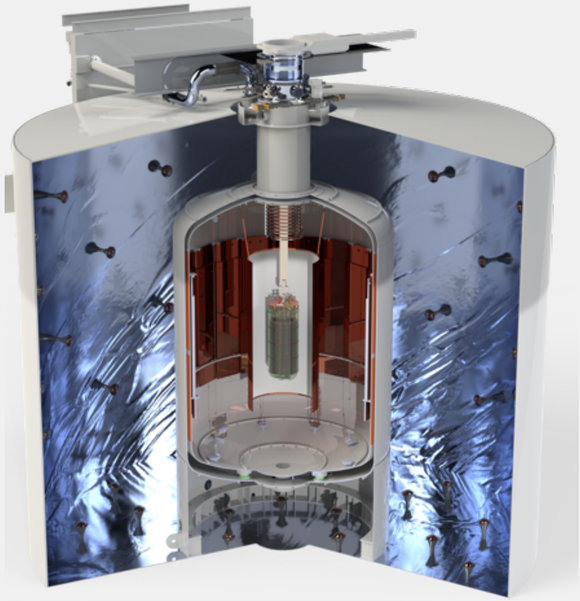
Large Enriched Germanium Experiment for Neutrinoless Double Beta Decay (LEGEND)

- Brady Bos (UNC-CH/TUNL)

  On behalf of the LEGEND collaboration

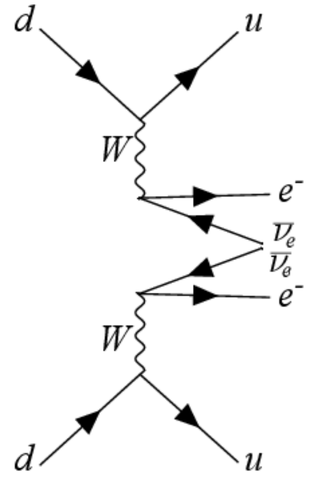


The LEGEND Collaboration

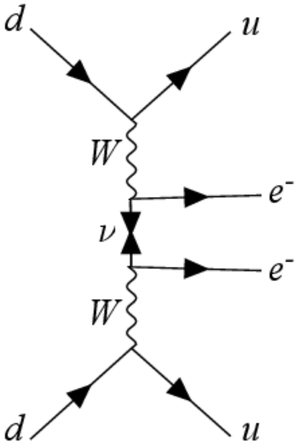
- The **L**arge **E**nriched **G**ermanium **E**xperiment for **N**eutrinoless double-beta **D**ecay
- Goal: “Develop a phased, ^{76}Ge based double-beta decay experimental program with discovery potential at a half-life beyond 10^{28} years”
- ~270 members from 56 institutions in 12 countries

Neutrinoless Double Beta Decay (0νββ)

- The discovery of 0νββ decay would dramatically revise our foundational understanding of physics and the cosmos
  - Lepton number is not conserved
  - The neutrino is a fundamental Majorana particle
  - There is a potential path for understanding the matter – antimatter asymmetry in the cosmos.
  - There is a new mechanism demonstrated for the generation of mass
- The search for 0νββ decay is one of the most compelling and exciting challenges in all of contemporary physics
- The LEGEND Collaboration aspires to meet this challenge through a ton-scale search for 0νββ decay of ^{76}Ge

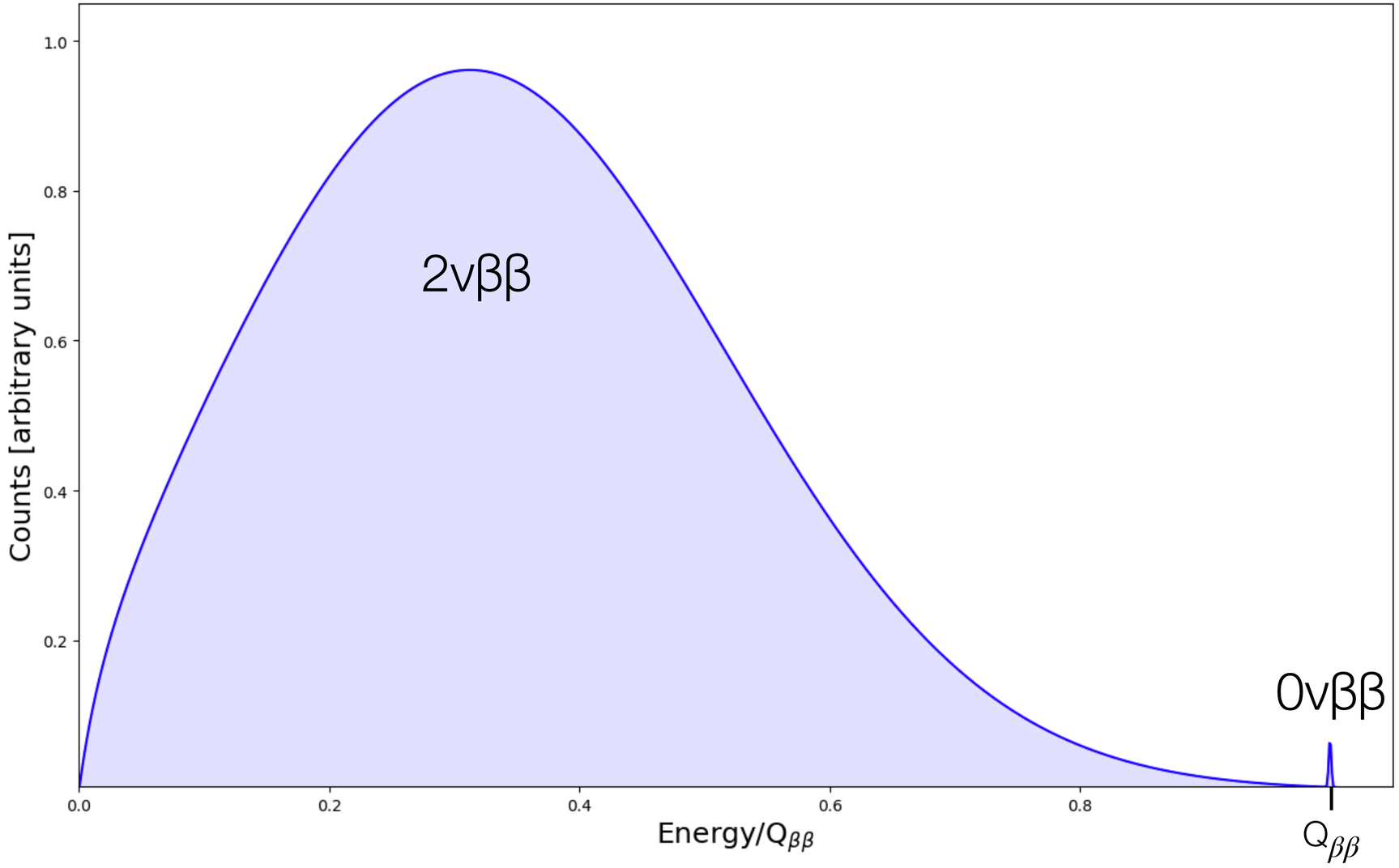


Standard double beta decay

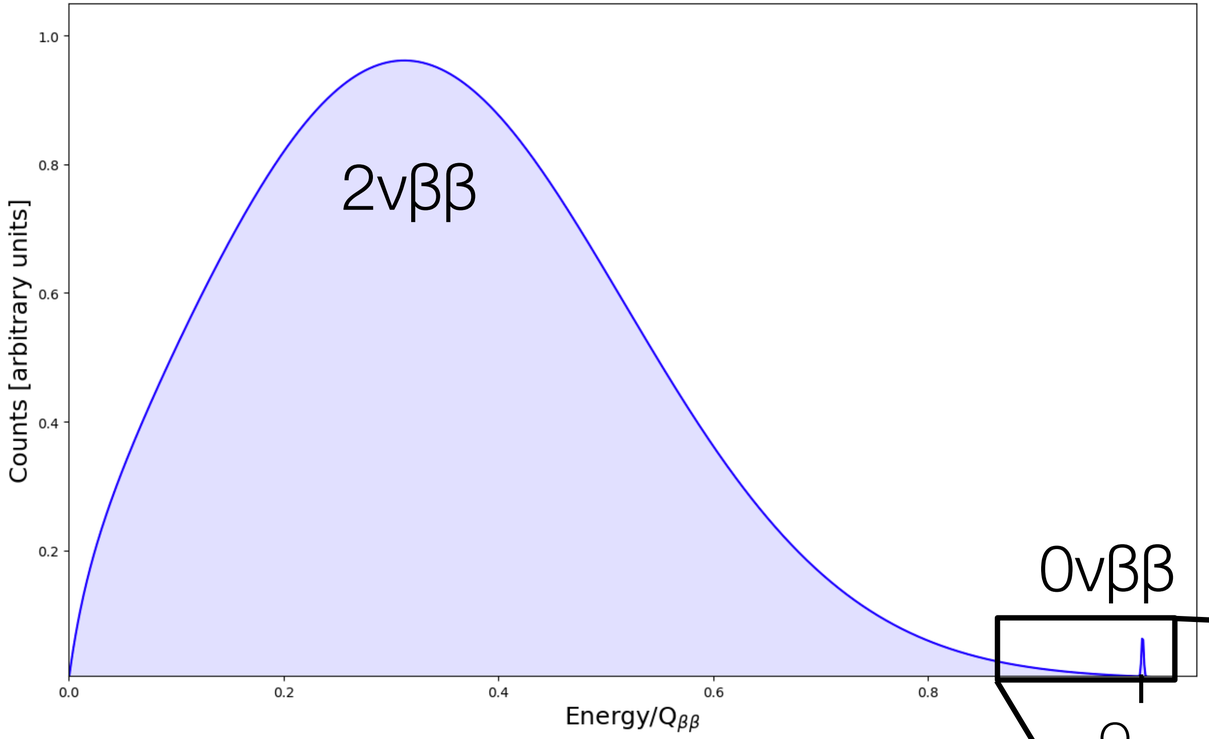


Neutrinoless double beta decay with some mechanism for the neutrino exchange

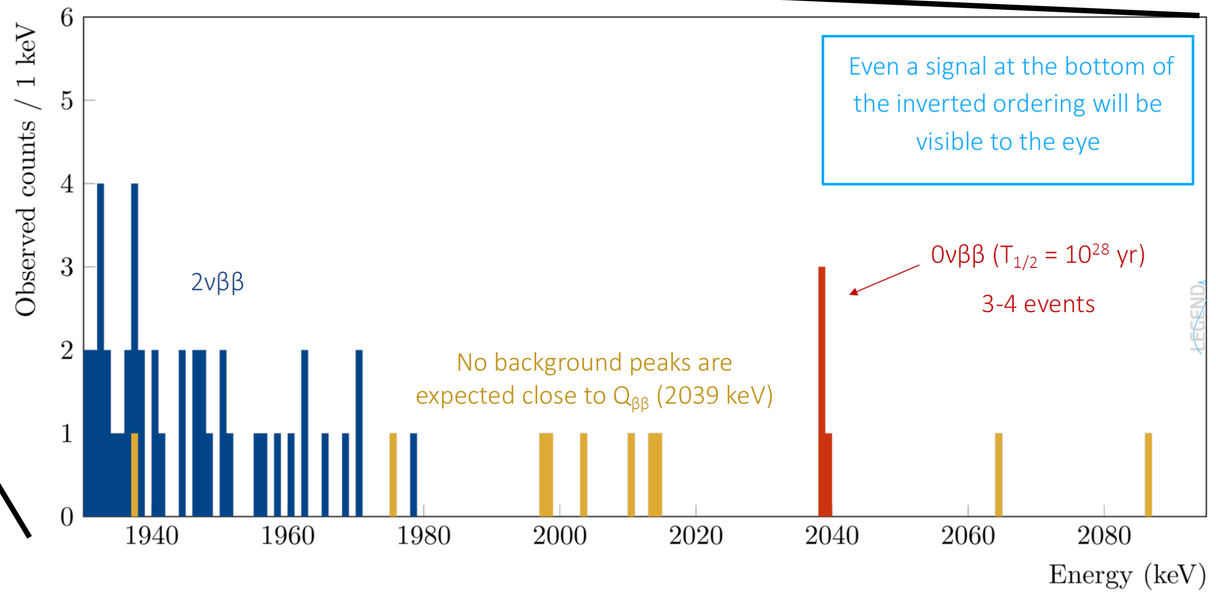
Neutrinoless Double Beta Decay (0νββ)



Neutrinoless Double Beta Decay (0νββ)

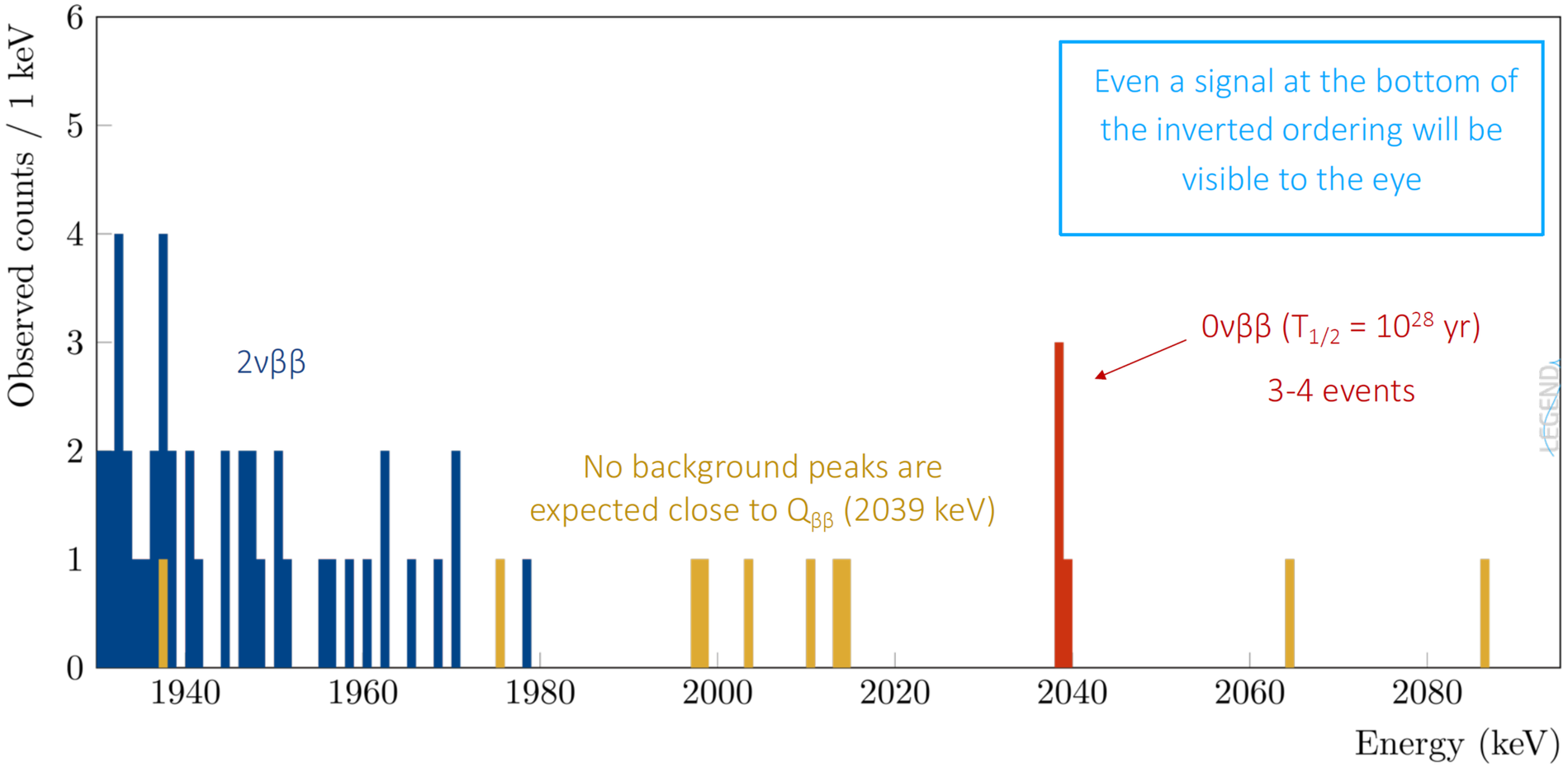


Monte Carlo Simulation of 10 tonne*year exposure of the proposed LEGEND-1000 tonne-scale ^{76}Ge experiment



Neutrinoless Double Beta Decay (0νββ)

Monte Carlo Simulation of 10 tonne*year exposure of the proposed LEGEND-1000 tonne-scale ^{76}Ge experiment



A Phased Approach

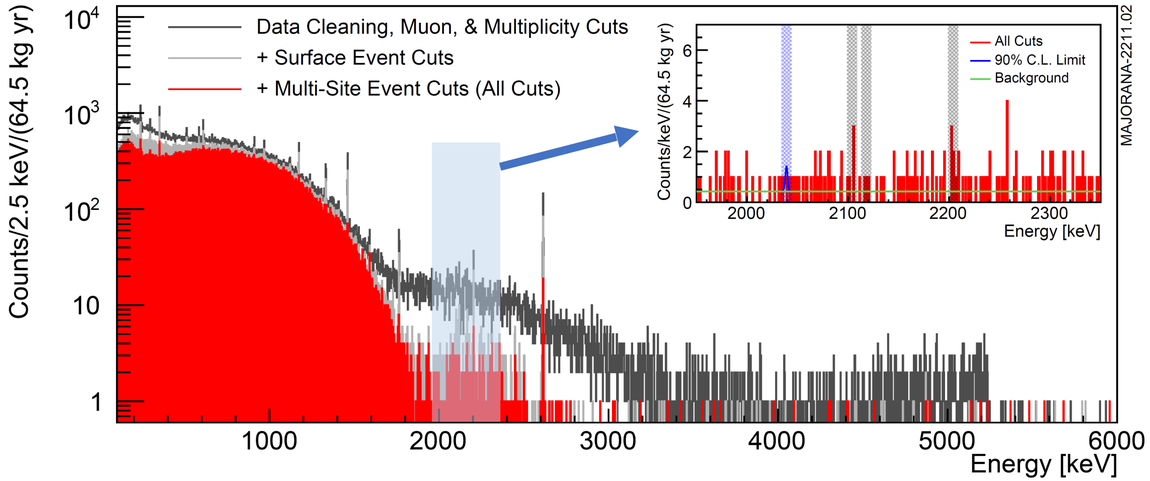
MAJORANA DEMONSTRATOR

(30 kg of 88% ^{76}Ge)

Vacuum cryostats in a passive graded shield with ultra-clean materials

Best resolution in ROI of all $0\nu\beta\beta$ Expts.

PRL **130** 062501 (2023)



$T_{1/2} > 8.3 \times 10^{25}$ yr (90% C.I.)

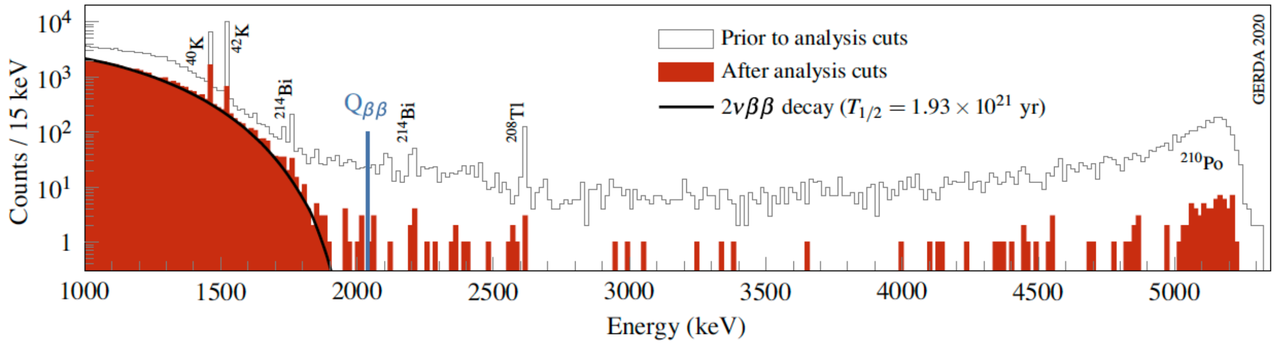
GERDA

(35.6 kg of 87% ^{76}Ge)

Direct immersion in active LAr shield with outer water shield

Lowest bkg. in ROI of all $0\nu\beta\beta$ Expts.

PRL **125** 252502 (2020)



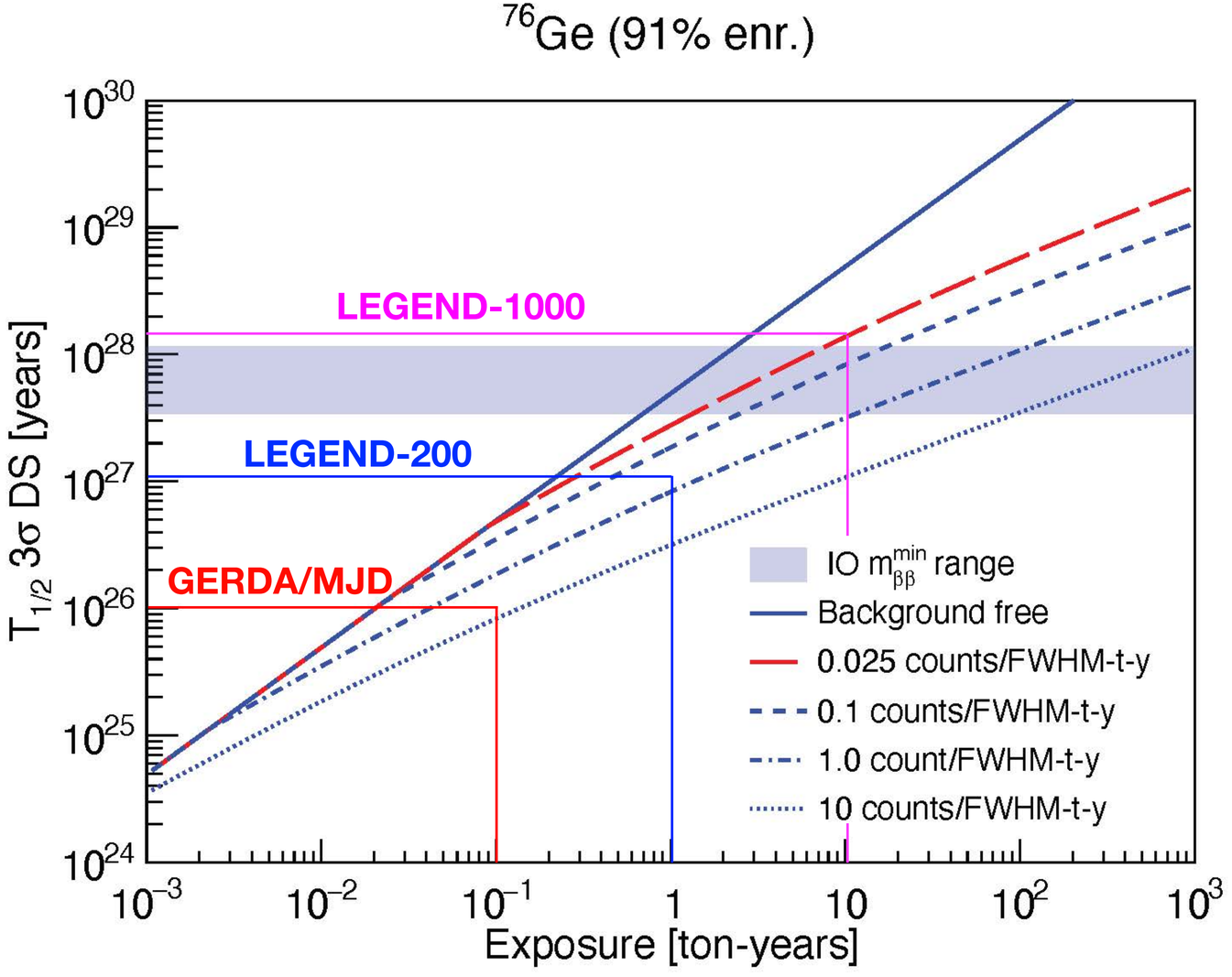
$T_{1/2} > 1.8 \times 10^{26}$ yr (90% C.I.)

A Phased Approach

LEGEND-200
(Up to 200 kg of >88% ^{76}Ge)
Operating with 142 kg of Ge since March 2023 at LNGS

LEGEND-1000
(Up to 1000 kg of >90% ^{76}Ge)
To be built predicated on funding process at LNGS beginning 2025

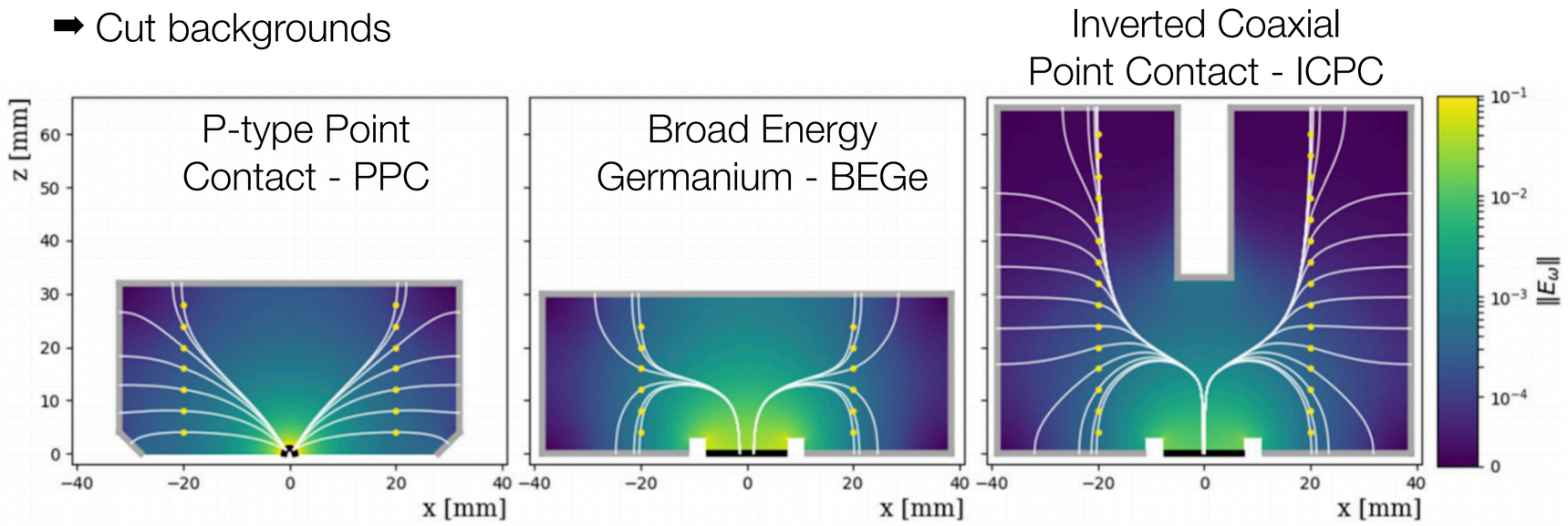
arXiv:2107.11462

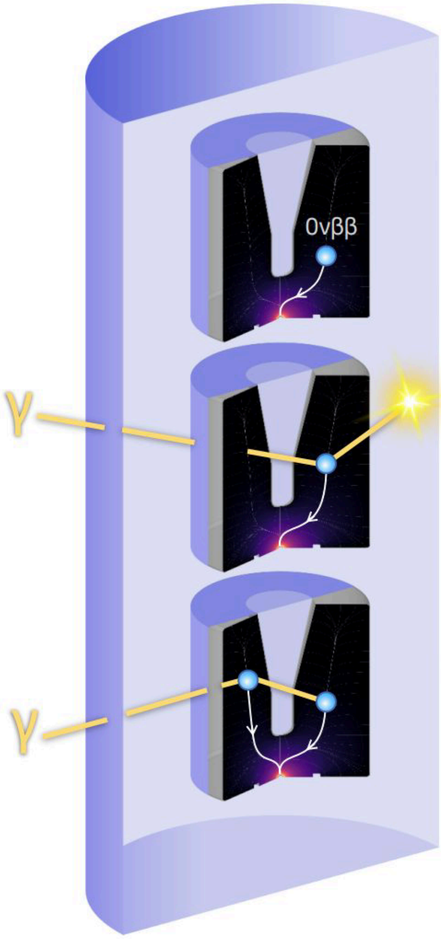


Germanium-76

- ^{76}Ge has many advantages for rare event searches
  - Germanium detectors are a well established technology
  - Enrichment to >90% in ^{76}Ge —> Detector = source —> high detection efficiency
  - High radiopurity
  - Excellent energy resolution = 0.12% FWHM @ $Q_{\beta\beta}$ (2039 keV)
  - Optimize geometry for mass & performance (PPC, BEGe, ICPC)
  - Pulse Shape Discrimination (PSD) & active shielding (liquid Argon)

➡ Cut backgrounds





(Above) Several different events occurring in Ge detectors. (Left) Electric field in Ge detectors of different geometries. HV contact in grey and signal readout contact in black with charge carrier drift paths in white.
Comellato, Agostini, Schonert, EPJ C 81 (2021)

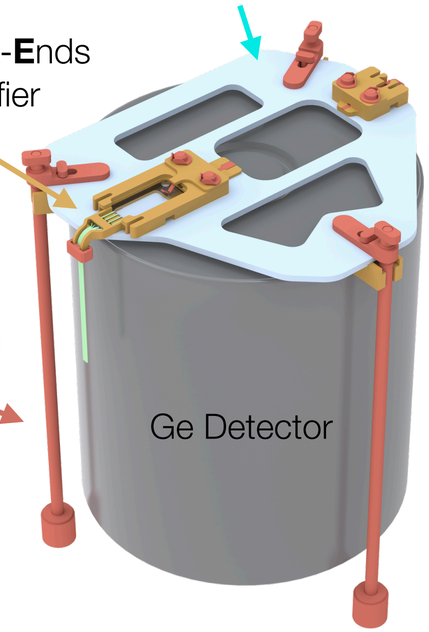
LEGEND-200 Experimental Setup

Ge Detector Unit:

Poly**e**thylene **N**apthalate (PEN) baseplate

Low **M**ass **F**ront-**E**nds (LMFE) amplifier

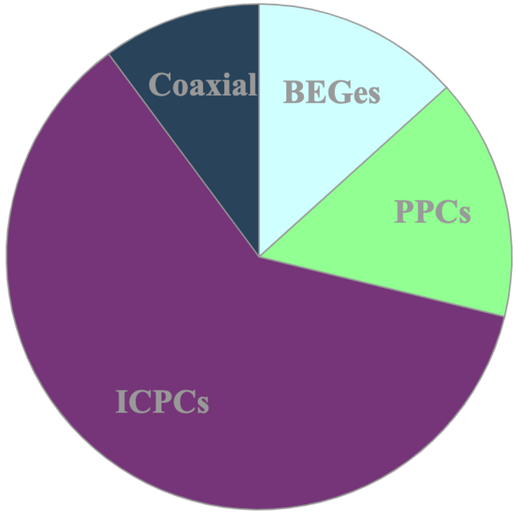
Underground electro-formed copper structure

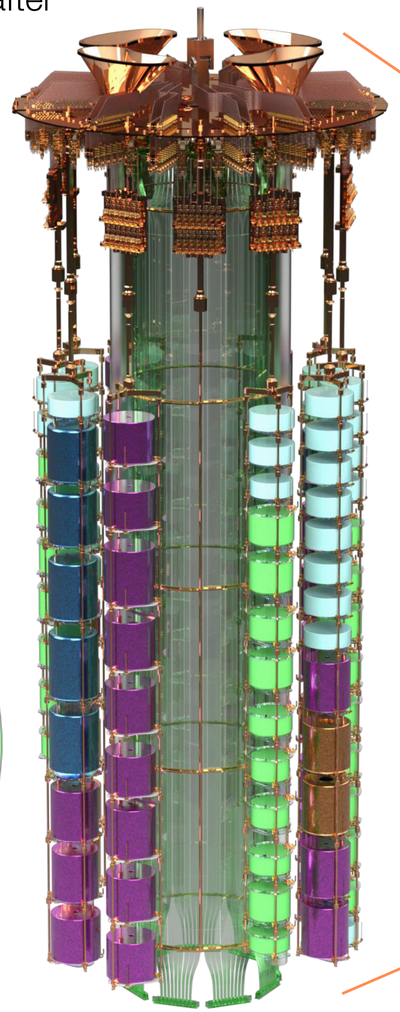


Inverted detector unit with an ICPC detector

Ge Array and LAr instrumentation:

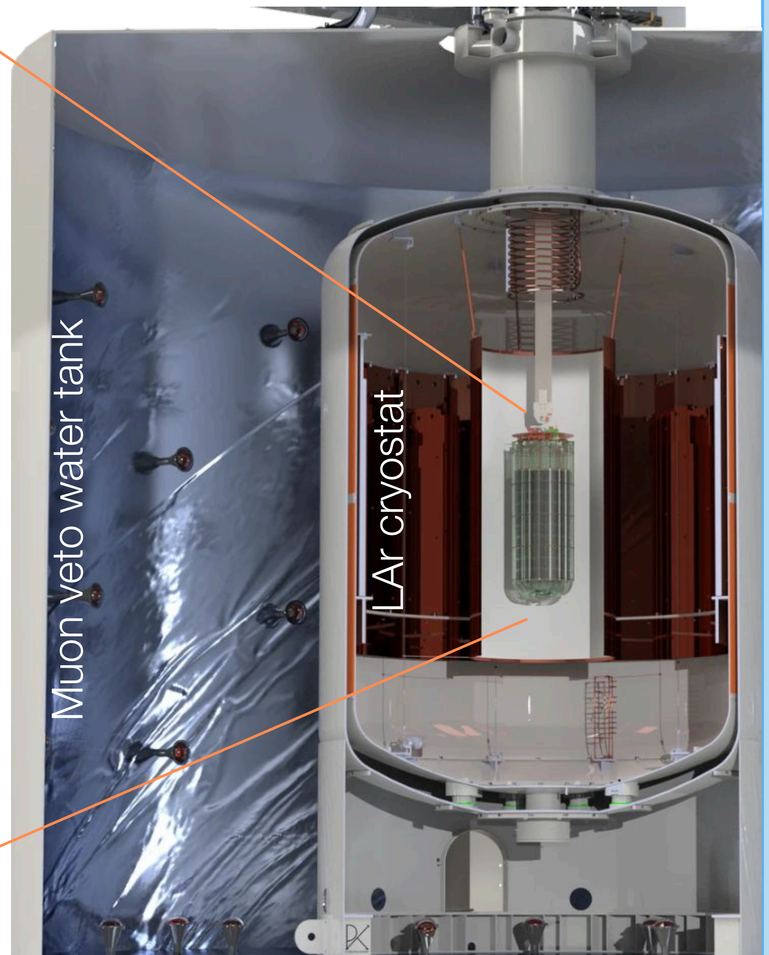
- Inner barrel of fiber shroud for LAr instrumentation
- 12 String locations
- Outer fiber shroud installed after detectors (not in rendering)



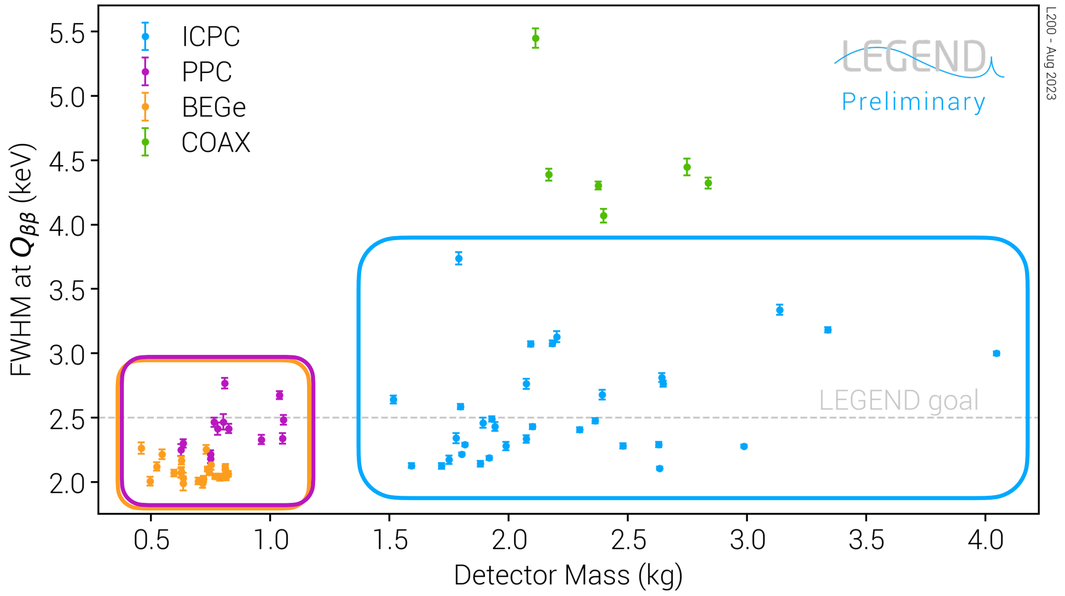


Infrastructure:

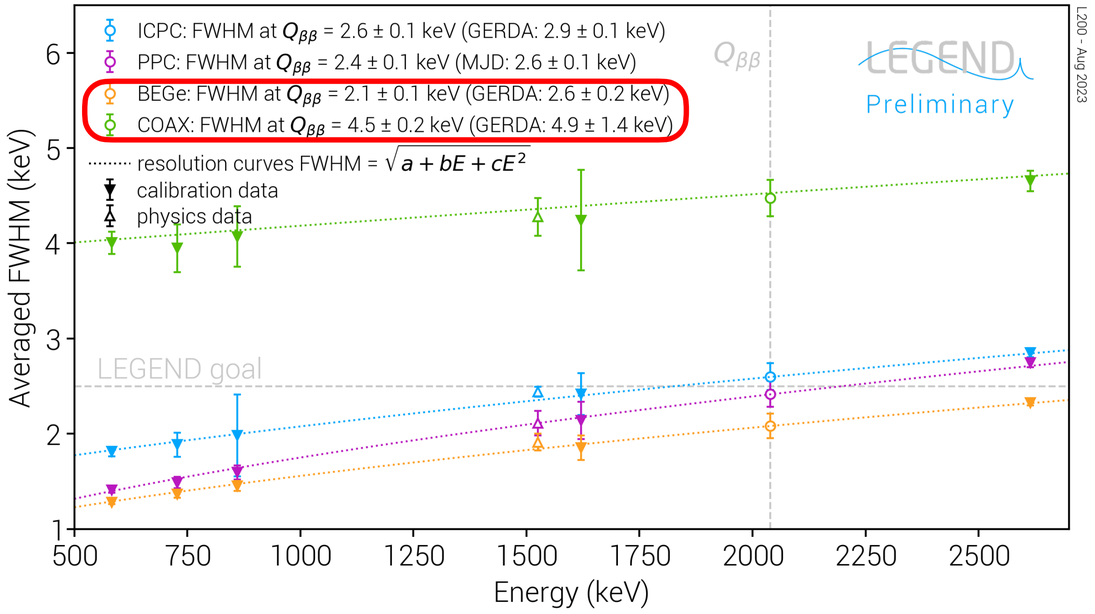
- LAr cryostat with wavelength shifting fibers
- LAr purification and quality monitoring
- Water tank equipped with PMTs for muon veto

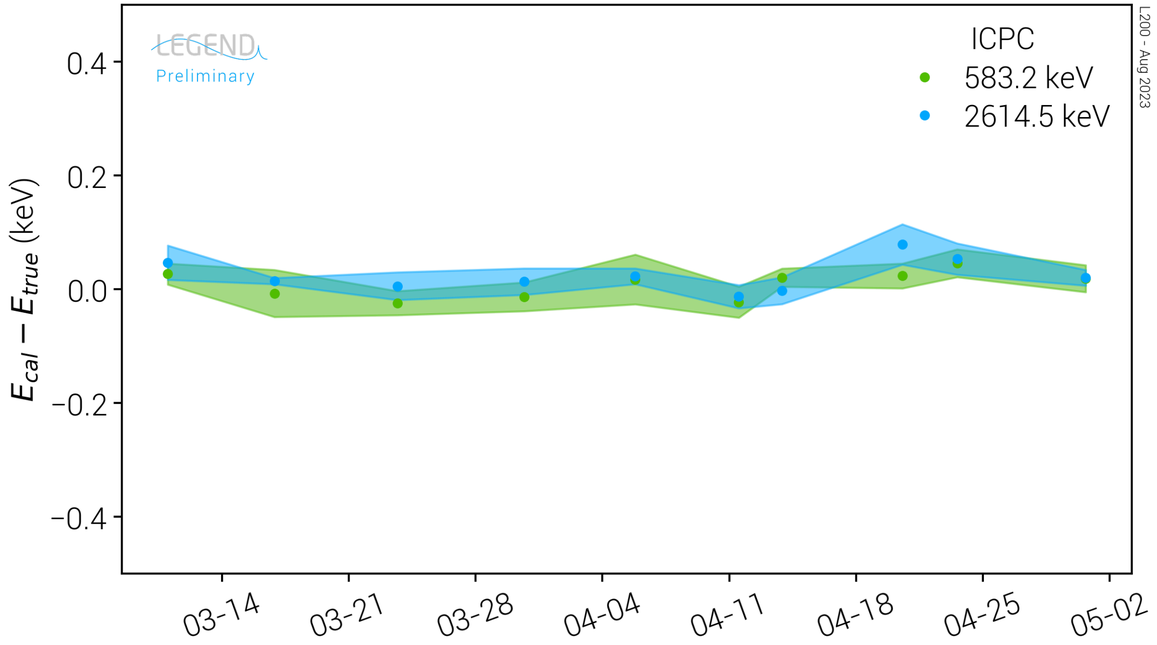


Ge Detector Performance

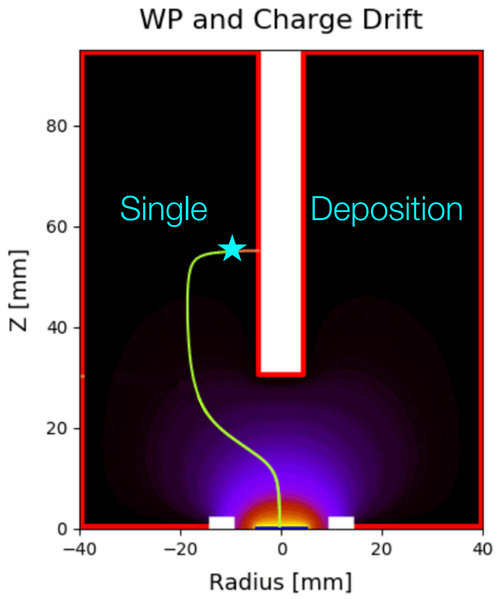


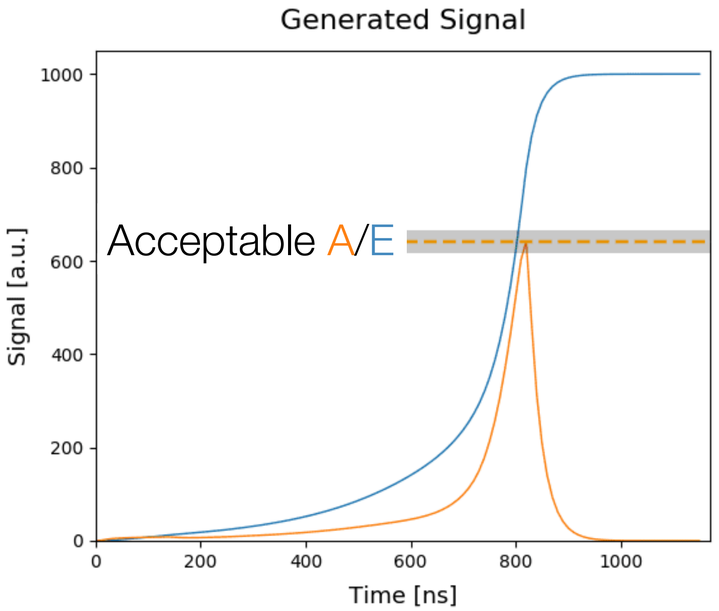
- Acquiring data for $0\nu\beta\beta$ search since March 2023
- ICPCs matching excellent energy resolution of PPCs and BEGes despite being ×2-×4 larger
- Improved energy resolution from BEGe and COAX detectors with MJD front-ends
- Stable energy gain over weekly calibrations

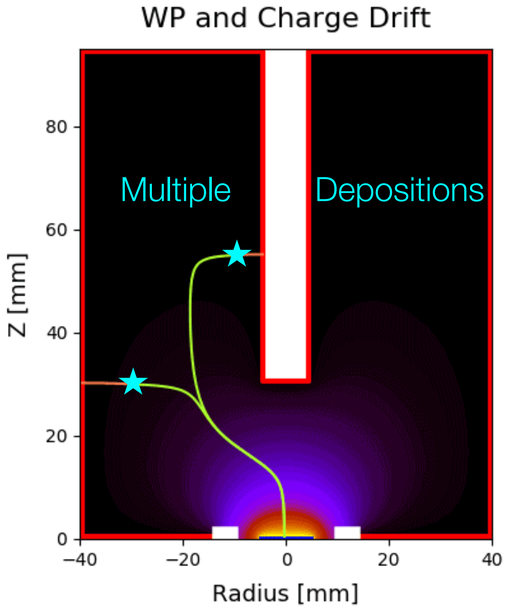


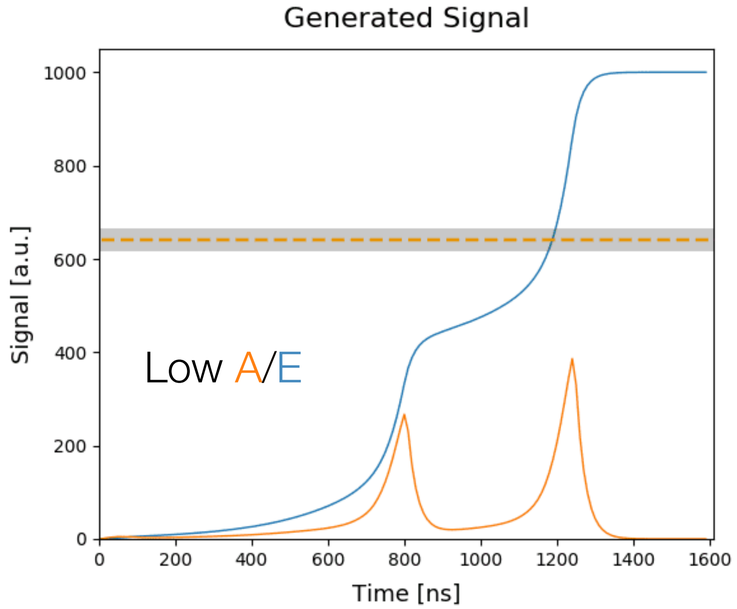


Pulse Shape Discrimination (PSD)

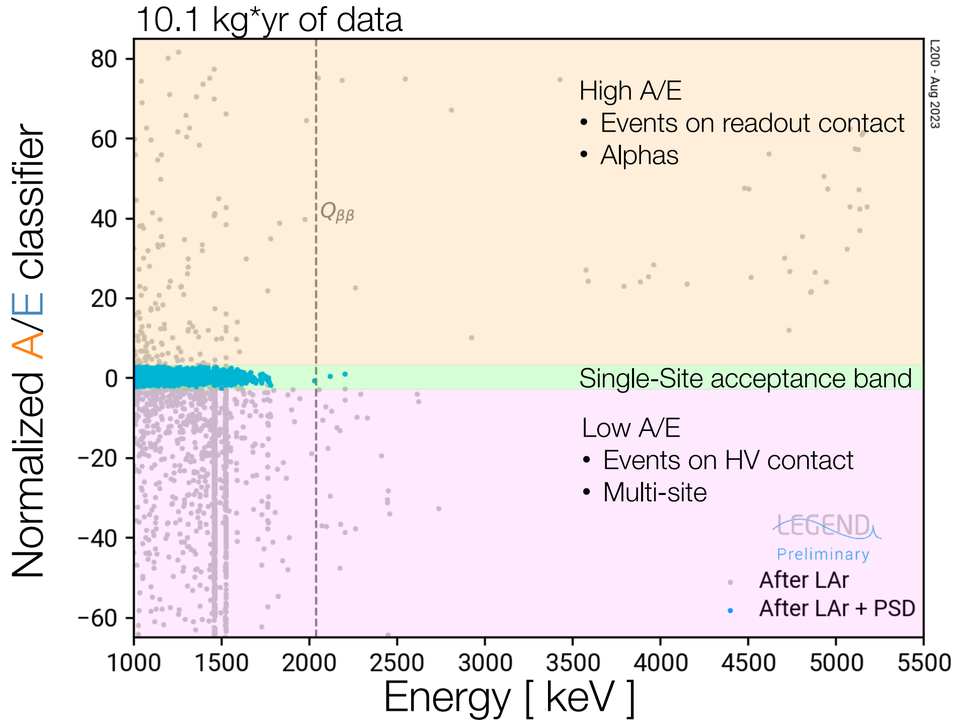




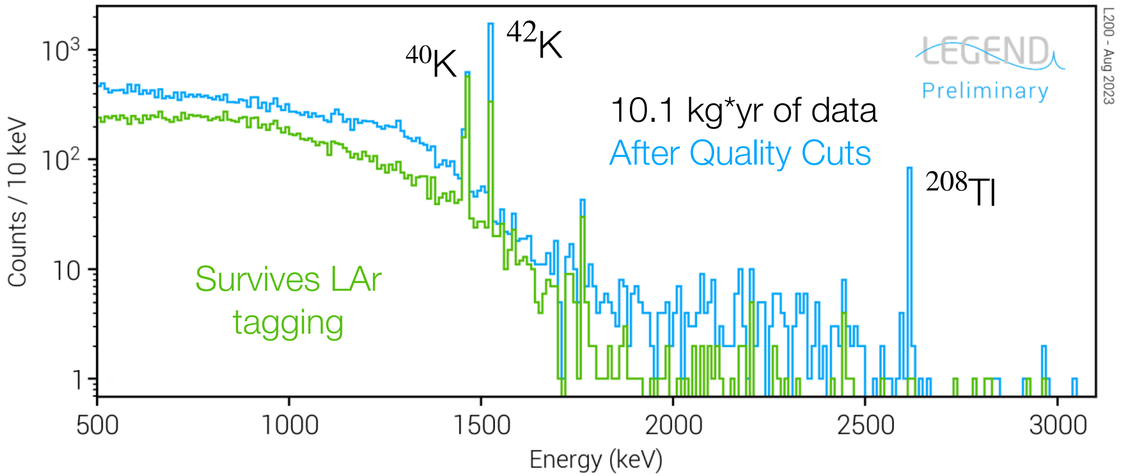


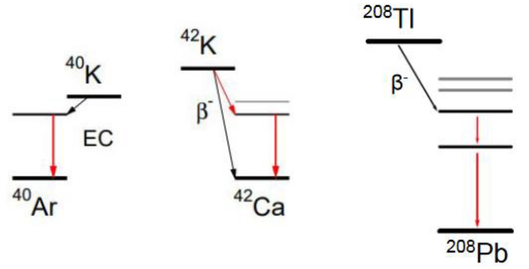


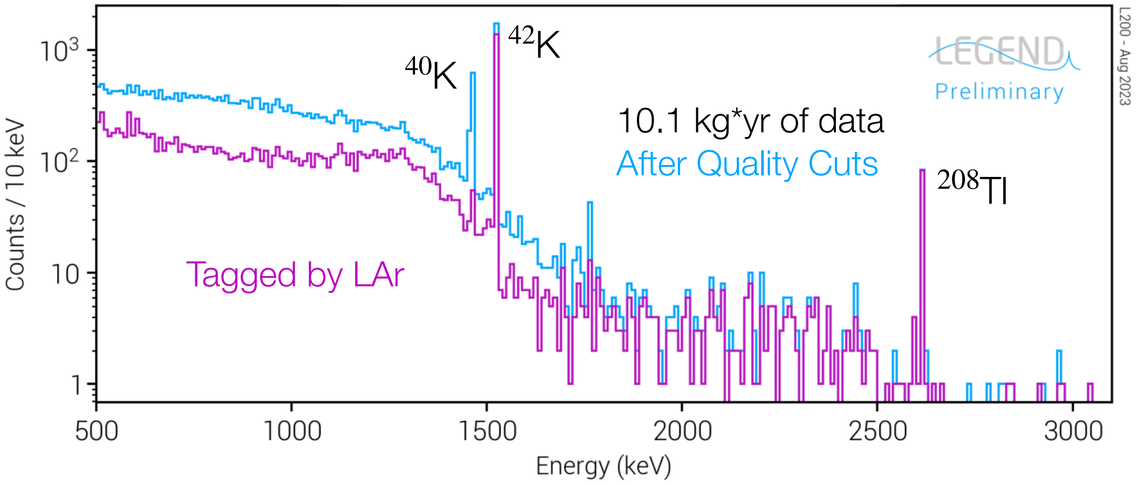
- Amplitude/Energy (A/E, Current/Charge)
  - Compare Charge induced on readout contact by event to the Current
  - Single site events ($0\nu\beta\beta$, DEP) have a narrow A/E parameter range
  - Calibrate with Th-228 calibration spectrum



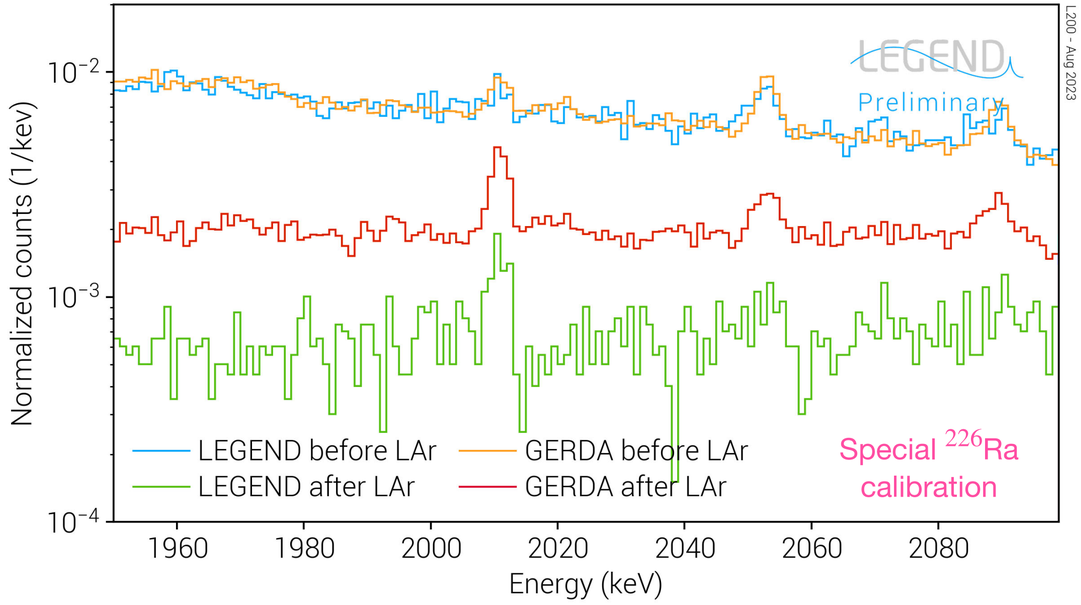
Liquid Argon Instrumentation Performance





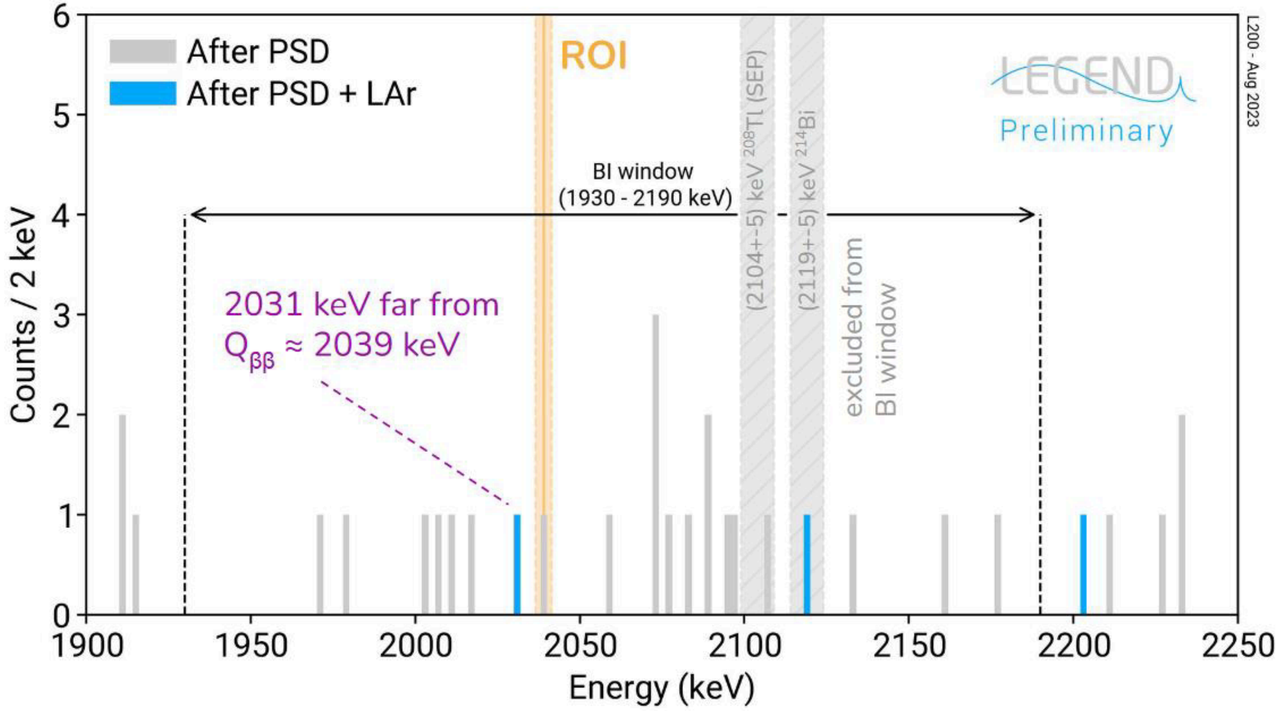


- Powerful suppression of α and β^- decays
- ×3 background suppression improvement from GERDA
  - Additional inner fiber barrel and more active PEN material
- Overall excellent performance from LAr instrumentation



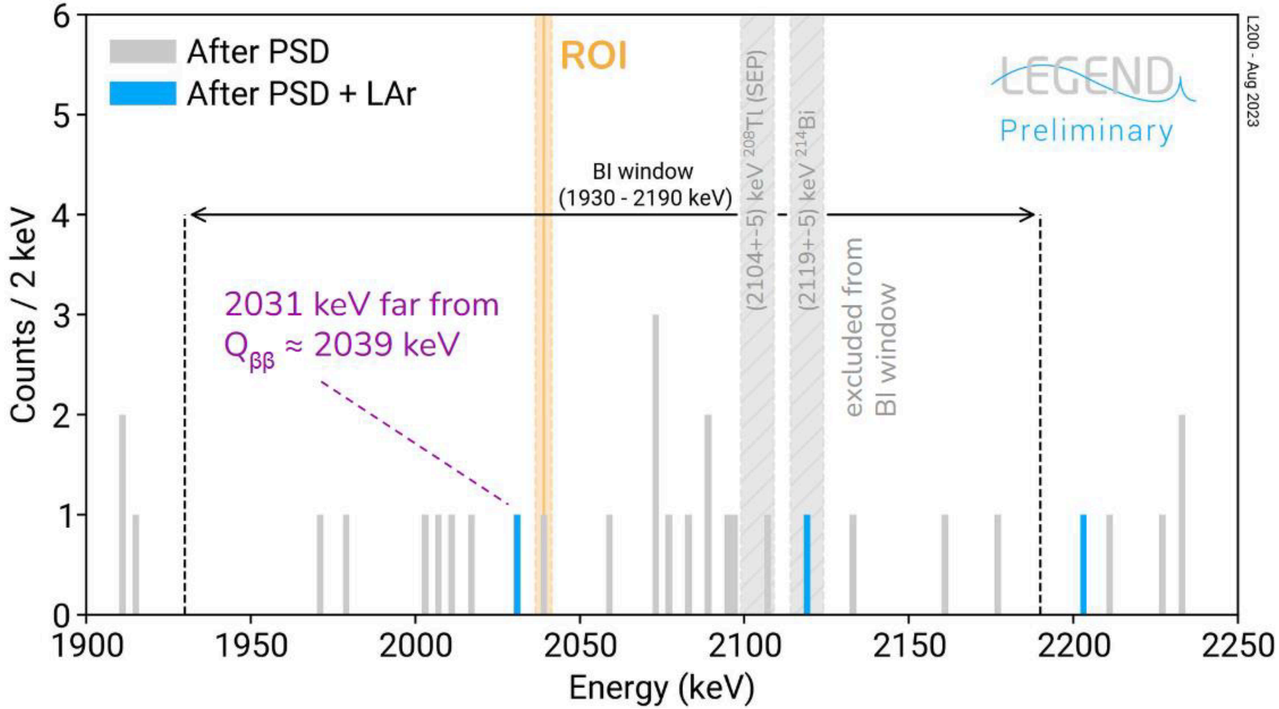
Background Index from First Data

- Initial look at 10.1 kg*yr of LEGEND-200 data after PSD cuts:
  - 240 keV background window
    - Background index calculated from this window excluding known U/Th gamma lines
  - 0.48 counts expected from simulations and assays —> 1 count observed
    - ~38% probability to observe >0 counts



Background Index from First Data

- Initial look at 10.1 kg*yr of LEGEND-200 data after PSD cuts:
  - 240 keV background window
    - Background index calculated from this window excluding known U/Th gamma lines
  - 0.48 counts expected from simulations and assays —> 1 count observed
    - ~38% probability to observe >0 counts



➡Background index is compatible with LEGEND-200 Background goal:
2×10^{-4} cts / (keV × kg × yr)

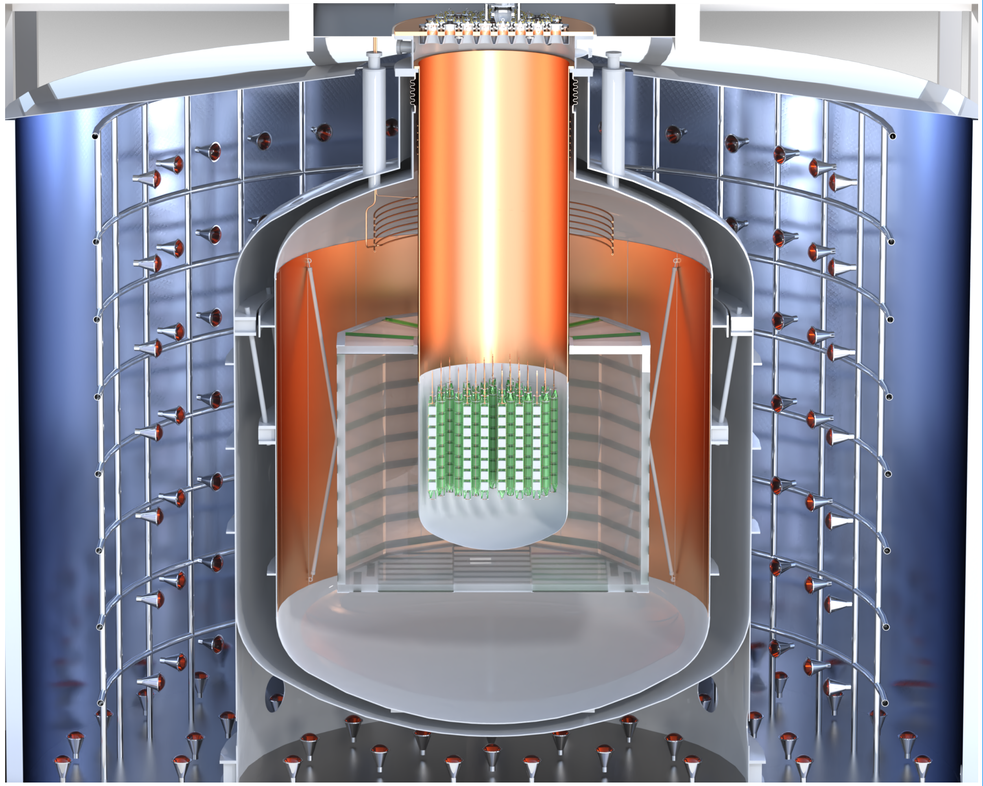
	LEGEND-200 BI 68% CL cts / (keV × kg × yr)	GERDA Phase II unblinded BI 68% CL cts / (keV × kg × yr)
After LAr and PSD	4.1 [1.5, 11.4] $\times10^{-4}$	5.2 [3.9, 6.8] $\times10^{-4}$

LEGEND Going Forward

LEGEND-200:

- Began data taking in March 2023 with 142 kg of detectors
- Continuing to acquire and analyze additional data
- Implementation of additional PSD
  - Machine learning and additional PSD cuts
- Planned maintenance period in 2024
  - Add more detectors (~40 kg)

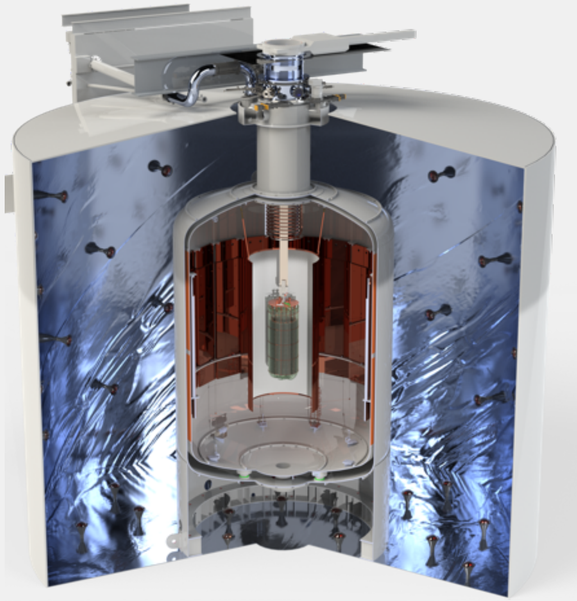
Rendering of LEGEND-1000 cross section



LEGEND-1000:

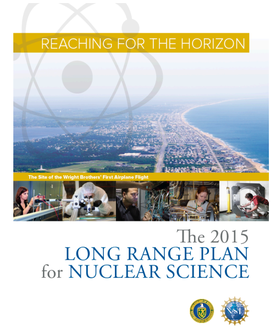
- Larger detectors (ICPC geometry)
  - ×4 lower backgrounds
  - Excellent background rejection of multi-site, β, and α events
- Argon obtained from underground source (UGLAr) for active shield
  - Background reduction of ^{42}Ar by ×1400 assumed from related DarkSide-50 measurement of UGLAr

Backup



U.S. Community and 0νββ

2015 Nuclear Science Long Range Plan — RECOMMENDATION 2 (of 4)



We recommend the timely development and deployment of a U.S.-led ton-scale neutrinoless double beta decay experiment.

2021 DOE Office of Nuclear Physics 0νββ Portfolio Review of CUPID, LEGEND, & nEXO

All were highly rated. Based on the findings of the review, a DOE strategy has been outlined:

"NP and its potential partners are jointly exploring the possibility of a campaign with more than one experiment to increase the likelihood of identifying and characterizing this rare decay mode"... "NP continues to pursue the possibility, in collaboration with national and international partners, of a multi-experiment campaign capable of providing contemporaneous verification of any apparent observation of 0νββ. Should it not prove possible to implement multiple projects in the search of 0νββ, LEGEND-1000 would receive priority based on it receiving the highest ranking from the portfolio review panel."

DOE ONP presentation by Paul Sorensen, Dec. 2022

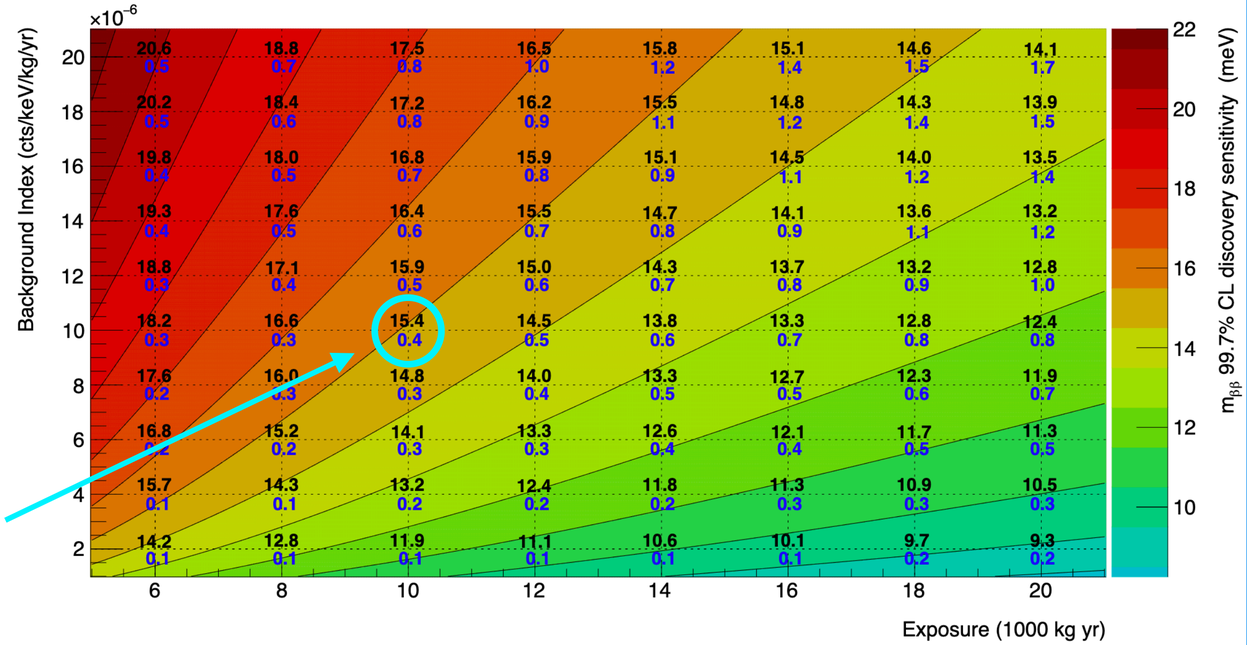
2023 Nuclear Science Long Range Plan - RECOMMENDATION 2 (of 4)

As the highest priority for new experiment construction, we recommend that the United States lead an international consortium that will undertake a neutrinoless double beta decay campaign, featuring the expeditious construction of ton-scale experiments, using different isotopes and complementary techniques.

$$\frac{1}{T^{0\nu}_{\beta\beta}} = G^{0\nu} * |M^{0\nu}|^2 * m_{\beta\beta}$$

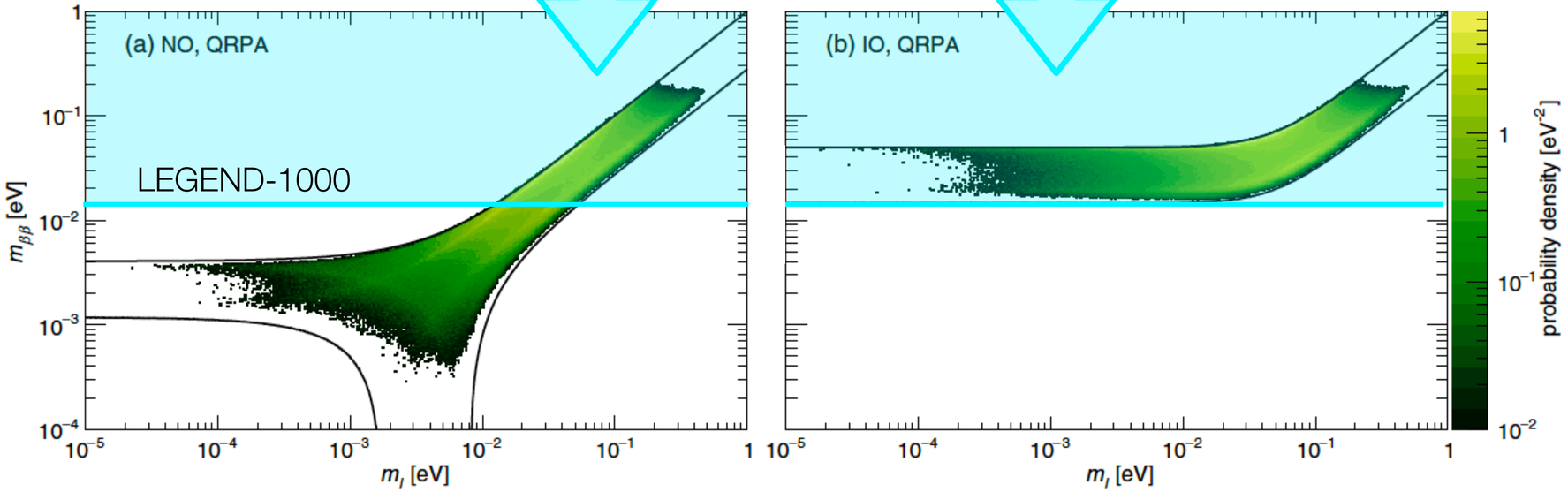
$G^{0\nu}$ = phase space factor

$|M^{0\nu}|^2$ = nuclear matrix elements



Effective majorana mass $m_{\beta\beta}$

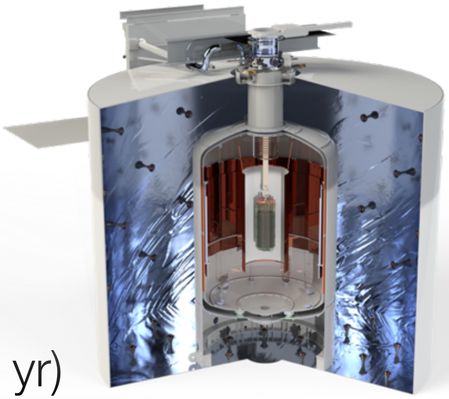
$\sum U_{ei}^2 m_i = m_{\beta\beta} = 15.4$ meV

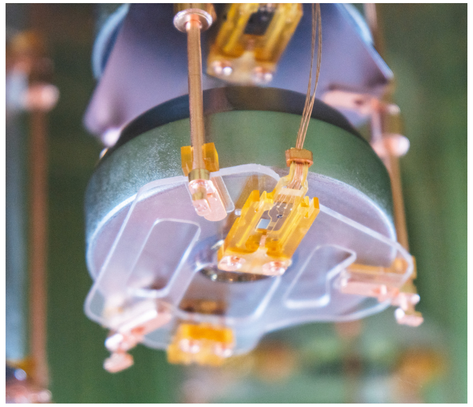


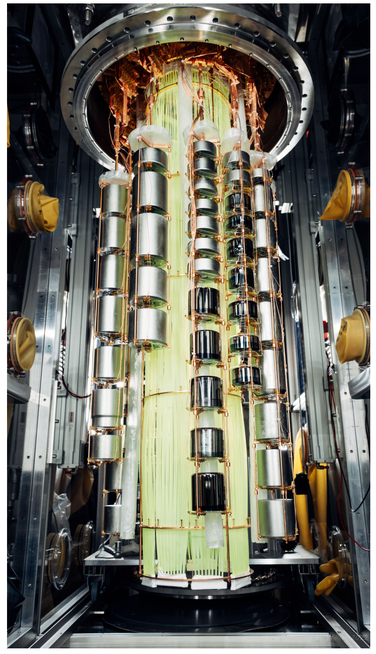
LEGEND is pursuing a phased approach

LEGEND-200

- 200 kg ^{76}Ge in upgrade of existing GERDA infrastructure at LNGS
- BG goal
  < 0.6 cts/(FWHM t yr)
  < 2.5 x 10^{-4} counts/(keV kg yr)
- Taking data with 10 strings (142 kg) of detectors.

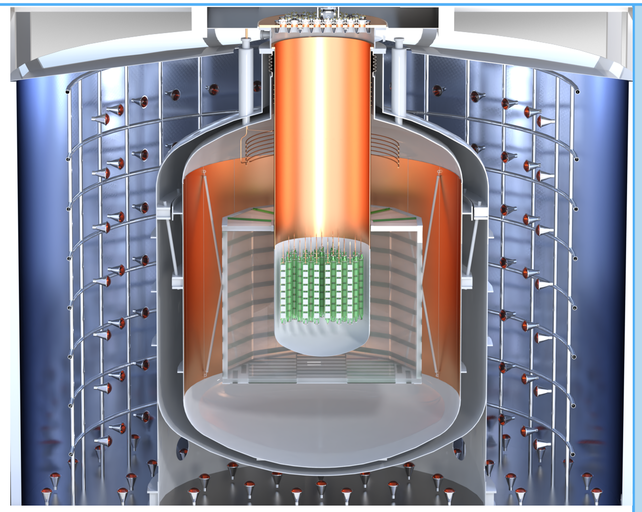


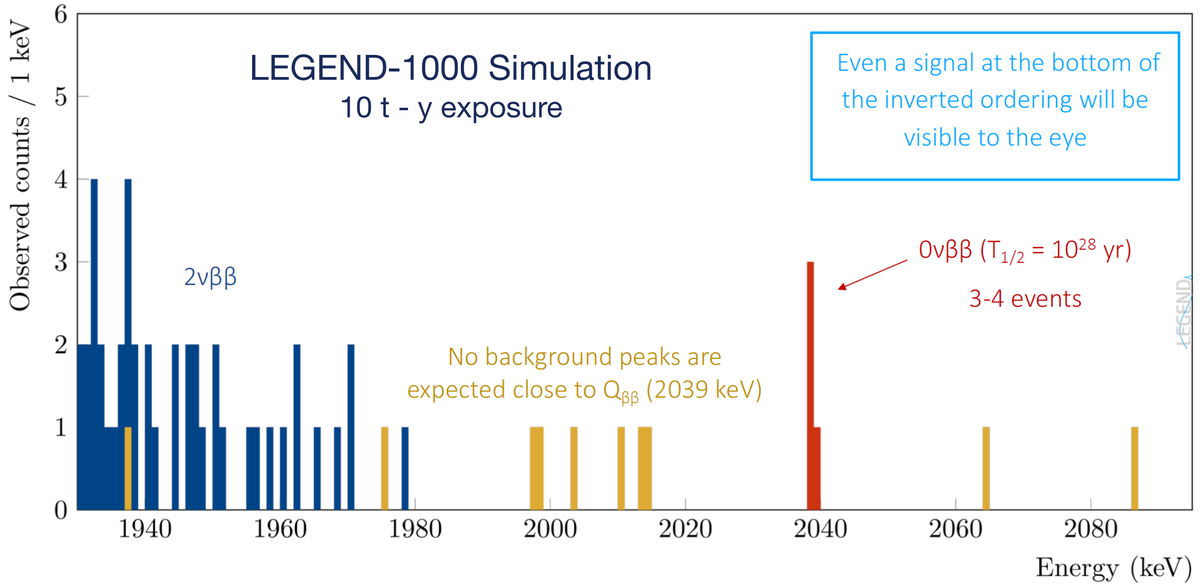




LEGEND-1000

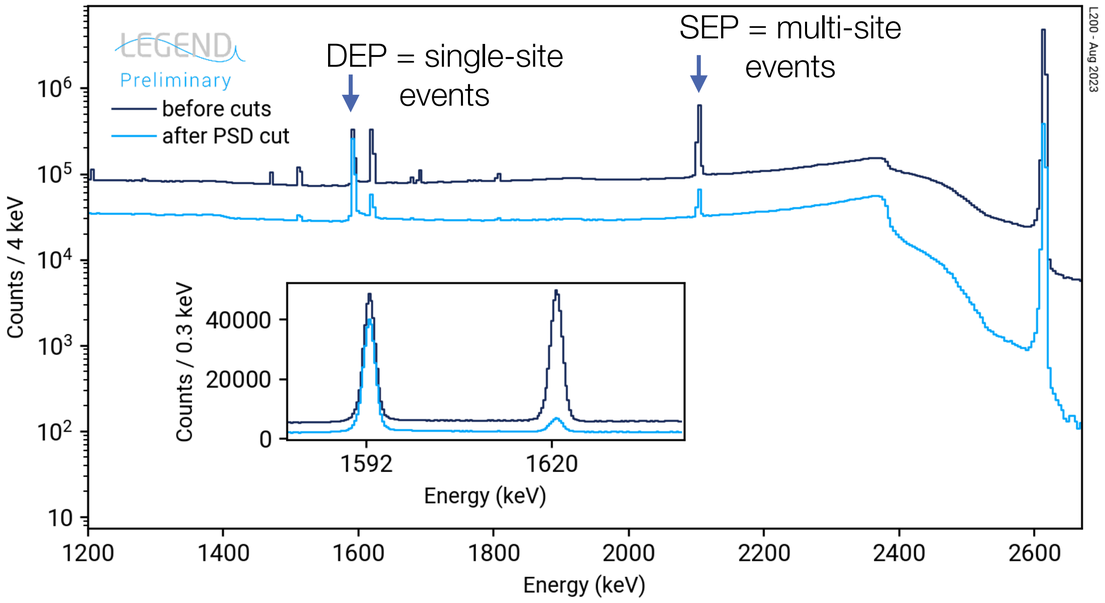
- 1000 kg ^{76}Ge (staged)
- BG goal
  < 0.025 cts/(FWHM t yr)
  < 1 x 10^{-5} counts/(keV kg yr)
- Location
  LNGS, Hall C
- Start construction 2025
- Time critical isotope enrichment

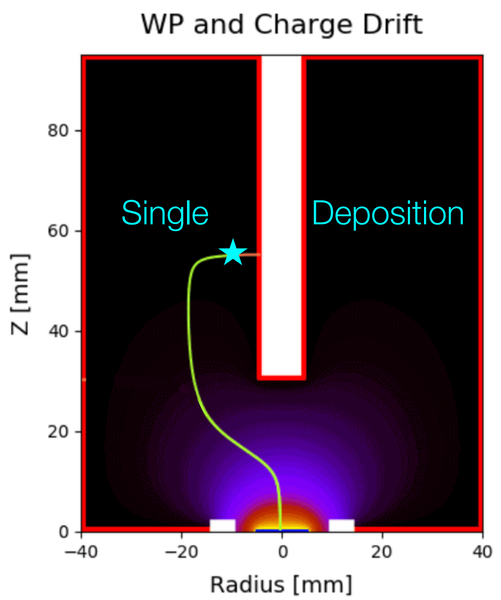


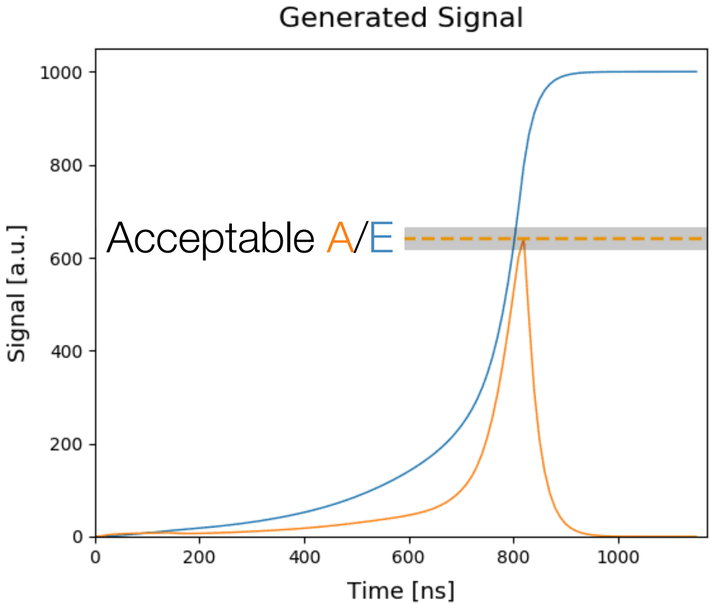


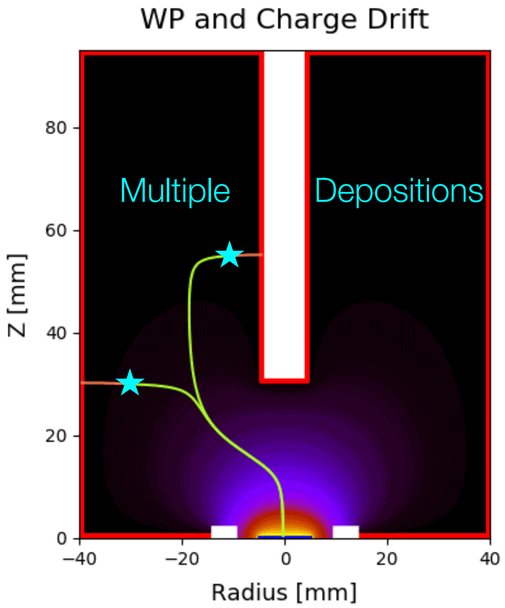
Pulse Shape Discrimination (PSD)

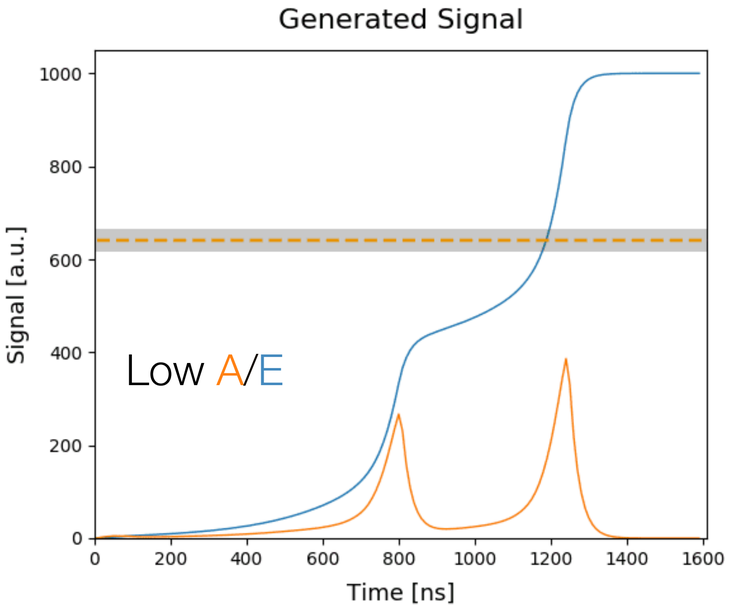
- (current) Amplitude/Energy (A/E)
  - Compare event Energy from waveform to the derivative Amplitude
  - Single site events ($0\nu\beta\beta$, DEP) have a narrow A/E parameter range
  - Calibrate with Th-228 calibration spectrum





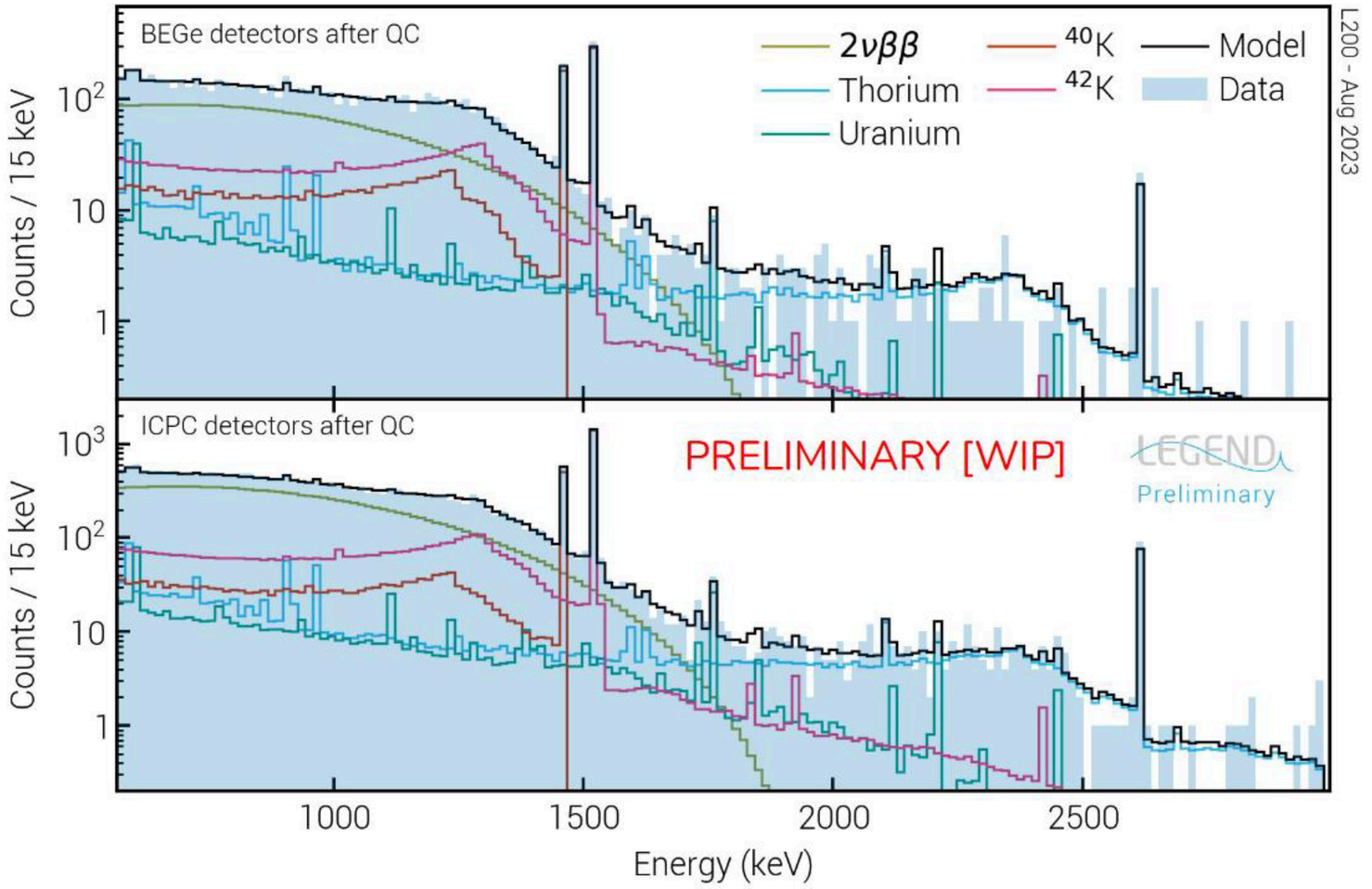






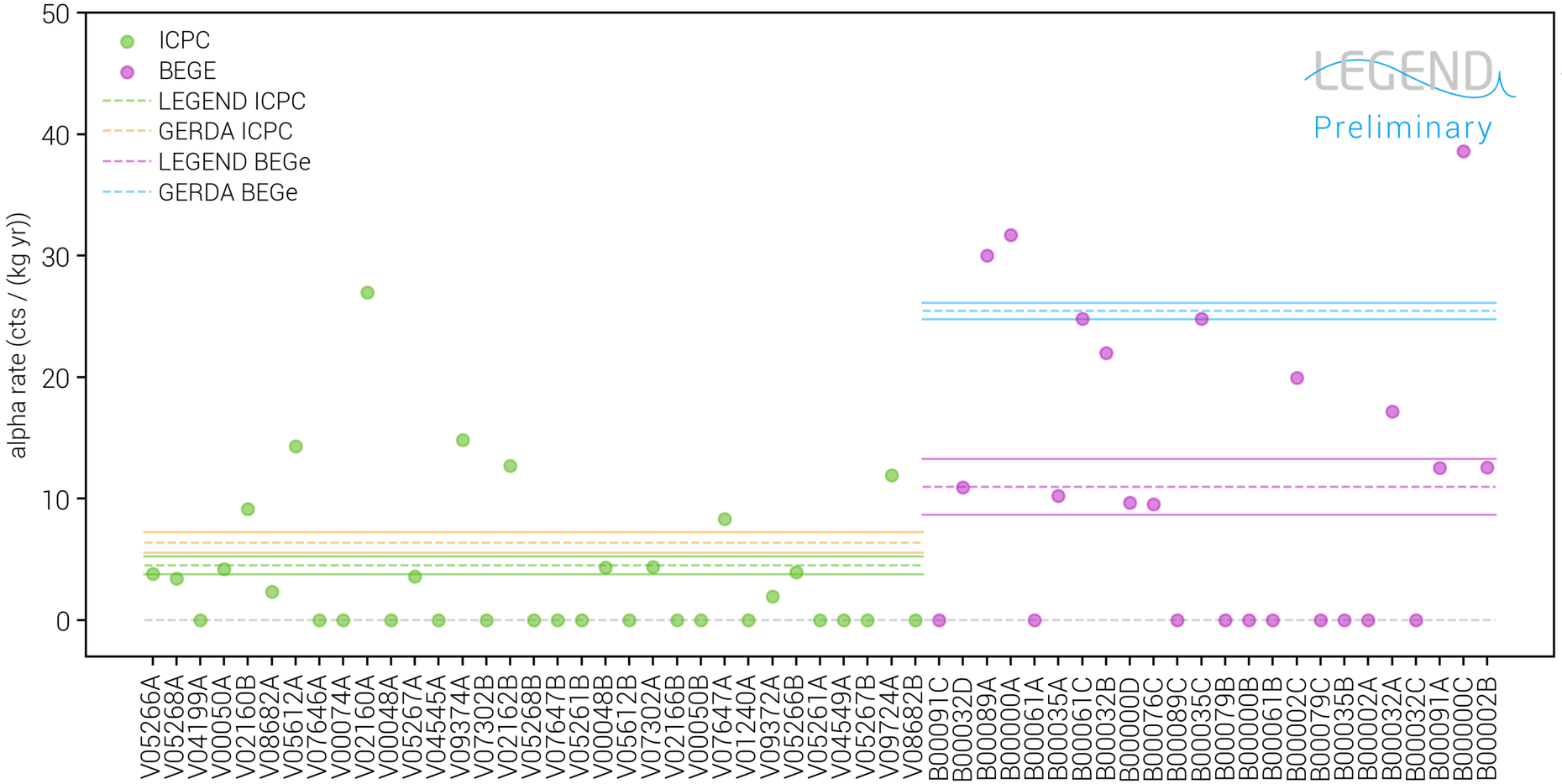
Background Modeling

- Modeling of background decomposition before analysis cuts
  - Backgrounds are well explained by expected contributions



Alphas Rates

- Lower alpha rate in ICPCs
  - Larger volume to passivate surface area ratio
  - Lower rate from GERDA due to better detector handling before deployment



$2\nu\beta\beta$ uniformity

- Count rate from featureless $2\nu\beta\beta$ spectrum (1000 keV — 1300 keV) after cuts