Second Leptogenesis

for large baryon-lepton asymmetry discrepancy

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Based on JHEP 03 (2024) 003, and arXiv: 2406.19694

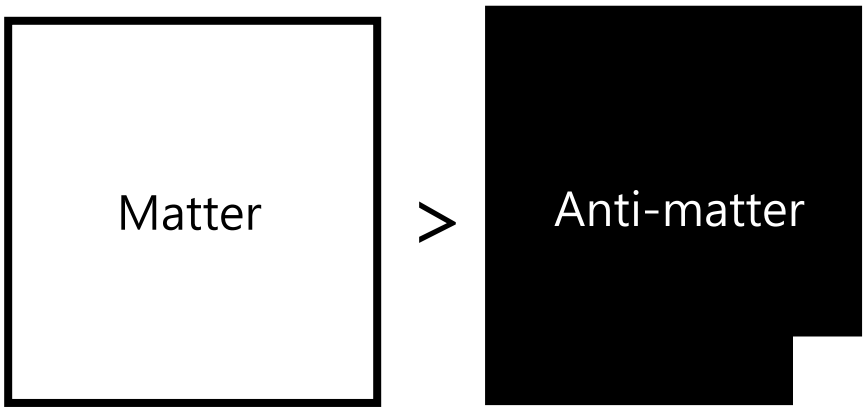
Collaborated with YeolLin ChoeJo, Kazuki Enomoto, and Hye-Sung Lee

The 12th KIAS Workshop on Particle Physics and Cosmology
& 2024 Korea-France STAR workshop (Nov. 2024)

Baryon Asymmetry of the Universe (BAU)

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

Baryon-to-photon ratio from BBN/CMB



Baryogenesis models:

EWBG, GUTBG, ADBG, LG, ...

Sakharov conditions

1. B violation
2. *C* and *CP* violations
3. Out-of-equilibrium

SM satisfies them, but not enough

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Baryogenesis models:

EWBG, GUTBG, ADBG, $\boxed{\text{LG}}$, ...

Large discrepancy!

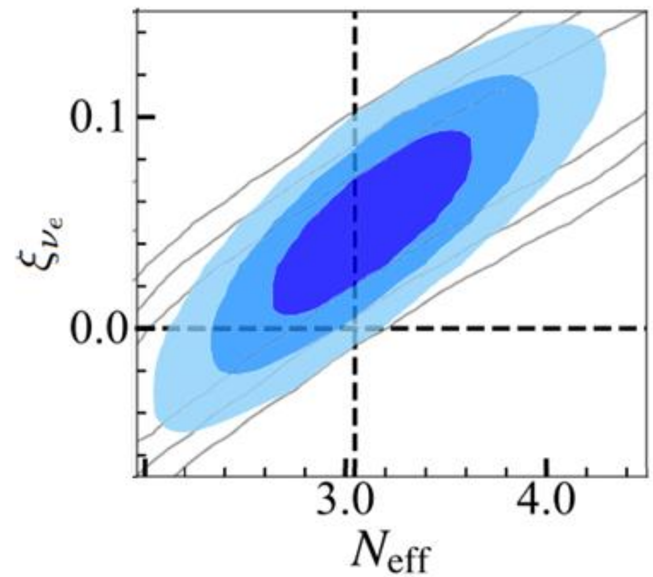
Lepton Asymmetry of the Universe (LAU)

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

$$\xi_{\nu_e} \equiv \frac{\mu_{\nu_e}}{T} = 0.05^{+0.03}_{-0.02}$$

reported by EMPRESS (Extremely Metal-Poor Representatives Explored by the Subaru Survey) with ^{4}He abundance observation

A. Matsumoto et al (2022)



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Baryogenesis models:

EWBG, GUTBG, ADBG, **LG** …

Leptogenesis

CP-violating out-of-equilibrium decay of **Heavy Majorana neutrino**

$$N_i \to \ell\Phi,\ N_i \to \bar{\ell}\Phi^\dagger$$

$\downarrow$

Lepton Asymmetry

Sphaleron $\downarrow$

Baryon Asymmetry

BAU is determined before EWSB

Sphaleron decoupling at EWSB

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~~Baryon Asymmetry~~

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Lepton Asymmetry of the Universe (LAU)

$$\eta_L \equiv \frac{n_L - n_{\bar{L}}}{n_\gamma} \simeq (7.5^{+4.5}_{-3.0}) \times 10^{-2}$$

LAU can be changed after EWSB (If LG exists)

Baryon Asymmetry of the Universe (BAU)

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

Large discrepancy!

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Baryogenesis models:

EWBG, GUTBG, ADBG, LG ...

First Leptogenesis

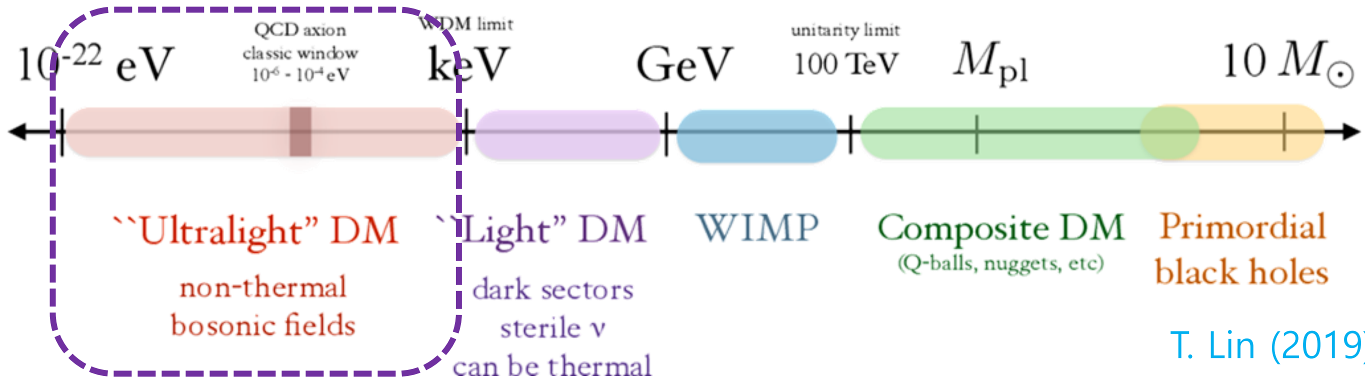
First Production and Decay of *N*

EWSB

"Second Leptogenesis"

... and Second Production and Decay of *N*

Realization of “Second Leptogenesis” with Wave Dark Matter

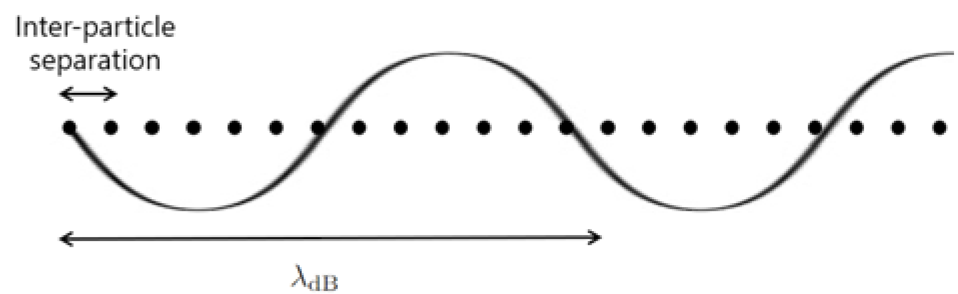


T. Lin (2019)

$$10^{-22}\ \mathrm{eV} < m_\phi < 30\ \mathrm{eV}$$

Lyman-α

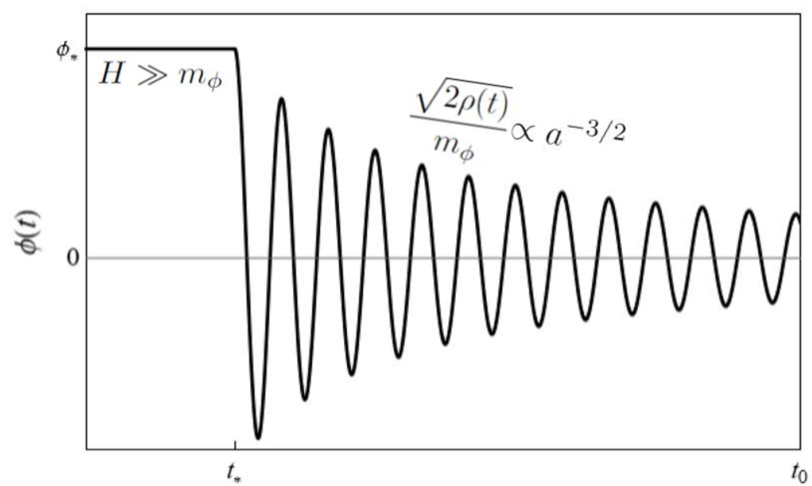
$\lambda_{\rm dB} = \dfrac{2\pi}{mv}$ > Inter-particle separation



Scalar field in expanding universe

$$\ddot{\phi} + 3H\dot{\phi} + m_\phi^2\phi = 0$$

$$\phi(t) = \begin{cases} \dfrac{\sqrt{2\rho_0}}{m_\phi} & H \gg m_\phi, \\ \dfrac{\sqrt{2\rho(t)}}{m_\phi}\cos m_\phi t & H \ll m_\phi \end{cases}$$



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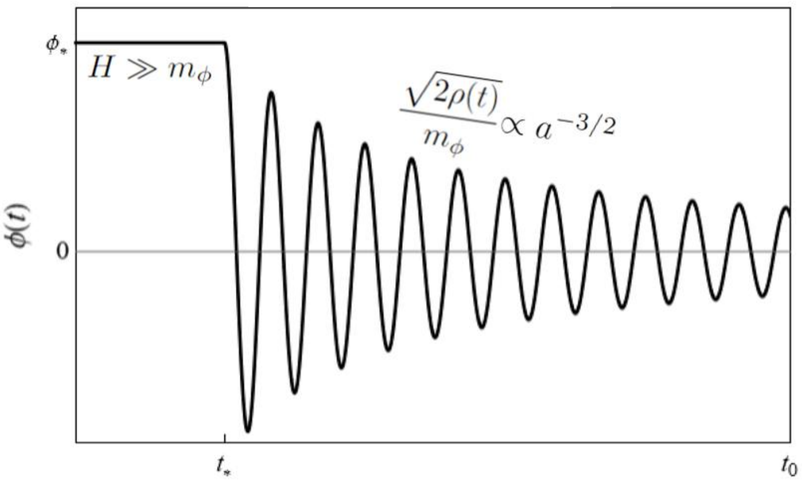


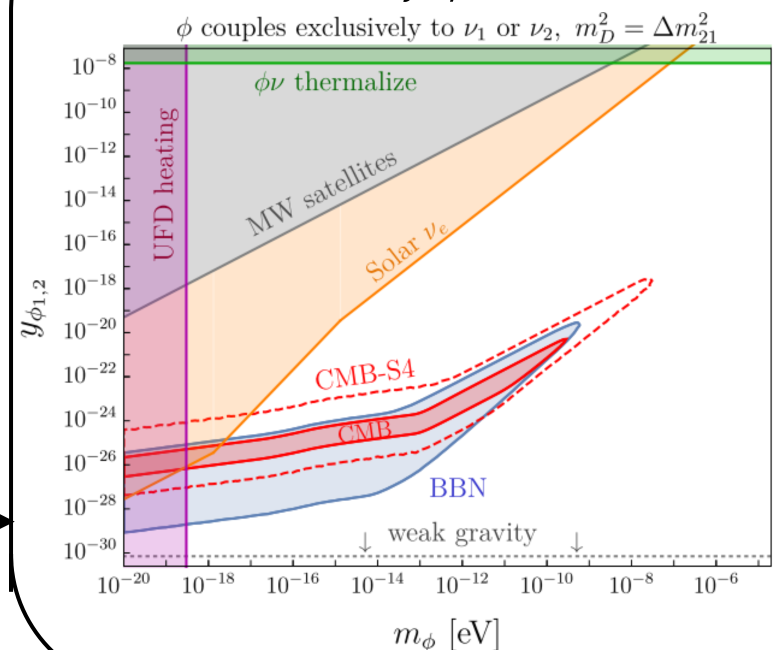
Majorana mass term variation

$$\mathcal{L} \supset -g\,\phi\,\overline{N^c}N + h.c.$$

A. Dev, G. Krnjaic, P. Machado, H. Ramani (2022)

Constraint on the coupling between Wave DM & RHN

y = g here, and some constraints holds for only quasi-Dirac limit



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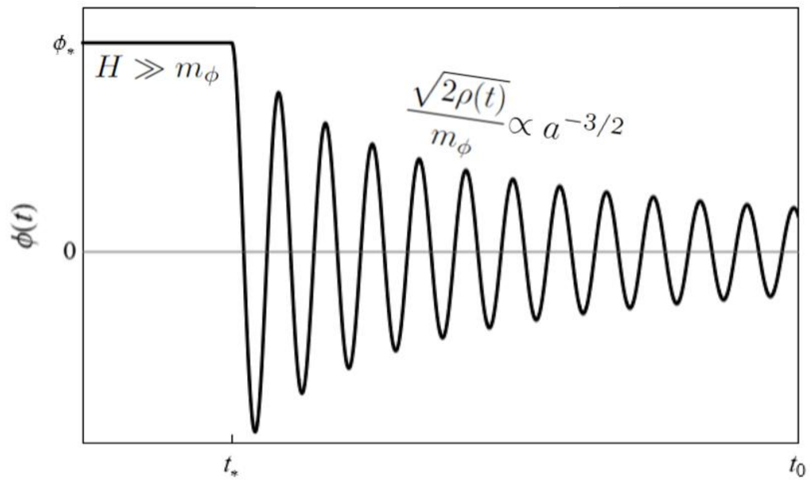
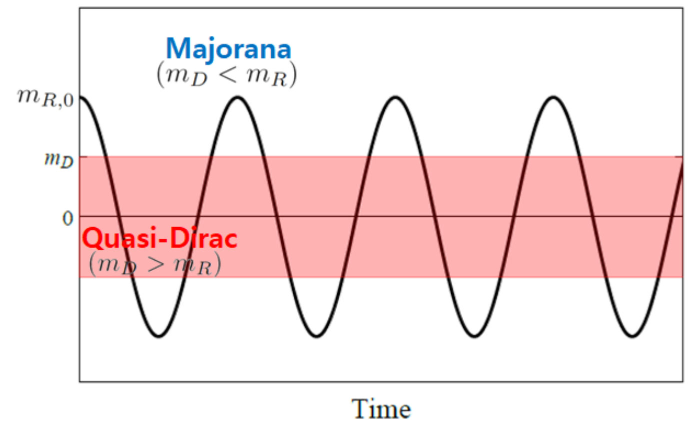
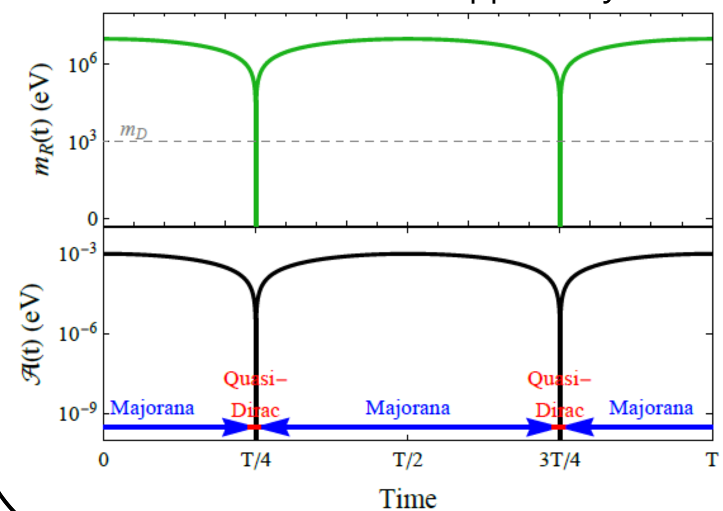


$$m_R(t) = m_{R,0} \cos m_\phi t$$



Modulation of 0νββ decay



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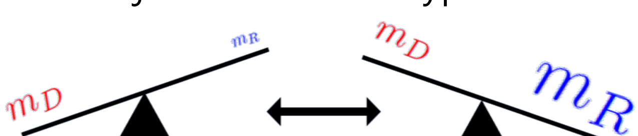
$$\mathcal{L} \supset -g\, \phi\, \overline{N^c} N + h.c.$$

A. Dev, G. Krnjaic, P. Machado, H. Ramani (2022)
Y.L. ChoeJo, **Y. Kim**, H.S. Lee (2023) …

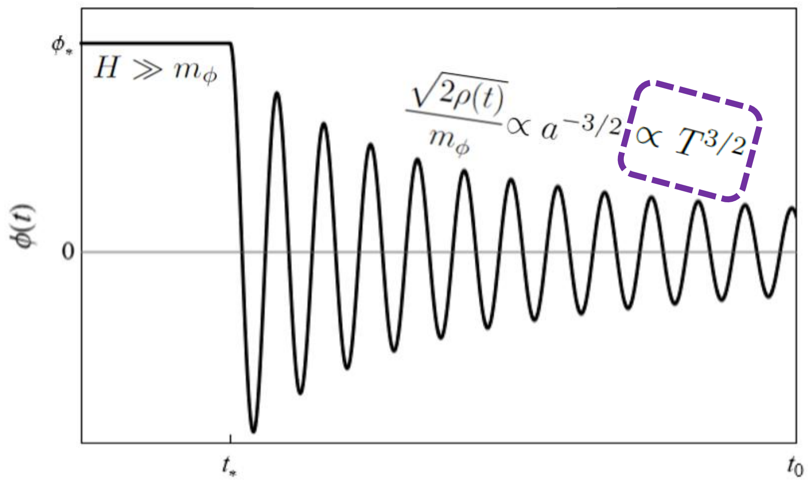
Dirac-Majorana neutrino type oscillation



Quasi-Dirac type   Majorana type

Realization of "Second Leptogenesis" with Wave Dark Matter

$$\ddot{\phi} + 3H\dot{\phi} + m_\phi^2 \phi = 0$$



$$\downarrow \quad \mathcal{L} \supset (M_0 + g\phi)\overline{N^c}N + h.c.$$

Temperature-dependent mass of *N*

$$M(T) \simeq \begin{cases} M_* & T > T_*, \\ M_0 + M_* \left(\frac{T}{T_*}\right)^{3/2} & T_* > T > T_N, \\ M_0 & T_N > T. \end{cases}$$

T_* from

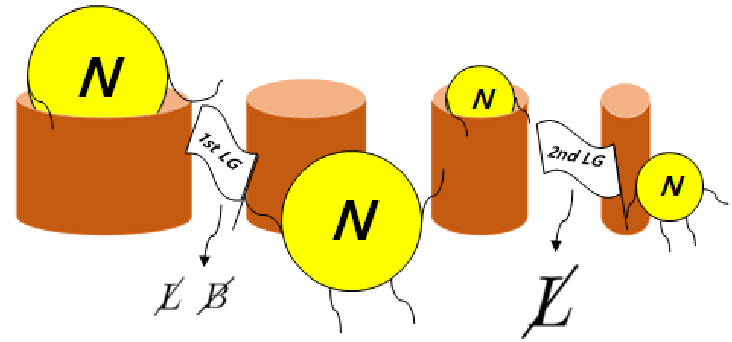
$$H(T_*) \simeq m_\phi$$

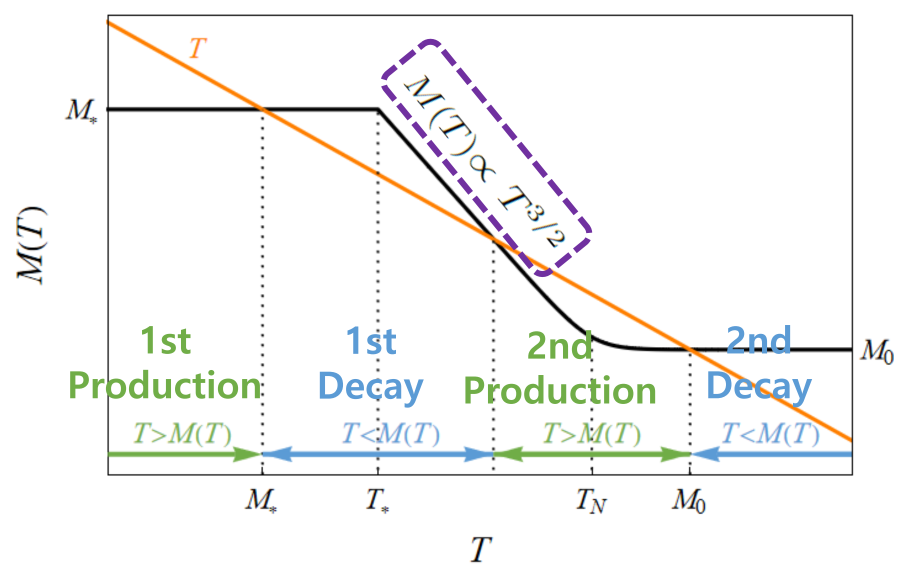
Mass variation starts

T_N from

$$M_0 \simeq M_* \left(\frac{T_N}{T_*}\right)^{3/2}$$

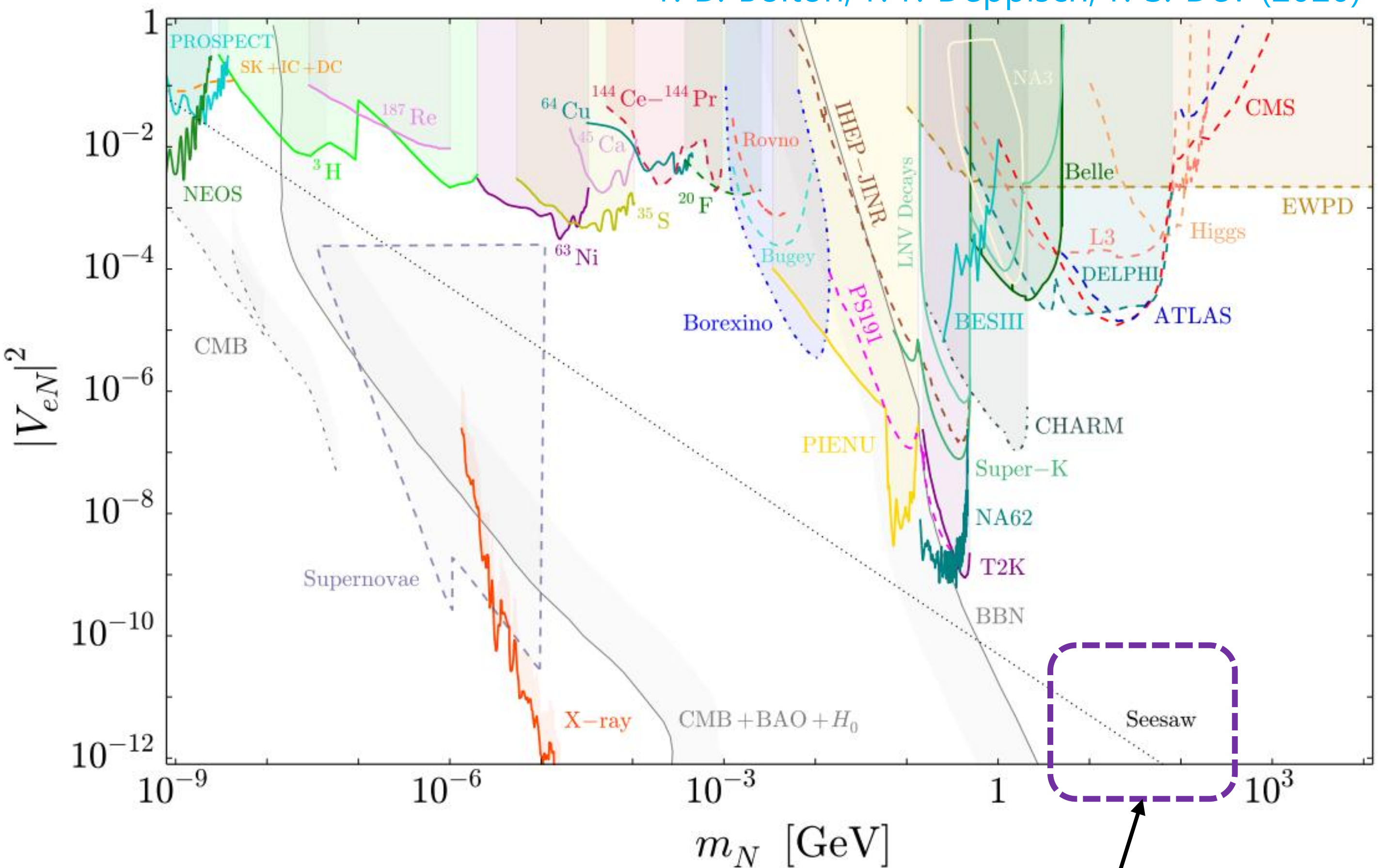
Mass variation term becomes negligible





Parameter space for Second LG

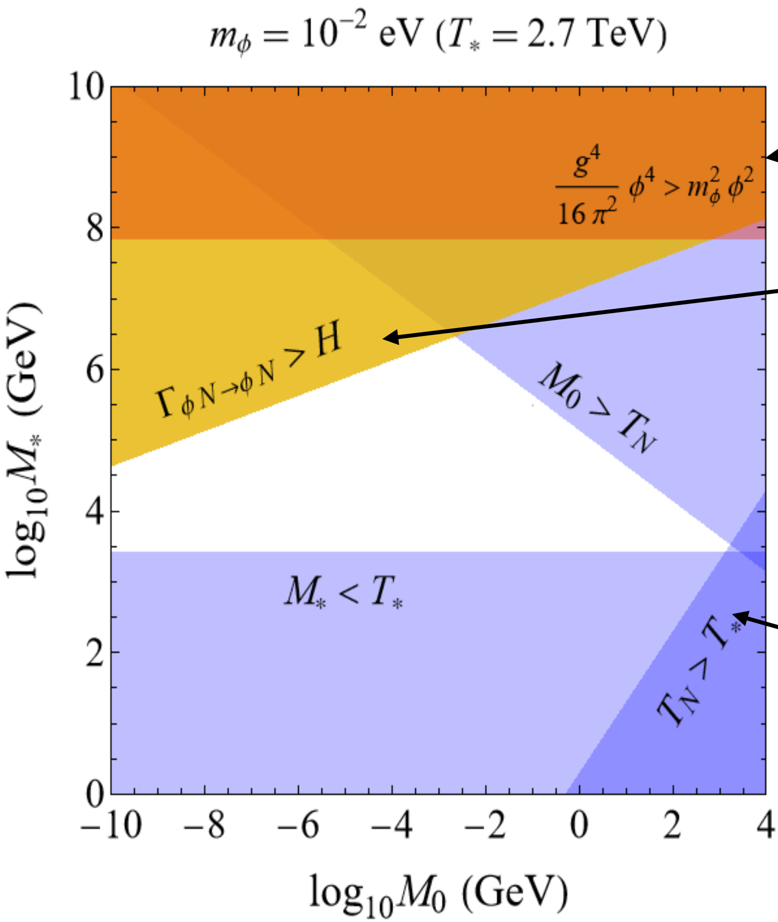
P. D. Bolton, F. F. Deppisch, P. S. Dev (2020)



$$M(T) \simeq \begin{cases} M_* & T > T_*, \\ M_0 + M_* \left(\dfrac{T}{T_*}\right)^{3/2} & T_* > T > T_N, \\ \boxed{M_0} & T_N > T. \end{cases}$$

M_0 > 1 GeV to avoid Neff constraint from BBN or CMB

Parameter space for Second LG



A. Dev, G. Krnjaic, P. Machado, H. Ramani (2022)

To avoid dominant quartic coupling

To avoid thermalization of wave DM by scattering

$M_* \;>\; T_* \;>\; T_N \;>\; M_0$

For 1st decoupling | For varying time interval | For 2nd decoupling

(These are naive conditions for 2nd LG,
Not ensuring 2nd production & decay of *N*)

Boltzmann equation (density matrix form)

$N_{N_i}, N_{\alpha\beta}$: Comoving number density of $N_i, B-L$

$$\frac{\mathrm{d}N_{N_i}}{\mathrm{d}z} = -(\boxed{D_i} + \boxed{S_i})(N_{N_i} - \boxed{N^{\mathrm{eq}}_{N_i}}),$$

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

where $z = M_{01}/T$, $i = 1, 2, 3$, and $\alpha, \beta = e, \mu, \tau$.

Insert

Temperature-dependent mass of *N*

$$M(T) \simeq \begin{cases} M_* & T > T_*, \\ M_0 + M_*\left(\frac{T}{T_*}\right)^{3/2} & T_* > T > T_N, \\ M_0 & T_N > T. \end{cases}$$

D_i : Decay term

S_i : Scattering term

Boltzmann suppression are includes in those terms

W_i : Washout term

$\varepsilon^{(i)}_{\alpha\beta}$: *CP* asymmetry

$N^{\mathrm{eq}}_{N_i}$: Equilibrium density

Decay channel alternation

under heavy neutrino mass variation

(1) Before EWSB: $N \to \ell\Phi$

(N decay to massless lepton & Higgs doublets)

EWSB

(2) $N \to h\ell,\ N \to Z\nu, N \to W\ell$

(N decay to massive on-shell bosons)

after $M(T) = m_H$ or $m_{W,Z}$

(3) $N \to 3\nu, N \to \nu_\mu \bar{\mu} e, N \to \nu_e \pi^0$ ...

(N decay to leptons & mesons ...)

Scattering channel $N\nu \to \ell\ell$ via Z

has resonance when $M(T)$ is around Z boson mass

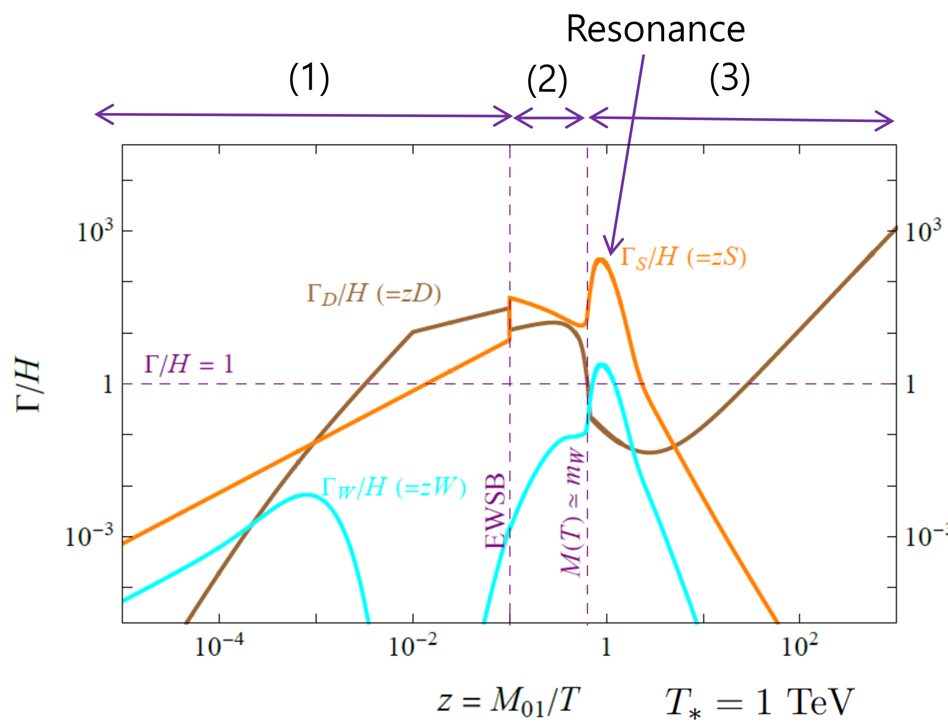
D_i : Decay term

S_i : Scattering term

W_i : Washout term

$\varepsilon_{\alpha\beta}^{(i)}$: *CP* asymmetry

$N_{N_i}^{\rm eq}$: Equilibrium density



$T_* = 1$ TeV

$M_{*1} = 40$ TeV

$M_{01} = 10$ GeV

CP asymmetry

: **resonant LG** is adopted for enough BAU in relatively small scale of *M*.

$$\varepsilon_{\alpha\beta}^{S(i)} = \frac{1}{16\pi(yy^\dagger)_{ii}} \sum_{j\neq i} \Big\{ i\big[y_{i\alpha}^* y_{j\beta}(yy^\dagger)_{ji} - y_{i\beta}y_{j\alpha}^*(yy^\dagger)_{ij}\big]\frac{M_j}{M_i} + i\big[y_{i\alpha}^* y_{j\beta}(yy^\dagger)_{ij} - y_{i\beta}y_{j\alpha}^*(yy^\dagger)_{ji}\big]\Big\} \boxed{\frac{(M_j^2-M_i^2)M_i^2}{(M_j^2-M_i^2)^2+M_i^4\Gamma_j^2/M_j^2}}$$

$i = 1, 2, 3,$ and $\alpha, \beta = e, \mu, \tau.$

Resonant condition

$|M_j - M_i| \simeq \Gamma_j/2$

(almost degenerate mass of *N* 's)

- D_i : Decay term
- S_i : Scattering term
- W_i : Washout term
- $\varepsilon_{\alpha\beta}^{(i)}$: *CP* asymmetry
- $N_{N_i}^{\text{eq}}$: Equilibrium density

EWSB

$$\varepsilon_{\alpha\beta}^{S(i)} = \frac{\Gamma_i}{2M_i\{(R^\dagger R)_{ii}\}^2} \sum_{j\neq i} \Big\{ i\big[R_{\alpha i}R_{\beta j}^*(R^\dagger R)_{ji} - R_{\beta i}^* R_{\alpha j}(R^\dagger R)_{ij}\big]\frac{M_j}{M_i} + i\big[R_{\alpha i}R_{\beta j}^*(R^\dagger R)_{ij} - R_{\beta i}^* R_{\alpha j}(R^\dagger R)_{ji}\big]\Big\}\frac{(M_j^2-M_i^2)M_i^2}{(M_j^2-M_i^2)^2+M_i^4\Gamma_j^2/M_j^2}.$$

$$= \frac{\Gamma_i}{2M_i\{(yy^\dagger)_{ii}\}^2} \sum_{j\neq i} \left(\frac{M_i}{M_j}\right)^2 \Big\{ i\big[y_{\alpha i}y_{\beta j}^*(y^\dagger y)_{ji} - y_{\beta i}^* y_{\alpha j}(y^\dagger y)_{ij}\big]\frac{M_j}{M_i} + i\big[y_{\alpha i}y_{\beta j}^*(y^\dagger y)_{ij} - y_{\beta i}^* y_{\alpha j}(y^\dagger y)_{ji}\big]\Big\}\frac{(M_j^2-M_i^2)M_i^2}{(M_j^2-M_i^2)^2+M_i^4\Gamma_j^2/M_j^2}.$$

Active-sterile mixing matrix

$R_{\alpha i} = y_{\alpha i} v/(\sqrt{2}M_i)$

CP asymmetry

: **resonant LG** is adopted for enough BAU in relatively small scale of *M*.

$$\varepsilon^{S(i)}_{\alpha\beta} = \frac{1}{16\pi (yy^\dagger)_{ii}} \sum_{j\neq i} \Big\{ i\big[y^*_{i\alpha} y_{j\beta} (yy^\dagger)_{ji} - y_{i\beta} y^*_{j\alpha} (yy^\dagger)_{ij}\big] \frac{M_j}{M_i} + i\big[y^*_{i\alpha} y_{j\beta} (yy^\dagger)_{ij} - y_{i\beta} y^*_{j\alpha} (yy^\dagger)_{ji}\big] \Big\} \boxed{\frac{(M_j^2 - M_i^2) M_i^2}{(M_j^2 - M_i^2)^2 + M_i^4 \Gamma_j^2 / M_j^2}}$$

$i = 1, 2, 3$, and $\alpha, \beta = e, \mu, \tau$.

Resonant condition

$|M_j - M_i| \simeq \Gamma_j / 2$

(almost degenerate mass of *N* 's)

D_i : Decay term

S_i : Scattering term

W_i : Washout term

$\boxed{\varepsilon^{(i)}_{\alpha\beta}}$: *CP* asymmetry

$N^{eq}_{N_i}$: Equilibrium density

Casas-Ibarra parametrization of Yukawa matrix

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

$\omega_1 = \omega_2 = 0,\ \omega_3 = 0.2 e^{i\pi/4}$ } Complex phase in *R* (source of *CP* violation)

Resonant condition is not satisfied exactly

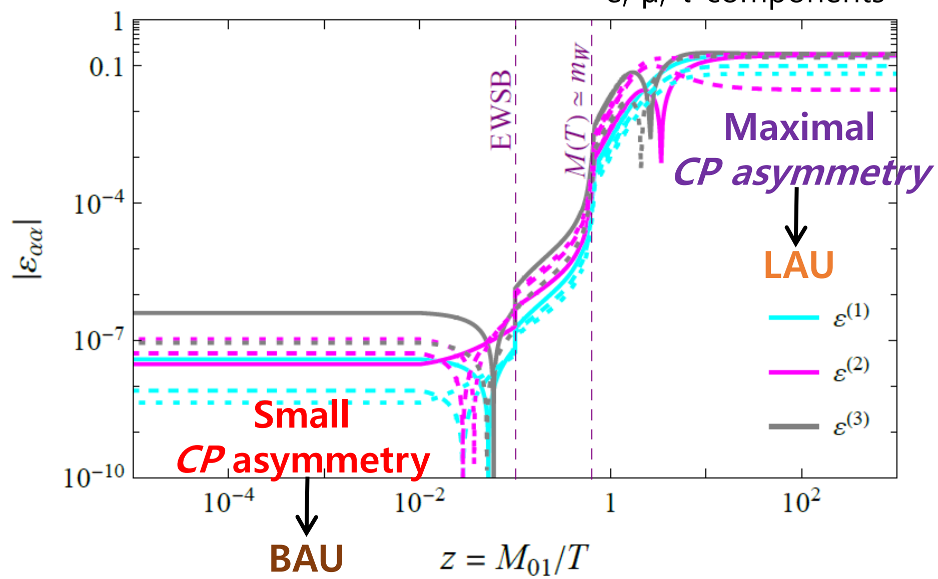
$$\boxed{\begin{aligned} \Delta M^*_{12} &\equiv M_{02} - M_{01} = -2.0 \times 10^{-9}\ \text{eV} \\ \Delta M_{13} &\equiv M_{03} - M_{01} = -2.0 \times 10^{-8}\ \text{eV} \end{aligned}}$$

$$\boxed{\begin{aligned} \Delta M^0_{12} &\equiv M_{02} - M_{01} \simeq \Gamma_2|_{T=T_0}/2 \\ \Delta M^0_{13} &\equiv M_{03} - M_{01} \simeq \Gamma_3|_{T=T_0}/2 \end{aligned}}$$

Resonant condition (exactly)

} 2nd/3rd heavy Neutrino (for resonant LG)

solid, dashed, small-dashed = e, μ, τ components



$$\frac{dN_{N_i}}{dz} = -(D_i + S_i)(N_{N_i} - N_{N_i}^{eq}),$$

$$\frac{dN_{\alpha\beta}}{dz} = \sum_i \left[\varepsilon^{(i)}_{\alpha\beta} D_i (N_{N_i} - N_{N_i}^{eq}) - \frac{1}{2} W_i \{P_i, N\}_{\alpha\beta}\right] - \frac{\Gamma_\tau}{Hz}[I_\tau, [I_\tau, N]]_{\alpha\beta} - \frac{\Gamma_\mu}{Hz}[I_\mu, [I_\mu, N]]_{\alpha\beta},$$

where $z = M_{01}/T$, $i = 1, 2, 3$, and $\alpha, \beta = e, \mu, \tau$.

$T_* = 1$ TeV $(m_\phi \simeq 1.4 \times 10^{-3}$ eV$)$ } Wave DM

$M_{*1} = 40$ TeV
$M_{01} = 10$ GeV } 1st heavy neutrino

$\omega_1 = \omega_2 = 0,\ \omega_3 = 0.2 e^{i\pi/4}$ } Complex phase in *R* (source of *CP* violation)

$\Delta M^*_{12} \equiv M_{02} - M_{01} = -2.0 \times 10^{-9}$ eV
$\Delta M_{13} \equiv M_{03} - M_{01} = -2.0 \times 10^{-8}$ eV
$\Delta M^0_{12} \equiv M_{02} - M_{01} \simeq \Gamma_2|_{T=T_0}/2$
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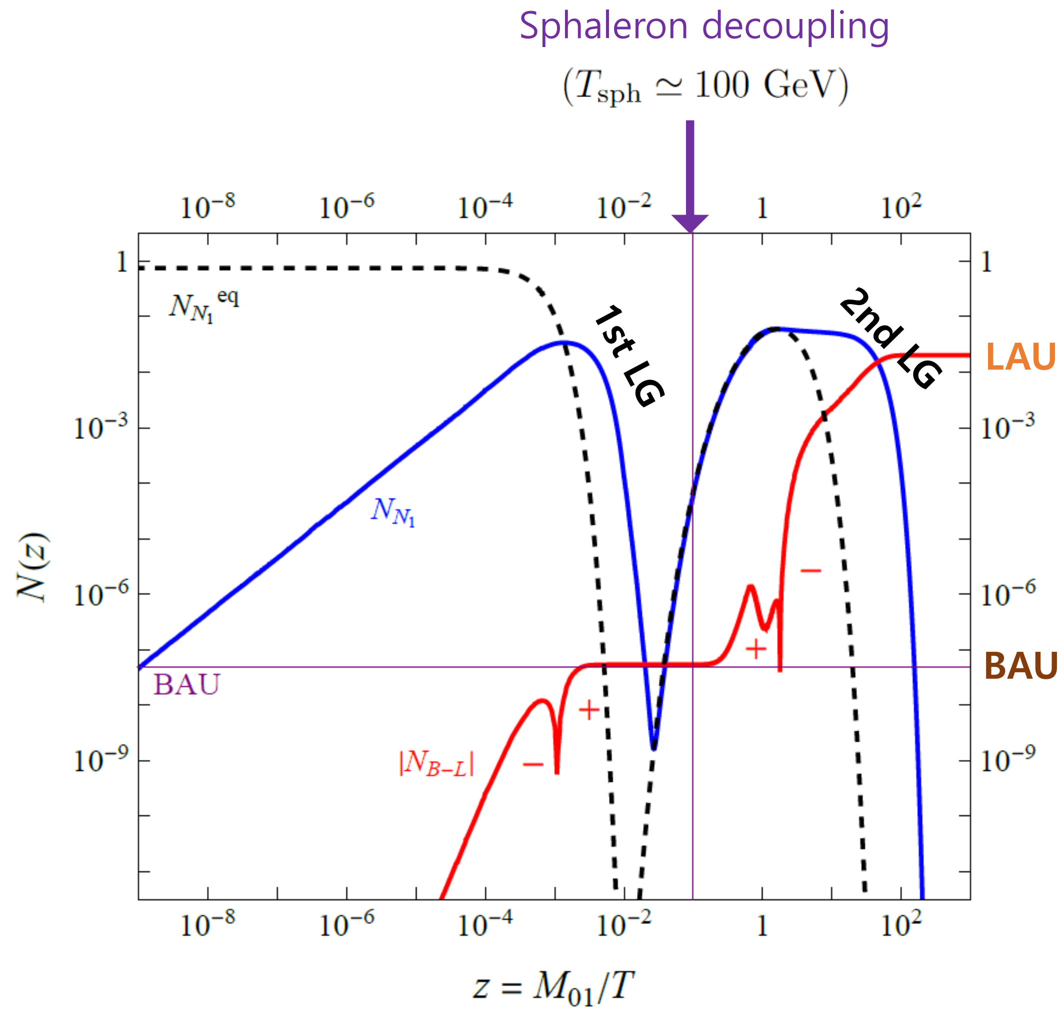
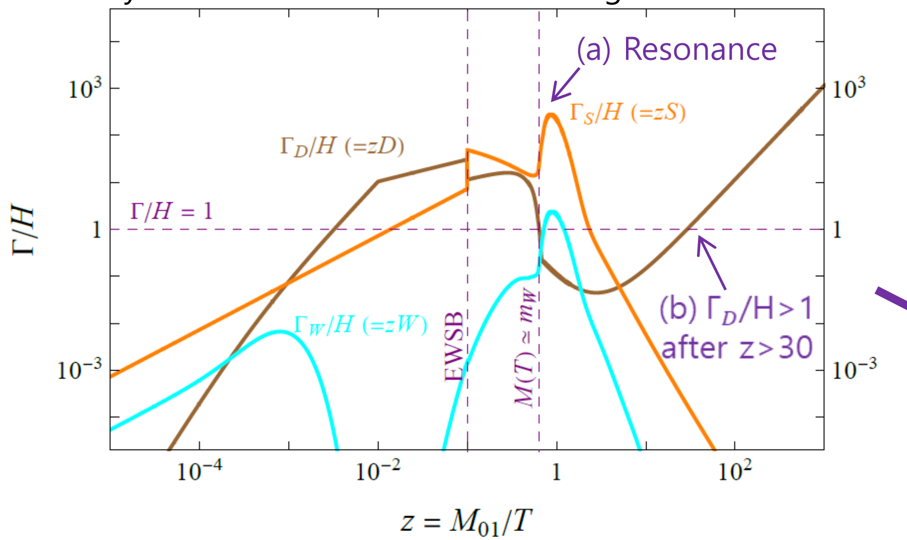
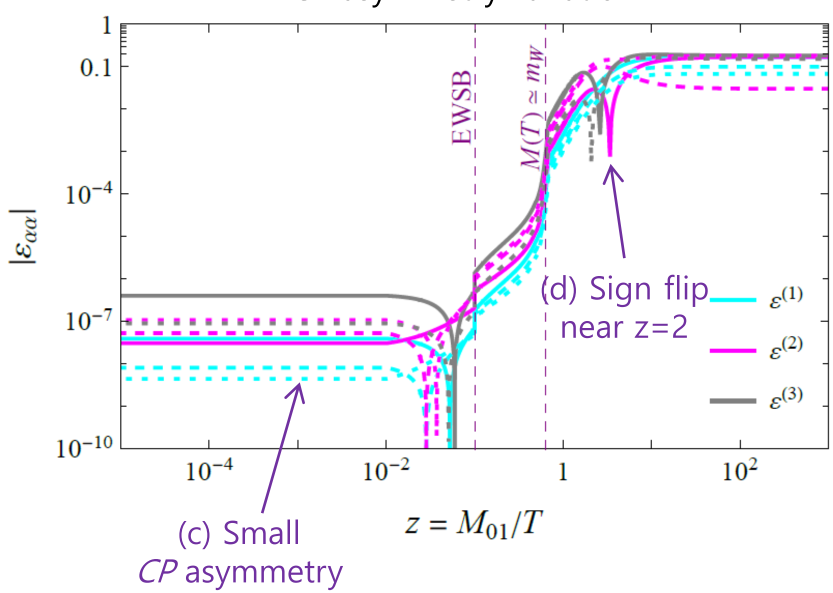
} 2nd/3rd heavy Neutrino (for resonant LG)

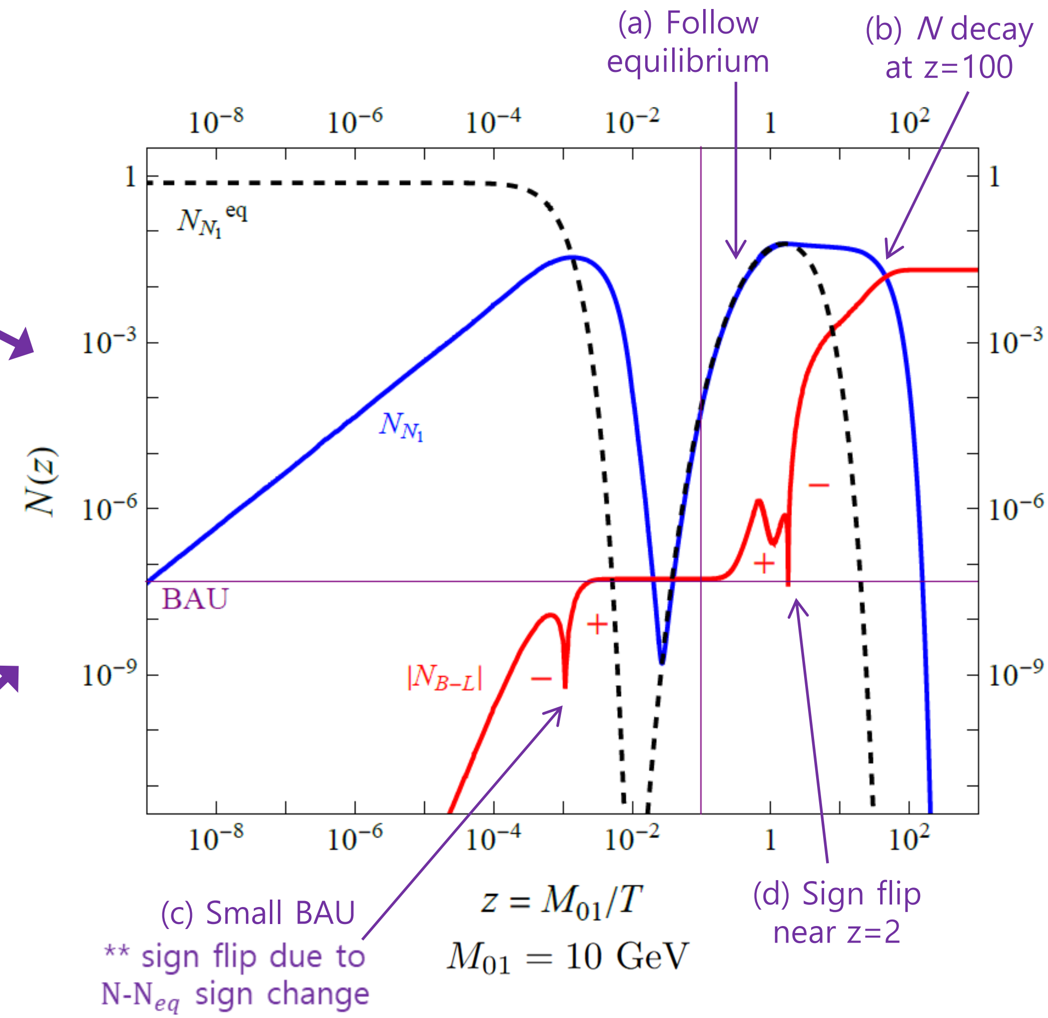


Decay channel alternation & Scattering channel resonance



CP asymmetry variation





Photon dilution and Sphaleron factors

$$f = \frac{n_\gamma(t)}{n_\gamma(t_*)} = \frac{g_*^s(T_*)}{g_*^s(T)}$$

Photon number increases by the annihilation process of the particles.

$$g(T_{*,1}) = 106.75\ (\mathrm{SM}) + \frac{7}{8}\cdot 3\cdot 2\ (3N) = 112$$

$$g(T_{*,2}) = 2\ (\gamma) + \frac{7}{8}\cdot 2\cdot 2\ (e) + \frac{7}{8}\cdot 3\cdot 2\ (\nu) + \frac{7}{8}\cdot 3\cdot 2\ = 16$$

$$g(T_{\mathrm{BBN}}) = 2\ (\gamma) + \frac{7}{8}\cdot 3\cdot 2\cdot \left(\frac{T_\nu}{T_\gamma}\right)^3\ (\nu) = \frac{43}{11}$$

$f = 1232/43$ Photon dilution from 1st LG to BBN

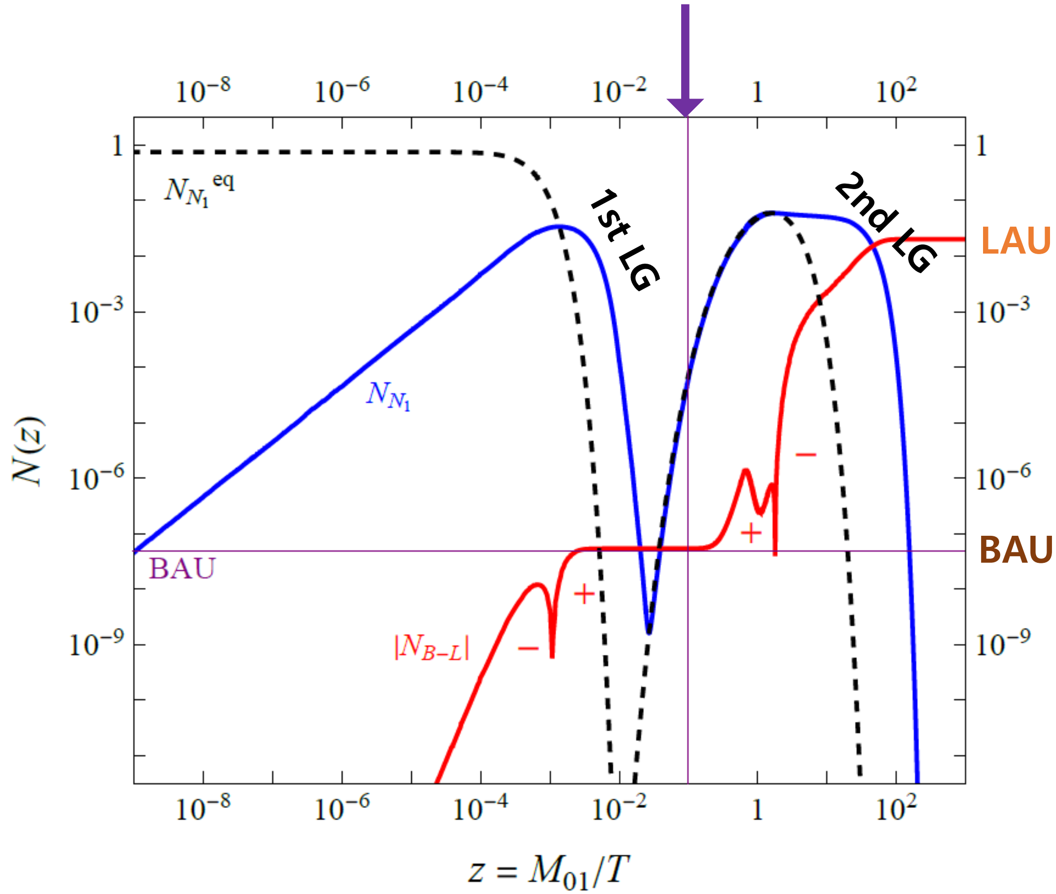
$f' = 176/43$ Photon dilution from 2nd LG to BBN

$$a_{\mathrm{sph}} = \frac{8N_F + 4N_\phi}{22N_F + 13N_\phi} = 28/79$$

Sphaleron factor (with the # of fermion generations & Higgs doublets)

Sphaleron decoupling

$(T_{\mathrm{sph}} \simeq 100\ \mathrm{GeV})$



$$\eta_B = \frac{a_{\mathrm{sph}}}{f} N_{B-L} \simeq \boxed{6.14\times 10^{-10}}\ \textbf{BAU}$$

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

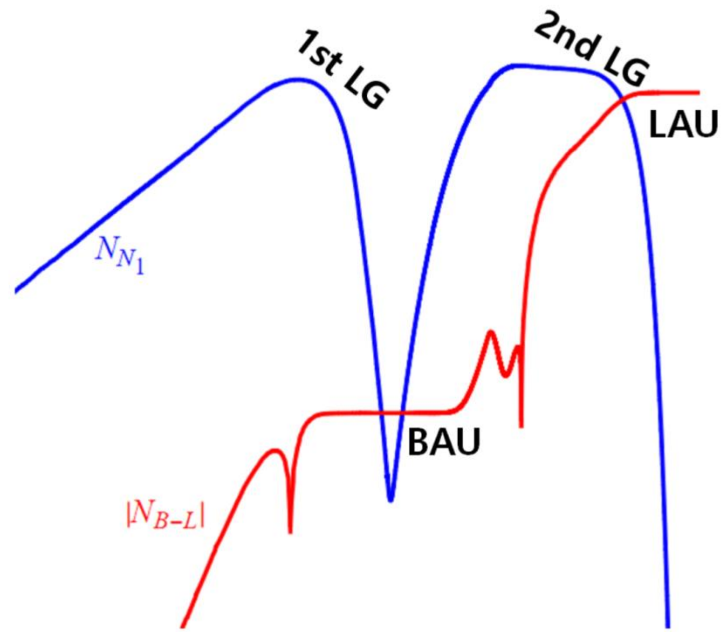
$$\eta_L = \frac{1}{f'} N_{B-L} \simeq \boxed{0.85\times 10^{-3}}\ \textbf{LAU}$$

$$\eta_L \equiv \frac{n_L - n_{\bar L}}{n_\gamma} \simeq (7.5^{+4.5}_{-3.0})\times 10^{-2}$$

Slightly smaller than desired value

Summary

- The **temperature-dependent mass** of the heavy Majorana neutrino by using wave DM provides the **second leptogenesis** with two moments of production and decay of N.
- The second leptogenesis can explain the **baryon-lepton asymmetry discrepancy** of the universe if the sphaleron decoupling appears between 1st and 2nd LG.



"Second Leptogenesis"

Thank You!