# Theoretical Impact of Neutrinoless Double Beta Decay Experiments

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# 1 Introduction

## Neutrinos: Windows to New Physics

**Neutrino Oscillations provided information**

- **Tiny** Neutrino Masses
- **Large** Neutrino Flavor Mixings

**Flavor Symmetry, Extra Dimensions . . . .**

Connecting Physical Phenomena

Neutrinoless Double Beta Decay

Leptogenesis . . . . . . ,

# Questions

★Tiny Neutrino Masses ?　Seesaw, Extra-Dimensions

★Large Flavor Mixings ?　Flavor symmetry

★Majorana Neutrinos ?　( L number violation? )

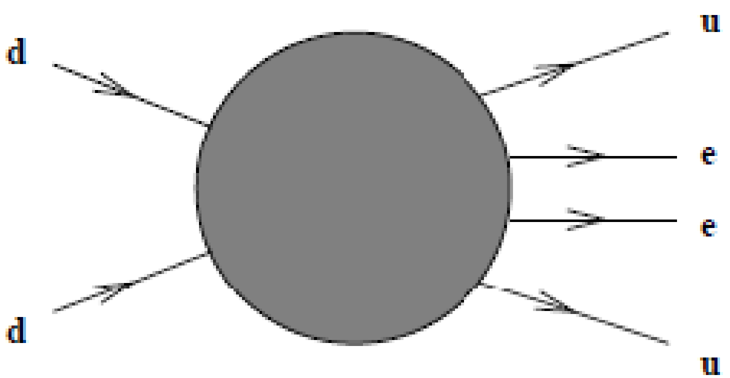
★Right-handed Neutrinos ?

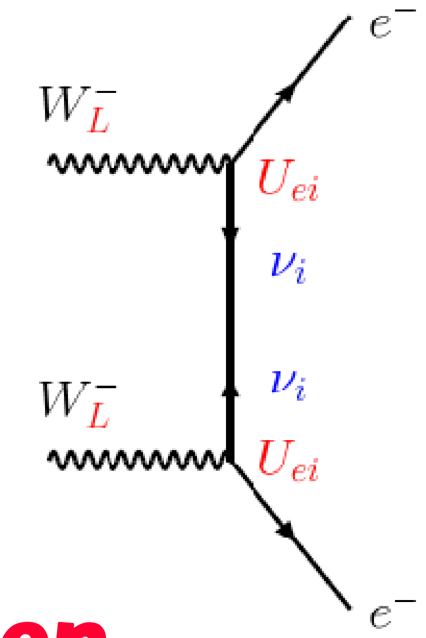
★Sterile Neutrinos ?

★New Interaction of Neutrinos ?

★Neutrino Soft Mass ?

# 2 Neutrinoless Double Beta Decay




**Majorana Neutrino**

***Lepton Number Violation***

**Baryon Asymmetry can be explained by Leptogenesis**

***due to violaton of $(B - L)$***

$$\frac{1}{T_{1/2}} = G^{0\nu}(E_0, Z)|M^{0\nu}|^2|\langle m_\nu \rangle|^2$$

$G^{0\nu}$ : phase space factor

$M^{0\nu}$ : nuclear matrix element

**Still Uncertainties**

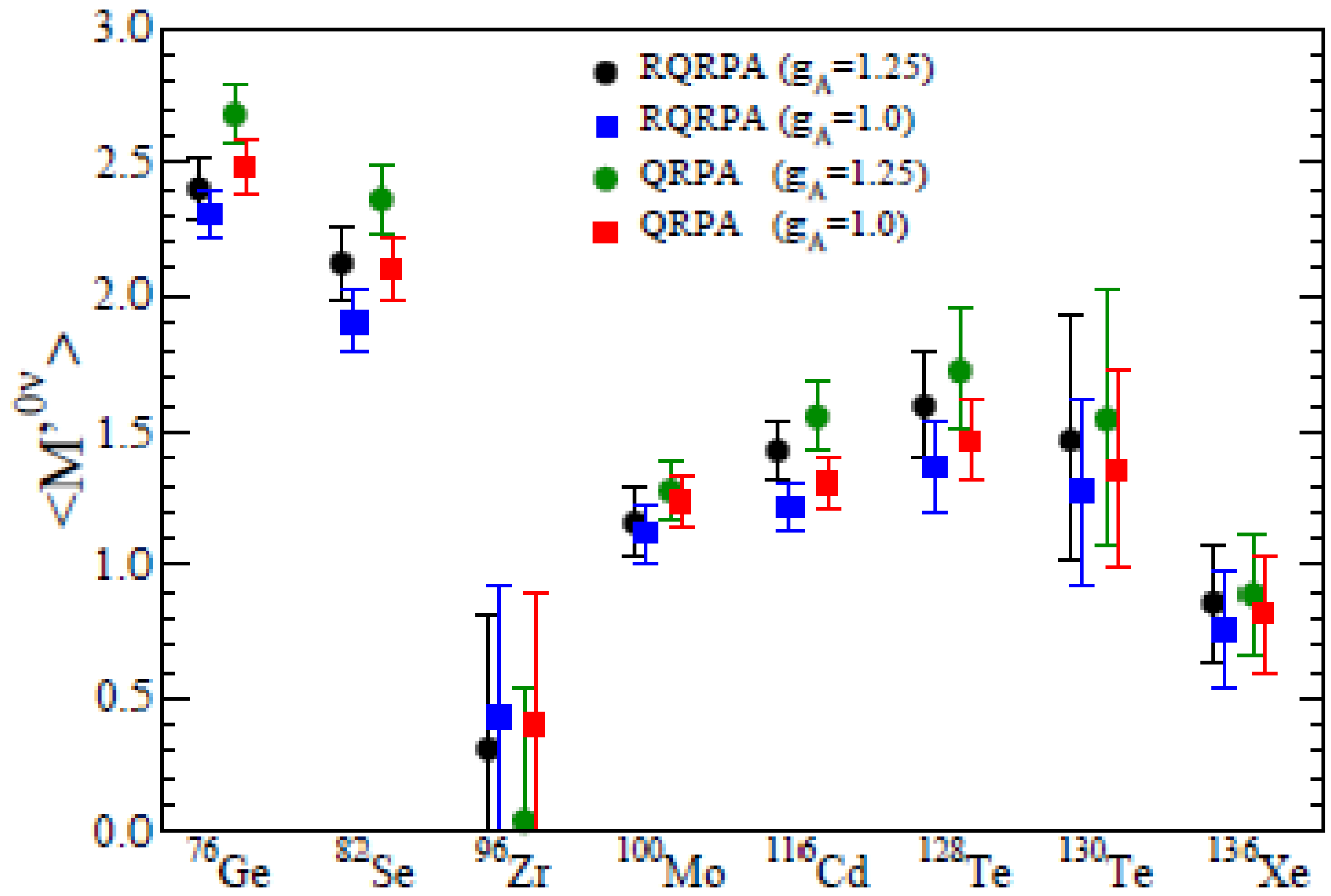
$$\langle m_\nu \rangle = |\sum_i^3 U_{ei}^2 \ e^{i\alpha_i} \ m_i|$$

$$= |\mathbf{M}_\nu(1, 1)|$$

$$\langle m_\nu \rangle = c_{12}^2 m_1 + s_{12}^2 c_{13}^2 e^{i\alpha_1} m_2 + s_{13}^2 e^{i\alpha_2} m_3$$

**The magnitude depends on neutrino mass hierarchy.**

**Generally, $\langle m_\nu \rangle$ is large in the case of inverted masses $m_2$, $m_1 >> m_3$ .**




Rodin, Simkovic, Faessler, Vogel, Nucl. Phys. A766(2006)107

# Best Present Bound

$$\langle m_\nu \rangle < 0.35 - 0.50 \text{ eV}$$

$$^{76}Ge \rightarrow ^{76}Se + e^- + e^-$$

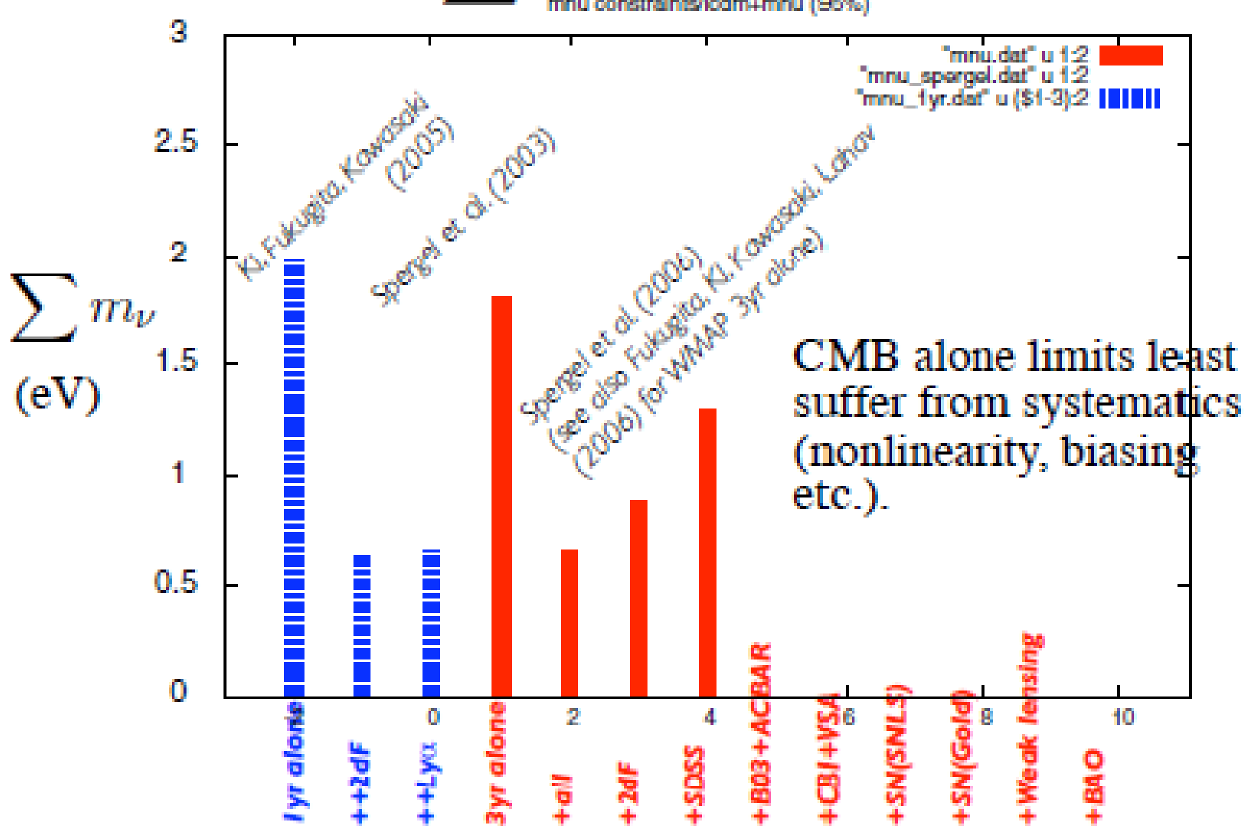
Heidelberg – Moscow

$^{76}$Ge half-live of $T_{1/2} > 1.2 \times 10^{25}$ ys

**which is consistent with cosmological bound:**

Neutrino mass: $\sum m_\nu < 2.0 \text{ eV}$ (95%)

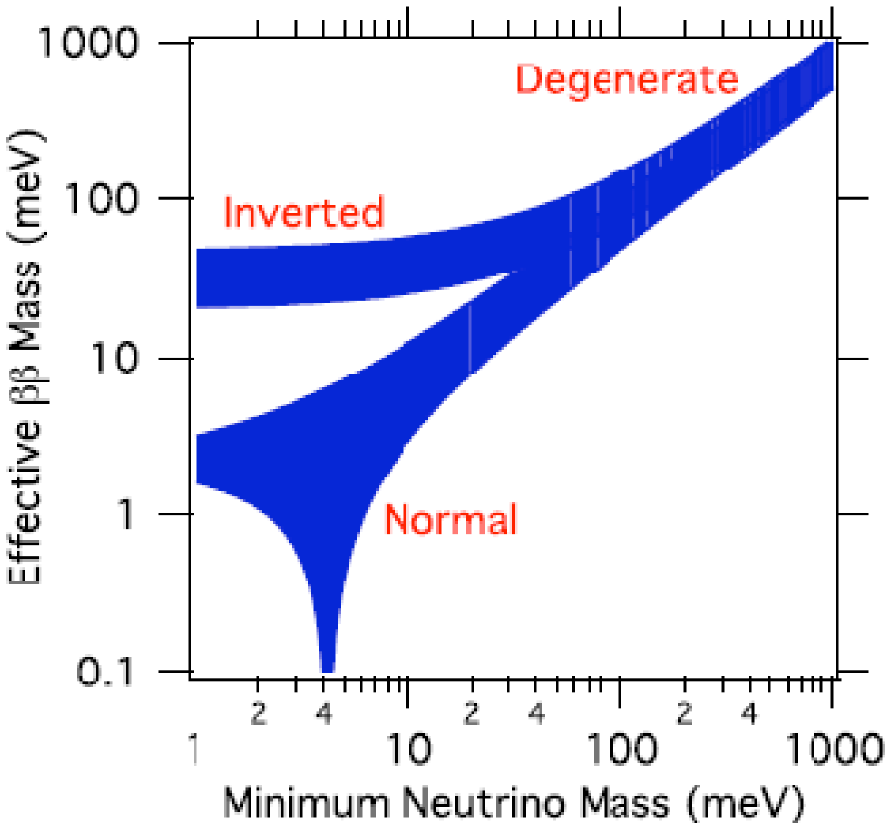
mnu constraints/lcdm+mnu (95%)

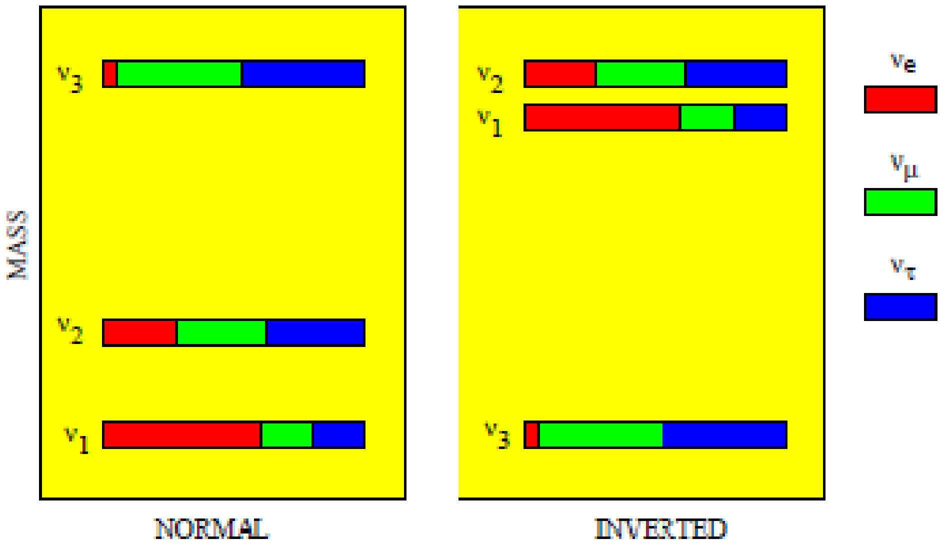



**K. Ichikawa 2006**

Avignone, Elliott, Enge : nucl-ex/07081033

# Estimate by using best fit values of parameters including uncertainties of Majorana phases.



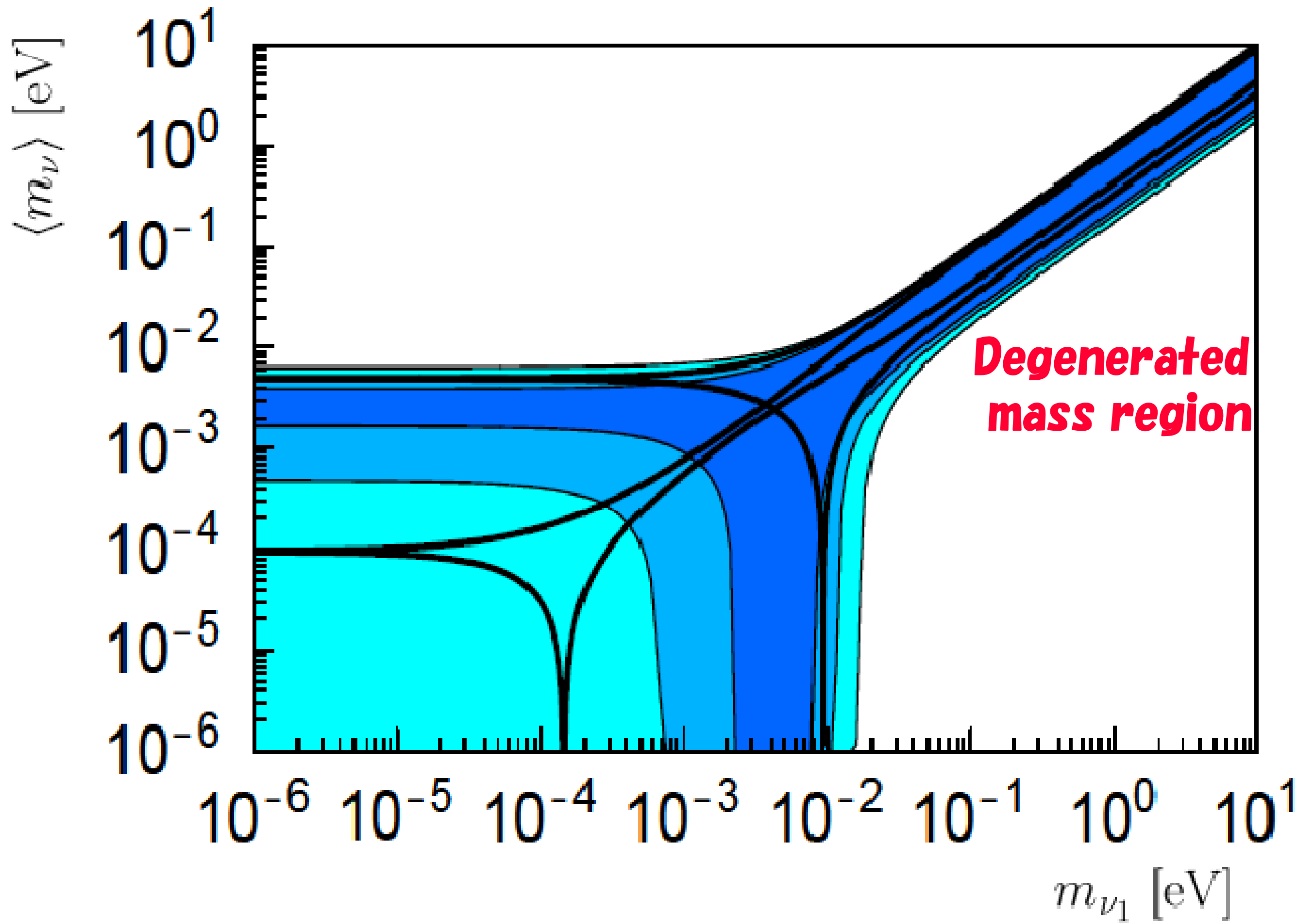



M. Hirsch : hep-ph/0609146

$m_1 < m_2 < m_3$

## Normal hierarchy

$$\langle m_\nu \rangle = c^2_{sun} c^2_{rea} m_1 + s^2_{sun} c^2_{rea} e^{i\alpha_1} \sqrt{m_1^2 + \Delta m^2_{sun}} + s^2_{rea} e^{i\alpha_2} \sqrt{m_1^2 + \Delta m^2_{sun} + \Delta m^2_{atm}}$$



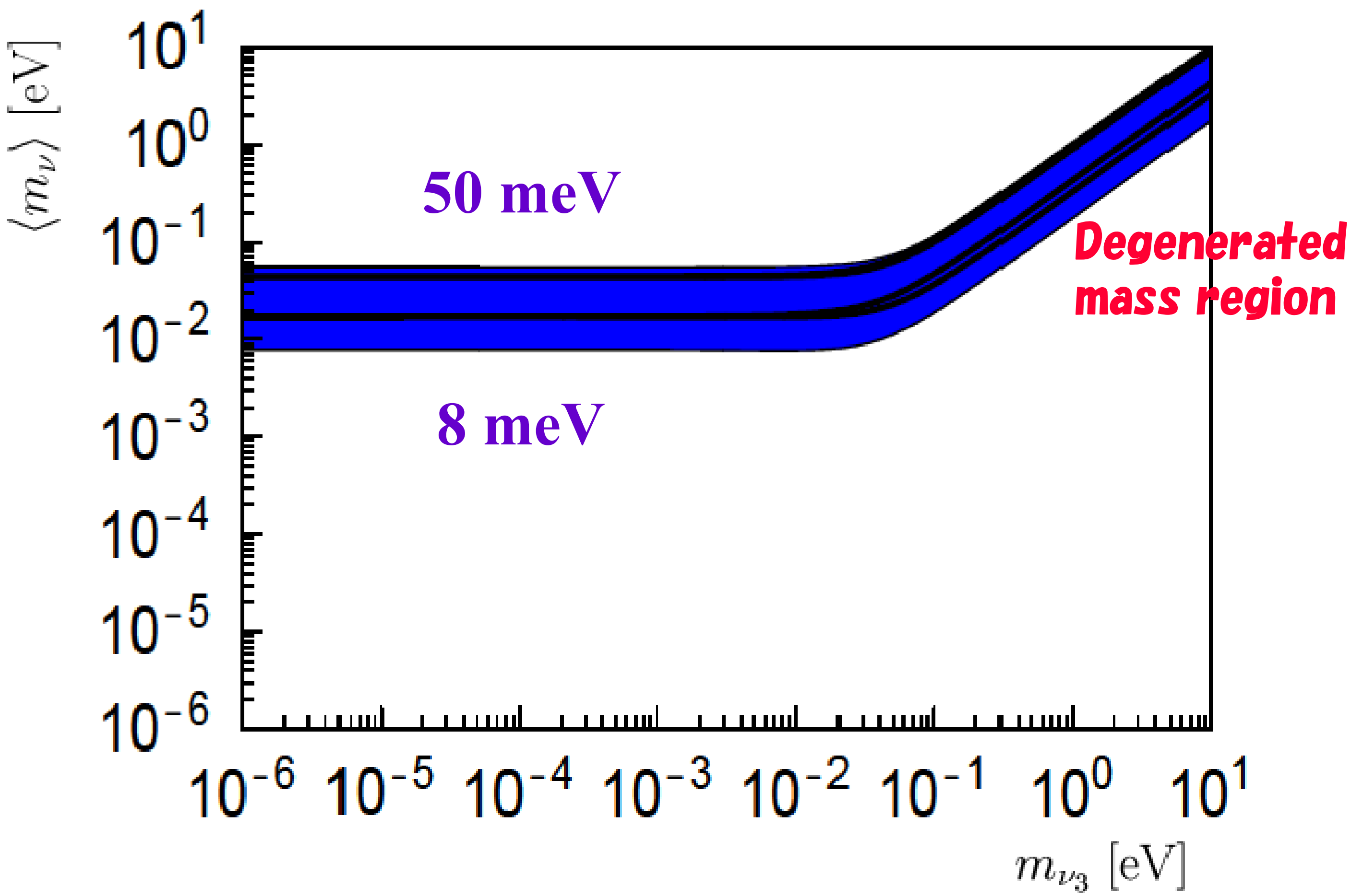

hierarchy, for which 3 different cases for the upper limit on $s^2_R$ are shown. These are $s^2_R \le 0.04$ (light blue), $s^2_R \le 0.025$ (medium blue), $s^2_R \le 0.005$ (darker blue).

**M. Hirsch : hep-ph/0609146**

**Inverted hierarchy**

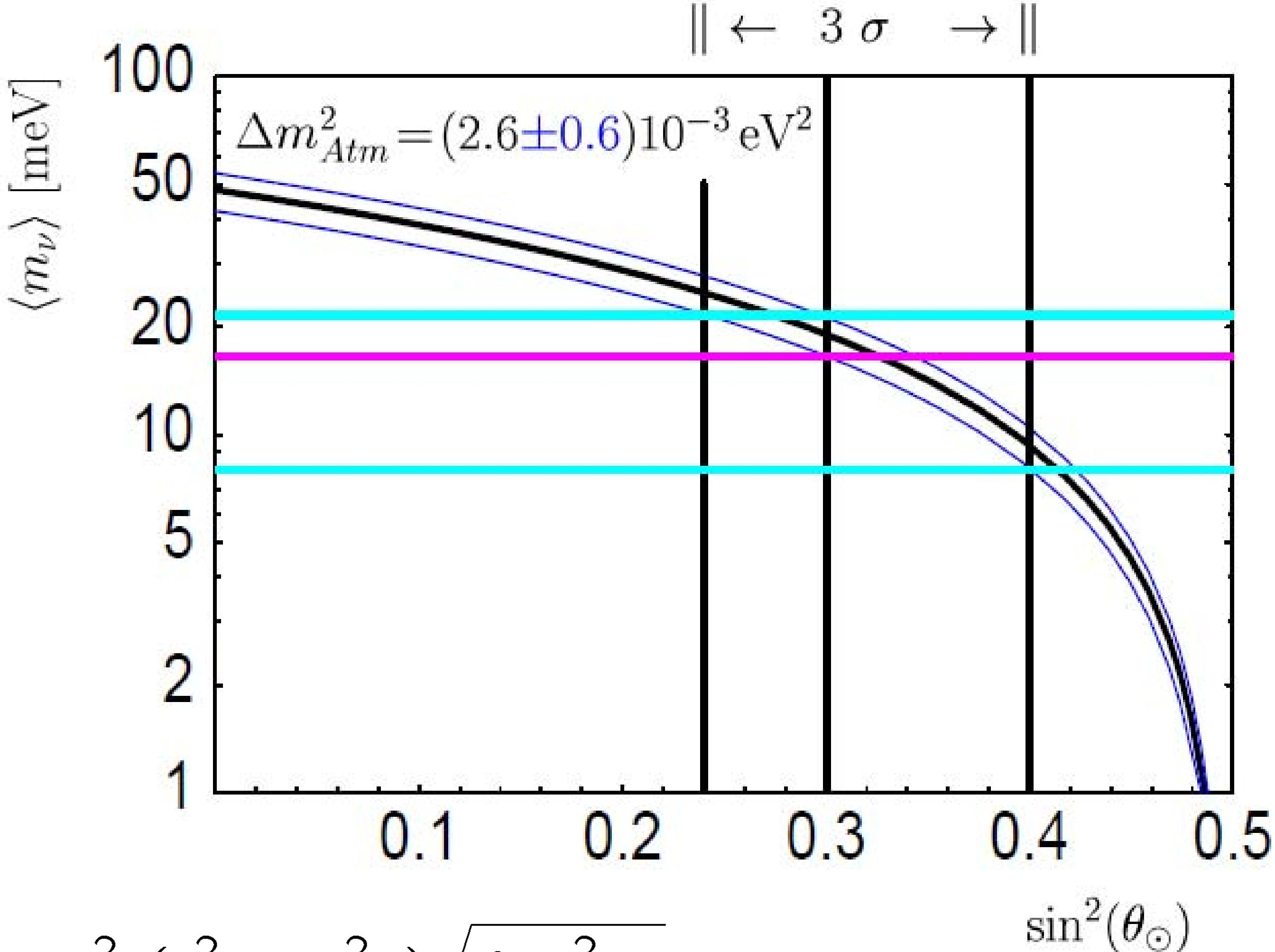
$$m_3 < m_1 < m_2$$

$$\langle m_\nu \rangle = c_{sun}^2 c_{rea}^2 \sqrt{m_3^2 - \Delta m_{sun}^2 + \Delta m_{atm}^2} + s_{sun}^2 c_{rea}^2 e^{i\alpha_1} \sqrt{m_3^2 + \Delta m_{atm}^2} + s_{rea}^2 e^{i\alpha_2} m_3$$



M. Hirsch : hep-ph/0609146 **Inverted hierarchy**

# Lower Limit 8meV




$$\langle m_\nu \rangle \simeq c_{13}^2 (c_{\mathrm{sol}}^2 - s_{\mathrm{sol}}^2) \sqrt{\Delta m^2_{\mathrm{Atm}}}$$

# 3 Neutrino Mass Matrix

**What is the impact on the models of neutrino mass matrix ?**

**Since there are a lot of models, it is difficult to distinguish models only by the neutrinoless double beta decay.**

**However, models can be tested within the framework of the specific flavor symetry, for example, A4 symmetry.**

**Let us show one example !**

# Experimental data favor
# Tri-Bi-Maximal mixings.

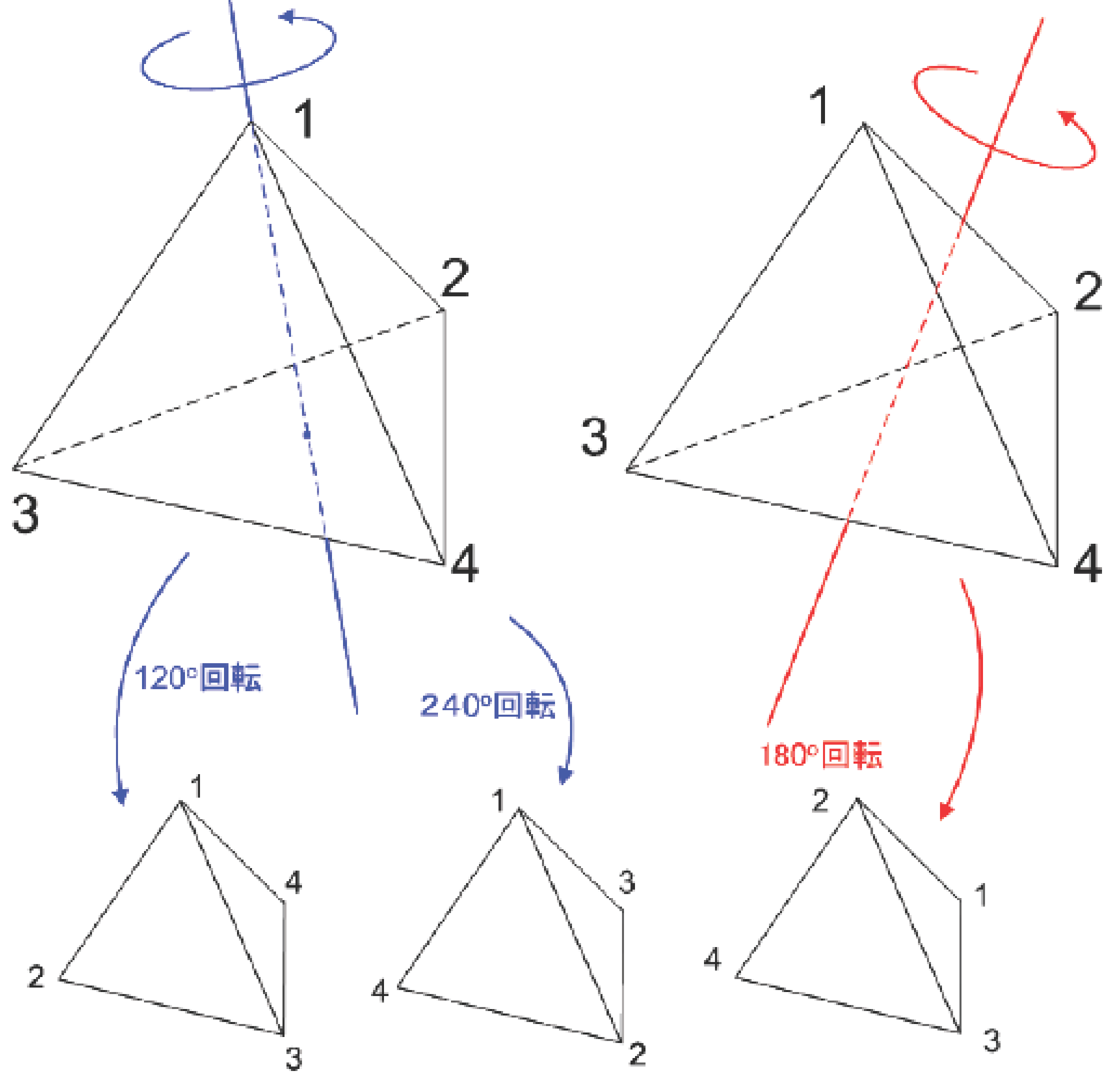
Harrison, Perkins, Scott (2002)

$$U_{\rm MNS} \sim \begin{pmatrix} \sqrt{\frac{2}{3}} & \frac{1}{\sqrt{3}} & 0 \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{2}} \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

$$\tan^2\theta_{12} = \frac{1}{2} \qquad \sin^2 2\theta_{23} = 1$$

$\theta_{12} \fallingdotseq 35^\circ$ $\theta_{23} = 45^\circ$ $\theta_{13} = 0$

# A4 flavor symmetry can easily realize (approximate or exact) Tri-Bi-maximal Mixing




**A4 symmetry**
**(Tetrahedral Symmetry)**

# Tetrahedral Symmetry $A_4$

For 3 families, we should look for a group with a $\underline{3}$ representation, the simplest of which is $A_4$, the group of the even permutation of 4 objects.

| class | $n$ | $h$ | $\chi_1$ | $\chi_{1'}$ | $\chi_{1''}$ | $\chi_3$ |
|---|---|---|---|---|---|---|
| $C_1$ | 1 | 1 | 1 | 1 | 1 | 3 |
| $C_2$ | 4 | 3 | 1 | $\omega$ | $\omega^2$ | 0 |
| $C_3$ | 4 | 3 | 1 | $\omega^2$ | $\omega$ | 0 |
| $C_4$ | 3 | 2 | 1 | 1 | 1 | –1 |

**1 1' 1" 3**

**by E. Ma**

$$\omega = \exp(2\pi i/3) = -1/2 + i\sqrt{3}/2$$

Multiplication rule:

$$\underline{3} \times \underline{3} = \underline{1}(11 + 22 + 33) + \underline{1}'(11 + \omega^2 22 + \omega 33)$$

$$+\underline{1}''(11 + \omega 22 + \omega^2 33) + \underline{3}(23, 31, 12) + \underline{3}(32, 13, 21).$$

Note that $\underline{3} \times \underline{3} \times \underline{3} = \underline{1}$ is possible in $A_4$,
i.e. $a_1 b_2 c_3$ + permutations,
and $\underline{2} \times \underline{2} \times \underline{2} = \underline{1}$ is possible in $S_3$,
i.e. $a_1 b_1 c_1 + a_2 b_2 c_2$.

**by E. Ma**

Hirsch, Ma, Moral, Valle: Phys. Rev. D72(2005)091301(R)

# Approximate Tribimaximal Mixing

| Fields | $L$ | $l^c$ | $\phi_1$ | $\phi_2$ | $\phi_3$ | $\eta_1$ | $\eta_2$ | $\eta_3$ | $\xi$ |
|---|---|---|---|---|---|---|---|---|---|
| $A_4$ | $\mathbf{3}$ | $\mathbf{3}$ | $\mathbf{1}$ | $\mathbf{1}'$ | $\mathbf{1}''$ | $\mathbf{1}$ | $\mathbf{1}'$ | $\mathbf{1}''$ | $\mathbf{3}$ |
| $SU(2)_L$ | $\mathbf{2}$ | $\mathbf{1}$ | $\mathbf{2}$ | $\mathbf{2}$ | $\mathbf{2}$ | $\mathbf{3}$ | $\mathbf{3}$ | $\mathbf{3}$ | $\mathbf{3}$ |
| $Y$ | $-1$ | 2 | $-1$ | $-1$ | $-1$ | 2 | 2 | 2 | 2 |

$L\, l^c \Phi i$ $3 \times 3 \times (1, 1', 1'')$ $\leftarrow$ **Diagonal matrix**

$L L \eta_i$ $3 \times 3 \times (1, 1', 1'')$ $L L \xi$ $3 \times 3 \times 3$

$$m_e = h_1 v_1 + h_2 v_2 + h_3 v_3$$
$$m_\mu = h_1 v_1 + \omega h_2 v_2 + \omega^2 h_3 v_3$$
$$m_\tau = h_1 v_1 + \omega^2 h_2 v_2 + \omega h_3 v_3$$

$< \Phi i > = v_1, v_2, v_3$

$$\omega = \exp(2\pi i/3)$$

$$M_\nu = \begin{pmatrix} a+b+c & f & e \\ f & a+\omega b+\omega^2 c & d \\ e & d & a+\omega^2 b+\omega c \end{pmatrix}$$

$$a = \lambda_1\langle\eta_1^0\rangle \qquad b = \lambda_2\langle\eta_2^0\rangle \qquad c = \lambda_3\langle\eta_3^0\rangle$$

$$d = \kappa\langle\xi_1^0\rangle \qquad e = \kappa\langle\xi_2^0\rangle \qquad f = \kappa\langle\xi_3^0\rangle$$

**Vacuum Alignment of ξ gives d=e=f**

$$\mathcal{M}_\nu = \begin{pmatrix} a+b+c & d & d \\ d & a+\omega b+\omega^2 c & d \\ d & d & a+\omega^2 b+\omega c \end{pmatrix}$$

Assume $b = c$ and rotate to the basis $[\nu_e, (\nu_\mu+\nu_\tau)/\sqrt{2}, (-\nu_\mu+\nu_\tau)/\sqrt{2}]$, then

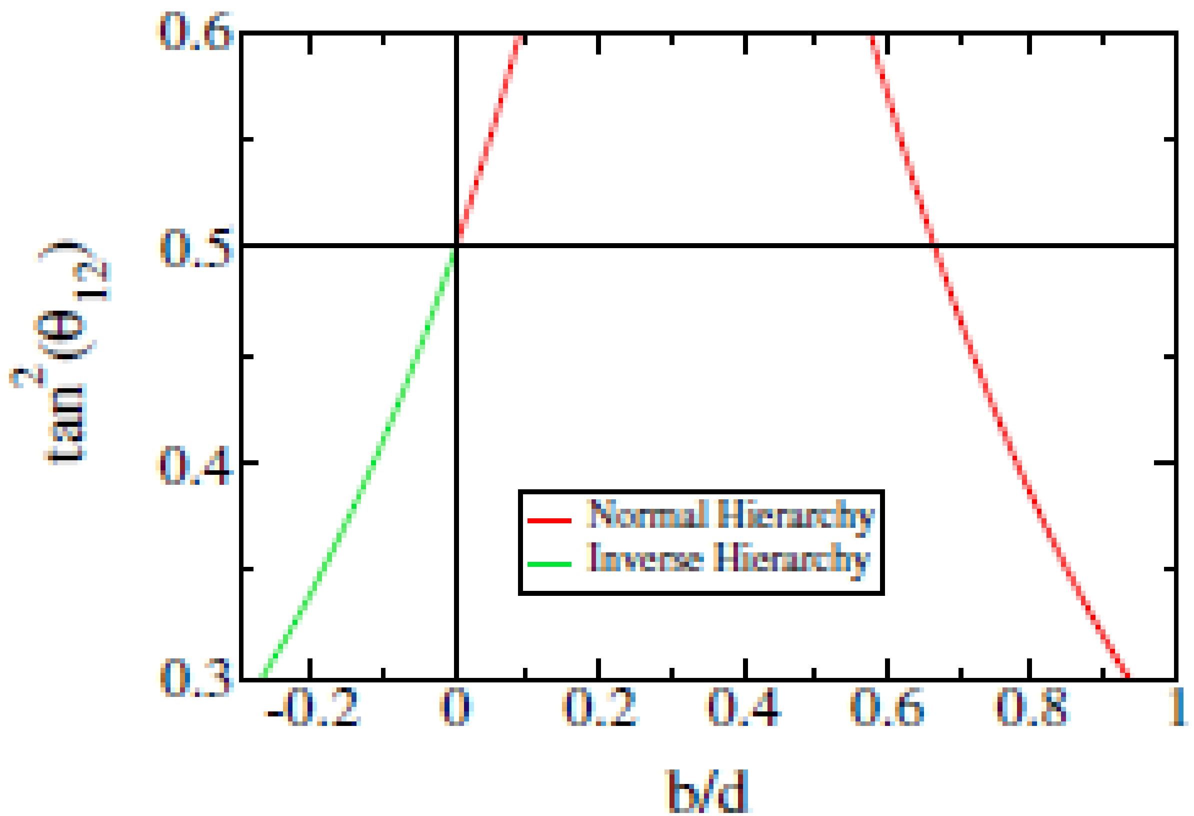
$$\mathcal{M}_\nu = \begin{pmatrix} a+2b & \sqrt{2}d & 0 \\ \sqrt{2}d & a-b+d & 0 \\ 0 & 0 & a-b-d \end{pmatrix},$$

i.e. maximal $\nu_\mu - \nu_\tau$ mixing and $U_{e3} = 0$.

$$t_{2s} = \tan(2\theta_{12}) = \frac{2\sqrt{2}d}{3b - d}$$

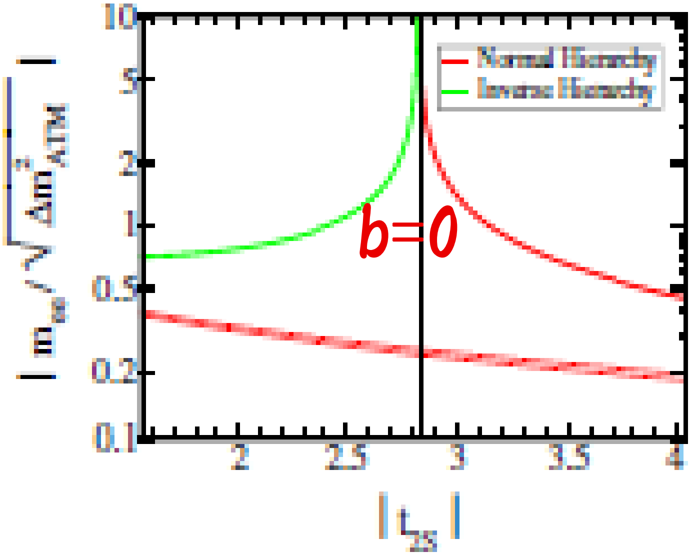
**depend on mass parameters**

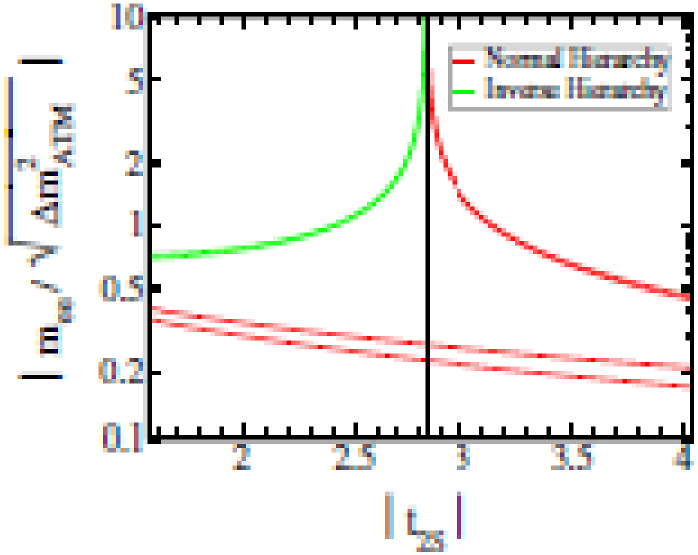
**Tri-Bi-Maximal mixings if b=0 or b=2/3 d**



$$\langle m_\nu \rangle = M_\nu(1,1) = a + b + c = a + 2b$$

$\frac{\Delta m^2_{\rm sol}}{\Delta m^2_{\rm atm}} =$ 0.022 0.065




**Lower Bound**

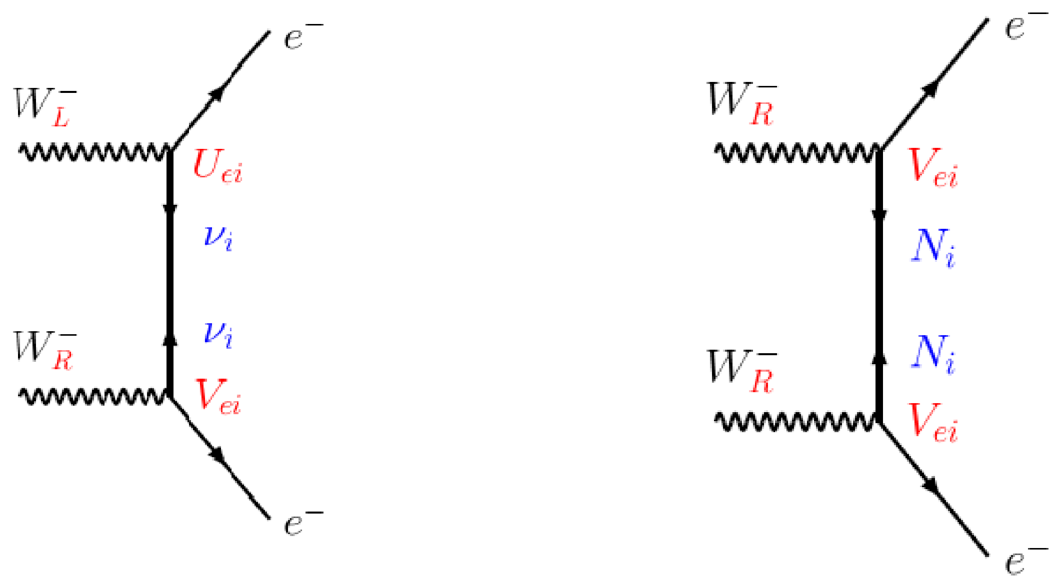
$0.17 < |\langle m_\nu \rangle / \sqrt{\Delta m^2_{\rm atm}}|$ for NH

$0.70 < |\langle m_\nu \rangle / \sqrt{\Delta m^2_{\rm atm}}|$ for IH

## 4 New Physics of Neutrinoless Double Beta Decay

# New Physics 1

### Right-handed W Bosons at 1 TeV Scale




**$^{76}$Ge half-live of $T^{1/2} > 1.2 \times 10^{25}$ ys**

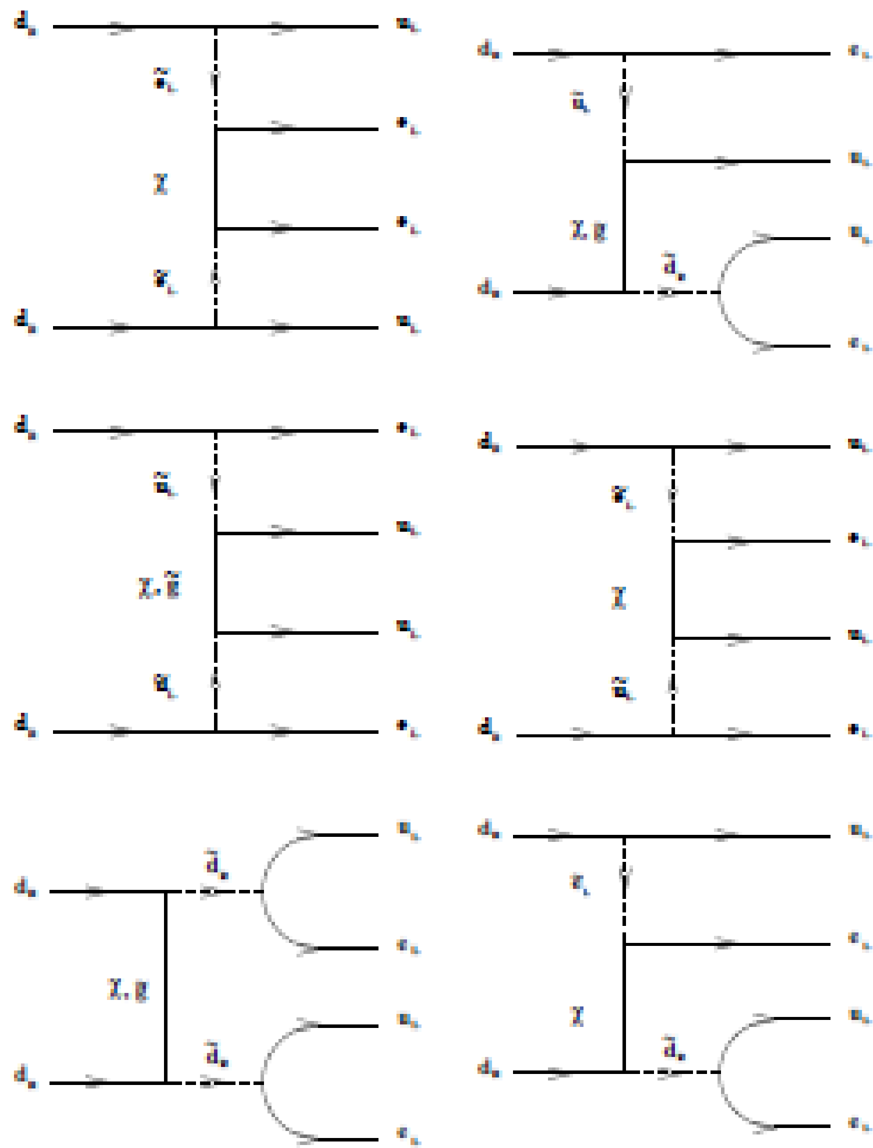
# New Physics 2

**Assume**
**R-parity**
**Violation**
**In SUSY**

**Appear**
**Lepton number**
**violating terms**

$$\mathcal{L} = -\lambda'_{111}\left[(\bar{e}_L \bar{\nu}_L)_j (d_R)_k \cdot \begin{pmatrix} \tilde{u}_L^* \\ -\tilde{d}_L^* \end{pmatrix}_j + \ldots + h.c.\right]$$

$$\lambda'_{111} \leq 3.2 \times 10^{-4} \left(\frac{m_{\tilde{q}}}{100\mathrm{GeV}}\right)^2 \left(\frac{m_g}{100\mathrm{GeV}}\right)^{1/2}$$



# New Physics 3

## Sterile Neutrinos

A Yu.Smirnov, and R Z.Funchal , PRD74(2006)013001

$$\begin{pmatrix} m_a & m_{aS} \\ m_{aS}^T & m_S \end{pmatrix} \Rightarrow (m_\nu)_{ij} \simeq (m_a)_{ij} + (m_I)_{ij}$$

$m_a$ : 3 × 3 active neutrino mass matrix

$$m_I \equiv -\frac{m_{aS} m_{aS}^T}{m_S} \qquad \sin\theta_{jS} \approx \frac{m_{jS}}{m_S}$$

$$(m_I)_{ij} = -\sin\theta_{iS}\sin\theta_{jS} m_S \Rightarrow -\sin^2\theta_S m_S$$

**if flavor blind mixing**

# New Physics 3

## Sterile Neutrinos

$$A^{(S)} \propto \frac{(m_I)_{ee}}{\overline{q}^2 - m_\nu^2} + \frac{m_S \sin^2\theta_{eS}}{\overline{q}^2 - m_S^2}, \qquad \overline{q} \approx 100\text{MeV}$$

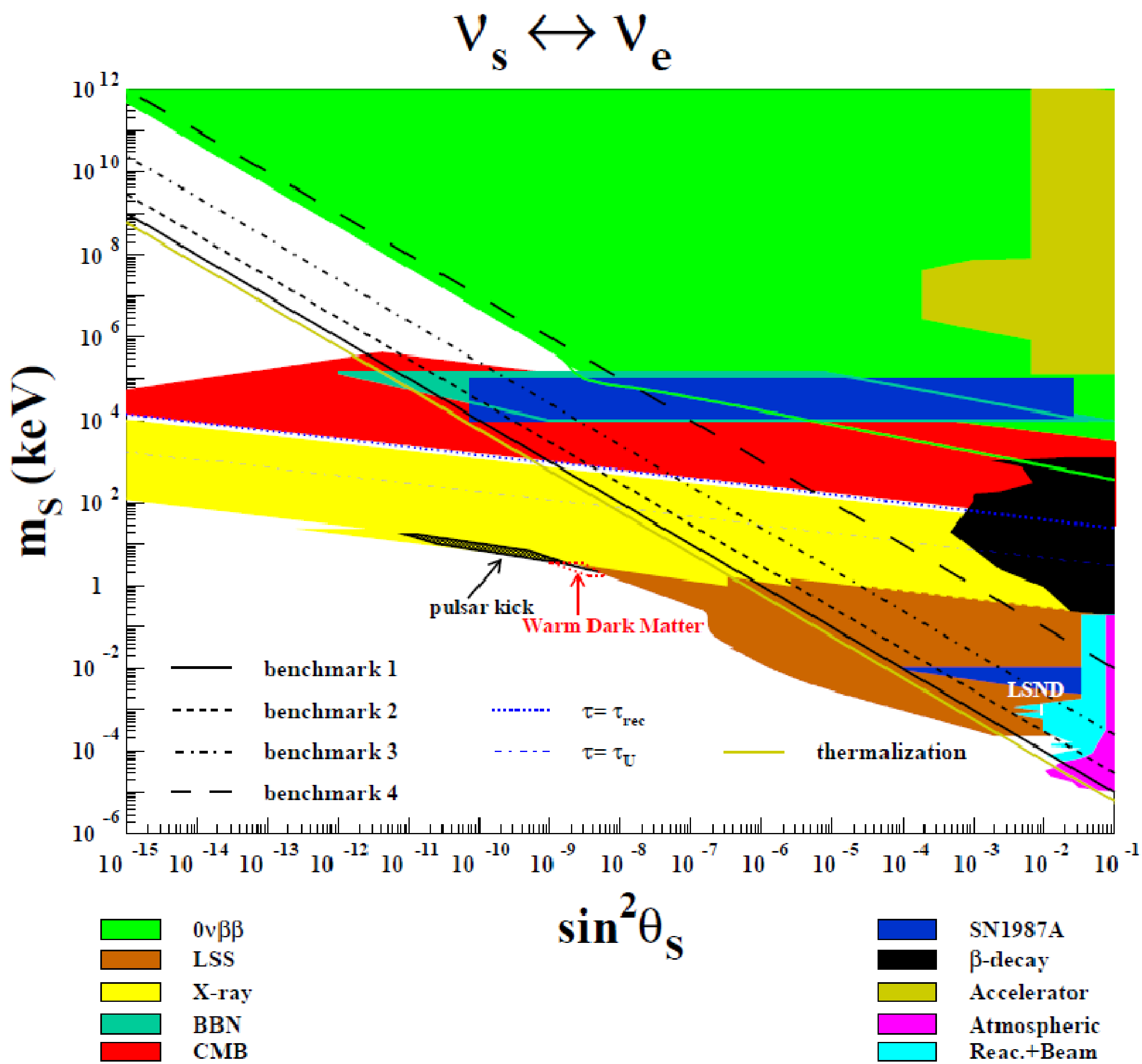
**If $m_S^2 << \bar{q}^2$,** $A^{(S)}$ is small due to $(m_I)_{ee} = -\sin^2\theta_{eS} m_S$ .

**If $m_S^2 >> \bar{q}^2$, the second term is neglected.**

**Since there is no cancellation, then** $\langle m_\nu^S \rangle = m_S \ \sin^2\theta_{eS}$

Future bound $\langle m_\nu \rangle < 30$ meV

will improve the bound on $\sin^2\theta_{eS}$ by a factor 10.



$\nu_s \leftrightarrow \nu_e$
$m_S$ (keV)
$\sin^2\theta_S$
pulsar kick
Warm Dark Matter
LSND
benchmark 1
benchmark 2
benchmark 3
benchmark 4
$\tau = \tau_{rec}$
$\tau = \tau_U$
thermalization
0νββ
LSS
X-ray
BBN
CMB
SN1987A
β-decay
Accelerator
Atmospheric
Reac.+Beam

# 5 Future

Are Neutrinos Majorana Particle ?

If yes, L number is violated !

Leptogenesis can be realized.

"Origin of Baryon Asymmetry"

By measurement of $\langle m_\nu \rangle$ :

Neutrino mass hierarchy is tested.

Some neutrino mass matrix is tested.

New physics bounds are given.

If not, Neutrino is Dirac Particle !

Why are neutrino masses tiny ? Extra Dimensions ?

Neutrinoless Double Beta Decay Experiments can give big answer "Majorana or not" !