LEGEND

Unterstützt von / Supported by

Alexander von Humboldt
Stiftung / Foundation

Status of LEGEND

Large Enriched Germanium Experiment for Neutrinoless ββ Decay

Michael Willers

LBNL / NSD - 08.10.2019

BERKELEY LAB

The Large Enriched Germanium Experiment for Neutrinoless ββ Decay

53 institutions, ~ 250 scientists

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."

The LEGEND Experiment

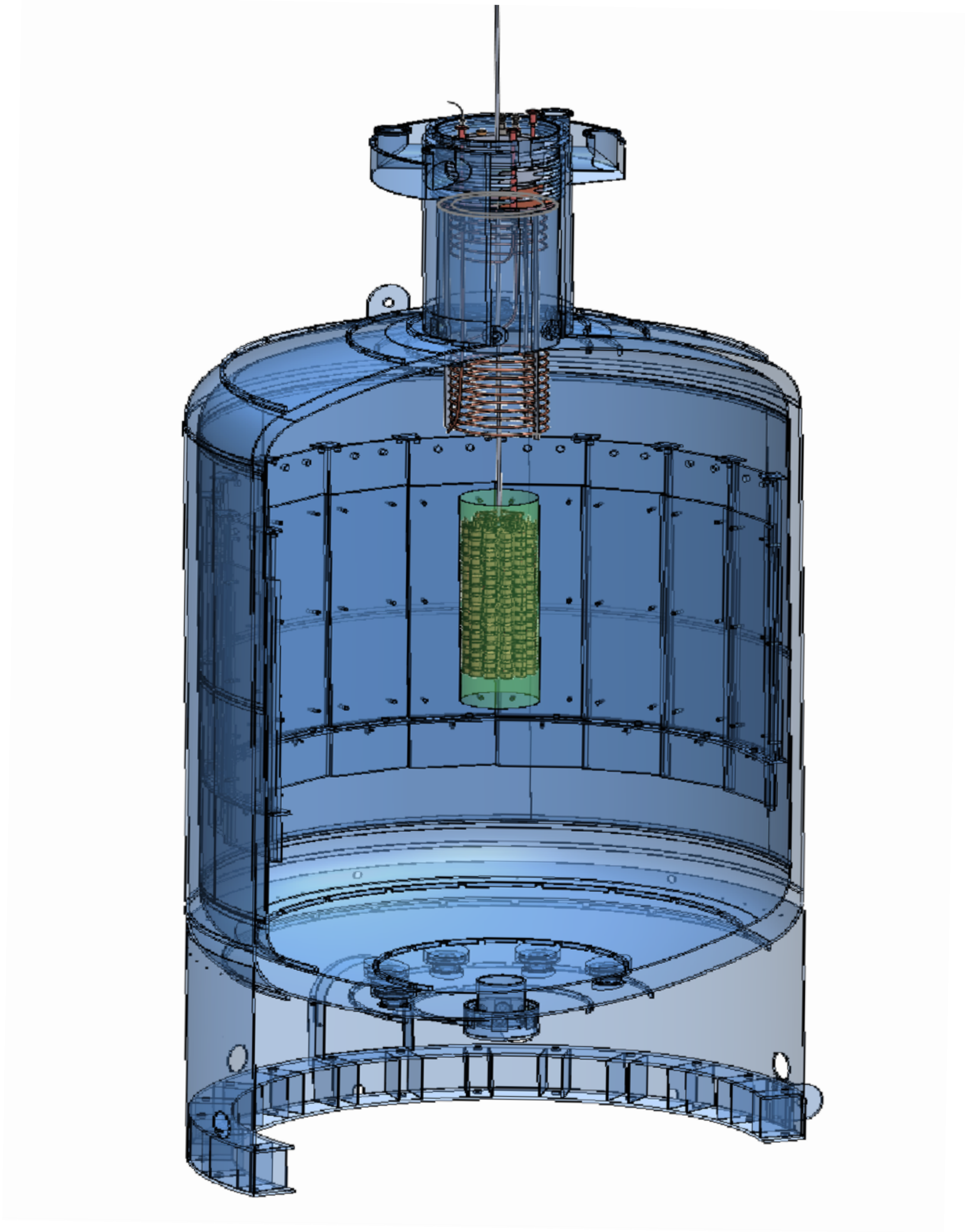
Strategy

Choose best technologies based on GERDA and MAJORANA DEMONSTRATOR and others

Increase mass towards 1000kg in phased approach

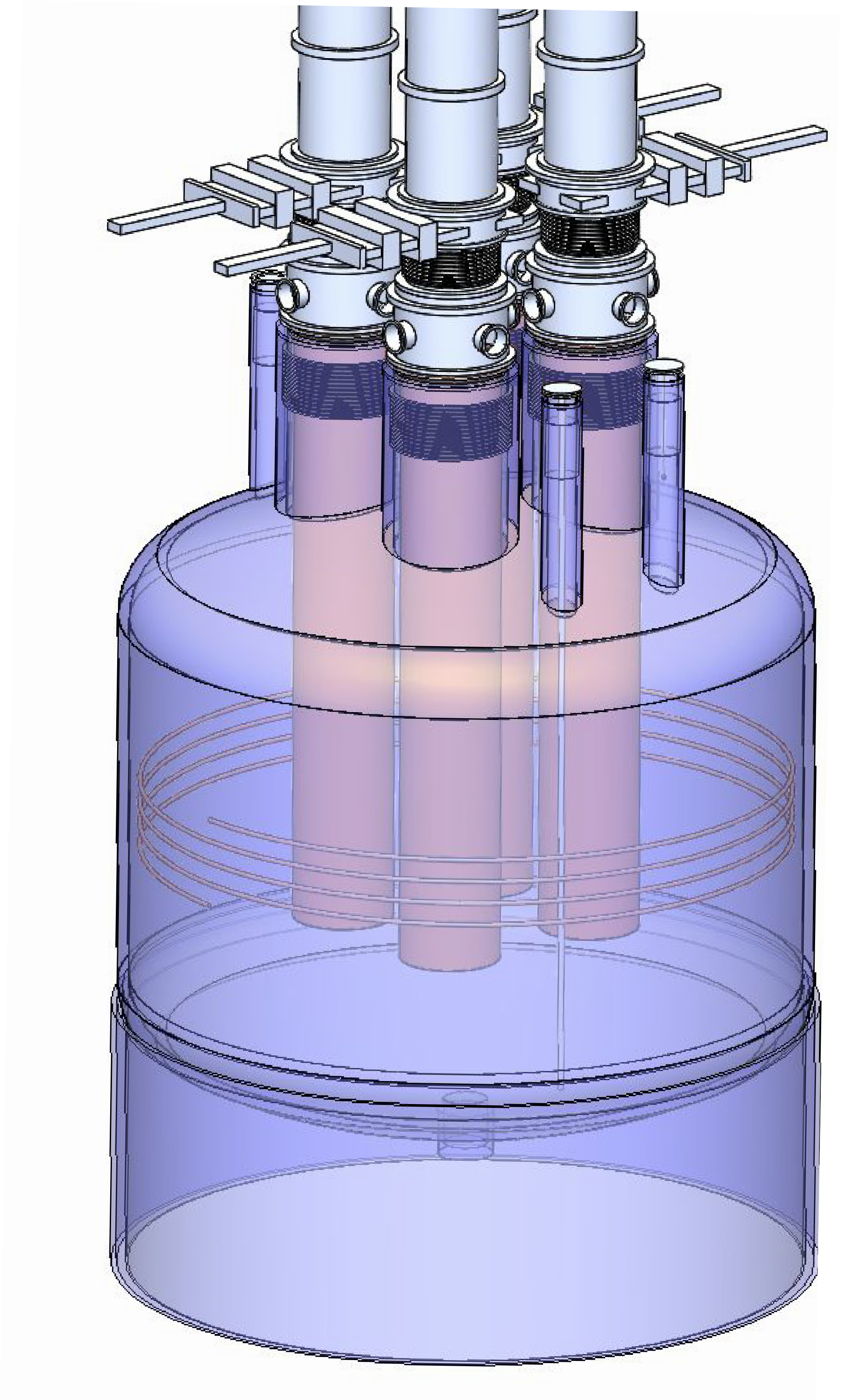
LEGEND-200

- 200 kg of HPGe detectors
- BG goal: 0.6 cts / (FWHM t yr)
- Update to existing infrastructure at LNGS



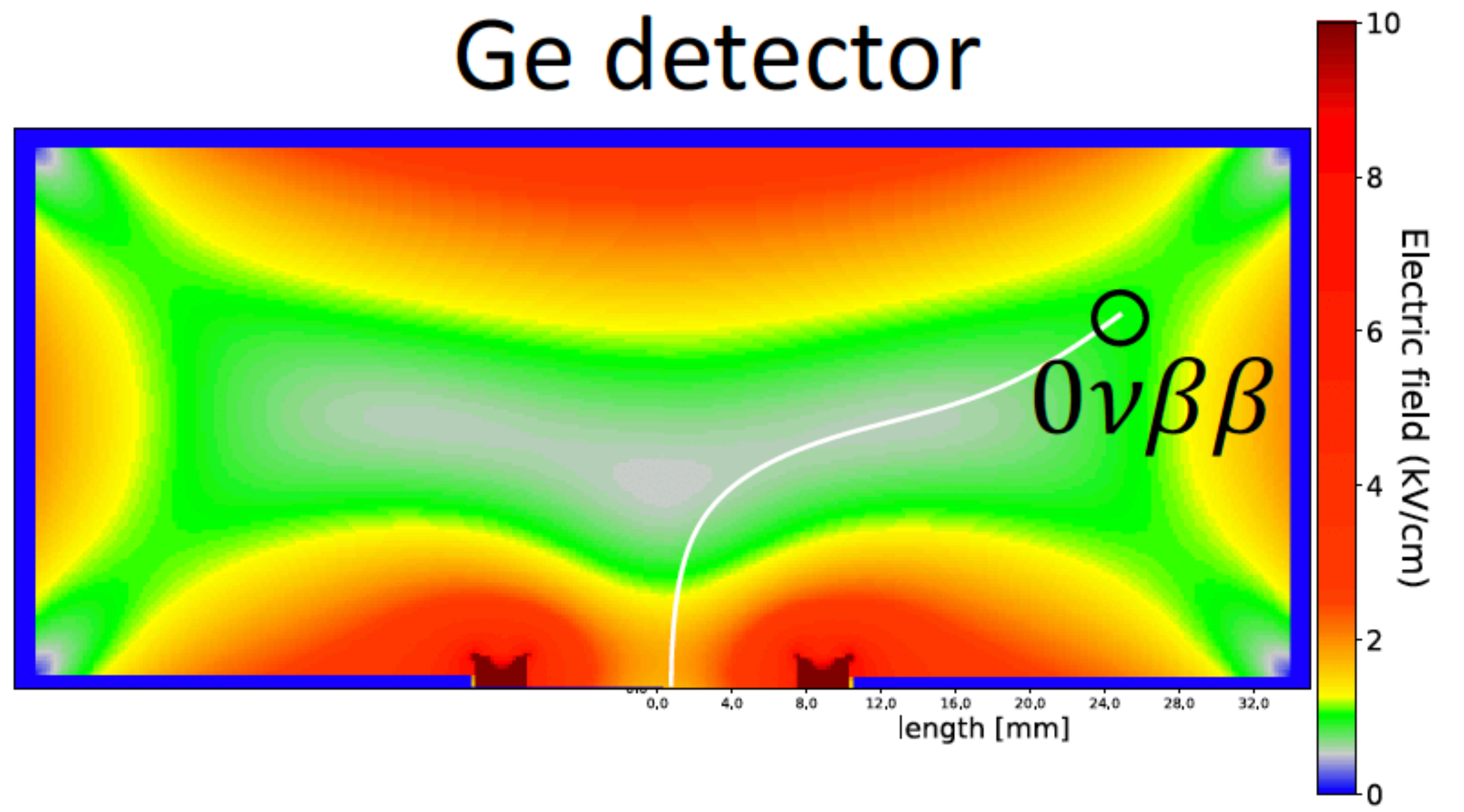
LEGEND-1000

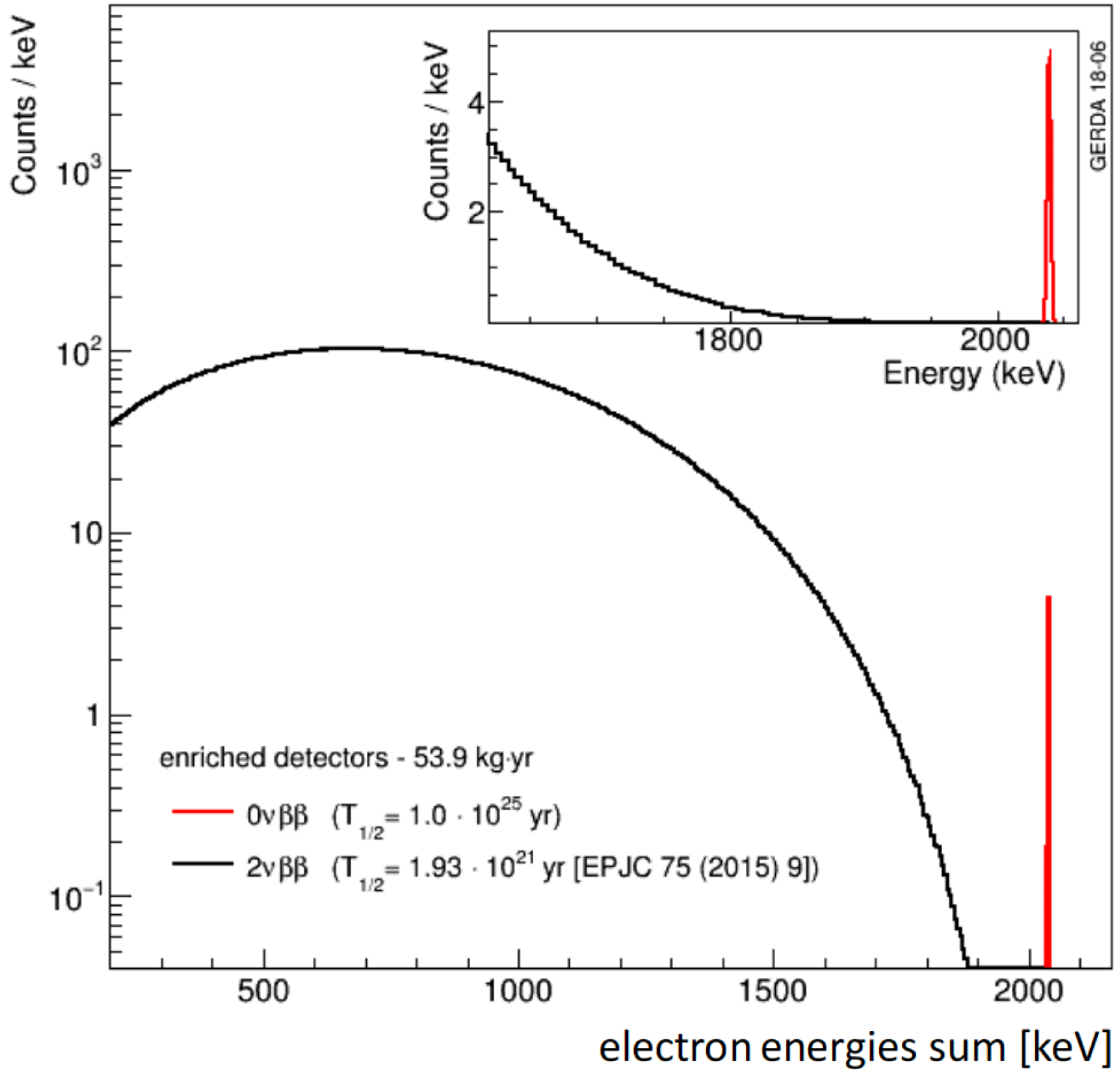
- 1000 kg of HPGe detectors
- BG goal < 0.1 cts / (FWHM t yr)
- Location TBD → required depth under investigation



^{76}Ge-based 0νββ decay search

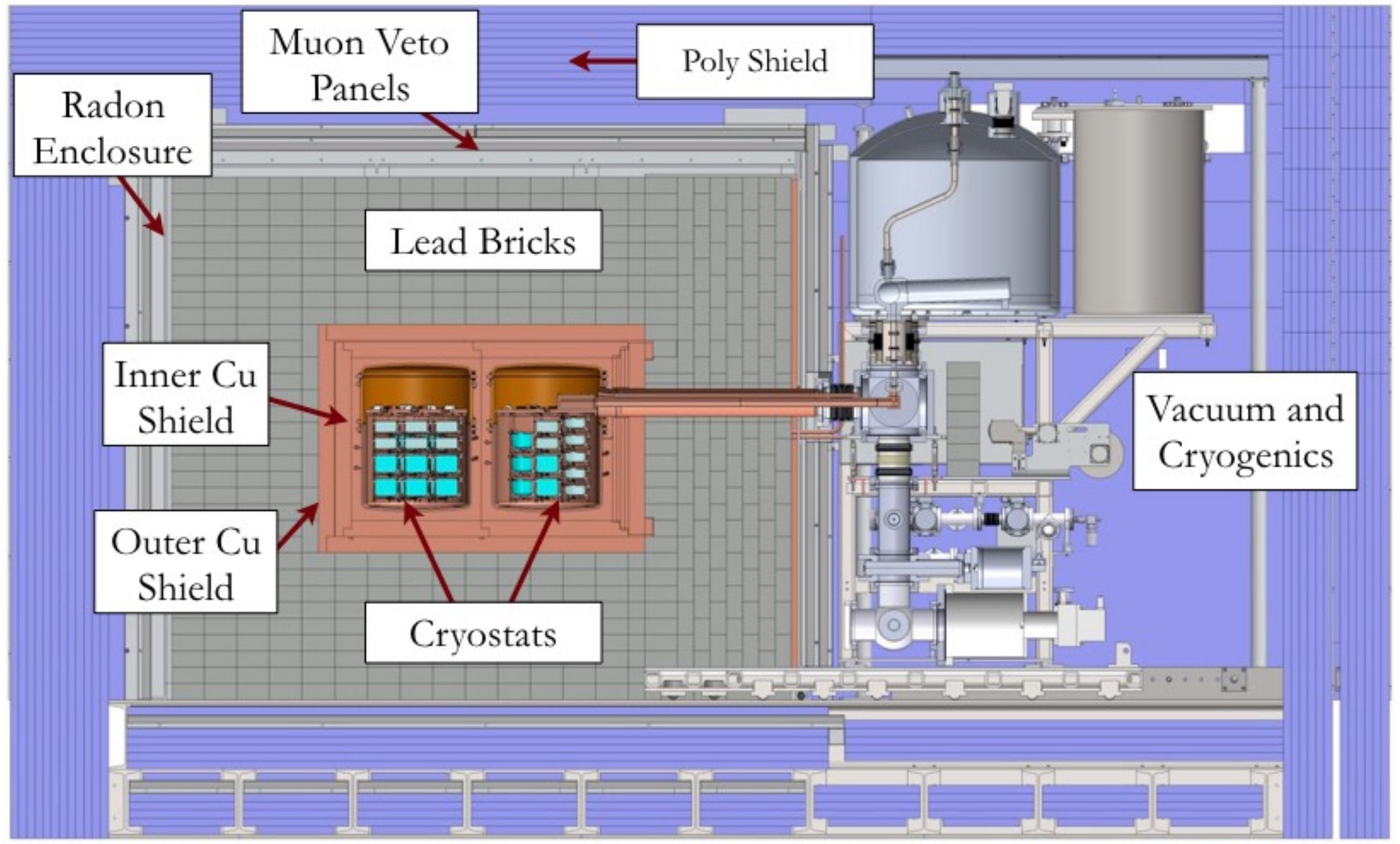
- $^{76}Ge \rightarrow {}^{76}Se + 2e^-$ $Q_{\beta\beta}$ = 2039 keV
- Enrichment to > 88% in ^{76}Ge possible
- Very high detection efficiency
  → source = detector
- High density material → ββ are point like
  → backgrounds can be discriminated and rejected
- Intrinsically pure material → low background
- Excellent energy resolution
  → 2.2 - 3 keV FWHM at $Q_{\beta\beta}$
  → 2νββ background rejection





Best of MAJORANA DEMOSTRATOR and GERDA

MAJORANA DEMONSTRATOR @ SURF



- Radiopurity of nearby parts (FETs, cables, Cu mounts, etc.)
- Low noise electronics improves pulse shape discrimination
- Low energy threshold (helps reject background & extended low-energy physics program)

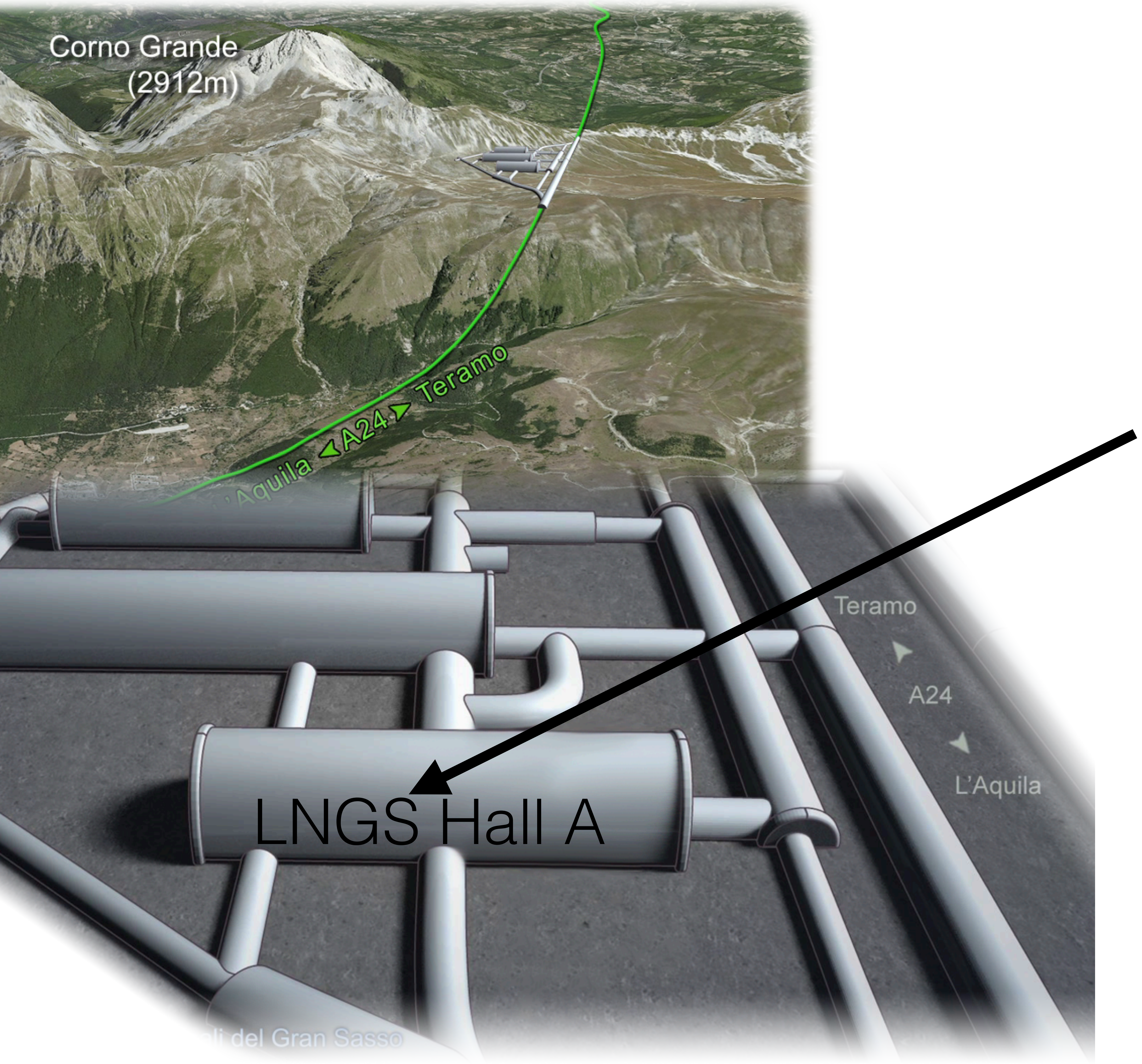
GERDA @ LNGS

- Detectors (^{enr76}Ge) in liquid argon (LAr)
- LAr acts as an active shield (no Pb)
  → background tagging by LAr scintillation light & coincident signals

Both:

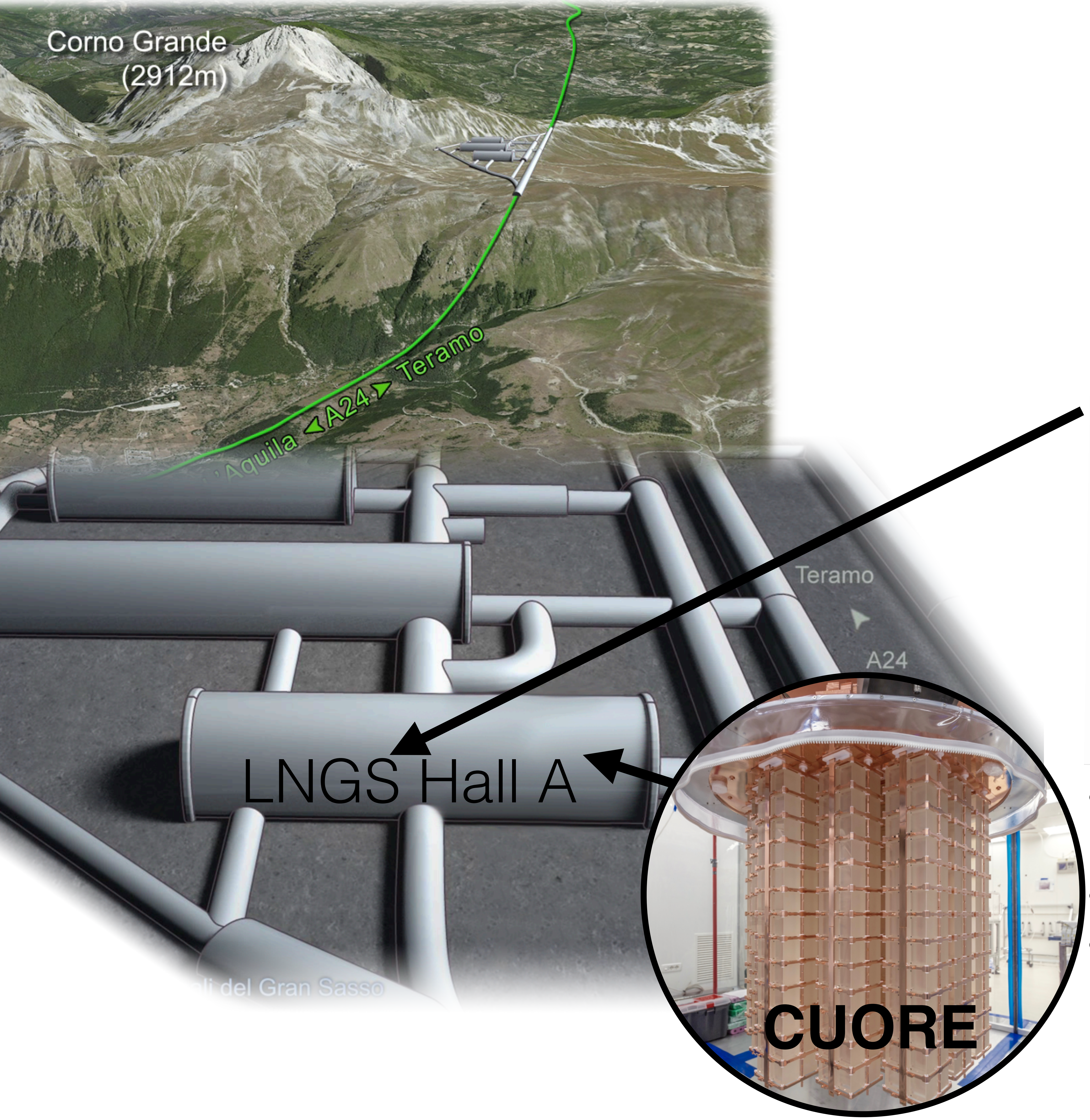
Clean fabrication techniques
Control of surface exposure (cosmogenic activation)
Development of large point-contact HPGe detectors
Lowest background and best resolution $0\nu\beta\beta$ decay experiments

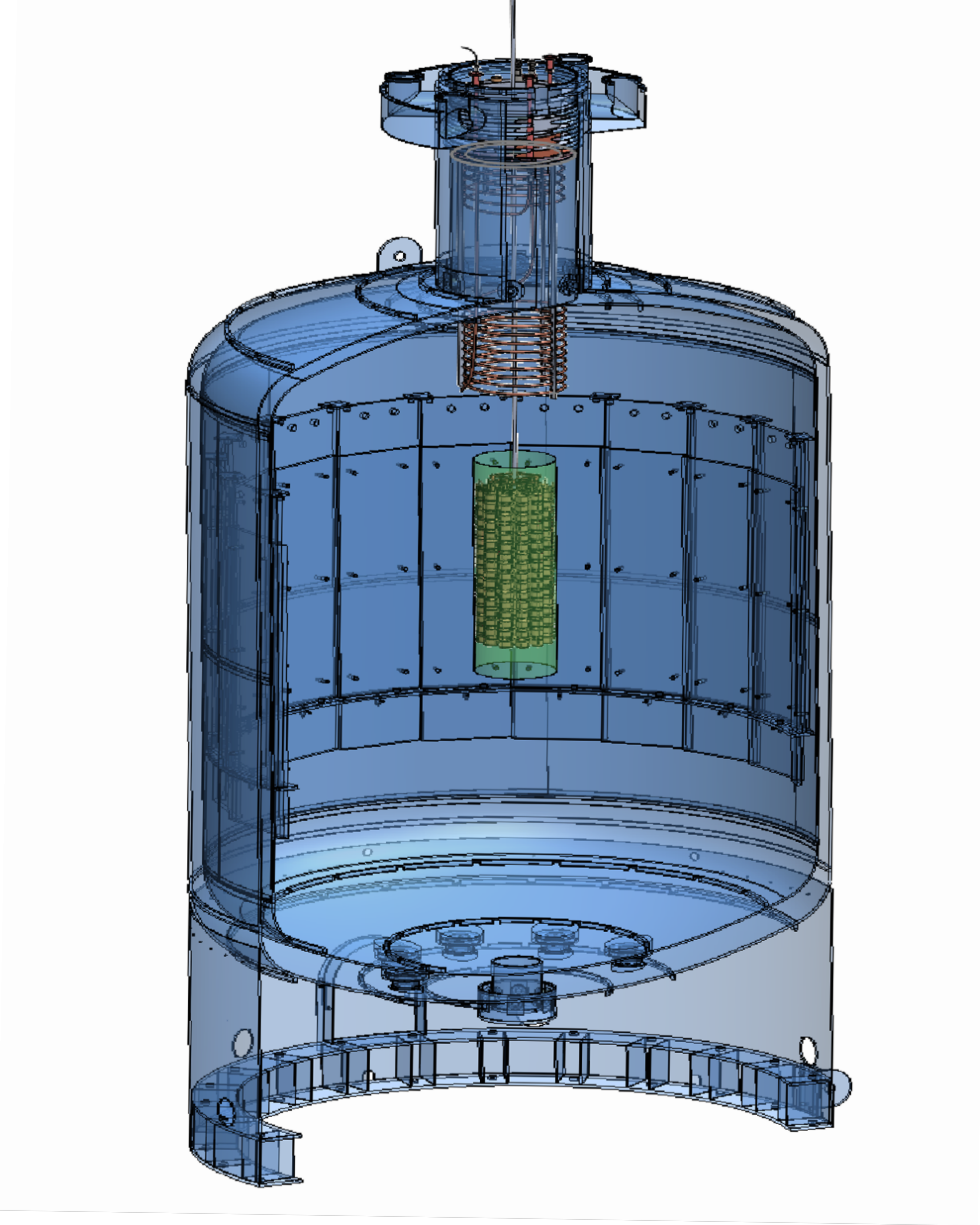
The LEGEND-200 Setup



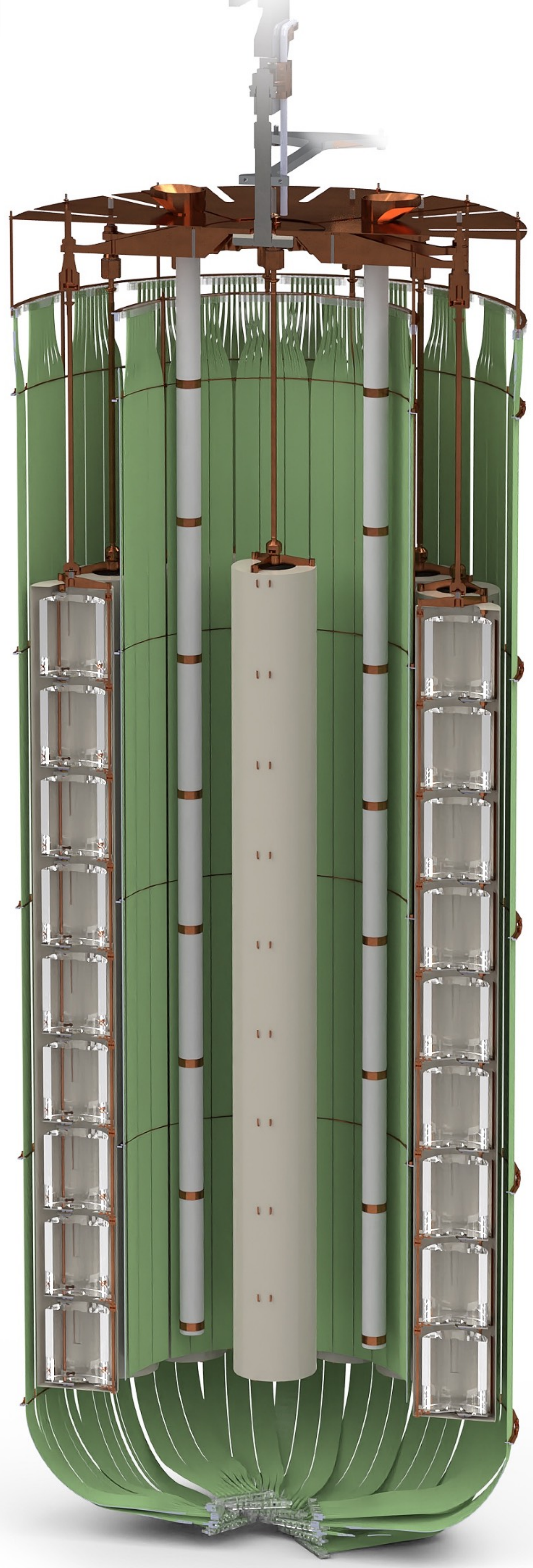
- Water tank & modified cleanroom from GERDA

The LEGEND-200 Setup

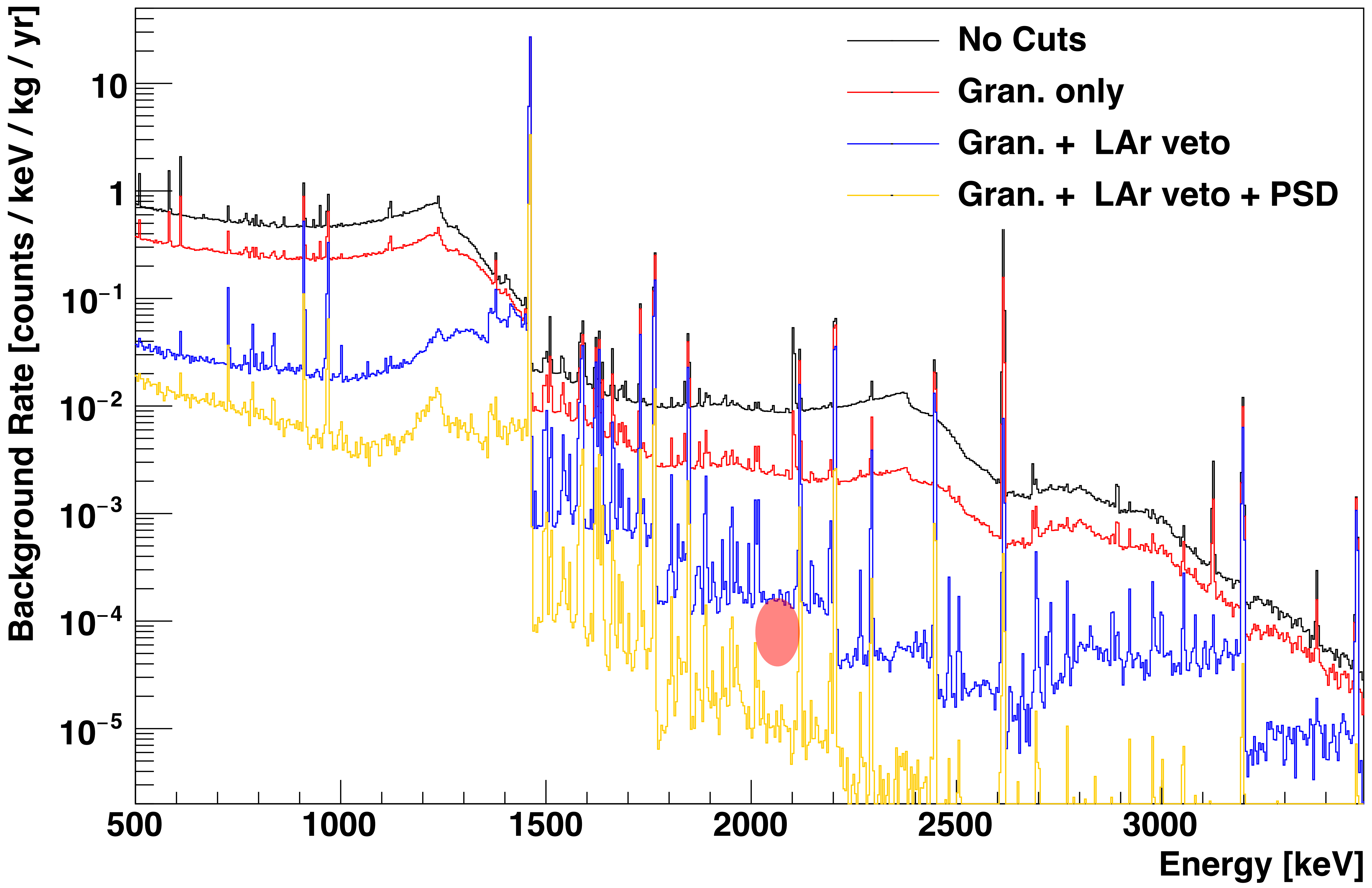




- Water tank & modified cleanroom from GERDA
- Upgraded cryostat (lock, cables)
- New detector array (200kg) and improved LAr veto



LEGEND-200 background projections



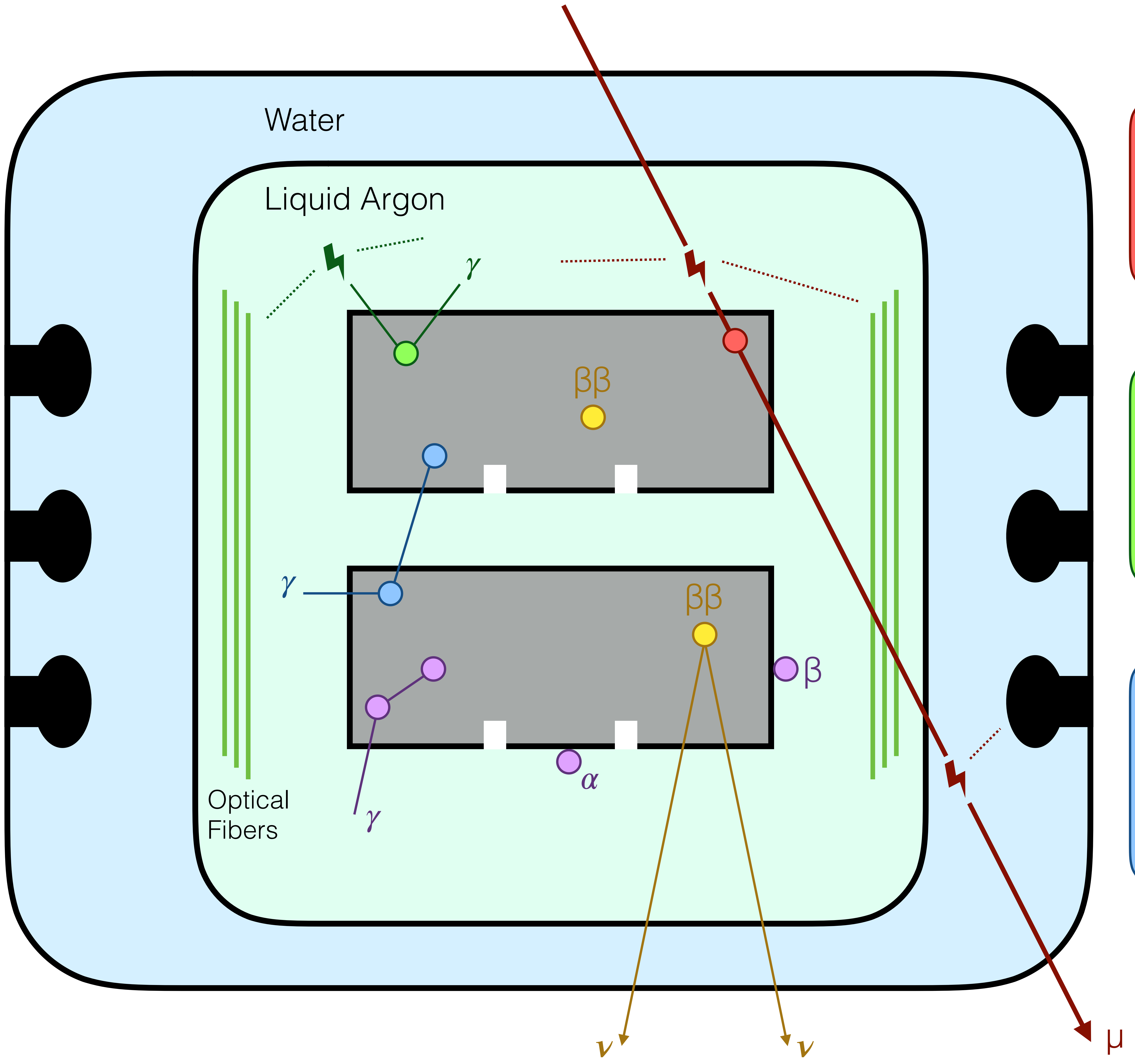
Background goal < $2 \cdot 10^{-4}$ cts / (keV kg year)

- Expected upper limit of total background contributions from **^{238}U** chain, **^{232}Th** chain and **^{40}K** (all components)
- Background reduction strategy improves background at $Q_{\beta\beta}$ by three orders of magnitude

LEGEND-200 background reduction strategy

ββ decay signal:
single energy deposition in ~ 1 mm³ volume

Pulse shape discrimination (PSD)
for multi-site and surface events



Muon veto:
→ Cherenkov photos in water tank

Liquid Argon veto:
→ scintillation light from γ and β

Detector anti-coincidence
over full array

LEGEND-200 background reduction

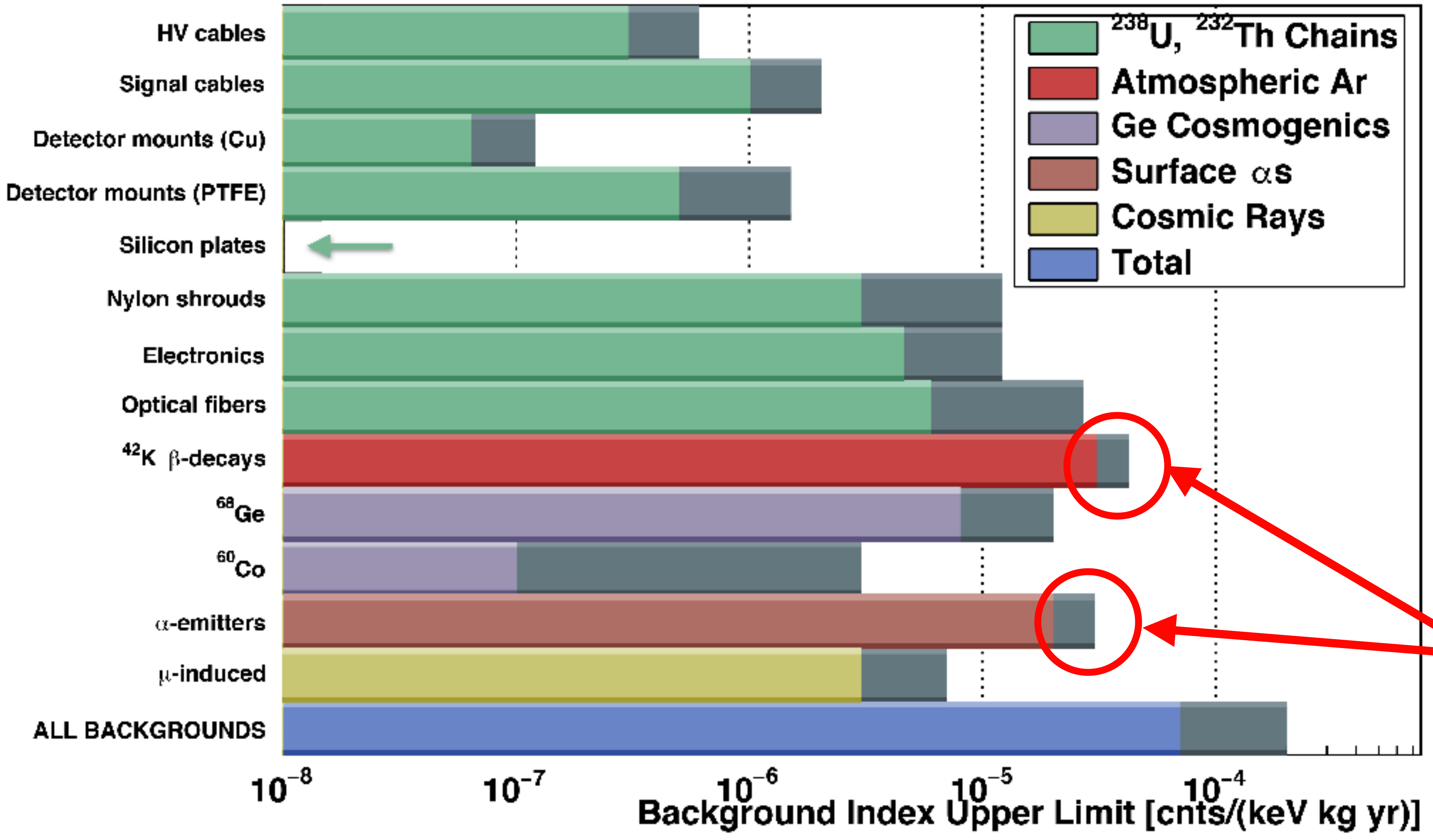
Feasibility of reducing the background from ^{42}K, ^{214}Bi, ^{208}Tl has been shown in GERDA, MAJORANA DEMONSTRATOR and in dedicated tests

- Improved radiopurity levels
  (cables, electro-formed Cu, PTFE, ...)
- Increased detector mass
  → leads to proportional reduction from near-by parts
  → better surface to volume ratio
- Higher purity LAr → increased light yield & attenuation length
- Improved scintillation light readout
- Reduction of electronic noise → to improved PSD
- Optimised pulse-shape analysis for surface events

^{214}Bi / ^{208}Tl

^{42}K

LEGEND-200 background projections

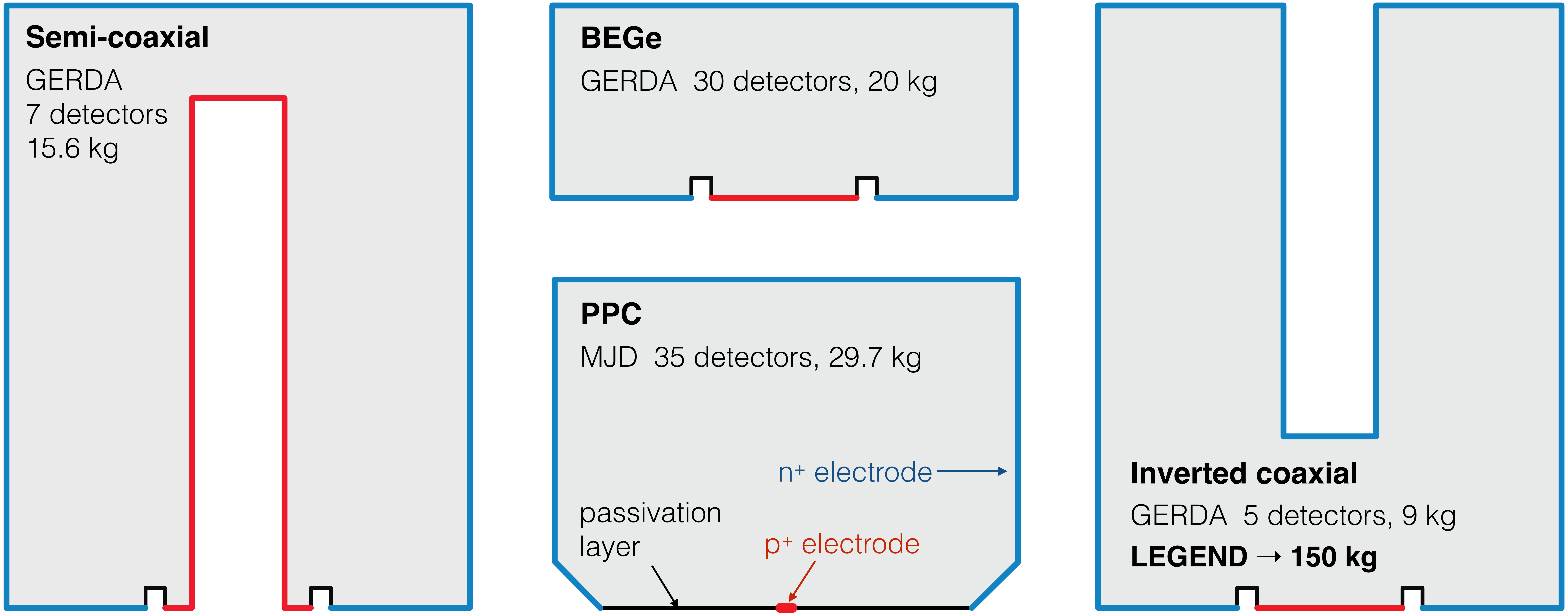


- Simulations based on experimental data and material assays.
- Background rate **after** cuts: **detector anti-coincidence, liquid Argon veto, PSD**
- Surface events from β and α interactions expected to be significant contribution

Background index < (0.7 - 2) 10^{-4} cts / (keV kg year) or **< (0.2 - 0.5) cts / (FWHM ton year)** at $Q_{\beta\beta}$

→ LEGEND-200 background goals will be met!

LEGEND-200 Germanium detectors

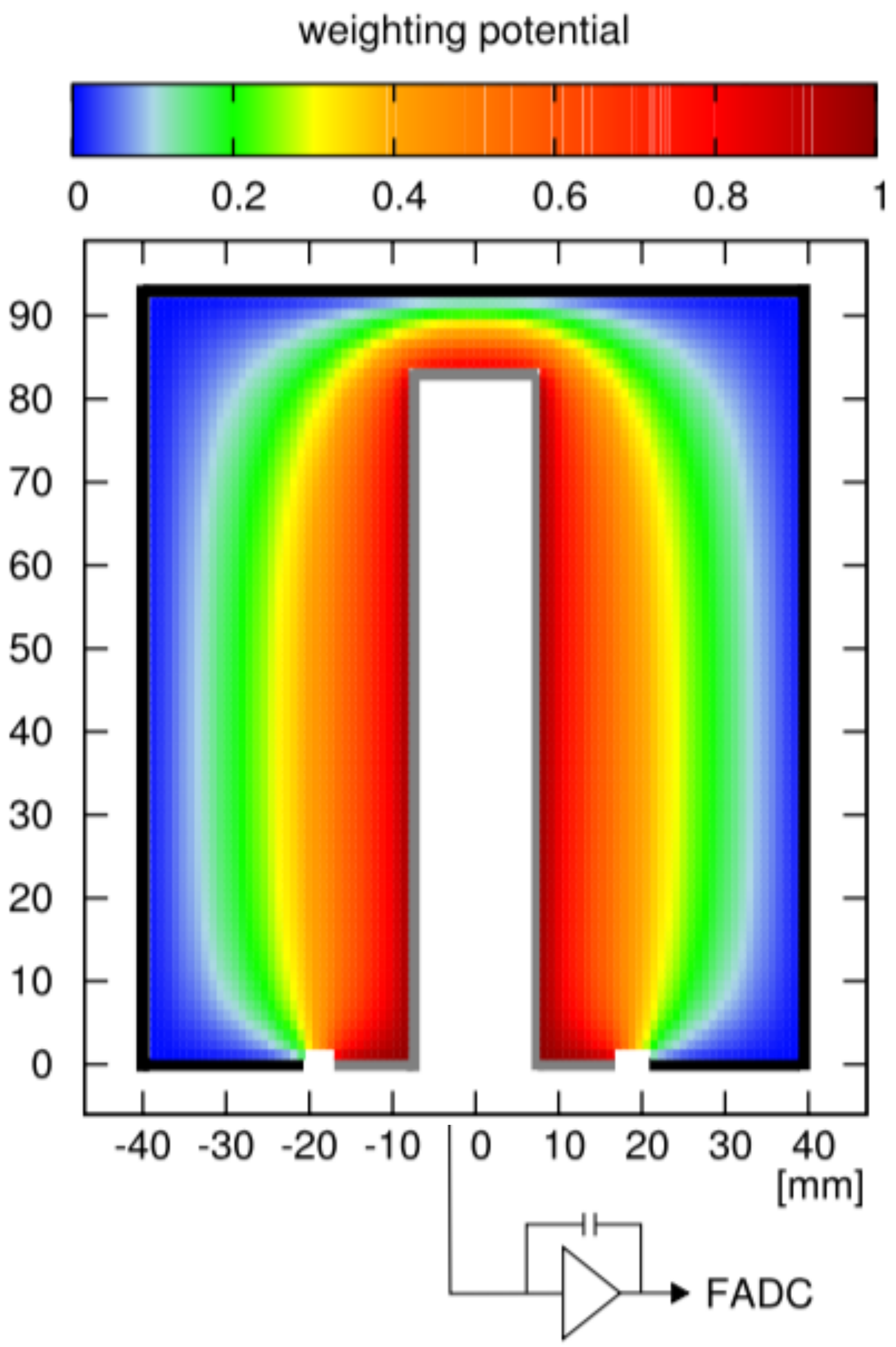


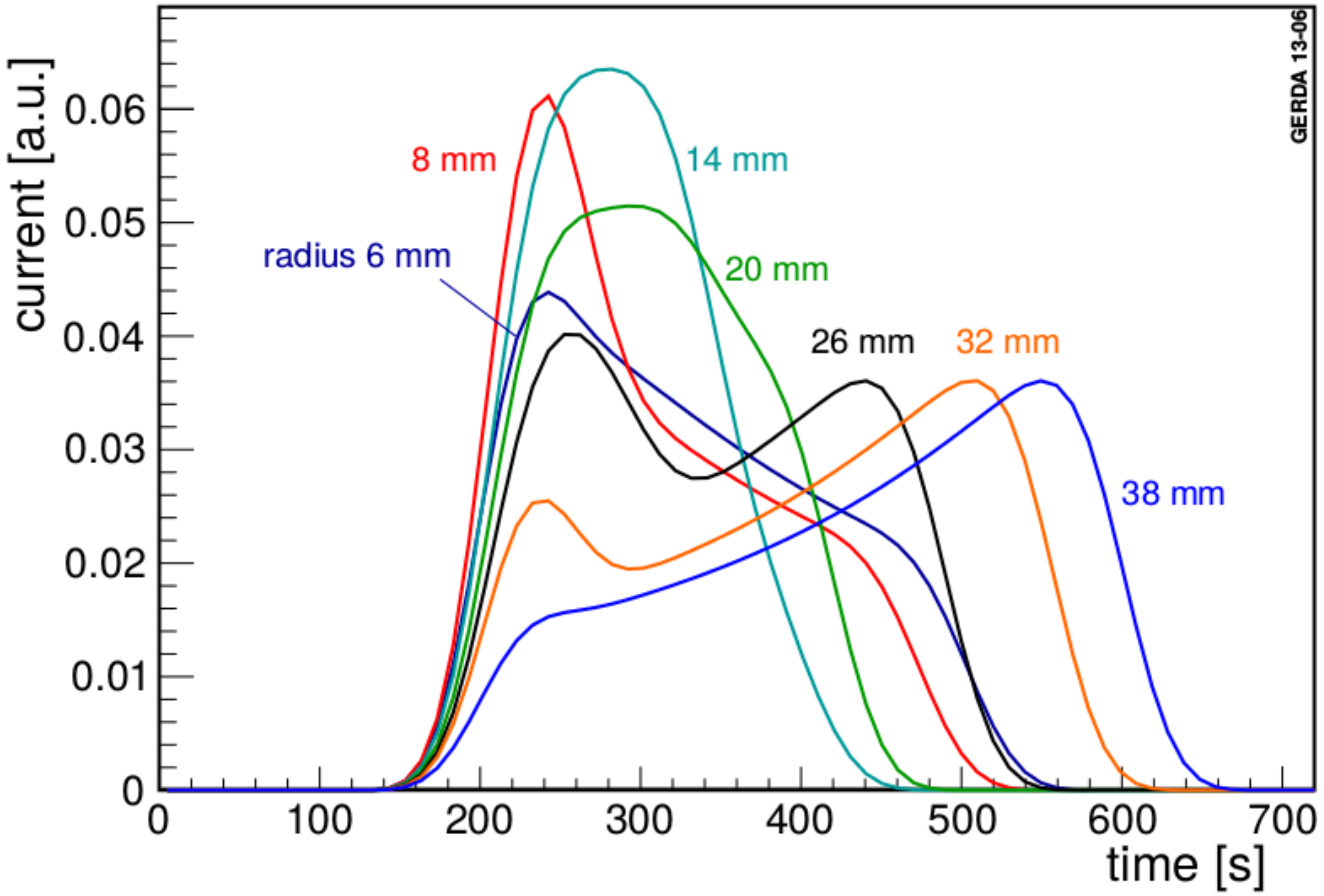
- 4 types of HPGe detectors from MAJORANA DEMONSTRATOR and GERDA
- Production of new enriched material and inverted coaxial detectors ongoing

LEGEND-200 - Inverted coaxial detectors

Semi-coaxial

- complicated signal shapes
  → less rejection power 👎
- large p+ surface
  → more sensitive to contamination 👎
- large mass (2-3 kg)
  → less nearby parts 👍





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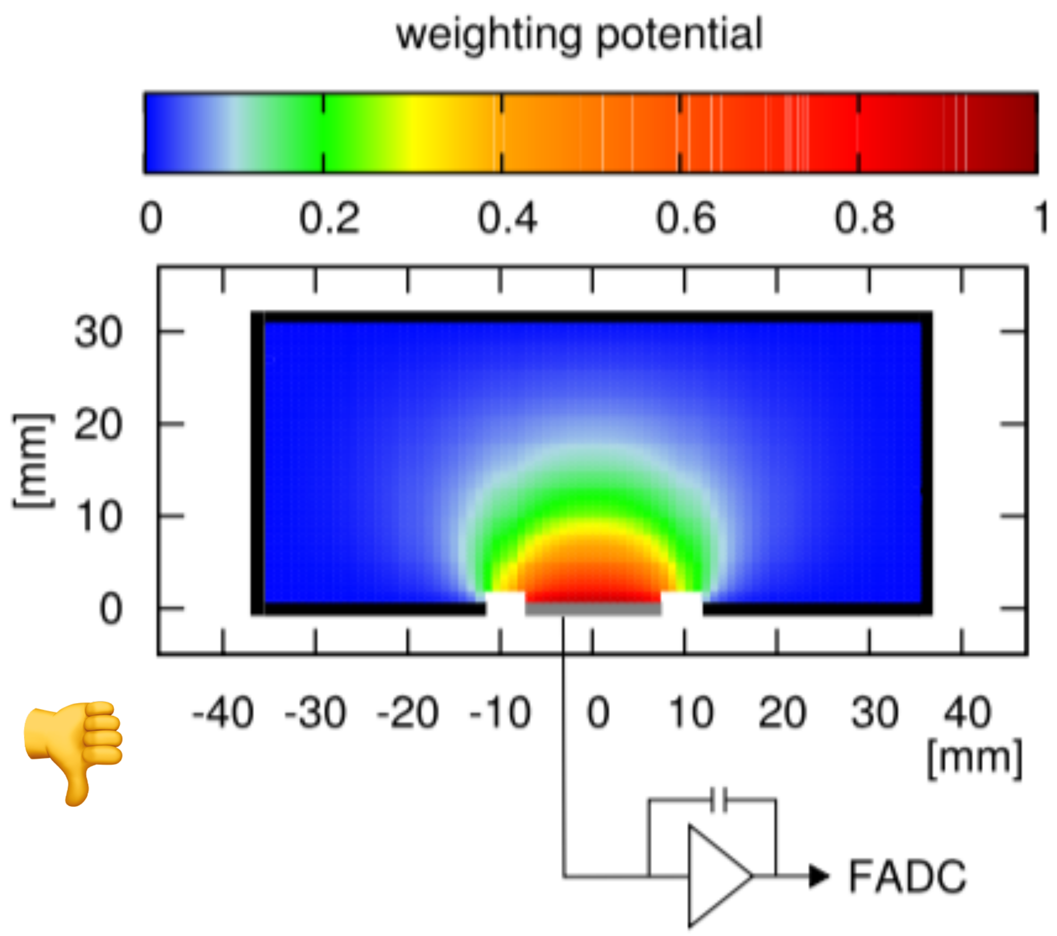
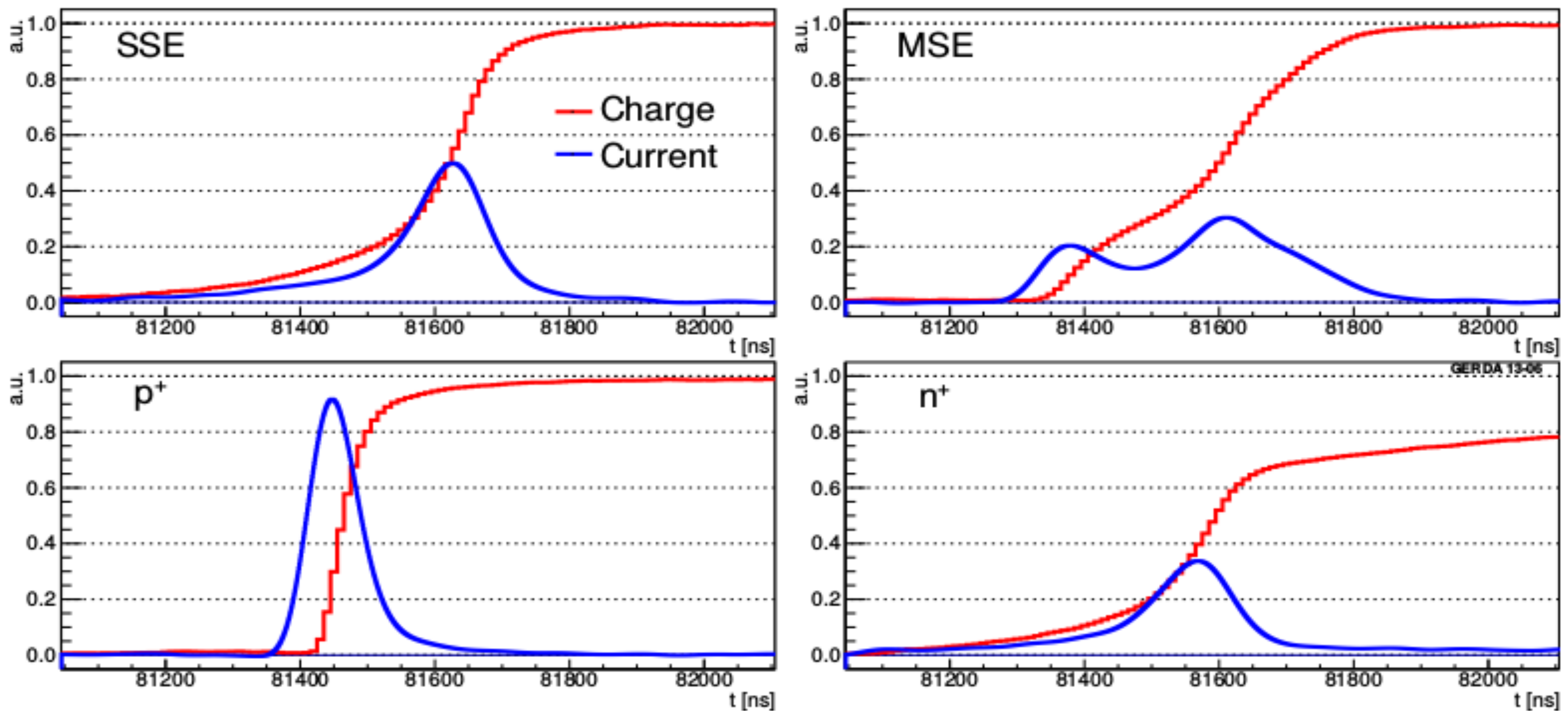
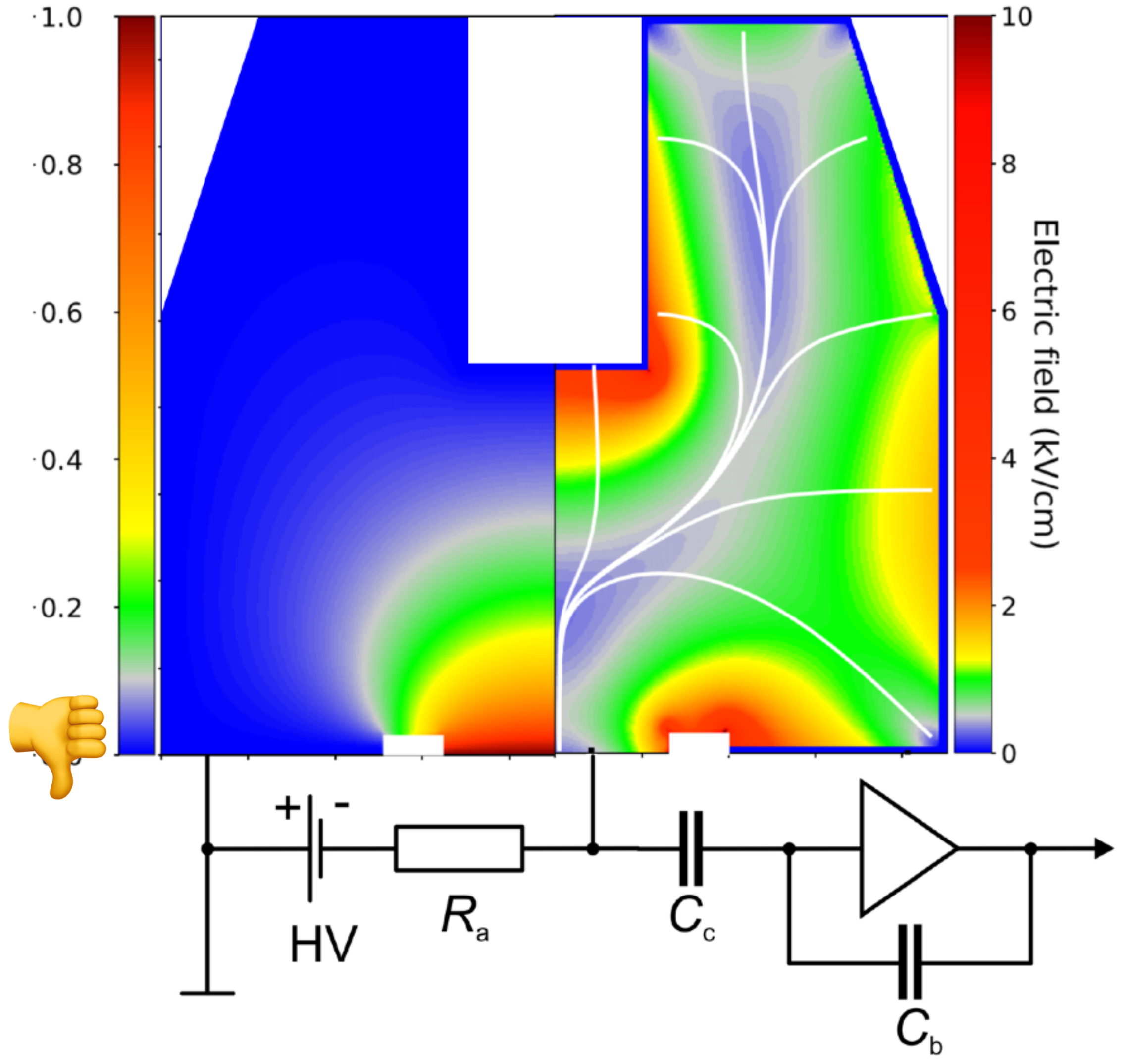


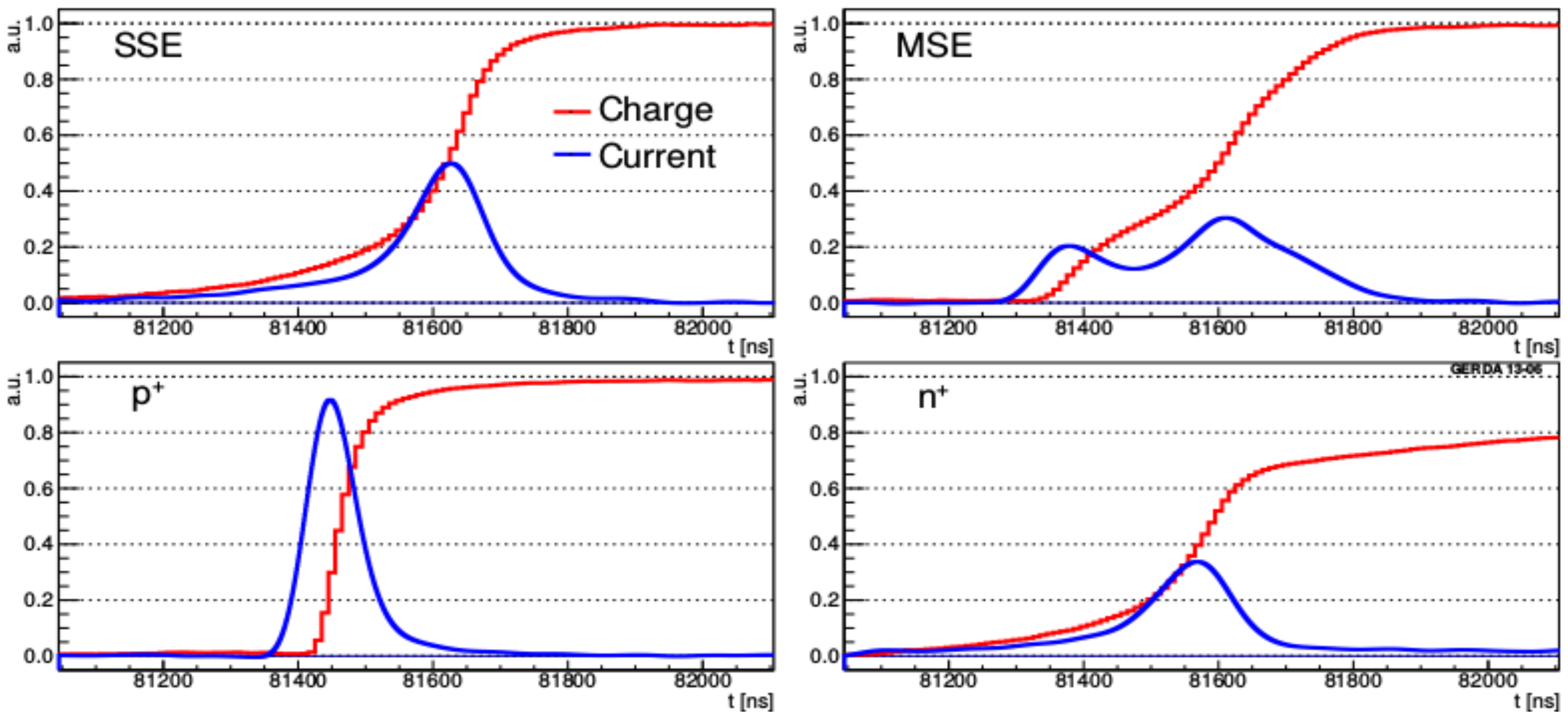


BEGe & PPC

- Small mass
  → many readout channels & cables 👎
- Excellent PSD performance
  → rejection of multi-site and surface events 👍

LEGEND-200 - Inverted coaxial detectors





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- complicated signal shapes
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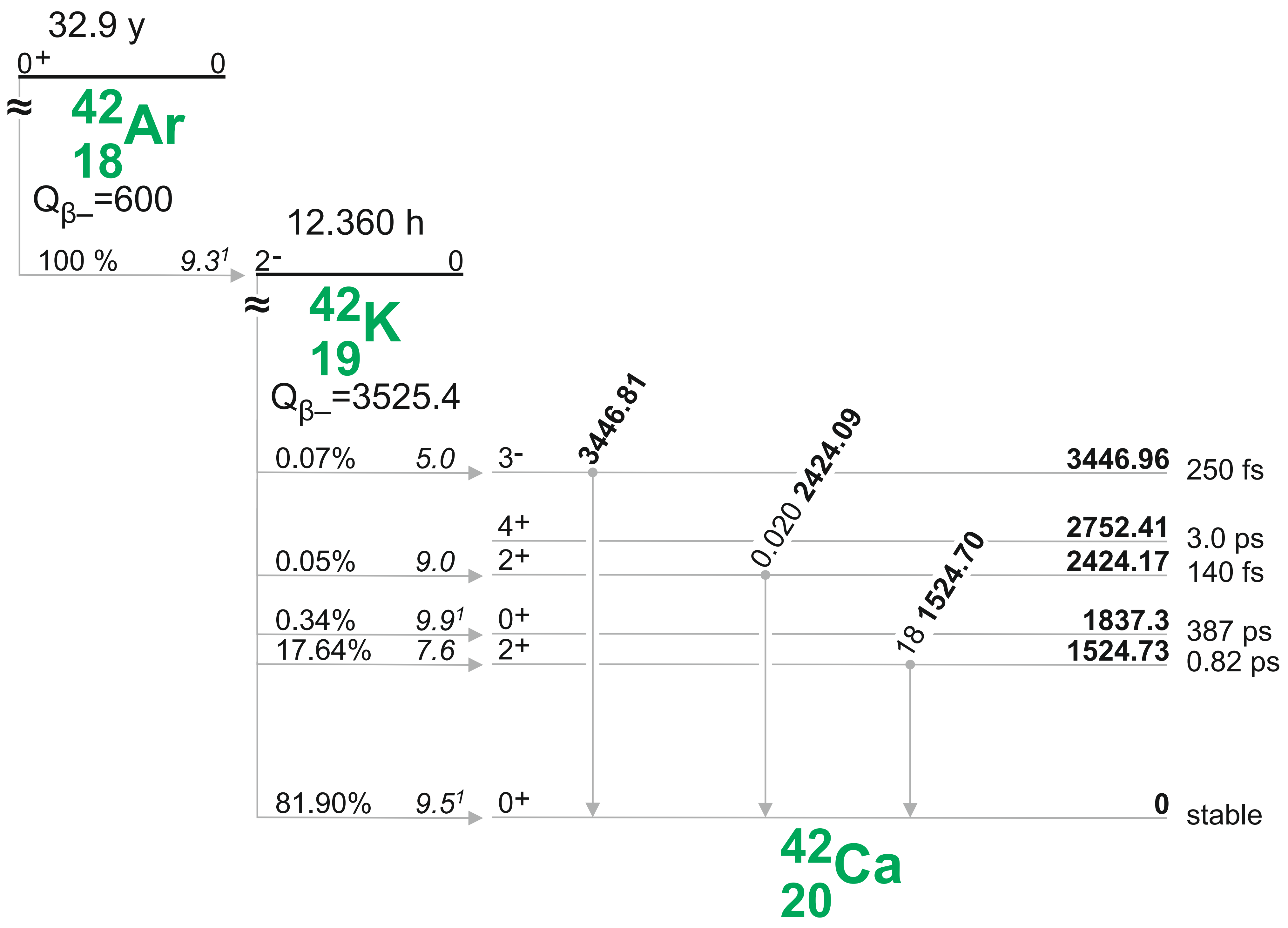
BEGe & PPC

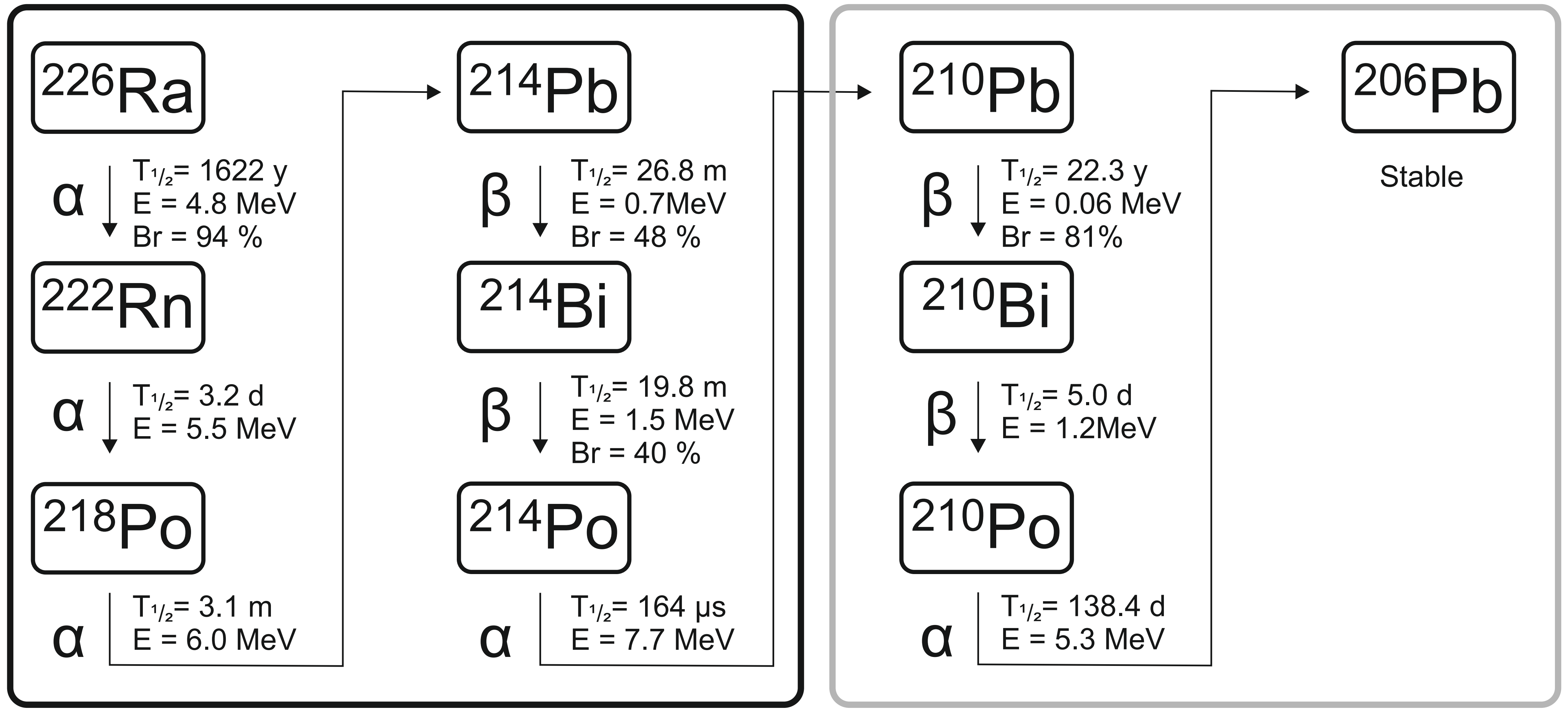
- Small mass
  → many readout channels & cables 👎
- Excellent PSD performance
  → rejection of multi-site and surface events 👍

Inverted coaxial

- Large mass
  → less nearby parts → lower background 👍
- Good PSD performance with small p+ contact 👍

LEGEND-200 - Understanding surface events



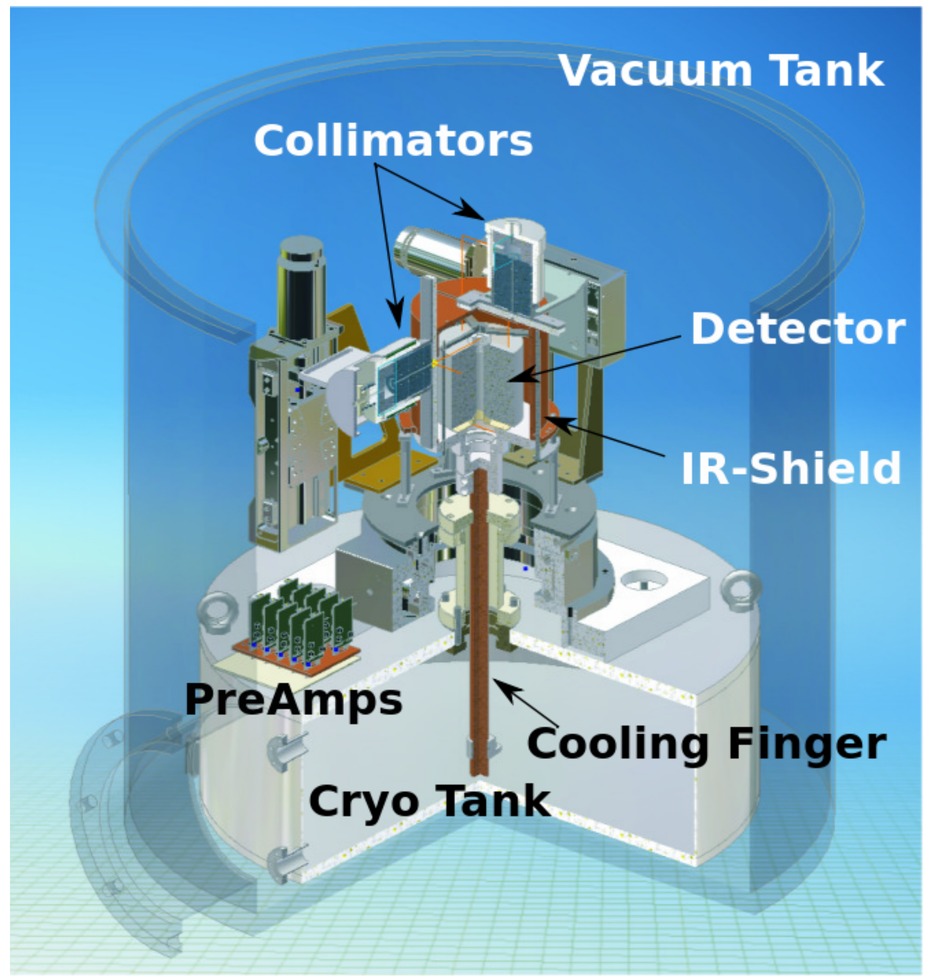


- ^{42}K in liquid Argon β-decays with Q_β ~ 3.5 MeV
- α (~ 5 MeV) can penetrate into the active volume only at the p+ contact, the groove of BEGe or at the passivated surface of PPCs

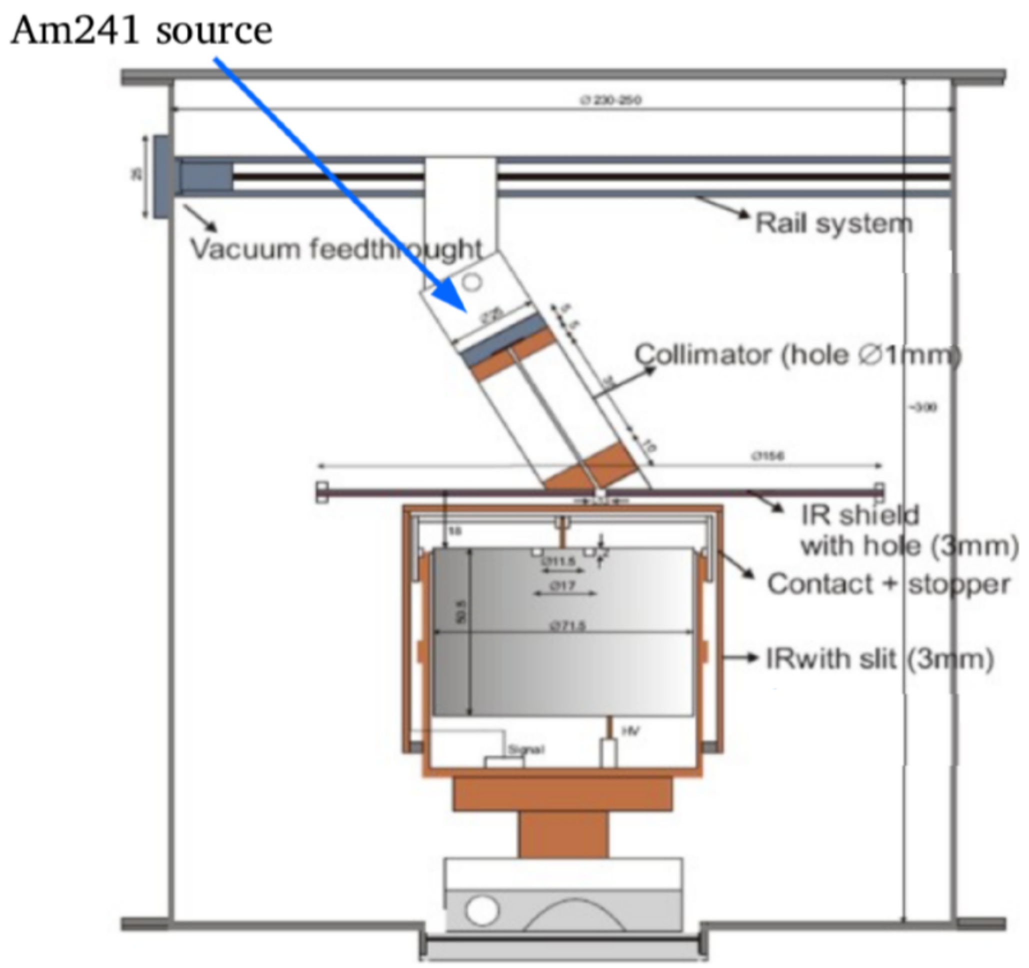
→ **partial charge collection of the α or β energy can lead to signal at $Q_{\beta\beta}$**

LEGEND-200 - Understanding surface events

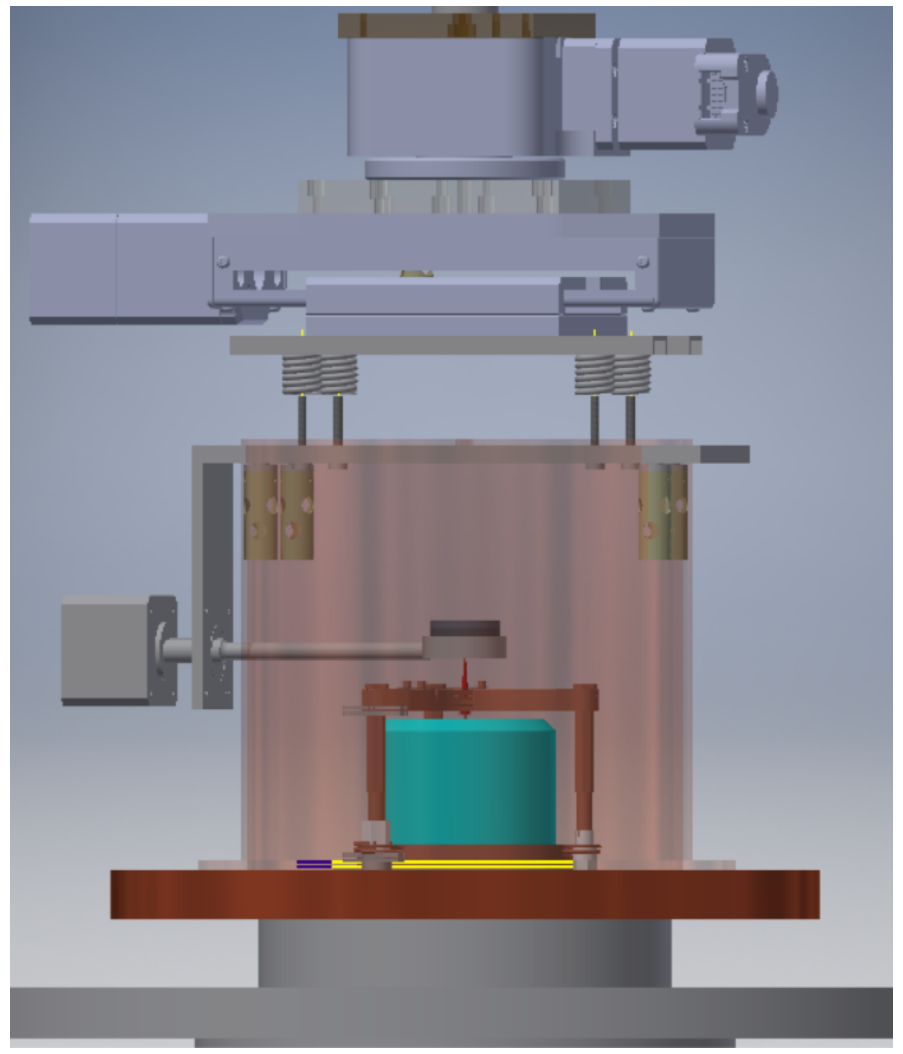
GALATEA @ MPP



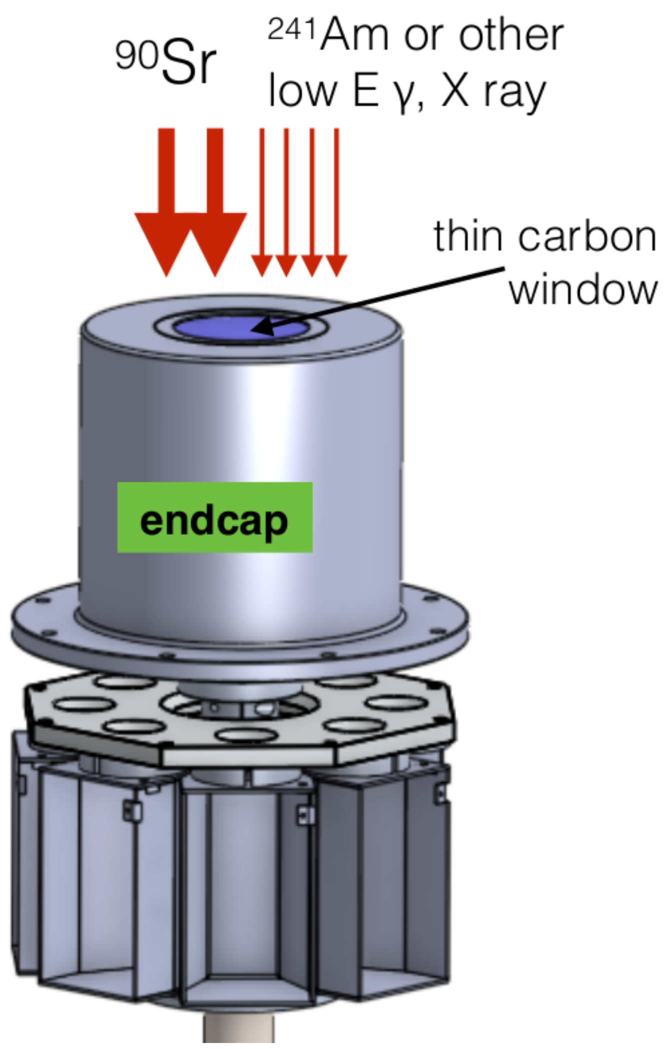
TUBE @ TUM



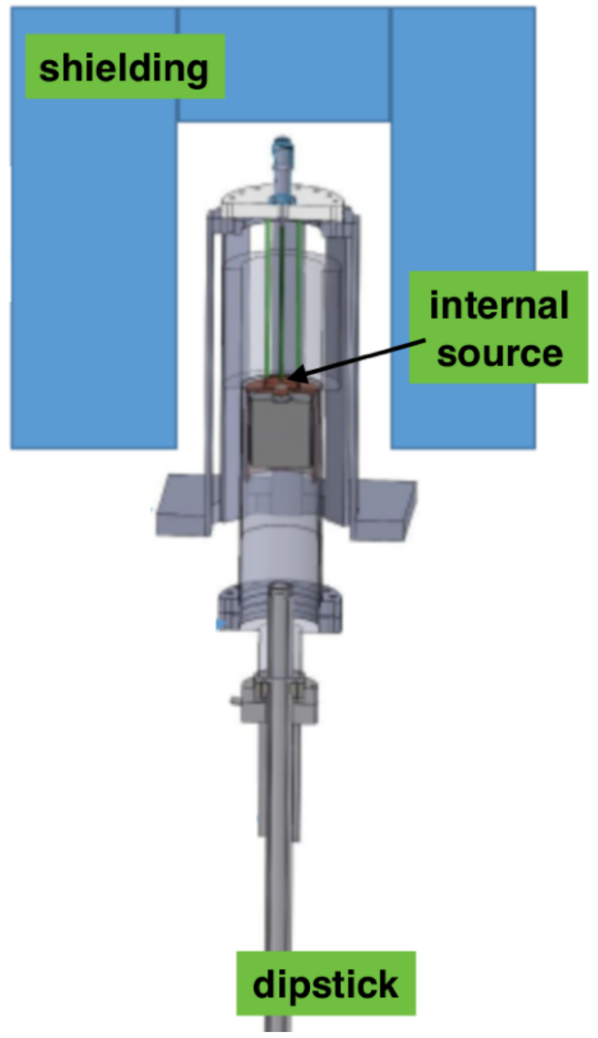
CAGE @ UW



LBL



UNC



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- α (~ 5 MeV) can penetrate into the active volume only at the p+ contact, the groove of BEGe or at the passivated surface of PPCs

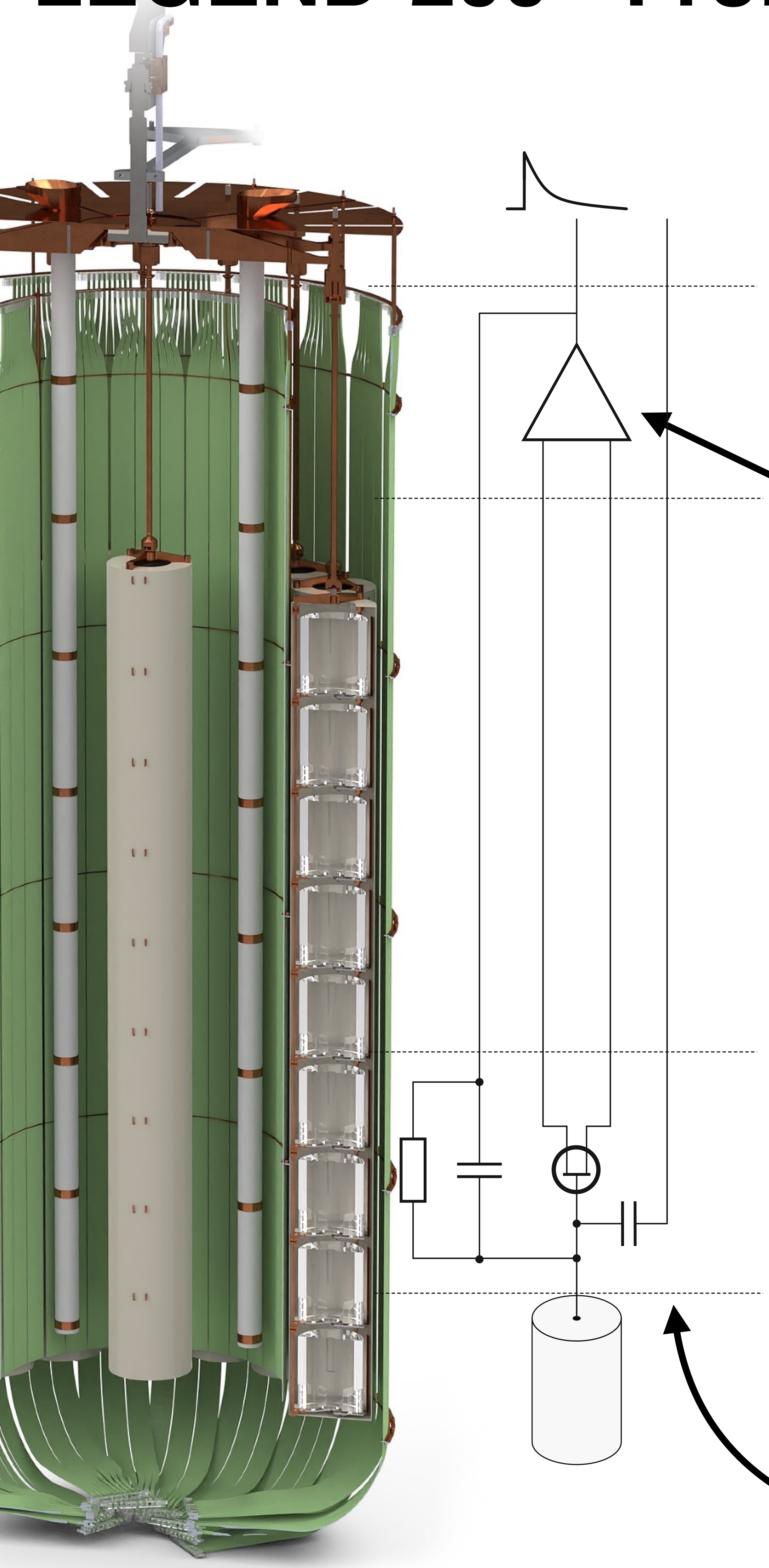
→ **partial charge collection of the α or β energy can lead to signal at $Q_{\beta\beta}$**

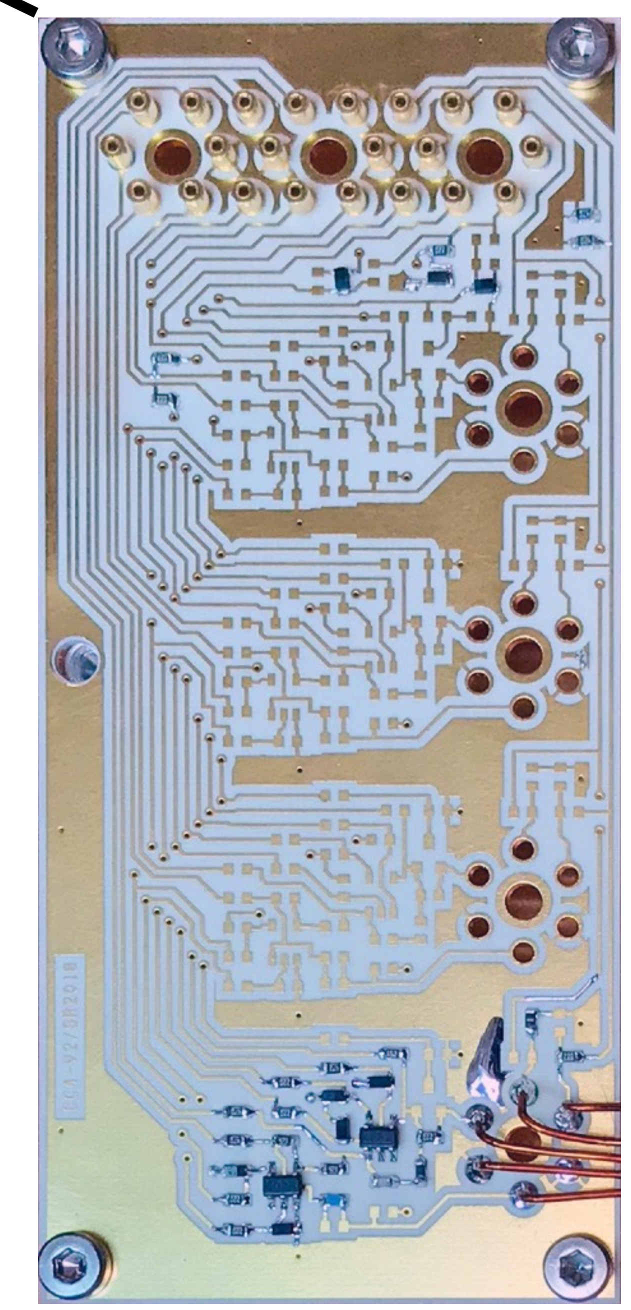
- Multiple characterisation measurements currently **ongoing** to understand signal shapes and develop analysis routines (currently taking data with PPC detector in GALATEA)
- Several new setups **under construction** or **planned**

LEGEND-200 - Front-End Electronics

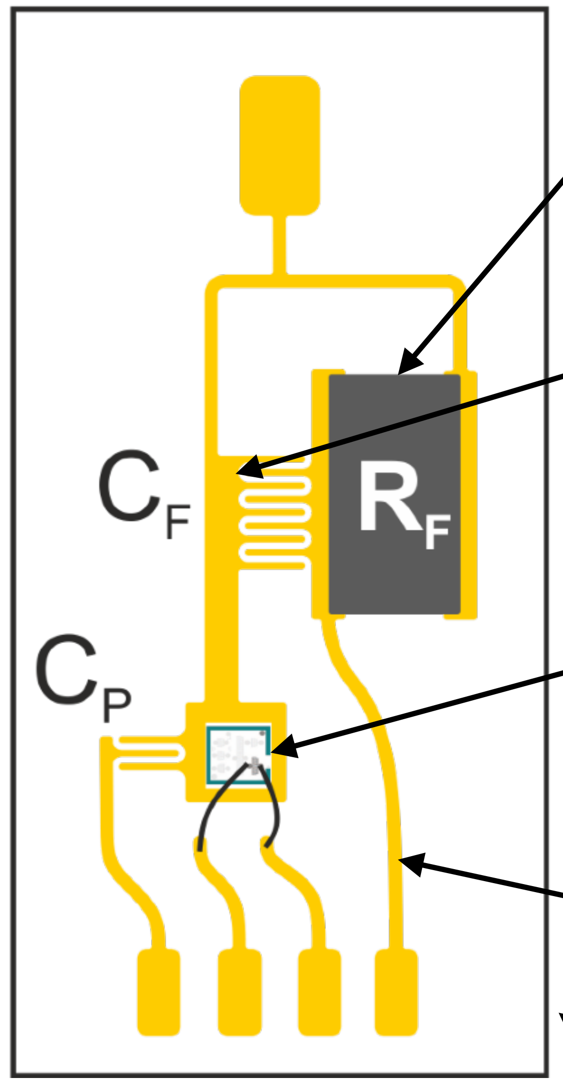
Combine Liquid Argon-operated preamplifier of GERDA with ultra-clean Low Mass Front-End of MAJORANA DEMONSTRATOR

→ Low Mass Front-End (LMFE) developed by **Berkeley Lab**
→ Charge sensitive preamplifier (CC4) developed by **University of Milan**, Italy





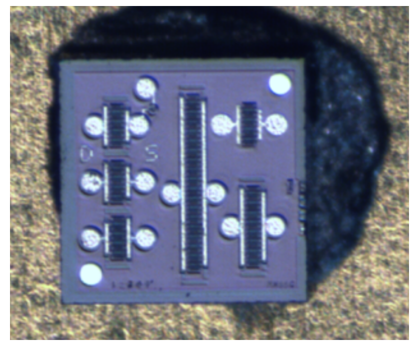
- Differential output driving ~10 m cable
- 7 Ch / board
- Clean PCB → Kapton / Cuflon



Amorphous germanium feedback resistor R_f (few GΩ in LAr)

Feedback and pulser (C_F and C_P): stray capacitance between traces

Bare die JFET: Moxtek MX11

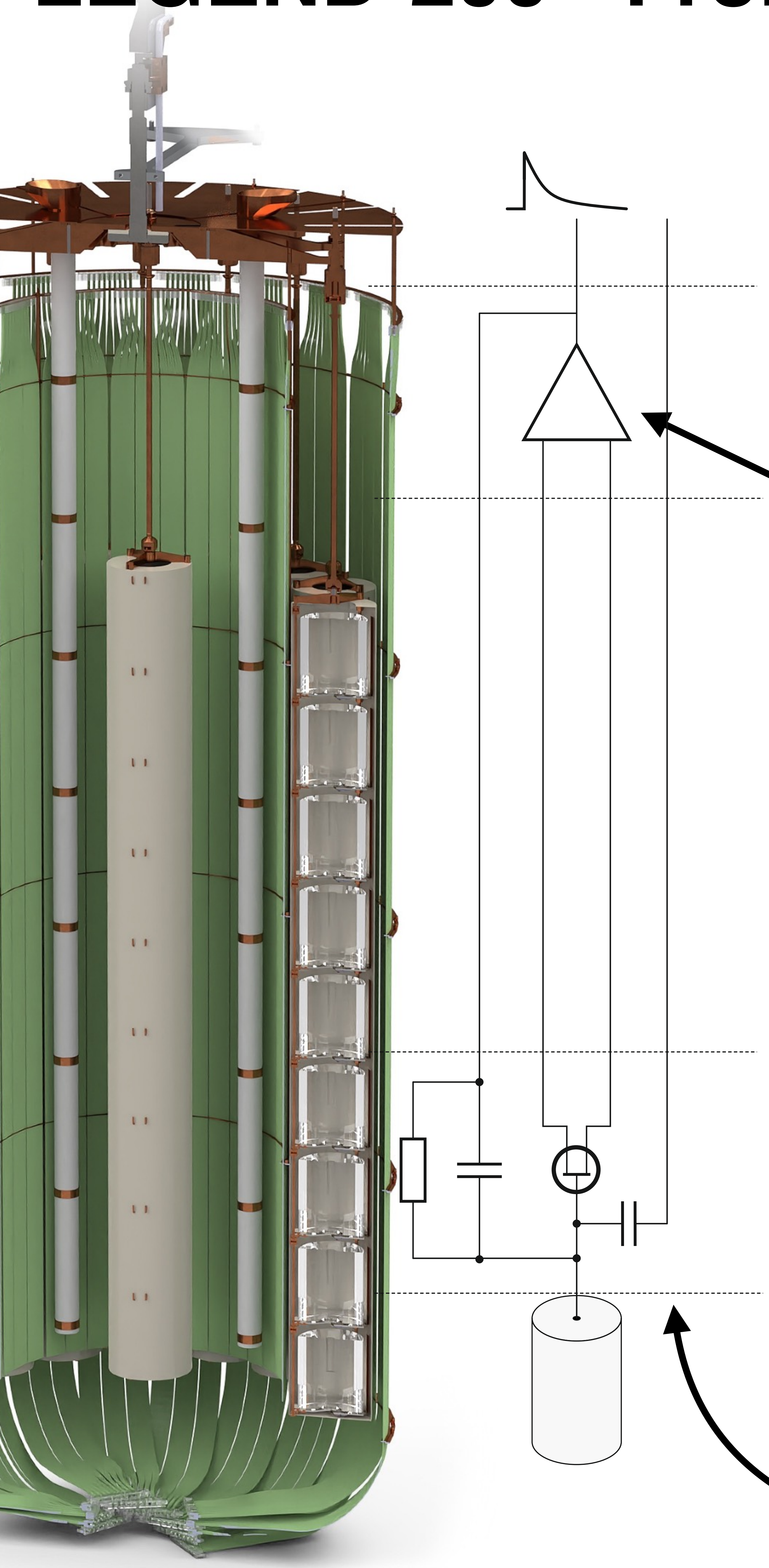


Sputtered Ti/Au traces

Fused silica substrate / Suprasil

+ new cables (Axon pico-Coax) & connectors
+ new LMFE mount

LEGEND-200 - Front-End Electronics



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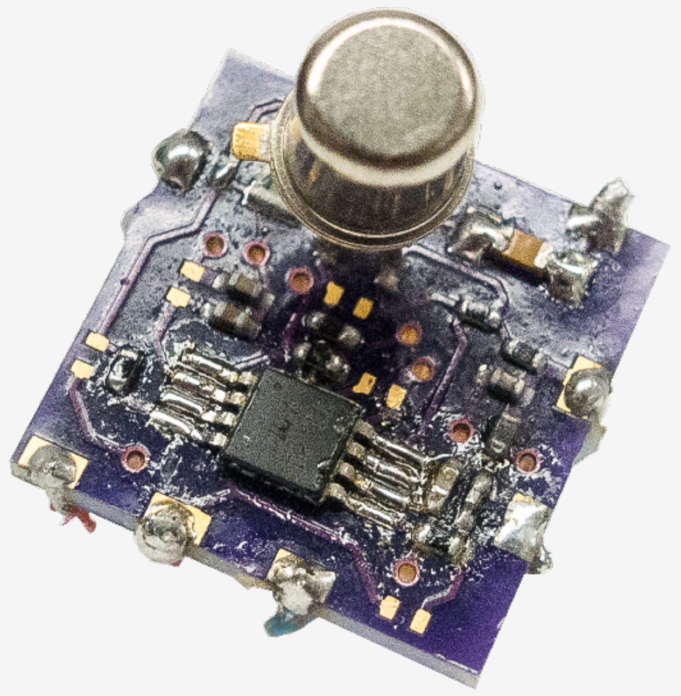
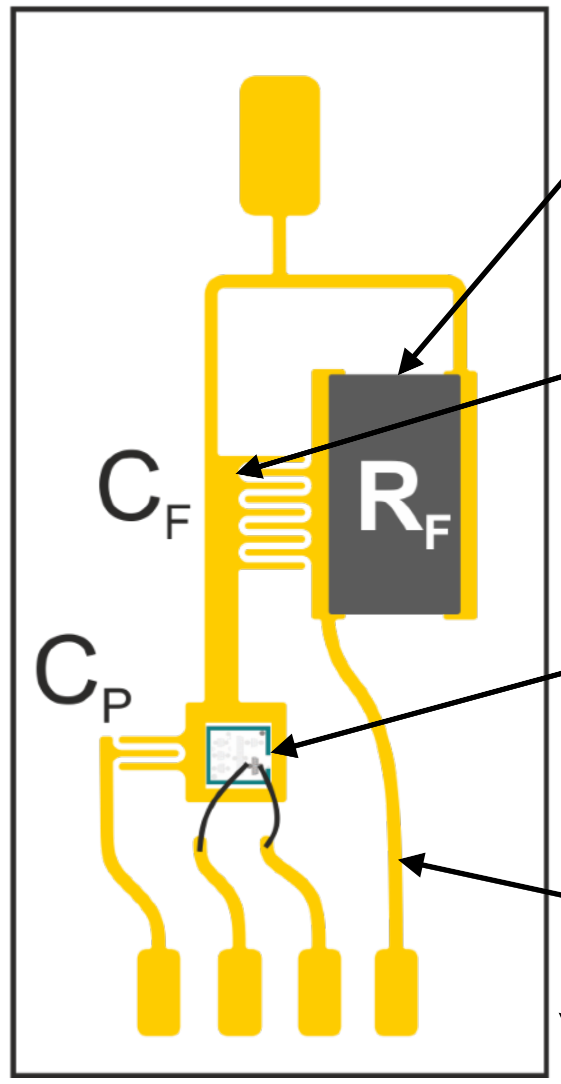
Also at Berkeley Lab:

R&D on alternative CSA

→ qAMP (M. Turqueti)





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+ new cables (Axon pico-Coax) & connectors
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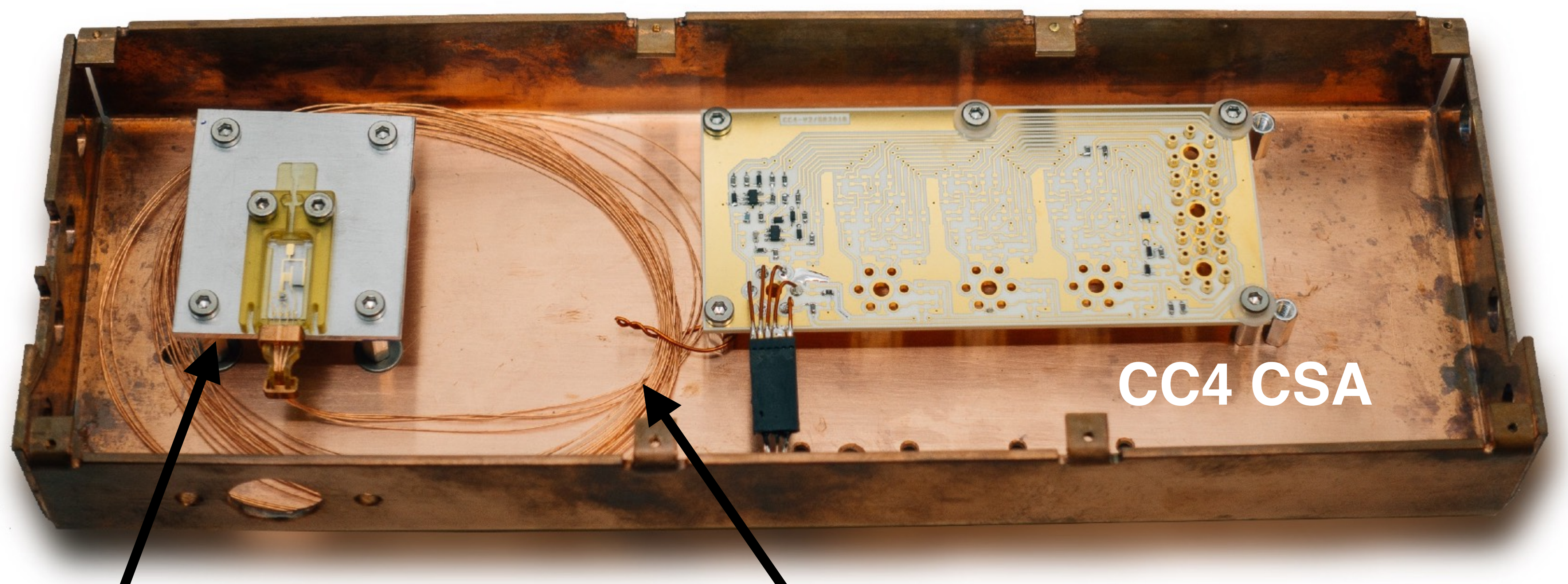
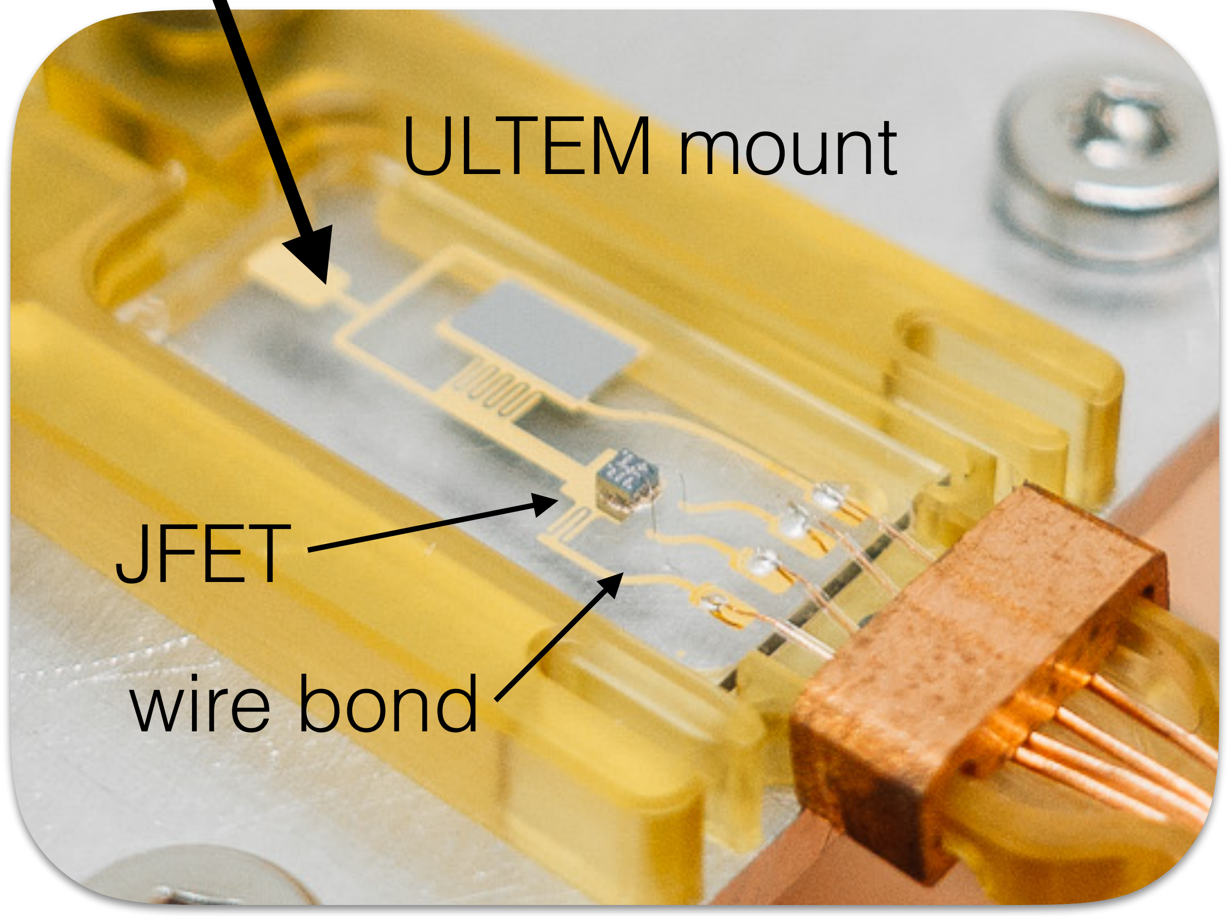
LEGEND-200 - Front-End Electronics / Integration testing

Liquid Argon bench-test at LBL



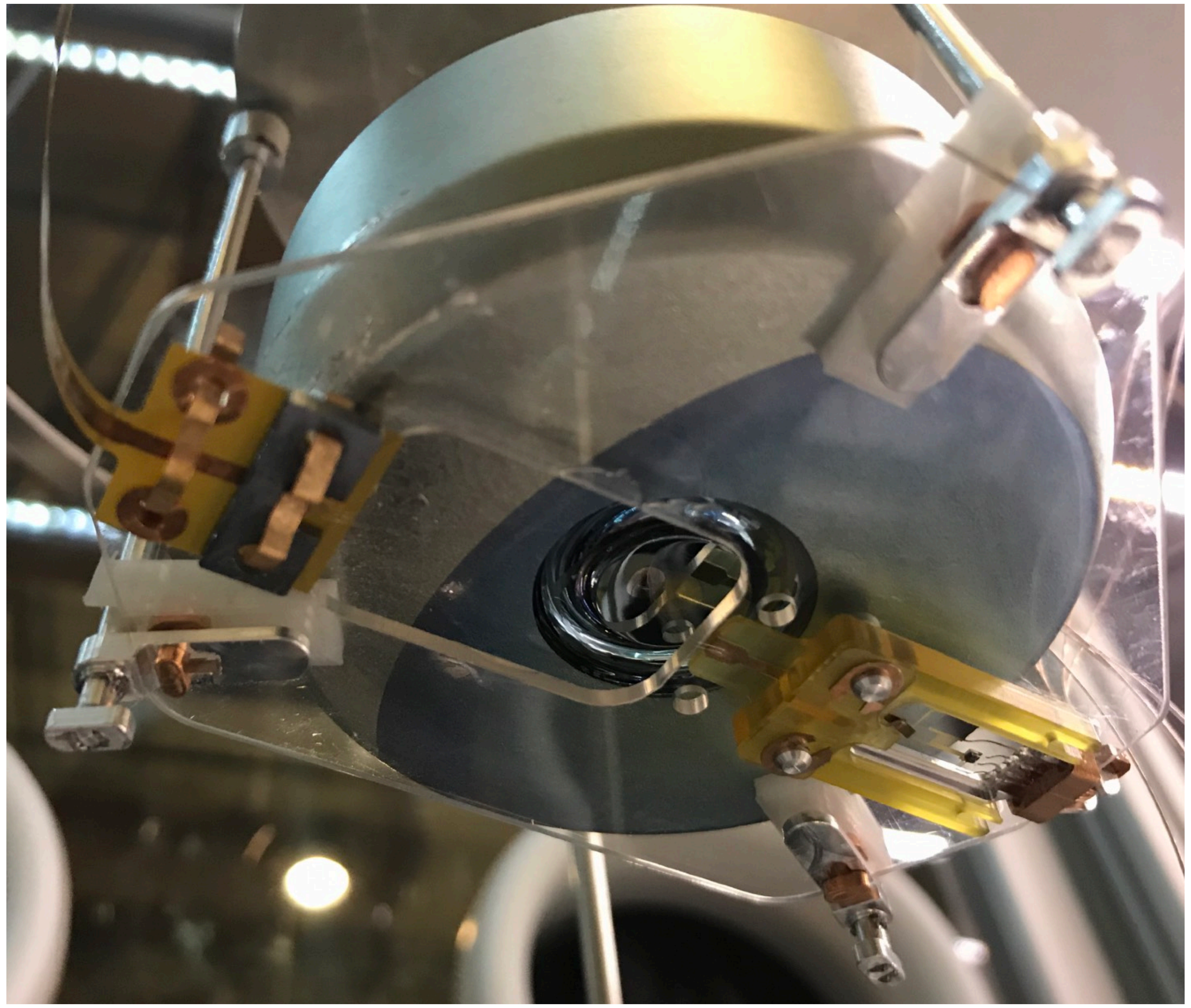
LMFE in ULTEM mount

1.5m Axon pico coax cables



- Warm & cold (77K / 87K) electronics characterisation
- Optimisation of CSA parameters
- Also:
  - aGe feedback resistor characterisation
  - JFET characterisation / test (e.g. bubbling)

Detector integration test at TUM

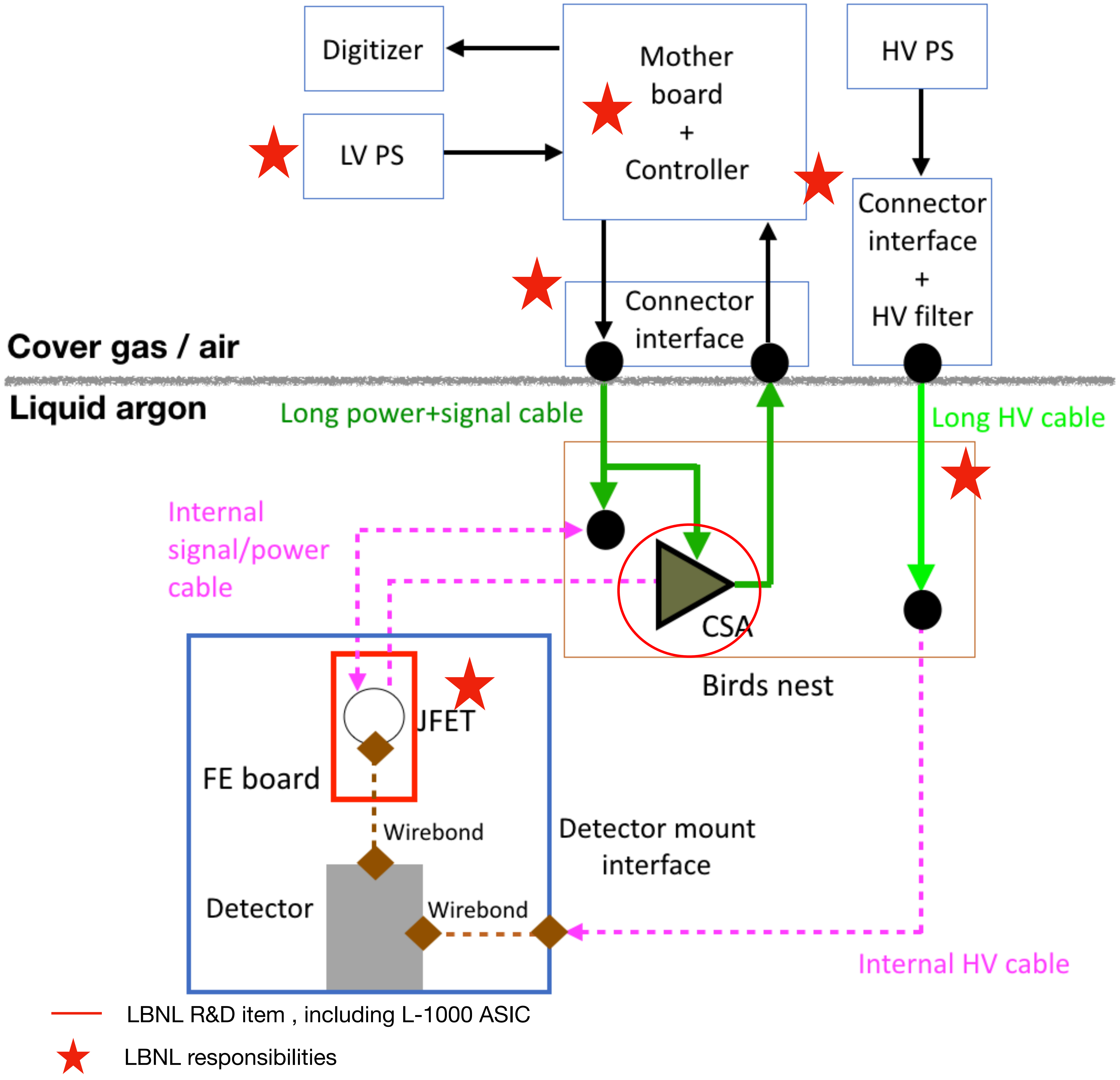


- Dedicated test stand at TUM
  ➝ Liquid argon instrumentation (PMT & fibers)
  ➝ string w/ 2 HPGe
- Test assembly, mounting procedure, readout

➝ Demonstrated resolution of 2.6 keV (FWHM) at 2.6 MeV

LBNL R&D activities for LEGEND-200

- LBNL provides unique expertise in low-noise, low-background readout electronics for LEGEND
- **Low Mass Front End**
  → Development, testing, production & final assembly
  → ASIC R&D for LEGEND-1000 *(LDRD Barton)*
- **Long HV cable**
  → development of a long (10m) flat cable for HV (+ testing & QA) *(Drobizhev)*
- **"Cryostat head electronics"**
  → Development, testing & production of CSA - DAQ interface, controller board, low voltage power supplies *(Turqueti)*



Present status of LEGEND-200

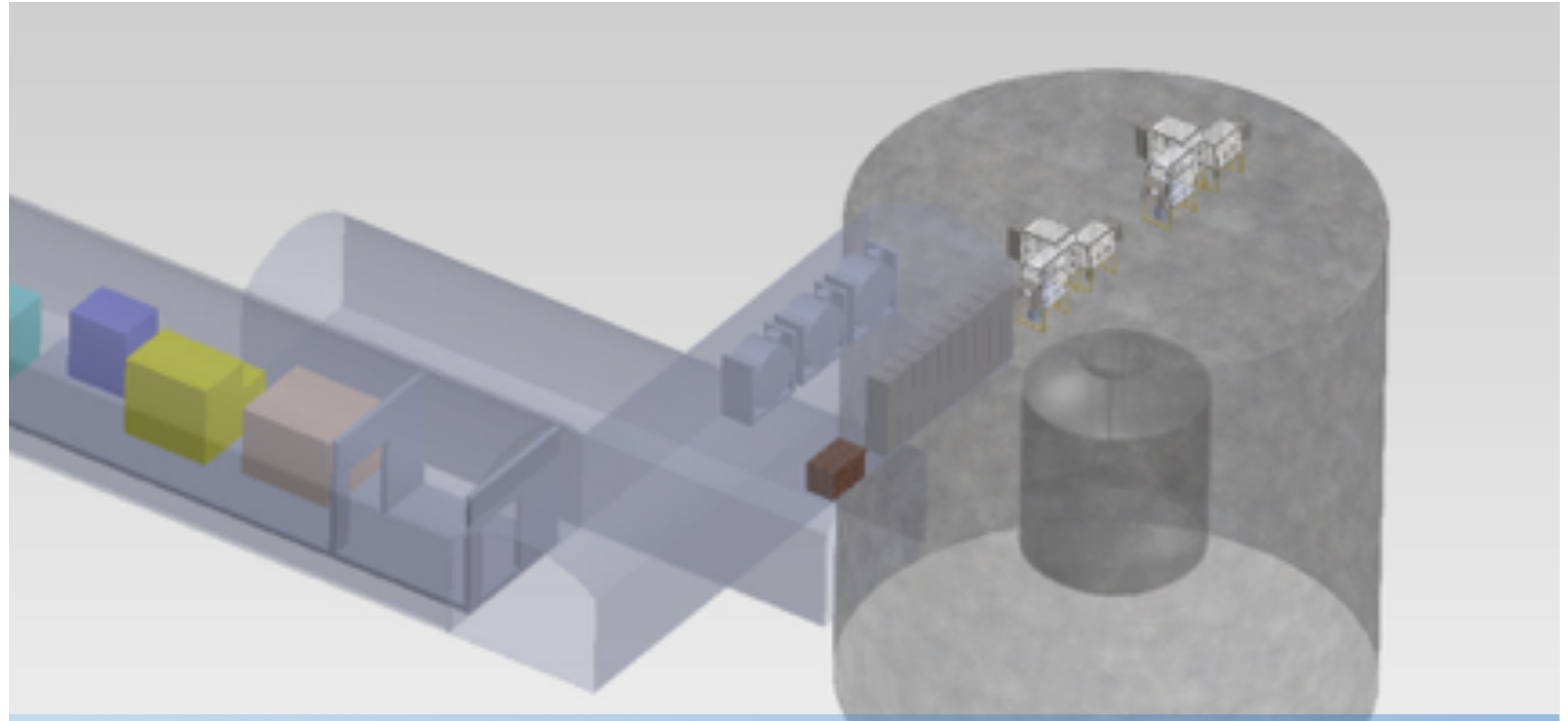
- Nearly all funding in place for LEGEND-200.
- All isotope is either in-hand, or on-order.
- Ge detector fabrication from two suppliers has started.
  - Detectors at HADES, ORNL and SURF in preparation.
  - ~ 80 inverted coax detectors (1.5-2 kg), ~ 150 kg
  - 28 BEGe's (0.7 kg) about 20 kg
  - 5 ICPC's (2.0 kg) about 10 kg
  - 35 PPC's (0.8 kg) about 28 kg
  - Semi Co-Ax detectors (either use as is, or recycle) about 15 kg
  - Total ~200 kg
- Front-end electronics and detector units → test ongoing.
- Lock and new deployment starting soon.
- LAr veto is under construction with all parts delivered or on order.
- Assay program is well underway.

→ **LEGEND-200 is on track to start data taking mid 2021.**

Outlook: LEGEND-1000

Design criteria:

- Current background models have large uncertainties due to the already very low background
  → LEGEND-200 will provide additional information and allow better estimates!
- Background requirement for LEGEND-1000 ~ 6x lower than LEGEND-200
  → reduce U/Th by optimising array geometry, reduce inactive materials, use larger HPGe detectors and better LAr light collection + use cleaner materials
  → eliminate ^{42}Ar background by using Ar from underground sources near detectors
  → reduce surface α contamination by improving assembly & handling process
- Staged approach → separate 1000kg of enriched detectors into individual payloads (few 100kg)
- Required depth of host lab under investigation

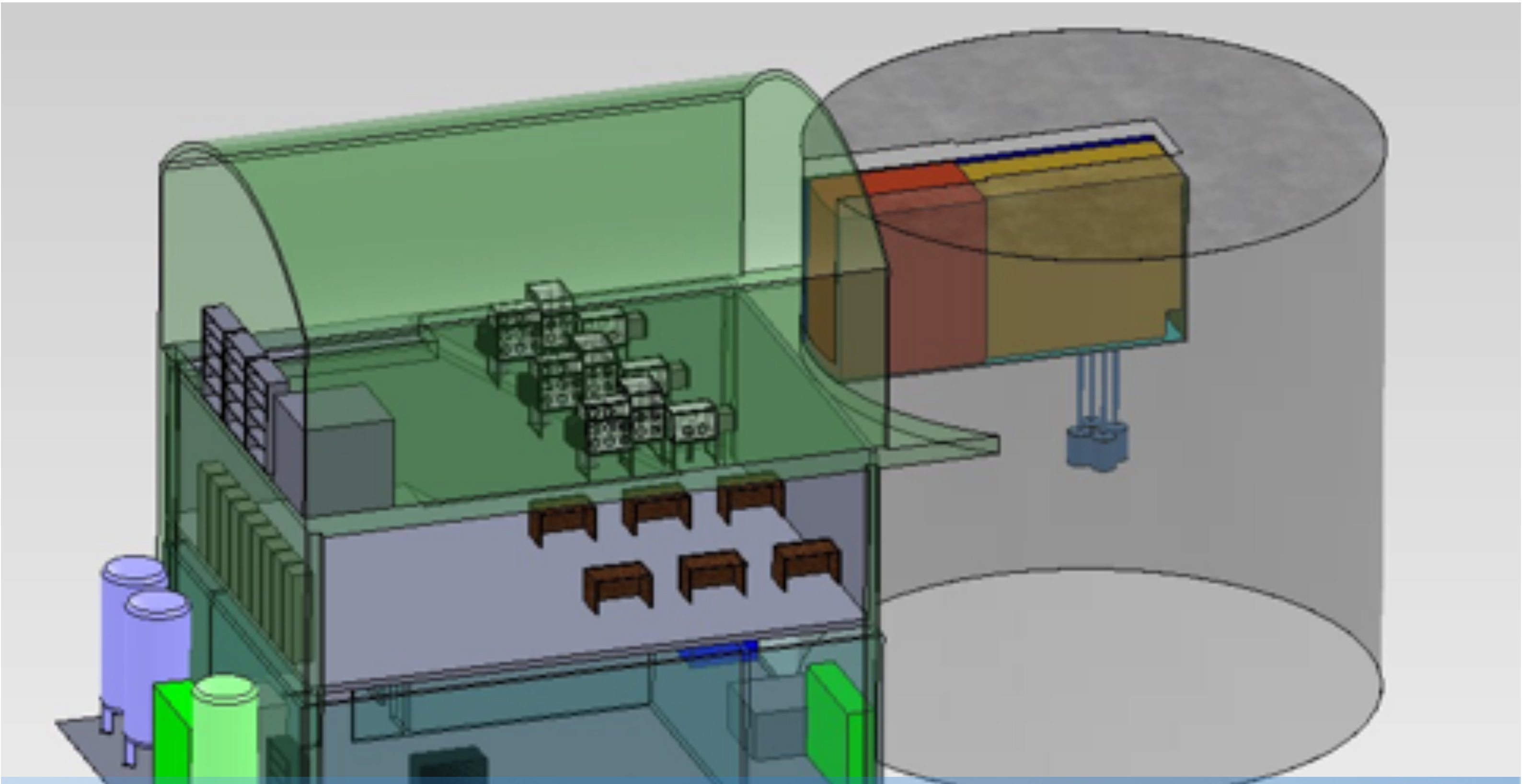


SNOLab cryopit concept

Baseline design:

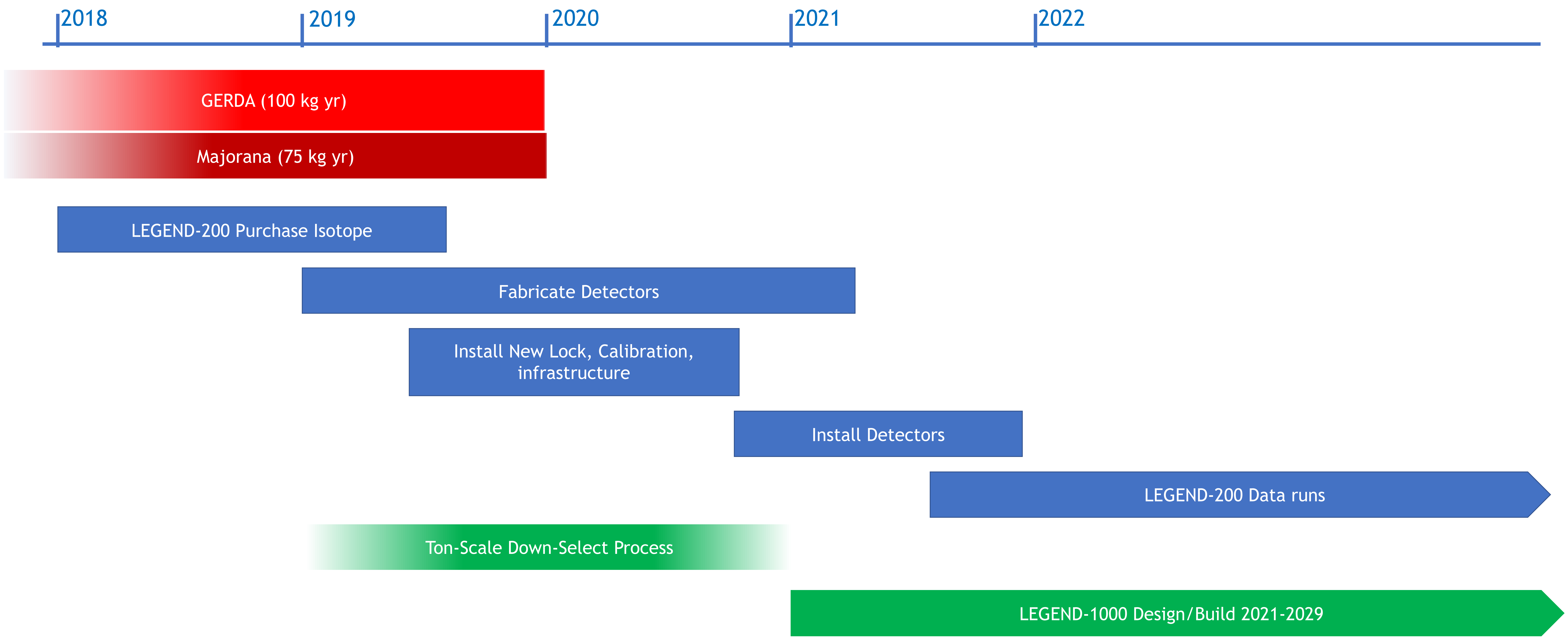
- 4 independent payloads
- Payloads surrounded by underground Ar
- Payloads surrounded by water tank

→ additional designs under investigation

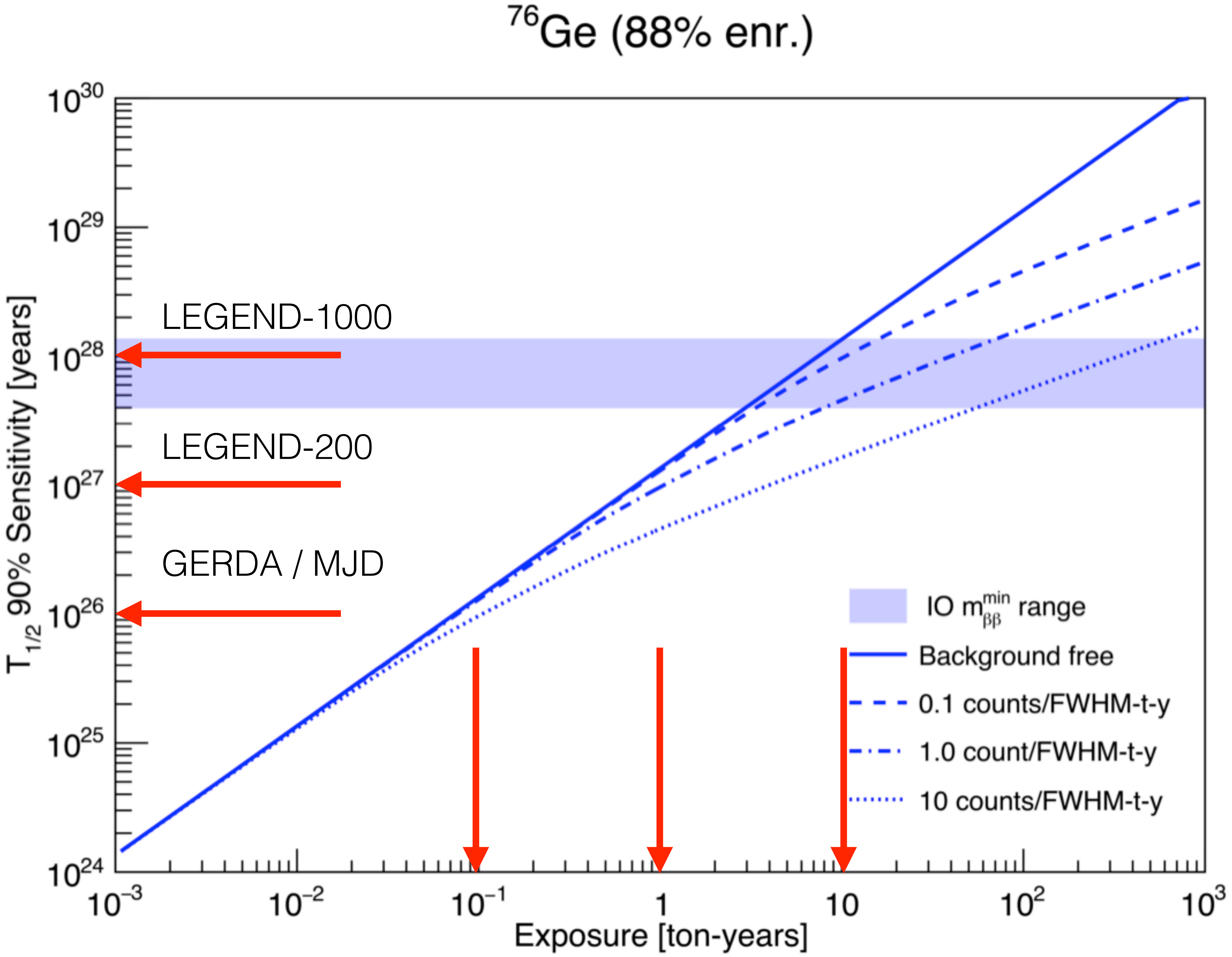


Generic cavity design

LEGEND - Schedule



Sensitivity for limit setting



- Goal to cover inverted ordering → sensitivity for $m_{\beta\beta}$ = 17 meV
- With worst case nuclear matrix element and unquenched g_A → sensitivity for $T_{1/2} = 10^{28}$ yr
- LEGEND-1000 should cover inverted ordering
- Background requirement for discovery is more stringent than for limit setting

Summary

- LEGEND builds on the success of Gerda and Majorana in the search for neutrinoless double-beta decay with 76Ge
- First stage **LEGEND-200** in existing infrastructure
  - funding secured
  - enriched material and detector production ongoing
  - construction starts next year
  - goal: **0.6 cts/(FWHM·t·yr)** background and **10^{27} yr** $T_{1/2}$ sensitivity for limit setting
- Design studies for **LEGEND-1000** is ongoing
  - goal: **0.1 cts/(FWHM·t·yr)** background and **10^{28} yr** $T_{1/2}$ sensitivity for limit setting

Acknowledgements

- We appreciate the support of our sponsors:
  - German Federal Ministry for Education and Research (BMBF)
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  - German Max Planck Society (MPG)
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  - U.S. Department of Energy, Office of Nuclear Physics (DOE-NP)
  - U.S. Department of Energy, Through the LANL, LBNL & ORNL LDRD programs (LDRD)
  - Italian Instituto Nazionale di Fisica Nucleare (INFN)
  - Swiss National Science Foundation (SNF)
  - Polish National Science Centre (NCN)
  - Foundation for Polish Science
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- We thank our hosts and colleagues at LNGS
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Thank you for your attention!