Enhancing $0\nu\beta\beta$ search sensitivity via combined multi-transition analysis

C. R. Ding[1], K. Han[2], S. B. Wang[2], and J. M. Yao[1]
丁晨蓉 韩柯 王少博 尧江明
1. SYSU 2. SJTU

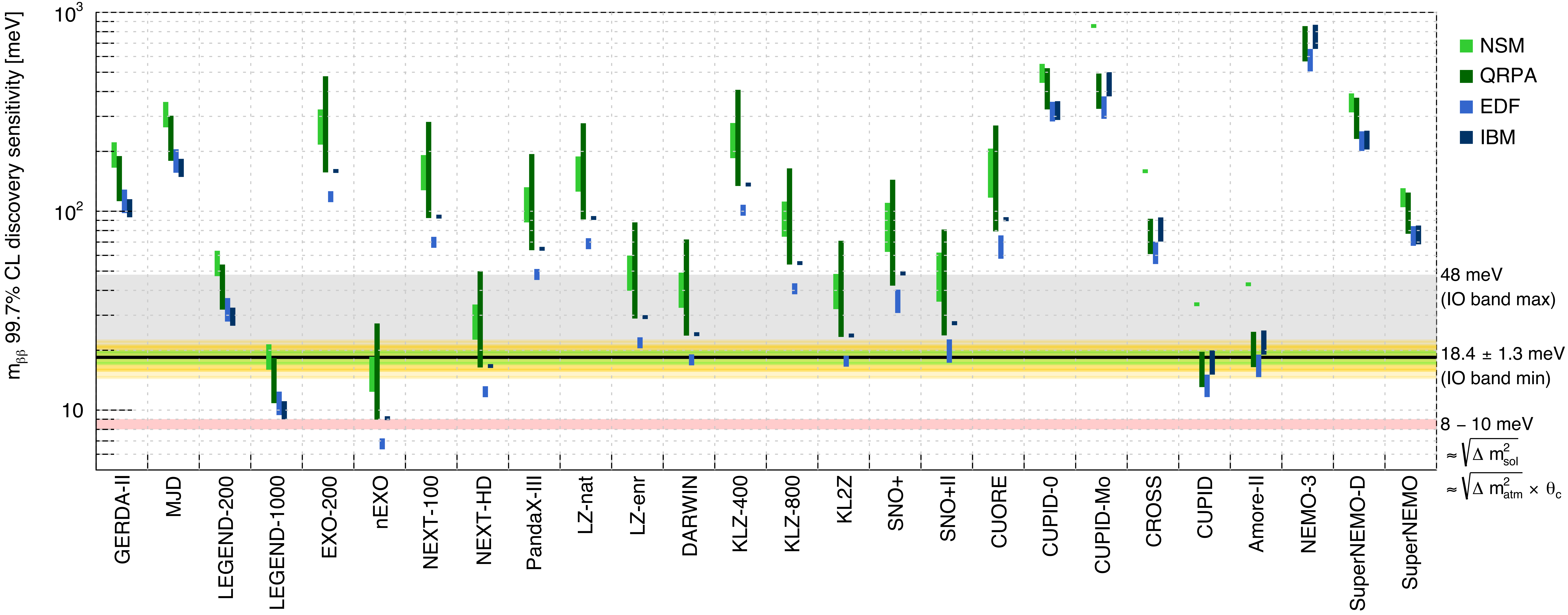
Aug 26, 2025

https://arxiv.org/abs/2508.17413

0νββ sensitivity on $m_{\beta\beta}$

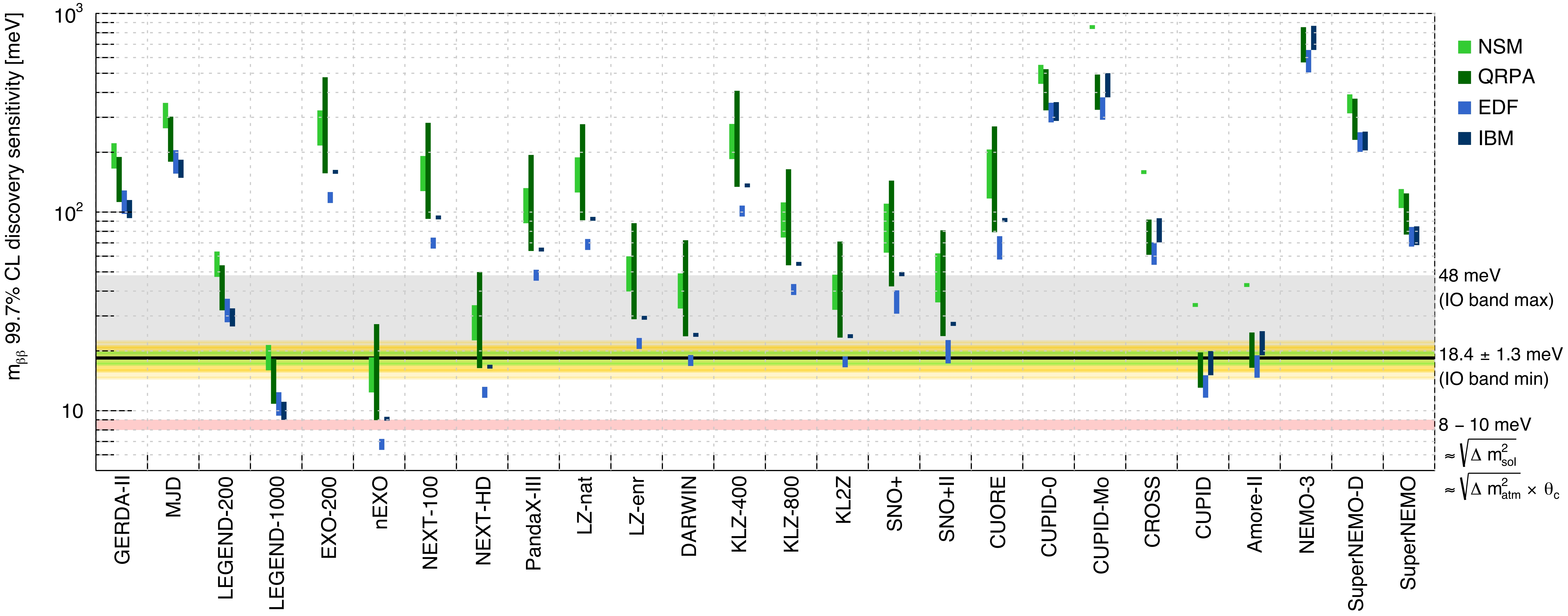
Improvement in $m_{\beta\beta}$ sensitivity is challenging. Every meV counts

0νββ sensitivity on $m_{\beta\beta}$



Rev.Mod.Phys. 95 (2023) 2, 025002

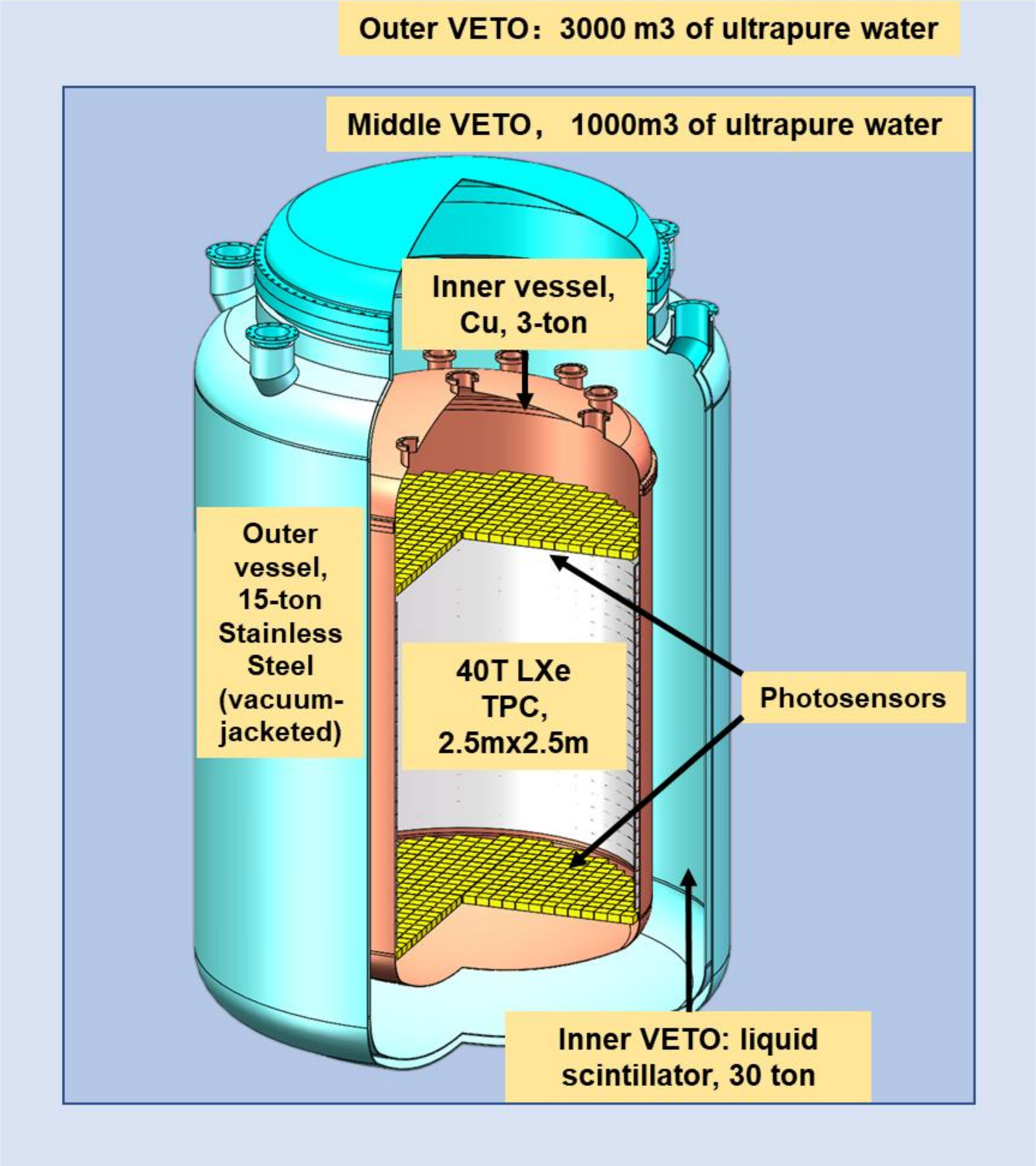
0νββ sensitivity on $m_{\beta\beta}$



- 0νββ search with next generation xenon TPCs: PandaX-xT/XLZD vs. nEXO
  - Natural xenon vs. Enriched
  - Multi-purpose vs. Specialized

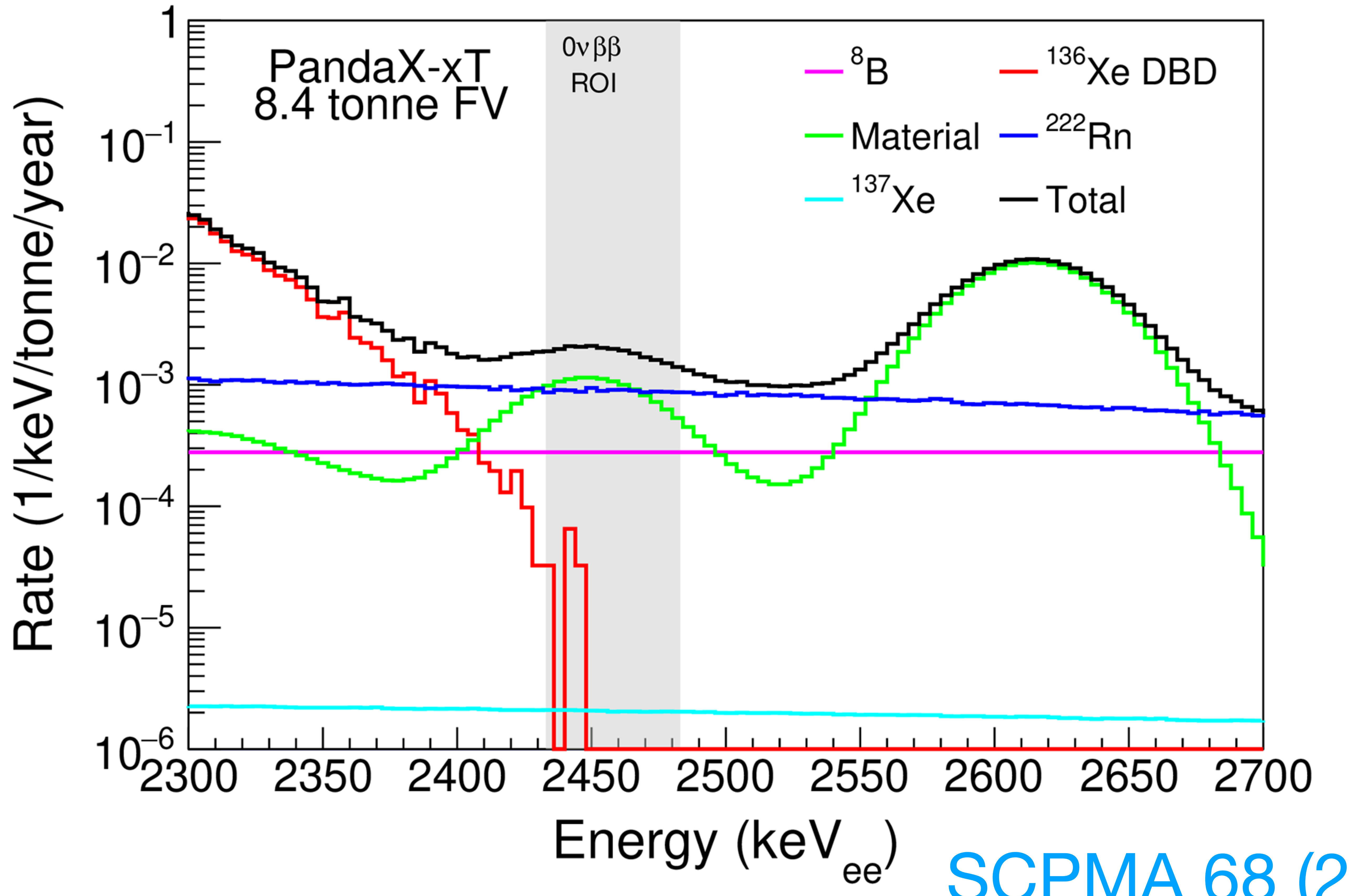
Future: PandaX-xT

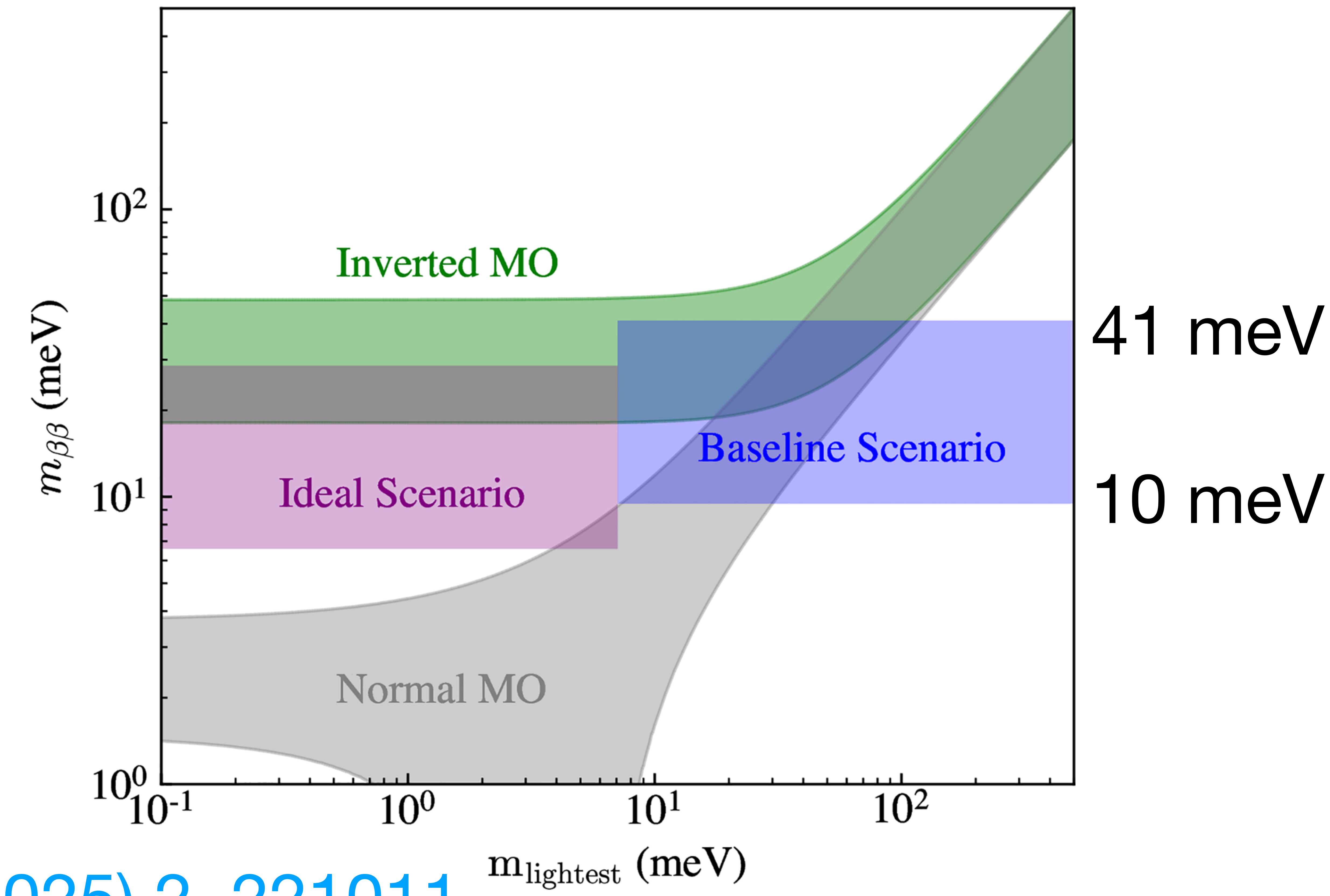
- Active target: 43 ton of Xenon
- Improved PMT, veto, vessel radiopurity, etc
- Staged upgrade utilizing isotopic separation on natural xenon.



PandaX-xT 0νββ sensitivity

	Baseline (event/(t·year))	Ideal (event/(t·year))
Photosensors	1.4×10^{-2}	2.8×10^{-3}
Copper vessel	2.9×10^{-2}	5.8×10^{-3}
^{222}Rn	4.5×10^{-2}	–
^{136}Xe DBD	5.2×10^{-4}	5.2×10^{-4}
^{137}Xe	1.0×10^{-4}	1.0×10^{-4}
Solar ^{8}B ν	1.4×10^{-2}	1.4×10^{-2}
Total	1.1×10^{-1}	2.4×10^{-2}

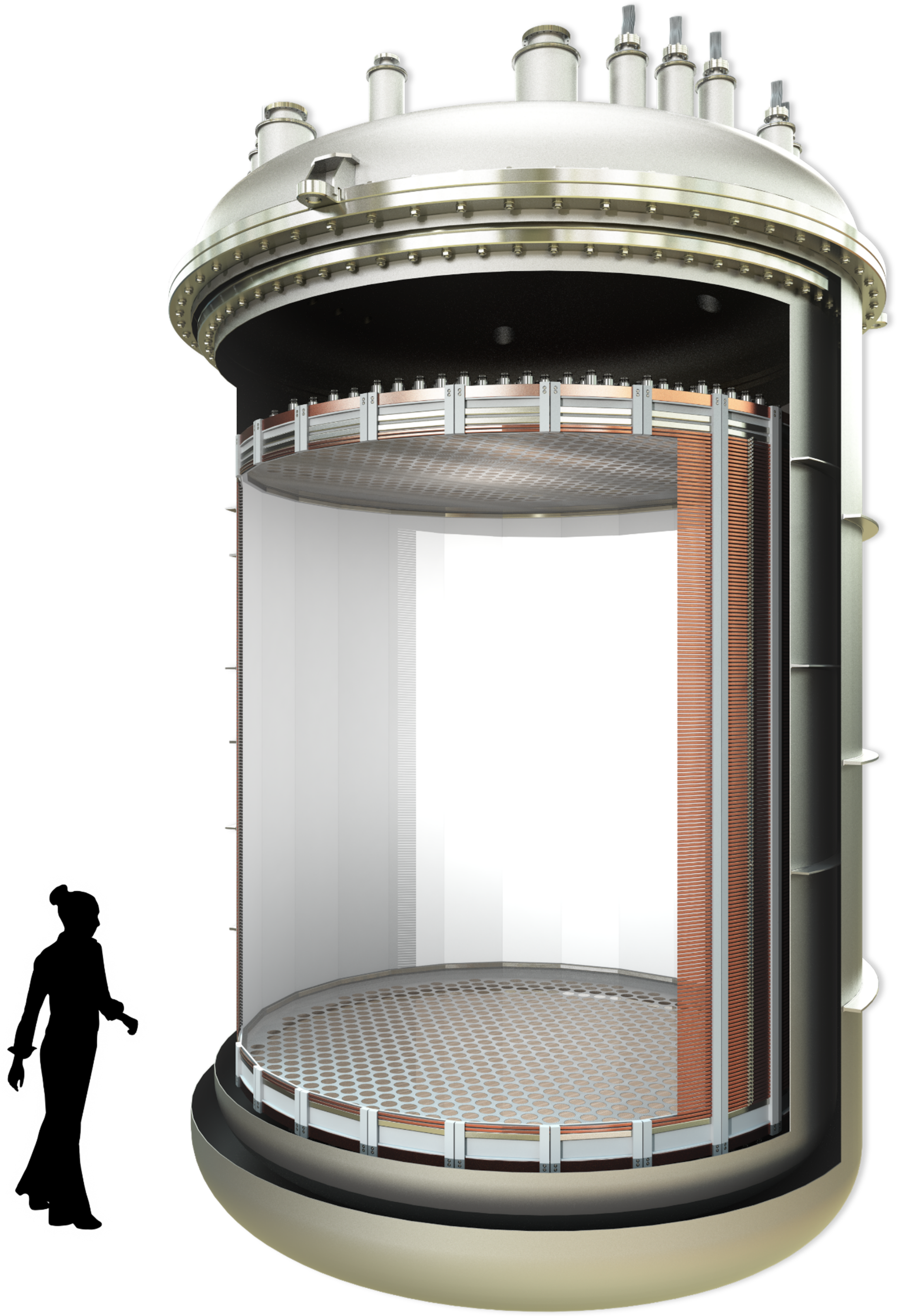




SCPMA 68 (2025) 2, 221011

Future: XLZD

- Dual-phase liquid xenon (LXe) TPC for DM and $0\nu\beta\beta$, etc
- 60 t LXe baseline design (80 t considered as well)
- Darwin + LZ + XENONnT experiments

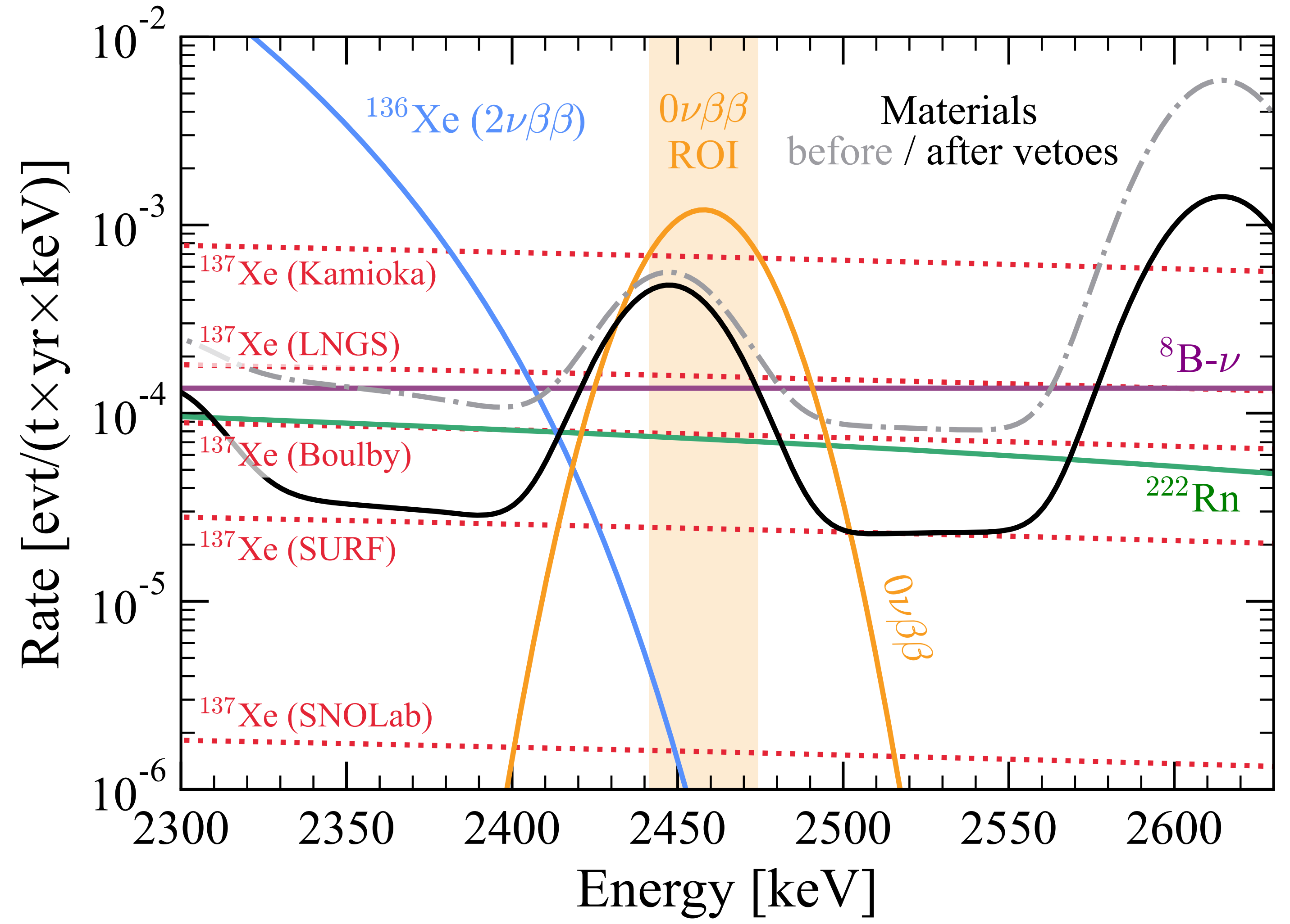


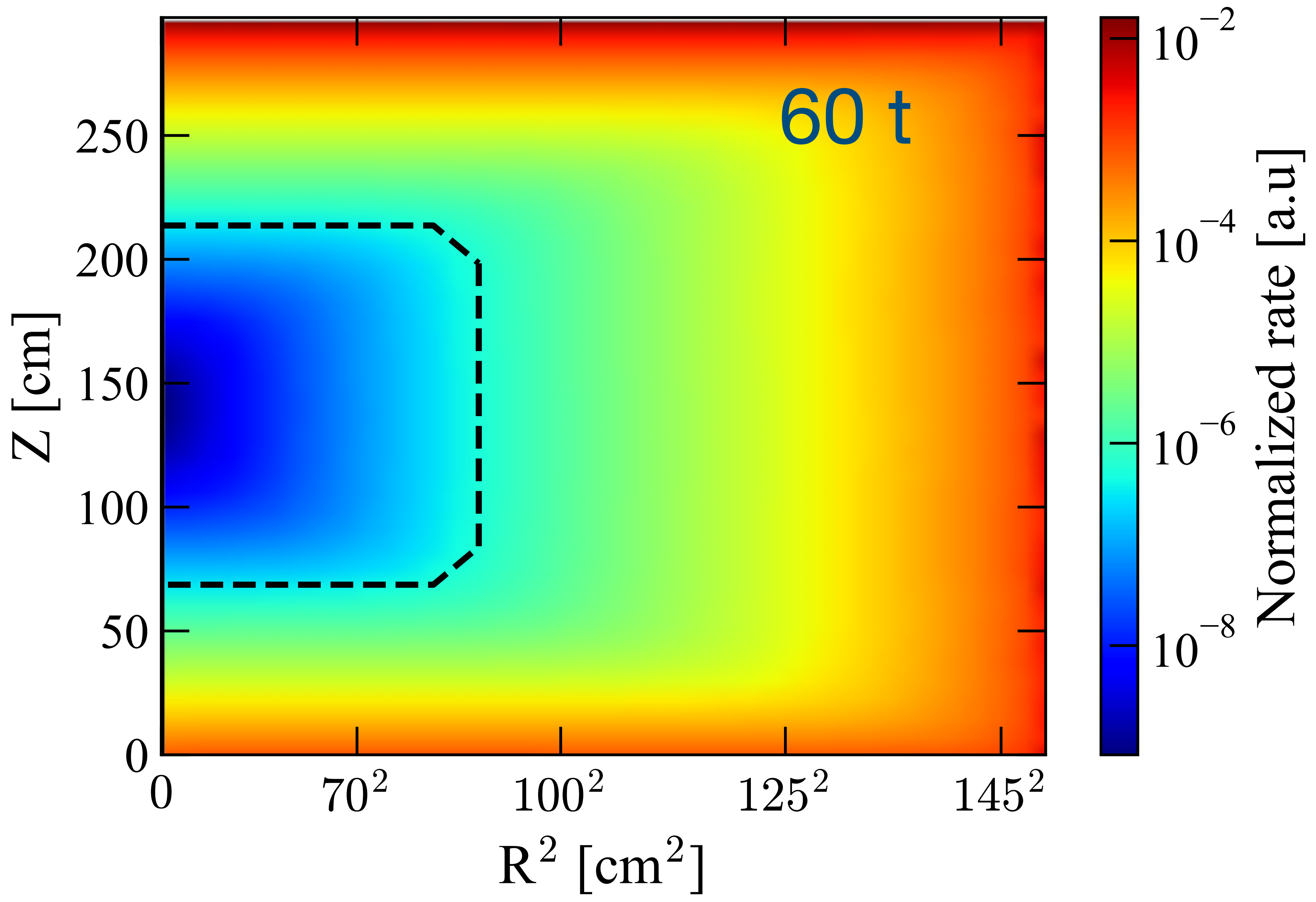
ArXiv: 2410.17137

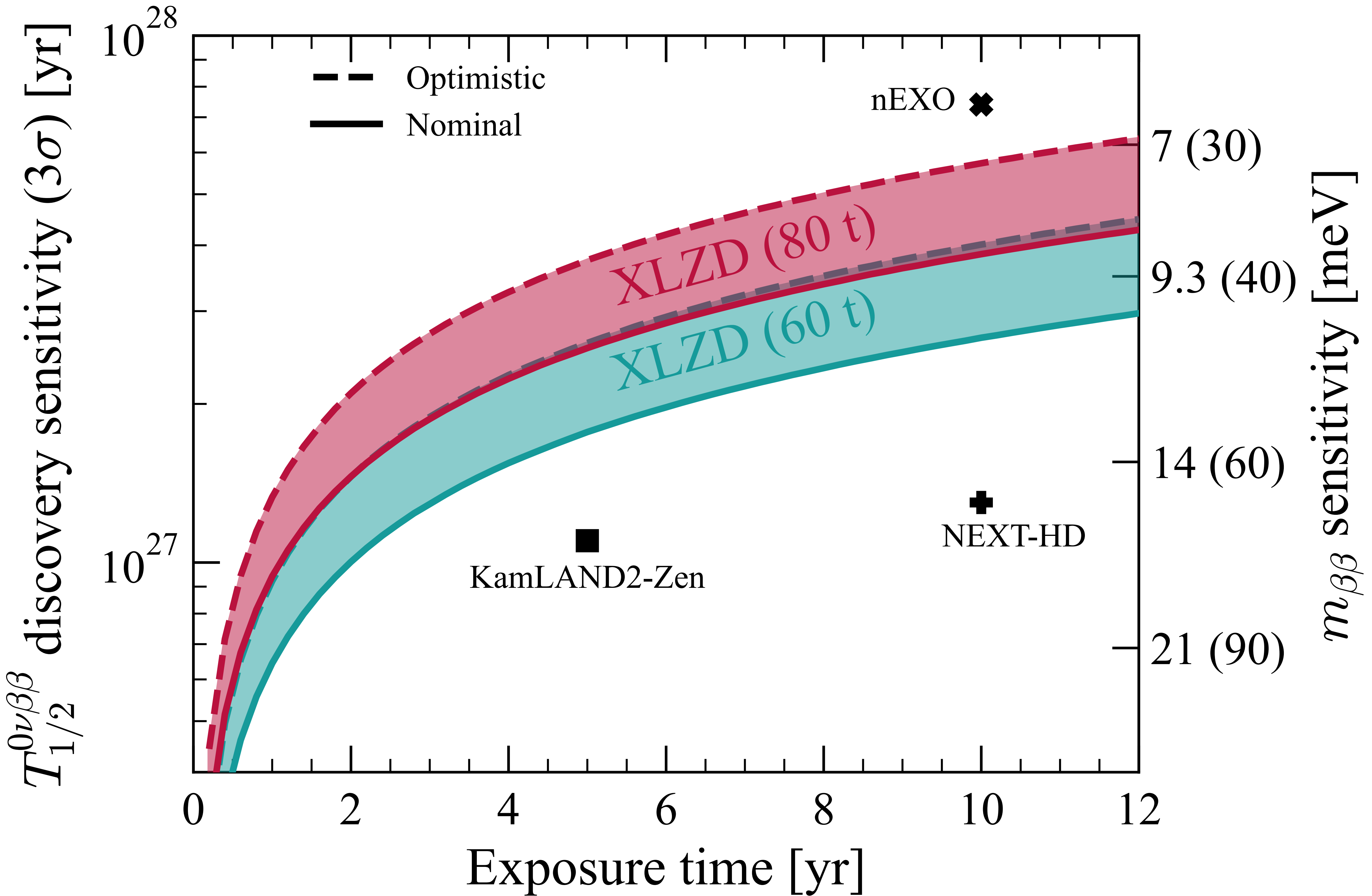
XLZD 0νββ sensitivity

J.Phys.G 52 (2025) 4, 045102

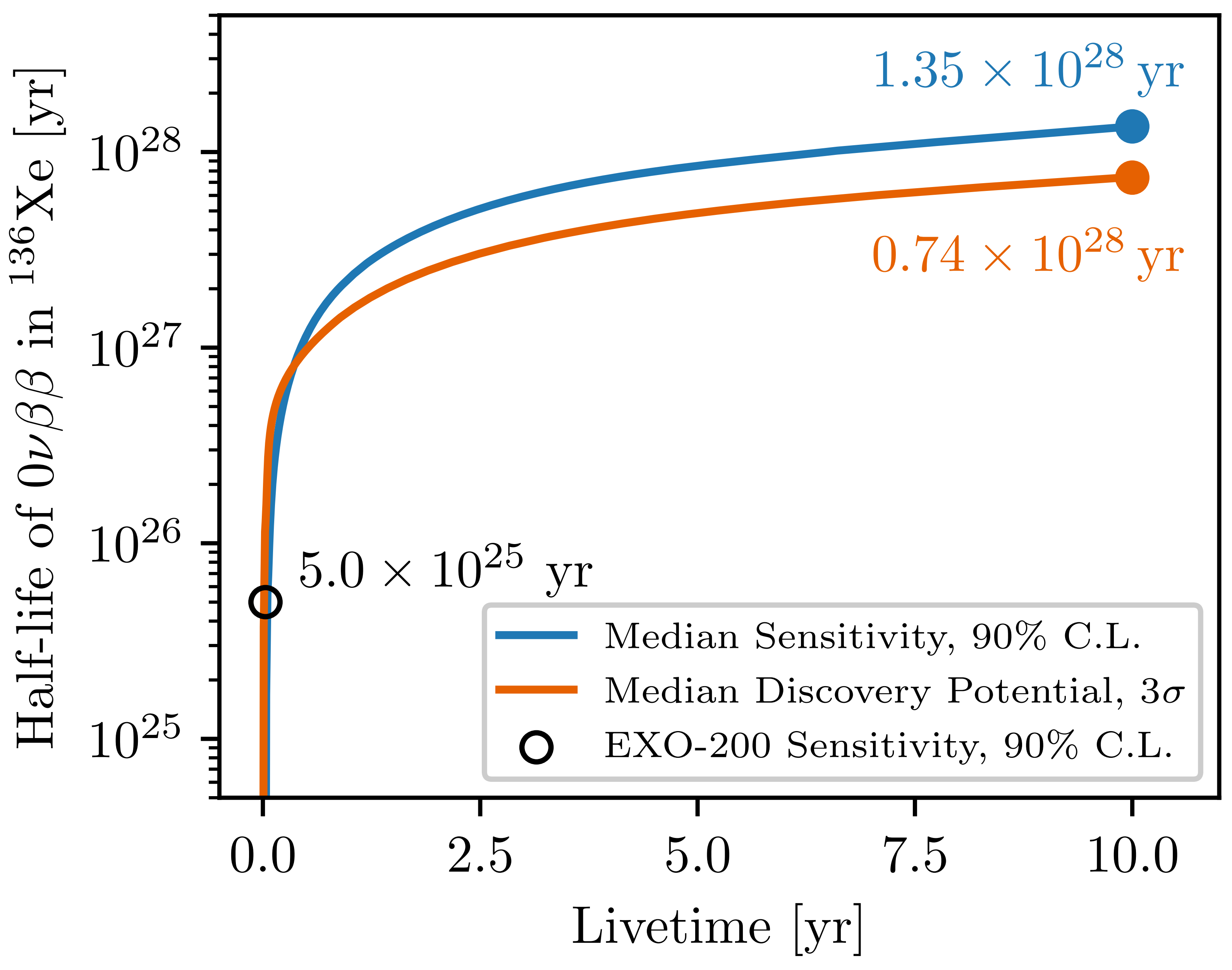
- Aggressive FV cuts
- Competitive sensitivity





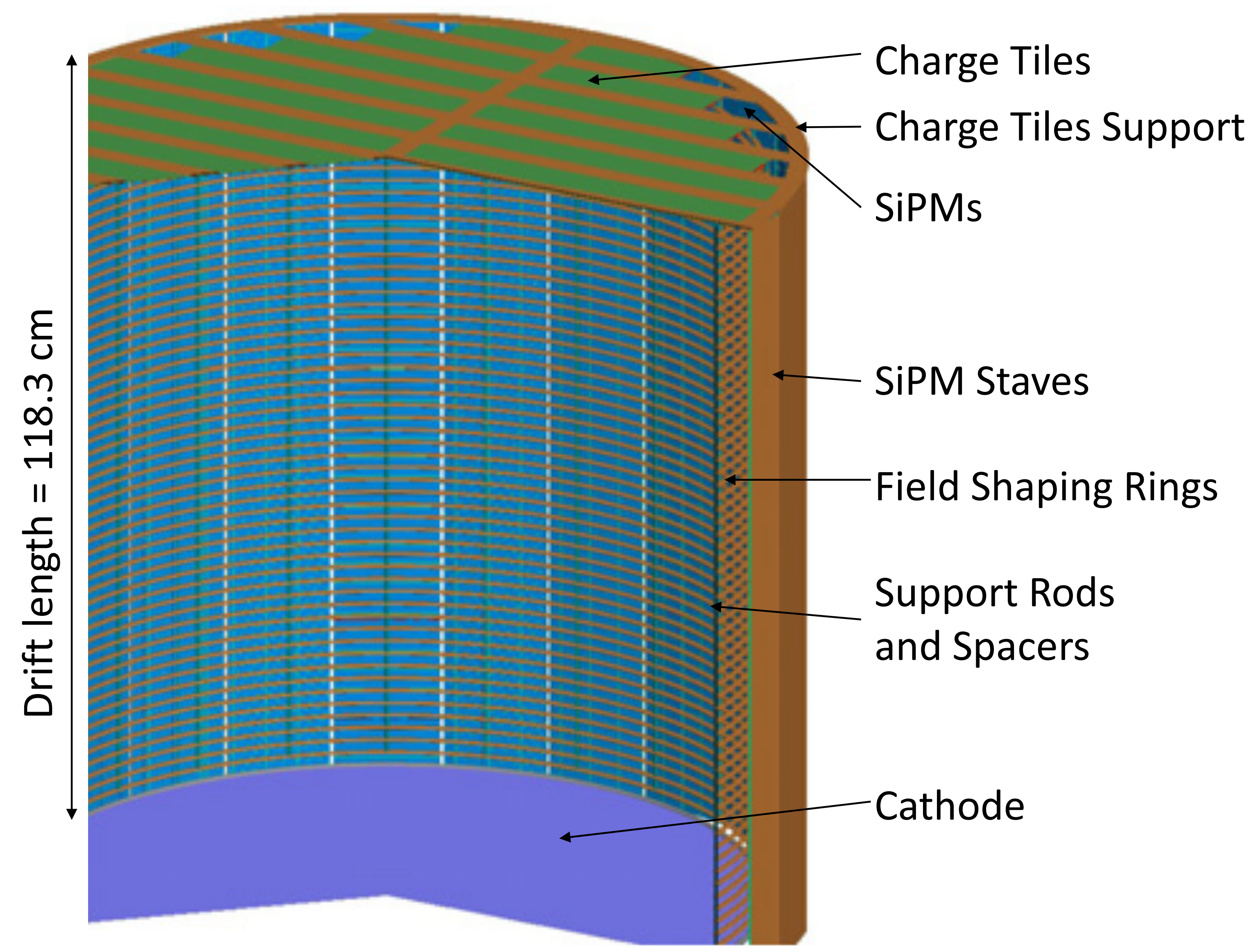


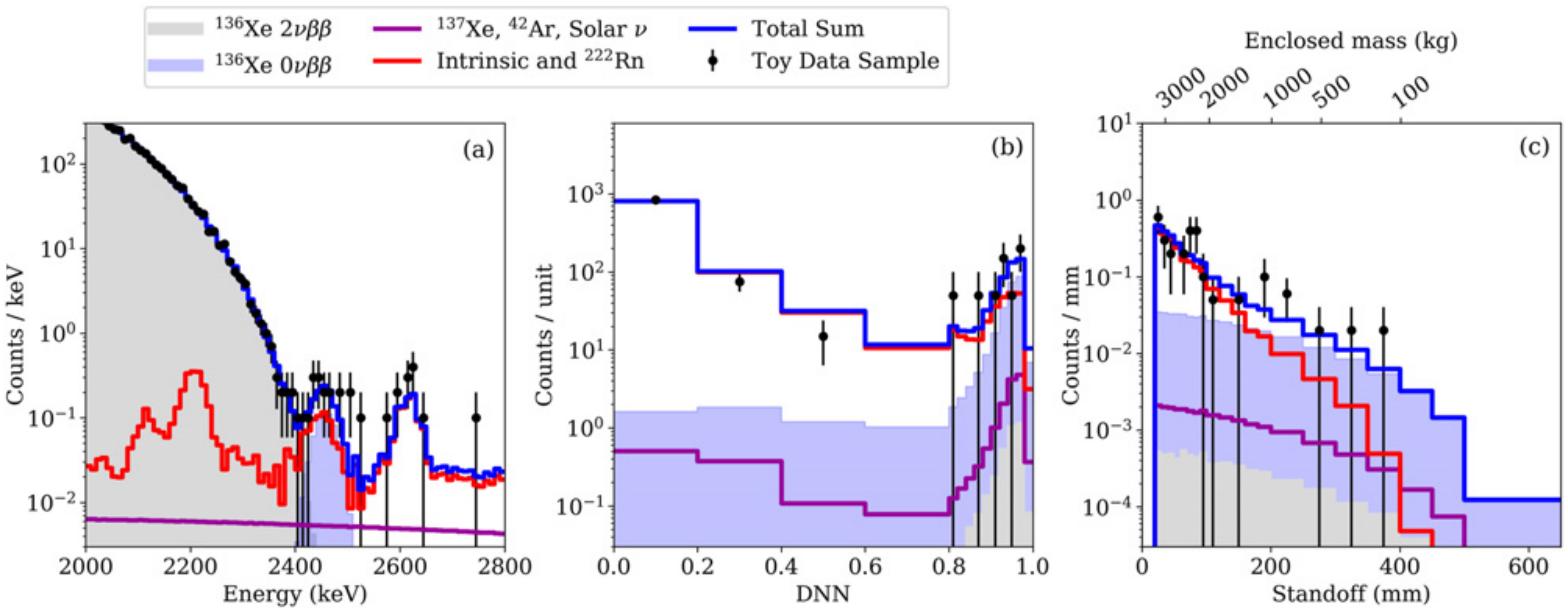
Future: nEXO



J.Phys.G 49 (2022) 1, 015104

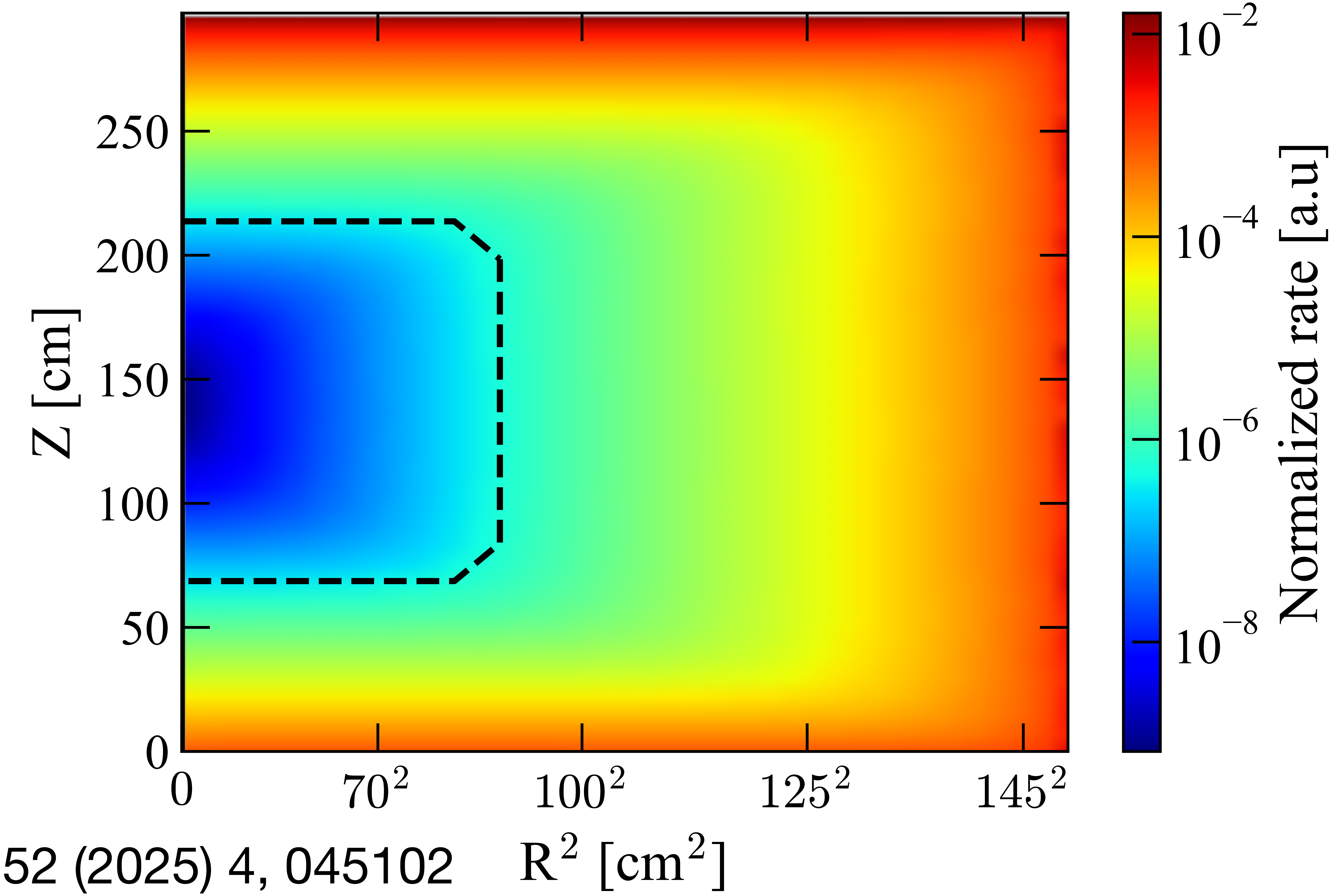
Description	Value
Liquid xenon mass in vessel	4811 kg
Liquid xenon mass in drift region	3648 kg
Fiducial xenon mass	3281 kg
TPC drift height	118.3 cm
TPC drift diameter	113.3 cm
TPC vessel height	127.7 cm
TPC vessel diameter	127.7 cm
Inner vessel diameter*	338 cm
Outer vessel diameter*	446 cm
Water tank height	13.3 m
Water tank diameter	12.3 m





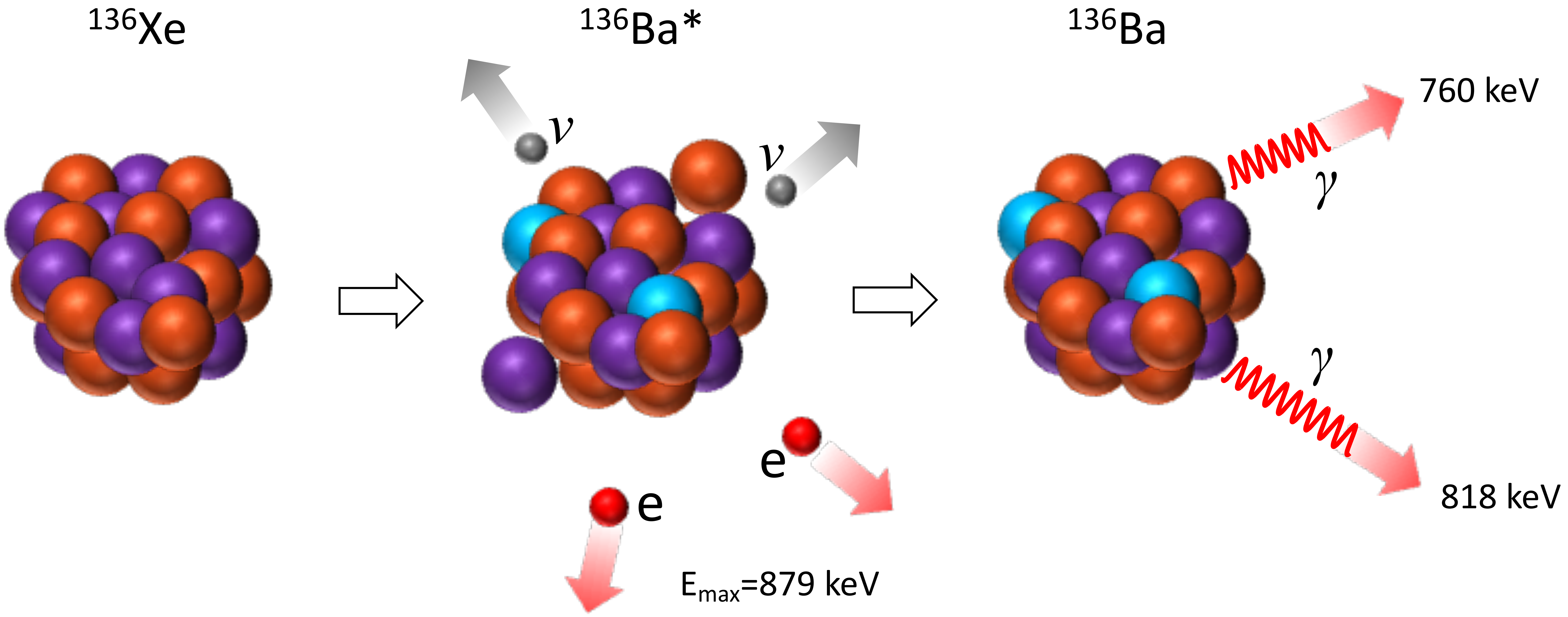
Background rate and FV in natural LXe TPC

- Outside of FV: Background rate too high to search for 0νββ?
- Wasted xenon?



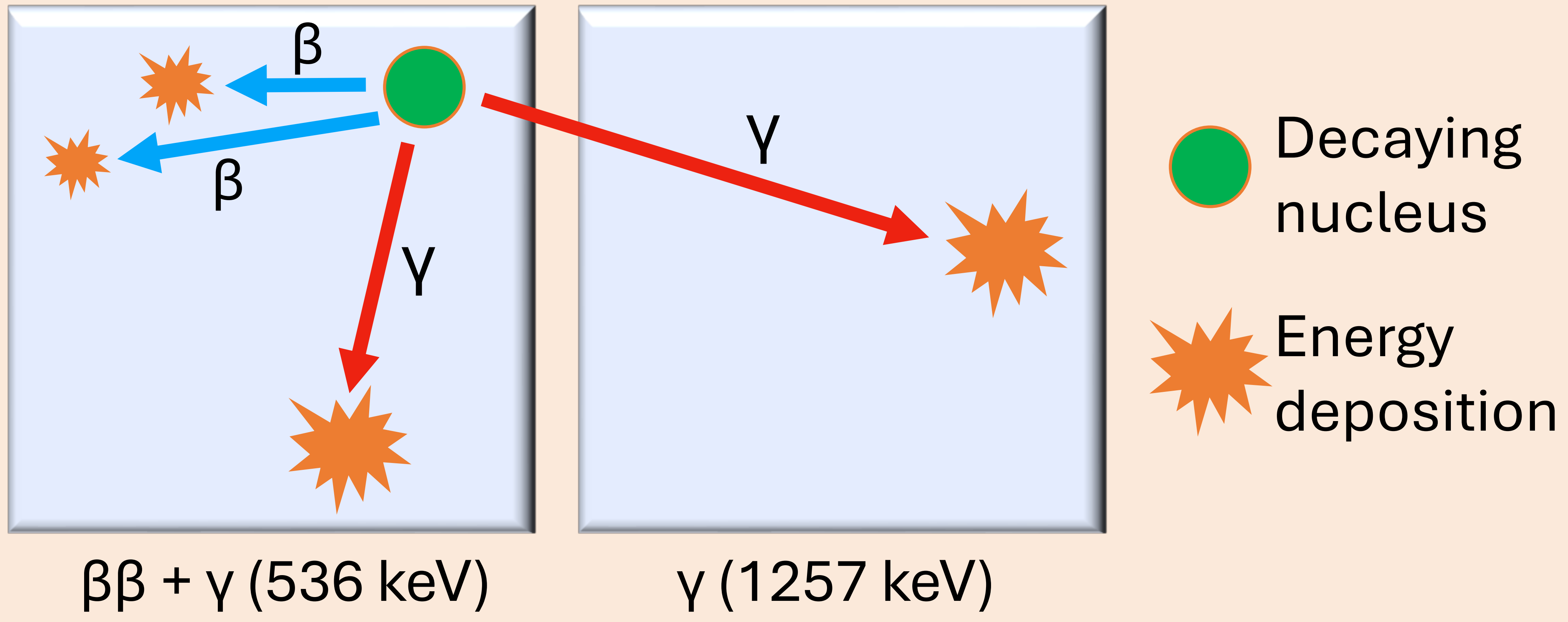
XLZD, *J.Phys.G* 52 (2025) 4, 045102

Decay to excited states (0vββ-ex)



Detector response

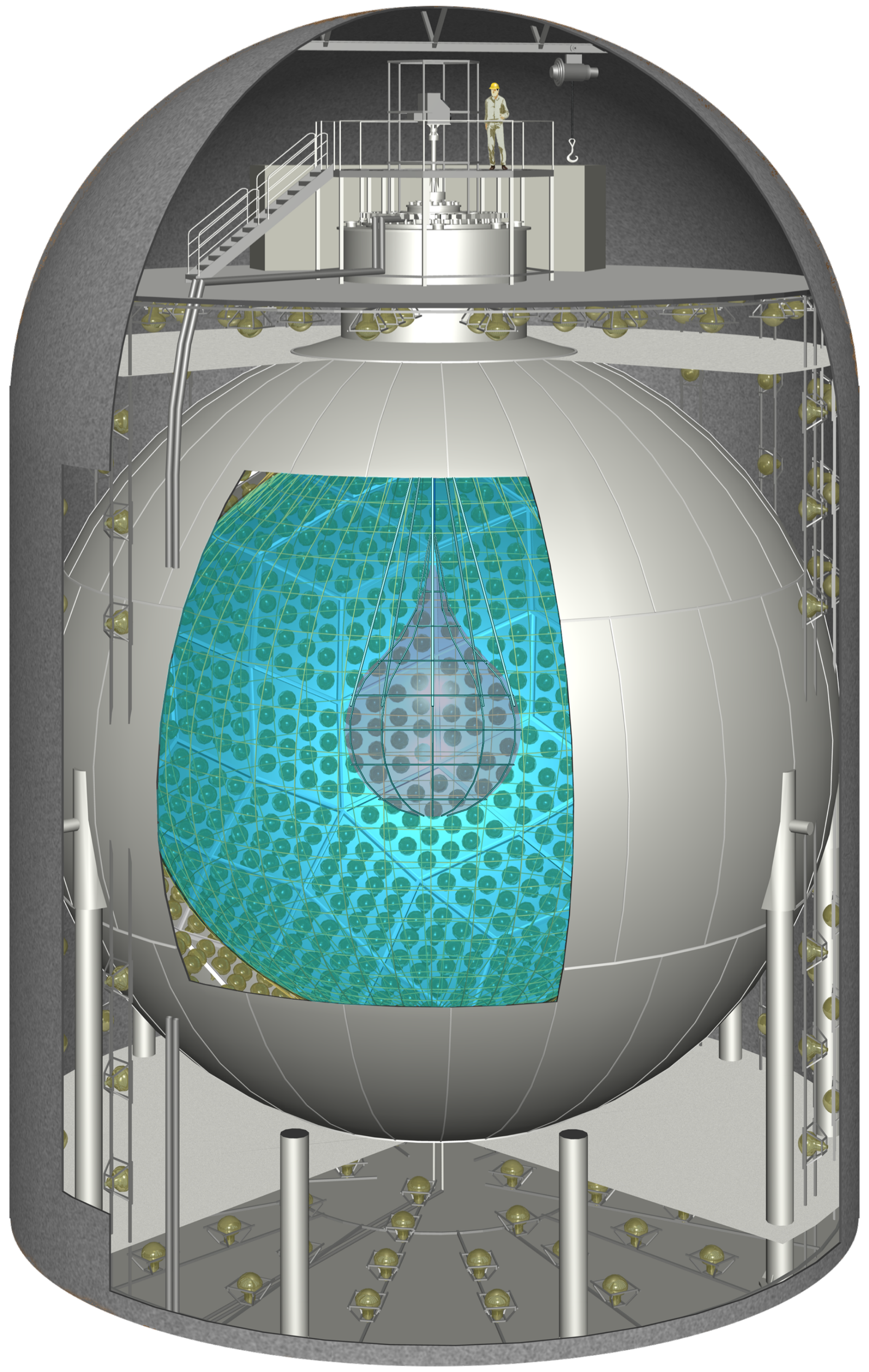
CUORE/CUPID style Modular detector

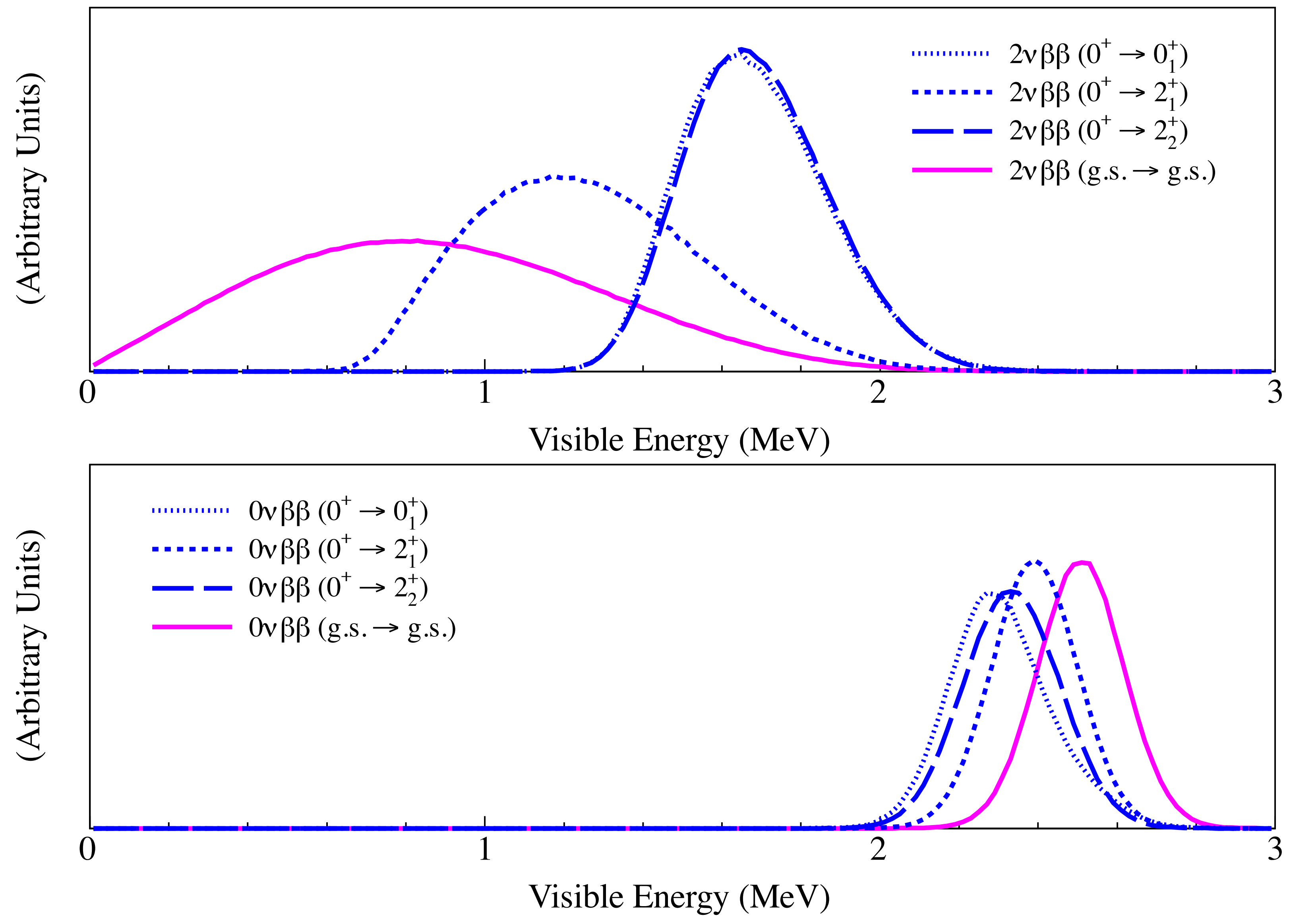


0νES ROI (signal fraction)	Multiplicity, energy cuts	Signal peak, fit axis
ROI 1 (4.6%)	$M=2$ $E_{\rm large}\in[1247,1280]$ $E_{\rm small}\in[1247,1280]$	734 keV $Q_{\beta\beta}$ + 536 keV γ in $E_{\rm large}$
ROI 2 (2.9%)	$M=2$ $E_{\rm large}\in[1981,2001]$ $E_{\rm small}\in[523,573]$	536 keV γ in $E_{\rm small}$
ROI 3 (2.5%)	$M=3$ $E_{\rm large}\in[1247,1267]$ $E_{\rm mid}\in[700,760]$ $E_{\rm small}\in[526,546]$	734 keV $Q_{\beta\beta}$ in $E_{\rm mid}$

Ridge Liu, Poster at this TAUP

KamLAND-ZEN LS detector

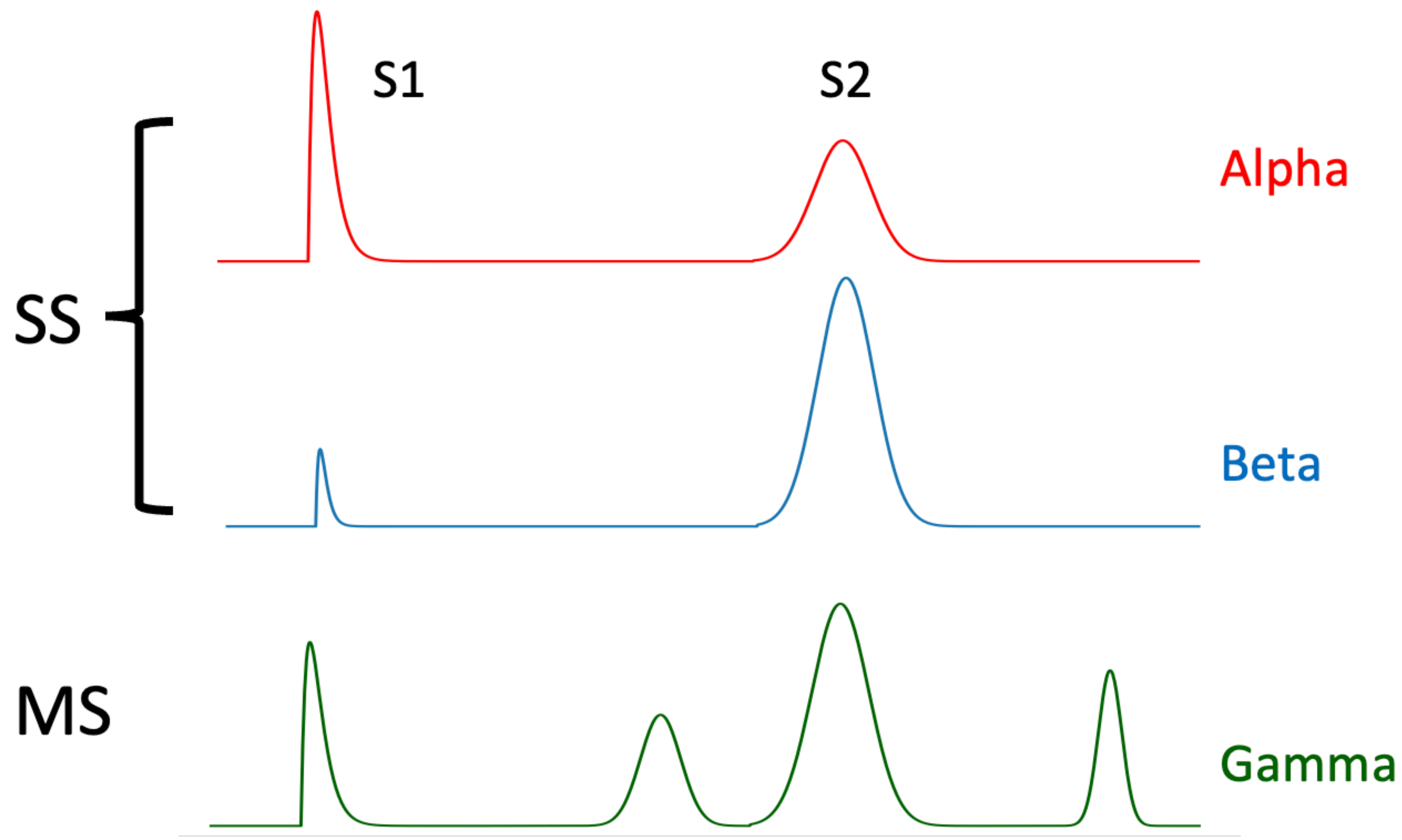


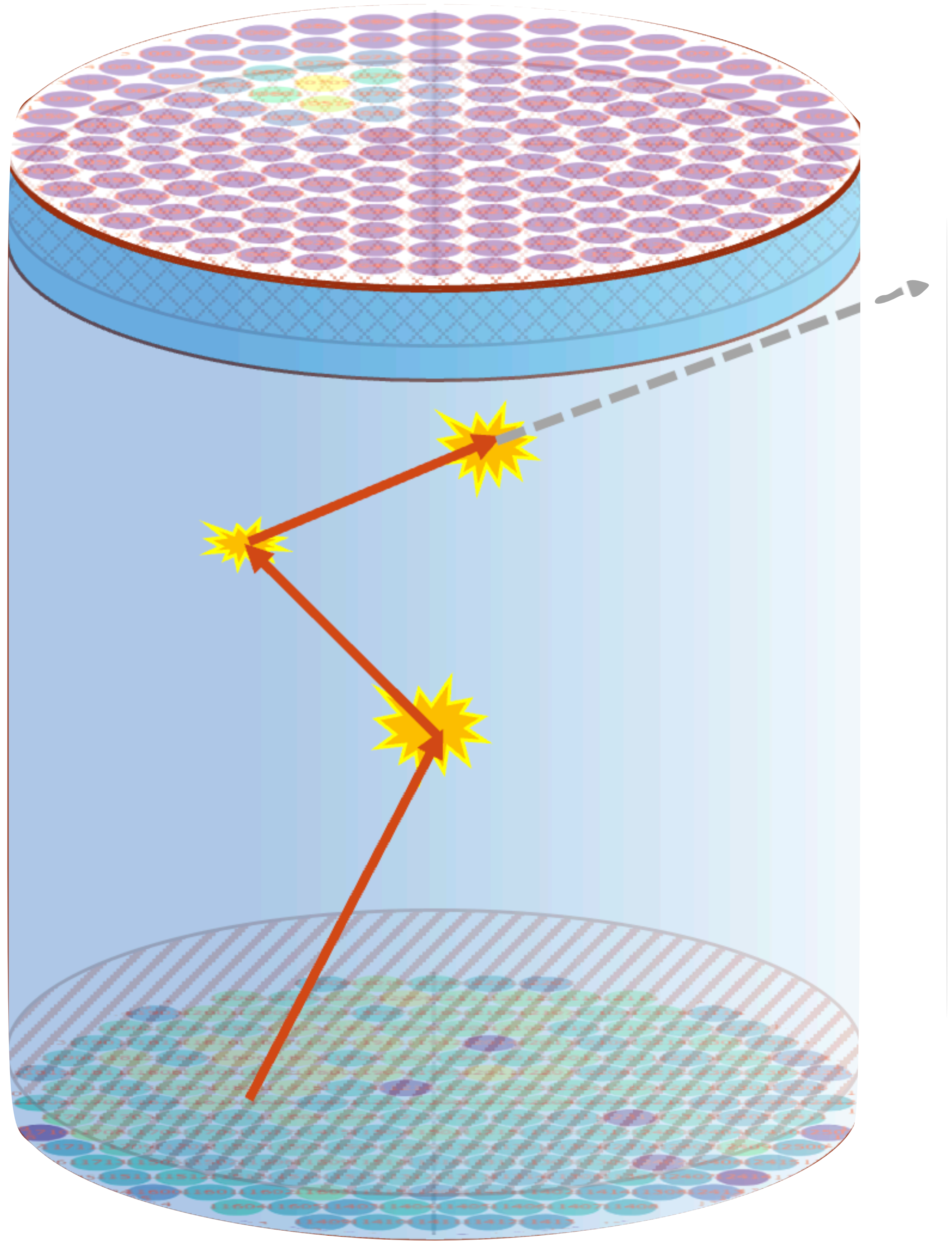


Nuclear Physics A 946 (2016) 171

LXe Detector technology

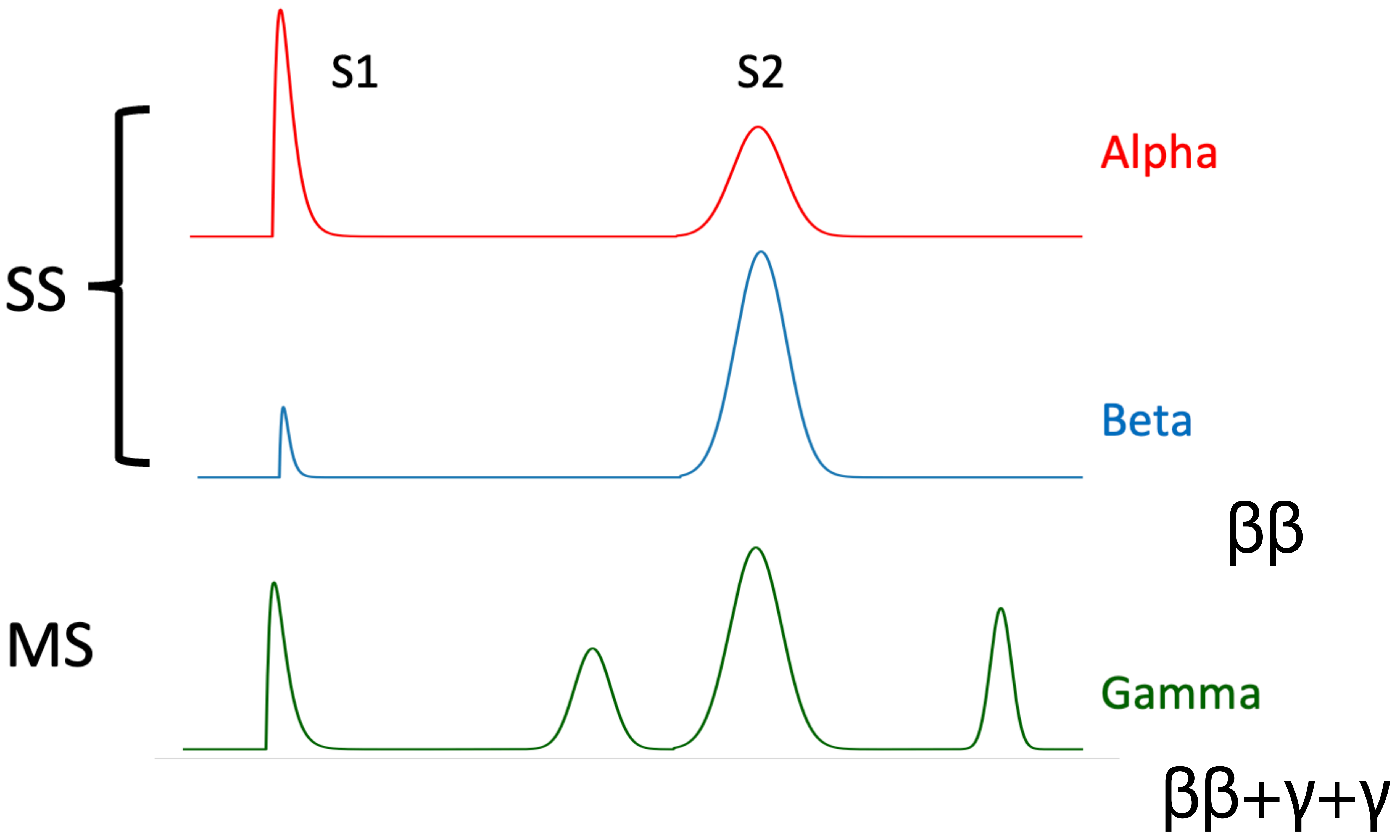
- Precisely measure 3D position, energy, and timing from sub-keV to 10MeV
- Large monolithic volume: **>20×** MeV ɣ attenuation length
- Single-site (SS) and multi-site (MS) event topology for particle ID

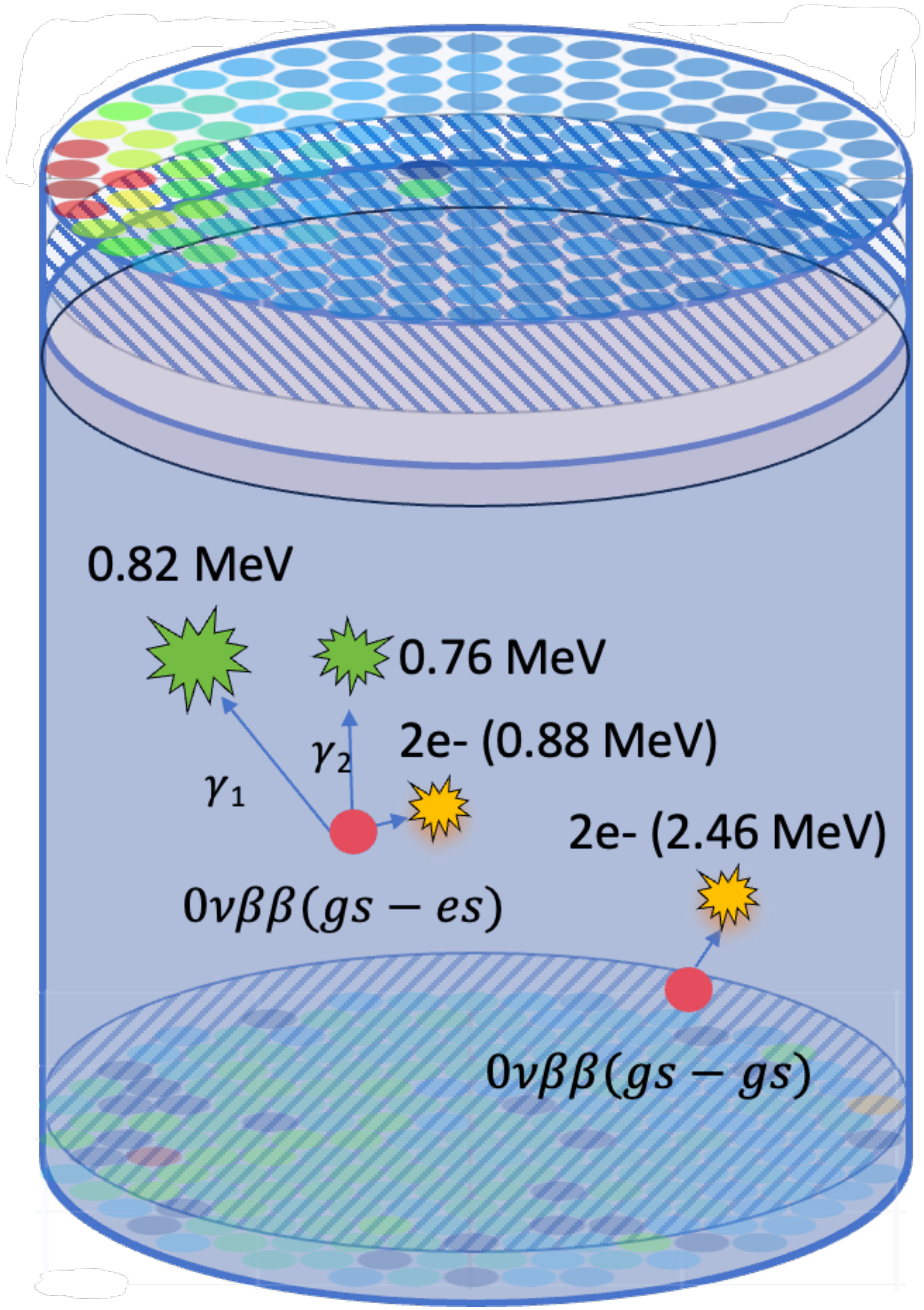




Response to 0νββ-ex

- High signal efficiency
- Clear signature for background suppression





Decay rate

$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}(Q,Z)\,|M^{0\nu}|^2\,\frac{|\langle m_{\beta\beta}\rangle|^2}{m_e^2}$$

Phase space factor

Nuclear matrix element

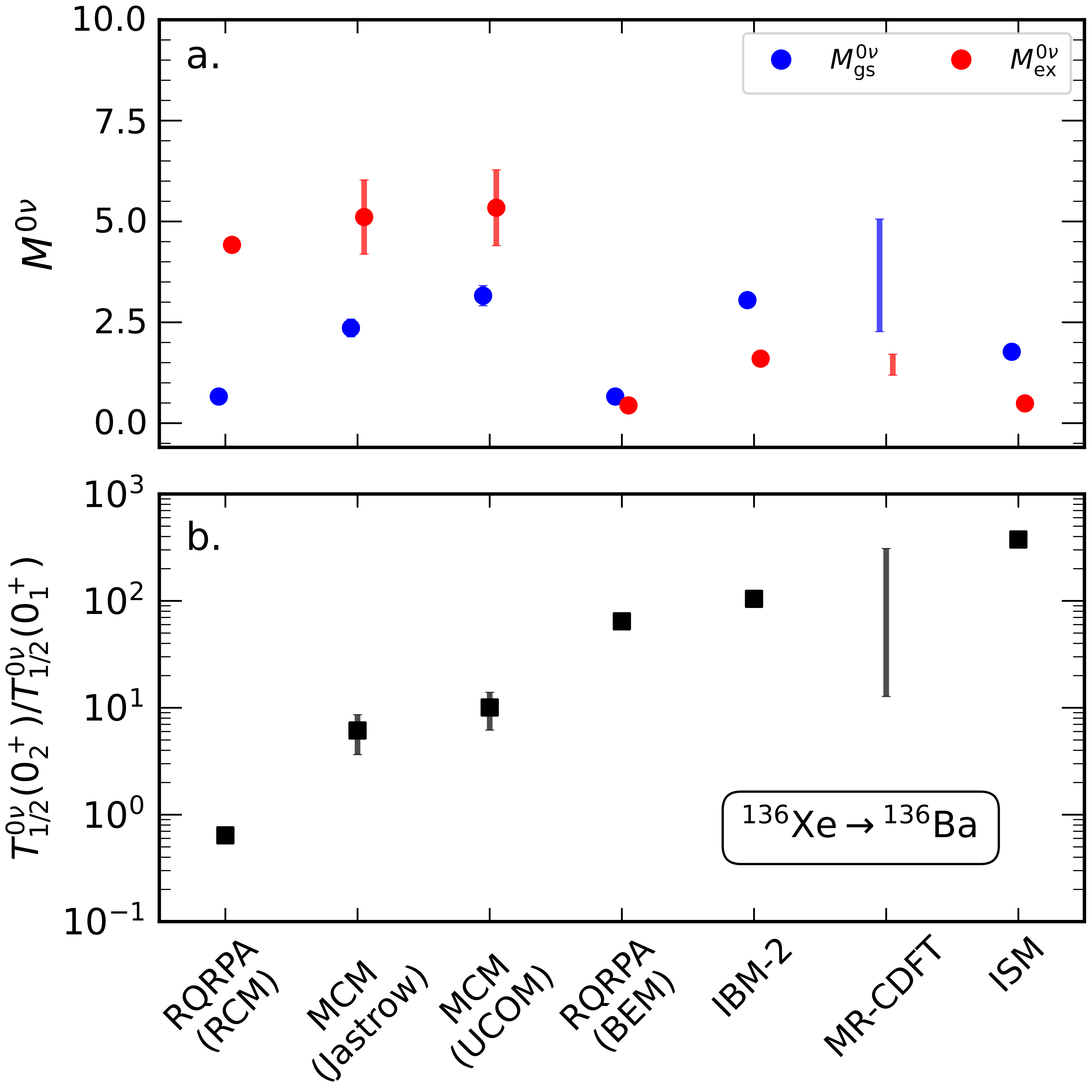
- $G^{0\nu} \propto Q^5$
- $M^{0\nu} \in [1,10]$ depending on isotopes, nuclear models

$$0\nu\beta\beta - gs:\ \ {}^{136}Xe \rightarrow {}^{136}Ba^{++} + 2e^- + Q\,(2458\,keV)$$

$$0\nu\beta\beta - ex:\ \ {}^{136}Xe \rightarrow {}^{136}Ba^{++} + 2e^- + \gamma_1 + \gamma_2 + Q\,(879\,keV)$$

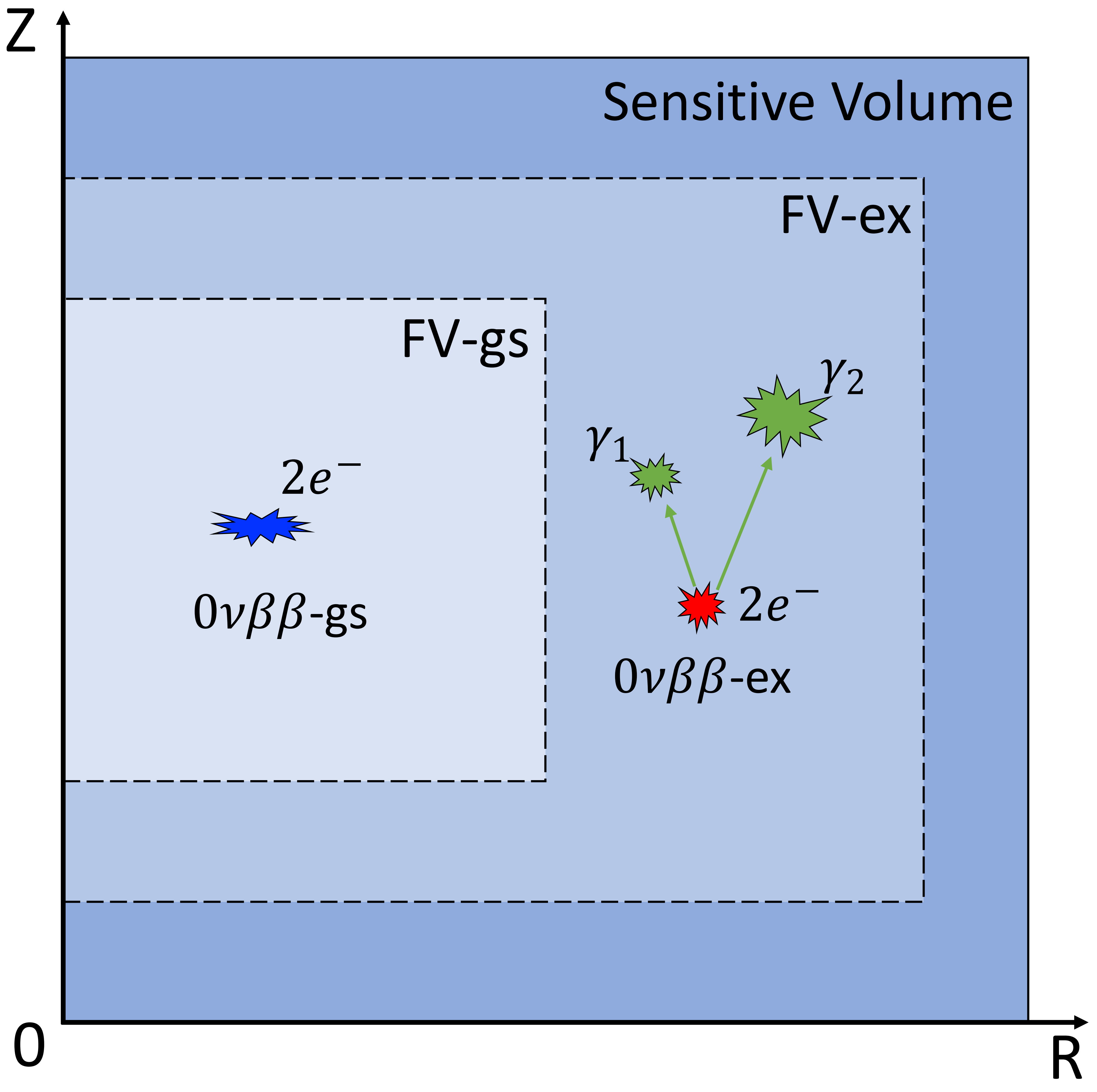
Expected half-lives

- Relative amplitude of NMEs for 0vββ-gs and 0vββ-ex depends on nuclear models
- The difference in expected half-lives may not be as significant as expected.
- Can 0vββ-ex help enhance the sensitivity to $m_{\beta\beta}$?



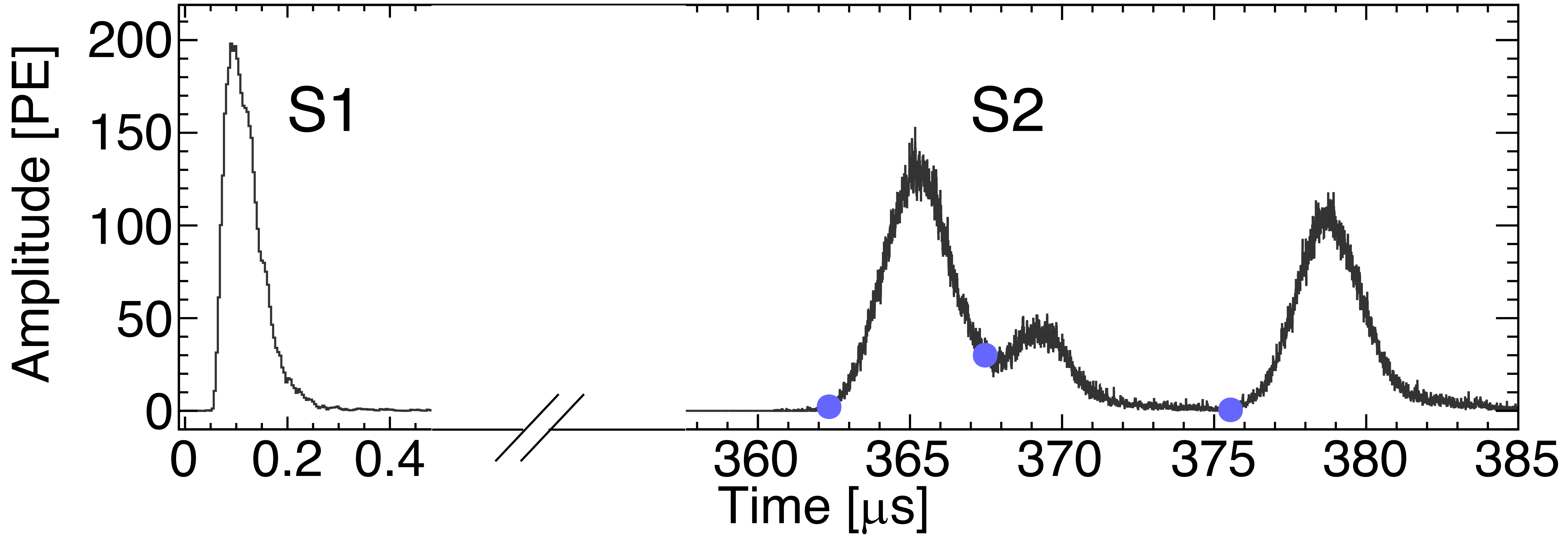
Clear signature in LXe TPC ➔ larger FV; lower background rate

- A reference detector (XLZD-like)
  - Detector size 60 t
  - Background counts of 0.32 per year
  - Resulution: 0.65% (sigma) at 2.46 MeV
  - Signal efficiency: 0.76
  - FV-gs = 8.2 t
- FV-ex = 20 t (a nominal scenario):
  - External radioactivity of 32 mBq ^{238}U
  - 0.12 events per year

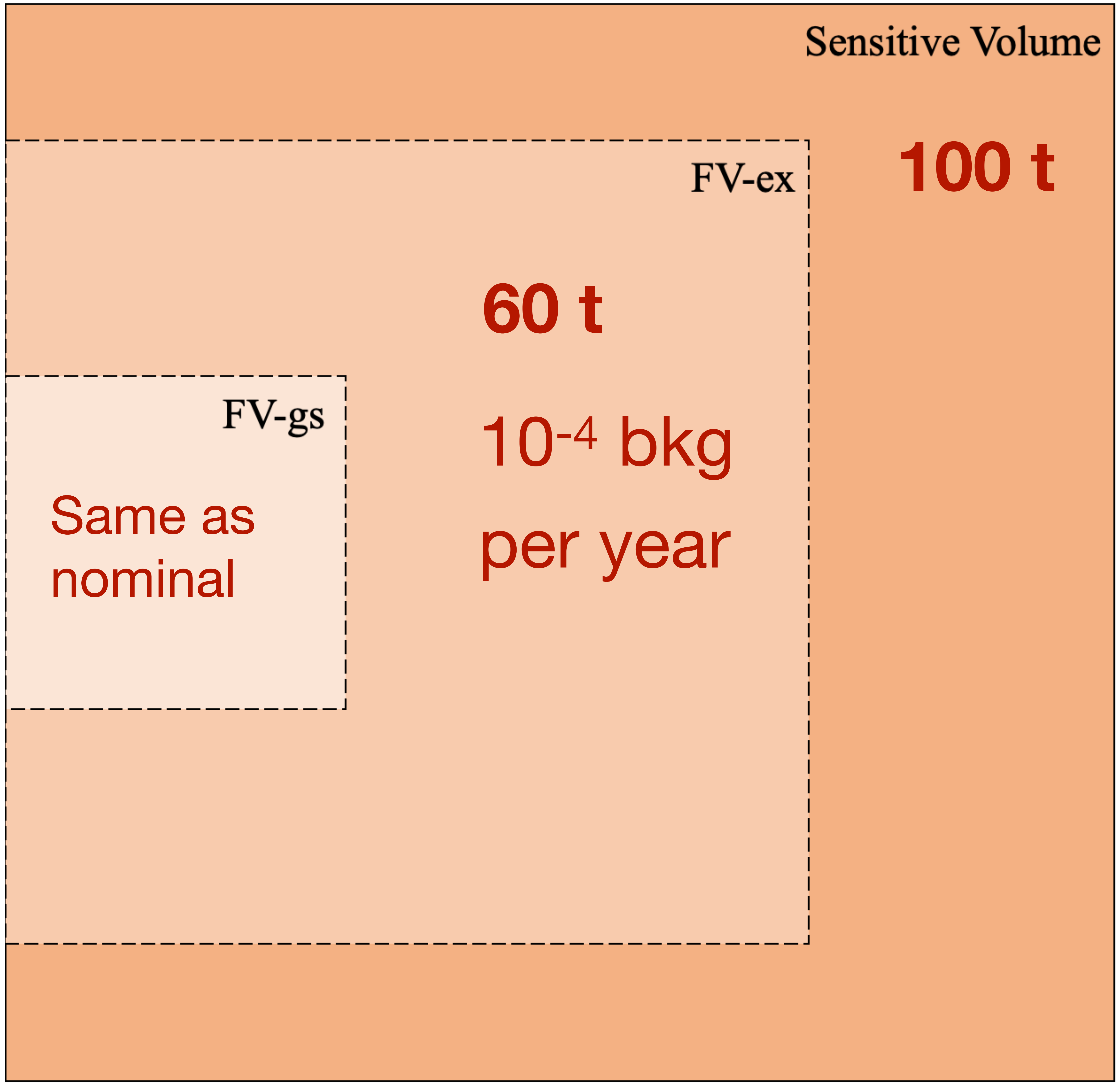


Simulation of LXe TPC SS/MS discrimination

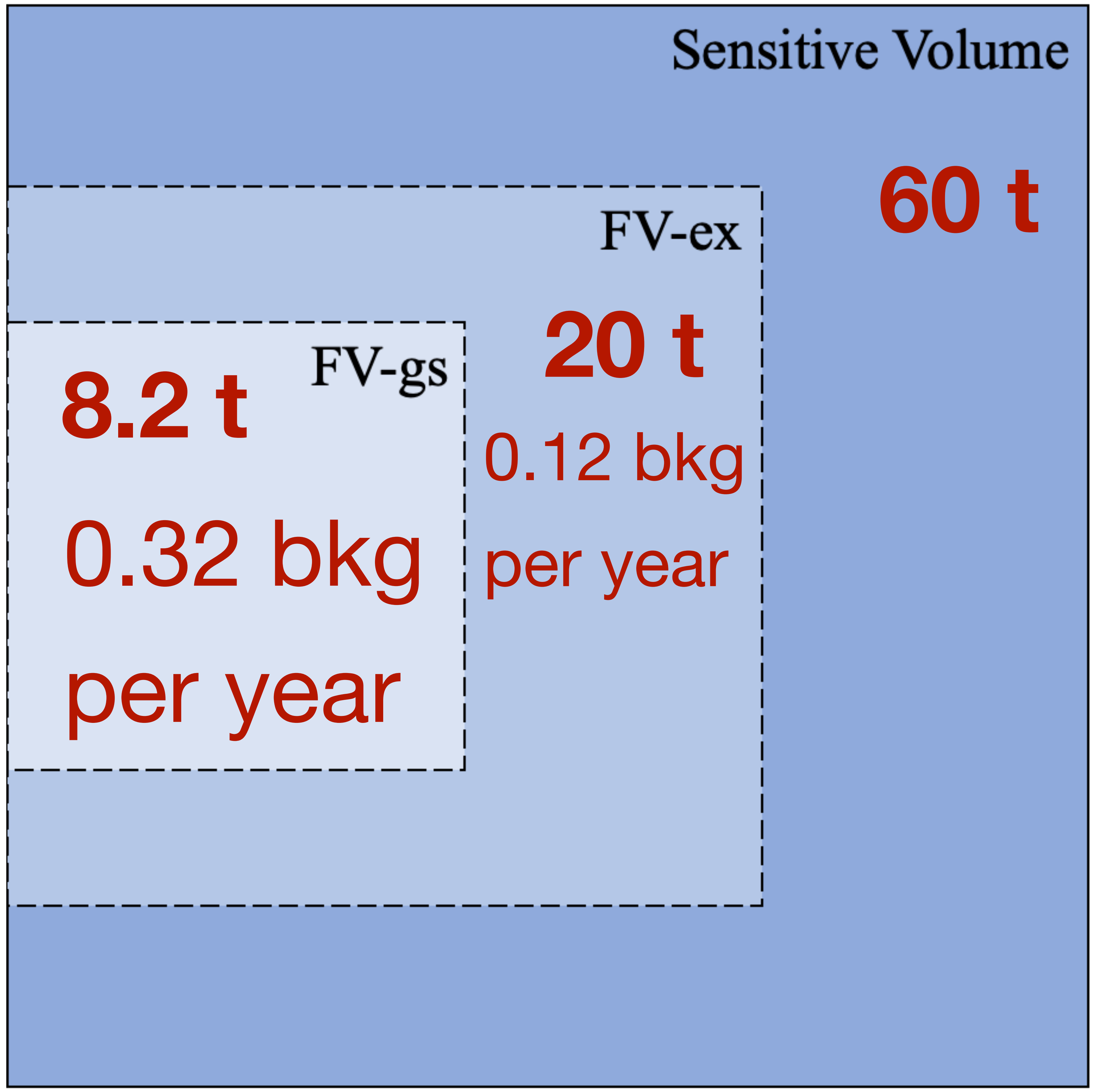
- Consider energy and position smearing in the TPC
- Only Z-direction information is utilized: 5 mm separation for a site
- Simple 0νββ-ex MS signal selection:
  - Total energy within the ROI;
  - Site energy (sum) is 0.88 MeV
  - No other site energy > 0.83 MeV.



An ideal scenario



Nominal scenario



Combined multi-transition analysis

- Consider the 0νββ-gs and 0νββ-ex simultaneously to constrain $m_{\beta\beta}$ more effectively
- $\Delta\chi^2 \geq 9$ defines the region of the 3σ confidence level.
- i is for 0νββ-gs and -ex

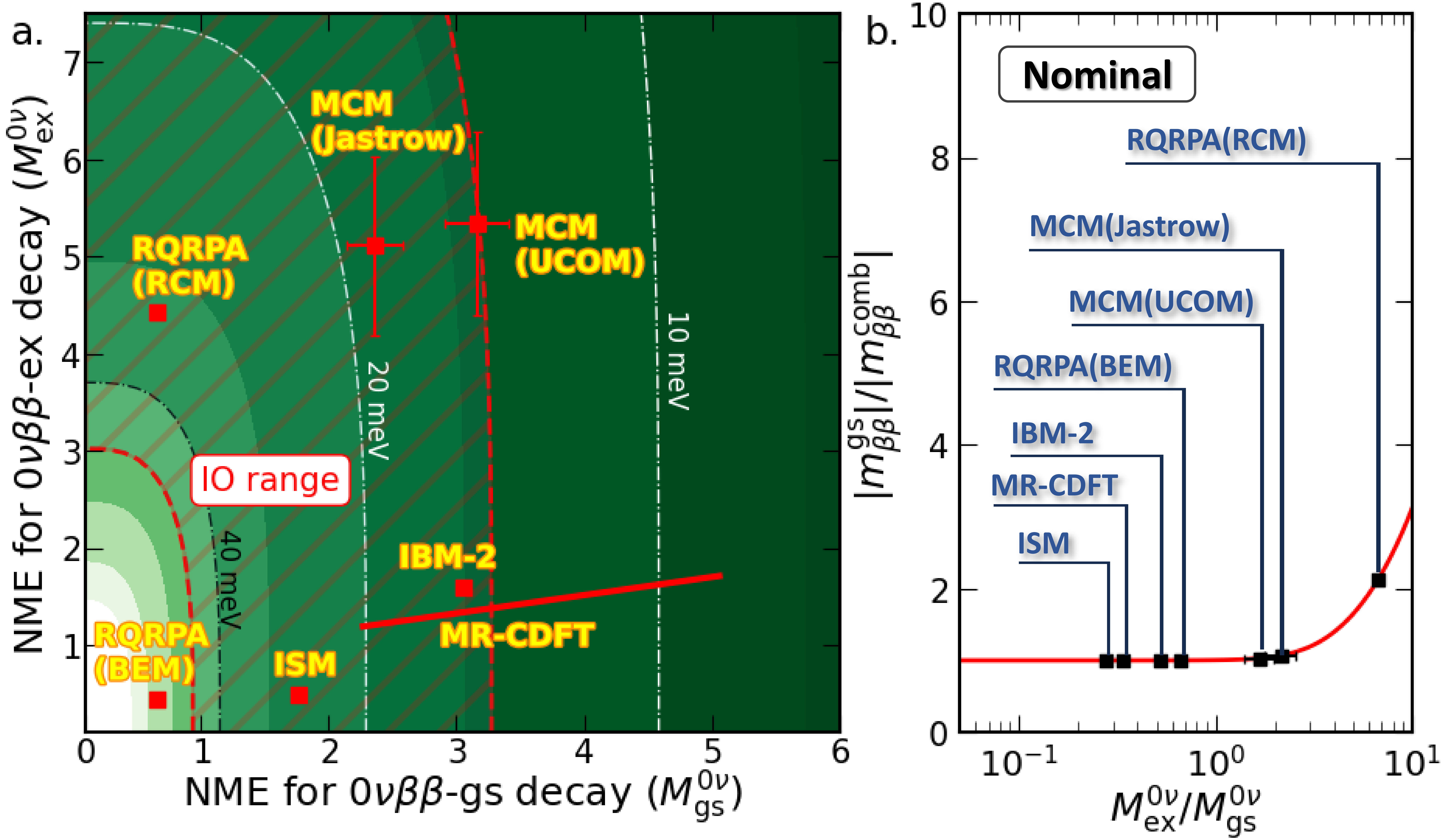
$$[T_{1/2}^{0\nu,i}]^{-1} = g_A^4 G_i^{0\nu} |M_i^{0\nu}|^2 \frac{|m_{\beta\beta}|^2}{m_e^2},$$

$$\Delta\chi^2 = -2[\ln \mathcal{L}(N|B) - \ln \mathcal{L}(N|N)]$$
$$= 2\sum_i \left[N_i \ln\left(1 + \frac{S_i}{B_i}\right) - S_i\right],$$

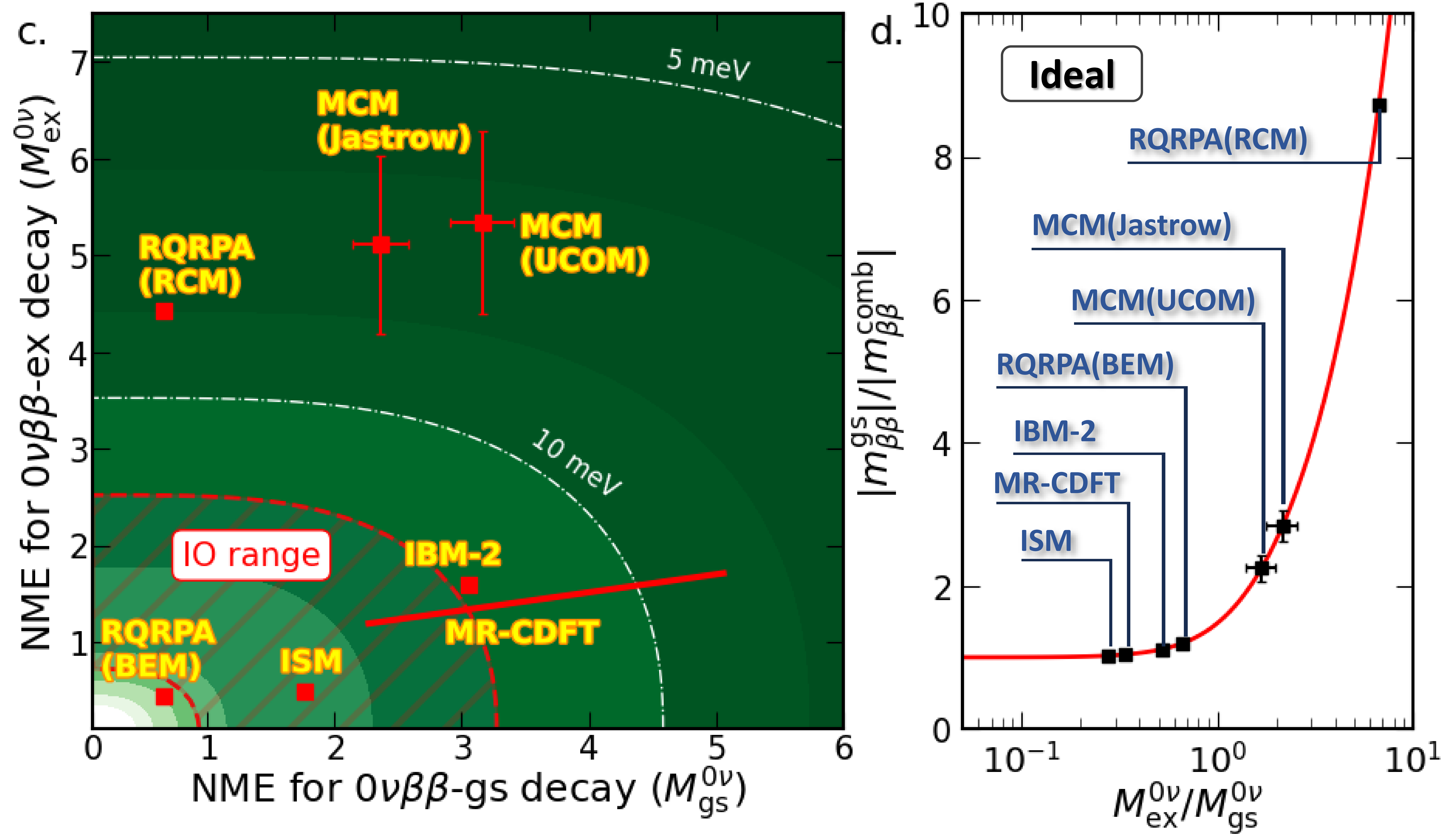
$$N_i = S_i + B_i.$$

$$S_i = \ln 2 \cdot \frac{N_A \cdot \epsilon_i \cdot \eta_i}{m_a} \cdot [T_{1/2}^{0\nu,i}]^{-1},$$
$$B_i = \eta_i \cdot \mathrm{BI}_i \cdot \Delta E_i,$$

Nominal scenario



Ideal scenario



Combined analysis accelerates our reach to IO

Conclusion

- $0\nu\beta\beta$-ex may contribute non-trivially to the sensitivity to $m_{\beta\beta}$
- Large Liquid Xe TPC offers a unique detector response to search for $0\nu\beta\beta$-ex of ^{136}Xe
  - Larger FV
  - Lower background rate
- Combining $0\nu\beta\beta$-gs and $0\nu\beta\beta$-ex improves the sensitivity to $m_{\beta\beta}$
- The combined analysis accelerates our reach to the IO

Backup

Sensitivity vs. background rate in FV-ex