

# LEGEND-1000

LEGEND

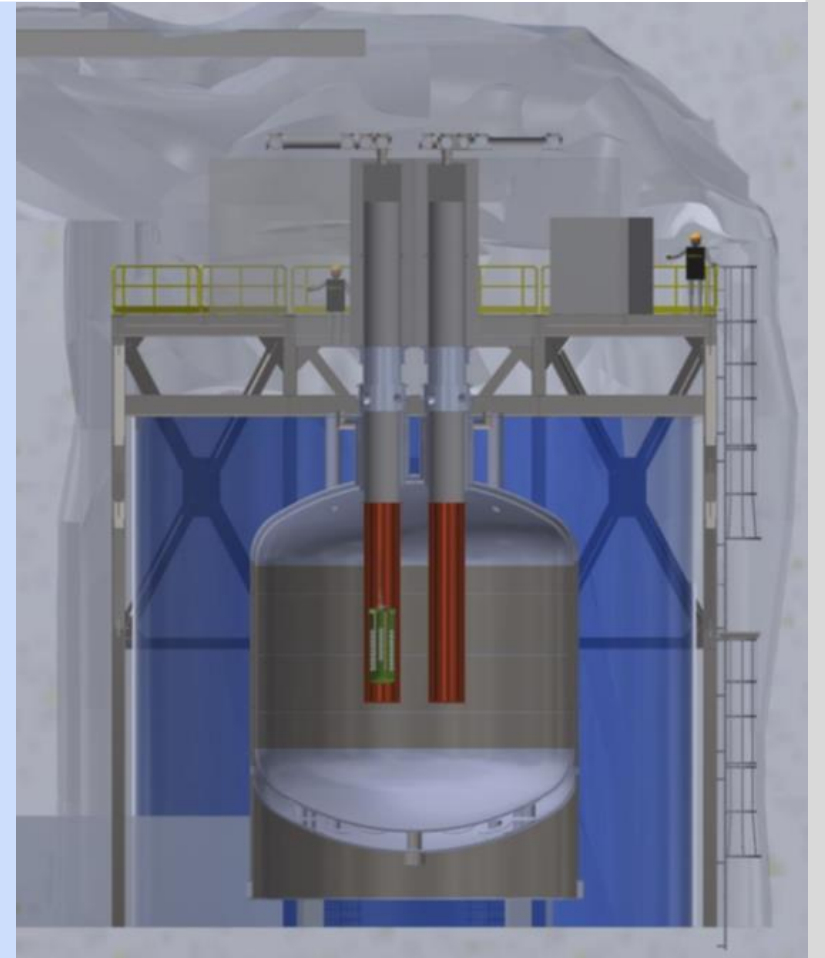
A stylized blue wave graphic that starts on the left, rises to a peak, falls to a trough, and then rises to a smaller peak on the right, passing through the word 'LEGEND'.

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

Chris Jillings

2024-02-08

SNOLAB SEF/EAC Meeting





CIEMAT  
 Comenius Univ.  
 Czech Tech. Univ. Prague and IEAP  
 Daresbury Lab.  
 Duke Univ. and TUNL  
 Gran Sasso Science Inst.  
 Indiana Univ. Bloomington  
 Inst. Nucl. Res. Rus. Acad. Sci.  
 Jagiellonian Univ.  
 Joint Inst. for Nucl. Res.  
 Joint Res. Centre Geel  
 Lab. Naz. Gran Sasso  
 Lancaster Univ.  
 Leibniz Inst. for Crystal Growth

Leibniz Inst. for Polymer Research  
 Los Alamos Natl. Lab.  
 Max Planck Inst. for Nucl. Phys.  
 Max Planck Inst. for Physics  
 Natl. Res. Center Kurchatov Inst.  
 Natl. Res. Nucl. Univ. MEPhI  
 North Carolina State Univ.  
 Oak Ridge Natl. Lab.  
 Polytech. Univ. of Milan  
 Princeton Univ.  
 Queen's Univ.  
 Roma Tre Univ. and INFN  
 Simon Fraser Univ.  
 SNOLAB

South Dakota Mines  
 Tech. Univ. Dresden  
 Tech. Univ. Munich  
 Tennessee Tech. Univ.  
 Univ. of California and LBNL  
 Univ. College London  
 Univ. of L'Aquila and INFN  
 Univ. of Cagliari and INFN  
 Univ. of Houston  
 Univ. of Liverpool  
 Univ. of Milan and INFN  
 Univ. of Milano Bicocca and INFN  
 Univ. of New Mexico  
 Univ. of North Carolina at Chapel Hill

Univ. of Padova and INFN  
 Univ. of Regina  
 Univ. of South Carolina  
 Univ. of South Dakota  
 Univ. of Tennessee  
 Univ. of Texas at Austin  
 Univ. of Tuebingen  
 Univ. of Warwick  
 Univ. of Washington and CENPA  
 Univ. of Zuerich  
 Williams College

+ UC San Diego

- Two collaboration developments
- Introduction to  $0\nu\beta\beta$  with Ge-76: “the inputs” to LEGEND
- Highlights from LEGEND-200 presentations at TAUP-2023
- LEGEND-1000 Goals and design to achieve them
- The “Analysis of Alternatives”
- Conceptual Design Report
- Final Remarks

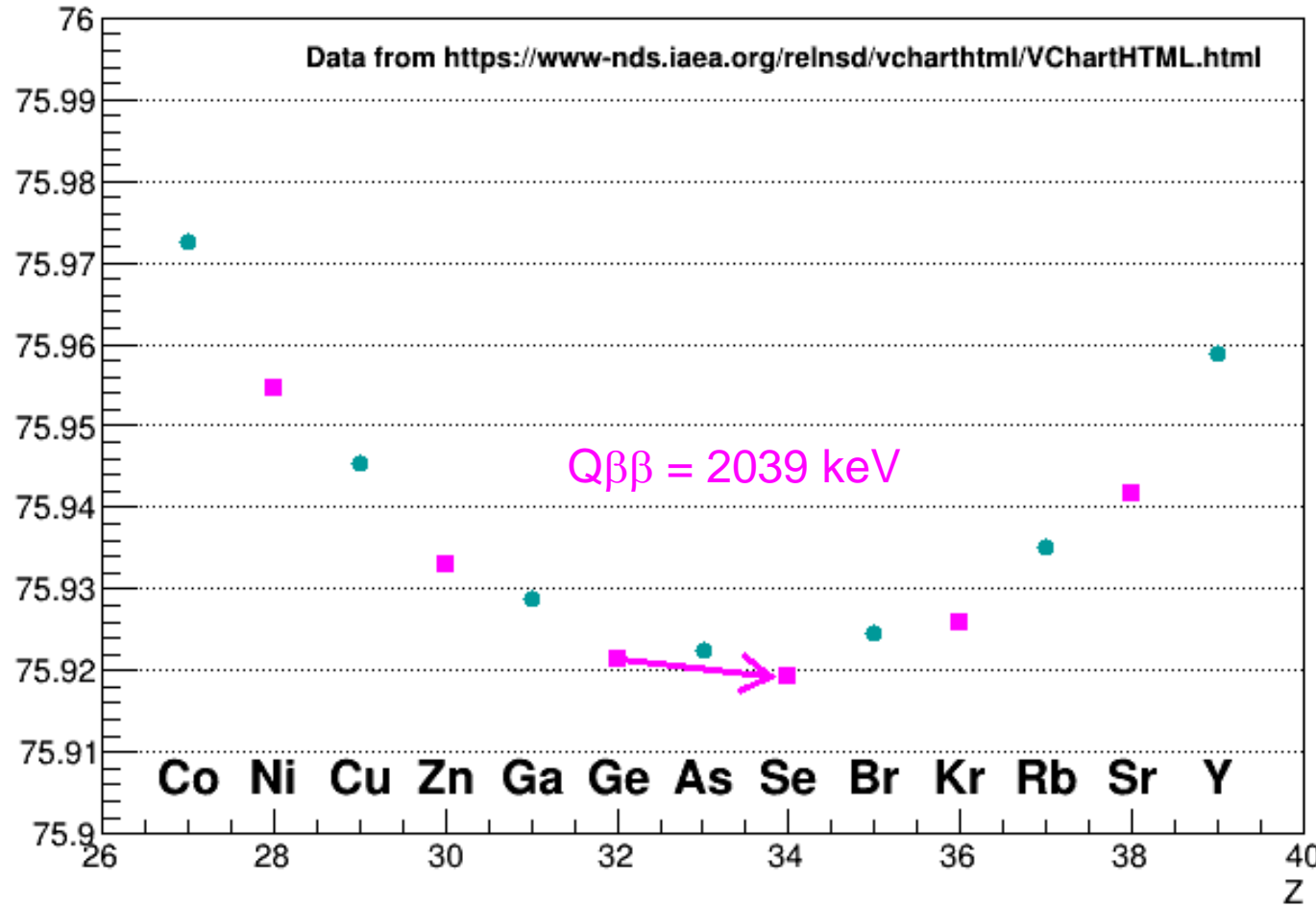
# Recently implemented both DEI and Mentorship committees

These committees have a variety of responsibilities including: meetings being conducted without inappropriate behavior, forming plans for developing the careers of our membership with a focus on early-career members, reviewing our policies to address inclusion issues.

$0\nu\beta\beta$  candidates are even-even nuclei as the mass parabola for odd-odd nuclei is shifted

76 AMU

Atomic Mass for A=76



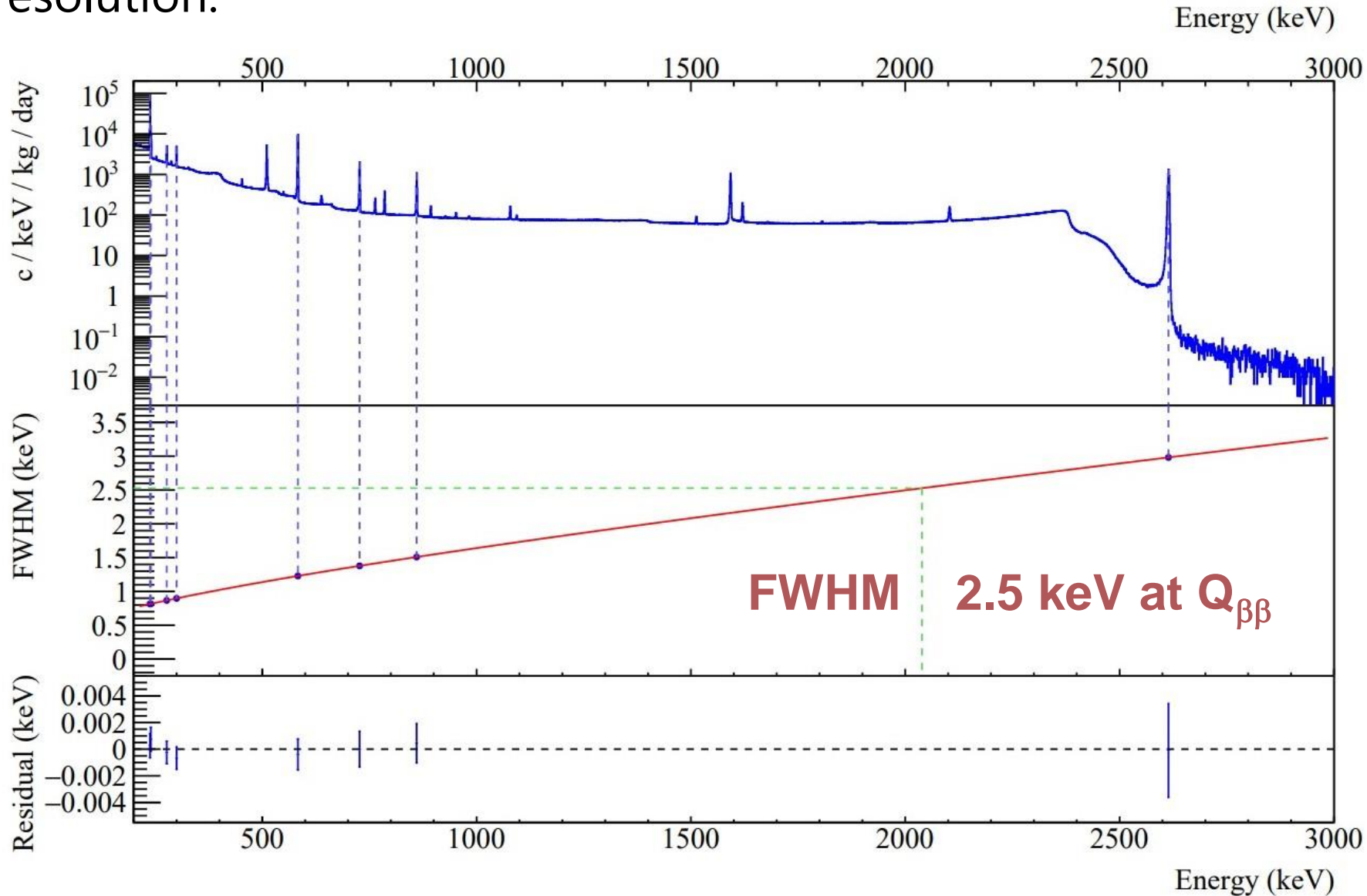
Odd odd nuclei

Even even nuclei

Single beta decay to As is energetically forbidden

75.9 AMU

Ge crystals with point-contact and electronics near crystal allows for exceptional pulse shape discrimination while maintaining energy resolution.

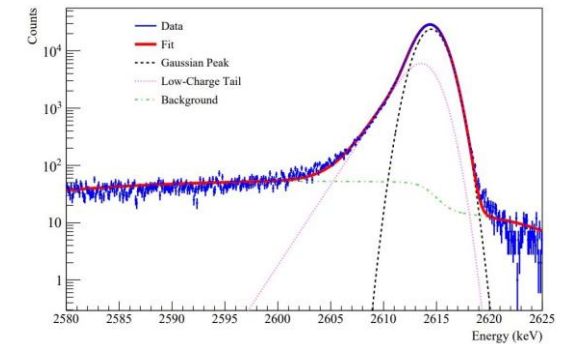


Combined energy calibration for DS0-6

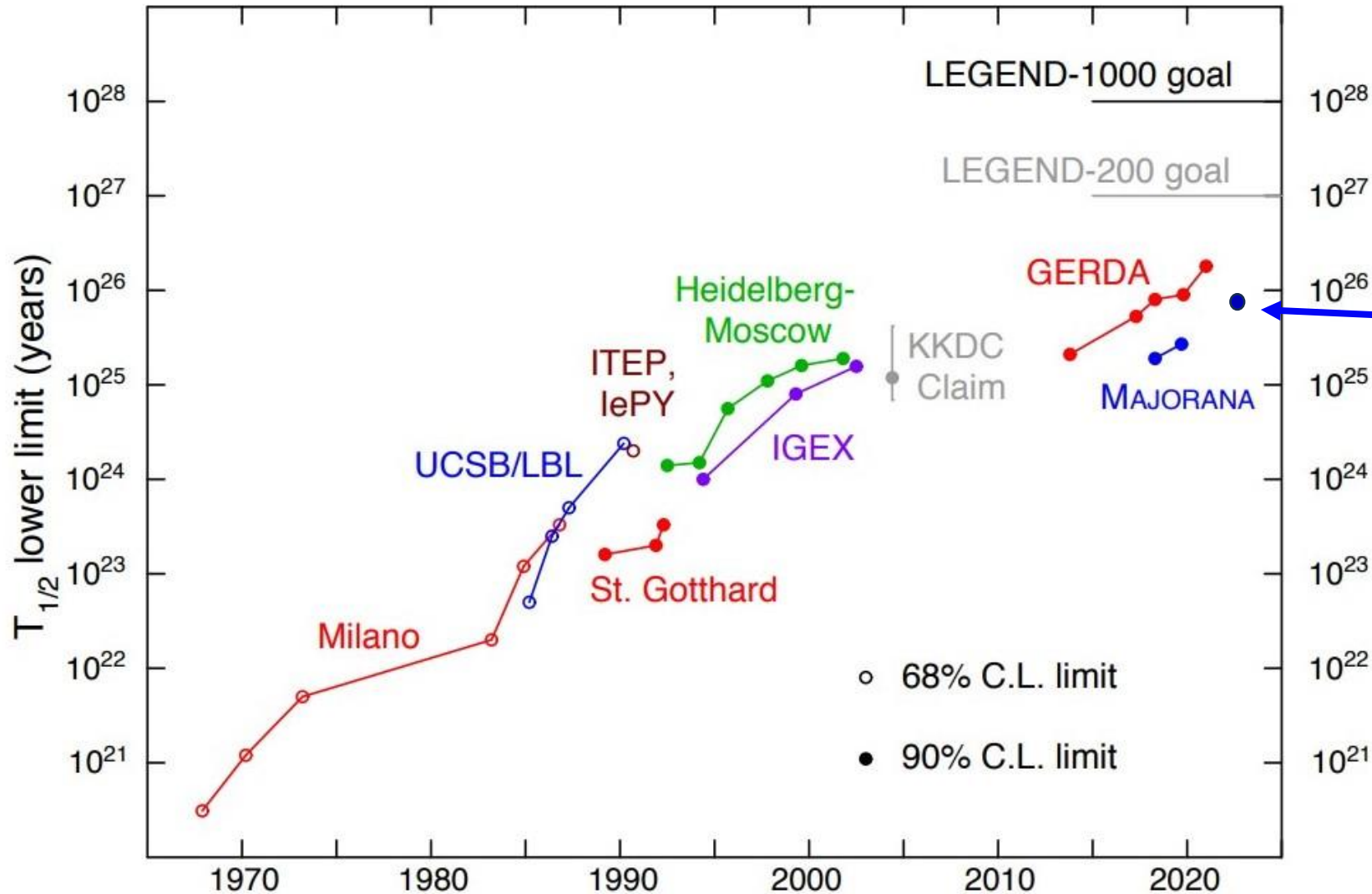
**Majorana Demonstrator**

<https://arxiv.org/abs/1902.02299>

Zoom into TI-208 peak



# Ge-76 has a long history in $0\nu\beta\beta$ searches



PRL 130, 062501 (2023)  
 $T_{1/2} > 8.3 \times 10^{25}$  yr (90%CL)

Data tabulated in review by Avignone and Elliott.  
<https://doi.org/10.3389/fphy.2019.00006>  
<https://arXiv.org/abs/1901.02805>

# LEGEND-200 highlights from TAUP-2023

## Integration & Commissioning

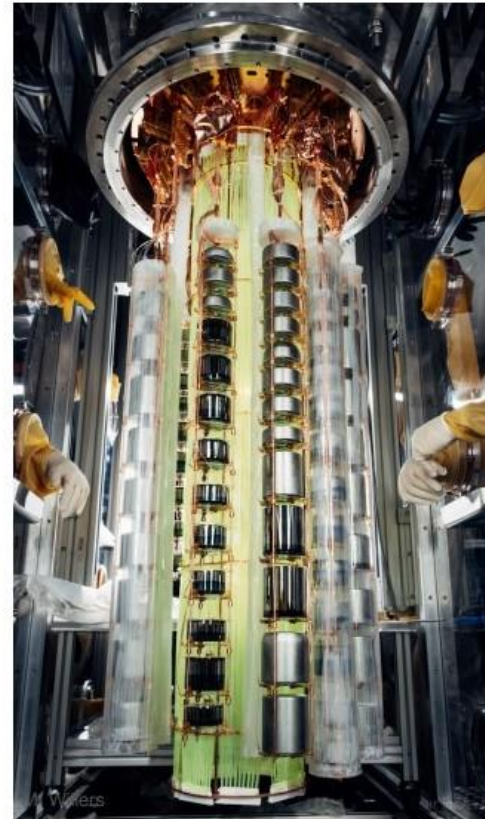


E. Sacchetti

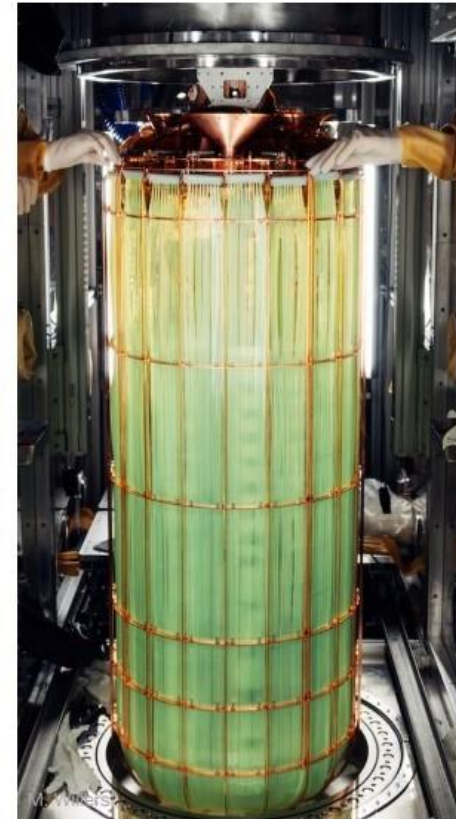


Photo: E. Sacchetti

**60 kg campaign:**  
First operation of 60 kg of HPGe detectors and full LAr instr.  
Final hardware optimisations  
Special calibration runs



**142 kg installation:**  
Installation of all available HPGe detectors as well as full LAr installation, DAQ, readout electronics



**LAr instrumentation:**  
Construction & commissioning of LAr instr. hardware & readout electronics.

M. Willers | L-200 from construction to physics data taking | 29. Aug. 2023





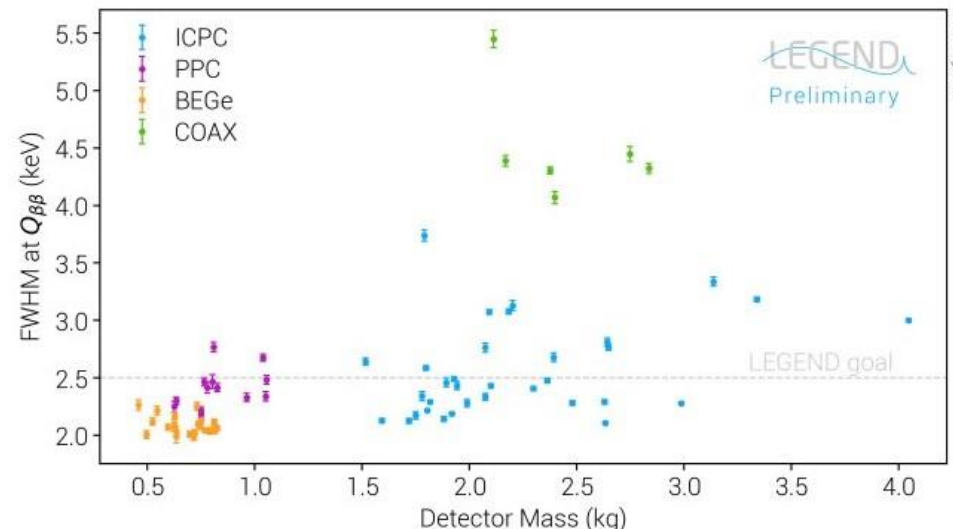
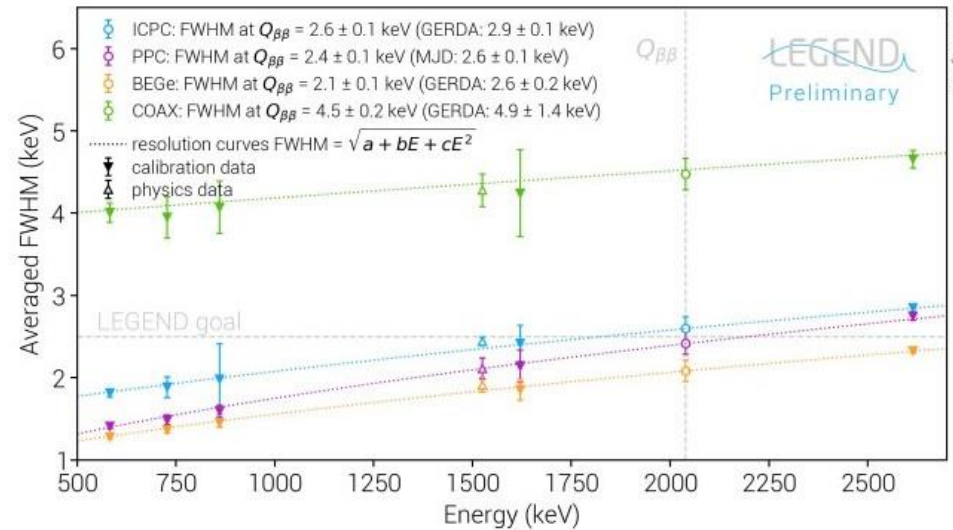
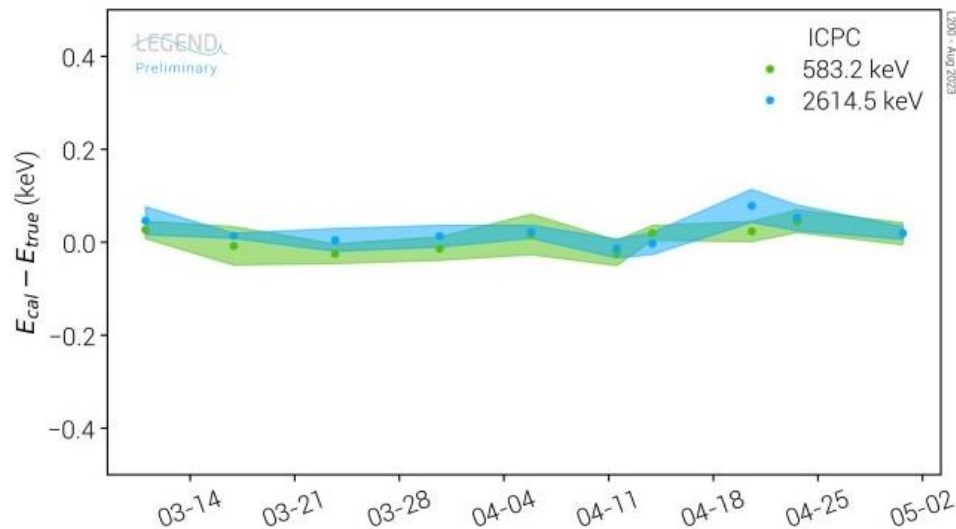
# LEGEND-200 highlights from TAUP-2023



## Energy Resolution & Stability

Weekly energy calibration between physics runs using  $^{228}\text{Th}$  sources

- Overall improvement in energy resolution @  $Q_{\beta\beta}$
- Energy scale very stable between calibrations



M. Willers | L-200 from construction to physics data taking | 29. Aug. 2023

# LEGEND-200 highlights from TAUP-2023

## Background Index

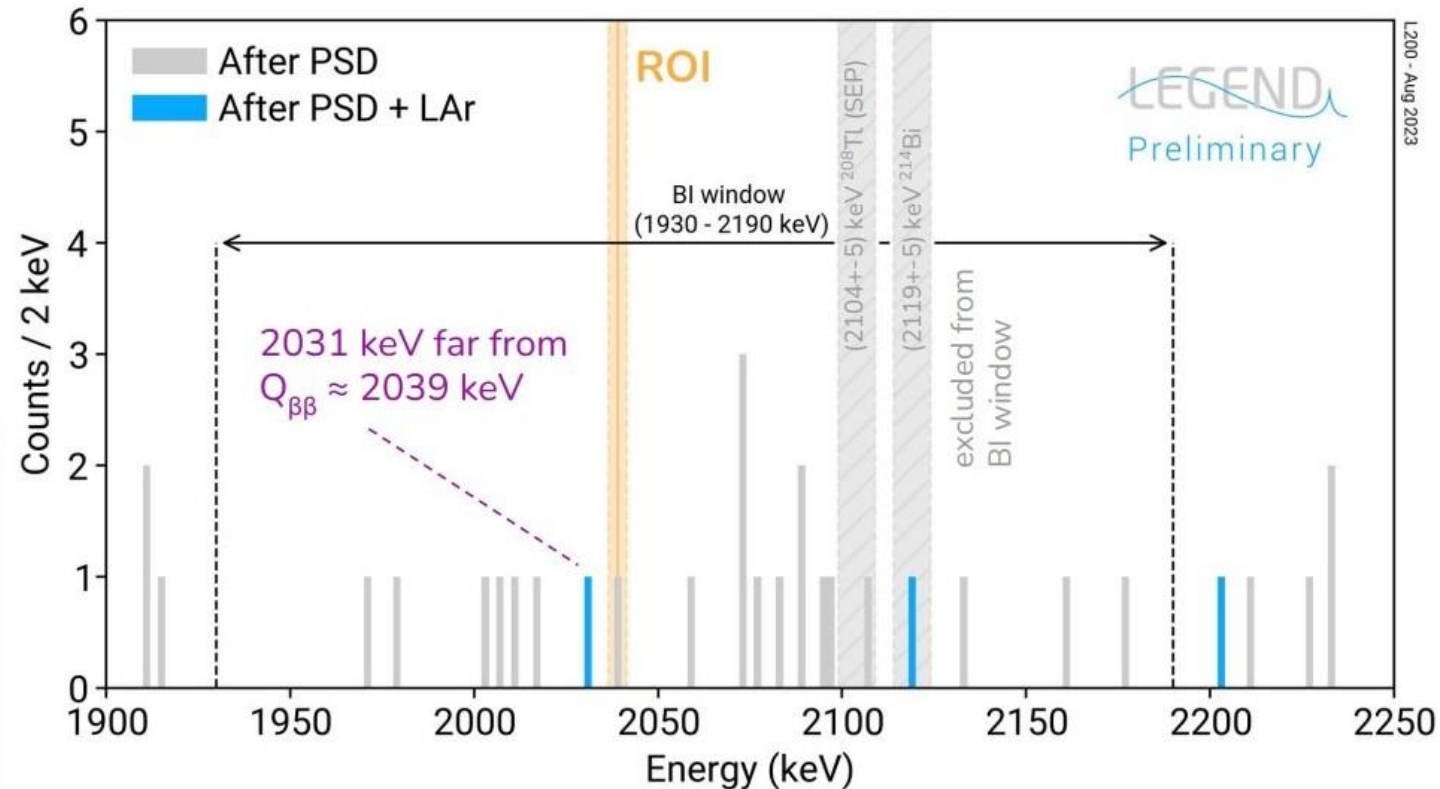
Wide background window: single event.  
It will take time to improve the background measurement.

- First 10.1 kg yr of LEGEND-200 data
- ICPC & BEGe
- LAr accepted
- PSD accepted

- BI is compatible with LEGEND-200 goal
- Expect 0.48 cts
- Probability to observe

#cts > 0 ~ 38%

window 240 keV & exposure 10.1 kg yr



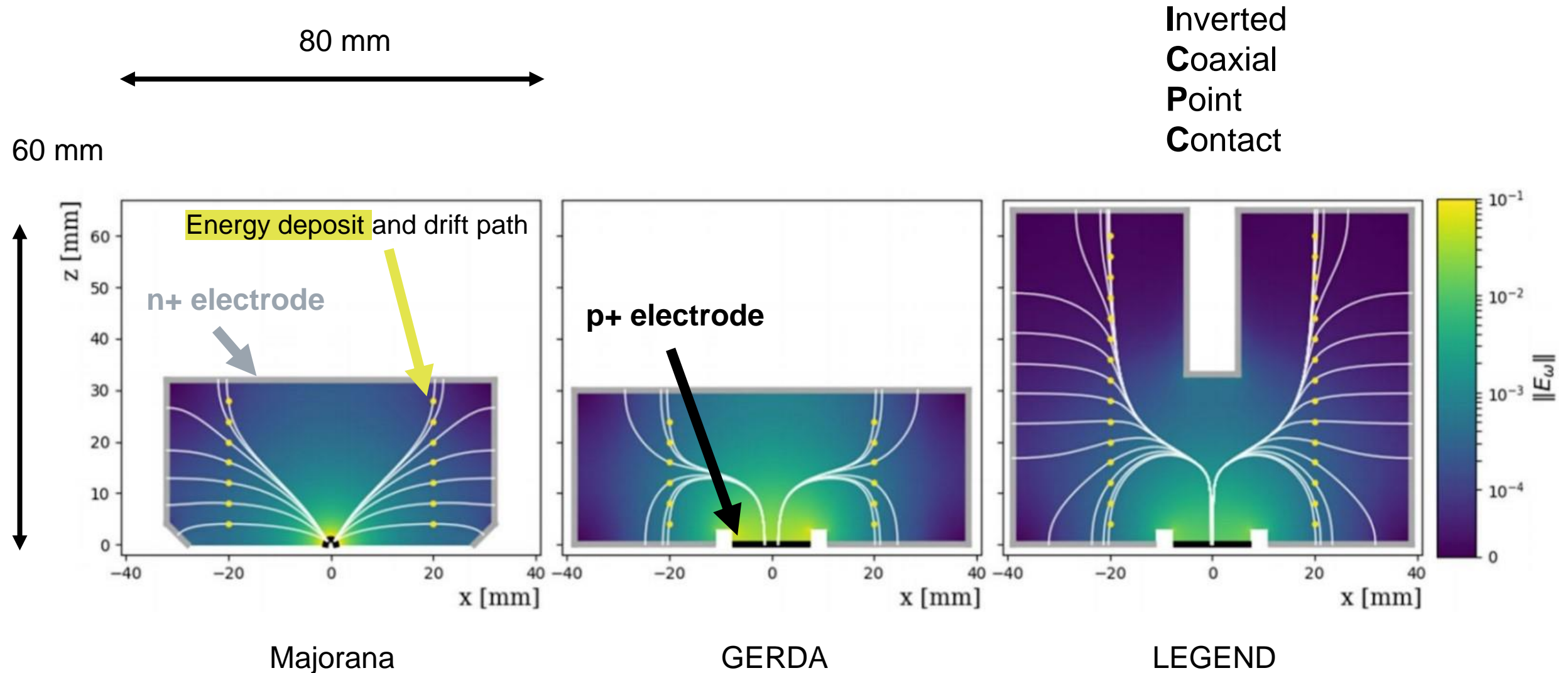
	LEGEND-200 BI 68% CL (cts/keV/kg/yr)	GERDA Phase II unblinded BI 68% CL (cts/keV/kg/yr)
After LAr & PSD	$4.1 [1.5, 11.4] \times 10^{-4}$	$5.2 [3.9, 6.8] \times 10^{-4}$

Maintenance of the liquid argon and detector systems and deployment of additional HPGe detectors

Detailed scheduling will take L-1000 review into account

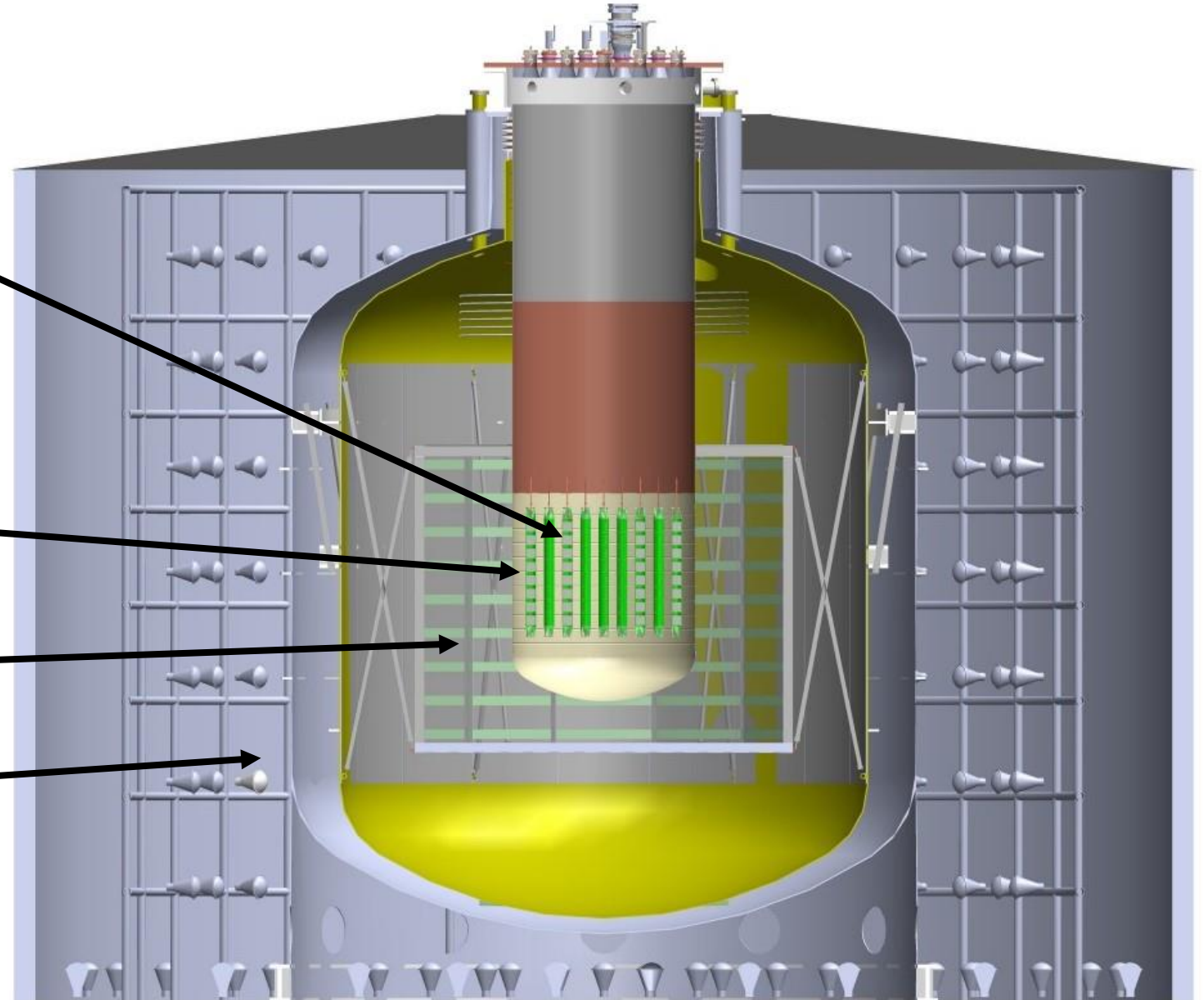
2-3 months work

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

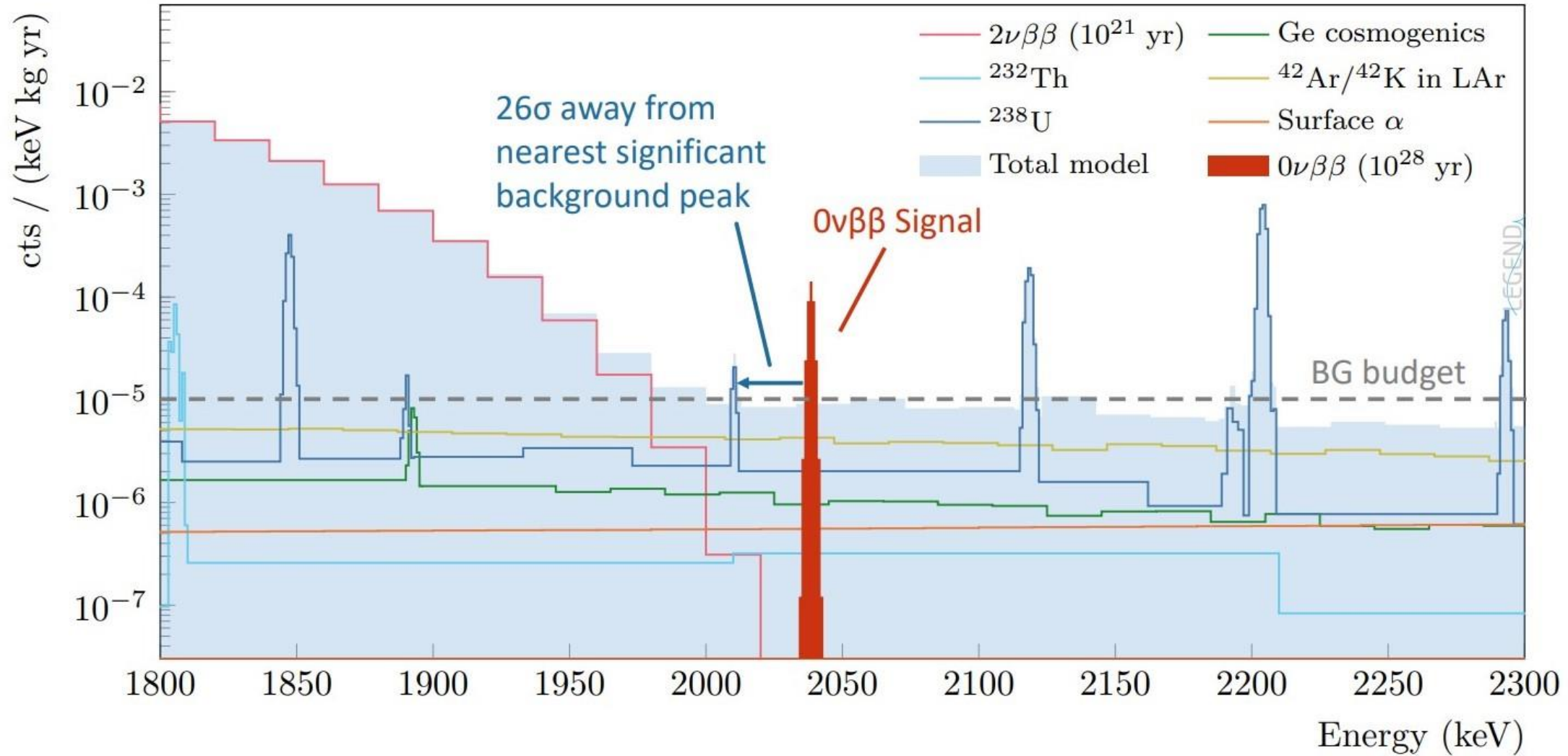


# Many techniques are used to control background:

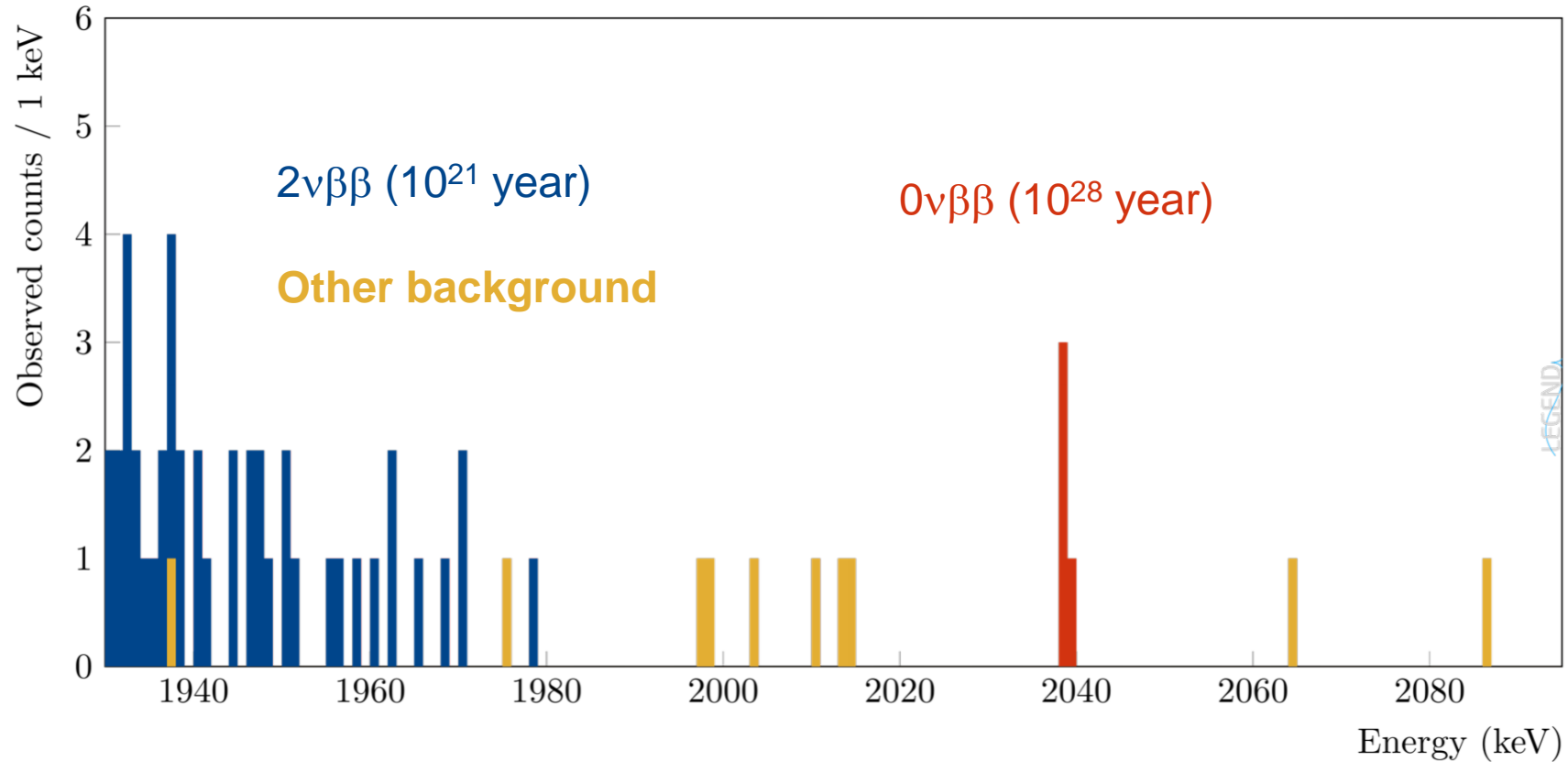
- Bare crystals with small-mass electronics (ASIC) near crystal: Exquisite energy resolution
- PSD in analysis to reject multi-site events
- Crystals in instrumented underground liquid-argon bath for cooling and Compton rejection
- Instrumented atmospheric argon shield
- Instrumented water shielding tank



# LEGEND-1000 Background Model



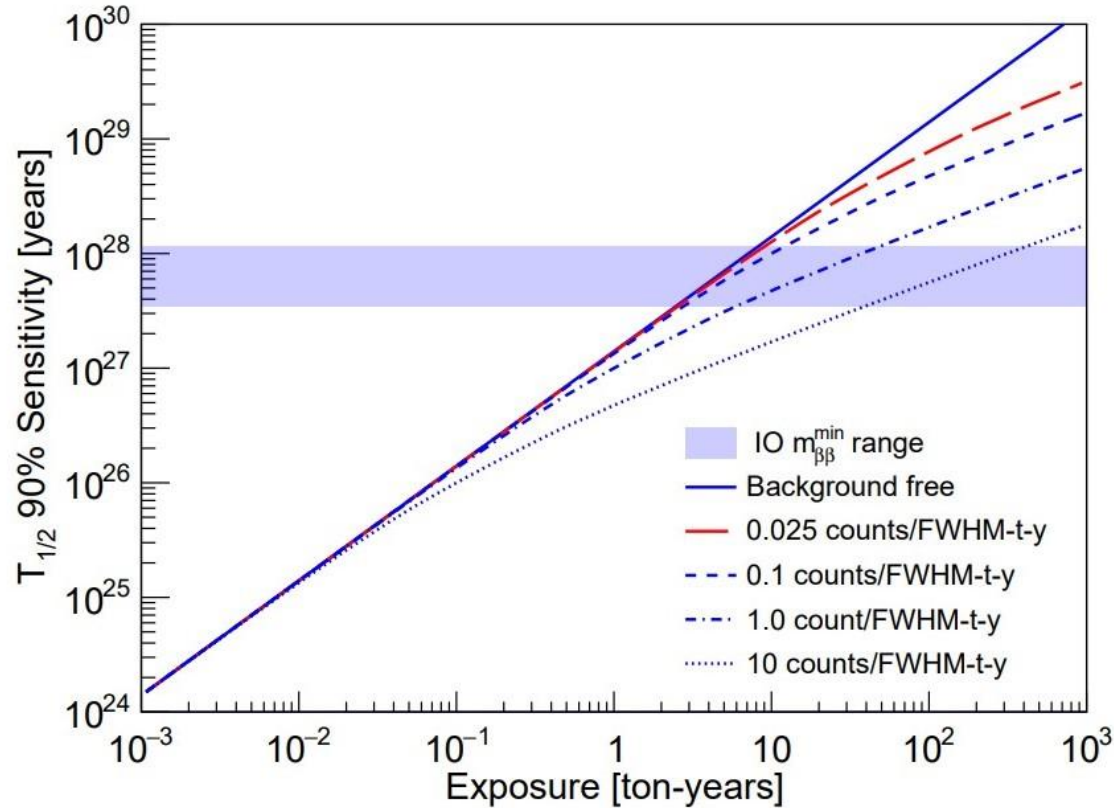
# A sample 10 t-yr synthetic data set illustrates discovery potential



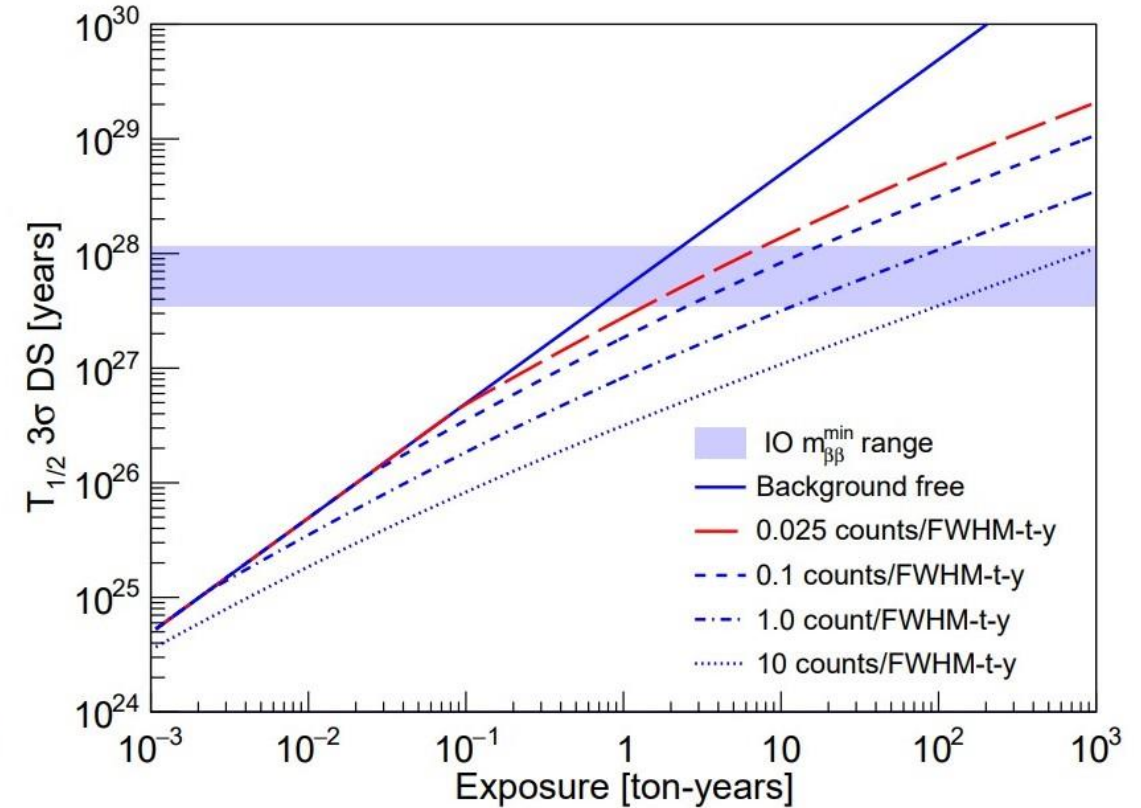
Discovery: a 50% chance or greater that a 10 tonne-year results in a signal  $3\sigma$  above null hypothesis

# LEGEND-1000 is designed to have $0\nu\beta\beta$ discovery potential at a $10^{28}$ year half life

$^{76}\text{Ge}$  (91% enr.)



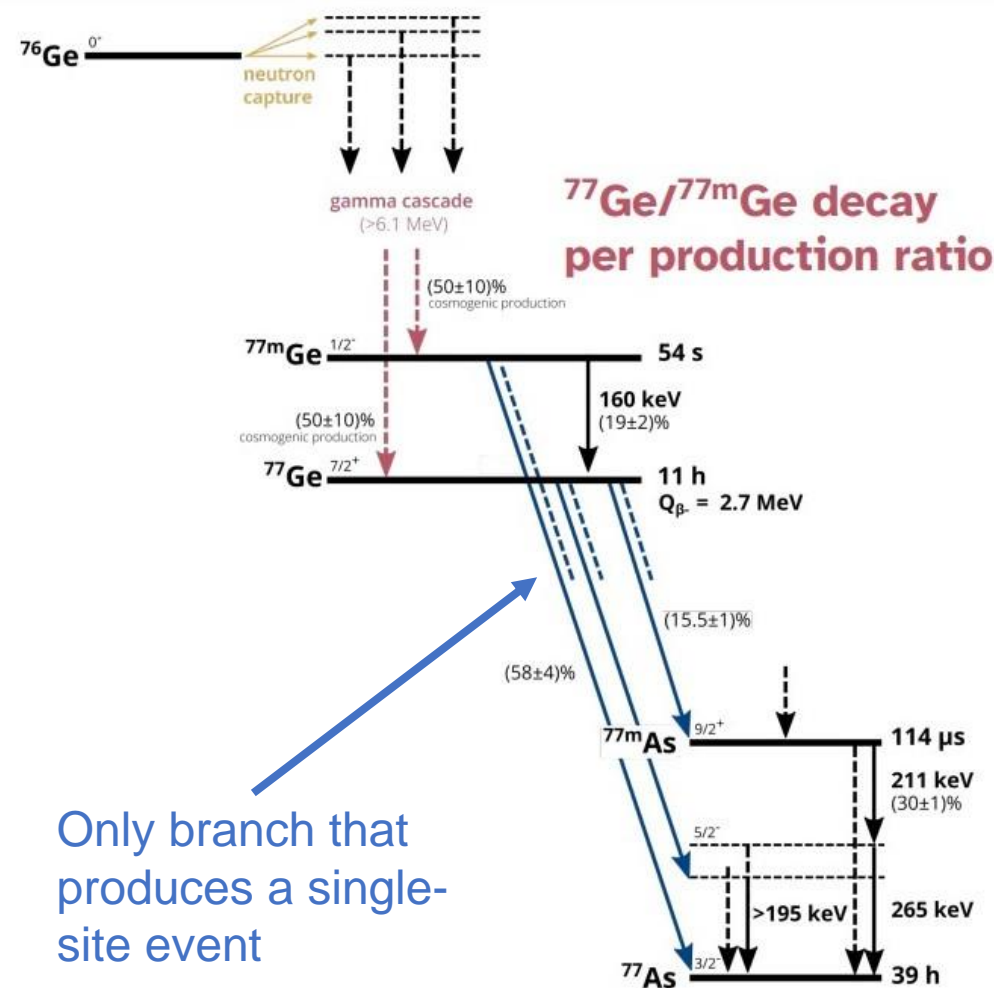
$^{76}\text{Ge}$  (91% enr.)





# Recent improvements: cosmogenic backgrounds

- Acrylic panels added to design in outer argon detector to thermalize neutrons
- A method for tagging cosmogenic fast neutrons has been developed in the instrumented outer (atmospheric) argon.
- Only one branch of Ge-77m produces a single-site event in LEGEND. Use a veto after a neutron signal.
- With a loss of ~3% livetime, the total background rate at LNGS similar to that at SNOLAB.
- With this improvement in place, the physics reach at LNGS and SNOLAB are very similar.
- The detailed study will be published shortly and included in the Conceptual Design Report
- A search for Ge-77m in LEGEND-200 is underway – will be upcoming publication.

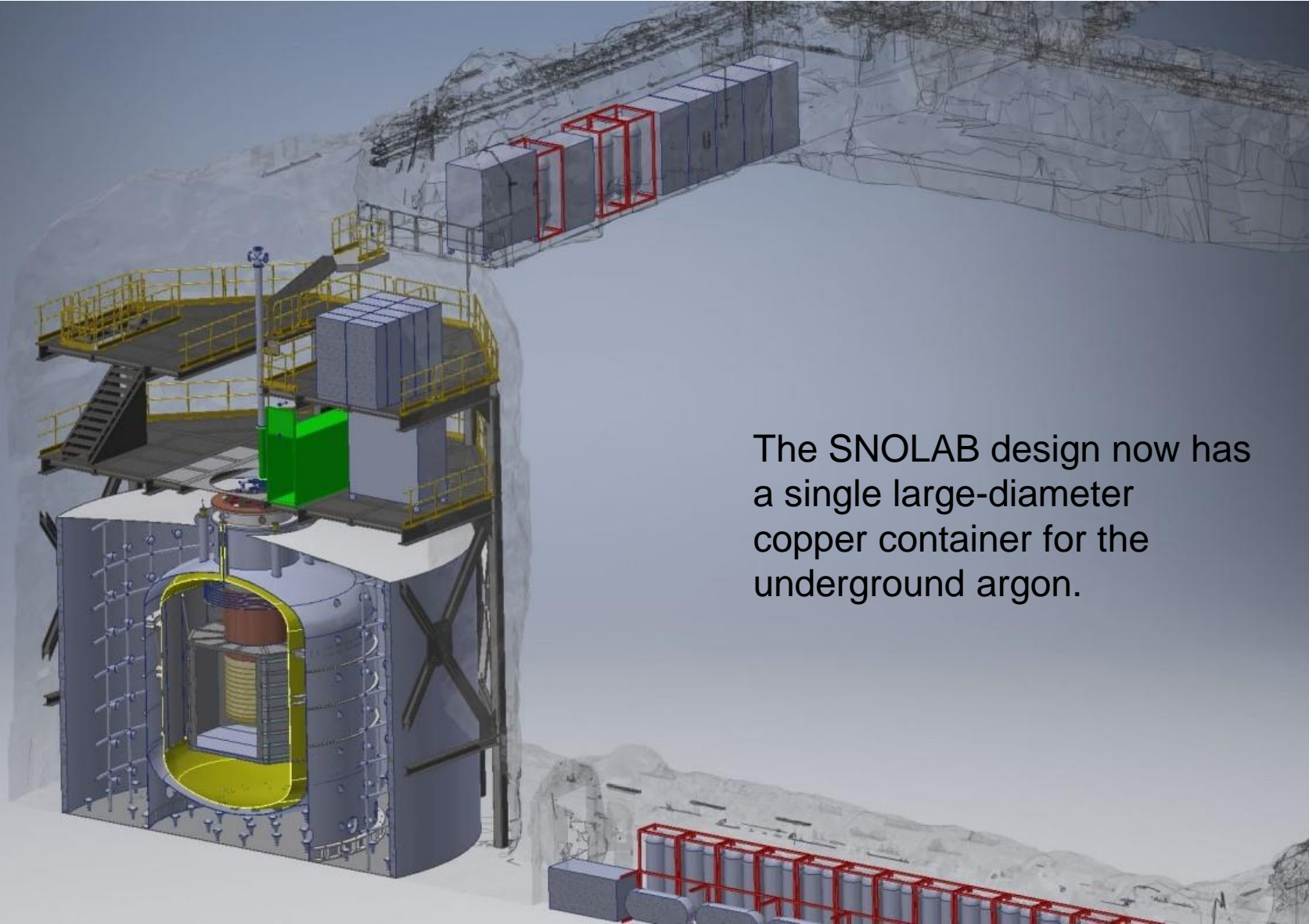


# Changes and updates since last meeting: Analysis of Alternatives

- The DOE launched an ongoing process to examine alternatives for LEGEND-1000.
- Draft recommendations include
  - LEGEND-1000 is needed to meet the  $10^{28}$  year half life sensitivity and therefore cover the inverted hierarchy space. (LEGEND-200 will reach  $10^{27}$  years.)
  - LNGS is the baseline location. The LNGS site has reduced cost to the DOE while maintaining the physics goal.

# Project developments:

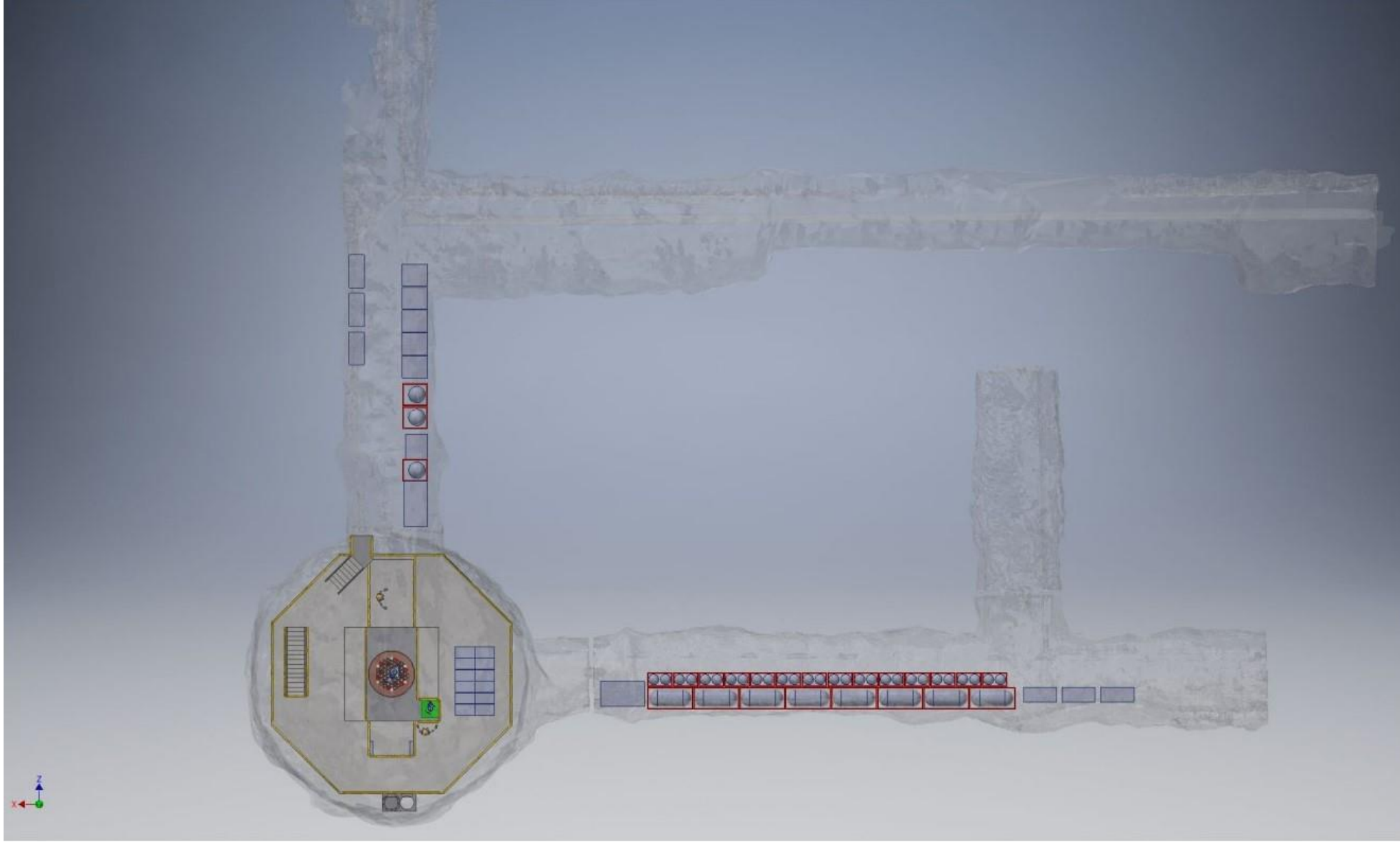
SNOLAB design moving to single large re-entrant tube



The SNOLAB design now has a single large-diameter copper container for the underground argon.

# Project developments:

A second set of layout drawings is in development for the CD-1 process



# Milestones: The CD-1 Process

- January 2024
  - Review at Oak Ridge National Lab to prepare for CD-1
- CD-1 IPR review first week in June.
- CD-1 ICR review not formally scheduled, but typically held two weeks prior to the IPR.

# Schedule and Project Overview

information from presentations by D. Radford this week

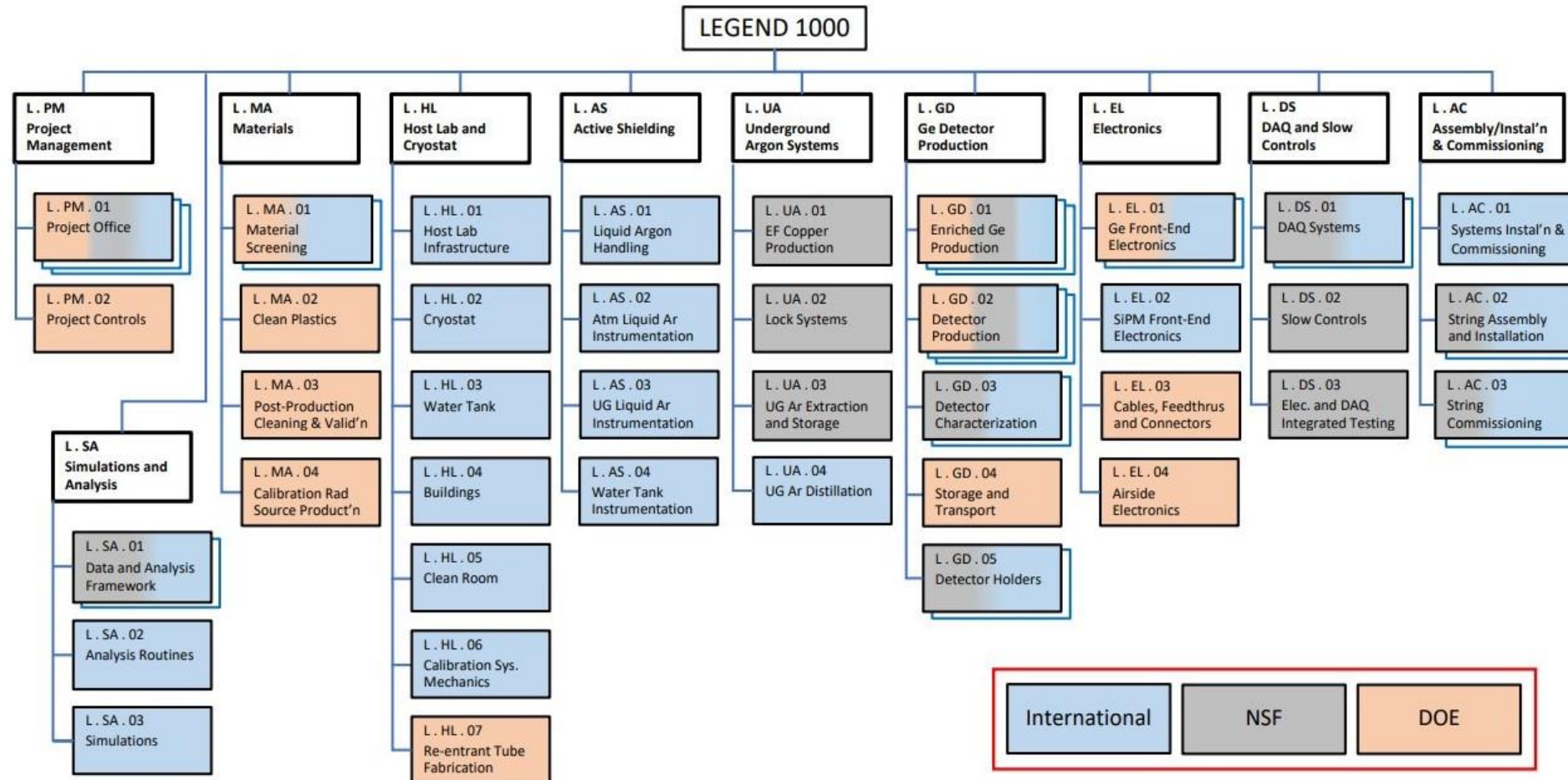
## Project Scope and Organization

- At the time of the Portfolio Review, the L1000 project scope was conceptually divided into
  - “DOE scope” (to be funded under a DOE Order 413.43b project) and
  - “International scope” (to be funded by non-US research agencies and institutions).
- It was anticipated that a proposal to NSF might also be submitted
  - NSF has been a major contributor to LEGEND-200
  - NSF partnered with DOE in the construction of the MAJORANA DEMONSTRATOR
- With the encouragement of DOE-NP, a preliminary proposal for a Mid-Scale Research Infrastructure 2 grant was submitted to NSF in June 2023, by UNC (PI: Wilkerson)
- This was successful, in that a final proposal was requested, due in December 2023
- To accommodate this proposal, the scope is now conceptually divided into three; DOE, NSF, and International
- Should the final NSF proposal be unsuccessful, DOE-NP has assured the collaboration that the DOE scope would again expand to include the NSF components

# Schedule and Project Overview

information from presentations by D. Radford this week

## Consolidated LEGEND-1000 WBS



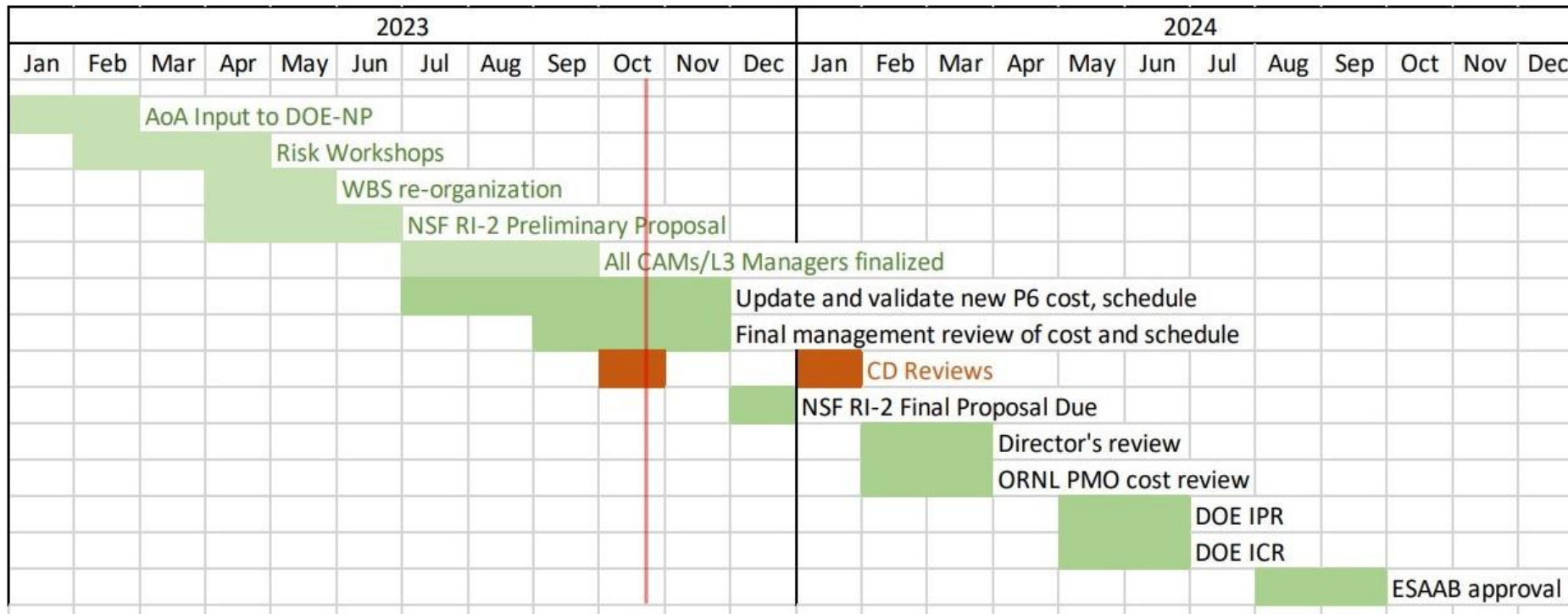
D. Radford | LEGEND Project and Charge | 2023-10-24

# Schedule and Project Overview

information from presentations by D. Radford this week

## The Path to CD-1: Schematic Schedule

- Depends on the scheduling of IPR and ICR



D. Radford | LEGEND Project and Charge | 2023-10-24

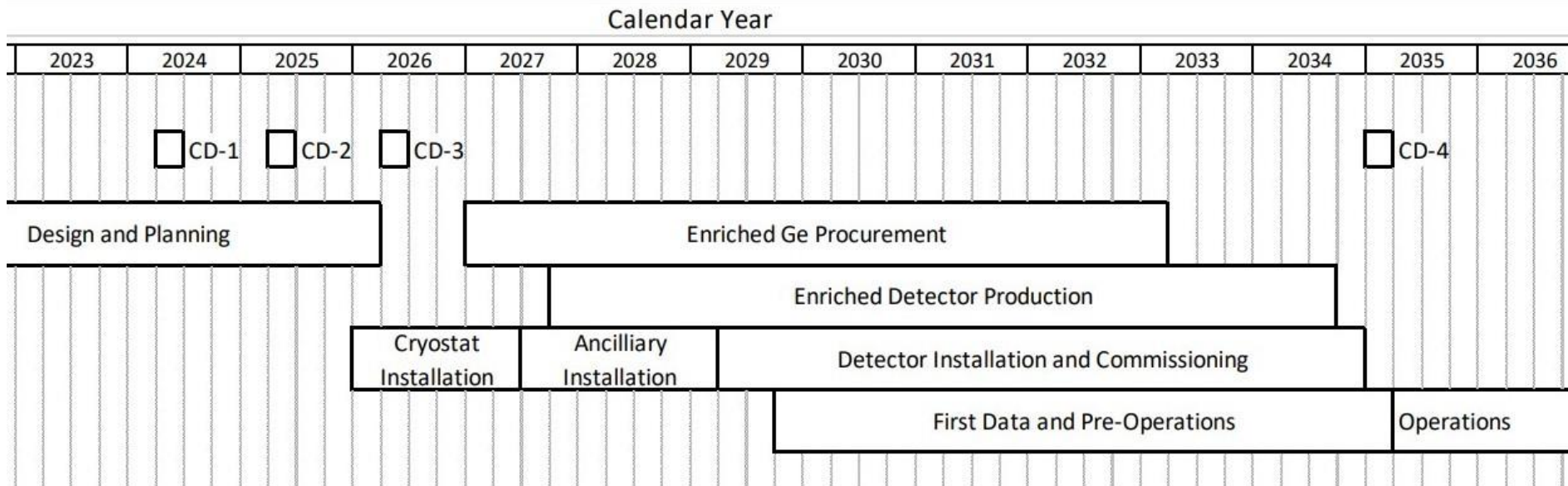


# Schedule and Project Overview

information from presentations by D. Radford this week

## Technically-driven Construction Schedule

- Notional schedule assuming technically-driven funding profile from DOE, NSF, and international partners



D. Radford | LEGEND Project and Charge | 2023-10-24

# Current work at SNOLAB

- Infrastructure and engineering
- Project management
- Radon exclusion from the lock system (assays of components to start this fall)
- Underground argon recovery
- Liquid argon process systems work and review
- Review of CDR documentation

- SNOLAB's material assay systems will be important to LEGEND.
  - Radon control and assay
  - Gamma assay
  - The SNOLAB ICP-MS system, when available

- LEGEND-200 is running at LNGS with first detector-performance and background results released at TAUP-2023
- LEGEND-1000 is in advanced design for deployment at LNGS with SNOLAB as the alternate site
- 1000 kg of enriched Ge crystals with exquisite energy resolution in an ultra-low background environment have discovery potential with a half life of  $10^{28}$  years for  $0\nu\beta\beta$  in  $^{76}\text{Ge}$
- The team at SNOLAB is working to ensure the required infrastructure and scientific contributions from the lab are ready. Radon emanation and other assay measurements will be needed.