Phenomenology of Double Beta Decay

M. Hirsch

Astroparticle and High Energy Physics Group
IFIC/CSIC - València, Spain

Contents

- Introduction: The Black Box
- Limits on BSM
- $0\nu\beta\beta$ decay and neutrino oscillations

$\mathcal{I}.$

The black box

Basic factors in $0\nu\beta\beta$ decay

$$\left[T_{1/2}^{0\nu\beta\beta}\right]^{-1} = \left(\sum_i \langle\epsilon_i\rangle \mathcal{M}_{\epsilon_i}\right)^2 F^{0\nu\beta\beta}$$

$F^{0\nu\beta\beta}$ - phase space integral

Basic factors in $0\nu\beta\beta$ decay

$$\left[T_{1/2}^{0\nu\beta\beta}\right]^{-1} = \left(\sum_i \langle\epsilon_i\rangle \mathcal{M}_{\epsilon_i}\right)^2 F^{0\nu\beta\beta}$$

$F^{0\nu\beta\beta}$ - phase space integral

$\mathcal{M}_{\epsilon_i}$ - nuclear matrix element Simkovic

Basic factors in $0\nu\beta\beta$ decay

$$\left[T_{1/2}^{0\nu\beta\beta}\right]^{-1} = \left(\sum_i \langle\epsilon_i\rangle \mathcal{M}_{\epsilon_i}\right)^2 F^{0\nu\beta\beta}$$

$F^{0\nu\beta\beta}$ - phase space integral

$\mathcal{M}_{\epsilon_i}$ - nuclear matrix element

$T_{1/2}^{0\nu\beta\beta}$ - experimental input

Elliott, Barabash

Schönert, Piepke

Maruyama, Wilson

Basic factors in $0\nu\beta\beta$ decay

$$\left[T_{1/2}^{0\nu\beta\beta}\right]^{-1} = \left(\sum_i \langle\epsilon_i\rangle \mathcal{M}_{\epsilon_i}\right)^2 F^{0\nu\beta\beta}$$

$F^{0\nu\beta\beta}$ - phase space integral

$\mathcal{M}_{\epsilon_i}$ - nuclear matrix element

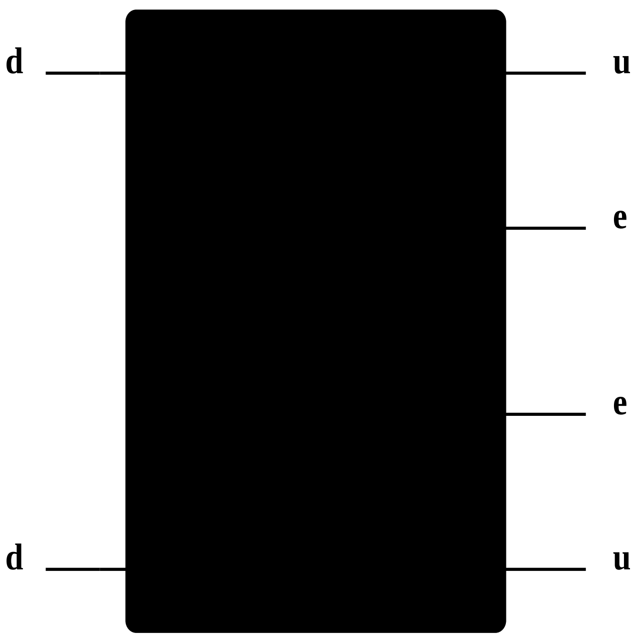
$T_{1/2}^{0\nu\beta\beta}$ - experimental input

$\langle\epsilon_i\rangle$ - particle physics factor

Black Box I.

Ideally experiments detect appearance of two electrons:

$$L = 0 \quad \Rightarrow \quad L = 2?$$



Observables?

i) Sum energy $\Rightarrow 0\nu\beta\beta$

ii) $\#$ Events $\Rightarrow$ Half-life

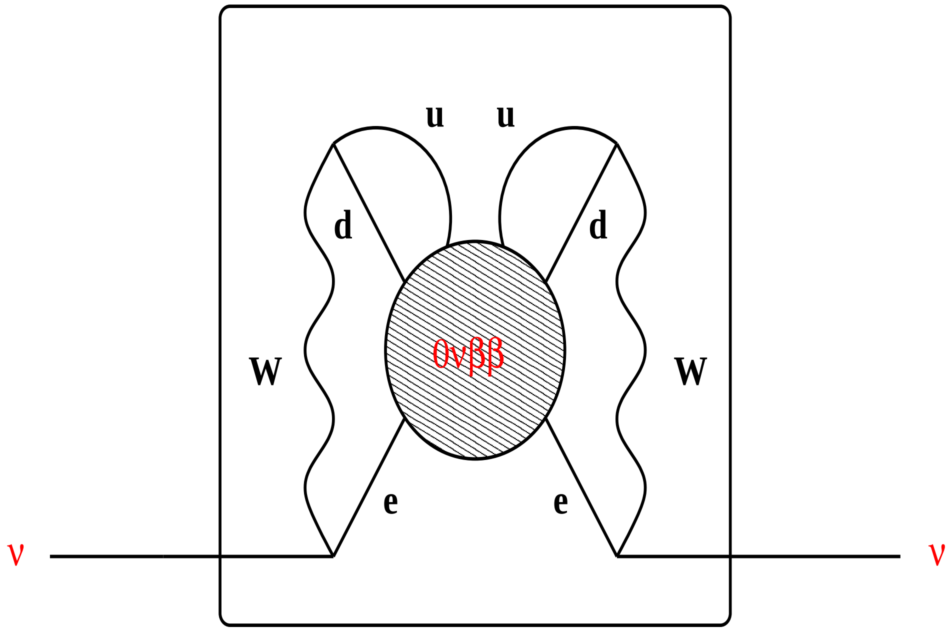
iii) Type of current (?)

(a) Angular correlation

(b) $\beta^+\beta^+$ versus β^+/EC

Black Box II.

In any gauge theory one can show that:



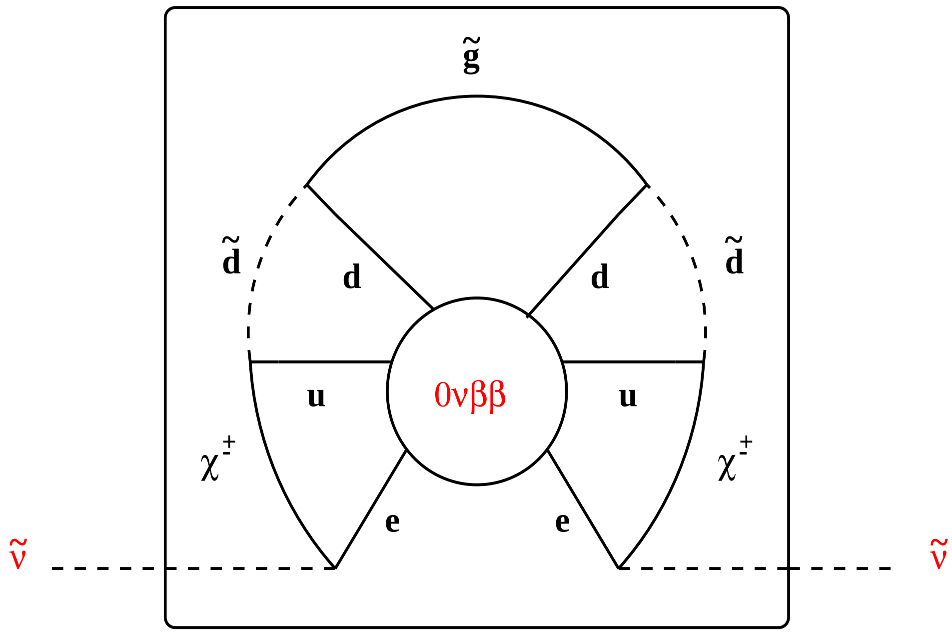
Schechter & Valle,
Takasugi

If $0\nu\beta\beta$
is observed
the neutrino is a
Majorana particle!

Qualitative statement only:
$\longrightarrow$ Value of m_ν depends on model

SUSY Black Box

In any supersymmetric gauge theory:



Hirsch, Klapdor-Kleingrothaus & Kovalenko

If $0\nu\beta\beta$ observed the scalar neutrino has a $\not{L}$ mass!

$\Rightarrow$ $0\nu\beta\beta$ decay, Majorana neutrinos and $\not{L}$ in scalar sector inseparably connected.

$\mathcal{II}.$

Limits from $0\nu\beta\beta$ decay

(a) Left-right symmetric models

(b) $\not{R}_P$ SUSY

Left-right symmetric models

In the notation of DKT:

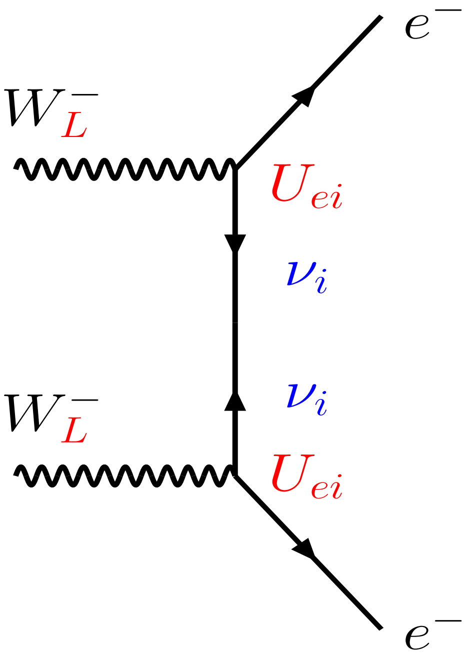
$$\mathcal{H}_W^{CC} = \frac{G}{\sqrt{2}}\left\{ J^{\dagger}_{\mu L} j^{-}_{\mu_L} + \kappa J^{\dagger}_{\mu R} j^{-}_{\mu_L} + \eta J^{\dagger}_{\mu L} j^{-}_{\mu_R} + \lambda J^{\dagger}_{\mu R} j^{-}_{\mu_R} \right\}$$

where

$$J^{\dagger}_{\mu_\alpha} = \overline{u}\gamma_\mu d_\alpha \qquad \text{and} \qquad j^{-}_{\mu_\alpha} = \overline{e}\gamma_\mu \nu_\alpha$$

Note: $\kappa \simeq \eta \simeq \tan\zeta$ and $\lambda \simeq (m_{W_L}/m_{W_R})^2$

Mass mechanism



Define in the limit of small neutrino masses:

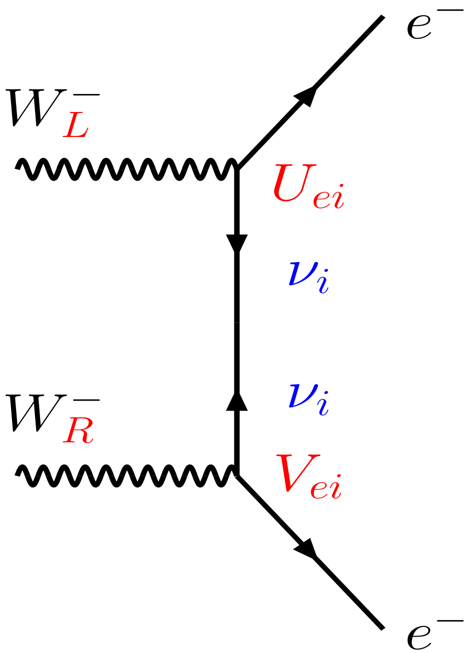
$$\langle m_\nu \rangle = \sum_i U_{ei}^2 m_{\nu_i}$$

Assume: $T_{1/2}^{0\nu\beta\beta}(^{76}Ge) \geq 1.2 \cdot 10^{25}$ ys:

$\Rightarrow \mathcal{M}_{m_\nu}$ Muto 97: $\langle m_\nu \rangle \sim 0.45$ eV

$\Rightarrow \mathcal{M}_{m_\nu}$ Rodin et al. 05: $\langle m_\nu \rangle \sim 0.6$ eV

Long range LR



Define in the limit
of small neutrino masses:

$$\langle\lambda\rangle = \lambda \sum_i U_{ei} V_{ei}$$

$$\langle\eta\rangle = \eta \sum_i U_{ei} V_{ei}$$

Assume: $T_{1/2}^{0\nu\beta\beta}(^{76}Ge) \geq 1.2 \cdot 10^{25}$ ys:

$$\Rightarrow \langle\lambda\rangle \lesssim 7.9 \cdot 10^{-7}, \quad \langle\eta\rangle \lesssim 4.3 \cdot 10^{-9}$$

Limit from long range LR?

“Seesaw“ motivated estimation:

$$\sum_i U_{ei} V_{ei} \sim \frac{m_D}{M_M} \sim \sqrt{\frac{m_\nu}{M_M}}$$

Limit from long range LR?

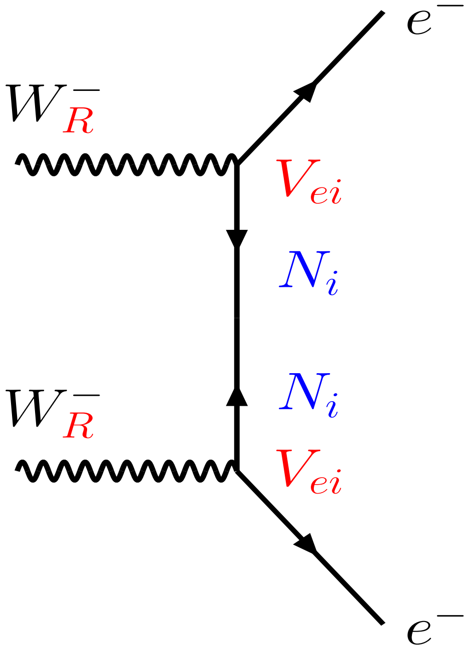
"Seesaw" motivated estimation:

$$\sum_i U_{ei} V_{ei} \sim \frac{m_D}{M_M} \sim \sqrt{\frac{m_\nu}{M_M}}$$

Recall: $\lambda \simeq (m_{W_L}/m_{W_R})^2$

$$m_{W_R} \gtrsim 1.1\, m_{W_L} \, (\frac{m_\nu}{1\mathrm{eV}})^{1/4} (\frac{M_M}{1\mathrm{TeV}})^{-1/4}$$

Short range LR



Define in the limit of large neutrino masses:

$$\frac{1}{\langle m_N \rangle} = \sum_i \frac{V_{ei}^2}{m_{N_i}}$$

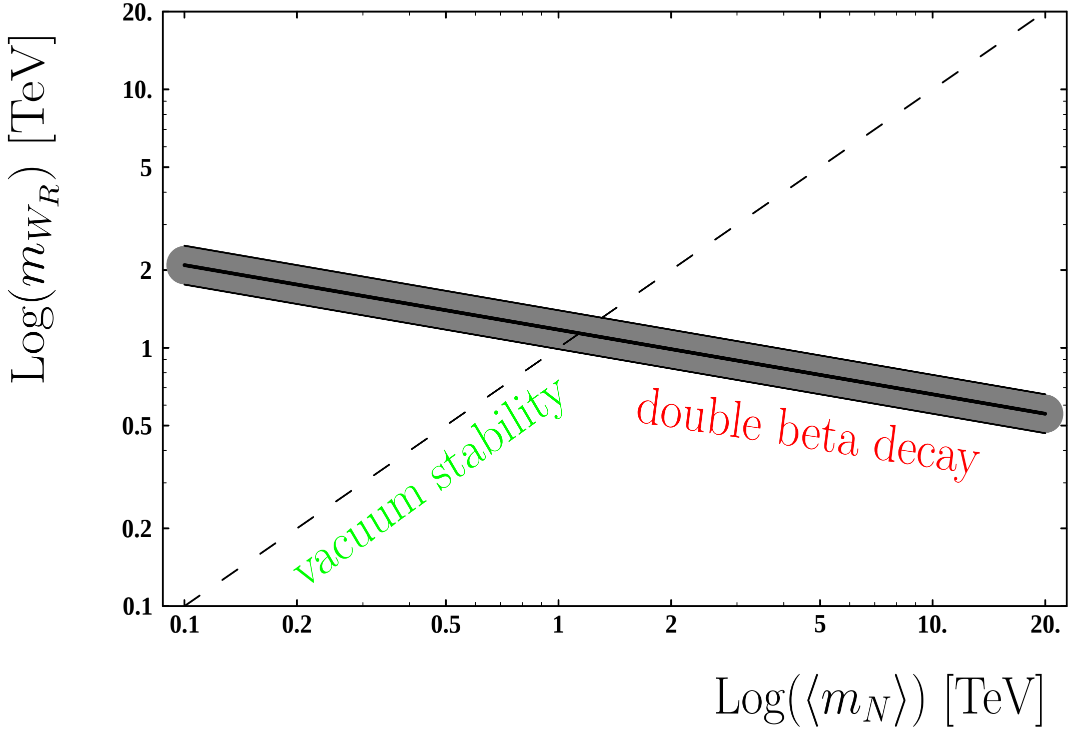
Define $\not{L}$ parameter:

$$\langle \epsilon \rangle = \frac{\lambda^2}{\langle m_N \rangle}$$

Assume: $T_{1/2}^{0\nu\beta\beta}(^{76}Ge) \geq 1.2 \cdot 10^{25}$ ys:

$$\Rightarrow \langle \epsilon \rangle \lesssim 1.4 \cdot 10^{-8}$$

Limit on m_{W_R} *from* $0\nu\beta\beta$



Mohapatra

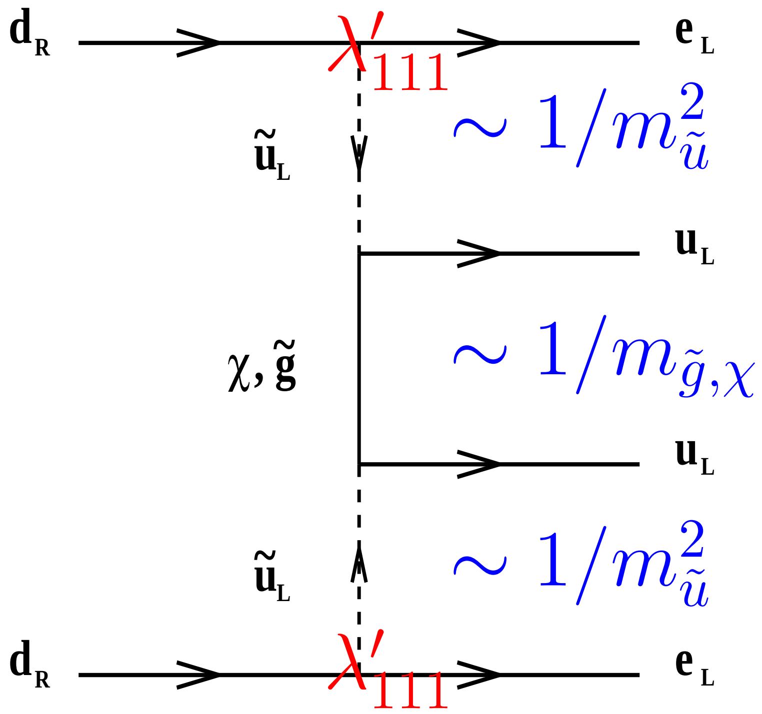
Hirsch et al.

Note: Width of band indicates NME uncertainty of ~ 2

$$m_{W_R} \gtrsim 1.3 \left(\frac{\langle m_N \rangle}{[1\text{TeV}]} \right)^{-1/4} \text{TeV}$$

$\not{R}_P$ $0\nu\beta\beta$ decay

Example graph:



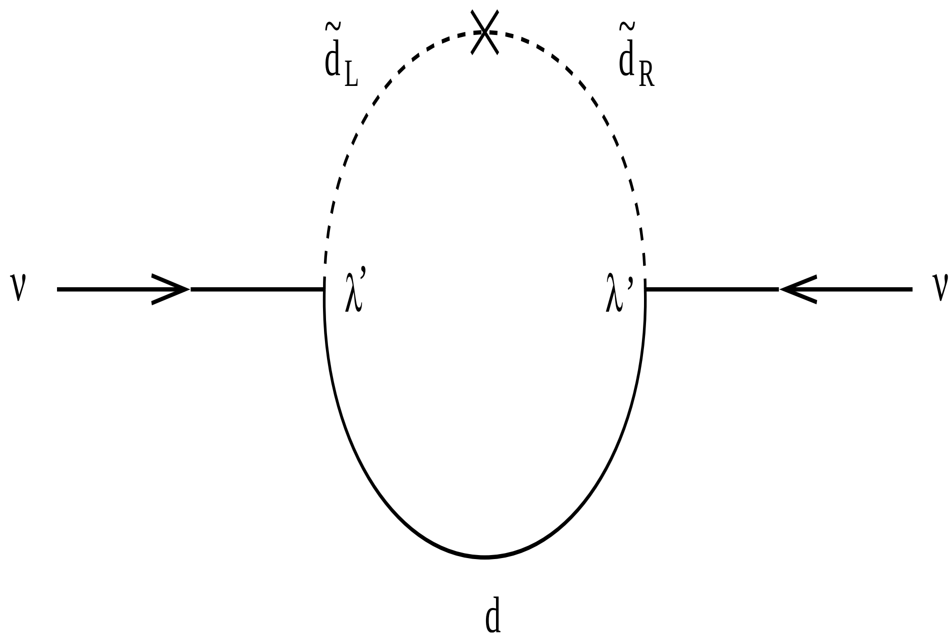
Vergados
Mohapatra
Hirsch et al.

Amplitude
$\sim$ 2 RPV vertices,
but limit
very stringent

Lengthy calculation:

$$\lambda'_{111} \leq 3 \times 10^{-4} \left(\frac{m_{\tilde{q}}}{100\mathrm{GeV}}\right)^2 \left(\frac{m_g}{100\mathrm{GeV}}\right)^{1/2}$$

Neutrino mass?



$$m_\nu \simeq 10^{-6}\mathrm{eV}\Big(\frac{\lambda'_{111}}{3\times 10^{-4}}\Big)^2\Big(\frac{m_{SUSY}}{100\mathrm{GeV}}\Big)^{-1}$$

$$\mathcal{III}.$$

$$\langle m_\nu \rangle$$

and neutrino oscillations

Kim, 1996; Minakata & Yasuda, 1996; Hirsch & Klapdor-Kleingrothaus, 1997; Bilenky, Giunti & Monteno, 1997; Fukuyama, Matsuda & Nishiura, 1997; Bilenky, Giunti, Kim & Monteno, 1998; Fukuyama, Matsuda & Nishiura, 1998; Vissani, 1999; Giunti, 1999; Bilenky, Giunti, Grimus, Kayser & Petcov, 1999; Ma, 1999; Wodecki & Kaminsky, 2000; Kalliomaki & Maalampi, 2000; Rodejohann, 2000; Matsuda, Takeda, Fukuyama & Nishiura, 2000; Klapdor-Kleingrothaus, Päs & Smirnov, 2001; Falcone & Tramontano, 2001; Bilenky, Pascoli & Petcov, 2001; Xing, 2001; Osland & Vigdel, 2001; Pascoli & Petcov, 2001; Barger, Glashow, Marfatia & Whisnant, 2002; Hambye, 2002; Minakata & Sugiyama, 2002; Klapdor-Kleingrothaus & Sarkar, 2002; Xing, 2002; Haba & Suzuki, 2002; Pakvasa & Roy, 2002; Rodejohann, 2002; Haba, Nakamura & Suzuki, 2002; Päs & Weiler, 2002; Barger, Glashow , Langacker, Marfatia, 2002; Civitarese & Suhonen, 2002; Pascoli, Petcov & Rodejohann, 2002; Sugiyama, 2002; Avignone & King, 2002; Minakata & Sugiyama, 2002; Cheung, 2003; Abada & Bhattacharyya, 2003; Giunti, 2003; Pascoli & Petcov, 2003; Elliott, 2003; Stoica, 2004; Brahmachari, 2004; Bilenky, Fäßler & Simkovic, 2004; Pascoli & Petcov; 2004; Deppisch, Päs & Suhonen, 2004; Joniec & Zralek, 2004; Pascoli & Petcov, 2005; Pascoli, Petcov & Schwetz, 2005; Goswami & Rodejohann, 2005; Choubey & Rodejohann, 2005; Bilenky, Fäßler, Gutsche, & Simkovic, 2005; Lindner, Merle & Rodejohann, 2005;

$\langle m_\nu \rangle$ and ν spectrum

Neutrinos mix, thus:

$$\begin{aligned} \langle m_\nu \rangle &= \sum_j U_{ej}^2 m_j \\ &= c_{12}^2 c_{13}^2 m_1 + s_{12}^2 c_{13}^2 e^{i\alpha} m_2 + s_{13}^2 e^{i\beta} m_3 \end{aligned}$$

A priori seven unknown quantities:

$\Rightarrow$ 3 masses: m_i

$\Rightarrow$ 2 angles: θ_{12} and θ_{13}

$\Rightarrow$ 2 CP violating phases: α and β

$\langle m_\nu \rangle$ and ν spectrum

Neutrinos mix, thus:

$$\begin{aligned} \langle m_\nu \rangle &= \sum_j U_{ej}^2 m_j \\ &= c_{12}^2 c_{13}^2 m_1 + s_{12}^2 c_{13}^2 e^{i\alpha} m_2 + s_{13}^2 e^{i\beta} m_3 \end{aligned}$$

+ Neutrino oscillation data:

$\Rightarrow$ 1 mass: m_{ν_1} + $\Delta m^2_{\rm Atm}$, $\Delta m^2_\odot$

$\Rightarrow$ 2 angles: $\theta_\odot$ and θ_R

$\Rightarrow$ 2 CP violating phases: α and β

Expectations for $\langle m_\nu \rangle$?

Current oscillation experiments can not tell difference between normal and inverse hierarchy. Can $0\nu\beta\beta$ help?

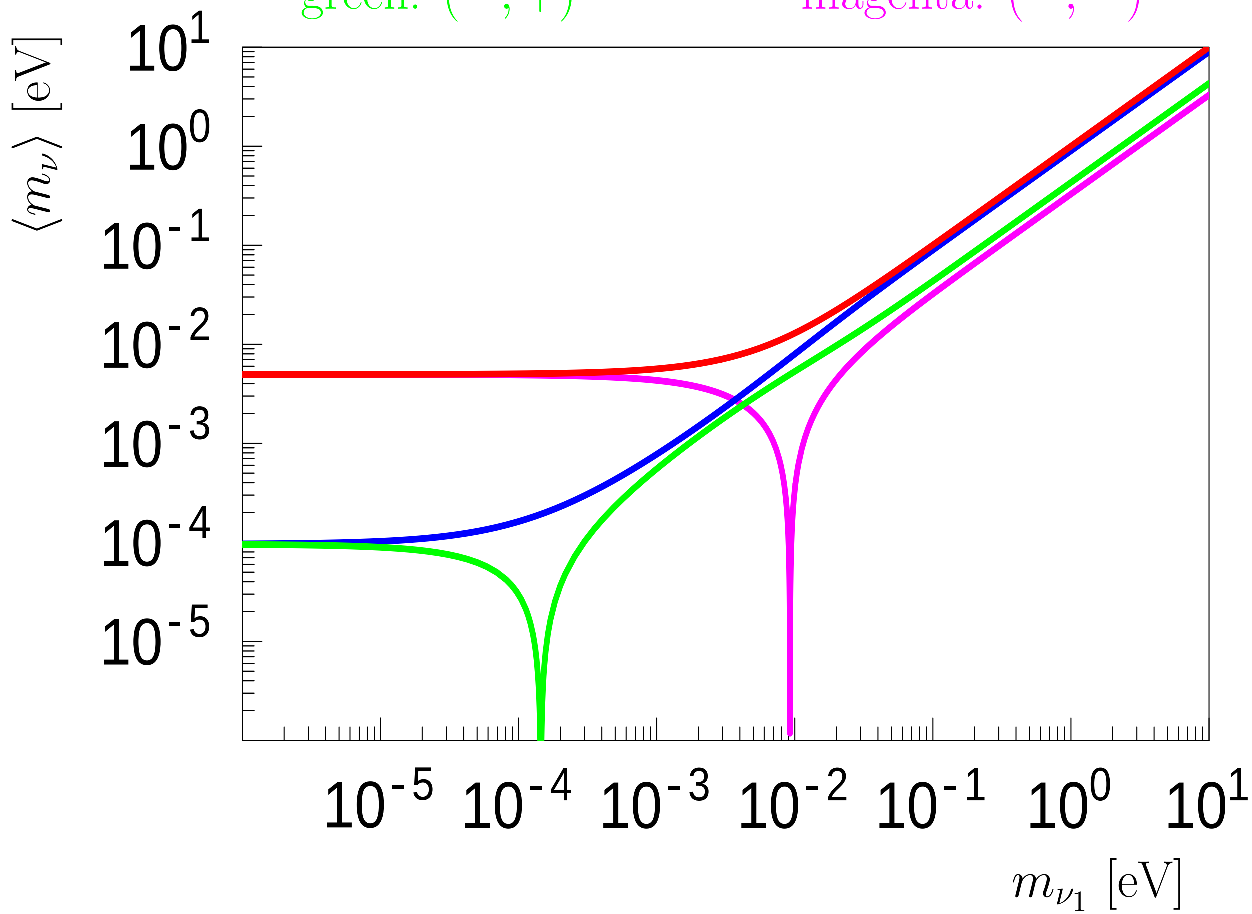
Normal hierarchy: $\langle m_\nu \rangle \simeq s_{12}^2 \sqrt{\Delta m_\odot^2} \simeq 3 \times 10^{-3}$ eV

Inverse hierarchy: $\langle m_\nu \rangle \simeq \sqrt{\Delta m_{Atm}^2} \simeq 5 \times 10^{-2}$ eV

$0\nu\beta\beta$ and ν oscillations

red: $(+,+)$ blue: $(+,-)$

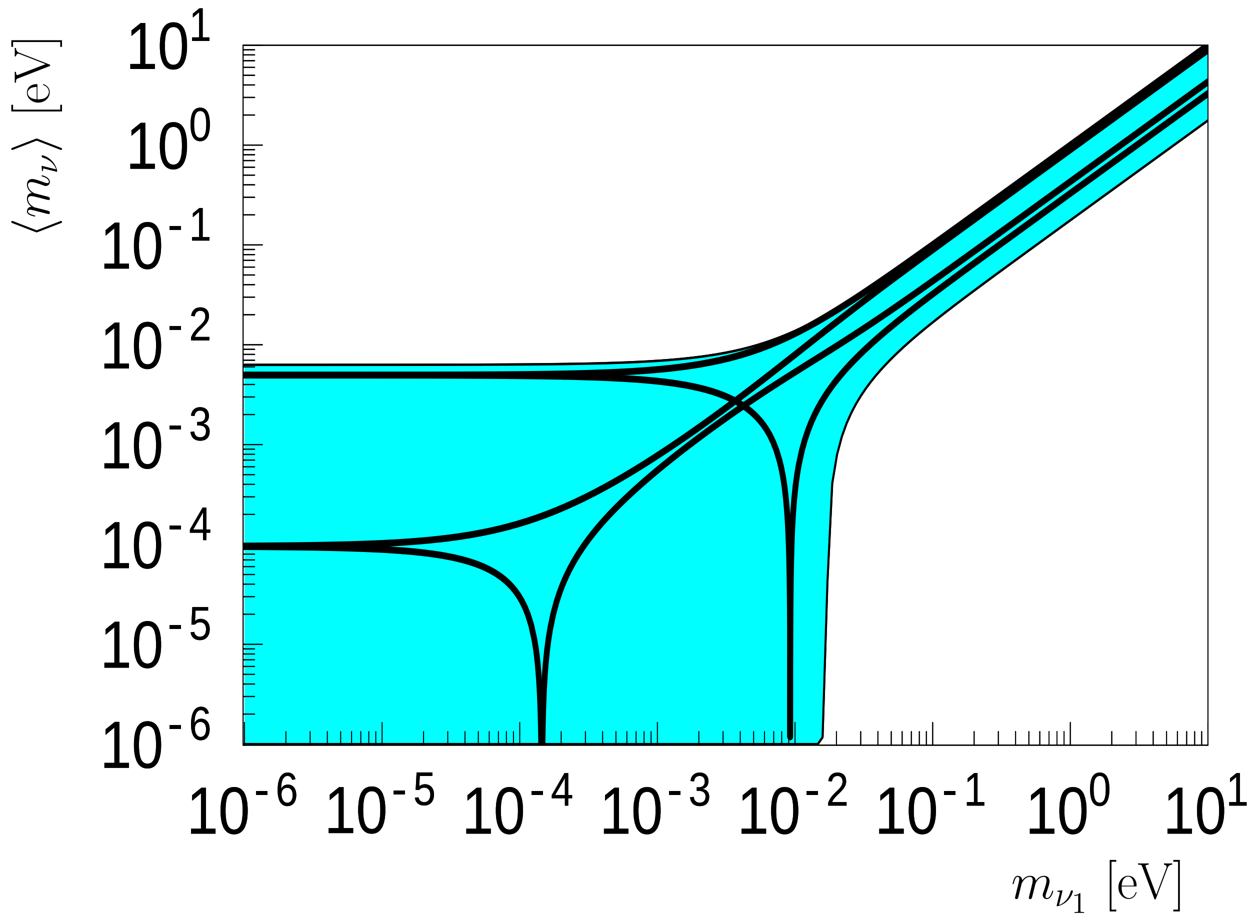
green: $(-,+)$ magenta: $(-,-)$



$$\Delta m^2_{Atm} = 2.2 \cdot 10^{-3}\ \text{eV}^2, \qquad \Delta m^2_\odot = 8.1 \cdot 10^{-5}\ \text{eV}^2,$$

$$\sin^2\theta_\odot = 0.3, \qquad \sin^2\theta_R = 0.051$$

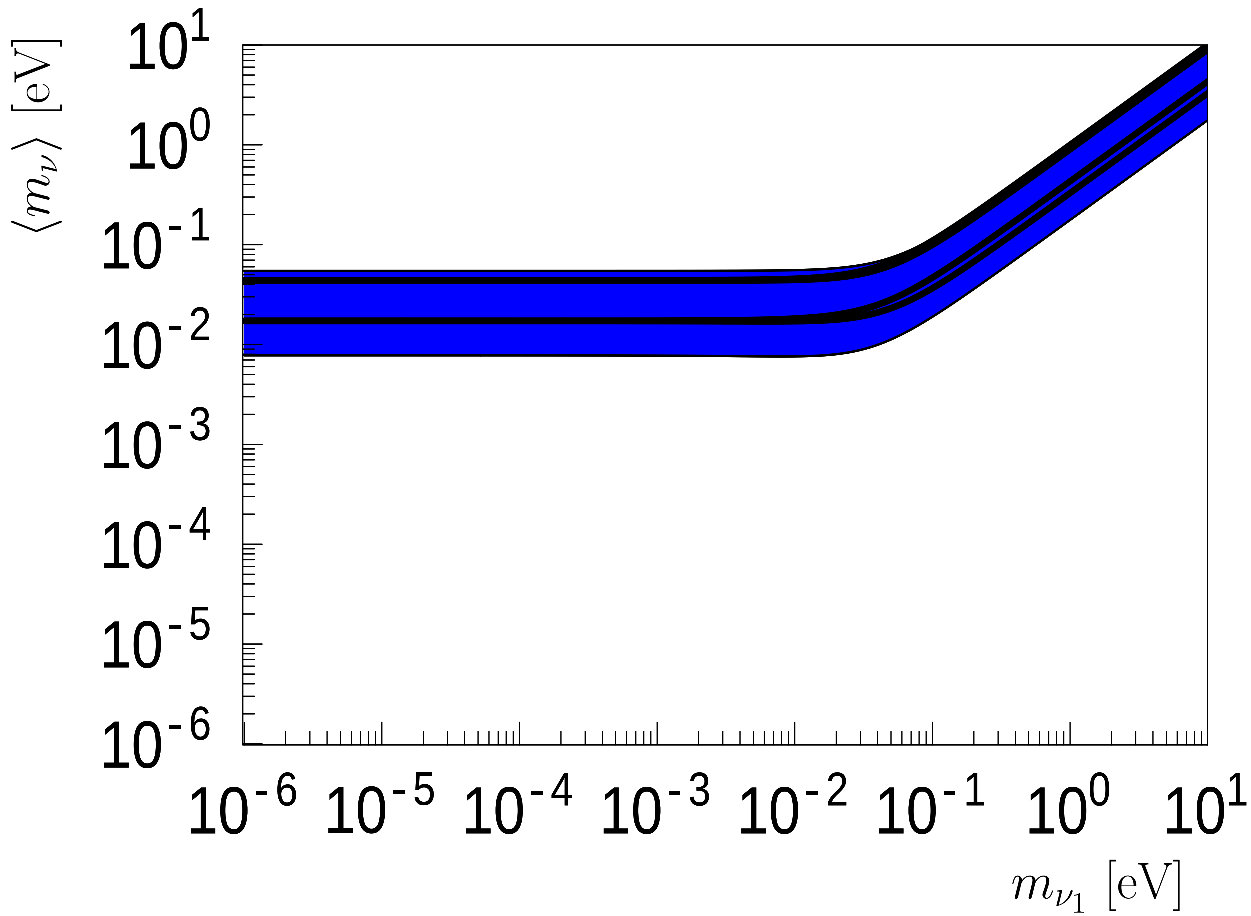
$0\nu\beta\beta$ and ν oscillations



$\Delta m^2_{Atm} = [1.4, 3.3] \cdot 10^{-3}$ eV^2, $\Delta m^2_{\odot} = [7.2, 9.1] \cdot 10^{-5}$ eV^2,

$\sin^2\theta_{\odot} = [0.23, 0.38]$, $\sin^2\theta_R = [0, 0.051]$

Inverse hierarchy



$\Delta m^2_{Atm} = [1.4, 3.3] \cdot 10^{-3}$ eV^2, $\quad \Delta m^2_\odot = [7.2, 9.1] \cdot 10^{-5}$ eV^2,

$\sin^2 \theta_\odot = [0.23, 0.38]$, $\quad \sin^2 \theta_R = [0, 0.051]$

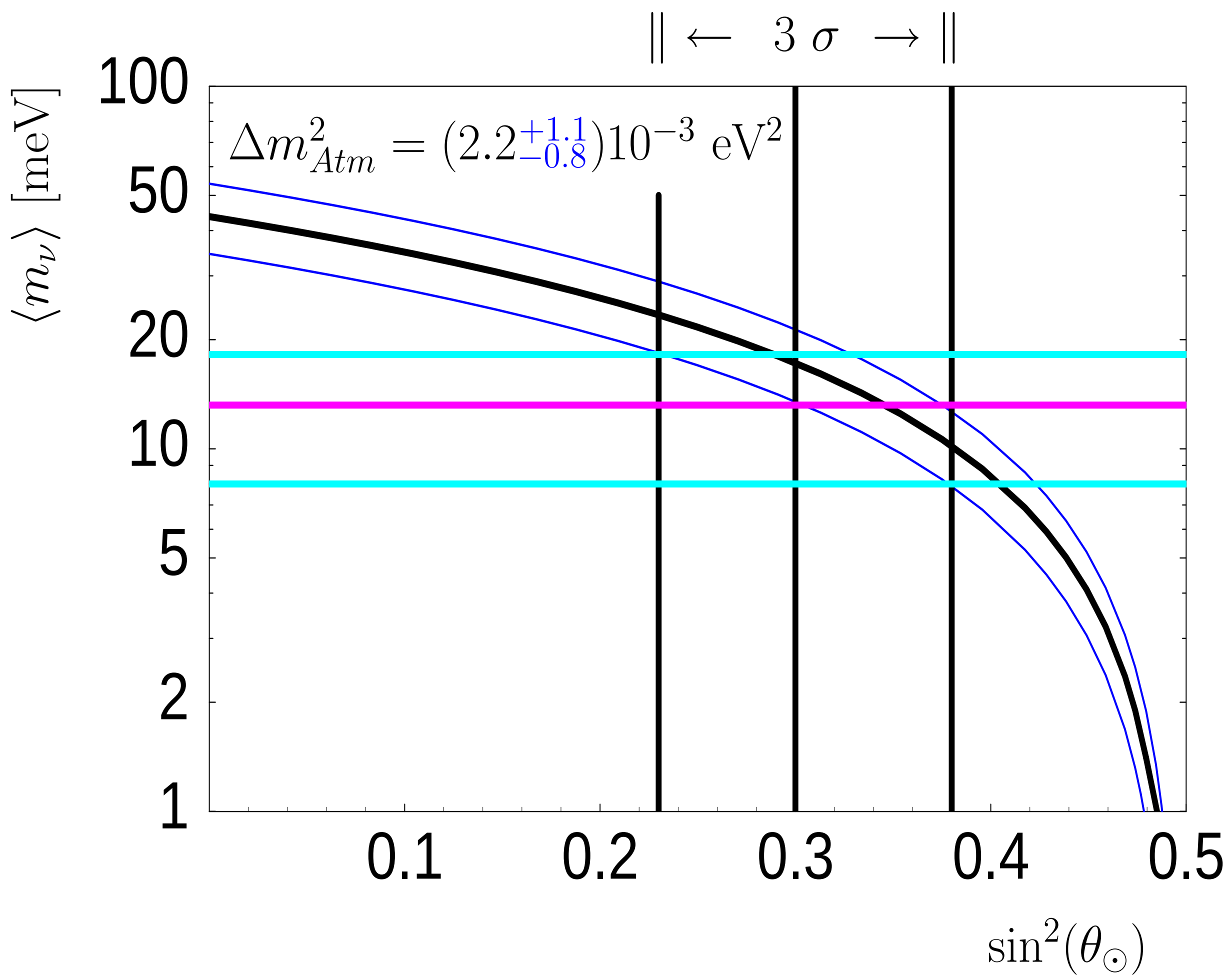
Lower limit - inverse hierarchy

Recall:

$$
\begin{aligned}
\langle m_\nu \rangle &= \sum_j U_{ej}^2 m_j \\
&\simeq c_{12}^2 c_{13}^2 m_1 + s_{12}^2 c_{13}^2 e^{i\alpha} m_2 \\
&\sim (c_\odot^2 - s_\odot^2)\sqrt{\Delta m_{Atm}^2} \\
&\simeq 0.4 \cdot \sqrt{2.2 \cdot 10^{-3}}\ \mathrm{eV} \ \simeq 19\ \mathrm{meV}
\end{aligned}
$$

$\Rightarrow$ Lower limit exists, if $\theta_\odot$ non-maximal

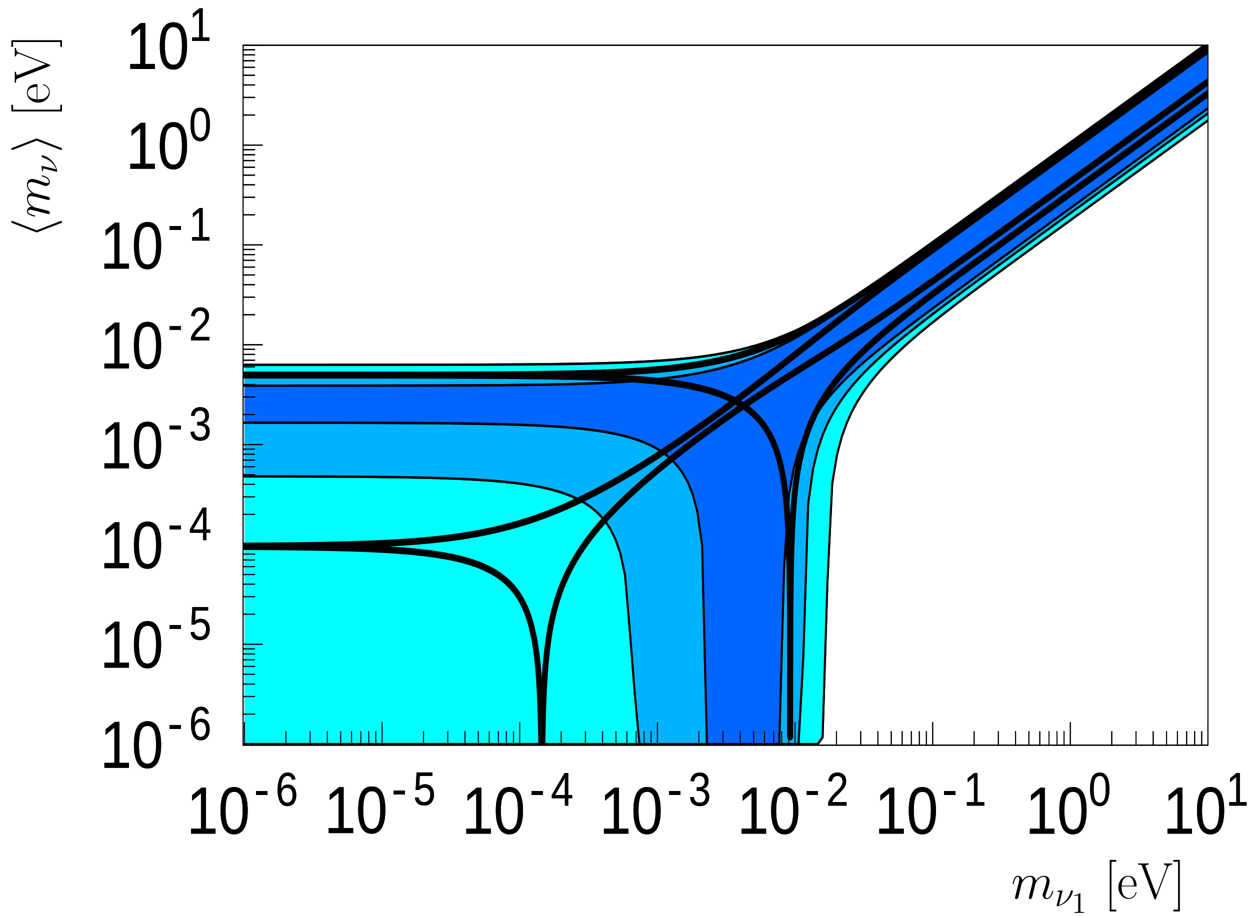
Future lower limit?



Current lower limit @ 3 σ c.l.: $\langle m_\nu \rangle \simeq 7.5$ meV

@ 2 σ c.l.: $\langle m_\nu \rangle \simeq 12$ meV

Reactor angle and $0\nu\beta\beta$



$\sin^2\theta_R =$

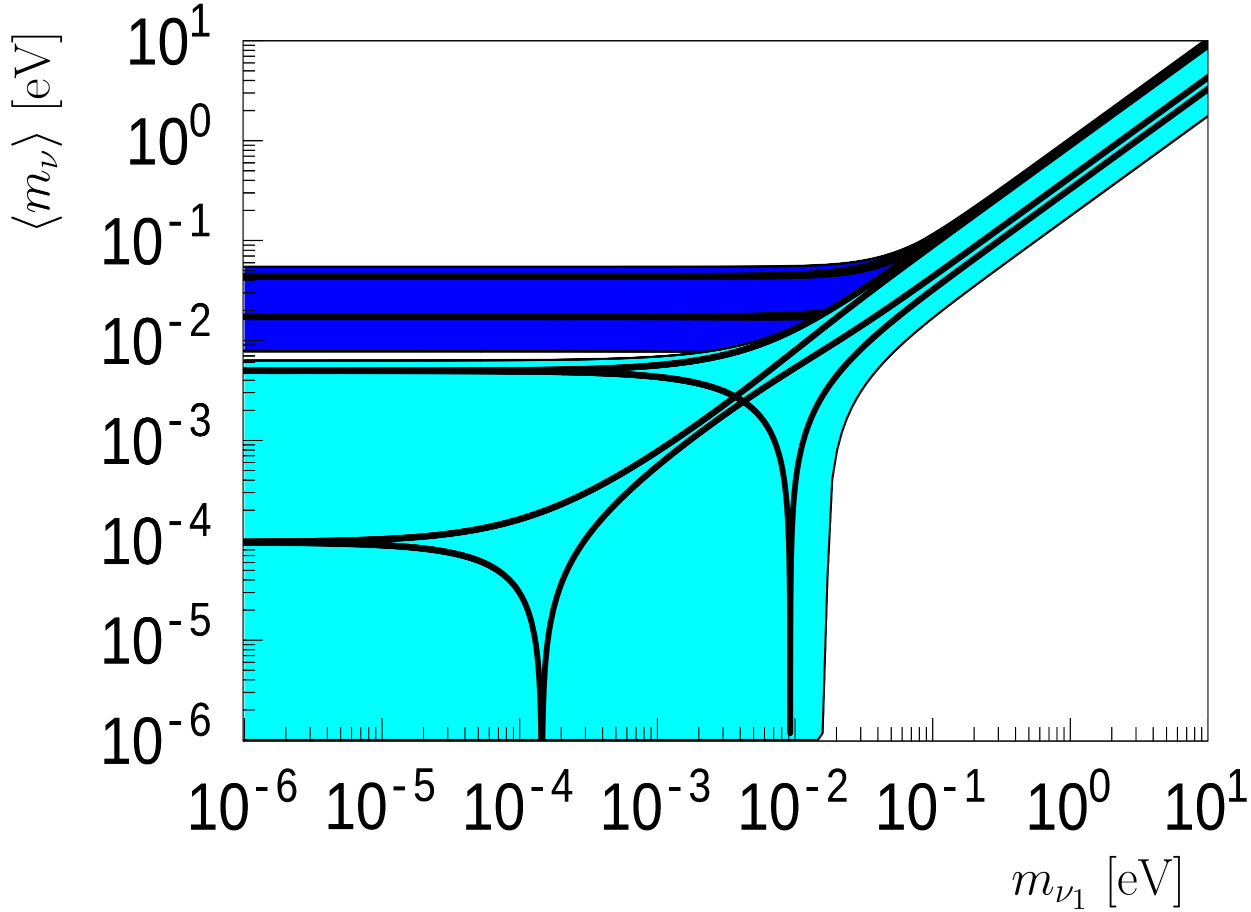
$[0, 0.051]$

$[0, 0.025]$

$[0, 0.0051]$

$\Delta m^2_{Atm} = [1.4, 3.3] \cdot 10^{-3}$ eV^2, $\Delta m^2_{\odot} = [7.2, 9.1] \cdot 10^{-5}$ eV^2,
$\sin^2\theta_{\odot} = [0.23, 0.38]$,

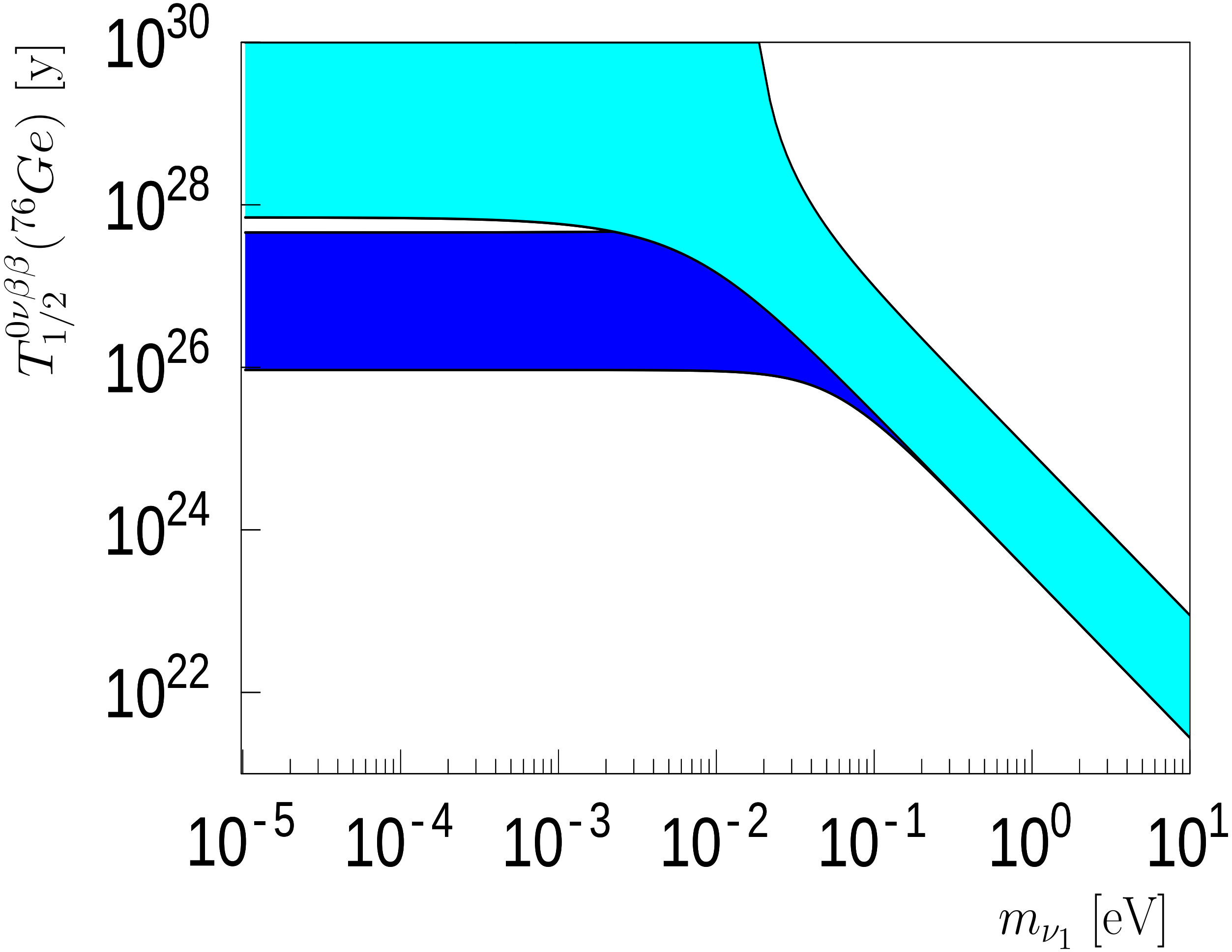
Normal + inverse hierarchy



$\Delta m^2_{Atm} = [1.4, 3.3] \cdot 10^{-3}$ eV^2, $\quad \Delta m^2_\odot = [7.2, 9.1] \cdot 10^{-5}$ eV^2,

$\sin^2\theta_\odot = [0.23, 0.38]$, $\quad \sin^2\theta_R = [0, 0.051]$

$T_{1/2}^{0\nu\beta\beta}$ and m_ν

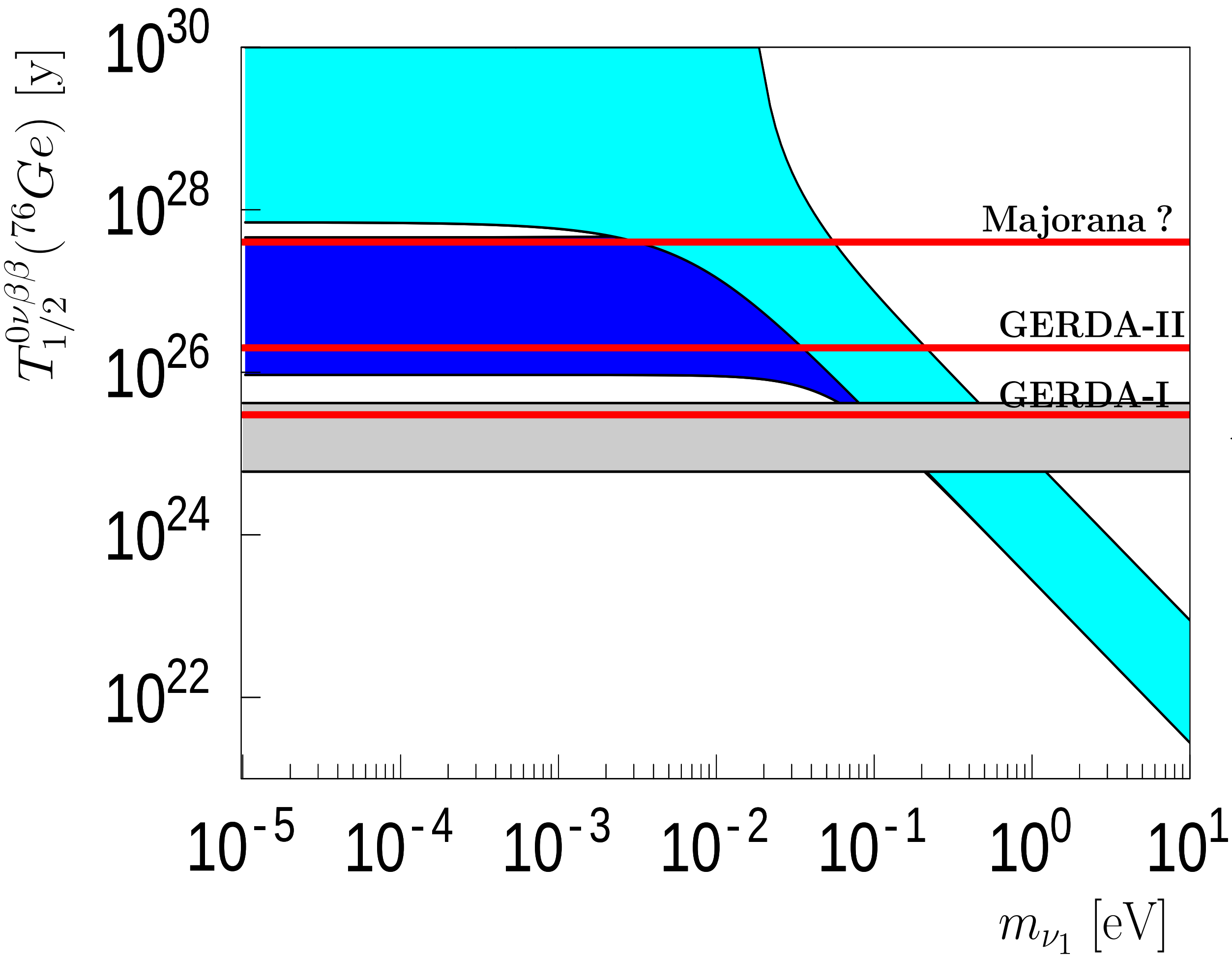


M_{m_ν} from
Muto, 1997

$\Delta m^2_{Atm} = [1.4, 3.3] \cdot 10^{-3}$ eV^2, $\Delta m^2_\odot = [7.2, 9.1] \cdot 10^{-5}$ eV^2,

$\sin^2\theta_\odot = [0.23, 0.38]$, $\sin^2\theta_R = [0, 0.051]$

$T_{1/2}^{0\nu\beta\beta}$: Status



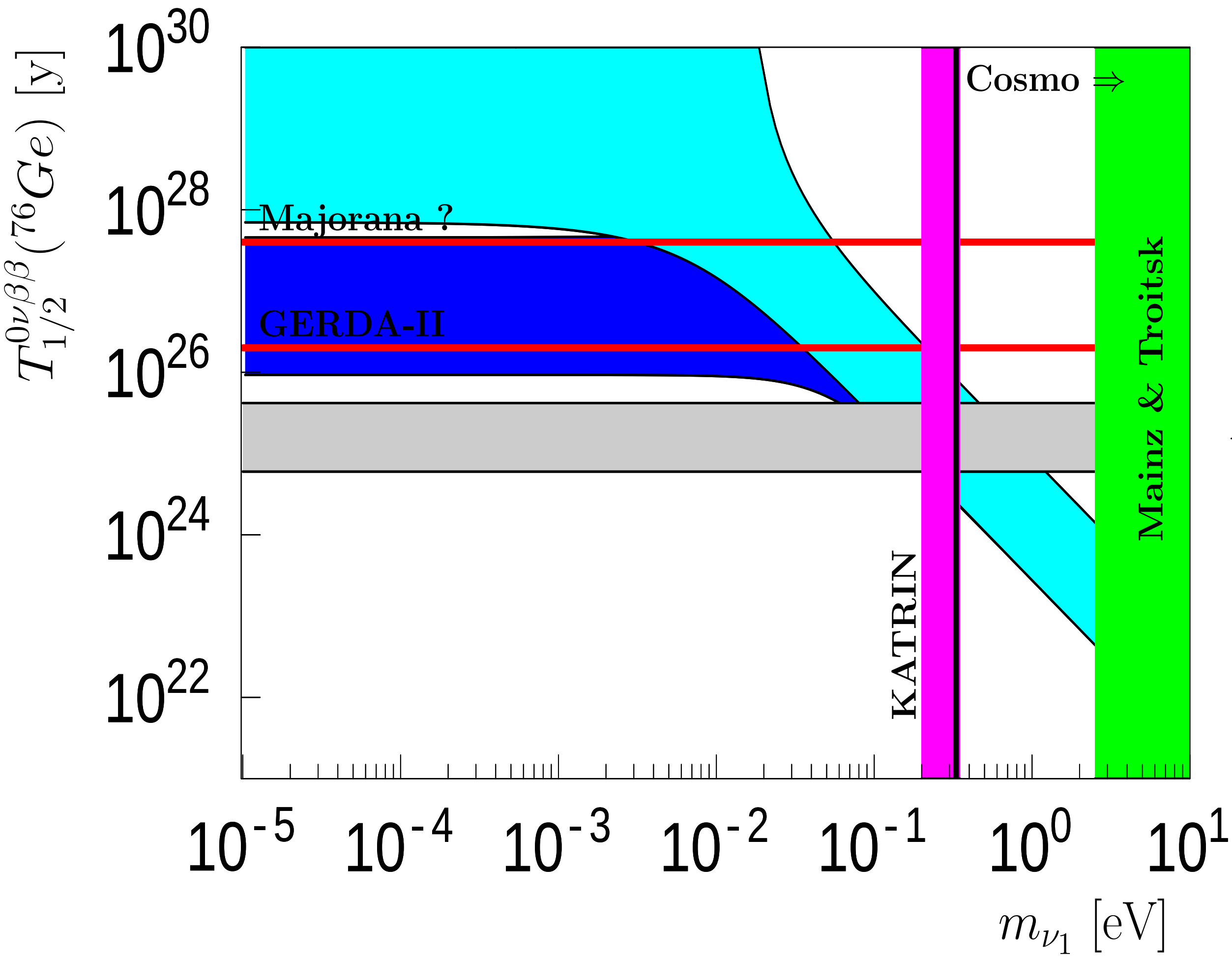
$\Leftarrow$ "KDHK" claim

NIMA 522

$\Delta m^2_{Atm} = [1.4, 3.3] \cdot 10^{-3}$ eV^2, $\quad \Delta m^2_{\odot} = [7.2, 9.1] \cdot 10^{-5}$ eV^2,

$\sin^2\theta_\odot = [0.23, 0.38], \quad \sin^2\theta_R = [0, 0.051]$

Current data: $0\nu\beta\beta$ and m_ν



⇐ "KDHK" claim
NIMA 522

$$\Delta m^2_{Atm} = [1.4, 3.3] \cdot 10^{-3} \text{ eV}^2, \qquad \Delta m^2_{\odot} = [7.2, 9.1] \cdot 10^{-5} \text{ eV}^2,$$

$$\sin^2\theta_{\odot} = [0.23, 0.38], \qquad \sin^2\theta_R = [0, 0.051]$$