Oak Ridge National Laboratory

LEGEND-1000

LEGEND

Large Enriched Germanium Experiment for Neutrinoless ββ Decay

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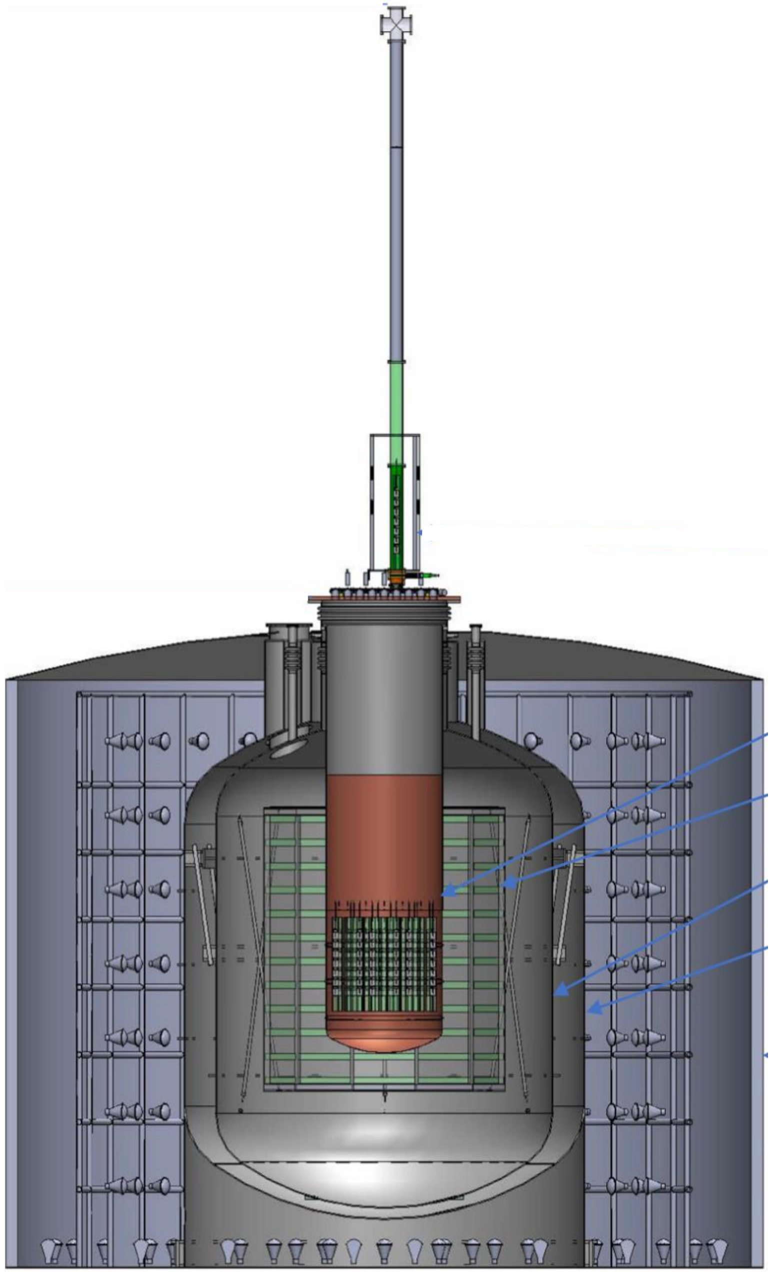
Second International Summit on the Future of DBD
SNOLAB
27 April 2023

U.S. DEPARTMENT OF ENERGY

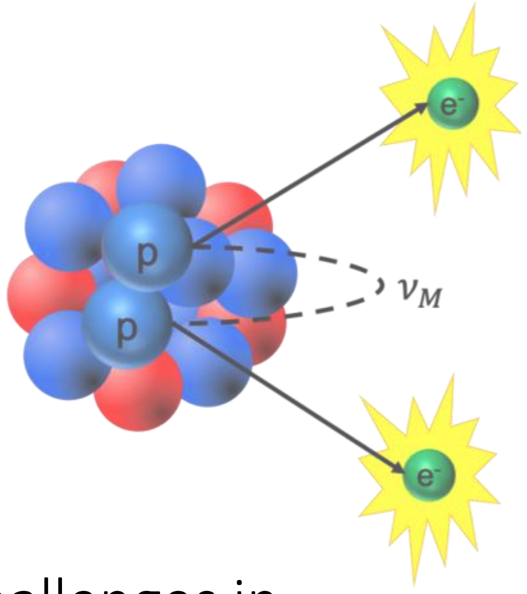
Outline

- Recap: Why 0νββ Decay? Why now?
- Why germanium-76?
- Requirements: Mass and backgrounds
  - Background sources and mitigation
- The LEGEND Design
  - Two possible sites
- Cost and Schedule
- Status and Progress
- Conclusion
  - Readiness
  - Timeliness
  - Cost-effectiveness
  - International Character



Recap: Why Neutrinoless Double Beta Decay?

- The discovery of 0νββ decay would dramatically revise our foundational understanding of physics and the cosmos
  - Lepton number is not conserved
  - The neutrino is a fundamental Majorana particle
  - There is a potential path for understanding the matter – antimatter asymmetry in the cosmos, through leptogenesis
  - There is a new mechanism demonstrated for the generation of mass



- The search for 0νββ decay is one of the most compelling and exciting challenges in all of contemporary physics

- The LEGEND Collaboration aspires to meet this challenge throughLEGEND-1000, a ton-scale search for 0νββ decay of ^{76}Ge

Why Now?

LEGEND

- The search for $0\nu\beta\beta$ decay at the ton scale was a priority recommendation in the 2015 Long Range Plan from the Nuclear Sciences Advisory Committee
- We anticipate the same priority being assigned to $0\nu\beta\beta$ decay in the new NSAC LRP (currently under development) with very strong community support
- There has been tremendous progress in developing and demonstrating the required technologies
- The projects and collaborations are in an advanced state of planning
- The field is now ready to proceed

Why Germanium-76?

I hope to convince you that ^{76}Ge provides

- A solid basis for unambiguous discovery
  - Superb energy resolution: $\sigma / Q_{\beta\beta} = 0.05\ \%$
  - Background around $Q_{\beta\beta}$ is flat and well understood
  - No background peaks anywhere near the energy of interest
  - Background will be measured, with no reliance on background modeling
  - All this leads to an excellent likelihood that an observed signal will be ***convincing***
- Low risk, high impact
  - Demonstrated performance of the entire technology chain
  - Requires no extrapolation from current detector performance
  - Previous Ge experiments have demonstrated the lowest background per FWHM of any experiment, and the best resolution
  - Proven track record, with history of leading limits

The LEGEND Collaboration

Our mission:

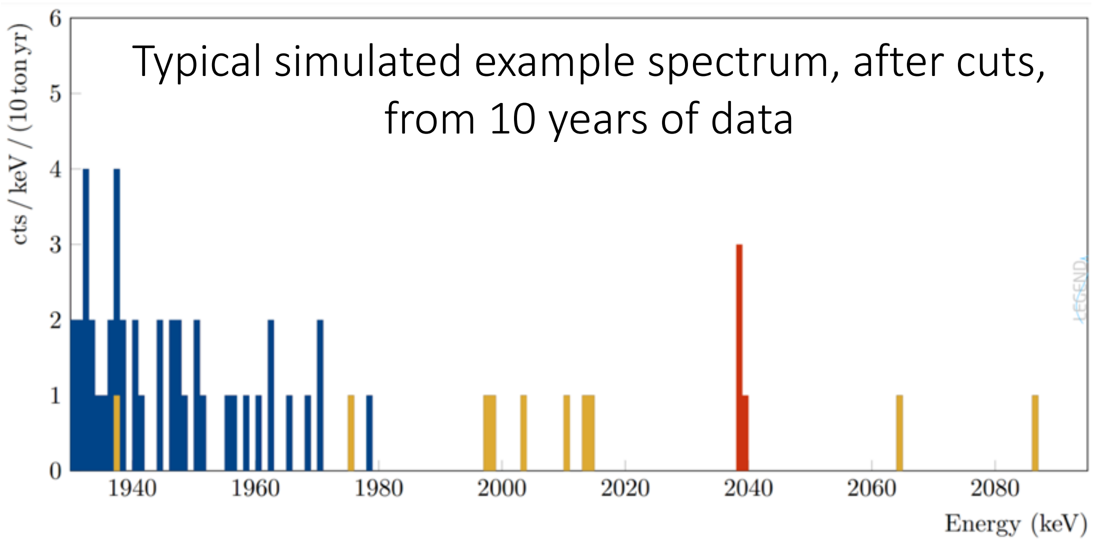
“Develop a phased, ^{76}Ge based double-beta decay experimental program with discovery potential at a half-life beyond 10^{28} years”

260 members

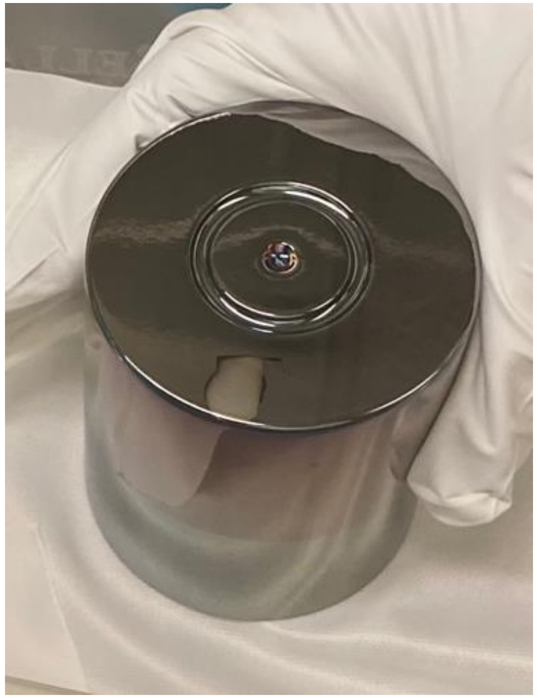
47 institutions around the world

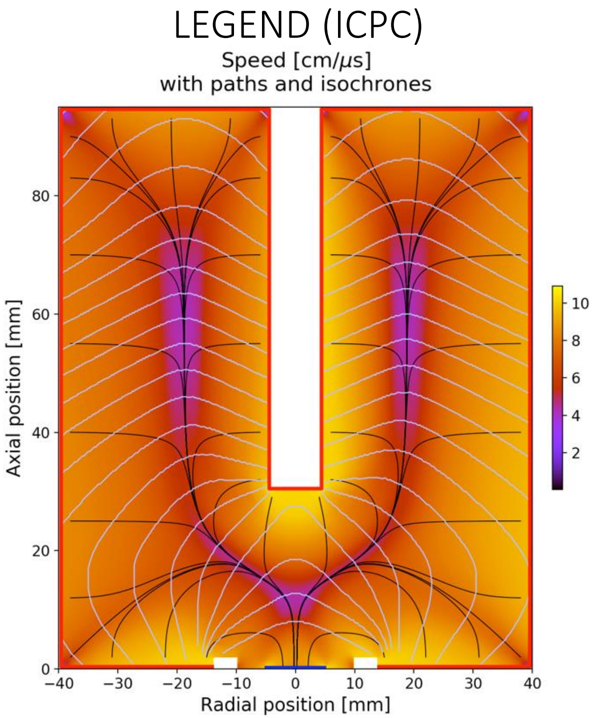
Requirements: Large Mass

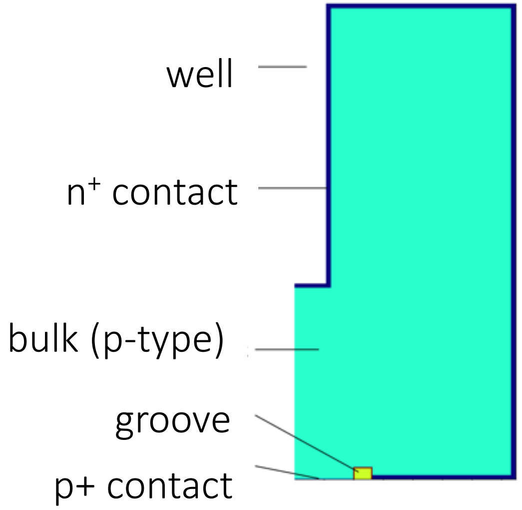
- The goal of the LEGEND-1000 project is to build an experiment with clear *discovery potential at a half-life beyond 10^{28} years*
  - For comparison, the age of the universe is 1.3×10^{10} years
- This is less than one decay per year per ton of material
- Strategy:
  - Amass an array of detectors totaling about 10^{28} Ge-76 atoms (1000 kg)
  - Operate the detectors for 10 years (accumulate 10 ton-years of "exposure")
  - Look for a handful of 0νββ decays (2039 keV)
- Need a very good signal-to-background ratio to get statistical significance
  - An extremely low background event rate
  - The best possible energy resolution



Enriched HPGe Detectors for LEGEND-1000





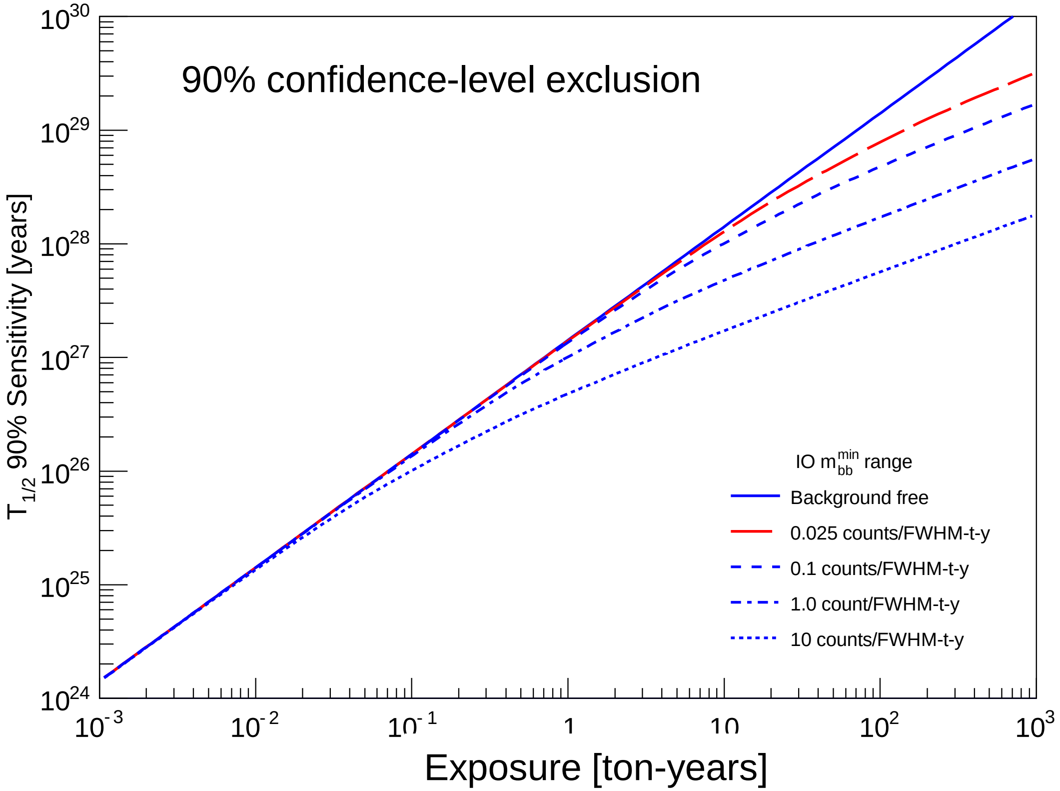


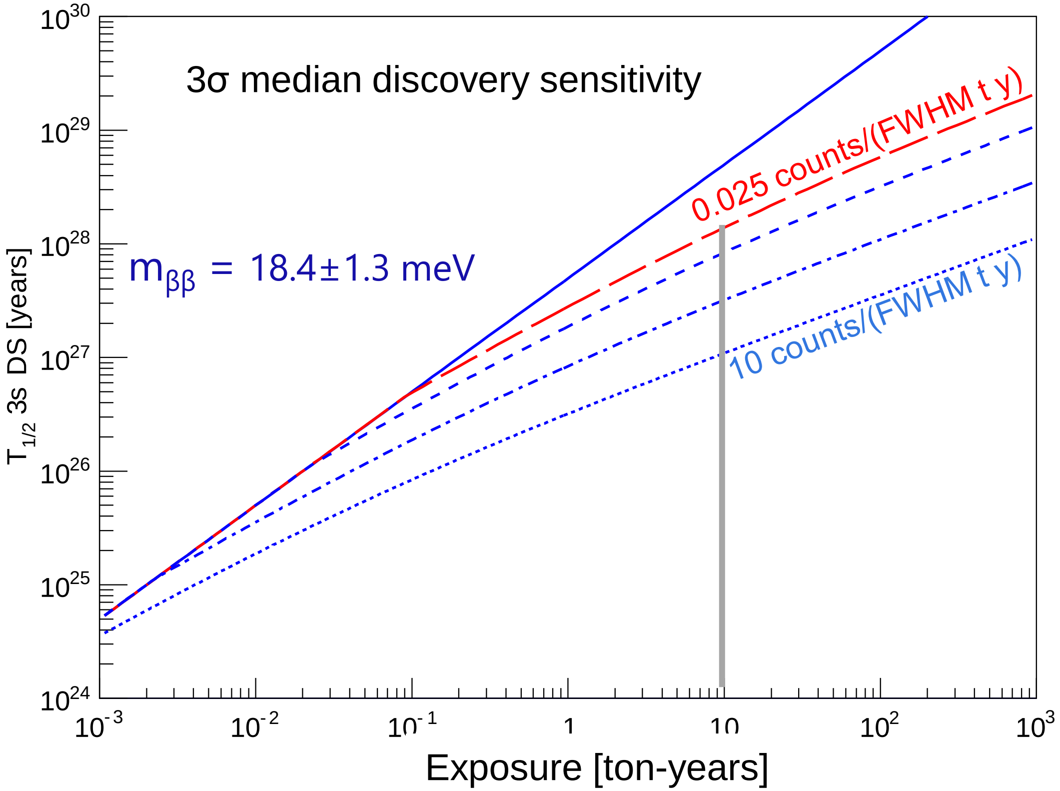
- Large-mass "Inverted-Coaxial Point-Contact" (ICPC) detectors: About four times lower backgrounds compared to detectors used in previous experiments
- Superb energy resolution: $\sigma / Q_{\beta\beta} = 0.05\ \%$
- Insensitive to alpha particles on outer high-voltage contact
- Small signal-readout contact: Event topology discrimination

Requirements: Low Backgrounds

- Background-free: Sensitivity rises linearly with exposure
  Background-limited: Sensitivity rises as the square root of exposure
- Our background goal is the red line, 0.025 counts/(FWHM t y), "quasi-background-free"
  - *Less than one background count* expected at the energy of interest after 10 t y of exposure

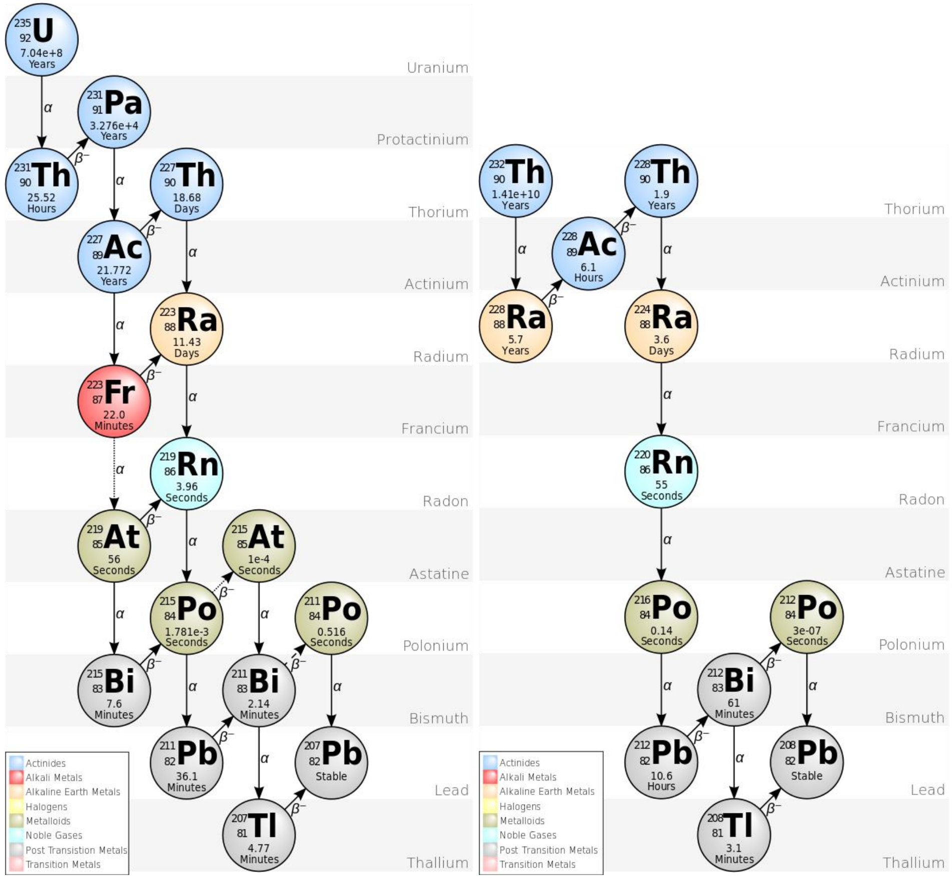
    (FWHM: Full Width at Half Maximum; 2.355 σ for a Gaussian peak)





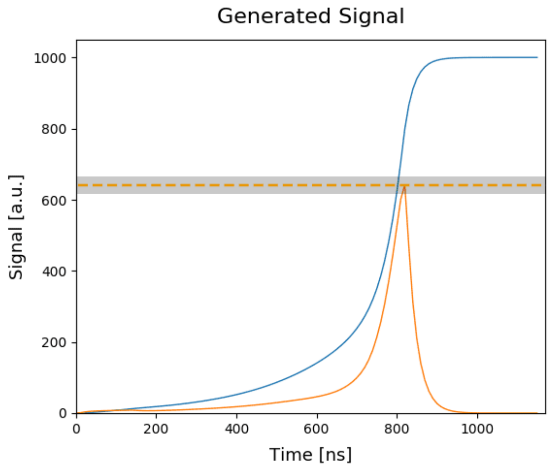
Sources of Background Events

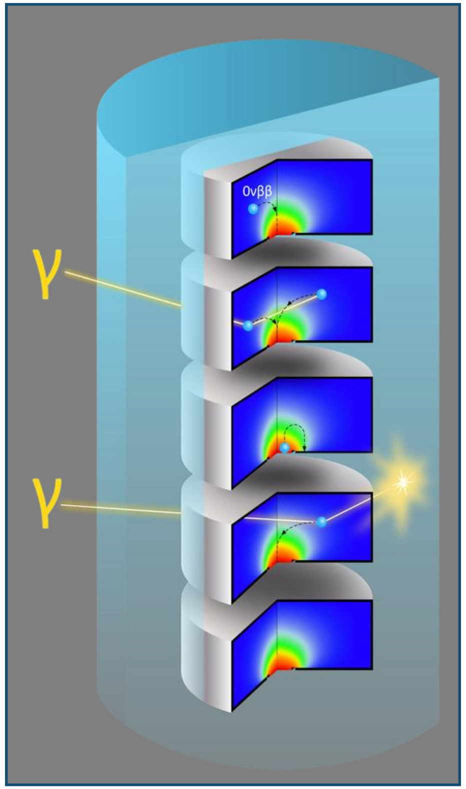
- Background events that can mimic a 0νββ decay can come from
  - Gamma rays from the uranium and thorium decay chains
  - Alpha and Beta particles hitting the surfaces of the detectors
  - Cosmogenic radioactive isotopes produced by cosmic rays at the earth's surface, or by neutron capture inside the deep-underground laboratory



Mitigation of Background Events

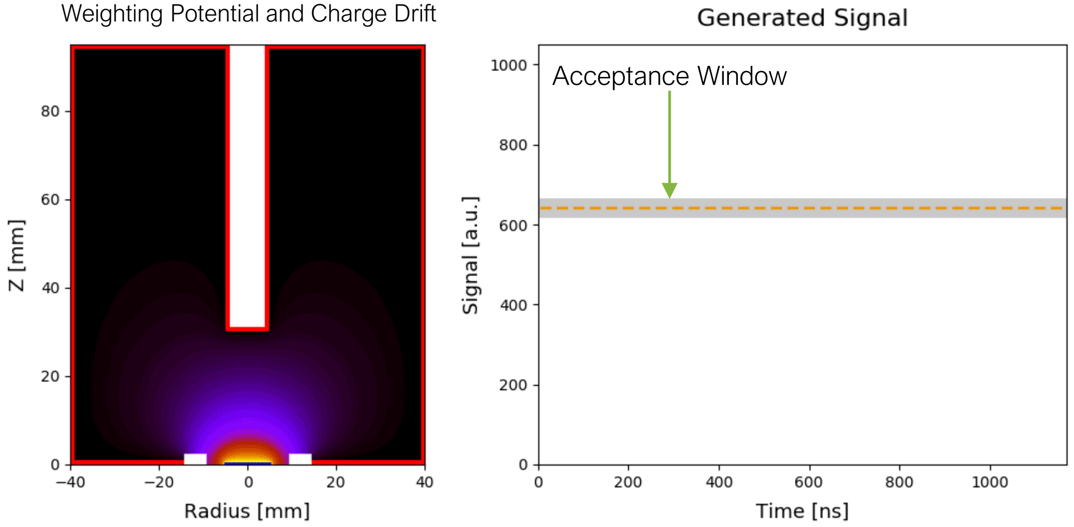
- Mitigation strategies
  - Use only ultra-pure materials, e.g. copper from electroforming underground
  - Minimize structural material around the Ge detectors
  - Use pulse-shape analysis of the Ge detector signals
    - Illustrated on next slide
  - Operate the Ge detectors in a bath of pure liquid argon
    - Cools the detectors to the correct operating temperature
    - Shields the detectors from incident gamma rays
    - Scintillates when energy is deposited from a gamma, beta, or alpha
    - Detecting the scintillation light lets us identify and reject background events
  - But argon extracted from the atmosphere contains radioactive ^{42}Ar
    - ^{42}Ar is itself a source of background events
    - Solution: Use **underground argon**; argon extracted from underground gas wells where ^{42}Ar production is strongly suppressed





Pulse-Shape Analysis: ICPC Ge Detector Event Topologies

0νββ signal candidate (**single-site**)



Charge signal

Current signal

Pulse-Shape Analysis: ICPC Ge Detector Event Topologies

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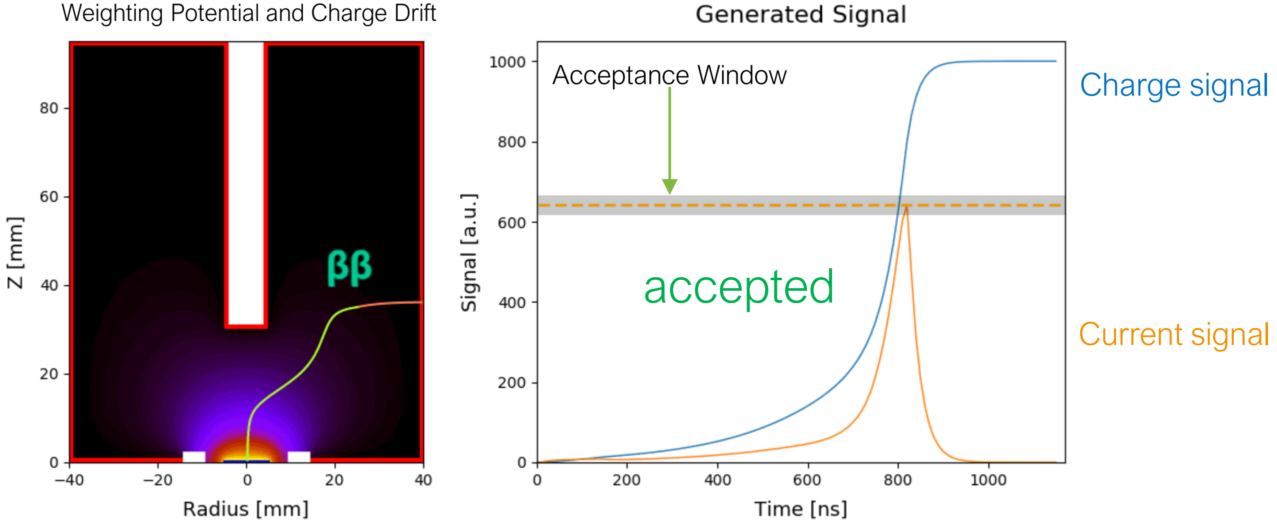
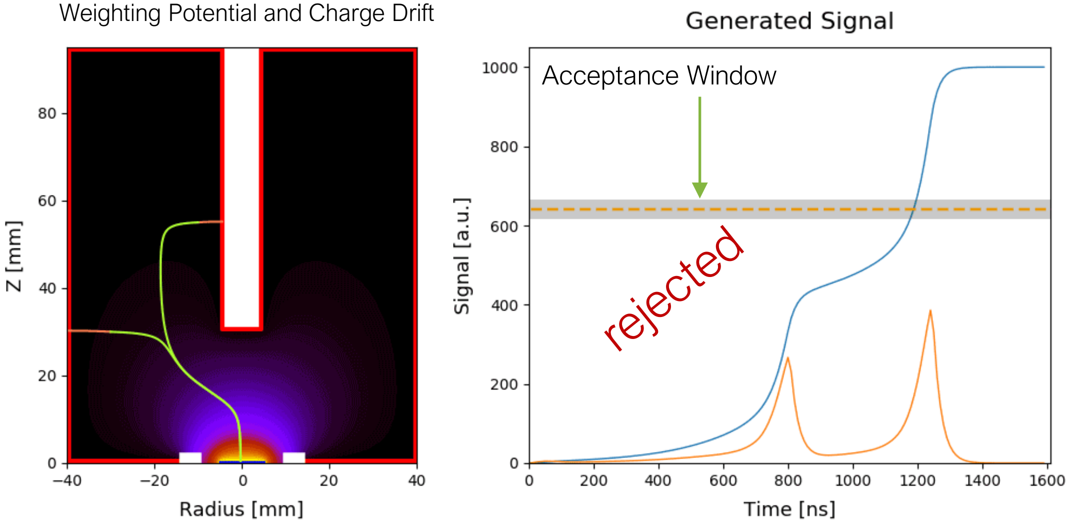
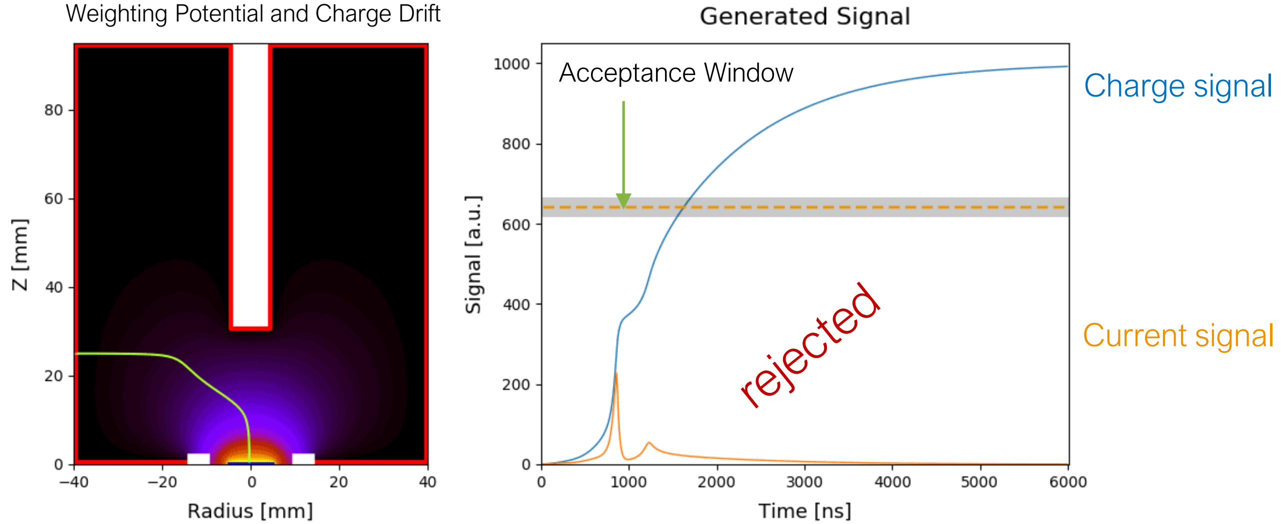


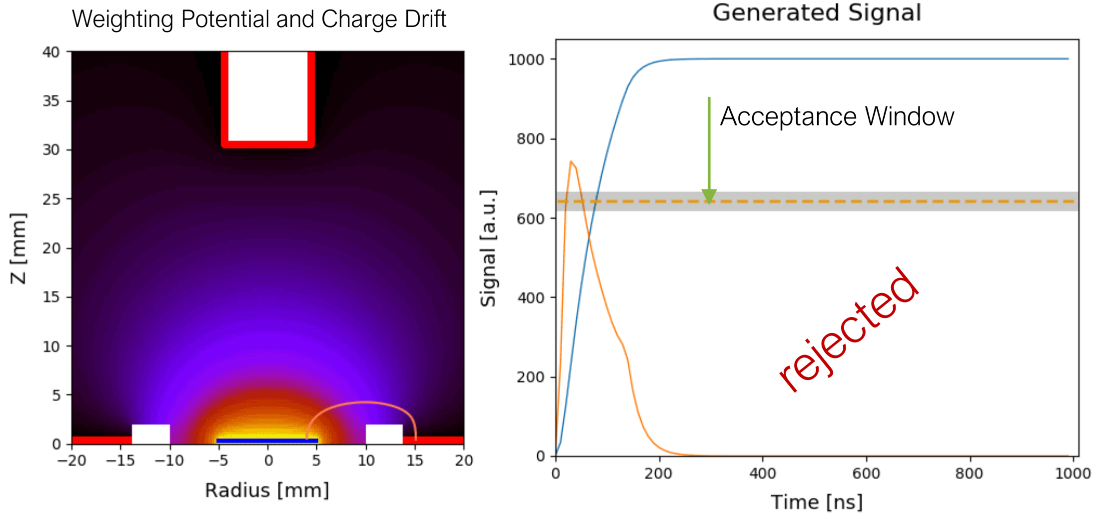
Gamma-ray background (multi-site)



Surface-β (^{42}K from ^{42}Ar) on outer contact



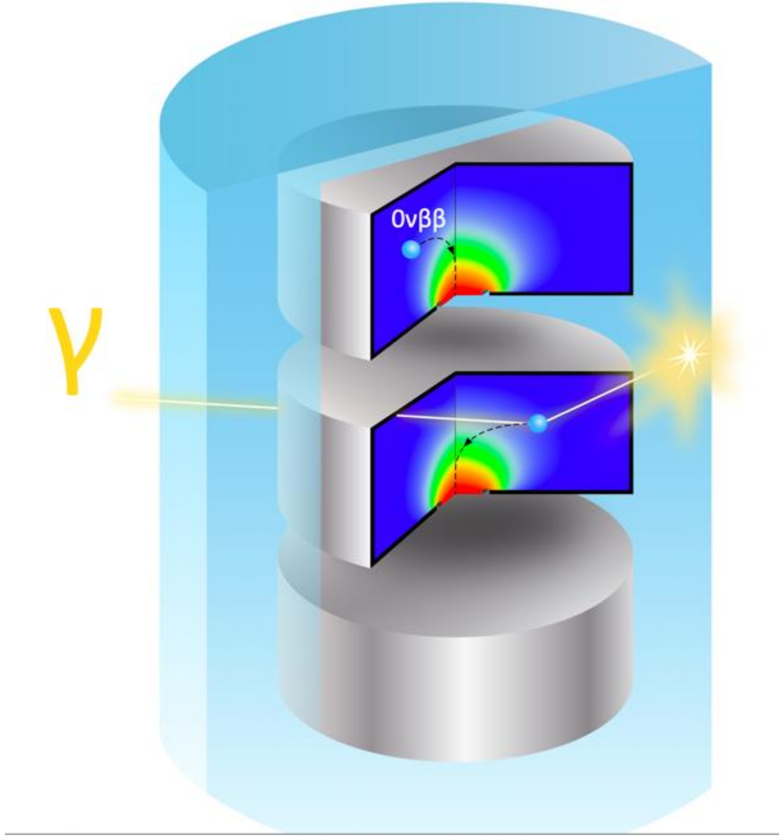
Alpha-particle on read-out contact

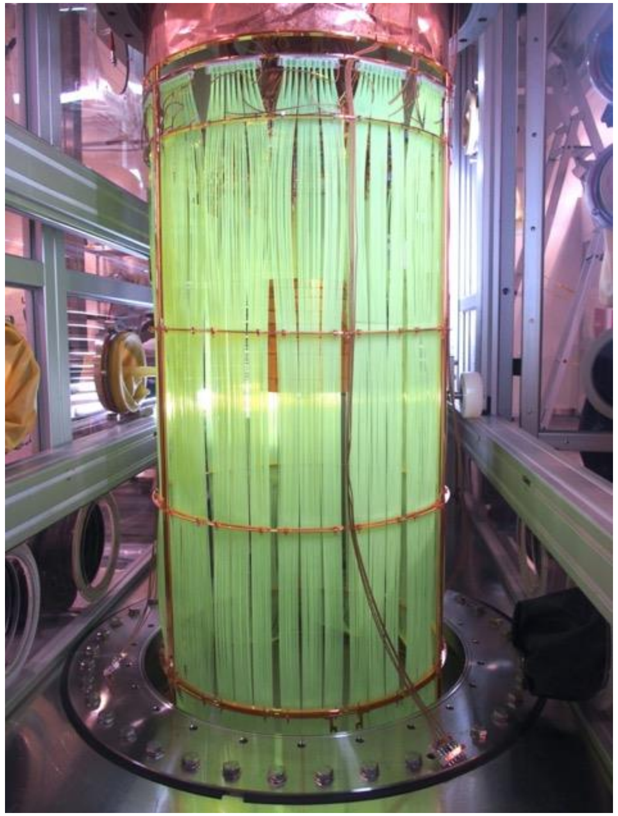


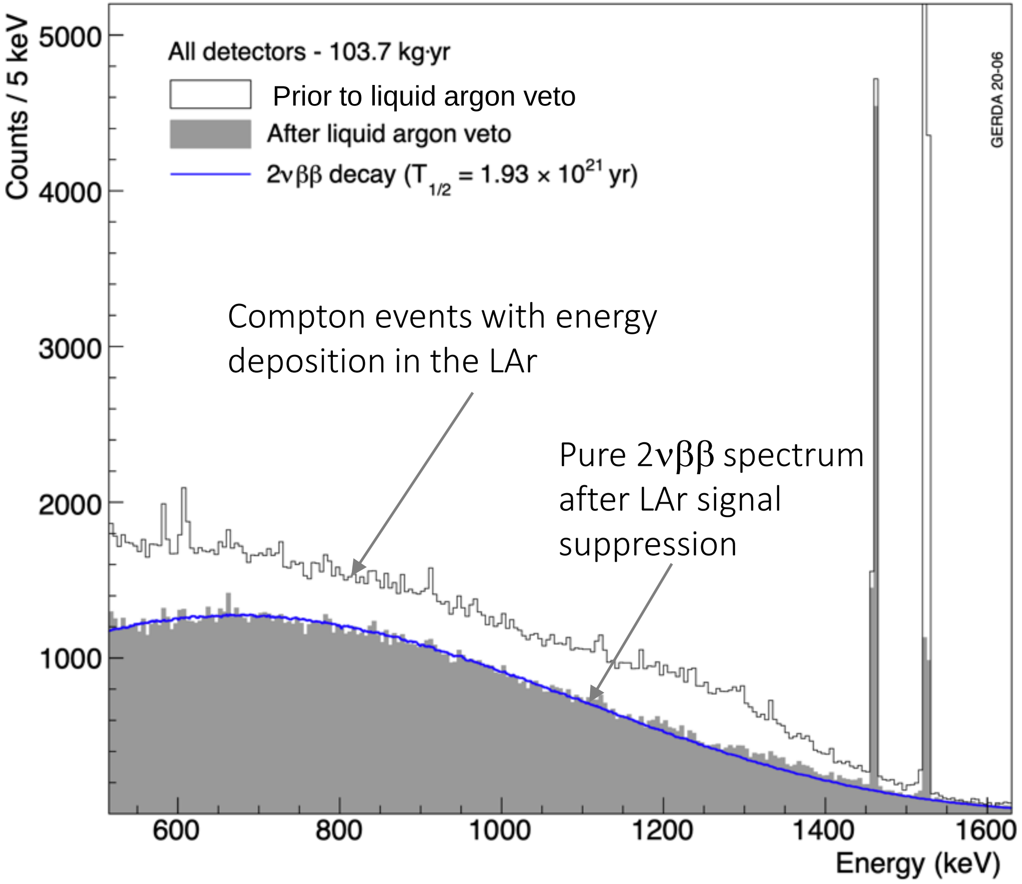
Liquid Argon Instrumentation

GERDA: Detection of liquid argon scintillation light

Low-background wavelength-shifting fibers and silicon photo-multiplier arrays for 128 nm single photon detection

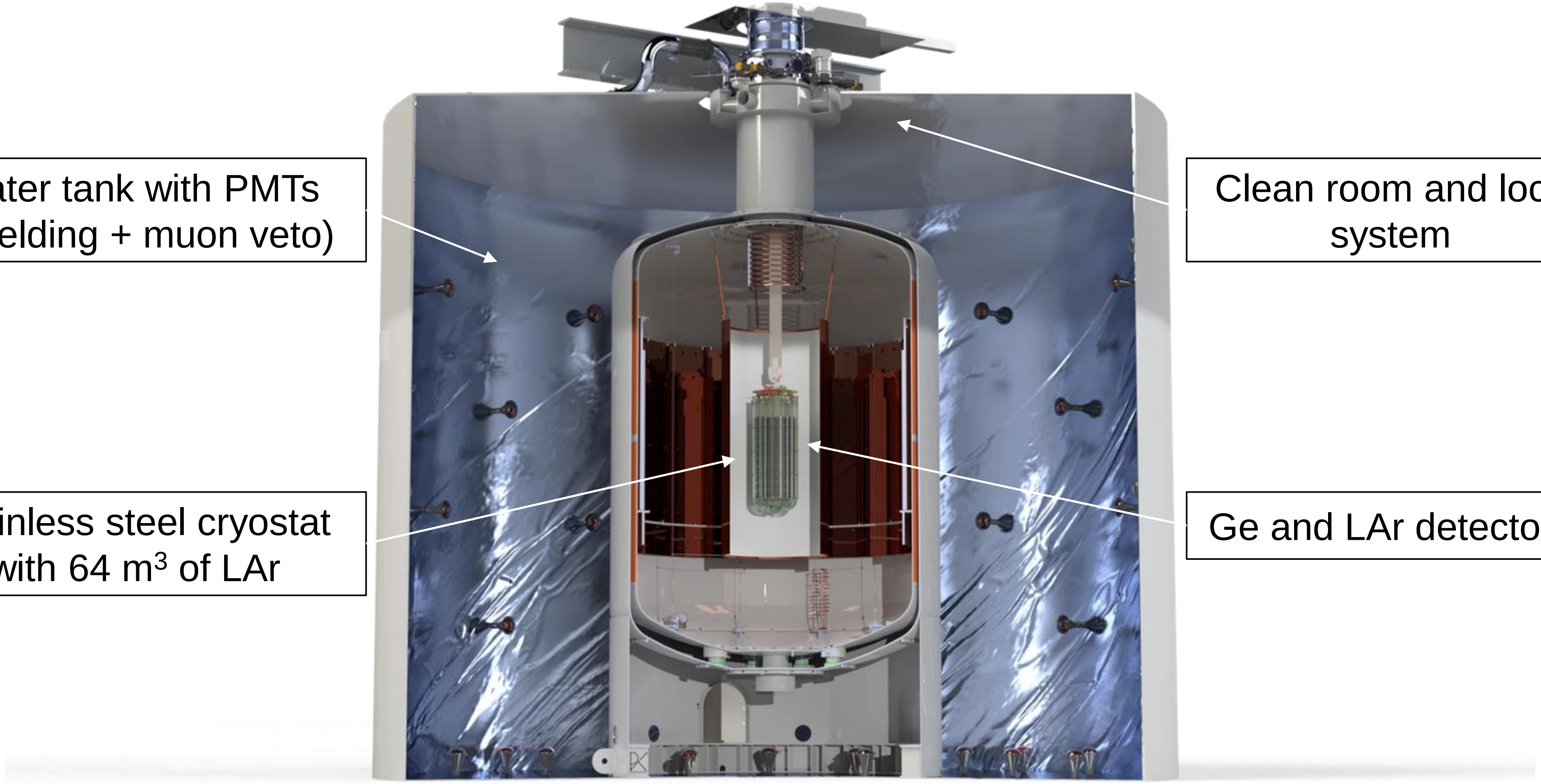






LEGEND-200

First phase of the LEGEND program, located at Laboratori Nazionali del Gran Sasso (LNGS)



Water tank with PMTs (shielding + muon veto)

Clean room and lock system

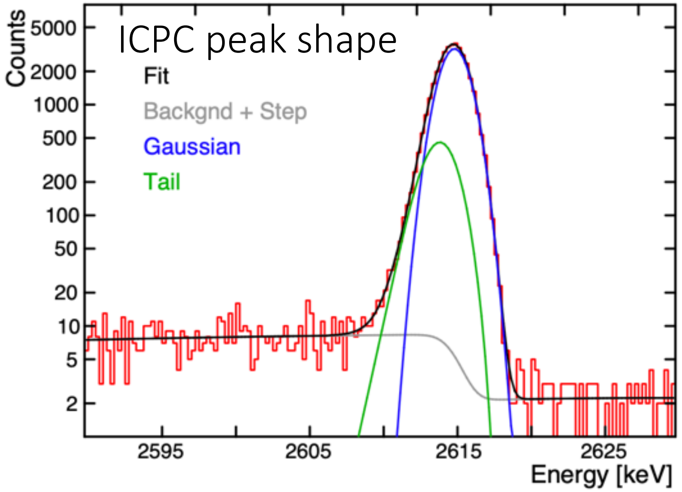
Stainless steel cryostat with 64 m^3 of LAr

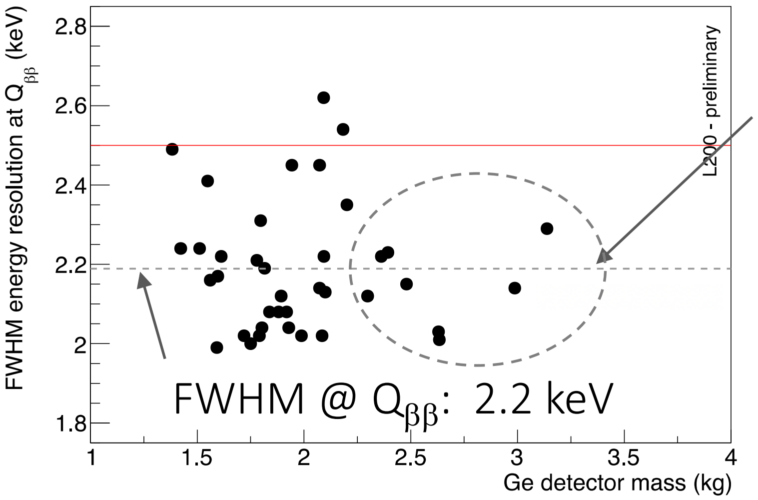
Ge and LAr detectors

LEGEND-200

First phase of the LEGEND program, located at Laboratori Nazionali del Gran Sasso (LNGS)

- Re-uses the GERDA cryostat and infrastructure
- With an improved liquid argon system
- Will have 135 kg of novel ICPC detectors (92% enr. ^{76}Ge) plus 62 kg of PPC and BEGe detectors
- Sensitivity goal: 10^{27} years half-life
- Recently transitioned from commissioning to physics data taking, with 10 strings of detectors (142 kg) installed





Large mass detectors show excellent energy resolution

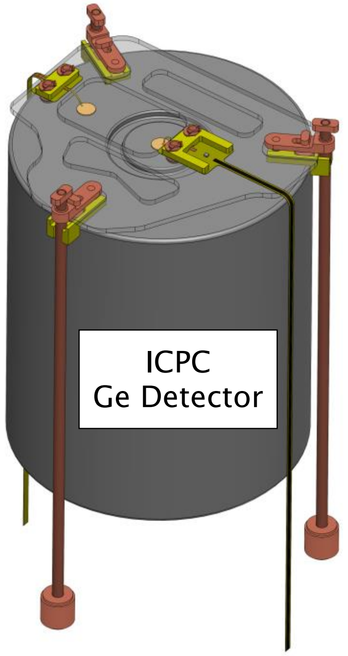
ICPC average resolution @ $Q_{\beta\beta}$: 2.2 keV (FWHM)

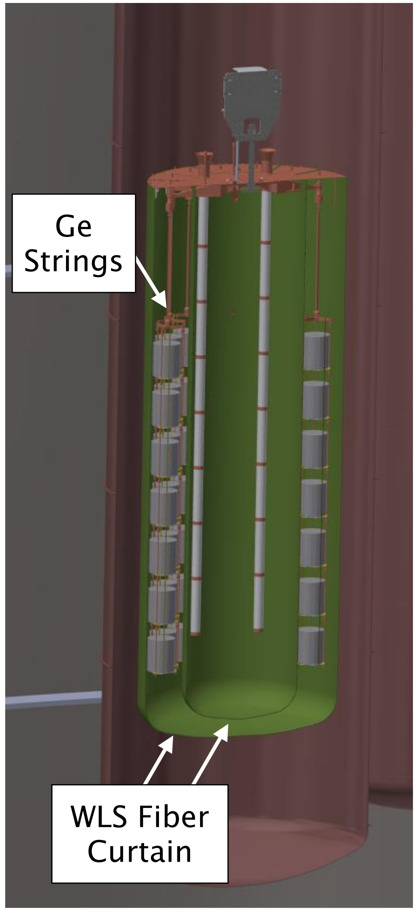
LEGEND-1000: Experiment Overview

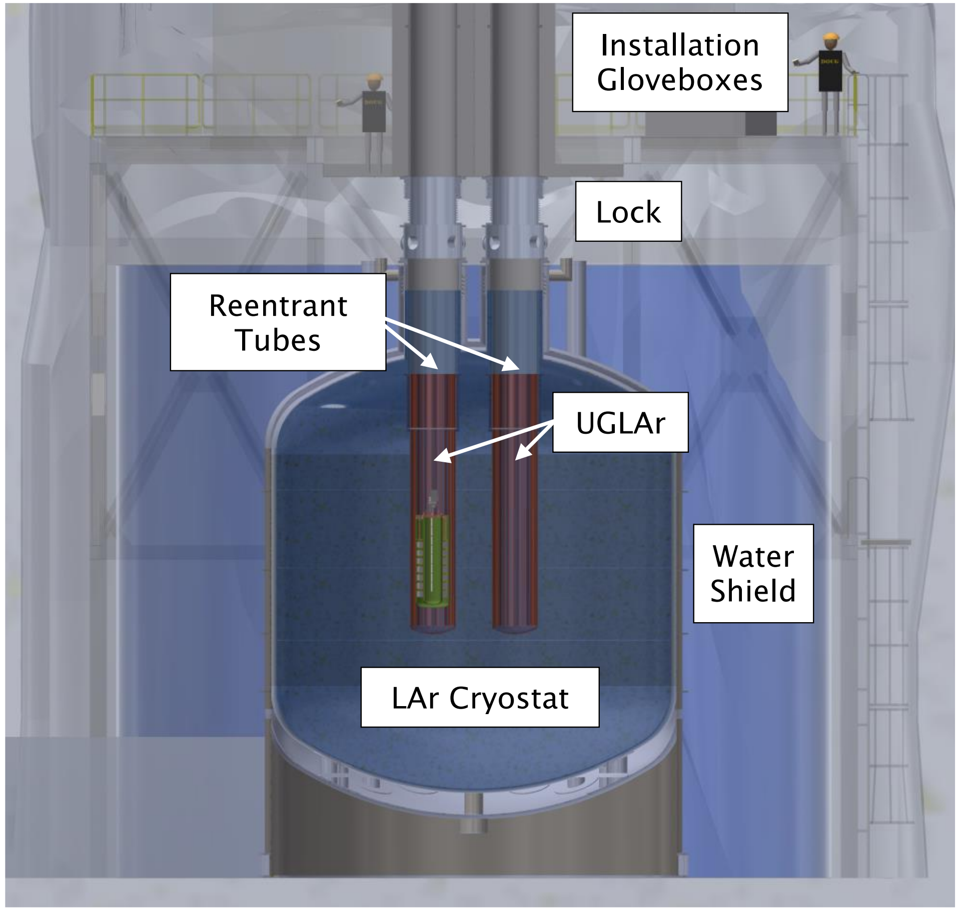
1000 kg of enriched Ge detectors (enriched to 92% ^{76}Ge)

- 2.6 kg average mass
- Mounted in "strings" using components made from electroformed copper and scintillating plastic, PEN
- ASIC readout front-end electronics

- Underground-sourced LAr active shield
- Dual fiber-curtain LAr instrumentation
- EFCu Reentrant tubes







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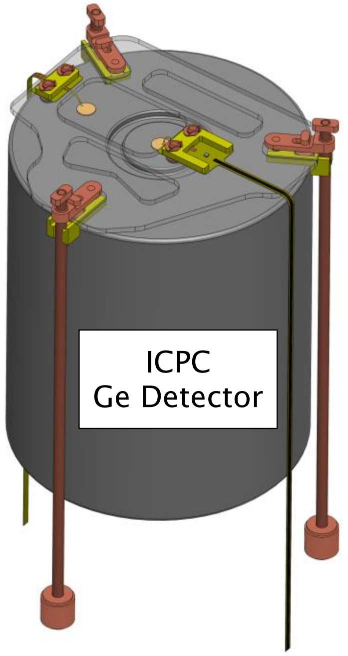
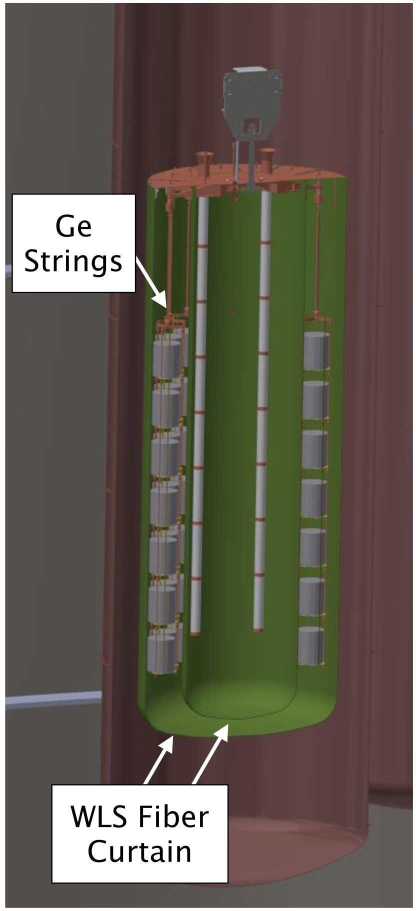
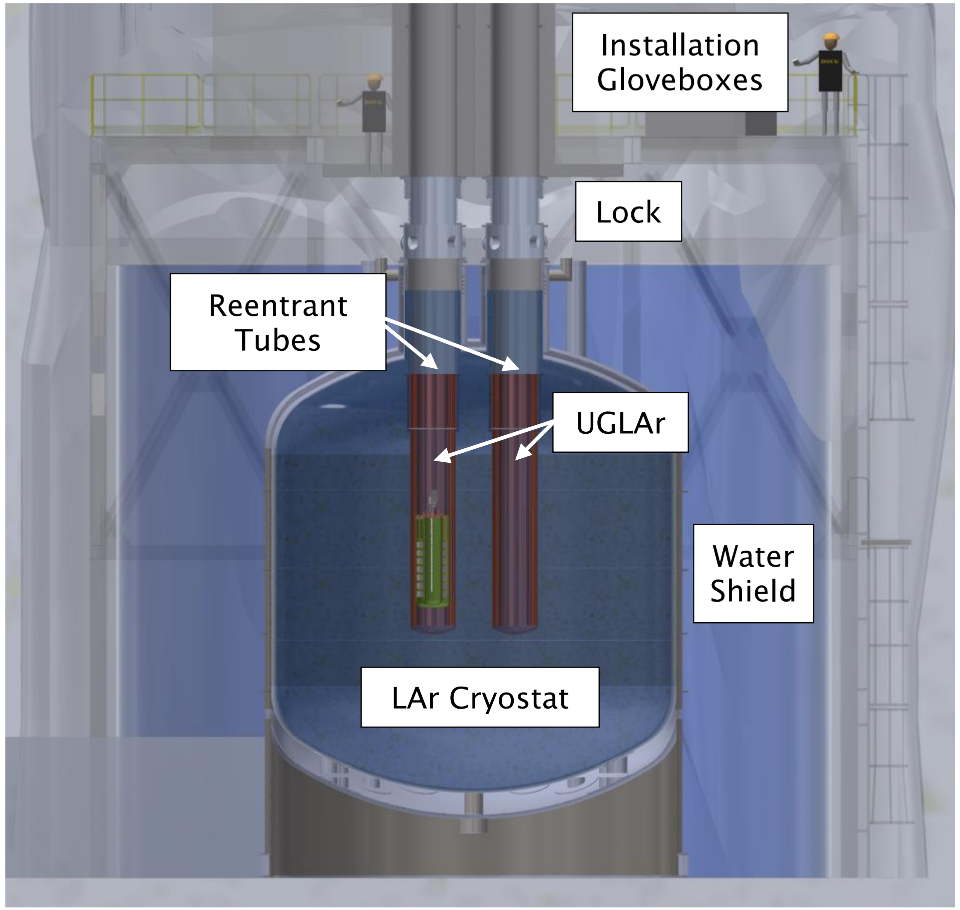






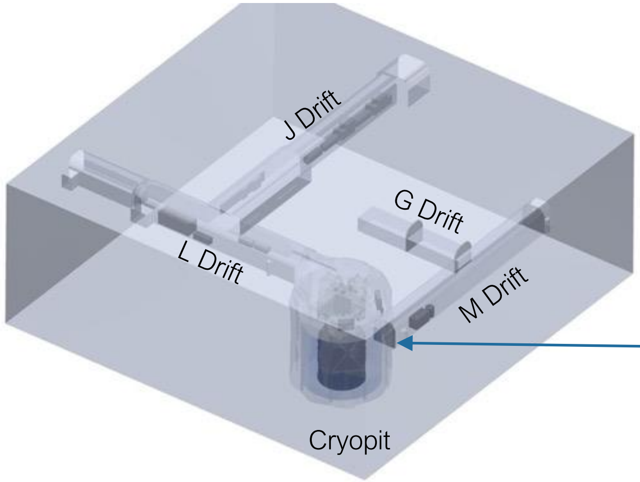
Enriched Germanium Procurement

- LEGEND-1000 requires 1100 kg of Ge enriched to 92% in ^{76}Ge
- New geopolitical realities prevent procurement of that material from major suppliers in Russia
- LEGEND-200 also procured some material from a second vendor in the Netherlands
- Negotiations to secure the isotope from that alternative source are advancing very well
  - Planning for a dedicated ^{76}Ge enrichment cascade with ~ 200 kg/year capacity

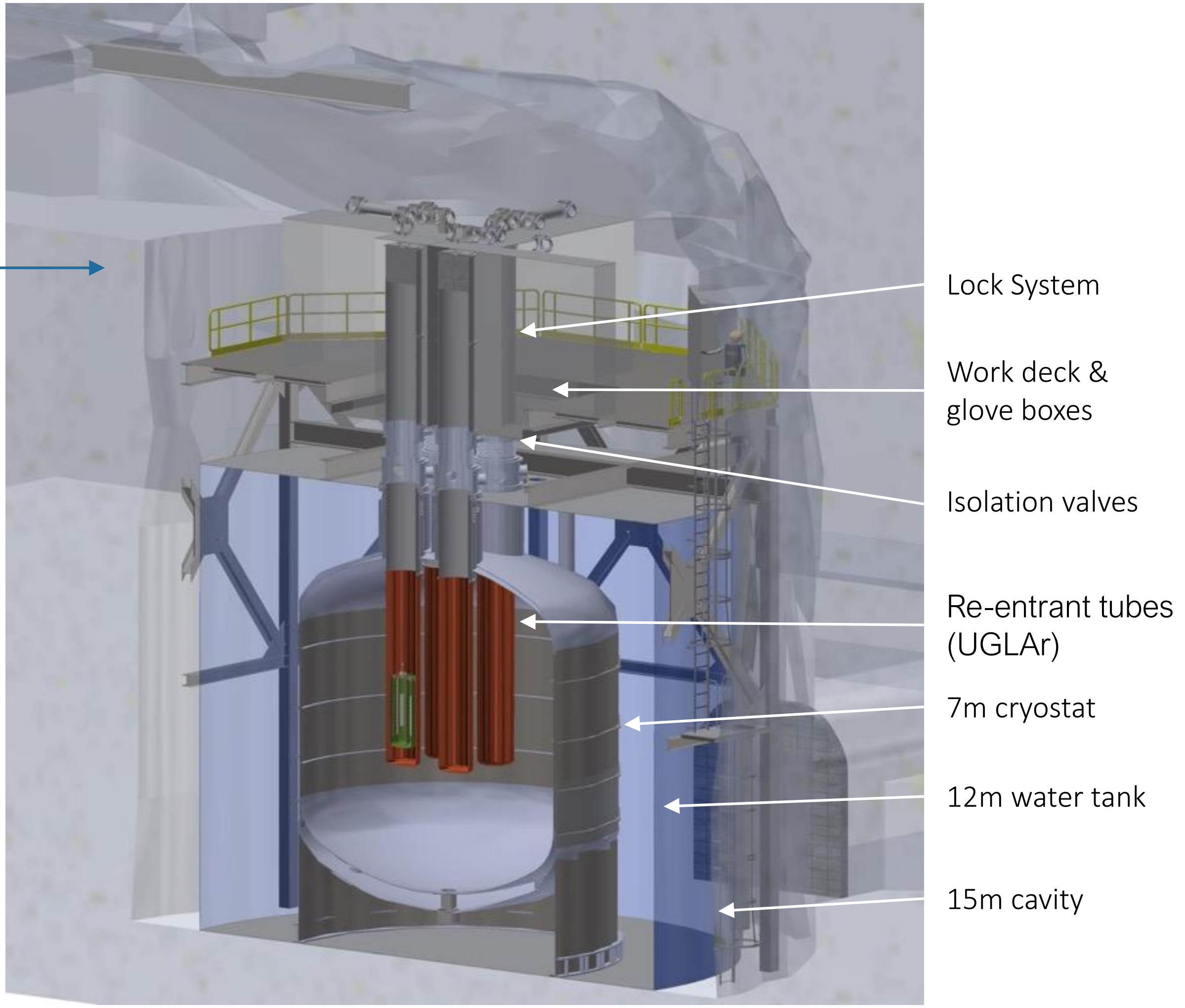
Underground-Sourced Argon Procurement

- Underground argon production has been pioneered by the DarkSide experiment
  - ^{39}Ar is a major background for dark-matter searches using liquid argon, like DarkSide
  - Argon extracted from the atmosphere contains trace quantities of ^{39}Ar and ^{42}Ar produced by cosmic rays
  - Extracting argon from underground gas reservoirs avoids that cosmogenic process
  - Production at the URANIA facility in Colorado, and purification at the ARIA facility in Sardinia
  - MOU with the Ar DM community (GADMC Collaboration) approved by both collaborations

LEGEND-1000 Underground Site



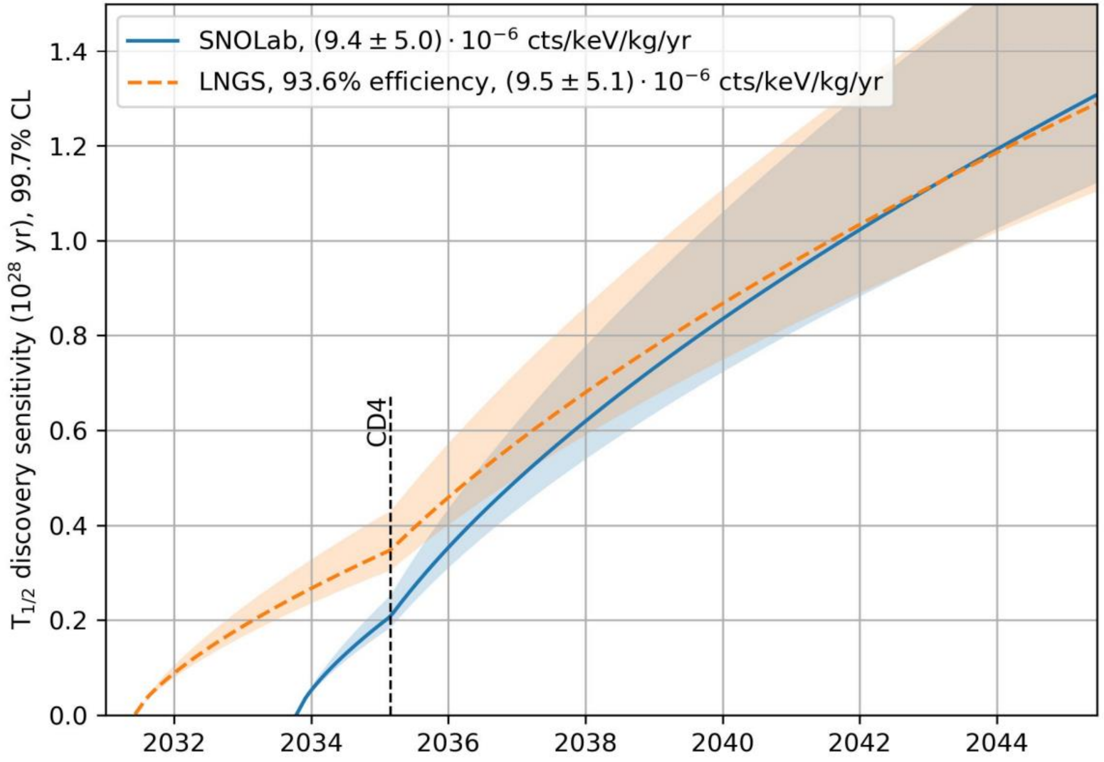
LEGEND-1000 at SNOLAB

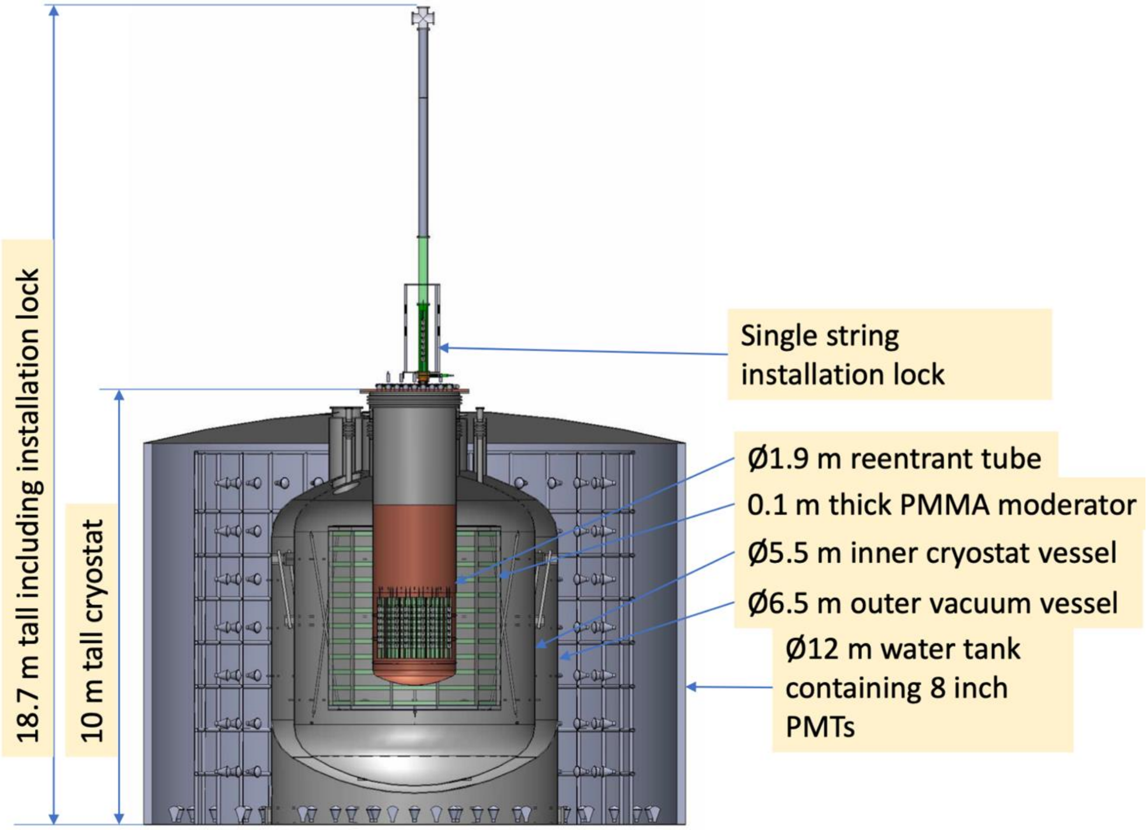


- Two reference designs to accommodate two sites
- SNOLAB Cryopit
  - Deepest site, rock overburden 6000 m.w.e.
  - Vertical access through mine shaft
  - All experimental areas are class 2000 clean rooms
- LNGS Hall C
  - Lower overburden increases background only slightly
  - Horizontal access reduces cost and schedule risk

LEGEND-1000 at LNGS

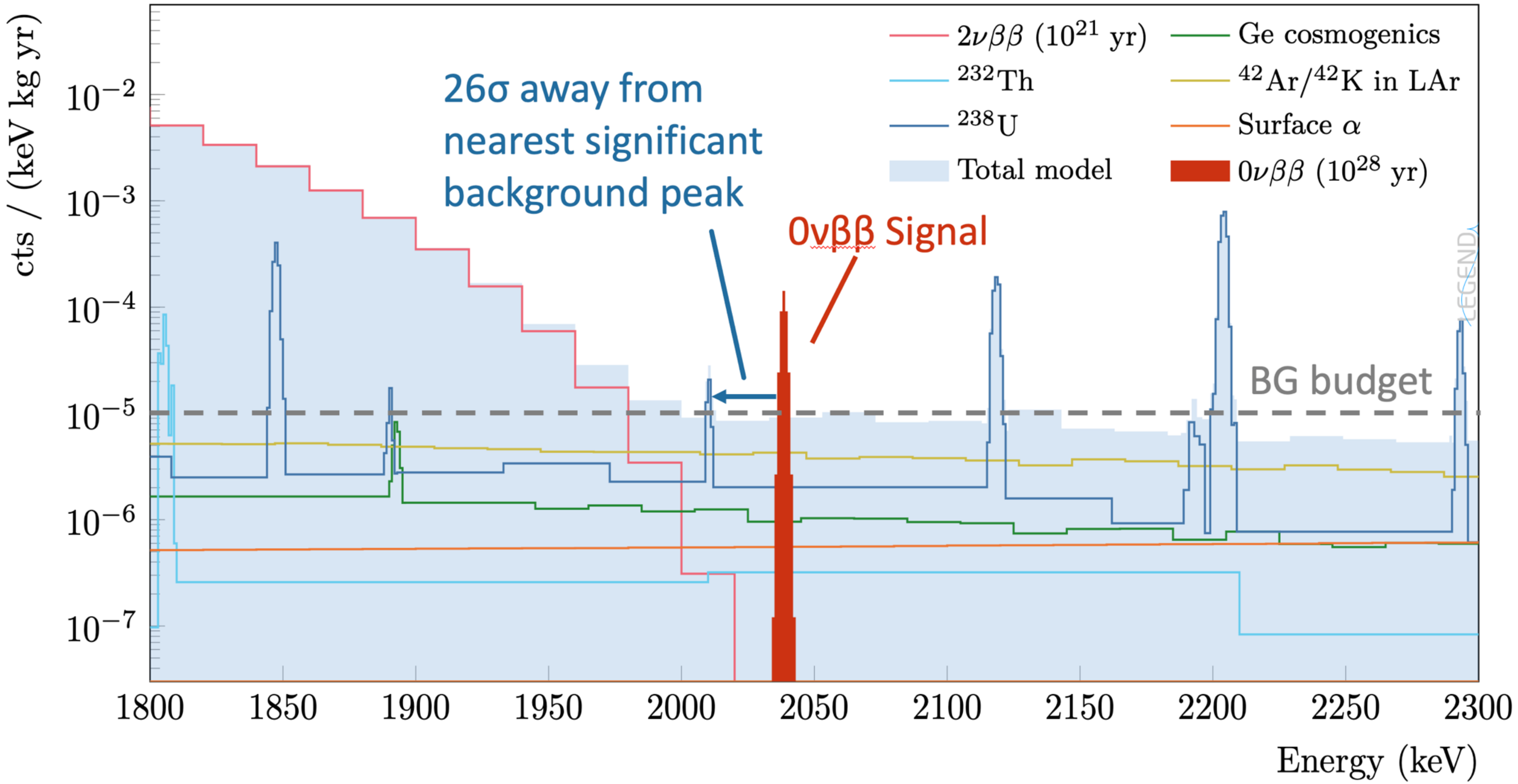
- Proposed location: Hall C, at Borexino location
- GERDA data show that we can achieve similar background to SNOLAB but with 7% efficiency loss
- Single re-entrant tube, rather than four
- Earlier start to phased data-taking





The LEGEND-1000 design for LNGS Hall C

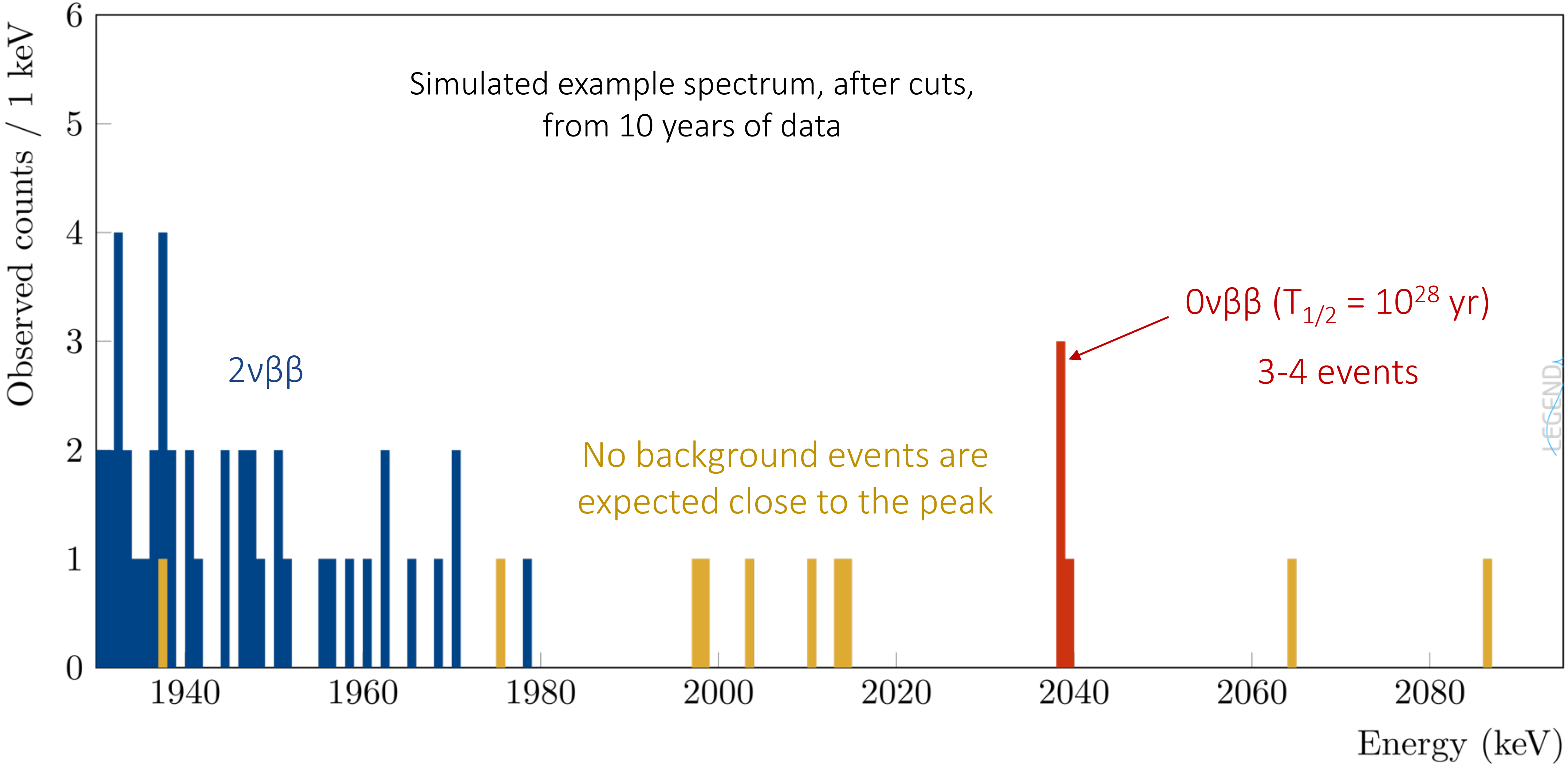
The LEGEND-1000 Background Model



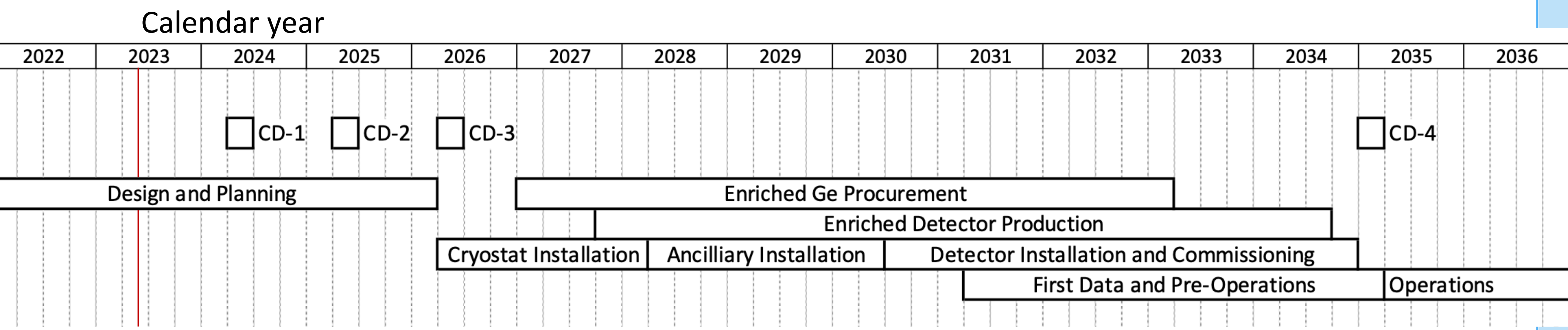
- Flat, featureless background is calculated to be below our requirements
- Will be measured; no need to rely on simulations

Designed for an Unambiguous Discovery

Even a signal at the bottom of the inverted ordering will be visible to the eye.



Technically Driven Schedule



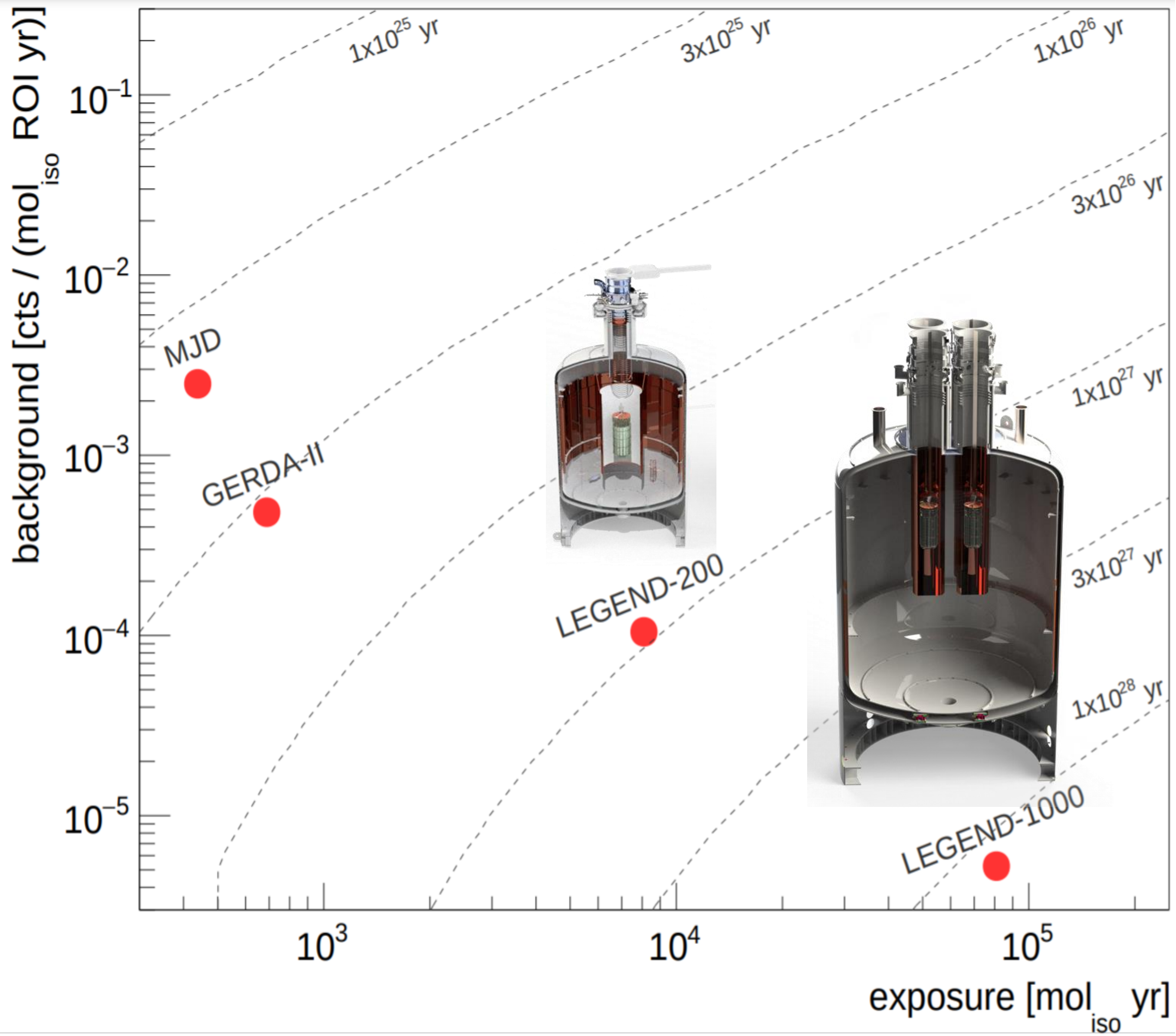
- Assumes technically driven funding profile
- Key Dates:
  - CD-1: Q3,FY24
  - **First 250 kg Commissioning Complete (start of physics data): Q3,FY31 – Q4,FY32**
  - Early Finish: Commissioning Complete: Q2,FY35
  - Late Finish (36 months of float): Q2,FY38

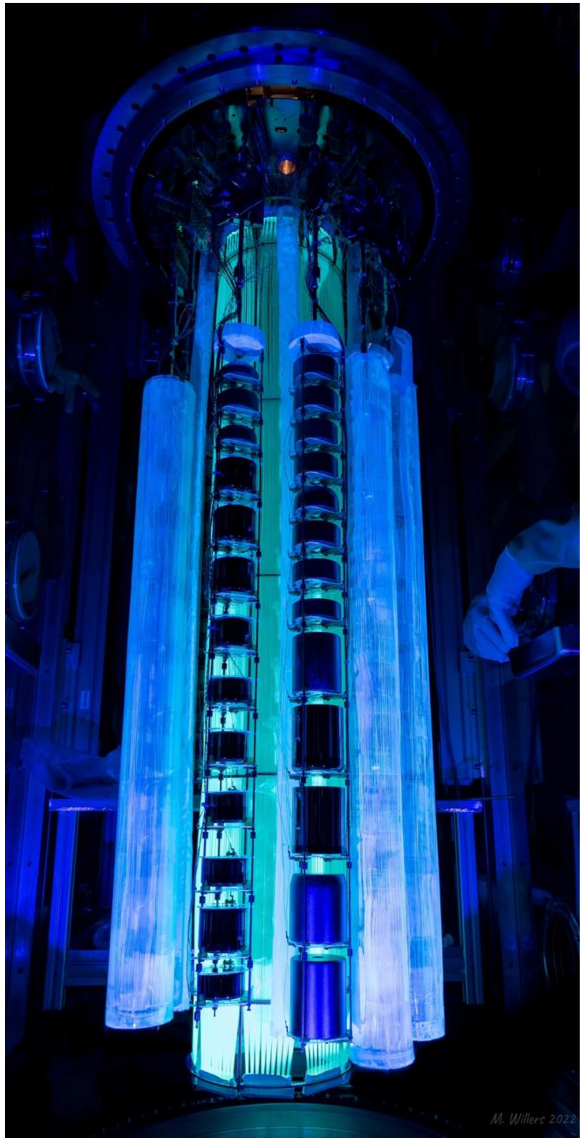
Cost

- Total US scope cost estimate is $380M (SNOLAB site) or $330M (LNGS site)
  - Fully burdened, escalated, includes management and engineering costs, and 48% contingency
  - Assumes technically driven funding profile
- Anticipated US Project scope is 55% to 60% of the total (DOE accounting)
  - Total scope estimate using DOE accounting; fully burdened & escalated costs, with 48% contingency
  - A proposal to NSF for a Mid-Scale Research Infrastructure 2 grant is under development
- Raw cost (unburdened procurements only) for anticipated non-US scope is approx. $70M

- Funding required for CD-1:
  - OPC funds in hand are sufficient for conceptual design and front-end planning through end of FY23
  - Expect to require ~ $2M additional OPC funding in FY24 Q1-2 (assuming CD-1 ESAAB approval in Q2)

Towards a ton-scale experiment





Summary

- The LEGEND-1000 project is ready to proceed to final design and construction
  - Demonstrated performance of the entire technology chain
  - Requires no extrapolation from current detector performance
  - Cost-effective and innovative design
- The physics is highly compelling and timely
- LEGEND-200 greatly reduces the risk for LEGEND-1000
  - Validates the design concepts and technologies
  - Provides an excellent test bed for LEGEND-1000 hardware
- The collaboration is
  - Experienced
  - Diverse and strongly international
  - Passionate about the physics and the LEGEND-1000 project
  - Ready to transition from LEGEND-200 commissioning to LEGEND-1000

Why Germanium-76?

- Solid basis for unambiguous discovery
  - Superb energy resolution: $\sigma / Q_{\beta\beta} = 0.05\ \%$
  - Background is flat and well understood, with no background peaks anywhere near the energy of interest
  - Background will be measured, with no reliance on background modeling
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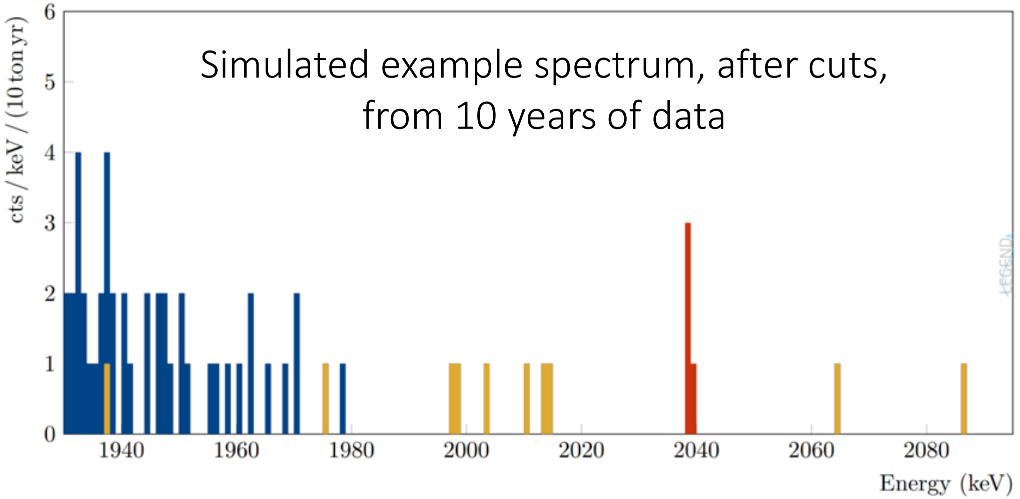
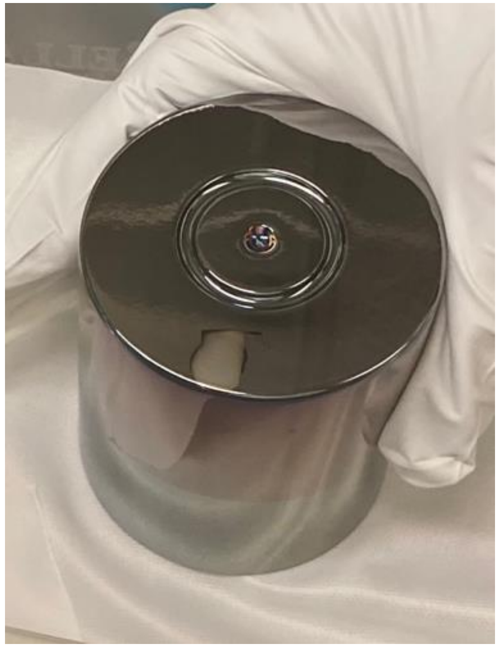


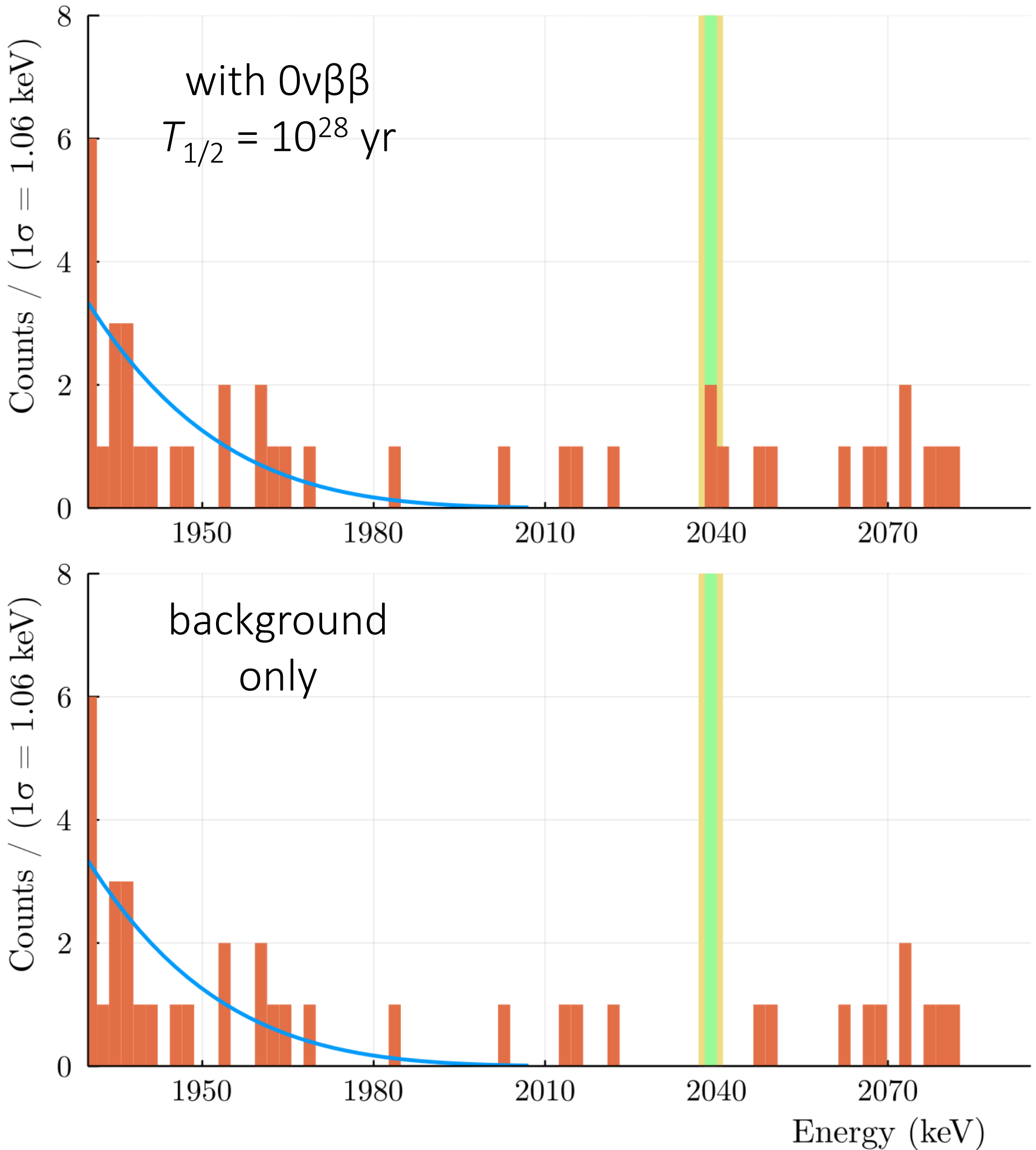


- Low risk, high impact
  - Demonstrated performance of the entire technology chain
  - Previous Ge experiments have demonstrated the lowest background per FWHM of any experiment, and the best resolution
  - Proven track record, with history of leading limits

Backup Slides

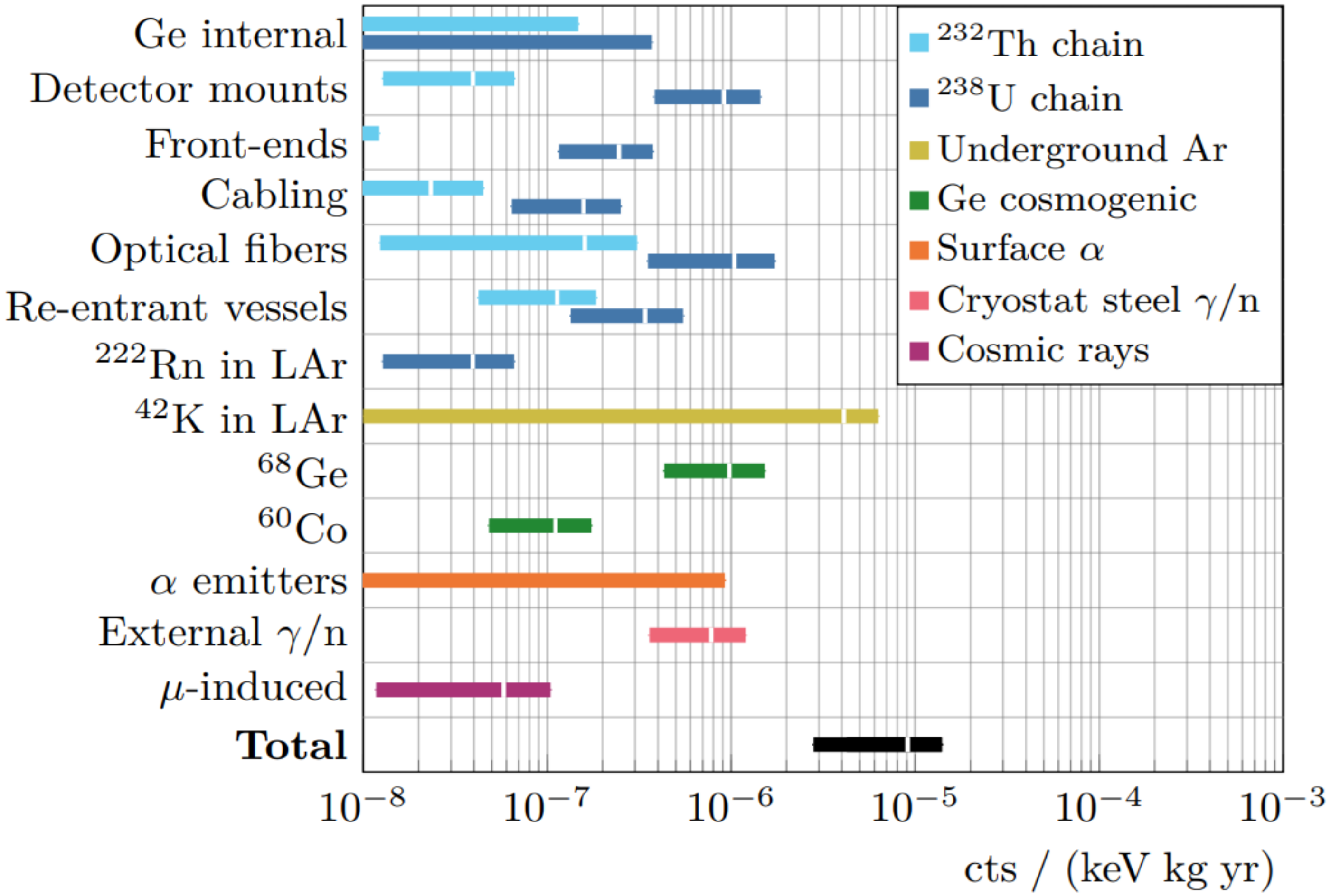
100 Simulated Experiments

- Background is flat and well understood.
- No reliance on background modeling
- No risk of $2\nu\beta\beta$ background



Total Backgrounds: Components

Background Index After Cuts



Projected background index after all cuts:

Approx. 9 x 10^{-6} counts / (keV kg yr)

Proposed US-DOE LEGEND-1000 Project Profile

DOE CAP costs only, technically driven

Have maintained 48% overall contingency (conservative)

This scenario assumes CD-1 ICR and IPR in FY24 Q1

Critical Decision	Date
CD-0	**FY19 Q1**
CD-1	FY24 Q2
CD-2	FY25 Q2
CD-3	FY26 Q3
CD-4 (early date)	FY35 Q2