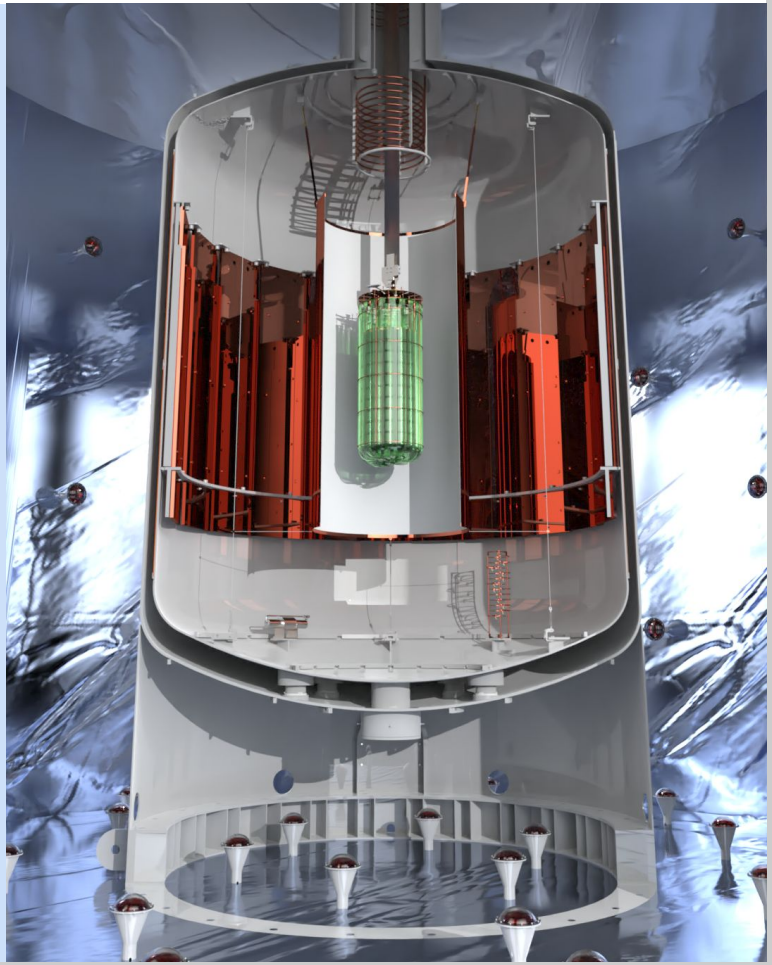
First Results of the LEGEND-200 Experiment

LEGEND

Large Enriched
Germanium Experiment
for Neutrinoless ββ Decay



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on behalf of the LEGEND Collaboration

INFN ROMA TRE

since 1966 Rencontres de Moriond

Rencontres de Moriond 2025

Electroweak Interactions & Unified Theories

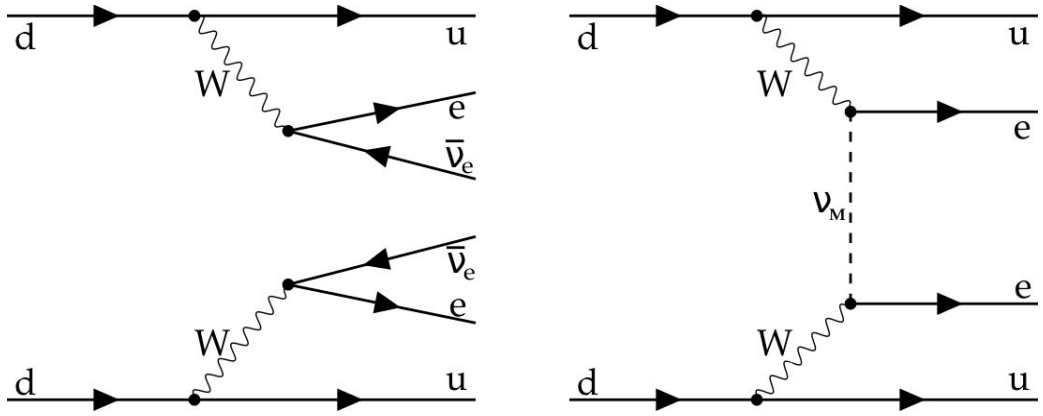
23–30 March 2025, La Thuile, Italy

Neutrinoless Double Beta (0νββ) Decay

Powerful method to study the unknown neutrino properties and explain matter–antimatter asymmetry in the Universe

Observation of 0νββ decay imply:

- neutrino has Majorana nature
- lepton number violation ($\Delta L = 2$)
- determination of ν absolute mass



Assuming light neutrino exchange:

$$(T_{1/2})^{-1} = G_{0\nu} \times |M_{0\nu}| \times (m_{\beta\beta}/m_e)^2$$

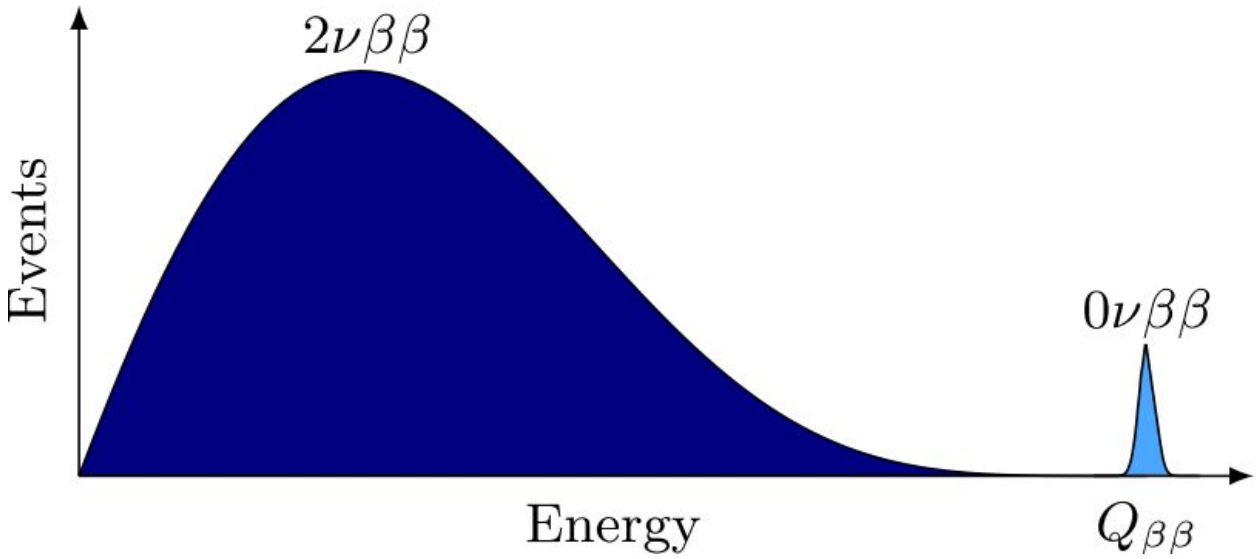
- **Phase Space Integral:** known quantity
- **Nuclear Matrix Element (NME):** model dependent, introduces uncertainty to determine $m_{\beta\beta}$ (quenching problem)
- **Neutrino Effective Mass Term ($m_{\beta\beta}$):** can be calculated by measuring the half-life

Search for 0νββ Decay

Experimental sensitivity

$$S \propto a \cdot \varepsilon \cdot [(M \cdot T)/(\Delta E \cdot BI)]^{1/2}$$

a = isotopically abundance
ε = detection efficiency
M · T = total mass x exposure time
ΔE = energy resolution
BI = background index

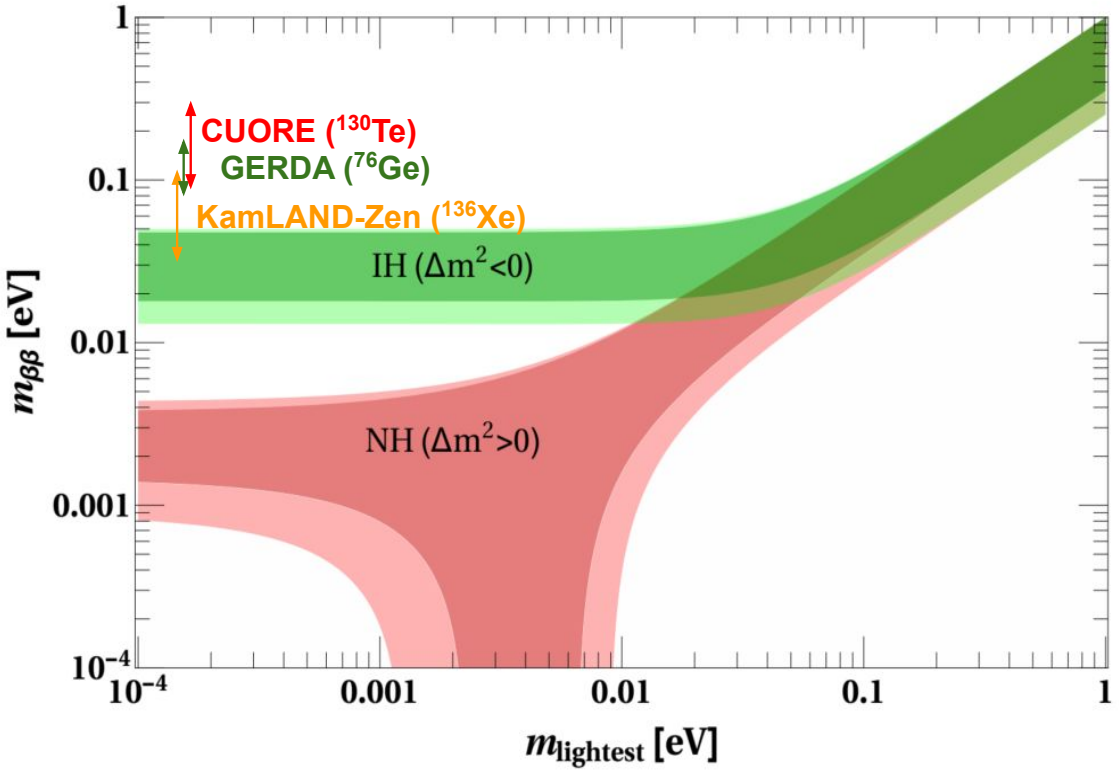


In case of background-free condition (N_{bkg} < 1 for full exposure)

$$S \propto a \cdot \varepsilon \cdot M \cdot T$$

0νββ decay signal will have a peak at $Q_{\beta\beta}$ of the decay process

Status of 0νββ Decay Search



Isotope	Experiment	Median Sensitivity (10^{25} yr)	Half-Life Limit (10^{25} yr)	$m_{\beta\beta}$ limit (meV)
^{13}Xe	KamLAND-Zen arXiv:2406.11438	23	38	28-122
^{76}Ge	GERDA PRL 125 252502 (2020)	18	18	79-180
^{130}Te	CUORE arXiv:2404.04453	4.4	3.8	70-240

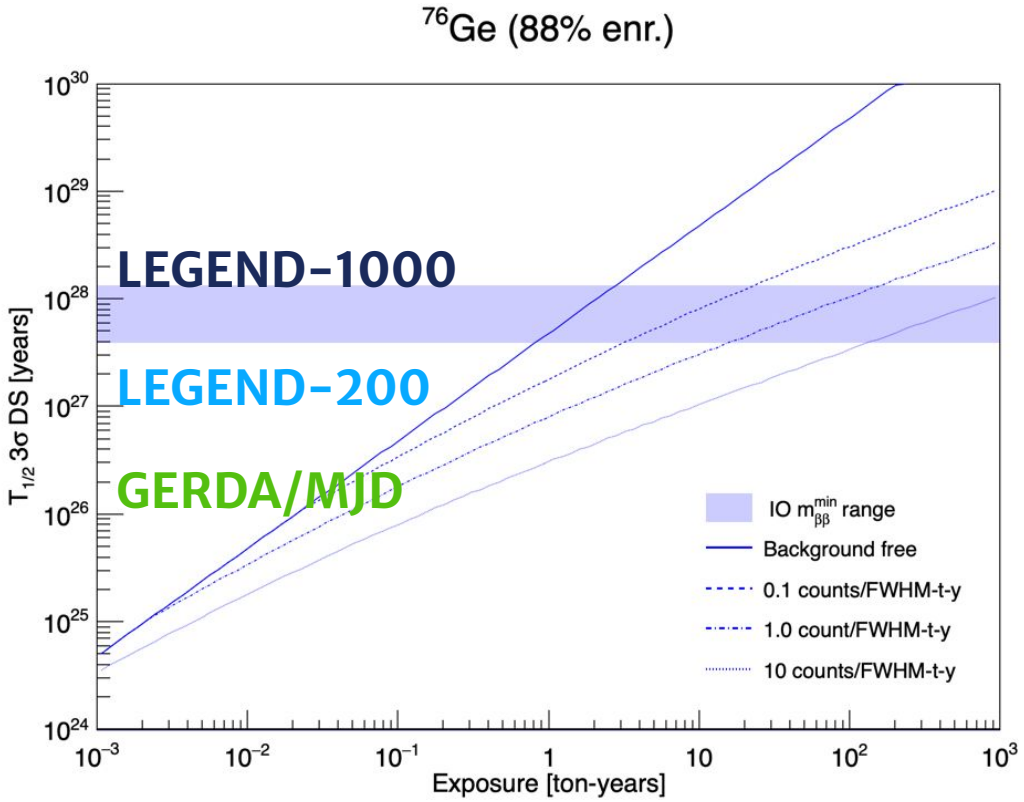
LEGEND Collaboration

The LEGEND collaboration was formed in 2016 through a merger of the MAJORANA DEMONSTRATOR (MJD) and GERDA Collaborations, along with several new institutions

12 countries, 55 institutions , ~300 members

LEGEND Program

LEGEND 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



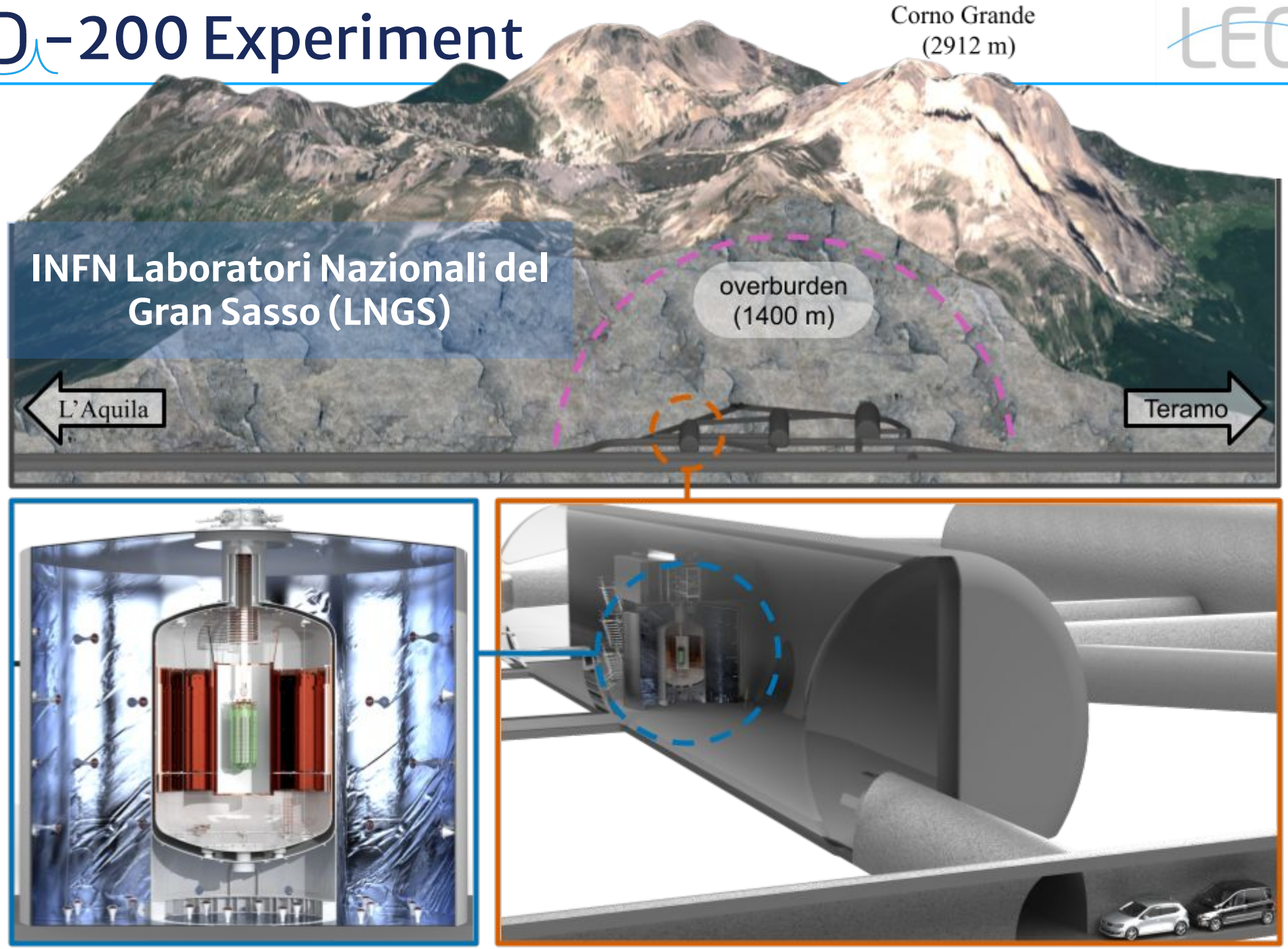
First Stage LEGEND-200

- up to 200 kg of ^{76}Ge
- modification of existing GERDA infrastructure at INFN Gran Sasso Laboratory (Italy)
- background goal of 0.6 cts/(FWHM·t·yr)

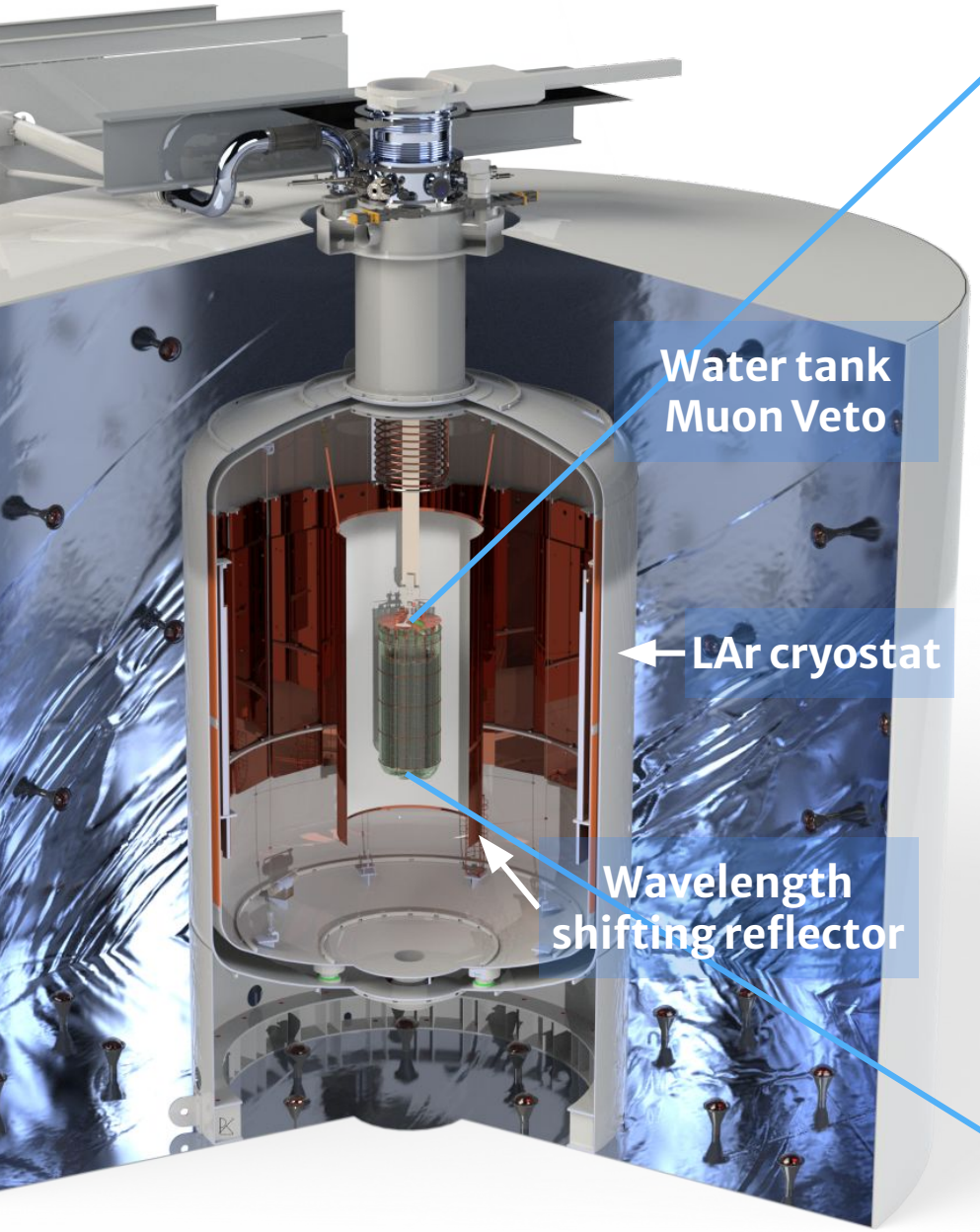
Subsequent Stage LEGEND-1000

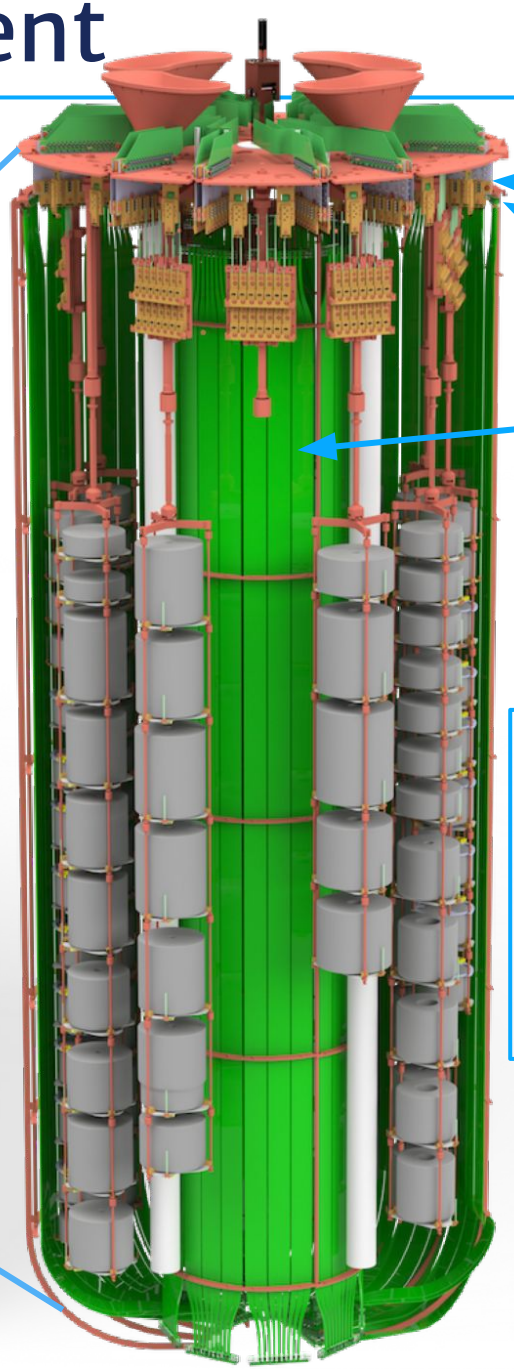
- 1000 kg of ^{76}Ge
- location to be selected
- background goal < 0.03 cts/(FWHM·t·yr)
- timeline connected to review process

LEGEND-200 Experiment



LEGEND-200 Experiment





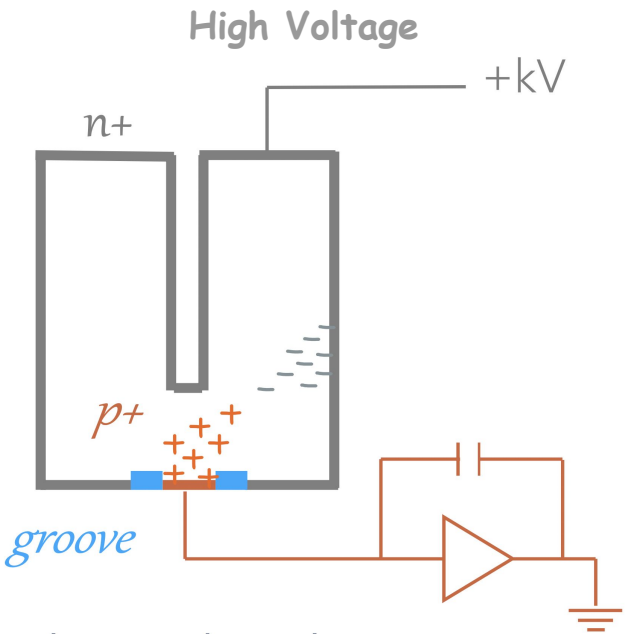
HPGe readout electronics based on MJD and GERDA

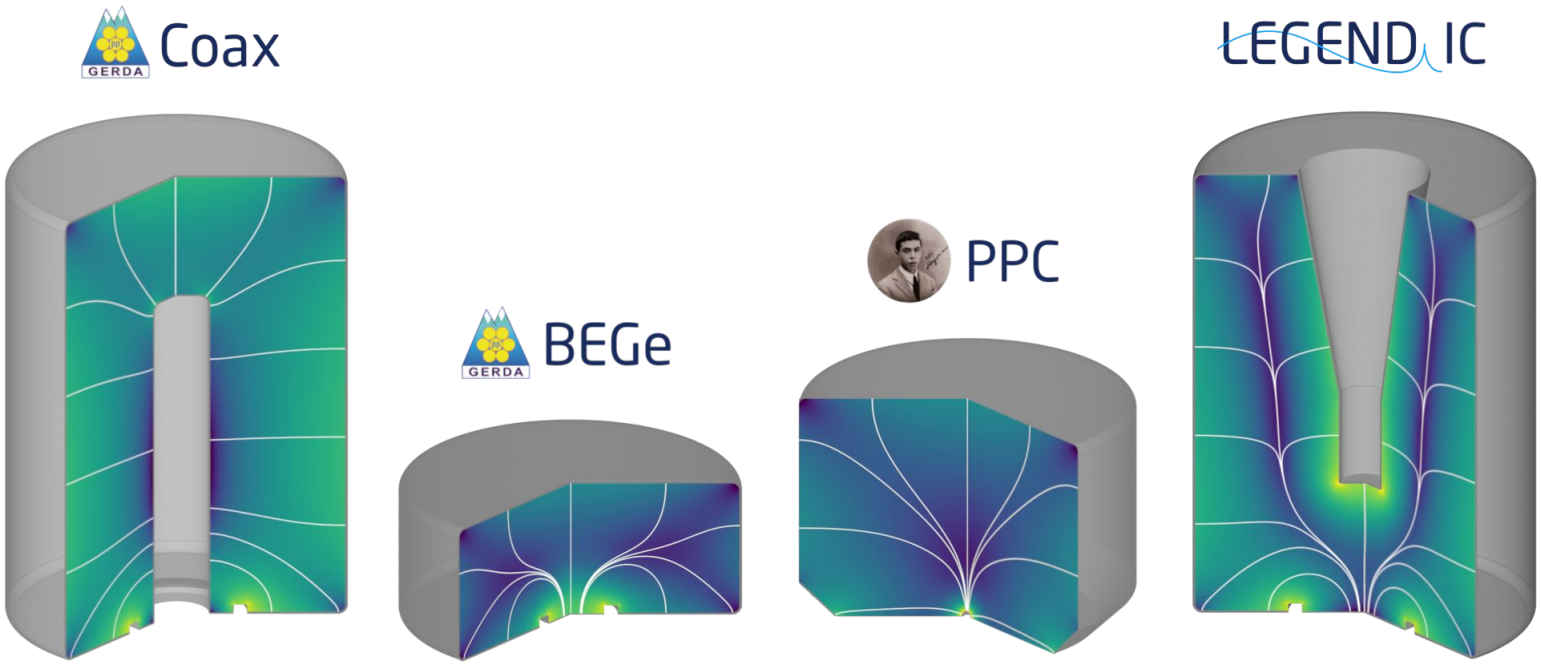
LAr instrumentation inner & outer barrels with SiPM readout

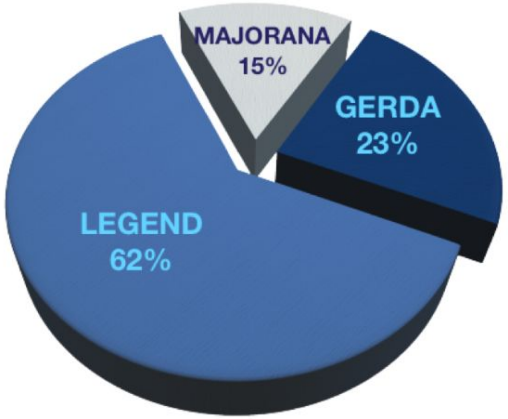
HPGe detector array holders in underground copper and PEN plates

Inverted Coaxial (IC) detector large mass up to 4 kg

LEGEND-200 HPGe Detectors





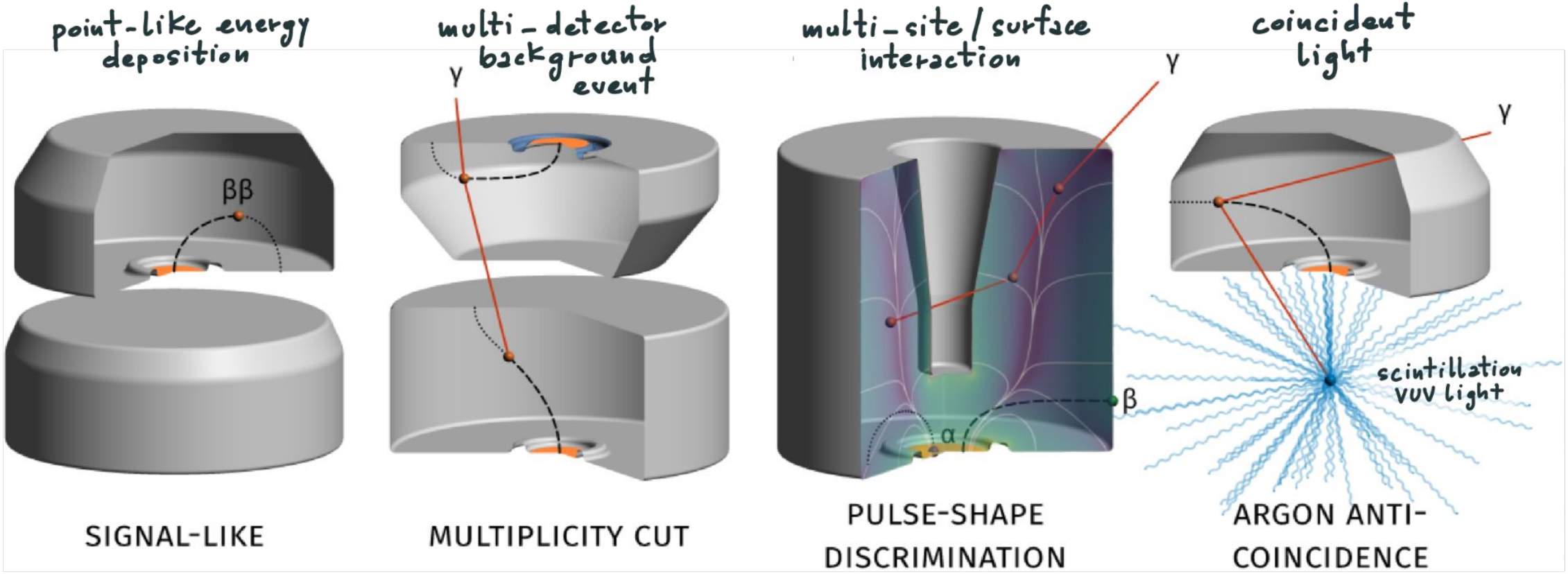


HPGe detectors have best energy resolution at the $Q_{\beta\beta}$ (0.12% FWHM) and best background level in the field (10^{-4} cts/(keV kg yr))

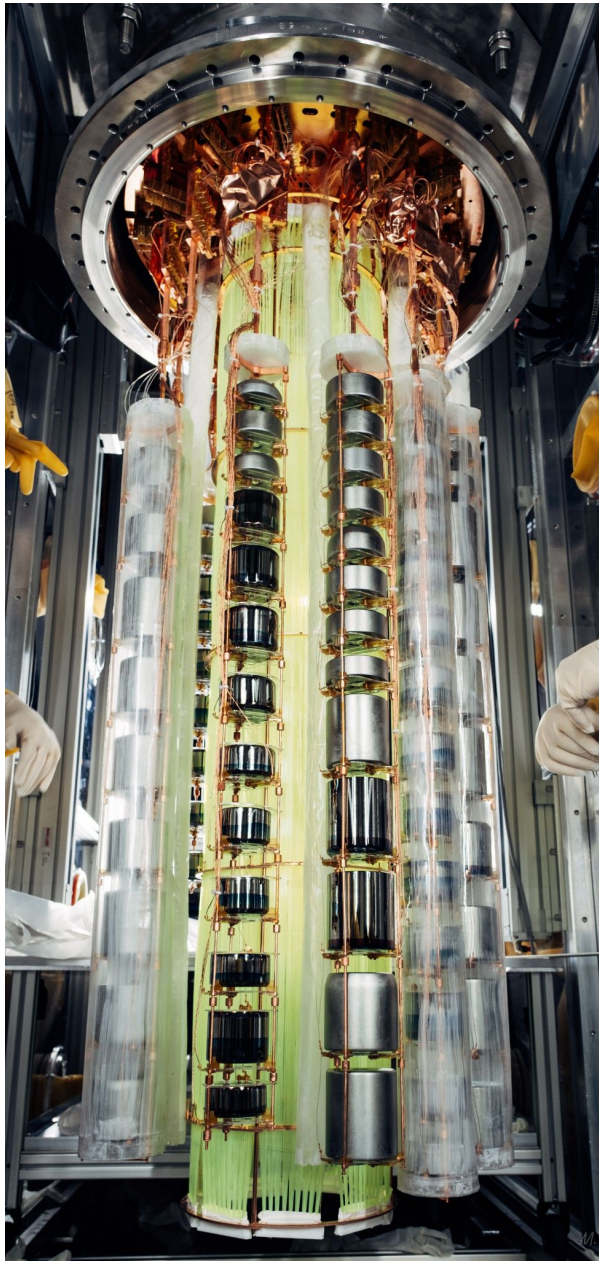
LEGEND-200 current using 4 HPGe detector types, from previous experiments and newly produced Inverted Coaxial (IC) geometry

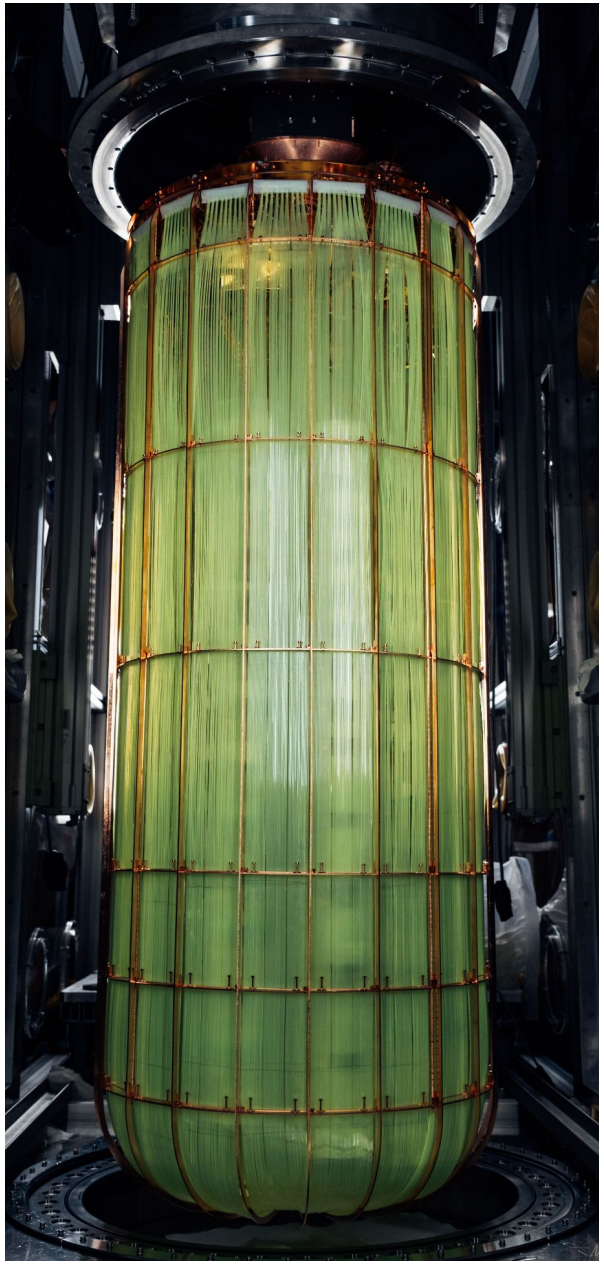
LEGEND-200 Active Background Reduction

in addition to careful material selection and handling during installation, active techniques allow to further reduce background components



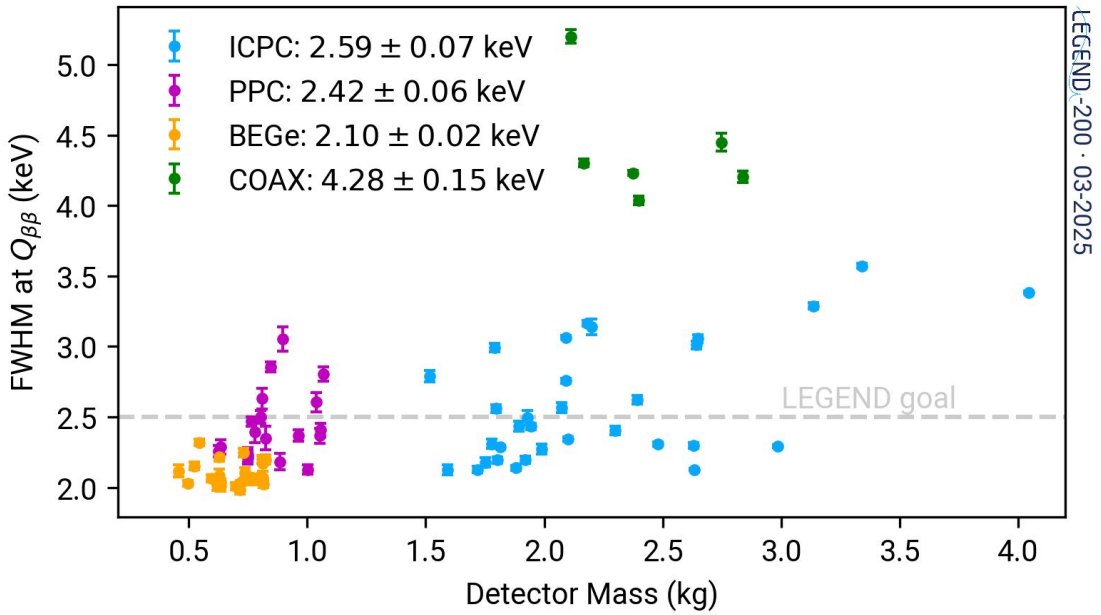
LEGEND-200 Status and Plan

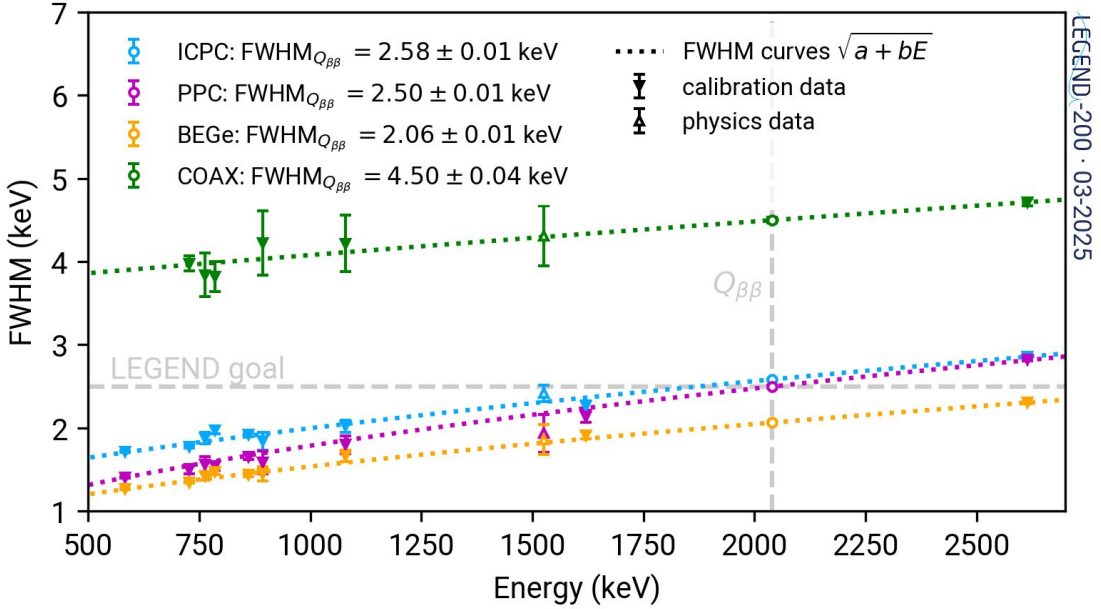




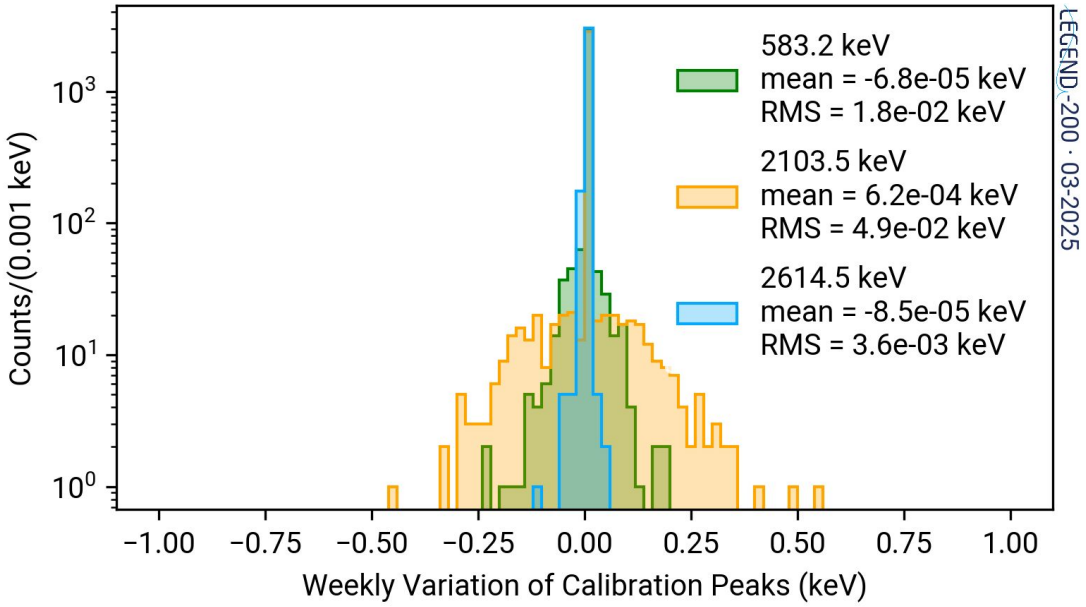
- **Successful installation of 142 kg** of HPGe detectors, 101 detectors in 10 string
- 130 kg operational (12 kg OFF due to hardware issues)
- **LAr instrumentation operational**
- First results with 48.3 kg · yr exposure, **updated with 61 kg · yr exposure**
- Maintenance work started in 2024 and now completed (to reduce background)
- Ongoing installation with 35 kg of new HPGe detectors
- **Restart data taking by spring 2025**

LEGEND-200 Energy Resolution and Stability

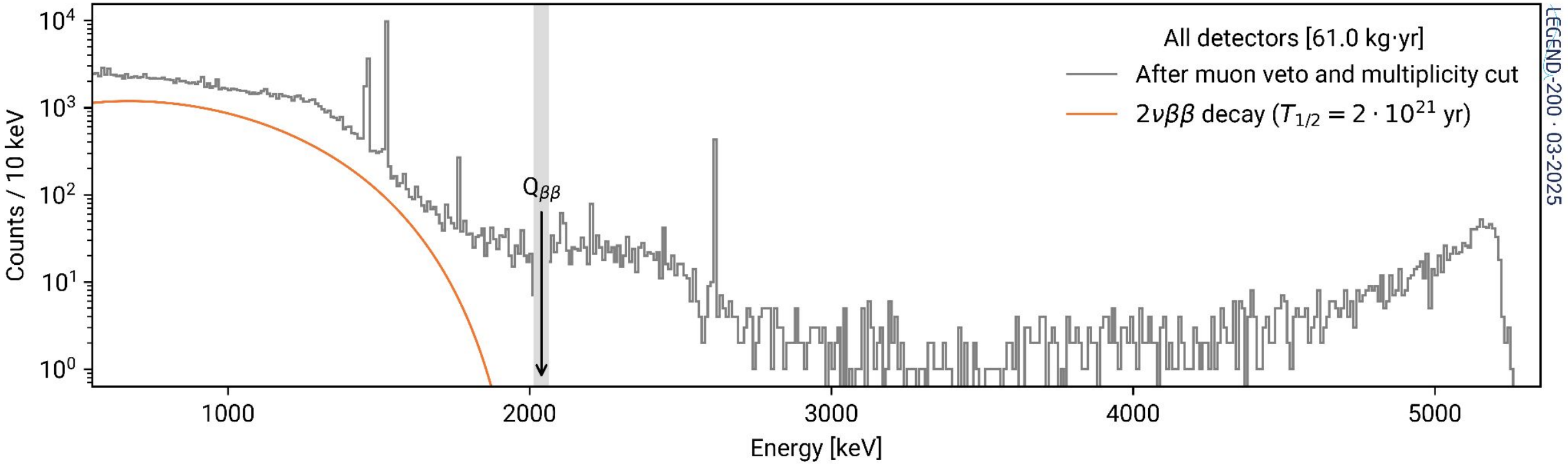




- Energy scale evaluated by weekly ^{228}Th calibration between physics runs
- Most of the detectors fulfilling LEGEND energy resolution goal (0.12% at $Q_{\beta\beta}$)
- Stable energy scale among calibrations
- Data partitioned according to stability of energy observables

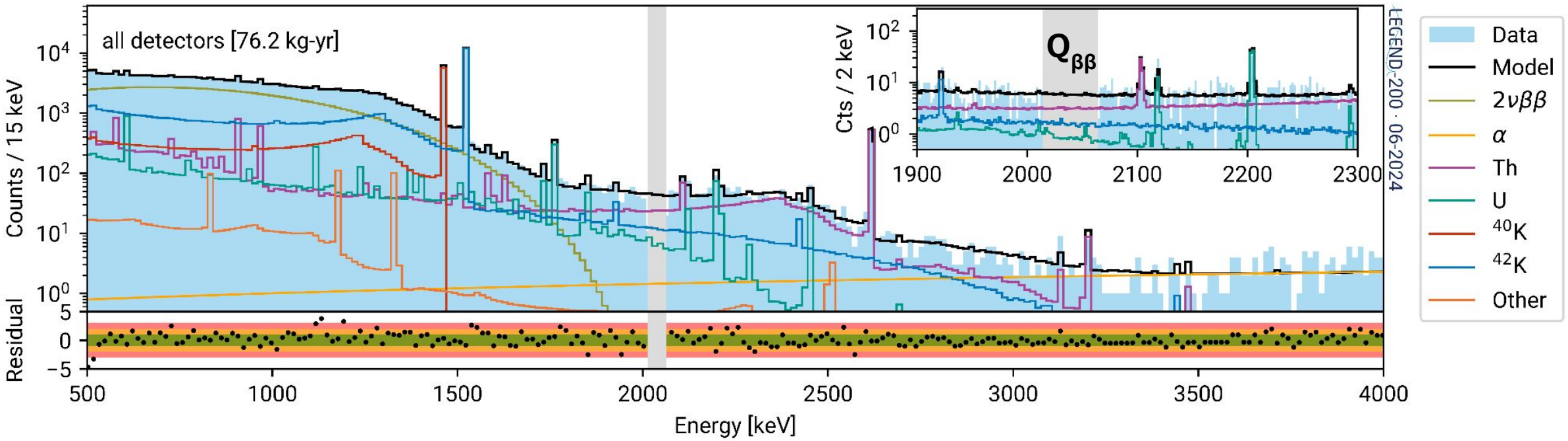


LEGEND-200 Background Spectrum



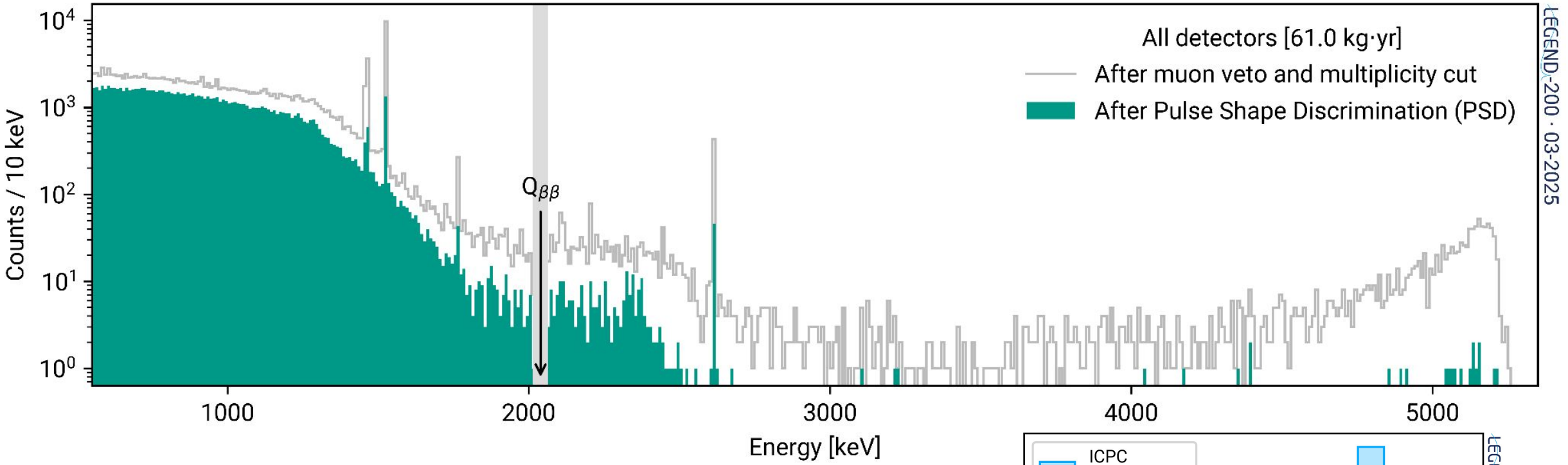
- **Blinded analysis in $Q_{\beta\beta}$ ± 25 keV**
- Spectrum after:
  - data cleaning → 95–99% survival after removal of unphysical events
  - muon veto → 2 events removed at $Q_{\beta\beta}$
  - multiplicity cut (Ge-anticoincidence) → 26% events removed at $Q_{\beta\beta}$

LEGEND-200 Background Model

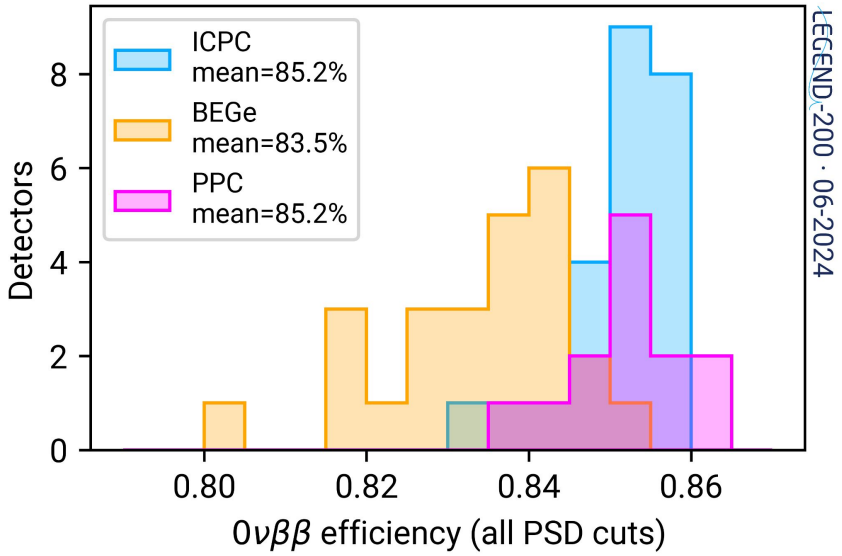


- No unexpected background components (^{238}U and ^{232}Th decay chains, γ-lines from ^{40}K and ^{42}K)
- Spectral shape reproduced well by Bayesian background model
- Higher ^{228}Th background compared to radioassay expectation (screening campaign currently ongoing to identify sources)
- Flat background in the region of interested for the 0νββ decay analysis

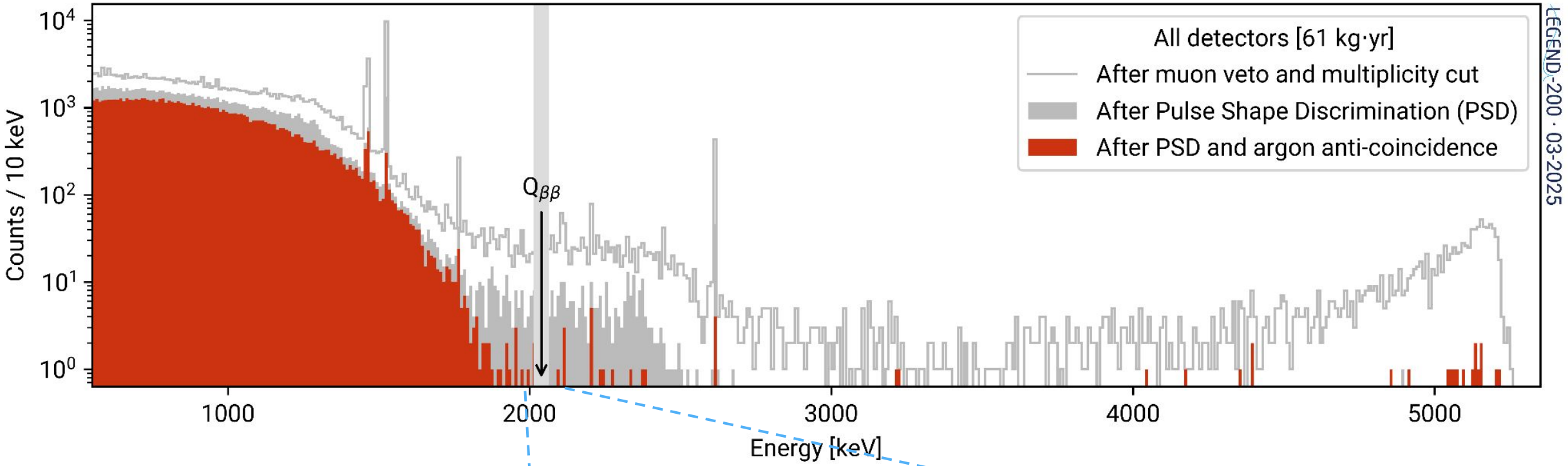
LEGEND-200 Background Spectrum after PSD



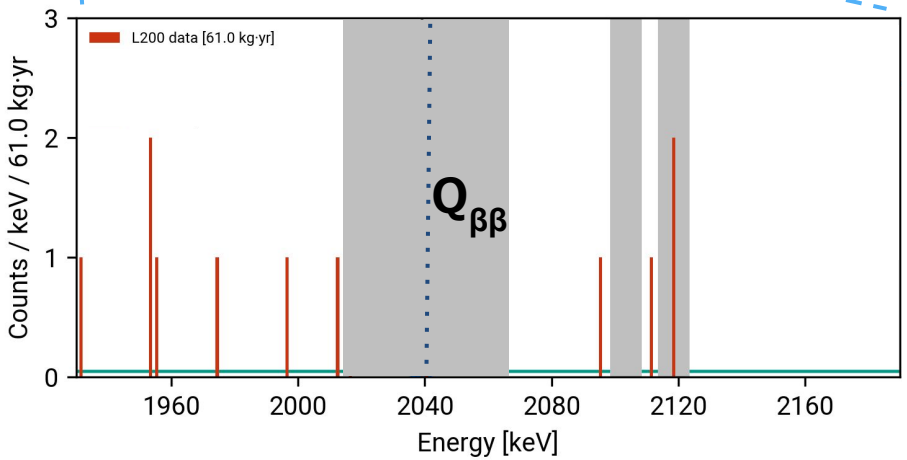
- Strong suppression of surface α and β (^{42}K) events
- ~60% suppression of Compton multi-site events at $Q_{\beta\beta}$
- 0νββ decay survival fraction of 85%



LEGEND-200 Background Spectrum after cuts



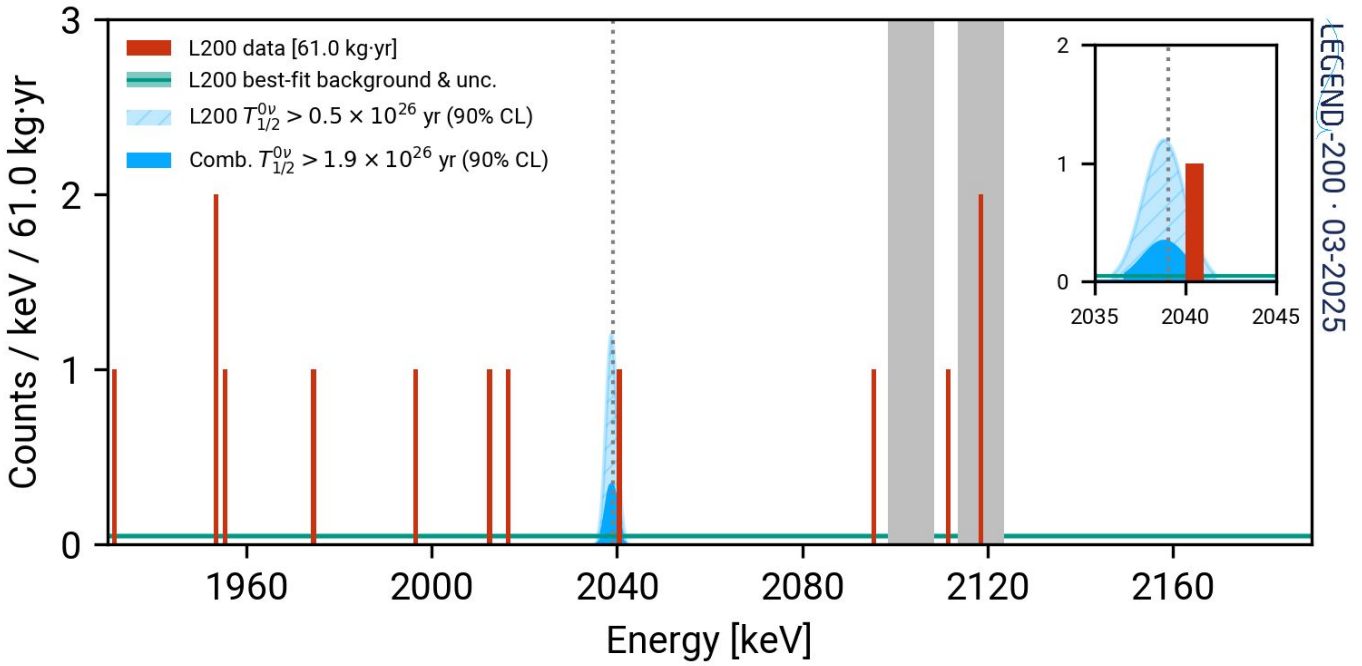
- ββ decay LAr cut signal acceptance ~93%
- Strong anti-correlation of LAr & PSD cuts
- Almost pure 2νββ distribution



- Analysis window E = (1930–2190 keV)
- Excluded γ-lines:
  - ^{208}Tl at (2104 ± 5) keV
  - ^{214}Bi at (2119 ± 5) keV

LEGEND-200 Unblinded Results

- **11 events surviving after cuts**
- **background indices:**
  - $BI_{gold} = 5.4^{+2.7}_{-2.0} \times 10^{-4}$ cts/(keV · kg · yr)
  - $BI_{silver} = 13^{+8.0}_{-5.4} \times 10^{-4}$ cts/(keV · kg · yr)
- silver dataset (13 kg · yr): primarily coaxial detectors with worse background rejection



Combined fit GERDA + MJD + LEGEND-200

- frequentist and Bayesian statistical analysis → **no evidence of 0νββ signal**
- **Lower limit $T_{1/2} > 1.9 \times 10^{26}$ yr @ 90% CL** → $m_{\beta\beta} < 70$–200 meV
- **Median Sensitivity 2.8×10^{26} yr @ 90% CL**
- world-leading sensitivity, one event at 1.4σ from $Q_{\beta\beta}$ weakens observed limit

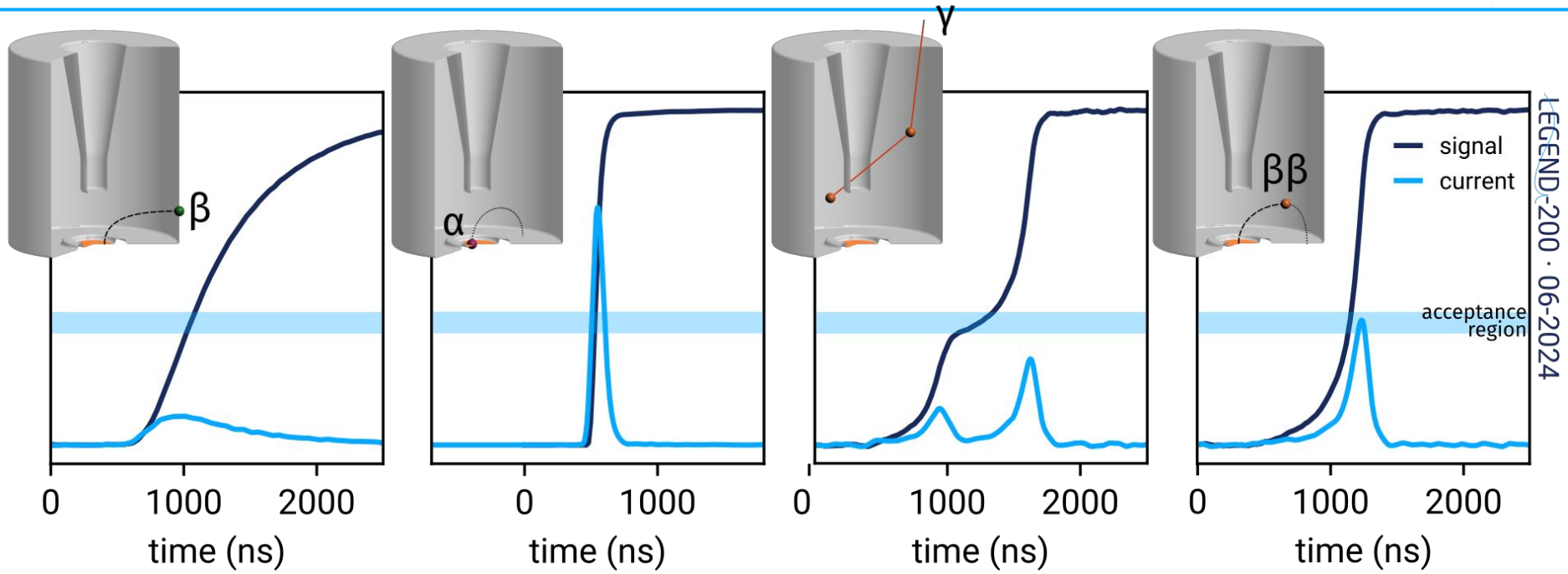
Summary and Outlook

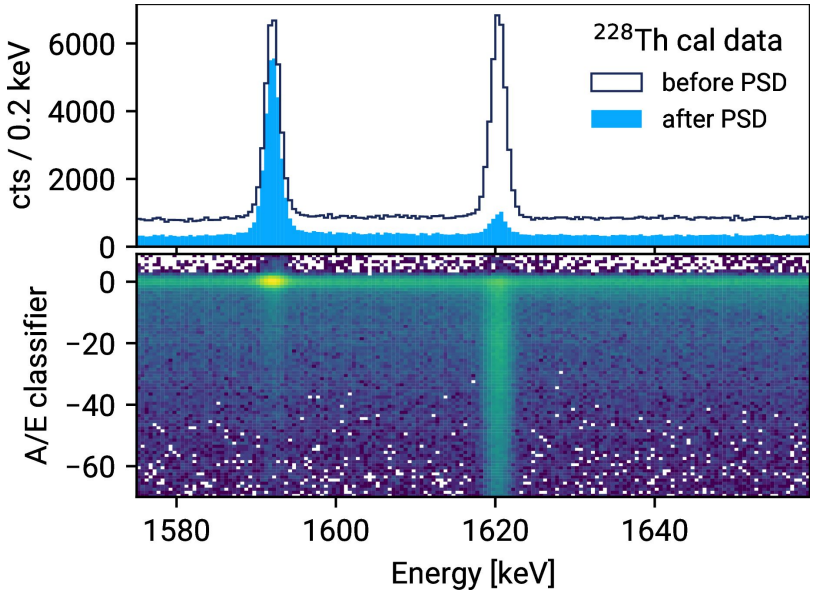
- **Successfully upgraded GERDA infrastructure to accommodate LEGEND-200 array**
  - Installed first 142 kg of HPGe detectors in LEGEND-200 in October 2022
  - Good performance of Ge detectors and LAr instrumentation
- **First LEGEND-200 results based on 61 kg · yr of exposure**
  - LAr cut and PSD reduce background in the ROI with high signal acceptance
  - **Combined analysis with GERDA and MJD set new limit on half-life of 1.9×10^{26} yr with world-leading sensitivity of 2.8×10^{26} yr**
- **LEGEND plans**
  - On-going installation with 35 kg of new HPGe detectors: **restart data taking soon**
  - LEGEND-1000 planning underway

Thanks for your attention!

Backup slides

Pulse Shape Discrimination

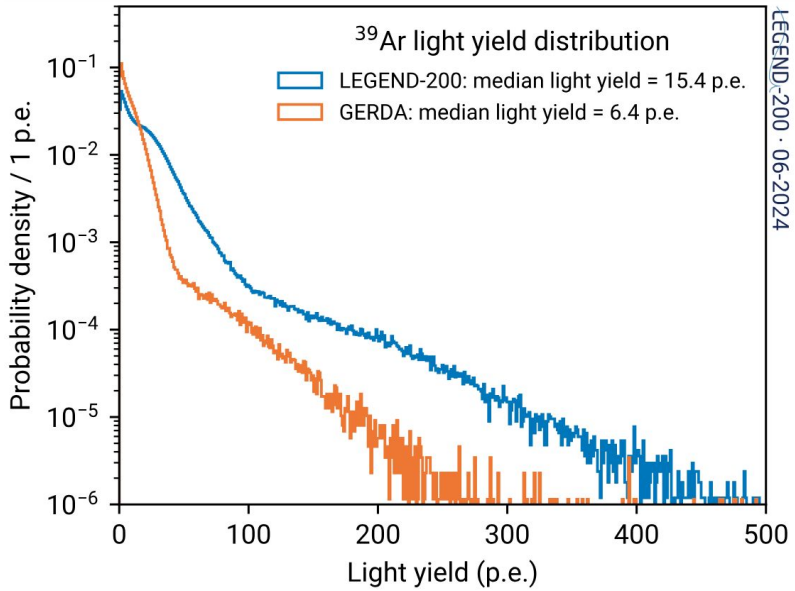


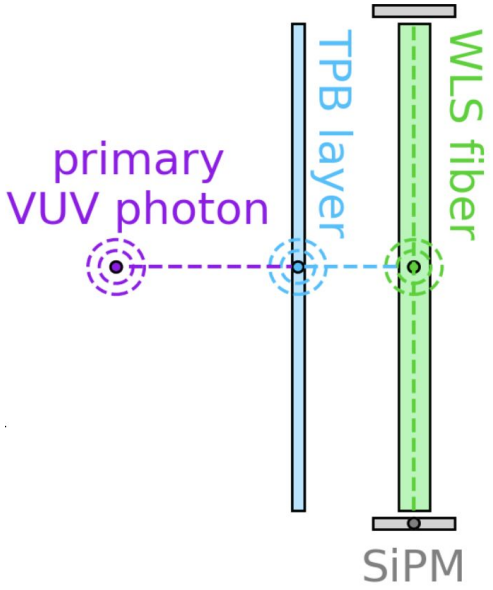


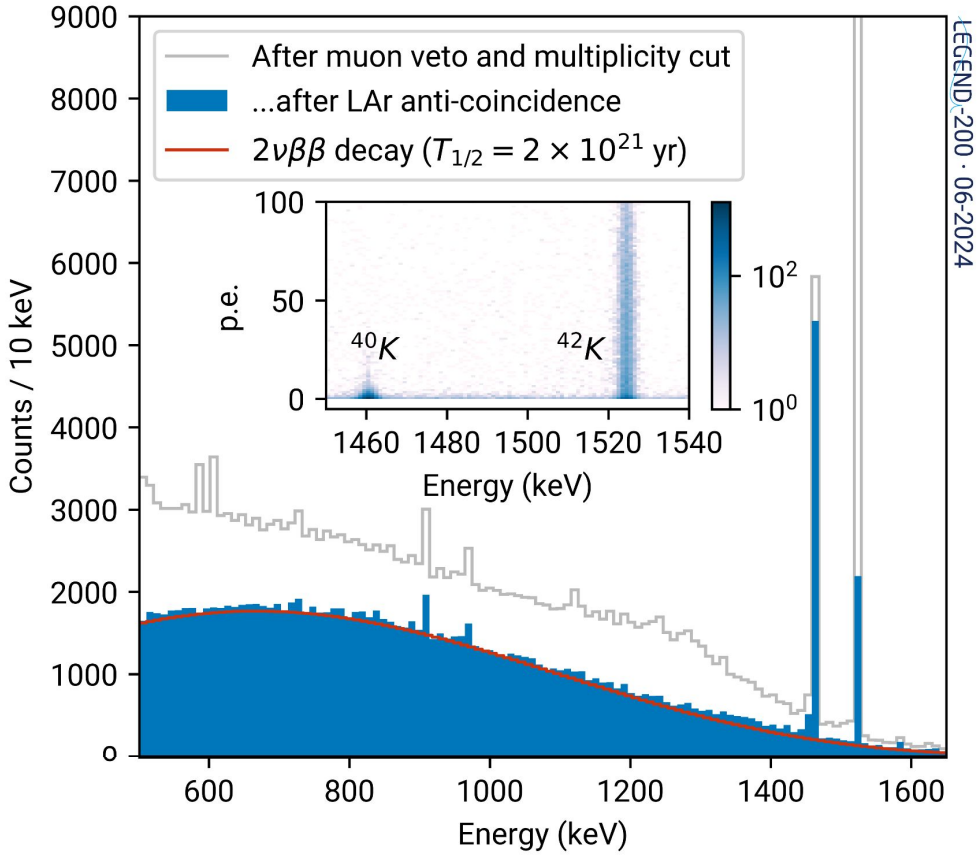
- for IC and BEGe detectors PSD based on A/E parameter: **rejects multi-site, surface and alpha events effectively**
- Double Escape Peak (DEP) of ^{208}Tl used as single-site event proxy, cut tuned to 90% DEP survival
- More powerful in IC detectors due to higher multi-site probability in larger detectors

LAr Instrumentation

- **Detects and suppresses background events through detection of LAr scintillation light**
- Background events can deposit energy in LAr creating 128 nm VUV photons, then shifted to visible light and read by SiPM arrays
- System successfully operated in GERDA, now with higher light yield and less shadowing

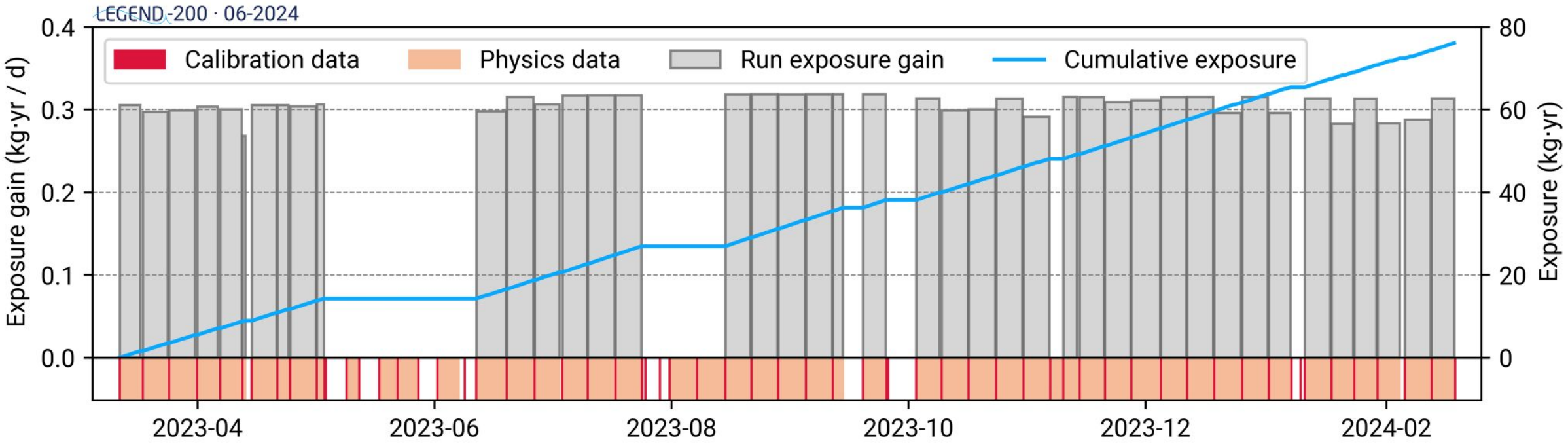




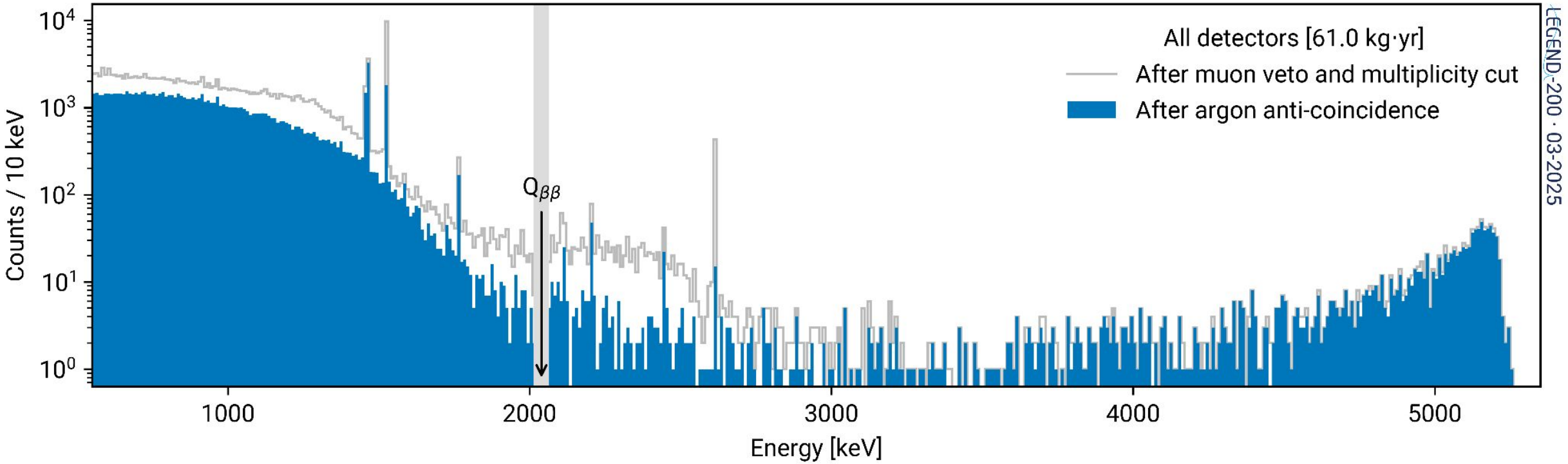


- ^{40}K EC process followed by a gamma not show coincidence with the LAr → **barely suppressed**
- ^{42}K beta followed by 1525 keV gamma have LAr coincidence → **strongly suppressed**

LEGEND-200 Data Taking



LEGEND-200 Background Spectrum after LAr cut



- LAr cut: nPE > 4 & N(SiPM) > 4
- Characterized via special runs: 1 PE per 10 keV
- Strong suppression of background above 2νββ
- ββ decay signal acceptance of 93%

LEGEND-1000