$\beta\beta_{0\nu}$ と m_ν hierarchy & Majorana CP phases

―$\beta\beta_{0\nu}$ 実験結果は理論にどのような impact があるか？？―

m_ν 質量階層構造, $m_{\nu 1,2,3}$ 符号 (Majo. CP)
models, cosmology

Naoyuki Haba (Mie U.)

1. Intro.
2. $\beta\beta_{0\nu}$ & m_ν, CP (standard scenario – 3世代, see-saw)
   - 2-1. m_ν, U_{MNS} 定義.
   - 2-2. $\beta\beta_{0\nu}$ ⟶ m_ν hierarchy (inverted or degenerate)
   - 2-3. model への制限 (GUT, democratic, Zee…)
3. cosmology
4. exotic models
   - 4-1. $\not{R}$ parity
   - 4-2. extra scalar
   - 4-3. L-R sym.
5. summary

1. Intro.

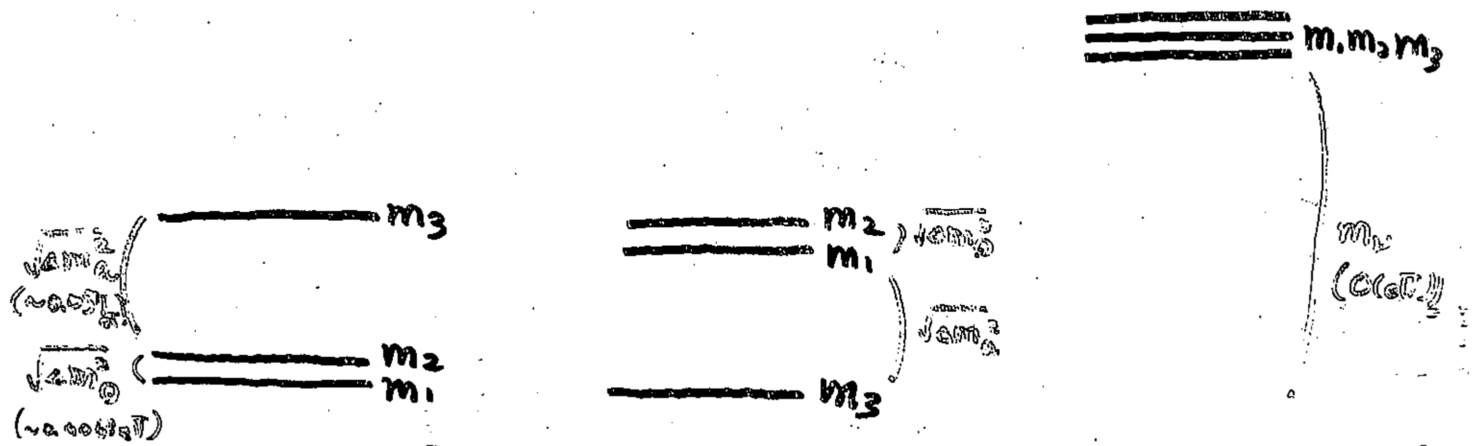
$\beta\beta_{0\nu}$ exp : $\langle m_{ee} \rangle = \left| \sum_{i=1}^{3} U_{ei}^2 m_i \right|$

$= \underline{(0.05 \sim 0.86)\,\mathrm{eV}}$ 95% c.l. (center 0.4 eV)

(K-Kleingrothaus et al MPLA 16 ('01) 2409)

ν : $m_\nu \neq 0$ Majo. mass を持つ!

ν- oscillation exp. :



Typ A　　Type B　　Type C

⟹ 理論

- m_ν mass hierarchy, $m_{1,2,3}$ 符号 (Majo. CP)
- models
- cosmology

に どのような影響を与えるか?!

Why $m_\nu \ll m_{e/L}$??

In the framework of the SM, gauge inv. dim5 OP.

$$\underline{\mathcal{L} \sim \gamma \frac{\nu_L \nu_L \langle\phi\phi\rangle}{M} + h.c.} \qquad M: \text{heavy}$$

$\not{\Delta}$ ~~lepton~~ # in 2 units

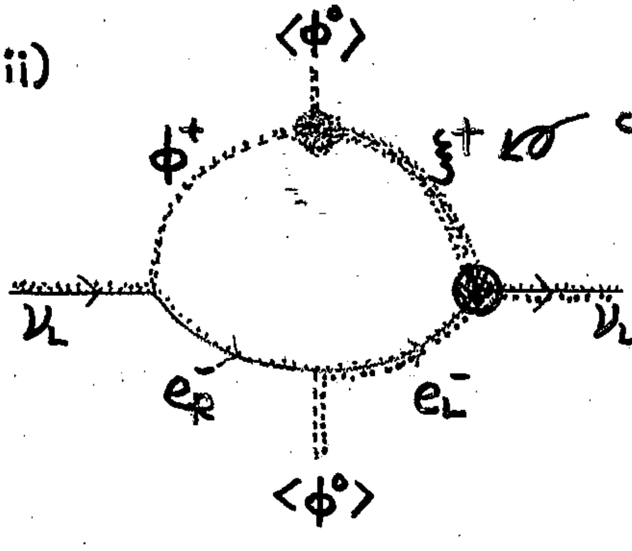
Renormalizability of the SM $\Longrightarrow$ $M \gg M_Z$ and/or $\gamma \ll 1$

i) $\underline{\mathcal{L}_{fund.} \sim \nu_L \phi N + MNN + h.c.}$ $\qquad N: \nu_R$

$\frac{\partial \mathcal{L}_{fund.}}{\partial N} = 0$ integrate out heavy N

$$\begin{array}{cc} L & R \end{array}$$
$$\begin{pmatrix} 0 & \langle\phi\rangle \\ \langle\phi\rangle & M \end{pmatrix} \xrightarrow[\langle\phi\rangle \ll M]{\text{"see-saw"}} \begin{pmatrix} \langle\phi\rangle^2/M & 0 \\ 0 & M \end{pmatrix}$$

ii) (Zee 1980)



ξ^+ ← charged Higgs ($SU(2)_L$ singlet with L#2)

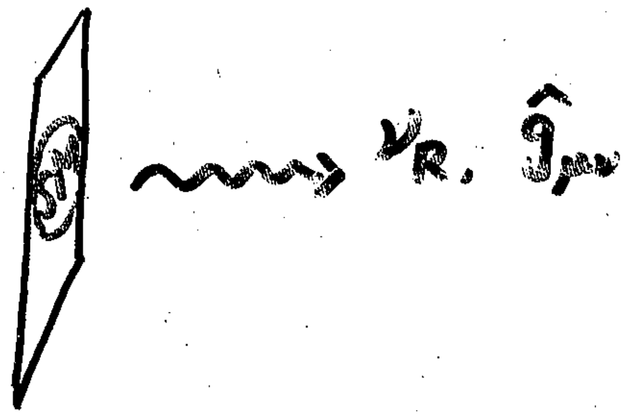
$$\gamma \sim \frac{1}{(4\pi)^2} \quad M \sim m_{\xi^+}$$

$$m_\nu \simeq \begin{pmatrix} 0 & m_{e\mu} & m_{e\tau} \\ m_{e\mu} & 0 & m_{\mu\tau} \\ m_{e\tau} & m_{\mu\tau} & 0 \end{pmatrix}$$

$\left\{ \begin{array}{l} \cdots\cdots \ L\# \\ \cdots\cdots \ SU(2)_L \end{array} \right\}$

iii) Large Extra Dimension

① volume factor suppression



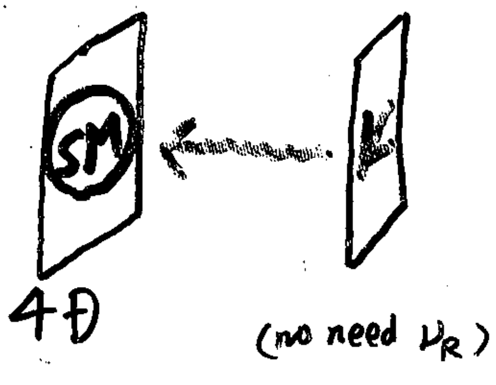
4D $\longrightarrow$ 5, 6, $\cdots$ D

$$m_\nu^D = \frac{1}{\underbrace{(M_S R)^{\delta/2}}}\, Y_\nu \langle H \rangle \qquad (D = 4 + \delta)$$

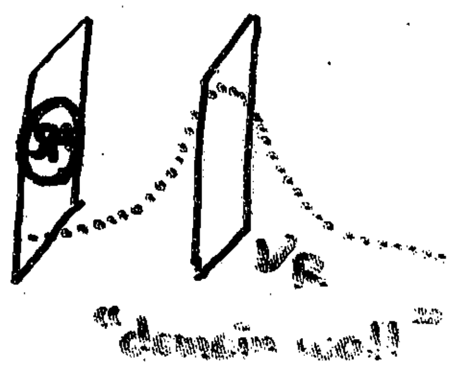
$$\simeq \begin{array}{c|cccccc} & \nu_R & \nu_R^{(1)} & \nu_R^{(2)} & \nu_R^{(3)} & \cdots \\ \hline \nu_L & m_D & m_D & m_D & m_D & \\ \nu^{(1)} & 0 & 1/R & 0 & 0 & \\ \nu^{(2)} & 0 & 0 & 2/R & 0 & \\ \nu^{(3)} & 0 & 0 & 0 & 3/R & \\ \vdots & \vdots & & & & \ddots \end{array}$$

∞ # of ν_s !

② distant br.



③ wave fuction supprecion



2. $\beta\beta_{0\nu}$ & m_ν, CP

2-1. notation

$$\mathcal{L}_\nu \simeq K_{ij}(L_i\phi)(L_j\phi)$$

$$\rightarrow m_{ij} = K_{ij}\langle\phi\rangle^2 = \begin{pmatrix} m_{11} & m_{12} & m_{13} \\ & m_{22} & m_{23} \\ \text{Sym.} & & m_{33} \end{pmatrix}$$

$$U^T m_{ij} U = \begin{pmatrix} \underline{m_1} e^{i\Phi_1} & & \\ & \underline{m_2} e^{i\Phi_2} & \\ & & \underline{m_3} \end{pmatrix}$$

$$\left(\begin{array}{l} \underline{m_{1,2,3} > 0} \\ \phi_{1,2} = \text{Majo. CP phase} \end{array} \right.$$

$$U = \begin{pmatrix} c_{13}c_{12} & c_{13}s_{12} & \underline{s_{13}e^{-i\delta}} \\ -c_{23}s_{12} - s_{23}s_{13}c_{12}e^{i\delta} & c_{23}c_{12} - s_{23}s_{13}s_{12}e^{i\delta} & s_{23}c_{13} \\ s_{23}s_{12} - c_{23}s_{13}c_{12}e^{i\delta} & -s_{23}c_{12} - c_{23}s_{13}s_{12}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

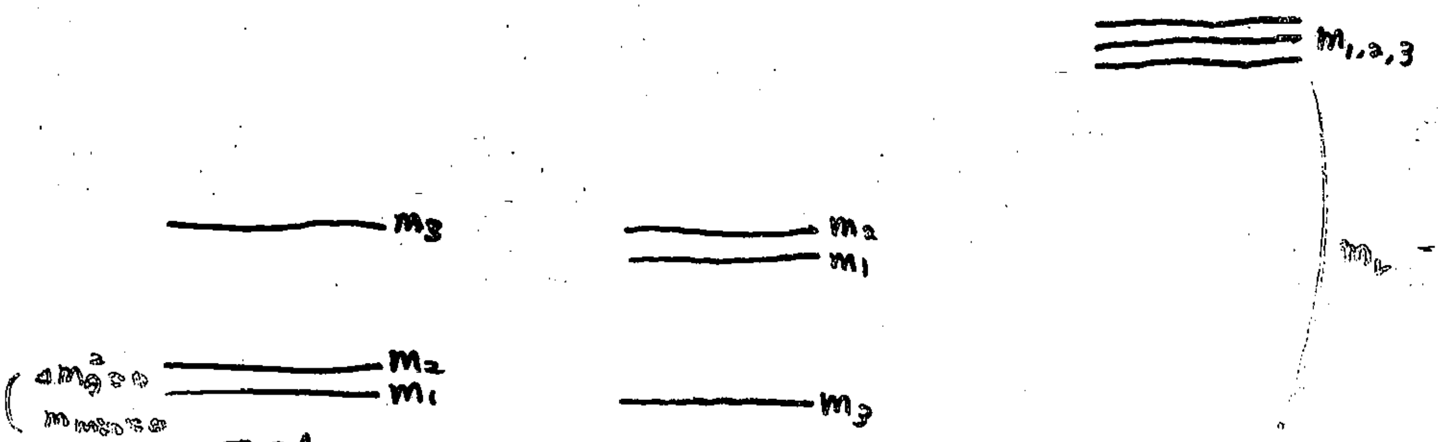
Dirac CP

ν-oscillation exp.

$$
\left(
\begin{array}{lll}
\text{Solar LMA} & : & \Delta m^2_\odot \simeq 4.5\times10^{-5}\,\mathrm{eV}^2, \quad \tan^2\theta_\odot \simeq 4.1\times10^{-1} \\
\text{ATM} & : & \Delta m^2_a \simeq 3.2\times10^{-3}\,\mathrm{eV}^2, \quad \sin^2 2\theta_a \simeq 1 \\
\text{CHOOZ} & : & \sin^2 2\theta_{13} < 0.1
\end{array}
\right)
$$

第0近似：

$$
U^{(0)} = \begin{pmatrix} 1/\sqrt{2} & 1/\sqrt{2} & 0 \\ -1/2 & 1/2 & 1/\sqrt{2} \\ 1/2 & -1/2 & 1/\sqrt{2} \end{pmatrix}
$$



TypeA　　TypeB　　TypeC

Type A

$$
\begin{pmatrix} 0 & 0 & 0 \\ 0 & 1/2 & 1/2 \\ 0 & 1/2 & 1/2 \end{pmatrix}\sqrt{\Delta m_a^2}
$$

B1 $(\phi_1 = -\phi_2)$

$$
\begin{pmatrix} 0 & -1/\sqrt{2} & 1/\sqrt{2} \\ -1/\sqrt{2} & 0 & 0 \\ 1/\sqrt{2} & 0 & 0 \end{pmatrix}\sqrt{\Delta m_a^2}
$$

B2 $(\phi_1 = \phi_2)$

$$
\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1/2 & -1/2 \\ 0 & -1/2 & 1/2 \end{pmatrix}\sqrt{\Delta m_a^2}
$$

C0 $(\phi_1 = \phi_2 = 0)$

$$
\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} m_\nu
$$

C1 $(\phi_1 = \pi, \phi_2 = 0)$

$$
\begin{pmatrix} 0 & 1/\sqrt{2} & -1/\sqrt{2} \\ 1/\sqrt{2} & 1/2 & 1/2 \\ -1/\sqrt{2} & 1/2 & -1/2 \end{pmatrix} m_\nu
$$

C2 $(\phi_1 = 0, \phi_2 = \pi)$

$$
\begin{pmatrix} 0 & -1/\sqrt{2} & 1/\sqrt{2} \\ -1/\sqrt{2} & 1/2 & 1/2 \\ 1/\sqrt{2} & 1/2 & 1/2 \end{pmatrix} m_\nu
$$

C3 $(\phi_1 = \phi_2 = \pi)$

$$
\begin{pmatrix} -1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix}
$$

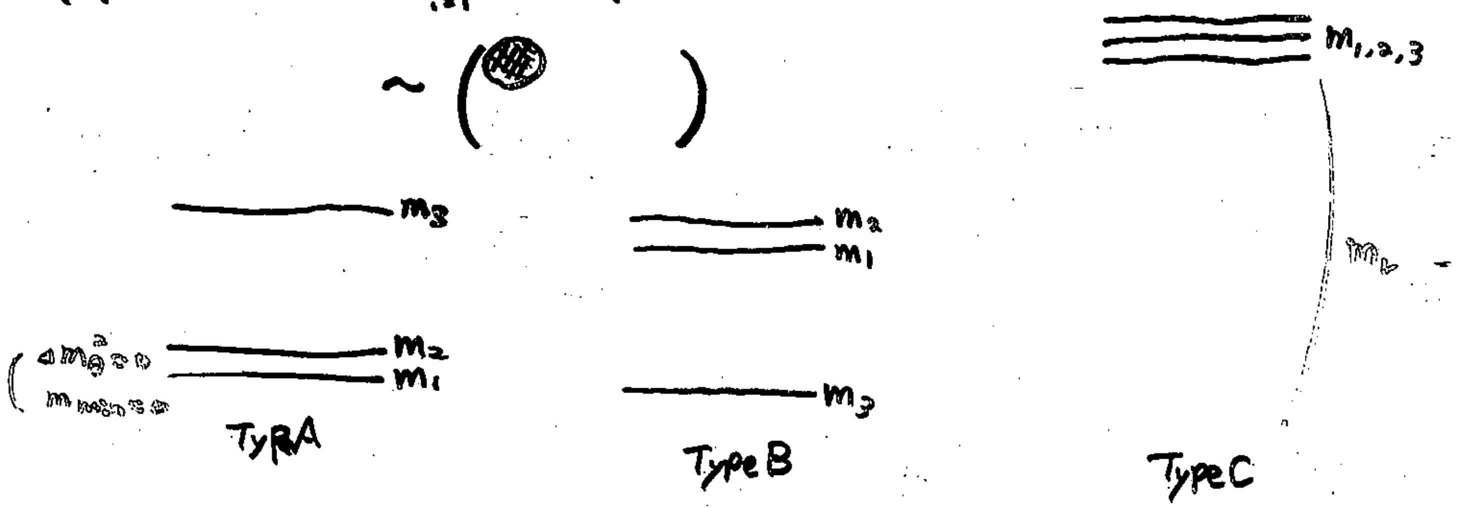
ν-oscillation exp.

$$\left(\begin{array}{lll} \text{Solar LMA} & : & \Delta m_\odot^2 \simeq 4.5\times10^{-5}\,\mathrm{eV}^2, \quad \tan^2\theta_\odot \simeq 4.1\times10^{-1} \\ \text{ATM} & : & \Delta m_a^2 \simeq 3.2\times10^{-3}\,\mathrm{eV}^2, \quad \sin^2 2\theta_a \simeq 1 \\ \text{CHOOZ} & : & \sin^2 2\theta_{13} < 0.1 \end{array}\right)$$

第0近似：
$$U^{(0)} = \begin{pmatrix} 1/\sqrt{2} & 1/\sqrt{2} & 0 \\ -1/2 & 1/2 & 1/\sqrt{2} \\ 1/2 & -1/2 & 1/\sqrt{2} \end{pmatrix}$$

$\beta\beta_{0\nu}$ $\langle m_{ee}\rangle = \left|\sum_{i=1}^{3} U_{ei}^2 m_i\right|$

$\sim$ (略)



$$\begin{pmatrix} 0 & 0 & 0 \\ 0 & 1/2 & 1/2 \\ 0 & 1/2 & 1/2 \end{pmatrix}\sqrt{\Delta m_a^2}$$

B1 $(\phi_1 = -\phi_2)$
$$\begin{pmatrix} 0 & -1/\sqrt{2} & 1/\sqrt{2} \\ -1/\sqrt{2} & 0 & 0 \\ 1/\sqrt{2} & 0 & 0 \end{pmatrix}\sqrt{\Delta m_a^2}$$

B2 $(\phi_1 = \phi_2)$
$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1/2 & -1/2 \\ 0 & -1/2 & 1/2 \end{pmatrix}\sqrt{\Delta m_a^2}$$

C0 $(\phi_1 = \phi_2 = 0)$
$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} m_\nu$$

C1 $(\phi_1 = \pi, \phi_2 = 0)$
$$\begin{pmatrix} 0 & 1/\sqrt{2} & -1/\sqrt{2} \\ 1/\sqrt{2} & 1/2 & 1/2 \\ -1/\sqrt{2} & 1/2 & -1/2 \end{pmatrix} m_\nu$$

C2 $(\phi_1 = 0, \phi_2 = \pi)$
$$\begin{pmatrix} 0 & -1/\sqrt{2} & 1/\sqrt{2} \\ -1/\sqrt{2} & 1/2 & 1/2 \\ 1/\sqrt{2} & 1/2 & 1/2 \end{pmatrix} m_\nu$$

C3 $(\phi_1 = \phi_2 = \pi)$
$$\begin{pmatrix} -1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix}$$

2-2. $\beta\beta_{0\nu} \rightarrow$ inverted (一部) or degenerate

Type A : $(m_{1,2} \ll m_3)$

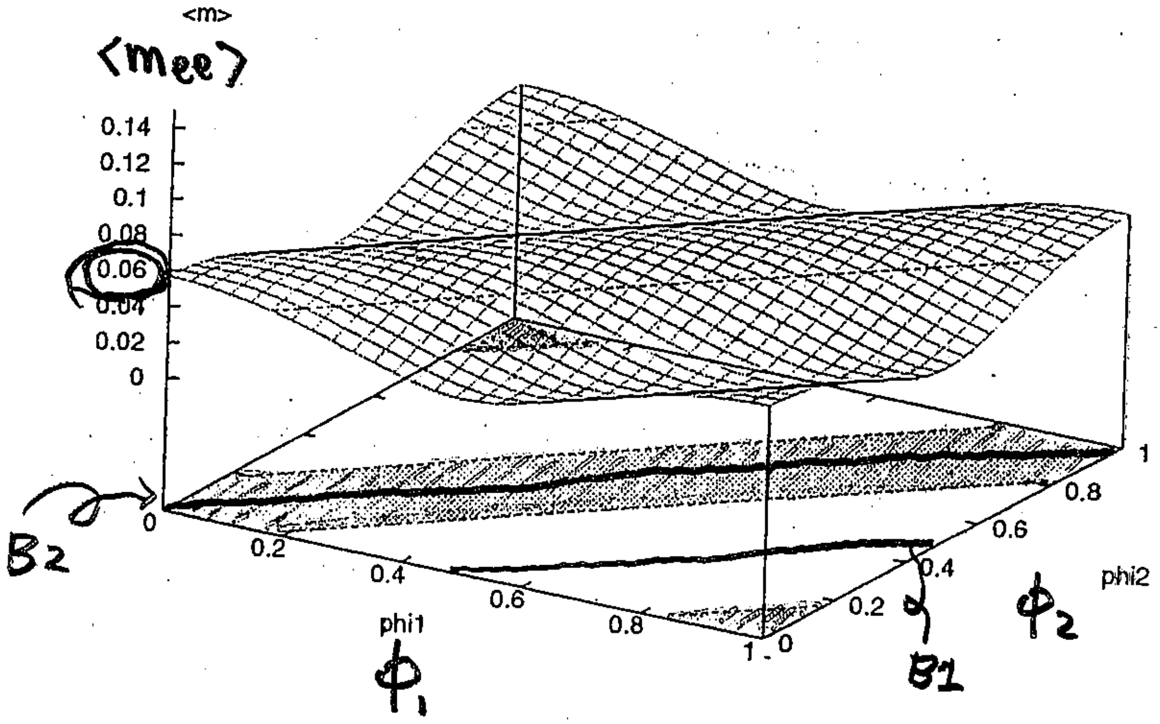
$$\langle m_{ee} \rangle = \left| U_{e1}^2 m_1 e^{i\phi_1} + U_{e2}^2 m_2 e^{i\phi_2} + U_{e3}^2 m_3 \right|$$

$$\leq \underbrace{|U_{e1}|^2 m_1 + |U_{e2}|^2 m_2}_{\sqrt{\Delta m_a^2} < 0.01} + |U_{e3}|^2 m_3$$

$0.16^2 \times \sqrt{\Delta m_a^2} \ll 0.01$

Type B : $(m_{1,2} \gg m_3)$

$$\langle m_{ee} \rangle \sim \left| \frac{1}{2}\sqrt{\Delta m_a^2}\, e^{i\phi_1} + \frac{1}{2}\left(\sqrt{\Delta m_a^2} + \frac{1}{2}\frac{\Delta m_\odot^2}{\sqrt{\Delta m_a^2}}\right) e^{i\phi_2} + U_{e3}^2 m_3 \right|$$

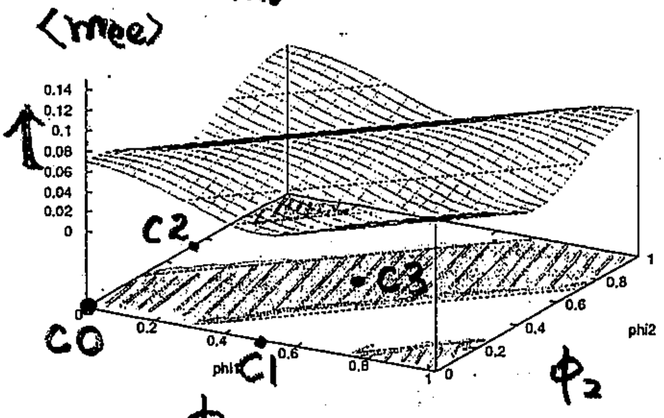


$\langle m_{ee} \rangle = 0.05 \sim 0.1$ eV

Type C : $(m_1 \sim m_2 \sim m_3)$

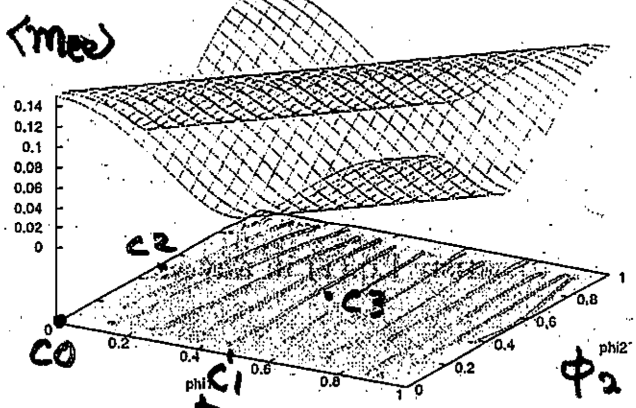
$$
\begin{cases}
m_1 = m_\nu \\
m_2 = m_\nu + \frac{1}{2}\frac{\Delta m_\odot^2}{m_\nu} \\
m_3 = m_\nu + \frac{1}{2}\frac{\Delta m_a^2}{m_\nu}
\end{cases}
$$

$m_\nu = 0.07\,eV$



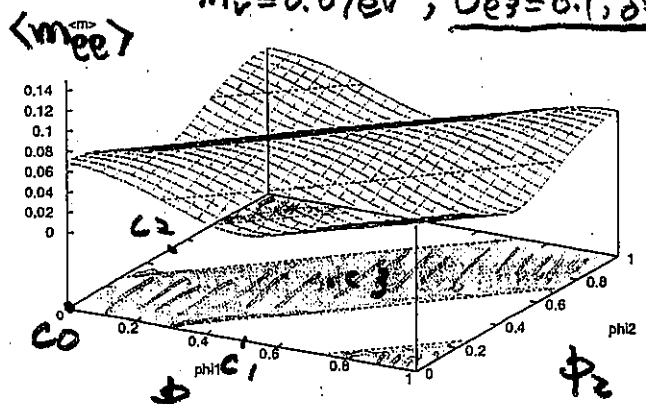
(a)

$m_\nu = 0.15\,eV$



(b)

$m_\nu = 0.07\,eV$, $\underline{U_{e3} = 0.1, \delta = \pi/2}$



(c)

2-3. model への制限

• inverted B2 ($m_1 \simeq m_2$) or degenerate でなくてはいけない!

• GUT → texture えらび

• Zee model, Shafi-Tavartkiladze model
($U(1)_F$, $2N_R$)

$$m_\nu \simeq \begin{pmatrix} 0 & m & m \\ m & 0 & 0 \\ m & 0 & 0 \end{pmatrix} \qquad L_e - L_\mu - L_\tau \text{ sym.}$$

Type B1 ✕

• democratic model ($S_{3L} \times S_{3R}$ sym.)

$$m_{u,d,e} = \begin{array}{c} L \\ \begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix} R \end{array} + \begin{pmatrix} -\varepsilon & & \\ & \varepsilon & \\ & & \delta \end{pmatrix} \qquad m_\nu = \begin{array}{c} L \\ \begin{pmatrix} 1 & & \\ & 1 & \\ & & 1 \end{pmatrix} L \end{array} \left(\text{or} \begin{pmatrix} 0 & 1 & 1 \\ 1 & 0 & 1 \\ 1 & 1 & 0 \end{pmatrix} \right) + \begin{pmatrix} 0 & & \\ & \varepsilon_\nu & \\ & & \delta_\nu \end{pmatrix} \text{ Type C0 } ◎$$

(
• 第3世代が重い!

• $F = \begin{pmatrix} 1/\sqrt{2} & 1/\sqrt{6} & 1/\sqrt{3} \\ -1/\sqrt{2} & 1/\sqrt{6} & 1/\sqrt{3} \\ 0 & -2/\sqrt{6} & 1/\sqrt{3} \end{pmatrix}$ $\begin{cases} \sin^2 2\theta_\odot = 8/9 \\ \sin^2 2\theta_{atm} = 1 \\ U_{e3} = 0 \end{cases}$ $\left(\begin{array}{l} U_{CKM} \sim F^\dagger F \sim 1 \\ U_{MNS} \sim F^\dagger \end{array} \right.$
)

予言 $\mapsto \sqrt{\frac{m_e}{m_\mu}} \sim 0.05$!

(Kageyama, Kaneko, Shimoyama, Tanimoto
Fukugita, Tanimoto, Yanagida

3. Cosmology ($\langle m_{ee} \rangle = 0.05 - 0.86\,\mathrm{eV}$)

- BBN : 1 MeV 以下の dof に sensitive (ex. ν_s)

  ほとんど影響なし

- Ω_ν (hot (ν) dark matter)

  CMB & galaxy $\rightarrow \Omega_\nu h^2 \leq 0.05$ 95% CL.

  $\rightarrow \sum = m_1 + m_2 + m_3 \leq 4.4\,\mathrm{eV}$ (Wang et al. 2001)

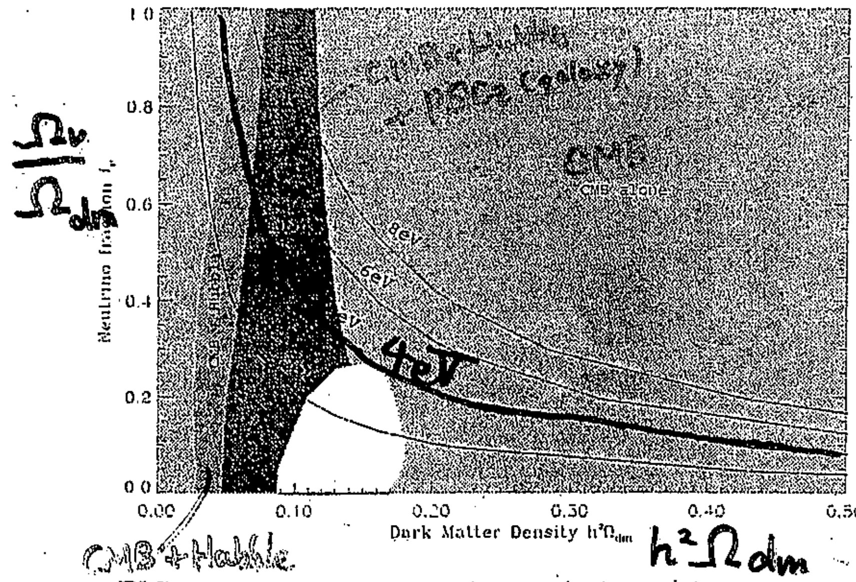


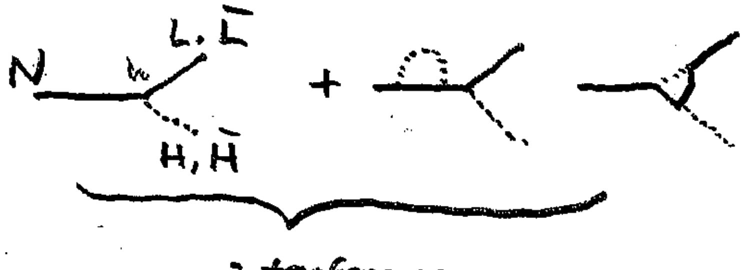
FIG. 8. Constraints in the (ω_{dm}, f_ν)-plane. The four curves show contours of constant neutrino mass sum. (physical density of total dark ma[tter])

- Leptogenesis (democratic) (Fujii・Hamaguchi・Yanagida 2002)

$$\text{Baryogenesis} \begin{cases} 1.\ \cancel{B} \longleftarrow \langle B+L \rangle \sim 0 \longleftarrow \cancel{L} \\ 2.\ \cancel{C},\ \cancel{CP} \\ 3.\ \text{非平衡} \end{cases}$$

(sphaleron)

$$N \rightarrow \begin{cases} L + H \\ \bar{L} + \bar{H} \end{cases} :$$



N の生成と非平衡の scenario

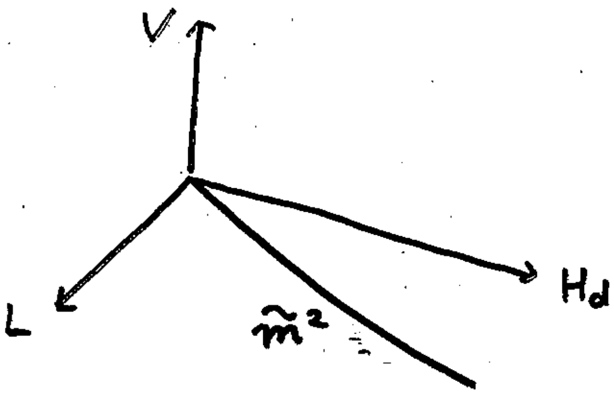
- thermal scattering　　(m_ν degenerate ※)
- inflaton decay　　○ ただし $M_R > T_r$

$$\epsilon_i = \frac{\sum_j \Gamma(N_{R_i} \to L_j + H) - \sum_j (N_{R_i} \to \bar{L}_j + \bar{H})}{\sum_j \Gamma(N_{R_i} \to L_j + H) + \sum_j (N_{R_i} \to \bar{L}_j + \bar{H})}$$

$$= -\frac{1}{8\pi} \frac{1}{(hh^\dagger)_{ii}} \sum_{k \neq i} \mathrm{Im}\left[\{(hh^\dagger)_{ik}\}^2\right]\left[F_V\left(\frac{M_k^2}{M_i^2}\right) + F_W\left(\frac{M_k^2}{M_i^2}\right)\right]$$

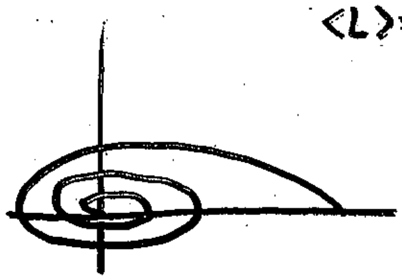
$$\longrightarrow \frac{n_L}{s} \simeq \frac{3}{2} \sum \epsilon_i B_r \frac{T_R}{m_\phi} \rightsquigarrow \frac{n_B}{s} = C \frac{n_L}{s}$$

- AD leptogenesis



$$V = (|L|^2 - |H_d|^2 + \cdots)^2 + \cdots\cdots$$

$\langle L \rangle = \langle H_d \rangle$



lightest
$m_\nu < 10^{-9}$ eV

$\Rightarrow$ Typ B for $0\nu\beta\beta$ (Fujii, Hamaguchi, Yanagida)

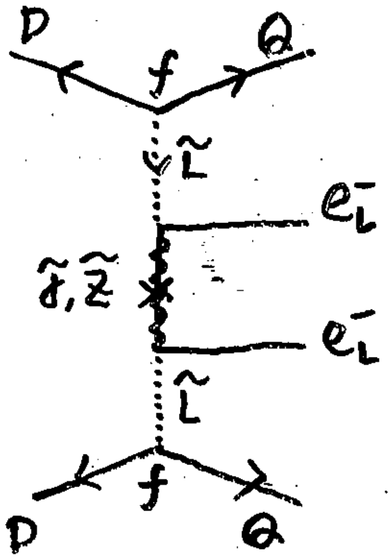
4. exotic models （m_ν 小でも $\beta\beta_{0\nu}$ あり！）

4-1. $\cancel{R}_2$ MSSM

	$(SU(3)_c, SU(2)_L, U(1)_Y)$	boson	fermion
L	$(1,\ 2,\ -1)_-$	$\tilde{L}\ (-)$	$+\ L\ (+)$
H_d	$(1,\ 2,\ -1)_+$	$H\ (+)$	$+\ \tilde{H}\ (-)$

$$W = y_u Q H_u U + y_d Q \underline{H_d} D + y_e L \underline{H_d} E + \mu H_u \underline{H_d}$$

$$+ f Q \underline{L} D + h L \underline{L} E + \mu' H_u \underline{L}$$



$$A_{\beta\beta 0\nu} \sim \frac{f^2 \alpha}{\tilde{m}_{SUSY}^5} \cdot M_{f.i.}$$

$$\sim 10^{-11}\ \mathrm{GeV}^{-5} \quad (\Leftrightarrow m_{ee} \sim 0.9\ \mathrm{eV})$$

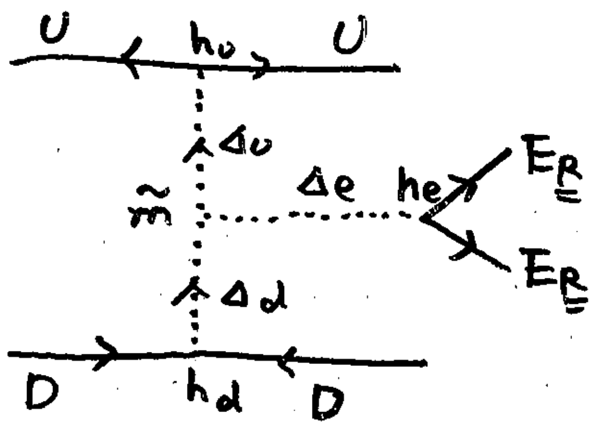
4-2. extra scalar

(THDM + extra scalar + Z_3 sym.) (Ma. et al ('03))

$$
\text{scalar}\left(\begin{array}{llll}
 & (3_c & 2_L & 1_Y) \\
\Delta_u & (6, & 1, & 4/3) & \omega \\
\Delta_d & (6, & 1, & -2/3) & \omega^2 \\
\Delta_e & (1, & 1, & -2) & \omega^2
\end{array}\right.
$$

$D, E \sim \omega$

$U \sim \omega^2$



$$A_{\bar{U}\bar{D}\bar{U}\bar{D}EE} \sim \frac{h_u h_d h_e \tilde{m}}{m_{\Delta u}^2 m_{\Delta d}^2 m_{\Delta e}^2}$$

$\sim 10^{-16}\ \mathrm{GeV}^{-5}$ ([illegible])

$$\left(\begin{array}{l}
h_{u,d,e} \sim 1 \\
m_{\Delta u,d,e} \sim 1\ \mathrm{TeV} \\
\tilde{m} \sim 100\ \mathrm{GeV}
\end{array}\right.$$

search for

$\Delta_u, \Delta_d \to 2\,\text{jet at LHC}$

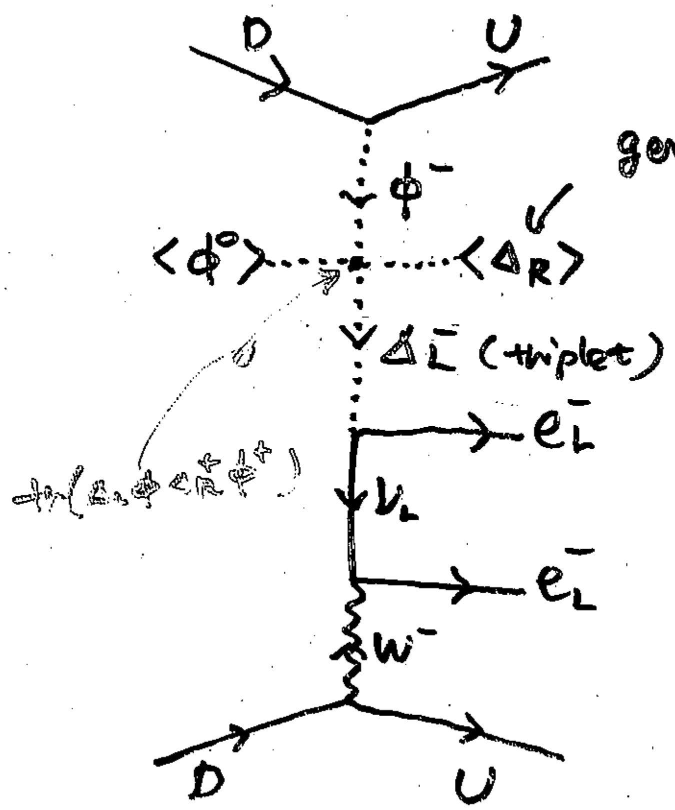
$\Delta_e :\ e^+e^- \to \Delta_e^+ \Delta_e$

($e^+e^- \to e^+e^-$ correction)

4.3. L-R sym. model

$(SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L})$

(Babu & Mohapatra (1995))

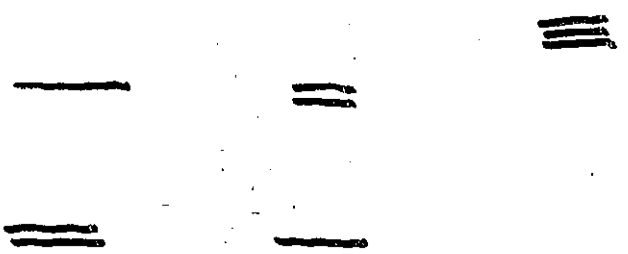


generating Majo. mass
$L \# 2$

5. summary

$$\beta\beta 0\nu = (0.05 - 0.86)\,\mathrm{eV}$$

★ "standard" 3-gen. scenario



× △ ◎

× Zee

同符号
近傍の値
しかも
~0.05eV

Majo CPに
よらず可能

• ν (hot) dark matter

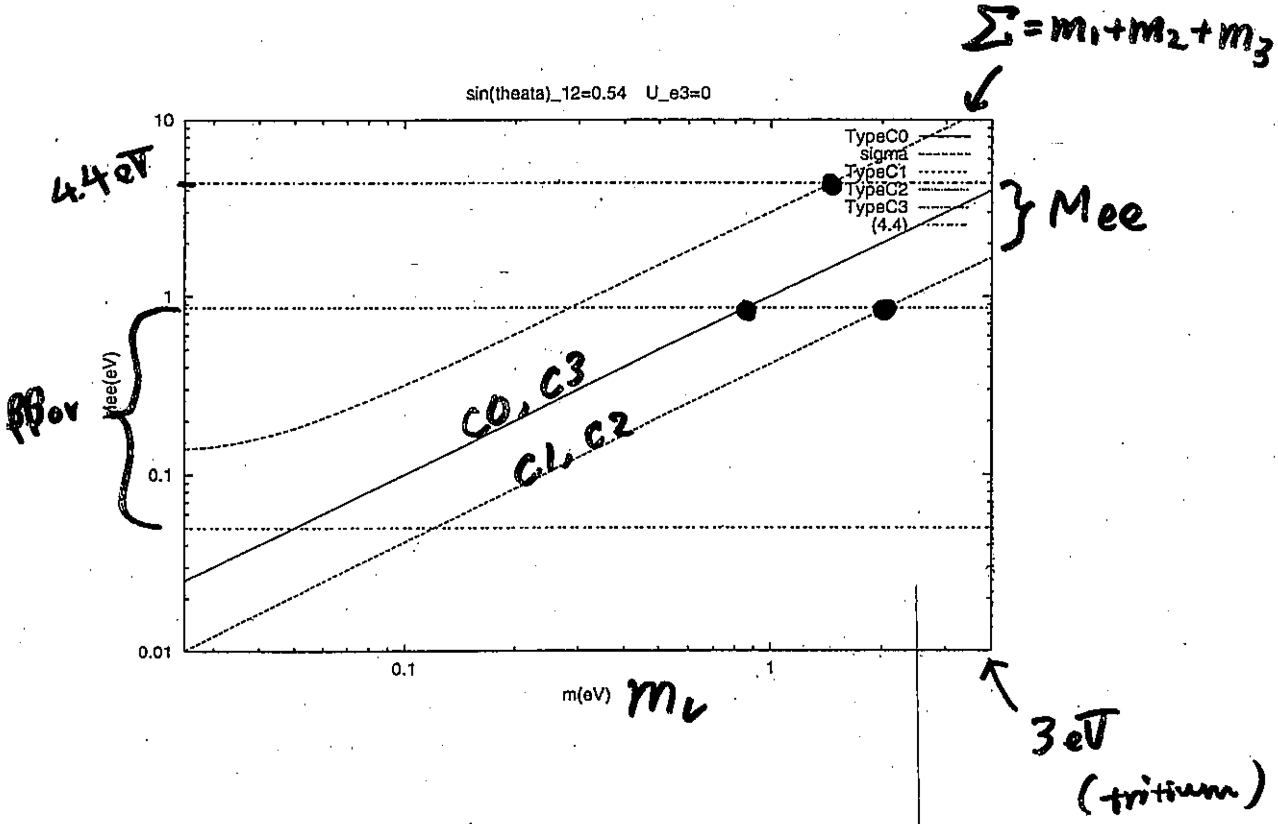
($\Sigma = m_1 + m_2 + m_3$ [illegible]) [illegible]

C1, C2 の上限

$\begin{pmatrix}0&*&*\\ *&*&*\\ *&*&*\end{pmatrix}$ $\begin{pmatrix}0&*&*\\ *&*&*\\ *&*&*\end{pmatrix}$

(MAP: $\Sigma \lesssim 0.5$ eV

★ exotic models の可能性



$\Sigma = m_1 + m_2 + m_3$
sin(theata)_12=0.54 U_e3=0
4.4eV
TypeC0
sigma
TypeC1
TypeC2
TypeC3
(4.4)
Mee
$\beta\beta_{0\nu}$
Mee(eV)
C0, C3
C1, C2
m(eV) m_ν
3eV
(tritium)
10
1
0.1
0.01
0.1
1