The Large Enriched Germanium Experiment for Neutrinoless ββ Decay (LEGEND)

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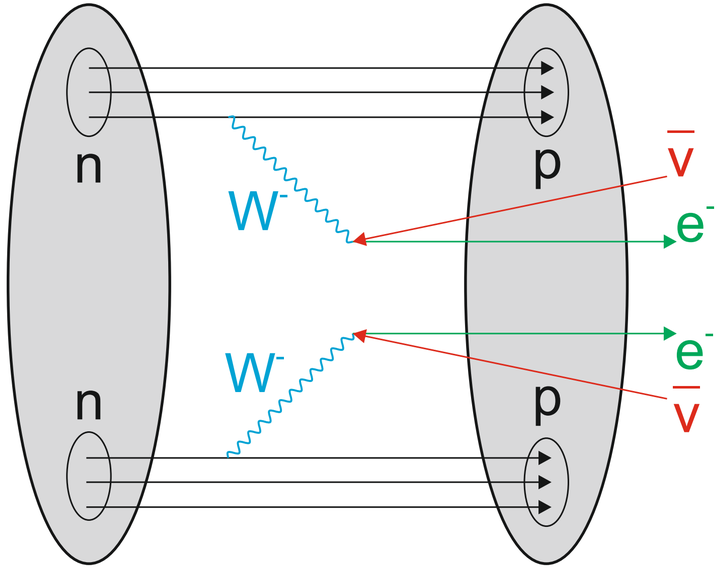
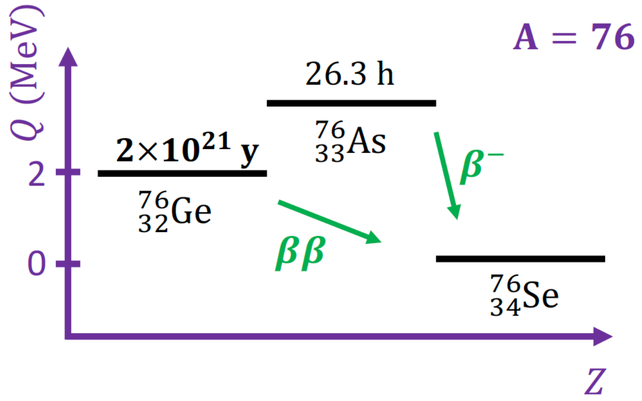
LEGEND
Large Enriched
Germanium Experiment
for Neutrinoless ββ Decay

Photo by Jacek Dylag (Unsplash)

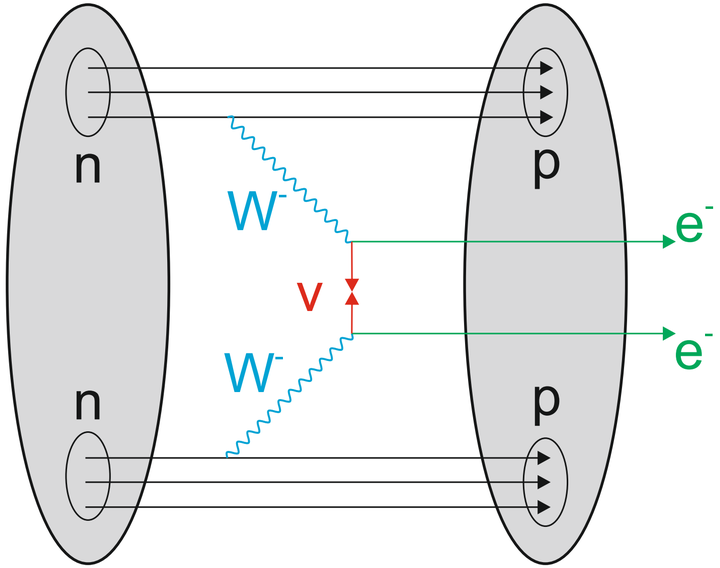
A very short introduction to neutrinoless double beta decay



$$(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\bar{\nu}$$



Example: light neutrino exchange



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

Two-neutrino double beta decay (2νββ)

- Only decay possible in certain isotopes (^{76}Ge, ^{82}Se, ^{130}Te, ^{136}Xe, ...)
- Predicted by the Standard Model
- Observed experimentally!

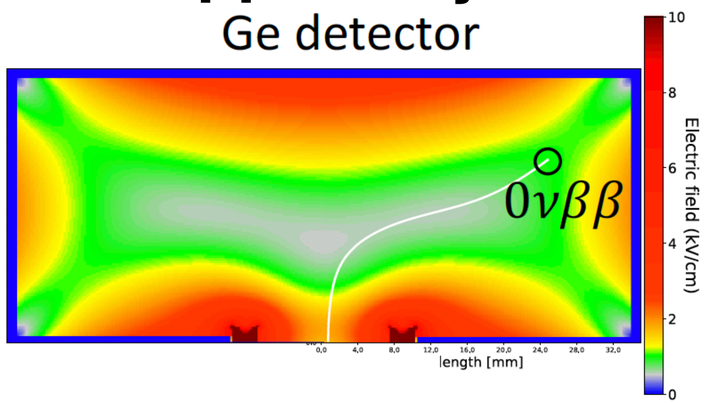
Neutrinoless double beta decay (0νββ)

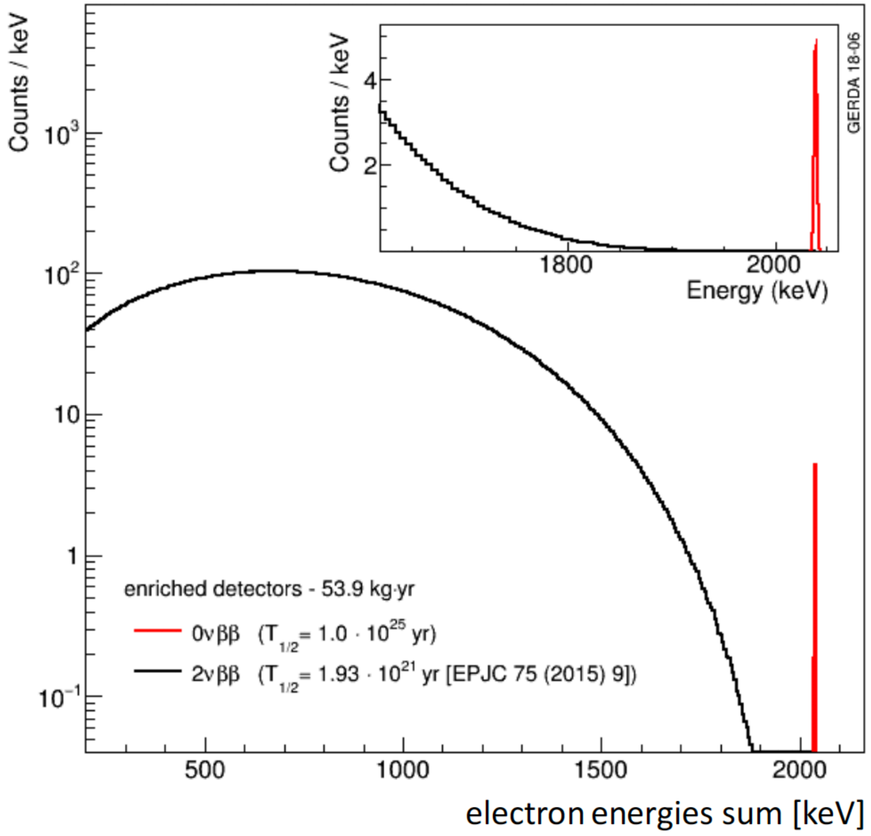
- Violates lepton number by 2 units → new physics
- Determines the nature of the neutrino → $\nu = \bar{\nu}$
- Can provide information on the ν mass
- so far unobserved

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."

^{76}Ge-based $0\nu\beta\beta$ decay search

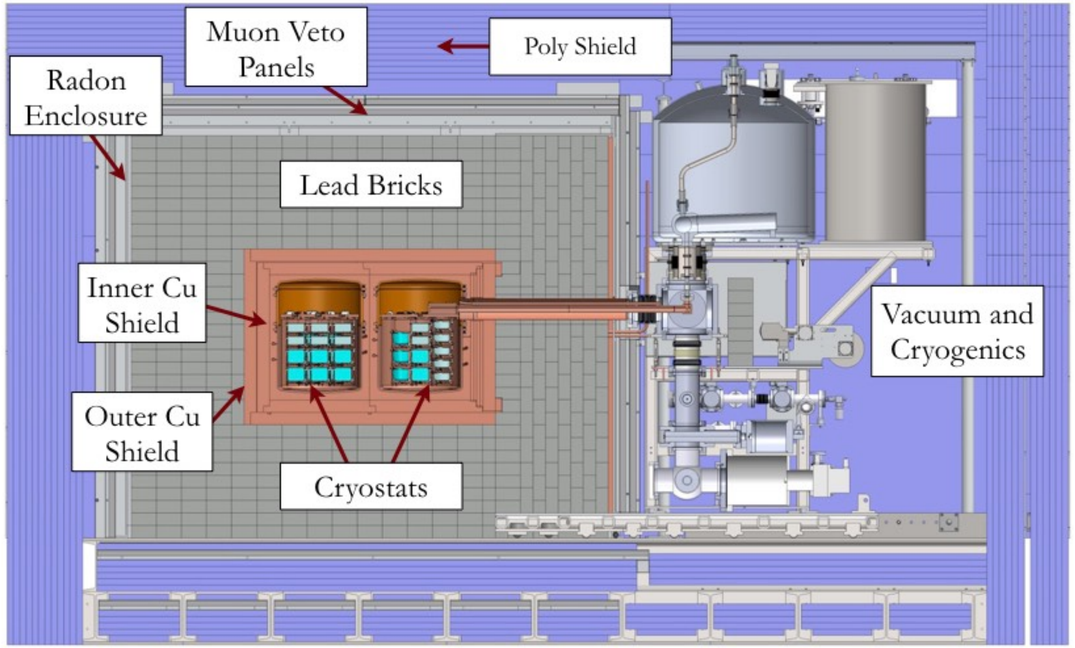




- $Q_{\beta\beta}$ = 2039 keV
- Excellent energy resolution
  → 2.2 - 3 keV FWHM at $Q_{\beta\beta}$
- Very high detection efficiency
  → source = detector
- Enrichment to > 88% in ^{76}Ge possible
- Excellent background rejection
  → pulse shape & detector granularity
- Very low backgrounds achieved

The MAJORANA DEMOSTRATOR and GERDA Experiments

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 (e.g. dark matter search))

GERDA @ LNGS

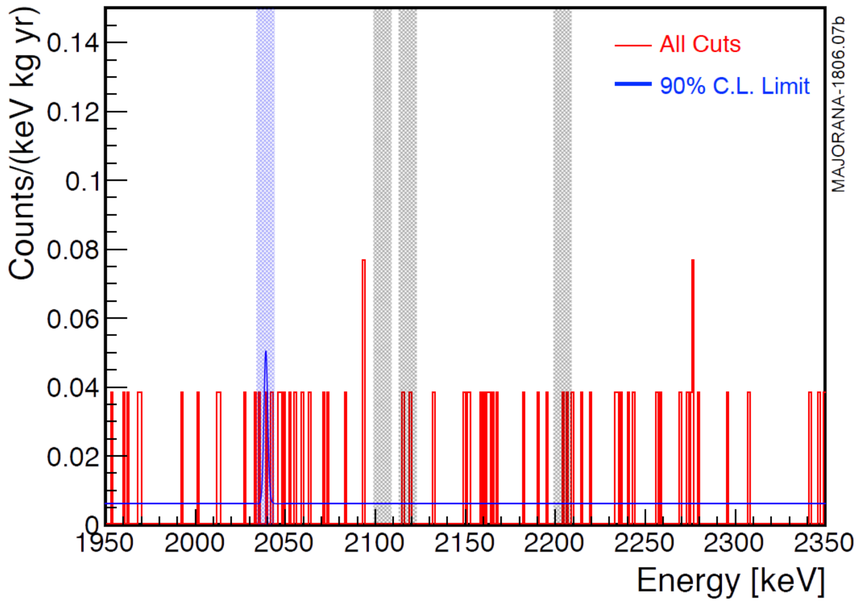
- Detectors (^{enr76}Ge) in liquid argon (LAr)
- LAr acts as an active shield (no Pb)
  → background tagging by LAr scintillation light & coincident signals

Both:

- Clean fabrication techniques
- Control of surface exposure (cosmogenic activation)
- Lowest background and best resolution $0\nu\beta\beta$ decay experiments
- Combined detector mass: ~ 65 kg of ^{enr76}Ge

The MAJORANA DEMOSTRATOR and GERDA Experiments

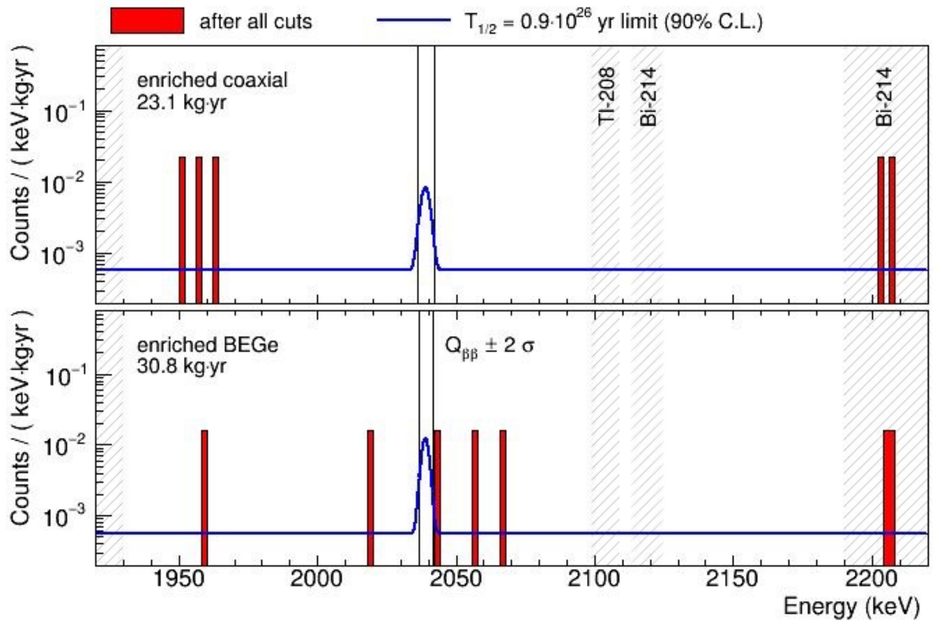
MAJORANA DEMONSTRATOR @ SURF



DOI 10.5281/zenodo.1286900

Background → 4.7±0.8 x 10^{-3} cts/(keV kg yr)
Resolution (FWHM) → 2.5 keV @ $Q_{\beta\beta}$
Sensitivity → 4.8 x 10^{25} yr (90% CL)
Limit → $T_{½}$ > 2.7 x 10^{25} yr

GERDA @ LNGS

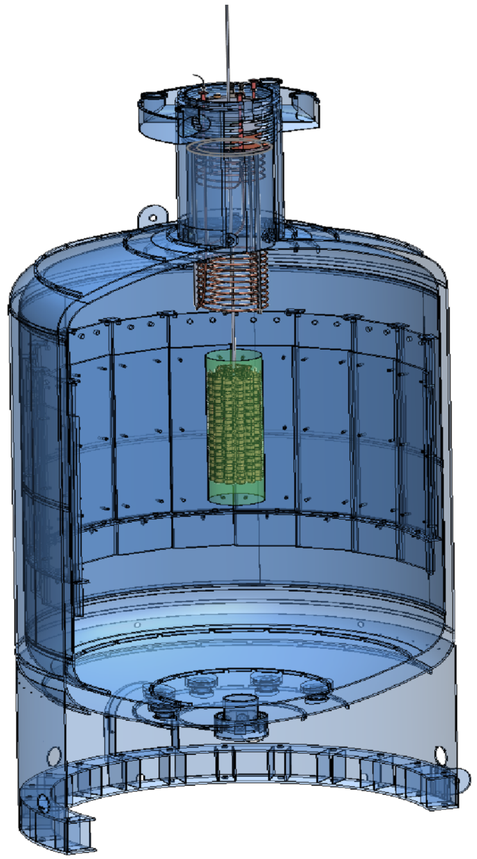


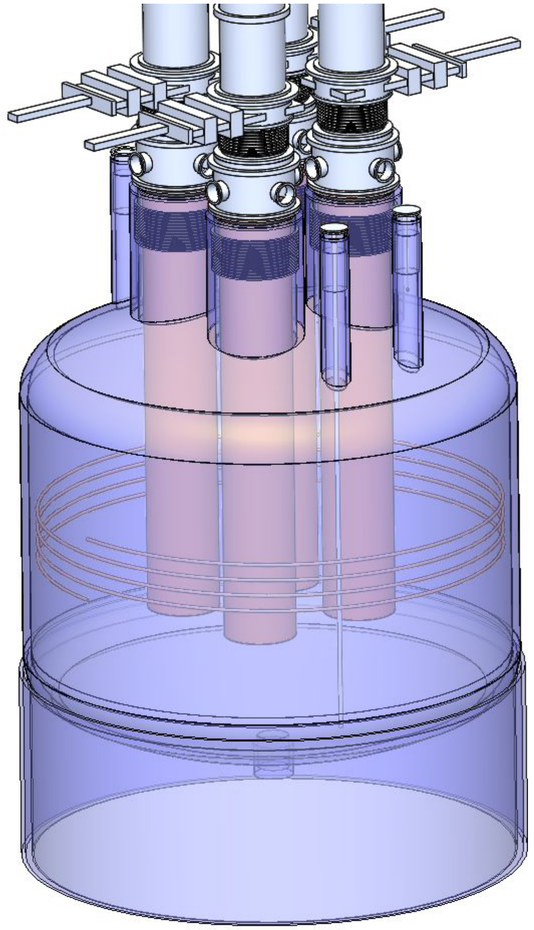
DOI 10.5281/zenodo.1287604

Background → $0.6^{+0.4}_{-0.2}$ x 10^{-3} cts/(keV kg yr)
Resolution (FWHM) → 3 keV @ $Q_{\beta\beta}$
Sensitivity → 1.1 x 10^{26} yr (90% CL)
Limit → $T_{½}$ > 0.9 x 10^{26} yr

LEGEND strategy: select best technologies based on experiences of MAJORANA DEMONSTRATOR and GERDA, as well as contributions from other groups and experiments

The LEGEND Experiment





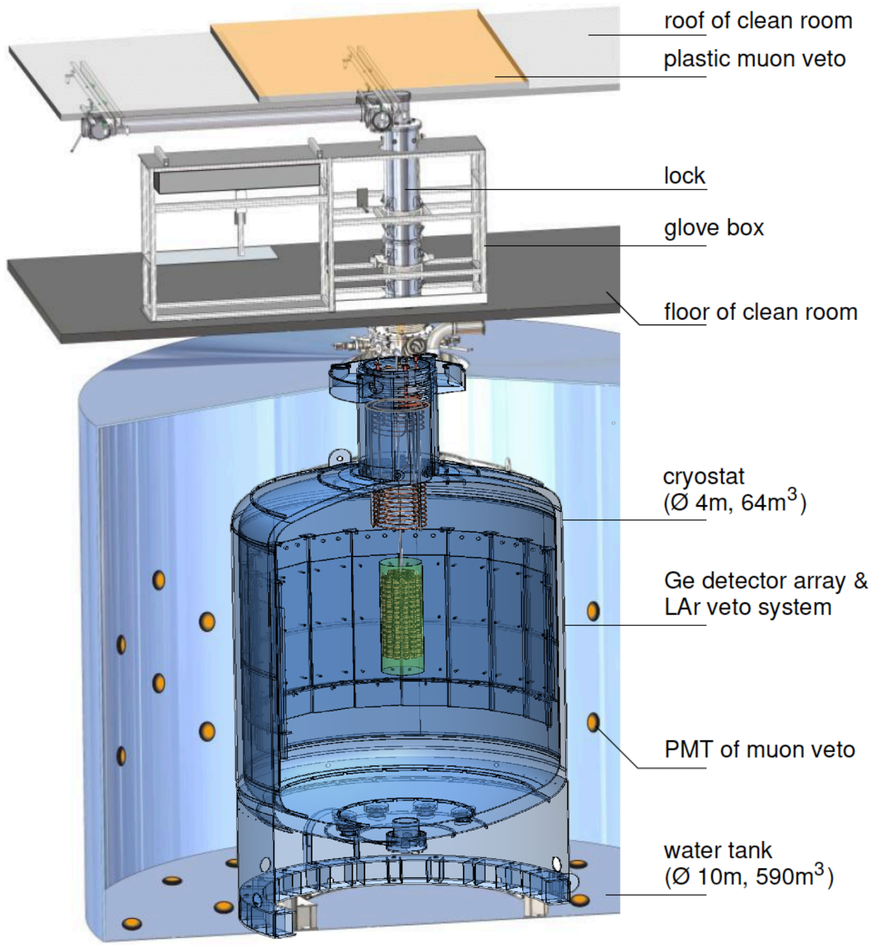
First stage (LEGEND-200):

- (Up to) 200 kg of detectors ($^{enr76}Ge$)
- Utilise existing GERDA infrastructure at LNGS + modifications as needed
- Target exposure: 1 t yr
- BG goal: 0.6 cts / (FWHM t yr)
- Data-taking start in ~ 2021

Subsequent stages (LEGEND-1000):

- 1000 kg of detectors ($enr^{76}Ge$) (staged)
- BG goal: reduction to < 0.1 cts / (FWHM t yr)
- Location: TBD
  → required depth (^{77m}Ge) under investigation

LEGEND-200



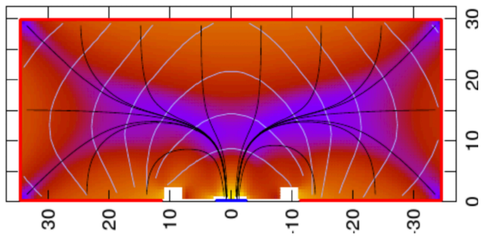
- Utilise existing GERDA infrastructure at LNGS
- Large enough for 200 kg of enriched detectors
- *Exposure*: 1 ton yr, *Sensitivity* > 10^{27} yr
- Background goal: 0.6 cts / (FWHM t yr)
- Modifications:
  - new electronics
  - raise clean room roof
  - new lock
  - new cabling, detector suspension, feedthroughs
- Detectors:
  - BroadEnergyGe (BEGe) detectors from GERDA
  - P-type Point Contact (PPC) detectors from MAJORANA
  - new inverted coaxial detectors (baseline 1.5 kg)
- Funding for LEGEND-200 almost secured, first orders for additional detectors placed!
- Data-taking start in ~ 2021

LEGEND-200: larger ^{enr}Ge detectors

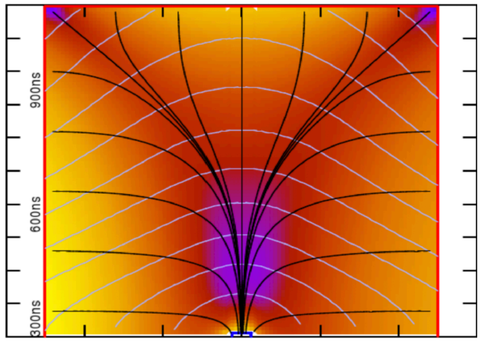
- GERDA BEGe: ~ 0.7 kg
- MJD PPCs: ~ 0.8 kg

- Larger detectors → less cables, connectors and readout electronics → **lower background**

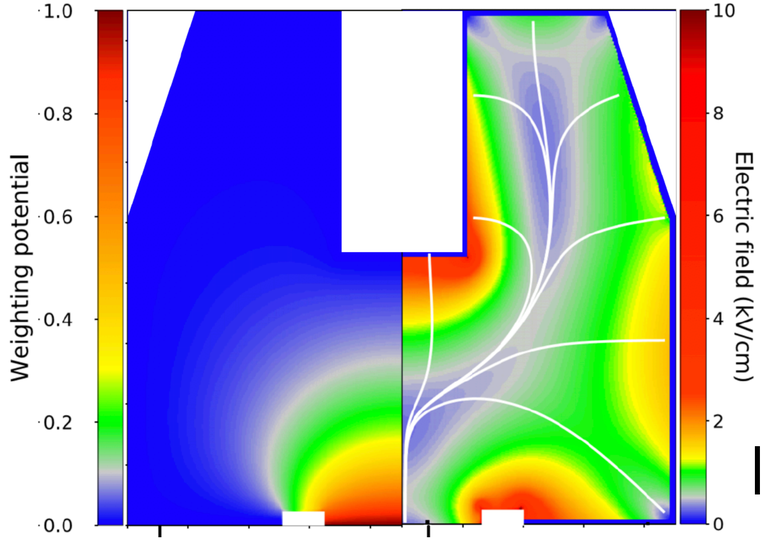
- **New concept:** Inverted Coaxial Point-Contact Ge detectors (ICPC) DOI 10.1016/j.nima.2011.10.008
  - Combines advantages of Coaxial and BEGe/PPC detectors: high mass / lower depletion voltage / excellent pulse shape discrimination
  - Large mass of up to 3 kg (R&D for 6 kg ongoing) → "production" ~ 1.5 kg
- **Orders for LEGEND-200 detectors placed early 2019!**



BEGe



PPC

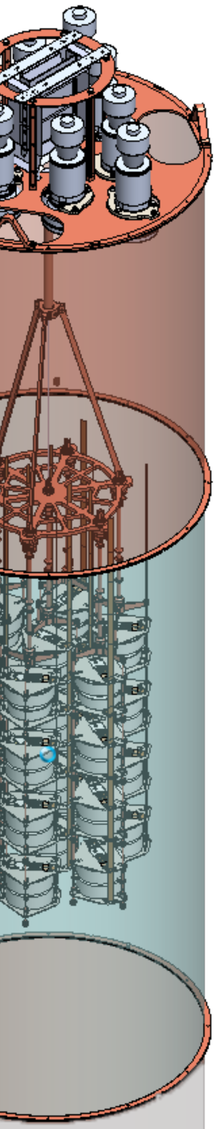


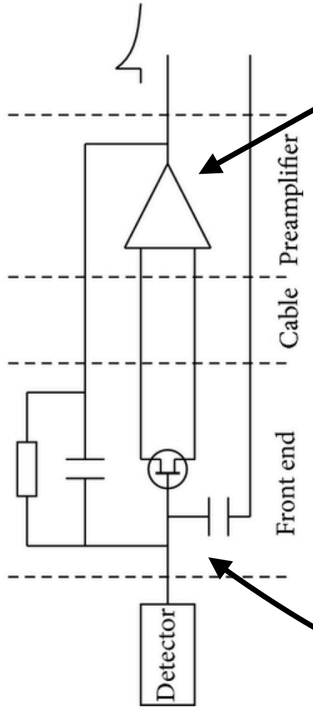
ICPC

LEGEND-200: Front-End Electronics

Baseline Design: Combine LAr-operated preamplifier of GERDA with the ultra-clean Low Mass Front-End of MAJORANA DEMONSTRATOR

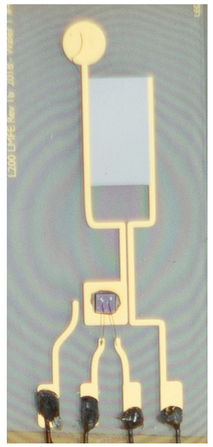
→ Preamplifier (CC4) developed by **INFN / University of Milan**, Italy
→ Low Mass Front-End (LMFE) developed by **Lawrence Berkeley Laboratory**

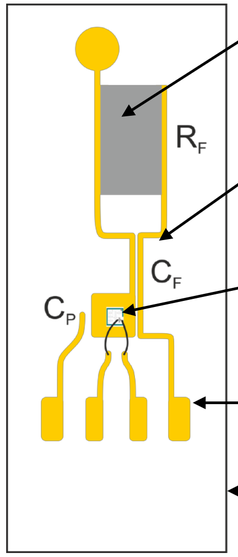




Preamplifier (CC4)

- Based on current GERDA preamplifier (CC3)
- Differential output
- Operation in LAr

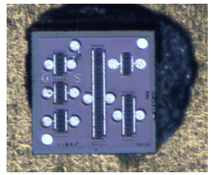




Amorphous germanium feedback resistor R_f (few GΩ in LAr)

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

Bare die JFET: Moxtek MX11

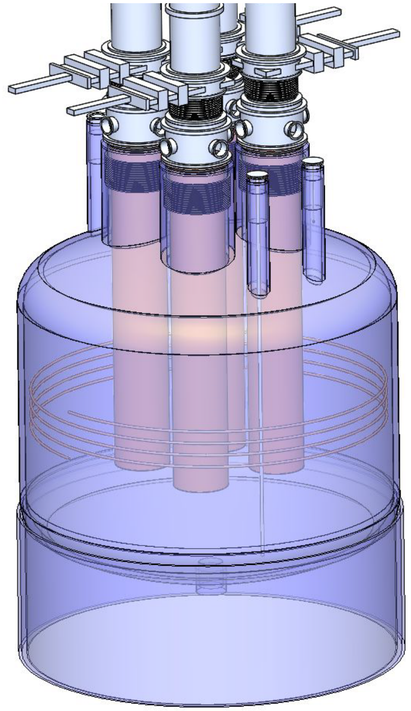


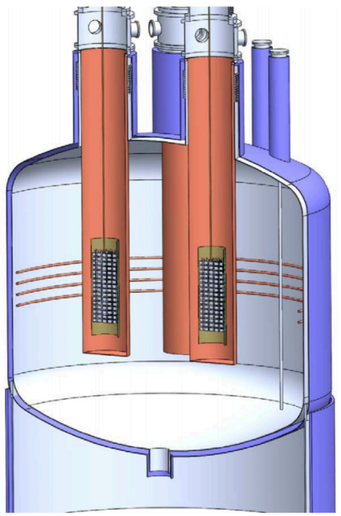
Sputtered Ti/Au traces

Fused silica substrate / Suprasil

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

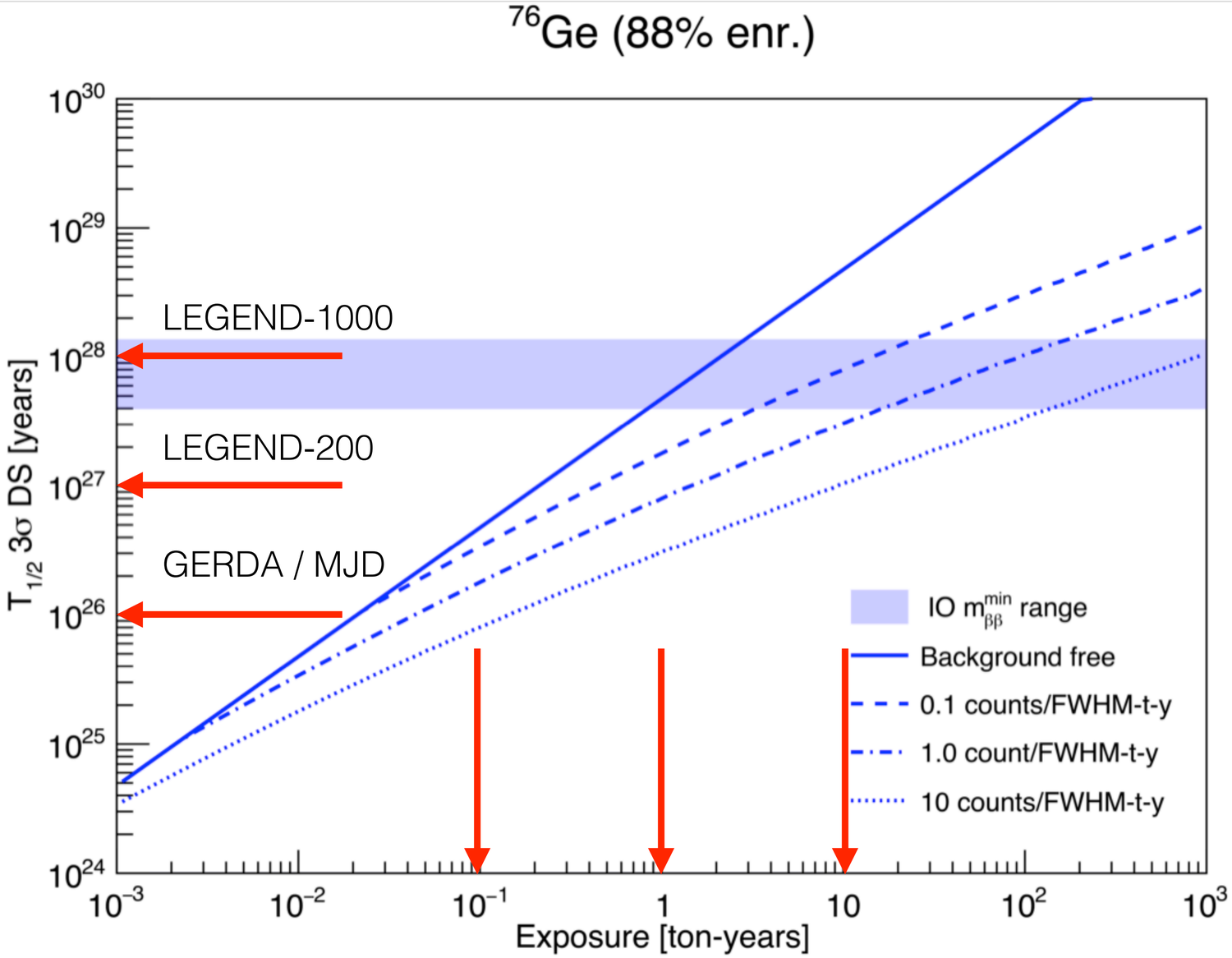
LEGEND-1000



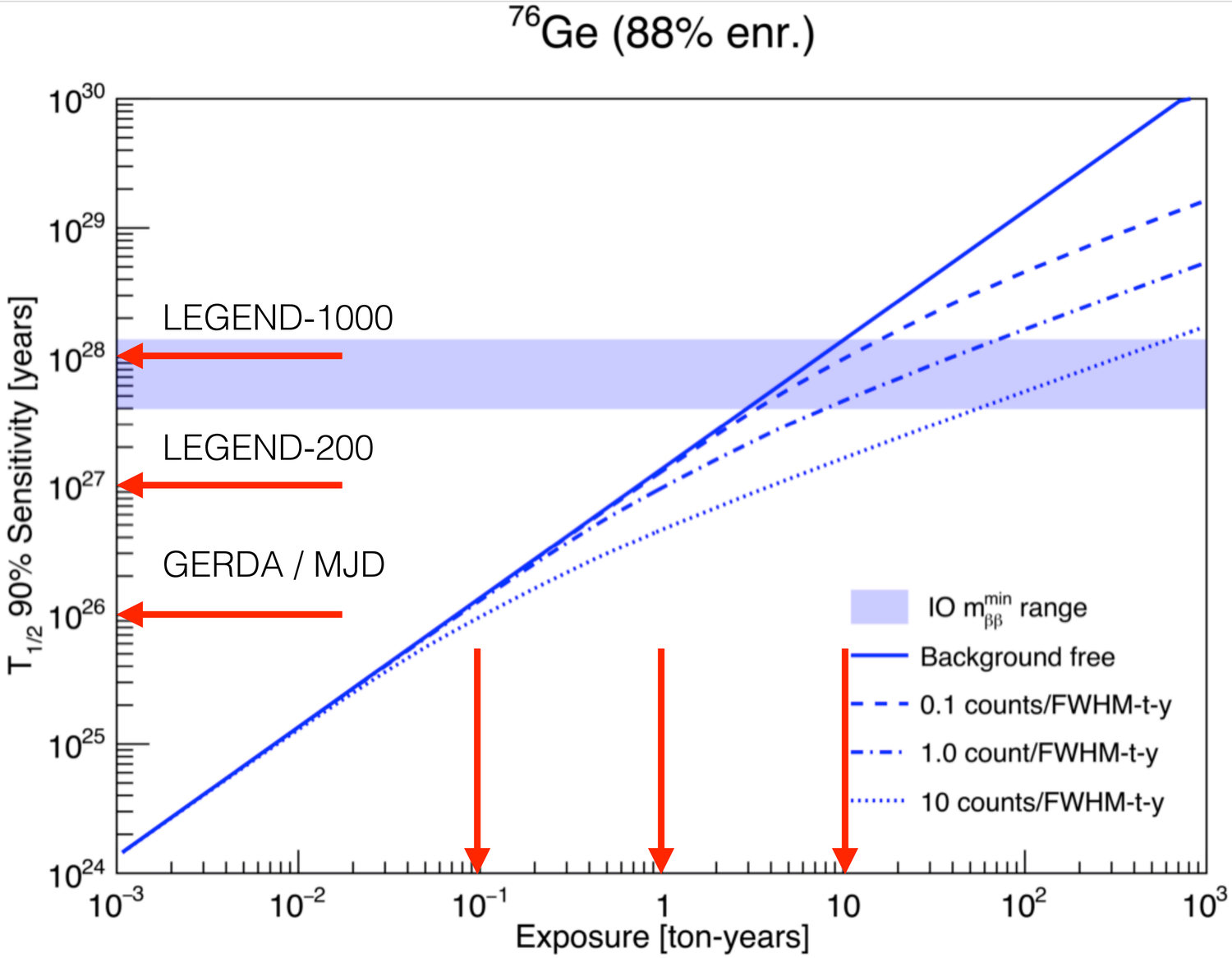


- Detector array: 1 t of ^{76}Ge(enr)
- Separate arrays, each payload ~ 200 - 250 kg
- Exposure: 10 t yr
- Sensitivity: > 10^{28} yr
- Background target: < 0.1 cts / (FWHM t yr)
- Location: TBD (studies concerning cosmogenic background from ^{77m}Ge onging)
- Potential to use depleted underground Ar is investigated (^{42}Ar background)
  → *divide LAr volume into small depleted volumes surrounding detectors and large natural LAr volume*
- Many R&D efforts → very high mass detectors, ...

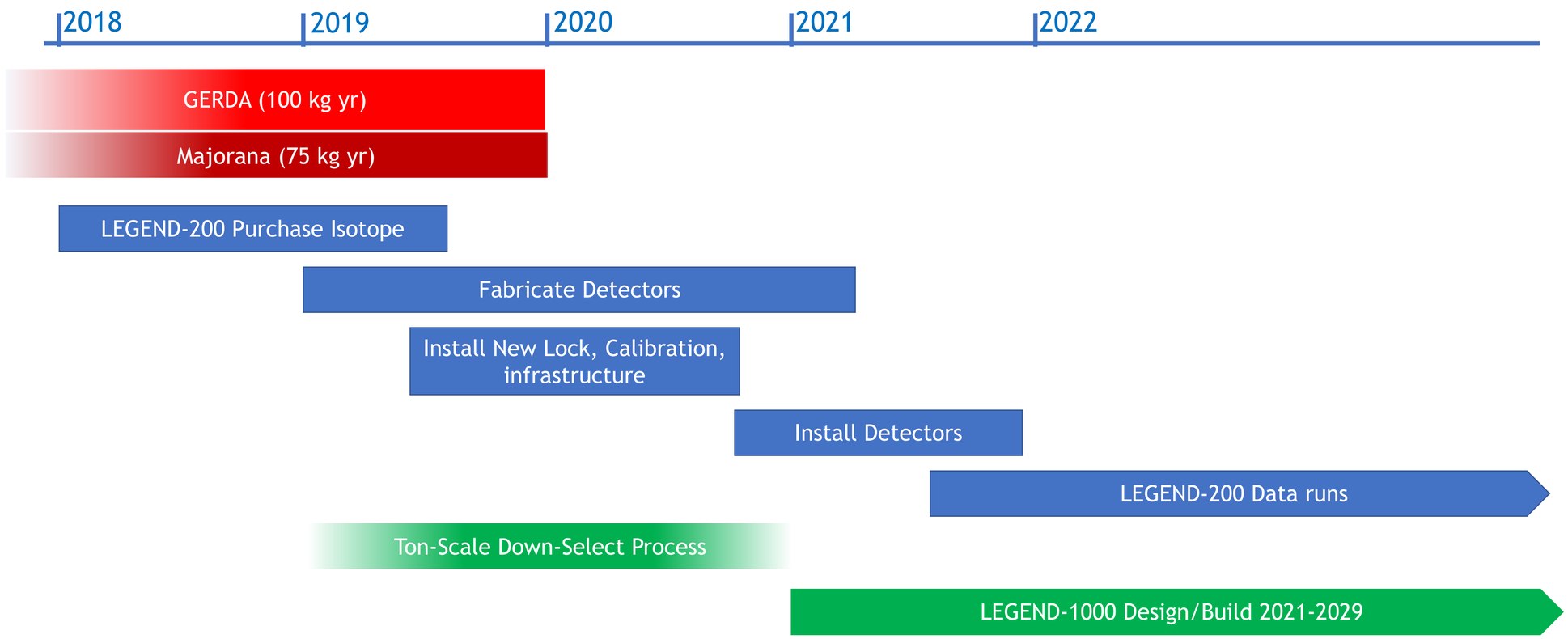
LEGEND - Discovery Potential



LEGEND - Exclusion Sensitivity



LEGEND - Schedule



Conclusions & Outlook

- Discovery of $0\nu\beta\beta$ would have far-reaching consequences in particle physics

  → $\nu = \bar{\nu}$ / Lepton Number Violation

- The next generation of $0\nu\beta\beta$ decay experiments will require reduced backgrounds and increased detector mass
- ^{76}Ge detectors have demonstrated the lowest backgrounds and best energy resolution

  → well suited technology for ton-scale $0\nu\beta\beta$ experiment

- LEGEND will build upon the success of MJD and GERDA

  → pursue a staged approach: starting with 200 kg (LEGEND-200) and gradually increasing (LEGEND-1000)

- Funding for LEGEND-200 almost secured, first orders for additional detectors placed!
- Design studies and R&D for LEGEND-1000 ongoing

Acknowledgements

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Thank you for your attention!