Sterile neutrino dark matter with lepton flavor asymmetries

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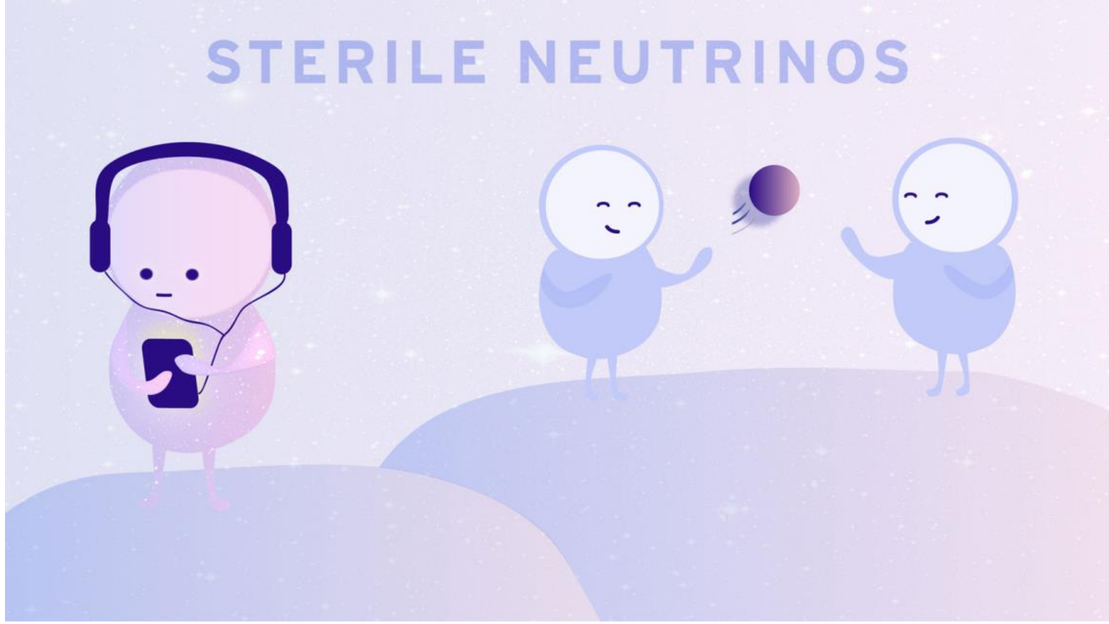
Introduction



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

Mixing angle between ν_α and ν_s

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

$\Delta = \frac{m_s^2}{2p}$

Matter potential

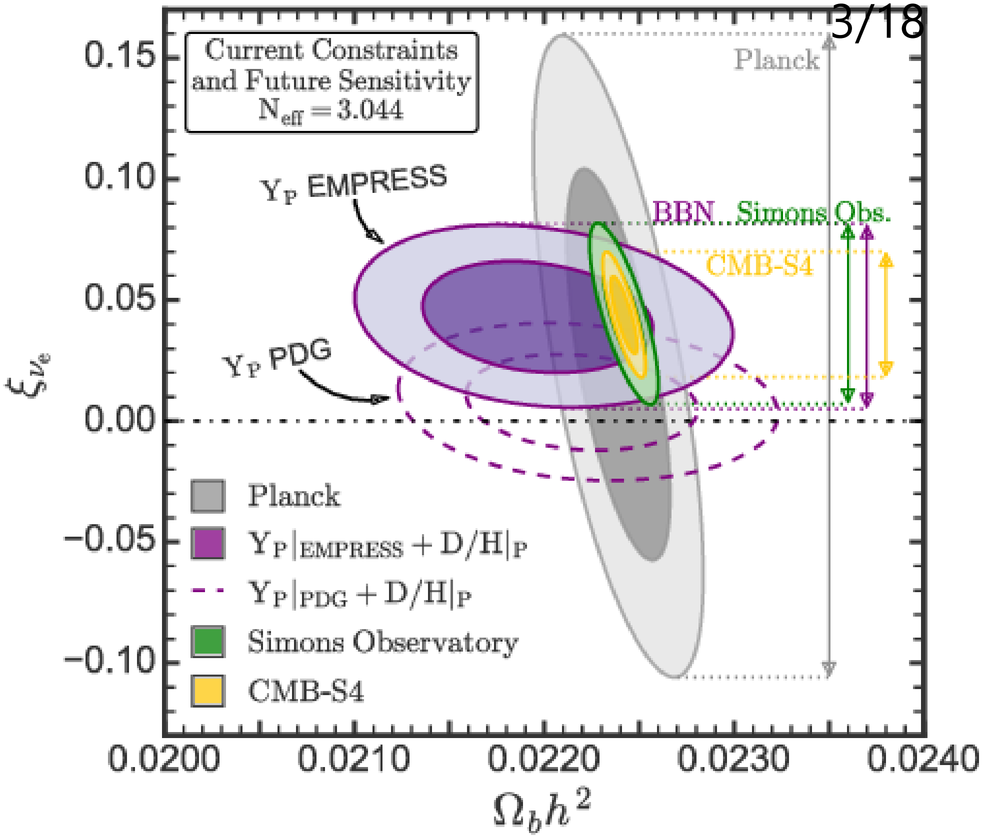
Quantum Zeno damping

Introduction

- Recently, the helium-4 anomaly (a smaller $^4\mathrm{He}$) in the universe is reported.

Matsumoto, et al., 2203.09617.
Yanagisawa et al., 2506.24050.

- <u>Positive</u> large ν_e asymmetry is one of resolutions in this anomaly.



Escudero, et al. 2208.03201

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

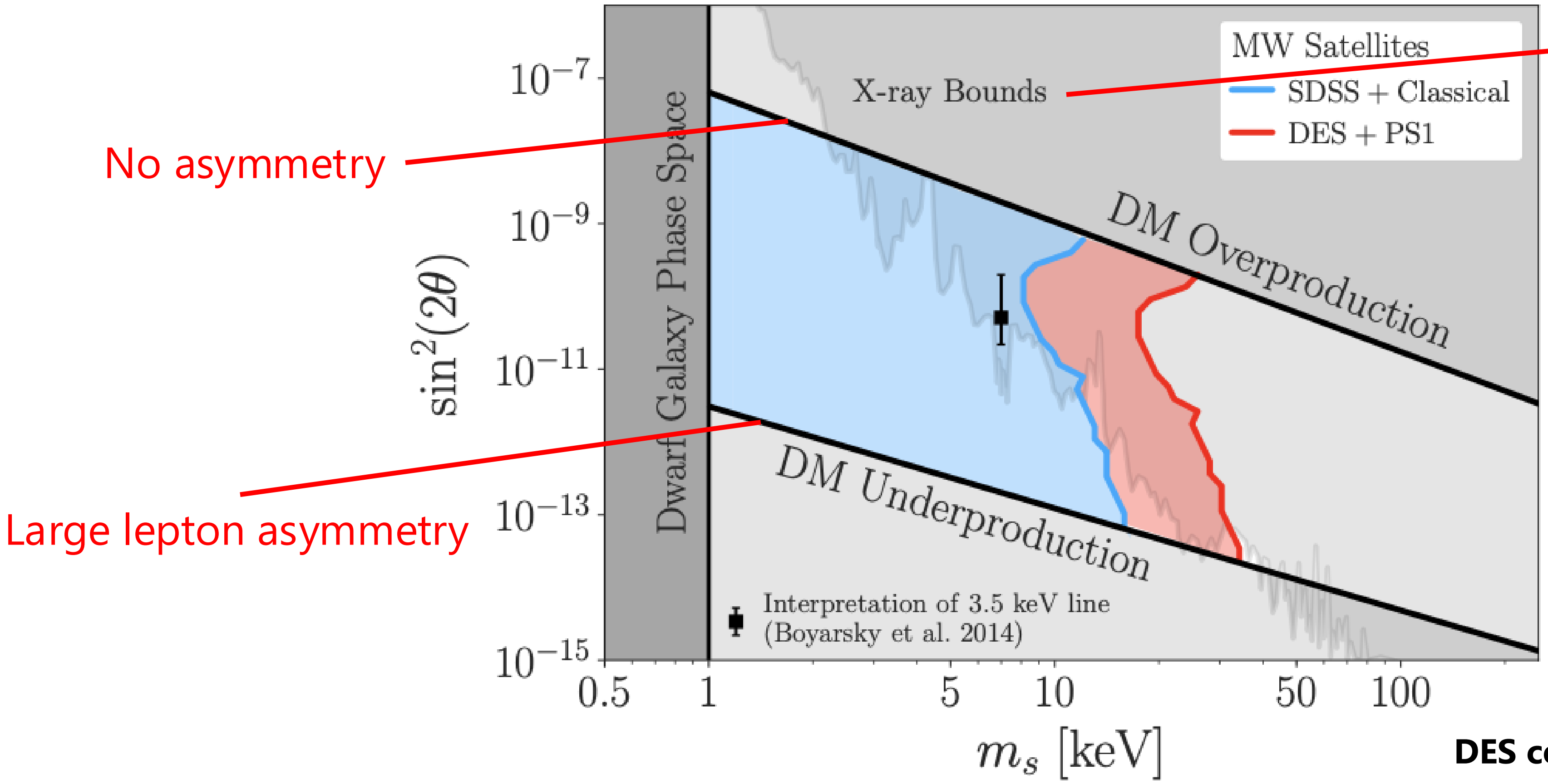
Shi and Fuller, 9810076, Abazajian et al., 0101524.

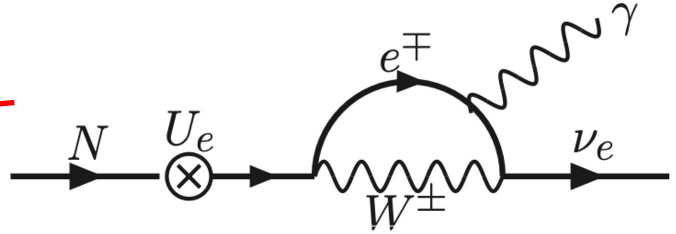
$$\langle P_m(\nu_\alpha \to \nu_s; p)\rangle = \frac{1}{2}\frac{\Delta^2 \sin^2 2\theta}{\Delta^2 \sin^2 2\theta + \underbrace{[\Delta \cos 2\theta - V_\alpha]^2}_{=0} + \left(\frac{\Gamma_\alpha}{2}\right)^2}.$$

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

Introduction

- However, sterile neutrino DM may be excluded even if large lepton asymmetry exist…





Drews, et al. 1602.04816

DES collaboration 2008.00022

Introduction

- By the way, lepton asymmetry may be related to the observed baryon asymmetry.

$$B^{\rm obs} = \frac{\Delta n_B^{\rm obs}}{s} \simeq 8.75 \times 10^{-11}$$

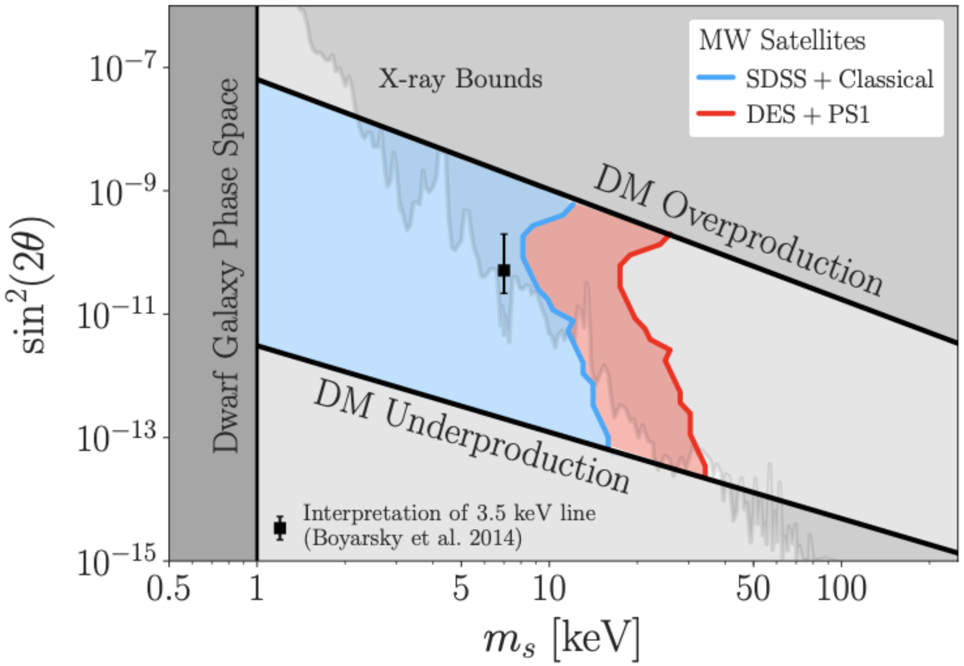
- However, ...

$$B \simeq -\frac{8}{23} L \quad \text{at} \quad T > T_{\rm sph} \simeq 130 \ {\rm GeV}$$

  - Baryon asymmetry may be overproduced by the sphaleron processes.
  - Positive lepton asymmetry may induce negative baryon asymmetry.

The helium-4 anomaly may be unrelated for other puzzles…?

Introduction



DES collaboration 2008.00022

- The lower black line is typically set as

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

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

Neutrino oscillations imply this.

- Active neutrino oscillations:

Ineffective at $T \gtrsim 15$ MeV

$$\begin{pmatrix} V_e + m_{ee} & m_{e\mu} & m_{e\tau} \\ m_{\mu e} & V_\mu + m_{\mu\mu} & m_{\mu\tau} \\ m_{\tau e} & m_{\mu\tau} & V_\tau + m_{\tau\tau} \end{pmatrix} \simeq \begin{pmatrix} V_e & 0 & 0 \\ 0 & V_\mu & 0 \\ 0 & 0 & V_\tau \end{pmatrix} \qquad V_\alpha \sim L_\alpha T^3 + \dots$$

Neutrino mass matrix

Effective at $T \lesssim 15$ MeV (before the BBN and neutrino decoupling start).

How is lepton flavor asymmetries with zero total asymmetry?

Introduction

T

Very large lepton flavor asymmetries are generated.

Sterile neutrinos are resonantly produced due to the asymmetries.

$$\langle P_m(\nu_\alpha \to \nu_s; p)\rangle = \frac{1}{2}\frac{\Delta^2 \sin^2 2\theta}{\Delta^2 \sin^2 2\theta + \underbrace{[\Delta \cos 2\theta - V_\alpha]^2}_{=0} + \left(\frac{\Gamma_\alpha}{2}\right)^2}. \quad \Leftrightarrow \quad T_{\rm res} \sim 27\ {\rm MeV} \left(\frac{10.75}{g_*}\right)^{1/4} \left(\frac{3}{y}\right)^{1/4} \left(\frac{0.1}{L}\right)^{1/4} \left(\frac{m_s}{5\ {\rm keV}}\right)^{1/2}$$

$$y = p/T$$

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

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

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

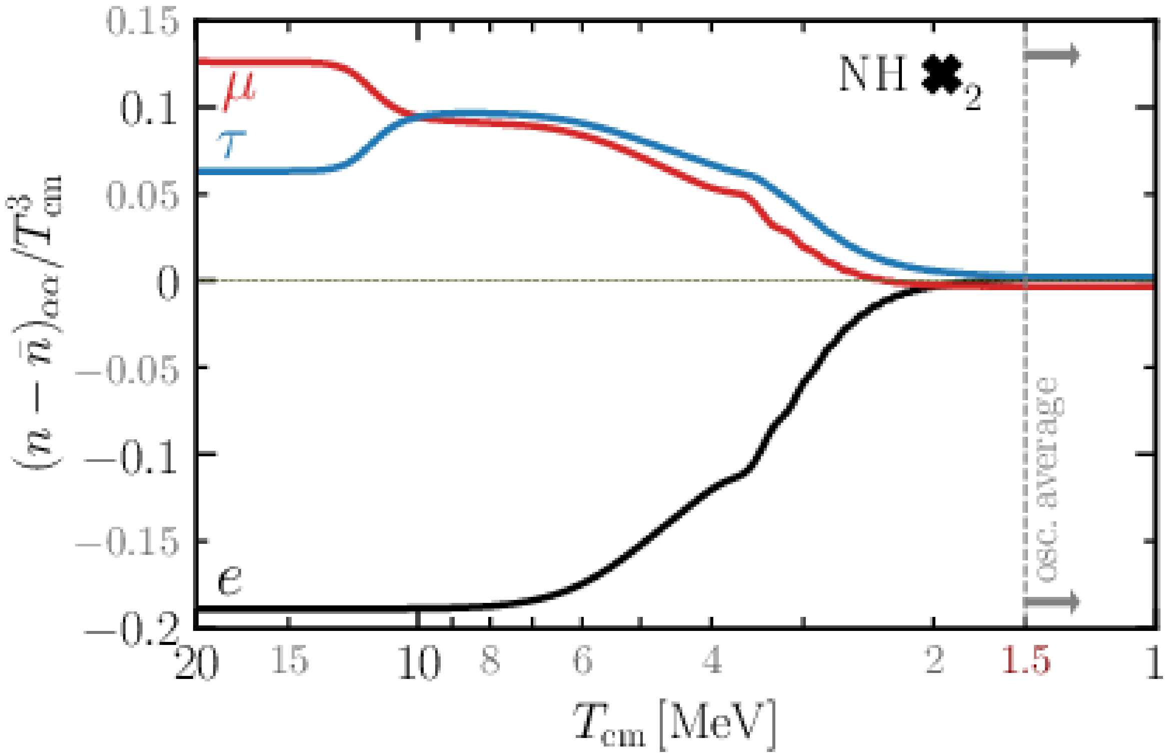
The BBN starts → No BBN bound on primordial lepton flavor asymmetries!?

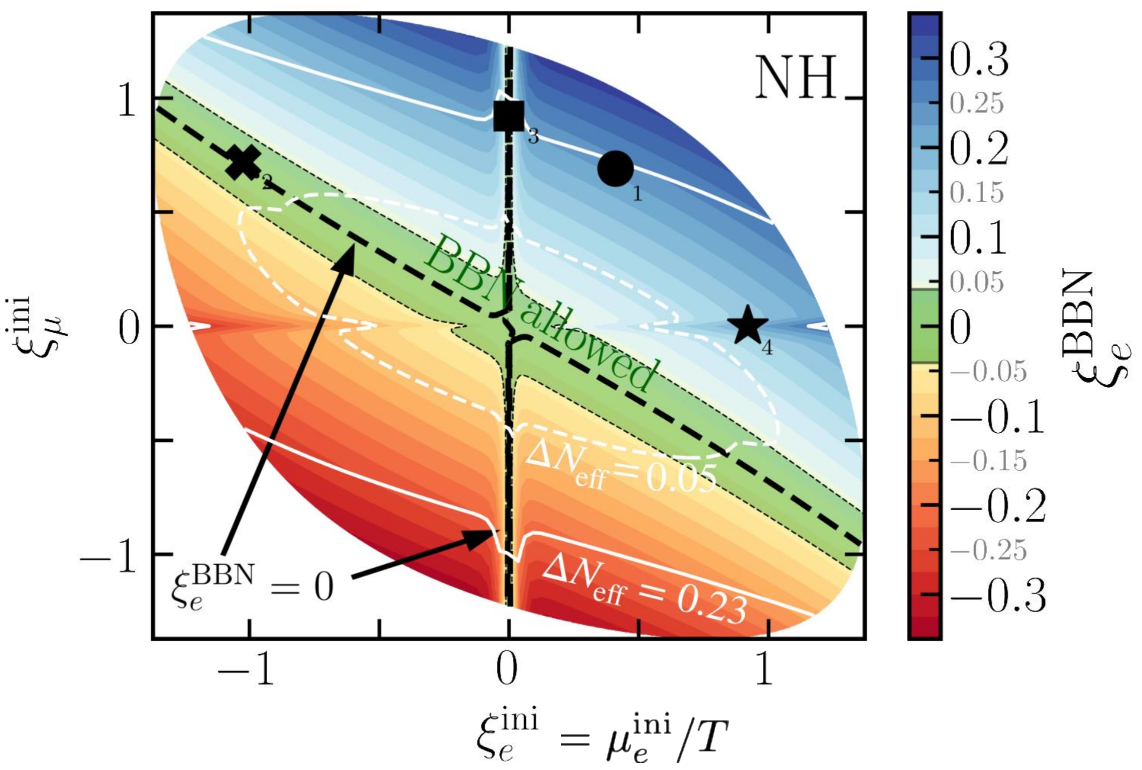
t

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 we use the previous formula for sterile neutrino production?

  In particular, neutrino oscillations can be averaged?

  *All previous literature use averaged procedures.

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

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

Neutrino oscillation at the resonance

- Neutrino oscillations can be averaged?

Resonance width

$$\frac{\delta t^{\rm ave}_{\rm res}}{l^{\rm res}_m} = \frac{1}{3HV_\alpha} \max\left[\Delta(p)\sin 2\theta, \frac{\Gamma_\alpha}{2}\right]^2, \qquad V_\alpha \propto L_\alpha$$

Oscillation length

$$\sim 0.05 \left(\frac{10.75}{g_*}\right)^{3/4} \left(\frac{y}{3.15}\right)^{13/4} \left(\frac{10^{-2}}{L}\right)^{9/4} \left(\frac{m_s}{10\ \mathrm{keV}}\right)^{5/2} \quad \text{if } \Delta \sin 2\theta < \Gamma_\alpha/2 \qquad \Delta = \frac{m_s^2}{2p}$$

→ Neutrino oscillations cannot be averaged for large L.

- Non-averaged oscillation probability

$$P_m(\nu_\alpha \to \nu_s; p, \delta t_{\rm res}) \approx \sin^2 2\theta_m \sin^2\left(\frac{m_m^2}{4p}\delta t_{\rm res}\right)\left[1+\left(\frac{\Gamma_\alpha \delta t_{\rm res}}{2}\right)^2\right]^{-1}, \qquad \frac{m_m^2}{2p} = l_m$$

$$\sim \sin^2 2\theta_m \left(\frac{m_m^2}{4p}\delta t_{\rm res}\right)^2\left[1+\left(\frac{\Gamma_\alpha \delta t_{\rm res}}{2}\right)^2\right]^{-1},$$

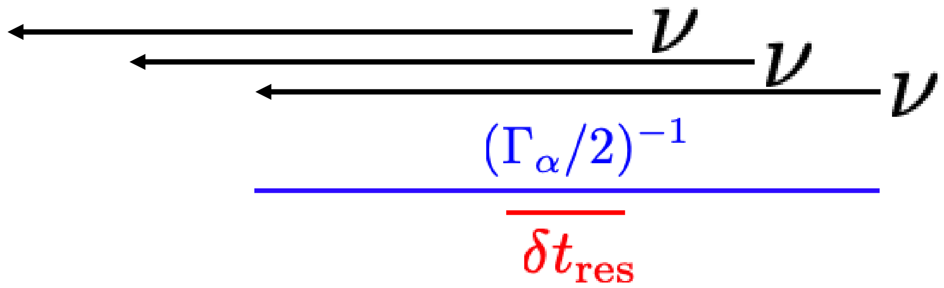
Damping factor by scattering

$$\ll \langle P_m(\nu_\alpha \to \nu_s; p)\rangle$$

$\ll 1$

System of the equations

- Enhancement by free-streaming accumulating neutrinos



Enhancement factor may be $\sim \dfrac{(\Gamma_\alpha/2)^{-1}}{\delta t_{\rm res}}$.

Effective oscillation probability

$$P_{\rm eff}(\nu_\alpha \to \nu_s) = P(\nu_\alpha \to \nu_s, \delta t_{\rm res}) \times \frac{(\Gamma_\alpha/2)^{-1}}{\delta t_{\rm res}}$$
$$\approx \frac{1}{2} \frac{\Delta(p)^2 \sin^2 2\theta}{[\Delta(p)\cos 2\theta - V_\alpha]^2 + \left(\frac{\Gamma_\alpha}{2}\right)^2}$$

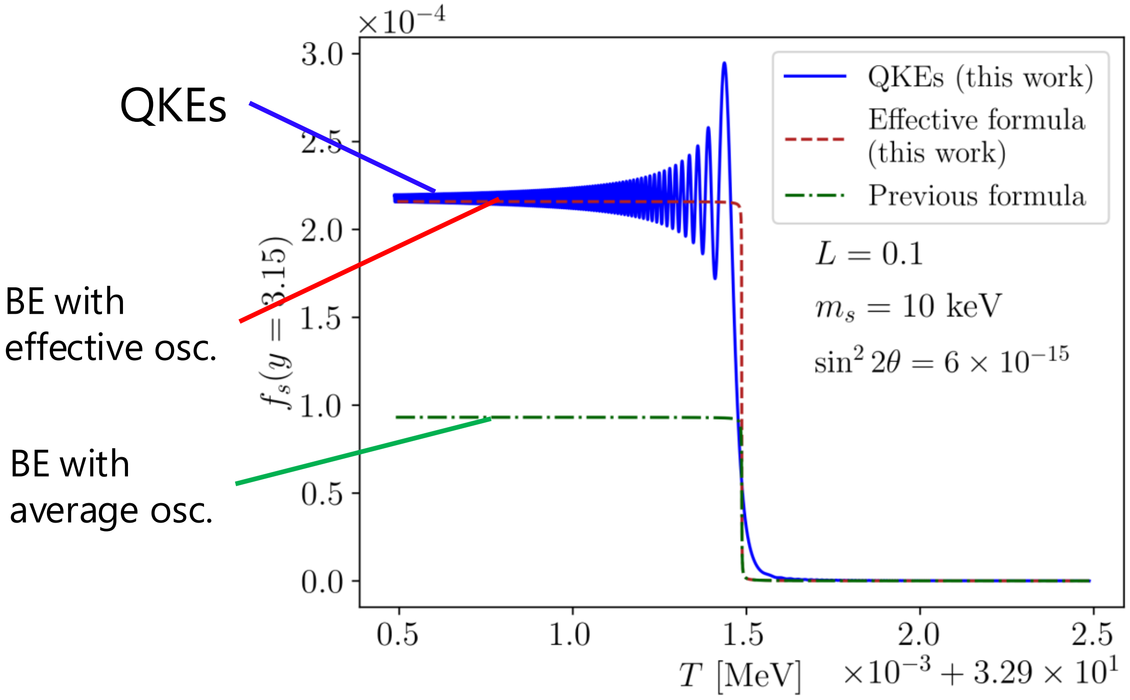
This is applicable to any lepton asymmetries.

- Effective Boltzmann equation for ν_s with non-averaged oscillations :

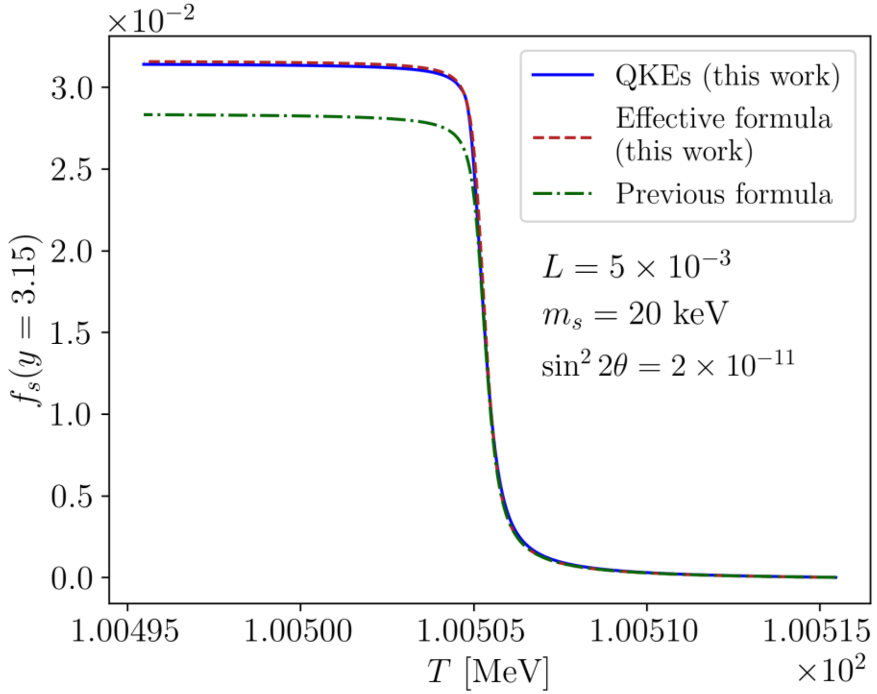
$$\left(\frac{\partial}{\partial t} - Hp\frac{\partial}{\partial p}\right) f_{\nu_s}(p,t) = \frac{\Gamma_\alpha(p,\mu)}{2} P_{\rm eff}(\nu_\alpha \to \nu_s)\left[f_{\nu_\alpha}(p,\mu) - f_{\nu_s}(p,t)\right] ,$$

Active neutrino interaction rate

Effective oscillations and QKEs



Non-averaged case



Averaged case

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

The equations for density matrix $\rho_{ij} = \langle a_i^\dagger a_j \rangle \quad (i, j = \alpha, s)$

The off-diagonal parts involve neutrino oscillations.

Comments on our numerical method

Solving the precise semi-classical Boltzmann eq, improving **Ghiglieri and Laine, 1506.06752. Venumadhav et al., 1507.06655.**

New!
- Non-averaged neutrino oscillation, which is in excellent agreement with QKEs.

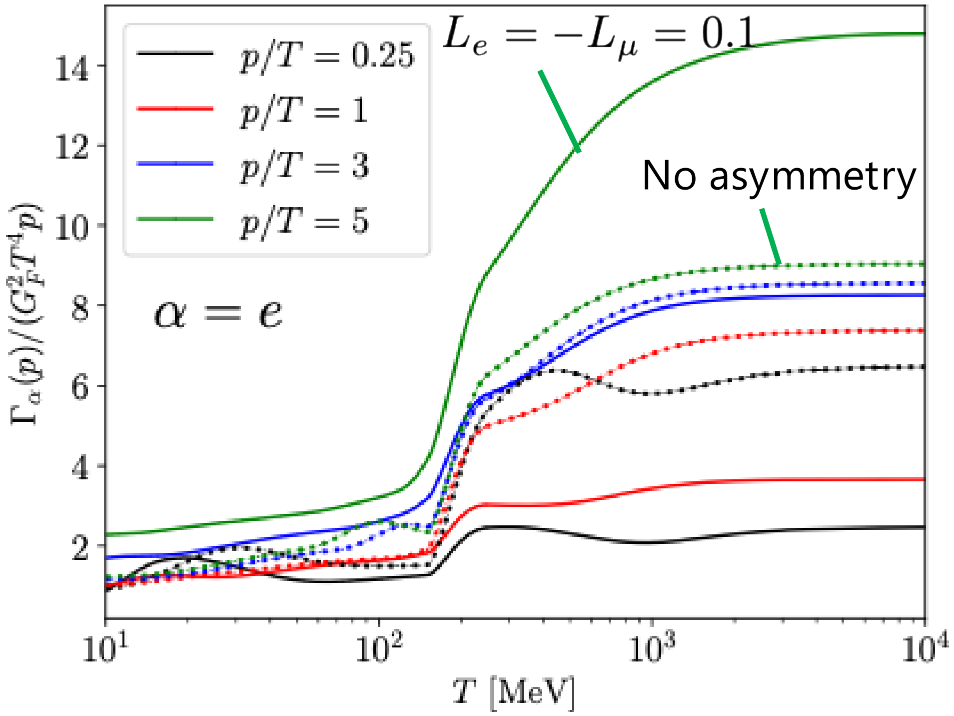
New!
- Full large chemical potentials are included.

Neutrino interaction rate: $\Gamma_\alpha = \Gamma_\alpha(p, \mu)$

Thermodynamics: $s(T, \mu) = s_0(T) + \delta s(T, \mu)$, ...

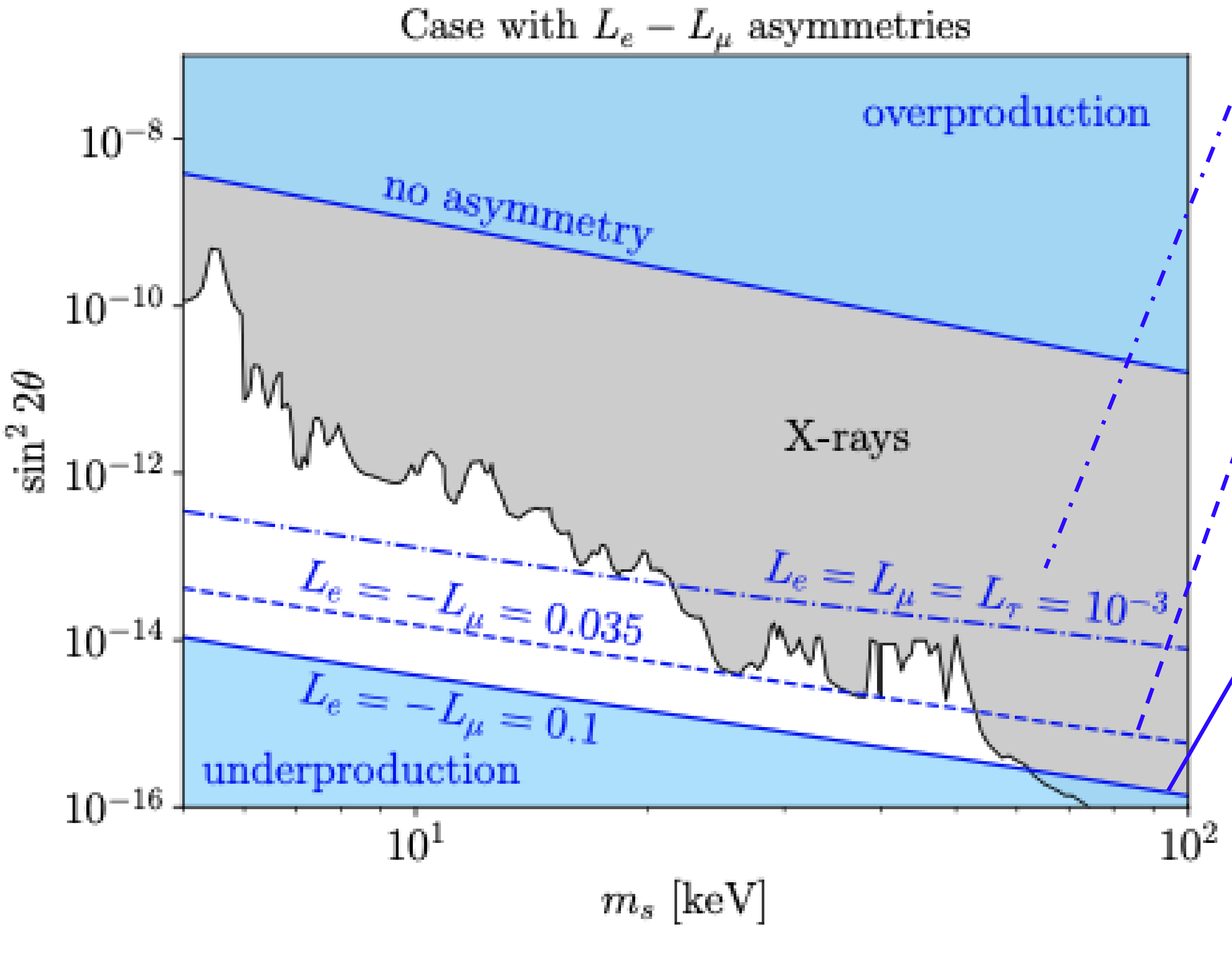
$$s_0(T) = \frac{2\pi^2}{45} g_{*,s}(T) T^3 \qquad \delta s(T, \mu) = \underline{s(T, \mu) - s(T)}$$

Ideal gas limit



New!
- Our code is publicly available: sterile-dm-lfa.

Parameter space



Current limit for universal lepton asymmetry allowed by the BBN and CMB

The target sensitivity of the ongoing Simons Observatory: $L_e = -L_\mu \gtrsim 0.035$ assuming normal neutrino mass ordering.

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

Typical constraints from structure formation: $m_s \lesssim 7\text{–}35$ 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

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

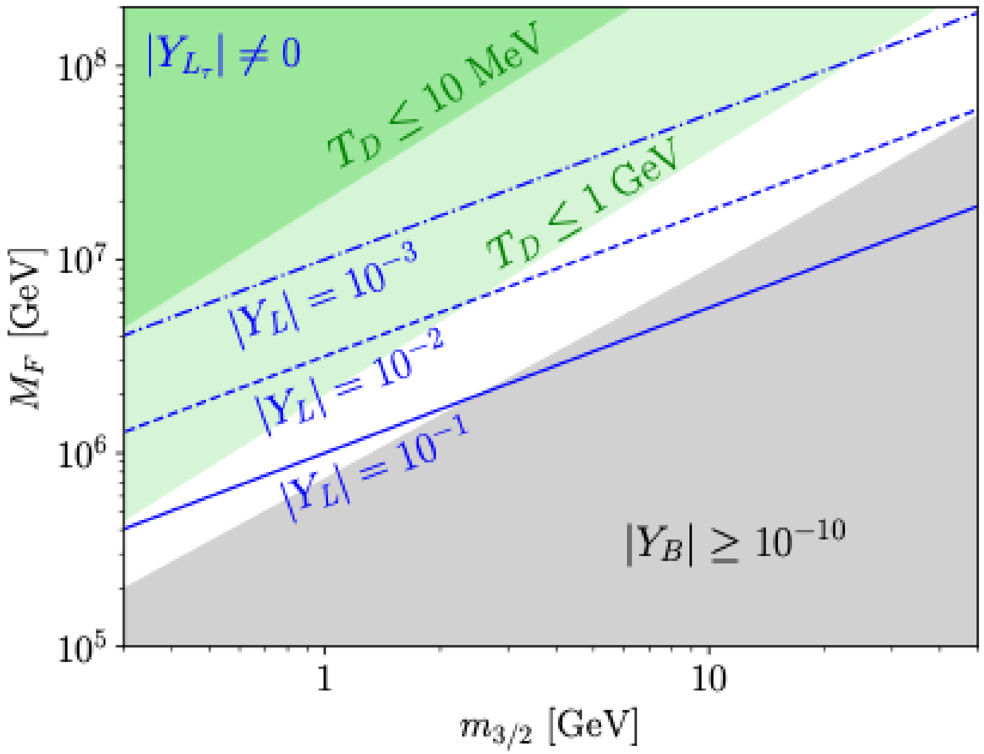
$$h_\tau \simeq 0.010, \quad h_\mu \simeq 6.1 \times 10^{-4}, \quad h_e \simeq 2.9 \times 10^{-6}$$

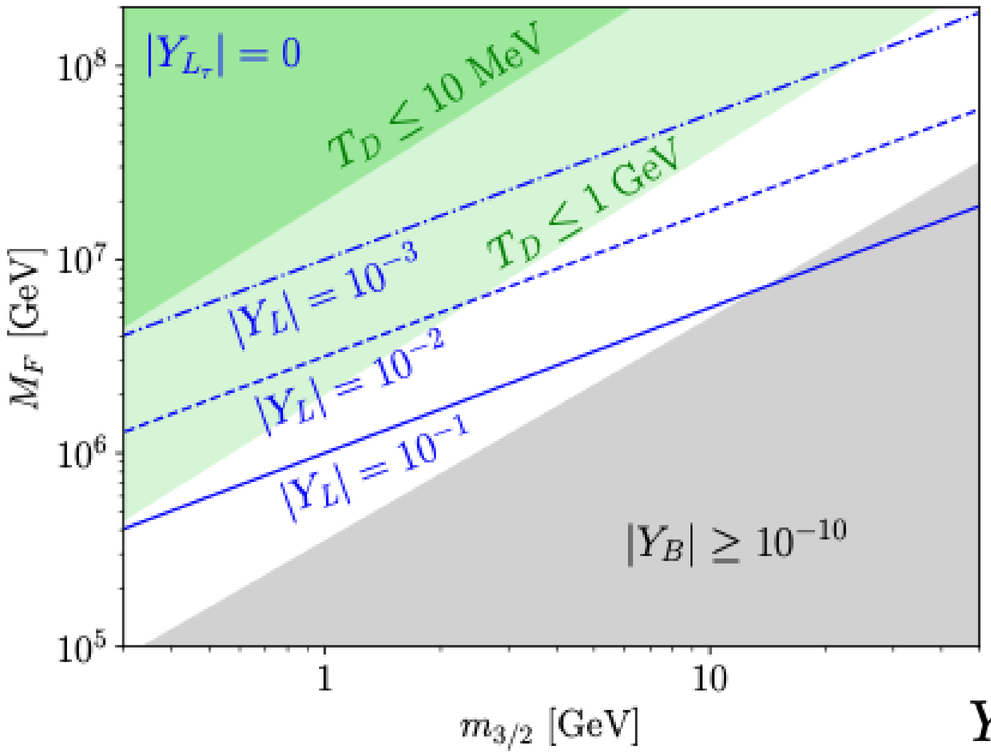
[March-Russell, Murayama, Riotto. 9908396.]
[Laine and Shaposhnikov. 9911473.]
[Mukaida, Schmmitz, Yamada, 2111.03082.]

- 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





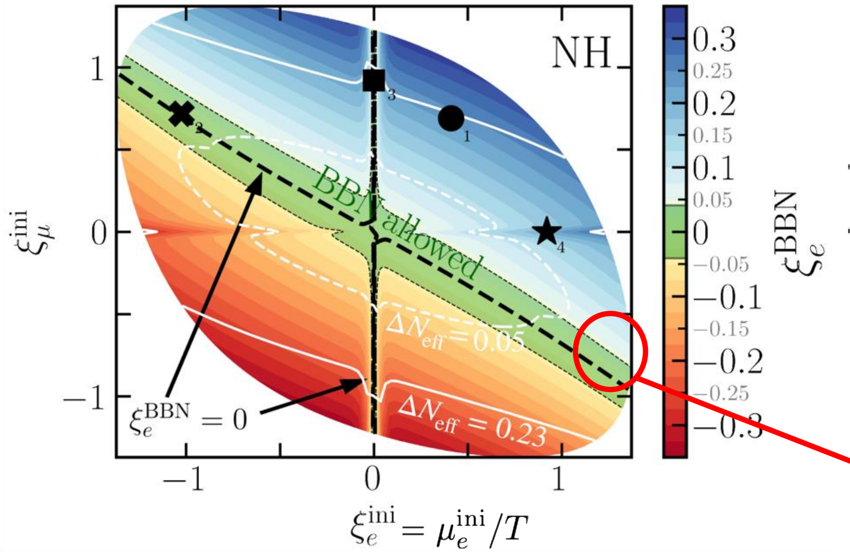
$$Y_L = \frac{\Delta n_L}{s}$$

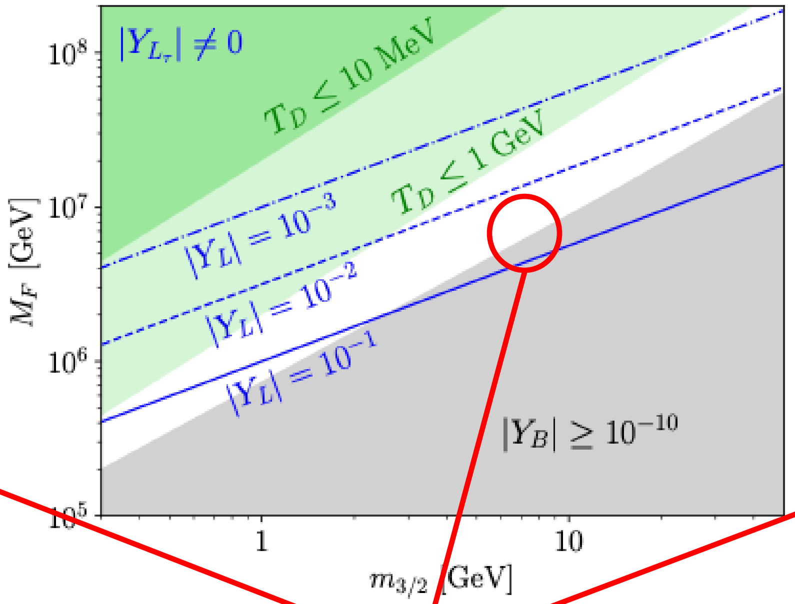
The AD leptoflavorgenesis scenario with Q-balls can generate large lepton flavor asymmetries to avoid an overproduction of baryon asymmetry.

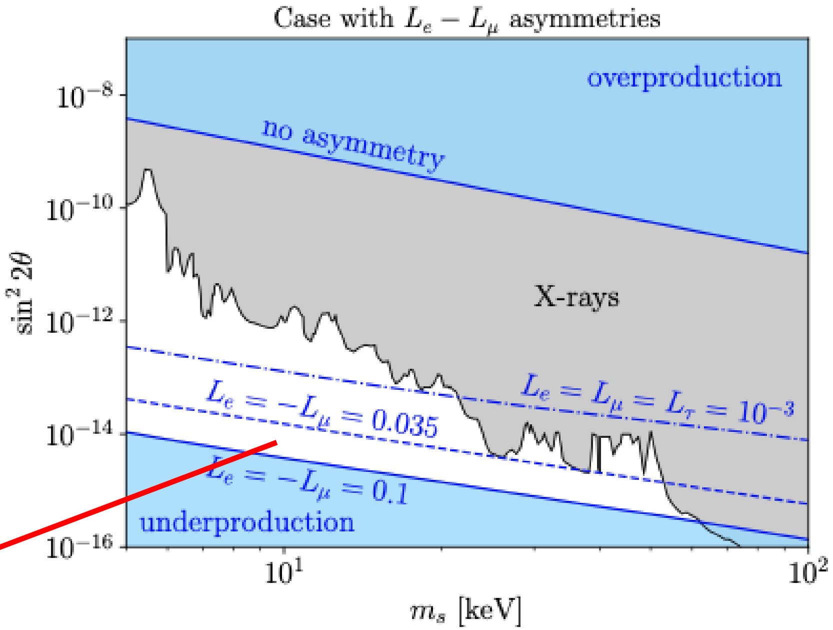
In the white region, the asymmetries are generated in $T \gtrsim 1\ \mathrm{GeV}$.

Benchmark point

Domcke, Escudero, Navarro and Sandner. 2502.14960







- We consider the benchmark point: $(L_e,\ L_\mu,\ L_\tau) = (0.06, -0.03, -0.03)$

$^* Y_{L_\alpha} = L_\alpha = \dfrac{\Delta n_{L_\alpha}}{s}$

- The baryon asymmetry (with Q-ball protection):

$$Y_B \simeq -0.030 \frac{\Delta Q}{Q} \left(h_\tau^2 \frac{n_\tau}{s} + h_\mu^2 \frac{n_\mu}{s} + h_e^2 \frac{n_e}{s} \right) \simeq \underline{+9} \times 10^{-11} \left(\frac{\Delta Q/Q}{10^{-3}} \right) \left(\frac{Y_{L_\tau}}{-0.03} \right)$$

The helium-4 anomaly, the observed baryon asymmetry and sterile neutrino DM are simultaneously resolved!

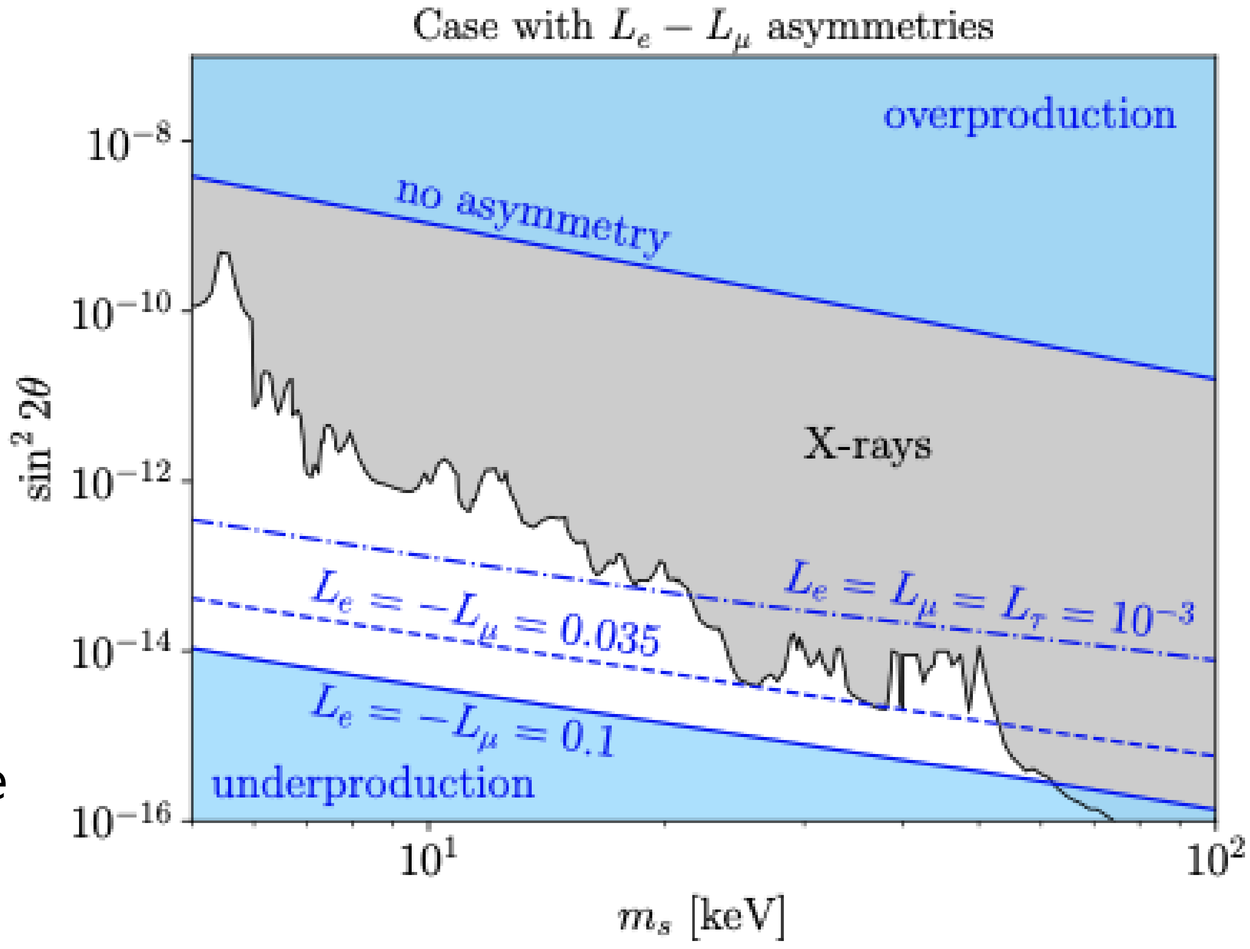
Conclusions

Lepton flavor asymmetries can (simultaneously)

1. explain the observed baryon asymmetry.
2. enhance the sterile neutrino DM production.
3. resolve the helium-4 anomaly.

We develop a new code, which traces the evolution of sterile neutrinos in the presence of lepton flavor asymmetries with $L_\alpha < 0.1$ in a precise and reliable way.

We also propose a scenario for Affleck-Dine leptoflavorgenesis with Q-balls for them.



Typical constraints from structure formation:
$m_s \lesssim 7\text{–}35$ keV

Thank you!

Backup

System of the equations

Effective Boltzmann equation for sterile neutrino +

- Evolution equation for the plasma temperature

$$\frac{dT}{dt} = -\frac{3H(\rho_{\rm SM} + P_{\rm SM}) + \partial\rho_{\nu_s}/\partial t}{d\rho_{\rm SM}/dT}$$

$$\frac{\partial\rho_{\nu_s}}{\partial t} \equiv \frac{1}{2\pi^2}\int dp\, p^2\sqrt{p^2+m_s^2}\,\frac{d}{dt}\left[f_{\nu_s}(p,t) + f_{\bar{\nu}_s}(p,t)\right]$$

- 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:

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

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

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