LEGEND-200

Large Enriched Germanium Experiment for Neutrinoless ββ Decay

Riccardo Brugnera

LEGEND-200

- L-200 uses the GERDA infrastructure (cryostat, clean room, water plan, ...) at LNGS
- new elements: part of the enriched Ge detectors, cables, LAr veto, FE electronics, DAQ
- **February 2020**: L-200 took over the GERDA infrastructure; **Nov 2021**: start commissioning
- **March 2023**: start of the physics run with ~140 kg of enriched detectors

- **L-200 Background Index goal at $Q_{\beta\beta}$:**

  $2 \cdot 10^{-4}$ cts/(keV·kg·yr)
- $T^{0\nu}_{1/2}$ after **1 ton·yr** of exposure:

  $9.7 \cdot 10^{26}$ years (99.7% CL discovery)

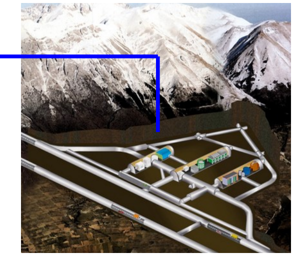
  $1.5 \cdot 10^{27}$ years (90% CL exclusion)
- **$m_{\beta\beta}$:**

  33 – 78 meV (99.7% CL discovery)

  27 – 64 meV (90% CL exclusion)

LEGEND-200: the experiment

Clean room lifted



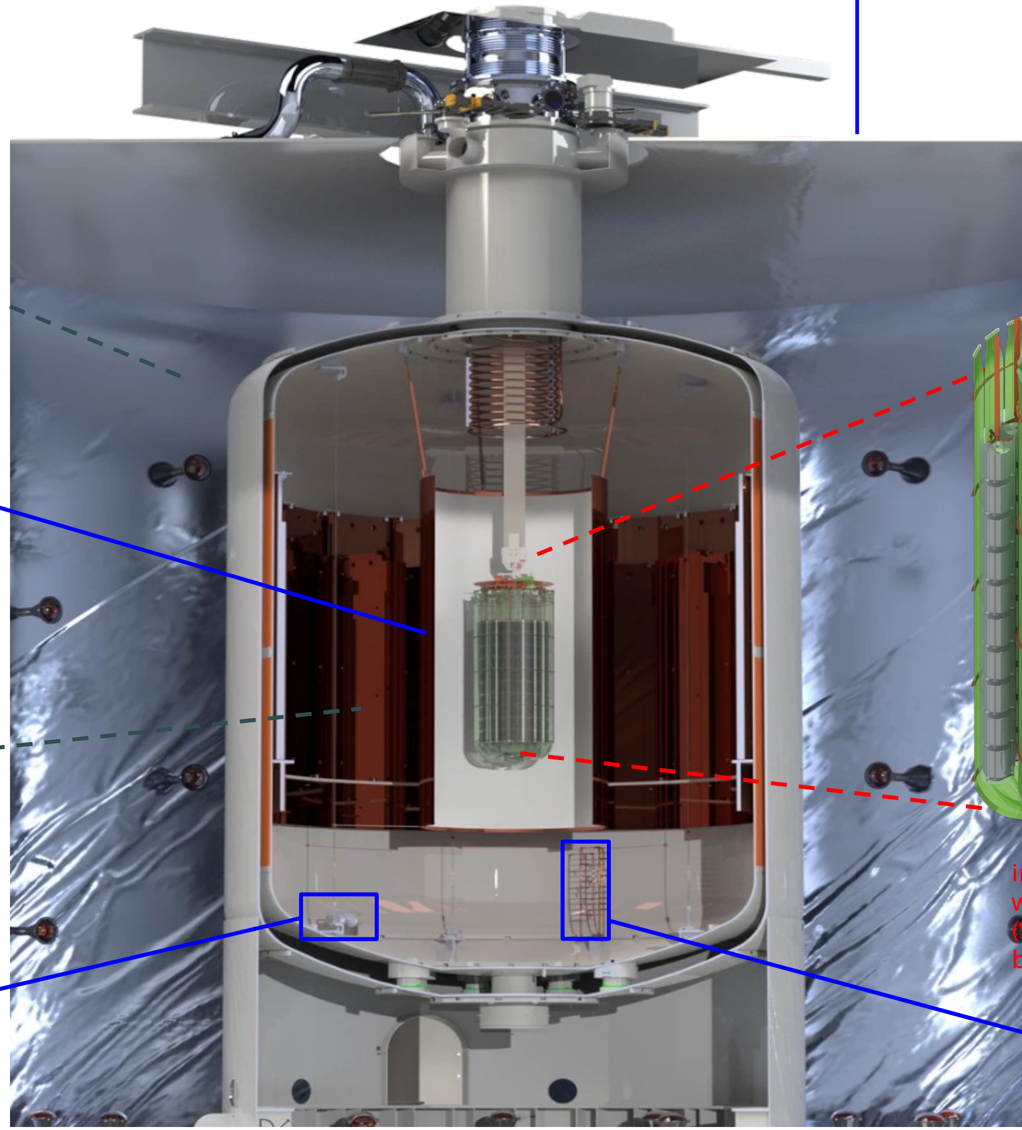
LNGS
Hall A
3600
m.w.e.

Water Cherenkov muon veto

Teflon Reflector for better light collection

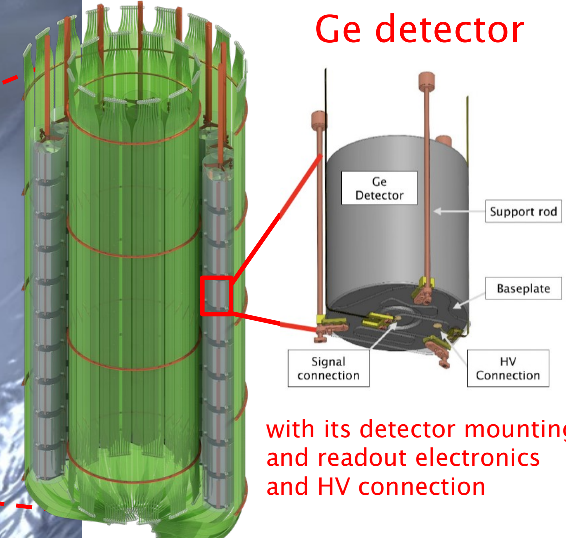
Copper lined stainless steel cryostat

LAr purification



LAr veto

Ge detector



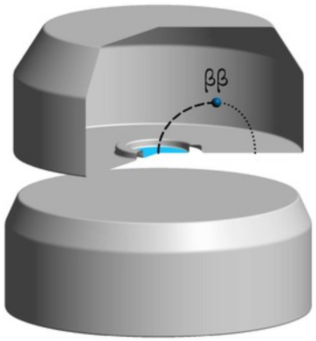
with its detector mounting and readout electronics and HV connection

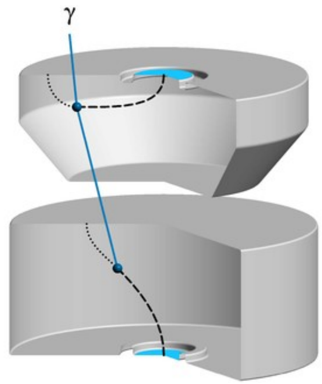
inner & outer fiber barrels with silicon photomultipliers (SiPM) readout at top & bottom

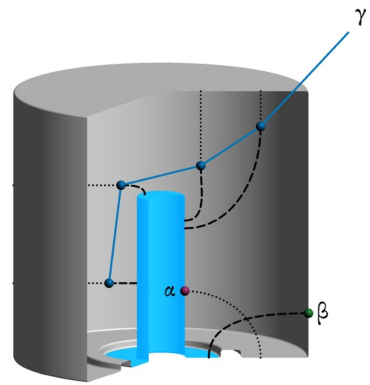
LLAMA
LAr quality monitoring

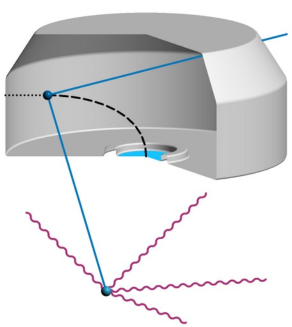
active background reduction tools

LEGEND









Single-site event topology (SSE)

- 2νββ
- 0νββ

Detector multiplicity

- scattered events

Pulse Shape Discrimination (PSD)

- scattered multi-site events (MSE)
- surface events

LAr-anti coincidence

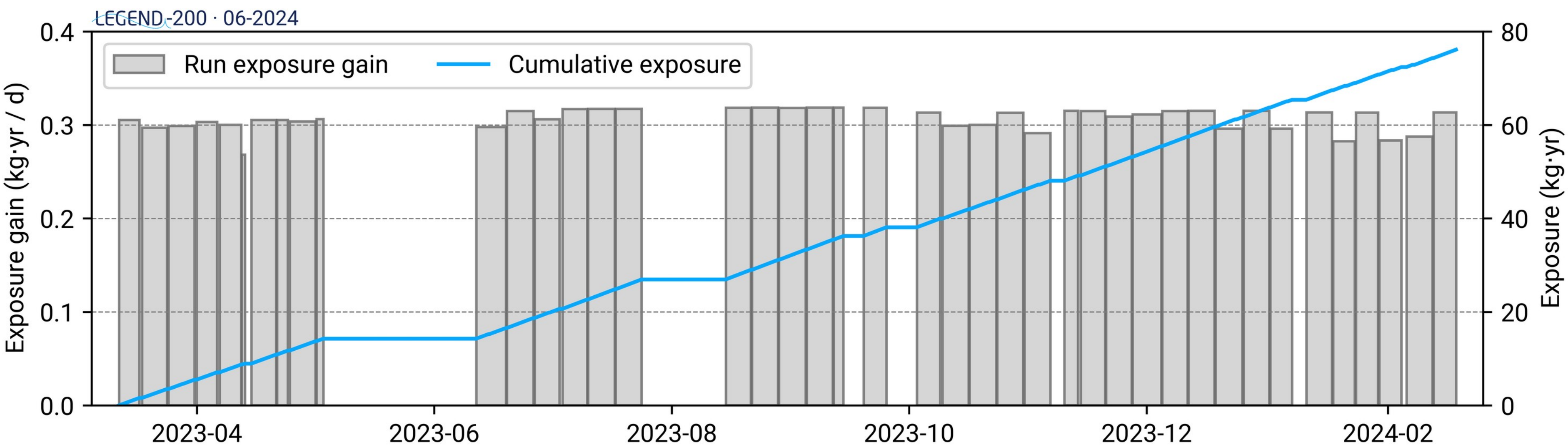
- intrinsic backgrounds
- Ge cosmogenics

Water Cherenkov anti-coincidence

- muons

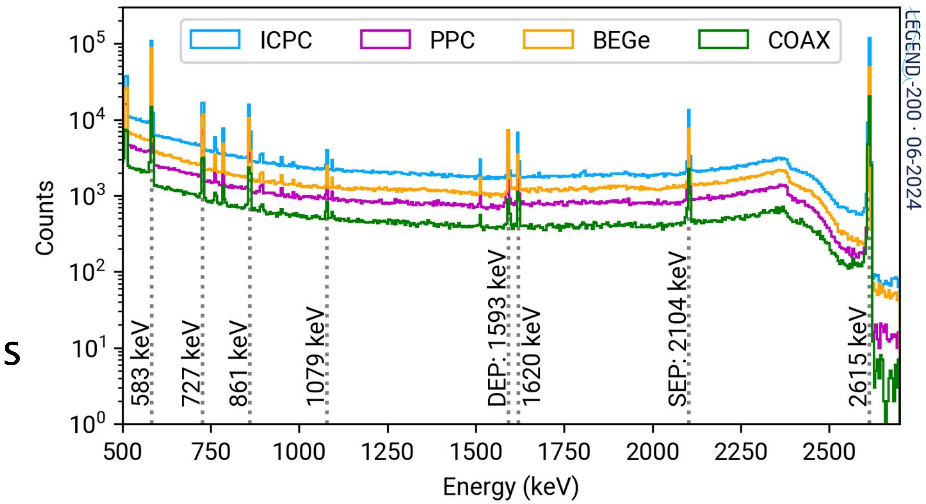
Collected Data

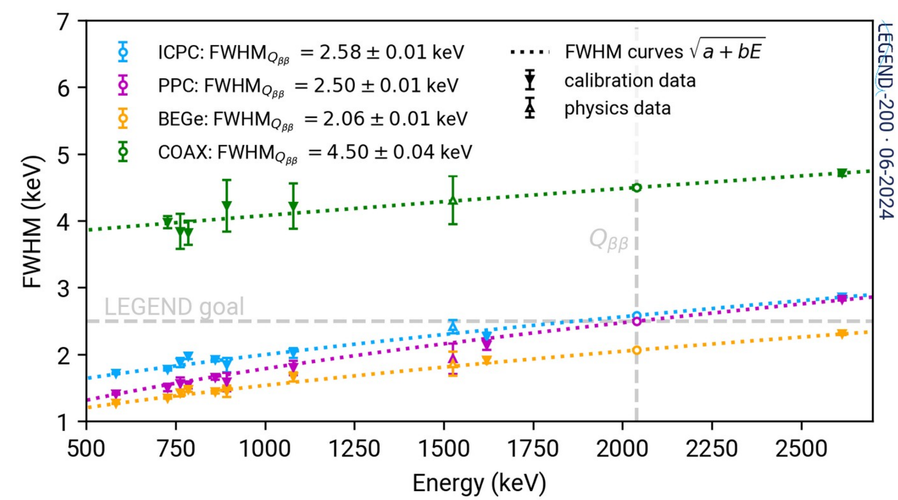
- **Exposure** accumulated over **1 year**:
  - **Silver**: background and performance characterization: **76.2 kg·yr**
  - **Golden**: 0νββ data set: **48.3 kg·yr** (using: ICPC, BEGe, PPC detectors)



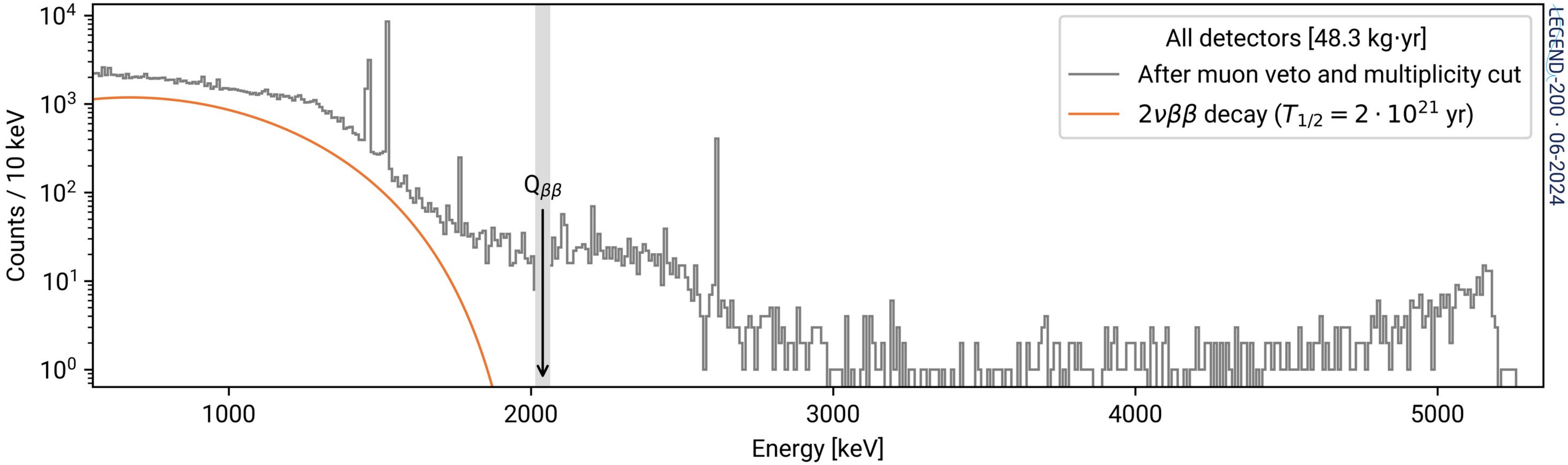
Energy Resolution

- **Energy resolution** for all types of Ge detectors used: **~0.1% FWHM at $Q_{\beta\beta}$**
- **Stable** energy observables
  - monitored with weekly ^{228}Th calibrations



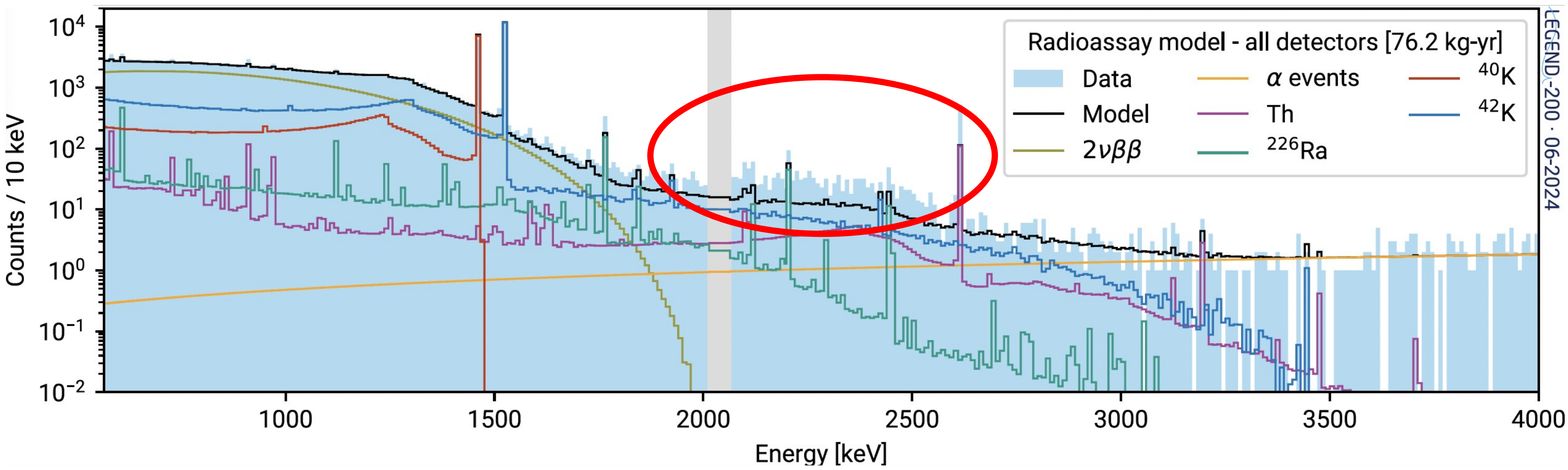


Energy spectrum after quality cuts



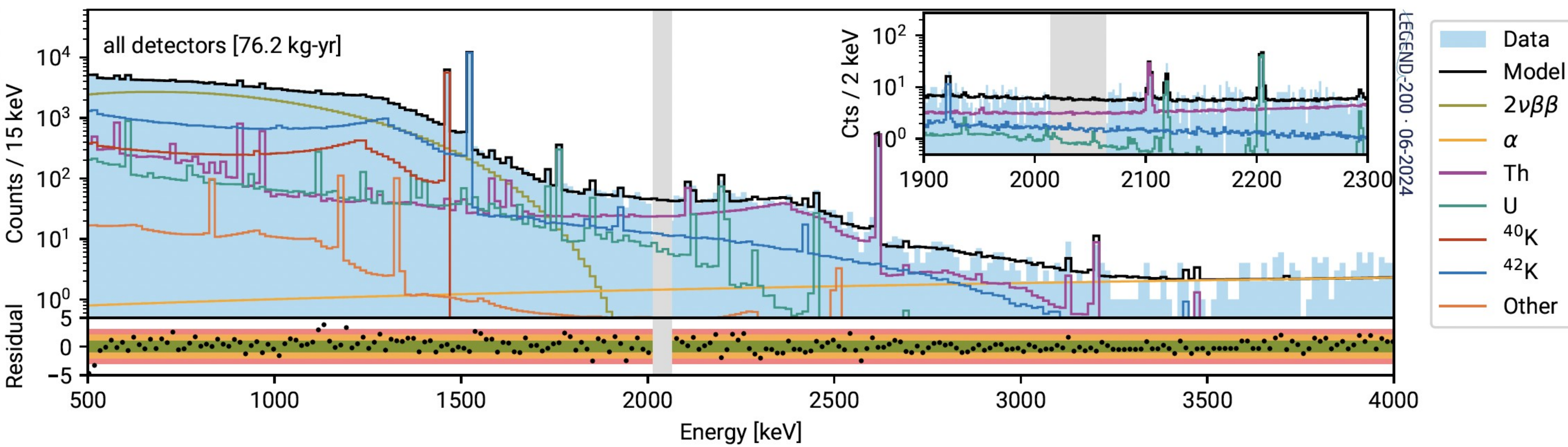
- **Exposure**: 48.3 kg·yr (golden data set)
- **Blinding** applied at $Q_{\beta\beta}$ = 2039 keV (50 keV window)
- 95–99% survival of physical events after **data cleaning** at $Q_{\beta\beta}$
- **Multiplicity cuts** rejects 26% of events $Q_{\beta\beta}$
- 2 events removed by **Muon Veto** at $Q_{\beta\beta}$

Modeling data before analysis cuts



- Simulations and material radioassay **underpredict ^{228}Th** in physics data
- This is not a fit
- Present strong efforts to understand the origins

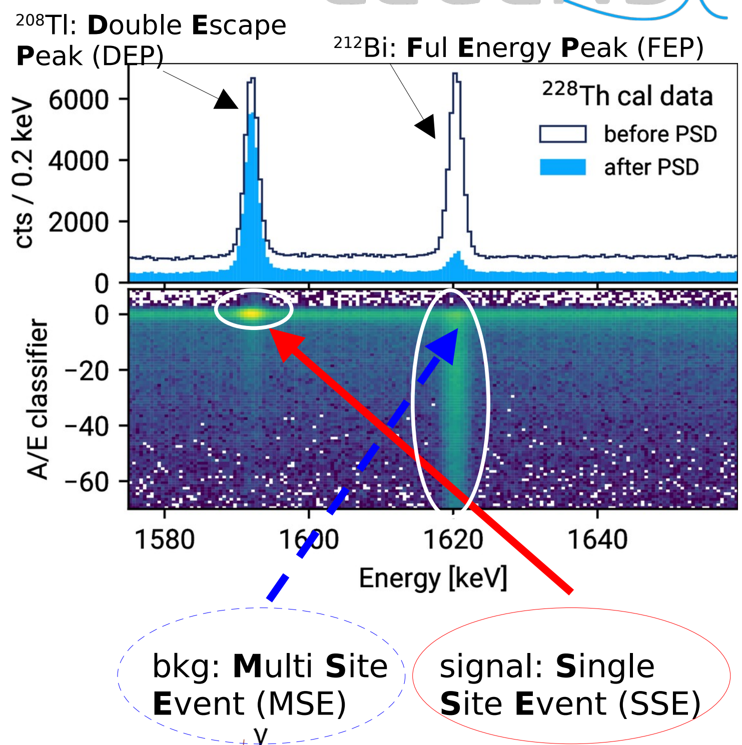
Modeling data before analysis cuts

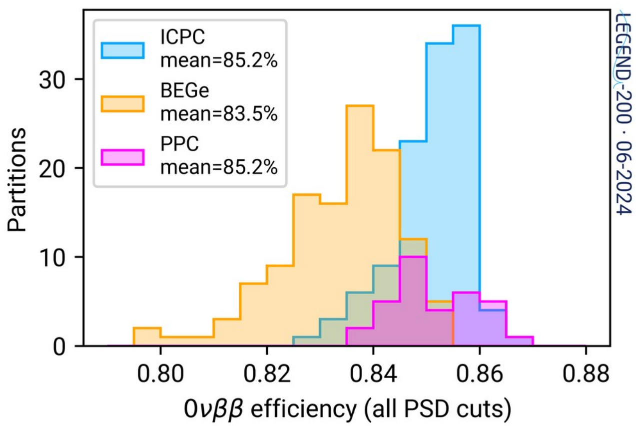


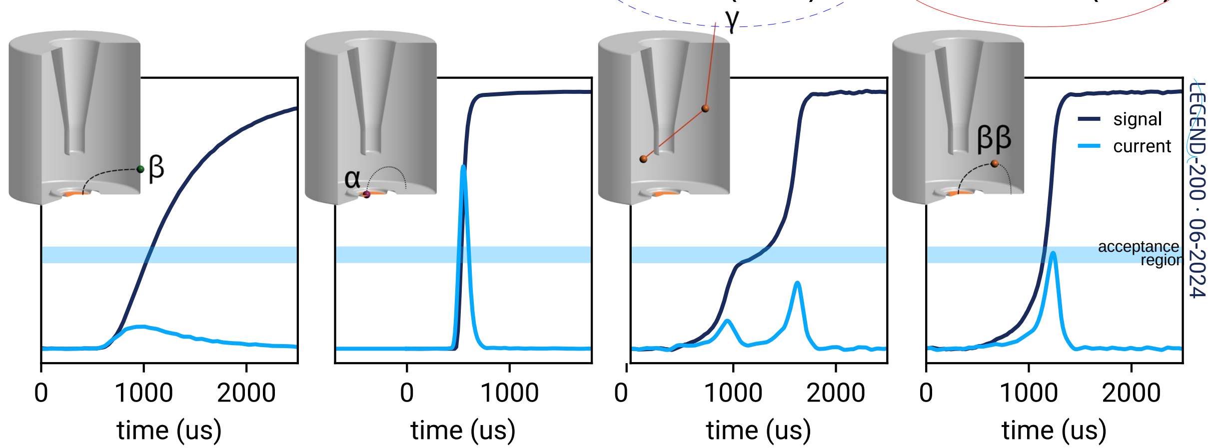
- **Bayesian background model** using data before analysis cuts
  - includes 10.2 kg·yr from special "background characterization runs"
- Data well reproduced, **model is flat at $Q_{\beta\beta}$**
  - no hotspot or significant asymmetry observed in data

Pulse Shape Discrimination (PSD)

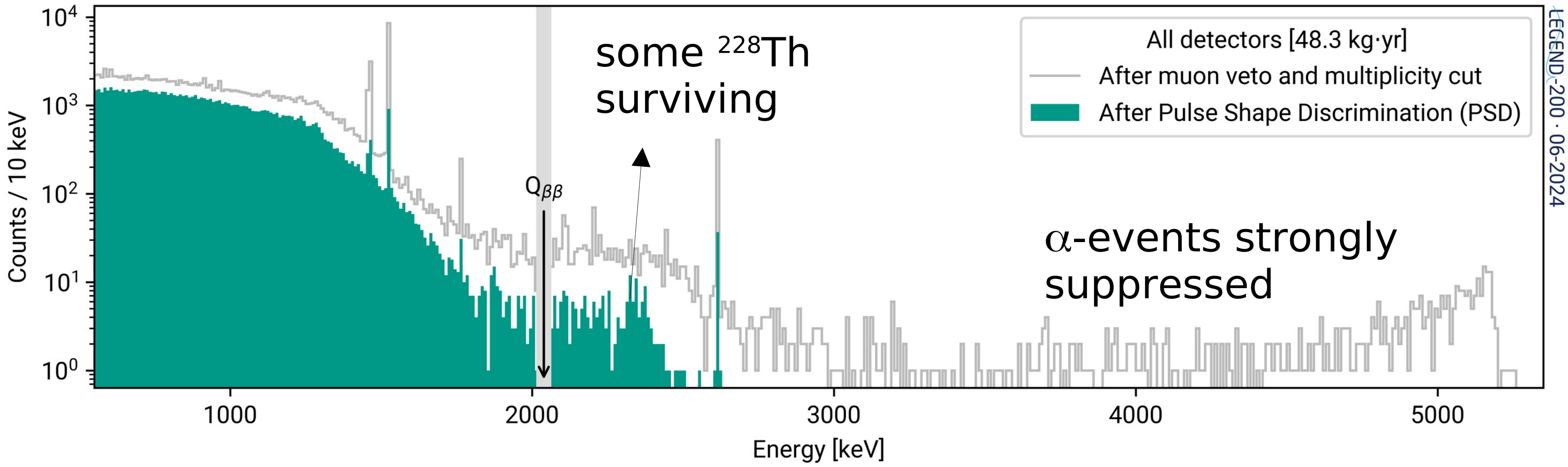
- **Pulse Shape classifier**:
  A/E = max current/Energy
  - "Late Charge" (LQ) cut instead of high A/E cut for detectors with large passivated surfaces
- **Stable** PSD observables
  - monitored with weekly ^{228}Th calibrations







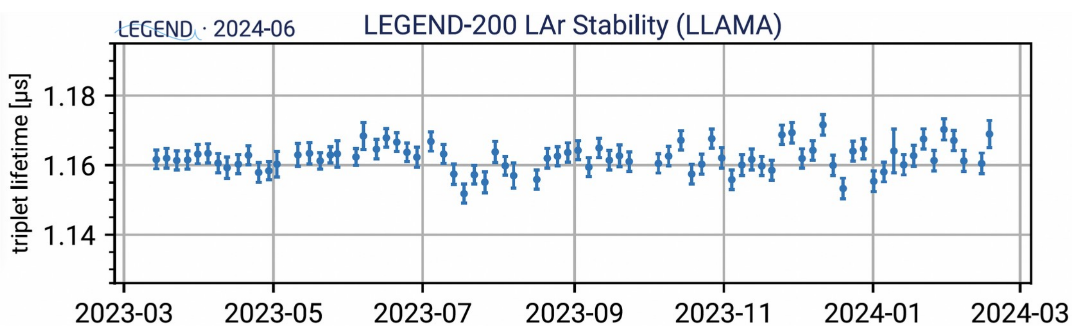
Data after Pulse Shape Discrimination

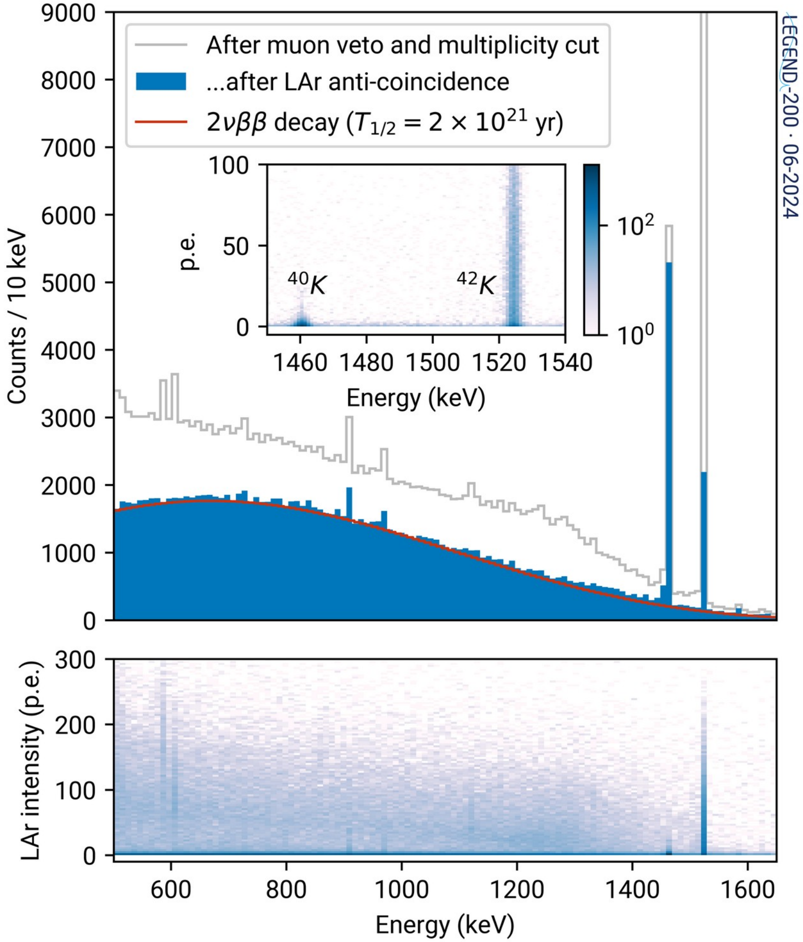


- Strong **suppression of surface α and β** (^{42}K) events
- ~60% suppression of Compton multi-site events at $Q_{\beta\beta}$
- $0\nu\beta\beta$ survival fraction of ~85%

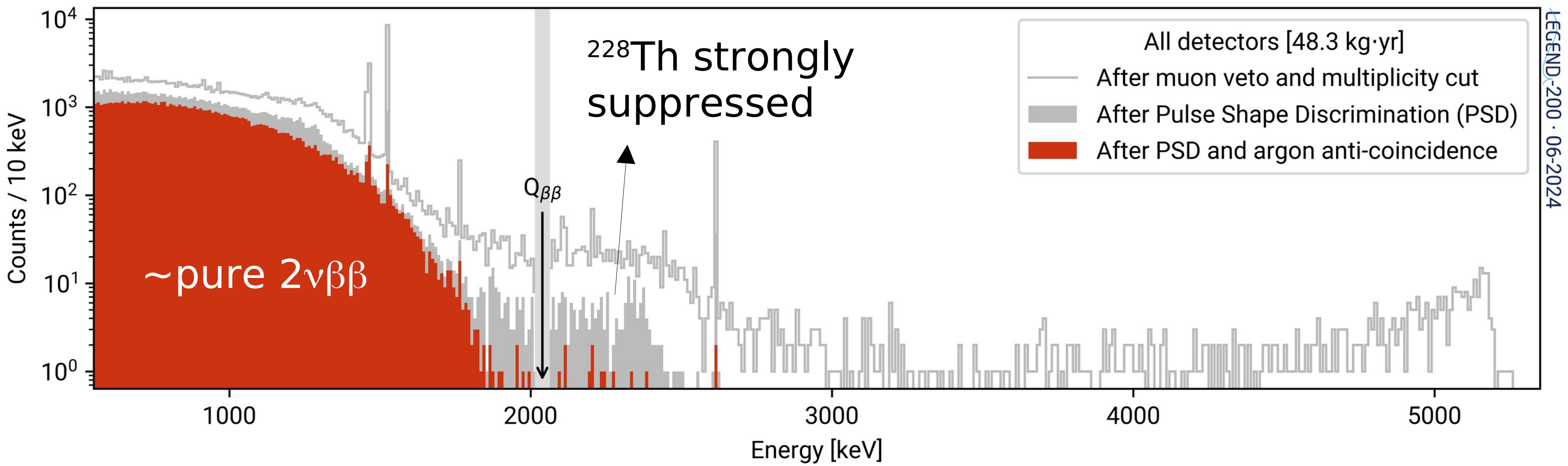
Argon Instrumentation

- **Improved light yield** compared to GERDA (x3)
- **Stable** argon properties
  - Monitoring through LLAMA instrumentation
- **Characterized** with special calibration runs
  - ~1 photoelectron per 10 keV deposited in Ar
- **Strong suppression** of background above 2νββ
  - ββ acceptance of ~93%





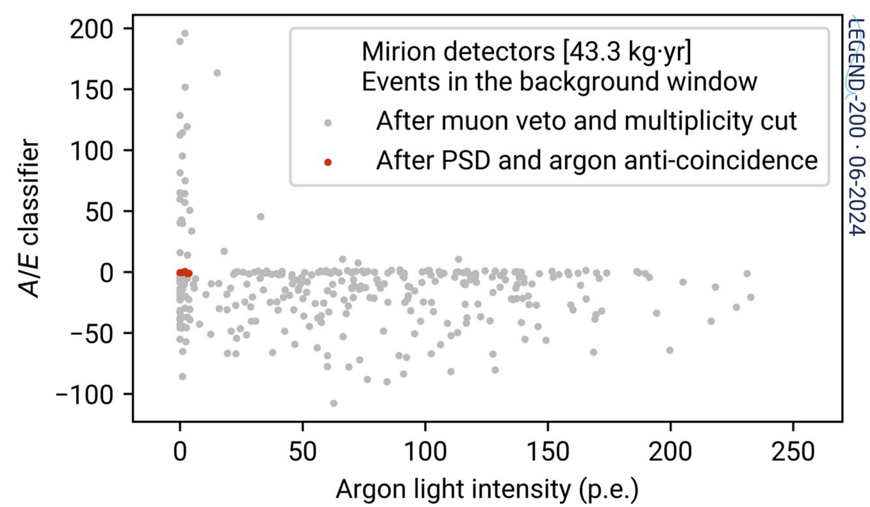
Data after PSD and Argon Anti-Coincidence Cut



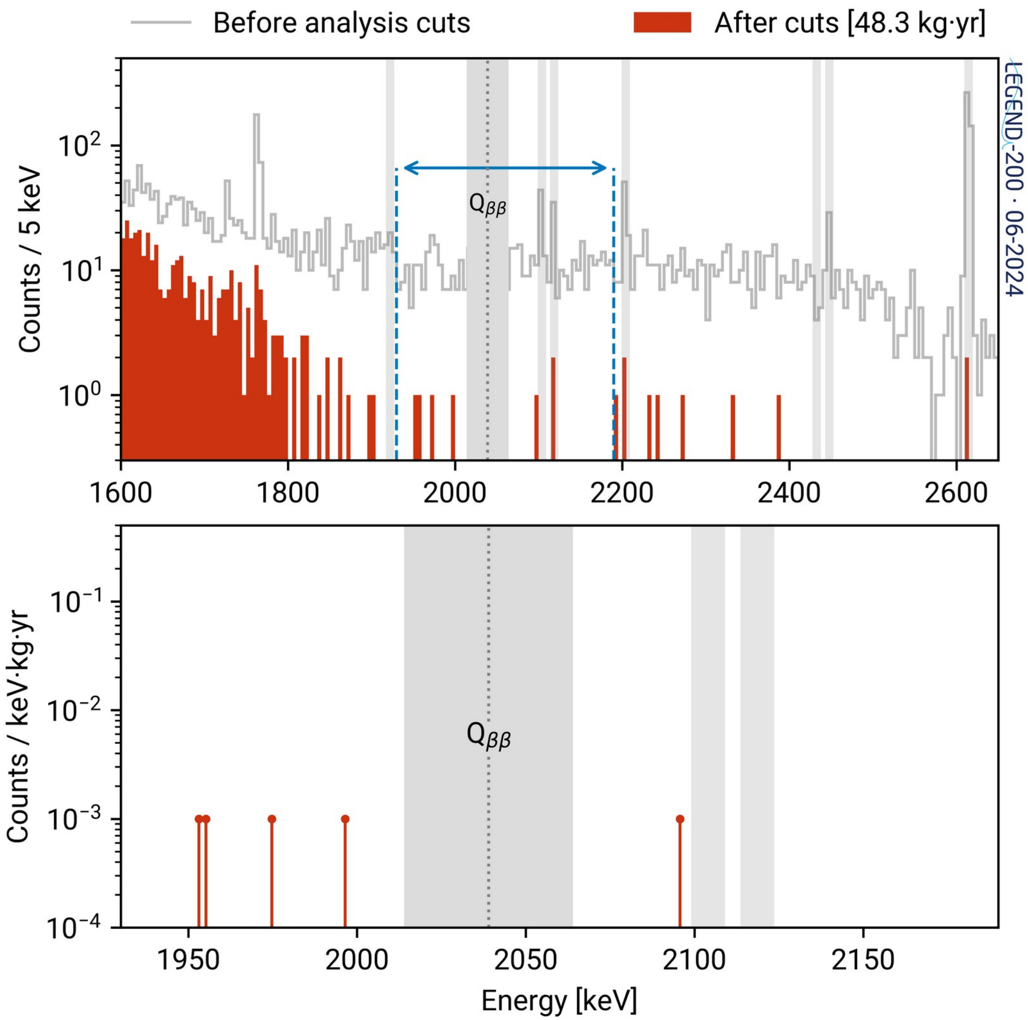
- Strong **anti-correlation** of argon and PSD cuts

- Overall $0\nu\beta\beta$ survival fraction of ~60%

- **"Pure" $2\nu\beta\beta$ distribution, few events surviving at $Q_{\beta\beta}$**

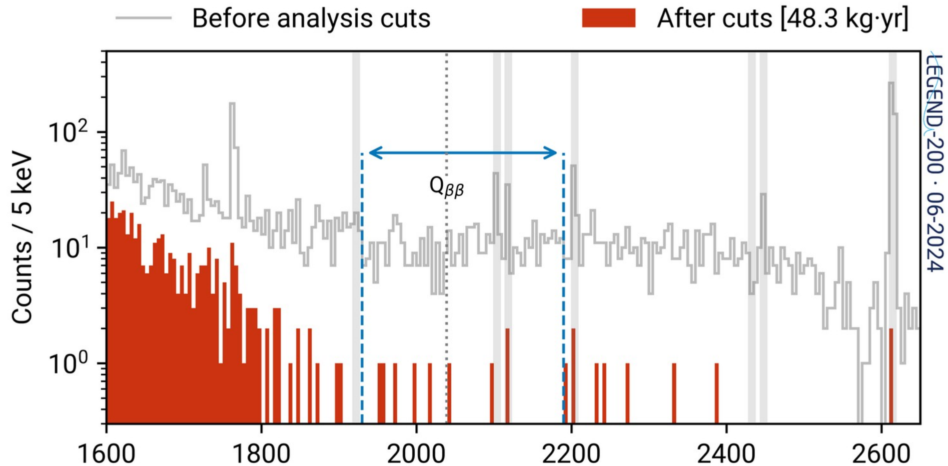


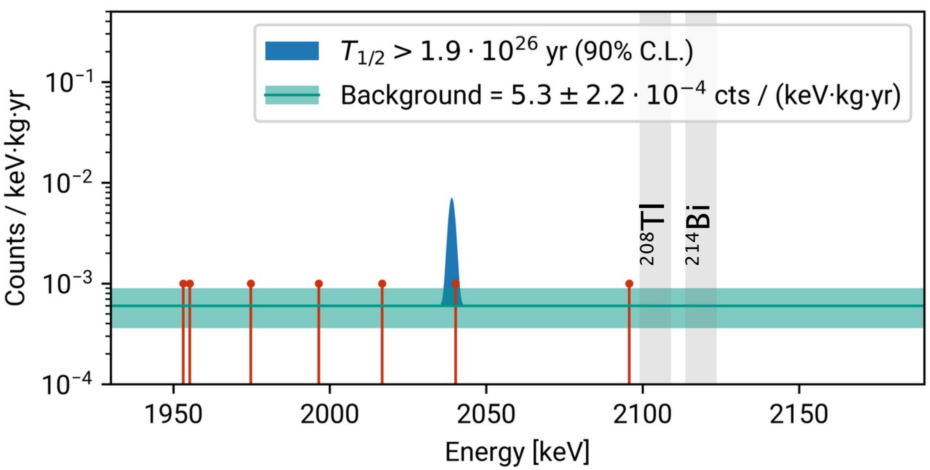
Data in the Region Of Interest



5 events surviving in the "background estimation window"

Data in the Region Of Interest: after unblinding





- 7 events surviving
- Background index: $5.3 \pm 2.2\ 10^{-4}$ cts/(keV kg yr)

GERDA, MAJORANA, LEGEND combined fit:

- p-value of background-only: 26%
- $T^{0\nu}_{1/2}$ lower limits (90% C.L.):

Observed	Sensitivity
$>1.9 \cdot 10^{26}$ yr	$2.8 \cdot 10^{26}$ yr

LEGEND-200 contribution

- +30% of limit median expectation
- event at 1.4 σ from $Q_{\beta\beta}$ weakens combined fit

E adesso ???

- In questo momento si sta aspettando l'esito dei radioassay di molti materiali (HV cables, PEN plates, LMFEs, Copper rods, nuts, ULTEM, Nylon Minishroud, Wls reflector, zip ties): ~ 1 mese

- e l'esito dell'analisi del run senza le minishroud

- Rivelatori a Ge:

  - si toglieranno 23 rivelatori (26.3 kg) malfunzionanti
  - aggiunta di 11 rivelatori ICPC nuovi (35.7 kg)
  - massa totale: **142.4 kg** → **151.6 kg**
  - nel 2015 altri rivelatori provenienti da: rivelatori Ortec riparati, rivelatori ICPC da materiale riprocessato dalla ditta VPMS, dalla fusione dei rivelatori malfunzionati
  - massa finale: ~183 kg in ~102 rivelatori

- Partenza del nuovo run: fine ottobre/inizio novembre 2024

Richieste finanziarie

- LNGS:
  - manutenzione water loop di LEGEND-200 e dei sistemi di raffreddamento criostato: 3k sj
  - servizi assistenza doganale per deposito doganale: 3k
  - trasporto LN2 e LAr, supervisione apparato ...: 6k
  - Common Fund: 54k

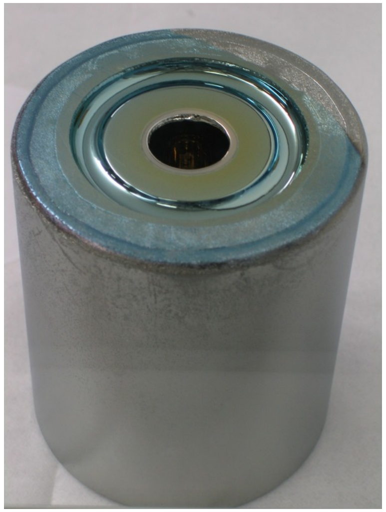
- Milano
  - Manutenzione elettronica installata per L200 a LNGS: 2.5k sj

- Roma 3
  - Manutenzione FE SiPM: 4k + 1k (sj)

backup slides

Searching in ^{76}Ge

$$S \sim \epsilon \cdot f \cdot \sqrt{\frac{M \cdot t_{run}}{BI \cdot \Delta E}}$$



Germanium detector

S: sensitivity
ε: efficiency
f: abundance of 0νββ isotope
M: detector mass

t_{run}: measurement time
BI: background index
ΔE: energy resolution at $Q_{\beta\beta}$

Advantages of Germanium:

- **High ε**: Source = Detector
- **Small instrinsic BI**: High purity Ge
- **Excellent ΔE**: FWHM ~ (0.1-0.2)%
- Well-established technology

Disadvantages of Germanium:

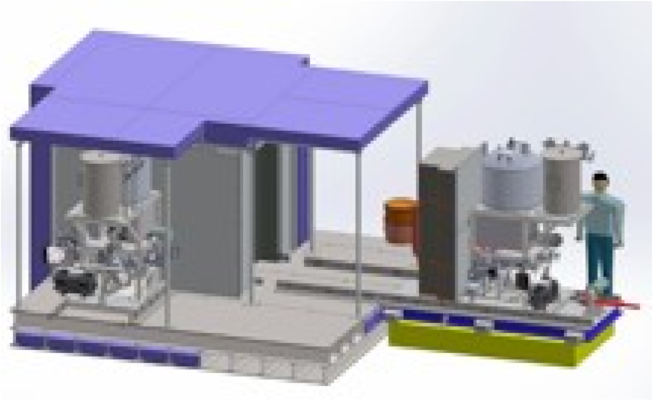
- at $Q_{\beta\beta}$= 2039keV more challenging to reach **low enough background**
- **Small f of ^{76}Ge:** 7.8% → Enrichment needed!
- Limited sources of crystal & detector manufacturers
- Small $G^{0\nu}$ $(Q_{\beta\beta},Z)$

The ^{76}Ge experiments: GERDA & MJD

GERDA

- Bare ^{enr}Ge array in liquid argon
- Shield: high-purity liquid Argon/H_2O
- Phase I: 17 kg (HdM/IGEX)
- Phase II: 35.8 kg enriched in ^{76}Ge

MAJORANA-DEMONSTRATOR (MJD)

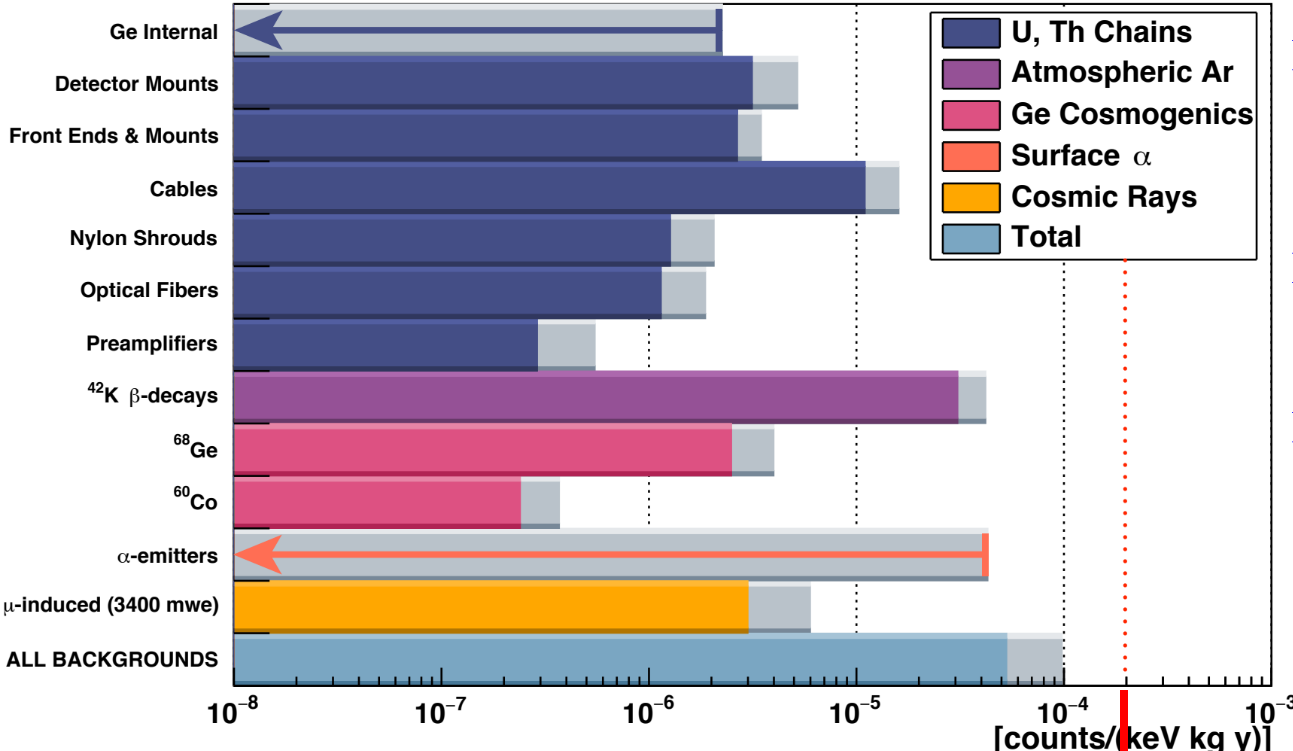


- Arrays of ^{enr}Ge housed in high-purity electroformed copper cryostat
- Shield: electroformed copper/lead
- 30 kg enriched in ^{76}Ge

> ➢ **Physics goals**: degenerate mass range
> ➢ **Technology**: study of backgrounds and exp. techniques

- exchange of knowledge & technologies (e.g. MaGe MC)
- intention to merge for future large scale ^{76}Ge experiment selecting the best technologies tested in GERDA & MJD

LEGEND-200 background projections



- Monte Carlo simulations based on experimental data and material assays
- Assay limits correspond to the 90% CL upper limit
- Grey bands indicate uncertainties in overall background rejection efficiency

L-200 Background Index goal at $Q_{\beta\beta}$: **$2\cdot10^{-4}$ cts/(keV·kg·yr)**

L-200 Sensitivity goal:

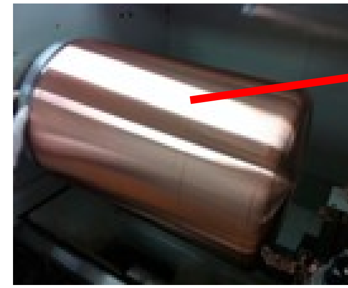
$T_{1/2} > 10^{27}$ years (90% CL) after **1 ton·yr** of exposure

$m_{\beta\beta}$ < 27 – 64 meV

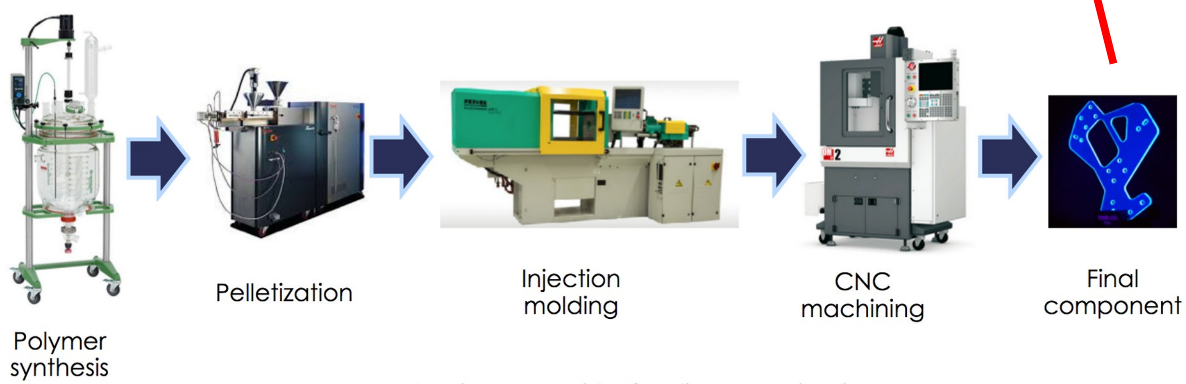
clean materials

- **Underground electroformed copper**
  reduces U/Th cosmogenic activation of ^{60}Co in Cu
  $< 0.017 \pm 0.03$ pg(^{238}U)/g
  $< 0.011 \pm 0.05$ pg(^{232}Th)/g

Underground electroformed copper

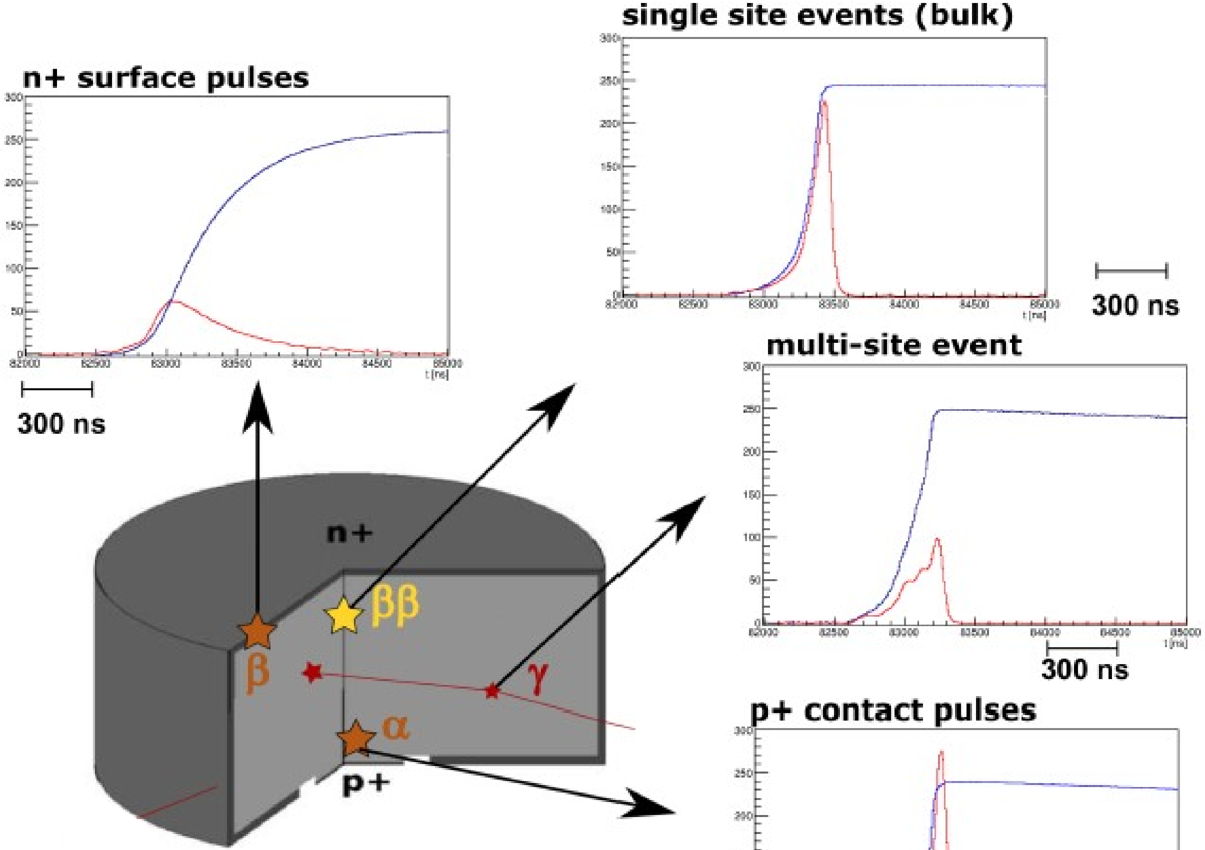


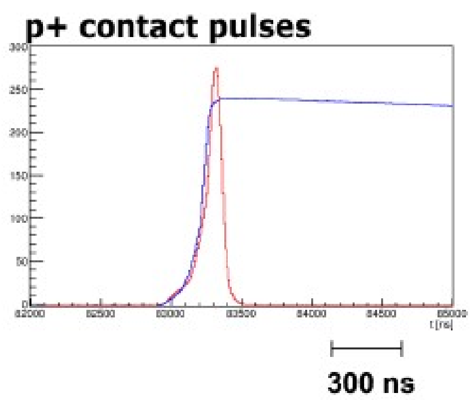
- **Polyethylene naphtalene (PEN)**
  replaces optically inactive structural materials
- Shift 128 nm LAr scintillation light to ~440 nm
- Yield strength higher than copper at cryogenic temperatures
- Evaluated in L-200



PEN: scintillating high purity detector support

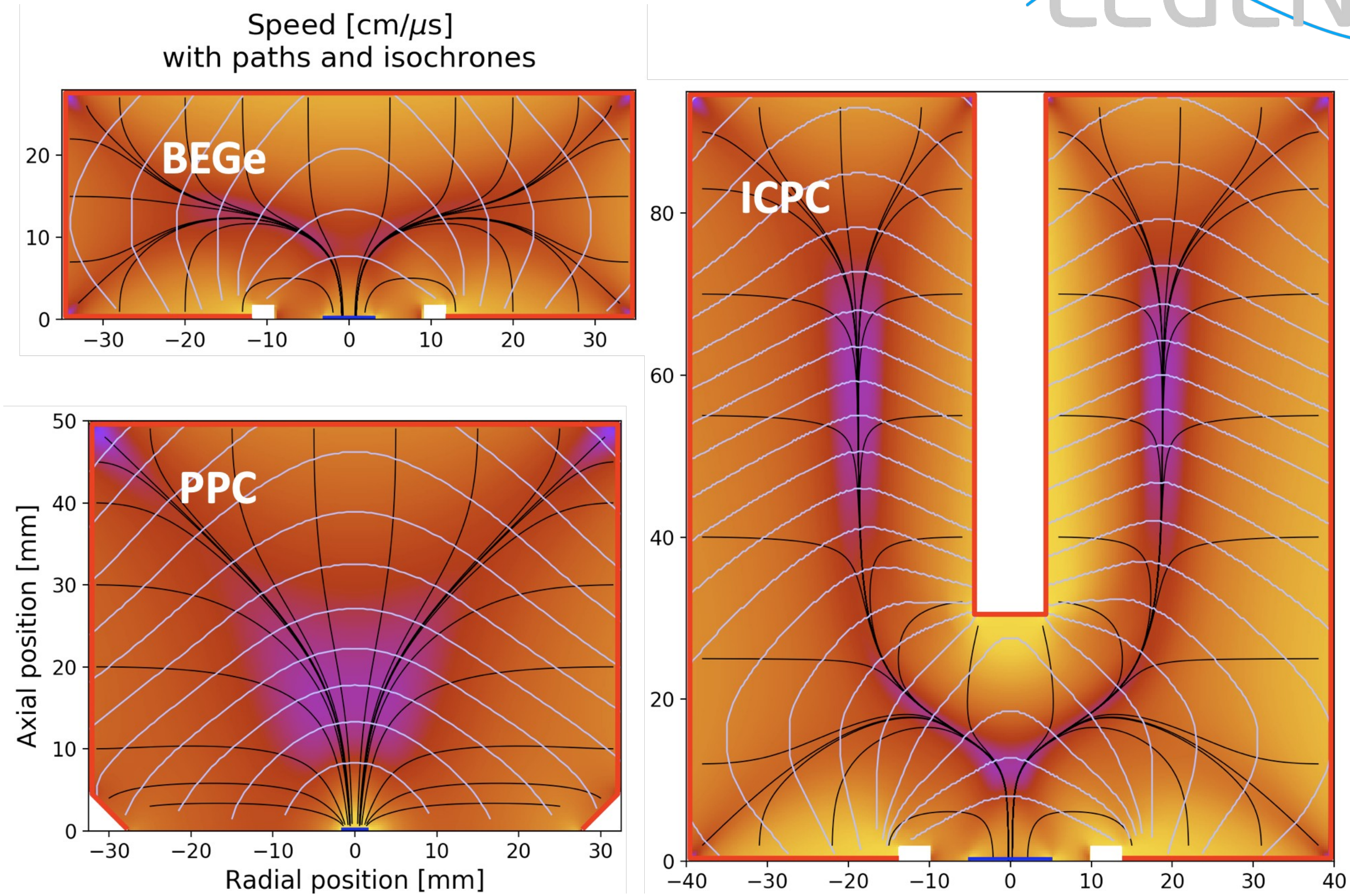
Pulse Shape Discrimination (PSD)





- Point-contact geometry allows for MS event rejection based on pulse shapes:
  - Compton continuum γ background reduced by 50%
- Distinctive pulse shapes near surfaces allow highly efficient surface event rejection:
  - α and β events reduced ≥ 99%

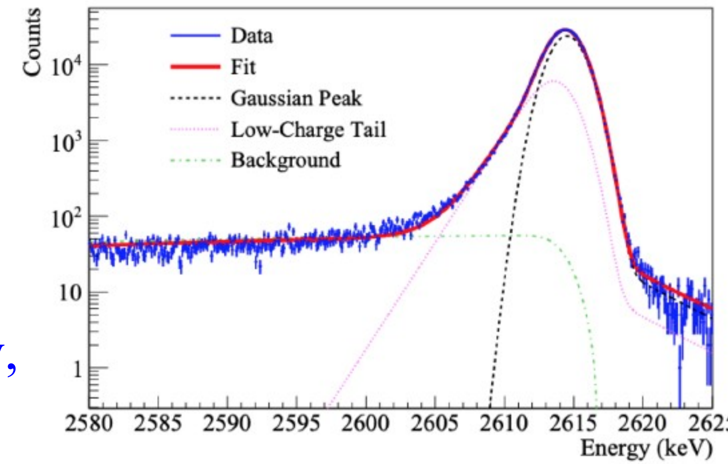
Ge Detectors



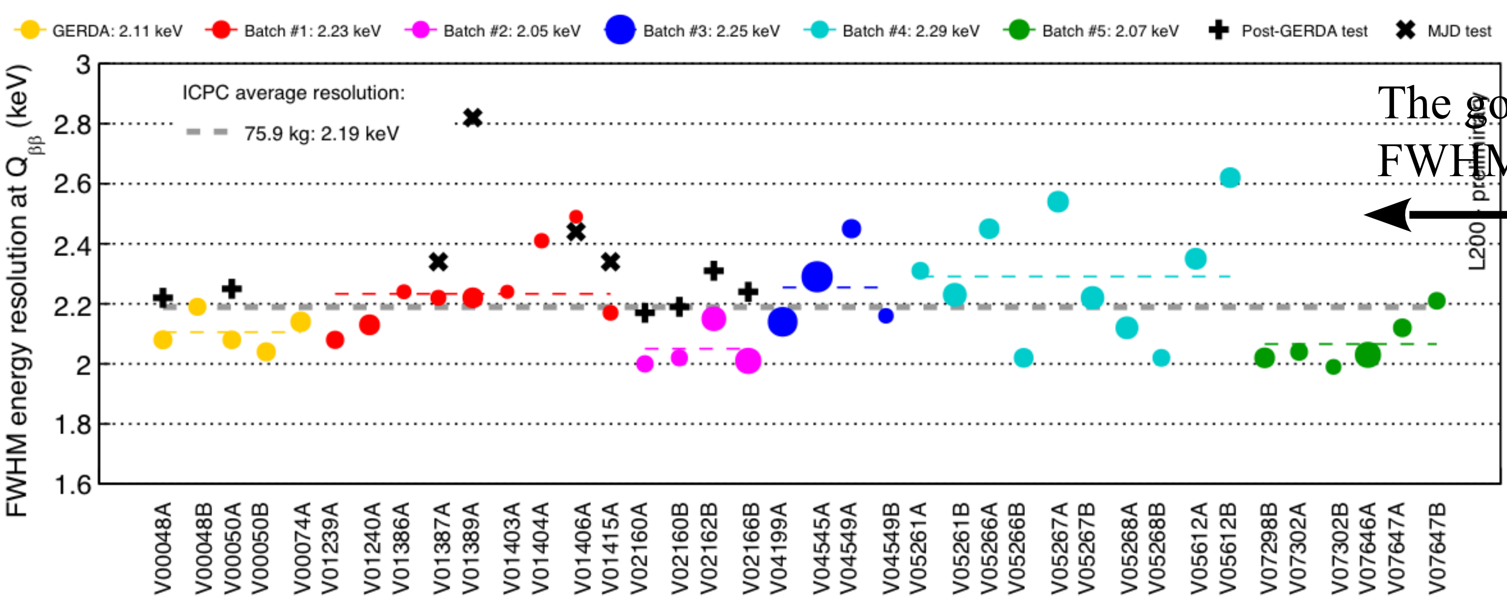
In LEGEND-200 four different types of enriched Ge detectors will be used:
BEGe (GERDA), PPC (Majorana), **ICPC** (GERDA, L-200) and semicoax (GERDA)

ICPC: energy resolution

- Excellent energy resolution leads to lower backgrounds and higher discovery potential
- No resolution degradation seen in higher-mass ICPCs
- Well-understood peak shape, energy scale stability, and linearity (better than 0.1%) lead to improved confidence in results

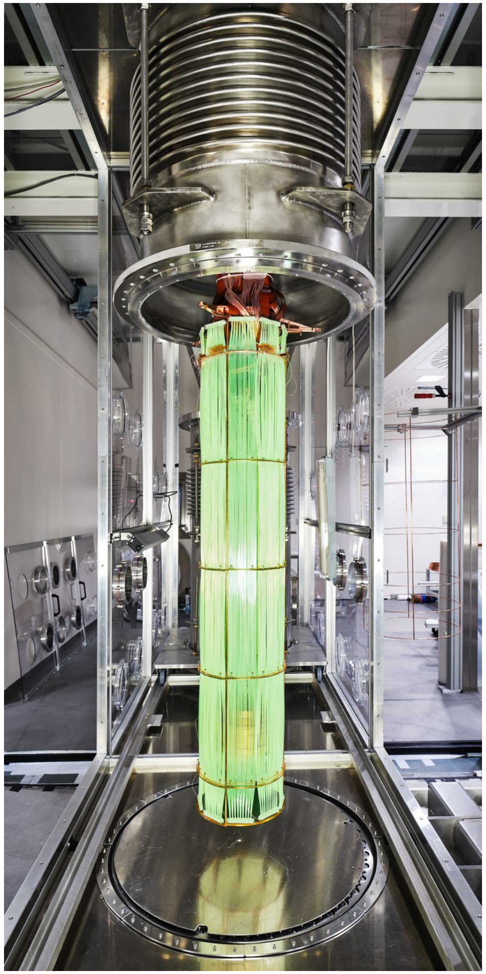


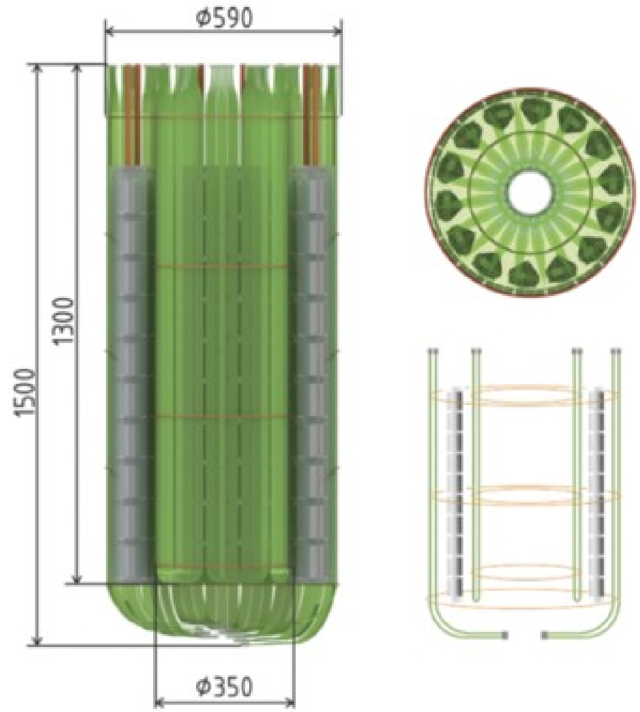
Energy resolution of ICPCs from characterization tests and calibration runs in GERDA and MJD

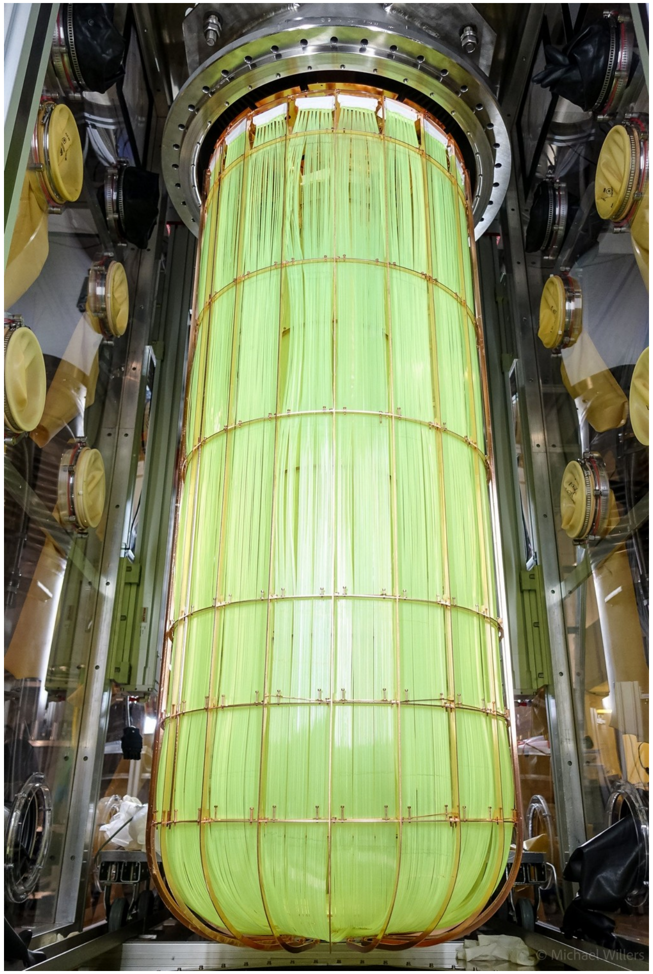


The goal is to reach a FWHM @ $Q_{\beta\beta}$ = **2.5 keV**

LAr veto





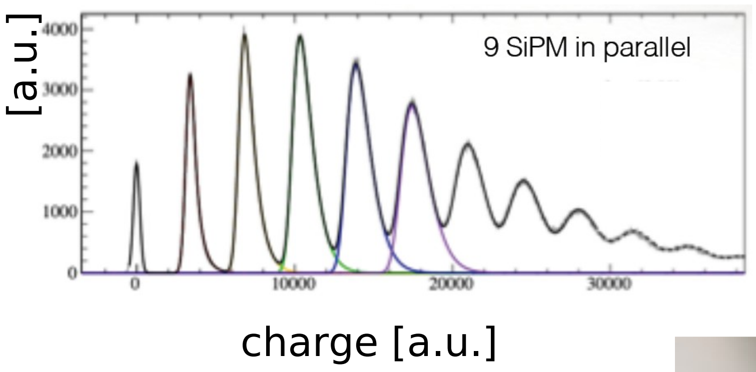


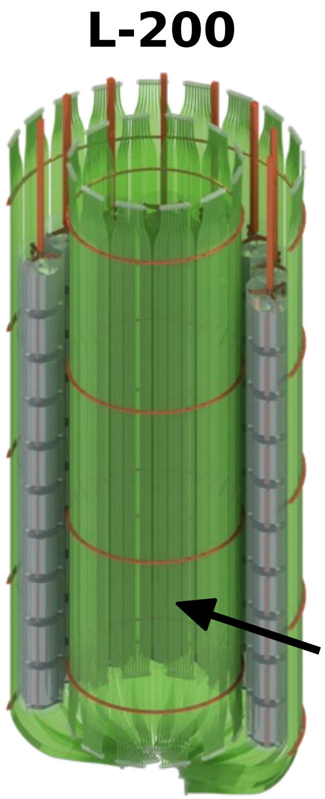
Internal LAr Veto :
9 modules, 18 readout channels

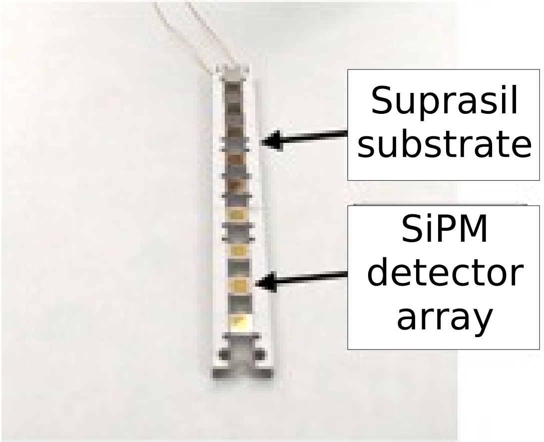
External LAr Veto:
20 modules, 40 readout channels

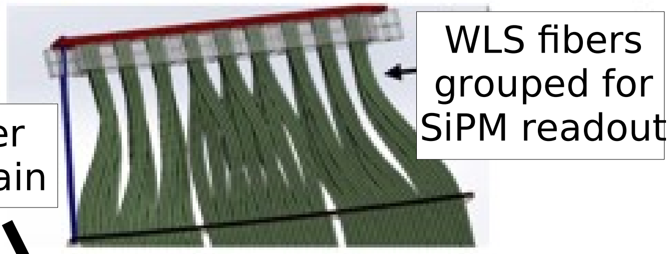
Liquid Argon Veto

- 128 nm LAr scintillation light readout by TPB coated WLS fibers coupled to SiPMs arrays
- Single photo-electron resolution

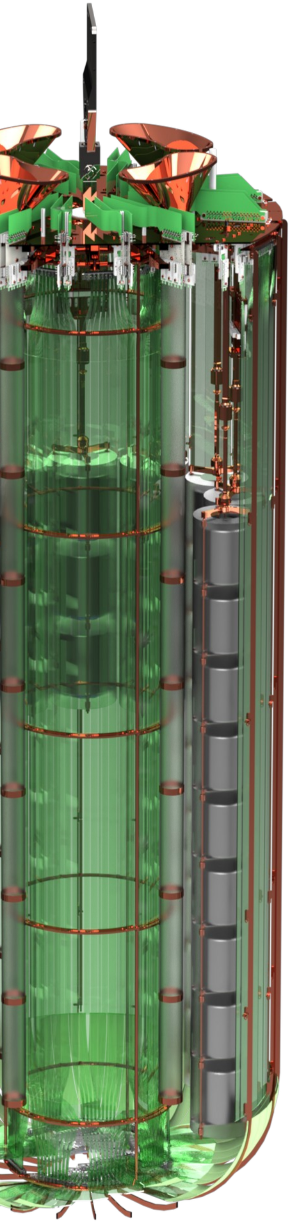








LAr Instrumentation



- Improved Si photo-multiplier (SiPM) readout
  Improved geometry + optically active PEN → less shadowing
- Improved wavelength-shifting (TPB) fiber coating

→ ~ 3 more light wrt. GERDA