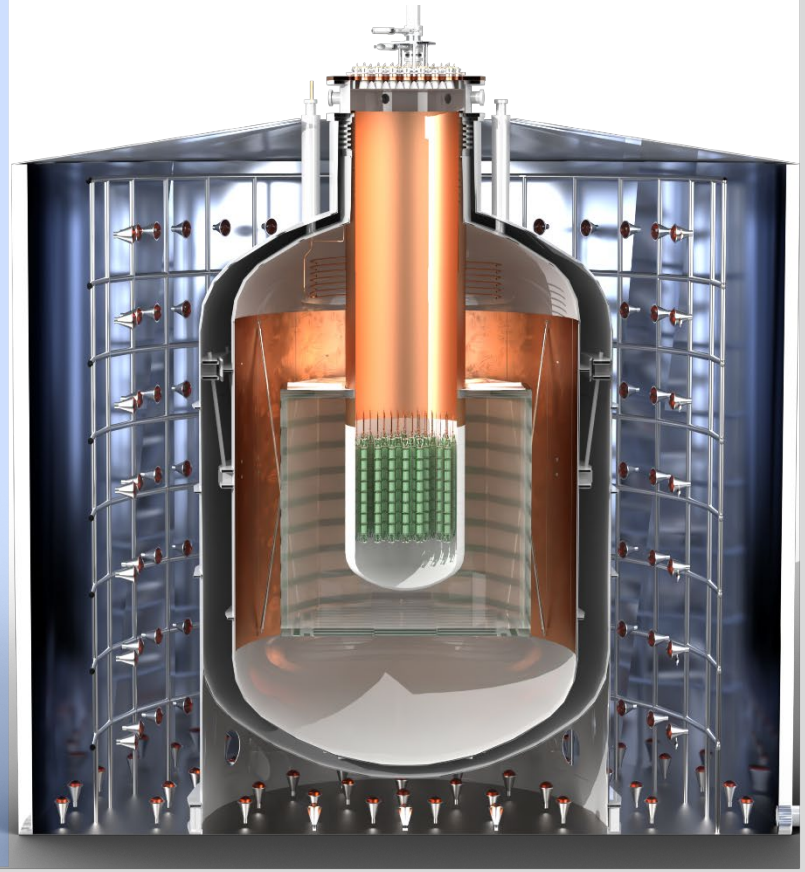
LEGEND

Large Enriched
Germanium Experiment
for Neutrinoless ββ Decay



Natalia Di Marco *on behalf of the LEGEND Collaboration*
GSSI&LNGS

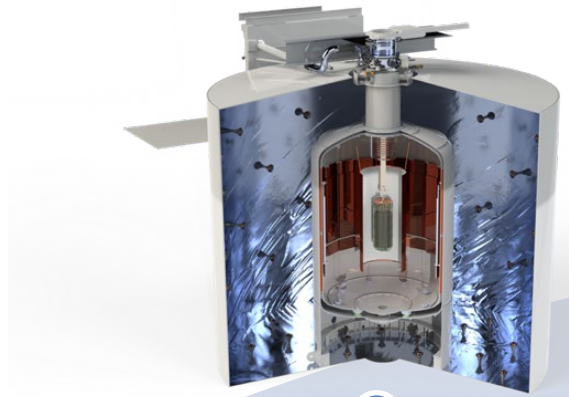
LX meeting LNGS Scientific Committee
16-17 October 2023

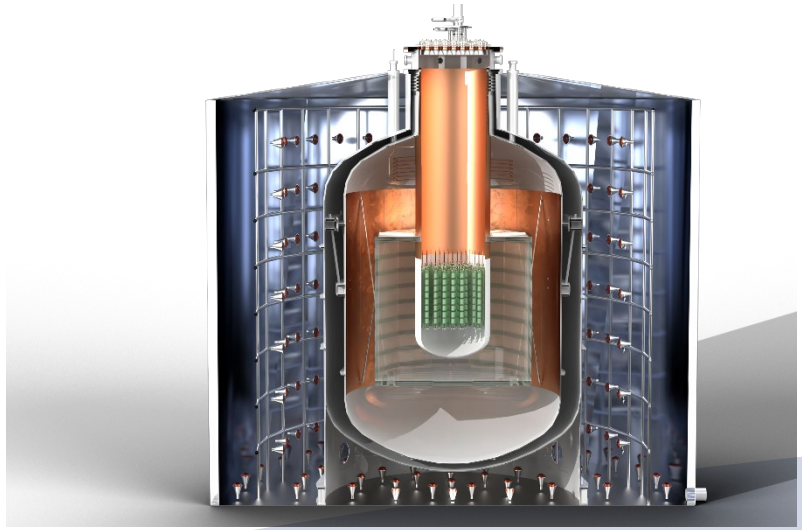
GRAN SASSO SCIENCE INSTITUTE
SCHOOL OF ADVANCED STUDIES
Scuola Universitaria Superiore

INFN
Istituto Nazionale di Fisica Nucleare
LABORATORI NAZIONALI DEL GRAN SASSO

The LEGEND project

The 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***





LEGEND-200

200 kg in upgrade of existing infrastructure at LNGS

BG goal: <0.6 c /(FWMH t y)

Discovery sensitivity at a half-life of 10^{27} years

Status: data taking with 140kg of HPGe

LEGEND-1000

1000 kg

Background goal <0.025 cts/(FWHM t yr)

Discovery sensitivity at a half-life beyond 10^{28} years

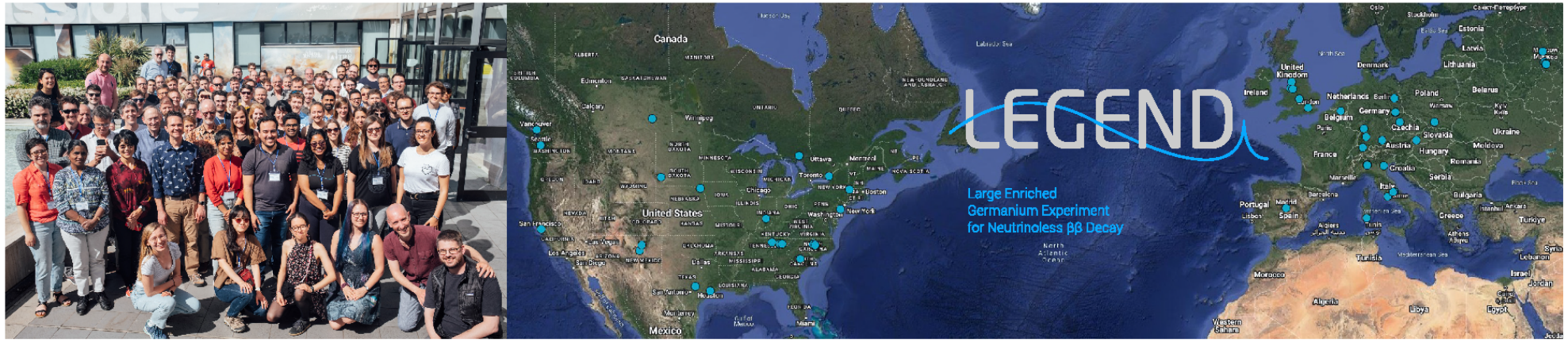
Status: CDR

GERDA

Majorana

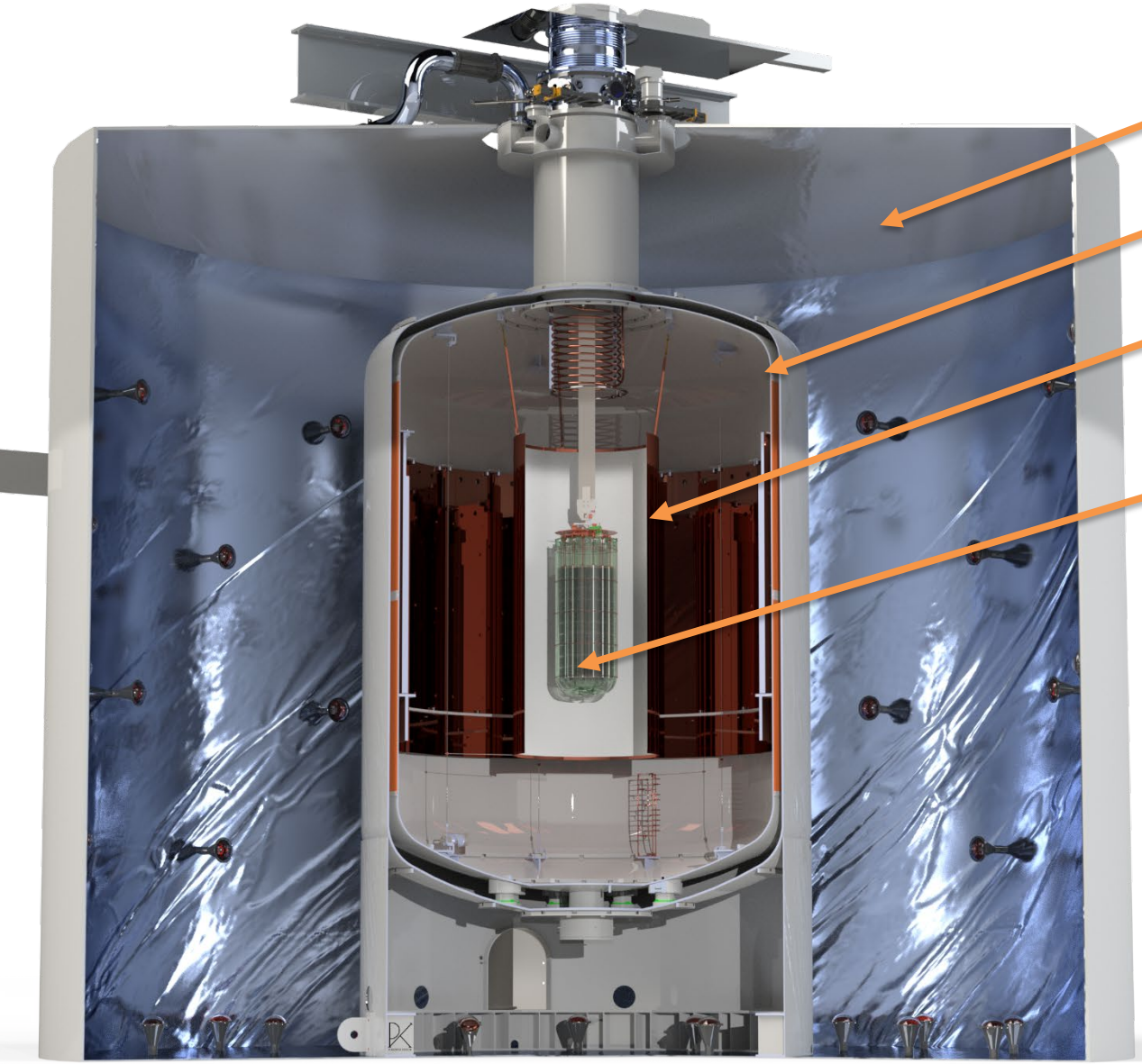
The LEGEND Collaboration

270 members, 58 Institutions, 12 Countries



CIEMAT
Comenius Univ.
Czech Tech. Univ. Prague and IEAP
Daresbury Lab.
Duke Univ. and TUNL
Gran Sasso Science Inst.
Indiana Univ. Bloomington
Inst. Nucl. Res. Rus. Acad. Sci.
Jagiellonian Univ.
Joint Inst. for Nucl. Res.
Joint Res. Centre Geel
Lab. Naz. Gran Sasso
Lancaster Univ.
Leibniz Inst. for Crystal Growth
Leibniz Inst. for Polymer Research
Los Alamos Natl. Lab.
Max Planck Inst. for Nucl. Phy.
Max Planck Inst. for Physics
Natl. Res. Center Kurchatov Inst.
Natl. Res. Nucl. Univ. MEPhI
North Carolina State Univ.
Oak Ridge Natl. Lab.
Polytech. Univ. of Milan
Princeton Univ.
Queen's Univ.
Roma Tre Univ. and INFN
Simon Fraser Univ.
SNOLAB
South Dakota Mines
Tech. Univ. Dresden
Tech. Univ. Munich
Tennessee Tech. Univ.
Univ. of California and LBNL
Univ. College London
Univ. of L'Aquila and INFN
Univ. of Cagliari and INFN
Univ. of Houston
Univ. of Liverpool
Univ. of Milan and INFN
Univ. of Milano Bicocca and INFN
Univ. of New Mexico
Univ. of North Carolina at Chapel Hill
Univ. of Padova and INFN
Univ. of Regina
Univ. of South Carolina
Univ. of South Dakota
Univ. of Tennessee
Univ. of Texas at Austin
Univ. of Tuebingen
Univ. of Warwick
Univ. of Washington and CENPA
Univ. of Zurich
Williams College

LEGEND-200

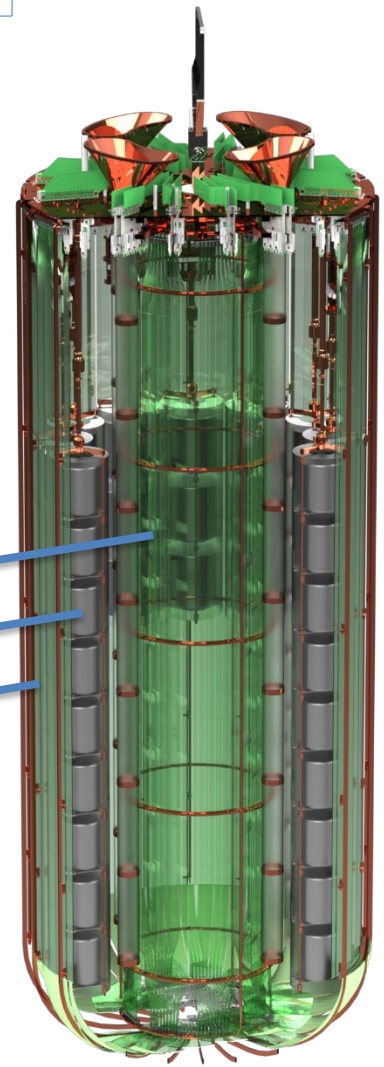


Water tank + PMTs (shielding + muon veto)

Stainless steel cryostat (64 m^3 LAr)

TPB-coated Copper-Tetratex foil

Payload with Ge detector strings and (new) LAr read-out system

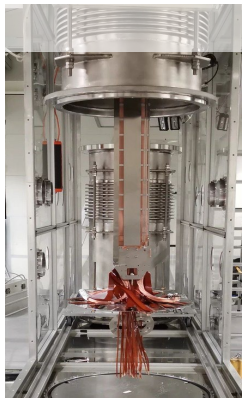


Inner WLS fiber barrel

HPGe string

Outer WLS fiber barrel

LEGEND-200 Timeline

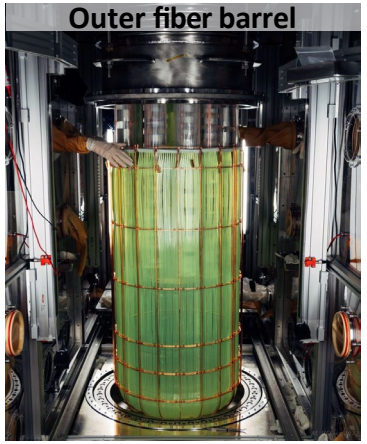


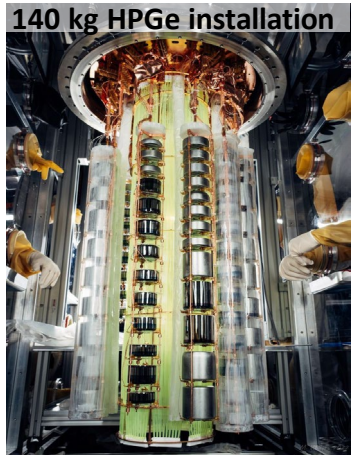
2020

- Post GERDA Test (PGT)
- Upgrade of cryostat infrastructure

2021

- Upgrade of cryostat infrastructure
- Electronics and DAQ test
- Mechanics & glovebox installation





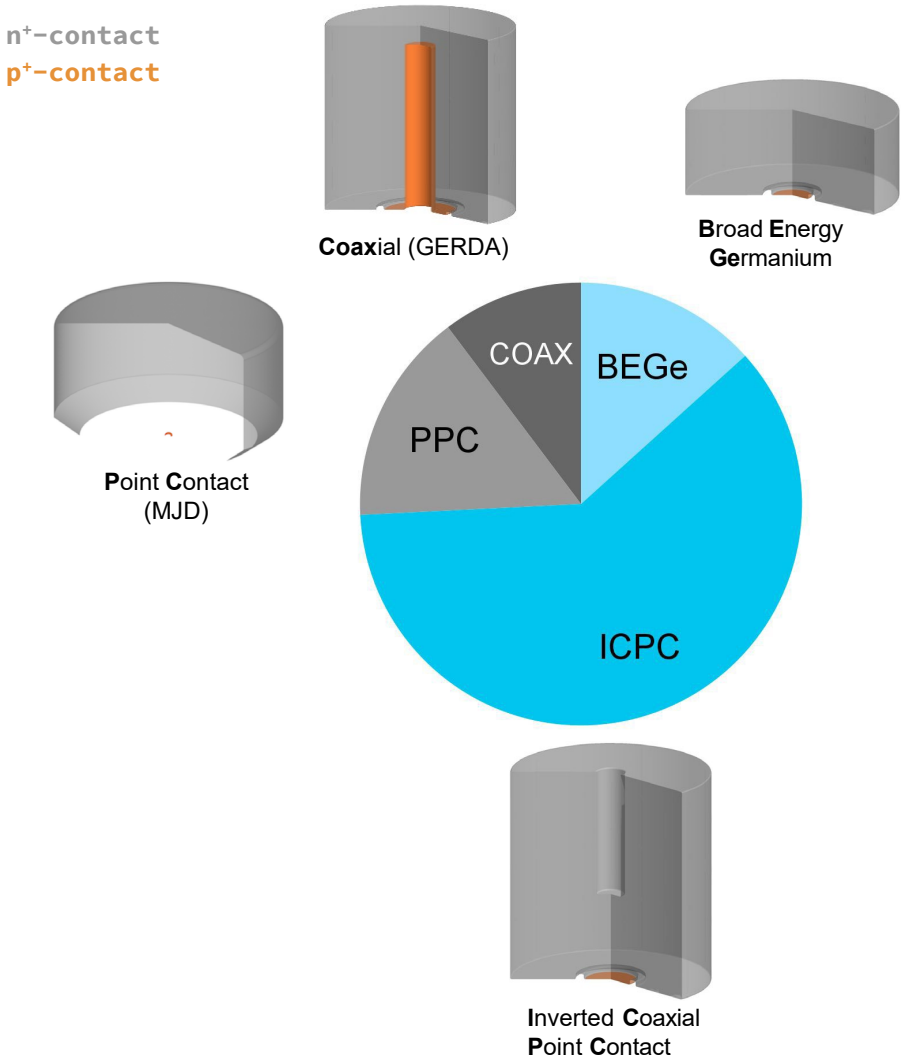
2022

- Construction & commissioning of LAr
- 60 kg campaign + special calibration
- 142 kg installation & commissioning

2023

- Commissioning
- Physics data taking (Spring 2023)

LEGEND-200 Timeline



@Today

- Deployed 101 detectors in 10 strings, 142.5 kg
- Electronics for full 200 kg installation available & tested
- DAQ & slow control fully available
- So far: focus on the analysis of BEGe & ICPC detectors

  PSD development for other detectors ongoing

> 2024 plan

- Data taking will continue until mid-April 2024
- Goal exposure: 90 kg·yr
- Fix hardware failure, perform maintenance
- May 2024: deployment of additional detectors (30-40 kg)
- 2025: final deployment:

  ~ 190 kg of enriched HPGe detectors in total

2023

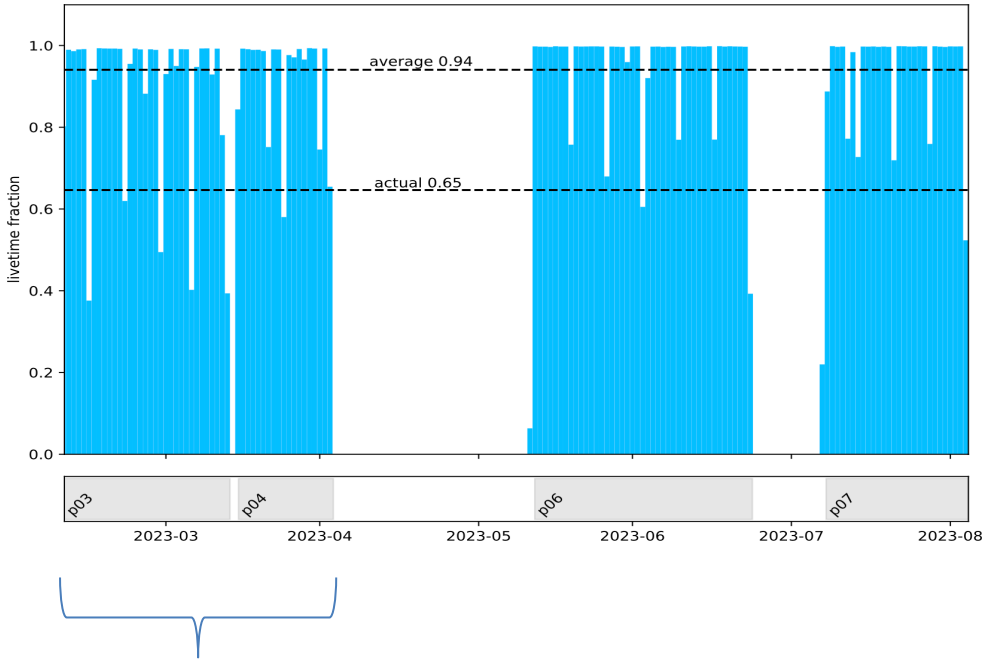
- Data taking
- New ICPC detectors currently in production

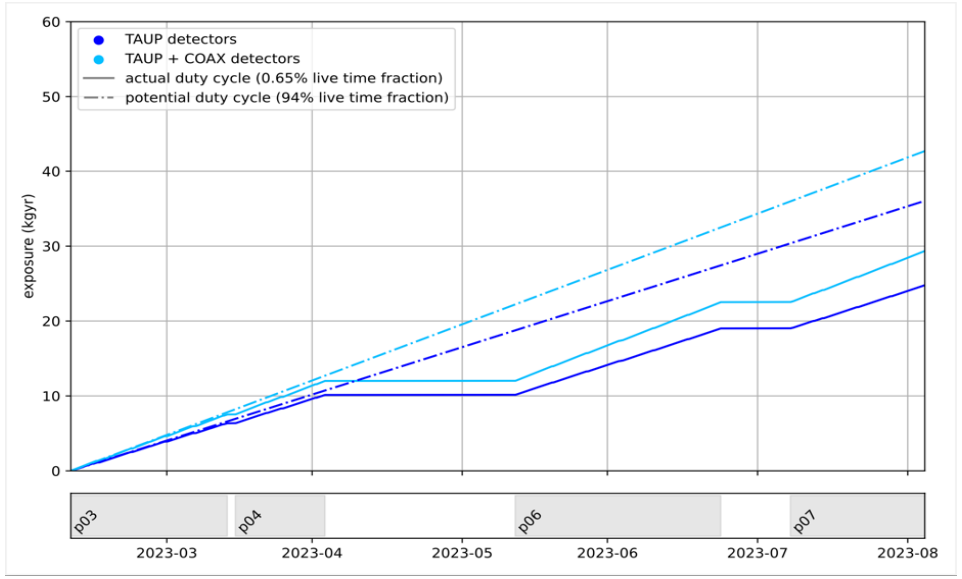
2024

- Complete the array with remaining detectors

LEGEND-200 Data taking performance

- ✓The averaged total lifetime was 65%
- ✓The average lifetime during periods p03, p04, p06, and p07 was 94% (limited by calibration operations).
- ✓Period p05 repeated weather-related power outages → temperature instabilities of the clean room → gain instabilities.
- ✓Extensive high-voltage scans and measurements with calibration sources were performed in July to optimize detector performance.





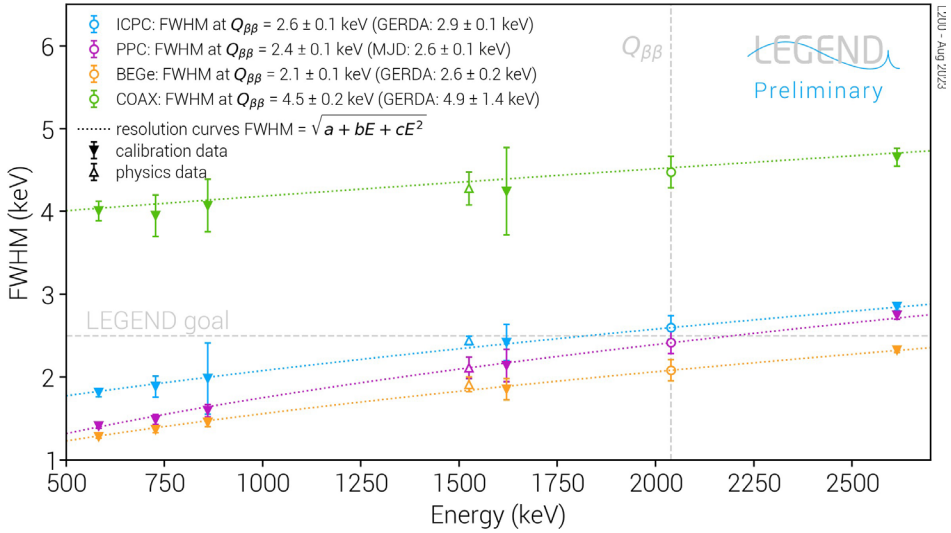
TAUP2023 data set

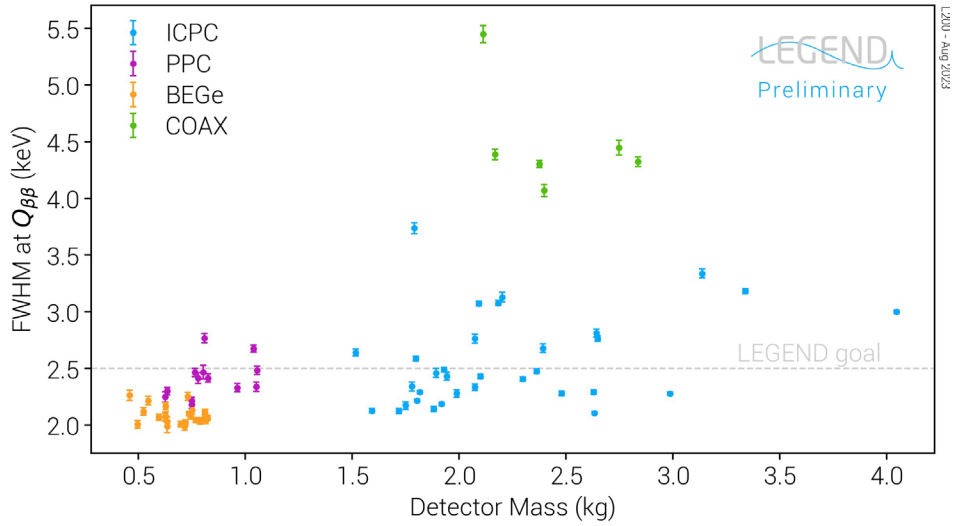
- ✓only BEGe and ICPC detectors considered for analysis (3/4 of the total mass)
- ✓Exposure 10.1 kg·yr

LEGEND-200 Energy Resolution and PSD

Energy Resolution

- ✓ Weekly energy calibration between physics runs using ^{228}Th sources
- ✓ Overall improvement in energy resolution @$Q_{\beta\beta}$
- ✓ Energy scale very stable between calibrations





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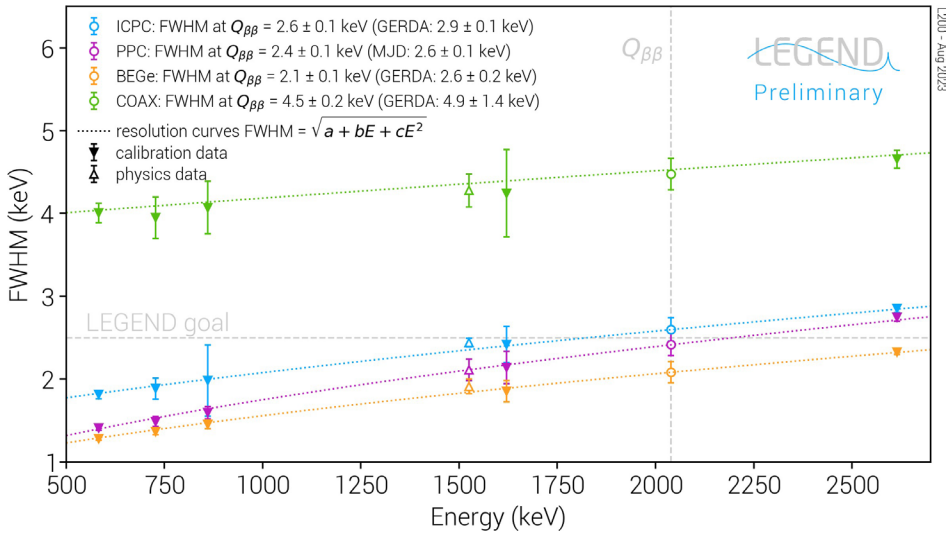
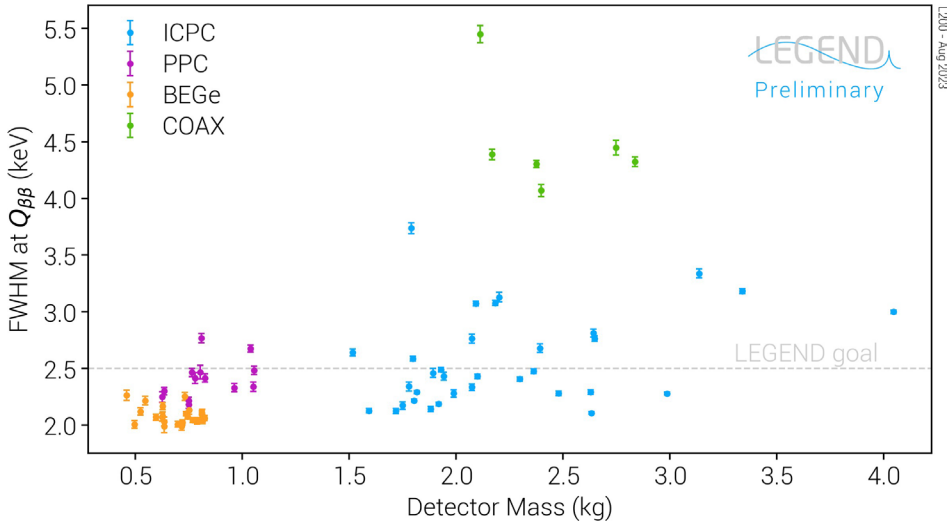
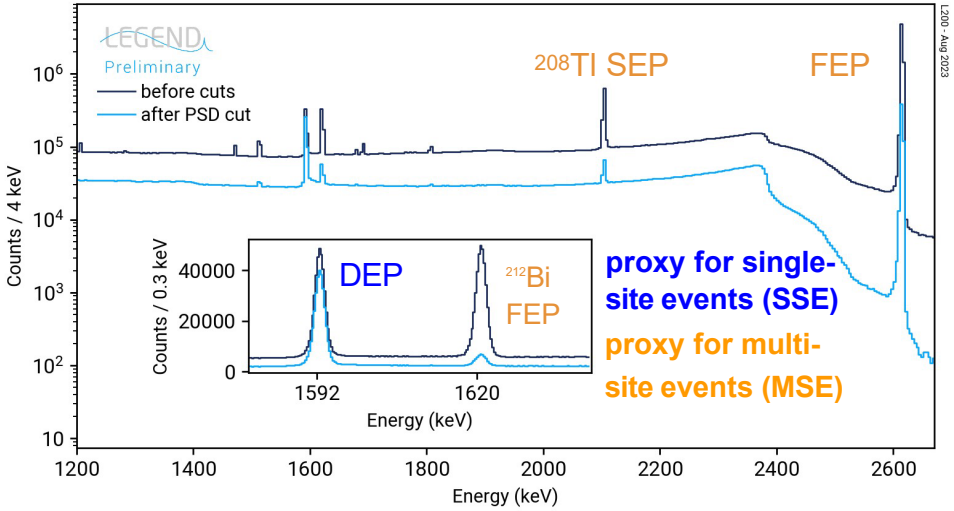


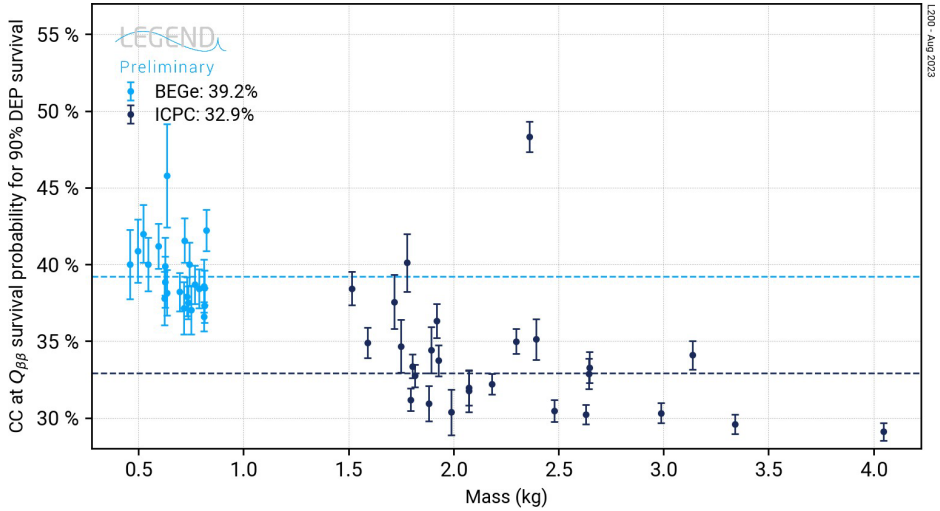


Pulse Shape Discrimination

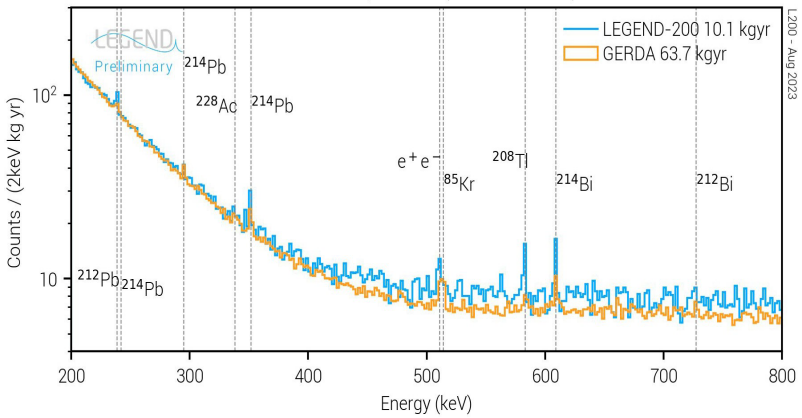
- ✓ Based on A/E parameter, evaluated for each event
- ✓ PSD tuned to 90% survival at ^{208}Tl DEP

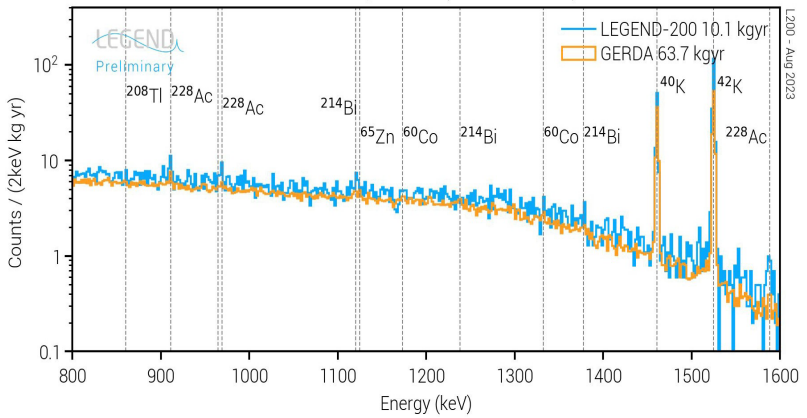
  → very good rejection of multi-site events



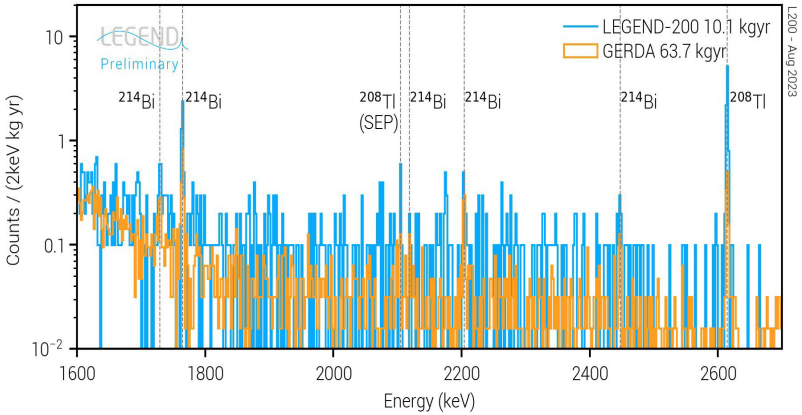


LEGEND-200 Background after QC





LEGEND vs. GERDA BEGe+ICPC

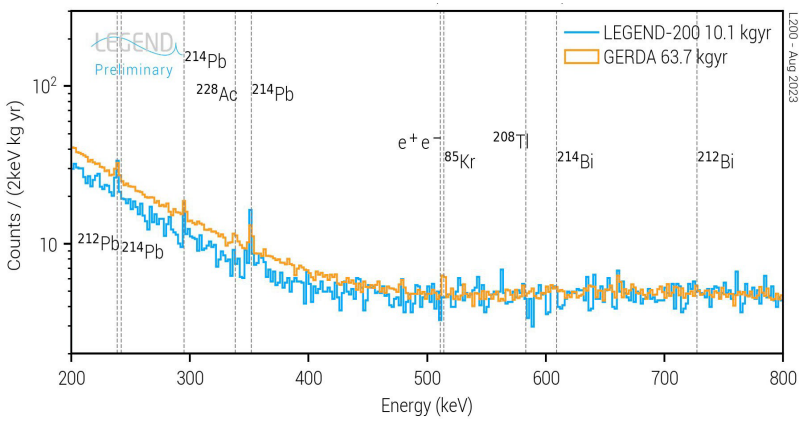


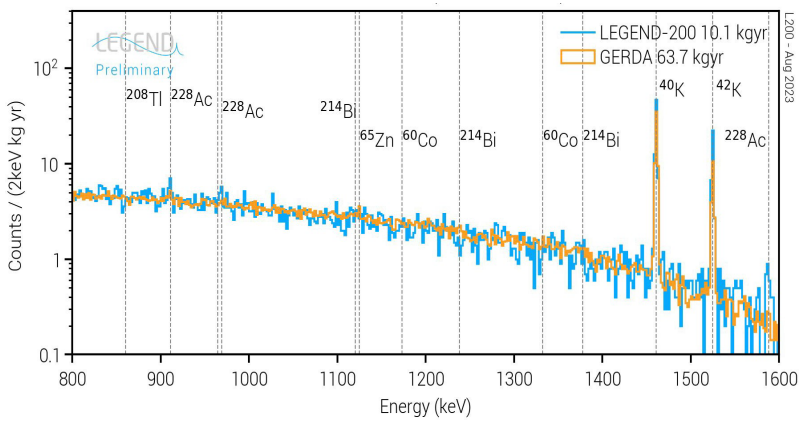
Quality Cuts (QC)

- Data cleaning (DC)
- Muon veto (μ)
- Ge-detector anti-coincidence (AC)

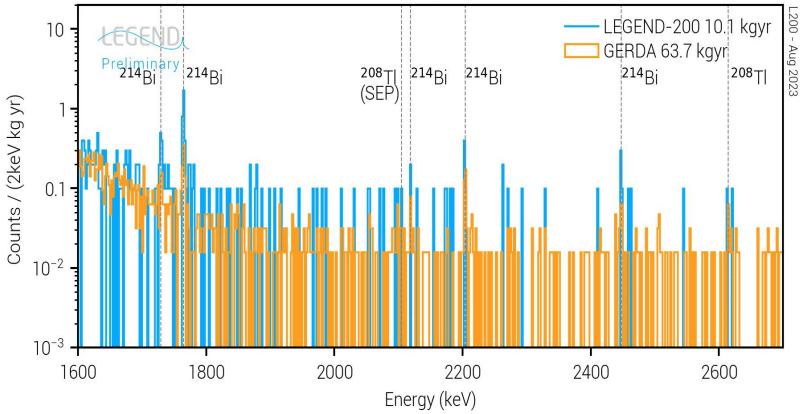
- ✓ No unexpected background components ^{238}U & ^{232}Th decay chains, ^{40}K, ^{42}K
- ✓ Improved peak-to-Compton ratio
  - Reduces Compton continuum background
  - Higher detection efficiency due to larger mass detectors
- ✓ Higher rate from ^{208}Tl compared to GERDA
  - Expected -> more construction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

LEGEND-200 Background after QC + LAr

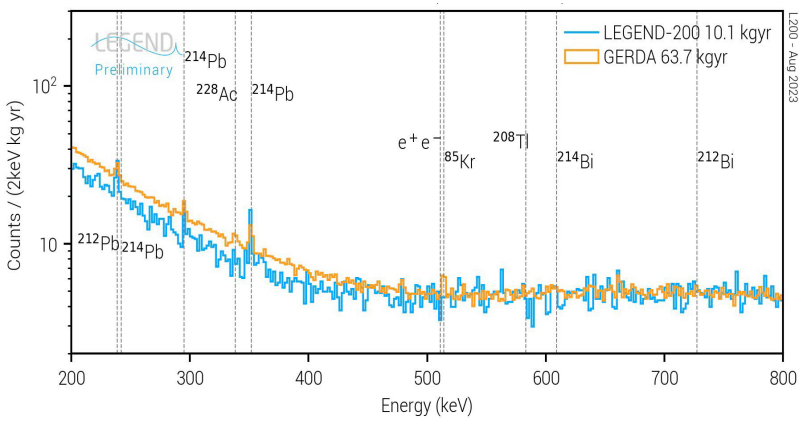


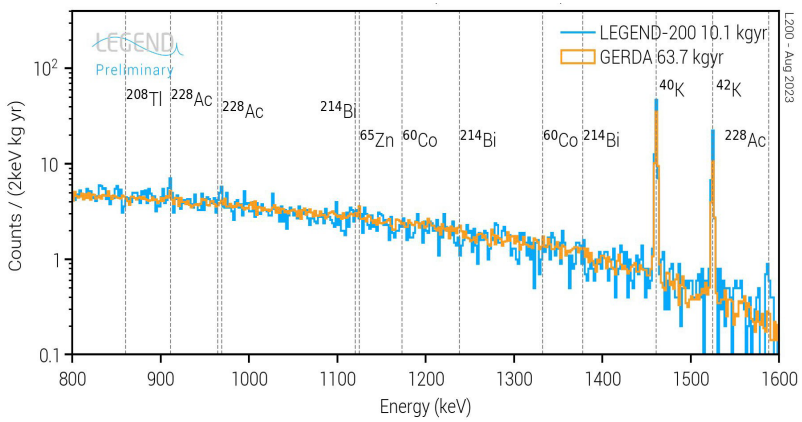


LEGEND vs. GERDA BEGe+ICPC

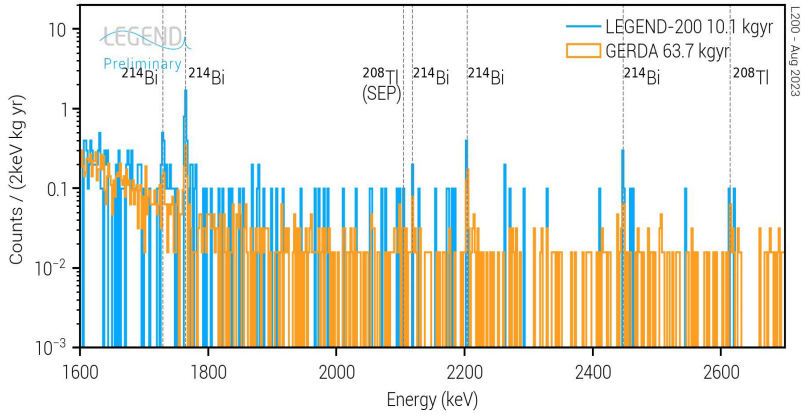


LEGEND-200 Background after QC + LAr

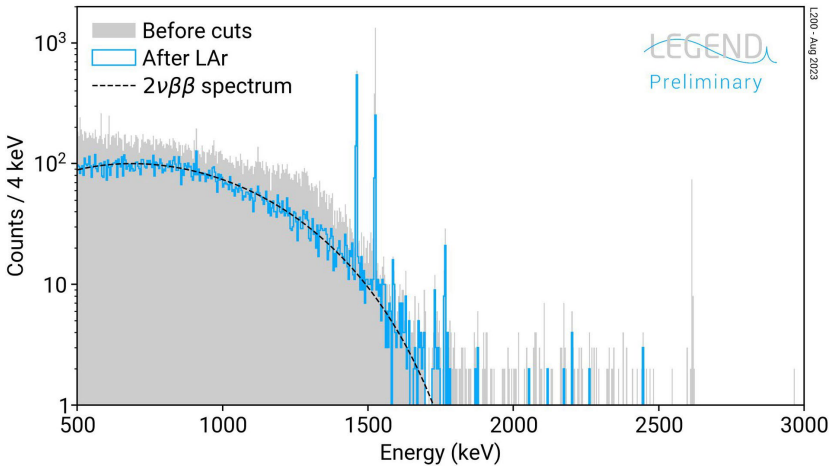


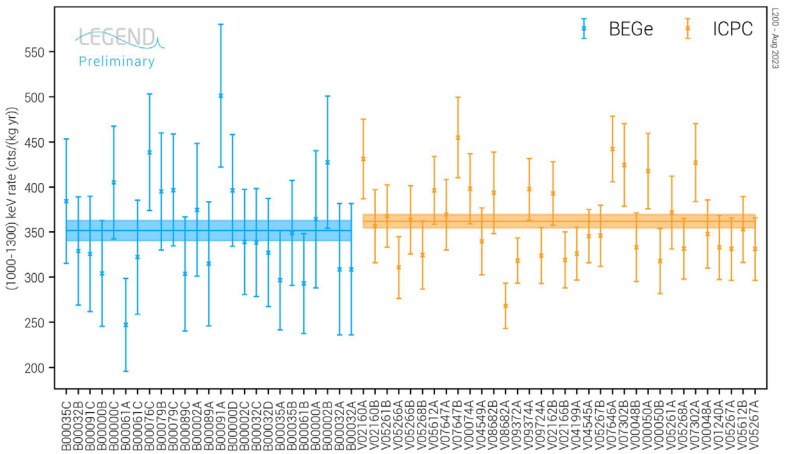


LEGEND vs. GERDA BEGe+ICPC

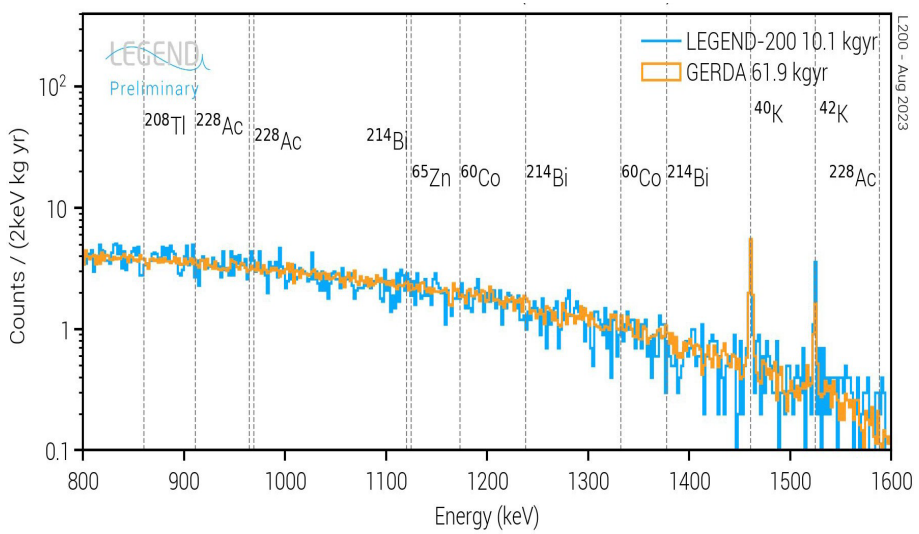


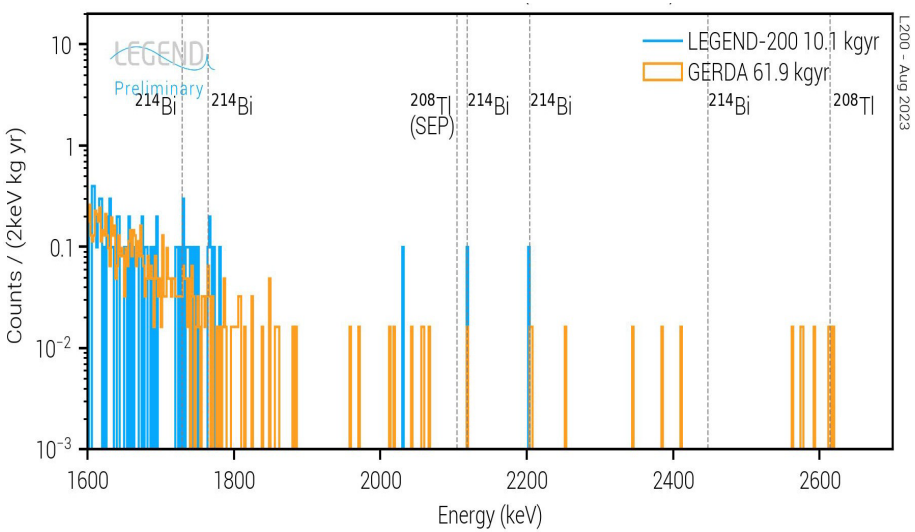
- ✓ Some gamma lines "vanish" & Compton continuum suppressed
  - ^{208}Tl peak is completely suppressed
  - ^{42}K peak survives to < 20%
  - ^{40}K peak fully accepted
  - Pure 2νββ at low energy
  - Uniform detector rate



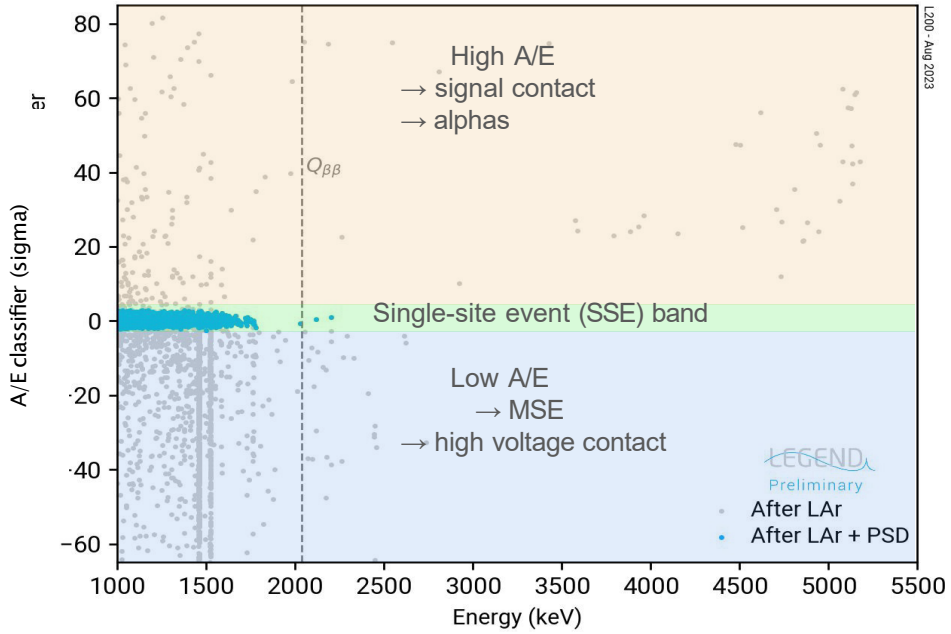


LEGEND-200 Background after QC + LAr + PSD





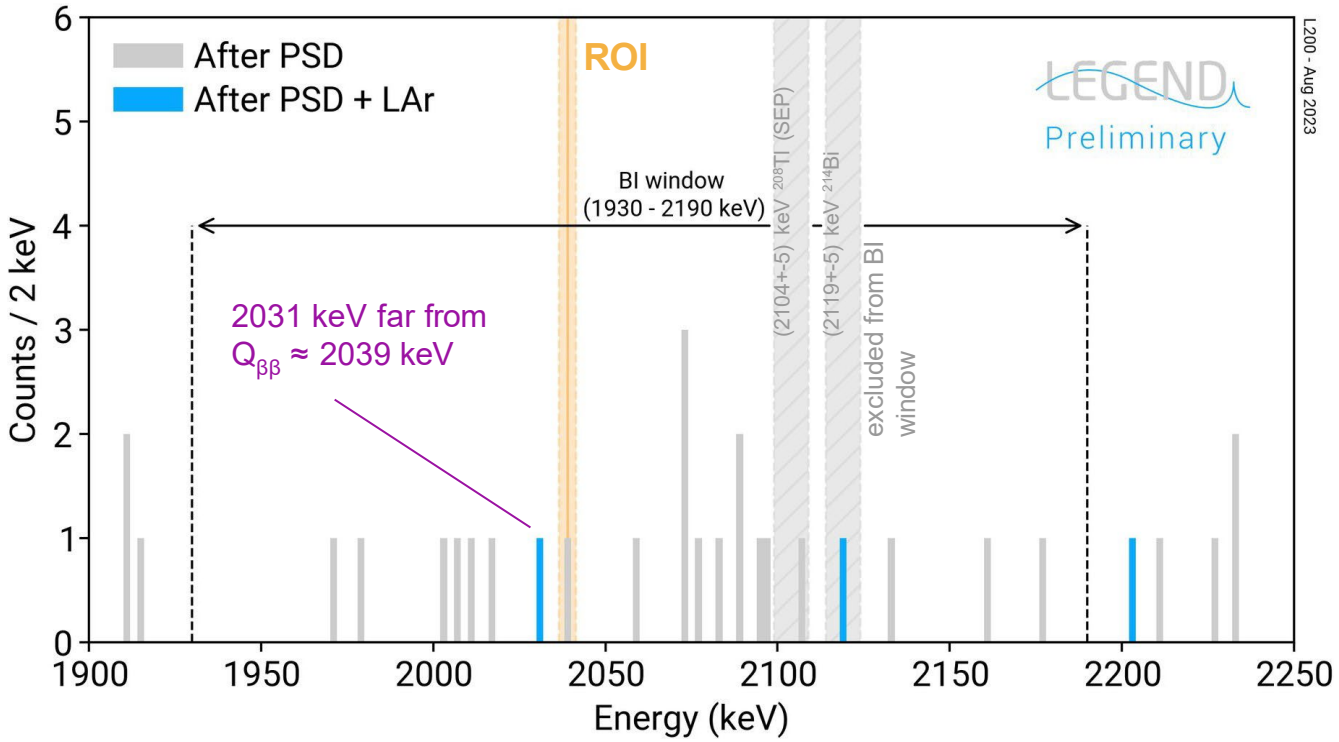
LEGEND vs. GERDA BEGe+ICPC



- ✓ PSD cuts multi-site and alpha events effectively
- ✓ More powerful due to higher MSE probability in larger ICPC detectors

LEGEND-200 Background Index

First ***10.1 kg yr*** of LEGEND-200 data
- ✓ ICPC & BEGe
- ✓ LAr accepted
- ✓ PSD accepted



- ✓ BI is compatible with LEGEND-200 goal

  2×10^{-4} cts/(keV kg yr)

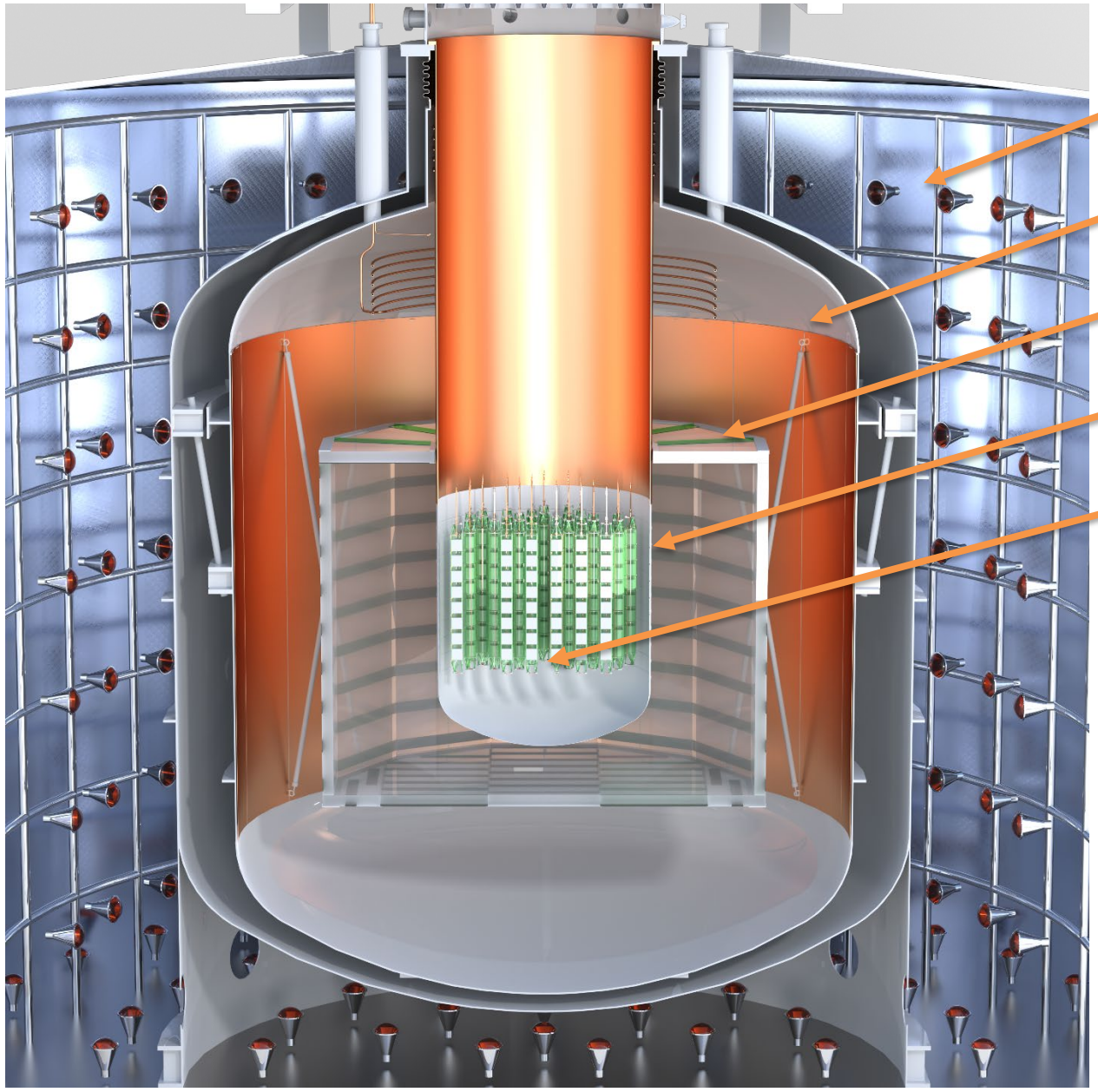
- ✓ Expect 0.48 cts
- ✓ Probability to observe
  - #cts > 0 ~ 38%
  - window 240 keV & exposure 10.1 kg yr

	LEGEND-200 BI 68% CL (cts/keV/kg/yr)	**GERDA Phase II unblinded** BI 68% CL (cts/keV/kg/yr)
After LAr & PSD	4.1 [1.5,11.4] x 10^{-4}	5.2 [3.9,6.8] x 10^{-4}

LEGEND-1000

Designed for an Unambiguous Discovery

LEGEND-1000



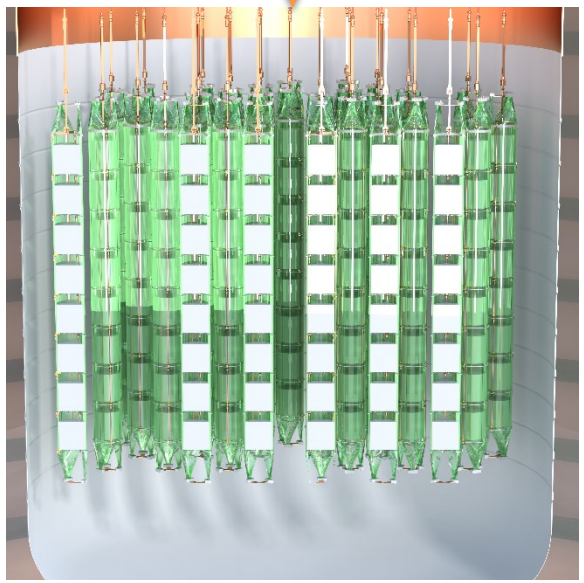
Water tank + PMTs (shielding + muon veto)

Stainless steel cryostat – Xenon doped atmospheric LAr

Neutron moderator + LAr read-out system

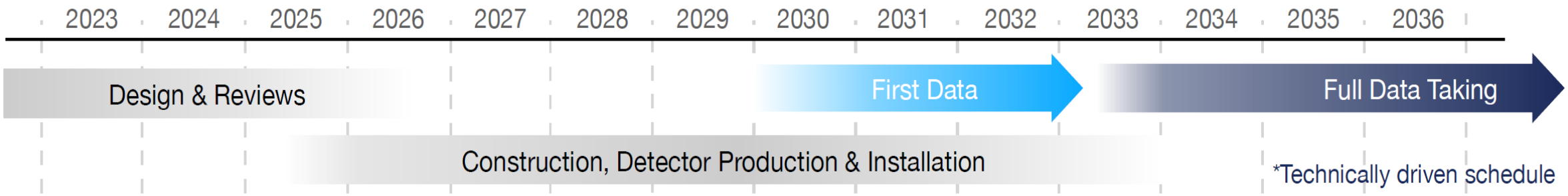
Reentrant tube – Underground LAr (Uar)

Ge detector strings and ULAr read-out system

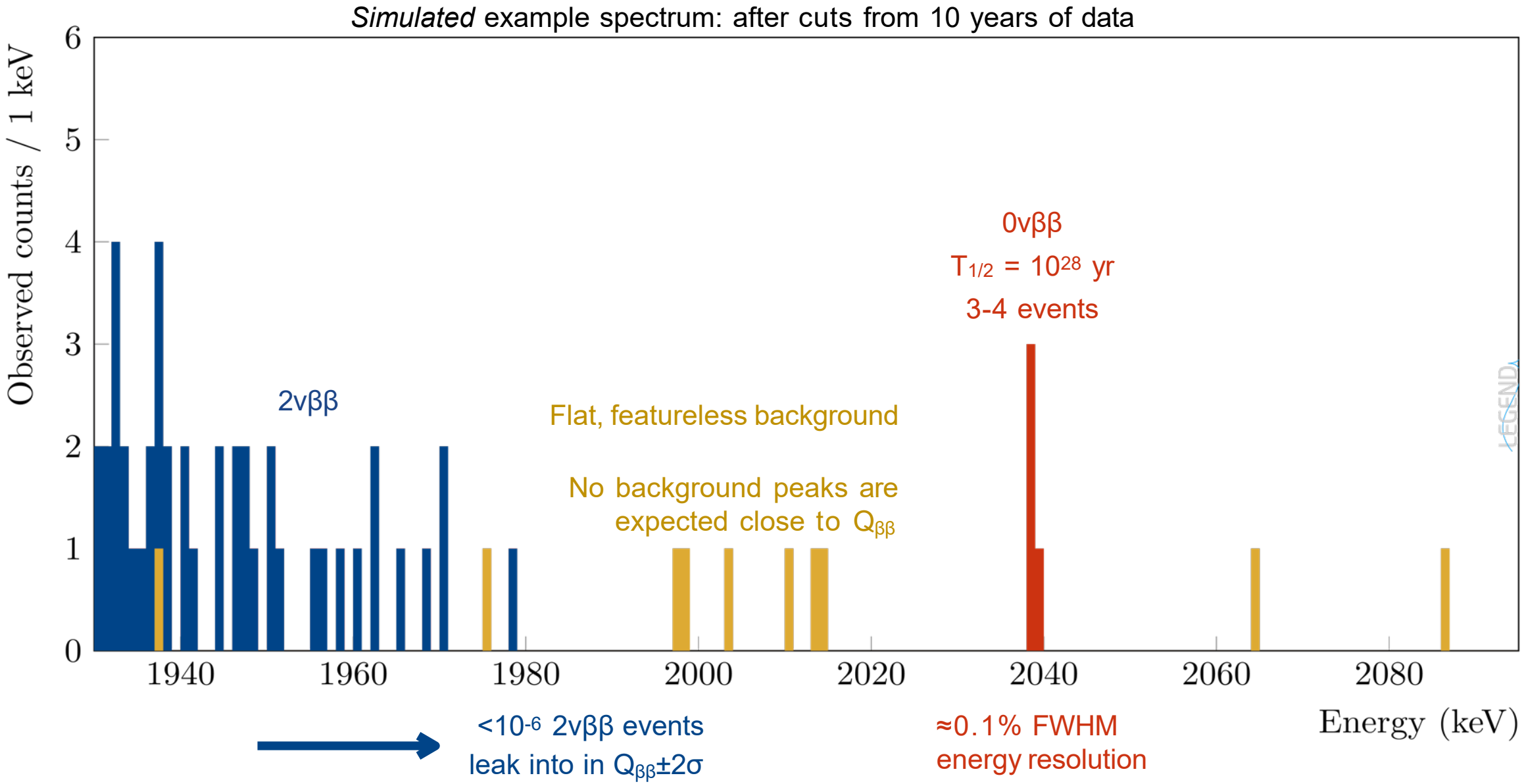


LEGEND-1000

- ✓ 336, large-mass ICPC detectors: ~3 kg avg. mass
- ✓ 1000 kg HPGe Detectors (ICPC)
- ✓ Single string, modular approach
- ✓ Detector strings can be individually installed: early data as detectors are produced



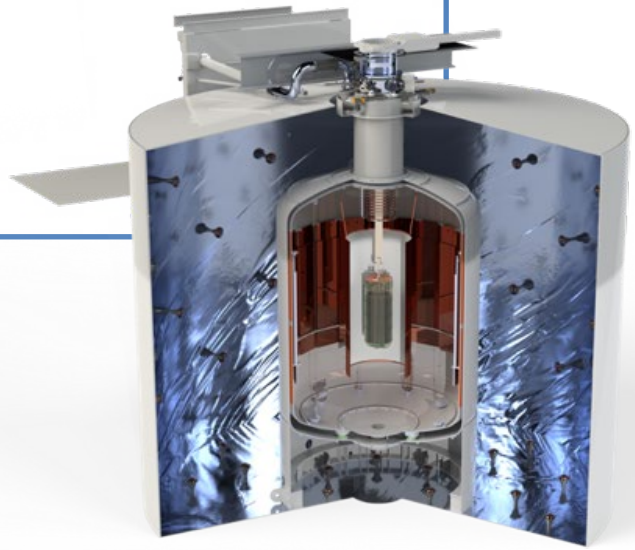
LEGEND-1000


Simulated example spectrum: after cuts from 10 years of data
Observed counts / 1 keV
0
1
2
3
4
5
6
1940
1960
1980
2000
2020
2040
2060
2080
Energy (keV)
2νββ
Flat, featureless background
No background peaks are expected close to $Q_{ββ}$
0νββ
$T_{1/2} = 10^{28}$ yr
3-4 events
<10^{-6} 2νββ events leak into in $Q_{ββ}$±2σ
≈0.1% FWHM energy resolution

Conclusions 1

LEGEND200

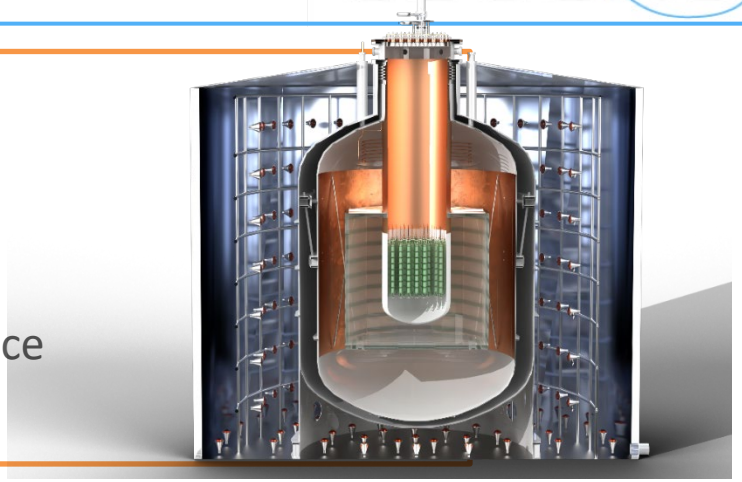
- ✓ Successfully migrated from GERDA / MAJORANA DEMONSTRATOR & upgraded infrastructure to accommodate larger LEGEND-200 detector array
- ✓ Installed first 142 kg of HPGe detectors in LEGEND-200 in October 2022
- ✓ Very good performance of all detector systems
- ✓ Background in first LEGEND-200 physics data (10.1 kg yr)
  - No unexpected background components
  - Background in the ROI after analysis cuts compatible with LEGEND-200 goal
- ✓ Data taking is currently ongoing & new detectors will be added in early 2024

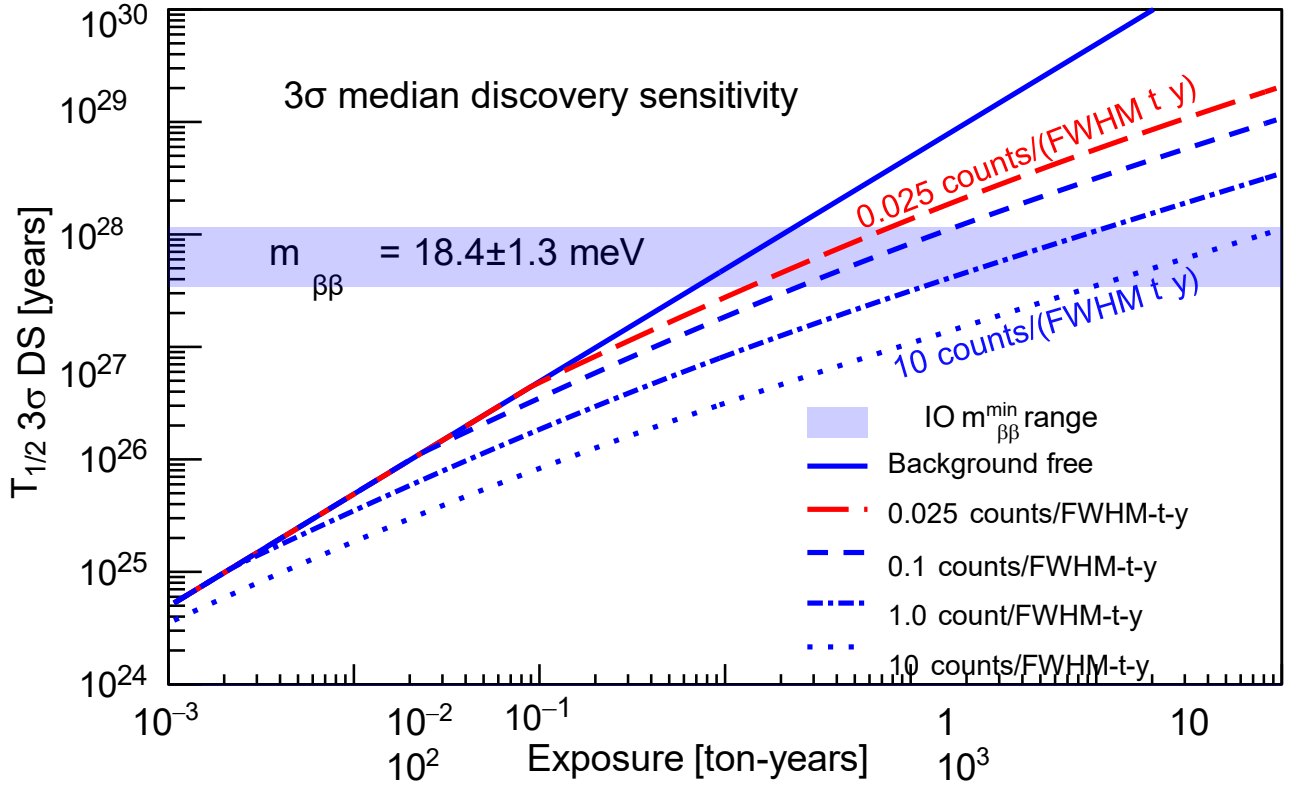


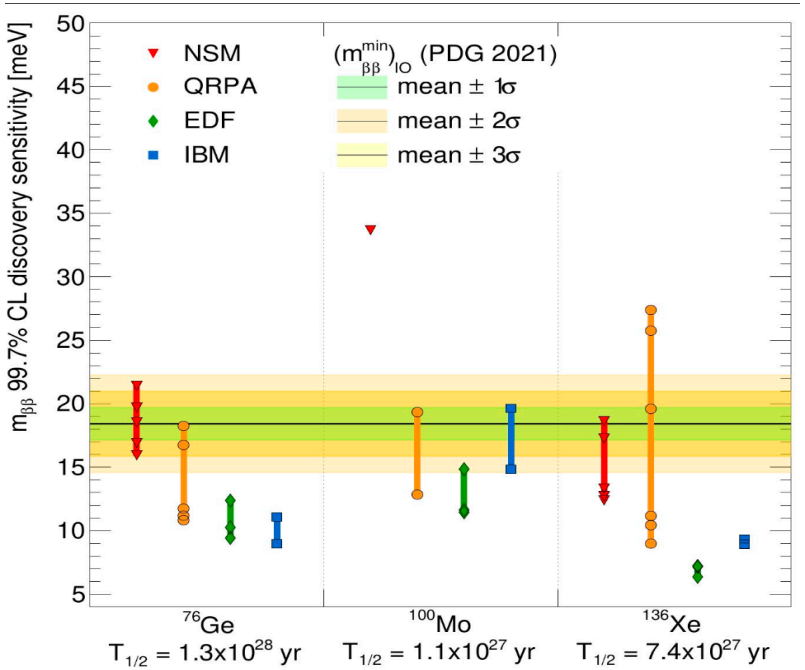
Conclusions 2

LEGEND1000

- ✓ Design and reviews on-going
- ✓ It builds on breakthrough developments by GERDA, MAJORANA, and LEGEND-200
- ✓ LEGEND will span the inverted ordering and a large part of the normal ordering space
- ✓ Discovery sensitivity <18.4 meV for 3/4 many-body methods & 12/15 calculations





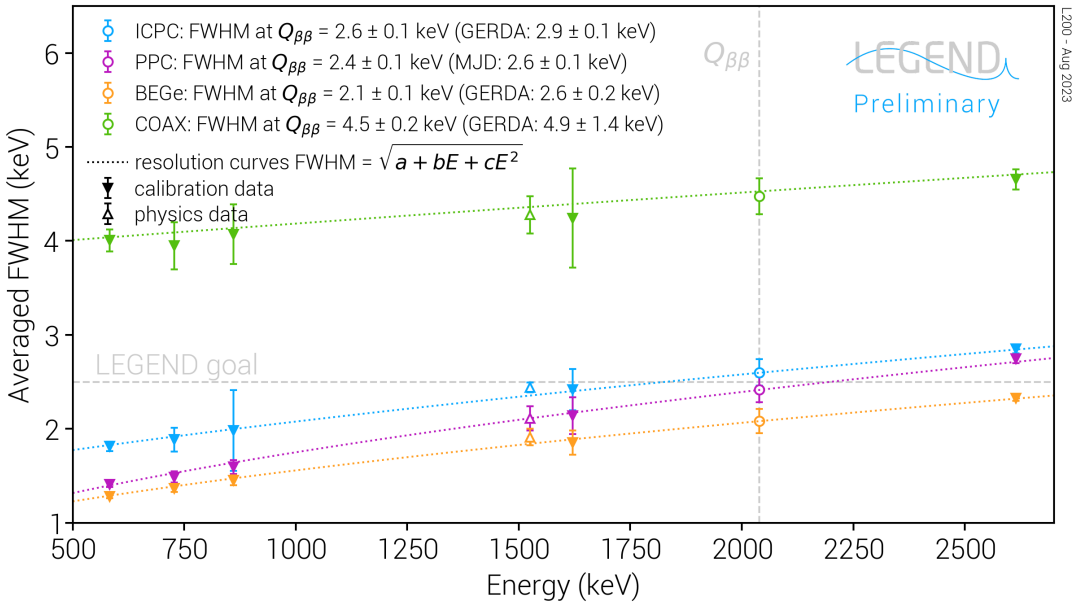


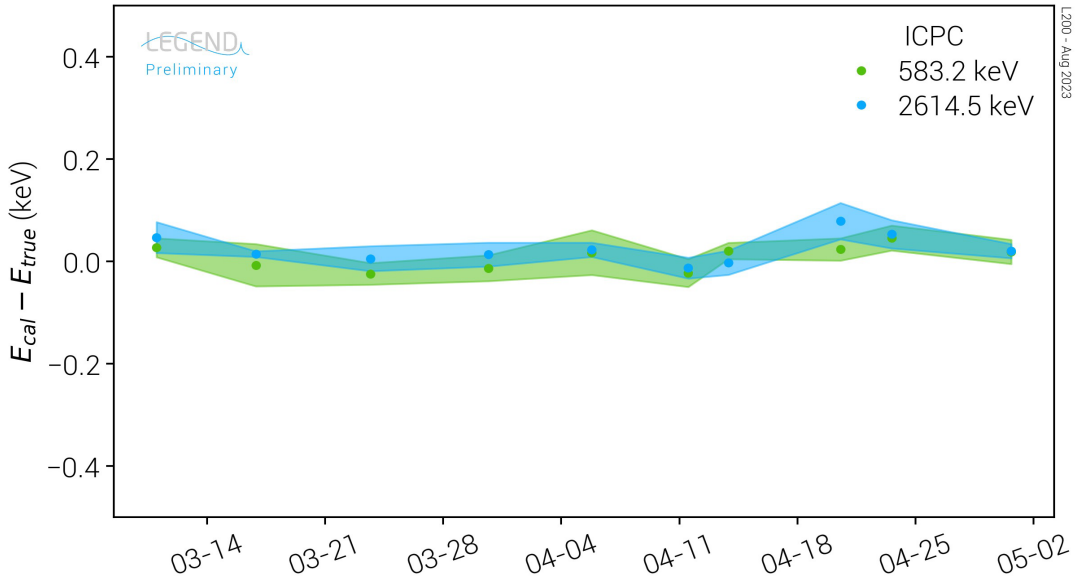
Agostini, Detwiler, Benato, Menendez, Vissani
"Testing the Inverted Neutrino Mass Ordering with 0νββ Decay"
Phys. Rev. C 104, L042501(2021)

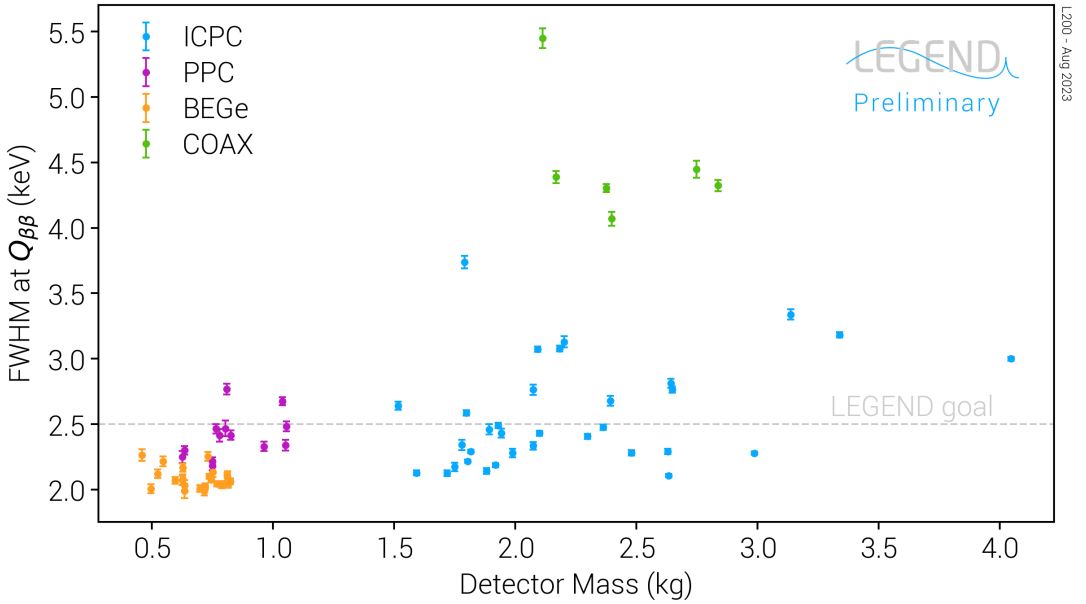
BACKUP

LEGEND-200 Energy resolution

- ✓ Weekly energy calibration between physics runs using ^{228}Th sources
- ✓ Overall improvement in energy resolution @$Q_{\beta\beta}$
- ✓ Energy scale very stable between calibrations

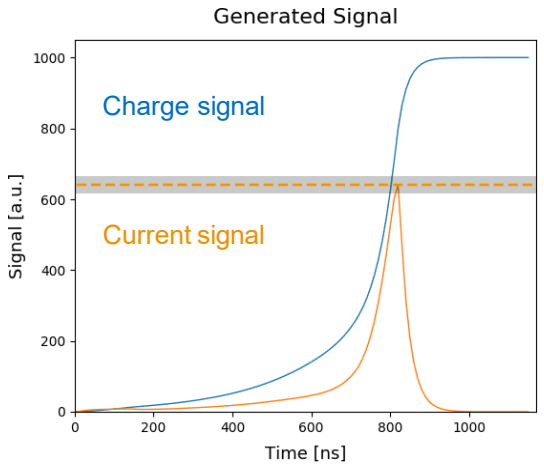


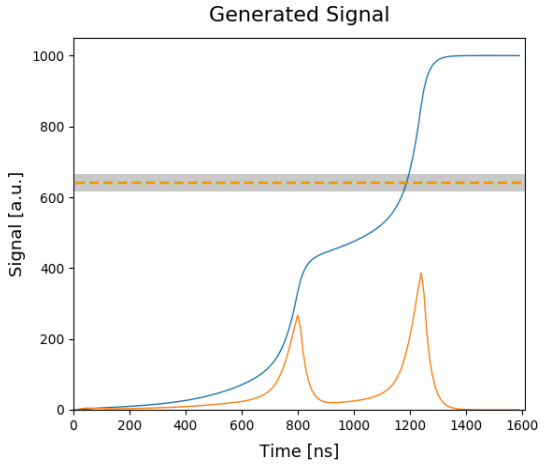


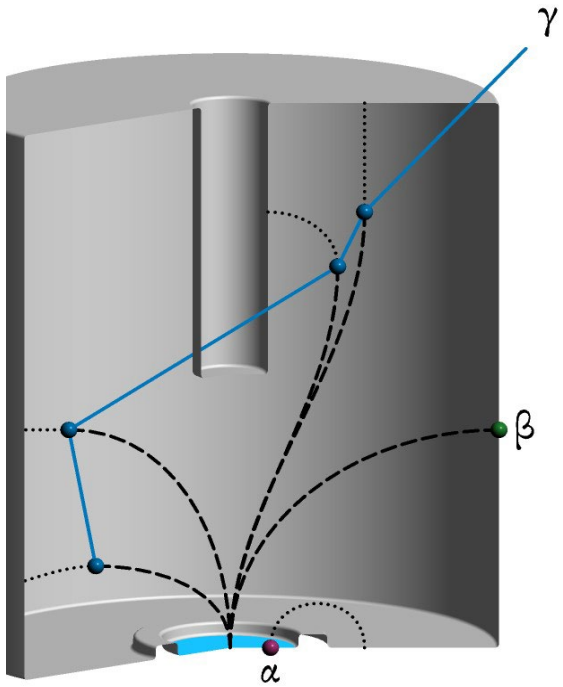


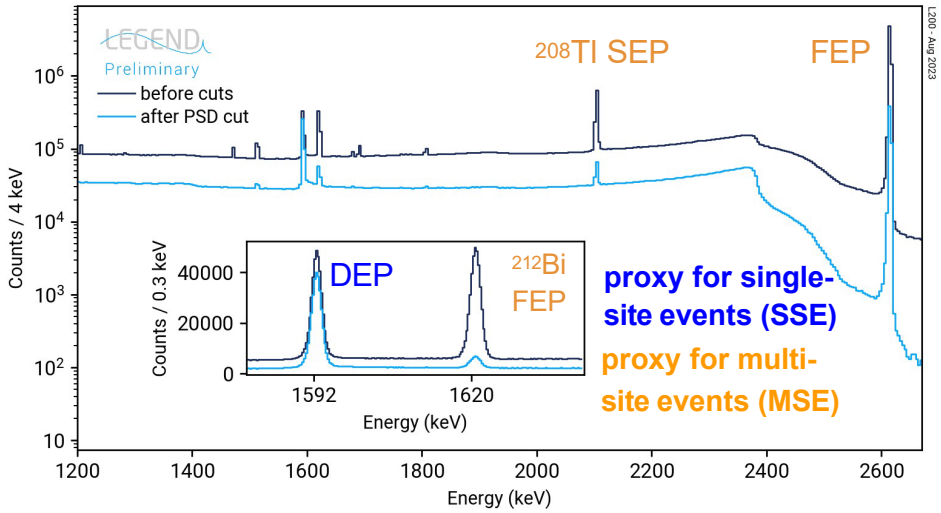
LEGEND-200 PSD performance

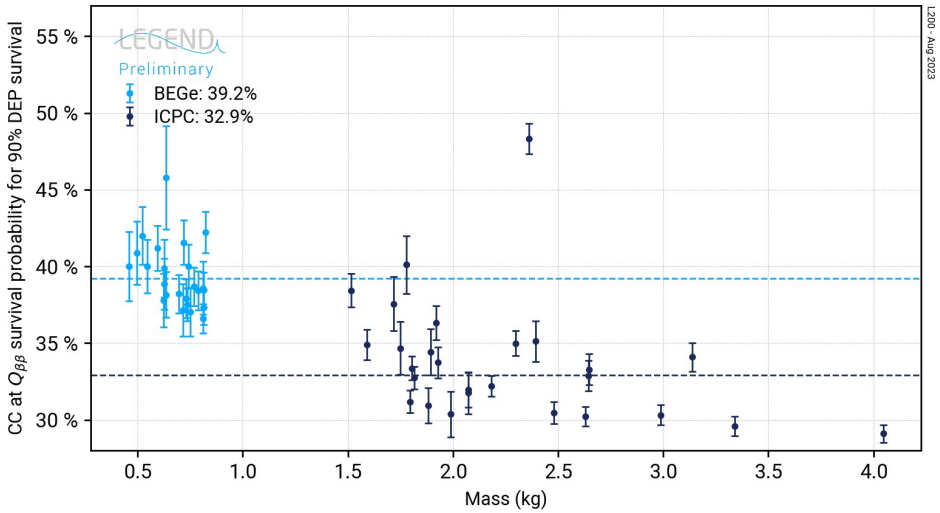
- ✓ Based on A/E parameter, evaluated for each event
- ✓ PSD tuned to 90% survival at ^{208}Tl DEP
  → very good rejection of multi-site events











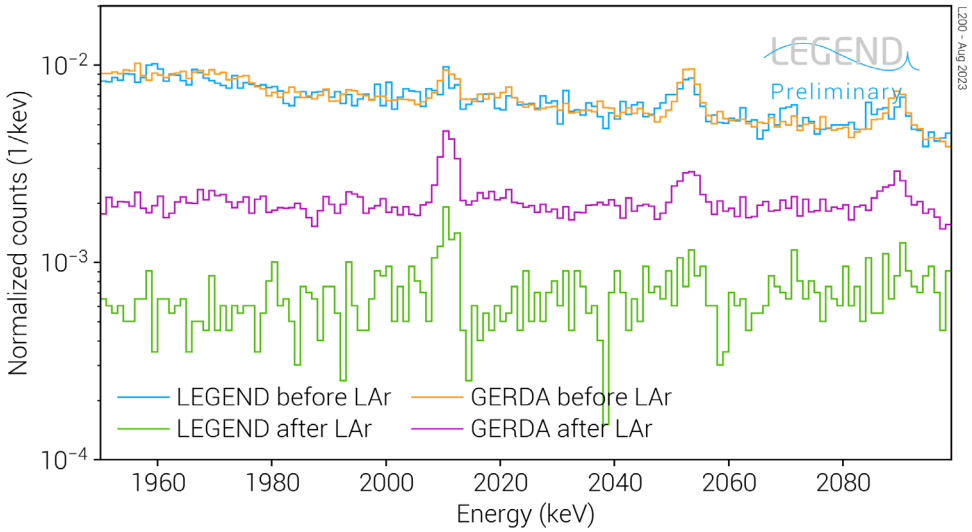
LEGEND-200 LAr perfomance

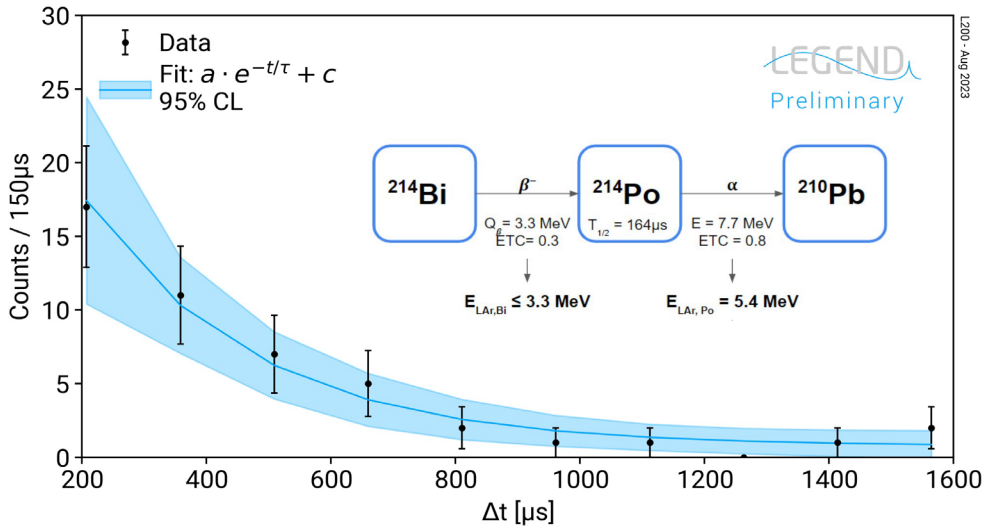
- ✓ Improved silicon photo-multiplier (SiPM) readout
- ✓ Improved geometry + optically active PEN → less shadowing
- ✓ Improved wavelength-shifting (TPB) fiber coating

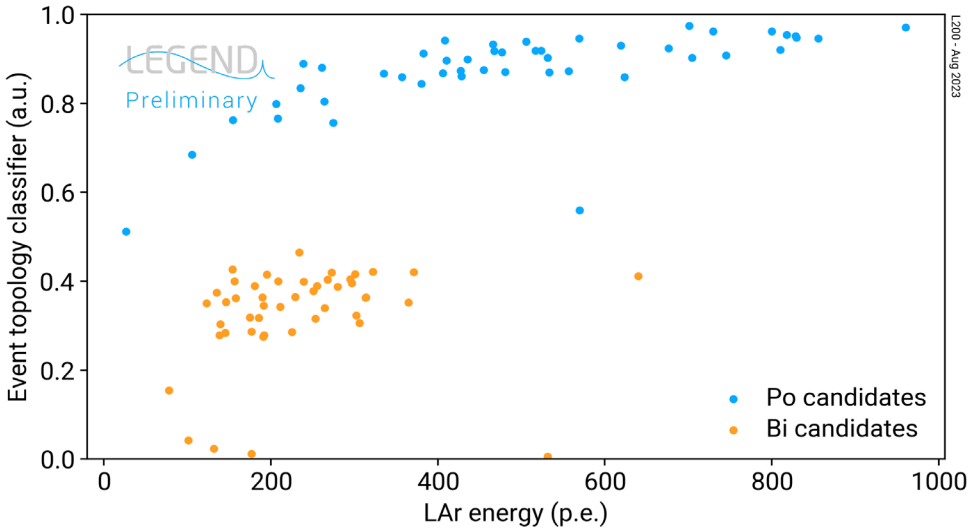
→ ~ 3x more light wrt. GERDA

- ✓ With improved p.e. yield comes improved background suppression
- ✓ We can use time information from LAr signal for particle identification

→ application e.g. BiPo tagging

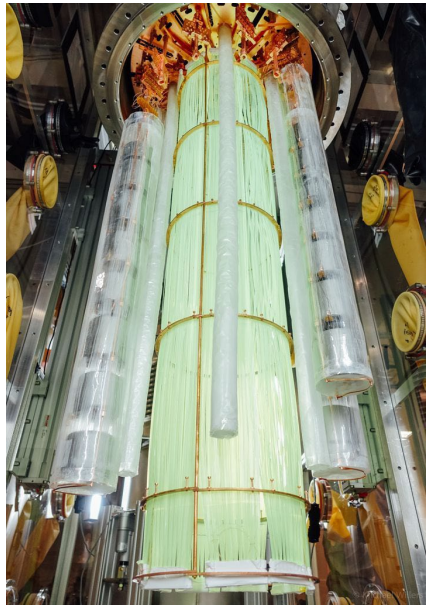




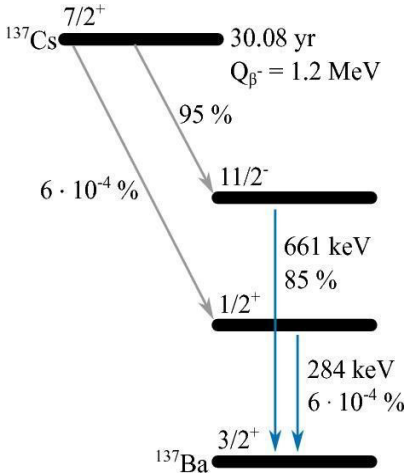


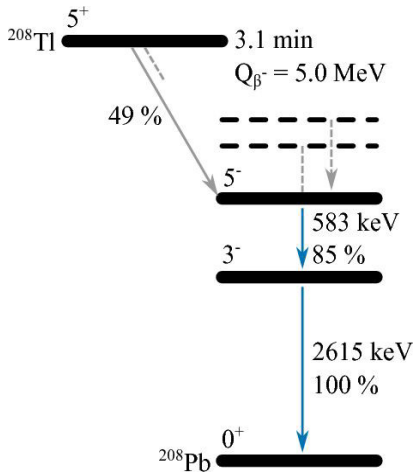
LAr instrumentation now acts as a full-fledged detector

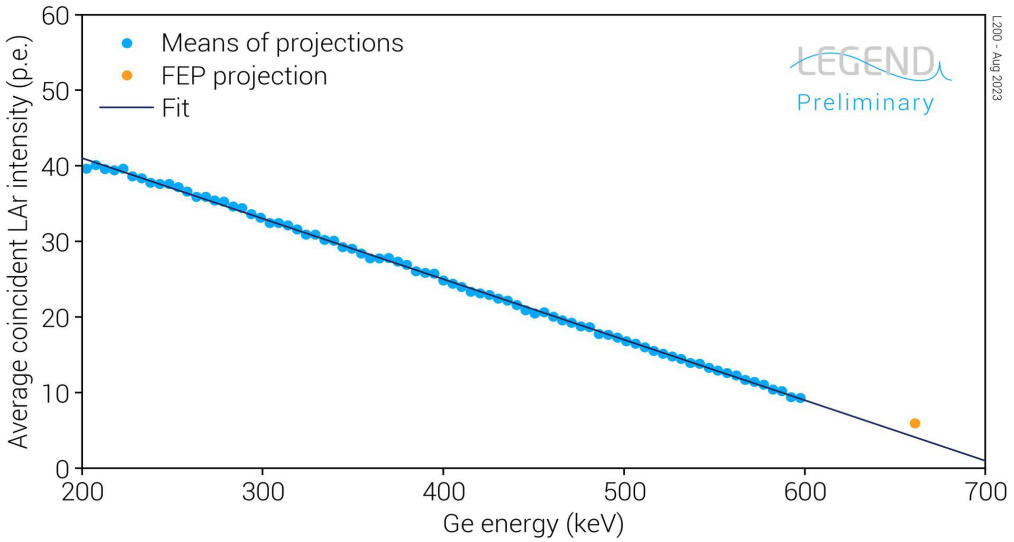
LEGEND-200 LAr performance

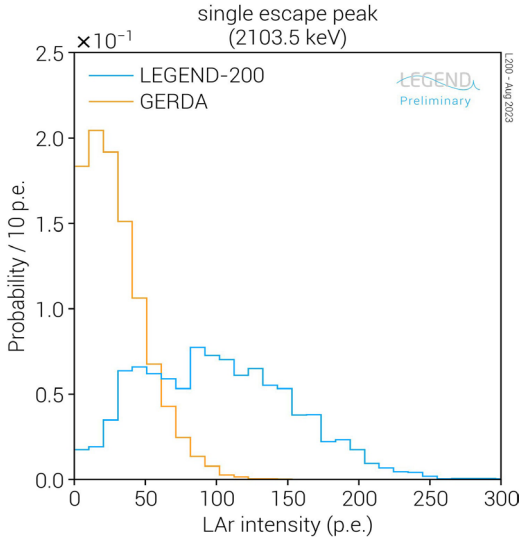


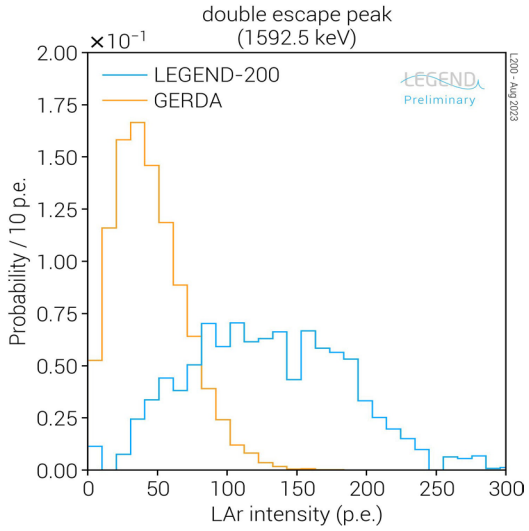
- 3x more light compared to GERDA
- Improved geometry + optically active PEN → less shadowing
- Cs-137 calibration allows estimate of p.e. yield → O(0.1) p.e./keV







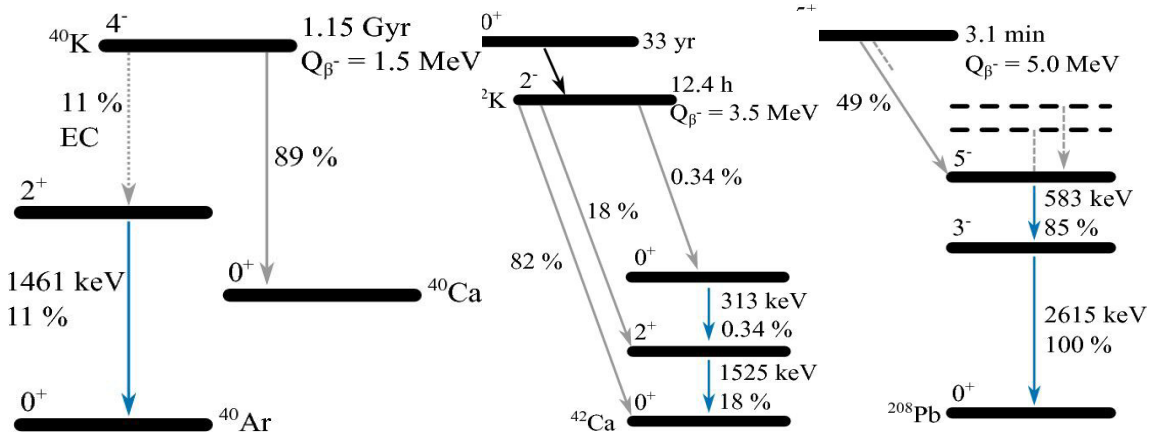


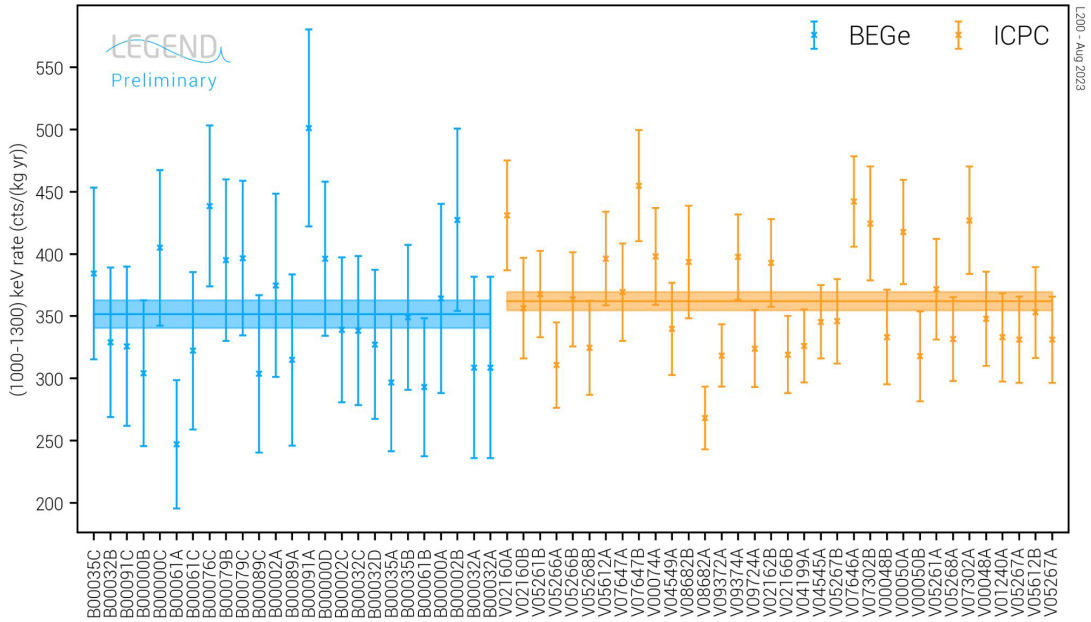


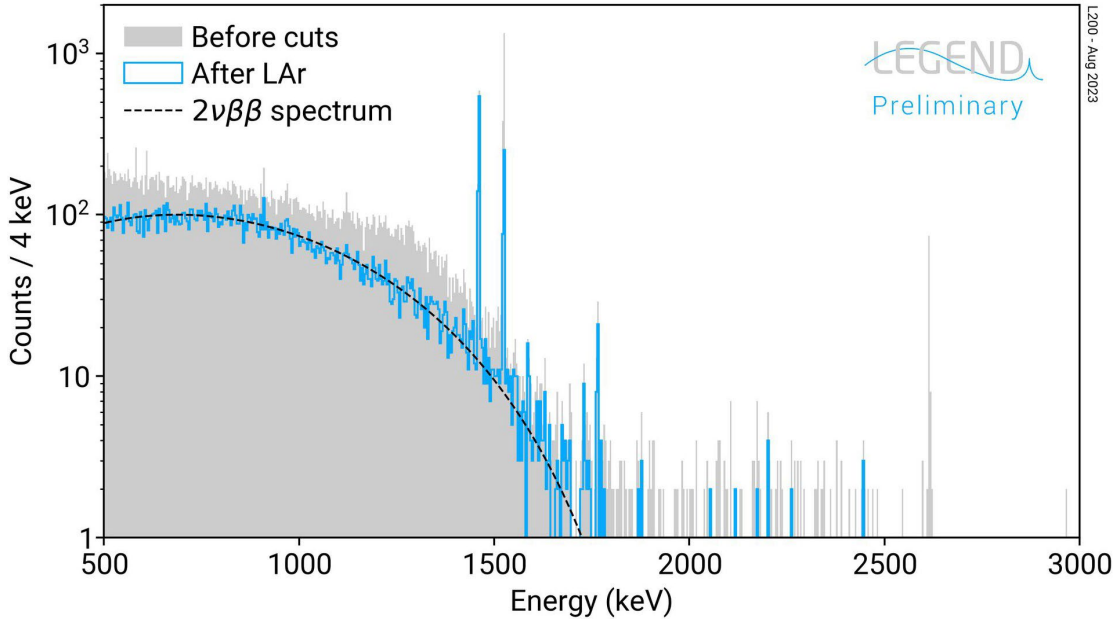
LEGEND-200 Background after QC + LAr

After LAr cut:

- ^{208}Tl peak is completely suppressed
- ^{42}K peak survives to < 20%
- ^{40}K peak fully accepted
- Pure 2νββ at low energy
- Uniform detector rate



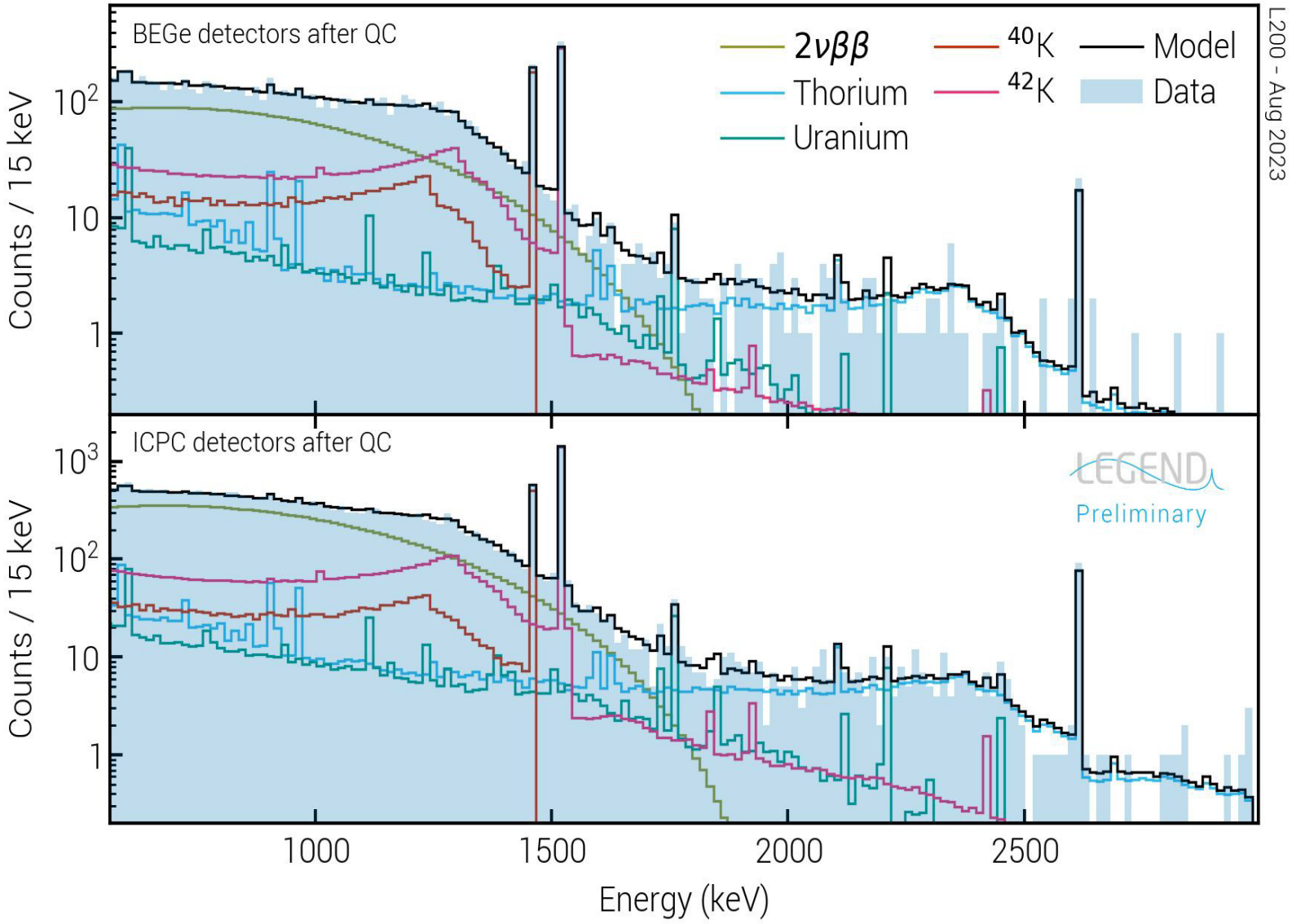




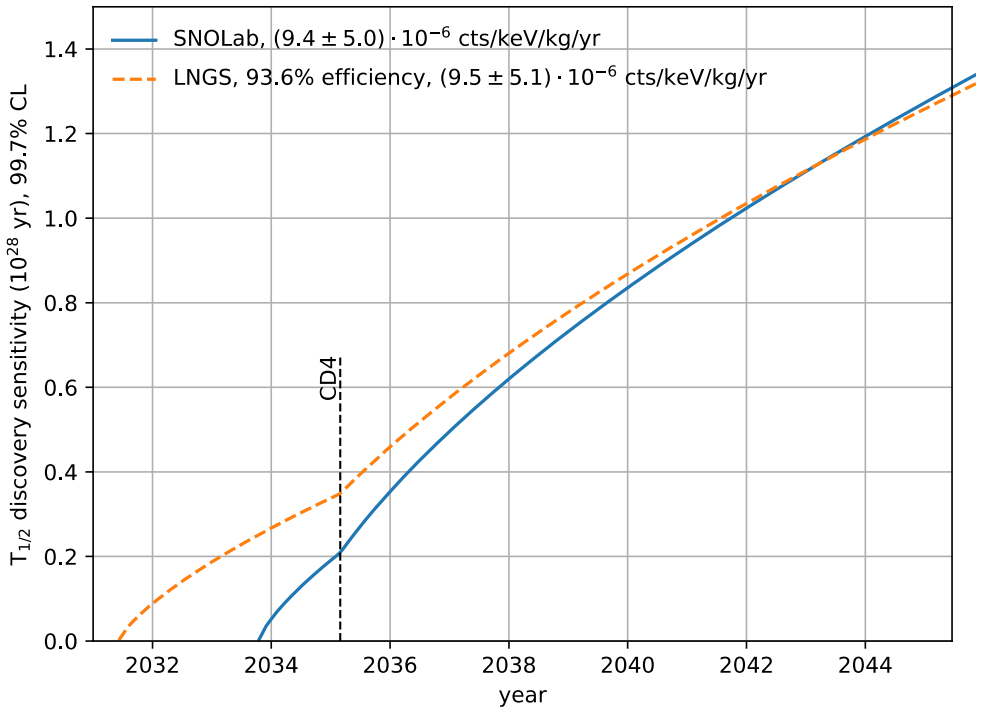
LEGEND-200 Background decomposition

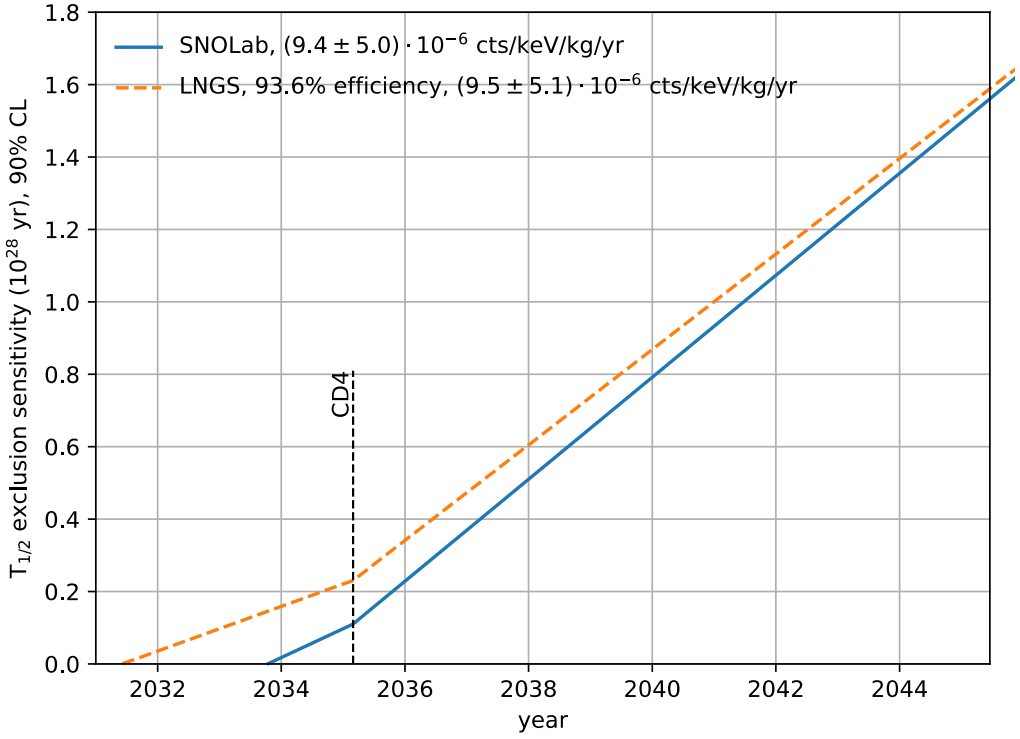
[WIP]
Decomposition before analysis cuts

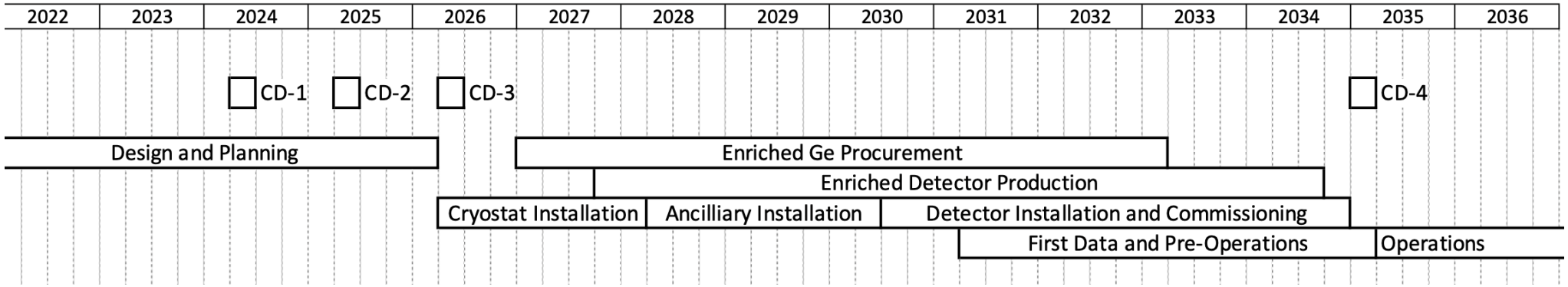
- Well described by expected contributions with current statistics



LEGEND-1000 Sensitivity



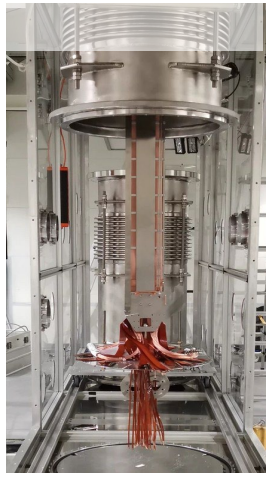




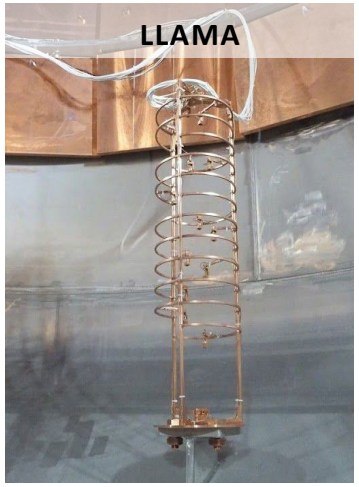
LEGEND-200 Timeline

Installation of the WLSR

Installation of new Lock system

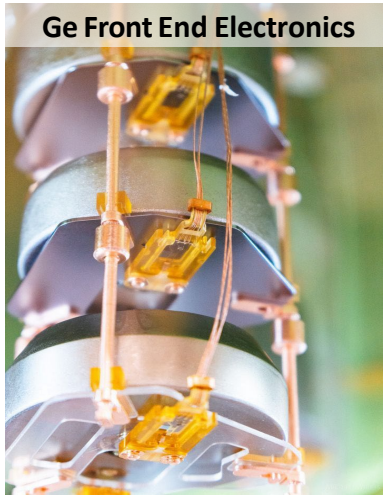


LLAMA

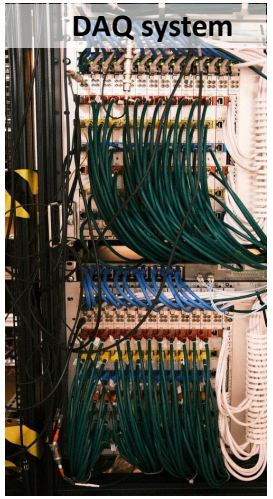


LAr pump

Ge Front End Electronics



DAQ system



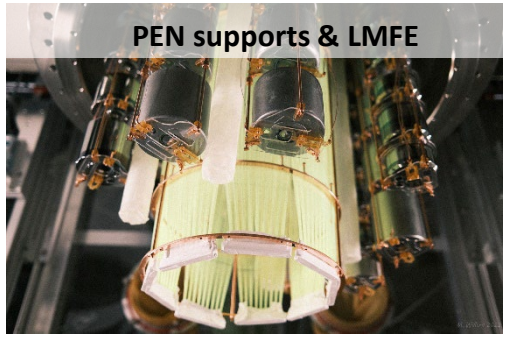
2020

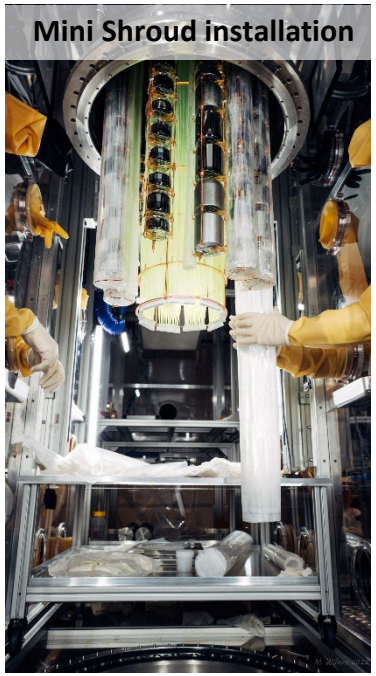
- Post GERDA Test (PGT)
- Upgrade of cryostat infrastructure

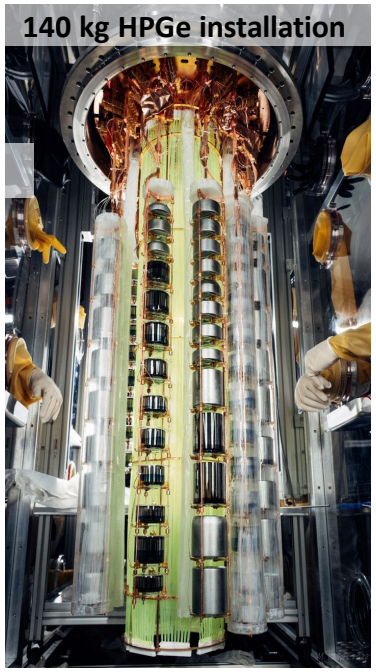
2021

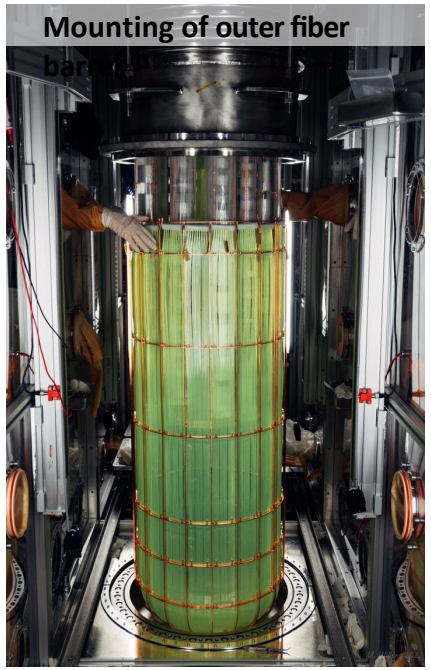
- Upgrade of cryostat infrastructure
- Electronics and DAQ test
- Mechanics & glovebox installation

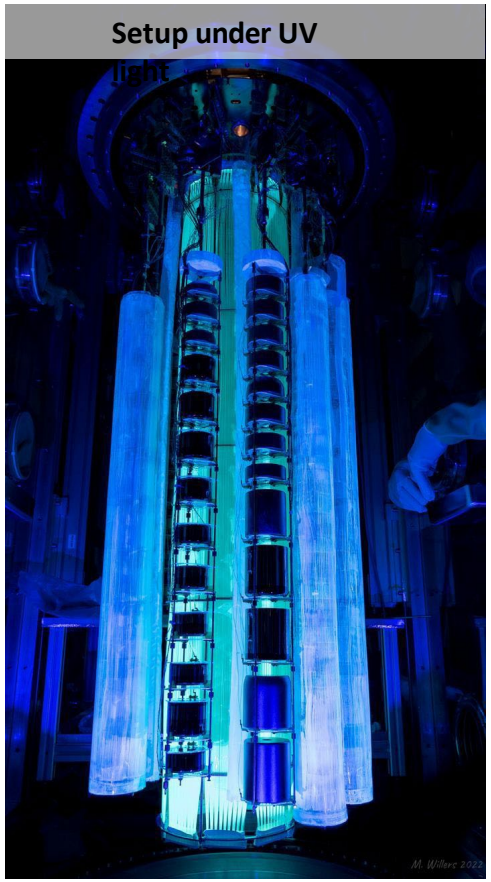
LEGEND-200 Timeline











2022

- Construction & commissioning of LAr
- 60 kg campaign + special calibration
- 142 kg installation & commissioning

2023

- Commissioning
- Physics data taking (Spring 2023)