Required Exposure and Background Levels in the Searches of Neutrinoless Double-β Decay

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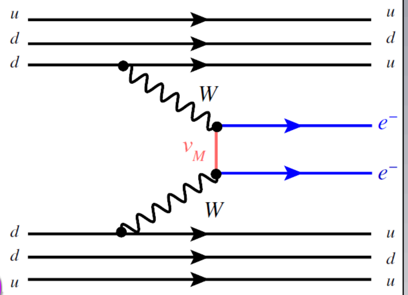
Based on: *M. K. Singh, H. T. Wong et al., Phys. Rev.* ***D 101****, 013006 (2020).*

Introduction

§ Neutrinoless double beta decay ($0\nu\beta\beta$) [Furry, 1939]

$${}^{N}_{Z}A_{\beta\beta} \rightarrow {}^{N-2}_{Z+2}A_{\beta\beta} + 2\bar{e}$$

- Forbidden in Standard Model !!!
- $\Delta L = 2$!!!



§ Observation of $0\nu\beta\beta$ implies new physics:

- Neutrinos are Majorana particles ($\nu = \bar{\nu}$)
- Lepton number violations
- Effective light Majorana Neutrino Mass $\langle m_{\beta\beta}\rangle \neq 0$

§ Energetically possible for 35 nuclei

- A few are experimentally relevant

§ Present work: Required Exposure vs Background

Formulation

▲ Half-life in Mass Mechanism : $\left[\frac{1}{T^{0\nu}_{1/2}}\right] = G^{0\nu} g_A^4 \left|M^{0\nu}\right|^2 \left|\frac{\langle m_{\beta\beta}\rangle}{m_e}\right|^2$

▲ Effective Mass: $\langle m_{\beta\beta}\rangle = |U^2_{e1}|m_1 + |U^2_{e2}|m_2 e^{i\alpha} + |U^2_{e3}|m_3 e^{i\beta}|$

▲ Experimentally measurable Half-life:

$$T^{0\nu}_{1/2} = \ln 2 \, . N(A_{\beta\beta}) . t_{DAQ} . \left[\frac{\varepsilon_{RoI}}{N^{0\nu}_{obs}}\right] = \ln 2 . \left[\frac{N_A}{M(A_{\beta\beta})}\right] . \Sigma . \left[\frac{\varepsilon_{RoI}}{N^{0\nu}_{obs}}\right]$$

▲ Combined Half-life:

$$\left|M^{0\nu}\right|^2 \left[g_A^4 . H^{0\nu}\right] = \frac{1}{\langle m_{\beta\beta}\rangle^2}\left[\frac{1}{\Sigma} . \frac{N^{0\nu}_{obs}}{\varepsilon_{RoI}}\right]; \; H^{0\nu} \equiv \ln 2 \left(\frac{N_A}{M(A_{\beta\beta}) . m_e^2}\right) . G^{0\nu}$$

Discovery Potential & Theme

❑ Poisson statistics handles:

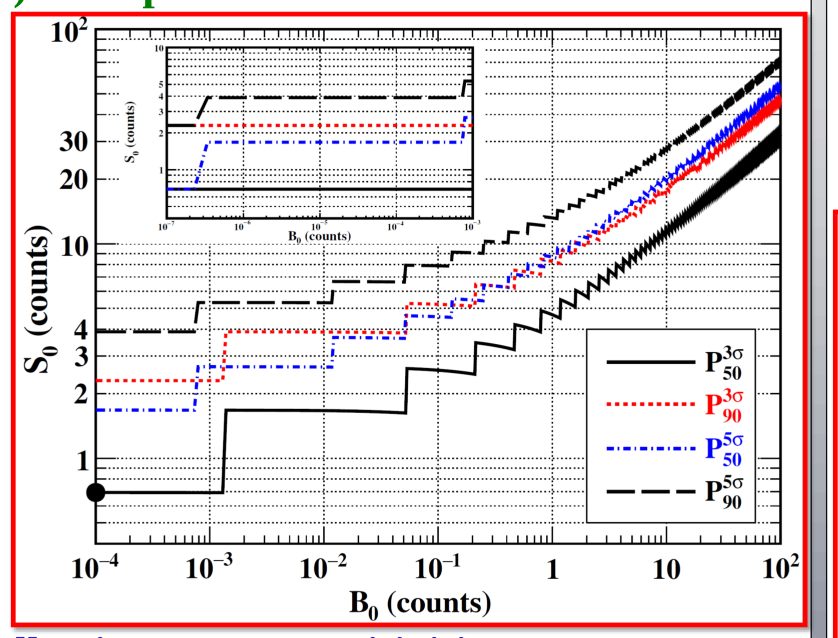
(i) Low background; (ii) Rare processes.

STEP-1

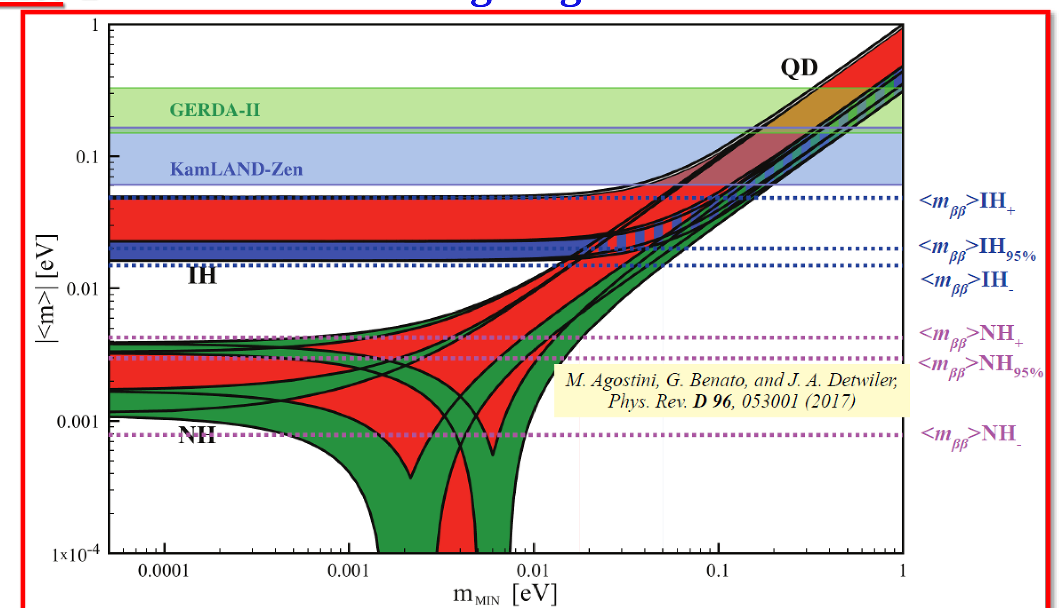
$$\sum_{i=0}^{N^{3\sigma-1}_{obs}} P(i; B_0) \geq (1 - 0.00135)$$

STEP-2

$$\sum_{i=N^{3\sigma}_{obs}}^{\infty} P(i; [B_0 + S_0]) \geq 0.5$$



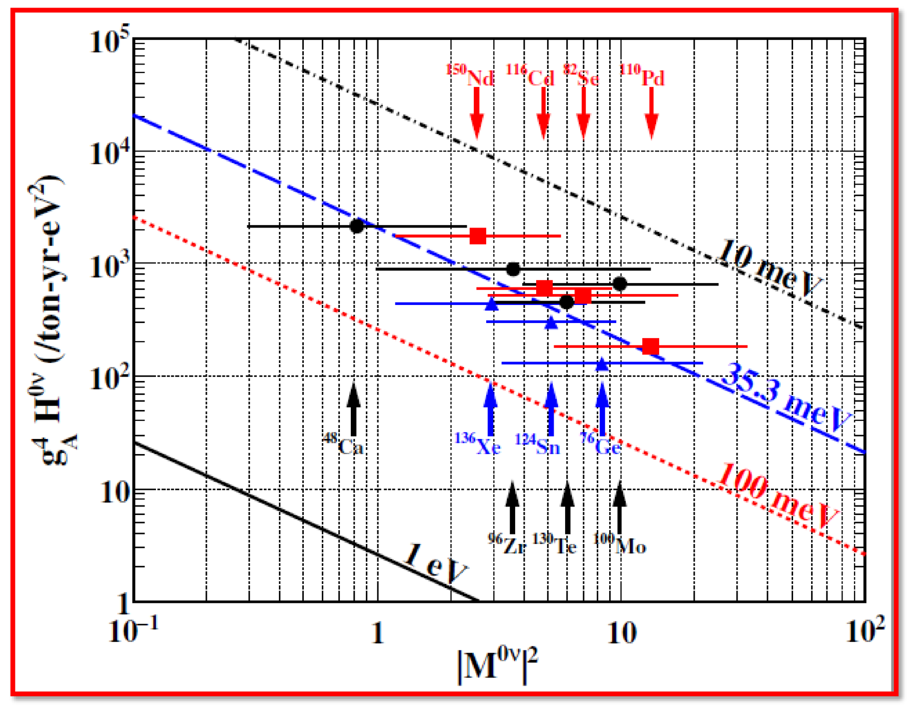
❑ Theme: To reach the following target sensitivities:



Relating $T^{0\nu}_{1/2}$ with $\langle m_{\beta\beta}\rangle$ - Model for $|M^{0\nu}|$

❖ Model - Inverse correlation between $G^{0\nu}$ and $|M^{0\nu}|^2$.

❖ Decay rates (1 event/ton-yr with full efficiency) are similar at given $\langle m_{\beta\beta}\rangle$ and constant g_A.



R. G. H. Robertson, Mod. Phys. Lett. A 28, 1350021 (2013).

❖ No favored $0\nu\beta\beta$ isotope.

$$\sum (\text{ton-year}) . \left(\frac{\varepsilon_{RoI}}{N^{0\nu}_{obs}}\right) \; \alpha \; \left(\frac{1}{\langle m_{\beta\beta}\rangle}\right)^2$$

❖ Realistic interpretation lies within a factor of [0.5, 2.0].

Required Exposure and Background

➢ RoI = $w_{1/2}$ (FWHM): Not the optimal choice when $B_0 \rightarrow 0$.

➢ Alternative choice: RoI = $w_{3\sigma}$ ($Q_{\beta\beta} \pm 3\sigma$), thus $\varepsilon_{RoI} \cong 100\%$.

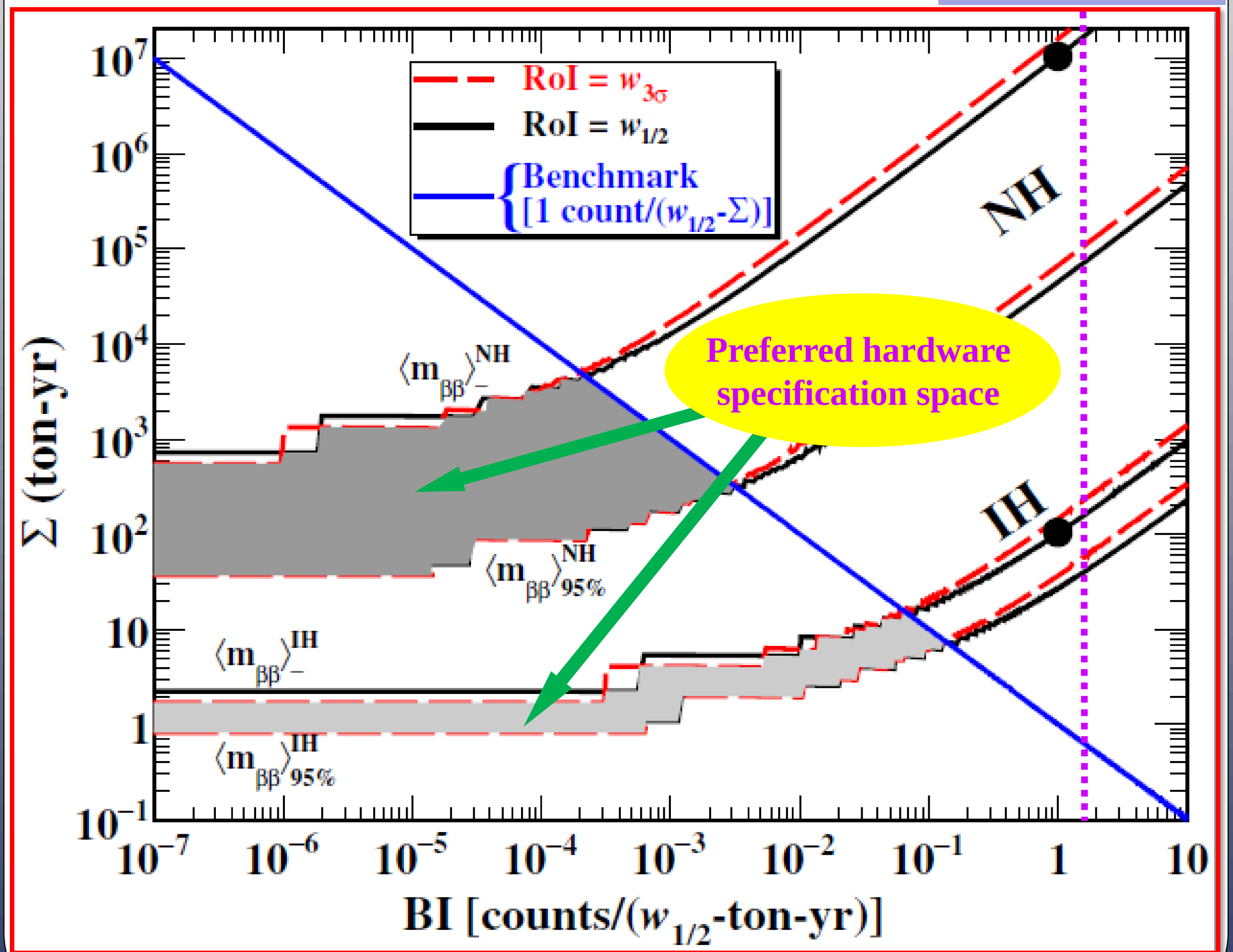
➢ Better sensitivity by a factor of ε_{RoI} ($w_{1/2}$ = 0.76).

➢ Covered $T^{0\nu}_{1/2}$ is 32% longer, or Σ is 24% less.

➢ Background Index (BI) defined as: BI= $\left(\frac{B_0\,(RoI)}{\Sigma}\right)$

➢ Universally applicable.

Best Measured Background-GERDA



Target exposure: Next-generation $0\nu\beta\beta$ projects
10 ton-year to cover IH

BI < 0.21 counts/$w_{1/2}$-ton-yr ➡ cover $\langle m_{\beta\beta}{}^{IH}_{95\%}\rangle$

BI < 0.033 counts/$w_{1/2}$-ton-yr ➡ cover $\langle m_{\beta\beta}{}^{IH}_{-}\rangle$

➢ GERDA: Background level = $1.0^{+0.6}_{-0.4}$ counts/keV-ton-yr or BI ~ 3 counts/$w_{1/2}$-ton-yr.

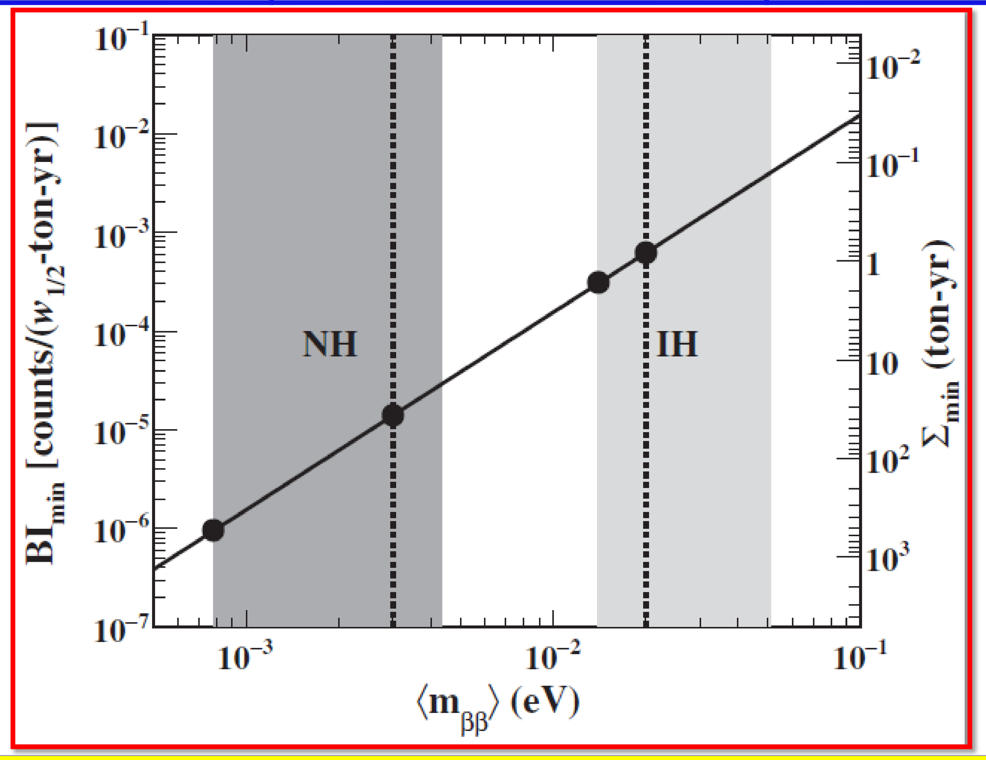
➢ Choice: BI = BI_0 = 1 count/$w_{1/2}$-ton-yr requires

110 ton-yr ➡ cover $\langle m_{\beta\beta}\rangle^{IH}_{-}$

11 Mton-yr ➡ cover $\langle m_{\beta\beta}\rangle^{NH}_{-}$

➢ Suppression in BI: [1 to 10^{-3}] counts/($w_{1/2}$-ton-yr) contributes reduction in exposure

Exposure @ BI = 1 (ton-yr)	Exposure @ BI = 10^{-3} (ton-yr)	Cover
27	1.1	$\langle m_{\beta\beta}{}^{IH}_{95\%}\rangle$
110	4.1	$\langle m_{\beta\beta}{}^{IH}_{-}\rangle$
44×10^3	0.17×10^3	$\langle m_{\beta\beta}{}^{NH}_{95\%}\rangle$
11×10^6	13×10^3	$\langle m_{\beta\beta}{}^{NH}_{-}\rangle$



BI_{min} equivalently Σ_{min} condition:
Single observed event can establish signal at $P^{3\sigma}_{50}$

BI_{min} (counts/$w_{1/2}$-ton-yr)	Σ_{min} (ton-yr)	Cover
$\leq 6.3\times10^{-4}$	0.83	$\langle m_{\beta\beta}{}^{IH}_{95\%}\rangle$
$\leq 3.1\times10^{-4}$	1.7	$\langle m_{\beta\beta}{}^{IH}_{-}\rangle$
$\leq 1.4\times10^{-5}$	37	$\langle m_{\beta\beta}{}^{NH}_{95\%}\rangle$
$\leq 0.96\times10^{-6}$	550	$\langle m_{\beta\beta}{}^{NH}_{-}\rangle$

Σ=10 ton-yr ⬇ Next generation:

$BI_{min} < 5.1\times10^{-5}$ counts/$w_{1/2}$-ton-yr ⬇

$\langle m_{\beta\beta}\rangle > (5.8\times10^{-3})$eV ⬇

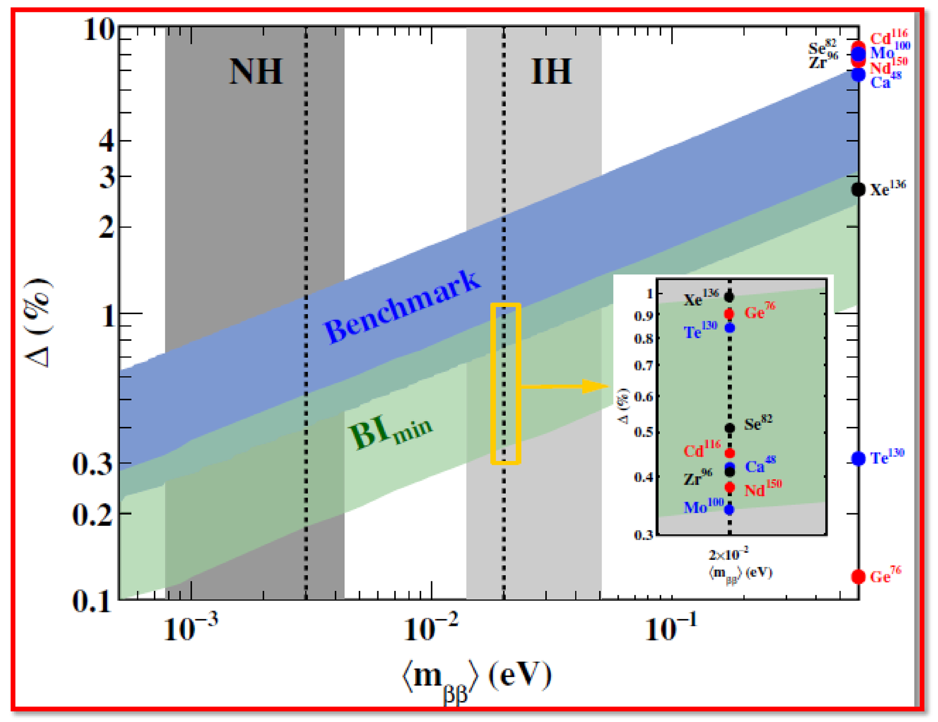
$\langle m_{\beta\beta}\rangle^{NH}_{+} = 4.3\times10^{-3}$eV

Limiting Irreducible Background

Standard-Model-allowed irreducible background

$${}^{N}_{Z}A_{\beta\beta} \rightarrow {}^{N-2}_{Z+2}A_{\beta\beta} + 2\bar{e} + 2\bar{\nu} \text{ [Goeppert-Mayer, 1935]}$$

Worse resolution (Δ) ⟺ Larger RoI ⟺ Larger $2\nu\beta\beta$ Background



Resolutions under BI_{min} conditions

$\Delta \leq$ (0.3-0.9)% ➡ cover $\langle m_{\beta\beta}{}^{IH}_{-}\rangle$

$\Delta \leq$ (0.1-0.3)% ➡ cover $\langle m_{\beta\beta}{}^{NH}_{-}\rangle$

♣ MJD Best Resolution $\Delta(^{76}Ge)$ = 0.12% ⬇ BI < 6×10^{-10} counts/($w_{1/2}$-ton-yr)

Conversion to Realistic Configurations

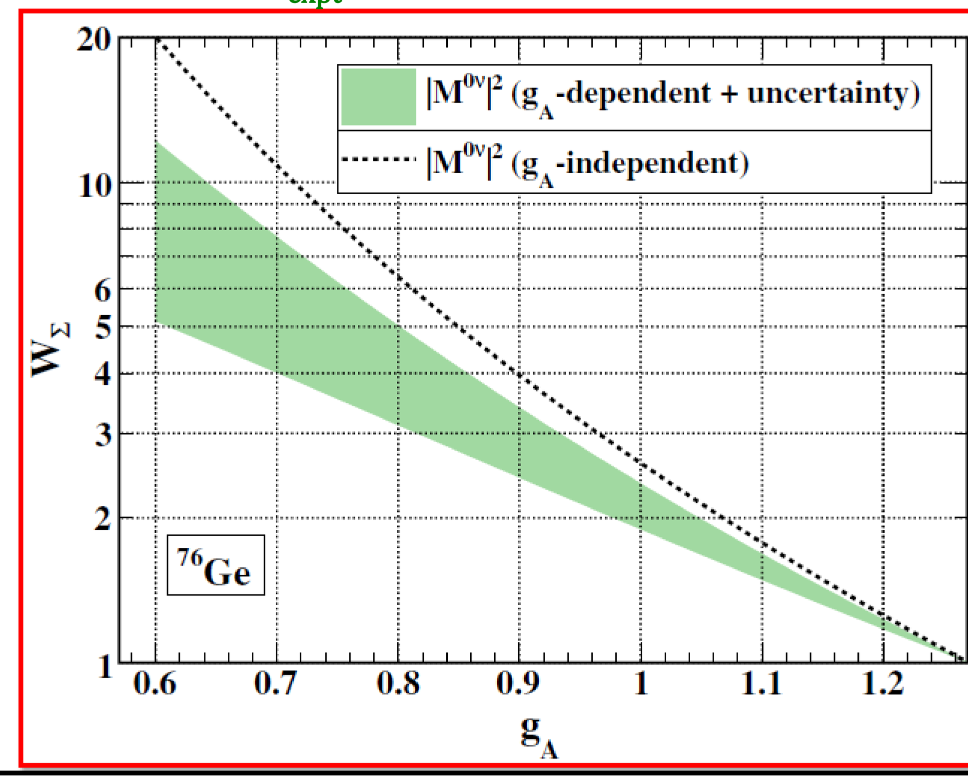
Considered:

IA = 100%, ε_{expt} = 100% and "unquenched" free nucleon value of g_A =1.27

Conversion:

In realistic experiments:

$$\Sigma' \simeq \Sigma . \frac{1}{IA} . \frac{1}{\varepsilon_{expt}} . W_{\Sigma}(g_A) \text{ and } BI'(\Sigma') \simeq BI . \left[\frac{\Sigma}{\Sigma'}\right]$$



Summary

✓ Covering $\langle m_{\beta\beta}{}^{NH}_{-}\rangle$ will require large and costly exposure.

✓ Reduction of BI will be playing increasingly significant.

✓ Same exposure can probe longer $T^{0\nu}_{1/2}$ and smaller $\langle m_{\beta\beta}\rangle$ with decreasing background.