The Large Enriched Germanium Experiment for Neutrinoless ββ Decay

LEGEND

Large Enriched Germanium Experiment for Neutrinoless ββ Decay

Dr. Michael Willers

Technische Universität München

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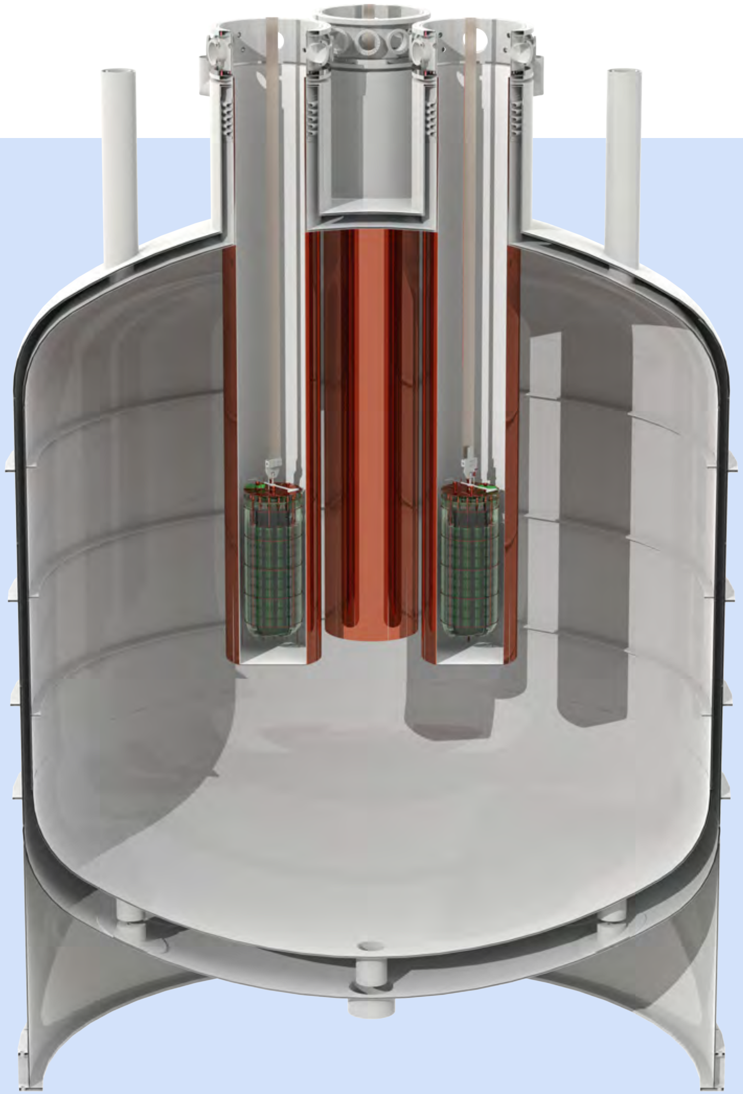
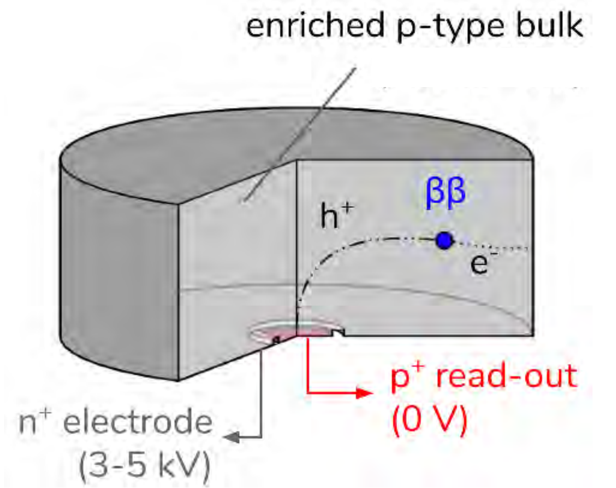


Search for 0νββ decay in high-purity ^{76}Ge detectors

$$(A, Z) \rightarrow (A, Z+2) + 2\,e^-$$

Neutrinoless double-beta decay is a so-far unobserved radioactive transition

- → violates Lepton Number conservation → new physics!
- → determines nature of the neutrino → Majorana particle
- → provides information on ν mass

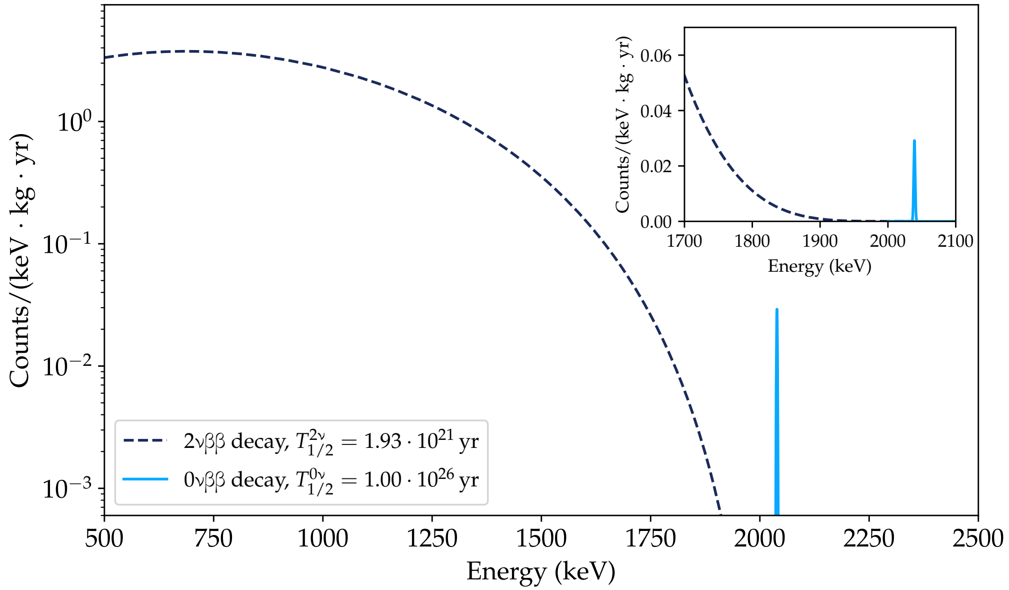


HPGe detectors are a potent technology to search for 0νββ decay

- → High isotopic enrichment in ^{76}Ge, high detection efficiency, best ΔE at the Q-value ($Q_{\beta\beta}$ = 2039 keV) in the field, extremely low intrinsic background

HPGe detectors provide rich topological event information

- → ββ decays are point-like interactions in HPGe detectors
- → 0νββ decay has a unique signature: narrow peak at the ^{76}Ge Q-value above 2νββ continuum
- → Event topology enables powerful background suppression routines



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The LEGEND Collaboration

GERDA + MAJORANA DEMONSTRATOR + new groups

50 institutions, 260 members, 11 countries

The 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 ..."

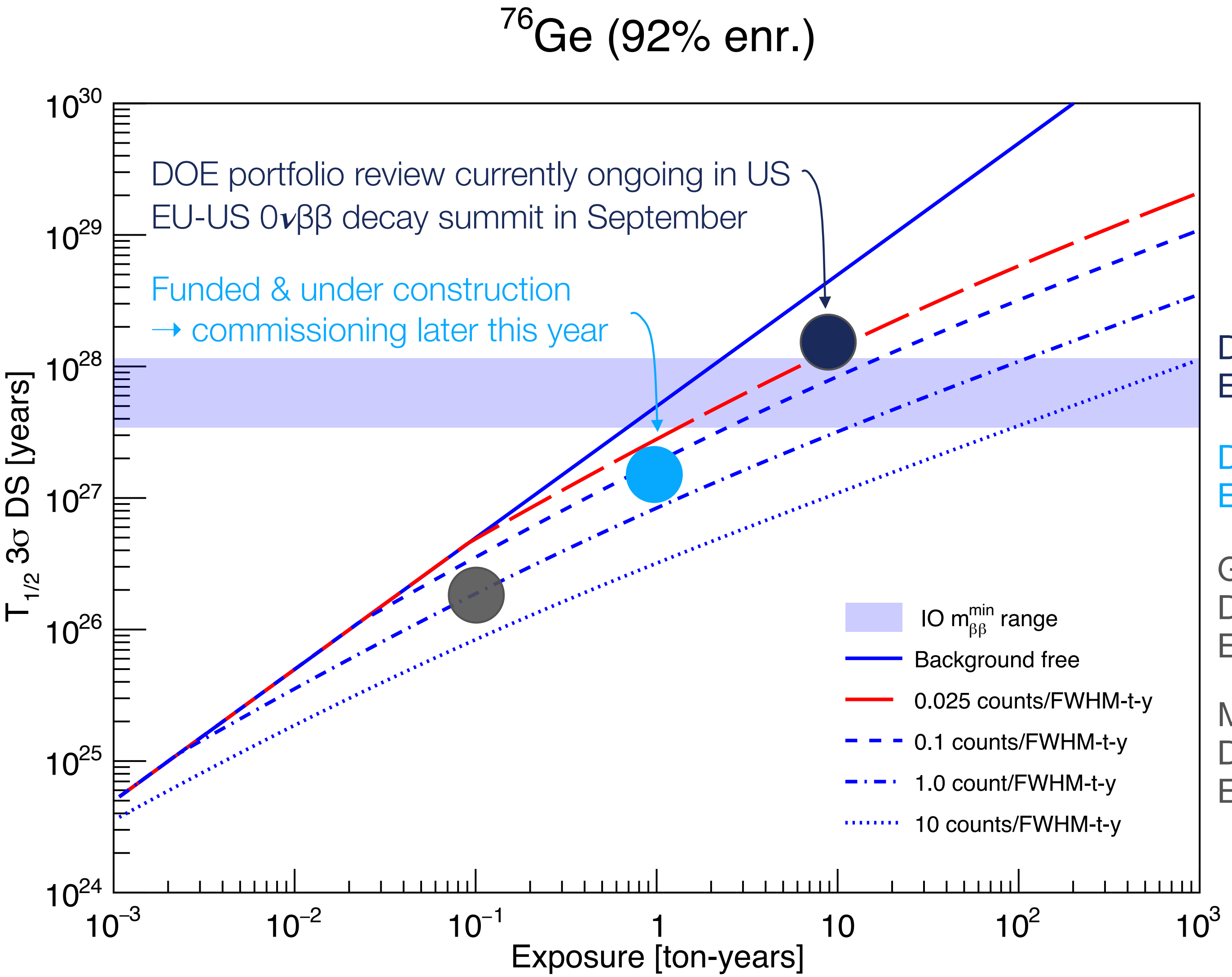
LEGEND-1000 Preconceptual Design Report: arXiv:2107.11462

The LEGEND Approach

LEGEND-1000

LEGEND-200

Current generation experiments



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

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

GERDA:
Detector mass: 44 kg
Exposure: 127 kg-yr
$T^{0\nu}_{1/2} > 1.8 \cdot 10^{26} yr$

MAJORANA DEMONSTRATOR:
Detector mass: 30 kg
Exposure: 26 kg-yr
$T^{0\nu}_{1/2} > 2.7 \cdot 10^{25} yr$

We combine well established technologies from GERDA & MAJORANA DEMONSTRATOR, gradually increase the detector mass and improve the background index

The LEGEND-1000 Discovery Sensitivity

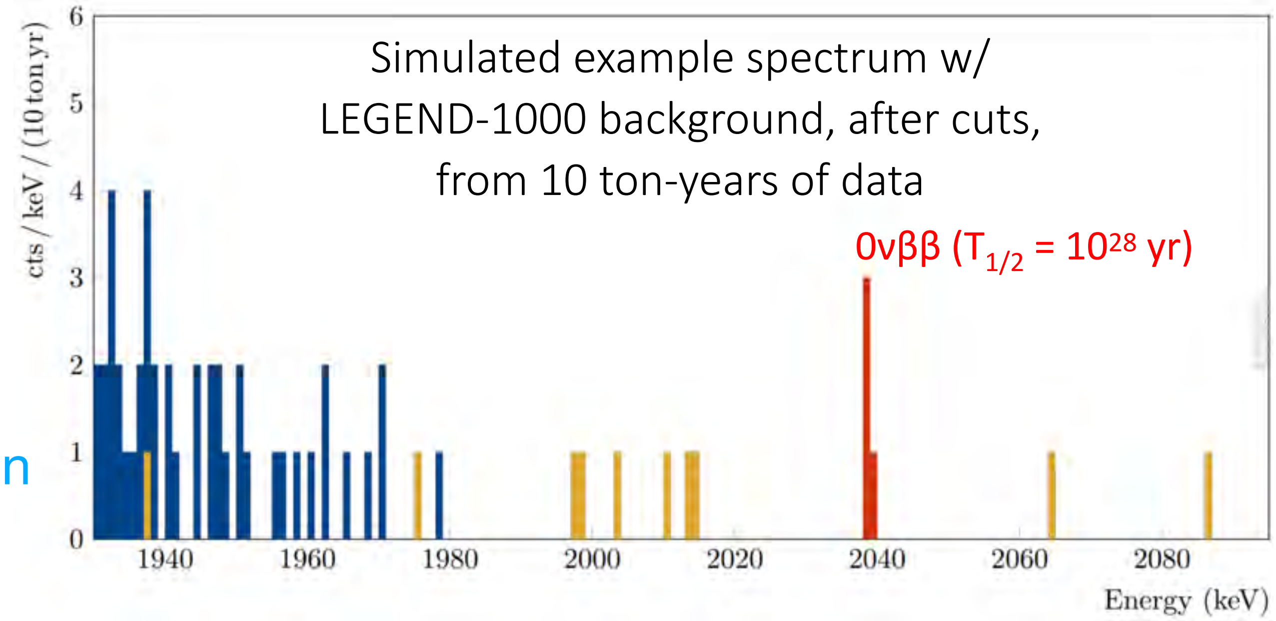
What is required for a discovery of 0νββ decay at a half-life of 10^{28} years?

→ 10^{28} years corresponds to less than 1 event per year per ton of material!

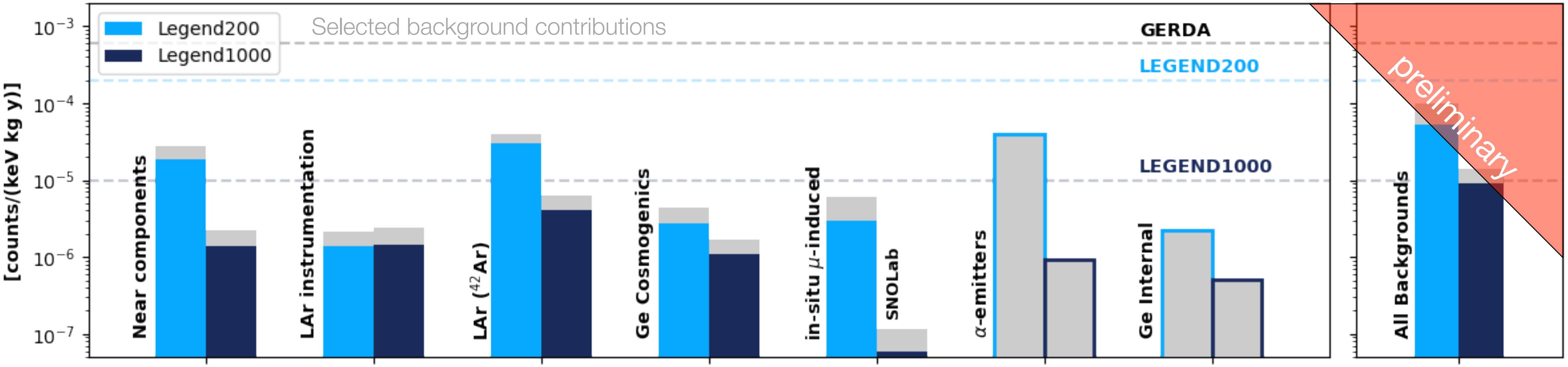
→ We need a good signal-to-background ratio to get statistical sensitivity

→ We need a very low background event rate

→ We need the best possible energy resolution



The LEGEND Background Model



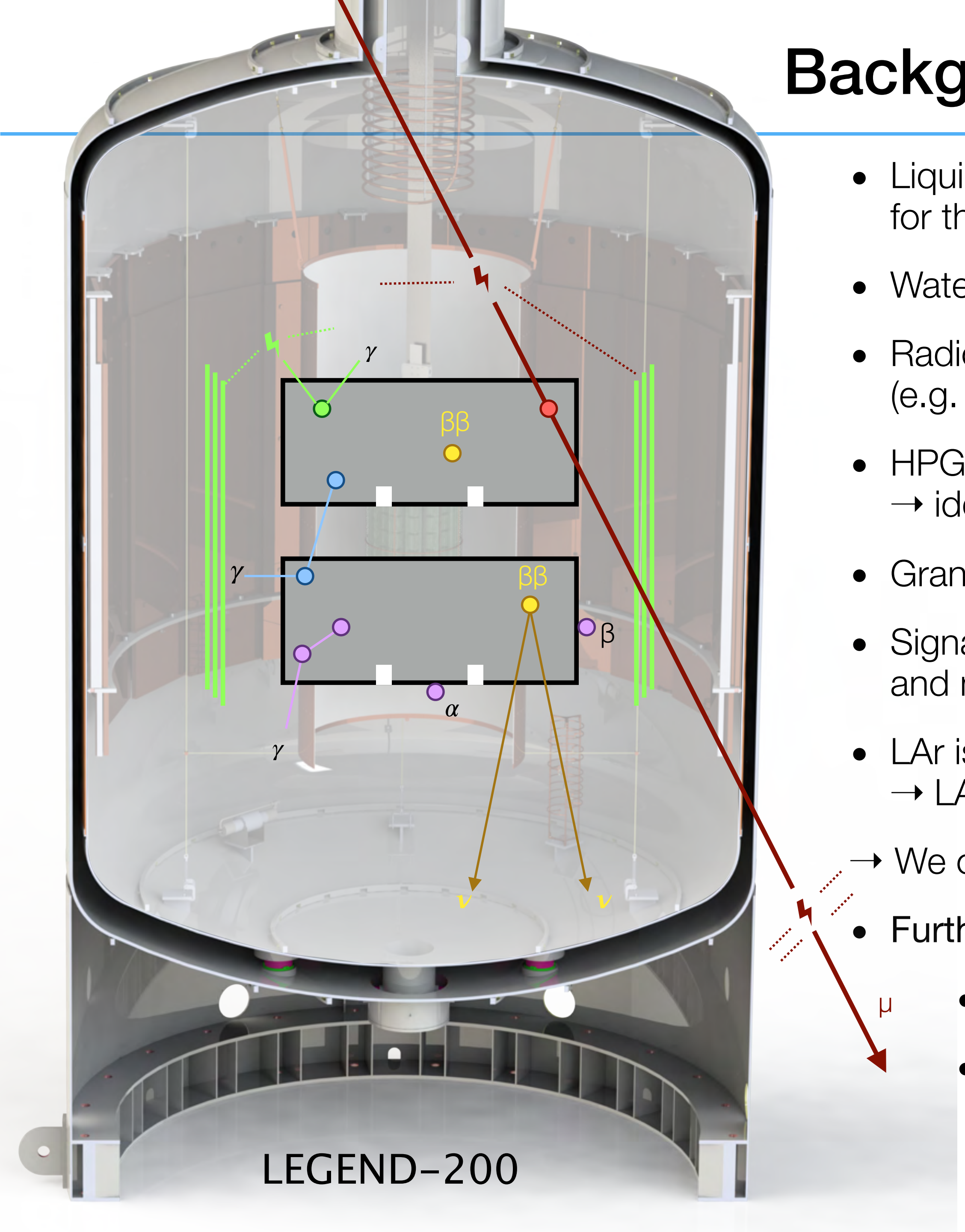
Cleaner materials: electronics, cables, detector mounts
Larger detectors → fewer parts

underground LAr

reduced μ flux at SNOLab

Using only larger ICPC detectors
→ better surface / volume ratio

Background Mitigation Strategy



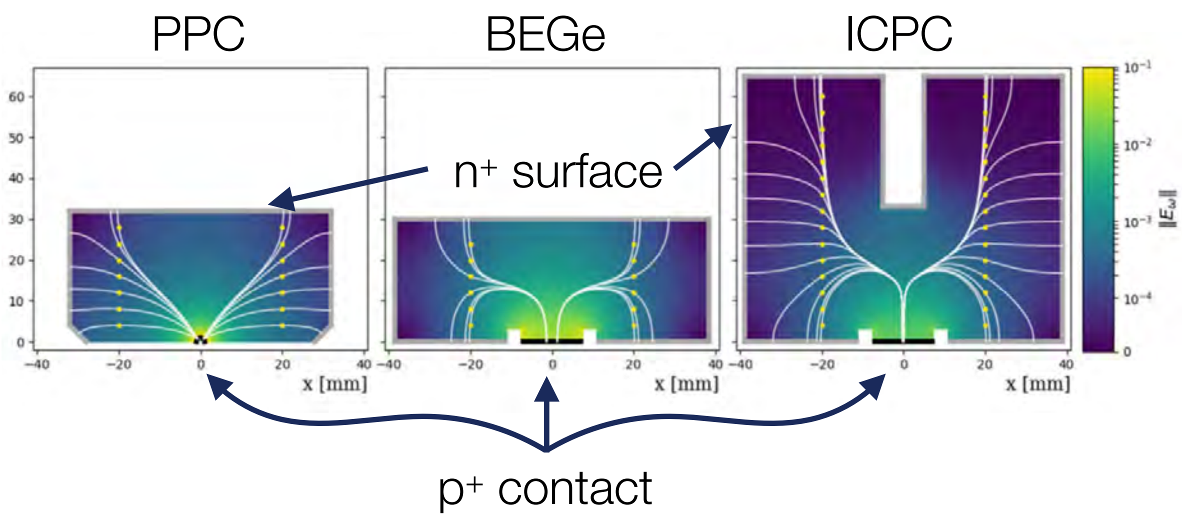
- Liquid argon is used as cooling agent & active (scintillating) shielding for the detector array
- Water tank surrounding LAr volume used as μ veto & neutron shielding
- Radiopure materials & electronics are used close to the detectors (e.g. underground electro-formed copper, PEN)
- HPGe detectors provide rich topological event information
  → identification of point-like interactions
- Granularity of detector array is used to identify ɣ backgrounds
- Signal pulse shape is used to discriminate surface backgrounds and multi-site events
- LAr is instrumented with wavelenght-shifting fibers and SiPM modules
  → LAr scintillation light provides additional topological information

→ We combine all available event information to reduce backgrounds

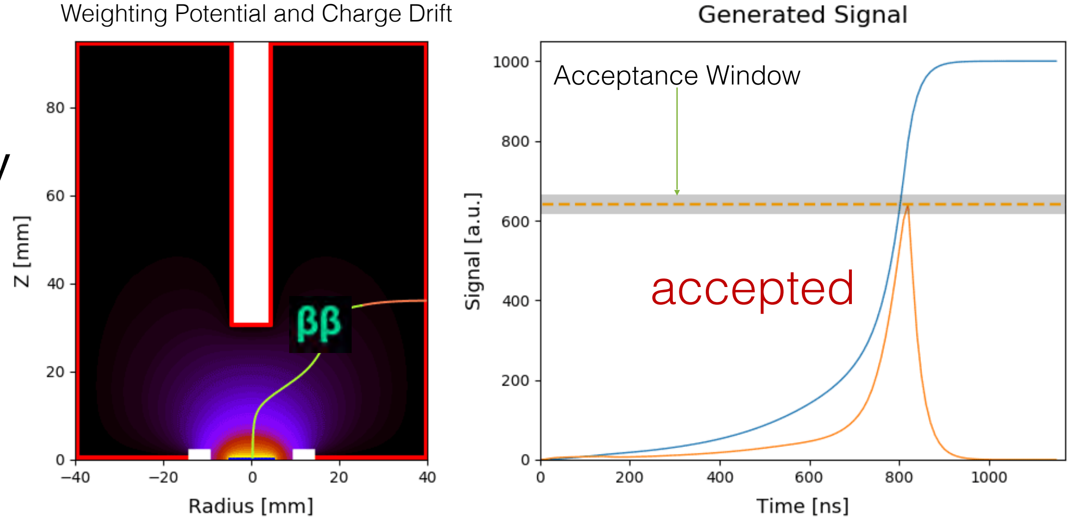
- **Further improvements for LEGEND-1000:**
  - Using underground-sourced argon reduces ^{42}Ar backgrounds
  - Using larger mass HPGe detectors lead to overall background reduction
    → fewer near components, cables, & electronics
    → less surface backgrounds due to improved surface / volume ratio

Background Mitigation Strategy - HPGe event topology

- 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



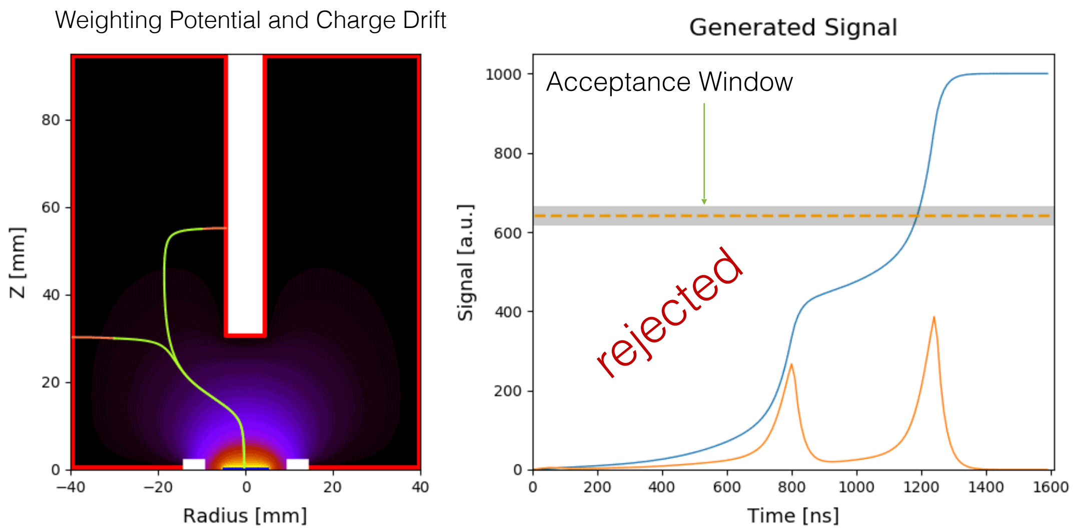
0νββ signal candidate (single-site)



Charge signal

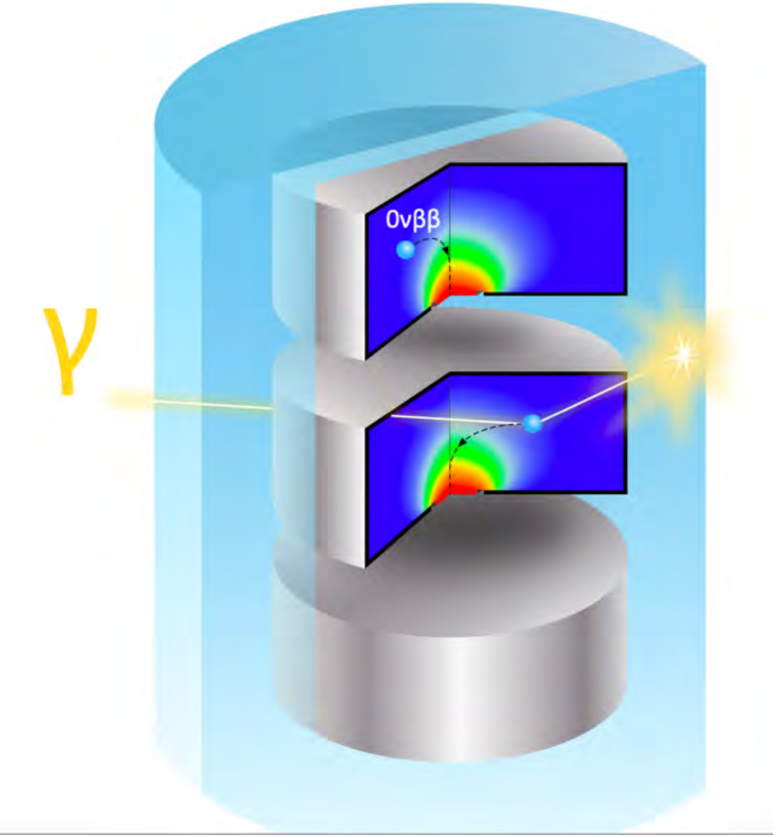
Current signal

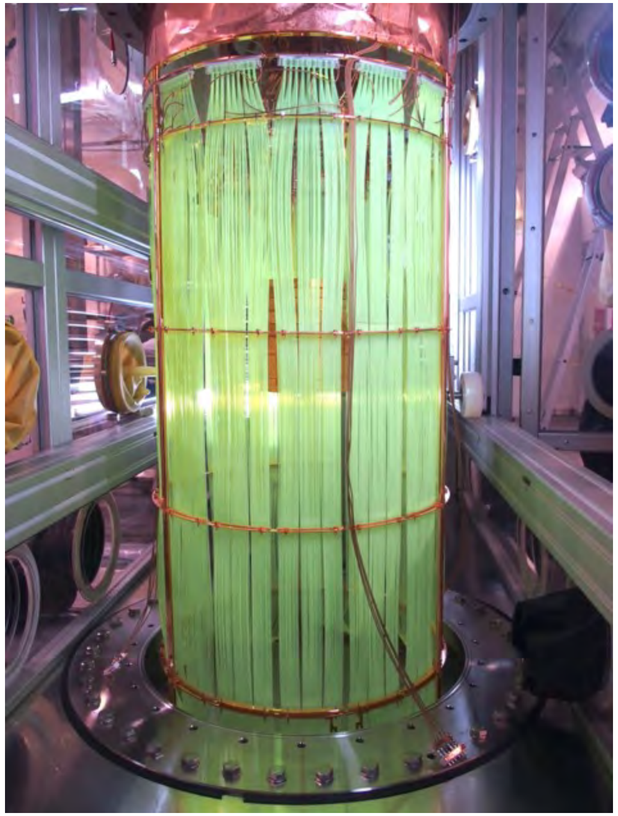
γ-background (multi-site)

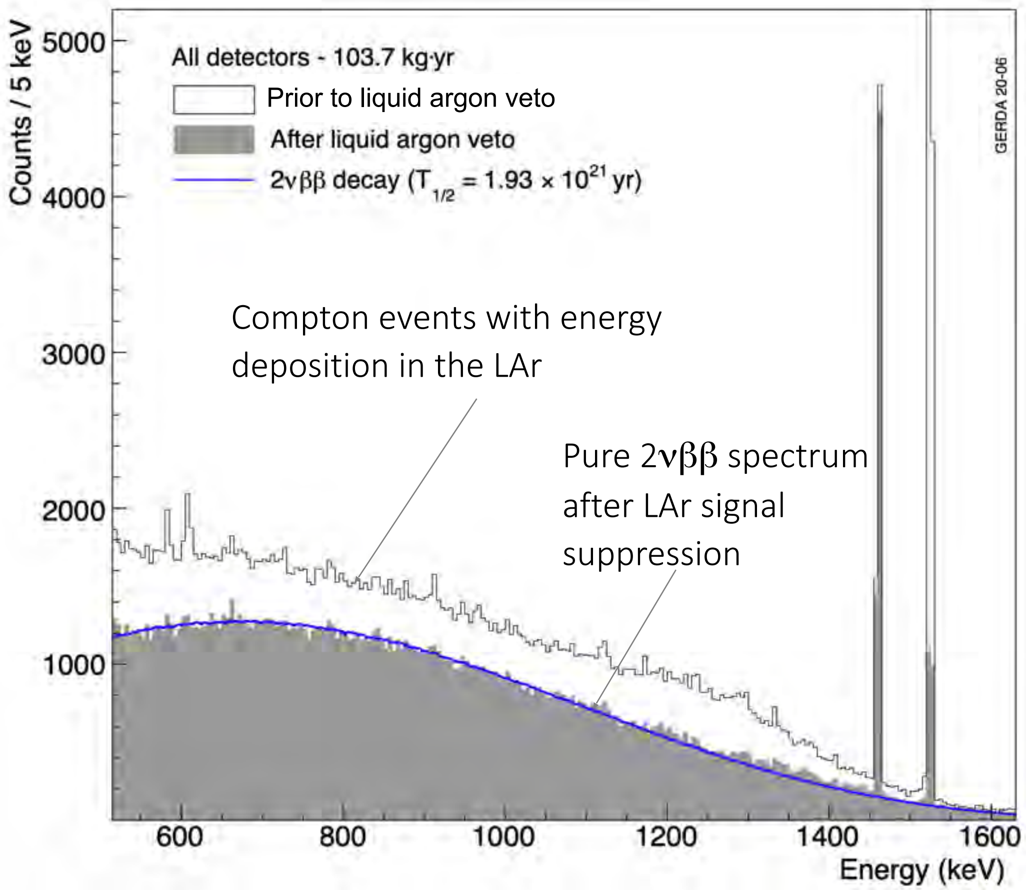


Background Mitigation Strategy - LAr instrumentation

LAr instrumentation pioneered by GERDA → detection of liquid argon scintillation light with low-background wavelength-shifting fibers and SiPM arrays for 128 nm single photon detection



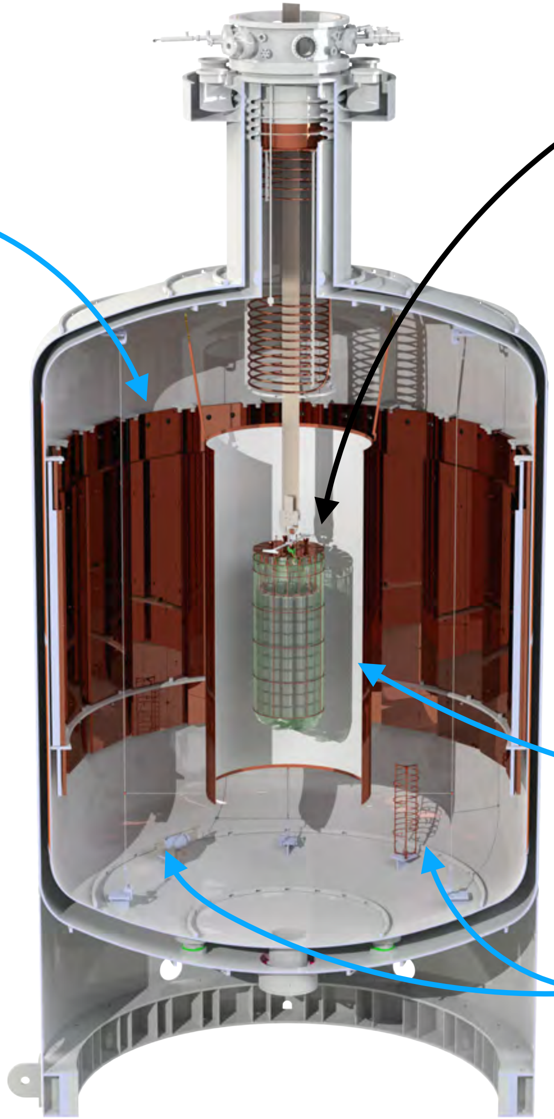




LEGEND-200 at LNGS (Laboratori Nazionali del Gran Sasso)

65 m³ (90 tons) of liquid Argon

Water tank as shielding
& muon veto system



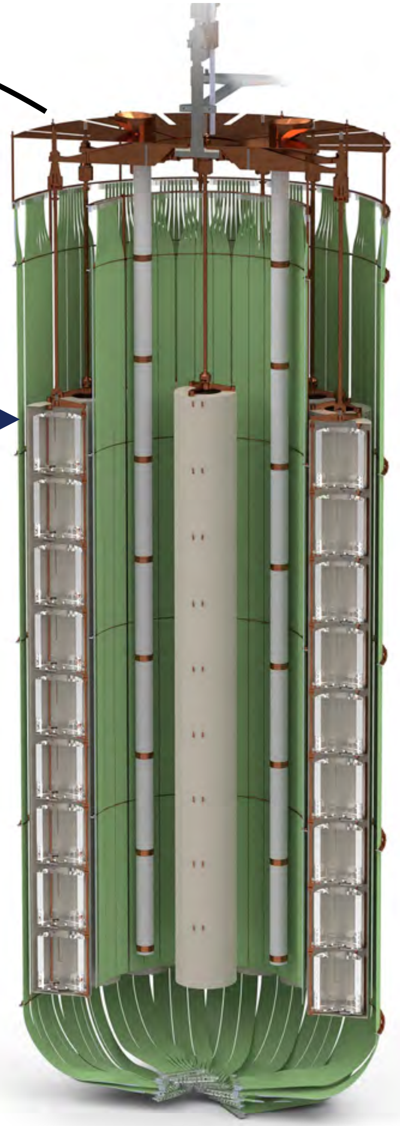
200 kg detector array equipped with
existing detectors from
GERDA & MAJORANA DEMONSTRATOR
+ new, larger mass, ICPC detectors

New HPGe detector readout electronics,
cleaner materials (EFCu, PEN),
new LAr instrumentation

New reflector surrounding
the detector array
improves light collection

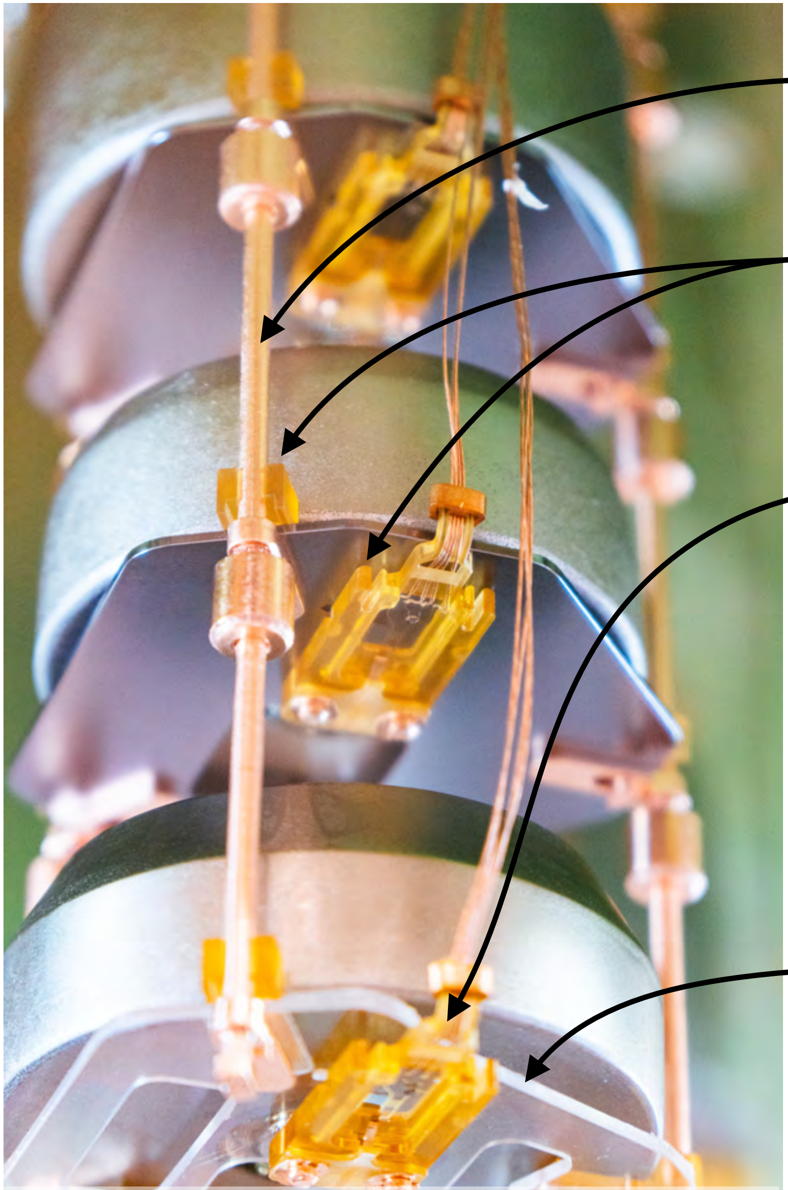
LAr quality monitoring
(scintillation properties) &
cryogenic pump to re-purify LAr

LEGEND-200 uses the existing GERDA
infrastructure at LNGS



An upgraded detector array houses 200kg
of HPGe detectors

LEGEND-200 - Radiopurity of near-detector components

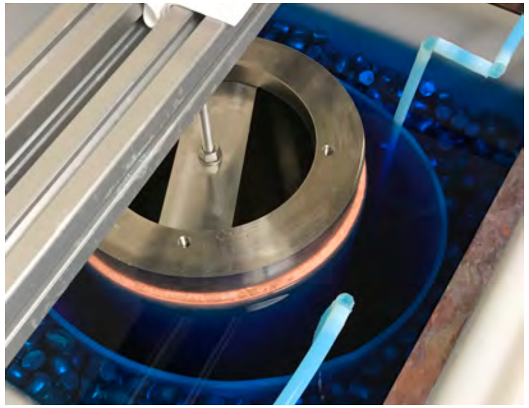


Detectors during the "Post GERDA test" in summer of 2020

Underground electro-formed Copper (UEF-Cu)

→ reduces U / Th and cosmogenic activation of ^{60}Co in Cu

→ extremely clean: ^{238}U & ^{232}Th < 0.1 µBq / kg

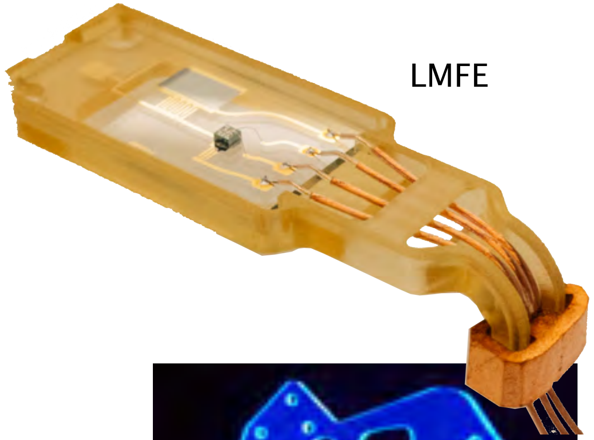


Clean engineering plastics (ULTEM)

Custom low-mass front end electronics

→ ultra-low radioactivity circuit board placed ~ 1 cm from signal contact → low electronic noise

→ based on earlier implementation by MAJORANA & optimised for operation in LAr



Detector support from optically active PEN

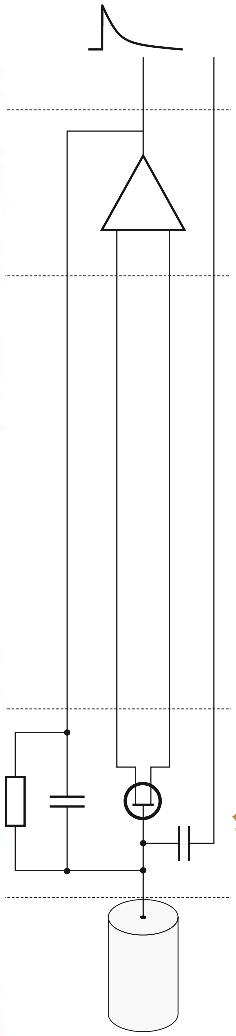
→ Polyethylene naphtalate replaces optically inactive silicon plates

→ shifts 128 nm LAr scintillation light to ~ 440 nm

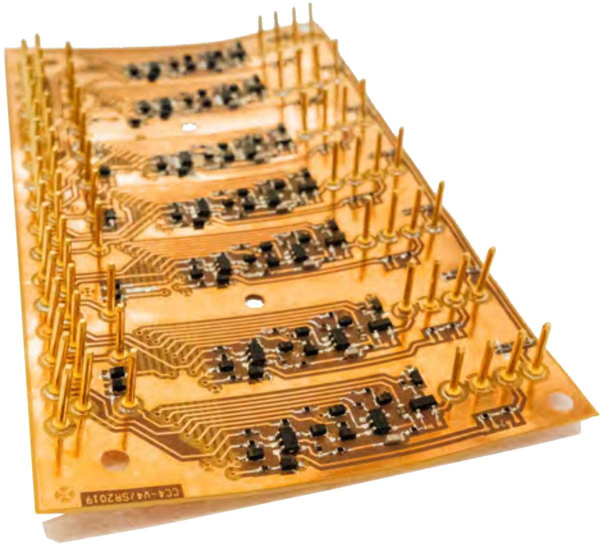
→ first use in LEGEND-200, R&D towards LEGEND-1000

Scintillating PEN sample

LEGEND-200 Front-End Electronics

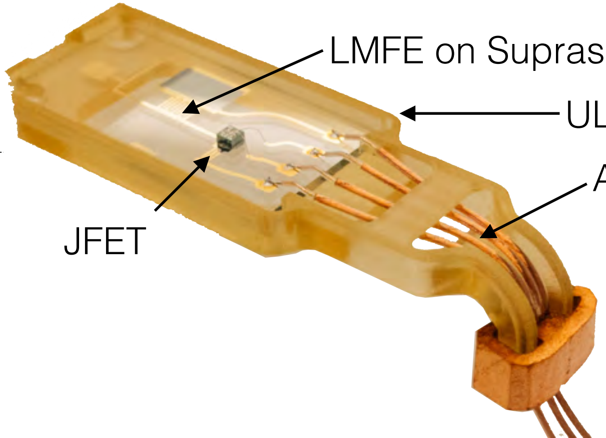


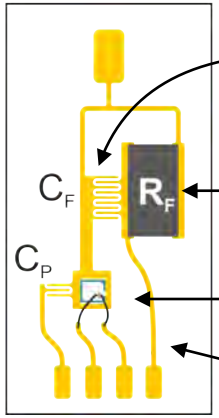
Combine Liquid Argon-operated preamplifier of GERDA with ultra-clean Low Mass Front-End of MAJORANA



Custom LAr-operated pre-amplifier (CC4)

- Differential output driving ~10 m cable
- 7 Ch / board
- Clean PCB → Kapton
- Commercial small-footprint components (assayed)
- Active receiver and power distribution at cryostat flange





Low Mass Front End

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

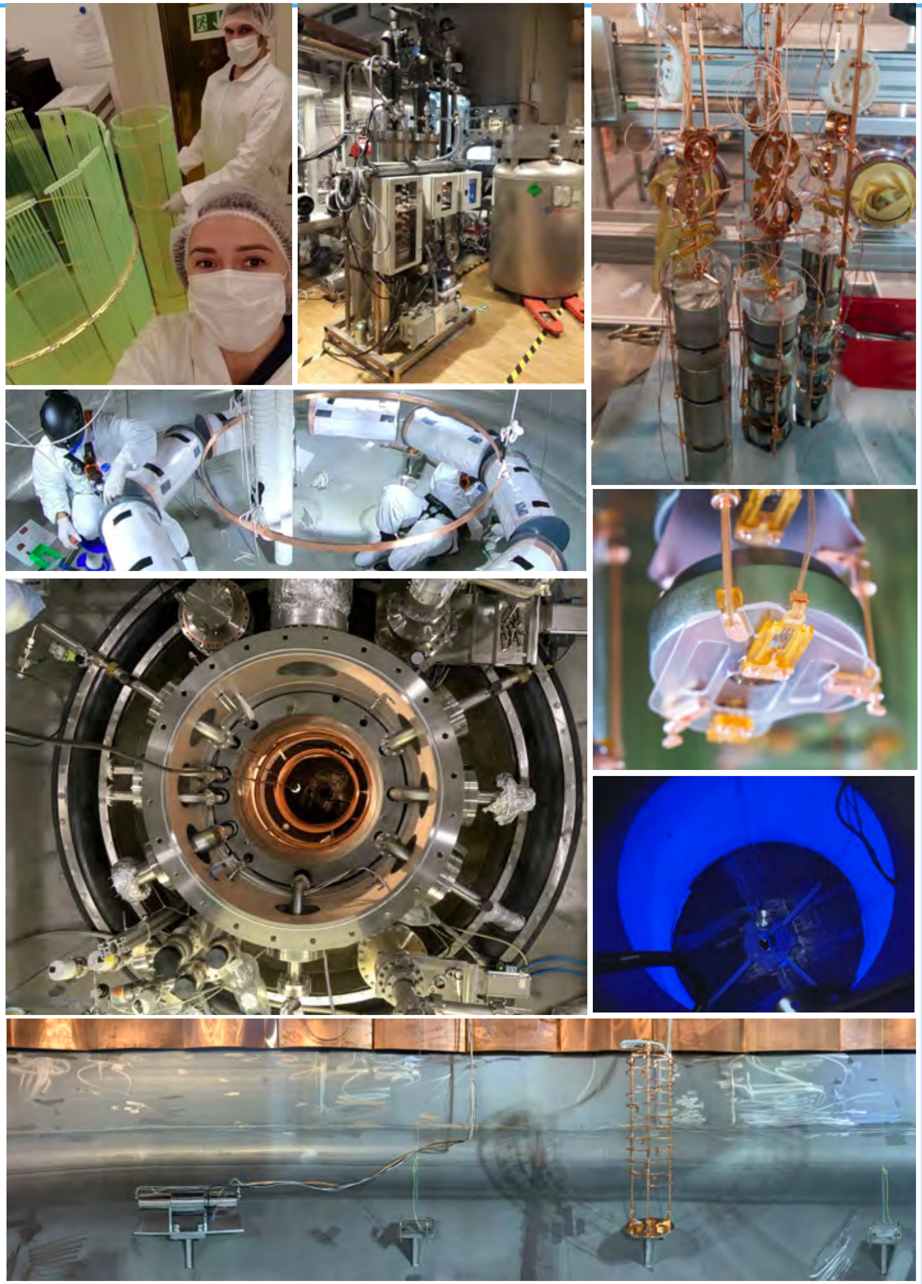
Amorphous germanium feedback resistor R_f (few GΩ in LAr)

Bare die JFET

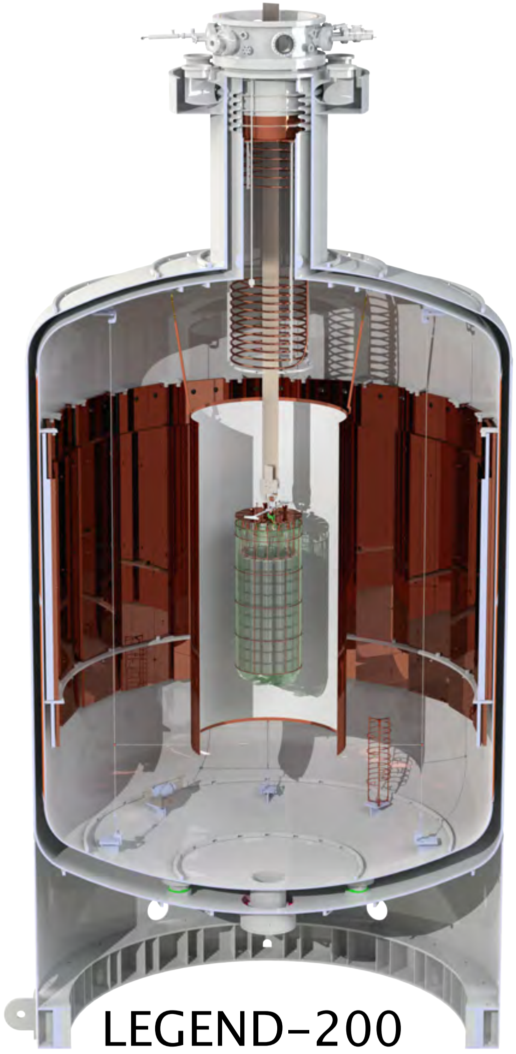
Sputtered Ti/Au traces

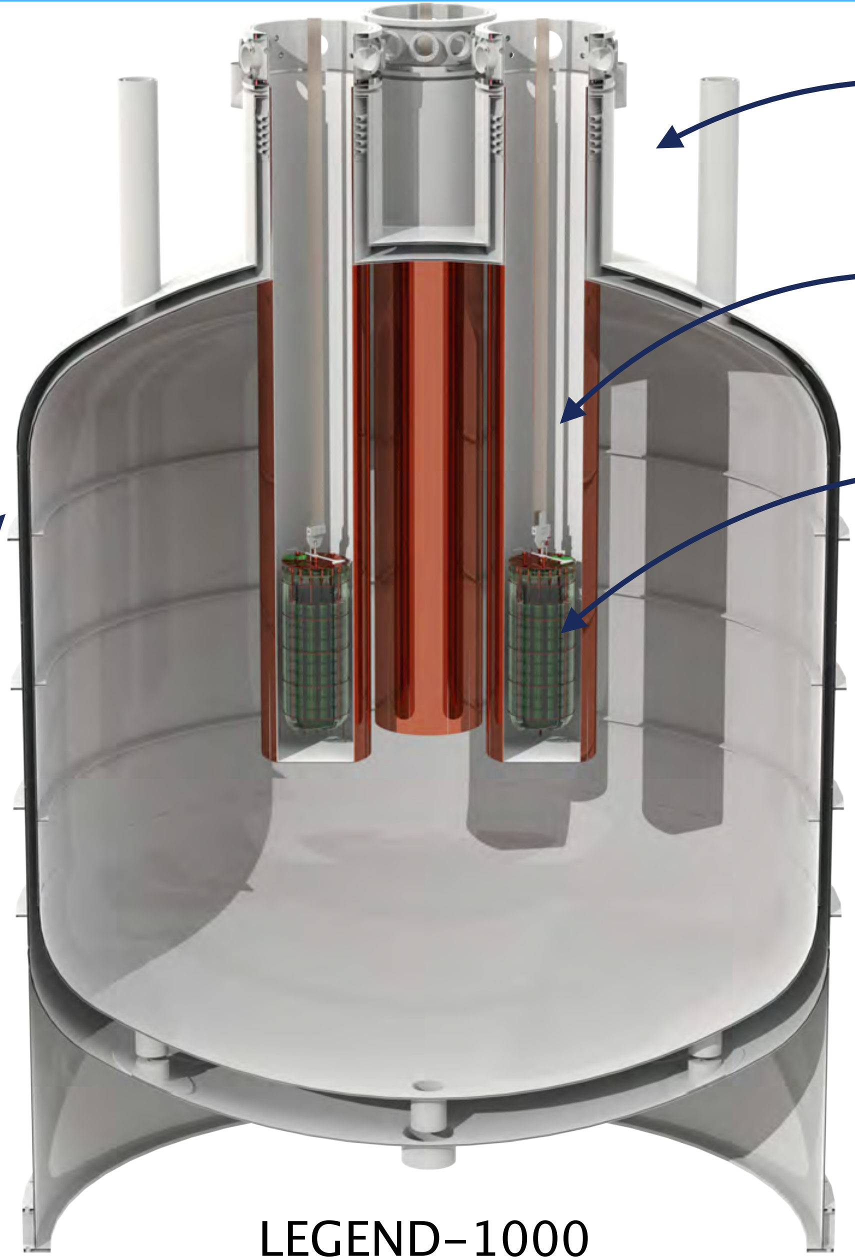
LEGEND-200 Status of Major Activities

- Fabrication and characterisation of 130 kg of new ICPC Detectors on track
- GERDA cryostat & infrastructure available to LEGEND since Feb. 2020
- Test of all major new components in Spring-Summer 2020 → readout electronics, DAQ, ICPC detectors, PPC detectors, detector mounts & PEN
- On-site test of production electronics → July 2021 at LNGS
- Calibration system: new sources produced, first components installed at LNGS in July 2021.
- Lock and cable assembly: tested and installed, ready for operation.
- Production of active shield system finished, installation in August 2021. LAr monitoring and recirculation/purification system installed at LNGS.
- Schedule : LAr fill started in June. On schedule to start commissioning and data taking in 2021 with ~140-150 kg of detectors. Plan to install final 50 kg of detectors in 2022.



The Path towards LEGEND-1000

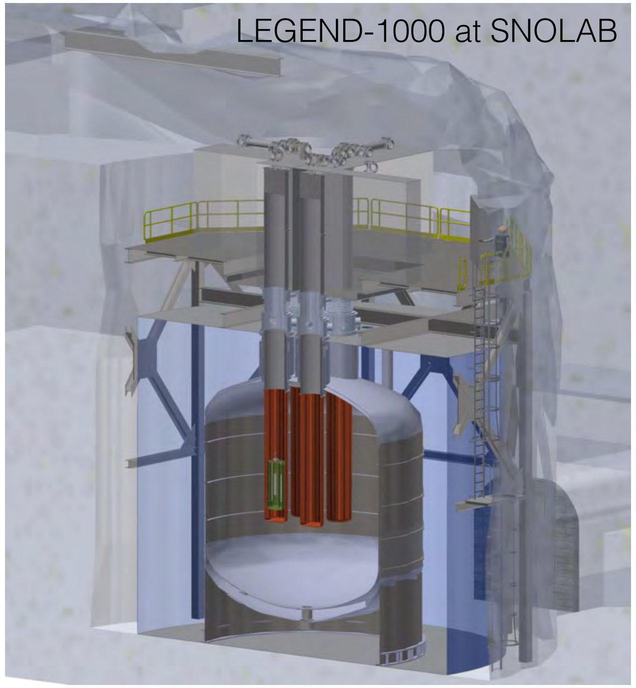




Larger cryostat with 4 payloads
→ enables modular assembly
& expedites measurement

Underground LAr in smaller volume around individual payloads
→ reduces ^{42}K background

Payload design based on LEGEND-200



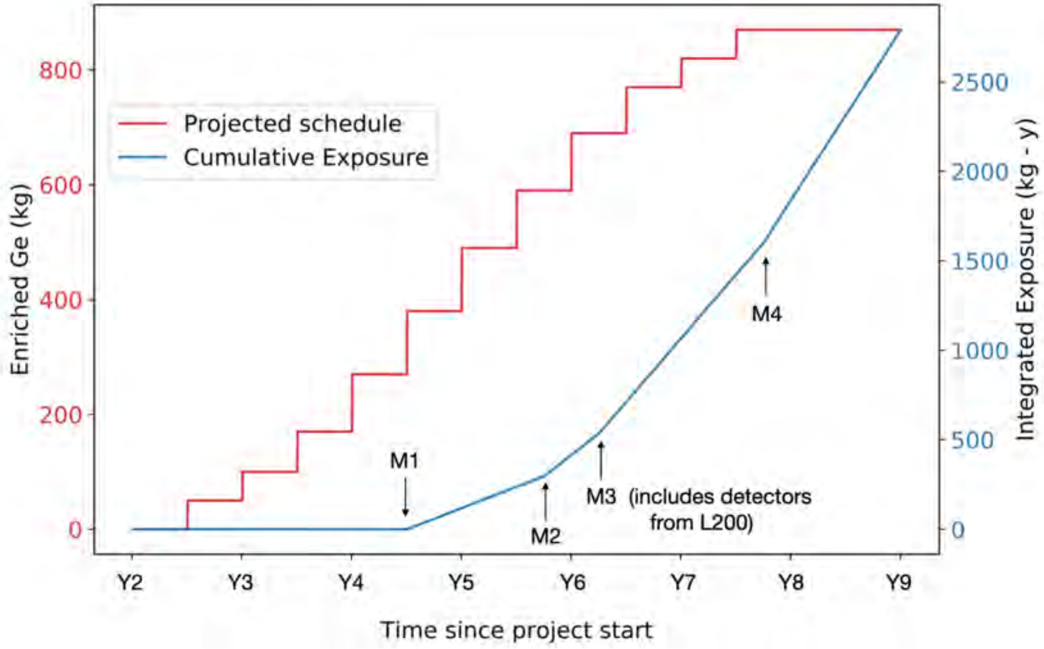
LEGEND-1000 Baseline Design

ICPC detector assembly:

- 2.6 kg average mass
- EFCu
- PEN
- ASIC front end
- Flat flex cables

Detector arrays:

- 4 arrays
- 100 ICPCs / array
- 1000 kg total mass
- 0.12% FWHM (0.05% σ) at $Q_{\beta\beta}$
- Double-barrel LAr instrumentation
- Underground argon
- Reentrant tubes



ICPC detector production:

LEGEND-1000 staged approach: Detectors for first module are ready 2.5 years after start of production

Summary & Outlook

- LEGEND-200 → first phase of the LEGEND program
    - Construction at Gran Sasso currently ongoing, Commissioning later this year!
    - On-track to achieve background goal of $< 2 \cdot 10^{-4}$ cts / (keV kg yr) and half-life sensitivity $> 10^{27}$ yrs after 5 years of data taking

- LEGEND-1000 is designed as a ton-scale 0νββ decay experiment with 3σ discovery potential at half-lives $> 10^{28}$ years
    - Optimised for a quasi-background-free 0νββ search
    - Builds on breakthrough developments by Gerda, MAJORANA, and LEGEND-200
    - DOE portfolio review currently ongoing in the US

Thank you!

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- German Max Planck Society (MPG)
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