BERKELEY LAB
Bringing Science Solutions to the World

U.S. DEPARTMENT OF ENERGY
Office of Science

Search for Majorana Neutrinos in the LEGEND Experiment

Alan Poon

Nuclear Science Division

Lawrence Berkeley National Laboratory

LEGEND

Outline

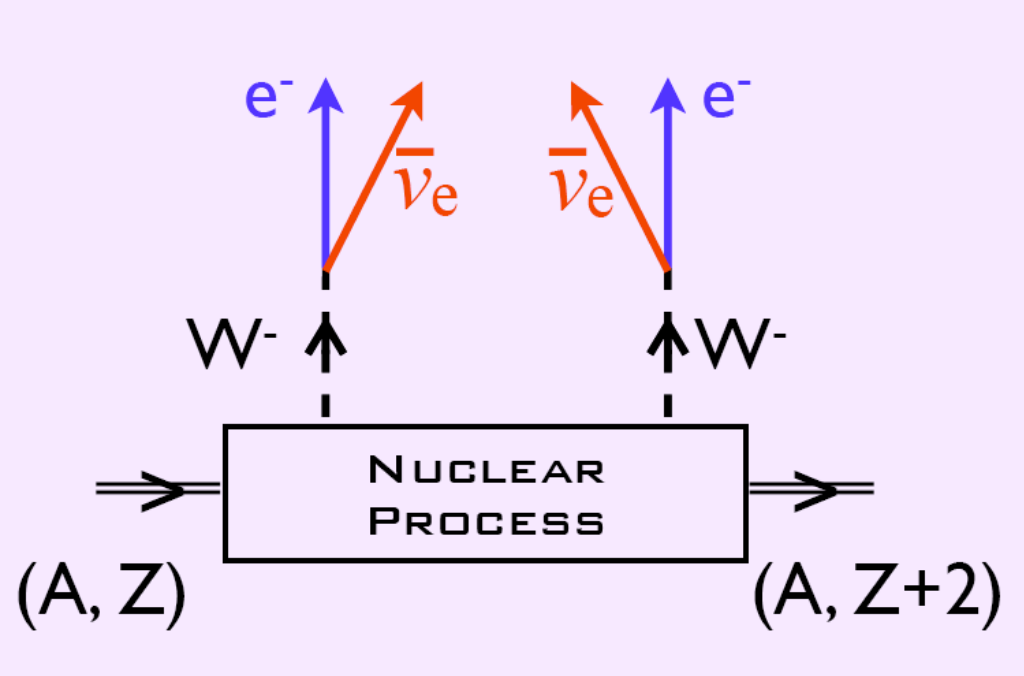
- Introduction - neutrinoless double-beta decays
- The LEGEND project
  - Phase I: 200 kg
  - Phase II: 1000 kg
- Summary

Neutrinoless Double-Beta Decays

- Double-Beta Decay:
  - 2νββ (lepton-number conserving):

$$(N, Z) \rightarrow (N-2, Z+2) + 2e^- + 2\bar{\nu}_e$$

R. Saakyan, Ann. Rev. Nucl. Part. Sci., 63, 503-529 (2013)

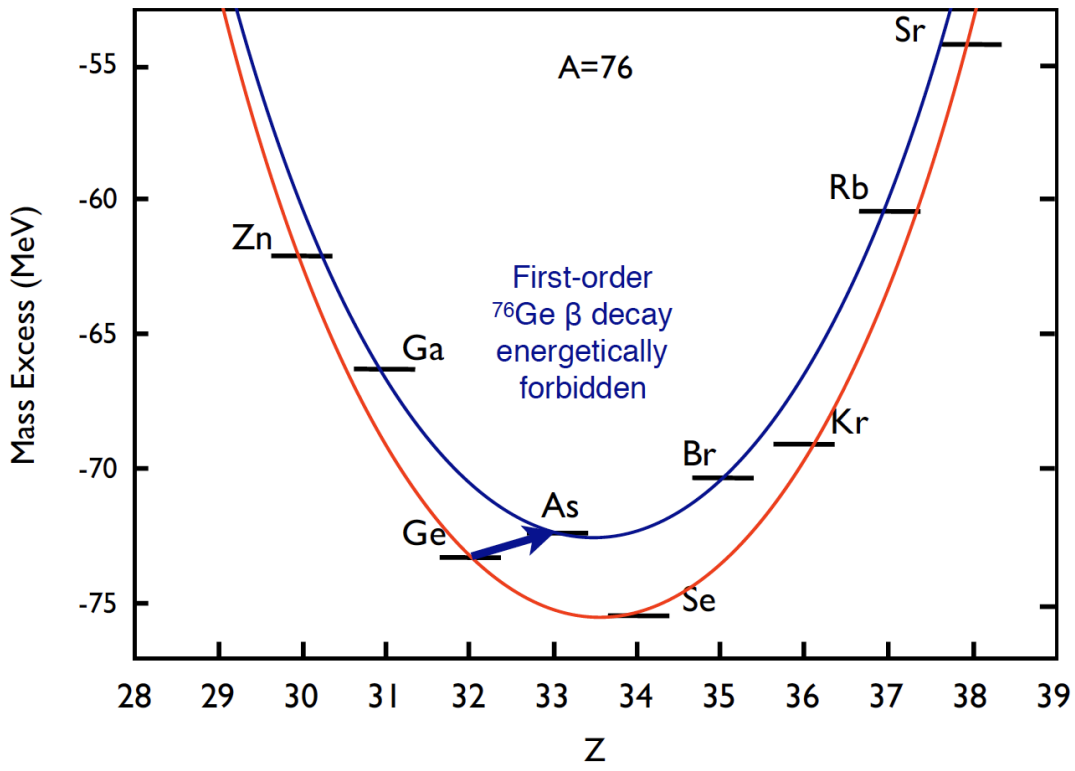


Neutrinoless Double-Beta Decays

- Double-Beta Decay:
  - 2νββ (lepton-number conserving):

$$(N, Z) \rightarrow (N-2, Z+2) + 2e^- + 2\bar{\nu}_e$$

R. Saakyan, Ann. Rev. Nucl. Part. Sci., 63, 503-529 (2013)

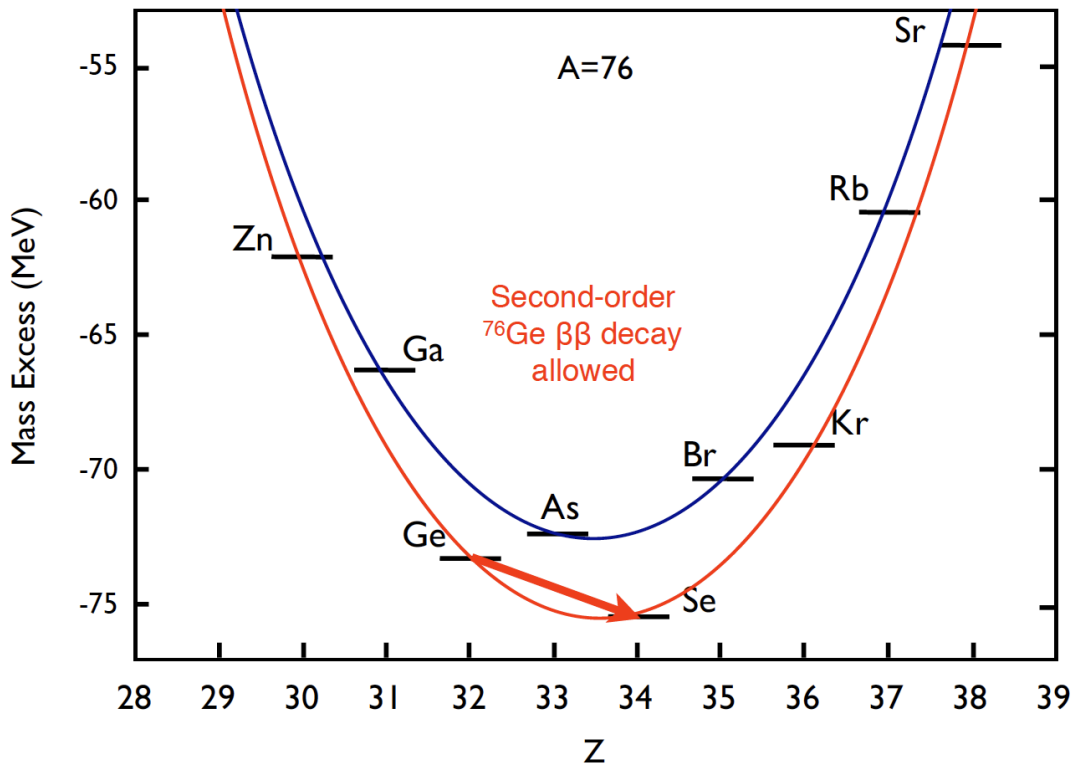


Neutrinoless Double-Beta Decays

- Double-Beta Decay:
  - 2νββ (lepton-number conserving):

$$(N, Z) \rightarrow (N-2, Z+2) + 2e^- + 2\bar{\nu}_e$$

R. Saakyan, Ann. Rev. Nucl. Part. Sci., 63, 503-529 (2013)



Neutrinoless Double-Beta Decays

- Double-Beta Decay:
  - 2νββ (lepton-number conserving):

$$(N, Z) \rightarrow (N-2, Z+2) + 2e^- + 2\bar{\nu}_e$$

R. Saakyan, Ann. Rev. Nucl. Part. Sci., 63, 503-529 (2013)

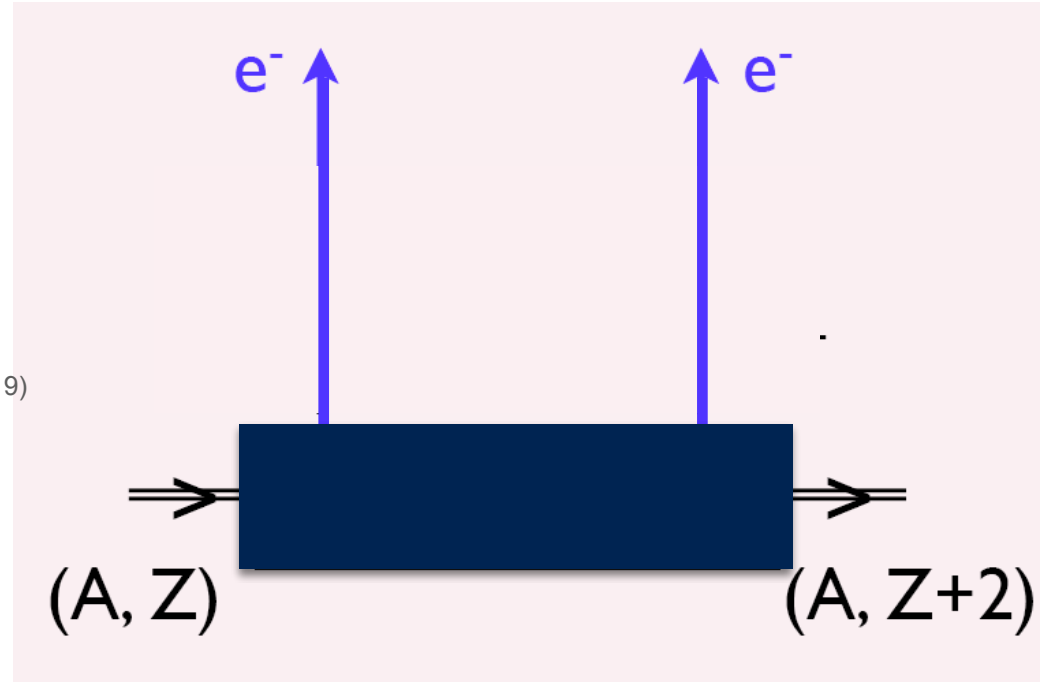
  - 0νββ (lepton-number violating):

$$(N, Z) \rightarrow (N-2, Z+2) + 2e^-$$

M. Dolinski, AP, W. Rodejohann, Ann. Rev. Nucl. Part. Sci., 69, 219-251 (2019)

- 0νββ:
  - ΔL=2 process
  - ∃ Majorana mass term

Schechter &Valle, Phys. Rev. D 25 (1982) 2951



Neutrinoless Double-Beta Decays

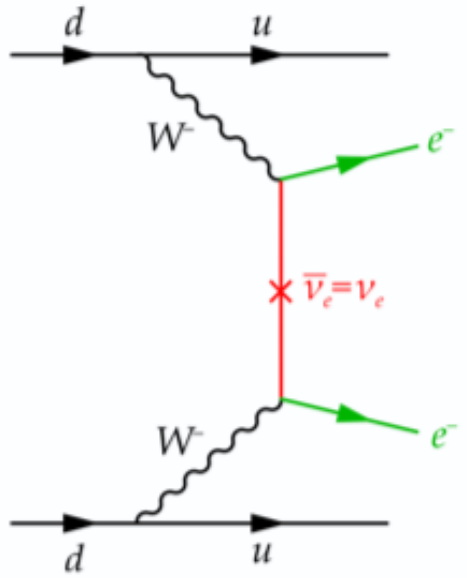
$$(A, Z) \rightarrow (A, Z+2) + 2\,e^- + Q_{\beta\beta}$$

Measure half-life $T_{1/2}^{0\nu}$

LEGEND

Neutrinoless Double-Beta Decays

$$(A, Z) \rightarrow (A, Z+2) + 2\,e^- + Q_{\beta\beta}$$



Light neutrino mechanism

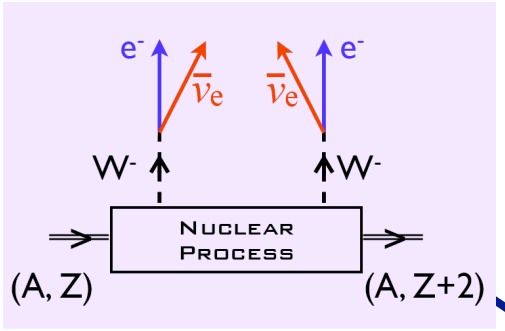
Measure half-life $T_{1/2}^{0\nu}$:

$$\left(T_{1/2}^{0\nu}\right)^{-1} = G_{0\nu}(Q_{\beta\beta}, Z)\,|\mathcal{M}_{0\nu}(A, Z)|^2\,\langle m_{\beta\beta}\rangle^2$$

$G_x(Q_{\beta\beta}, Z)$	➡ Calculable phase-space factor
$\mathcal{M}_x(A, Z)$	➡ Hard-to-calculate nuclear matrix elements (NME)
$\langle m_{\beta\beta}\rangle$	➡ "effective neutrino mass"

$$m_{\beta\beta} = \left|\sum_{i=1}^{3} U_{ei}^2 m_i\right|$$

Neutrinoless Double-Beta Decays

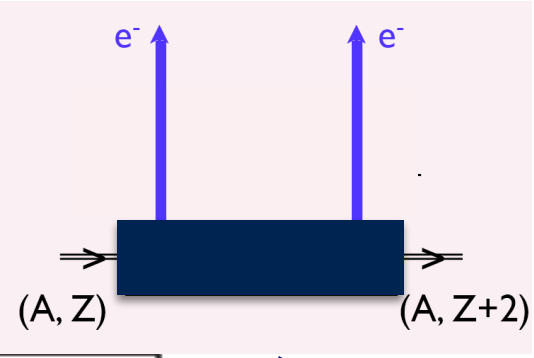


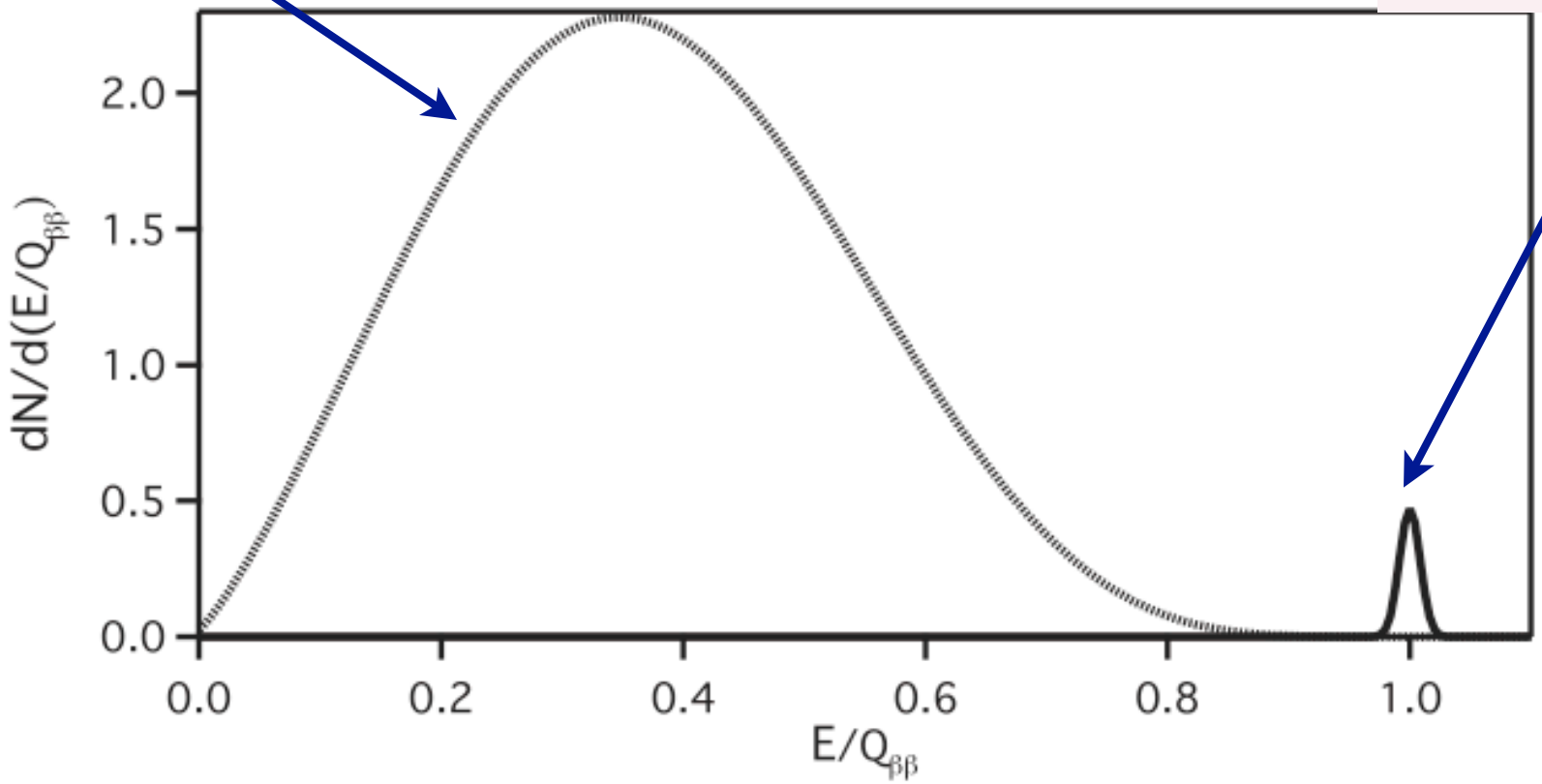
Background

$T_{1/2}^{2\nu} \sim 10^{18-24}$ y

Signal

$T_{1/2}^{0\nu} > 10^{26}$ y





$Q_{\beta\beta}$ = 2039 keV
for ^{76}Ge

Neutrinoless Double-Beta Decays

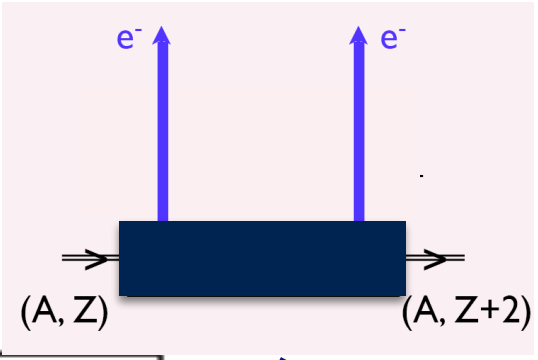
$$T_{1/2}^{0\nu} \propto \sqrt{\frac{M \cdot t}{b \cdot \Delta E}}$$

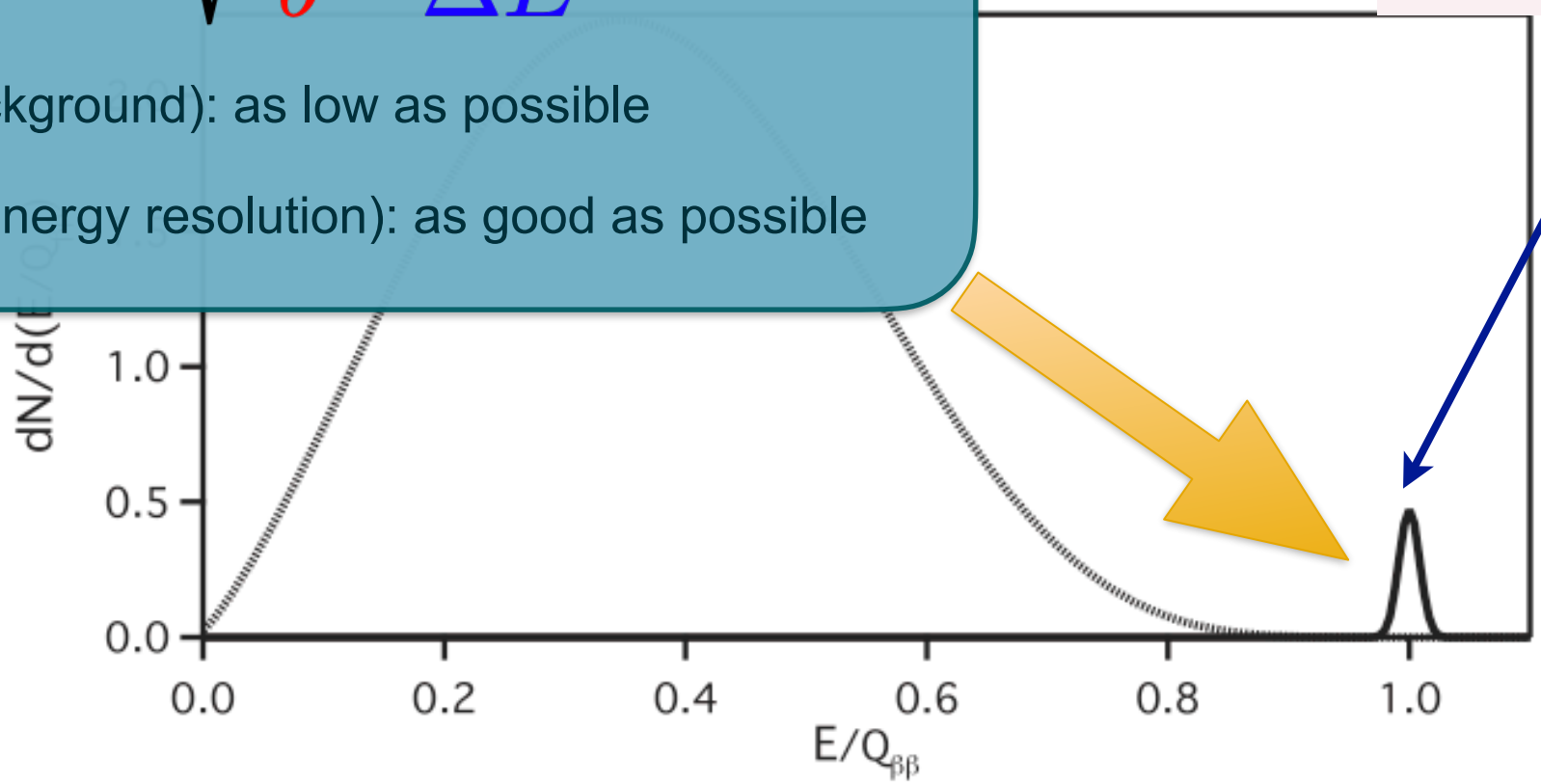
b (background): as low as possible

ΔE (energy resolution): as good as possible

Signal

$T_{1/2}^{0\nu} > 10^{26}$ y





$Q_{\beta\beta}$ = 2039 keV for ^{76}Ge

Large Enriched Germanium Experiment for Neutrinoless ββ Decay (LEGEND)

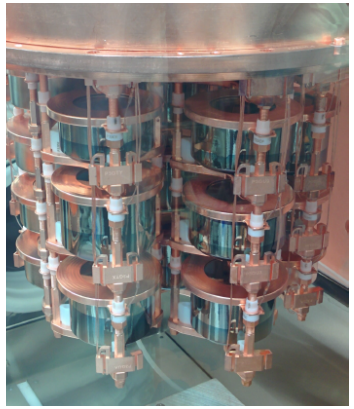
A phased ^{76}**Ge**-based double-beta decay experimental program with **discovery potential** at a half-life **beyond 10^{28} years** using **existing resources** as appropriate to expedite physics results.

MAJORANA DEMONSTRATOR

- Radiopurity of nearby parts
- Low noise electronics
- Best resolution of any 0νββ experiment

2.53 ± 0.08 keV (FWHM)

[PRC 100 (2019) 025501]

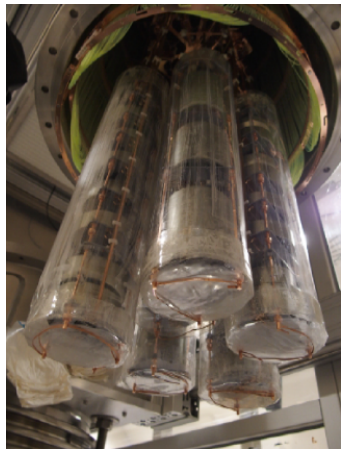


GERDA

- LAr veto
- Low-A shield, no Pb
- Lowest background of any 0νββ experiment

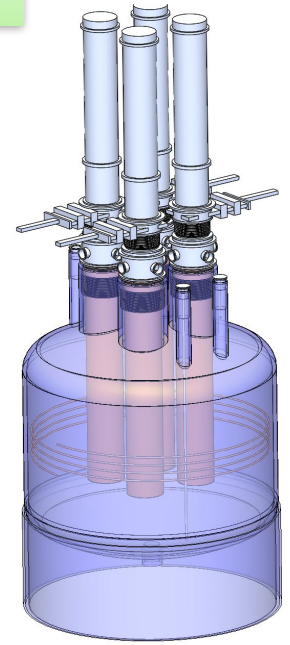
$(5.2^{+1.6}_{-1.3}) \times 10^{-4}$ cts/(keV kg yr)

[PRL 125 (2020) 252502]



LEGEND-200

- Use existing GERDA infrastructure at LNGS
- Up to 200 kg (70 kg of GERDA/MJD detectors + 130 kg of ICPC)
- BG goal: 1/2.5 of existing
- **$T_{1/2} > 10^{27}$ years**
- Start: 2021



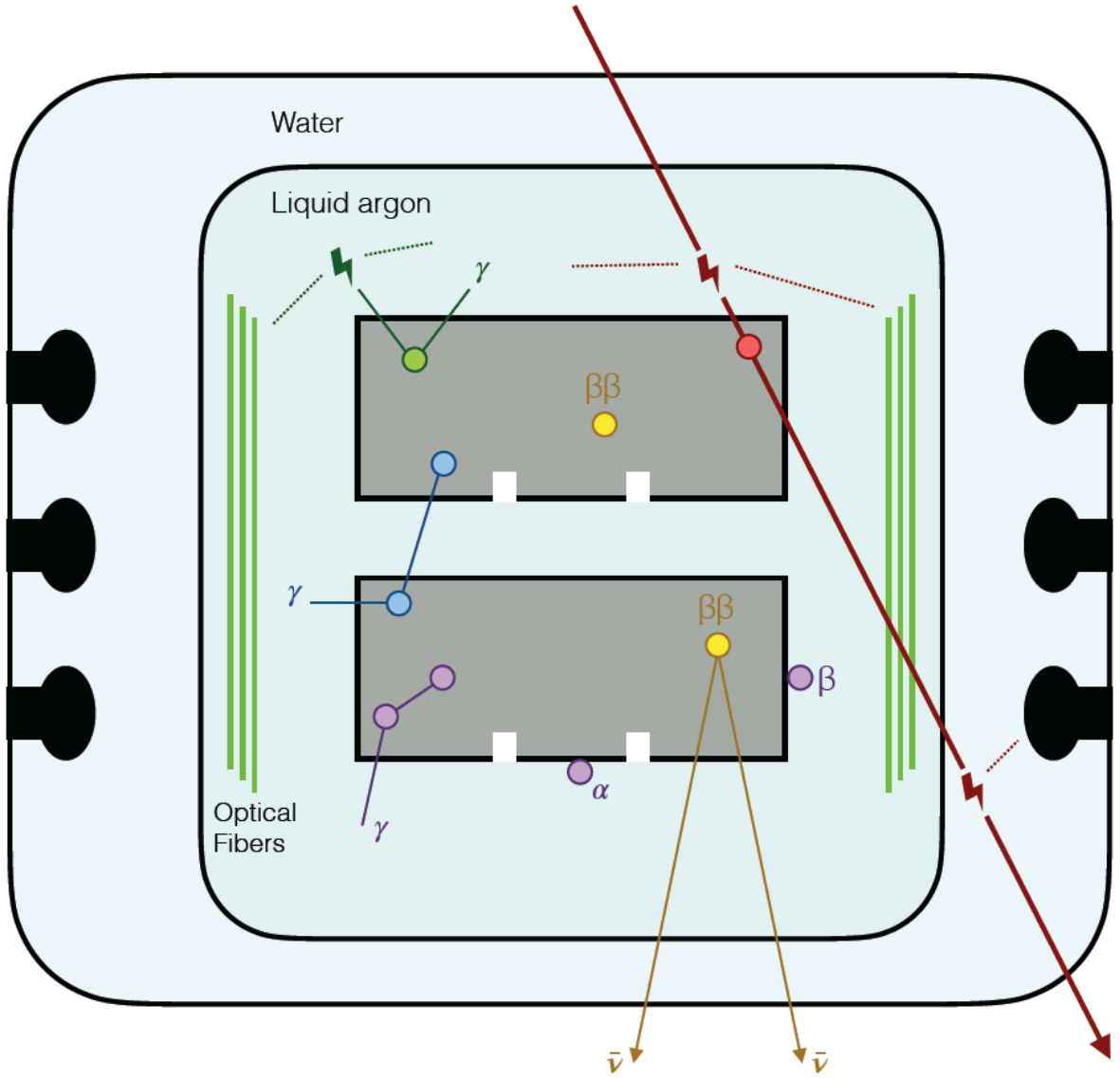
LEGEND-1000

- 1000 kg
- UG LAr
- Phased implementation
- BG goal: 1/50 of existing
- **$T_{1/2} > 10^{28}$ years**
- Site: SNOLAB preferred

LEGEND Background Mitigation

ββ decay signal:
single energy deposition in ~ 1 mm³ volume

Pulse shape discrimination (PSD)
for multi-site and surface events



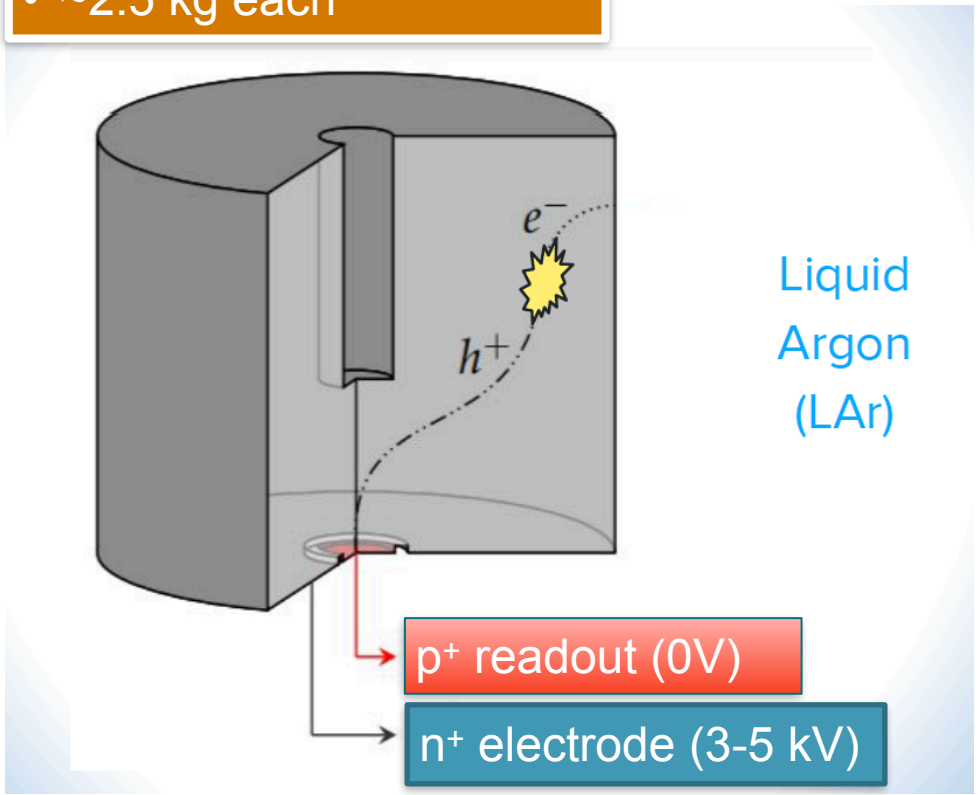
Muon veto:
→ Cherenkov photos in water tank

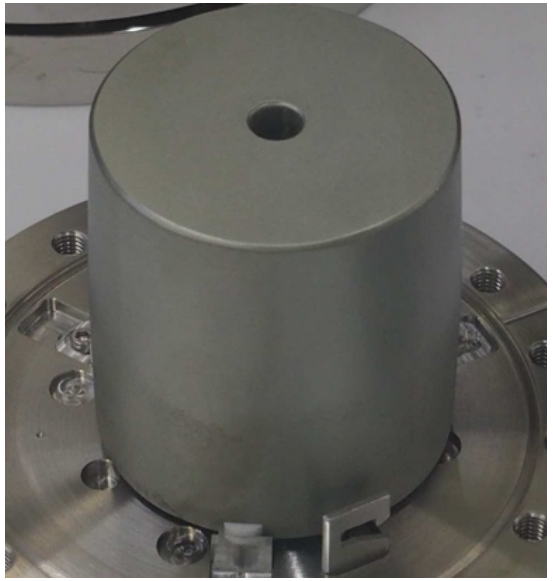
Liquid Argon instrumentation:
→ scintillation light from γ and β

Detector anti-coincidence
over full array

Inverted Coaxial Point-Contact Ge Detectors for 0νββ

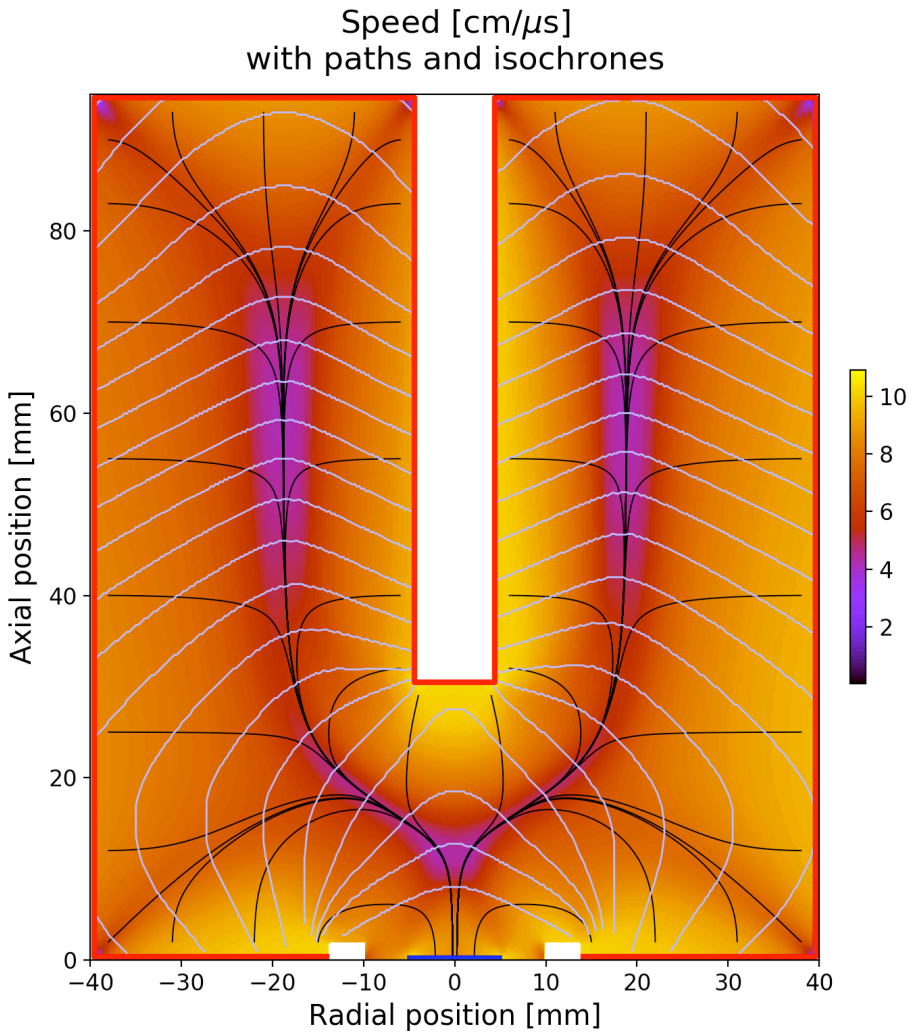
- Enriched to ~92% ^{76}Ge
- ~2.5 kg each

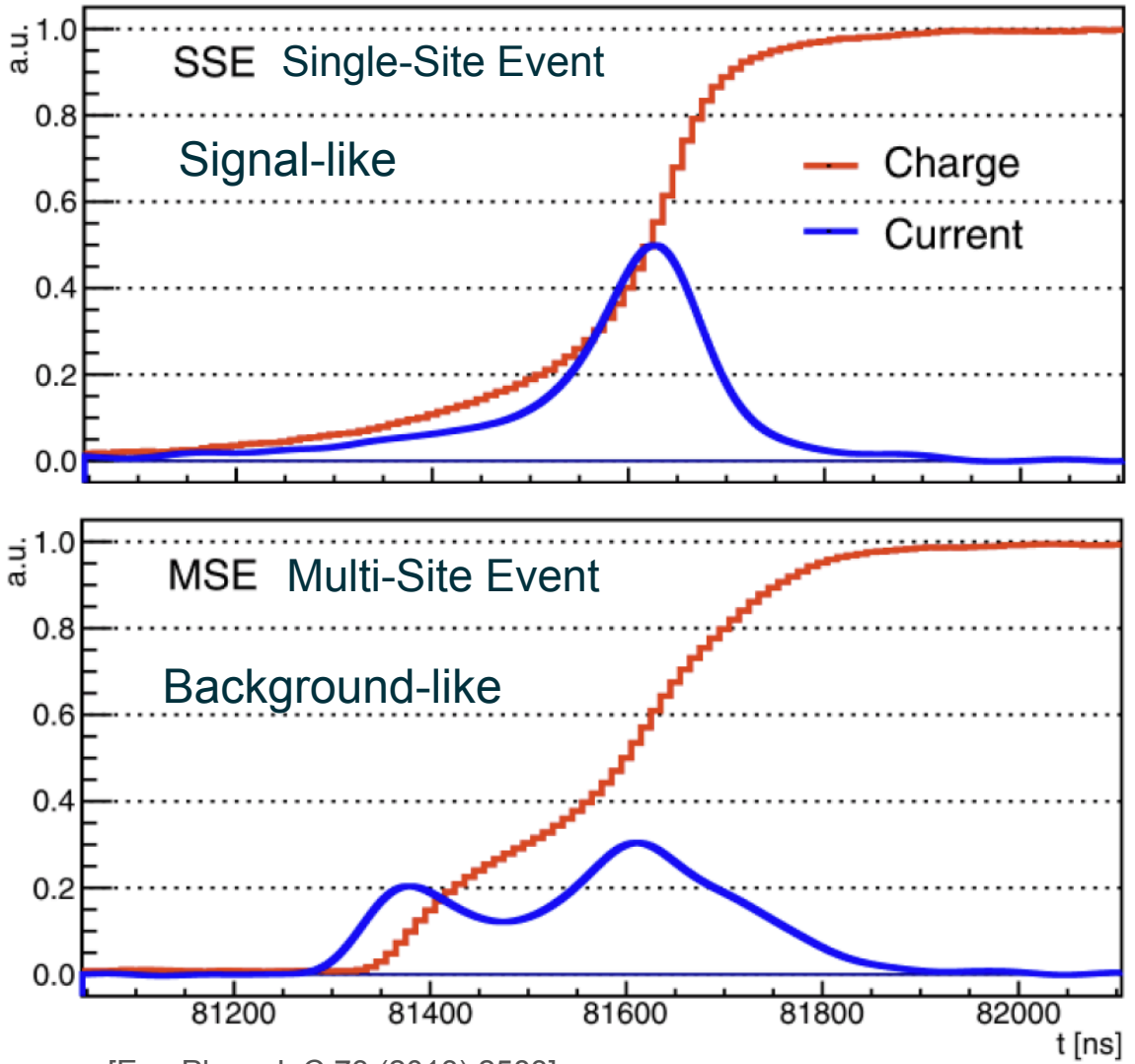




[Nucl. Instrum. Meth. A665, 25, 25-32 (2011)]

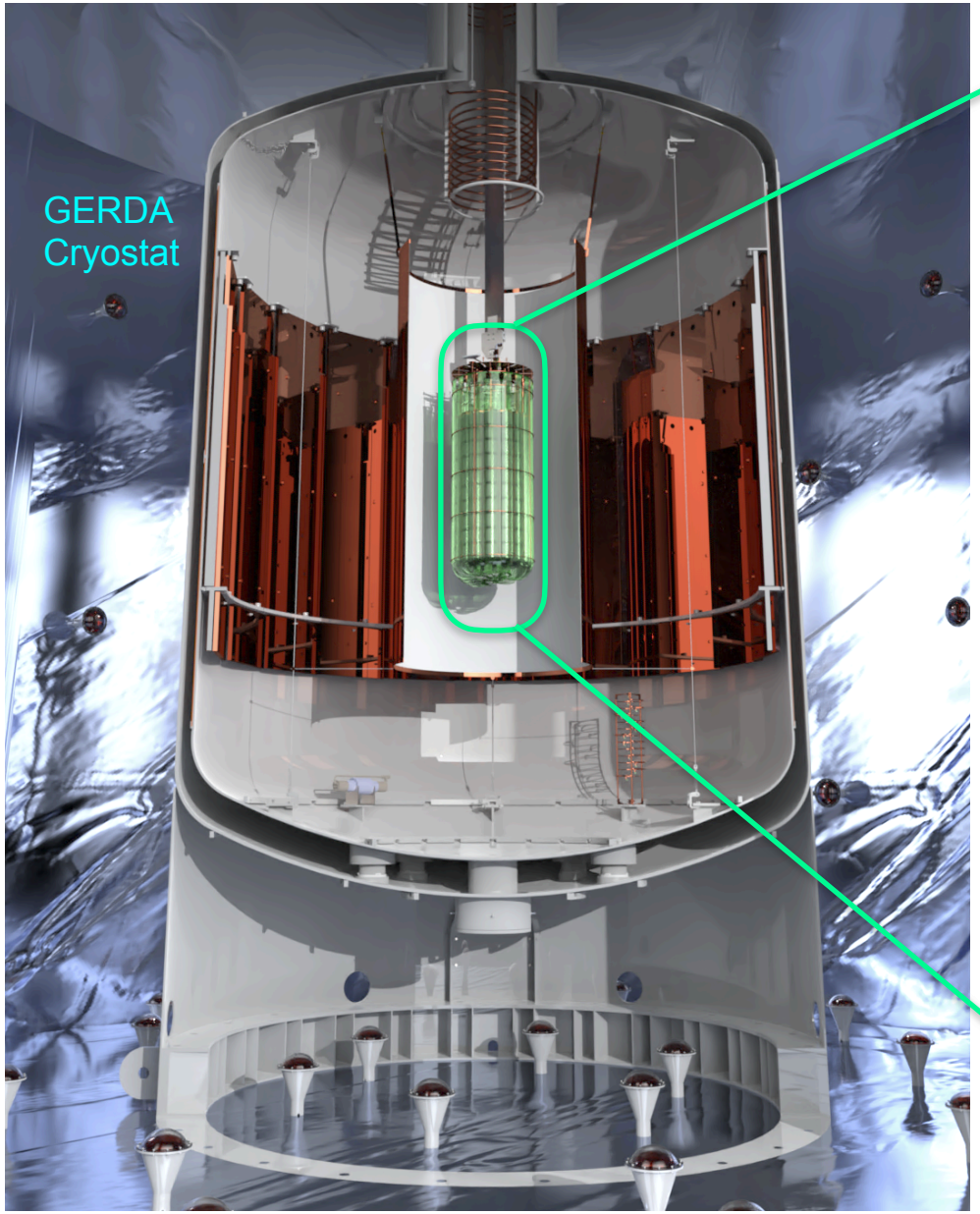
Inverted Coaxial Point-Contact Ge Detectors for 0νββ

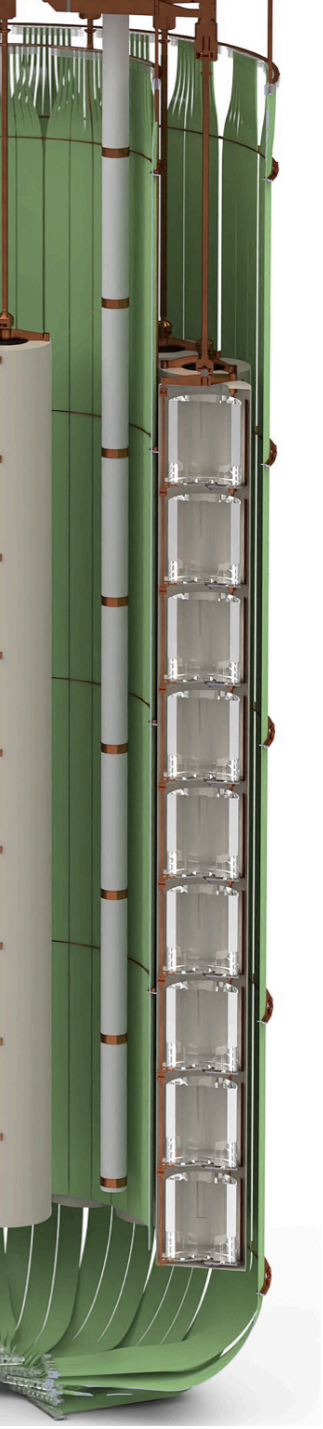


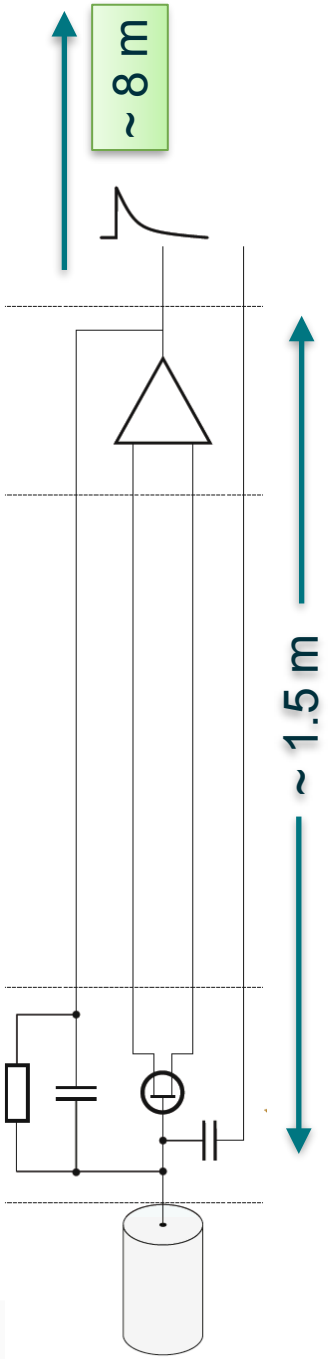


[Eur. Phys. J. C 73 (2013) 2583]

LEGEND-200

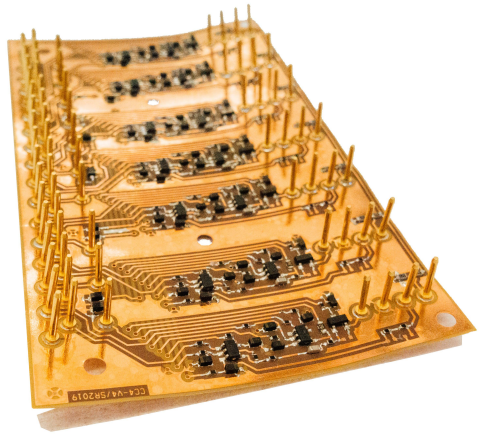


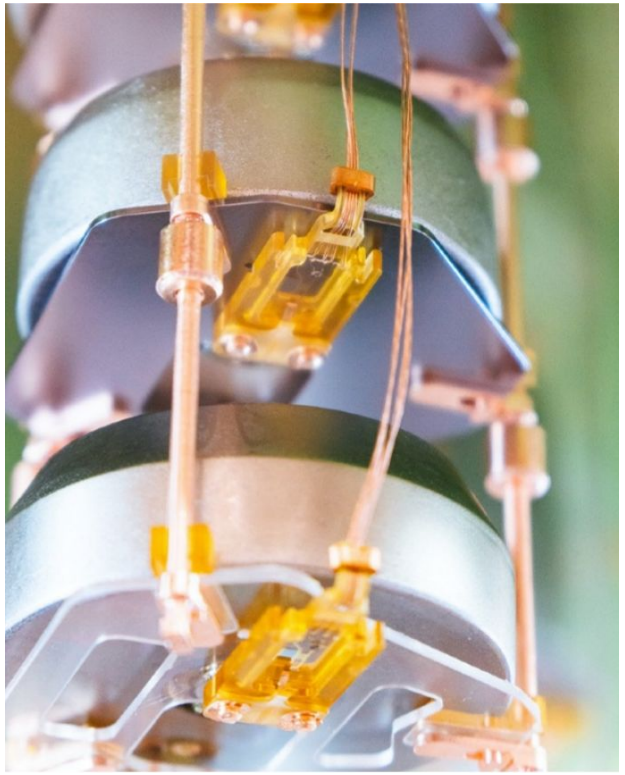




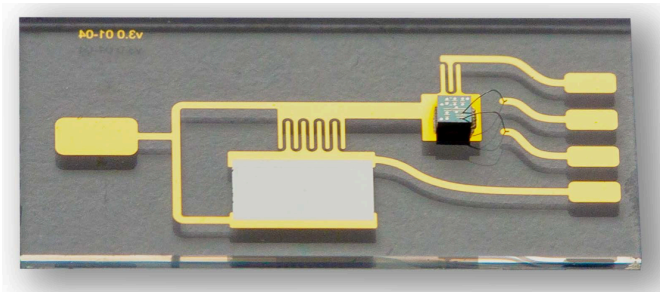
MJD+GERDA example: LEGEND-200 readout

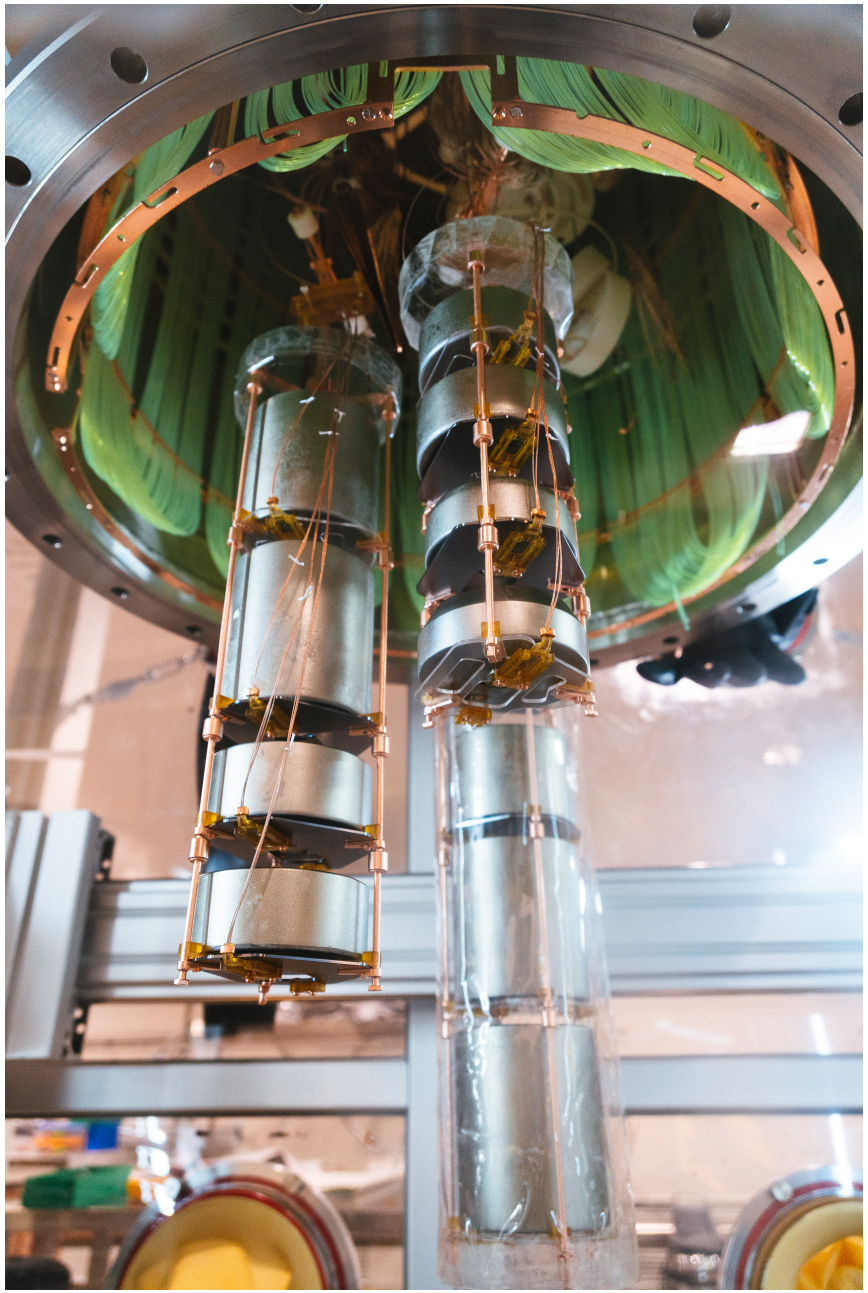
- LAr-operated preamplifier of GERDA





- Ultra-clean Low Mass Front-End of MAJORANA.



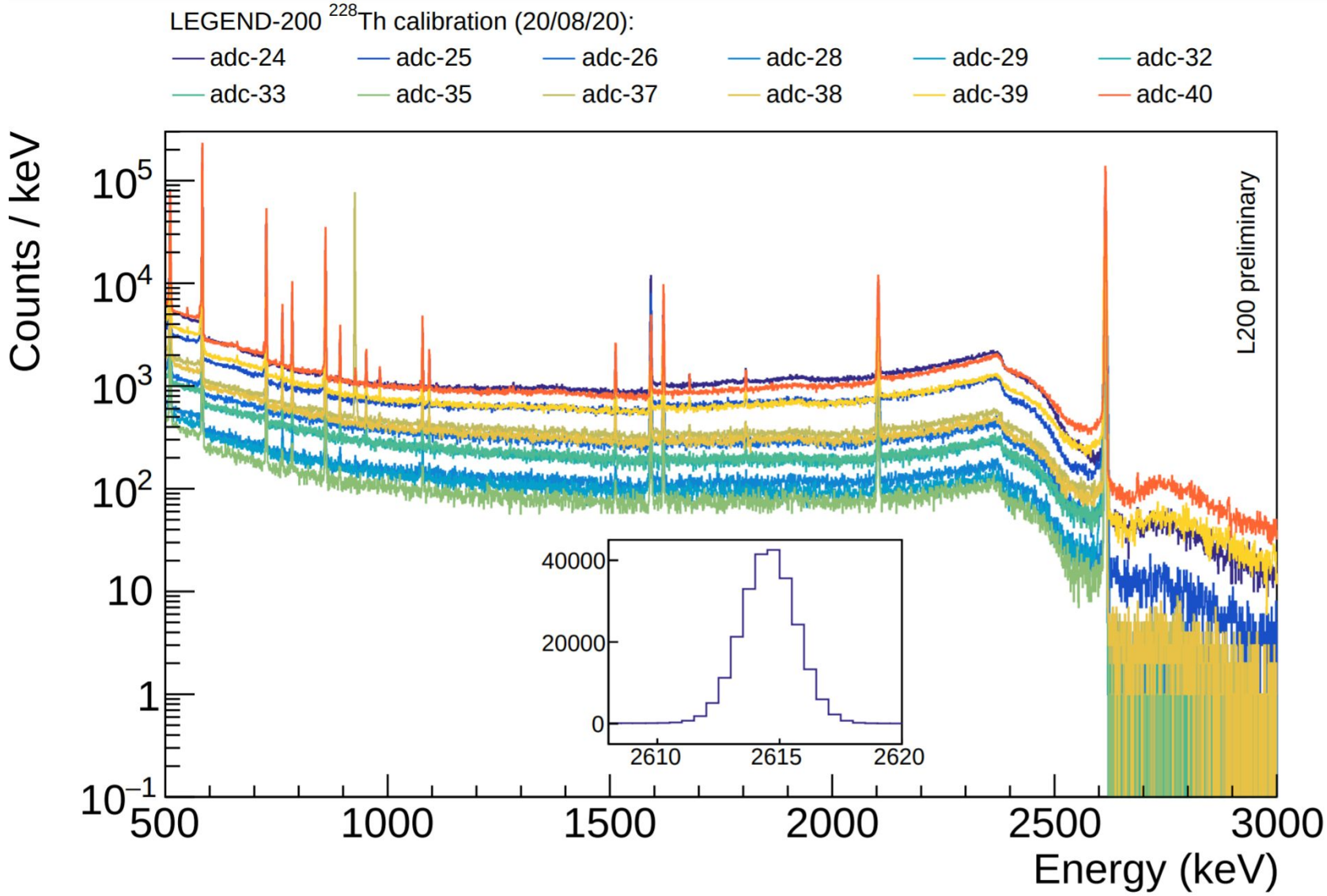


LEGEND-200: Post-GERDA Test (PGT)

- On-site integration test with existing GERDA infrastructure
- Tested new components (readout electronics, detector mount, DAQ) for L-200
- 2020.02 - 2020.08 (with some pandemic-related delays)
- Operation of all LEGEND-200 detector types (ICPC, BEGe, PPC)
- Test new data acquisition system, readout electronics & detector mounts
- ~ 1 month physics data + calibrations
- Demonstrate reliable operation of new components in LAr → Improved energy resolution in good operating detectors :

$\langle \Delta E \rangle \approx 2.2$ keV (FWHM) @ $Q_{\beta\beta}$

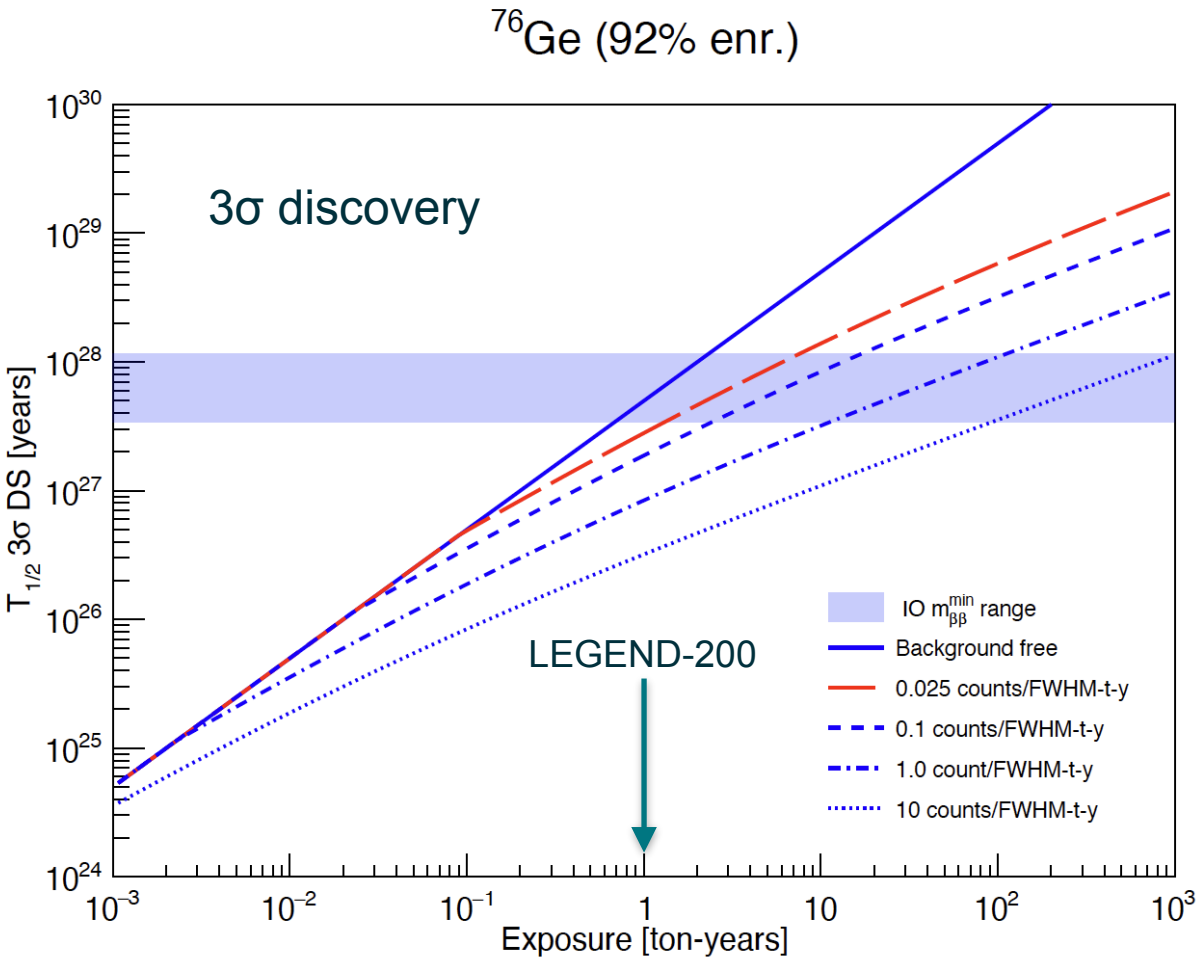
LEGEND-200: Post-GERDA Test

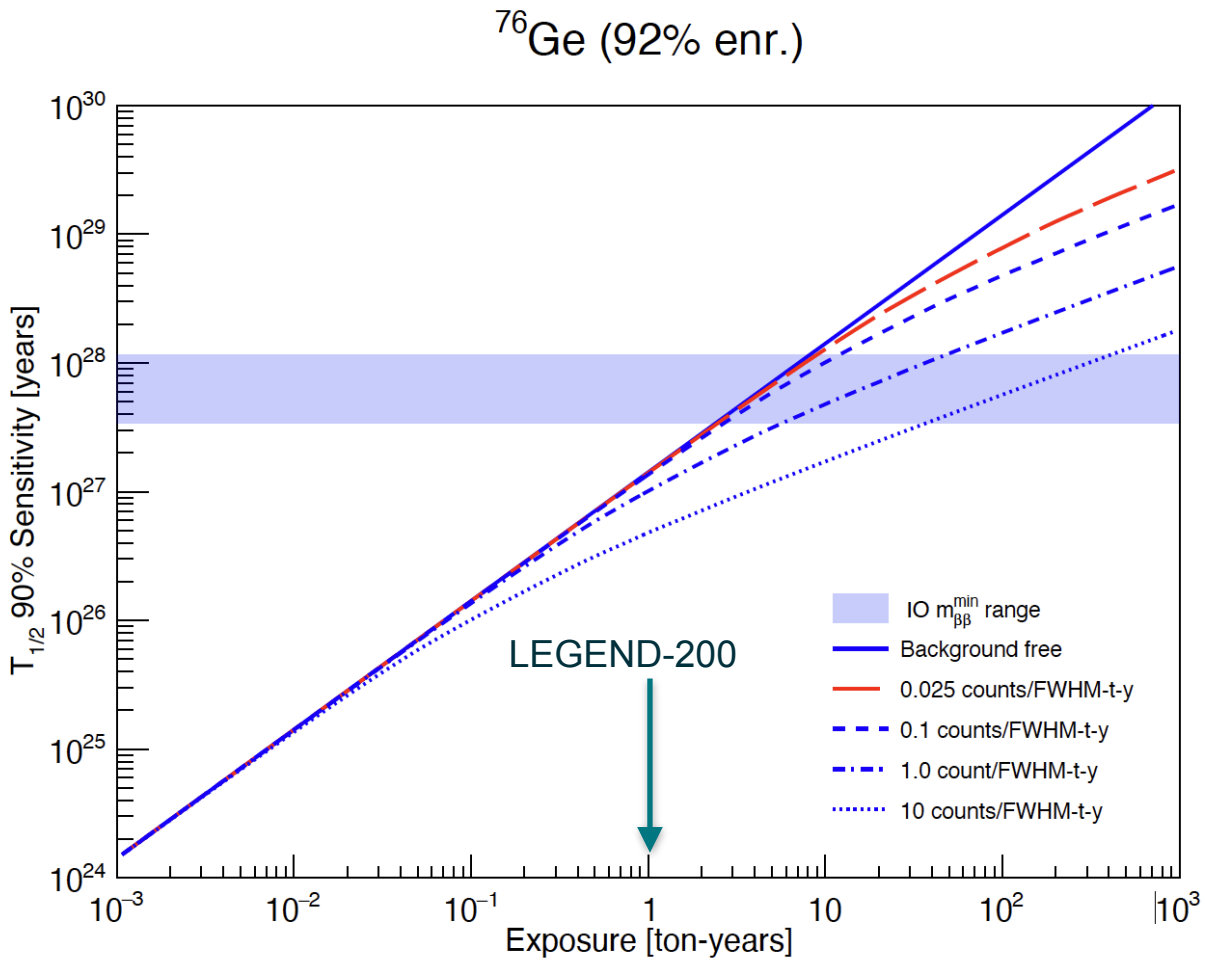


LEGEND-200: Status

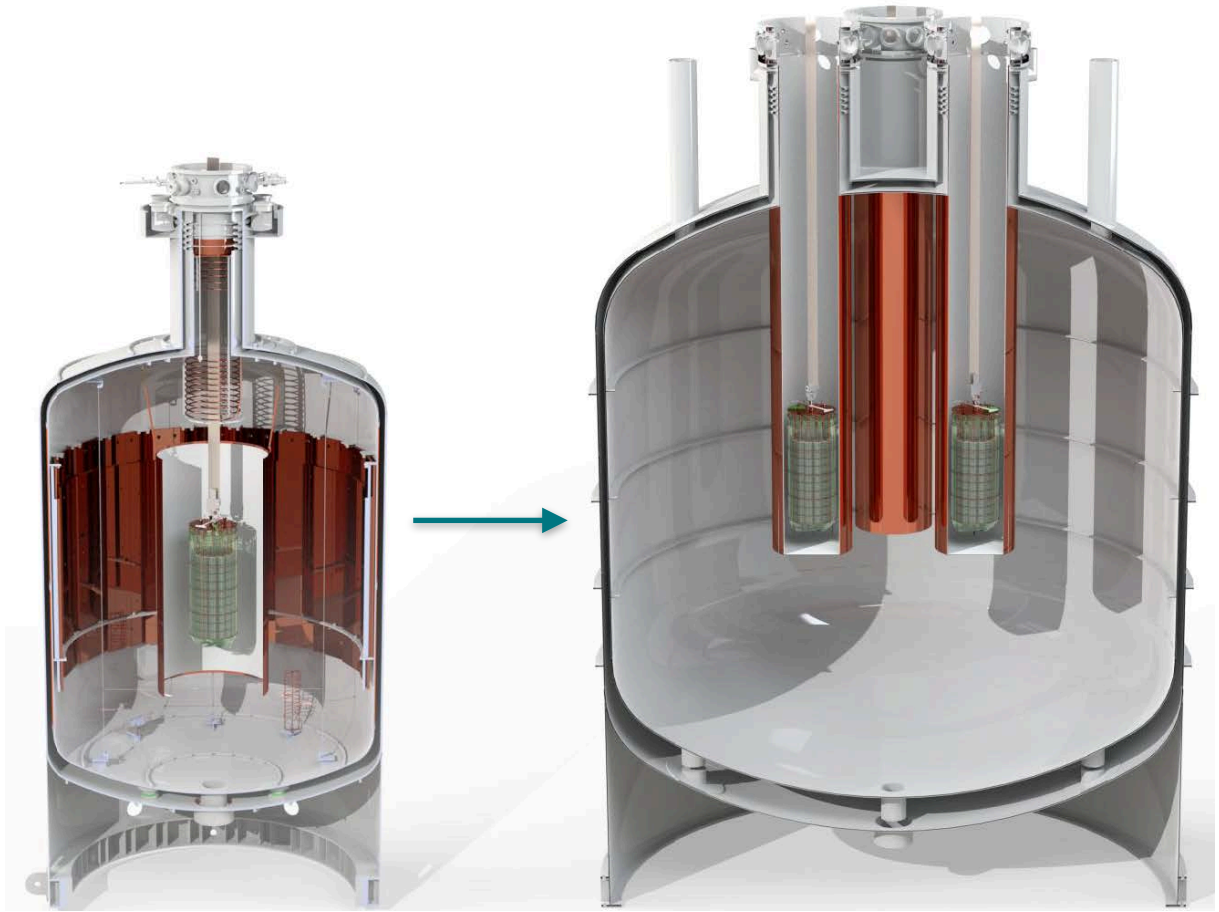
- Funding: Fully funded
- Transfer of GERDA dewar and infrastructure to LEGEND : 2020.02.17
- Enriched ^{76}Ge: 177 kg from two vendors delivered
- Detectors: Production (~2 kg/det) from two vendors in progress
- Screening, assays, and electroformed Cu: underway
- Lock: assembled and tested at MPIK; being installed right now
- Calibration system: multi-source deployment; new system used in PGT
- Active shield system : production of fiber shroud & SiPM array on schedule
- Simulations and Analysis: L-200 model in place, analysis of PGT
- Ge detector characterization after vendor delivery: underway
- Detector units: tested in PGT; production in progress
- Electronics: worked well in PGT
- Data acquisition system: in use for PGT

Sensitivity



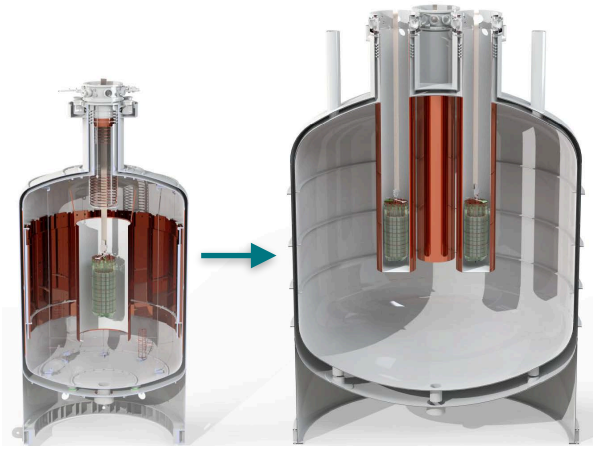


LEGEND-200 to LEGEND-1000

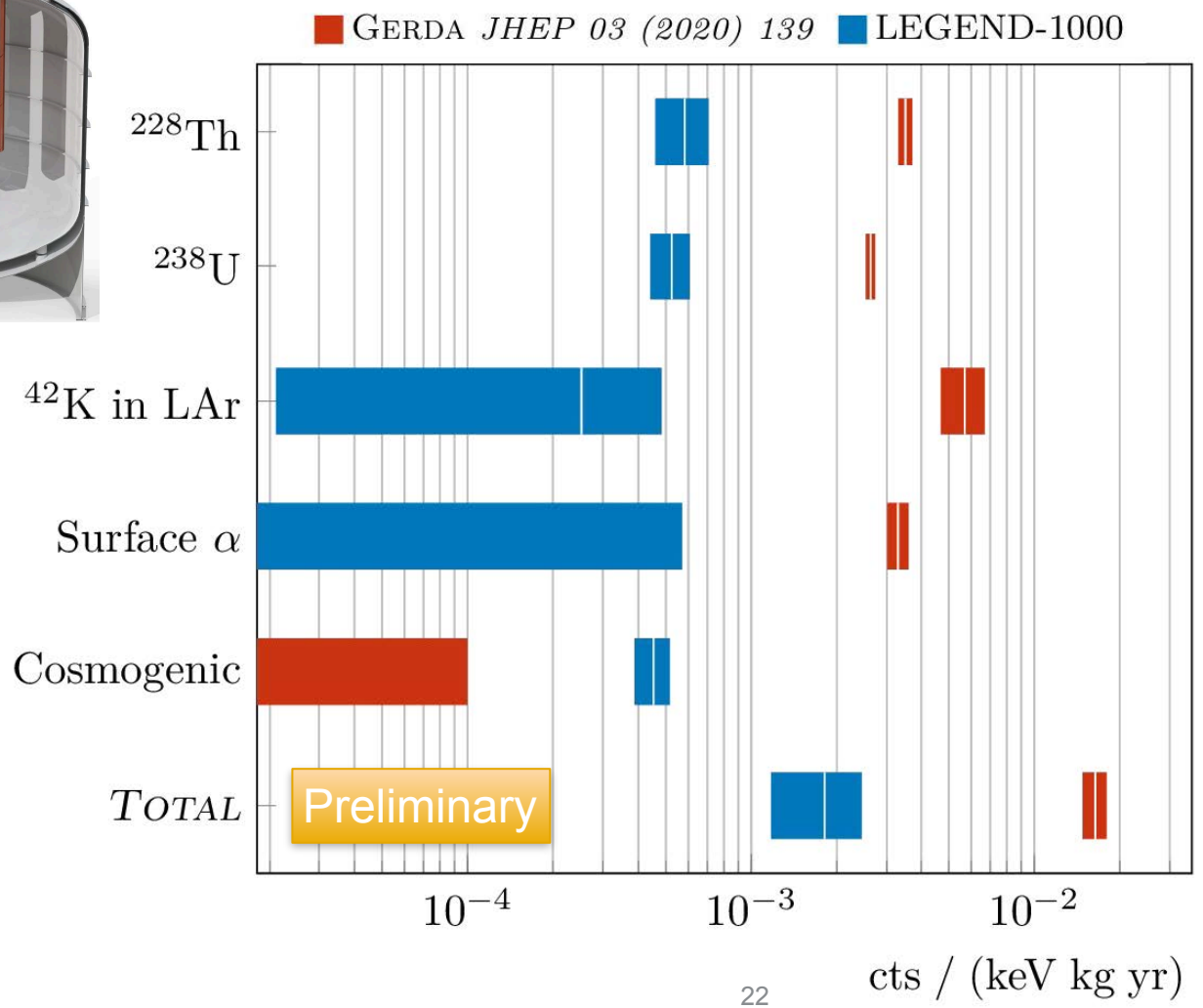


4 payloads with up to 300 kg detectors each
in underground Ar containment

LEGEND-200 to LEGEND-1000



Backgrounds before analysis cuts



Larger detectors - fewer cables and holders
New cables & ASIC read-out
Increased detector spacing

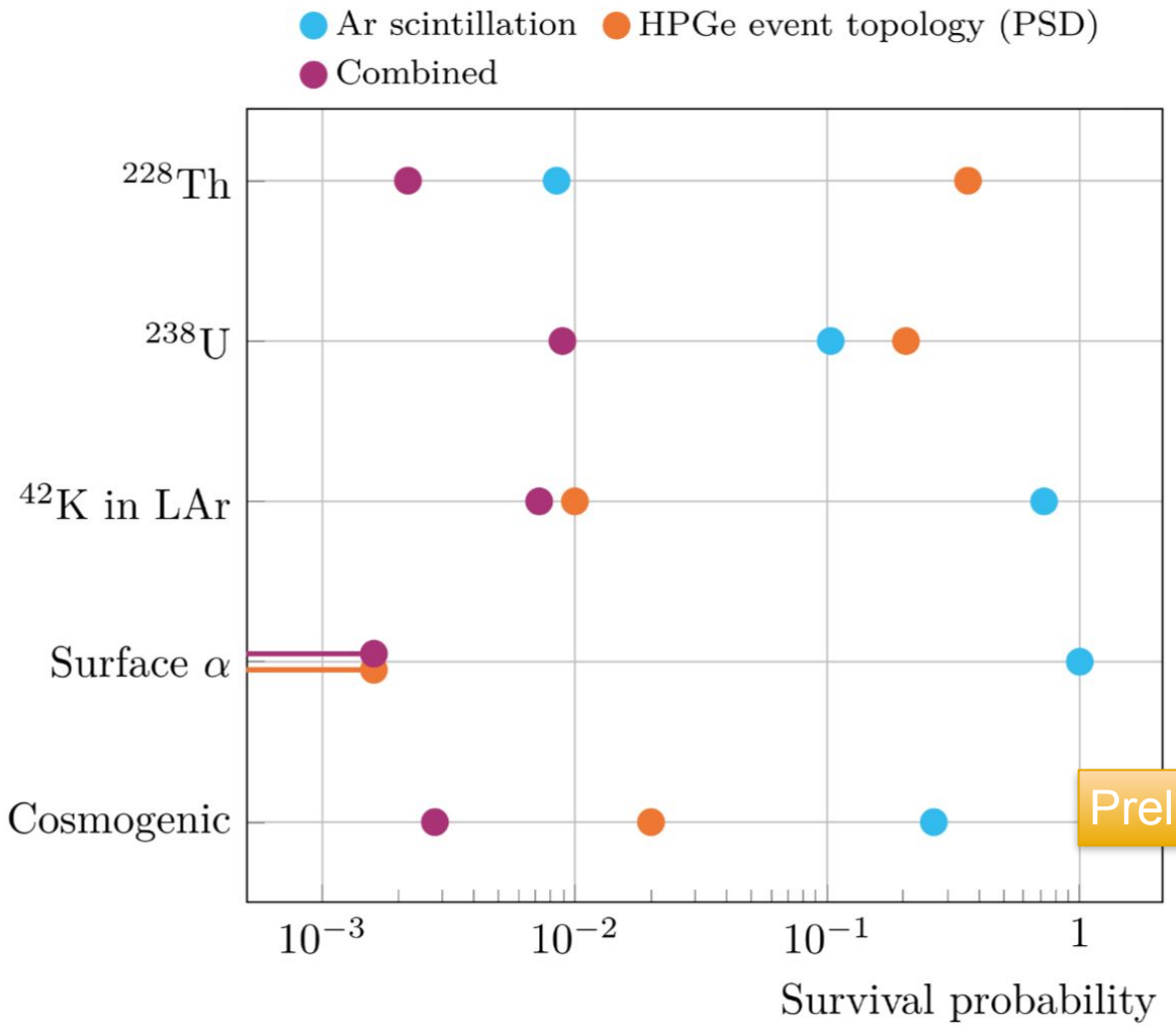
Underground argon

Larger detectors - surface-volume ratio
Only ^{210}Pb supported term

^{68}Ge decays away
[4 yr cool down in GERDA]

Reduction driven mainly by UGLAr

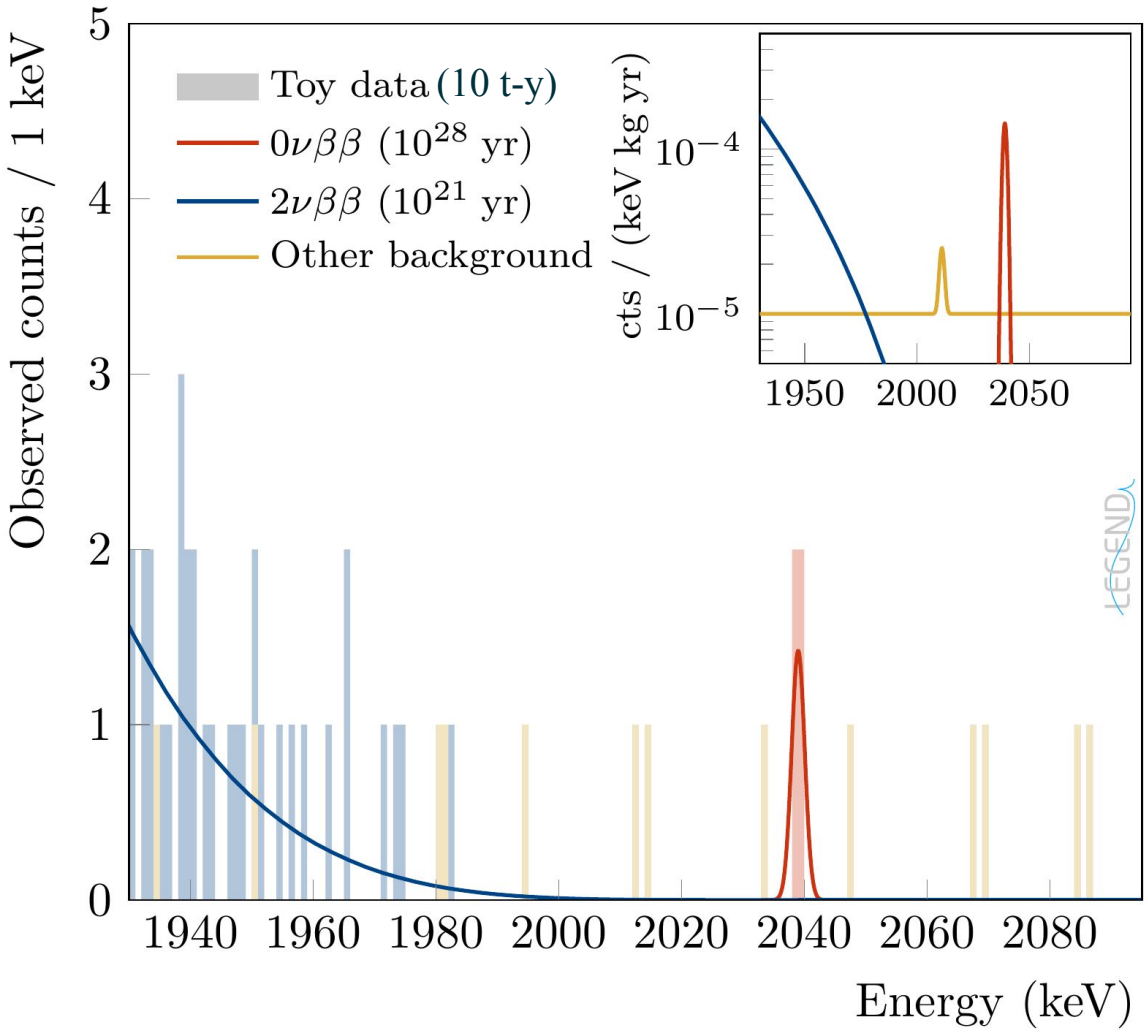
Background differentiation in LEGEND-1000

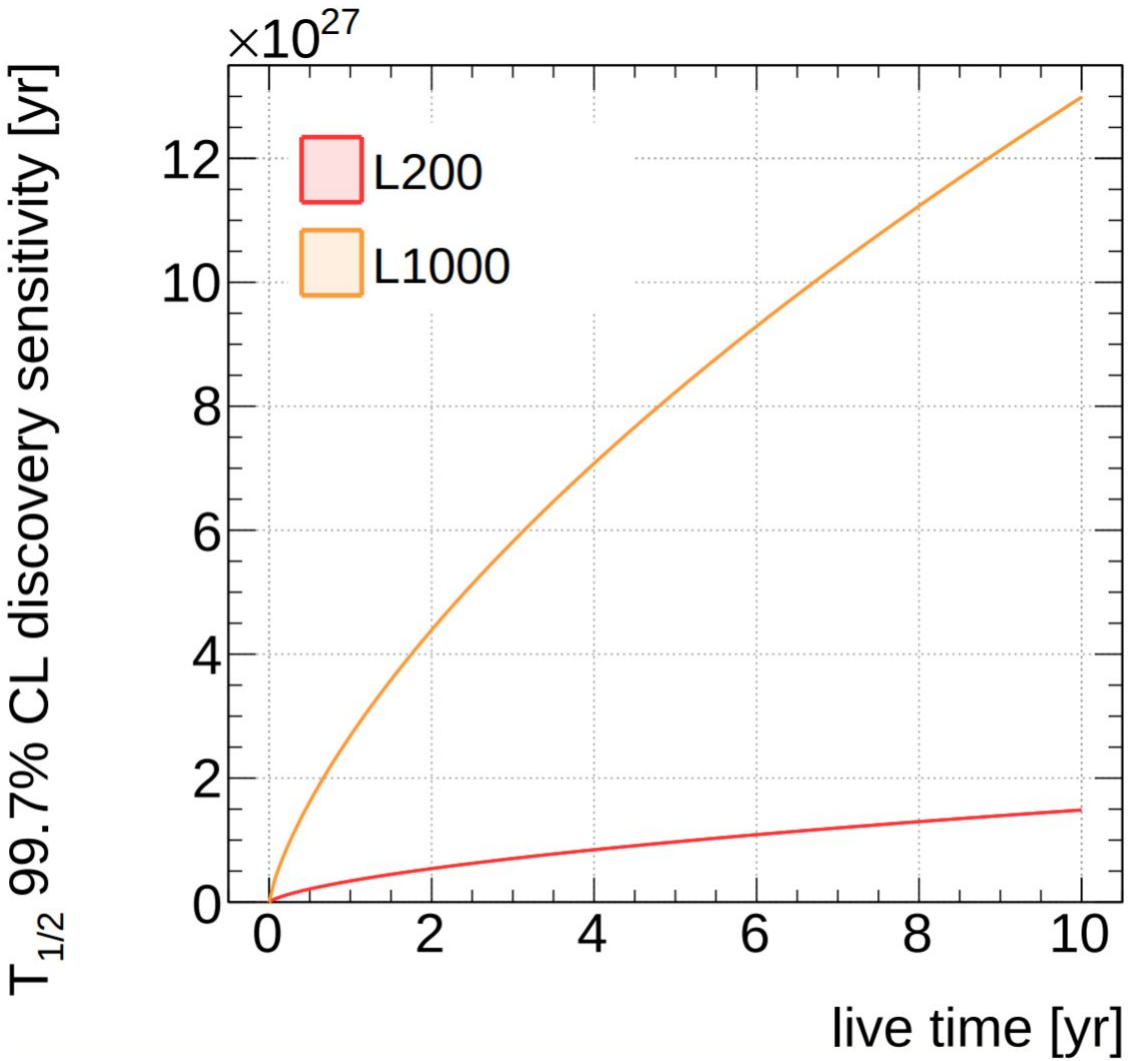


LEGEND dominant backgrounds

- U/Th in fibers & PEN plates
- Cosmogenic and ^{42}Ar

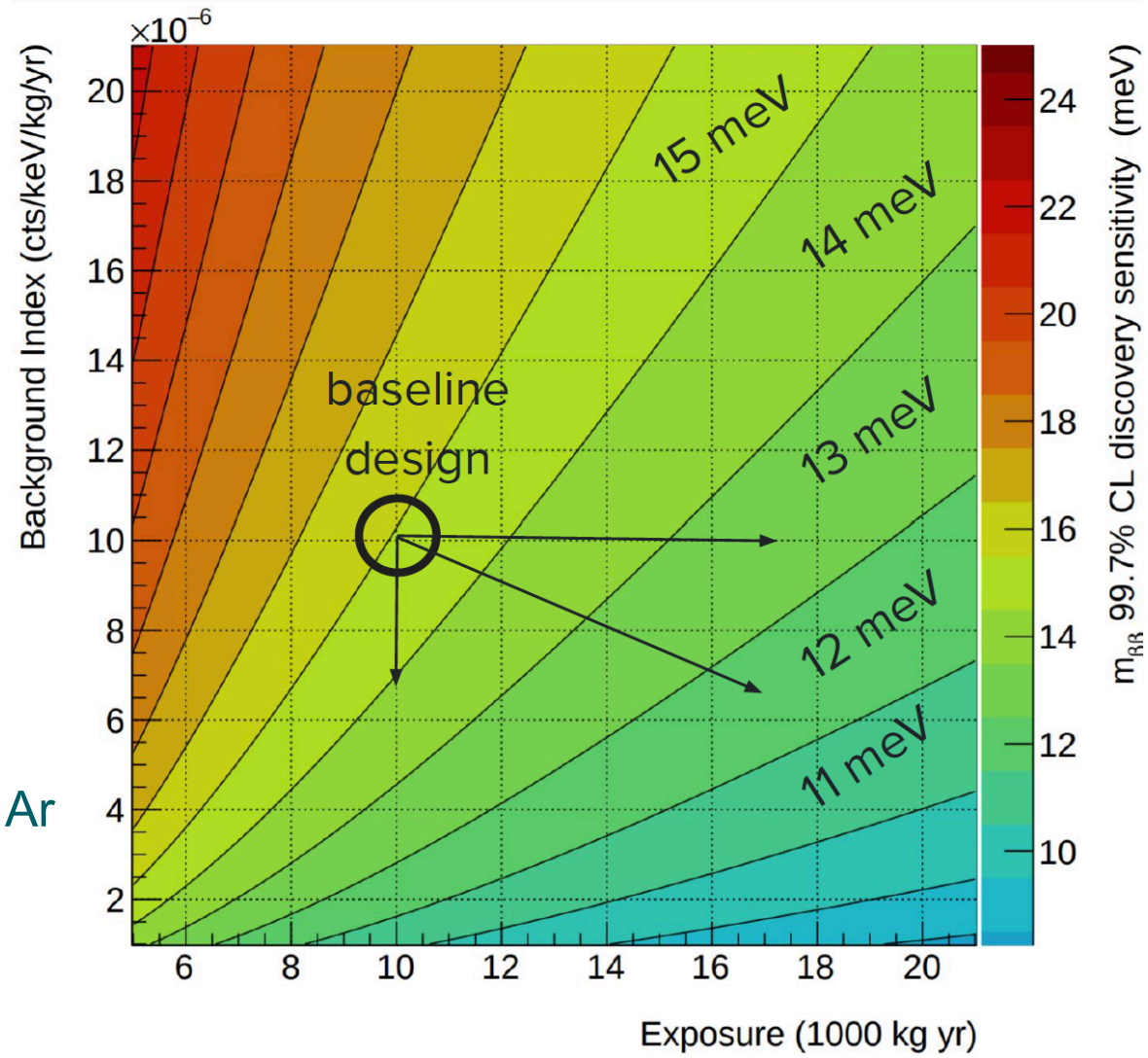
LEGEND-1000


Toy data (10 t-y)
$0\nu\beta\beta$ (10^{28} yr)
$2\nu\beta\beta$ (10^{21} yr)
Other background
cts / (keV kg yr)
10^{-4}
10^{-5}
1950
2000
2050
Observed counts / 1 keV
0
1
2
3
4
5
1940
1960
1980
2000
2020
2040
2060
2080
Energy (keV)


$\times 10^{27}$
L200
L1000
$T_{1/2}$ 99.7% CL discovery sensitivity [yr]
0
2
4
6
8
10
12
live time [yr]

Summary

- The LEGEND project aims to achieve a half-life sensitivity in ^{76}Ge 0νββ of:
  - >10^{27} years in phase I (200-kg phase), and
  - >10^{28} years in phase II (1-ton phase)
- LEGEND-200 will start at LNGS in Italy in 2021
- LEGEND-1000 is pending funding approval.
  - Target host lab is SNOLAB. 🇨🇦
  - Scalable payload design
  - Potential to increase sensitivity
  - Beyond-Standard-Model physics with underground Ar and low-threshold electronics (unique among 0νββ experiments).



The LEGEND Collaboration

Univ. New Mexico
L'Aquila University and INFN LNGS
University Texas, Austin
Lawrence Berkeley Natl. Lab.
University California, Berkeley
Leibniz Inst. Crystal Growth
Indiana University
Comenius University
Simon Fraser University
University of North Carolina
University of South Carolina
Tennessee Tech University
University of Warwick
Jagiellonian University
Technical University Dresden
Joint Inst. Nucl. Res.
Duke University
Triangle Univ. Nuclear. Lab.
Joint Research Centre, Geel
Max Planck Institute, Heidelberg
Queen's University
University of 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 of Regina
University Washington
University Tübingen
University South Dakota
Williams College
University Zurich

We appreciate the support of our sponsors: • German Federal Ministry for Education and Research (BMBF) • German Research Foundation (DFG), Excellence Cluster Universe • 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 • 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 • We thank our hosts and colleagues at LNGS and SURF • We thank the ORNL Leadership Computing Facility and the LBNL NERSC Center

BERKELEY LAB
Bringing Science Solutions to the World

U.S. DEPARTMENT OF ENERGY
Office of Science

Thank You