

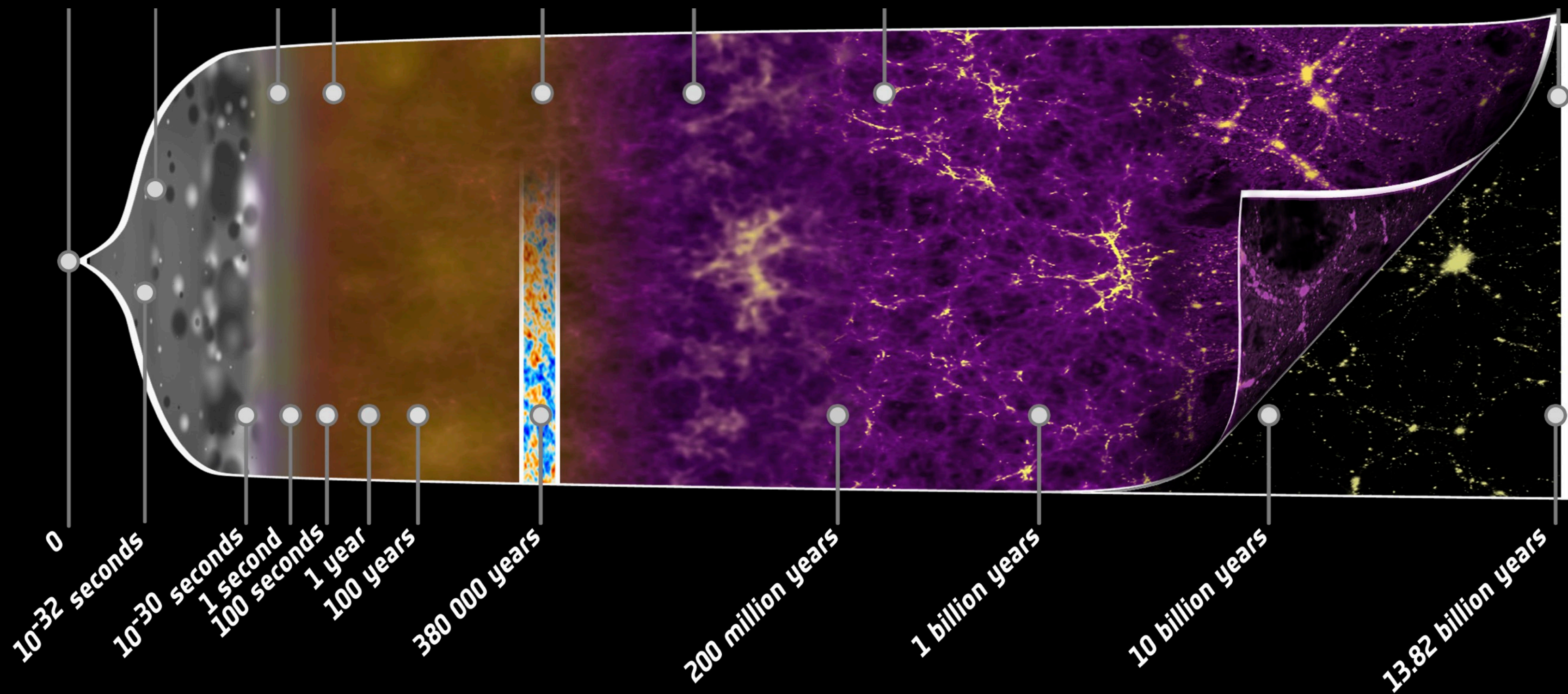
Primordial lepton asymmetries: new constraints and consequences for sterile neutrino dark matter

Julien Froustey

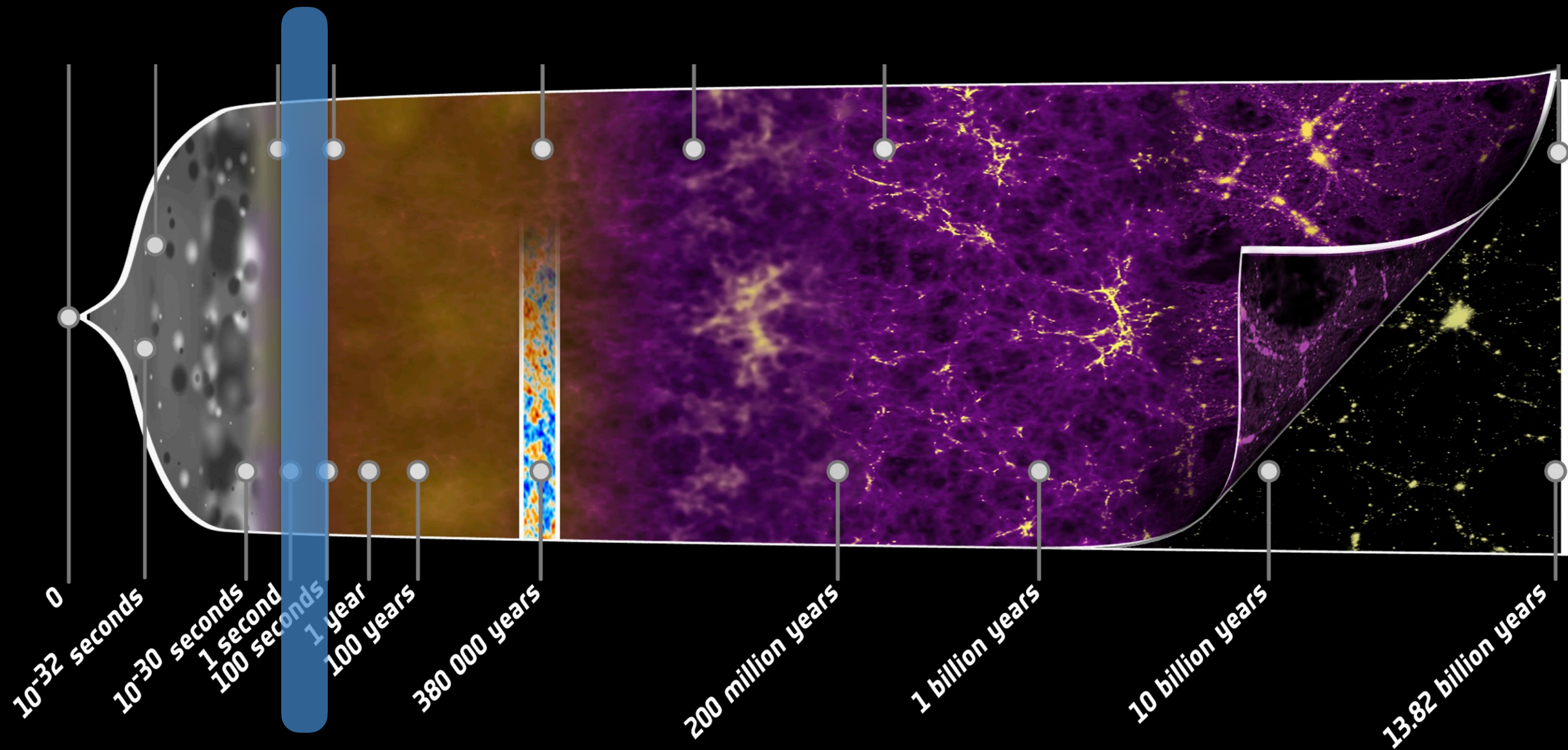
*Severo Ochoa Postdoctoral Fellow,
IFIC, Valencia*

IRN Neutrino Meeting

02/06/2026

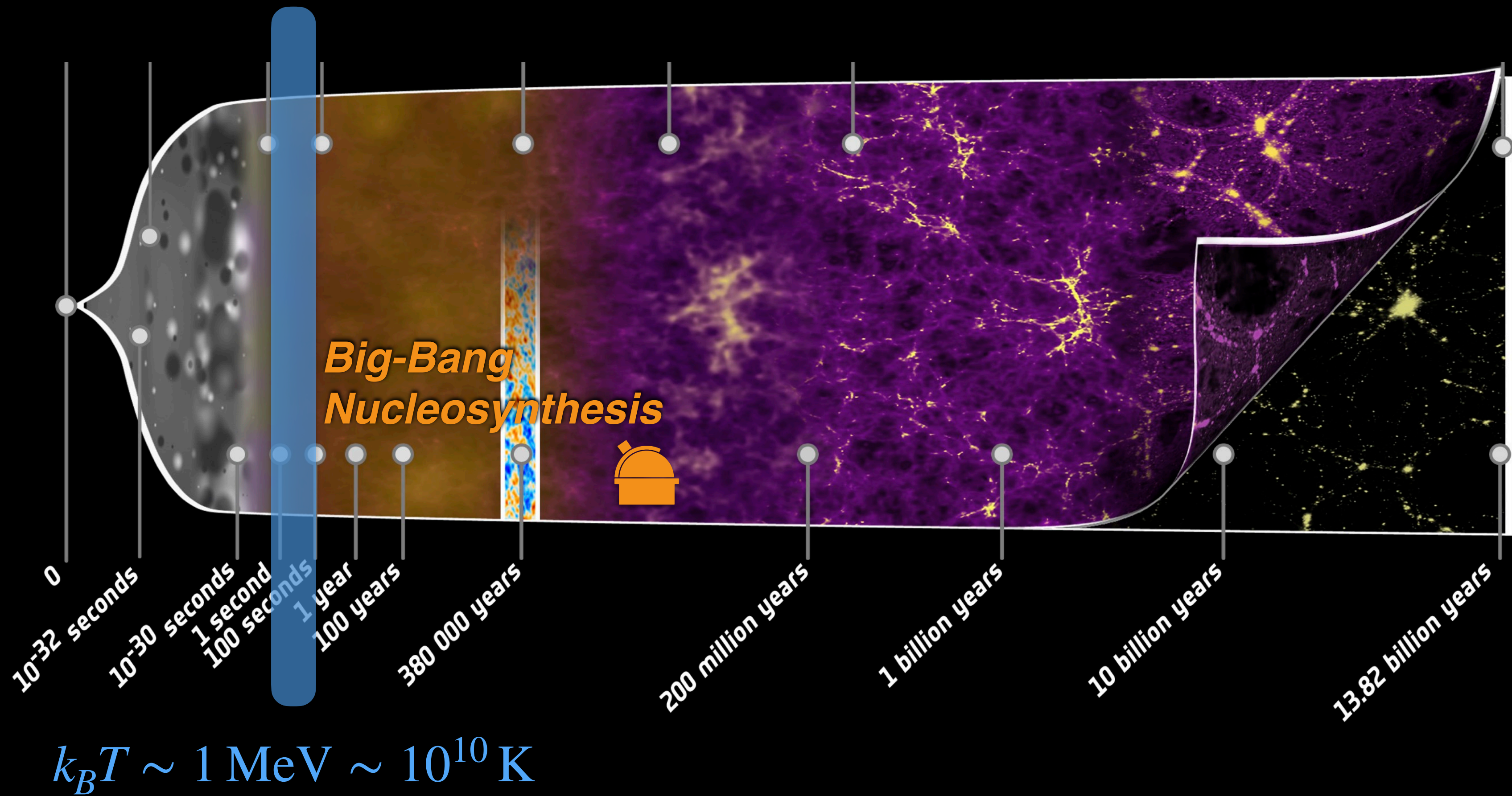


Formation of the Cosmic Neutrino Background

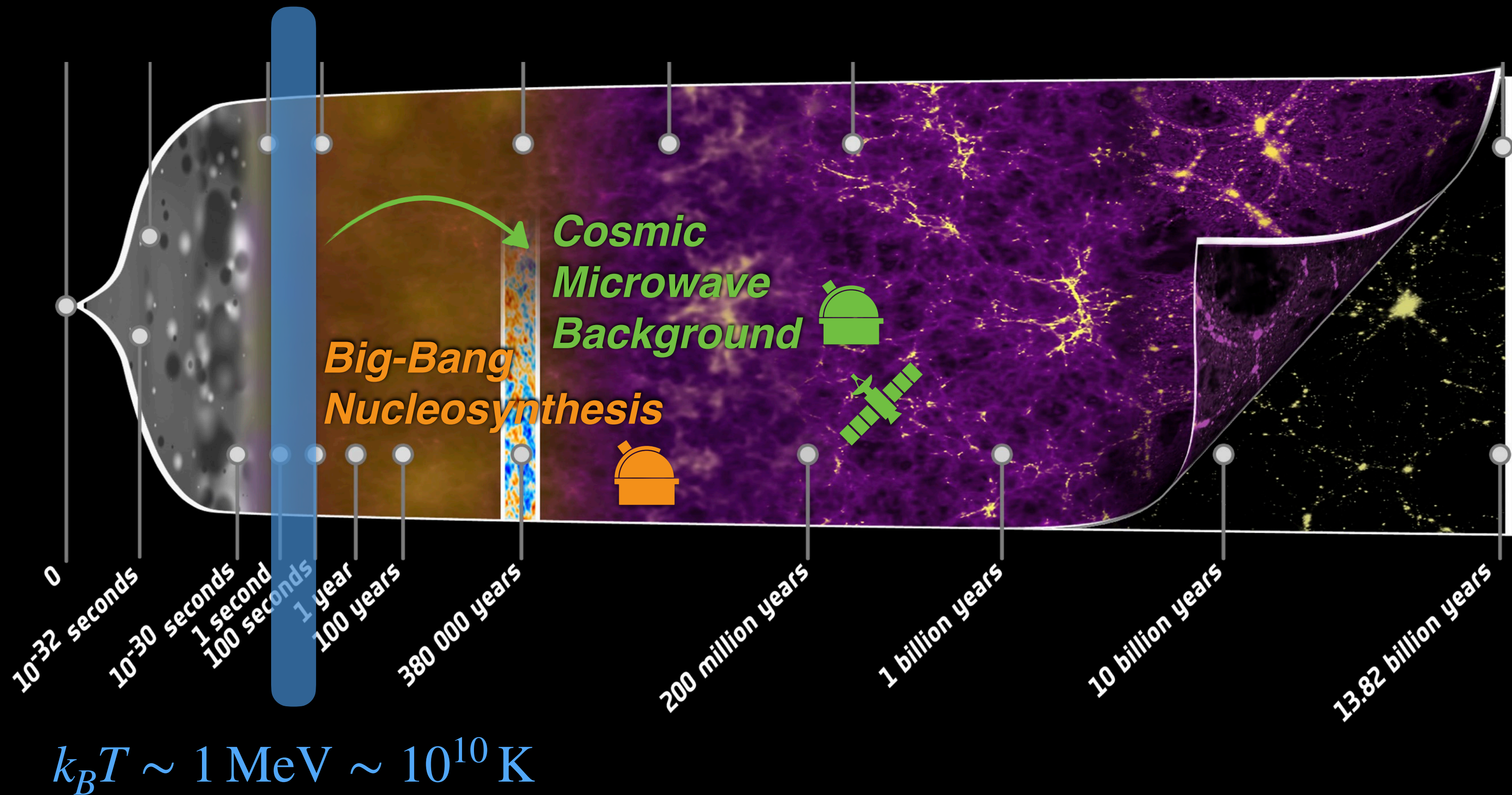


$$k_B T \sim 1 \text{ MeV} \sim 10^{10} \text{ K}$$

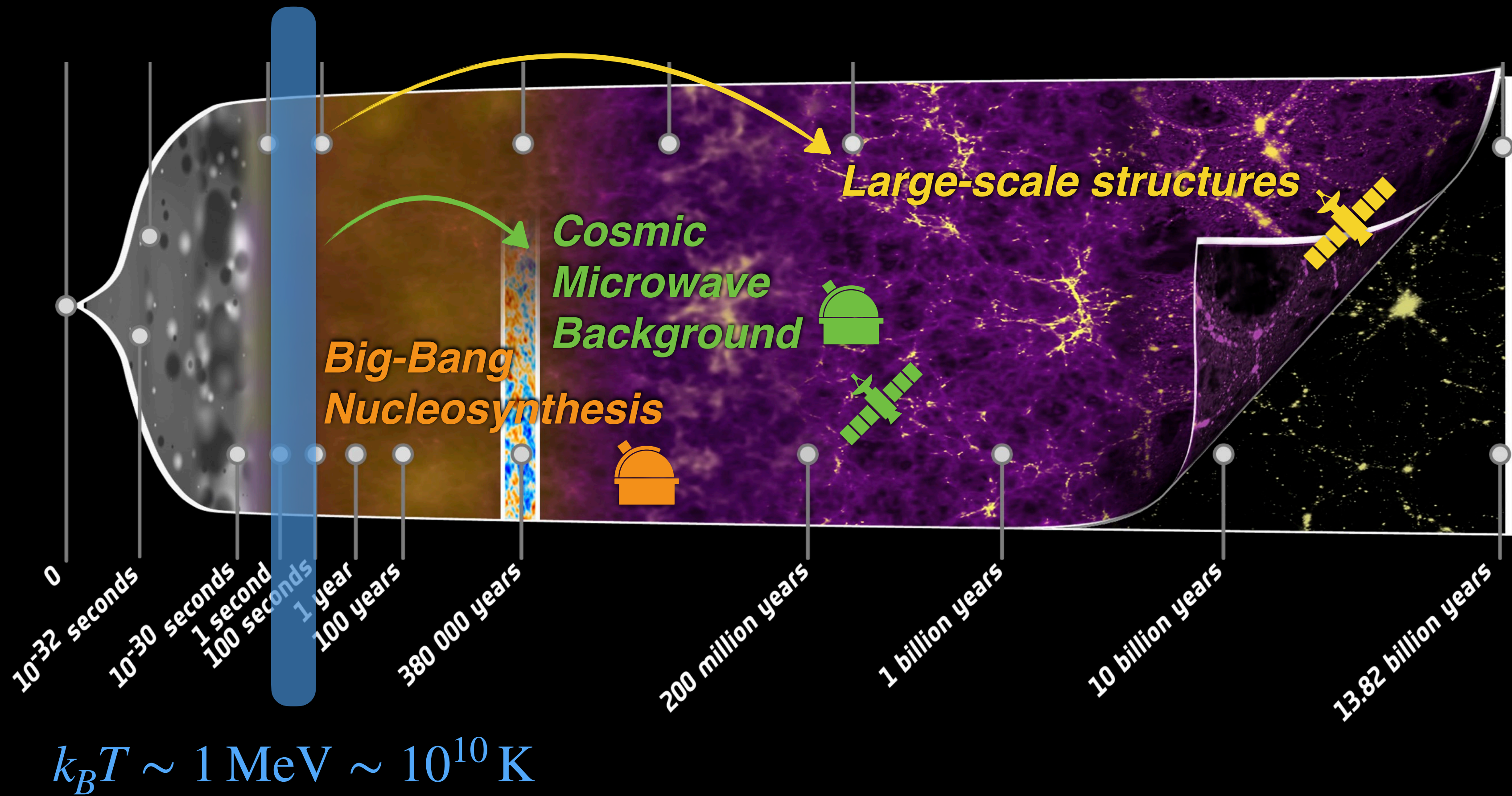
Formation of the
**Cosmic Neutrino
Background**



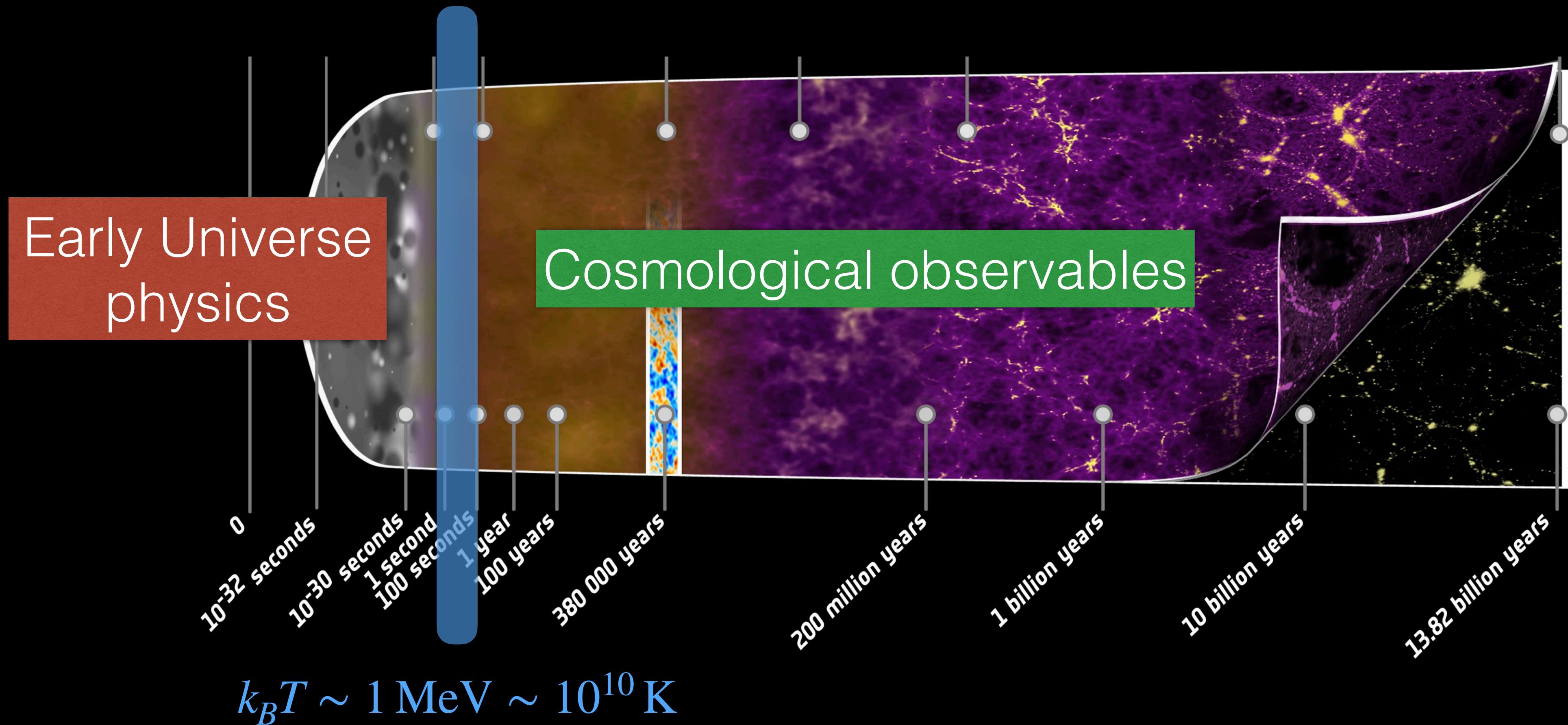
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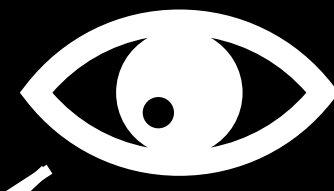
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Formation of the Cosmic Neutrino Background

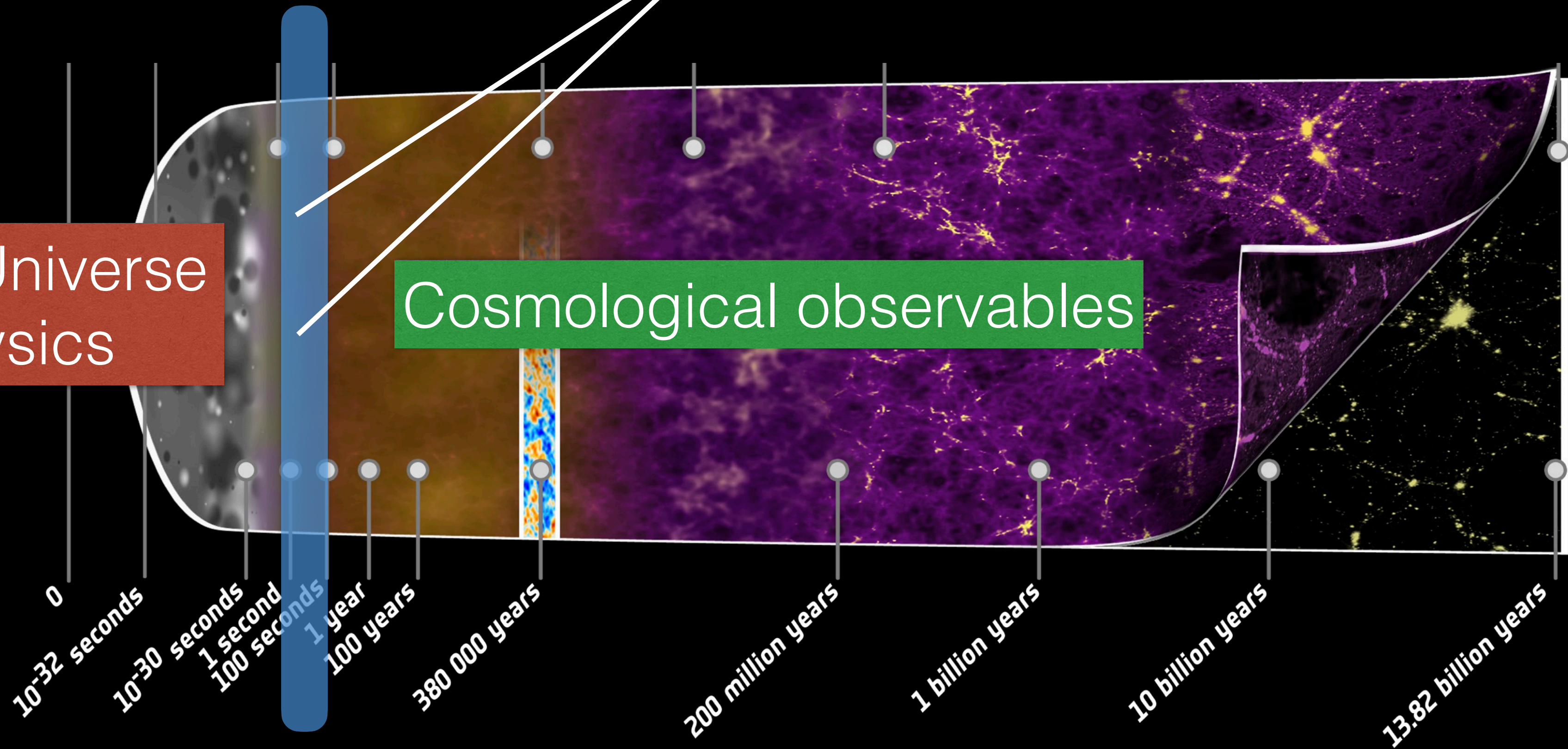


Formation of the Cosmic Neutrino Background



Early Universe
physics

Cosmological observables



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

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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- Standard formalism: **Quantum Kinetic Equations**, used extensively in the last decades

$$\frac{\partial \varrho}{\partial t} - H p \frac{\partial \varrho}{\partial p} = -i [\mathcal{H}_{\text{vac}} + \mathcal{H}_{\text{mat}} + \mathcal{H}_{\nu\nu}, \varrho] + \mathcal{C}$$

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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P. de Salas and S. Pastor [[1606.06986](#)]

G. Barenboim *et al.* [[1609.01584](#)]

G. Barenboim and W. Park [[1703.08258](#)]

...

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Liouville term **Oscillations** **Collisions**

G. Mangano *et al.* [[astro-ph/0111408](#)]
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...

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](#)]

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

Neutrino transport in the early Universe

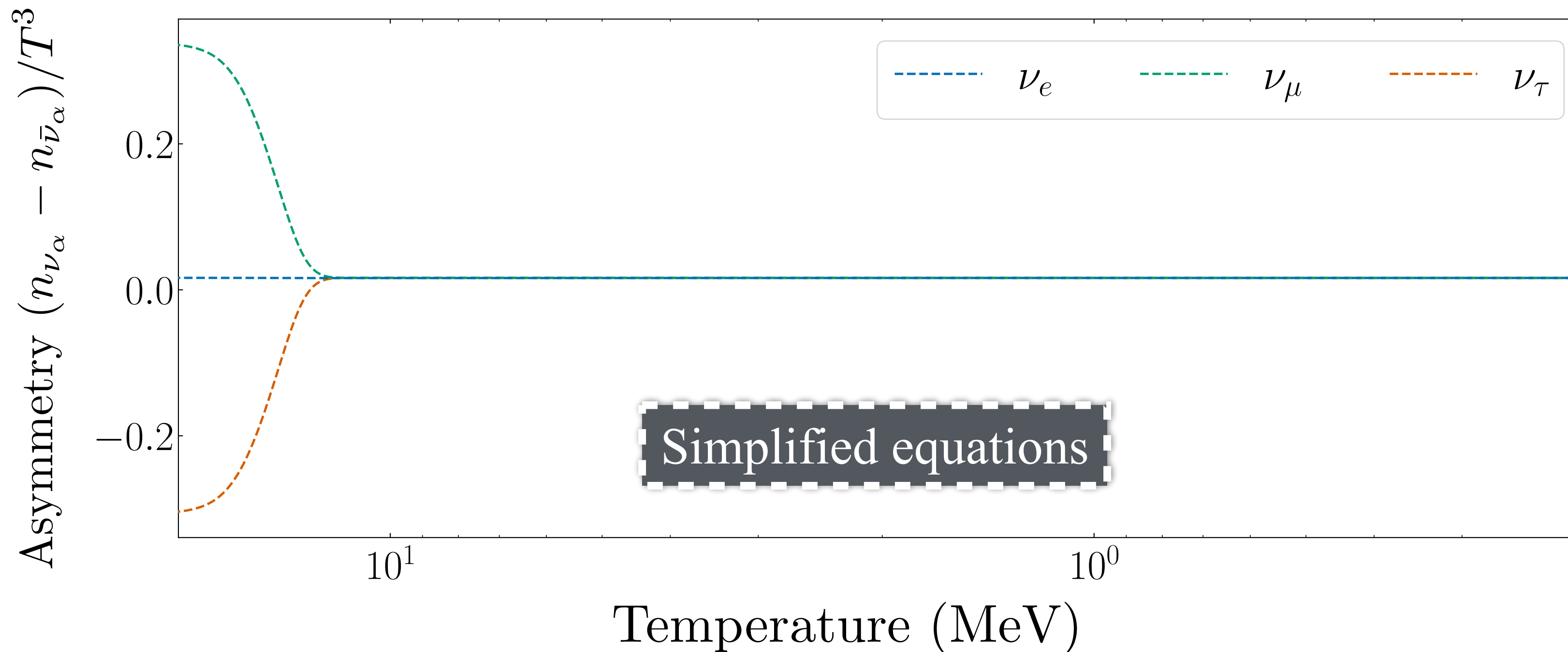
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JF, C. Pitrou, M.C. Volpe [2008.01074]
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- Extension to the case of **nonzero neutrino/antineutrino asymmetries**

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



Neutrino transport in the early Universe

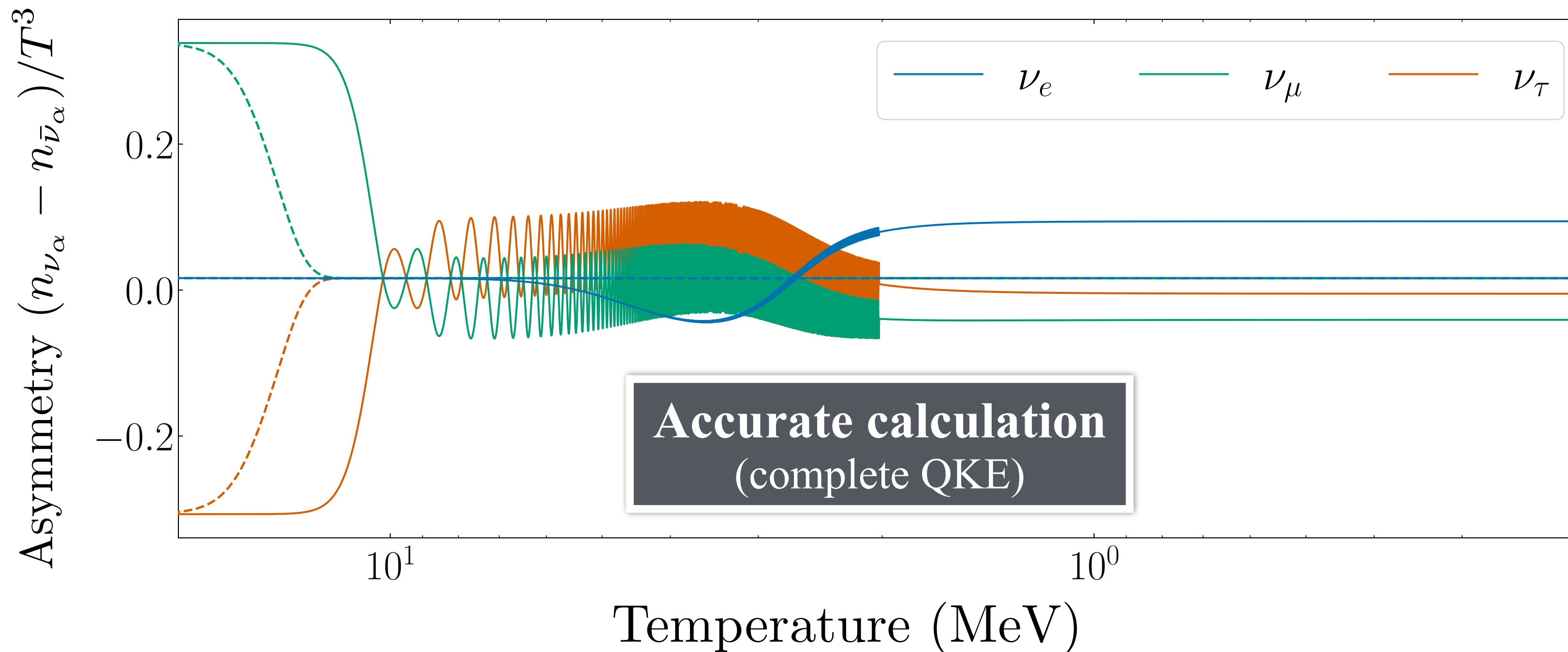
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JF, C. Pitrou [[2110.11889](#)]
JF, C. Pitrou [[2405.06509](#)]

Neutrino transport in the early Universe

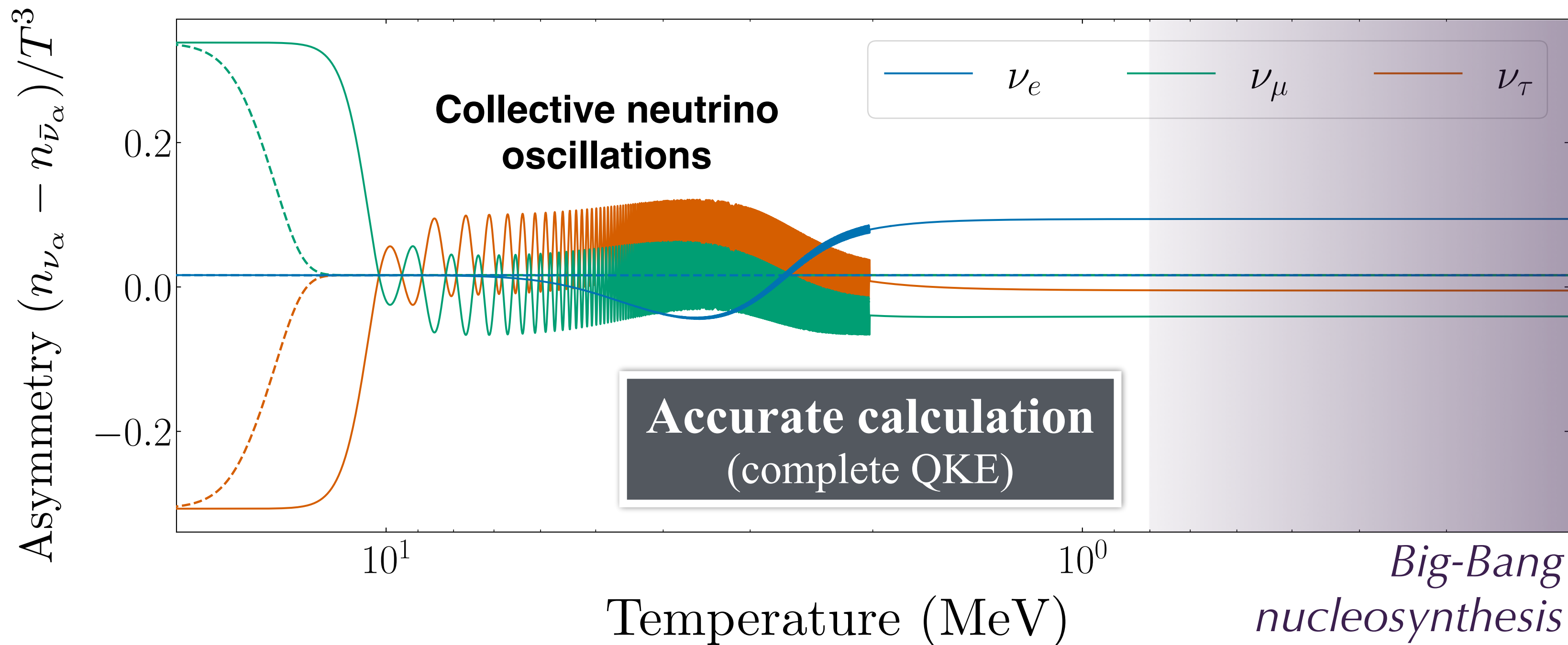
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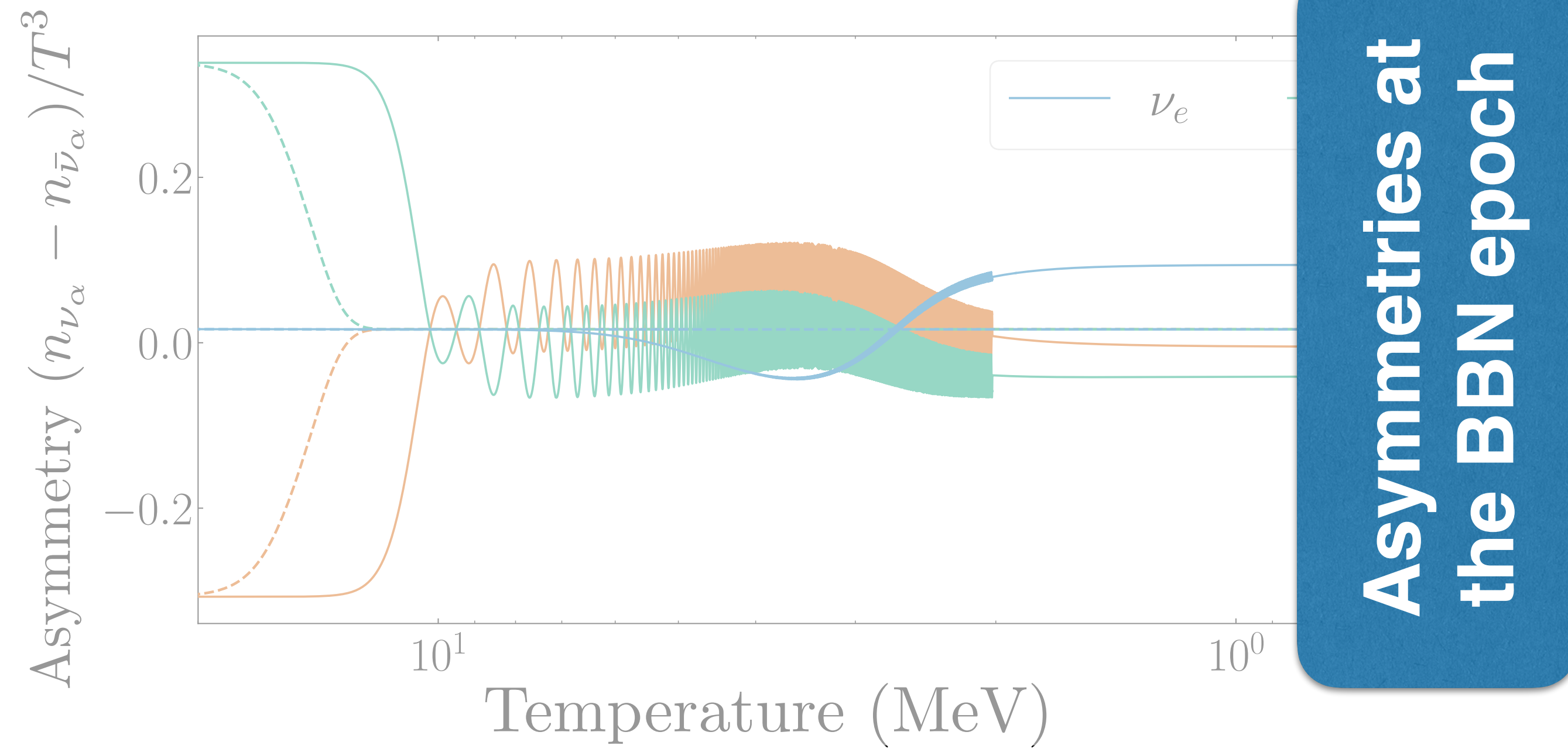
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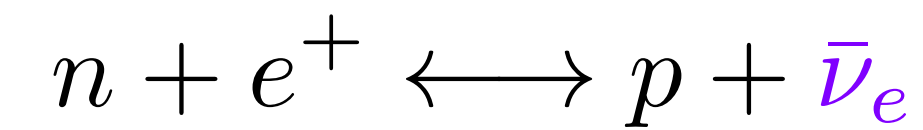
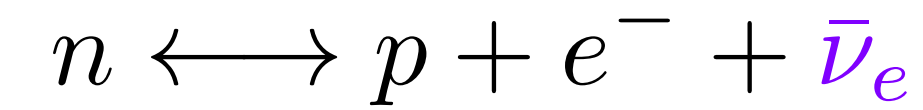
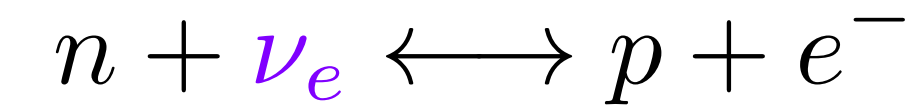
Constraining primordial neutrino asymmetries



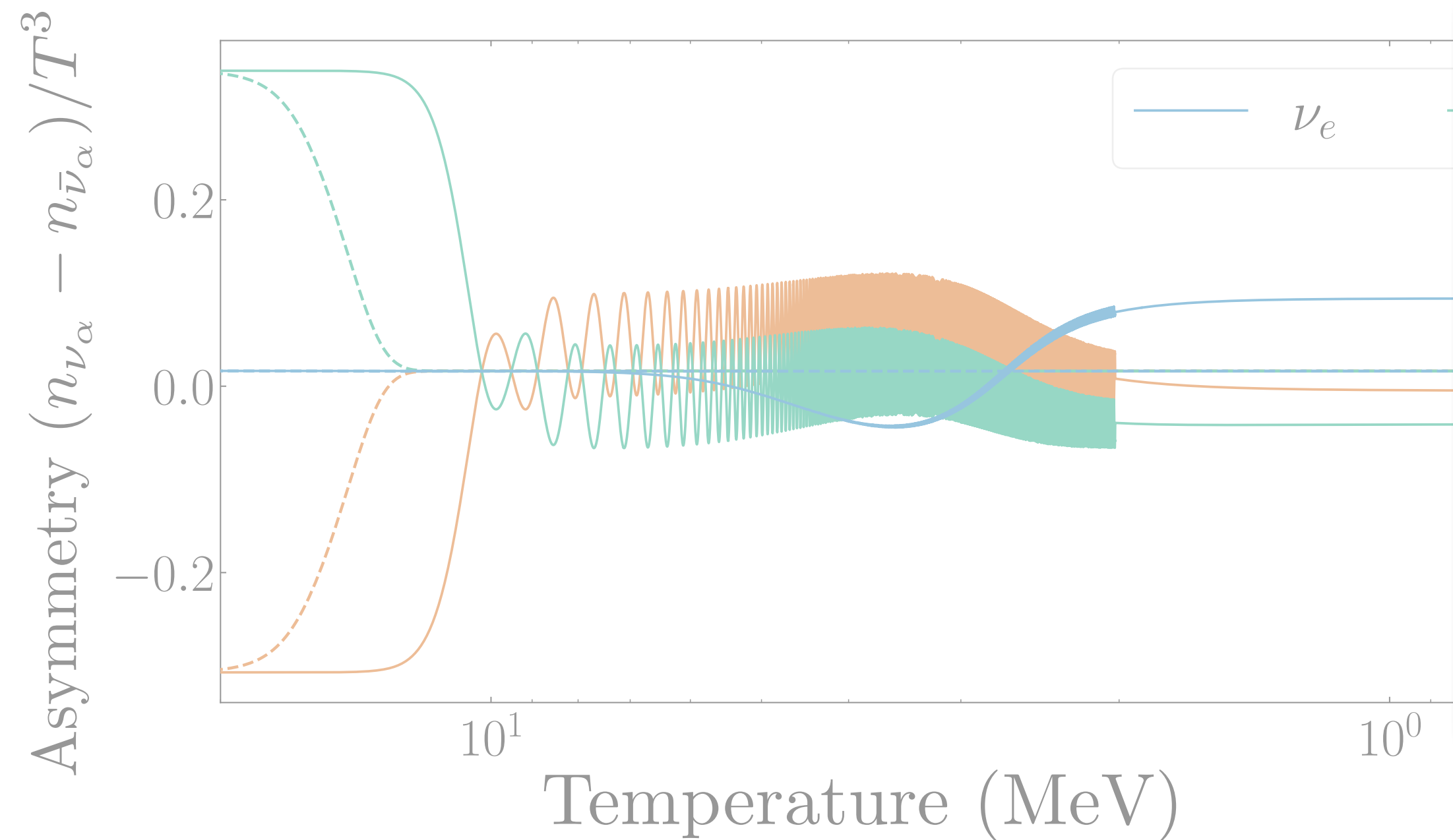
Constraining primordial neutrino asymmetries

Effects of asymmetries:

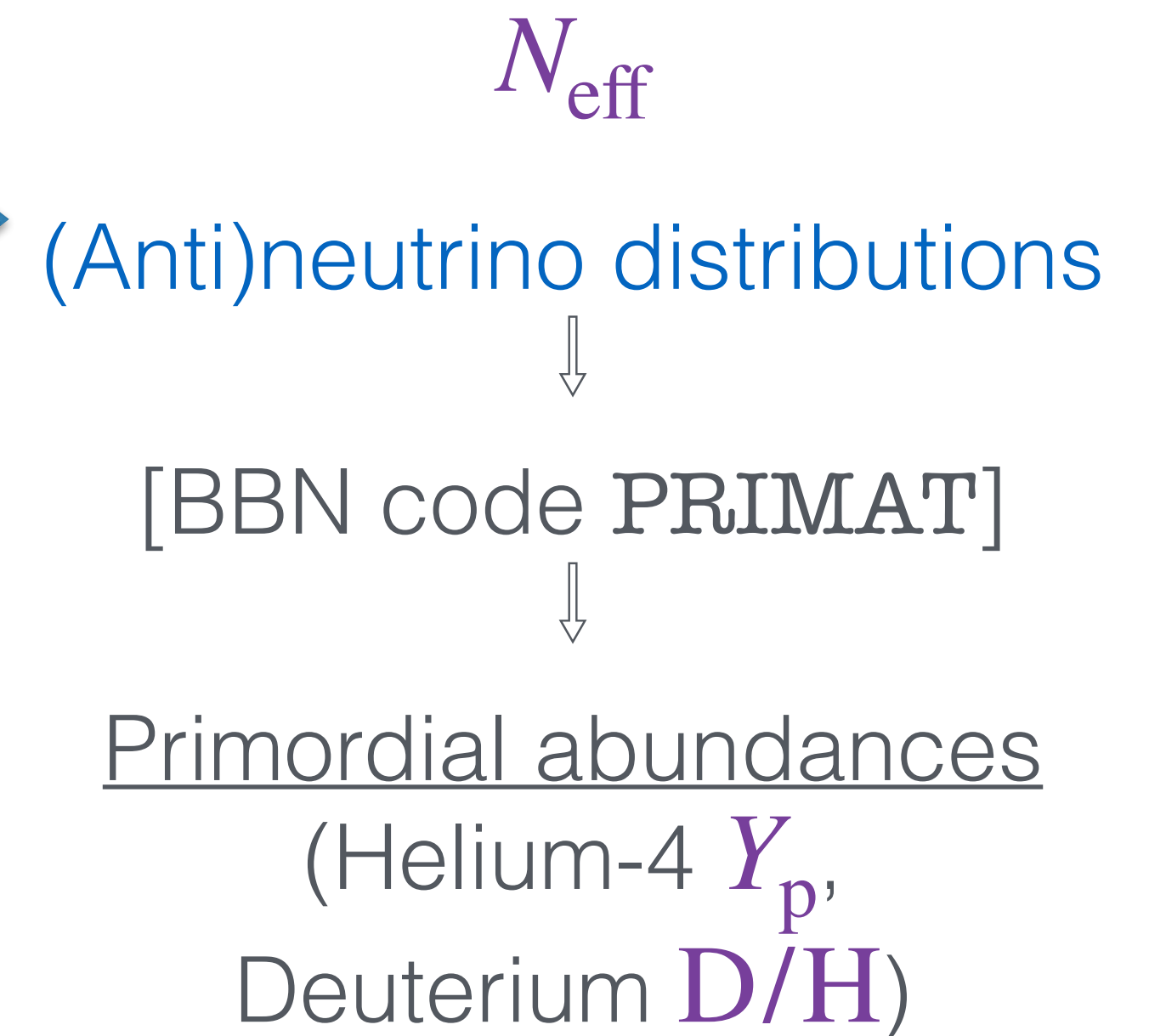
$$\eta_\alpha \equiv \frac{n_{\nu_\alpha} - n_{\bar{\nu}_\alpha}}{T^3}$$



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



Asymmetries at the BBN epoch



Constraining primordial neutrino asymmetries

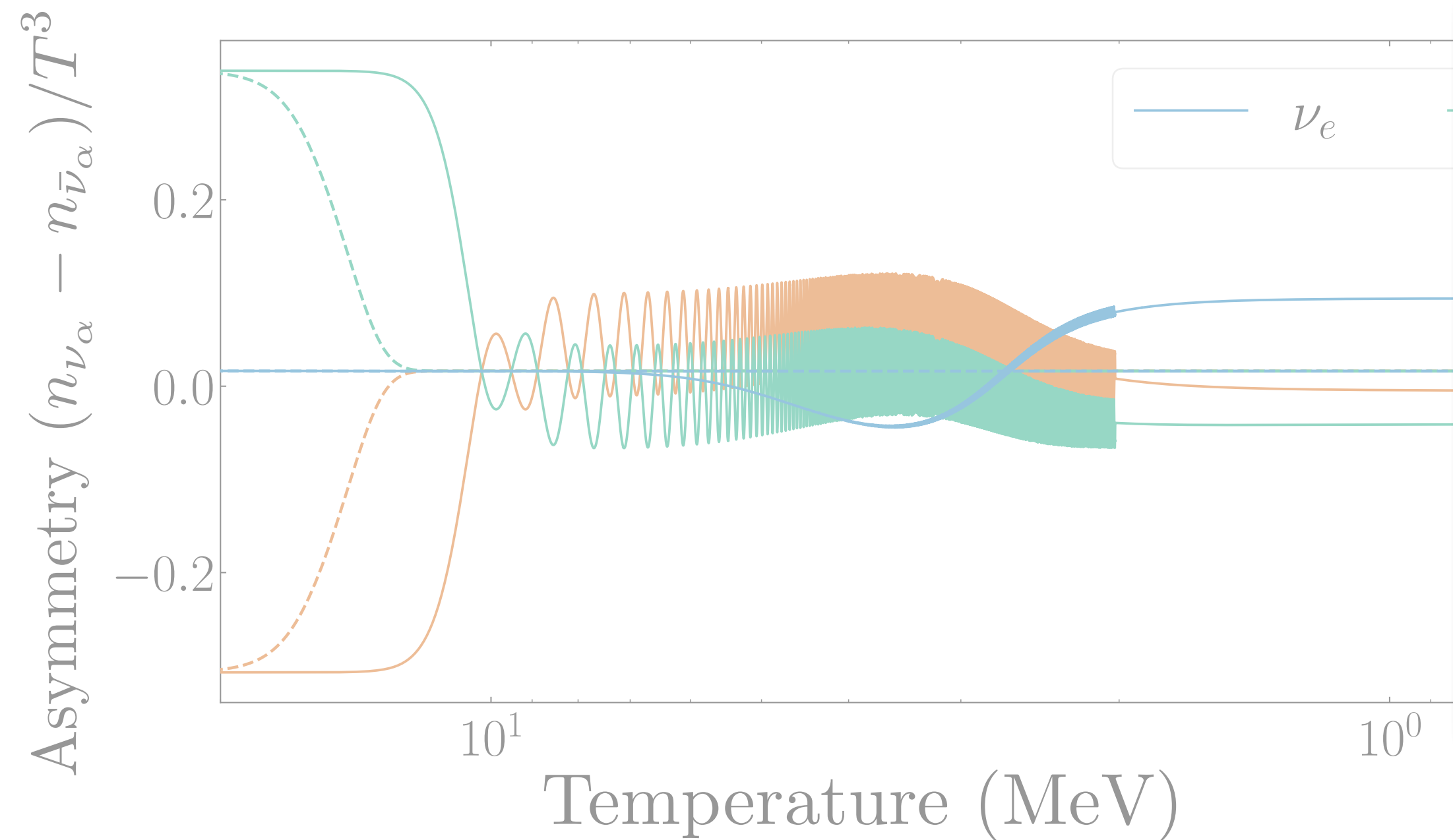
Oldengott & Schwarz [[1706.01705](#)],

Burns *et al.* [[2206.00693](#)],

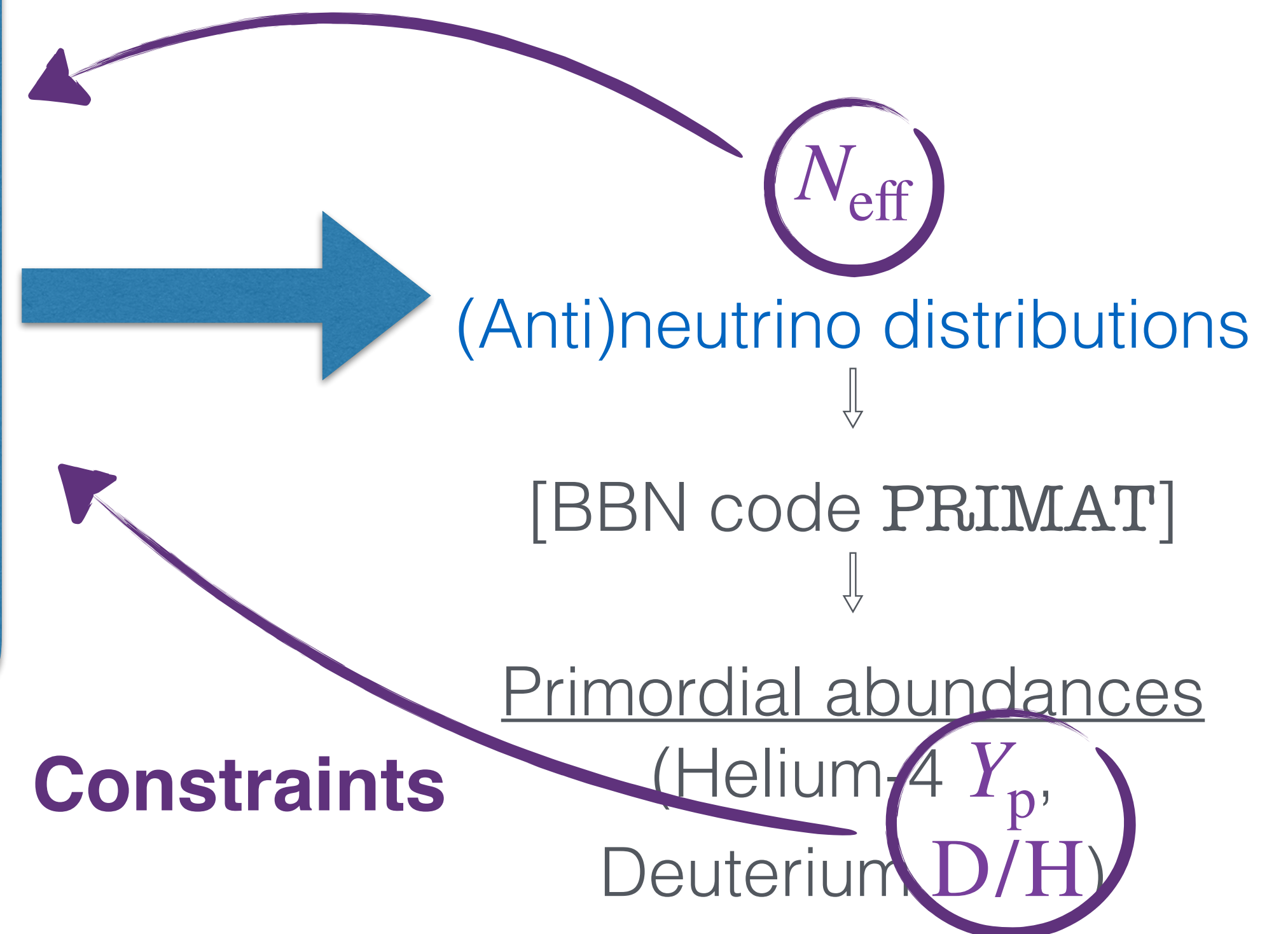
Escudero *et al.* [[2208.03201](#)],

...

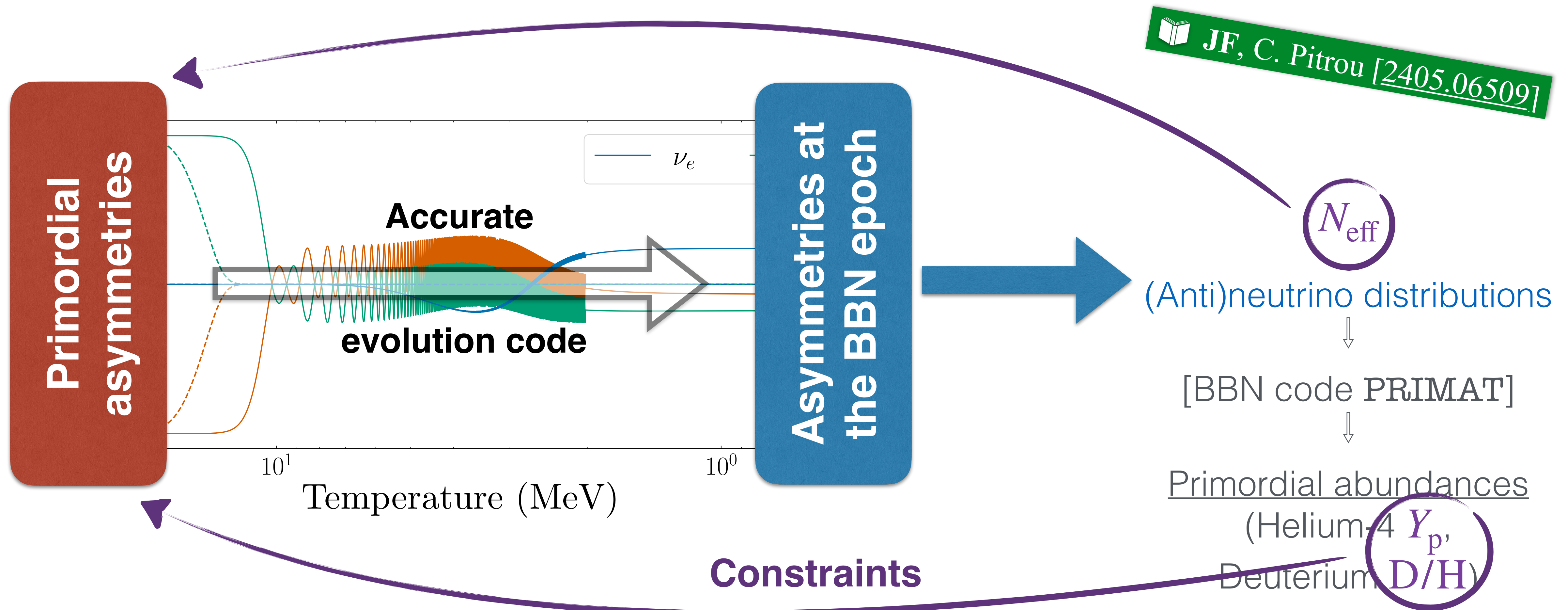
$$\eta_e^{\text{BBN}} = 0.0024 \pm 0.0030$$



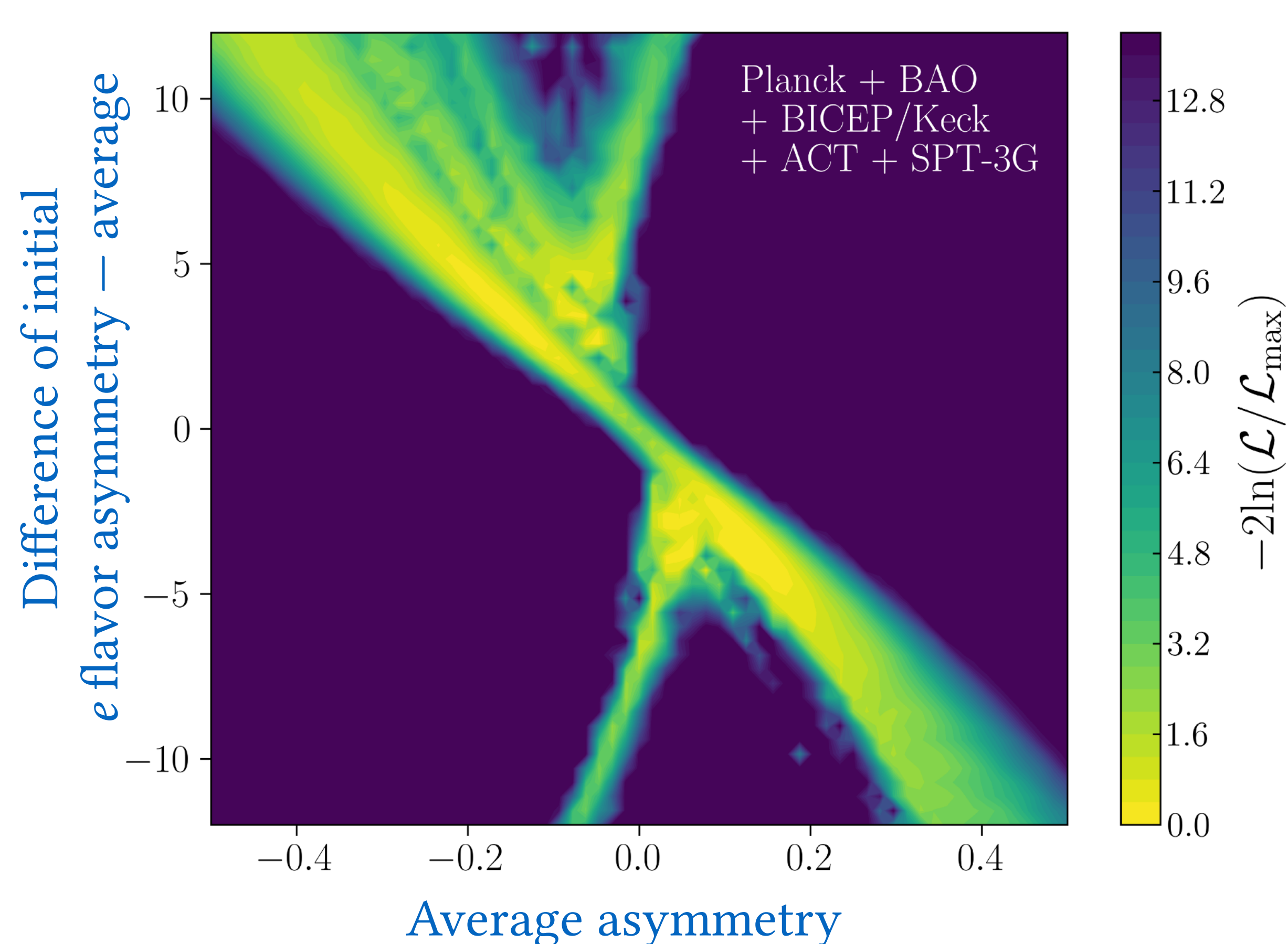
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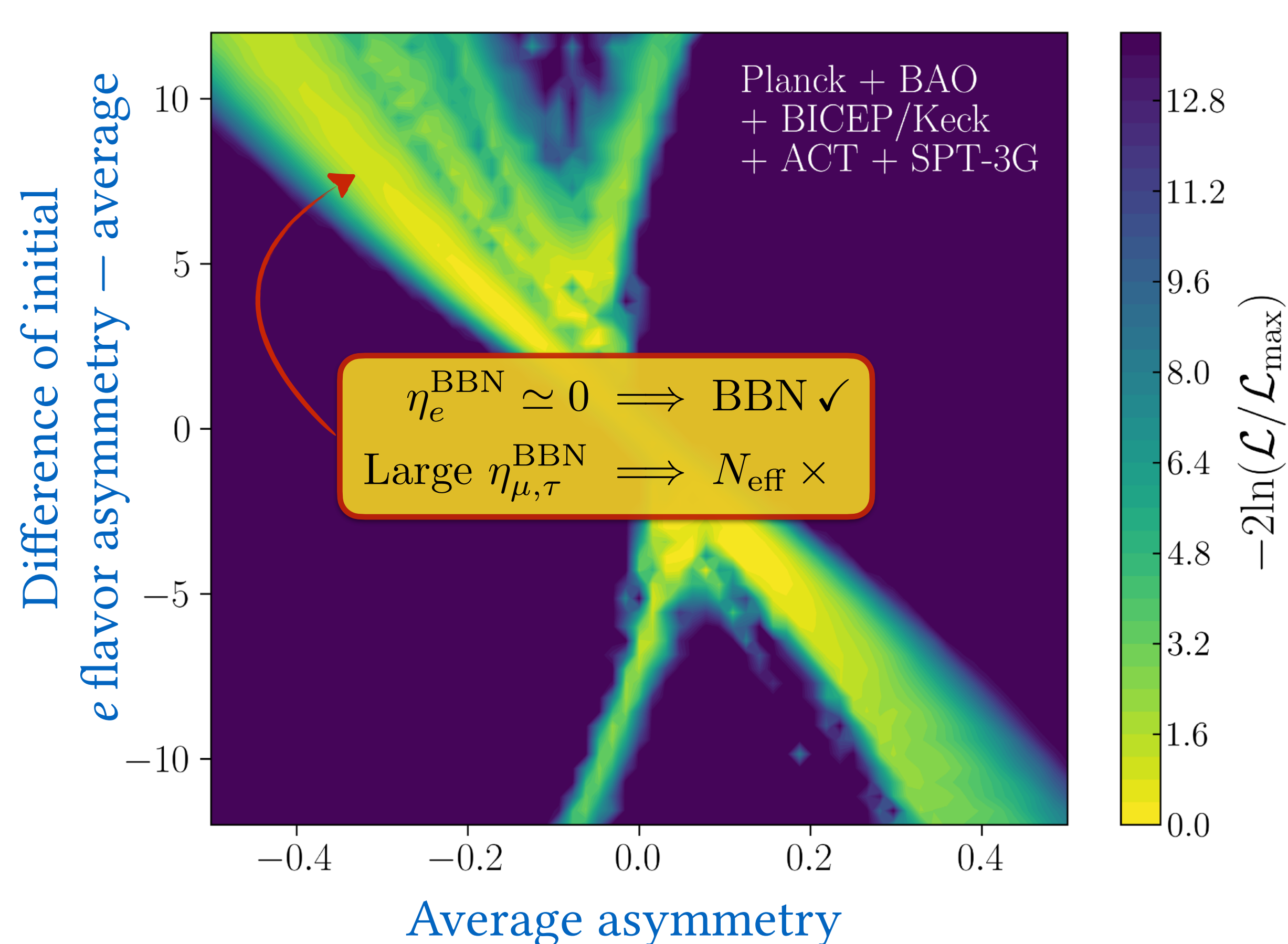
Constraining primordial neutrino asymmetries



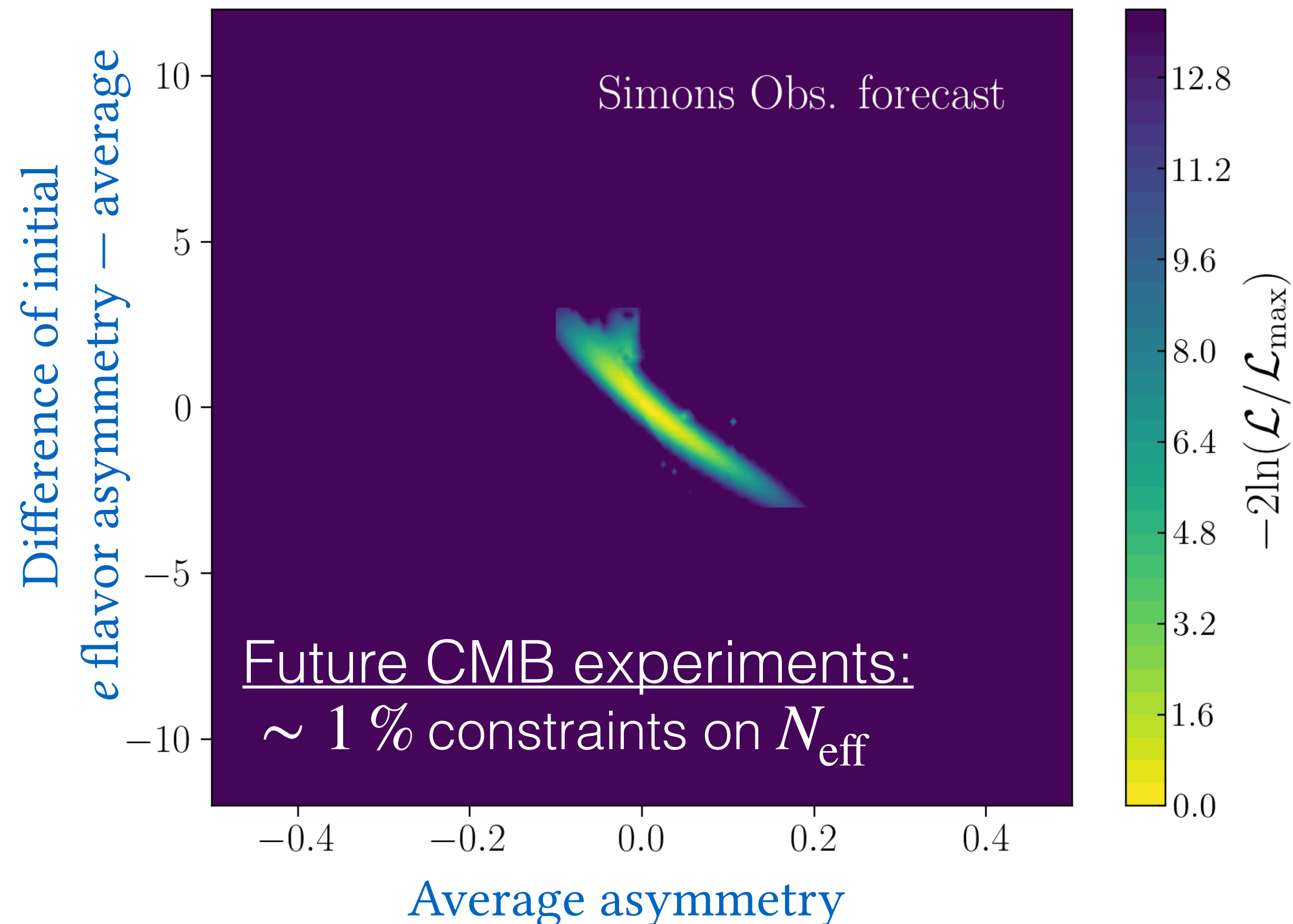
- **Large lepton asymmetries are allowed**, with a complicated landscape due to the dynamics of flavor oscillations.



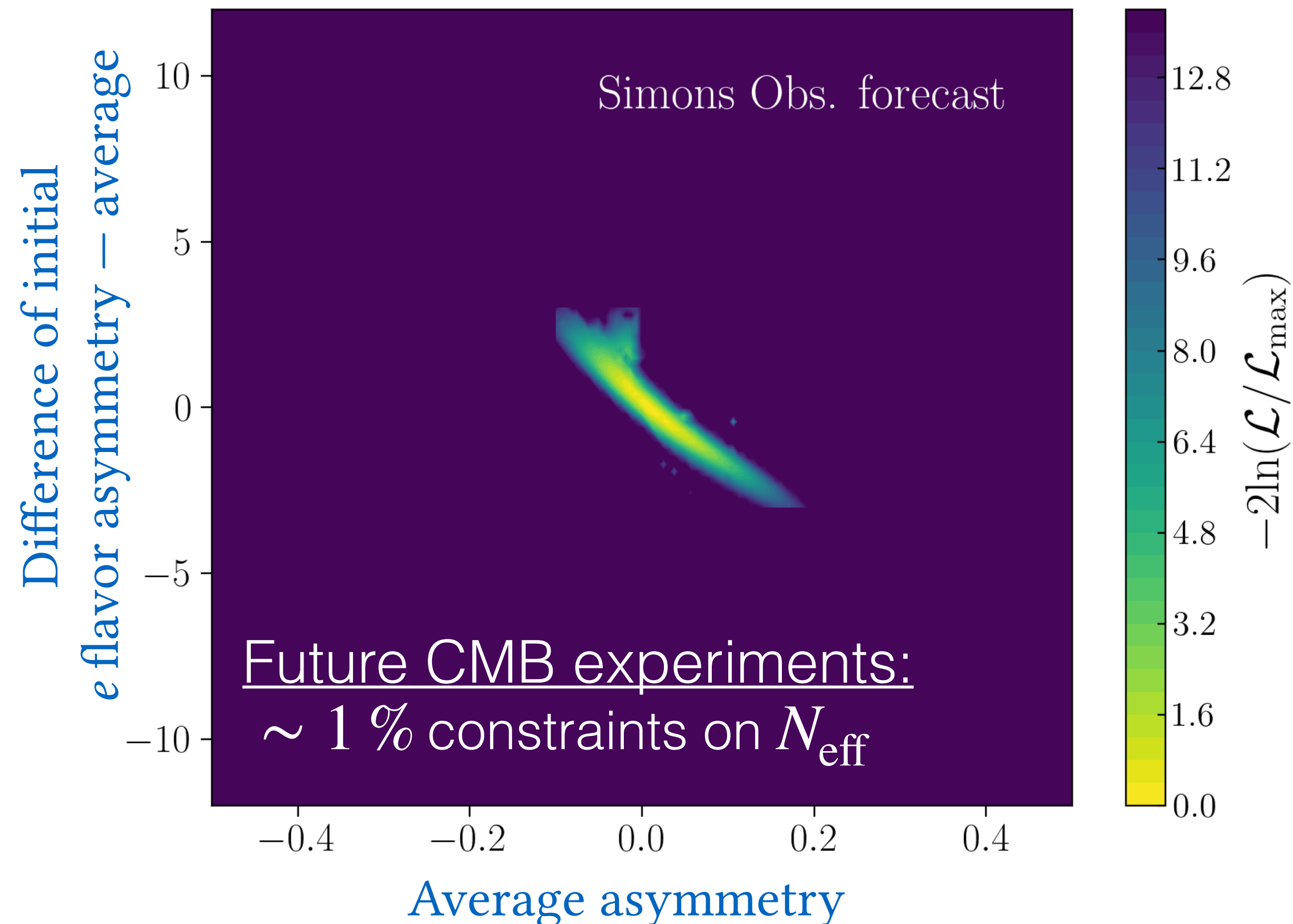
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- Large lepton numbers are needed for some nonstandard scenarios, e.g., the **resonant production of sterile neutrino dark matter** (*Shi-Fuller* mechanism).

 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. Ovchinnikov [2507.20659]

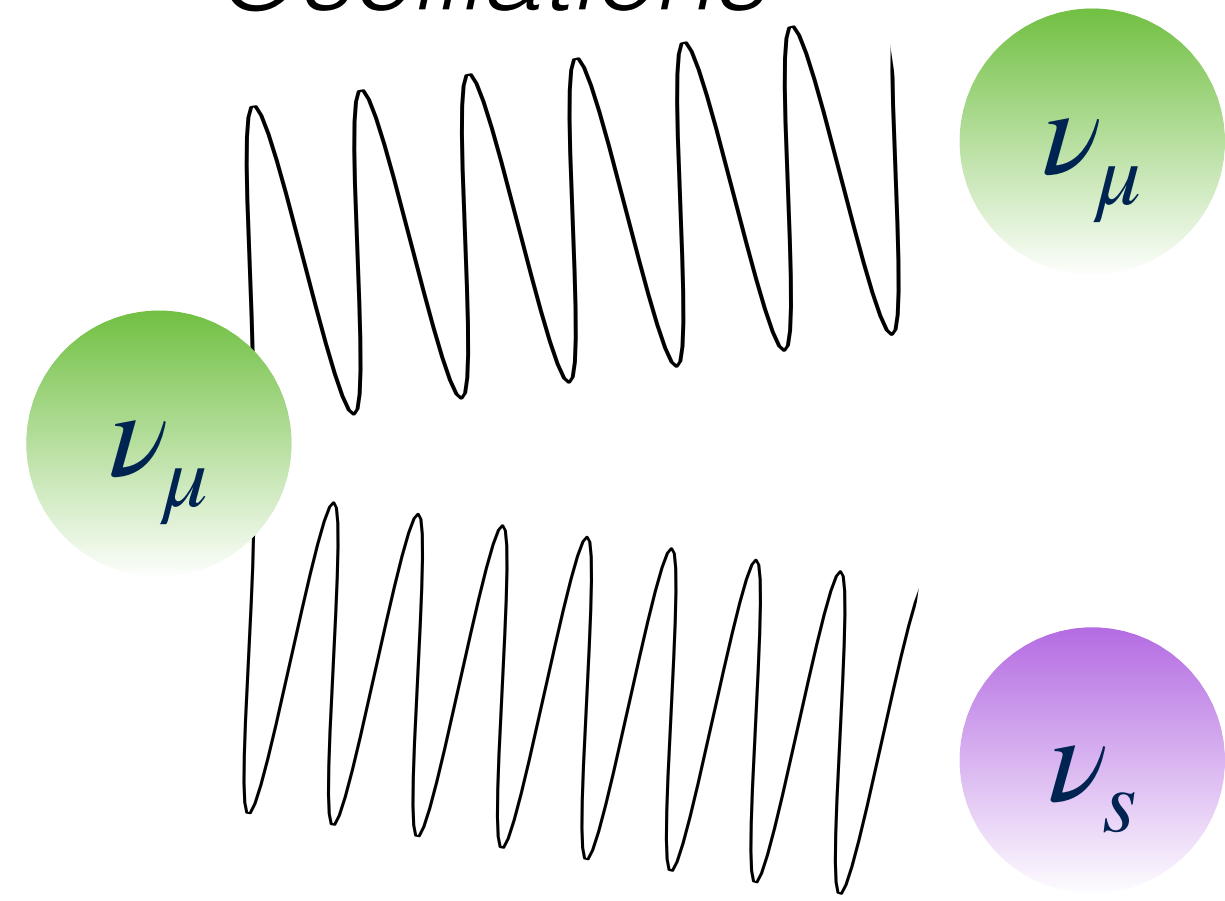
Sterile neutrino dark matter production



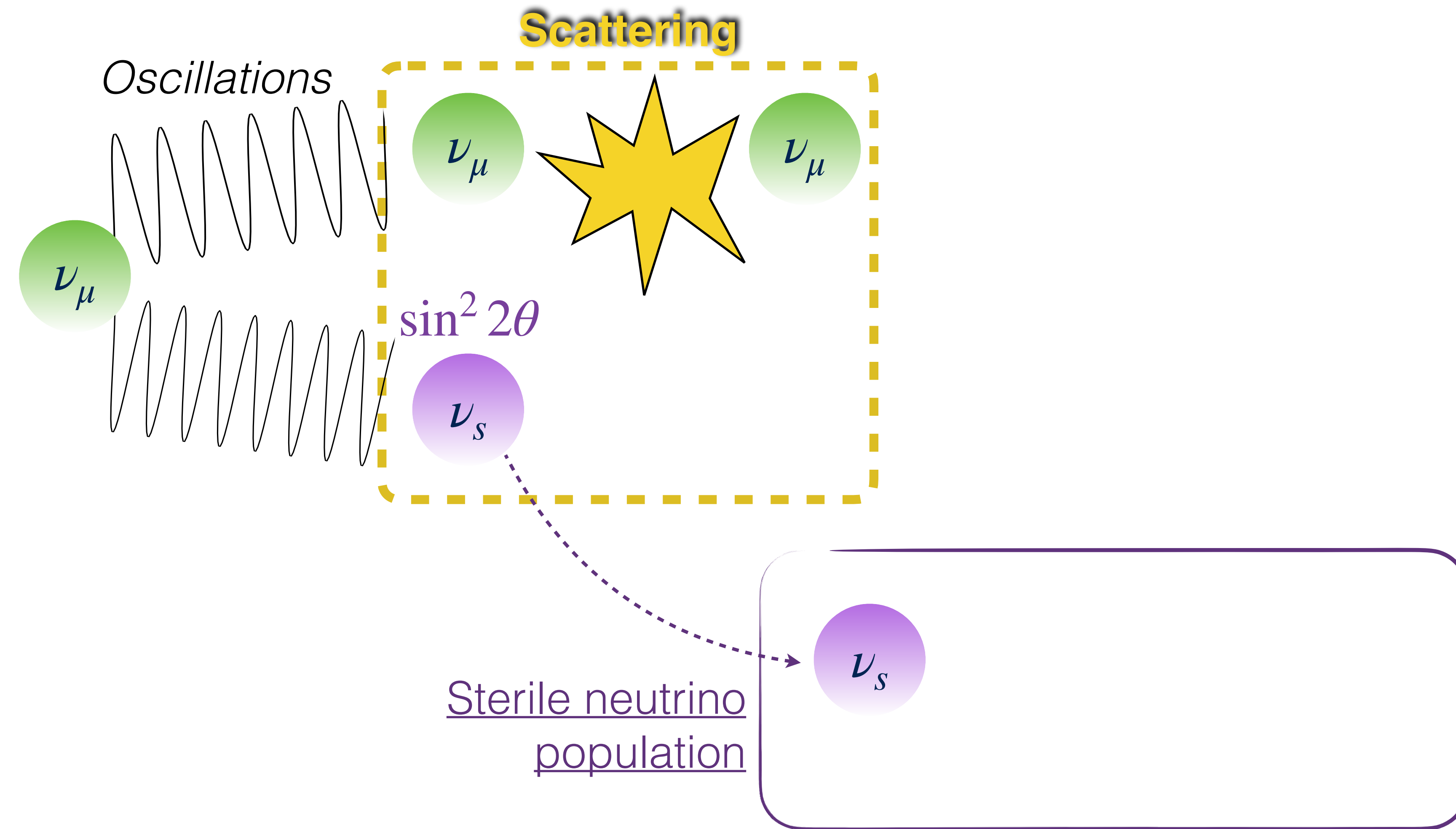
ν_μ

Sterile neutrino dark matter production

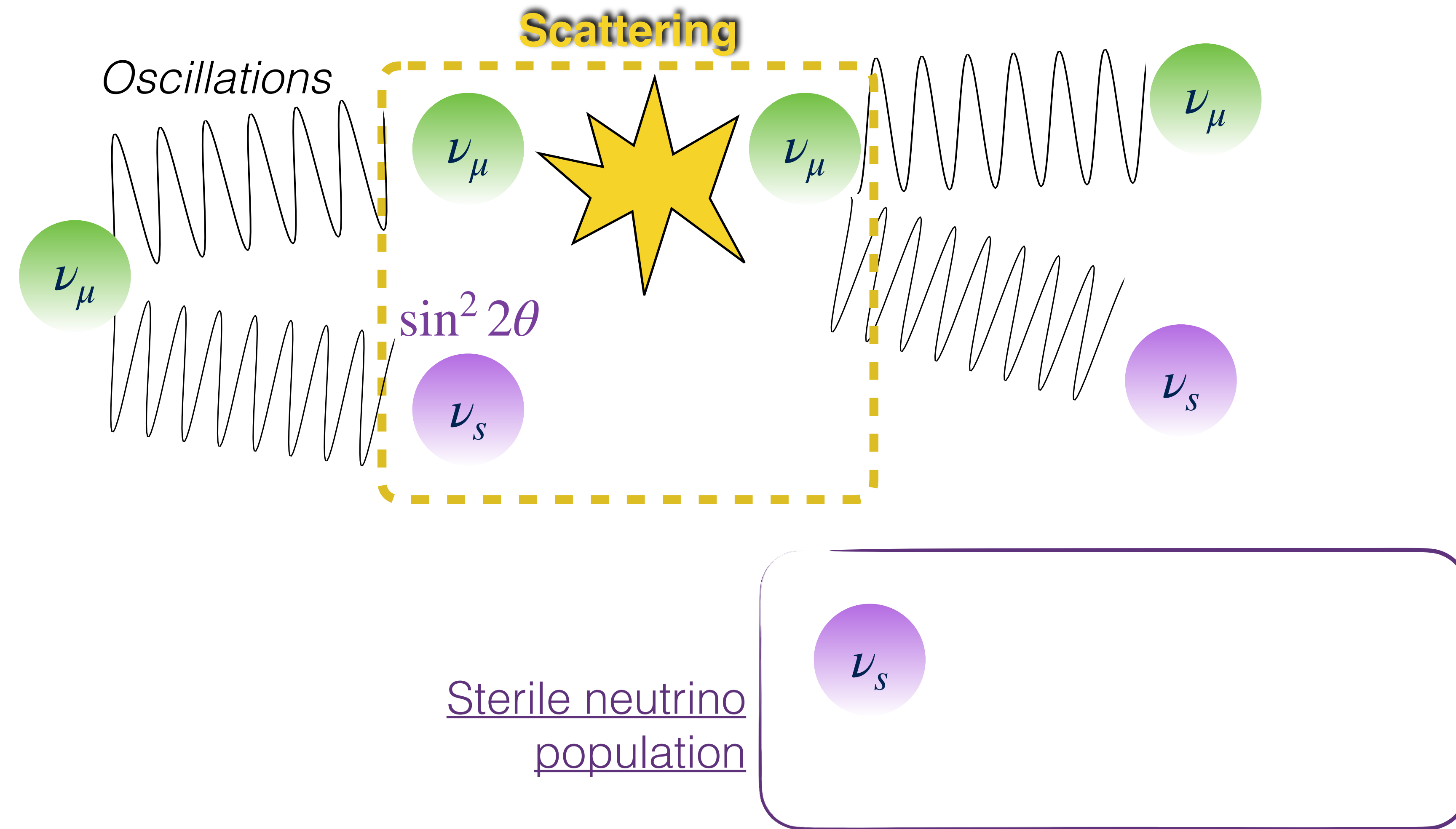
Oscillations



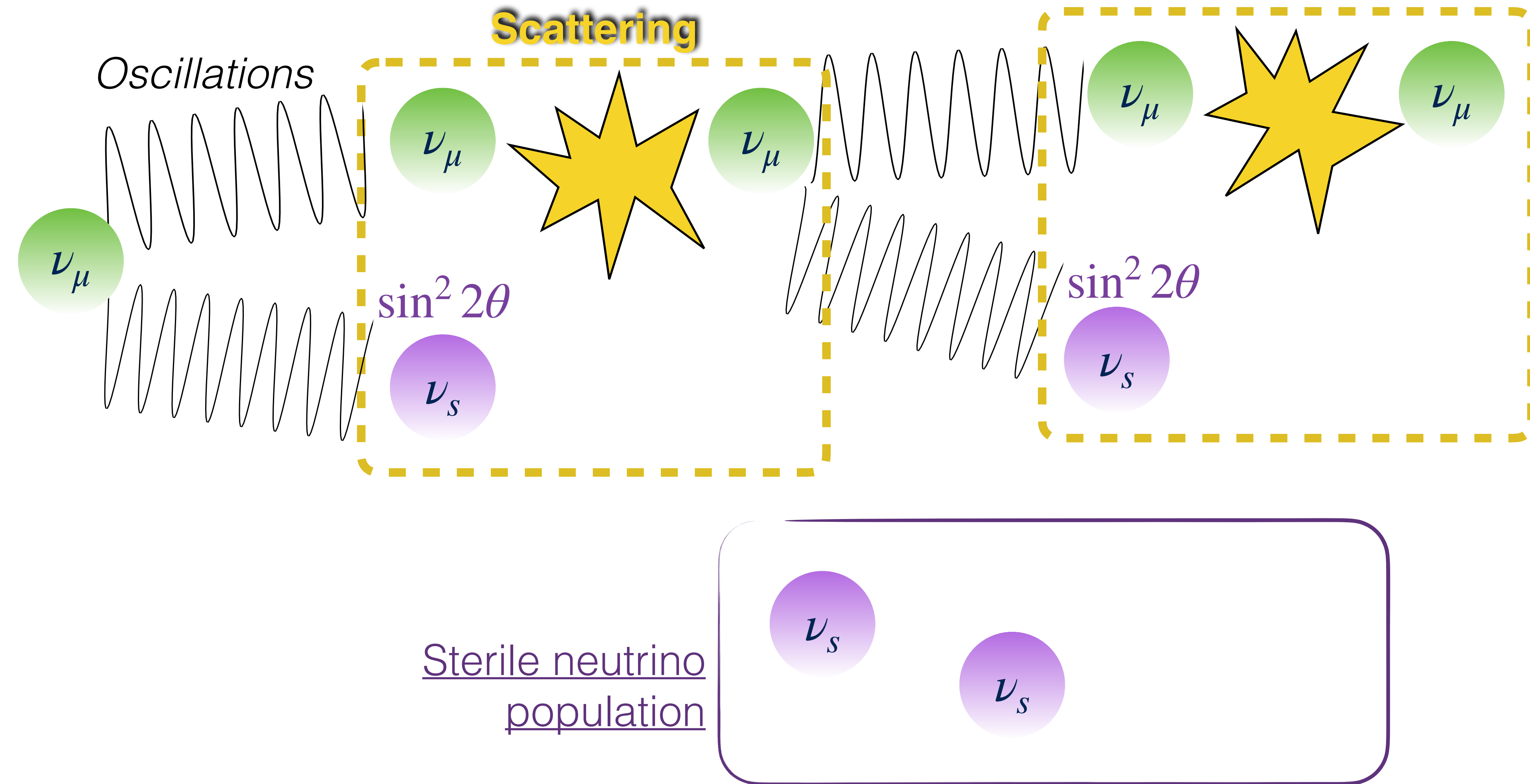
Sterile neutrino dark matter production



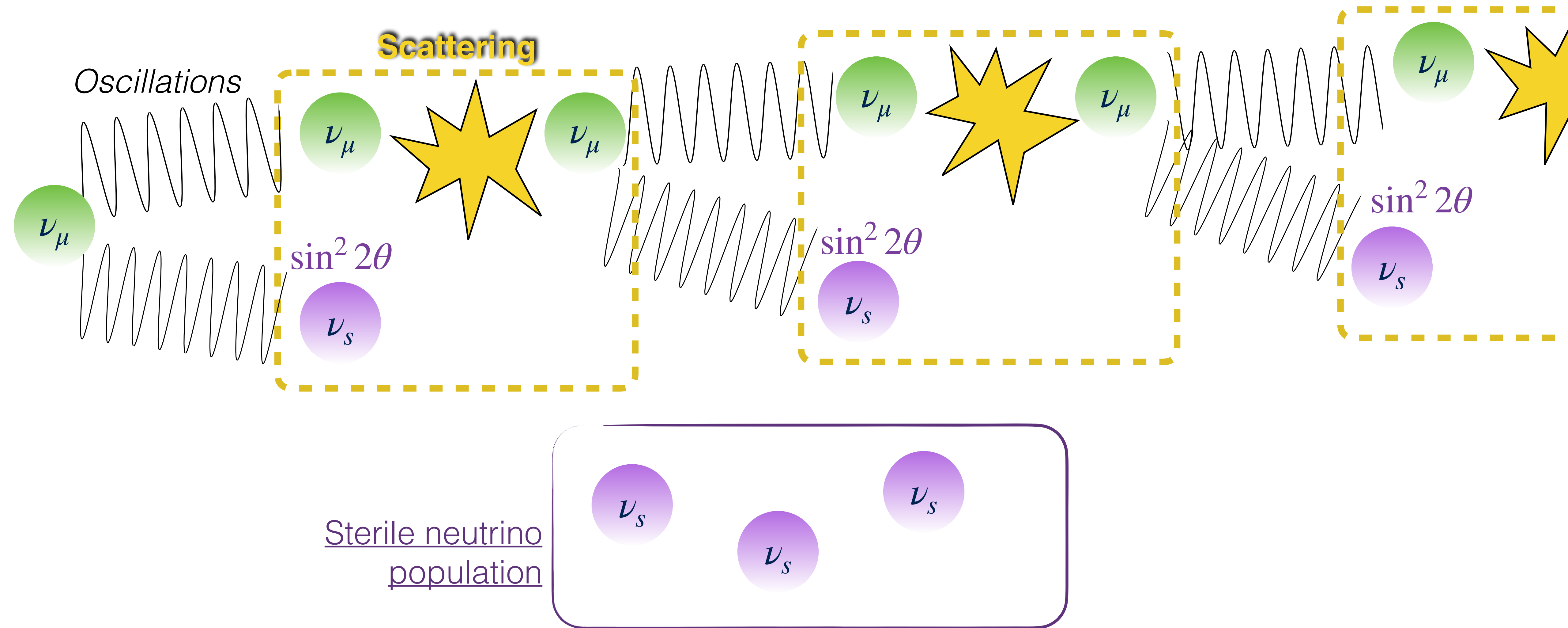
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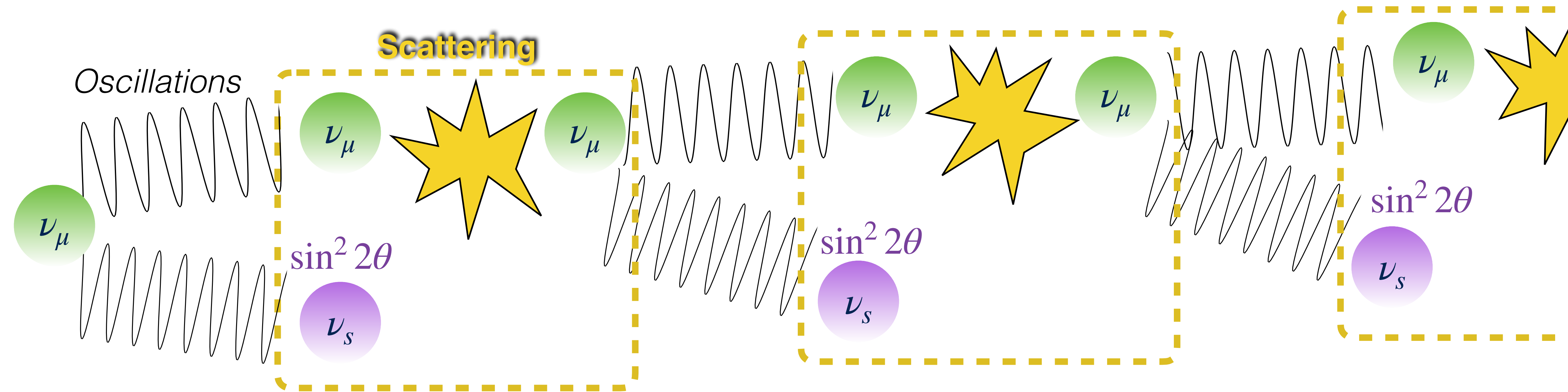
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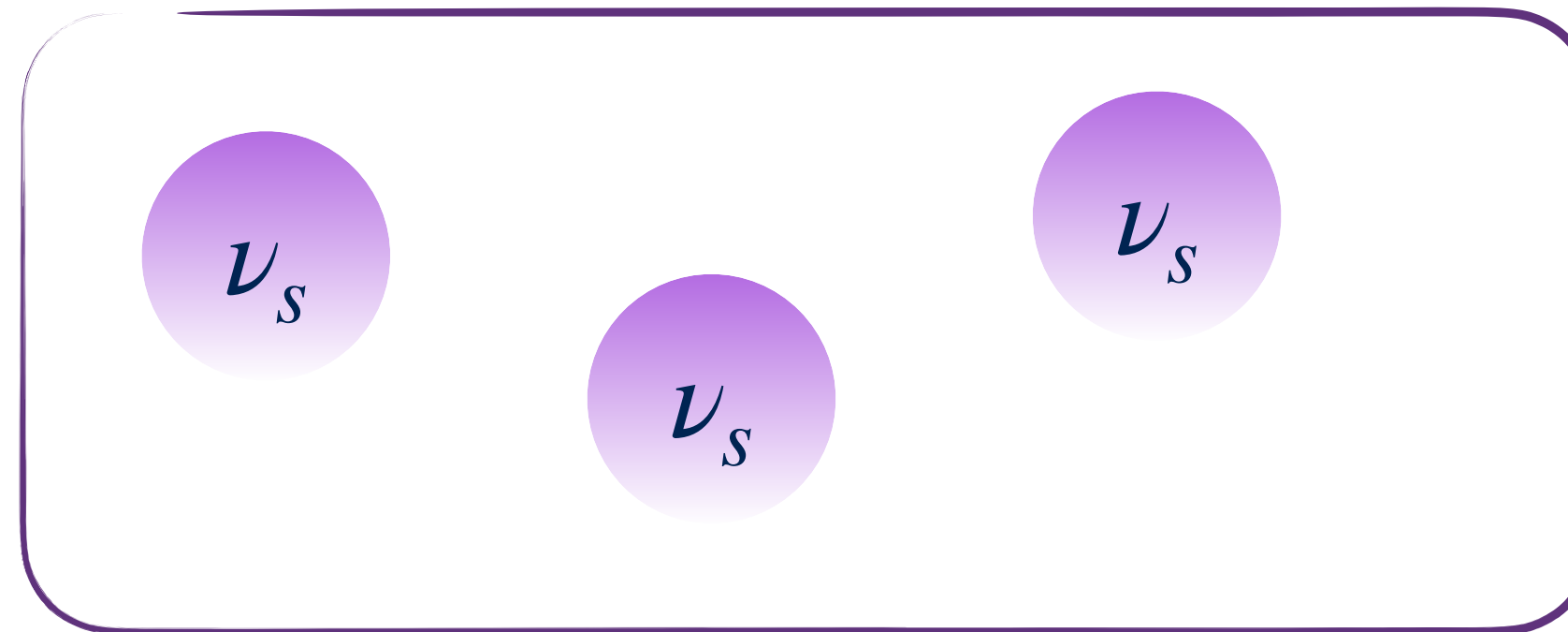
Sterile neutrino dark matter production



Sterile neutrino dark matter production



Sterile neutrino population
 $\propto \sin^2(2\theta)$



DODELSON-WIDROW MECHANISM

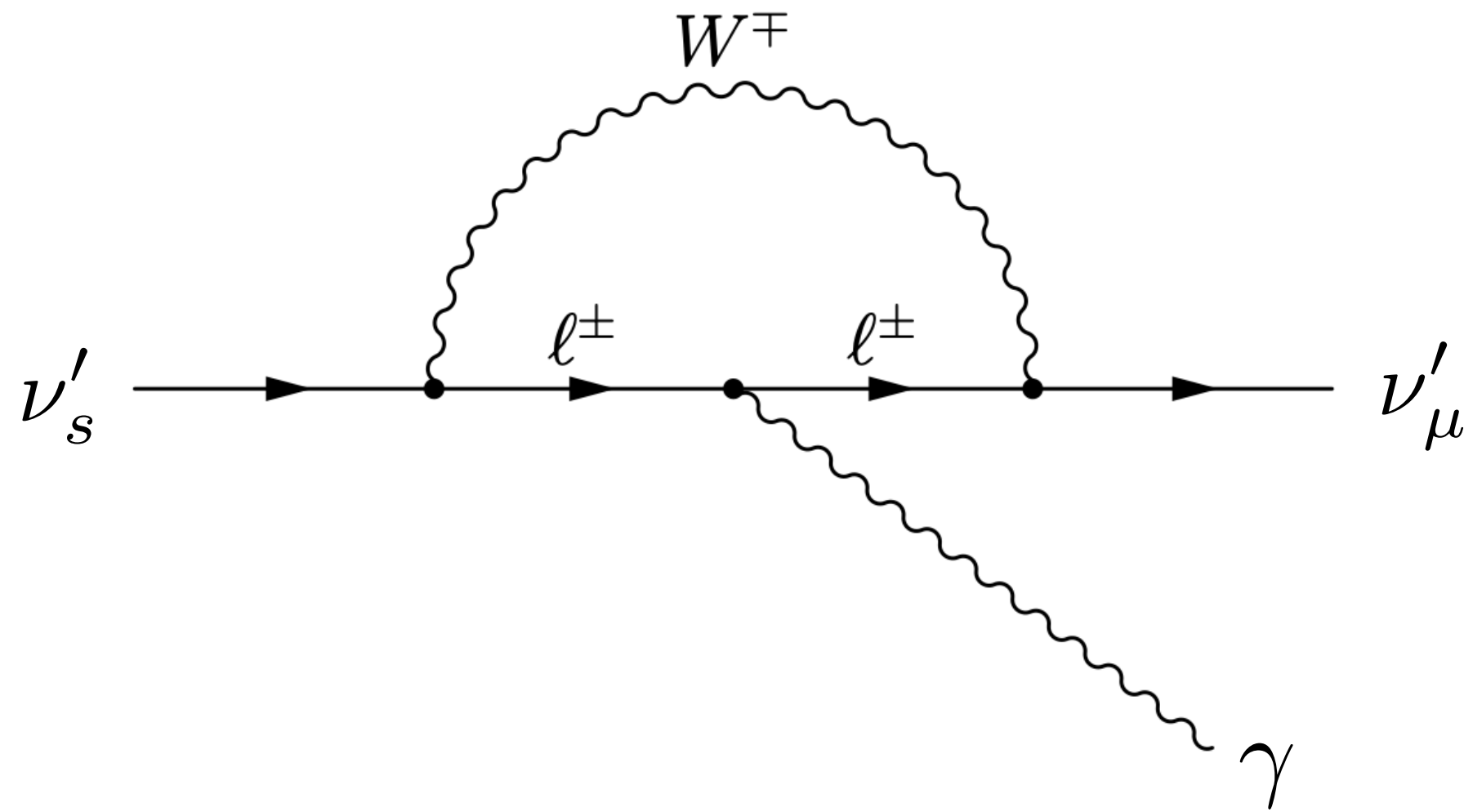
“Scattering-induced decoherence”

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

$\sin^2 2\theta$

Sterile neutrino population
 $\propto \sin^2(2\theta)$

ν_s

ν_s

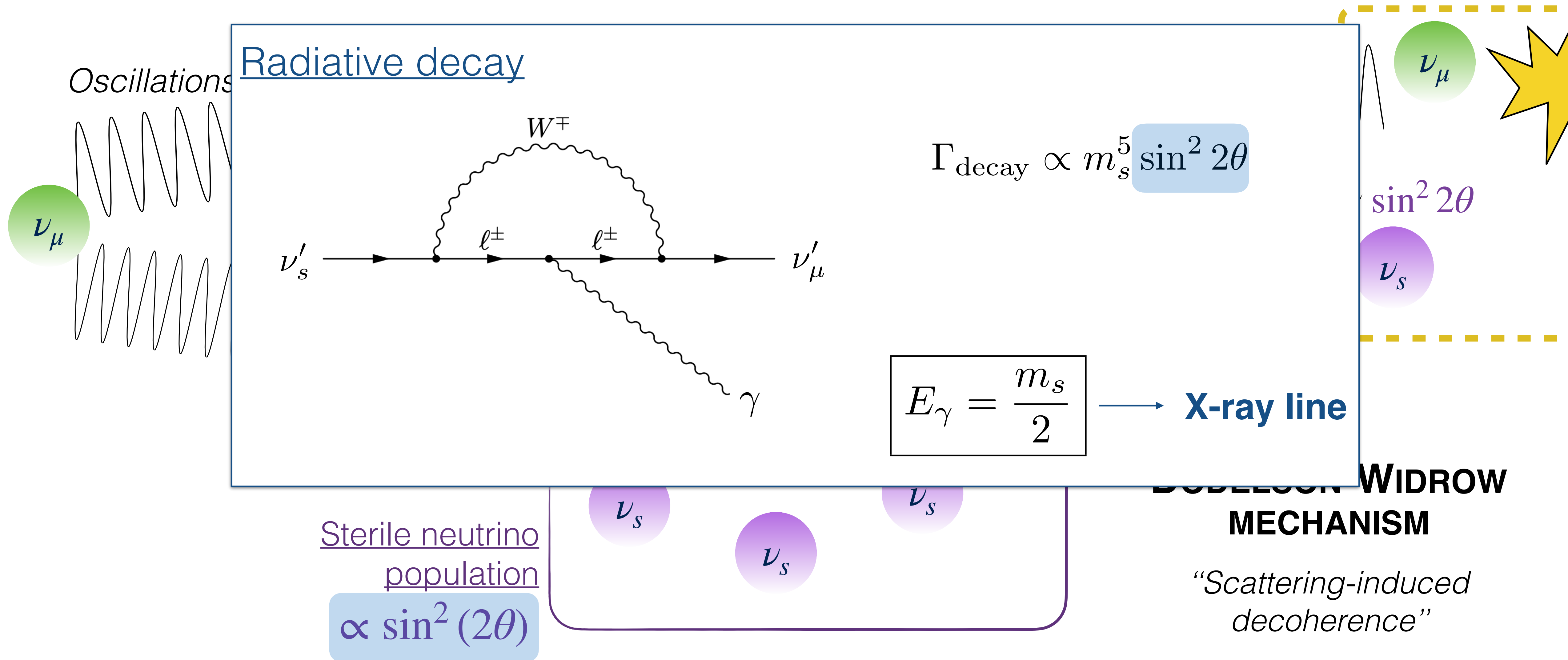
ν_s

**DODELSON-WIDROW
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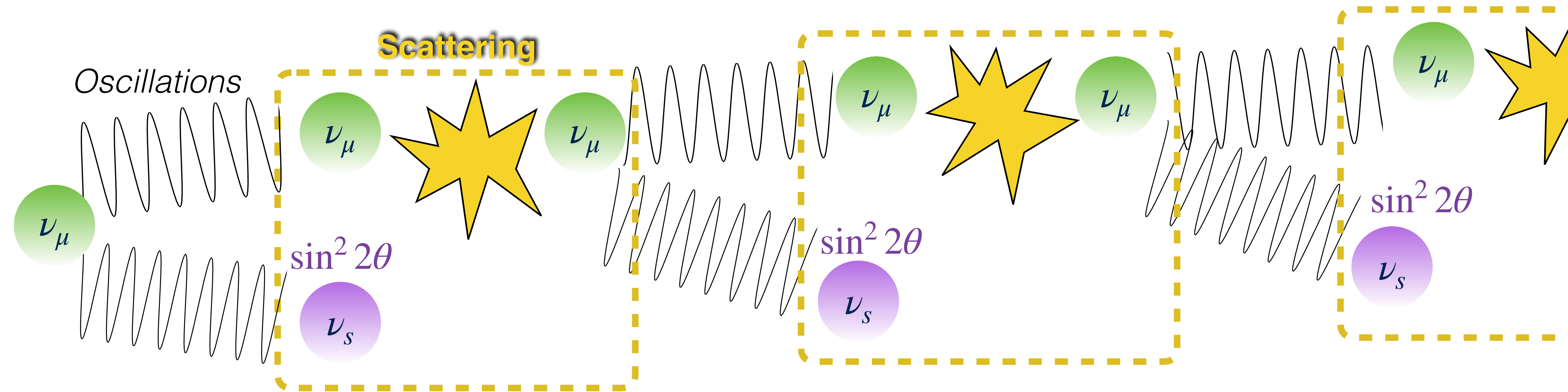
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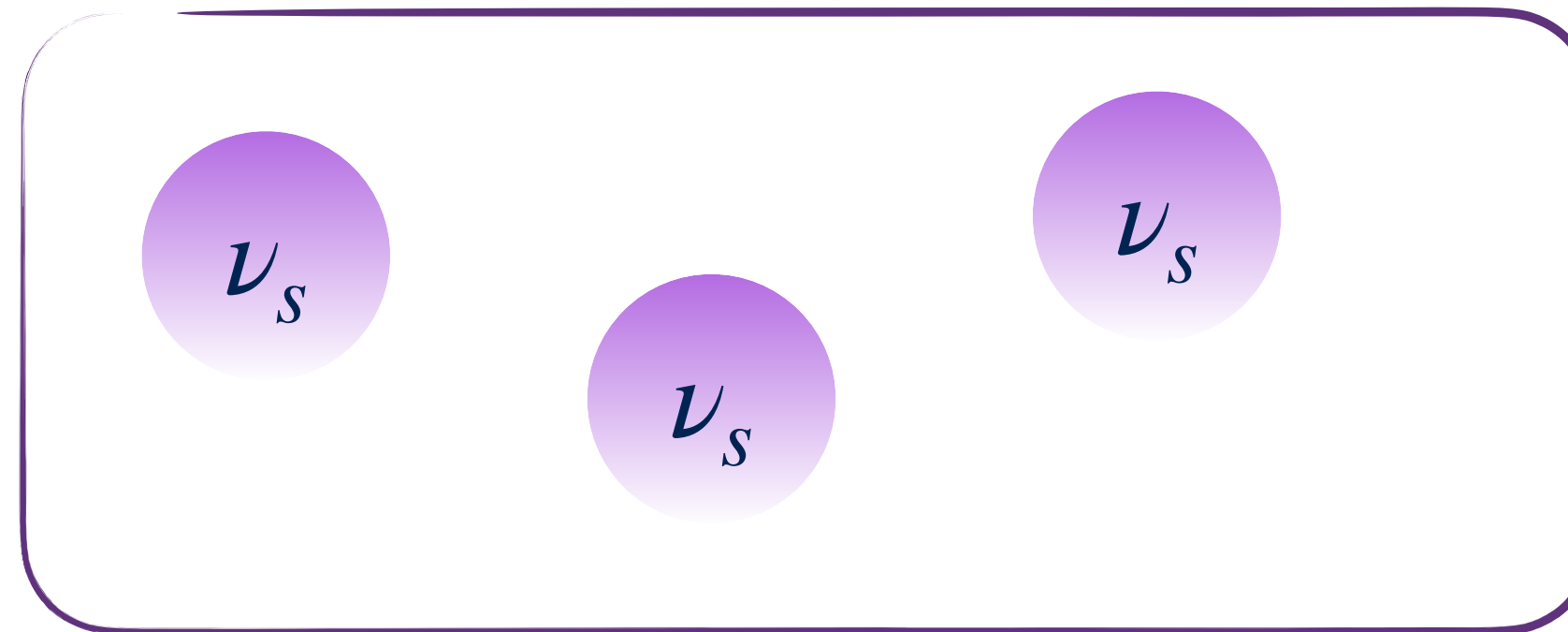


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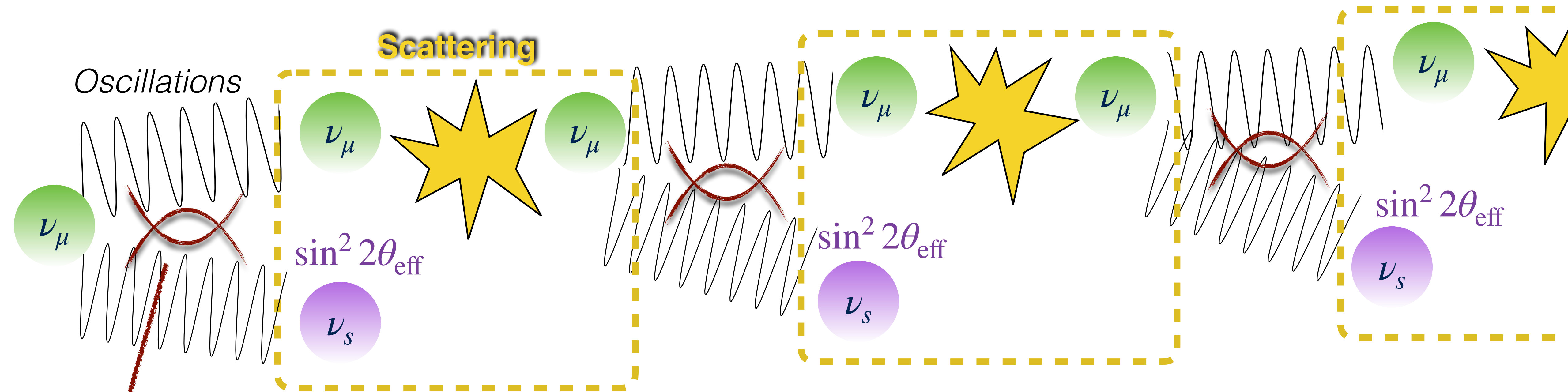


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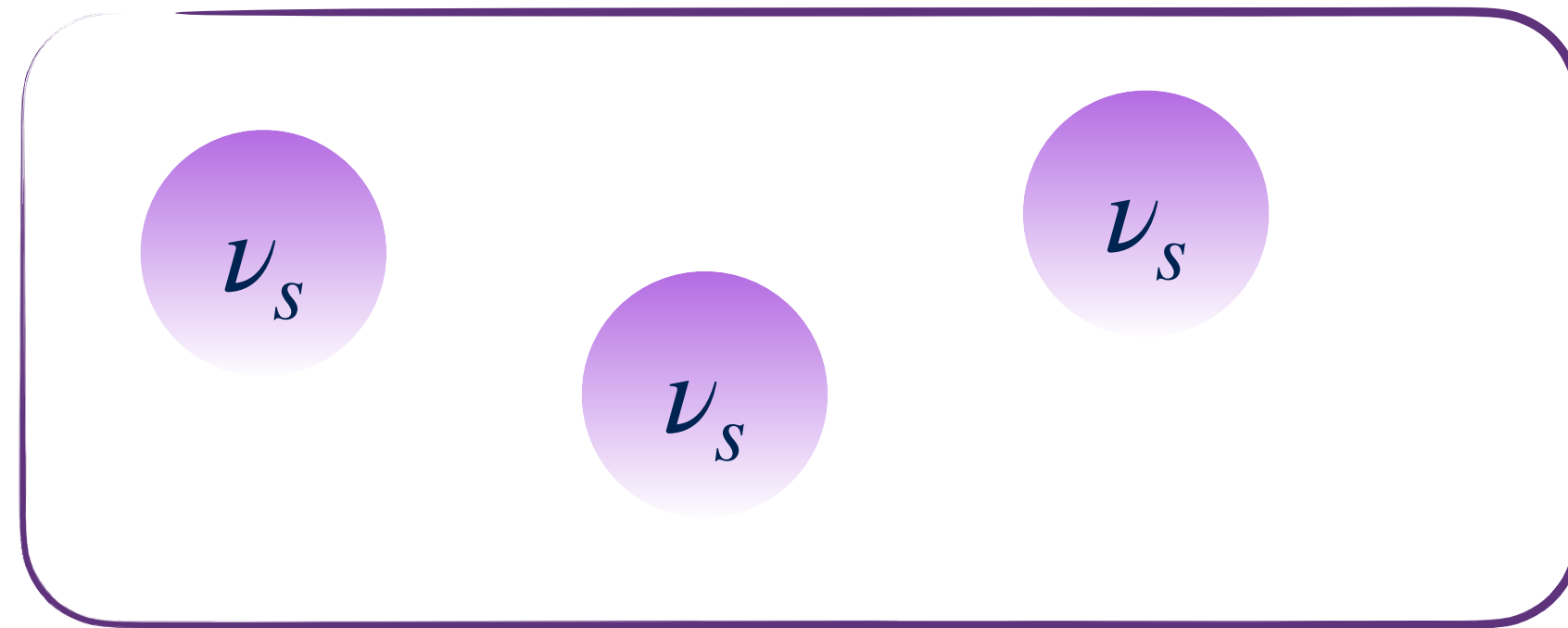
Dodelson & Widrow,
Phys. Rev. Lett. **72**, 17 (1994)

Sterile neutrino dark matter production



**Asymmetry-
induced
resonance**

Sterile neutrino
population
 $\propto \sin^2(2\theta_{\text{eff}}) \gg \sin^2(2\theta)$



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](#)]

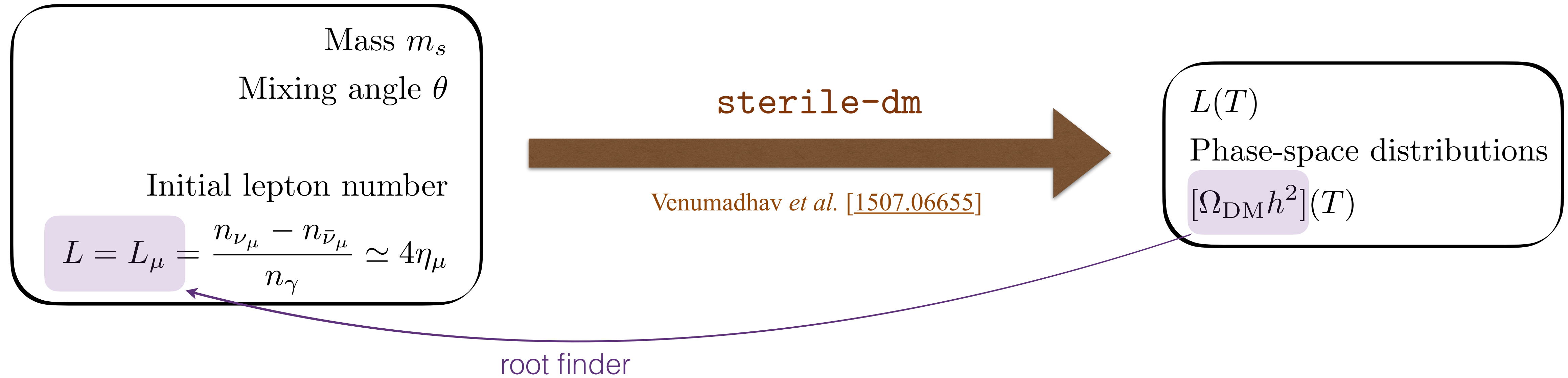
$L(T)$

Phase-space distributions

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

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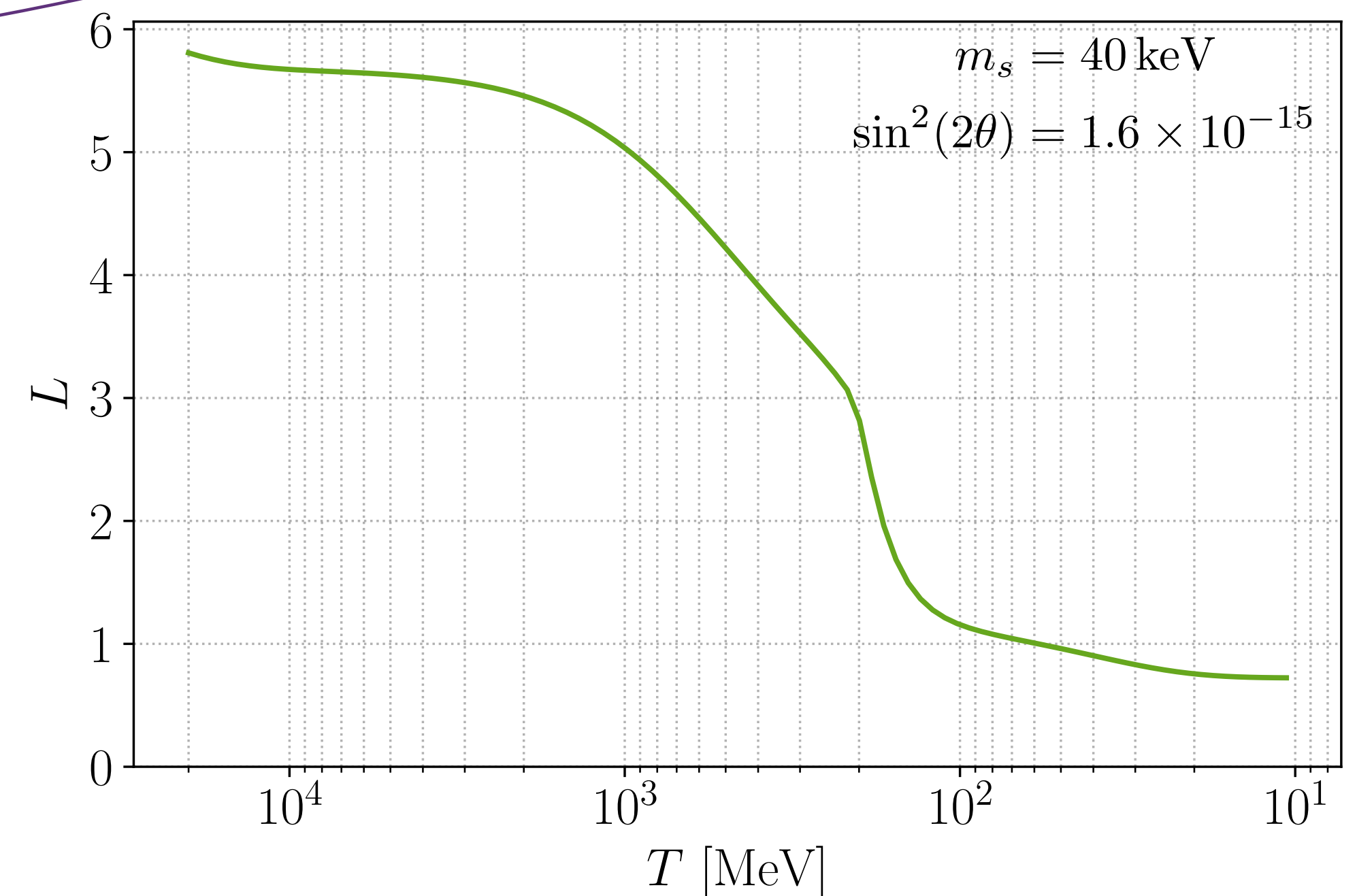
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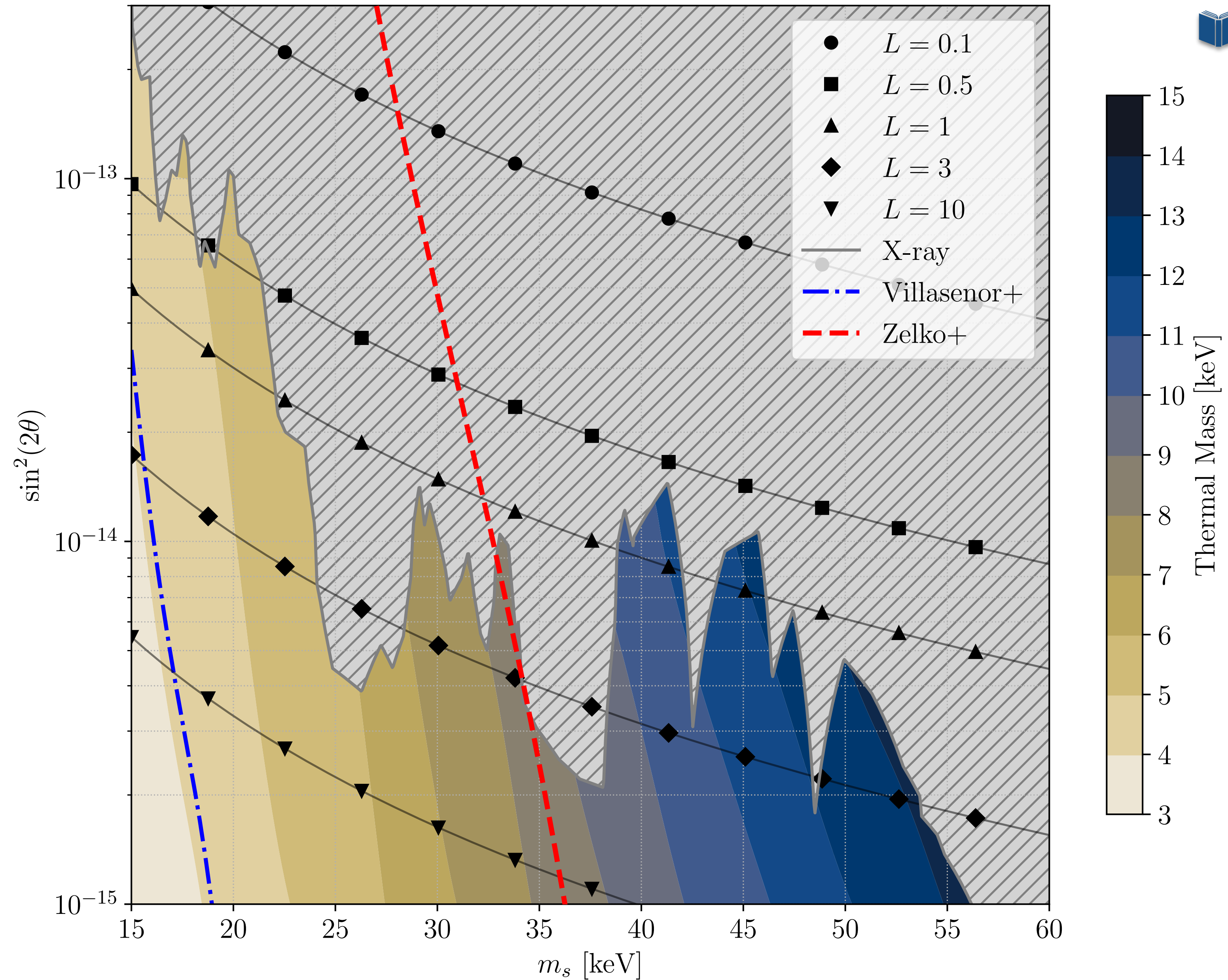
$[\Omega_{\text{DM}} h^2](T)$

root finder



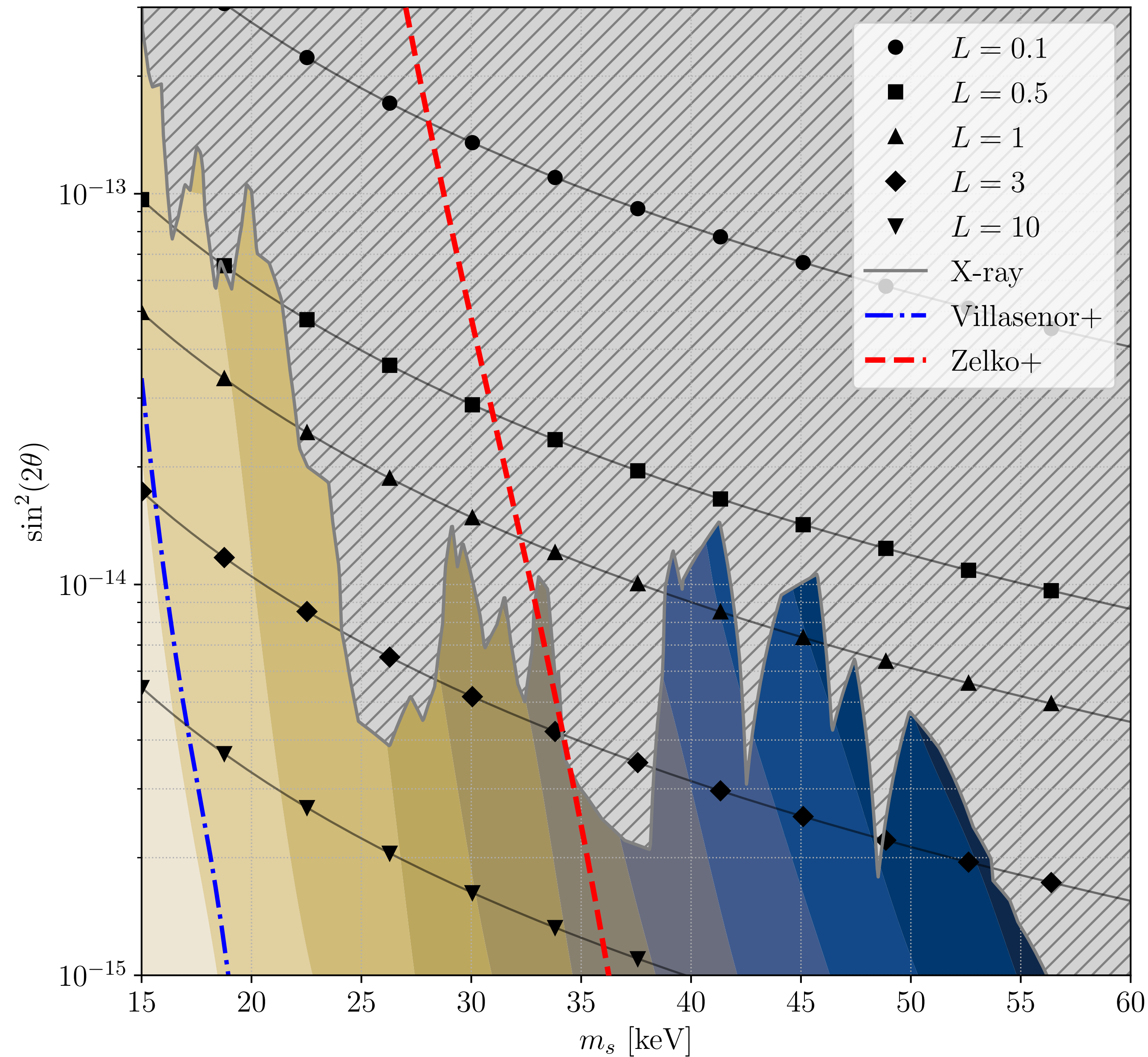
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 C. Vogel et al. [[2507.18752](https://arxiv.org/abs/2507.18752)]



Constraints on SF sterile neutrino dark matter

C. Vogel et al. [2507.18752]




Equivalent thermal warm dark matter mass, for structure formation constraints

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**.
- Asymmetries are mixed, but **not perfectly equilibrated** in general
→ 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](#)]

... 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

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

Vacuum

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

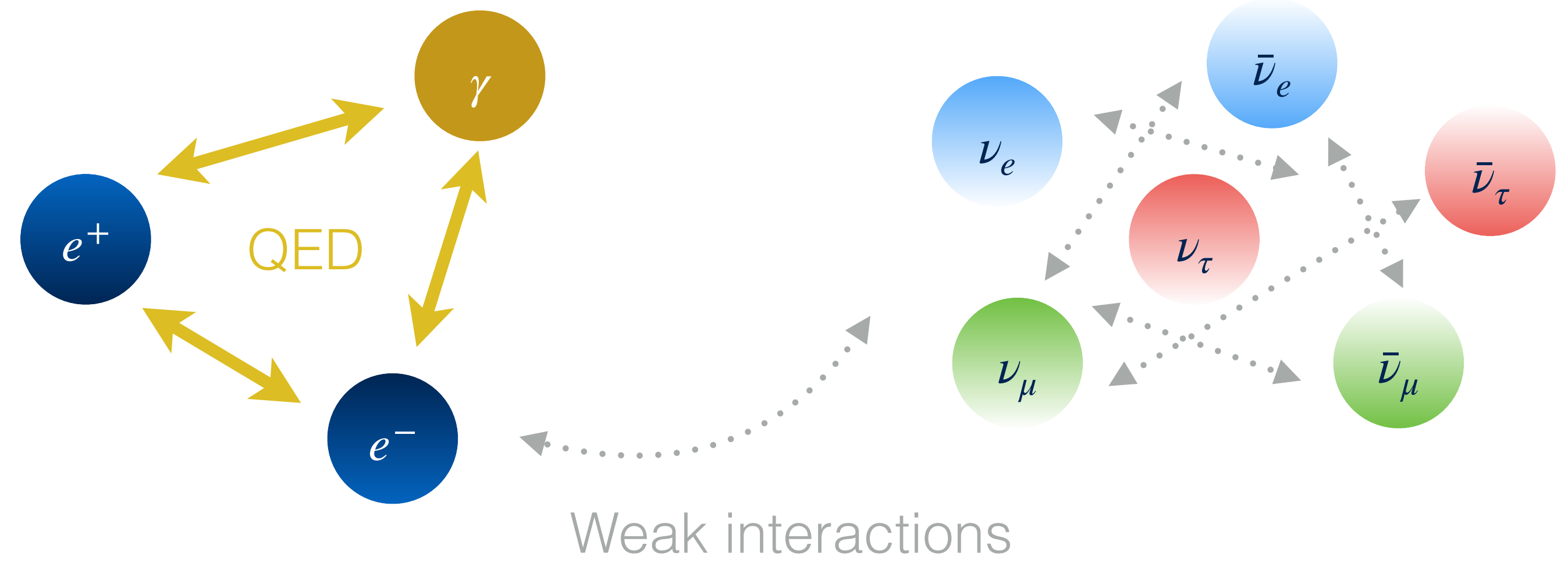
$$\mathbb{E}_{\text{lep}} + \mathbb{P}_{\text{lep}} = \begin{pmatrix} \rho_{e^\pm} + P_{e^\pm} & 0 & 0 \\ 0 & \rho_{\mu^\pm} + P_{\mu^\pm} & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

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

Collisions

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

Neutrinos in the MeV age

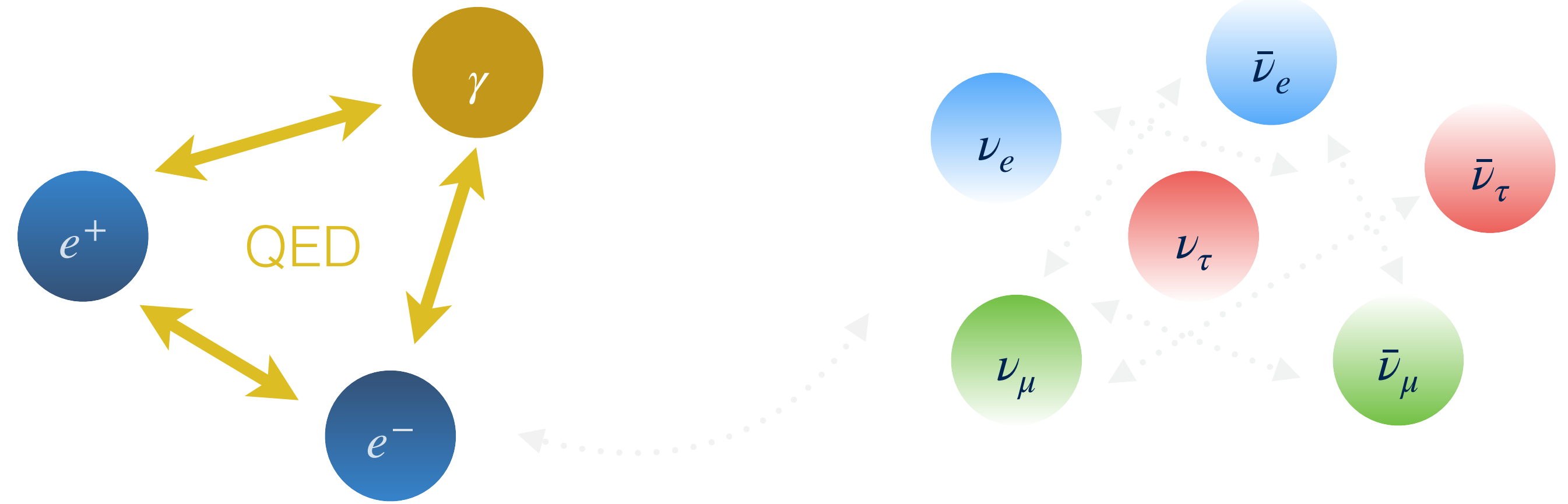


Neutrinos in the MeV age

NEUTRINO DECOUPLING

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

$$\Gamma/H = 1 \iff T_{\text{dec}} \simeq 1 \text{ MeV}$$

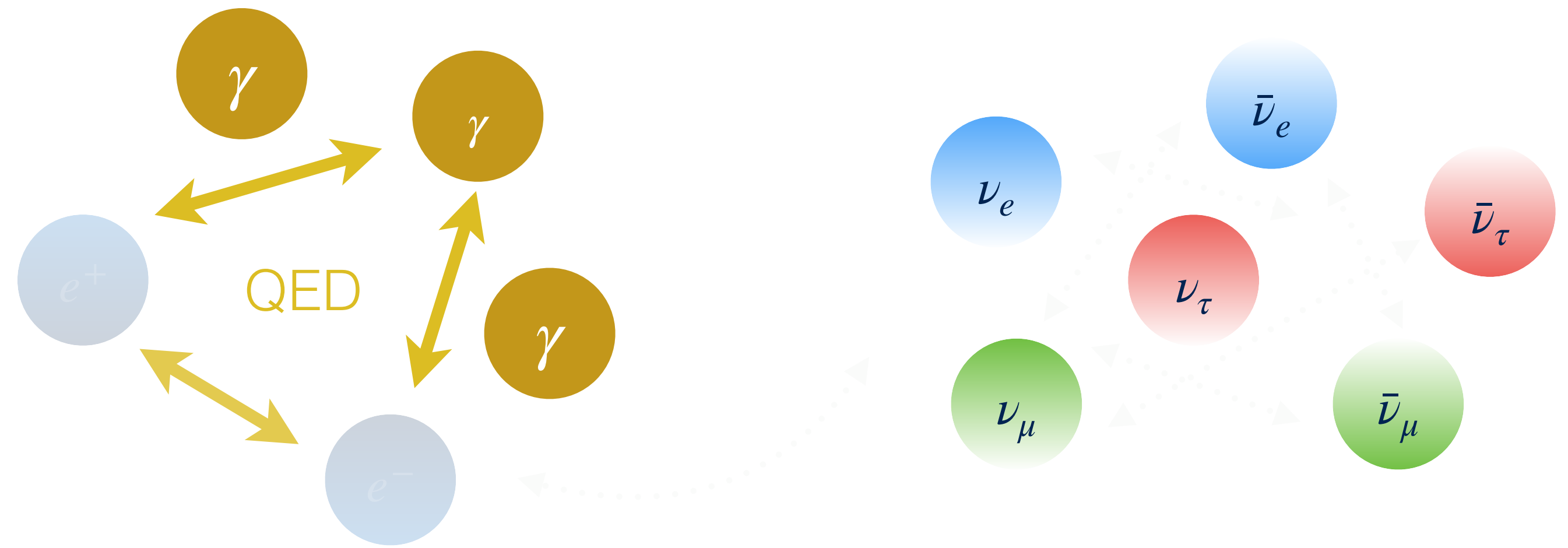


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ELECTRON-POSITRON ANNIHILATIONS

→ entropy release

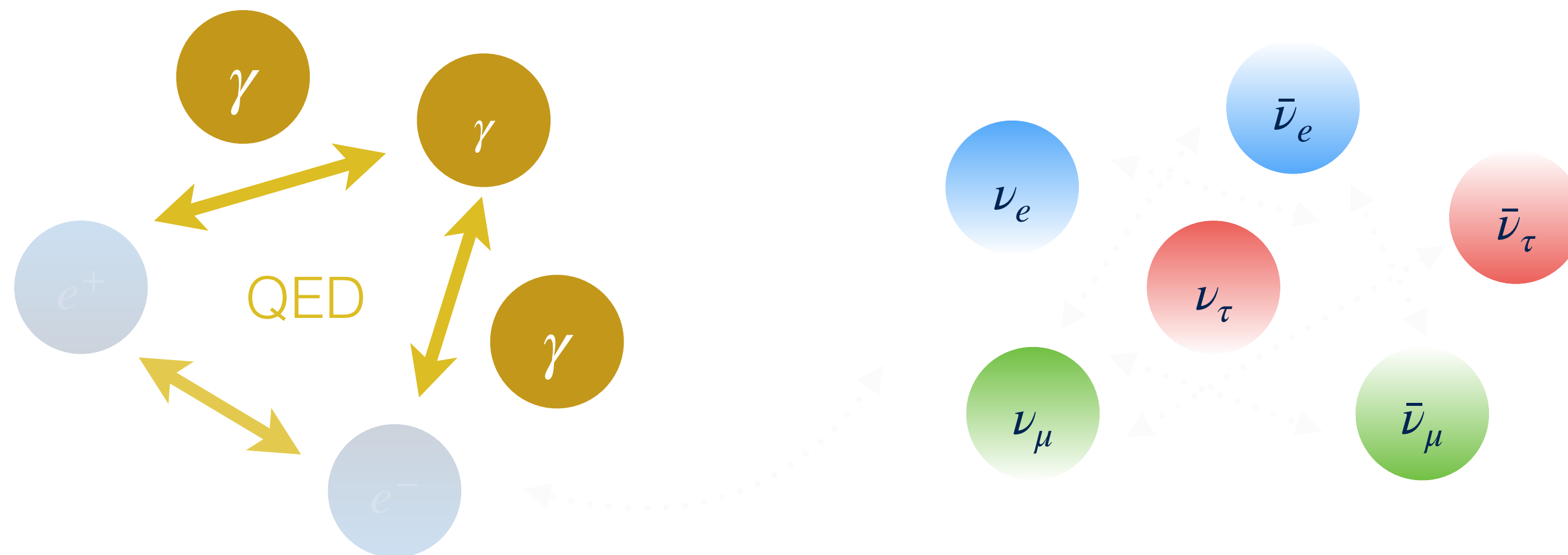
$$T_{e^\pm} = 0.511 \text{ MeV}$$

Neutrinos in the MeV age

NEUTRINO DECOUPLING

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NEUTRINO OSCILLATIONS

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

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

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

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

ELECTRON-POSITRON ANNIHILATIONS

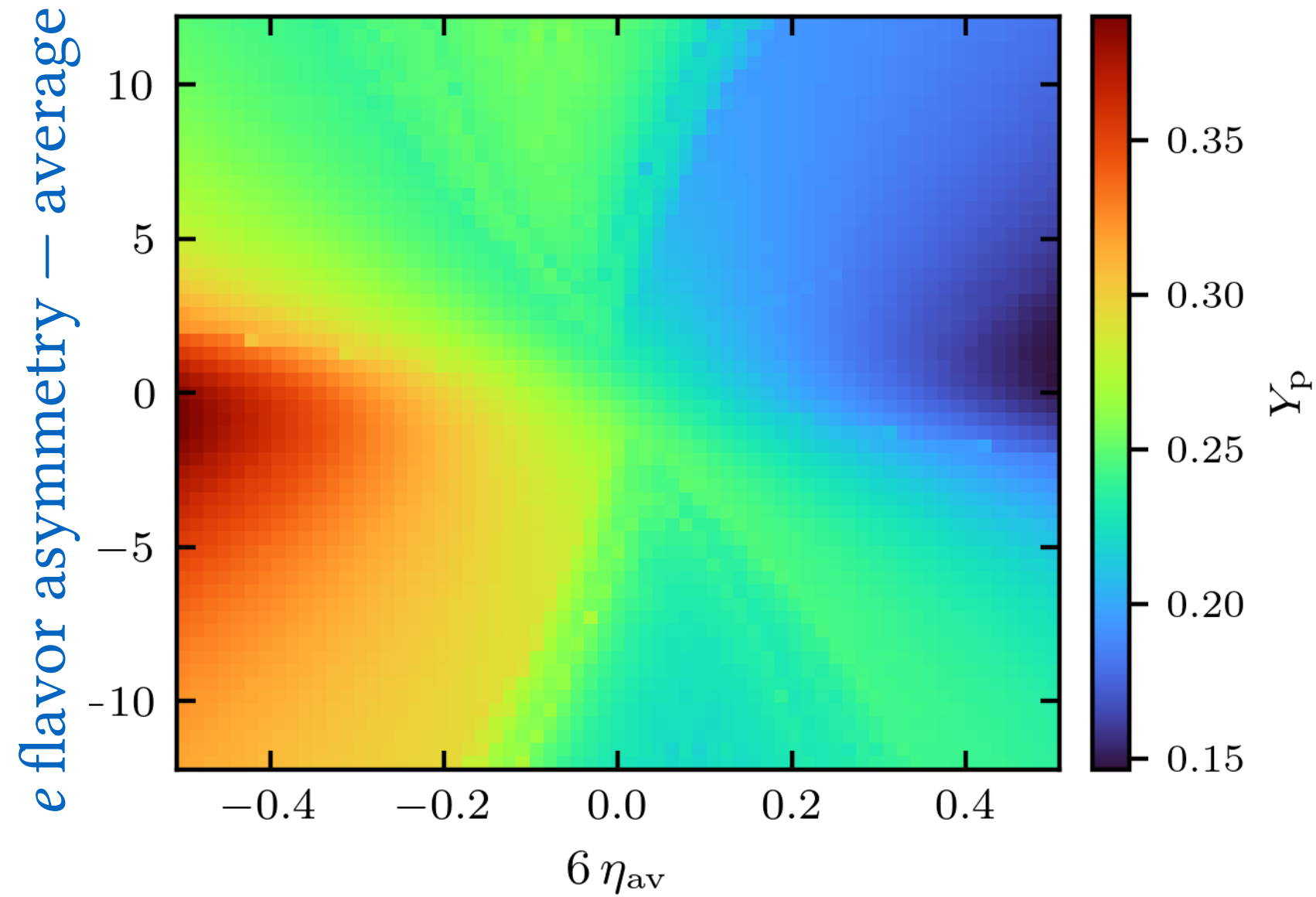
→ entropy release

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

Output of neutrino + BBN calculation

$$\eta_\mu = \eta_\tau$$

Helium-4 abundance



Spectroscopic measurements

$$Y_p = 0.2453 \pm 0.0034$$

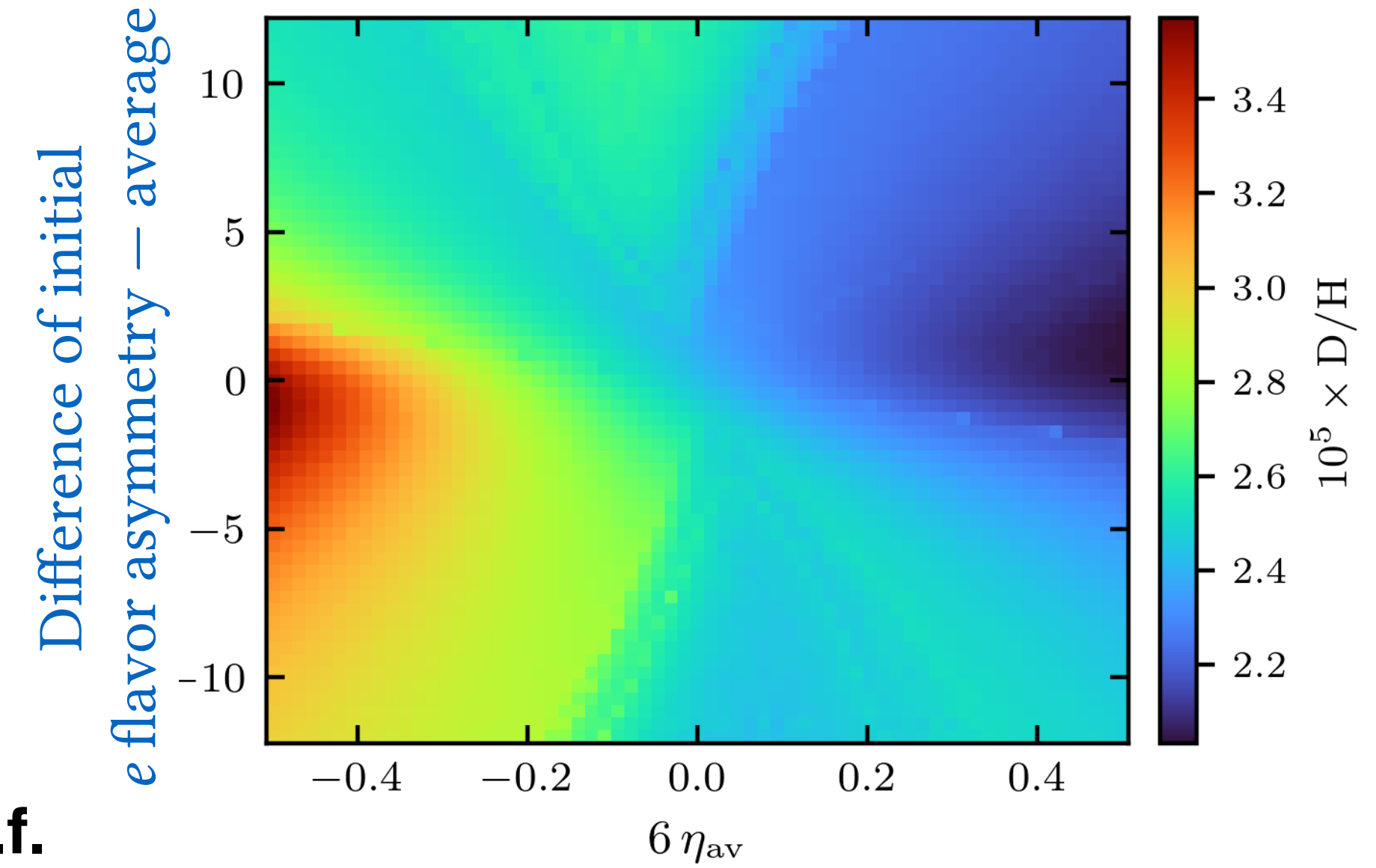
$$D/H = (2.53 \pm 0.03) \times 10^{-5}$$

Aver et al. [2010.04180]

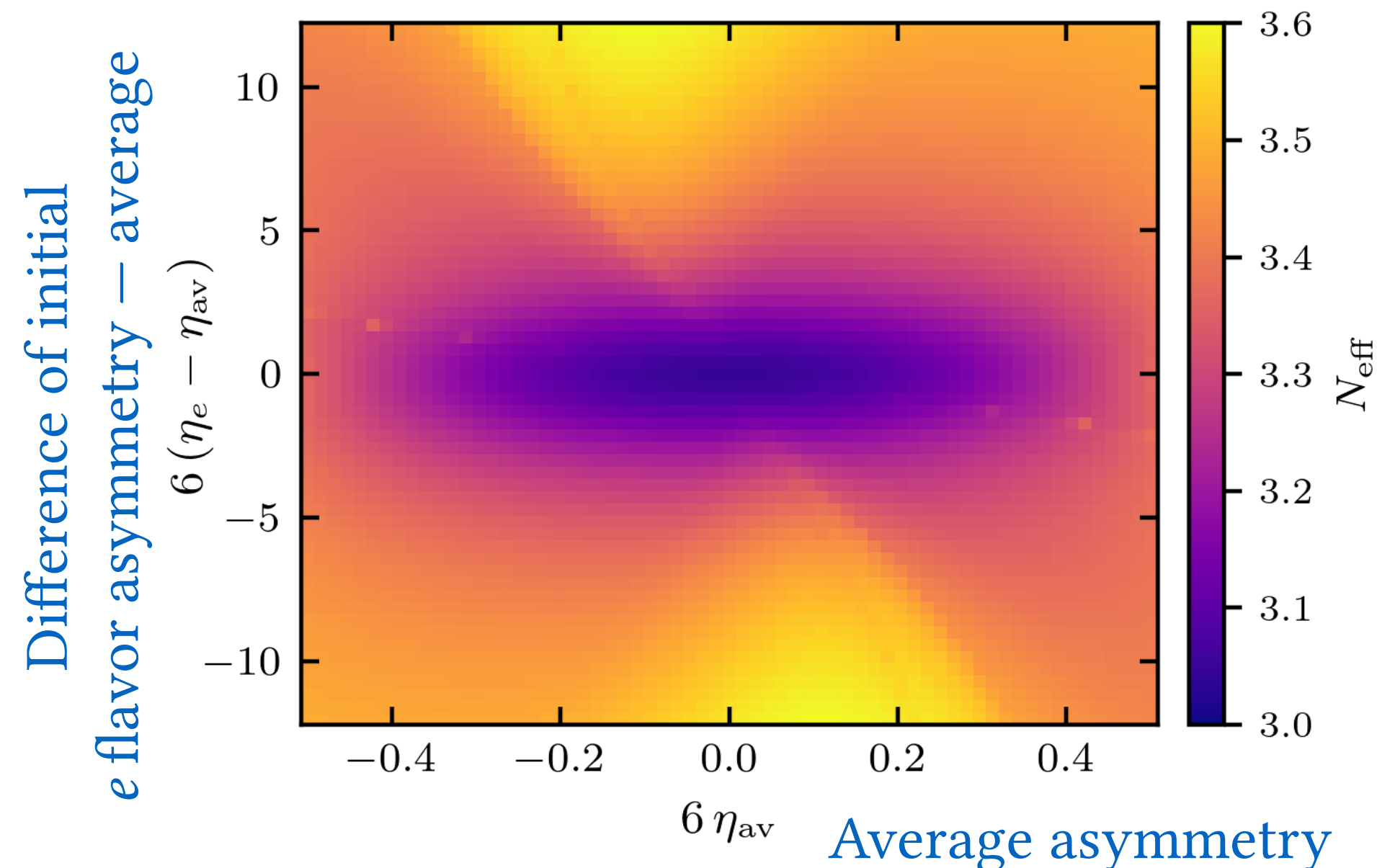
Cooke et al. [1710.11129]

Kislitsyn et al. [2401.12797]

Deuterium abundance



Effective number of relativistic d.o.f.



Average asymmetry

Planck + SPT + ACT+ BAO

$$N_{eff} = 2.86 \pm 0.13 \quad (68\%)$$

[2411.06000]

Connection with thermal warm dark matter

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

