

# LEGEND-1000:

## A Ton-Scale Search for Neutrinoless Double-Beta Decay in $^{76}\text{Ge}$

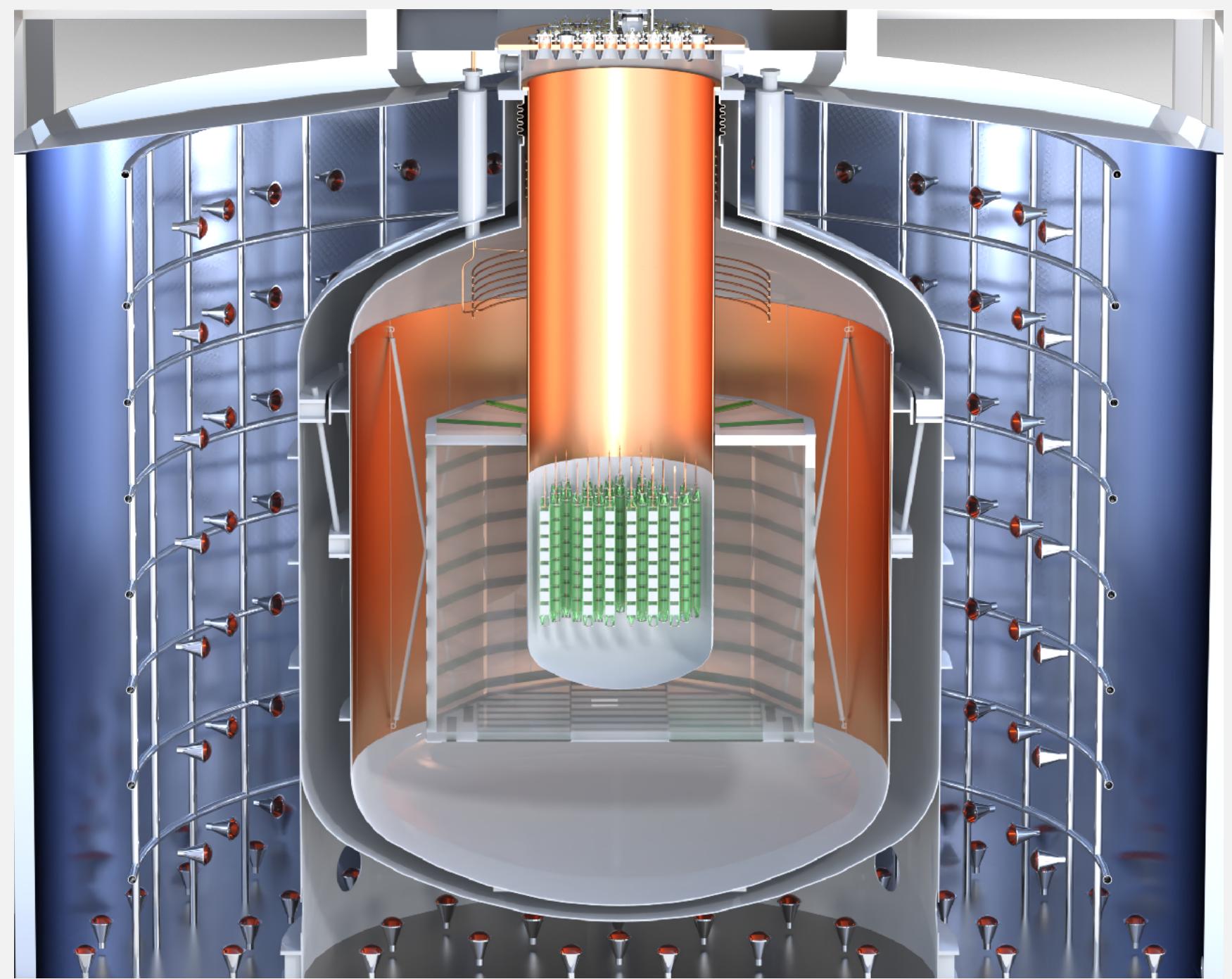
Vincente Guiseppe  
On behalf of the LEGEND Collaboration

30 August 2023



LEGEND

Large Enriched  
Germanium Experiment  
for Neutrinoless  $\beta\beta$  Decay



OAK RIDGE  
National Laboratory

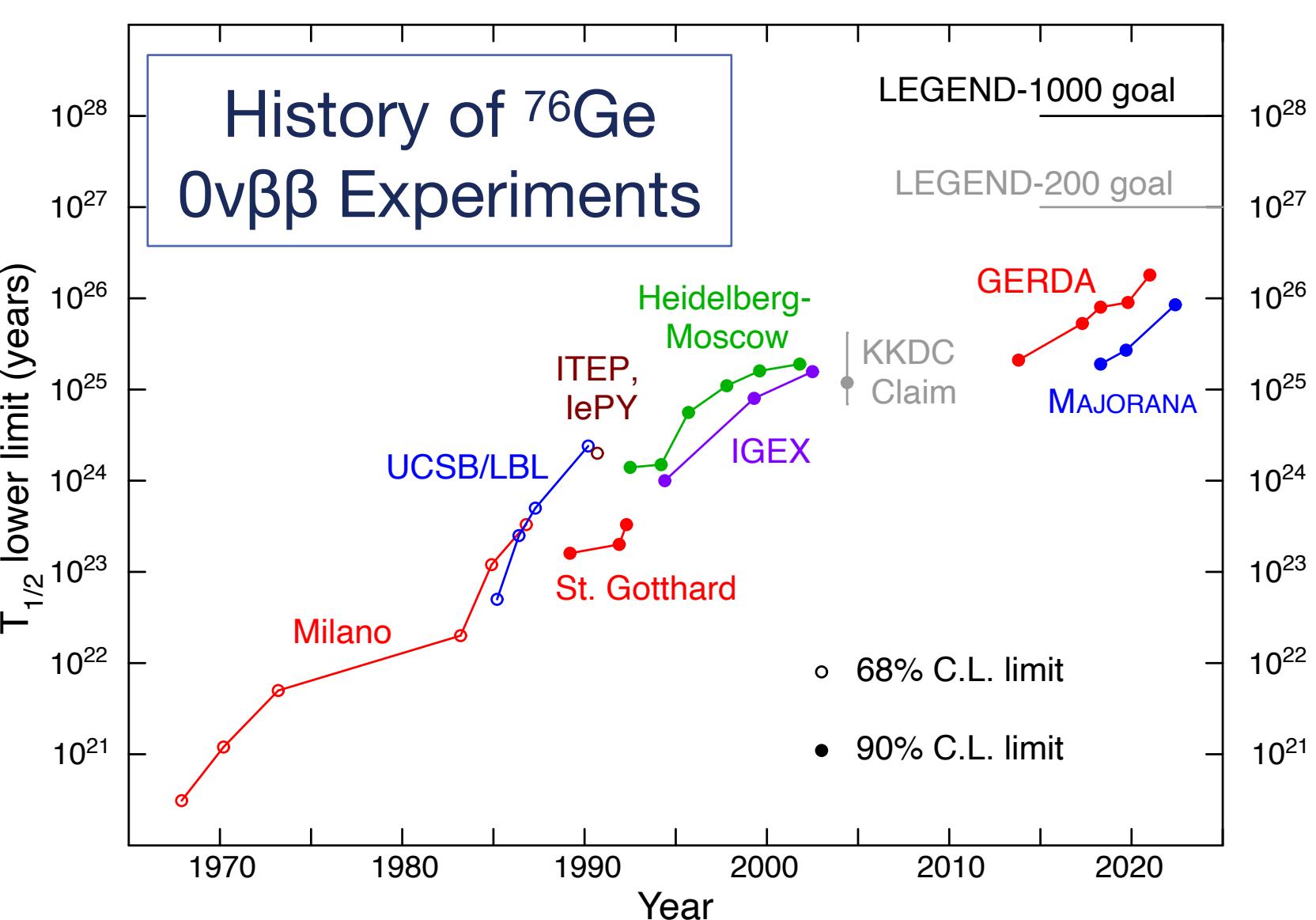
U.S. DEPARTMENT OF  
**ENERGY**

# The LEGEND Program

LEGEND



270 members, 55 institutions, 12 countries



- The LEGEND collaboration combines the innovations of the MAJORANA and GERDA collaborations, with additional institutions
- A phased,  $^{76}\text{Ge}$ -based double-beta decay program with discovery potential at a half-life beyond  $10^{28}$  yr
- Strengths of  $^{76}\text{Ge}$  experiments:
  - ✓ Superb energy resolution: 0.1% FWHM @  $Q_{\beta\beta}$
  - ✓ Discrimination of backgrounds via multivariate event topology
  - ✓ The background is flat, well understood, and does not require modeling
  - ✓ Lowest background rate per FWHM of all previous experiments



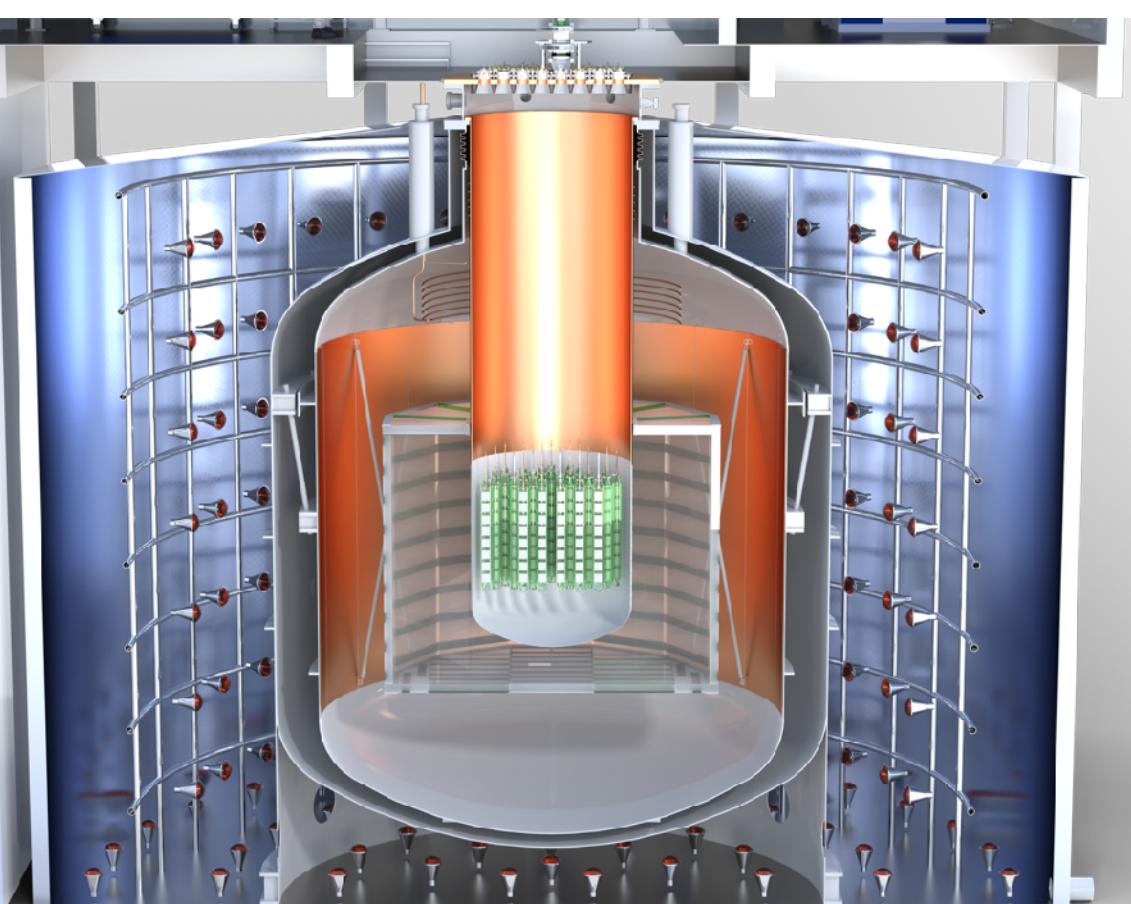
LEGEND-200 @LNGS

[LEGEND-200: First glance at the background in physics data](#)

Katharina von Sturm

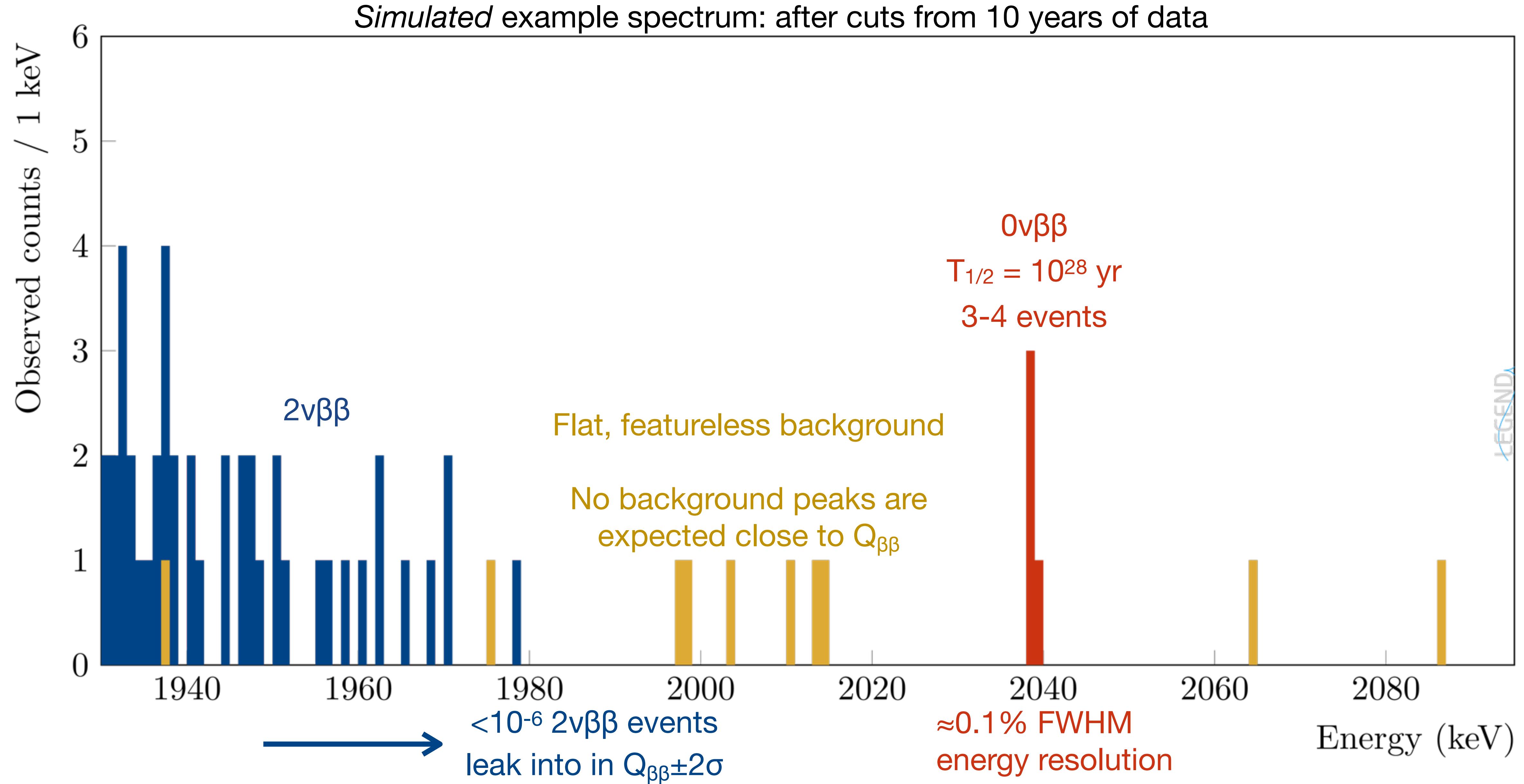
[LEGEND-200: From Construction to Physics Data Taking](#)

Michael Willers



LEGEND-1000

# LEGEND-1000: Designed for an Unambiguous Discovery



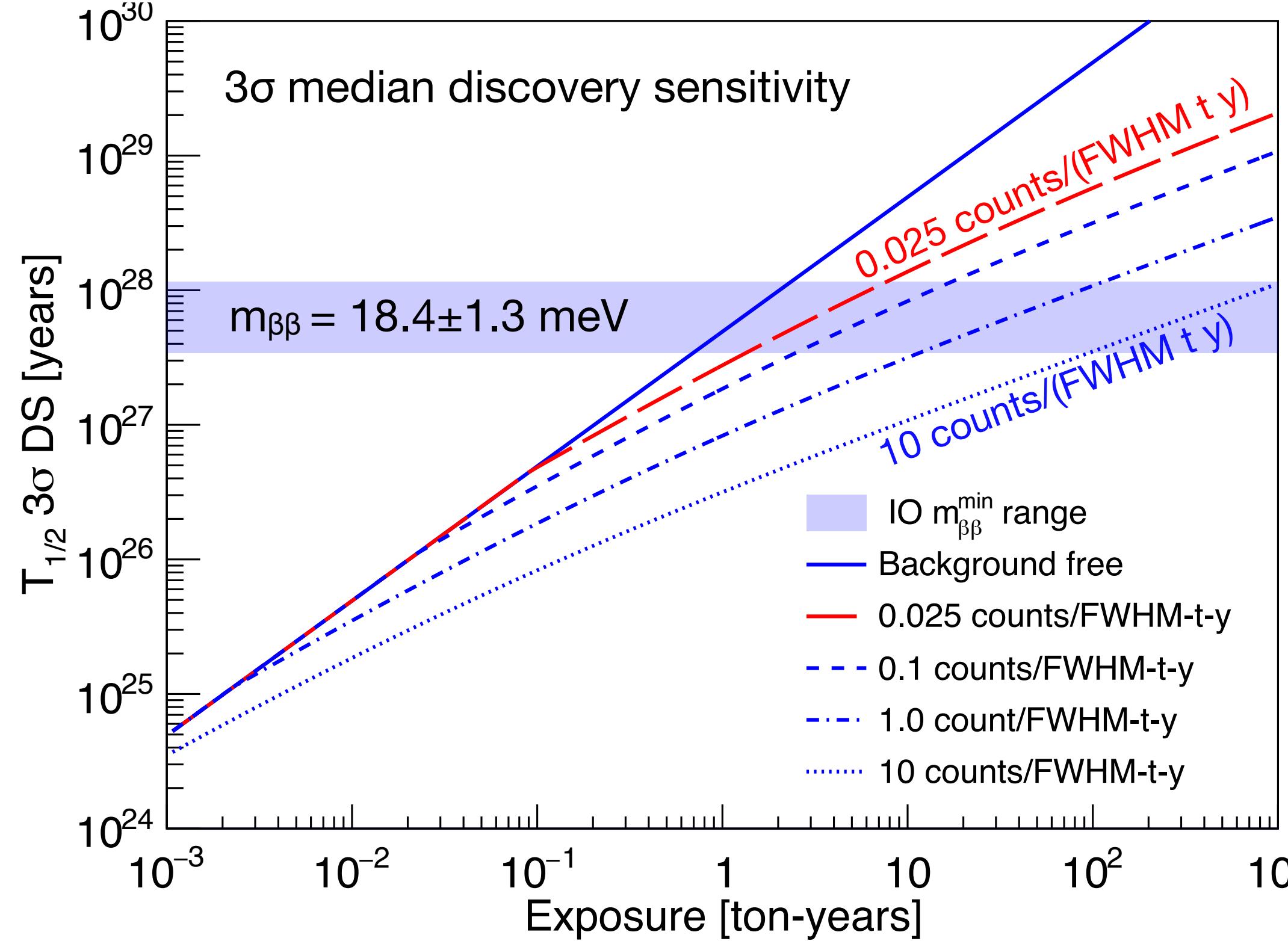
# LEGEND-1000 Sensitivity

LEGEND

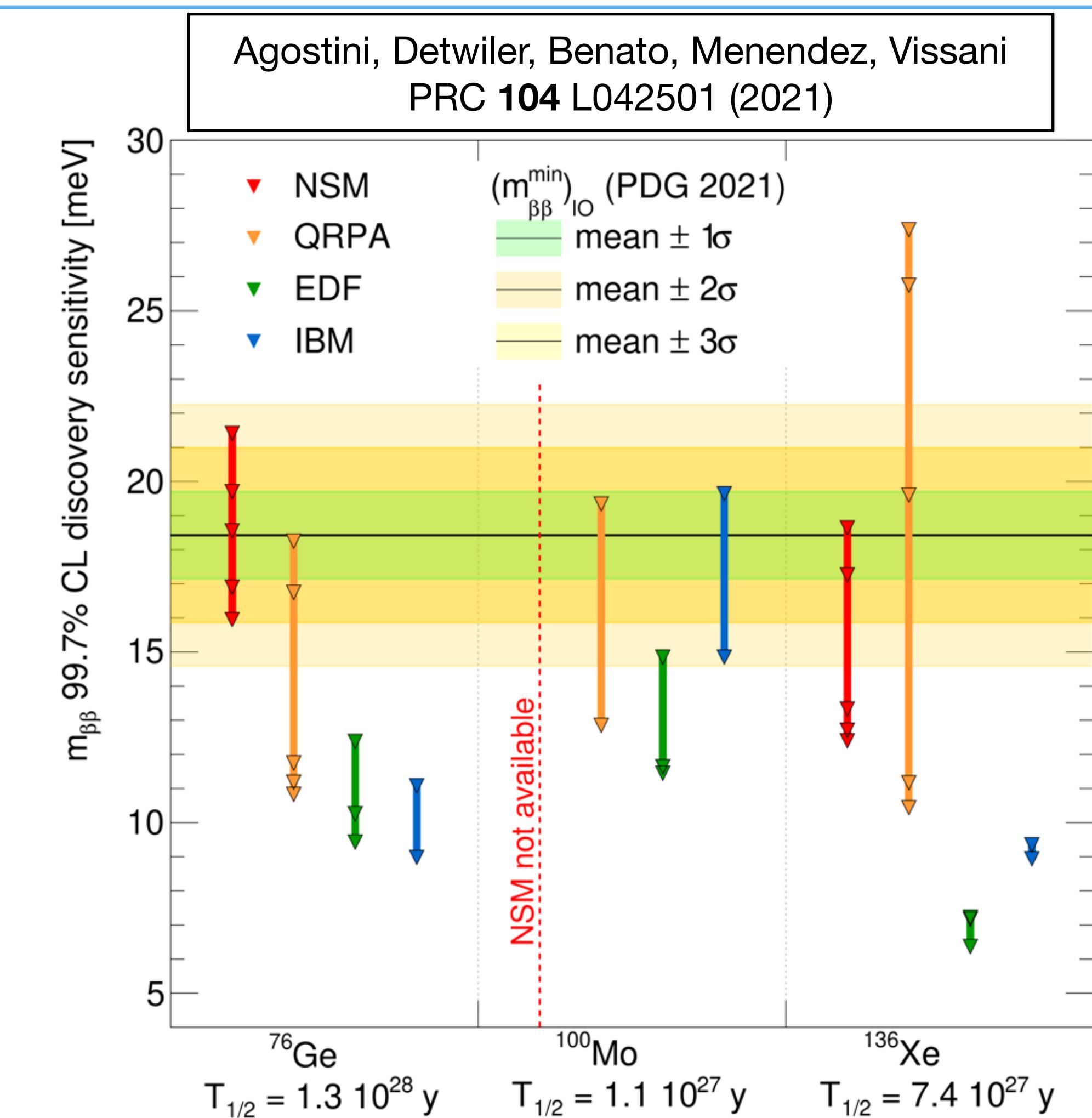
Background Goal:  $< 1 \times 10^{-5}$  counts/(keV kg yr)

$T_{1/2}$  discovery sensitivity ( $3\sigma$ ):  $1.3 \times 10^{28}$  yr

Requires a background level **50x lower** than GERDA



LEGEND will span the inverted ordering and a large part of the normal ordering space  
Discovery sensitivity  $< 18.4$  meV for 3/4 many-body methods & 12/15 calculations

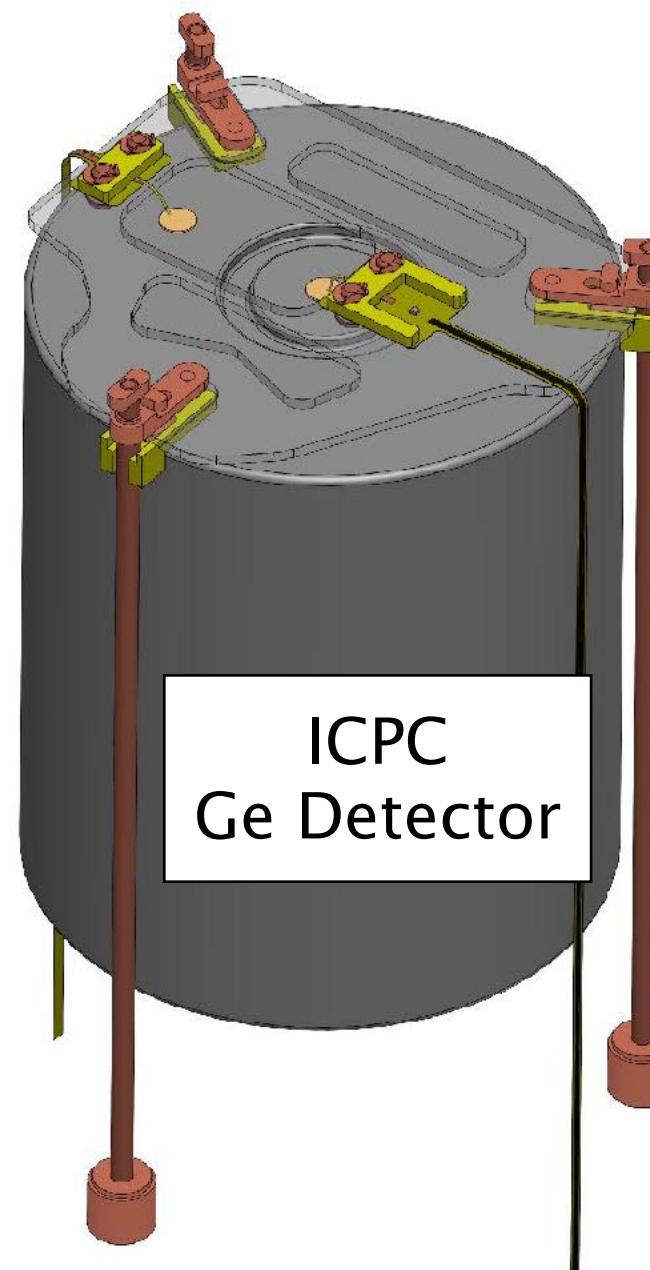


$$m_{\beta\beta} = m_e / \sqrt{G g_A^4 M^2 T_{1/2}}$$

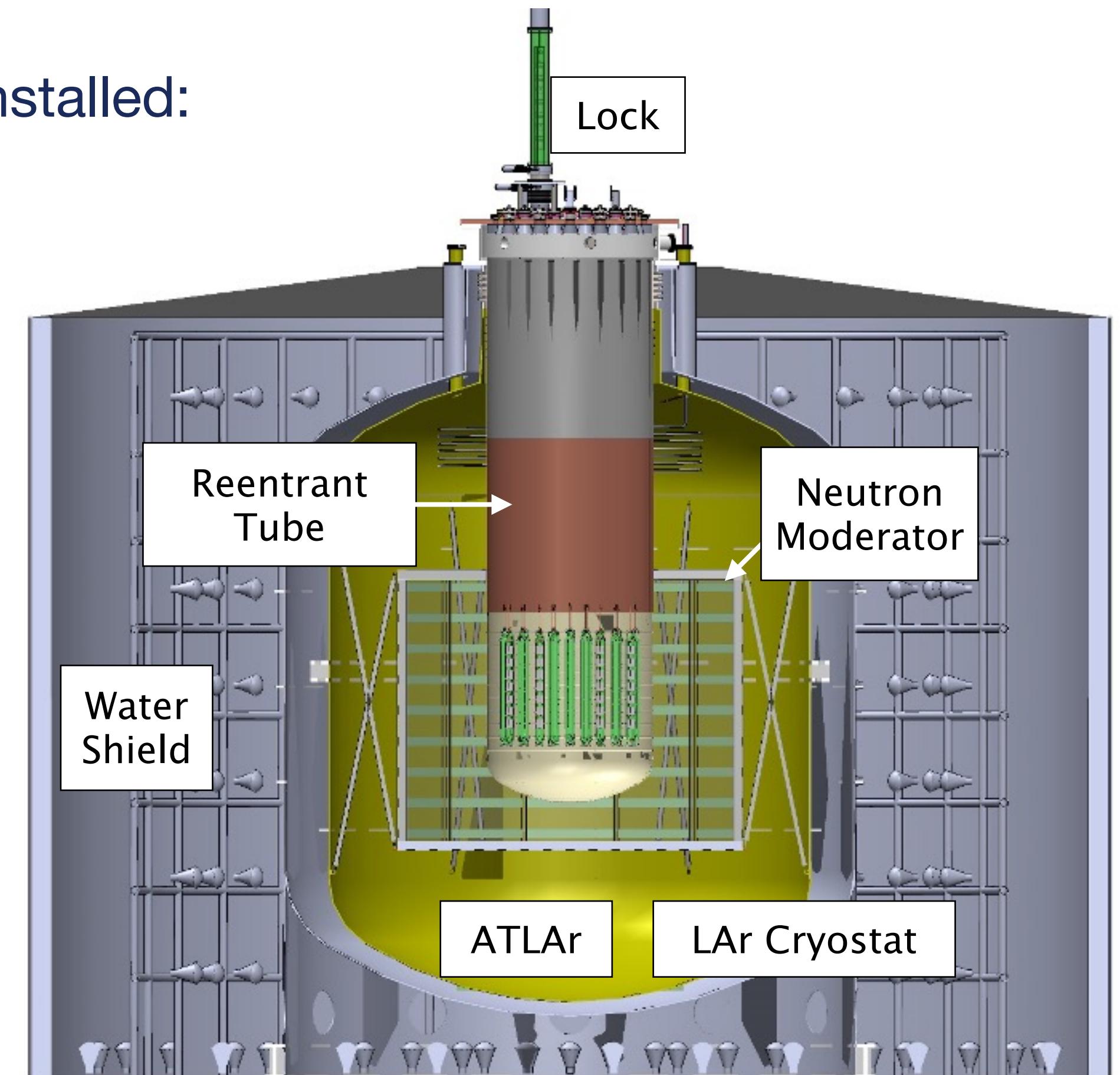
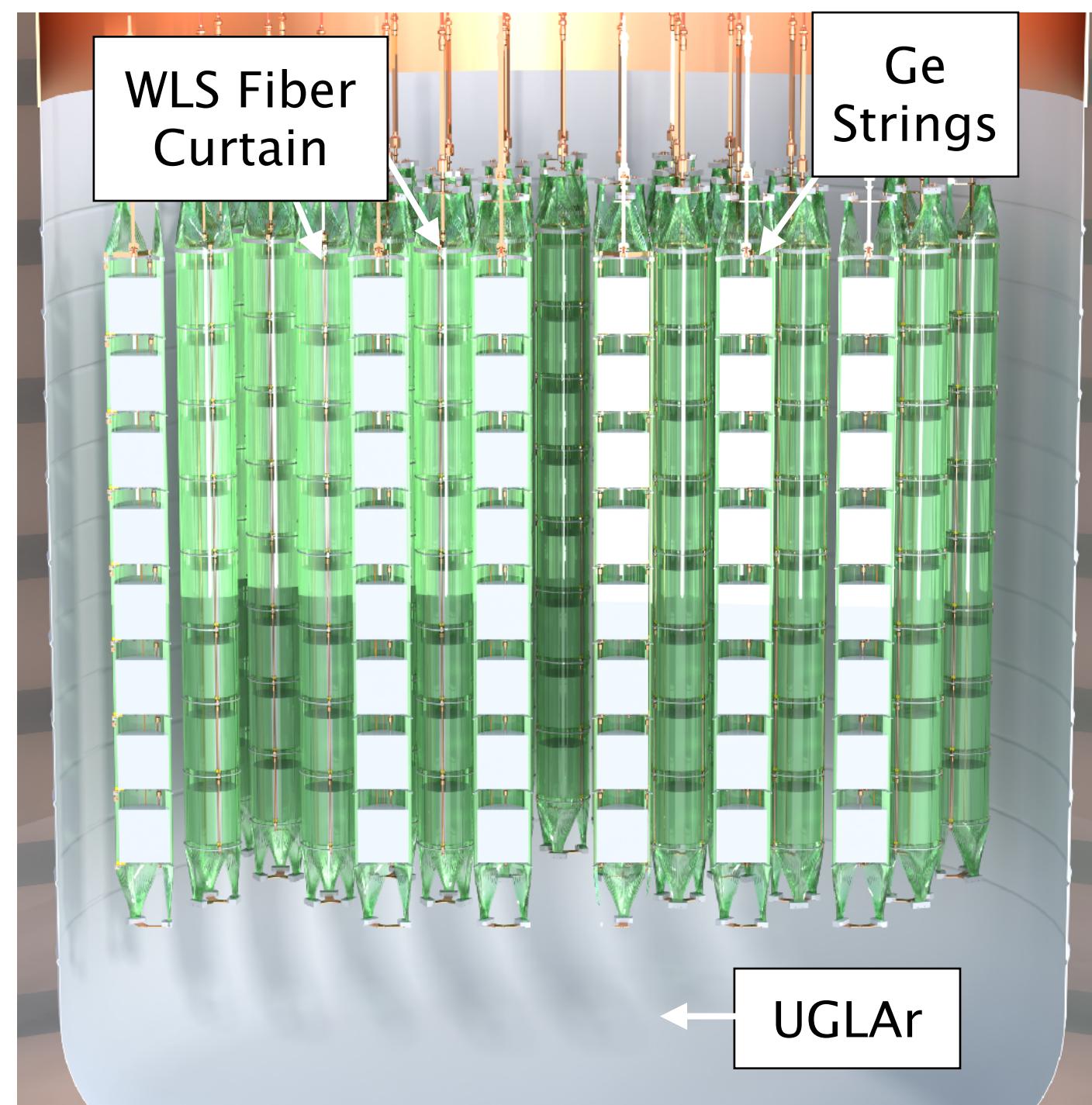
# LEGEND-1000: A discovery experiment for $0\nu\beta\beta$ of $^{76}\text{Ge}$

LEGEND

336 detectors  
3 kg avg. mass



Detector strings can be individually installed:  
Early data as detectors are produced



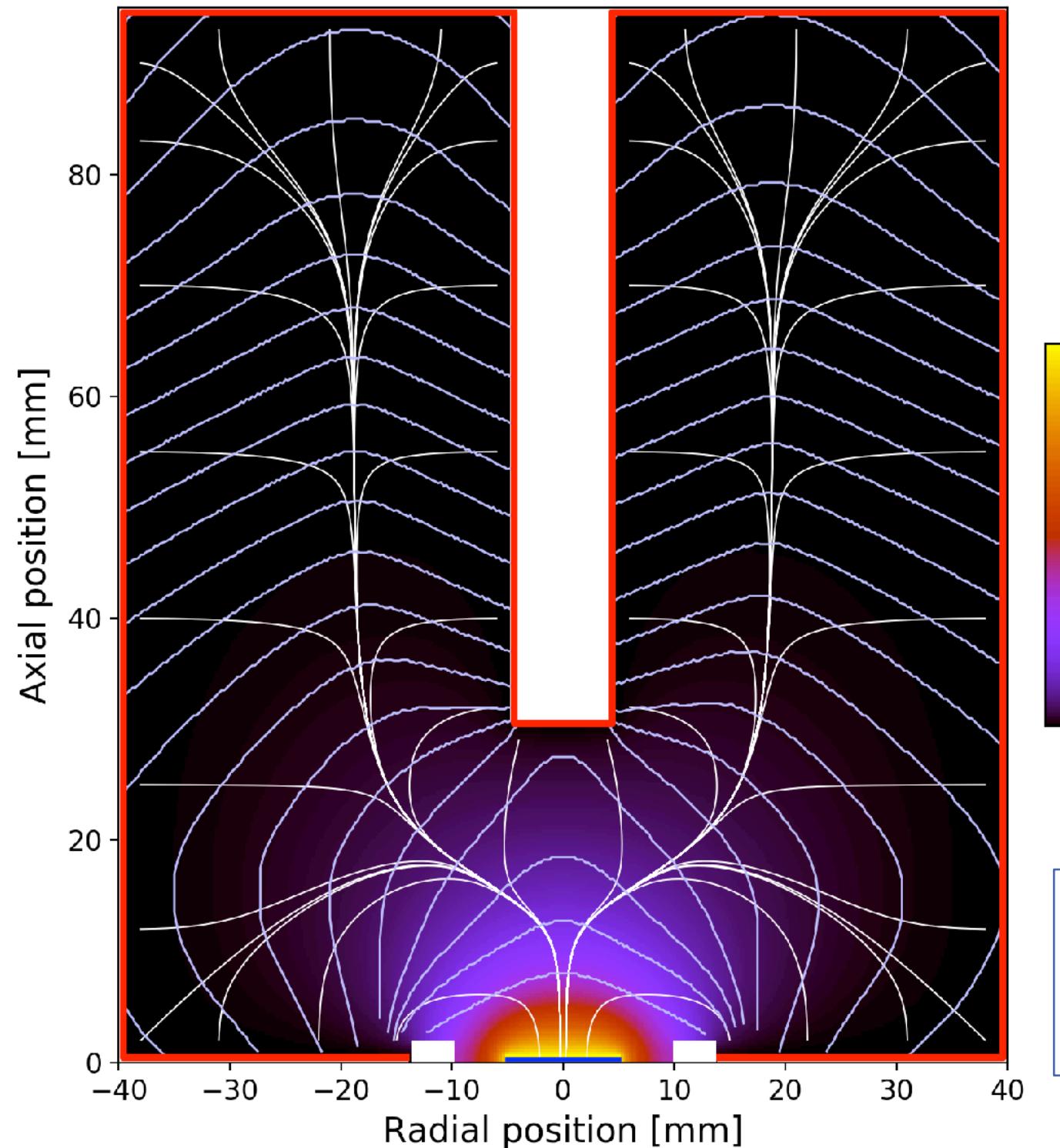
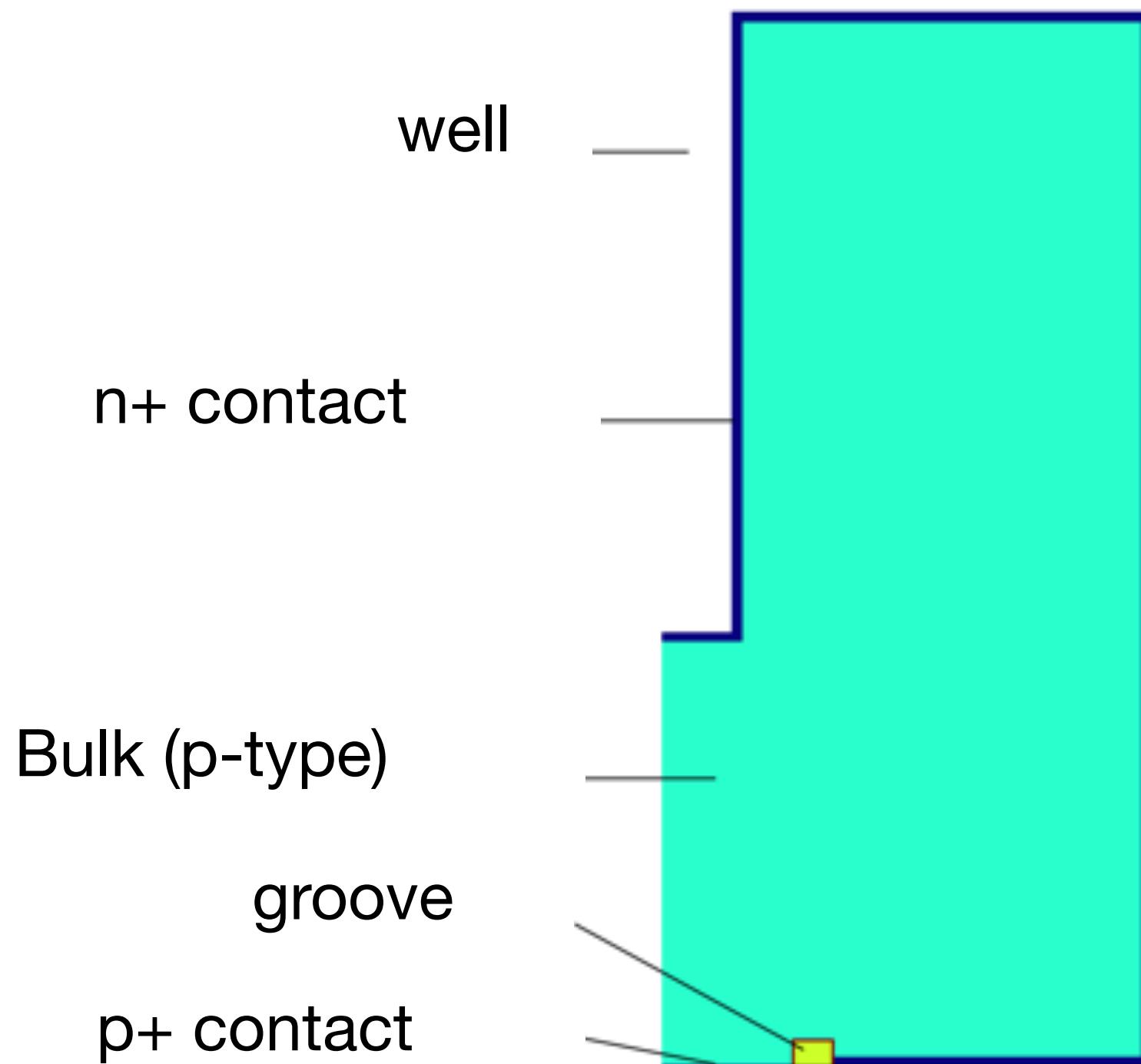
ICPC: Inverted-Coaxial Point Contact  
WLS: Wavelength-shifting  
UGLAr: Underground Liquid Ar  
ATLar: Atmospheric Liquid Ar

LEGEND-1000  
Pre-Conceptual Design Report  
[arXiv:2107.11462](https://arxiv.org/abs/2107.11462)

The reference design accommodates siting  
in LNGS Hall C or the SNOLAB Cryopit

# LEGEND-1000: 76Ge ICPC Detectors

LEGEND



The detector weighting field and ionization charge drift paths

- Large-mass ICPC detectors: ~3 kg avg. mass (compare to ~1 kg in past experiments)
- Lower backgrounds with respect to BEGe/PPC style used by GERDA and MAJORANA
- P-type detectors: Insensitive to alphas on n+ contact
- Small p+ contact: Event topology discrimination

Ge-76 Detectors of LEGEND experiment:  
Production, Characterization,

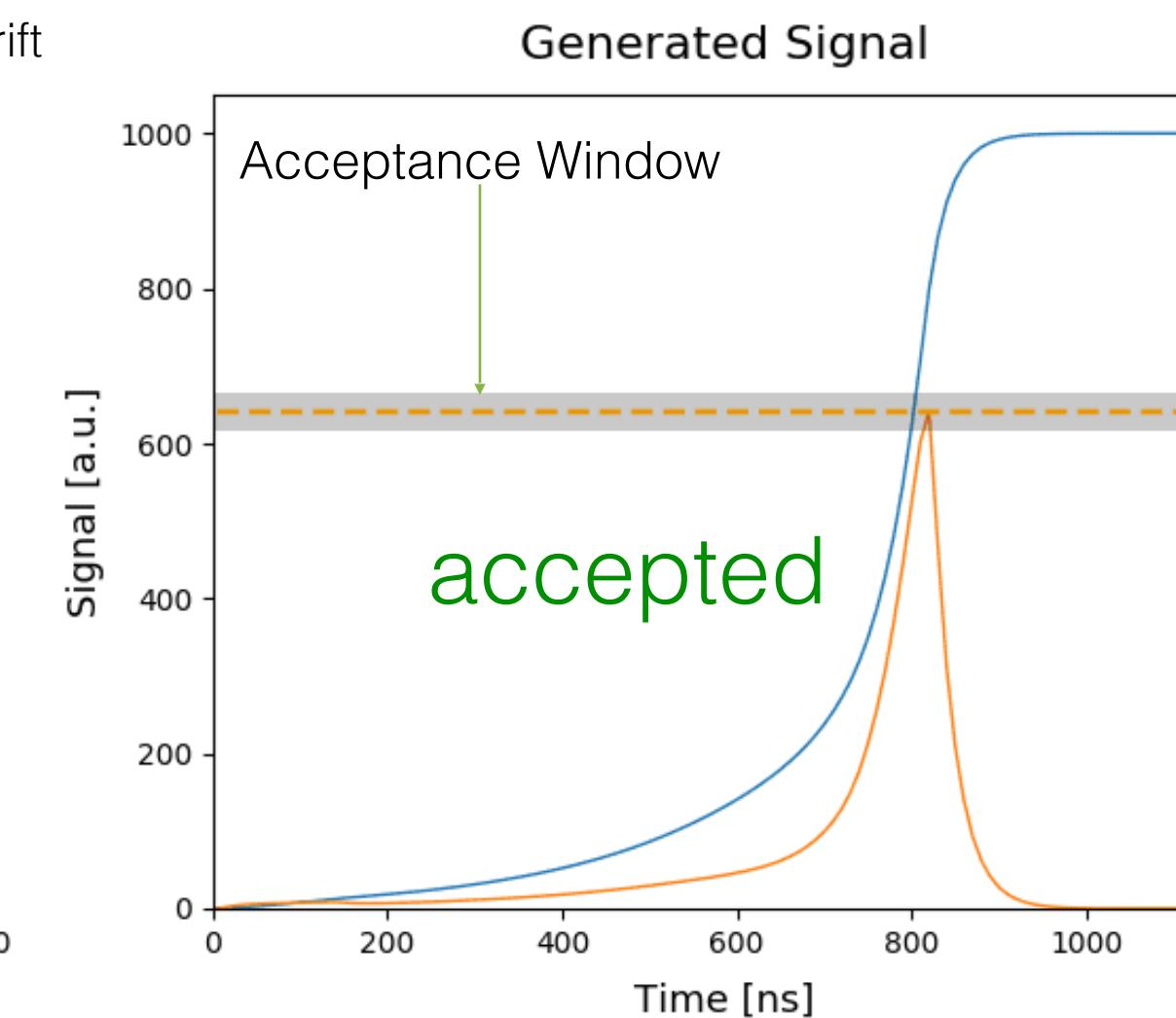
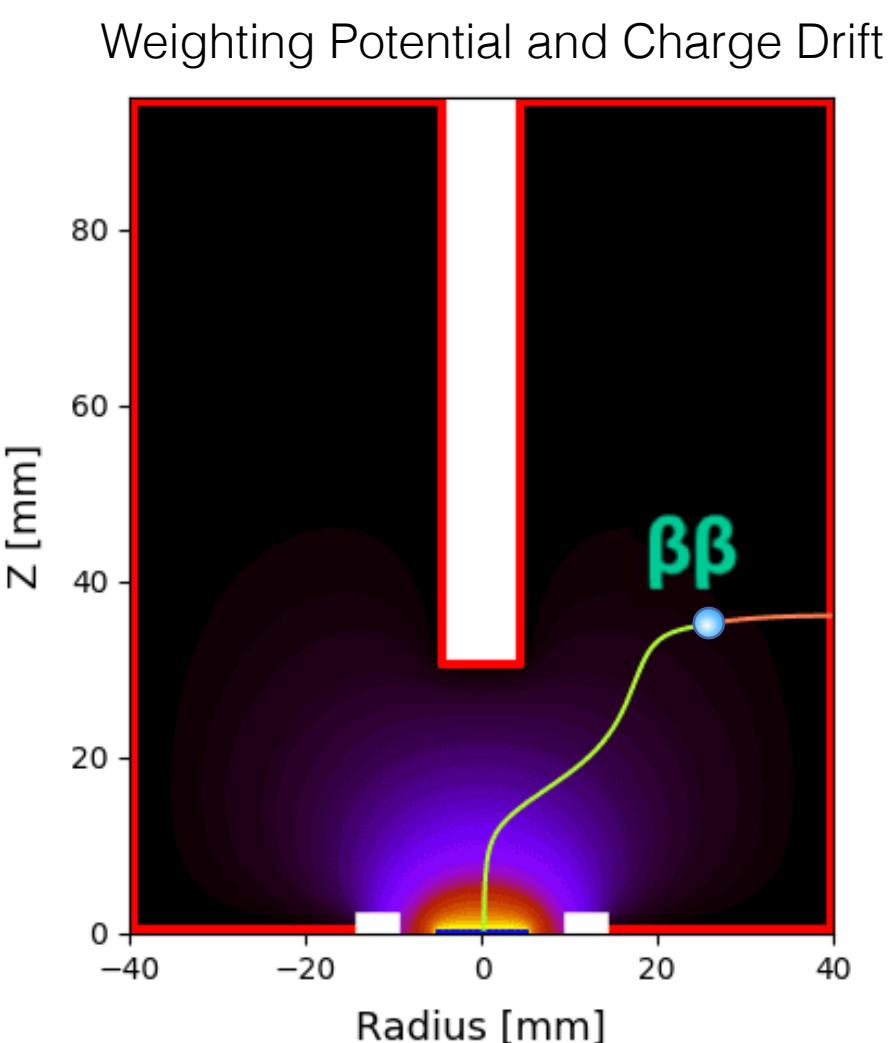


Valentina Biancacci

# LEGEND-1000: Pulse Shape Discrimination

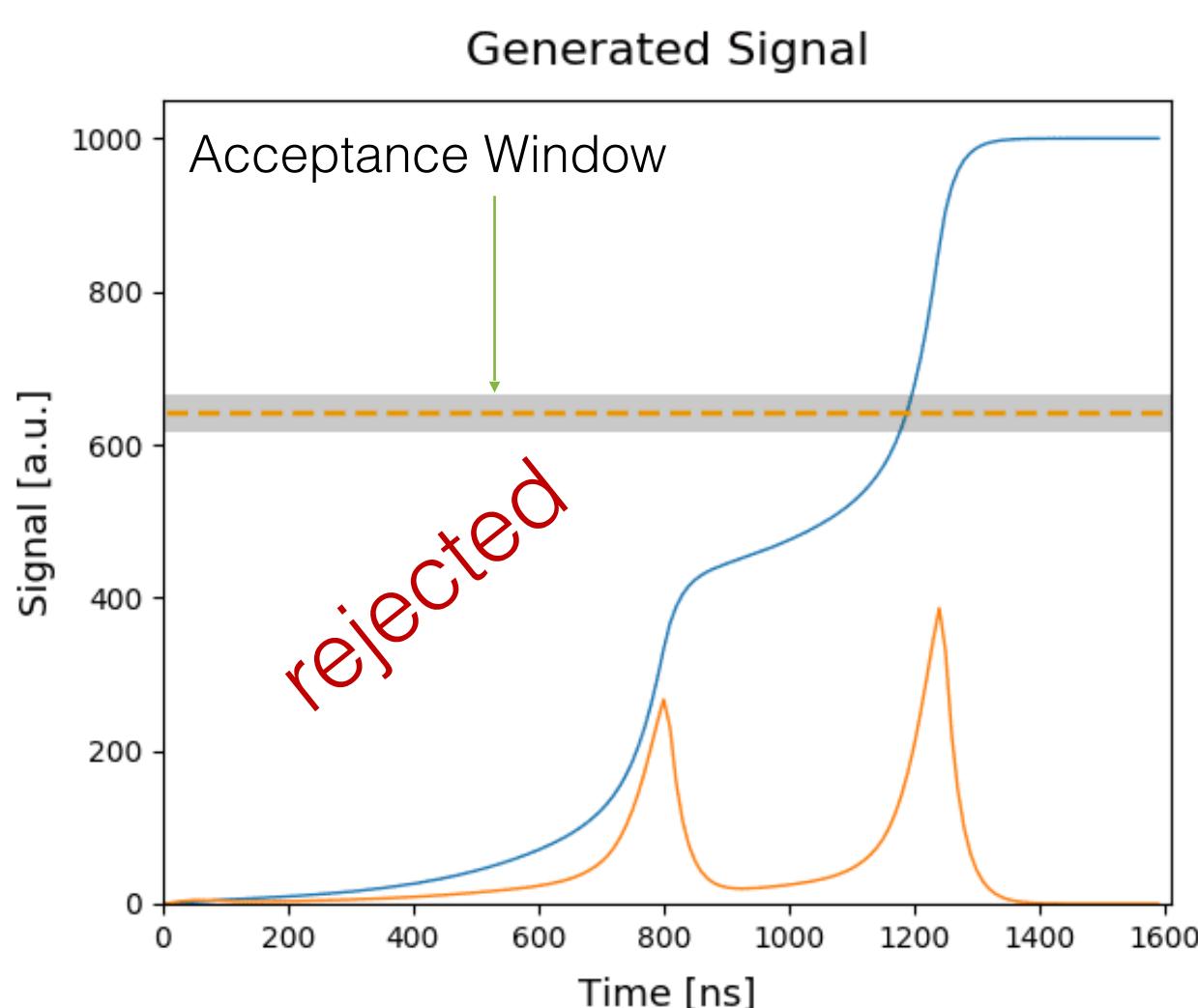
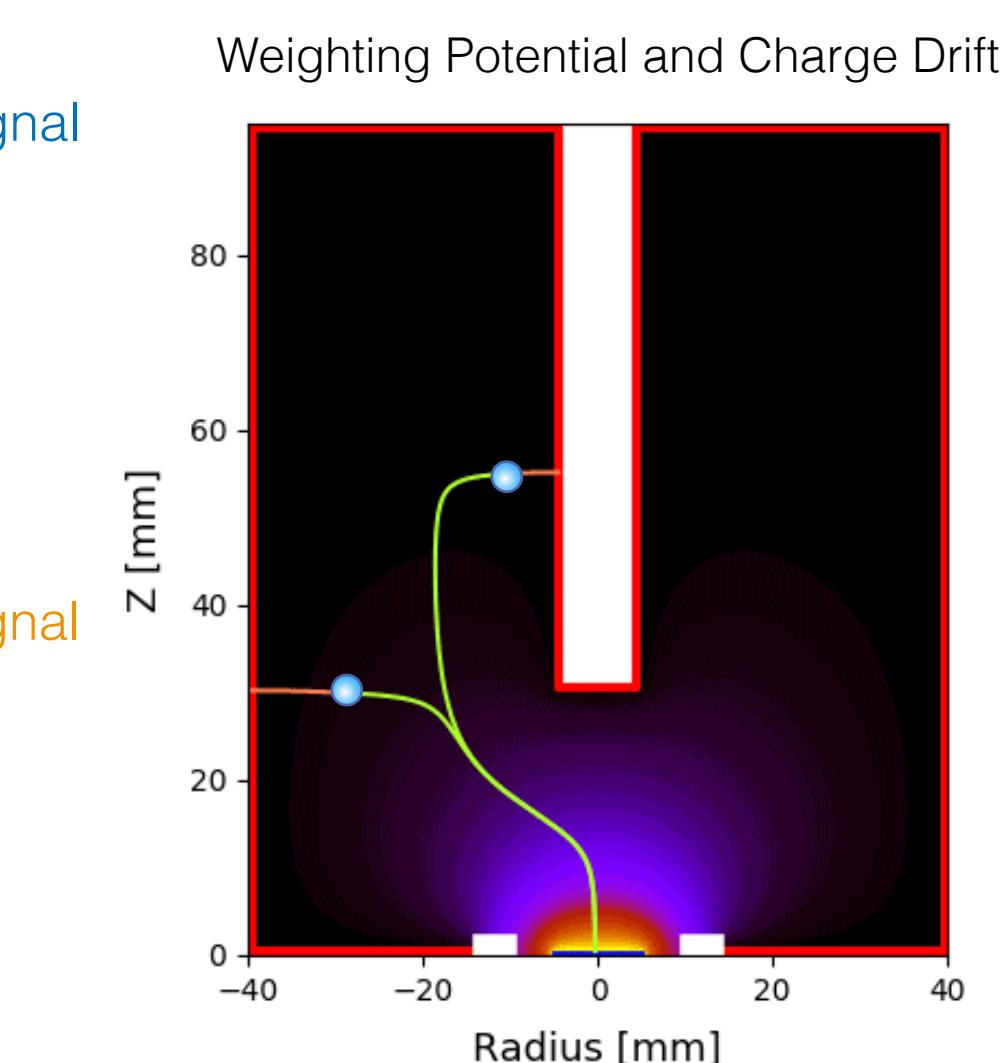
LEGEND

## $0\nu\beta\beta$ signal candidate (single-site)

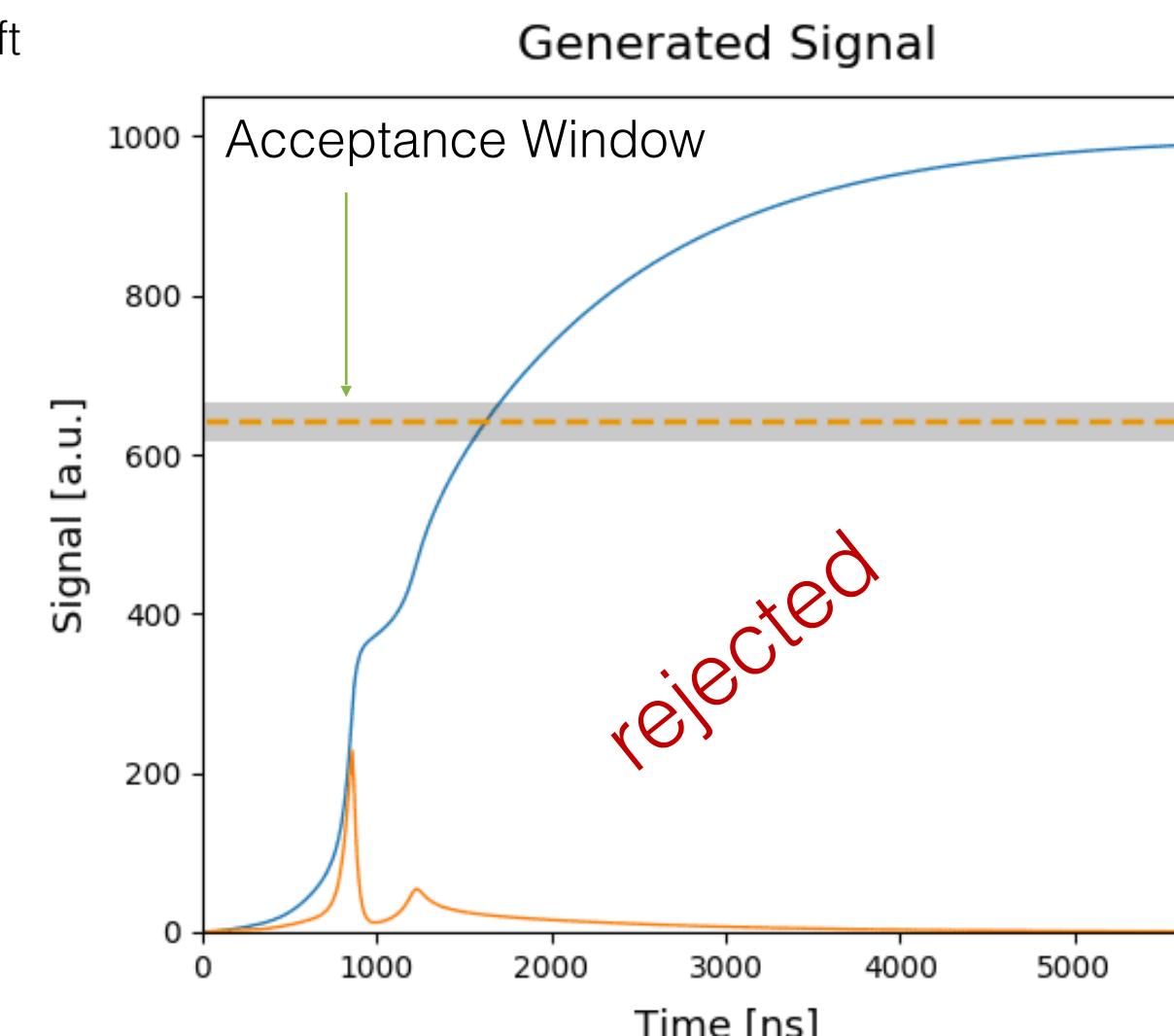
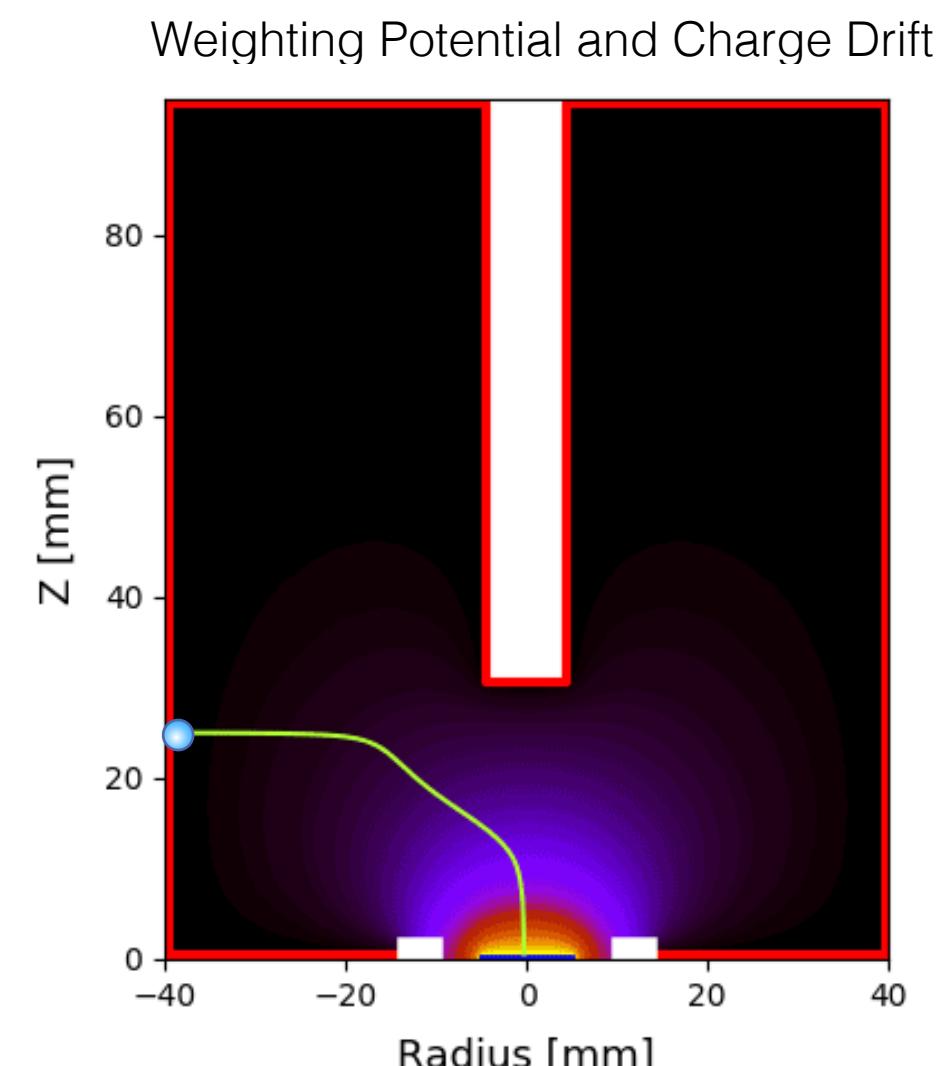


## Event Topologies

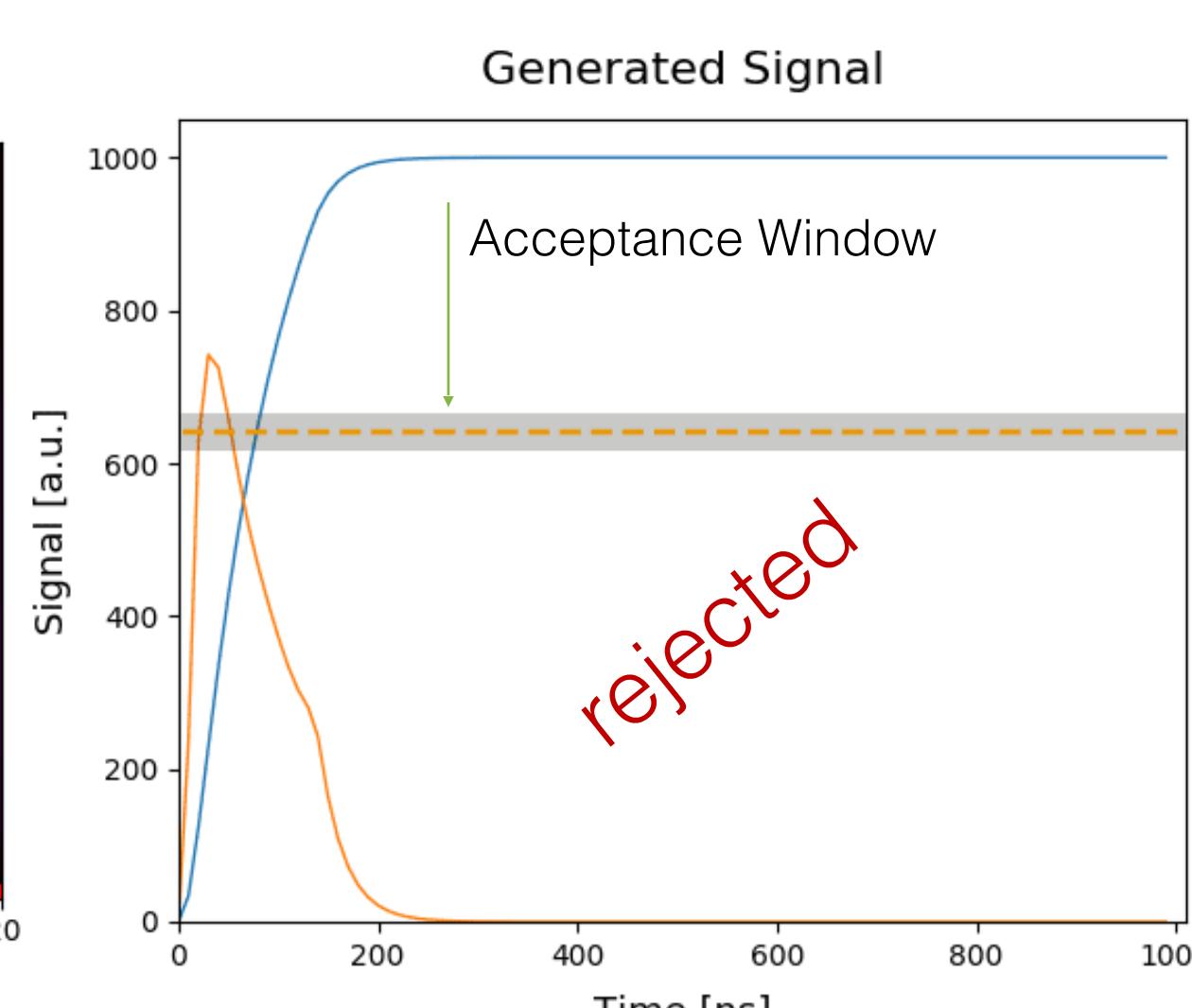
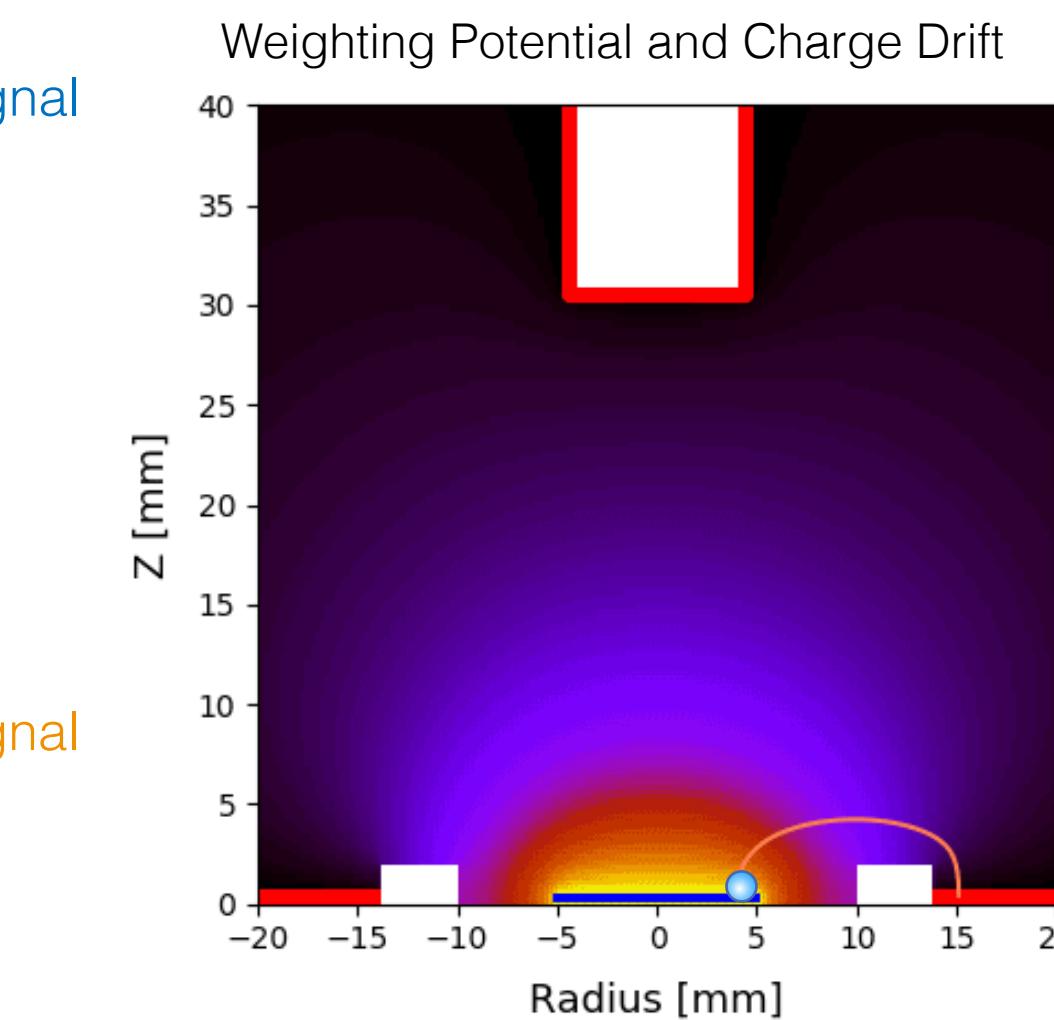
## $\gamma$ -background (multi-site)



## Surface $\beta$ background ( $^{42}\text{K}/^{42}\text{Ar}$ ) on n+ contact

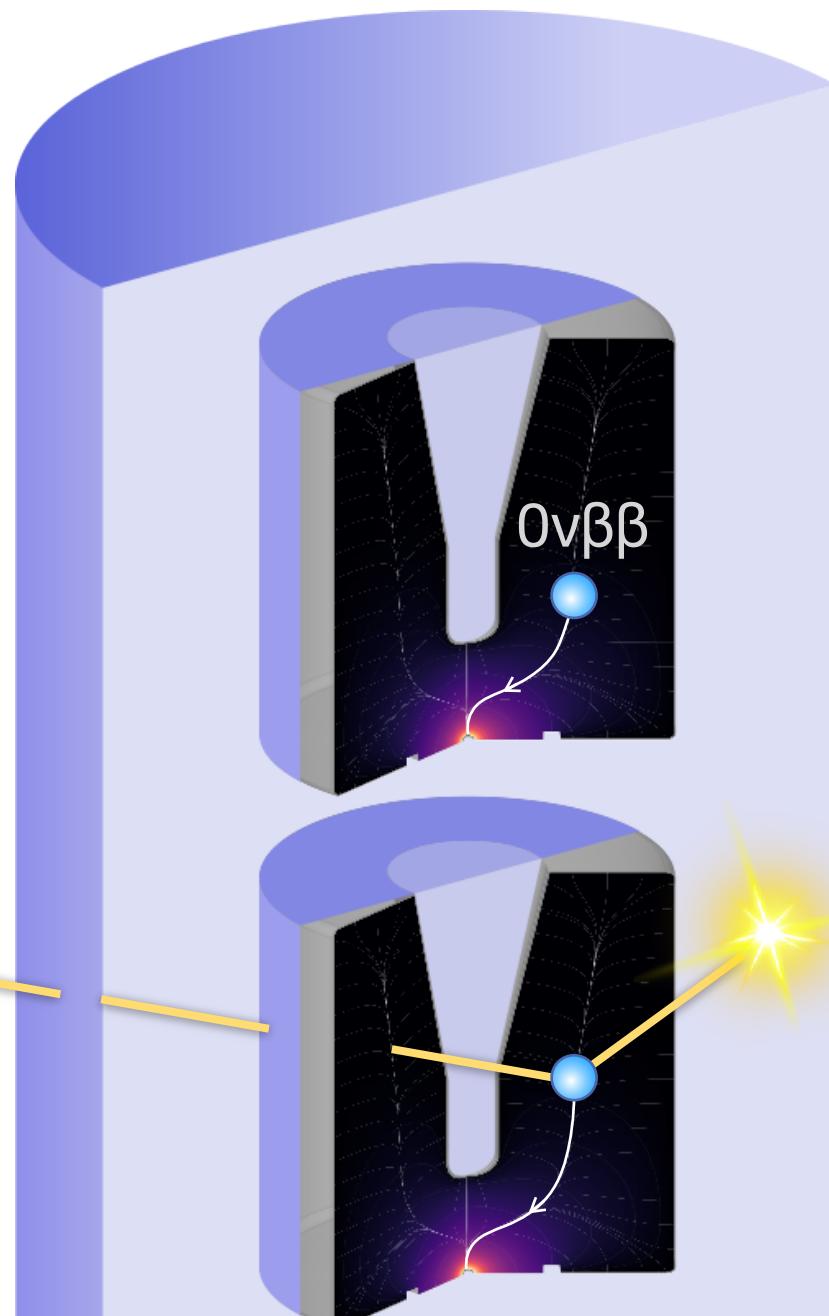


## $\alpha$ -background on p+ contact



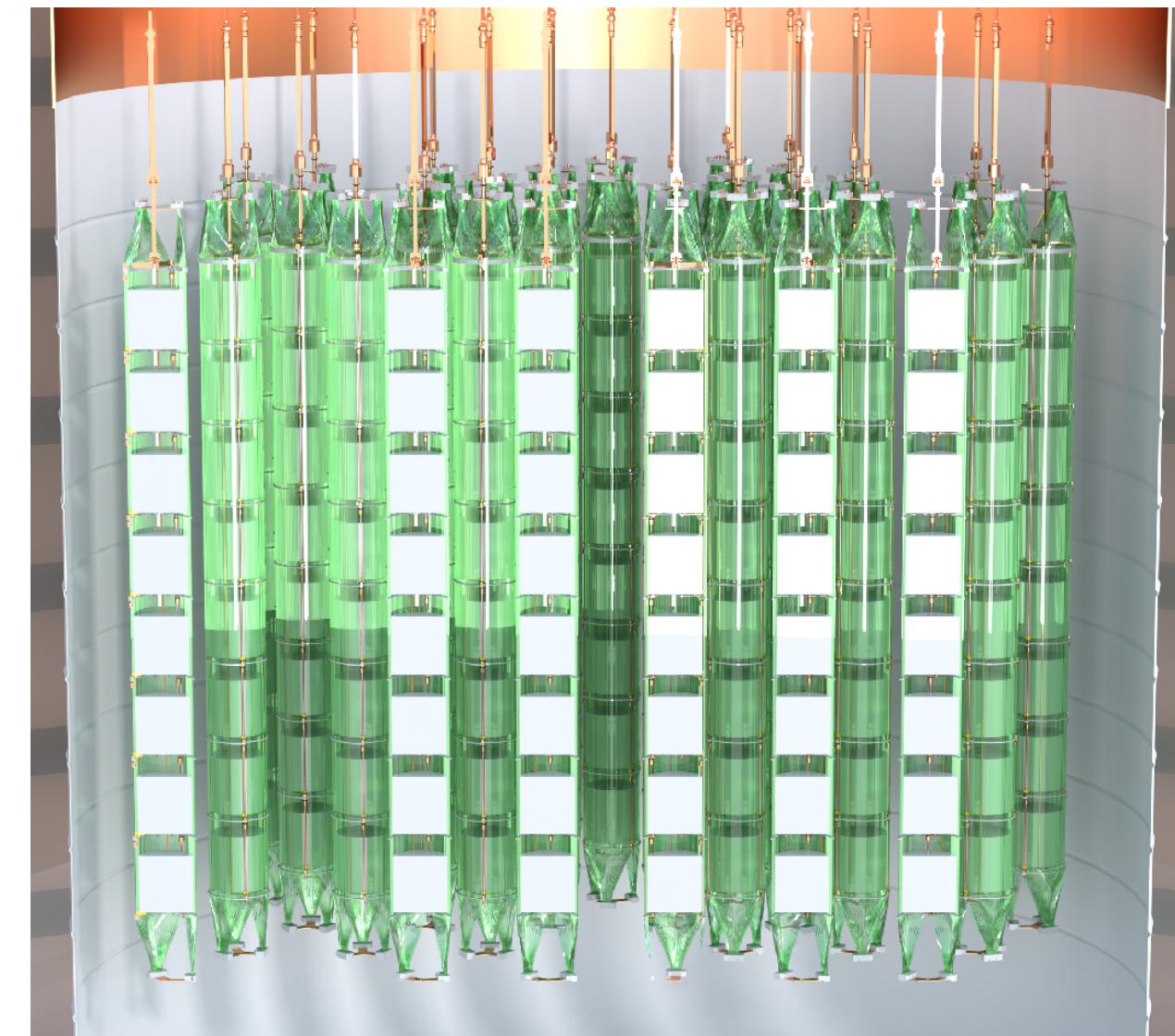
# LEGEND-1000: Argon Instrumentation

LEGEND

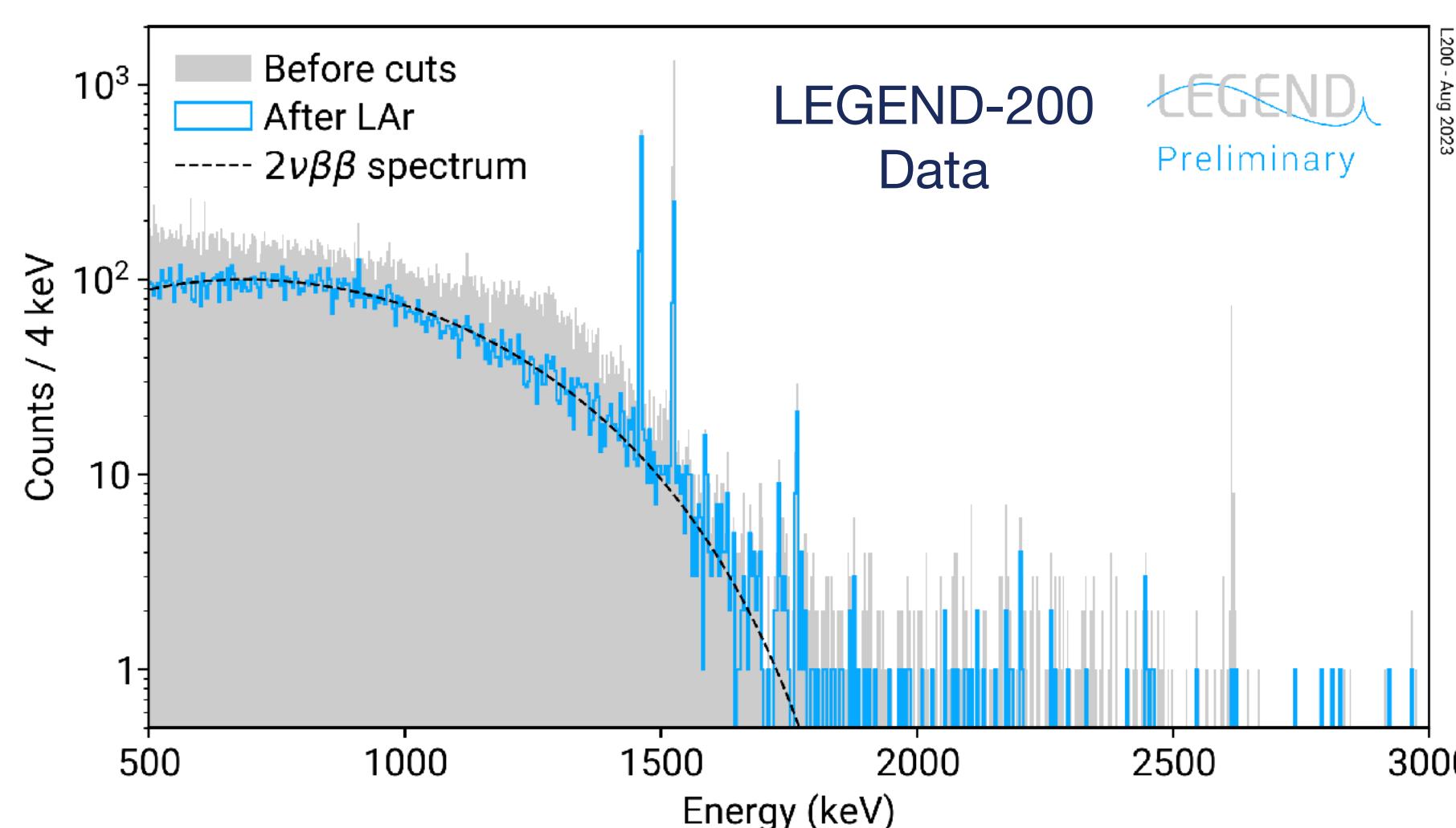
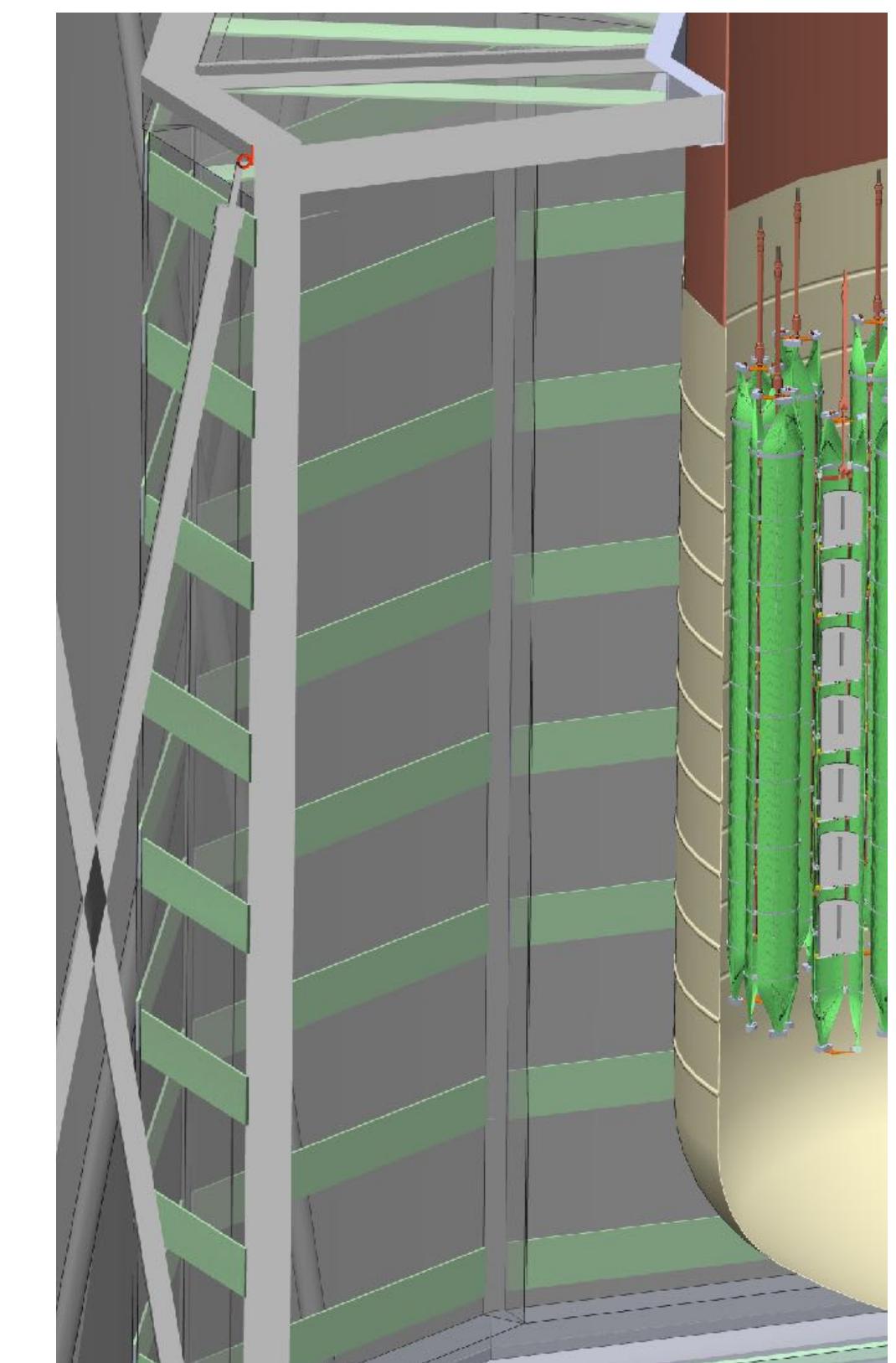


Instrumentation  
to detect LAr  
scintillation light

**Wavelength-shifting (WLS) fibers and SiPM arrays**  
for 128 nm single photon detection



Neutron moderator with  
WLS light guides *outside*  
reentrant tube;  
Xe-doped atmospheric LAr



Strings of Ge detectors surrounded by  
WLS fibers *inside* reentrant tubes

The LEGEND-200 Liquid Argon Instrumentation: From a simple veto to a full-fledged detector

Rosanna Deckert

Muon Veto of the LEGEND Experiment

Gina Grünauer

Neutron Veto Instrumentation for LEGEND-1000

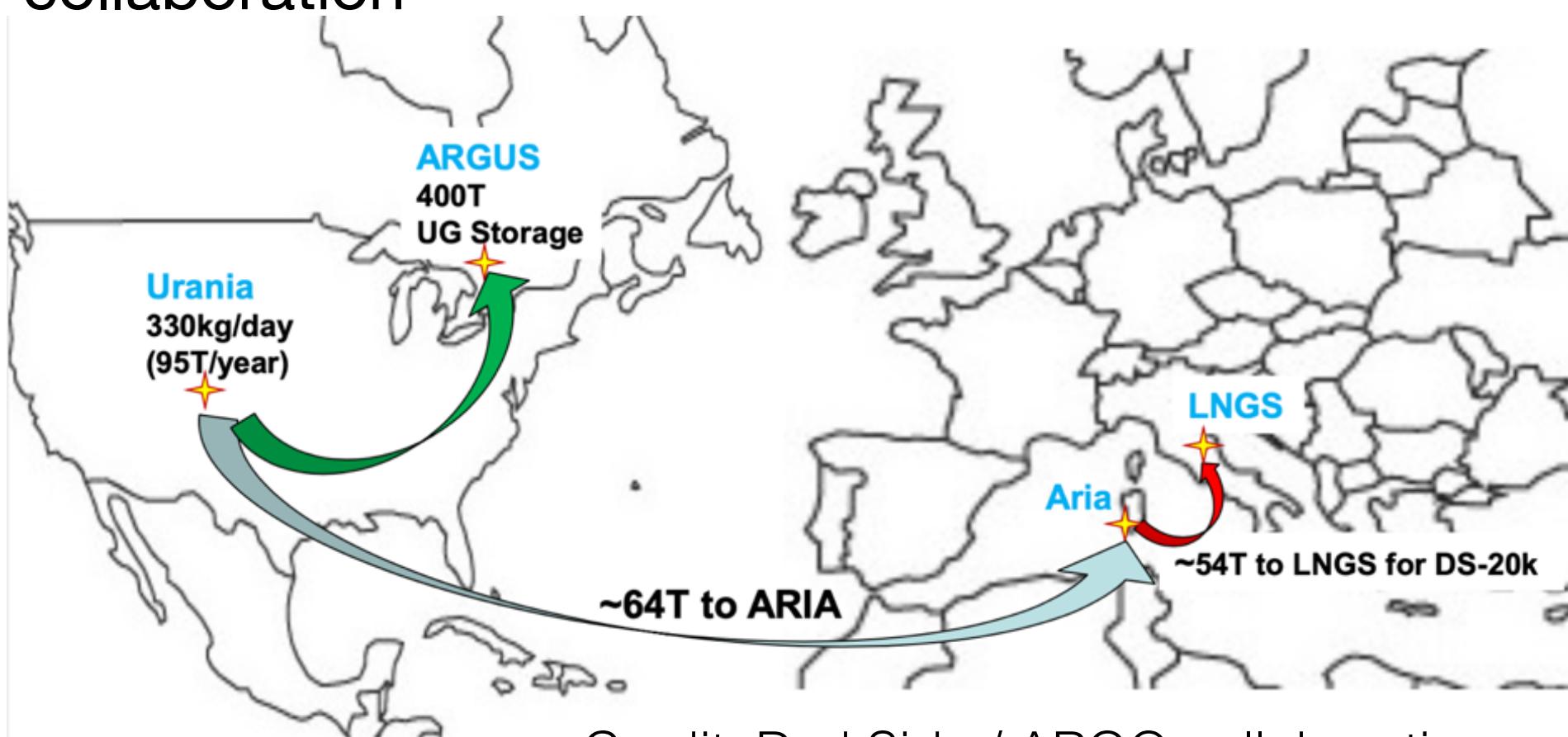
Michele Morella



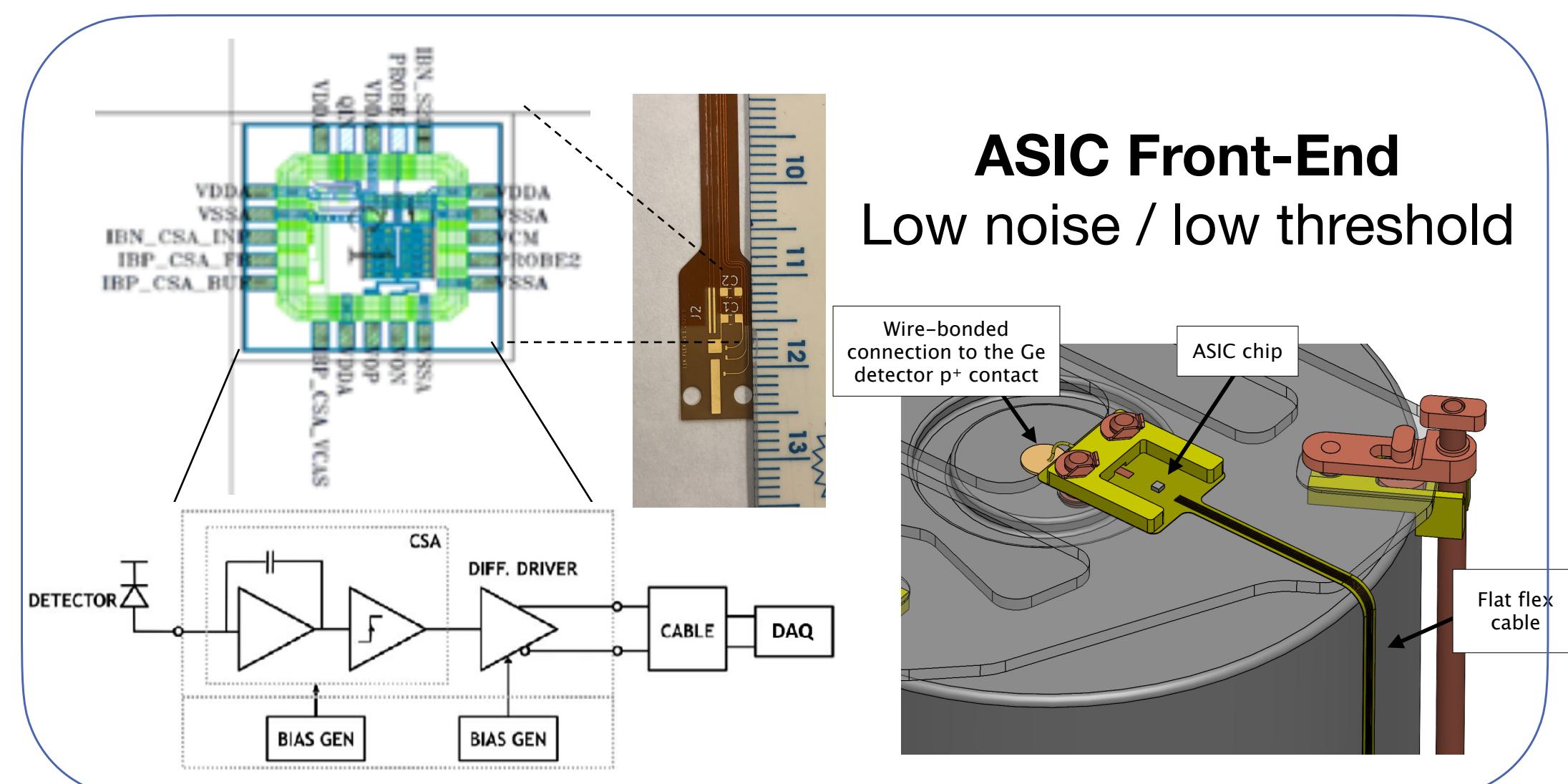
# LEGEND-1000: Radiopure Components

LEGEND

20-25 t of **underground-sourced LAr** reduced in  $^{42}\text{Ar}$   
Acquisition builds on pioneering work of DarkSide  
collaboration

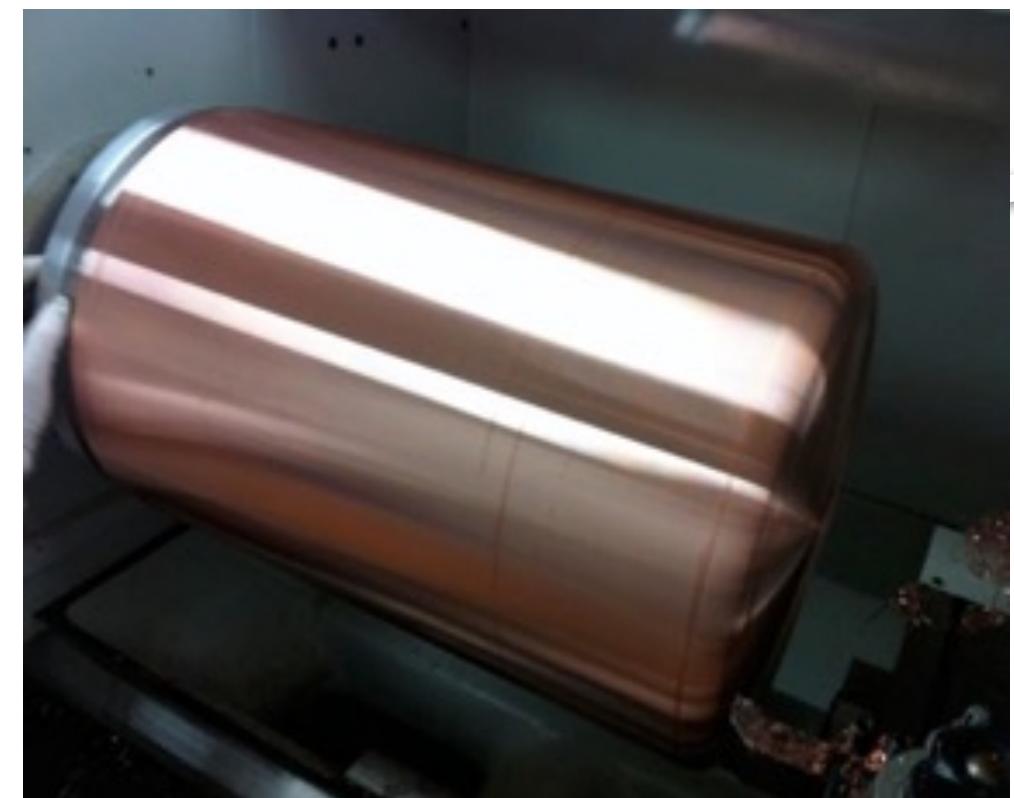


Credit: DarkSide / ARGO collaboration

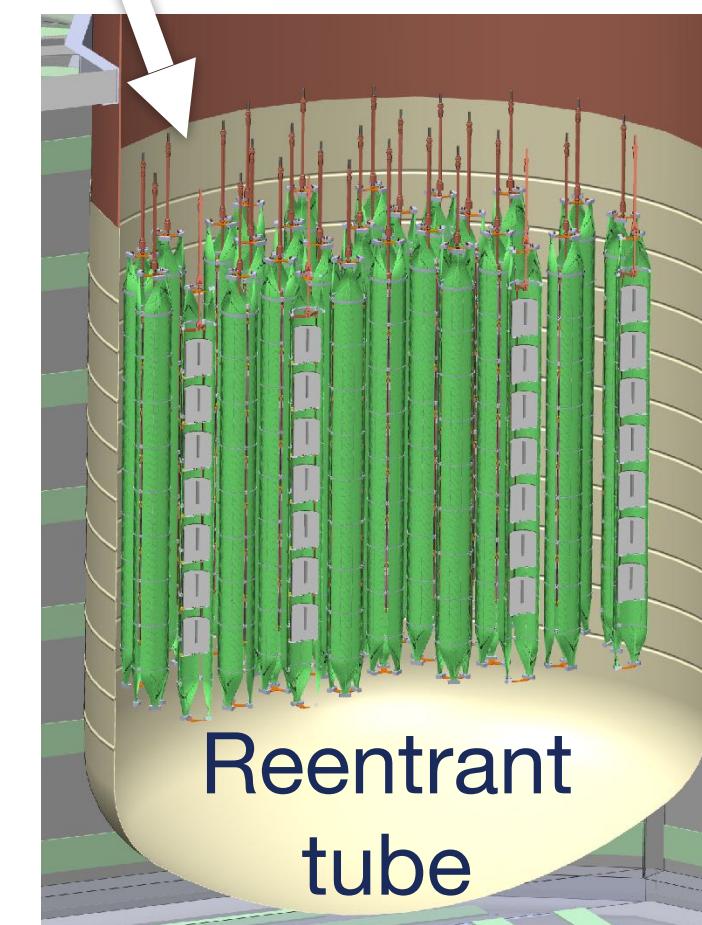
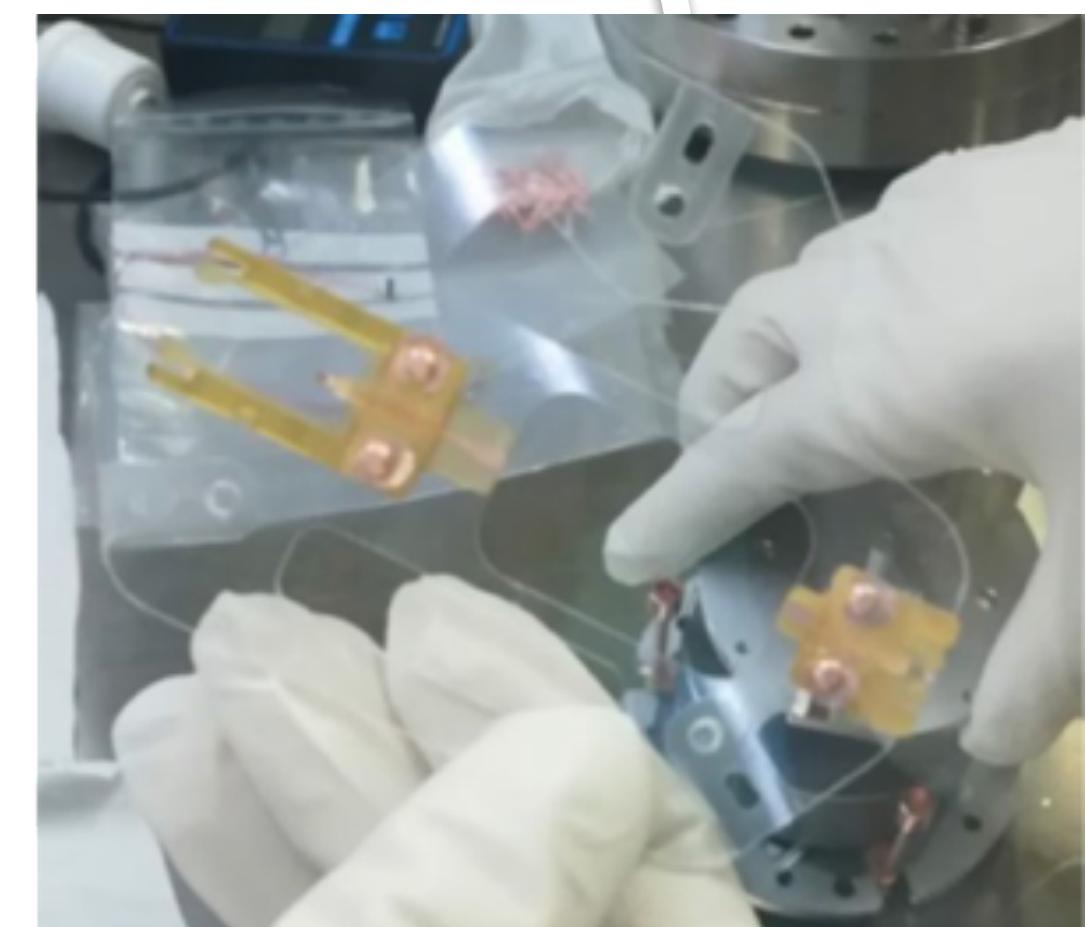
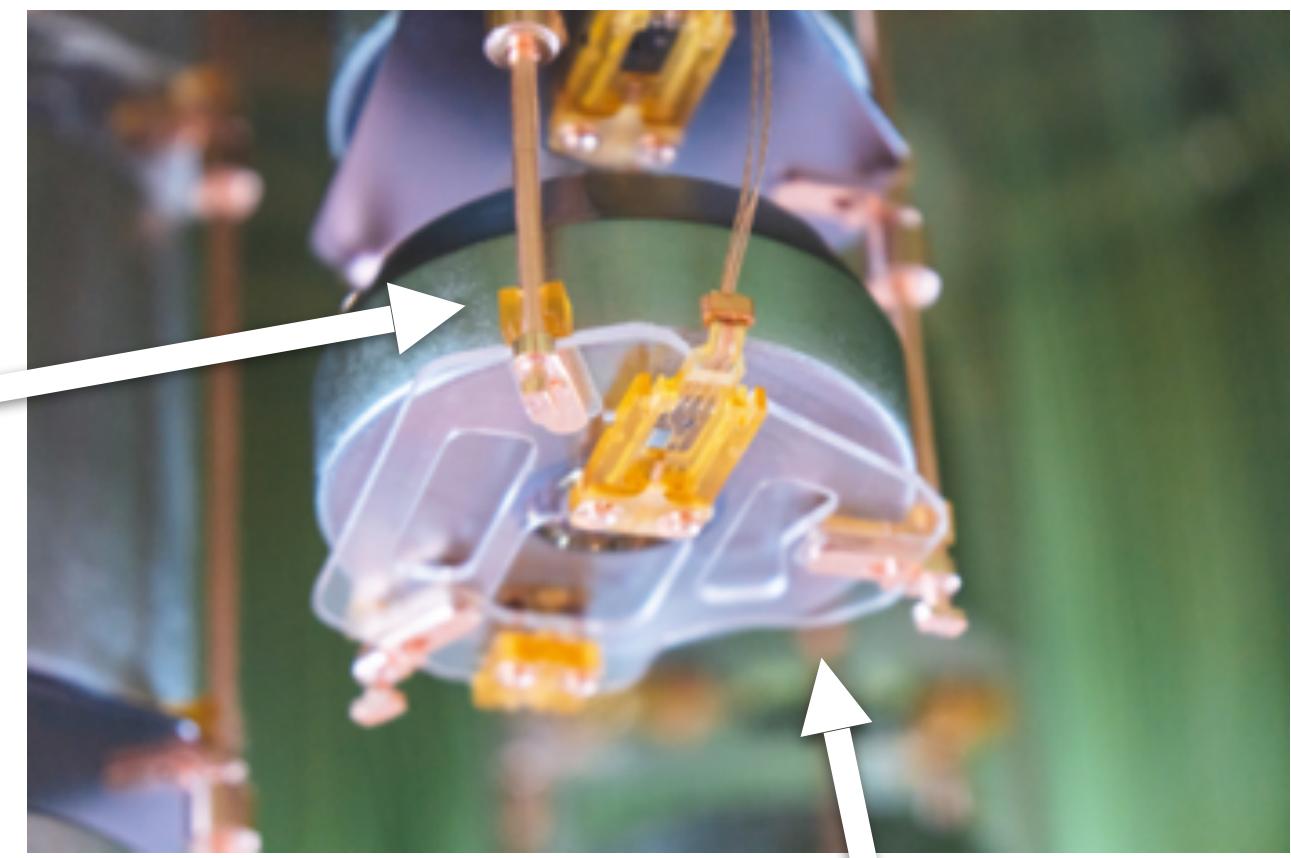


**ASIC Front-End**  
Low noise / low threshold

**Underground electroformed Cu** for detector holders and reentrant tube



Example LEGEND-200 Detector holder

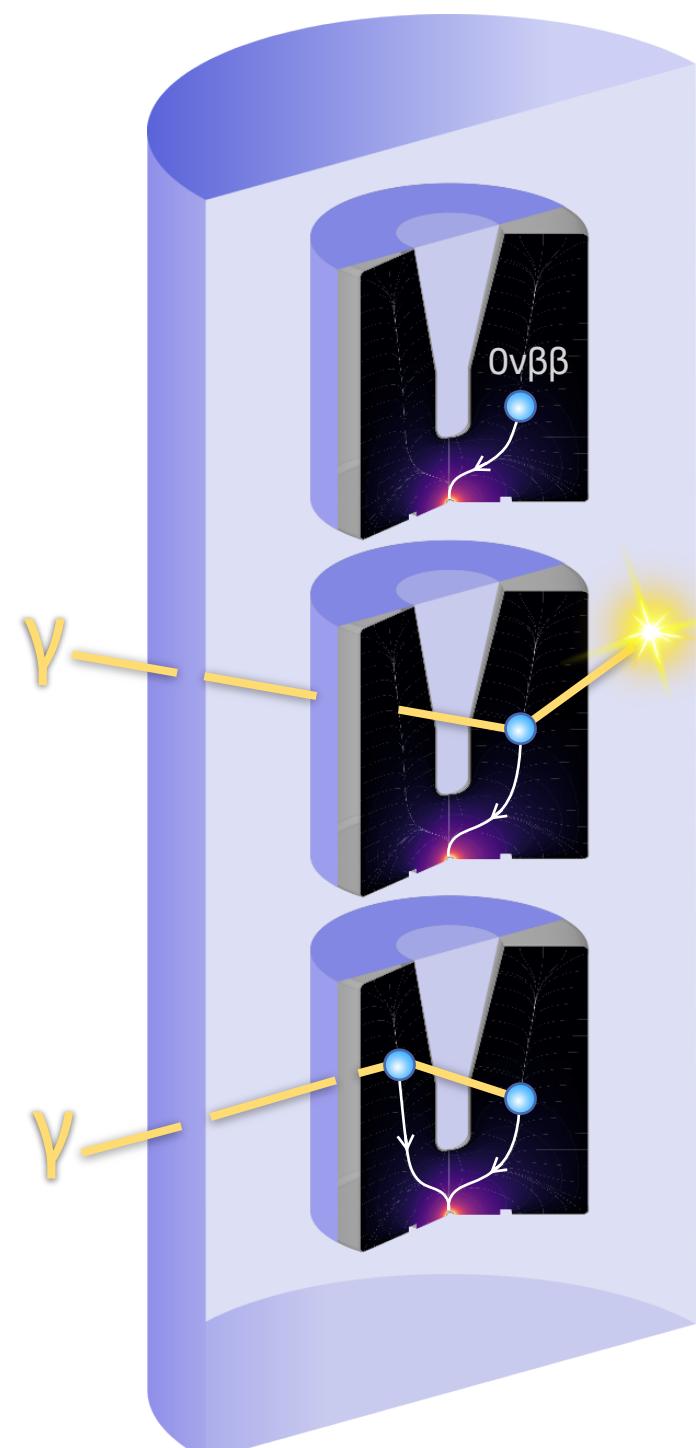


**Reentrant tube**

**PEN:** scintillating (self-vetoing)  
high-purity detector support

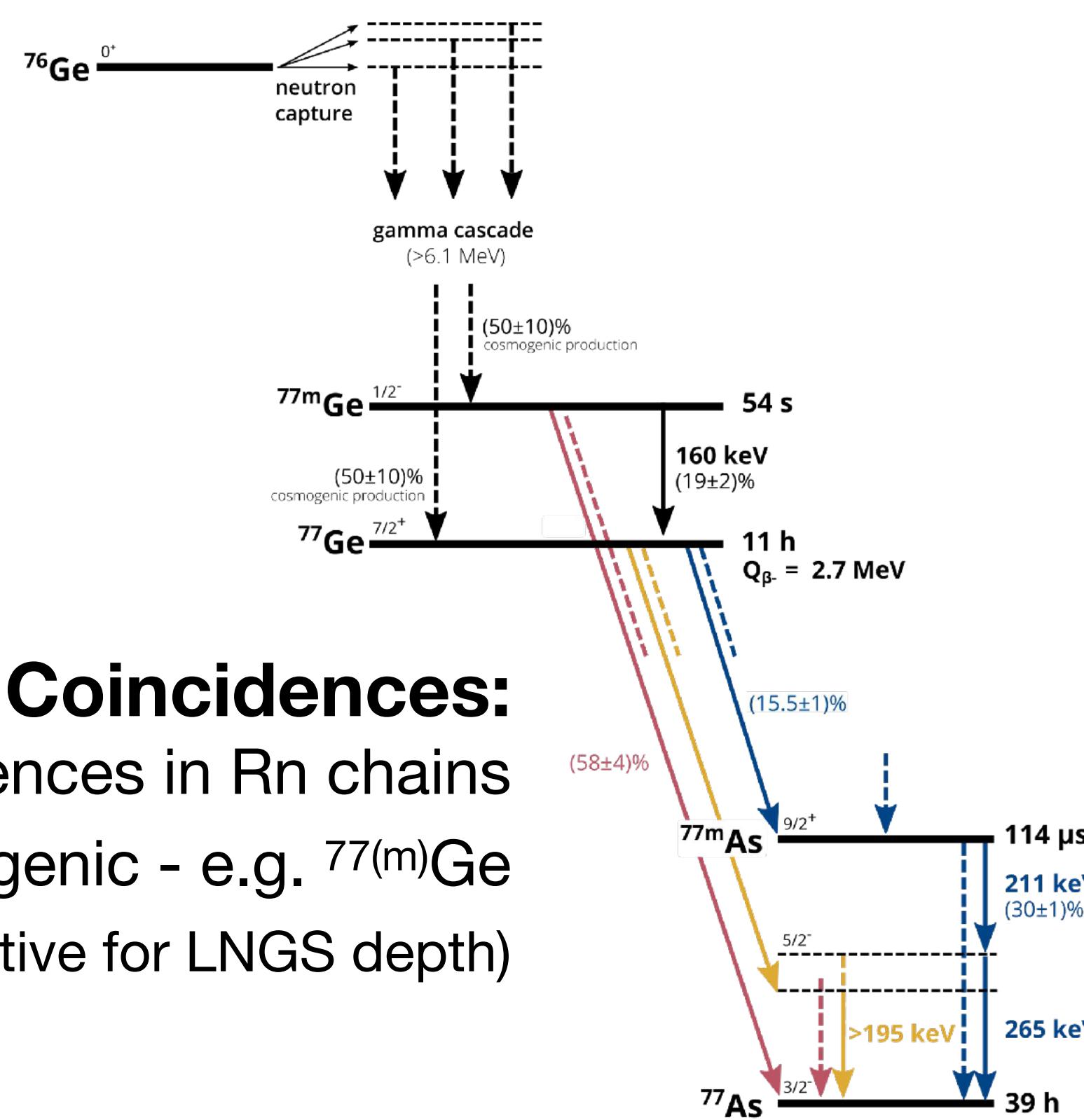
# Distinguishing Signal from Background

LEGEND



## Active Background Suppression:

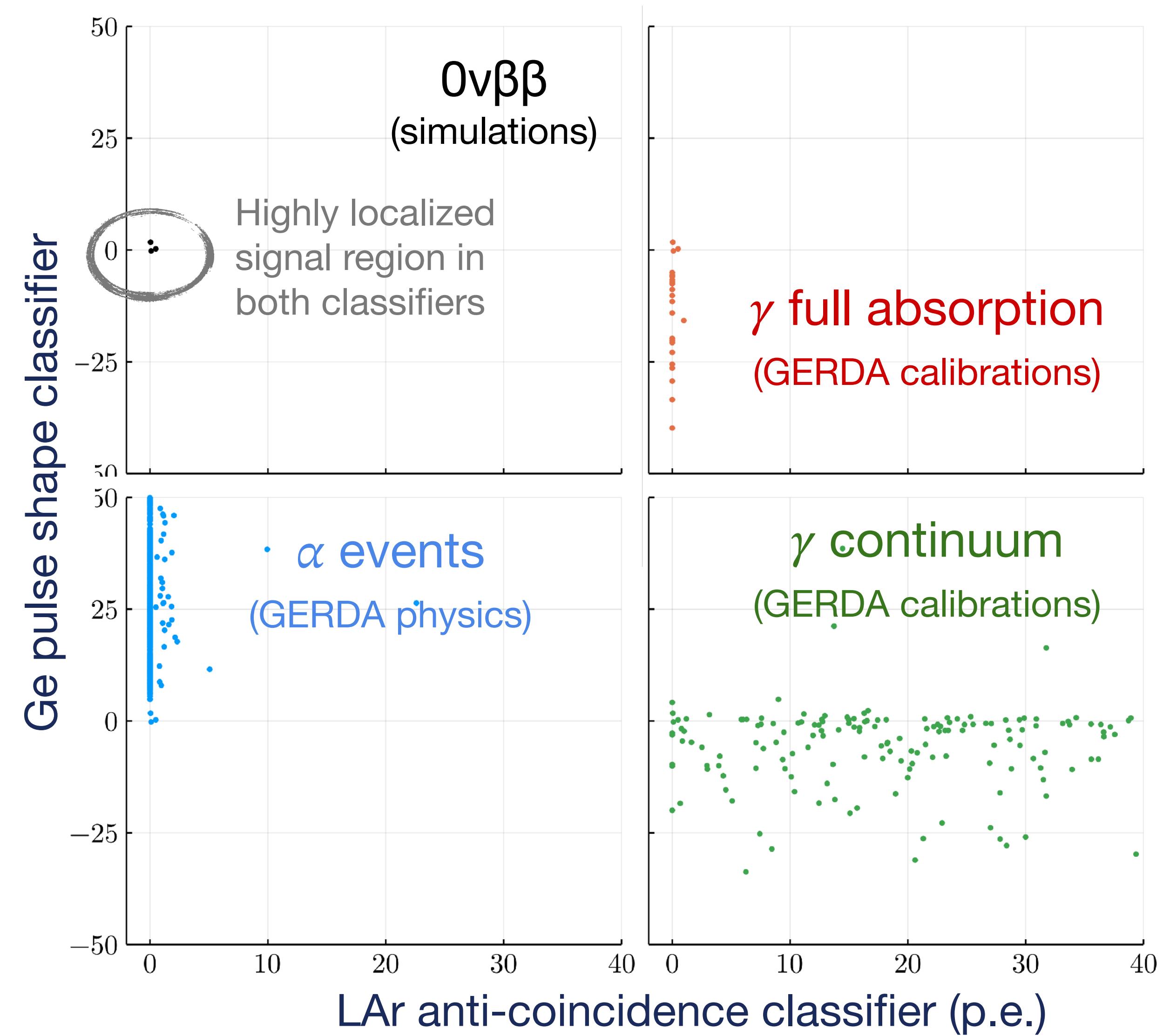
LAr Anti-Coincidence (external depositions)  
+ Pulse Shape Discrimination (multi-site and surface events)



## Tag Delayed Coincidences:

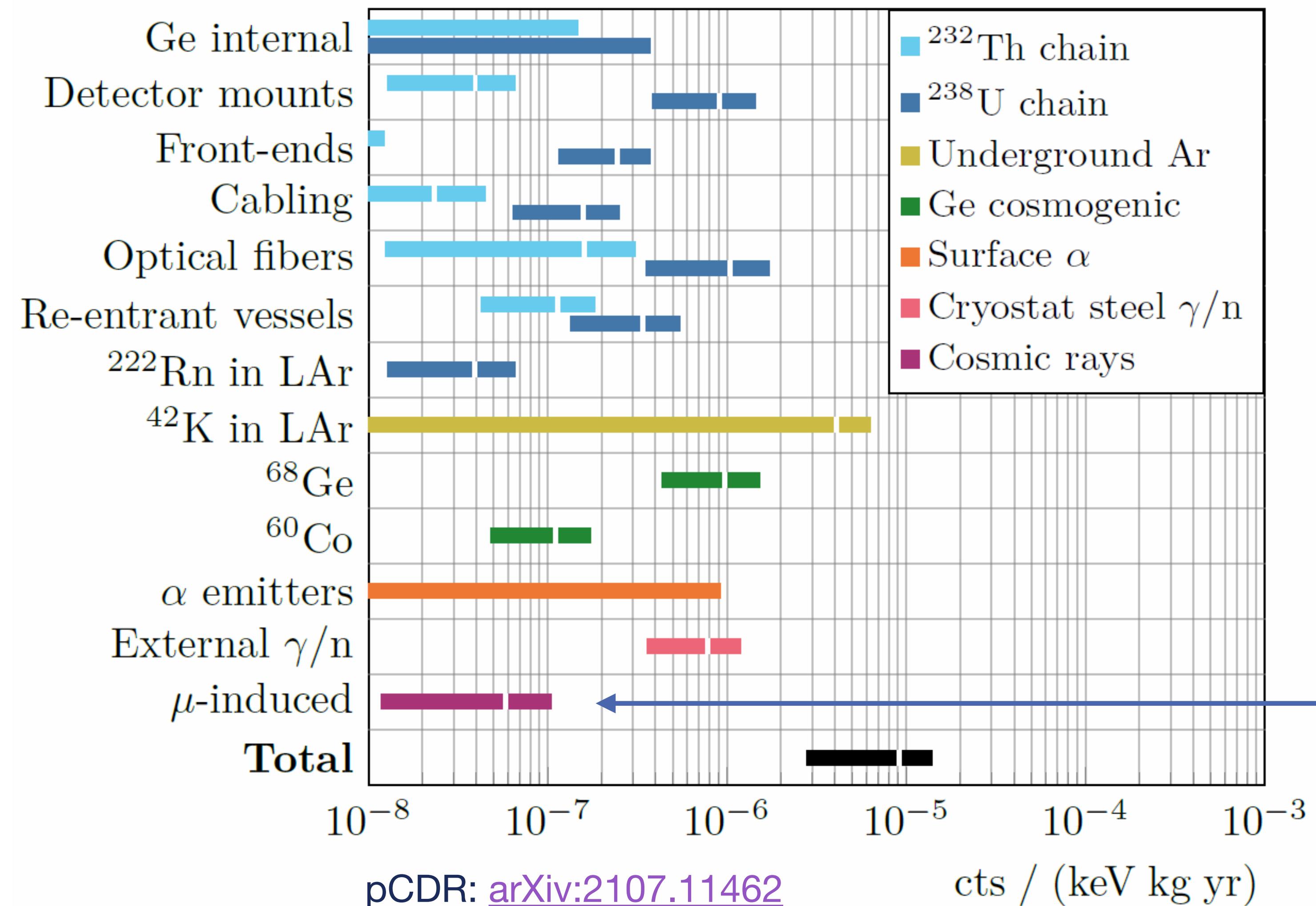
Bi-Po coincidences in Rn chains  
μ-induced cosmogenic - e.g. 77(m)Ge  
(Important and effective for LNGS depth)

Comparison of signal and background populations



# Total Backgrounds: Components

## Background Index After Cuts



Projected background index  
after all cuts:

$$< 10^{-5} \text{ cts} / (\text{keV kg yr})$$

The background model is being refined  
based on the latest conceptual design:

- Updated detector layout and spacing
- New material radiopurity assays
- Additional detail of internal components

Estimate based on SNOLAB depth

At LNGS, recent estimates bring  $\mu$ -induced component to  $4 \times 10^{-7} \text{ cts}/(\text{keV kg yr})$   
→ tagging delayed coincidences of cosmogenic  $^{77(m)}\text{Ge}$

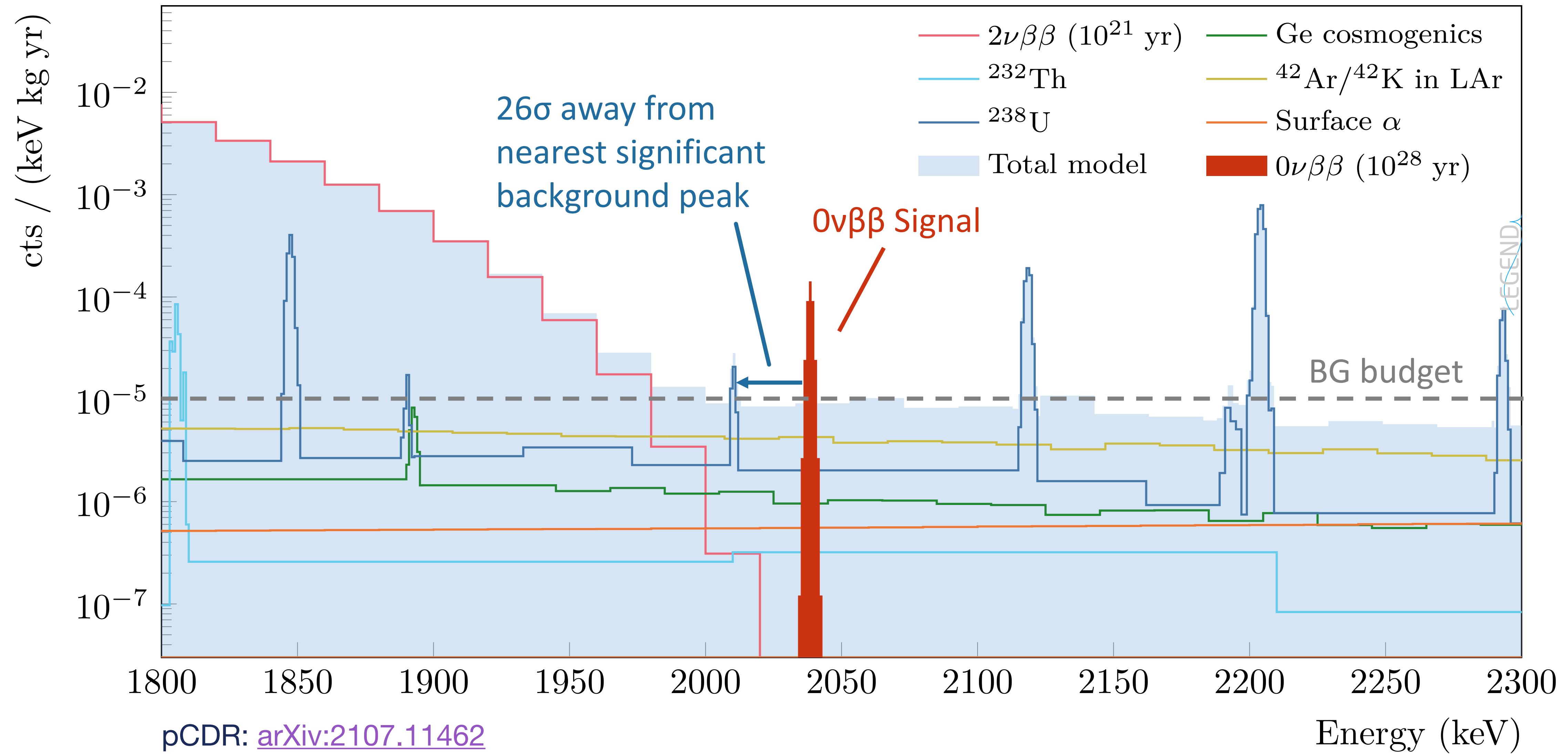
[Constraining the Ge-77\(\*m\*\) Production with GERDA](#)

[Data and Implications for LEGEND-1000](#)

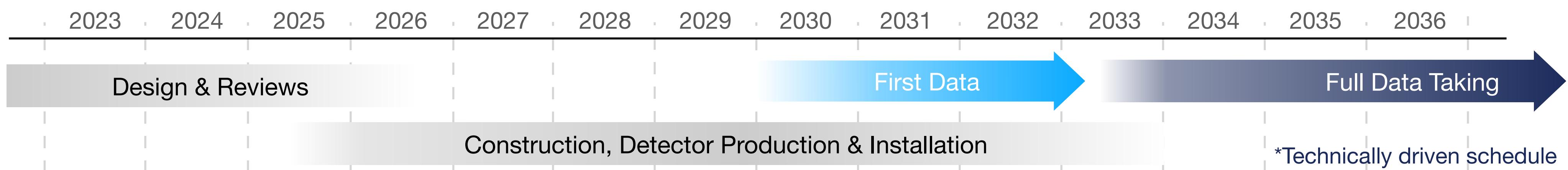
Moritz Neuberger

# The LEGEND-1000 Background Model

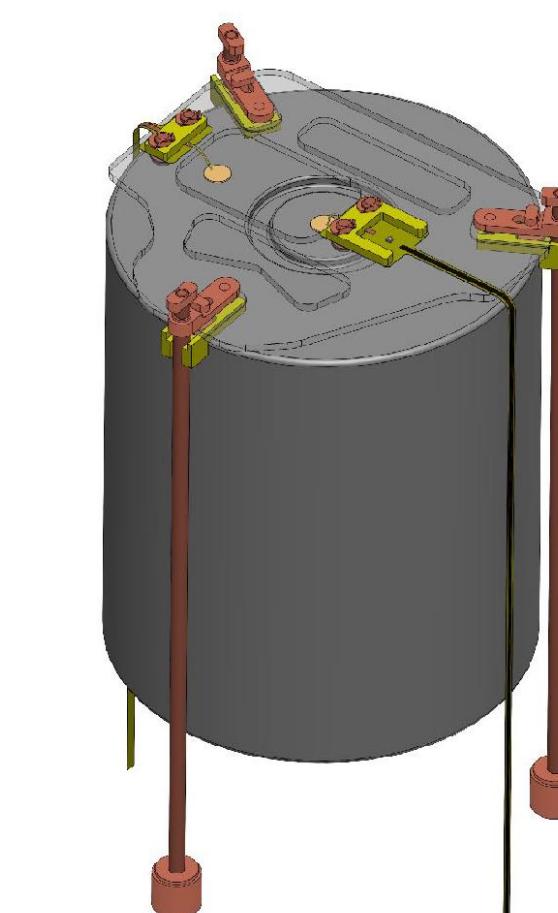
LEGEND



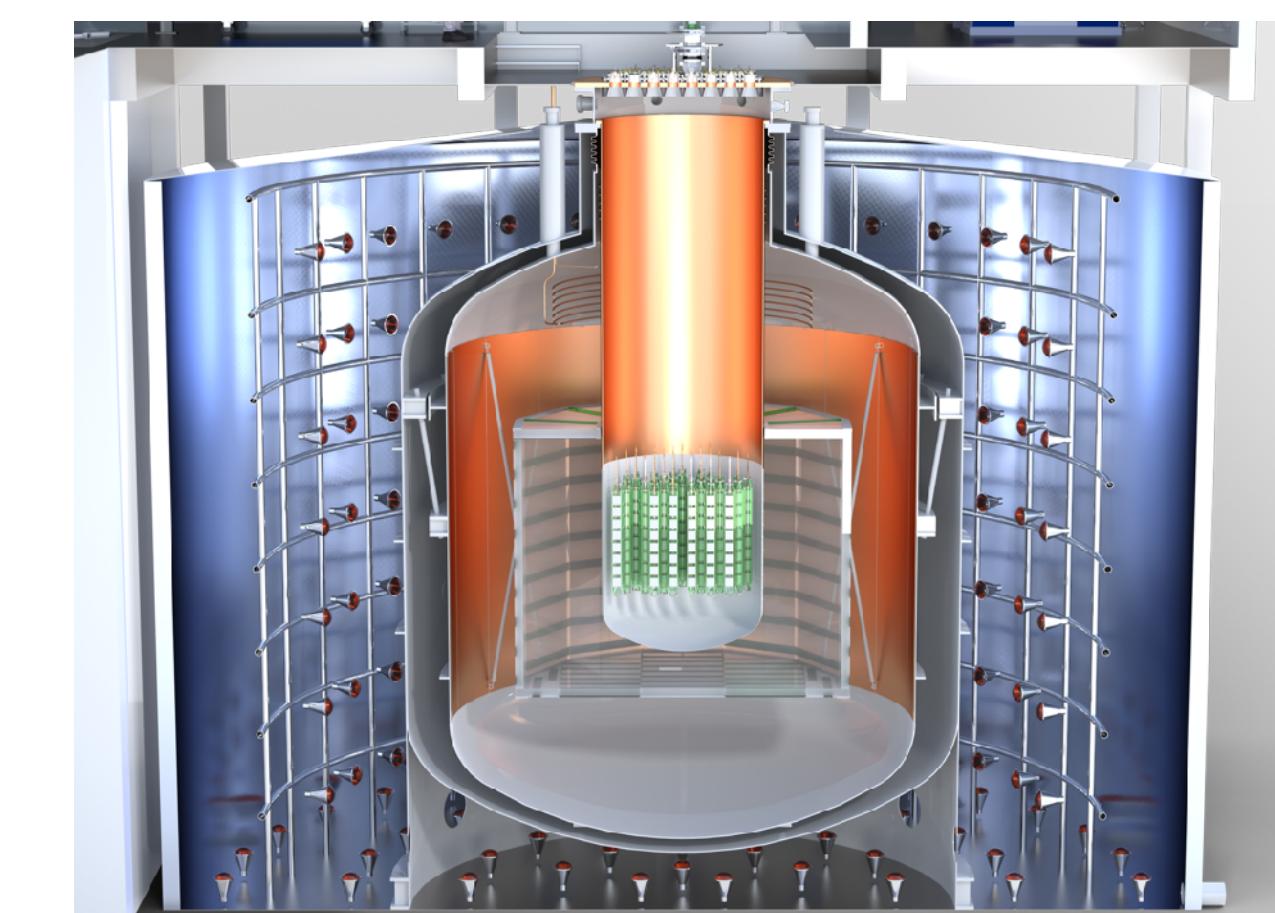
# LEGEND-1000 Timeline & Outlook



- LEGEND-1000 is optimized for a quasi-background-free  $0\nu\beta\beta$  search
  - It builds on breakthrough developments by GERDA, MAJORANA, and LEGEND-200
  - LEGEND has a low-risk path to meeting its background goal of  $10^{-5}$  counts/(keV kg yr)
  - Low backgrounds, excellent resolution, and event topology discrimination allow for an unambiguous discovery of  $0\nu\beta\beta$  decay at  $T_{1/2} = 10^{28}$  years
- The reference design accommodates siting in SNOLAB Cryopit or LNGS Hall C



LEGEND Website  
<https://legend-exp.org/>



**Talks:**

[LEGEND-200: First glance at the background in physics data](#)

Katharina von Sturm

[LEGEND-200: From Construction to Physics Data Taking](#)

Michael Willers

**Posters:**

[LEGEND-200 Data Acquisition, Monitoring and Calibration](#)

Brady Bos

[The LEGEND-200 Liquid Argon Instrumentation: From a simple veto to a full-fledged detector](#)

Rosanna Deckert

[Background Modeling for LEGEND-200](#)

Rushabh Gala

[Ge-76 Detectors of LEGEND experiment: Production, Characterization, Performance](#)

Valentina Biancacci

[Muon Veto of the LEGEND Experiment](#)

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[Neutron Veto Instrumentation for LEGEND-1000](#)

Michele Morella

[Searching for Beyond-Standard-Model Physics with LEGEND-1000](#)

Samuel Watkins

[Constraining the Ge-77\( \$m\$ \) Production with GERDA Data and Implications for LEGEND-1000](#)

Moritz Neuberger

