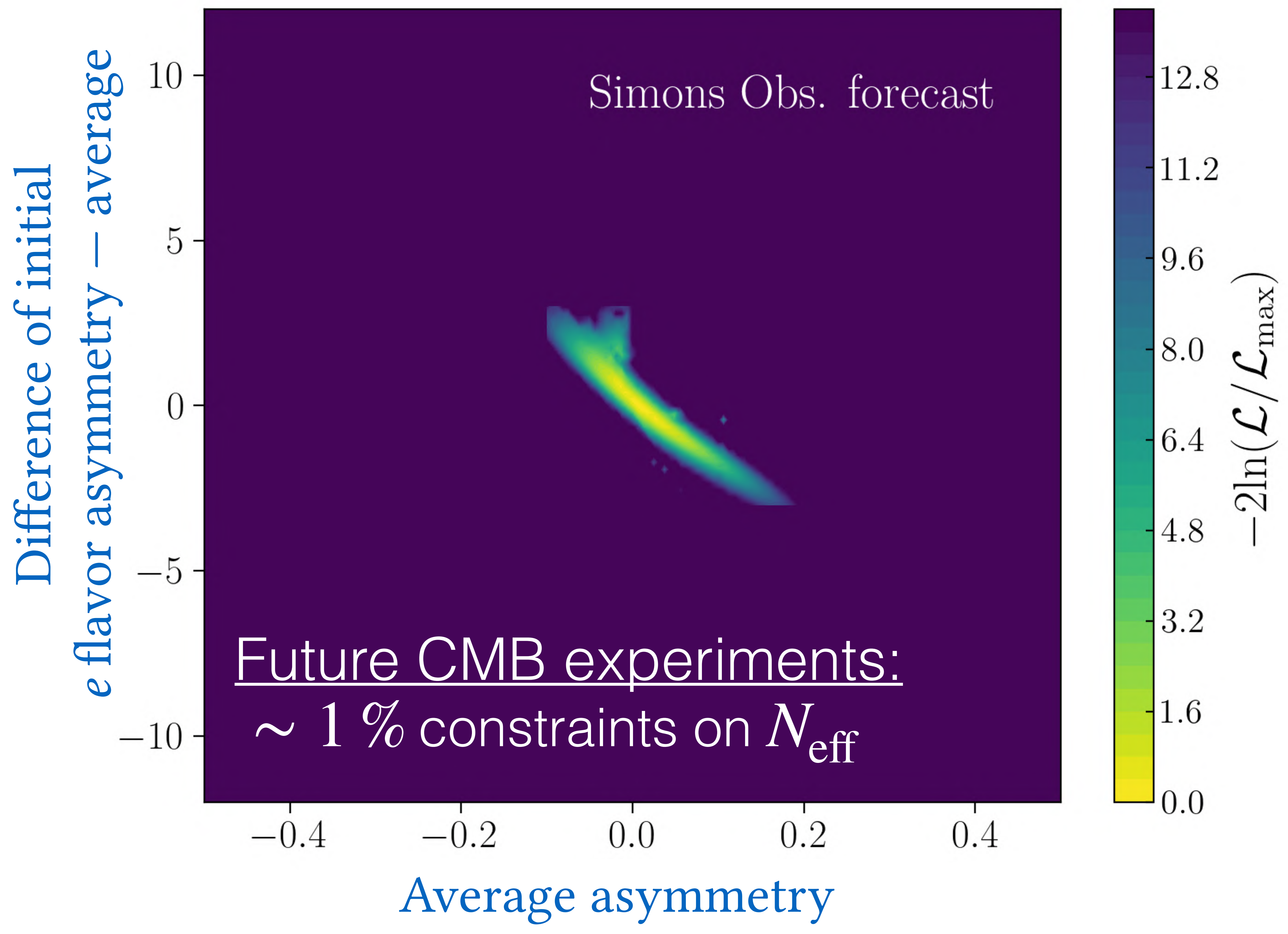

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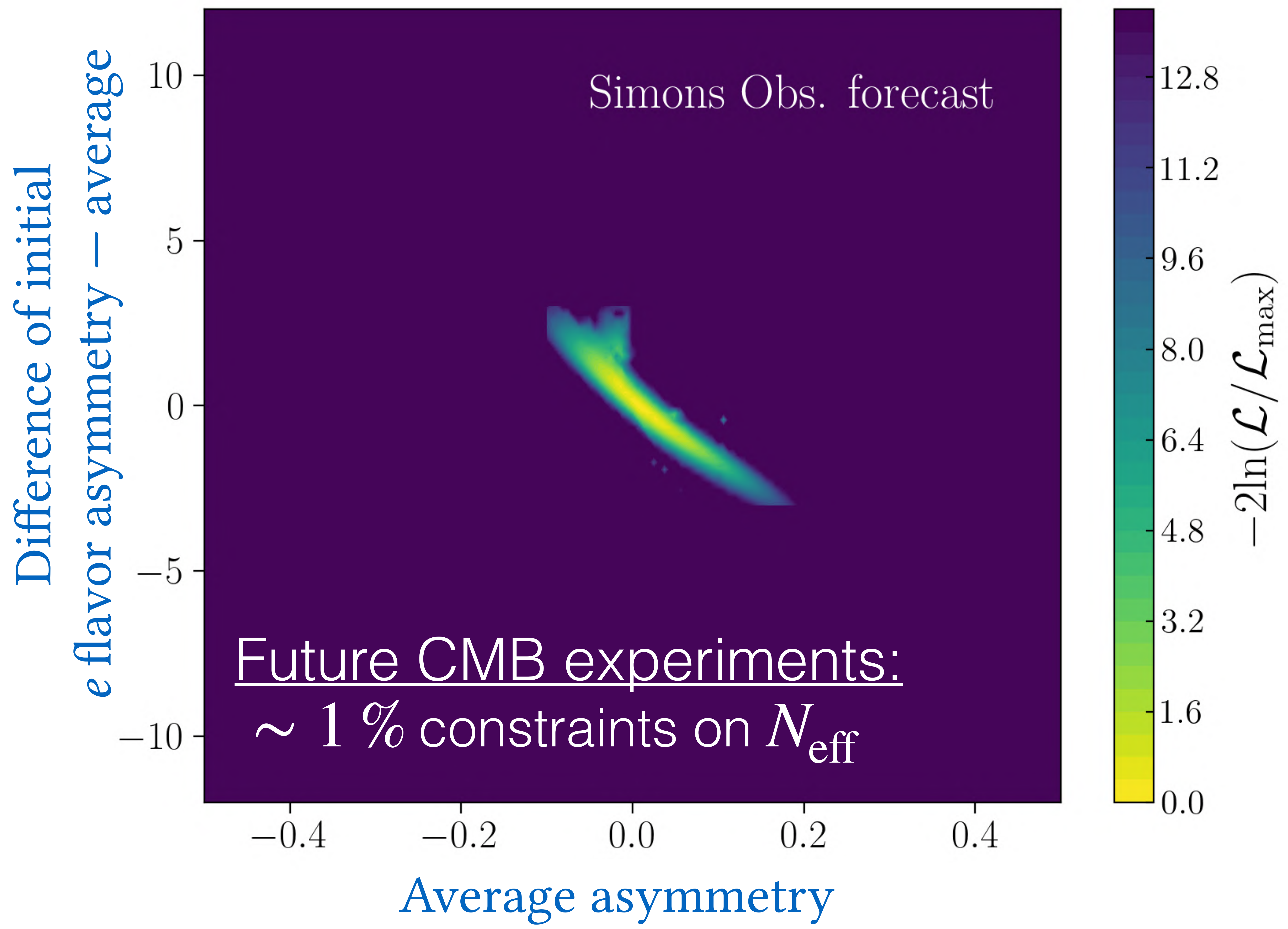

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D. Gorbunov, D. Kalashnikov and G. Krugan [2502.17374]
C. Vogel, H. Escudero, **JF** and K. Abazajian [2507.18752]
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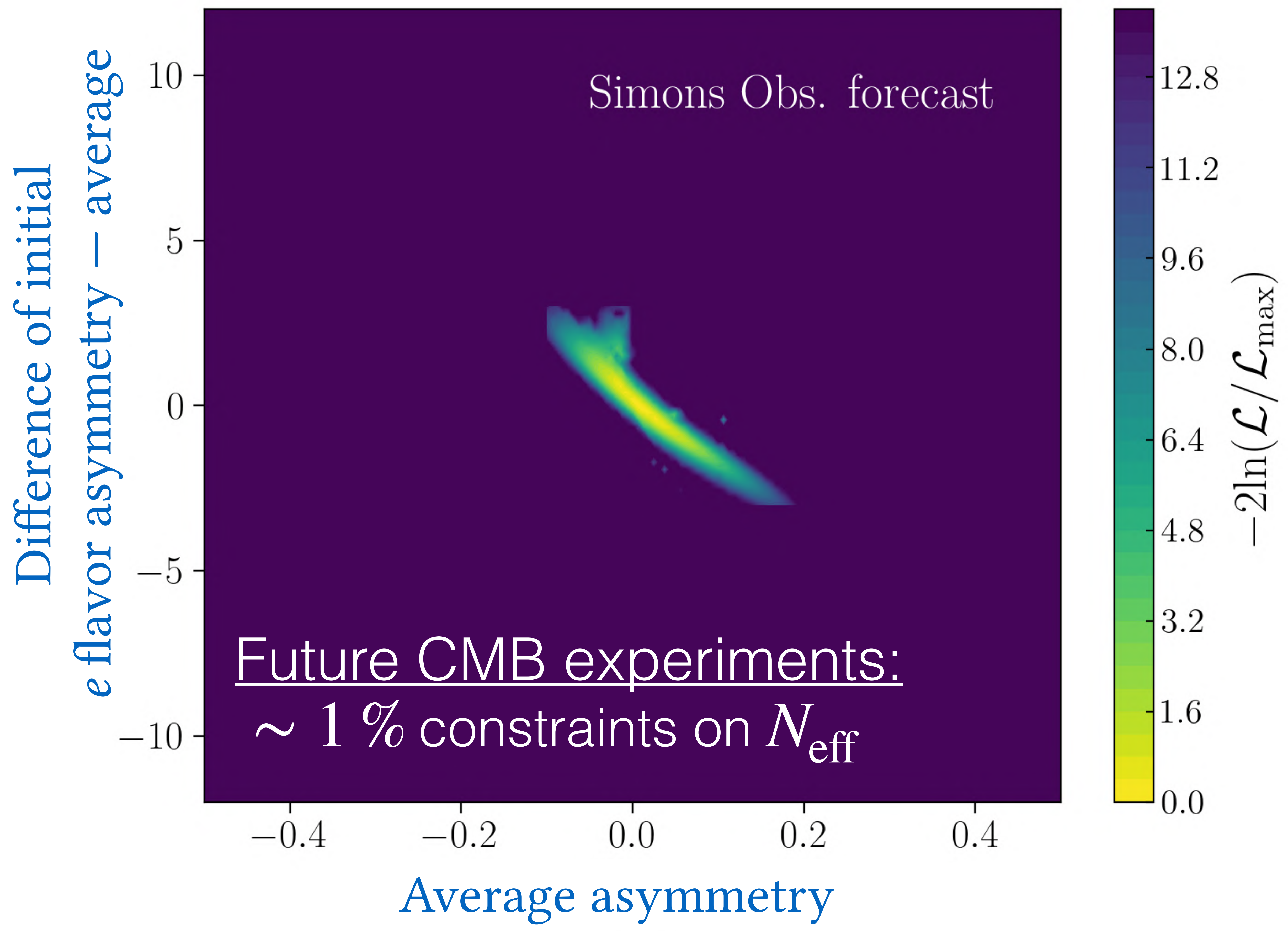

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- Nonzero asymmetries leave an imprint on the equation of state (EoS) of the Universe, which in turn affect the **production of primordial black holes**.

D. Bödeker *et al.* [2502.17374]
M. Gonin, **JF** *et al.* [2608.22240]

2. Large lepton number and sterile neutrino dark matter

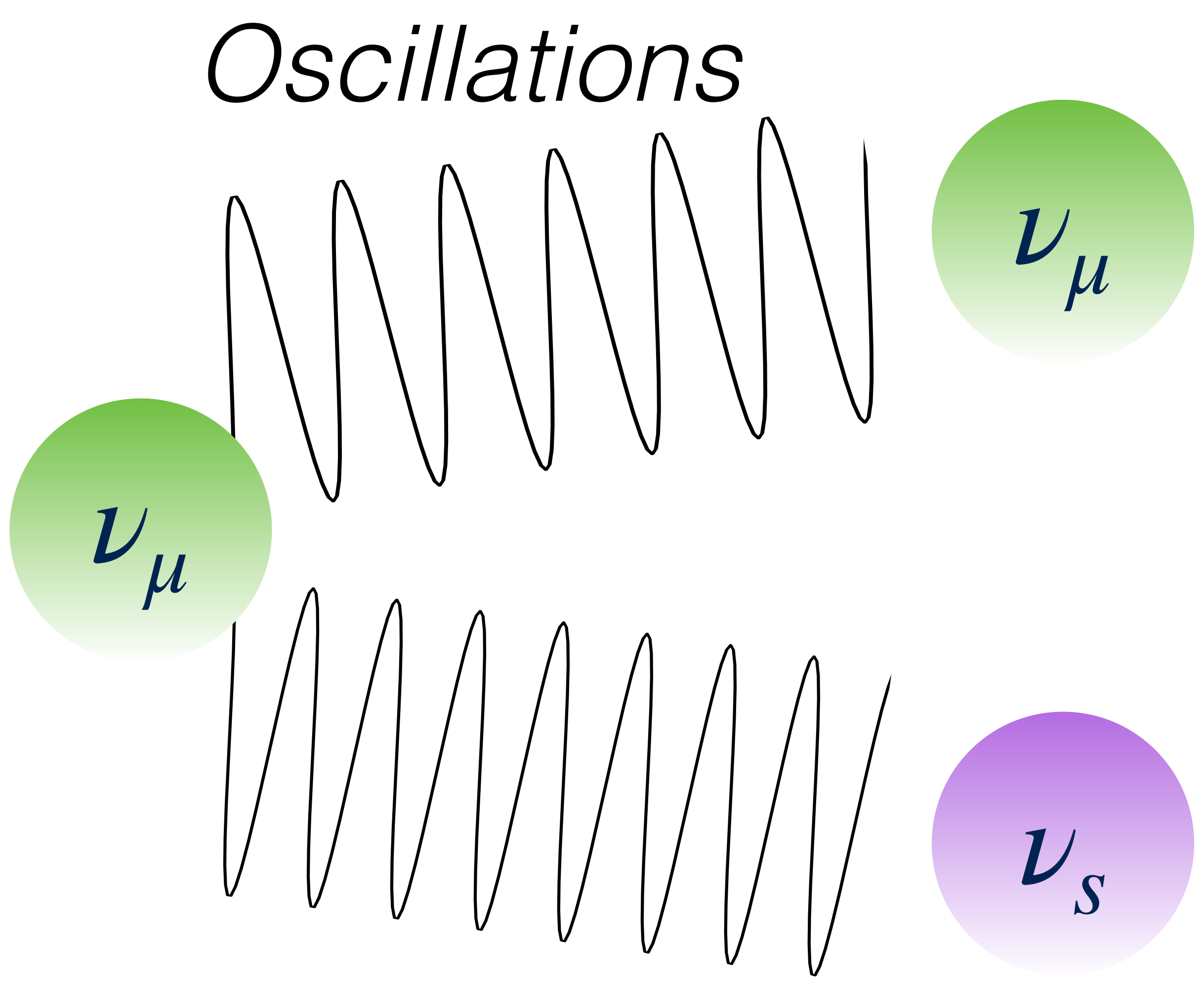
<u>Based on:</u>

C. Vogel, H. Escudero, K. Abazajian and **JF**,
Phys. Rev. D **112**, 123508 (2025) [2507.18752]

Sterile neutrino dark matter production

ν_μ

Sterile neutrino dark matter production



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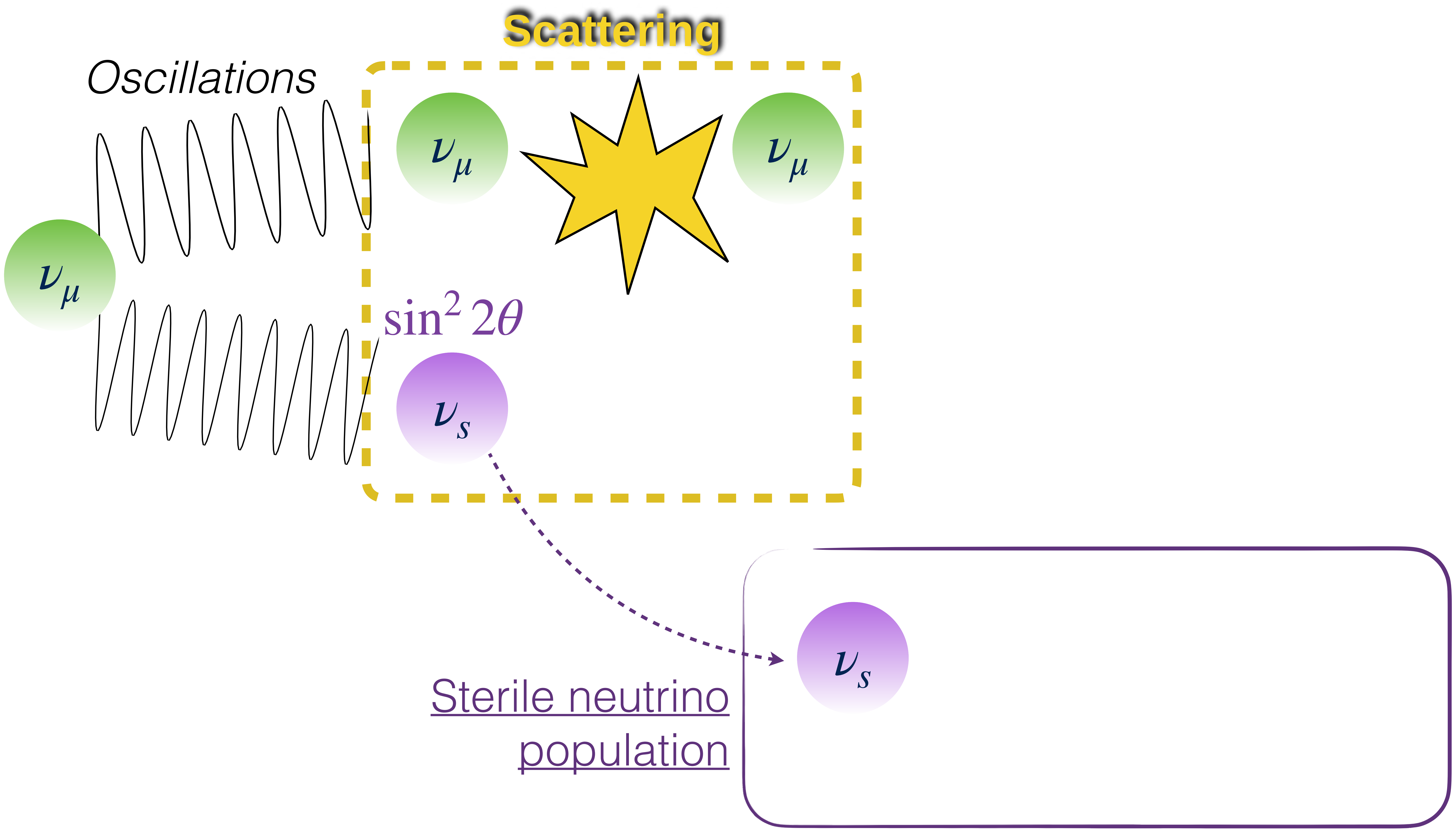

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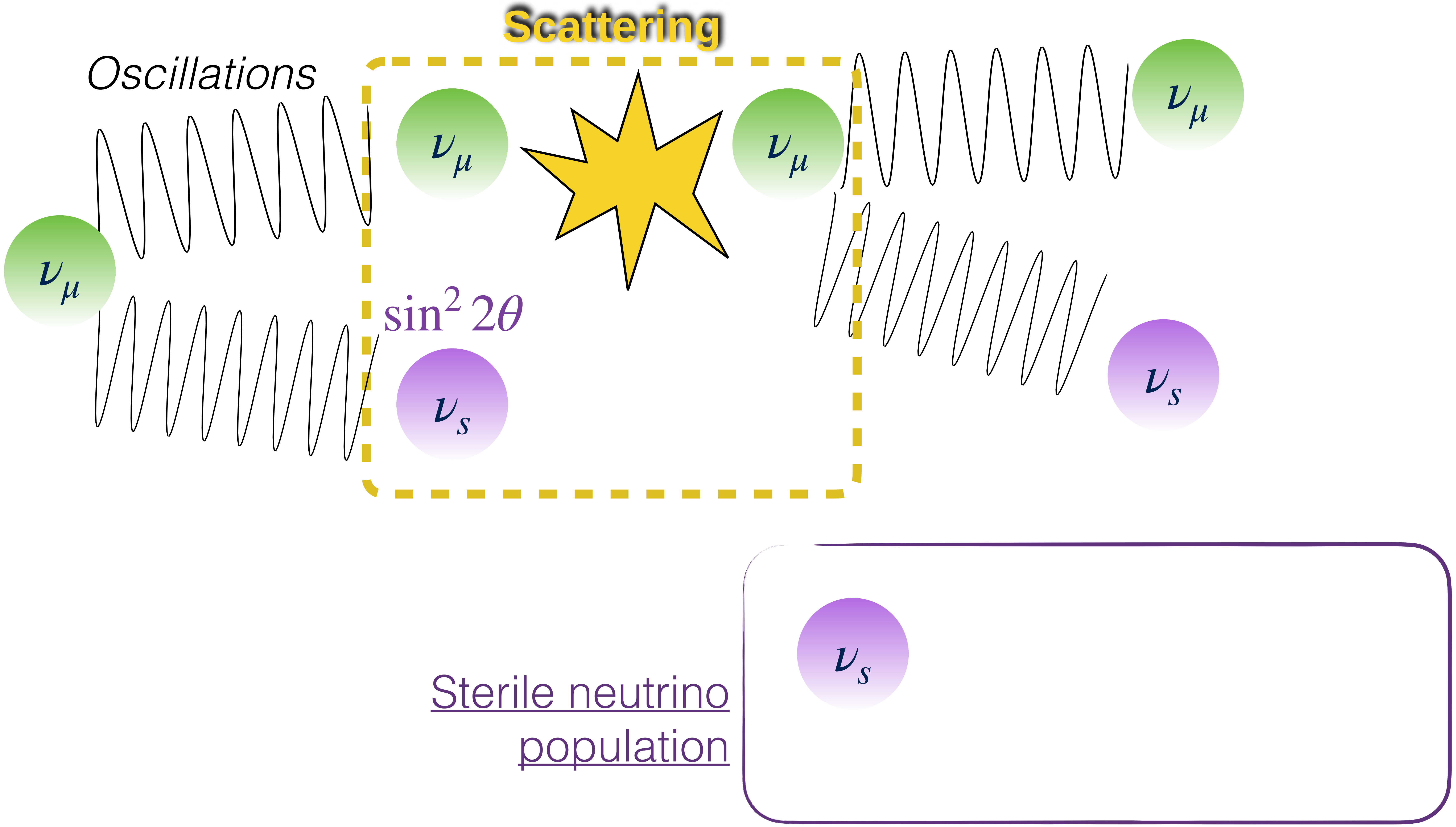

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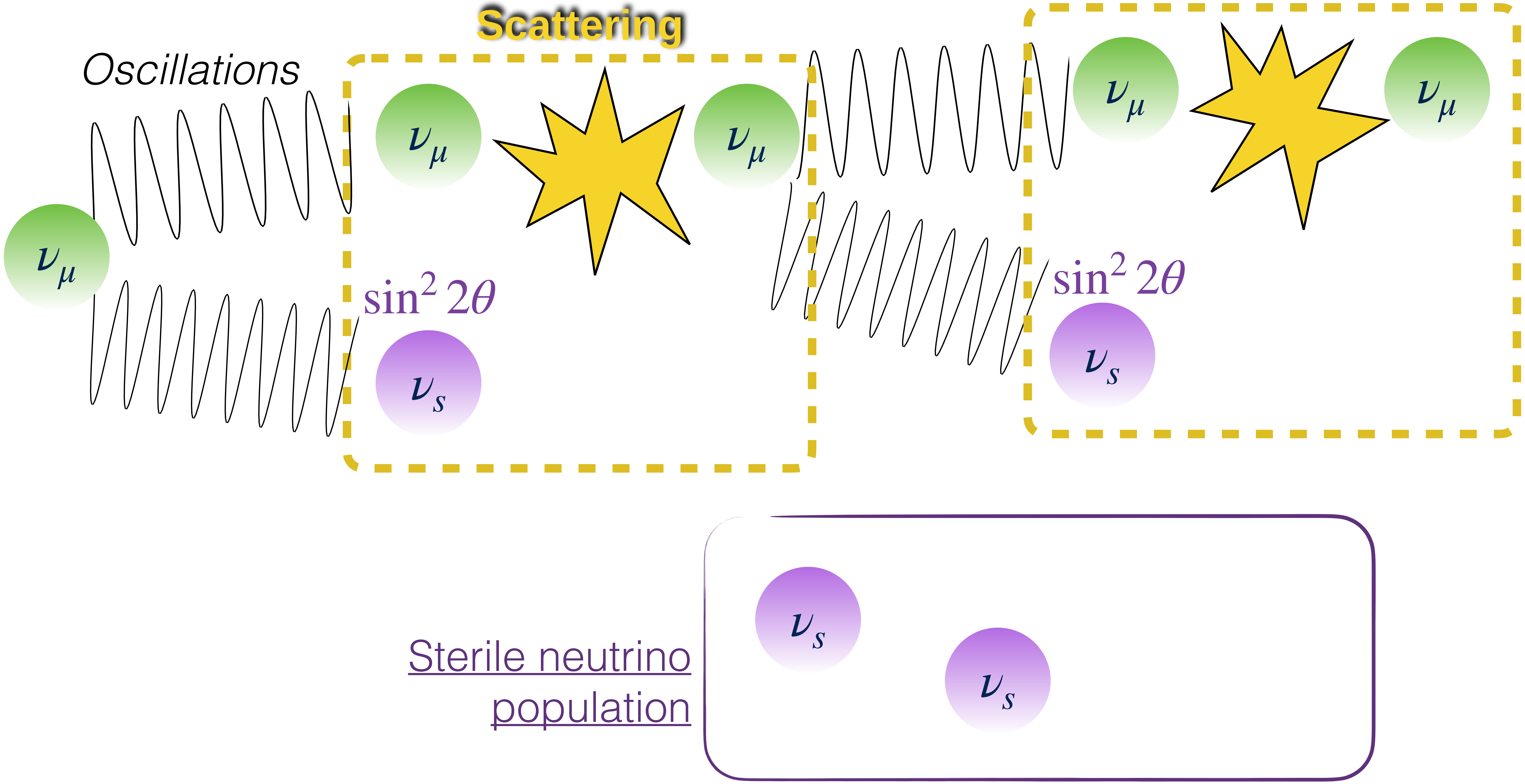


Sterile neutrino dark matter production

Sterile neutrino dark matter production

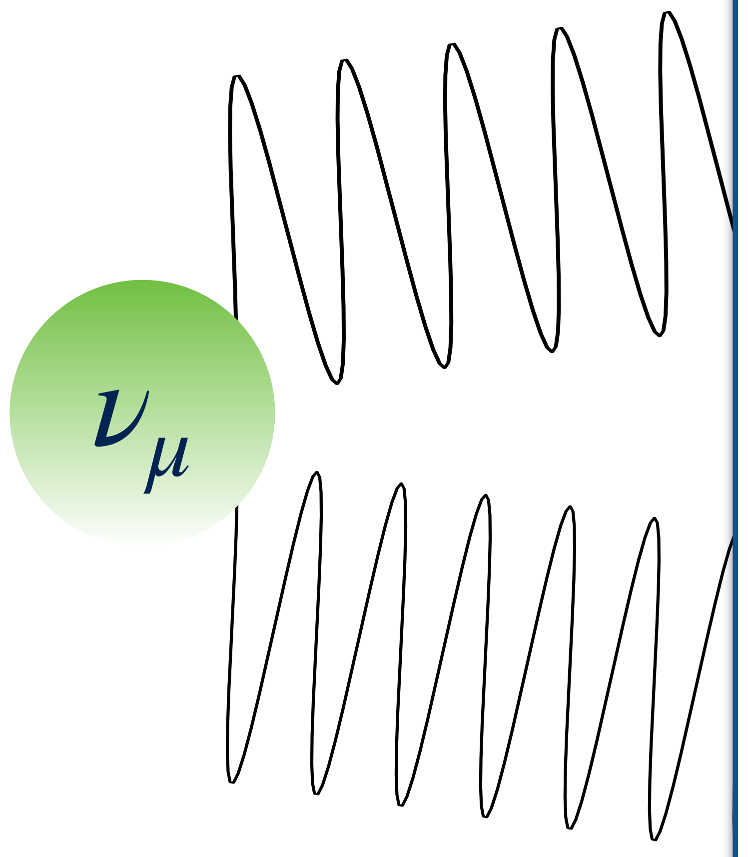
DODELSON-WIDROW MECHANISM

"Scattering-induced decoherence"

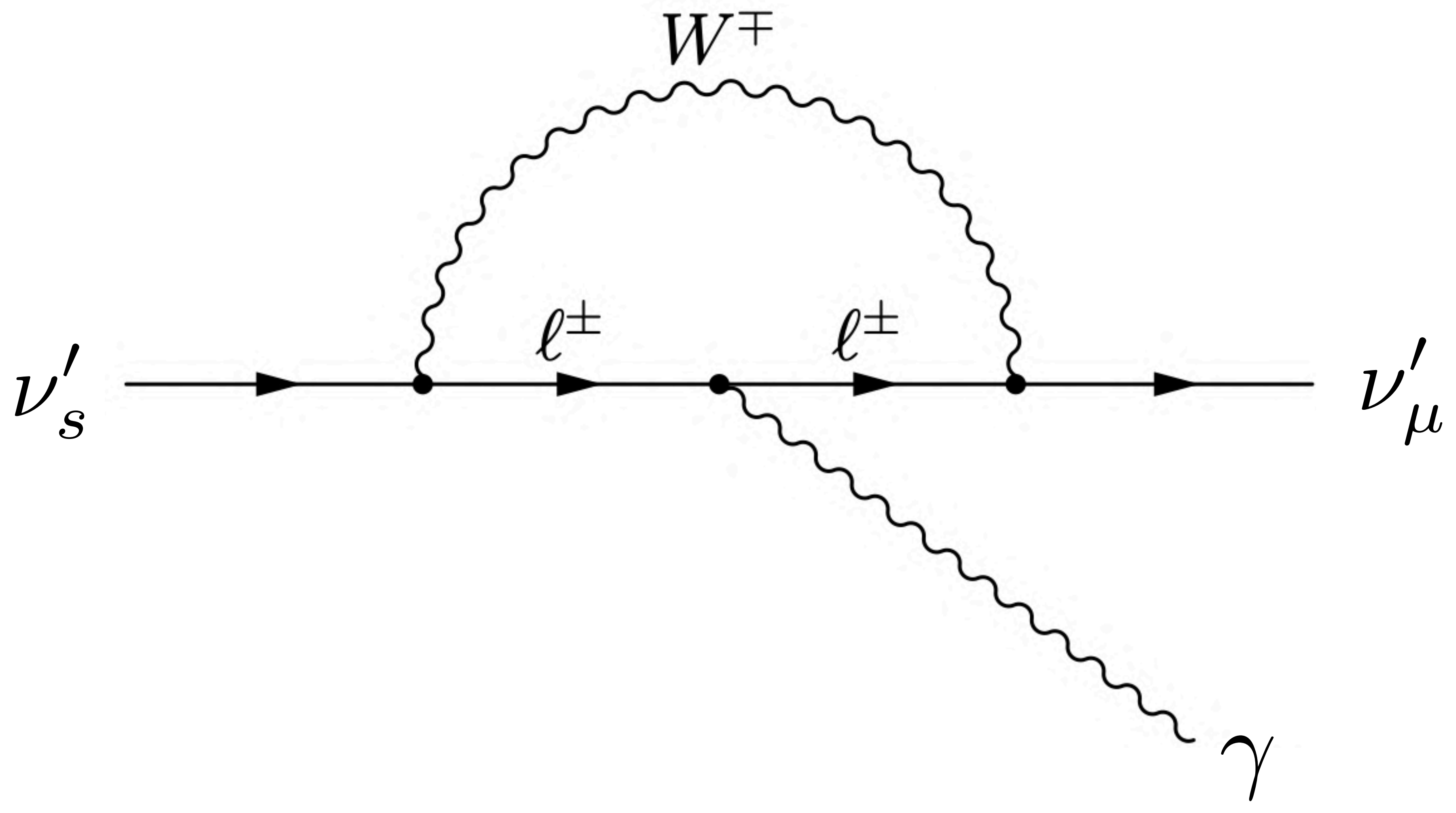
Dodelson & Widrow,
Phys. Rev. Lett. **72**, 17 (1994)

Sterile neutrino dark matter production

Oscillations



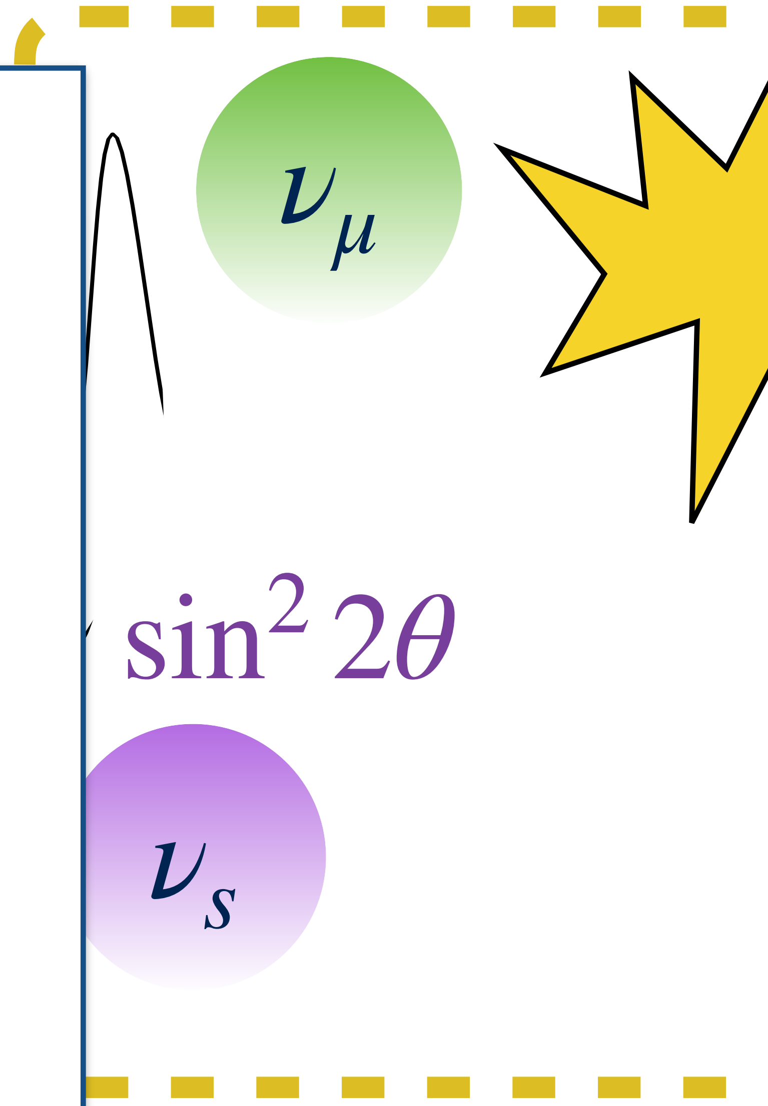
Radiative decay



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

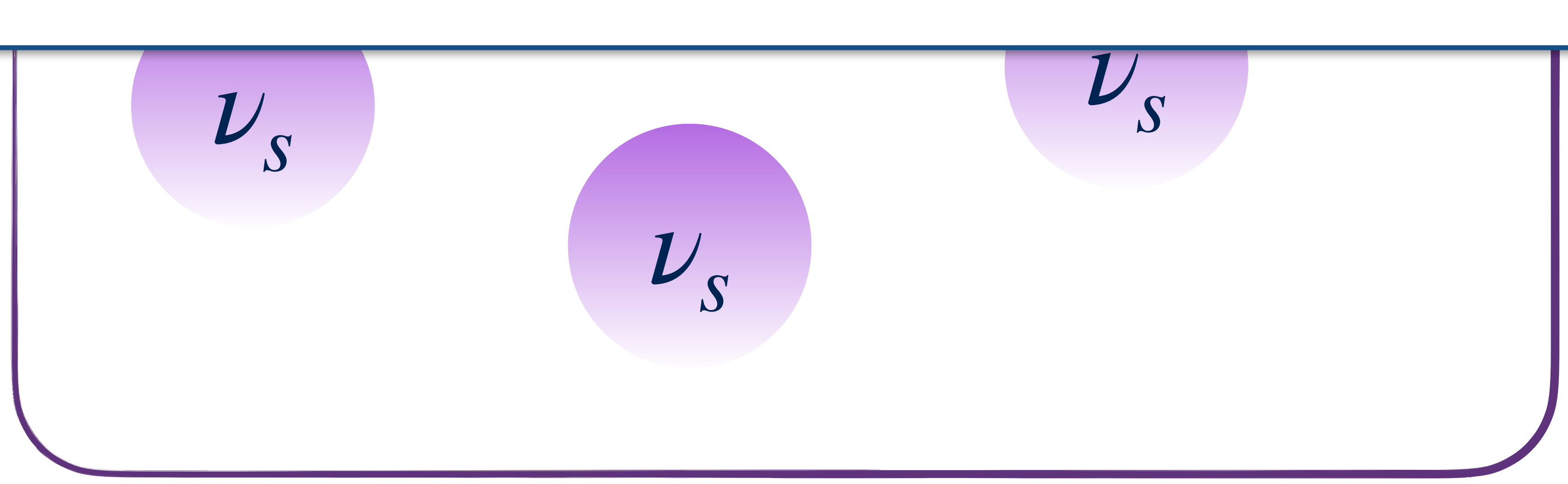
$$E_\gamma = \frac{m_s}{2}$$

→ **X-ray line**



Sterile neutrino population

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



WIDROW MECHANISM

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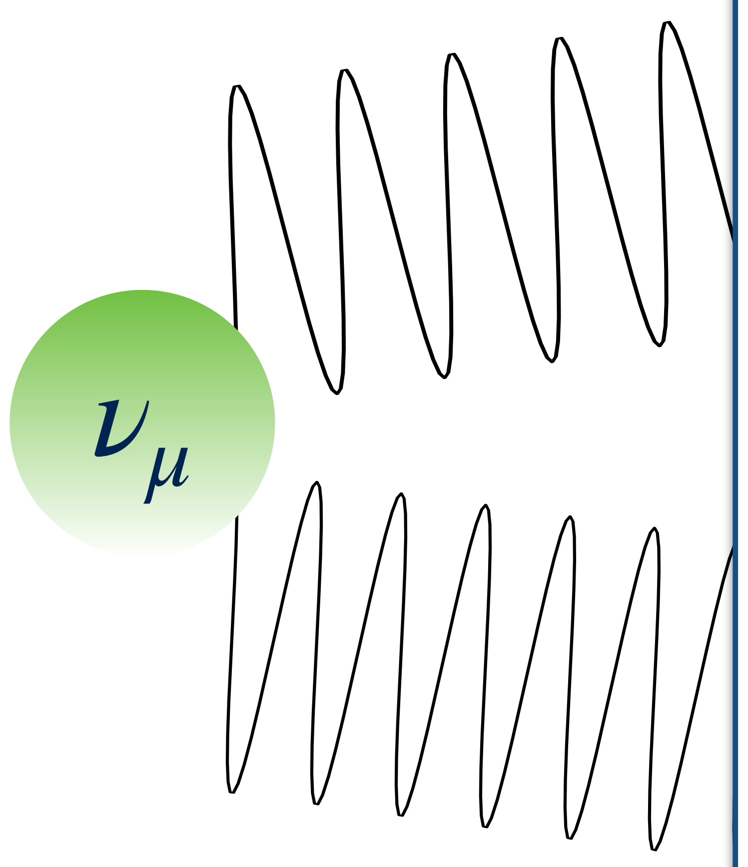
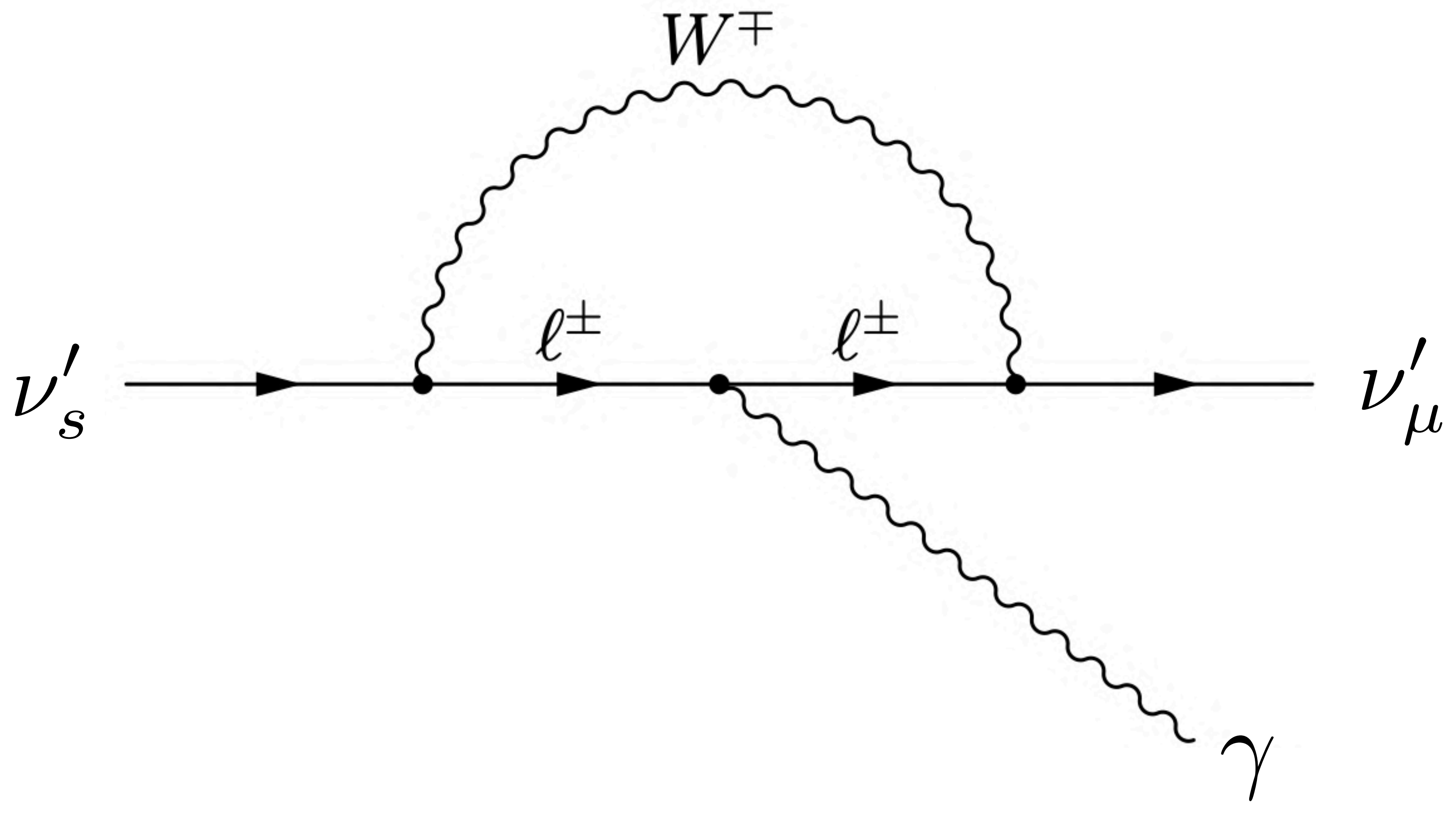


Radiative decay



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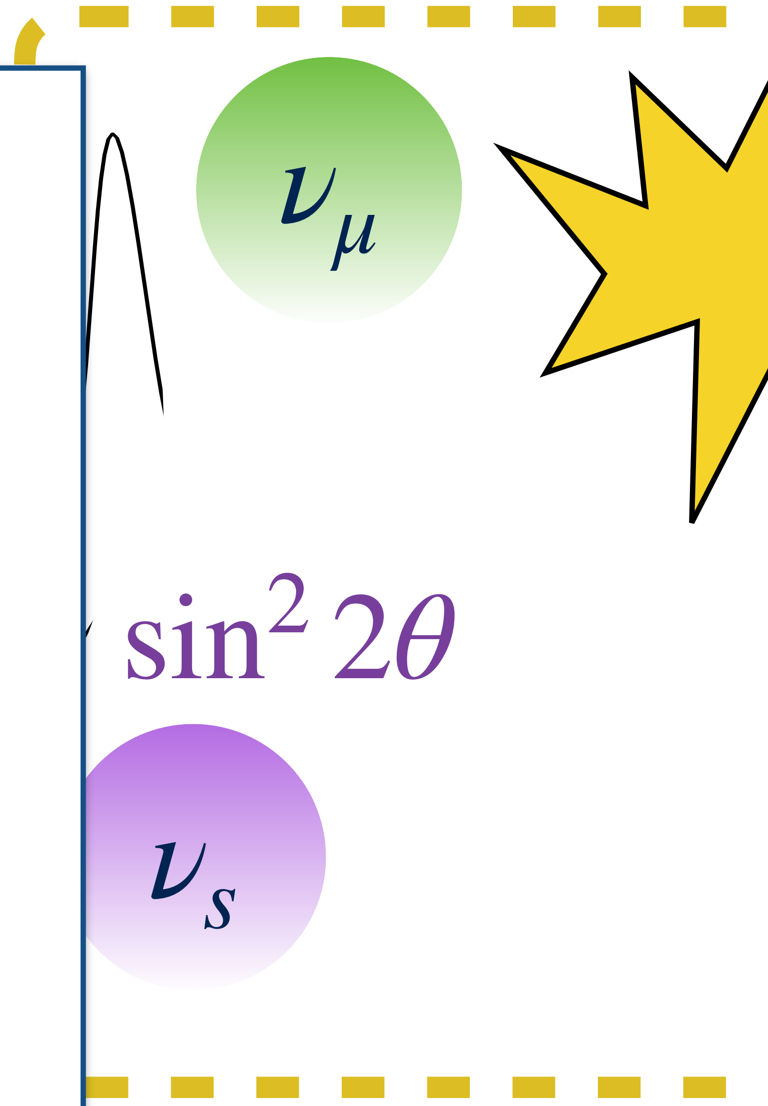

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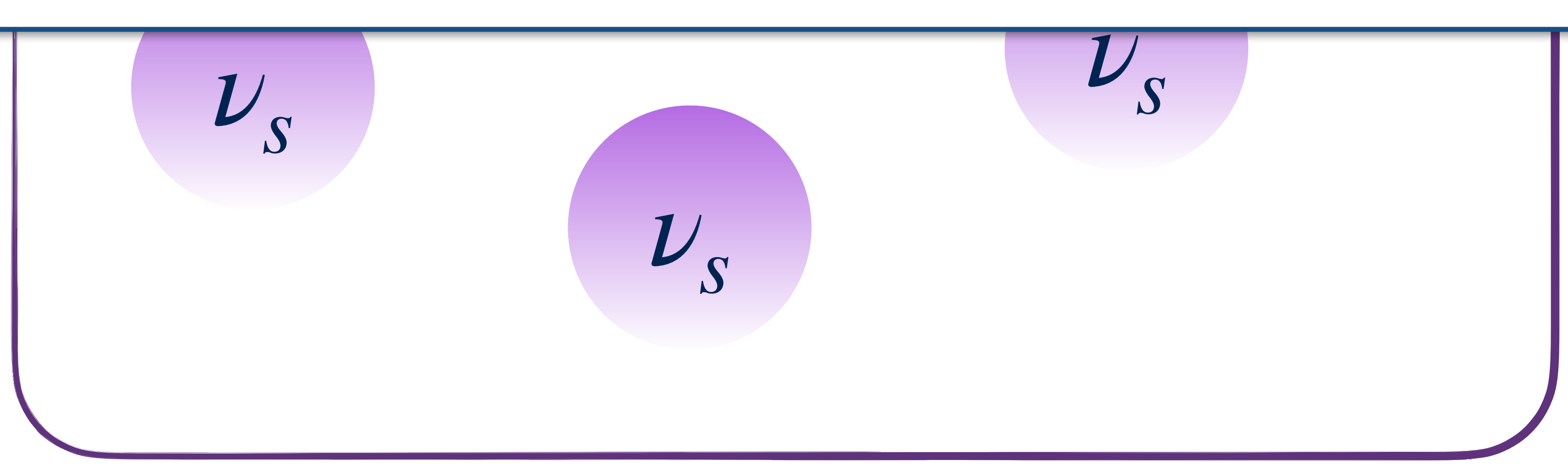

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Sterile neutrino dark matter production

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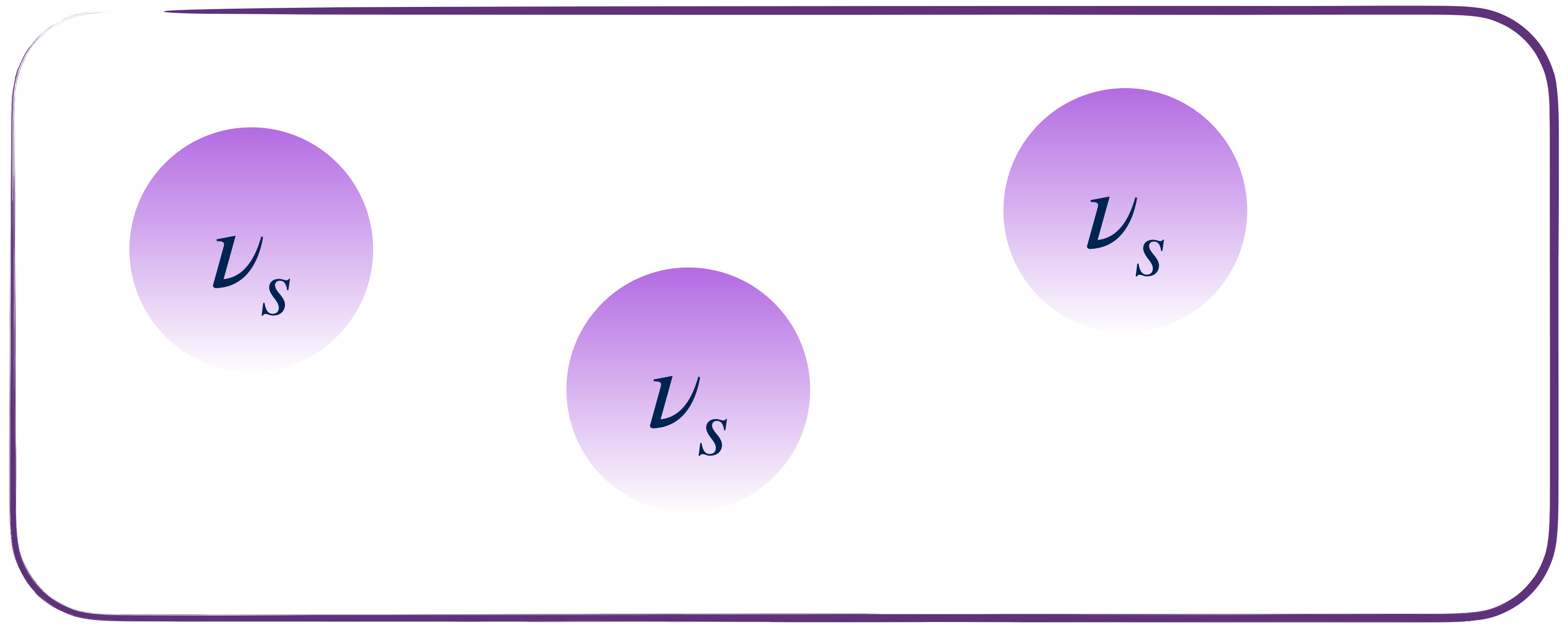

Dodelson-Widrow mechanism

"Scattering-induced decoherence"

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

Sterile neutrino dark matter production

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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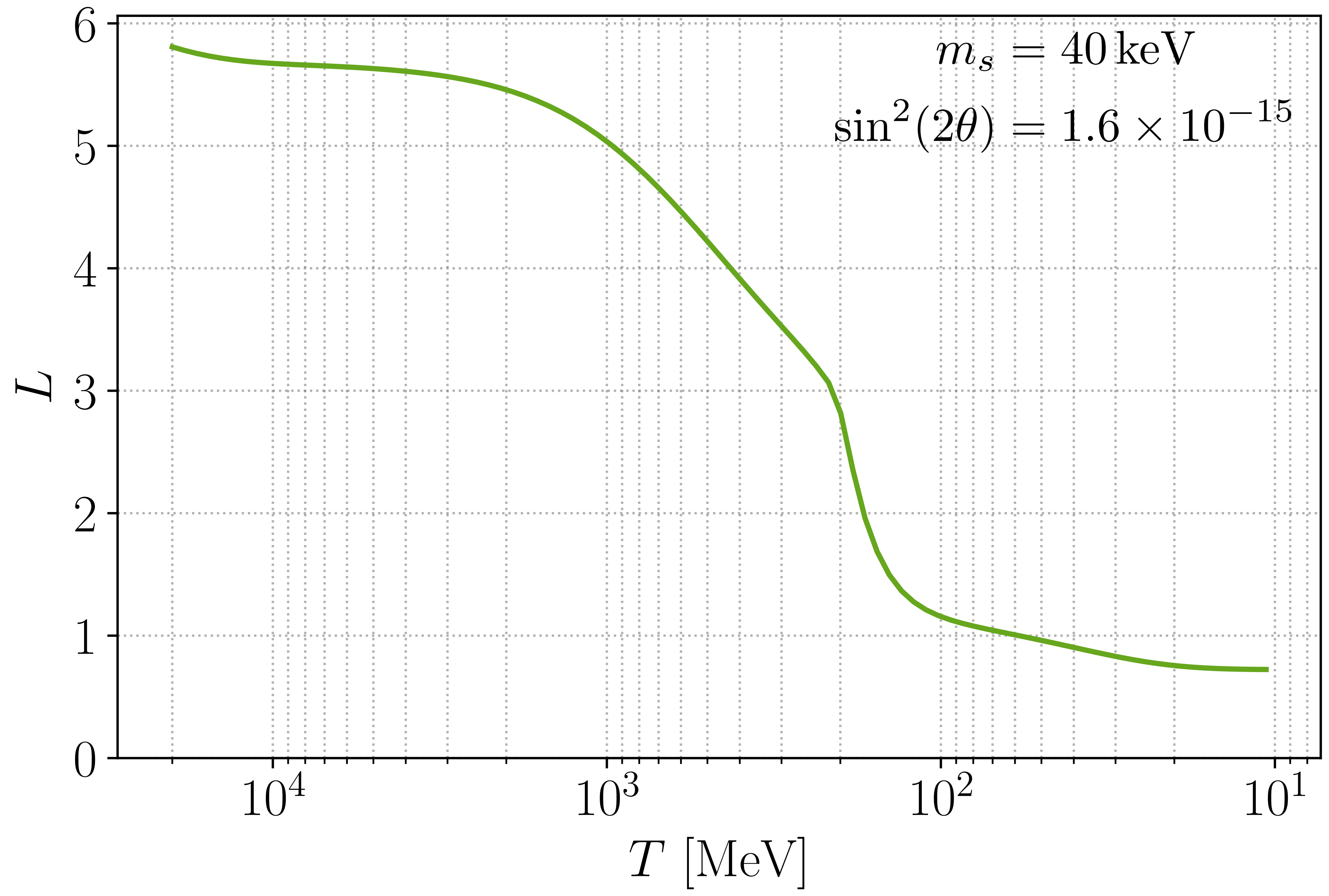

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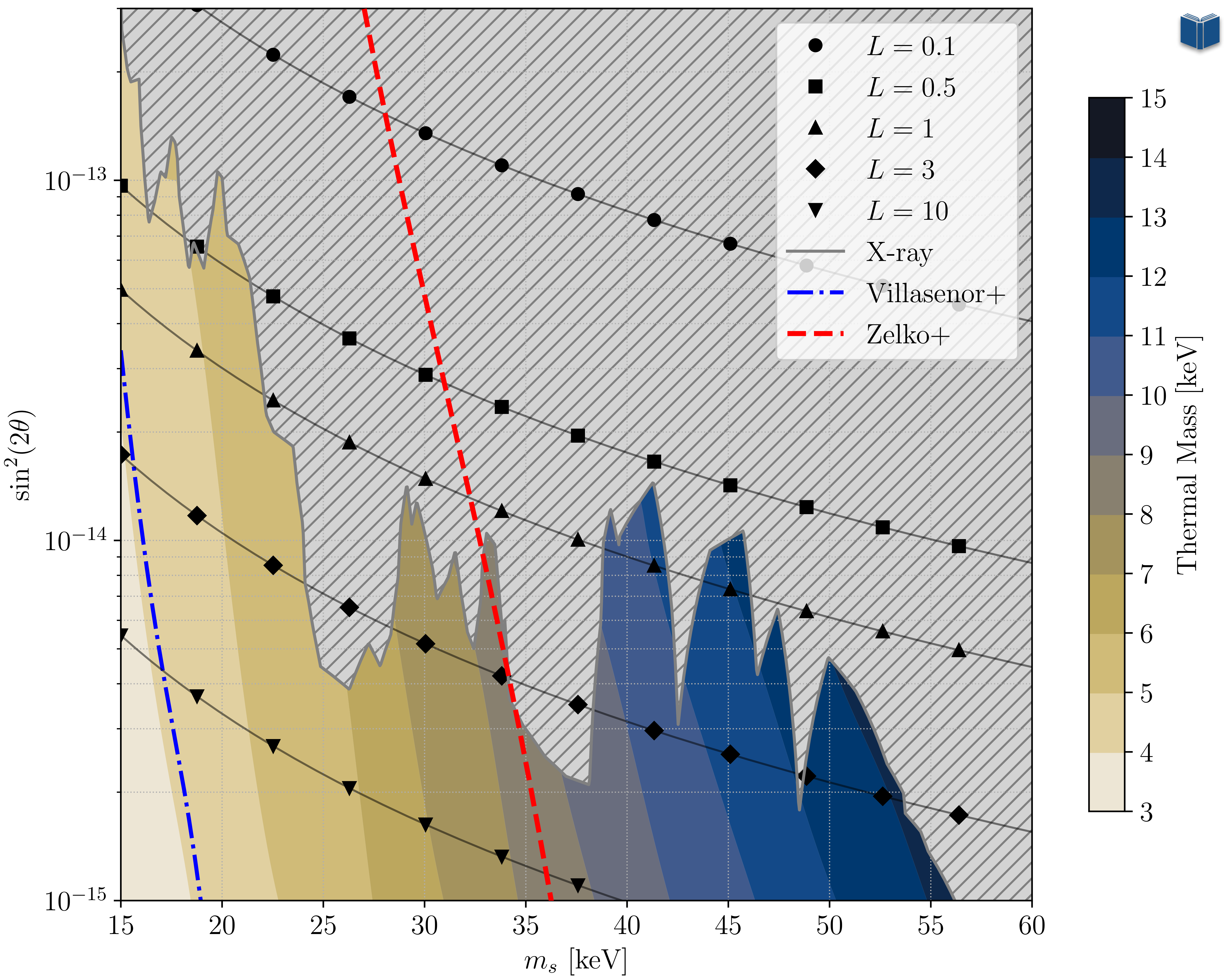

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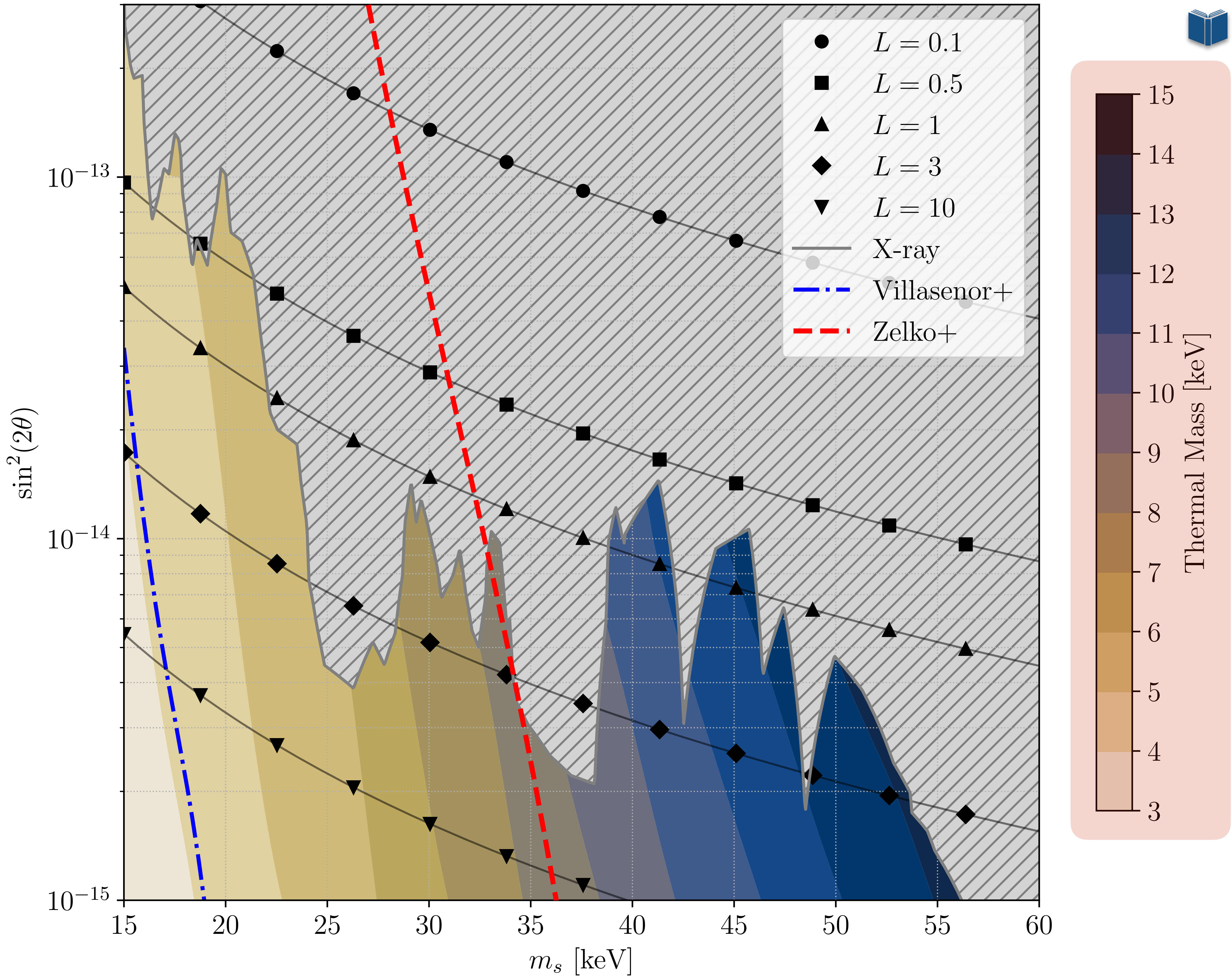

Equivalent thermal warm dark matter mass, for structure formation constraints

3. Lepton asymmetries and primordial black hole formation

Based on: M. Gonin, **JF**, A. Escrivà, A. Magaraggia, G. Hasinger and F. Kühnel, [2608.22240]

Imprint of thermal history on the PBH mass spectrum

Scenario	b	ℓ_e	ℓ_μ	ℓ_τ
Standard	8.6×10^{-11}	$\ell = \ell_e + \ell_\mu + \ell_\tau = -\frac{51}{28}\, b$		
Type I – 0.1	8.6×10^{-11}	0	-0.1	0.1
Type I – 0.08	8.6×10^{-11}	0	-0.08	0.08
BKOS-like	8.6×10^{-11}	-0.08	0.04	0.04

$$l_\alpha = \frac{n_\alpha - n_{\bar{\alpha}} + n_{\nu_\alpha} - n_{\bar{\nu}_\alpha}}{s}$$

M. Gonin, **JF**, A. Escrivà, A. Magaraggia, G. Hasinger and F. Kühnel, [2608.22240]

Maël Gonin,
PhD student @TU Dresden

Cosmic trajectories

$$\eta_i(T) \equiv \frac{n_i - n_{\bar{i}}}{T^3}$$

Combination of numerical codes

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EoS modifications

$$w = \frac{P}{\rho} = \frac{\sum_i P_i(T, m_i, \eta_i)}{\sum_i \rho_i(T, m_i, \eta_i)}$$

Deviation from w=1/3 at each phase transition / nonrelativistic transition

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PBH mass spectrum

$$f_{\rm PBH}(M)$$

Critical conditions for collapse (relativistic numerical simulations) + Peak theory

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⇒

PBH mass spectrum

$$f_{\rm PBH}(M)$$

Critical conditions for collapse (relativistic numerical simulations) + Peak theory

⇒

Grav. wave signal

$$\frac{{\rm d}^2 \mathcal{R}_{\rm late}}{{\rm d}\ln M_A \; {\rm d}\ln M_B}$$

Late-merger rate × LVK sensitivity

Asymmetry evolution from $T = 10\,\mathrm{GeV}$ to $T = 10\,\mathrm{keV}$

	b	ℓ_e	ℓ_μ	ℓ_τ
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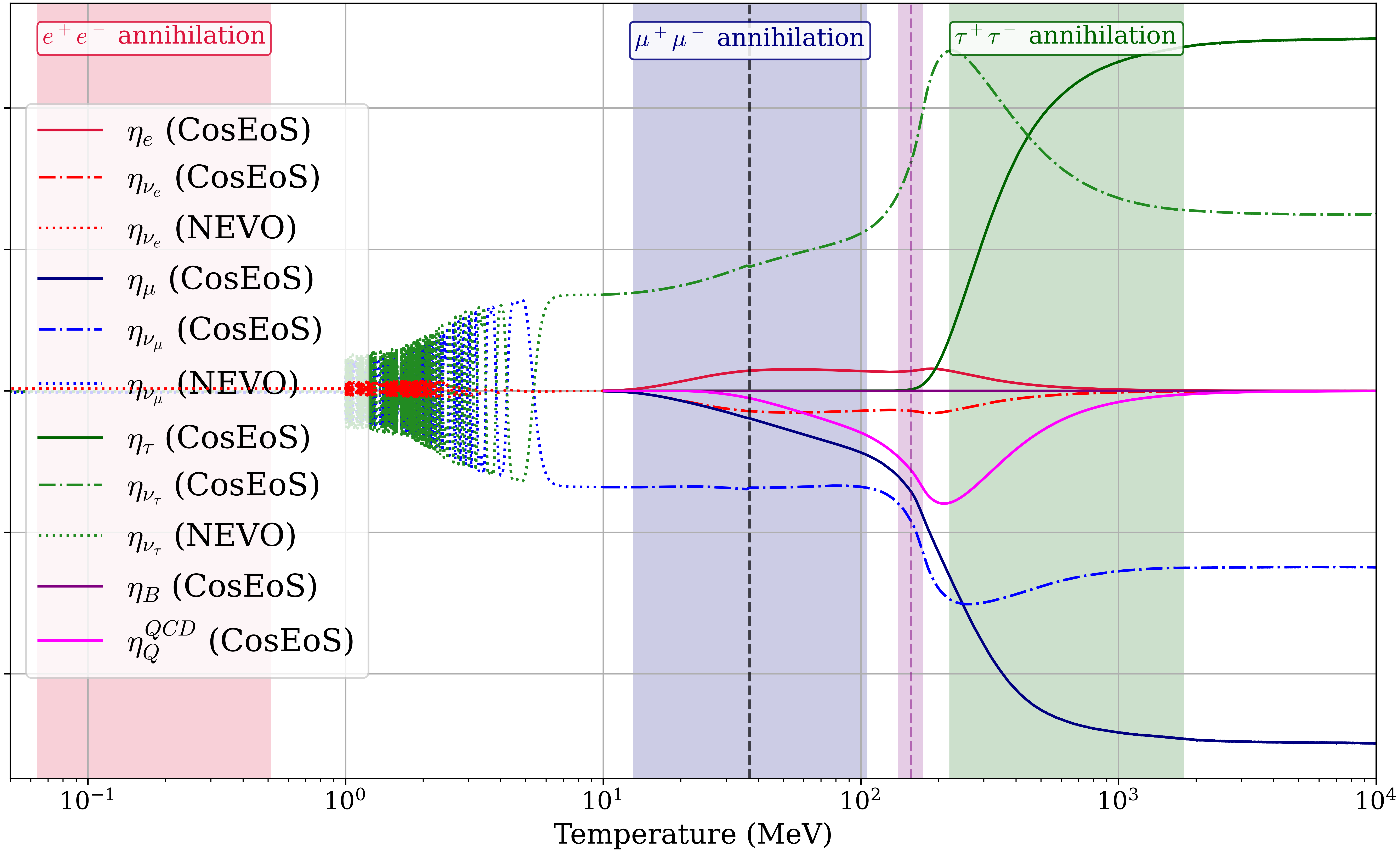

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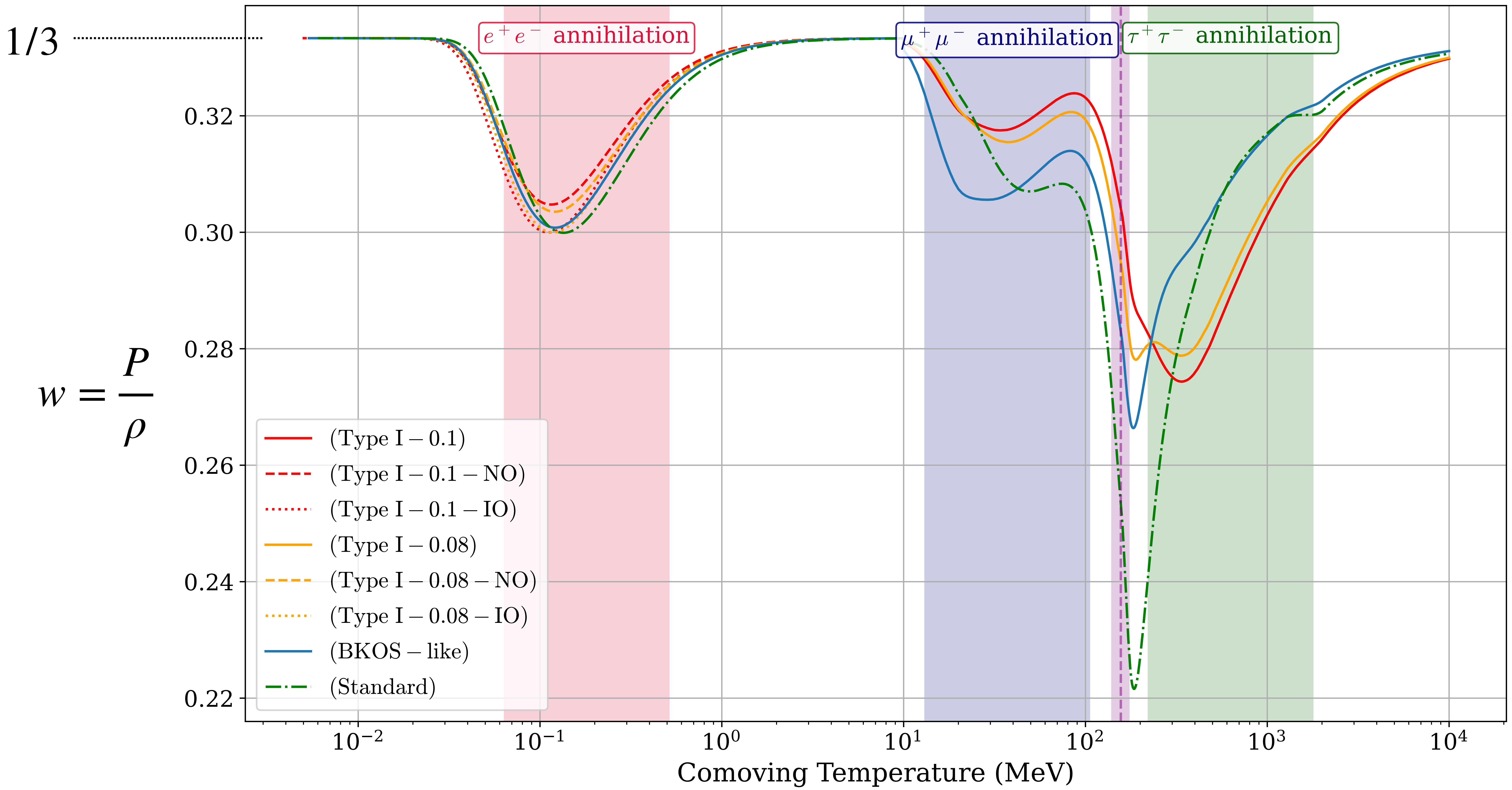
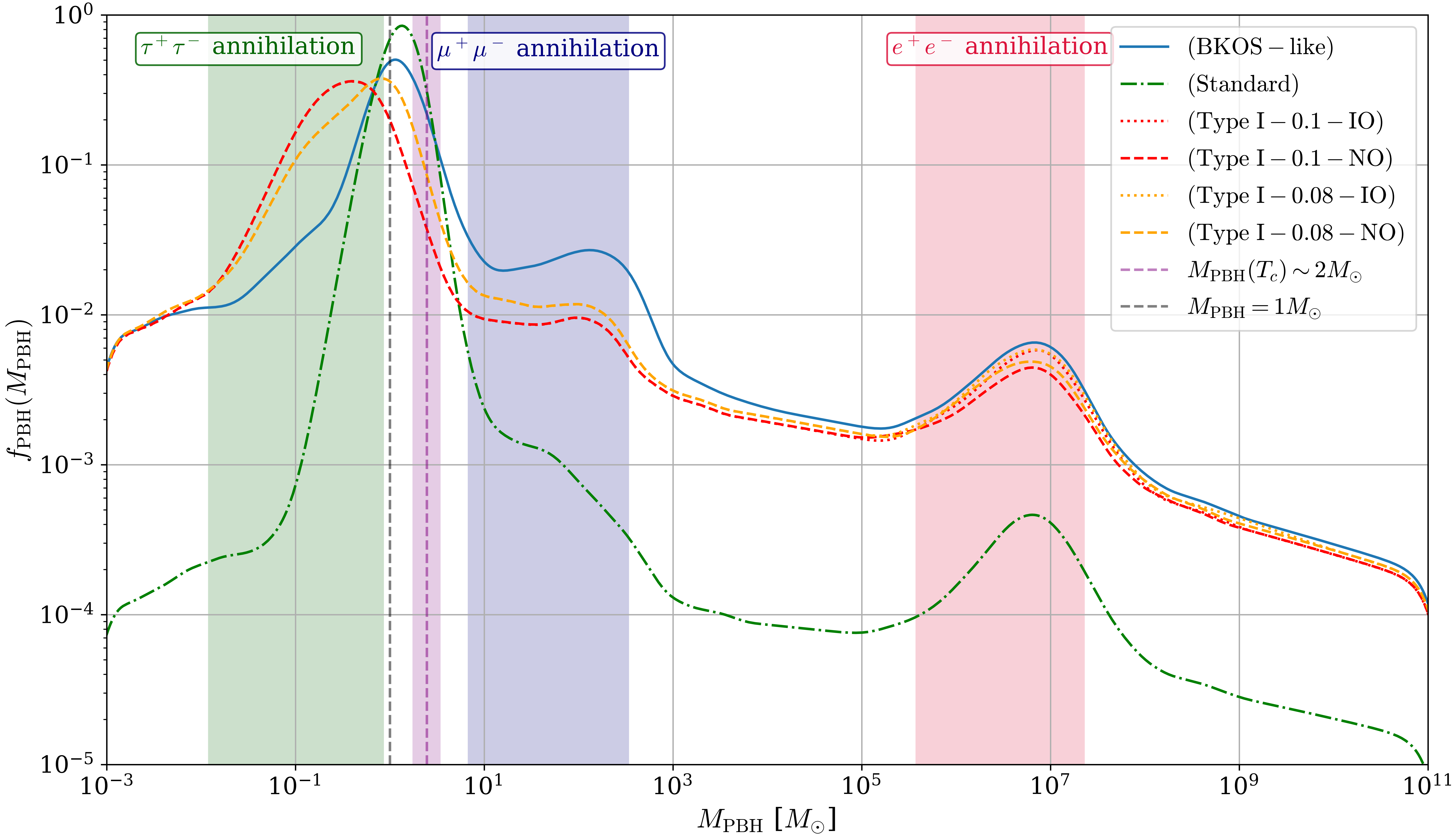
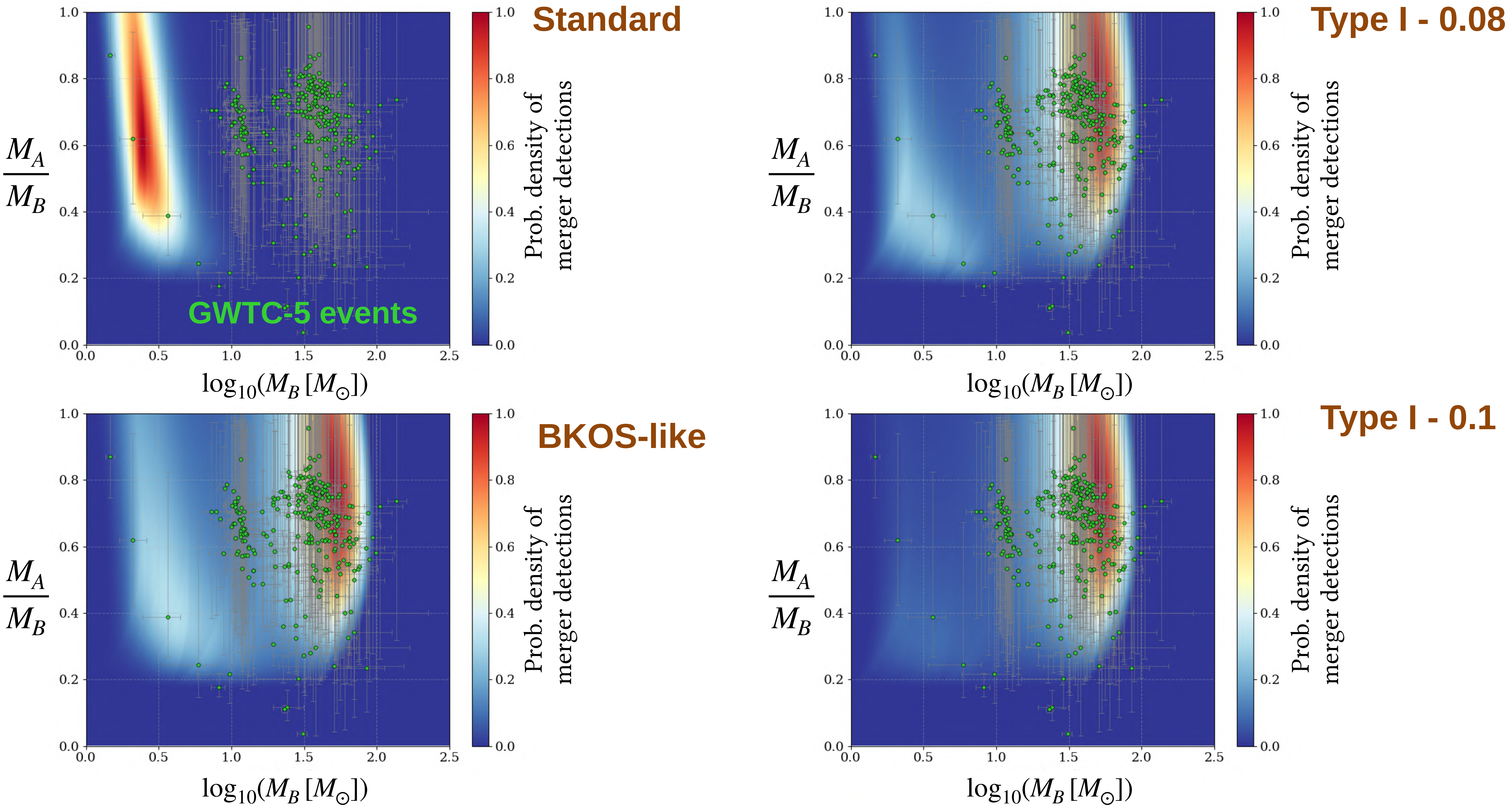


PBH mass spectrum



GW signal



Standard
Type I - 0.08
BKOS-like
Type I - 0.1
GWTC-5 events
$\frac{M_A}{M_B}$
$\log_{10}(M_B\,[M_\odot])$
Prob. density of merger detections

Summary

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.
- Large *primordial* neutrino asymmetries **are allowed** in some directions.

⟶ complicated landscape of allowed asymmetries

- Future CMB experiments will have a much larger constraining power!

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

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

… consequences on sterile neutrino dark matter models…

- This (re-)opens the parameter space for **resonant production of sterile neutrino dark matter** (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]

… and PBH formation

- A modified thermal history leaves an imprint on the **PBH mass spectrum**.

⟶ connection between PBH mass spectra and fundamental cosmic parameters

M. Gonin *et al.* [2608.22240]

Quantum Kinetic Equation

<u>*Classical distribution functions*</u>

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

<u>**Density matrix**</u>

<u>**Generalization of Boltzmann's equation for quantum transport**</u>

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

Vacuum

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

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

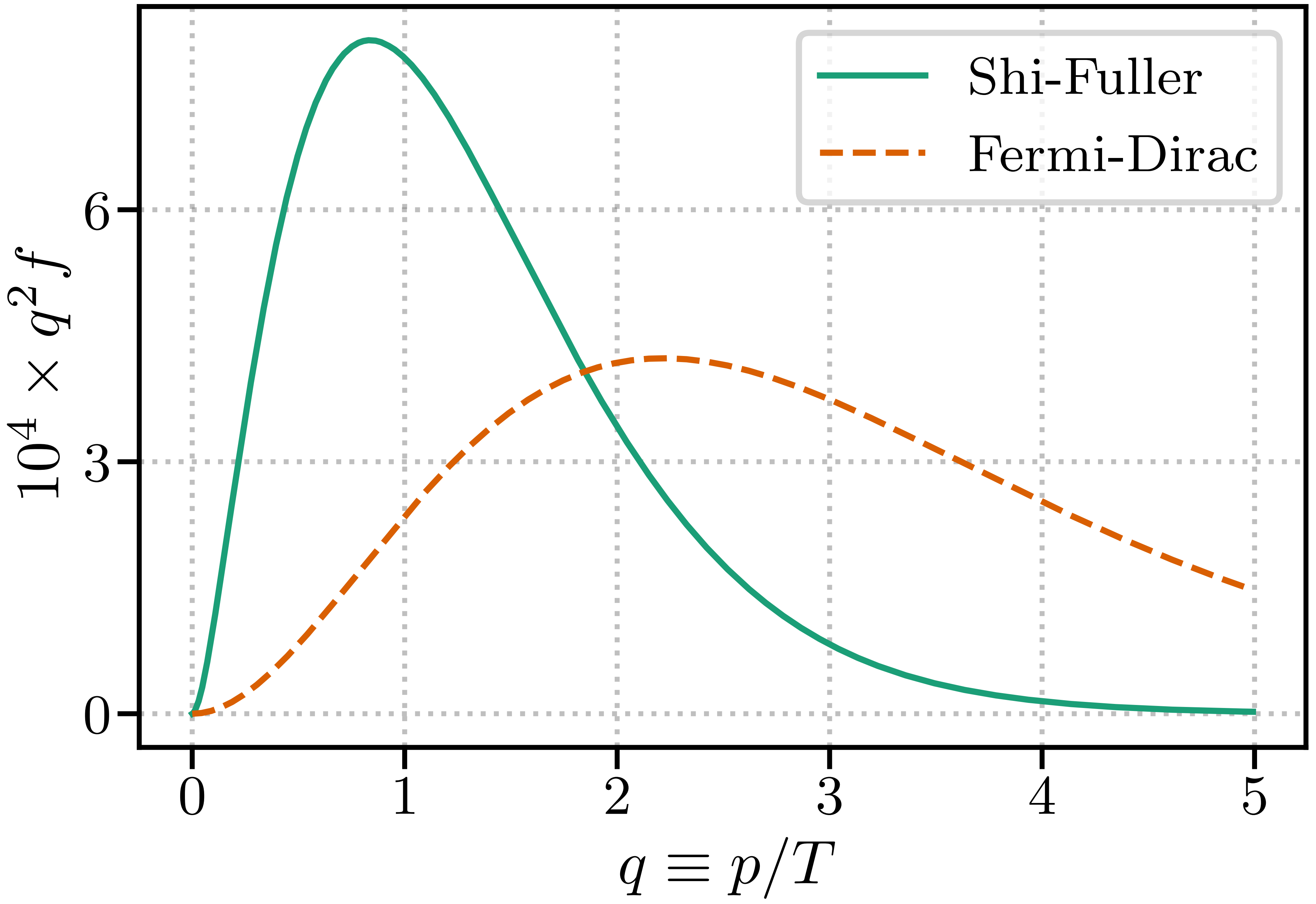
Lepton mean-field
(effective potential due to the charged lepton background)

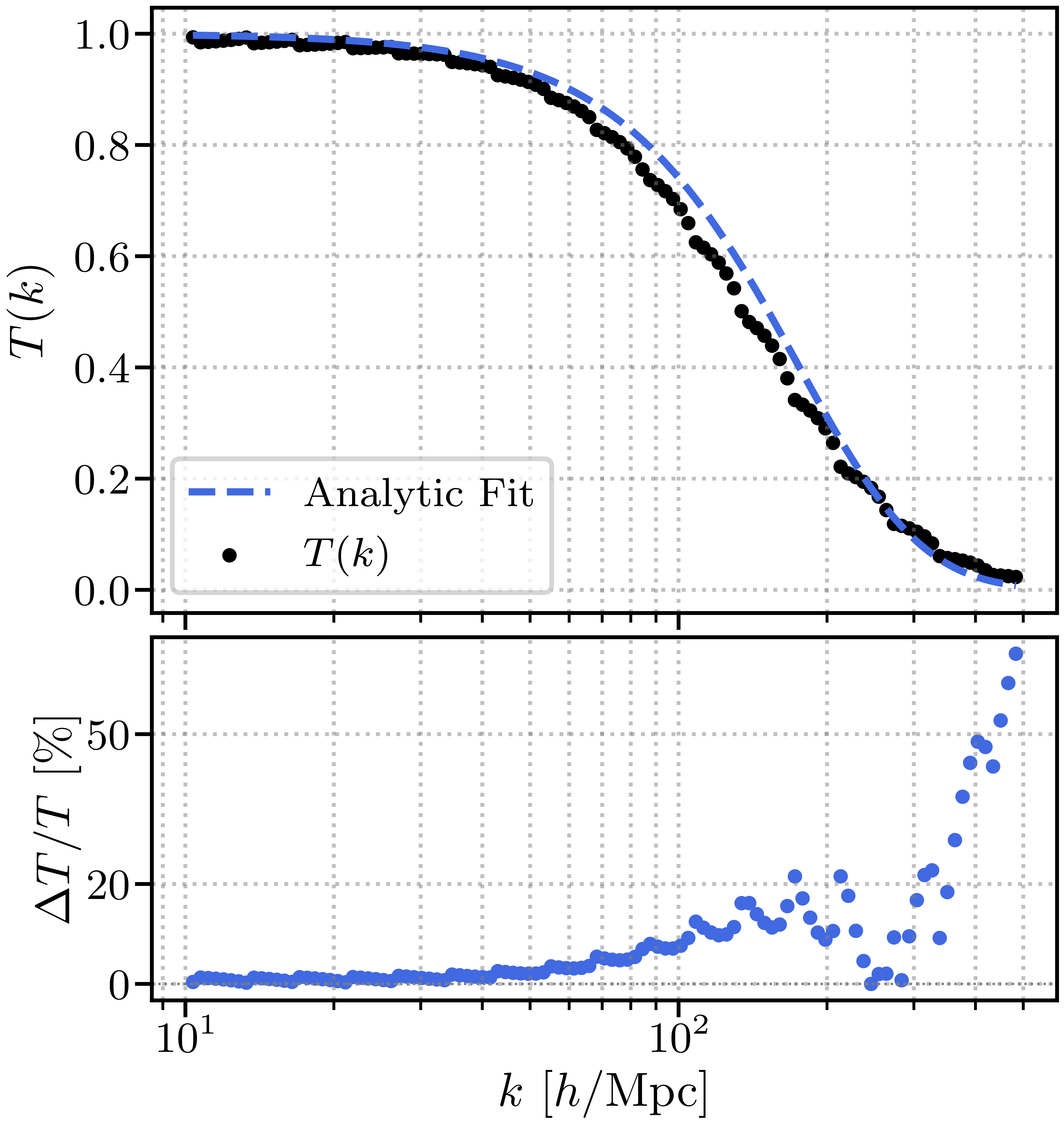
Collisions

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

Connection with thermal warm dark matter

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





Threshold values for PBH formation

Critical value of the curvature-profile amplitude

Critical peak value fo the compaction function