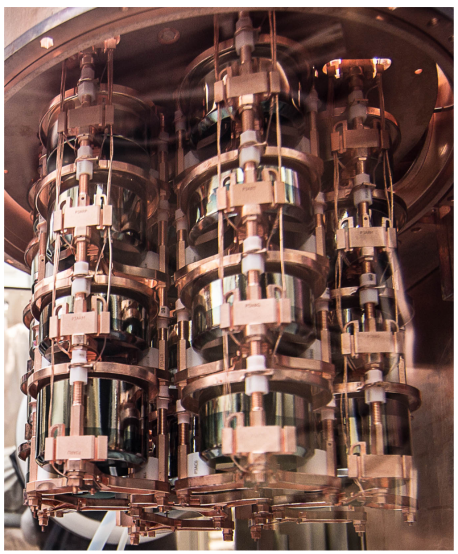
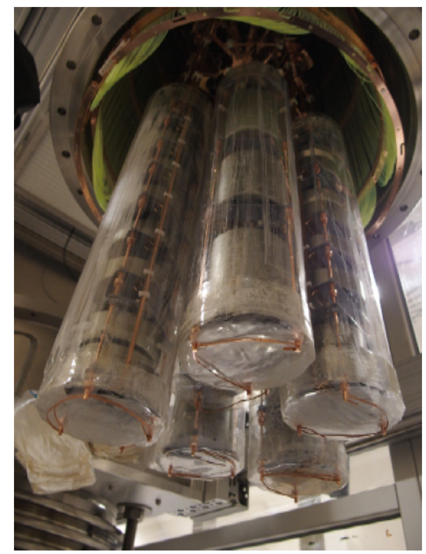
Double-Beta Decay Experiments with ^{76}Ge



Jason Detwiler

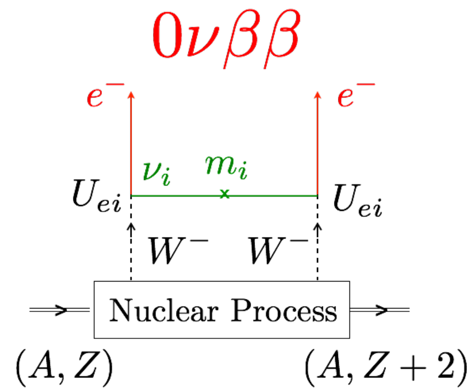
NNR16, Sep 29, 2016



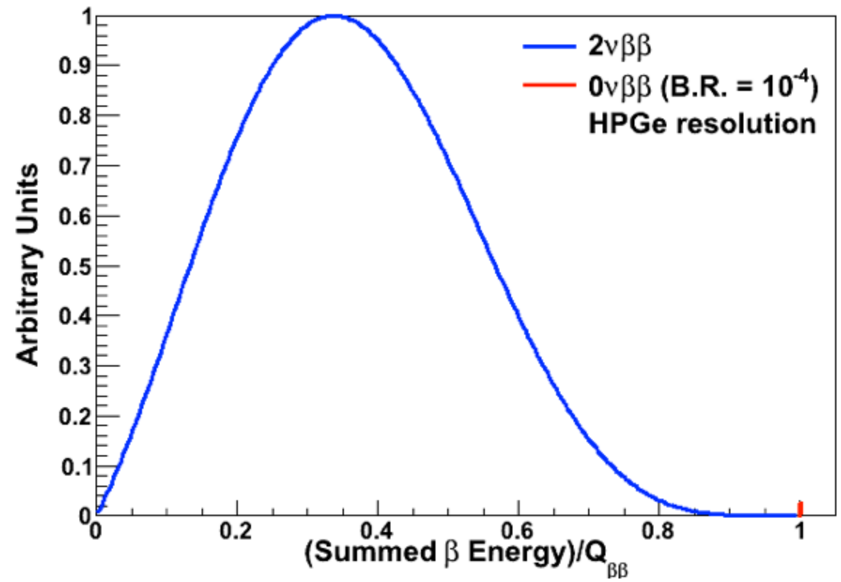
Acknowledgement:
Many slides from Elliott and Agostini talks, Nu16

Neutrinoless Double-Beta Decay

- Neutrino mass requires BSM physics
  - Dirac mass: new particle N_R and/or extra-small Higgs coupling
  - Majorana mass: new unrenormalizable mass mechanism
- Motivation for Majorana neutrinos
  - L violation
  - “Minimally” non-renormalizable
  - Emerge “naturally” from GUTs (seesaw mechanism)
  - Predicted by leptogenesis
- Only feasible detection method: 0νββ decay



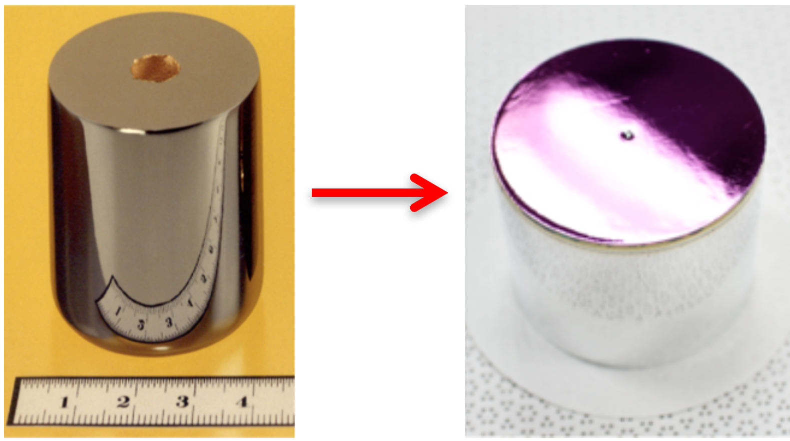
$$\Gamma^{0\nu}_{1/2} = G^{0\nu}|M^{0\nu}|^2 \left| \sum_{i=1}^{3} U_{ei}^2 m_i \right|^2$$

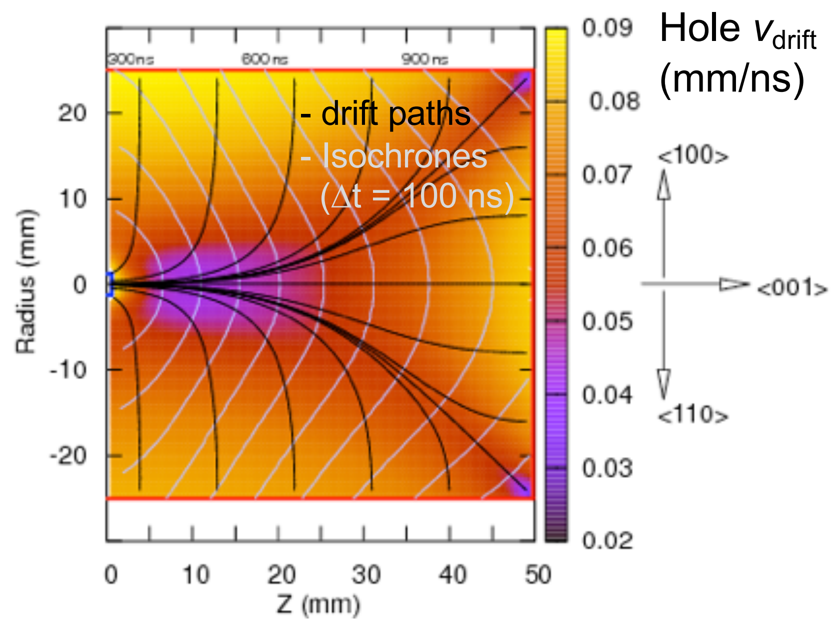


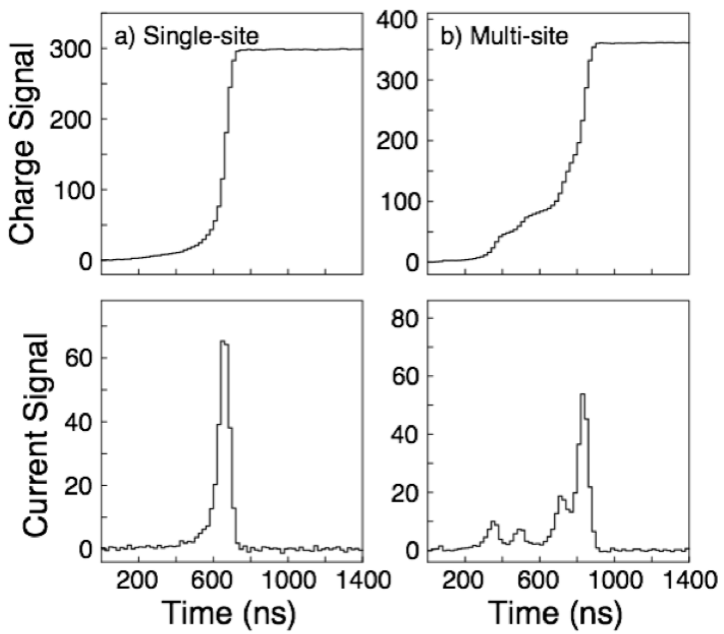
Advantages of ^{76}Ge

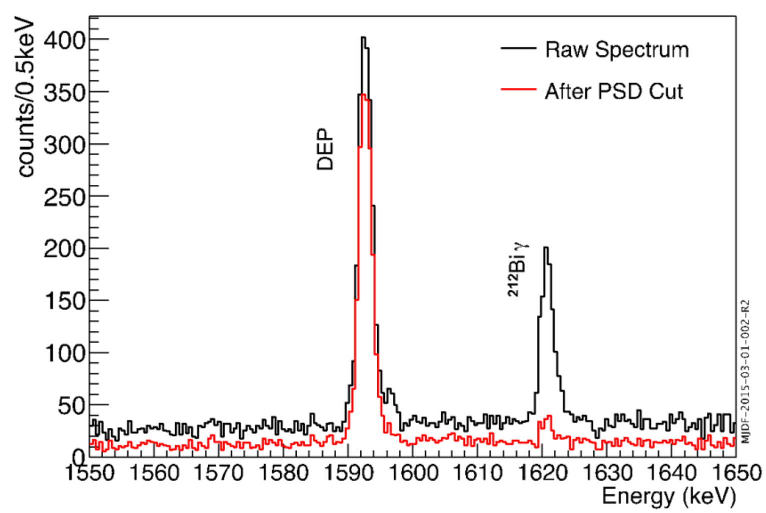
- Intrinsic high-purity Ge detectors = source
- Excellent energy resolution: approaching 0.1% at 2039 keV (~3 keV ROI)
- Demonstrated ability to enrich from 7.44% to ≥87%
- Powerful background rejection: multiplicity, timing, pulse-shape discrimination

$0\nu\beta\beta$ with Point Contact Detectors





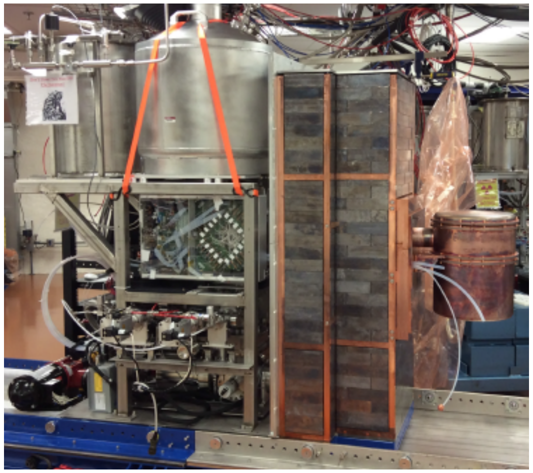


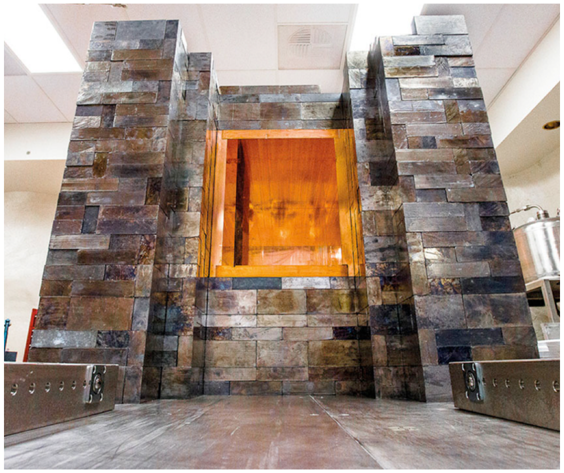


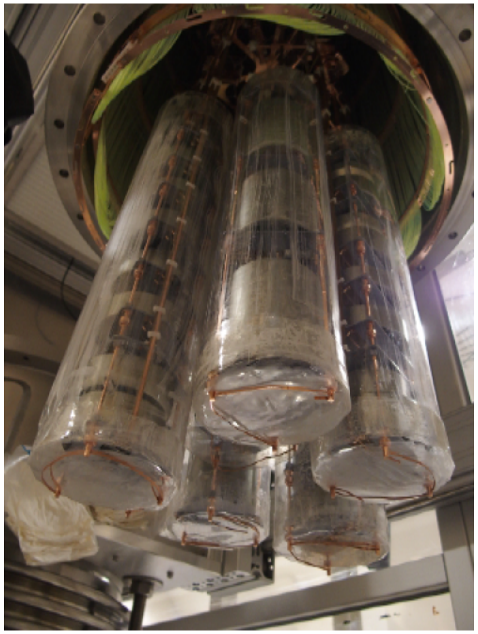
Luke et al., IEEE trans. Nucl. Sci. 36 , 926 (1989)
Barbeau, Collar, and Tench, J. Cosm. Astro. Phys. 0709 (2007).

MAJORANA and GERDA

MAJORANA
“Traditional” configuration:
Vacuum cryostats in a
passive graded shield
with ultraclean materials







GERDA
Direct immersion
in active LAr shield

The MAJORANA Collaboration

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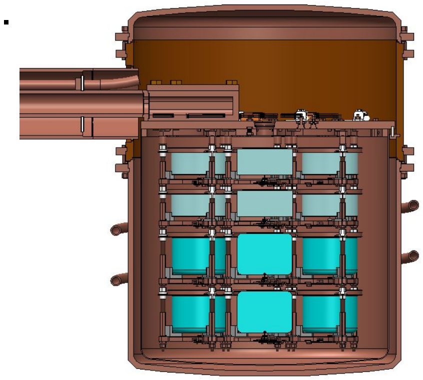
U.S. DEPARTMENT OF ENERGY | Office of Science
Office of Nuclear Physics

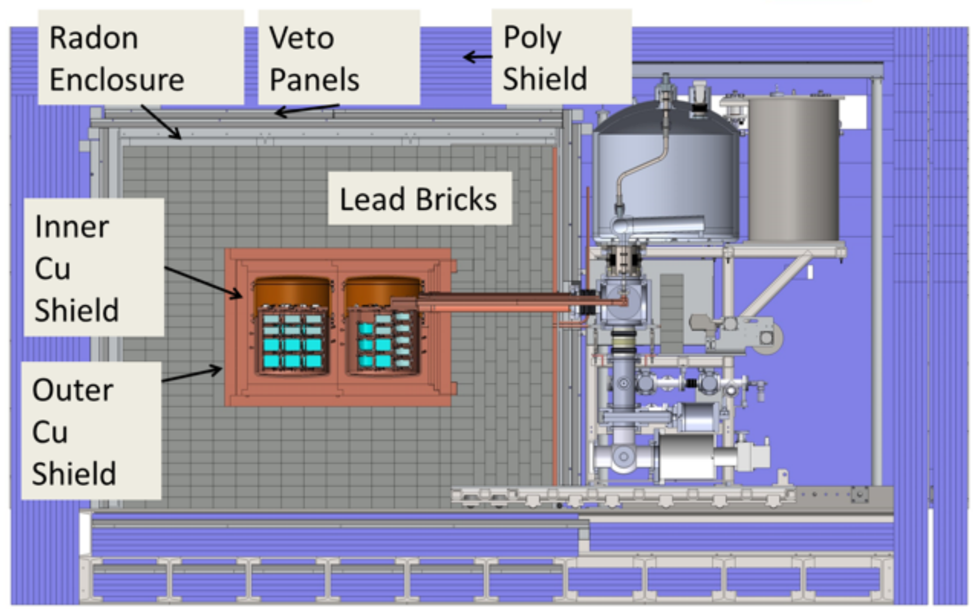
The MAJORANA DEMONSTRATOR

Funded by DOE Office of Nuclear Physics, NSF Particle Astrophysics, NSF Nuclear Physics
with additional contributions from international collaborators.

Goals: - Demonstrate backgrounds low enough to justify building a tonne scale experiment.
- Establish feasibility to construct & field modular arrays of Ge detectors.
- Searches for additional physics beyond the standard model.

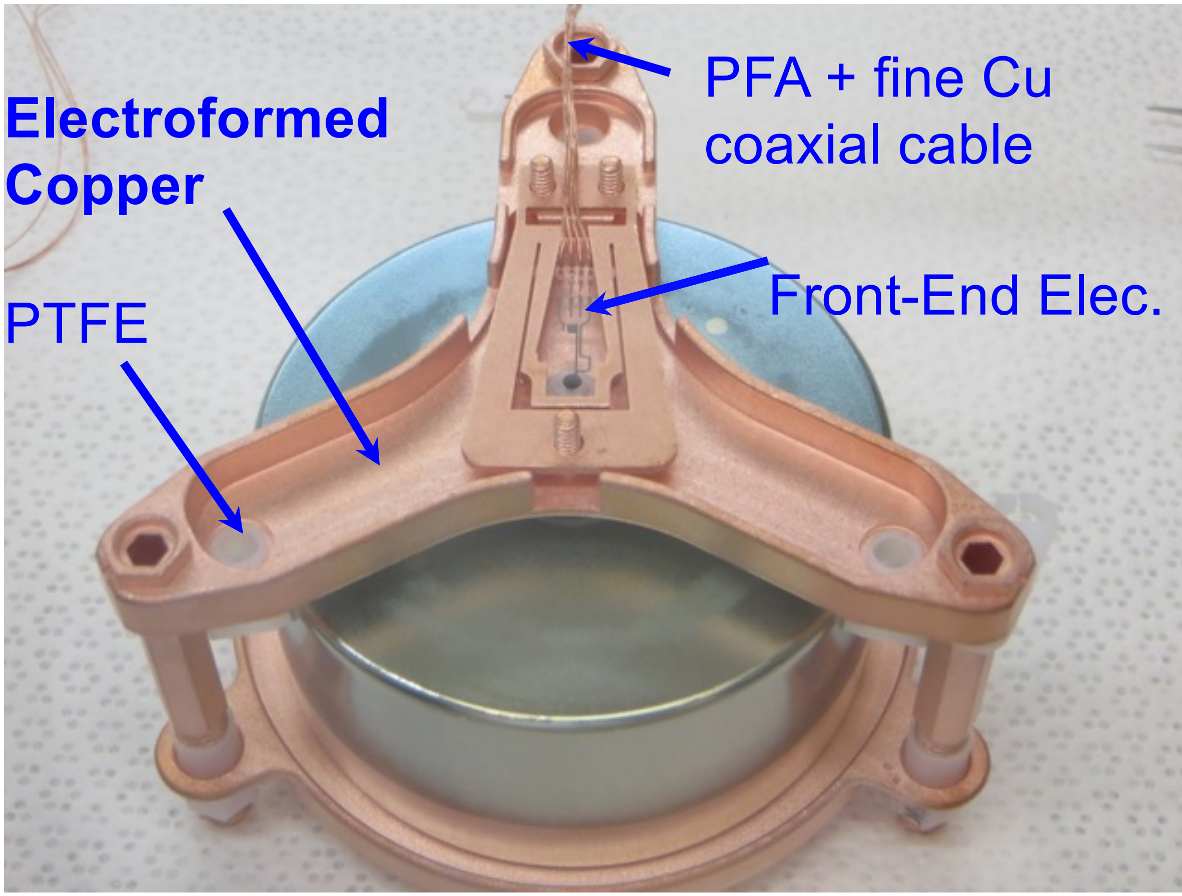


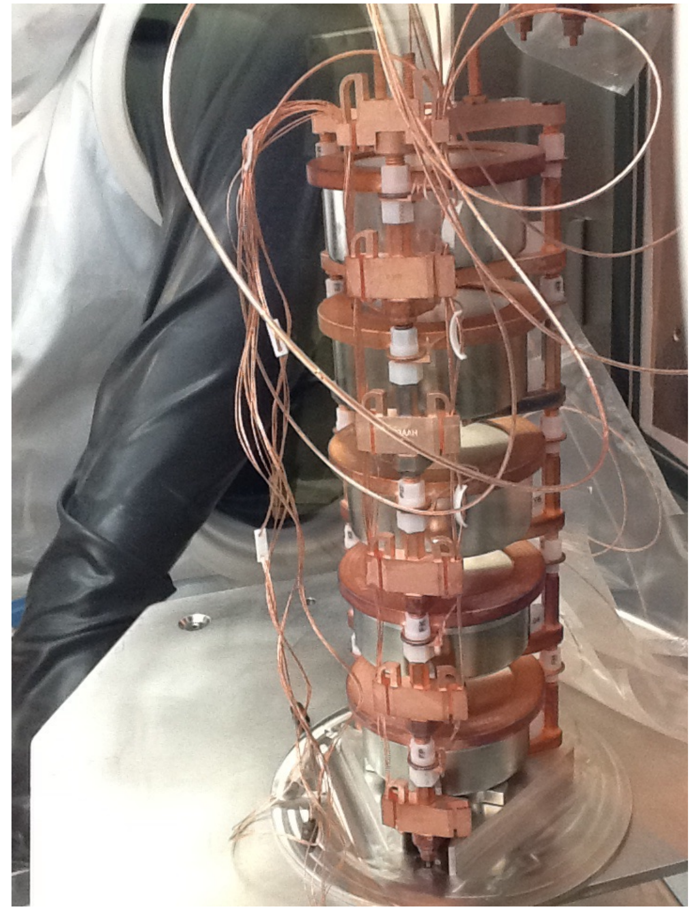
- Located underground at 4850' Sanford Underground Research Facility
- Background Goal in the $0\nu\beta\beta$ peak region of interest (4 keV at 2039 keV)
  3 counts/ROI/t/y (after analysis cuts) Assay U.L. currently ≤ 3.5
  scales to 1 count/ROI/t/y for a tonne experiment
- 44.8-kg of Ge detectors
  - 29.7 kg of 88% enriched ^{76}Ge crystals
  - 15.1 kg of ^{nat}Ge
  - Detector Technology: P-type, point-contact.
- 2 independent cryostats
  - ultra-clean, electroformed Cu
  - 22 kg of detectors per cryostat
  - naturally scalable
- Compact Shield
  - low-background passive Cu and Pb shield with active muon veto



Assembled Detector Unit and String

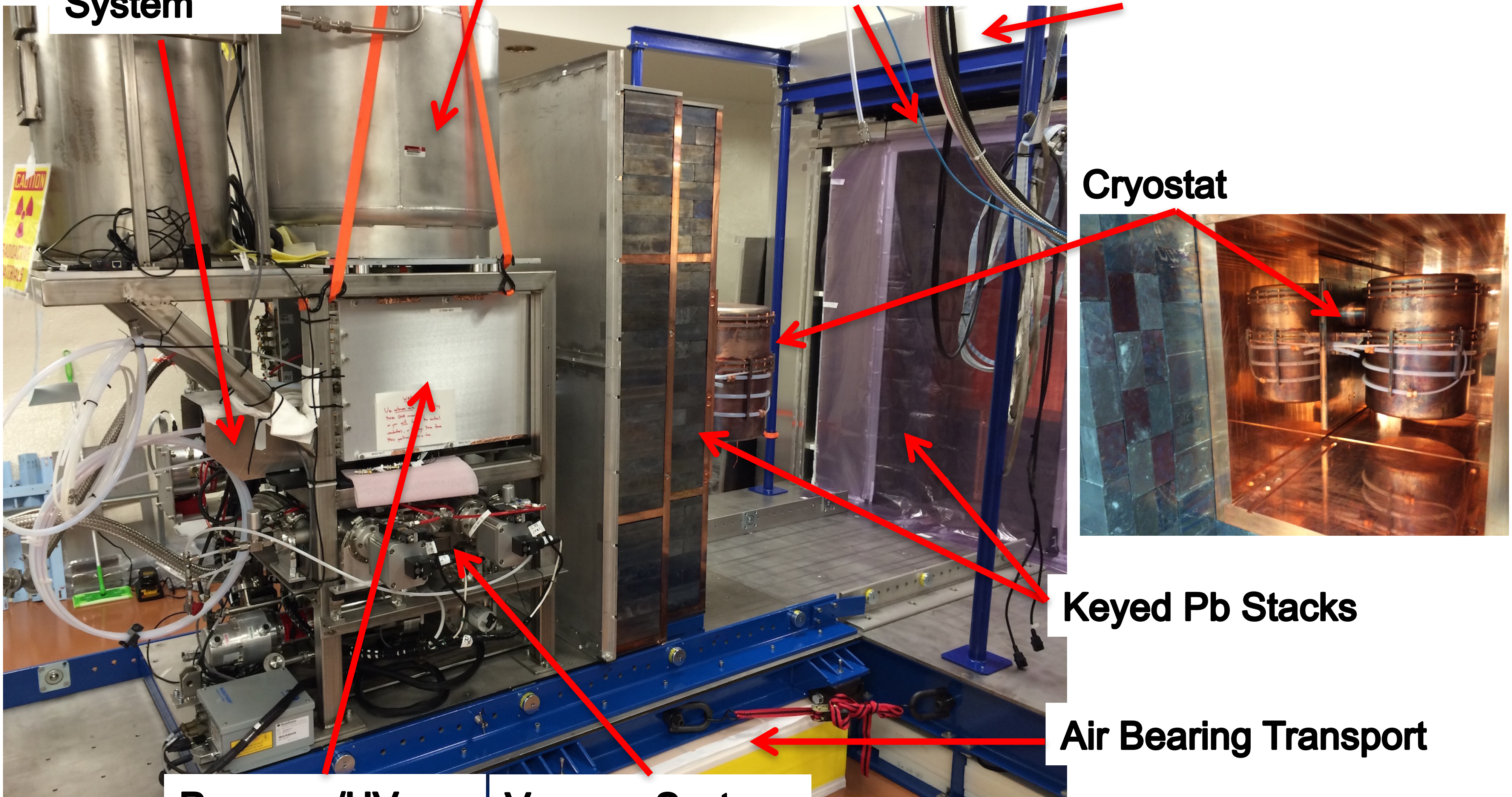
AMETEK (ORTEC) fabricated enriched detectors.
35 Enriched detectors at SURF 29.7 kg, 88% ^{76}Ge.
20 kg of modified natural-Ge BEGe (Canberra) detectors in hand (33 detectors UG).





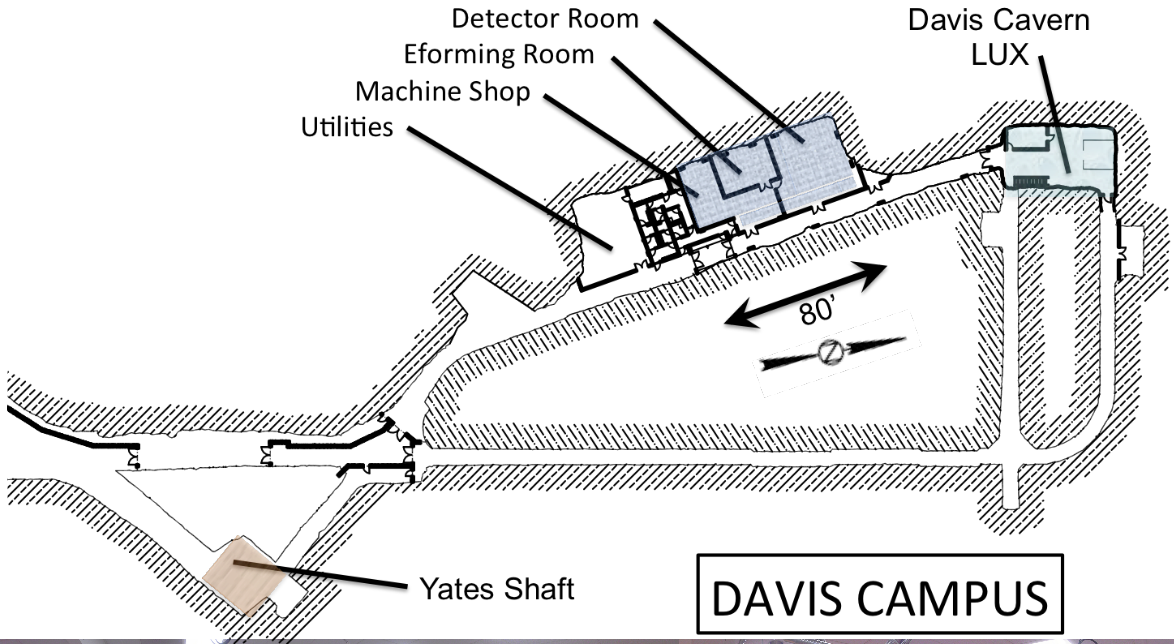
All detector assembly performed in N_2 purged gloveboxes.
All detectors' dimensions recorded by optical reader.

Module and Shield Details



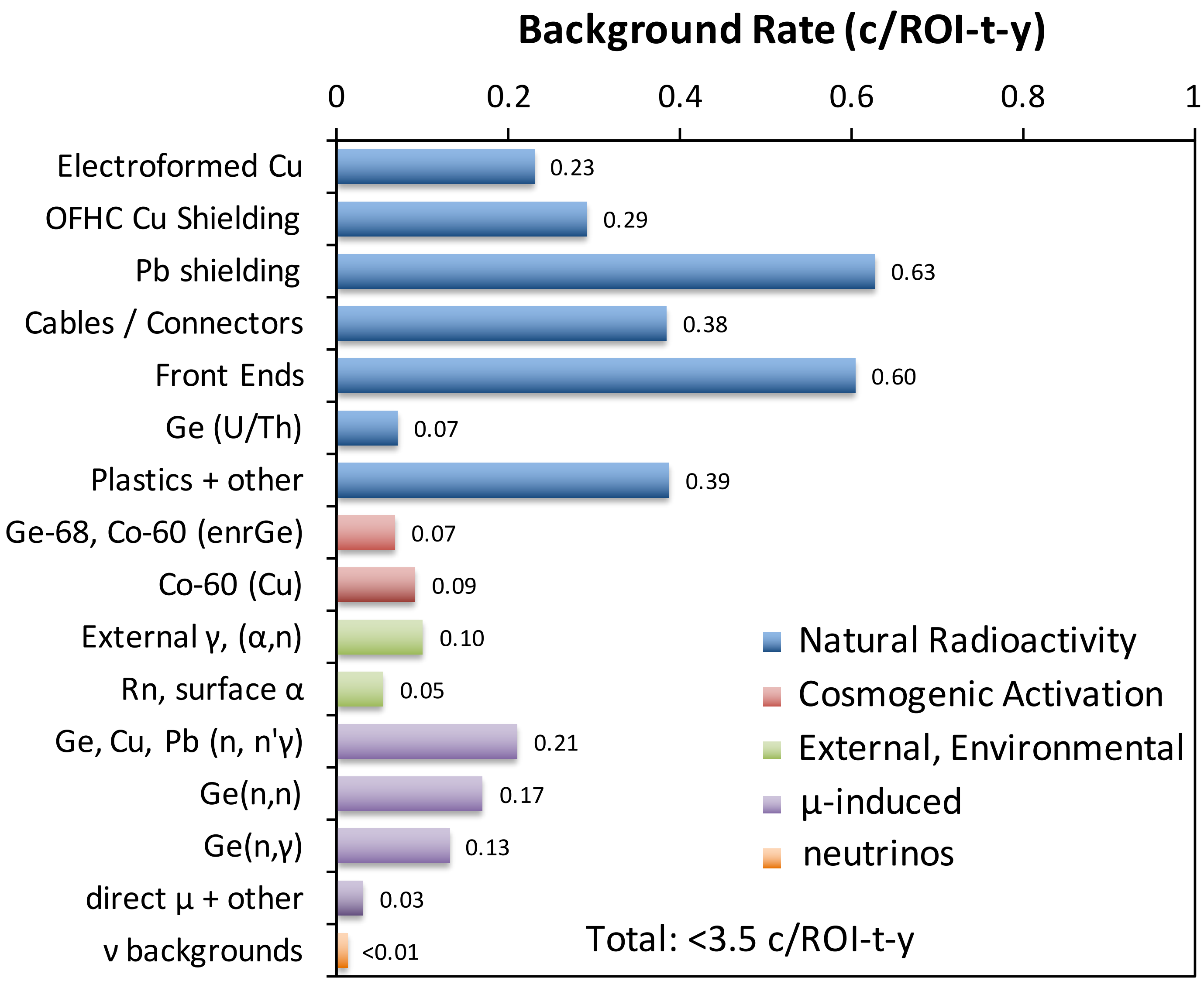
MAJORANA Underground Laboratory

4850’ level, SURF, Lead SD
Clean room conditions
Muon flux: 5 x 10^{-9} μ/cm^2 s
(arXiv:1602.07742)



DEMONSTRATOR Background Model

Background based on Assay Program (NIMA **828** (2016) 22)

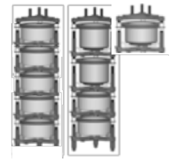


MAJORANA DEMONSTRATOR Implementation

Three Steps

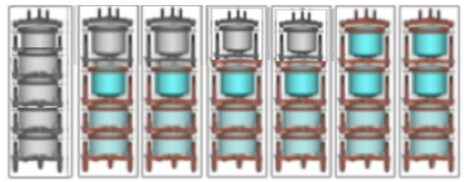
Prototype cryostat: 7.0 kg (10) ^{nat}Ge

Same design as Modules 1 and 2, but fabricated using commercial Cu Components



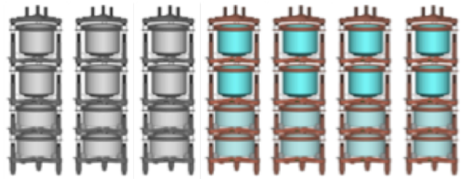
June 2014-June 2015

Module 1: 16.8 kg (20) ^{enr}Ge
5.7 kg (9) ^{nat}Ge

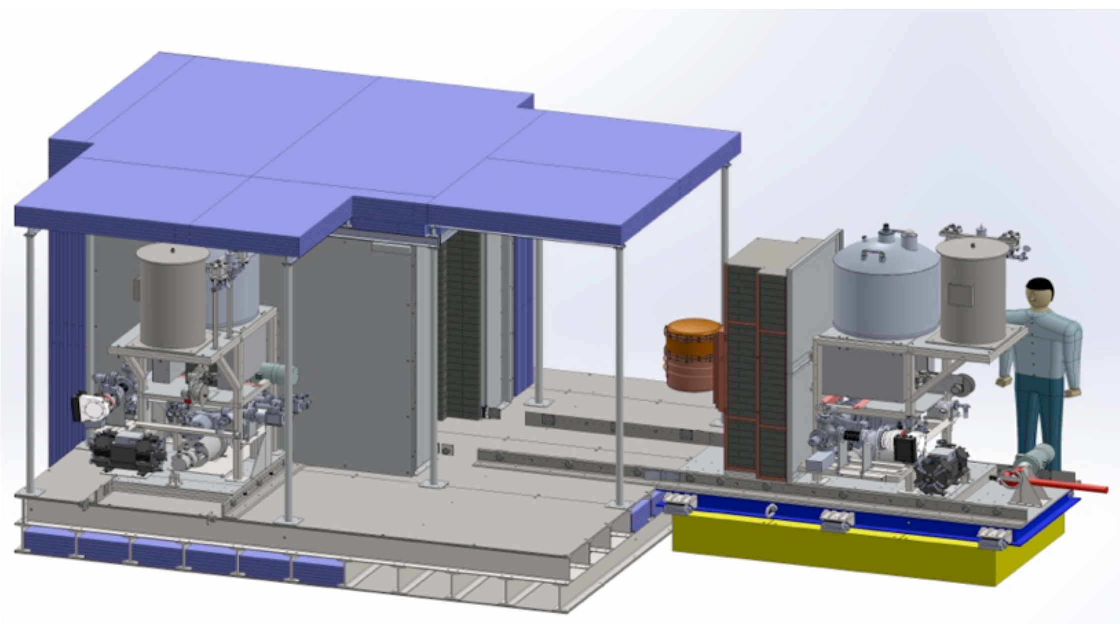


May–Oct. 2015 (DS0)
Final Installations,
Dec. 2015–July 2016 (DS1)

Module 2: 12.8 kg (14) ^{enr}Ge
9.4 kg (15) ^{nat}Ge

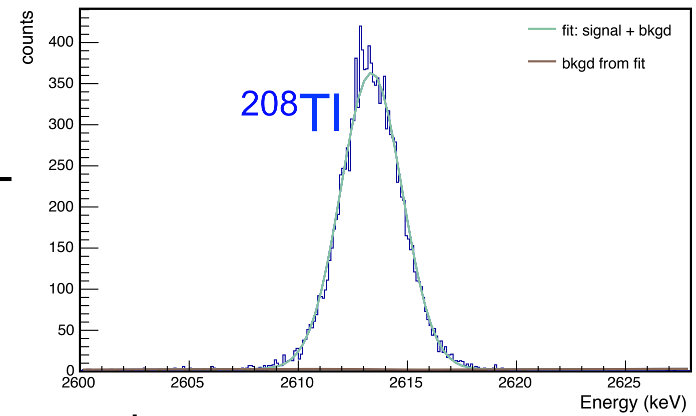


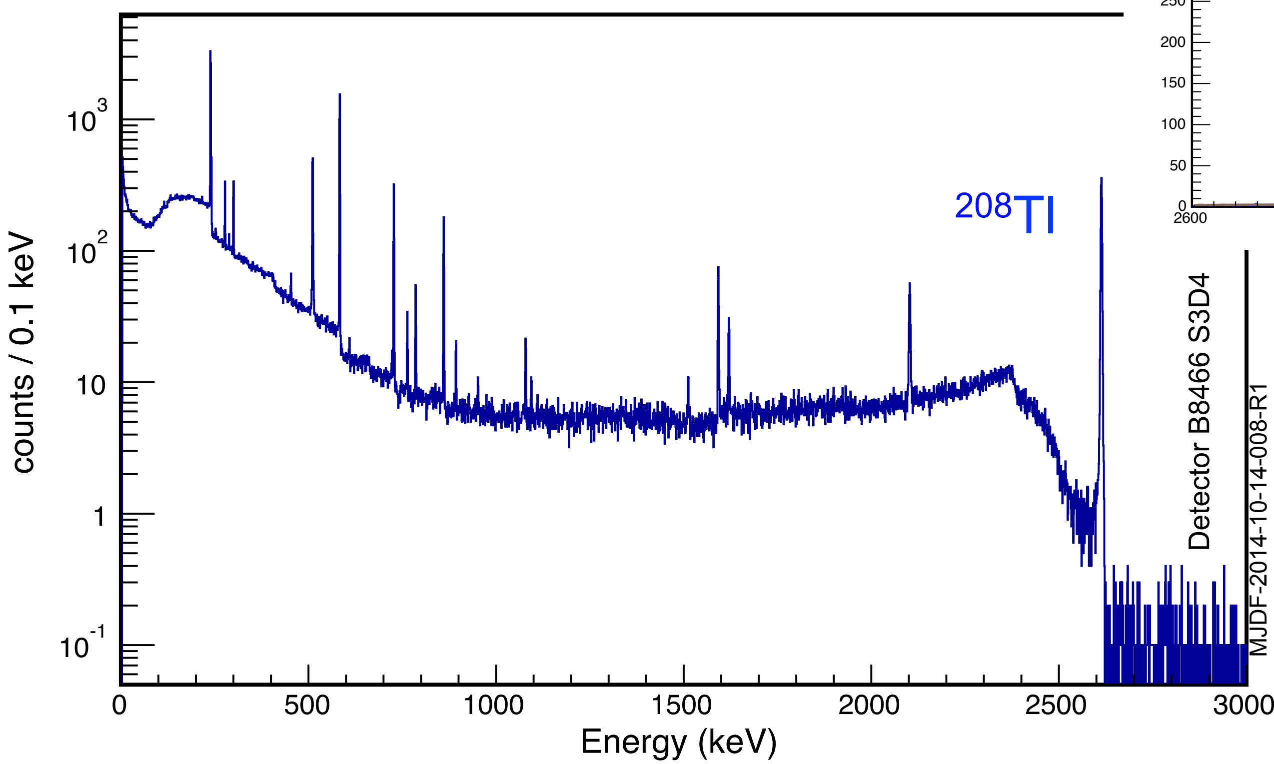
Aug. 2016 (with Module 1)



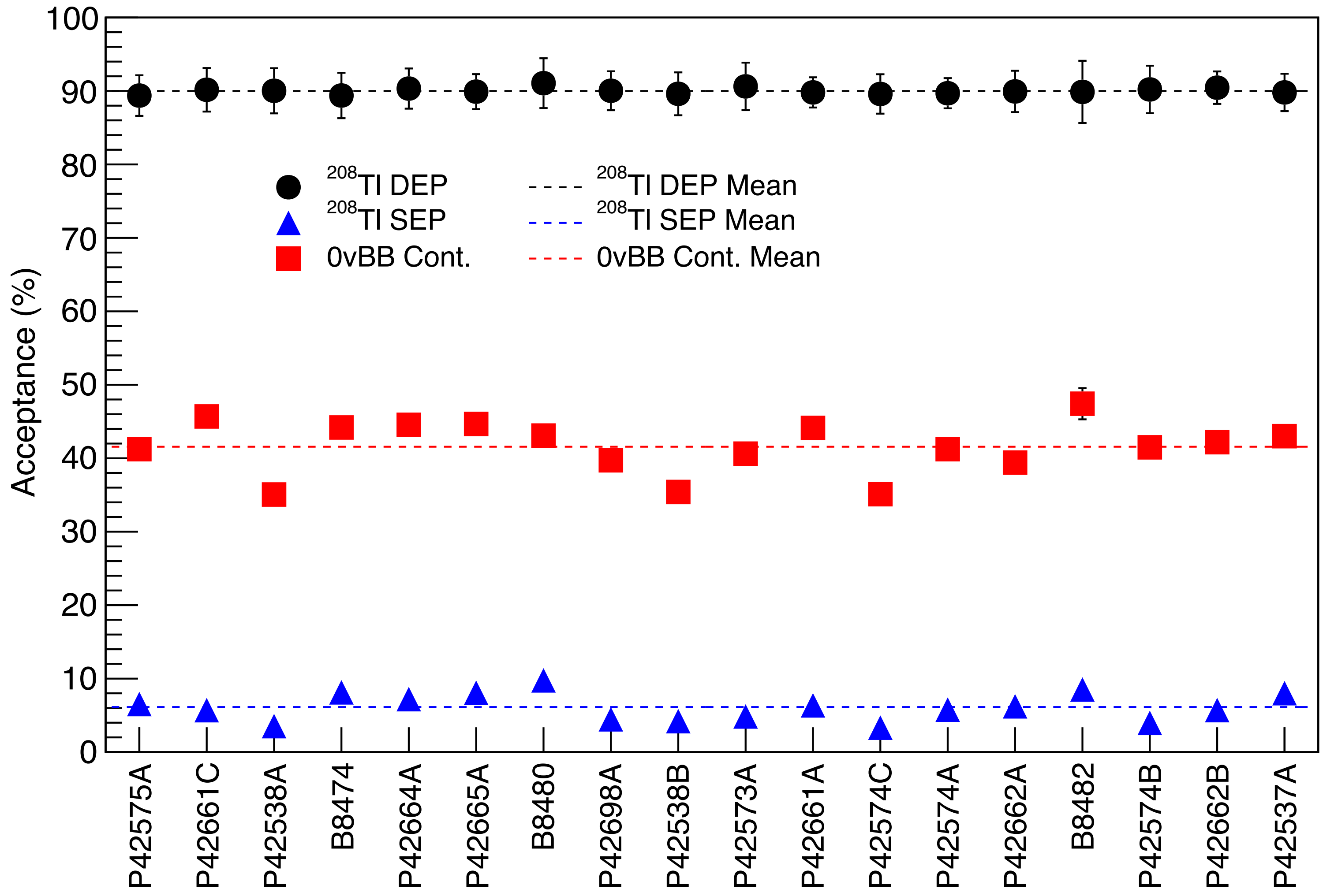
^{228}Th Calibration Spectrum in Prototype Cryostat

One detector spectrum within a string mounted in the prototype cryostat and inside shield. FWHM 3.2 keV at 2.6 MeV.





Ge Detector PSD Performance in Module 1 (DS1)



^{208}Tl DEP (single site events) fixed to 90%

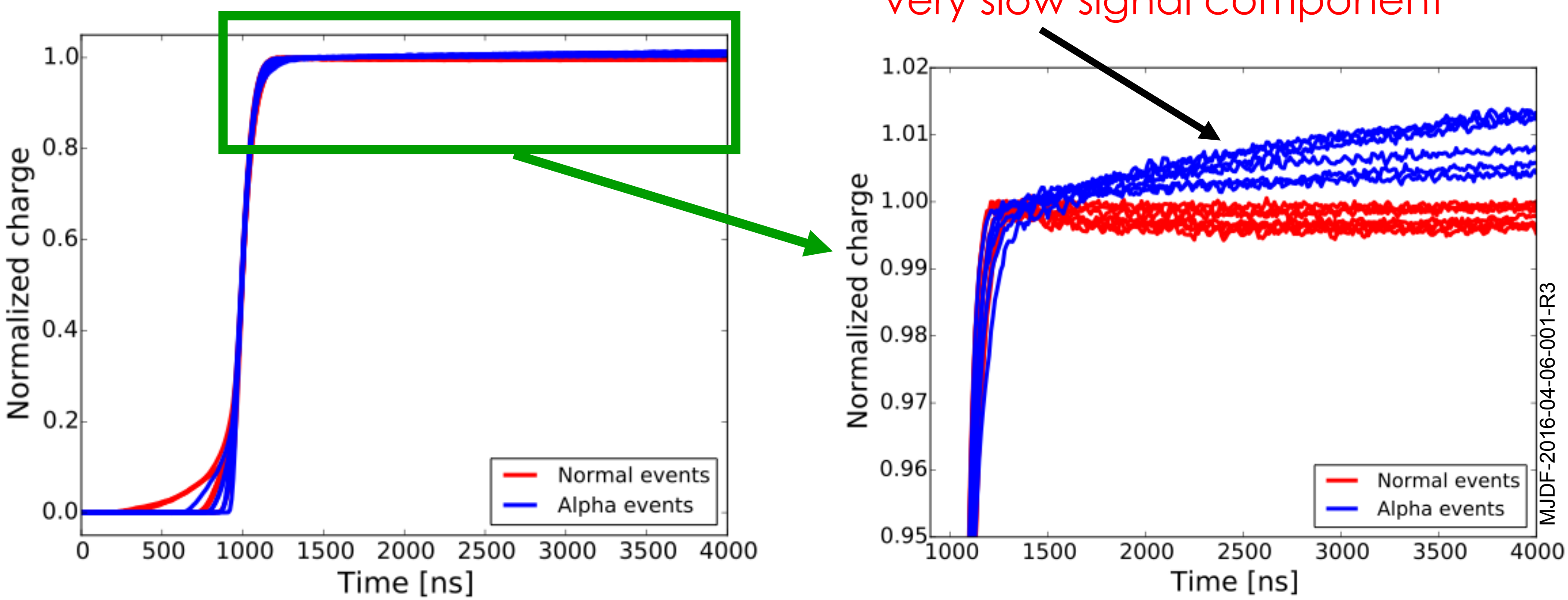
^{208}Tl SEP (Multiple site events) reduced to 6%

The Delayed Charge Recovery Cut for α's

- Alpha background response observed in Module 1 commissioning (DS0)
- Identified as arising from alpha particles impinging on passivated surface.
- Results in prompt collection of some energy, plus very slow collection of remainder.
- Produces a distinctive waveform allowing a high efficiency cut.

Example pole-zero corrected waveforms

Slow drift of charges along passivated surface results in very slow signal component



DS1 DCR Cut and Bulk-Event Response

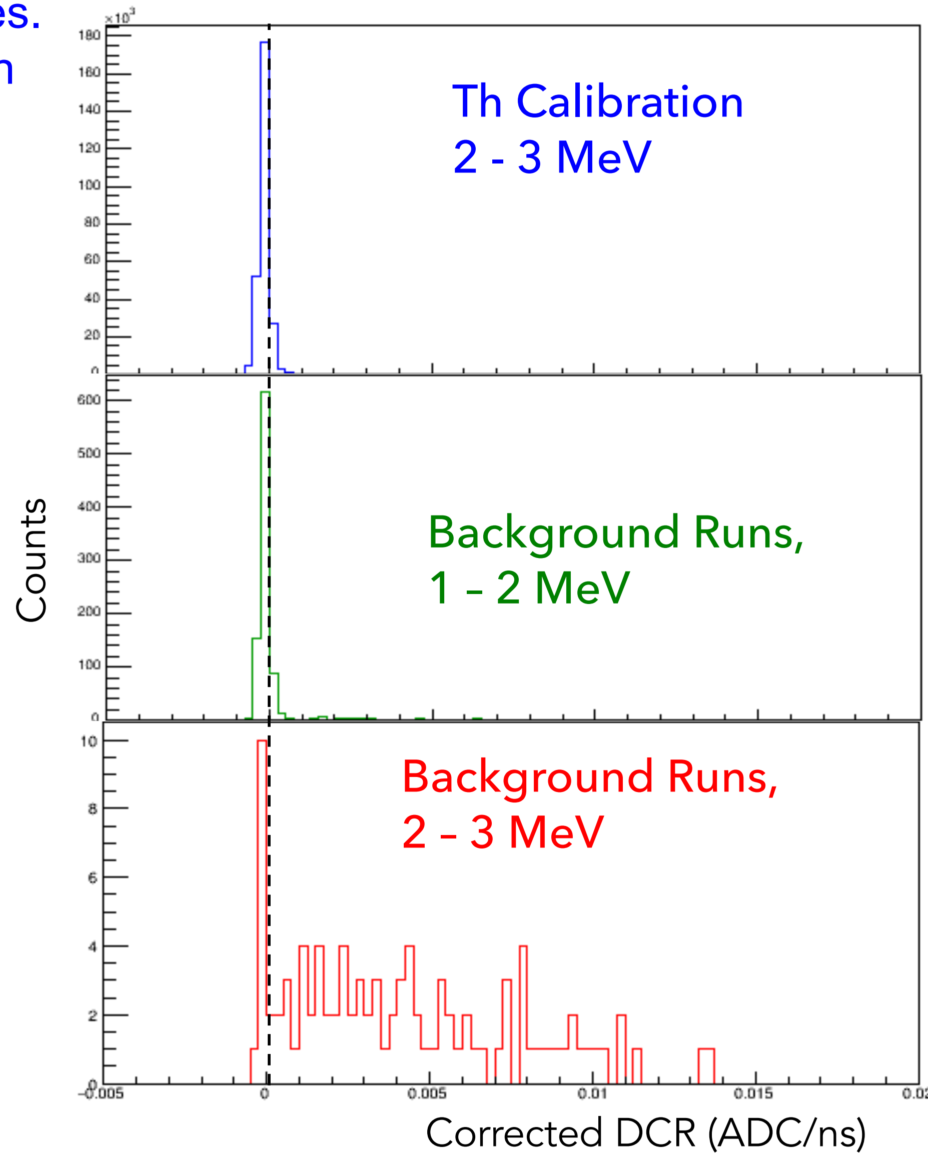
Removes most events above 2 MeV in the background spectrum, which are α candidates. Cut is 90% efficient for retaining events within detector bulk. Only ~5% of α's survive cut.

DS1, Enriched Detectors

During calibration runs
γ events survive cut.

During Background runs
$\beta\beta(2\nu)$ events survive cut.

Candidate α events from
background runs are removed.

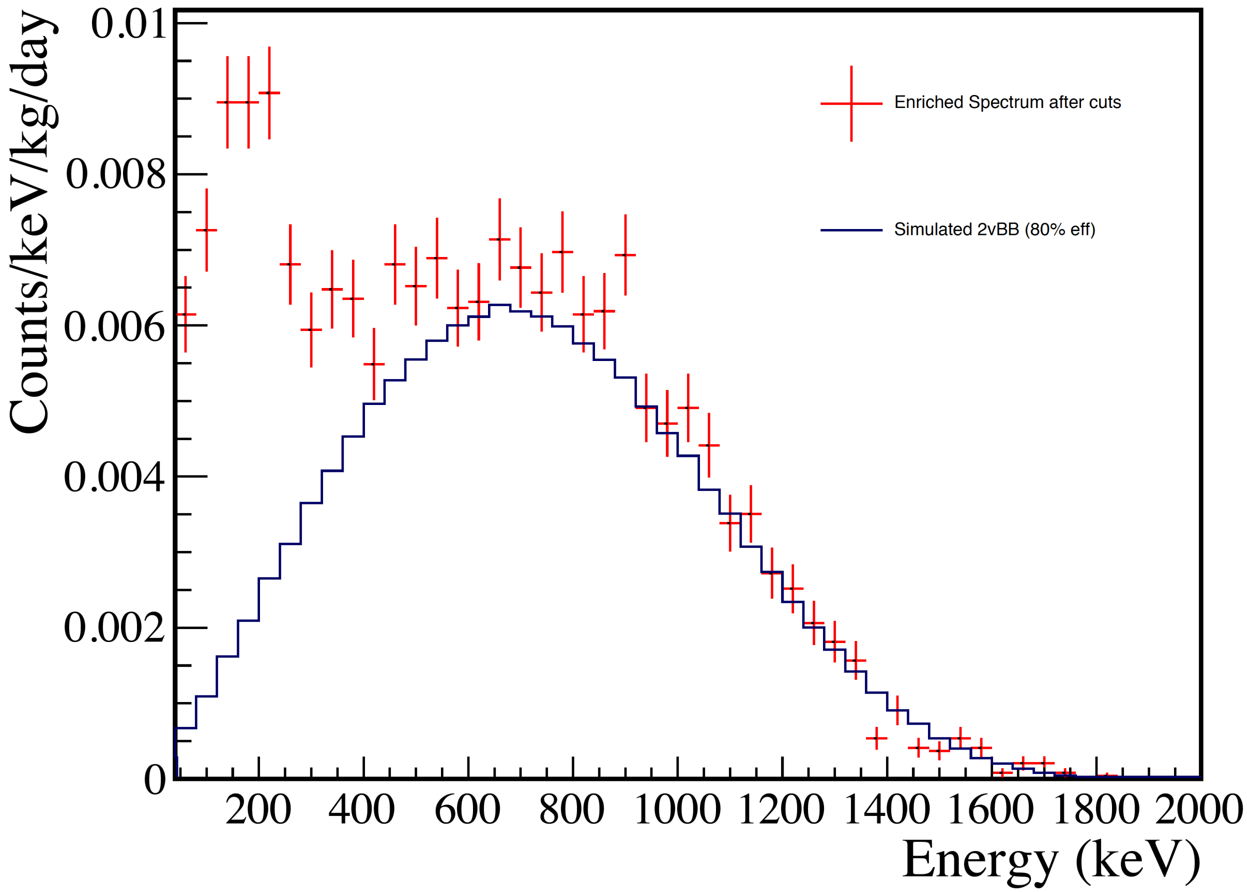


DS1: 500-2000 keV, ββ(2ν)

Data Set 1 spectrum after all cuts.

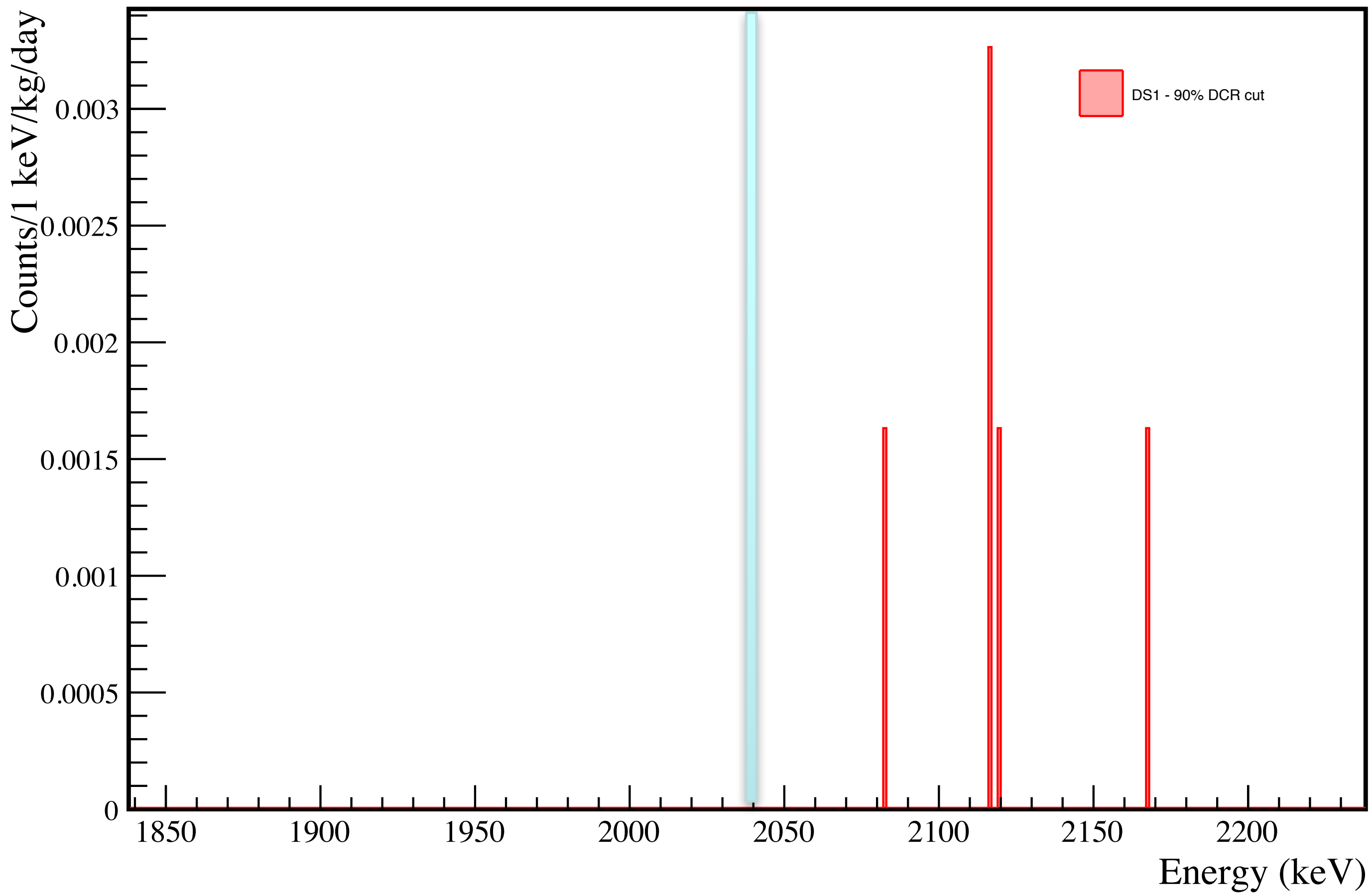
Above ~500 keV the spectrum is dominated by ββ(2ν).

Simulated rate using previously measured half-life (Eur. Phys. J. C **75** (2015) 416).



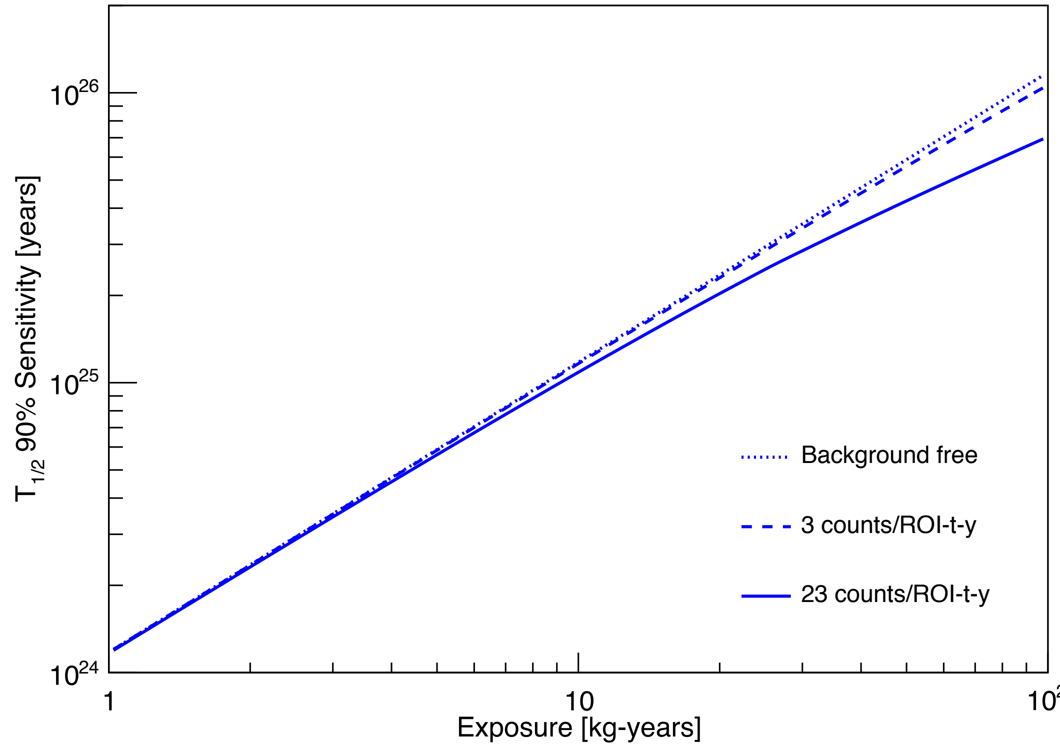
The ROI and DCR in DS1

The enriched detectors in Data Set 1 are used to estimate the background.
Most events near ROI are removed by the DCR cut. Only 5 survive in 400 keV window.
Background rate is 23^{+13}_{-10} counts/(ROI t y) for a 3.1 keV ROI, (68% CL).
Background index is $(7.5^{+4.5}_{-3.4})\text{x}10^{-3}$ counts/(keV kg y).
All analysis cuts are still being optimized.



DEMONSTRATOR $0\nu\beta\beta$ Sensitivity

- DS0 & DS1: No ROI events. Total exposure: 3.03 kg y
  DS0 1.37 kg-y, DS1 1.66 kg y
- Efficiency for $0\nu\beta\beta$ is 0.61 ± 0.04
  0.61 = (0.84)(0.9)(0.9)(0.9)
  = (Resol.)(Full Energy)(A/E)(DCR)
- $T_{1/2} > 3.7 \times 10^{24}$ y (90% CL)
- Background is very low. Sensitivity almost linear with exposure.
- We are exploring additional techniques for reducing background
  - Fast rise-time cut, improved MS PSD, longer traces for improved DCR, improved energy resolution…
- This analysis is on open data. Blind data taking began on April 14. Data taking with Module 2 began in August
- We are studying the possibility of repairing cables/connectors. Could increase mass by 50%



DS0: Tritium with Cosmogenic X rays

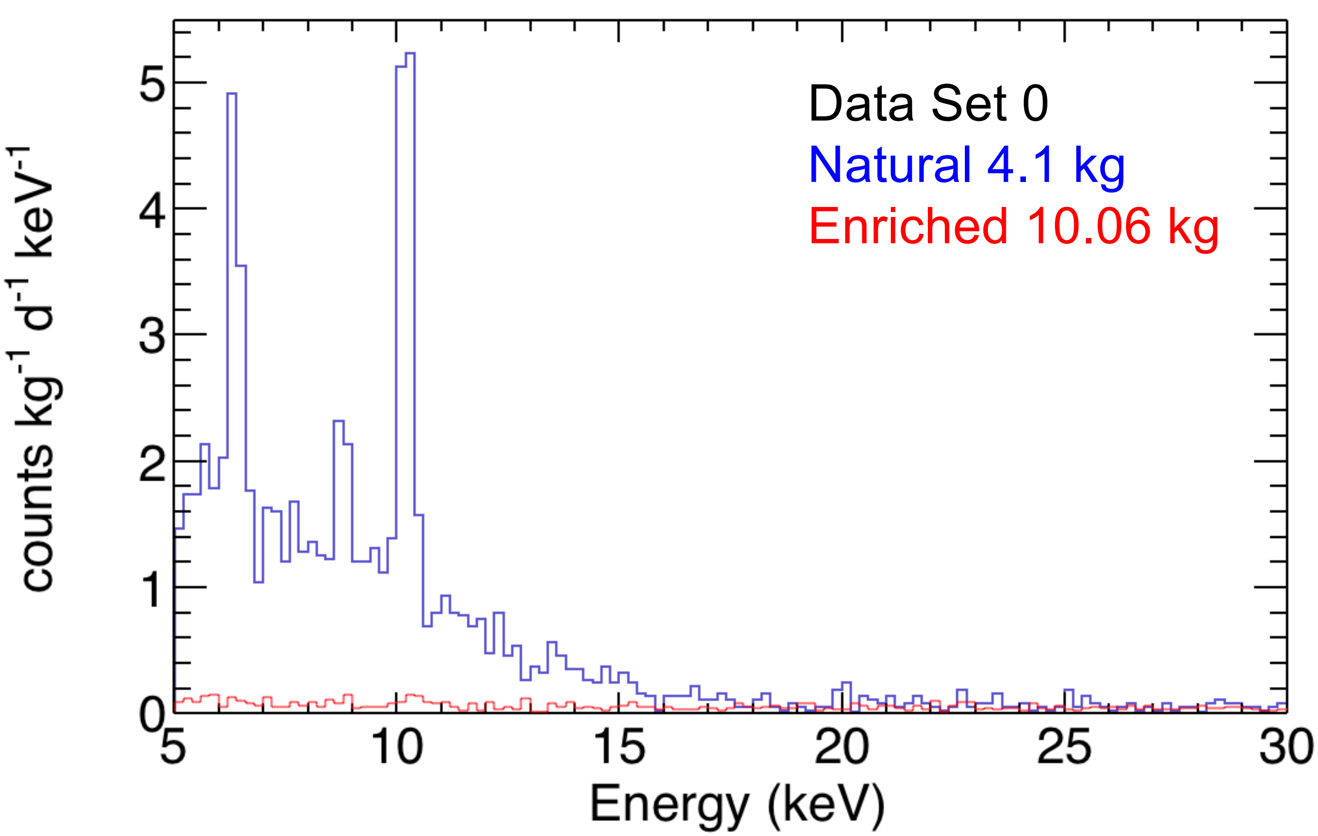
Controlled surface exposure of enriched material.

The enriched detector ^{68}Ge rate is low enough that an X-ray delayed coincidence cut will not be necessary.

Significant reduction of cosmogenics in the low-energy region. Factor of a few better in DS1.

Tritium is obvious and dominates in natural detectors below 20 keV.

Efficiency below 5 keV is under study.



<u>Permits Low-Energy physics</u>

Pseudoscalar dark matter
Vector dark matter
14.4-keV solar axion
$e^- \rightarrow 3\nu$
Pauli Exclusion Principle

MAJORANA Status

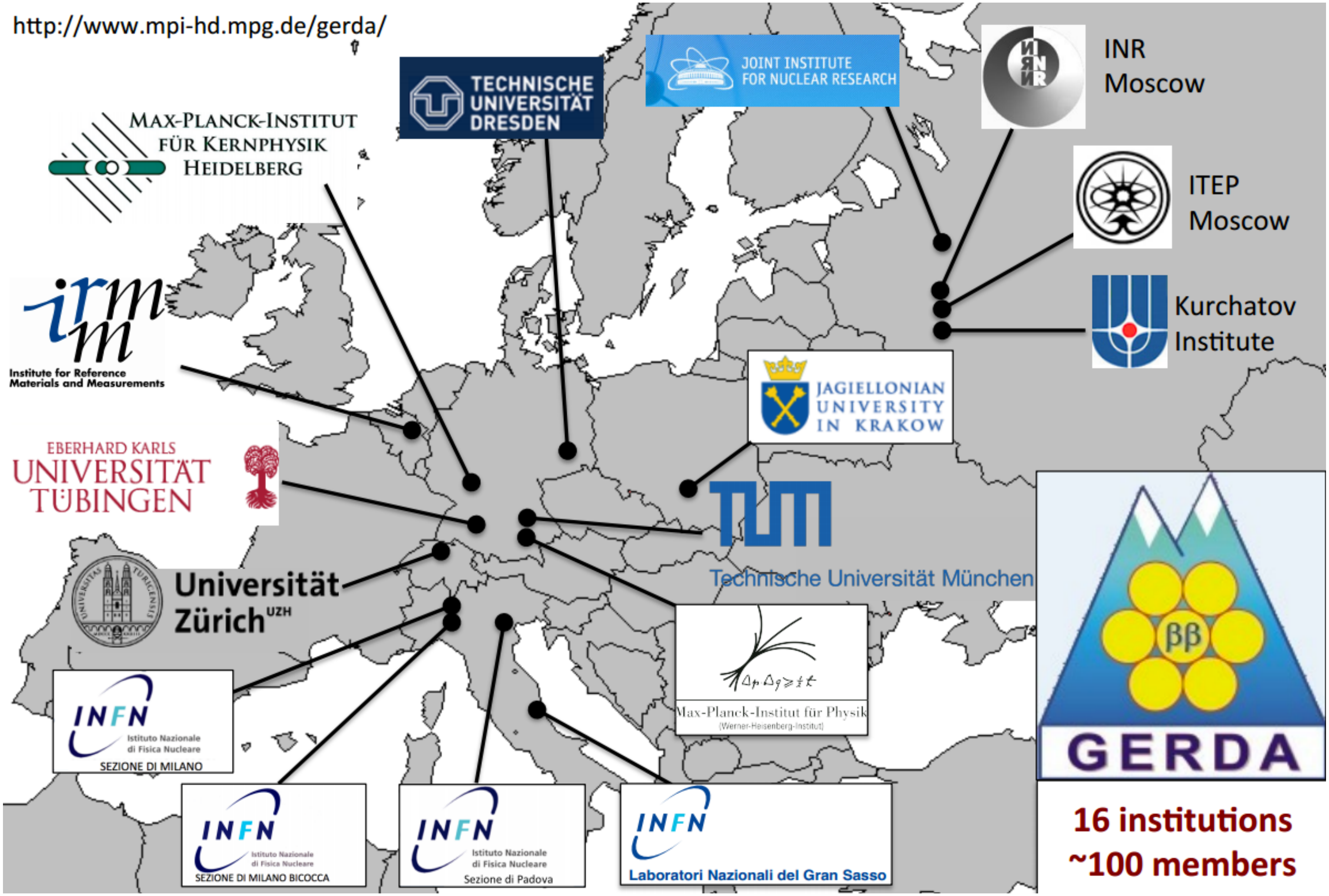
- Module 1 improvements
  - 6 more channels now online from Module 1
  - Improved charge trapping correction for energy
  - Improved multi-site and alpha discrimination

- Module 2 deployed Summer 2016
  - Data taking commenced mid-August
  - Backgrounds under study

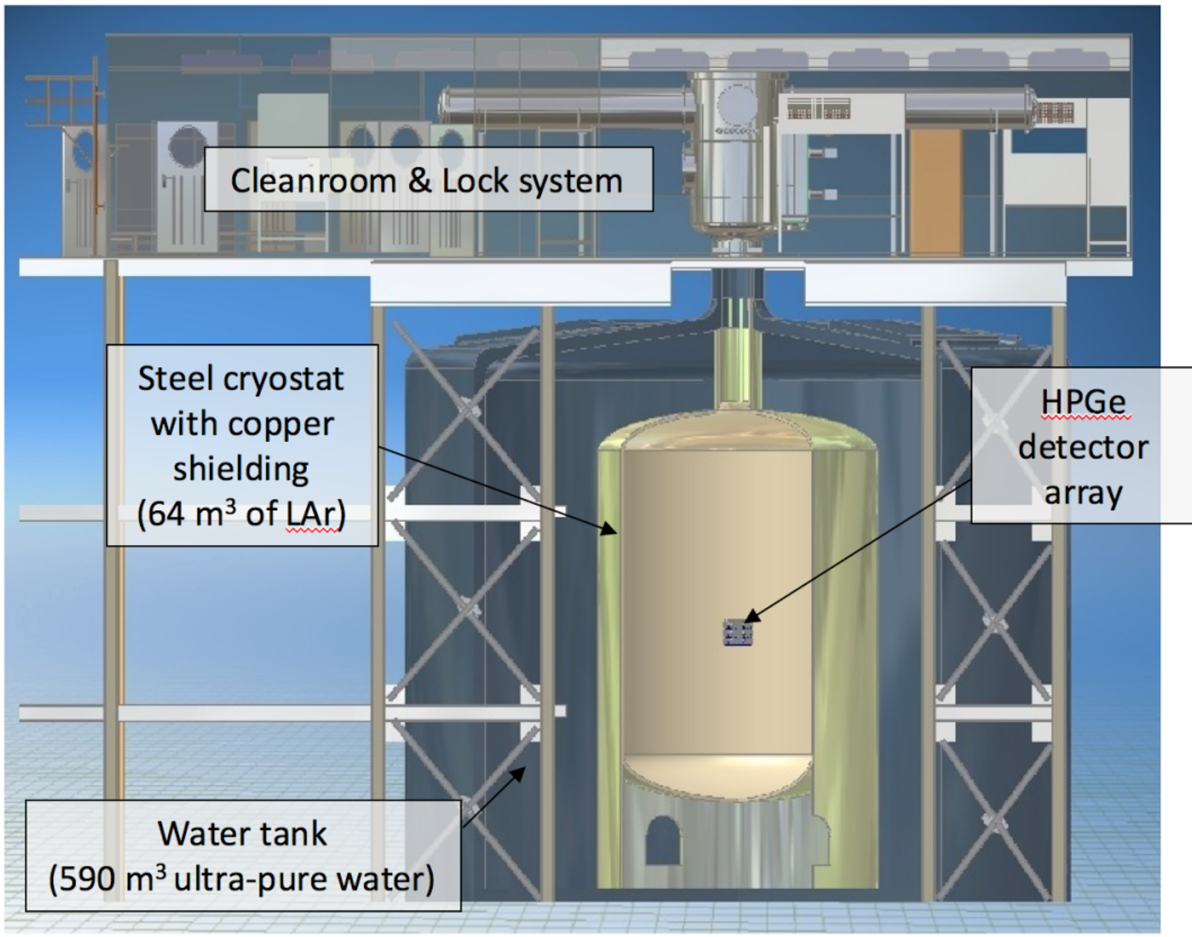
- DAQ upgrade planned for Fall 2016
  - Merge Module 1 and Module 2 DAQs
  - New digitizer firmware for improved performance, especially for triggering at low energies

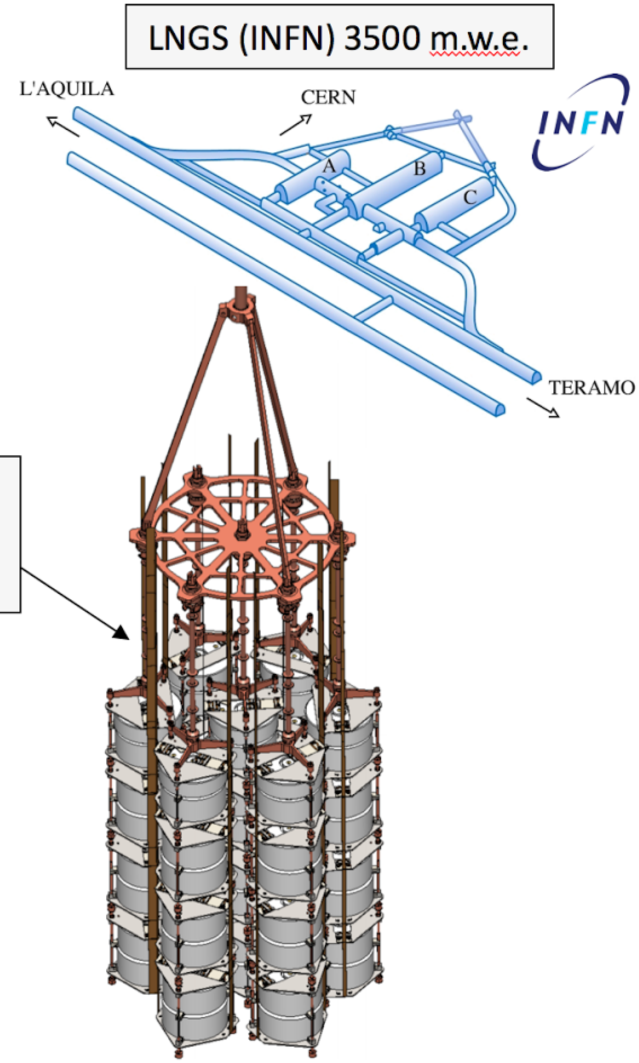
- Possible upgrade Summer 2017
  - Cables and connectors upgrade
  - Potential hot spot mitigation: component swap or improved shielding

The GERDA Collaboration

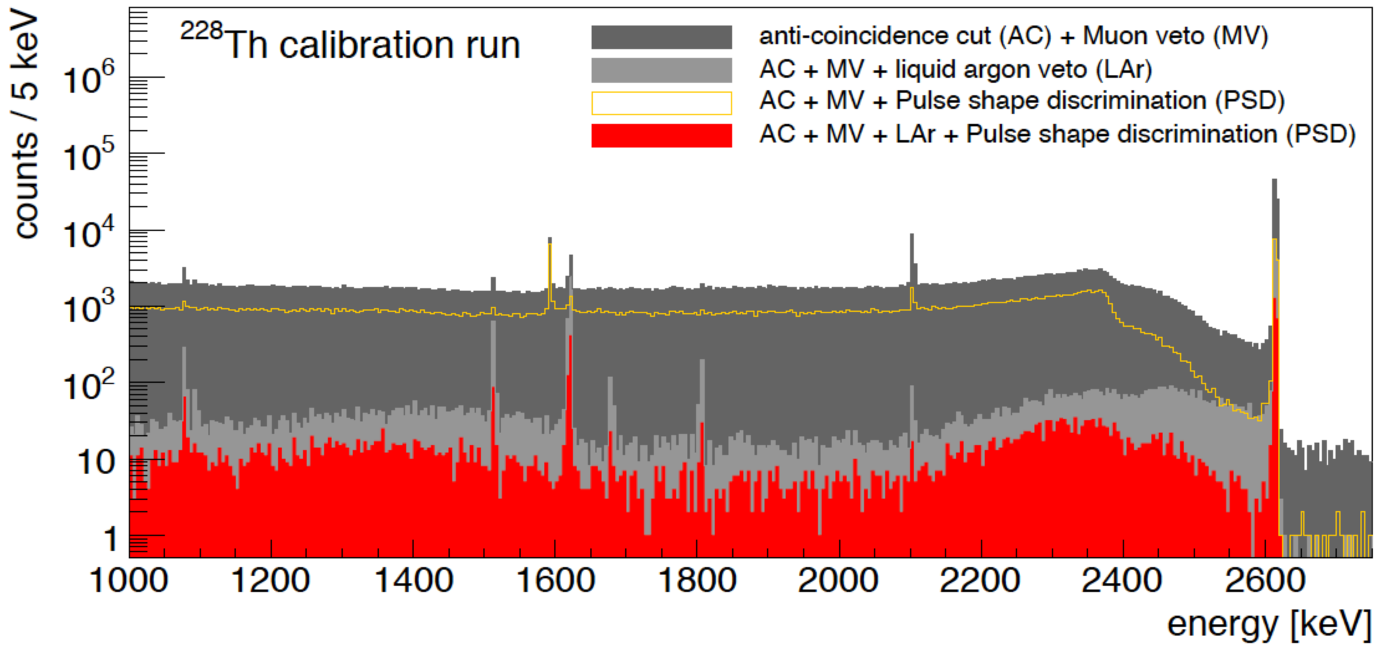


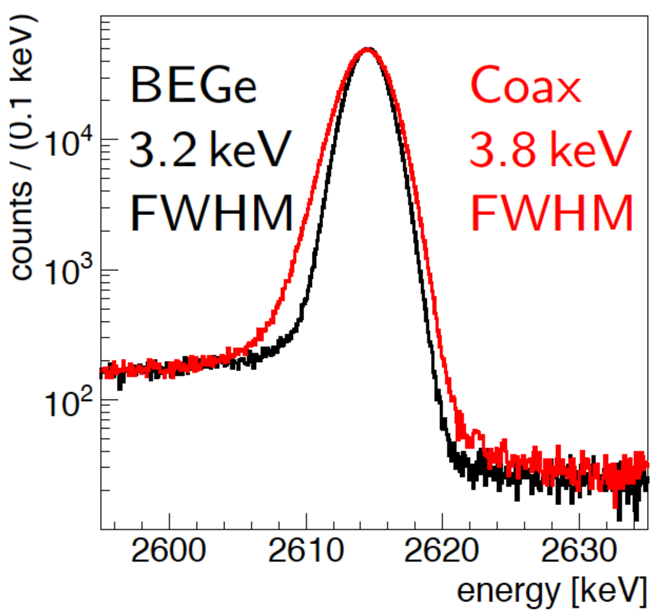
GERDA Configuration

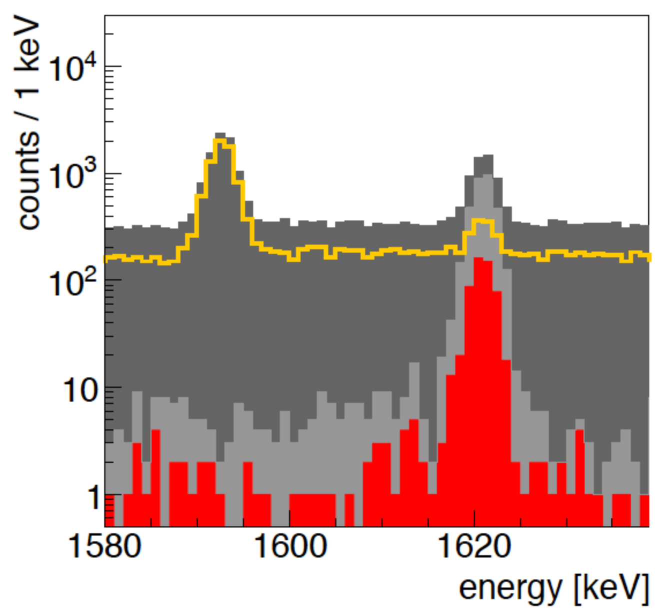




Detector Performance







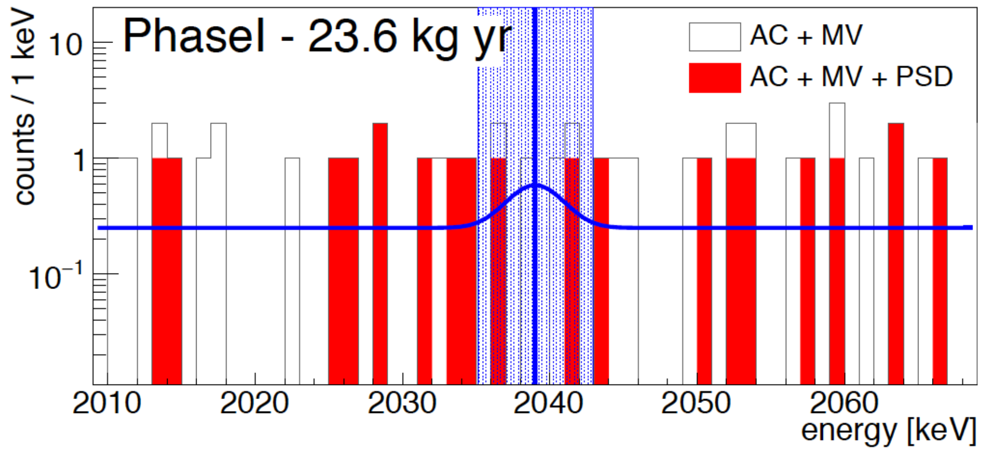
Direct immersion and active rejection work beautifully!

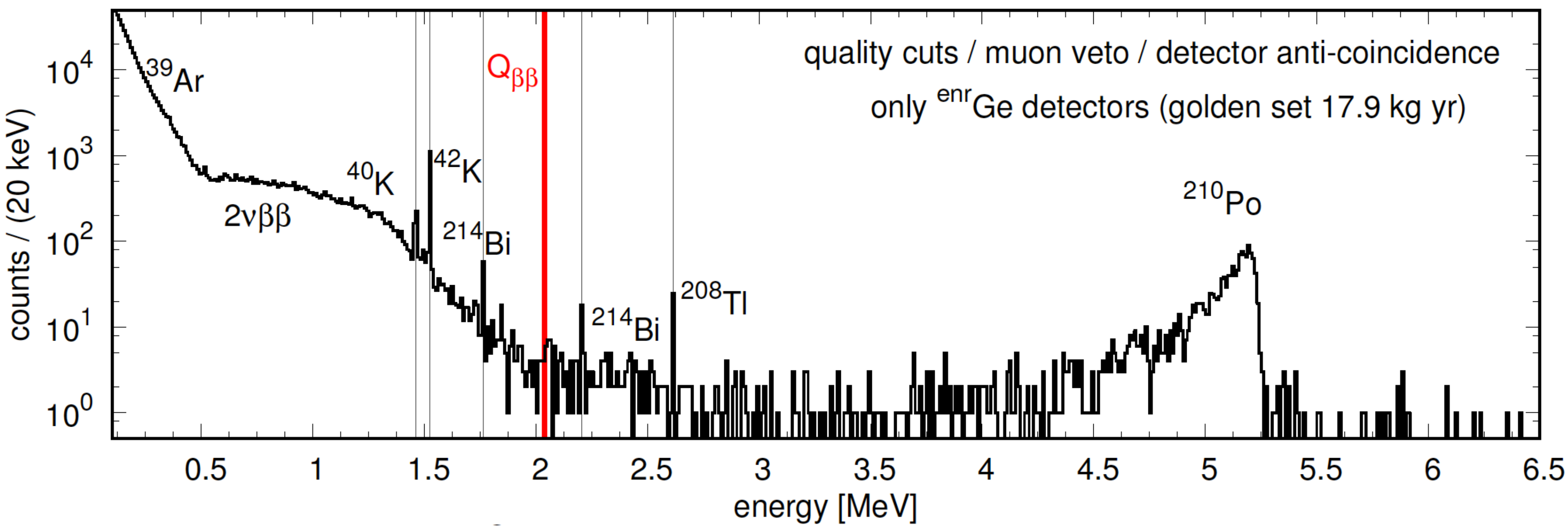
GERDA Phase I

Mostly refurbished coaxial detectors from previous-generation experiments, no LAr active veto

Analysis cuts:

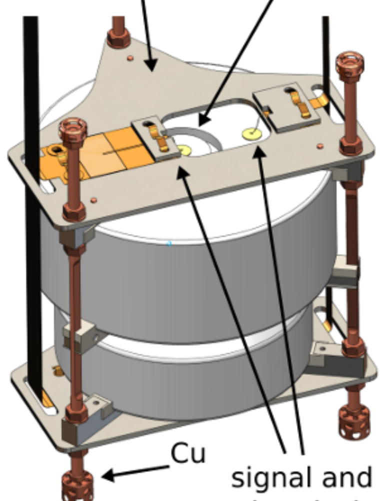
- Anti-coincidence (AC)
- Muon veto (MV)
- Pulse-shape discrimination (PSD)



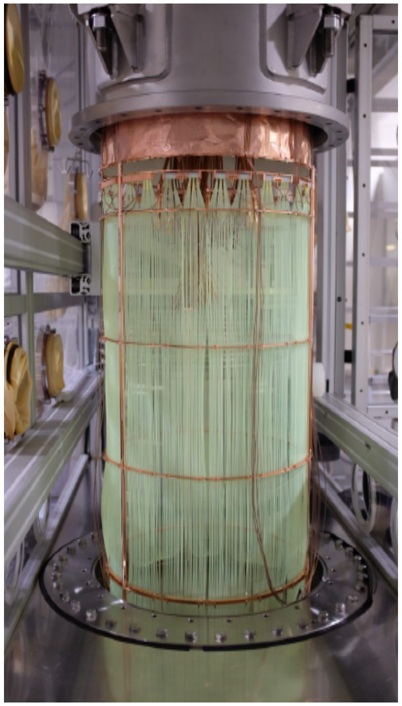


Phase II Upgrades

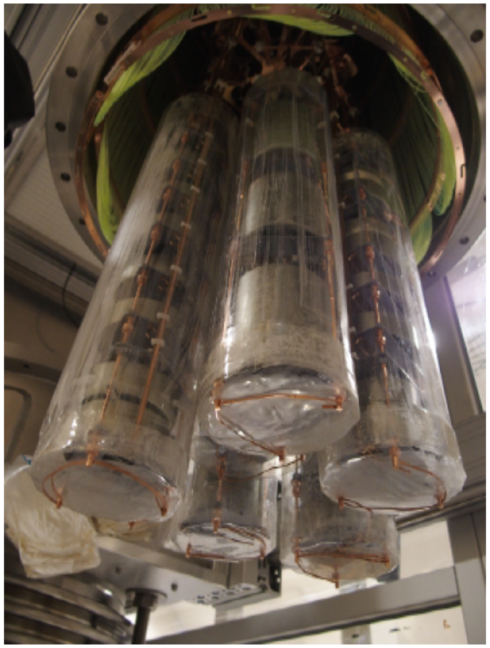
Double the mass with BEGe's (PPCs), lower-BG mounts



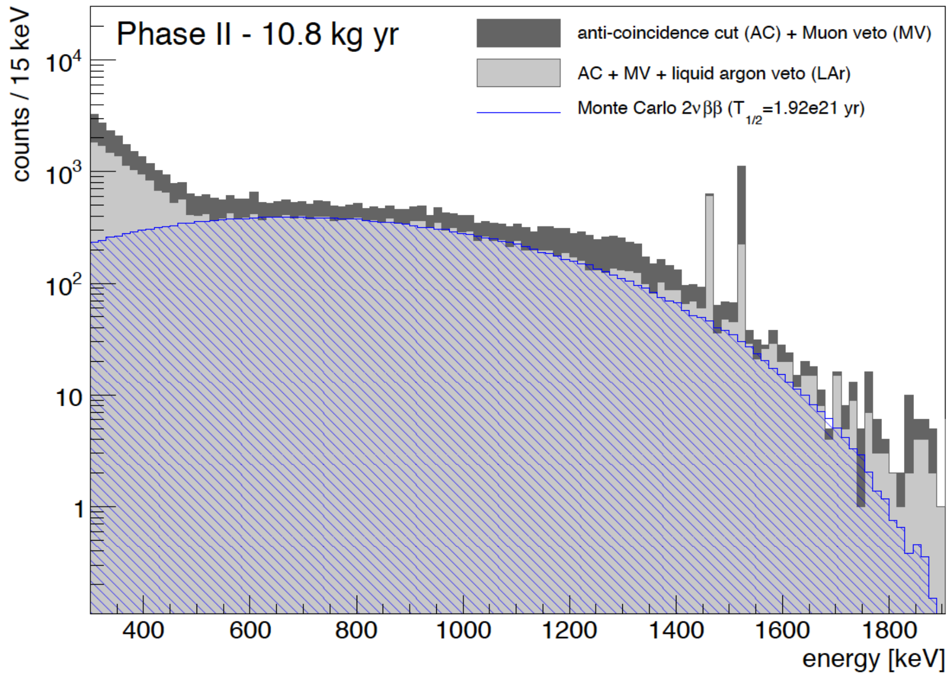
Instrument the LAr veto with SiPM's plus WLS fibers



Enshroud strings in WLS nylon



Phase II Background Performance

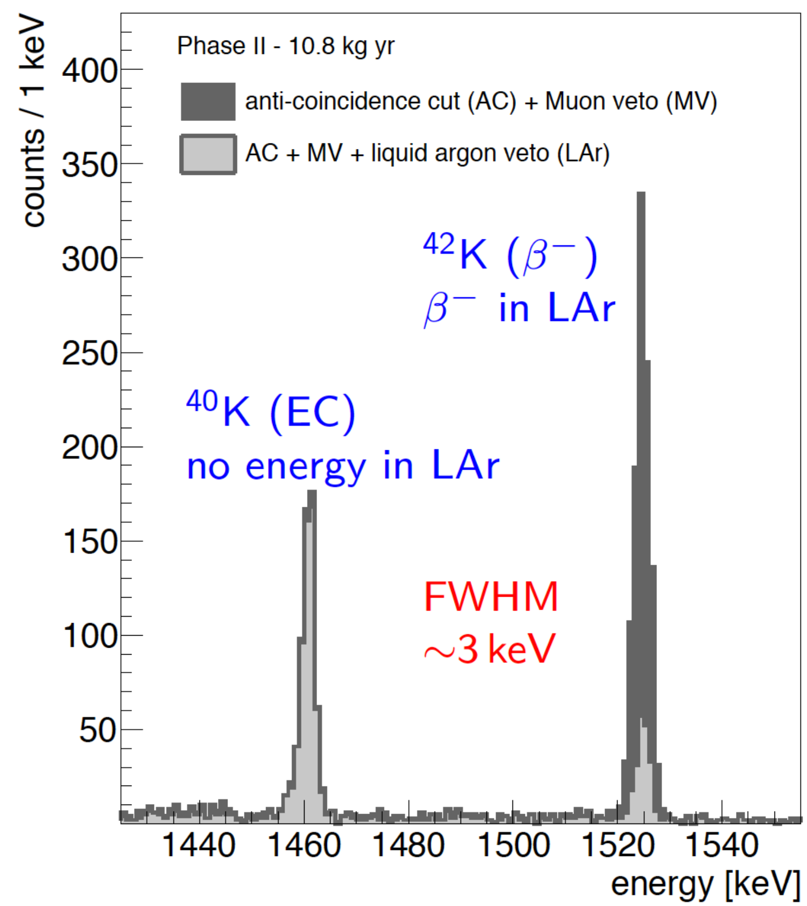


- ^{40}K/^{42}K Compton continuum fully suppressed
- (70.4±0.3)% survival fraction (0.6-1.3 MeV)
- LAr veto generates 2.3% dead time
- $T^{2\nu}_{1/2} = 1.9 \cdot 10^{21}$ yr taken from Phase I [EPJC 75 (2015) 416]

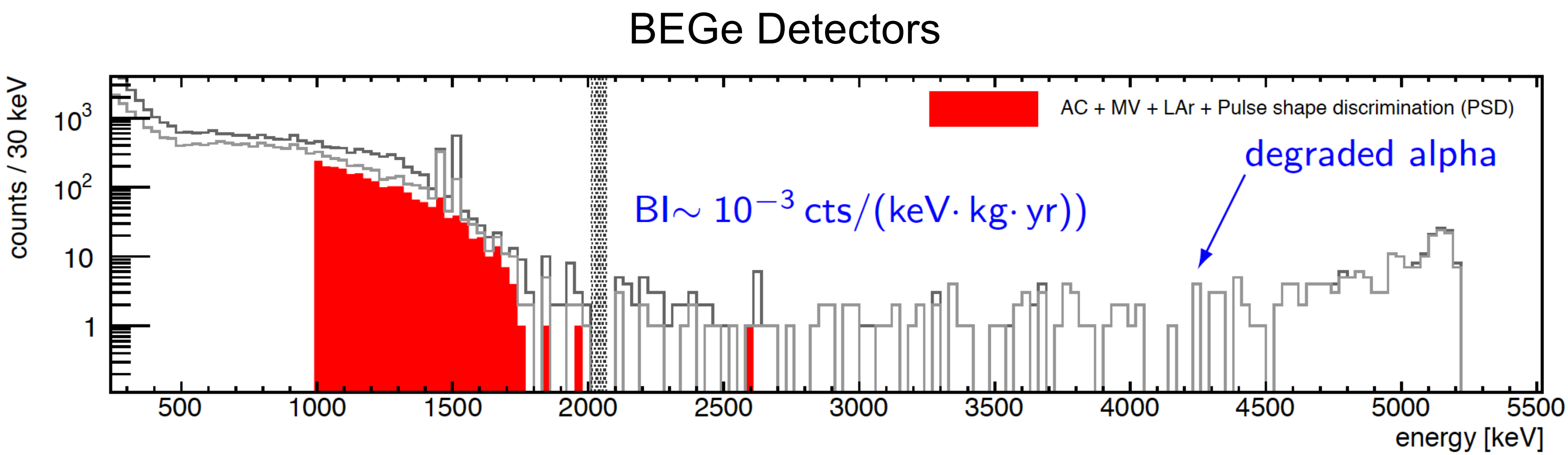
γ-lines from:

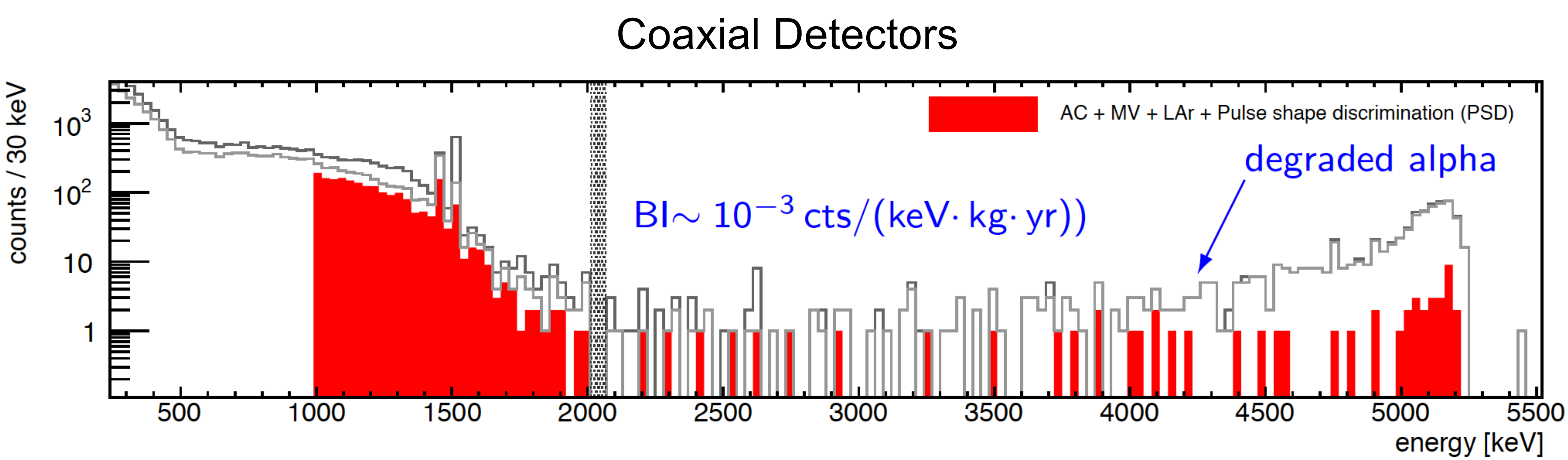
$$^{40}\mathrm{K} \rightarrow {}^{40}\mathrm{Ar} + \gamma\ (1.4\,\mathrm{MeV})\ [\mathrm{EC}]$$

$$^{42}\mathrm{K} \rightarrow {}^{42}\mathrm{Ca} + \gamma\ (1.5\,\mathrm{MeV}) + e^-\ (\text{up to } 2\,\mathrm{MeV})$$

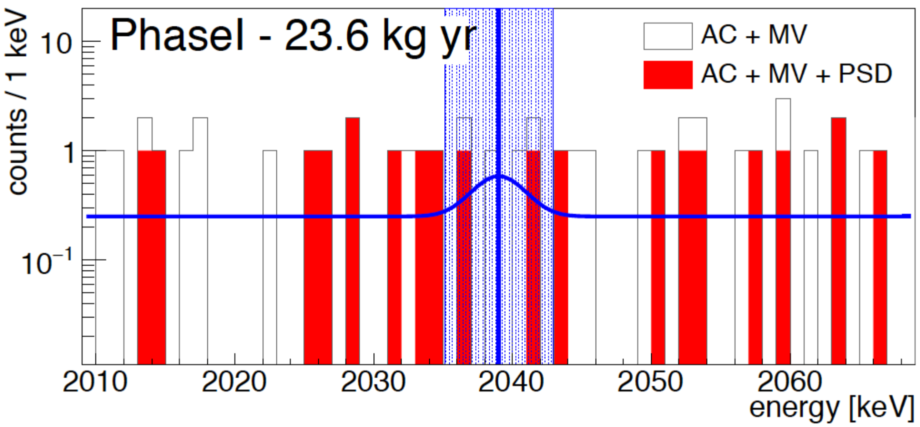


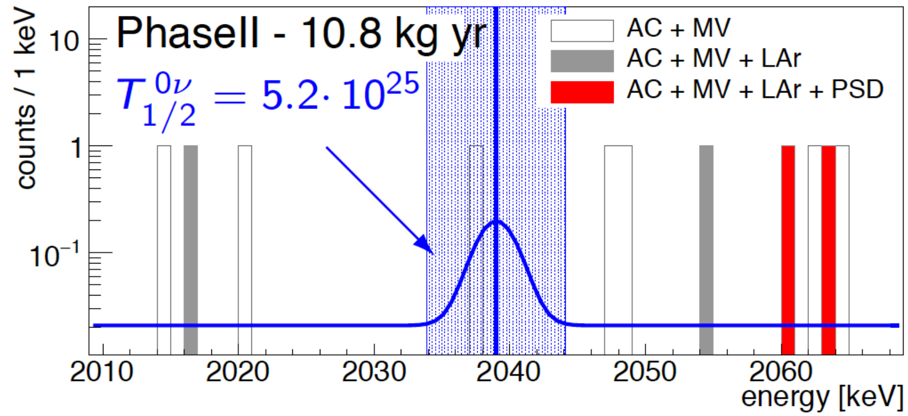
Phase II Background Performance





Phase I + II Results



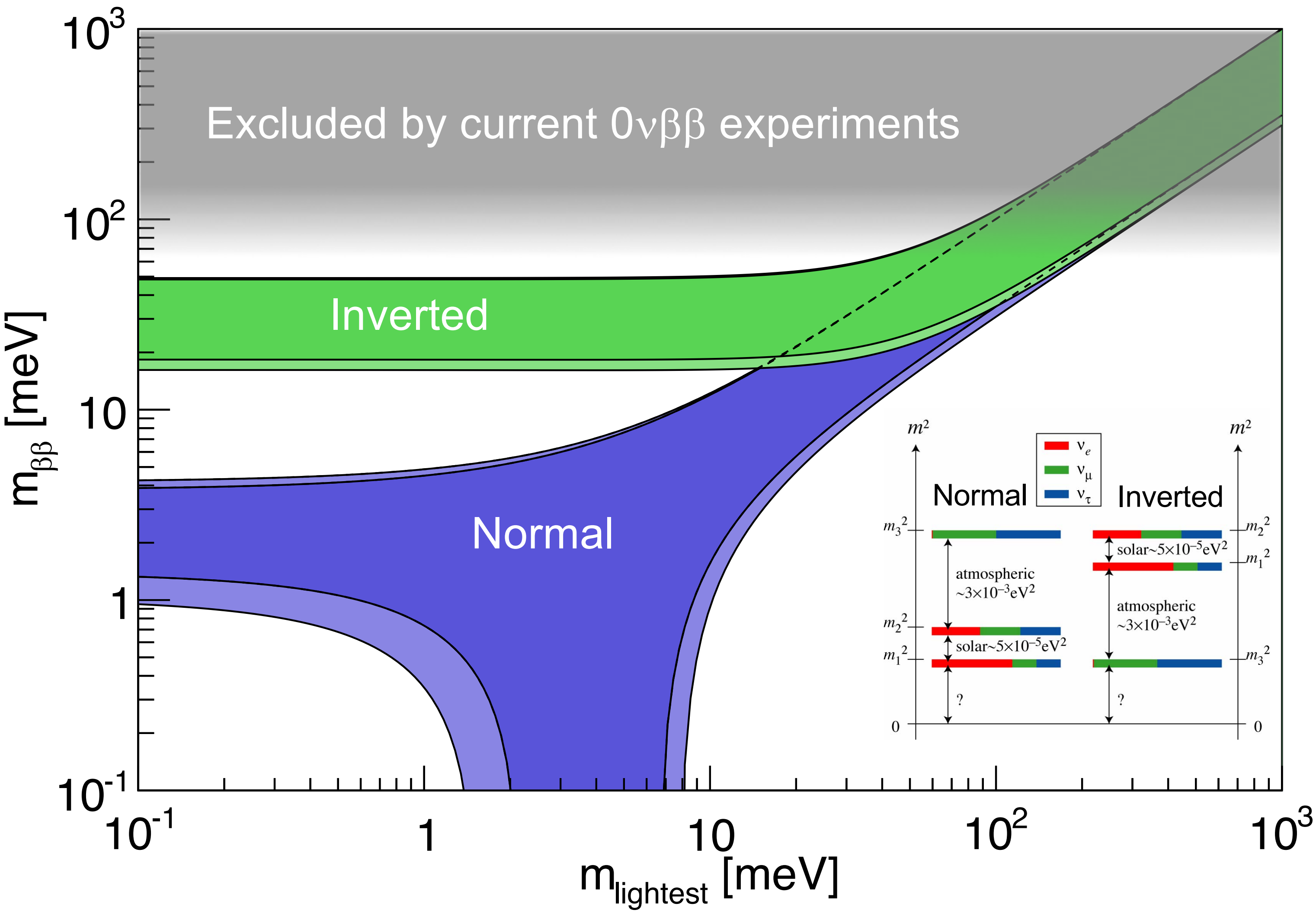


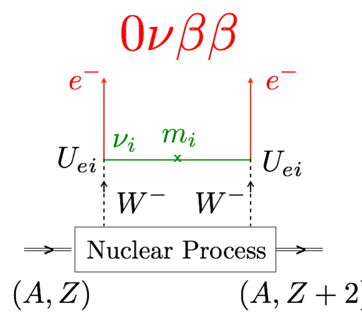
	profile likelihood 2-side test-stat	Bayesian flat prior on cts
$0\nu\beta\beta$ cts best fit value [cts]	0	0
$T^{0\nu}_{1/2}$ lower limit [10^{25} yr]	$>$5.2 (90% CL)	$>$3.5 (90% CI)
$T^{0\nu}_{1/2}$ median sensitivity [10^{25} yr]	$>$4.0 (90% CL)	$>$3.0 (90% CI)

preliminary!

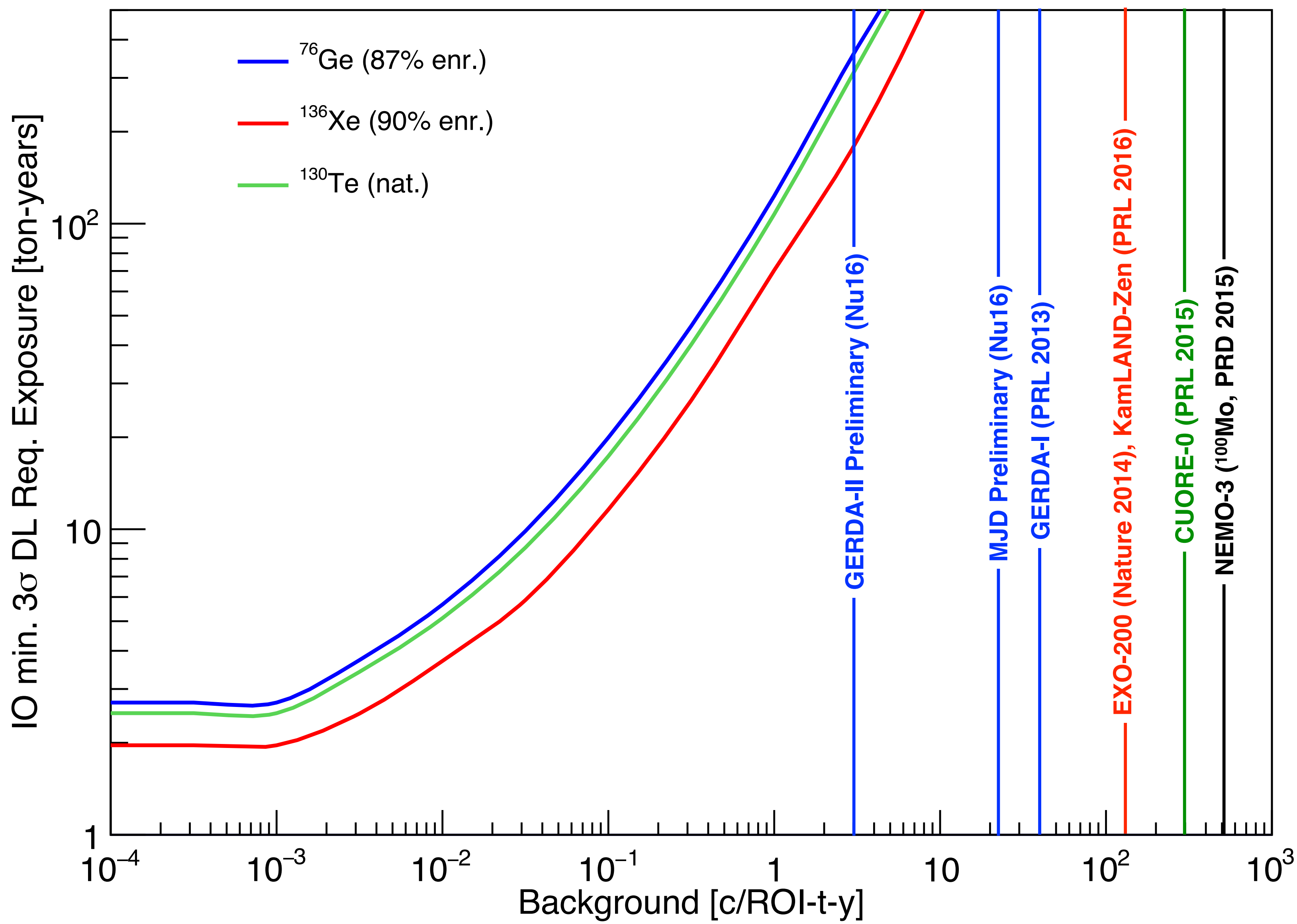
- unbinned profile likelihood: flat background (1930-2190 keV) + Gaussian signal
- frequentist test-statistics and methods *Cowan et al.*, EPJC 71 (2011) 1554
- ϵ^{PSD}_{coax} to be finalized

Light Neutrino Exchange





Required Exposure to Cover the IH



Next Generation ^{76}Ge Experiment

Working cooperatively with GERDA and other interested groups toward the establishment of a next-generation ^{76}Ge $0\nu\beta\beta$-decay experimental collaboration to build an experiment to explore the inverted ordering region of the effective mass.

Joint MAJORANA-GERDA Meeting
Nov. 2015 Kitty Hawk

Meeting of Interested Parties
April 2016 Munich

Next Meeting
End of Oct. Atlanta

Next Generation ^{76}Ge Experiment

Combine the best aspects of MAJORANA and GERDA:
Use ultra-low-background materials and an active veto

- Avoid 'inactive' material near detectors
  - measure all energy depositions
  - active veto
- Ge diodes, electroformed Cu, and plastics are clean enough
  - R&D for improved small components purity (electronics, cables, etc.)
- Muon-induced background is uncertain and a concern
  - low Z shielding
  - deeper site
- Improved α and ^{42}Ar background reduction (^{42}K β)
  - thicker passivated layer
  - active components
  - improved PSD
  - underground argon

Summary

- MAJORANA and GERDA are both up and running with their full arrays: combined mass >60 kg ^{enr}Ge
- ^{76}Ge experiments have demonstrated the lowest background of any isotope for $0\nu\beta\beta$ searches
- Covering the inverted hierarchy is in reach for a ton-scale apparatus – planning is underway