LEGEND and the Ge-76-based experimental program

Large Enriched
Germanium Experiment
for Neutrinoless ββ Decay

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LEGEND UK Open Workshop

Technical University of Munich

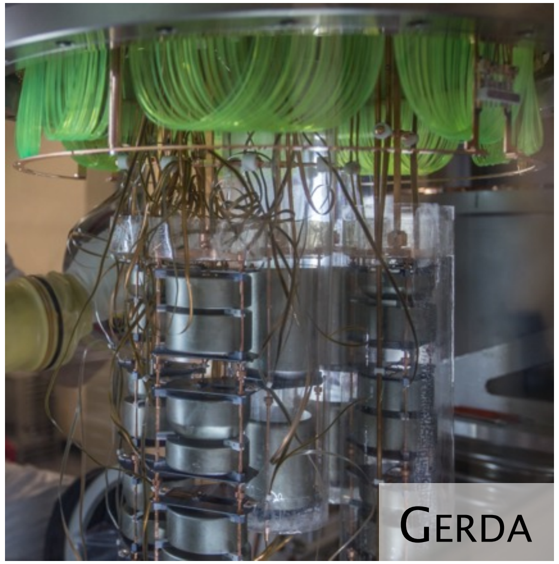
Outline

- LEGEND collaboration: history & goals
- The LEGEND project: staging and plans
- Why germanium
- Innovation towards LEGEND
- Liquid argon instrumentation
- LEGEND 200 commissioning

The LEGEND Collaboration

- The goal of the LEGEND Collaboration is to design, construct, and field LEGEND-1000, a ton-scale experiment
  - *“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, using existing resources as appropriate to expedite physics results.”*

- The LEGEND collaboration was formed in 2016 through a merger of the MAJORANA and GERDA collaborations, along with several new institutions
- It includes 266 members, 48 institutions, 11 countries



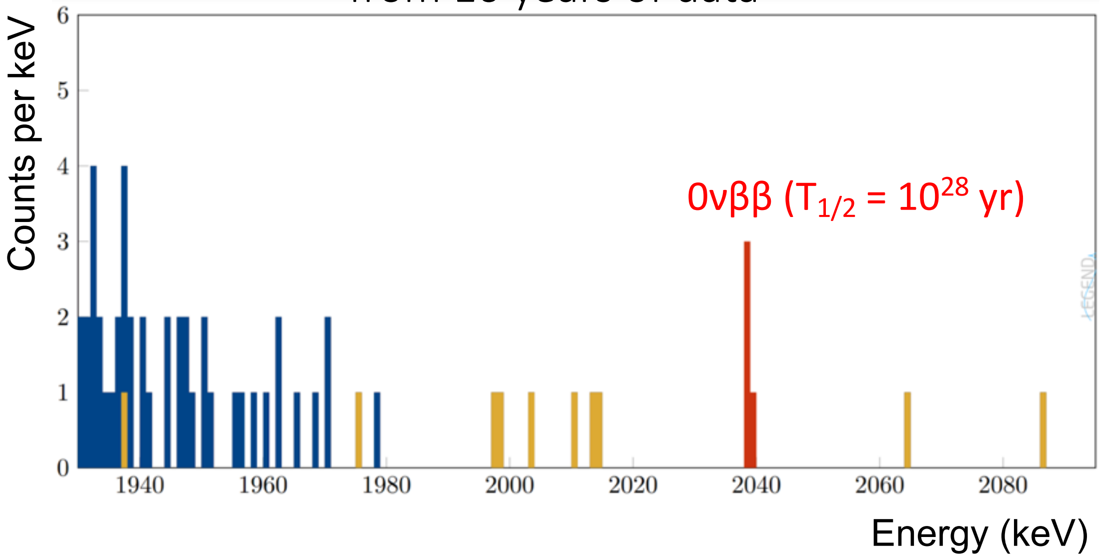
The LEGEND Collaboration

The LEGEND-1000 Discovery Sensitivity

"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..."

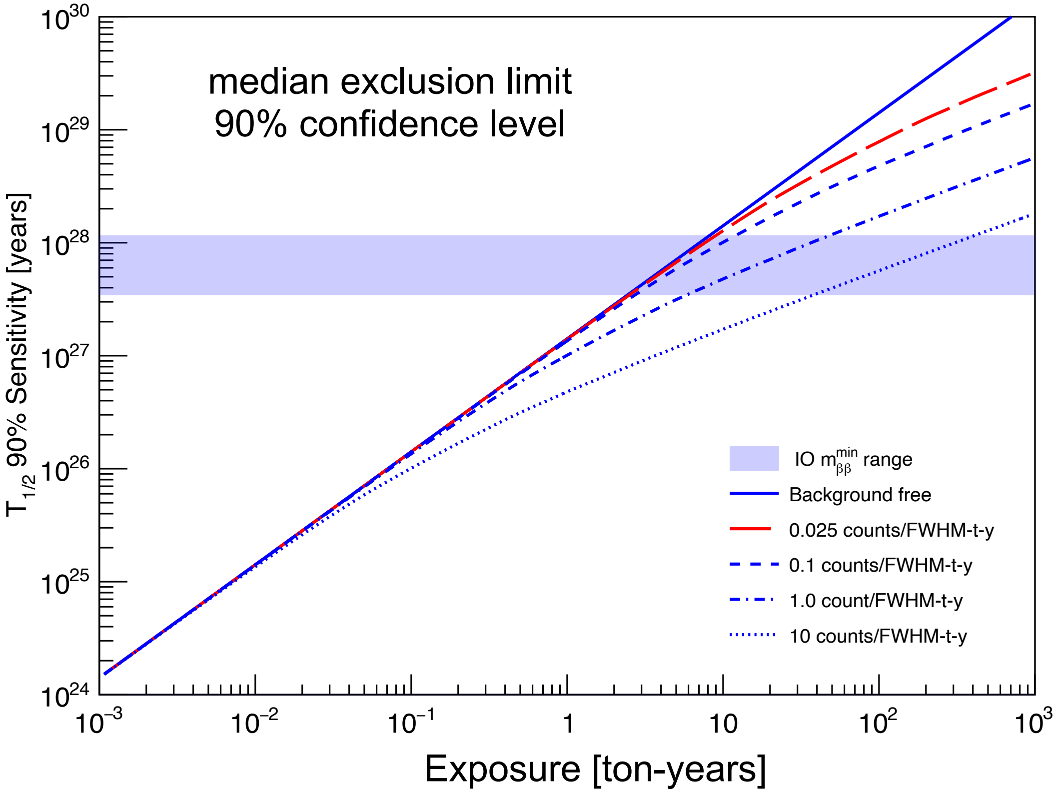
- What is required for a discovery of 0νββ decay at a half-life of 10^{28} years?
- This is less than one decay per year per ton of material
  - Need 10 ton-years of data to get a few counts
  - Need a good signal-to-background ratio to get statistical significance
    - A very low **background event rate**
    - The best possible **energy resolution**

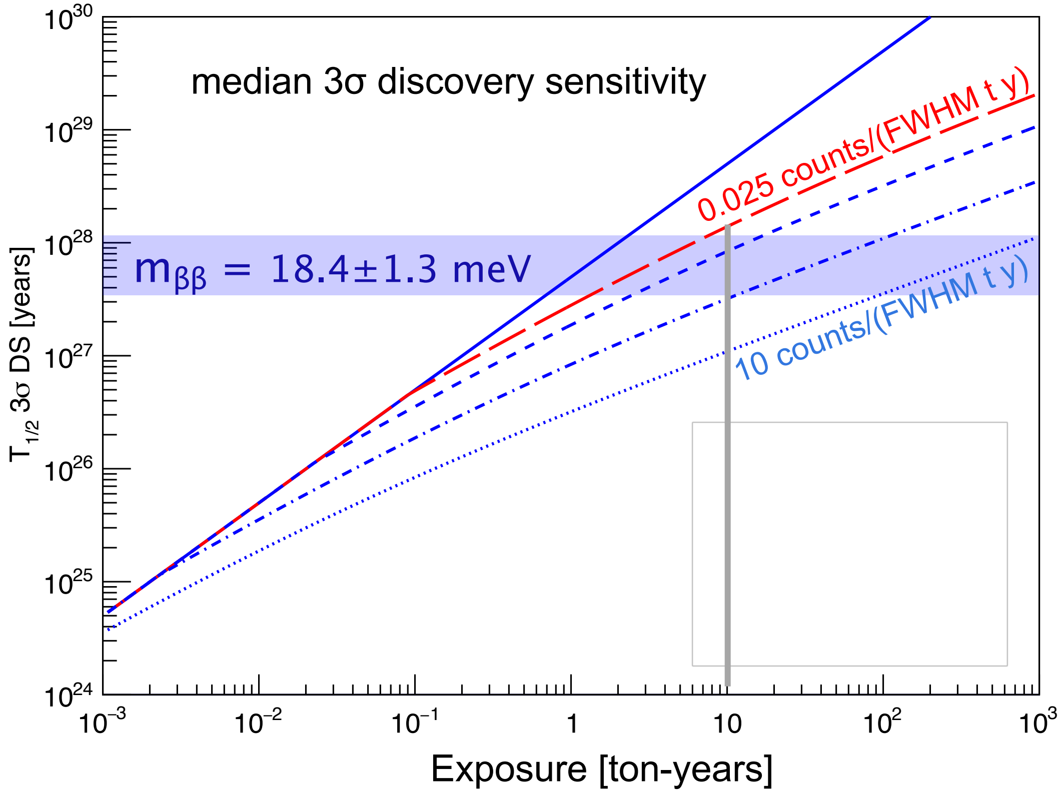
Simulated example spectrum, after cuts, from 10 years of data



The Effect of Background

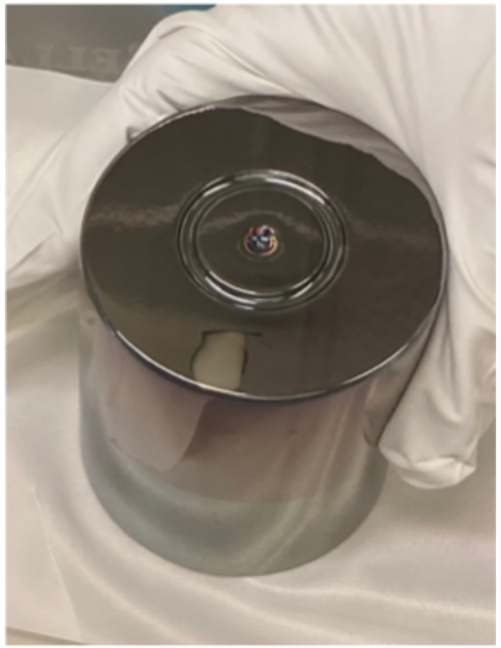
- Background-free: Sensitivity rises linearly with exposure
  Background-limited: Sensitivity rises as the square root of exposure
- Our background goal is the red line, 0.025 counts/(FWHM t y), “quasi-background-free”
  - *Less than one background count* expected in a 4σ Region of Interest (ROI) with 10 t y exposure
    (FWHM: Full Width at Half Maximum; 2.355 σ for a Gaussian peak)



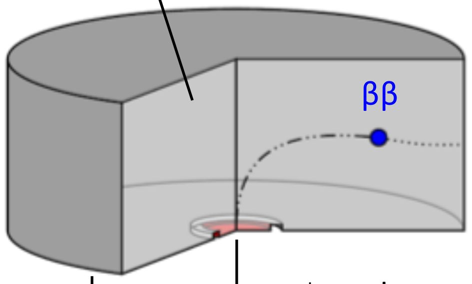


Why Germanium?

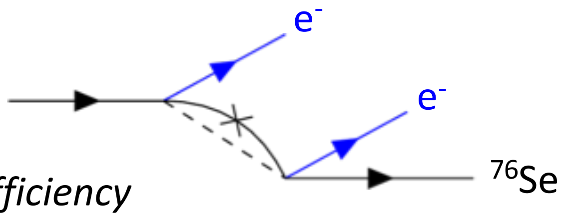
- Solid basis for unambiguous discovery
  - Superb energy resolution: $\sigma / Q_{\beta\beta} = 0.05$ %
  - Therefore, no background peaks anywhere near the energy of interest
  - Background is flat and well understood
  - Background will be measured, with no reliance on background modeling
  - All this leads to an excellent likelihood that an observed signal will be ***convincing***
- Low risk, high impact
  - Demonstrated performance of the entire technology chain
  - GERDA has produced the lowest background per FWHM of any experiment
  - MAJORANA has produced the best resolution
  - Requires no extrapolation from current detector performance
  - Proven track record, with history of leading limits
  - The team is experienced and ready to transition from LEGEND-200 construction to LEGEND-1000
  - A stable cost estimate, with appropriate contingency



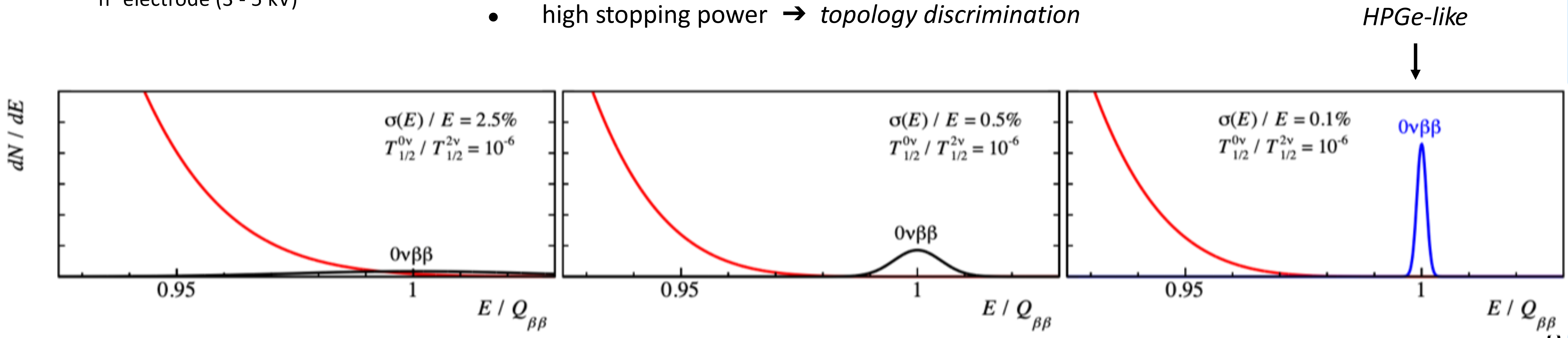
Experimental approach



HPGe detectors enriched in ^{76}Ge

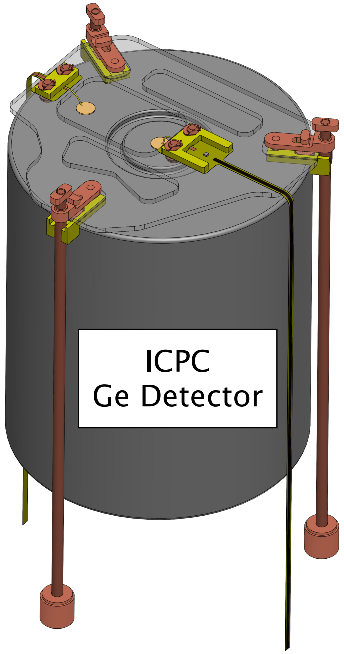


- source = detector ➔ *high efficiency*
- energy resolution **$\sigma(E)$ / E = 0.05%** at **$Q_{\beta\beta}$ = 2039 keV**
- **high-purity** material ➔ *no intrinsic background*
  [Astropart.Phys. 91 (2017) 15-21]
- high stopping power ➔ *topology discrimination*

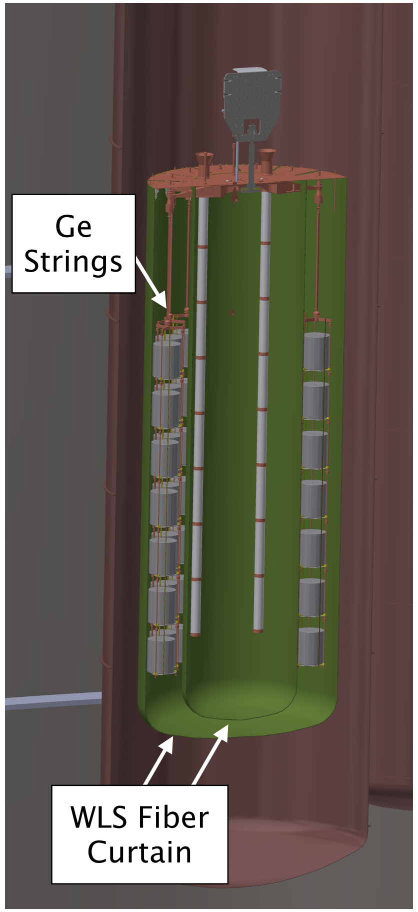


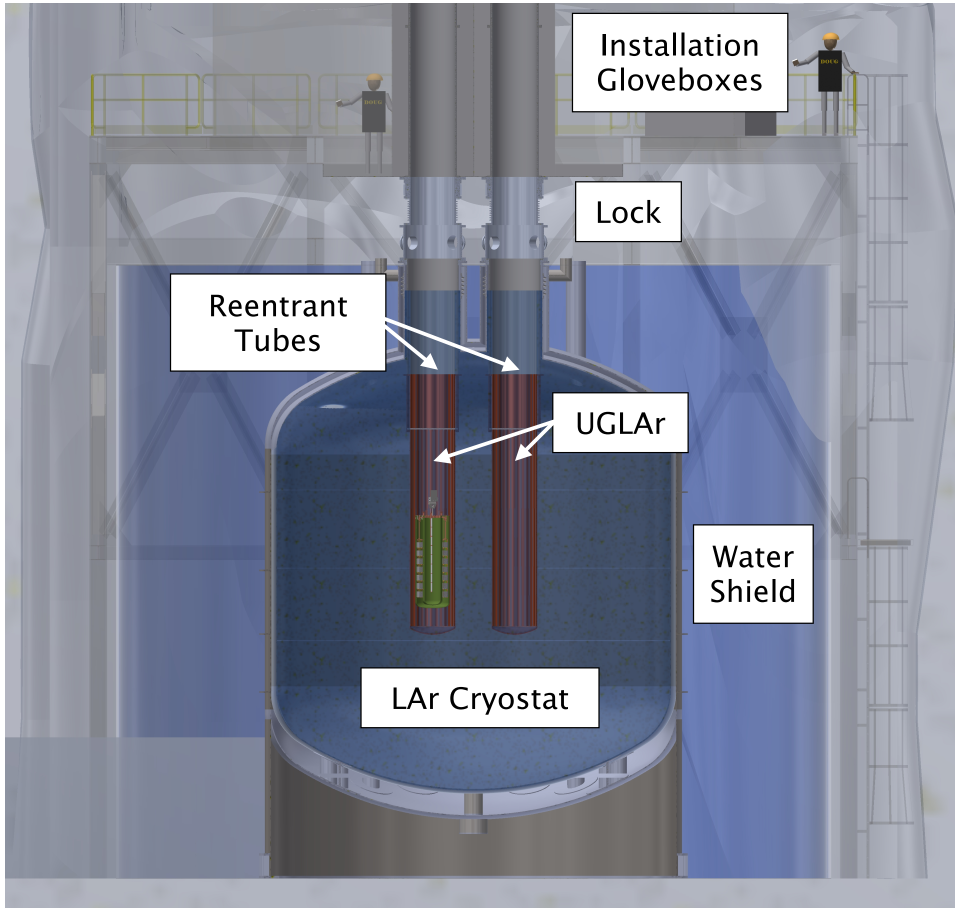
LEGEND-1000: A discovery experiment for $0\nu\beta\beta$ of ^{76}Ge

Quasi-background-free search for $0\nu\beta\beta$ decays of ^{76}Ge at $Q_{\beta\beta}$ = 2039.06 keV

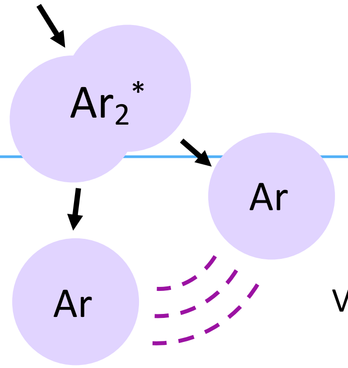


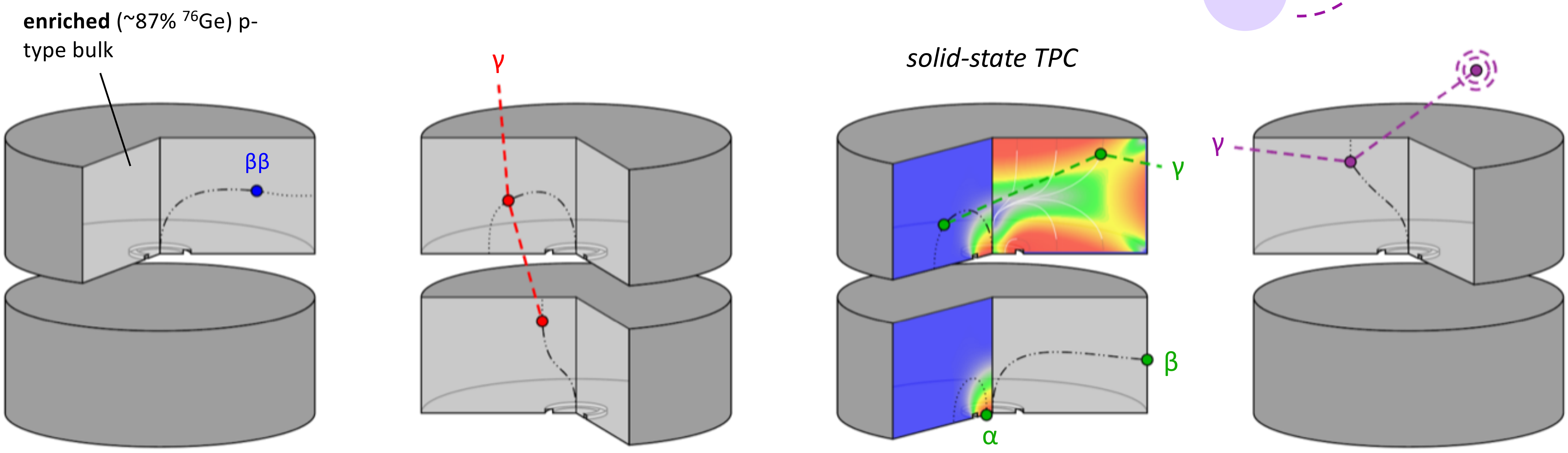
ICPC: Inverted-Coaxial Point Contact
WLS: Wavelength-shifting
UGLAr: Underground Liquid Ar





Topology discrimination





differentiate **point-like** *ββ* topology from:

multi-detector interactions

multi-site/surface interactions

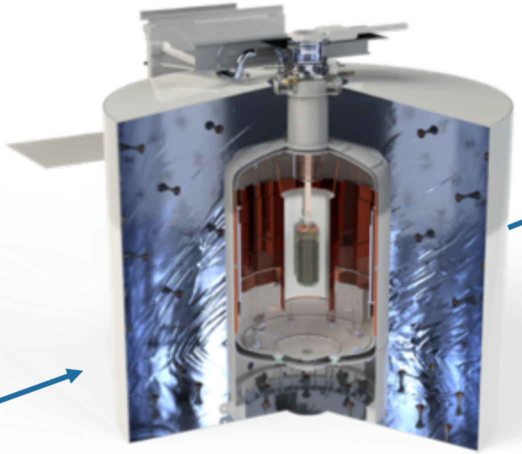
interactions with **partial energy depositions**

Innovation toward LEGEND-1000

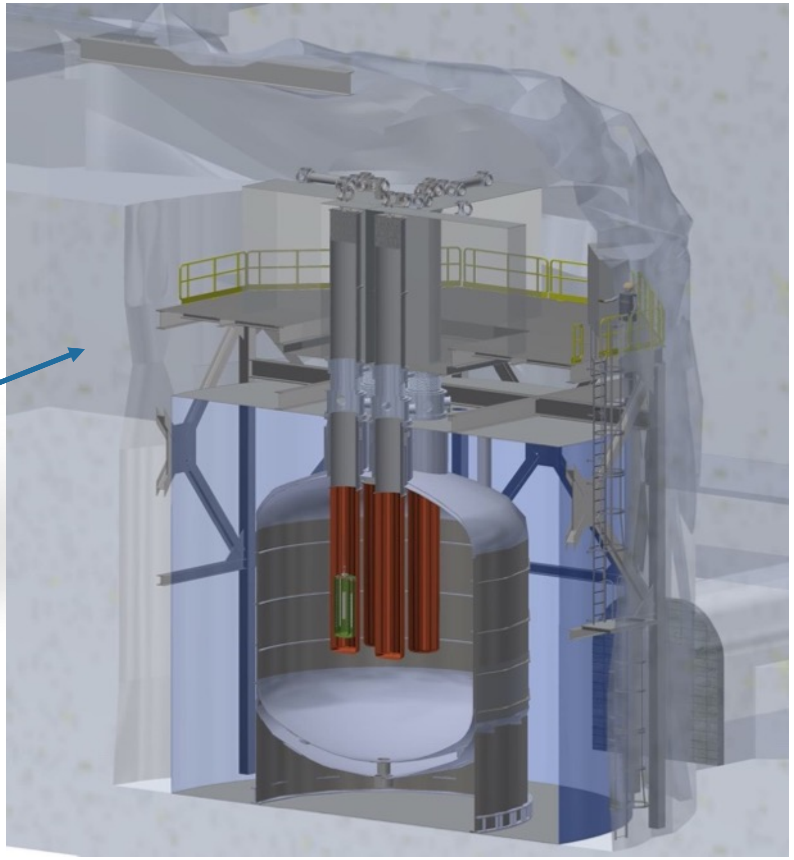
The LEGEND-1000 design builds on a track record of breakthrough developments

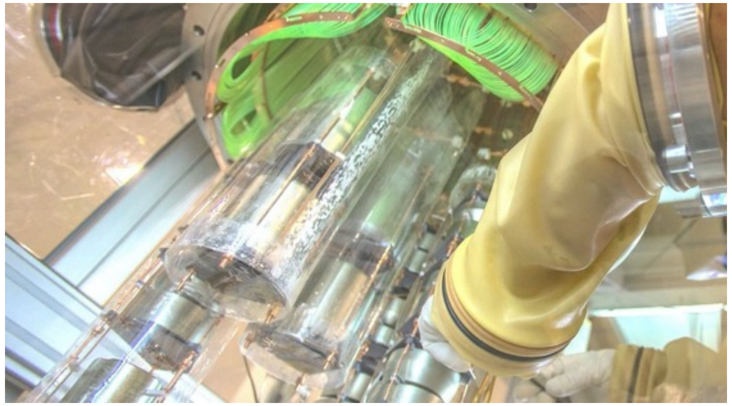
- GERDA : BEGe, LAr instrumentation, cryostat in water shield, fast detector deployment, …
- MAJORANA DEMONSTRATOR (MJD): PPC, EFCu, low-noise front-end electronics,…
- LEGEND-200 (commissioning 2021): Inverted-Coaxial Point Contact (ICPC) detectors, polyethylene naphthalate (PEN)…
- UK: Super-Nemo low-background techniques

LEGEND-200



LEGEND-1000





GERDA

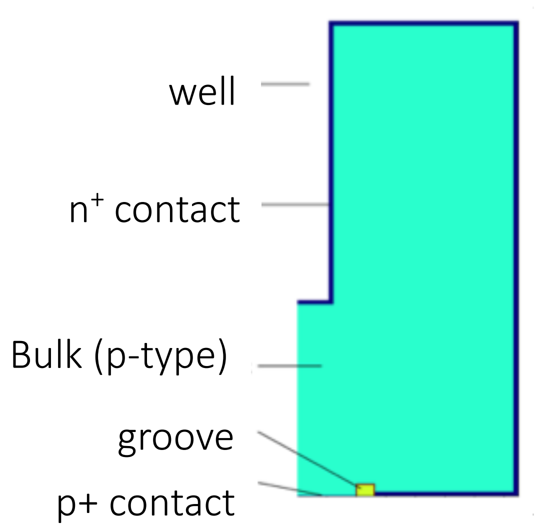
MJD

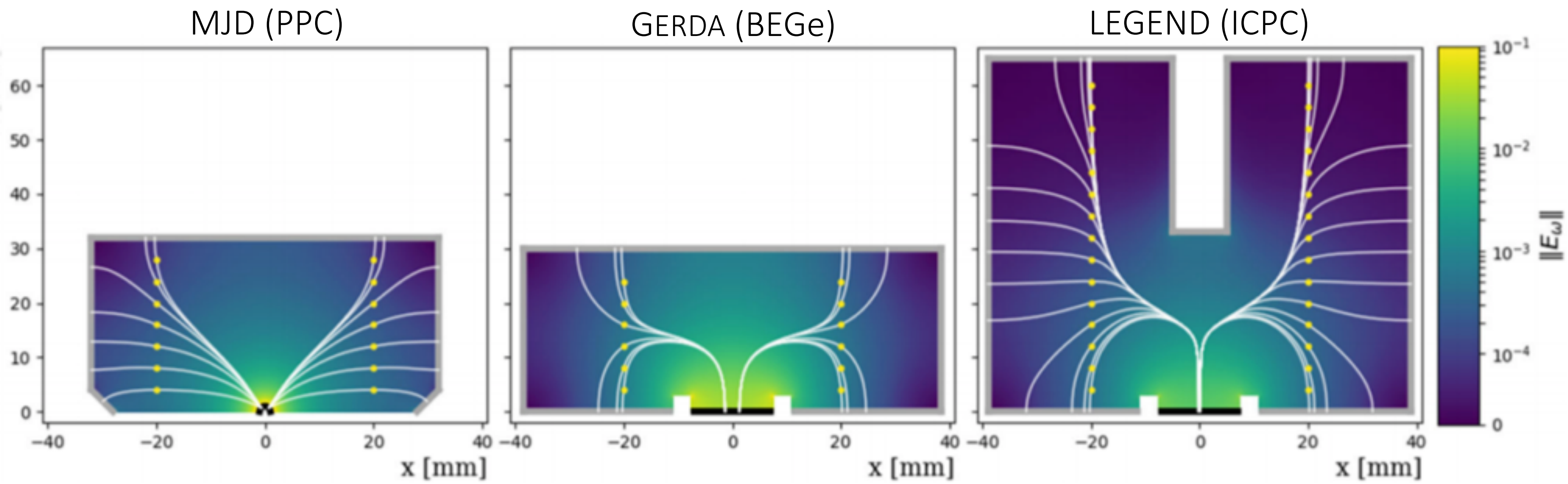
PPC: p-type Point Contact Ge detectors

BEGe: (modified) Broad Energy Ge detectors

EFCu: Electroformed copper

Innovation toward LEGEND-1000: ^{enr}Ge Detectors



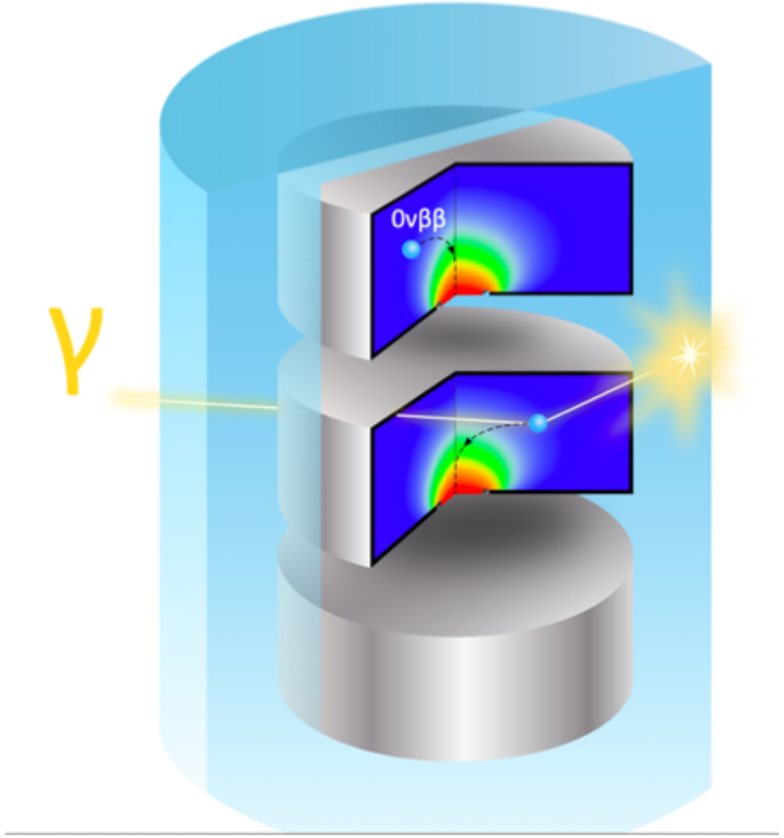


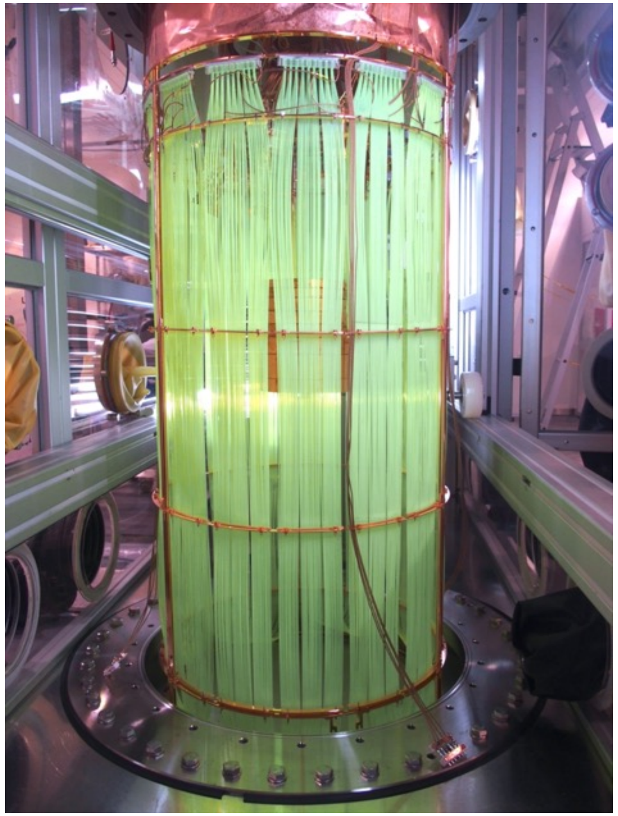
- P-type detectors: Insensitive to alphas on n$^+$ contact
- Small p$^+$ contact: Event topology discrimination
- Large-mass ICPC detectors: About 4 times lower backgrounds with respect to BEGe/PPC
- Proven long-term stable operation in liquid argon

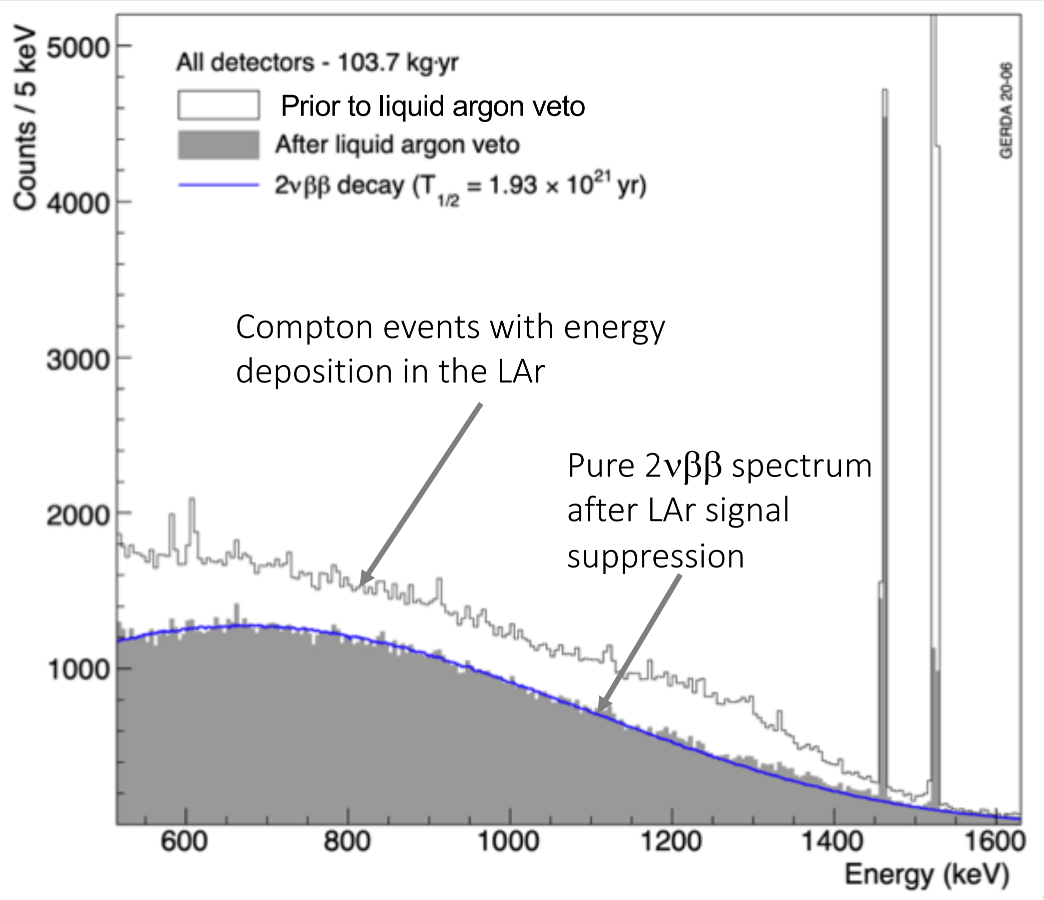
Innovation toward LEGEND-1000: LAr Instrumentation

GERDA: Detection of liquid argon scintillation light

Low-background wavelength-shifting fibers and SiPM arrays for 128 nm single photon detection

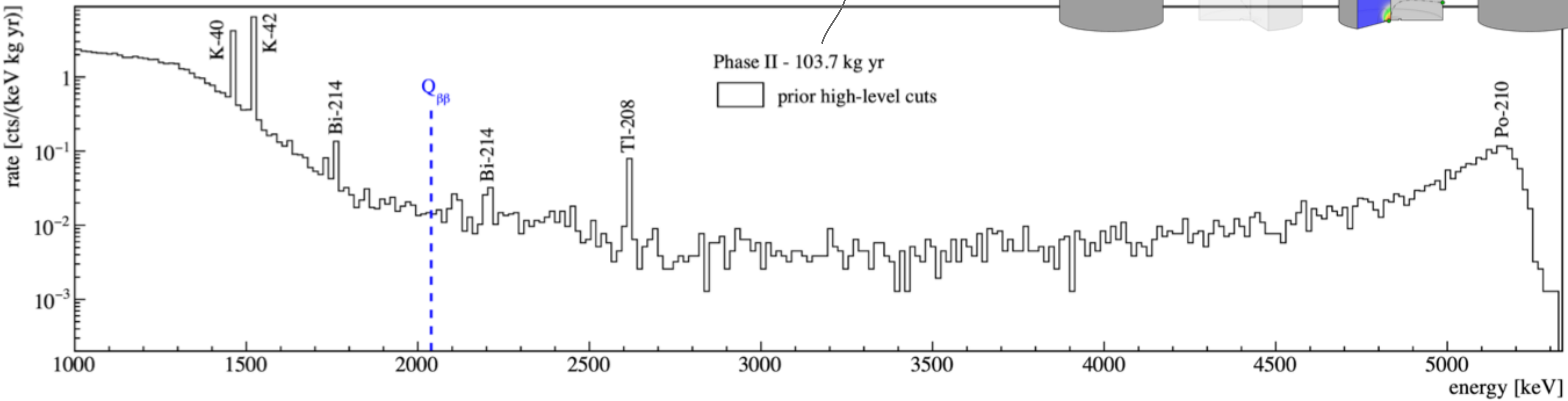


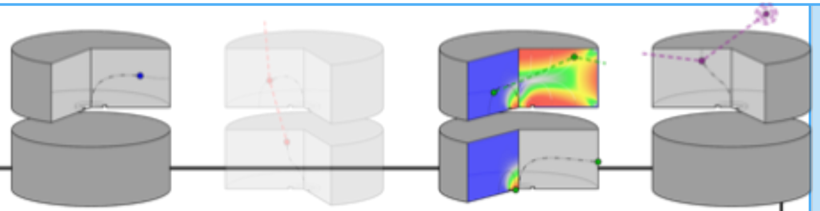




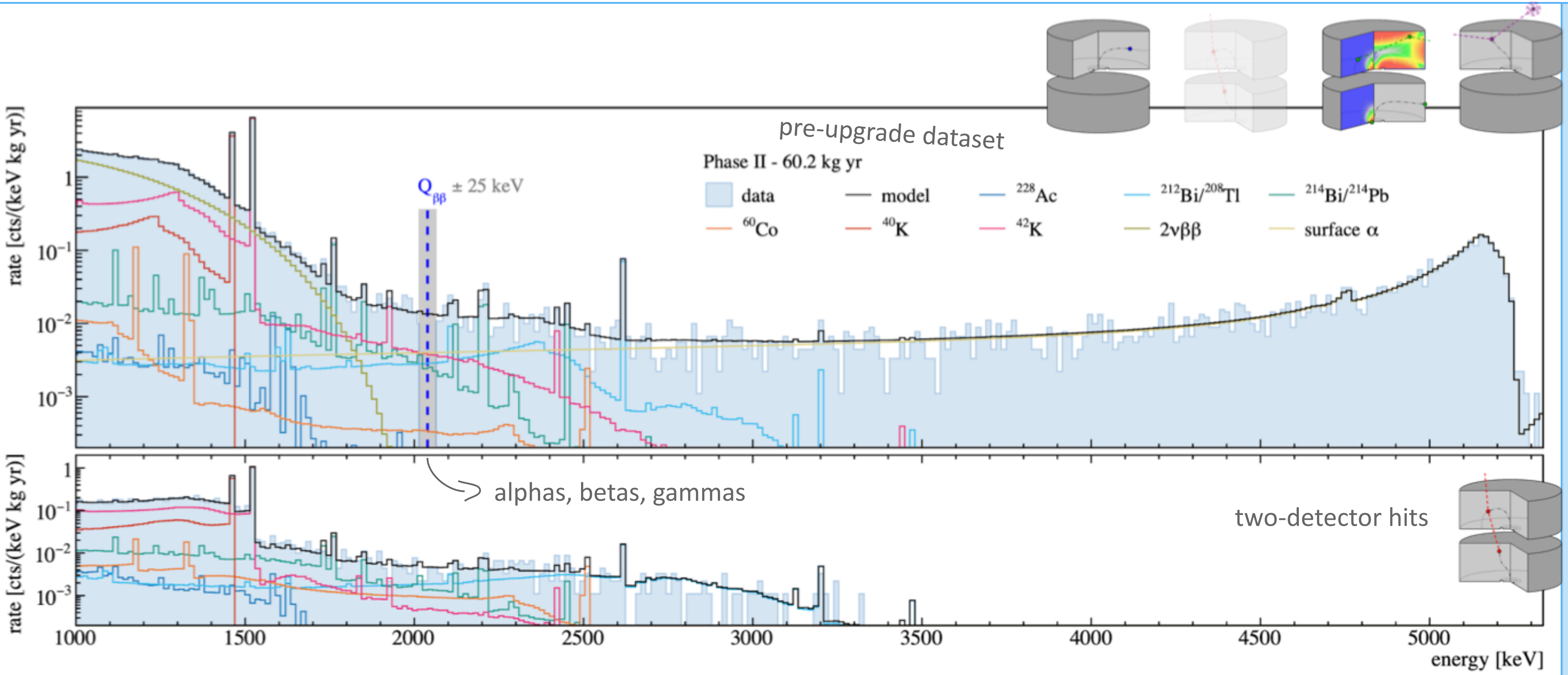
Background spectrum before analysis cut

largest exposure
^{76}Ge spectrum ever taken





Background decomposition before analysis cuts

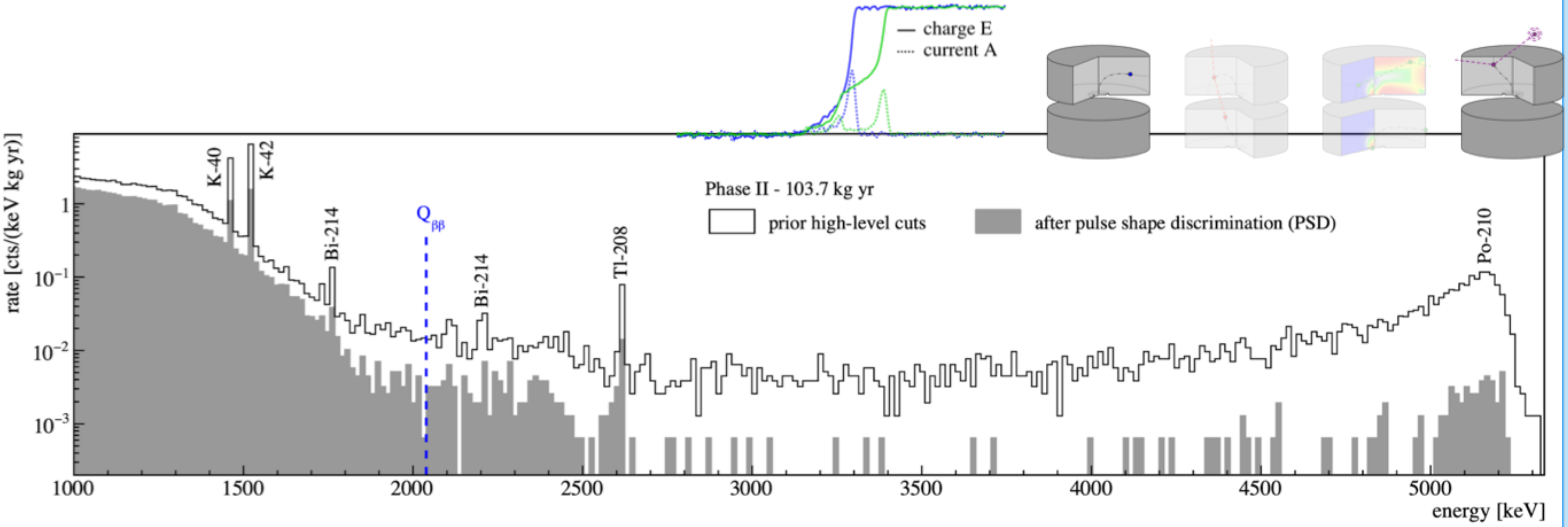


- combined Bayesian fit to multiple datasets with Monte Carlo *pdf*s for **nearby components**

[JHEP 03 (2020) 139]

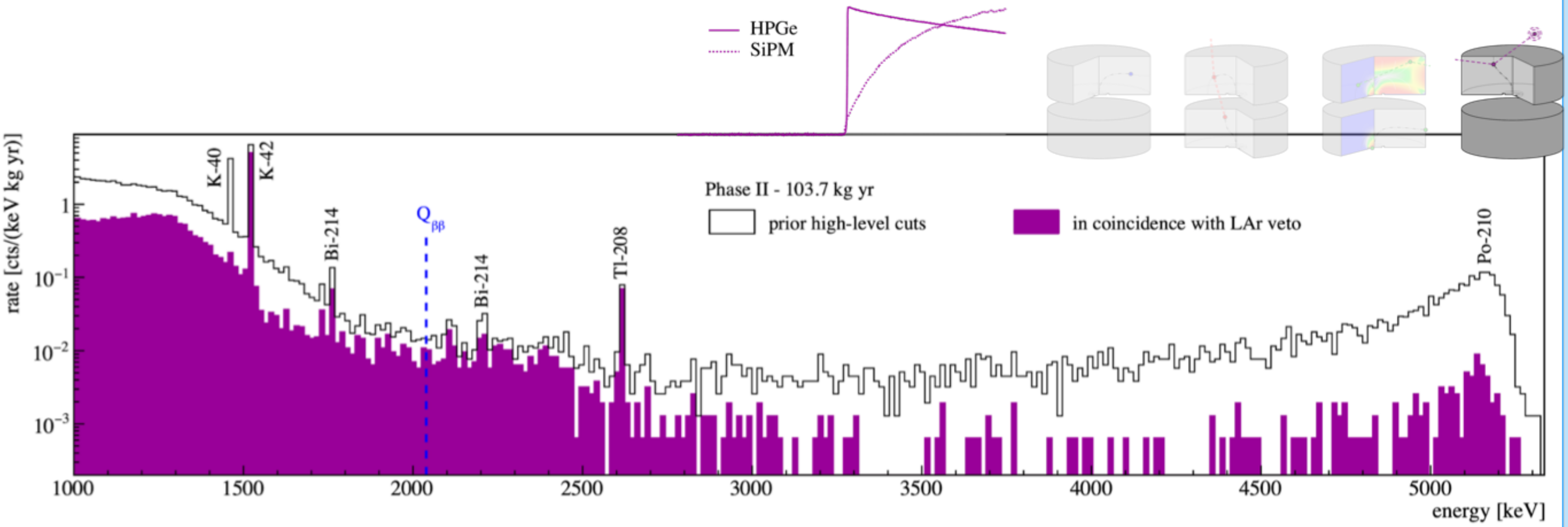
screening measurements as priors

Pulse shape discrimination



- two-sided **mono-parametric** A/E cut for **BEGe / ICPC** detectors
  [Budjas et al., JINST 4 (2009) P10007]
- artificial neural network analysis plus consecutive risetime cut for coaxial detectors
  [Eur. Phys. J. C73 (2013) 2583]
- cut definition / training with ^{228}Th **calibration data** -> ^{208}Tl DEP as signal proxy
- 0νββ signal efficiency **~90%** (~70% for coaxials)

Liquid argon read-out

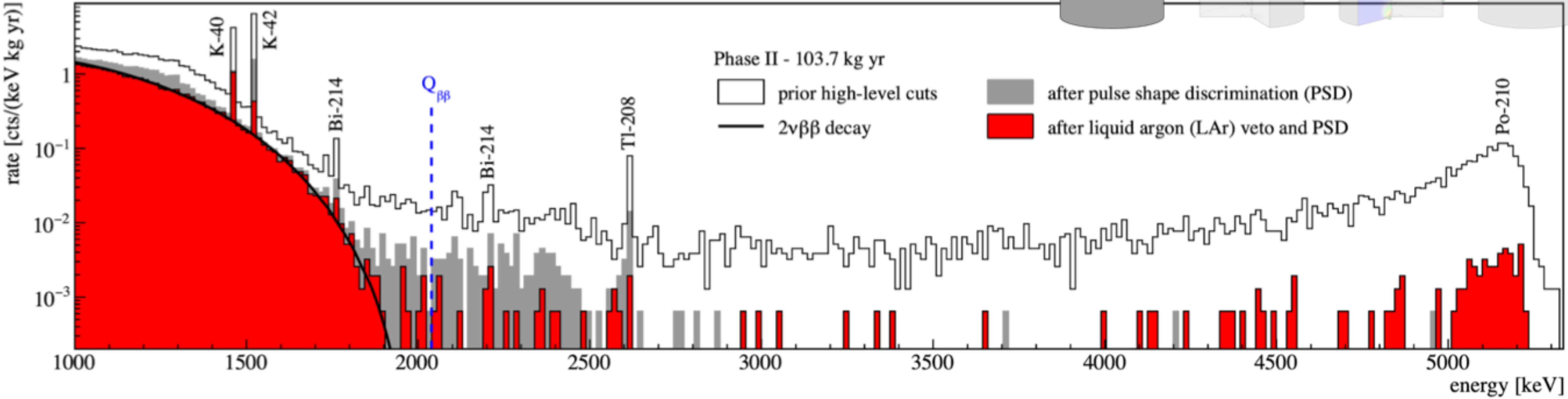


- channel-wise **(anti-)coincidence condition** (PMTs/SiPMs)
- **sub-PE threshold**, contains characteristic scintillation **timing** (triplet emission)
- 0νββ signal efficiency (1 - random coincidence rate) **> 97%**

lifetime ~1 μs

^{39}Ar, dark rate

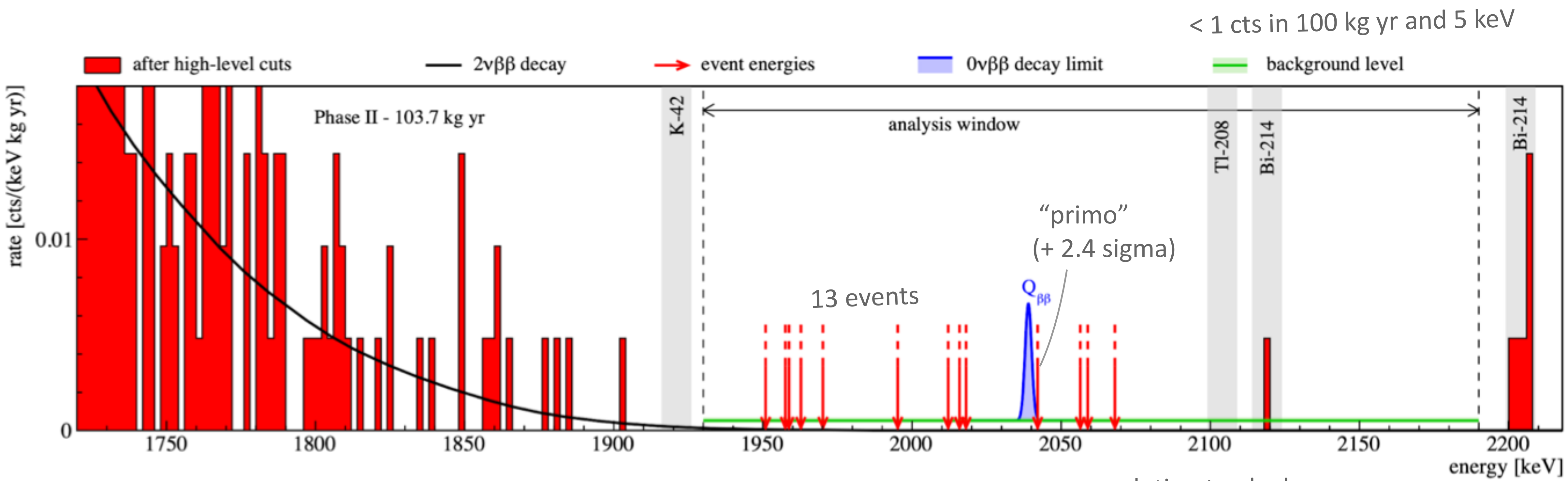
Final Phase II spectrum



- “clean” **2νββ continuum** shape analysis in preparation
- sparse **single counts at > $Q_{\beta\beta}$**

no alphas in BEGe / ICPC

Final GERDA result



resolution tracked per detector/period

- background index **$5.2^{+1.6}_{-1.3} \cdot 10^{-4}$ cts/(keV kg yr)**, energy resolution **~3 keV** (FWHM)
- combined (data partitions, Phase I) **unbinned maximum likelihood fit**
  [Nature 544 (2017) 47]

Gaussian signal on flat background

- **Frequentist**: $N^{0\nu}$ = 0 best fit, ***$T_{1/2}$* > $1.8 \cdot 10^{26}$ yr** (median sensitivity -"-) at 90% C.L.,
  Bayesian: flat prior on rate, $T_{1/2} > 1.4 \cdot 10^{26}$ yr at 90% C.I.

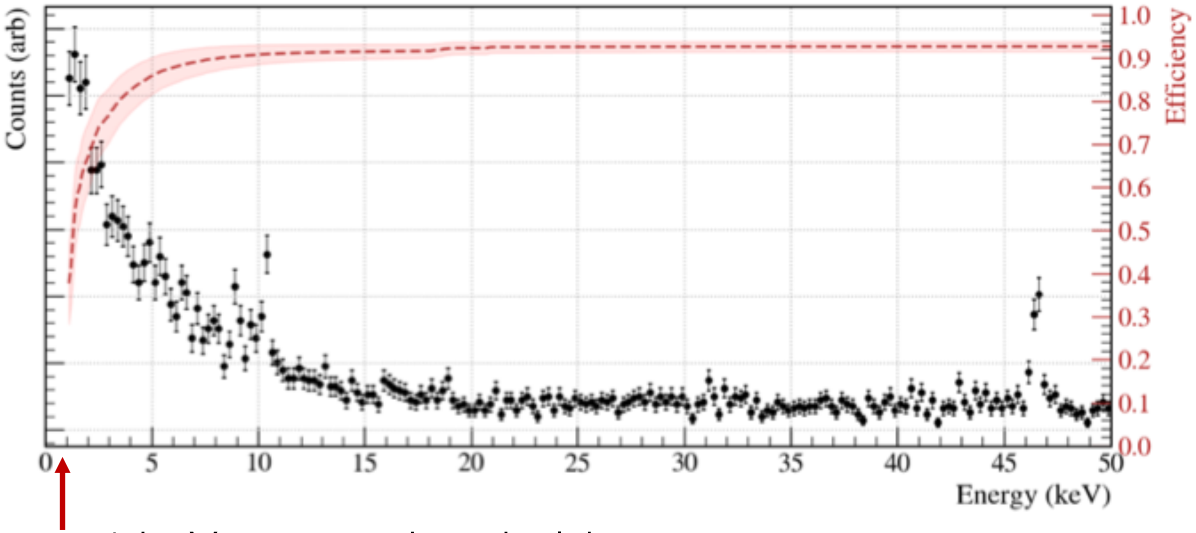
> $2.3 \cdot 10^{26}$ yr for flat prior on m_{bb}

GERDA

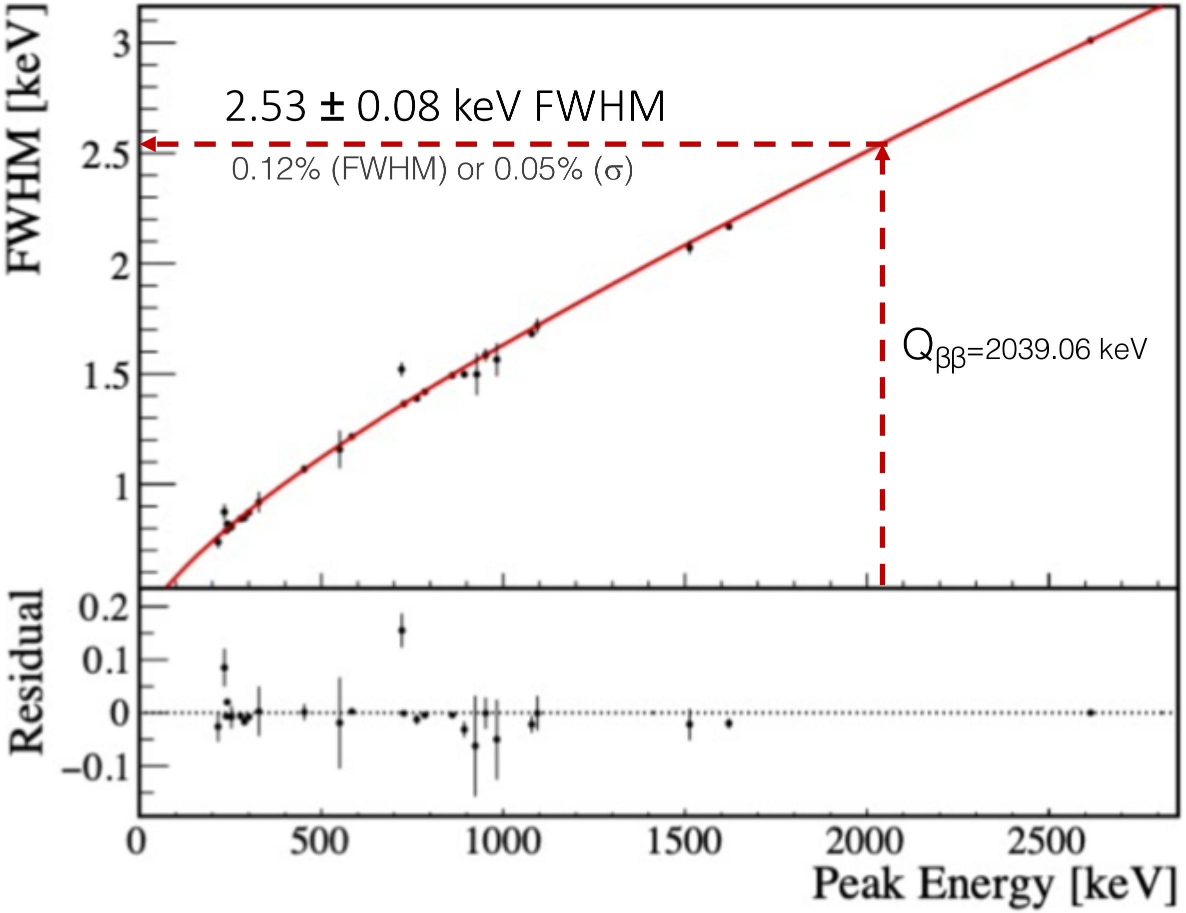
Innovation toward LEGEND-1000: Electronics & Materials

MJD: Low noise front-end electronics required for

- excellent energy resolution
- optimal pulse shape analysis
- low-energy threshold



~1 keV energy threshold



MJD: APS April Meeting D19.00007 (2021)

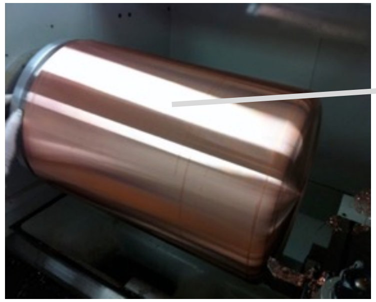
Innovation toward LEGEND-1000: Electronics & Materials

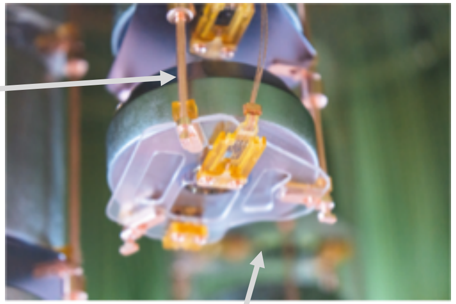
- **Minimize** materials close to Ge detectors and use of **highest purities**:
  - Underground electroformed copper (EFCu) reduces U, Th, and cosmogenic activation

    $< 0.017 \pm 0.03$ pg/g ^{238}U

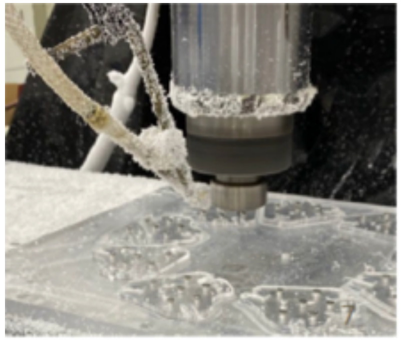
    $< 0.011 \pm 0.05$ pg/g ^{232}Th
  - Copper-Kapton laminated cables
- **Optically active** structural materials:
  - Polyethylene naphthalate (PEN) shifts 128 nm LAr scintillation light to ~440 nm and scintillates
  - Yield strength higher than copper at cryogenic temperatures

EFCu for holders and reentrant tube

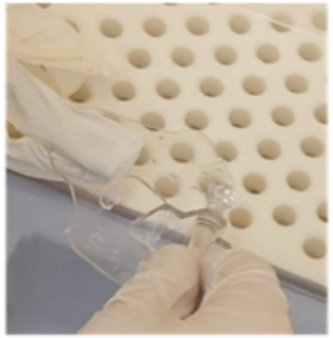




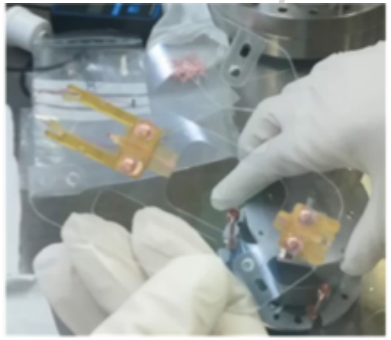
PEN: scintillating (self-vetoing) high-purity detector support



Machining



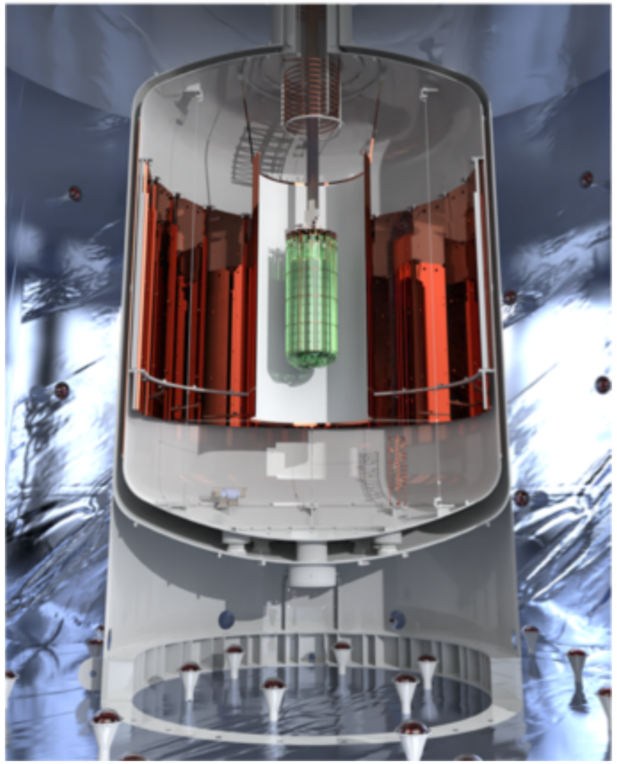
Cleaning

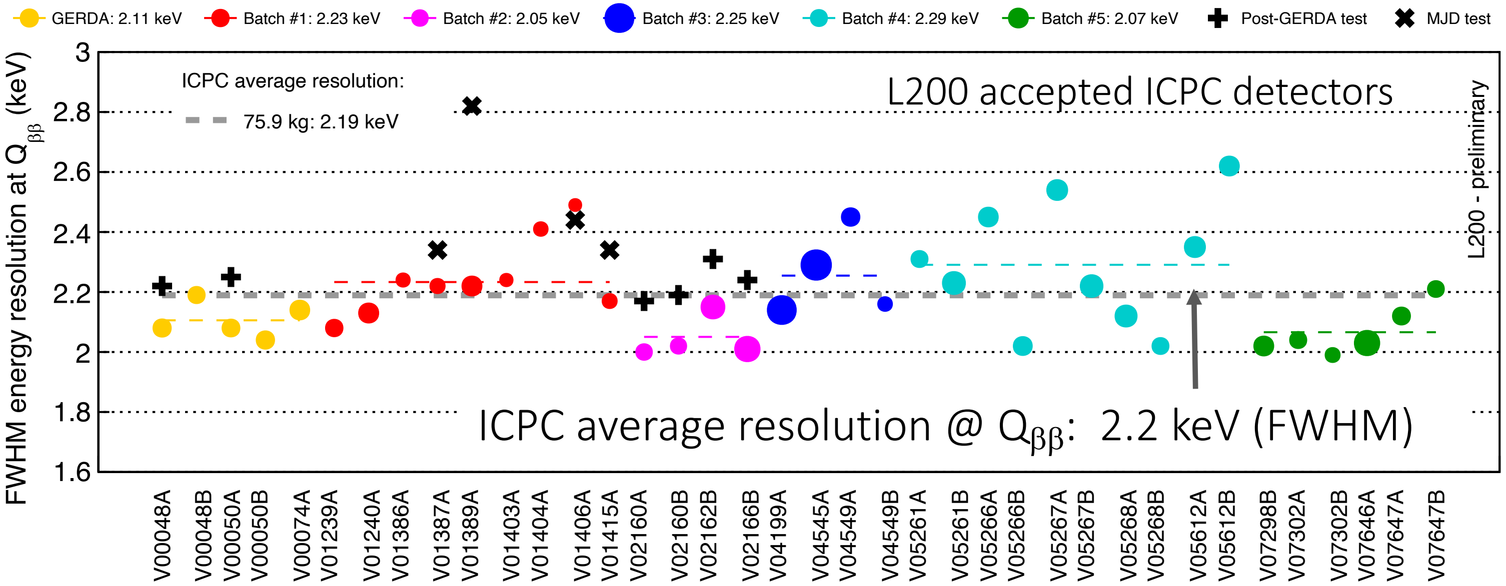


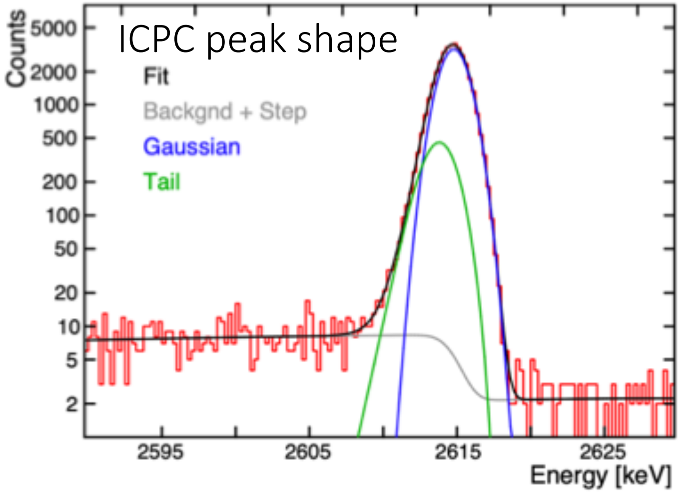
PEN plate

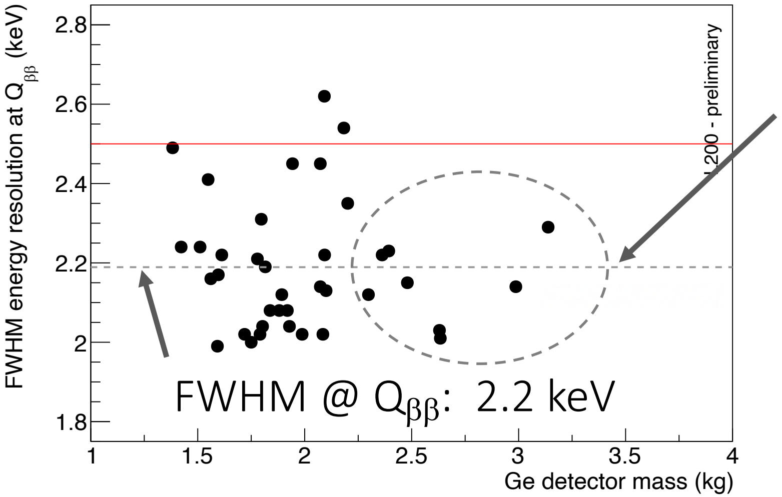
Innovation toward LEGEND-1000: LEGEND-200

- Procurement of ^{76}Ge (92% enr.)
- Novel ICPC detectors
- Improved LAr system
- Low-background materials
- Commissioning 2021



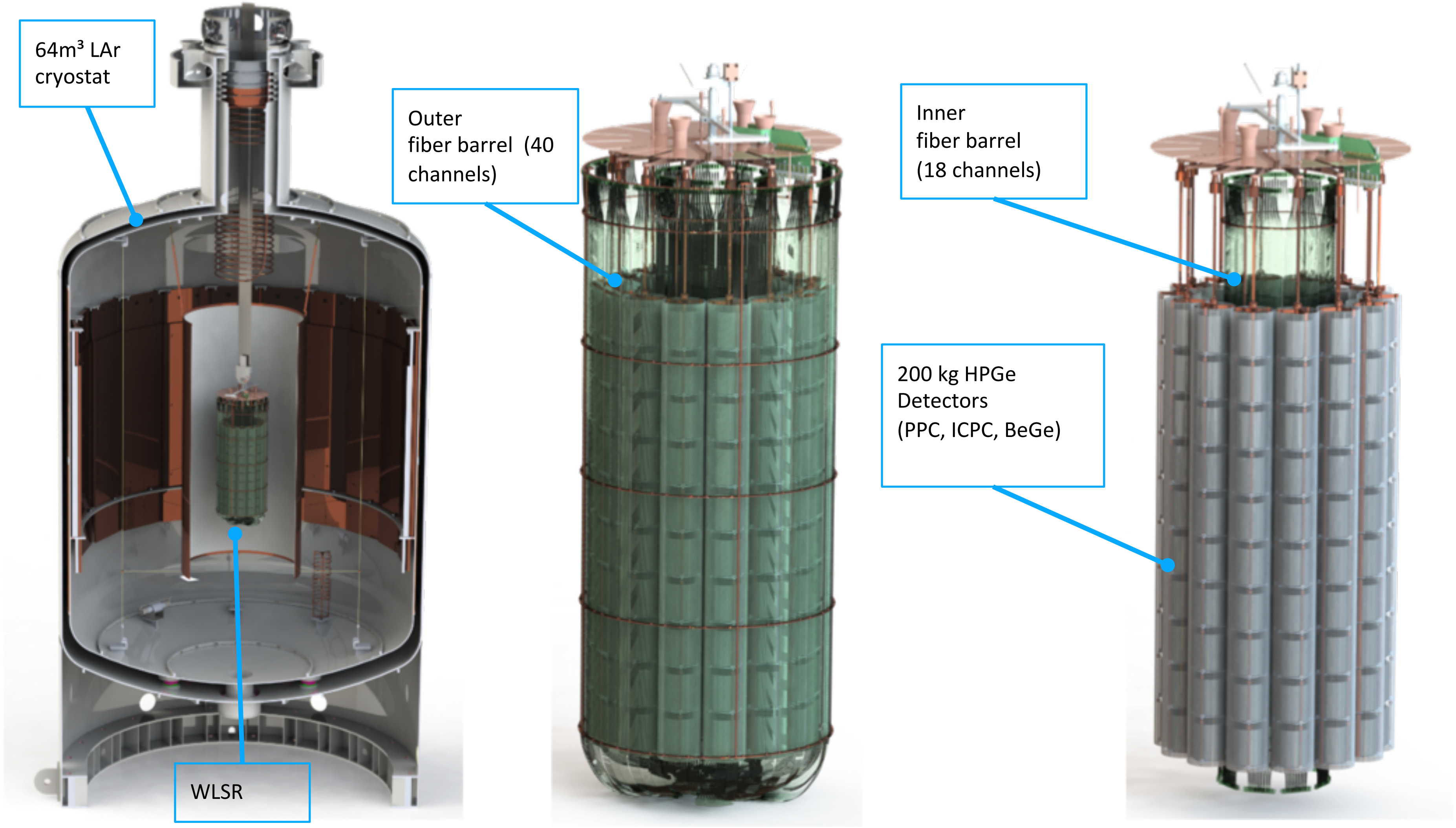




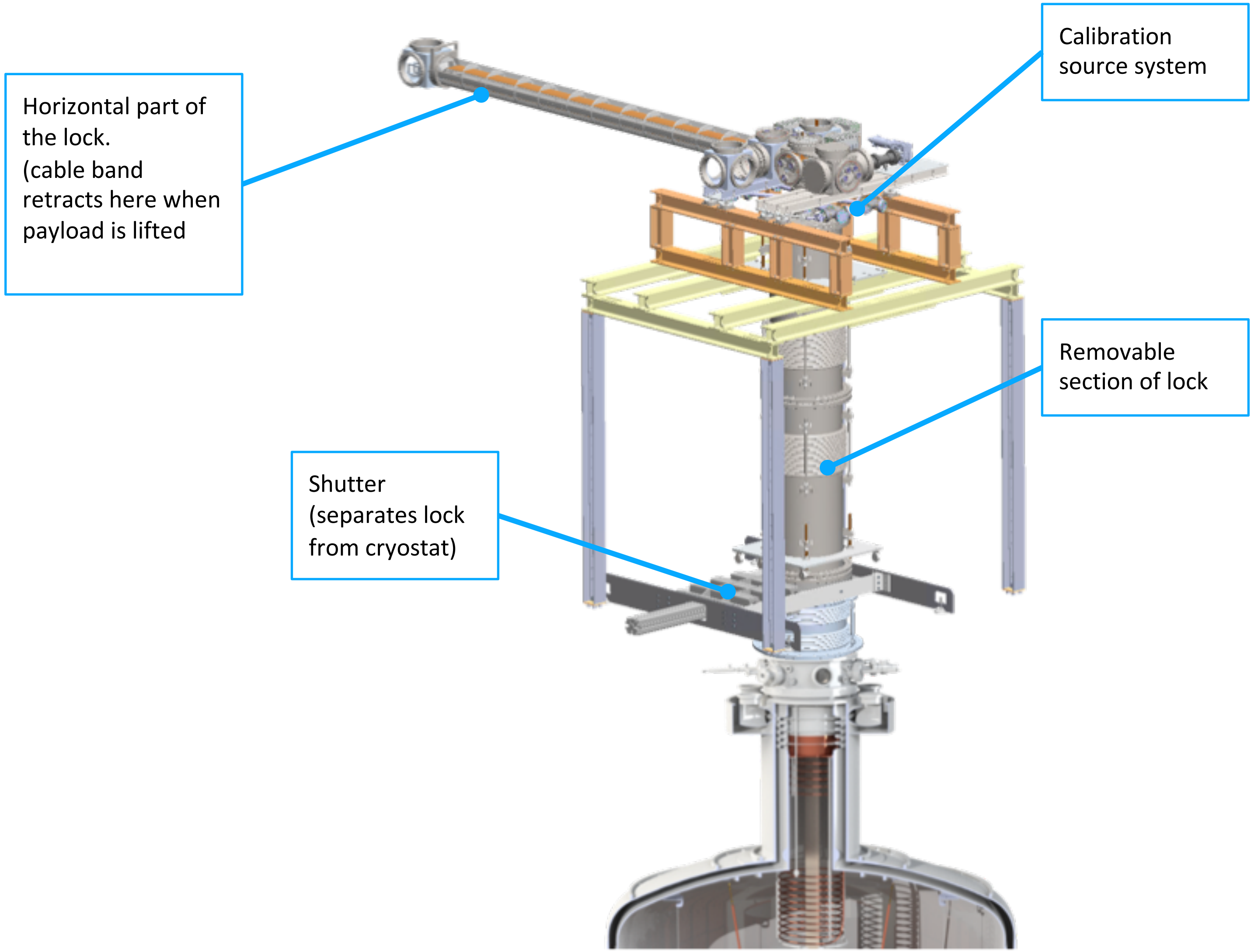


Large mass detectors show excellent energy resolution

LEGEND-200


64m³ LAr cryostat
WLSR
Outer fiber barrel (40 channels)
Inner fiber barrel (18 channels)
200 kg HPGe Detectors (PPC, ICPC, BeGe)

LEGEND-200: Lock System

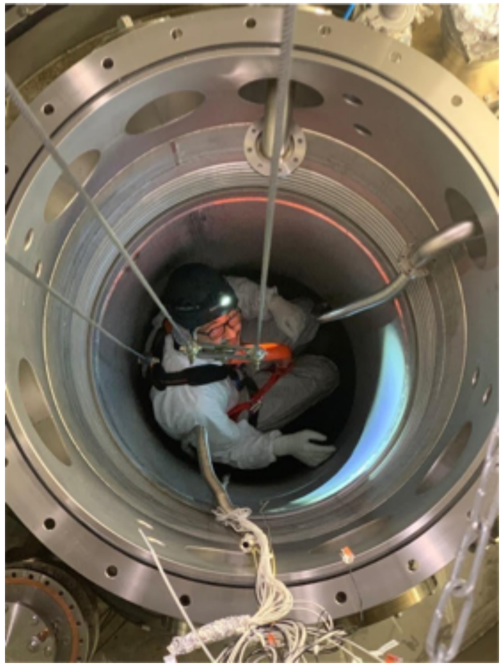


LEGEND-200: the lock system

Cleanroom roof is opened and the components for the lock system are lifted into the cleanroom.

As soon as the roof is closed again & everything is cleaned the lock components are aligned with the cryostat.

LEGEND-200: Inside the cryostat

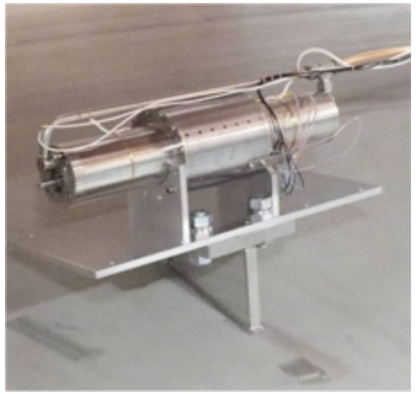


Liquid Argon is evaporated
GERDA Lock is removed.
Enter the cryostat

Wavelength Shifting Reflector (WLSR) is installed.
It restricts the LAr volume around the detectors.
Also shifts scintillation light to blue and reflects it back towards the LAr instrumentation

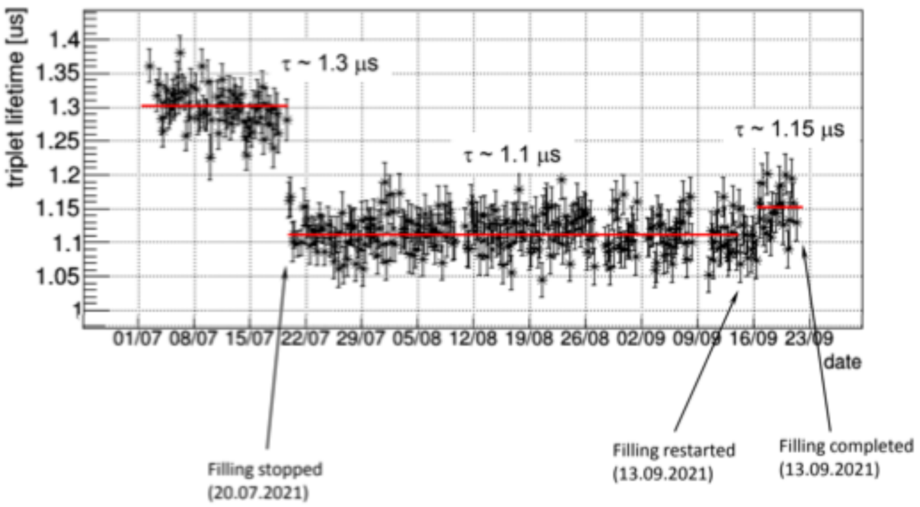
LEGEND
Liquid
Argon **M**onitoring
Apparatus

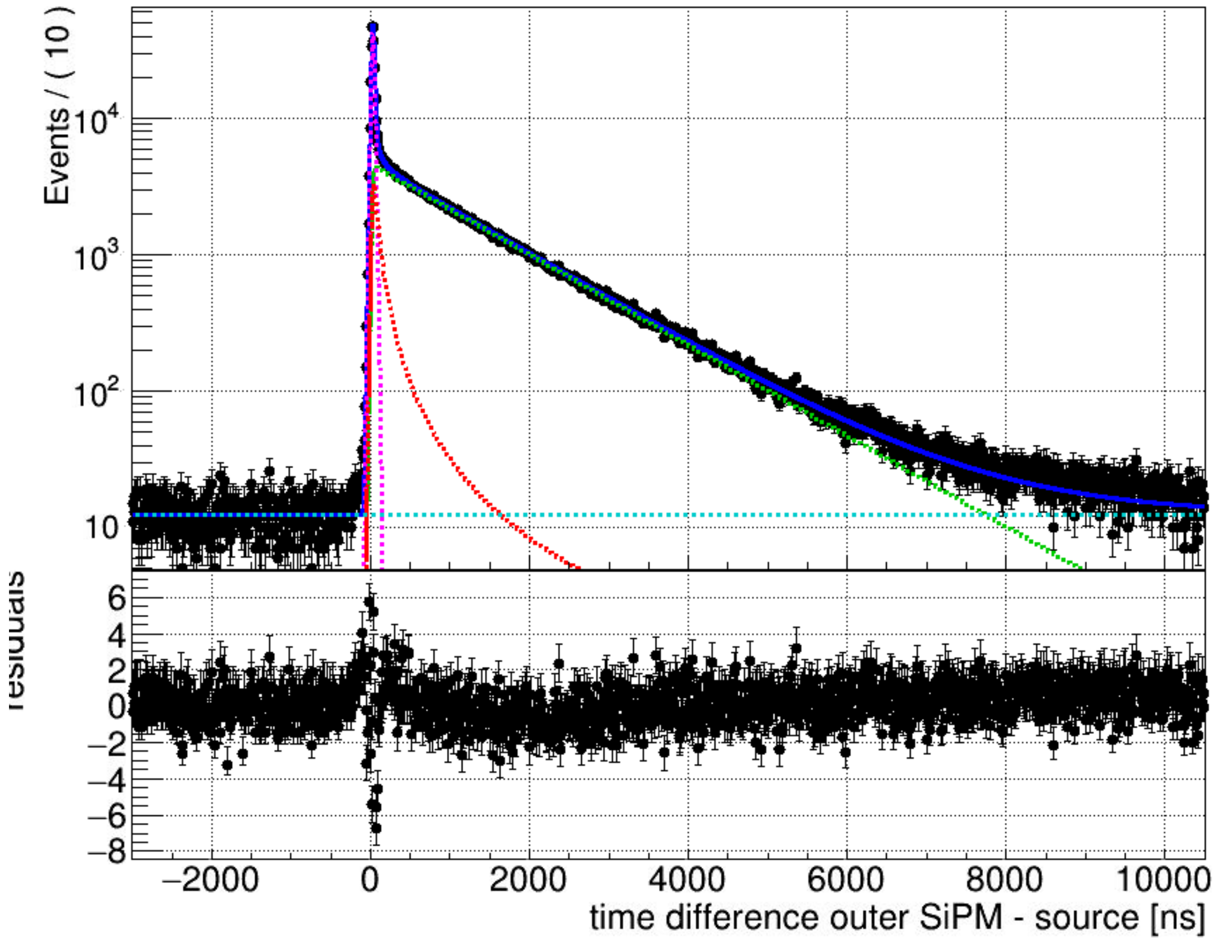
Continuously monitors Triplet lifetime and light yield of the LAr scintillation light



Liquid Argon pump allows if needed to pump LAr out of the cryostat for a liquid phase purification cycle

LEGEND-200: liquid argon purification and filling



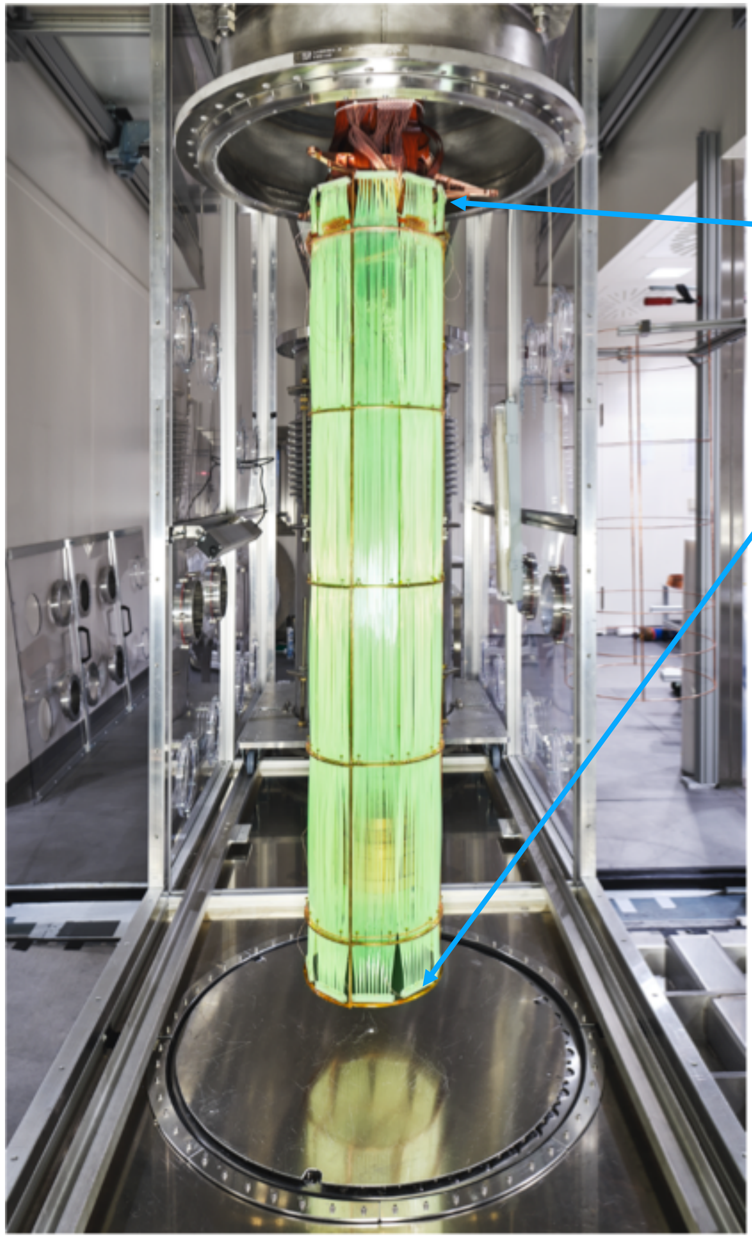


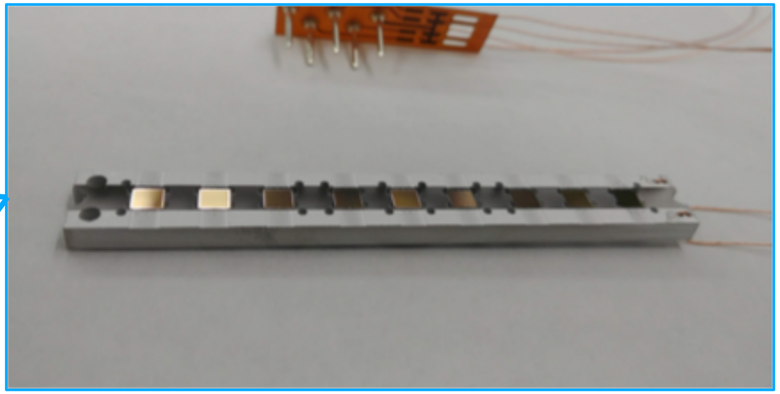
LEGEND-200: glove box and lock system

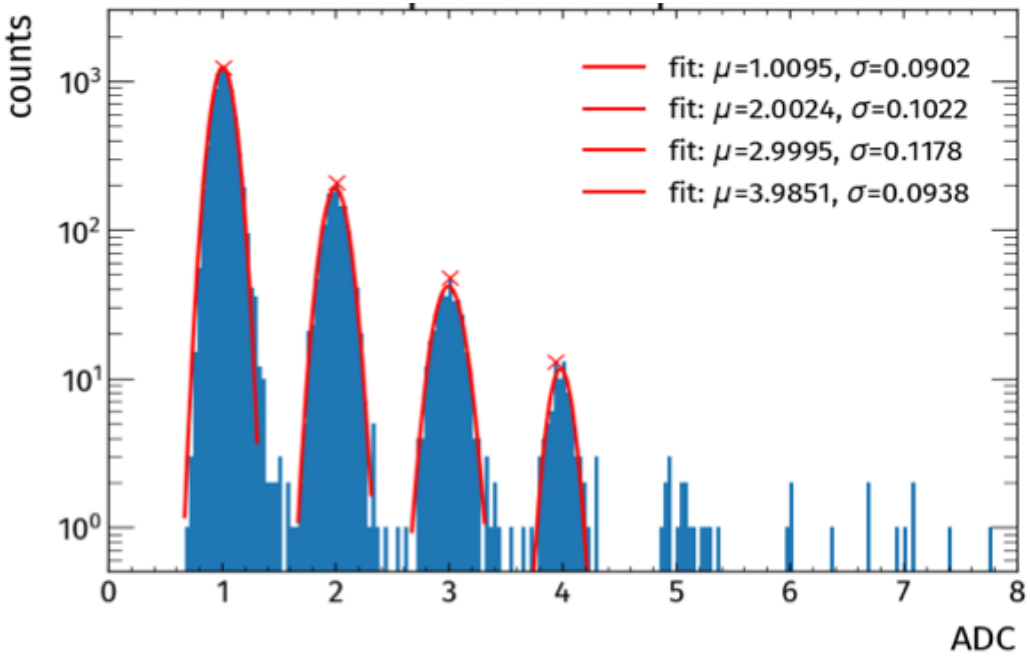
After the works on the lock system is concluded (e.g. installation of motors, cable bands, potting HV feedthrough…), a gas tight glovebox is erected around the lock and the cryostat.

Rails allow the middle section of the lock to be pushed aside to access the experimental payload.

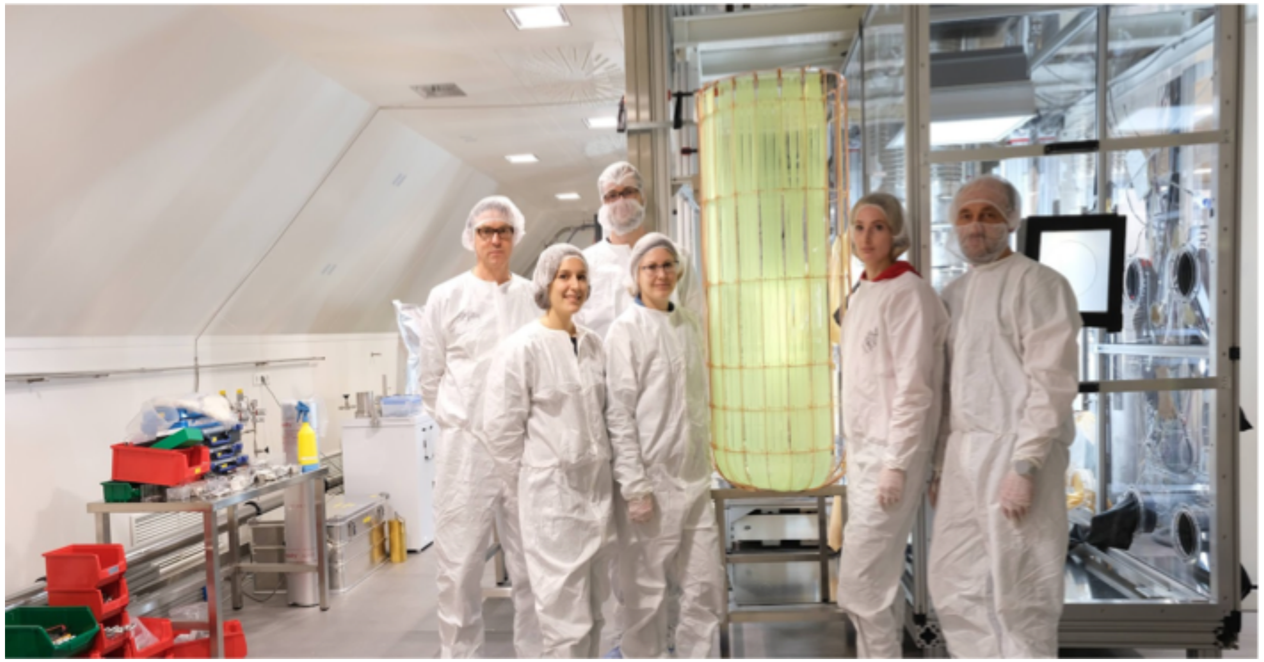
LEGEND-200: Commissioning of LAr Inner Barrel

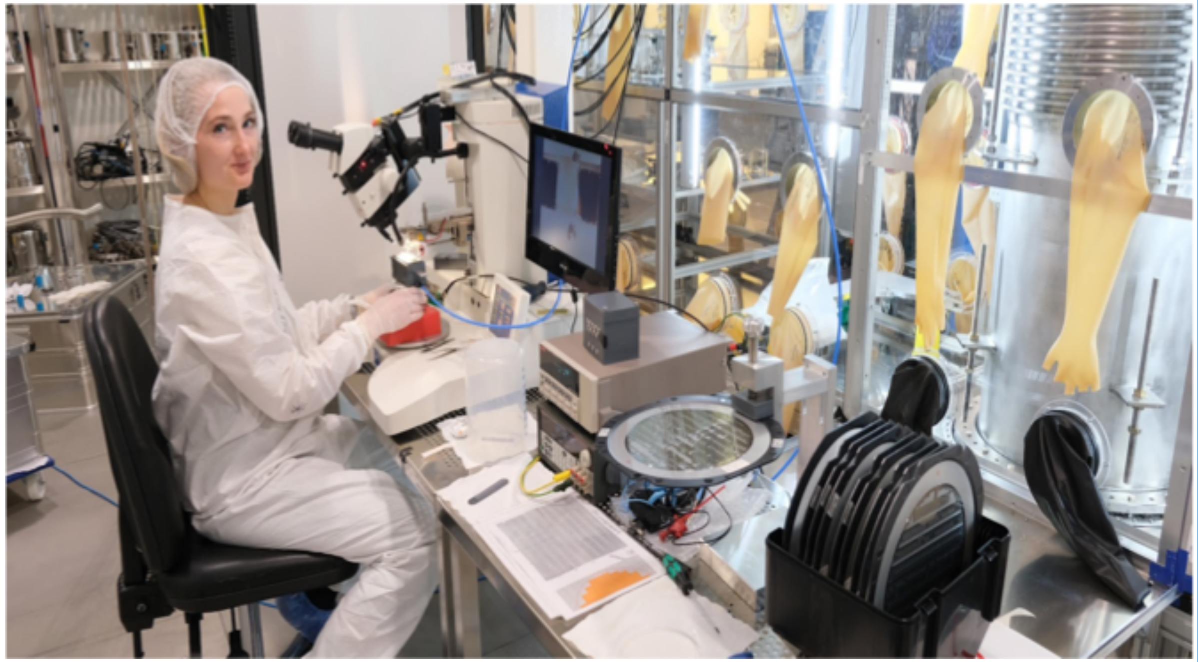




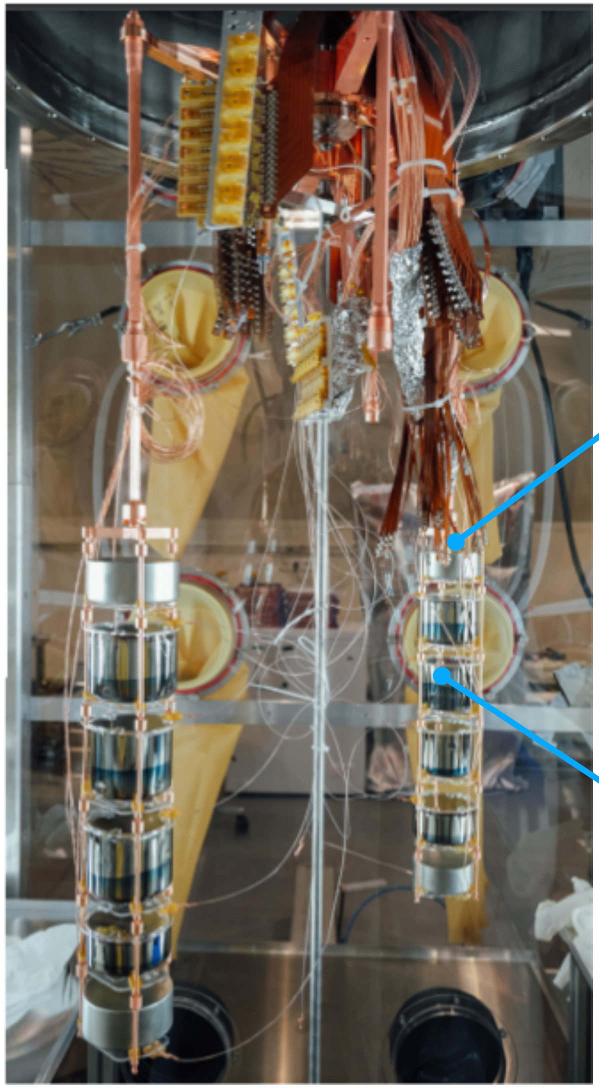


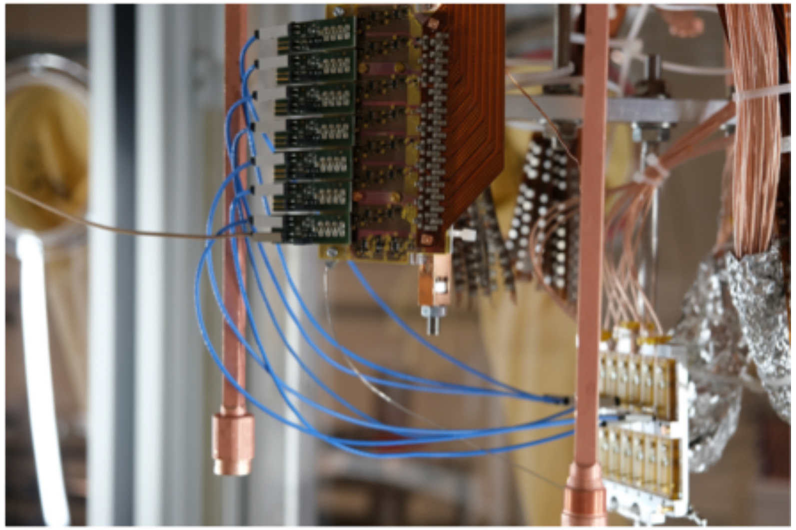
LEGEND-200: commissioning of Outer Barrel





LEGEND-200 commissioning: HPGe and electronics



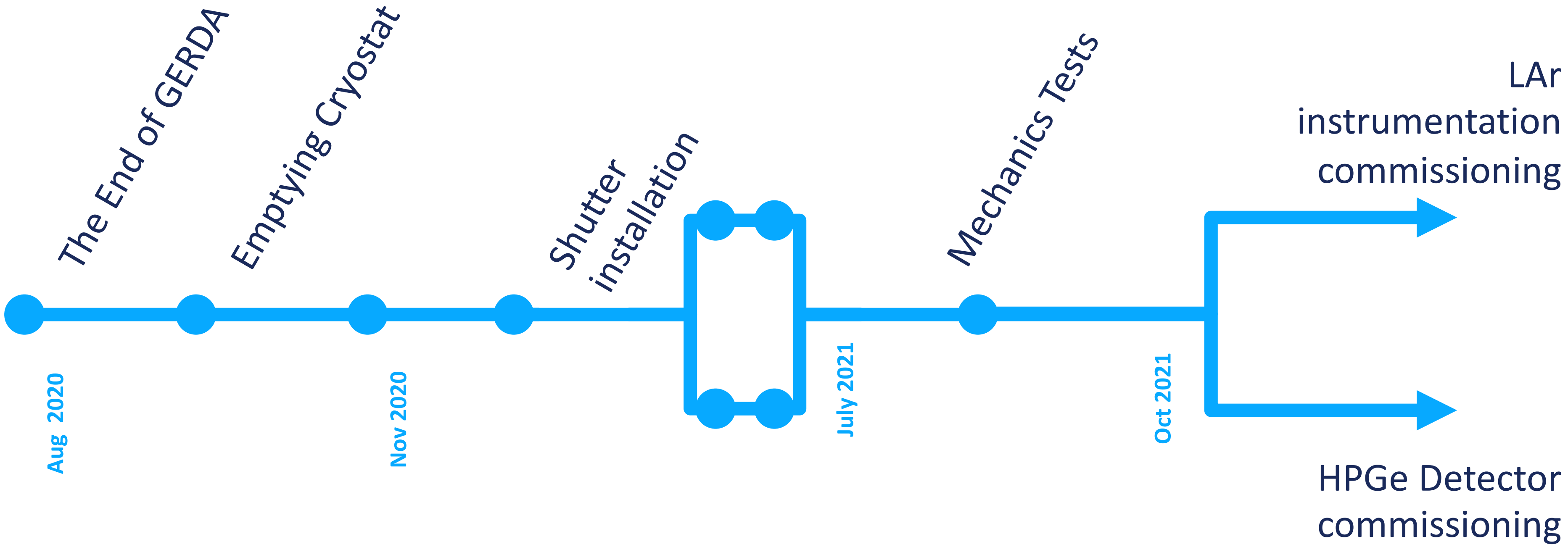


Dec 21-Feb 22: First HPGe Detectors are deployed in the cryostat.

Testing HPGe Detectors, Front End Electronics & novel materials (i.e PEN plates)

LEGEND-200: HPGe and electronics commissioning

LEGEND-200: Start of physics data taking in 2022



Conclusions

$T_{1/2} \propto$ **m·t** scaling ➔ *quasi background-free*