Neutrinoless Double-Beta Decay Searches in Germanium

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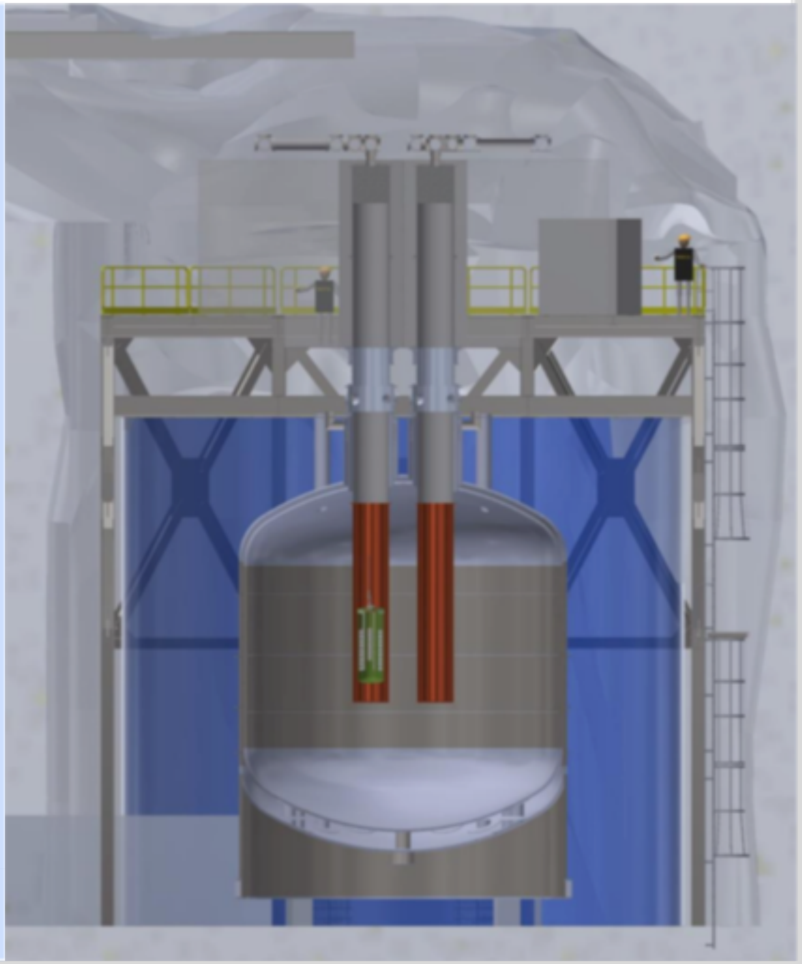
THE UNIVERSITY *of* NORTH CAROLINA *at* CHAPEL HILL

TUNL
TRIANGLE UNIVERSITIES NUCLEAR LABORATORY

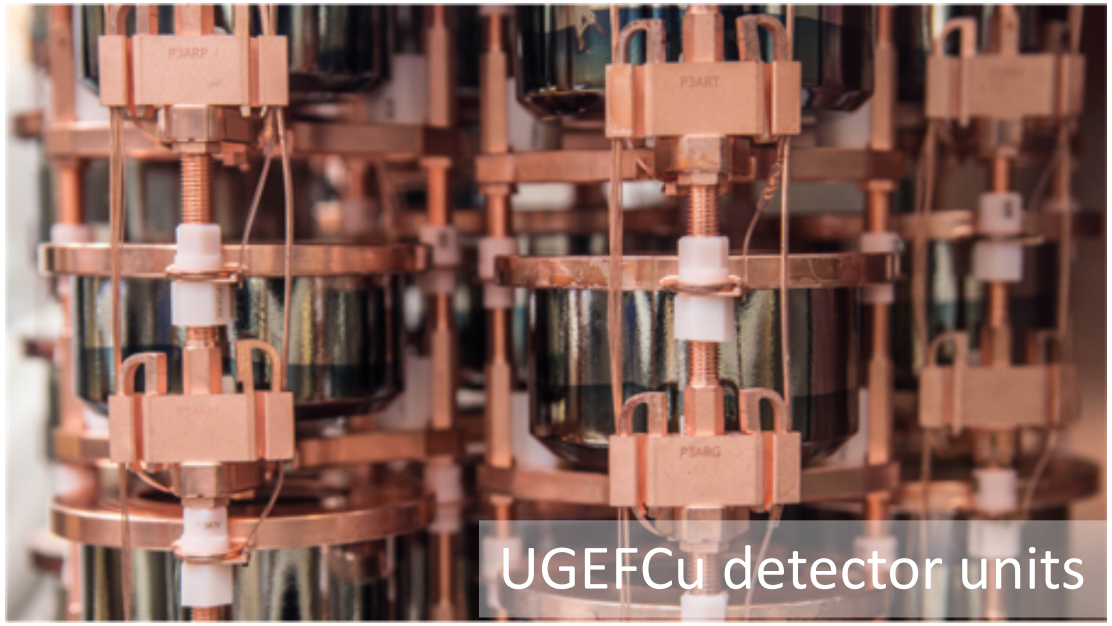


GERDA

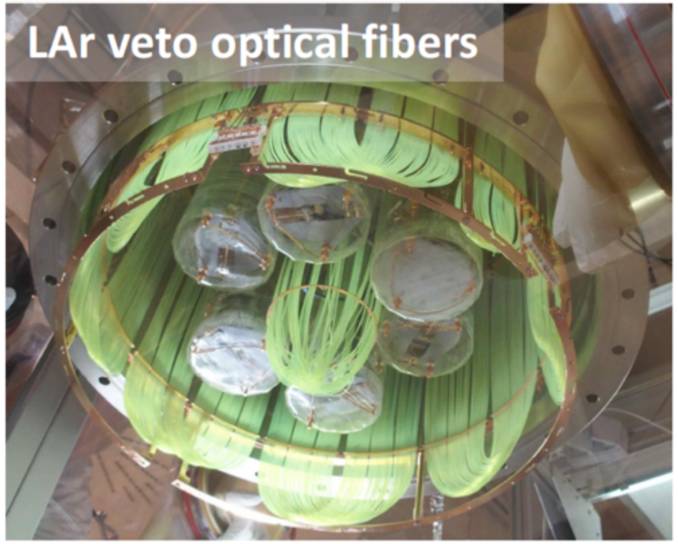
LEGEND

On behalf of the MAJORANA and LEGEND Collaborations, with thanks to the GERDA Collaboration

Outline

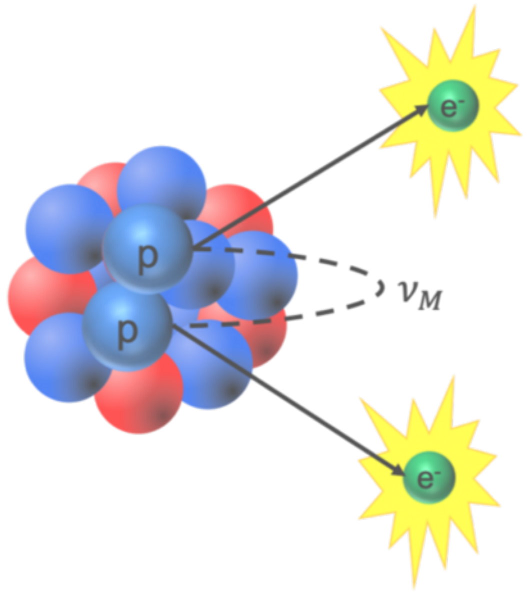


- Double-Beta Decay in ^{76}Ge
- Current-generation experiments
  - New Results from the MAJORANA DEMONSTRATOR
  - Final results from GERDA
- Joining forces: LEGEND
  - Status and progress



Why Neutrinoless Double Beta Decay?

- 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, through leptogenesis
  - There is a new mechanism demonstrated for the generation of mass

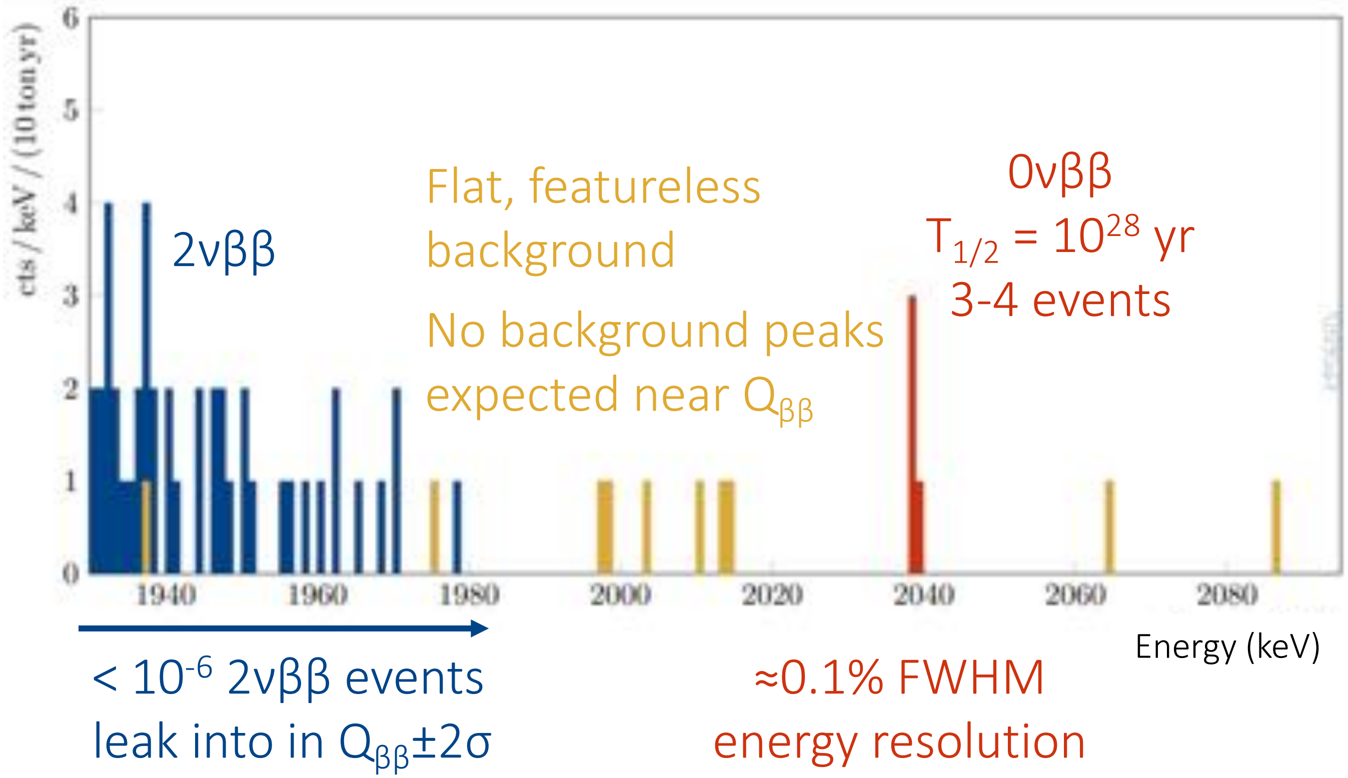


- The search for 0νββ decay is one of the most compelling and exciting challenges in all of contemporary physics
- The LEGEND Collaboration aspires to meet this challenge through a ton-scale search for 0νββ decay of ^{76}Ge

Designing for Unambiguous Discovery

- What is required for a discovery of 0νββ decay?
- Long half-lives mean you need large exposures. For 3-4 counts of 0νββ at…
  - 10^{26} years: 100 kg-years
  - 10^{27} years: 1 ton-year
  - 10^{28} years: 10 ton-years
- Need a good signal-to-background ratio to get statistical significance
  - A very low **background event rate**
  - The best possible **energy resolution**

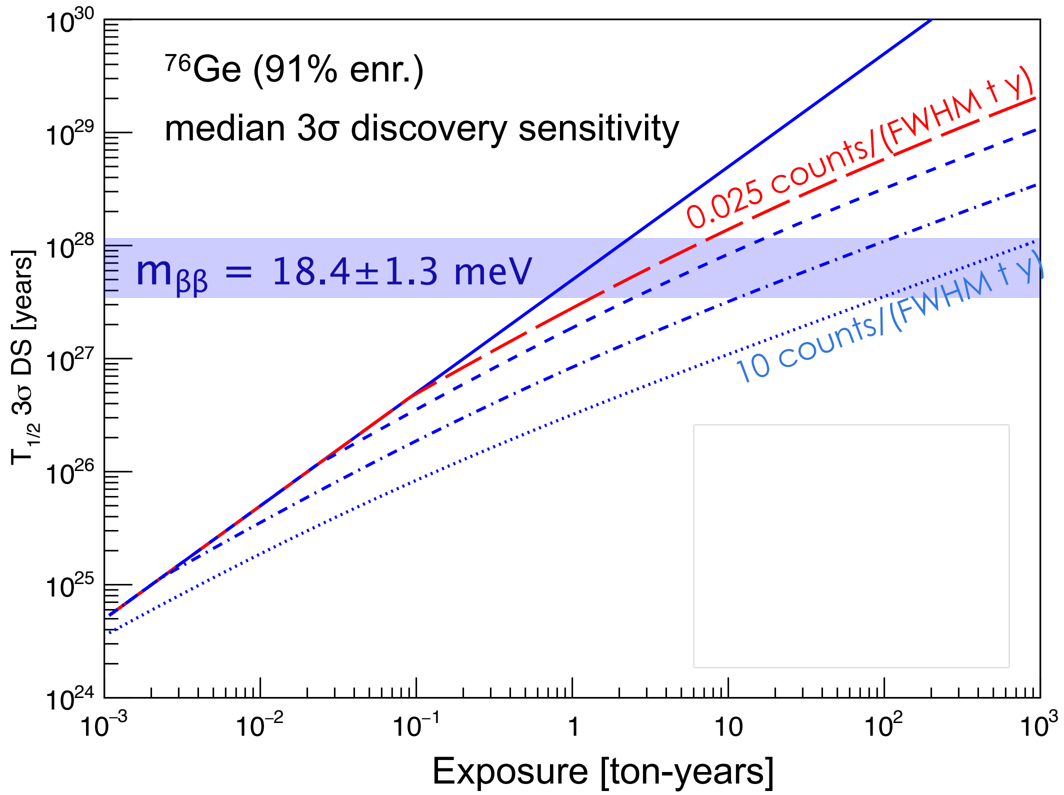
Simulated LEGEND-1000 example spectrum for $T_{1/2} = 10^{28}$ yrs, BI < 10^{-5} cts/keV kg yr, after cuts, from 10 years of data



At every stage, 0νββ searches in ^{76}Ge are designed for unambiguous discovery: their goal is quasi-background free operation for their full exposure

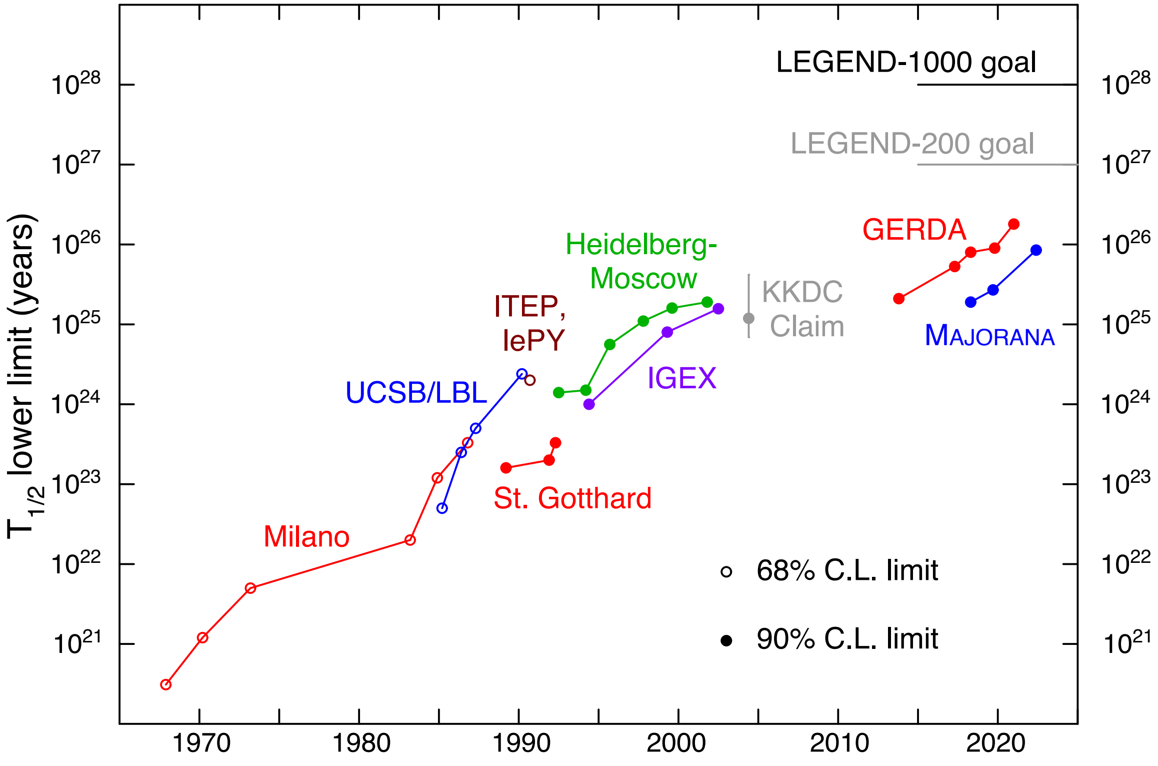
Backgrounds and Discovery

- Background-free: Sensitivity rises linearly with exposure
  Background-limited: Sensitivity rises as the square root of exposure
- Our background goal is "quasi-background-free" operation
  - *Less than one background count* expected in a 4σ Region of Interest (ROI) with the full exposure
    (FWHM: Full Width at Half Maximum; 2.355 σ for a Gaussian peak)



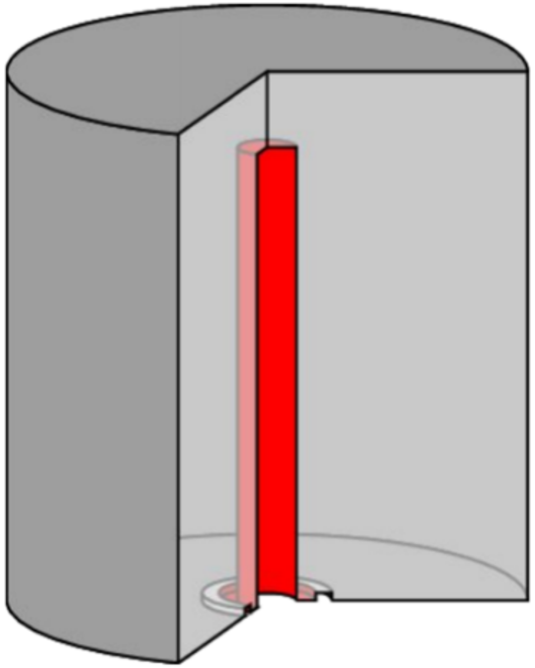
HPGe Detectors for 0νββ

- Easily available material, enrichment, and detector production
- Highly efficient: >90% ^{76}Ge use, ~70% signal efficiency after all cuts
- Easy operation: low operating voltage (< 5 kV) and cryogenic requirements (77-90K)
- Many tools to reduce backgrounds
  - Multiplicity, timing, active veto shielding
  - Pulse-shapes used for event topology discrimination
  - Demonstrated lowest (GERDA) and 2nd lowest (MJD) backgrounds



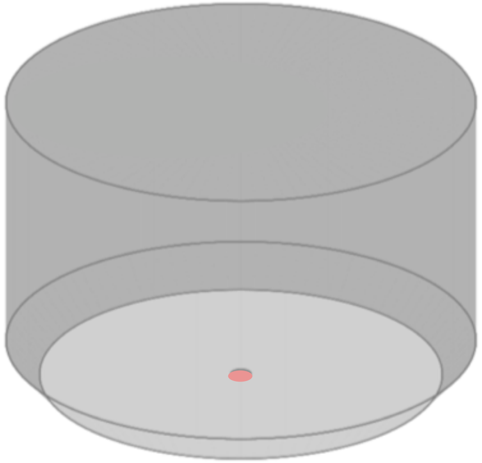
- Solid basis for unambiguous discovery
  - Superb energy resolution: $\sigma / Q_{\beta\beta} = 0.05$ %
  - Therefore, no background peaks anywhere near the energy of interest
  - Background is flat and well understood
  - Background are measured, with no reliance on background modeling
  - All this leads to an excellent likelihood that an observed signal will be convincing

Germanium Detector Innovation



(Semi)-Coaxial

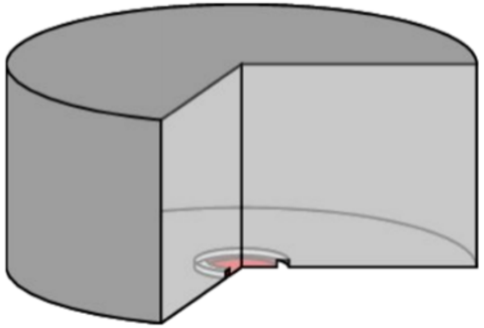
- Large mass (2-3 kg)
- Imperfect background rejection



PPC

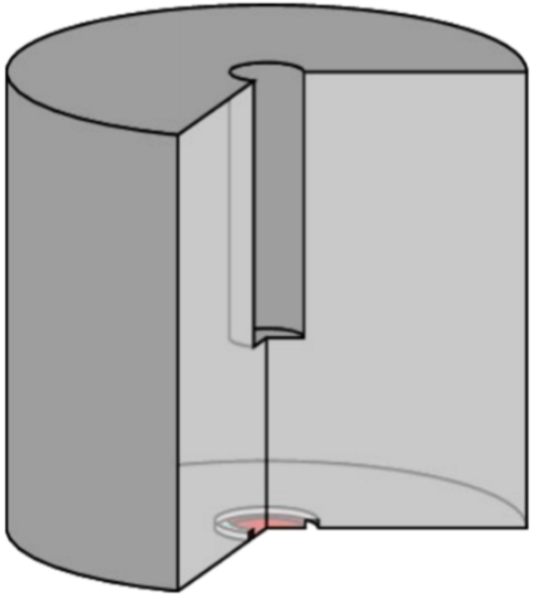
IEEE Trans. on Nuc. Sci., 36, 1, 926-930 (1989)

- Small mass (< 1 kg)
- Excellent background rejection



BeGe

Eur. Phys. J. C 79, 978 (2019)



Inverted-Coaxial

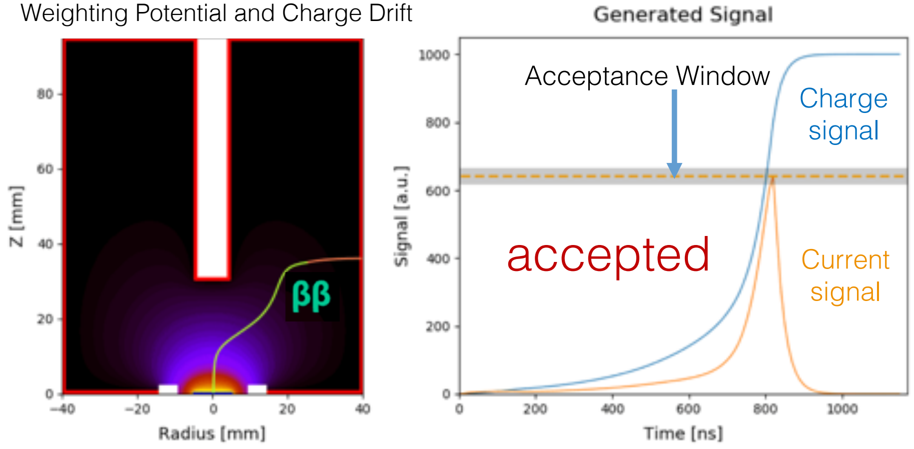
NIMA ,891, 106-110, (2018)

- Newly developed for LEGEND
- Large mass (up to 4 kg)
- Excellent background rejection

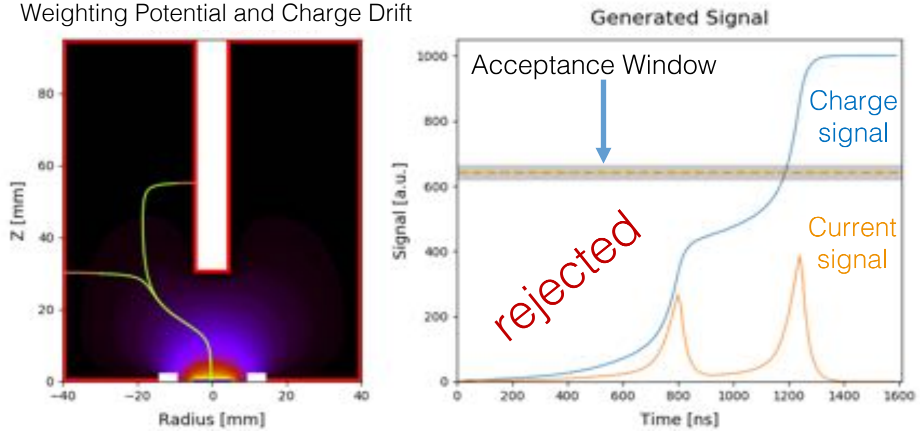
Materials from the GERDA and MAJORANA Collaborations

Background Rejection in Point Contact Detectors

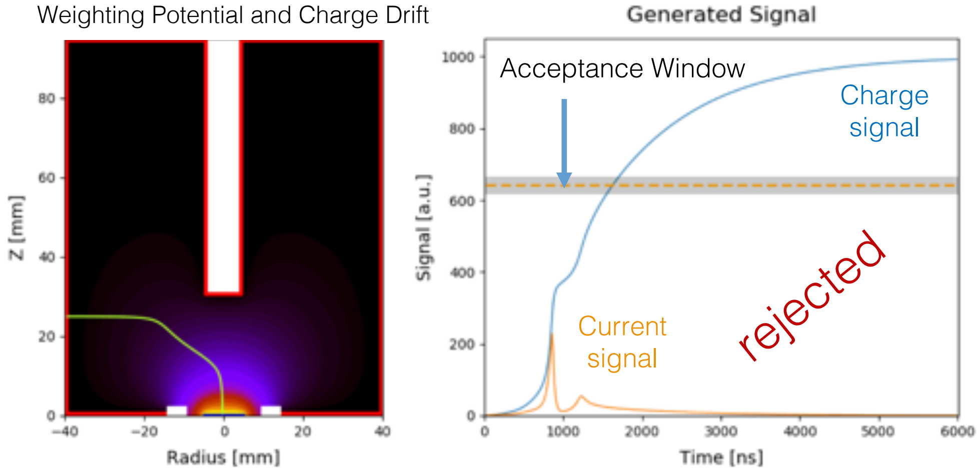
$0\nu\beta\beta$ signal candidate (single-site)



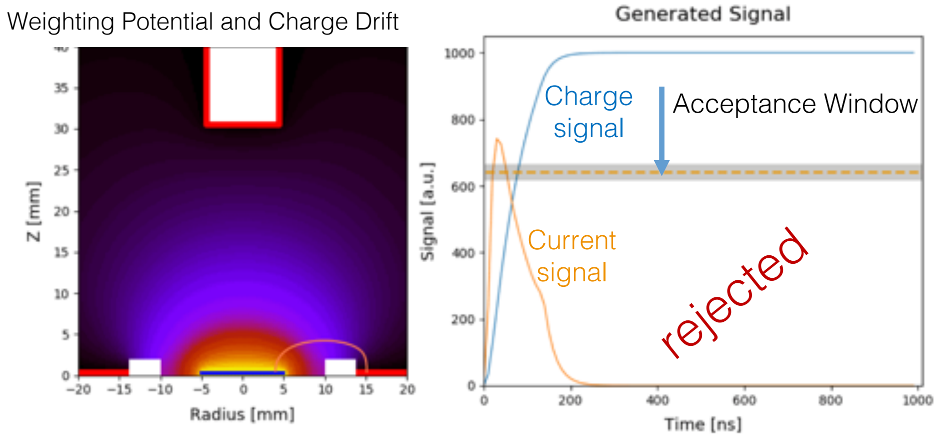
γ-background (multi-site)



Surface background on n+ contact



Surface background on p+ contact



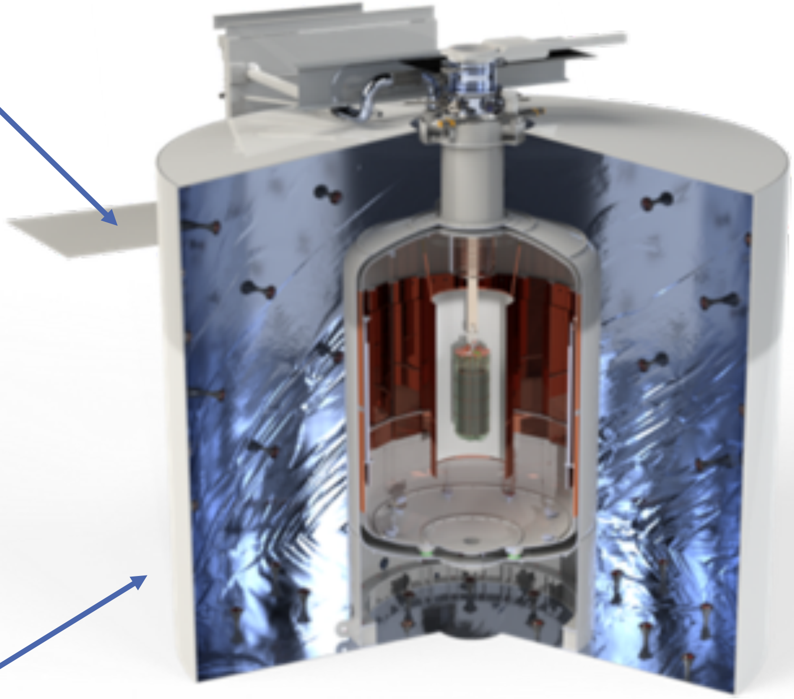
External α, β, and γ backgrounds all create distinctive pulse shapes, allowing for highly efficient ββ decay event selection

From the Current Generation to the Ton Scale

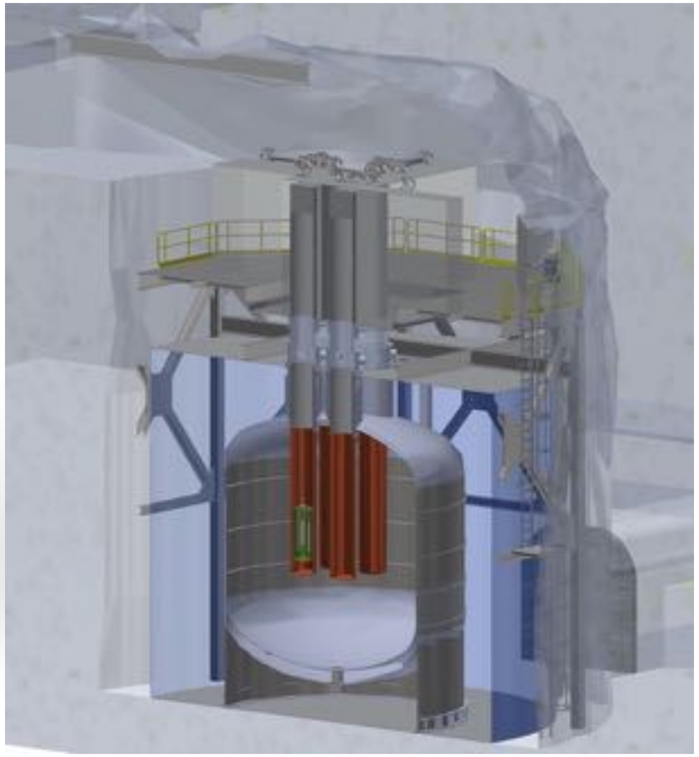
MJD: New final exposure results

GERDA: Final 0νββ results published

PRL 125, 252502 (2020)



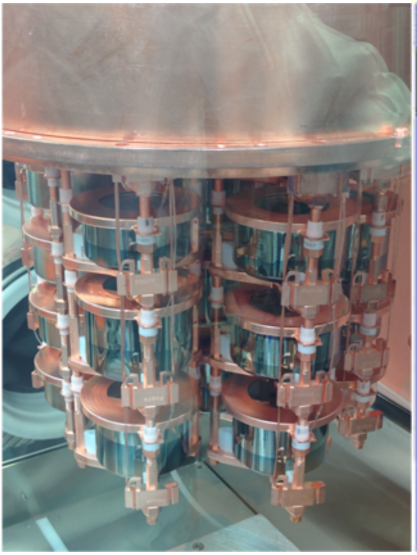
LEGEND-200: Now in commissioning

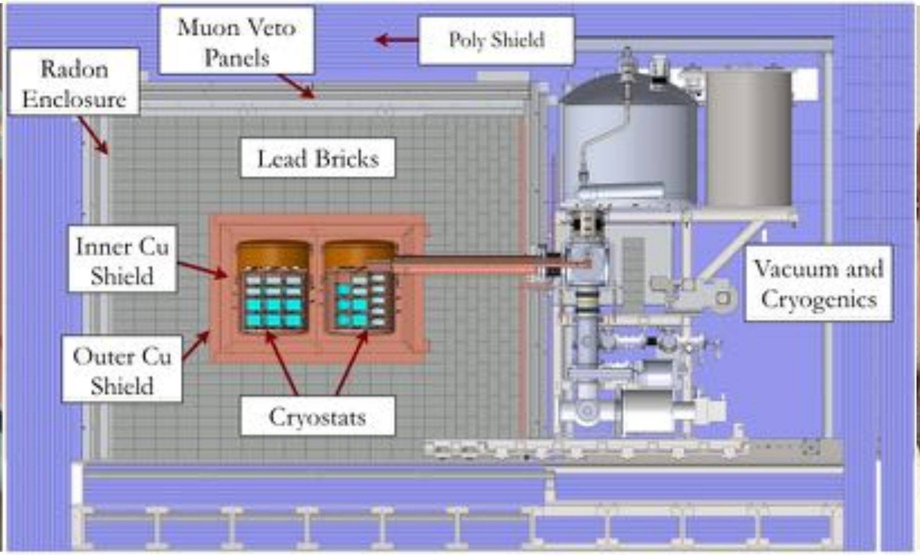


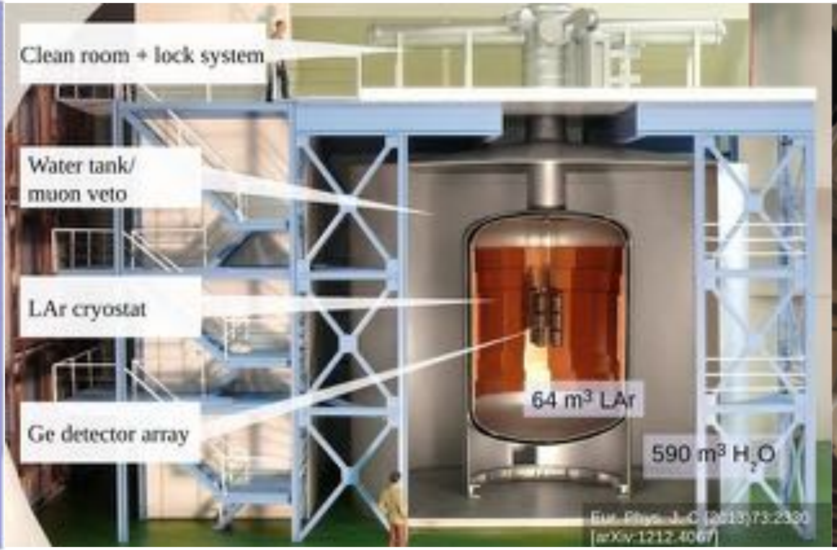
LEGEND-1000: Conceptual design development continuing

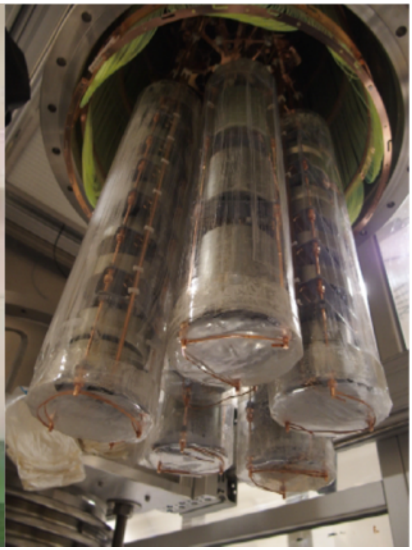
arXiv: 2107.11462

Current-Generation Experiments: The MAJORANA DEMONSTRATOR and GERDA









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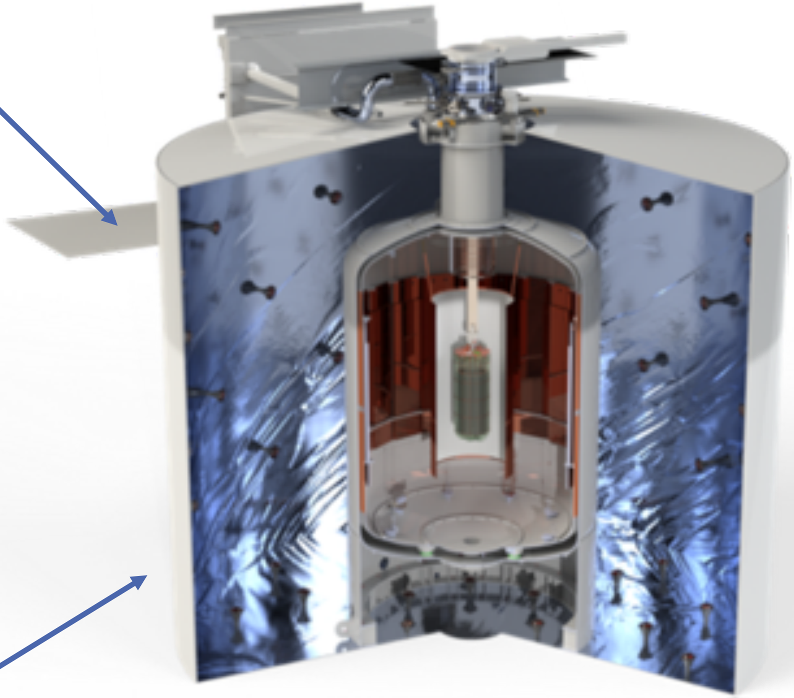

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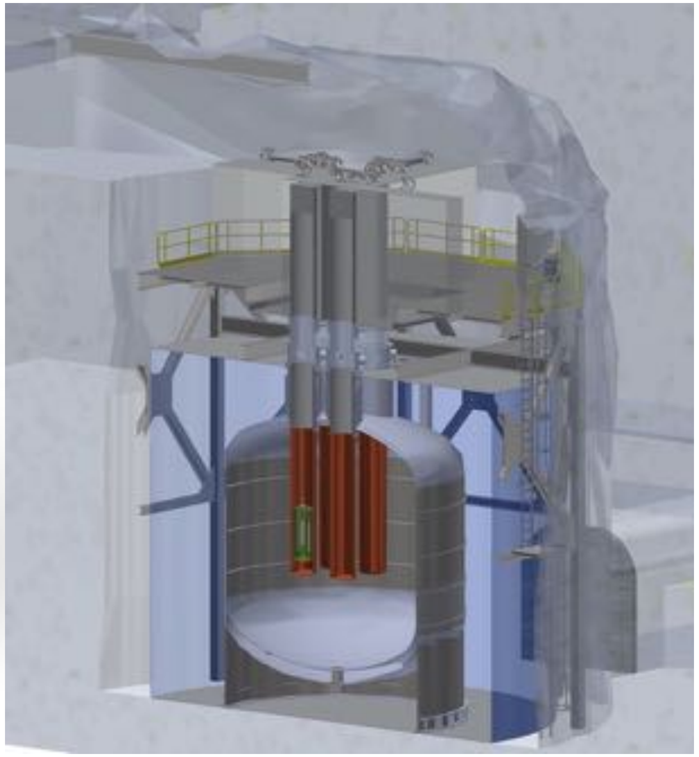

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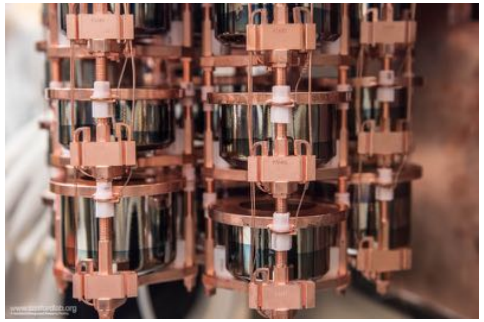
The MAJORANA DEMONSTRATOR

Searching for neutrinoless double-beta decay of ^{76}Ge in HPGe detectors, probing additional physics beyond the standard model, and informing the design of the next-generation LEGEND experiment

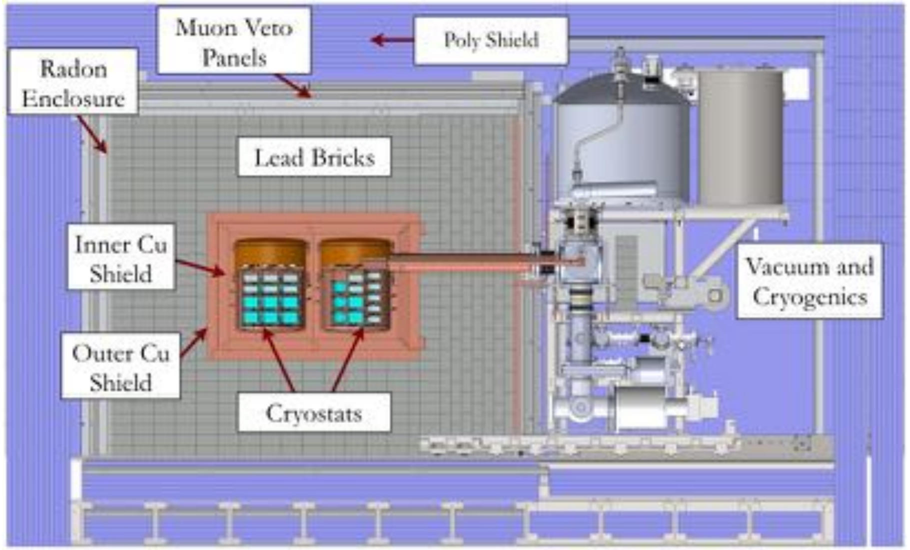
Source & Detector: Array of p-type, point contact detectors
- 29.7 kg of 87% enriched ^{76}Ge crystals
- Included 6.7 kg of inverted coaxial, point contact detectors in final run

Excellent Energy resolution: 2.5 keV FWHM @ 2039 keV
and Analysis Threshold: 1 keV

Low Background: 2 modules within a compact graded shield and active muon veto using ultra-clean materials



Reached an ultimate exposure of ~65 kg-yr before removal of enriched detectors for the LEGEND-200 experiment at LNGS
Continuing to operate at the Sanford Underground Research Facility with natural detectors for background studies and other physics



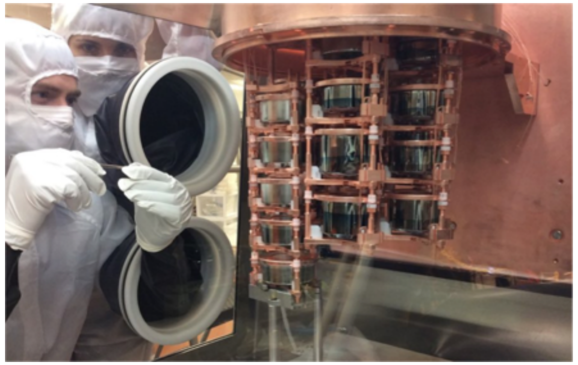
Background Reduction

Ultra-pure materials

- Low-mass design NIM A 828 22 (2016)
- Custom cable connectors and front-end boards
- Selected plastics and low-mass Cu coax cables
- Underground electroformed copper

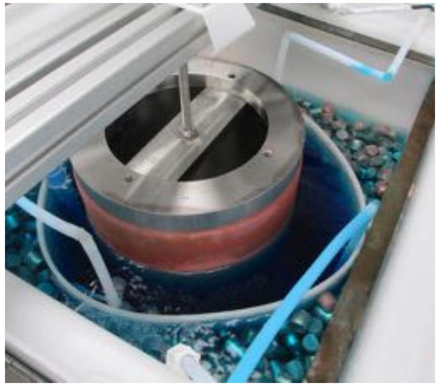
  Th decay chain ≤ 0.1 μBq/kg NIM A 775 93 (2015)

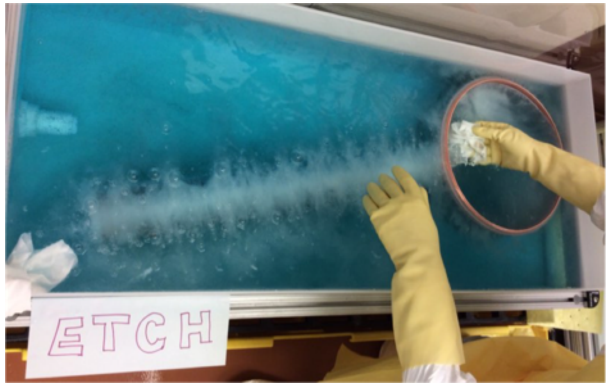
  U decay chain ≤ 0.1 μBq/kg



Machining, cleaning, and assembly

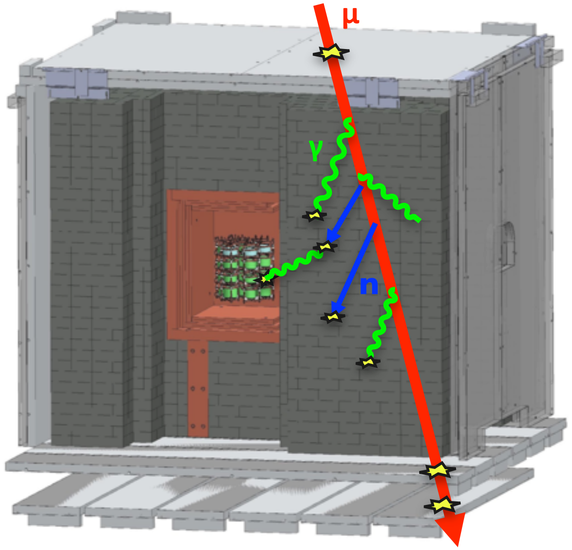
- Cu machining in an underground cleanroom
- Cleaning of Cu parts by acid etching and passivation
- Nitric leaching of plastic parts
- Dedicated glove boxes with a purged N_2 environment





Cosmogenic backgrounds

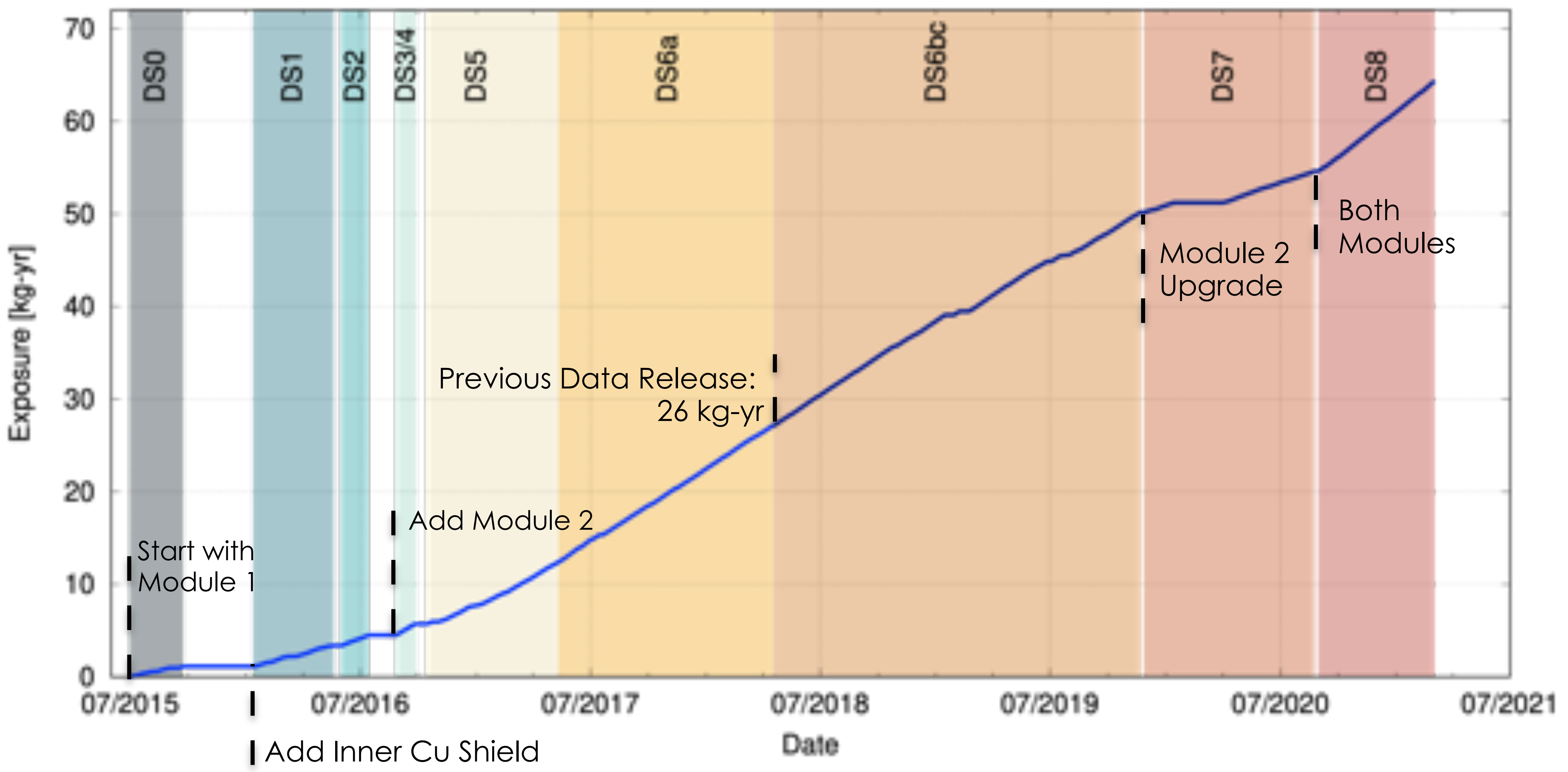
- Limit and track Ge above-ground exposure to prevent cosmic activation. NIM A 877 314 (2018) NIM A 779 52 (2015)
- Veto events coincident with muons Astropart. Phys. 93 70 (2017)



65 kg-yr of Exposure in Enriched Detectors

Total collected active exposure over time in enriched detectors.

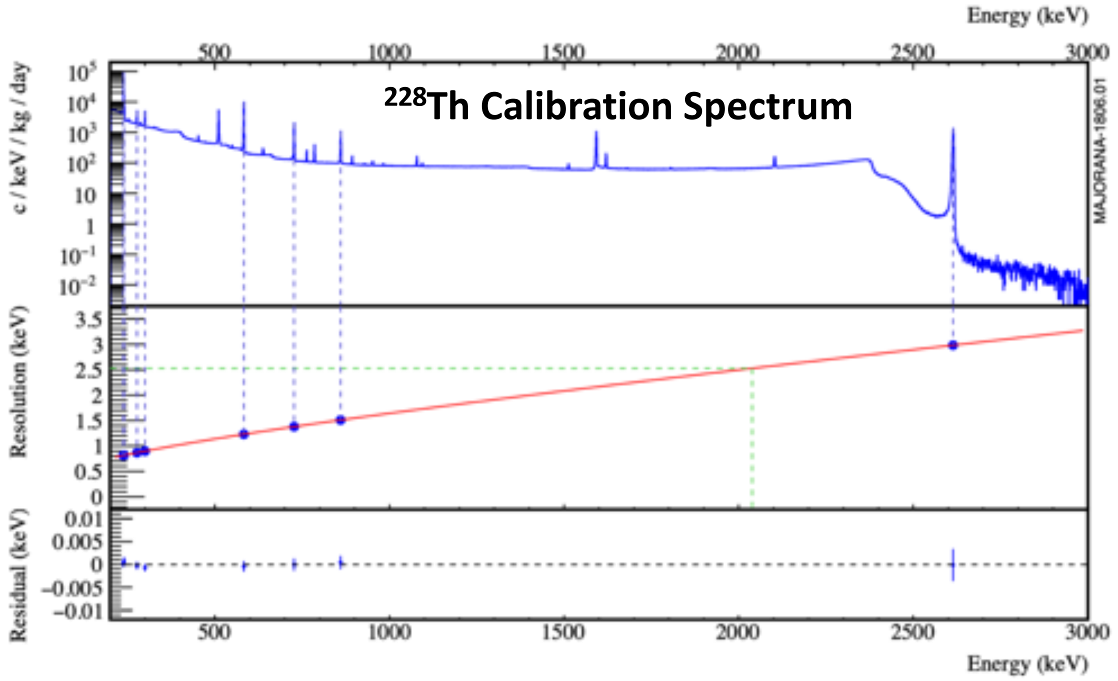
Datasets (DSs) represent changes in experimental configuration



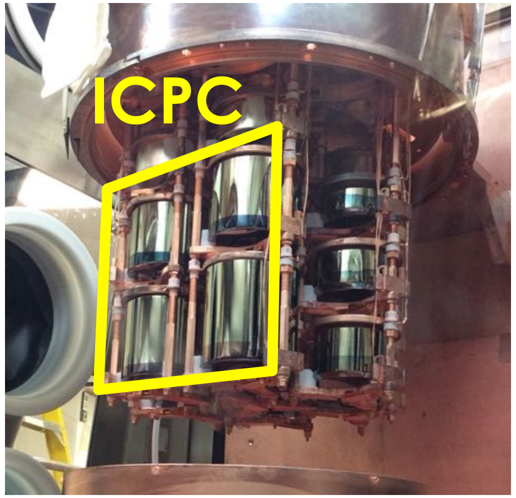
Energy Reconstruction and ICPC Detectors

Energy estimated via optimized trapezoidal filter of ADC-nonlinearity-corrected* traces with charge-trapping correction

FWHM of 2.5 keV at $Q_{\beta\beta}$ of 2039 keV (0.12%) is a record for 0νββ searches

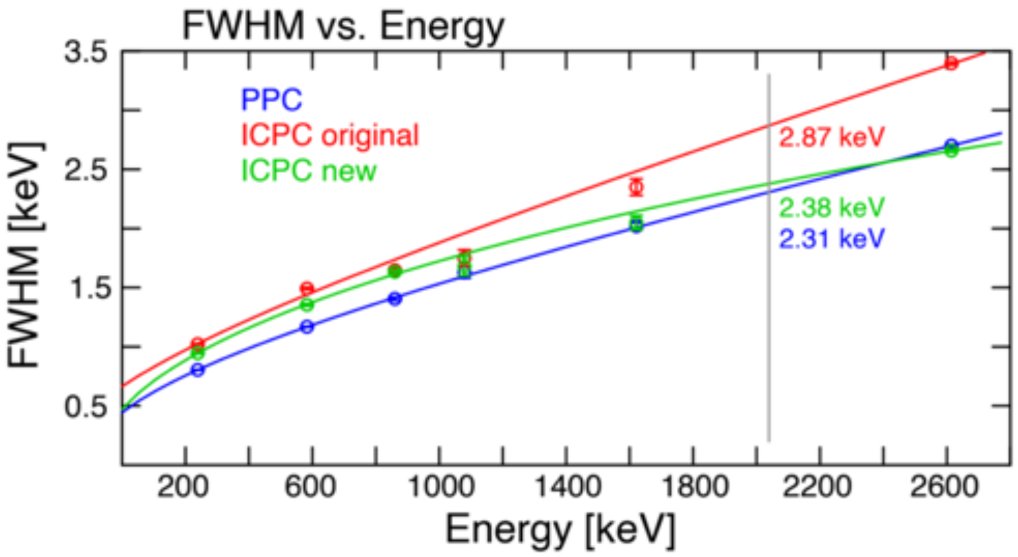


FWHM of combined enriched detectors in the MAJORANA DEMONSTRATOR, measured using ^{228}Th calibration data



MAJORANA operated 4 Inverted-Coaxial Point Contact Detectors from Aug. 2020 to Mar. 2021

- Larger range of drift times requires new analysis techniques
- Best energy resolution for ICPCs to date!



Combined energy resolution of ICPCs improved from 2.9 keV to 2.4 keV FWHM at 2039 keV with new technique

NIMA 872 (2017) 16

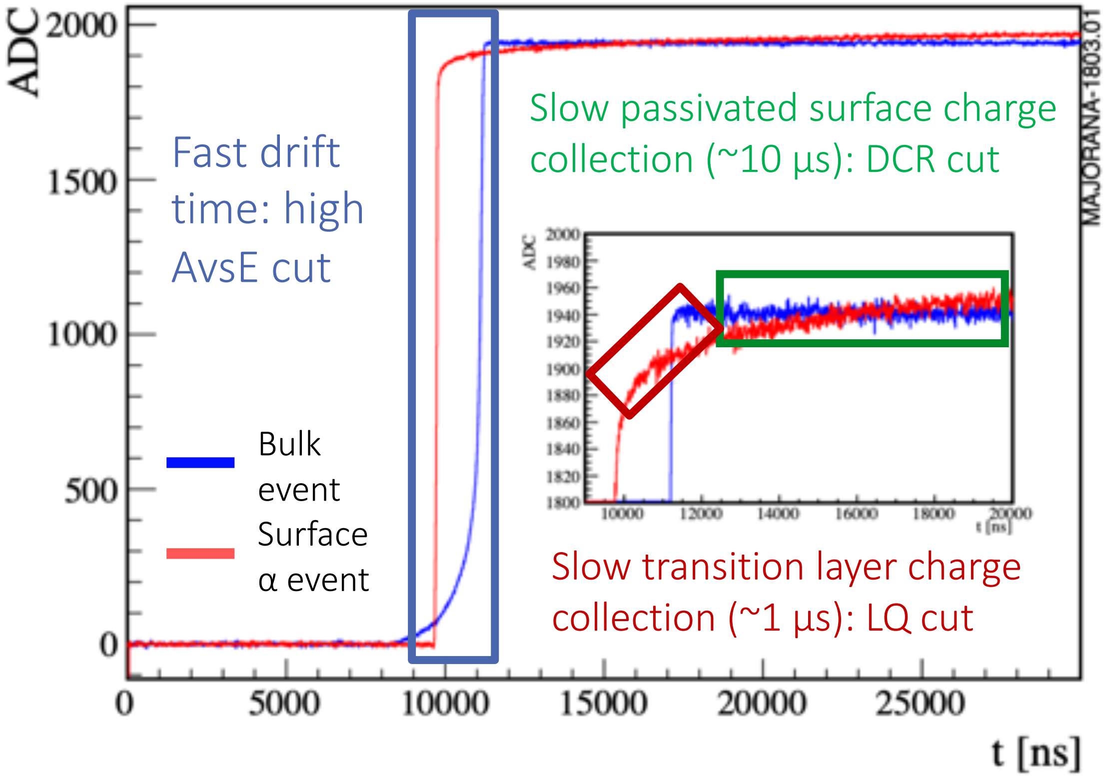
* IEEE Trans. on Nuc Sci 10.1109/TNS.2020.3043671

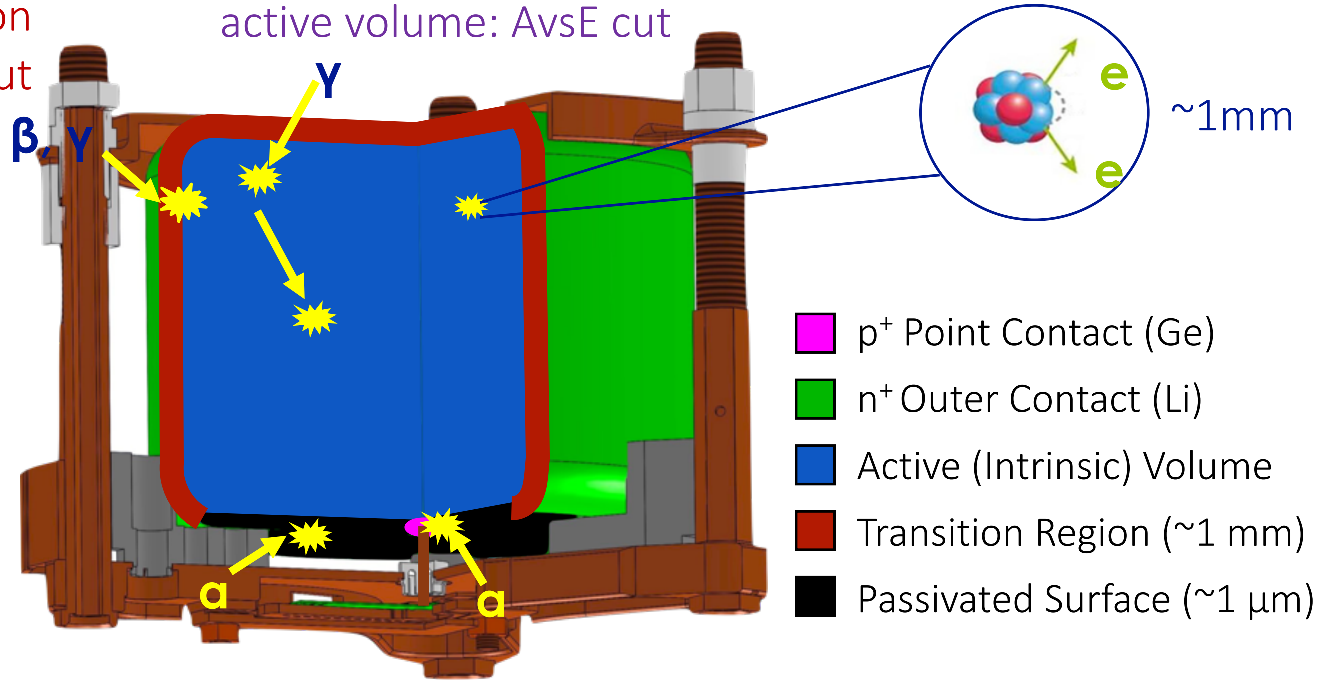
Analysis Techniques for Reducing Backgrounds

0νββ is most likely single-site and located in the bulk of the detector. Many backgrounds are multi-site or located near detector surfaces. Pulse-shape discrimination is used to distinguish between these event topologies.

PRC 99 065501 (2019)

EPJC 82 (2022) 226



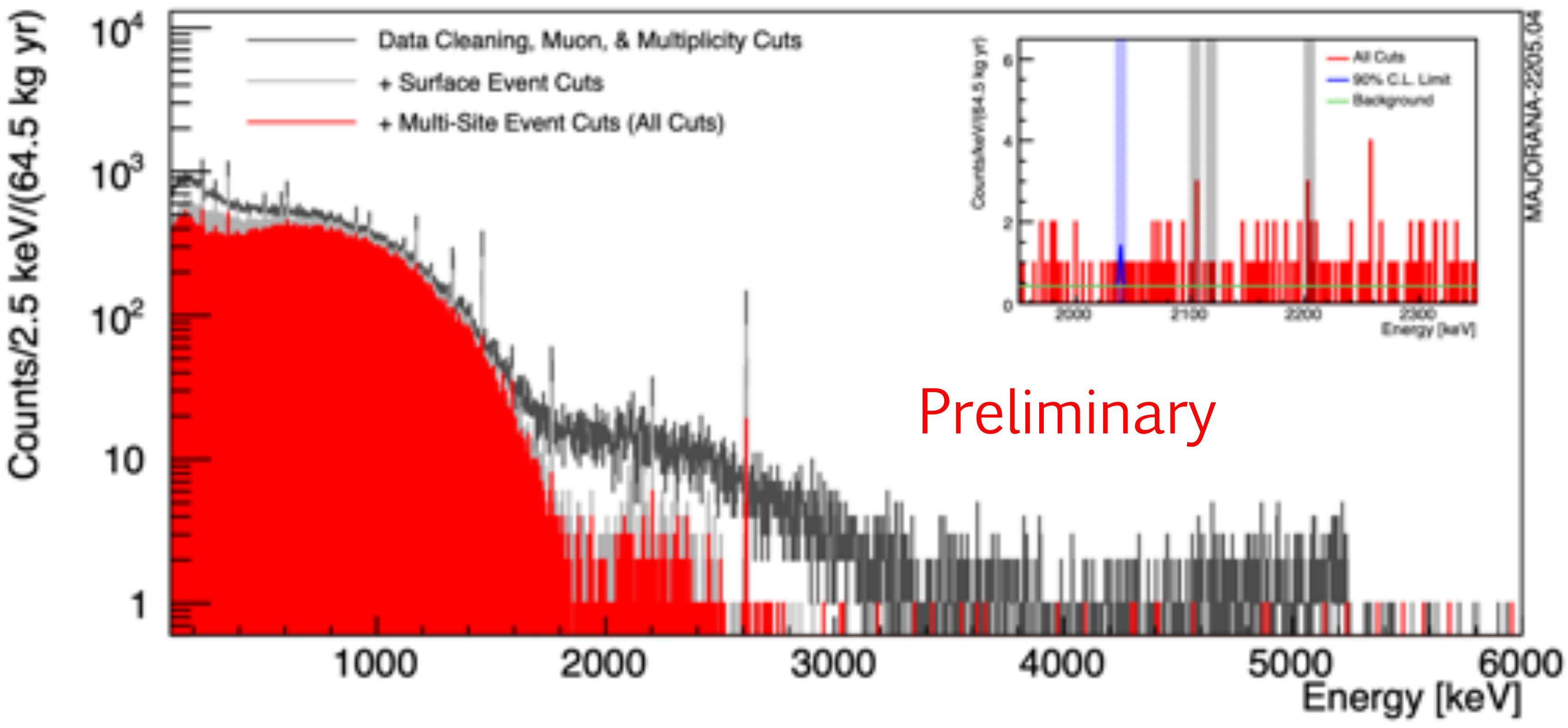


Detector surface: for particle incident on passivated surface: DCR cut

Detector surface: for particle incident on surface near point contact: high AvsE cut

Final-Exposure Spectrum

Operated in a low background regime, benefiting from excellent energy resolution



Final enriched detector active exposure:

64.5 ± 0.9 kg yrs

Background Index at 2039 keV in lowest background config:

15.7 ± 1.4 cts/(FWHM t yr)

Module 1:

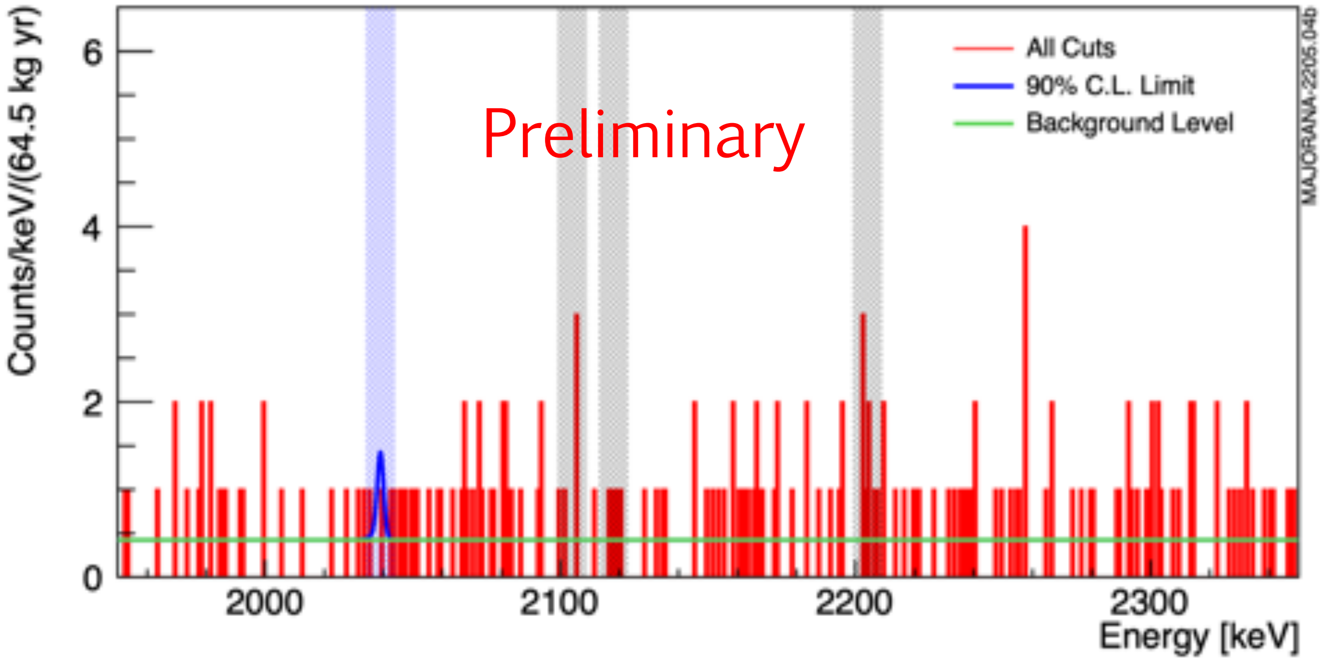
18.6 ± 1.8 cts/(FWHM t yr)

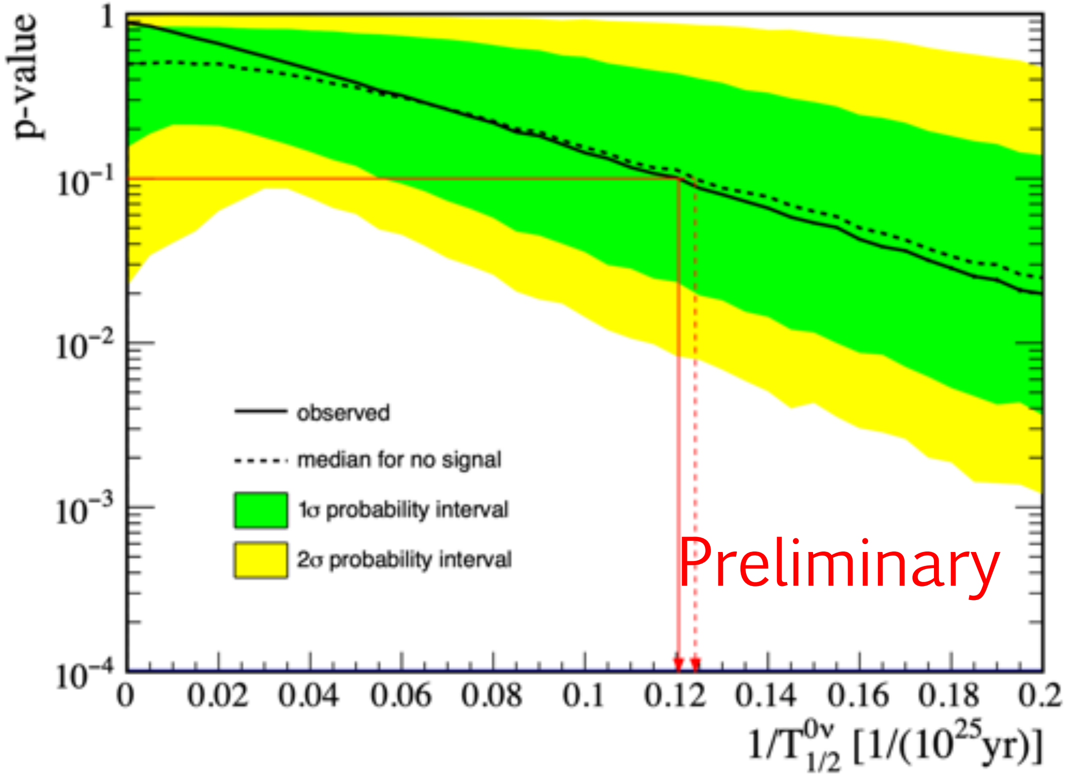
Module 2:

$8.4^{+1.9}_{-1.7}$ cts/(FWHM t yr)

Full spectrum with combined total of 65 kg-yr.

Results





Background Index: (6.2 ± 0.6) × 10^{-3} cts/(keV kg yr)

Energy resolution: 2.5 keV FWHM @ $Q_{\beta\beta}$

Frequentist Limit:

Median $T_{1/2}$ Sensitivity: 8.1 × 10^{25} yr (90% C.I.)

65 kg-yr Exposure Limit: **$T_{1/2}$ > 8.3 × 10^{25} yr** (90% C.I.)

Bayesian Limit: (flat prior on rate)

65 kg-yr Exposure Limit: **$T_{1/2}$ > 7.0 × 10^{25} yr** (90% C.I.)

$m_{\beta\beta}$ < 113 - 269 meV

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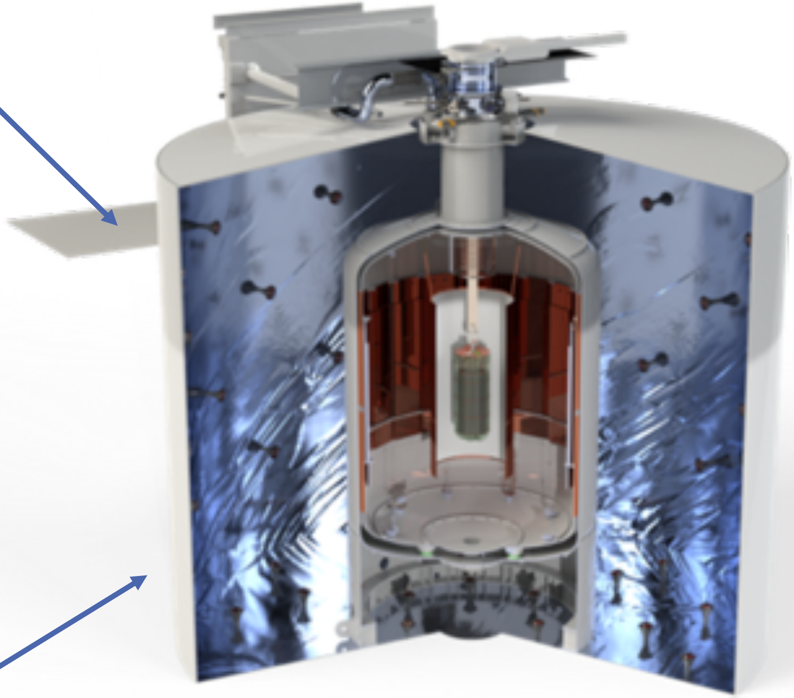
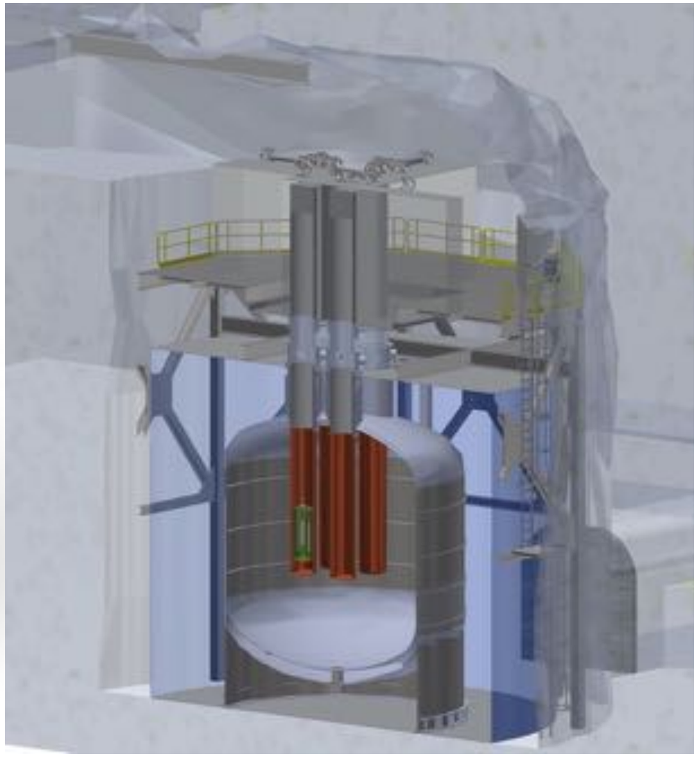
PRL 125, 252502 (2020)



LEGEND-200: Now in commissioning



LEGEND-1000: Conceptual design development continuing

arXiv: 2107.11462

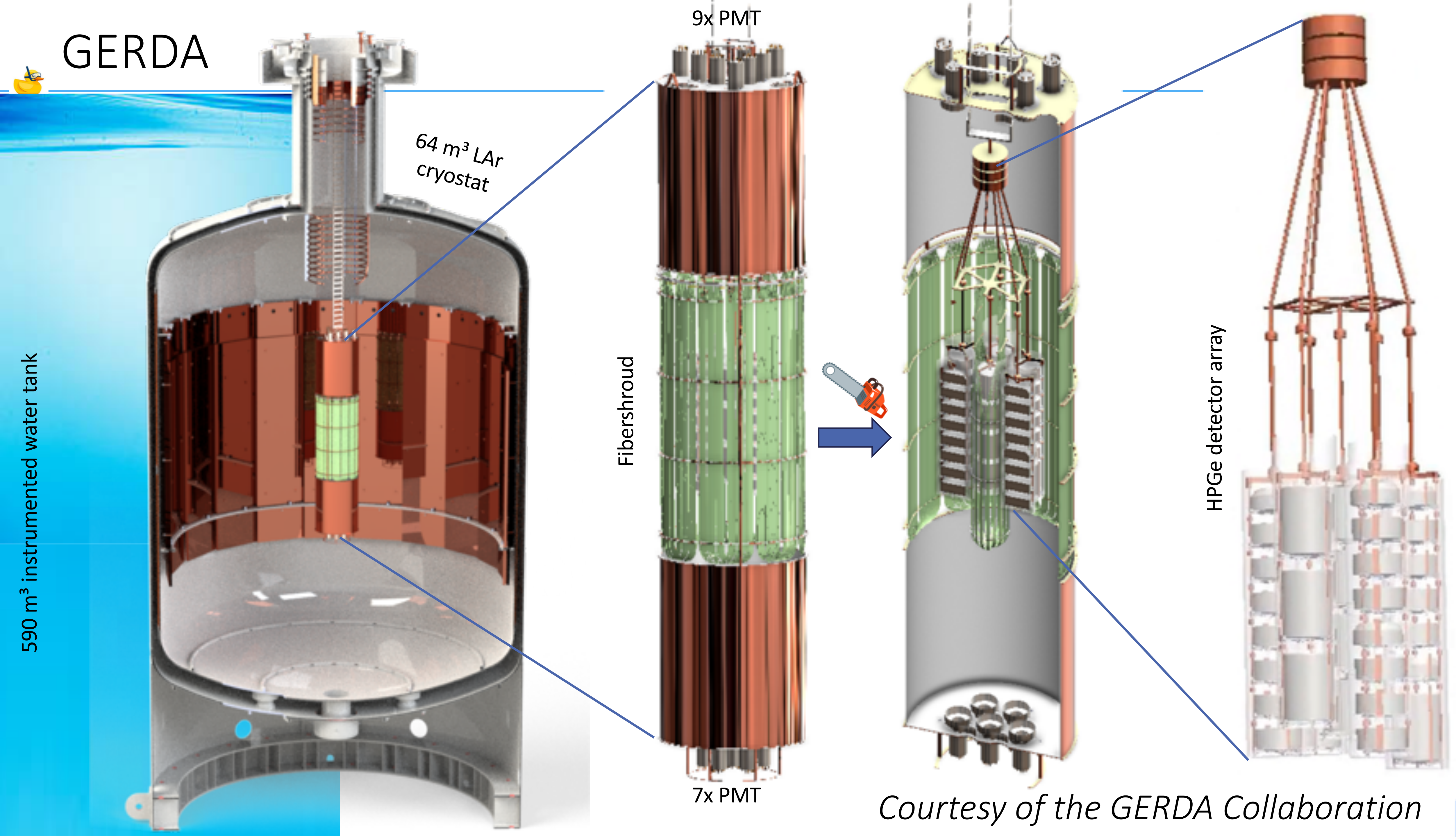
GERDA at Laboratori Nazionali del Gran Sasso in Italy

http://www.mpi-hd.mpg.de/gerda/

About 100 scientists
from Europe

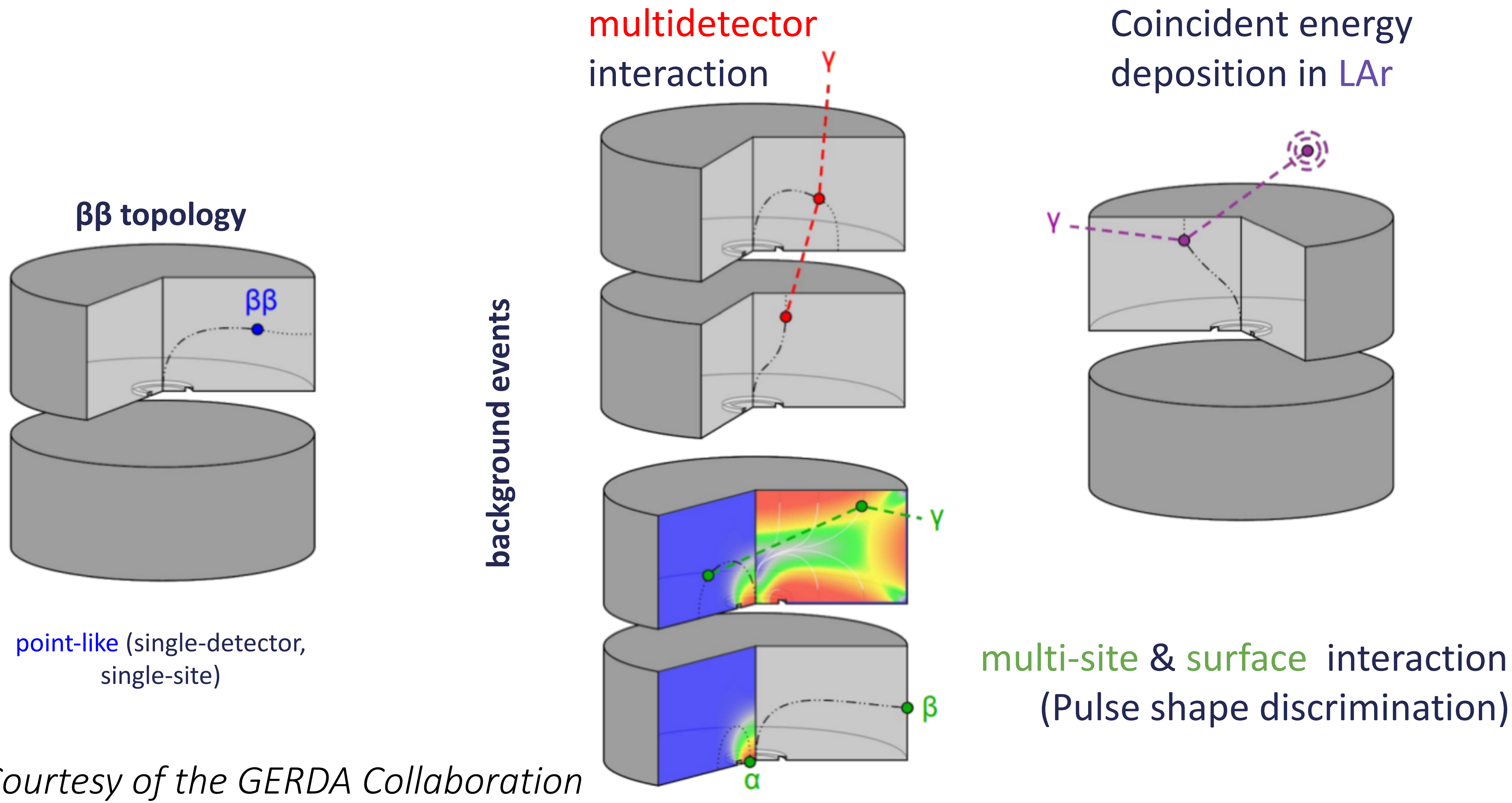
Courtesy of the GERDA Collaboration

GERDA



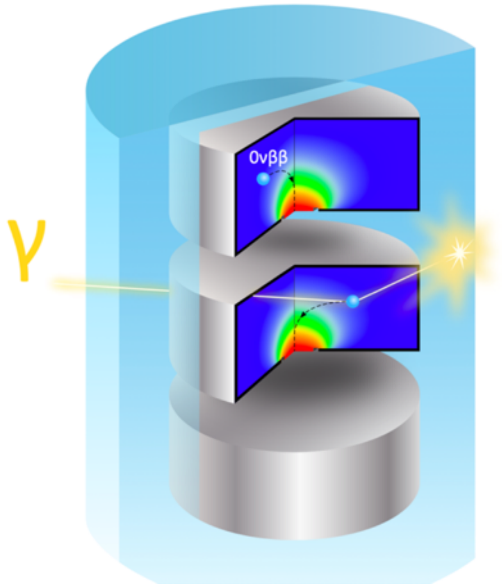
Courtesy of the GERDA Collaboration

Background Rejection in GERDA



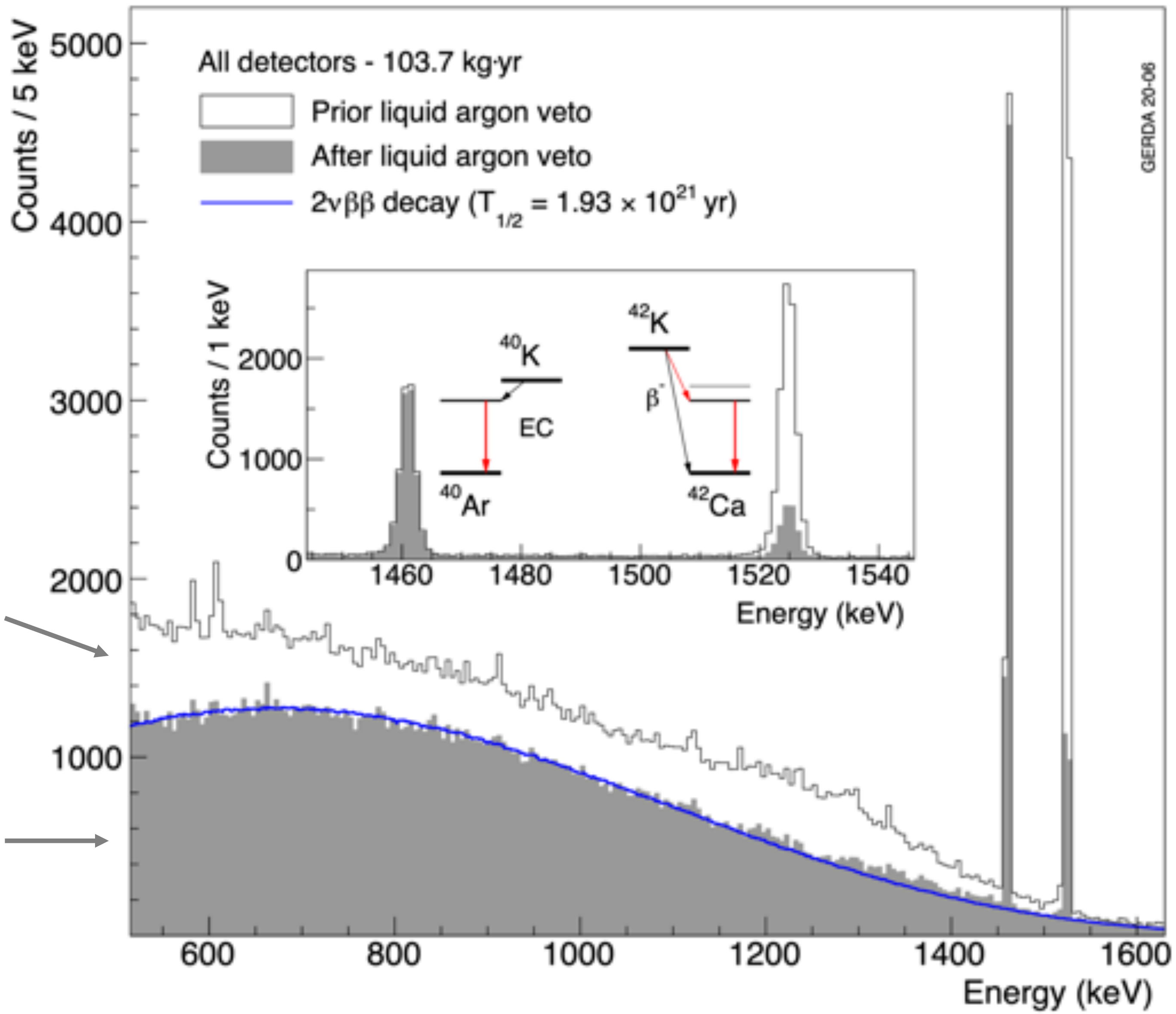
Courtesy of the GERDA Collaboration

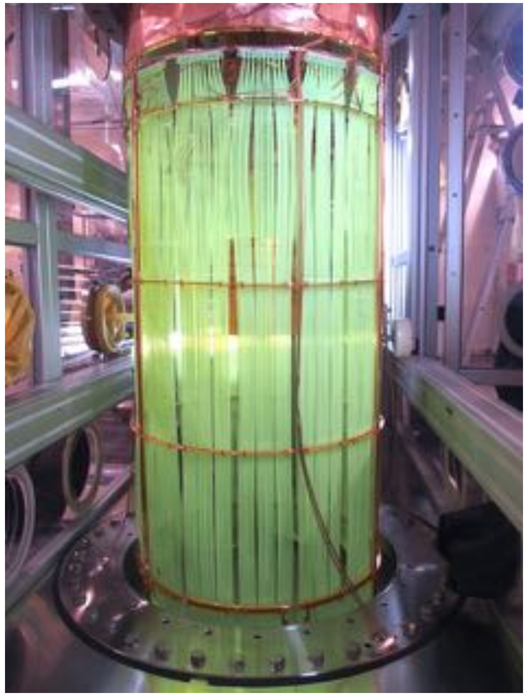
LAr Active Veto



Compton events with energy deposition in the LAr

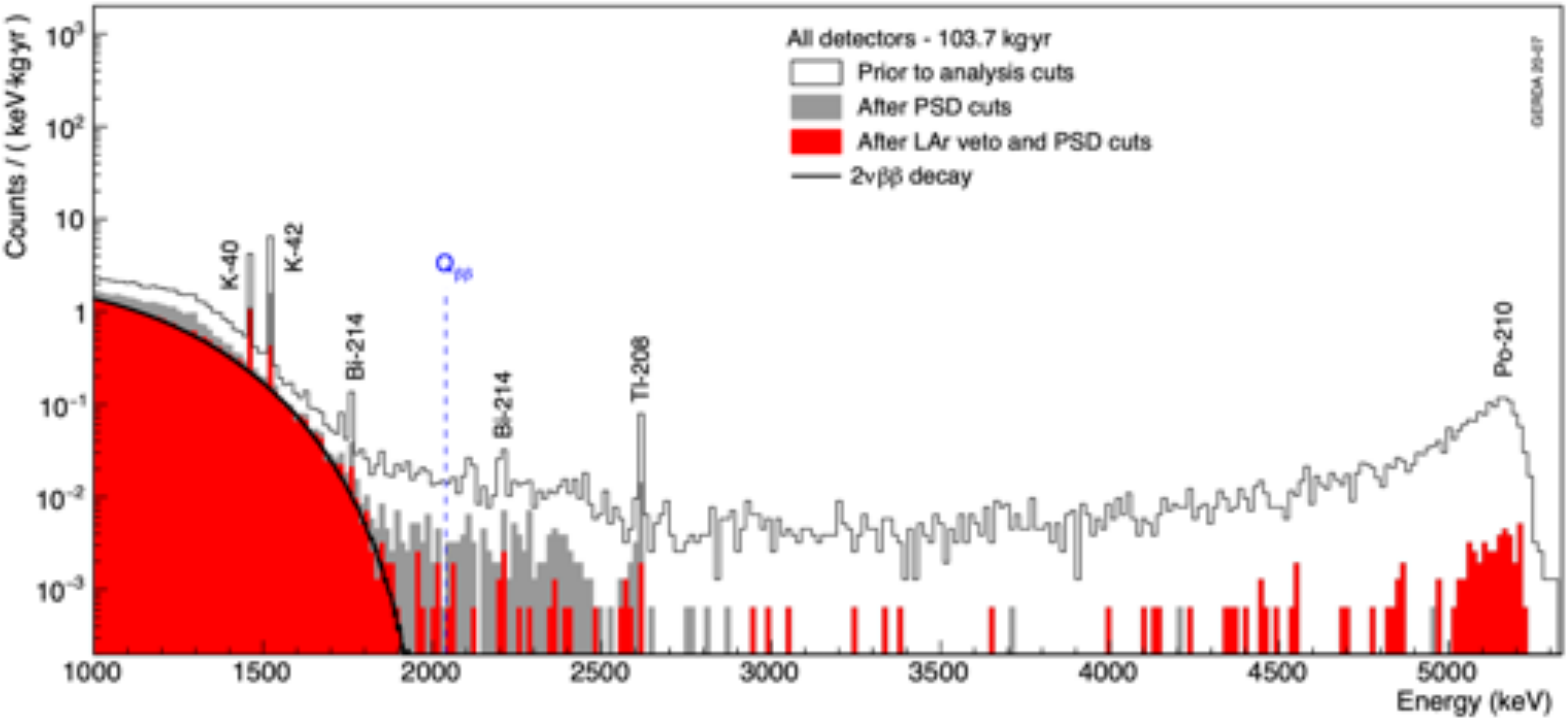
Pure 2νββ spectrum after LAr signal suppression





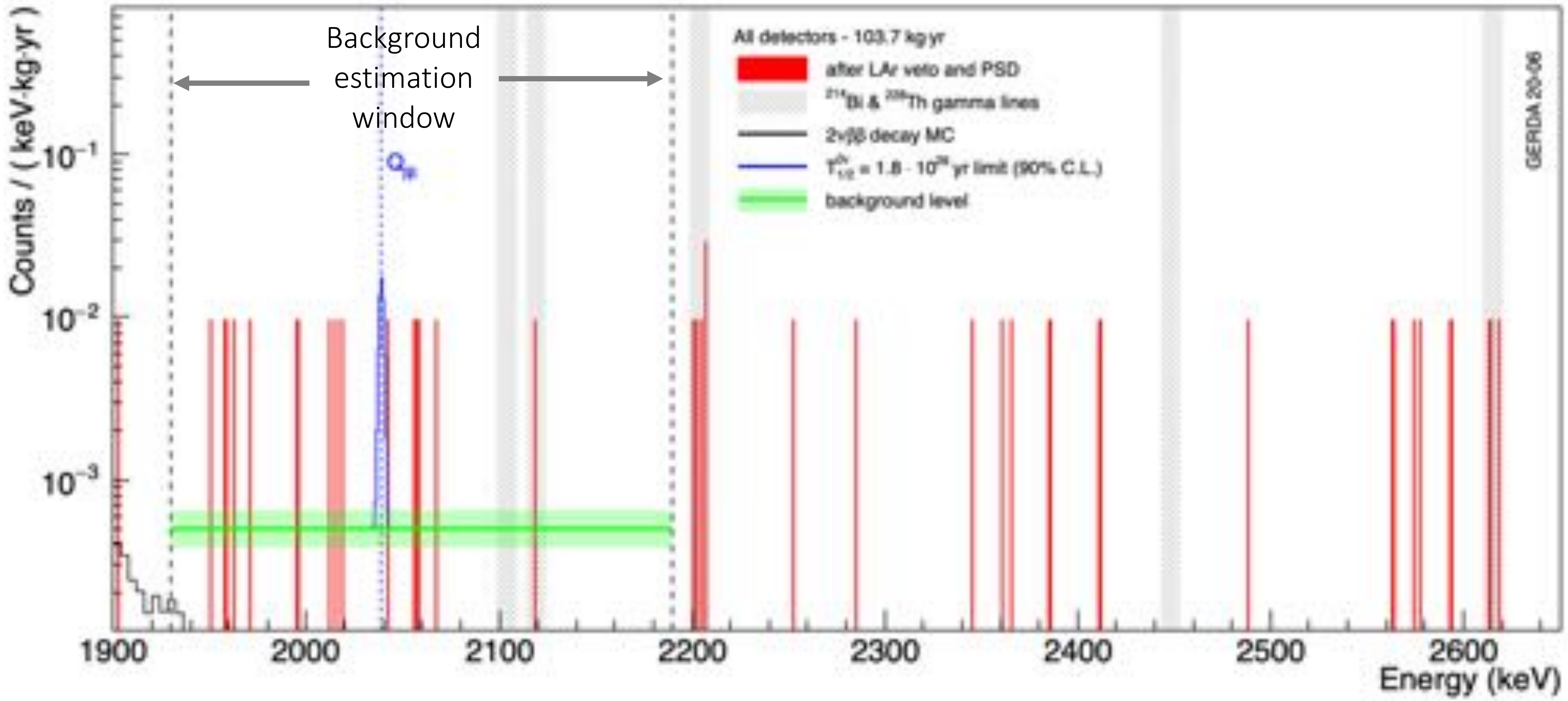
Courtesy of the GERDA Collaboration

Final-Exposure Spectrum



Courtesy of the GERDA Collaboration

Results



PRL 125, 252502 (2020)

Background index: $5.2^{+1.6}_{-1.3} \cdot 10^{-4}$ cts/(keV kg yr),

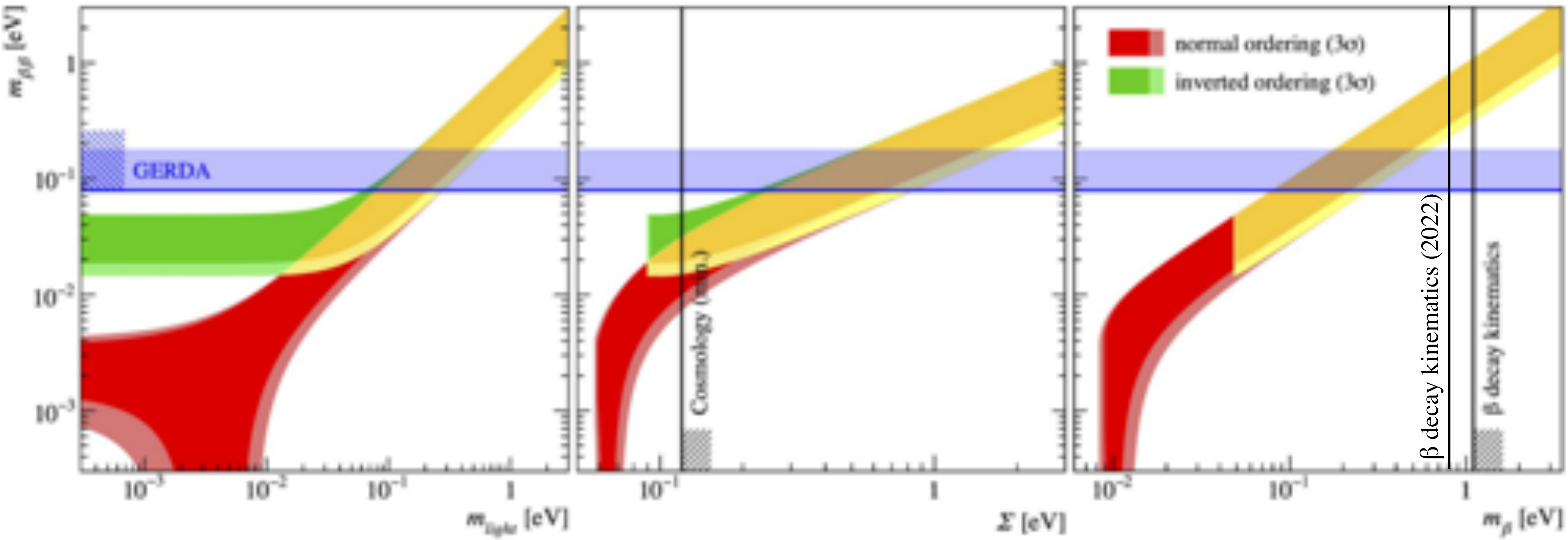
Energy resolution ~3 keV (FWHM)

Frequentist: $N^{0\nu} = 0$ best fit, $T_{1/2} > 1.8 \cdot 10^{26}$ yr at 90% C.L.

Bayesian: flat prior on rate, $T_{1/2} > 1.4 \cdot 10^{26}$ yr at 90% C.I.

Courtesy of the GERDA Collaboration

Constraints on $m_{\beta\beta}$



$m_{\beta\beta}$ < 79 - 180 meV

Planck+BAO: Σ < 0.12 eV
[Aghanim et al., A&A 641 A6 (2020)]

KATRIN: m_{β} < 0.8 eV
[Nat. Phys. 18, 160–166 (2022)]

GERDA finished by surpassing all design goals
(100 kg yr exposure , < 10^{-3} cts/(keV kg yr) background, >10^{26} yr sensitivity)

Courtesy of the GERDA Collaboration

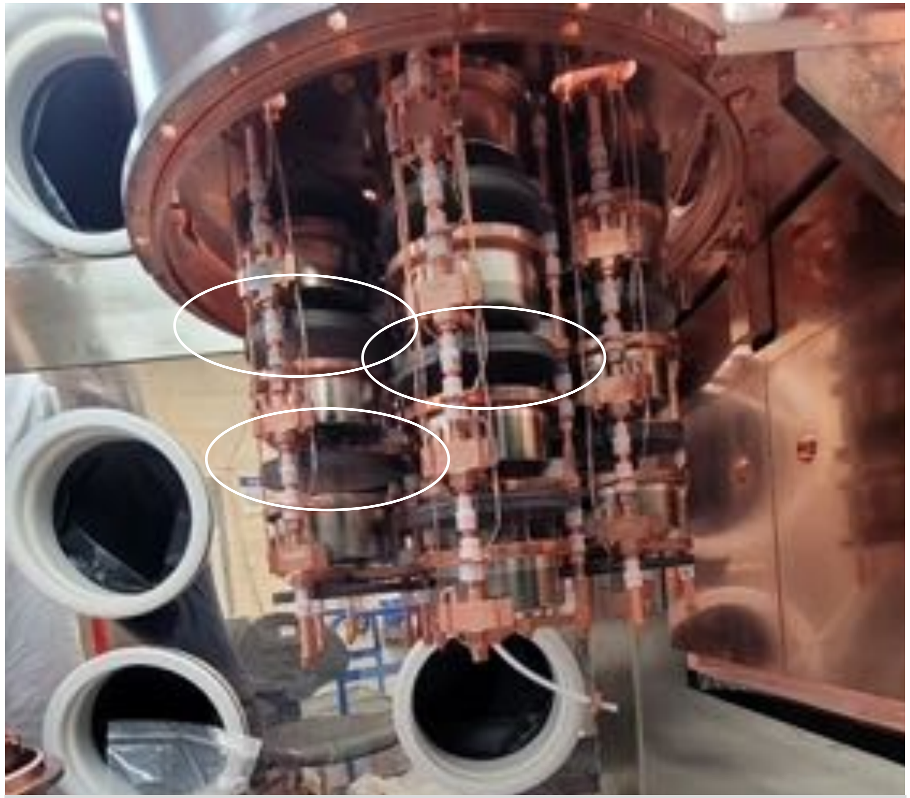
Future Plans for the MAJORANA DEMONSTRATOR and GERDA

The MAJORANA DEMONSTRATOR:

- New BSM physics results coming soon
- Continuing to take data with natural isotopic abundance detectors
- Further background measurements to refine background model
- Ongoing measurement of ^{180m}Ta half-life, nature's longest-lived metastable state

GERDA:

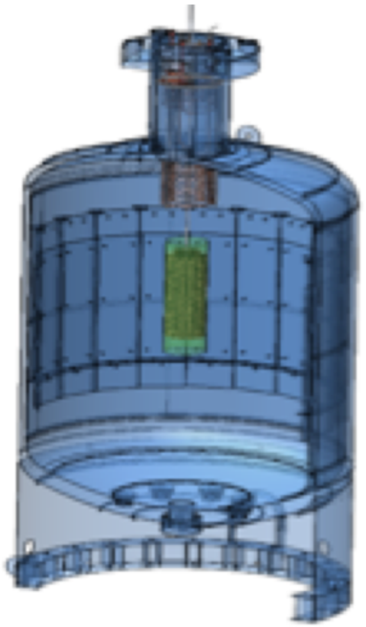
- New BSM physics results coming soon

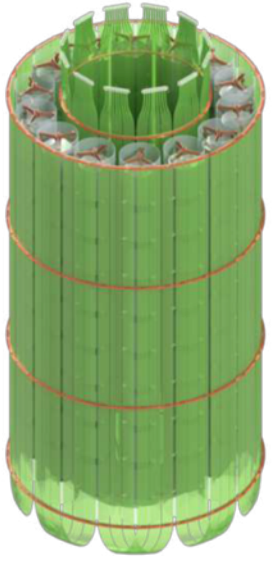


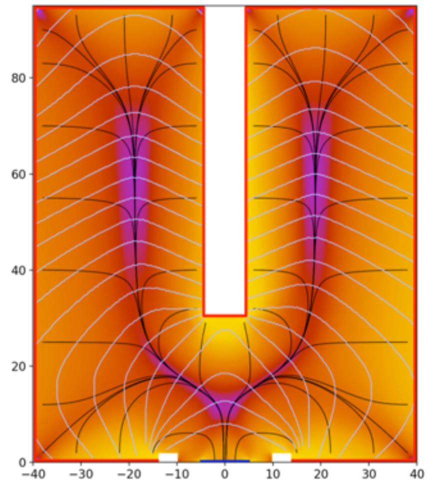
^{180m}Ta plates inserted between detectors

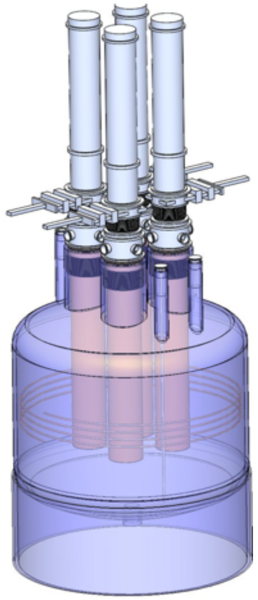
Many MAJORANA and GERDA collaborators, techniques, detectors, and infrastructure are now involved in LEGEND.

Joining Forces: LEGEND







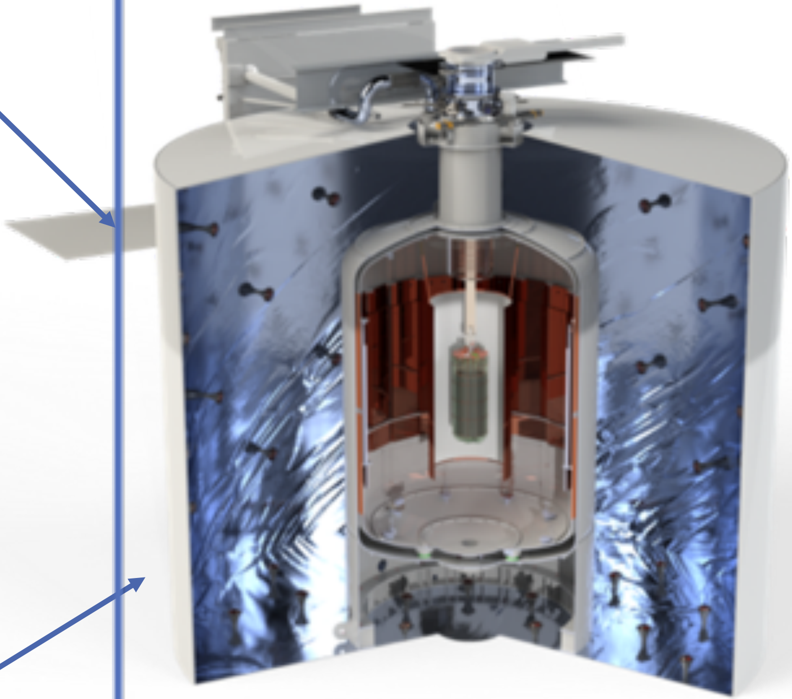


From the Current Generation to the Ton Scale

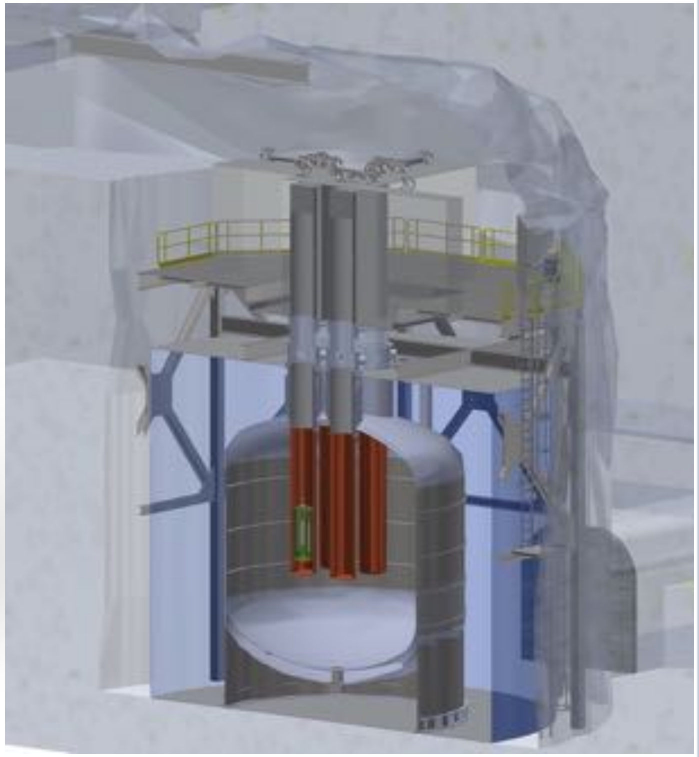
MJD: New final exposure results

GERDA: Final $0\nu\beta\beta$ results published

PRL 125, 252502 (2020)



LEGEND-200: Now in commissioning



LEGEND-1000: Conceptual design development continuing

arXiv: 2107.11462

The LEGEND Collaboration

LEGEND mission: "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."

Approx. 260 members, 50 institutions, 11 countries

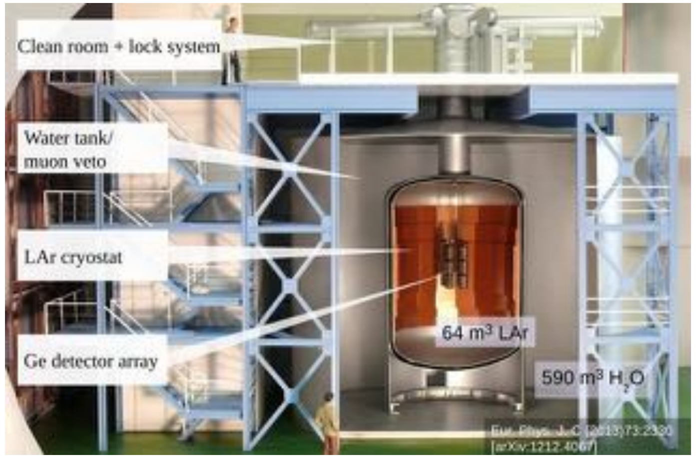
LEGEND Approach: Proven Technologies

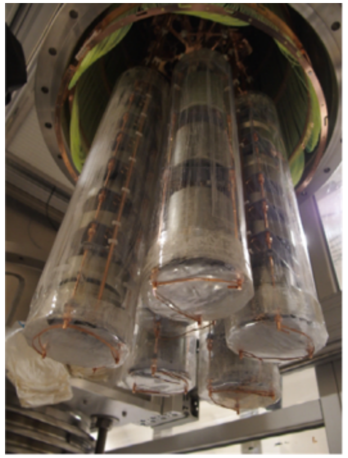
GERDA achieved the lowest background rate: 5×10^{-4} cts/(keV kg yr)

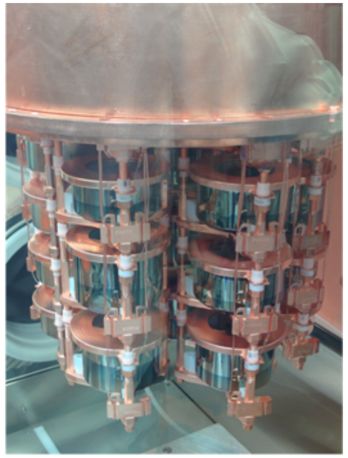
LEGEND-200 plans to improve by only x2.5

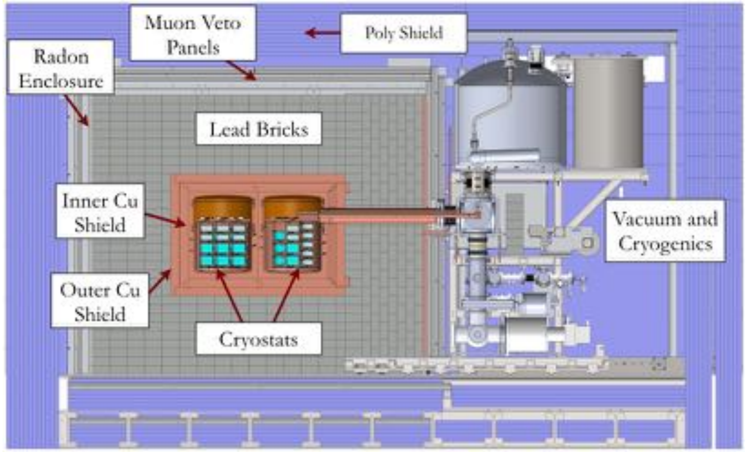
MAJORANA achieved best energy resolution: 2.5 keV FWHM at $Q_{\beta\beta}$

LEGEND plans to maintain this performance









Combine the best of GERDA:

- LAr active veto and instrumentation
- Low-A shielding, no Pb

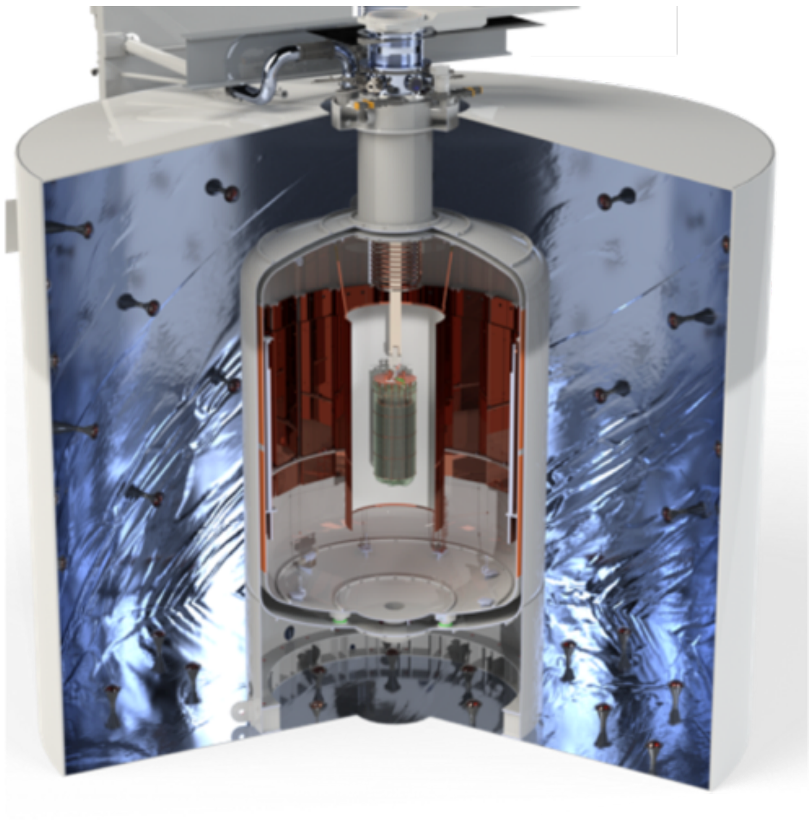
… with the best of MAJORANA:

- Radiopurity of near-detector parts
- Low-noise electronics improves PSD

and techniques developed in both experiments:

- Clean fabrication techniques
- Control of surface exposure
- Development of large point-contact detectors

LEGEND Approach: Phased Deployment



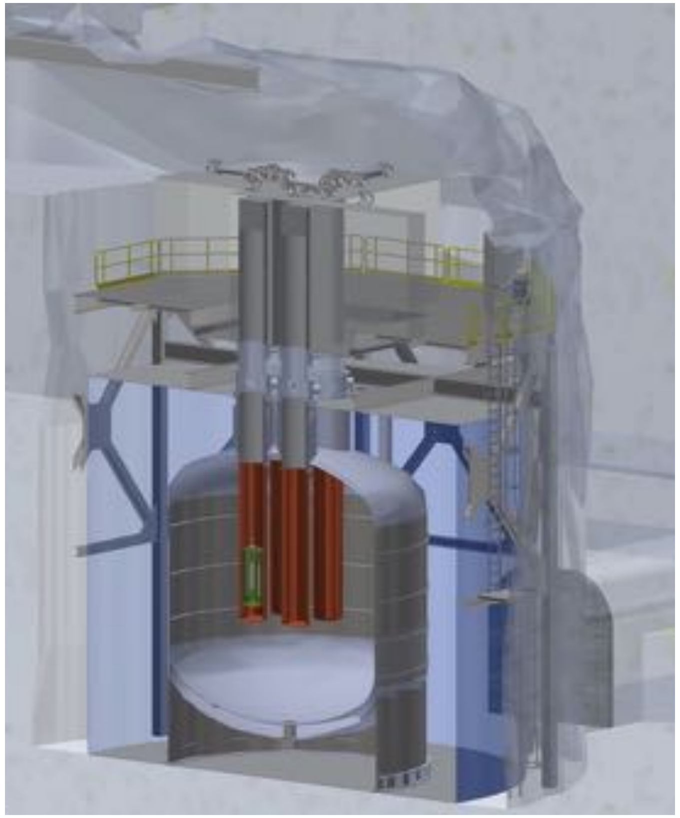
arXiv: 2107.11462

LEGEND-200:

- 200 kg, upgrade of existing GERDA infrastructure at Gran Sasso
- 2.5 keV FWHM resolution
- Background goal

  < 0.6 cts/(FWHM t yr)

  < $2x10^{-4}$ cts/(keV kg yr)
- Now in commissioning, physics data starting in 2022



LEGEND-1000:

- 1000 kg, staged via individual payloads (~400 detectors)
- Timeline connected to review process
- Background goal <0.025 cts/(FWHM t yr),<$1x10^{-5}$ cts/(keV kg yr)
- Location to be selected

LEGEND-200 Design and Commissioning

Improvements from GERDA/MJD:

- Larger detectors
- Improved LAr light collection: higher purity Ar and improved readout
- Cleaner, lower mass cables
- Lower noise electronics
- UGEFCu and self-vetoing PEN plated for detector mounts

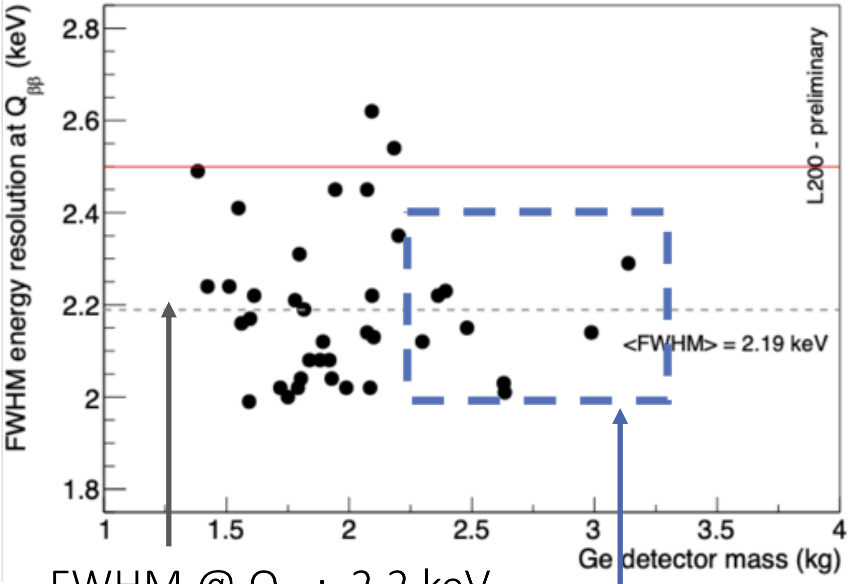
→ Factor of 3 reduction in backgrounds relative to GERDA

Quasi-background free operation up to 1 ton-year exposure, for unambiguous discovery up to 10^{27} yrs

Photo: Enrico Sacchetti

Detector Characterization:

ICPC Energy Resolution



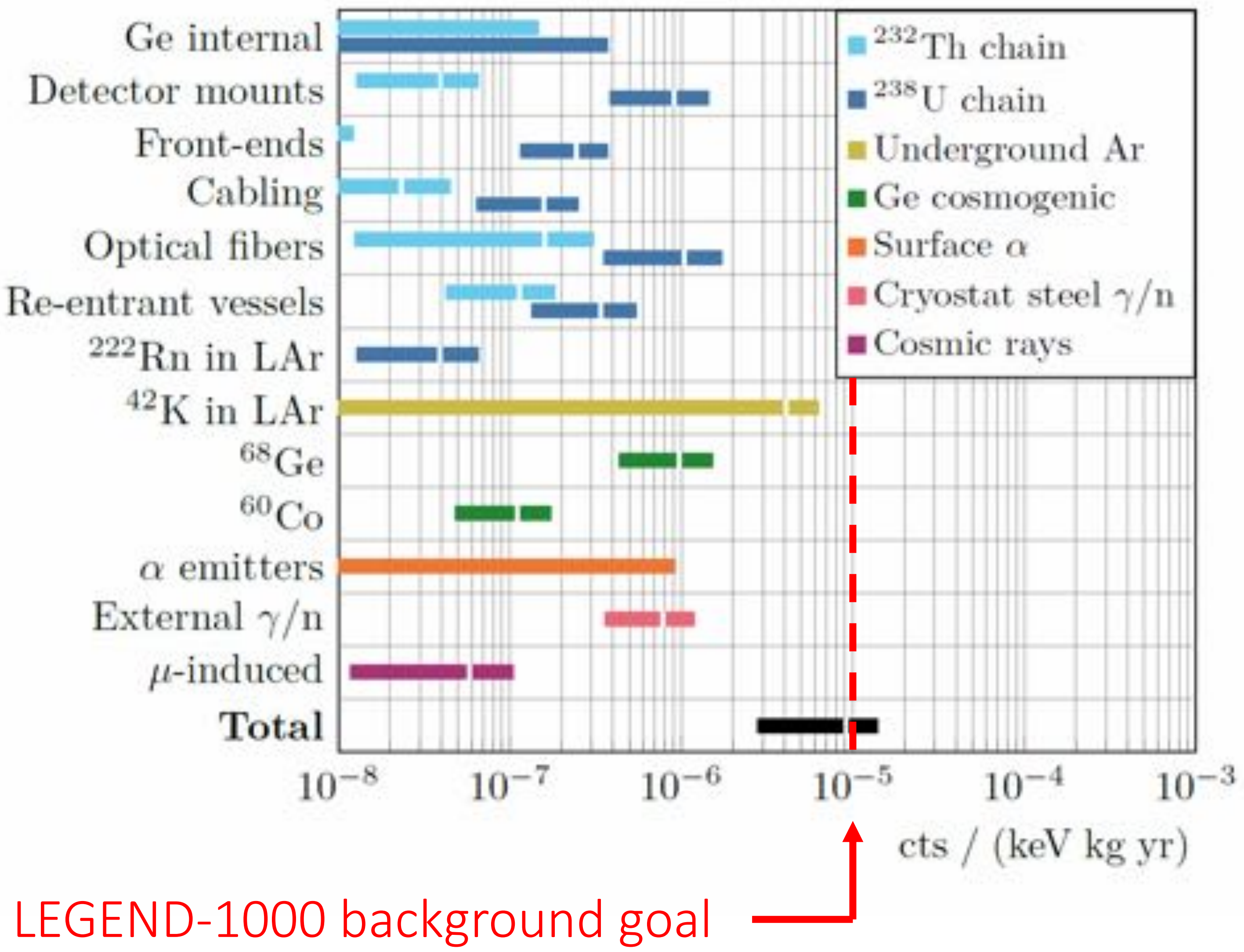
FWHM @ $Q_{\beta\beta}$: 2.2 keV

Large-mass detectors show excellent energy resolution

First integrated commissioning run now underway:
4 strings of HPGe detectors, operating with full LAr system

LEGEND-1000 Background Projections

Background index at $Q_{\beta\beta}$ after all cuts



Improvements from LEGEND-200:

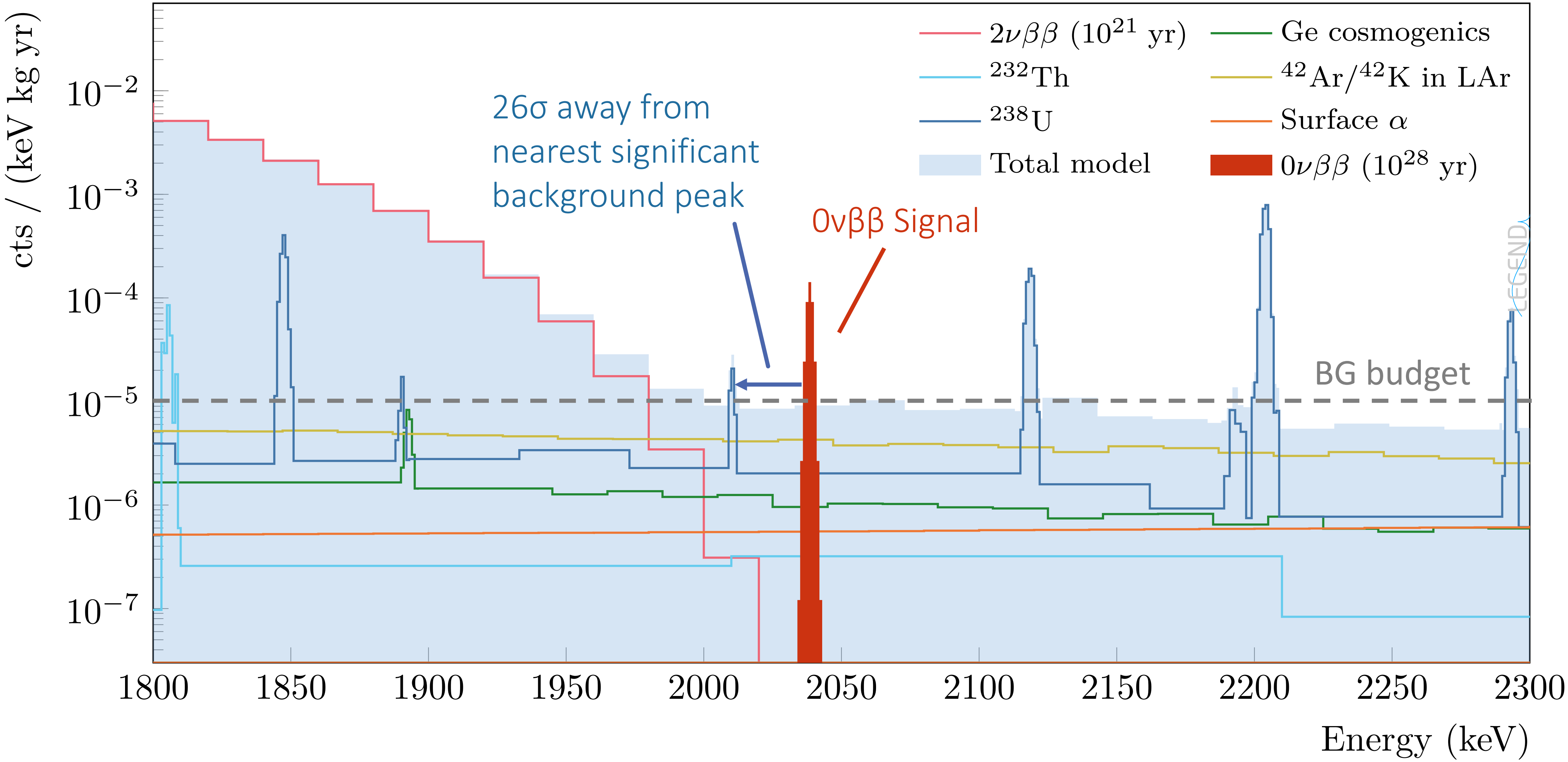
- Larger detectors (2.6 kg avg)
- New cables and ASIC read-out
- Underground Ar surrounding detectors
- Optimized array spacing and LAr instrumentation
- Deeper underground site or additional neutron shielding & tagging: SNOLAB and LNGS options

Projected background index after all cuts:

$$9.4^{+4.9}_{-6.3} \times 10^{-6}\ \text{counts/(keV kg yr)}$$

Quasi-background free operation up to 10 ton-year exposure, for unambiguous discovery beyond 10^{28} years

The LEGEND-1000 Background Model



LEGEND Status

LEGEND-200:

- Upgrade and stand-alone commissioning of the LAr system completed
- 2020 ICPC deployment in LAr with LEGEND electronics demonstrated excellent energy resolution
- First integrated commissioning run now underway!
- First physics data-taking this year

Initial Commissioning: 4 Detector Strings *Ongoing* → Follow-up Commissioning & Physics Data: 10 Detector Strings *Fall 2022* → LEGEND-200 Final Goal: 14 Detector Strings *2023*

LEGEND-1000:

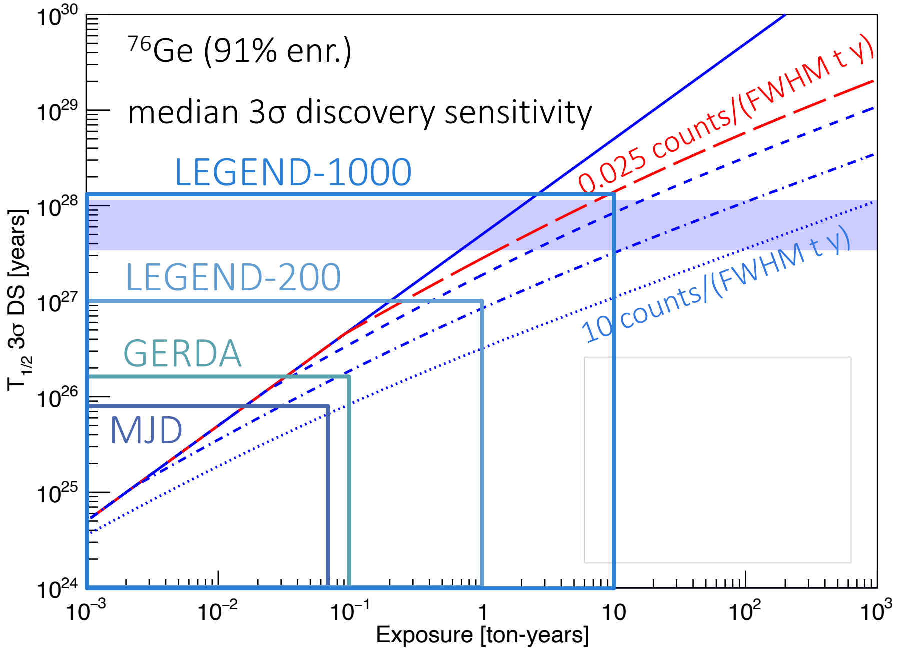
- Pre-Conceptual Design Report:
  arXiv: 2107.11462
- Developing a conceptual design with an refined technical design and background model, proceeding to CD-1
- R&D activities are ongoing

Currently underway:

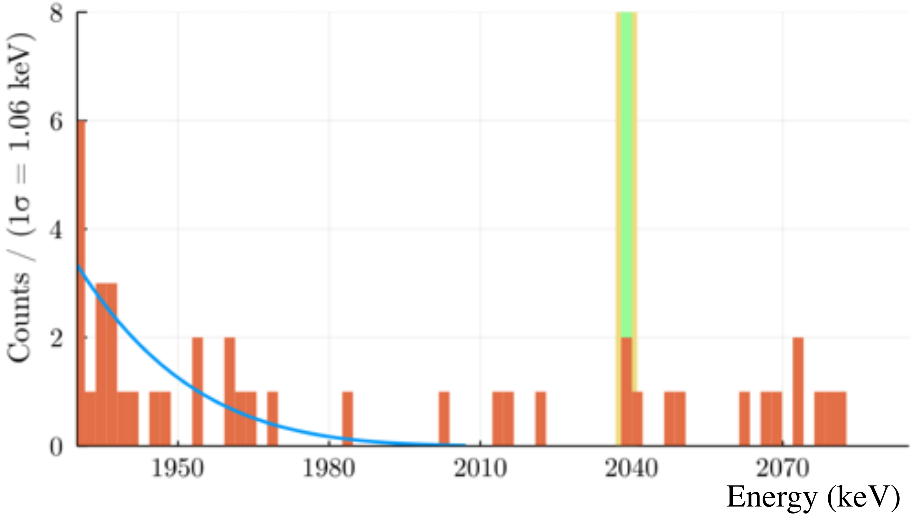
4 string commissioning

Discovering 0νββ with ^{76}Ge

- ^{76}Ge is a clear leading choice for a ton-scale search: experiments are optimized for an unambiguous discovery of 0νββ
- Current-generation experiments have led the field
  - New full-exposure results from the MAJORANA DEMONSTRATOR: $T_{1/2} > 8.3 \times 10^{25}$ yr
  - Full-exposure results from GERDA: $T_{1/2} > 1.8 \times 10^{26}$ yr
- The LEGEND program builds on these successes for a low-risk path to exploring half-lives beyond 10^{28} yrs
  - LEGEND-200 is in commissioning, with data-taking beginning later this year
  - LEGEND-1000 pre-conceptual design available, with R&D and conceptual design development ongoing



Simulated LEGEND-1000 example spectra for $T_{1/2} = 10^{28}$ yrs, BI < 10^{-5} cts/keV kg yr, after cuts, from 10 years of data



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- We thank our hosts and colleagues at LNGS and SURF
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MJD, GERDA, and LEGEND Posters at this Conference

- Background Modeling for the Majorana Demonstrator, E. Bialock, C. Haufe, and A. Reine
- The Analysis and New Results from the Full Dataset of the Majorana Demonstrator, I. Guinn, A. Hostiuc, T. Oli, and N. W. Ruof
- The analysis and performance of the Inverted-Coaxial Point-Contact detectors in the Majorana Demonstrator experiment, J.M.López-Castaño
- New limits on the sterile neutrino transition magnetic moment from the Majorana Demonstrator, C. Wiseman, I. Kim, and J. M. López-Castaño
- Topologies of 76Ge $0\nu\beta\beta$-decay events and precision of calibration procedures, T. Comellato, M. Agostini, S. Schönert
- New results on exotic double-beta decay modes of 76Ge from GERDA Phase II, E. Bossio
- The LEGEND-200 LAr instrumentation: from design to commissioning, N. Burlac and E. Shevchik
- Integration & Commissioning of LEGEND-200, M. Willers
- Filling and purification of large volume of liquid argon for LEGEND-200, M. Harańczyk
- Photon emission time spectra in liquid argon, M. Schwarz
- Strategies for cosmogenic $^{77(m)}$Ge reduction for LEGEND-1000 experiment, M. Morella and M. Neuberger
- Optical properties of liquid argon with sub-ppm level nitrogen doping, M. Harańczyk and M. Schwarz
- BSM physics searches with LEGEND-1000, I. Kim
- Preliminary Background Model for LEGEND-1000, R. Gala