Dark matter from split seesaw (review)

The first B-E group joint meeting for young researchers @ Kobe Univ.

Nov. 22, 2016

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I introduce

“Dark matter from split seesaw”

A. Kusenko, F. Takahashi and T. Yanagida, Phys. Lett. B **693** (2010) 144 [arXiv/hep-ph:1006.1731].

○ Contents

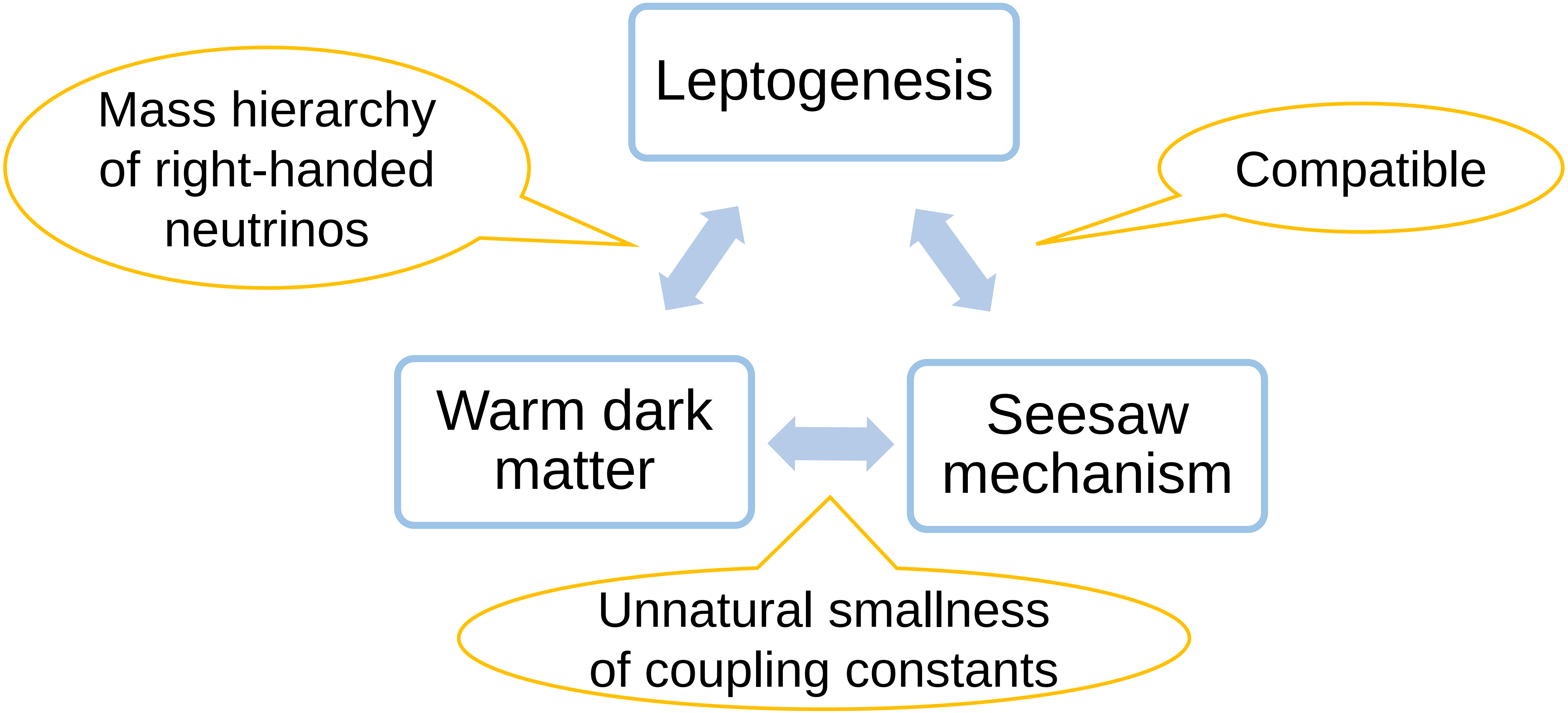
- Leptogenesis model
  (introduced three right-handed neutrinos, Higgs boson
  and B-L symmetry)

- The lightest right-handed neutrino fills the role of dark matter.
  $\rightarrow O($keV

◯ Motivation

1. Leptogenesis
2. Seesaw mechanism
3. Warm dark matter
4. Natural mass hierarchy & smallness of Yukawa couplings

“Dark matter from split seesaw”



Warm dark matter ⟷ Leptogenesis

1, Angular momentum problem
2, Satellite galaxy problem
3, Core-cups problem

Warm dark matter

$$M_{N_1} \sim \mathcal{O}(\mathrm{keV})$$

Second and third lightest right-handed neutrinos

$$M_{R2}, M_{R3} > \mathcal{O}(10^{11-12})\mathrm{GeV}$$

$$M_{R1} \ll M_{R2}, M_{R3}$$

Unnatural

Warm dark matter

Seesaw mechanism

1, Angular momentum problem
2, Satellite galaxy problem
3, Core-cups problem

Warm dark matter

$$M_{N_1} \sim \mathcal{O}(\mathrm{keV})$$

Seesaw formula

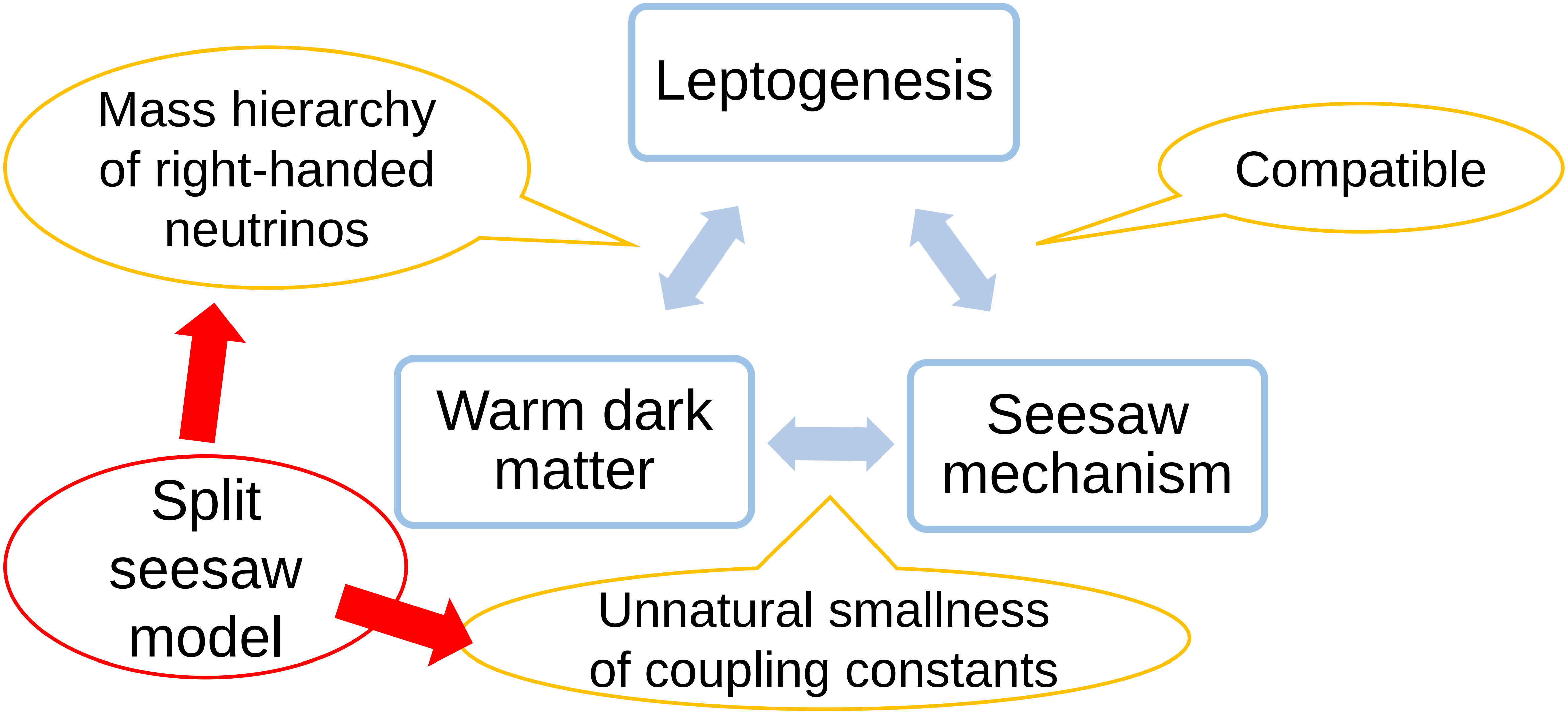
$$(m_\nu)_{\alpha\beta} = \sum_i \lambda_{i\alpha}\lambda_{i\beta}\frac{\langle\phi^0\rangle^2}{M_{Ri}}$$

$$\lambda_{i\alpha} \sim \mathcal{O}(10^{-11})$$

Unnatural

$$\text{for } m_\nu \sim \mathcal{O}(10^{-2})\mathrm{eV}$$

“Dark matter from split seesaw”

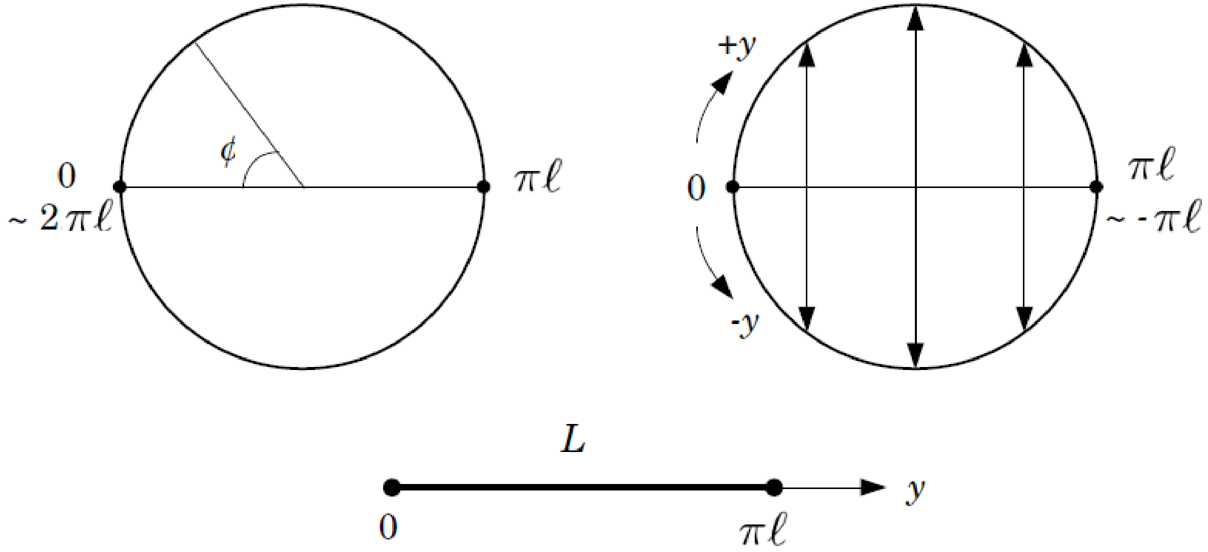


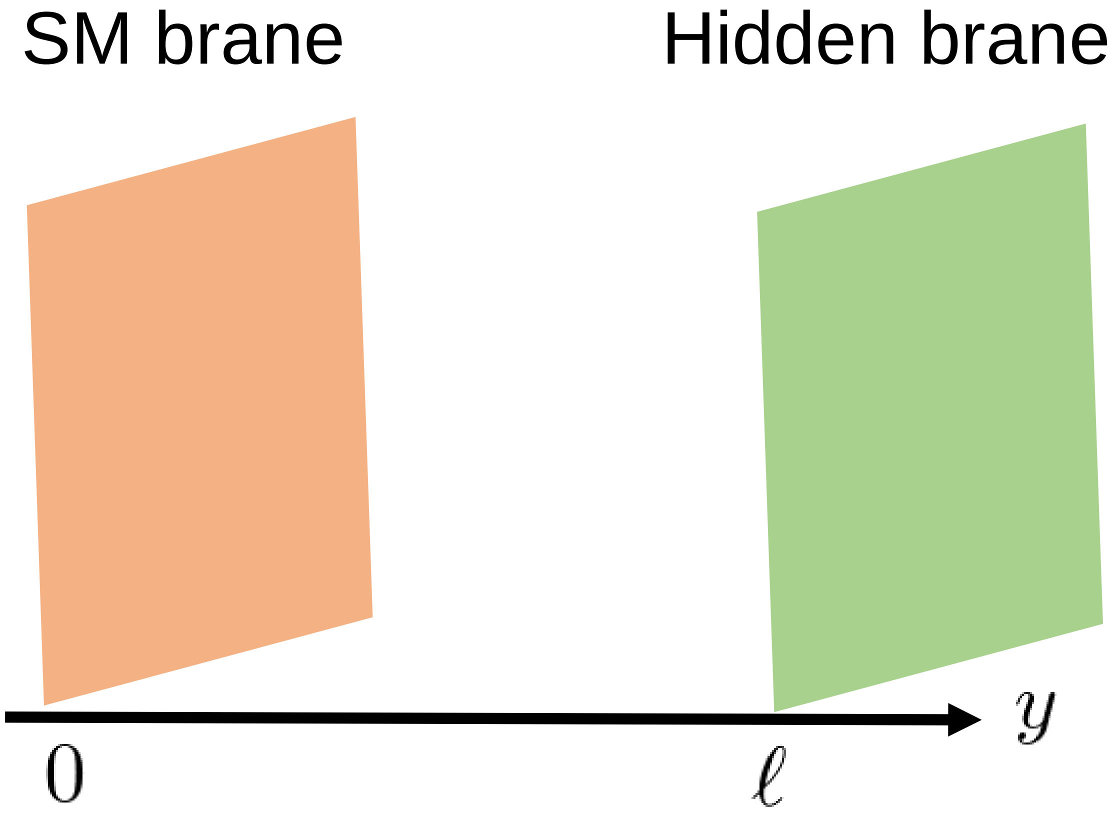
○ Split seesaw model

・Extra dimension

Compactification

Fifth dimension compactified on an S^1/Z_2 orbifold





○ Split seesaw model

5D action (fermion)

$$S=\int d^4x dy M\left(i\bar{\Psi}\Gamma^A\partial_A\Psi+m\bar{\Psi}\Psi\right)$$

$$\Gamma^\mu=\begin{pmatrix}0 & \sigma^\mu\\ \bar{\sigma}^\mu & 0\end{pmatrix},\quad \Gamma^5=-i\begin{pmatrix}1 & 0\\ 0 & -1\end{pmatrix}$$

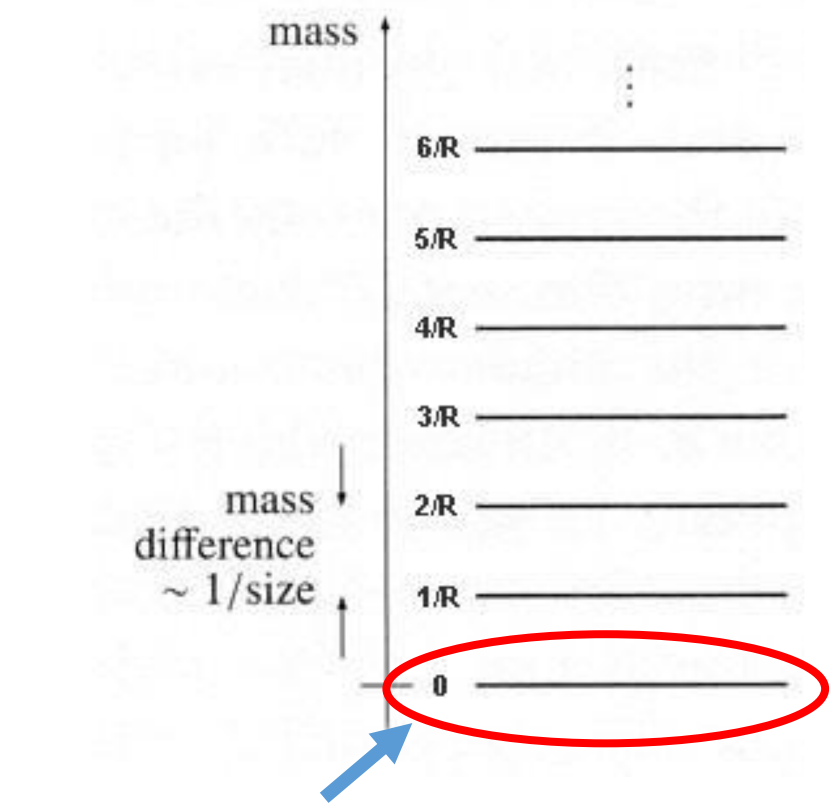
The zero mode of Ψ satisfies

$$\left(i\Gamma^5\partial_5+m\right)\Psi^{(0)}=0$$

[redacted]

Fourier series expansion

$$\Psi_{L,R}(x,y)=\sum_{n=0}^{\infty}\Psi^{(n)}_{L,R}(x)f^{(n)}_{L,R}(y)$$



SM fermion

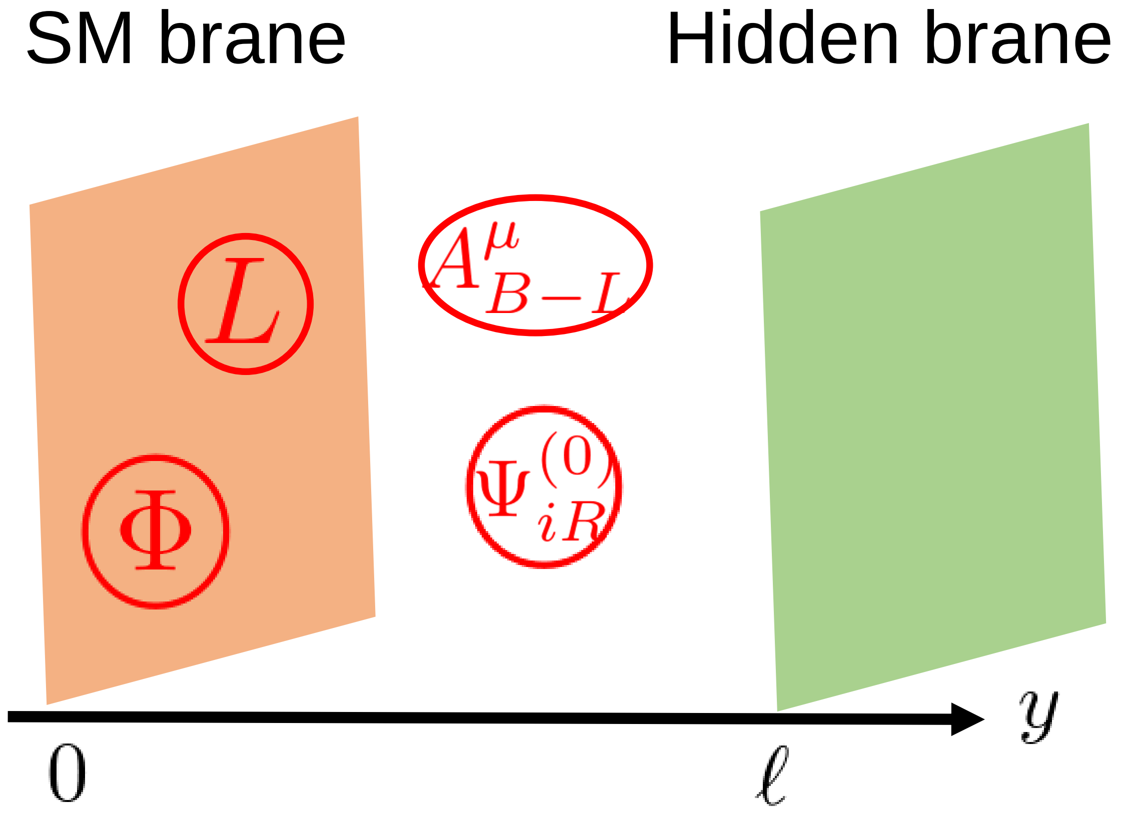
○ Split seesaw model

$$\frac{\kappa_i}{2}\Phi\bar{\Psi}^{(0)c}_{iR}\Psi^{(0)}_{iR}$$

$$\Downarrow \langle\Phi\rangle = v_{B-L} \sim 10^{15}\mathrm{GeV}$$

$$\frac{\kappa_i}{2}v_{B-L}\bar{\Psi}^{(0)c}_{iR}\Psi^{(0)}_{iR}$$

Majorana mass



$\Psi^{(0)}_{iR}$: zero mode of Ψ_R = right-handed neutrino N_i

Φ : scalar field with $U(1)_{B-L}$ charge -2

○ Split seesaw model

Action for zero mode

$$S = \int d^4x dy \left\{ M \left(i\Psi_{iR}^{(0)} \Gamma^A \partial_A \Psi_{iR}^{(0)} + m_i \Psi_{iR}^{(0)} \Psi_{iR}^{(0)} \right) \right.$$
$$\left. + \delta(y) \left(\frac{\kappa_i}{2} v_{B-L} \bar{\Psi}_{iR}^{(0)c} \Psi_{iR}^{(0)} + \tilde{\lambda}_{i\alpha} \bar{\Psi}_{iR}^{(0)} L_\alpha \phi + h.c. \right) \right\}$$

Effective 4D mass and Yukawa couplings

$$2m_i$$

$$\frac{2m_i}{e^{2m_i\ell} - 1} = \tilde{\lambda}_{i\alpha} \sqrt{\frac{M_{Ri}}{\kappa_I v_{B-L}}} \quad \lambda_{i\alpha} = \frac{\tilde{\lambda}_{i\alpha}}{\sqrt{M}} \sqrt{\cdots}$$

Suppressed by exponential factor

○ Split seesaw model

$$M_{Ri} = \kappa_i v_{B-L} \frac{2m_i}{e^{2m_i\ell} - 1}$$

$$\frac{2m_i}{e^{2m_i\ell} - 1} = \tilde{\lambda}_{i\alpha}\sqrt{\frac{M_{Ri}}{\kappa_I v_{B-L}}} \quad \lambda_{i\alpha} = \frac{\tilde{\lambda}_{i\alpha}}{\sqrt{M}}\sqrt{\frac{\ }{e}}$$

Seesaw formula

$$(m_\nu)_{\alpha\beta} = \left(\sum_i \frac{1}{\kappa_i}\tilde{\lambda}_{i\alpha}\tilde{\lambda}_{i\beta}\right)\frac{\langle\phi^0\rangle^2}{v_{B-L}}$$

$$M_{R2} \sim 10^{12}(10^{11})\mathrm{GeV}$$

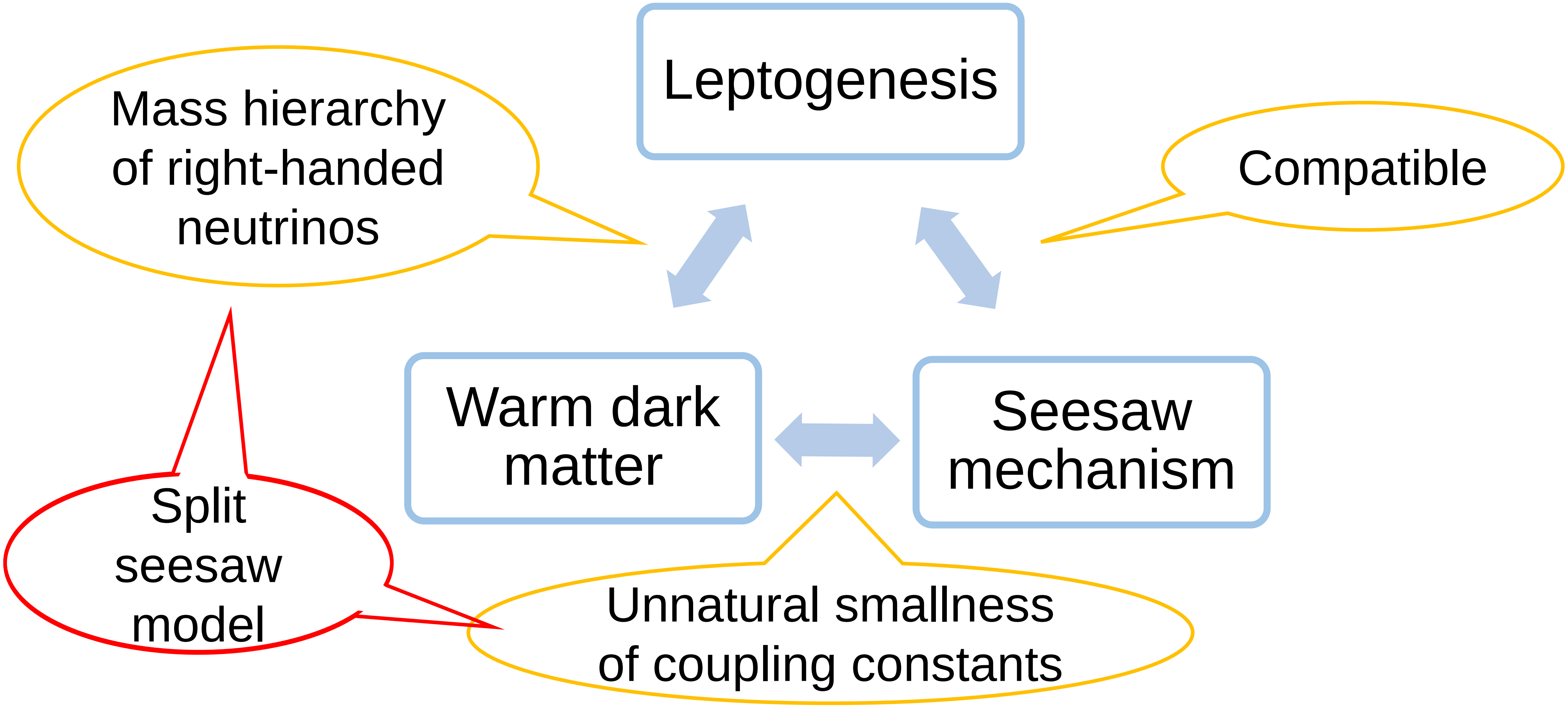
$$M_{R1} \sim \mathrm{keV}$$

$$\text{for } m_2 \simeq \underline{2.3(3.6)}\ell^{-1}$$

$$m_1 \simeq \underline{24}\ell^{-1}$$

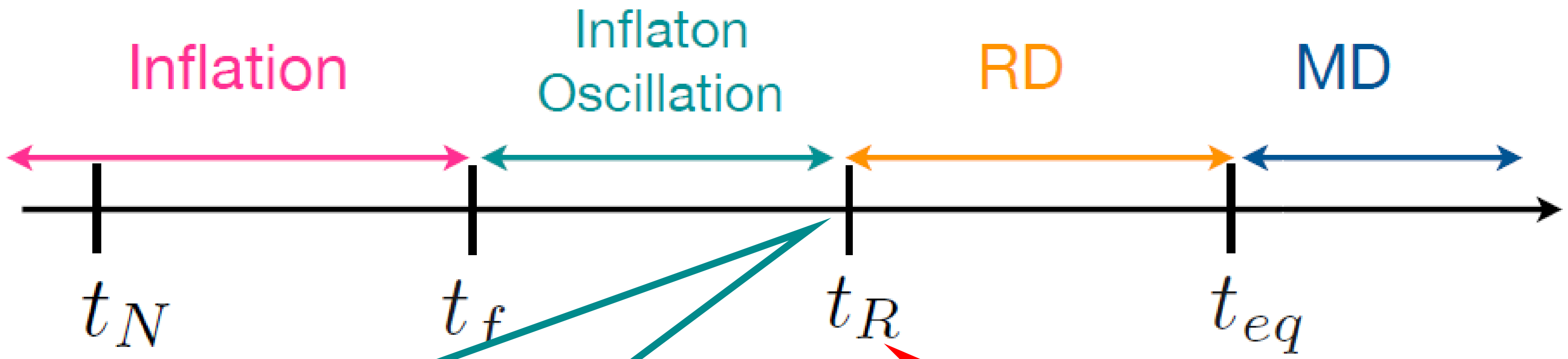
Only $O(10^1)$ hierarchy

“Dark matter from split seesaw”

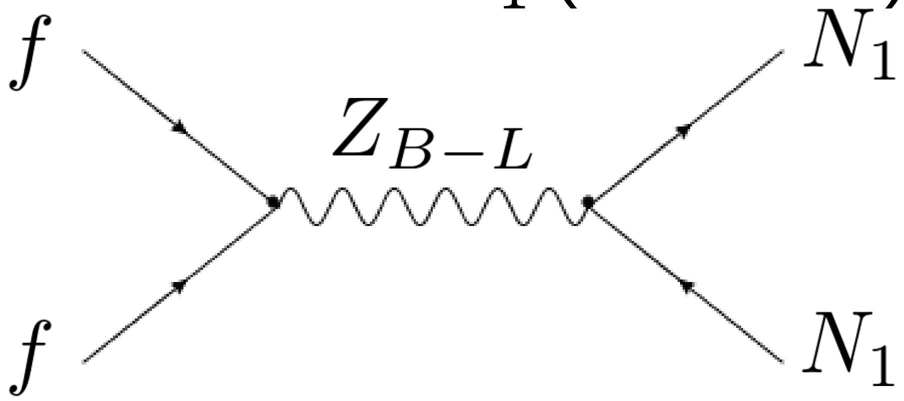


○ Production of RHN

Process of producing RHN



Production of N_1 (dominant)



For successful leptogenesis

$$T_R > 10^{11}\mathrm{GeV}$$

○ Production of RHN

The number to entropy ratio of N_{R1}

$$Y_{N_1} = \frac{n_{N_1}}{s} \sim \frac{\langle \sigma v \rangle \, n_f^2 / H}{\frac{2\pi^2}{45} g_* T^3}$$

$$\sim 10^{-4} \left(\frac{g_*}{10^2} \right)^{\frac{3}{2}} \left(\frac{v_{B-L}}{10^{15}\mathrm{GeV}} \right)^{-4} \left(\frac{T_R}{5 \times 10^{13}\mathrm{GeV}} \right)^{3}$$

$\langle \sigma v \rangle \sim \frac{T^2}{v_{B-L}^4}$: production cross section

H : Hubble parameter

g_* : relativistic degrees of freedom at the reheating

[illegible] : number density of the SM fermions in plasma

○ Production of RHN

The number to entropy ratio of N_{R1}

$$Y_{N_1} = \frac{n_{N_1}}{s} \sim \frac{\langle \sigma v \rangle n_f^2 / H}{\frac{2\pi^2}{45} g_* T^3}$$

$$\sim 10^{-4} \left(\frac{g_*}{10^2} \right)^{\frac{3}{2}} \left(\frac{v_{B-L}}{10^{15}\mathrm{GeV}} \right)^{-4} \left(\frac{T_R}{5 \times 10^{13}\mathrm{GeV}} \right)^3$$

Dark matter abundance

$$\Omega_{dark} = 0.2 \times \left(\frac{m_{N_1}}{5\mathrm{keV}} \right) \left(\frac{Y_{N_1}}{0.7 \times 10^{-4}} \right)$$

$$\Longrightarrow T_R \sim 10^{13}\mathrm{GeV}$$

○ Conclusion

- Compact leptogenesis model that includes warm dark matter

- Natural mass hierarchy of RHNs and smallness of Yukawa coupling

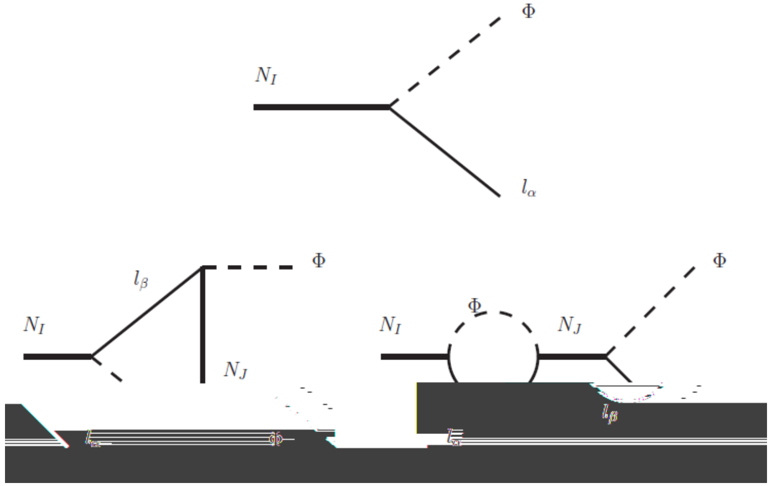
- For producing dark matter with the correct abundance, the reheating temperature have to be about 10^{13}GeV.

Backup

○ Leptogenesis

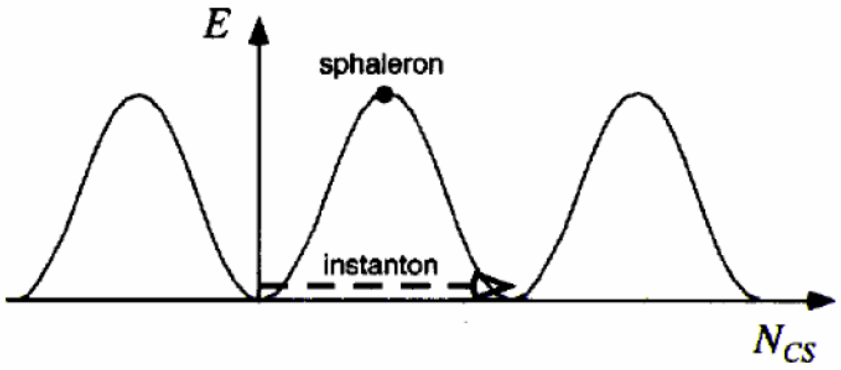
A kind of baryogenesis that produced an asymmetry between matters and antimatters

Decays of RHN



$$B = 0, L \neq 0$$

Sphaleron process



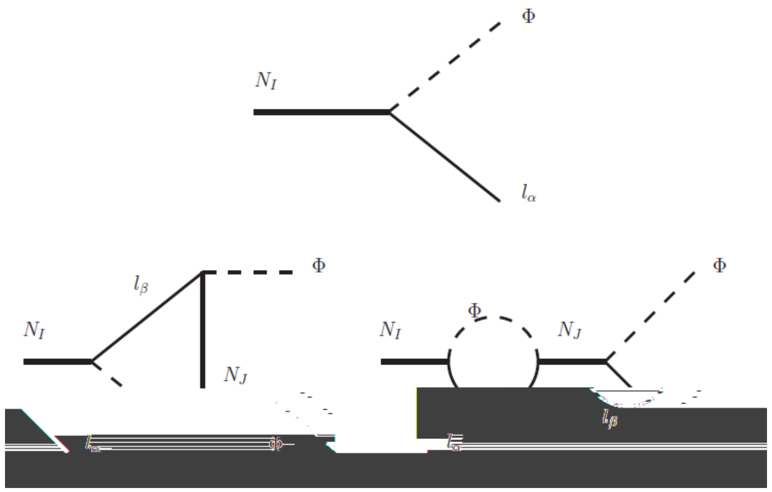
$$B \neq 0, L \neq 0$$

○ Leptogenesis

A kind of baryogene[…]etry between matters and anti[…]

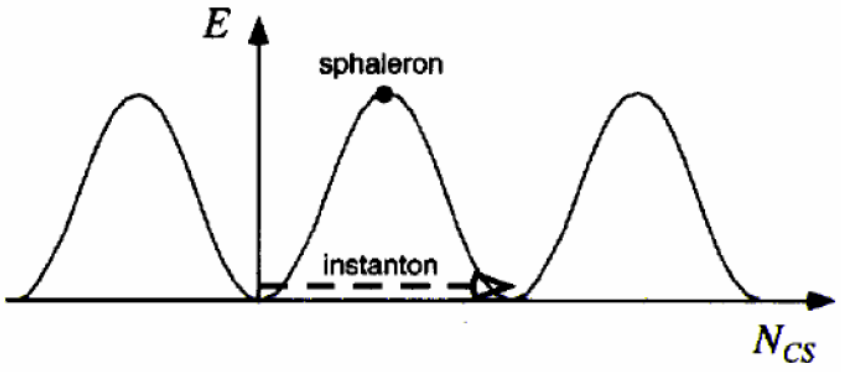
$$\Delta(B-L)=0, \Delta(B+L)\neq 0$$

Decays of RHN



$$B=0, L\neq 0$$

Sphaleron process



$$B\neq 0, L\neq 0$$

○ Seesaw mechanism

A generic model that explains
the smallness of observed neutrino mass

$$\mathcal{L} = i\bar{N}_i \gamma^\mu \partial_\mu N_i + \left(\lambda_{i\alpha} \bar{N}_i L_\alpha \phi - \frac{1}{2} M_{Ri} \bar{N}_i^c N_i + h.c. \right)$$

Mass matrix

$$\mathcal{M} = \begin{pmatrix} 0 & \lambda_{i\alpha} \langle \phi_0 \rangle \\ \lambda_{i\alpha}^T \langle \phi_0 \rangle & -M_{Ri} \end{pmatrix}$$

Seesaw formula

$$(m_\nu)_{\alpha\beta} = \sum_i \lambda_{i\alpha} \lambda_{i\beta} \frac{\langle \phi^0 \rangle^2}{M_{Ri}}$$

○ Warm dark matter

Small scale problem

1. Angular momentum problem

CDM simulation
⇒ galaxies have developed bulges

The milky way galaxy
⇒ disk galaxy

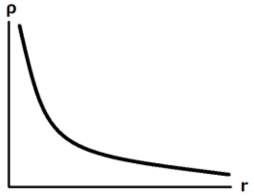
2. Satellite galaxy problem

CDM simulation
⇒ about 200 satellite galaxies

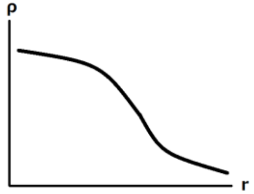
The milky way galaxy
⇒ about 20 satellite galaxies

3. Cusp-core problem

CDM simulation
⇒ cusp structure



dwarf galaxies
⇒ core structure



Seesaw mechanism ⟷ Leptogenesis

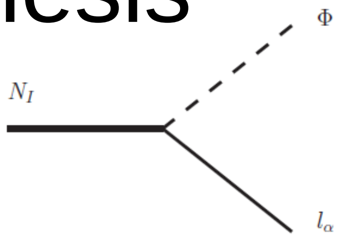
Lagrangian

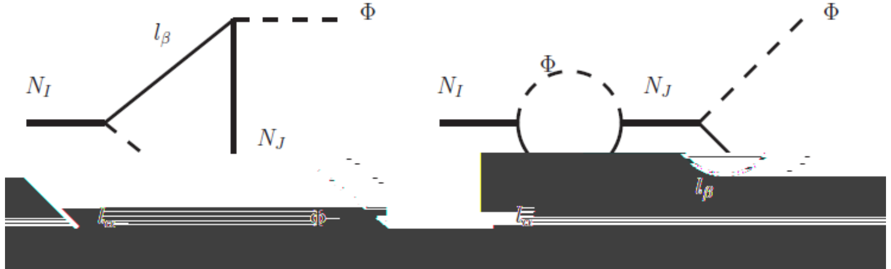
$$\mathcal{L} = i\bar{N}_i\gamma^\mu\partial_\mu N_i + \left(\underline{\lambda_{i\alpha}\bar{N}_i L_\alpha \phi} - \frac{1}{2}M_{Ri}\bar{N}_i^c N_i + h.c.\right)$$

Seesaw formula

$$(m_\nu)_{\alpha\beta} = \sum_i \lambda_{i\alpha}\lambda_{i\beta}\frac{\langle\phi^0\rangle^2}{M_{Ri}}$$

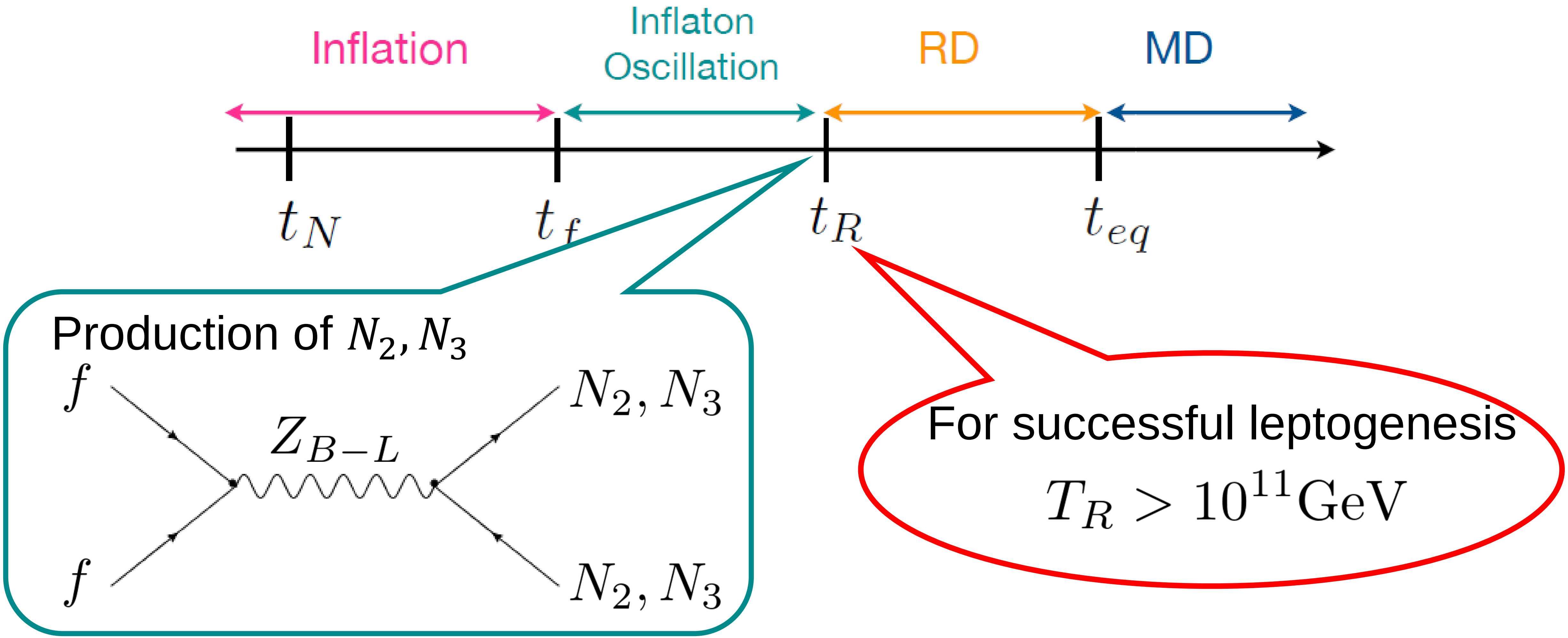
Leptogenesis





○ Production of RHN

Process of leptogenesis



○ Production of RHN

Process of leptogenesis