# Maximal parameter space of sterile neutrino dark matter with lepton asymmetries

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with

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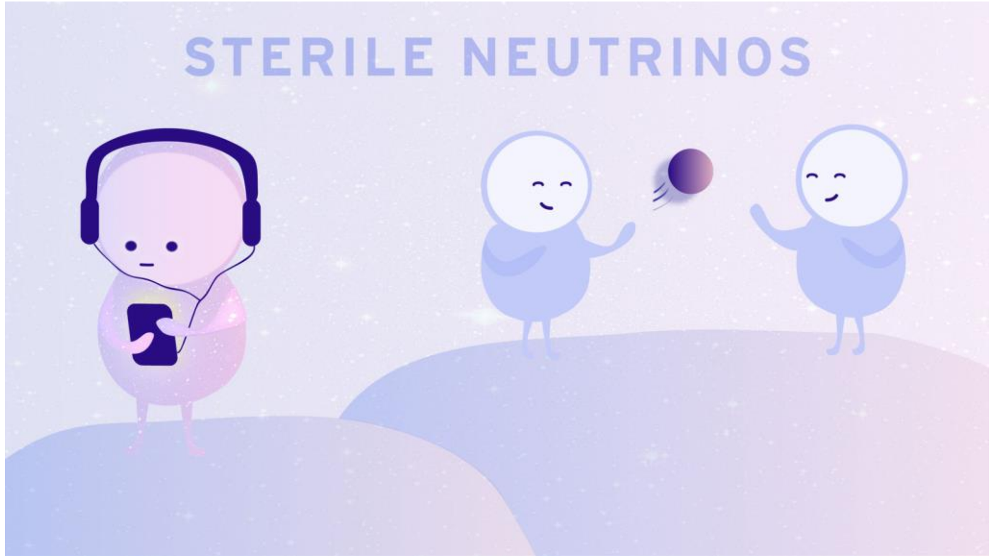
2507.20659 and 2509.08175

Seminar at DESY, October 20 2025

# Introduction

# Sterile neutrinos




- Sterile neutrinos are
  an excellent dark matter (DM) candidates.

- They are motivated by neutrino masses, …

- Sterile neutrinos are singlets under the SM gauge group,
  mixing with SM neutrinos $\nu_\alpha$ .

Singlet fermions

$$\nu_s = \cos\theta\nu'_s + \sin\theta\nu_\alpha$$

$\nu_s$ : physical mass eigenstate

$\theta$ : active-sterile mixing in vacuum

# Production in the early Universe

- Production by SM process :

  Oscillations with active neutrinos, with scatterings in thermal bath.

  Averaged oscillation probability:

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

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

Matter potential

Reset of phase by scatterings (quantum Zeno damping)

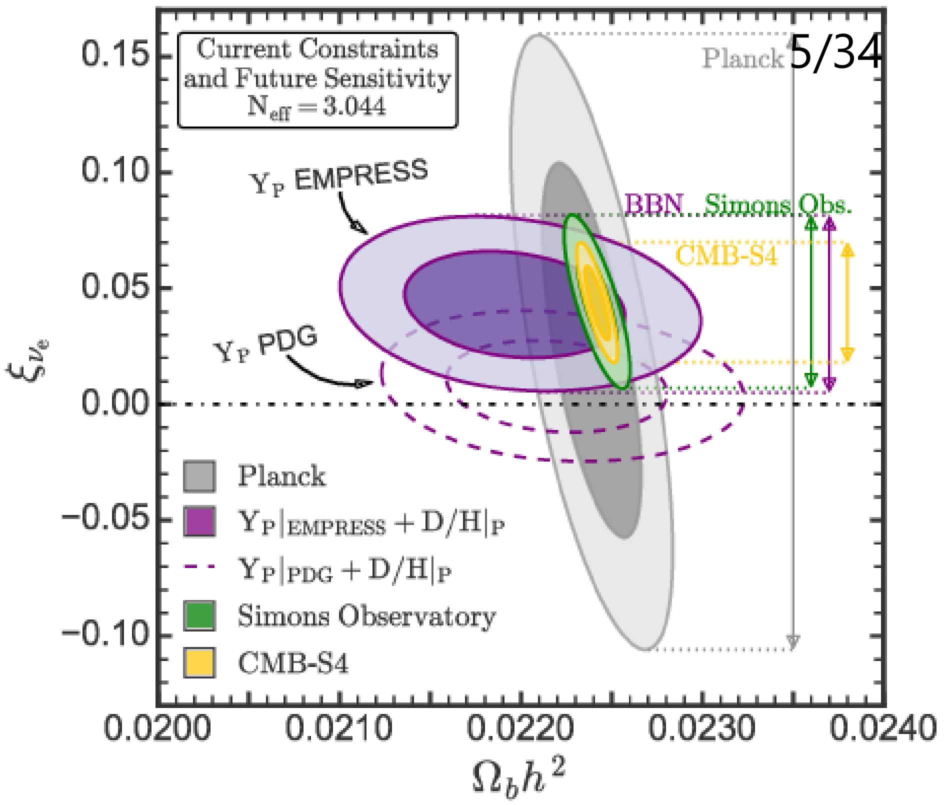
- At high $T$ , the oscillation probability is significantly suppressed.

  → Sterile neutrinos freeze-in and small $\theta$ can explain the DM abundance.

# Lepton asymmetry

- 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.**

- Positive large $\nu_e$ 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.**

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

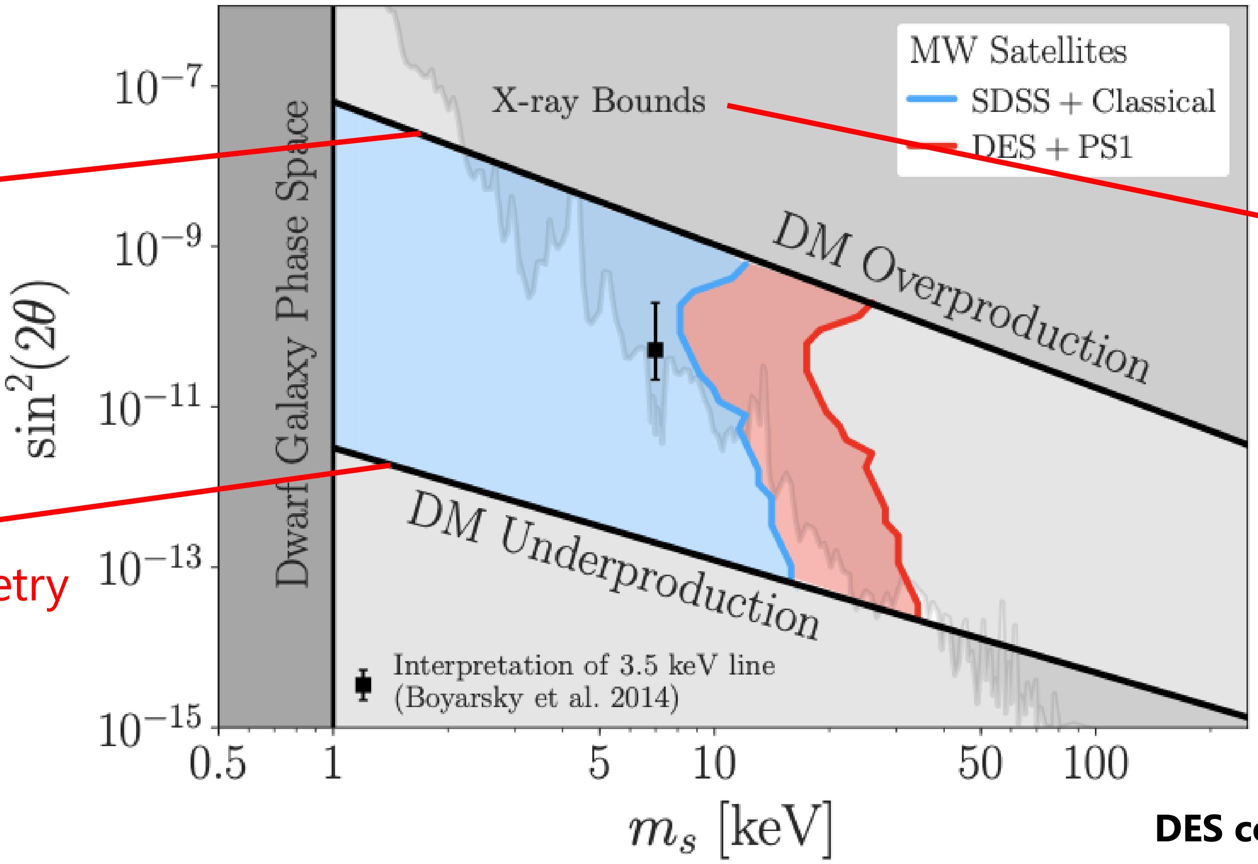
$$V_\alpha \approx \sqrt{2} G_F L s \qquad L = \frac{n_L - n_{\bar{L}}}{s}$$

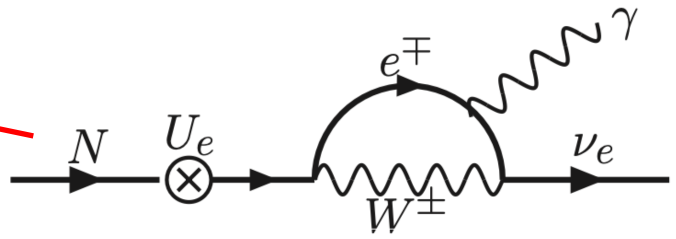
# Constraints

- However, sterile neutrino DM is severely constrained even if large lepton asymmetry exist … (but astrophysical constraints may include large uncertainties.)

No asymmetry

Large lepton asymmetry




**Drews, et al. 1602.04816**

**DES collaboration 2008.00022**

Let us consider
the sterile neutrino production with lepton asymmetry more carefully.

But, before this topic,
let's discuss another motivation on lepton asymmetry and the helium-4 anomaly.

# Lepton asymmetry (cont.)

- Lepton asymmetry may be related to the well-observed baryon asymmetry.

$$B^{\rm obs} = \frac{\Delta n_B^{\rm obs}}{s} \simeq 8.75 \times 10^{-11}$$ **Planck 2018**

- Sphaleron processes transfer lepton asymmetry to baryon asymmetry

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

- The helium-4 anomaly can be resolved by positive large $\nu_e$ asymmetry

However, naively,

  - Baryon asymmetry is overproduced …
  - Positive lepton asymmetry induces negative baryon asymmetry …

# Helium-4 anomaly

The Helium-4 anomaly
a mild $(1-2)\sigma$ tension with the standard scenario

Positive large $\nu_e$ asymmetry can resolve it.

It can enhance the sterile neutrino DM production.
However, such a scenario is severely constrained.

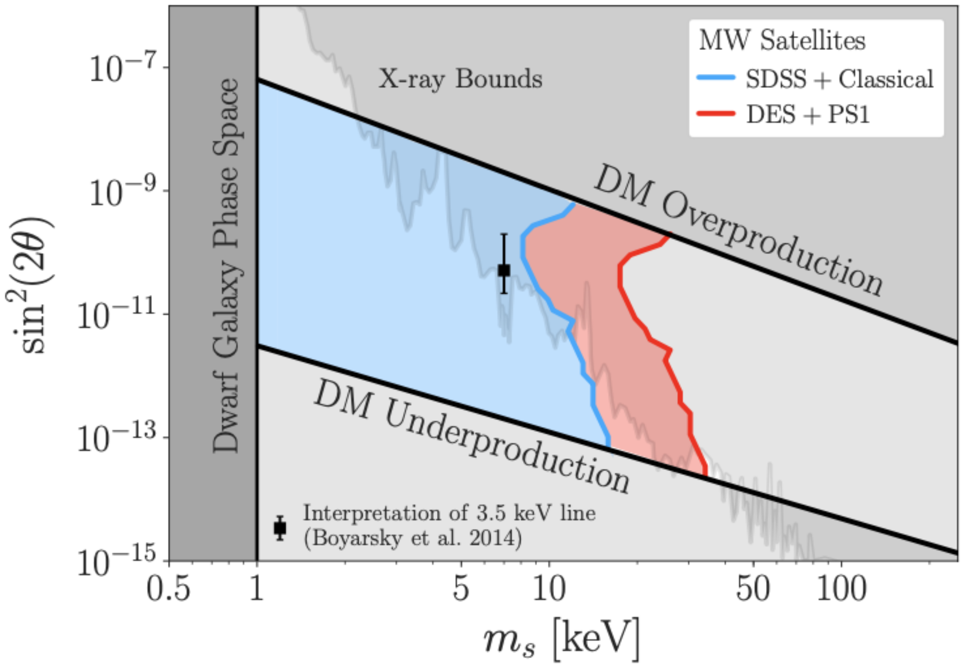
Large baryon asymmetries with incorrect sign may be produced.
After sphaleron decoupling, $\nu_e$ asy can be produced, but it's not related with baryon asy.

The heium-4 anomaly may not be related with theoretical puzzles in cosmology?

Let us consider

the sterile neutrino production and lepton asymmetry more carefully.

# Where is the mixing floor?




**DES collaboration 2008.00022**

- The lower black line is typically set as

$$L = \frac{n_L - n_{\bar{L}}}{s} \simeq 10^{-3}$$

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

Neutrino oscillations imply this.

- Active neutrino oscillations:

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

$$\begin{pmatrix} V_e + m_{ee} & m_{e\mu} & m_{e\tau} \\ m_{\mu e} & V_\mu + m_{\mu\mu} & m_{\mu\tau} \\ m_{\tau e} & m_{\mu\tau} & V_\tau + m_{\tau\tau} \end{pmatrix} \simeq \begin{pmatrix} V_e & 0 & 0 \\ 0 & V_\mu & 0 \\ 0 & 0 & V_\tau \end{pmatrix}$$

Neutrino mass matrix

$$V_\alpha \sim \sqrt{2} G_F L_\alpha s + \frac{8\sqrt{2} G_F p}{3 m_W^2} E_\alpha$$

Effective at $T \lesssim 15\ \mathrm{MeV}$ before the BBN and neutrino decoupling start.

How is lepton flavor asymmetries with zero total asymmetry?

# Sterile neutrinos with lepton flavor asymmetries

$T$

Large lepton flavor asymmetries with zero are generated.

Sterile neutrinos are resonantly produced due to the asymmetries.

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

$$y = p/T$$

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

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

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

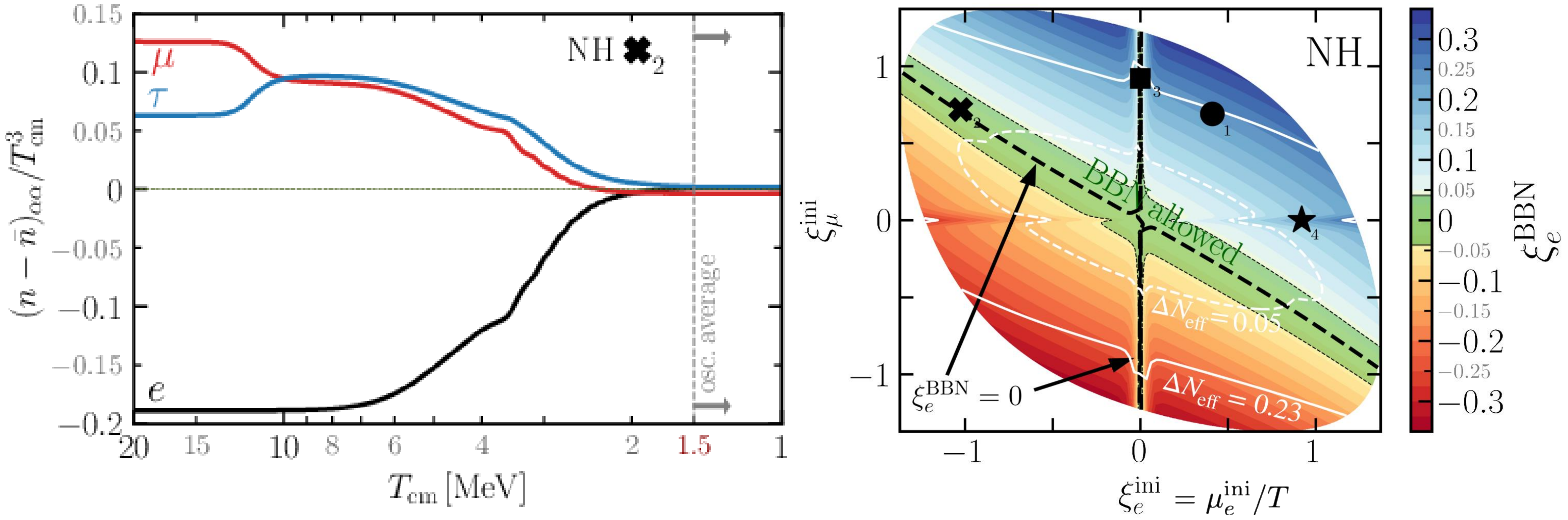
The BBN starts → No BBN bound on primordial lepton flavor asymmetries?

$t$

$\boxed{\text{Lepton flavor asymmetries open up a new parameter space for sterile neutrino DM?}}$

# Lepton flavor asymmetries and BBN

**Domcke, Escudero, Navarro and Sandner. 2502.14960**




- The asymmetries of $L_e \simeq -L_\mu, L_\tau \simeq 0$ and $L_\mu = -L_\tau, L_e = 0$ are much less constrained!
- The green contour $(\xi_e^{\rm BBN} \simeq +0.04)$ can resolve the helium-4 anomaly.

# How about baryon asymmetry?

Baryon asymmetry can be produced, utilizing zero total lepton asymmetry?

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

0

Lepton flavor asymmetries do not completely cancel out:

$$B \simeq -\frac{8}{23} L - \underline{0.030 \left(h_\tau^2 L_\tau + h_\mu^2 L_\mu + h_e^2 L_e\right)}$$

0

SM lepton Yukawa coupling

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

$h_\tau \simeq 0.010,$

$h_\mu \simeq 6.1 \times 10^{-4},$

$h_e \simeq 2.9 \times 10^{-6}$

Lepton flavor asymmetries may open a new direction
for sterile neutrino dark matter, baryon asymmetry and helium-4 anomaly.

# Open questions

- How can we reliably estimate sterile neutrino production?
  - In particular, neutrino oscillations can be averaged?

    *All previous literature use averaged procedures.

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

- What is the origin of lepton flavor asymmetries: leptoflavorgenesis?
  - What is the connection between the model and other cosmological problems?

# A closer look at the sterile neutrino production

# Semi-classical Boltzmann equation

- A most precise way in the literature to study neutrino evolution is solving the Quantum Kinetic Equations (QKEs) for neutrinos:

$$i\left(\frac{\partial}{\partial t} - Hp\frac{\partial}{\partial p}\right)\rho_{ij}(p,t) = [\mathcal{H}, \rho_{ij}] - i\{\Gamma, \rho_{ij}\} + i\{\Gamma^p, 1-\rho_{ij}\}$$

$\rho_{ij} = \langle a_i^\dagger a_j \rangle \quad (i,j=\alpha,s)$ The off-diagonal parts involve neutrino oscillations.

- An economical way is solving the semi-classical Boltzmann equation:

A commonly used formula:

$$\left(\frac{\partial}{\partial t} - Hp\frac{\partial}{\partial p}\right) f_{\nu_s}(p,t) = \underbrace{\frac{\Gamma_\alpha(p,\mu)}{2}}_{\text{Neutrino production rate}} \underbrace{\langle P(\nu_\alpha \to \nu_s)\rangle}_{\text{Averaged oscillation probability}} \underbrace{f_{\nu_\alpha}(p,\mu)}_{\text{Active neutrino distribution}}$$

However, neutrino oscillations can be averaged in the short resonance?

# Neutrino oscillation at the resonance

- Neutrino oscillations can be averaged?

$$\langle P_m(\nu_\alpha \to \nu_s; p)\rangle \approx \sin^2 2\theta_m \left\langle \sin^2\left(\frac{m_m^2}{4p}t\right)\right\rangle \underbrace{\left[1+\left(\frac{\Gamma_\alpha l_m}{2}\right)^2\right]^{-1}}_{\text{Damping factor by scattering}},$$

$$= \frac{1}{2}\frac{\Delta^2 \sin^2 2\theta}{\Delta^2 \sin^2 2\theta + \underbrace{[\Delta\cos 2\theta - V_\alpha]^2}_{=0 \text{ at the resonance}} + \left(\frac{\Gamma_\alpha}{2}\right)^2}.$$

If the resonance width $\delta t_{\rm res}^{\rm ave}$ < the oscillation length $l_m$ , the oscillations cannot be averaged

Time width

in $|\Delta \cos 2\theta - V_\alpha| < \max\left[\Delta \sin 2\theta, \frac{\Gamma_\alpha}{2}\right]$

$$l_m = \left(\frac{m_m^2}{2p}\right)^{-1} = \left\{\Delta^2 \sin^2 2\theta + [\Delta\cos 2\theta - V_\alpha]^2\right\}^{-1/2}$$

$$\frac{\delta t_{\rm res}^{\rm ave}}{l_m^{\rm res}} \sim 0.05\left(\frac{10.75}{g_*}\right)^{3/4}\left(\frac{y}{3.15}\right)^{13/4}\left(\frac{10^{-2}}{L}\right)^{9/4}\left(\frac{m_s}{10\ \mathrm{keV}}\right)^{5/2}$$

$$V_\alpha \propto L_\alpha$$

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

→ Neutrino oscillations cannot be averaged for large L.

# Neutrino oscillation at the resonance

- Averaged oscillation probability

$$\langle P_m(\nu_\alpha \to \nu_s; p)\rangle \approx \sin^2 2\theta_m \underline{\left\langle \sin^2\left(\frac{m_m^2}{4p} t\right)\right\rangle} \left[1 + \left(\frac{\Gamma_\alpha l_m}{2}\right)^2\right]^{-1},$$

$\simeq \frac{1}{2}$

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

- Non-averaged oscillation probability

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

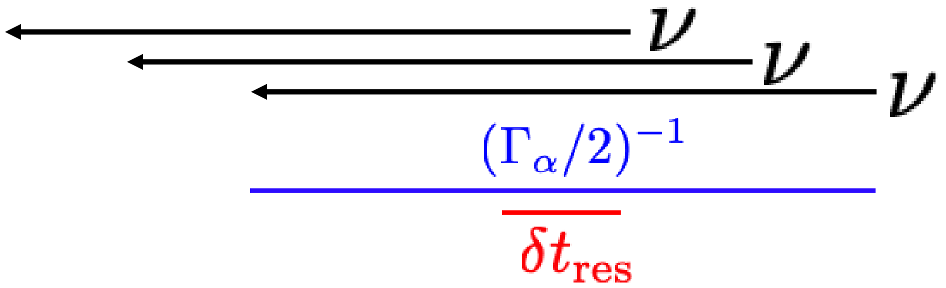
$$\ll \langle P_m(\nu_\alpha \to \nu_s; p)\rangle$$

$\ll 1$

Production rate of sterile neutrinos is significantly suppressed?

# System of the equations

- Enhancement by free-streaming accumulating neutrinos




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

- <u>Effective oscillation probability</u>

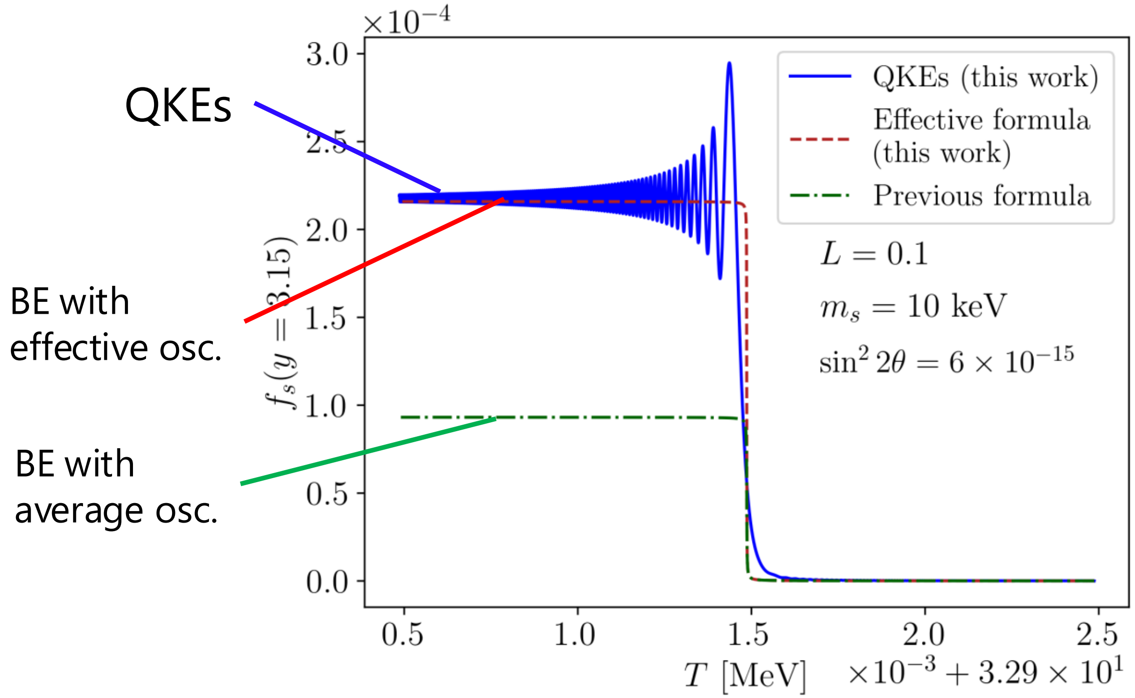
$$P_{\rm eff}(\nu_\alpha \to \nu_s) = P(\nu_\alpha \to \nu_s, \delta t_{\rm res}) \times \frac{(\Gamma_\alpha/2)^{-1}}{\delta t_{\rm res}}$$
$$\approx \frac{1}{2} \frac{\Delta(p)^2 \sin^2 2\theta}{[\Delta(p) \cos 2\theta - V_\alpha]^2 + \left(\frac{\Gamma_\alpha}{2}\right)^2}$$

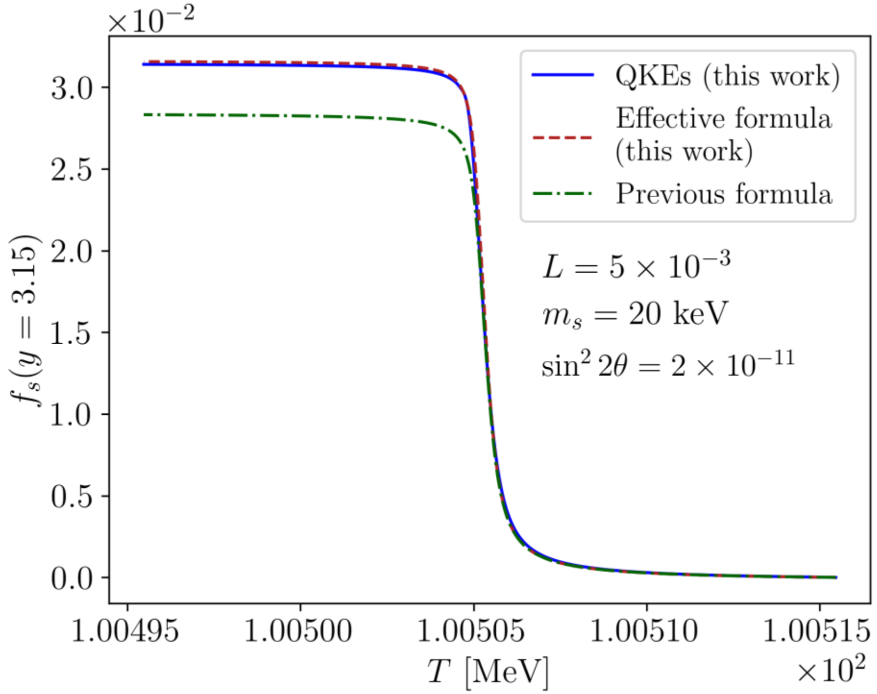
This is applicable to any lepton asymmetries.

- Effective Boltzmann equation for $\nu_s$ with non-averaged oscillations :

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

# Comparison of Boltzmann eqs with QKEs




Boltzmann equations with effective oscillation probability is in excellent agreement with QKEs rather than with averaged oscillation probability!

# Parameter space of sterile neutrino DM with lepton asymmetries

# System of equations

- Boltzmann equations with non-averaged oscillations

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

- Evolution equation for the plasma temperature (all SM particles in thermal equilibrium)

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

- Evolution equation for lepton flavor asymmetries

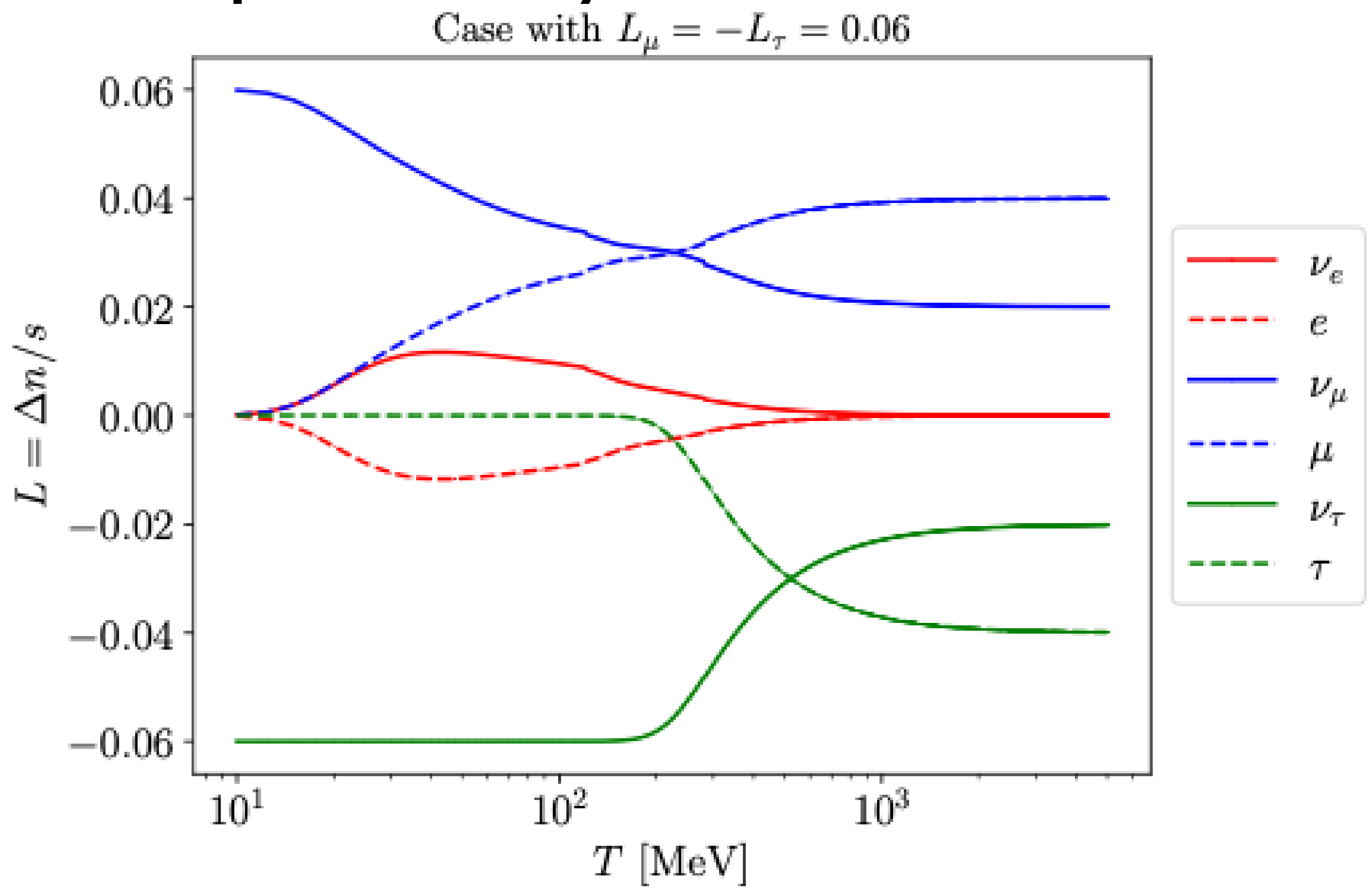
$$\frac{d}{dt}L_\alpha = -\frac{1}{s}\int dp\; p^2\frac{d}{dt}\left[f_{\nu_s}(p,t) - f_{\bar\nu_s}(p,t)\right]$$

Each particle asymmetry is redistributed when a particle becomes non-relativistic.

$$\frac{\Delta n_{\nu_\alpha} + \Delta n_\alpha}{s} = L_\alpha\,, \quad \sum_i \frac{b_i \Delta n_i}{s} = B, \quad \sum_i \frac{q_i \Delta n_i}{s} = 0$$

Ex) $\mu^-$ asymmetry may be restored to $\nu_\mu$ through $\nu_e + \mu^- \leftrightarrow \nu_\mu + e^-$.

# Evolution of lepton asymmetries




Redistribution may change each asymmetry by a factor of a few,
which may also affect the $\nu_s$ abundance by a factor of a few since $V_\alpha \propto L_\alpha$ .

# Full chemical potentials

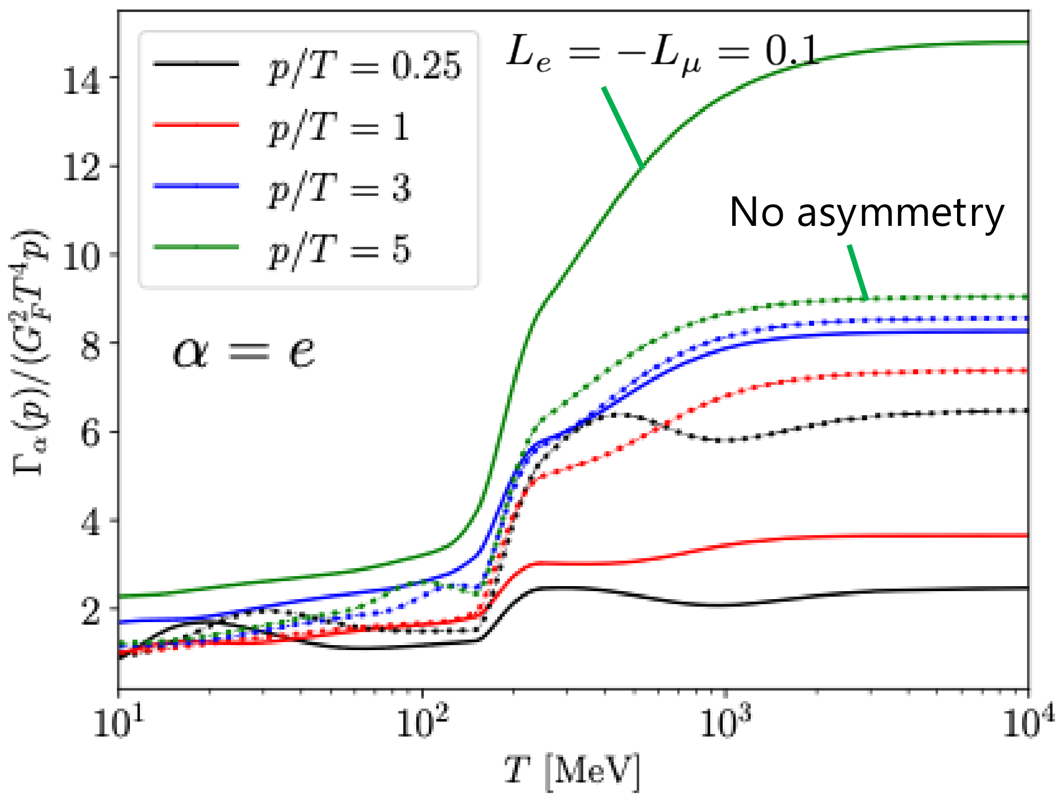
We consider very large lepton asymmetries: $L = \frac{\Delta n_L}{s} \simeq 0.1$

For a precise calculations,
we fully include large chemical potentials.

- Neutrino interaction rate: $\Gamma_\alpha = \Gamma_\alpha(p,\mu)$
- Thermodynamics: $s(T,\mu) = s_0(T) + \delta s(T,\mu)$ , ...

$$s_0(T) = \frac{2\pi^2}{45} g_{*,s}(T) T^3 \qquad \delta s(T,\mu) = \underbrace{s(T,\mu) - s(T)}_{\text{Ideal gas limit}}$$

We use the fitting formula
proposed by **Saikawa and Shirai, 1803.01308.**



# Comments on our numerical method

Our code is publicly available: [sterile-dm-lfa](sterile-dm-lfa).

This code is improving and generalizing the approach by **Ghiglieri and Laine, 1506.06752. Venumadhav et al., 1507.06655.**

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

New!
- <u>Full</u> large chemical potentials are included.

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

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

README GPL-3.0 license

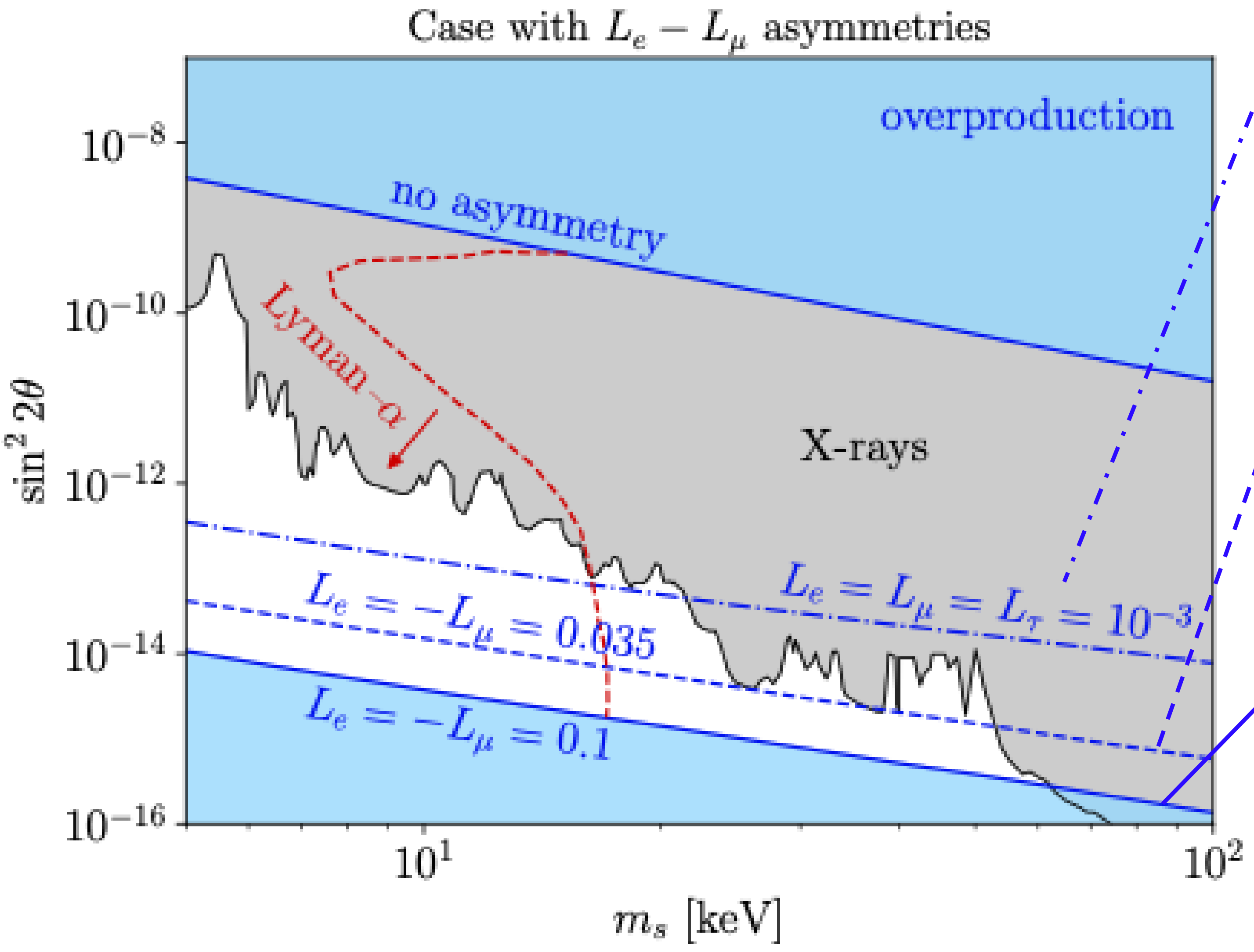
## sterile-dm-lfa: Sterile neutrino dark matter with lepton flavor asymmetries

The code "sterile-dm-lfa" has been developed by Kensuke Akita and Maksym Ovchynnikov to trace the evolution of sterile neutrino dark matter in the presence of primordial lepton flavor asymmetries. The underlying physics and thechnical details are described in the associated preprint arXiv:2507.20659. If you use this code, please cite this reference.

The code is made of two parts:

1. The Python-based code ("discretization solver") solving the system governing the evolution of the Universe and production of sterile neutrinos in full generality, using the discretization approach.
2. The Mathematica-based code ("analytic solver") that solves the system governing the evolution of the Universe and production of sterile neutrinos under two assumptions: the narrow width approximation, and negligible back-reaction of sterile neutrinos on the lepton flavor asymmetry. The code is located in the directory `Analytic solver`.

# Parameter space




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

**Froustey and Pitrou, 2405.06509.**

The target sensitivity of the ongoing Simons Observatory, assuming normal neutrino mass ordering.

The currently reliable region allowed by BBN and CMB: $L_e = -L_\mu = 0.1$ .

*Further investigation on the BBN and CMB constraints on $L_e = -L_\mu > 0.1$ may open up more parameter space.

A conservative Lyman-α bound: $m_s < 17\ \mathrm{keV}$

# An origin of lepton flavor asymmetries: Affleck-Dine leptoflavorgenesis

# Affleck-Dine mechanism

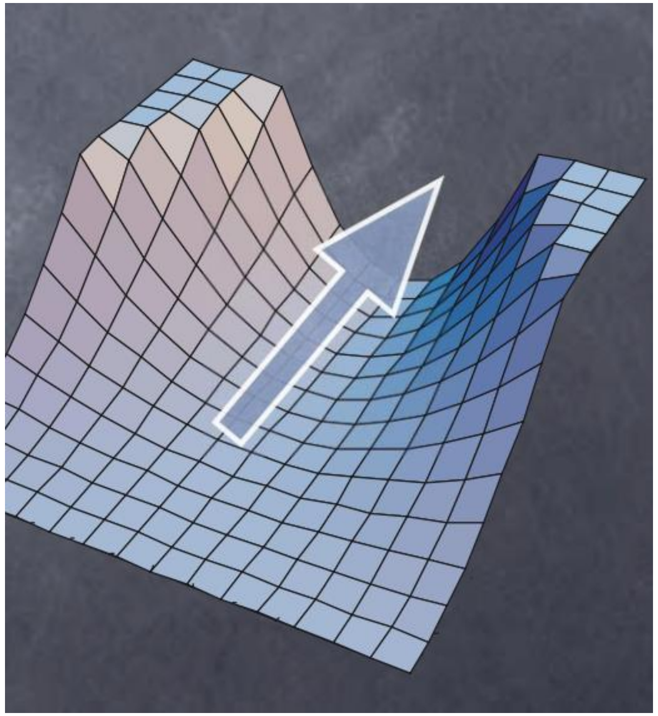
- The Affleck-Dine mechanism is one of the mechanisms that naturally explain large asymmetries.
  **Affleck and Dine. 1985**

- In a SUSY theory, there are flat directions in the scalar potential that have no total lepton charge but lepton flavor charge,

  $$Q_i \bar{u}_j L_k \bar{e}_l$$

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

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



Flat direction
A figure from F. Takahashi's slide

# Affleck-Dine mechanism

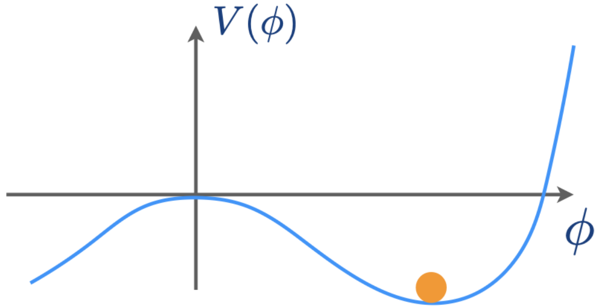
- Possible scalar potential for the AD mechanism: $\boxed{Q \sim \bar{u} \sim L \sim \bar{e} \sim \phi}$

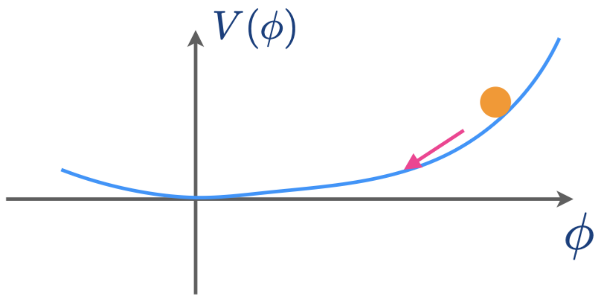
$$V(\phi) \simeq \left(\underbrace{m_\phi^2}_{\text{SUSY-breaking mass}} - \underbrace{c_1 H^2}_{\text{Hubble-induced mass}}\right)|\phi|^2 + \underbrace{\left(\frac{\lambda m_{3/2}^2}{4{\mathrm{M_P}}^2}\phi^4 + \mathrm{h.c.}\right)}_{\text{A-term (CP-violating term)}} + \underbrace{c_2 H^2 \frac{|\phi|^4}{{\mathrm{M_P}}^2}}_{\text{Non-renormalizable term}} + \cdots$$

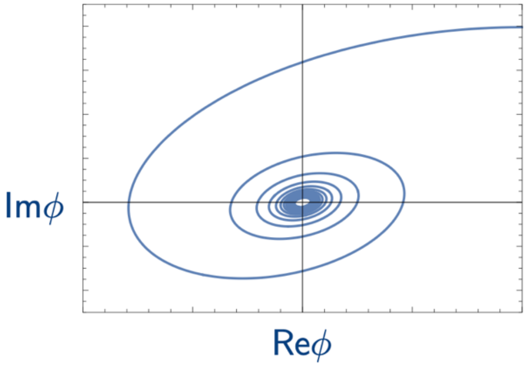
SUSY-breaking mass | Hubble-induced mass | A-term (CP-violating term) | Non-renormalizable term

- During inflation ($H \gg m_\phi$), $\phi$ has a large value of $\lesssim \mathrm{M_P}$ if $c_1, c_2 > 0$
- After inflation, when $H \sim m_\phi$ , $\phi$ starts to oscillate.
- $\phi$ is kicked in phase direction by A-term.

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

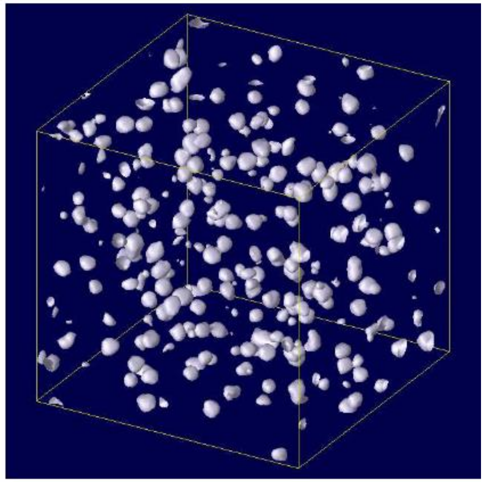



Figures from Kawasaki-san's slide

# Q-ball formation



Figures from Kawasaki-san's slide

- $\phi$ has spatial instabilities if the potential is flatter than the quadratic one.
- $\phi$ is deformed into non-topological solition called Q-ball.
- We consider gauge-mediated SUSY breaking models and right after the $\phi$-oscillation,

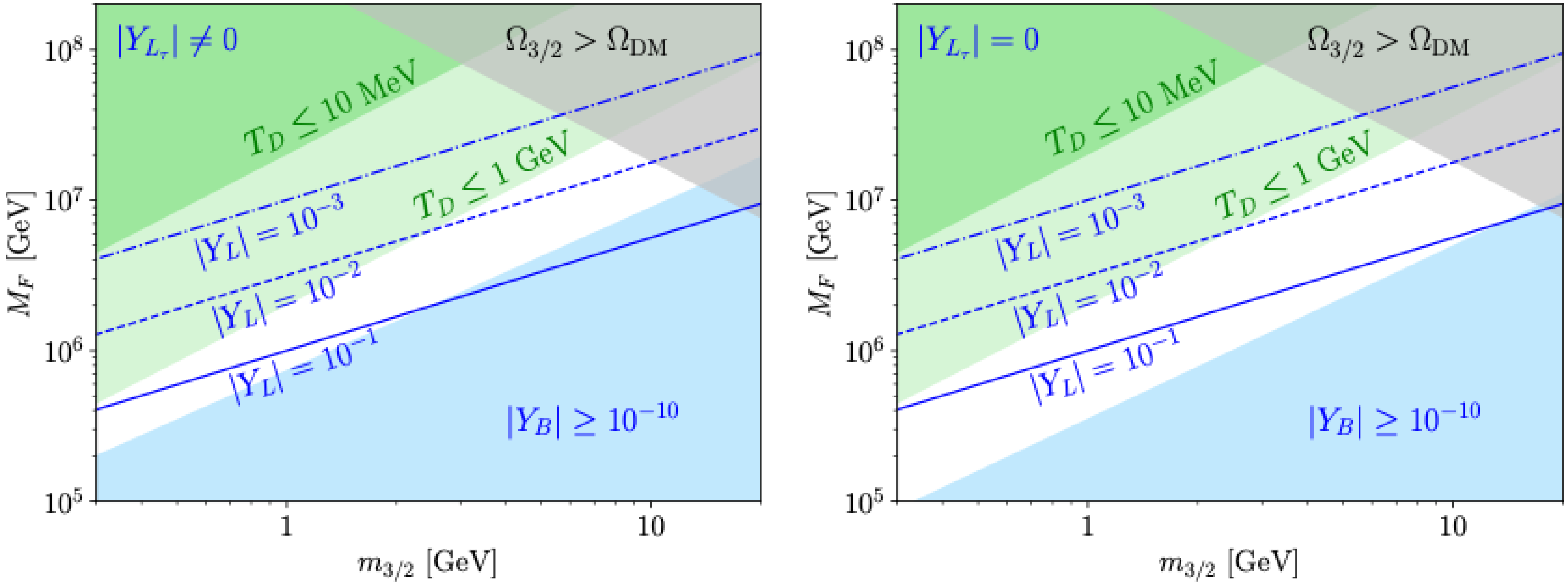
$$V(\phi) = \underline{M_F^4 \left[ \log \left( \frac{|\phi|^2}{M_S} \right)^2 \right]} + m_{3/2}|\phi|^2$$

- Q-balls can protect the asymmetry from the sphaleton processes, and their decay rate is saturated (delayed) due to the Pauli excursion principle:

$$B \simeq -0.030 \underbrace{\frac{\Delta Q}{Q}}_{\text{Decayed fraction at } T \simeq T_{\rm sph} \sim 130\ \text{GeV}} \left( h_\tau^2 L_\tau + h_\mu^2 L_\mu + h_e^2 L_e \right)$$

$\Rightarrow$ Even larger asymmetries can be generated.

# Results



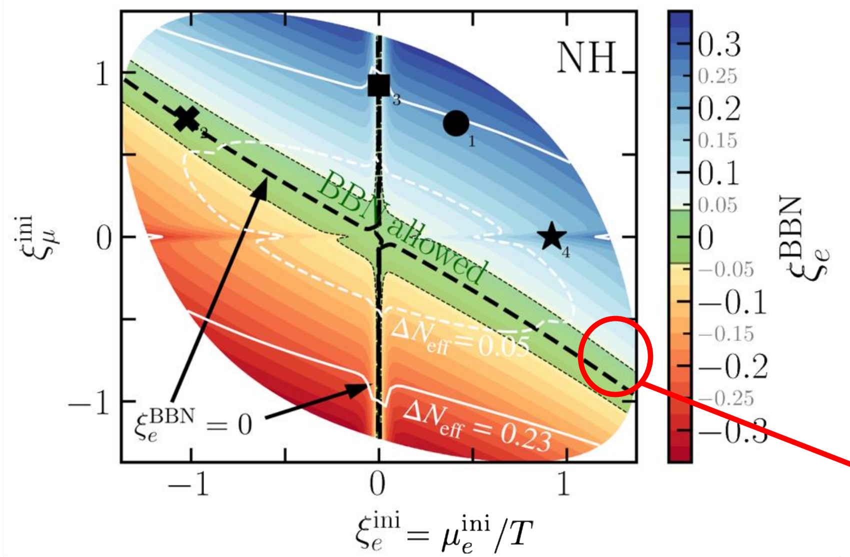

$$Y_L = \frac{\Delta n_L}{s}$$

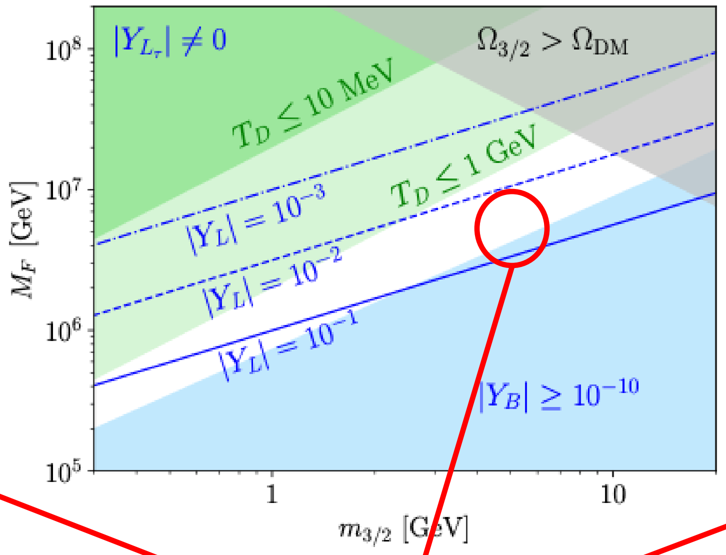
The AD leptoflavorgenesis scenario with Q-balls can generate large lepton flavor asymmetries to avoid an overproduction of baryon asymmetry.

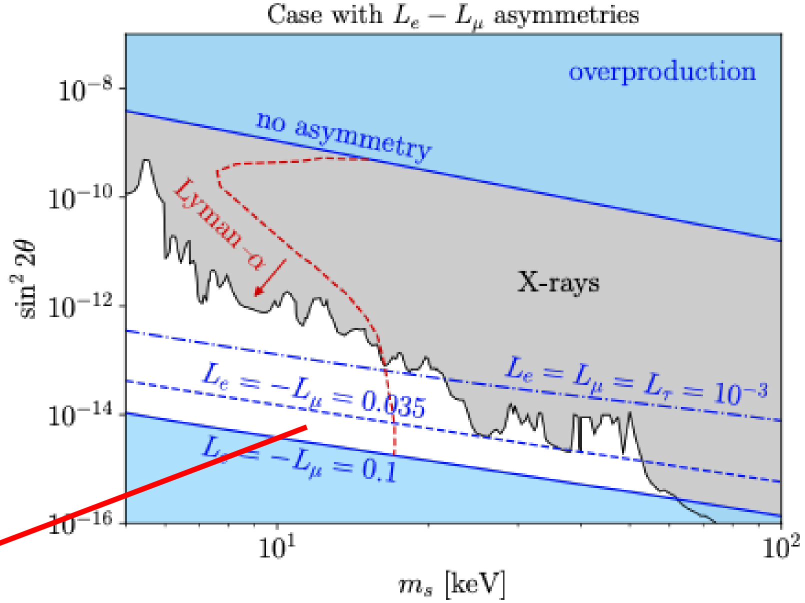
In the white region, the asymmetries are generated in $T \gtrsim 1\ \mathrm{GeV}$ .

# Benchmark point (rough estimate)

Domcke, Escudero, Navarro and Sandner. 2502.14960




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

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

- The baryon asymmetry with Q-ball protection:

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

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

# Conclusions

Lepton flavor asymmetries with zero total lepton 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 methodology, 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 propose a new scenario for Affleck-Dine leptoflavorgenesis with Q-balls, which can produce $L_\alpha \lesssim 0.1$ .

*Thank you!*