Recent Neutrino Parameters Impact on the Effective Majorana Neutrino Mass in $0\upsilon\beta\beta$ Decay

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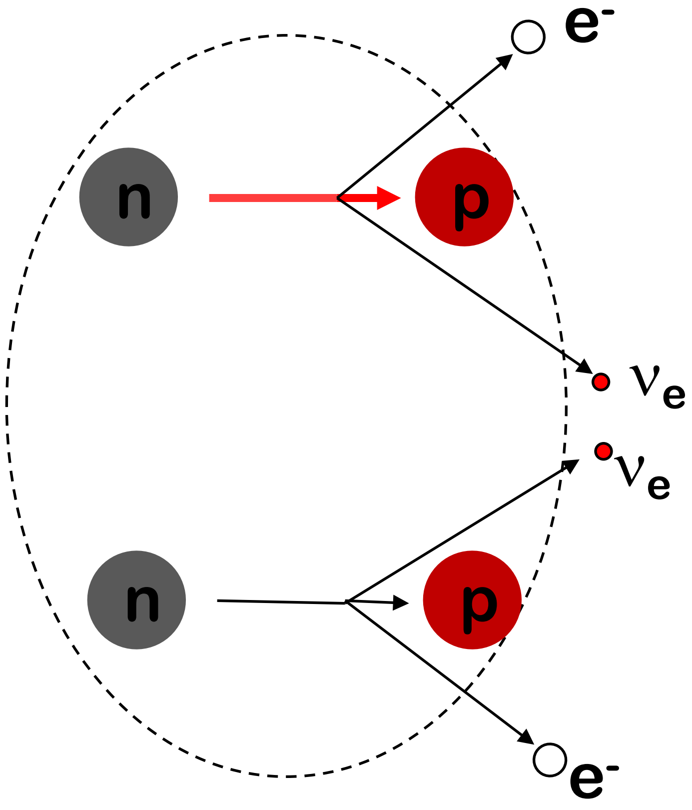
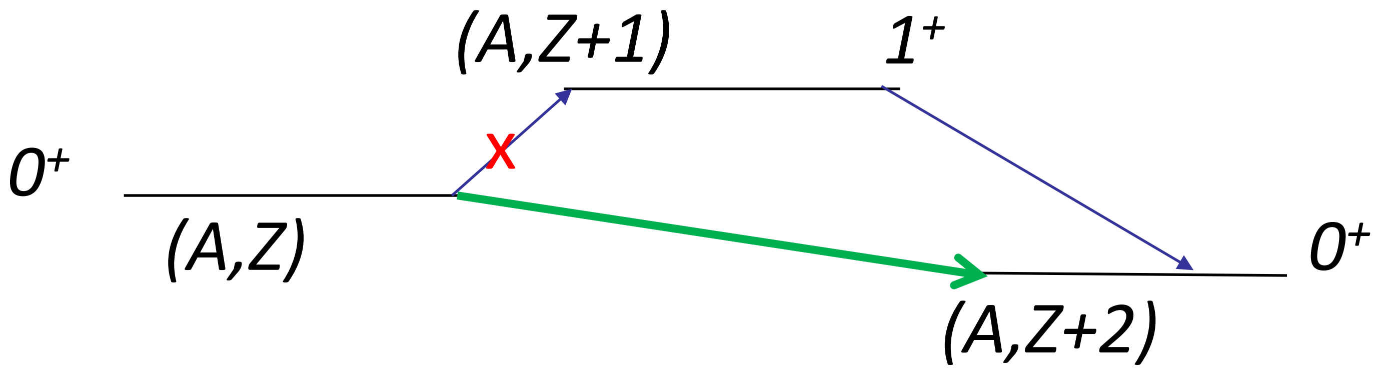
Double Beta Decay



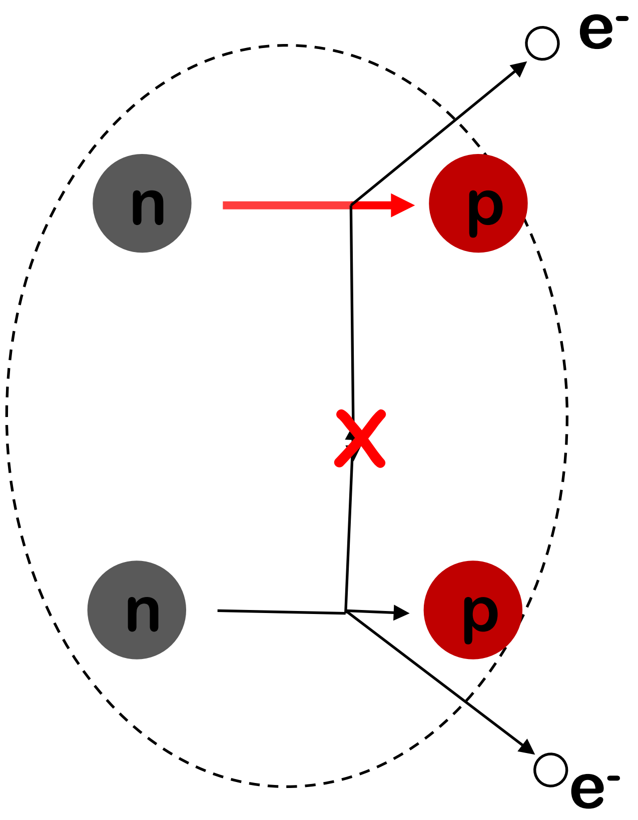
$(A,Z) \rightarrow (A,Z+2) + 2\,e^- + 2\nu_e$



Lifetime: ~10^{21} years

Naturally Occurring
only 35 isotopes

Neutrinoless Double Beta Decay $(0\nu\beta\beta)$



$(A,Z) \rightarrow (A,Z+2) + 2\ e^-$

$\Delta L = 2$

Physics Beyond the Standard Model

Lifetime > 10^{26} years

Naturally Occurring
only 35 isotopes

What Can We Learn?

- Dirac or Majorana?

$$\begin{pmatrix} \nu_\uparrow \\ \nu_\downarrow \\ \bar{\nu}_\downarrow \\ \bar{\nu}_\uparrow \end{pmatrix} \quad \textbf{or} \quad \begin{pmatrix} \nu_\uparrow \\ \nu_\downarrow \end{pmatrix}$$

- Absolute Mass Scale

$$\left(T_{1/2}^{0\nu}\right)^{-1} = G^{0\nu}(E_0, Z)\left|\frac{m_{\beta\beta}}{m_e}\right|^2 \left|M_f^{0\nu} - \left(\frac{g_A}{g_V}\right)^2 M_{GT}^{0\nu}\right|^2$$

- Mass Hierarchy?

Neutrino Oscillation

Flavor neutrino is the mixing between mass eigenstates

$$|v_\alpha >= \sum_{\alpha}^{3} U_{\alpha i}|v_i >$$

$|v_\alpha >$ is a neutrino with definite flavor $\alpha = e, \mu, ot\ \tau$

$$|v_i >= \sum_{i}^{3} U^*_{\alpha i}|v_\alpha >$$

$|v_i >$ is a neutrino with definite mass m_i $\mathrm{i} = 1, 2, ot\ 3$

The asterisk (*) represents a complex conjugate

Most Recent Neutrino Parameters

$\Sigma = m_1 + m_2 + m_3$ Where $m_1, m_2, and\ m_3$ are the masses of three mass eigenstates

$\Sigma = 0.099\ eV\ \ or\ 0.102\ eV\ \ from\ Cosmology\ 2022$

$m_2^2 - m_1^2 = 7.41^{+0.21}_{-0.20} \times 10^{-5}$ eV
$m_3^2 - m_2^2 = 2.437^{+0.028}_{-0.027} \times 10^{-3}$ eV
$\theta_{12} = 33.41^{+0.75}_{-0.72}$; $\theta_{13} = 8.54^{+0.11}_{-0.12}$
$\theta_{23} = 49.1^{+1.0}_{-1.3}$

$m_1 < m_2 < m_3$

Normal Mass Hierarchy - NH

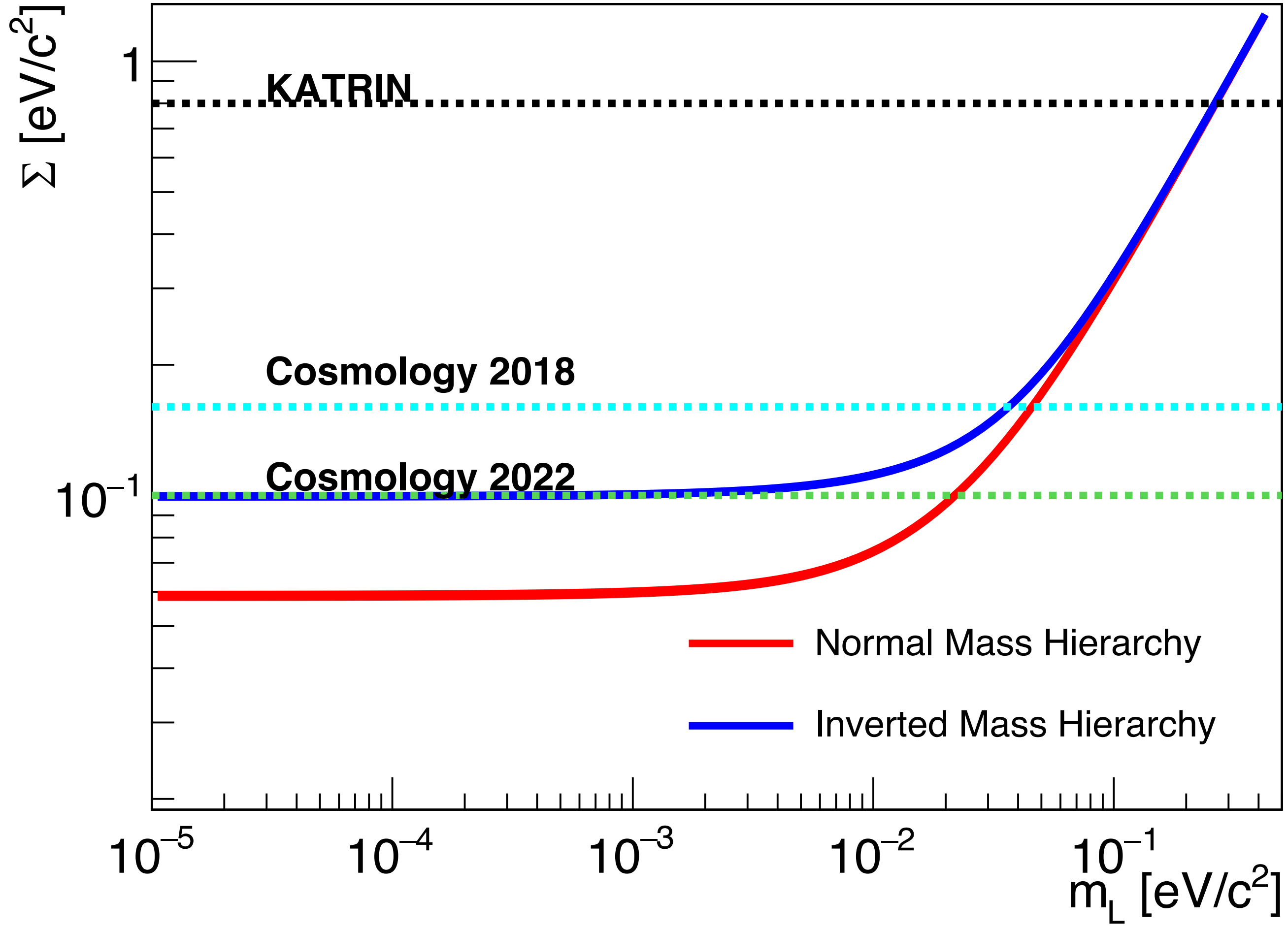
$m_2^2 - m_1^2 = 7.41^{+0.21}_{-0.20} \times 10^{-5}$ eV
$m_3^2 - m_2^2 = -2.498^{+0.032}_{-0.025} \times 10^{-3}$ eV
$\theta_{12} = 33.41^{+0.75}_{-0.72}$; $\theta_{13} = 8.57^{+0.12}_{-0.11}$
$\theta_{23} = 49.5^{+0.9}_{-1.2}$

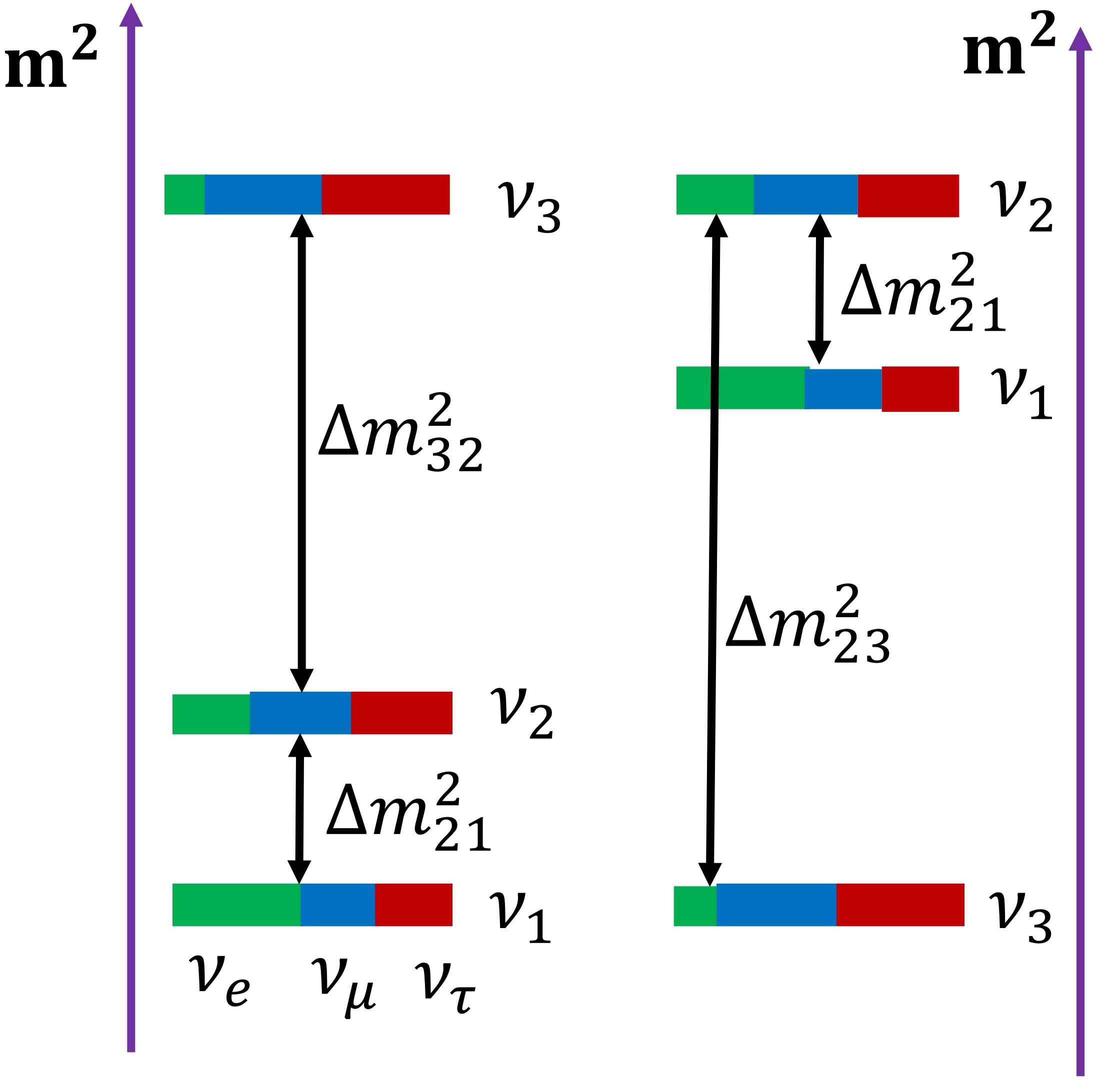
$m_3 < m_1 < m_2$

Inverted Mass Hierarchy - IH

PDG, 2023

Sum of Masses Versus the Minimum Mass





Connection with Neutrinoless Double-Beta Decay

$$\left(T_{1/2}^{0\nu}\right)^{-1} = G^{0\nu}(E_0, Z)\left|\frac{m_{\beta\beta}}{m_e}\right|^2 \left|M_f^{0\nu} - \left(\frac{g_A}{g_V}\right)^2 M_{GT}^{0\nu}\right|^2$$

$$\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & c_{13}s_{12} & e^{-i\delta}s_{13} \\ -c_{23}s_{12} - e^{i\delta}c_{12}s_{13}s_{23} & c_{12}c_{23} - e^{i\delta}s_{12}s_{13}s_{23} & c_{13}s_{23} \\ s_{12}s_{23} - e^{i\delta}c_{12}c_{23}s_{13} & -c_{12}s_{23} - e^{i\delta}c_{23}s_{12}s_{13} & c_{13}c_{23} \end{pmatrix} \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \end{pmatrix}$$

$$|m_{\beta\beta}| = |\textstyle\sum_i m_i U_{\beta i}^2| = |m_1 c_{12}^2 c_{13}^2|e^{2i\alpha} + |m_2 s_{12}^2 c_{13}^2| + |m_3 s_{13}^2|e^{2i\beta}$$

Upper Bound and Lower Bound

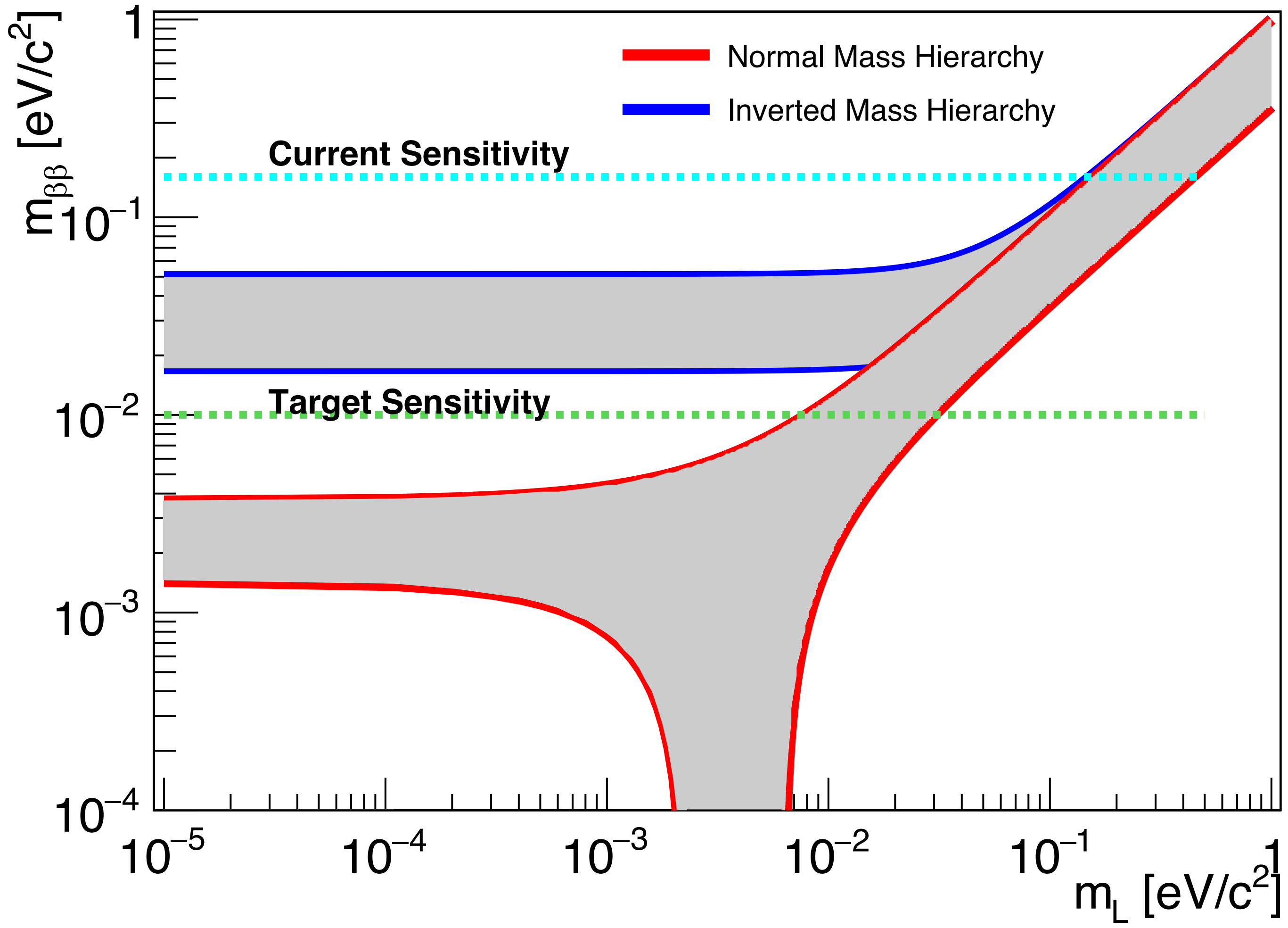
$$m_{\beta\beta}^{NHUpper} = m_2 \sin^2\theta_{12}\cos^2\theta_{13}\left[1+\sqrt{1-\frac{\Delta m_{21}^2}{m_2^2}}\cot^2\theta_{12}+\sqrt{1-\frac{\Delta m_{21}^2}{m_2^2}+\frac{\Delta m_{31}^2}{m_2^2}}\frac{\tan^2\theta_{13}}{\sin^2\theta_{12}}\right] \quad (1)$$

$$m_{\beta\beta}^{NHLower(1)} = m_2 \sin^2\theta_{12}\cos^2\theta_{13}\left[1-\sqrt{1-\frac{\Delta m_{21}^2}{m_2^2}}\cot^2\theta_{12}-\sqrt{1-\frac{\Delta m_{21}^2}{m_2^2}+\frac{\Delta m_{31}^2}{m_2^2}}\frac{\tan^2\theta_{13}}{\sin^2\theta_{12}}\right] \quad (2)$$

$$m_{\beta\beta}^{NHLower(2)} = m_2 \sin^2\theta_{12}\cos^2\theta_{13}\left[\sqrt{1-\frac{\Delta m_{21}^2}{m_2^2}}\cot^2\theta_{12}-1-\sqrt{1-\frac{\Delta m_{21}^2}{m_2^2}+\frac{\Delta m_{31}^2}{m_2^2}}\frac{\tan^2\theta_{13}}{\sin^2\theta_{12}}\right] \quad (3)$$

For the case of IH, $m_3 < m_1 < m_2$, (1) and (3) are used for the upper and lower bounds

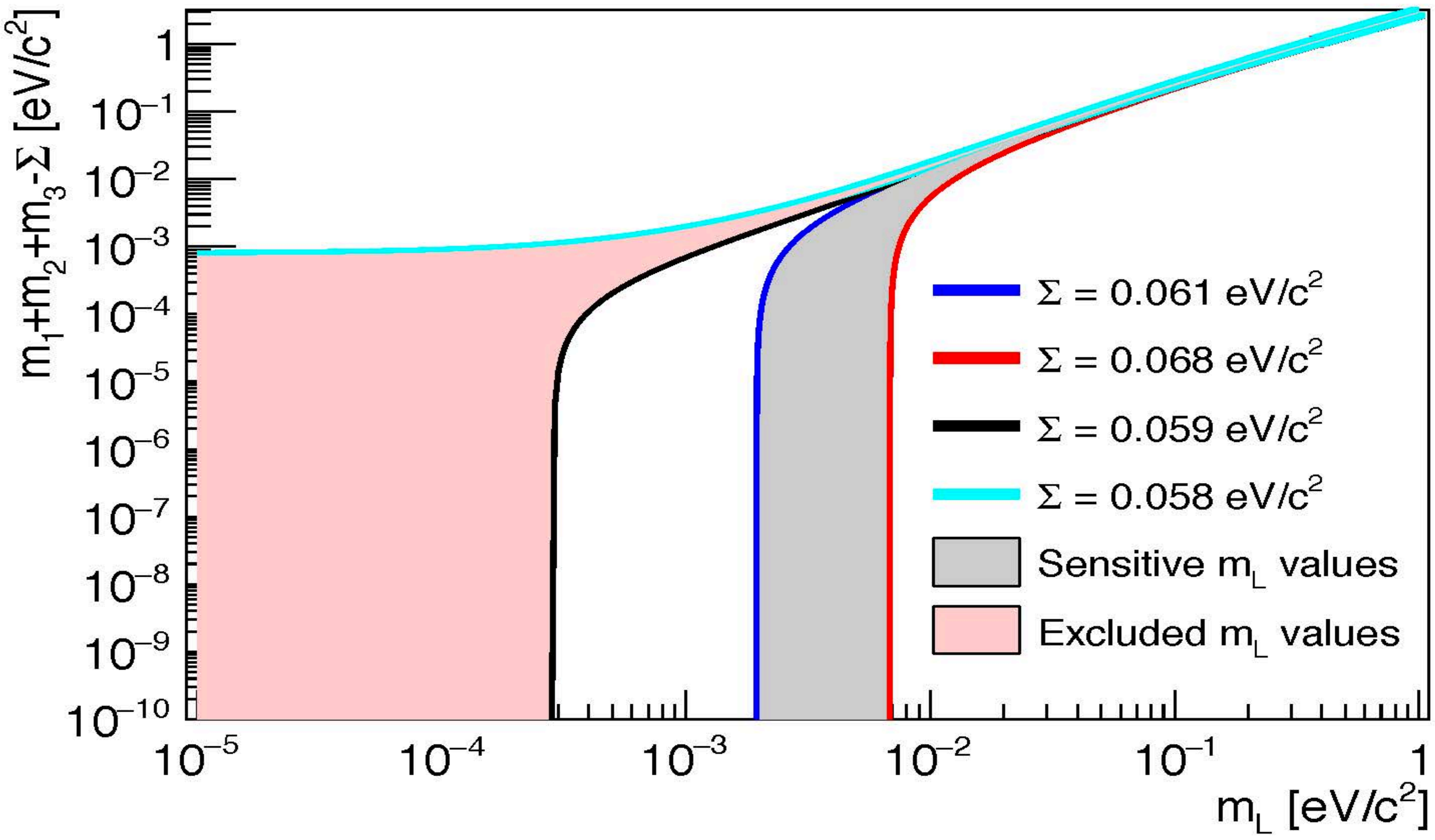
Impact on Neutrinoless Double Beta Decay



Remarks:

- The planned ton-scale experiment will fully access the region of IH
- ~100 ton-scale will access NH region

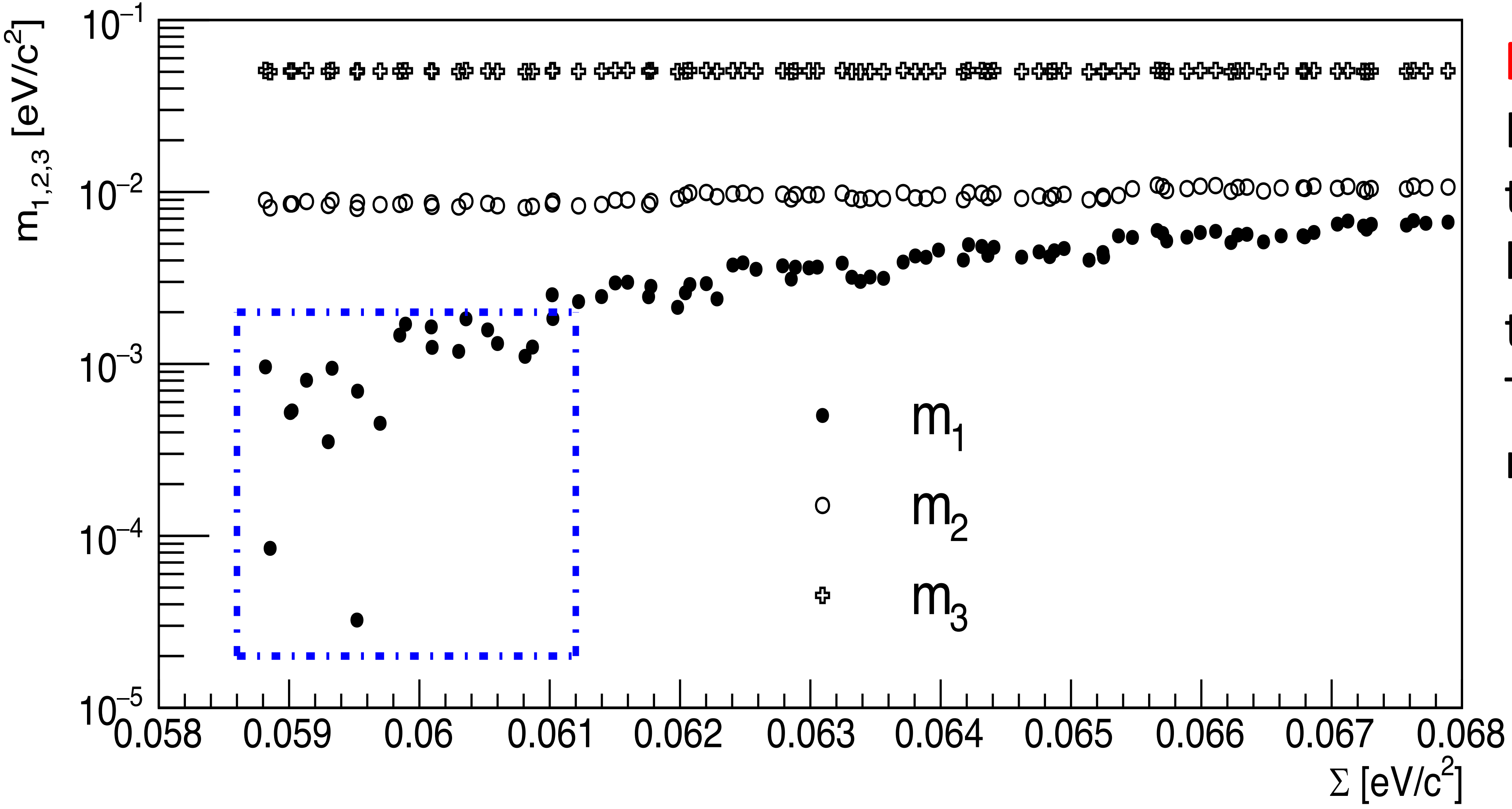
Probable Region in the NH



Remarks:

In the case of NH, the probable region is quite narrow between $3\times10^{-4} < m_L < 2\times10^{-3}$

Non-Zero Minimum Neutrino Mass

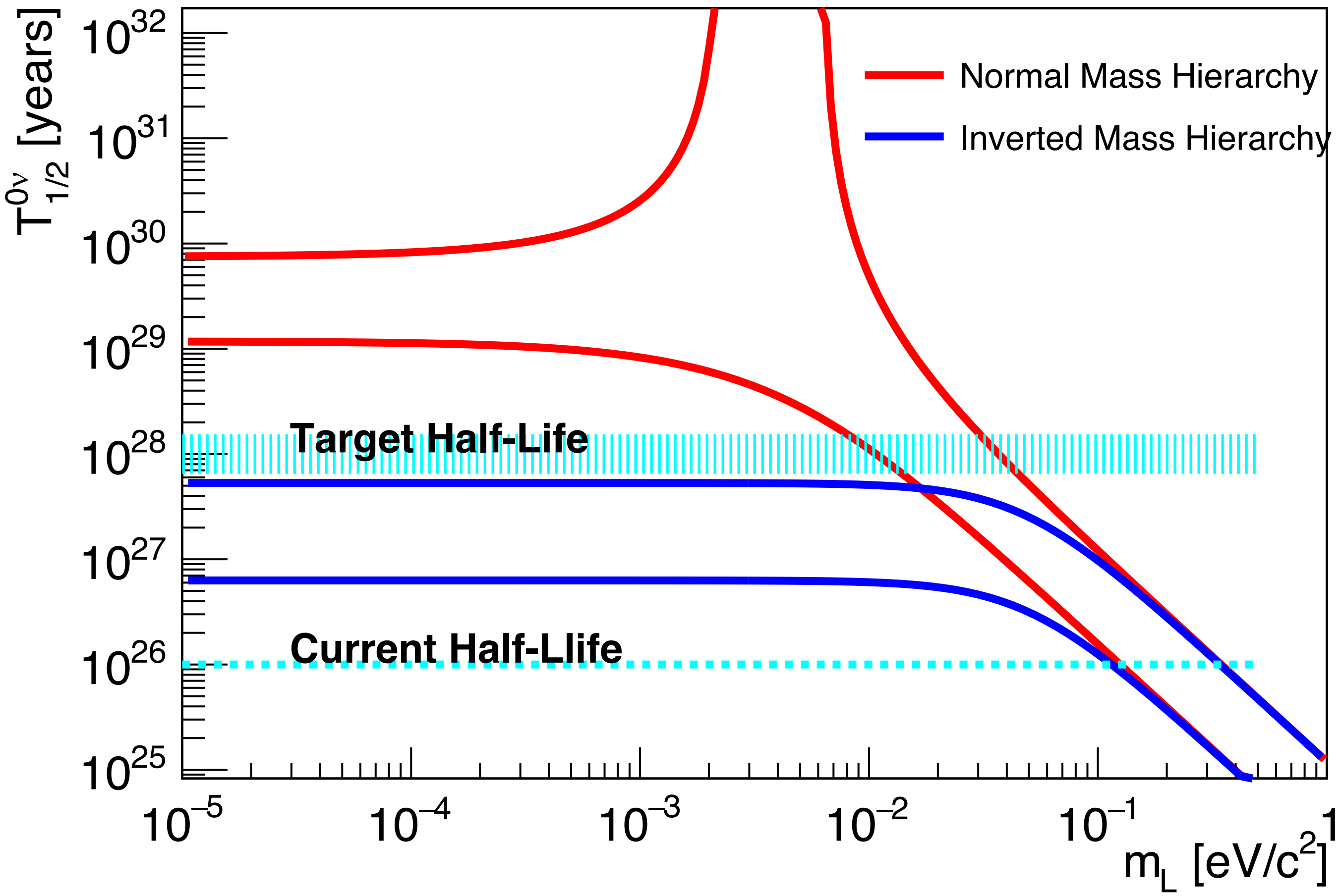


Remarks:

In the case of NH, the sum of masses lies within 0.0585 to 0.061

The corresponding m_1 is non-zero

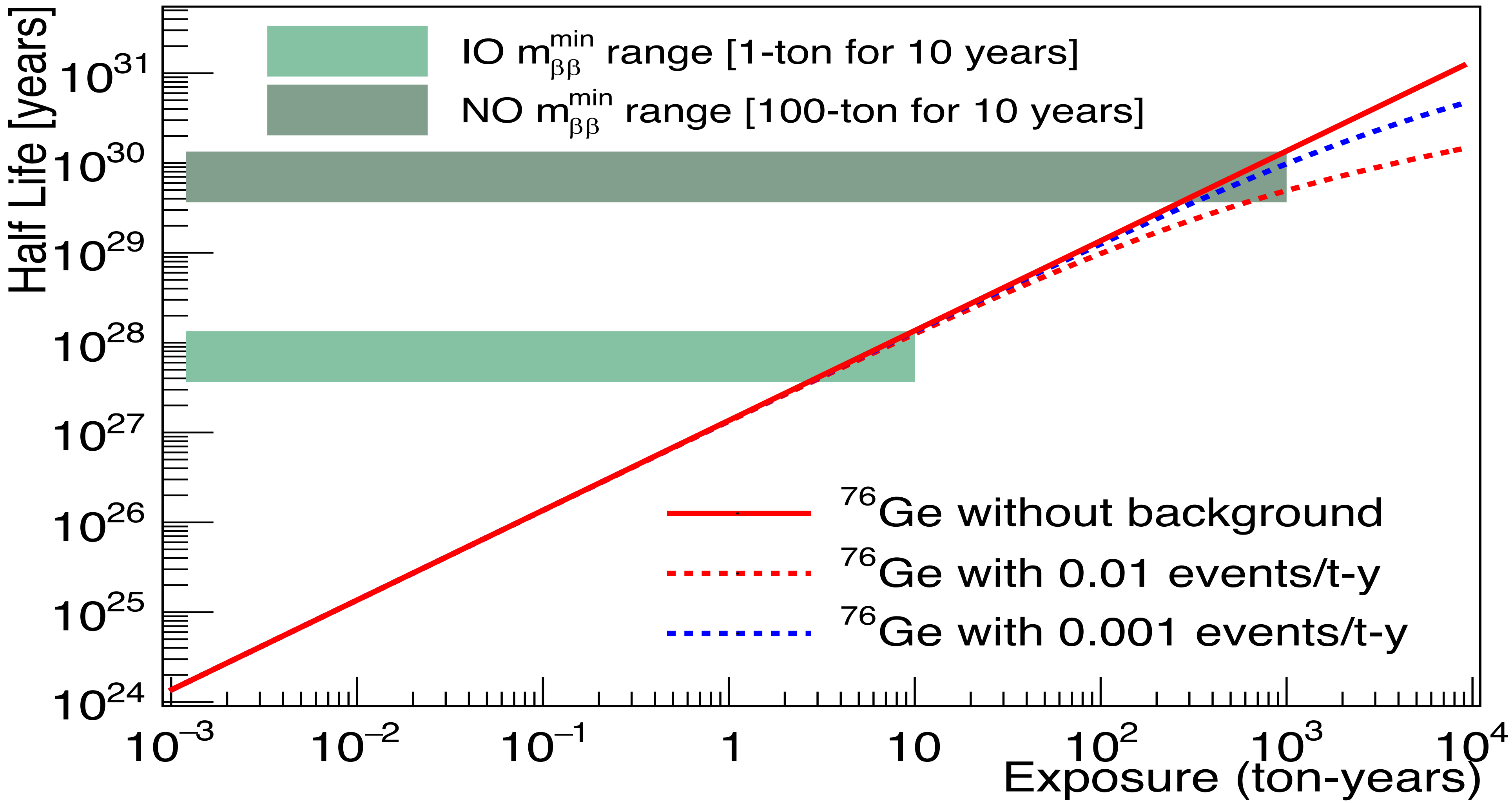
Impact on the Sensitivity for Half-life Measurements



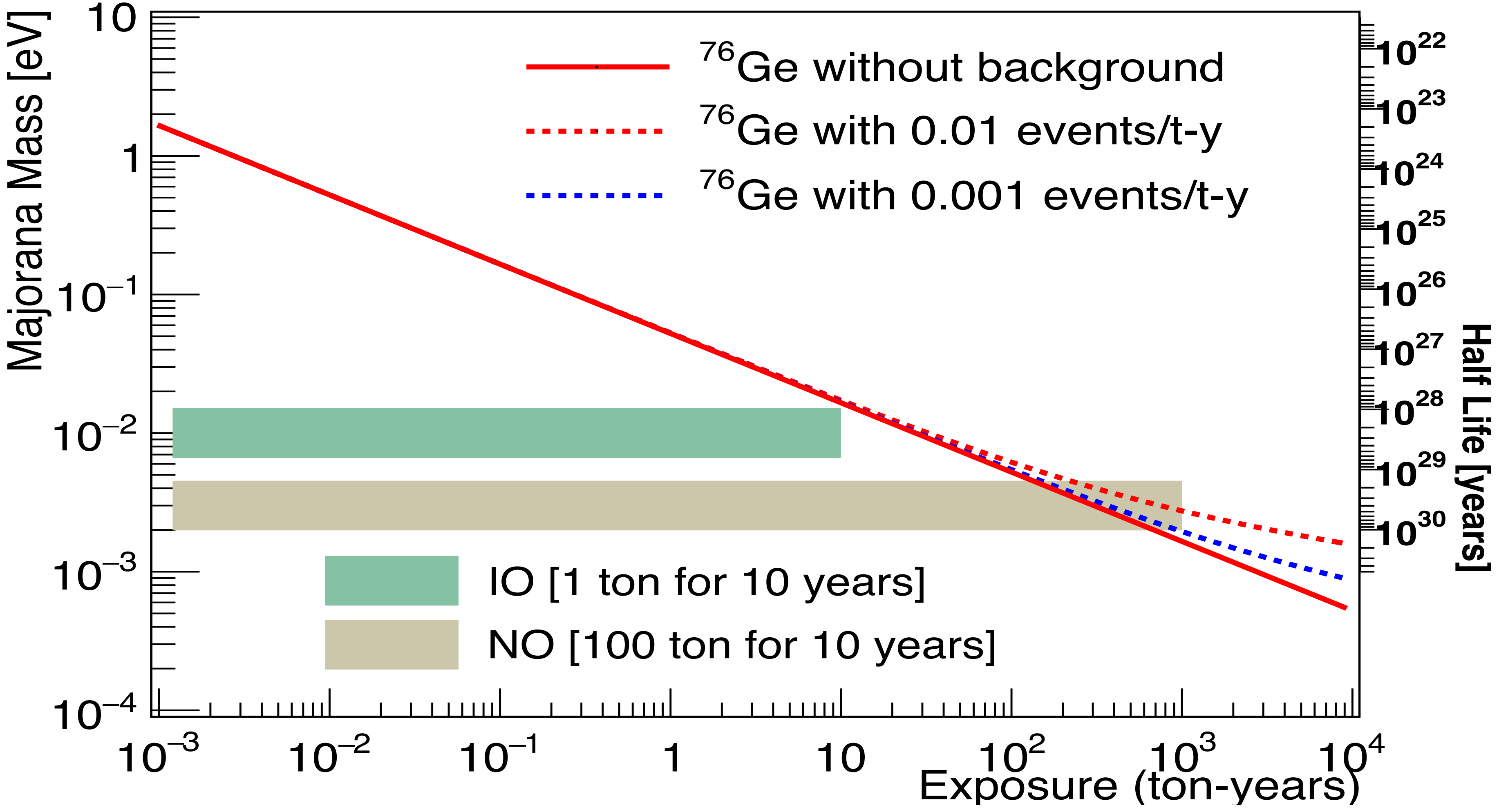
Remarks:

- Ton-scale experiments can fully access the region of IH
- 100 ton-scale experiments can fully access NH region
- The chance for the half-life beyond ~10^{31} years is small

Sensitivity for Future Ge-based Experiments



Effective Mass Versus Exposure



Summary

- Planned ton-scale experiment will fully explore IH – 10 meV
- Future 100-ton experiments are required to probe NH – 1 meV
  - Required Background Index – 1 event per kton per year in the region of interest
- The minimum neutrino mass is non-zero