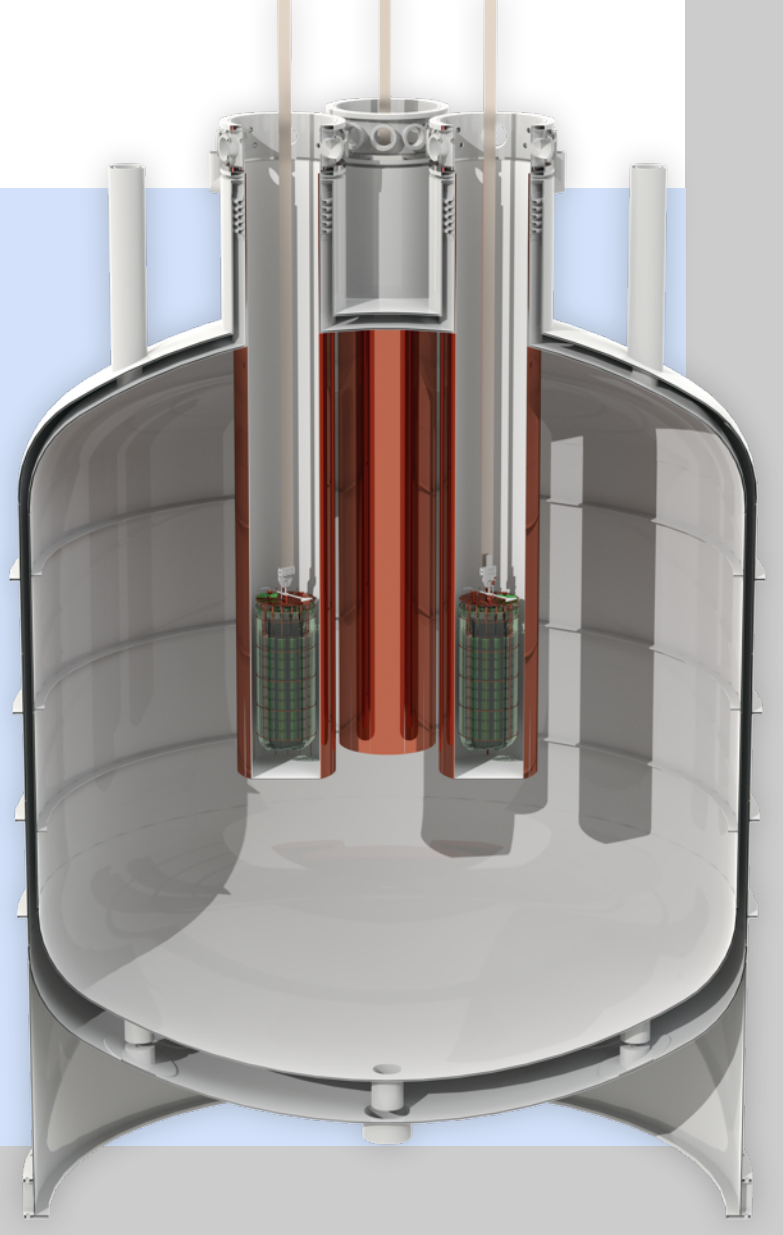
Search for Neutrinoless Double-Beta Decay with LEGEND-1000



LEGEND

Large Enriched
Germanium Experiment
for Neutrinoless ββ Decay

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Technical University of Munich

09.07.2022

ICHEP 2022 - Bologna

Technische Universität München

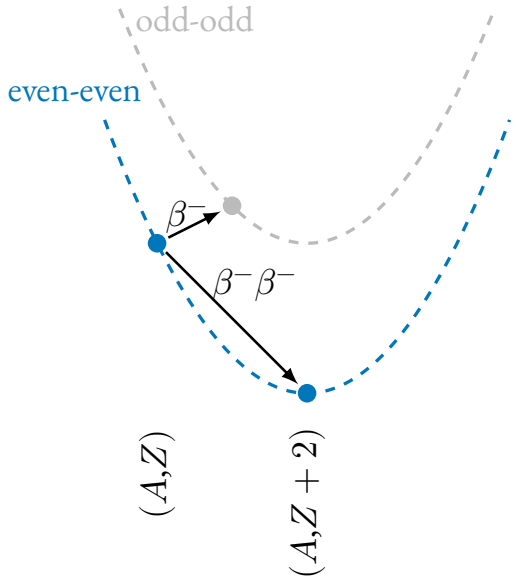
SFB 1258 Neutrinos Dark Matter Messengers

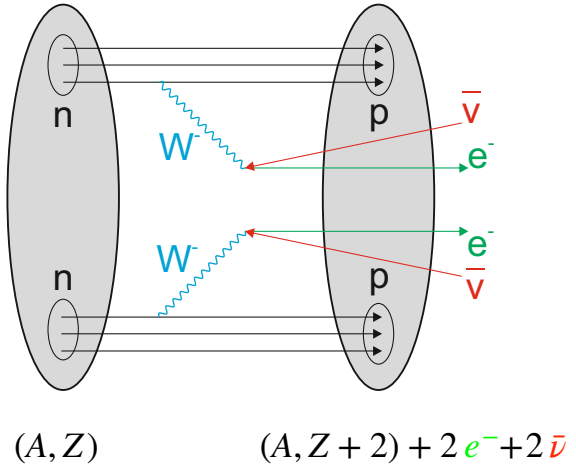
ORIGINS Excellence Cluster

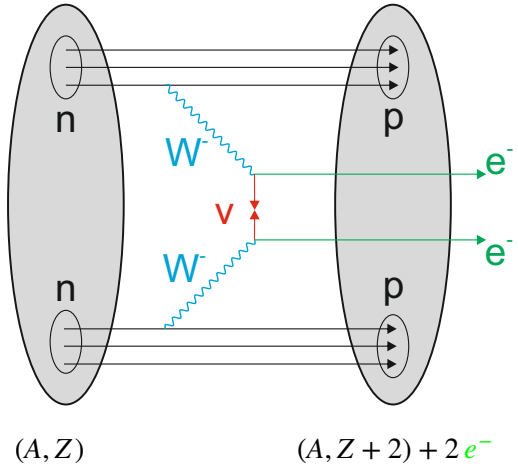
The Large Enriched Germanium Experiment for Neutrinoless ββ Decay

LEGEND mission: "The collaboration aims to develop a phased, ^{76}Ge based double-beta decay experimental program with **discovery potential** at a half-life beyond **10^{28}** years, using existing resources as appropriate to expedite physics results."

(Neutrinoless) Double-Beta (ββ) Decay







In several isotopes (e.g. **^{76}Ge**, ^{82}Se, ^{100}Mo, ^{130}Te, ^{136}Xe) β decay is forbidden → ββ decay becomes observable

→ 2νββ predicted by the Standard Model & measured experimentally → Half-lifes $\mathcal{O}$ (10^{18} - 10^{21} years)

Neutrinoless ββ decay:

→ violates Lepton Number conservation by 2 units → new physics!

→ determines nature of the neutrino → Majorana particle

→ provides information on ν mass via $m_{\beta\beta}$ (light neutrino exchange scenario)

→ current best limits: $T_{1/2} > \mathcal{O}$ 10^{25} - 10^{26} yr

Designing for an unambiguous discovery

What is required for a discovery of 0νββ?

Long half-lives require large exposure!

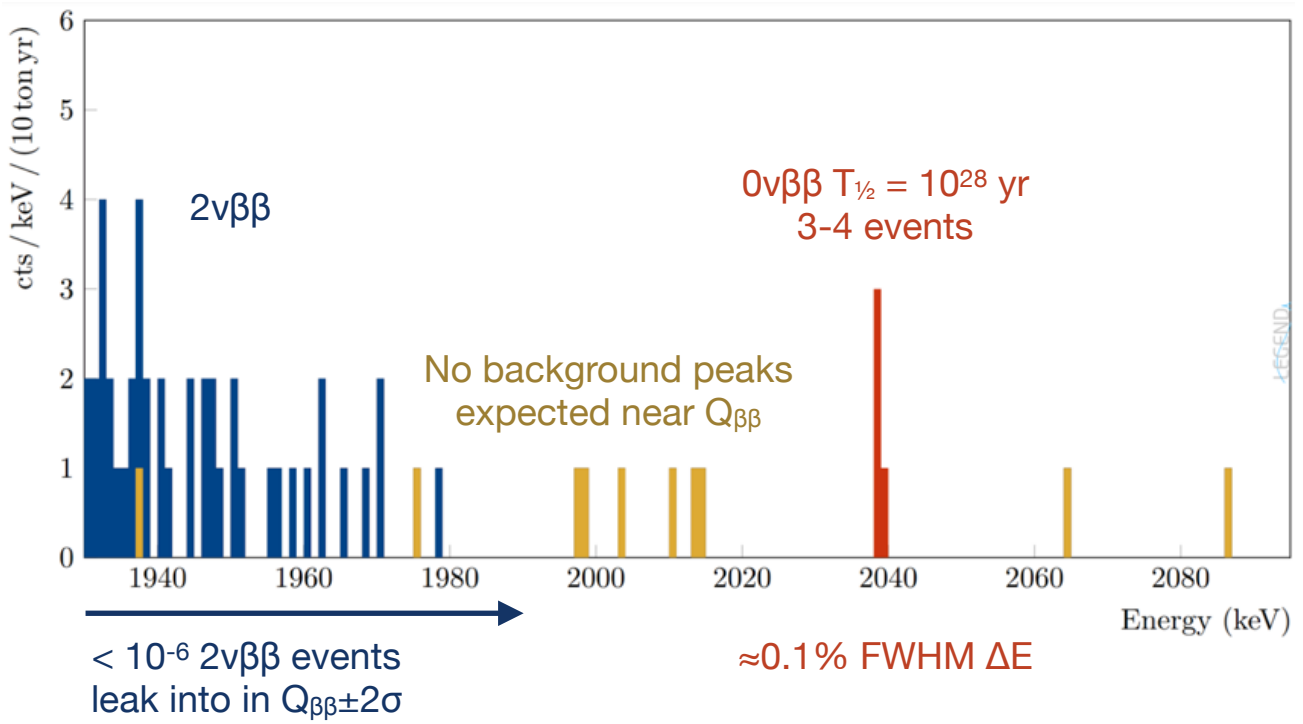
For 3 - 4 counts of 0νββ we need:

- 100 kg-years @ 10^{26} years
- 1 ton-year @ 10^{27} years
- 10 ton-years @ 10^{28} years

Achieving statistical significance requires a good signal-to-background ratio

- Very low background event rate
- The best possible energy resolution

Simulated LEGEND-1000 example spectrum for $T_{½} = 10^{28}$ yrs
BI < 10^{-5} cts/keV kg yr, after cuts, 10 years of data



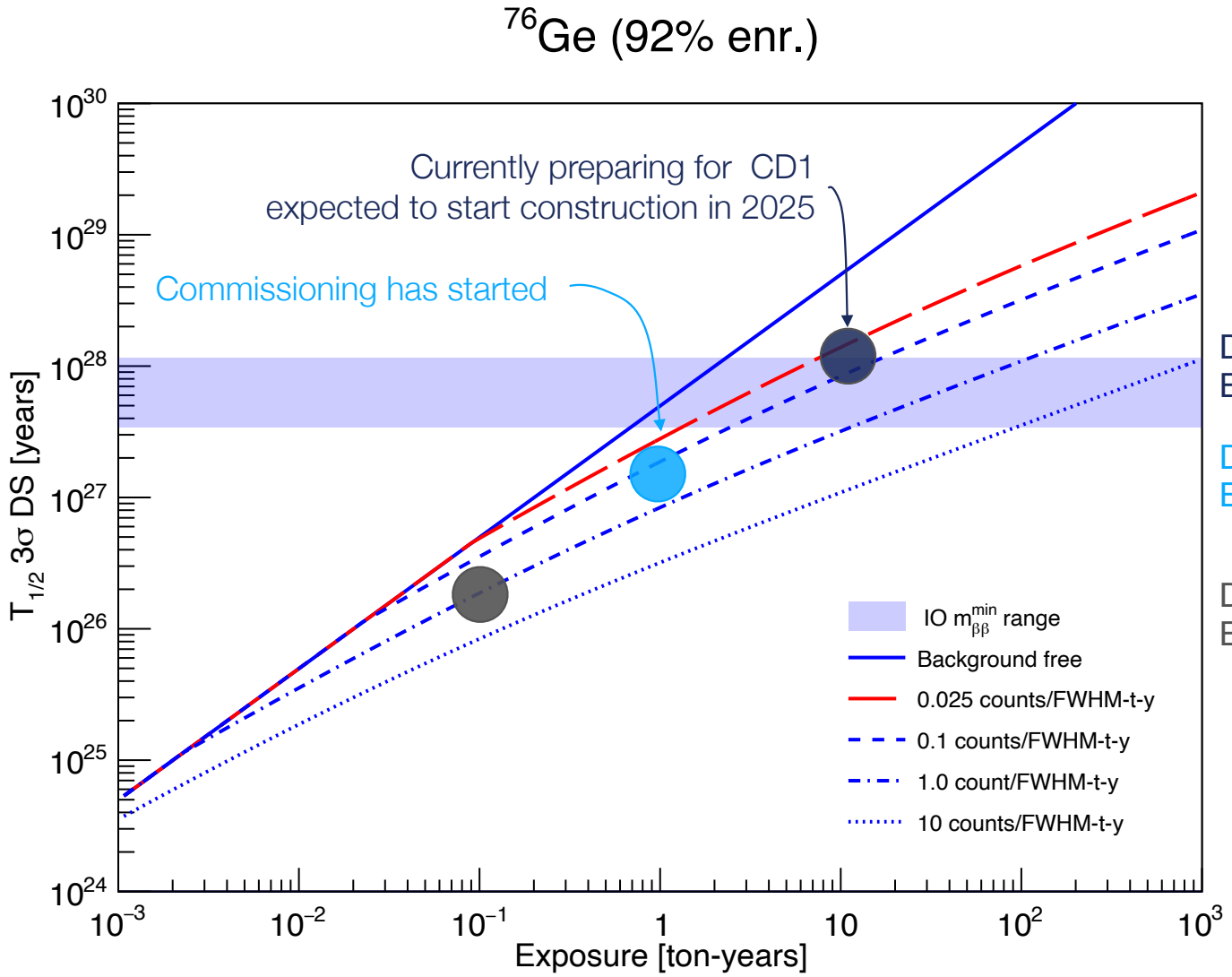
Even a signal at the bottom of the inverted ordering will be visible to the eye!

Designing for an unambiguous discovery

LEGEND-1000

LEGEND-200

GERDA & MAJORANA DEMONSTRATOR



Detector mass: 1000 kg
Exposure: 10 ton-yr
$T_{1/2}^{0\nu} > 10^{28} yr$

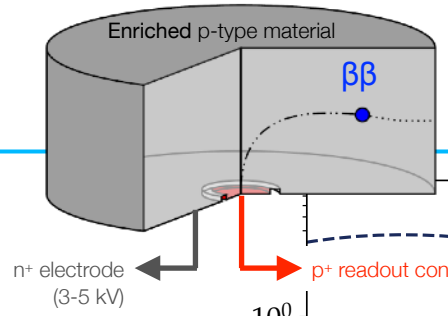
Detector mass: 200 kg
Exposure: 1 ton-yr
$T_{1/2}^{0\nu} > 10^{27} yr$

Detector mass: 44 kg
Exposure: 127 kg-yr
$T_{1/2}^{0\nu} > 10^{26} yr$

→ Goal: "quasi-background free"* operation

*"quasi-background free":
Less than one background count in the signal ROI with the full exposure

HPGe Detectors for 0νββ

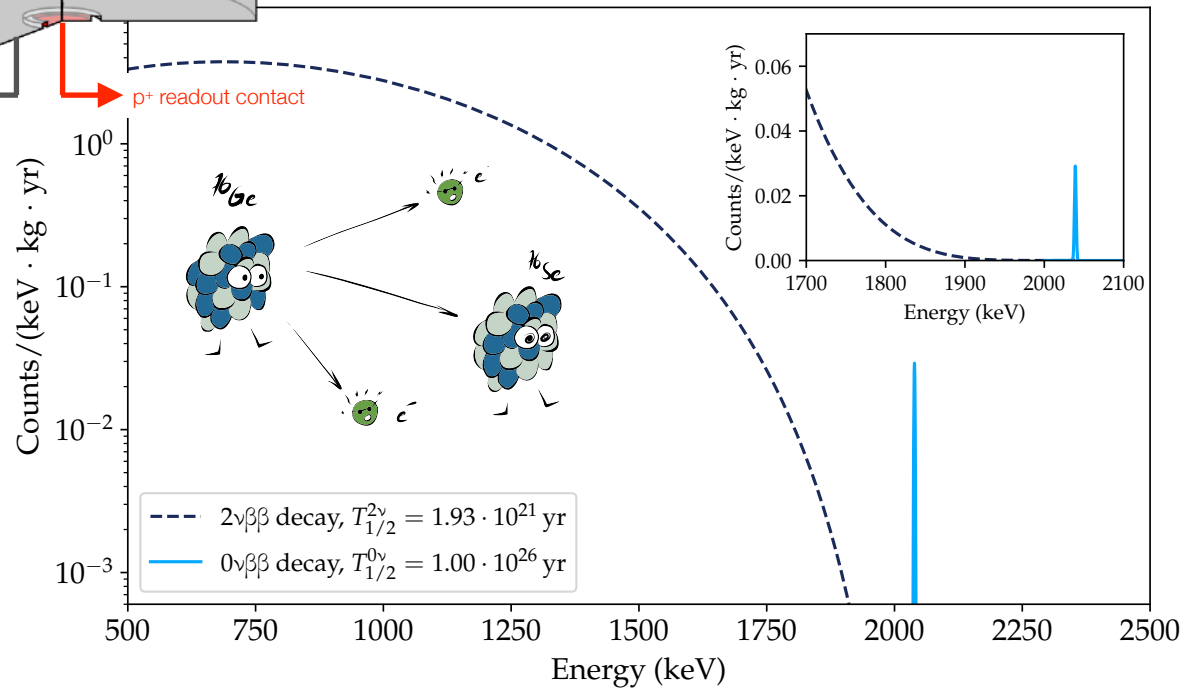


Experimental signature:

→ Detector = ββ source

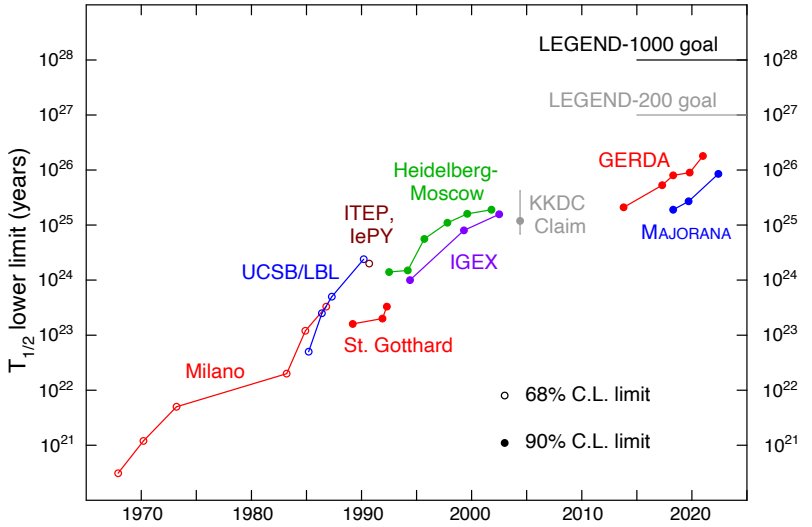
→ ββ decay very localised interaction

→ peak at the ^{76}Ge Q-value ($Q_{\beta\beta}$ = 2039 keV) above 2νββ continuum



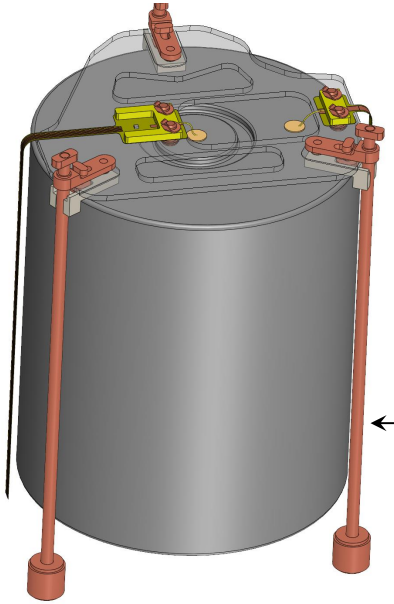
Advantages of HPGe detectors:

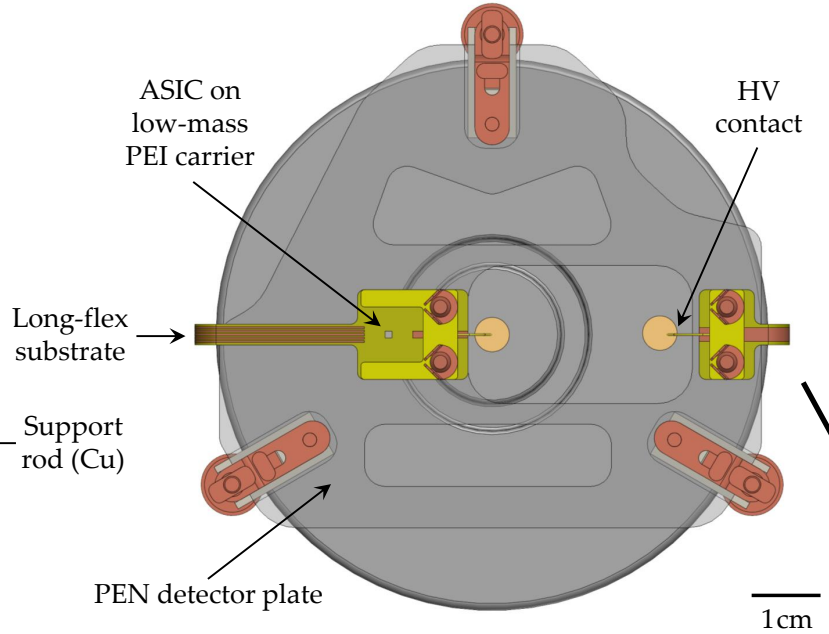
- **Isotope enrichment** from 7.7% to ~ 92 % & commercial detector production
- **Highly efficient:** > 90 % ^{76}Ge use & ~70 % signal efficiency after all cuts
- **Easy operation:** low operating voltage (< 5 kV) & moderate cryogenic requirements (77-90 K)
- **Superb energy resolution** @ $Q_{\beta\beta}$ (~ 0.1 % FWHM)
- **Lowest background** per FWHM energy resolution in the field [Science 365 (2019) 1445] [PRL 125 (2020) 252502]
- **Many tools for background reduction**
  – Multiplicity, timing, active veto shielding
  – Pulse-shape used for event topology discrimination

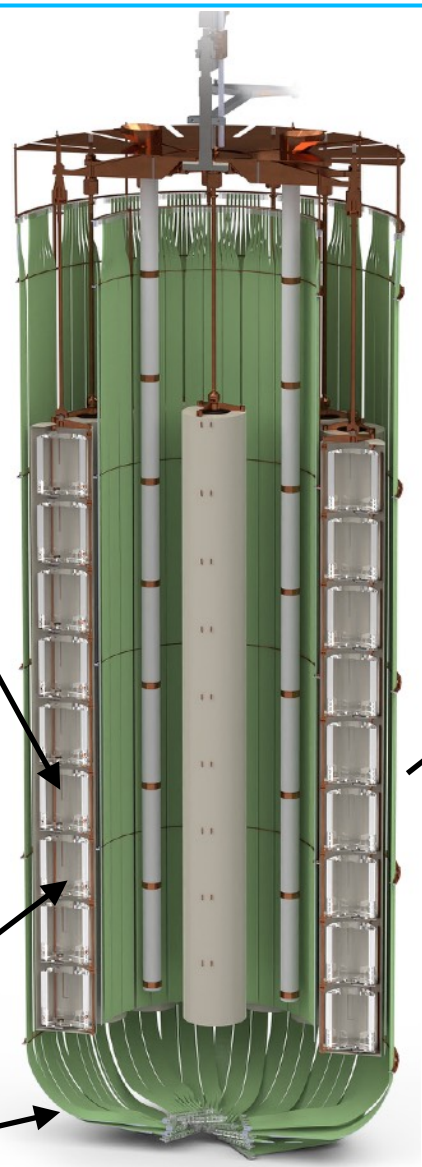


LEGEND-1000: Concept & Design

Inverted-Coaxial Point Contact (ICPC) detector module

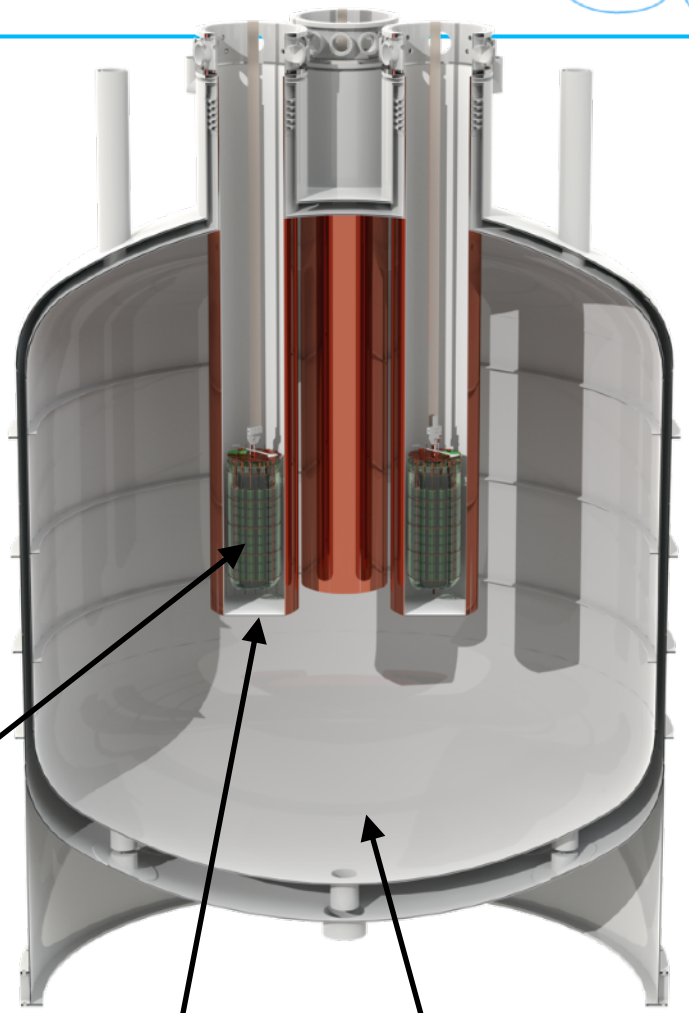






Ge detector strings

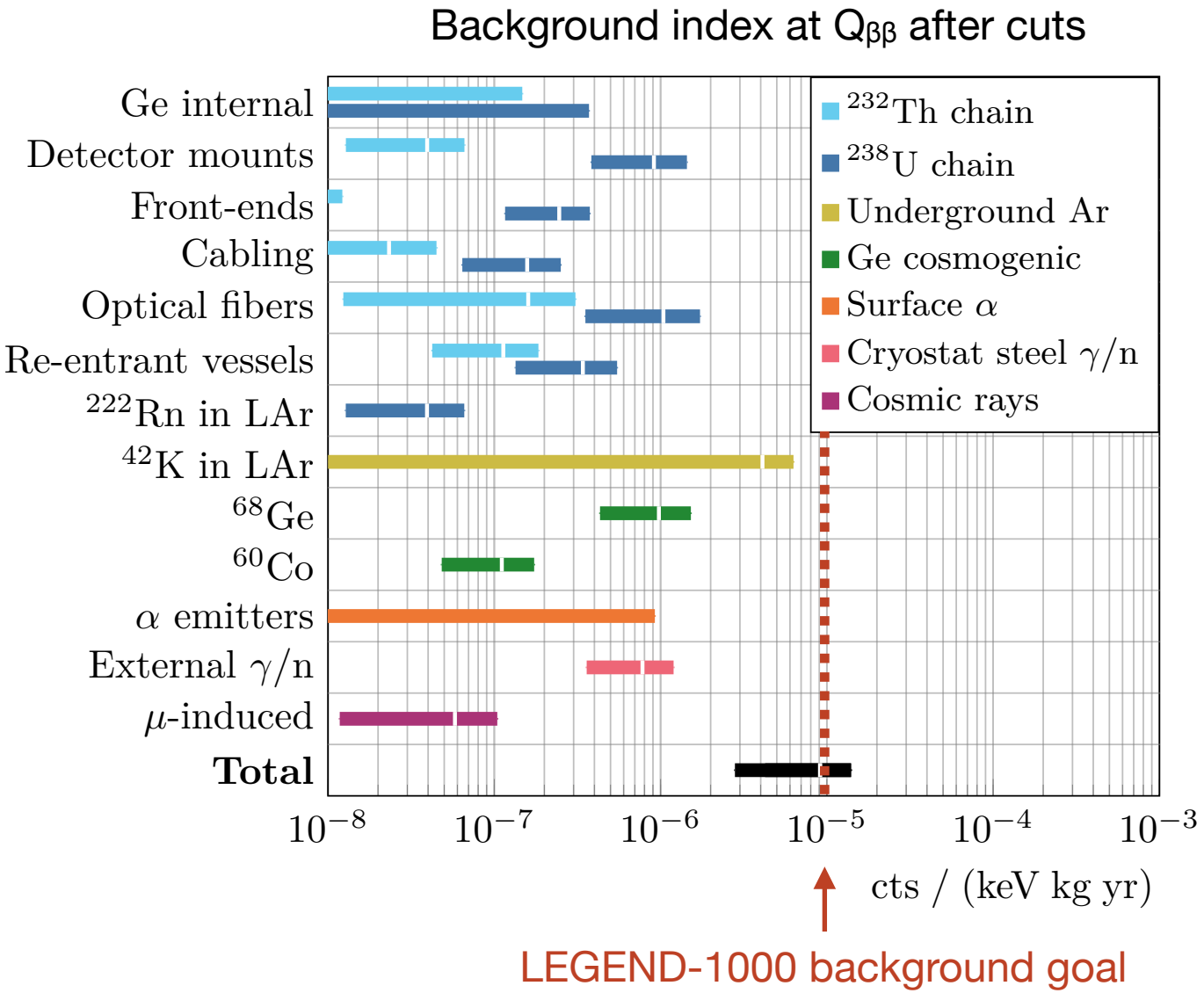
Wavelength shifting fiber curtain



Underground Liquid Argon

Liquid Argon

LEGEND-1000: Background Projections

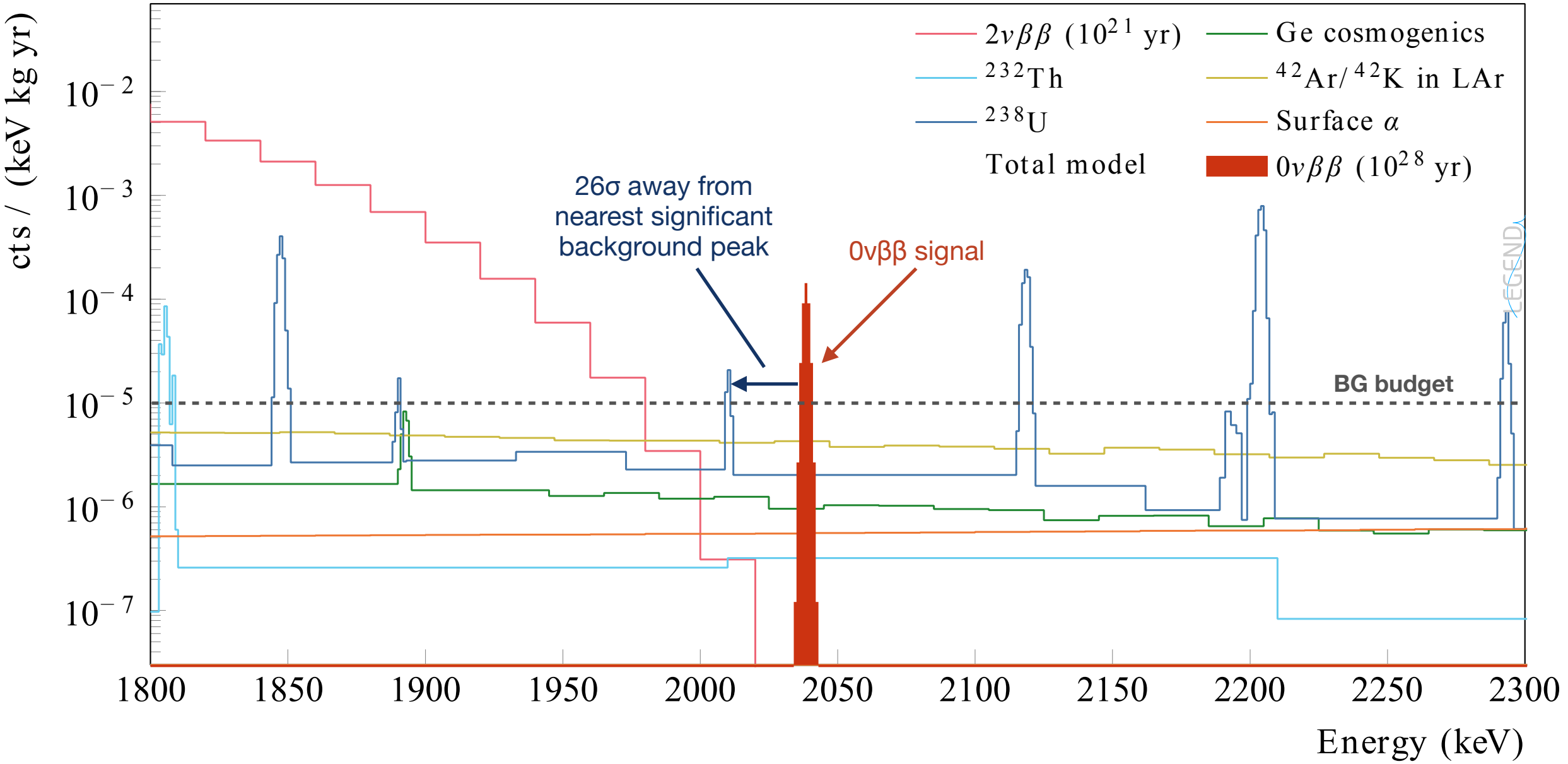


Projected background index after all cuts:

$$9.4^{+4.9}_{-6.3} \times 10^{-6} \frac{\text{counts}}{\text{keV kg yr}}$$

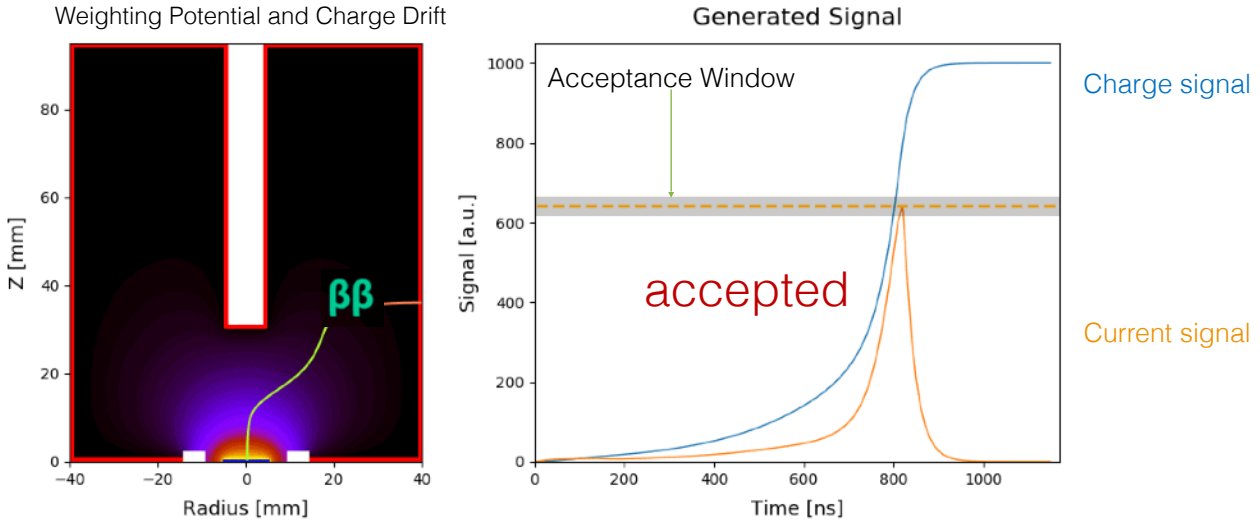
Quasi-background free operation up to 10 ton-years of exposure, for unambiguous discovery beyond 10^{28} years

LEGEND-1000: Background Model

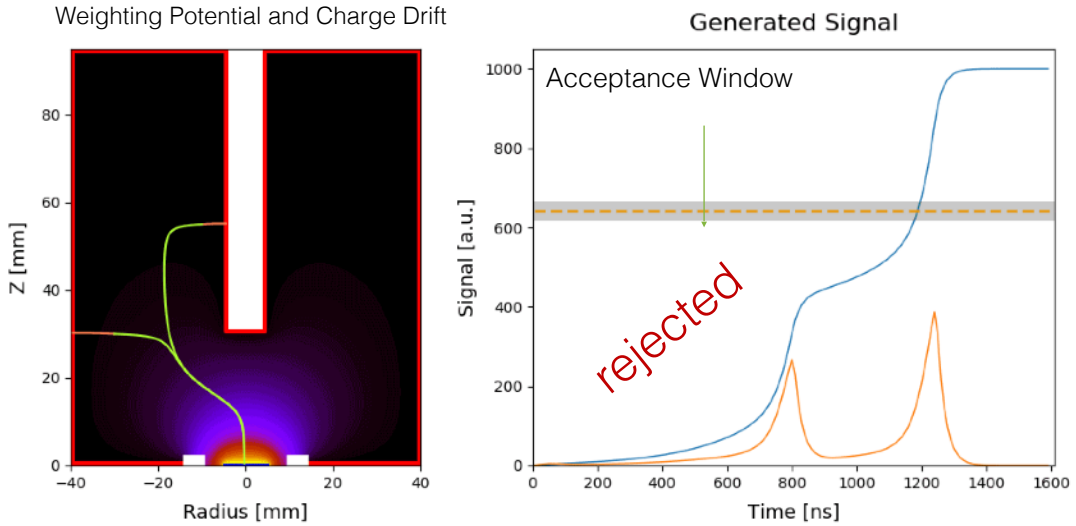


Background rejection in point contact HPGe detectors

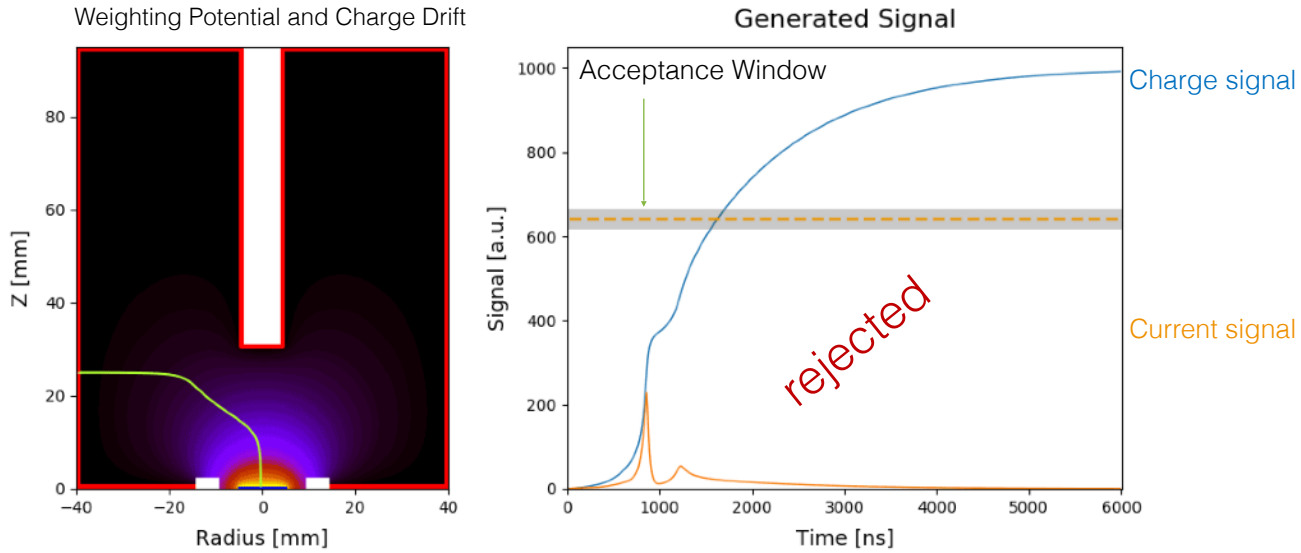
0νββ signal candidate (single-site)



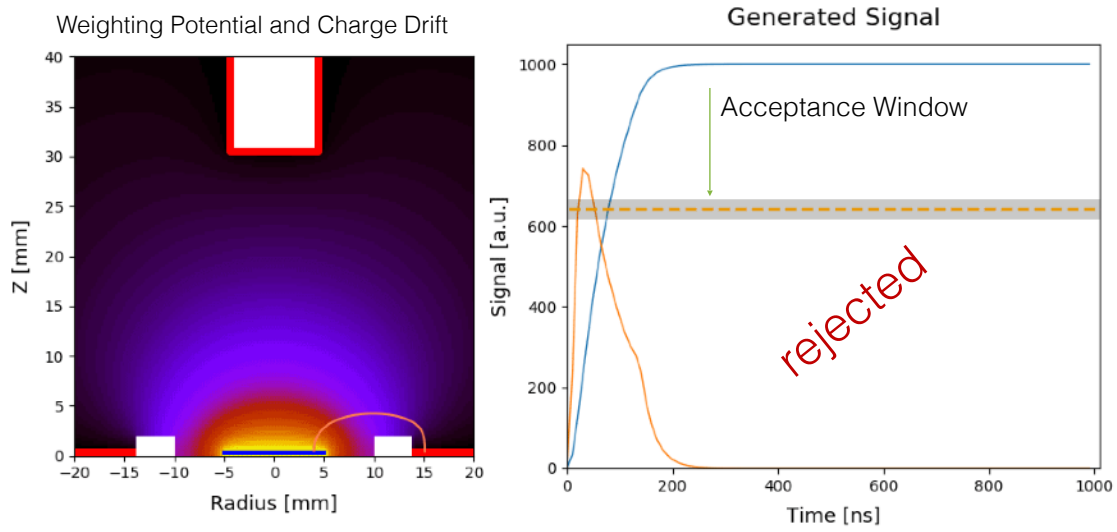
γ-background (multi-site)



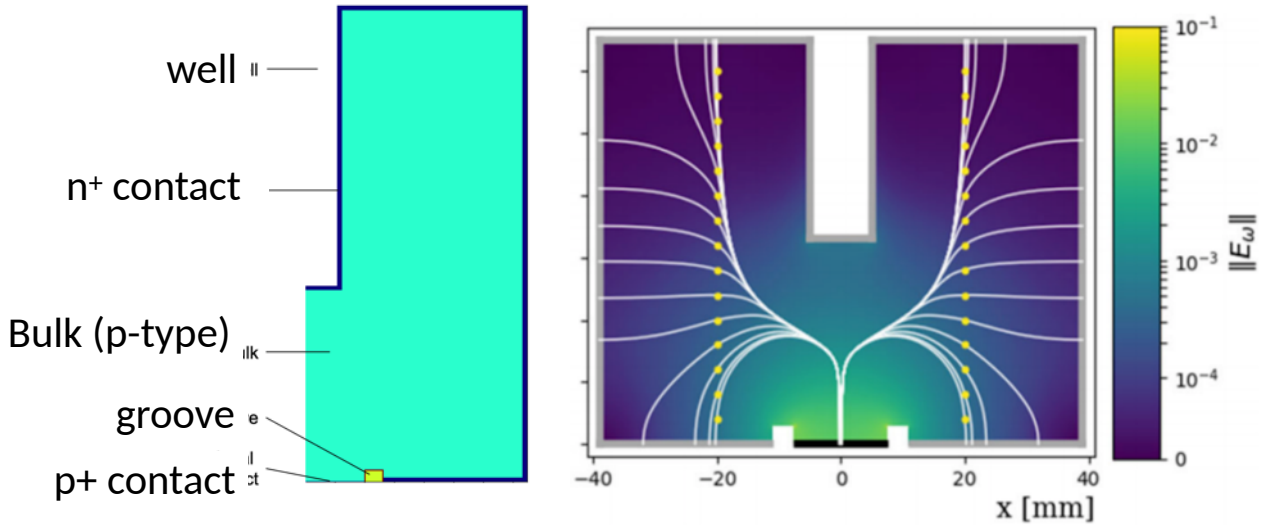
Surface-β-background ^{42}K (^{42}Ar) on n+ contact



α-background on p+ contact



Innovations toward LEGEND-1000



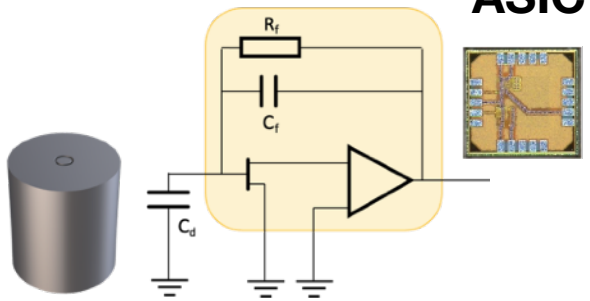
^{enr}Ge detectors

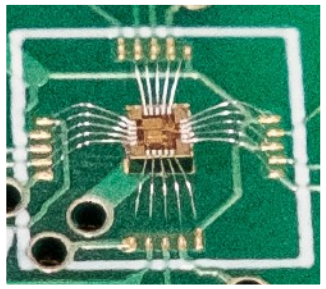
- p-type detectors
  → large n+ surface insensitive to α backgrounds
- Small p+ signal contact
  → field geometry allows to reconstruct event topology
- Larger mass of ICPC benefits background reduction
  → near backgrounds scale with # of detectors (electronics, cables, detector supports)
- Proven long-term stable operation in liquid argon

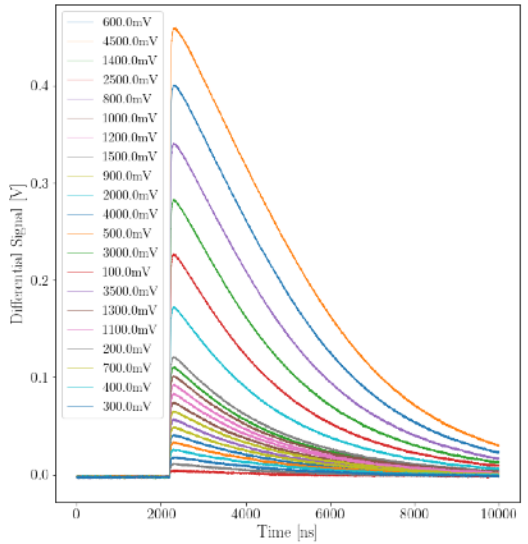
ASIC-based HPGe readout electronics

- Low-mass, low-noise charge sensitive amplifier ASIC operated close to detector
- Multiple implementations: LBNL (baseline) & TUM / Milano (alternative)
- Lower electronic noise, higher bandwidth & faster signals
- Rich international characterisation & integration efforts in Europe & US

ASIC

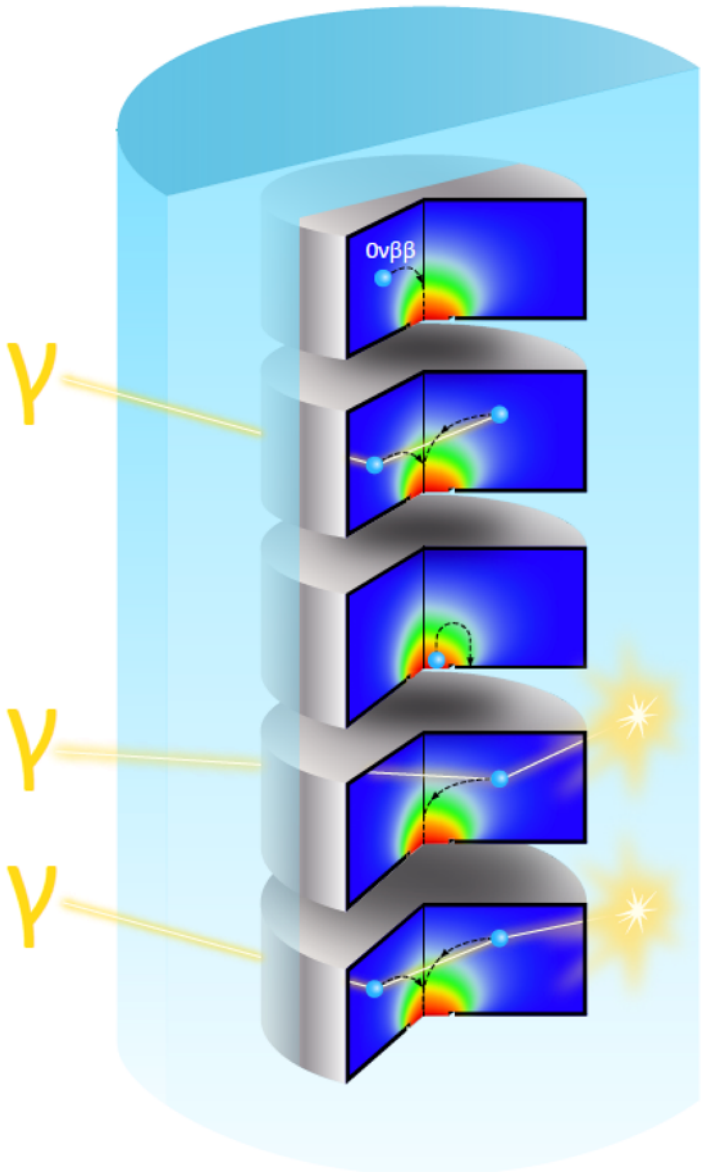


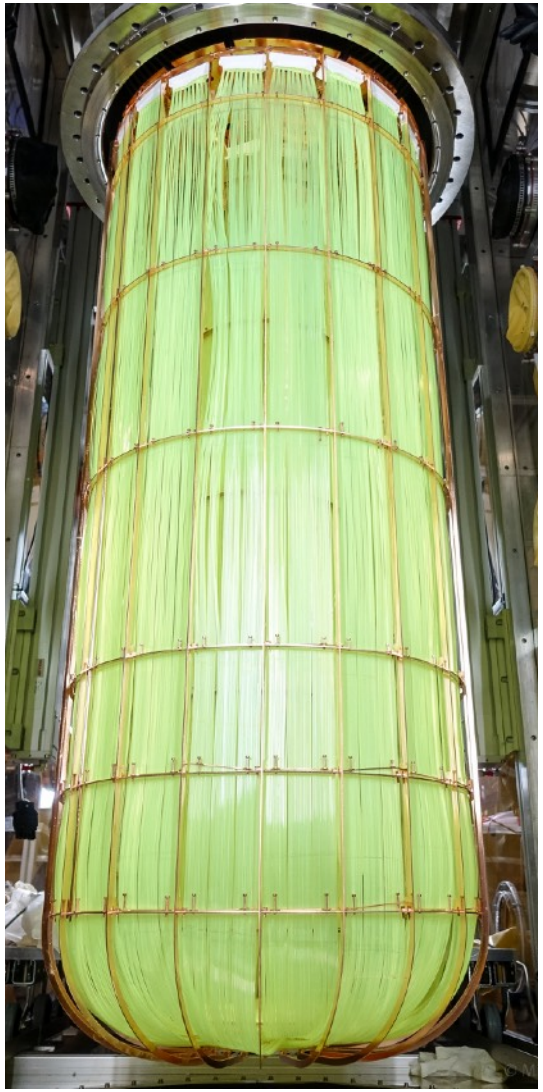




Signal transients from baseline ASIC implementation

Innovations toward LEGEND-1000



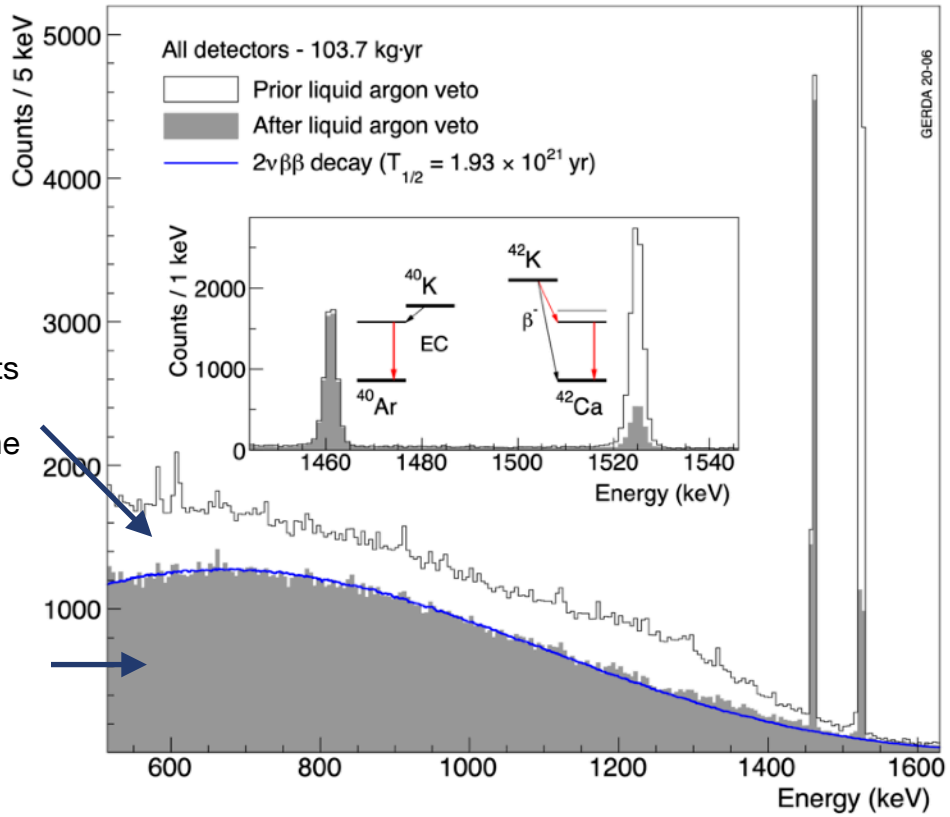


LAr instrumentation

- Detection of liquid argon scintillation light with low-background wavelength-shifting fibers and SiPM arrays
- Powerful background suppression tool!

Compton events with energy deposition in the LAr

Pure 2νββ spectrum after LAr signal suppression



Innovations toward LEGEND-1000

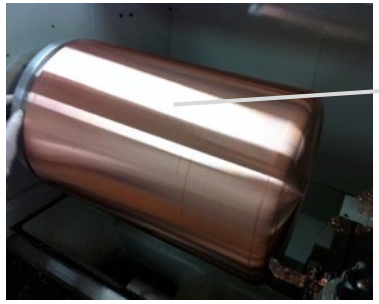
Clean Materials

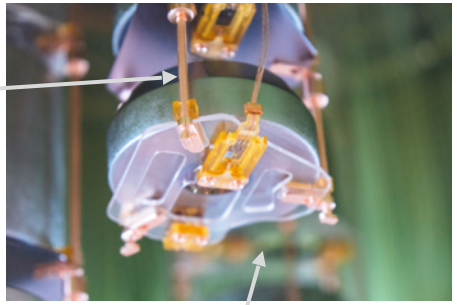
- Minimize materials close to Ge detectors and use of highest purities:
  - Underground electroformed copper (EFCu) reduces U, Th, and cosmogenic activation

    $< 0.017 \pm 0.03$ pg/g ^{238}U

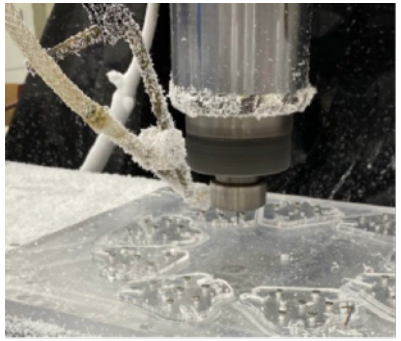
    $< 0.011 \pm 0.05$ pg/g ^{232}Th
  - Copper-Kapton laminated cables
- Optically active structural materials:
  - Polyethylene naphthalate (PEN) shifts 128 nm LAr scintillation light to ~440 nm and scintillates
  - Yield strength higher than copper at cryogenic temperatures

EFCu for holders and reentrant tube

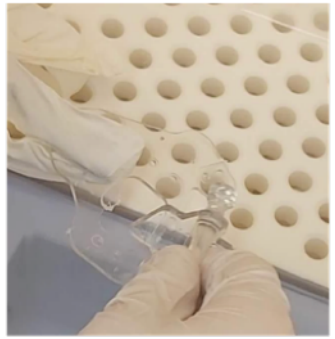




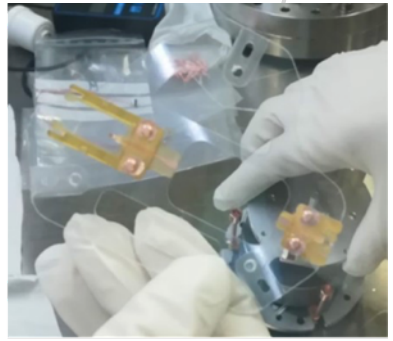
PEN: scintillating (self-vetoing) high-purity detector support



Machining



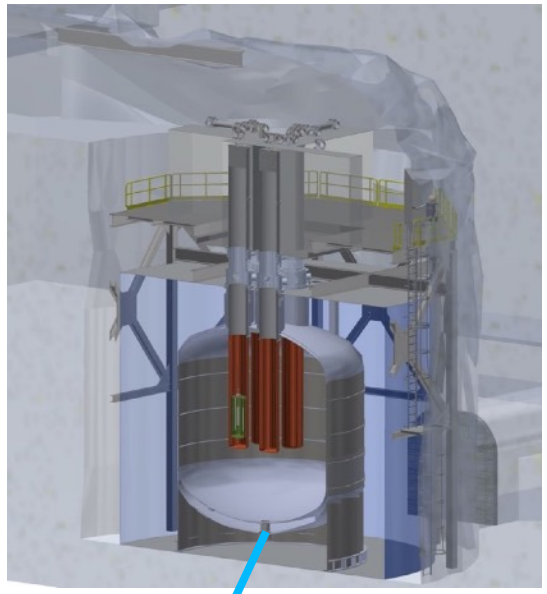
Cleaning

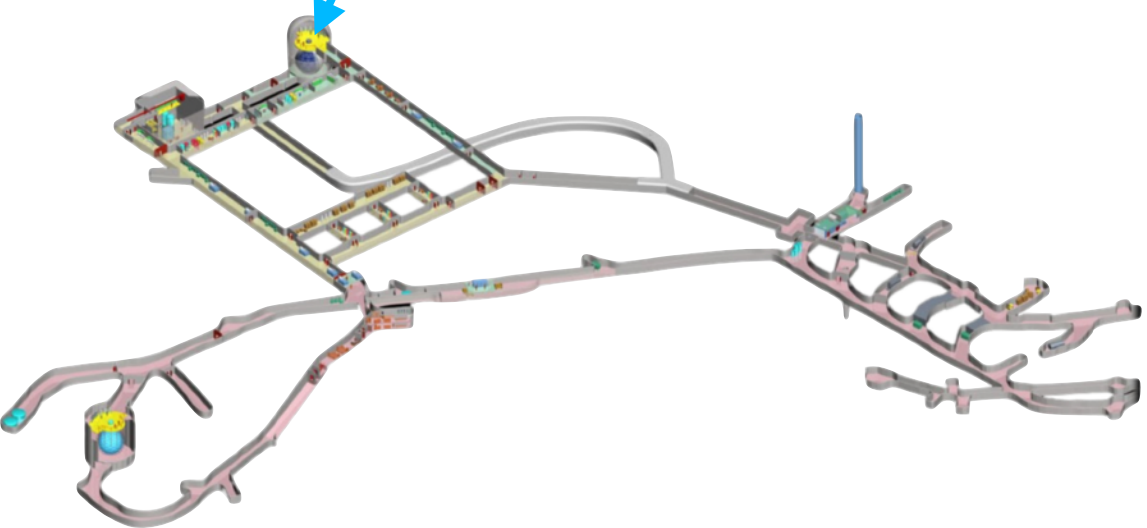


PEN plate

LEGEND-1000: Underground Sites

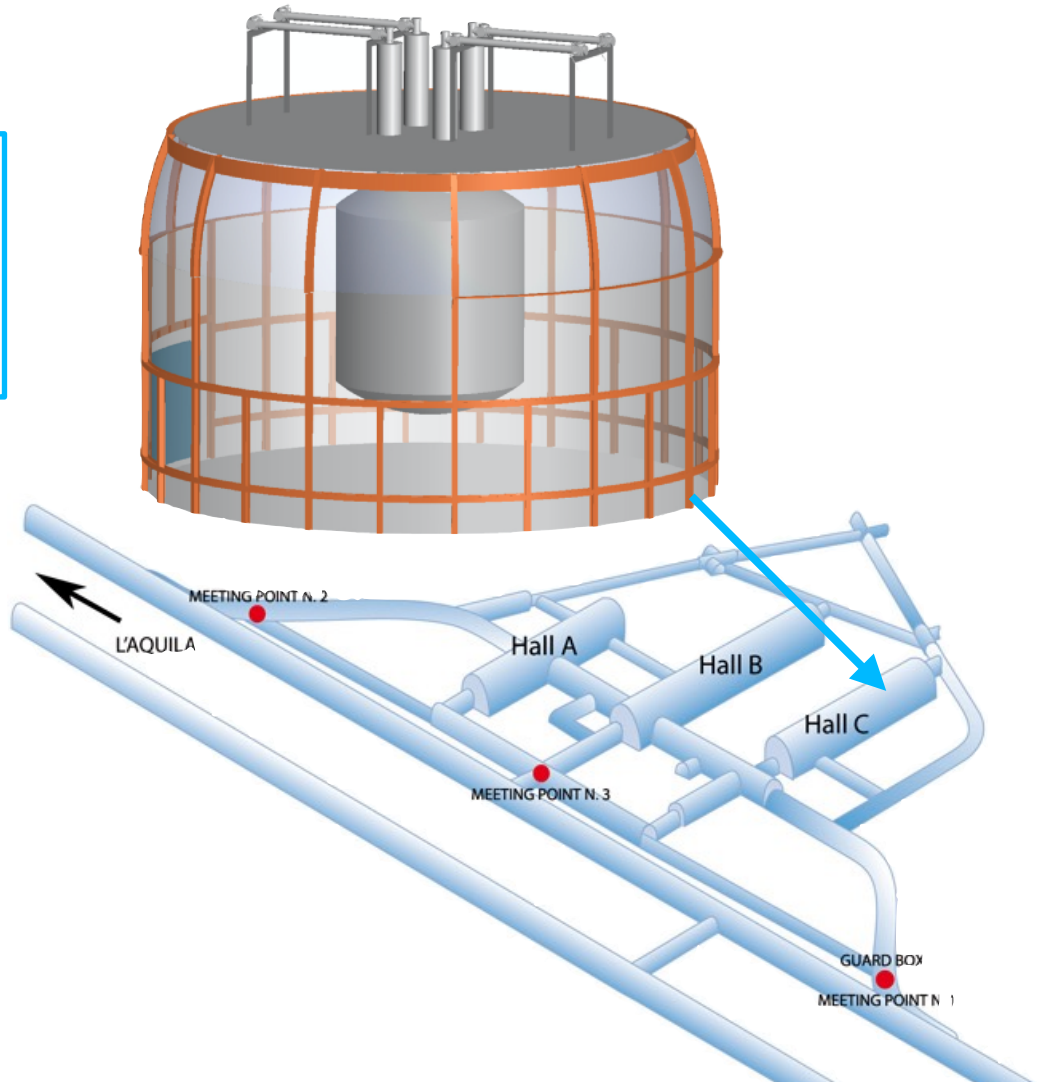
SNOLAB: cryopit is committed for ton-scale 0νββ experiment





- SNOLAB is **deeper** than LNGS
- LNGS **depth is sufficient** with tagging in-situ produced cosmogenic isotopes

LNGS: Re-purpose BOREXINO tank and infrastructures



Summary & Outlook

- LEGEND-1000 is a ton-scale 0νββ experiment designed for unambiguous discovery of 0νββ decay at half-lives > 10^{28} years
  - Optimised for a quasi-background-free 0νββ search at 10 ton-years of exposure
  - Builds on breakthrough developments by GERDA, MAJORANA, and LEGEND-200 and novel developments & innovations
- LEGEND-1000 emerged successful from the DOE portfolio review in 2021
  - currently preparing for CD-1
  - conceptual design report is in preparation
  - construction is expected to start ~ 2025

Acknowledgements

- We appreciate the support of our sponsors:
  - German Federal Ministry for Education and Research (BMBF)
  - German Research Foundation (DFG), Excellence Cluster ORIGINS
  - German Max Planck Society (MPG)
  - South Dakota Board of Regents
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  - Italian Instituto Nazionale di Fisica Nucleare (INFN)
  - Swiss National Science Foundation (SNF)
  - Polish National Science Centre (NCN)
  - Foundation for Polish Science
  - Russian Foundation for Basic Research (RFBR)
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  - European Research Council
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- We thank our hosts and colleagues at LNGS and SURF
- We thank SNOLAB for their engineering support in LEGEND-1000 planning
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