Search for neutrinoless double-beta decays in ^{76}Ge in the LEGEND experiment

Large Enriched
Germanium Experiment
for Neutrinoless ββ Decay

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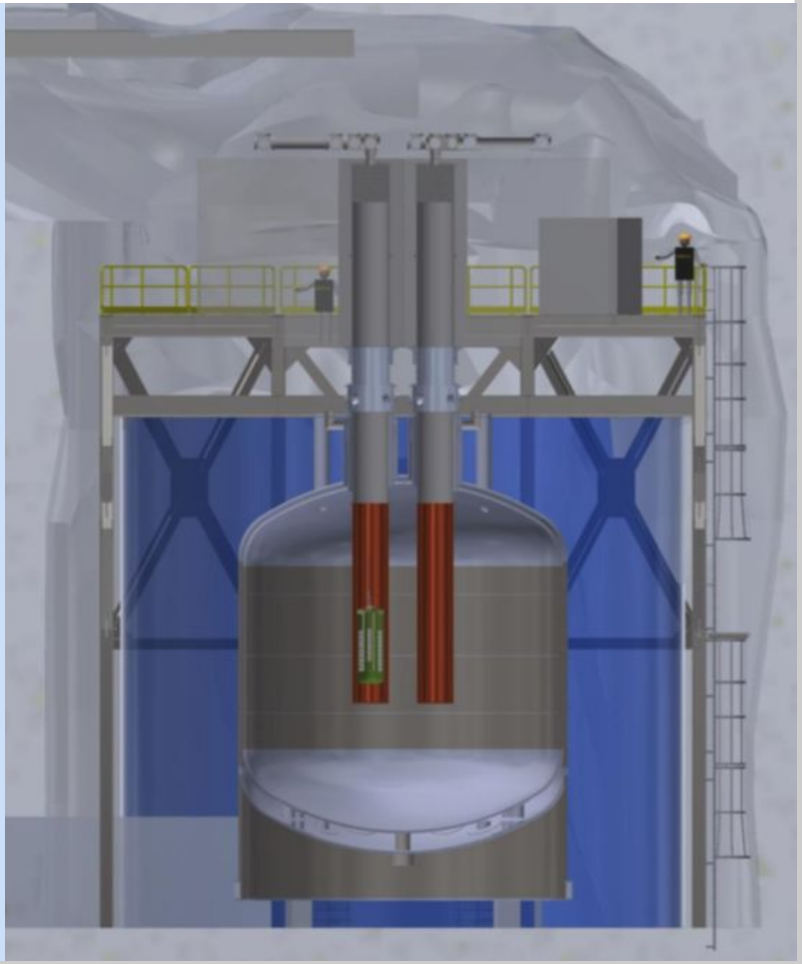
on behalf of the LEGEND collaboration

PPC 2022

08.06.2022

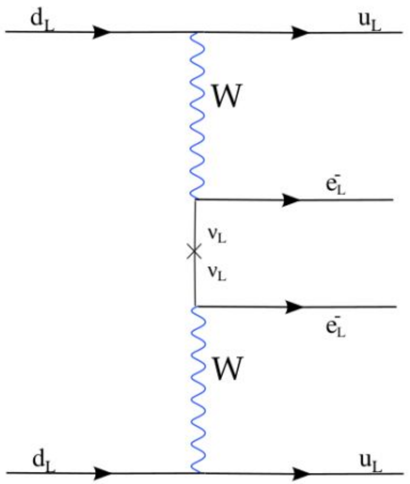


Double beta-decay without neutrinos

The neutrinoless double beta (0νββ) decay is a hypothesized nuclear transition.

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

0νββ can be mediated by the exchange of two massive Majorana neutrinos.



$$\frac{1}{T^{0\nu}_{1/2}} = |M^{0\nu}|^2 G^{0\nu}(Q,Z) \left(\frac{\langle m_{\beta\beta} \rangle}{m_e} \right)^2$$

nuclear matrix element

phase space factor

$$\langle m_{\beta\beta} \rangle = \left| \sum_i U_{ei}^2 m_i \right|$$

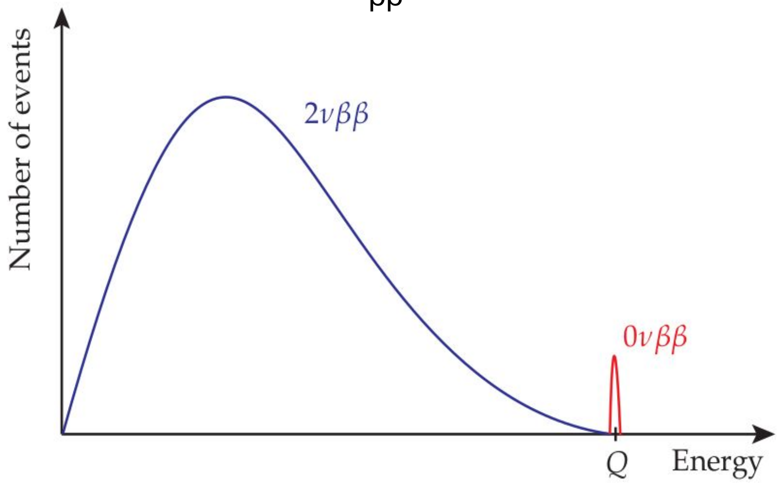
effective neutrino mass

Motivation for 0νββ decay searches

- Establish **lepton number violation** (LNV) → ΔL=2
- Best way to determine **if neutrino is its own antiparticle** ($\nu = \bar{\nu}$)
- Important to understand the **origin of the neutrino mass**
- Probe the **absolute neutrino mass scale** and **neutrino mass ordering**
- Provide important **input to cosmology**

0νββ signature and half-life

$Q_{\beta\beta}$ = 2039 keV for ^{76}Ge



0νββ signal = monoenergetic peak

$$T_{1/2}^{0\nu} \propto \begin{cases} \epsilon \cdot a \cdot \sqrt{\dfrac{M \cdot t}{BI \cdot \Delta E}} & \text{with background} \\ \epsilon \cdot a \cdot M \cdot t & \text{without background} \end{cases}$$

ϵ: detection efficiency

a: isotopic abundance

M: total detector mass

t: run time

BI: background index

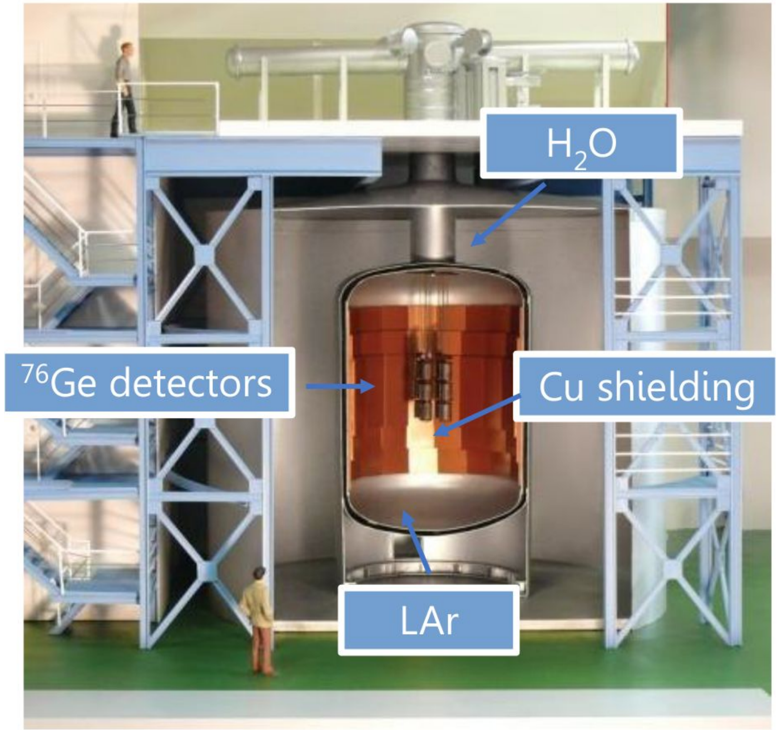
ΔE: energy resolution at $Q_{\beta\beta}$

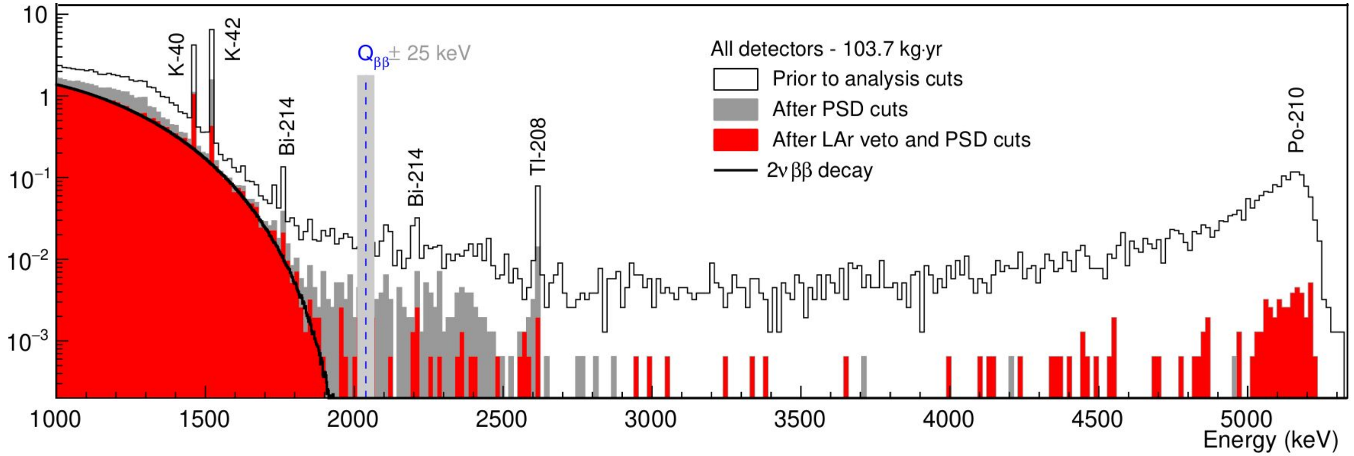
low background level and good energy resolution

GERDA experiment

- The GERDA experiment was proposed in 2004 as a new ^{76}Ge double-beta decay experiment at LNGS (Italy).
- Up to **41 enriched ^{76}Ge** detectors deployed from Dec 2015 to Dec 2019.

- The array of germanium detectors was placed in a liquid argon (**LAr**) cryostat.
- A tank filled with 590 m^3 pure water surrounded the cryostat.
- The water tank was equipped with PMTs detecting Cherenkov light.





	Goals	*Achievements*
Background	10^{-3} cts/(keV kg yr)	$5.2^{+1.6}_{-1.3}\cdot 10^{-4}$ cts/(keV kg yr)
Exposure	≥ 100 kg yr	103.7 kg yr *phase II*
Sensitivity	$T^{0\nu\beta\beta}_{1/2} \geq 10^{26}$ yr	$T^{0\nu\beta\beta}_{1/2} \geq 1.8\cdot 10^{26}$ yr

[GERDA , PRL 125 (2020) 252502]

MAJORANA DEMONSTRATOR experiment

- MAJORANA DEMONSTRATOR experiment is still operating at Sanford Underground Research Facility (SURF) but it finished its ^{76}Ge program in 2021.
- Array of 44.1 kg P-type Point Contact (PPC) detectors
- ~30kg detectors are up to 88% ^{76}Ge enrichment
- High-purity electroformed copper cryostat
- Ultra-clean detector near-parts

[MAJORANA, PRC100, 025501 (2019)]

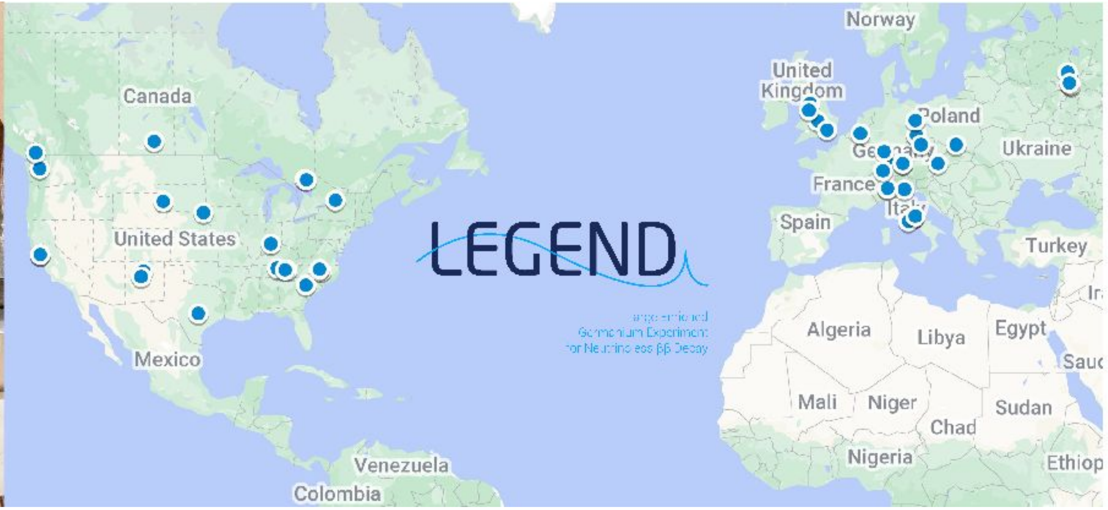
Achievements

- $\Delta E = 2.5$ keV FWHM at $Q_{\beta\beta}$ (0.13%)
- $BI = 4.7 \times 10^{-3}$ cts/(keV kg yr)
- $T_{1/2} > 2.7 \times 10^{25}$ yr (90%C.L.)
- $|m_{\beta\beta}| < 200 - 433$ meV

LEGEND collaboration

LEGEND = **L**arge **E**nriched **G**ermanium **E**xperiment for **N**eutrinoless Double-Beta **D**ecay

260 members, 50 institutions, 11 countries Collaboration formed in October 2016



SNOLAB
Roma Tre
Duke Univ.
Univ. Zurich
Queens Univ.
Padova Univ.
INFN Padova
Laurentian Univ.
Univ. Tennessee
Univ. of Indiana
Comenius Univ.
Lancaster Univ.
Univ. of Regina
Univ. Liverpool
Tennessee Tech
Univ. of Warwick.
Jagiellonian Univ.

Simon Fraser Univ.
Univ. New Mexico
Univ. Texas, Austin
Univ. Washington
Univ. Tuebingen
Tech. Univ. Munich
Oak Ridge Natl. Lab.
Univ. South Dakota
South Dakota Mines
Univ. of North Carolina
Univ. of South Carolina
L'Aquila Univ. and INFN
Gran Sasso Science Inst.
Lab. Naz. Gran Sasso
Univ. College London
Los Alamos Natl. Lab.
Tech. Univ. Dresden

Joint Res. Centre, Geel
Lawrence Berkeley Natl. Lab.
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Milano Univ. and INFN
Triangle Univ. Nuclear. Lab.
Max Planck Inst., Heidelberg
Inst. Nucl. Res. Russ. Acad. Sci.
Natl. Res. Center Kurchatov Inst.

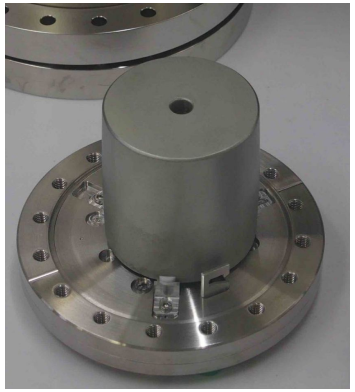
LEGEND mission:

> *“The collaboration aims to develop a phased Ge-76 based double beta decay experimental program with discovery potential at a half-life significantly longer than 10^{28} years, using existing resources as appropriate to expedite physics results”.*

Germanium detectors

Why germanium?

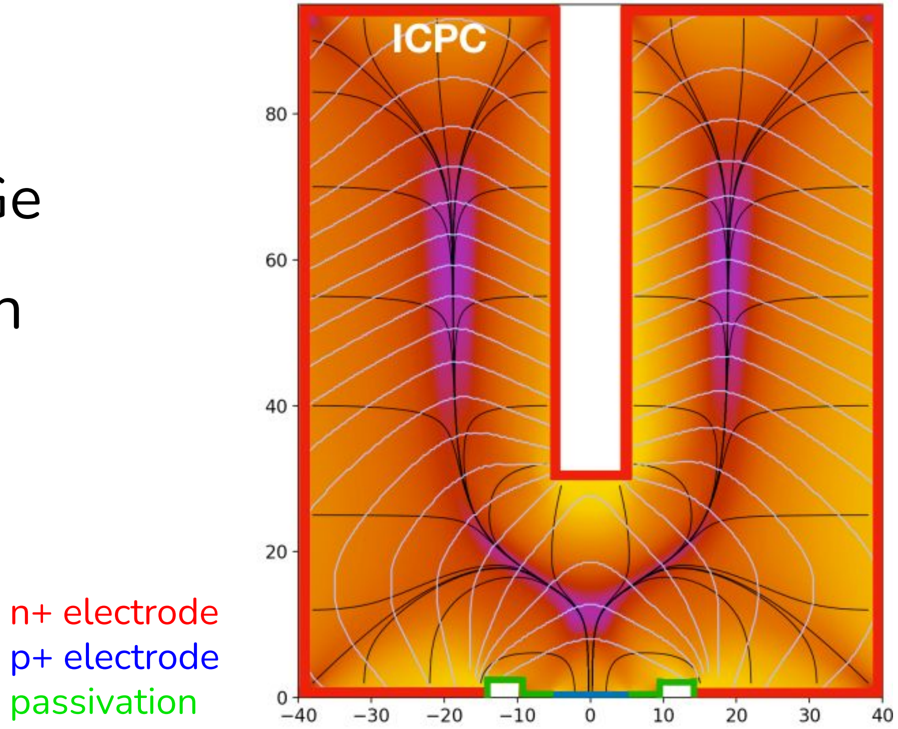
- High detection efficiency (detector = ββ source)
- Best proved energy resolution at the Q-value
- High pulse shape analysis capabilities
- Lowest background per FWHM energy resolution in the field
- Well-established technology



new

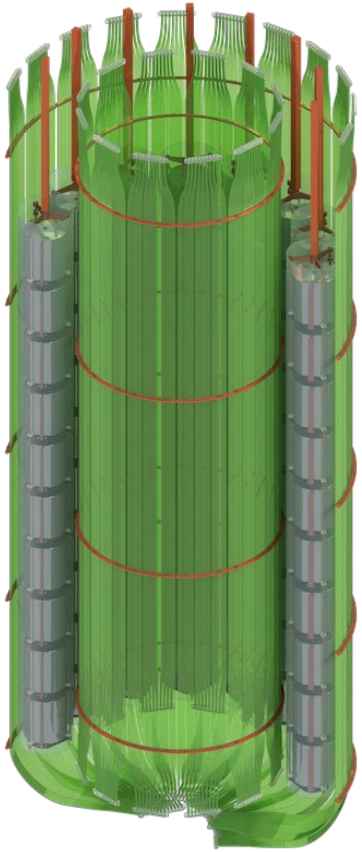
Inverted Coaxial Point Contact (ICPC) detectors:

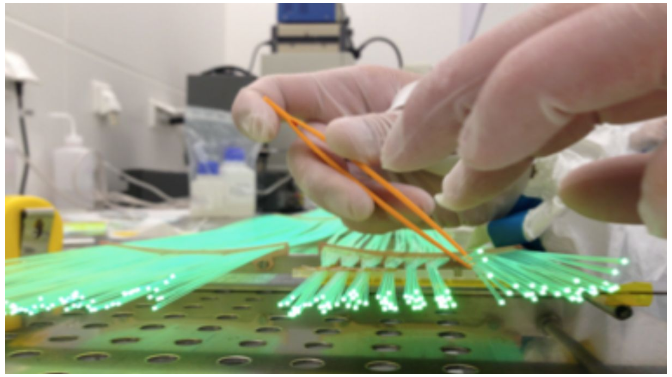
- Enriched detectors, 92% of detector material is ^{76}Ge
- Excellent resolution and pulse shape discrimination
- Significantly larger w.r.t. BEGe or PPC (up to 3 kg)
- Less channels, less background
- Better surface to volume-ratio (30-40%)



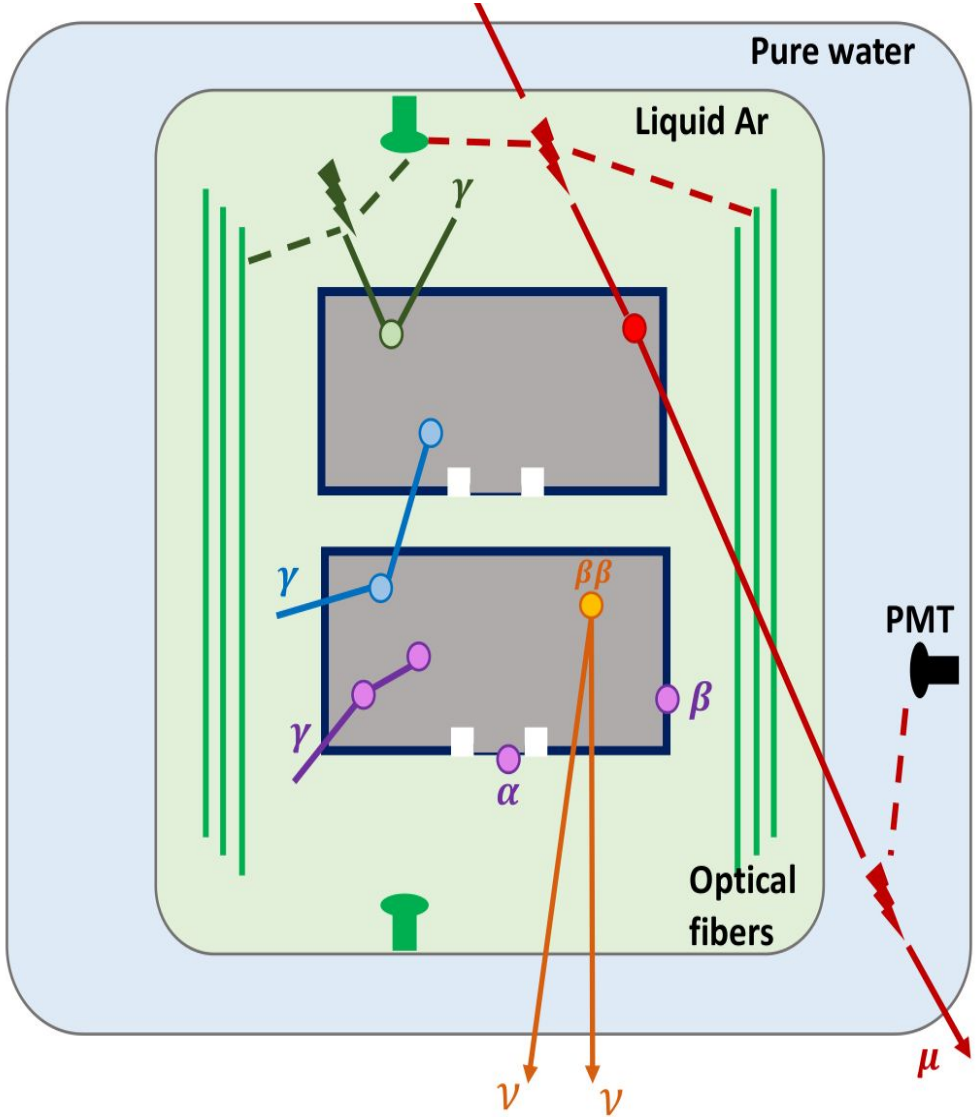
Liquid Argon veto and monitoring

- The LAr scintillation-light detector acts as an active shield from any backgrounds source in the materials surrounding the array
- It suppresses background events that deposit energy in the Ar.
- It is read out via wavelength-shifting (WLS) fibers coupled to SiPMs.
- It has proven successful in GERDA and is being implemented in LEGEND-200 as two-barrel geometry.

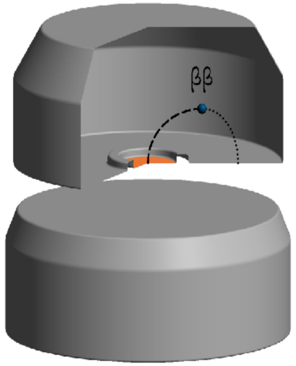




Active background reduction tools



- ββ decay signal: single-site event energy deposition in a 1 mm^3 volume



- Anti-coincidence with the muon veto
- Anti-coincidence between detectors (cuts multi-site)
- Active veto using LAr scintillation (LAr Veto)
- Pulse shape discrimination (PSD)

LEGEND-200

First Stage

- Upgrade of the existing infrastructure of GERDA experiment
- Reduction of the BI of a factor 5 w.r.t. GERDA Phase II goal
- ~200 kg of detector mass: 35 kg from GERDA + 30 kg from MJD + 140 kg which are new, distributed to 14 strings
- Total planned exposure 10 times larger than GERDA, up to 1000 kg yr
- Expected energy resolution at $Q_{\beta\beta}$ equal to 2.5 keV FWHM

L200 Goals

half-life discovery sensitivity	10^{27} yrs
mass sensitivity	30-70 meV
background index	$2 \cdot 10^{-4}$ cts/(keV · kg · yr)

[LEGEND, AIP 894:020027 (2017)]

LEGEND-1000

Further Stage

- Staged installation of 1000 kg detector mass (ICPC)
- Detector strings immersed in radiopure underground LAr (UGLAr)
- Background reduction of a factor 100 w.r.t. GERDA Phase II goal
- Location to be defined (SNOLAB or LNGS)

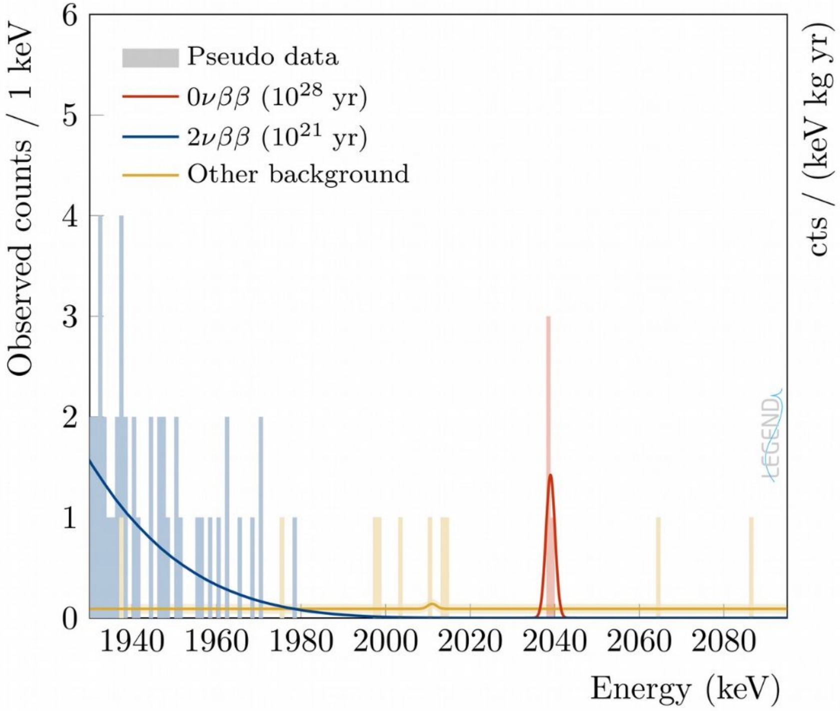
L1000 Goals

half-life discovery sensitivity	10^{28} yrs
mass sensitivity	10-20 meV
background index	10^{-5} cts/(keV · kg · yr)

[LEGEND, arxiv:2107.11462 (2021)]

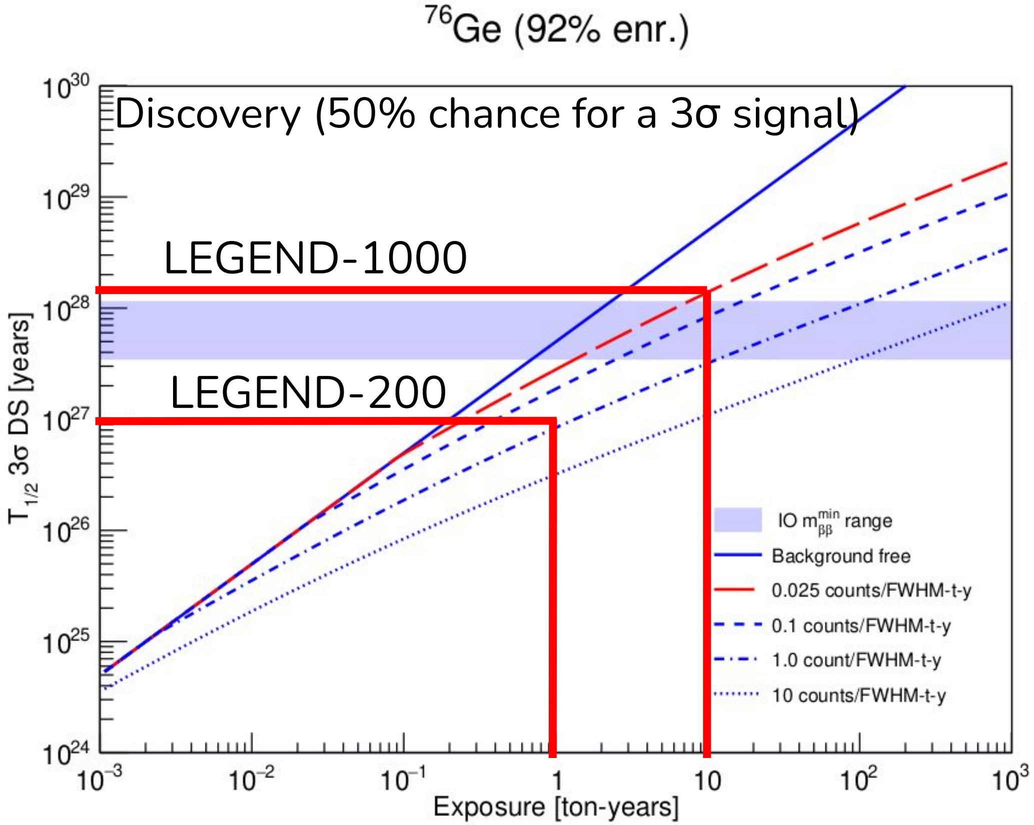
LEGEND prospects

- Flat background - no γ peaks close to $Q_{\beta\beta}$
- Unambiguous discovery of 0νββ achievable even with a handful of counts - signal will be visible to the eye



Bkg Index
cts/(FWHM·ton·yr)

LEGEND-200	0.6
LEGEND-1000	0.025



Conclusion

- **LEGEND** will search for 0νββ decay in ^{76}Ge via 2 stages.
- LEGEND-200 is currently being commissioned; data taking test with the first ~60kg of HPGe detectors is ongoing.
- The next stage LEGEND-1000 aims to fully cover inverted hierarchy
- More about LEGEND in https://legend-exp.org

...stay tuned!

Backup

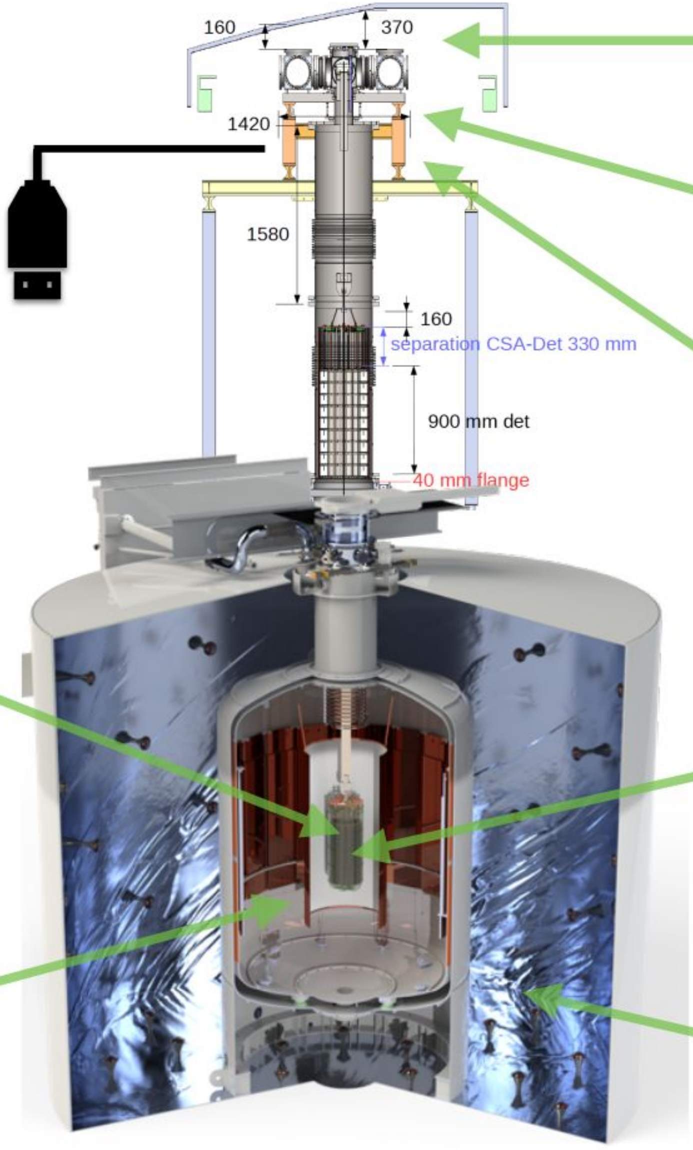
Upgrades

Electronics:
- New low-mass front-end
- Custom-made readout

Software:
- Two new analysis pipelines based on Python and Julia

Detectors:
- 33 PPC's, 28 BEGe's, and 42 ICPC's ready to use
- 3 BEGe's re-characterized for aging effects

Liquid argon:
- Emptied and refilled
- New LAr instrumentation for larger detector array
- LLAMA installed
- Continuous purification



Clean room:
- Height extended

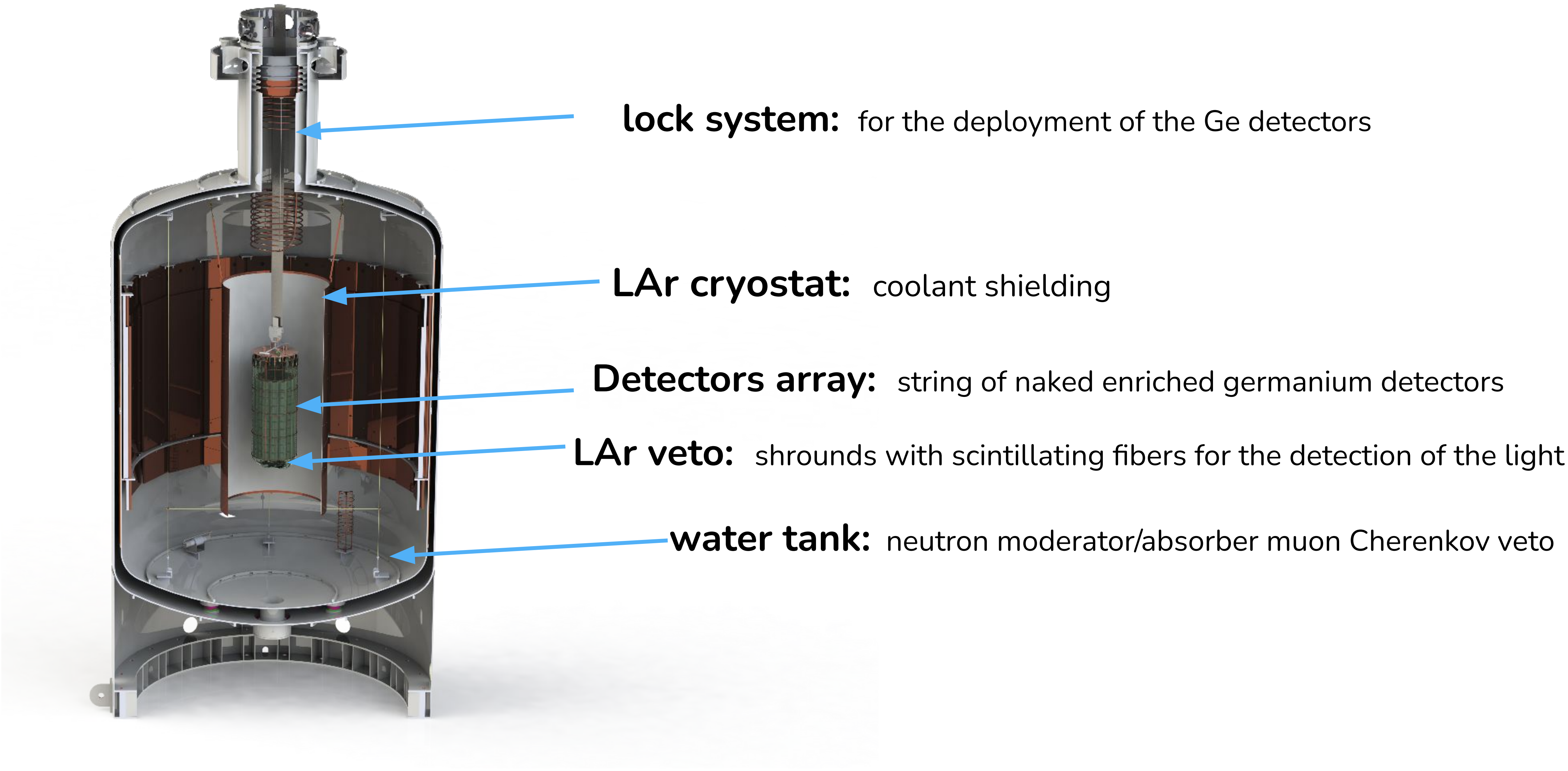
Lock system:
- Built and installed
- Currently commissioned

Calibration sources:
- Custom build ^{228}Th sources
- New deployment system

Detectors modules:
- Electroformed copper
- PEN holders produced
- New cables

Water tank:
- Internal maintenance
- Damaged PMT exchanged

General layout of LEGEND-200



lock system: for the deployment of the Ge detectors

LAr cryostat: coolant shielding

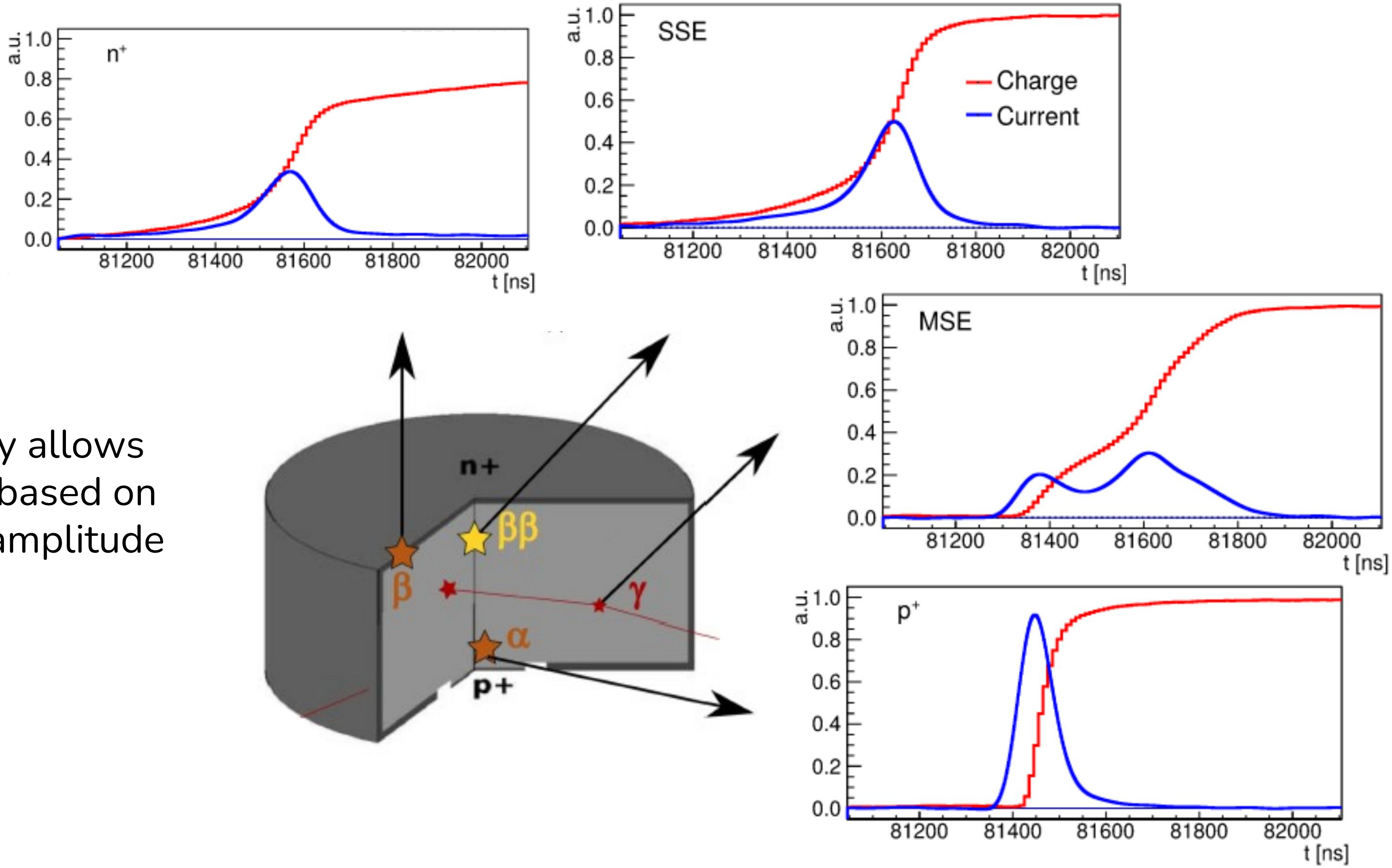
Detectors array: string of naked enriched germanium detectors

LAr veto: shrounds with scintillating fibers for the detection of the light

water tank: neutron moderator/absorber muon Cherenkov veto

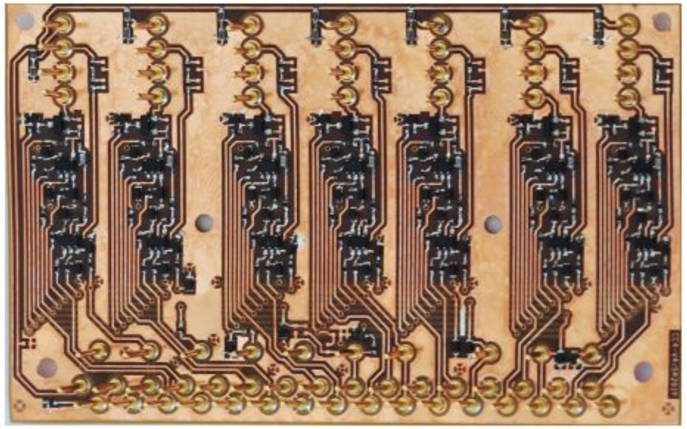
Pulse Shape Discrimination (PSD)

- Point-contact geometry allows for MS event rejection based on pulse shapes, current amplitude over energy (A/E)

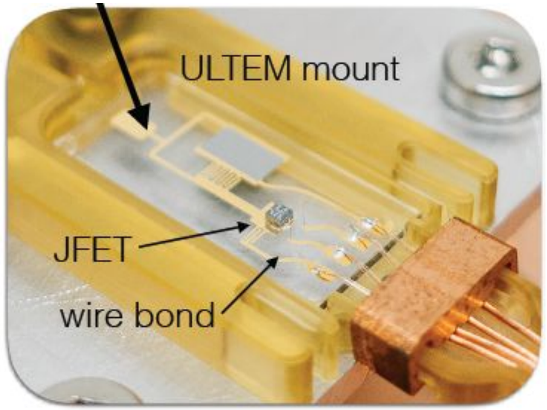


Low-mass front-end electronics

- A combination of the Liquid Argon (LAr) operated preamplifier of Gerda with the ultra-clean Low-Mass Front-End Electronics (LMFE) of the Majorana Demonstrator has been developed. The LMFE couples an amorphous germanium (aGe) feedback resistor (1 – 5 GΩ) to a bare die junction gate field-effect transistor (JFET).

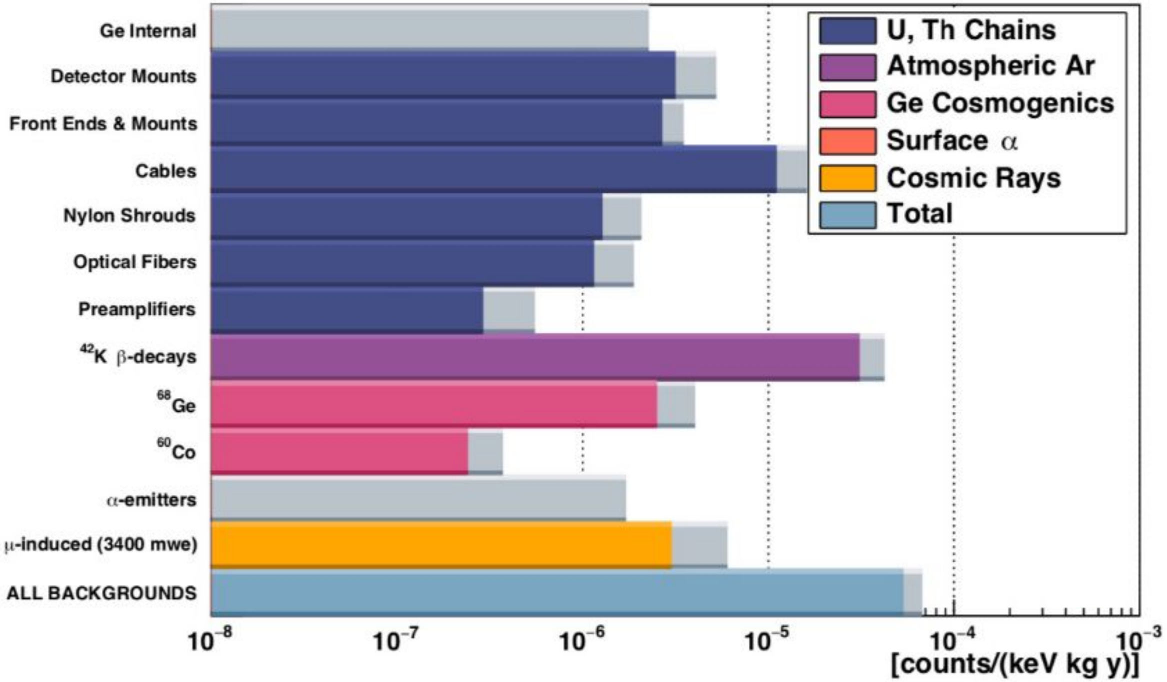


preamplifier operated in LAr

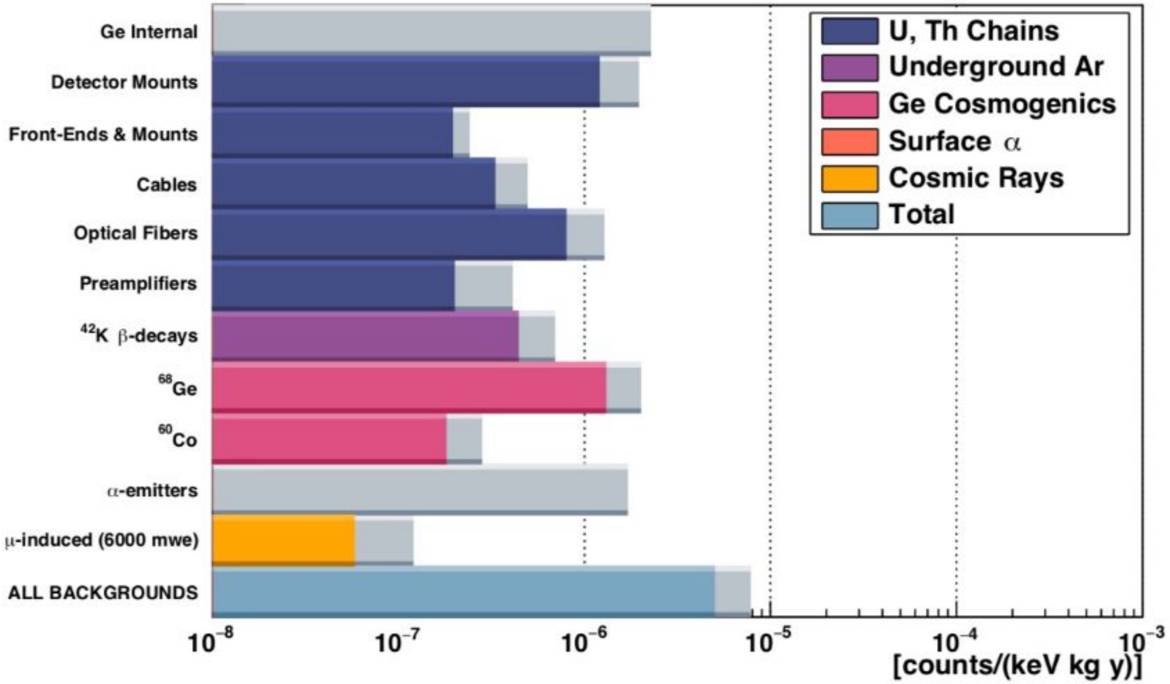


aGe + bare fie JFET LMFE

Backgrounds



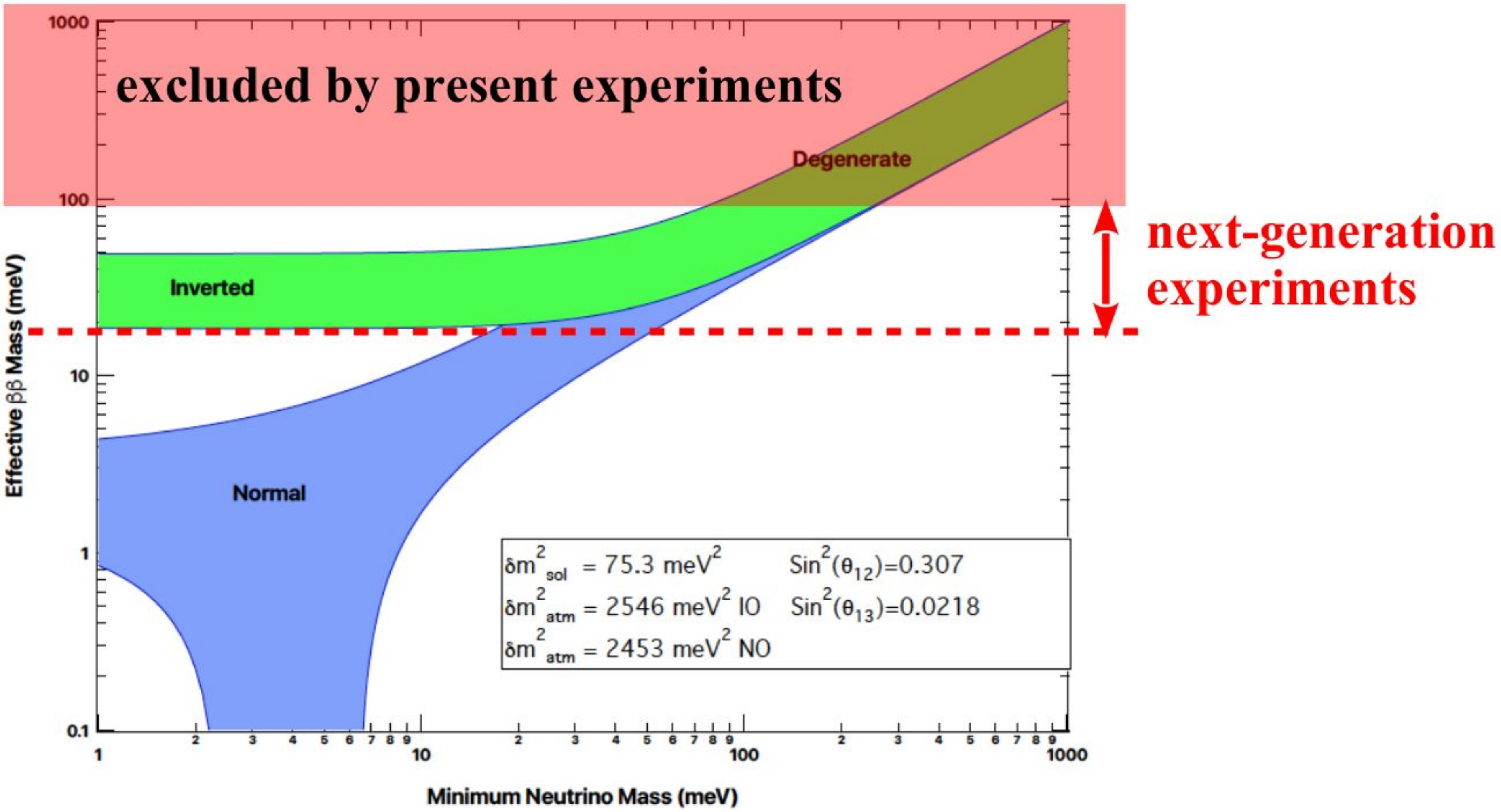
L-200 Background Summary



L-1000 Background Summary

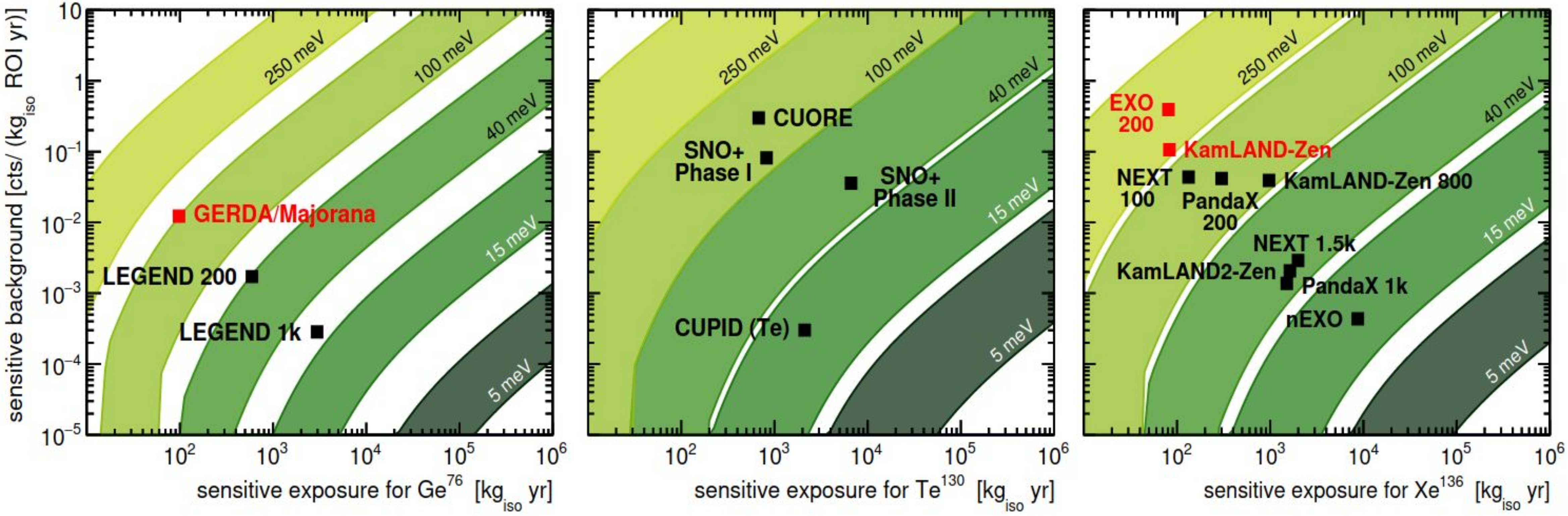
Results and goals

$$\langle m_{\beta\beta} \rangle = \left| \sum_i U_{ei}^2 m_i \right|$$



Discovery sensitivity for ^{76}Ge, ^{130}Te, and ^{136}Xe

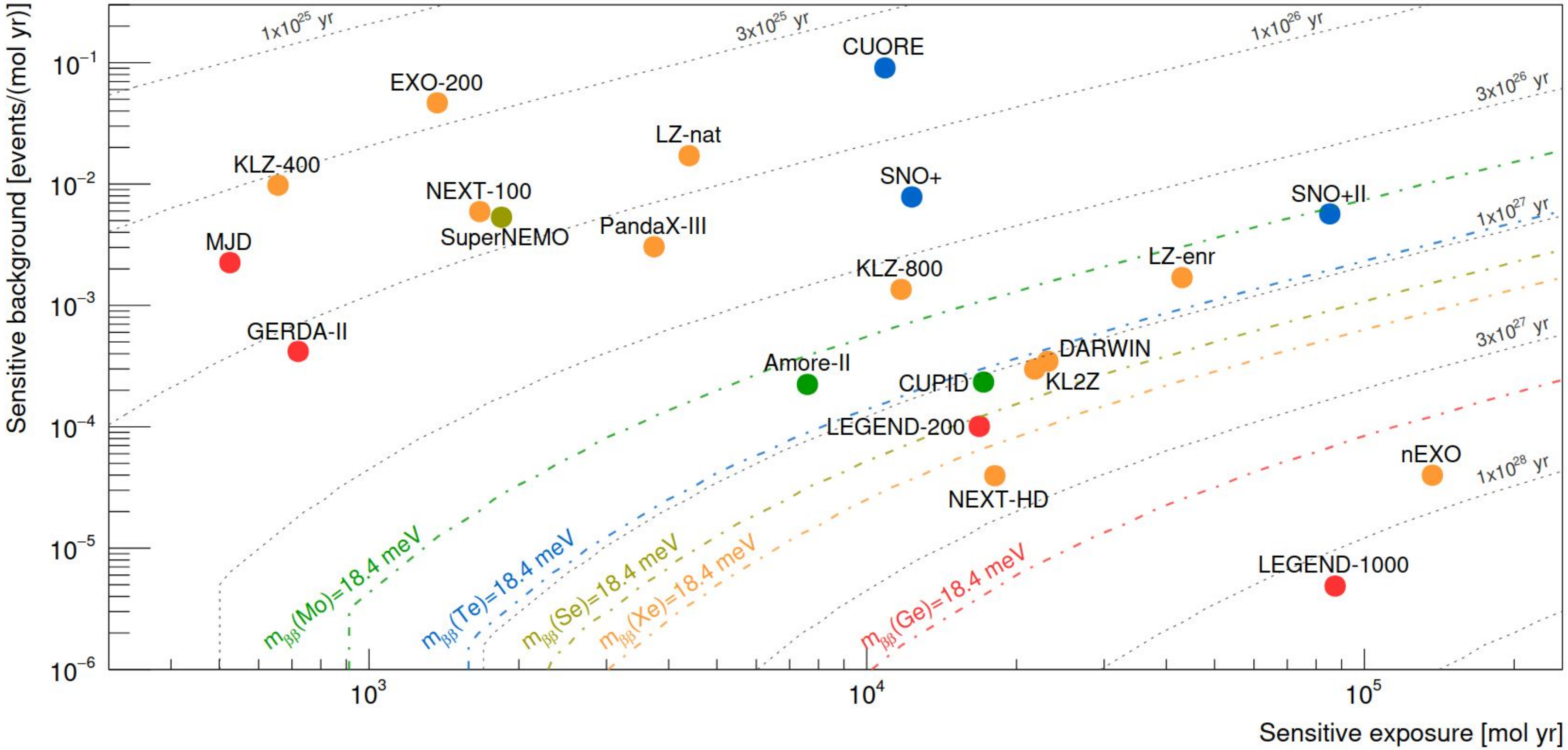
Comparison of rough sensitivity between ongoing & planned experiments



Agostini, Benato, Detwiler, Phys. Rev. D 96 053001 (2017)

Discovery sensitivity

Comparison of rough sensitivity between ongoing & planned experiments

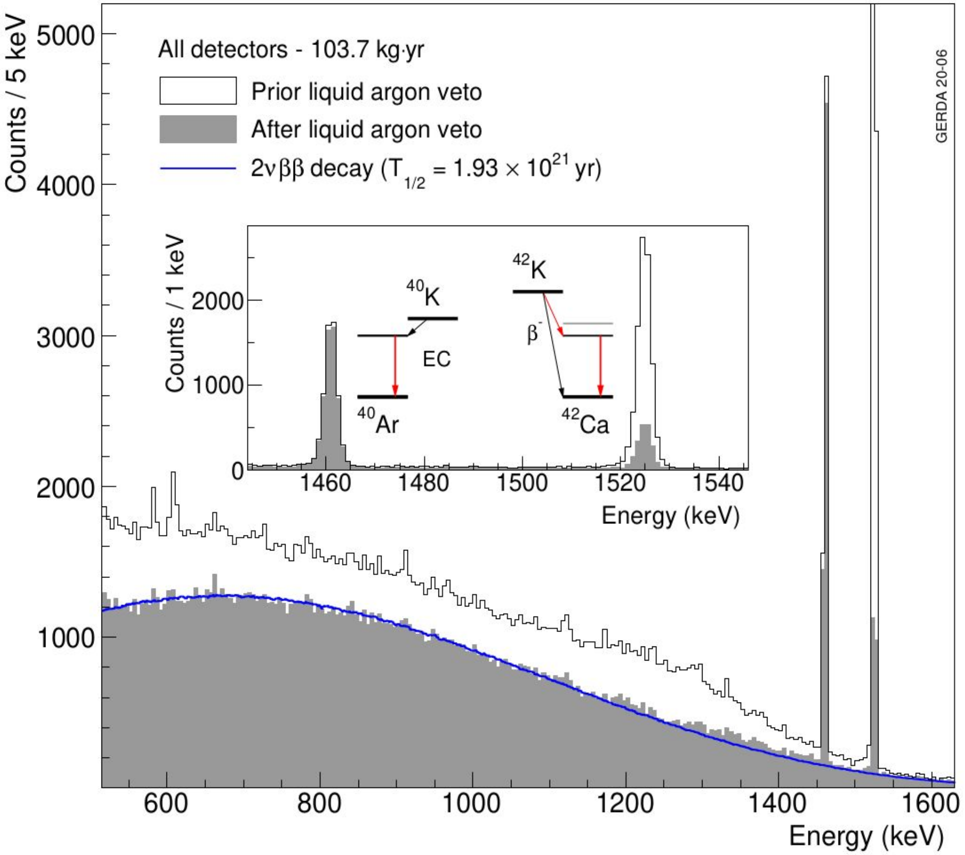


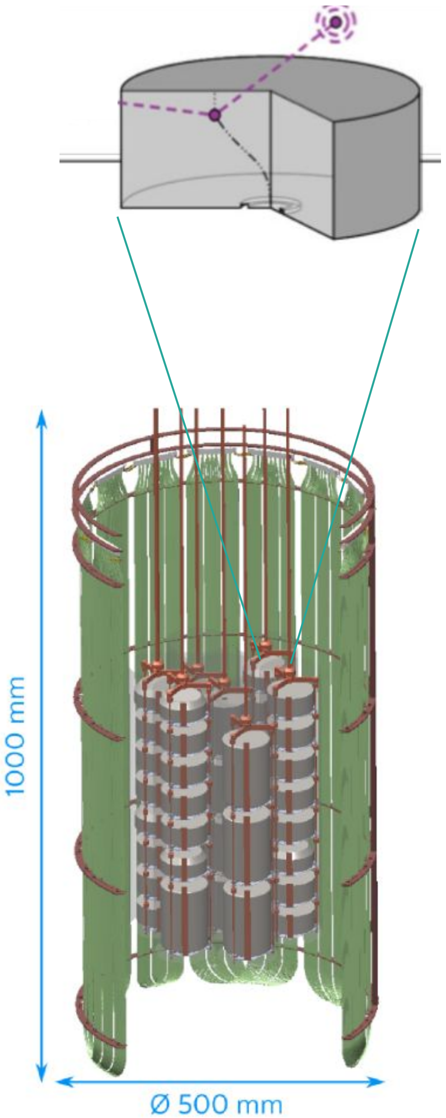
ArXiv:2202.01787

Liquid Argon Veto

- Stable operations over 4 years of data taking:
  - ○ 16 PMts
  - ○ 1.5 km light guiding fibers + SiPM readout
  - ○ Vetoes events in coincidence with Germanium

- Acceptance (0νββ) ~ 98%
- Crucial role in background suppression after PSD: ÷ 6 in the ROI

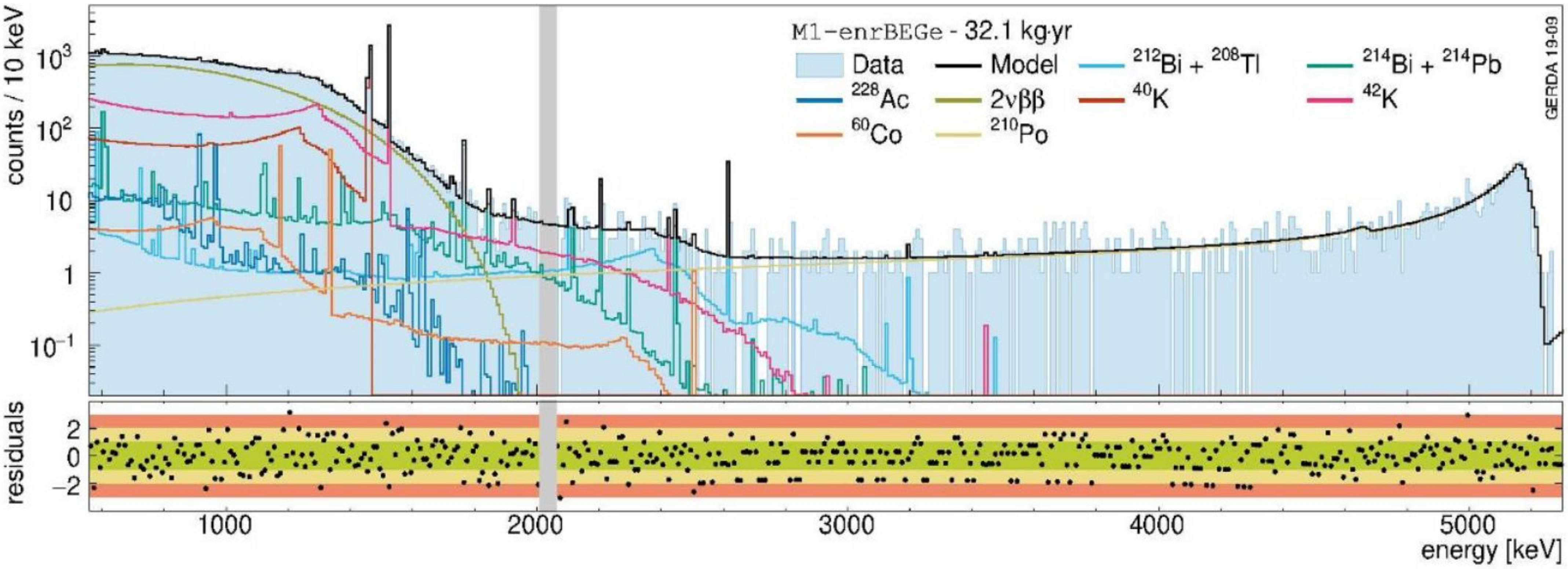




[GERDA, European Phys J C 78 (2018), 388]

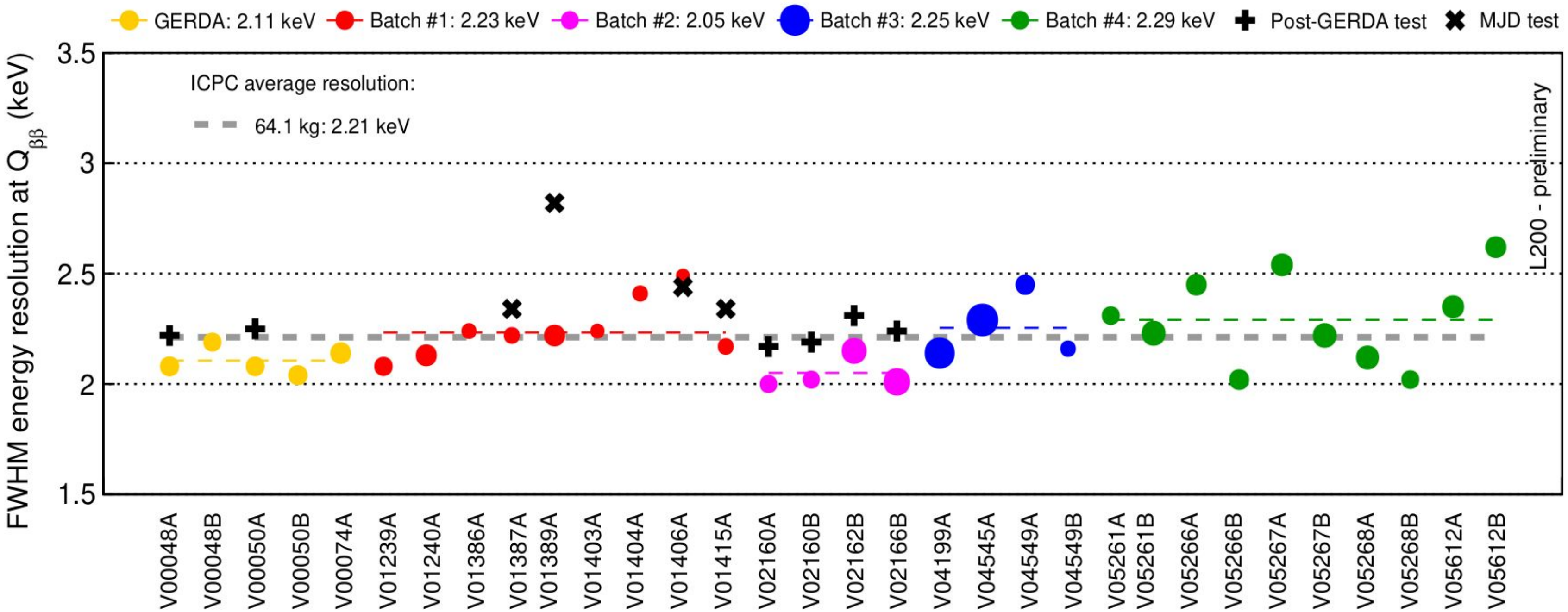
Background model

[GERDA , J High Energy Phys, 2020 (2020), no. 3, 139]



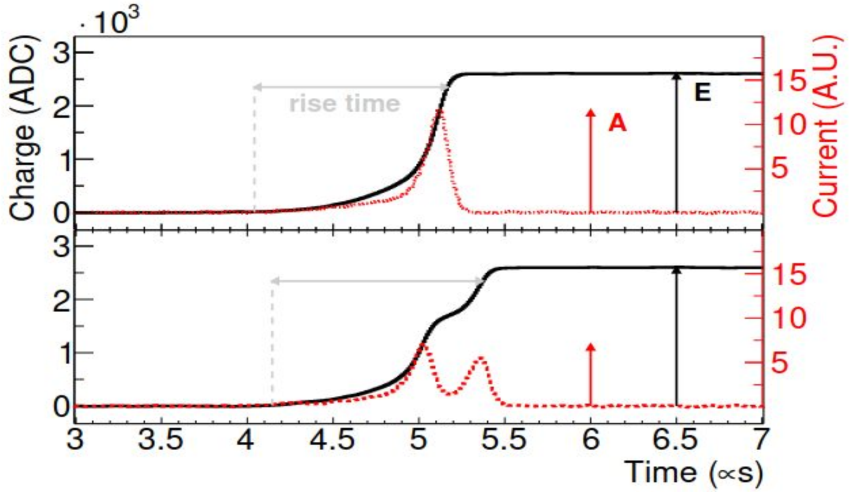
All the background components are well known

Energy resolution and PSD performance



resolution

- No resolution degradation seen in ICPCs
- Well-understood peak shape, energy scale stability, and linearity (better than 0.1%) lead to improved confidence in results



pulse shape discrimination

- The multi-site events (bkg) can be rejected looking at pulse shapes
- Compton continuum γ background reduced (~50%)
- α and β events reduced (≥ 99%)