2022/05/29

# Status of nEXO & LEGEND

**Erica Caden, (she/her)**
SNOLAB Research Scientist

Many thanks to Giorgio Gratta and Ryan Martin for slides!

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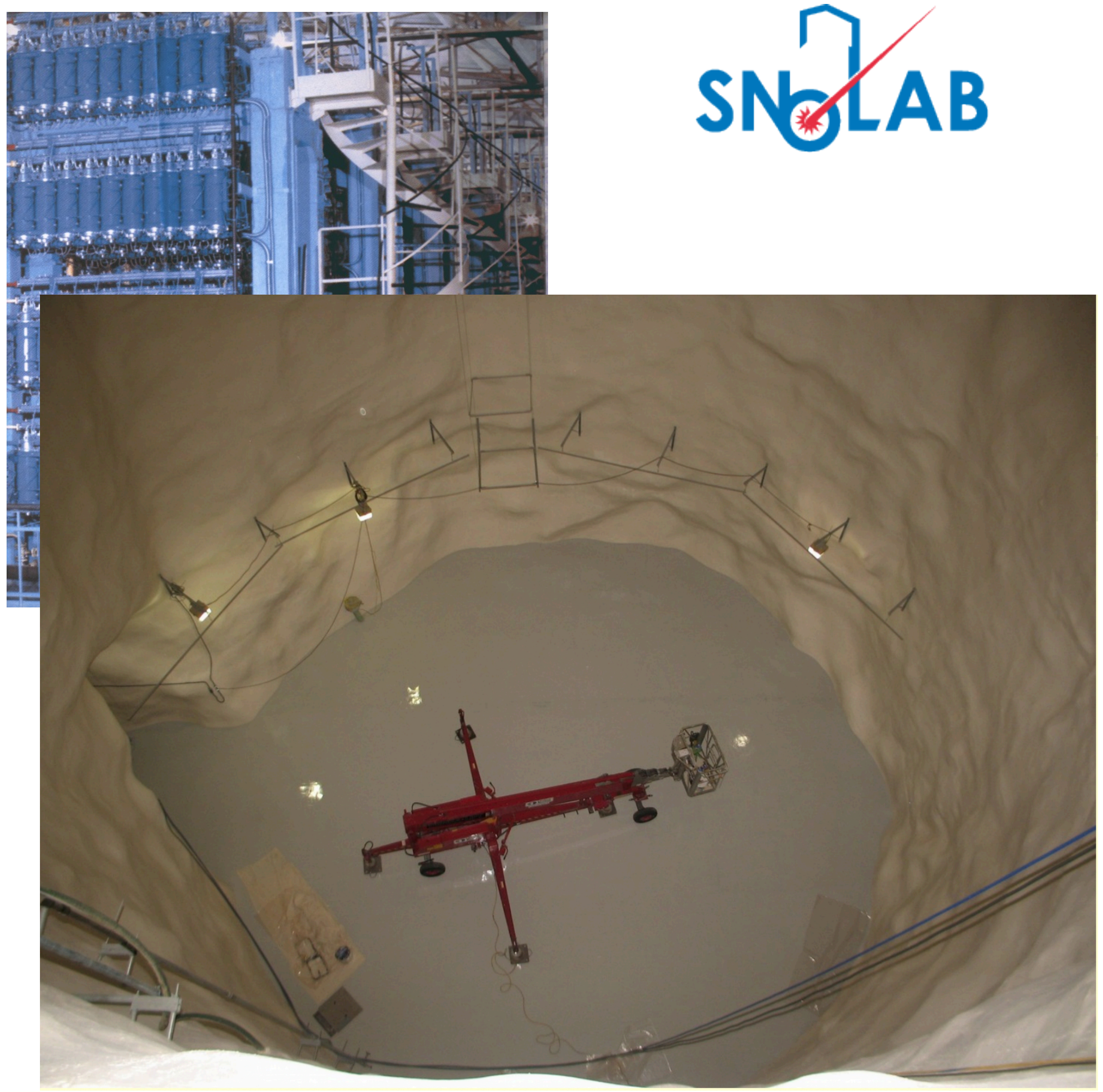

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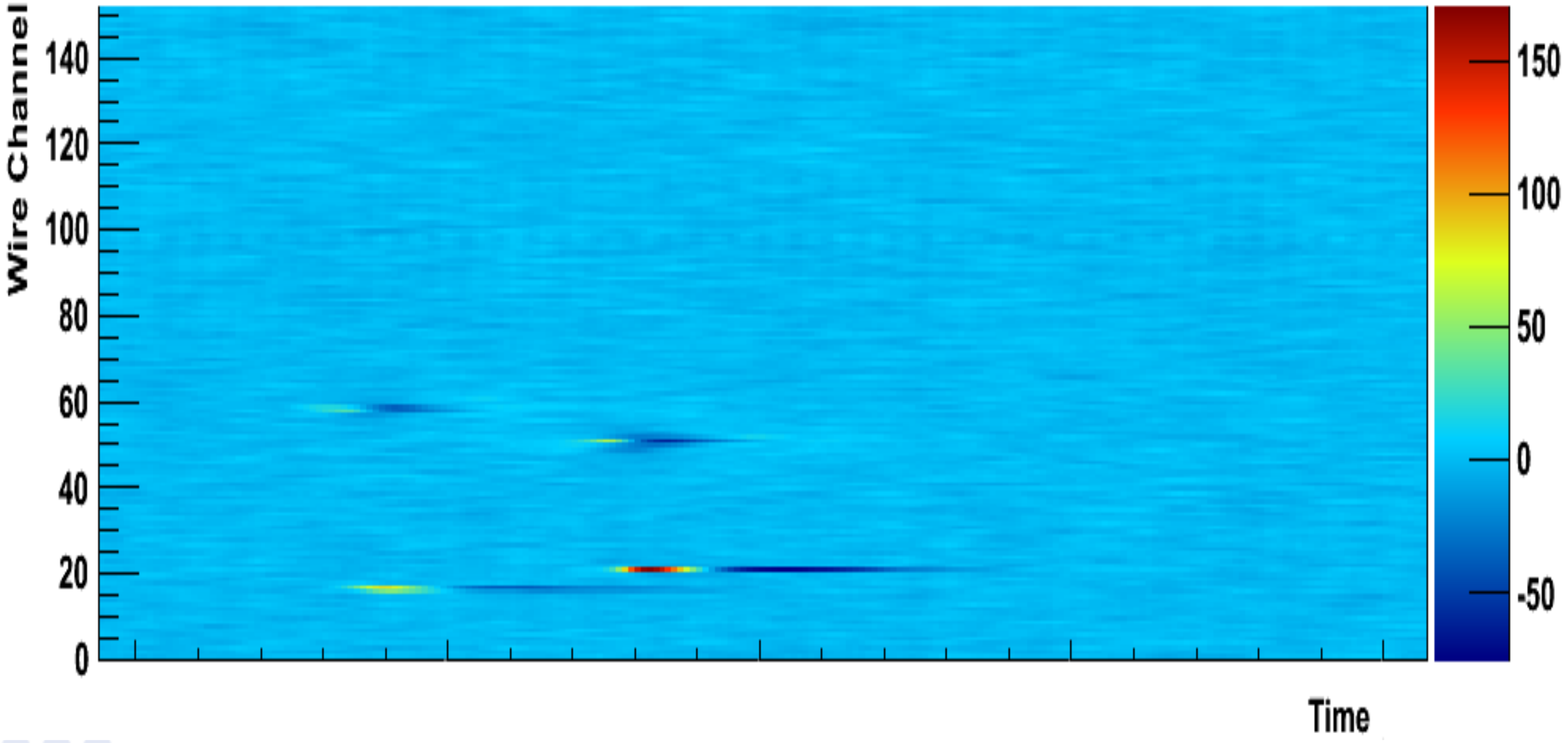

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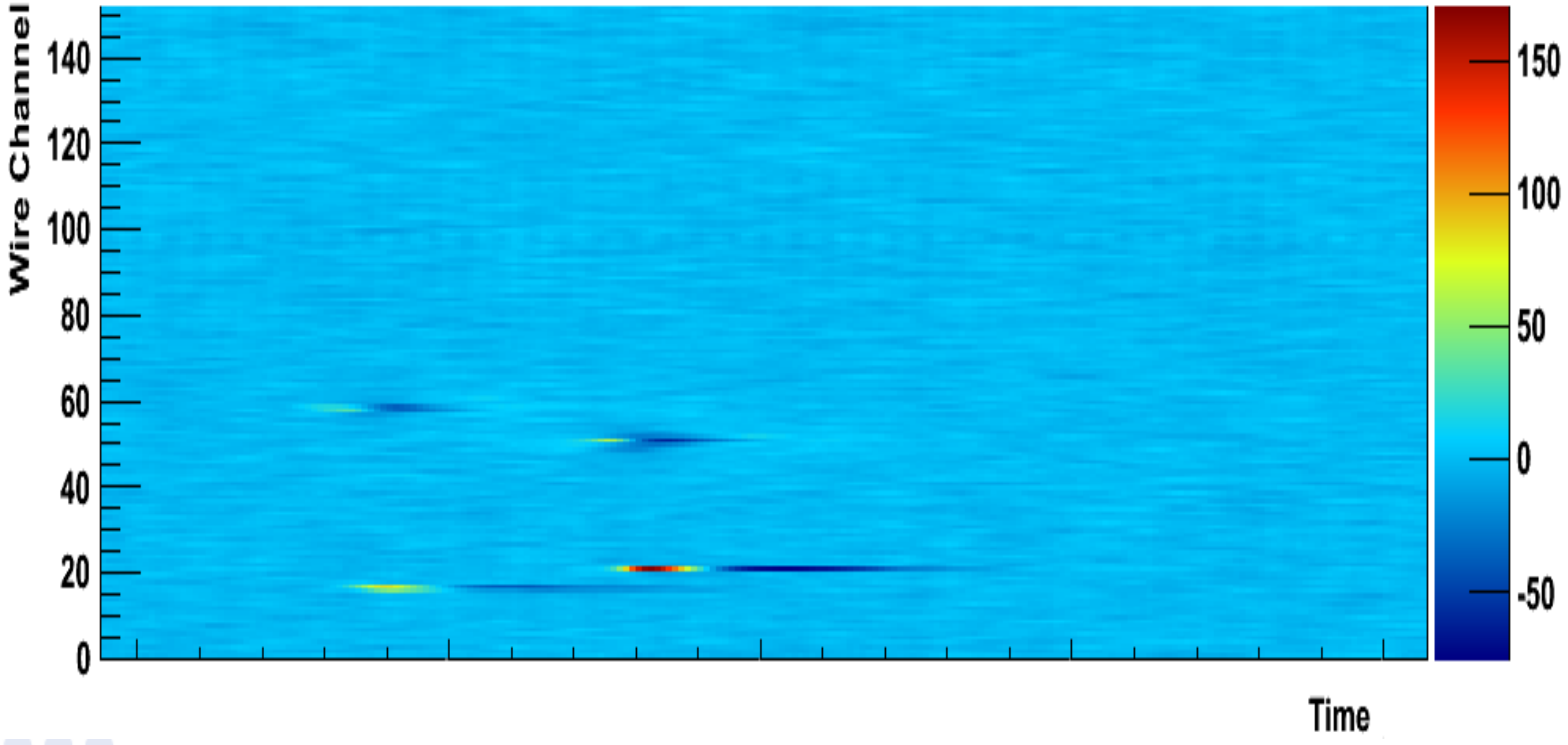


The next step: ton-scale detectors entirely covering the inverted hierarchy

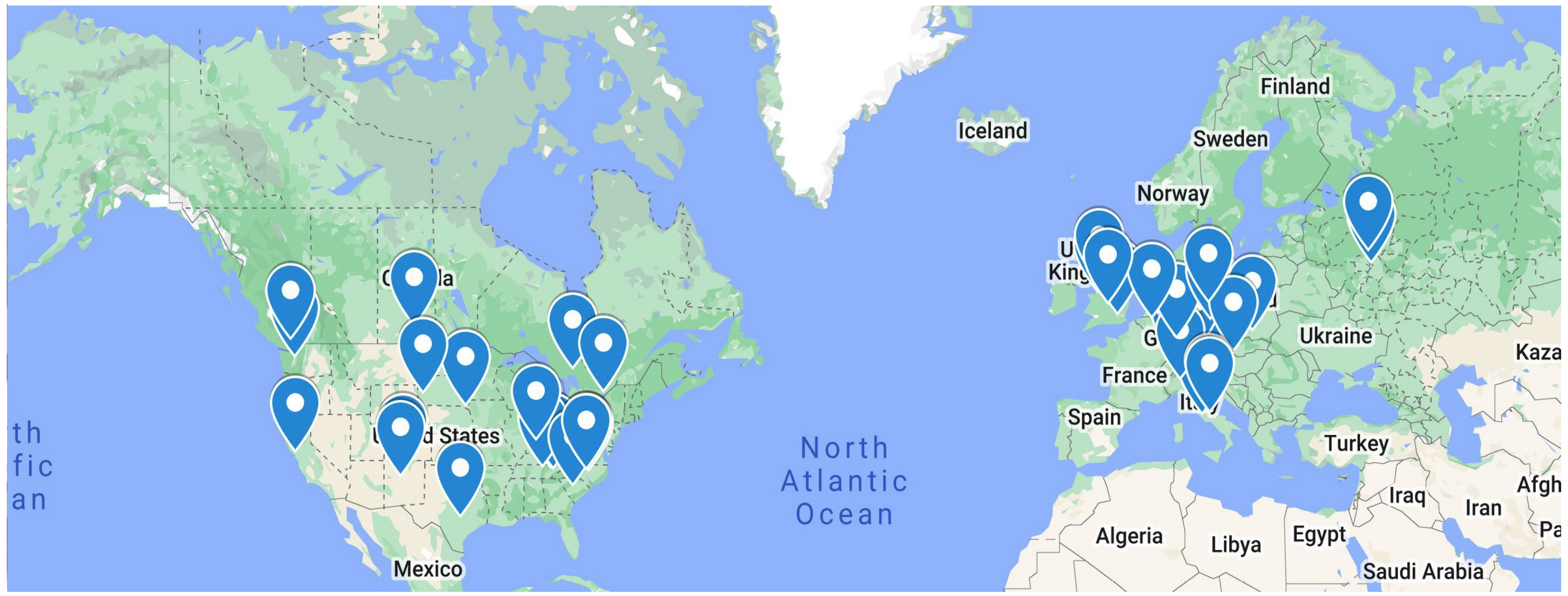
Testing lepton number violation with 100x the current sensitivity

# 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

# nEXO

# LEGEND

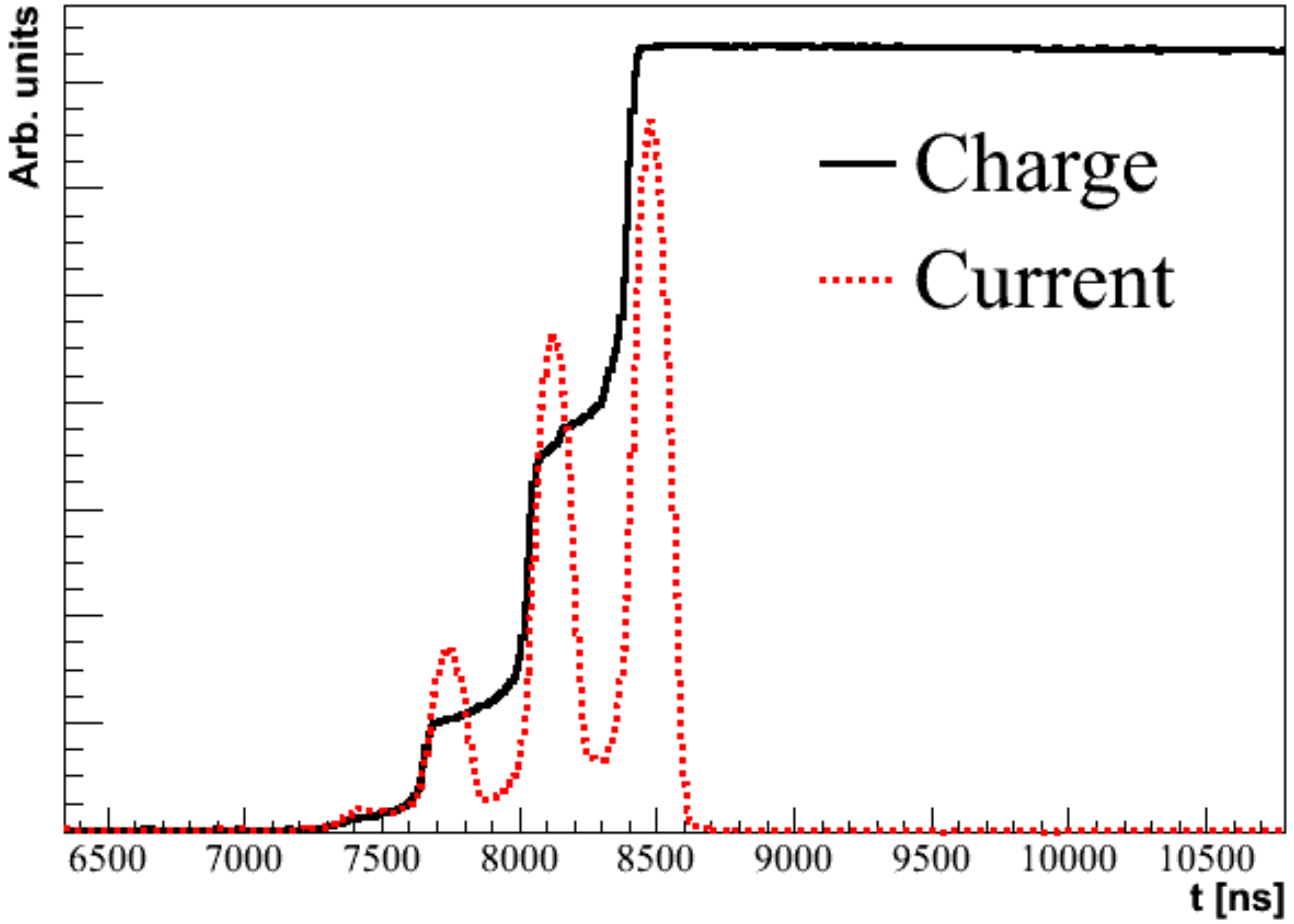


9 Countries, 33 institutions, ~200 collaborators

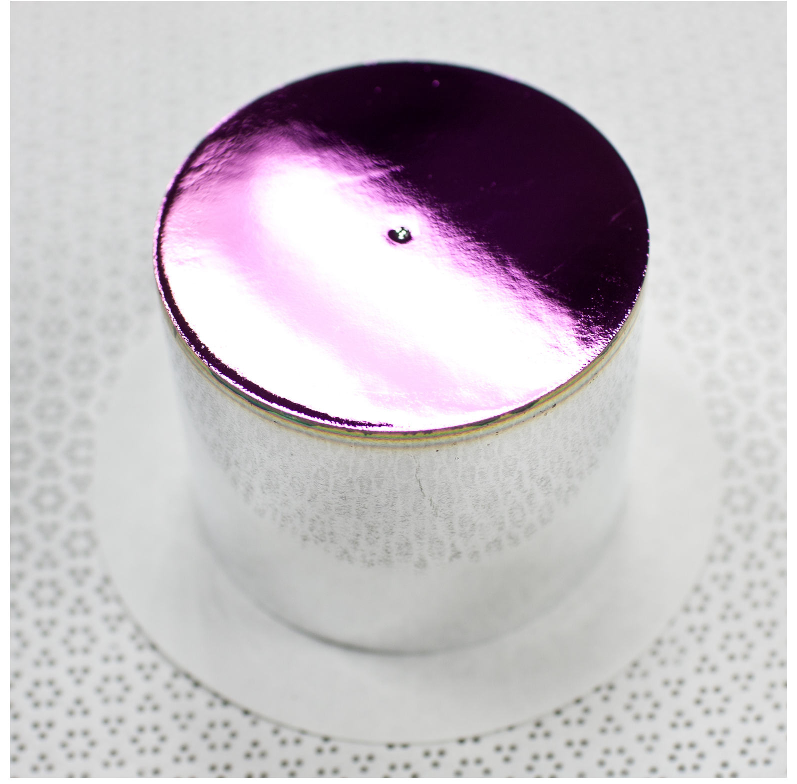
49 institutions, about 250 scientists

# Germanium for 0νββ searches

- ${}^{76}$Ge is a candidate isotope for 0νββ-decay with a Q-value of 2039 keV.
- HPGe detectors are a well-established technology that is intrinsically low background (high purity germanium).
- Germanium detectors can be made from material enriched to >90% in ${}^{76}$Ge (natural abundance ~ 7%).
- Excellent energy resolution (0.1% FWHM at Q-value).
- Novel detector technologies allow for efficient background rejection through pulse shape discrimination.

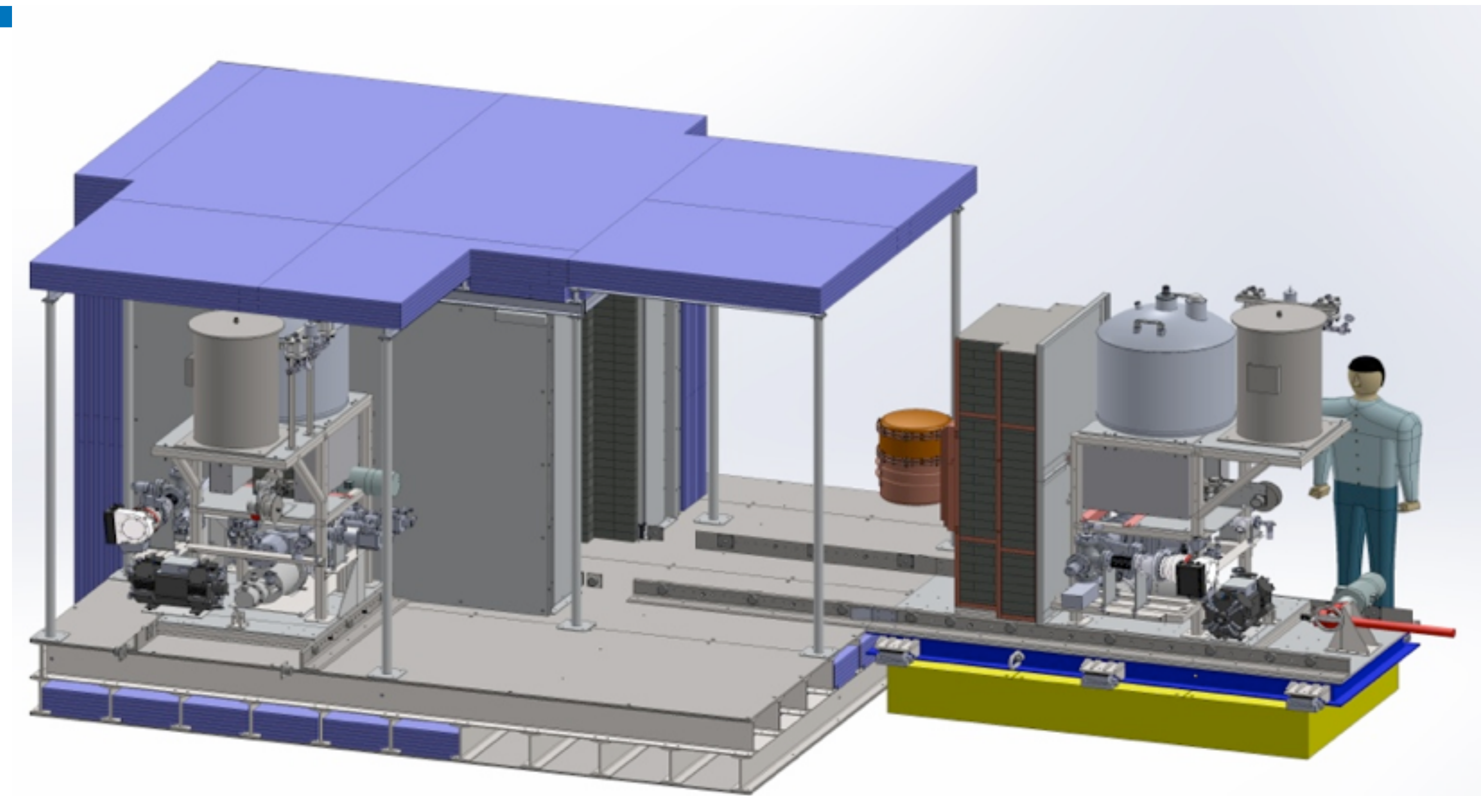


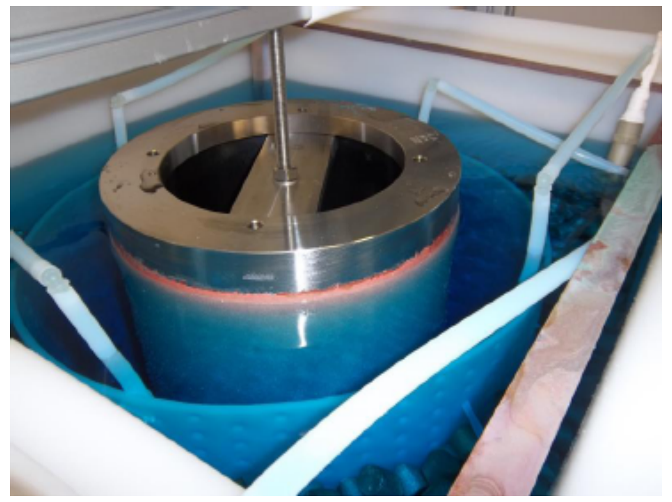
*Identification of a 1332keV gamma ray "multi-site" (Compton scattering) event by pulse shape discrimination.*

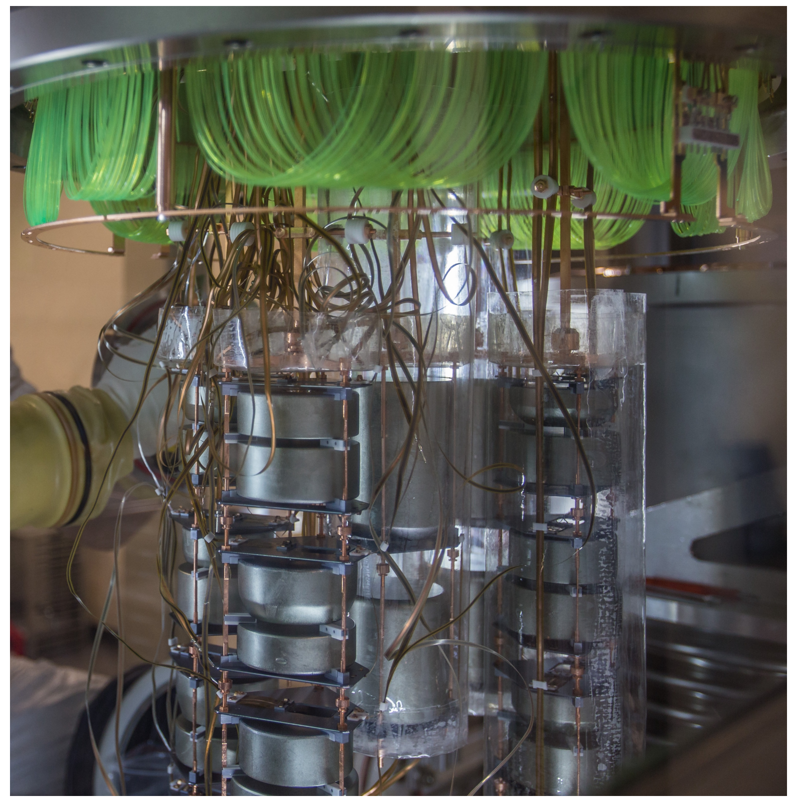


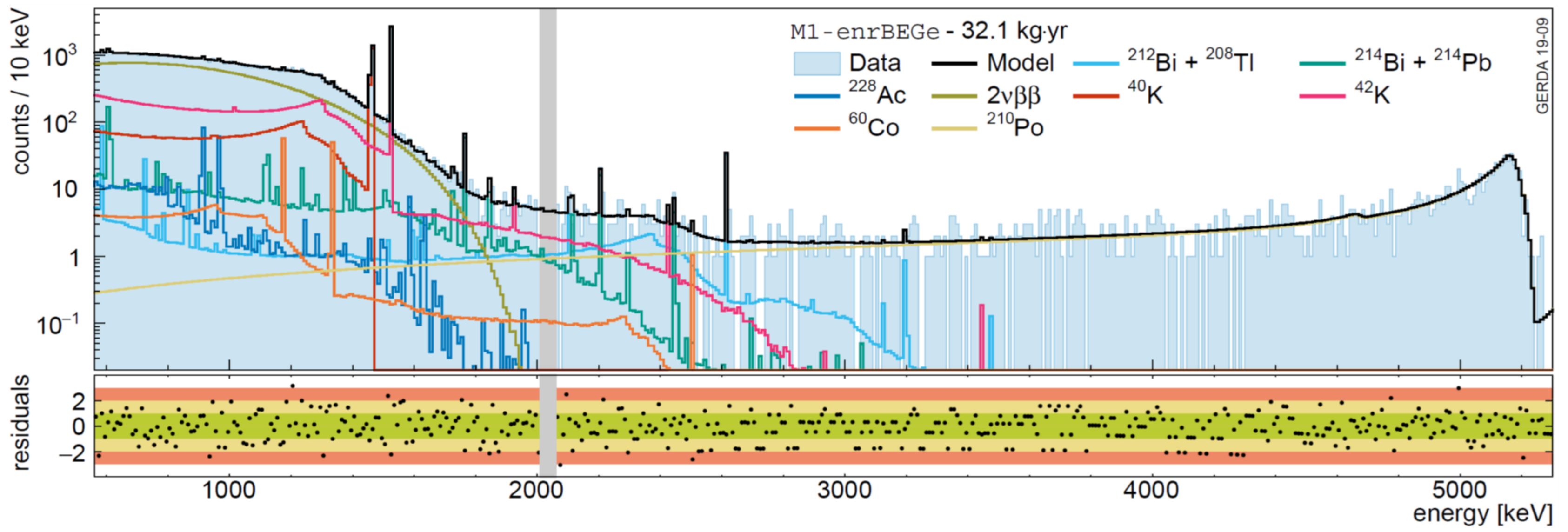
*900g R&D HPGE Point Contact detector*

# MAJORANA Demonstrator & GERDA exp'ts









Majorana Demonstrator at SURF (USA):

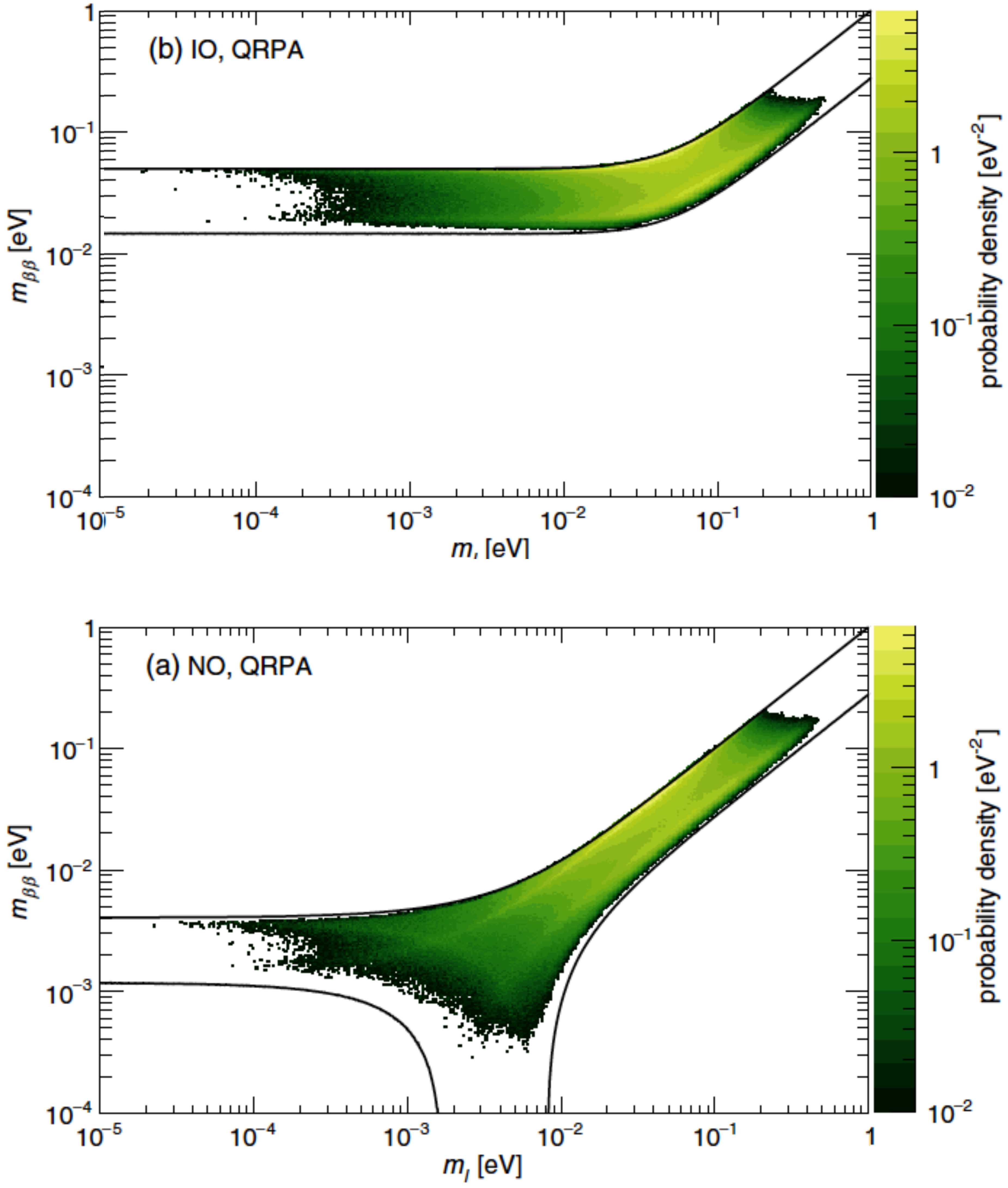
- Two compact vacuum cryostats + shielding (Cu/Pb)
- 29kg enriched detectors, 15kg natural abundance
- Custom Low Mass Front End electronics
- Extensive use of underground electroformed copper
- **Best energy resolution of any 0νββ experiment**

GERDA at LNGS (EU):

- Detectors deployed in liquid argon as scintillating veto
- 35kg of enriched detectors (coax + BEGe)
- Complete background modelling over large energy range
- **Lowest background index of any 0νββ experiment**

# The LEGEND program

- LEGEND: Large Enriched Germanium Experiment for Neutrinoless Double Beta Decay
- Originally formed by members of the MAJORANA and GERDA collaborations
- Goal: $3\sigma$ detection of a $0\nu\beta\beta$ signal in $^{76}$Ge for half-lives of $10^{28}$ years
- Method:
  - Phased approach to retire technological risks
  - Re-use of demonstrated technologies from the MAJORANA DEMONSTRATOR and GERDA experiments:
    - Electroformed copper, Low mass front-end electronics, Immersion in liquid argon
  - Develop new technologies:
    - ICPC detectors, Scintillating structural materials, Electronics
- Program:
  - LEGEND-200 experiment to deploy 200 kg of enriched detectors and make use of the existing GERDA infrastructure at LNGS
  - LEGEND-1000 proposed for 1000 kg of enriched detectors (baseline at SNOLAB)



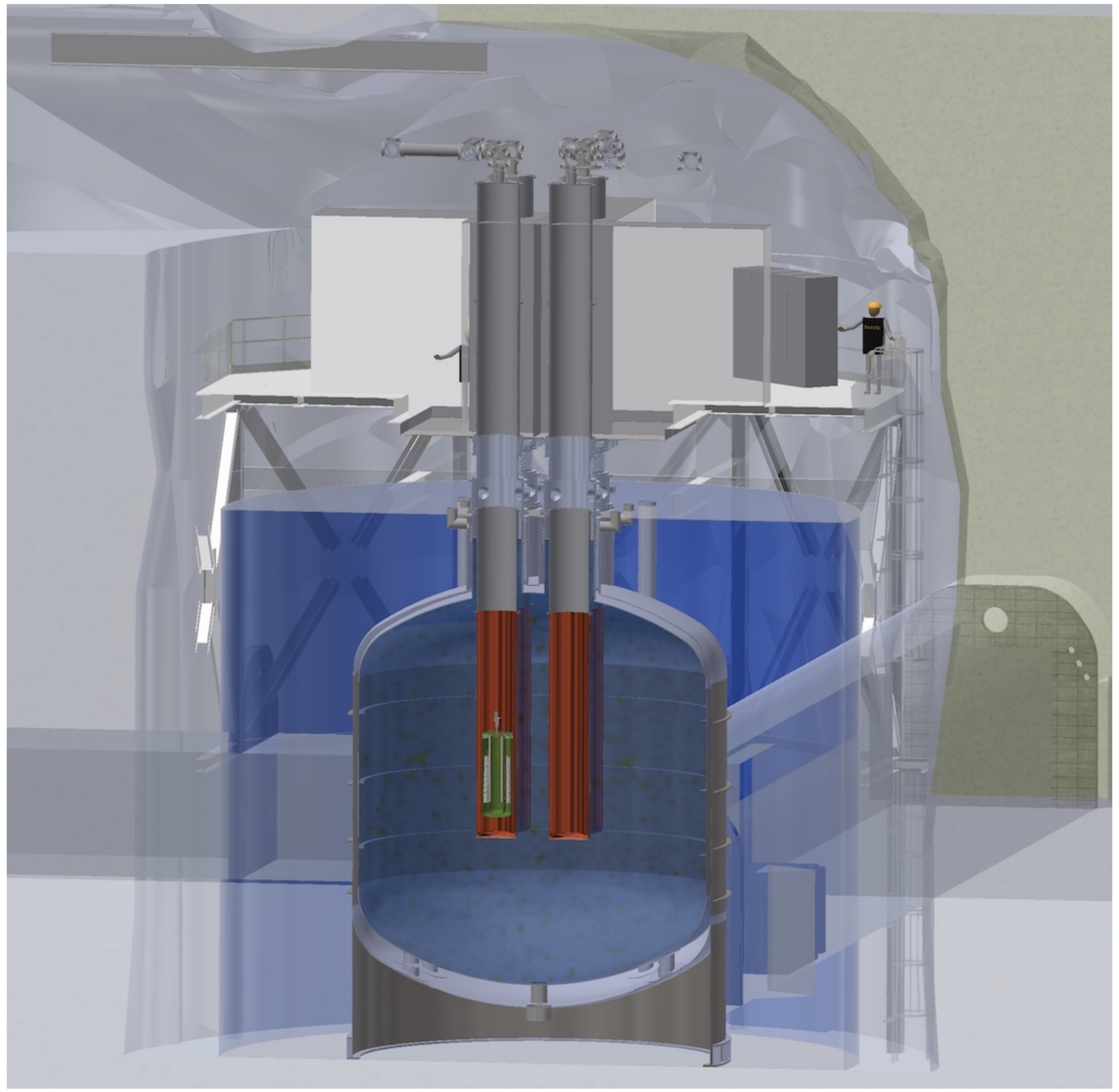
*Marginalized posterior for $m_{\beta\beta}$ versus lightest neutrino mass using $3\sigma$ range for oscillation parameters (Agostini et. al, PRD **96** 053001 2017)*

# LEGEND-200

- LEGEND-200 target is to explore half-lives of **$10^{27}$ years** with 5 years of data taking using 200kg of enriched Ge detectors
- Reuse 70kg of enriched detectors from GERDA and MJD + 130 kg of new material
- Required reduction in background level by a factor of 2.5 compared to GERDA achieved through:
  - Use of MJD low mass front-end electronics
  - Use of electroformed copper near detectors
  - More efficient readout of scintillation light
  - Larger mass ICPC detectors
- LEGEND-200 an ideal test bench for technologies aimed at LEGEND-1000
- Status:
  - Currently commissioning (185kg acquired), cryostat filled, lock-system upgraded, started commissioning of first detectors.
  - Expect background index measurements and first physics runs to start mid 2022

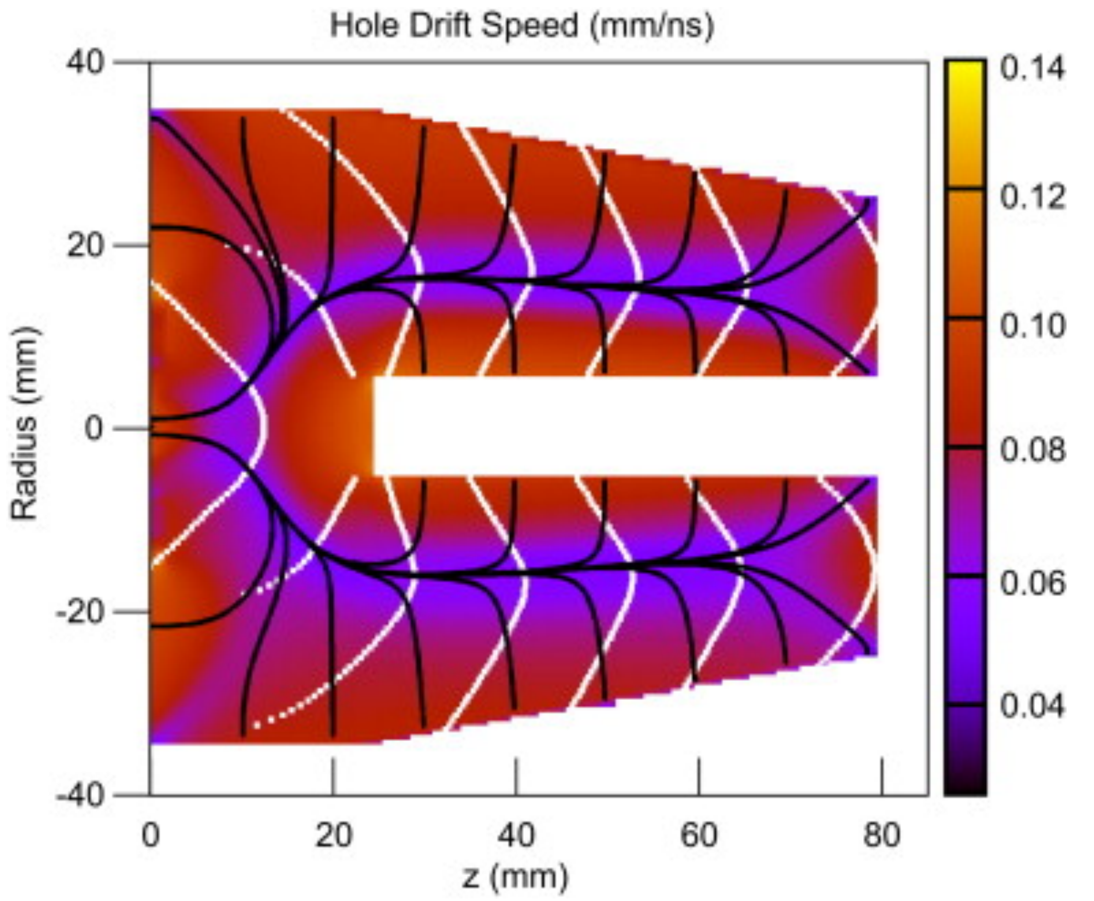
# LEGEND-1000

- LEGEND-1000 target is to explore half-lives of **$10^{28}$ years** ($m_{\beta\beta}$ = 10-20 meV) with 10 years of data taking using 1000 kg of enriched Ge detectors
- Baseline design at SNOLAB using large cryostat with 4 re-entrant tubes
- Requires reduction in background by 20x compared to LEGEND-200:
  - Larger volume/surface ratio of detectors
  - Low mass ASIC electronics
  - Low background liquid argon
  - Deeper underground
- For more information: LEGEND Pre-conceptual report: https://arxiv.org/abs/2107.11462

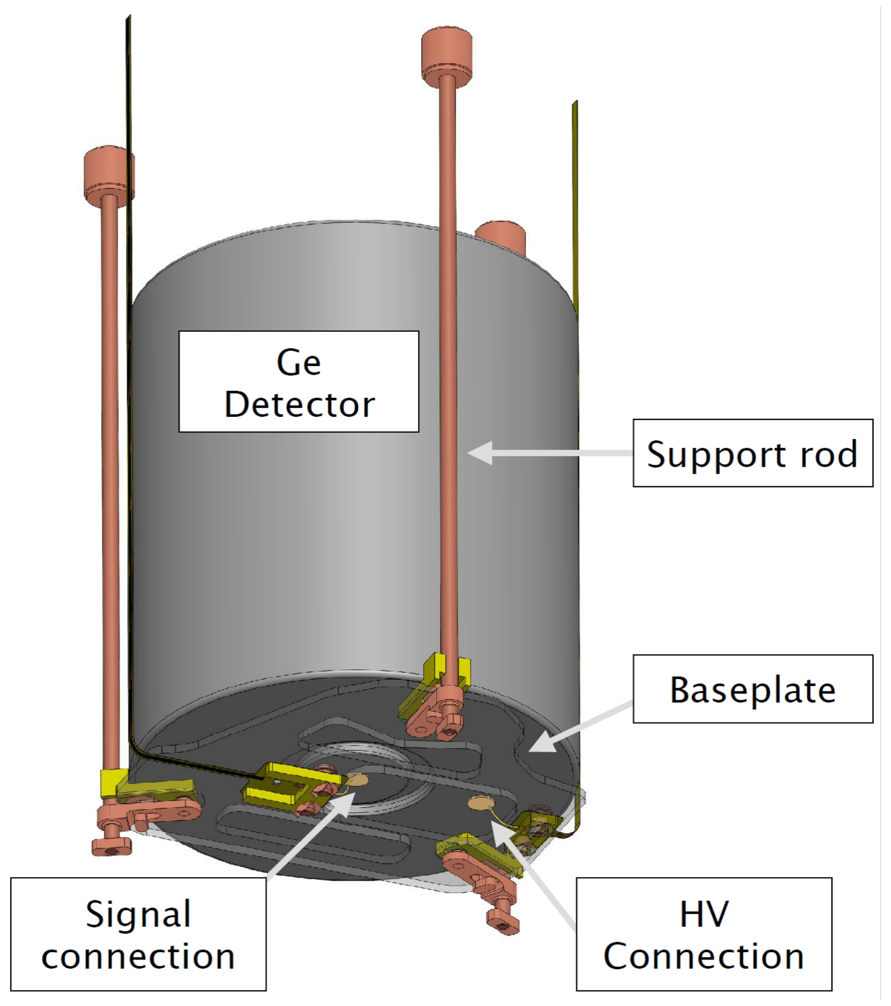


# LEGEND Technology – ICPC Detectors

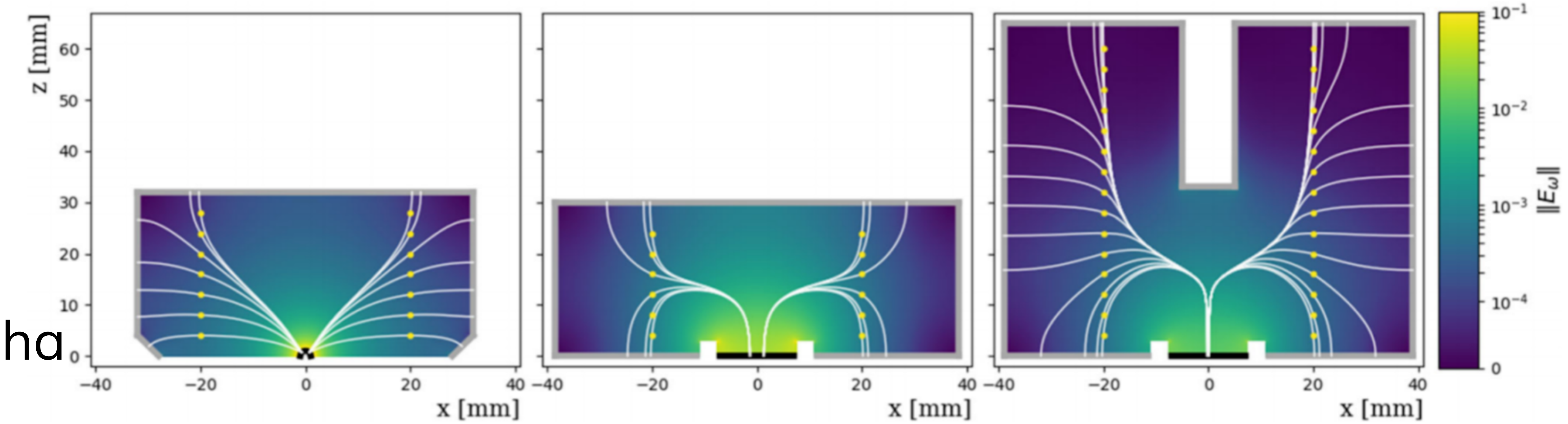
- Inverted Coaxial Point Contact detectors:
  - The semi-coaxial "well" allows for larger mass detectors that will still deplete with a "reasonable" (<5 kV) reverse-bias voltage
  - Detectors with mass larger than 3 kg possible (compare with ~1kg for "standard" PPC). 2.6 kg average mass expected for LEGEND-1000.
  - Larger detectors →
    - Less detectors →
      - Less radioactive components near detectors
    - Larger volume/passivated surface →
      - **Less surface backgrounds** from alpha radiation



*Drift paths in an ICPC, NIM* ***665*** *p.25 (2011)*



*ICPC in low-background LEGEND mount*

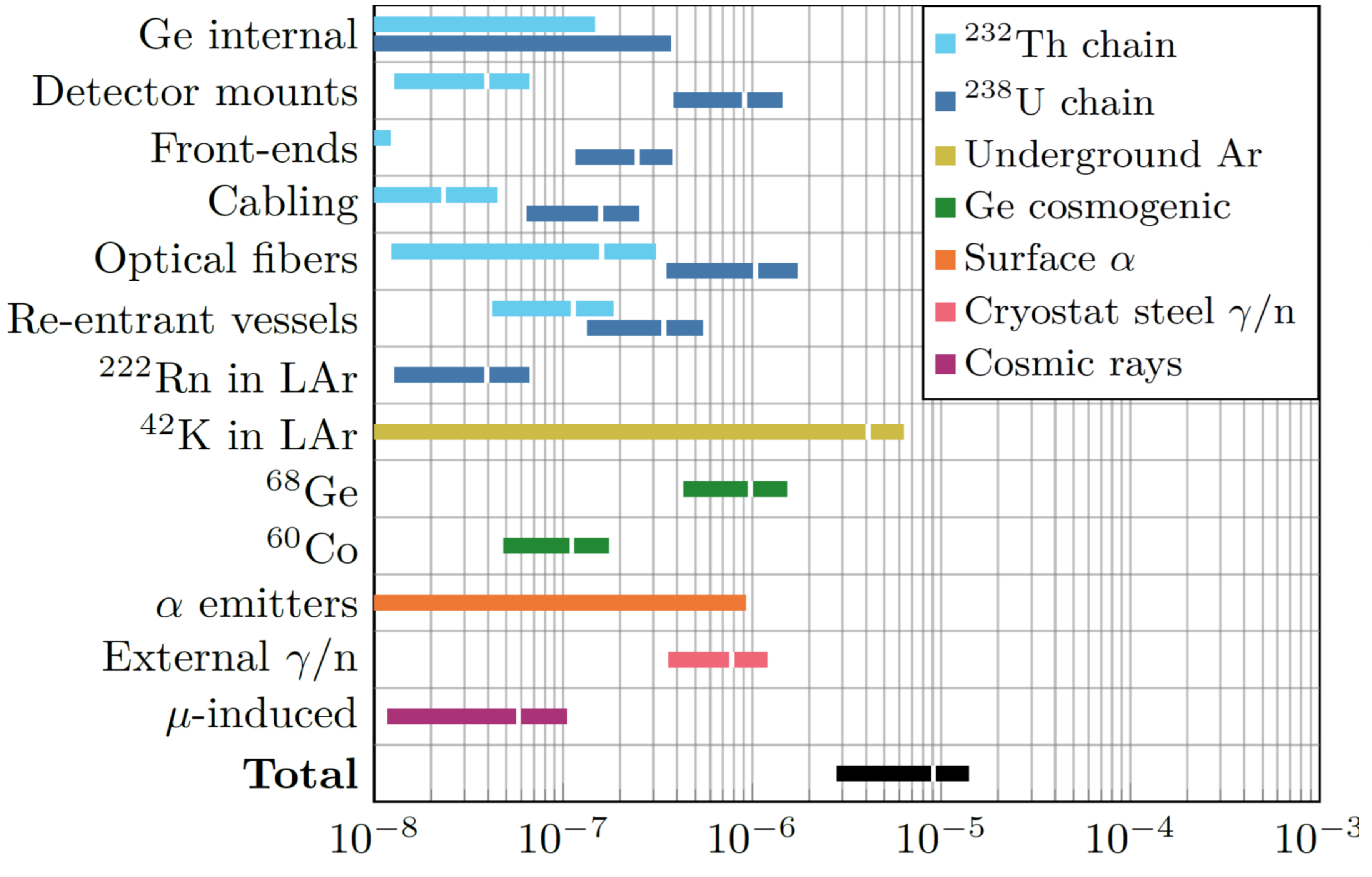


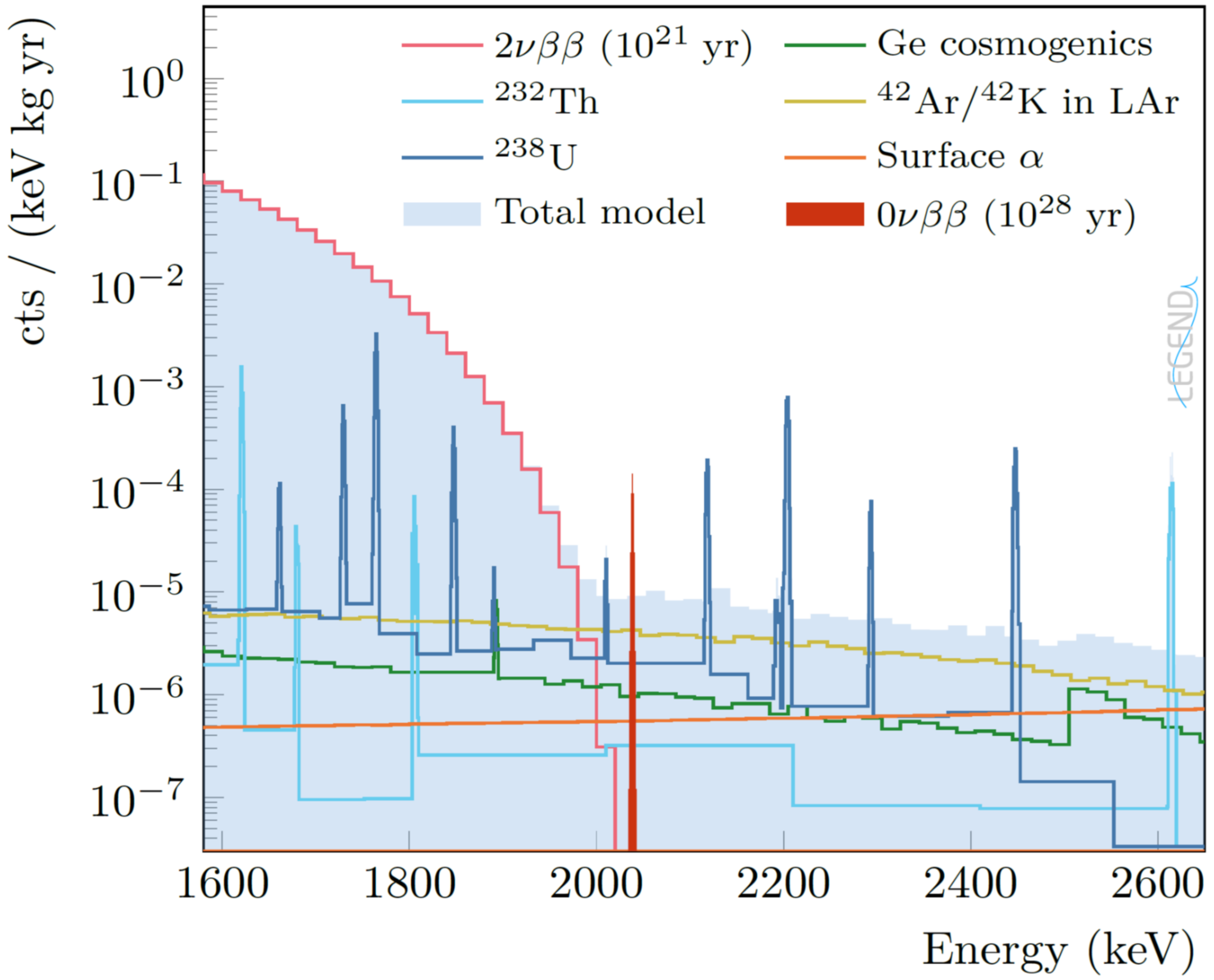
*MJD-style Point Contact, BEGE, and ICPC detectors compared for typical size*

# LEGEND-1000 backgrounds & projections

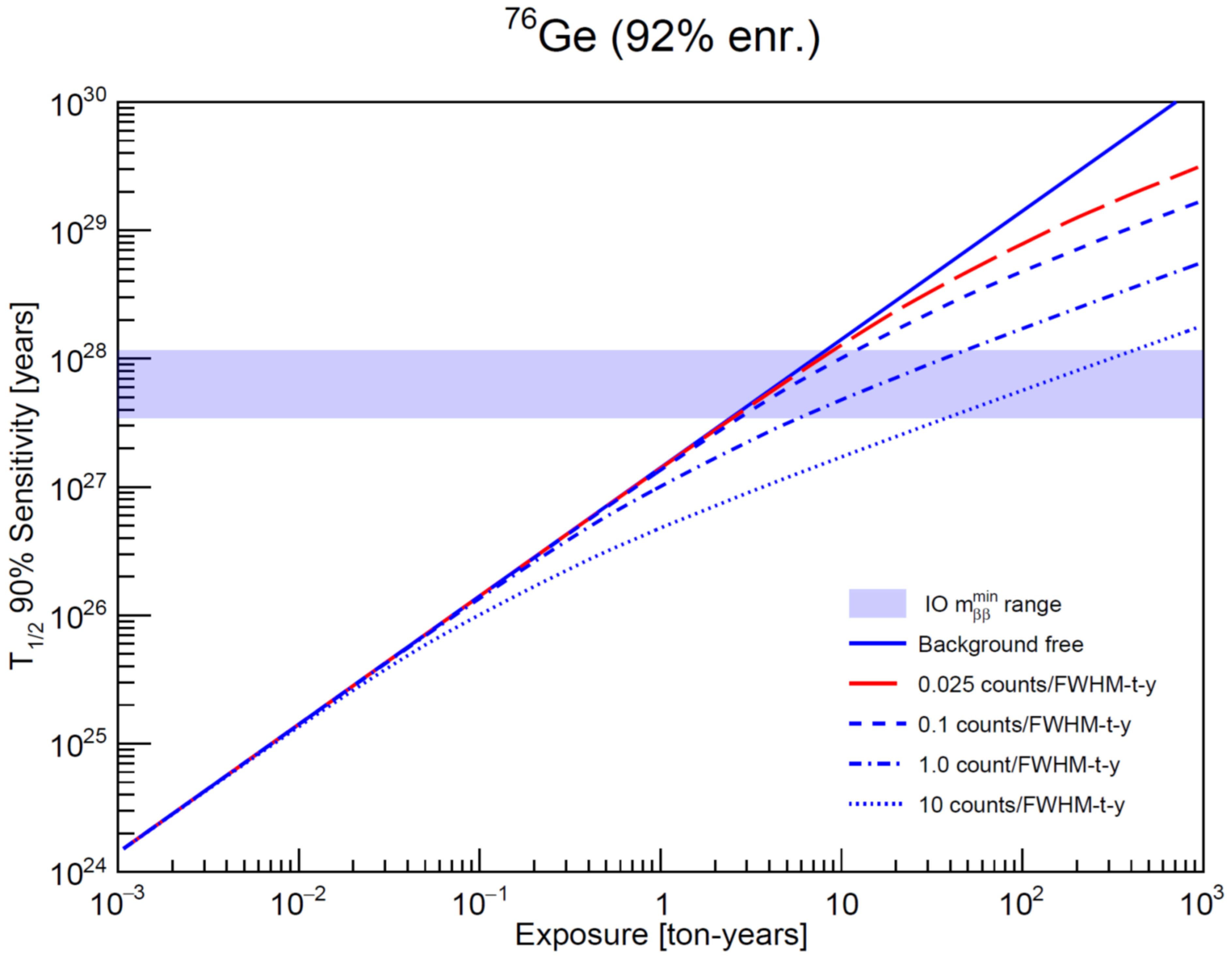
Main backgrounds in LEGEND:

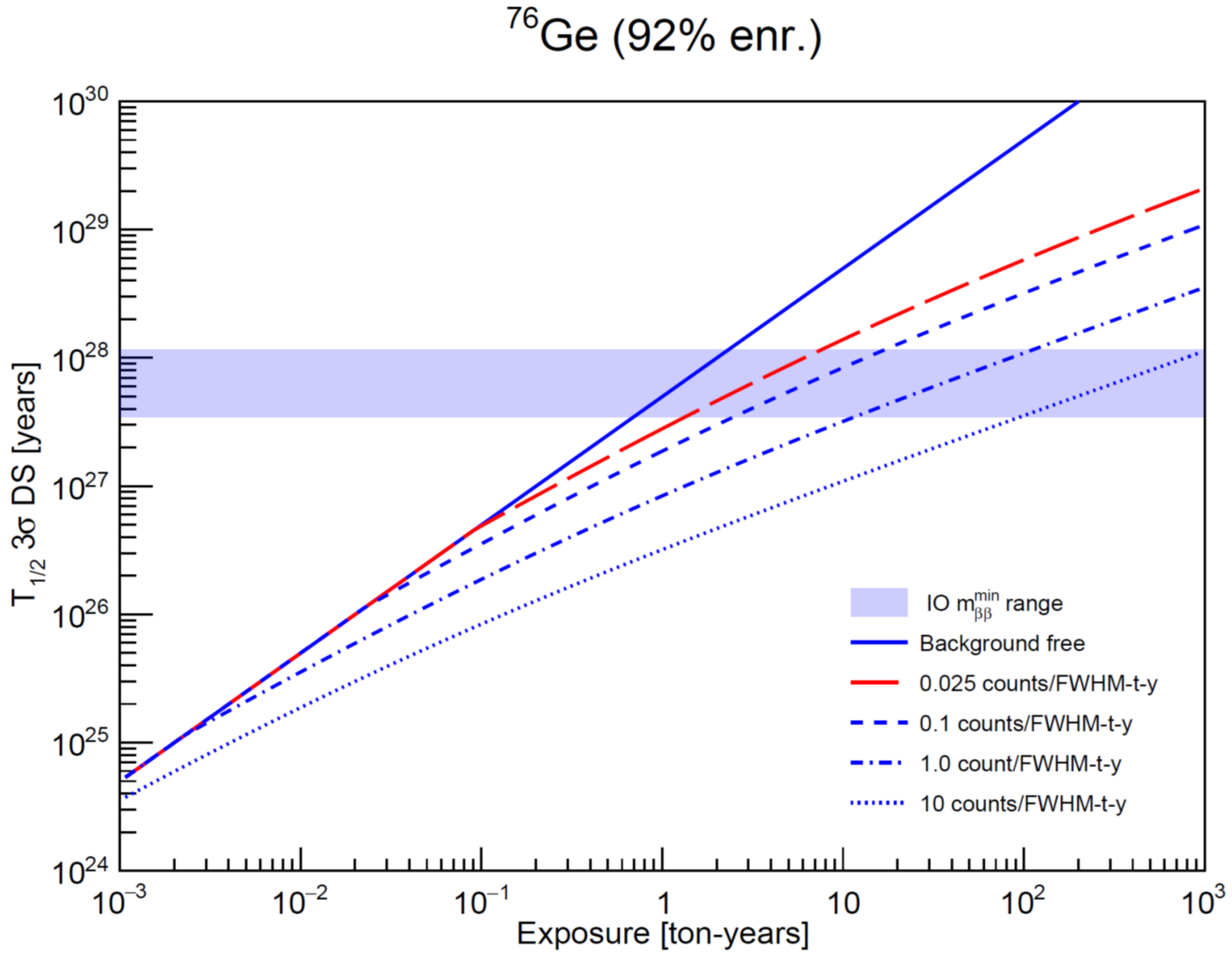
- U/Th decay chains: Gamma rays from the chain can deposit energy above the Q-value. *Reduced by using larger detectors with fewer smaller and cleaner readout components*.
- $^{42}$K decays: *Reduced by using underground LAr*
- Alpha decays on detector surfaces: *Reduced by a factor ~4 compared to GERDA (larger volume/surface for ICPC detectors)*
- Cosmogenically produced isotopes in Ge: *Will be comparable or slightly increased if detectors have less cooldown time ($^{68}$Ge has 271d half-life)*
- For more information: LEGEND Pre-conceptual report: [https://arxiv.org/abs/2107.11462](https://arxiv.org/abs/2107.11462)





# LEGEND sensitivity

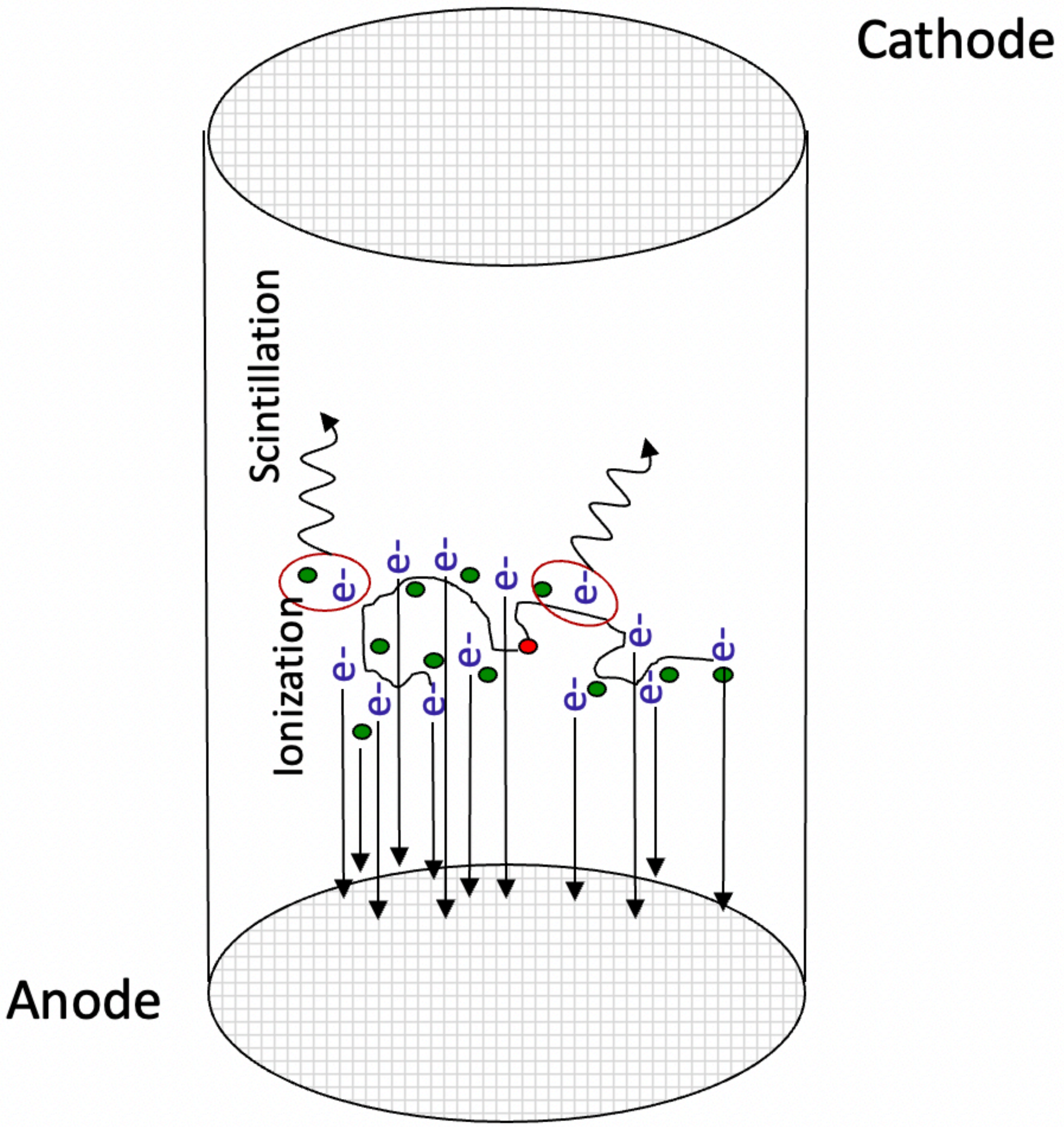




- Current background projections put LEGEND-1000 on the red line
- Left: 90% sensitivity (to exclude half-lives)
- Right: 3-sigma detection sensitivity (50% chance of detecting a signal with 3σ significance)

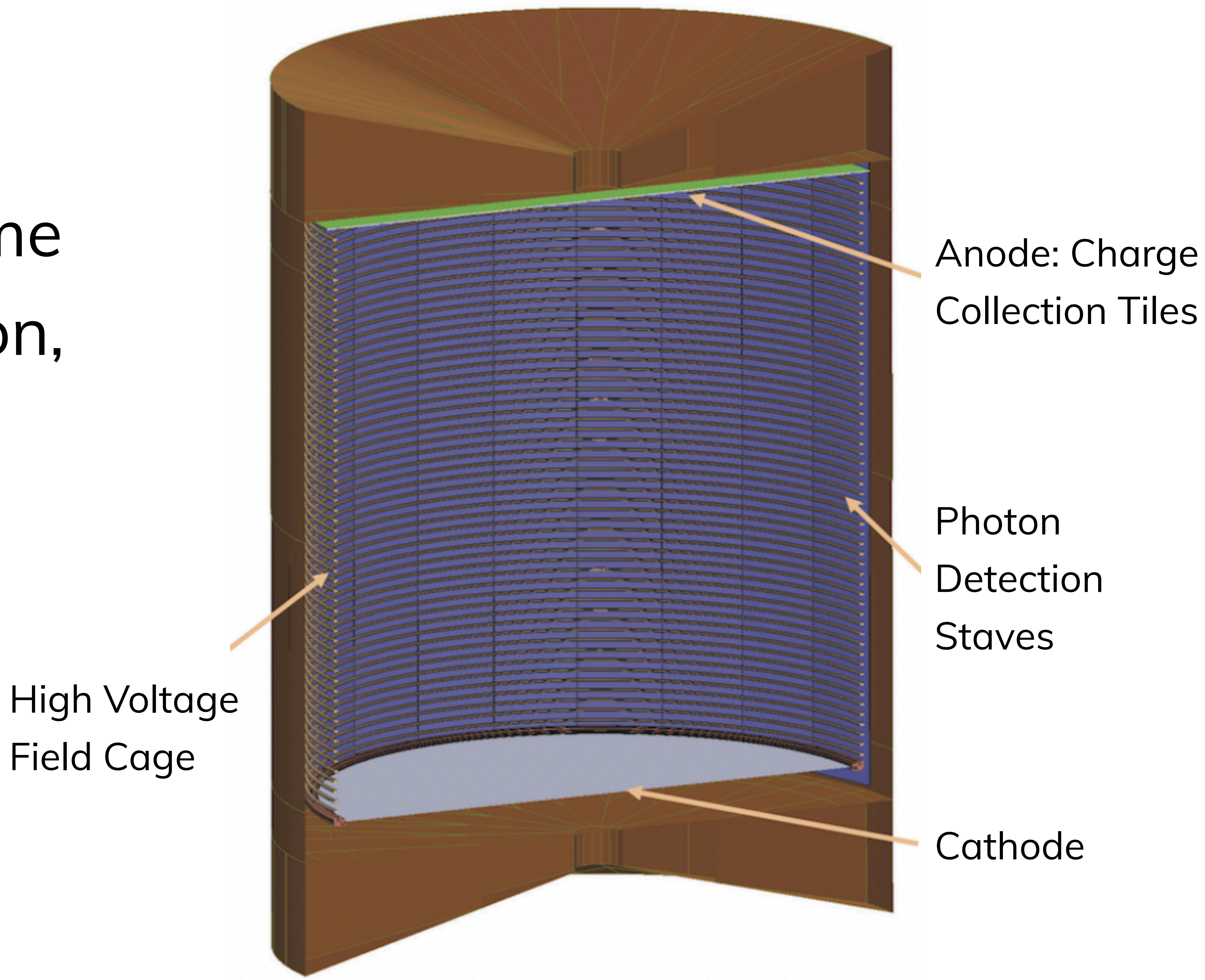
# Liquid Xe TPCs

- Liquid Xe is Source and Detection Medium
- Monolithic detector structure -> excellent background rejection
- Cryogenic electronics in LXe
- Active self-shielding
- Detection of scintillation light and secondary charges
  - Good energy resolution
  - Particle ID
  - Event Topology

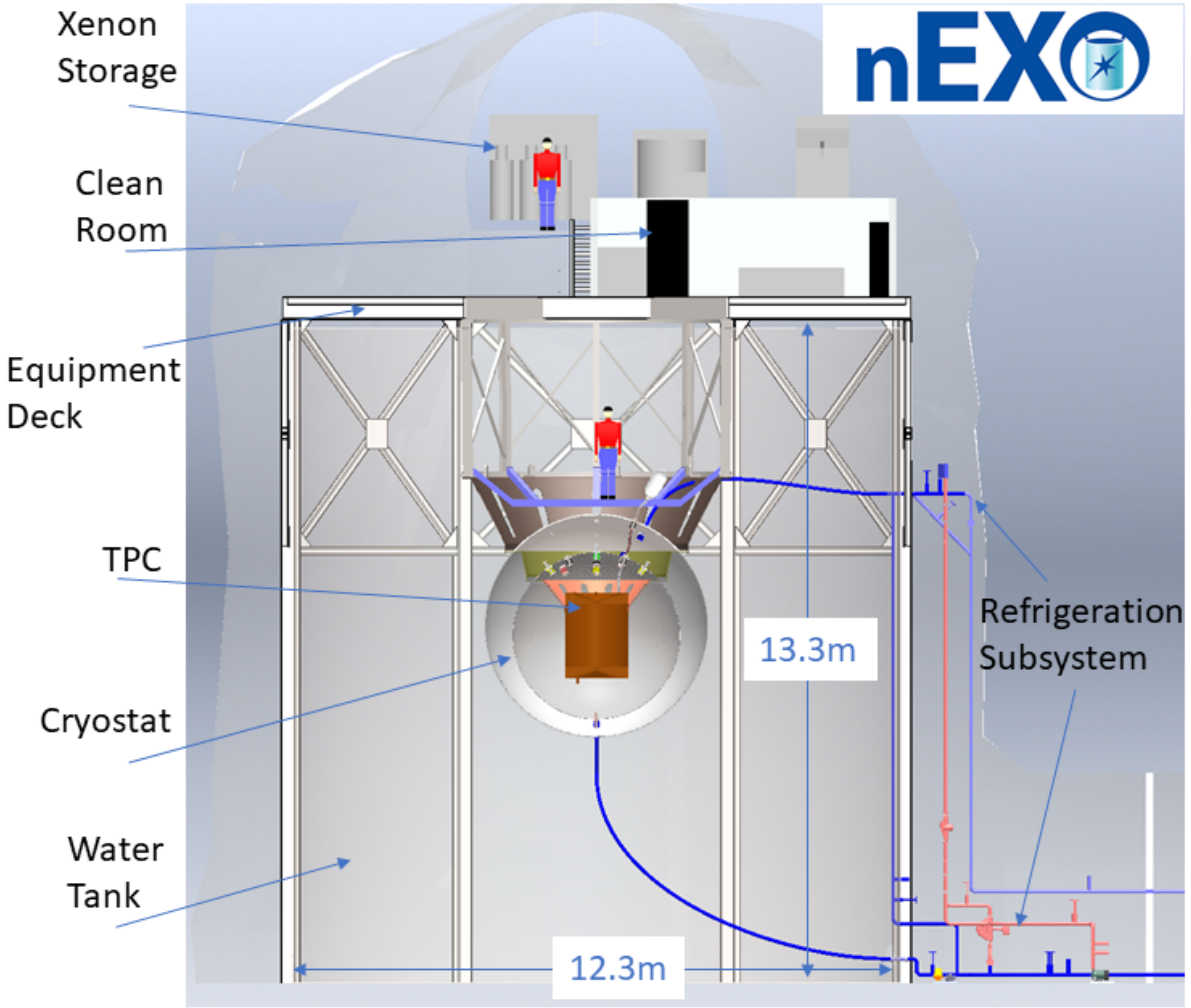


# The nEXO TPC

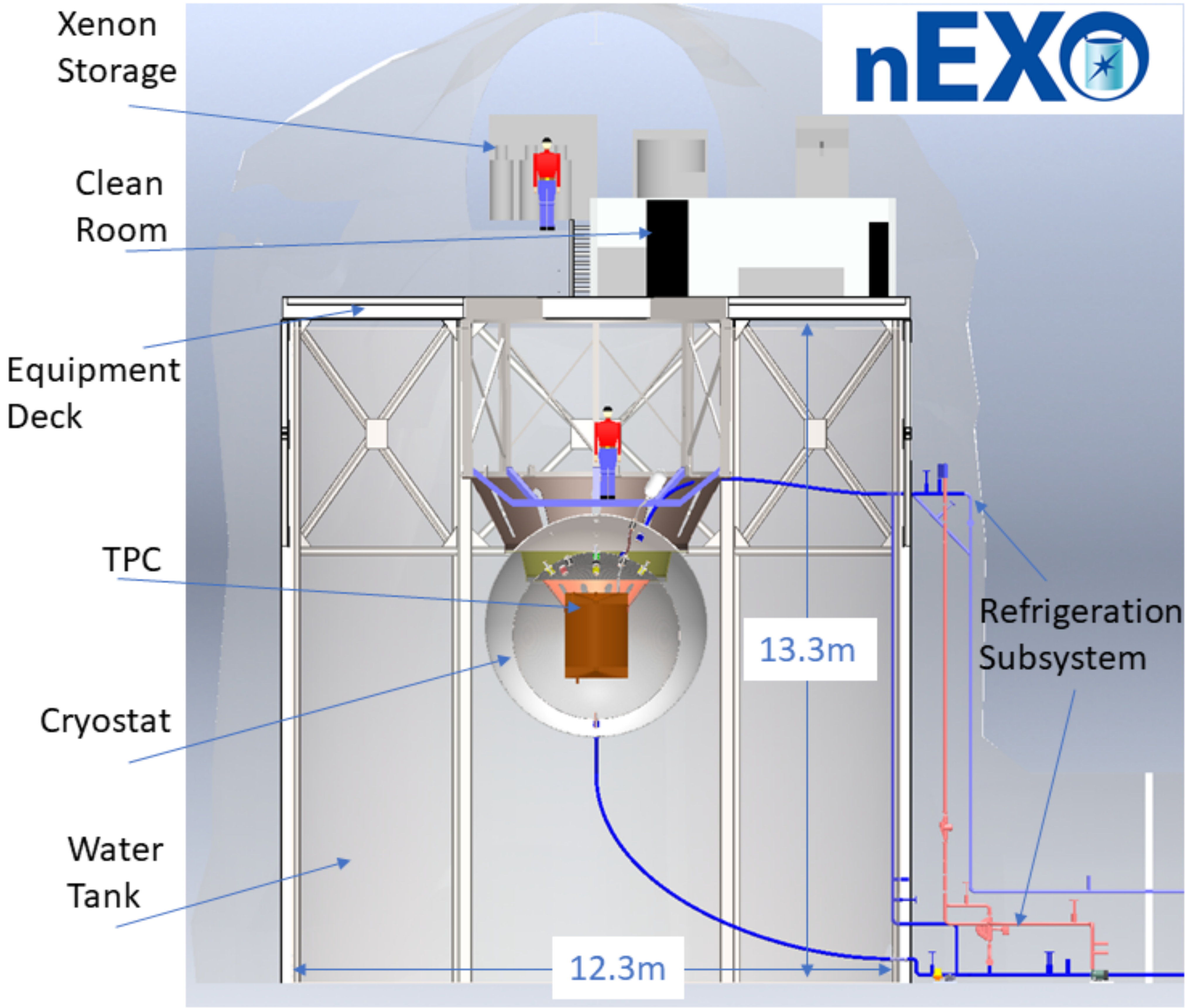
- Next generation 0νββ detector
- 5 t liquid Xenon TPC,  28x EXO-200 volume
- SiPM for 175nm scintillation light detection, ~4.5 m$^2$ array in LXe
- Tiles for charge read out in LXe
- In-cold electronics inside TPC in liquid Xe
- 3D event reconstruction



# nEXO Layout


nEXO
Xenon Storage
Clean Room
Equipment Deck
TPC
Cryostat
Water Tank
13.3m
12.3m
Refrigeration Subsystem

# nEXO Layout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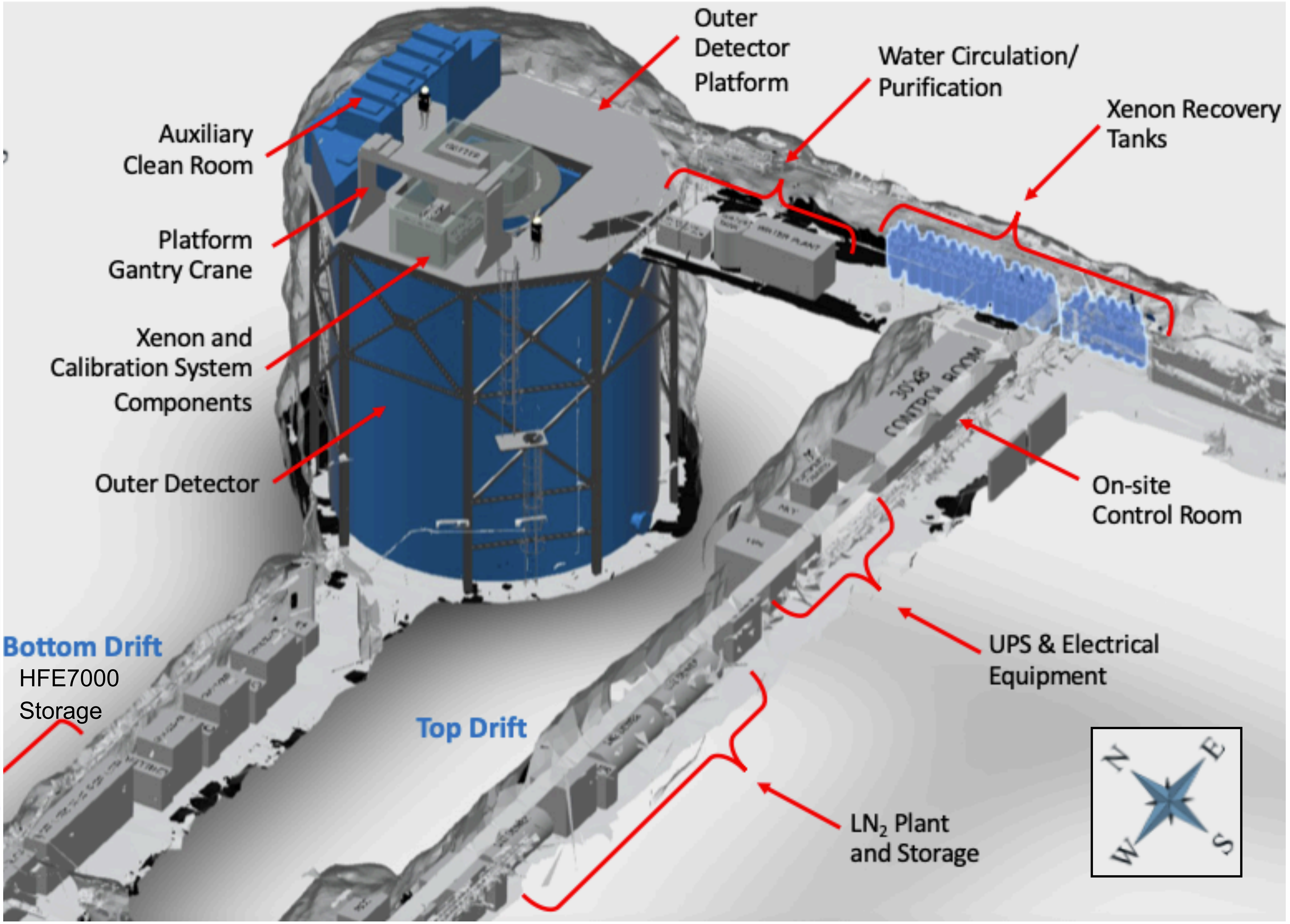
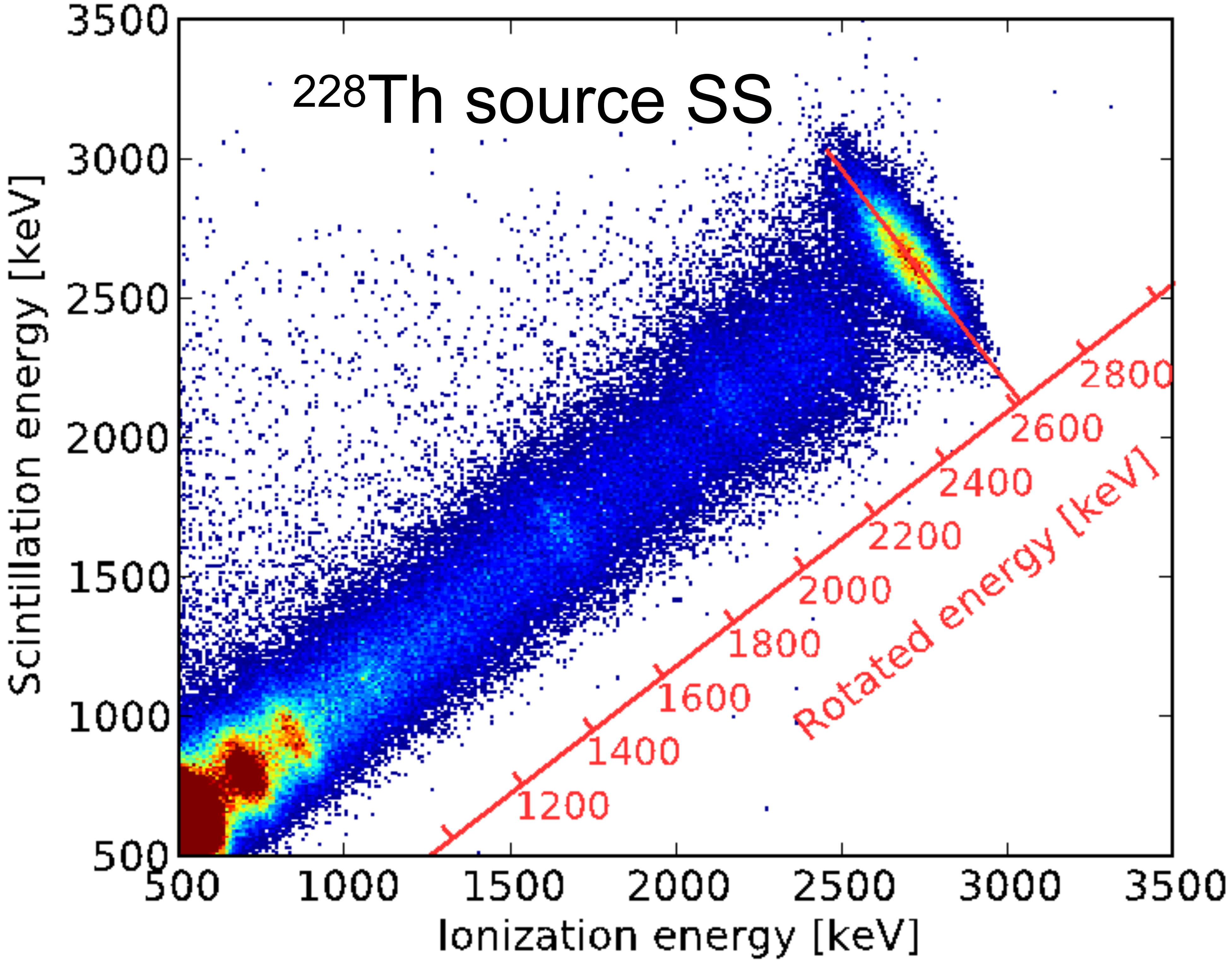

Outer Detector Platform
Water Circulation/ Purification
Xenon Recovery Tanks
Auxiliary Clean Room
Platform Gantry Crane
Xenon and Calibration System Components
Outer Detector
On-site Control Room
UPS & Electrical Equipment
Bottom Drift
HFE7000 Storage
Top Drift
$LN_2$ Plant and Storage
N
E
S
W

# Combining Ionization & Scintillation

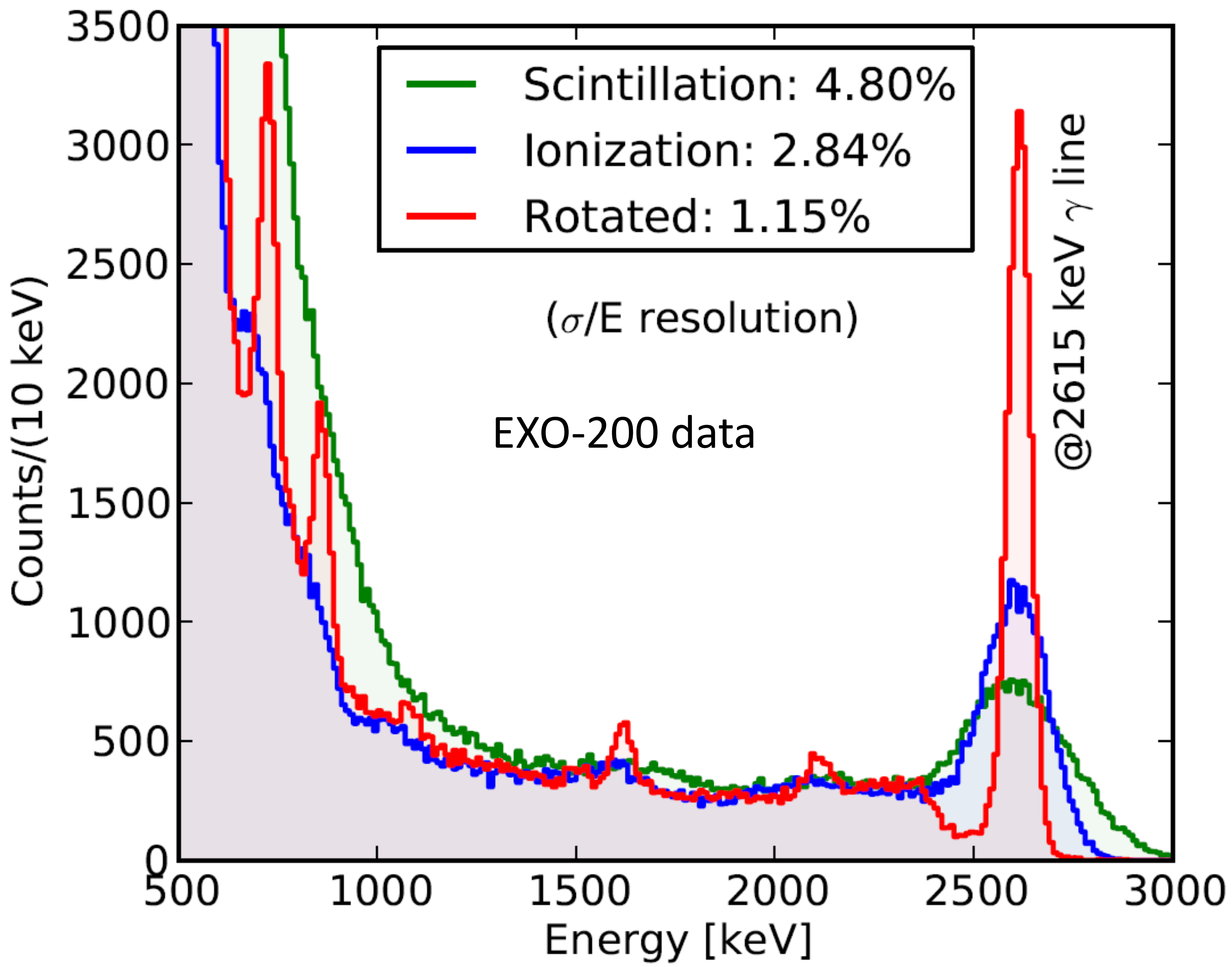
Anti-correlation between scintillation and ionization in LXe known since early EXO R&D *(E.Conti et al. Phys Rev B 68 (2003) 054201)*



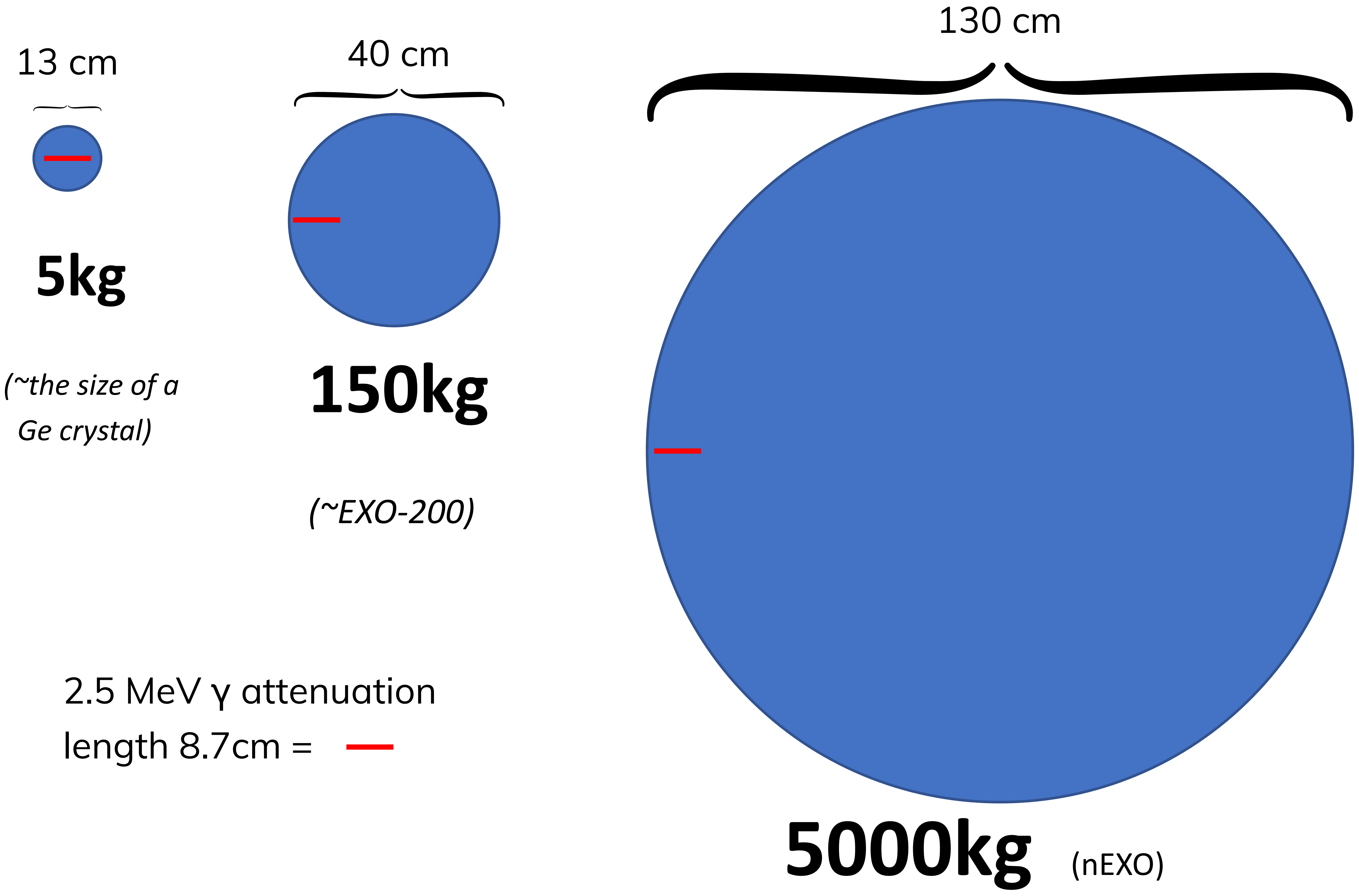
Rotation angle chosen to optimize energy resolution at 2615 keV

nEXO will have a resolution <1% at the Q-value (2458 keV).

The ratio of scintillation to ionization entirely removes α backgrounds.



# nEXO is the best option for a very large detector



13 cm

**5kg**

*(~the size of a Ge crystal)*

40 cm

**150kg**

*(~EXO-200)*

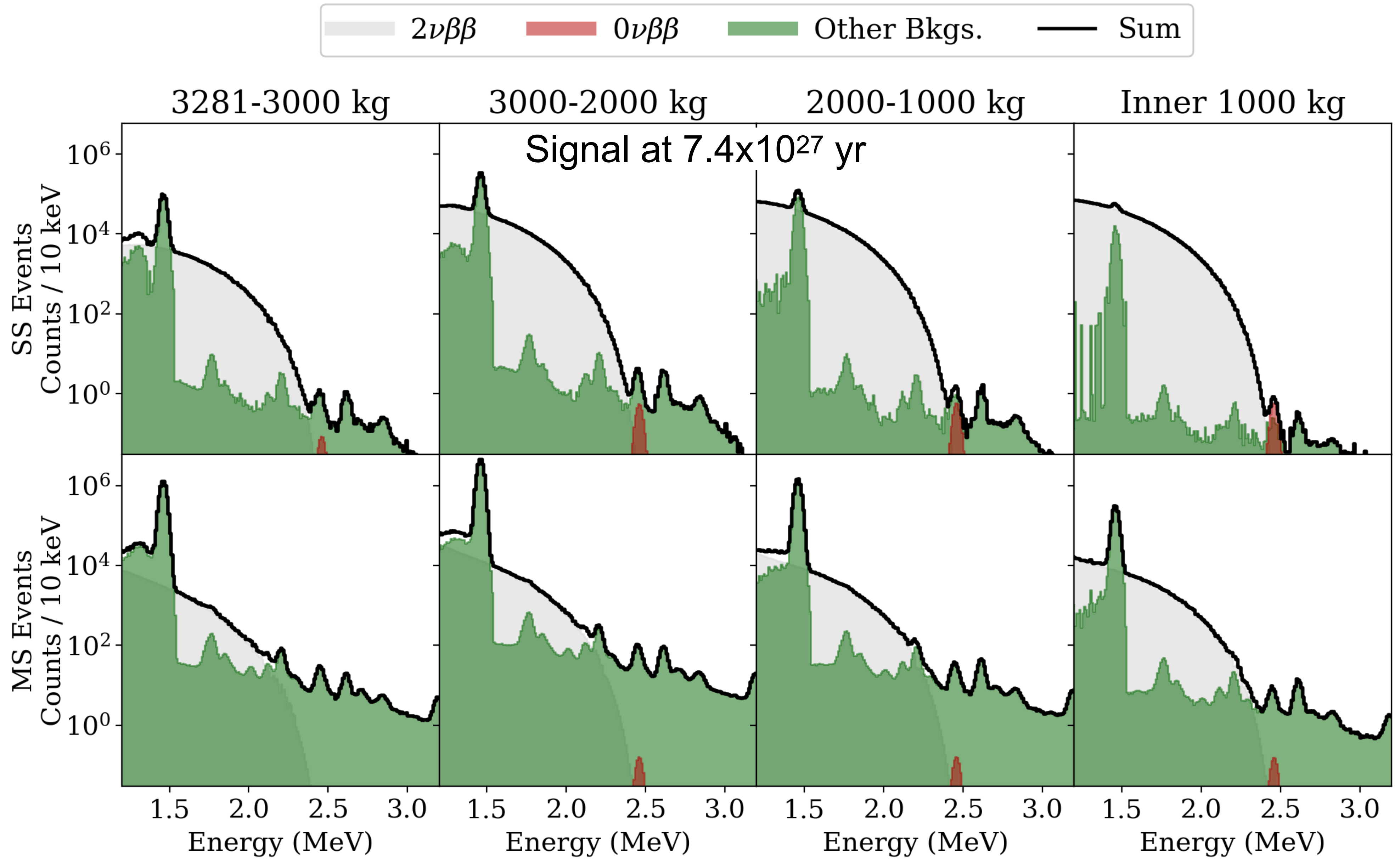
130 cm

**5000kg** (nEXO)

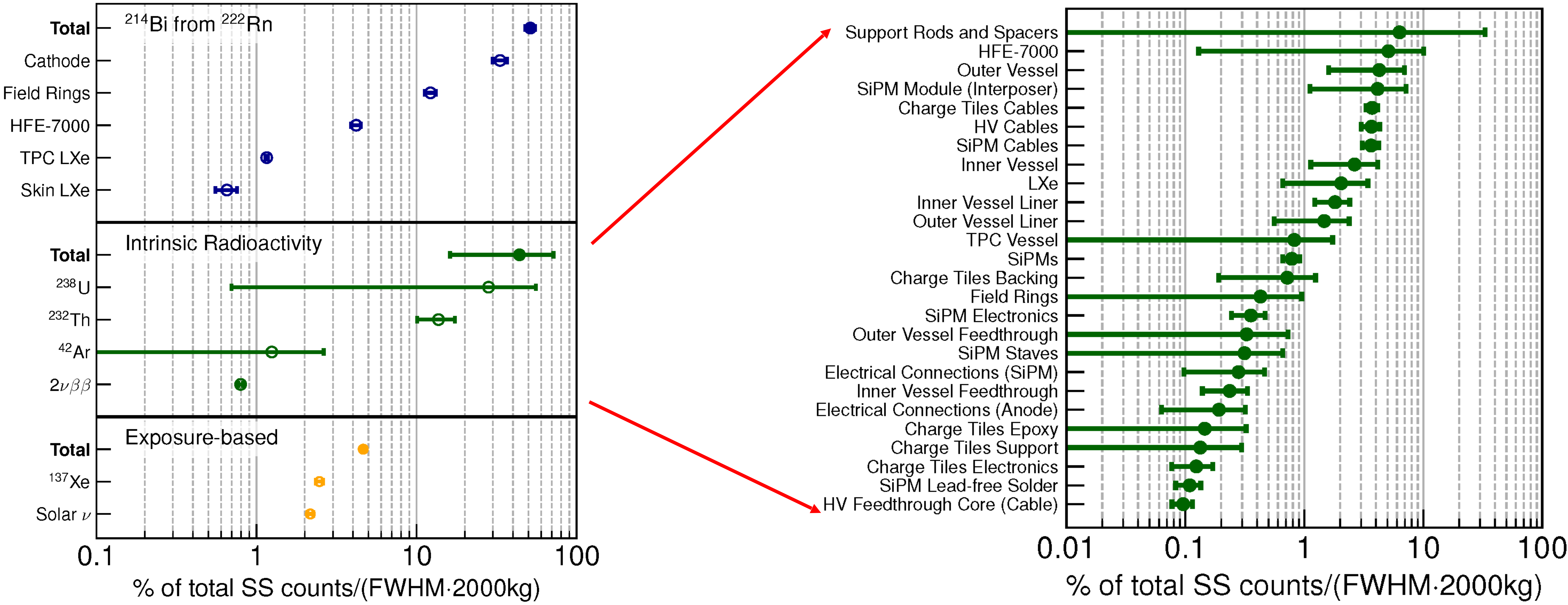
2.5 MeV γ attenuation length 8.7cm = —

The homogeneous detector with advanced topological reconstruction has a proven track record for γ background identification and rejection.

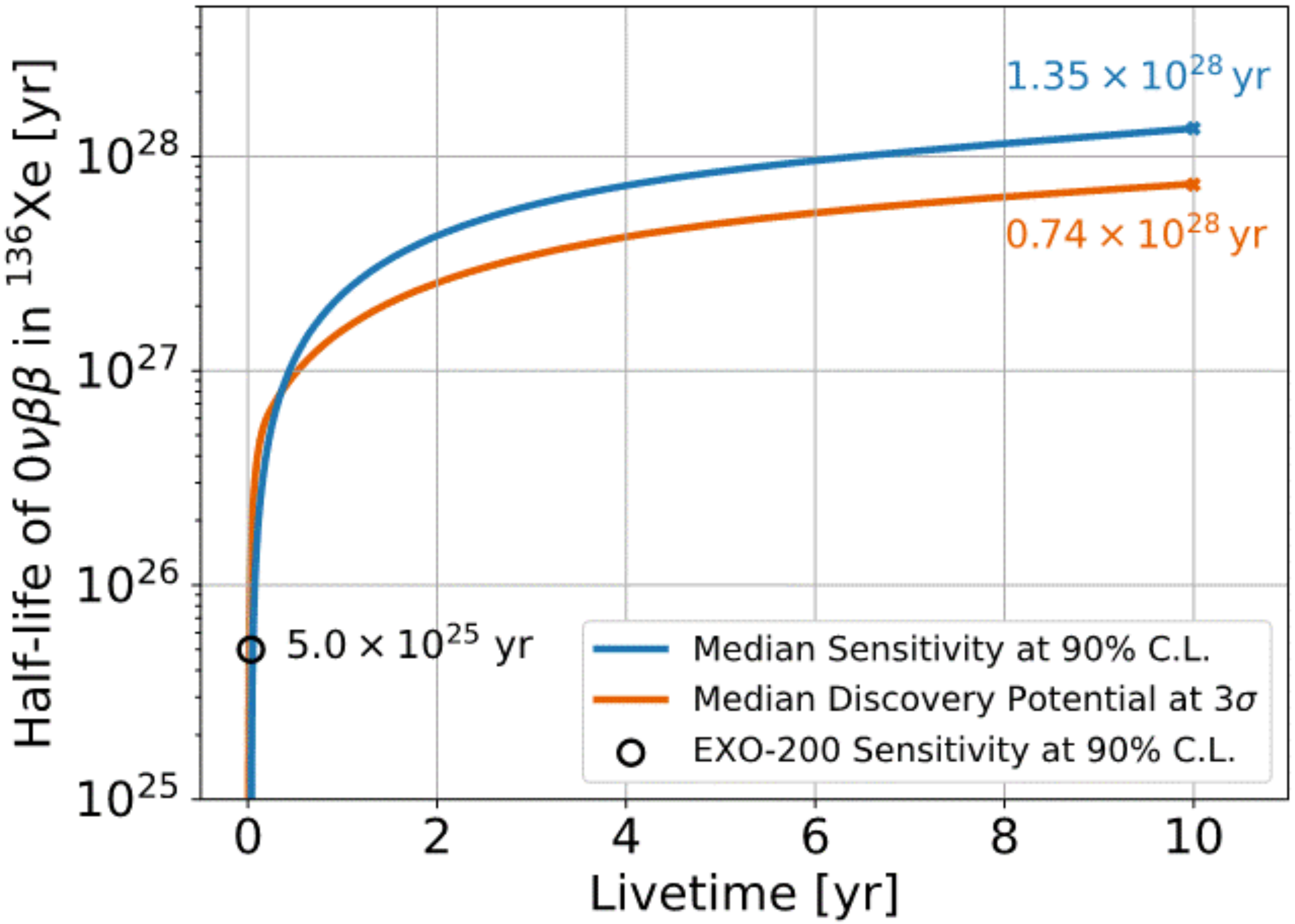
Multi-parameter analysis also makes the measurement robust even for currently unknown backgrounds.

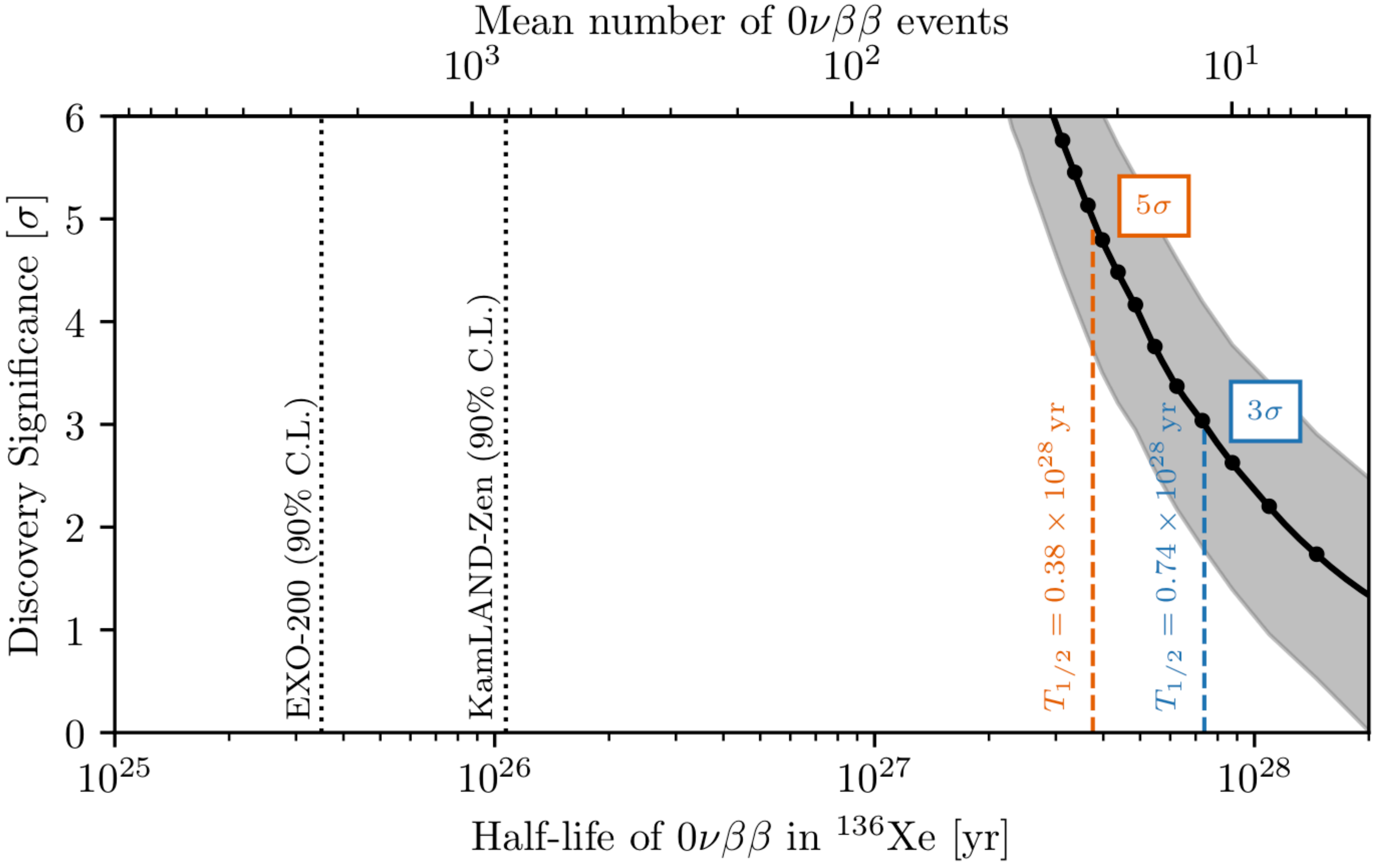


# nEXO is well optimized



# Sensitivity and Discovery Potential





|  | **Limit / Discovery Sensitivity** | **Reference:** |
|---|---|---|
| **EXO-200** | $3.5 \times 10^{25}$ yr (90% CL) | PRL 123, 161802 (2019) |
| **KamLAND-Zen** | $2.3 \times 10^{26}$ yr (90% CL) | arXiv:2203.02139 (2022) |
| **nEXO** | $0.38 \times 10^{28}$ (5)<br>$0.74 \times 10^{28}$ (3) | J. Phys. G: Nucl. Part. Phys. 49 (2022) 015104 |

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

# Physics reach in terms of effective Majorana mass. This is also useful to compare different experiments.

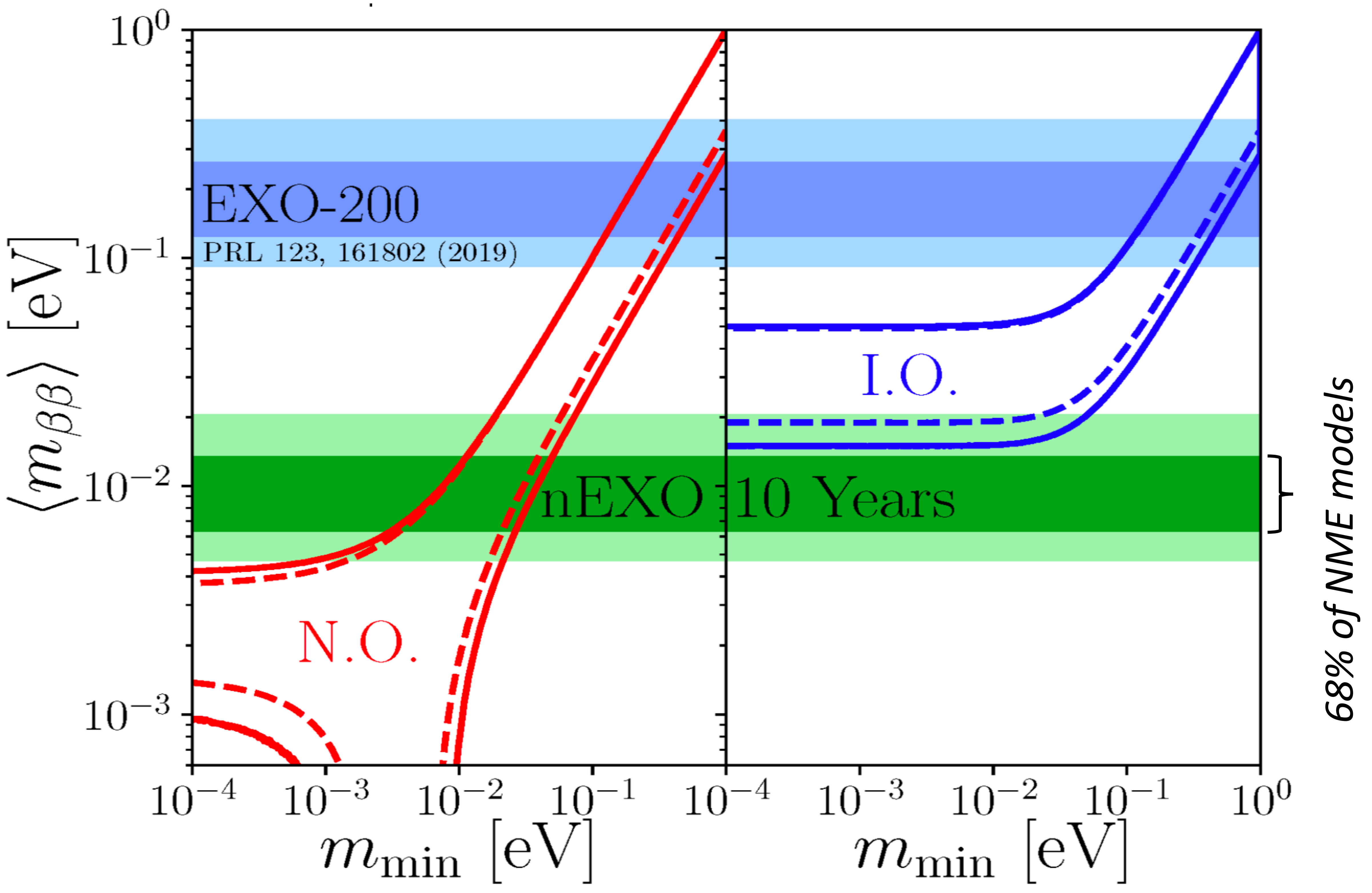
$$\left(T^{0\nu}_{1/2}\right)^{-1} = \frac{\langle m_{\beta\beta}\rangle^2}{m_e^2} G^{0\nu} g_A^4 |M^{0\nu}|^2$$

Phase space factor
*J. Kotila and F. Iachello,*
*Phys Rev C 85, 034316 (2012)*

Axial coupling, $g_A$ = 1.27

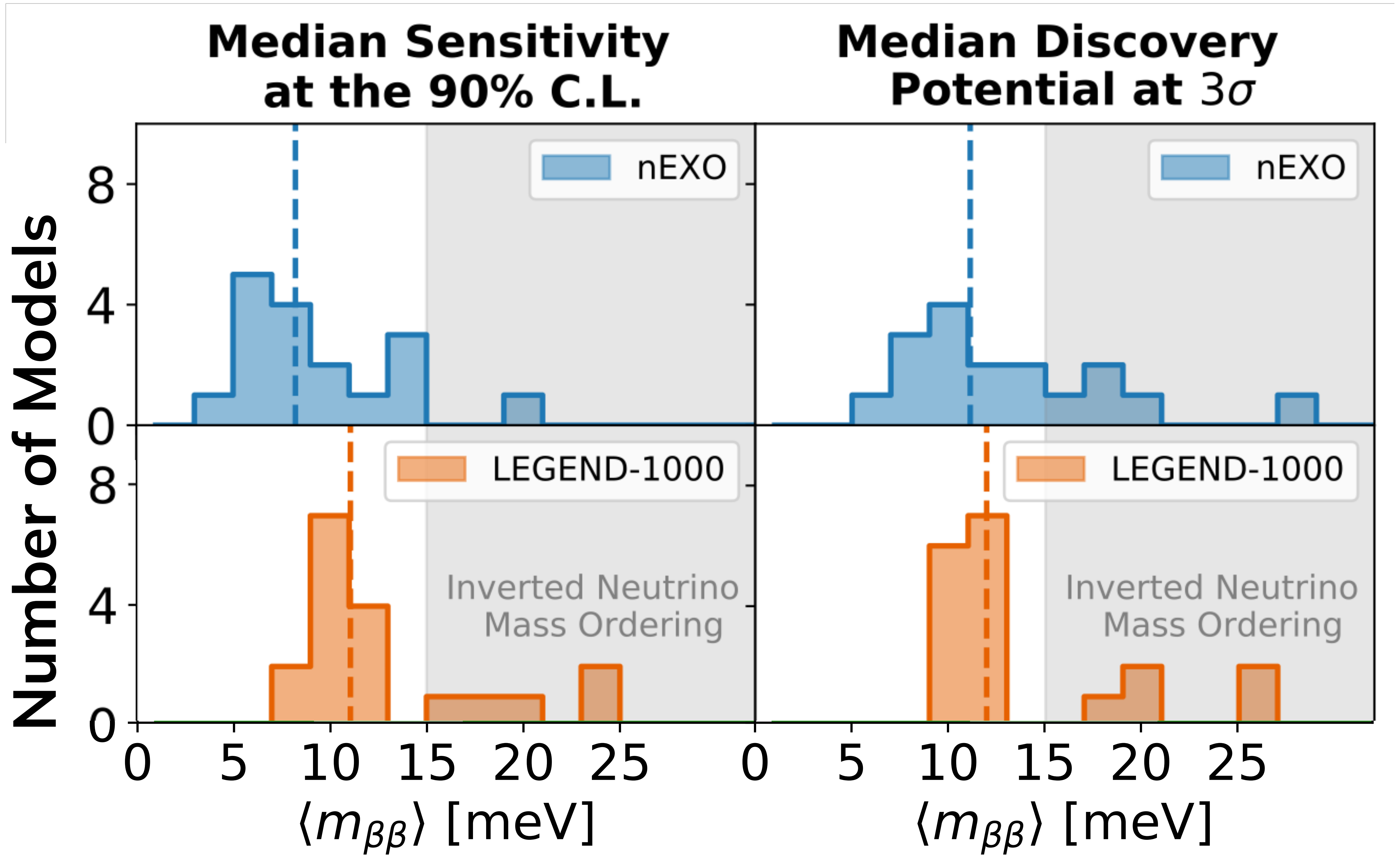
- $^{136}$Xe benefits from larger $G^{0\nu}$ than lighter isotopes ($G^{0\nu}$ is known precisely)
- Significant theoretical uncertainty in NMEs
    - ○ Adopt agnostic approach considering all published NMEs not directly superseded by later publications
    - ○ Conclusions not qualitatively changed if *all* published NMEs are considered

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



# Summary

- A solid international 0νββ program explores at least two different isotopes.
- LEGEND-1000 and nEXO are next-generation experiments with competitive sensitivities looking for 0νββ in Germanium-76 and Xenon-136.
- Both have established technologies with new features being developed.
- Both are looking to be sited in the SNOLAB Cryopit.



| | [meV], (*median NME*) | |
|---|---|---|
| | *90% excl. sens.* | discov. potential |
| **nEXO** | **8.2** | **11.1** |
| **LEGEND** | **11.1** | **12.0** |

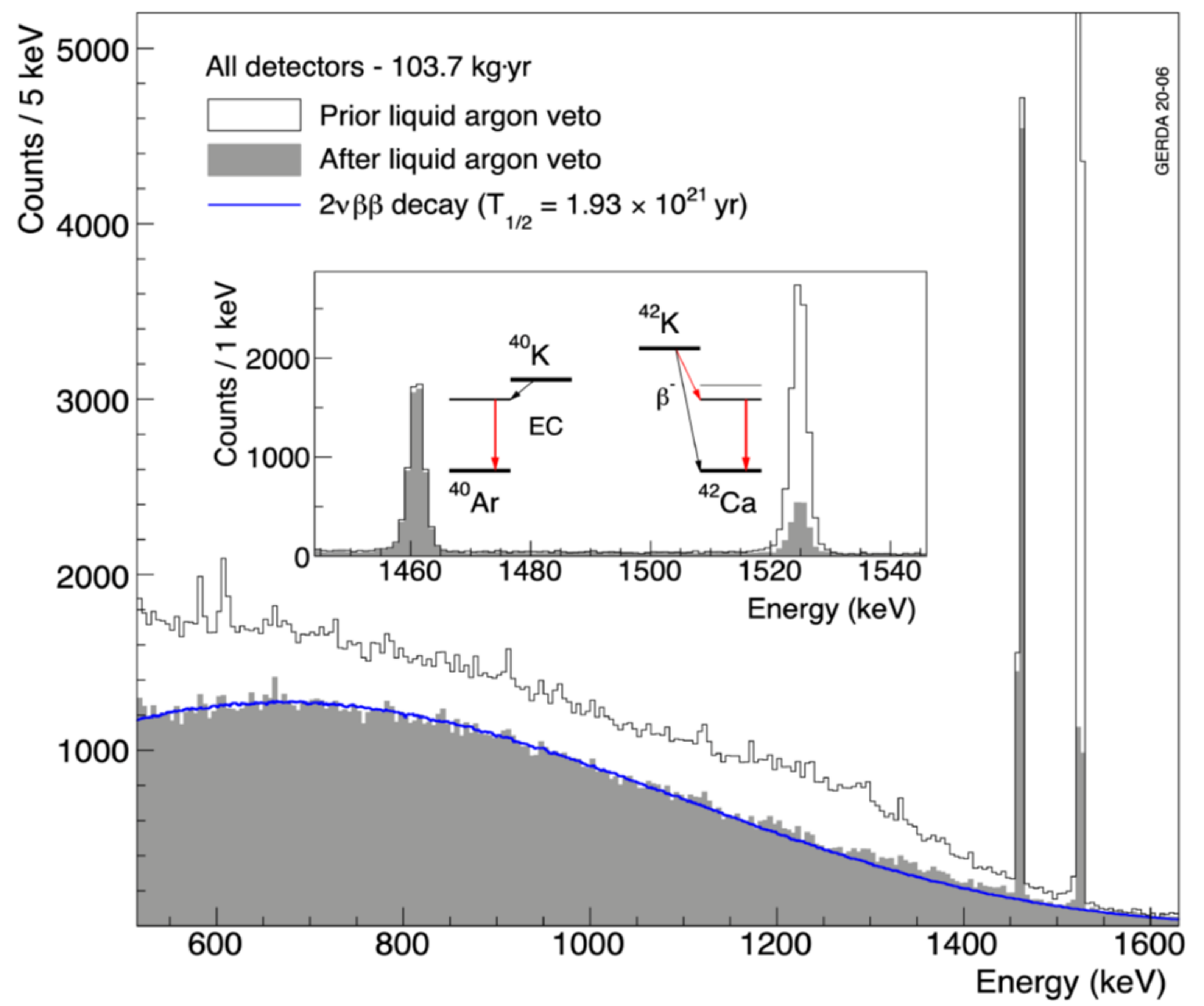
# LEGEND Overview and Status

- Prepared by R. Martin (Queen's U.) to be given by E. Caden (SNOLAB) during **IPP (Institute of Particle Physics) 50th anniversary symposium**, 28-29 May 2022.
- Will be integrated into a 20min presentation of nEXO+LEGEND

https://indico.cern.ch/event/1077282/

# LEGEND Technology – Liquid argon

- GERDA pioneered the use of liquid argon as:
  - Cooling medium
  - Shielding
  - Active veto
- $^{42}$Ar is a background of concern (the subsequent decay of $^{42}$K has a Q-value of 3.5 MeV)
- Reduction in $^{42}$Ar by procuring “Underground Liquid Argon”, UGLAr
- $^{42}$Ar is cosmogenically produced, much like $^{39}$Ar which is of interest to the dark matter community
- DarkSide-20k is developing a plant to extract underground argon from Colorado and purify it in Italy, at 90 tonnes/year → after 1 year (~2025), can easily produce ~20 tonnes required for L-1000 (to fill the re-entrant tubes)
- Reduction of order 1400x for $^{39}$Ar



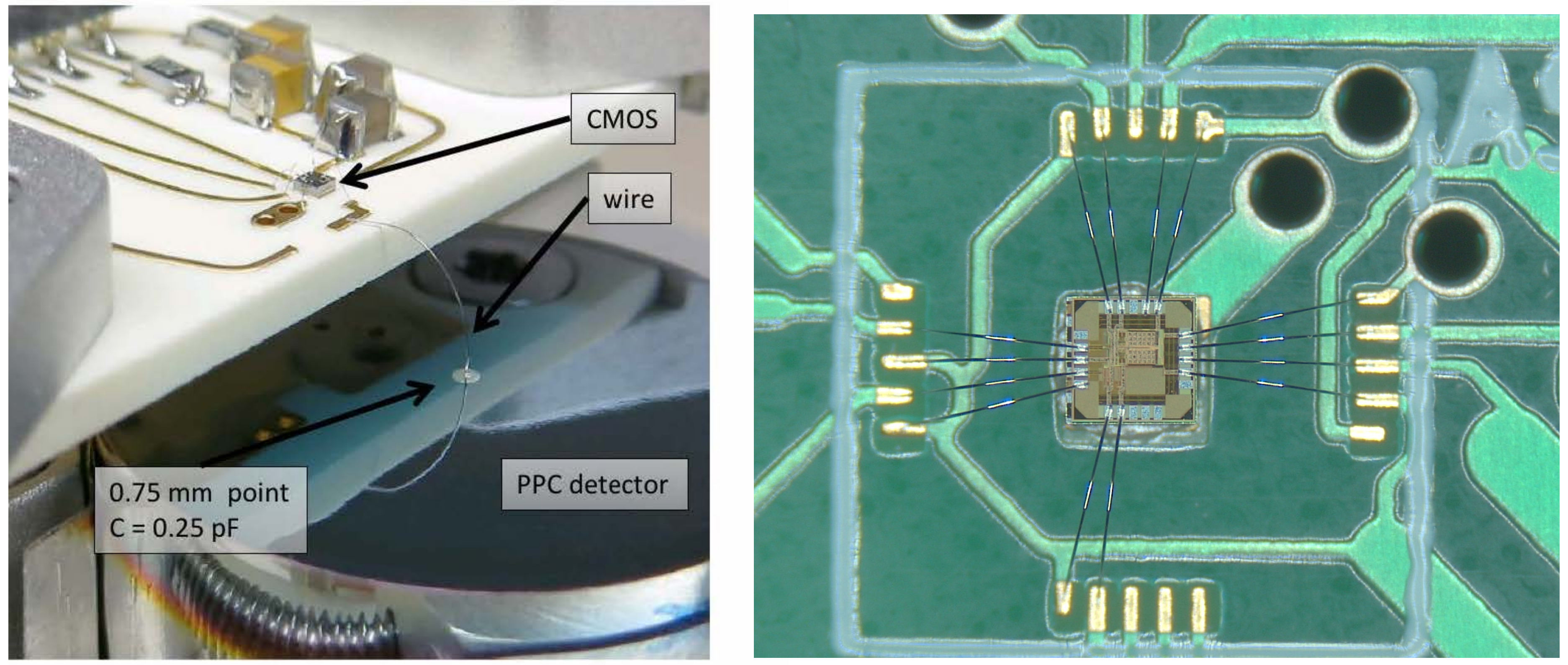
*The blue line is the 2nbb rate assumed from detector mass, it’s not a fit!*

# LEGEND Technology – ASIC electronics

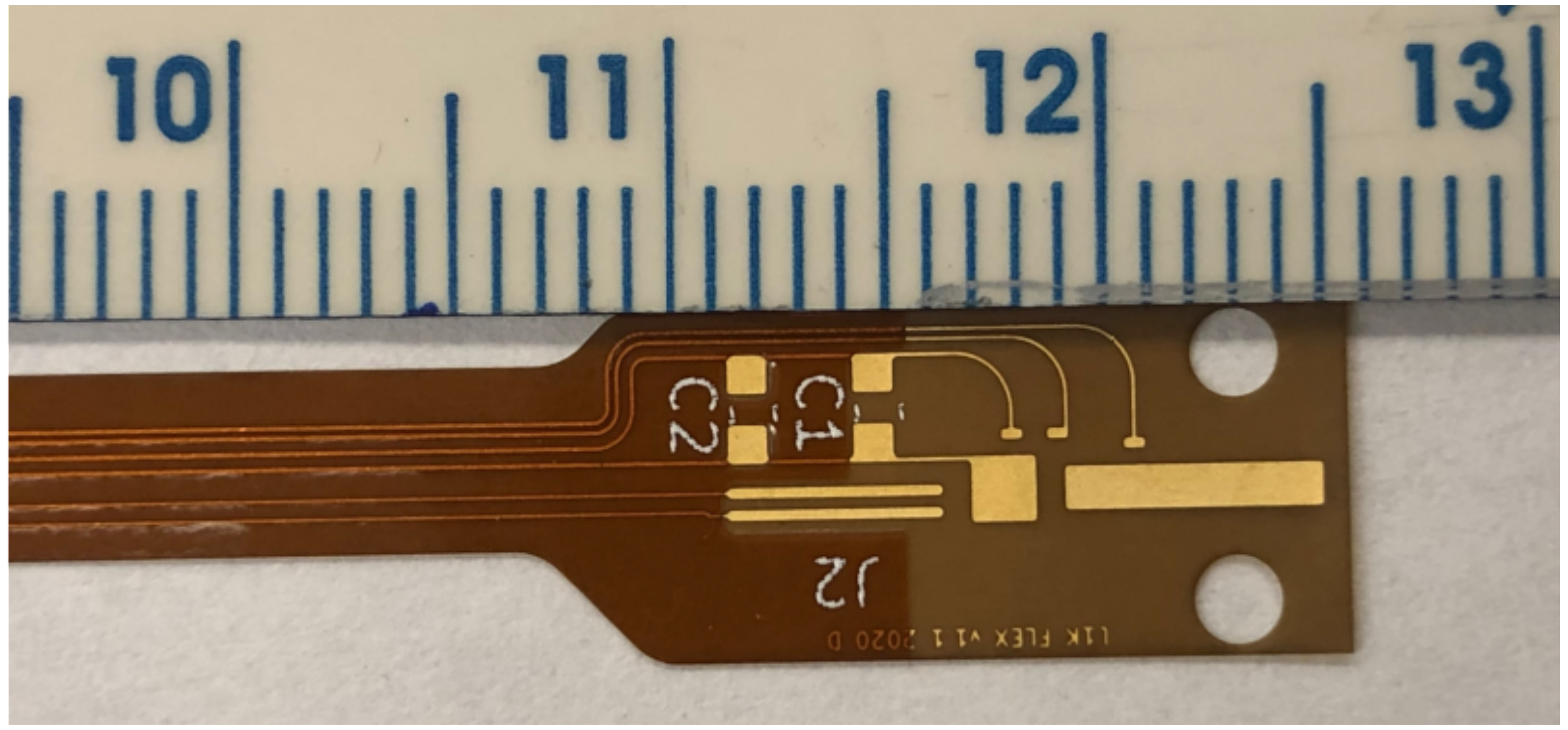
Application Specific Integrated Circuits:

- Low-mass electronics, a whole CSP in a cubic mm!
- Collaboration has tested the CUBE ASIC fabricated by XGLab
- Collaboration developing the L1K ASIC specifically for L-1000 to be tailored to the ICPC detectors
- Integrate ASIC directly onto low-background flex cable and wire-bond to the detectors
- Initial testing indicates excellent performance with ASICs (noise, energy resolution, pulse shape discrimination)

P.Barton et. al., NIMA **812** p.17 (2016)



*Example of CUBE ASIC mounted on PC detector*

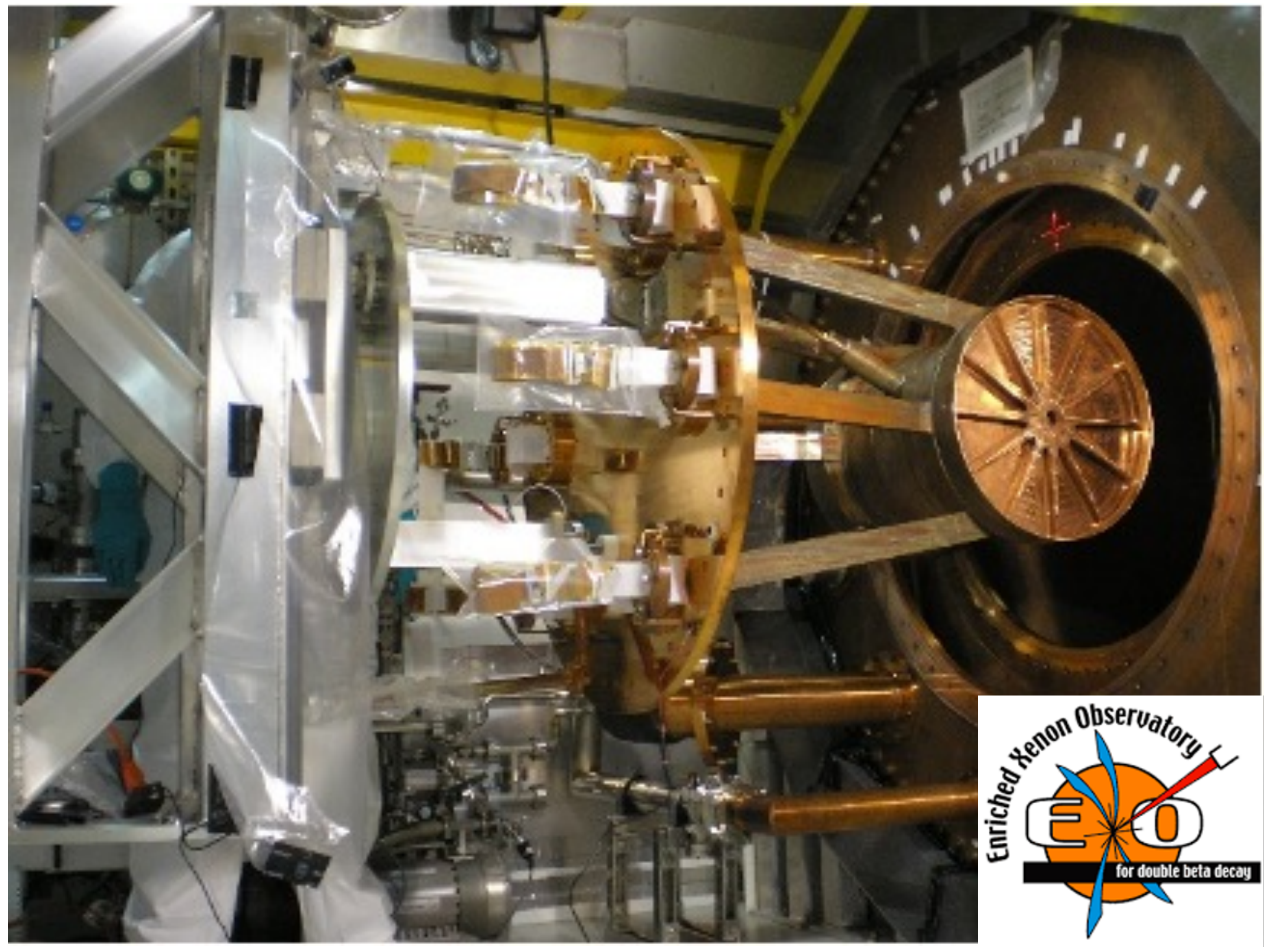


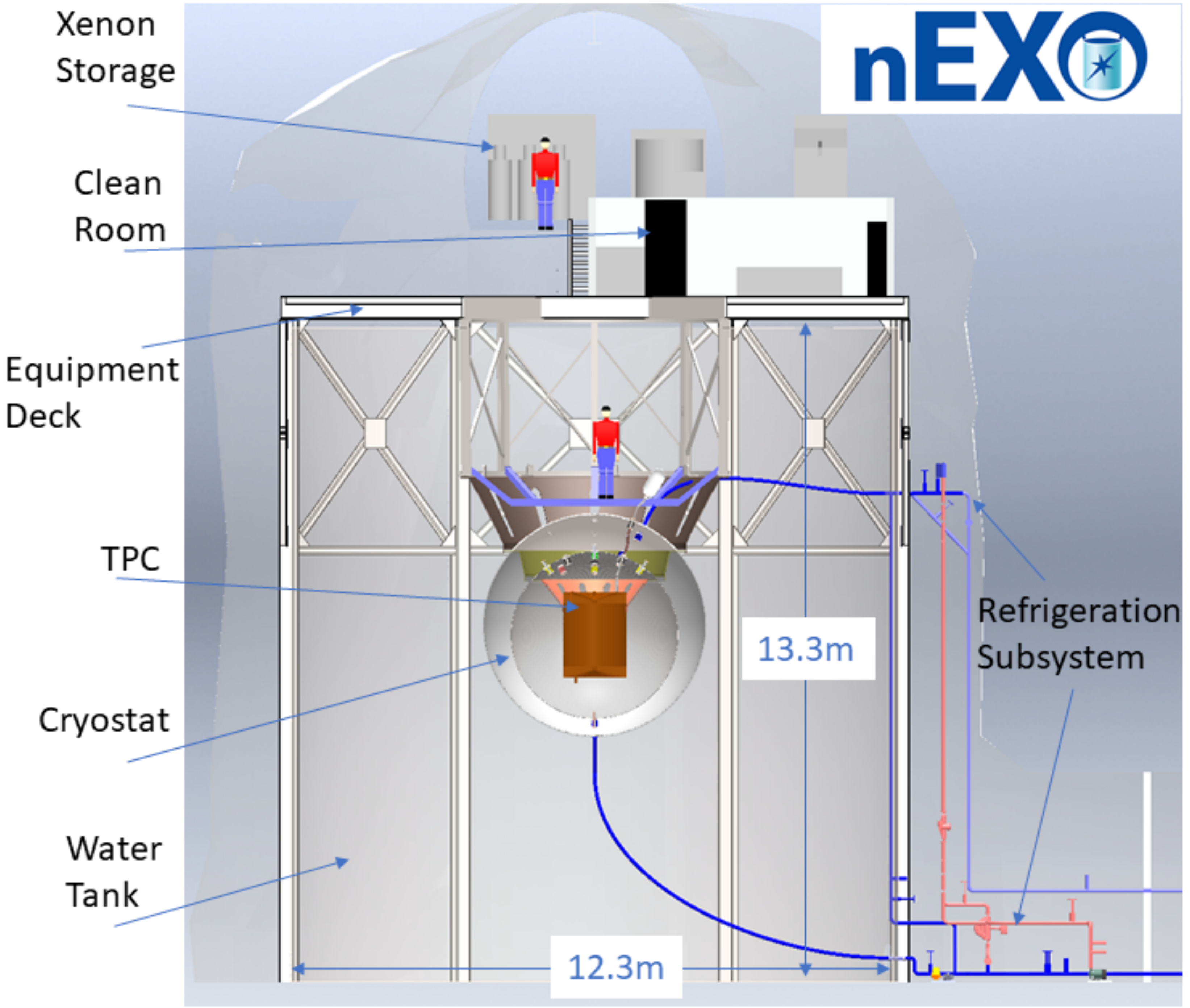
*Kapton flex-caple designed to hold ASIC*

# Searching for 0νββ in $^{136}$Xe with liquid Xe TPC

**EXO-200:**

- EXO-200 First 100-kg class ββ experiment
- 175 kg liquid-Xe TPC with ~80% $^{136}$Xe
- WIPP Mine in NM, USA
- Decommissioned in Dec 2018
- End-of-run Calibration campaign informs nEXO Design





nEXO:

- Next-generation liquid-Xe TPC
- 5-tonne enriched in $^{136}$Xe at ~90%
- Designed to go beyond $T_{1/2}$~$10^{28}$ years
- Preferred location: SNOLAB Cryopit
- Design of detector and components are advanced
- DOE Decision on funding 0νββ projects anticipated this year

# Physics reach in terms of effective Majorana mass. This is also useful to compare different experiments.

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

Text

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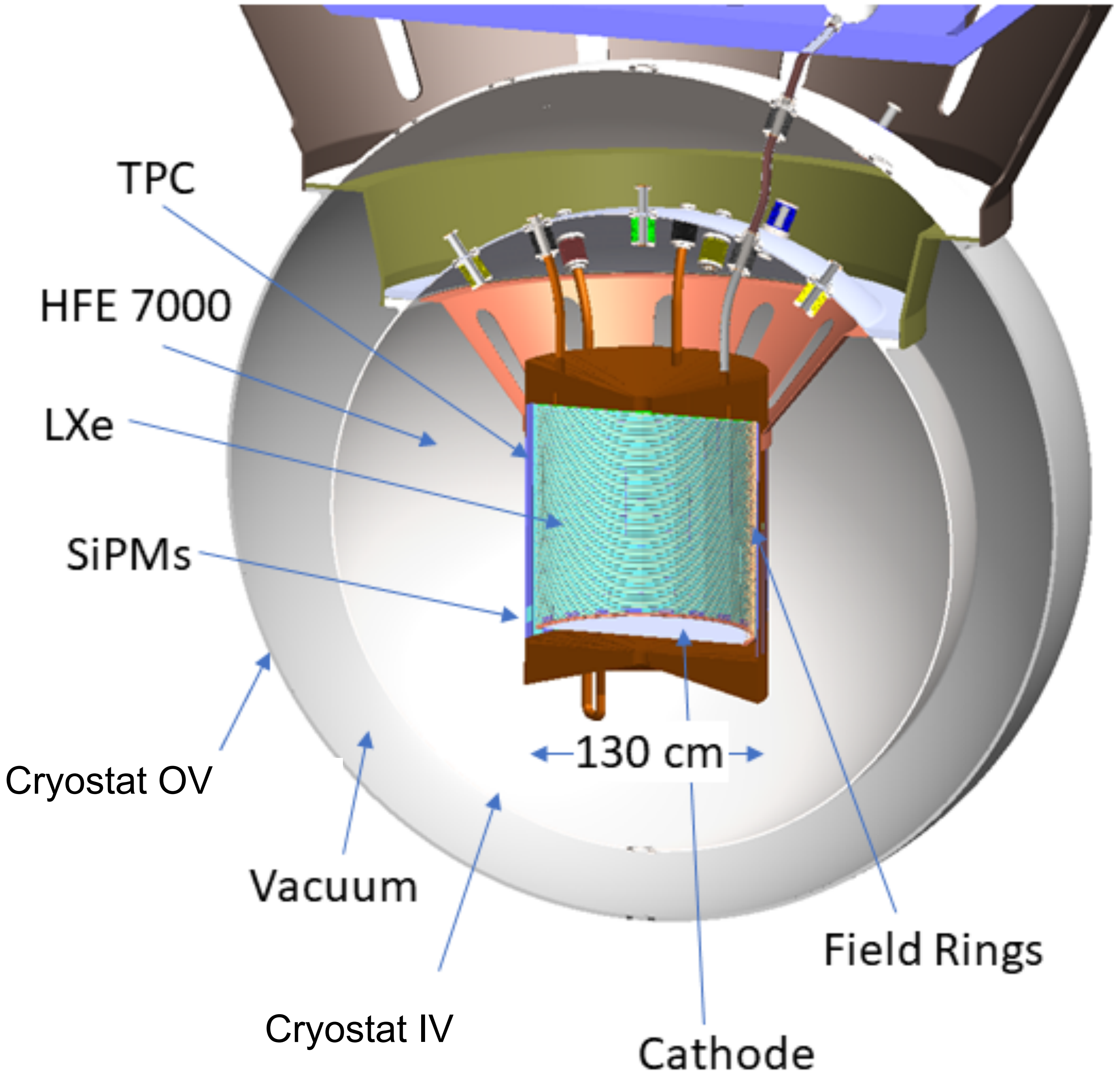
  - Conclusions not qualitatively changed if *all* published NMEs are considered

References for the NMEs used

| Method | Year | Citation |
|---|---|---|
| IBM | 2015 | PRC 91 034304 (2015) |
| NSM | 2008 | PRL 100, 052503 (2008) |
| IBM | 2020 | PRD 102, 095016 (2020) |
| QRPA | 2014 | PRC 89, 064308 (2014) |
| NSM | 2016 | PRC 93, 024308 (2016) |
| QRPA | 2015 | PRC 91, 024613 (2015) |
| QRPA | 2018 | PRC 98, 024608 (2018) |
| NSM | 2018 | JPS Conf. Proc. 23, 012036 (2018) |
| QRPA | 2013 | J. High Energ. Phys. 2013, 25 (2013) |
| QRPA | 2013 | PRC 87, 064302 (2013) |
| QRPA | 2013 | PRC 87, 045501 (2013) |
| QRPA | 2018 | PRC 97, 034315 (2018) |
| QRPA | 2010 | Nucl.Phys.A 847 (2010) 207 |
| EDF | 2013 | PRL 111, 142501 (2013) |
| EDF | 2015 | PRC 91, 024316 (2015) |
| QRPA | 2018 | PRC 97, 045503 (2018) |
| EDF | 2017 | PRC 96, 054310 (2017) |
| QRPA | 2015 | PRC 91, 024613 (2015) |
| EDF | 2010 | Prog.Part.Nucl.Phys. 66 (2011) 436 |

# The nEXO detector is an evolution from EXO-200



| | **EXO-200:** | ***nEXO:*** | **Improvements:** |
|---|---|---|---|
| **Vessel and cryostat** | Thin-walled commercia Cu w/HFE | *Thin-walled electroformed Cu w/HFE* | Lower background |
| **High voltage** | Max voltage: 25 kV (end-of-run) | *Operating voltage: 50 kV* | Full scale parts tested in LXe prior to installation to minimize risk |
| **Cables** | Cu clad polyimide (analog) | *Cu clad polyimide (digital)* | Same cable/feedthrough technology, R&D identified 10x lower bkg substrate and demonstrated digital signal transmission |
| **$e^-$ lifetime** | 3-5 ms | *5 ms (req.), 10 ms (goal)* | Minimal plastics (no PTFE reflector), lower surface to volume ratio, detailed materials screening program |
| **Charge collection** | Crossed wires | *Gridless modular tiles* | R&D performed to demonstrate charge collection with tiles in LXe, detailed simulation developed |
| **Light collection** | APDs + PTFE reflector | *SiPMs around TPC barrel* | SiPMs avoid readout noise, R&D demonstrated prototypes from two vendors |
| **Energy resolution** | 1.2% | *1.2% (req.), 0.8% (goal)* | Improved resolution due to SiPMs (negligible readout noise in light channels) |
| **Electronics** | Conventional room temp. | *In LXe ASIC-based design* | Minimize readout noise for light and charge channels, nEXO prototypes demonstrated in R&D and follow from LAr TPC lineage |
| **Background control** | Measurement of all materials | *Measurement of all materials* | RBC program follows successful strategy demonstrated in EXO-200 |
| **Larger size** | >2 atten. length at center | *>7 atten. length at center* | Exponential attenuation of external gammas and more fully contained Comptons |

# At the core of the TPC are Light and Charge collection devices