Neutrinoless double-beta decay with the LEGEND Experiment

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Outline:
- The LEGEND Experiment: general aspects
- The first stage: LEGEND-200
- LEGEND-1000

The LEGEND Experiment: general aspects

➢ For the **physics motivation** in the 0νββ research field: *talk of Prof. Fedor Šimkovic*

Large Enriched Germanium Experiment for Neutrinoless ββ Decay - LEGEND

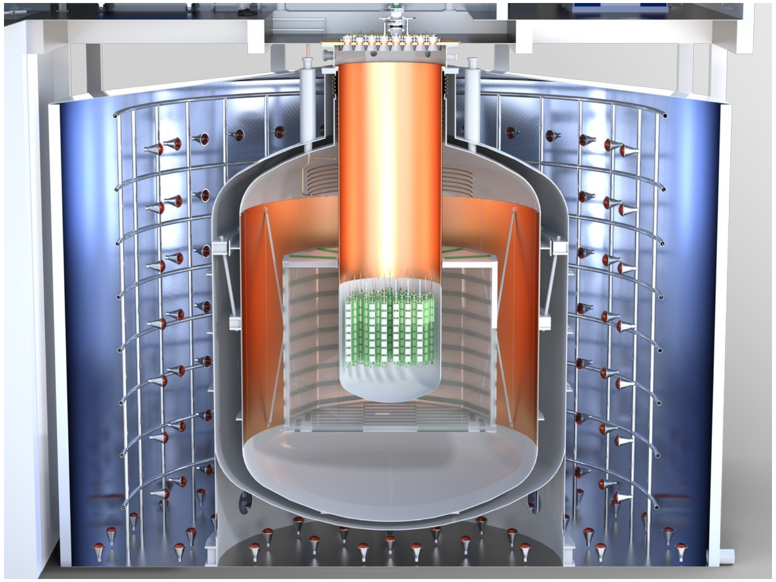
~270 members, 55 institutions, 12 countries
from GERDA and MJD experiments + other groups
Collaboration formed in October 2016

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^{27} years, using existing resources as appropriate to expedite physics results"

LEGEND: a staged approach

First Stage (LEGEND-200):

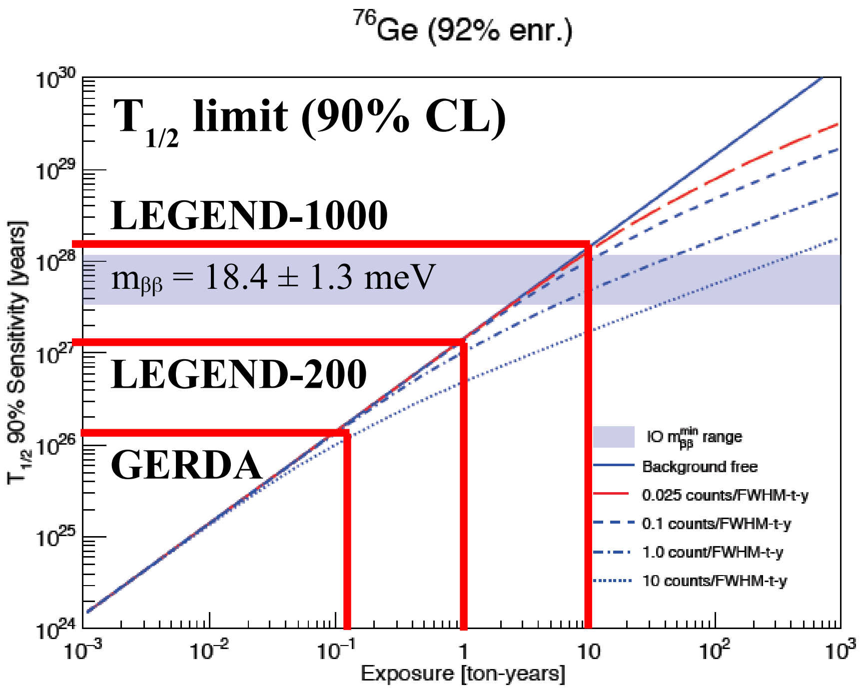
- upgrade of the existing infrastructure of GERDA up to 200 kg
- reduction of the BI of a factor 5 w.r.t. GERDA Phase II goal
- to reach 200 kg: 35 kg from GERDA + 30 kg from MJD. The remaining 140 kg are new

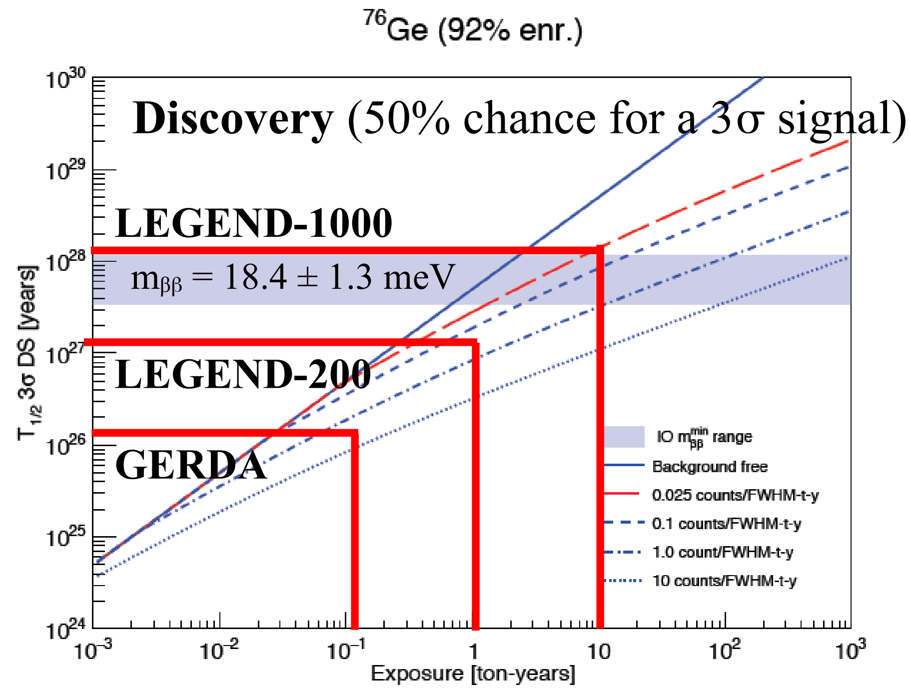


Further Stages (LEGEND-1000):

- 1000 kg (staged)
- timeline and budget: highest priority from DOE after the Portfolio review (July 2021)
- Background reduction of a factor 20 w.r.t. LEGEND-200
- LNGS is the preferred site, SNOLAB is the alternative

sensitivity and discovery





Plots details:

- ~69% efficiency (including: isotopic fraction, active volume fraction, analysis cuts)
- GERDA Phase II: 1.5 counts/(FWHM·ton·yr)
- LEGEND-200: 0.5 counts/(FWHM·ton·yr)
- LEGEND-1000: 0.025 counts/(FWHM·ton·yr)

N.B.: **background-free(*) condition is a prerequisite for a discovery**

(*) average expected bkg events < 1.0 in the ROI for the entire exposure

The first stage: LEGEND-200

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
- **November 2021**: start commissioning
- **March 2023**: start of the physics run with ~140 kg of enriched detectors

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

  $2\cdot10^{-4}$ cts/(keV·kg·yr)

- **L-200 Sensitivity goal:**

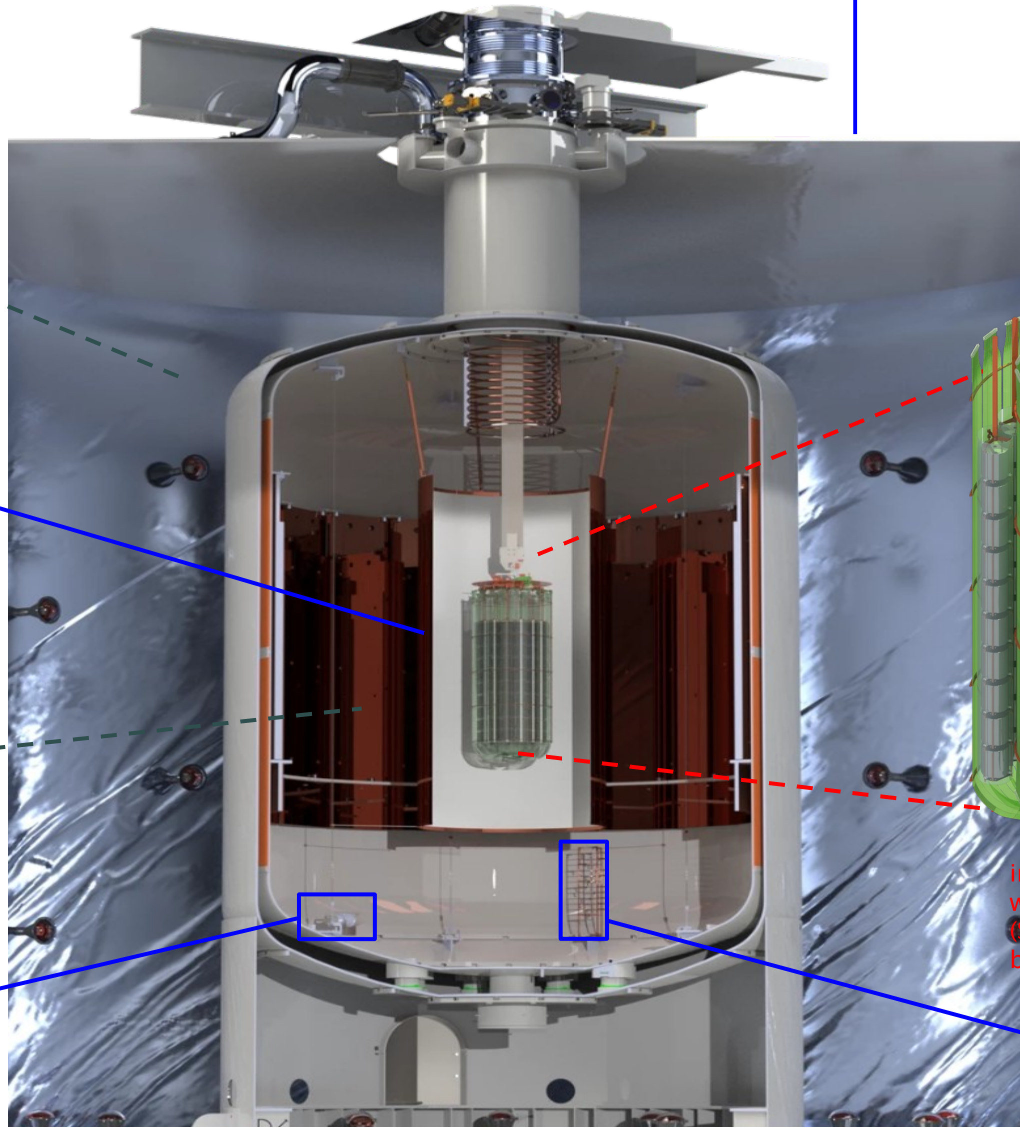
  $T_{1/2} > 1.5\cdot10^{27}$ years (90% CL exclusion)

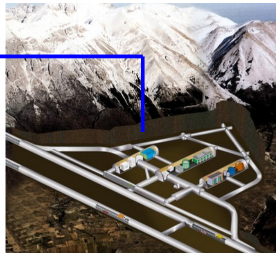
  after **1 ton·yr** of exposure

  $m_{\beta\beta} < 27 – 64$ meV (90% CL exclusion)

LEGEND-200: the experiment

Clean room lifted





LNGS
Hall A
3600
m.w.e.

Water Cherenkov muon veto

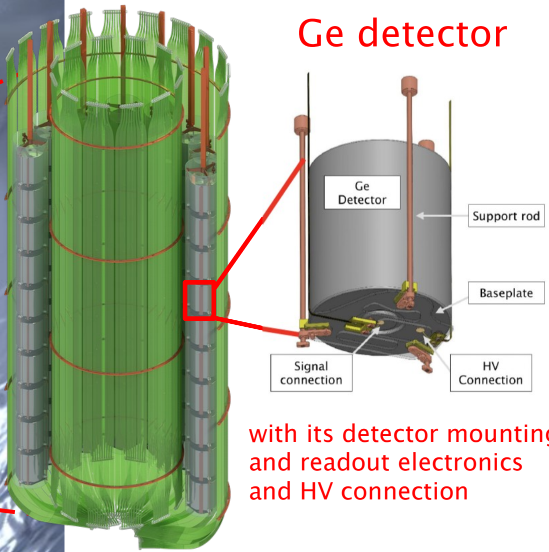
Teflon Reflector for better light collection

Copper lined stainless steel cryostat

LAr purification

LAr veto

Ge detector

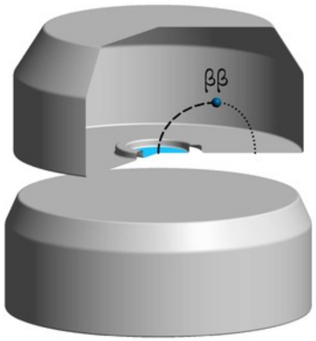


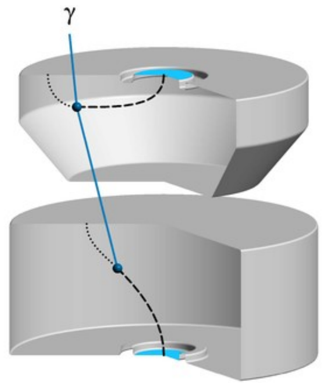
with its detector mounting and readout electronics and HV connection

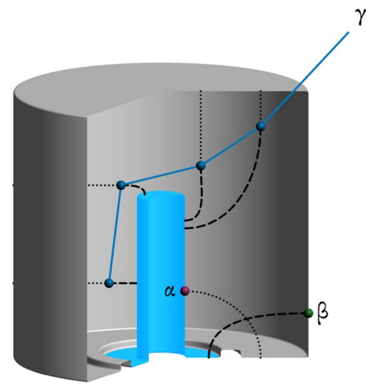
inner & outer fiber barrels with silicon photomultipliers (SiPM) readout at top & bottom

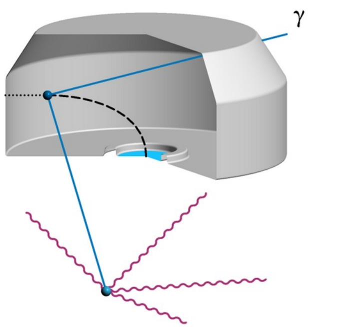
LLAMA
LAr quality monitoring

active background reduction tools









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

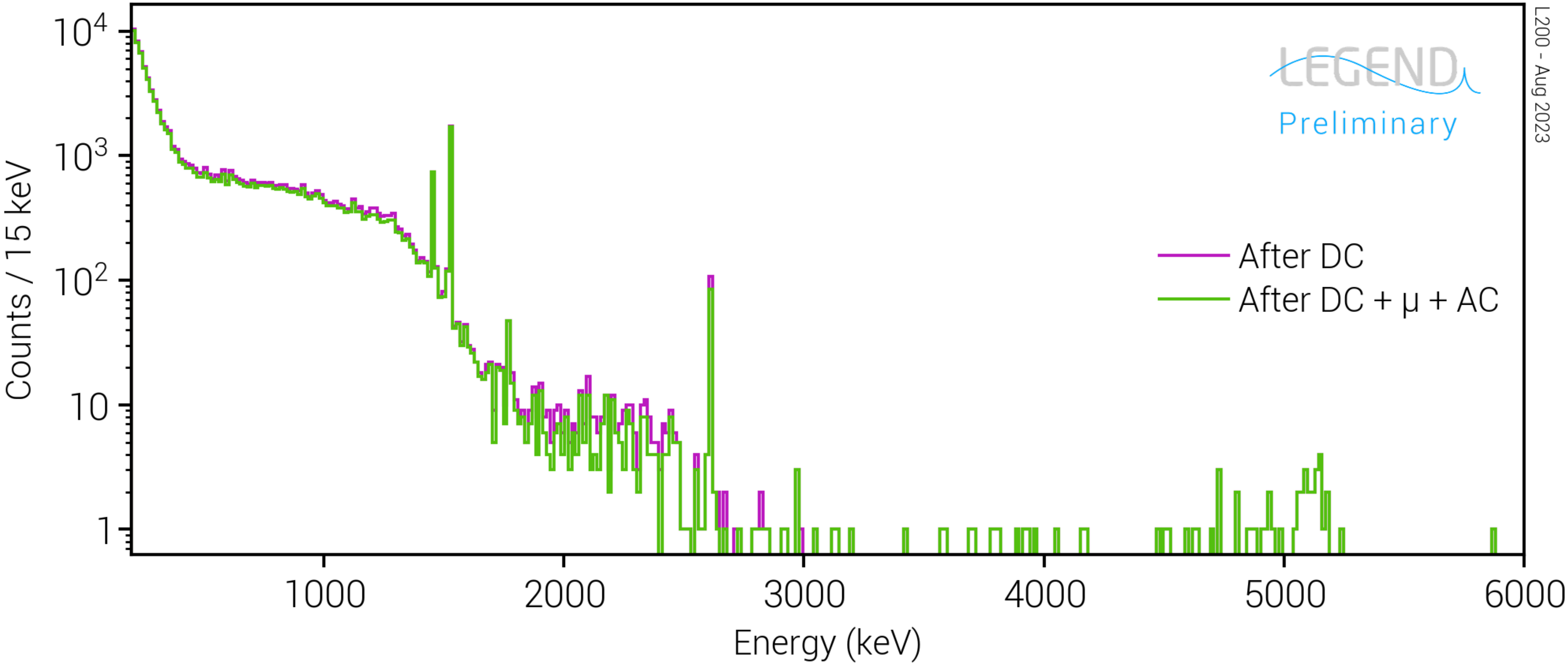
- intrinsic backgrounds
- Ge cosmogenics

Water Cherenkov anti-coincidence

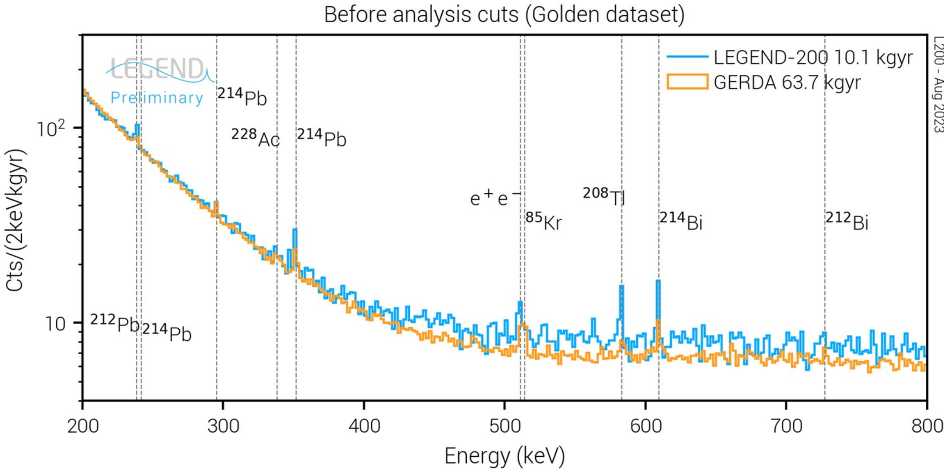
- muons

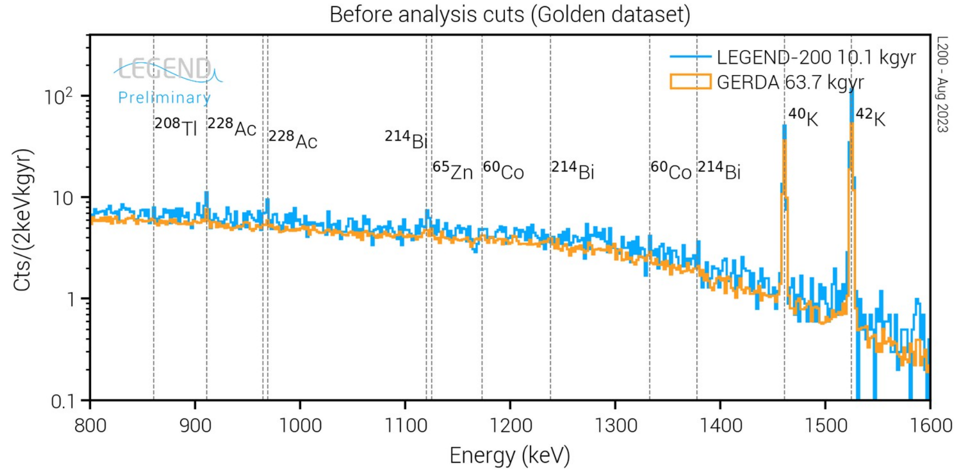
First LEGEND-200 background data:
Energy spectrum after quality cuts

- Only a small exposure shown here
- Exposure: 10.1 kg·yr
- used only BEGe (2.1 kg·yr) + ICPC (8 kg·yr) detectors
- Data cleaning (DC)
- Muon veto (μ)
- Ge-detector anticoincidence (AC)

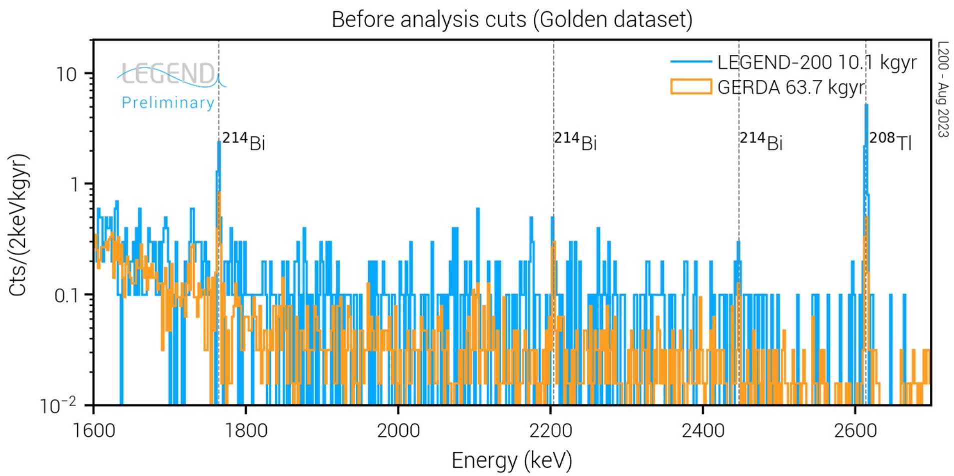


Background after quality cuts





- No unexpected background components
  - ^{238}U & ^{232}Th decay chains, ^{40}K, ^{42}K
- Improved peak to Compton ratio
  - Reduced Compton continuum
  - Higher detection efficiency due to larger detectors
- Higher rate from ^{208}Tl compared to GERDA
  - Expected → more construction material
- Similar spectra

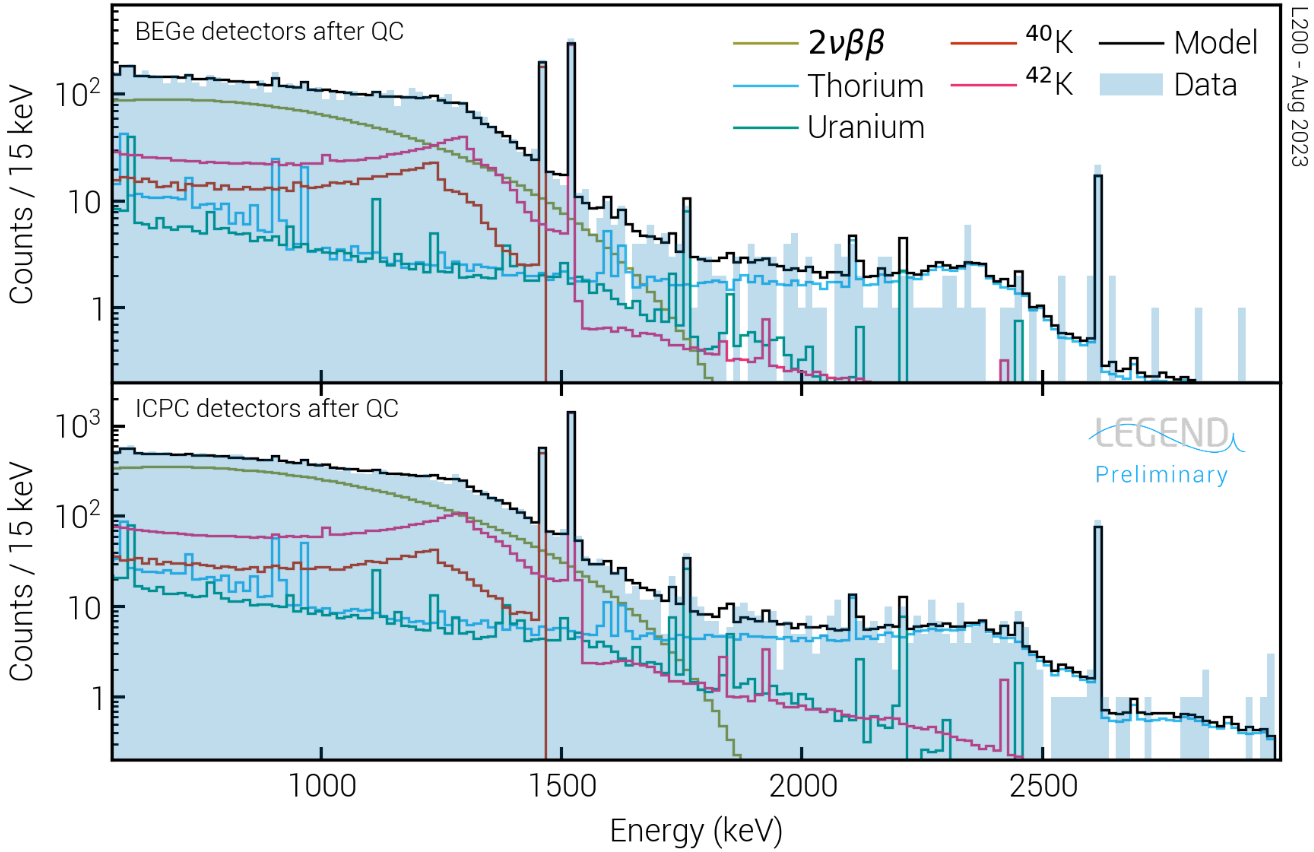


LEGEND vs. GERDA BEGe +ICPC

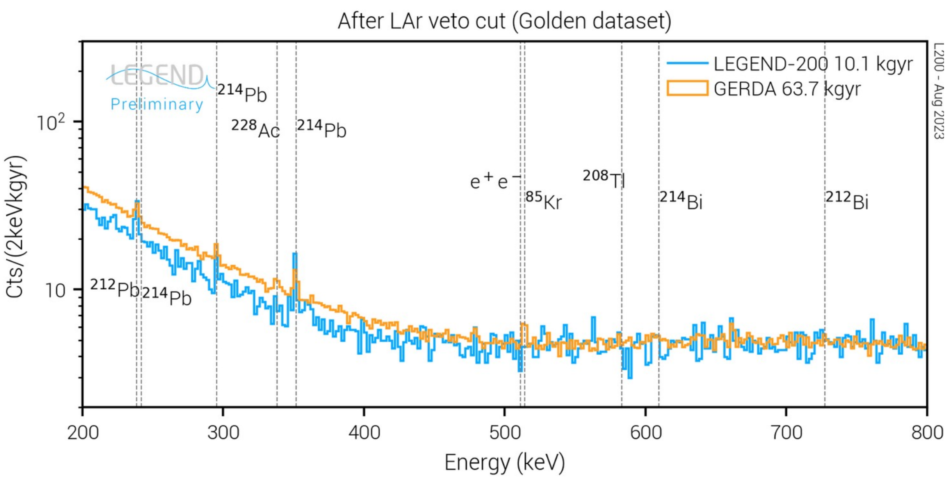
Background decomposition after quality cuts

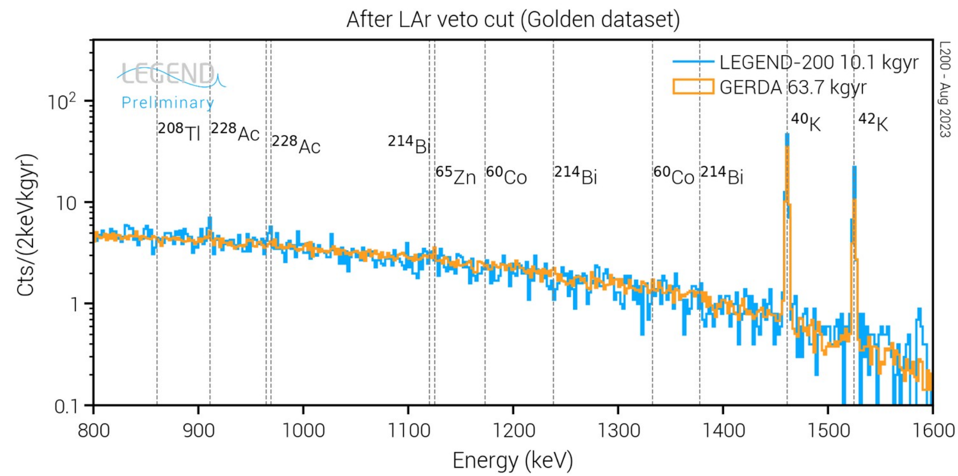
Decomposition before analysis cuts

- Well described by expected contributions with current statistics

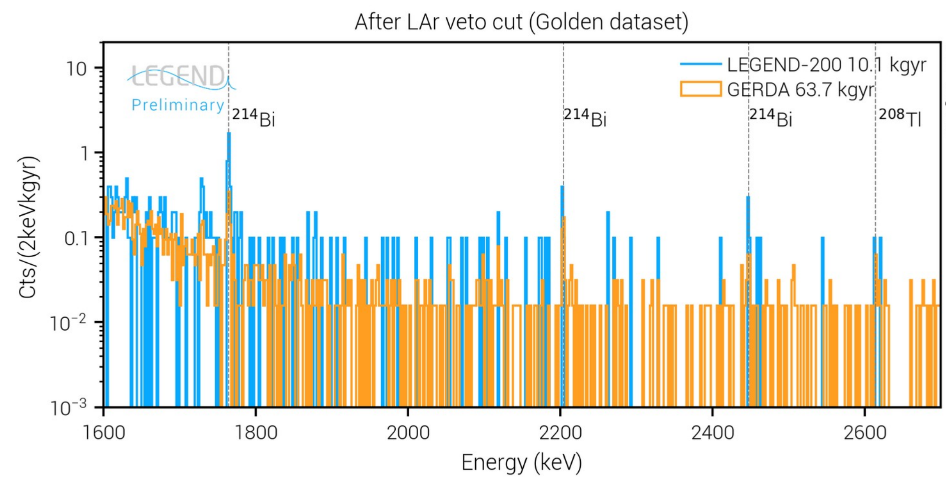


Background after QC + LAr AC





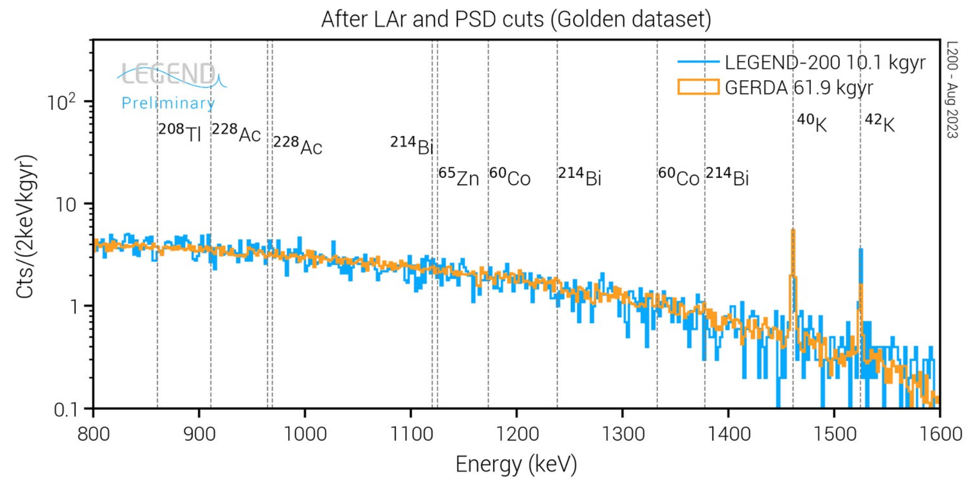
- Some gamma lines “vanishes” & Compton continuum suppressed
- LAr instrumentation
  - Improved background suppression higher light yield & less shadowing
  - More self-vetoing material: fibers of the LAr veto & PEN plates

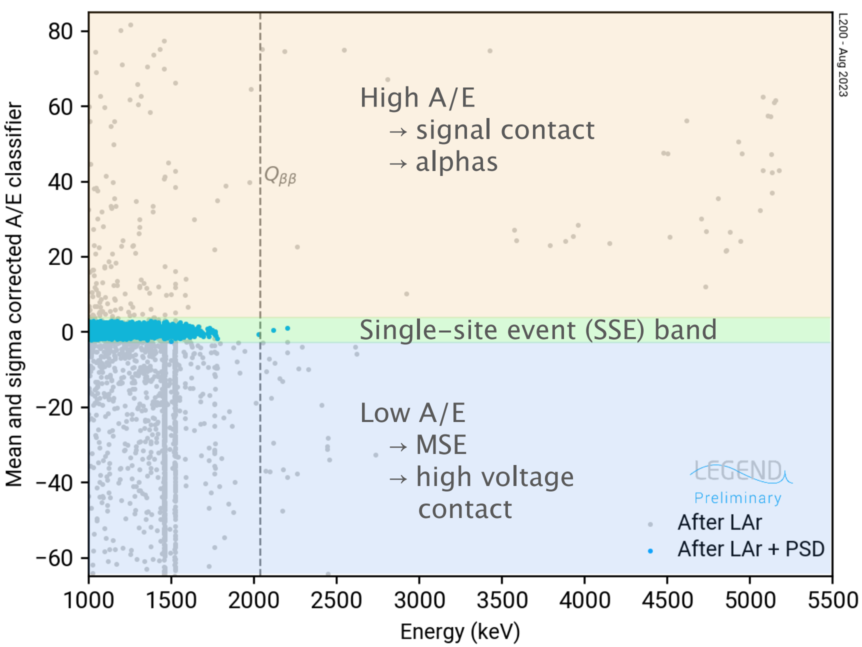


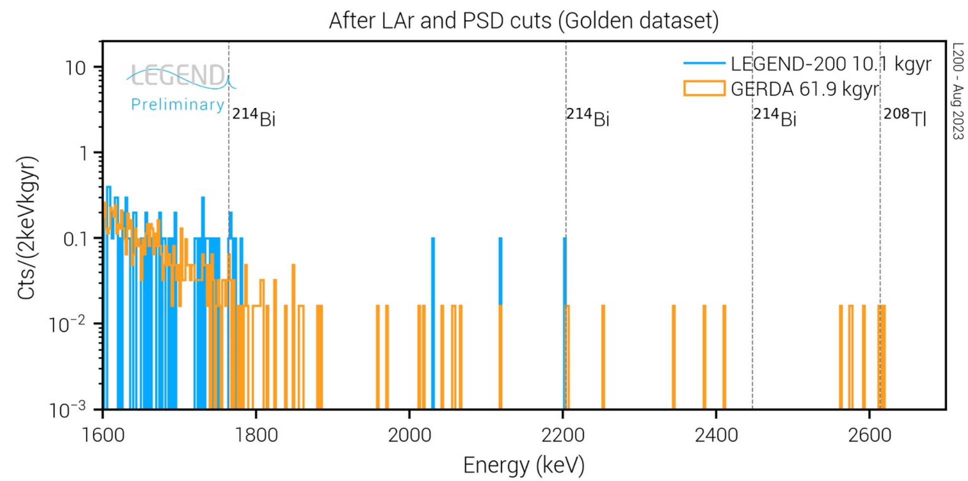
LEGEND vs. GERDA BEGe +ICPC

Background after QC + LAr AC + PSD

- PSD cuts multi-site and alpha events effectively
- More powerful due to higher MSE probability in larger ICPC detectors
- PSD suppression in physics data depends on actual background composition and location







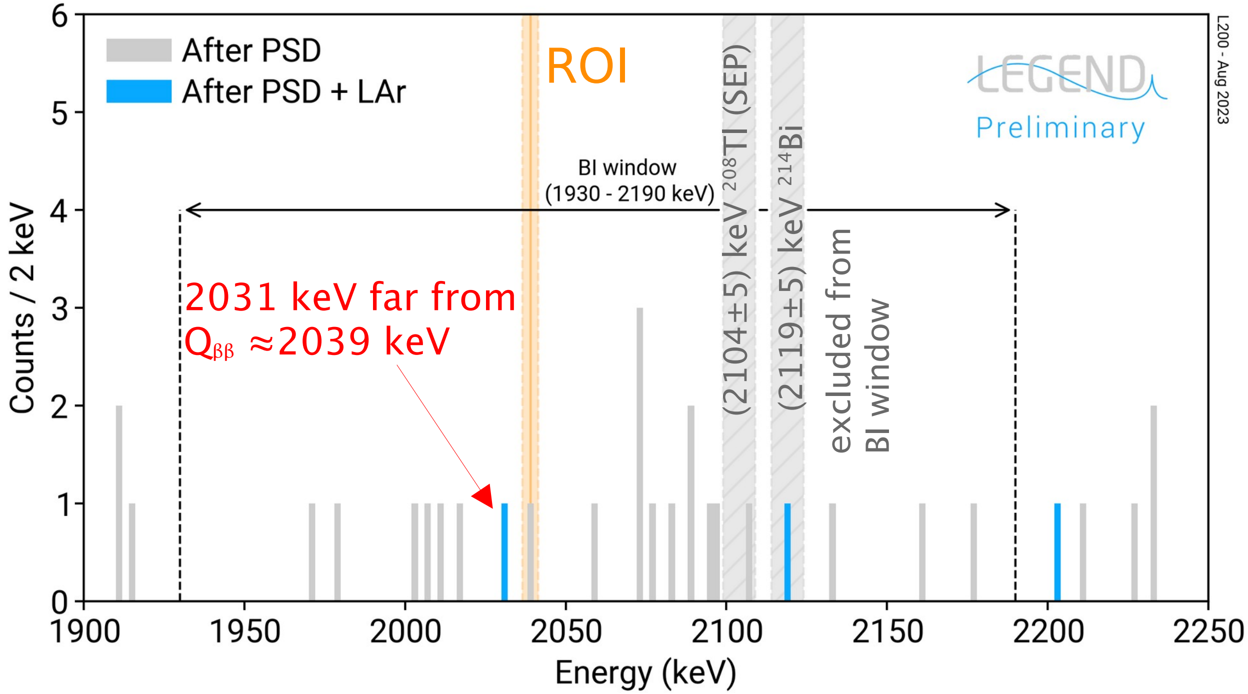
LEGEND vs. GERDA BEGe +ICPC

Background Index

- Analized first 10.1 kg·yr of LEGEND-200 data
- ICPC&BEGe detectors
- Events in the BI-window (1930–2190) keV after QC + LAr and PSD cuts
- BI is compatible with LEGEND-200 goal:

  $2 \cdot 10^{-4}$ cts/(keV·kg·yr)
- Expect 0.4 cts
- Probability to observe

  #cts > 0 ~38%



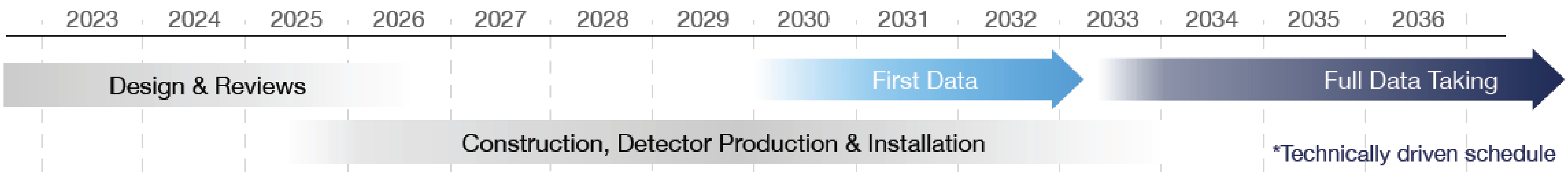
	LEGEND-200 BI 68%CL(cts/keV/kg/yr)	GERDA Phase II unblinded BI 68% CL(cts/keV/kg/yr)
After LAr & PS	$4.1\ [1.5\text{–}11.4] \cdot 10^{-4}$	$5.2\ [3.9\text{–}6.8] \cdot 10^{-4}$

LEGEND-1000

performance parameters & timeline

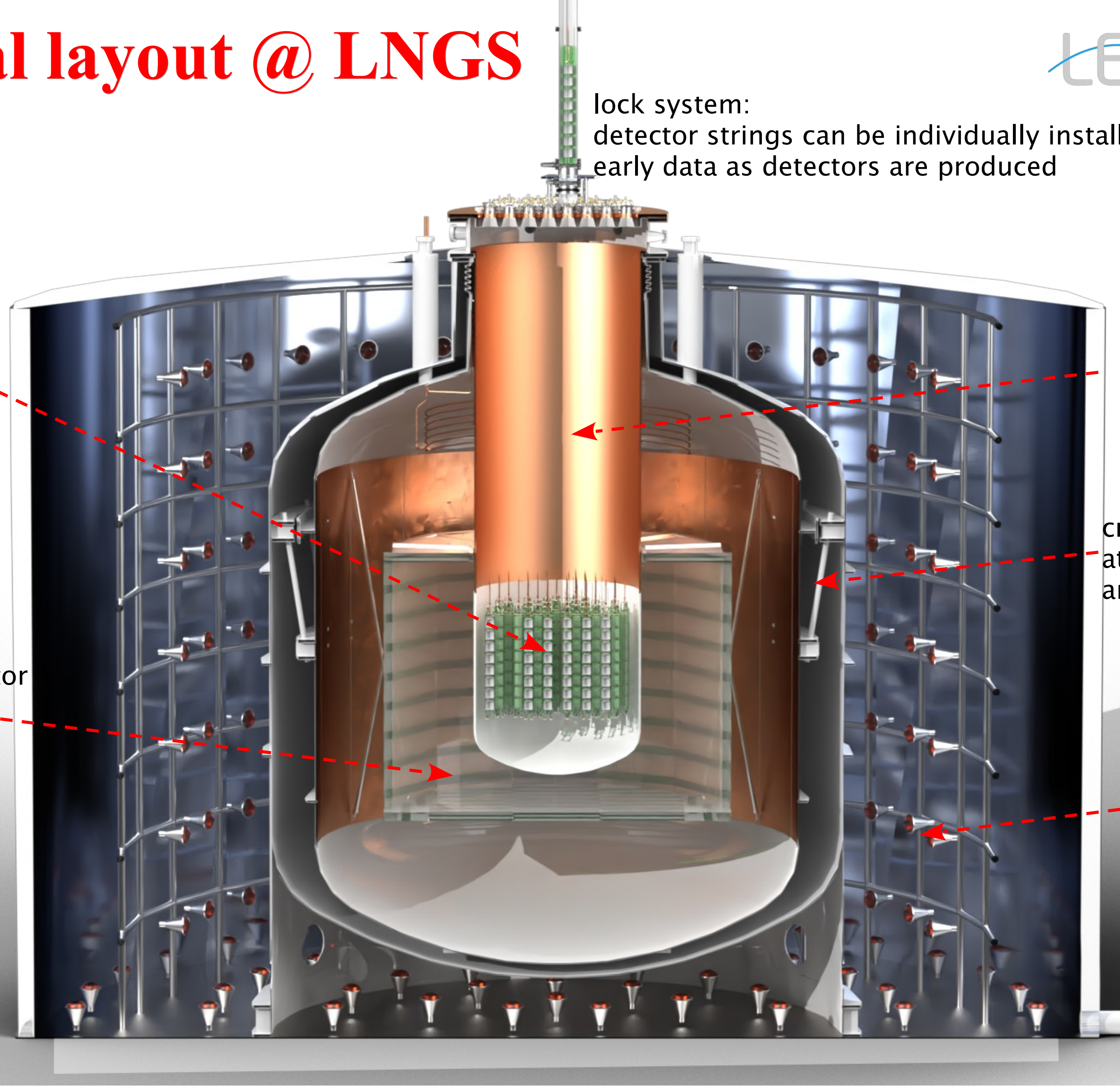
LEGEND

$0\nu\beta\beta$ decay isotope	^{76}Ge
$Q_{\beta\beta}$	2039 keV
Total mass	1000 kg
Energy resolution at $Q_{\beta\beta}$	2.5 keV FWHM
Overall signal acceptance	0.69
Total exposure	10 t·yr
Background goal	$< 10^{-5}$ cts/(keV·kg·yr) < 0.025 cts/(FWHM·t·yr)
$T^{0\nu}_{1/2}$	$1.3 \cdot 10^{28}$ yr (90% C.L. discovery) $1.8 \cdot 10^{28}$ yr (90% C.L. sensitivity)
$m_{\beta\beta}$	9.4 – 21.4 meV (99.7% C.L. discovery) 8.5 – 19.4 meV (90% C.L. sensivity)

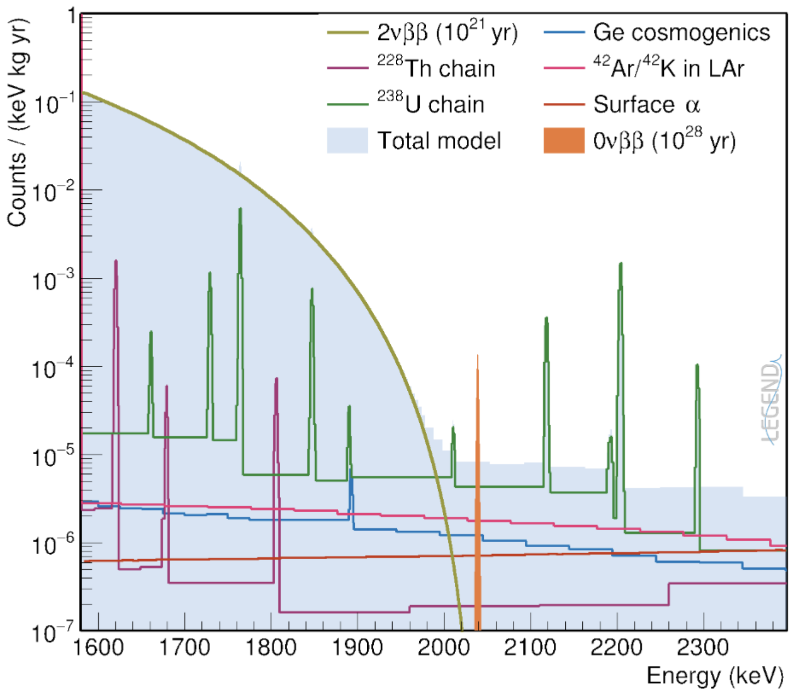


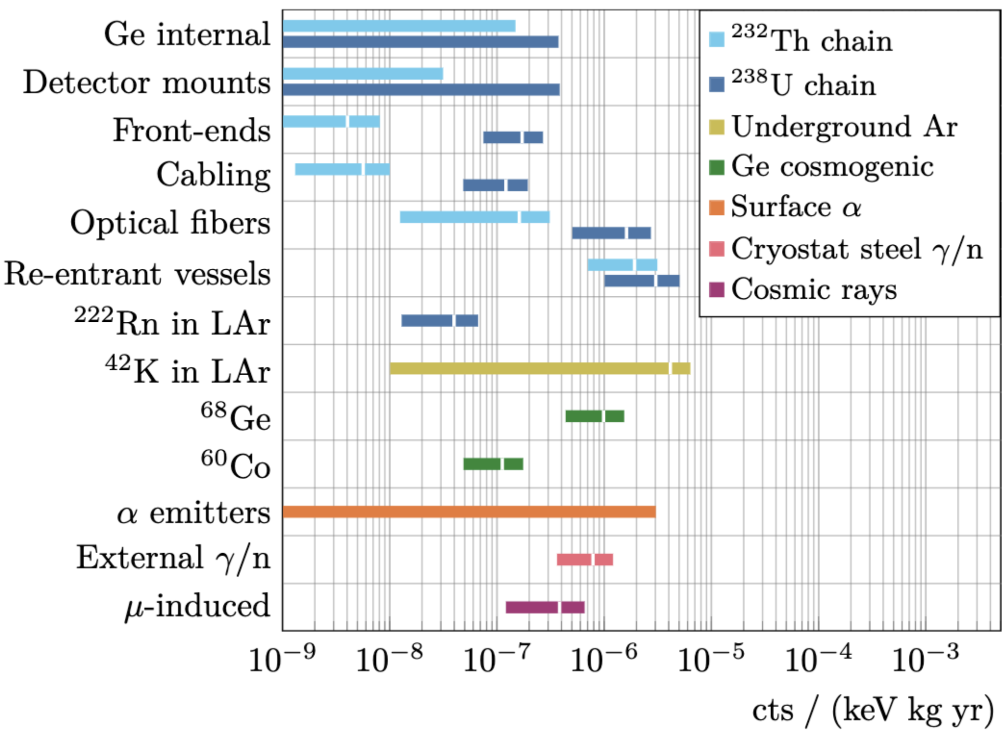
General layout @ LNGS

LEGEND



LEGEND-1000 background projections





Expected total spectrum from 2νββ decay and from all background components after all cuts

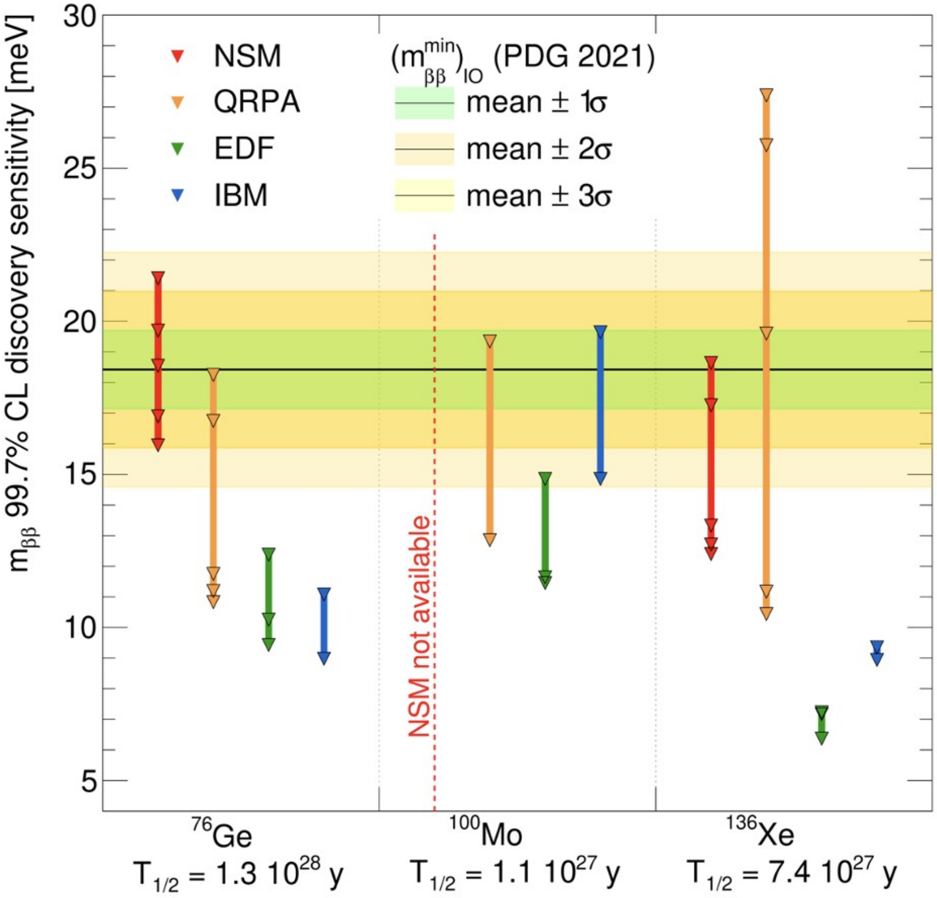
Projected background index after all cuts:

$13.2^{+7.4}_{-8.4} \cdot 10^{-6}$ cts/(keV·kg·yr)

LEGEND-1000 target sensitivities

- $m_{\beta\beta} = m_e / \sqrt{G g_A^4 M^2 T_{1/2}}$
- Inverted Ordering: $m_{\beta\beta} > 18.4 \pm 1.3$ meV
- the discovery sensitivity required depends on the matrix element used
- the range of values given depends on the matrix elements that has been calculated for each isotope
- LEGEND-1000 will fully test inverted order and a large part of the normal ordering

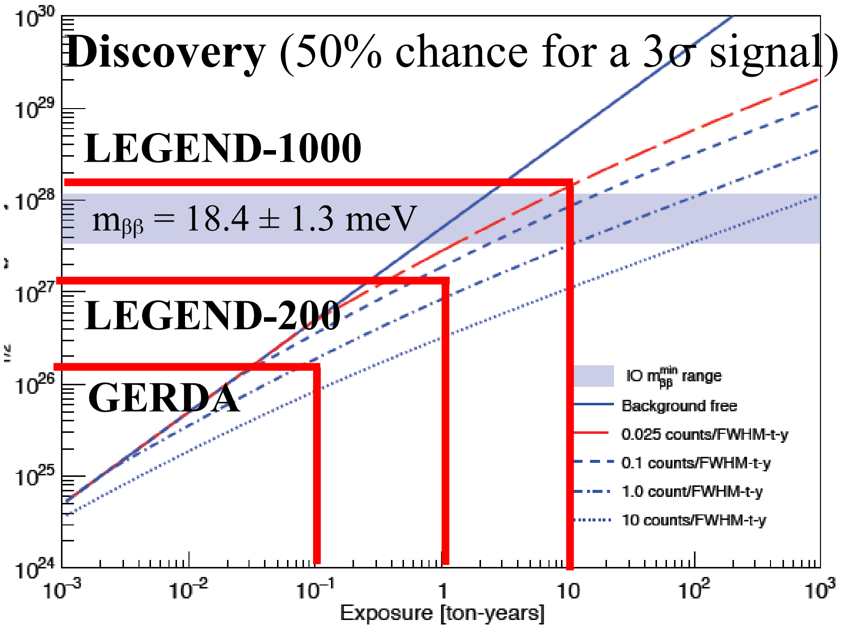
Agostini, Detwiler, Benato, Menendez, Vissani
PRC, 104 (4) L042501 (2021)



LEGEND CUPID NEXO

Summary

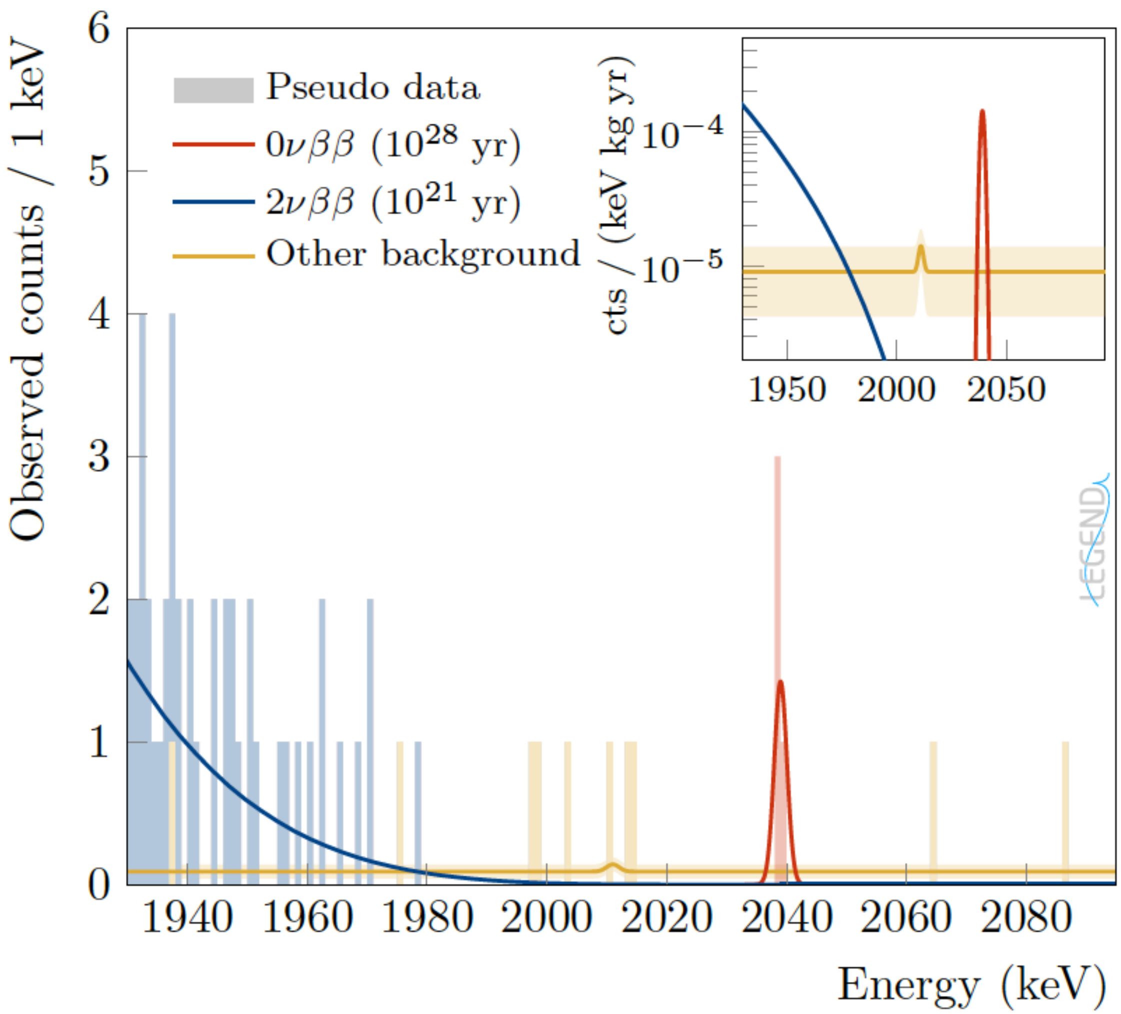
- The LEGEND experiment combines the best technologies from the two Ge experiments: GERDA and MAJORANA-DEMONSTRATOR
- Key feature is the staged approach: leading results at each phase
- The **first phase is LEGEND-200 at LNGS** using the GERDA infrastructure: the aim is to reach the limit of 10^{27} yr in the half-life of the $0\nu\beta\beta$ decay of ^{76}Ge



- LEGEND-200 is **now taking data:** the first data show that the BI is not far from the LEGEND-200 goal. With much more statistics, we are now studying the background sources in detail
- **The ultimate phase will be LEGEND-1000** able to reach an half-life greater than 10^{28} yr covering the entire inverted ordering region
- The LEGEND-1000 approval process is already begun: DOE Portfolio review (July 2021) for the choice of the best Ton-scale experiment put highest priority on LEGEND-1000.

backup slides

discovering 0νββ with LEGEND-1000



… zooming around the signal region

efficiencies

Efficiencies	MJD/GERDA Achieved	LEGEND-1000 Projected
Active volume fraction	88.5%	92.0%*
Containment efficiency	89.0%	92.0%*
Fraction of isotopic mass	87.5%	91.0%
Analysis cuts	90.0%	90.0%
Total (w/o ROI)	62.0%	**69.3%**
Events in ROI	95.0%	95.0%
Total (w/ ROI)	58.9%	**65.9%**

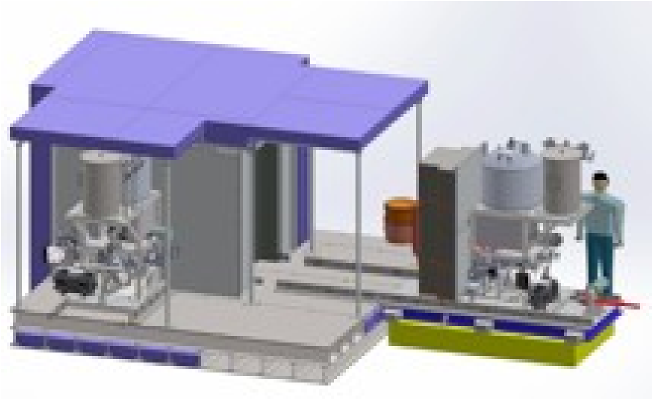
*Improvement due to larger-mass ICPC detectors

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)

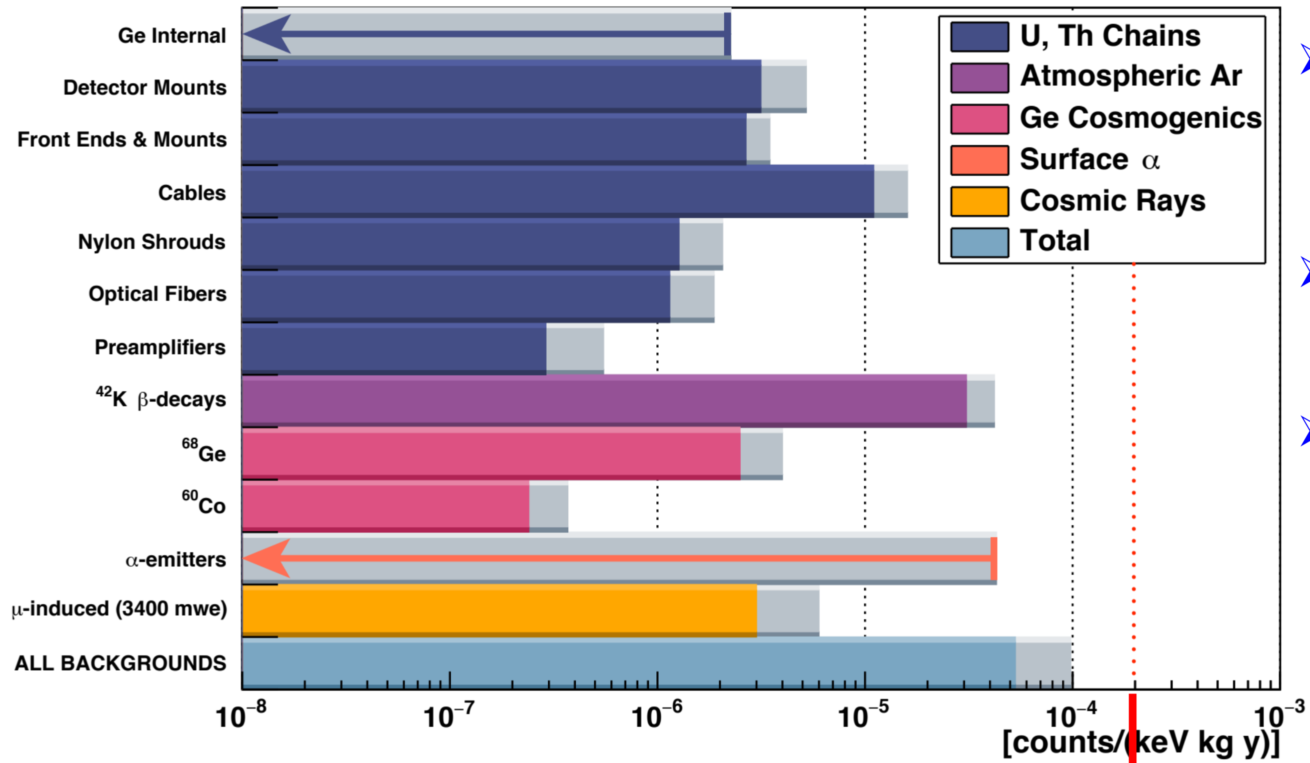


- Arrays of ^{enr}Ge housed in high-purity electroformed copper cryostat
- Shield: electroformed copper/lead
- 30 kg enriched in ^{76}Ge

> ➢ **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:

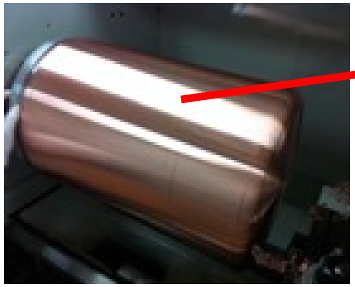
$T_{1/2} > 10^{27}$ years (90% CL) after **1 ton·yr** of exposure

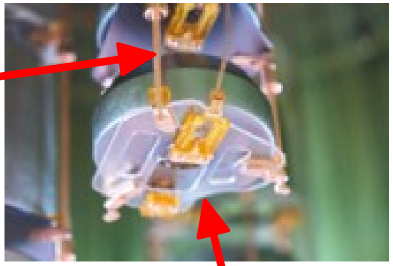
$m_{\beta\beta} < 27 - 64$ meV

clean materials

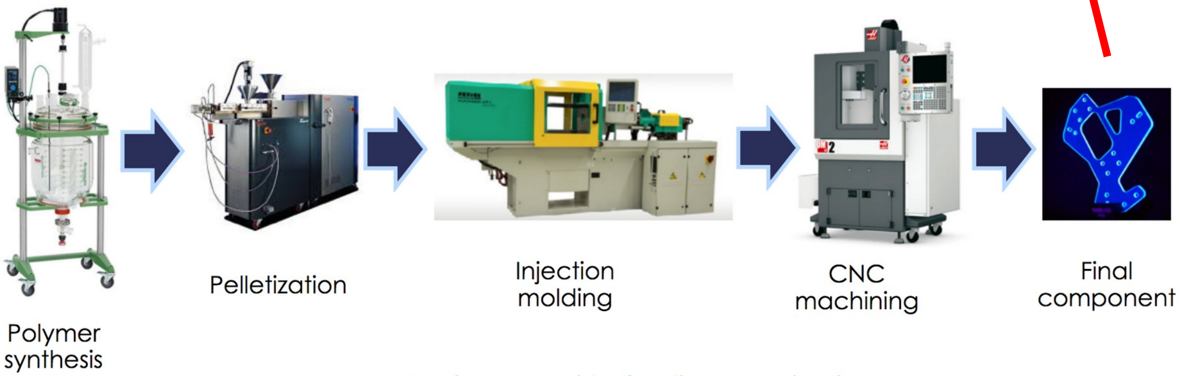
- **Underground electroformed copper**
  reduces U/Th cosmogenic activation of ^{60}Co in Cu
  $< 0.017 \pm 0.03$ pg(^{238}U)/g
  $< 0.011 \pm 0.05$ pg(^{232}Th)/g

Underground electroformed copper



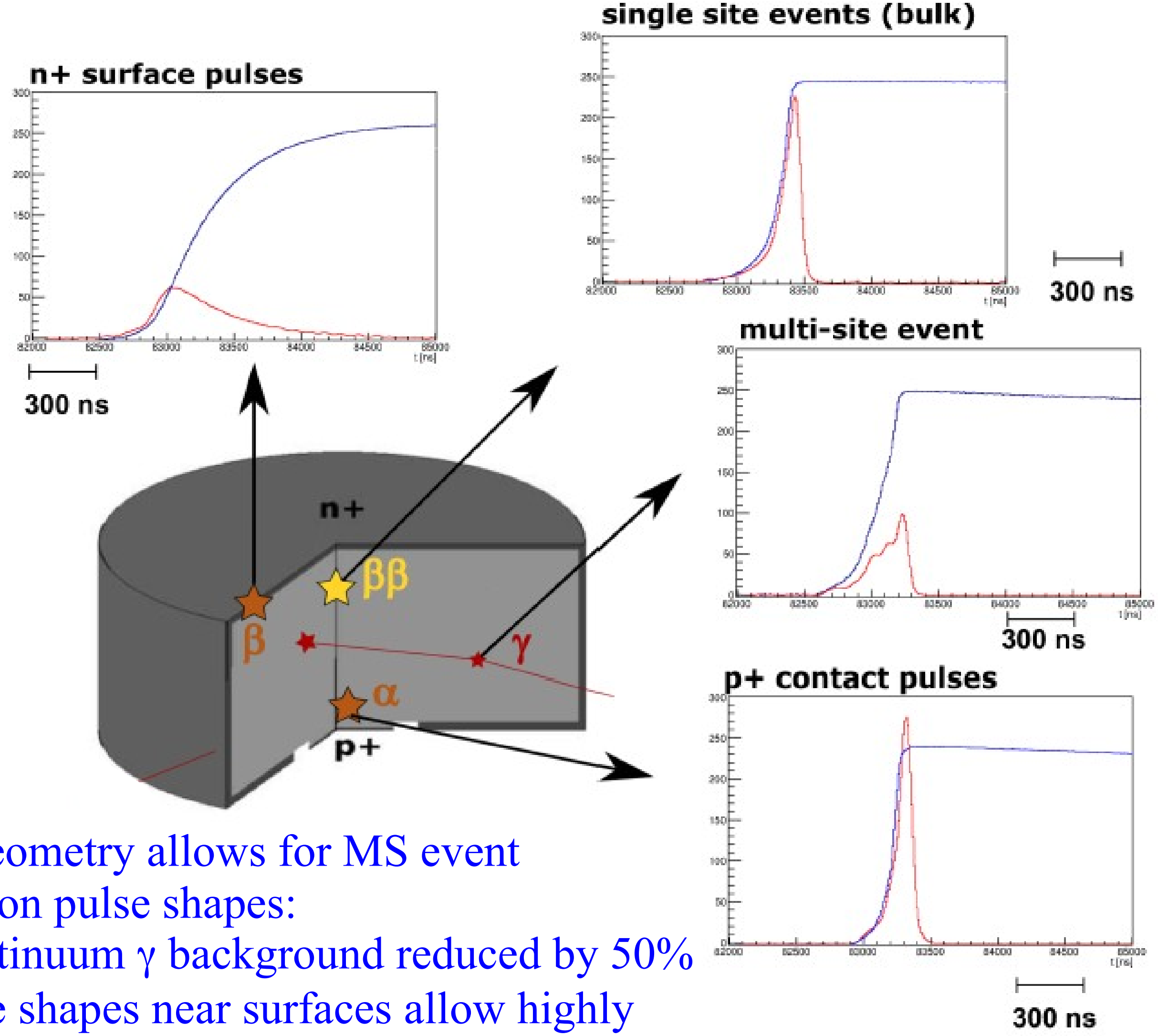


- **Polyethylene naphtalene (PEN)**
  replaces optically inactive structural materials
- Shift 128 nm LAr scintillation light to ~440 nm
- Yield strength higher than copper at cryogenic temperatures
- Evaluated in L-200



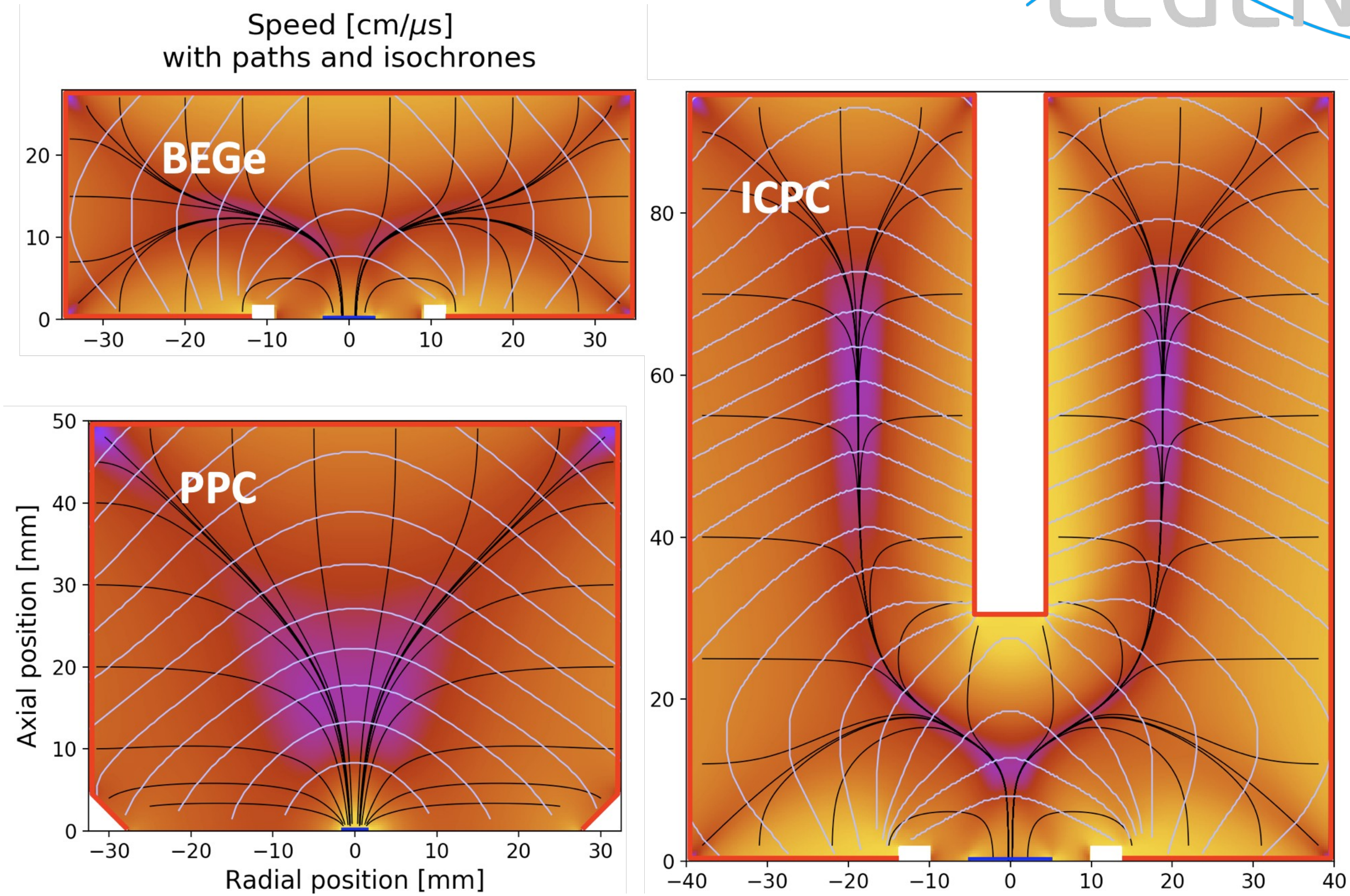
PEN: scintillating high purity detector support

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%

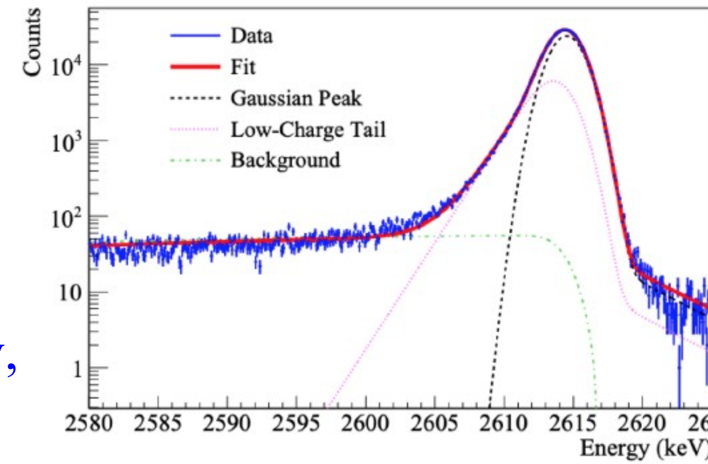
Ge Detectors



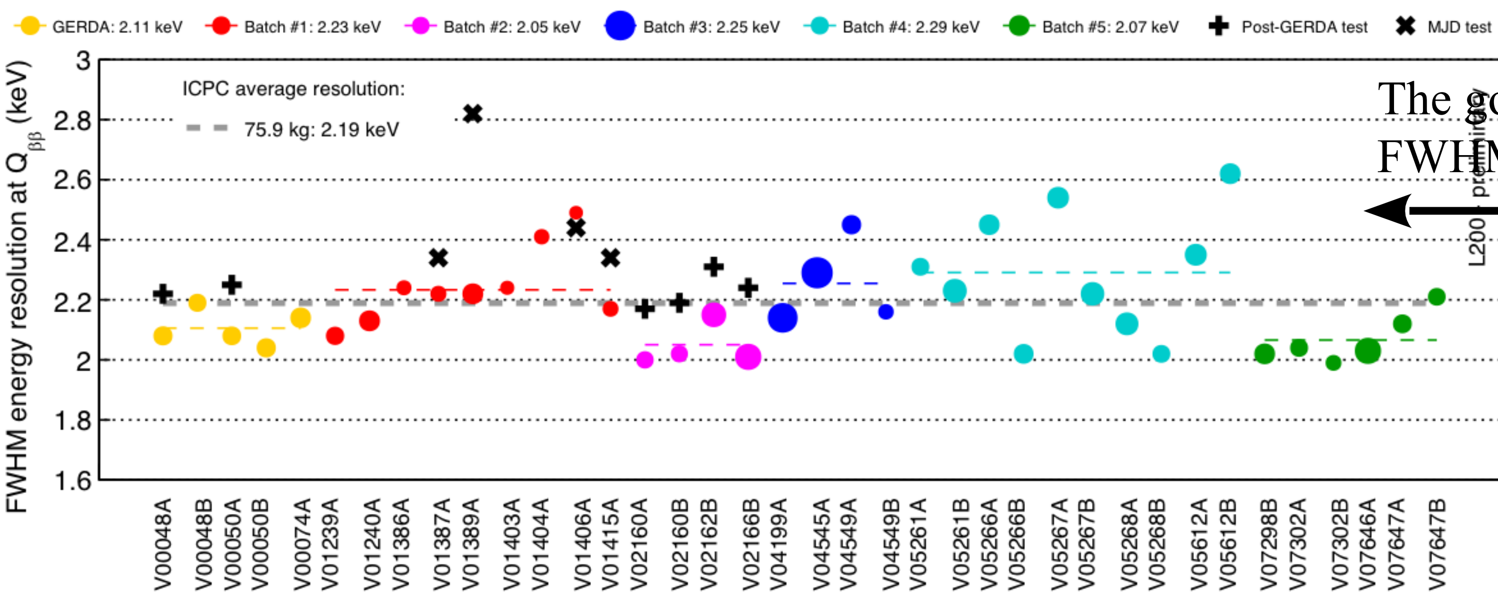
In LEGEND-200 four different types of enriched Ge detectors will be used:
BEGe (GERDA), PPC (Majorana), **ICPC** (GERDA, L-200) and semicoax (GERDA)

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

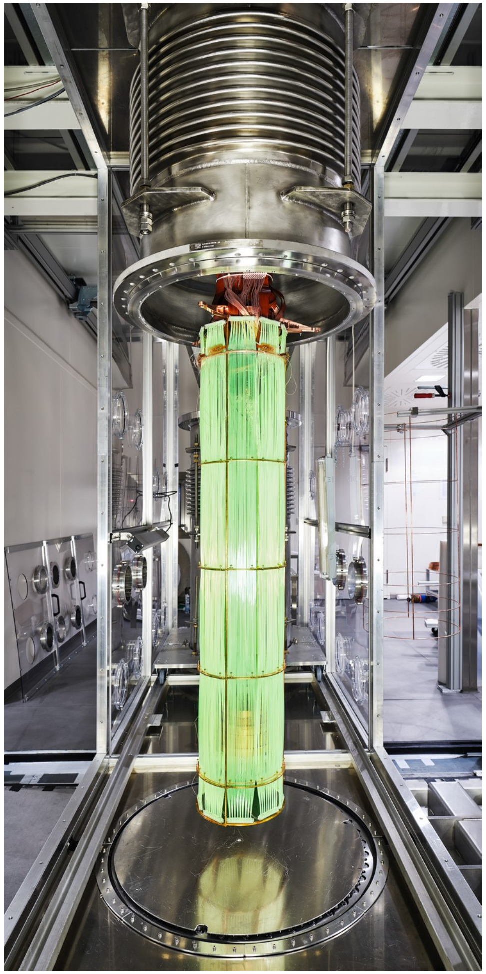


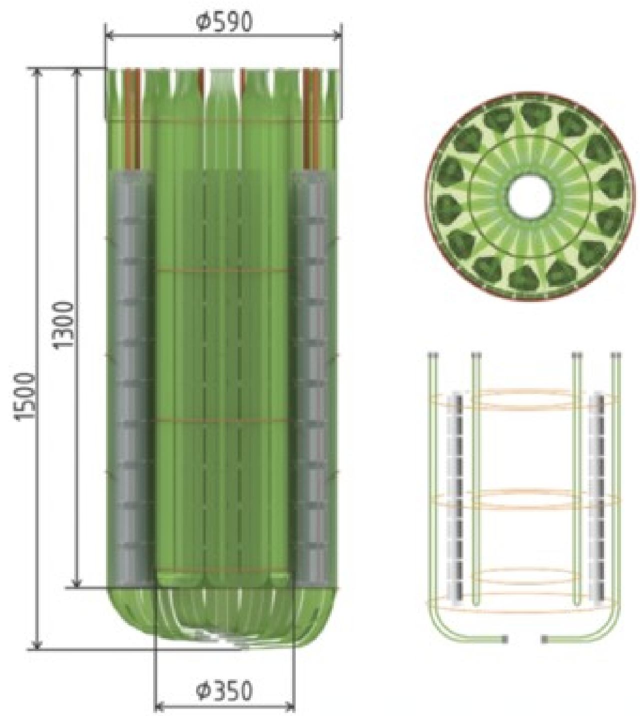
Energy resolution of ICPCs from characterization tests and calibration runs in GERDA and MJD



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

LAr veto



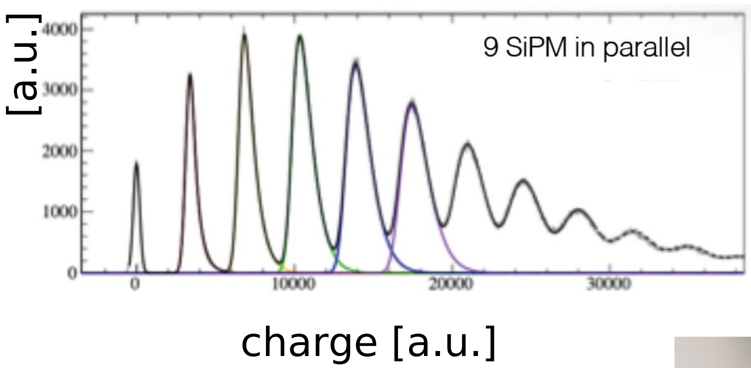


Internal LAr Veto :
9 modules, 18 readout channels

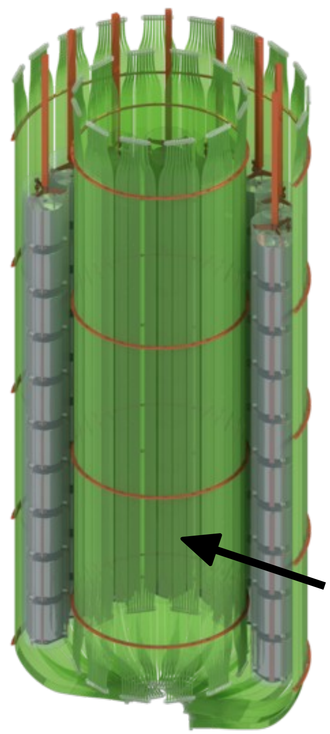
External LAr Veto:
20 modules, 40 readout channels

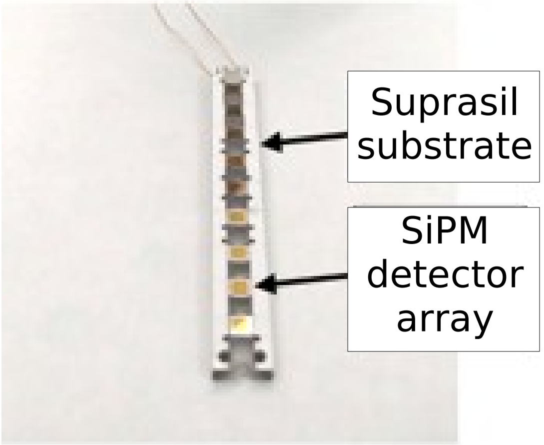
Liquid Argon Veto

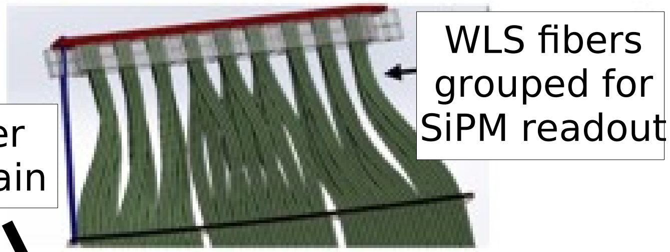
- 128 nm LAr scintillation light readout by TPB coated WLS fibers coupled to SiPMs arrays
- Single photo-electron resolution



L-200

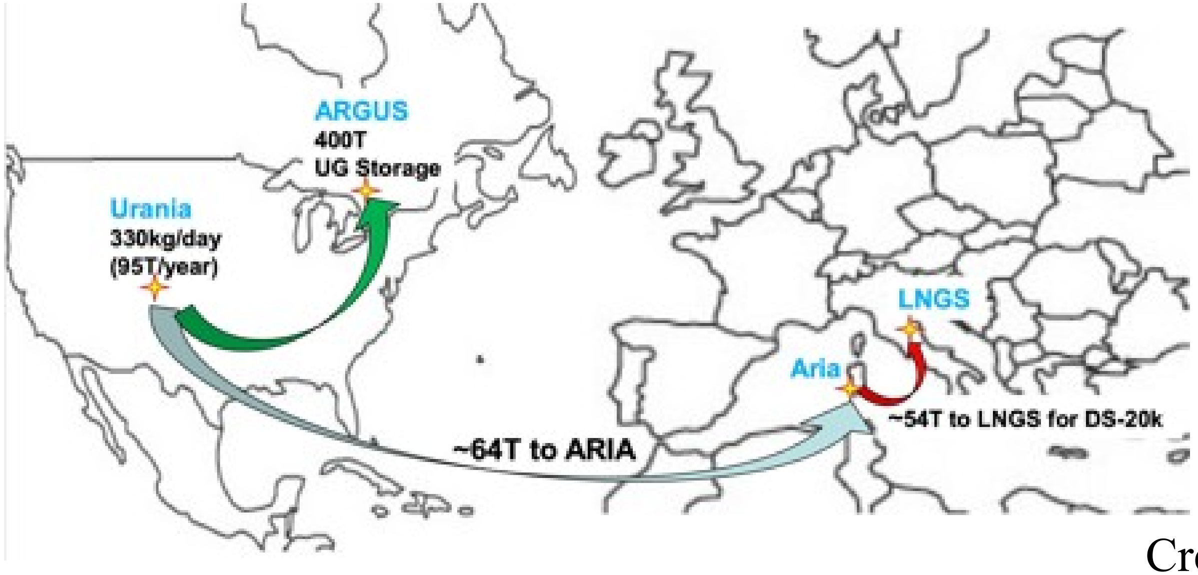






Underground Liquid Argon

- one of the most important background: ^{42}K from ^{42}Ar (produced in atmosphere by cosmic rays)
- in GERDA and in LEGEND-200 under control thanks to nylon minishrouds and PSD
- in LEGEND-1000 we think to use underground Ar (~18.5 t in the 4 re-entrant tubes)
- technology developed by the DarkSide collaboration
- expected a reduction factor of ~1400 in ^{42}Ar respect to the ^{42}Ar content in atmospheric Ar (similar to the reduction of ^{39}Ar)



Credit: DarkSide/Argo collaboration

First LEGEND-200 background data

Look at
- Background before and after LAr and PSD cuts

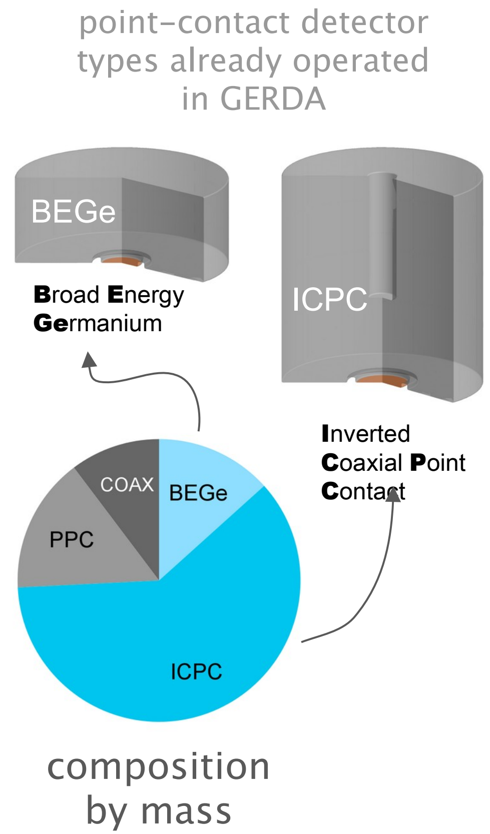
- Compare with GERDA

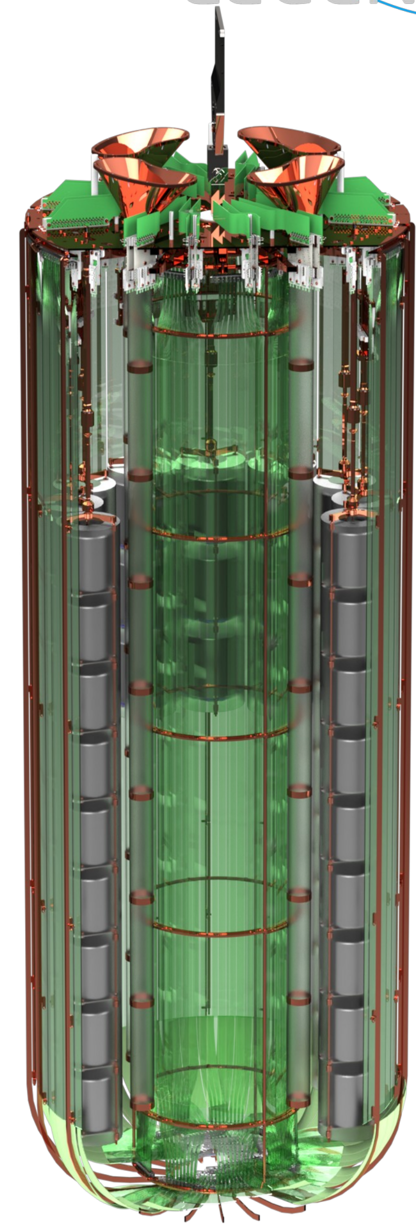
Dataset based on BEGe & ICPC detectors
- Directly comparable with GERDA

- Mono-parametric PSD (A/E)

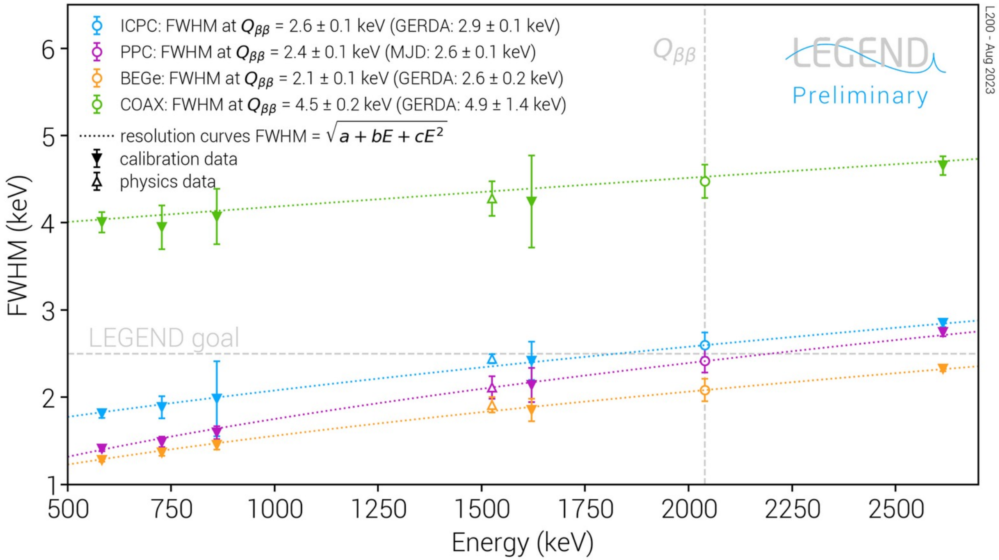
- No blinding applied

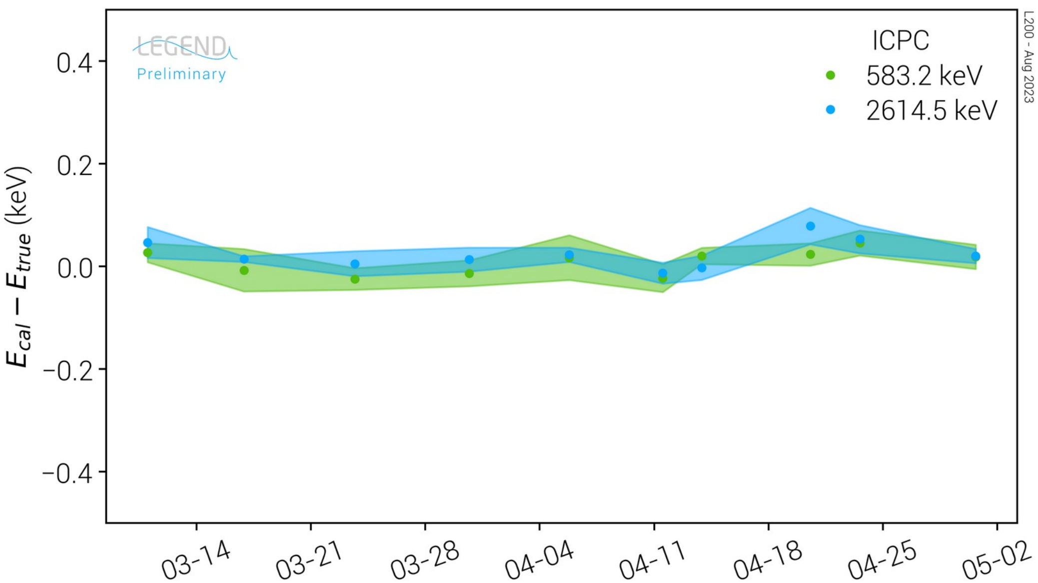
Exposure (kg·yr)	BEGe	ICPC
10.1	2.1	8.0





Energy Resolution and Stability



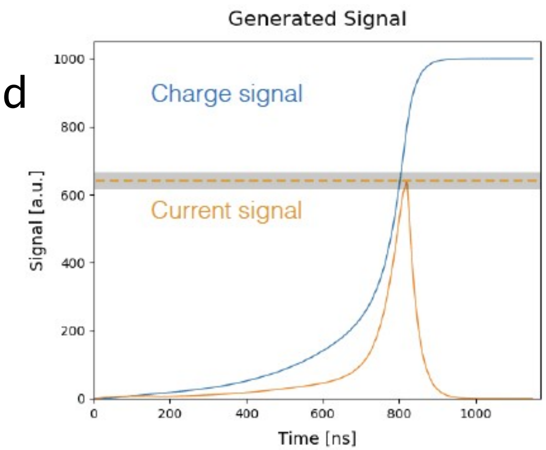


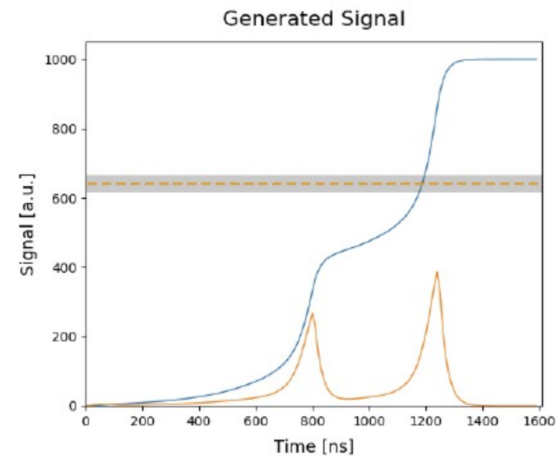
Weekly energy calibration between physics runs using ^{228}Th sources

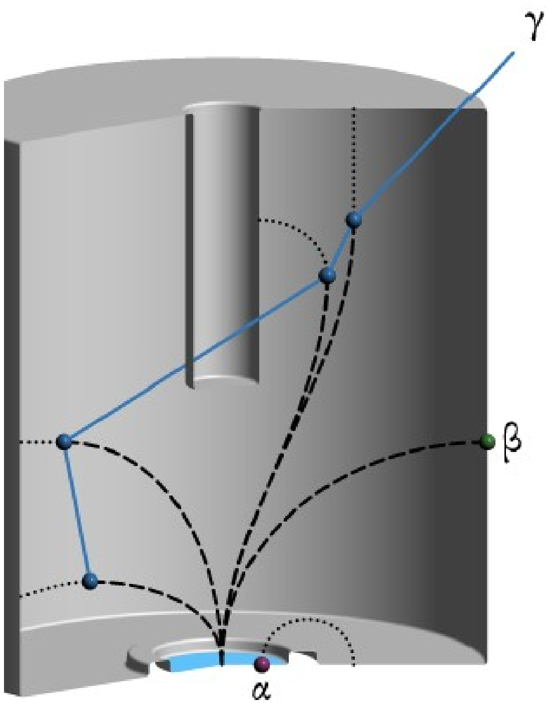
- Excellent energy resolution @ $Q_{\beta\beta}$
- Energy scale very stable between calibrations

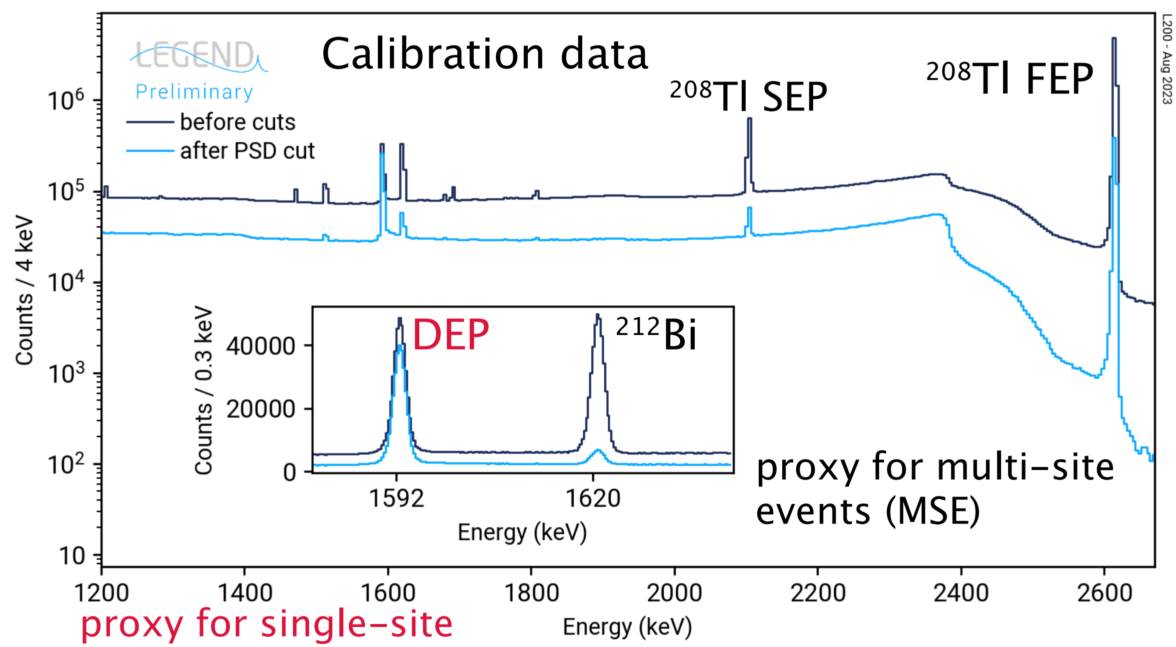
Pulse Shape Discrimination

- based on A/E parameter, evaluated for each event
- PSD tuned to 90% survival at ^{208}Tl DEP
  → very good rejection of MSE
  →



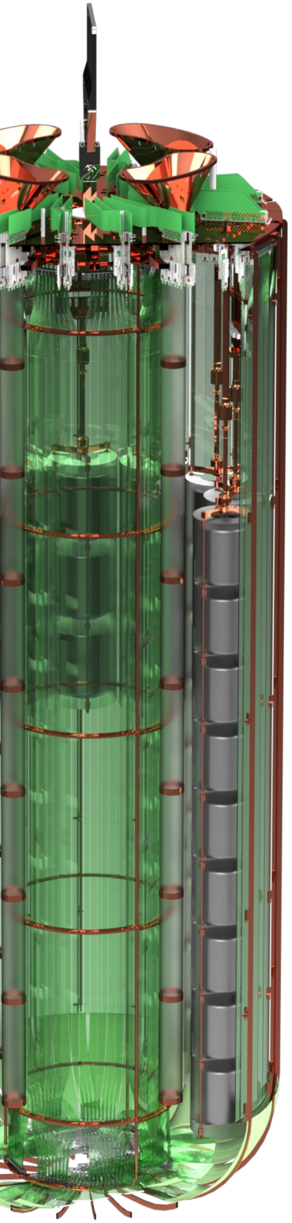






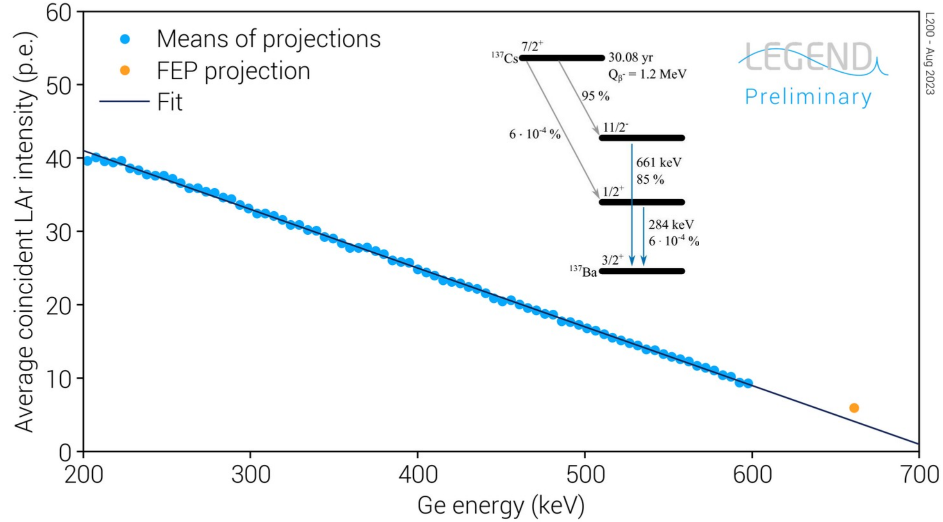
proxy for single-site events (SSE)

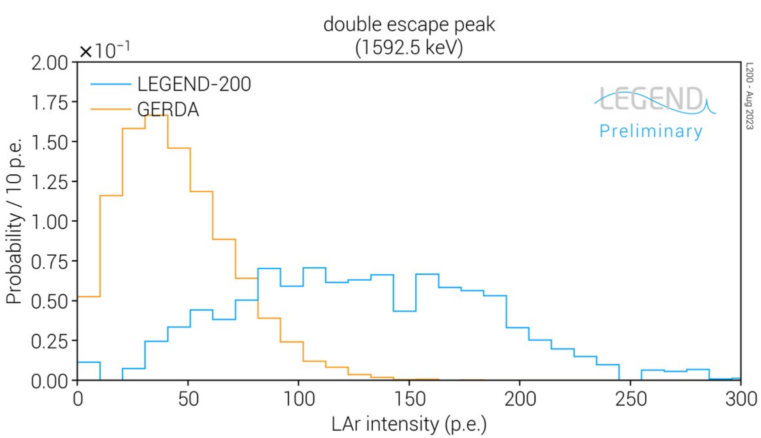
LAr Instrumentation

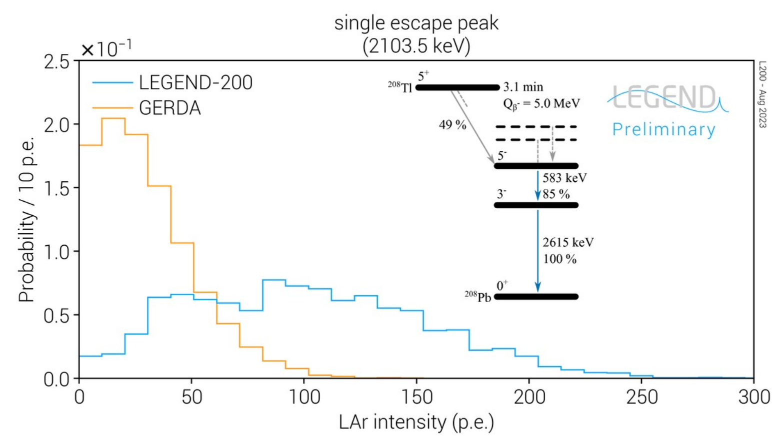


- Improved Si photo-multiplier (SiPM) readout
  Improved geometry + optically active PEN → less shadowing
- Improved wavelength-shifting (TPB) fiber coating

→ ~ 3 more light wrt. GERDA







2νββ shape and uniformity after QC + LAr AC

- Spectral shape compatible with 2νββ after LAr instrumentation anti-coincidence (LAr AC)
- ^{40}K & ^{42}K Compton edges vanish

- Uniform rate/detector in (1000-1300) keV
  - Normalized to detector specific exposure
  - BEGe/ICPC different containment eff.
- After LAr AC: Medium energy region dominated by 2νββ events