Neutrinoless double-beta decay search with the LEGEND Experiment

Riccardo Brugnera

Università degli Studi di Padova e INFN Padova

on behalf of the LEGEND Collaboration

Outline:

- Double-beta decay
- The LEGEND Experiment: general aspects
- The first stage: LEGEND-200
- LEGEND-1000

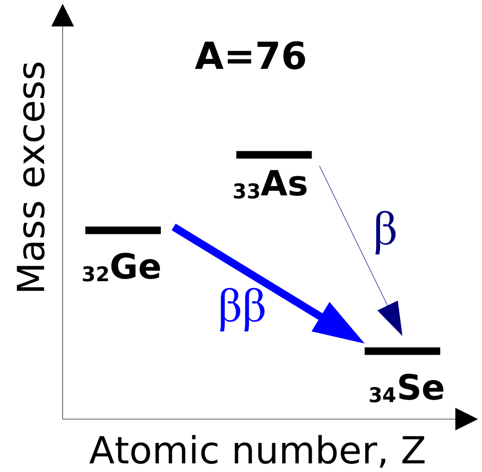
LEGEND

$2\nu\beta\beta$ and $0\nu\beta\beta$ decays

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

2nd order process, observed, $T_{1/2} \sim 10^{19}$–10^{24} yrs

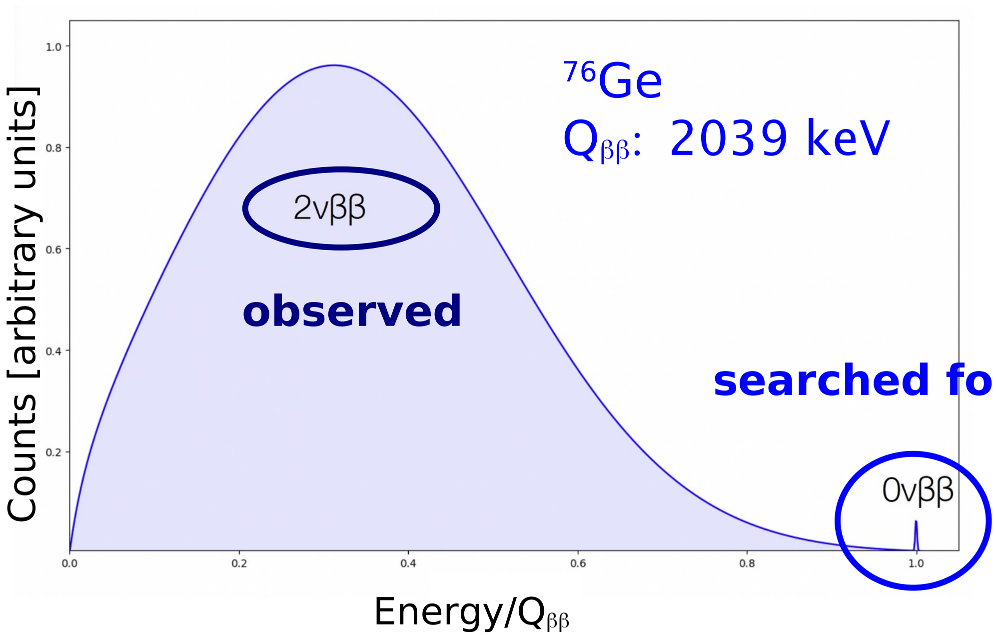
^{76}Ge: $T_{1/2} \sim 10^{21}$ yrs



$0\nu\beta\beta$: $(A,Z) \rightarrow (A,Z+2) + 2e^-$

new physics, $T_{1/2} > 10^{26}$ yrs

Signature for $0\nu\beta\beta$ decays:

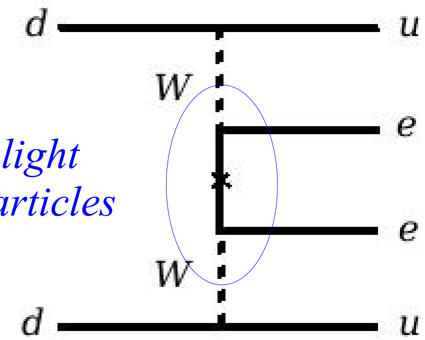


motivation for $0\nu\beta\beta$ decay searches

- would establish ***lepton number violation*** $\Delta L = 2$
- more ***physics beyond standard model***
- Only way to determine if neutrino is its own antiparticle:

$\nu = \bar{\nu}$ ⟶ ***Majorana particle***

exchange of light Majorana particles



If YES:

- would provide access to ***absolute neutrino mass scale***

$$\left(T^{0\nu}_{1/2}\right)^{-1} = G^{0\nu}(Q_{\beta\beta}, Z)\ \left|M^{0\nu}\right|^2 \left(\frac{\langle m_{\beta\beta}\rangle}{m_e}\right)^2 \qquad \langle m_{\beta\beta}\rangle = \left|\sum_i U^2_{ei} m_i\right|$$

nuclear matrix element

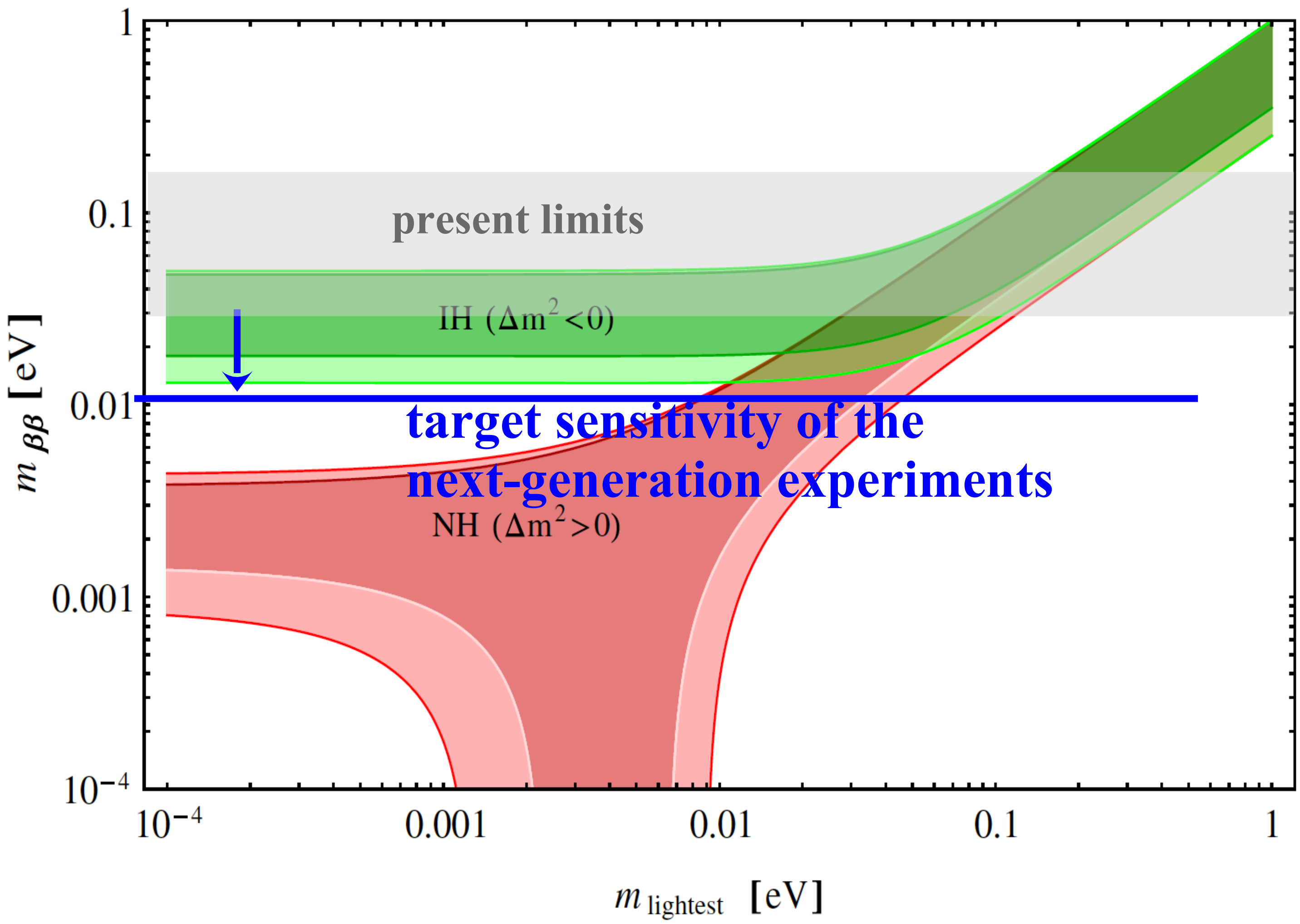
phase space factor

effective Majorana neutrino mass

- would provide ***important input to cosmology***

$m_{\beta\beta}$ vs. lightest ν mass

deduced from oscillation data and scan of Majorana phases



S. Dell'Oro, S. Marcocci, F. Vissani, PRD 90 (2014)

! Plot applies for 3 generations & light neutrinos

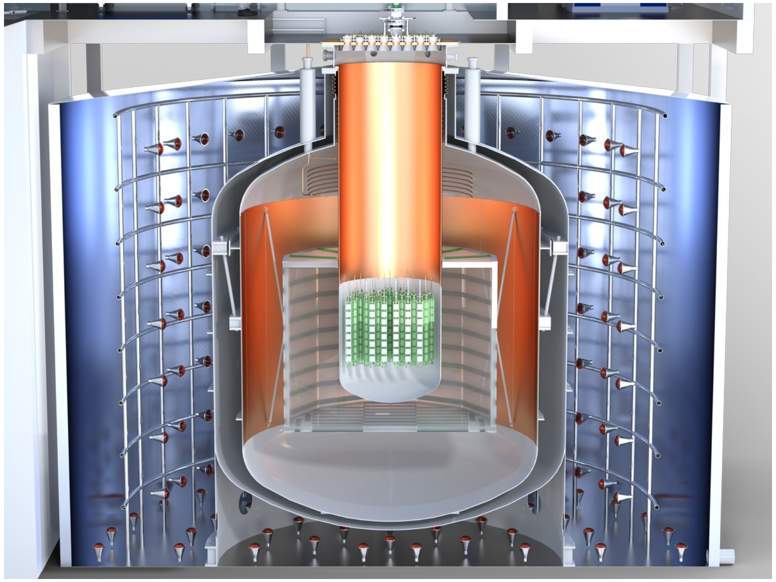
Large Enriched Germanium Experiment for Neutrinoless ββ Decay - LEGEND

~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"

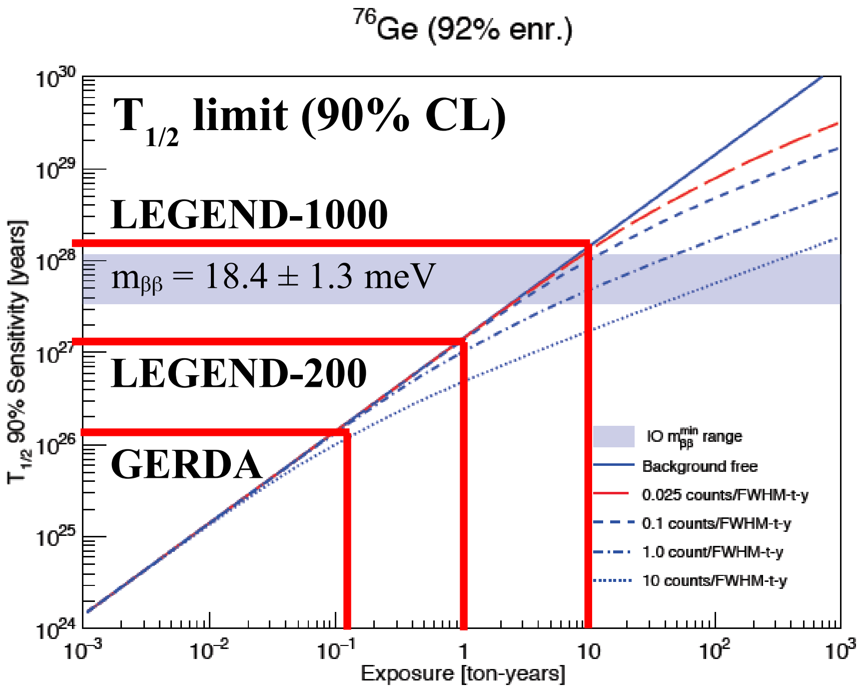
LEGEND: a staged approach

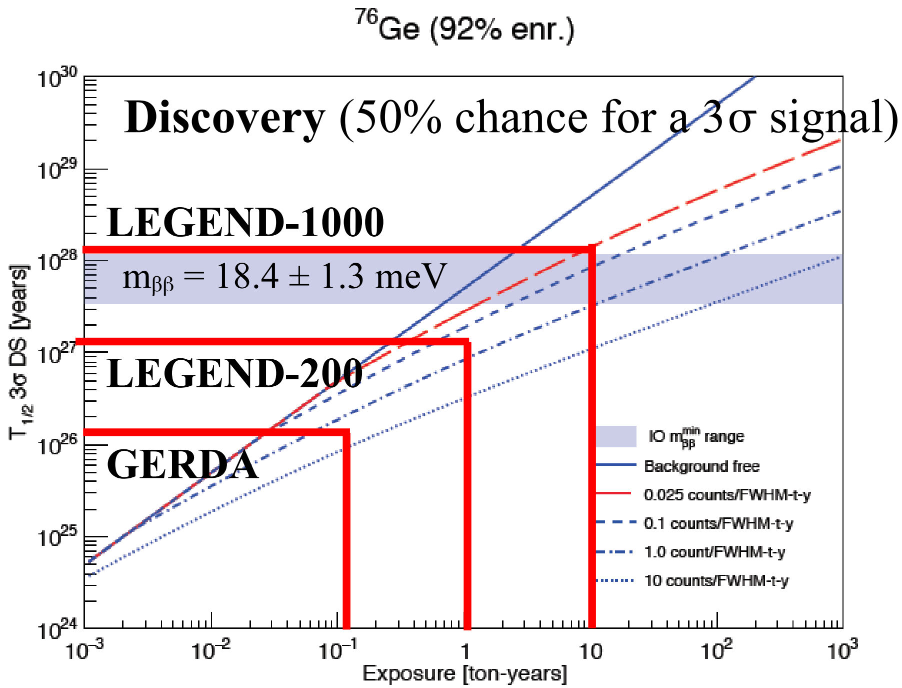
First Stage (LEGEND-200):
- upgrade of the existing infrastructure of GERDA up to 200 kg
- reduction of the Background Index (BI) of a factor 5 w.r.t. GERDA Phase II goal
- to reach 200 kg: 35 kg from GERDA + 30 kg from MJD. The remaining 140 kg are new



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; **Nov 2021**: start commissioning
- **March 2023**: start of the physics run with ~140 kg of Ge detectors made of material isotopically enriched in ^{76}Ge to ~86%-92%

- **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

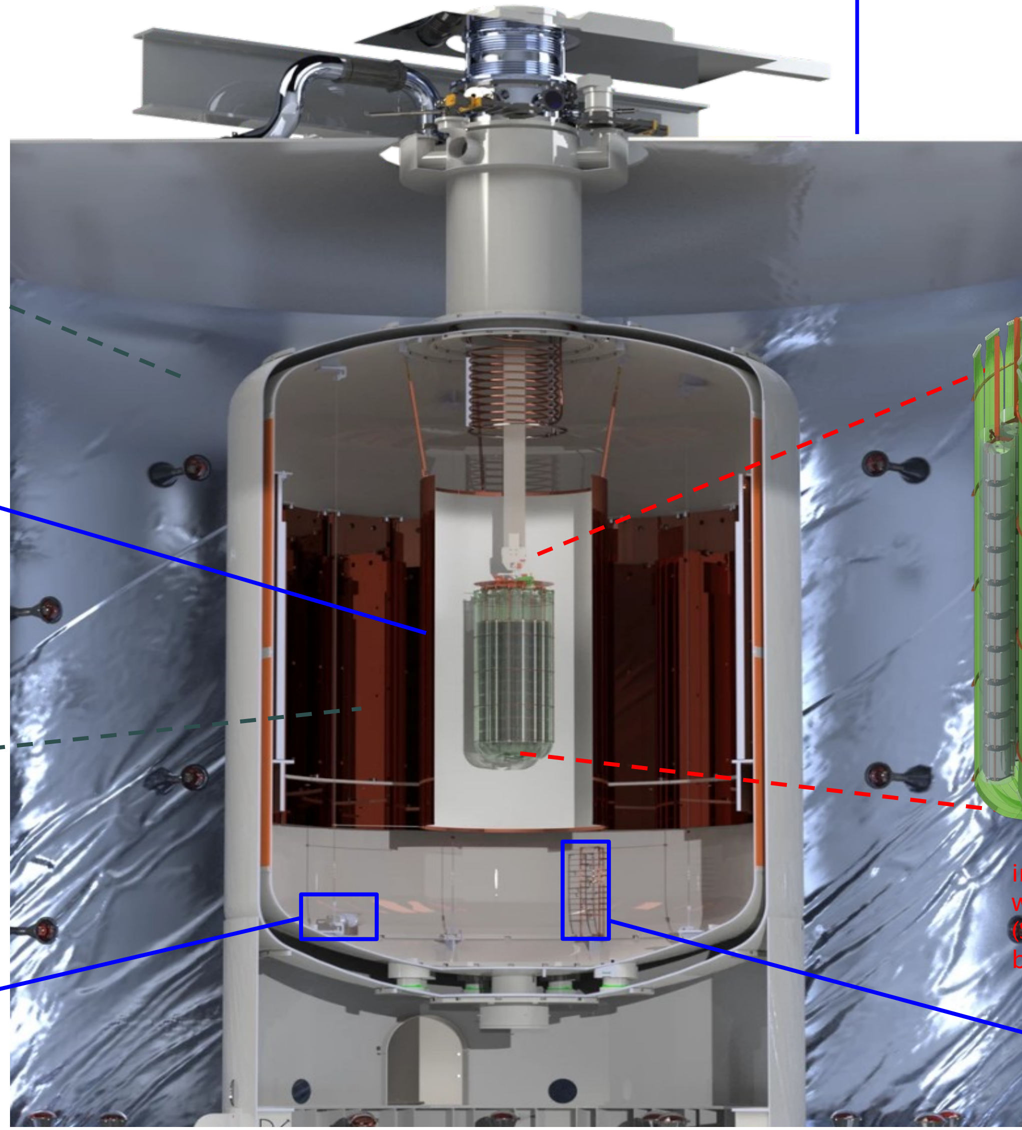
Clean room lifted

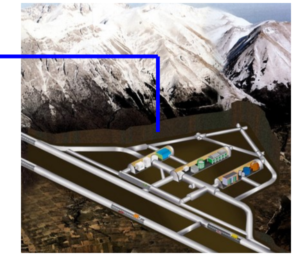
Water Cherenkov muon veto

Teflon Reflector for better light collection

Copper lined stainless steel cryostat

LAr purification

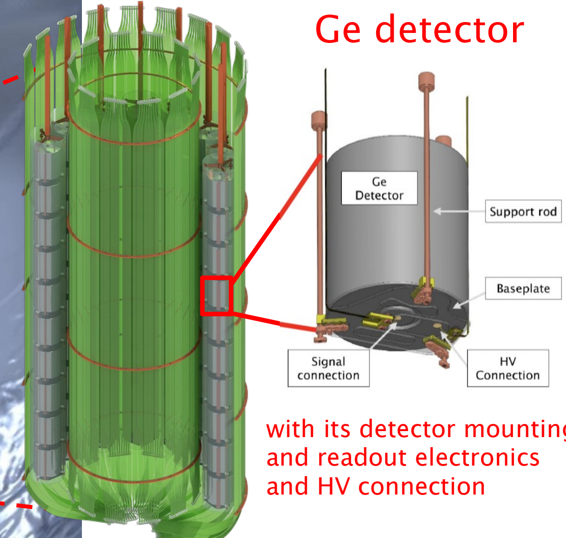




LNGS
Hall A
3600 m.w.e.

LAr veto

Ge detector

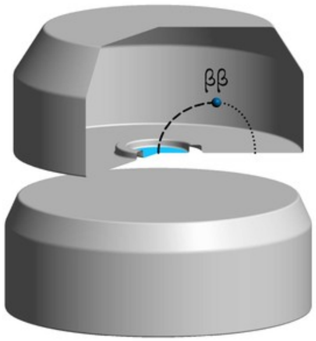


with its detector mounting and readout electronics and HV connection

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

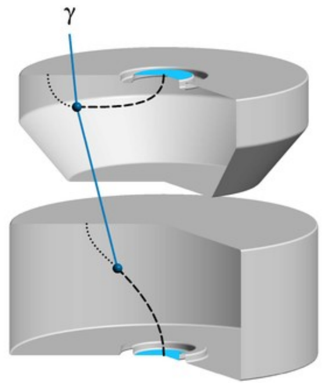
LLAMA
LAr quality monitoring

active background reduction tools



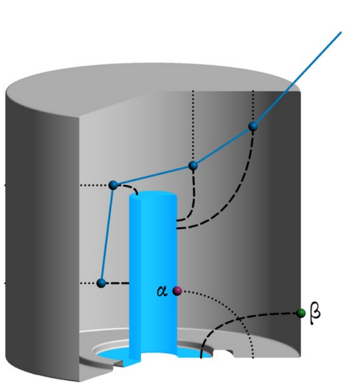
Single-site event topology (SSE)

- 2νββ
- 0νββ



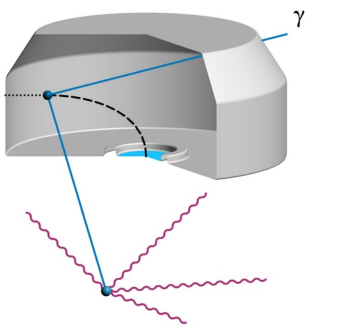
Detector multiplicity

- scattered events



Pulse Shape Discrimination (PSD)

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



LAr-anti coincidence

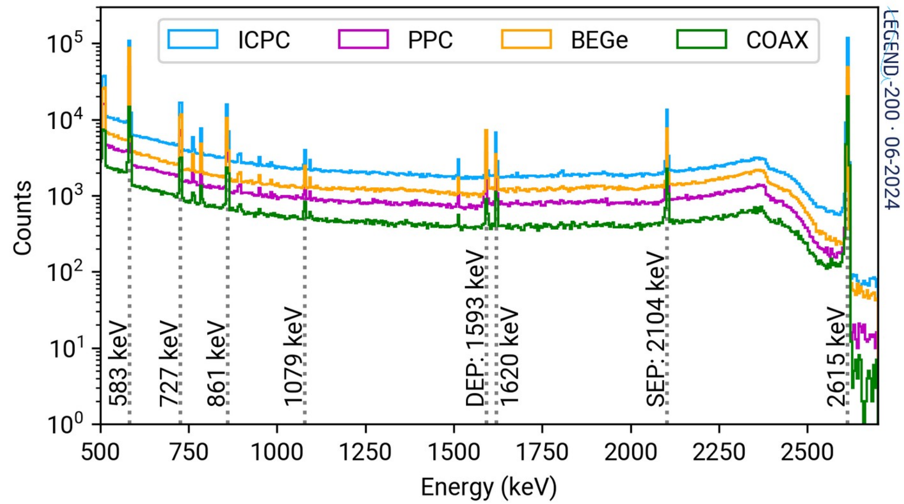
- intrinsic backgrounds
- Ge cosmogenics

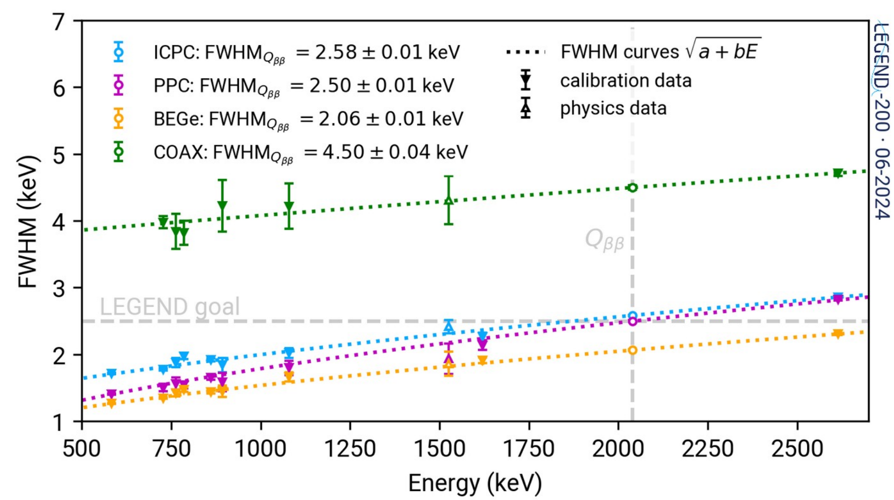
Water Cherenkov anti-coincidence

- muons

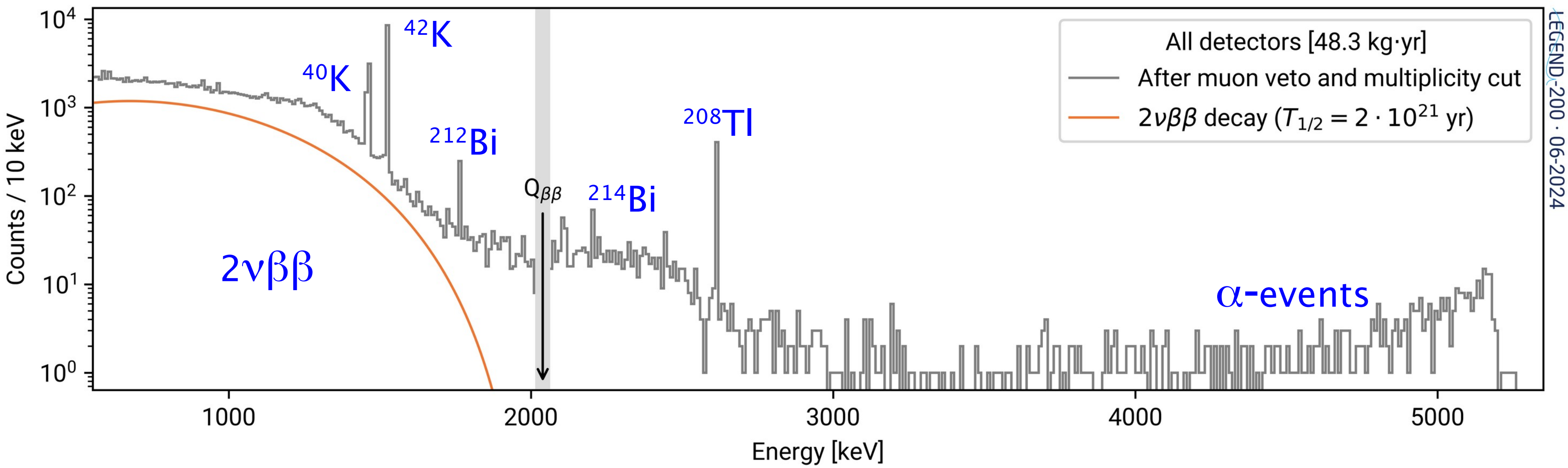
Collected Data and Energy Resolution

- 4 types of Ge detectors are used: **ICPC, BEGe, PPC, Coax**
  - enriched in ^{76}Ge at the level **86%–92%**
- **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** for all types of Ge detectors used: **~0.1% FWHM at $Q_{\beta\beta}$**
- **Stable** energy observables
  - monitored with weekly ^{228}Th calibrations



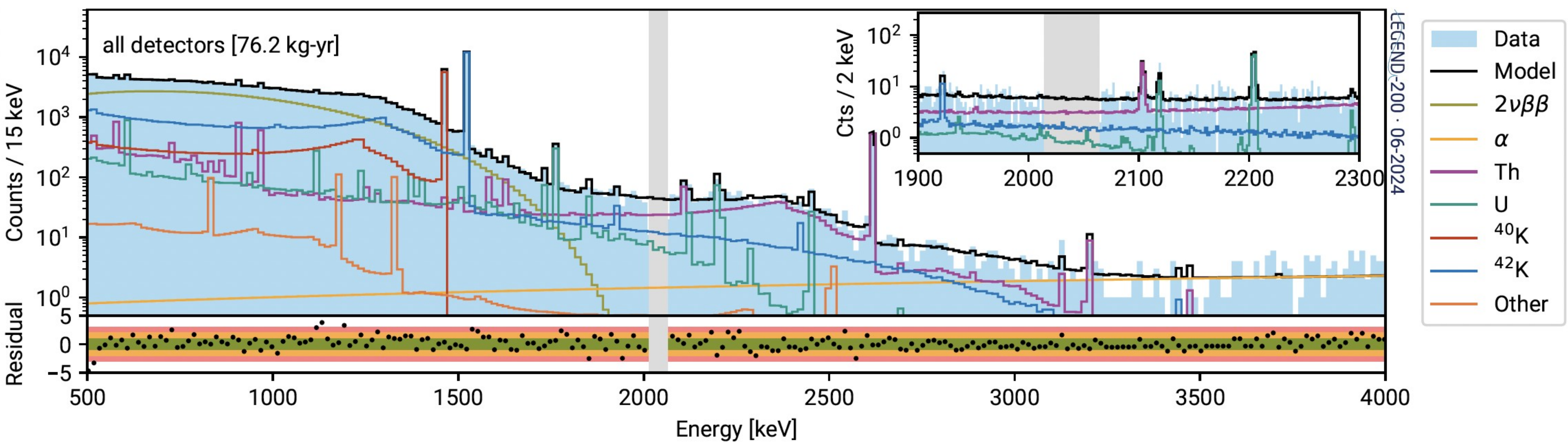


Energy spectrum after quality cuts



- **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 $Q_{\beta\beta}$

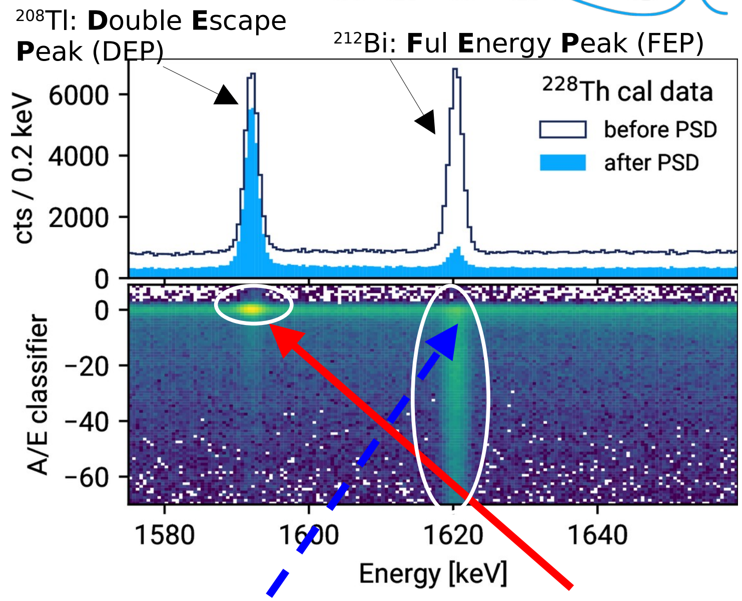
Modeling data before analysis cuts

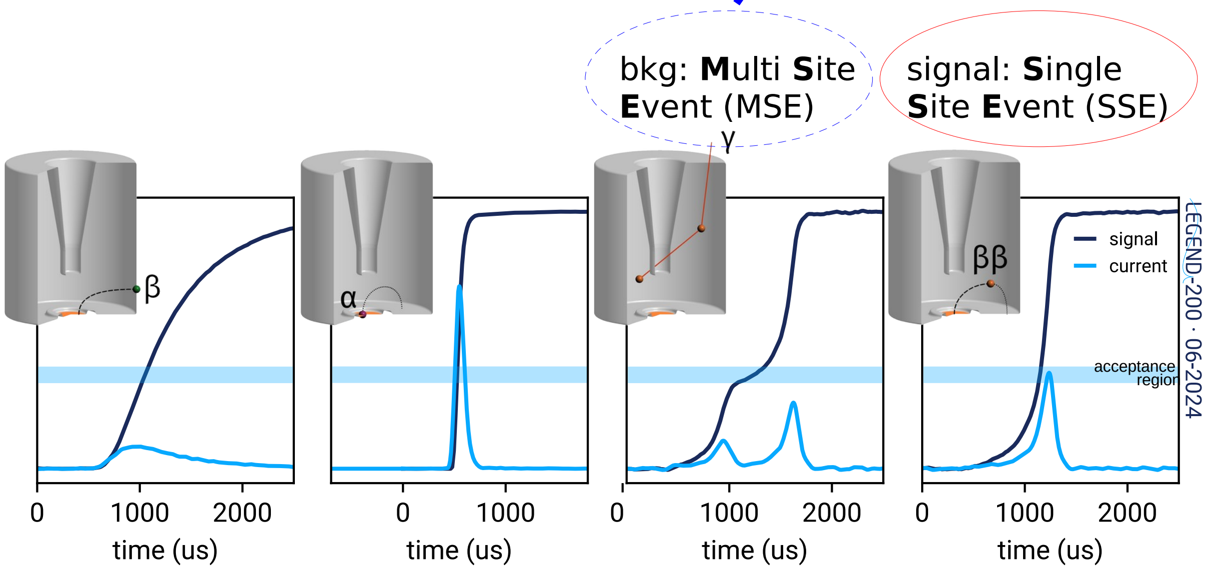


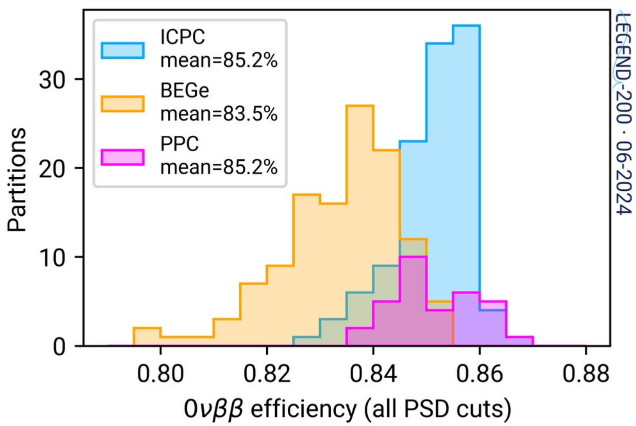
- **Bayesian background model** using data before analysis cuts
  - includes 10.2 kg·yr from special "background characterization runs"
- Data well reproduced, **model is flat at $Q_{\beta\beta}$**
  - no hotspot or significant asymmetry observed in data
- Slightly higher background level around the $Q_{\beta\beta}$ from ^{228}Th respect to the material radioassay: *work in progress to understand its origin*

Pulse Shape Discrimination (PSD)

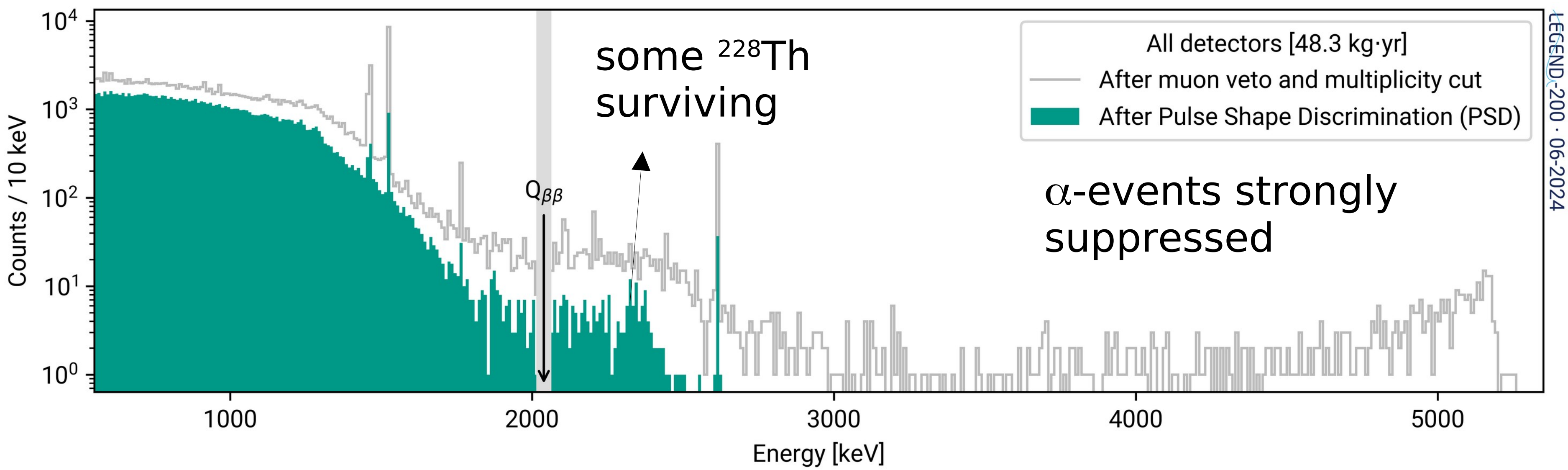
- **Pulse Shape classifier**:
  A/E = max current/Energy
  - "Late Charge" (LQ) cut instead of high A/E cut for detectors with large passivated surfaces
- **Stable** PSD observables
  - monitored with weekly ^{228}Th calibrations





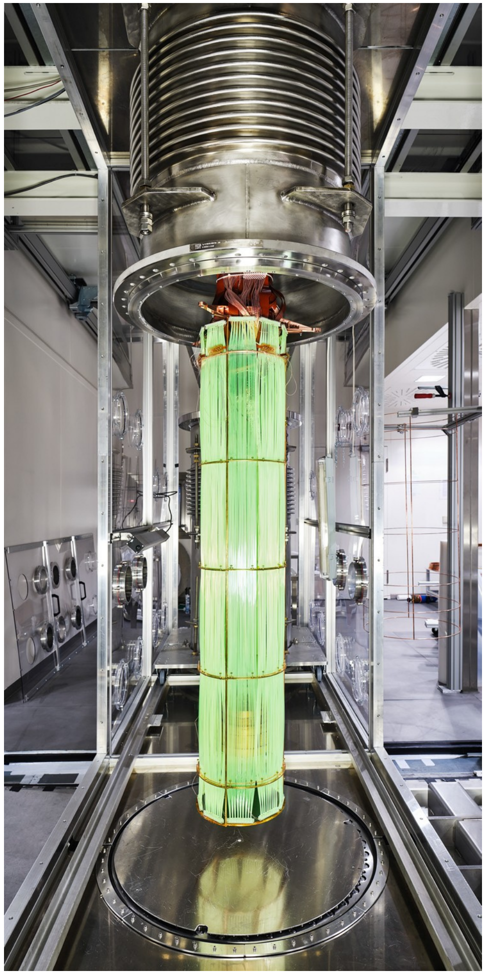


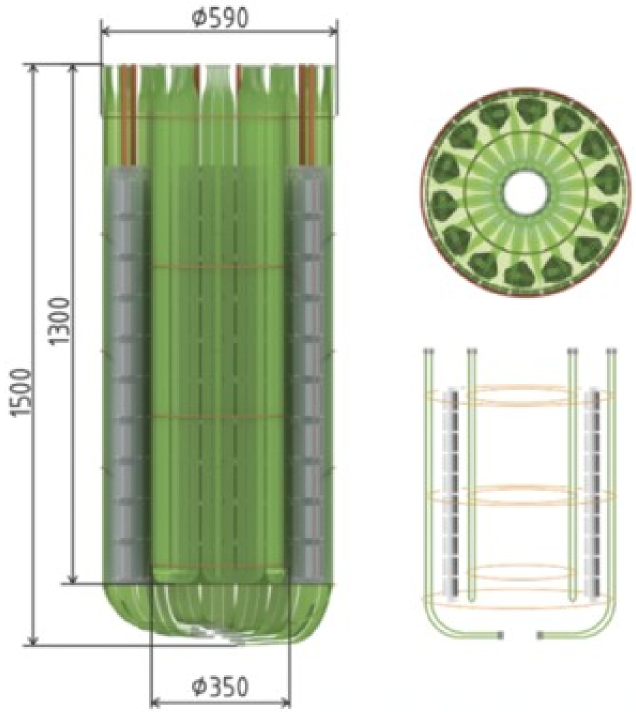
Data after Pulse Shape Discrimination

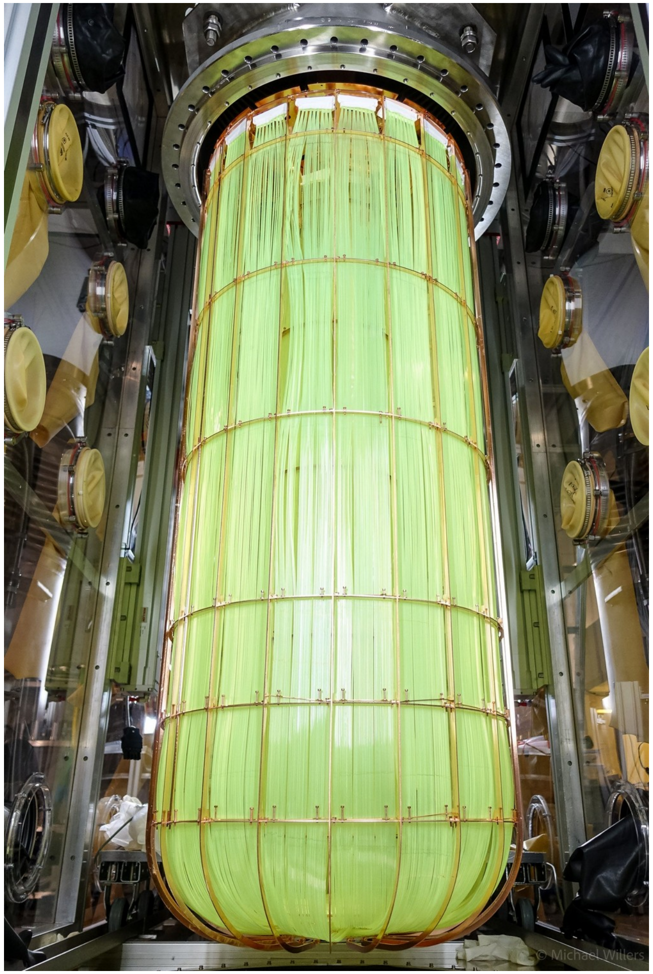


- Strong **suppression of surface α and β** (^{42}K) events
- ~60% suppression of Compton multi-site events at $Q_{\beta\beta}$
- $0\nu\beta\beta$ survival fraction of ~85%

Liquid Argon Instrumentation





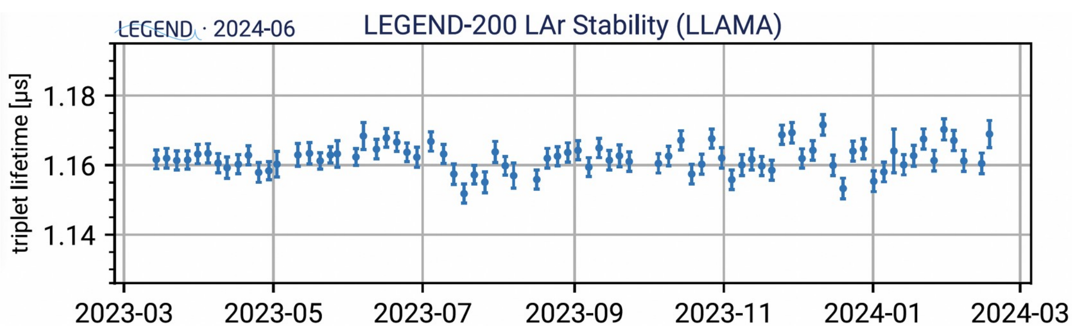


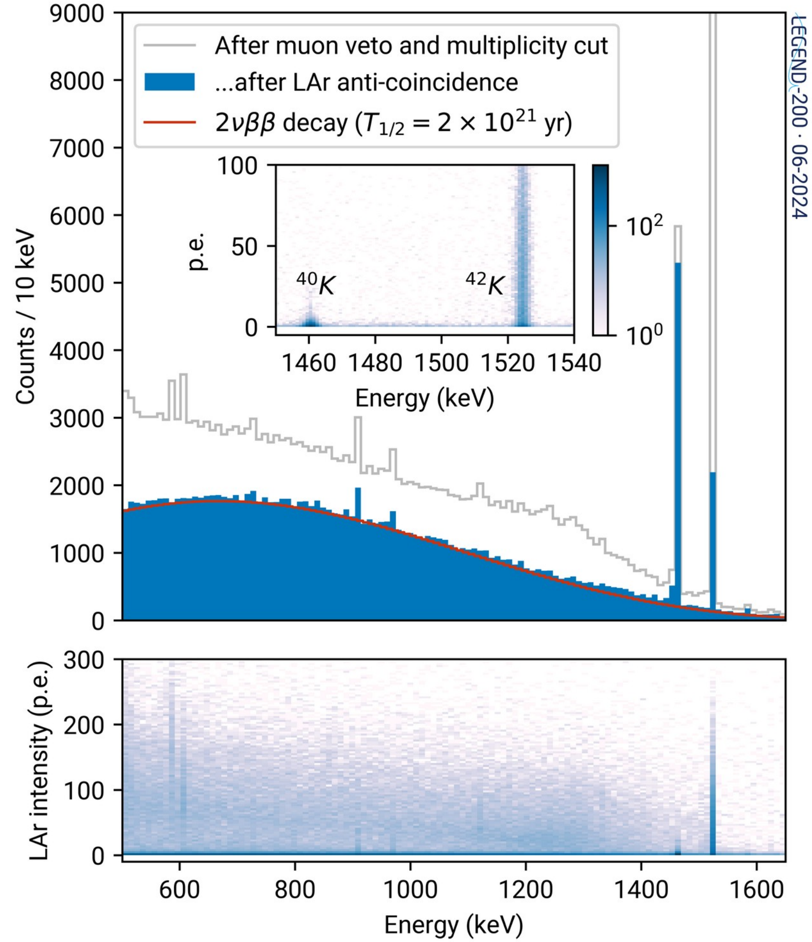
Internal LAr Veto :
9 modules, 18 readout channels

External LAr Veto:
20 modules, 40 readout channels

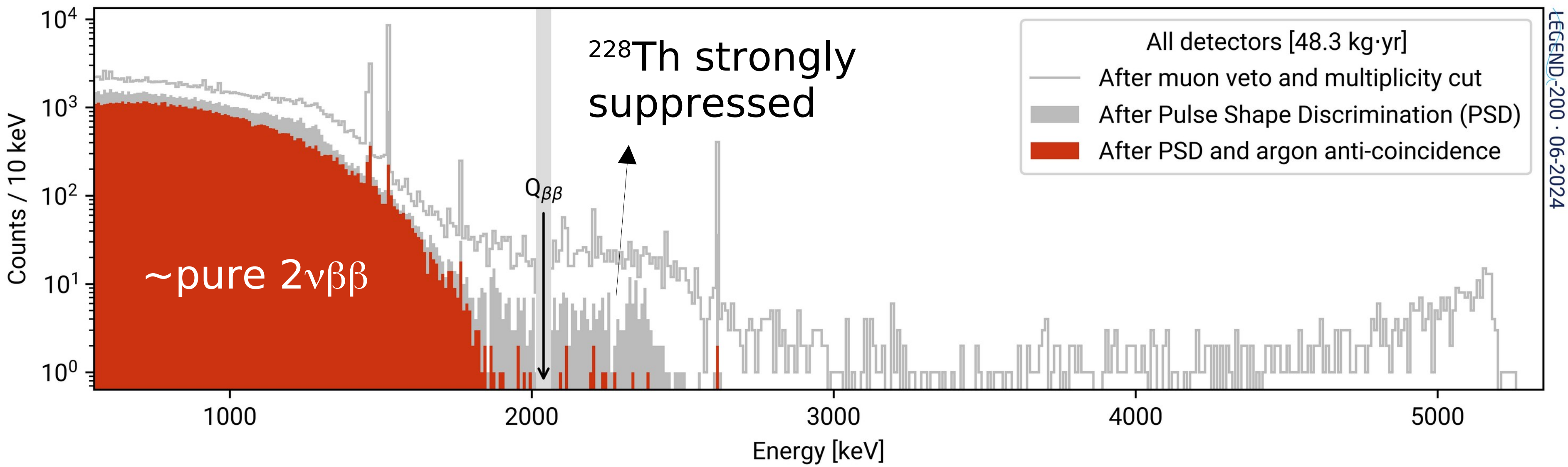
Liquid Argon Instrumentation

- **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 $2\nu\beta\beta$
  - $\beta\beta$ acceptance of ~93%





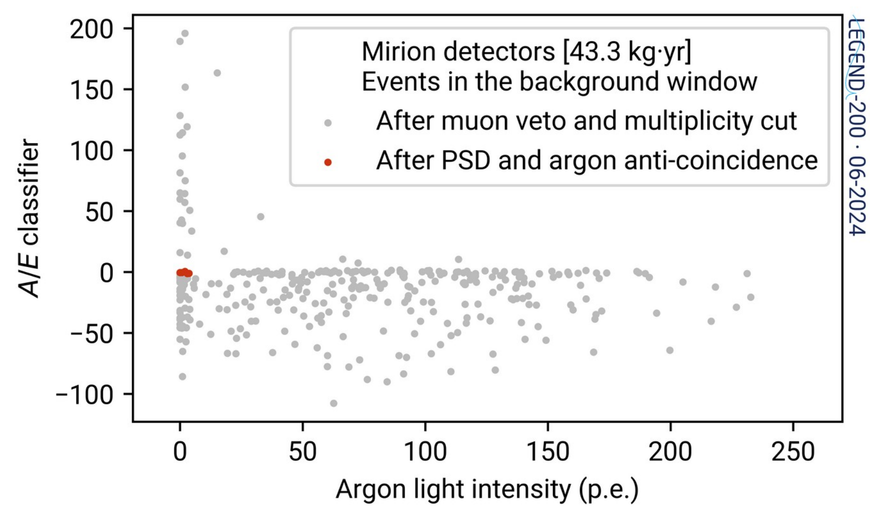
Data after PSD and Argon Anti-Coincidence Cut



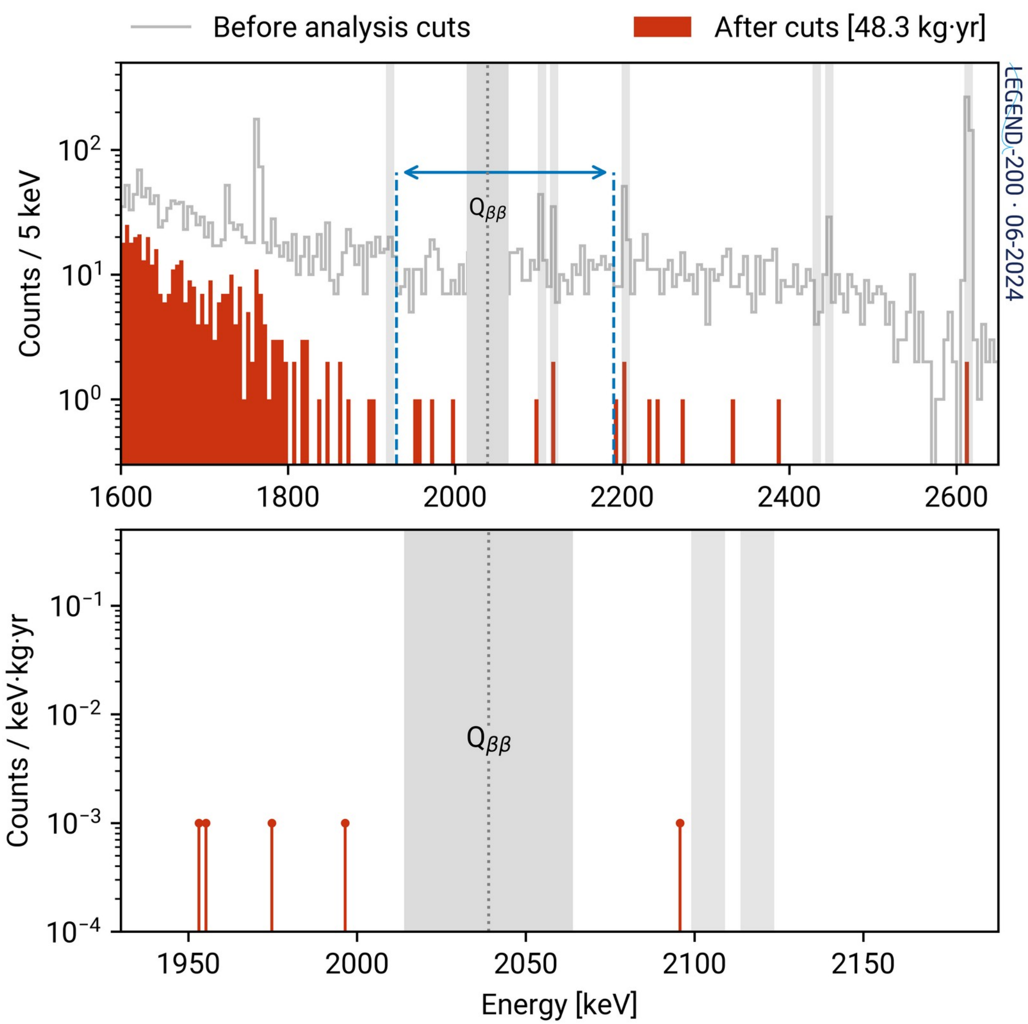
- Strong **anti-correlation** of argon and PSD cuts

- Overall 0νββ survival fraction of ~60%

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

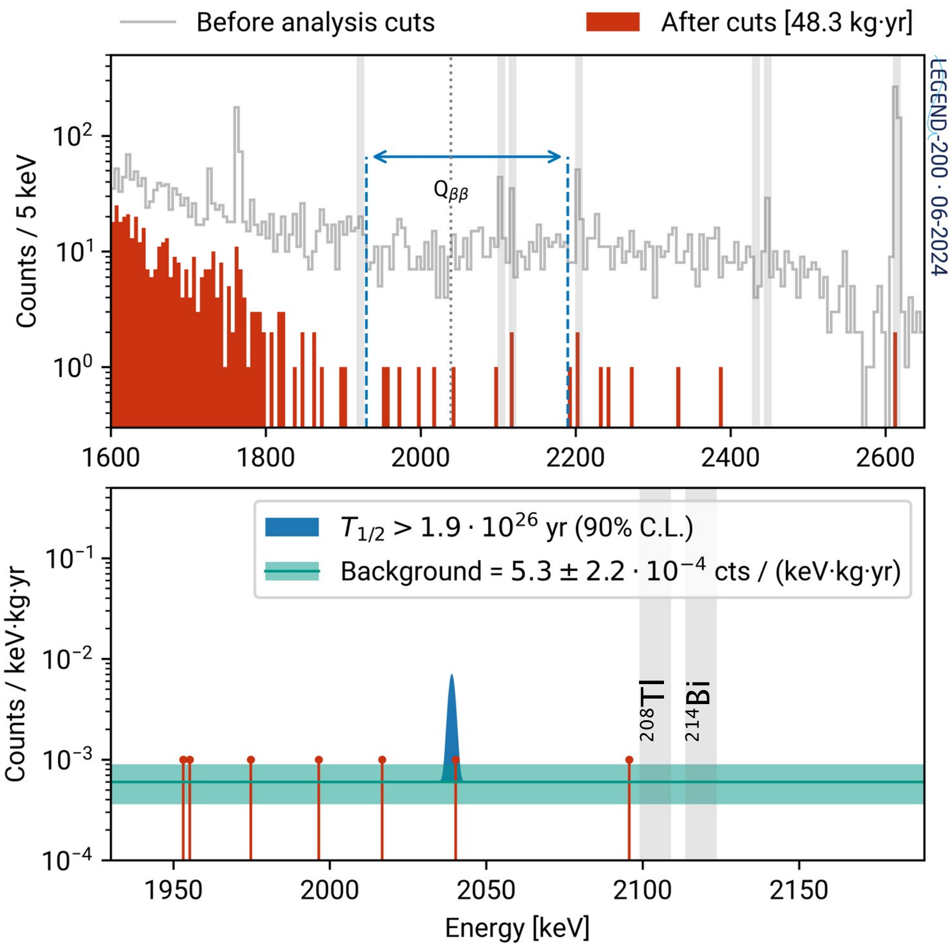


Data in the Region Of Interest



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

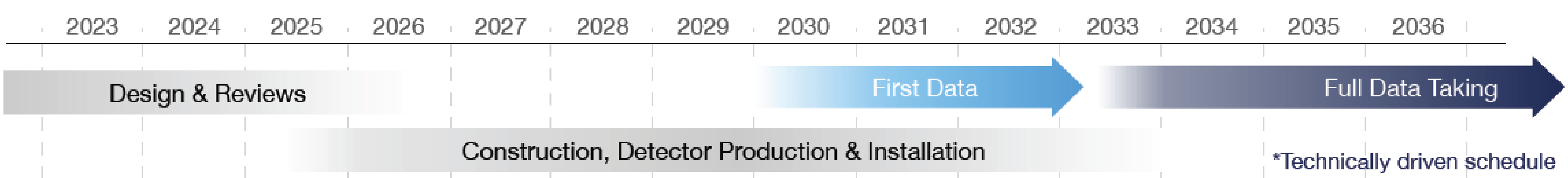
LEGEND-200 contribution

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

The last stage: LEGEND-1000

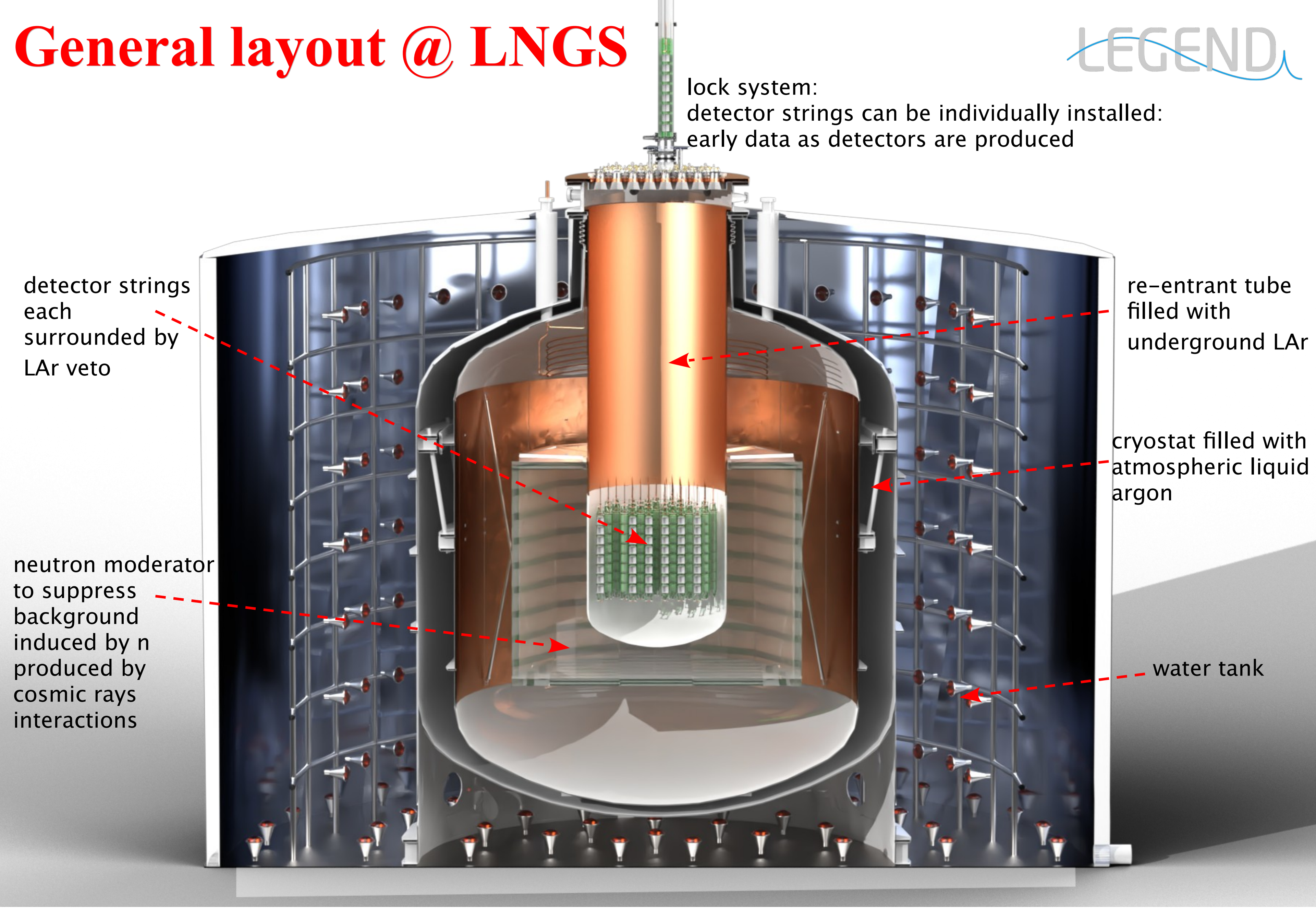
performance parameters & timeline

$0\nu\beta\beta$ 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)
$T^{0\nu}_{1/2}$	$1.3\cdot10^{28}$ yr (90% C.L. discovery) $1.8\cdot10^{28}$ 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)

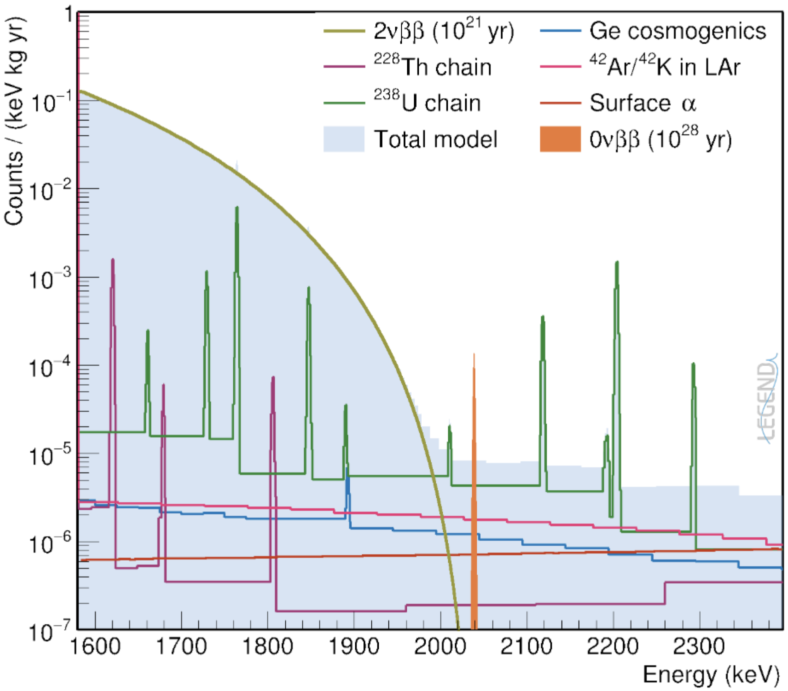


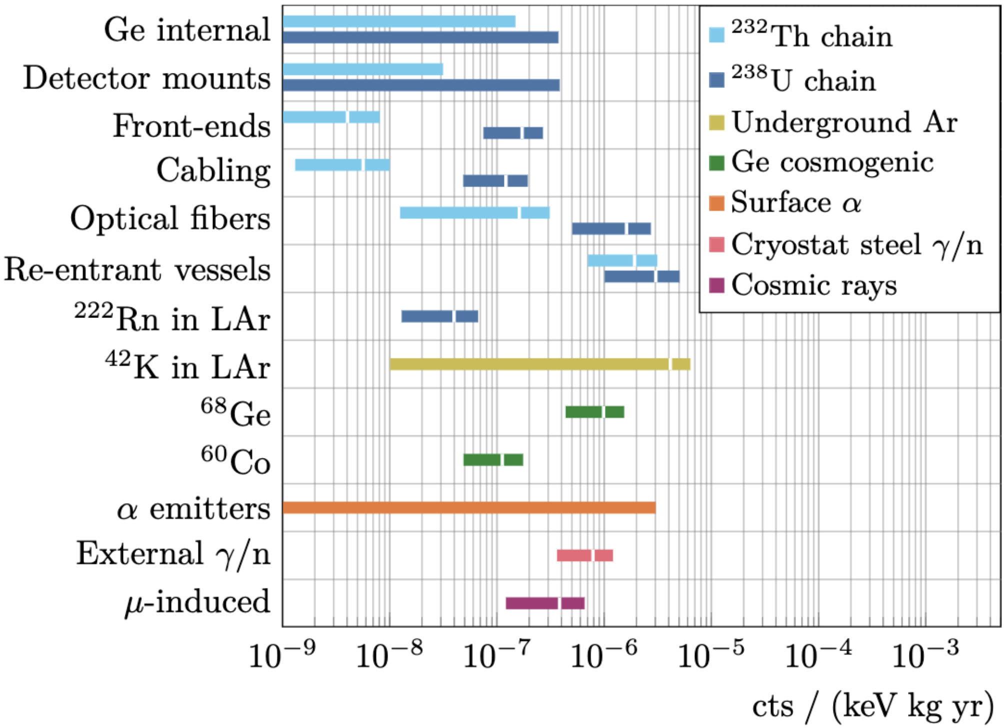
General layout @ LNGS

LEGEND



LEGEND-1000 background projections





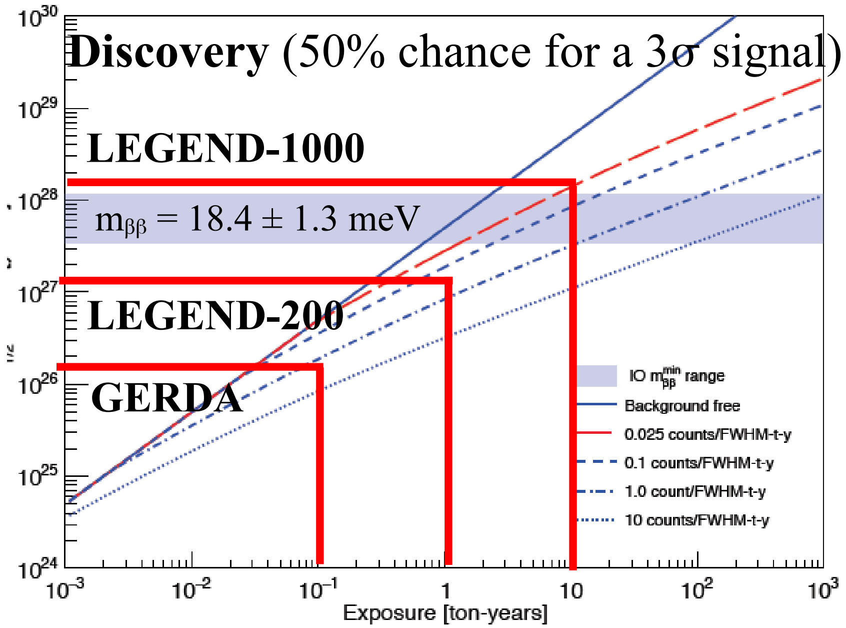
Expected total spectrum from 2νββ decay and from all background components after all cuts

Projected background index after all cuts:

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

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



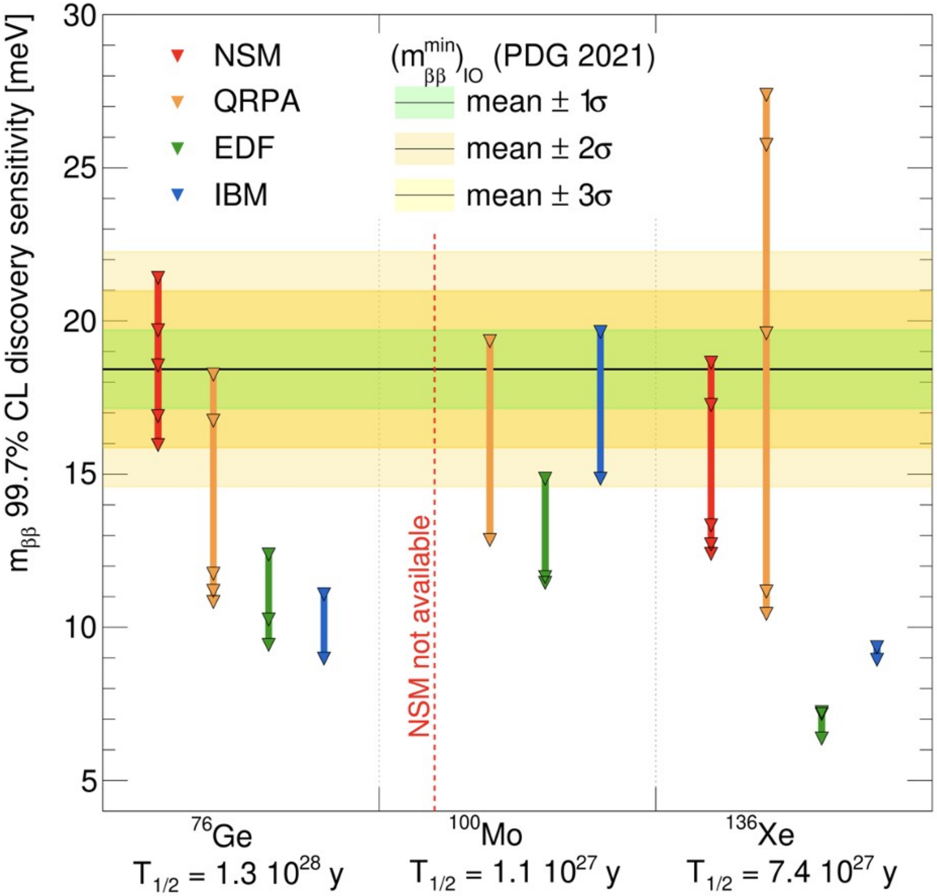
- LEGEND-200 is **now taking data:** the first data show that the BI is not far from the LEGEND-200 goal. With much more statistics, we are now studying the background sources in detail
- **The ultimate phase will be LEGEND-1000** able to reach an half-life greater than 10^{28} yr covering the entire 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

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

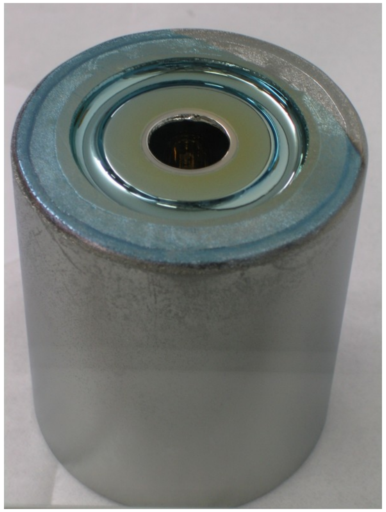
Agostini, Detwiler, Benato, Menendez, Vissani
PRC, 104 (4) L042501 (2021)



LEGEND CUPID NEXO

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 $Q_{\beta\beta}$

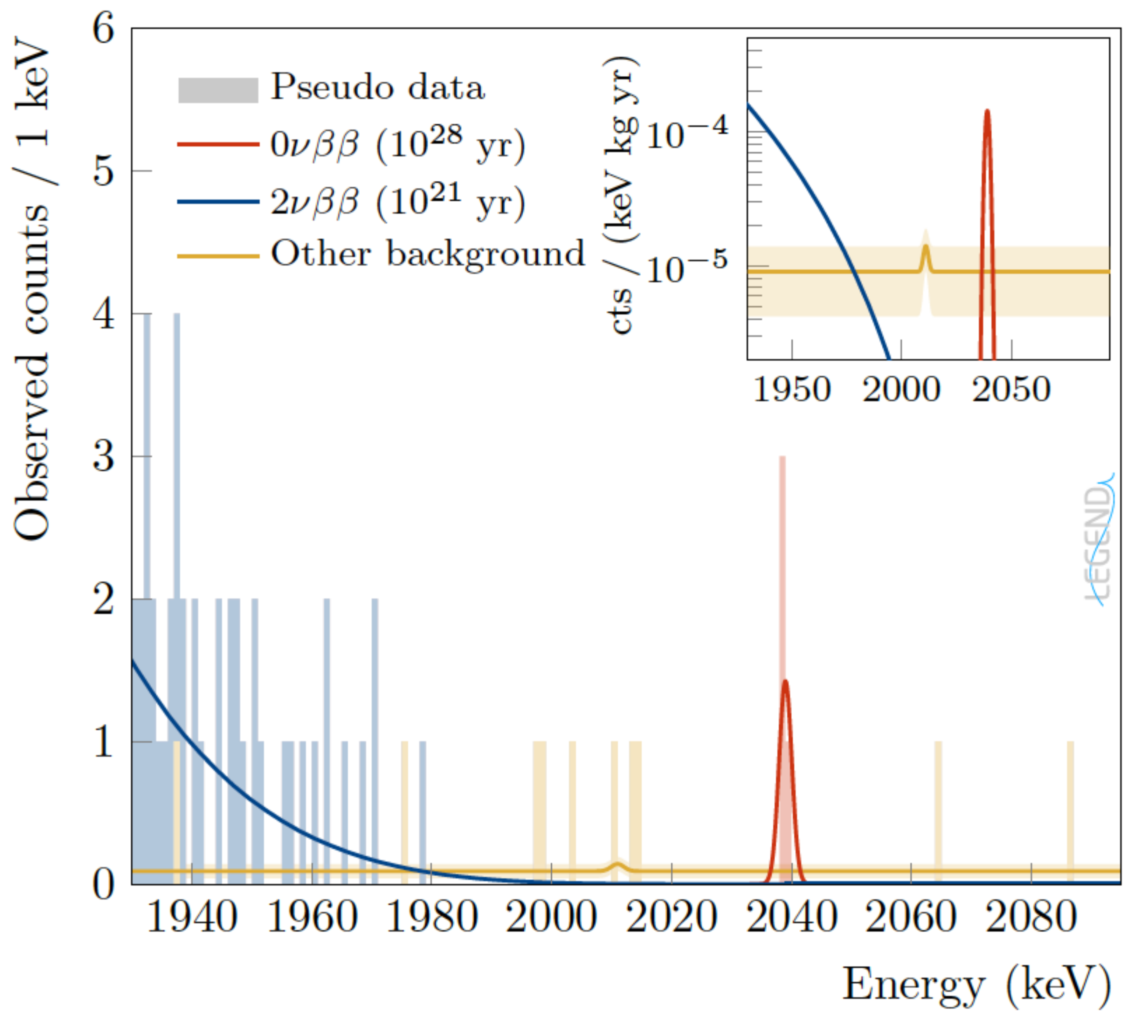
Advantages of Germanium:

- **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 $G^{0\nu}(Q_{\beta\beta},Z)$

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%**

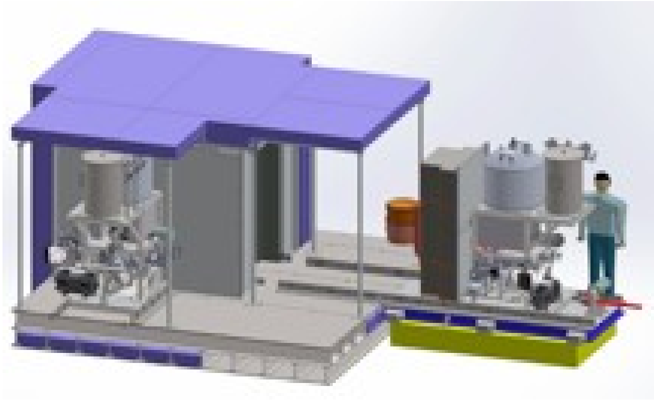
*Improvement due to larger-mass ICPC detectors

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)

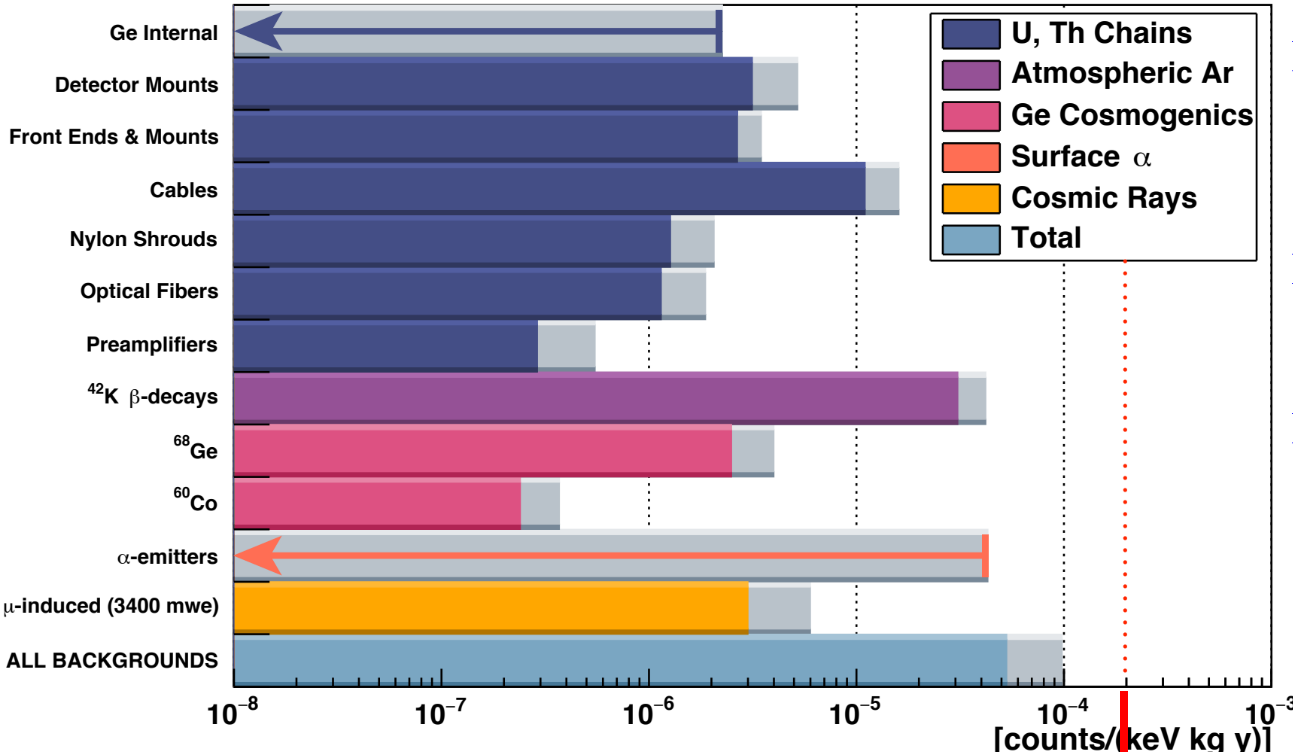


- Arrays of ^{enr}Ge housed in high-purity electroformed copper cryostat
- Shield: electroformed copper/lead
- 30 kg enriched in ^{76}Ge

➢ **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 $Q_{\beta\beta}$: **$2 \cdot 10^{-4}$ cts/(keV·kg·yr)**

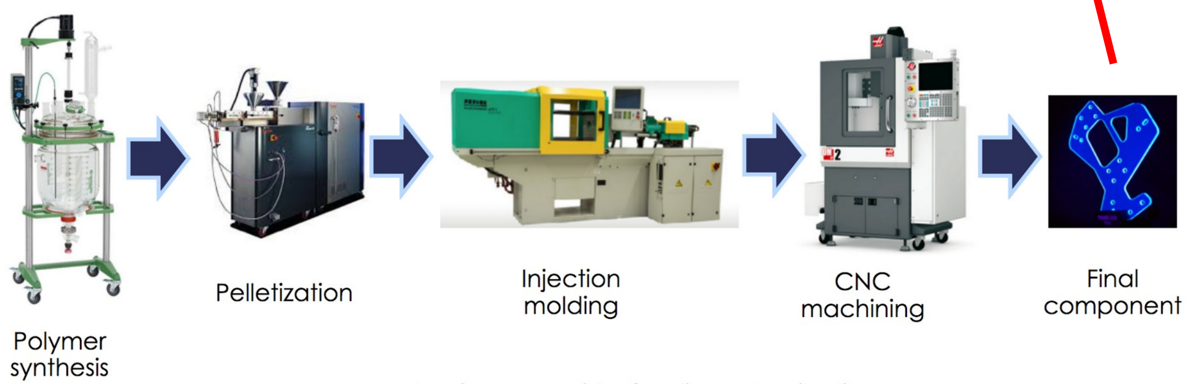
L-200 Sensitivity goal:
$T_{1/2} > 10^{27}$ years (90% CL) after **1 ton·yr** of exposure
$m_{\beta\beta} < 27 - 64$ meV

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

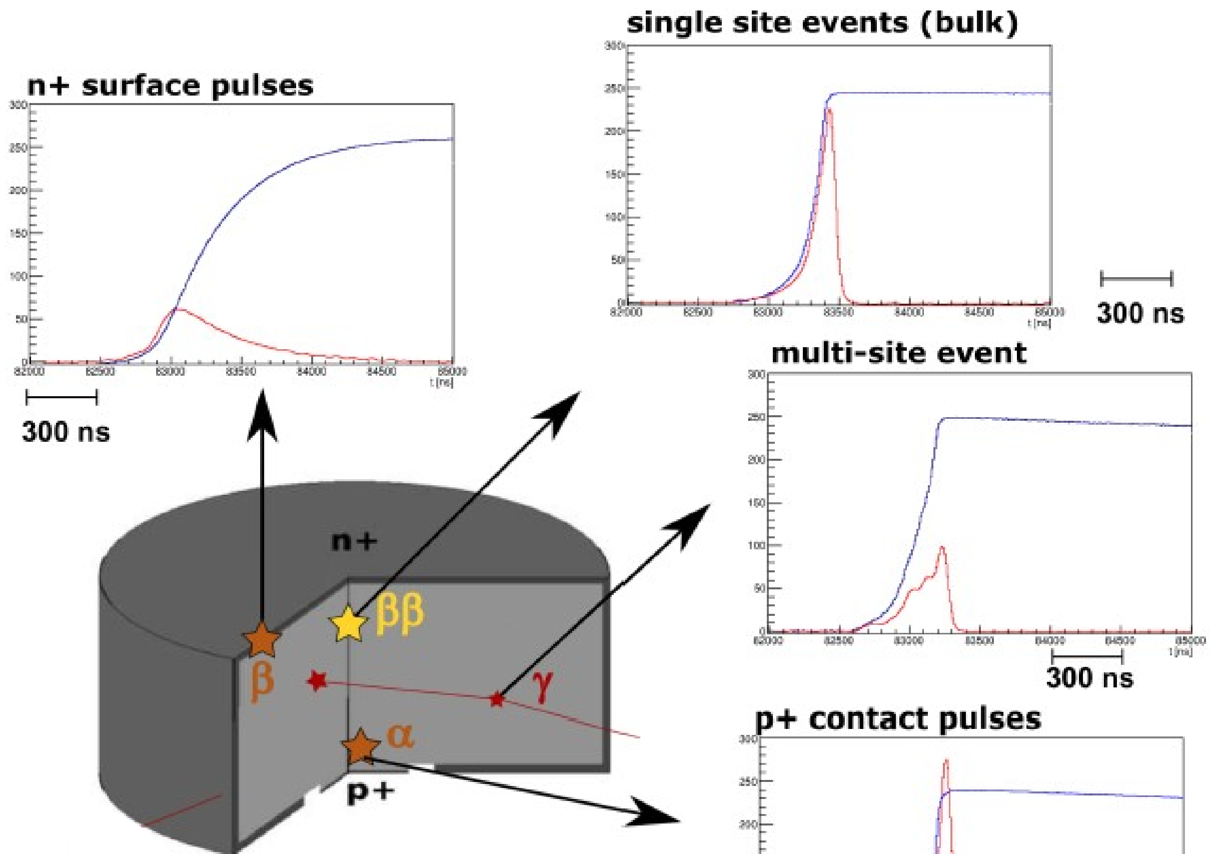
Underground electroformed copper

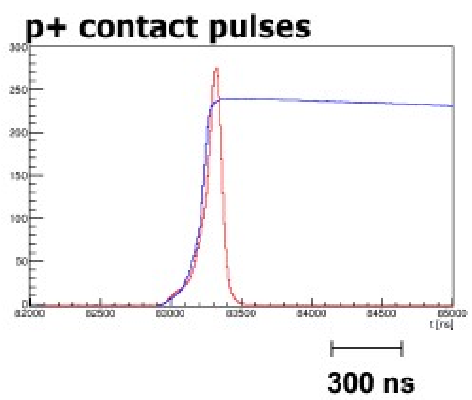
- **Polyethylene naphtalene (PEN)** replaces optically inactive structural materials
- Shift 128 nm LAr scintillation light to ~440 nm
- Yield strength higher than copper at cryogenic temperatures
- Evaluated in L-200



PEN: scintillating high purity detector support

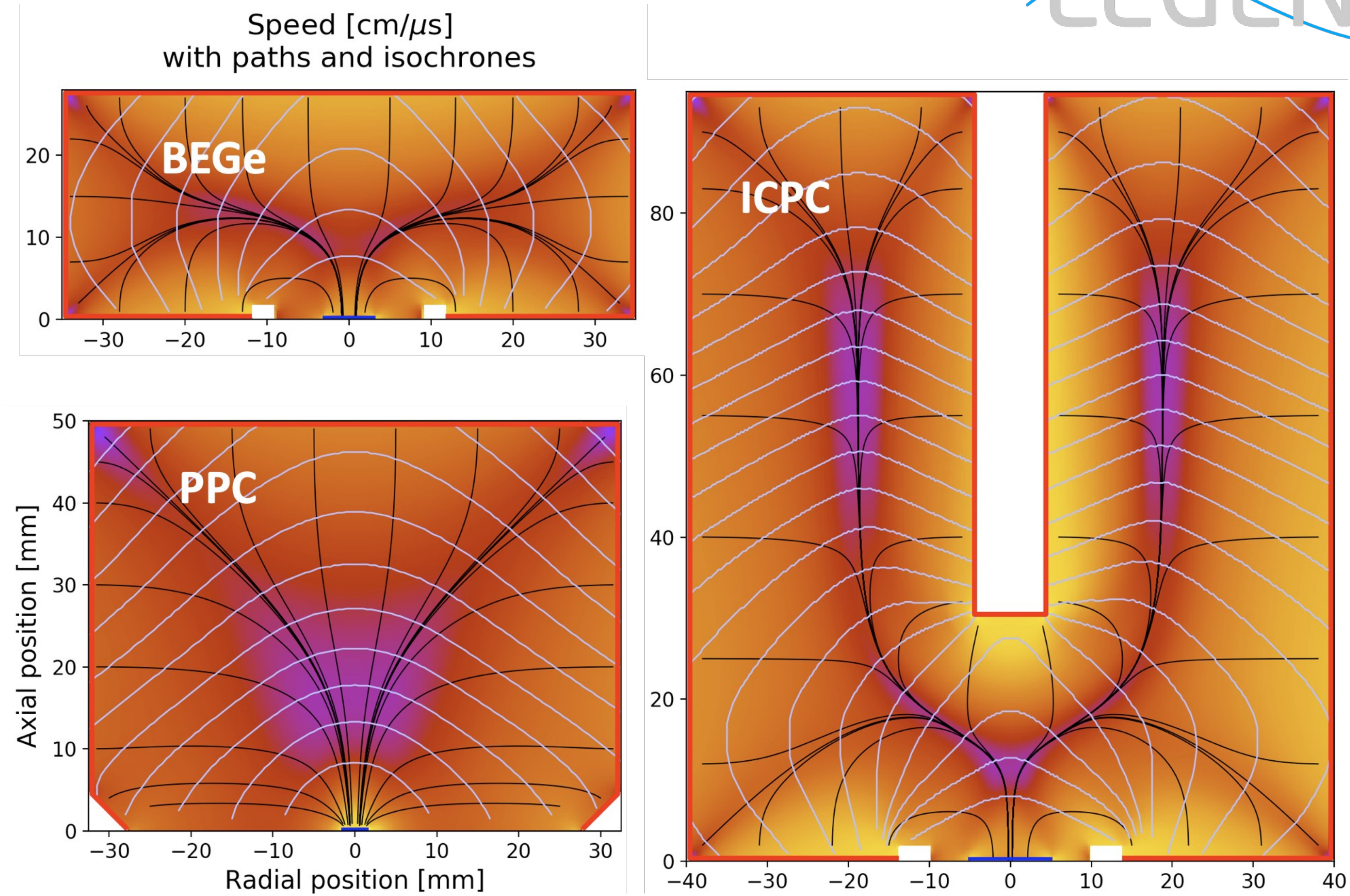
Pulse Shape Discrimination (PSD)





- 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%

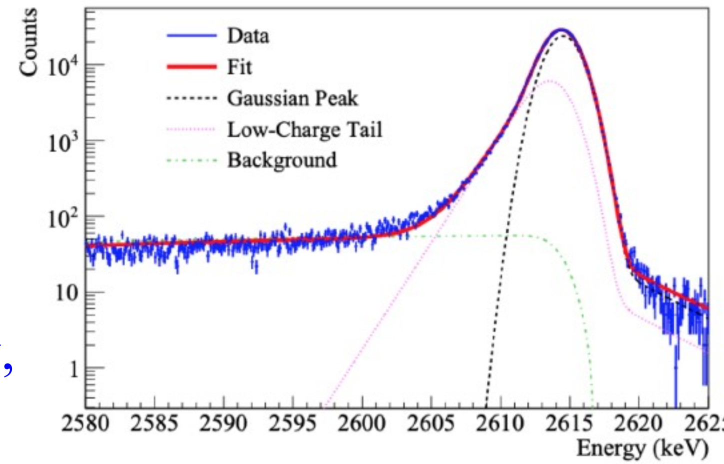
Ge Detectors



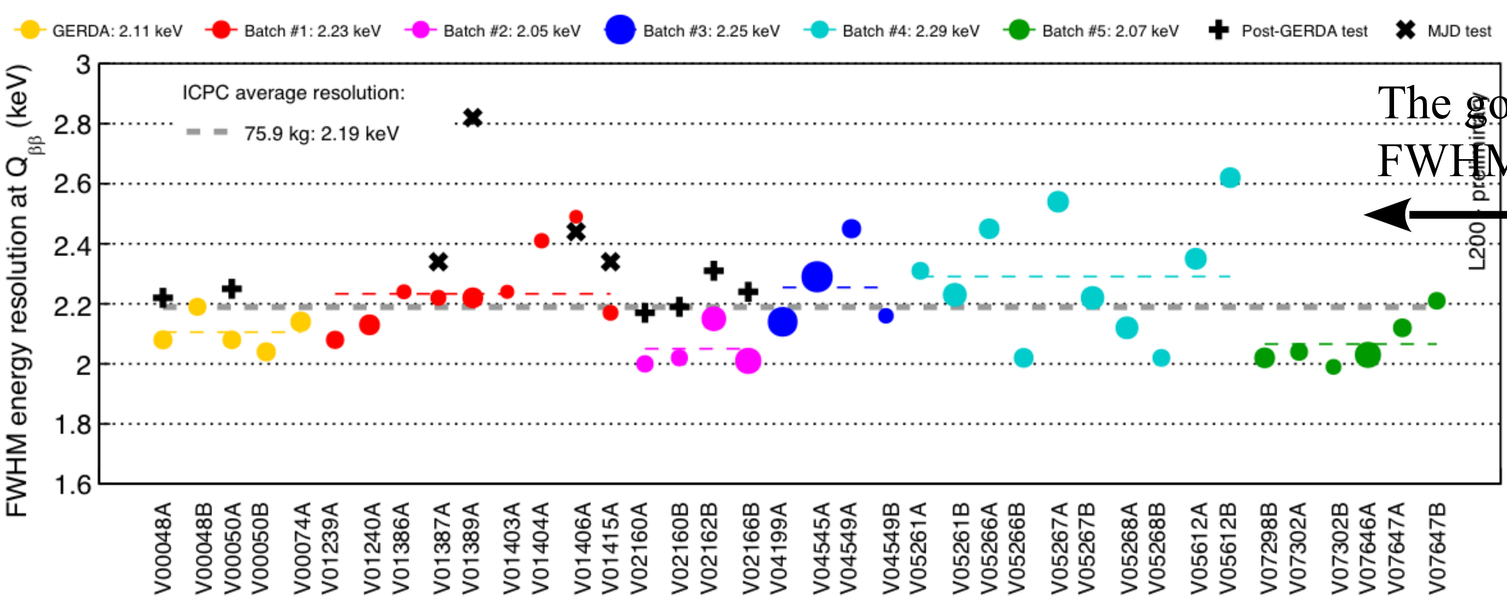
In LEGEND-200 four different types of enriched Ge detectors will be used:
BEGe (GERDA), PPC (Majorana), **ICPC** (GERDA, L-200) and semicoax (GERDA)

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

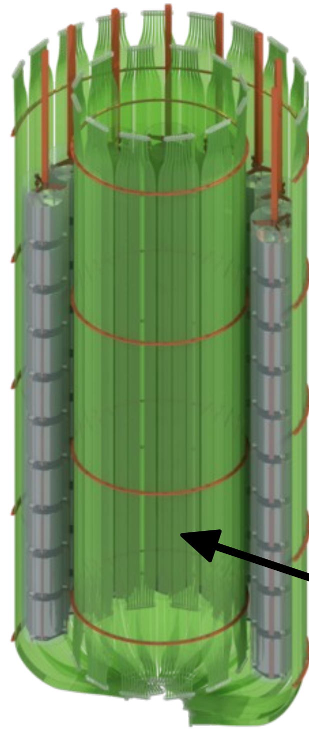


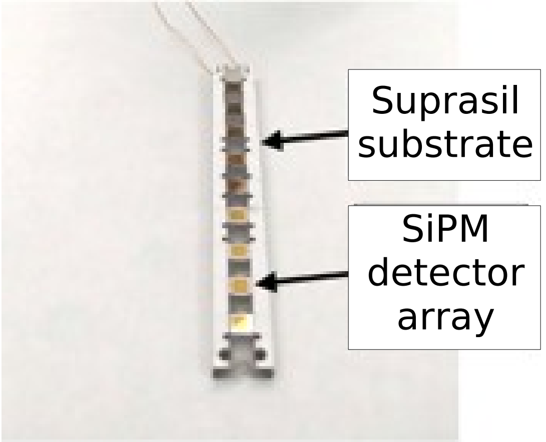
The goal is to reach a FWHM @ $Q_{\beta\beta}$ = **2.5 keV**

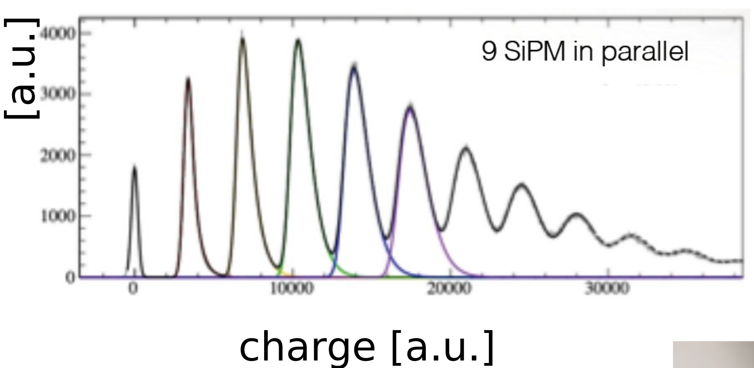
Liquid Argon Veto

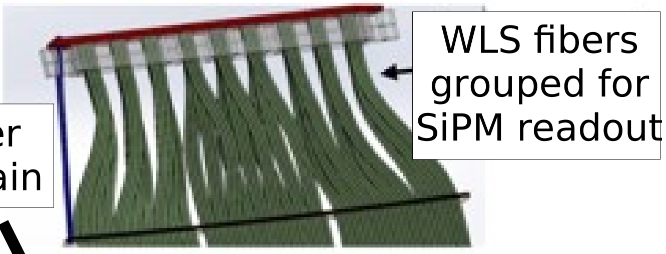
- 128 nm LAr scintillation light readout by TPB coated WLS fibers coupled to SiPMs arrays
- Single photo-electron resolution

L-200



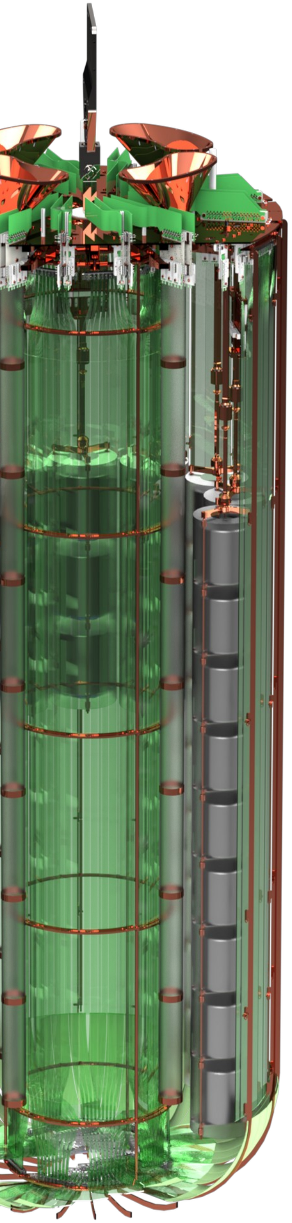






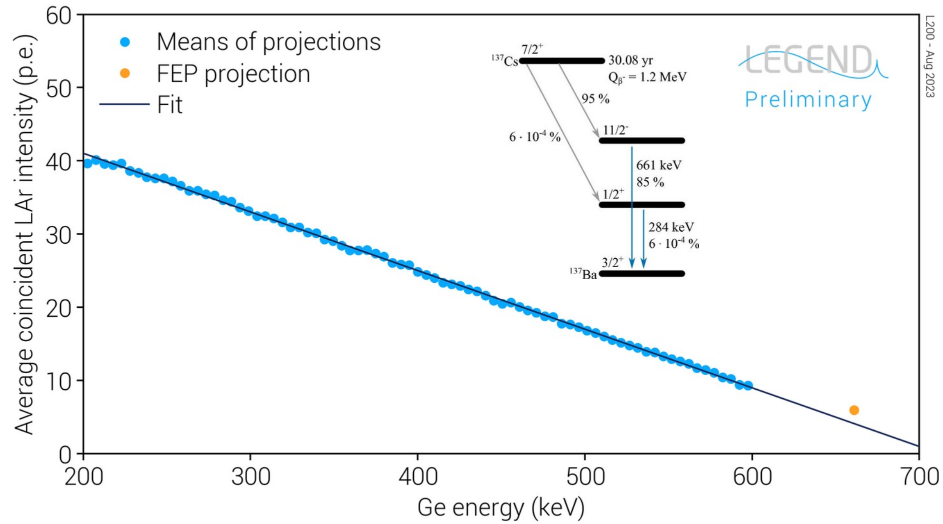
fiber curtain

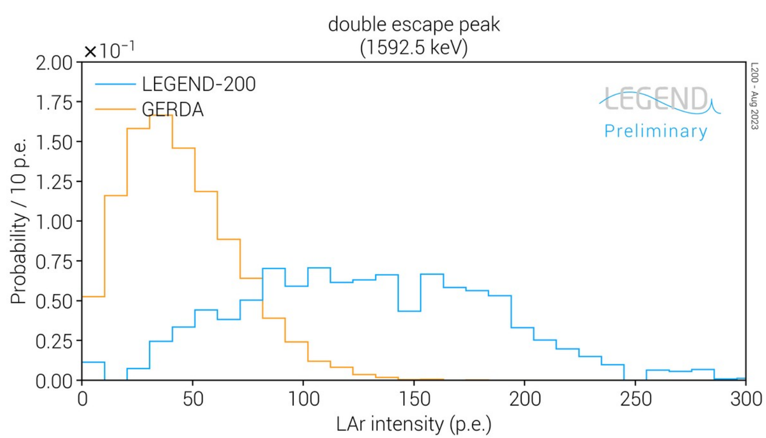
LAr Instrumentation

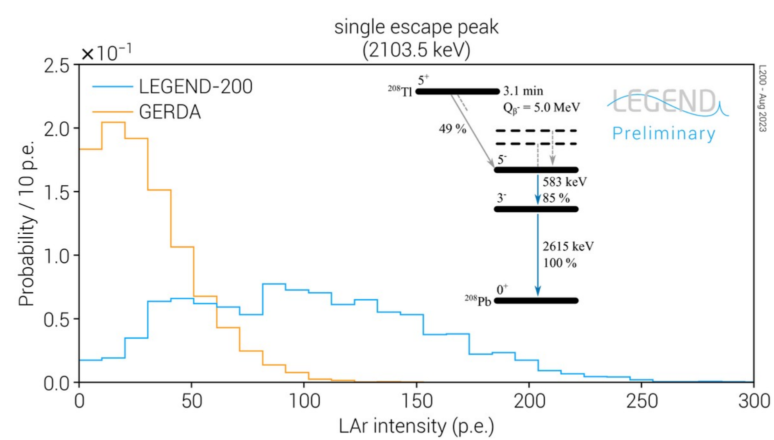


- Improved Si photo-multiplier (SiPM) readout
  Improved geometry + optically active PEN → less shadowing
- Improved wavelength-shifting (TPB) fiber coating

→ ~ 3 more light wrt. GERDA

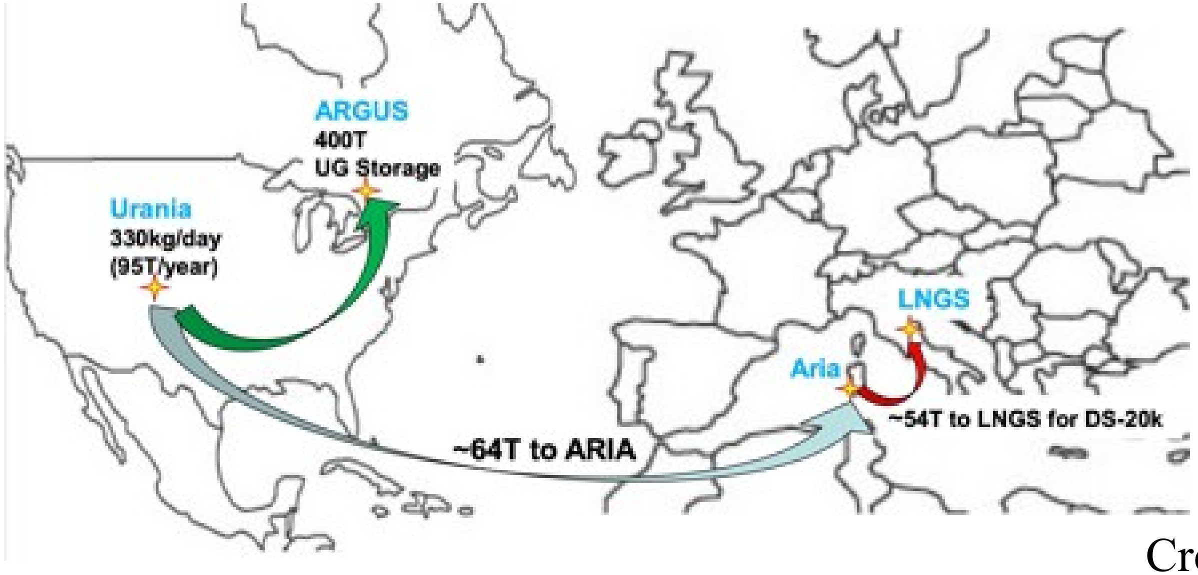






Underground Liquid Argon

- 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