LEGEND: Background-free hunt for the neutrinoless double-beta decay

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on behalf of the LEGEND Collaboration

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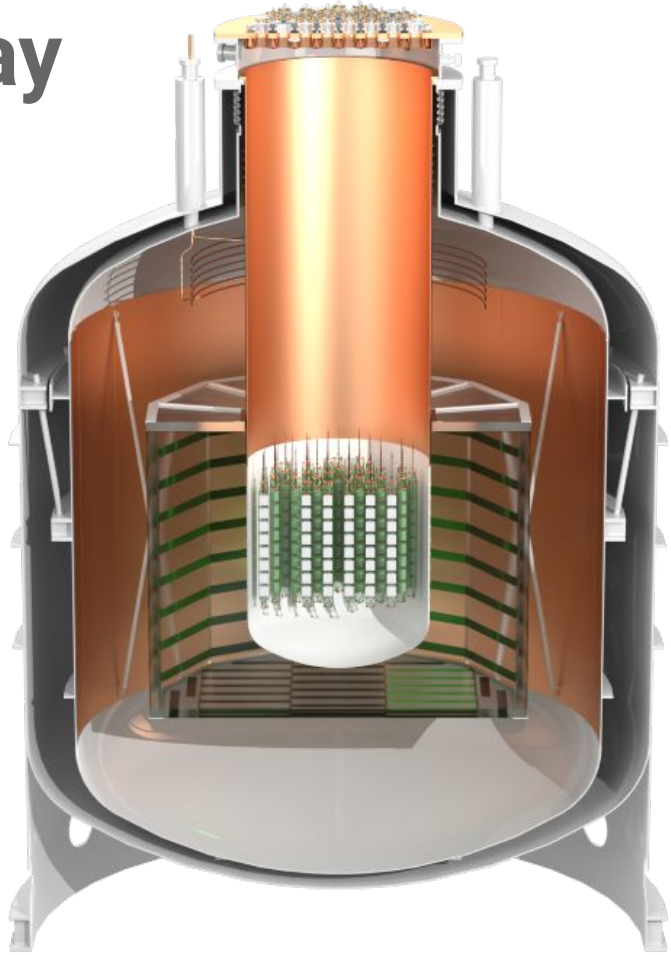
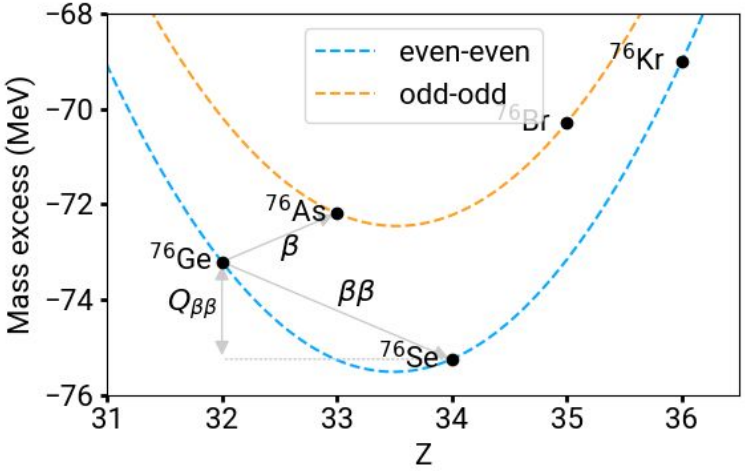
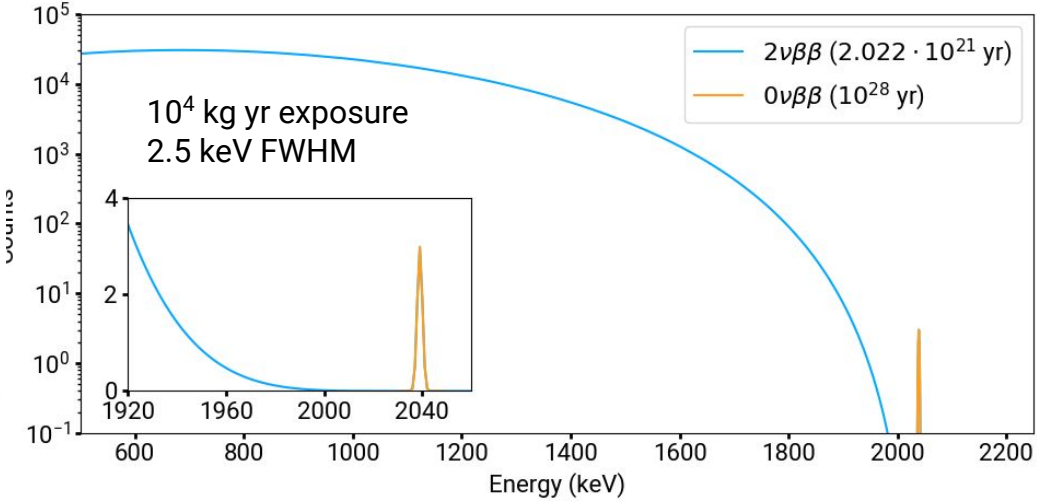
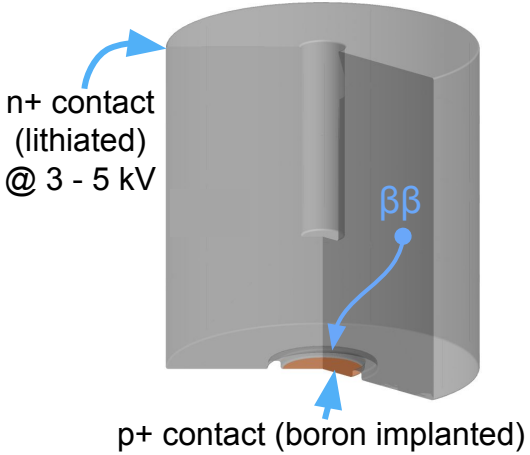
07. September 2023 – TIPP2023



Searching for 0νββ with Germanium

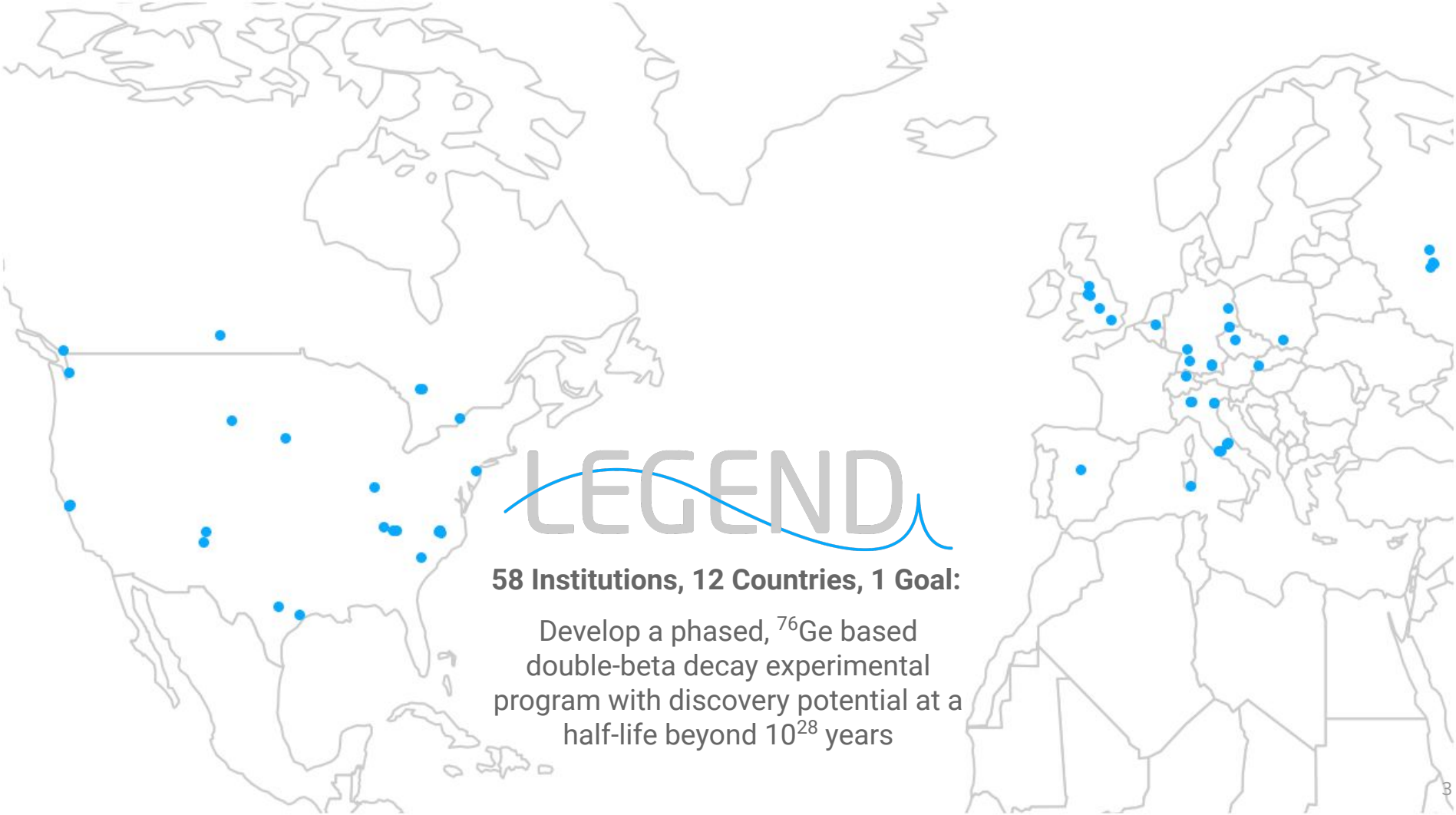






High-Purity Germanium detectors enriched in ^{76}Ge

- ββ source = detector → no additional detector needed
- high purity → low intrinsic background
- isotope enrichment → ≳ 90 % ^{76}Ge
- outstanding energy resolution → ~ 0.1 % FWHM @ $Q_{\beta\beta}$
- topological discrimination → pulse shape analysis

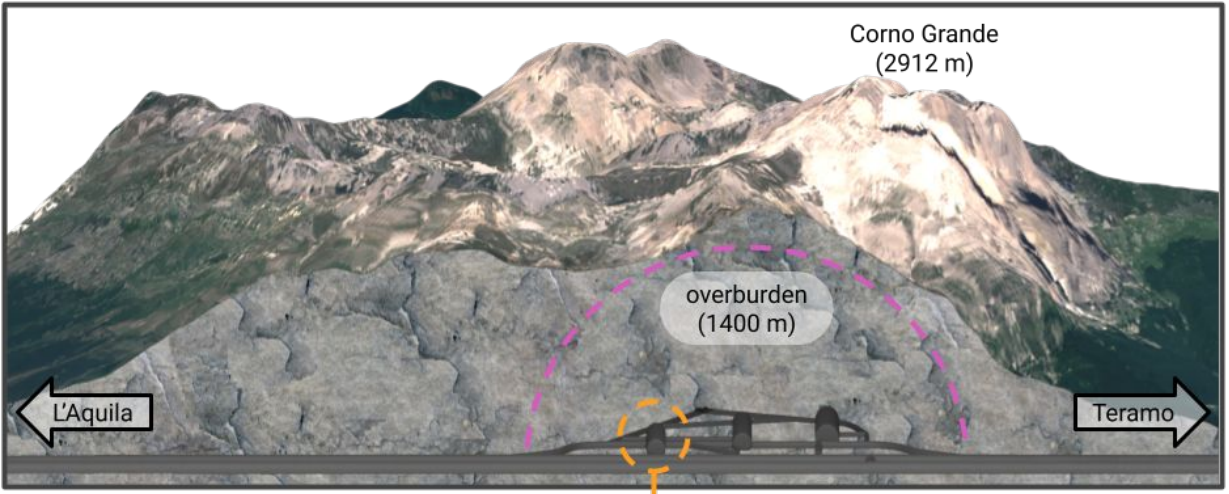


LEGEND

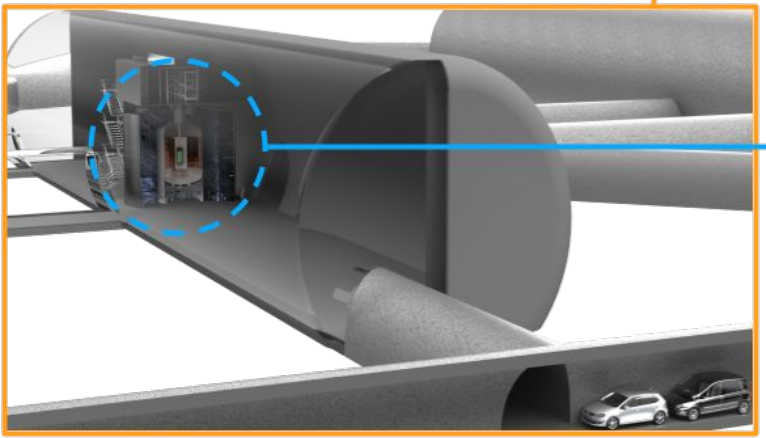
58 Institutions, 12 Countries, 1 Goal:

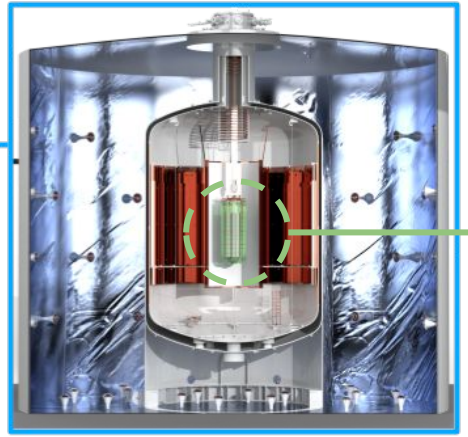
Develop a phased, ^{76}Ge based double-beta decay experimental program with discovery potential at a half-life beyond 10^{28} years

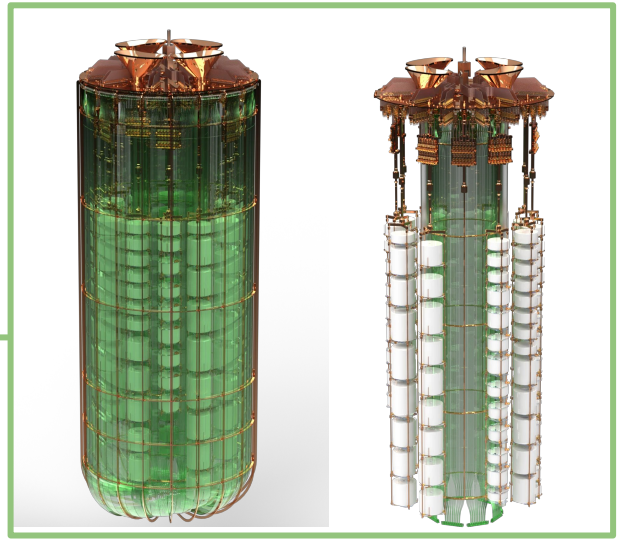
LEGEND-200



- 200 kg HPGe Detectors
- LAr instrumentation (Two fiber shrouds)
- Infrastructure of GERDA
- $T_{DP} \sim 1 \cdot 10^{27}$ yr
- $< 2 \cdot 10^{-4}$ cts/(keV kg yr)





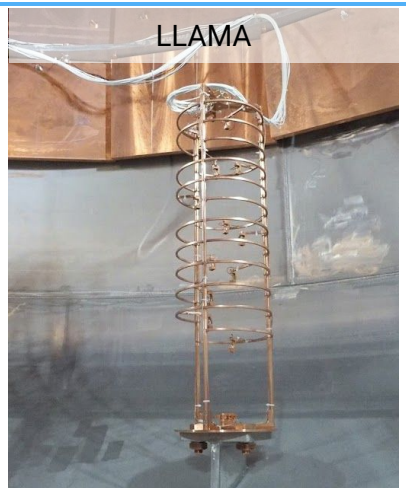


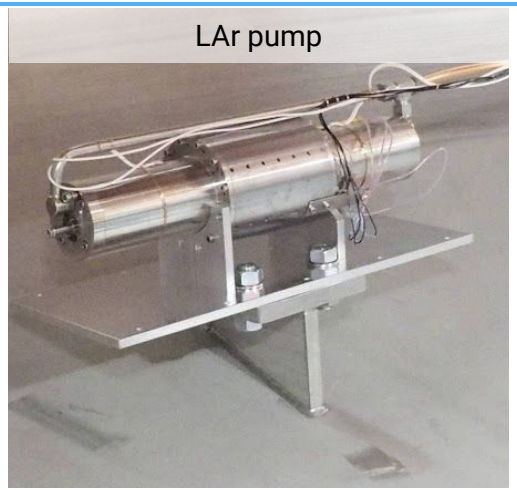
LEGEND-200: Commissioning

Nov 2020

Works in the cryostat


Installation of the WLSR


LLAMA


LAr pump

Mar 2021

Installation of new lock system

Start of cryostat filling


Installation of new Lock system

LEGEND-200: Commissioning

Jul 2021

Mechanics tests

Oct 2021

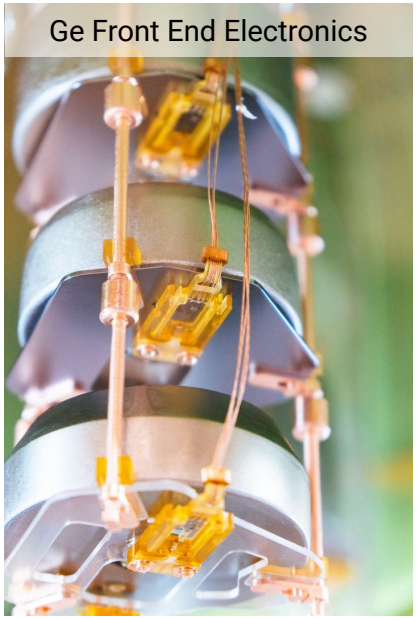
LAr instrumentation commissioning

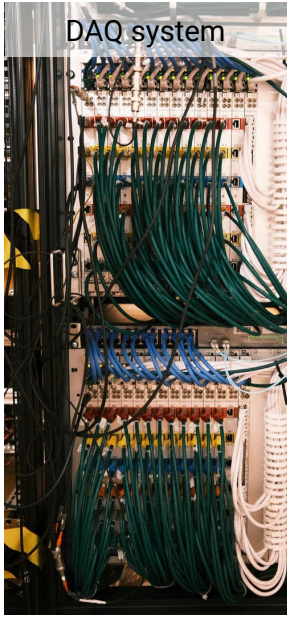
Front end electronics commissioning

Glove Box installation


Fiber module assembly

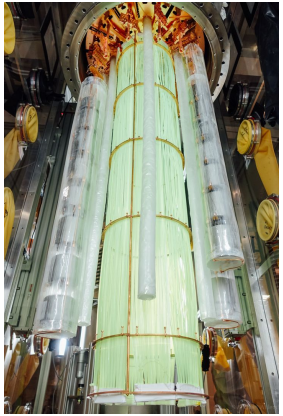

Inner fiber barrel

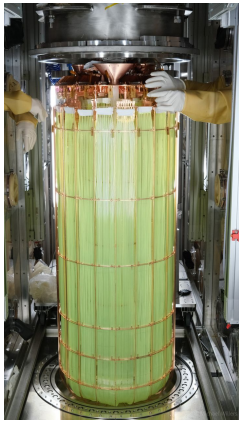

Ge Front End Electronics


DAQ system

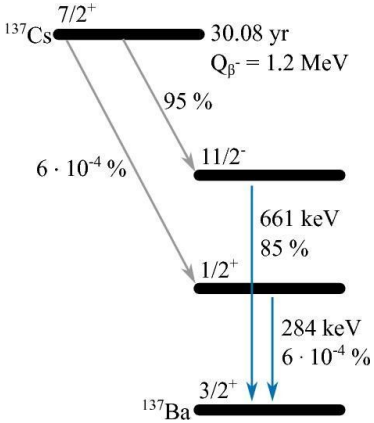
LEGEND-200: 60 kg test & special LAr calibration runs

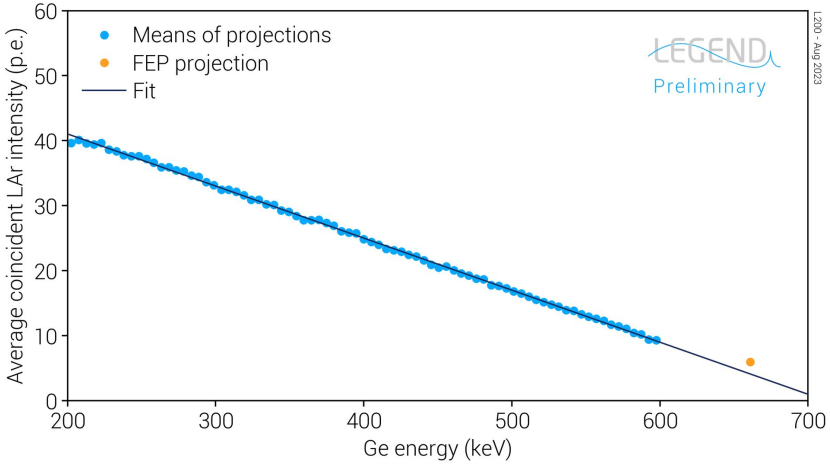
May 2022

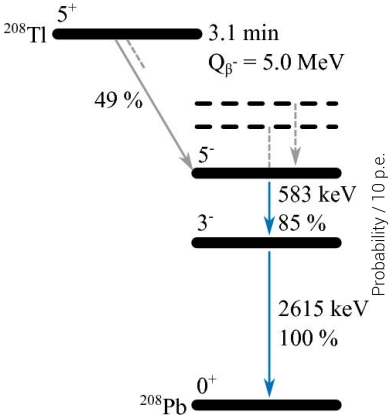


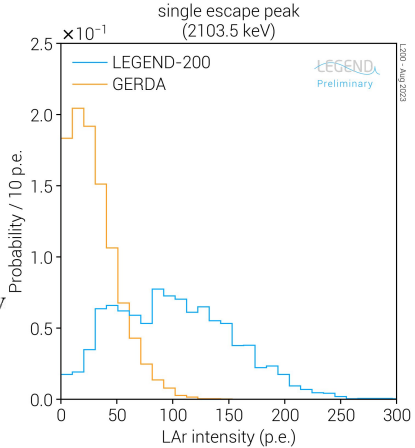


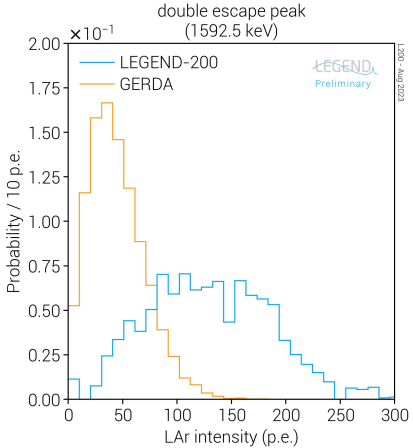
- 3x more light compared to GERDA
- Improved geometry + optically active PEN → less shadowing
- Cs-137 calibration allows estimate of p.e. yield → O(0.1) p.e./keV







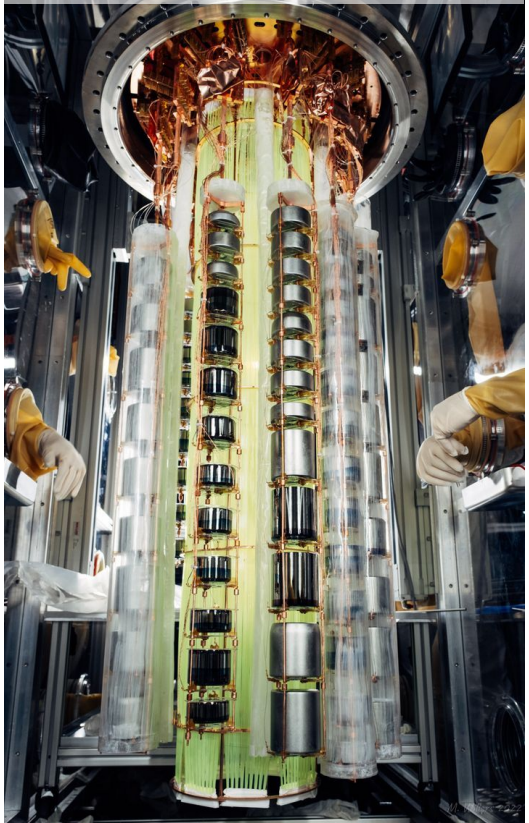




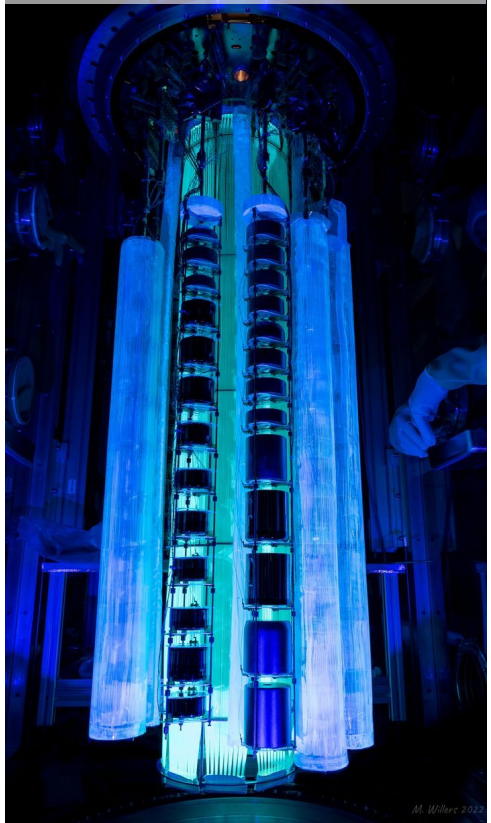
LEGEND-200: 140 kg installation and commissioning

Oct 2022

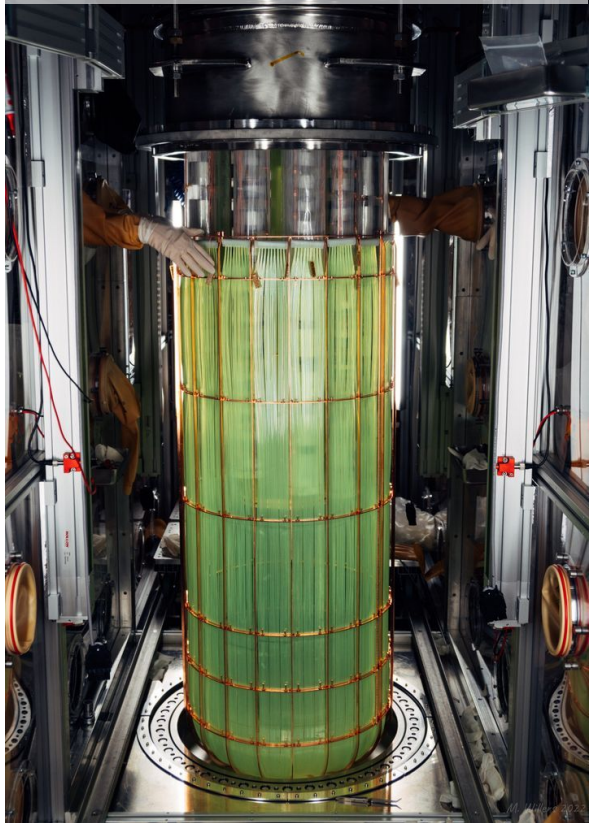
140 kg HPGe detectors installation



Setup under UV light

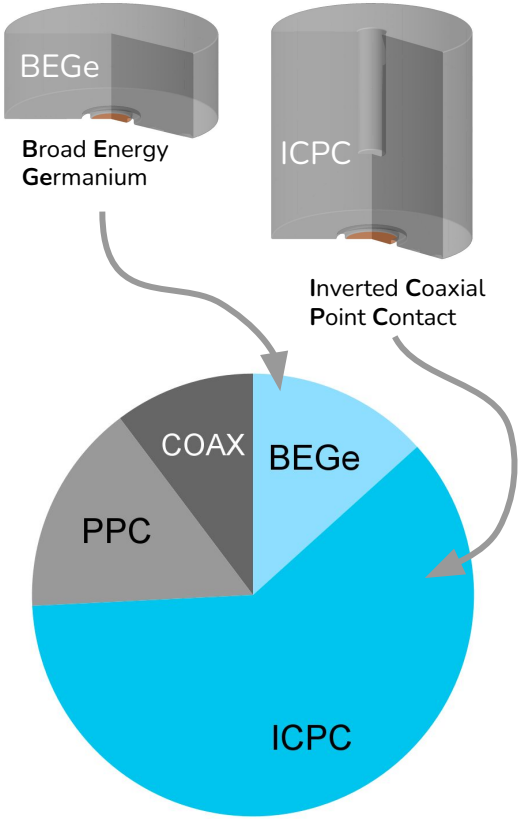


Mounting of outer fiber barrel



LEGEND-200: 140 kg physics data taking

Mar 2023

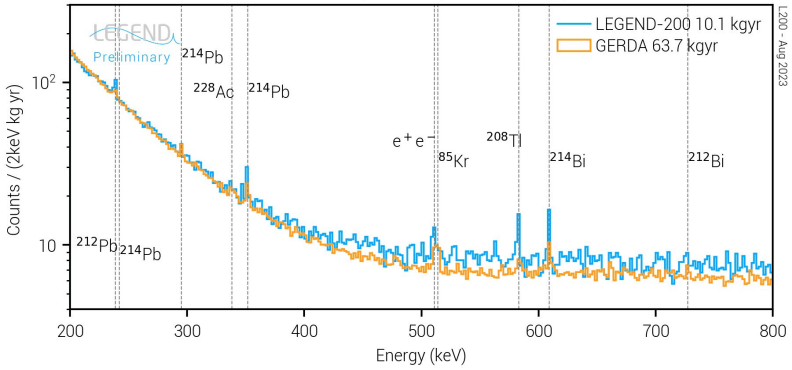


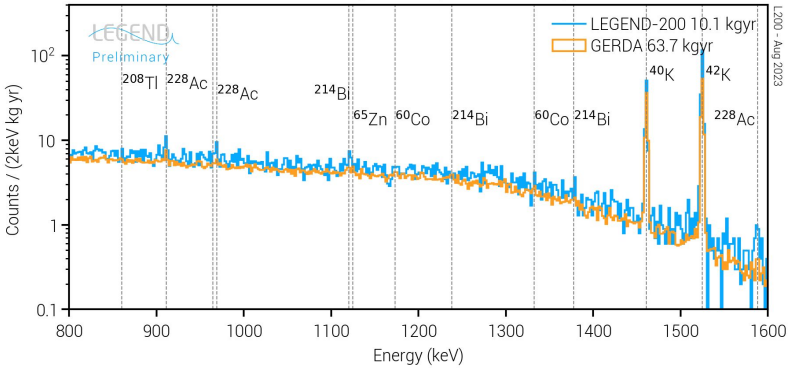
- 101 detectors in 10 strings
- Electronics for full 200 kg installation available & tested
- DAQ & slow control fully available
- LAr instrumentation operational
- 130 kg operational. (12 detectors off due to hardware failure)
- So far: focus on analysis of BEGe & ICPC detectors
- PSD development for other detectors ongoing

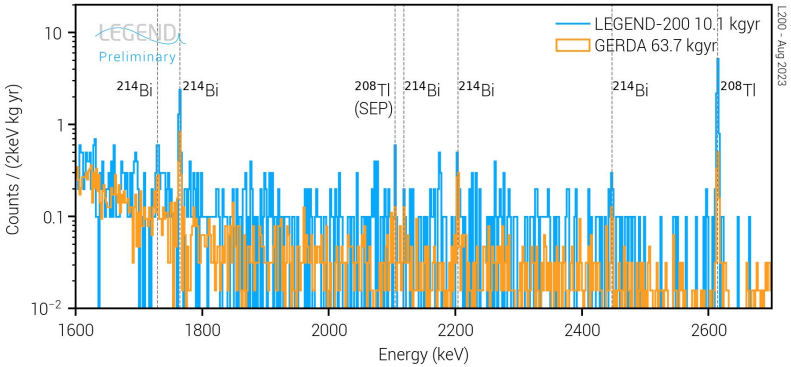
Exp (kg yr)	BEGe	ICPC
10.1	2.1	8.0

LEGEND-200: After Quality Cuts

Today







- 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

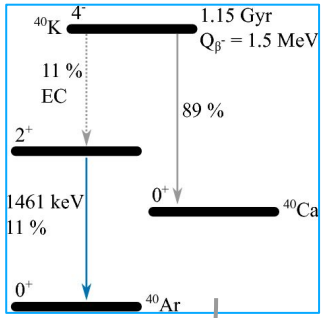
LEGEND vs. GERDA BEGe+ICPC

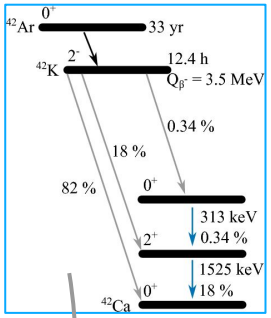
LEGEND-200: After LAr Cut

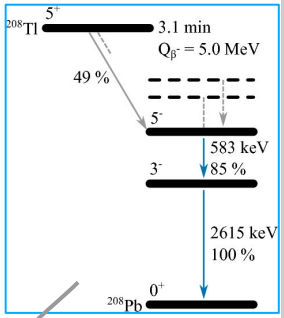
Today

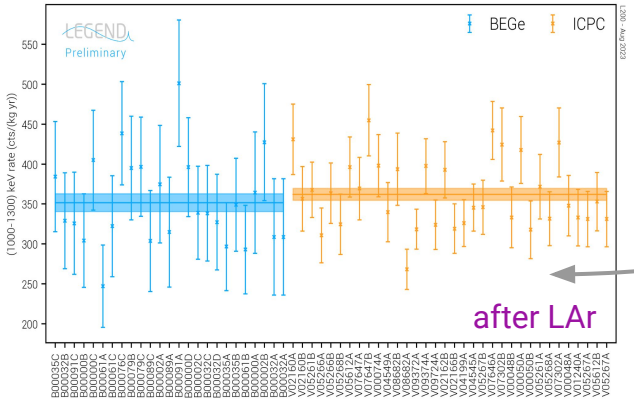
After LAr cut:

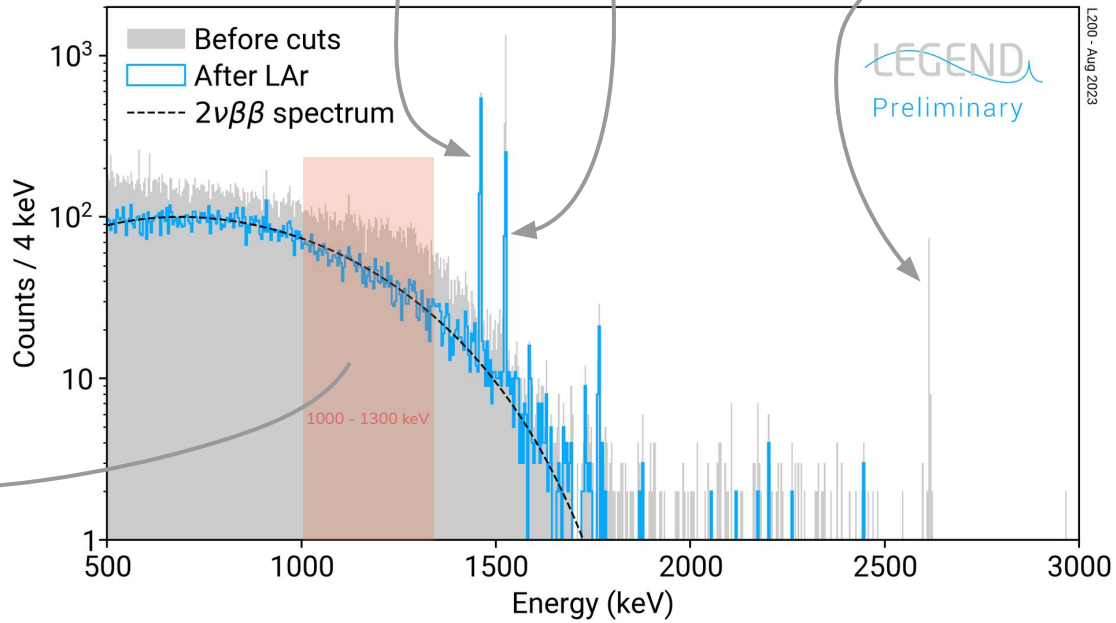
- Tl-208 peak is completely suppressed
- K-42 peak survives to < 20%
- K-40 peak fully accepted
- Pure 2vbb
- Uniform detector rate







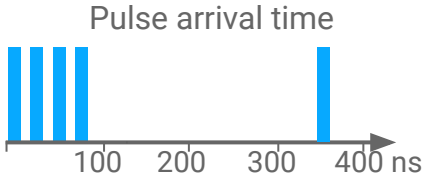




LEGEND-200: LAr Instrumentation, from a Veto to a full detector system

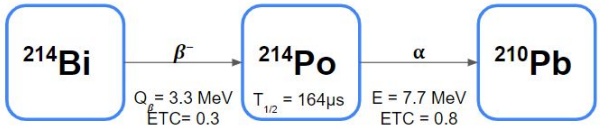
Today

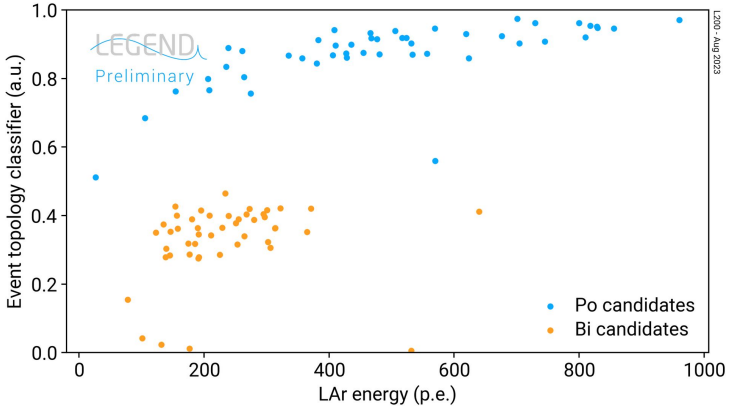
- Data also acquired with trigger on LAr events
- Ratio of singlet to triplet scintillation pulses is intrinsic to the radiation type
- Event topology classifier utilizes ratio to identify particle types
- Allows advanced background tagging methods

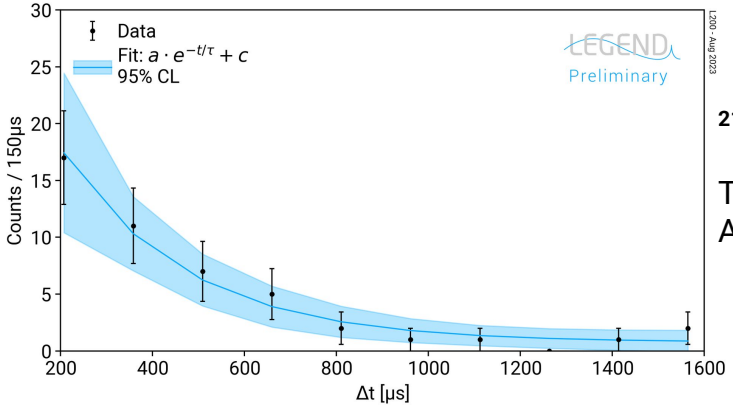


Low ETC ~ 0.4 → γ/β radiation

High ETC ~ 0.8 → α radiation







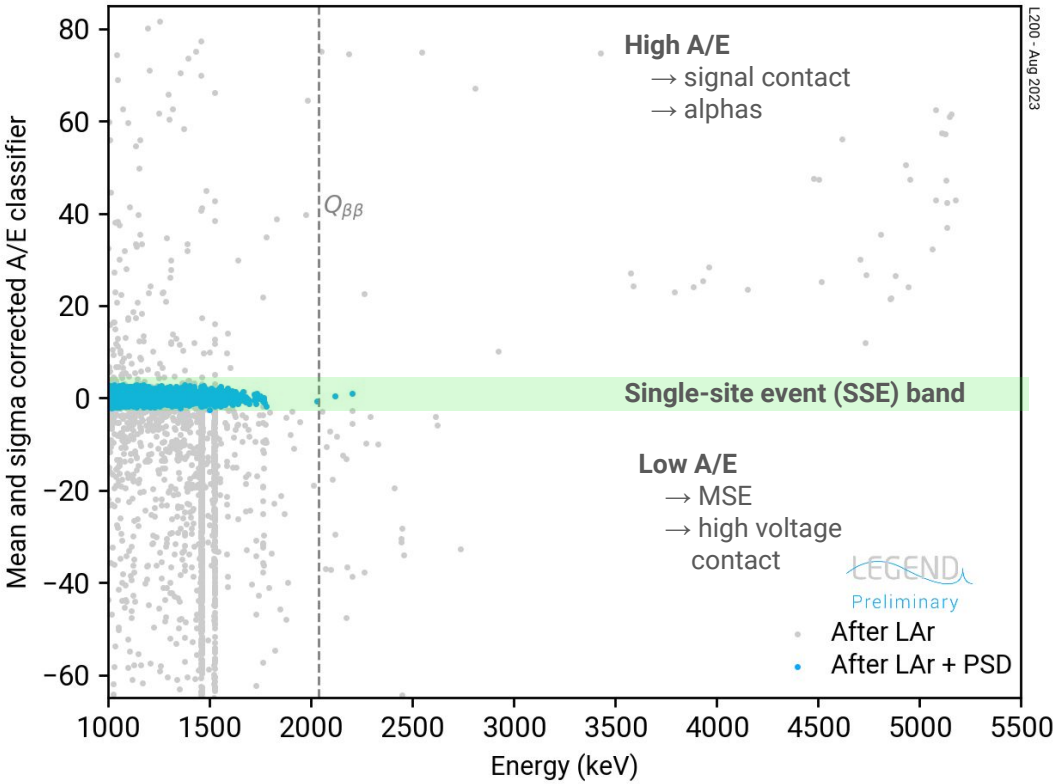
^{214}Bi-Po tagging:

$T_{1/2}$ = 188 +- 46 μs
A = 4.1 +- 0.8 nBq/kg

LEGEND-200: After PSD Cut

Today

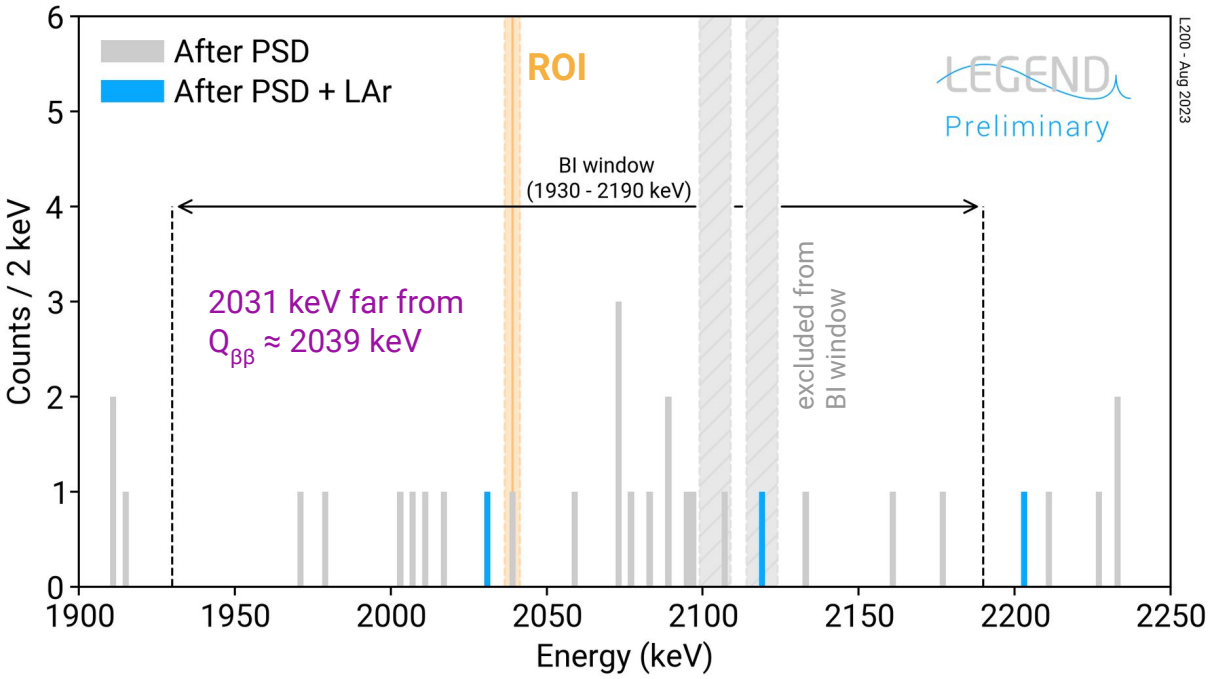
- Depending on the interaction type (multi-site, single-site, or surface event), different A/E → Pulse shape discrimination
- PSD cuts multi-site and alpha events effectively
- More powerful due to higher MSE probability in larger ICPC detectors
- PSD suppression in physics data depends on actual background composition and location



LEGEND-200: First Background Index

Today

	BI 68% CL (cts/keV/kg/yr)
LEGEND-200	4.1 [1.5,11.4] x 10^{-4}
GERDA	5.2 [3.9,6.8] x 10^{-4}



- BI is compatible with LEGEND-200 goal

  2 x 10^{-4} cts/(keV kg yr)

- Expect 0.48 cts -> Probability to observe cts > 0 = 38%

LEGEND-200: Whats Next?

Today

- Background in the ROI after analysis cuts:
  - ✓ Evaluated on first 10.1 kg yr of physics data compatible with LEGEND-200 goal
- Continue data taking
- New ICPC detectors currently in production

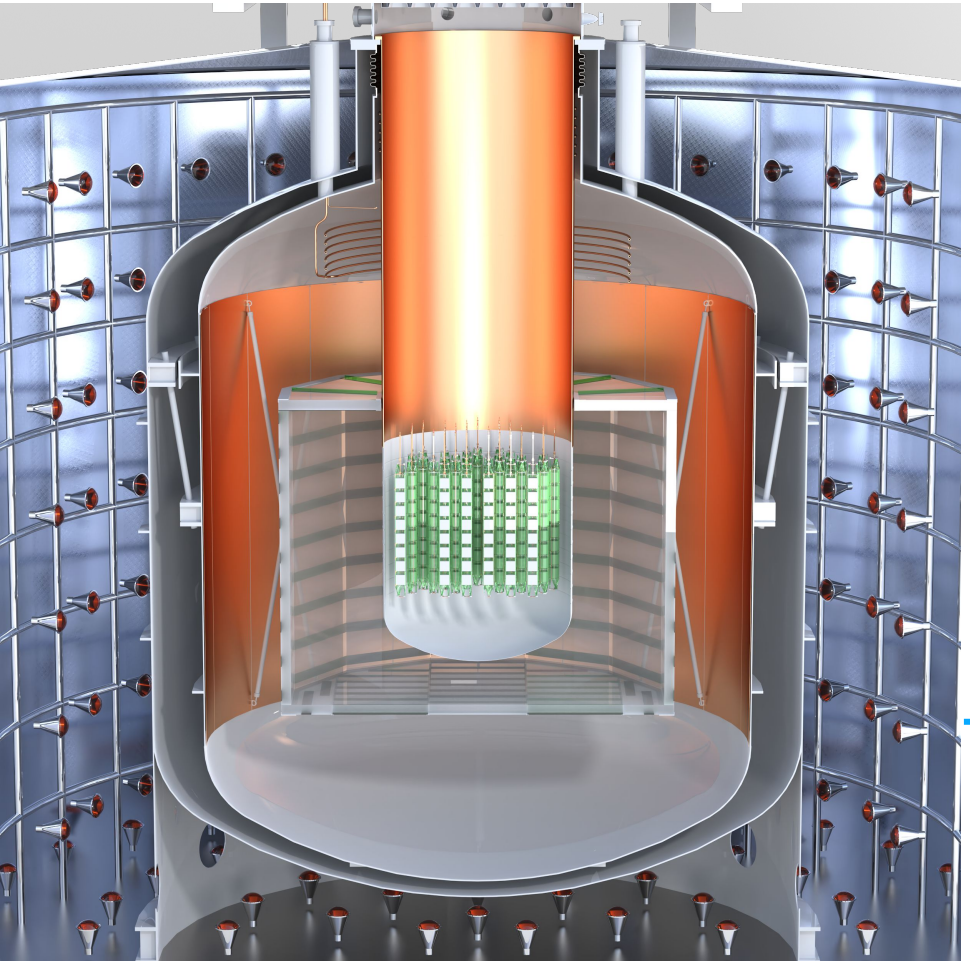
Early 2024

- Fix hardware issues
- Complete the array with remaining detectors

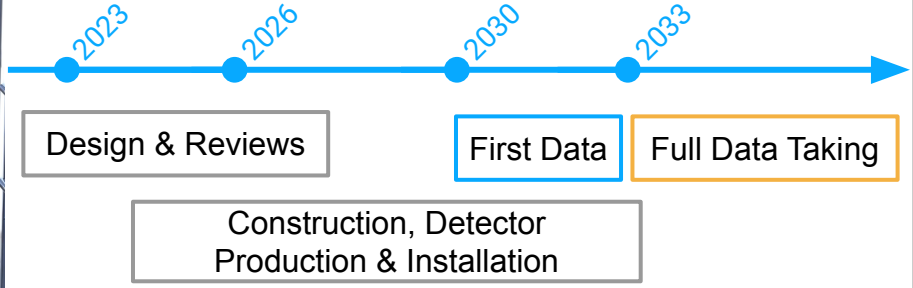
LEGEND-1000

Designed for an Unambiguous Discovery

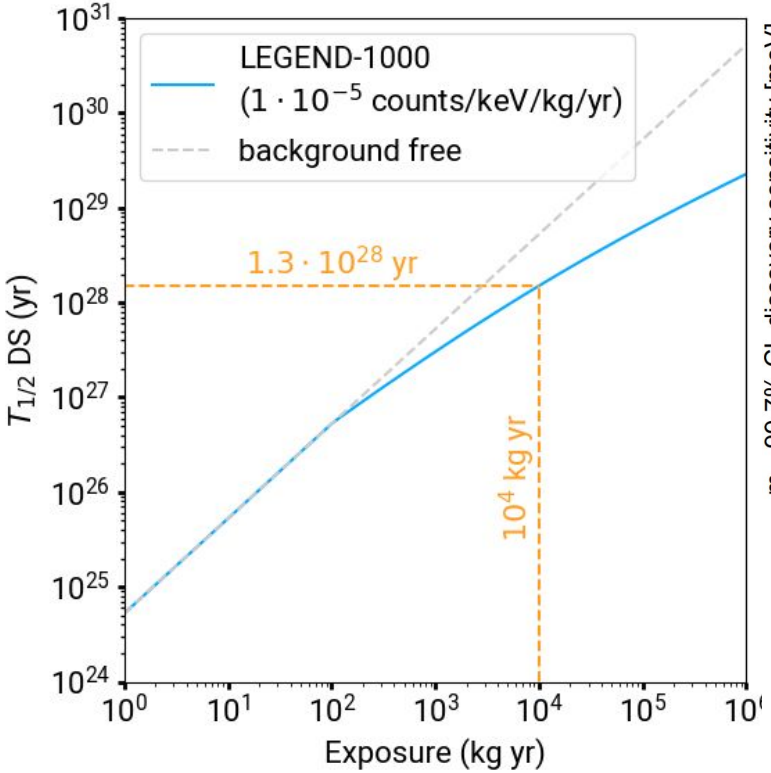
LEGEND-1000: Designed for an Unambiguous Discovery

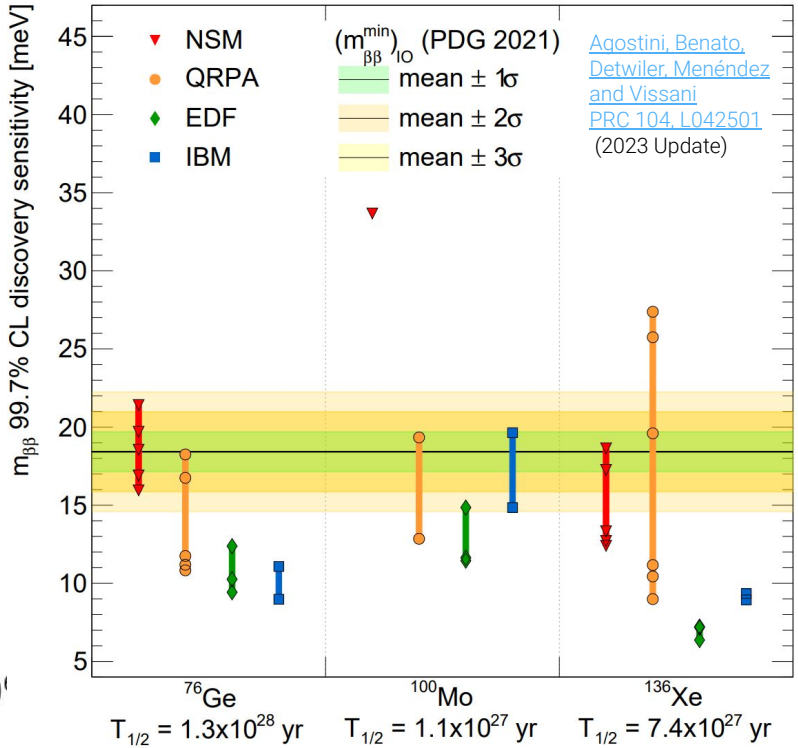


- 1000 kg HPGe Detectors (ICPC)
- New cryostat at LNGS or SNOLAB
- $T_{DP} > 1 \cdot 10^{28}$ yr
- Background: $<1 \times 10^{-5}$ cts/(keV kg yr)
- Underground LAr reentrant tube in a atmospheric LAr cryostat
- Single string, modular approach
- Large-mass ICPC detectors: ~3 kg avg. mass



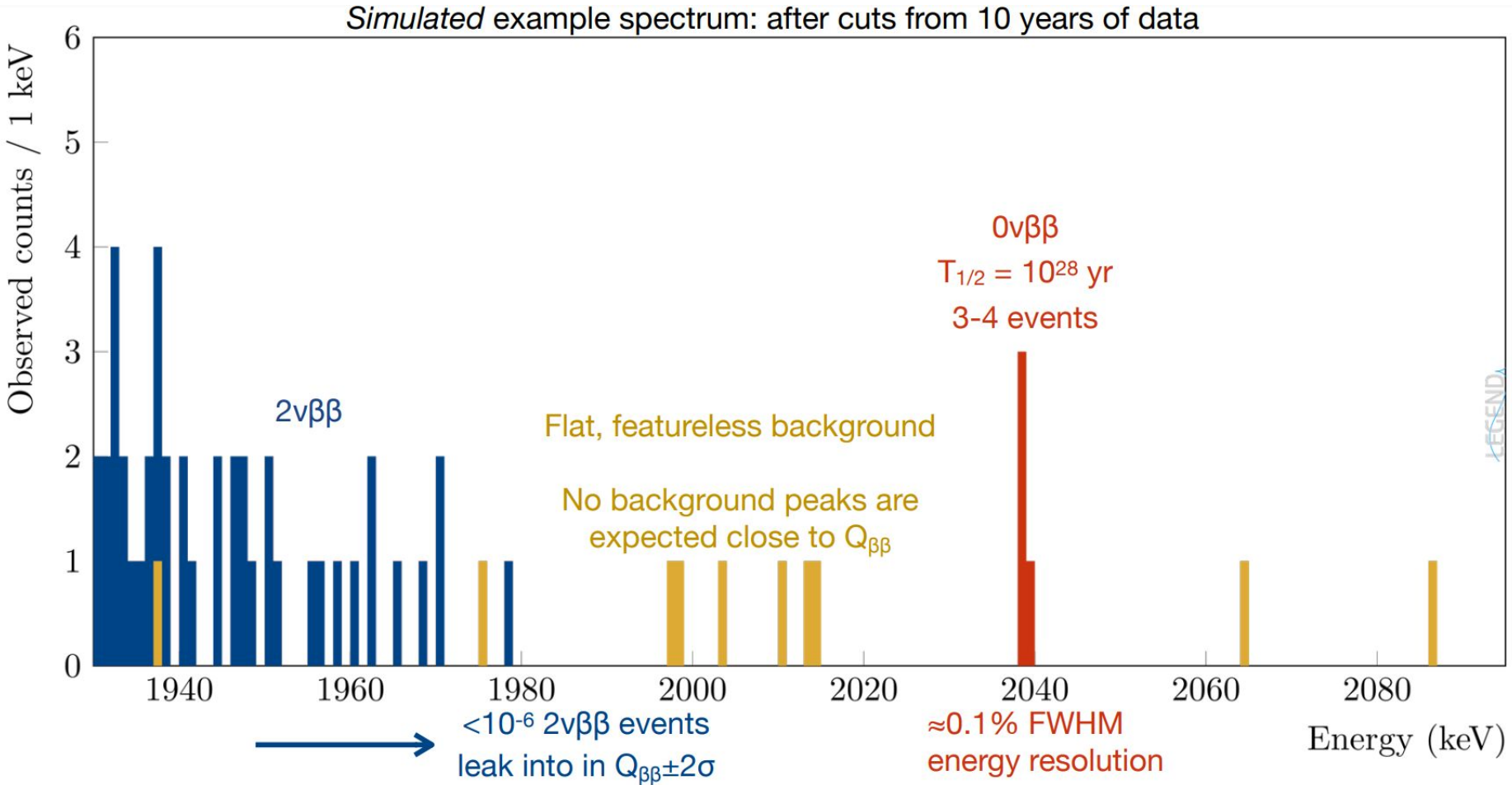
LEGEND-1000: Sensitivity





- LEGEND will span the inverted ordering and a large part of the normal ordering space
- Discovery sensitivity <18.4 meV for 12/15 calculations

LEGEND-1000: Designed for an Unambiguous Discovery



Conclusion

LEGEND-200

- Successful Commissioning of LEGEND-200
- First LEGEND-200 physics data
  - ✓ No unexpected background components
  - ✓ LAr instrumentation and PSD work as expected
  - ✓ Evaluated on first 10.1 kg yr of physics data
  - ✓ Compatible with LEGEND-200 goal
- Early 2024 remaining detectors will be installed

legend-exp.org

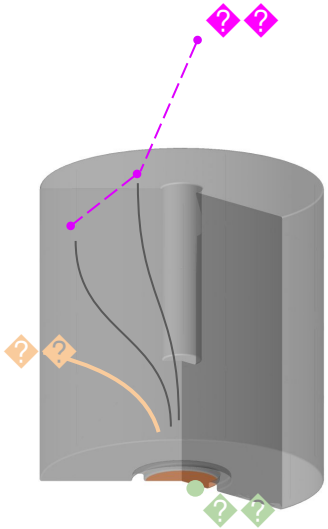
LEGEND-1000

- Design for a a discovery
- Low risk scaling due to the experience from LEGEND-200
- R&D already underway
- Will cover full inverted mass ordering and large part of normal ordering

BACKUP

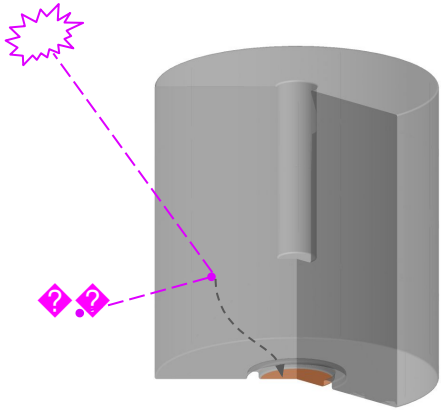
Background Rejection Methods

Background



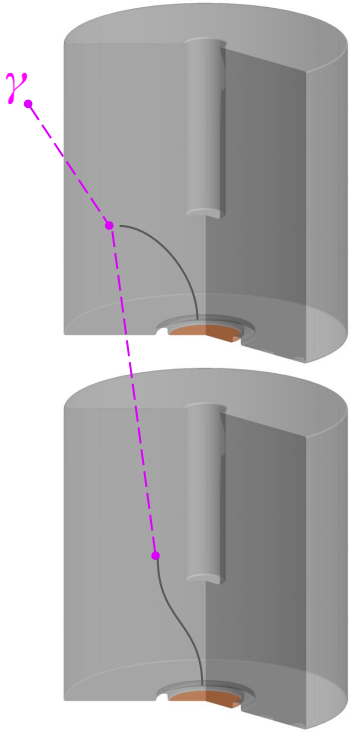
Pulse Shape Discrimination

- Multisite events
- Surface events



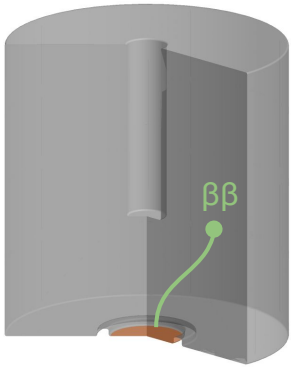
Anticoincidence

- Liquid Argon
- Water Cherenkov



Detector Multiplicity

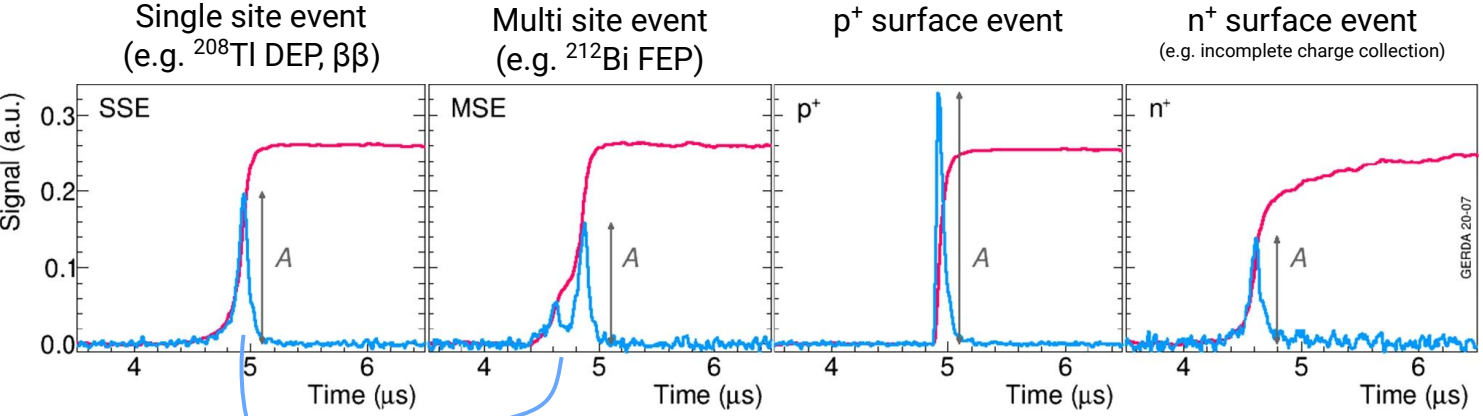
Signal

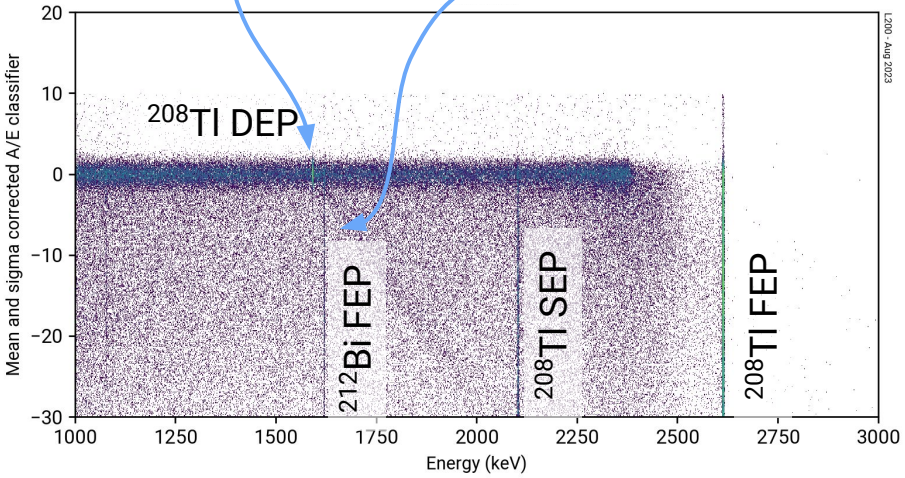


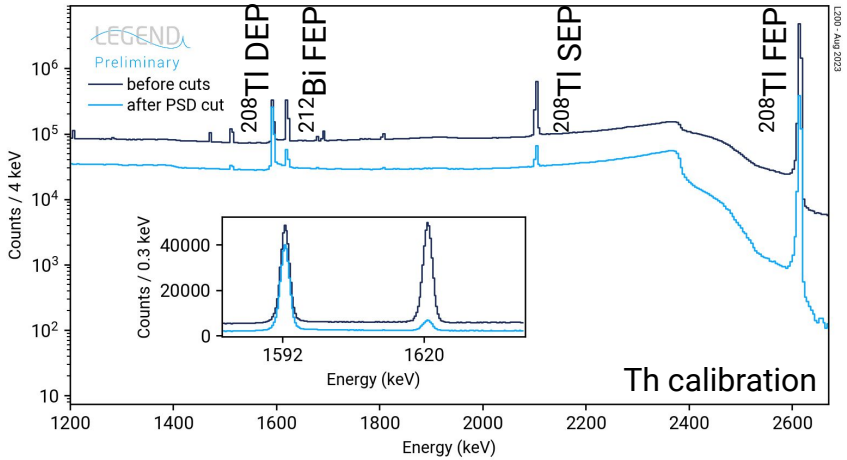
Single site event

- $2\nu\beta\beta$
- $0\nu\beta\beta$

PSD in Detail

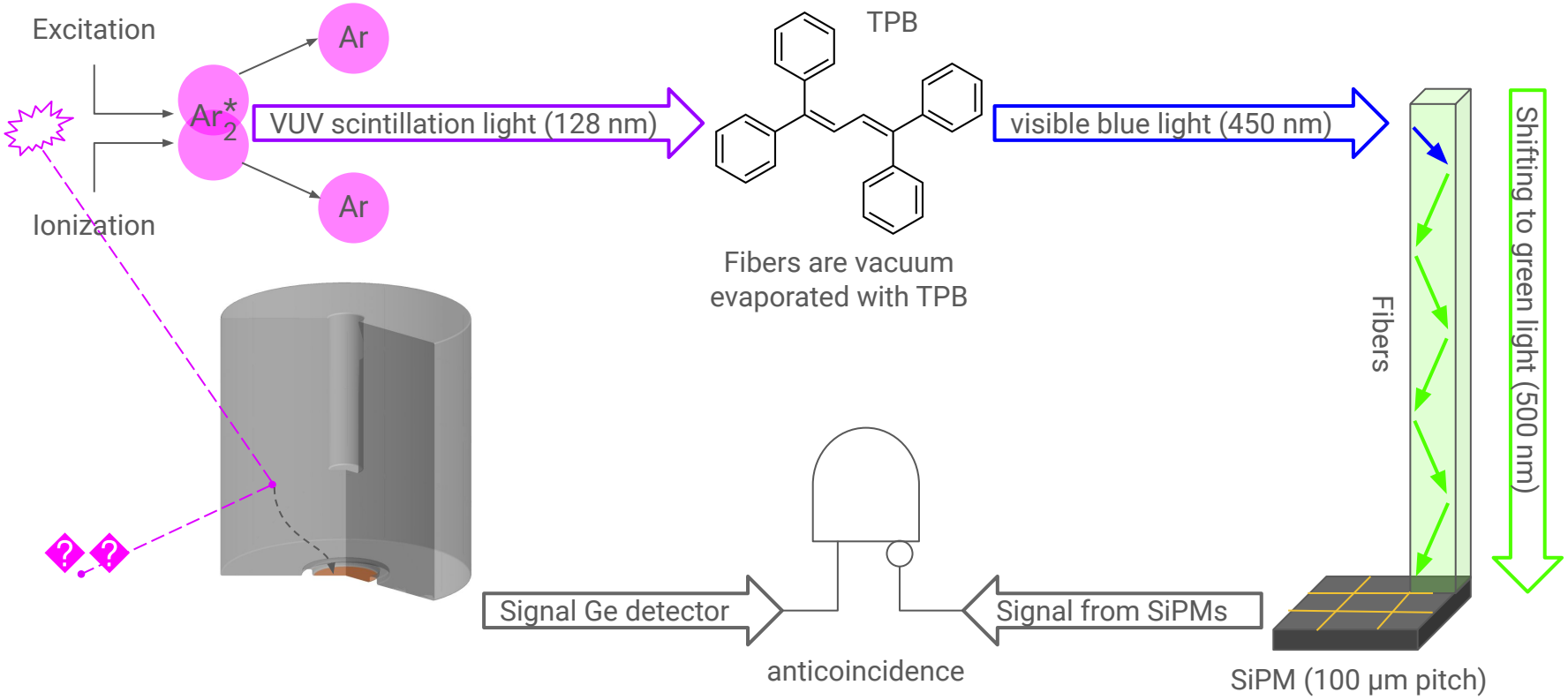




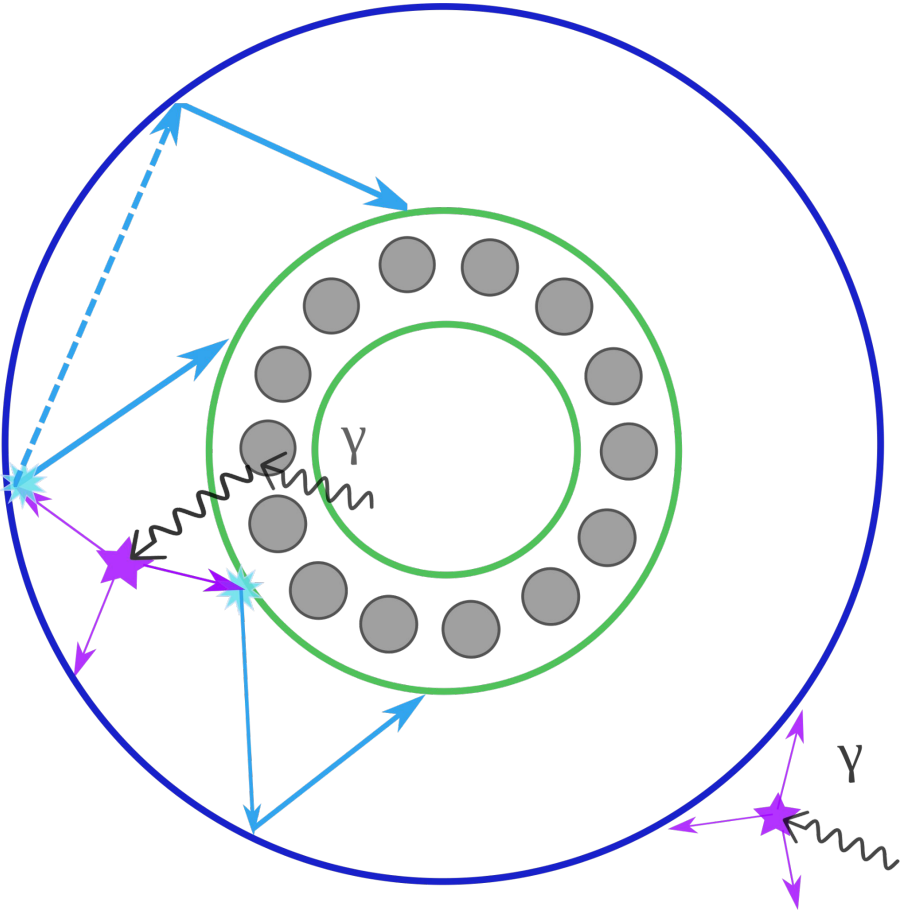


- Need to accept SSE (e.g. ββ)
- Reject the rest
- Optimize with calibration

LAr scintillation principle



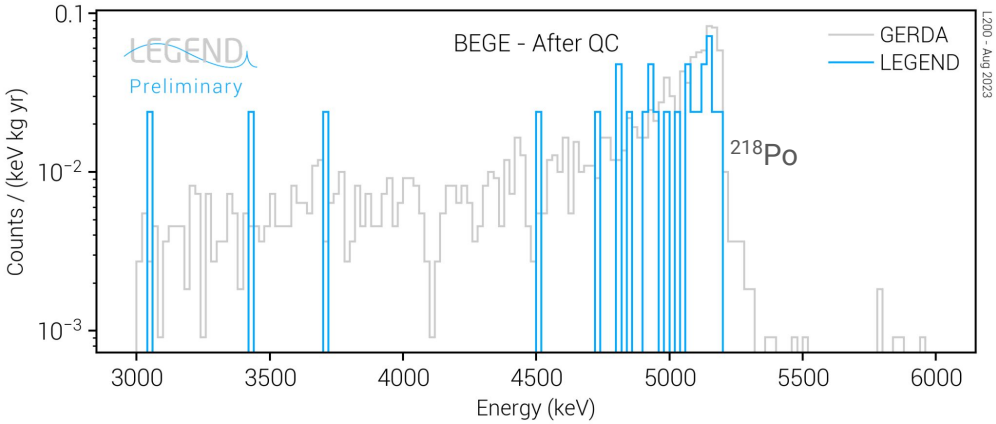
Wavelength Shifting Reflector

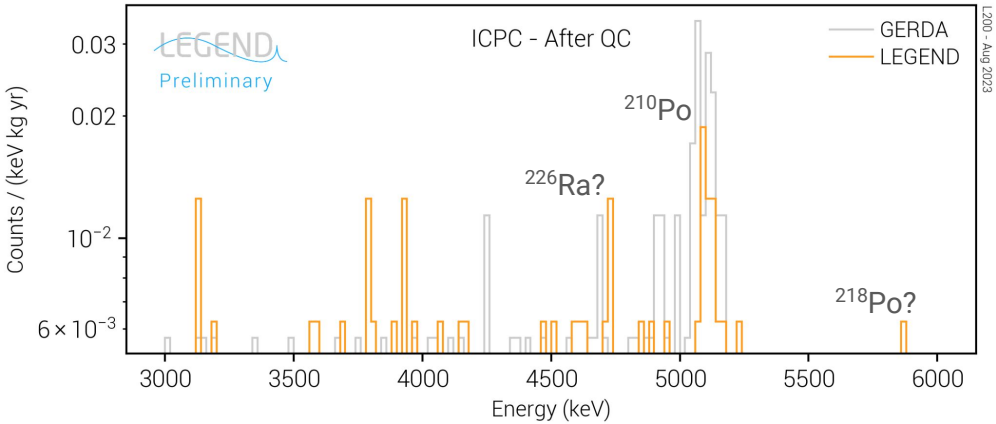


It restricts the LAr volume around the detectors.

Also shifts scintillation light to blue and reflects it back towards the LAr instrumentation

Alphas



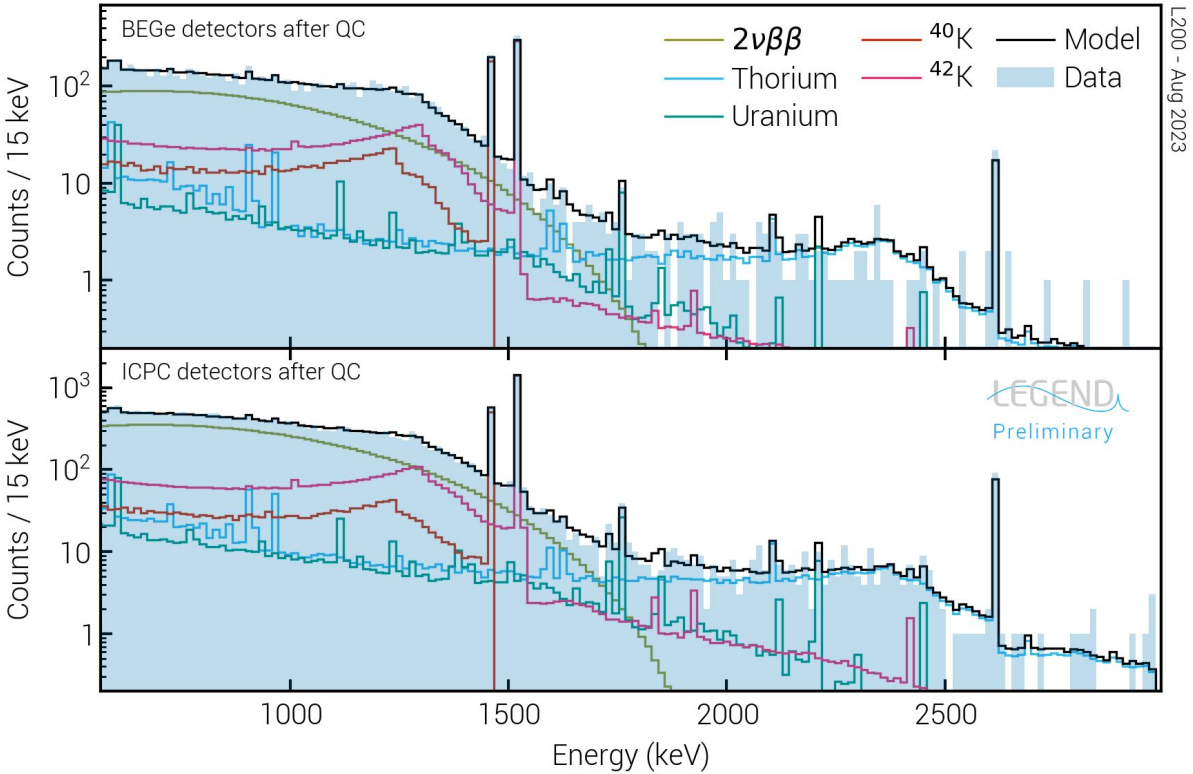


- High energy events are compatible with ^{210}Po
- Can not distinguish ^{210}Po ($T_{1/2}$~138d) from ^{210}Pb ($T_{1/2}$~22.3yr) supported ^{210}Po yet
- Weak evidence for ^{226}Ra and ^{222}Rn & ^{218}Po & ^{214}Po chain
- smaller contact surface to volume ratio → Less alphas/kg in ICPC
- Less alphas in LEGEND compared to GERDA → successful detector handling procedures

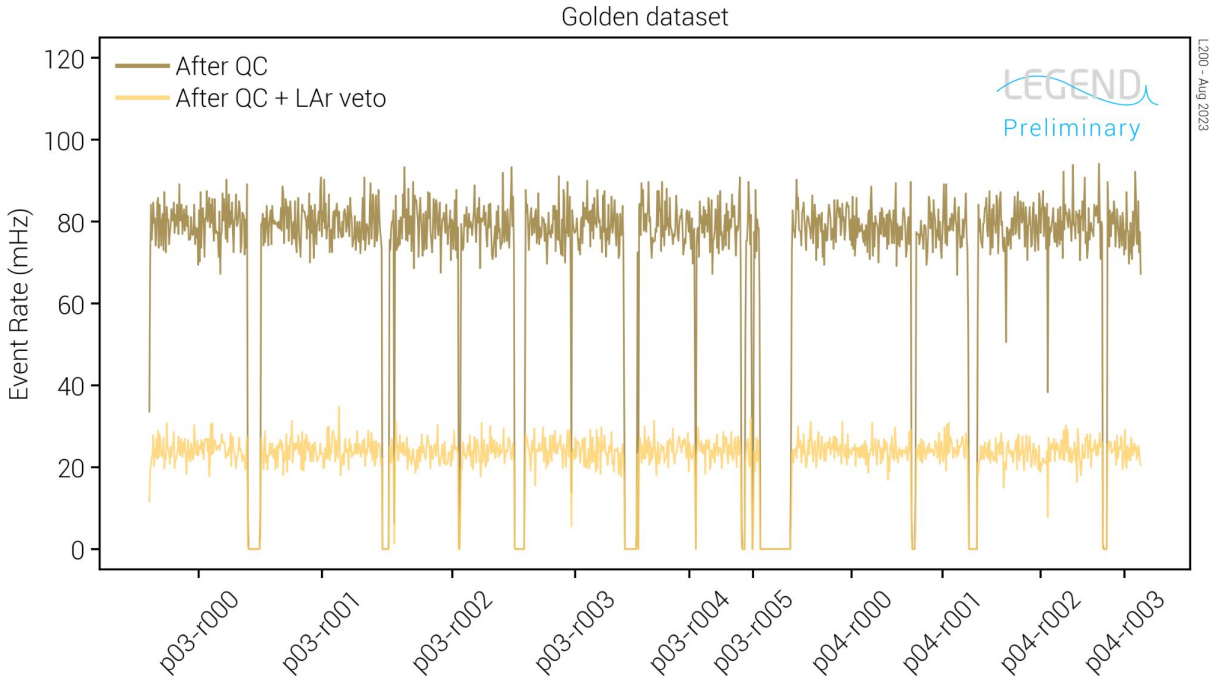
Background decomposition

[WIP]

Well described by expected contributions with current statistics



Event Rates



- Uniform germanium event rate
- No event “bursts”
- No evident “hot-spots” in the array