Dark Matter Induced Neutrino Mass Variation and the Second Leptogenesis

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2311.16672 w/ Kazuki Enomoto, Yechan Kim, Hye-Sung Lee

Introduction

- Neutrino mass model with the Majorana mass term given by the coupling with wave dark matter
- The Majorana mass of neutrino varies in time following the ϕ
- Previous works considering the Majorana mass term given via coupling as small perturbation
- What if the coupling term is dominant in determining the Majorana mass of neutrinos?

⇒ **Completely new phenomenology: second leptogenesis etc.**

Contents

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Dark Matter and the Majorana Mass of Neutrinos

The Majorana Mass of Neutrinos

$$\mathcal{L} = -\, m_D \bar{\nu}_D \nu_D - \frac{1}{2} m_R \bar{\nu}_M \nu_M = -\frac{1}{2} \begin{pmatrix} \bar{\nu}_L & \bar{\nu}_R^c \end{pmatrix} \begin{pmatrix} 0 & m_D \\ m_D & m_R \end{pmatrix} \begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix} + h.c.$$

Dirac (SM extension)

Majorana

Mass eigenstates

$$\begin{pmatrix} \nu_l \\ \nu_h \end{pmatrix} = \begin{pmatrix} \cos\theta_{LR} & \sin\theta_{LR} \\ -\sin\theta_{LR} & \cos\theta_{LR} \end{pmatrix} \begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix} + h.c.$$

$$\text{where } \sin^2\theta_{LR} = \frac{1}{2}\left(1 - \frac{m_R}{\sqrt{m_R^2 + 4m_D^2}}\right)$$

m_D is dominant: mixing is maximal

→ **Quasi-Dirac** (or pseudo-Dirac) neutrinos

m_R is dominant: mixing is small

→ **Majorana** neutrinos

Majorana Mass Term and Wave Dark Matter

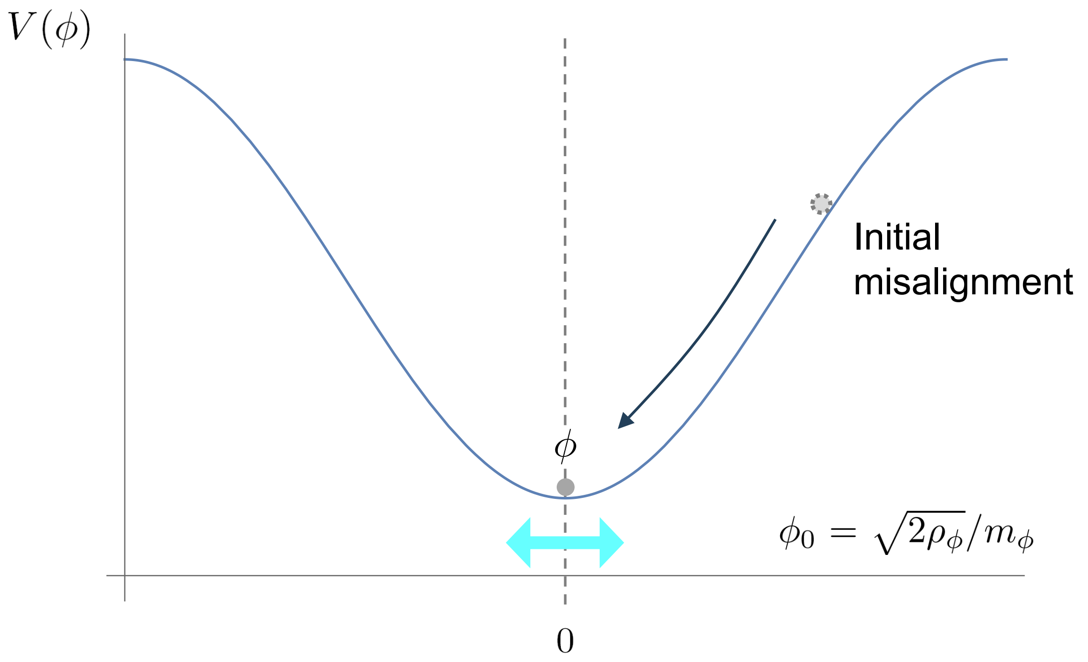
Majorana mass term by Yukawa coupling

$$\mathcal{L} = -\frac{1}{2}(M_{0i} + g_i\phi)\bar{\nu}^c_{R,i}\nu_{R,i} + h.c.$$

- We assume that this scalar field ϕ is a dark matter field, with its oscillation generated by some initial misalignment from its potential minimum at 0.
- The equation of motion is given as

$$\ddot{\phi} + 3H\dot{\phi} + \frac{\partial V(\phi)}{\partial \phi} = 0 \qquad V(\phi) = \frac{1}{2}m_\phi^2\phi^2$$

→ Harmonic oscillation $\phi(t) = \phi_0 \cos m_\phi t$



Majorana Mass Term and Wave Dark Matter

Wave dark matter ϕ

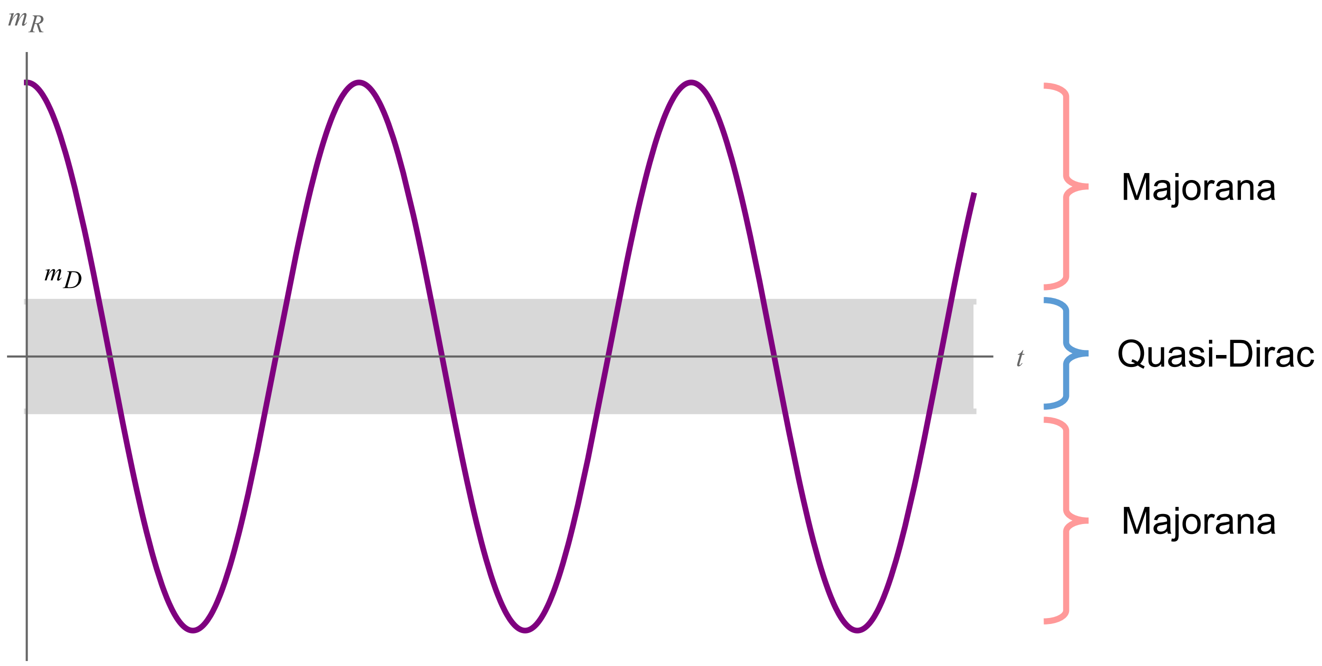
- Small mass in the range of $10^{-22}\ \mathrm{eV} < m_\phi < 30\ \mathrm{eV}$
- Slow and coherent oscillation with period of $T = 2\pi/m_\phi = \mathcal{O}(\mathrm{ps}) \sim \mathcal{O}(\mathrm{year})$

Varying Majorana mass

- Amplitude of the Majorana mass oscillation $m_{R,0} = g\phi_0$
- Value of Majorana mass varies in time: $m_R(t) = M_0 + g\phi(t) \approx M_0 + m_{R,0}\cos m_\phi t$

⇒ Modulation of ν_l and ν_h

Zero Bare Mass: Dirac-Majorana Type Oscillation



- If bare mass is zero, the Majorana mass can be smaller than Dirac mass at some time period.
- Neutrinos behave as Majorana particles when m_D/m_R is small, and as quasi-Dirac particles when m_D/m_R is large.
- Periodic modulation of m_R makes neutrinos oscillate between quasi-Dirac and Majorana states.

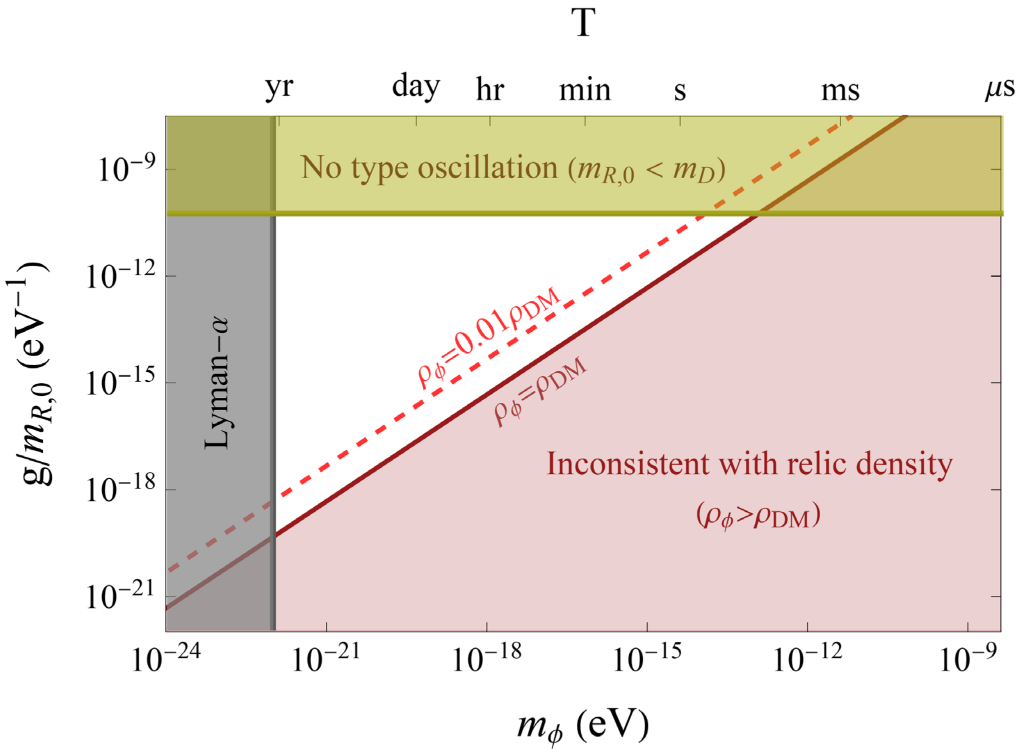
‘Dirac-Majorana Neutrino Type Oscillation’

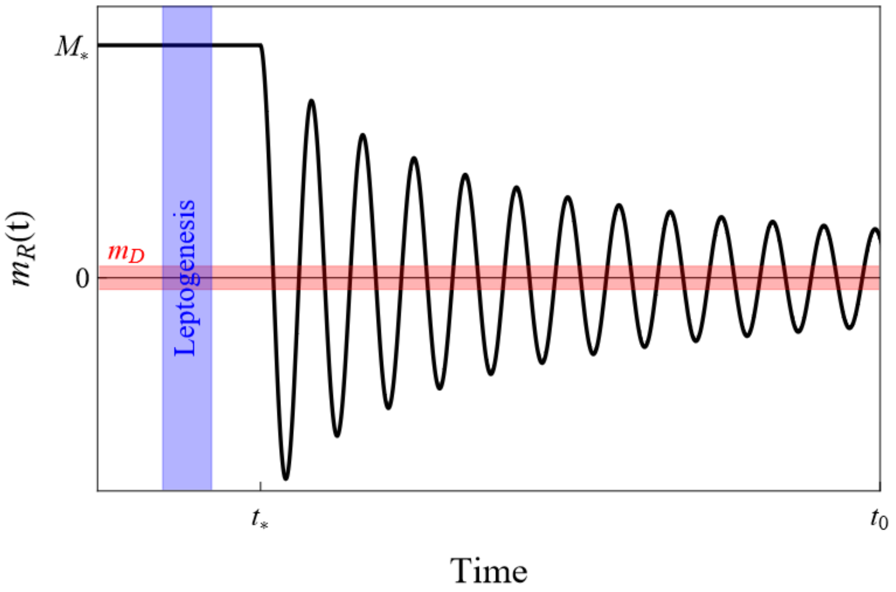
2305.16900, YL. ChoeJo, Y. Kim, H-S. Lee

Zero Bare Mass: Dirac-Majorana Type Oscillation

Conditions and Characteristics

$$m_{R,0} \simeq 10^{19}\ \mathrm{eV} \left(\frac{g}{1}\right) \left(\frac{\rho_\phi}{\rho_{\rm DM}}\right)^{1/2} \left(\frac{10^{-22}\ \mathrm{eV}}{m_\phi}\right)$$





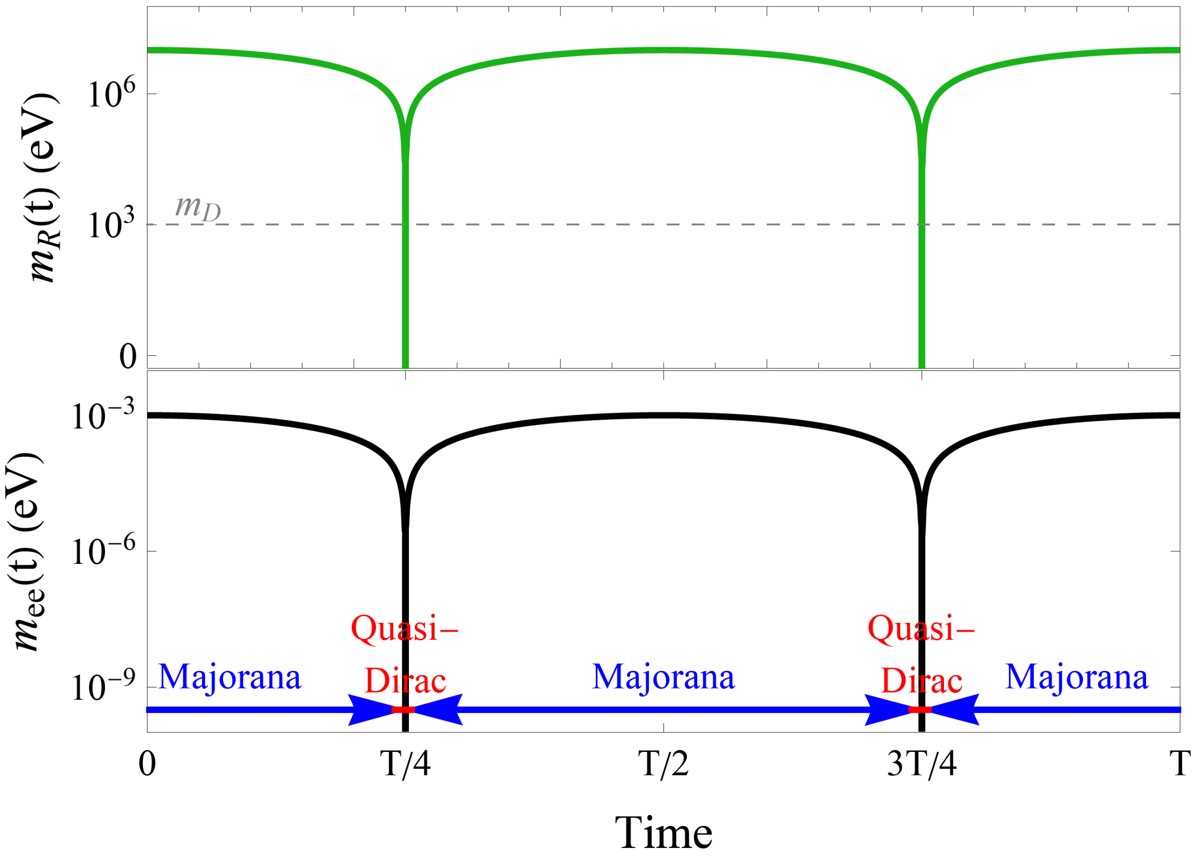
$$m_R(T) = m_{R,0} \left(\frac{T}{T_0}\right)^{\frac{3}{2}}$$

→ Likely significant for the present time, while negligible in the early universe

Zero Bare Mass: Dirac-Majorana Type Oscillation

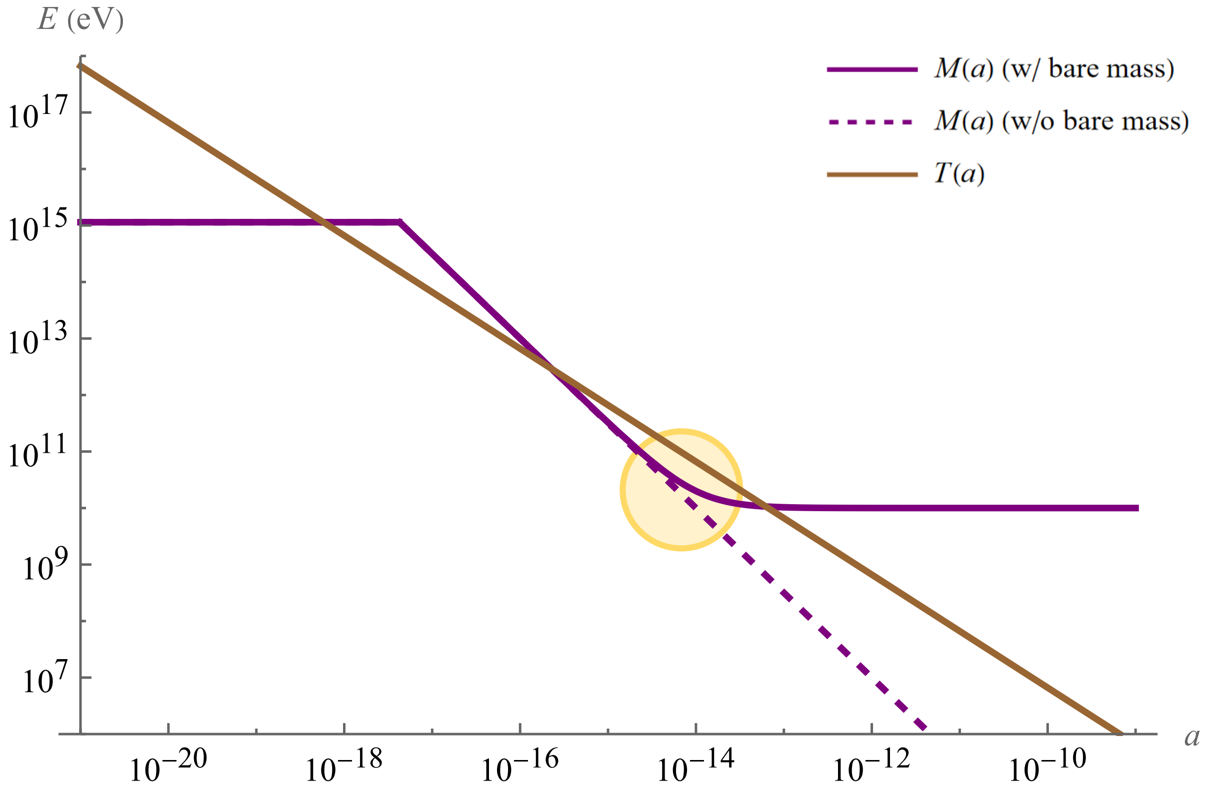
Implications on 0vββ experiments

- Neutrinoless double beta decay (0vββ) turns off when the neutrinos are in quasi-Dirac phase.
- The length of this ‘off’ period is determined by the ratio of m_D and $m_{R,0}$
- If $m_{R,0}$ is much bigger, neutrinos are mostly in Majorana phase
- If m_D is comparable to $m_{R,0}$, significant D-M oscillation effect



Zero vs. Nonzero bare mass

- The decreasing of Majorana mass term stopped by nonzero M_0

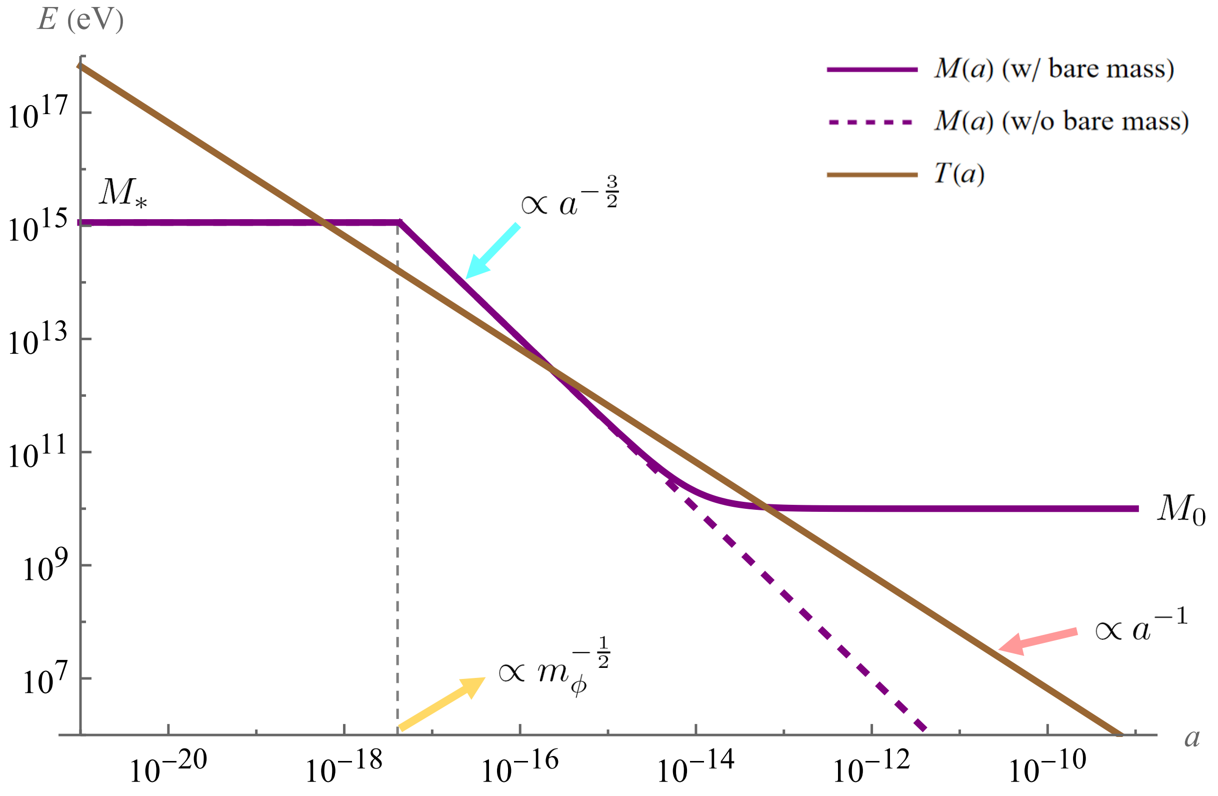


Leptogenesis may occur multiple times!

Nonzero Bare Mass

Parameters for Majorana mass

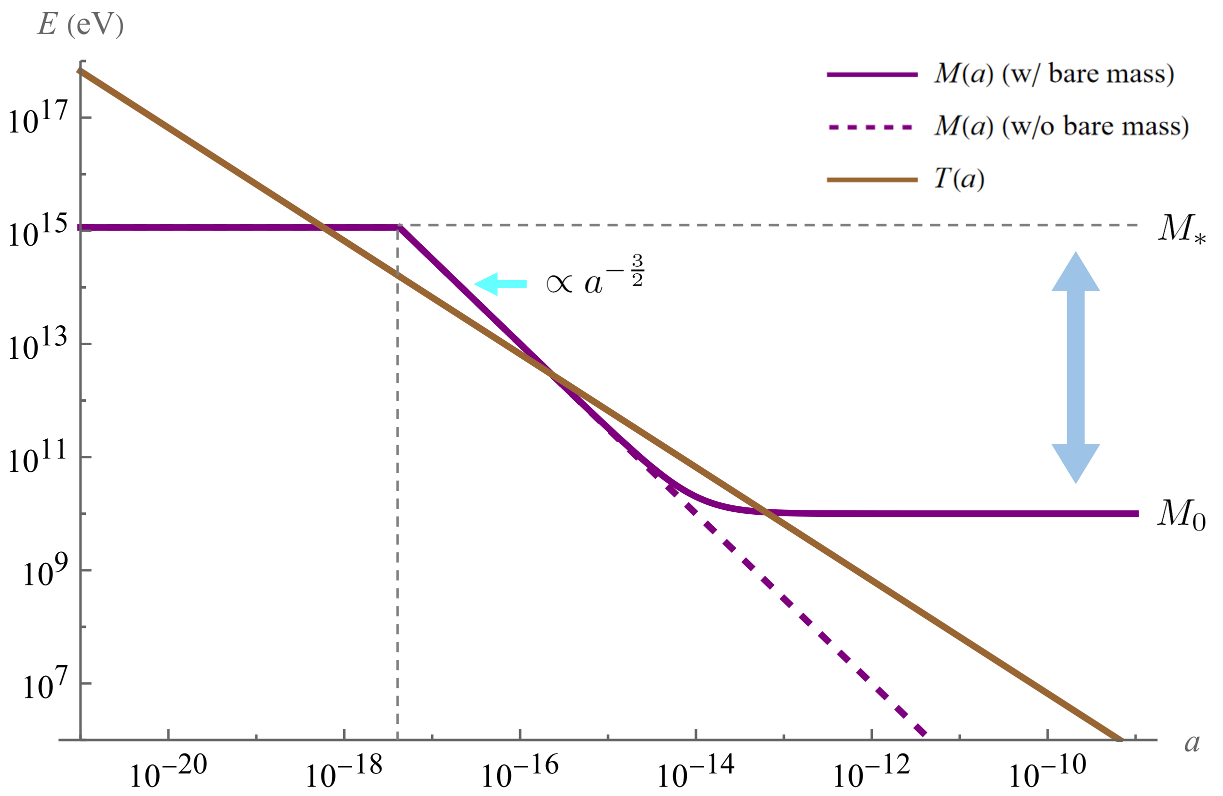
- Majorana mass determined by M_*, M_0 and m_ϕ



- We assume that $M_* \gg M_0$
- The neutrino Majorana mass starts to decay as $a^{-\frac{3}{2}}$
- To ensure that the neutrinos are Majorana particles along the evolution of the universe, one also assume $M_0 \gg m_D$

Nonzero Bare Mass

Cosmological expansion and the Majorana mass



- Heavy neutrino mass can be extremely high in the early universe while being small in the current universe.
- Important implications on the leptogenesis scenarios

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Heavy Majorana Neutrinos and Leptogenesis

Matter-Antimatter Asymmetry and Leptogenesis

Leptogenesis: Natural explanation of baryon asymmetry of the universe (BAU)

- Process of lepton number violating decay of heavy Majorana neutrinos
- Denoting the right-handed neutrino as N,

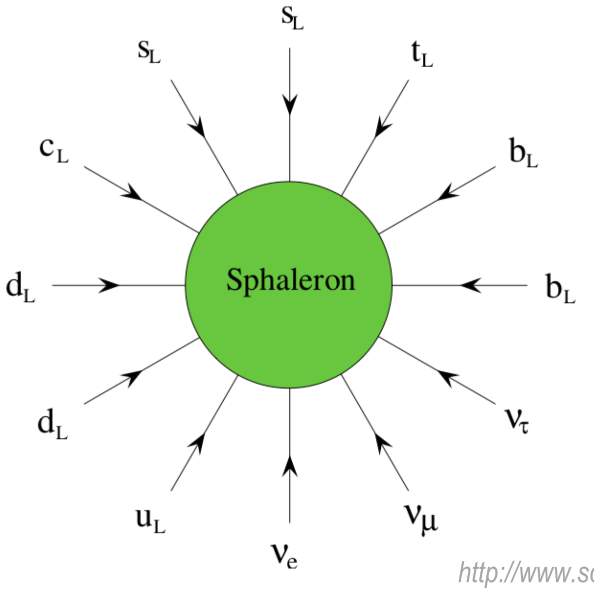
$N \to \ell\Phi$ ⟷ (Difference) $N \to \bar{\ell}\Phi^\dagger$ → Net lepton number generated

CP asymmetry factor $$\epsilon_i = \frac{\Gamma(N_i \to \ell\Phi) - \Gamma(N_i \to \bar{\ell}\Phi^\dagger)}{\Gamma(N_i \to \ell\Phi) + \Gamma(N_i \to \bar{\ell}\Phi^\dagger)}$$

Standard leptogenesis-baryogenesis model

- Production of nonzero lepton number by different amount of $N \to \ell\Phi$ and $N \to \bar{\ell}\Phi^\dagger$

- Lepton number converts into baryon numbers via $B-L$ conserving sphaleron process



http://www.scholarpedia.org/article/Leptogenesis

$$\Delta B = \Delta L = 3$$

$$B = \frac{28}{79}(B-L),\ \ L = \left(\frac{28}{79} - 1\right)(B-L)$$ → same order

Leptogenesis and the Scale of Majorana Mass

Mininal leptogenesis scenario and the neutrino mass

- Heaviest neutrino mass with $M_3 \sim 10^{15}\ \mathrm{GeV}$ and adapting the same mass hierarchy $\frac{M_1}{M_3}, \frac{M_2}{M_3}$ with the charged leptons

→ Light neutrino mass $\frac{v^2}{M_3} \sim 10^{-2}\ \mathrm{eV}$

- Lightest heavy neutrino mass $M_1 \sim 10^{10}\ \mathrm{GeV}$
- Asymmetry mostly generated by the lightest (M_1)

Leptogenesis and the Scale of Majorana Mass

Casas-Ibarra parametrization

Yukawa coupling strength $y = \sqrt{2}\hat{M}_N^{1/2} R \hat{m}_\nu^{1/2} U^\dagger / v$

Heavy neutrino mass

Light neutrino mass

- Heavy neutrino mass with $M_1 \sim 10^{10}\ \mathrm{GeV}$ gives large enough coupling and asymmetry.
- Coupling is suppressed for much lower heavy neutrino mass, cannot generate enough baryon numbers using the minimal scheme.

Leptogenesis and the Scale of Majorana Mass

Resonant leptogenesis scenario

- Heavy neutrinos with nearly degenerate mass spectra gives the enhancement of asymmetry

$$\varepsilon^{(j)}_{\alpha\beta} \propto \sum_{k\neq j} (\cdots) \frac{(M_k^2 - M_j^2) M_j^2}{(M_k^2 - M_j^2)^2 + M_j^4 \Gamma_k^2 / M_k^2}$$

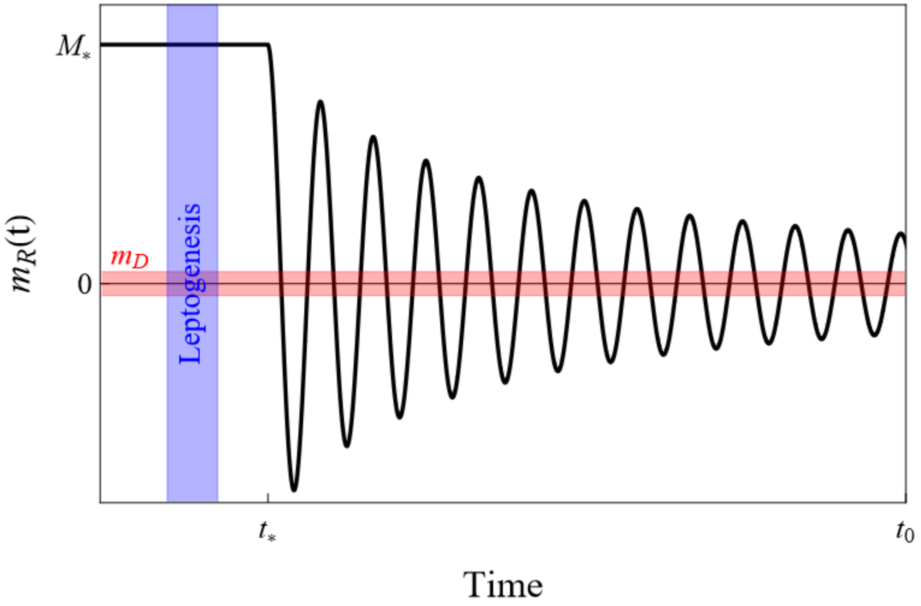
Same asymmetry with smaller neutrino mass

- The mass now can be low as order of TeV (should be higher than the sphaleron decoupling scale)

Leptogenesis and the Scale of Majorana Mass

Mass varying neutrinos and BAU generation

- In our model of varying Majorana mass, the heavy neutrino masses can be even lower than TeV scale since the neutrino mass can be decreased after the sphaleron decoupling.
- Since this small heavy neutrino mass results in small coupling, we adapt the resonant leptogenesis scenario in our calculations in order to produce enough asymmetry.



➡ Sub-GeV heavy neutrinos can successfully explain BAU!

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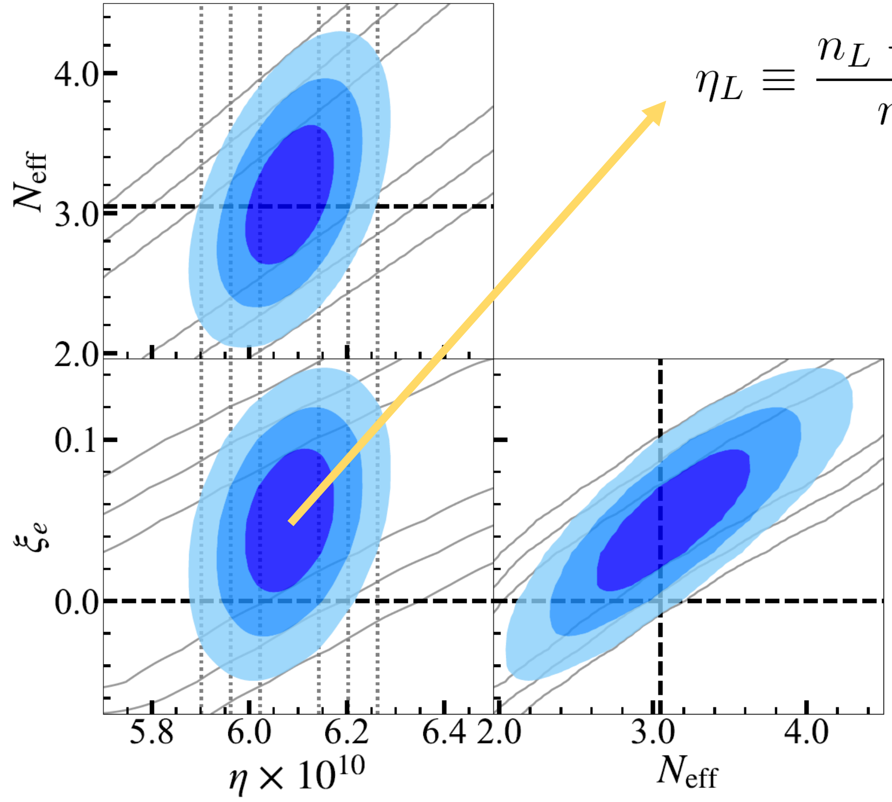
Second Leptogenesis

Second Leptogenesis: Decoupling the BAU & LAU

Motivation for the second phase of leptogenesis



2203.09617, A. Matsumoto et al.

$$\eta_L \equiv \frac{n_L - n_{\bar{L}}}{n_\gamma} \simeq \frac{\pi^2 \sum_{i=e,\mu,\tau} \xi_{\nu_i}}{6\zeta(3)} \left(\frac{T_\nu}{T_\gamma}\right)^3 \simeq (7.5^{+4.5}_{-3.0}) \times 10^{-2}$$

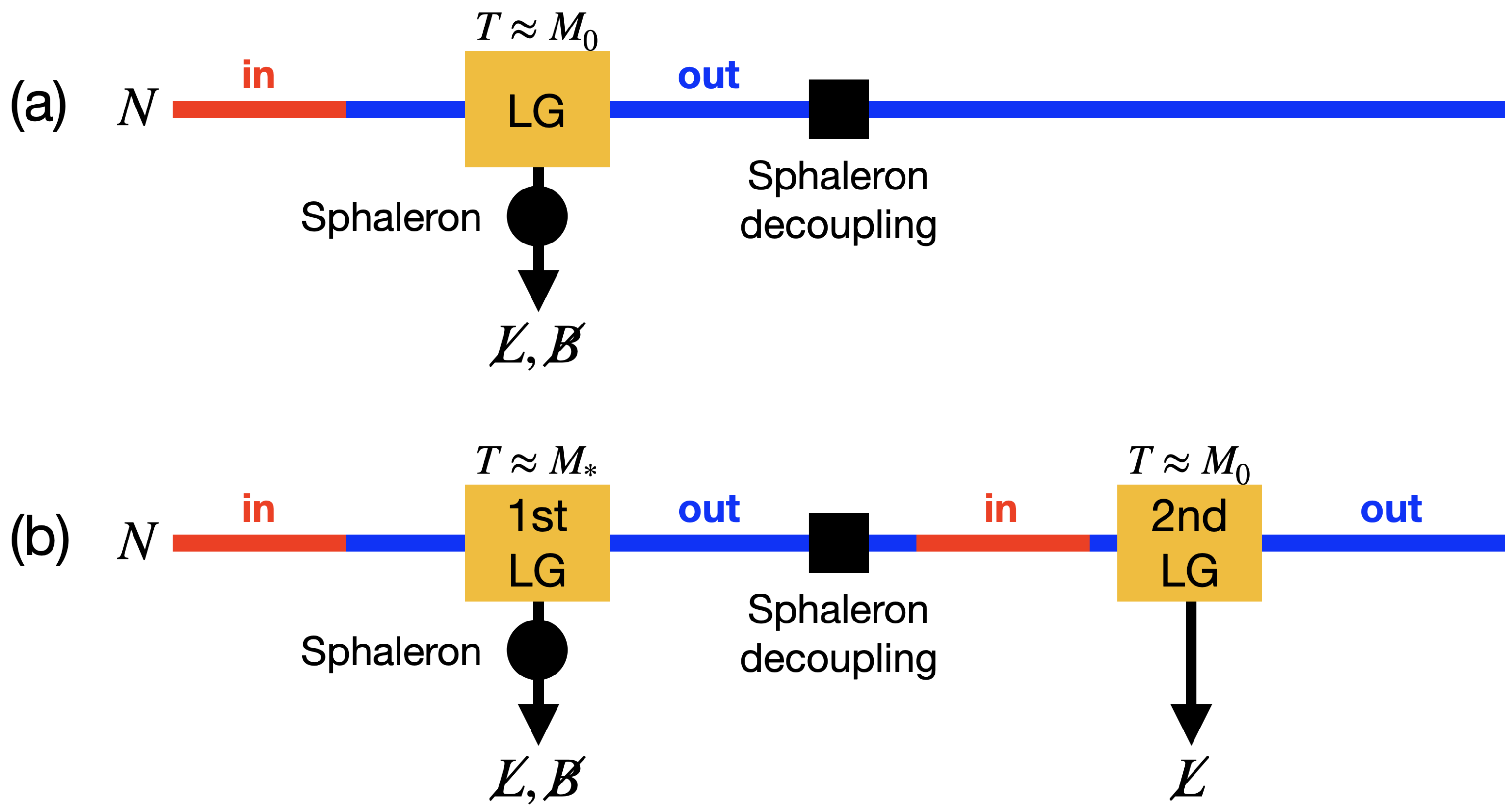
10^8 Discrepancy

$$\eta_B \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma} \simeq (6.14 \pm 0.25) \times 10^{-10}$$

- Adding another leptogenesis stage after the sphaleron energy can boost only lepton asymmetry!

Second Leptogenesis: Decoupling the BAU & LAU

Schematic diagram for second leptogenesis

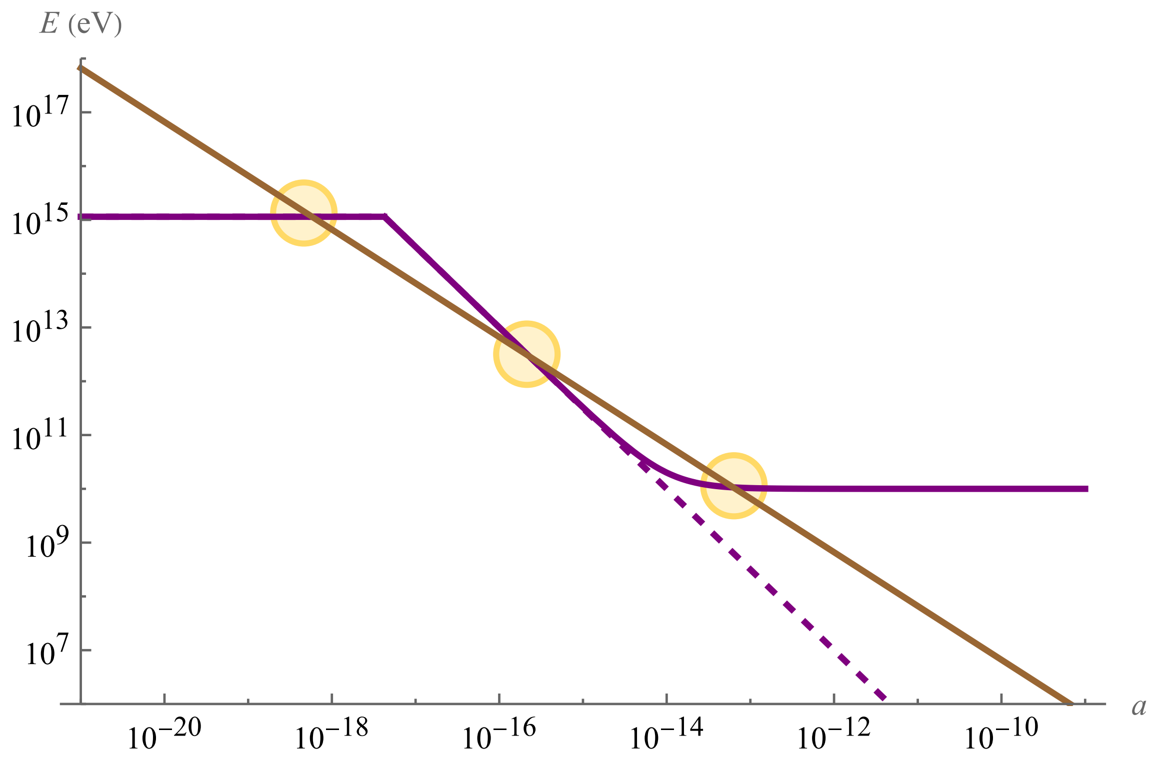


Second Leptogenesis: Decoupling the BAU & LAU

Triple crossing of the temperature and mass

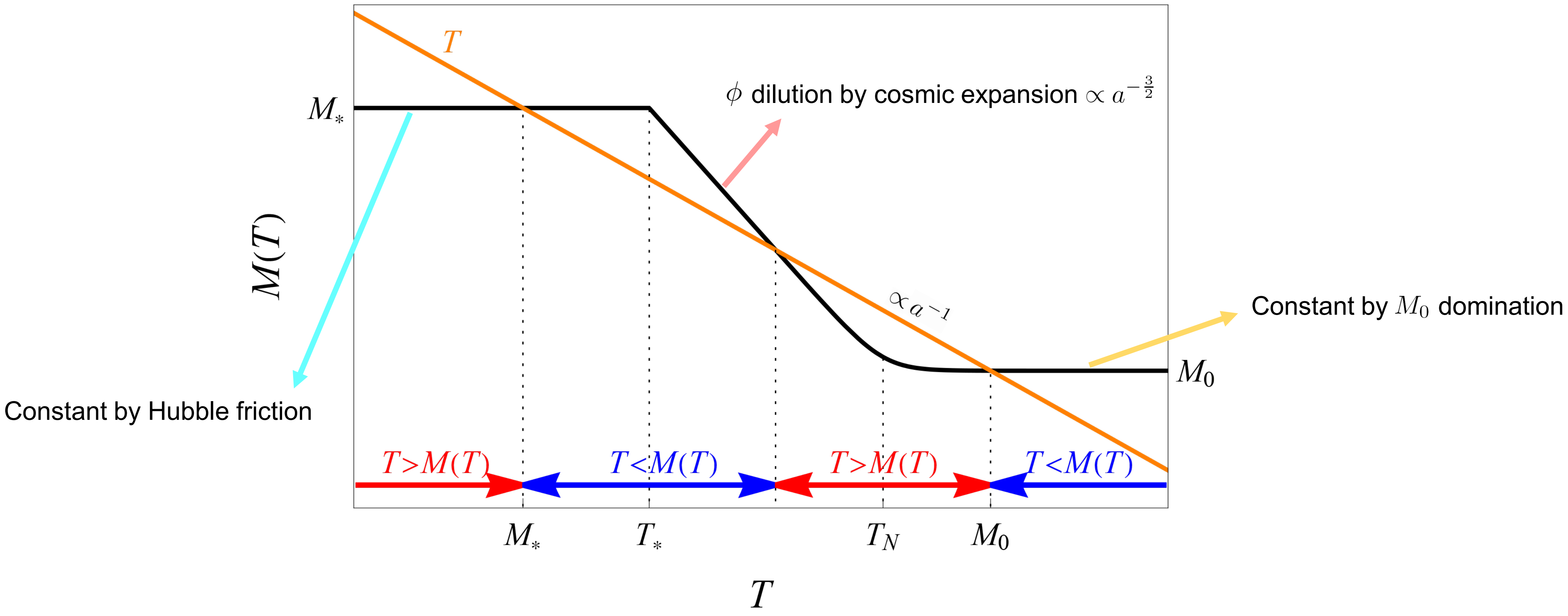
- Neutrinos out of the initial thermal bath → re-enter → re-exit: triple crossing
- Temperature of the universe is monotonically decreasing
- The neutrino mass should not be constant in order to realize this condition

➡ DM induced mass variation of neutrinos can achieve this!



Variation of Mass and the Second Leptogenesis

Natural achievement of triple crossing

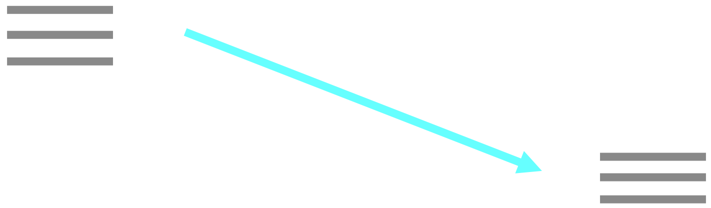


Variation of Mass and the Second Leptogenesis

3 flavor resonant leptogenesis scenario

- Since we will use resonant leptogenesis model, the mass of three heavy neutrinos are almost identical, which ensures same behavior of three masses.
- Mass differences can come from both bare mass term and the coupling term, where those from the bare mass does not change but those from the DM coupling follows scaling behavior by cosmic expansion as shown before.
- In this work, we assumed that the ratio between three Majorana masses are constant along the expansion of the universe, where bare and coupling terms have same ratio for each flavor.

$M_1,\ M_2,\ M_3$



Mass ratio unchanged

Variation of Mass and the Second Leptogenesis

Necessary conditions for second leptogenesis

1. Triple crossing: $M_{*i} > T_*$, $T_{N_i} > M_{0i}$, $T_* > T_{N_i}$

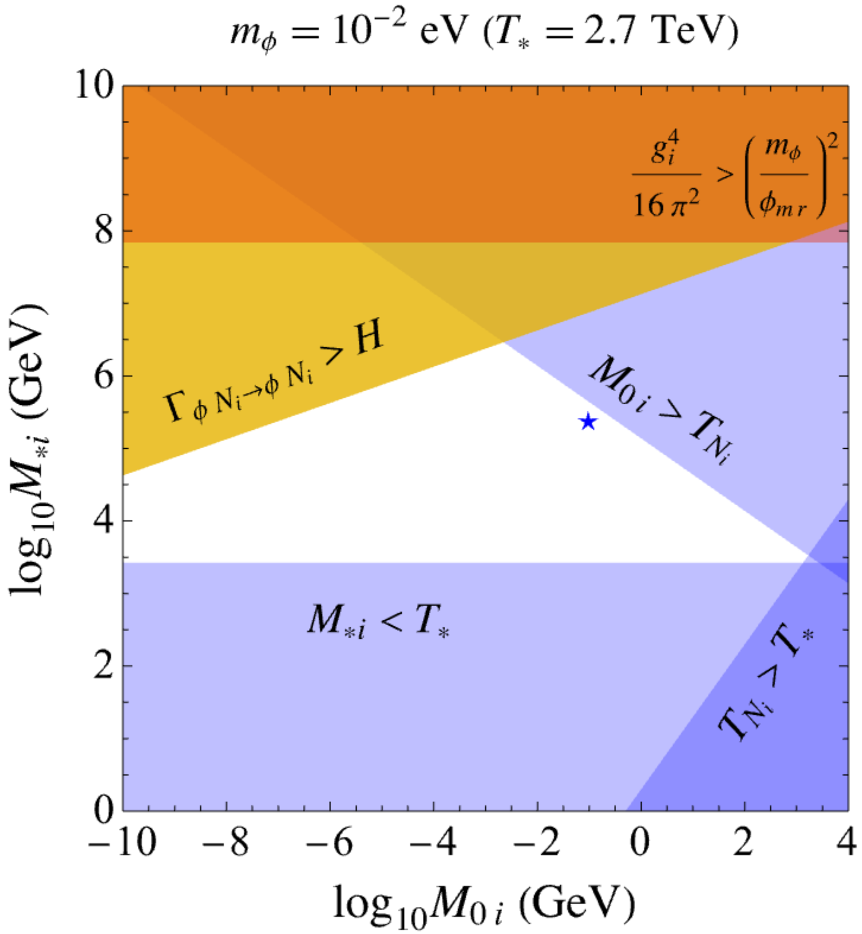
2. Theoretical constraints
   - Matter-like ϕ: $\dfrac{m_\phi^2}{\phi_{mr}^2} > \dfrac{g_i^2}{16\pi^2}$
   - Avoid thermalization: $\Gamma < H(T)$

3. Coupling g constraints
   - Majoron, CMB free streaming, neutrino oscillations etc. (m_ϕ dependent)

Model Setup and Simulations for Second Leptogenesis

Parameter regions satisfying the necessary conditions

- The shape and area of the region is dependent on the value of m_ϕ .
- Weaker constraints are not shown in the figure.
- Sub-GeV heavy neutrino mass favored!



Model Setup and Simulations for Second Leptogenesis

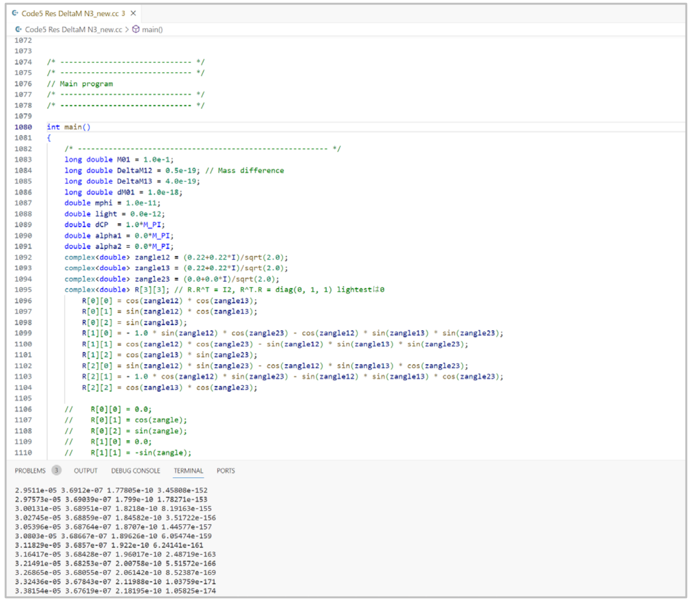
Density equations for 3 flavor leptogenesis

$$\frac{\mathrm{d}N_{N_i}}{\mathrm{d}z} = -\, D_i(N_{N_i} - N_{N_i}^{\mathrm{eq}})$$

$$\frac{\mathrm{d}N_{\alpha\beta}}{\mathrm{d}z} = \sum_i \left[\epsilon_{i,\alpha\beta} D_i (N_{N_i} - N_{N_i}^{\mathrm{eq}}) - \frac{1}{2} W_i \{P_i, N\}_{\alpha\beta}\right]$$

D_i: Decay term

W_i: Washout term (from inverse decay)



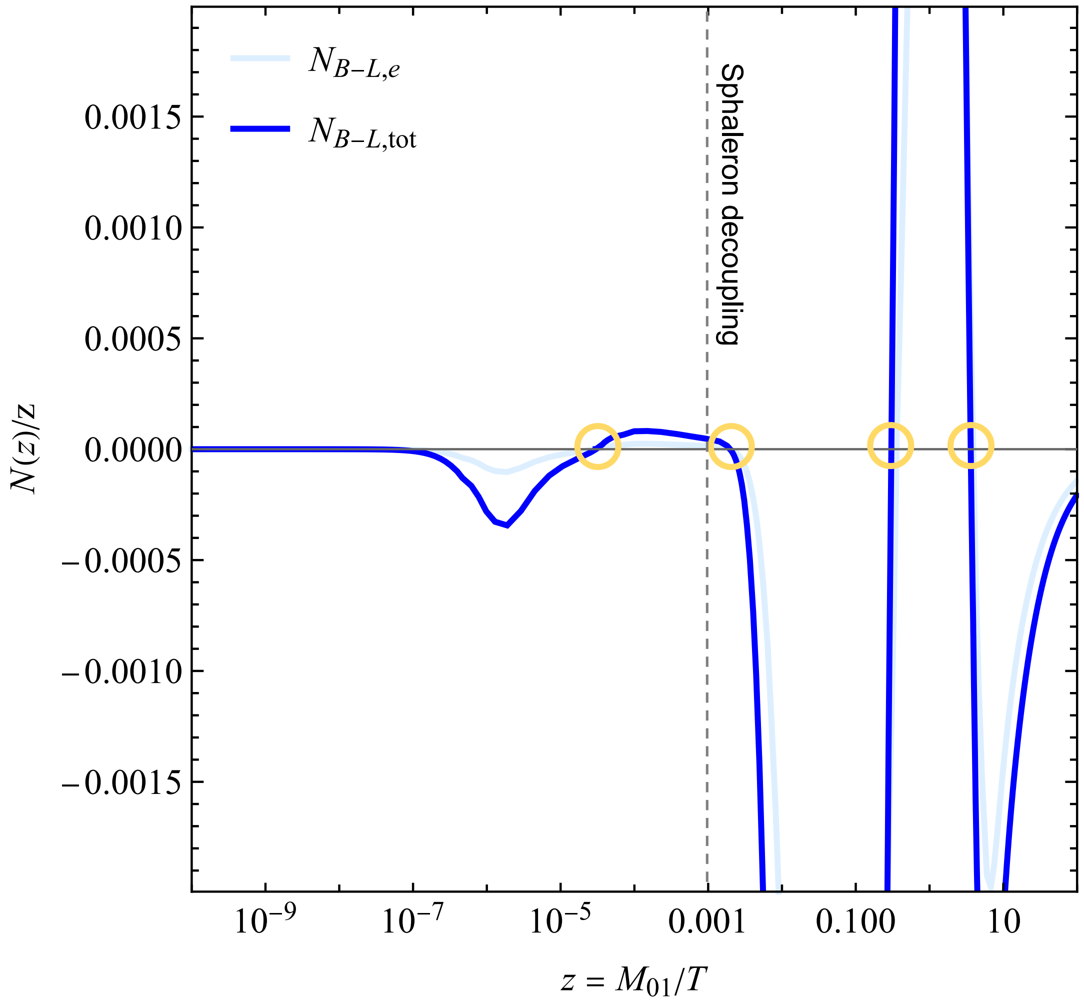
```
Code5 Res DeltaM N3_new.cc 3 ×
Code5 Res DeltaM N3_new.cc > main()


/* ----------------------------- */
/* ----------------------------- */
// Main program
/* ----------------------------- */
/* ----------------------------- */

int main()
{
    /* -------------------------------------------------------- */
    long double M01 = 1.0e-1;
    long double DeltaM12 = 0.5e-19; // Mass difference
    long double DeltaM13 = 4.0e-19;
    long double dM01 = 1.0e-18;
    double mphi = 1.0e-11;
    double light = 0.0e-12;
    double dCP  = 1.0*M_PI;
    double alpha1 = 0.0*M_PI;
    double alpha2 = 0.0*M_PI;
    complex<double> zangle12 = (0.22+0.22*I)/sqrt(2.0);
    complex<double> zangle13 = (0.22+0.22*I)/sqrt(2.0);
    complex<double> zangle23 = (0.0+0.0*I)/sqrt(2.0);
    complex<double> R[3][3]; // R.R^T = I2, R^T.R = diag(0, 1, 1) lightestは0
        R[0][0] = cos(zangle12) * cos(zangle13);
        R[0][1] = sin(zangle12) * cos(zangle13);
        R[0][2] = sin(zangle13);
        R[1][0] = - 1.0 * sin(zangle12) * cos(zangle23) - cos(zangle12) * sin(zangle13) * sin(zangle23);
        R[1][1] = cos(zangle12) * cos(zangle23) - sin(zangle12) * sin(zangle13) * sin(zangle23);
        R[1][2] = cos(zangle13) * sin(zangle23);
        R[2][0] = sin(zangle12) * sin(zangle23) - cos(zangle12) * sin(zangle13) * cos(zangle23);
        R[2][1] = - 1.0 * cos(zangle12) * sin(zangle23) - sin(zangle12) * sin(zangle13) * cos(zangle23);
        R[2][2] = cos(zangle13) * cos(zangle23);

    //    R[0][0] = 0.0;
    //    R[0][1] = cos(zangle);
    //    R[0][2] = sin(zangle);
    //    R[1][0] = 0.0;
    //    R[1][1] = -sin(zangle);

PROBLEMS 3   OUTPUT   DEBUG CONSOLE   TERMINAL   PORTS

2.9511e-05 3.6912e-07 1.77805e-10 3.45808e-152
2.97573e-05 3.69039e-07 1.799e-10 1.78271e-153
3.00131e-05 3.68951e-07 1.8218e-10 8.19163e-155
3.02745e-05 3.68859e-07 1.84582e-10 3.51722e-156
3.05396e-05 3.68764e-07 1.8707e-10 1.44577e-157
3.0803e-05 3.68667e-07 1.89626e-10 6.05474e-159
3.11829e-05 3.6857e-07 1.922e-10 6.24141e-161
3.16417e-05 3.68428e-07 1.96017e-10 2.48719e-163
3.21491e-05 3.68253e-07 2.00758e-10 5.51572e-166
3.26865e-05 3.68055e-07 2.06142e-10 8.52387e-169
3.32436e-05 3.67843e-07 2.11988e-10 1.03759e-171
3.38154e-05 3.67619e-07 2.18195e-10 1.05825e-174
```

→ Numerical solving of differential equations using C++ code

Model Setup and Simulations for Second Leptogenesis

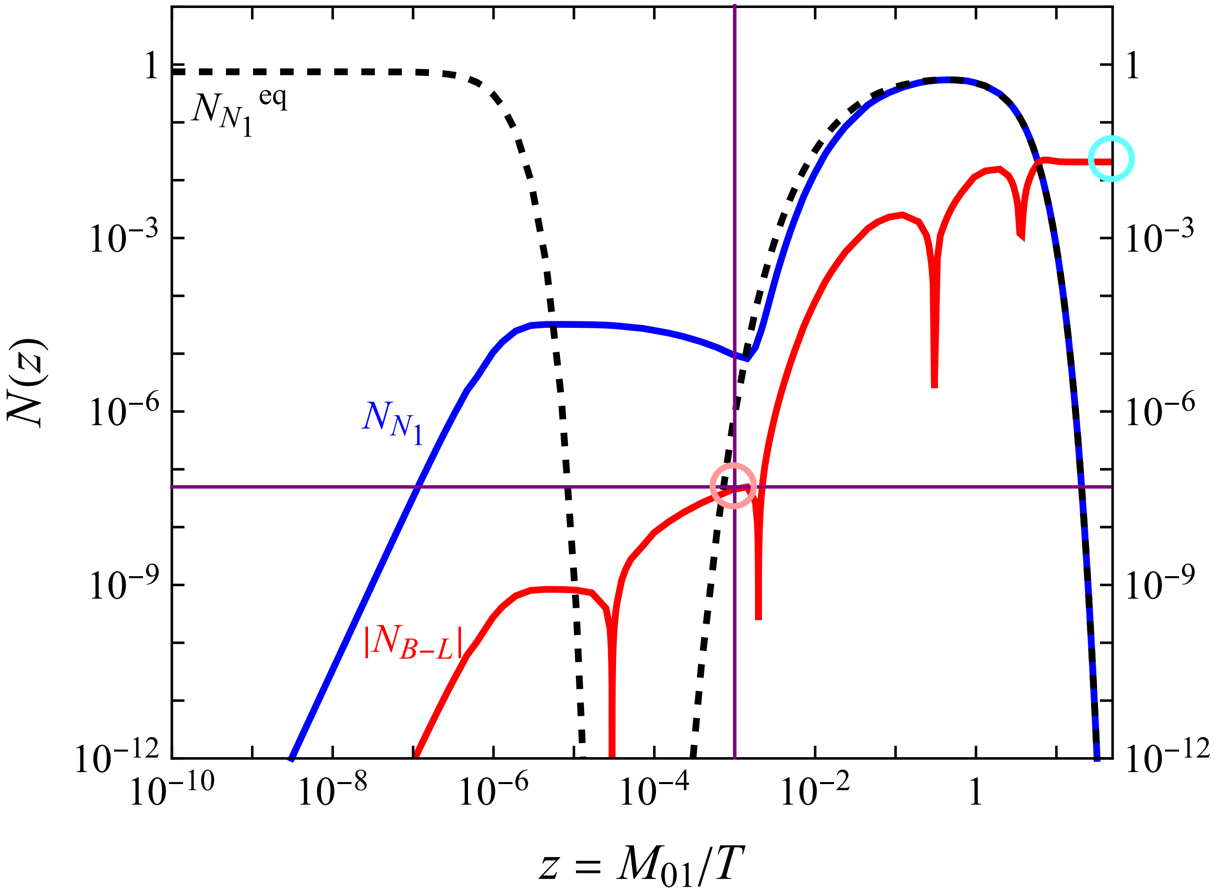
Behavior of B-L

- The value of B-L starts from zero.
- During the evolution of the universe, the sign of the B-L changes by the production and decay of heavy neutrinos.
- B-L is positive at the time when sphaleron process occurs, giving the positive baryon number.
- B-L is negative at the time at the current universe, since the observed lepton asymmetry is also positive.



Model Setup and Simulations for Second Leptogenesis

Benchmark results



- $M_{01} = 0.1\ \text{GeV}$ and $M_{*1} = 2.4 \times 10^5\ \text{GeV}$
- Splitting $\Delta M_{12} \sim \Delta M_{13} \sim 10^{-19}\ \text{GeV}$
- Gives the lepton asymmetry of $\eta_L \simeq 5.0 \times 10^{-3}$
- Baryon asymmetry fixed at sphaleron decoupling with value of $\eta_B \simeq 6.14 \times 10^{-10}$
- Downward peaks represents sign flips of $B - L$

LAU increased with factor of 10^7

Summary

- Varying neutrino Majorana mass via coupling with the wave dark matter
- The Majorana mass of neutrinos decreases by the dilution of the dark matter due to cosmic expansion
- Heavy neutrino mass can triple cross the thermal bath temperature, enabling **second leptogenesis**
- Possible explanation of the significant discrepancy between baryon and lepton asymmetries

Rich phenomenology expected in this new model!