Sterile neutrino dark matter with lepton flavor asymmetries

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with

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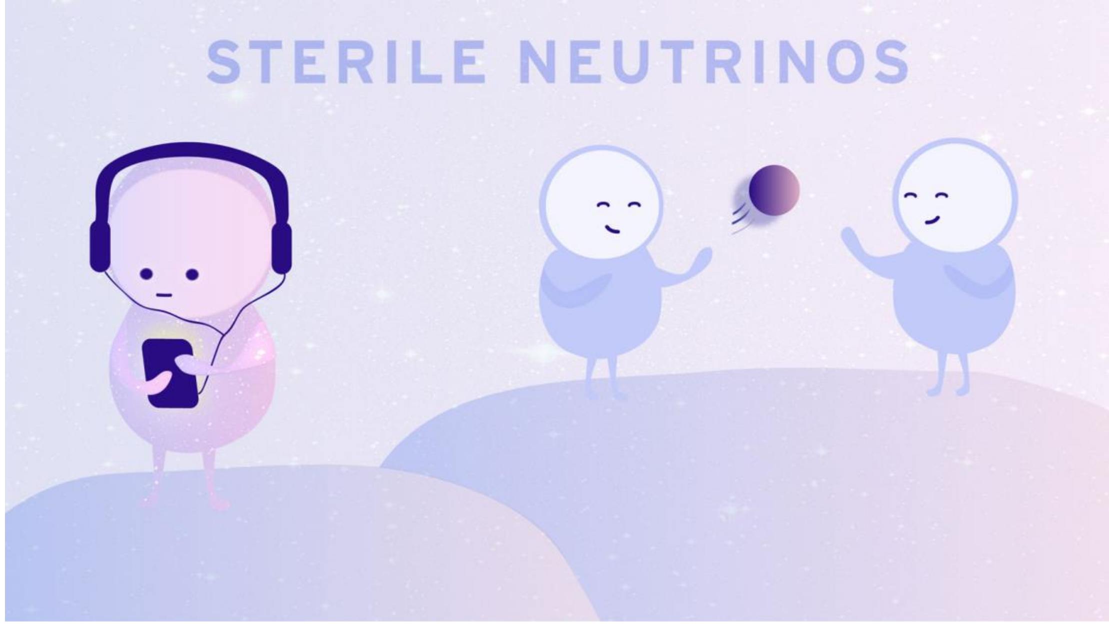
Ongoing work

The Frontier of Particle Physics: Exploring Muons, Quantum Science and the Cosmos, June 20th

Introduction



- Sterile neutrinos are one of good dark matter candidates,
- They can also give neutrino masses.
- Sterile neutrinos freeze-in via oscillations in the early universe.

Mixing angle between ν_α and ν_s

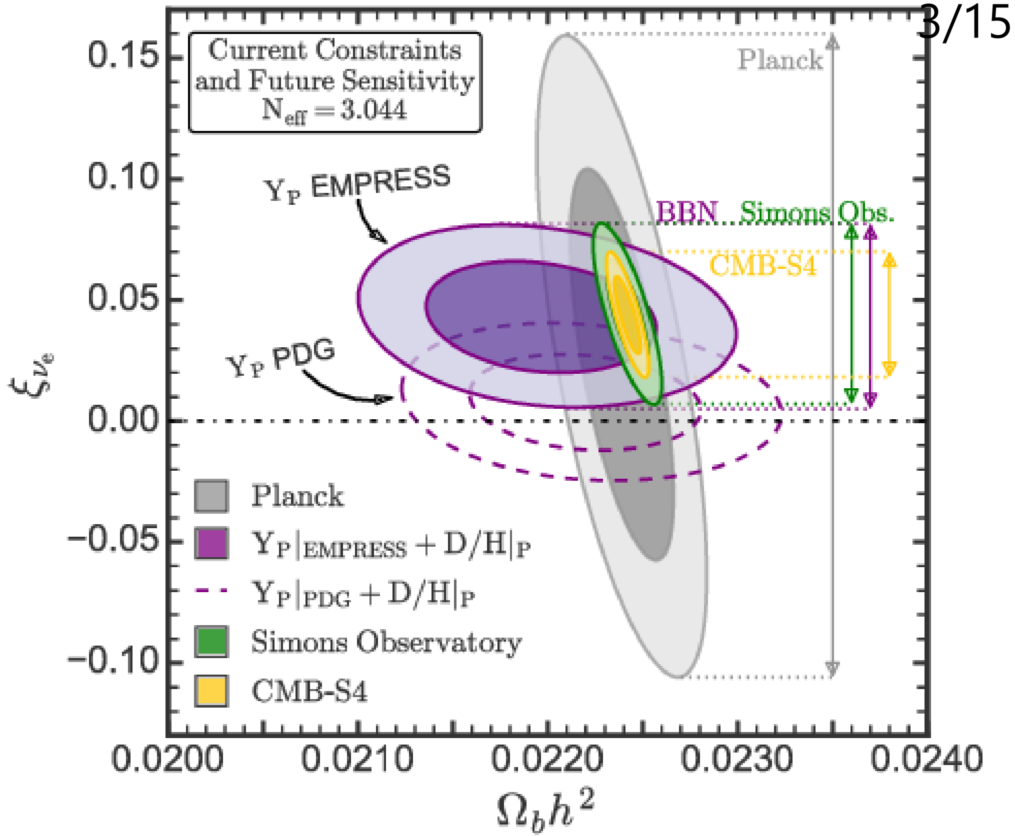
$$\langle P_m(\nu_\alpha \to \nu_s; p)\rangle = \frac{1}{2}\frac{\Delta^2 \sin^2 2\theta}{\Delta^2 \sin^2 2\theta + [\Delta \cos 2\theta - V_\alpha]^2 + (\frac{\Gamma_\alpha}{2})^2}.$$

$\Delta = \frac{m_s^2}{2p}$ Matter potential Quantum Zeno damping

Introduction

- Recently, the heliim-4 anomaly in the universe is reported.
  Matsumoto, et al. 2203.09617

- Large lepton asymmetry is one of resolutions in this anomaly.



Escudero, et al. 2208.03201

- If large lepton asymmetry exist, the active-sterile oscillation is enhanced!

$$\langle P_m(\nu_\alpha \to \nu_s; p)\rangle = \frac{1}{2}\frac{\Delta^2 \sin^2 2\theta}{\Delta^2 \sin^2 2\theta + \underbrace{[\Delta\cos 2\theta - V_\alpha]^2}_{=0} + \left(\frac{\Gamma_\alpha}{2}\right)^2}.$$

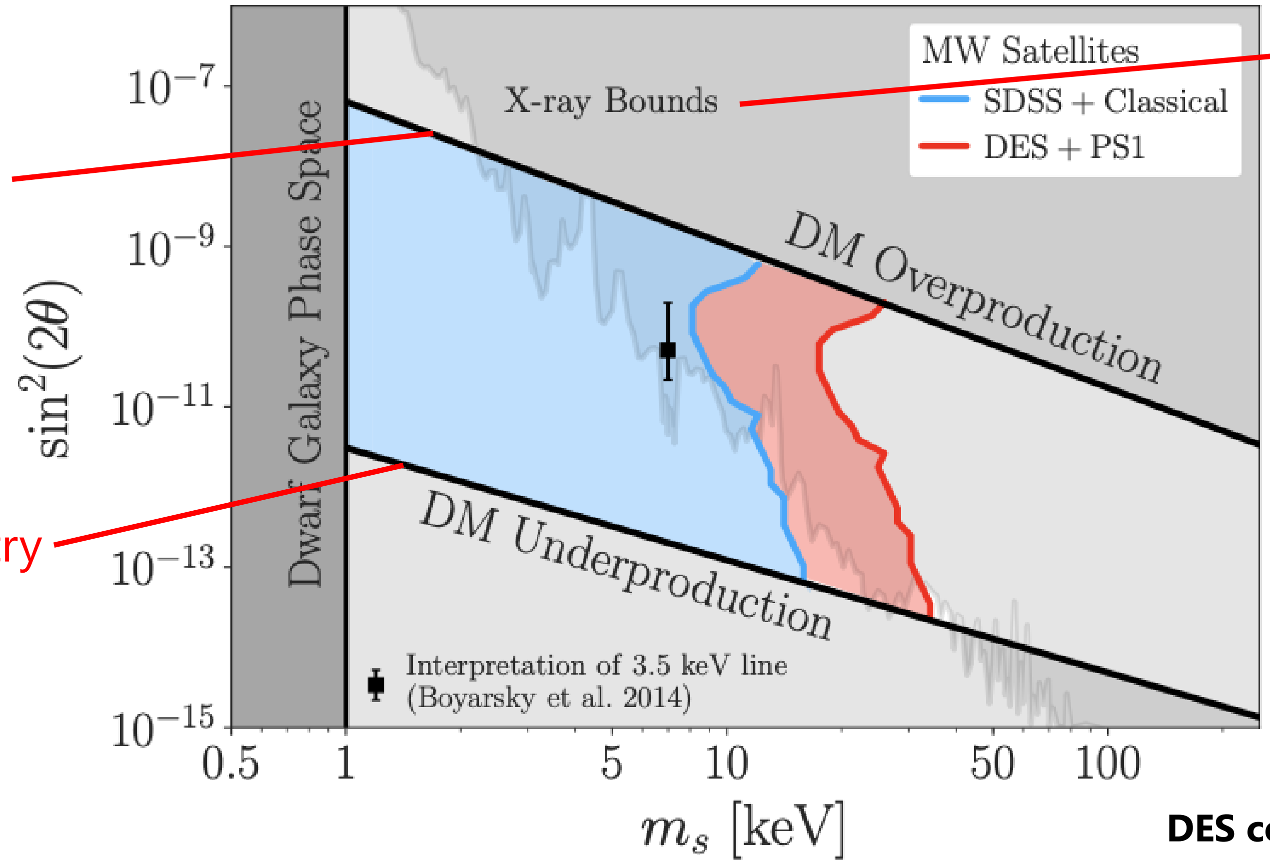
$$V_\alpha \approx \sqrt{2} G_F L s \qquad L = \frac{\Delta n_L}{s}$$

Introduction

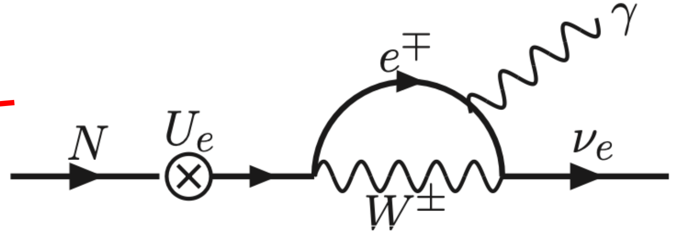
- However, sterile neutrino DM might be (almost) excluded even if large lepton asymmetry exist…

No asymmetry

Large asymmetry

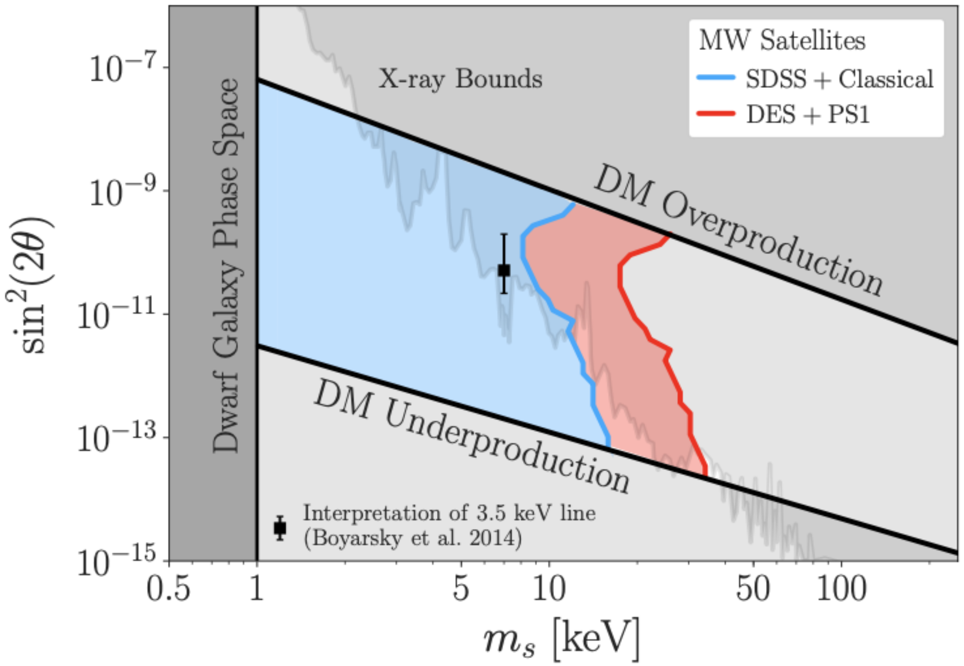


DES collaboration 2008.00022



Drews, et al. 1602.04816

Introduction



DES collaboration 2008.00022

- The lower black line is typically set as

$$\frac{\Delta n_L}{s} \simeq 2.5 \times 10^{-3}$$

The BBN bound assuming $n_{L_e} = n_{L_\mu} = n_{L_\tau}$

Neutrino oscillations implies this.

- Active neutrino oscillations:

Ineffective at $T \gtrsim 15\ \mathrm{MeV}$

$$\underbrace{\begin{pmatrix} V_e + m_{ee} & m_{e\mu} & m_{e\tau} \\ m_{\mu e} & V_\mu + m_{\mu\mu} & m_{\mu\tau} \\ m_{\tau e} & m_{\mu\tau} & V_\tau + m_{\tau\tau} \end{pmatrix}}_{\text{Neutrino mass matrix}} \simeq \begin{pmatrix} V_e & 0 & 0 \\ 0 & V_\mu & 0 \\ 0 & 0 & V_\tau \end{pmatrix} \qquad V_\alpha \propto L_\alpha T^3$$

Effective at $T \lesssim 15\ \mathrm{MeV}$ (before the BBN starts).

How is lepton flavor asymmetries with zero total asymmetry?

Introduction

- We can easily imagine the following scenario.

T

Very large lepton flavor asymmetries are generated.

Sterile neutrinos are resonantly produced due to the asymmetries.

$T_{\rm osc} \sim 15\ \mathrm{MeV}$

Neutrino oscillations wash out the flavor asymmetries to (almost) zero.

$T_{\rm BBN} \sim 1\ \mathrm{MeV}$

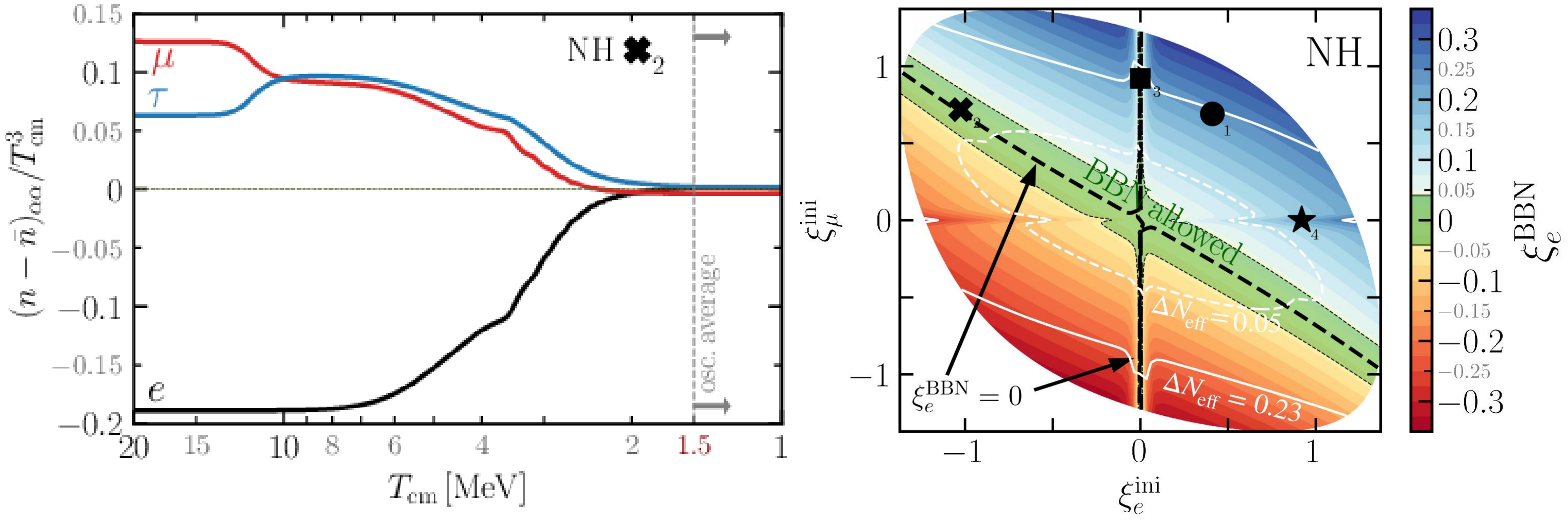
The BBN starts → No BBN bound on primordial lepton flavor asymmetries!?

t

Lepton flavor asymmetries open up a new parameter space for sterile neutrino DM!?

Lepton flavor asymmetries and BBN

Domcke, Escudero, Navarro and Sandner. 2502.14960



- The asymmetries of $L_e \simeq -L_\mu$ and $L_\mu = -L_\tau$ are much less constrained!
- The green contour ($\xi_e^{\rm BBN} \simeq +0.04$) can resolve the helium-4 anomaly.

Open questions

- Can the evolution equations in the previous literature be used for short resonance? In particular, neutrino oscillations can be averaged?

  [Shi and Fuller. 9810076], [Abazajian, Fuller, Patel. 0101524], [Kasai , Kawasaki, Murai. 2402.11902], …
  gave such a concern for very large asymmetry, but does not offer this solution.

- What is the parameter space of sterile neutrino dark matter with lepton flavor asymmetries?

- What is the origin of lepton flavor asymmetries: leptoflavorgenesis?

System of the equations

- We construct the semi-classical Boltzmann equations with non-averaged oscillations

This is applicable to any lepton asymmetries.

$$\left(\frac{\partial}{\partial t} - Hp\frac{\partial}{\partial p}\right) f_{\nu_s}(p,t) = \frac{\Gamma_\alpha(p,\mu)}{2} P_{\text{eff}}(\nu_\alpha \to \nu_s)\left[f_{\nu_\alpha}(p,\mu) - f_{\nu_s}(p,t)\right] ,$$

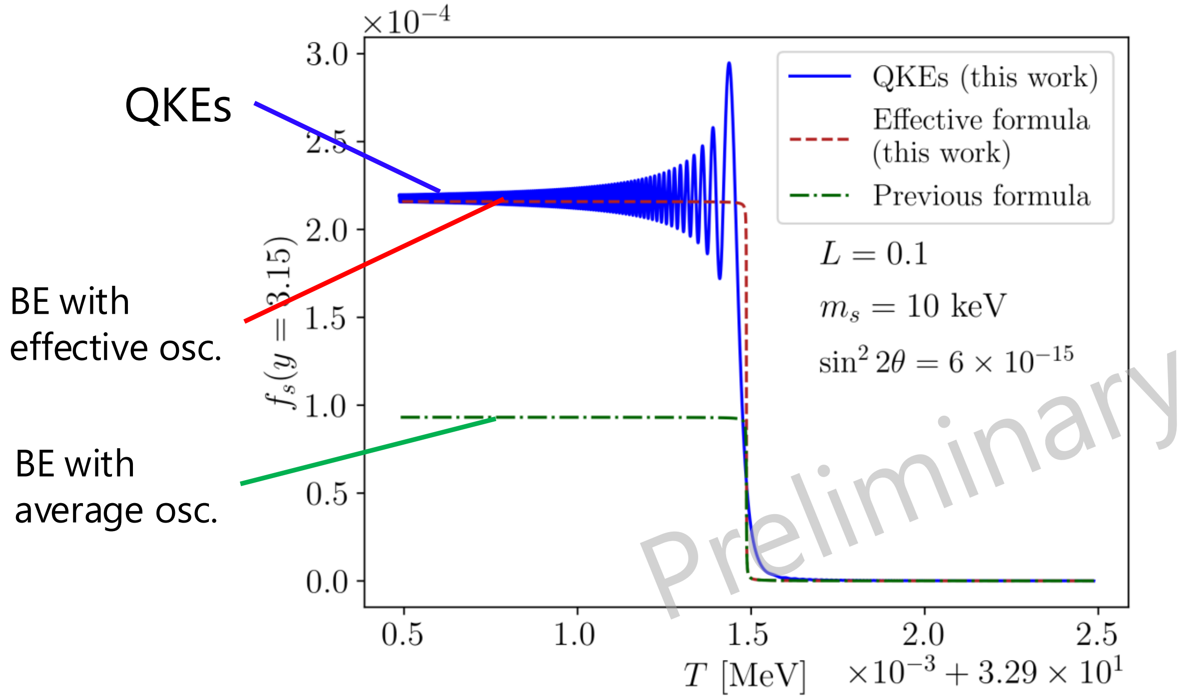
Active neutrino interaction rate

$P_{\text{eff}}(\nu_\alpha \to \nu_s)$: effective oscillation probability

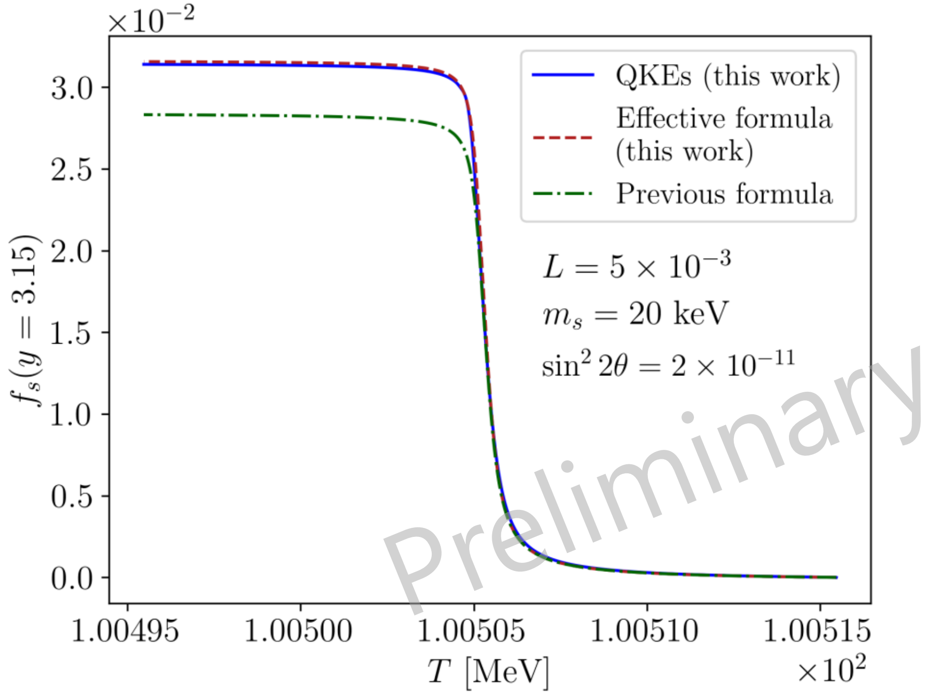
$$P_{\text{eff}}(\nu_\alpha \to \nu_s) = \underbrace{P(\nu_\alpha \to \nu_s, \delta t_{\text{res}})}_{\text{Usual probability with typical resonance time}} \times \underbrace{\frac{(\Gamma_\alpha/2)^{-1}}{\delta t_{\text{res}}}}_{\text{Enhancement by free-streaming accumulating neutrinos}}$$

$$\approx \frac{1}{2}\frac{\Delta(p)^2 \sin^2 2\theta}{[\Delta(p)\cos 2\theta - V_\alpha]^2 + \left(\frac{\Gamma_\alpha}{2}\right)^2}$$

Effective oscillations and QKEs



Narrow resonance width



Wide resonance width

- A more fundamental (but computational expensive) way to follow sterile neutrino evolution is solving the quantum kinetic equations (QKEs).

The equations for density matrix

System of the equations

- Evolution equation for the plasma temperature

$$\frac{dT}{dt} = -\frac{3H(\rho_{\rm SM} + P_{\rm SM}) + \partial\rho_{\nu_s}/\partial t}{d\rho_{\rm SM}/dT} \qquad \frac{\partial \rho_{\nu_s}}{\partial t} \equiv \frac{1}{2\pi^2}\int dp\, p^2 \sqrt{p^2+m_s^2}\,\frac{d}{dt}\left[f_{\nu_s}(p,t) + f_{\bar{\nu}_s}(p,t)\right]$$

- Evolution equation for lepton flavor asymmetries

$$\frac{d}{dt}L_\alpha = -\frac{1}{s}\int dp\, p^2 \frac{d}{dt}\left[f_{\nu_s}(p,t) - f_{\bar{\nu}_s}(p,t)\right]$$

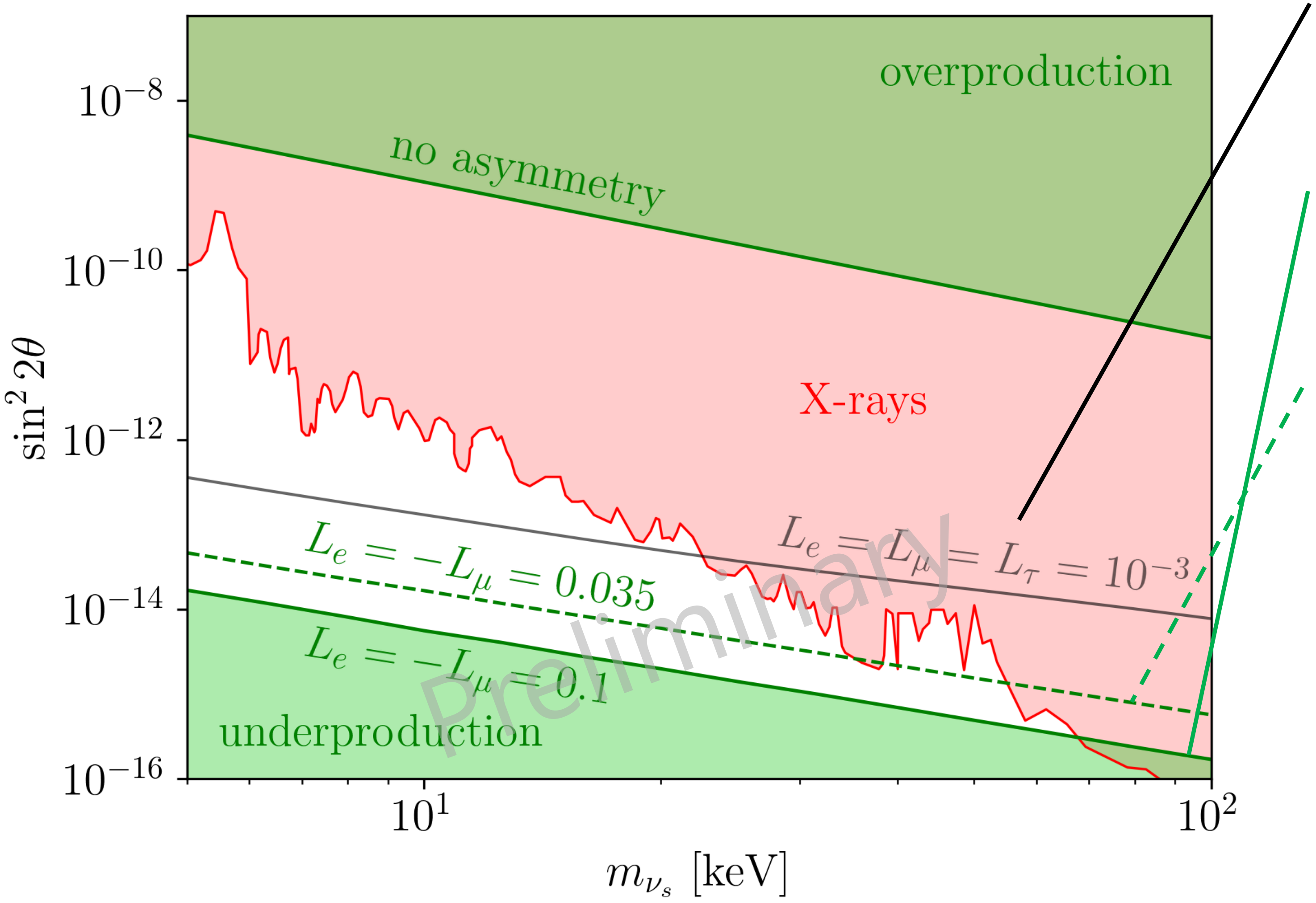
Each particle asymmetry is satisfied in the $B,\ L_\alpha,\ Q$ conservation:

$$\frac{\Delta n_{\nu_\alpha} + \Delta n_\alpha}{s} = L_\alpha \quad (\alpha = e,\ \mu,\ \tau)\,,$$

$$\sum_i \frac{b_i \Delta n_i}{s} = B,$$

$$\sum_i \frac{q_i \Delta n_i}{s} = 0\,,$$

Parameter space



Current limit for lepton asymmetry allowed by the BBN and CMB

We set a fiducial value of lepton flavor asymmetries: $L_e = -L_\mu = 0.1$.

The target sensitivity of the ongoing Simons Observatory:

$$L_e = -L_\mu \simeq 0.035$$

assuming normal neutrino mass ordering.

*Inverted ordering might be disfavored by the DESI+CMB observation. **[Jiang et al. 2407.18047]**

Typical constraints from structure formation:

$$m_{\nu_s} \lesssim 7\text{–}35 \text{ keV}$$

Origin of lepton flavor asymmetries

- The Affleck-Dine mechanism is one of the mechanisms that naturally explain large asymmetries.
  [Affleck, Dine. 1985]

- In the supersymmetric theory, there are flat directions that have no total lepton charge but lepton flavor charge, e.g., $Q_i \bar{u}_j L_k \bar{e}_l$.

- Scalar leptons can have large VEVs and rotate, generating lepton flavor asymmetries.

$$n_\phi \simeq 2|\phi|^2 \dot{\theta}$$

- Lepton flavor asymmetries with zero total asymmetry can partially convert to baryon asymmetry via sphaleron processes

$$\frac{n_B}{s} \simeq -0.030 \left(h_\tau^2 \frac{n_\tau}{s} + h_\mu^2 \frac{n_\mu}{s} + h_e^2 \frac{n_e}{s} \right),$$

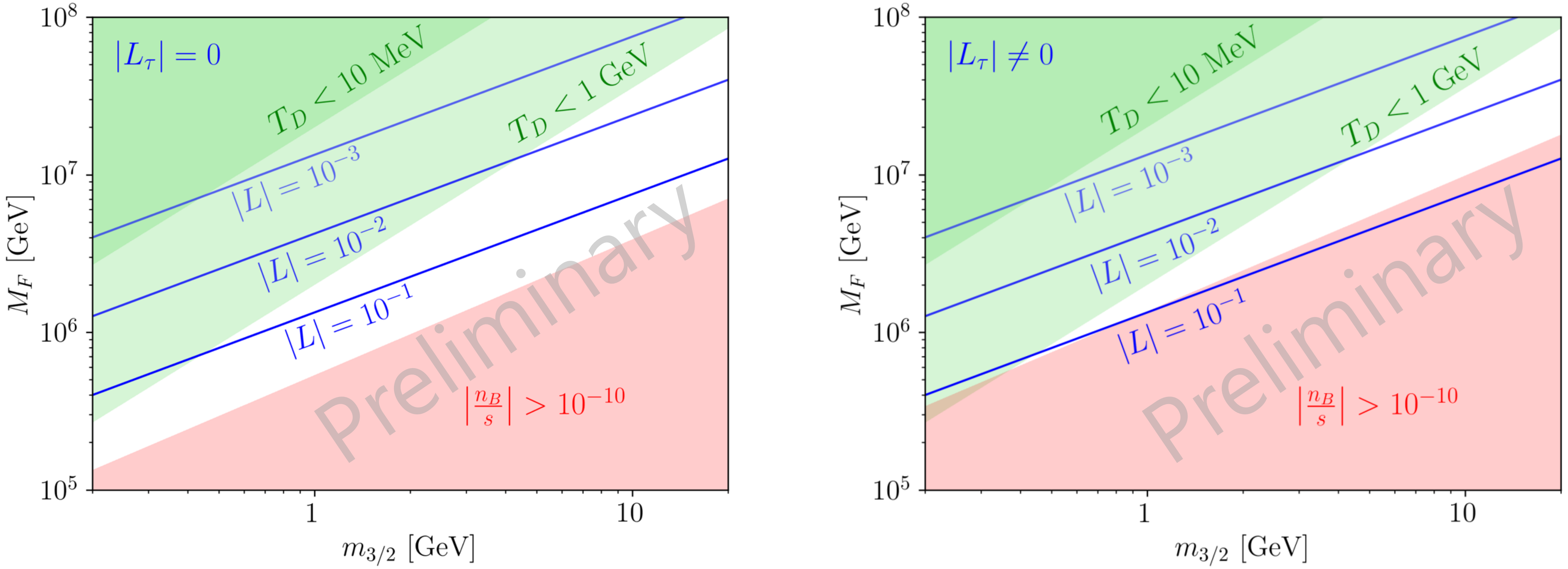
$$h_\tau \simeq 0.010, \quad h_\mu \simeq 6.1 \times 10^{-4}, \quad h_e \simeq 2.9 \times 10^{-6}$$

[March-Russell, Murayama, Riotto. 9908396.]
[Laine and Shaposhnikov. 9911473.]
[Mukaida, Schmmitz, Yamada, 2111.03082.]

- Scalar leptons can deform to the non-topological solitons, protected by the sphaleron processes. Even larger asymmetries can be generated.

[Kawasaki et al. 0205101], [Kawasaki et al. 2203.09713], [Kasai et al. 2402.11902]

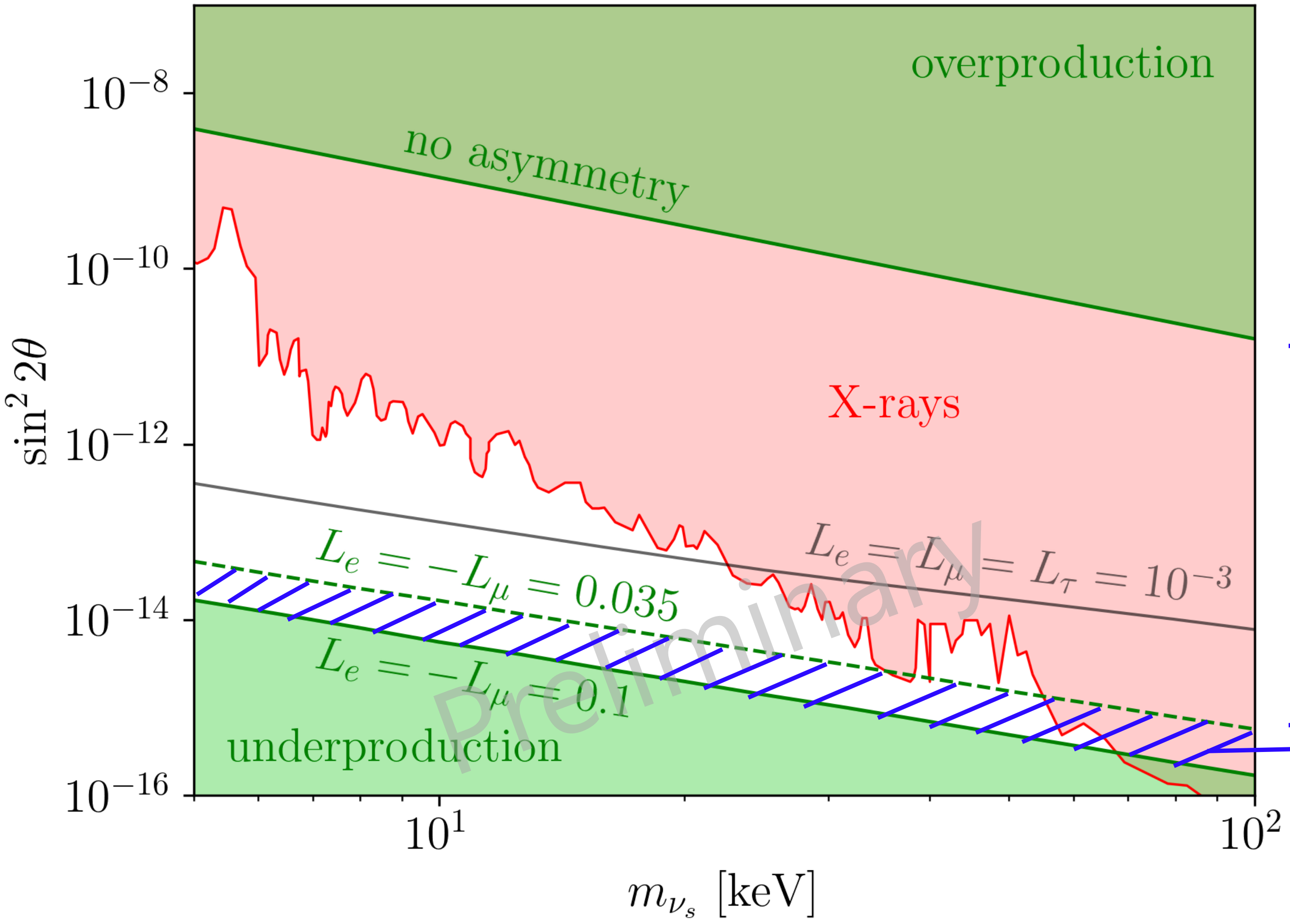
Origin of lepton flavor asymmetries



The AD leptoflavorgenesis scenario with Q-balls can generate large lepton flavor asymmetries with $|L| \gtrsim 0.1$ to avoid an overproduction of baryon asymmetry.

In the white region, the asymmetries are generated in $T \gtrsim 1\ \mathrm{GeV}$.

Conclusions



Lepton flavor asymmetries are motivated by the helium-4 anomaly.

We recommend
the future search in X-rays and structure formation should test this region.

The ongoing Simons Observatory could test this region indirectly.

Thank you!