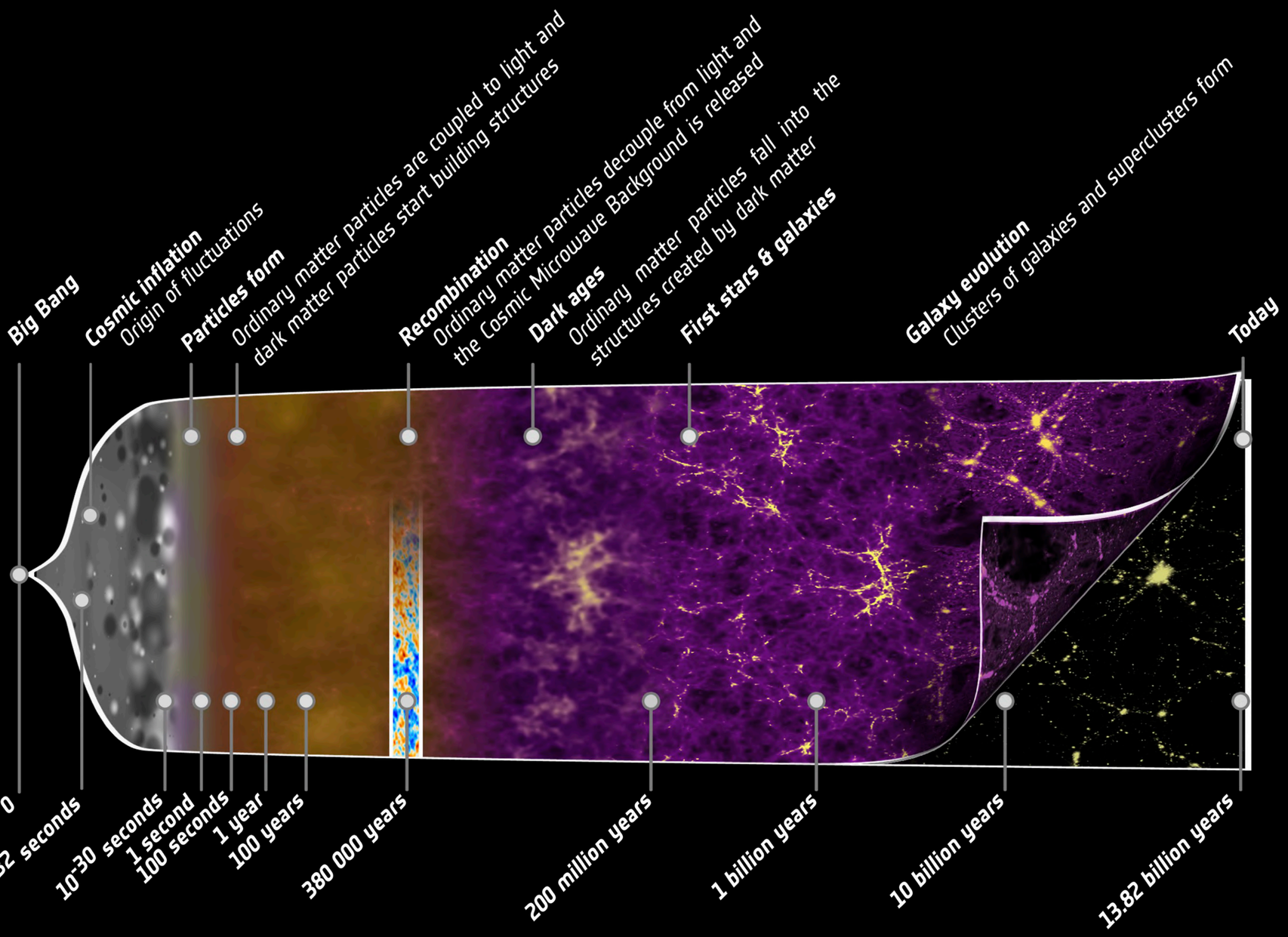
Primordial lepton asymmetries:
new constraints and consequences for sterile neutrino dark matter

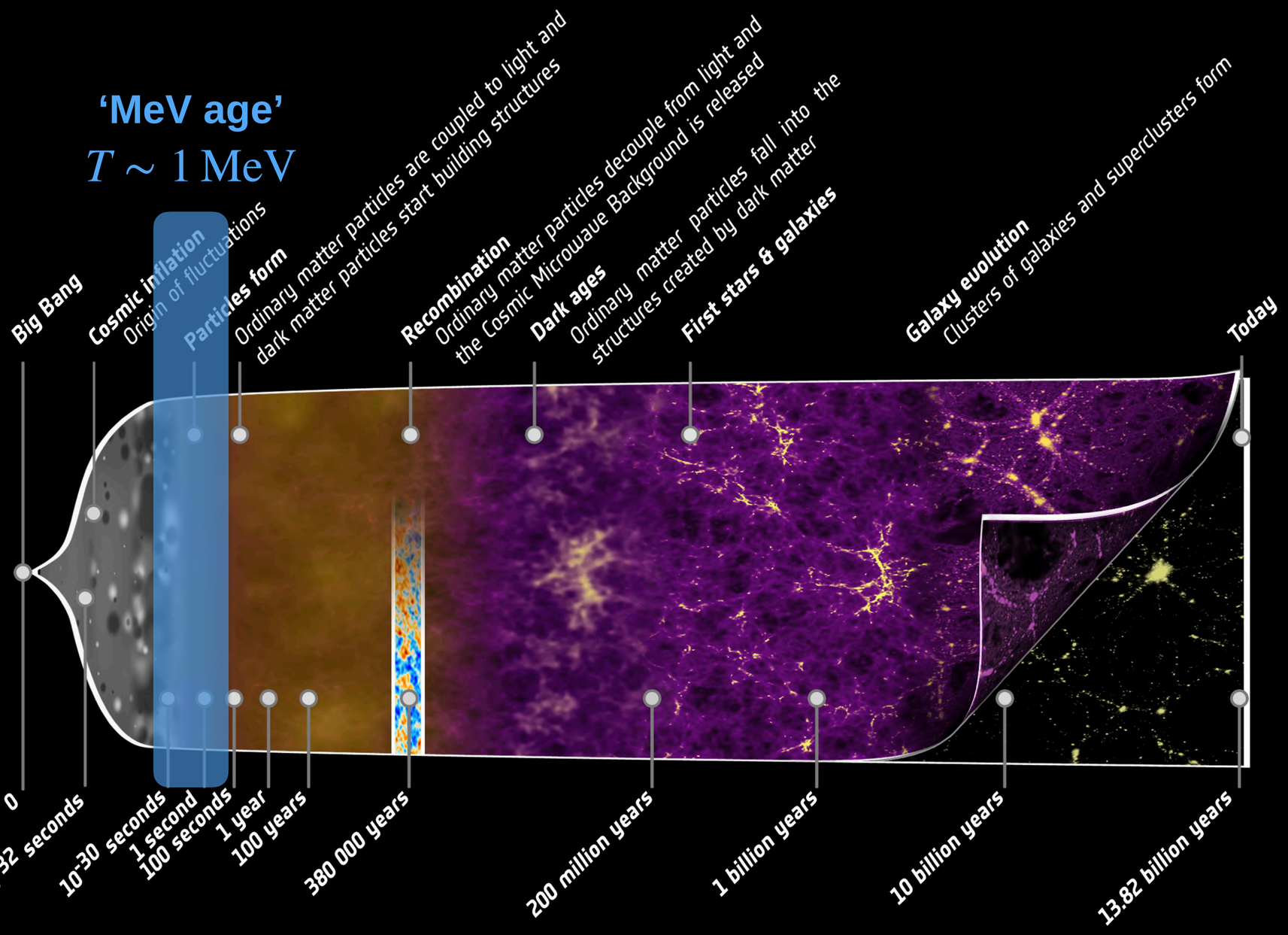
Julien Froustey

Severo Ochoa Postdoctoral Fellow,
IFIC, Valencia

Rencontres de Physique des Particules
11/03/2026


Big Bang
0
Cosmic inflation
Origin of fluctuations
10-32 seconds
Particles form
Ordinary matter particles are coupled to light and dark matter particles start building structures
10-30 seconds
1 second
100 seconds
1 year
100 years
Recombination
Ordinary matter particles decouple from light and the Cosmic Microwave Background is released
380 000 years
Dark ages
Ordinary matter particles fall into the structures created by dark matter
200 million years
First stars & galaxies
1 billion years
Galaxy evolution
Clusters of galaxies and superclusters form
10 billion years
Today
13.82 billion years

Credits: ESA


‘MeV age’
$T \sim 1\,\mathrm{MeV}$
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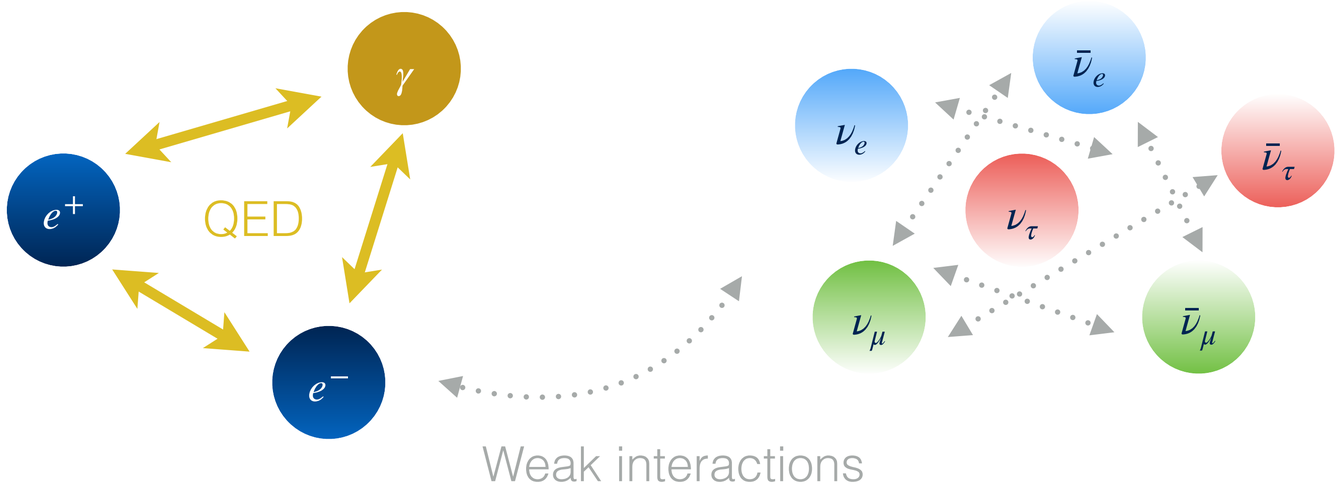
Neutrinos in the MeV age

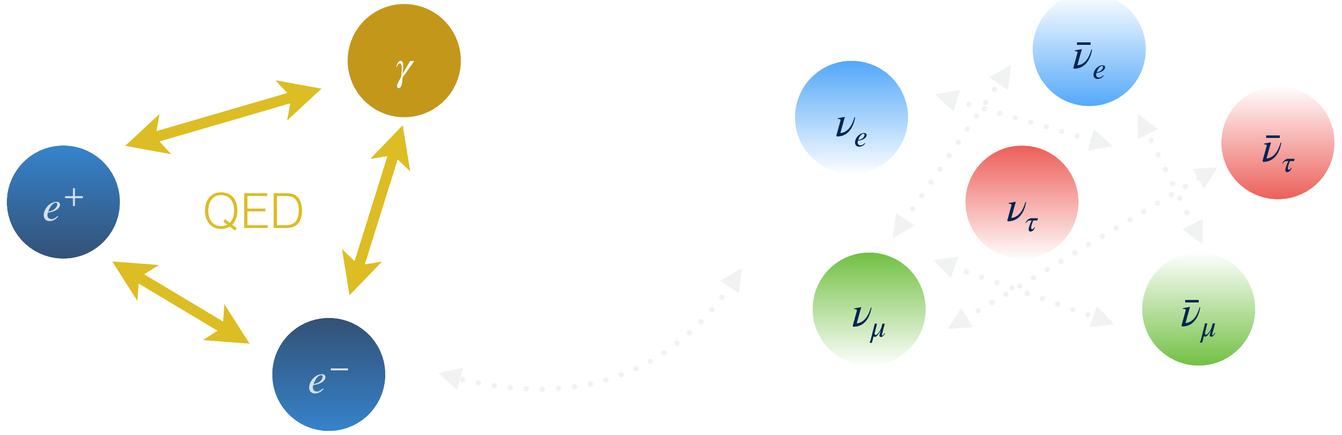


Neutrinos in the MeV age

NEUTRINO DECOUPLING

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

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



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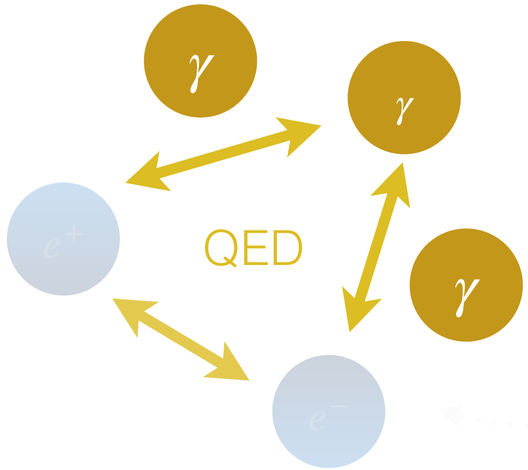

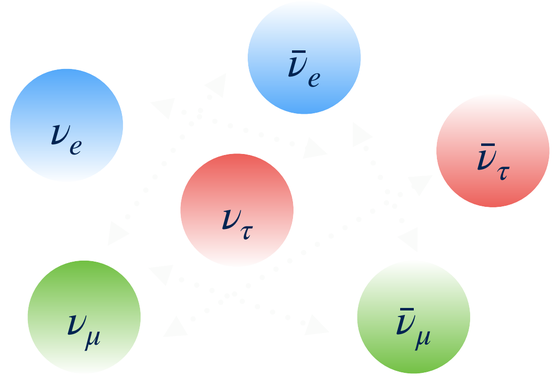

ELECTRON-POSITRON ANNIHILATIONS

→ entropy release

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

Neutrinos in the MeV age

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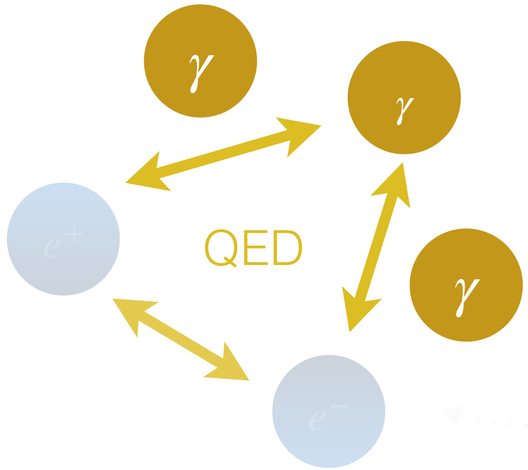
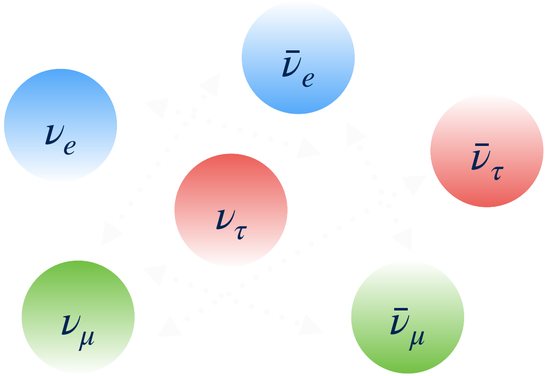




Neutrino oscillations

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

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

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

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

Electron-positron annihilations

→ entropy release

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

Neutrino flavor oscillations

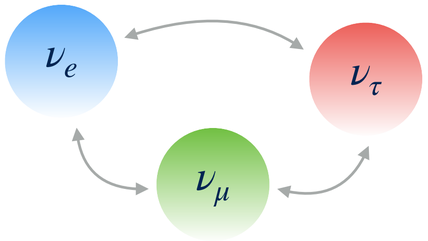
- Standard Model: 3 species of massless neutrinos ν_L

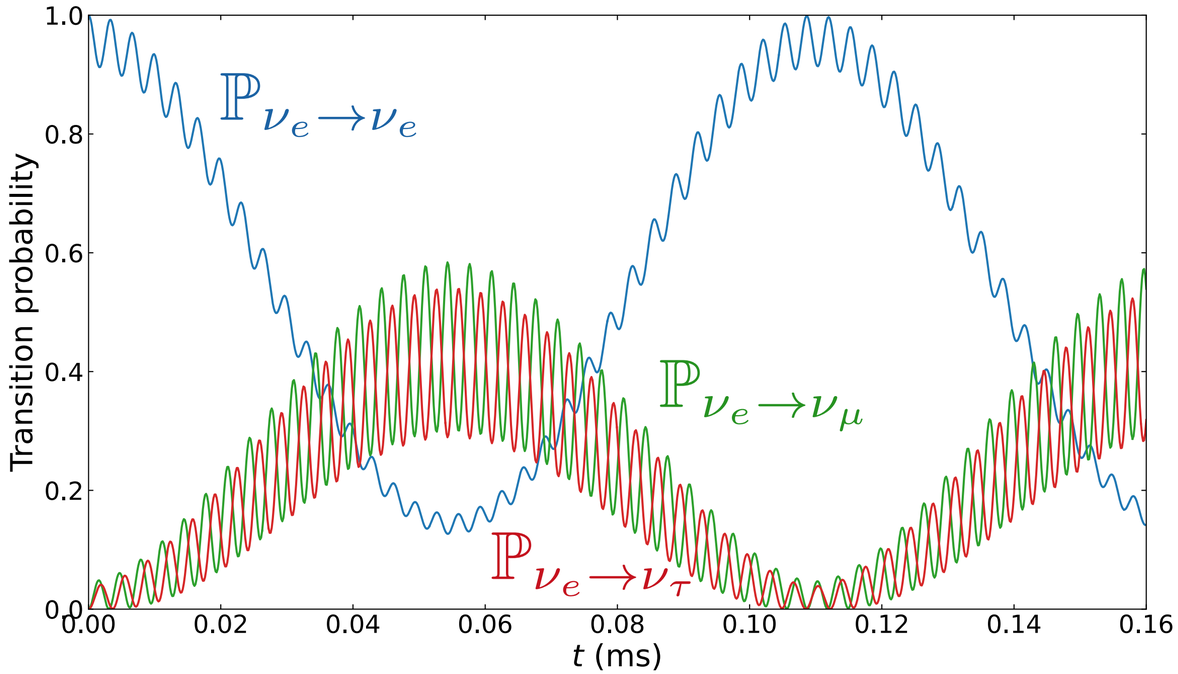
- Experimental evidence in the second half of the 20th century
  → massive neutrinos

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

PMNS mixing matrix

$\Longrightarrow$ neutrino oscillations





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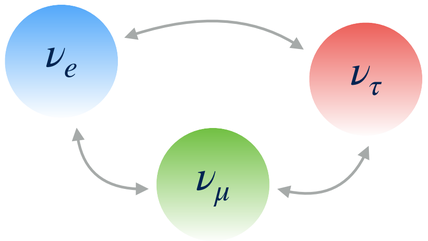
$$\begin{pmatrix} \nu_e \\ \end{pmatrix} \qquad \begin{pmatrix} \nu_1 \\ \end{pmatrix} \qquad \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ \end{pmatrix} \begin{pmatrix} \nu_1 \\ \end{pmatrix}$$

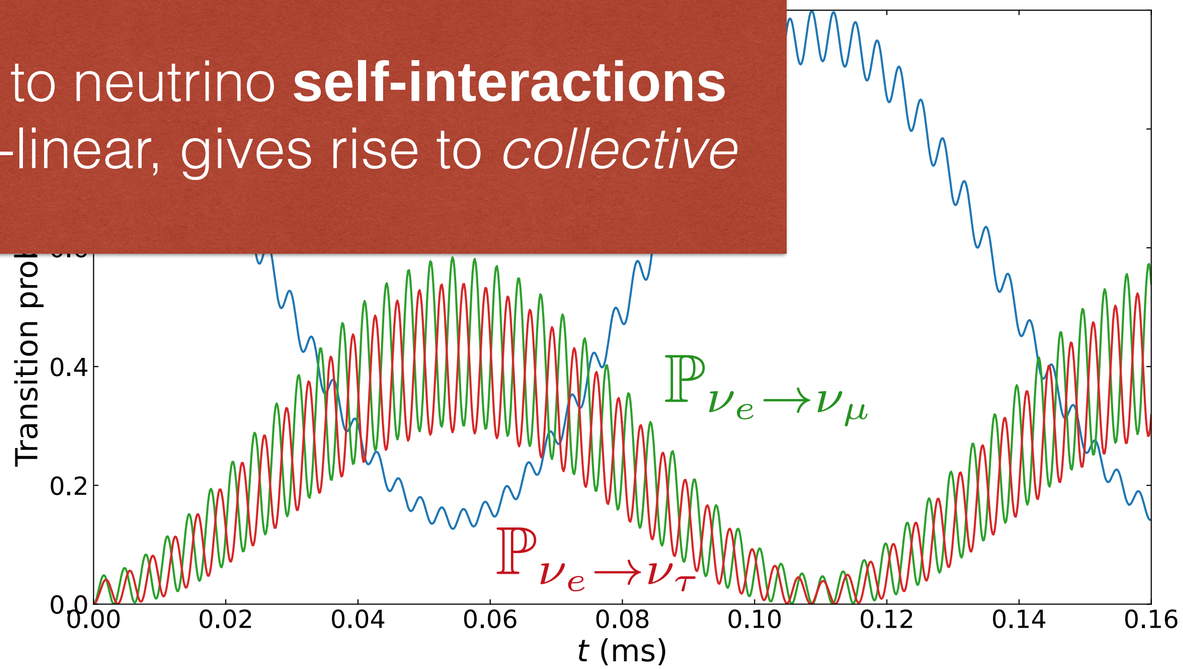
Flavor st … s states

$\Longrightarrow$ neutrino oscillati…

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*)





Neutrino transport in the early Universe

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

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

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

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

See G. Jackson's upcoming talk

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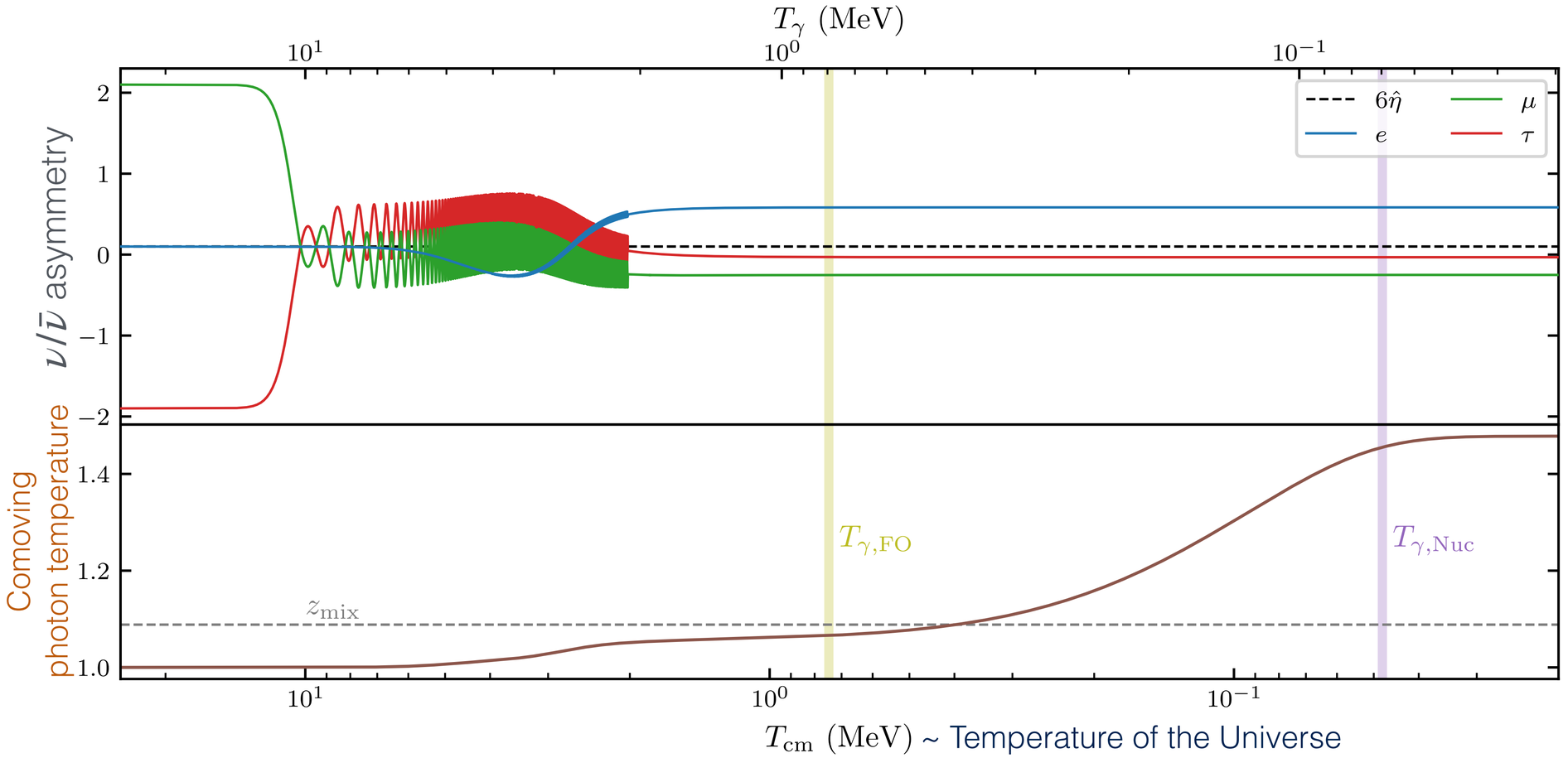
- Extension to the case of **nonzero neutrino/antineutrino asymmetries**



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

Initial values

$$\eta_{\rm av} = \eta_e = 0.1$$
$$\eta_\mu - \eta_\tau = 4$$

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

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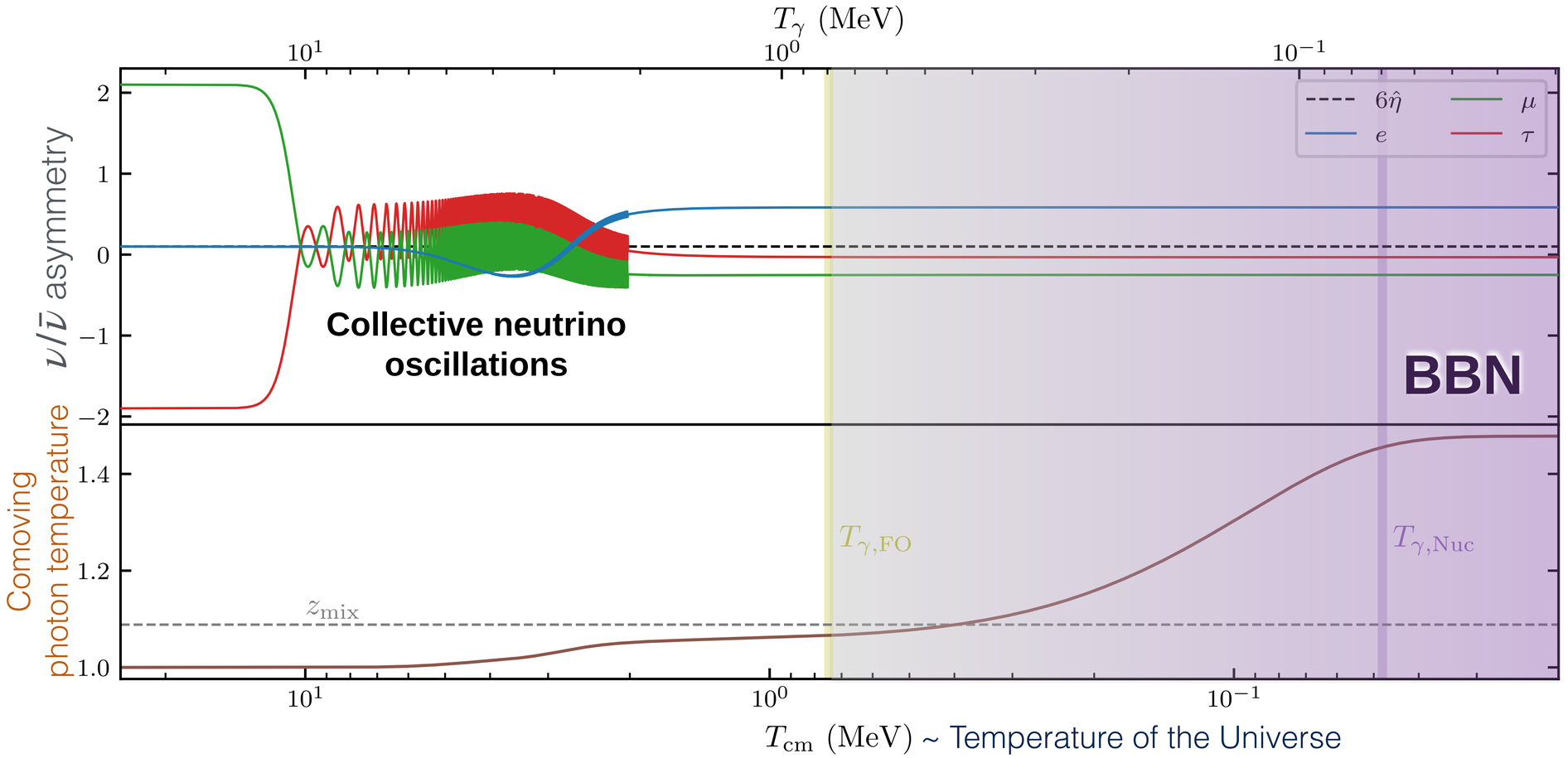

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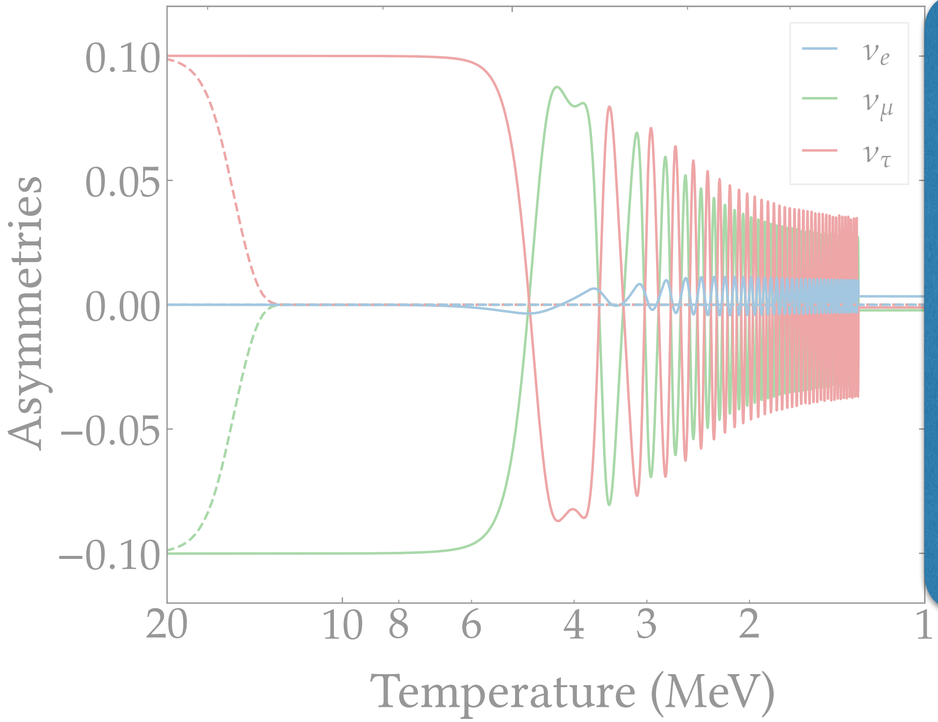
Constraining primordial neutrino asymmetries

Effects of asymmetries:

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

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



Asymmetries at the BBN epoch

$N_{\rm eff}$

(Anti)neutrino distributions

⇓

[BBN code **PRIMAT**]

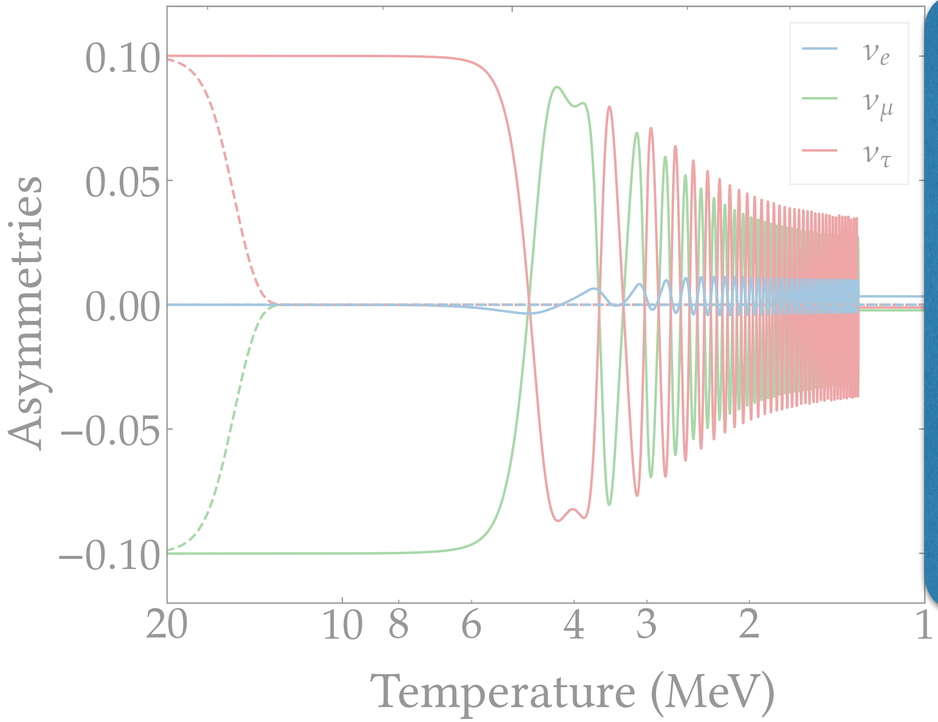
⇓

Primordial abundances
(Helium-4 $Y_{\rm p}$,
Deuterium $\rm D/H$)

Constraining primordial neutrino asymmetries

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

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



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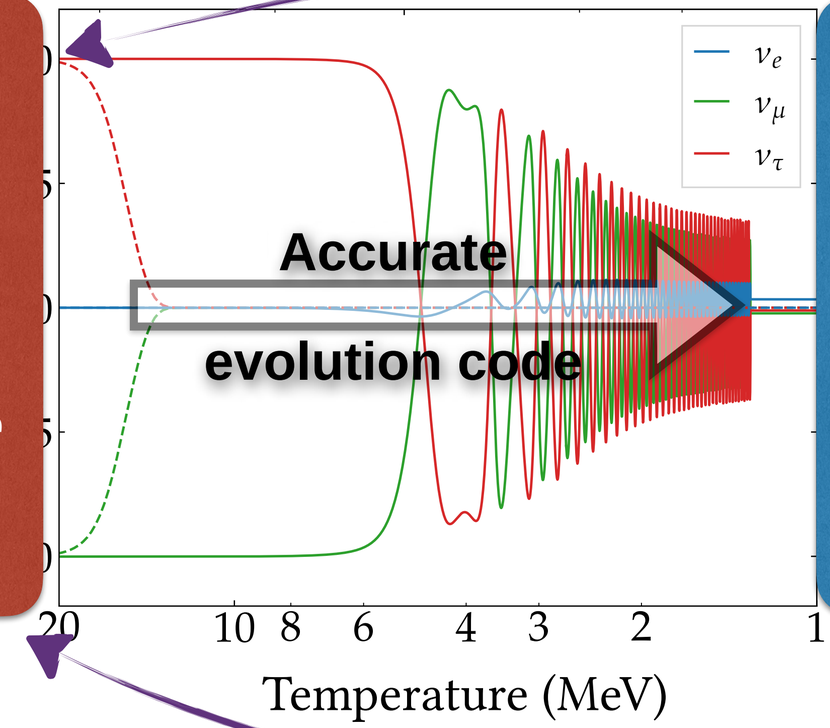
Constraints

Constraining primordial neutrino asymmetries

JF, C. Pitrou [2405.06509]

Primordial asymmetries



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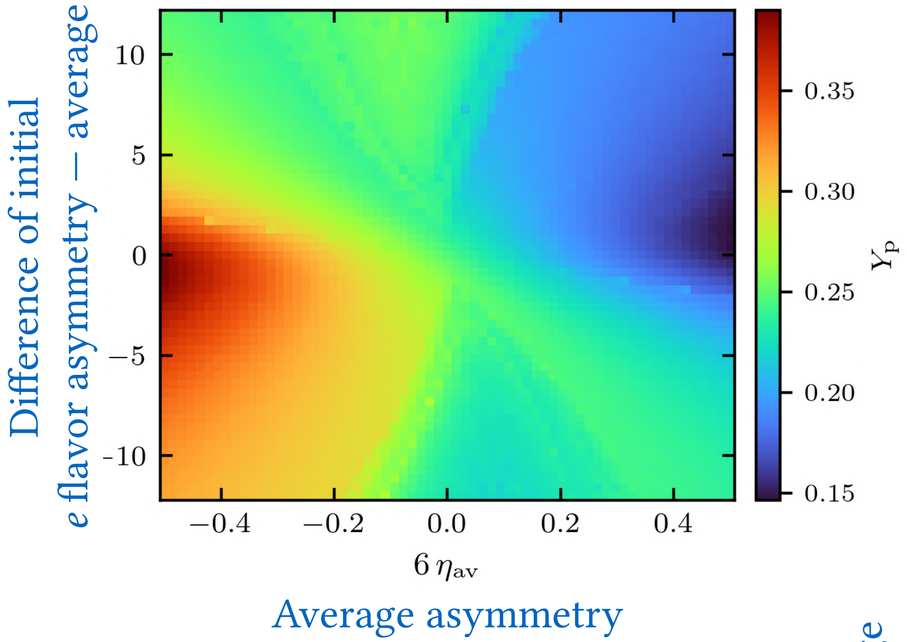
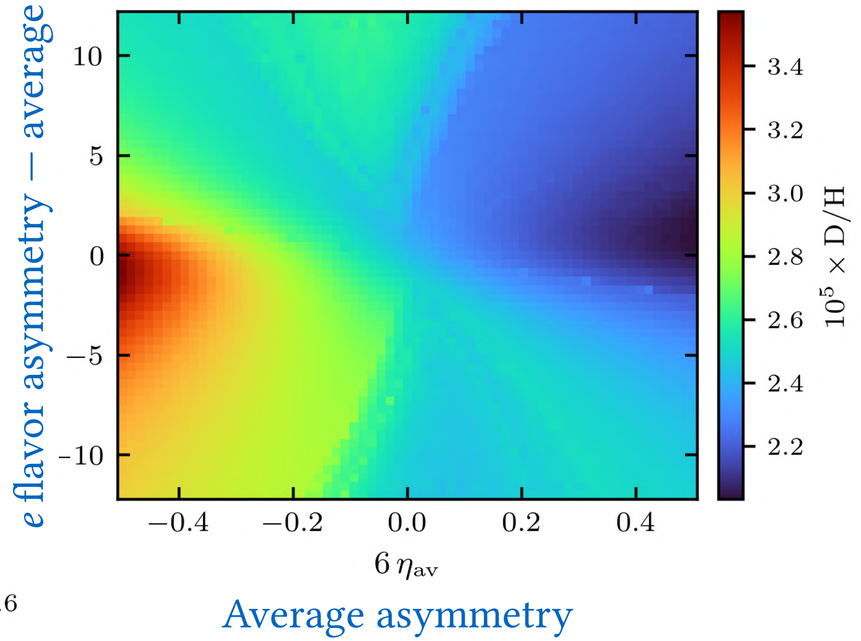
Output of neutrino + BBN calculation

$\eta_\mu = \eta_\tau$

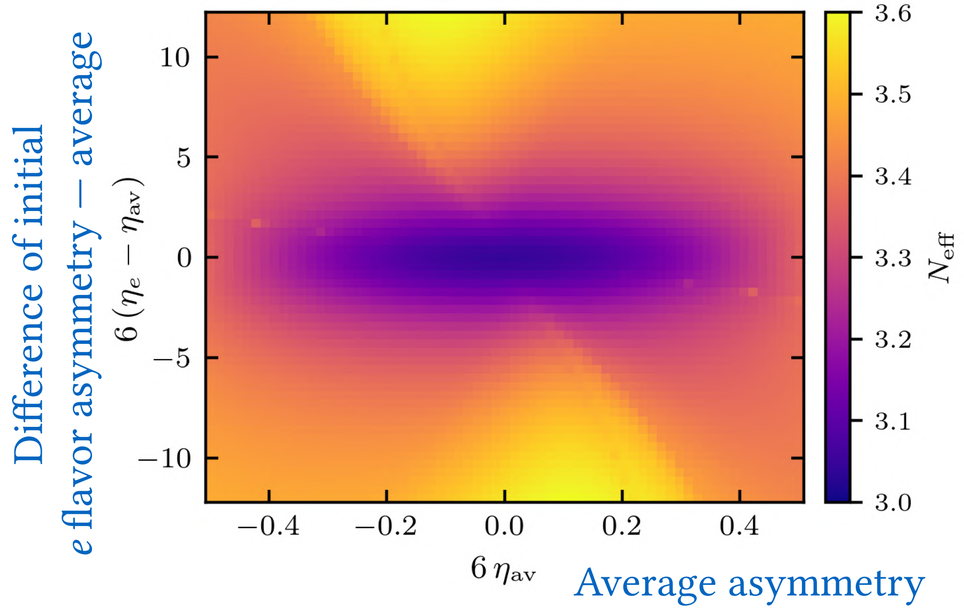
Helium-4 abundance



Deuterium abundance



Effective number of relativistic d.o.f.



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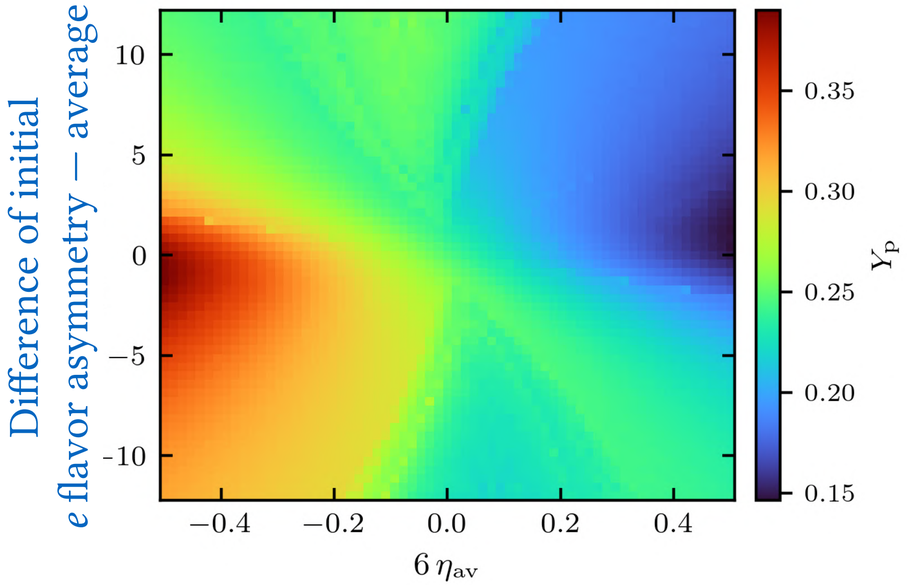


Average asymmetry

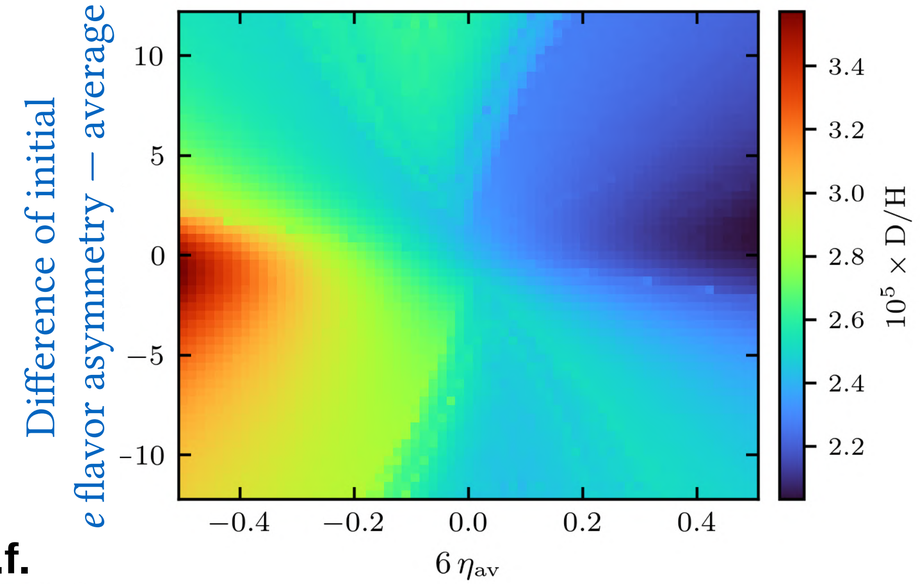
Spectroscopic measurements

$Y_p = 0.2453 \pm 0.0034$

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

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

Deuterium abundance



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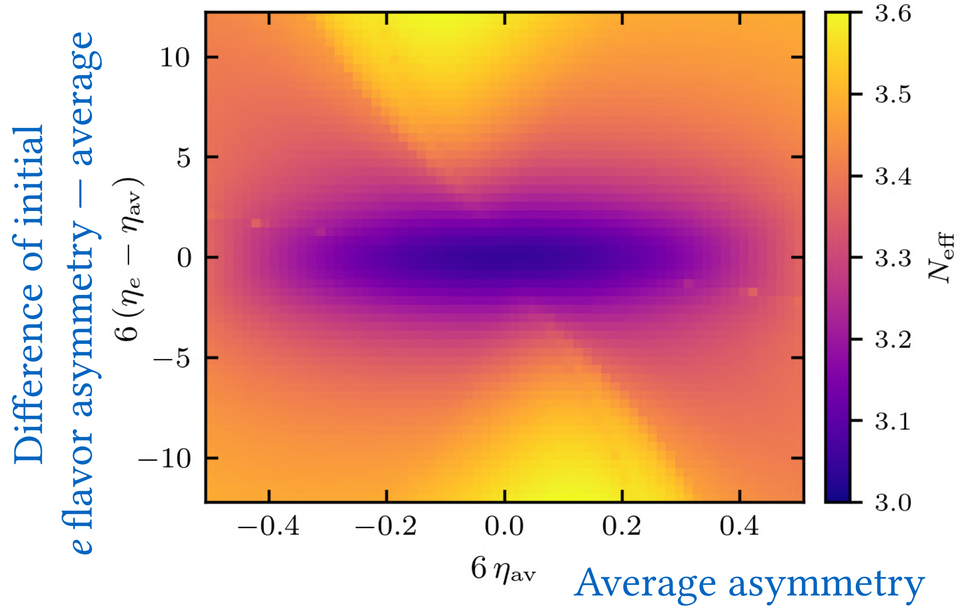


Average asymmetry

Planck + SPT + ACT+ BAO

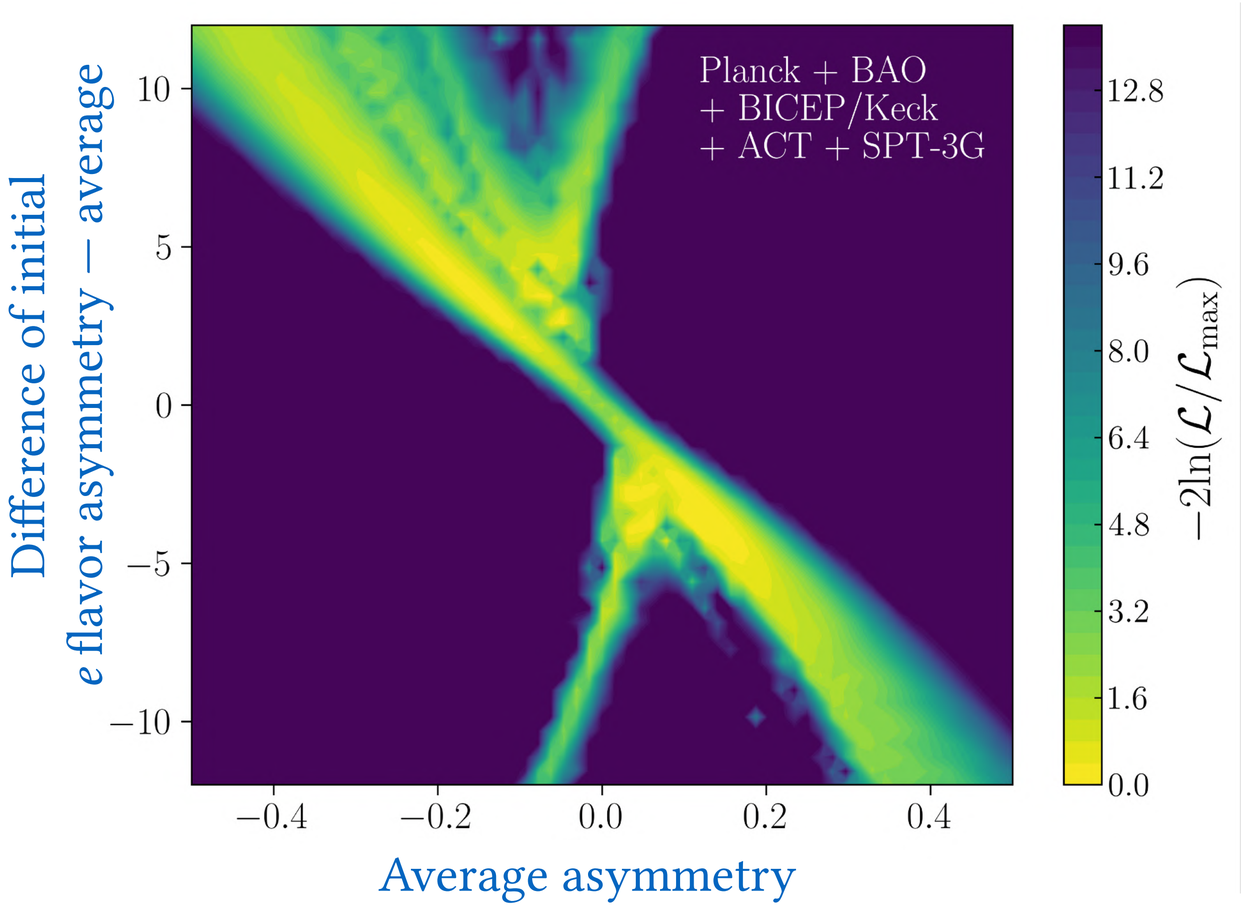
$N_{\mathrm{eff}} = 2.86 \pm 0.13$ (68 %)

[2411.06000]

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.



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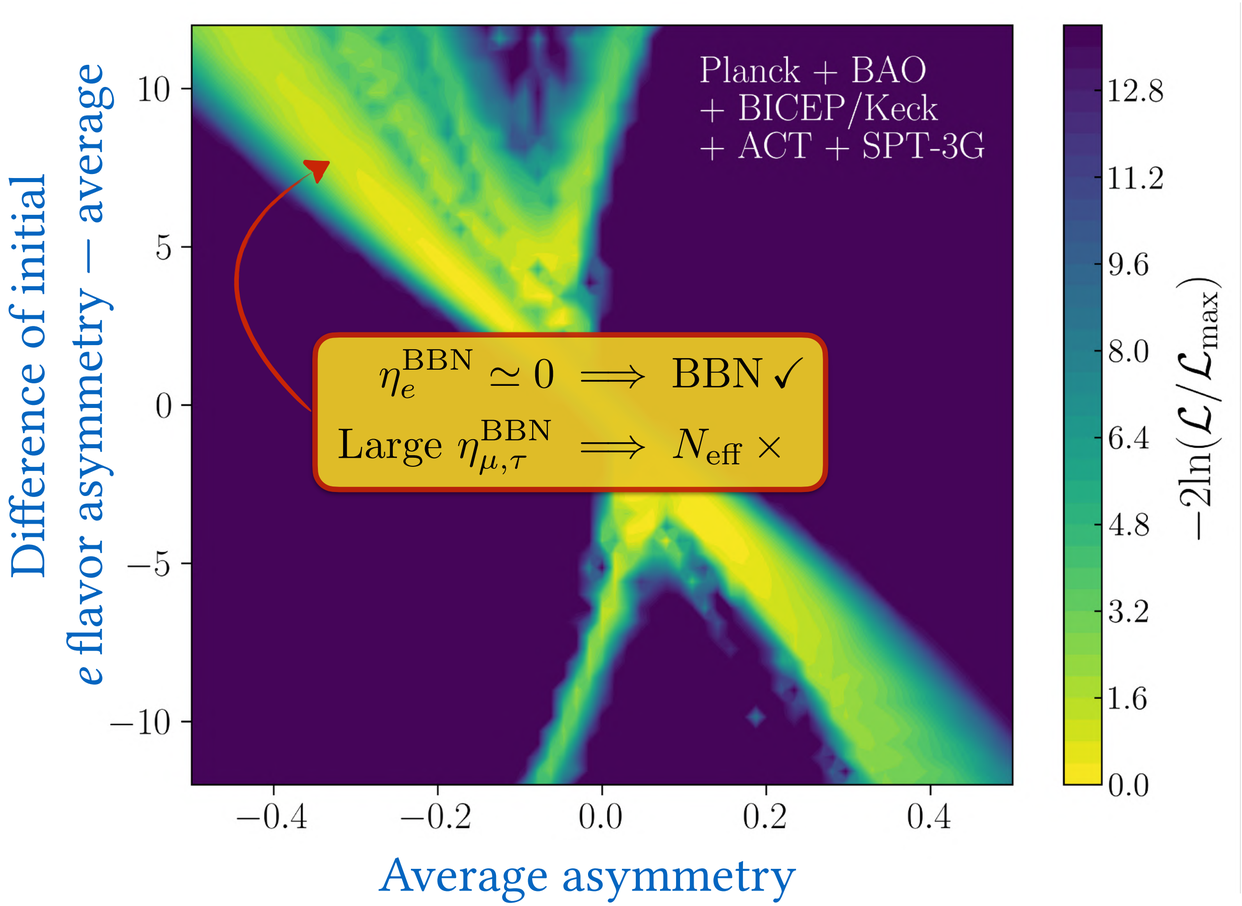

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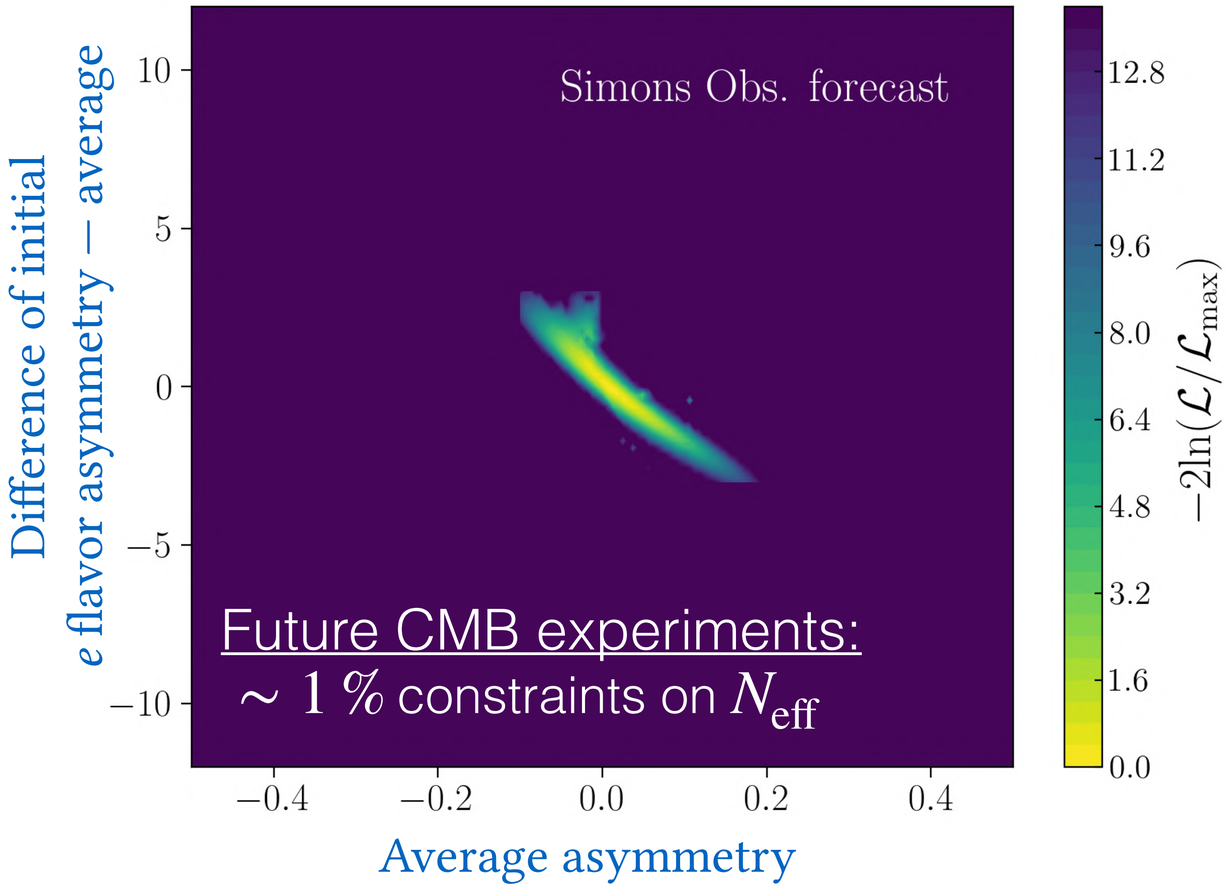

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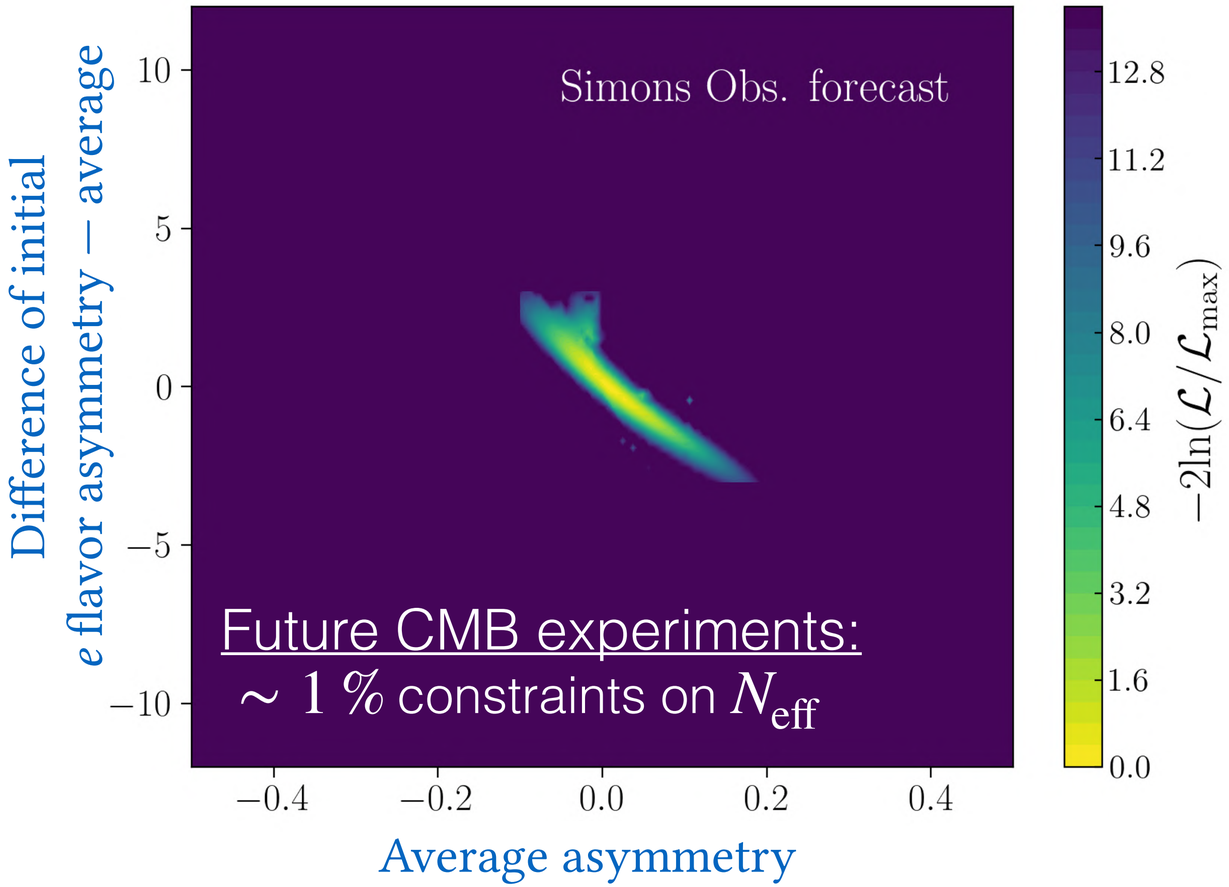
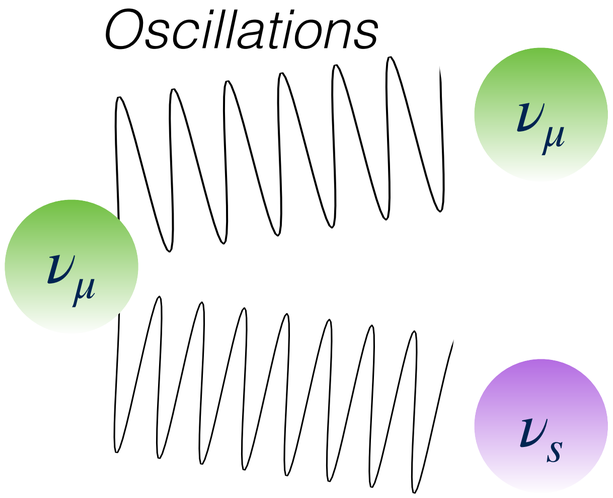


- Large lepton numbers are needed for some nonstandard scenarios, e.g., the **resonant production of sterile neutrino dark matter** (*Shi-Fuller* mechanism).

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. Ovchynnikov [2507.20659]

Sterile neutrino dark matter production

Sterile neutrino dark matter production



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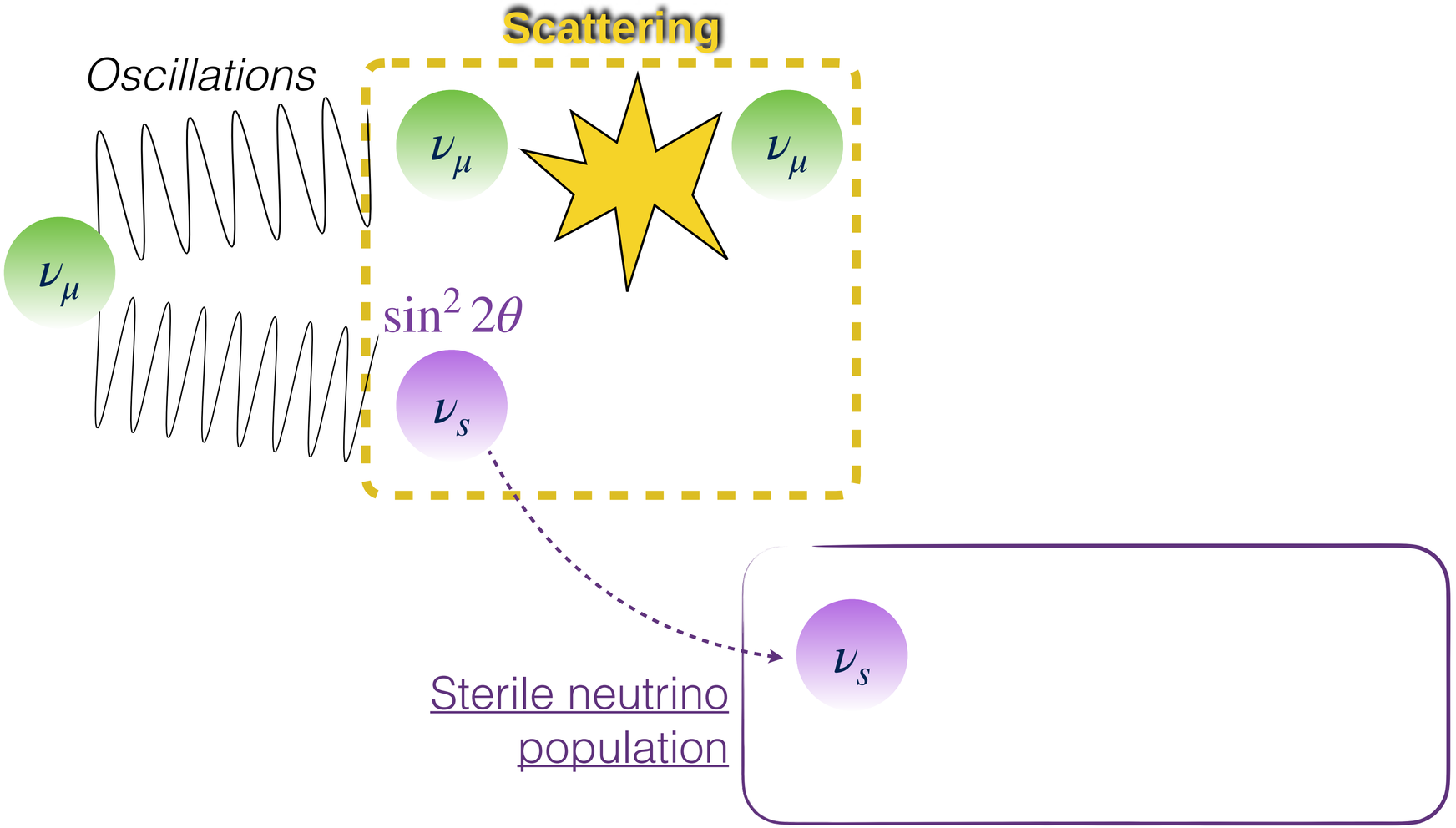

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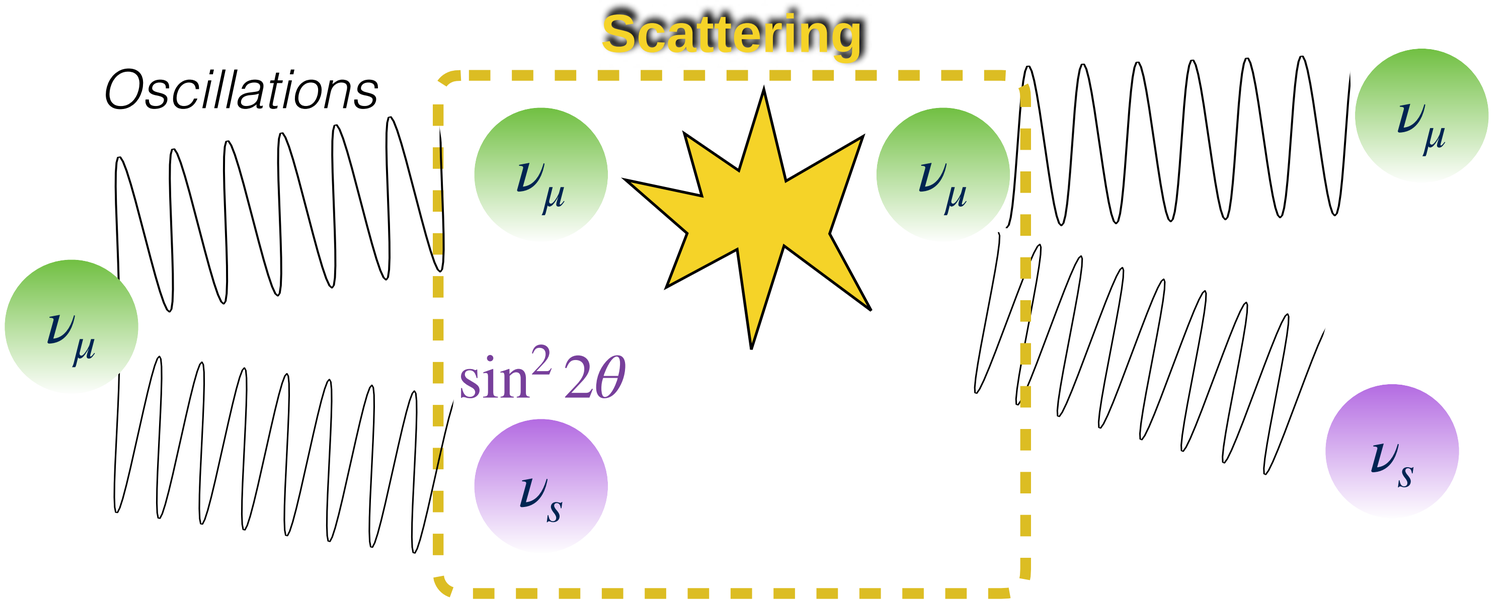
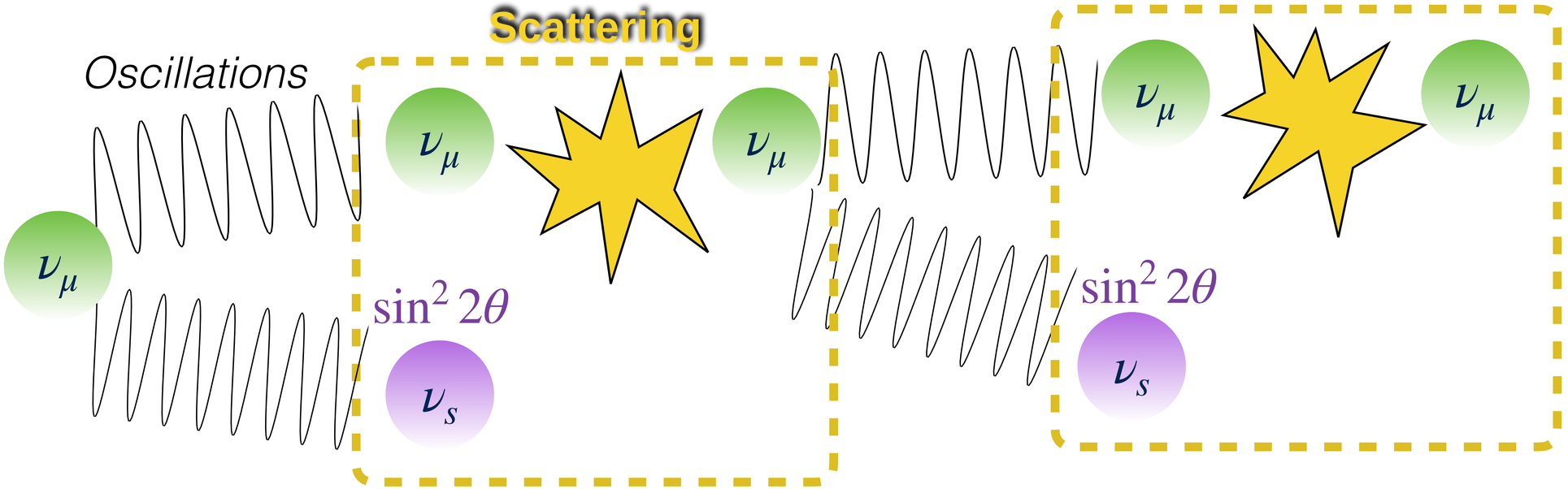


Sterile neutrino population

Sterile neutrino dark matter production



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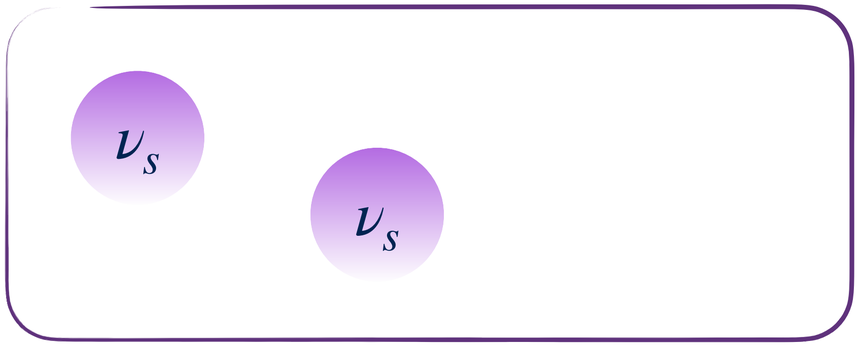

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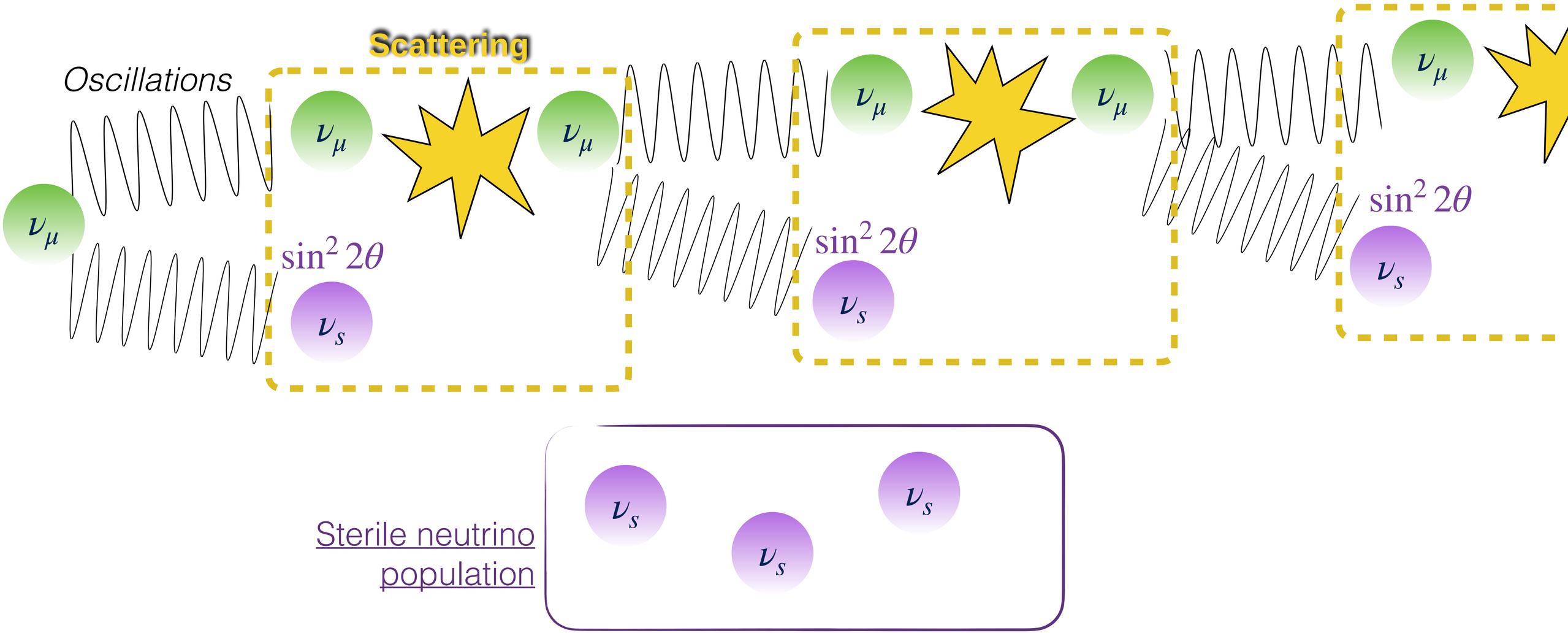

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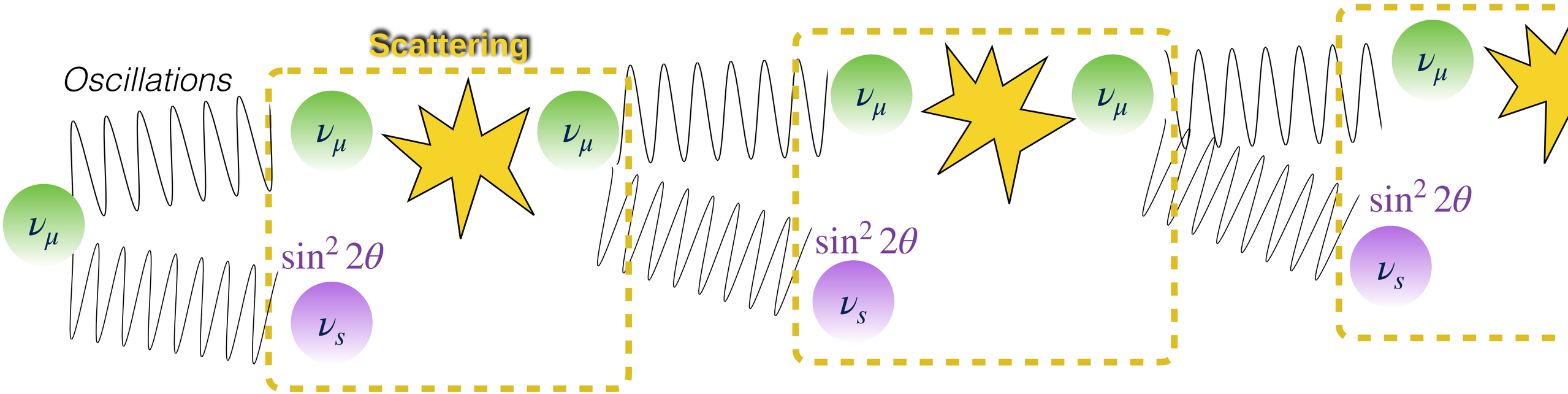
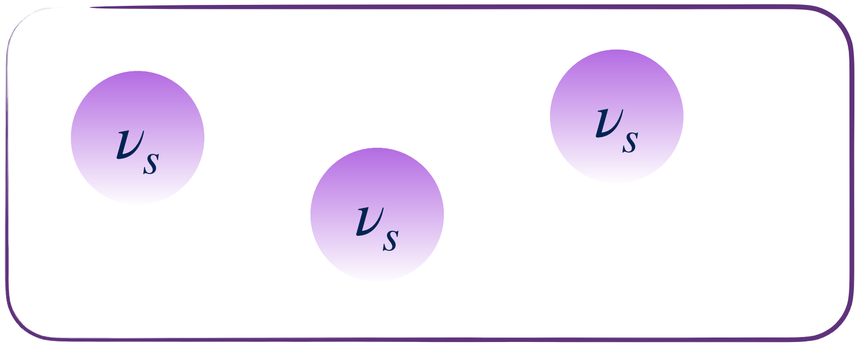


Sterile neutrino population

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



DODELSON-WIDROW MECHANISM

"Scattering-induced decoherence"

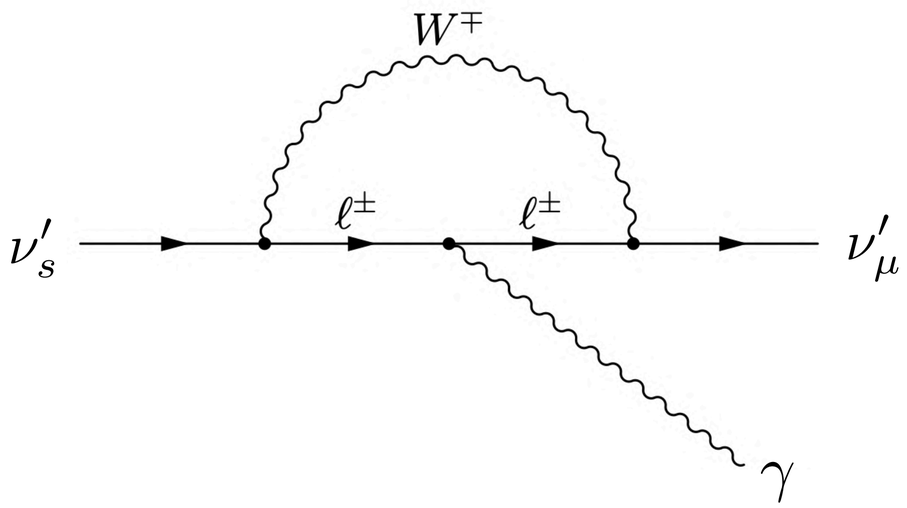
Dodelson & Widrow,
Phys. Rev. Lett. **72**, 17 (1994)

Sterile neutrino dark matter production

Oscillations

ν_μ

Radiative decay



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

$$E_\gamma = \frac{m_s}{2} \longrightarrow \textbf{X-ray line}$$

ν_μ

$\sin^2 2\theta$

ν_s

ν_s

ν_s

ν_s

Sterile neutrino population

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

DODELSON-WIDROW MECHANISM

"Scattering-induced decoherence"

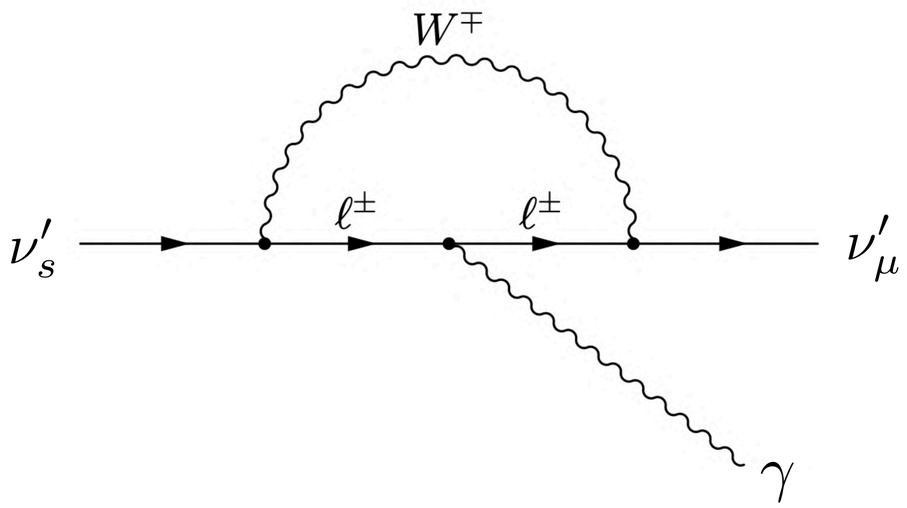
Dodelson & Widrow,
Phys. Rev. Lett. **72**, 17 (1994)

Sterile neutrino dark matter production

Oscillations

ν_μ

Radiative decay



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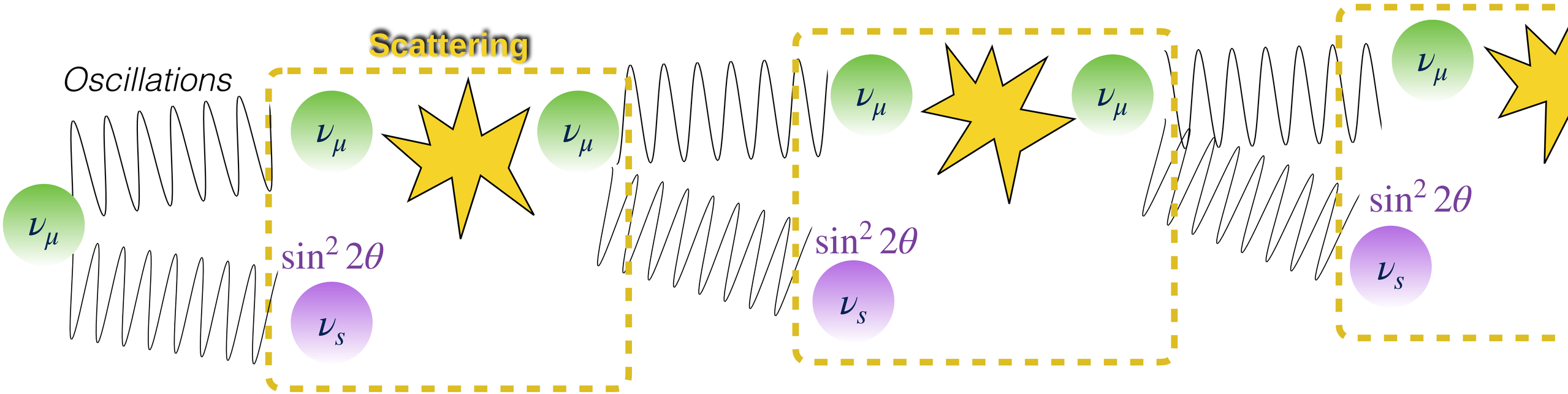

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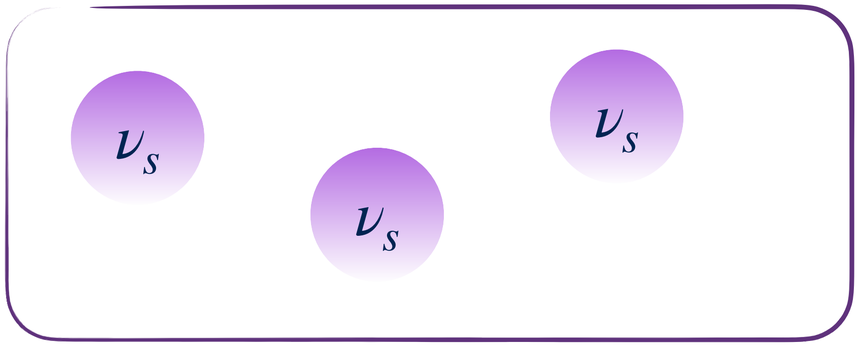

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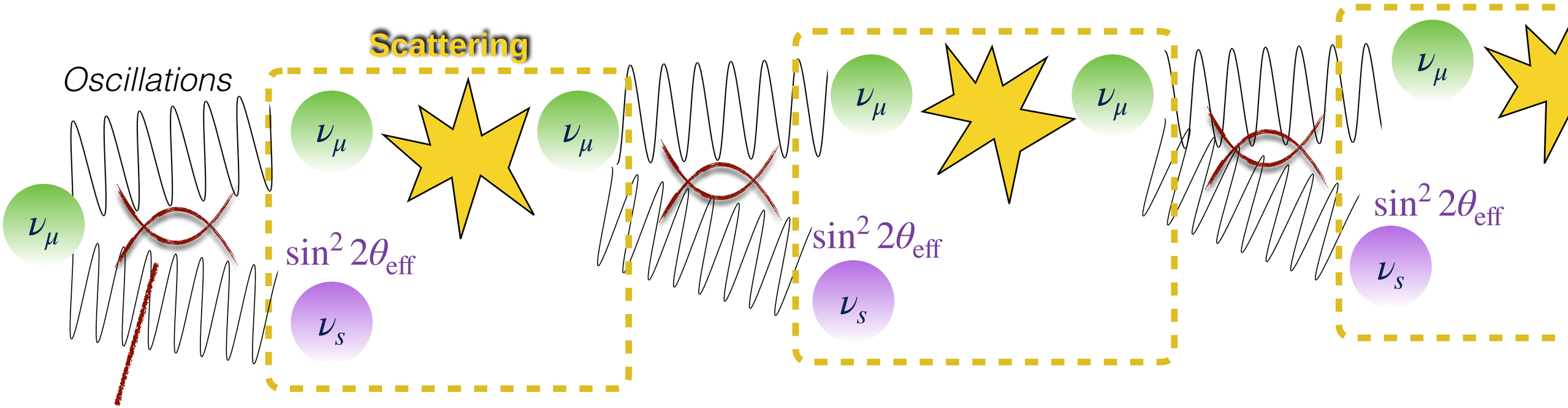
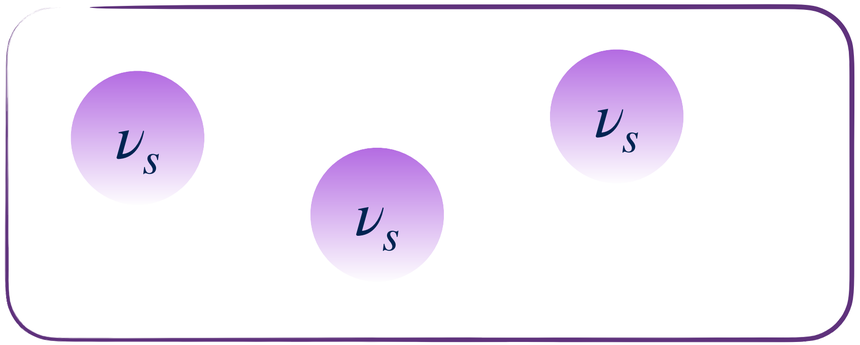


Asymmetry-induced resonance

Sterile neutrino population

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



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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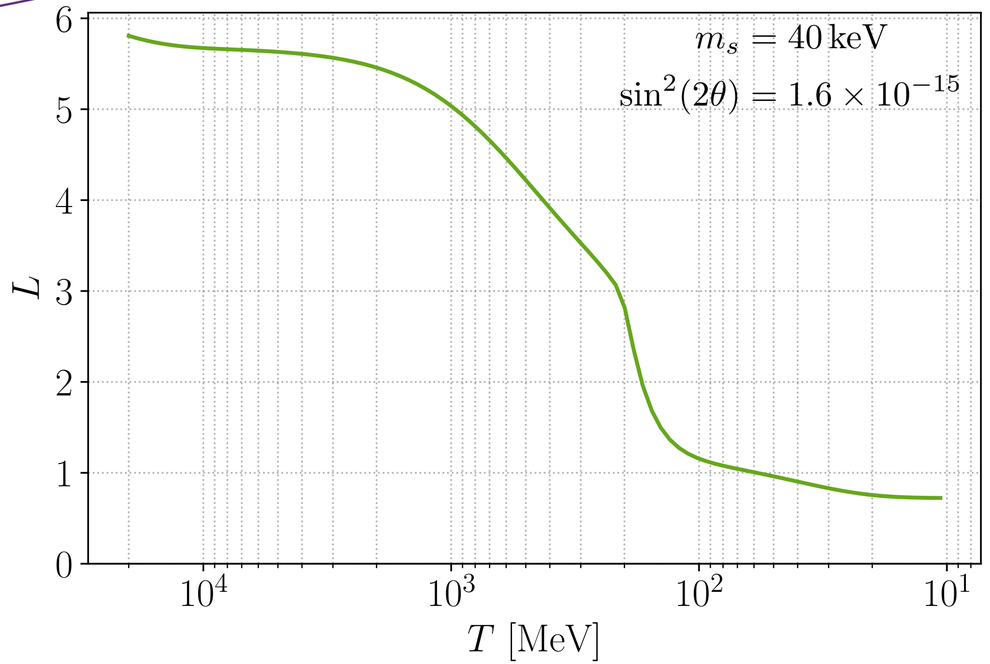

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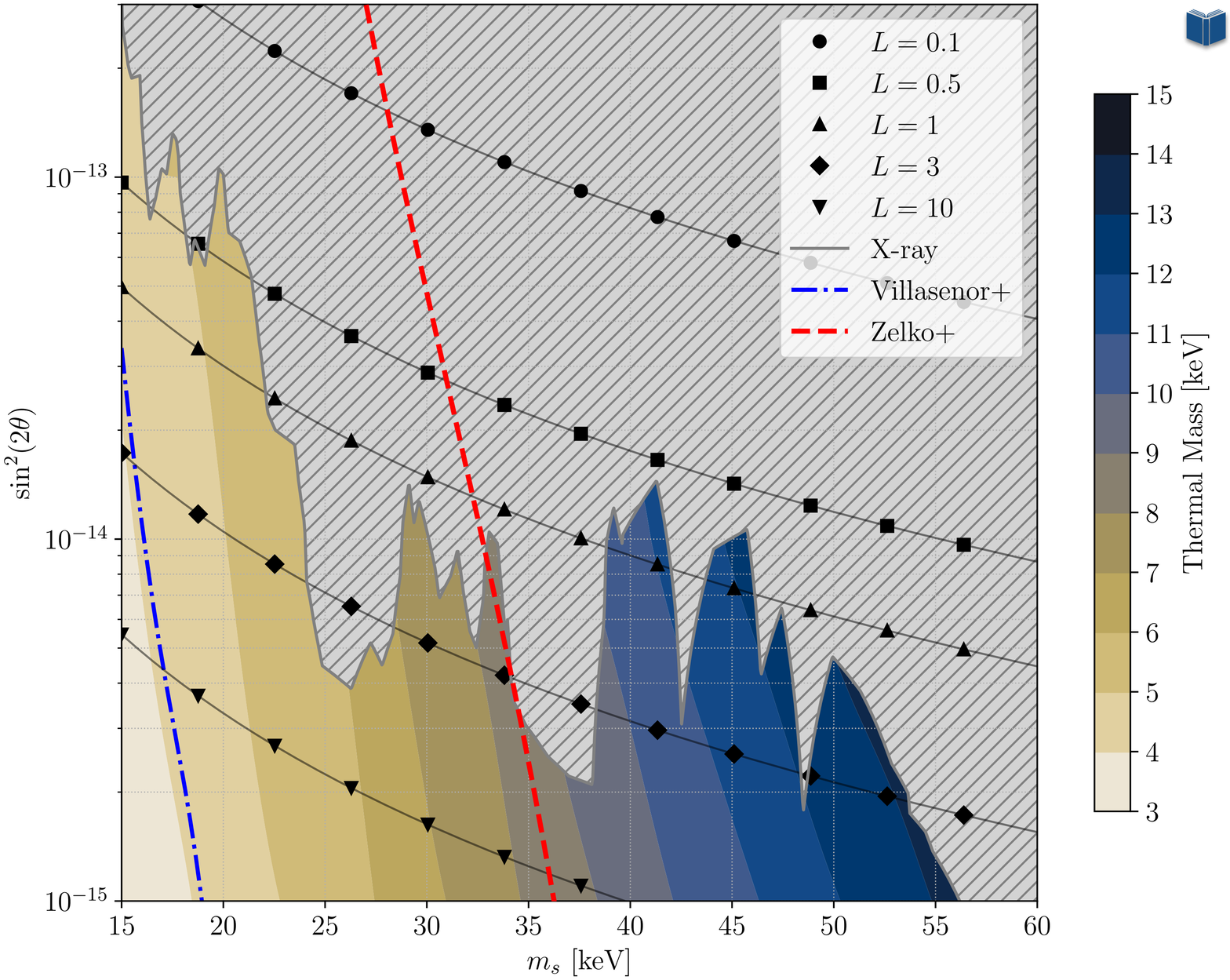
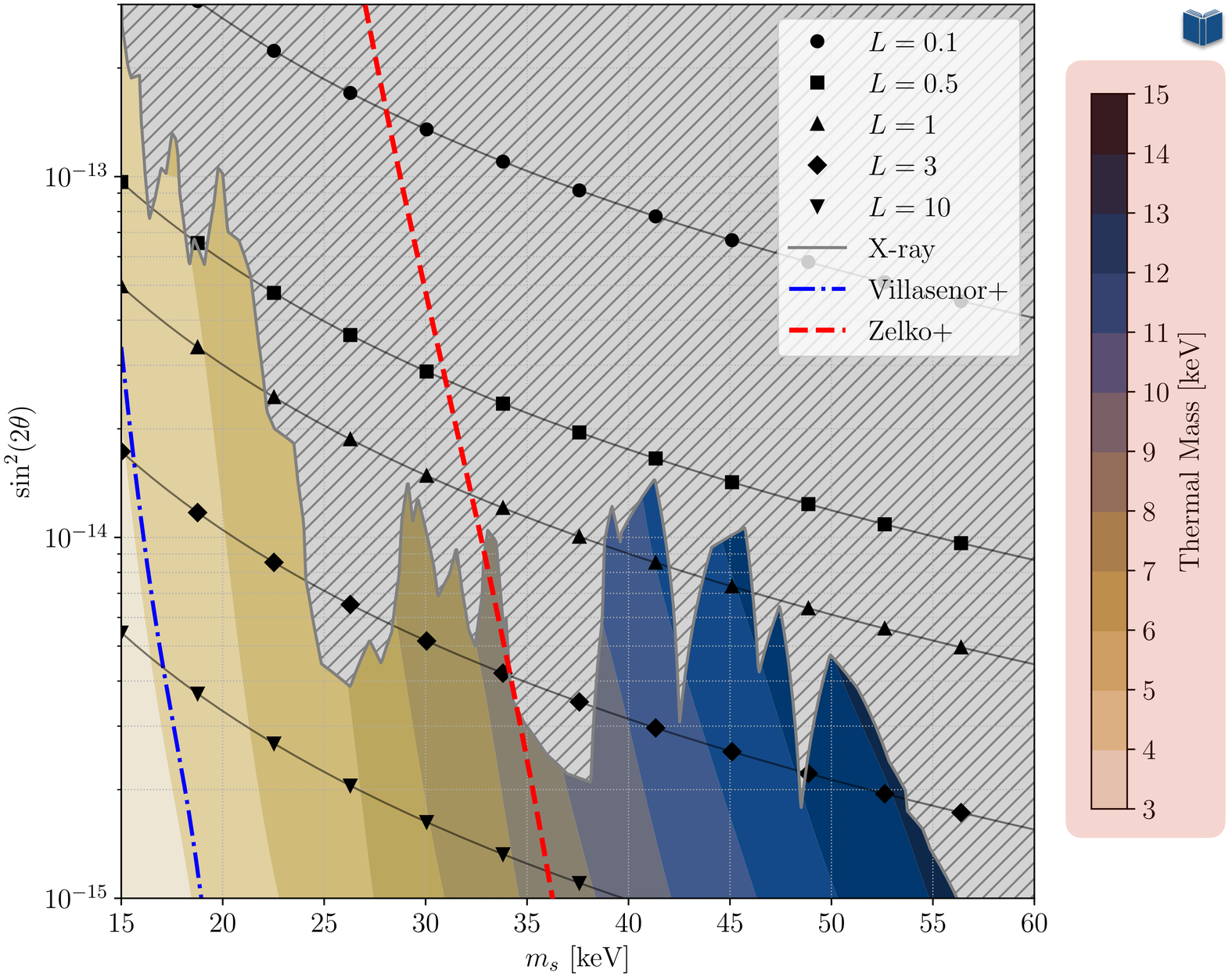


Constraints on SF sterile neutrino dark matter



C. Vogel *et al.* [2507.18752]

Equivalent thermal warm dark matter mass, for structure formation constraints

Summary

- 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

JF, C. Pitrou [2110.11889]
JF, C. Pitrou [2405.06509]
V. Domcke *et al.* [2502.14960, 2510.02438]

- Future CMB experiments should have enough constraining power to be able to set actual constraints.

- 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!

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

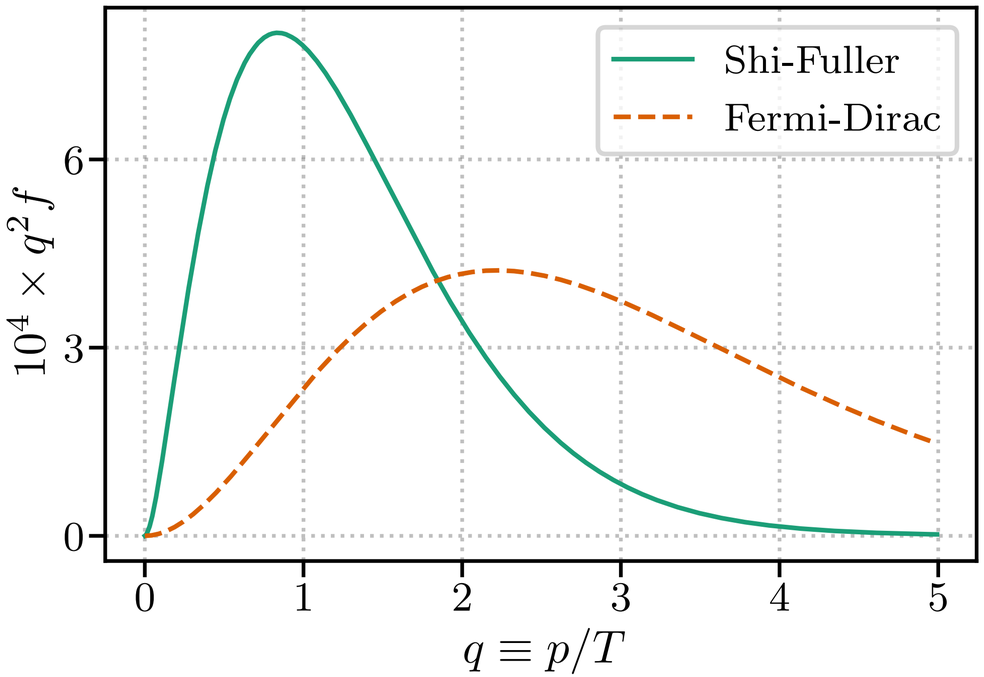
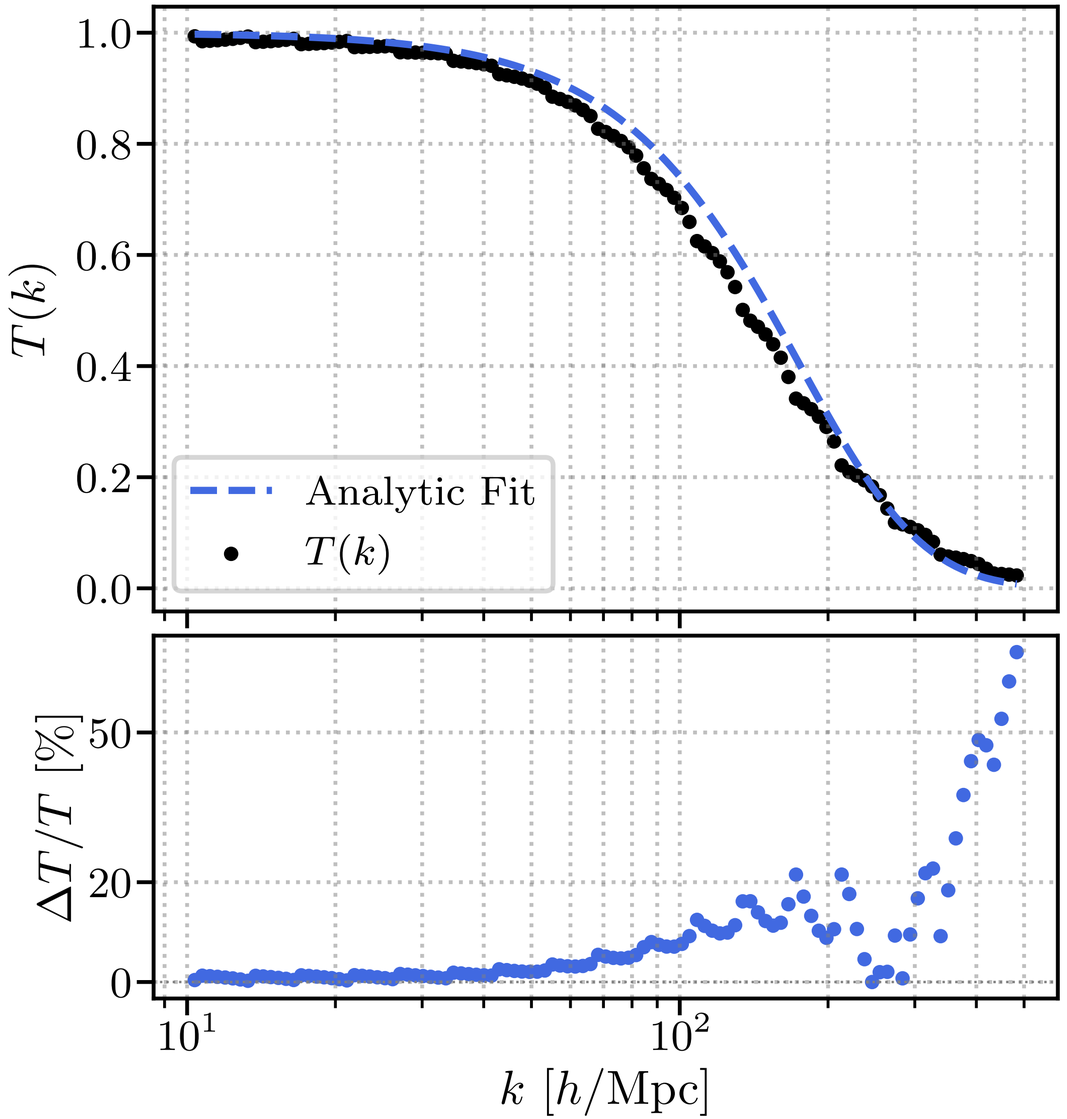
Lepton mean-field
(effective potential due to the charged lepton background)

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

Collisions

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

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

Connection with thermal warm dark matter

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