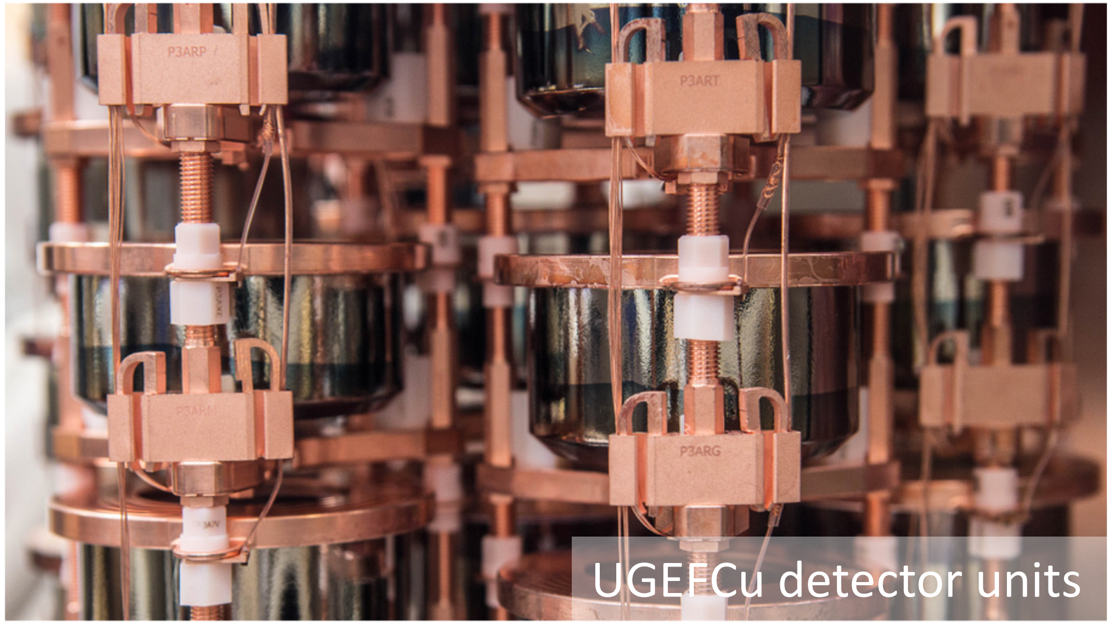
Neutrinoless Double-Beta Decay with Germanium

Julieta Gruszko

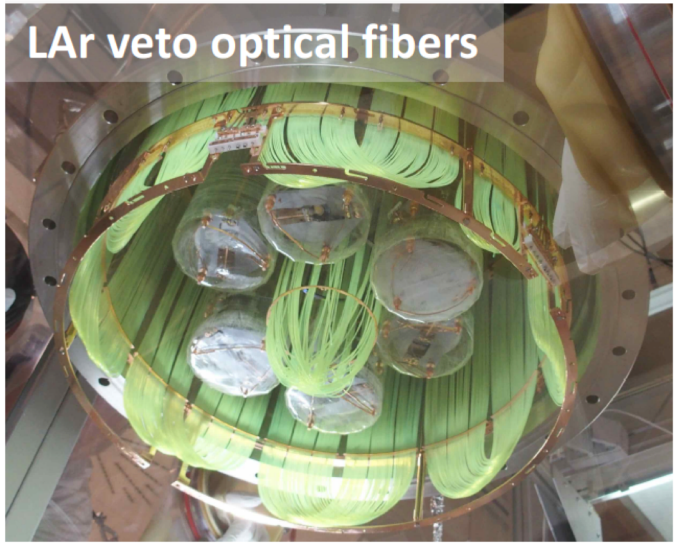
SNOWMASS Mini Workshop:
$0\nu\beta\beta$ Experiment I

August 5, 2020

Outline



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

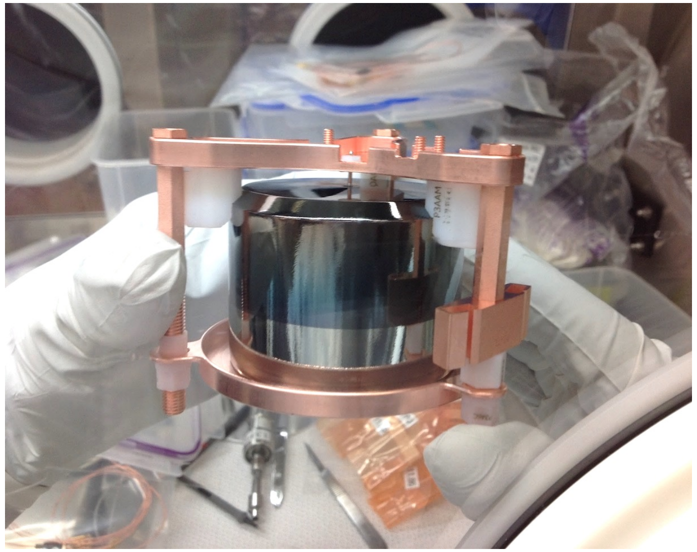


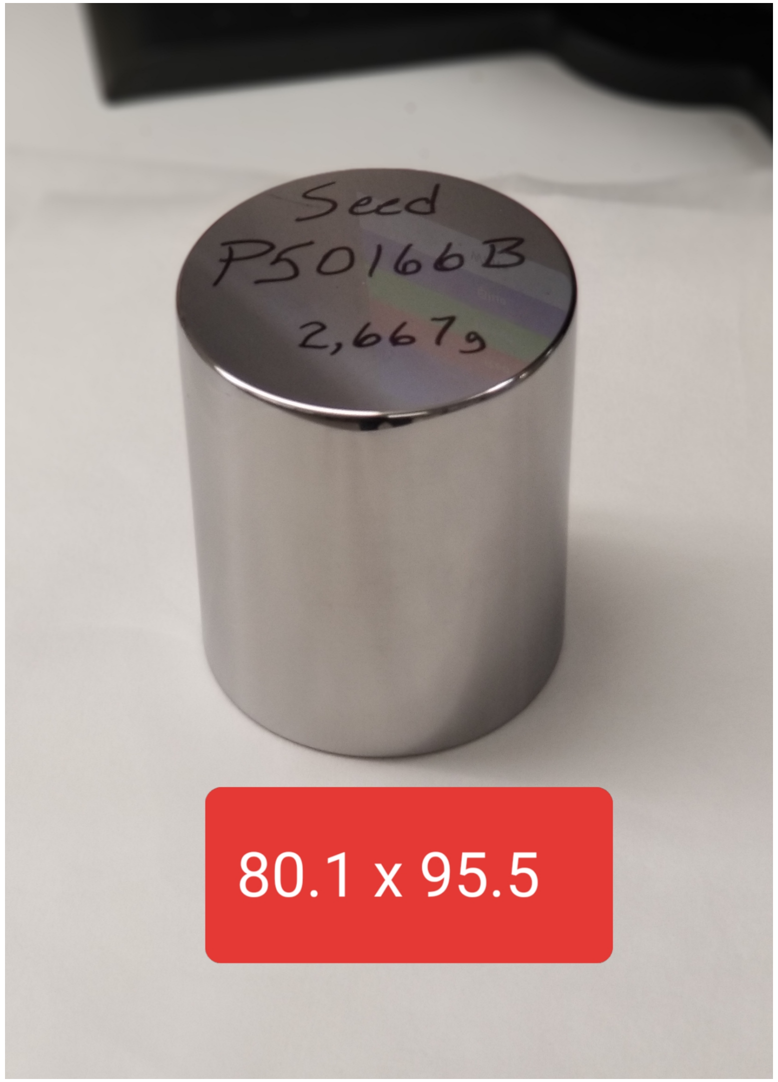
GERDA

LEGEND

HPGe Detectors

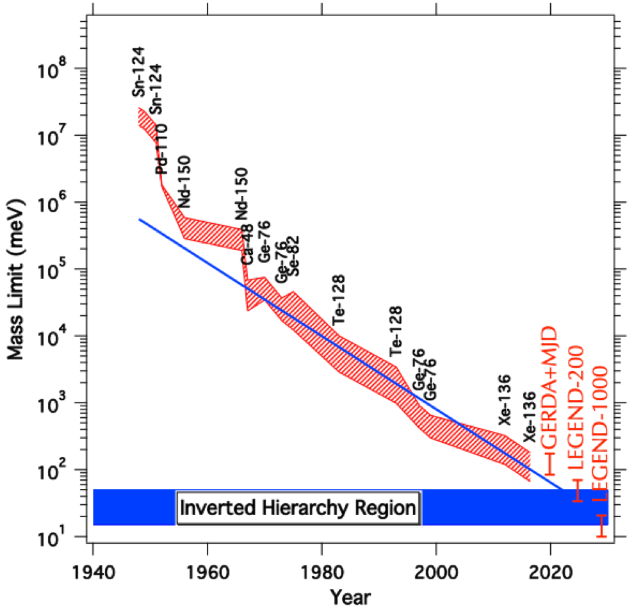
- Single-crystal diodes operated under reverse bias, at 77-90K
- Best energy resolution among 0νββ candidate technologies: approaching 0.1% at 2039 keV (~2.5 keV FWHM)
- Energy scale linear to ~0.01%, stable long-term operation with minimal maintenance
- Compact non-volatile solid, 2-3 kg detectors
- Commercial-scale production by several companies



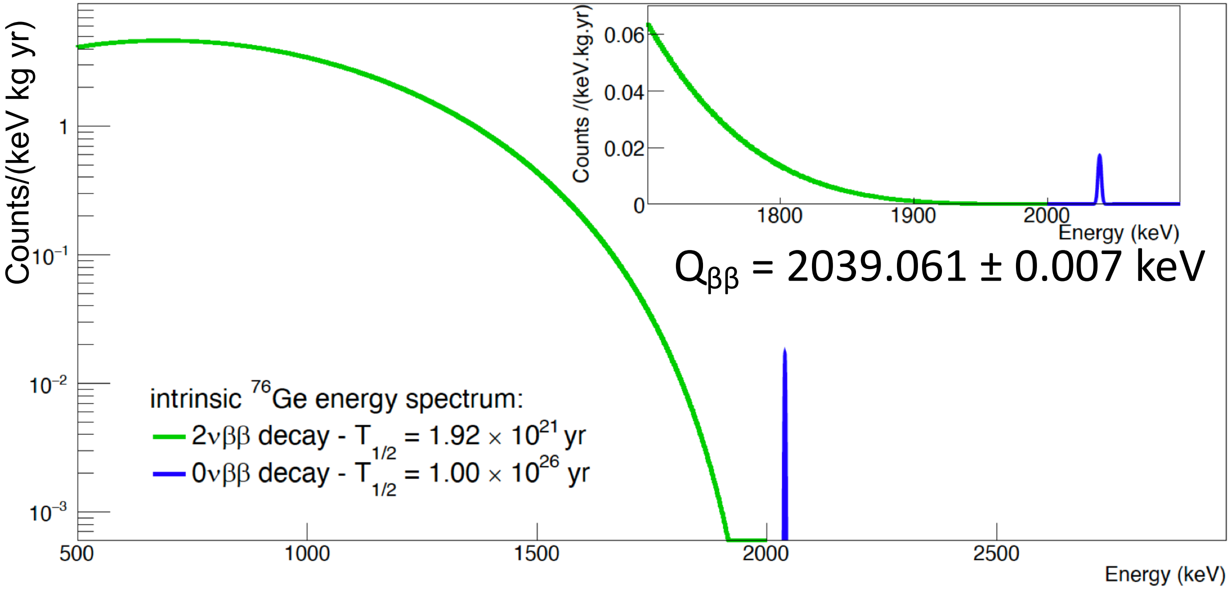


HPGe Detectors for 0νββ

- Able to enrich from 7.75% to ≥92% ^{76}Ge
  - Total natural mass required for ton scale <10% yearly world production
  - Enrichment costs stable; large, reliable global supply
- Intrinsic high-purity Ge detectors = source
  - Effective use of all enriched material (>90%)
  - High efficiency (~70% after all cuts)
- No prominent background lines within many FWHM, 2νββ background negligible
- Lowest (GERDA) and 2nd lowest (MJD) achieved $Q_{\beta\beta}$ background levels per FWHM
  - Multiplicity, timing, active veto shielding
  - Pulse-shapes used for fiducialization and event topology discrimination



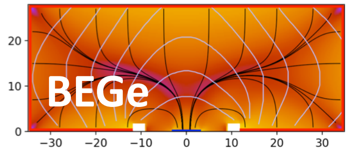
Courtesy of S. Elliott

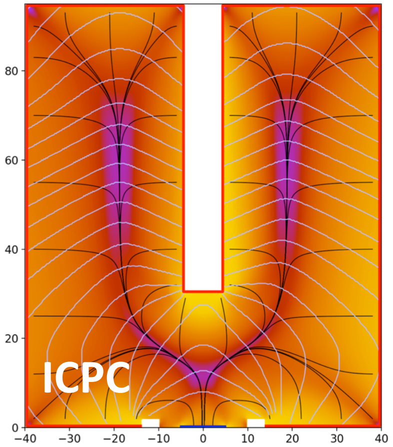


$Q_{\beta\beta}$ = 2039.061 ± 0.007 keV

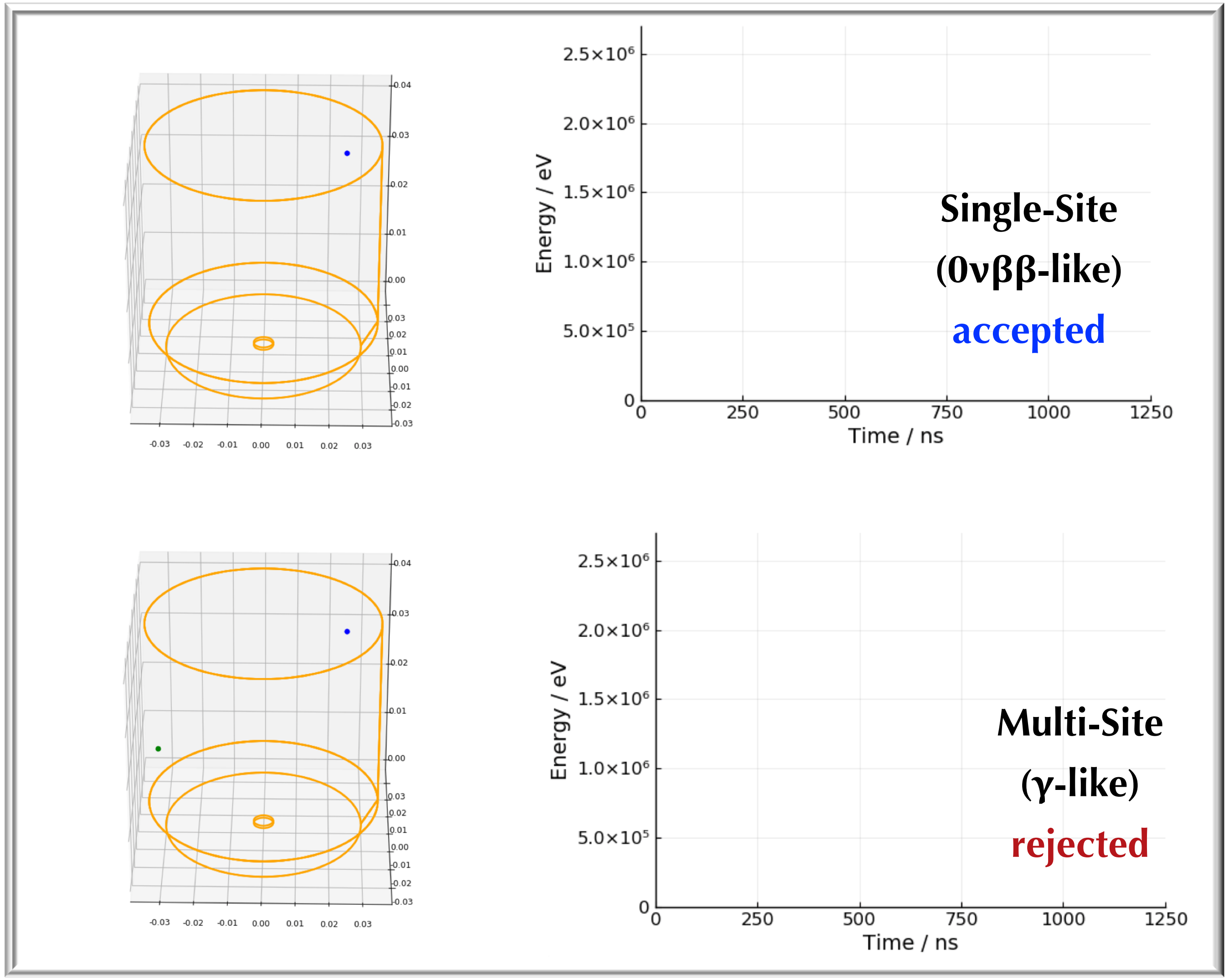
Fiducialization and Event Topology in HPGe

- Point-contact geometry allows for multi-site event rejection based on pulse shapes
  - Compton continuum gamma backgrounds reduced by 50%
  - New ICPC geometry keeps event topology while increasing mass x2-3
- Distinctive pulse shapes near surfaces allow for fiducialization
  - Surface α and β events reduced ≥ 99%





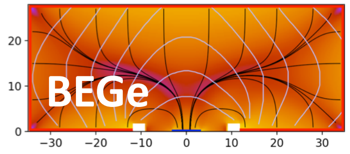
Speed (cm/μs) with paths and isochrones

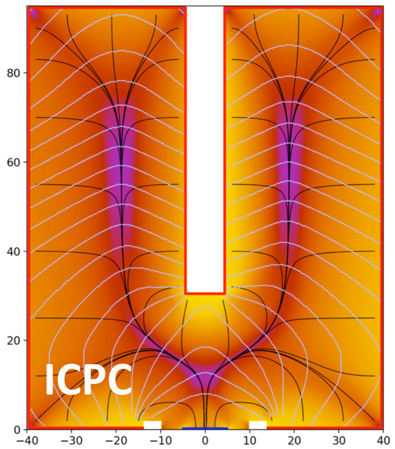


Courtesy of David Hervas

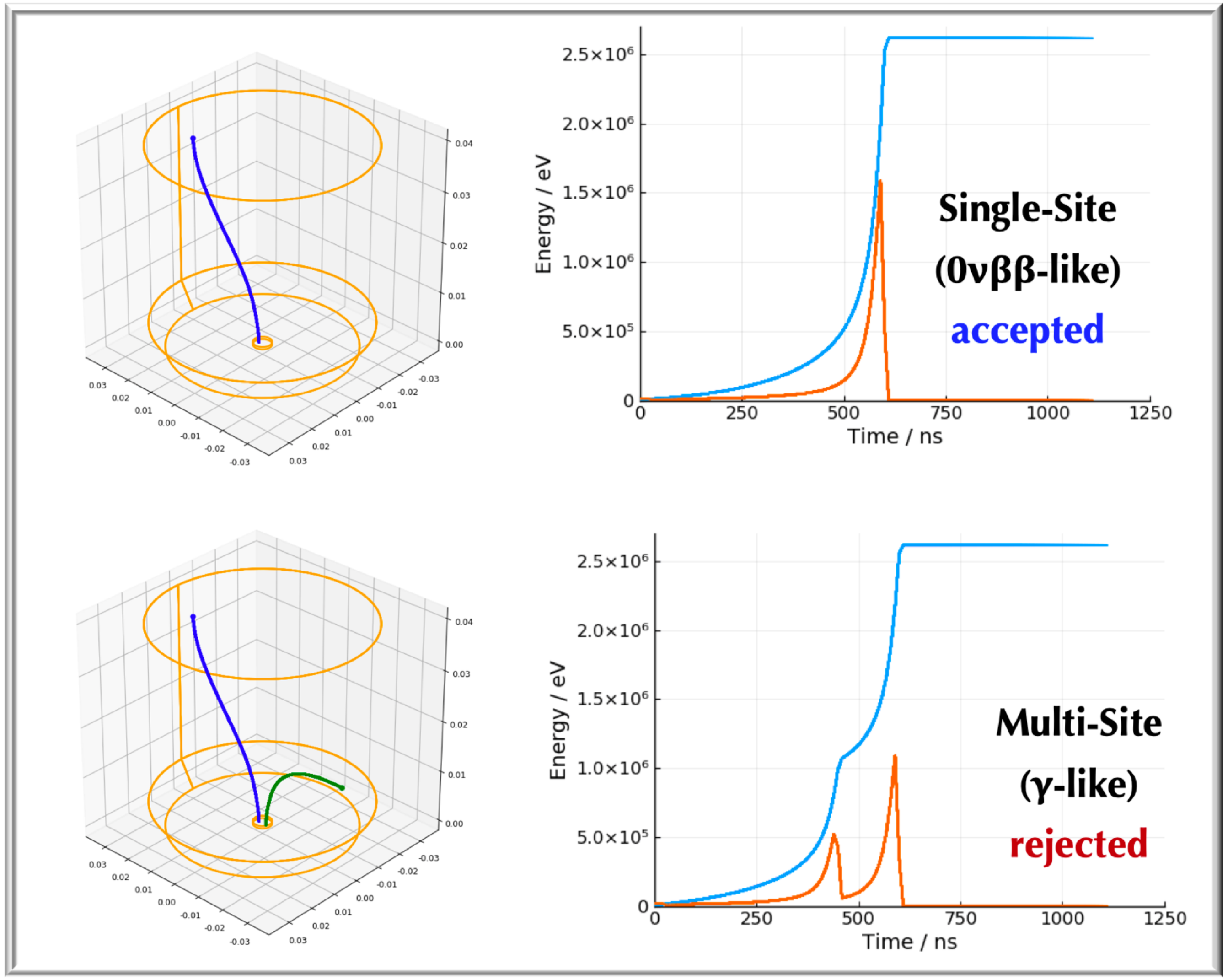
Fiducialization and Event Topology in HPGe

- Point-contact geometry allows for multi-site event rejection based on pulse shapes
  - Compton continuum gamma backgrounds reduced by 50%
  - New ICPC geometry keeps event topology while increasing mass x2-3
- Distinctive pulse shapes near surfaces allow for fiducialization
  - Surface α and β events reduced ≥ 99%





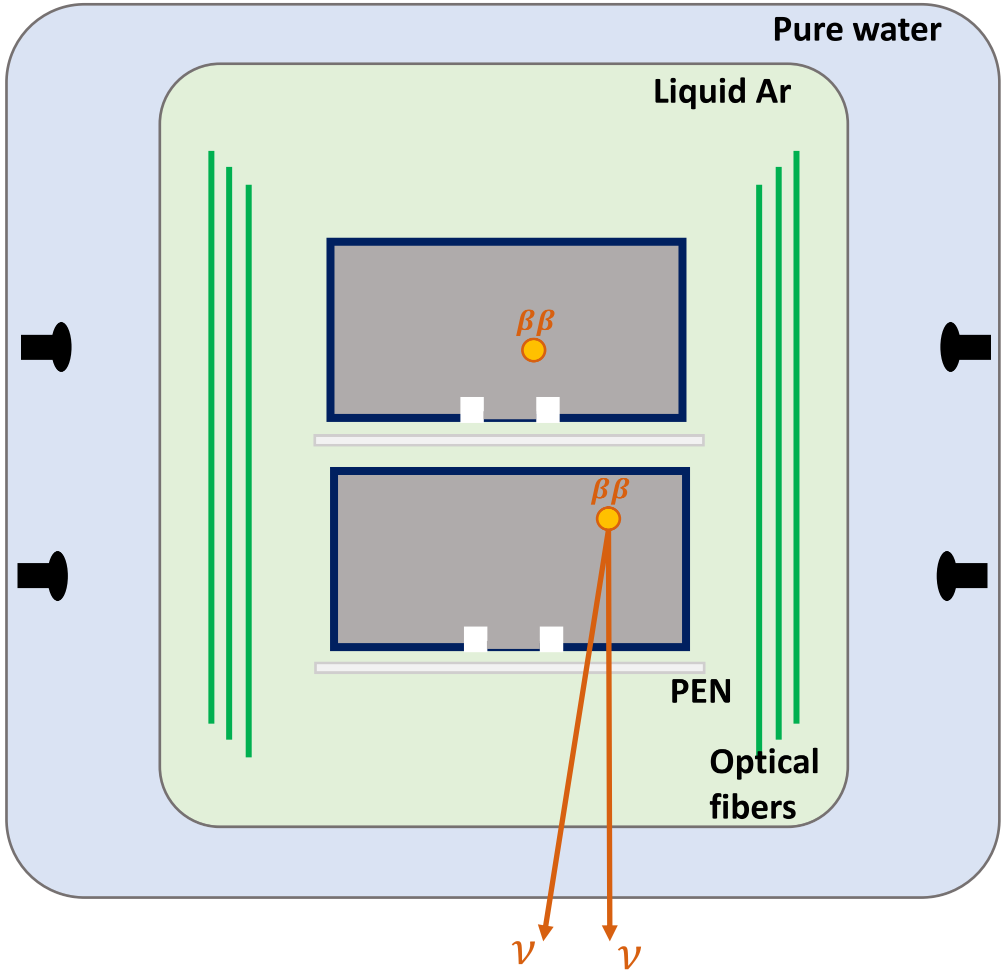
Speed (cm/µs) with paths and isochrones



Courtesy of David Hervas

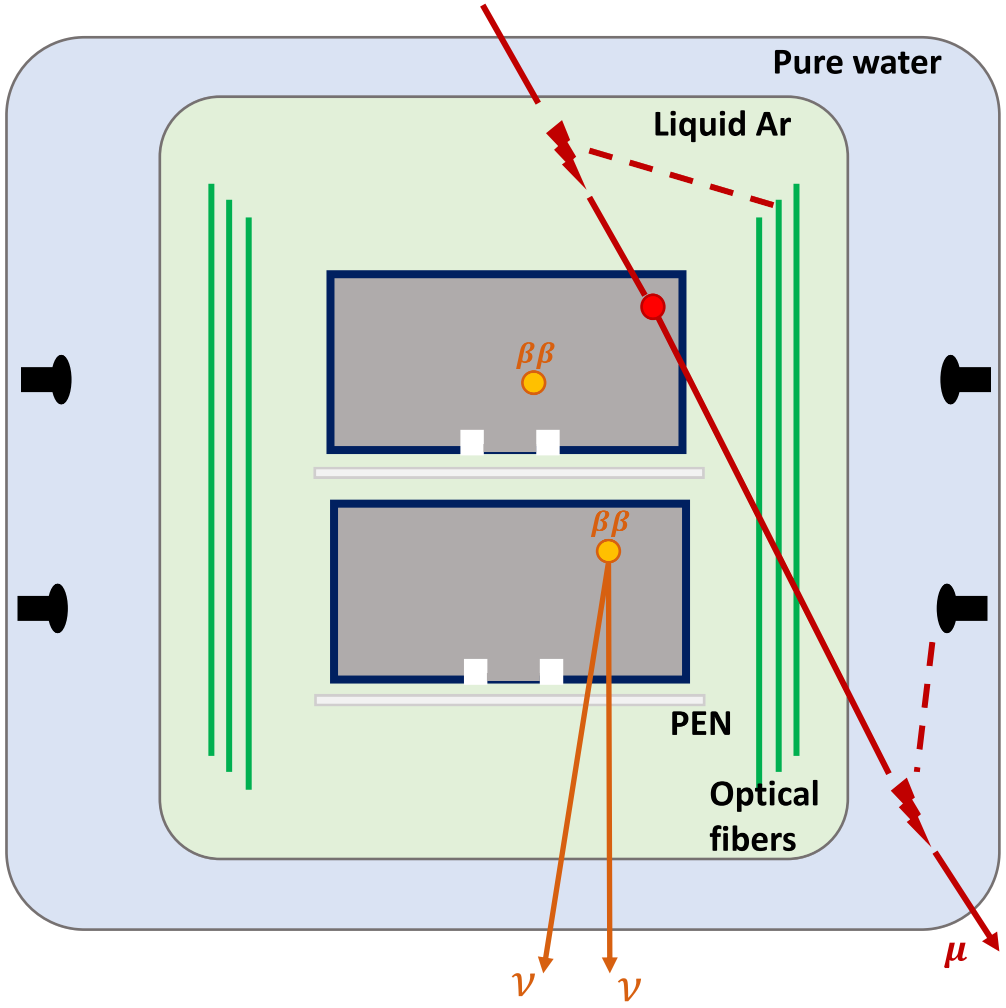
Background Reduction in HPGe Experiments

$\beta\beta$ decay signal: single energy deposition in a 1 mm^3 volume



Background Reduction in HPGe Experiments

$\beta\beta$ decay signal: single energy deposition in a 1 mm^3 volume

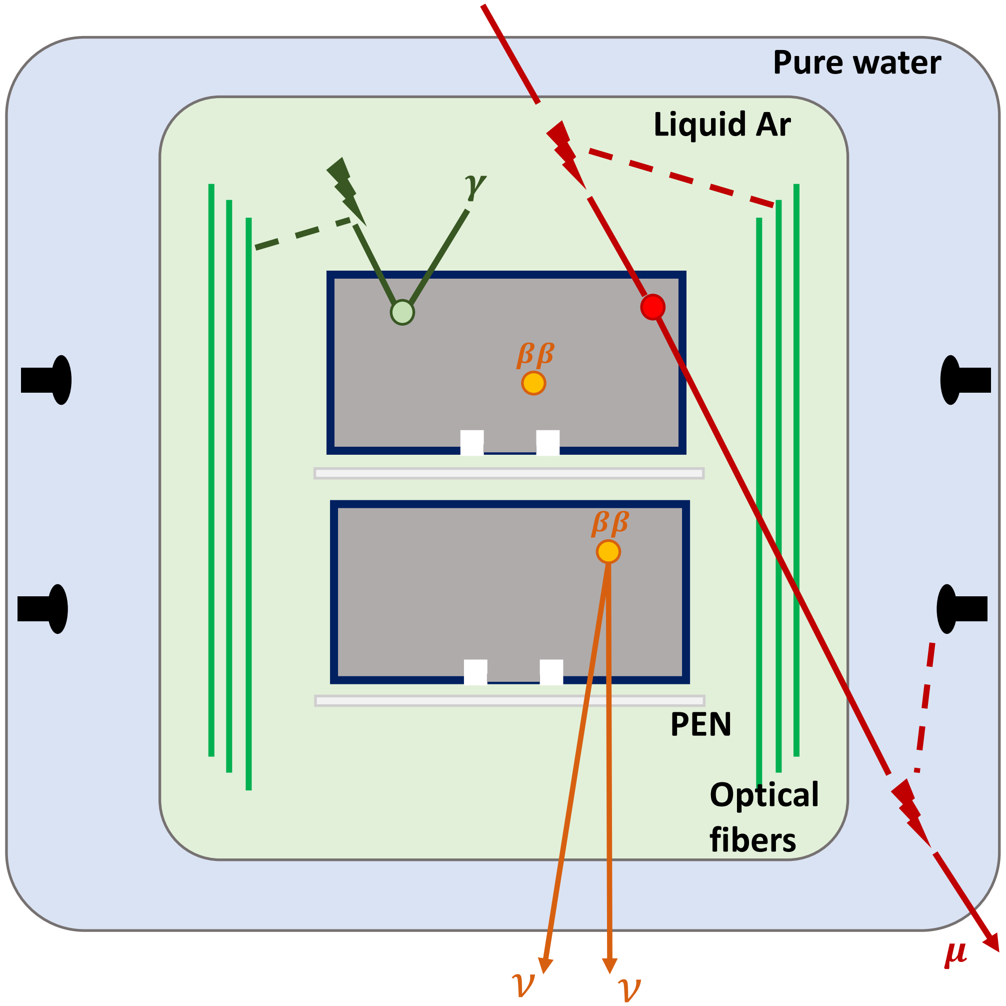


Muon veto based on Cherenkov light and/or plastic scintillator

MJD, GERDA, LEGEND

Background Reduction in HPGe Experiments

$\beta\beta$ decay signal: single energy deposition in a 1 mm^3 volume



LAr veto based on Ar scintillation light read by fibers and PMT

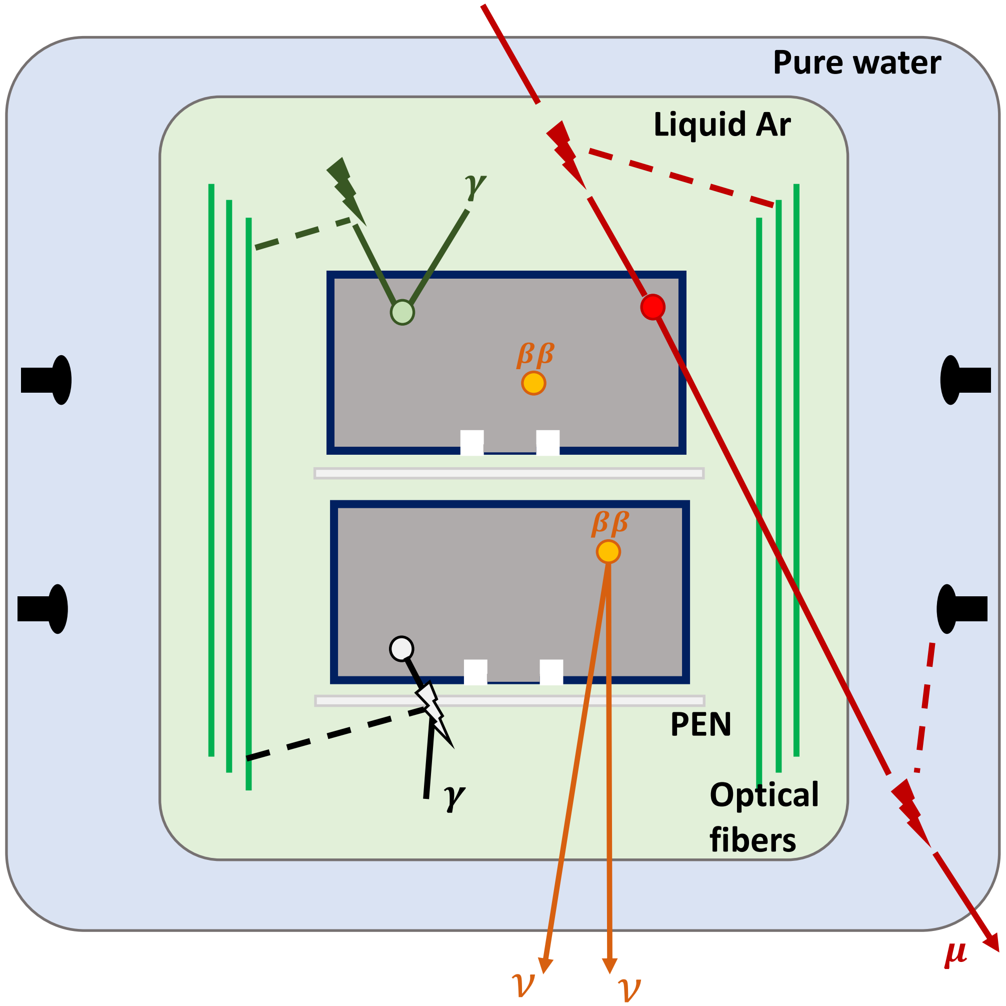
GERDA, LEGEND

Muon veto based on Cherenkov light and/or plastic scintillator

MJD, GERDA, LEGEND

Background Reduction in HPGe Experiments

$\beta\beta$ decay signal: single energy deposition in a 1 mm^3 volume



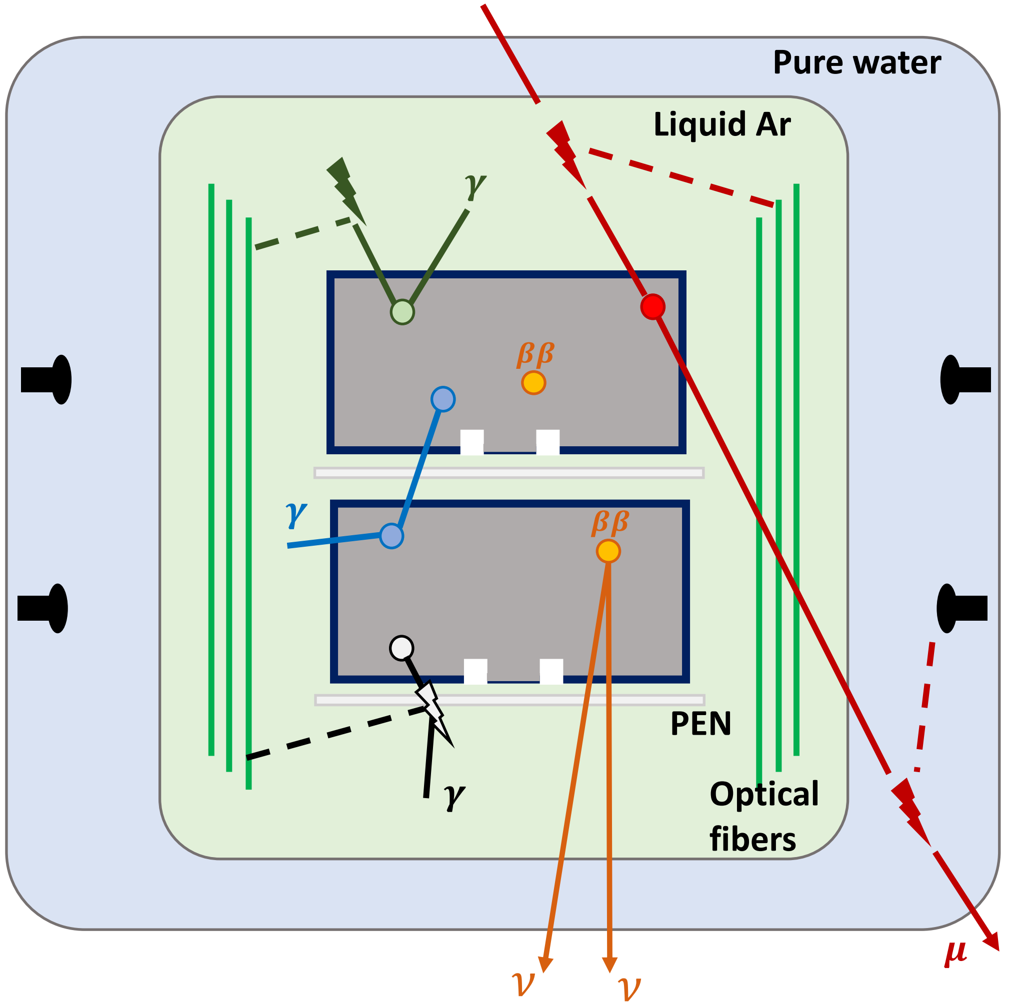
Scintillating PEN plate holder (under test) — LEGEND

LAr veto based on Ar scintillation light read by fibers and PMT — GERDA, LEGEND

Muon veto based on Cherenkov light and/or plastic scintillator — MJD, GERDA, LEGEND

Background Reduction in HPGe Experiments

$\beta\beta$ decay signal: single energy deposition in a 1 mm^3 volume



Ge detector anti-coincidence — MJD, GERDA, LEGEND

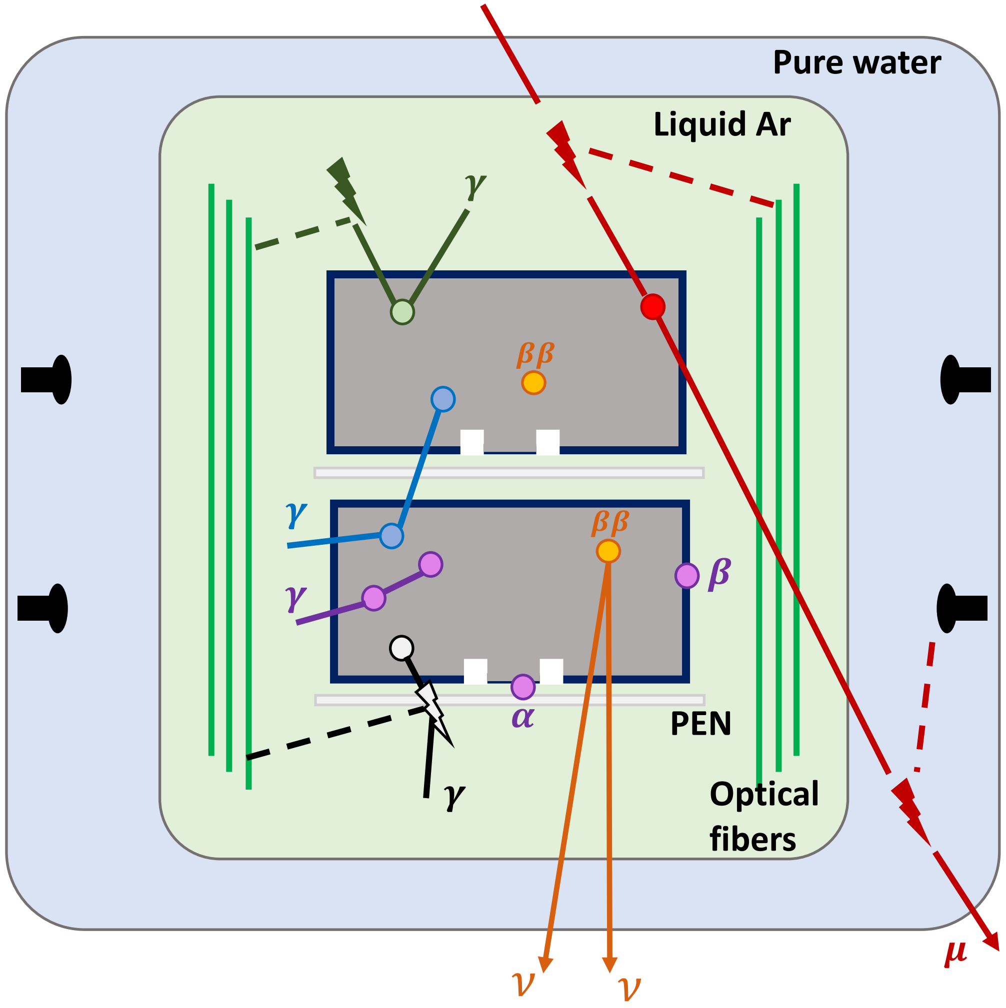
Scintillating PEN plate holder (under test) — LEGEND

LAr veto based on Ar scintillation light read by fibers and PMT — GERDA, LEGEND

Muon veto based on Cherenkov light and/or plastic scintillator — MJD, GERDA, LEGEND

Background Reduction in HPGe Experiments

$\beta\beta$ decay signal: single energy deposition in a 1 mm^3 volume



Pulse shape discrimination (PSD) for multi-site and surface α events — MJD, GERDA, LEGEND

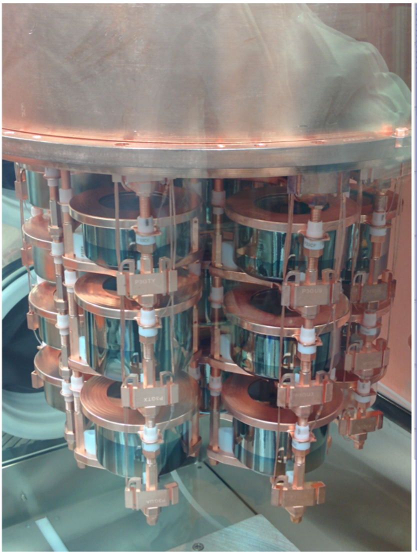
Ge detector anti-coincidence — MJD, GERDA, LEGEND

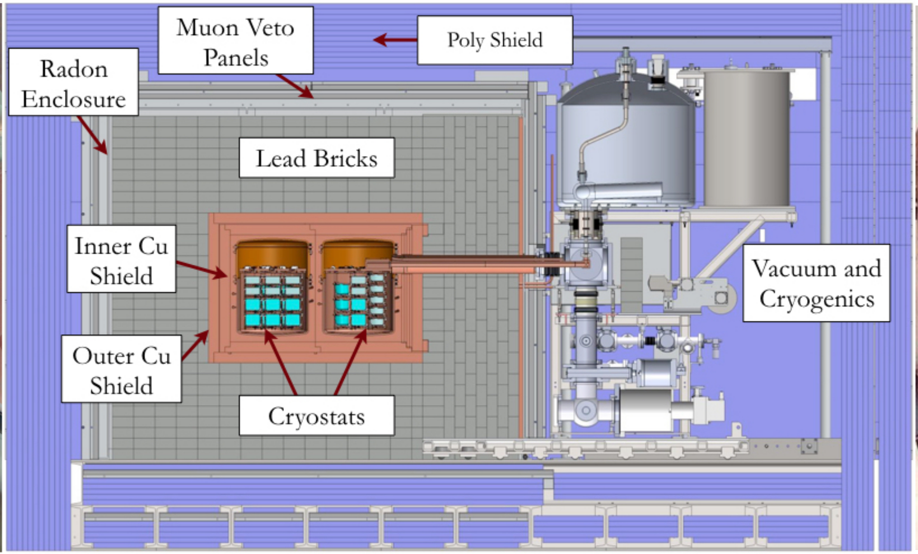
Scintillating PEN plate holder (under test) — LEGEND

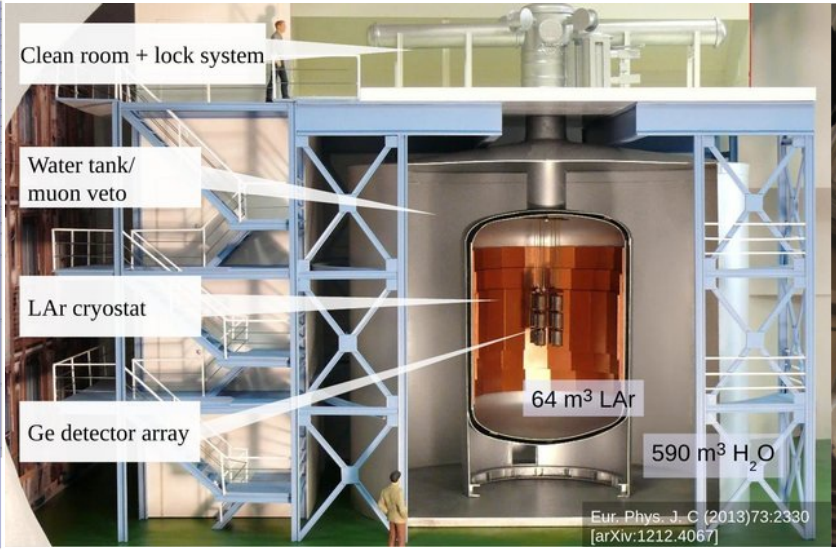
LAr veto based on Ar scintillation light read by fibers and PMT — GERDA, LEGEND

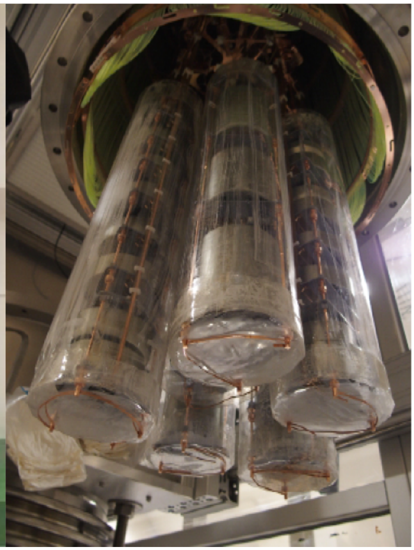
Muon veto based on Cherenkov light and/or plastic scintillator — MJD, GERDA, LEGEND

Current-Generation Experiments: MJD and GERDA









The MAJORANA DEMONSTRATOR

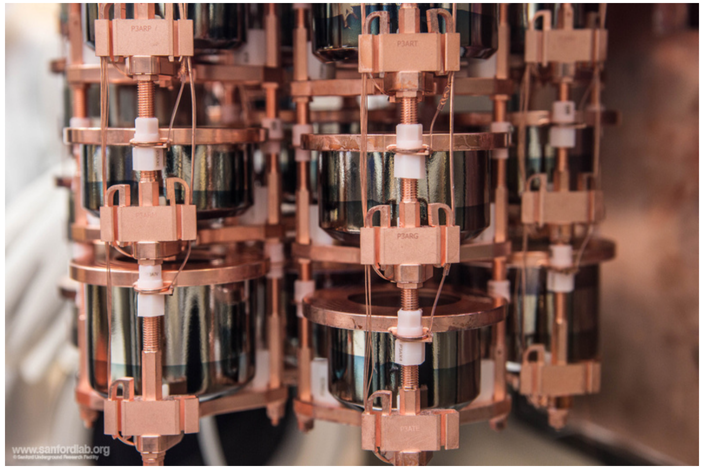
Searching for neutrinoless double-beta decay of ^{76}Ge in HPGe detectors and additional physics beyond the standard model

Source & Detector: Array of p-type, point contact (PPC) detectors

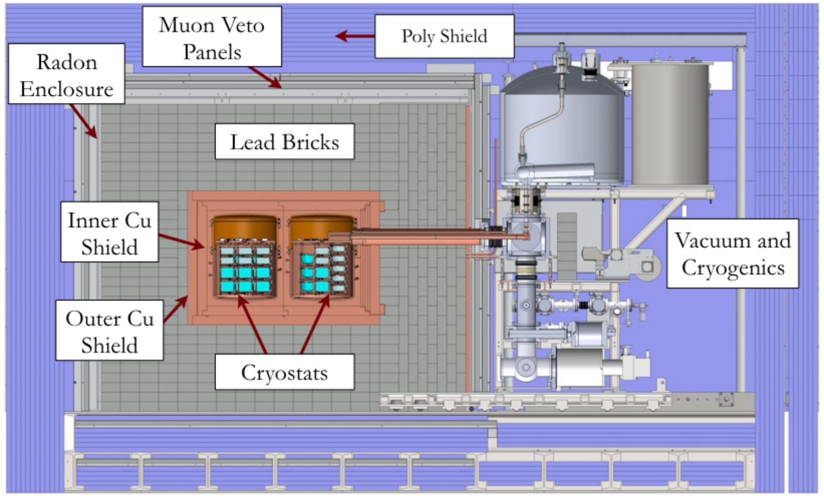
29.7 kg of 88% enriched ^{76}Ge crystals

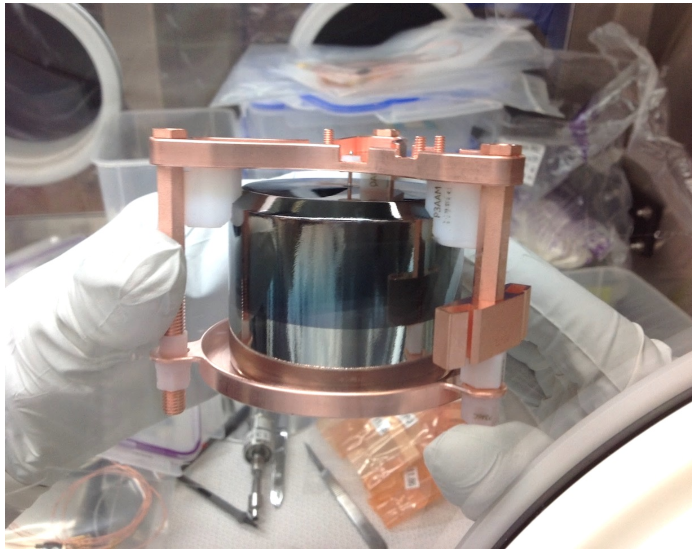
Best Energy resolution: 2.5 keV FWHM @ 2039 keV

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



Operating underground at the 4850' level of the Sanford Underground Research Facility since 2015





Sanford Underground Research Facility

U.S. DEPARTMENT OF ENERGY | Office of Science

The MAJORANA Collaboration

Duke University, Durham, NC, and TUNL:
Matthew Busch

Joint Institute for Nuclear Research, Dubna, Russia:
Sergey Vasilyev

Lawrence Berkeley National Laboratory, Berkeley, CA:
Yuen-Dat Chan, Jordan Myslik, Alan Poon

Los Alamos National Laboratory, Los Alamos, NM:
Pinghan Chu, Trevor Edwards, Steven Elliott, In Wook Kim, Ralph Massarczyk, Samuel J. Meijer, Keith Rielage, Bade Sayki, Matthew Stortini

National Research Center *'Kurchatov Institute' Institute of Theoretical and Experimental Physics, Moscow, Russia:*
Alexander Barabash

North Carolina State University, Raleigh, NC and TUNL:
Matthew P. Green, Ethan Blalock, Rushabh Gala

Oak Ridge National Laboratory, Oak Ridge, TN:
Vincente Guiseppe, Charlie Havener, David Radford, Robert Varner, Chang-Hong Yu

Osaka University, Osaka, Japan:
Hiroyasu Ejiri

Pacific Northwest National Laboratory, Richland, WA:
Isaac Arnquist, Maria-Laura di Vacri, Eric Hoppe, Richard T. Kouzes

Queen's University, Kingston, Canada:
Ryan Martin

South Dakota School of Mines & Technology, Rapid City, SD:
Cabot-Ann Christofferson, Brandon DeVries, Abigail Otten, Tyler Ryther, Jared Thompson

Technische Universität München, and Max Planck Institute, Munich, Germany:
Tobias Bode, Susanne Mertens

Tennessee Tech University, Cookeville, TN:
Mary Kidd

University of North Carolina, Chapel Hill, NC, and TUNL:
Brady Bos, Thomas Caldwell, Morgan Clark, Aaron Engelhardt, Julieta Gruszko, Ian Guinn, Chris Haufe, Reyco Henning, David Hervas, Eric Martin, Gulden Othman, Anna Reine, John F. Wilkerson

University of South Carolina, Columbia, SC:
Frank Avignone, David Edwins, Thomas Lannen, Ben Ranson, David Tedeschi

University of South Dakota, Vermillion, SD:
C.J. Barton, Jóse Mariano Lopez-Castaño, Laxman Paudel, Tupendra Oli, Wenqin Xu

University of Tennessee, Knoxville, TN:
Yuri Efremenko, Andrew Lopez

University of Washington, Seattle, WA:
Micah Buuck, Clara Cuesta, Jason Detwiler, Alexandru Hostiuc, Walter Pettus, Nick Ruof, Clint Wiseman

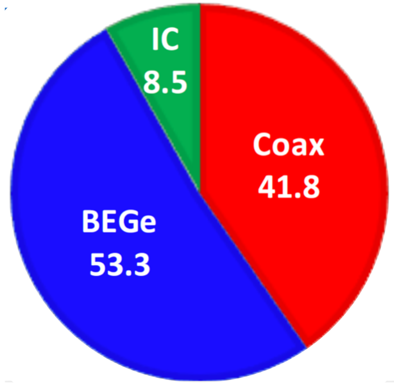
Williams College, Williamstown, MA:
Graham K. Giovanetti

5

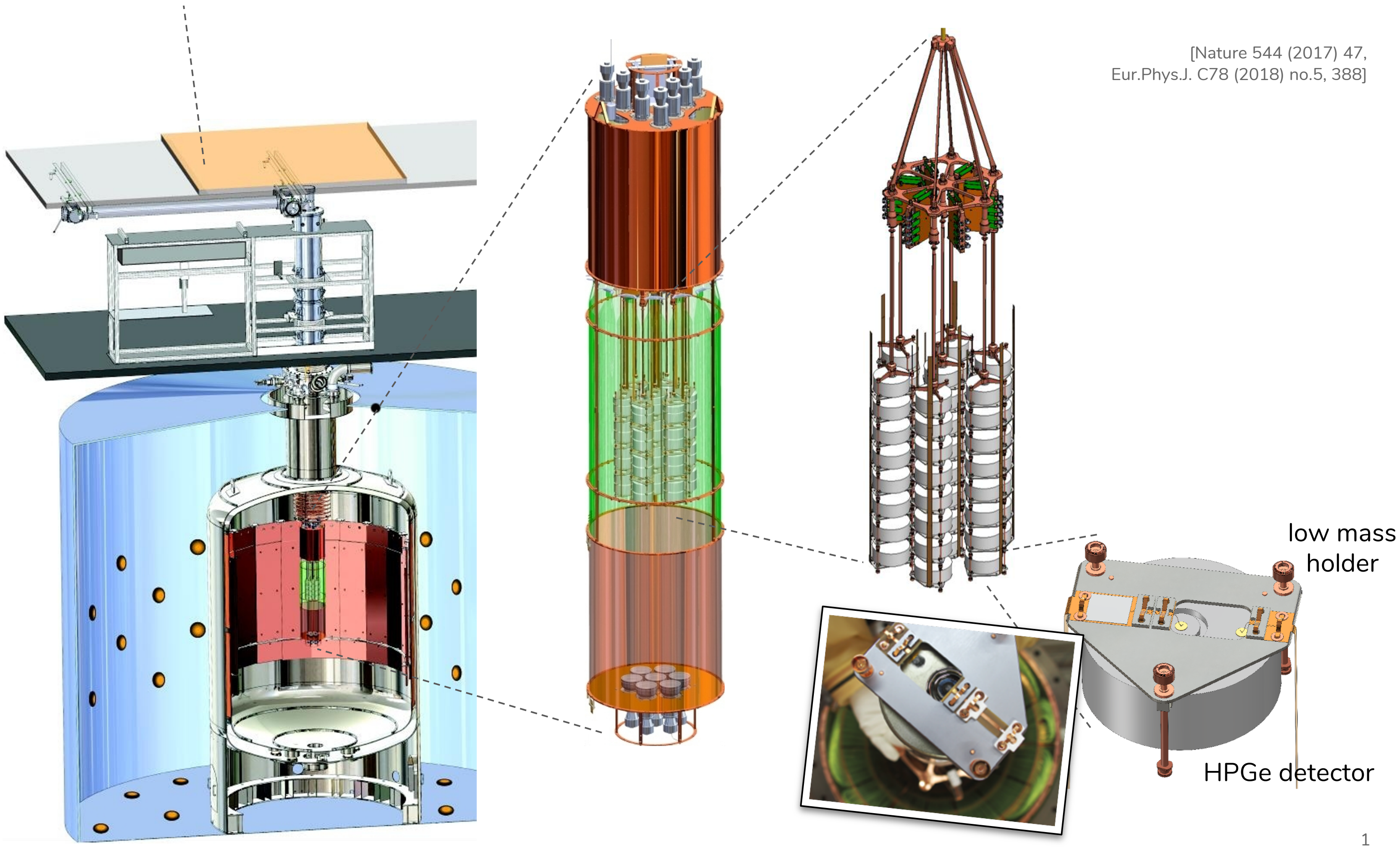
***students**

GERDA

- Novel configuration: bare crystals in LAr active veto
- Located at LNGS: 3000 m.w.e of rock
- Water Cherenkov veto, 64 m^3 of LAr (diameter 4m) with SIPM and PMT readout
- Ge detector array
  - 30 BeGe (20kg), 7 Coax (15.6kg), 3 nat (7.6kg)
  - + ICPC string as of May 2018
- 103.7 kg yr Phase II exposure (Neutrino 2020)



[Nature 544 (2017) 47, Eur.Phys.J. C78 (2018) no.5, 388]



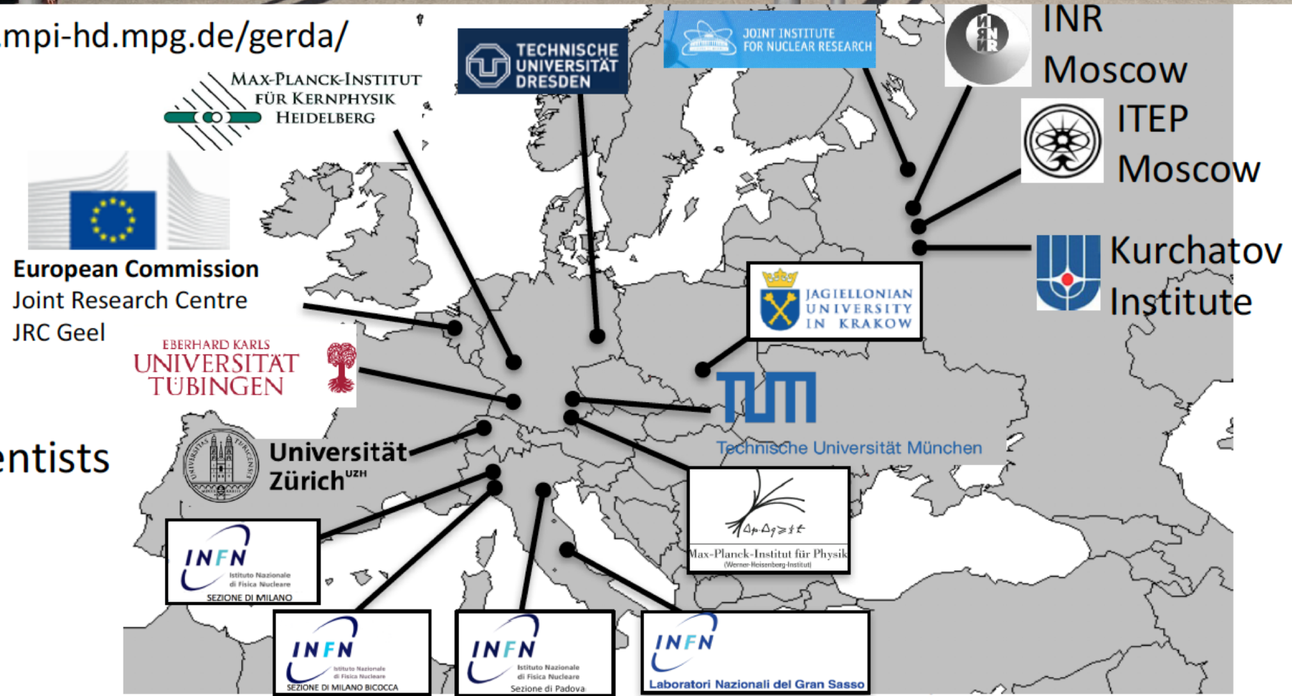
1

See Y. Kermaïdic, Neutrino 2020 for more details

Wiesinger, TAUP19

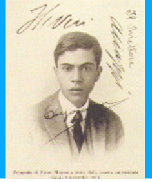
GERDA at Laboratori Nazionali del Gran Sasso in Italy

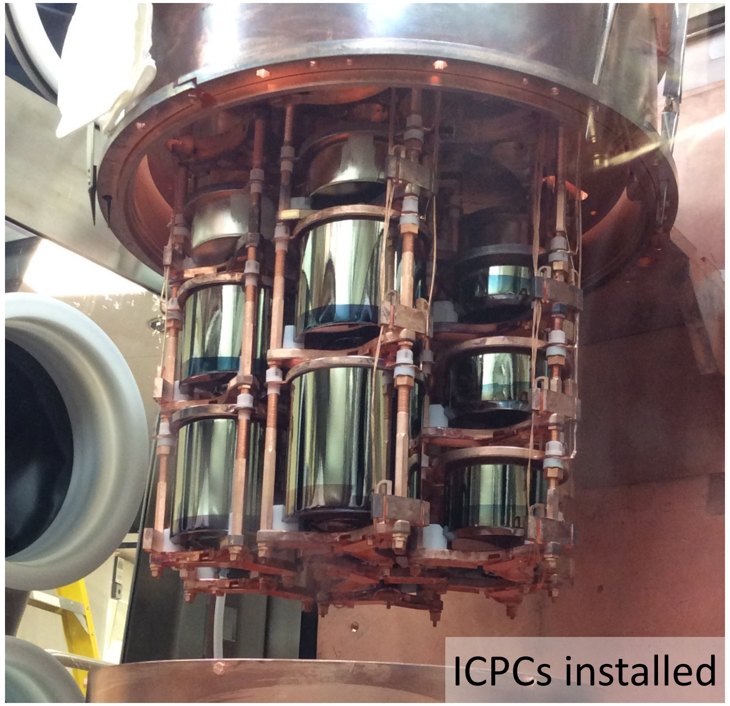
http://www.mpi-hd.mpg.de/gerda/

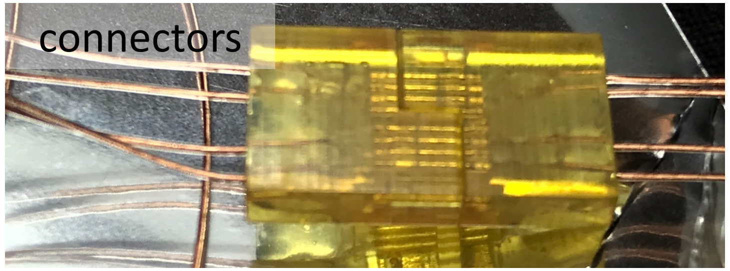


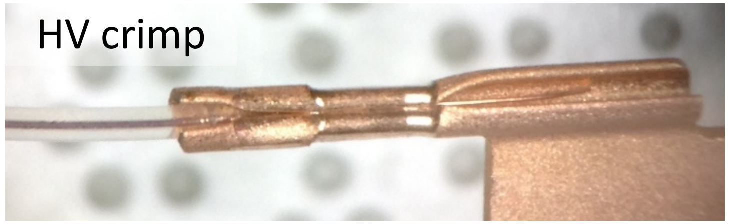
About 100 scientists from Europe

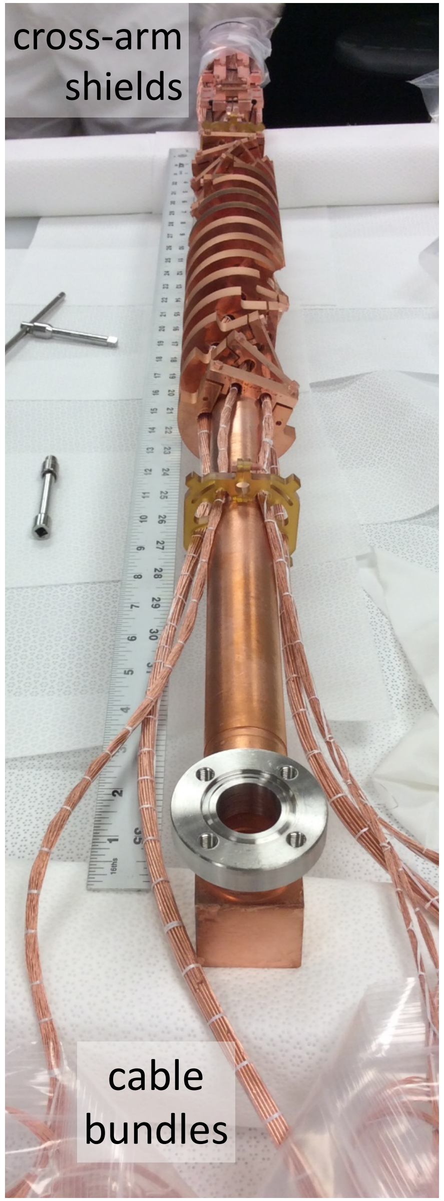
MJD Detector Upgrade and Status











Upgrade

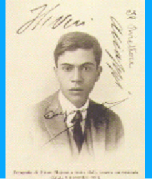
- **5 p-type point contact (PPC) ^{enr}Ge detectors removed and shipped to LNGS for LEGEND-200 tests in LAr**
- Improved connectors and cabling: new ultra-clean, low mass signal conn.; improved HV conn.; NASA spec cable bundling
- Installed extra cross-arm shielding
- **Installed 4 ORTEC inverted coaxial point contact (ICPC) ^{enr}Ge detectors for LEGEND-200 for low background vacuum testing**

	Before Upgrade	After Upgrade
Working signal conn.	24/29 (82%)	27/27 (100%)
Reliable HV conn.	19/24 (79%)	27/27 (100%)
Operational	18/29 (62%)* *Used for final analysis	27/27 (100%)$^{+}$ $^{+}$Final selection not yet made

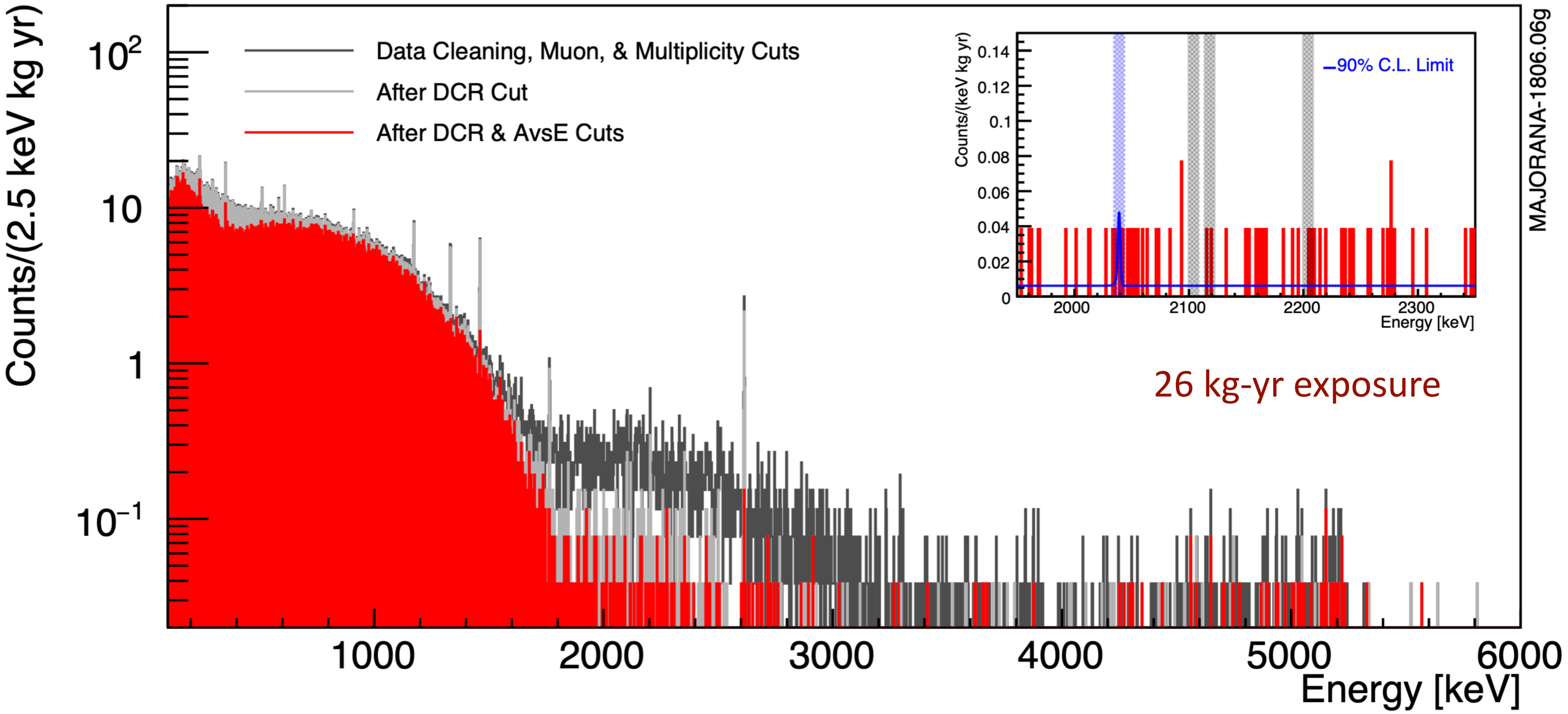
Status and Next Steps

- Run for ~6+ months to measure performance and background
- Ultimate integrated exposure: ~65 kg y
- ICPC performance will inform LEGEND-200
- Stop as-late-as-possible to install enriched det. in LEGEND-200
- Continue background studies with natural detectors

MAJORANA DEMONSTRATOR 0νββ Results



Operating in a low background regime and benefiting from excellent energy resolution



Initial Release:

9.95 kg-yr open data

[PRL 120 132502 (2018)]

Latest Release:

First unblinding of data

26 kg-yr exposure

[PRC 100 025501 (2019)]

Median $T_{1/2}$ Sensitivity:

4.8×10^{25} yr

Full Exposure Limit:

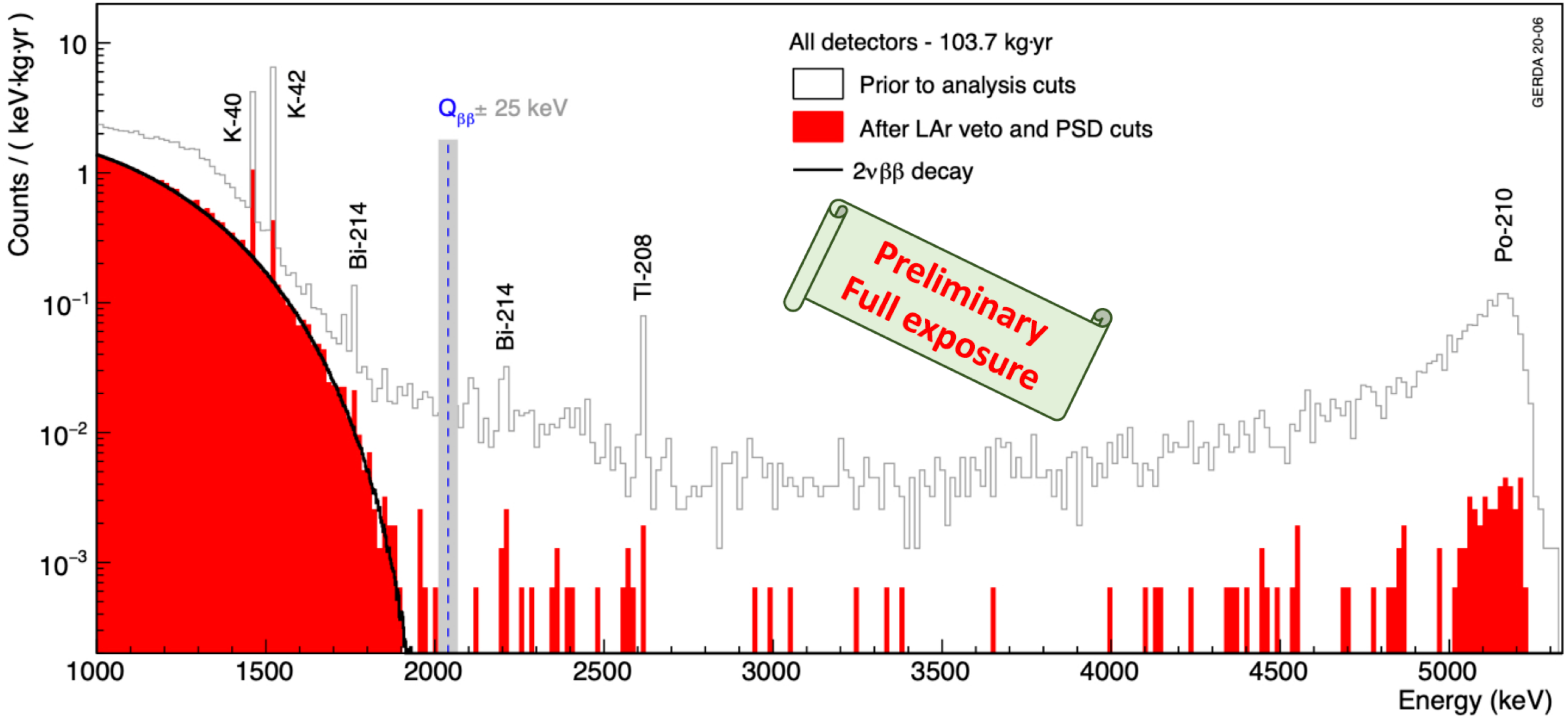
$T_{1/2} > 2.7 \times 10^{25}$ yr (90% CL)

Background Index at 2039 keV in lowest background config:

11.9 ± 2.0 cts/(FWHM t yr)

A new result, with a combined total of ~50 kg-yr and analysis improvements, is to be released this Fall

GERDA Full Exposure



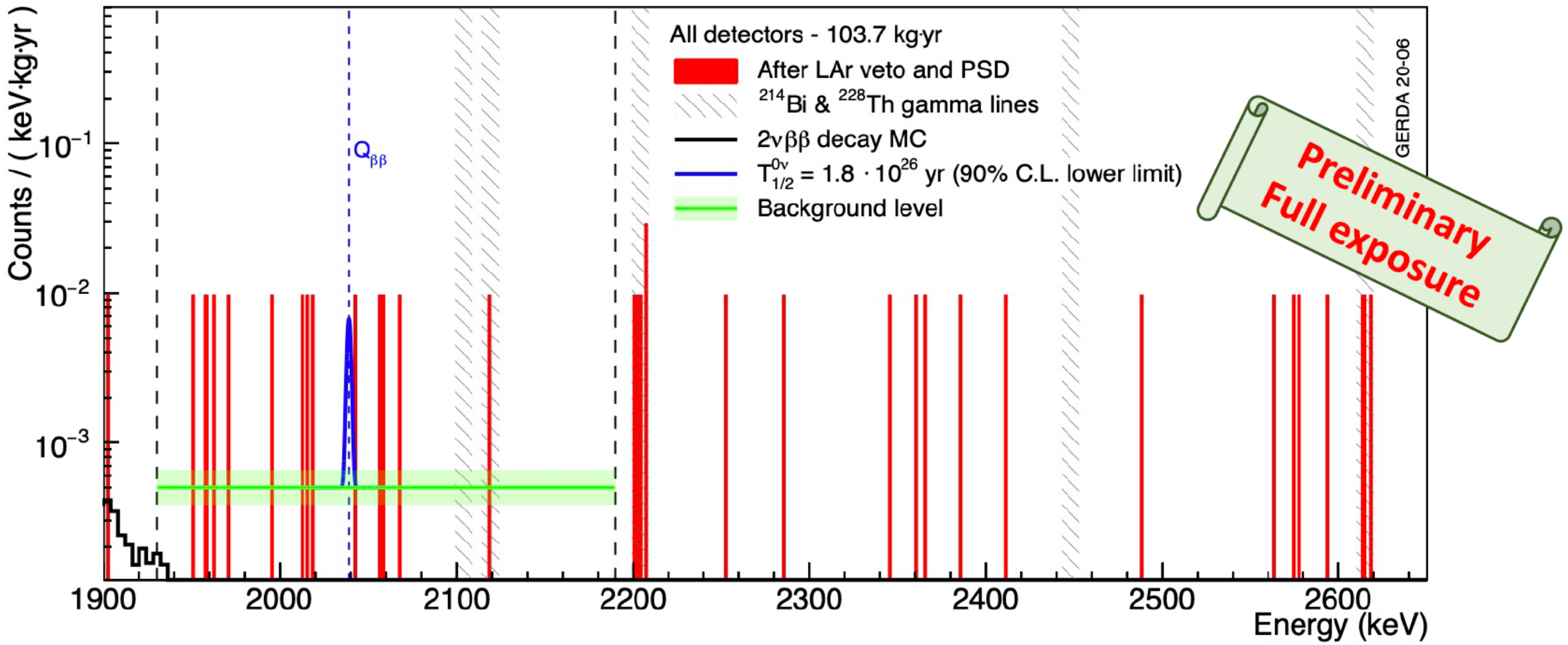
- Multiplicity, event topology, fiducial, and LAr cuts are highly complementary: factor of 30 reduction in BI
- BI analysis window: [1930-2190] keV, excluding ^{208}Tl SEP, ^{214}Bi FEP, and $Q_{\beta\beta}$ ± 25 keV
- After all cuts:

BI = $5.2^{+1.6}_{-1.3} \times 10^{-4}$ cnts/(keV·kg·yr)

0νββ record

- [600 - 1900] keV – Almost pure **$2\nu\beta\beta$ decays** sample
- [1450 - 1530] keV – Strong suppression of **^{40}K and ^{42}K gamma lines** (LAr veto + MSE)
- [1900 - 2620] keV – Strong suppression of **^{214}Bi and ^{228}Th gamma lines** + Compton
- > 3500 keV – Suppression of almost all **α events** (p+ contact)

GERDA Full Exposure



Frequentist analysis*:

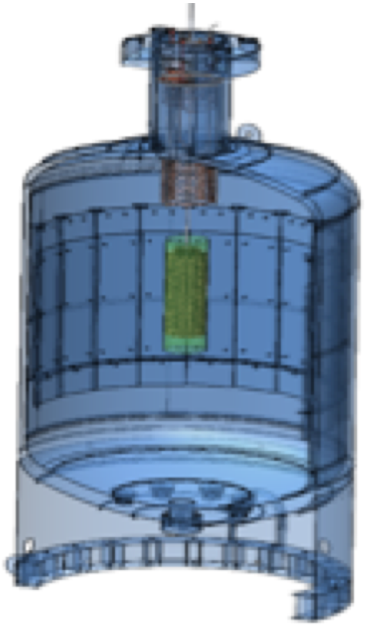
- Median sensitivity for limit setting:
  $\mathbf{1.8 \times 10^{26}\ yr\ (90\%\ C.L.)}$
- Best fit → no signal
- 90% C. L. lower limit:
  $\boldsymbol{T^{0\nu}_{1/2} > 1.8 \times 10^{26}}$ **yr**

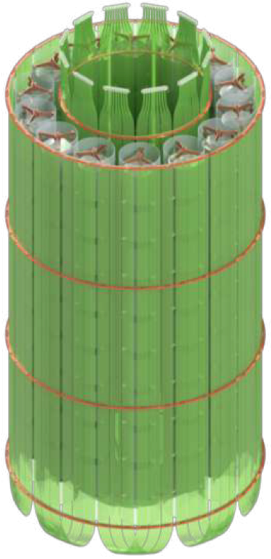
Bayesian analysis with uniform prior*:

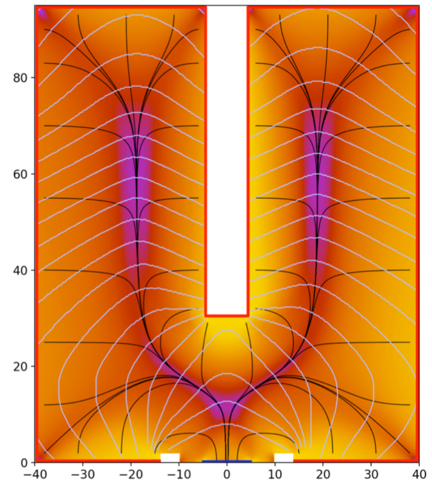
- Median sensitivity for limit setting:
  1.4×10^{26} yr (90% C. I.)
- $T^{0\nu}_{1/2} > 1.4 \times 10^{26}$ yr (90% C. I.)

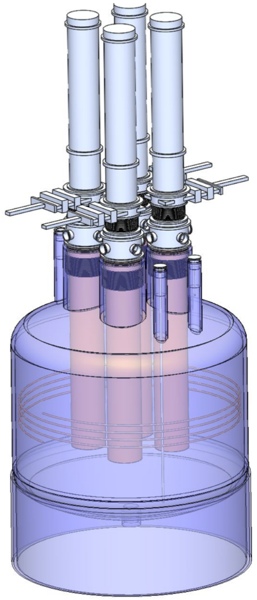
Statistical treatment found in* [Nature **544, 47–52 (2017)]
+ includes 23.5 kg·yr phase I exposure

Joining Forces: LEGEND









Large Enriched Germanium Experiment for Neutrinoless ββ Decay – LEGEND

Seattle, Dec. 2019

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."

48 institutions, About 240 scientists

Univ. New Mexico
L'Aquila University and INFN
Lab. Naz. Gran Sasso
University Texas, Austin
Tsinghua University
Lawrence Berkeley Natl. Lab.
University California, Berkeley
Leibniz Inst. Crystal Growth
Comenius University

University of North Carolina
University of Warwick
Sichuan University
University of South Carolina
Tennessee Tech University
Jagiellonian University
University of Dortmund
Technical University Dresden
Joint Inst. Nucl. Res.

Duke University
Triangle Univ. Nuclear. Lab.
Joint Research Centre, Geel
Max Planck Institute, Heidelberg
Queens University
University Tennessee
Lancaster University
University Liverpool
University College London

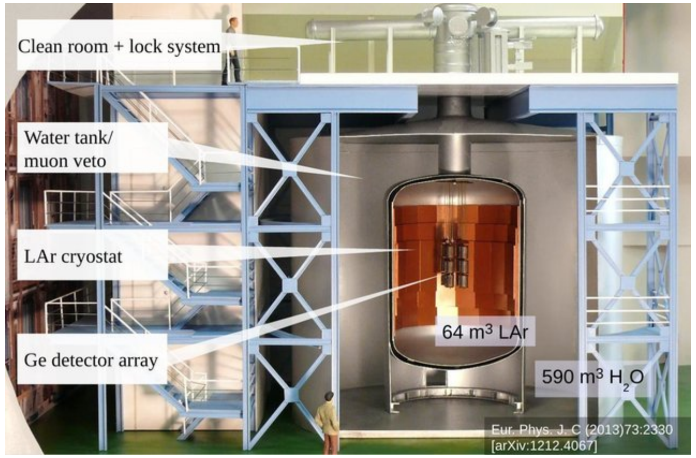
Los Alamos National Lab.
INFN Milano Bicocca
Milano University and Milano INFN
Institute Nuclear Research Russ. Acad. Sci.
National Research Center Kurchatov Inst.
Lab. Exper. Nucl. Phy. MEPhI
Max Planck Institute, Munich
Technical University Munich
Oak Ridge National Laboratory

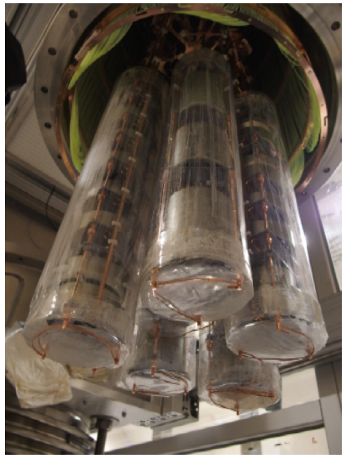
Padova University
Padova INFN
Czech Technical University Prague
North Carolina State University
South Dakota School Mines Tech.
University Washington
Academia Sinica
University Tübingen
University South Dakota
University Zurich

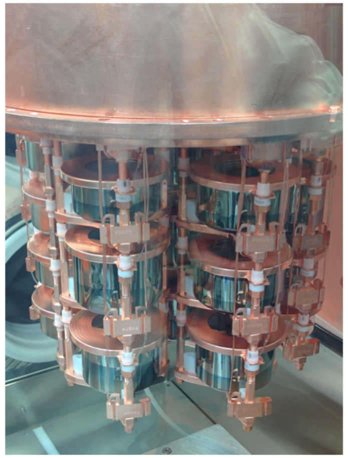
LEGEND Approach: Proven Technologies

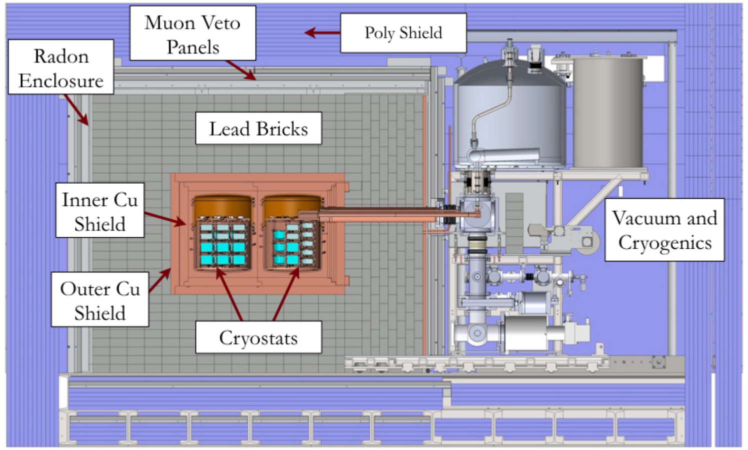
GERDA achieved the lowest background index: 5×10^{-4} cts/(keV kg yr)
LEGEND-200 needs only x3 better

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









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
- Low energy threshold

and techniques developed in both experiments:

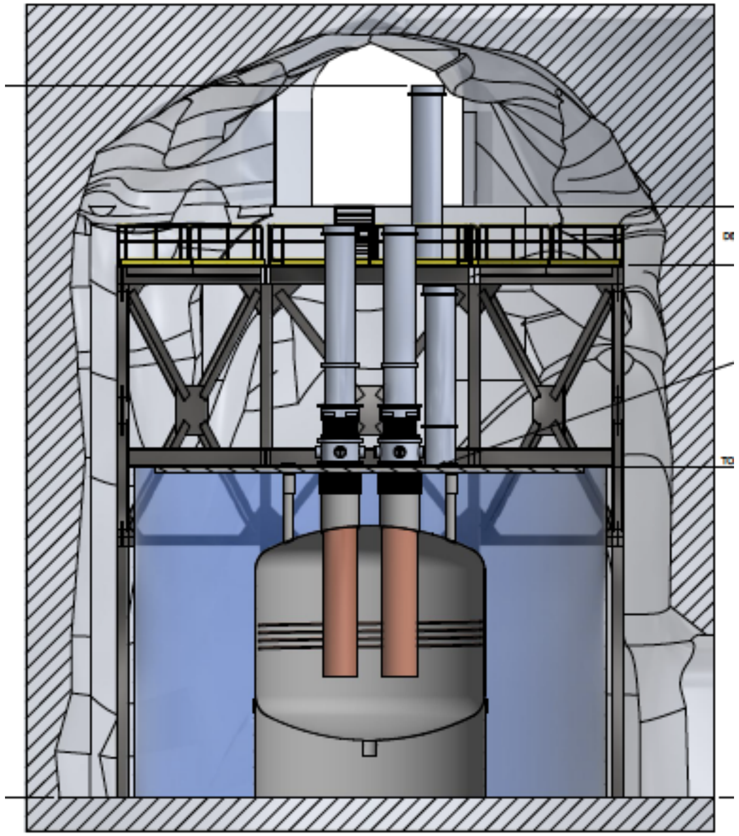
- Clean fabrication techniques
- Control of surface exposure
- Development of large point-contact detectors

LEGEND Approach: Phased Deployment

See arXiv:1709.01980

LEGEND-200:

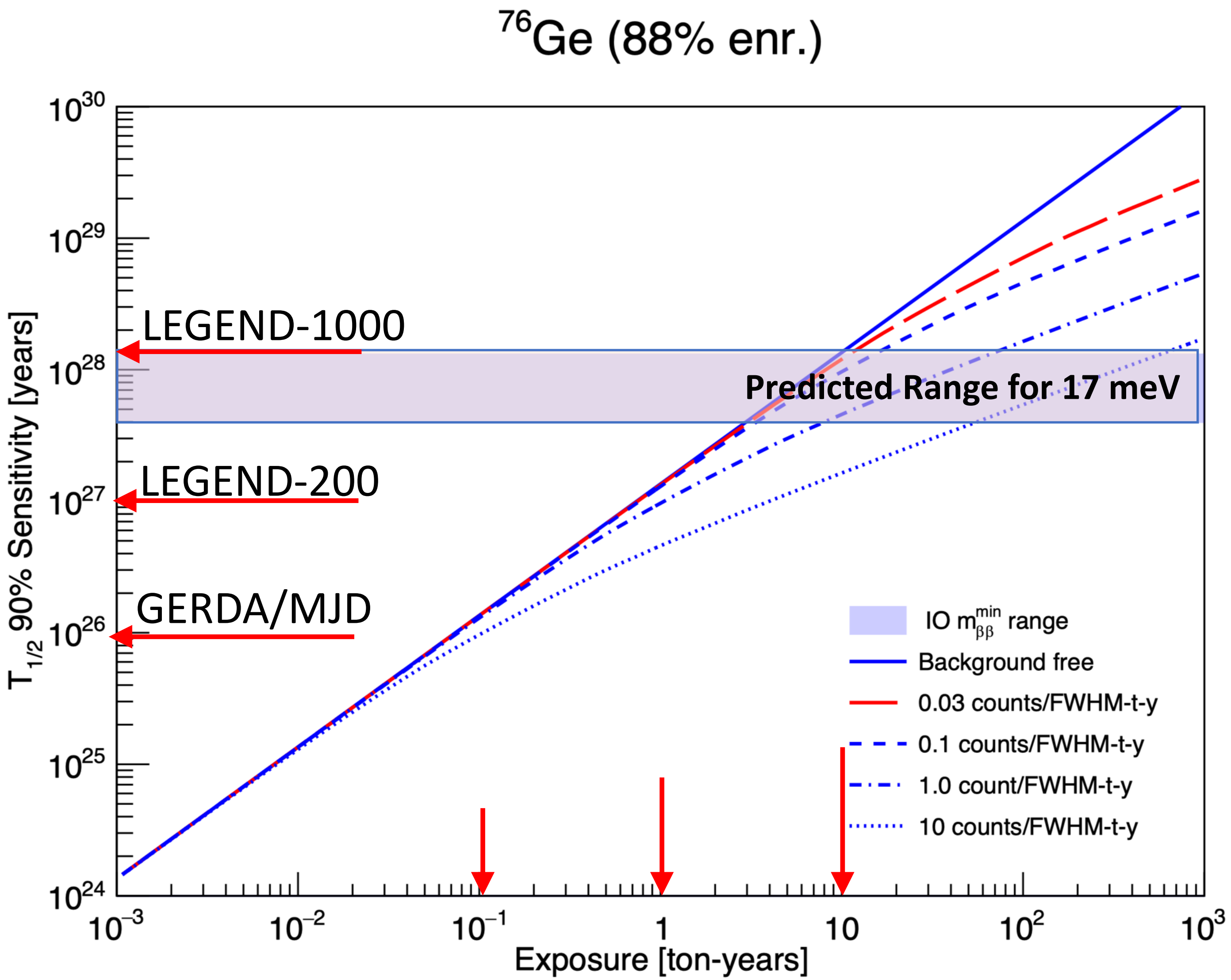
- 200 kg in upgrade of existing GERDA infrastructure at Gran Sasso
- 2.5 keV FWHM resolution
- Background goal
  <0.6 cts/(FWHM t yr)
  <2×10^{-4} cts/(keV kg yr)
- Data start ~2021



LEGEND-1000:

- 1000 kg, staged via individual payloads (300-500 detectors)
- Timeline connected to review process
- Background goal <0.03 cts/(FWHM t yr),<1×10^{-5} cts/(keV kg yr)
- Location to be selected

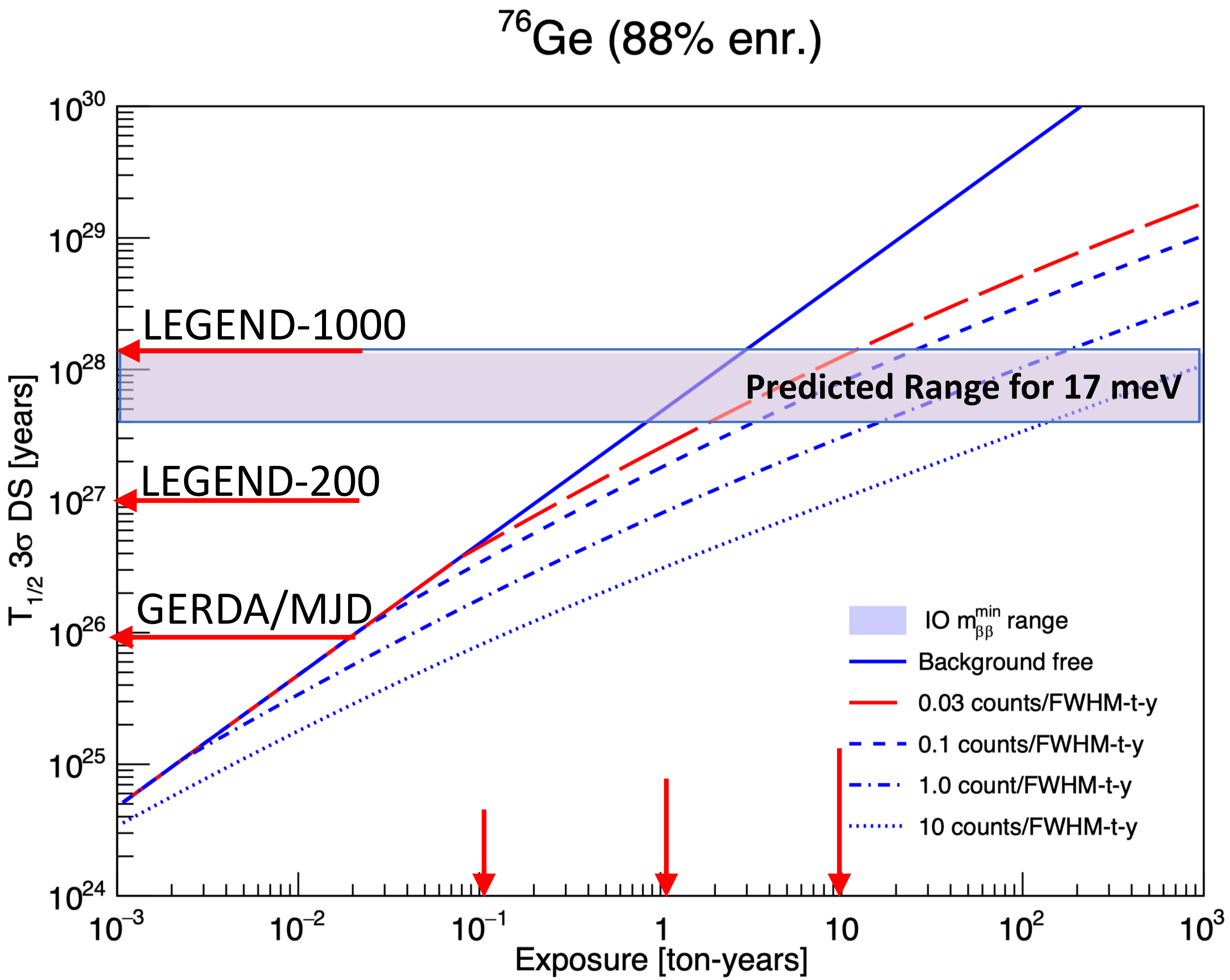
Ge Sensitivity



$>10^{28}$ yr or $m_{\beta\beta}$=17 meV for worst case matrix element of 3.5 and unquenched g_A.

3-σ discovery level to cover inverted ordering, given matrix element uncertainty.

Ge Discovery Potential



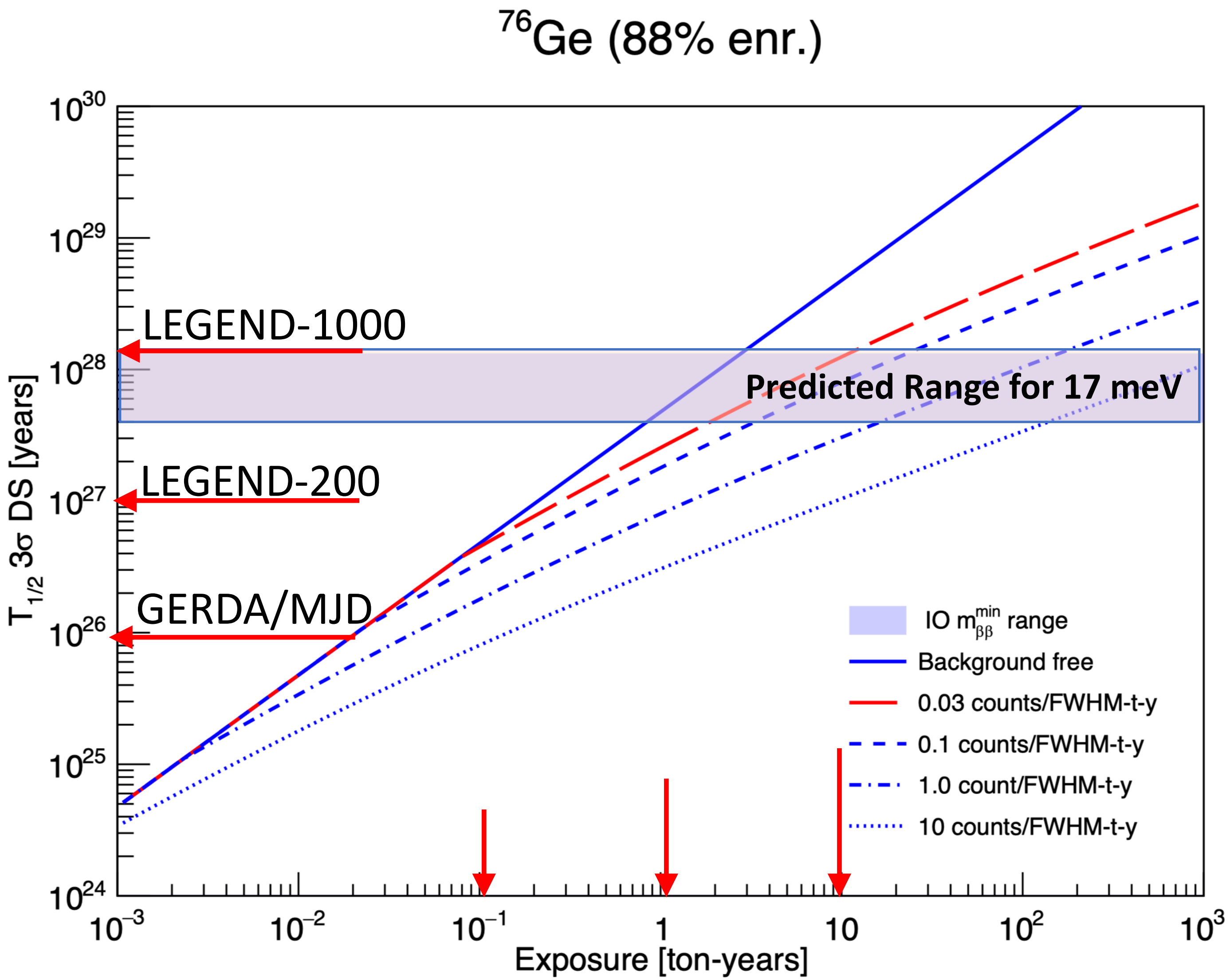
>10^{28} yr or $m_{\beta\beta}$=17 meV for worst case matrix element of 3.5 and unquenched g_A.

3-σ discovery level to cover inverted ordering, given matrix element uncertainty.

Note: background requirement for discovery more stringent than for sensitivity.

Ge Discovery Potential

LEGEND

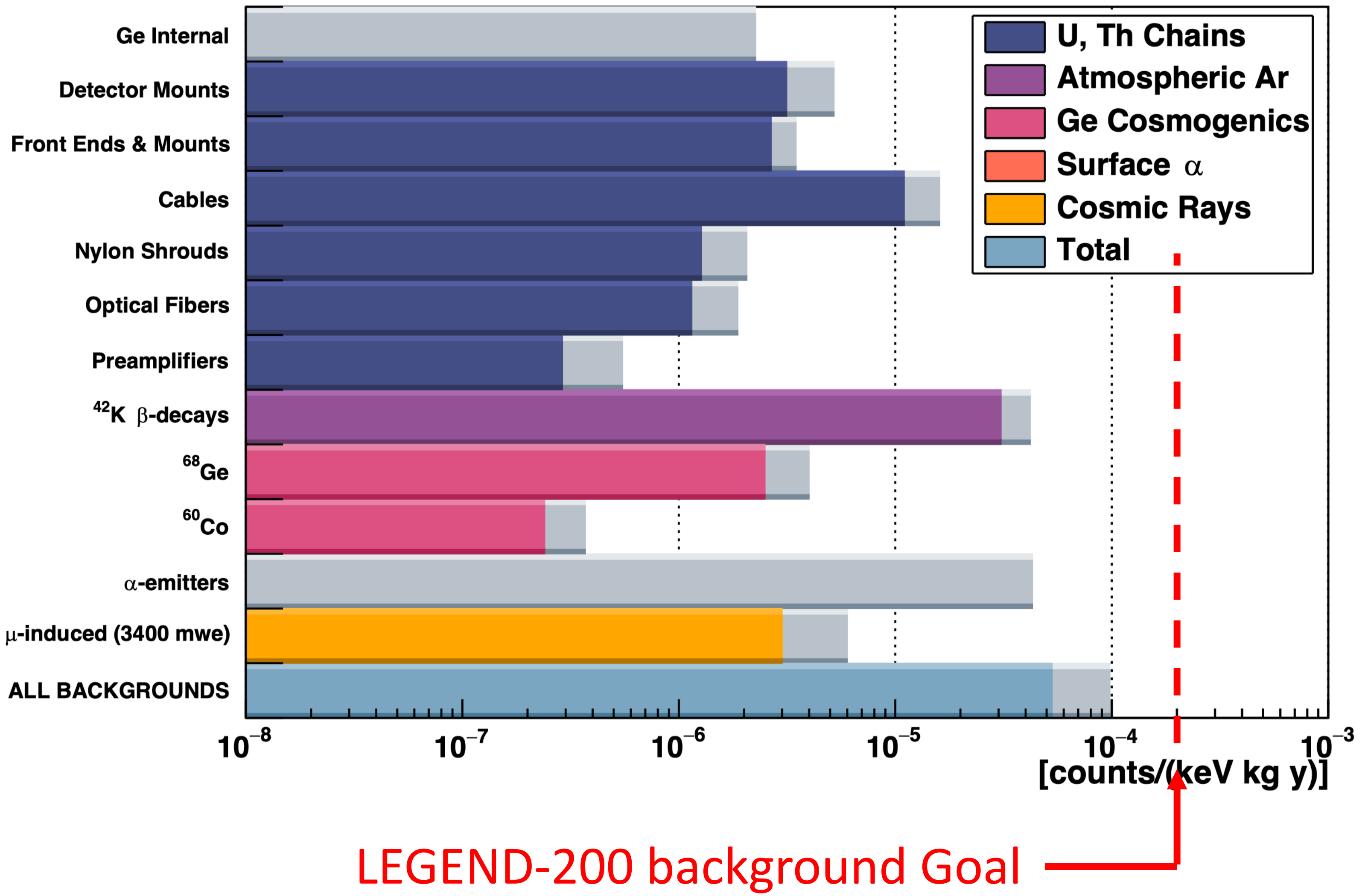


>10^{28} yr or $m_{\beta\beta}$=17 meV for worst case matrix element of 3.5 and unquenched g_A.

3-σ discovery level to cover inverted ordering, given matrix element uncertainty.

While a limit can be set independent of the energy resolution or background index, a convincing discovery requires good energy resolution and its significance strongly depends on the uncertainty of the background level and shape.

LEGEND-200 Background Projections



Improvements from GERDA/MJD:

- Larger detectors (≥x2)
- 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

Background contributions near $Q_{\beta\beta}$ after all cuts

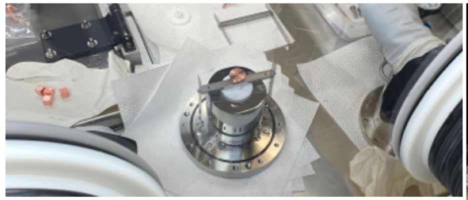
Monte Carlo + data-driven projections of Ge U/Th, ^{42}K, α based on GERDA, MJD data

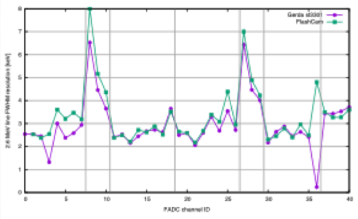
All others: Monte Carlo + assay-based projections

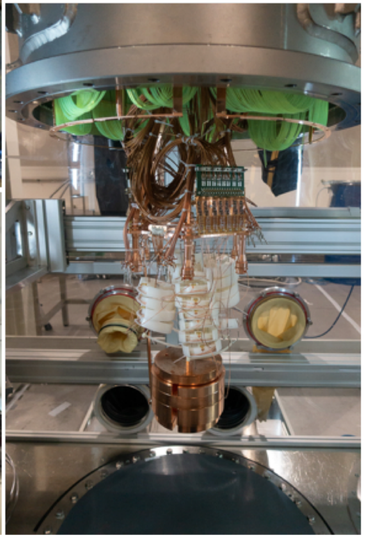
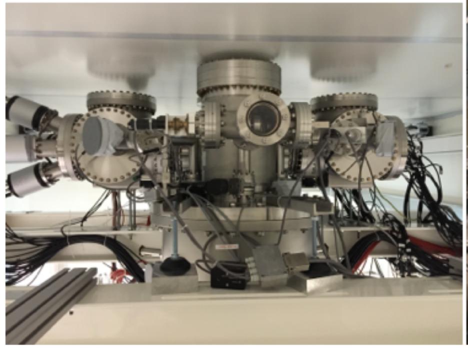
Grey bands indicate uncertainties in assays and background rejection

LEGEND-200 Status

- Fully funded
- GERDA experimental infrastructure now operated by LEGEND : Feb. 17, 2020
- Installation of hardware for Post-Gerda tests (PGT) : Feb. 23, 2020
- Screening, assays, and electroformed Cu: all on schedule
- Enriched ^{76}Ge: 176 kg from two vendors
- New Detectors: 155 kg of ICPC detectors (~2 kg/det) from two vendors
- Lock: assembled and tested at MPIK
- Active shield system: production of fiber shroud and SiPM array progressing
- Characterization, Simulations, Analysis Software: In preparation
- Schedule : Ready for data taking in 2021 (pending COVID-19 Impacts)

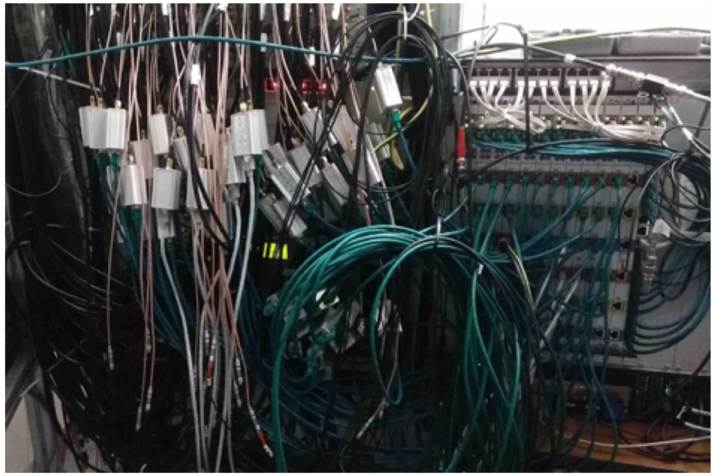


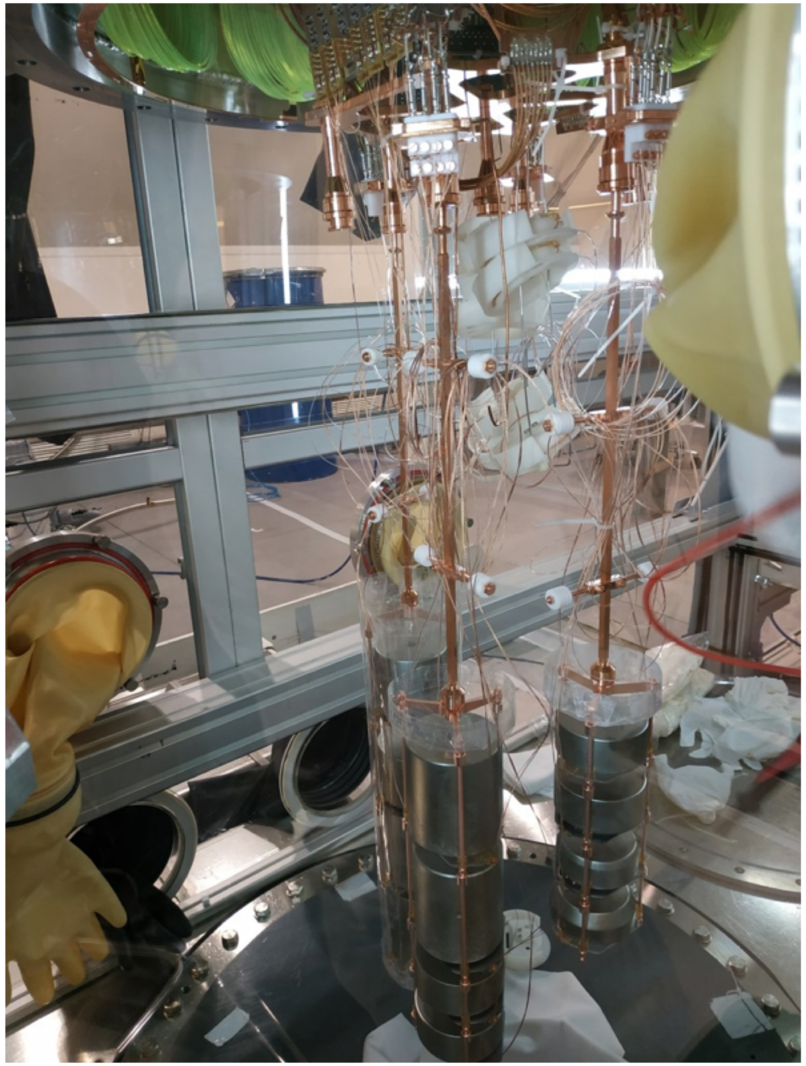



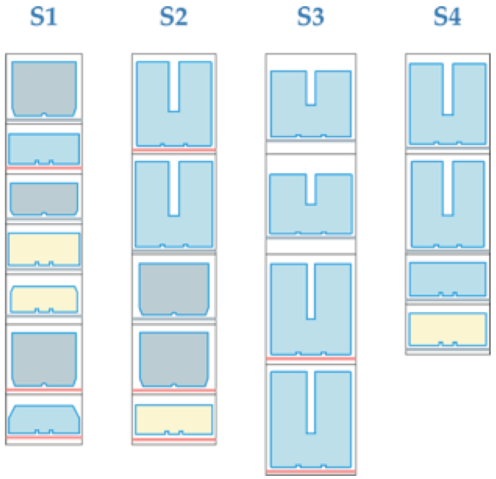
Post-GERDA Test: Start of DAQ Commissioning

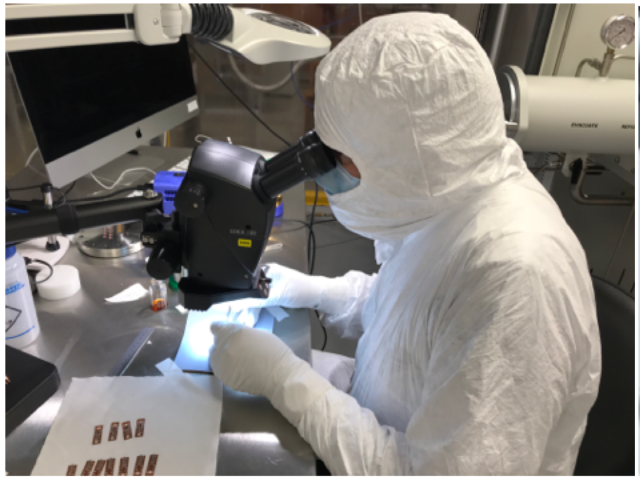
- Test with 20 GERDA, MJD, and new detectors
  - 4 new LEGEND-200 ICPC (Mirion)
  - 9 existing GERDA detectors
  - 5 MJD PPC detectors
  - 2 new LEGEND-200 ICPC (ORTEC)
- PEN based detector unit parts
- Full electronics chain (cables, LMFE, CC4, Head)
- LEGEND-200 DAQ System using FlashCam digitizers
- LEGEND-200 Analysis stream
- Lab access has resumed following COVID closures
- 14 detectors operating starting in July

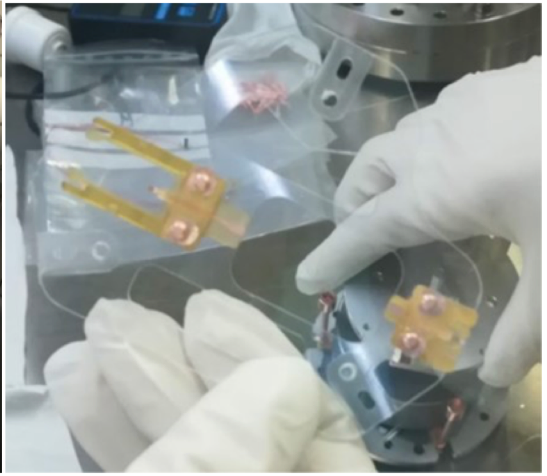




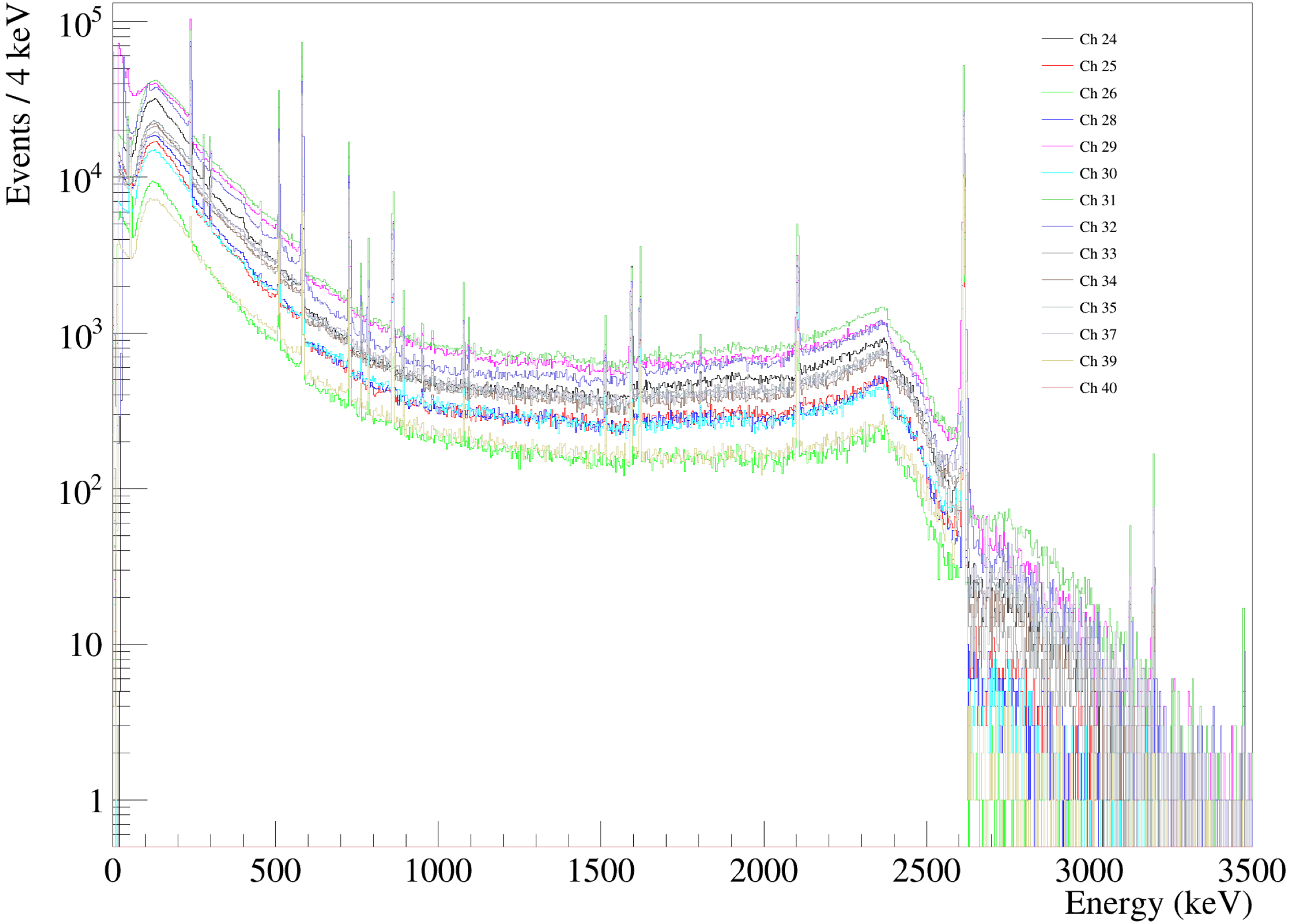
PGT Strings



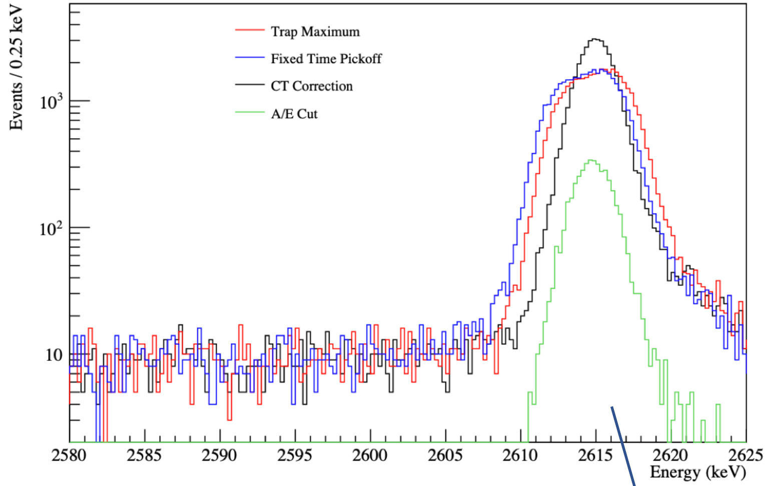


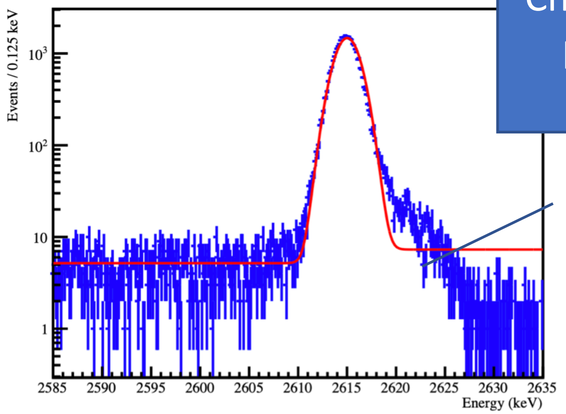


Post-GERDA Test: Data



Example ICPC Peak Shape:

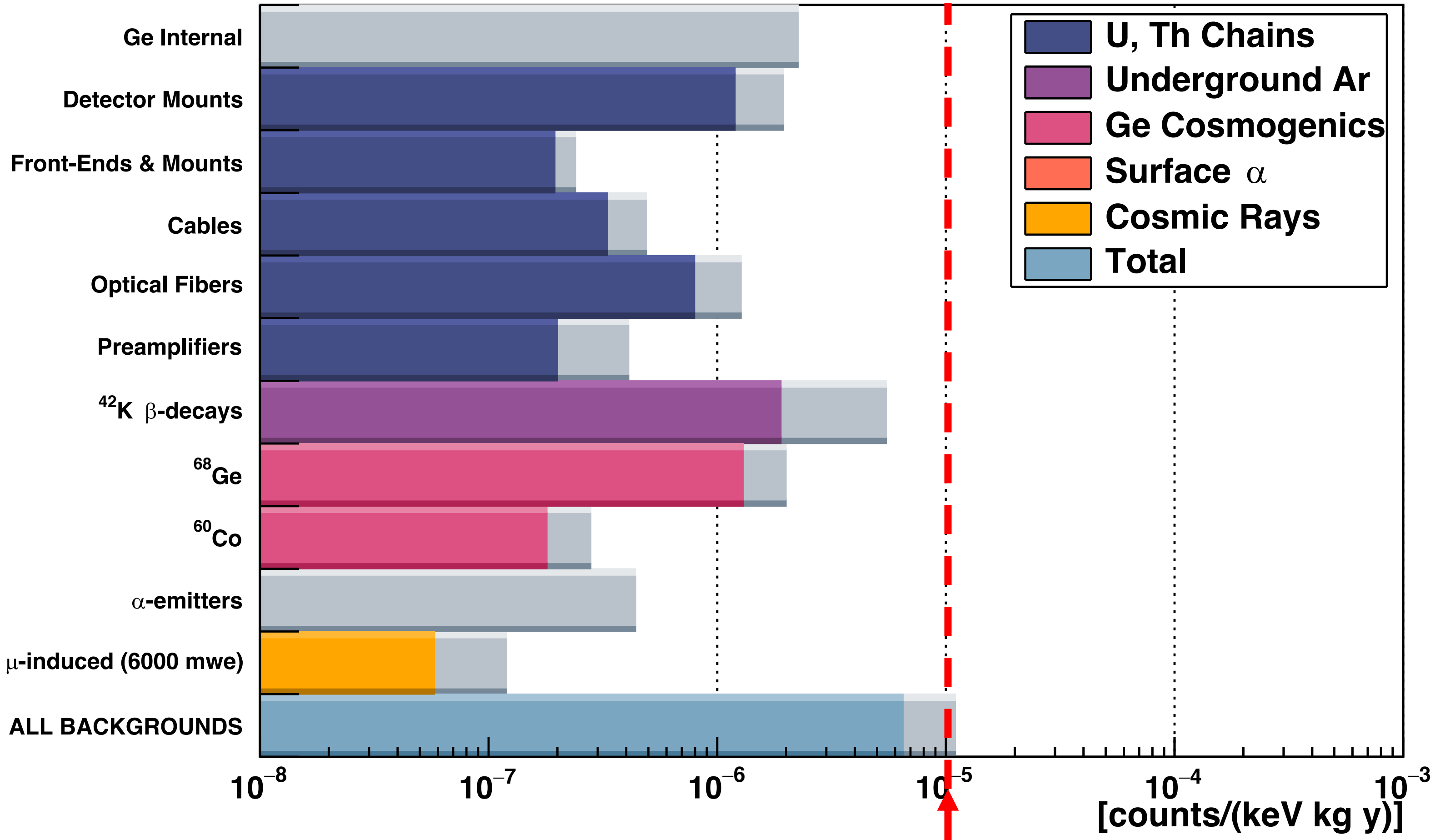




Charge trapping present but correctable

Pile-up rejection not applied

LEGEND-1000 Background Projections



LEGEND-1000 background Goal

Reductions for LEGEND-1000:
U/Th: optimized array spacing, minimize opaque materials, larger detectors, better light collection, cleaner materials

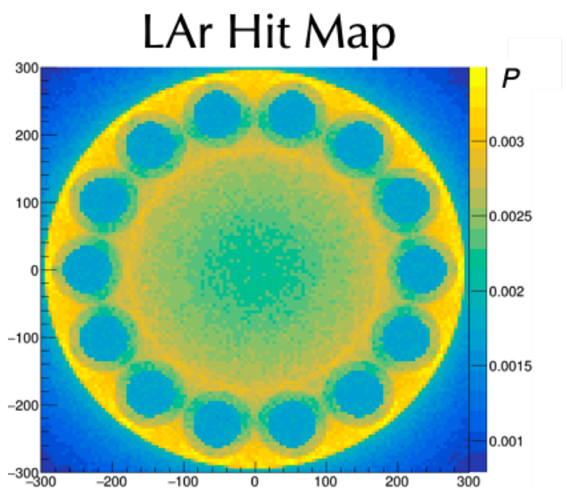
μ-induced: Improved shielding, SNOLab depth assumed

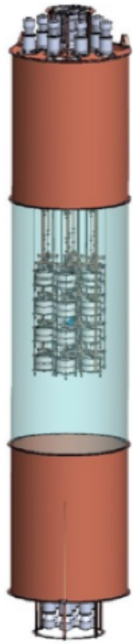
Surface α's: assumes achieved UL for BEGes and ICPCs in GERDA

^{42}Ar: reduce by using underground sourced Ar

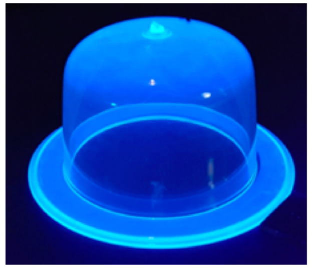
Recent Progress for L1000

- First phase (LEGEND-200) has already shown:
  - ≥92% enriched ^{76}Ge from two vendors with good throughput
  - 2-3 kg ICPC detectors from two vendors
  - Viable string geometry, payloads, electronics chain, DAQ
- Design / alternatives analysis / R&D
  - Background modeling
  - Lab-specific infrastructure and cyrostats design underway
  - larger detectors (>4 kg)
  - additional PEN-based components
  - ASIC electronics
  - improvements to light readout
- Documenting pre-conceptual design
- US Lead Lab selected: ORNL
- Awaiting US downselect process

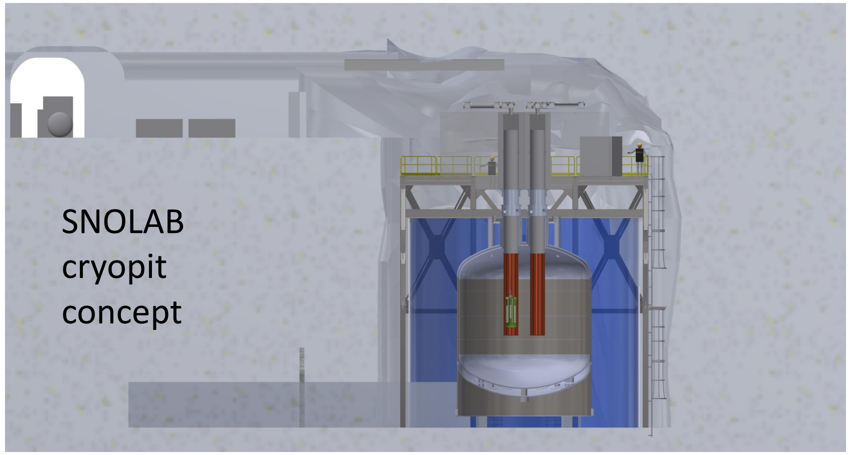




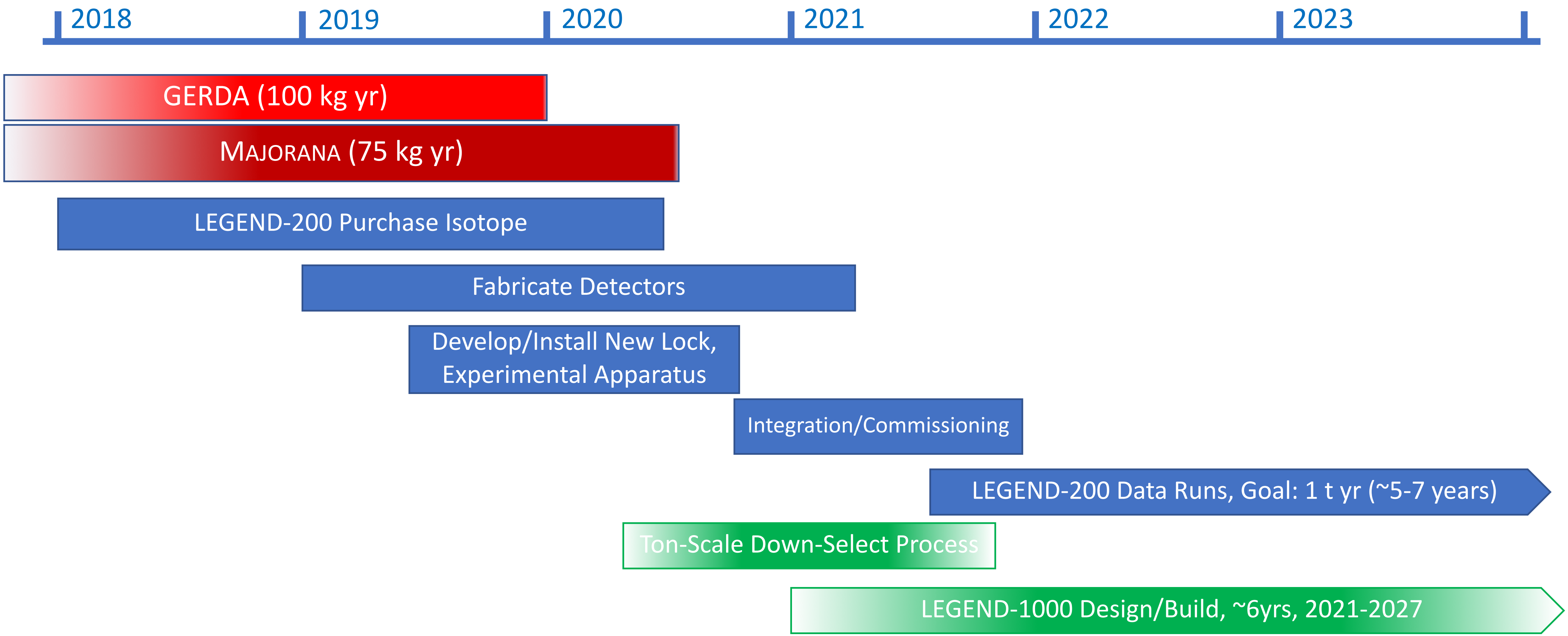
PEN crystal capsule



ICPCs up to 6kg under development



Schedules



Earliest, and optimistic, LEGEND-1000 Data Start 2025/6

Summary

LEGEND

- ^{76}Ge is a clear leading choice for a tonne-scale experiment
- World-leading backgrounds, energy resolution, and sensitivity have been demonstrated by Majorana and GERDA
- LEGEND combines the best techniques of Majorana and GERDA to achieve the highest discovery sensitivity with the lowest risk
- First phase LEGEND-200 will be the first to probe the next ~order of magnitude of half-life sensitivity starting next year
- We continue to make progress toward following phases in LEGEND-1000 while funding is pending

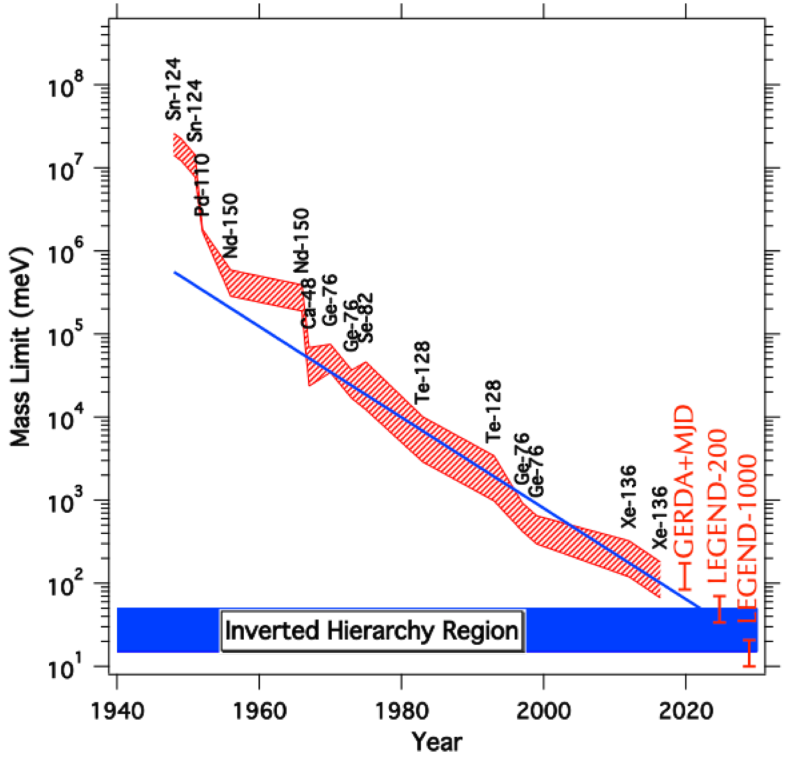
Acknowledgements

- We appreciate the support of our sponsors:
  - German Federal Ministry for Education and Research (BMBF)
  - German Research Foundation (DFG), Excellence Cluster ORIGINS
  - German Max Planck Society (MPG)
  - U.S. National Science Foundation, Nuclear Physics (NSF)
  - U.S. Department of Energy, Office of Nuclear Physics (DOE-NP)
  - U.S. Department of Energy, Through the LANL, ORNL & LBNL LDRD programs (LDRD)
  - Italian Instituto Nazionale di Fisica Nucleare (INFN)
  - Swiss National Science Foundation (SNF)
  - Polish National Science Centre (NCN)
  - Foundation for Polish Science
  - Russian Foundation for Basic Research (RFBR)
  - Research Council of Canada, Natural Sciences and Engineering
  - Canada Foundation for Innovation, John R. Evans Leaders Fund
  - European Research Council
  - Science and Technology Facilities Council, part of UK Research and Innovation
- We thank our hosts and colleagues at LNGS and SURF
- We thank SNOLAB for their engineering support in LEGEND-1000 planning
- We thank the ORNL Leadership Computing Facility and the LBNL NERSC Center

Extra Slides

Extra Slides

History of Ge and Double Beta Decay

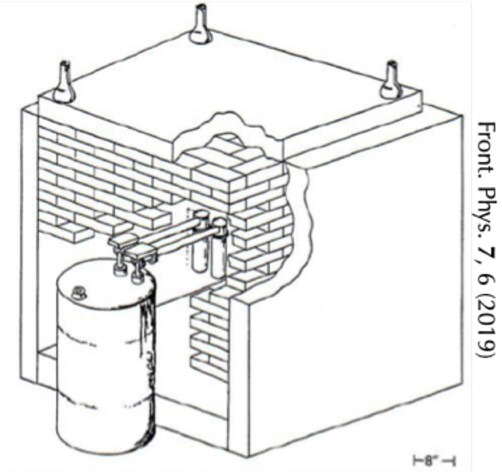


Courtesy of S. Elliott

Heidelberg-Moscow

Prog. Part. Nucl. Phys. 32, 261 (1994)

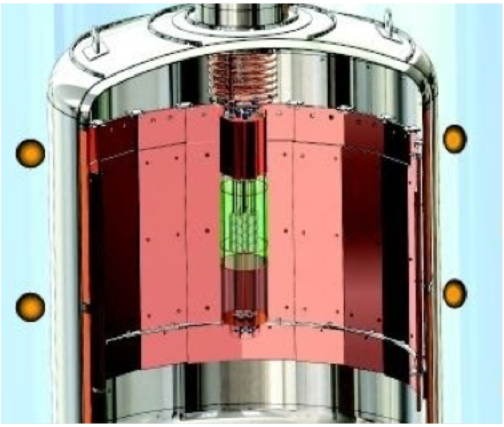
IGEX



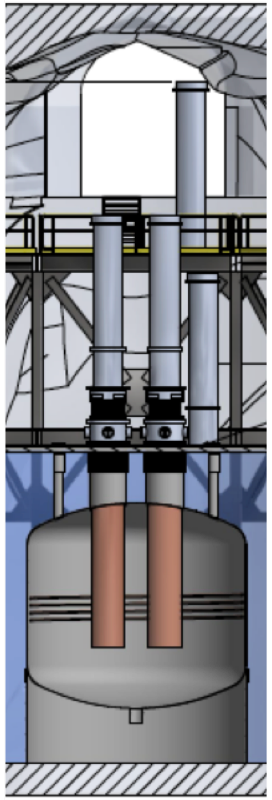
Front. Phys. 7, 6 (2019)

MAJORANA: ultra-pure materials electronics, PPCs

GERDA: LAr direct immersion Coax + BEGes

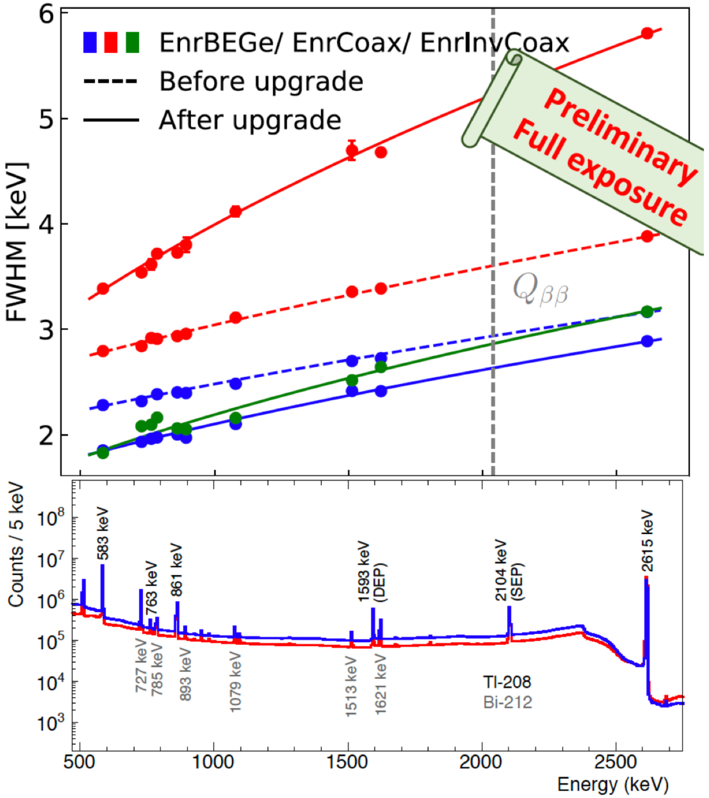


LEGEND



GERDA Detector and LAr Performance

Energy Estimation

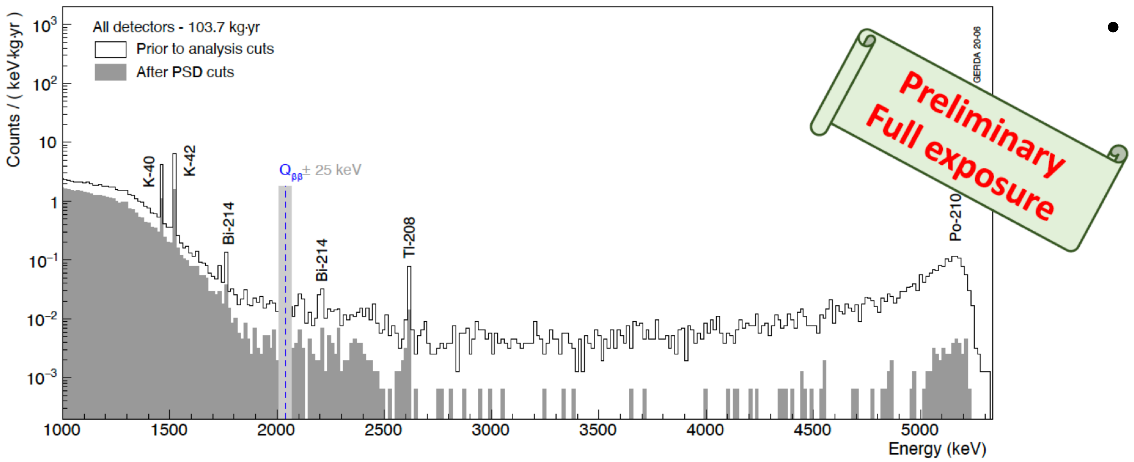


FWHM resolution @ $Q_{\beta\beta}$ (keV)

period	BEGe*	Coax**	IC
pre-upgrade	2.9 ± 0.3	3.6 ± 0.3	
post-upgrade	2.6 ± 0.2	5.2 ± 1.9	2.9 ± 0.1

*post-upgrade improvement due to better cable routing, less xtalk
**worsening driven by one detector featuring higher leakage current

Event Topology and Fiducialization



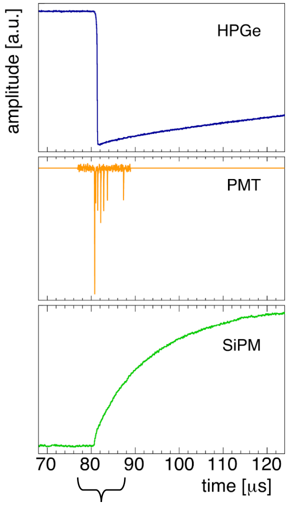
- Charge collection time profile used to identify multi-site and surface events

$0\nu\beta\beta$ decay signal efficiency:

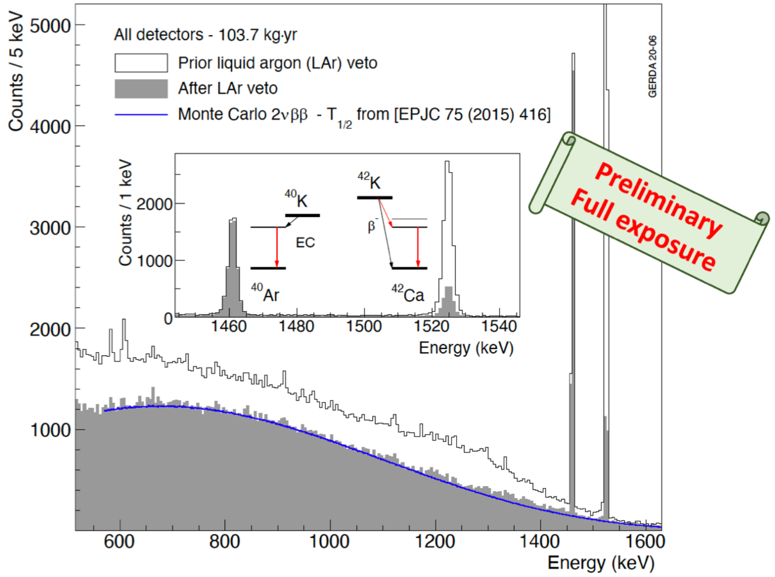
- $\epsilon_{PSD}^{BEGe} = (88.7 \pm 3.2)\%$
- $\epsilon_{PSD}^{IC} = (90.0 \pm 1.7)\%$
- $\epsilon_{PSD}^{Coax} = (68.9 \pm 3.1)\%$

LAr Veto

- Stable operation over 4 years of data-taking
- $0\nu\beta\beta$ decay signal efficiency:
  ϵ_{LAr} = (97.9 ± 0.1)%
- Complementary to PSD: additional x6 reduction in ROI



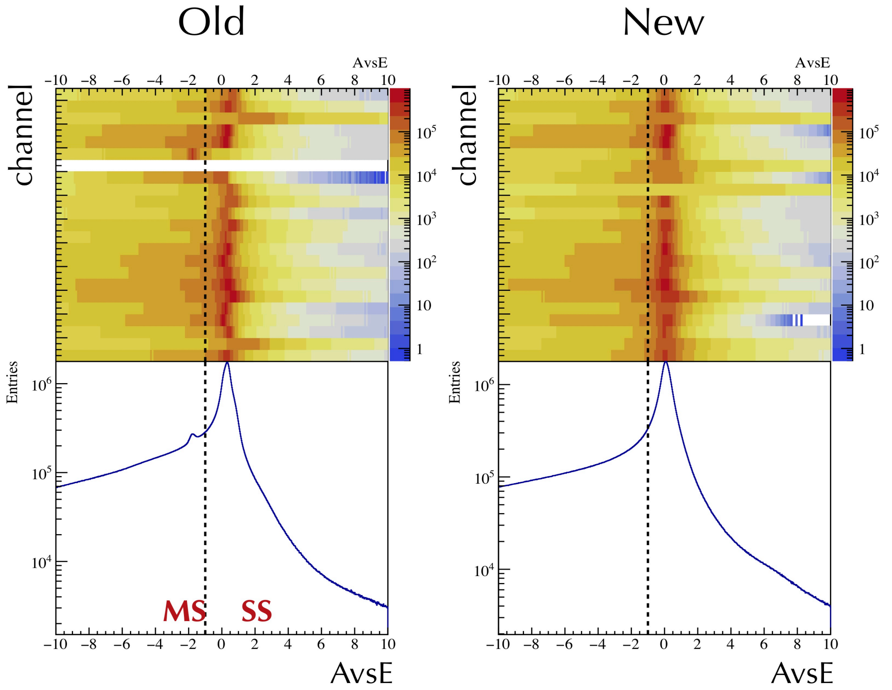
channelwise (PMT/SiPM) **coincidence** condition (threshold ~0.5 PE)

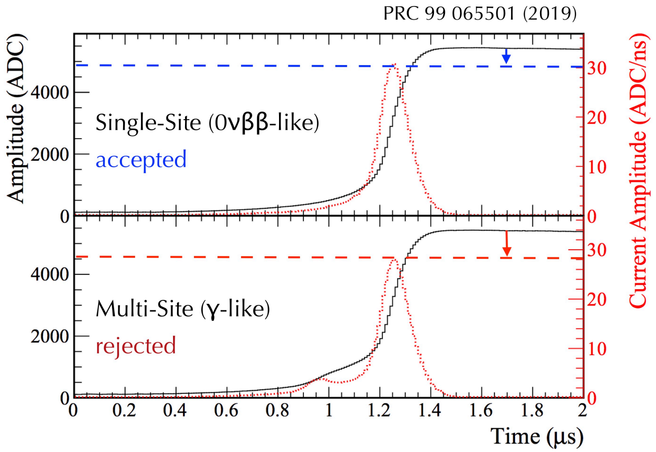


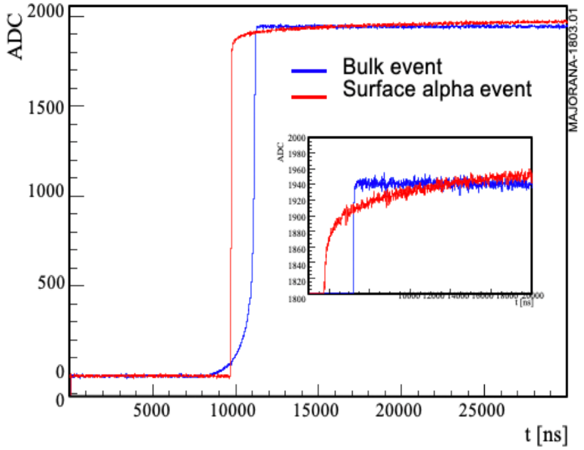
Improvements to γ and α Rejection

A vs. E: multi-site γ event rejection

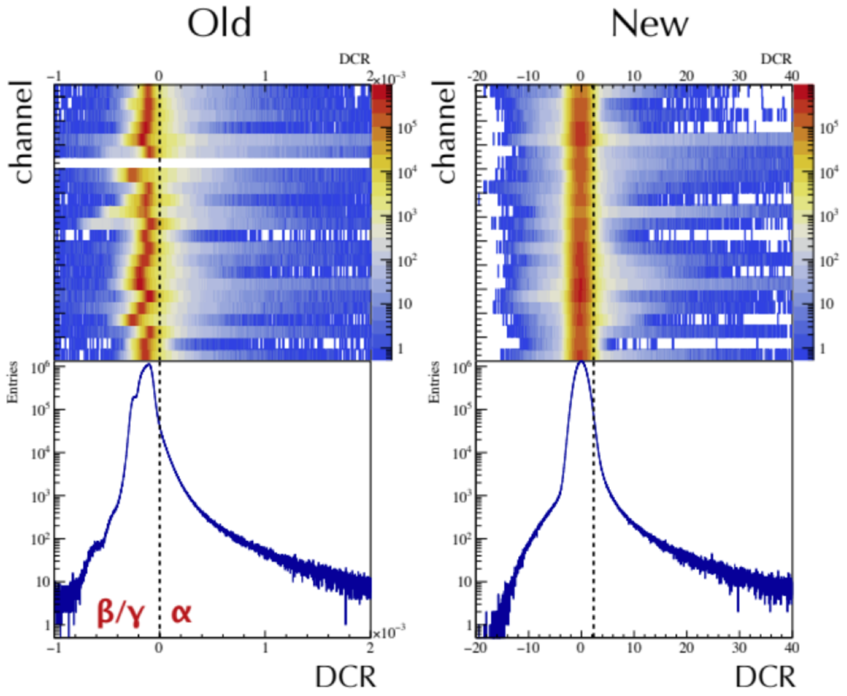
- Retains 90% of known single-site events, evaluated based on DEP data
- 50% reduction in Compton continuum
- Improved stability, uniformity, and single-site acceptance at higher energies
- Now corrects for correlation with drift time: improved discrimination expected







arXiv:2006.13179

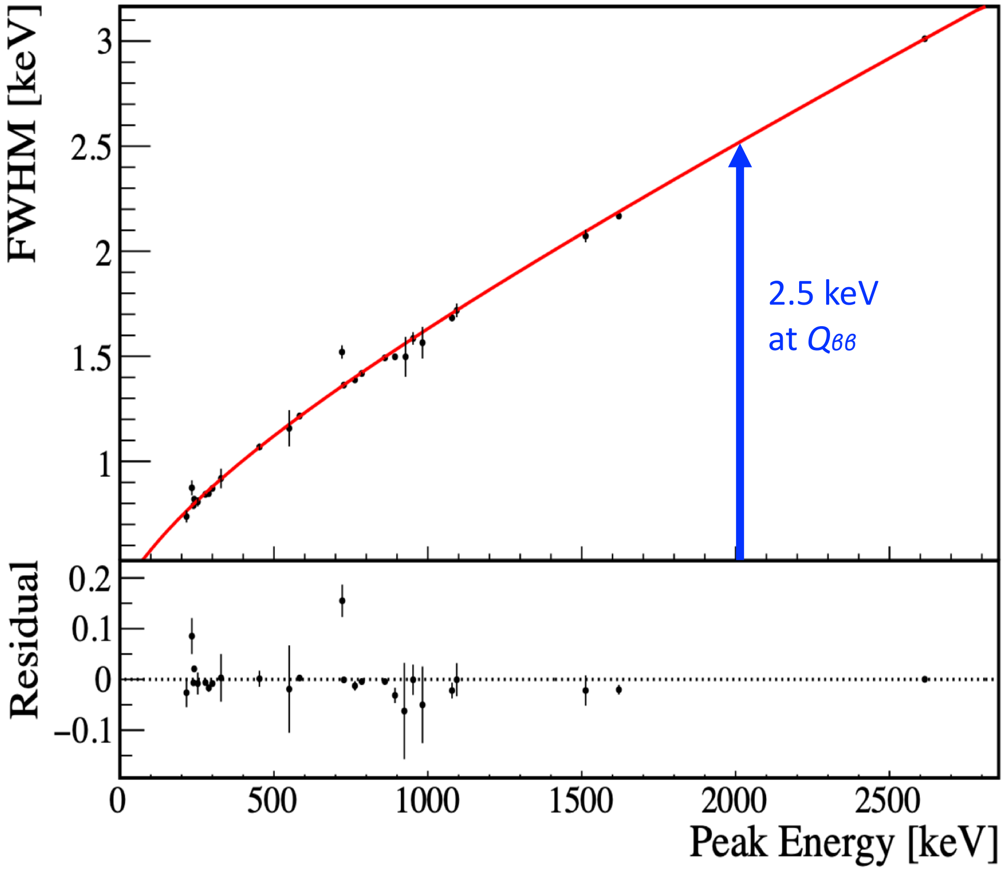


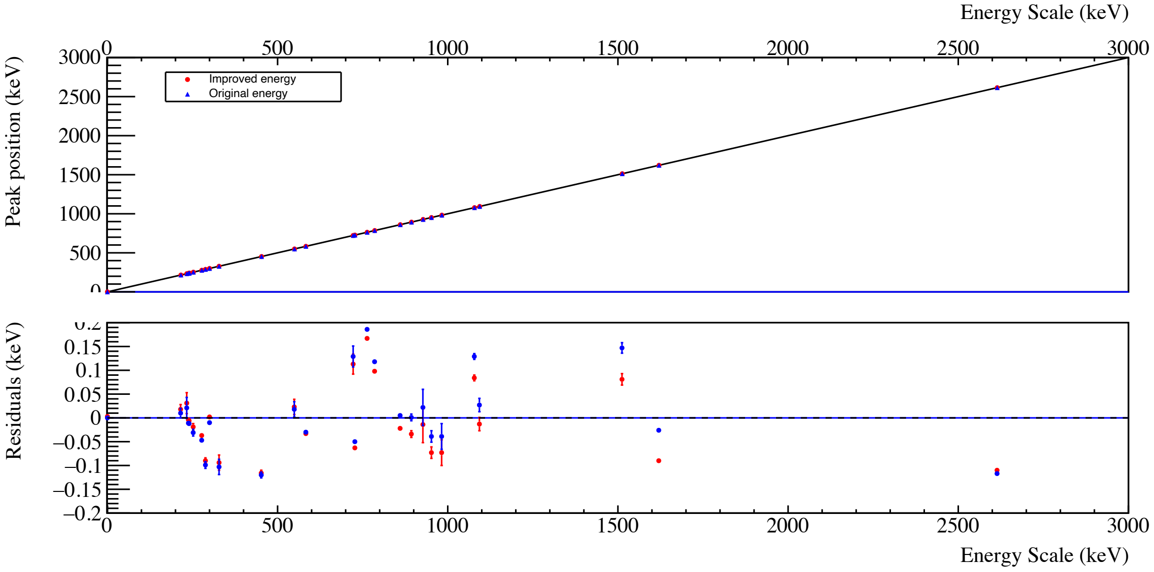
DCR: α event rejection

- Retains 99% of $\boldsymbol{\beta/\gamma}$ events, evaluated based on ^{228}Th data
- Improved stability, increased exposure
- Now corrects for bulk charge trapping: improved discrimination expected

Improved Energy Estimation

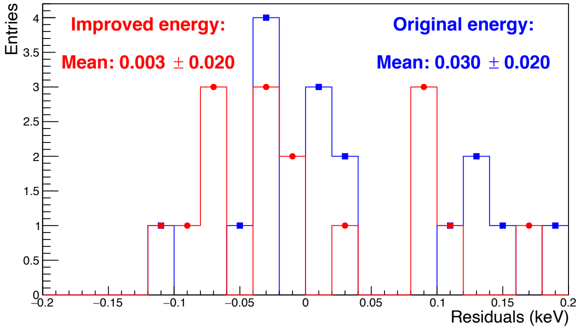
Record FWHM for 0νββ searches: 2.5 keV at Q-value, approaching 0.1%
Record energy linearity for 0νββ searches: better than 0.2 keV up to 3 MeV





Recent improvements:

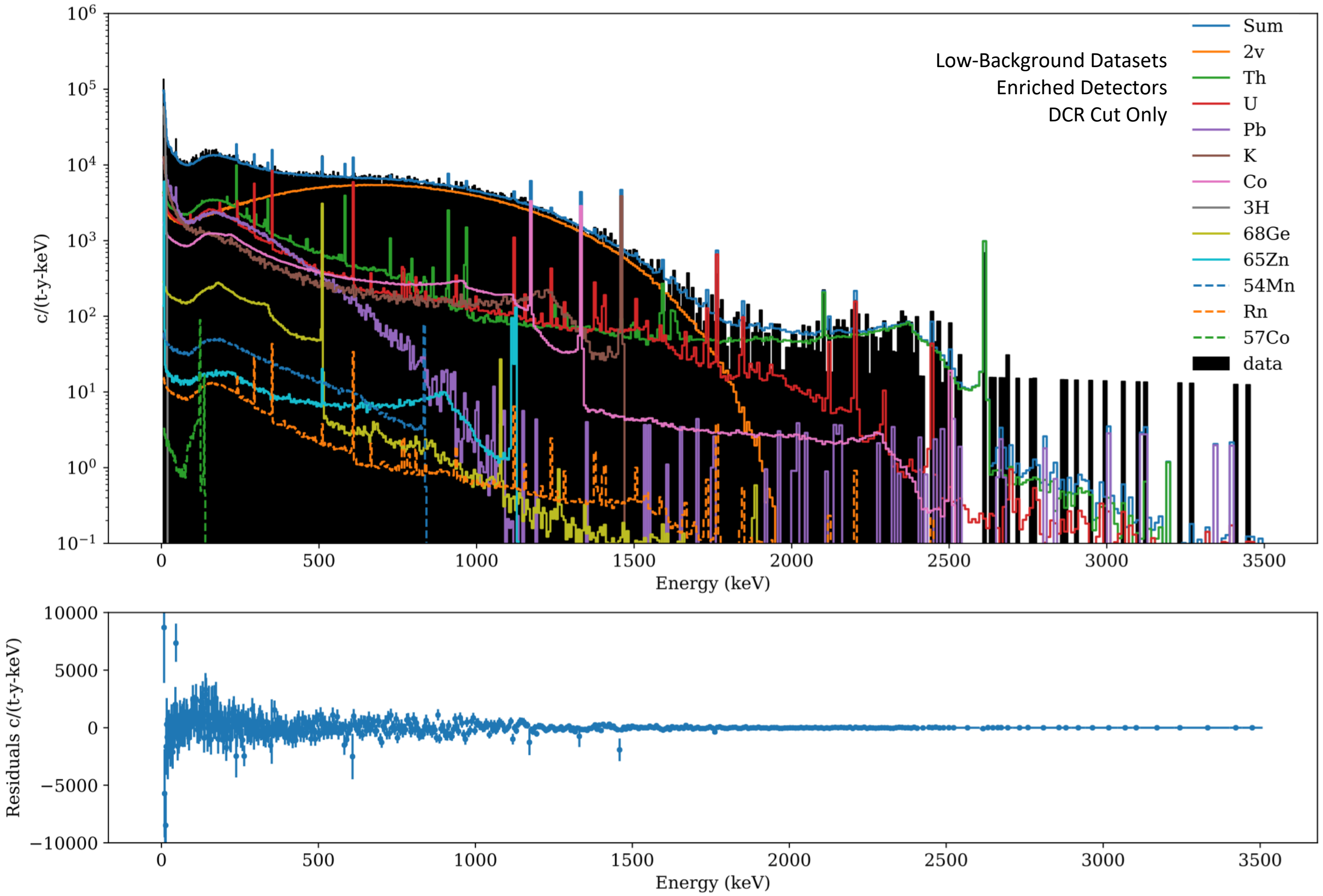
- Corrected for t_0 “trigger walk”
- Quadratic correction for charge recombination



ADC non-linearity correction:
arXiv:2003.04128 [physics.ins-det]

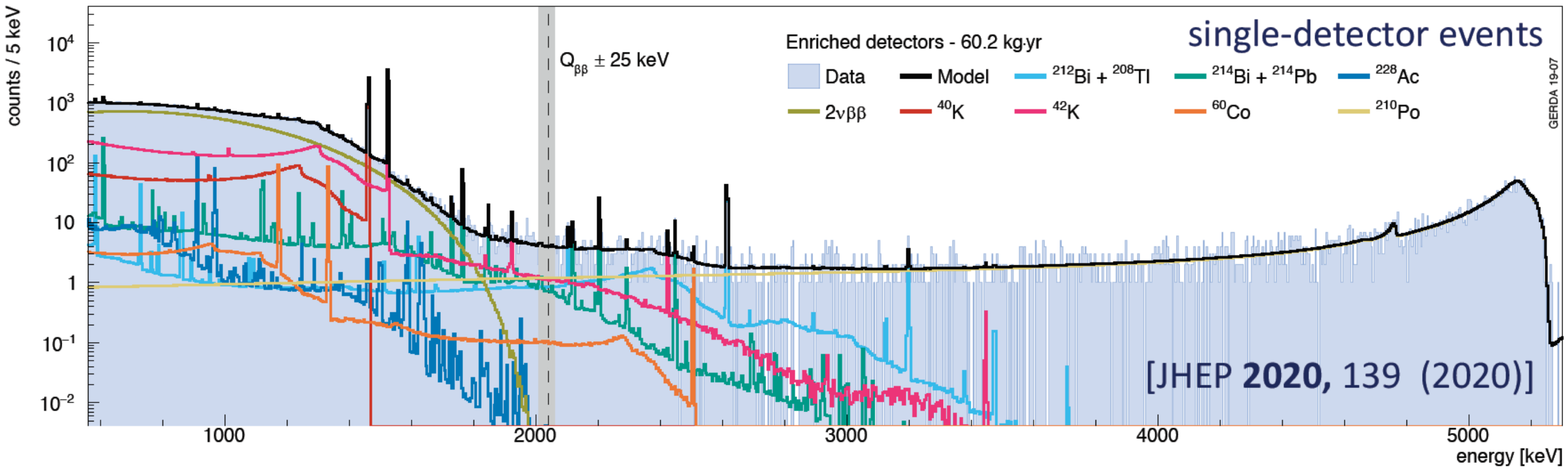
MJD Background Modeling

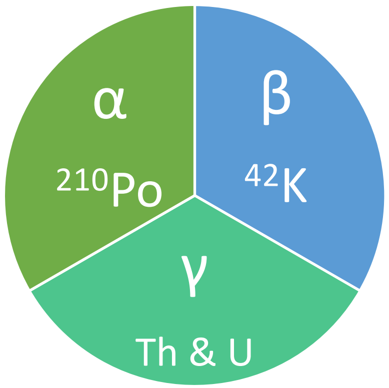
- Investigating observed background near $Q_{\beta\beta}$: 11.9 c/(FWHM t y) measured after all cuts
- Preliminary background model fits to data perform well
- Background at $Q_{\beta\beta}$ clearly due primarily to ^{232}Th chain
    - Fits indicate a preference for excess from distant components
    - Supporting evidence for distant Th contribution from peak intensity and coincidence studies
- Extensive simulation campaign underway with higher statistics to complete the model
    - Improved component groupings
    - Higher-fidelity modeling of distant components



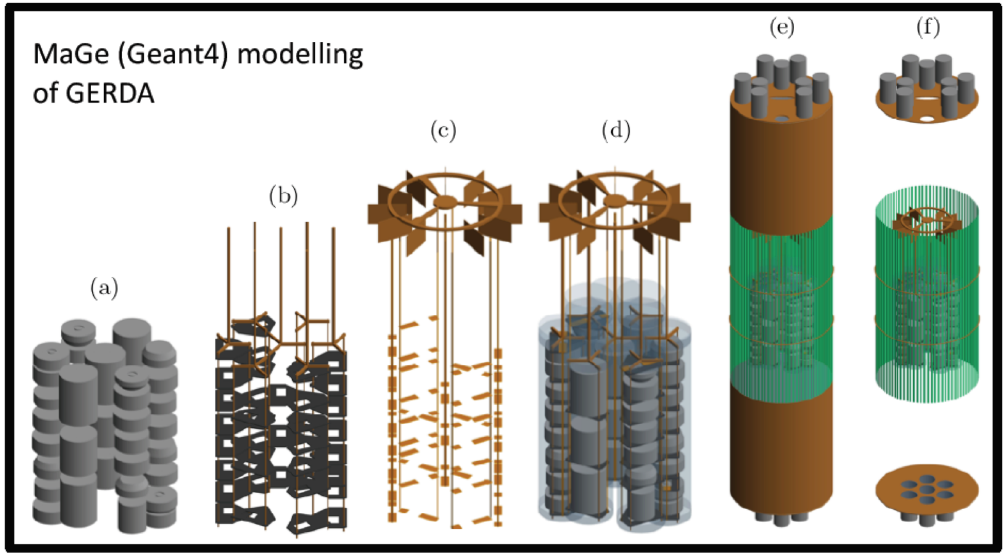
M. Buuck, UW, PhD Dissertation 2019

GERDA Background Modeling





ROI Backgrounds



K. Von Sturm poster
Modeling of
GERDA Phase II data

Fine modelling of all individual parts:

Priors: Constraints from screening measurements

Weakness: Fairly high spatial degeneracy of some components (K, ^{214}Bi)

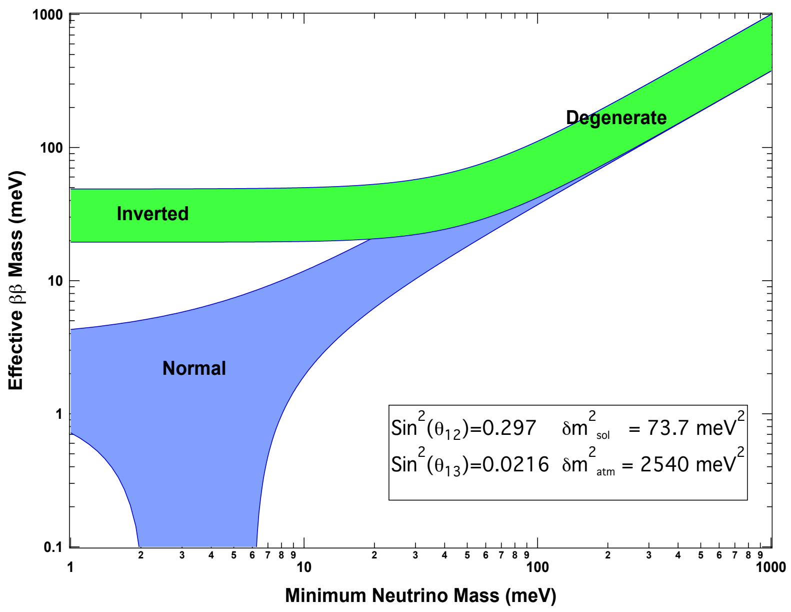
Main outcome: no full energy peak or other structures close to $Q_{\beta\beta}$

Underground LAr

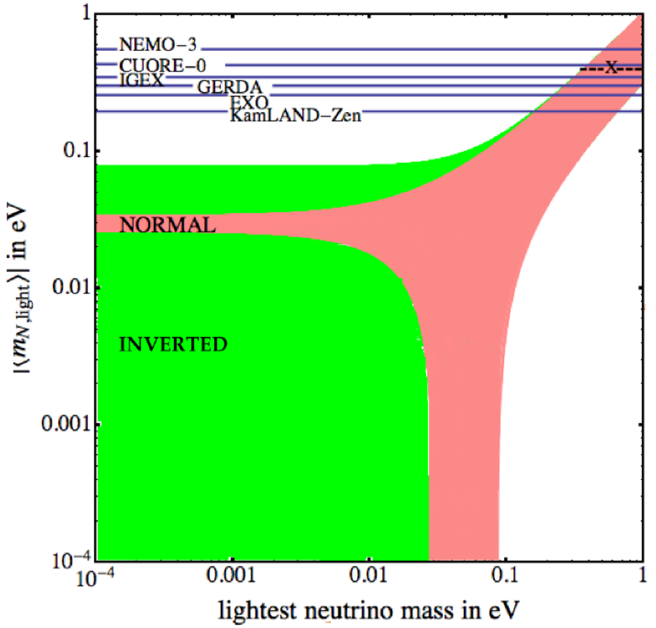
- UAr for detector volumes would be low in ^{42}K, reducing β backgrounds
- Removes mini-shrouds, geometry can be optimized for light collection efficiency
- Estimated UAr needed: 21 tons, 15 m^3
- URANIA expected to produce 100 kg/d of low-background UGLAr
- ARIA purification plant under construction
  - Planned to process ~1 ton/day
- Discussions underway with DarkSide, NSF, INFN, and SNOLAB

J. Ordan/CERN

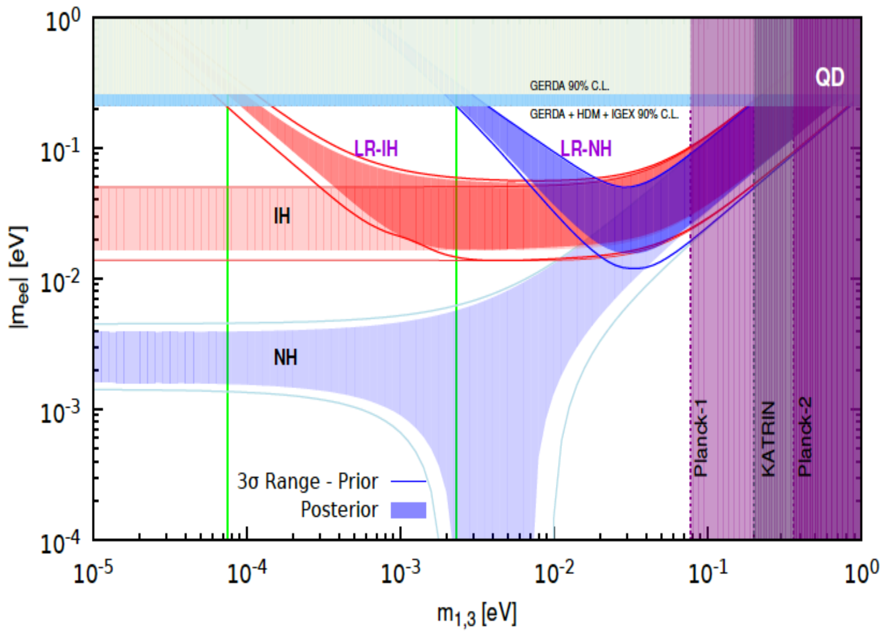
ββ Addresses Key Physics Regardless of Mass Ordering



3 neutrino paradigm



Light sterile neutrino contribution
An example: PRD92, 093001 (2015)



Left-Right symm., Type II contributions
From J. HEP 10, 077 (2015)

Many physics possibilities alter the 3ν paradigm conclusions.
Necessary measurement regardless of upcoming conclusions on ordering.

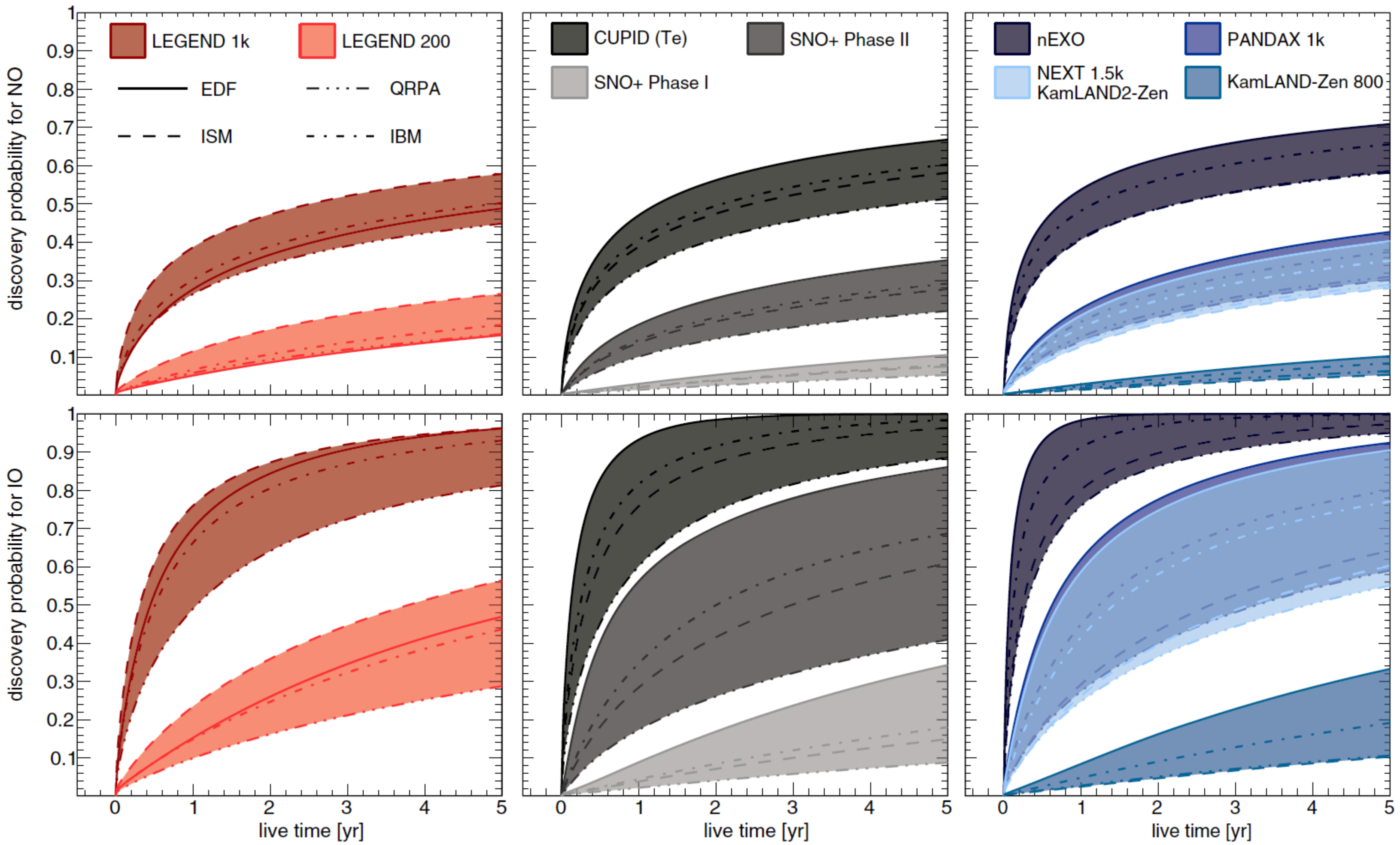
- Additional neutrinos
- Heavy neutrino exchange
- Right handed currents
- R-parity violating susy
- Various heavy particle proposals (short-range physics)

If ββ is seen, the qualitative conclusions are profound, but observations in several nuclei will be required to fully understand the underlying physics.

ββ discovery potential high, even for NO

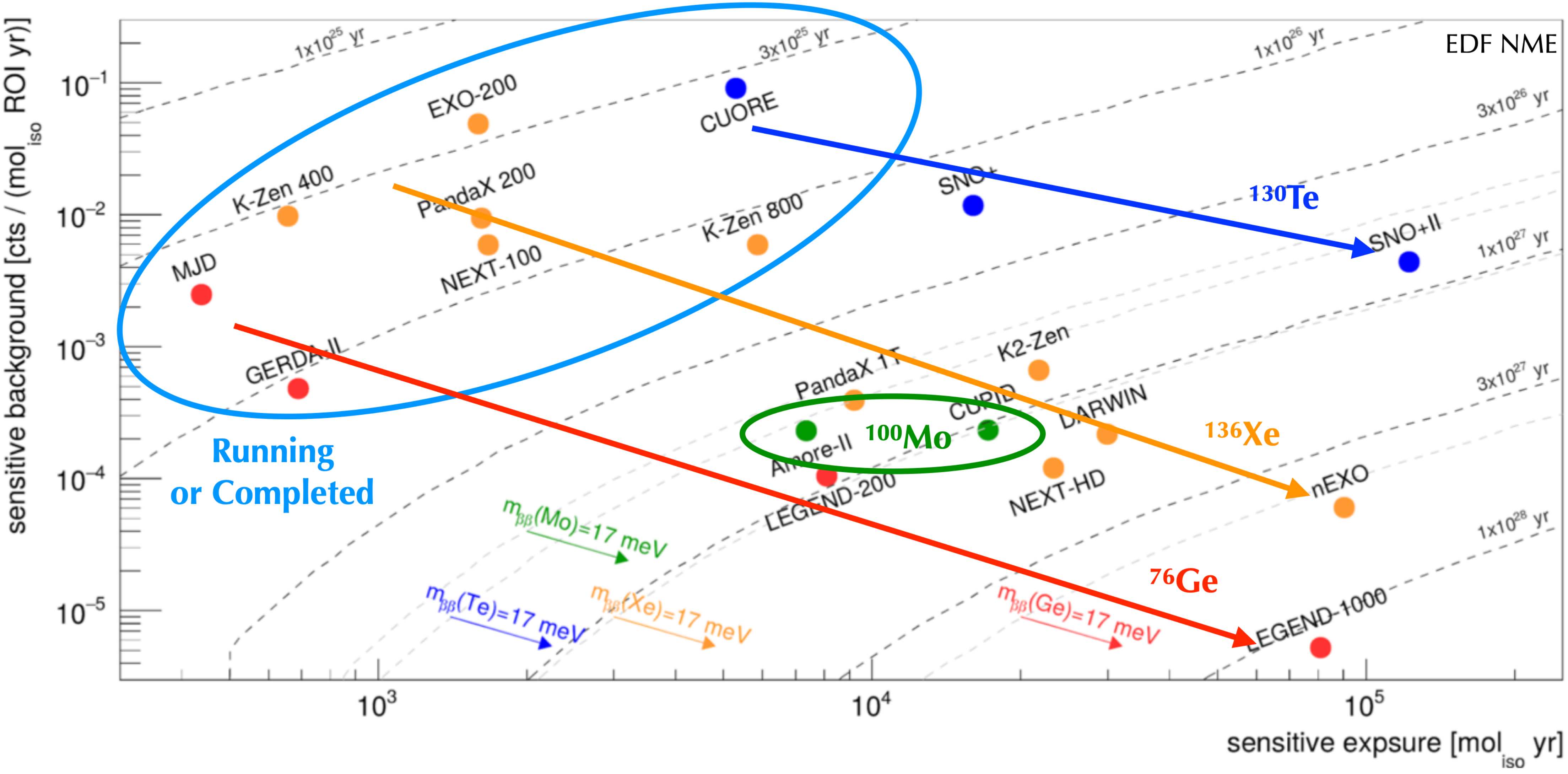
Even for the case of normal ordering of neutrino masses in a 3-ν paradigm, the discovery potential is high because the phases and lightest neutrino mass value have no a priori preferred values.

This qualitative conclusion is not changed due to cosmological constraints or if g_A quenching is included.



Example analysis from PRD 96, 053001 (2017) preliminary

Discovery Sensitivity Comparison



Discovery Sensitivity Comparison