Status of the MAJORANA DEMONSTRATOR

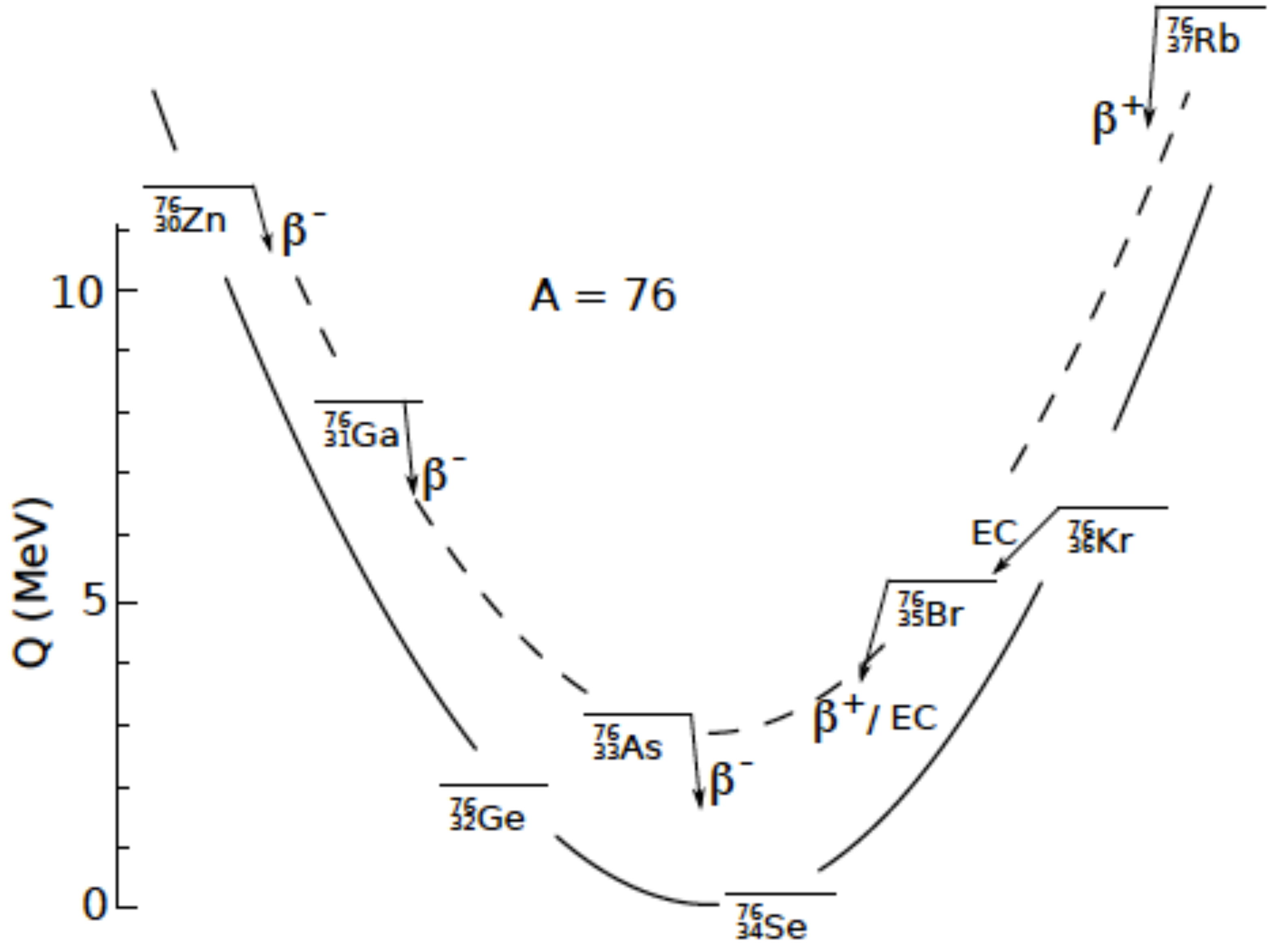
Tom Caldwell, on behalf of the MAJORANA Collaboration
28 September 2021

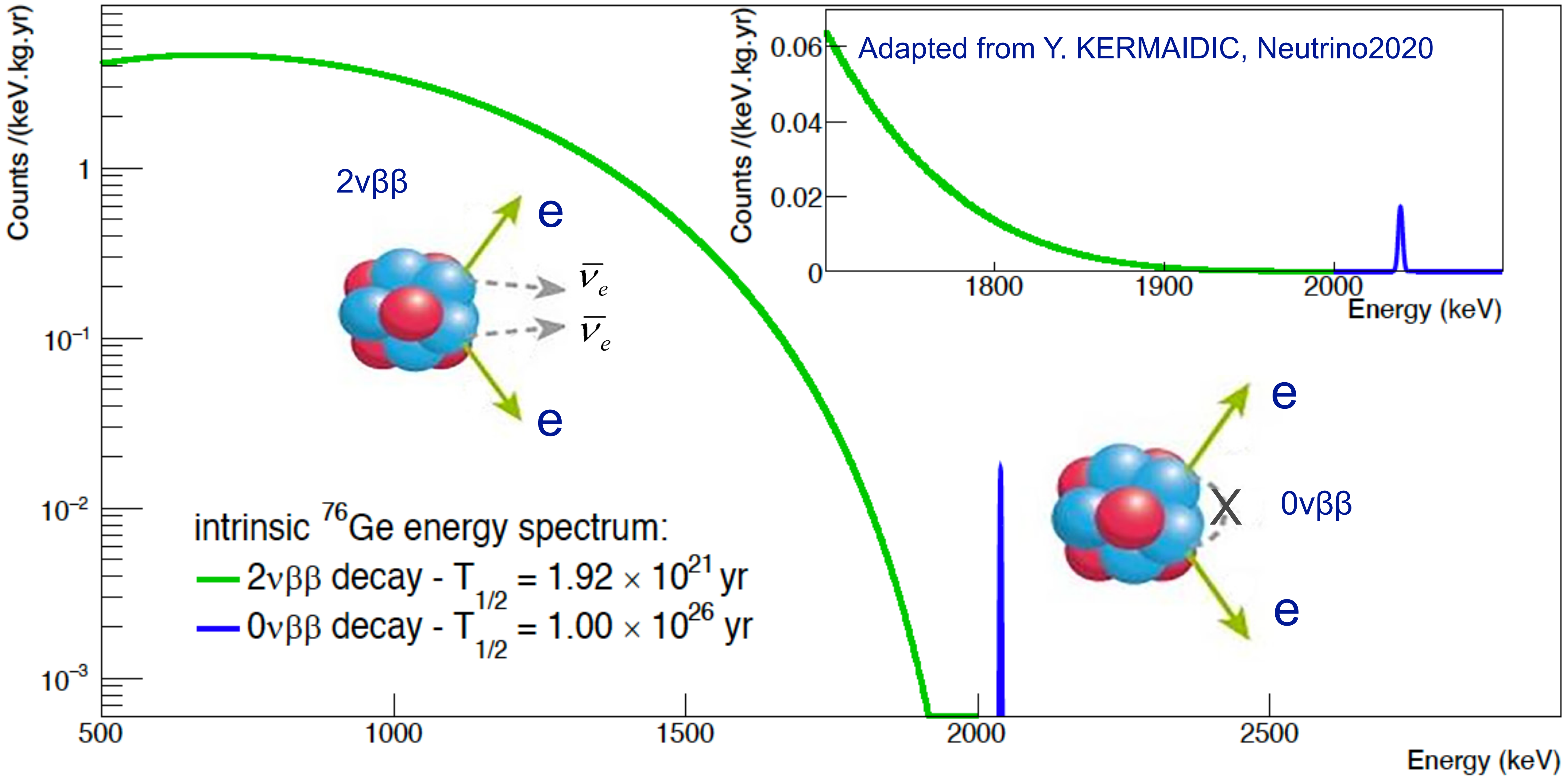
Sanford Underground Research Facility

U.S. DEPARTMENT OF ENERGY | Office of Science

NSF

Neutrinoless Double-Beta Decay





Double-beta decay is possible when energetically favored

Neutrinoless double-beta decay (0vββ) searches
➢ test total lepton number conservation
-- 0vββ violates total lepton number by 2 units ($\Delta L = 2$)
➢ probe the Majorana or Dirac nature of massive neutrinos
-- observation of 0vββ would imply neutrinos are Majorana fermions
➢ if observed, shed light on the absolute scale of neutrino mass

Nuclear Matrix Element — Effective Neutrino Mass

$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}\,|M_{0\nu}|^2 \left(\frac{\langle m_{\beta\beta}\rangle}{m_e}\right)^2$$

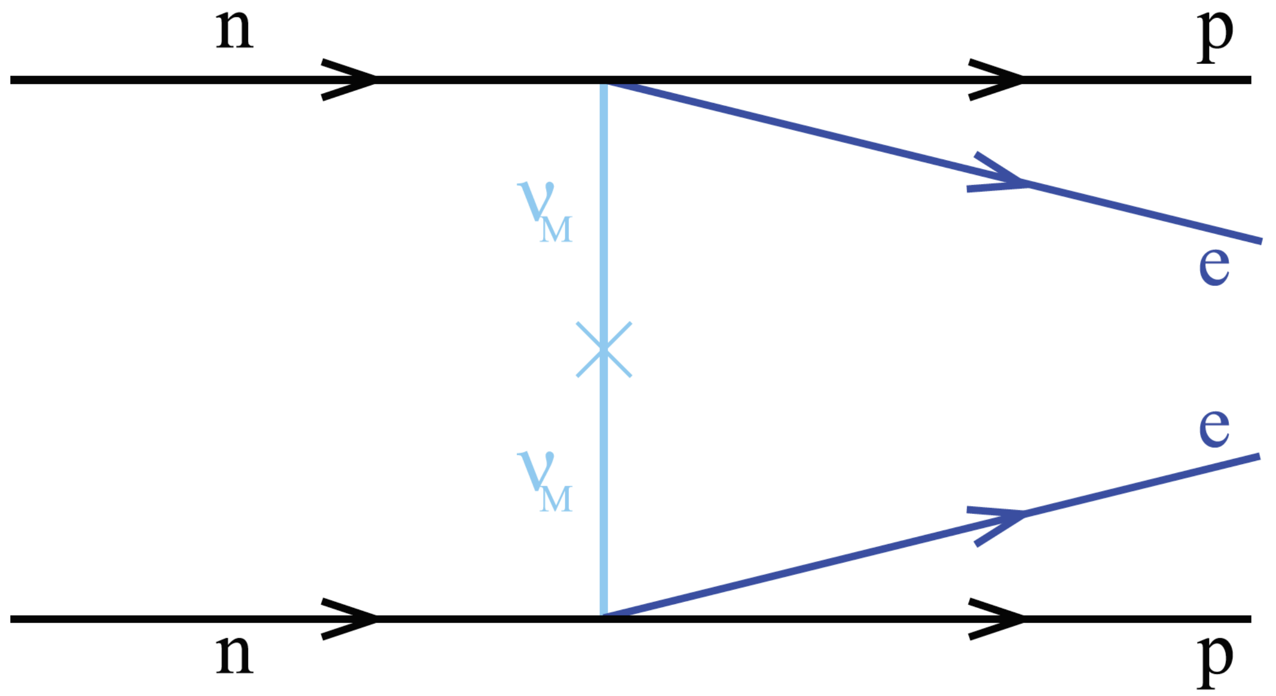
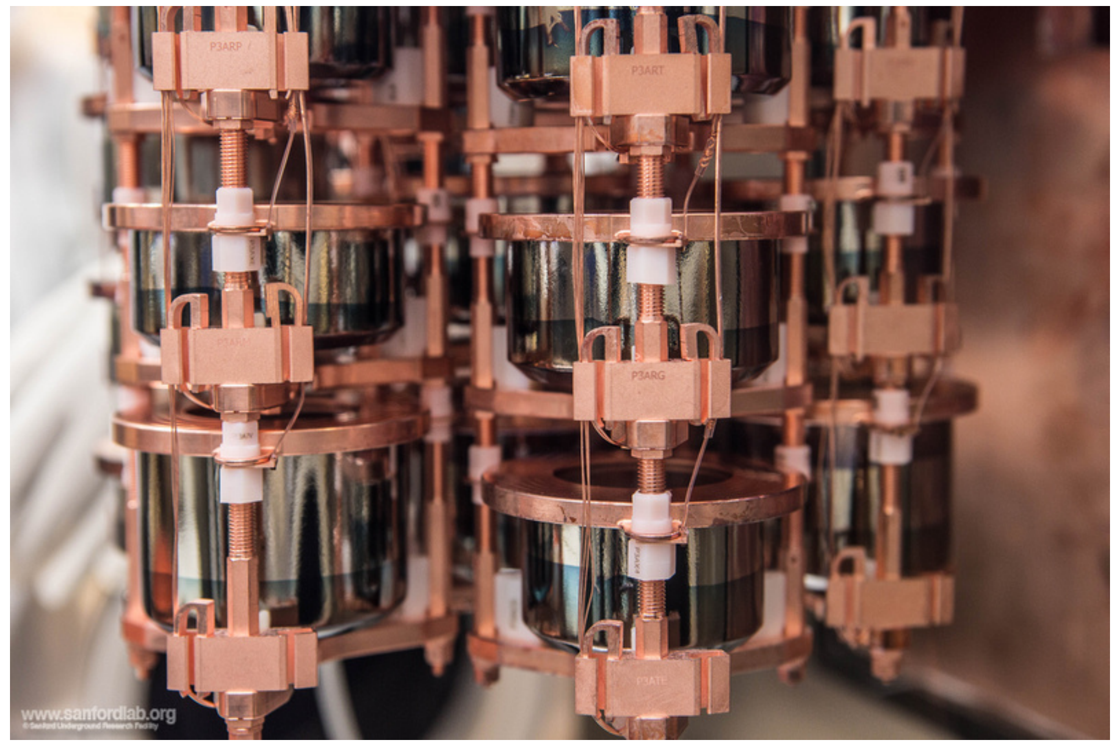


Diagram for Light neutrino exchange
J. Engel and J. Menéndez, Rep. Prog. Phys. 80 (2017) 046301

MAJORANA DEMONSTRATOR

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

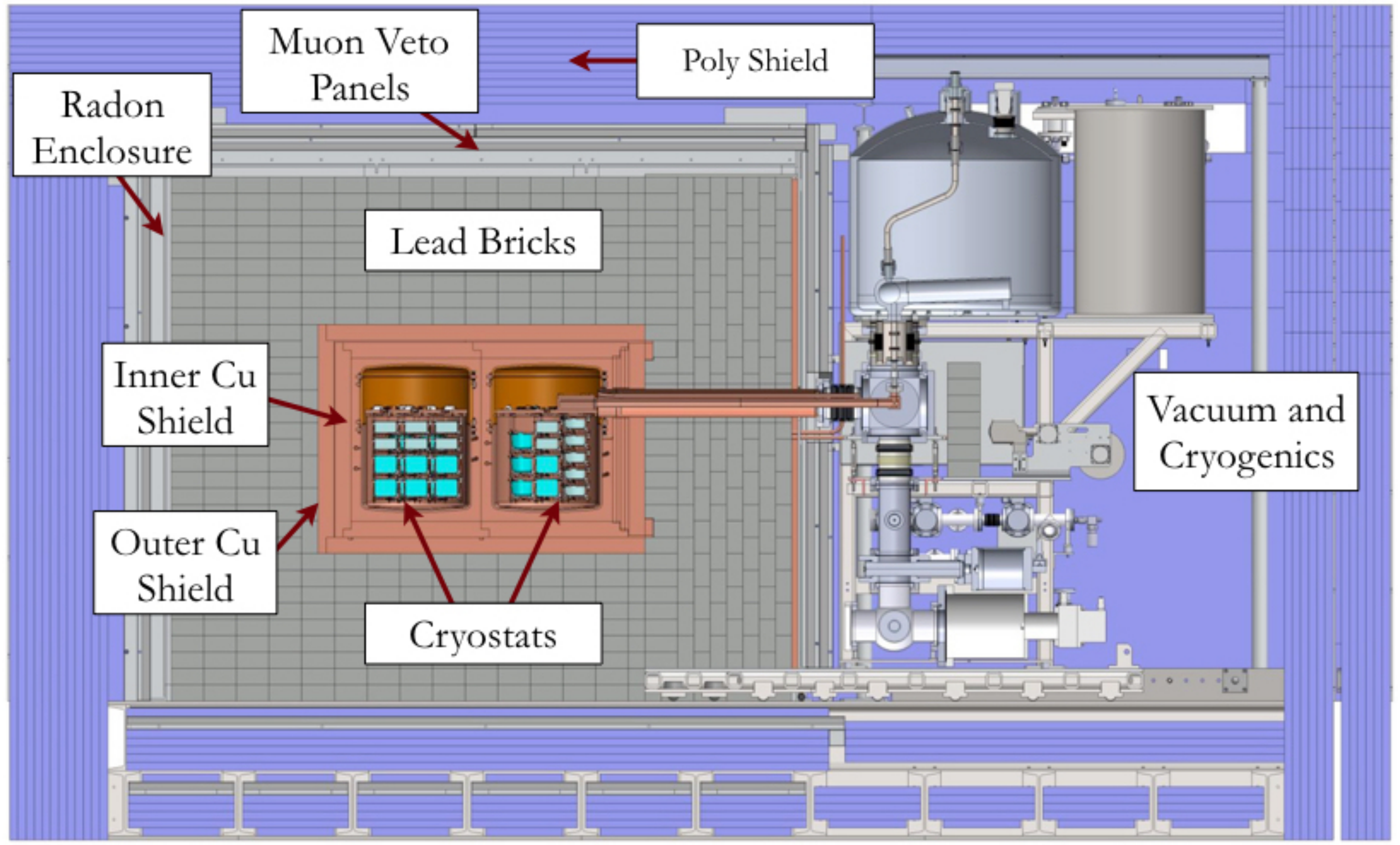
Source & Detector: Array of p-type, point contact detectors
- 30 kg of 88% enriched ^{76}Ge crystals
  - Included 6.7 kg of inverted coaxial, point contact detectors in final run



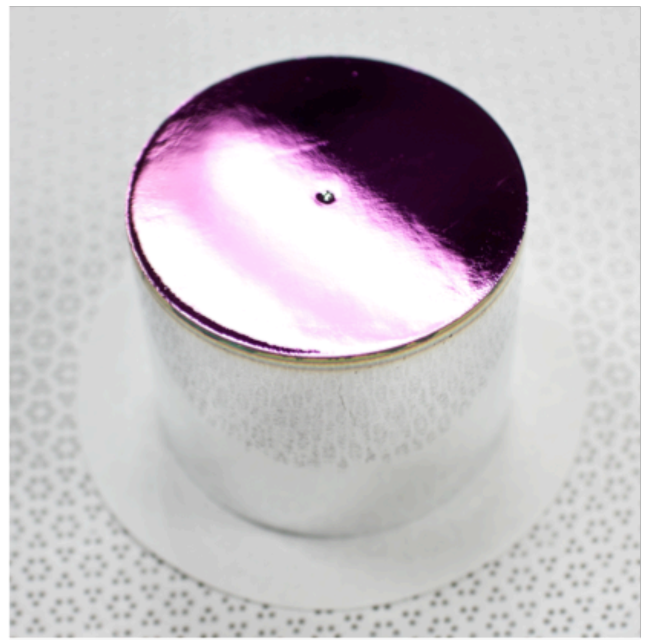
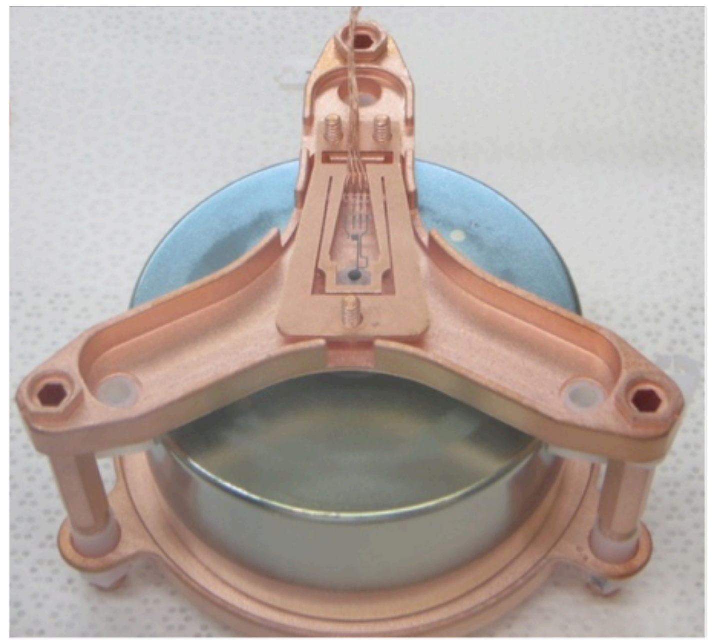
Excellent Energy resolution: 2.5 keV FWHM @ 2039 keV

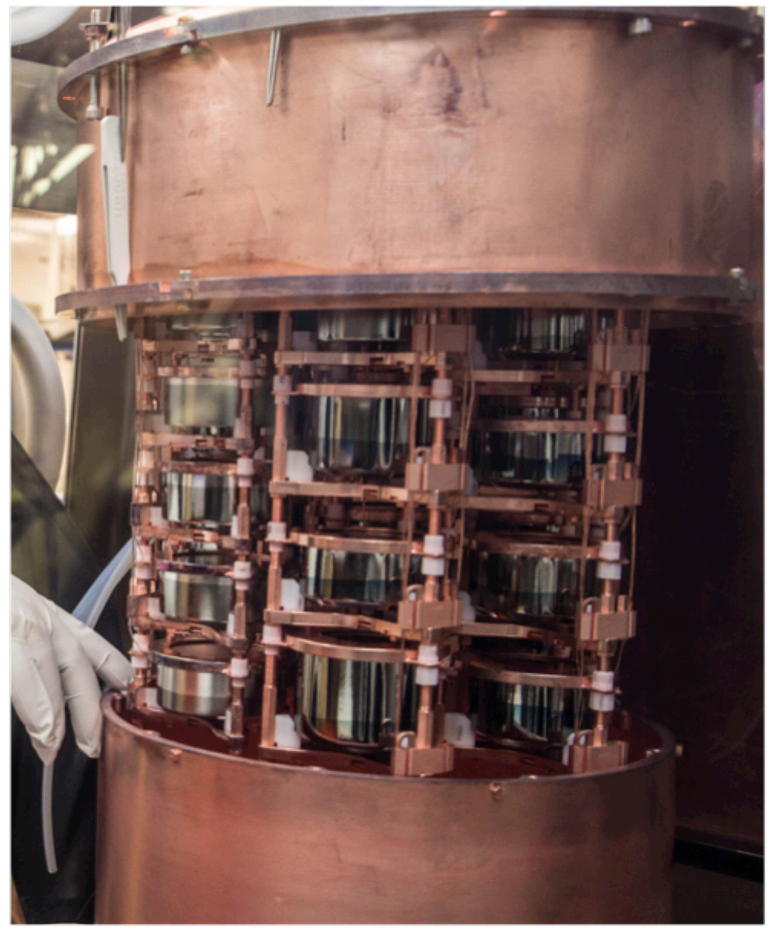
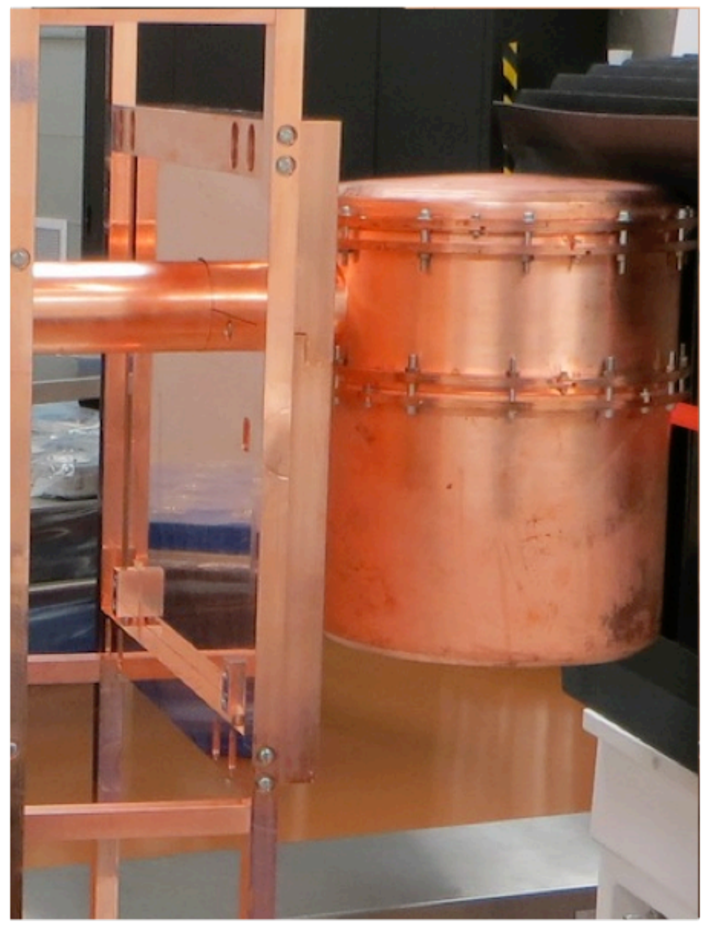
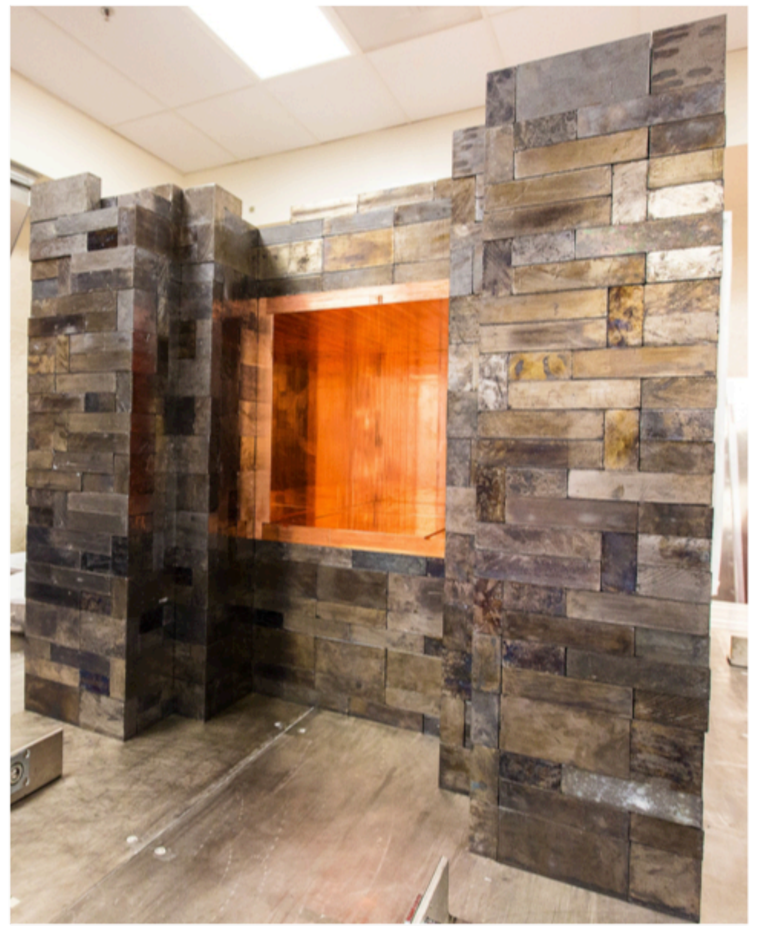
Low Background: 2 modules within a compact graded shield and active muon veto using ultra-clean materials

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



MAJORANA DEMONSTRATOR

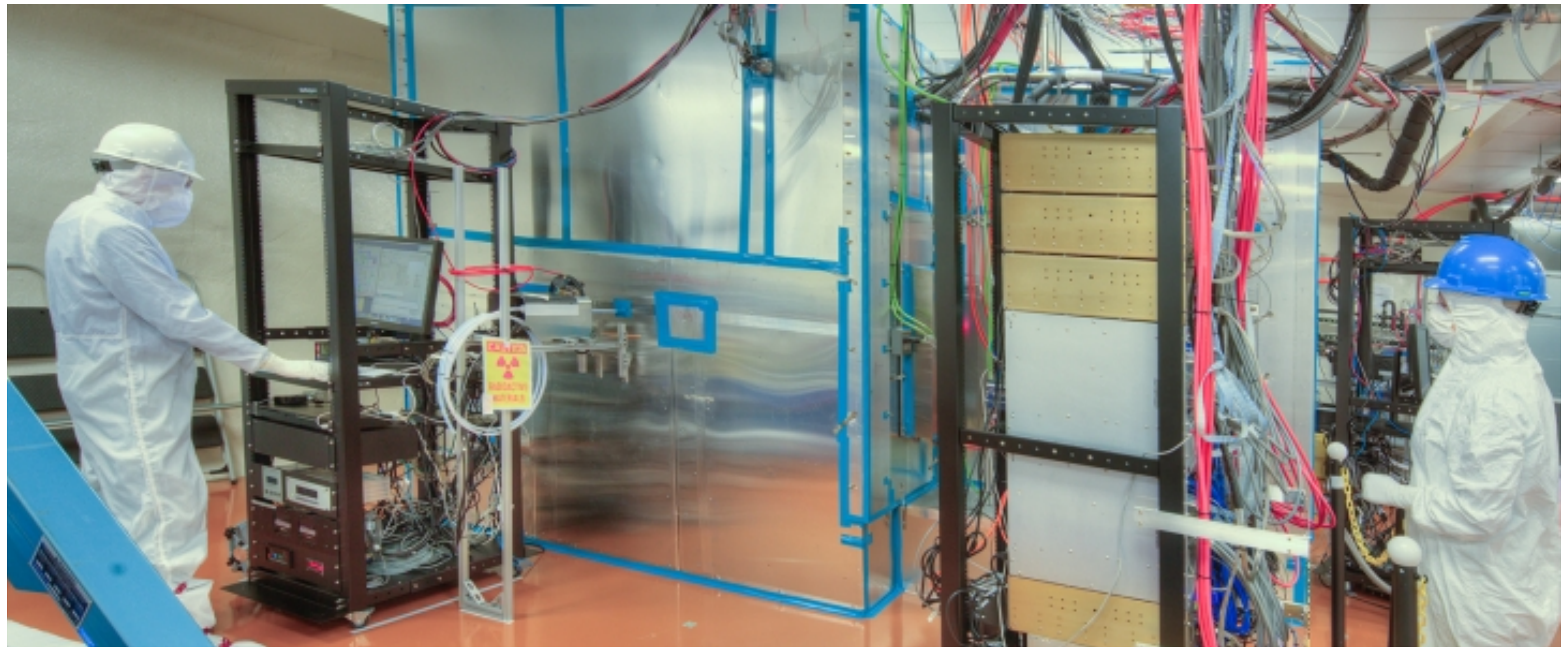




Photos by Matt Kapust and James Loach

PPC HPGe Detector → Low-Mass Mount → String → Cryostat → Module → Passive Shield →

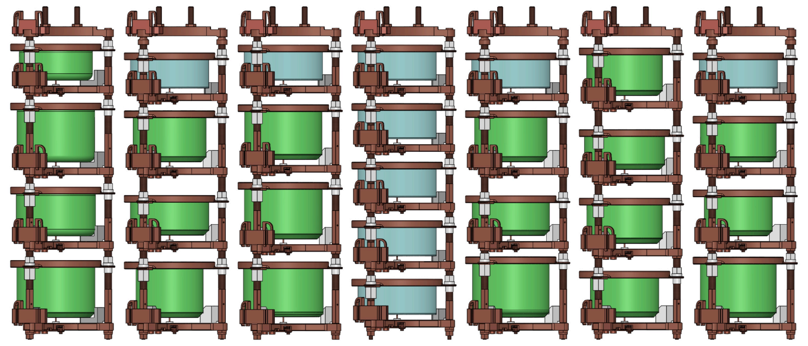
Active μ veto
Neutron shielding
Pure N_2 enclosure

- 44.1-kg of Ge detectors
  - 29.7 kg of 87% enriched ^{76}Ge crystals
  - 14.4 kg of ^{nat}Ge



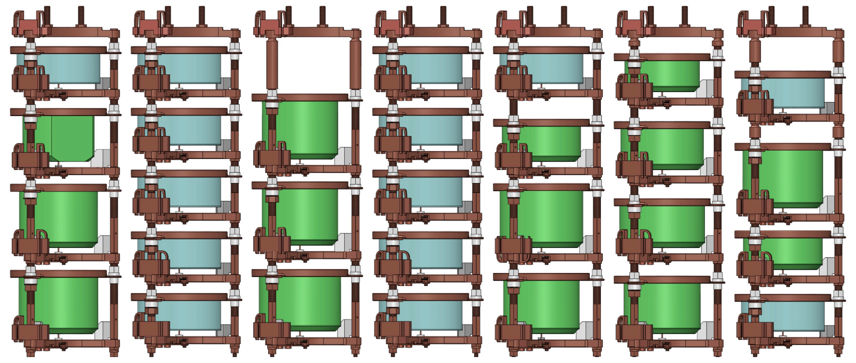
MAJORANA Run Configuration & Timeline

Jun. 2015 - Module 1:
16.8 kg (20) ^{enr}Ge
5.6 kg (9) ^{nat}Ge



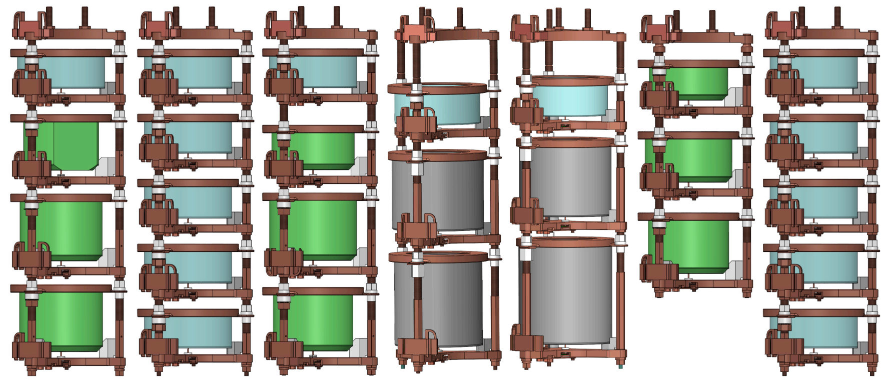
Deploy Module 1 in shield

Aug. 2016 - Module 2:
12.9 kg (15) ^{enr}Ge
8.8 kg (14) ^{nat}Ge



Deploy Module 2 in shield

Sept. 2020 - Module 2 Upgrade:
14.1 kg (13) ^{enr}Ge
8.8 kg (14) ^{nat}Ge

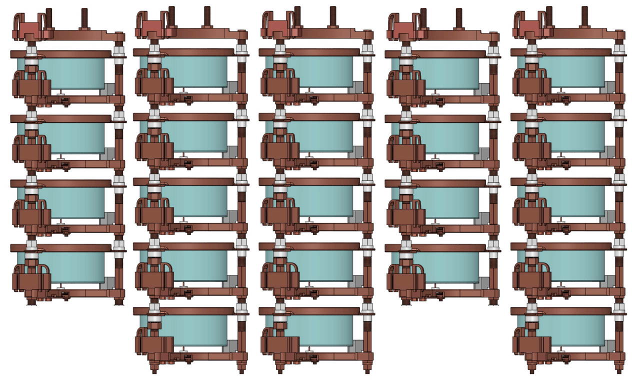


6.7 kg (4) as ICPC

Cable/Connector Upgrade of Module 2
Removed 5 PPC detectors for LEGEND Testing
Installed 4 LEGEND ICPC Detectors

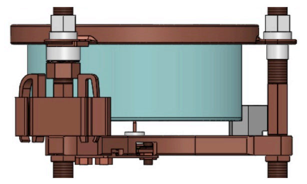
Mar. 2021:
Stopped ^{enr}Ge Operation
Removed all ^{enr}Ge for LEGEND-200

May 2021 - Module 2:
14.3 kg (23) ^{nat}Ge

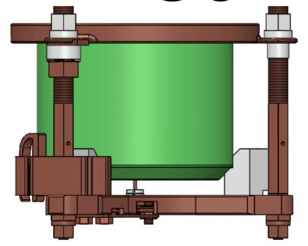


Continuing operation with natural Ge detectors

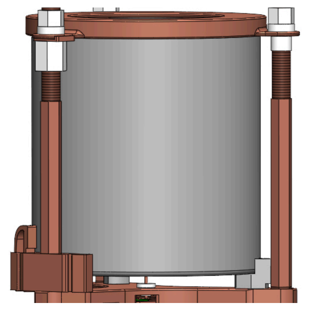
Mirion/Canberra BEGe ^{nat}Ge



Ortec PPC ^{enr}Ge



Ortec ICPC ^{enr}Ge



2020 Module 2 Upgrade

Installed new cables & connectors to improve overall robustness

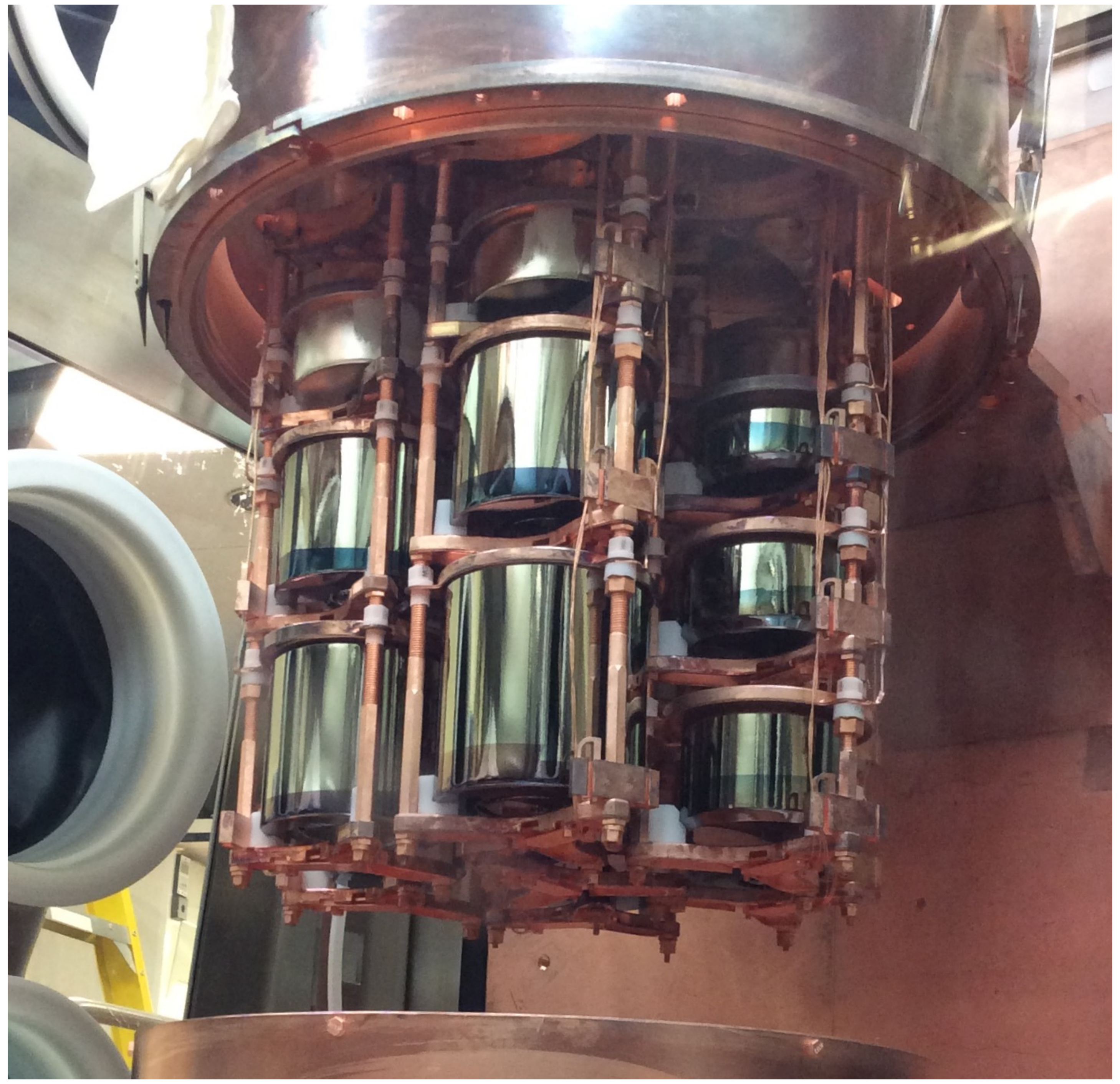
Improved cable bundling and increased cross-arm shielding

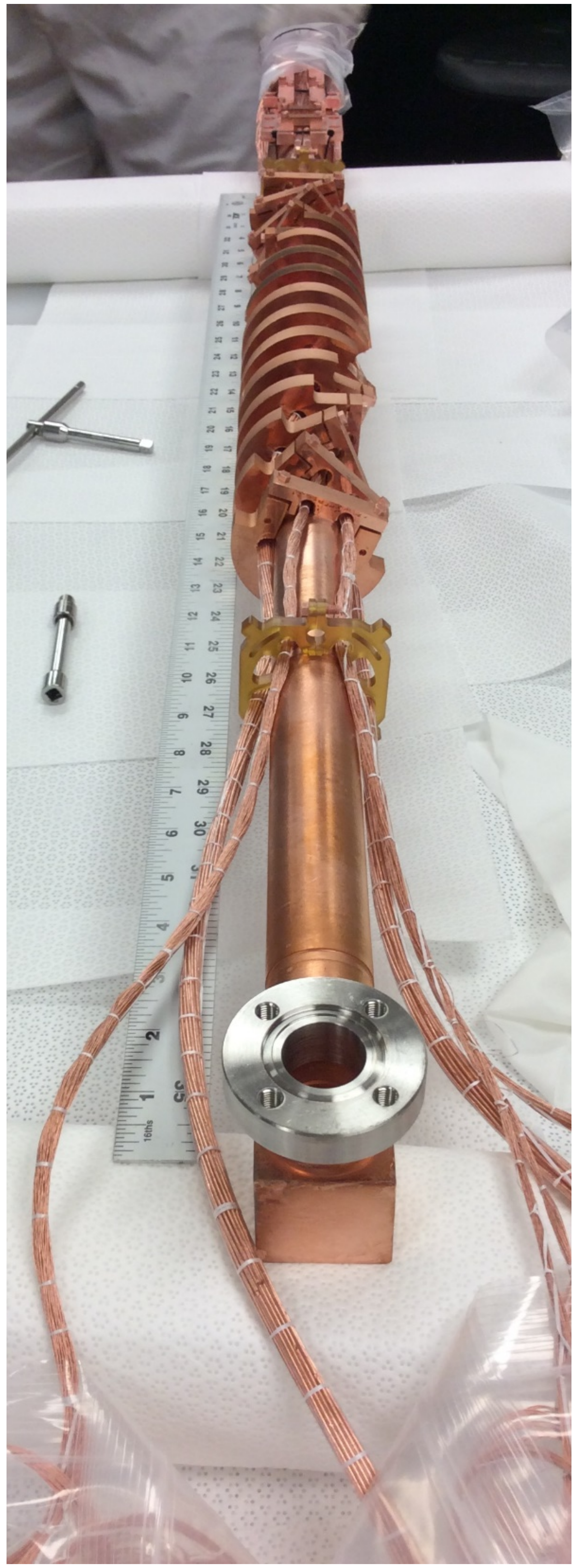
Removed 5 p-type point contact (PPC) ^{enr}Ge detectors

- Early LEGEND-200 tests in LAr at LNGS

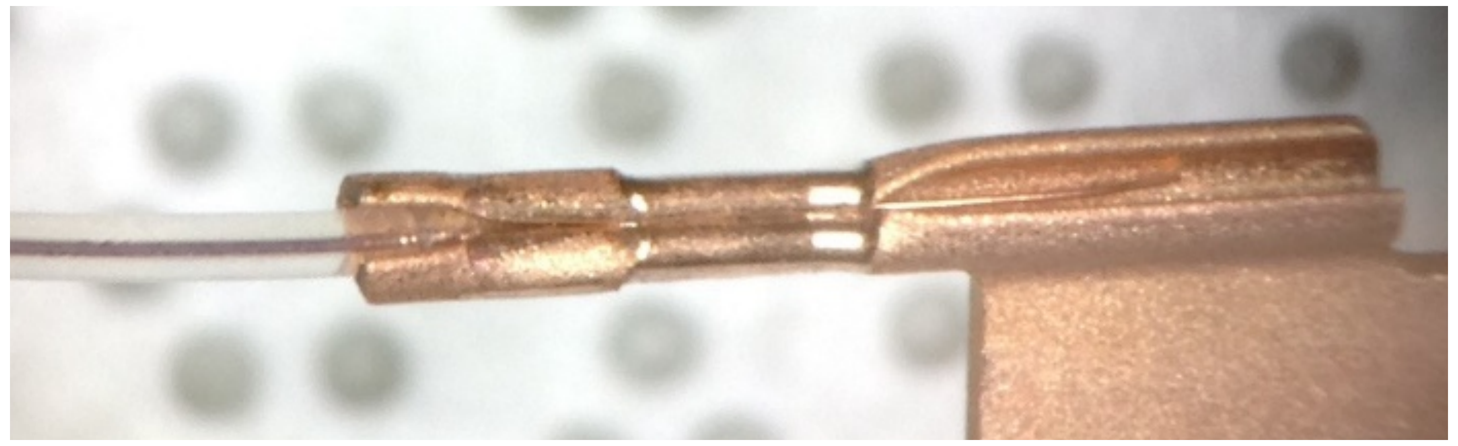
Operated with 4 ORTEC inverted-coaxial point-contact (ICPC) ^{enr}Ge detectors

- Low background vacuum testing in advance of LEGEND-200



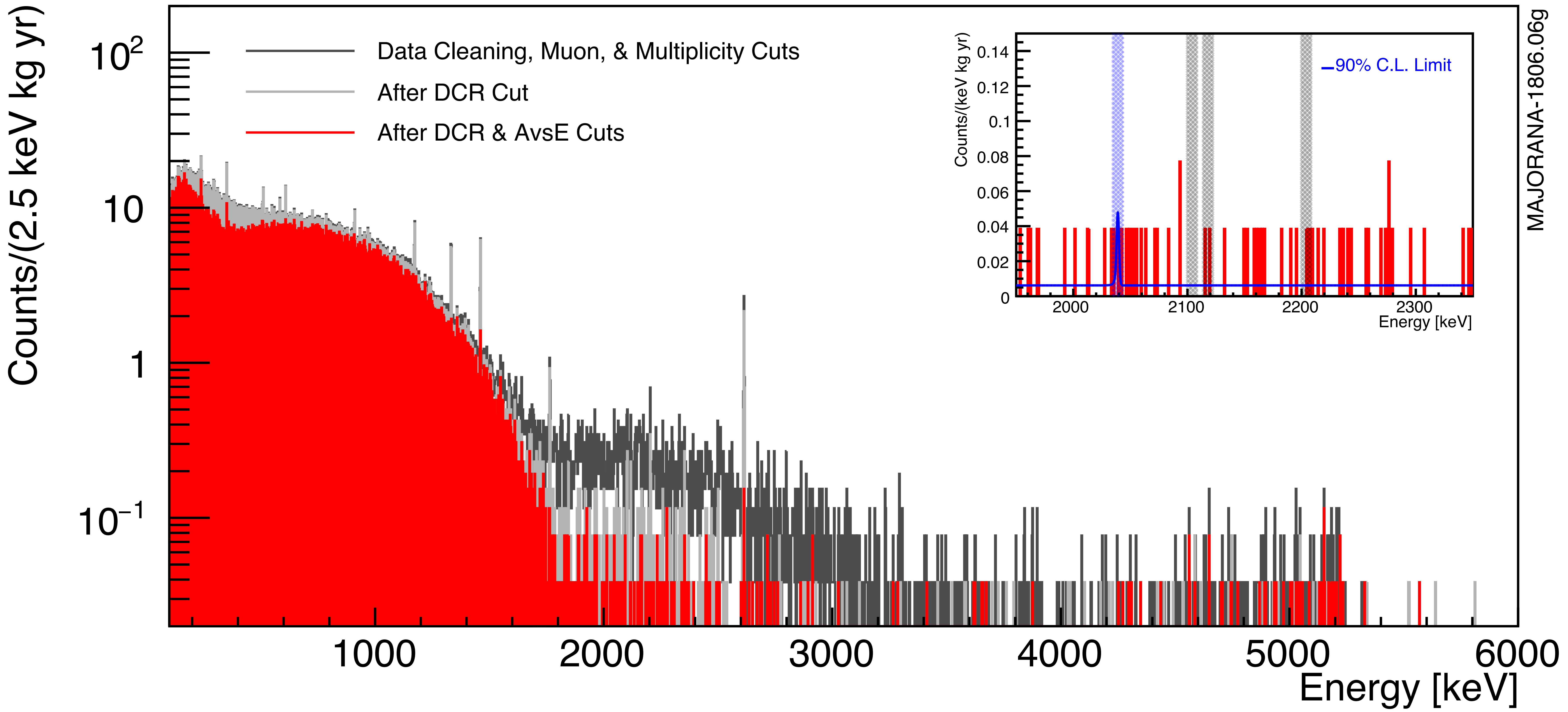


	Before Upgrade	After Upgrade
Working signal conn.	24/29 (82%)	27/27 (100%)
Reliable HV conn.	19/24 (79%)	27/27 (100%)
Operational	18/29 (62%)* *Used for final analysis	27/27 (100%)** **Final selection not yet made



MAJORANA DEMONSTRATOR 2019 0νββ Result

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



Initial Release:

9.95 kg-yr open data

Latest Release:

First unblinding of data

26 kg-yr exposure

Median $T_{1/2}$ Sensitivity:

4.8×10^{25} yr

Full Exposure Limit:

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

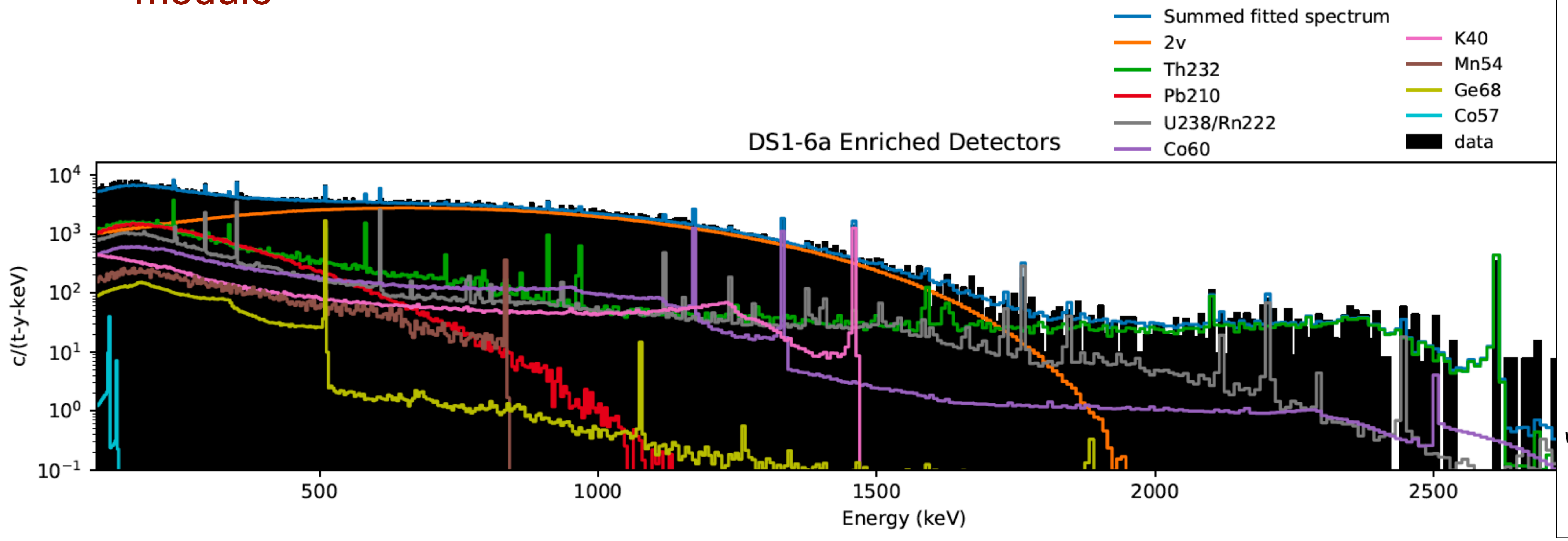
Background Index at 2039 keV in lowest background config:

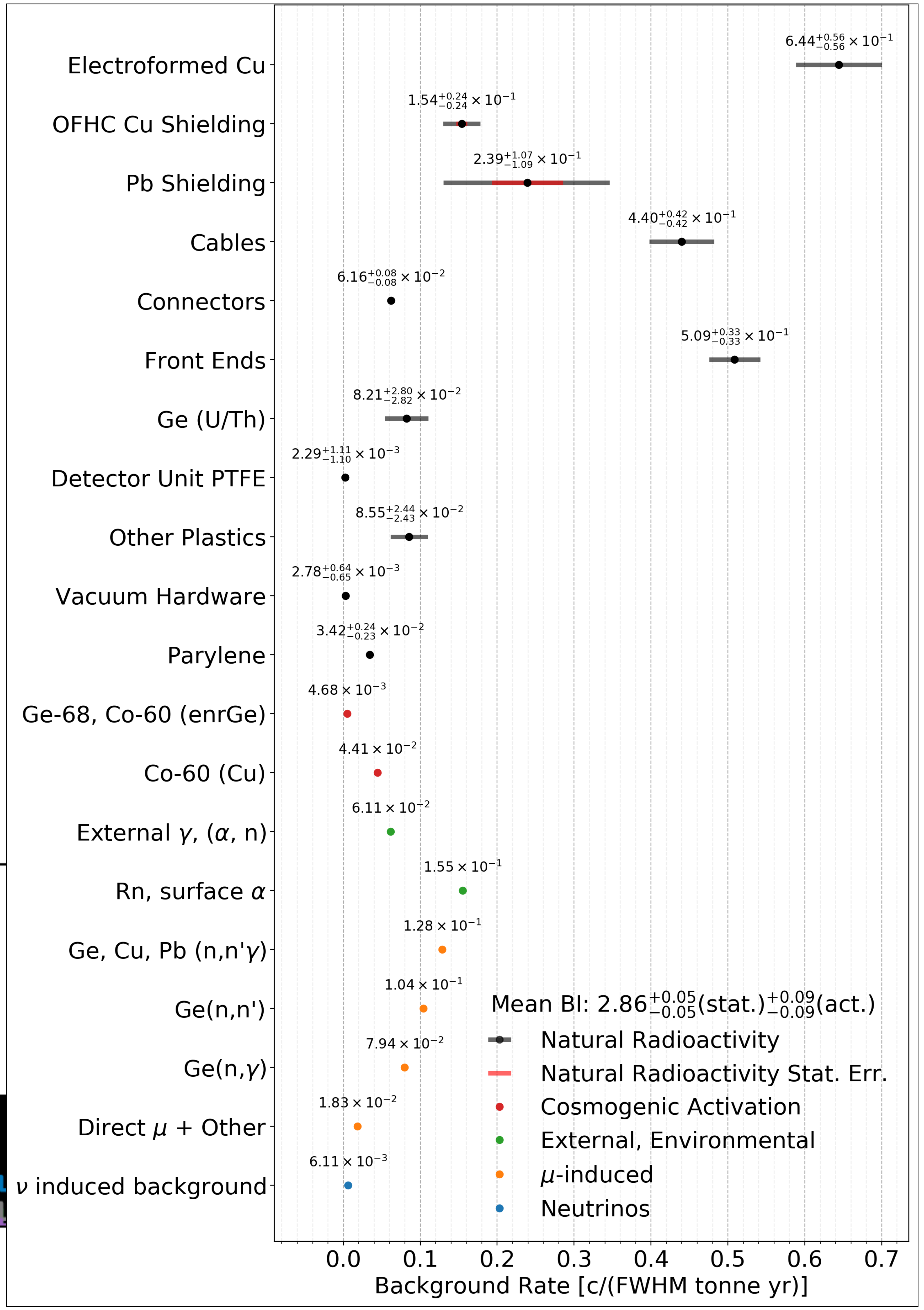
11.9 ± 2.0 cts/(FWHM t yr)

A new result, with a combined total of ~65 kg-yr from the complete data set and analysis improvements, is being prepared for release

Background Modeling

- Reviewing new assay information, as-built geometry and simulations, detector configurations, and updated physics lists
  - Projected Background Index increased from 2.2 to 2.9 cts/FWHM-t-y but continues to under-predict observed background 11.9 cts/(FWHM t yr)
- New techniques have been used to quantify uncertainties in our assay-based background model
- New high statistic simulations allow for modeling of regions with low efficiency
- Improved Frequentist and Bayesian fitting efforts underway in order to more precisely locate source of excess Th background
  - Components grouped by location (e.g. “far vs. near”) and separated by module



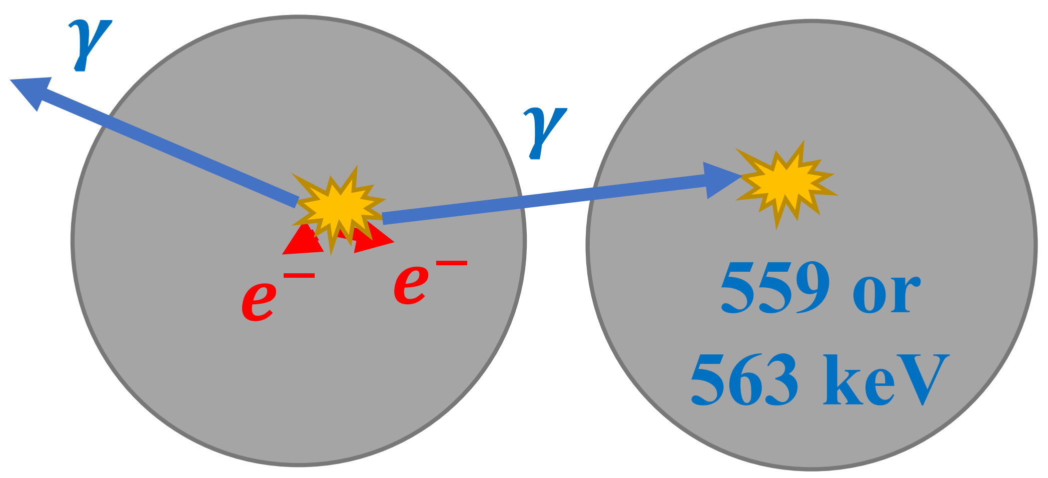


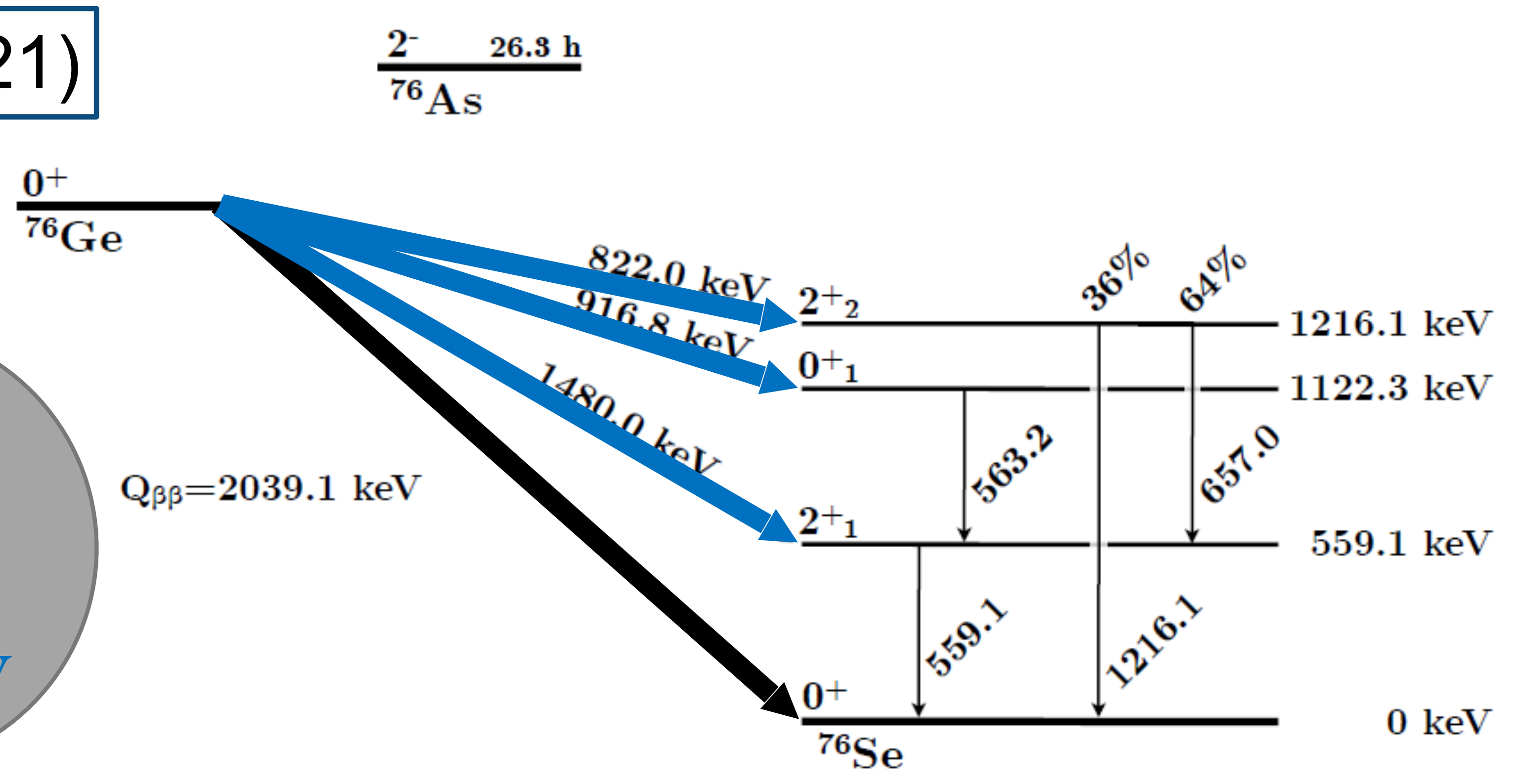
Double-Beta Decay to Excited States

An inherently multi-site signal topology:

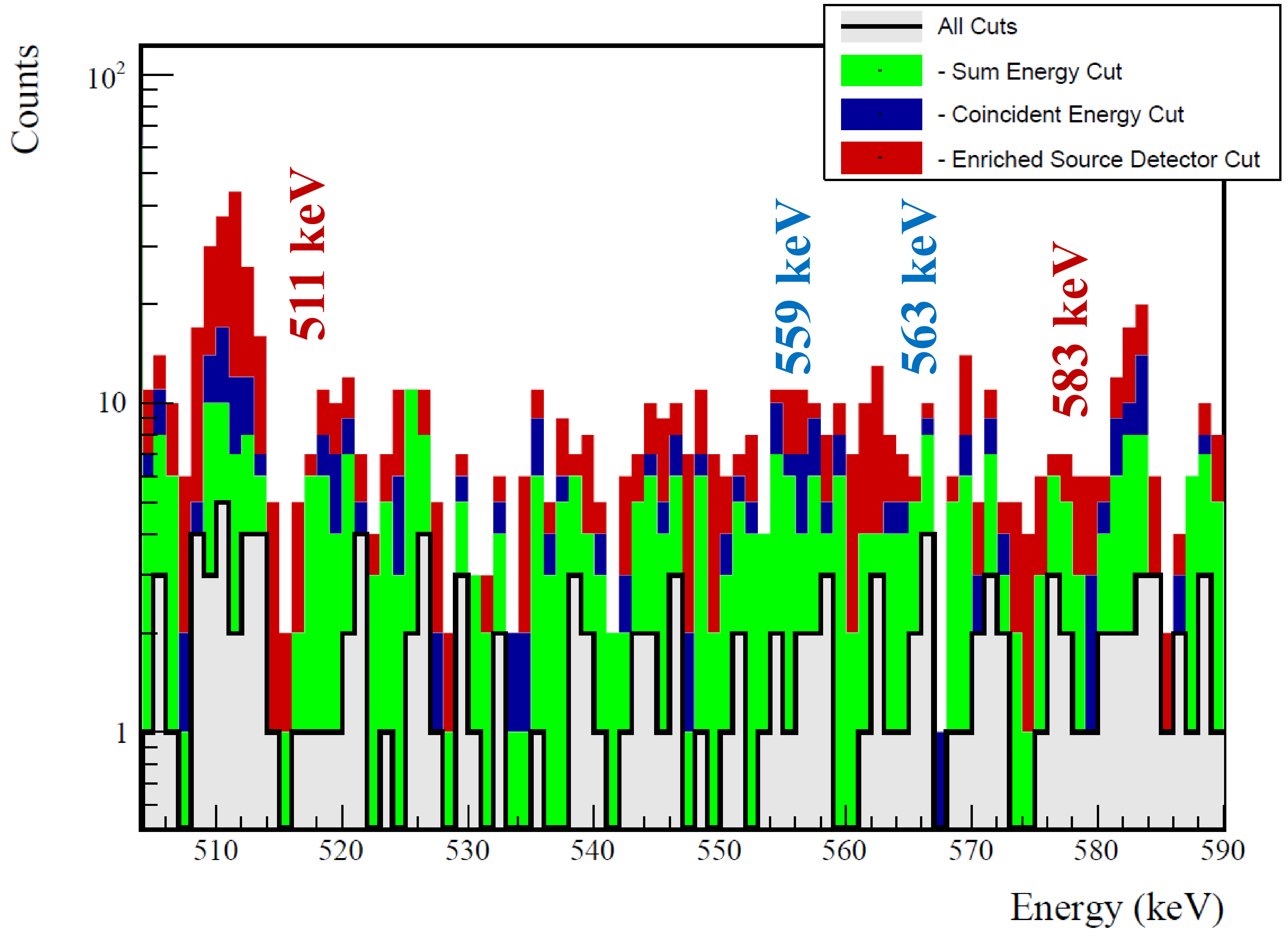
- A "source" detector will have a broad energy spectrum from ββ
- The "gamma" detector will measure energy peaked at the γ energies

PRC **103** 015501 (2021)





41.9 kg y of isotopic exposure
(20.6 kg y of which was blinded)



Decay Mode	Det. efficiency (M1, M2)	$T_{1/2}$ prev. limit (90% CI)	$T_{1/2}$ new limit (90% CI)	$T_{1/2}$ sensitivity (90% CI)
$0^+_{g.s.} \xrightarrow{2\nu\beta\beta} 0^+_1$	2.4%, 1.0%	$> 3.7 \cdot 10^{23} y$ [1]	$> \mathbf{7.5 \cdot 10^{23} y}$	$> \mathbf{10.5 \cdot 10^{23} y}$
$0^+_{g.s.} \xrightarrow{2\nu\beta\beta} 2^+_1$	1.4%, 0.6%	$> 1.6 \cdot 10^{23} y$ [1]	$> \mathbf{7.7 \cdot 10^{23} y}$	$> \mathbf{10.2 \cdot 10^{23} y}$
$0^+_{g.s.} \xrightarrow{2\nu\beta\beta} 2^+_2$	2.2%, 0.8%	$> 2.3 \cdot 10^{23} y$ [1]	$> \mathbf{12.8 \cdot 10^{23} y}$	$> \mathbf{8.2 \cdot 10^{23} y}$
$0^+_{g.s.} \xrightarrow{0\nu\beta\beta} 0^+_1$	3.0%, 1.2%	$> 1.3 \cdot 10^{22} y$ [2]	$> \mathbf{39.9 \cdot 10^{23} y}$	$> \mathbf{39.9 \cdot 10^{23} y}$
$0^+_{g.s.} \xrightarrow{0\nu\beta\beta} 2^+_1$	1.6%, 0.7%	$> 1.3 \cdot 10^{23} y$ [3]	$> \mathbf{21.2 \cdot 10^{23} y}$	$> \mathbf{21.2 \cdot 10^{23} y}$
$0^+_{g.s.} \xrightarrow{0\nu\beta\beta} 2^+_2$	2.3%, 1.0%	$> 1.4 \cdot 10^{21} y$ [4]	$> \mathbf{9.7 \cdot 10^{23} y}$	$> \mathbf{18.6 \cdot 10^{23} y}$

The most stringent limits to date for ββ to each excited state of ^{76}Se due to:

- Operating an array in vacuum: high detection efficiency
- Exquisite energy resolution for identifying peaks
- Low environmental backgrounds & analysis cuts

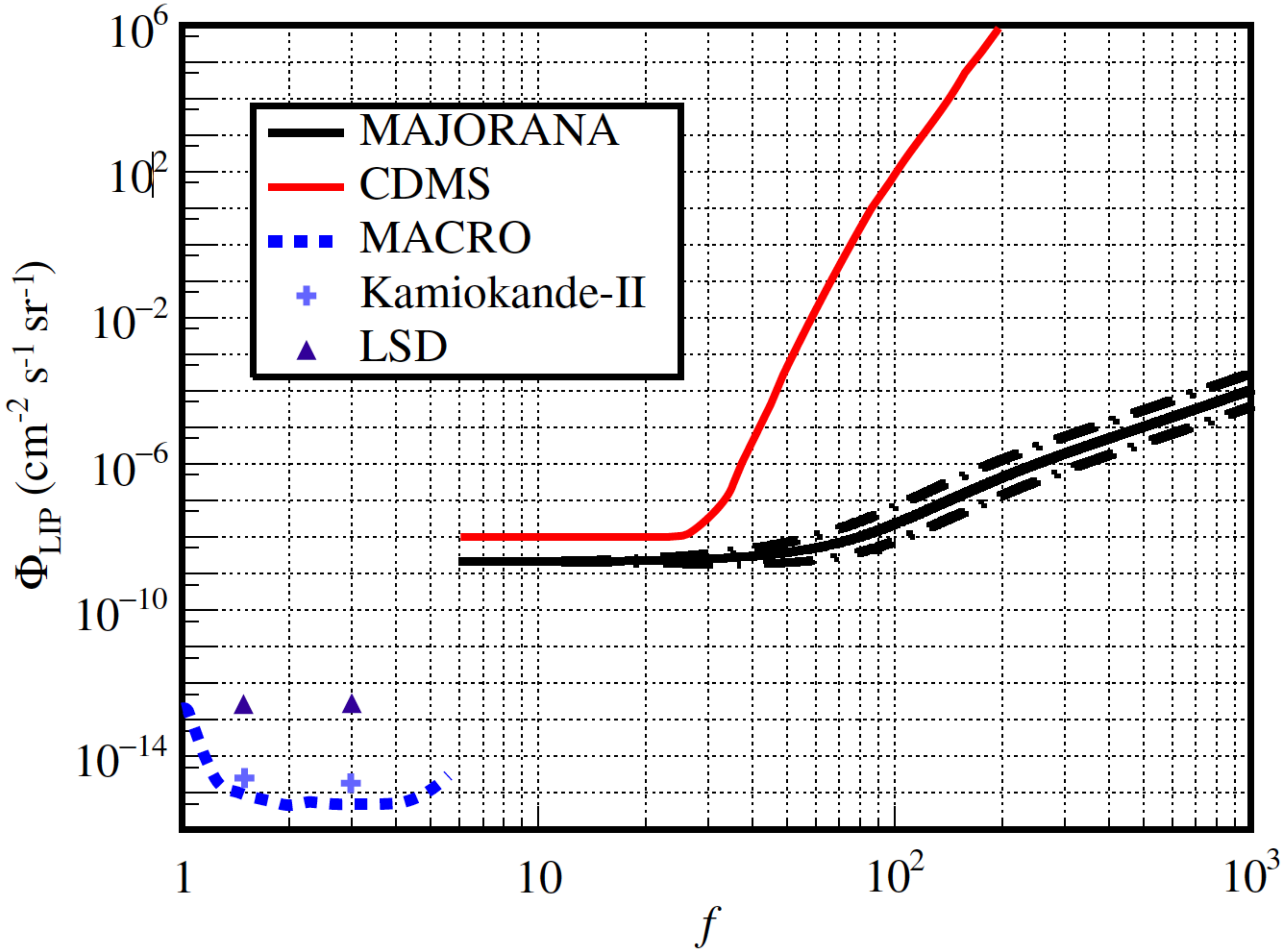
[1] M. Agostini et al. (GERDA Collaboration), J. Phys. G 43, 044001 (2015).
[2] A. Morales, et al., Nuovo Cim. A 100, 525 (2008).
[3] B. Maier (Heidelberg Moscow Collaboration), Nucl. Phys. B – Proc. Suppl. 35, 358 (1994).
[4] A. S. Barabash, A. V. Derbin, L. A. Popeko, and V. I. Umatov, Z. Phys. A 352, 231 (1995).

Beyond the Standard Model Searches

The low backgrounds, low threshold, high resolution spectra allows additional searches

First Limit on the direct detection of Lightly Ionizing Particles for Electric Charge as Low as *e*/1000

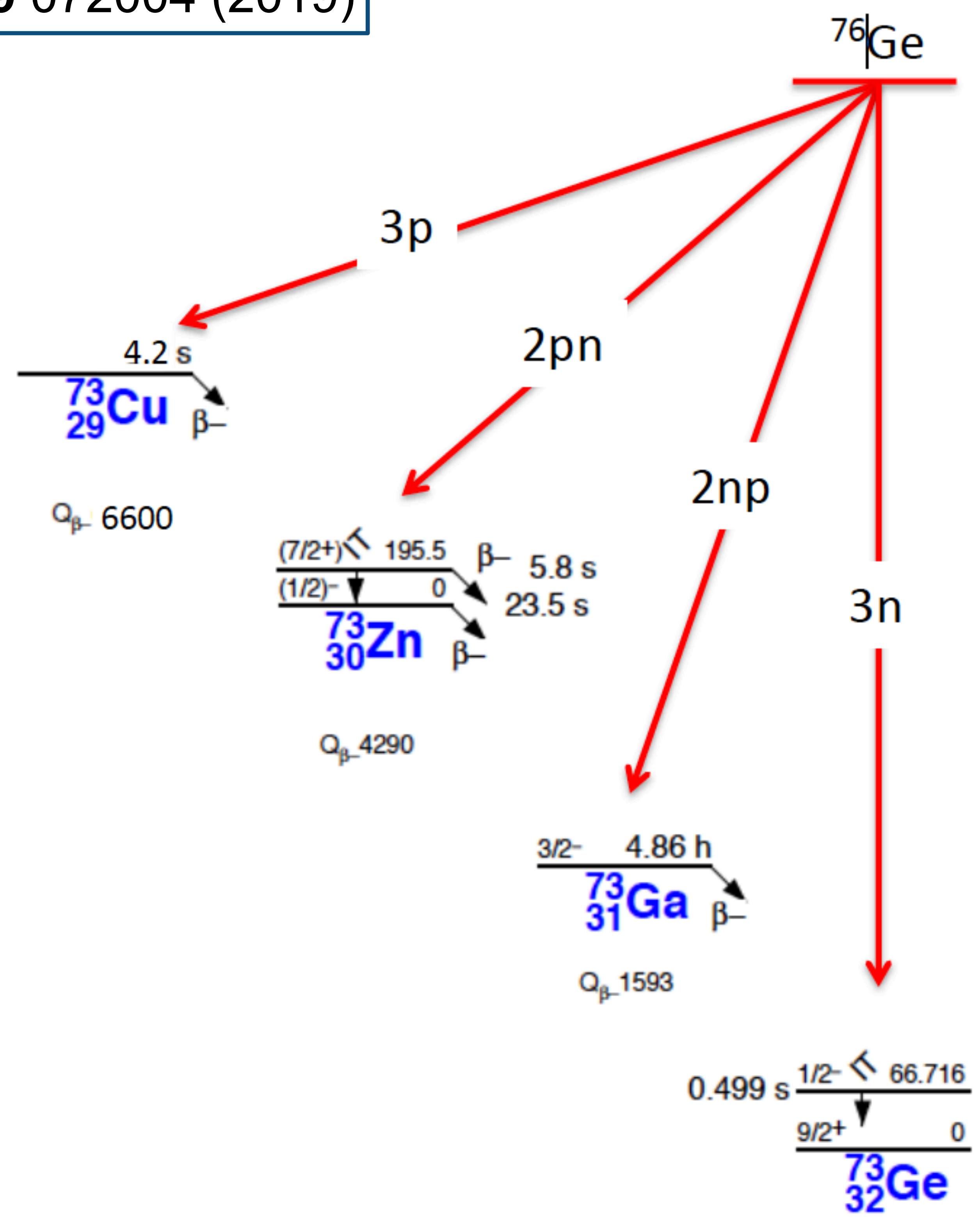
PRL **120** 211804 (2018)



The 90% UL on the Lightly Ionizing Particle flux with 1σ uncertainty bands

Search for Tri-Nucleon Decay: A test of baryon number violation

PRD **99** 072004 (2019)



The 90% UL for two tri-nucleon decay-specific modes

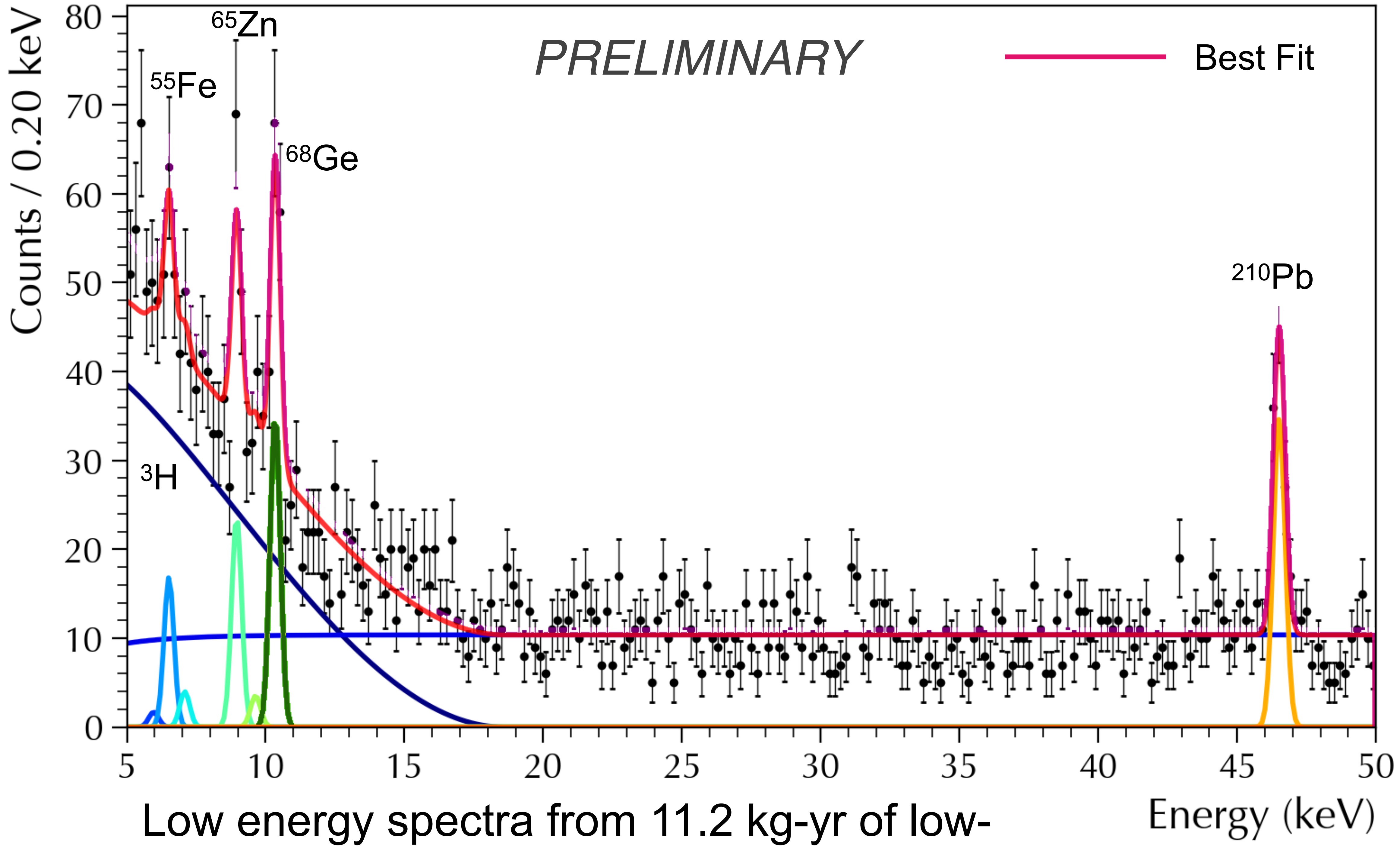
Beyond the Standard Model Searches

The low backgrounds, low threshold, high resolution spectra allows additional physics searches

- Controlled surface exposure of enriched material to minimize cosmogenics

Excellent energy resolution: ~0.4 keV FWHM at 10.4 keV

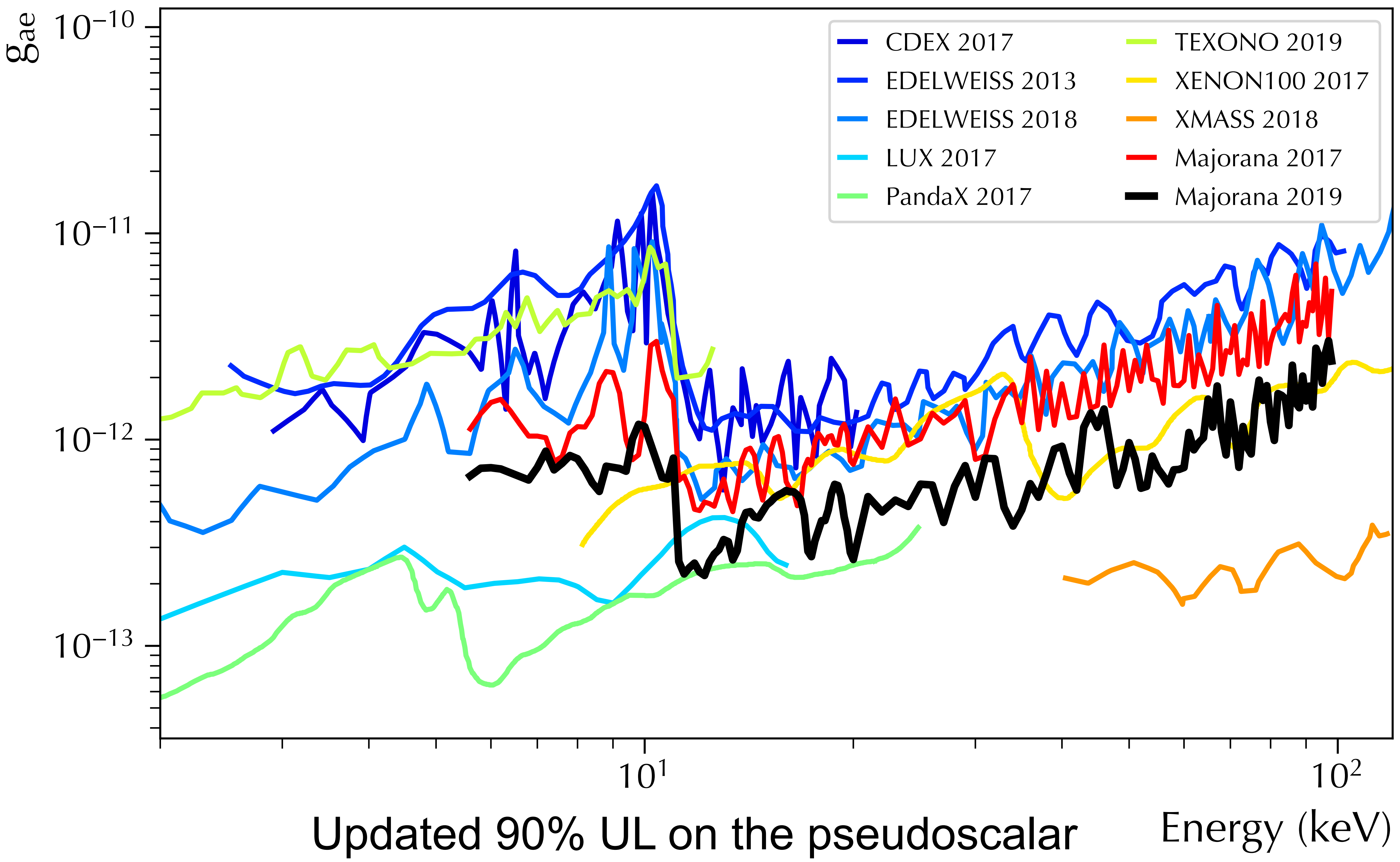
- Progress towards a low-E background model
- Applying a dynamic threshold calculation to lower the **analysis threshold to 1 keV**



Low energy spectra from 11.2 kg-yr of low-background open physics running (DS1-6a)

Permits low-energy physics PRL **118** 161801 (2017)

- pseudoscalar dark matter, vector dark matter, 14.4-keV solar axion, $e^- \rightarrow 3\nu$, Pauli Exclusion Principle



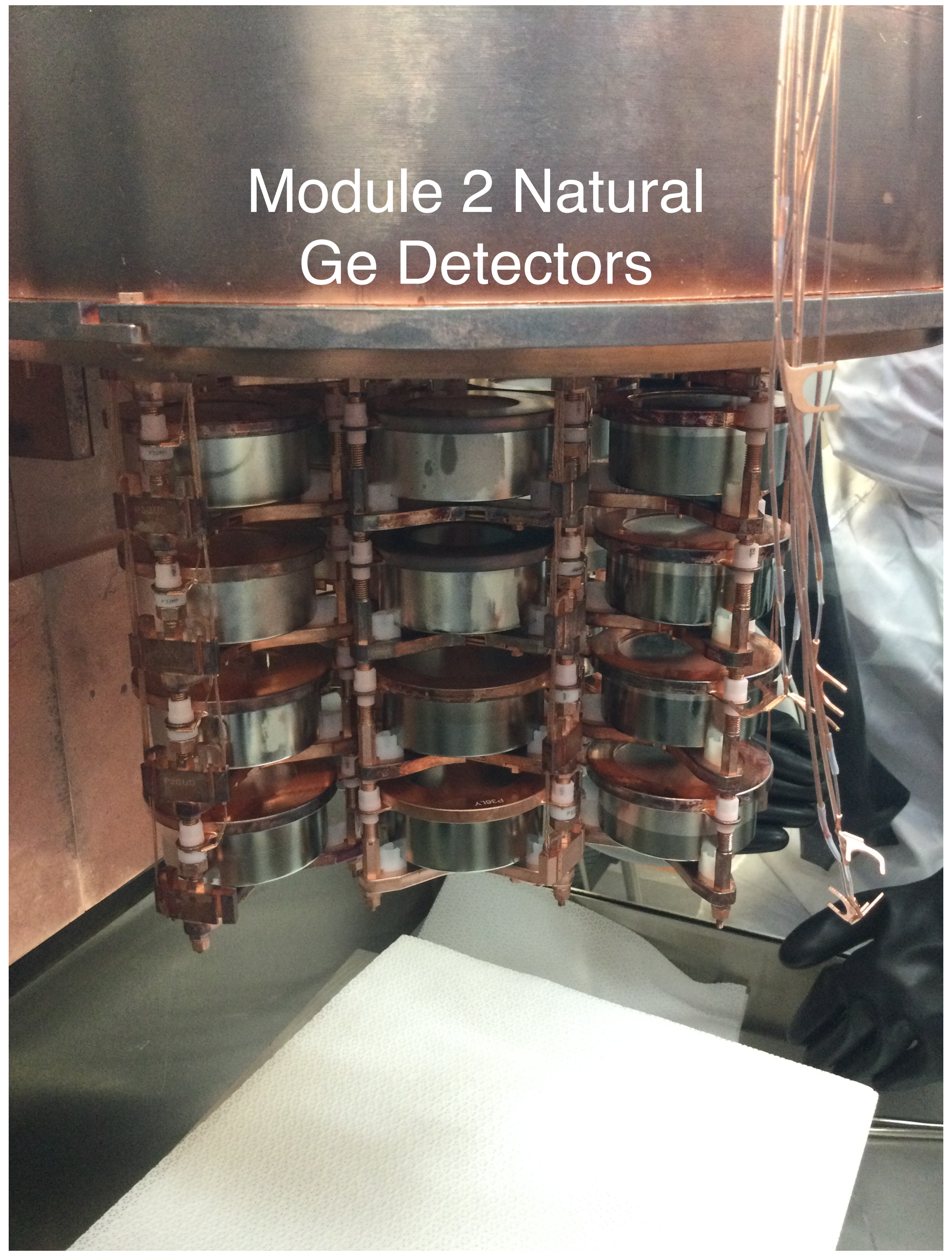
Updated 90% UL on the pseudoscalar axionlike particle dark mater coupling

J. Phys. Conf. Ser. 1468, 012040 (2020)

2021 Operations

^{enr}Ge detector operation completed in March. 2021

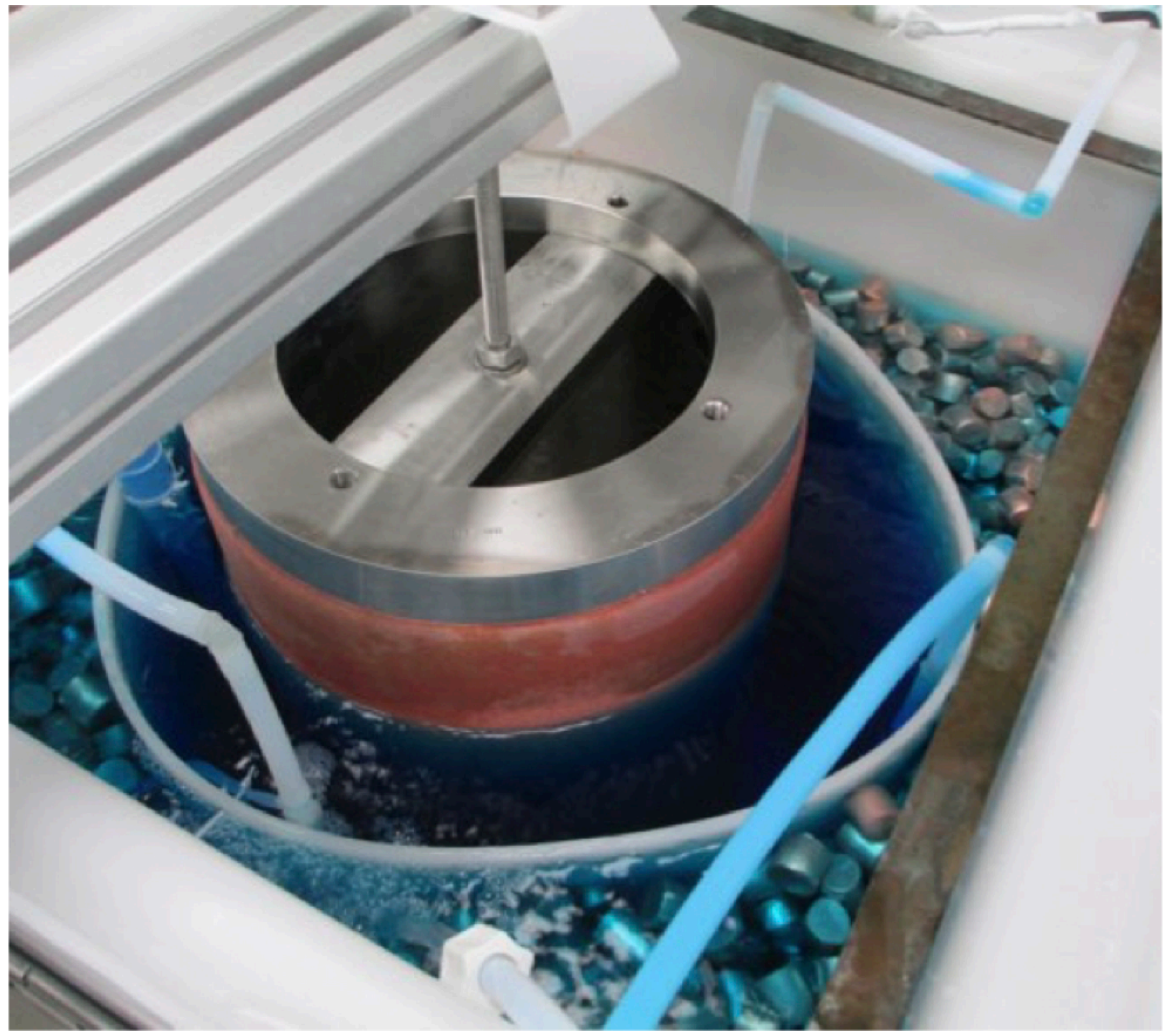
- Ultimate integrated exposure: ~65 kg y (^{enr}Ge)
- Removed all ^{enr}Ge detectors and packaged for shipment
- ^{enr}Ge detectors shipped to LNGS for installation in LEGEND-200



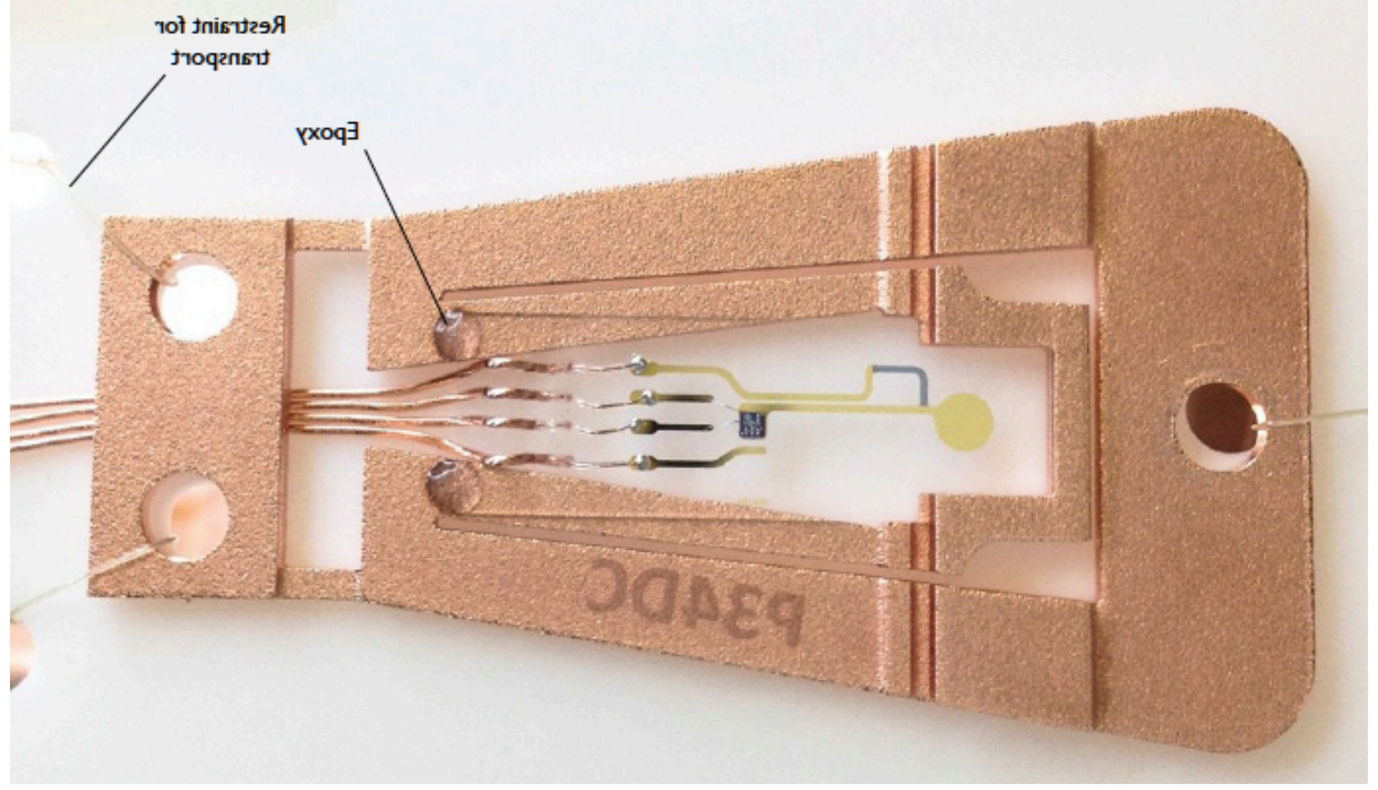
Continuing operation with natural detectors

- All remaining natural Ge detectors consolidated into Module 2
- 23 BEGe detectors filling 5 of the 7 string positions
- Background studies to refine background model
- Additional physics studies planned

Copper Electroformoing



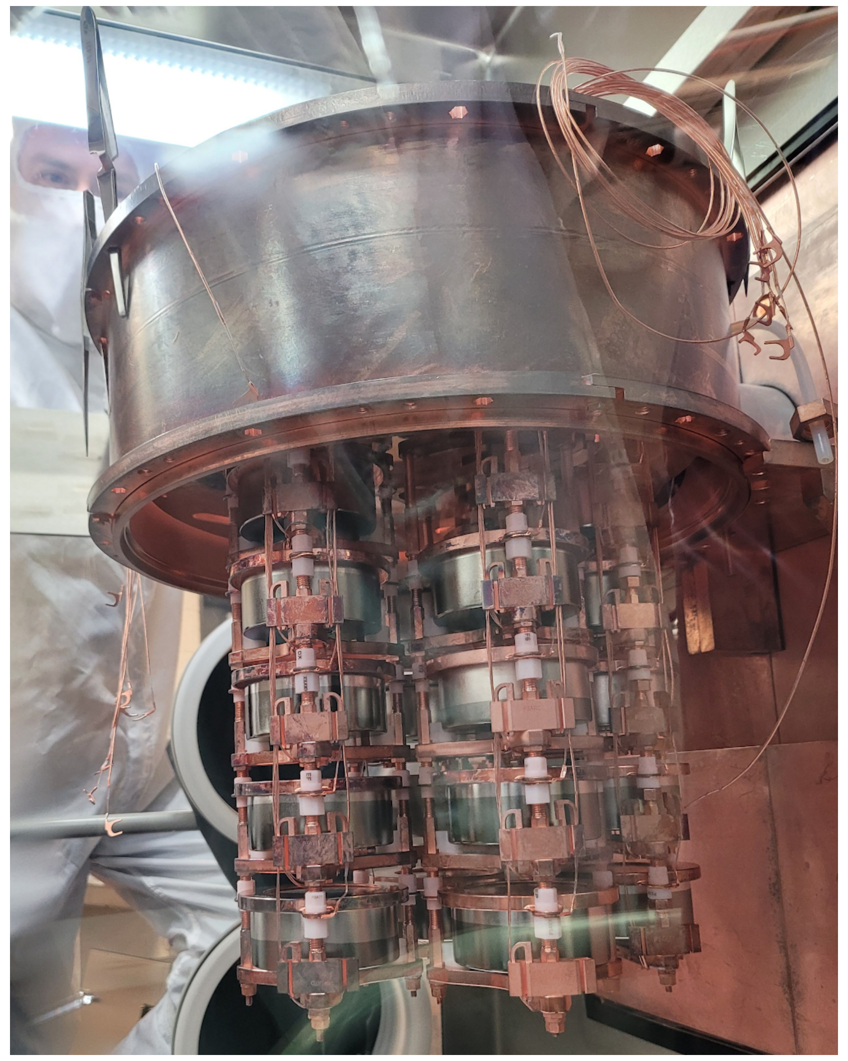
- Cu electroforming continues at the Davis campus:
  - Th decay chain ≤ 0.1 μBq/kg
  - U decay chain ≤ 0.1 μBq/kg
- Machining and cleaning in underground clean room
- Assembly and parts storage in N_2 purged environment
- Ultra-pure parts being produced for MJD activities and also in support of LEGEND



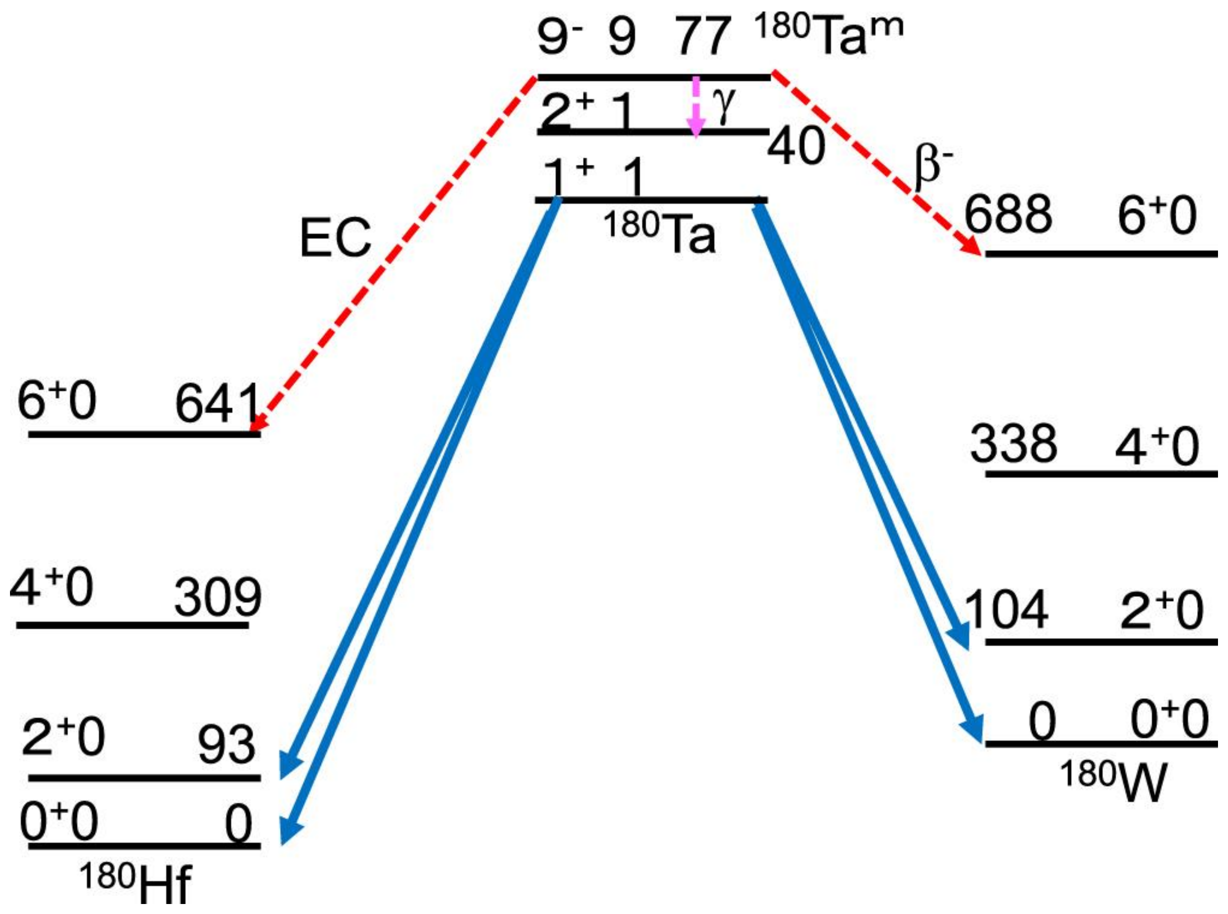
Searching for Ta-180 Decay in MJD

- 2 ppm (0.0002%) tantalum in earth's crust
- Ta-180 is only 0.012% abundant in natural Ta
- All of the Ta-180 is metastable
- The **only** known metastable nuclear decay that has not been observed ($T_{1/2} > 10^{17}$ years)
- **Using MJD's unique features**
  - Array of detectors
  - Ultra-clean, low background environment for rare event search
  - Excellent energy resolution to clearly identify the decay signature
- Installation of 12-15 kg of Ta for one year
- Search for decay signatures at specific energies that have their origin in the Ta-180 decay

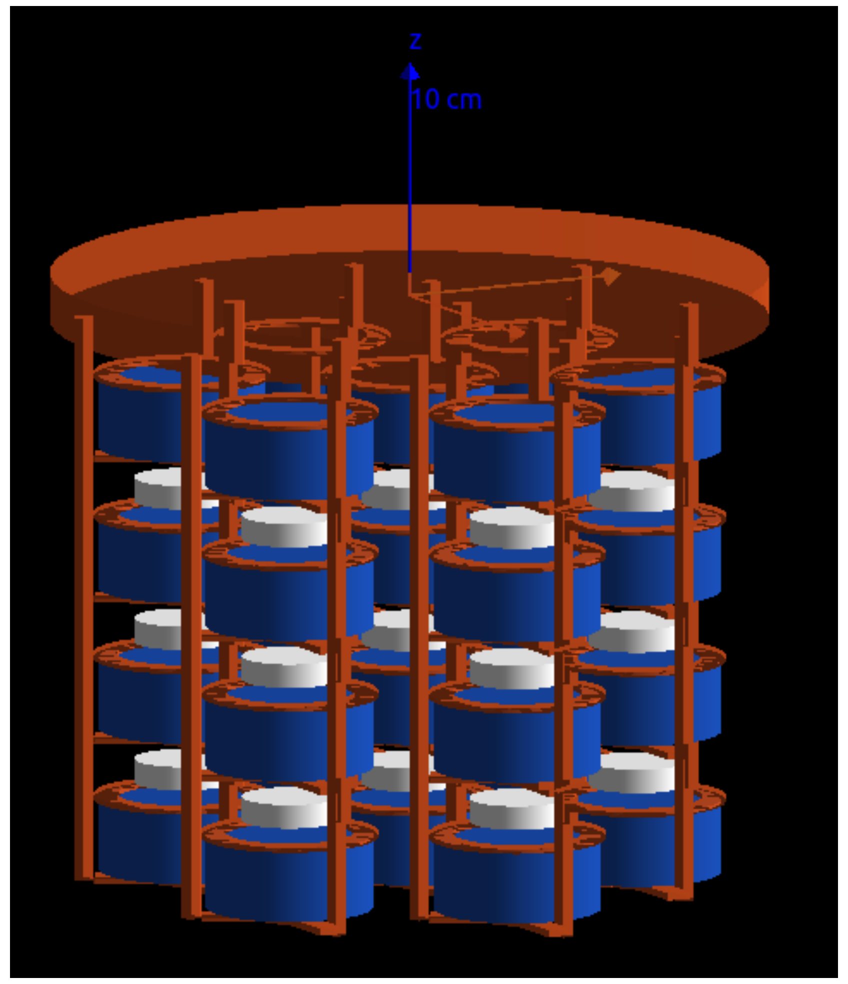
Rare Tantalum bars



MJD's natural Ge module in Spring 2021



Tantalum decay scheme



Simulation of Ta disks (white) in MJD

MAJORANA DEMONSTRATOR Summary and Outlook

- Started taking ^{enr}Ge data with first module in 2015 and operated both modules from 2016 — 2021
  - Latest limit from 26 kg-yr exposure: >2.7 x 10^{25} yr (90% C.L.); sensitivity 4.8 x 10^{25} yr (90% C.L.)
  - Excellent energy resolution of 2.5 keV FWHM @ 2039 keV, best of all 0νββ experiments

PRC **100** 025501 (2019)

- Background model being investigated and refined
  - Initial background fits are informing possible distribution of background sources
  - Goal of a full background model consistent with the data - inform design of next generation experiments
- Optimization of analysis cuts is being finalized to improve background rejection
  - New results to be released from the complete enriched Ge data set
- Low background + low threshold + energy resolution allows for broad physics program

PRL **118** 161801 (2017) | PRL **120** 211804 (2018) | PRD **99** 072004 (2019)

- Completed an upgrade to cables and connectors, including deployment of new ICPC detectors, as part of LEGEND R&D. Copper electroforming continues in support of MJD and LEGEND.
- Reached an estimated ultimate exposure of ~65 kg-yr with a half-life sensitivity in the range of 10^{26} yr with the removal of enriched detectors for redeployment in LEGEND-200
  - Continuing operation with natural detectors for background studies, R&D, and other physics
  - Plan to deploy 12-15 kg of Ta to search for metastable decay of Ta-180 with LANL LDRD funding

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