2023/08/10

Status of Neutrinoless Double Beta Decay Experiments in Canada

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SNOLAB Research Scientist

MI Community Meeting

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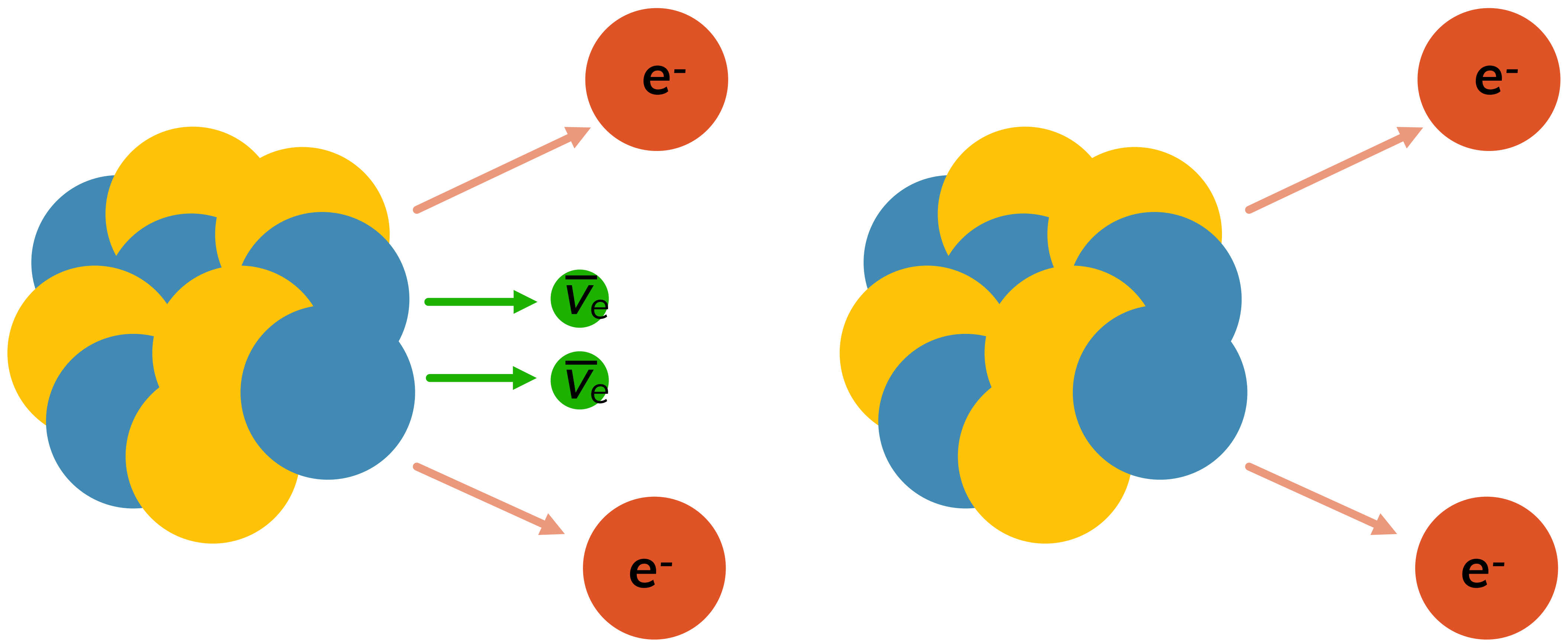
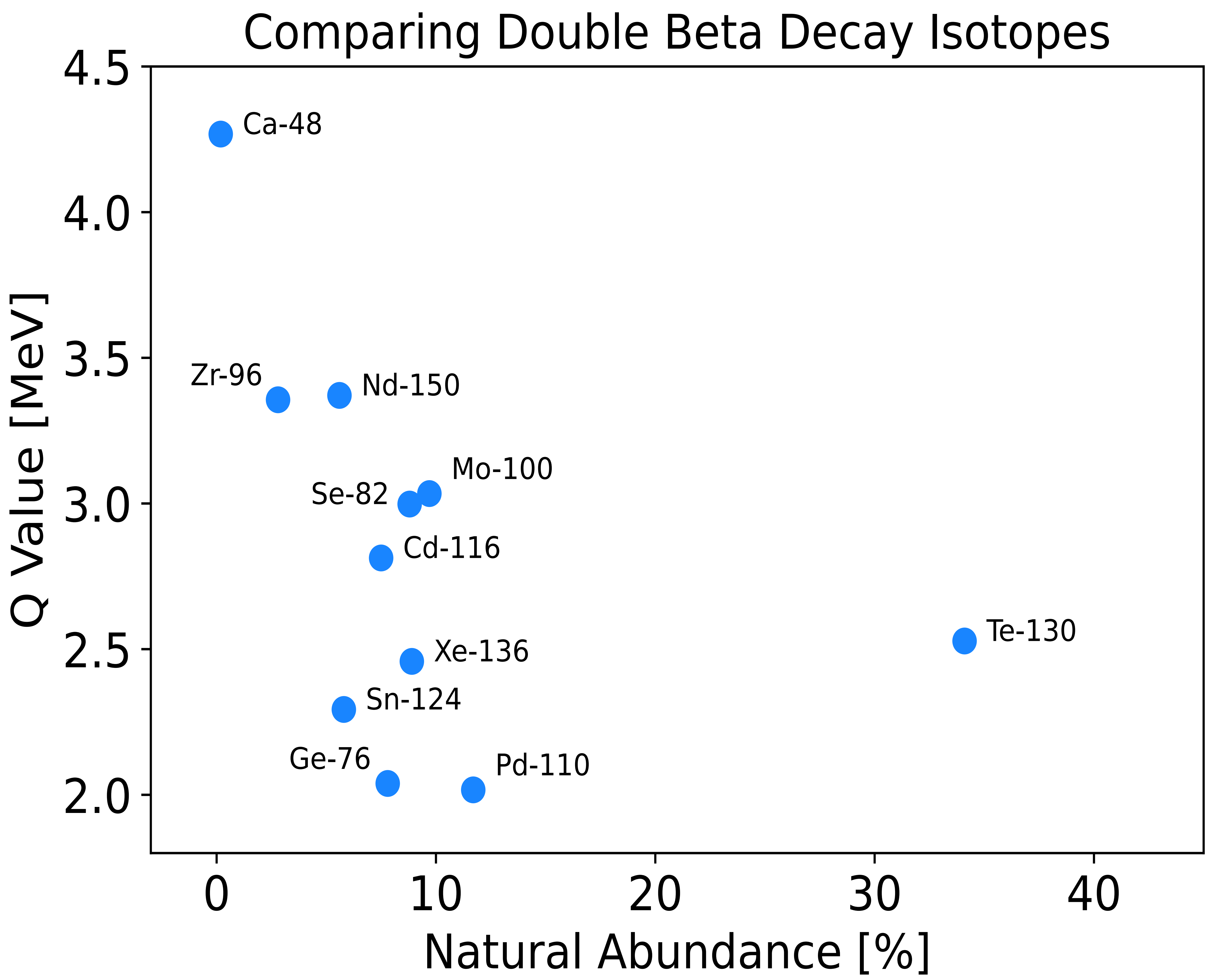
Double Beta Decay

- Rare Nuclear Process
- Available to even-even isotopes where single beta decay is energetically-forbidden

- If neutrino is a Majorana fermion, then those isotopes could undergo neutrino-less double beta decay ($0\nu\beta\beta$)

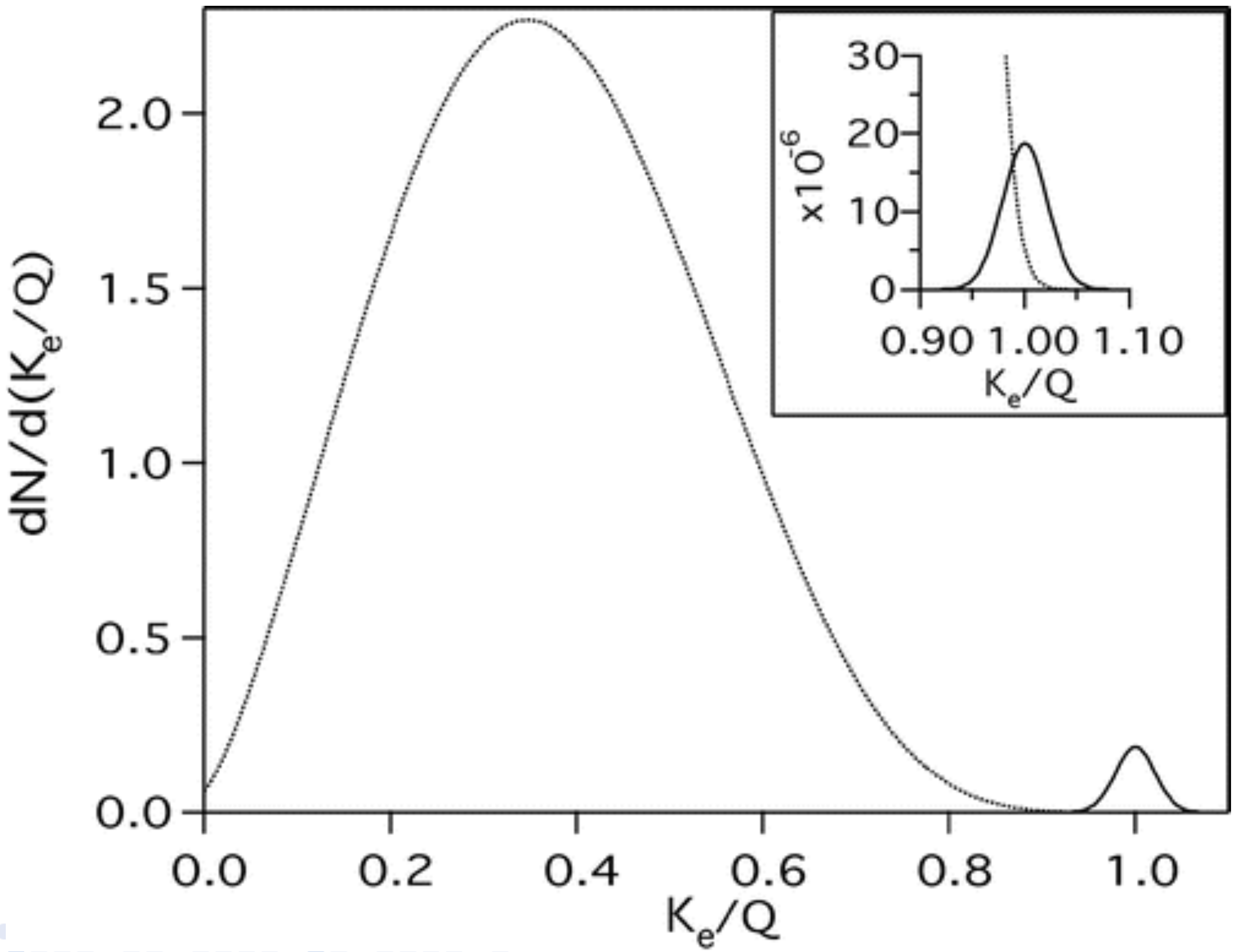




Double Beta Decay

- Key experimental signature for 0νββ is a peak in visible energy at the Q-value of the nucleus, smeared by detector resolution.

- Experiments are designed to minimize backgrounds around the Q-value.

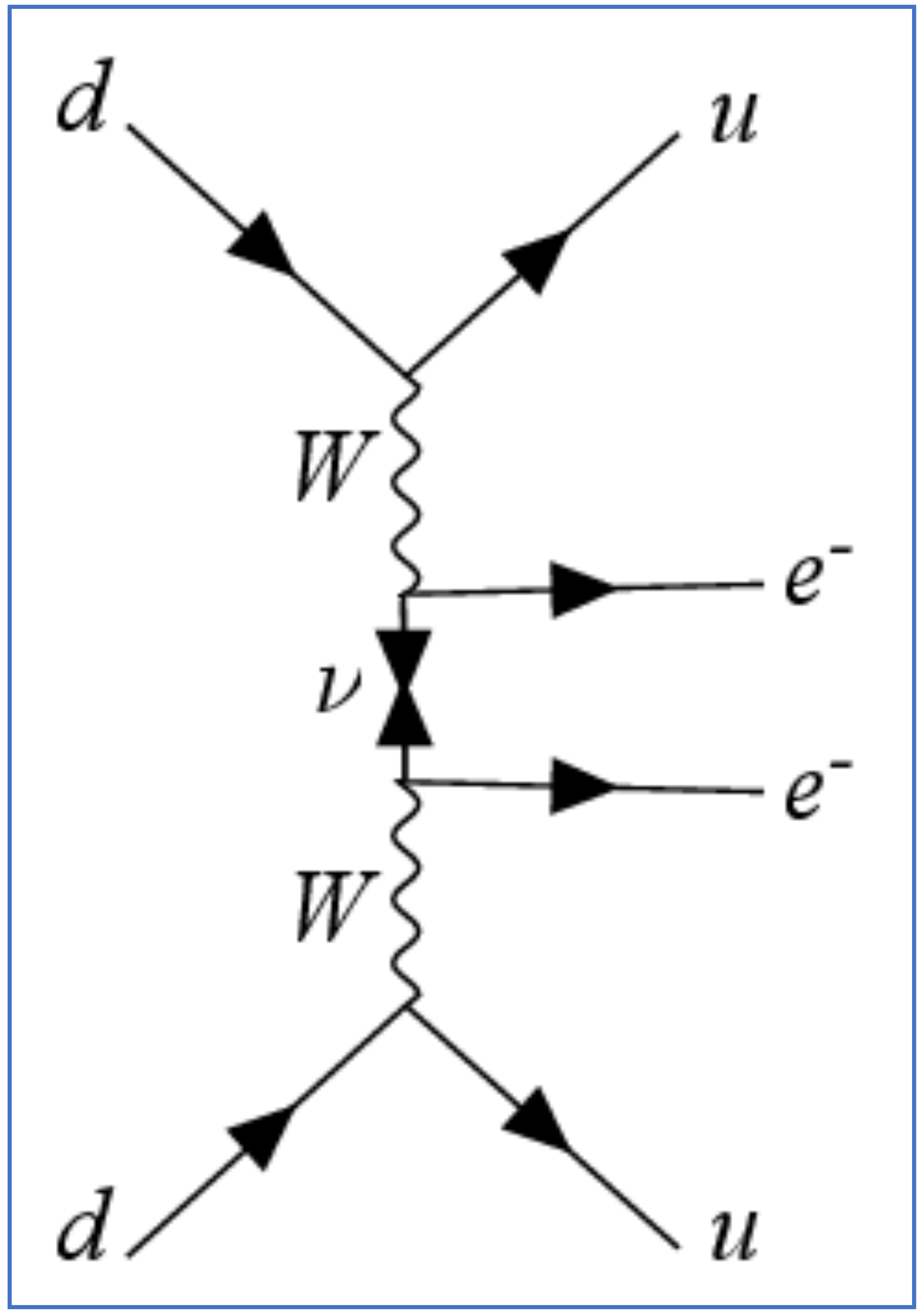


Neutrinoless Double Beta Decay

- There is no scenario in which observing 0νββ decay would not be a great discovery:
  - Majorana neutrinos
  - Lepton number violation
  - Probe new mass mechanism up to the GUT scale
  - Probe key ingredients in generating cosmic baryon asymmetry

$$(T^{0\nu}_{1/2})^{-1} = \frac{\langle m_{\beta\beta}\rangle^2}{m_e^2} G^{0\nu} g_A^4 |M^{o\nu}|^2$$

- The connection with the effective ν mass also means that the observation of 0νββ decay can provide information on the ν mass scale, provided that:
  - The mechanism producing the decay is understood
  - The nuclear matrix element is calculated with sufficiently small uncertainty

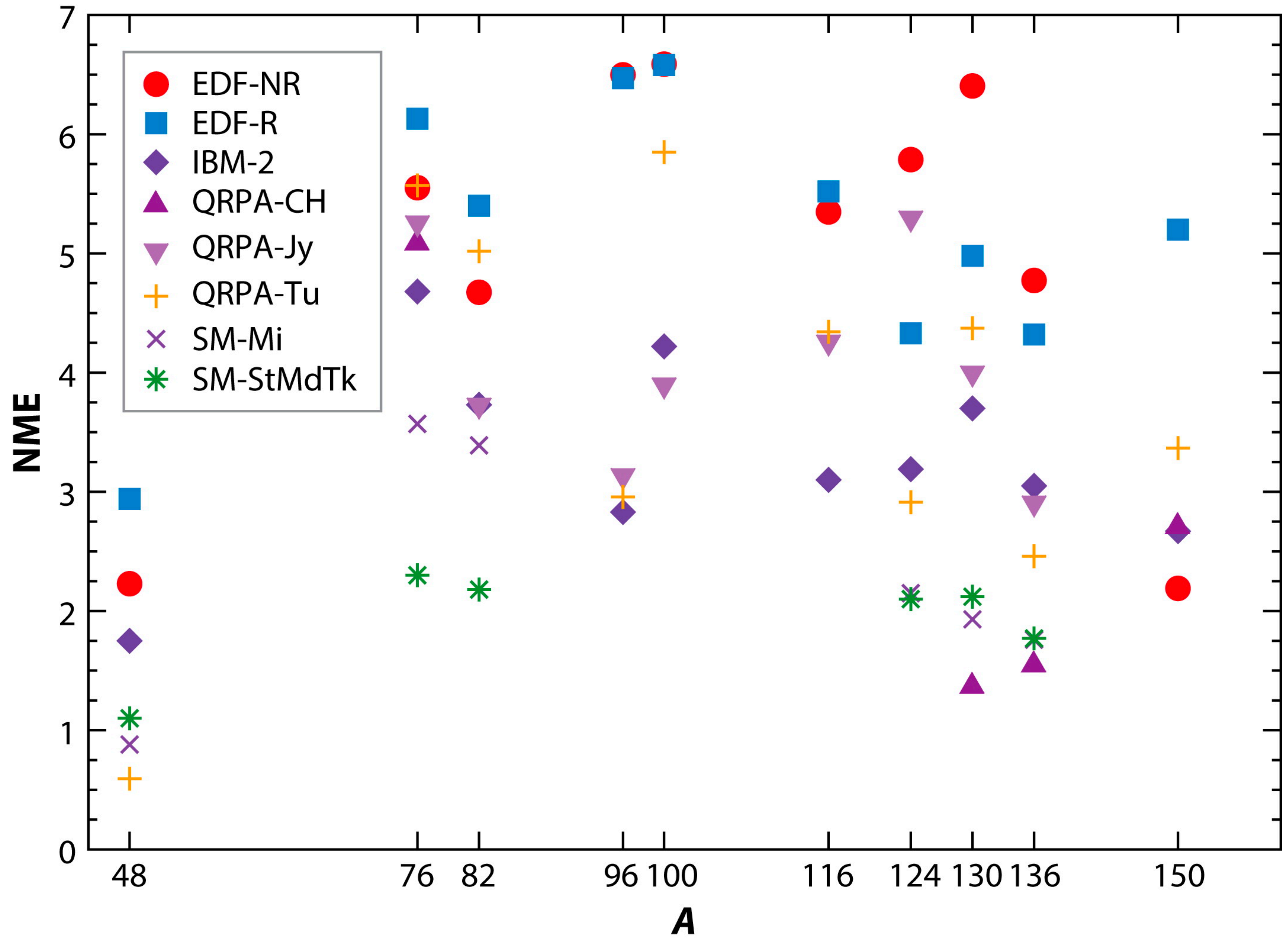


Neutrinoless Double Beta Decay

- Significant theoretical uncertainty in NMEs
- Useful to use $m_{\beta\beta}$ to compare different isotopes

$$(T^{0\nu}_{1/2})^{-1} = \frac{\langle m_{\beta\beta}\rangle^2}{m_e^2} G^{0\nu} g_A^4 \, | M^{o\nu} |^2$$

$$\langle m_{\beta\beta}\rangle = \left| \sum_{i=1}^{3} U_{ei}^2 m_i \right|$$



https://doi.org/10.1146/annurev-nucl-101918-023407

Neutrinoless Double Beta Decay

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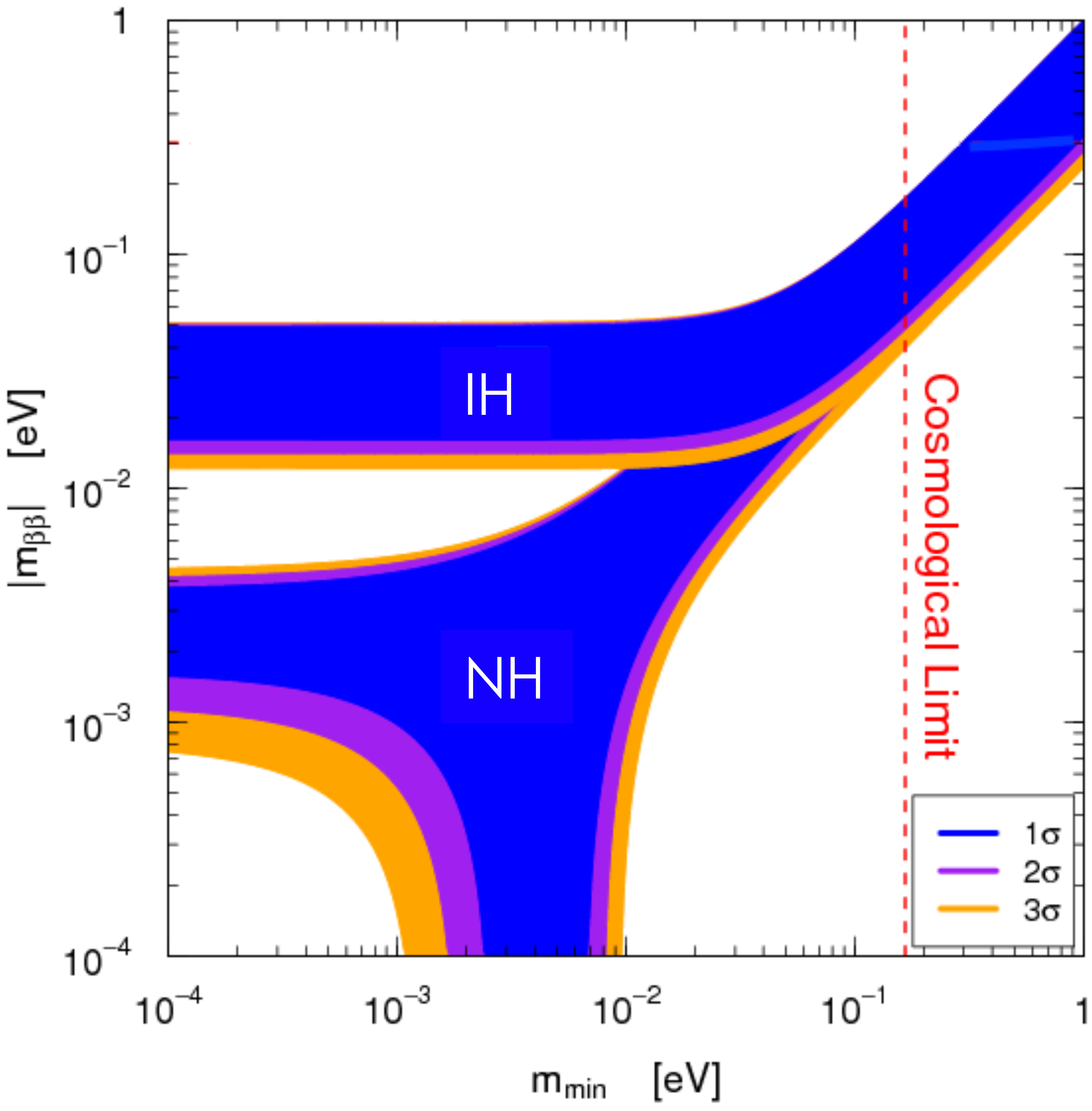
- New physics sensitivity can be parameterized by $m_{\beta\beta}$ reach

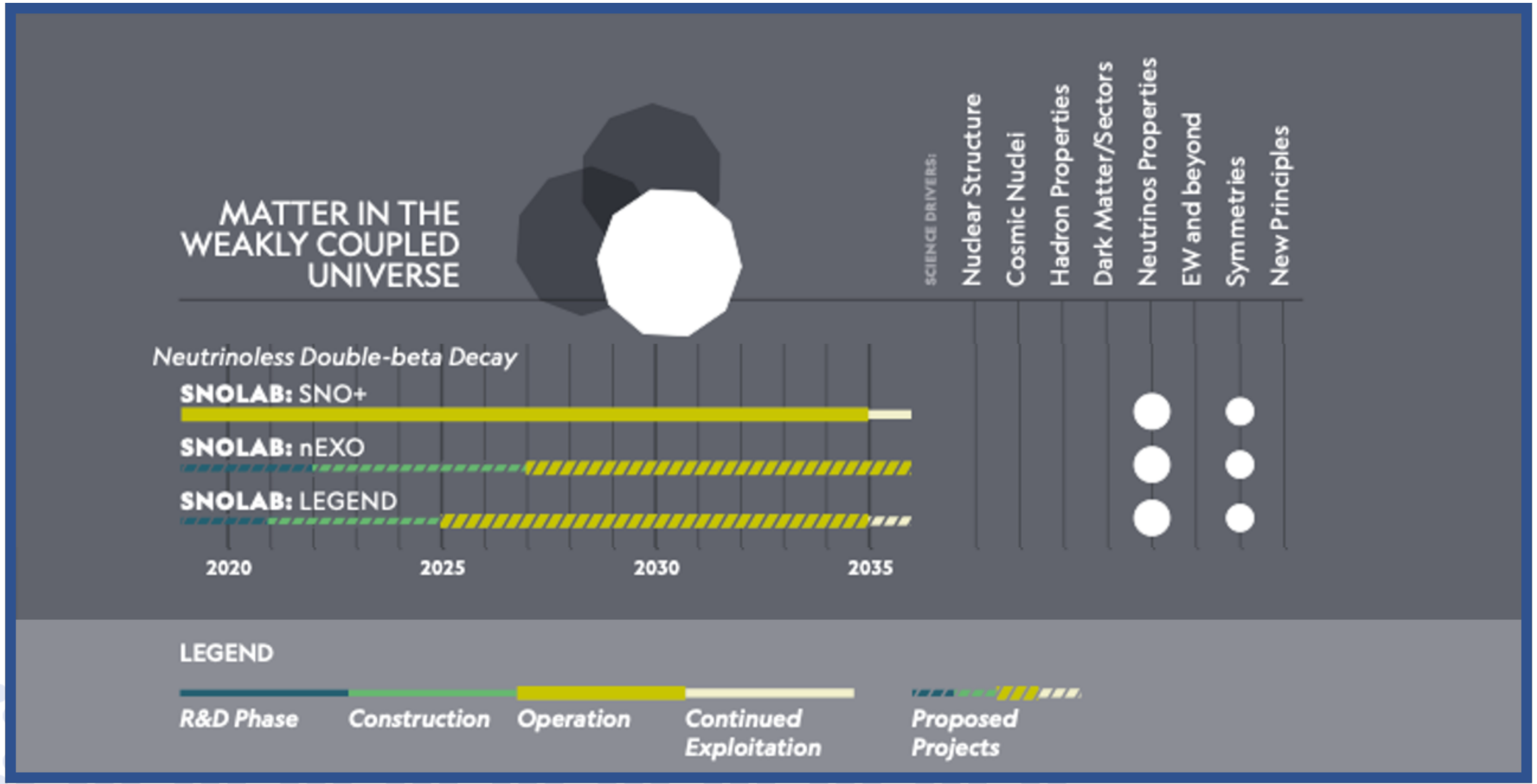


Canadian Subatomic Physics 2022–2026
LONG-RANGE PLAN

SNOLAB

SCIENCE RECOMMENDATION 3 — EXPERIMENTAL PROGRAMS

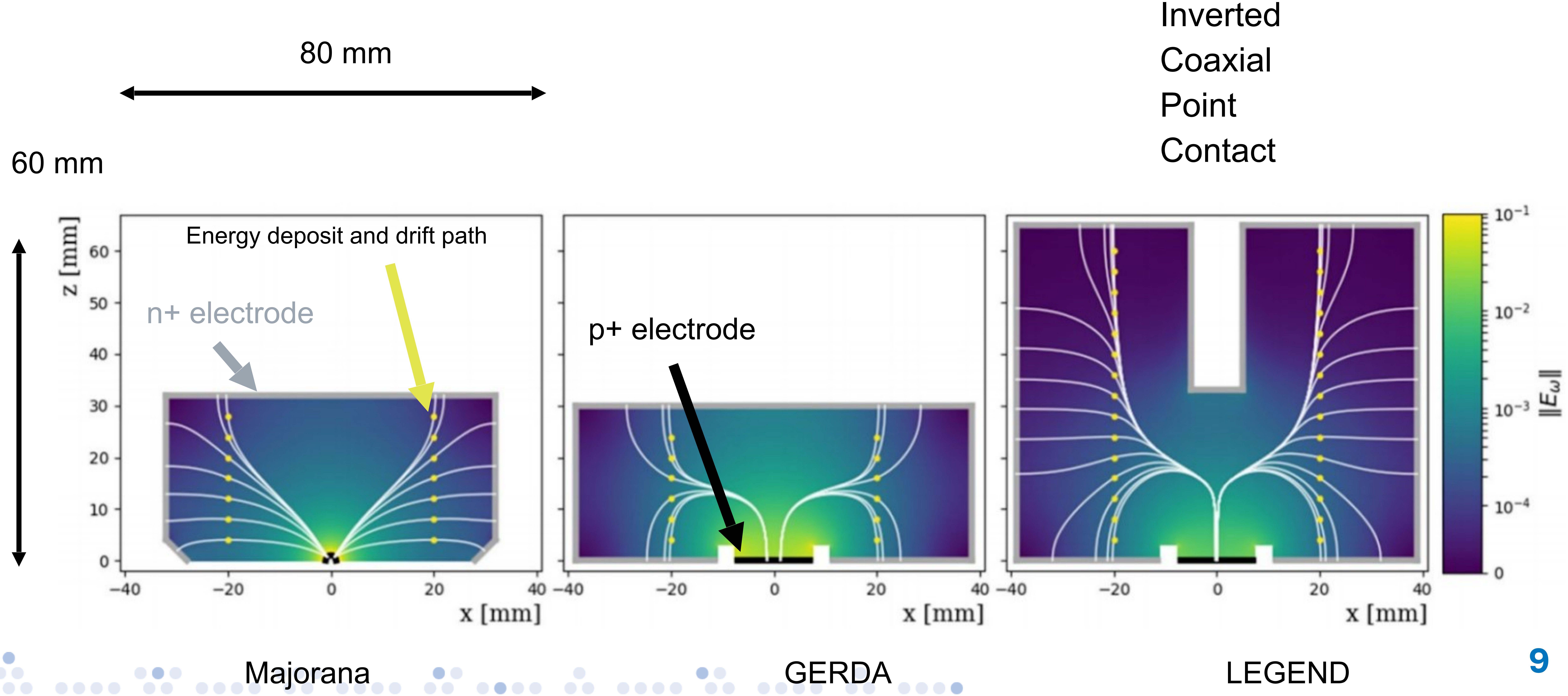
- **MATTER IN THE WEAKLY COUPLED UNIVERSE** — *The future program should incorporate the search for dark matter using complementary direct and indirect techniques, including via multi-ton scale direct detection. The future program should include the further exploration of neutrino properties via neutrinoless double-beta decay experiments, long baseline experiments and neutrino observatories.*



LEGEND

from C. Jillings and D. Radford

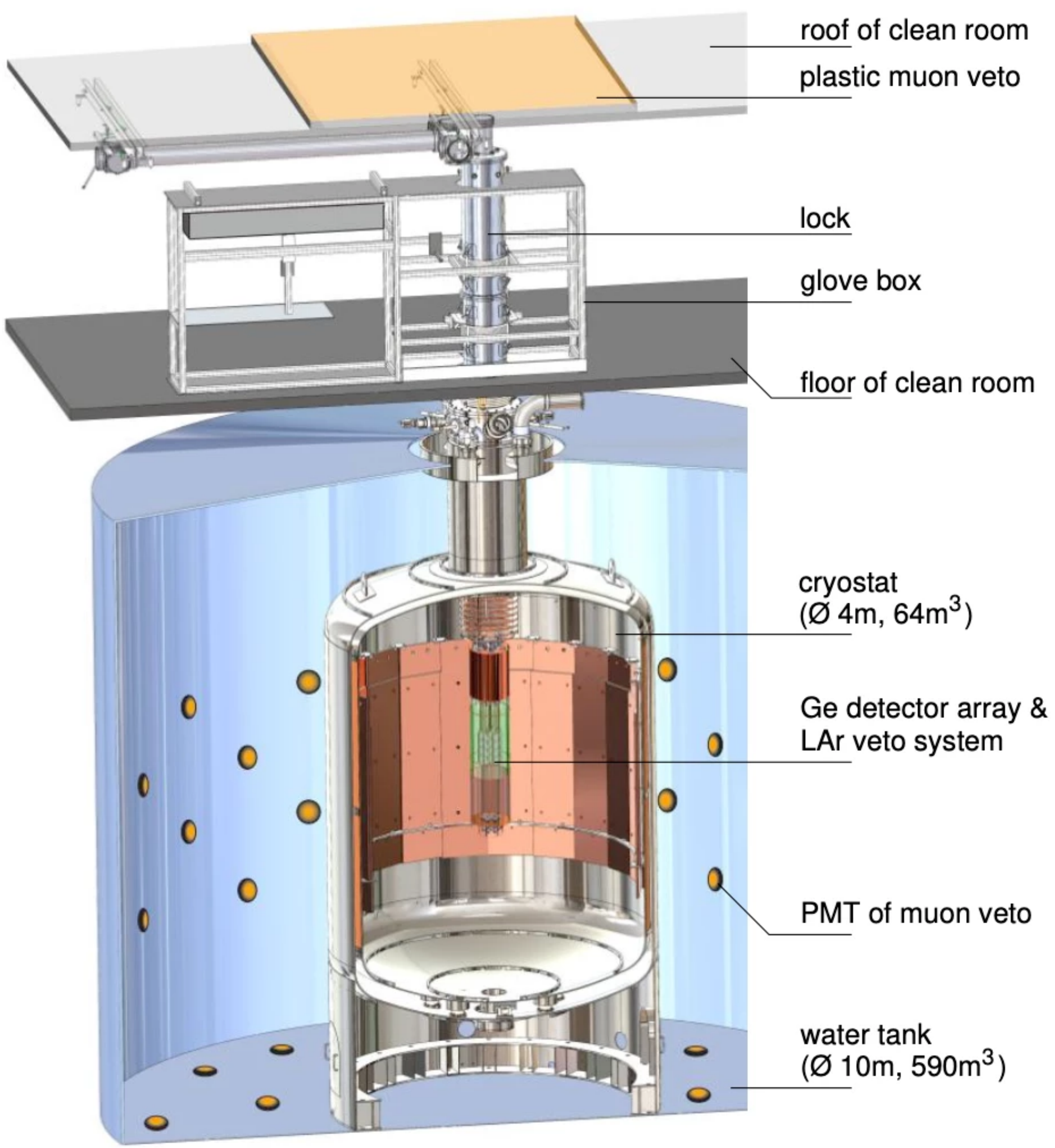
LEGEND uses sophisticated large enriched Ge-76 detectors building on work by Majorana and GERDA.



LEGEND

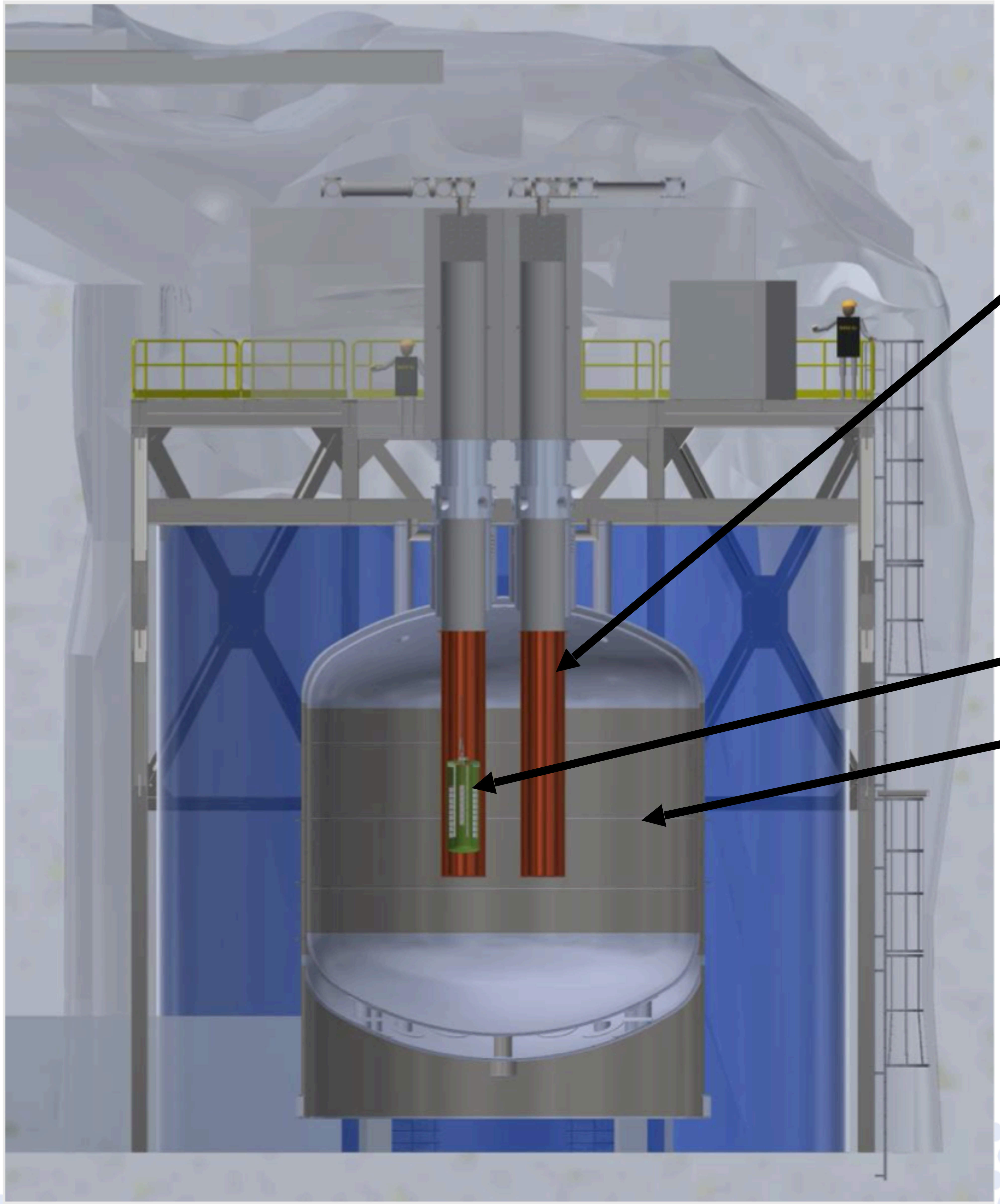
- Ge Crystals > 90% enriched in ^{76}Ge
- Energy Resolution: 0.1% @ $Q_{\beta\beta}$
- New Inverted Coaxial Point Contact Detectors
- Liquid argon shielding
  - Supplies an active veto / multi-site suppression
  - Cools crystals
- Staged approach, possible siting at LNGS or SNOLAB

LEGEND-200



arXiv:2107.11462

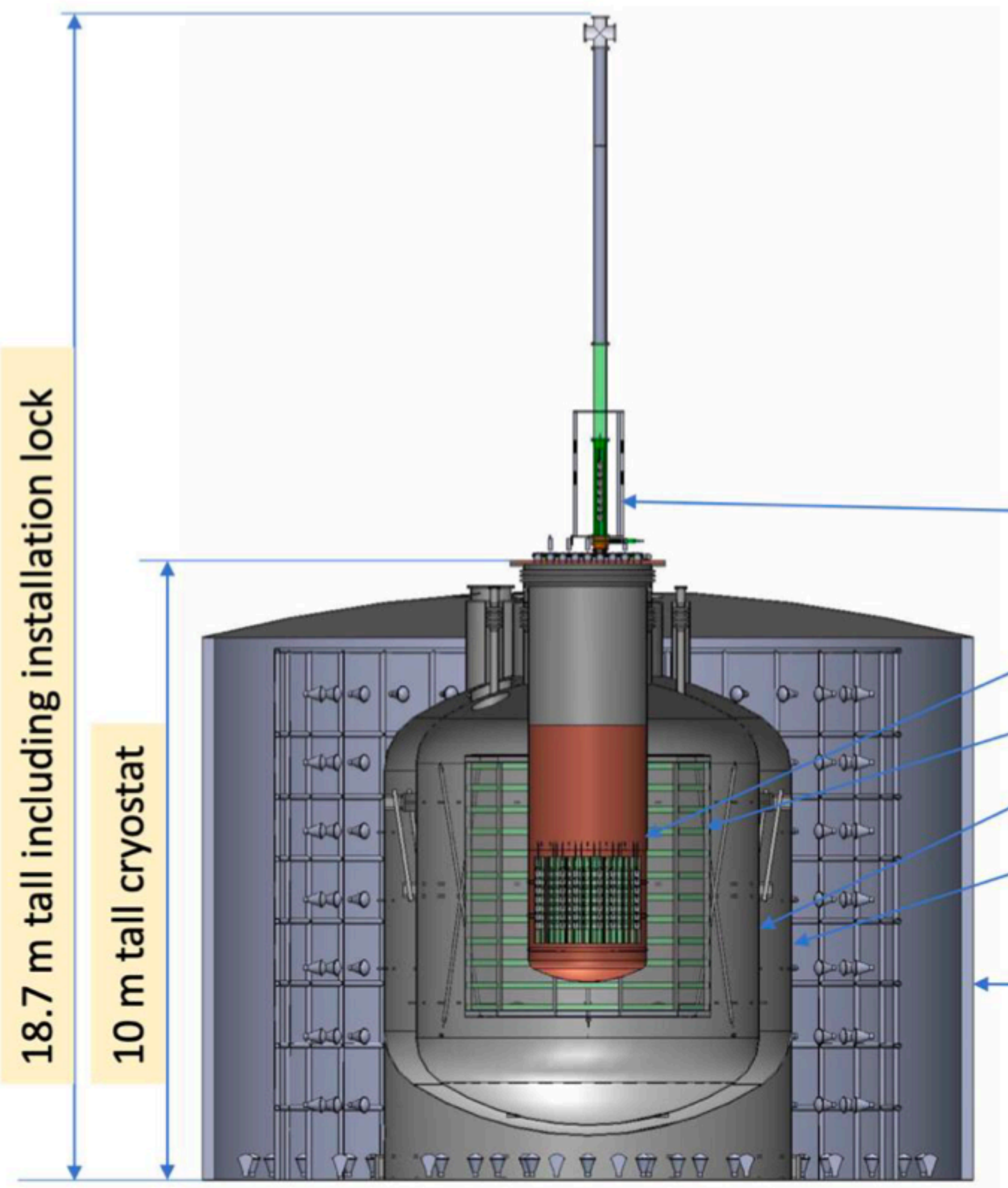
LEGEND-1000



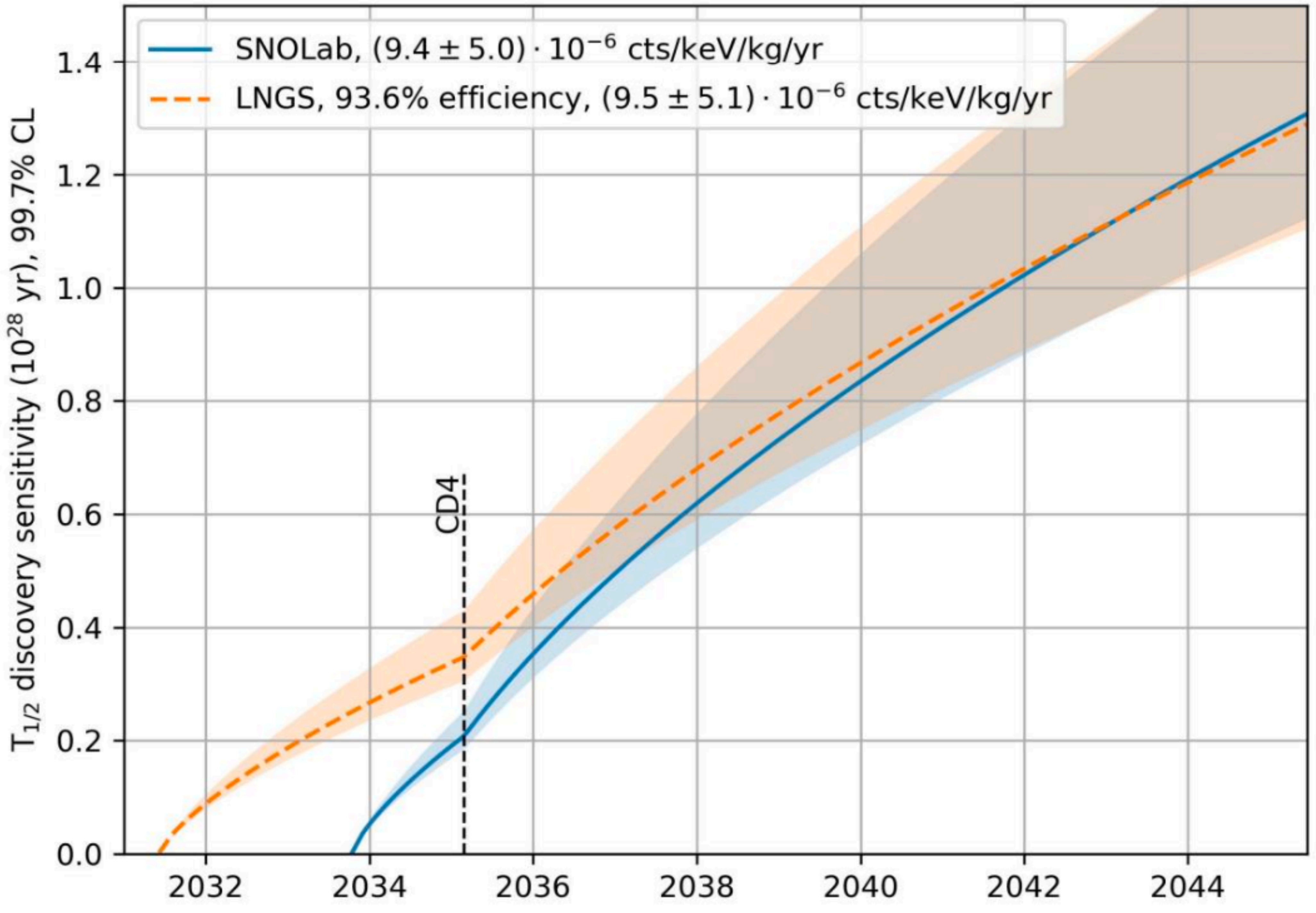
- Electroformed copper stored underground to avoid cosmogenic production of Co-60
- Use underground argon in re-entrant copper tubes to reduce Ar-42/Kr-42 background
- Crystals and underground liquid argon
- Atmospheric liquid argon
- Two designs under consideration:
  - LNGS: One large re-entrant tube
  - SNOLAB: Four smaller re-entrant tubes

LEGEND-1000 at LNGS

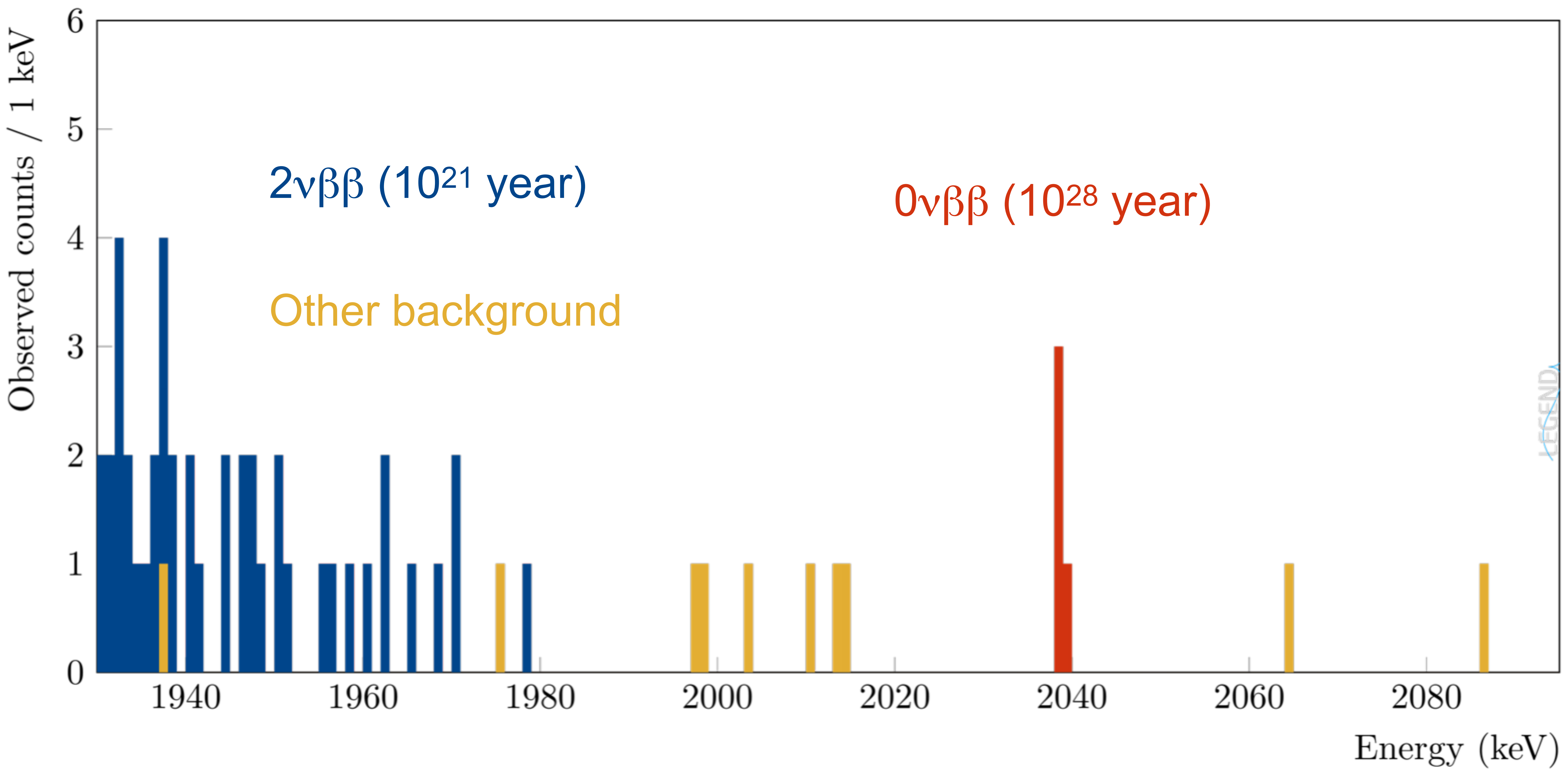
- Horizontal access reduces cost and schedule risk
- Lower overburden increases background only slightly
- Use an acrylic moderator in the atmospheric argon and veto/tag with only small loss in livetime



The LEGEND-1000 design for LNGS Hall C



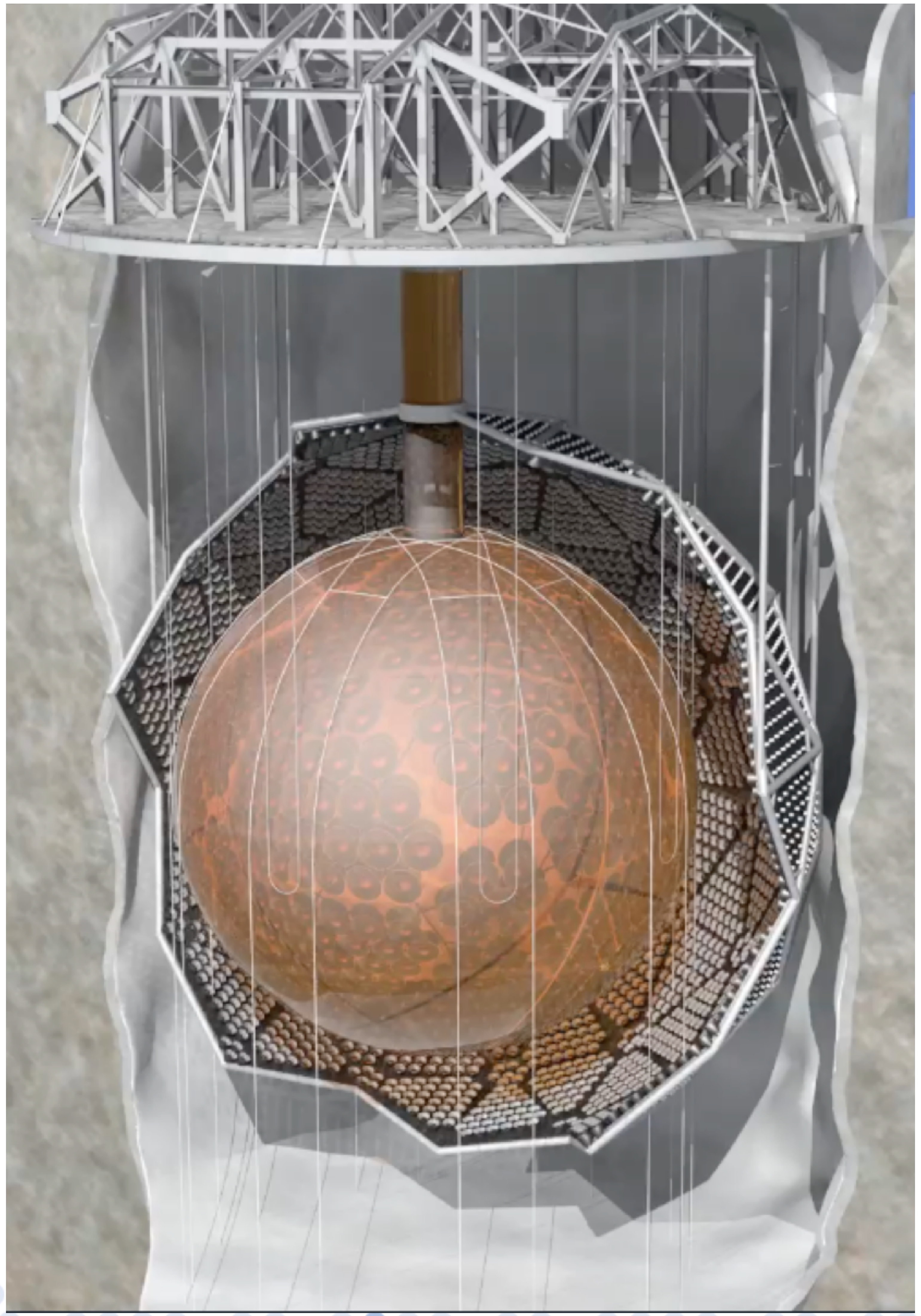
LEGEND-1000 has discovery potential for a $0\nu\beta\beta$ half life of 10^{28} years

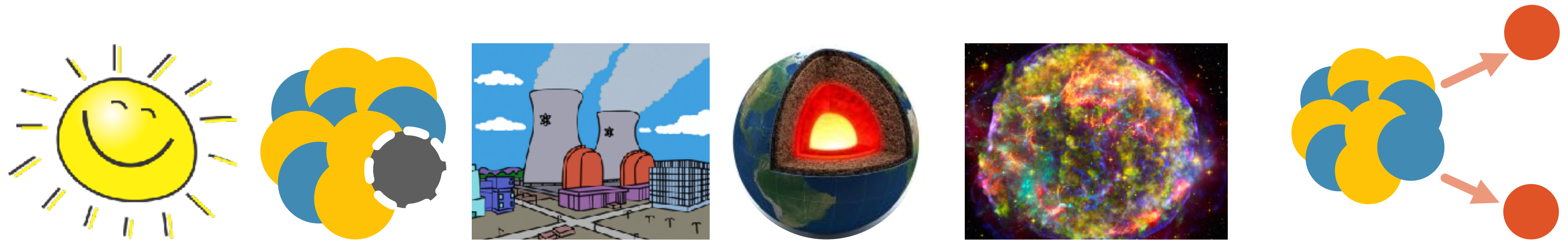


SNO+

SNO+

- 2 km rock overburden
- Acrylic Vessel ∅ 12 m
- 900 tonnes ultra pure water
- 780 tonnes LAB
  - 2.2g/L PPO
  - 5 mg/L bis-MSB
  - 8 µg/L BHT
- 9300 photo-multiplier tubes
- 5400 tonnes water shielding





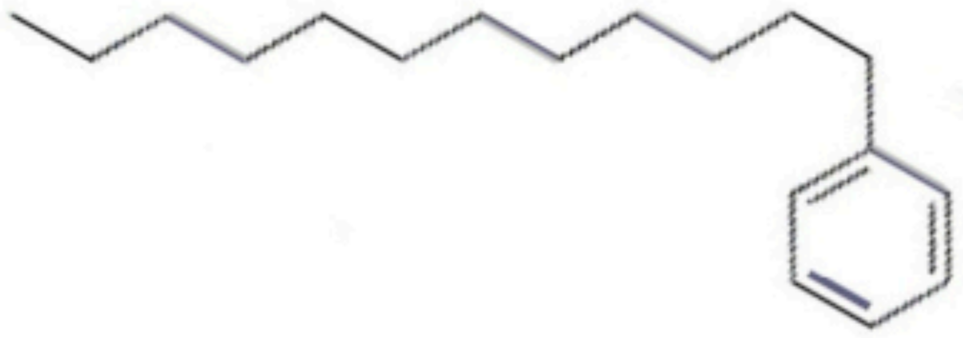
SNOLAB

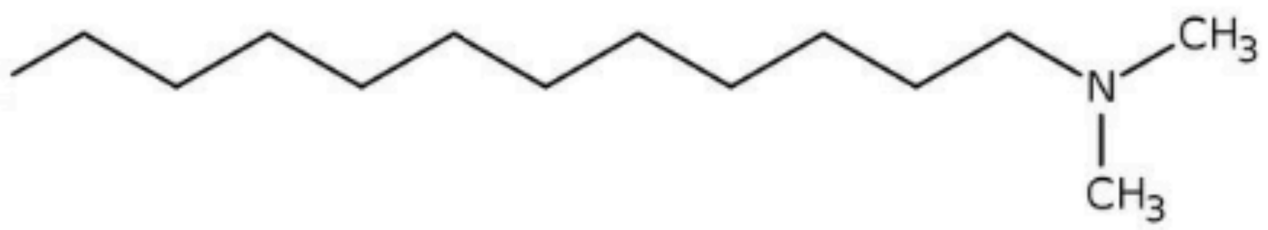
Multi-purpose Physics Detector

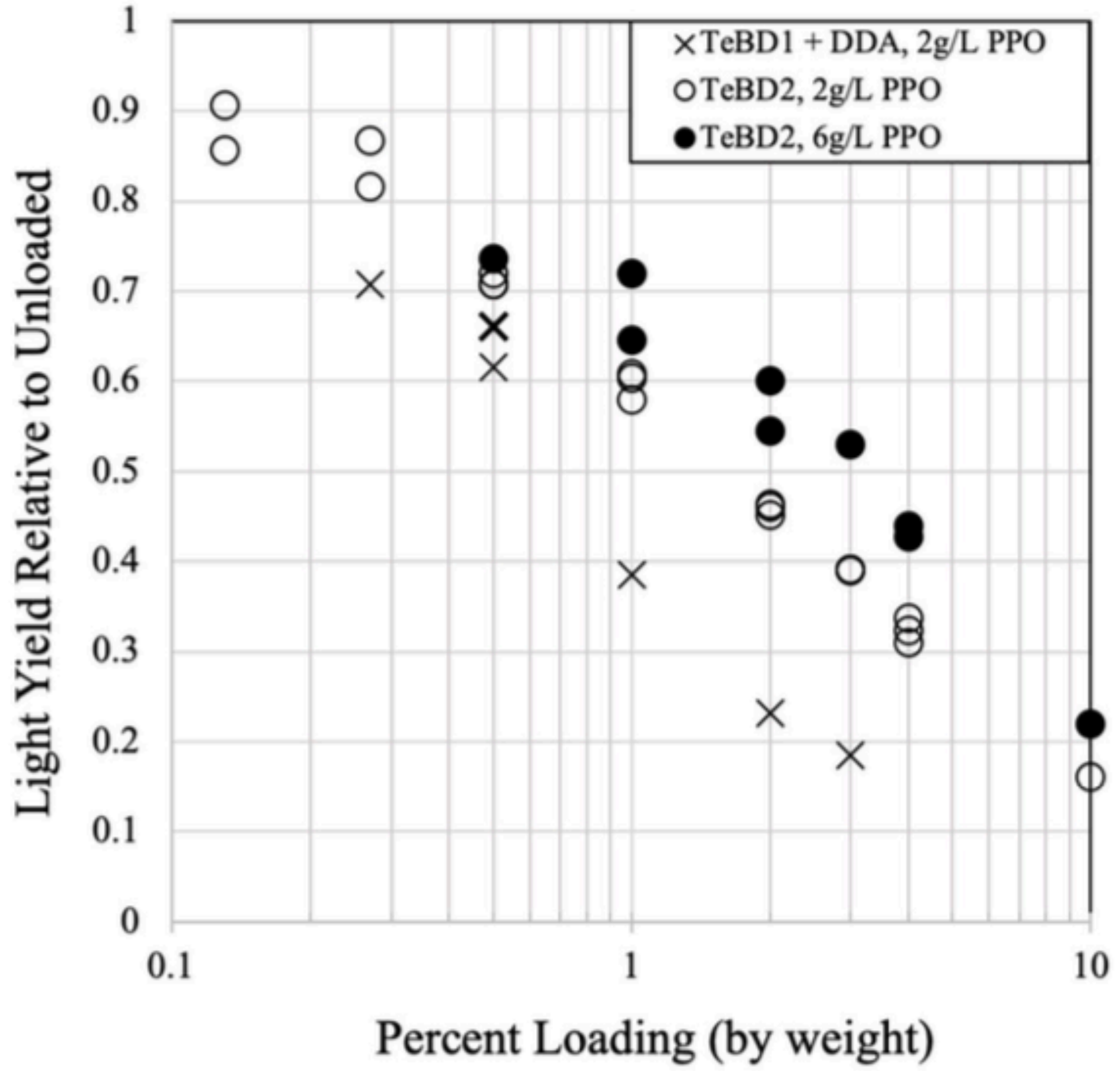
- Measurement of ^{8}B solar neutrinos with very low backgrounds: [Phys. Rev. D 99, 012012 (2019), update in prep]
- World-leading limits in invisible nucleon decay: [Phys. Rev. D 99, 032008 (2019), Phys. Rev. D 105 112012 (2022)]
- High efficiency neutron detection in ultra pure water: [Phys. Rev. C 102 014002 (2020)]
- Full Detector Description: [JINST 16 P08059 (2021)]
- Detector Optics in Water Phase: [JINST 16 P10021 (2021)]
- Scintillator Characterization: [JINST 16 P05009 (2021)]
- Detection of antineutrinos from distant reactors using pure water [PRL 130, 091801 (2023)]
- Event-by-Event Directionality in Scintillator: [in prep]

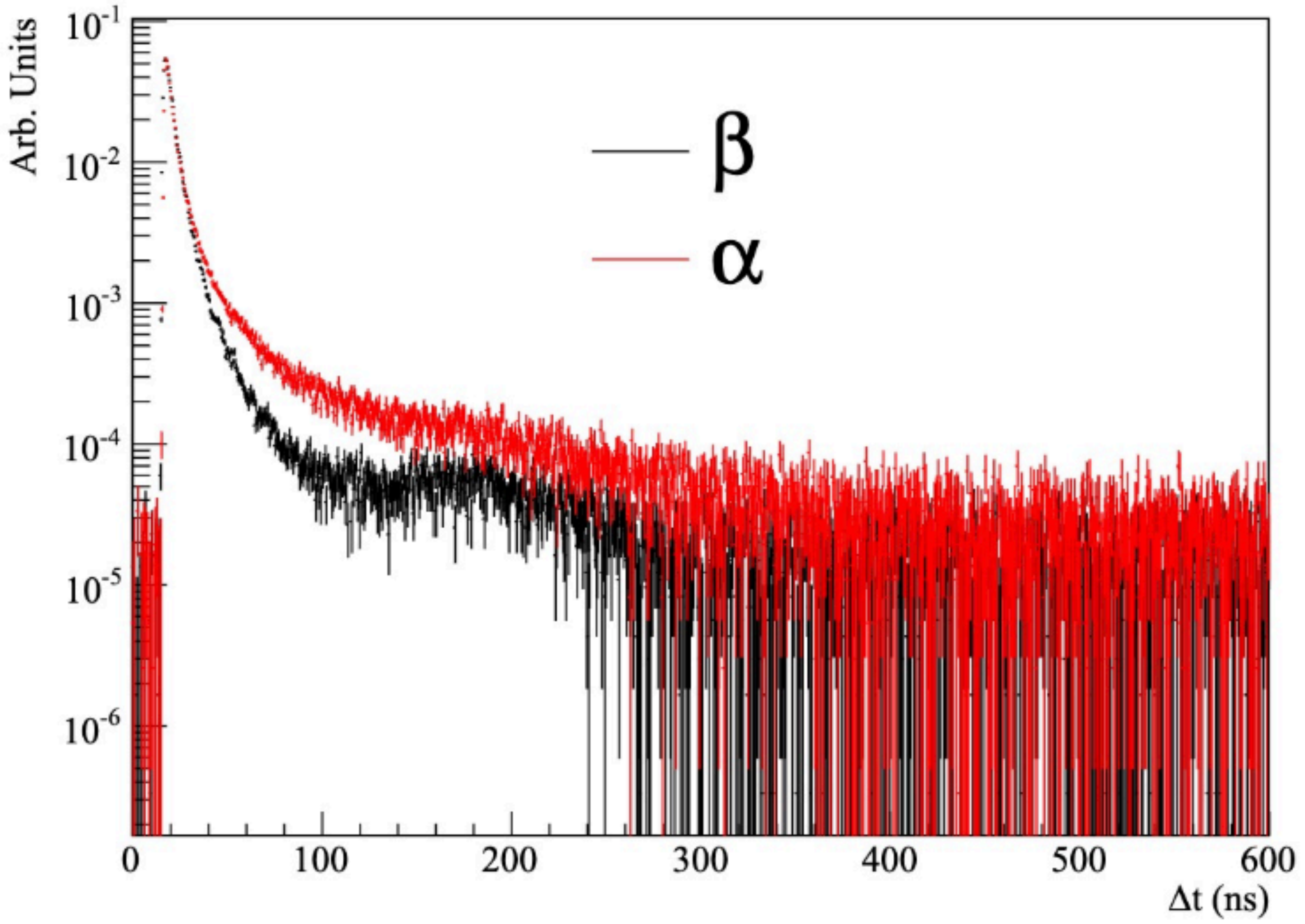
SNO+ Te Phase

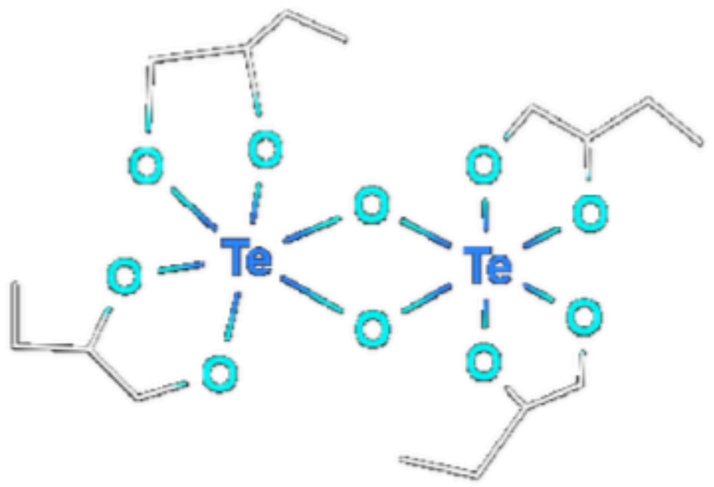
- 780 T Linear Alkylbenzene (LAB)
  + 2.2 g/L PPO (Primary Fluor)
  + 5 mg/L bisMSB (WS)
- Tellurium Butanediol (TeDiol) 0.5% Te in LAB
- DDA (stabilizing amine) 0.2% in LAB







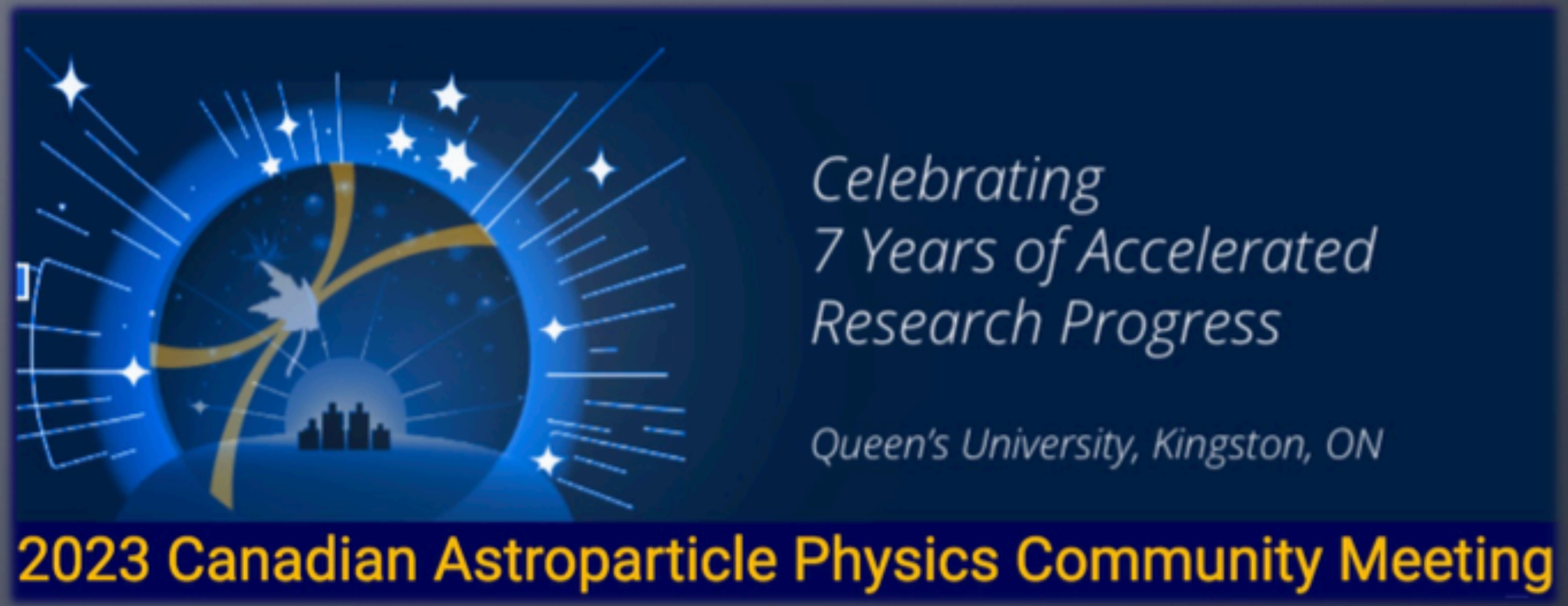


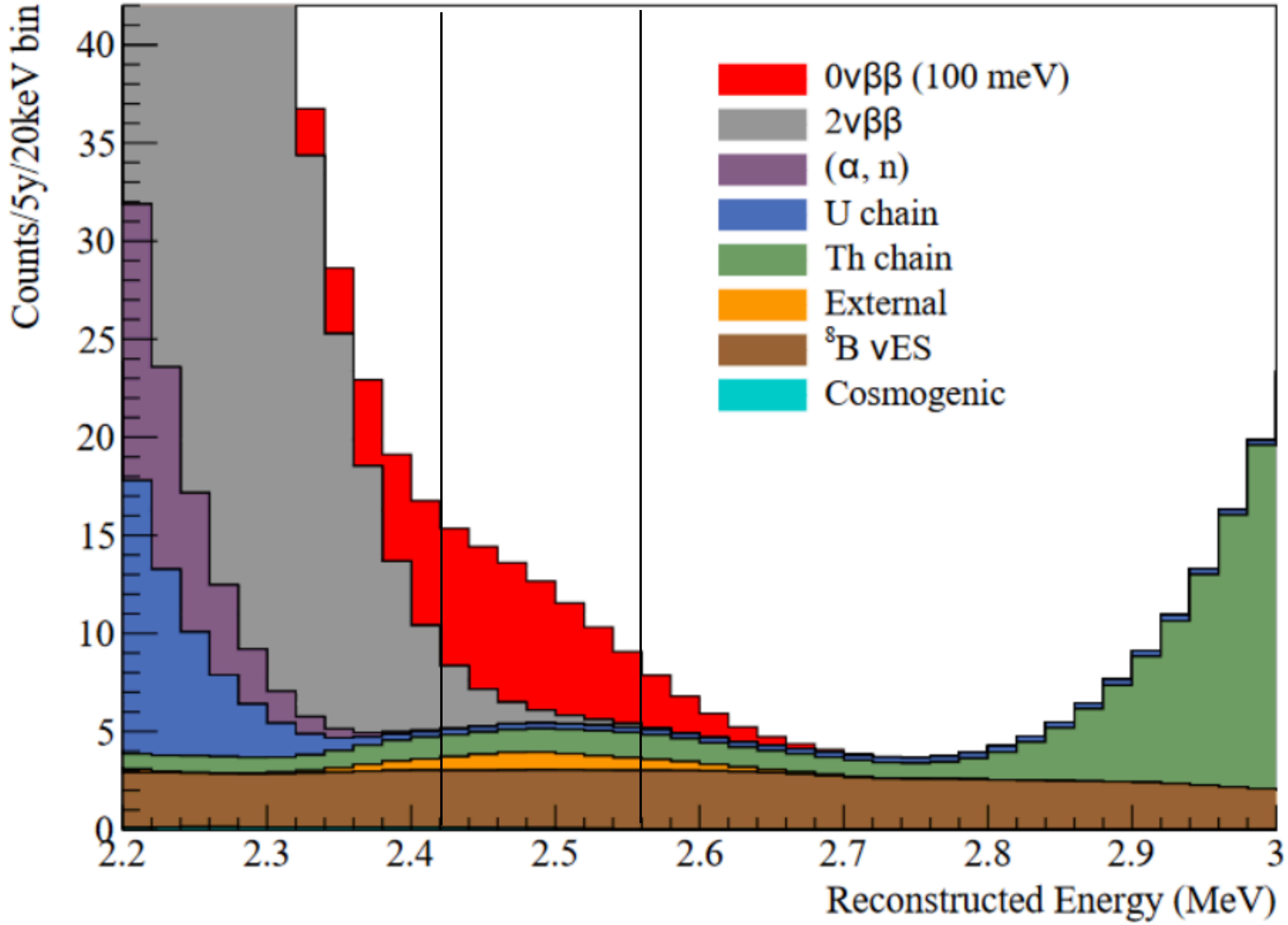


NIM.A. 1051:168204

SNO+
Status and Outlook

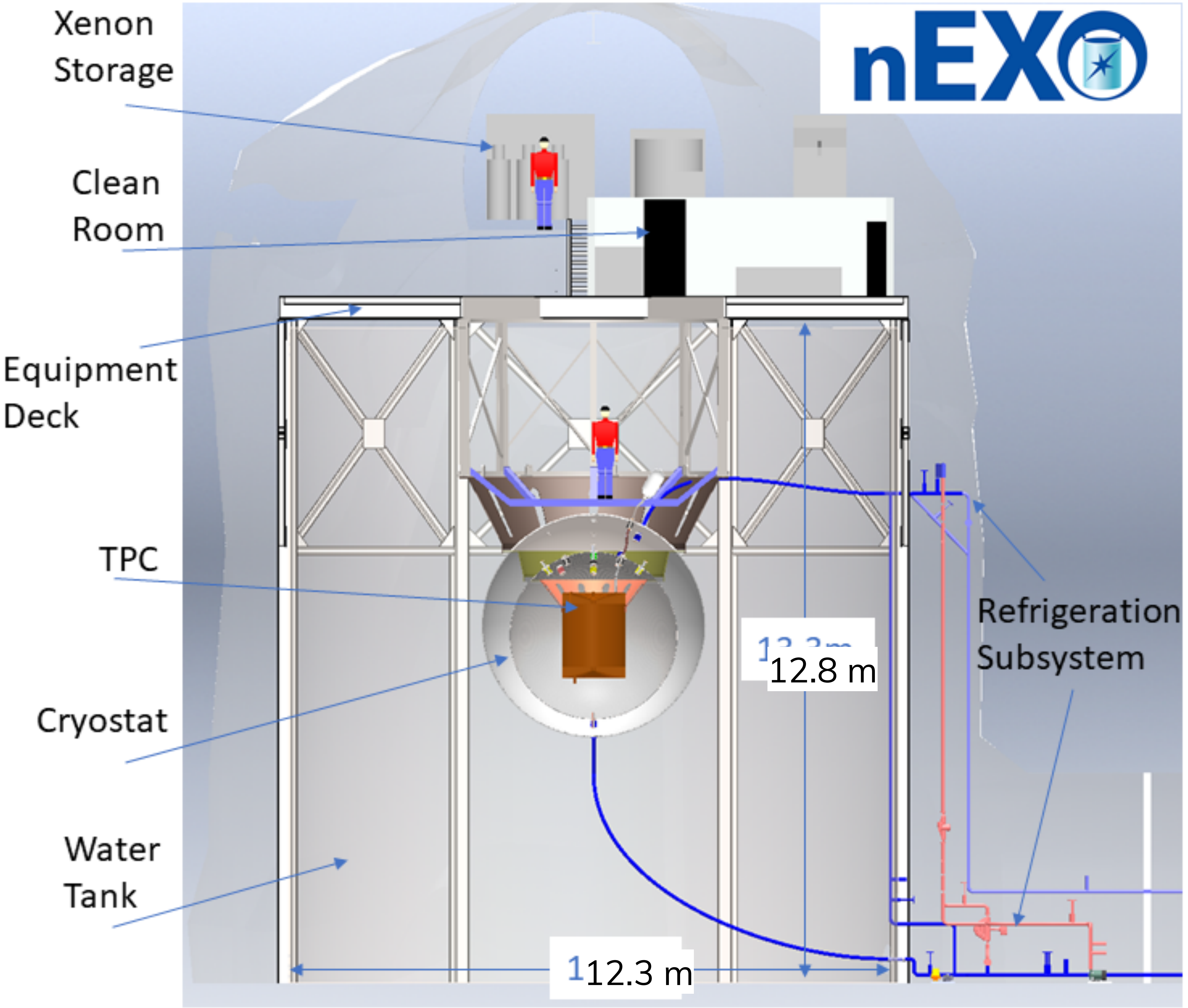
Szymon Manecki
August 9, 2023

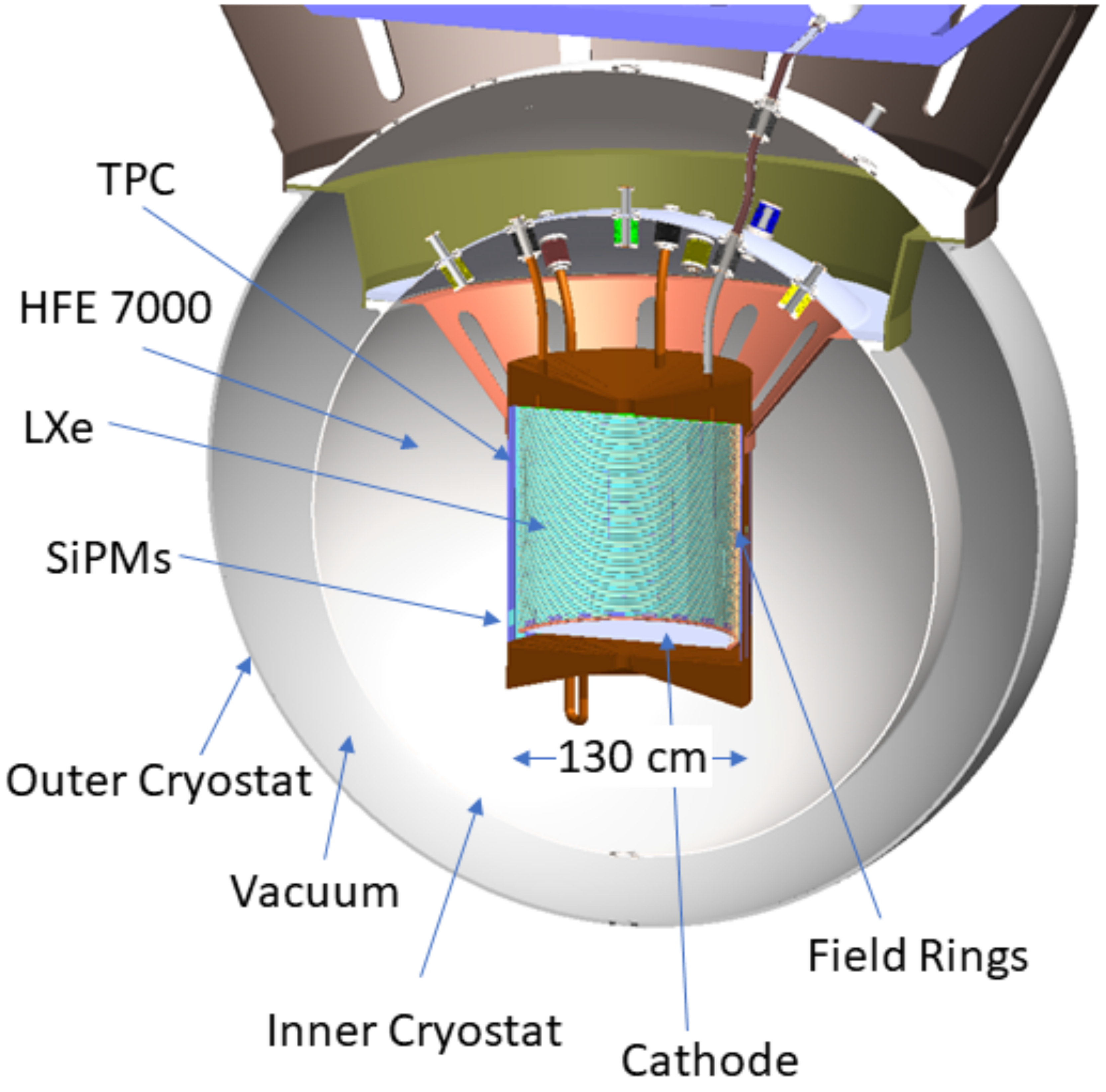




- R&D on higher (up to 3%) Te-loading ongoing [10.1088/1742-6596/888/1/012084]

nEXO

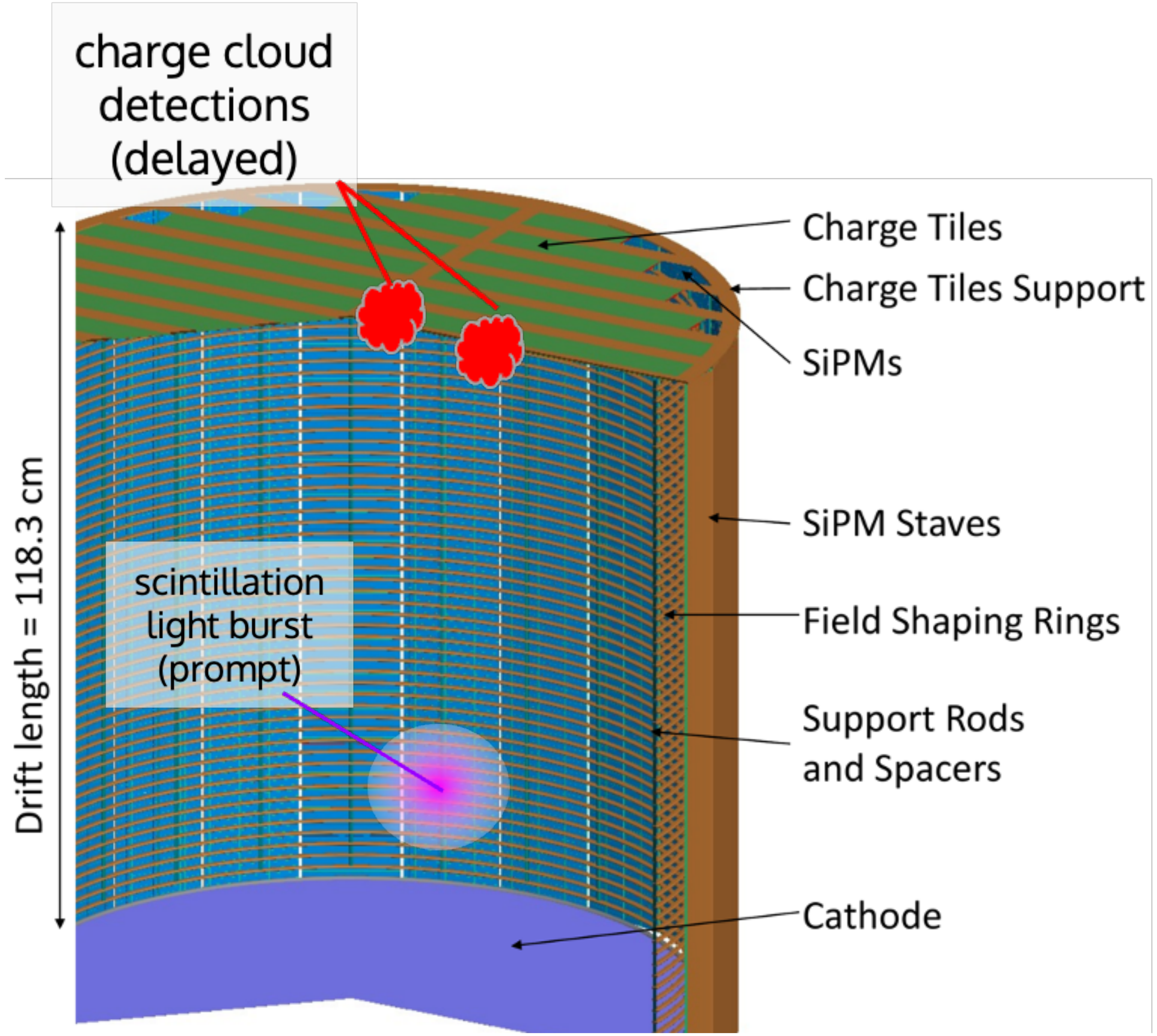




arXiv:1805.11142

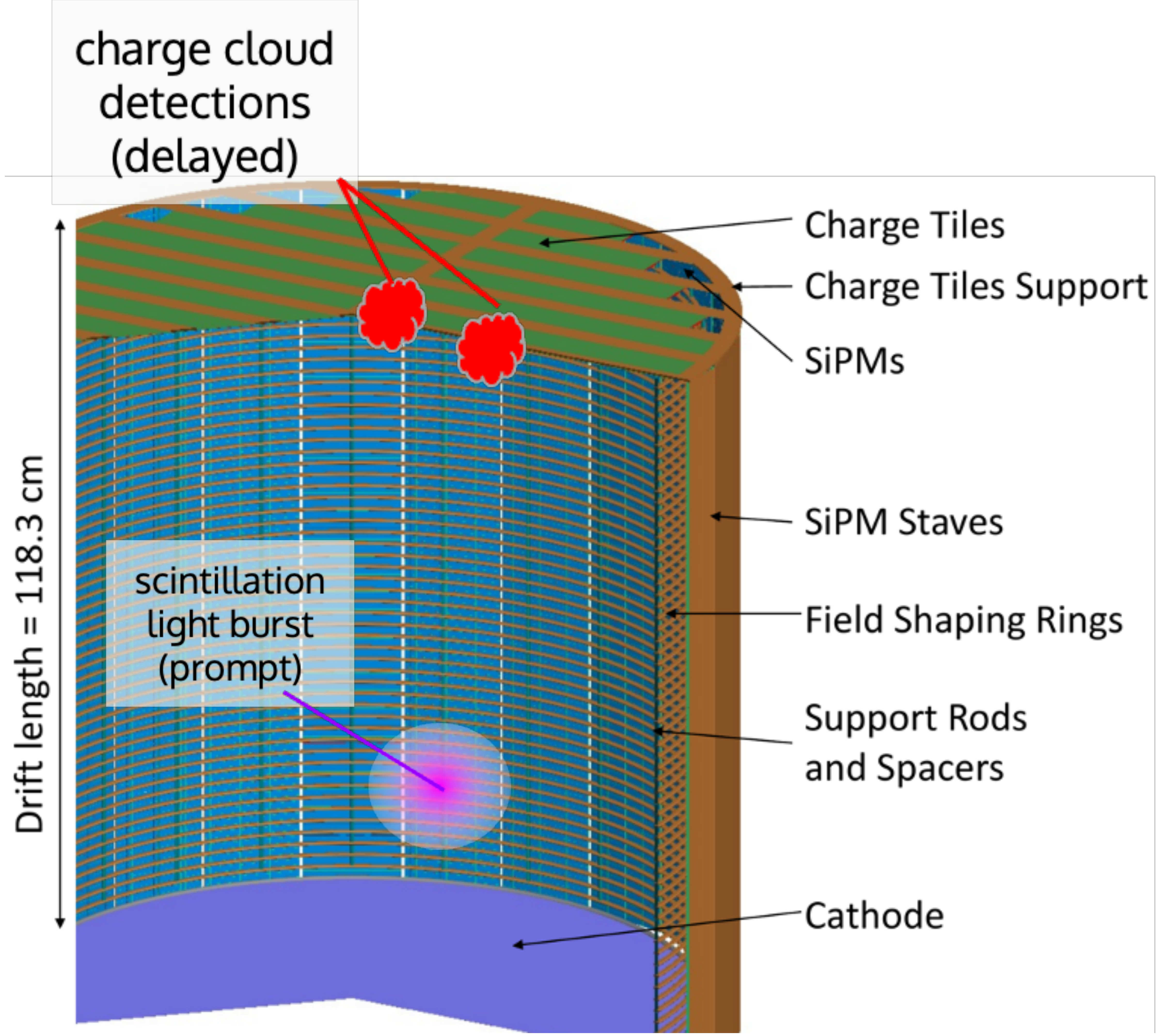
nEXO TPC

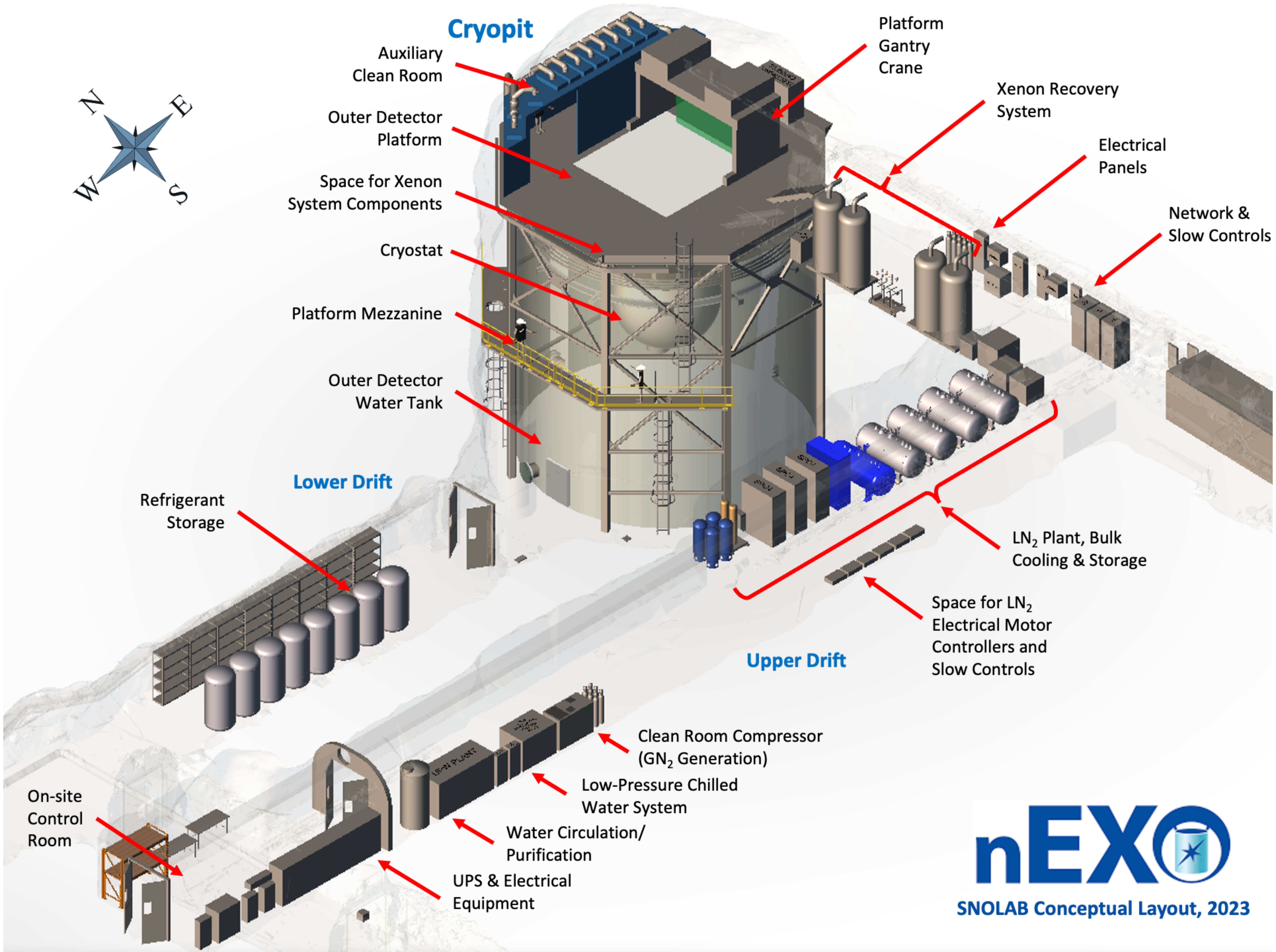
- Energy deposits in the LXe liberate electrons, ionize the surrounding liquid
- Excited dimers of Xe_2 release ~175 nm scintillation light
- Ionization clouds drift to segmented anode in applied E-field
- Combination of light + charge readout gives us:
  - Improved energy resolution <1% at $Q_{\beta\beta}$
  - Improved spatial positioning (event localization)
  - Discriminator between α, β, and γ events



nEXO's Distinguishing Features

- Homogeneous, dense, liquid detector medium with high-Z nucleus
  - online purification
  - self-shielding of γ radiation
  - scalability
- Multiparameter Analysis
  - Less sensitive to background fluctuations
  - Robust against unknown backgrounds
- Possibility to tag daughter nucleus; “Ba-tagging” upgrade
  - [Nature 569, no. 7755 (2019): 203-207]
- Possibility for control run in case of discovery
  - use unenriched xenon & repeat the experiment!

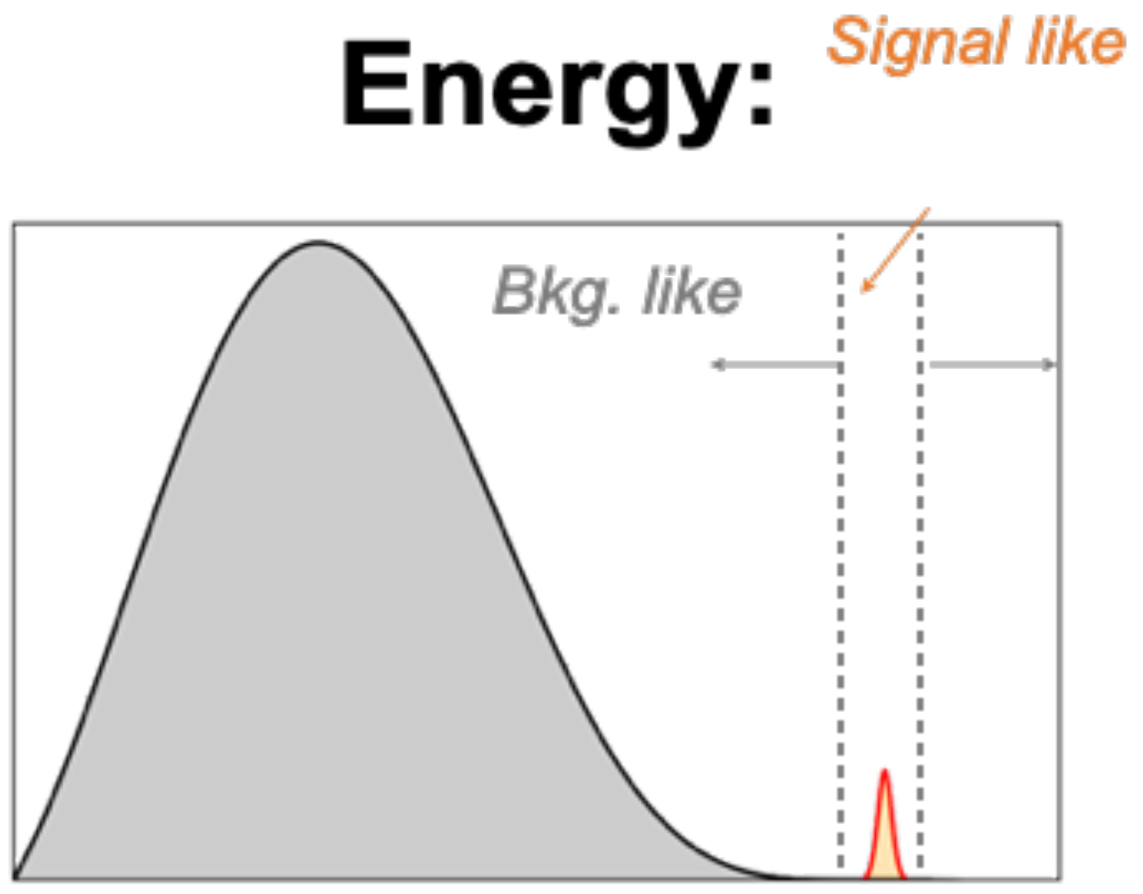


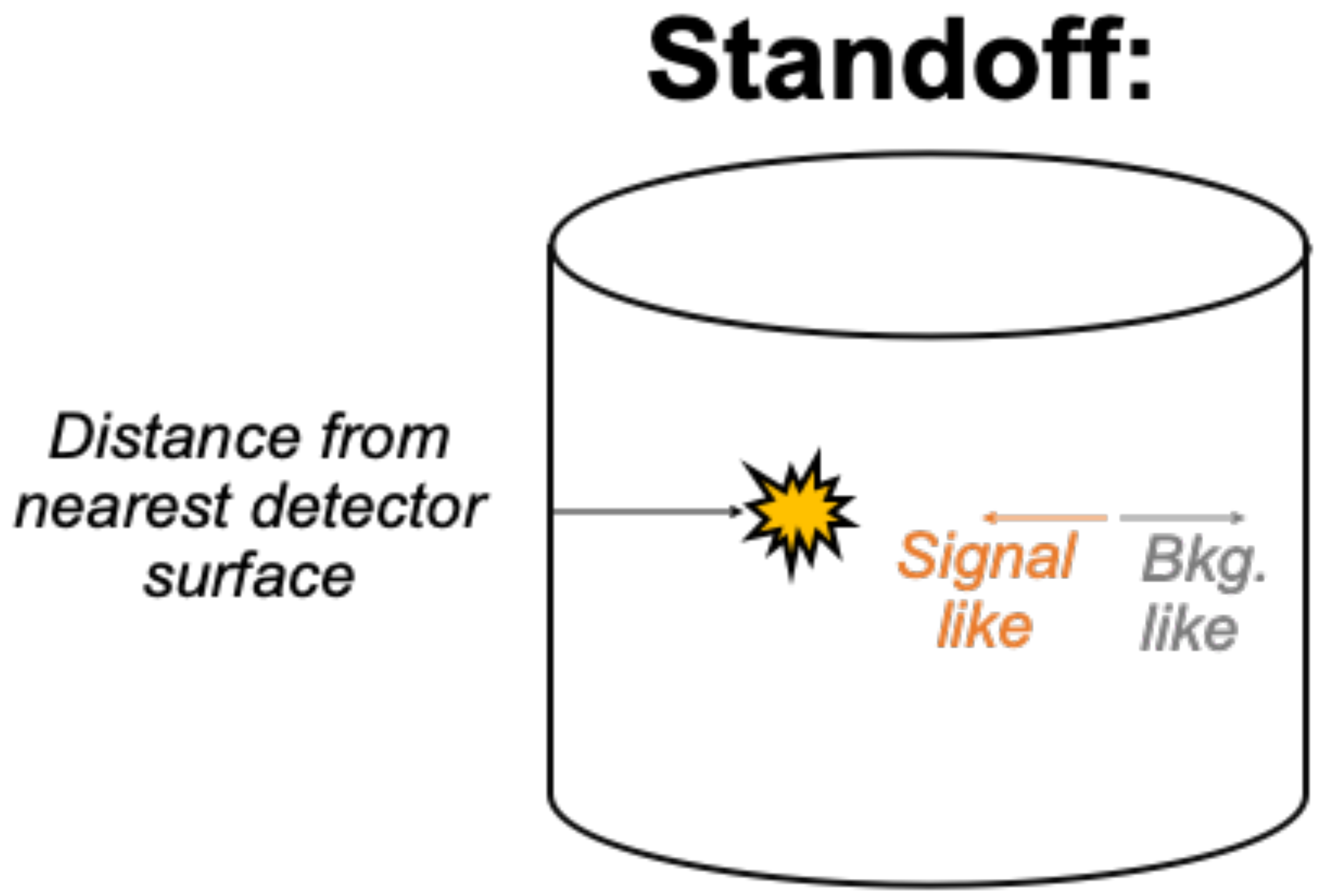

Cryopit
Auxiliary Clean Room
Outer Detector Platform
Space for Xenon System Components
Cryostat
Platform Mezzanine
Outer Detector Water Tank
Platform Gantry Crane
Xenon Recovery System
Electrical Panels
Network & Slow Controls
N
E
S
W
Lower Drift
Refrigerant Storage
LN_2 Plant, Bulk Cooling & Storage
Space for LN_2 Electrical Motor Controllers and Slow Controls
Upper Drift
Clean Room Compressor (GN_2 Generation)
Low-Pressure Chilled Water System
Water Circulation/ Purification
UPS & Electrical Equipment
On-site Control Room
nEXO
SNOLAB Conceptual Layout, 2023

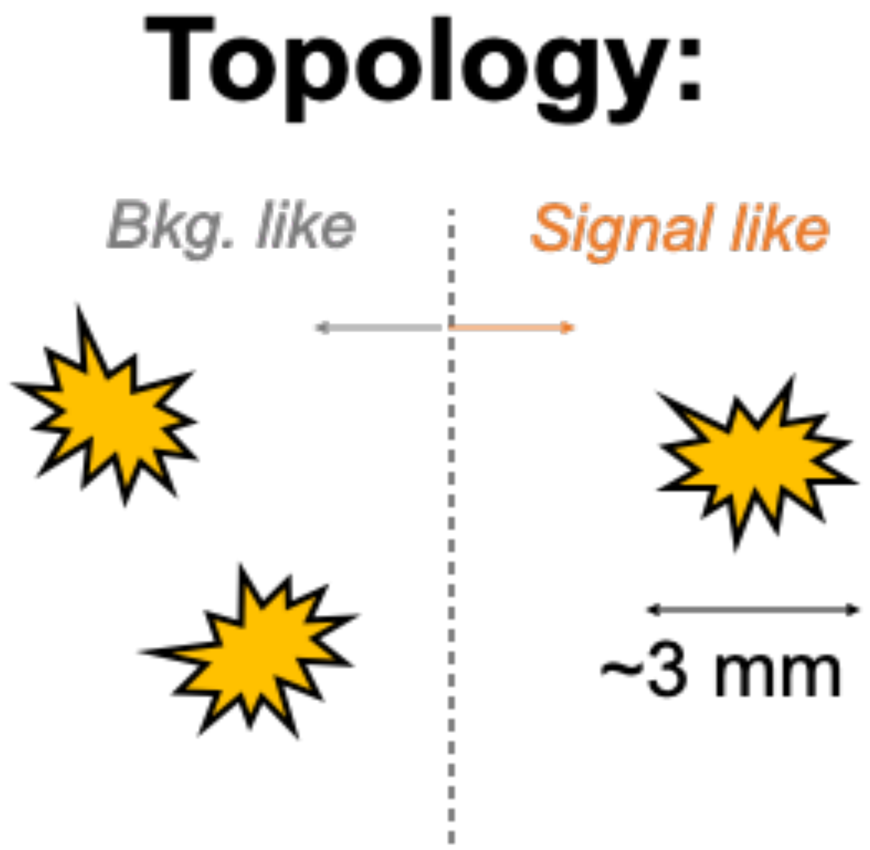
Multiparameter Analysis

Three high-level variables:

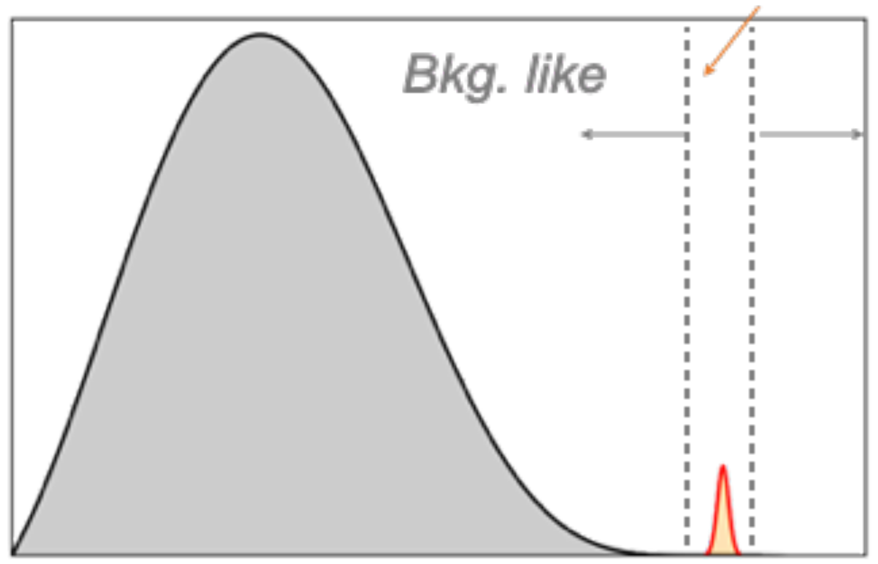
- ~1% **Energy** resolution at $Q_{\beta\beta}$
- **Standoff** distance to detector components (precise event localization, **depth in xenon**)
- **Topology** score (DNN): single- and multi-site discrimination (β-like vs γ-like event separation)

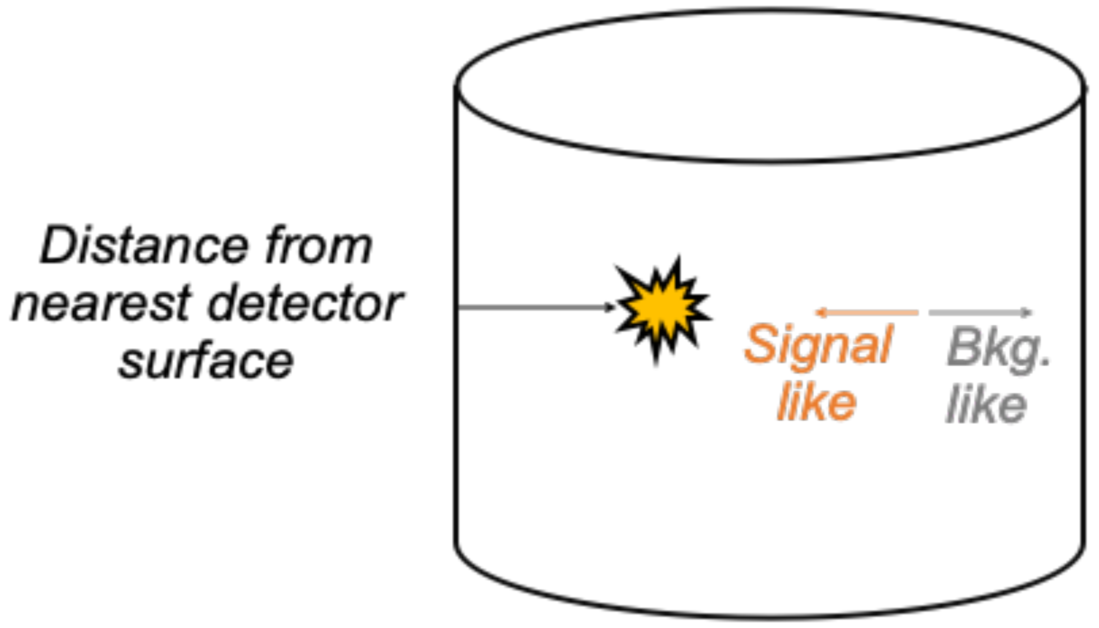


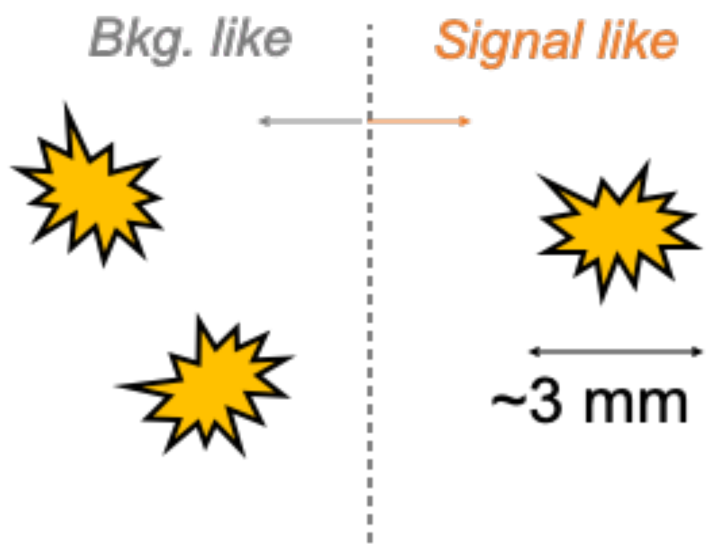


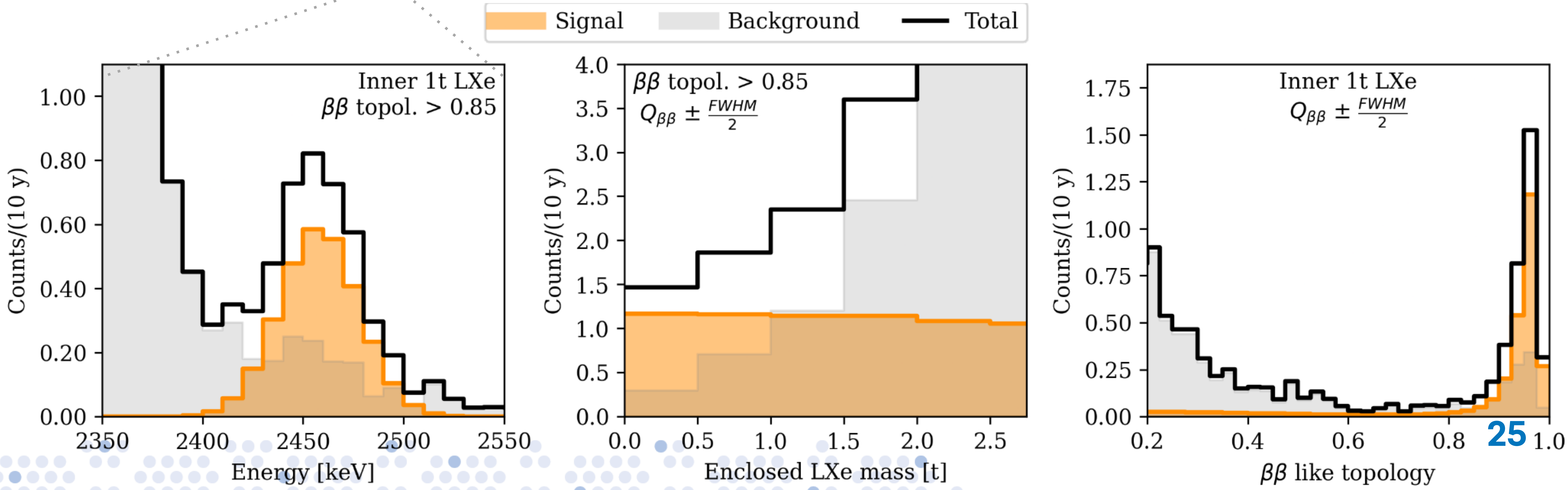


Multiparameter Analysis





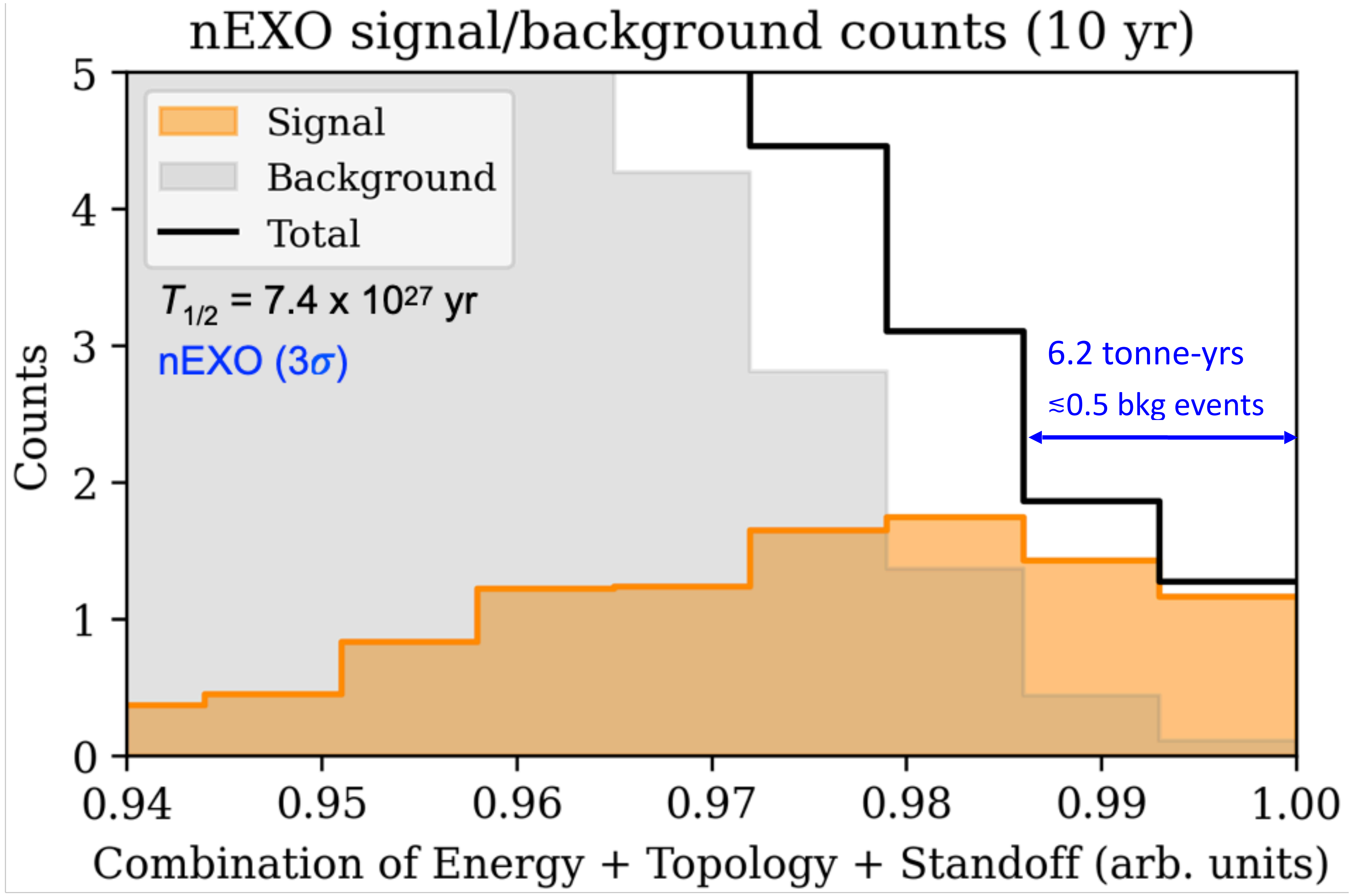




Multiparameter Analysis

- Arranging the 3D bins into 1D, ordered by signal-to-background ratio, helps visualize the signal and background separation in nEXO

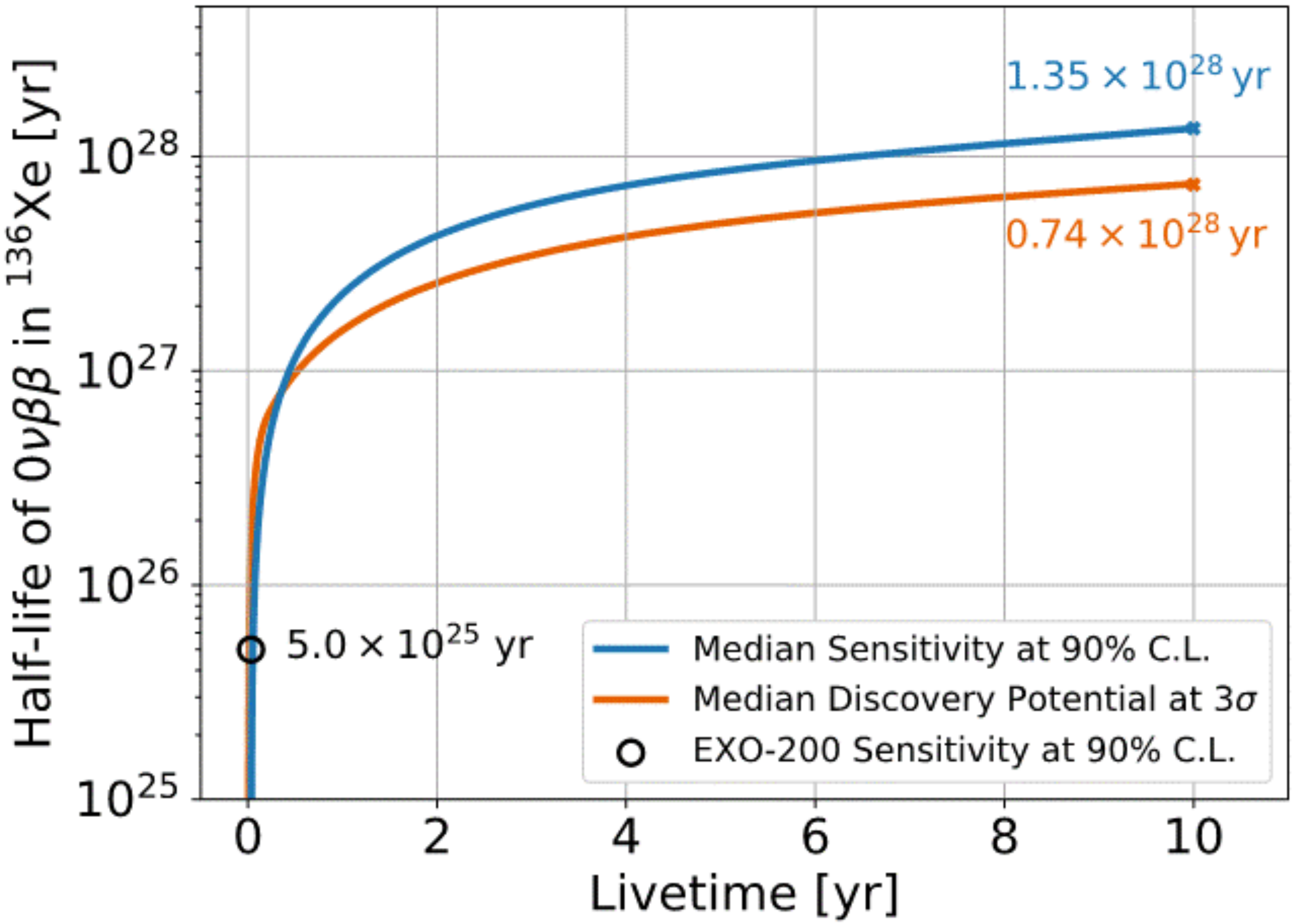
Combine energy, topology, and standoff (preserving correlations)



0 ← Background-like ***Signal-like → 1***

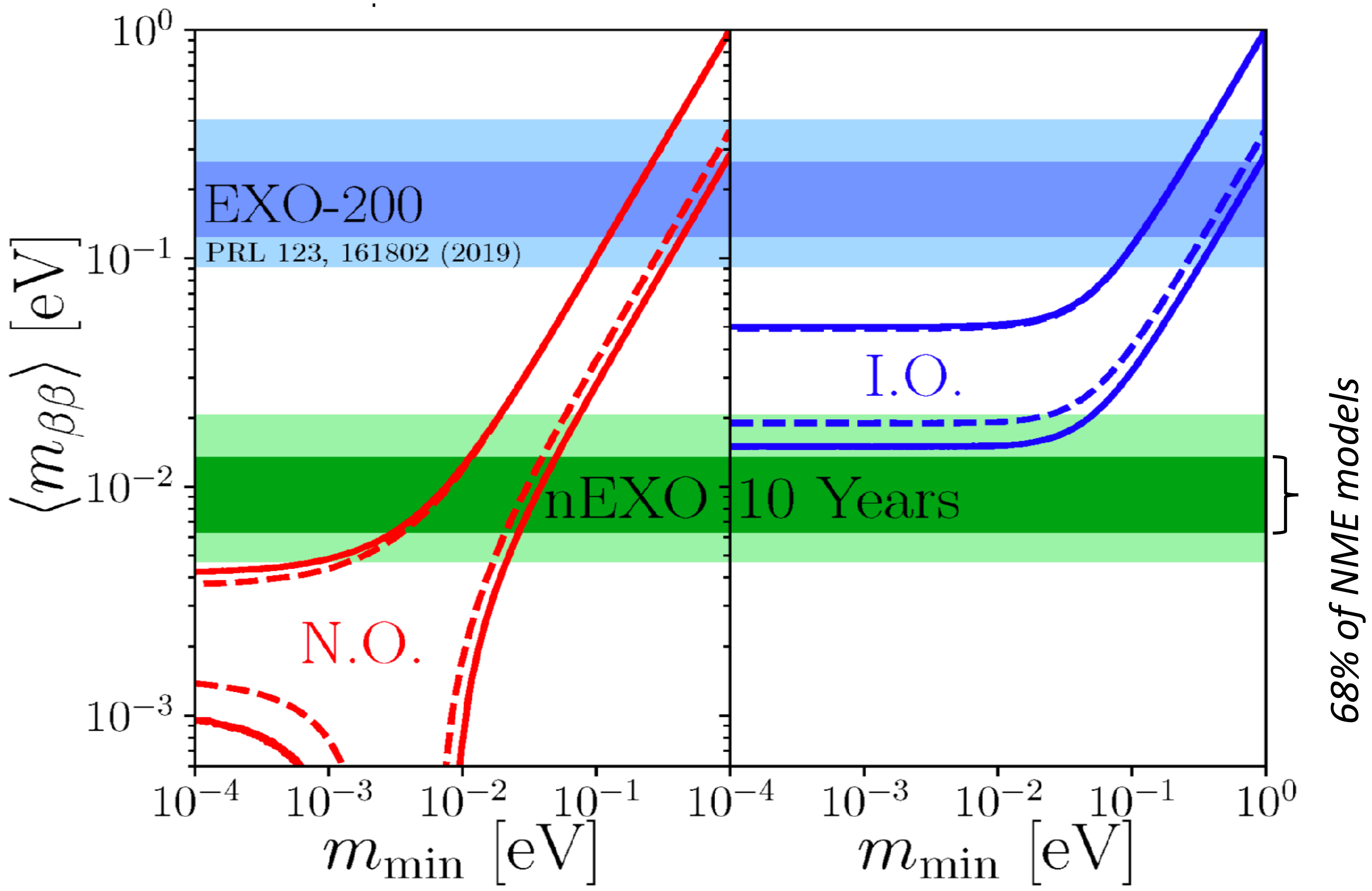
nEXO is a "background-free" experiment

nEXO



nEXO sensitivity reaches 10^{28} yr in 6.5 yr data taking

Allowed parameter space and nEXO exclusion sensitivity (90% CL):

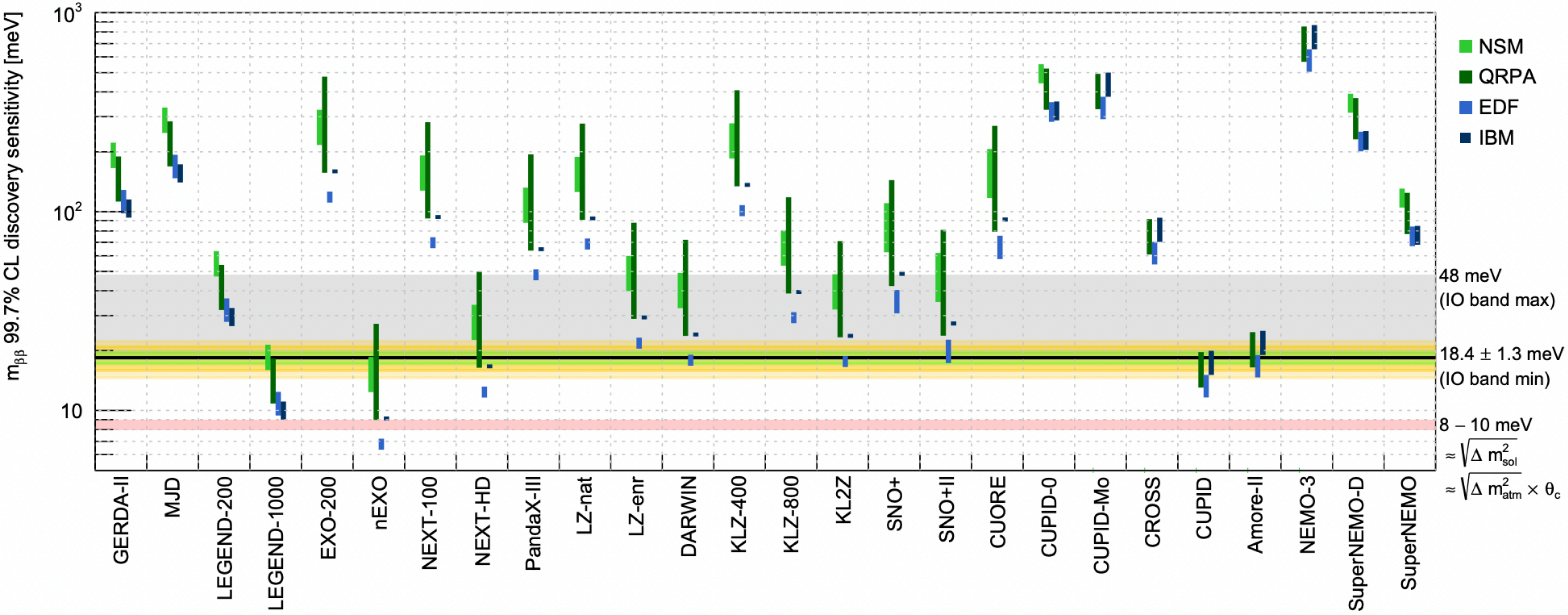


[J. Phys. G: Nucl. Part. Phys. 49 (2022) 015104]

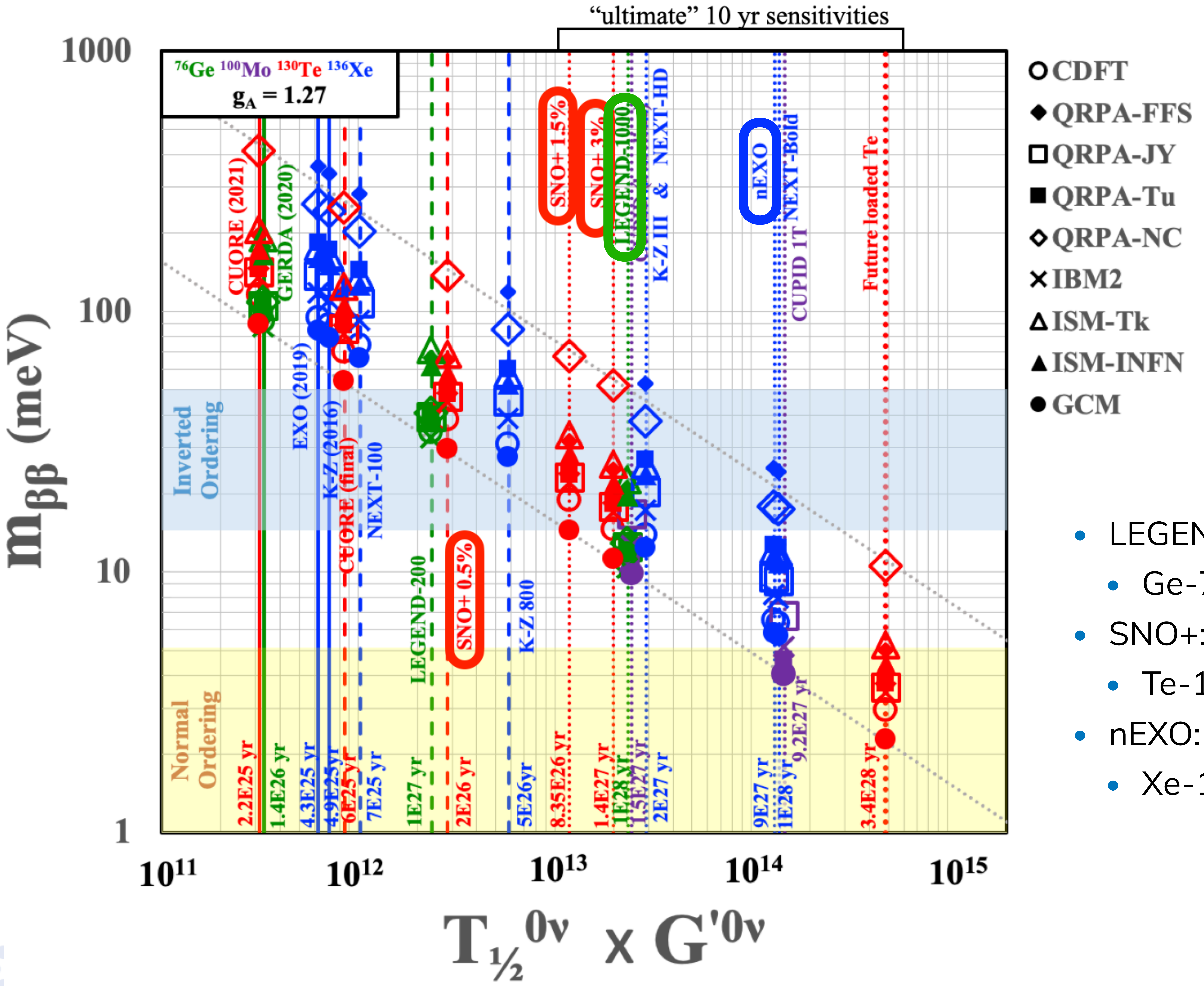
What's Next?

Schönert, Nu'22

Discovery sensitivities of current- and next-generation 0νββ experiments



[arXiv:2202.01787]



- LEGEND:
  - Ge-76, $Q_{\beta\beta}$ = 2039 keV, 7.8% NA
- SNO+:
  - Te-130, $Q_{\beta\beta}$ = 2528 keV, 34% NA
- nEXO:
  - Xe-136, $Q_{\beta\beta}$ = 2458 keV, 8.9% NA

A healthy neutrinoless double-beta decay program requires more than one isotope.

- Nuclear matrix elements are not very well known and any given isotope could come with unknown liabilities
- Different isotopes correspond to vastly different experimental techniques
- 2 neutrino background is different for various isotopes
- Understanding the mechanism producing the decay requires the analysis of more than one isotope

2ND INTERNATIONAL SUMMIT ON THE FUTURE OF NEUTRINOLESS DOUBLE-BETA DECAY

SNOLAB

coordinated. The stakeholders welcome additional international partnerships.

Readout from In Camera Sessions

- The international stakeholders in neutrinoless double beta decay research who attended this summit (agencies representing Canada, France, Germany, Italy, UK, and USA) agree in principle the best chance for an unambiguous discovery is an international campaign with multiple isotopes and more than one large tonne-scale experiment implemented in the next decade.
- These stakeholders discussed a scenario that could accomplish the goals of the first bullet by deploying CUPID, LEGEND-1000, and nEXO with one tonne-scale experiment in Europe and one tonne-scale experiment in North America.
- **These stakeholders agree on the need for a coordinated effort to efficiently and cost-effectively advance the field for the proposed double beta decay experiments, as well as the future of the field. To that purpose, these stakeholders agree that a structure for international collaboration on this research should be explored. (e.g., an international virtual observatory for neutrinoless double beta decay).**
- These funding agencies intend to create a working group to explore how such an international effort could be coordinated. The stakeholders welcome additional international partnerships.

Summary

- 0νββ is a priority for Canadian and International Long Range Plans
- Canada contributes to multiple 0νββ experiments, with significant leadership roles in SNO+ and nEXO
- Globally, the community needs more than one experiment to best position ourselves to understand 0νββ