Dirac-Majorana neutrino type oscillation induced by a wave dark matter

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based on [arXiv: 2305.16900]

with YeolLin ChoeJo and Hye-Sung Lee

Unknown in Neutrino Physics

Neutrino oscillation parameters $\theta_{23} > \pi/4, \text{ or } < \pi/4$ $\Delta m_{13} > 0, \text{ or } < 0$

CP violation in PMNS δ_{CP}

Neutrino absolute mass m_ν

Sterile neutrino ν_4

…

Neutrino is

Dirac type or **Majorana type** ?

$\nu \neq \bar{\nu}$ $\nu = \bar{\nu}$

Dirac mass　　Majorana mass

$$\mathcal{L} = \boxed{- m_D \bar{\nu}_D \nu_D} \boxed{- \frac{1}{2} m_R \, \bar{\nu}_M \nu_M}$$

$\nu_D = \nu_L + \nu_R$

$\nu_M = \nu_R + \nu_R^c$
$(\nu_M = \nu_M^c)$

Majorana type $\nu = \bar{\nu}$
$(m_D \ll m_R)$

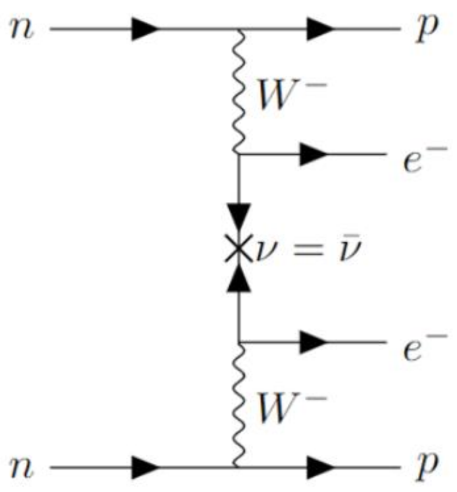
Seesaw mechanism

(for small m_ν)

$$m_\nu = -\frac{m_D^2}{m_R}$$

Neutrinoless double beta decay

(as LNV process)



Leptogenesis

(for BAU)

$$\Gamma(N_i \to \ell\Phi) - \Gamma(N_i \to \bar{\ell}\Phi^\dagger)$$

(N_i is mass eigenstate)

Dirac mass Majorana mass

$$\mathcal{L} = \boxed{-\, m_D \bar{\nu}_D \nu_D} \boxed{-\, \frac{1}{2} m_R \, \bar{\nu}_M \nu_M}$$

$\nu_D = \nu_L + \nu_R$

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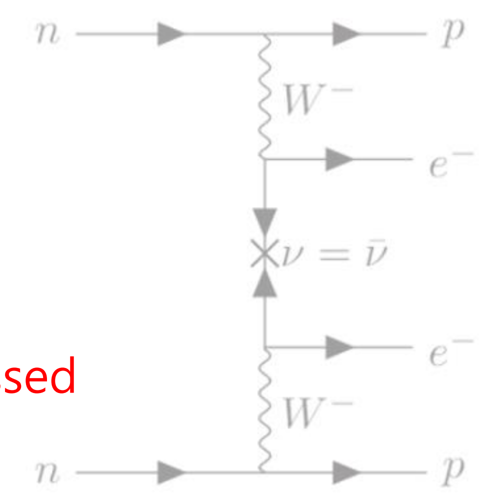
Neutrinoless double beta decay



Also, LNV is suppressed

Leptogenesis

(for BAU)

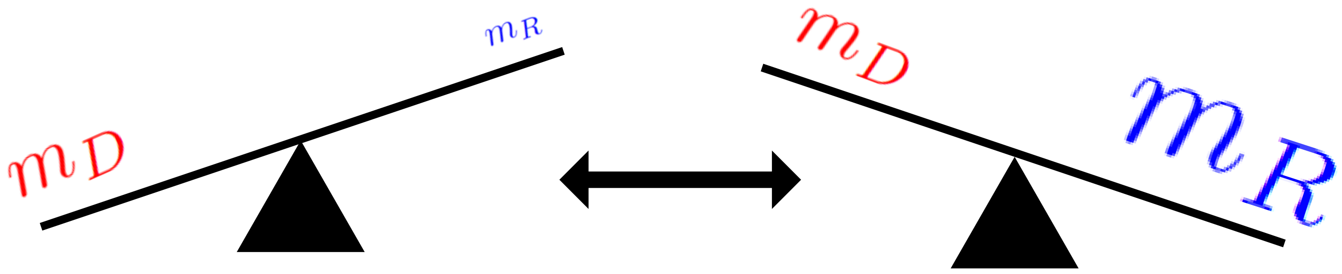
$$\Gamma(N_i \to \ell\Phi) - \Gamma(N_i \to \bar{\ell}\Phi^\dagger)$$

Quasi-Dirac type

$(m_D \gg m_R)$

Neutrino is still Majorana spinor $\nu = \bar{\nu}$

But it behaves like Dirac spinor



Quasi-Dirac type

Majorana type

“Dirac-Majorana neutrino type oscillation”

Wave dark matter ϕ has an oscillating scalar behavior.

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

$T = 2\pi/m_\phi = \mathcal{O}(\mathrm{ps}) \sim \mathcal{O}(\mathrm{year})$

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

Sol: $\phi(t) = \frac{\sqrt{2\rho_\phi}}{m_\phi} \cos m_\phi t$

Neutrino mass variation

$\mathcal{L} \supset -g\phi\bar\nu\nu + h.c.$

$\rightarrow m_\nu(t) = g\frac{\sqrt{2\rho_\phi}}{m_\phi} \cos m_\phi t$

[A. Berlin (2016),
Y. Zhao (2017),
G. Krnjaic et al (2017),
V. Brdar et al (2017) …]

(Effects on neutrino flavor oscillation, etc)

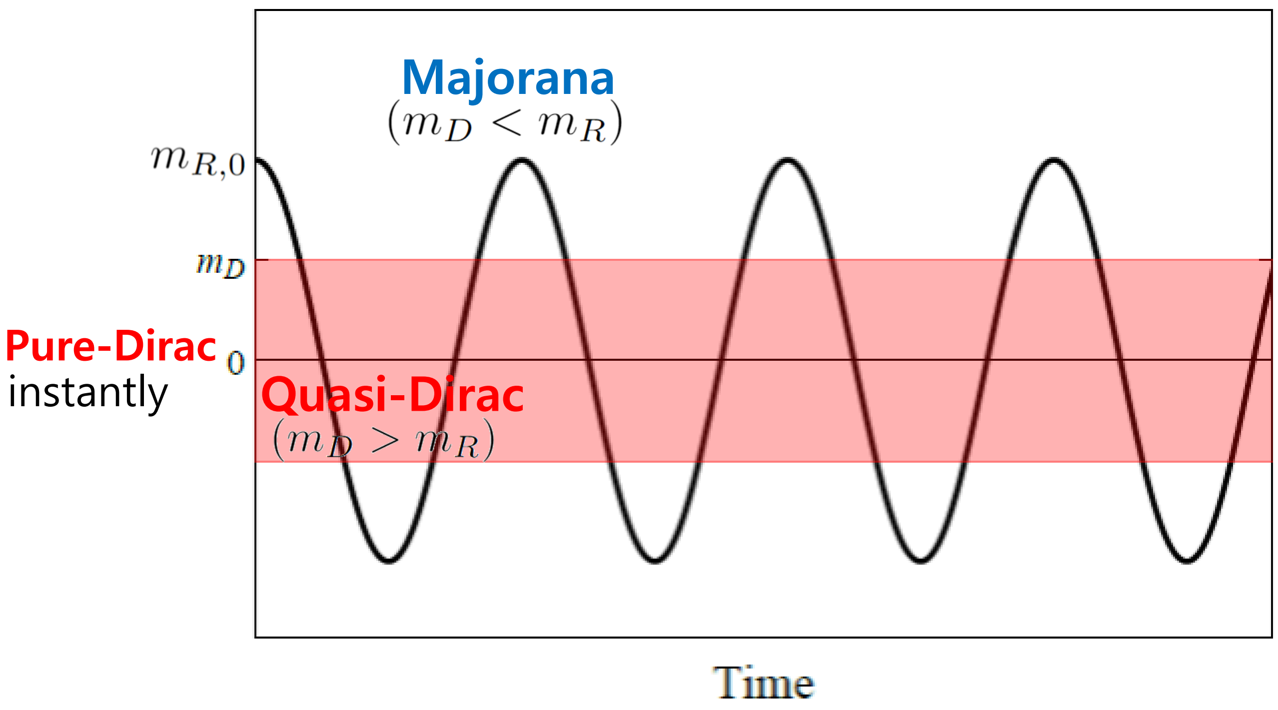
$$\mathcal{L} = -yHLN - g\,\phi NN + h.c.$$

$$m_D = \frac{yv}{\sqrt{2}}$$

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

where $m_{R,0} = g\frac{\sqrt{2\rho_\phi}}{m_\phi}$

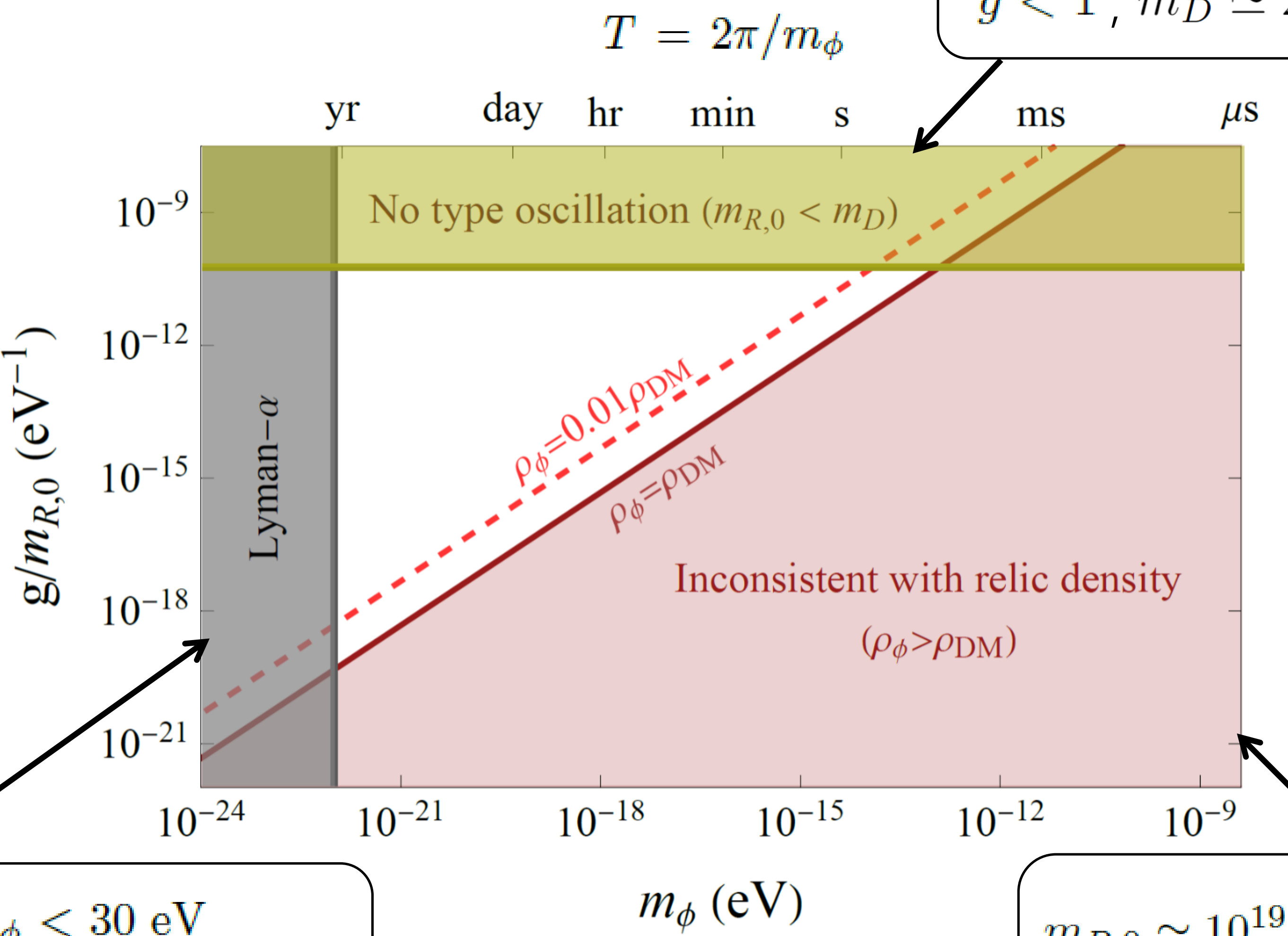
$$m_R(t) = m_{R,0}\cos m_\phi t$$



Constraints & Disfavored region

Disfavored region of type oscillation

$g < 1\,,\ m_D \simeq 246\ \mathrm{GeV}$



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

Constraint on wave DM mass

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

Constraint on DM relic density

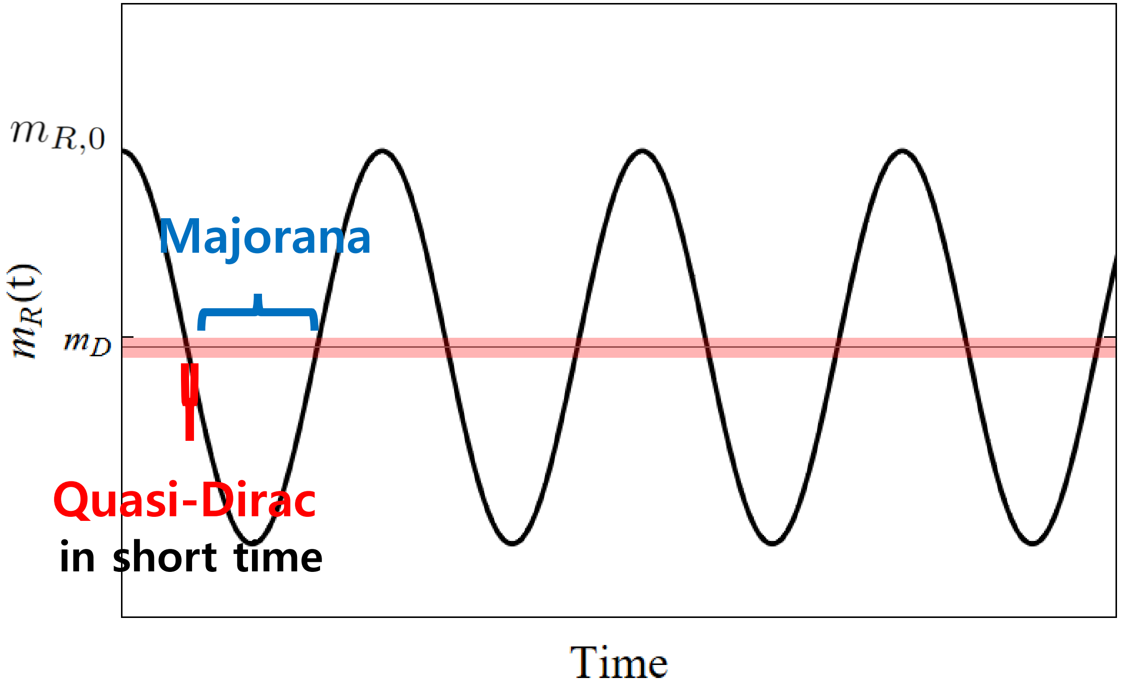
Neutrino mass variation → Neutrino-related physics (flavor oscillation, cosmological observables, etc)

Ex) Active neutrino mass

$$m_\nu \simeq m_D \qquad \longleftrightarrow \qquad m_\nu \simeq -\frac{m_D^2}{m_R}$$

~~Seesaw~~ ⟷ Seesaw

Quasi-Dirac type — Majorana type



Time average

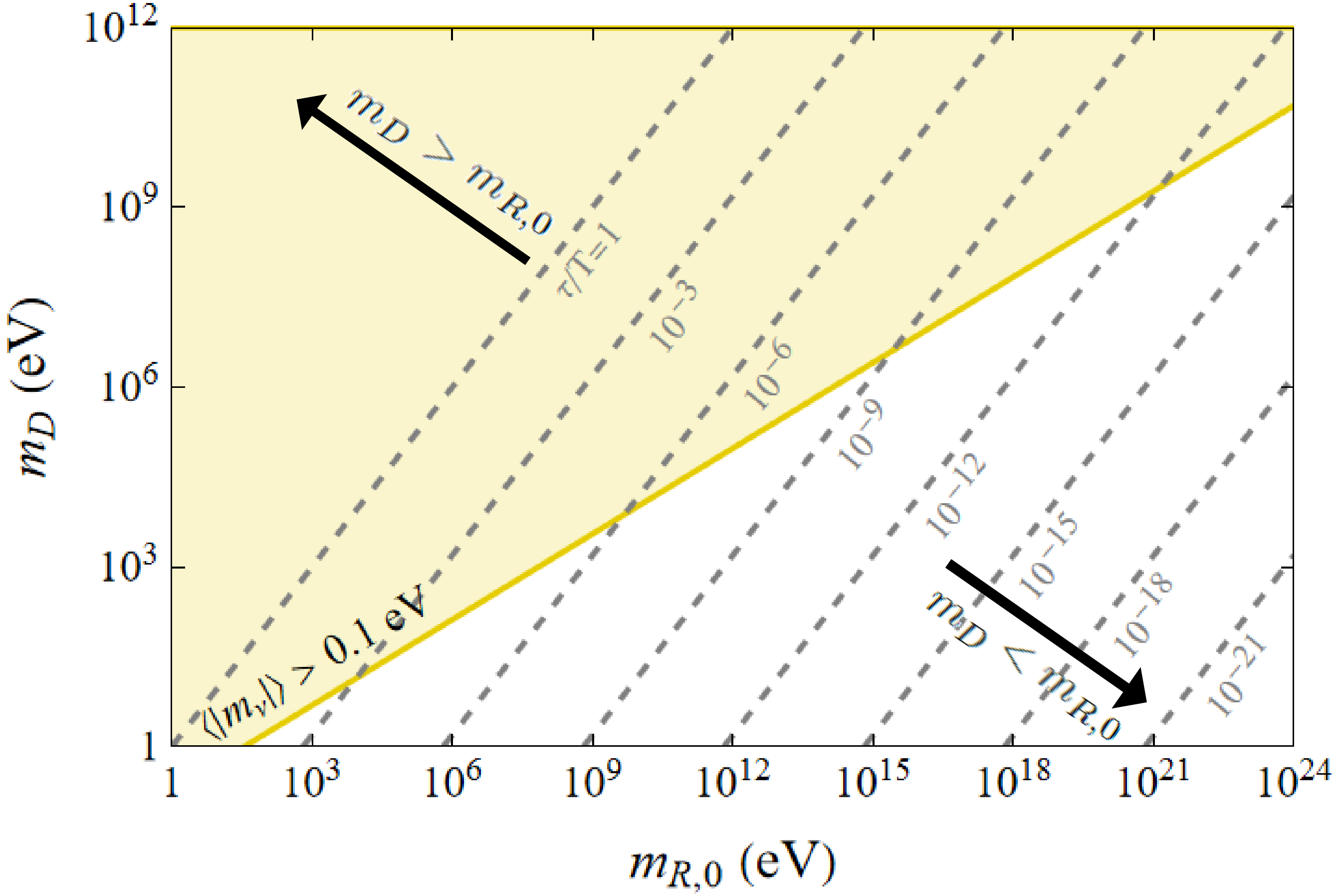
$$\langle |m_\nu| \rangle = \frac{1}{T}\int_0^T |m_\nu(t)| dt < 0.1 \text{ eV}$$

Mass bound
from CMB/ ^3H decay

Quasi-Dirac time ratio τ/T

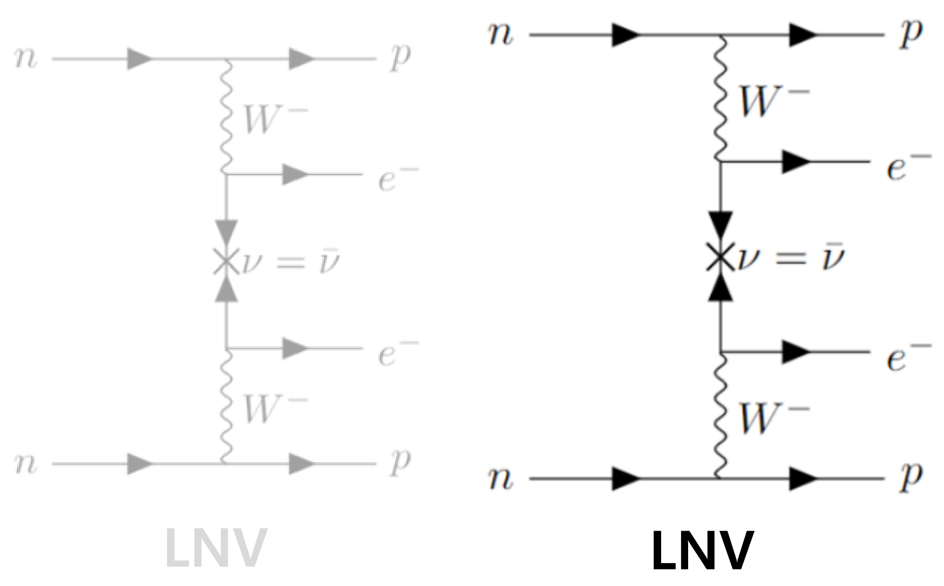
$$\frac{\tau}{T} = 1 \qquad \text{for } m_D > m_{R,0}$$

$$\frac{m_D}{m_{R,0}} = \sin\left(\frac{\pi}{2}\frac{\tau}{T}\right) \qquad \text{for } m_D < m_{R,0}$$



Time-averaged quantity < Known bound ➔ Quasi-Dirac type in only short time

Neutrinoless double beta ($0\nu\beta\beta$) decay



Quasi-Dirac type ⟷ Majorana type

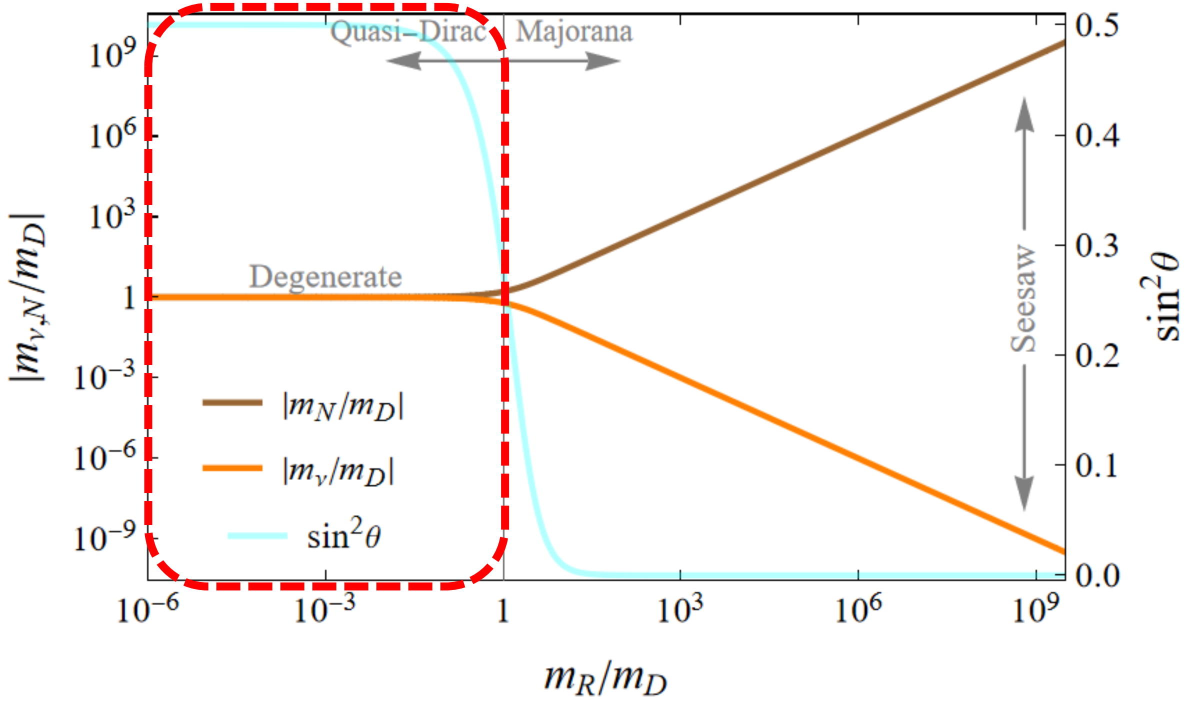
$$\Gamma_{0\nu\beta\beta} \propto \mathcal{A}^2 = \left|\sum_i U_{ei}^2 m_i \mathcal{M}(m_i)\right|^2$$

Ex) single-flavor case:

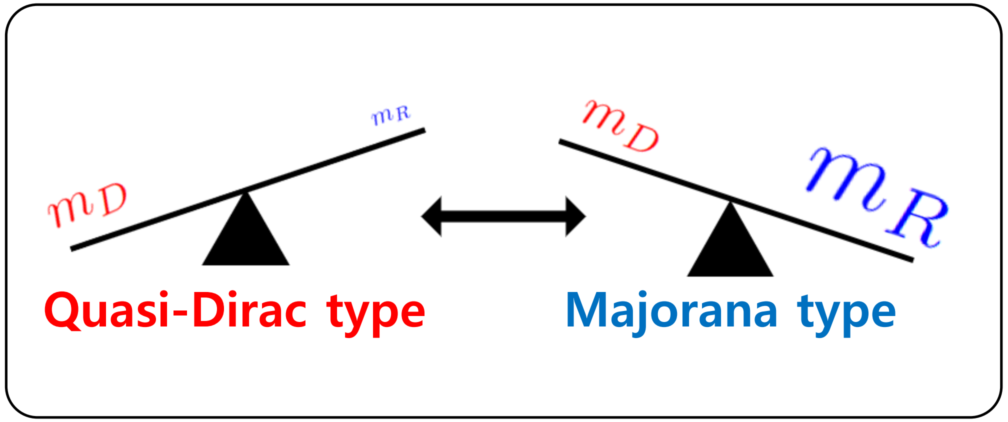
$$\mathcal{A} = \left| m_\nu \cos^2\theta\, \mathcal{M}(m_\nu) + m_N \sin^2\theta\, \mathcal{M}(m_N) \right|$$

$|m_\nu| \simeq |m_N|$, $\cos^2\theta \simeq \sin^2\theta$ in quasi-Dirac limit

→ $\mathcal{A}$ is strongly suppressed

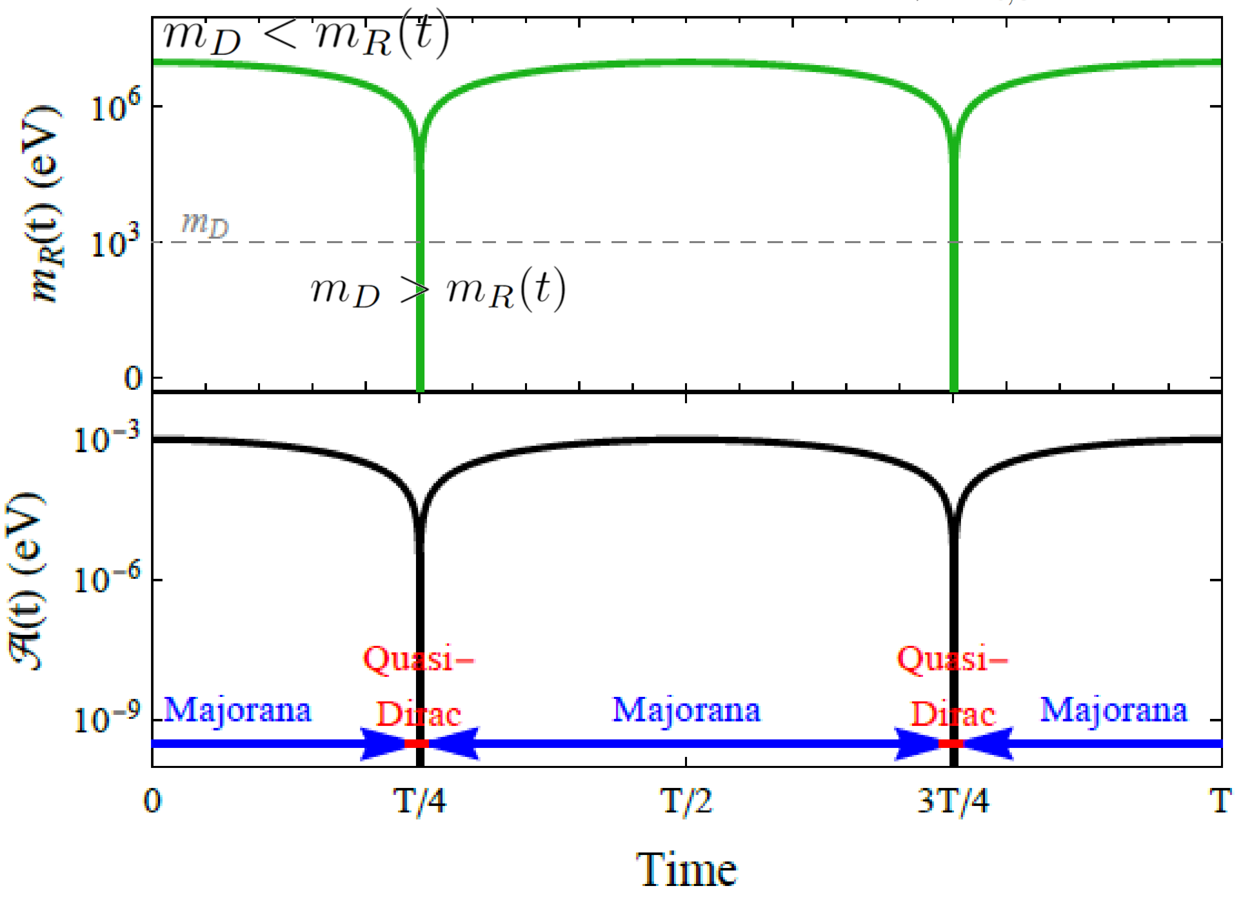


Neutrino type oscillation



Turn-on/off behavior of 0νββ decay

$m_D = 10^3$ eV, $m_{R,0} = 10^7$ eV



Neutrino type oscillation ➔ Modulation behavior

* Other process: Cosmic neutrino background (CνB) $\Gamma^M_{C\nu B} = 2\Gamma^D_{C\nu B}$

Leptogenesis (LG)

Heavy Majorana neutrino decay (N_i is mass eigenstate)

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

Lepton asymmetry

Sphaleron process

(B-L is conserved)

Baryon asymmetry of the universe (BAU)

$$\eta_B = \frac{n_B - n_{\bar{B}}}{n_\gamma} \sim \mathcal{O}(10^{-10})$$

CP asymmetry

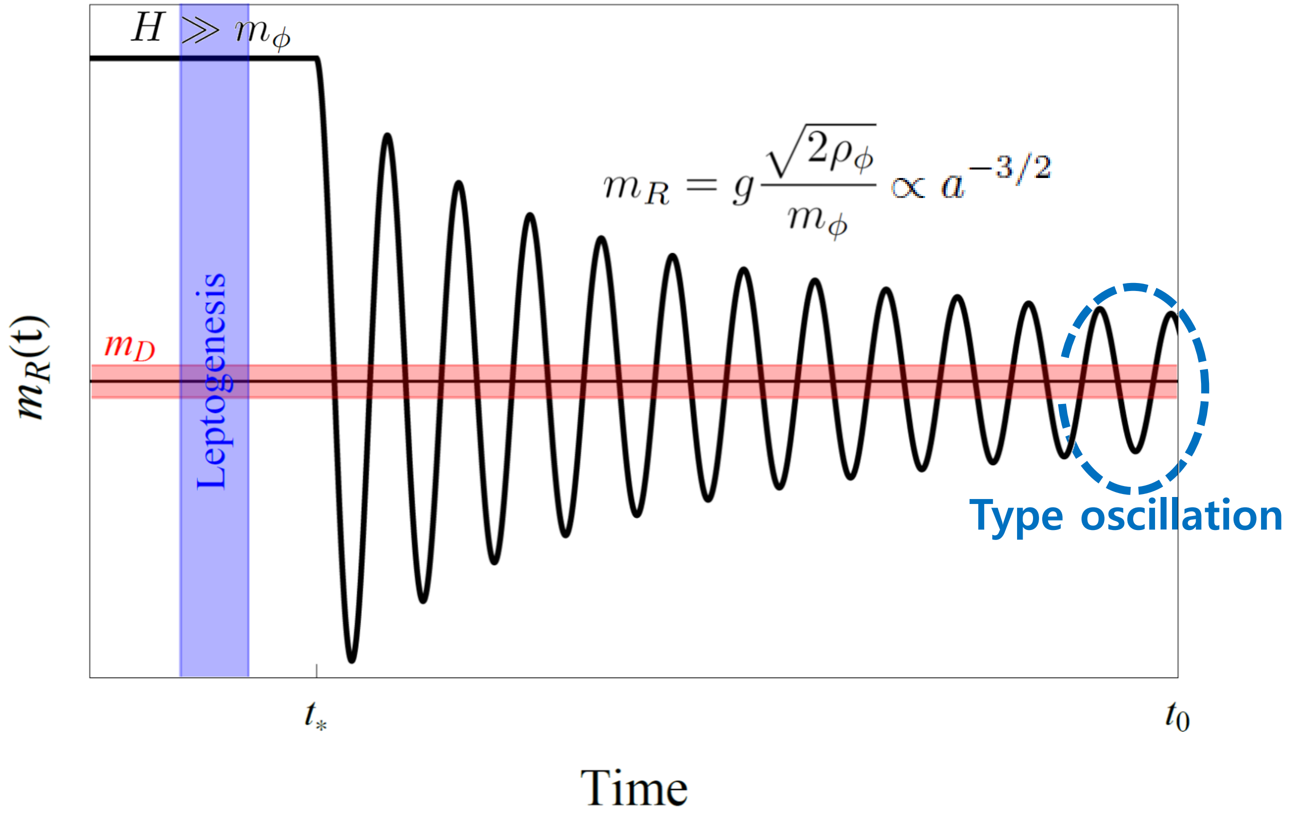
$$\epsilon_i = \frac{\Gamma(N_i \to \ell\Phi) - \Gamma(N_i \to \bar{\ell}\Phi^\dagger)}{\Gamma(N_i \to \ell\Phi) + \Gamma(N_i \to \bar{\ell}\Phi^\dagger)} \approx 10^{-6}$$ for observed BAU

→ Majorana mass scale is important parameter in leptogenesis

$$m_R \xrightarrow{m_R = g\frac{\sqrt{2\rho_\phi}}{m_\phi} \propto a^{-3/2}} m_R$$

Early universe — Present

LG — Type oscillation



→ Link between early universe and present-time

$$\frac{m_{R,*}}{m_{R,0}} \simeq 10^{11} \left(\frac{m_\phi}{10^{-22}\ \mathrm{eV}} \right)^{3/4}$$

Ex) $m_\phi = 10^{-22}\ \mathrm{eV}$

$m_{R,*} = 10^{15}\ \mathrm{GeV} \rightarrow m_{R,0} = 10\ \mathrm{TeV}$

(GUT) (Testable scale)

Casas-Ibarra parametrization

$$y = \sqrt{2}\hat{M}_N^{1/2} R \hat{M}_\nu^{1/2} U_{\mathrm{PMNS}}^\dagger / v, \quad R = \begin{pmatrix} 0 & \cos z & \sin z \\ 0 & -\sin z & \cos z \end{pmatrix}$$

$\downarrow$

$$y \propto \sqrt{m_{R,0}}$$

Yukawa matrix is proportional to the current Majorana mass.

***CP* asymmetry**

$$\epsilon_i \propto \sum_{k \neq i} \frac{\mathrm{Im}(y^\dagger y)_{ik}^2}{(y^\dagger y)_{ii}(y^\dagger y)_{kk}} \frac{(M_i^2 - M_k^2) M_i \Gamma_k}{(M_i^2 - M_k^2)^2 + M_i^2 \Gamma_k^2}$$

Resonance by the degenerate mass spectrum

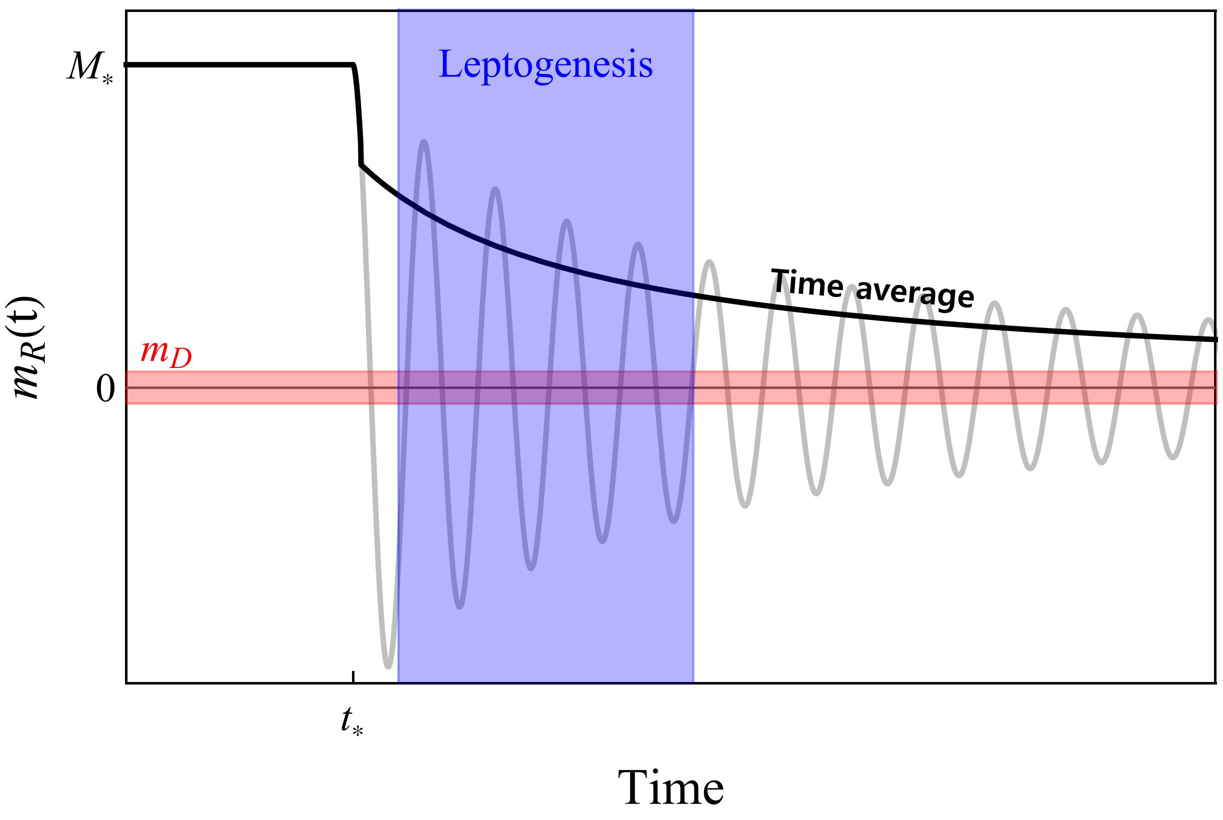
($M \simeq m_R$ is mass eigenvalue)

➔ **The current Majorana mass scale is testable, but it requires the resonant leptogenesis.**

Leptogenesis with the **Neutrino mass variation** *(ongoing project)*

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

If wave DM oscillation starts earlier than leptogenesis…



… the behavior of leptogenesis can be changed.

Ex) Production rate of heavy neutrino gets

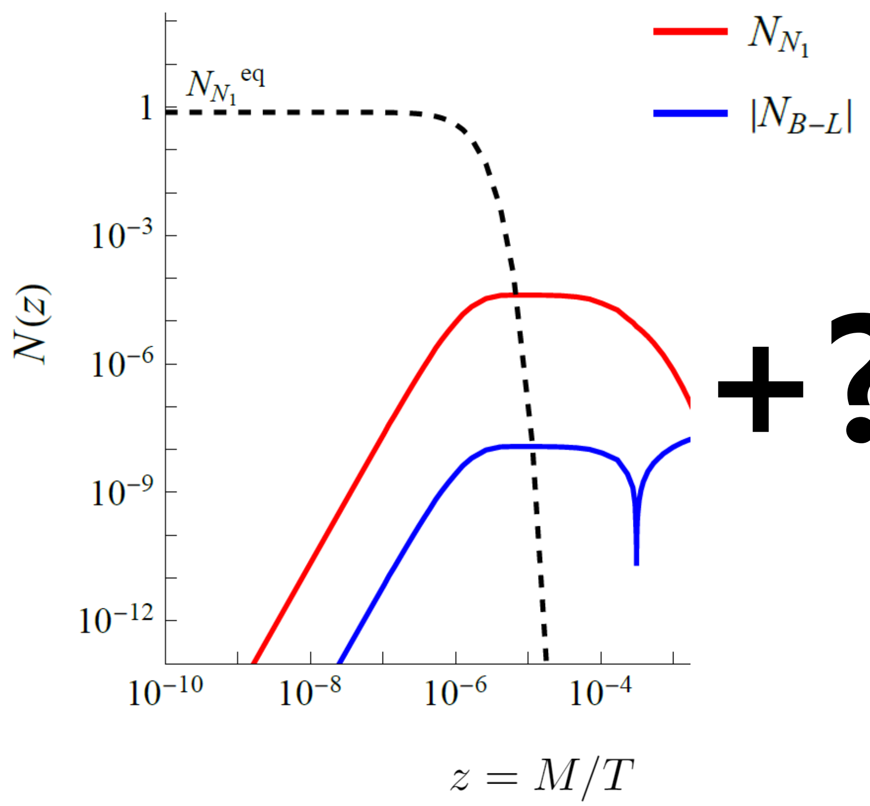
$\Gamma_{\mathrm{prod}} \propto e^{-M/T}$ with $M \propto a^{-3/2}$

Boltzmann equations

$$\frac{\mathrm{d}N_{N_1}}{\mathrm{d}z} = -D(N_{N_1} - N_{N_1}^{\mathrm{eq}}),$$
$$\frac{\mathrm{d}N_{B-L}}{\mathrm{d}z} = -\epsilon_1 D(N_{N_1} - N_{N_1}^{\mathrm{eq}}) - W N_{B-L}$$

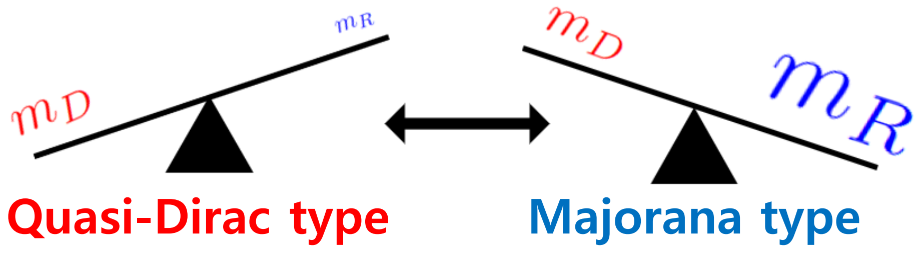
Plug the mass varying effect

(ongoing project)



+?

Summary



- The ratio of the Dirac/Majorana masses can changes in time if they arise from the wave dark matter. It provides "**Dirac-Majorana neutrino type oscillation**."
- Quasi-Dirac moment should be short to explain the small neutrino mass by the seesaw mechanism.
- The neutrino type oscillation predicts the modulation behavior of lepton number violation (LNV) process like as $0\nu\beta\beta$ decay.
- There is interesting connection between early universe physics and present-time physics because the mass scale decreases over time.
- The heavy neutrino mass is important parameter in leptogenesis, so the neutrino mass variation scenario may change the behavior of leptogenesis.

Backup Slides

Dirac/Majorana spinors formalism

$$\mathcal{L} = -yHLN - MNN + h.c.$$

Dirac neutrino $\nu_D = \nu_L + \nu_R$

Majorana neutrino $\nu_M = \nu_R + \nu_R^c$

Dirac mass term Majorana mass term

$$\mathcal{L} = \boxed{- m_D \bar{\nu}_D \nu_D} \boxed{- \frac{1}{2} m_R \bar{\nu}_M \nu_M}$$

$$= -\frac{1}{2} \begin{pmatrix} \bar{\nu}_L & \bar{\nu}_R^c \end{pmatrix} \begin{pmatrix} 0 & m_D \\ m_D & m_R \end{pmatrix} \begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix} + h.c.$$

light/heavy mass eigenvalues:

$$m_{l,h} = \frac{1}{2}\left(m_R \mp \sqrt{m_R^2 + 4m_D^2}\right)$$

light/heavy mass eigenstates:

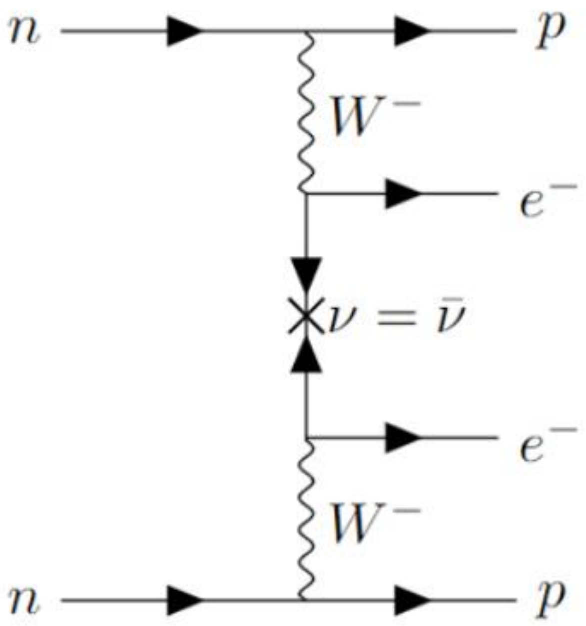
$$\begin{pmatrix} \nu_l \\ \nu_h \end{pmatrix} = \begin{pmatrix} \cos\theta_{LR} & \sin\theta_{LR} \\ -\sin\theta_{LR} & \cos\theta_{LR} \end{pmatrix} \begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix} + h.c.$$

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

Quasi-Dirac & Majorana limits

	Pure Dirac case $(m_R = 0)$	Quasi-Dirac limit $(m_D \gg m_R)$	Majorana limit $(m_D \ll m_R)$
Mass eigenvalues	$\lvert m_{l,h} \rvert = m_D$	$\lvert m_{l,h} \rvert \simeq m_D(1 \mp 2\delta)$ where $\delta = m_R/4m_D$	$\boxed{m_l \simeq -\frac{m_D^2}{m_R}}$, $m_h \simeq m_R$ Seesaw mechanism
Mixing angle	$\sin^2\theta_{LR} = \frac{1}{2}$	$\sin^2\theta_{LR} \simeq \left(\frac{1-\delta}{\sqrt{2}}\right)^2$	$\sin^2\theta_{LR} \simeq \left(\frac{m_D}{m_R}\right)$
Mass eigenstates	$\nu_{l,h} = \frac{1}{\sqrt{2}}\left((\nu_L + \nu_L^c) \pm (\nu_R + \nu_R^c)\right)$	$\nu_{l,h} \simeq \pm\frac{1 \pm \delta}{\sqrt{2}}(\nu_L + \nu_L^c) + \frac{1 \mp \delta}{\sqrt{2}}(\nu_R + \nu_R^c)$	$\nu_l \simeq \nu_L + \nu_L^c,\ \nu_h \simeq \nu_R + \nu_R^c$
Mass term	$\frac{1}{2}(m_l\bar{\nu}_l\nu_l + m_h\bar{\nu}_h\nu_h) = m_D\bar{\nu}_D\nu_D$	$\frac{1}{2}(m_l\bar{\nu}_l\nu_l + m_h\bar{\nu}_h\nu_h) \simeq m_D\bar{\nu}_D\nu_D + \mathcal{O}(\delta)$	$\frac{1}{2}(m_l\bar{\nu}_l\nu_l + m_h\bar{\nu}_h\nu_h)$

Neutrinoless double beta decay (0νββ): only for massive Majorana neutrinos



$$\Gamma_{0\nu\beta\beta} \propto \mathcal{A}^2$$

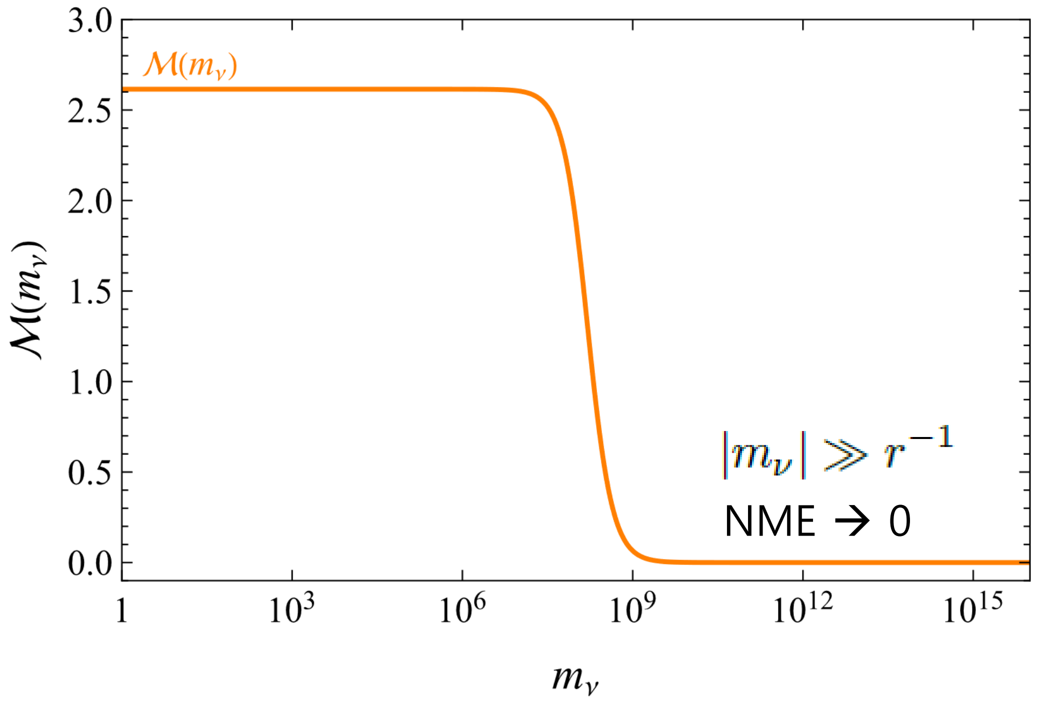
$$\mathcal{A} = \left| \sum_i \underline{U_{ei}^2} m_i \underline{\mathcal{M}(m_i)} \right|$$

Extended PMNS matrix

Nuclear matrix element (NME)

$$\mathcal{M}(m_\nu) = m_p m_e \frac{|\mathcal{M}_N^{0\nu}|}{\langle p \rangle^2 + m_\nu^2}$$

$$\text{where } \langle p \rangle^2 = m_p m_e \left| \frac{\mathcal{M}_N^{0\nu}}{\mathcal{M}_\nu^{0\nu}} \right|$$



r : inter-nucleon distance (fm)

Single-flavor case:

$$\mathcal{A} = \left| m_l \cos^2\theta_{LR} \mathcal{M}(m_l) + m_h \sin^2\theta_{LR} \mathcal{M}(m_h) \right|$$

Majorana limit in the most of the time:

$\sin^2\theta_{LR} \simeq 0$, $\mathcal{M}(m_h) \simeq 0$ → 0νββ bound is reduced into $\langle |m_l| \rangle$ bound

Three-flavors case: $\mathcal{A} = \left| \sum_i U_{ei}^2 m_i \mathcal{M}(m_i) \right|$

Mixing matrix element

$$U_{e1} = \cos\theta_{13}\cos\theta_{12}\cos\theta_{LR}^{11}$$
$$U_{e2} = \cos\theta_{13}\sin\theta_{12}\cos\theta_{LR}^{22}$$
$$U_{e3} = \sin\theta_{13}\cos\theta_{LR}^{33}$$
$$U_{e4} = \cos\theta_{13}\cos\theta_{12}\sin\theta_{LR}^{11}$$
$$U_{e5} = \cos\theta_{13}\sin\theta_{12}\sin\theta_{LR}^{22}$$
$$U_{e6} = \sin\theta_{13}\sin\theta_{LR}^{33}$$

Three pairs of light/heavy mass term → $\mathcal{A}$ is suppressed in quasi-Dirac limit

Observed BAU

$$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma} = 6.21 \cdot 10^{-10}$$

Sphaleron process (above EWPT):

B-L is conserved, but *B+L* is violated.

Leptogenesis: Heavy Majorana neutrino decay → lepton asymmetry → B-L asymmetry

CP asymmetry

$$\epsilon_i = \frac{\Gamma(N_i \to \ell\Phi) - \Gamma(N_i \to \bar{\ell}\Phi^\dagger)}{\Gamma(N_i \to \ell\Phi) + \Gamma(N_i \to \bar{\ell}\Phi^\dagger)} \approx 10^{-6}$$ for observed BAU

notation

$N \equiv \nu_h,\ M \equiv m_h$

$$\epsilon_i \propto \sum_{k \neq i} \frac{\mathrm{Im}(y^\dagger y)^2_{ik}}{(y^\dagger y)_{ii}(y^\dagger y)_{kk}} \frac{(M_i^2 - M_k^2)M_i\Gamma_k}{(M_i^2 - M_k^2)^2 + M_i^2\Gamma_k^2}$$

1) Minimal leptogenesis

$M_1 \ll M_{2,3}$ → $\epsilon_1 \propto M_1$

Lower bound: $M_1 > 10^9$ GeV

2) Resonant leptogenesis

Nearly degenerate M_i's

Mass bound can be lowered down to TeV