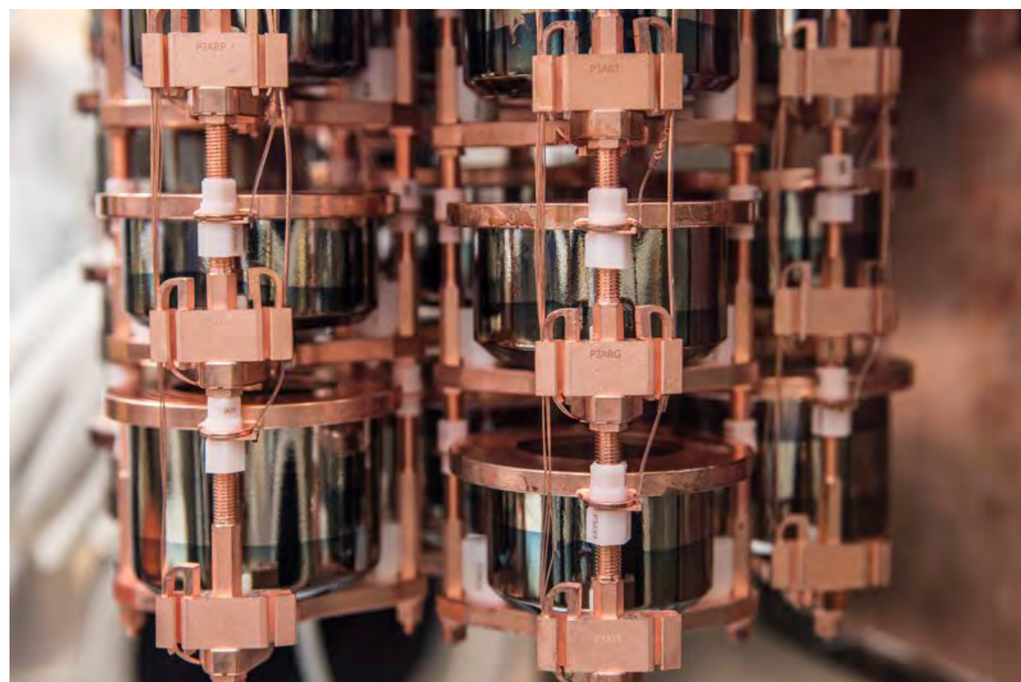
# Germanium detectors and neutrinoless double-beta decay: MAJORANA DEMONSTRATOR

**Ryan D. Martin**

**Symposium of the Sino-German GDT Cooperation**

**Ringberg Castle, October 2015**

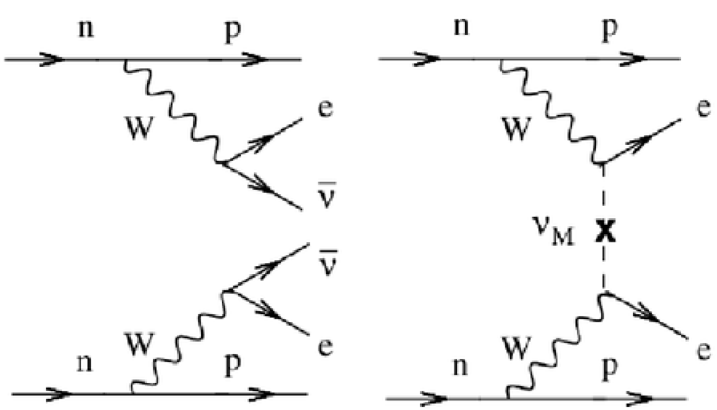


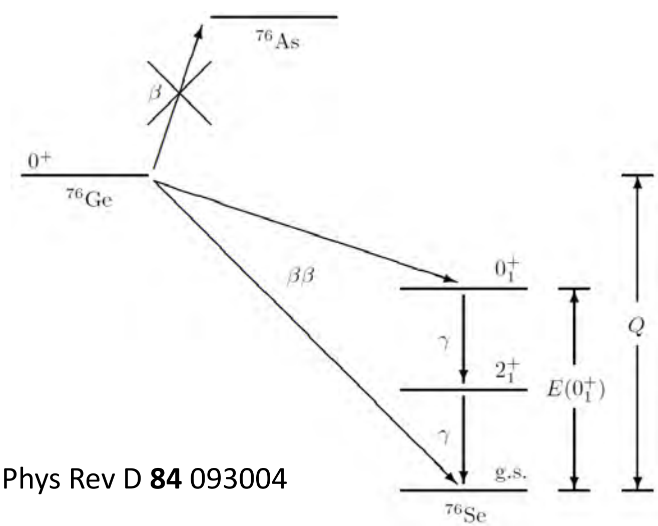
# Outline

- Neutrinoless double-beta decay in germanium
- The MAJORANA DEMONSTRATOR:
  - Electroformed copper
  - Shielding
  - Detectors
  - Projected backgrounds
  - Current status

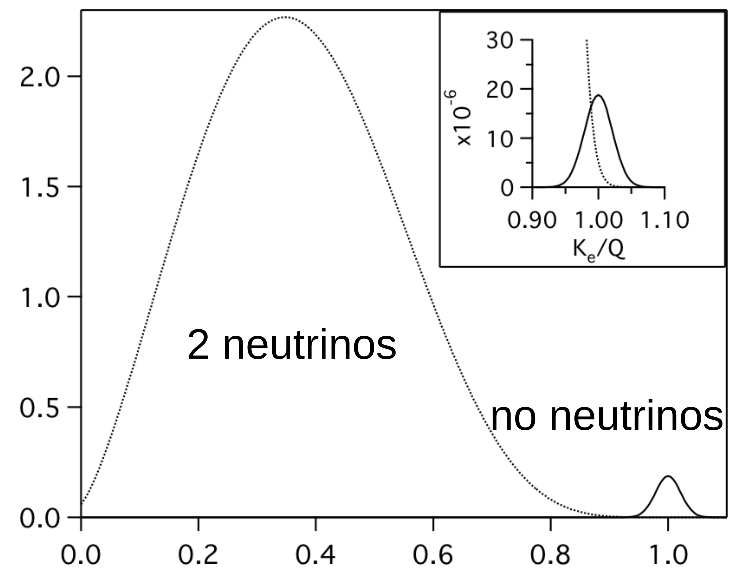
# Neutrinoless double-beta decay

- Beta decay is forbidden in certain isotopes, while double beta decay is allowed
- If neutrinos are Majorana, a fraction of those decays may be “neutrinoless”
- This is the only practical way to show that neutrinos are Majorana
- Experimental signature is a peak at the end of the energy spectrum of the emitted electrons




Phys Rev D **84** 093004



# Experimental searches for 0νββ

- Perform a "counting experiment":
  - *If no counts are seen, the half-life is at least as long as…*

$$T_{1/2}^{0\nu} = \left( G_{0\nu} |M_{0\nu}|^2 \left( \frac{m_{ee}}{m_e} \right)^2 \right)^{-1}$$

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

Sensitivity:

mass

live-time

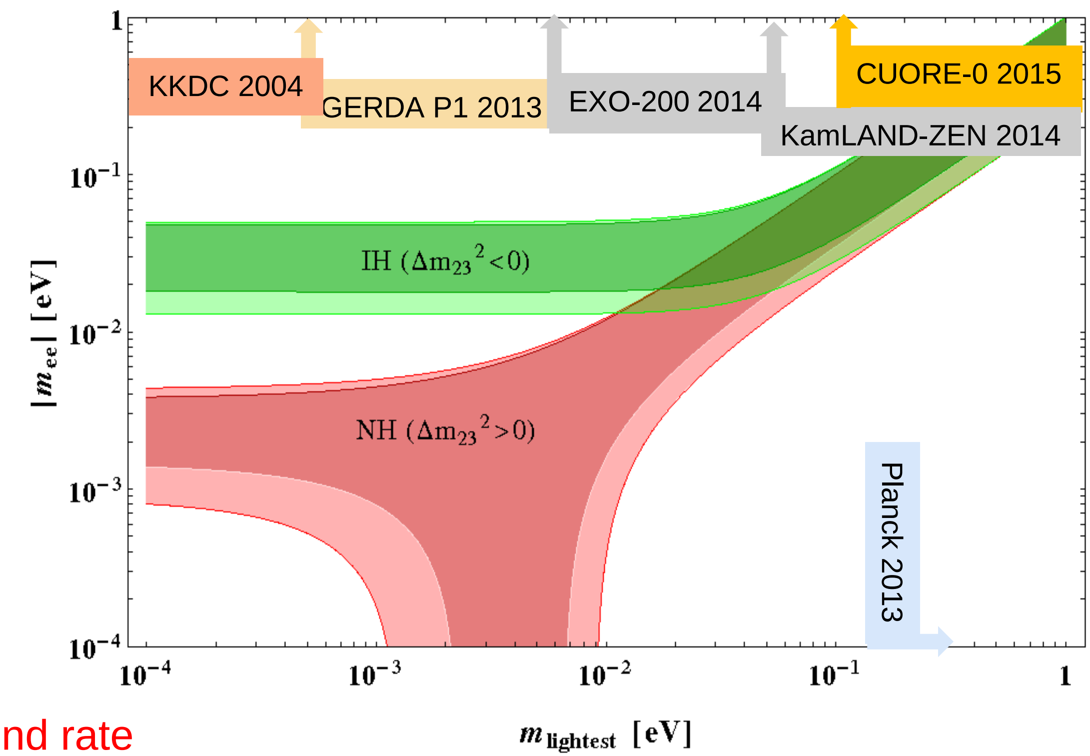
abundance

$$T_{1/2}^{0\nu} \propto a\epsilon \sqrt{\frac{Mt}{\sigma_E B}}$$

Detect eff.

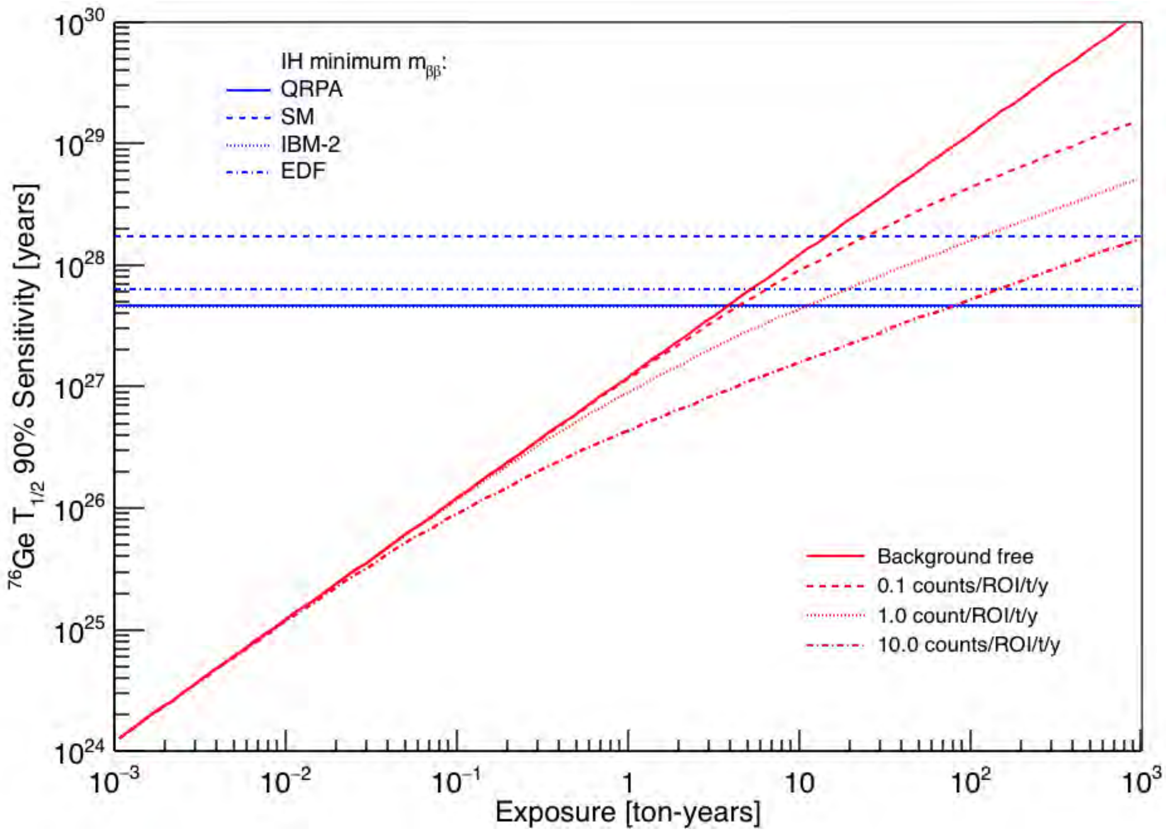
energy resolution

background rate



# Germanium sensitivity

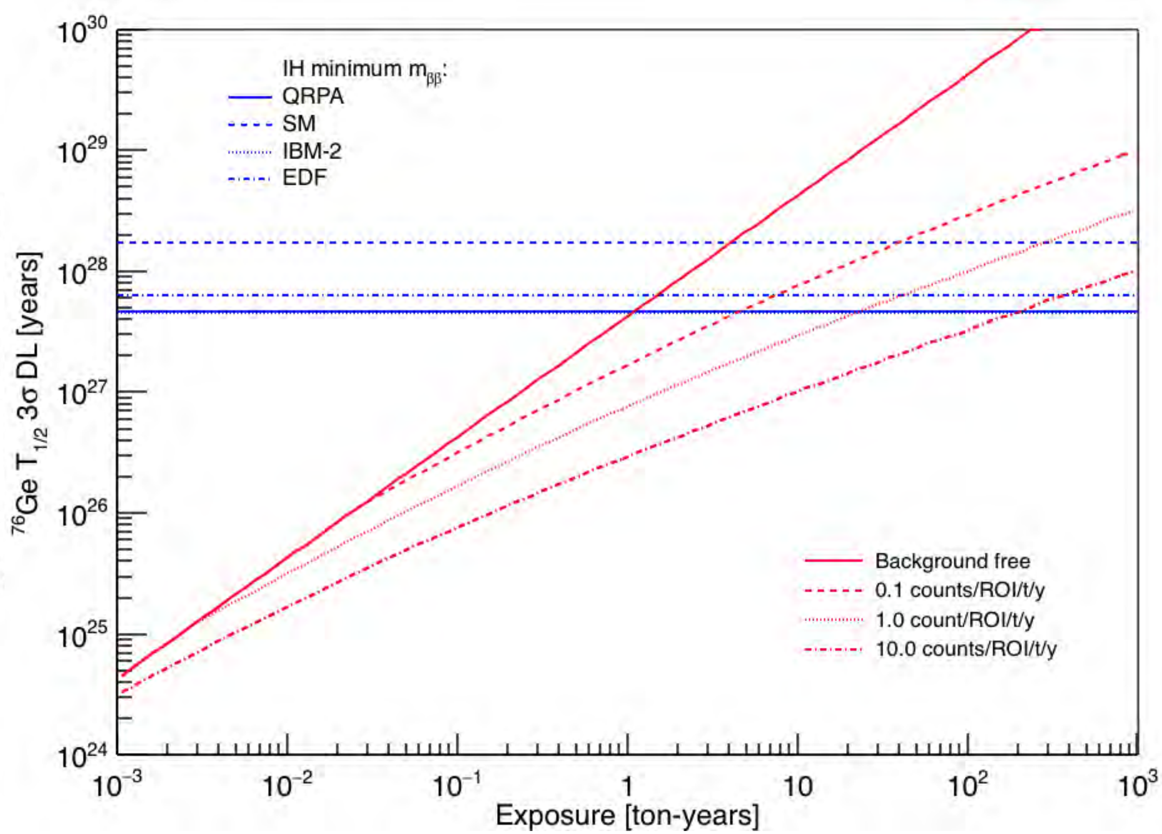
- $^{76}$Ge isotope for $0\nu\beta\beta$:
  - Q-value of 2039keV above most backgrounds
  - Can be enriched to >87% in $^{76}$Ge (nat. abundance ~ 8%)
  - Slow $2\nu\beta\beta$ rate ($10^{21}$ yr)
- Germanium detectors:
  - Source is detector (efficiency is high)
  - Good energy resolution
  - Well established technology
  - Intrinsically ultra-clean (high-purity germanium)




*Probing the inverted hierarchy requires exposures of tonne years for background rates of 1 count per tonne per year in the region of interest!*

# Germanium detection limit

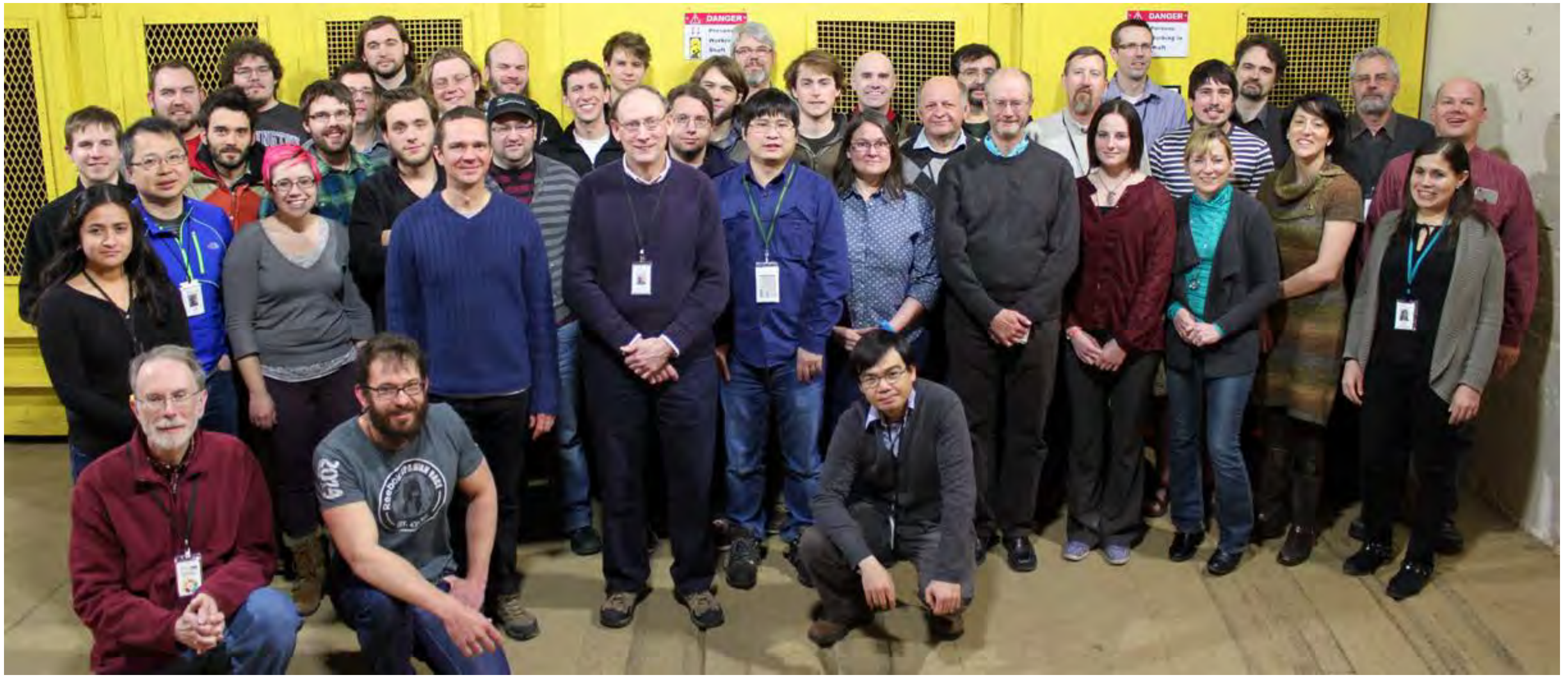
- $^{76}$Ge isotope for $0\nu\beta\beta$:
  - Q-value of 2039keV above most backgrounds
  - Can be enriched to >87% in $^{76}$Ge (nat. abundance ~ 8%)
  - Slow $2\nu\beta\beta$ rate ($10^{21}$ yr)
- Germanium detectors:
  - Source is detector (efficiency is high)
  - Good energy resolution
  - Well established technology
  - Intrinsically ultra-clean (high-purity germanium)




*Probing the inverted hierarchy requires exposures of tonne years for background rates of 1 count per tonne per year in the region of interest!*

# The MAJORANA collaboration

Queen's University



Black Hills State University

Duke University

ITEP

Joint Institute for Nuclear Research

Berkeley Lab

Los Alamos National Laboratory

Oak Ridge National Laboratory

TUNL

The University of North Carolina at Chapel Hill

University of South Carolina

Tennessee Tech University

NC State University

The University of Tennessee

Osaka University

Pacific Northwest National Laboratory

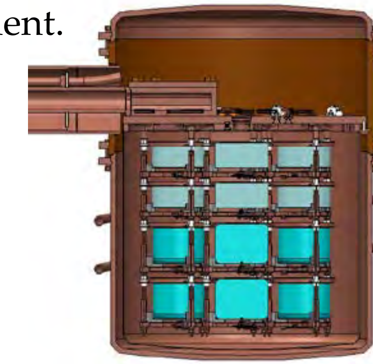
Queen's University

University of South Dakota

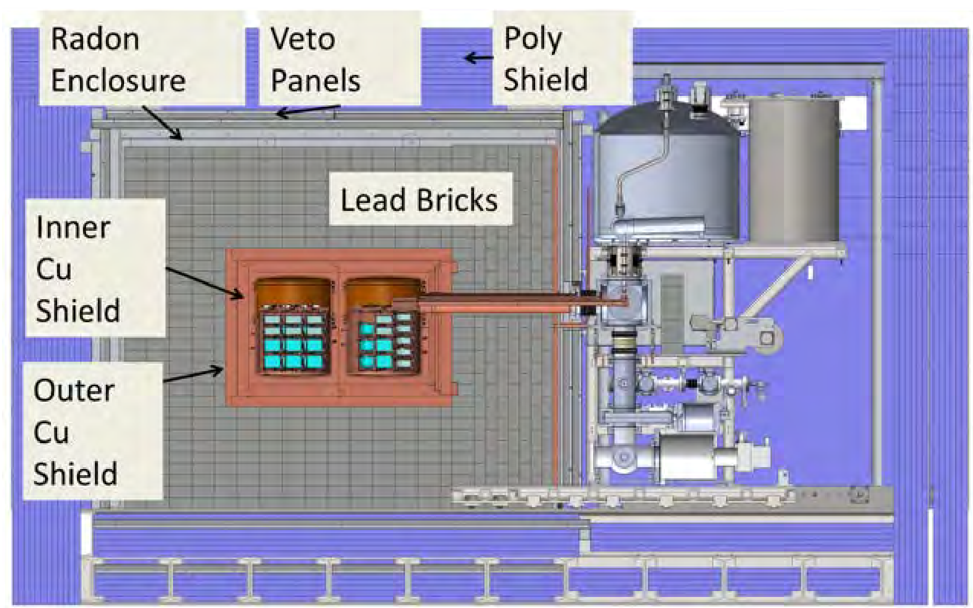
# The Majorana Demonstrator

Funded by DOE Office of Nuclear Physics and NSF Particle Astrophysics,
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-kg of Ge detectors
  - 29 kg of 87% enriched $^{76}$Ge crystals
  - 15 kg of $^{nat}$Ge
  - Detector Technology: P-type, point-contact.
- 2 independent cryostats
  - ultra-clean, electroformed Cu
  - 20 kg of detectors per cryostat
  - naturally scalable
- Compact Shield
  - low-background passive Cu and Pb shield with active muon veto



# MAJORANA DEMONSTRATOR implementation

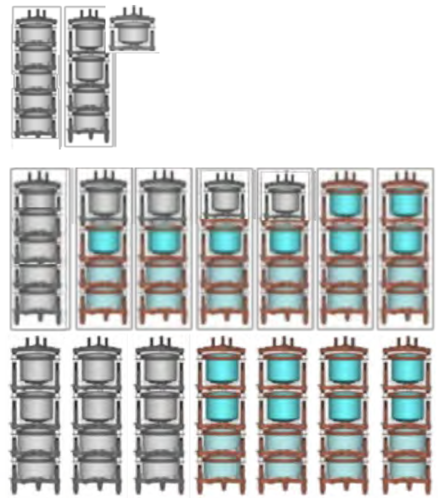
**Three Steps:**

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

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

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

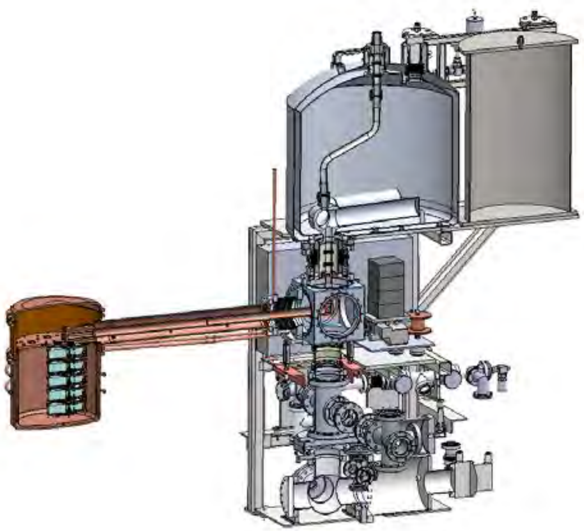
3) Module 2: **12.8 kg (14) $^{enr}$Ge**
**9.4 kg (15) $^{nat}$Ge**

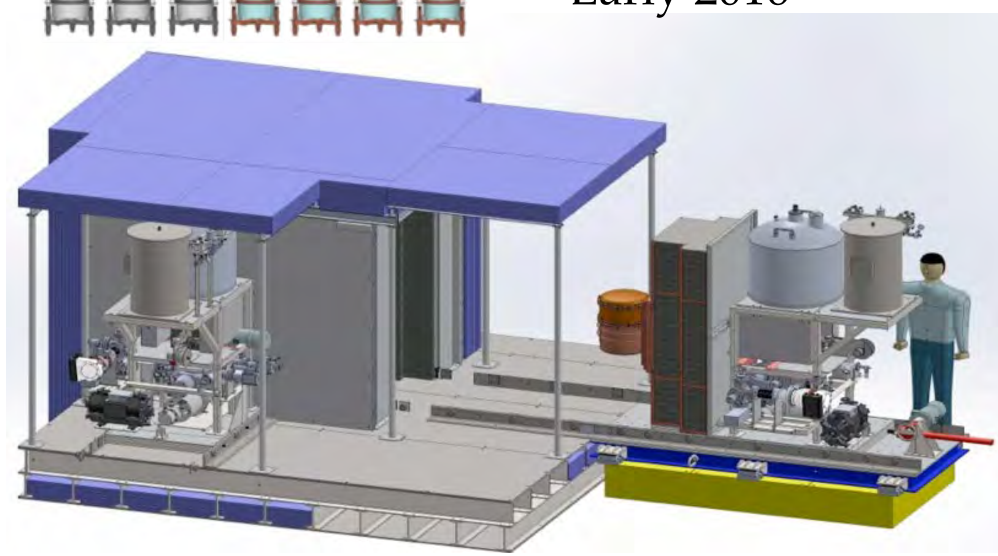


June 2014-
June 2015

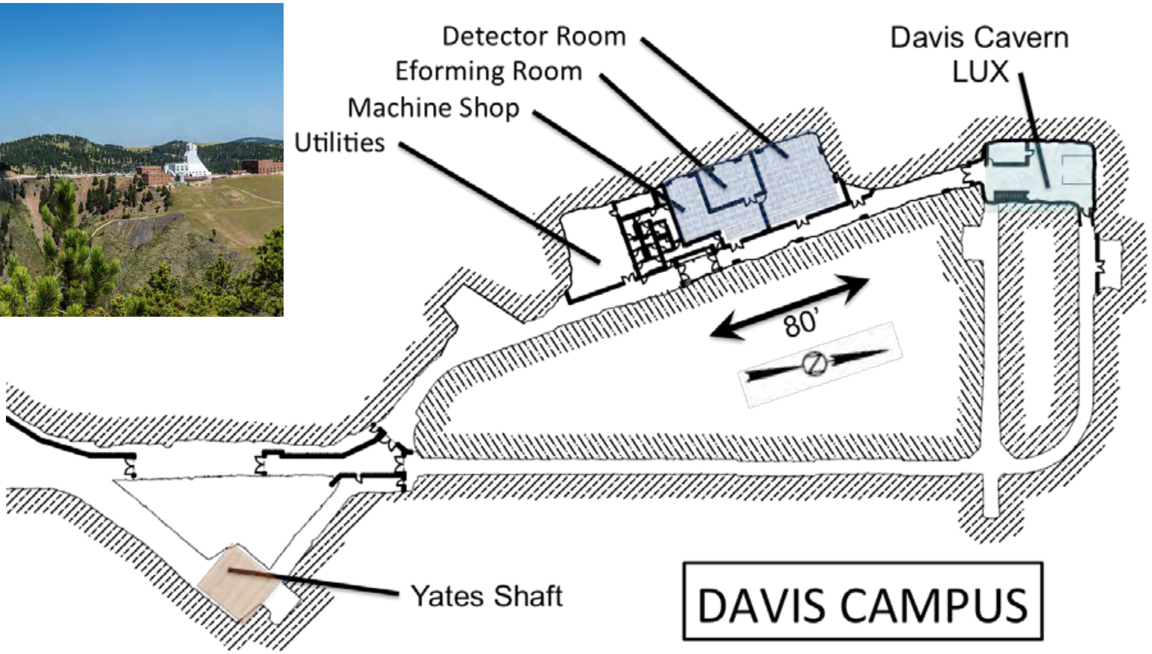
May 2015
Operating

Early 2016



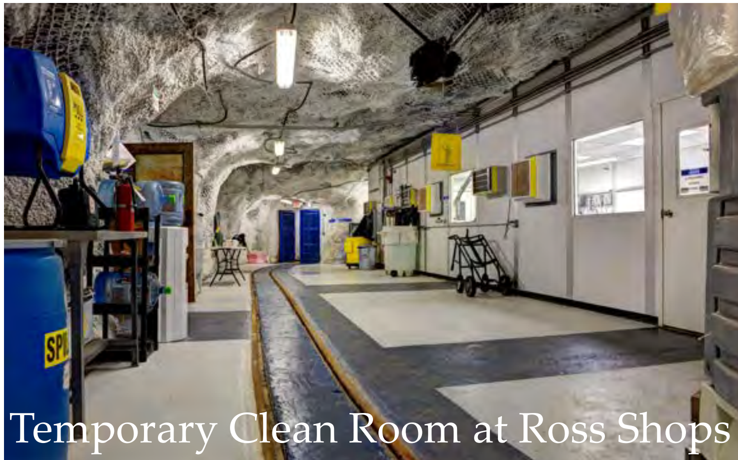


# Sanford Underground Research Facility




# Copper electroforming

- Eforming at PNNL and at 4850′ at SURF
- Eforming complete in May 2015
- Machine shop production continuing


Temporary Clean Room at Ross Shops


Installation of mandrel in bath


Copper ready to cut

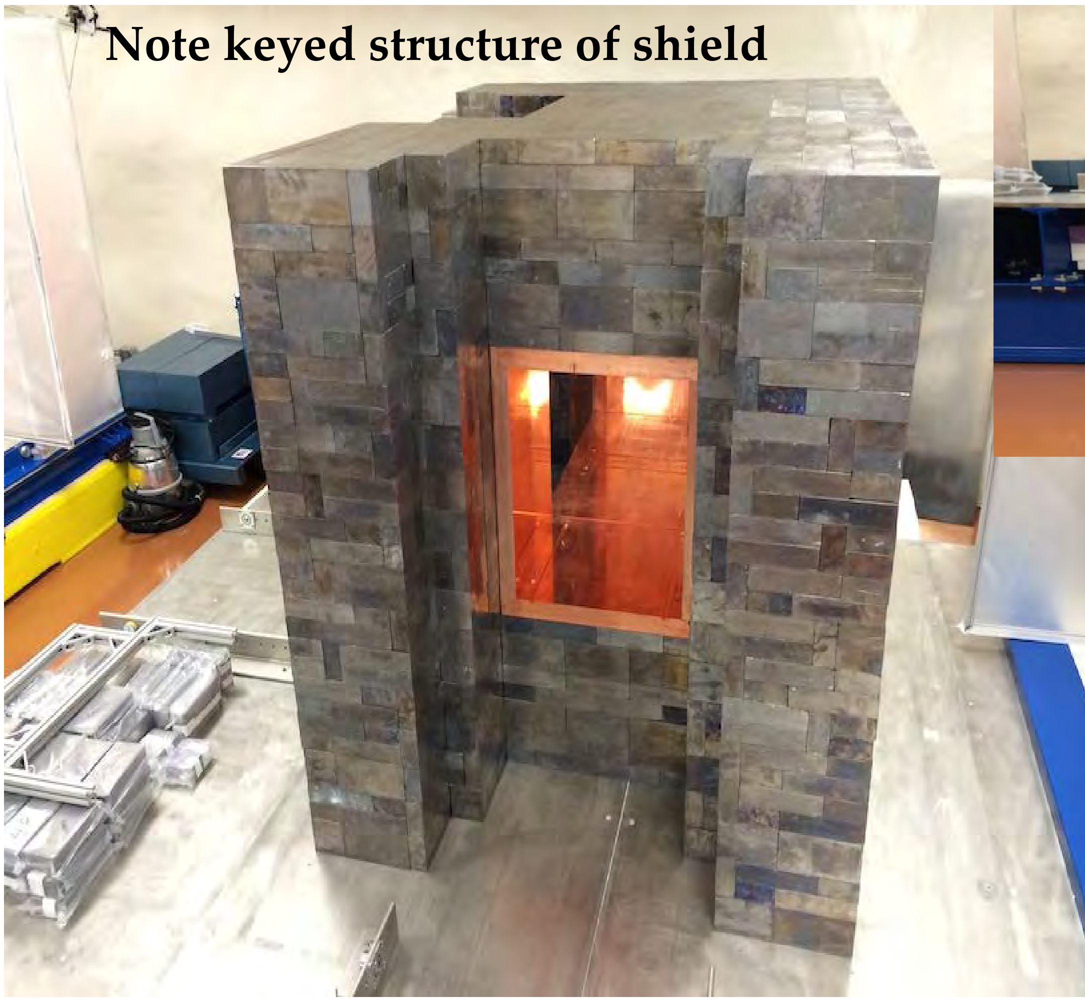

Flattened Plate

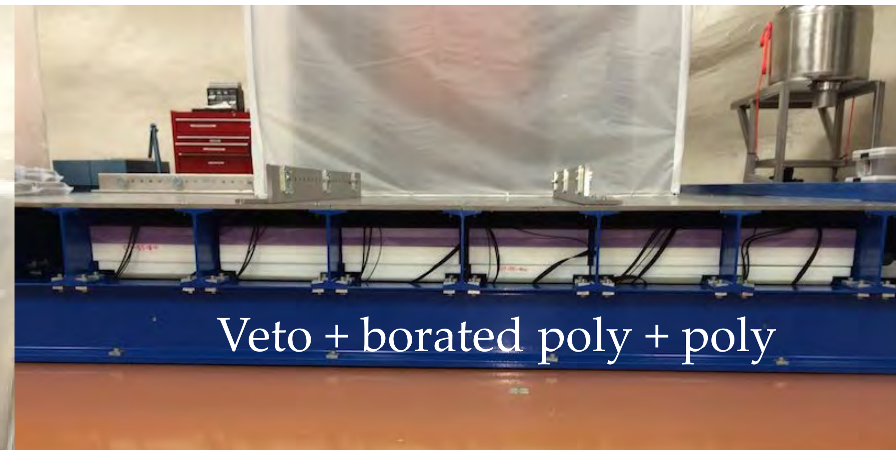

Bake/Quench


Lathe installed UG

# Electroformed parts stored in nitrogen

# Shield



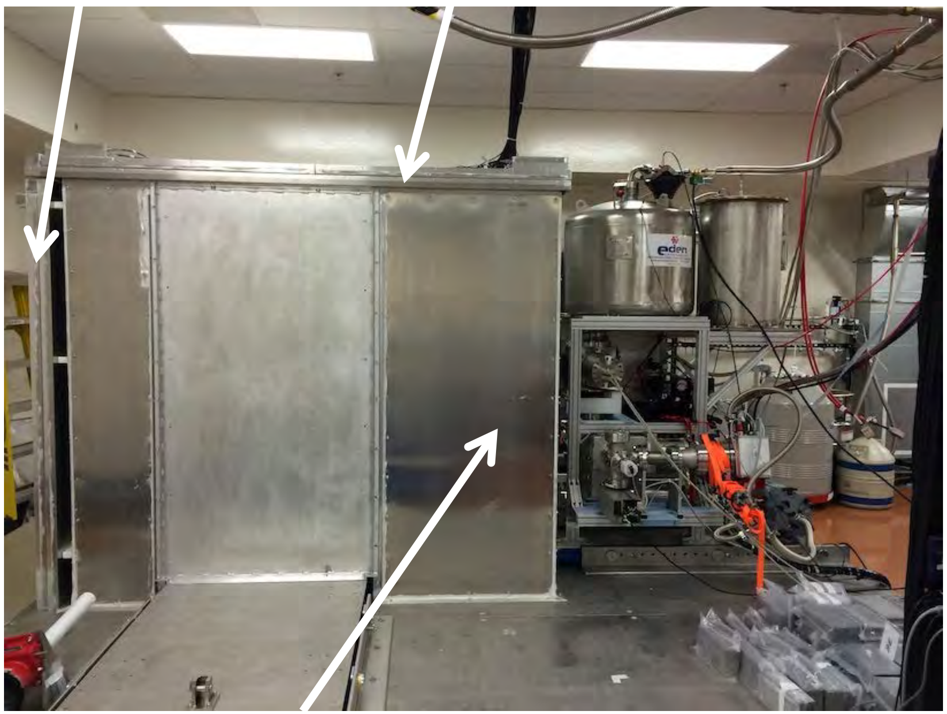




- Pb shield constructed
- Outer Cu shield layer installed
- Rn exclusion box installed
- Poly layers being installed
- Hovair in-use underground
- Veto panels operational
- Calibration system demonstrated

# Shield Details

Side Veto

Upper Veto



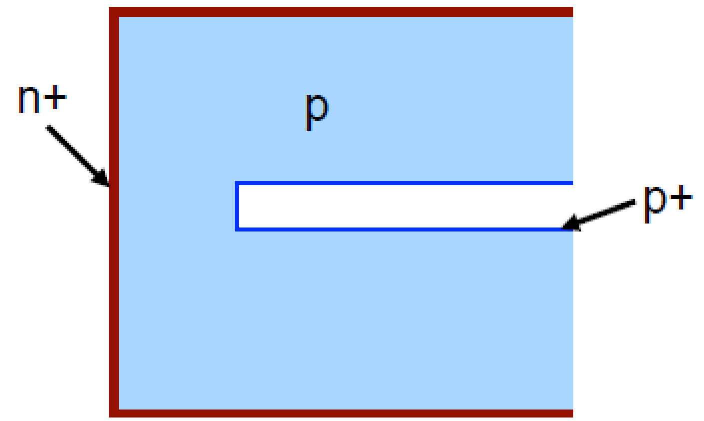
Panel of Rn exclusion box

Prototype Module Cryostat

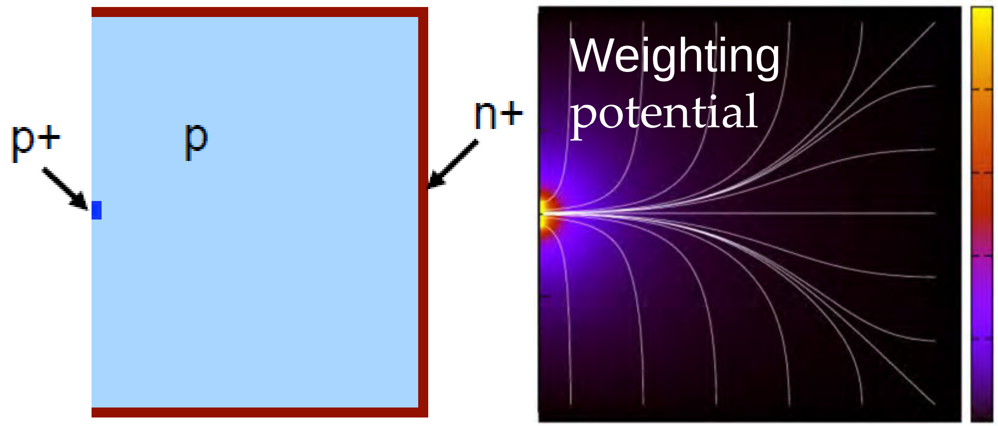
# Monolith

# PPC detectors

- P-type Point Contact HPGe
- Introduced by P.N. Luke in 1989 (n-type), popularized by Collar and Barbeau (~2008)
- Small point contact to readout charge, low capacitance, low noise
- Thick outer contact (n+, lithium diffused), strongly attenuates alphas
- Large variation in drift times across the detector volume

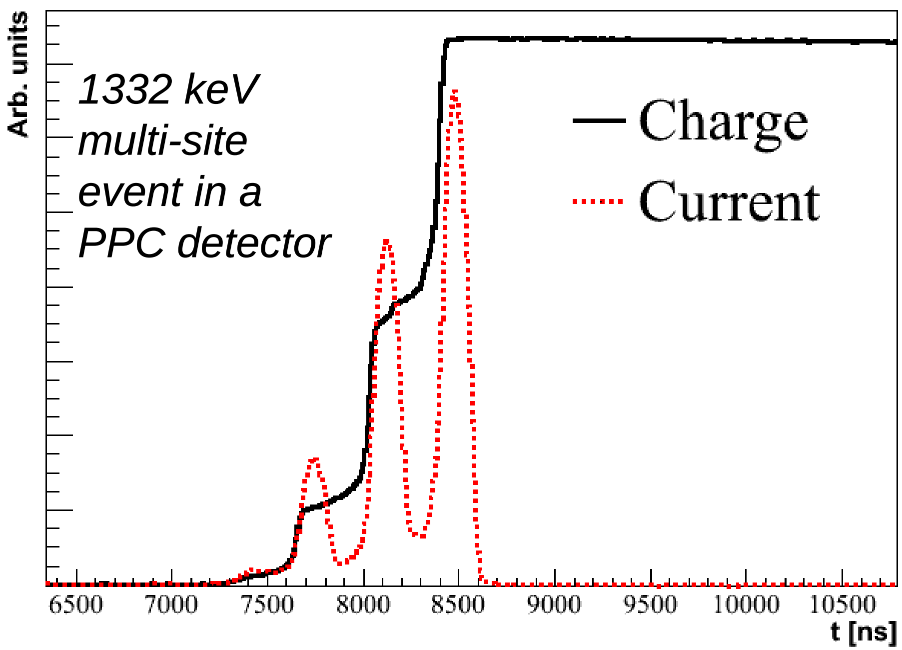



*Semi coaxial detector*

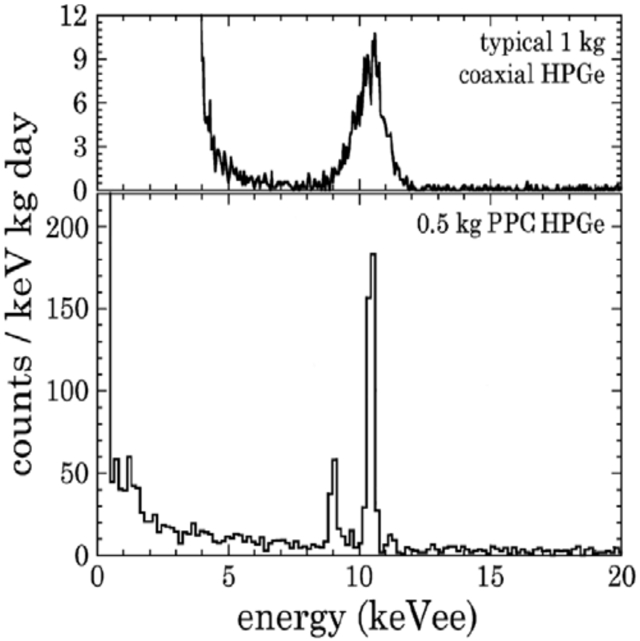



*Point contact detector*

# Properties of PPC detectors




PRL **101** 251301 (2008)

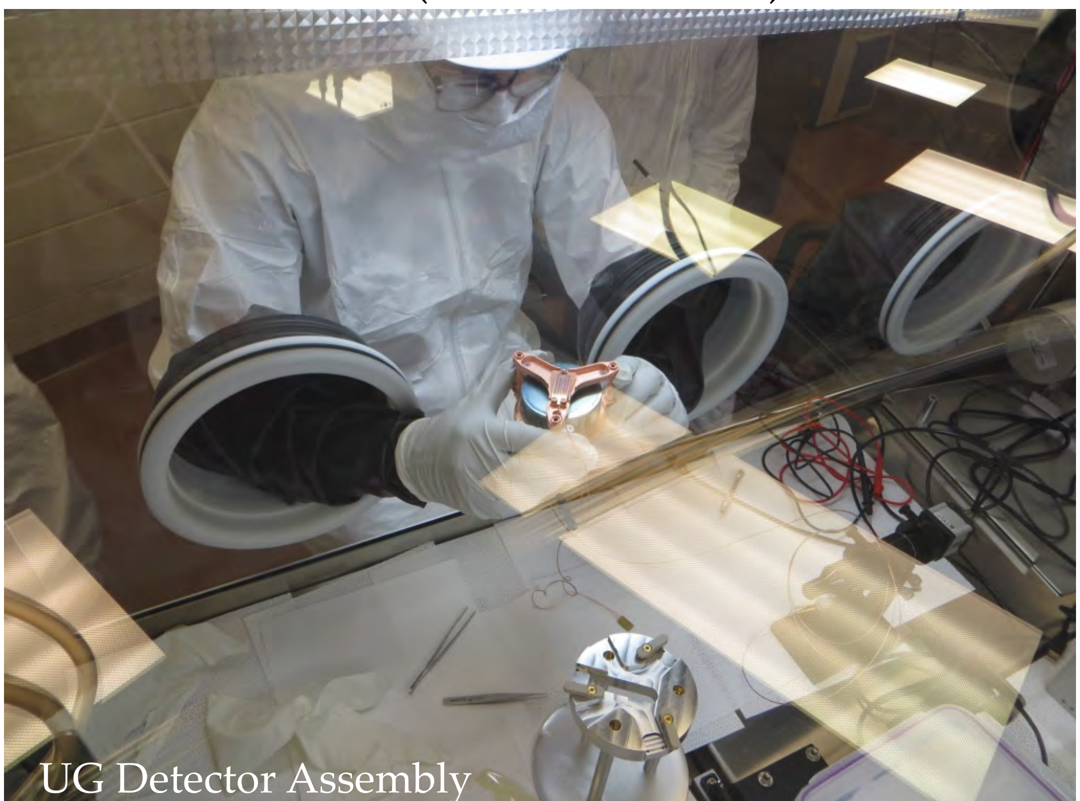



- Sharp weighting potential allows multi-site events to be identified
- Gamma rays at 2MeV typically scatter more than once

- Small capacitance results in low noise and excellent performance at low energies

# Detectors

- ORTEC selected for enriched detectors.
- 35 Enriched detectors at SURF 29.68 kg, 87% $^{76}$Ge
- 20 kg of modified natural-Ge BEGe (Canberra) detectors in hand (33 detectors UG).


UG Detector Assembly


Dimensional Measurement

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

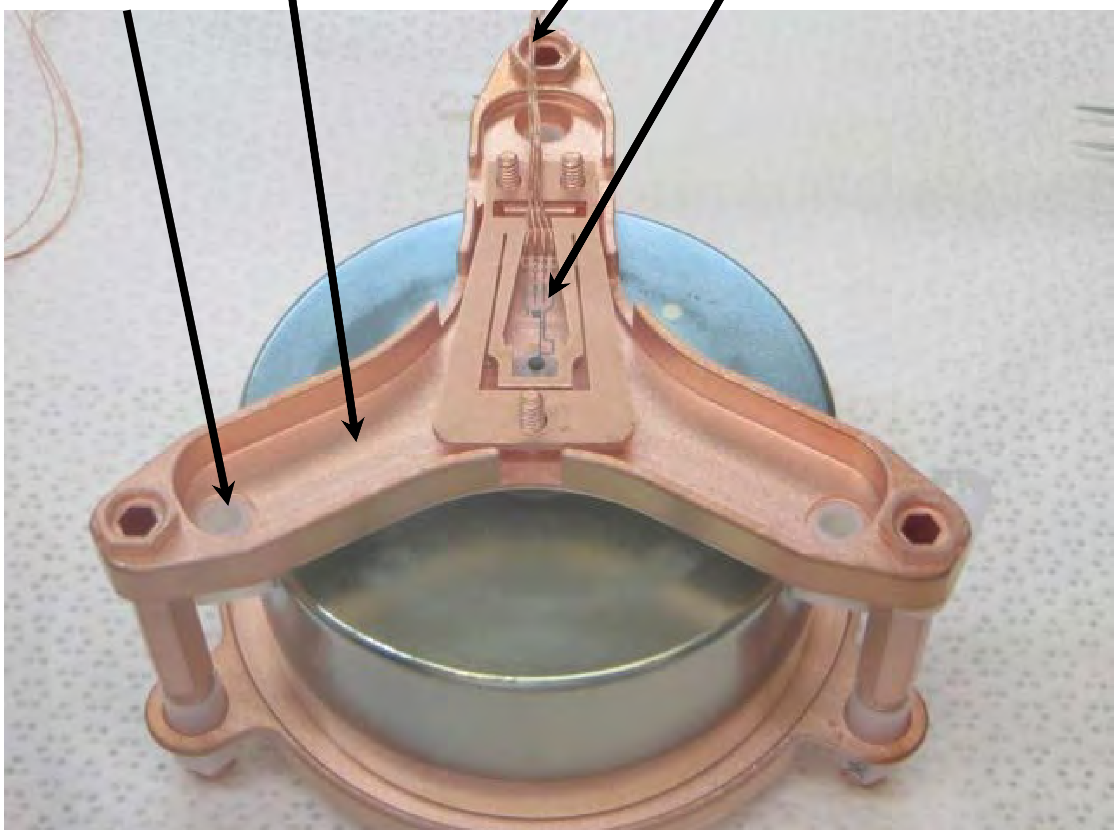
# Assembled detector unit and string

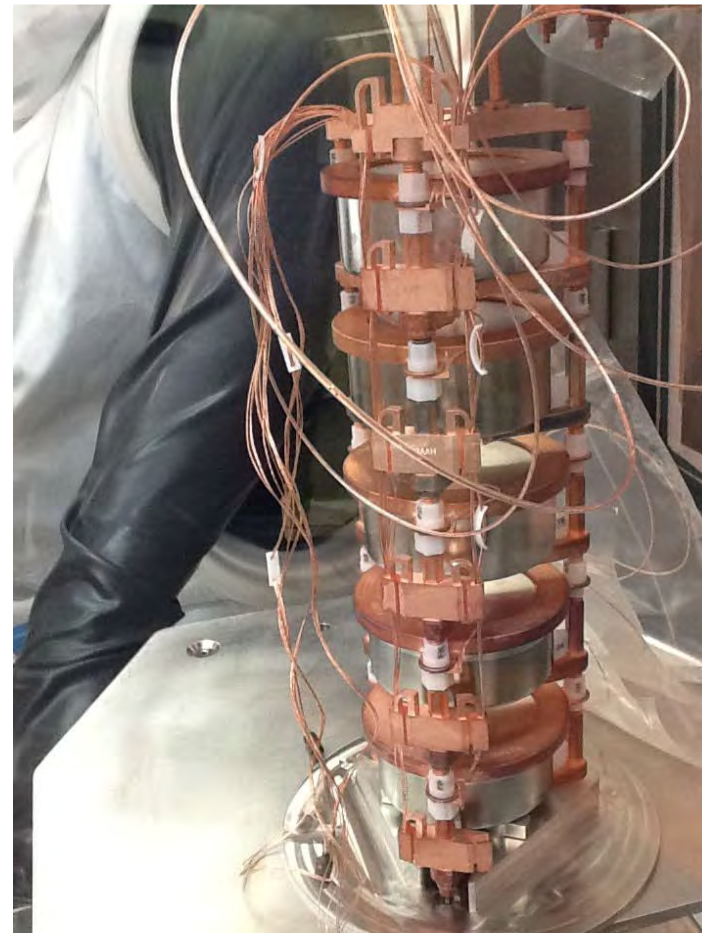
Electroformed Copper

PTFE

PFA + fine Cu coaxial cable

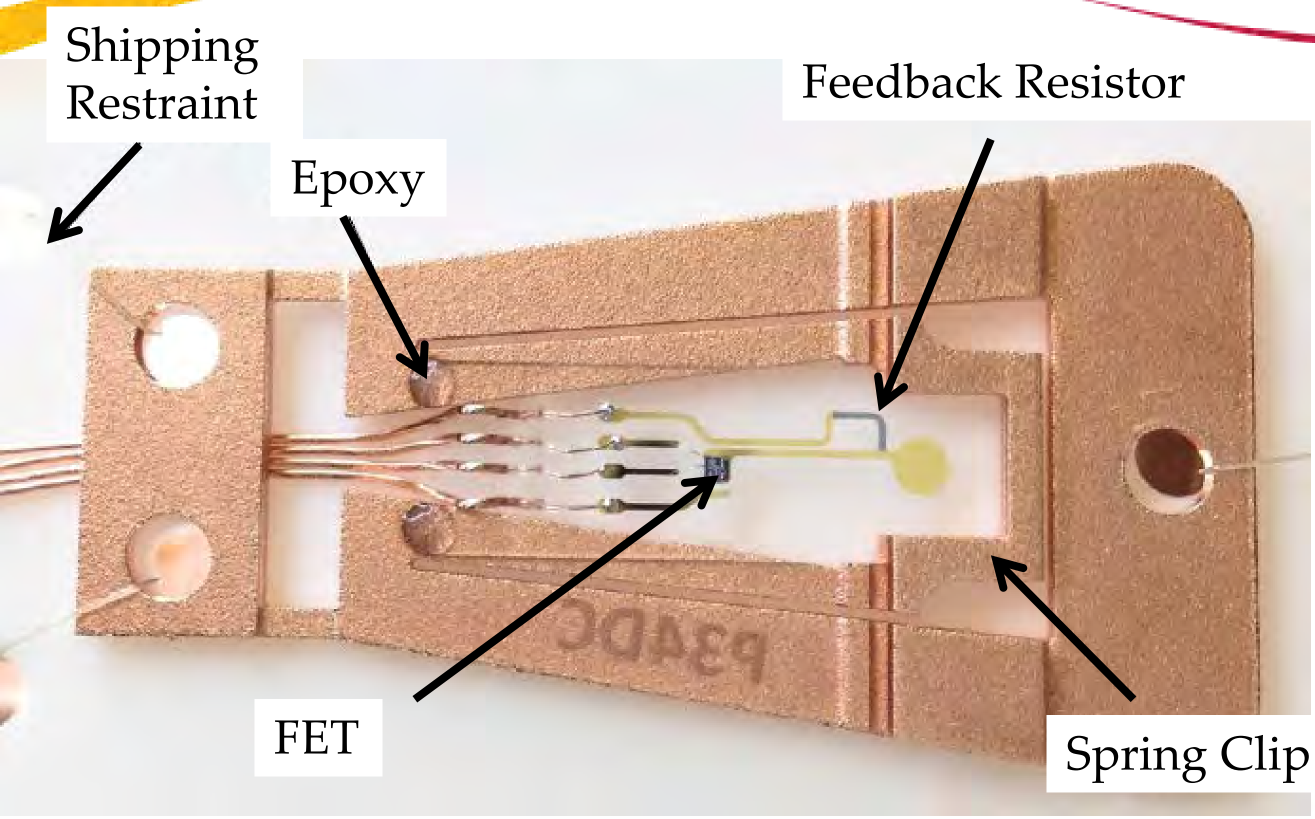
Front-End Elec.



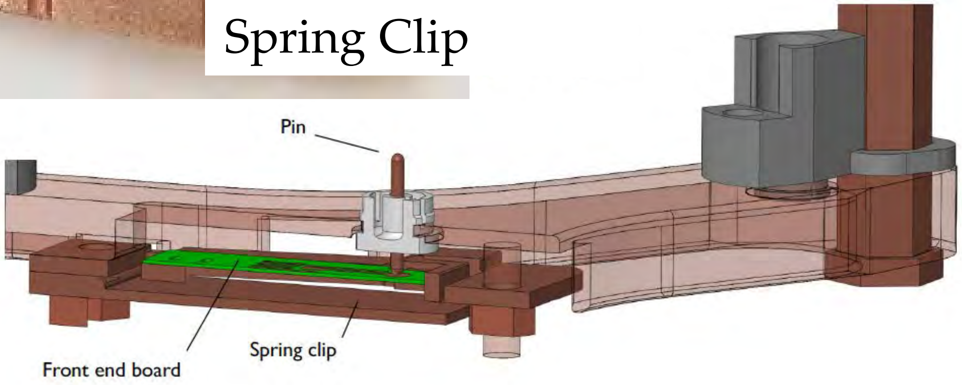


String Assembly

# Front-end board

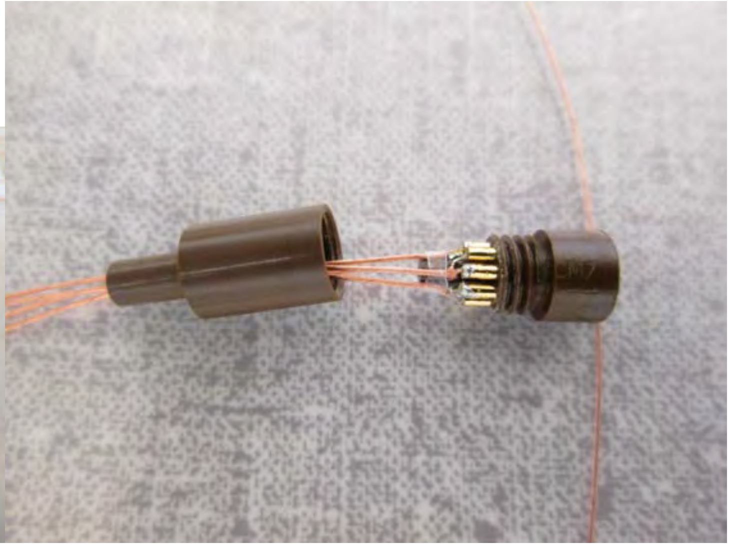



Clean Au+Ti traces on fused silica, amorphous Ge resistor, FET mounted with silver epoxy, EFCu + low-BG Sn contact pin

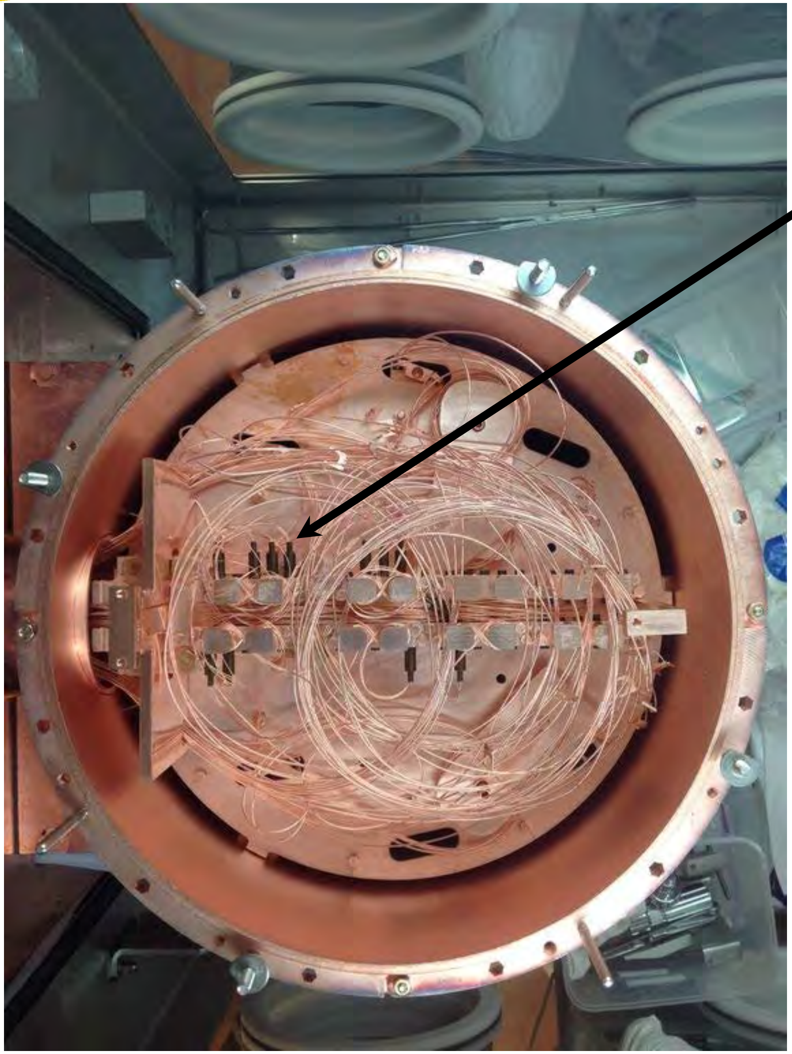


# Signal and HV Connections

- Signal connectors reside on top of cold plate.
  - In-house machined from vespel. Axon' pico co-ax cable.
  - Low background solder and flux.
- HV connection done at detector unit.
  - Small `fork' is clamped to HV ring.
- Tension between radio-purity constraints and connection robustness.
  - Ongoing R&D to improve performance.

# Top of cold plate



Vespel connectors

- HV cables are run from vacuum feed-through to detector
- Connections made in the glove box

# Modules

Prototype Module

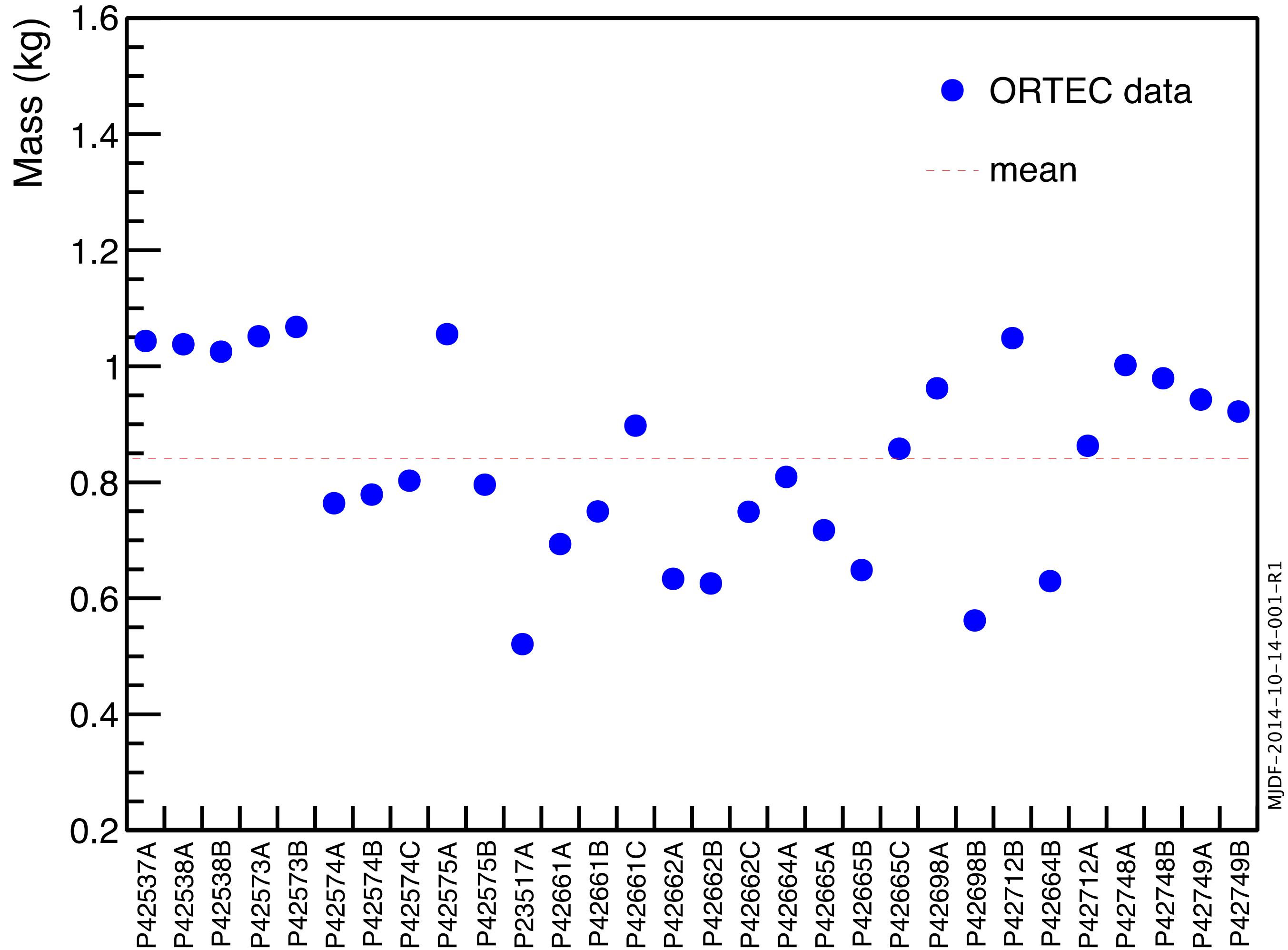
Module 1

Photo: M. Kapust

- Prototype Module Run complete.
- Module 1 cryostat with enriched detectors. Now inside shield.
  - Started cooling May 2015

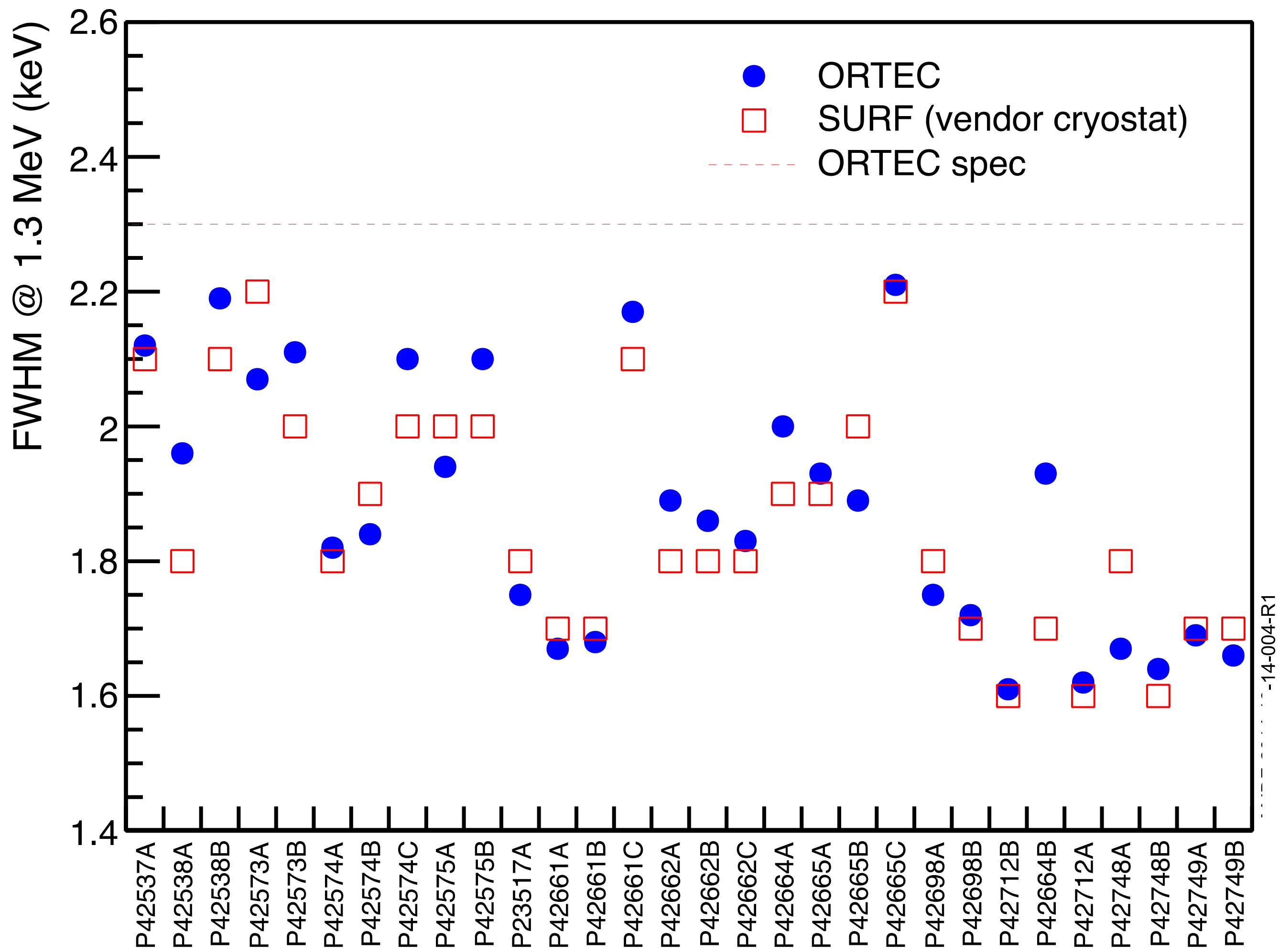
# $^{enr}$Ge detector mass

- Mean detector mass = 840g
- 29.7kg of enriched detectors underground
- 35 detectors



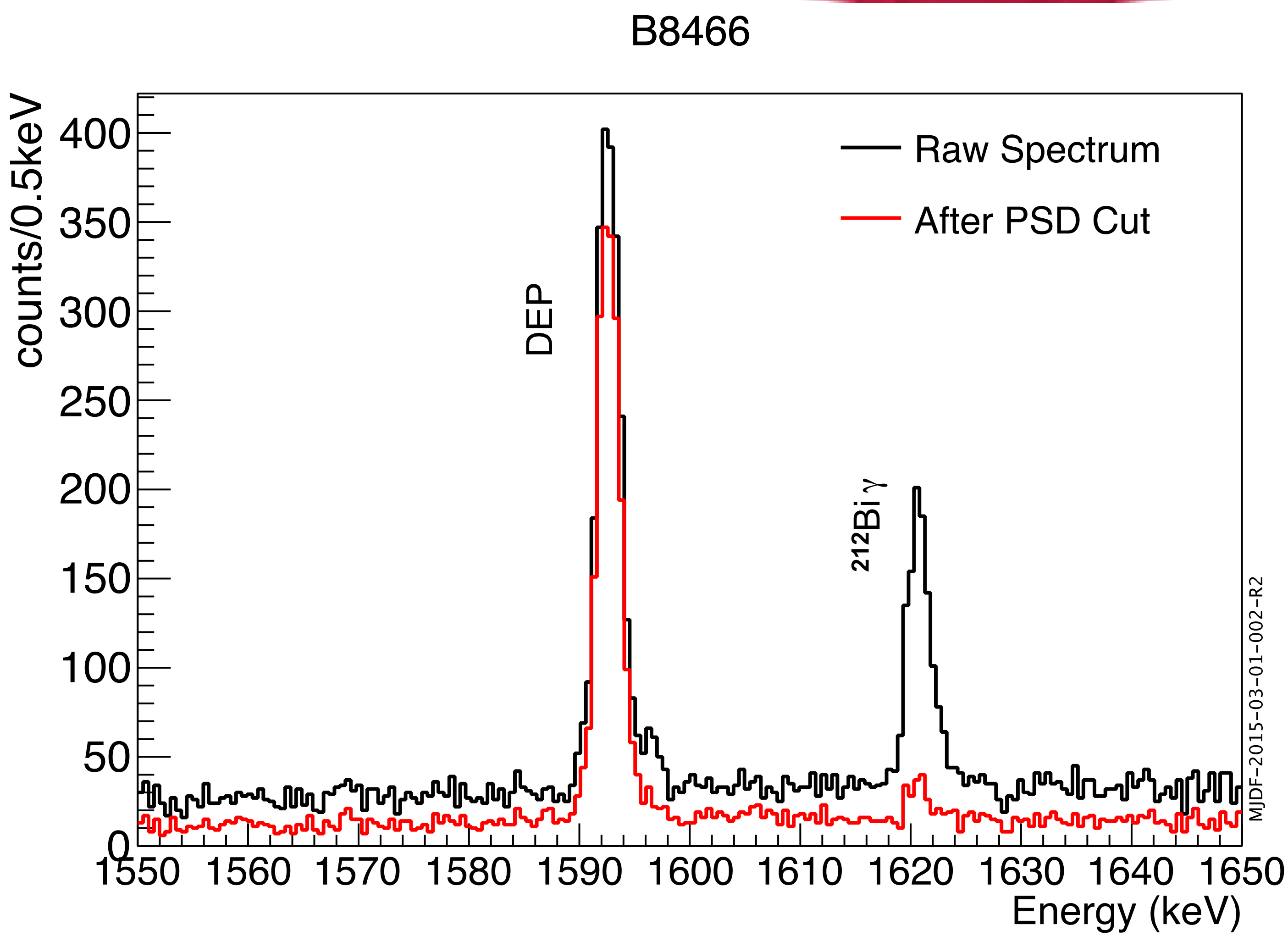
# $^{enr}$Ge detector energy resolution

- Comparison of measurements done at ORTEC and SURF within the vendor cryostat. All are better than specification.

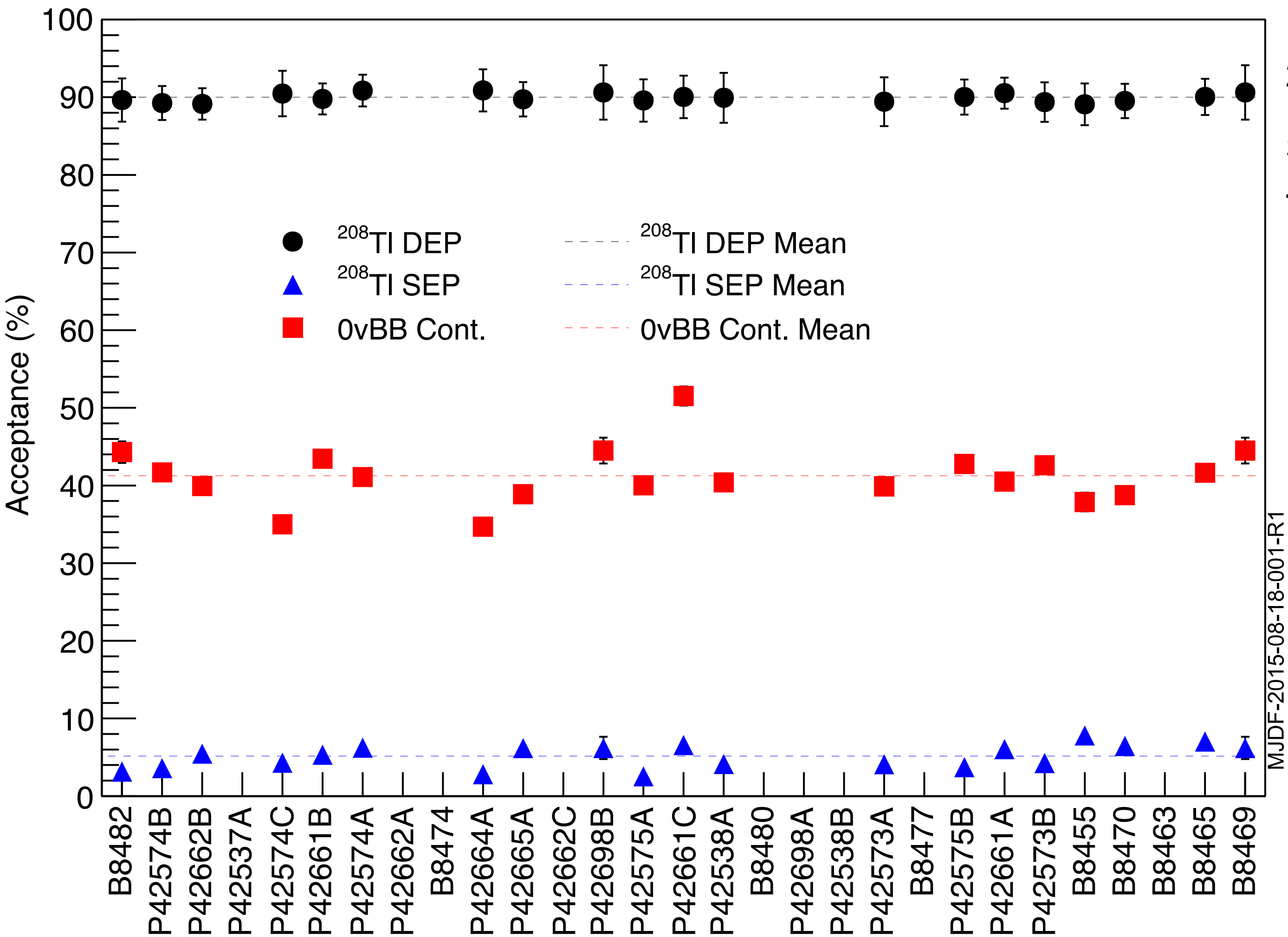


# Pulse shape discrimination: A/E

- Natural BEGe detector in Prototype Cryostat



# Ge detector PSD in Module 1

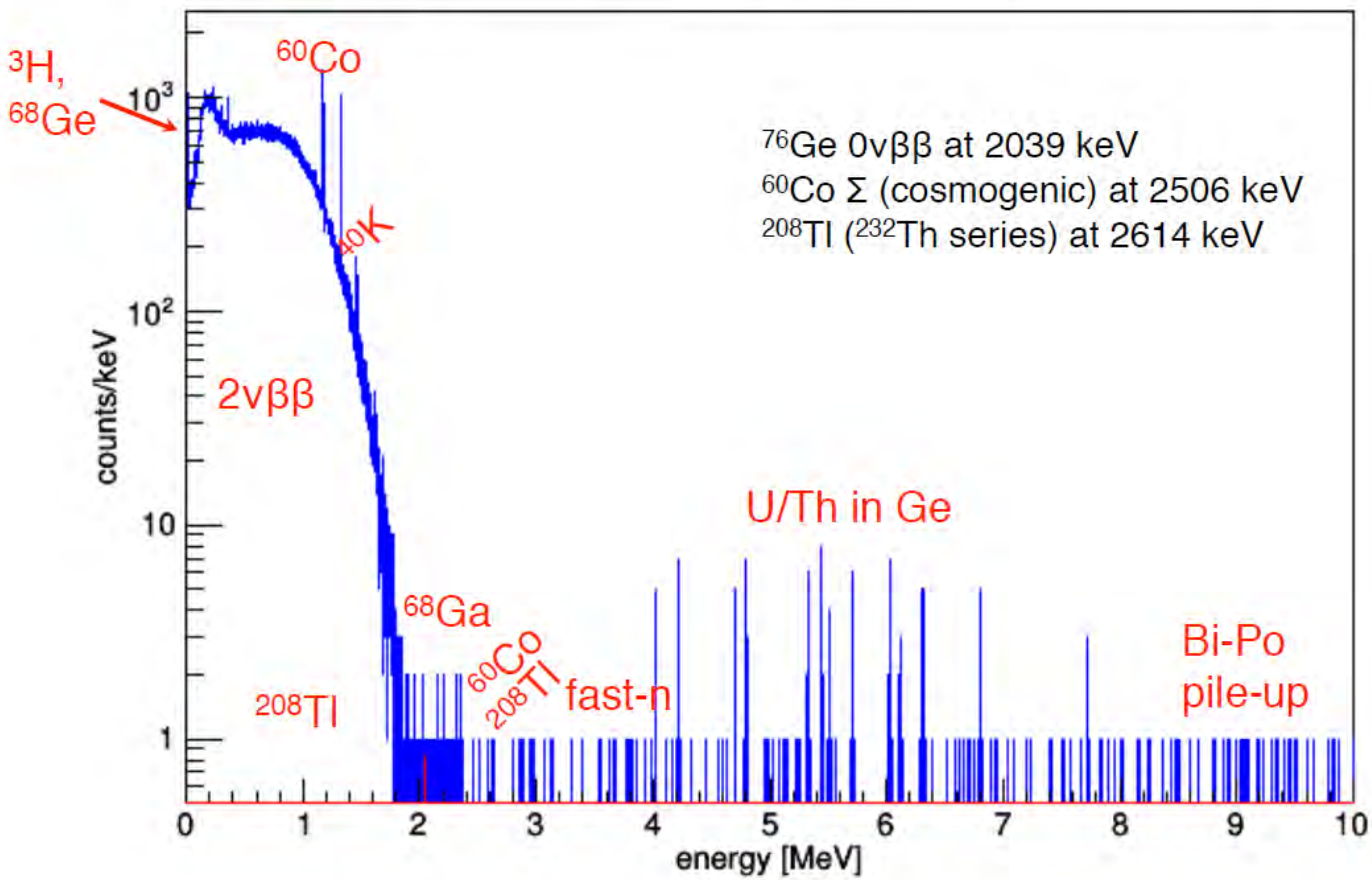



$^{208}$Tl DEP (single site events) fixed at 90%

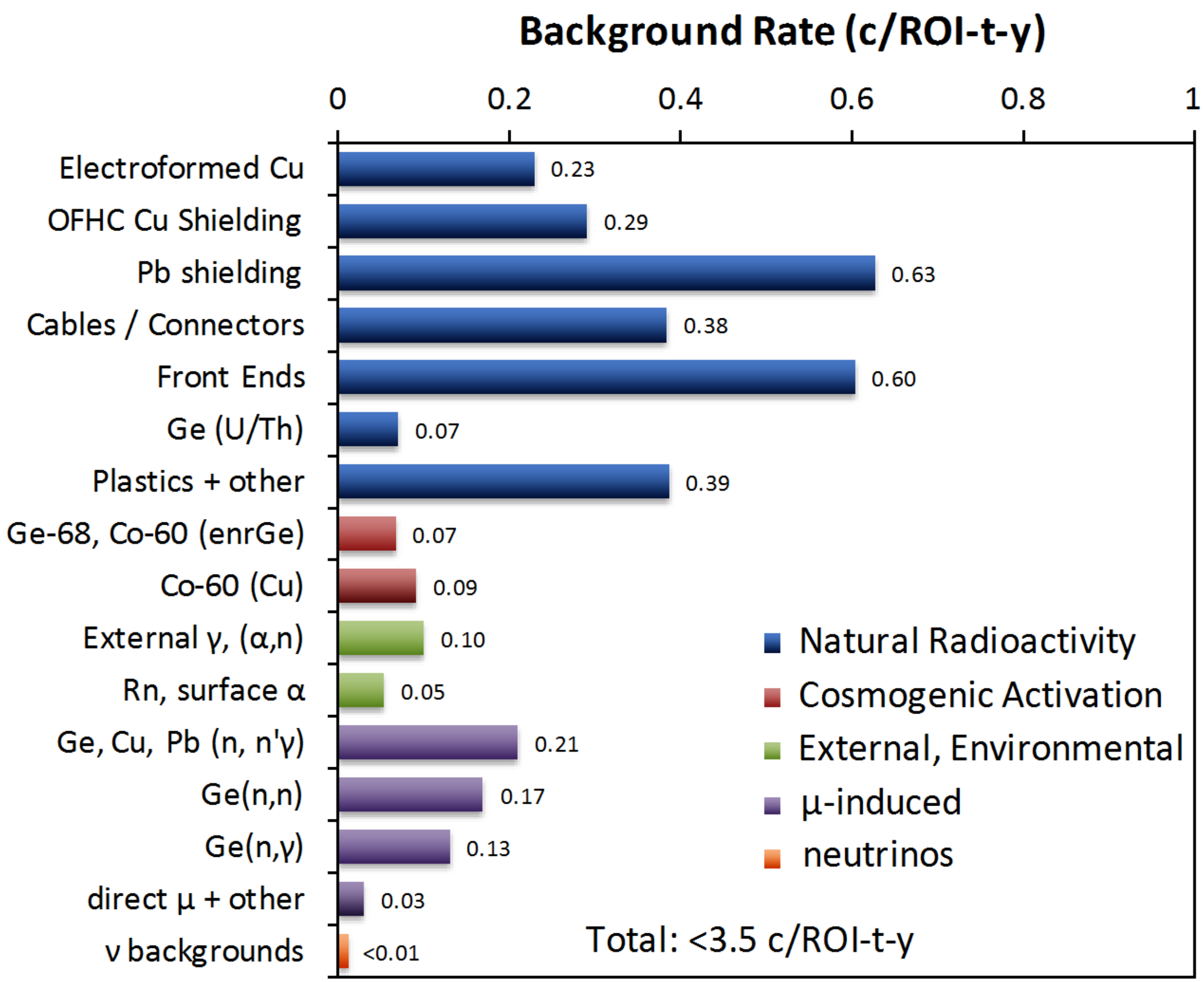
$^{208}$Tl SEP (multi-site events) reduced to <10%

# Demonstrator simulations

- 5 year run
- 30kg 87% $^{enr}Ge$
- 92% fiducial
- 90% livetime
- 108 kg-yr



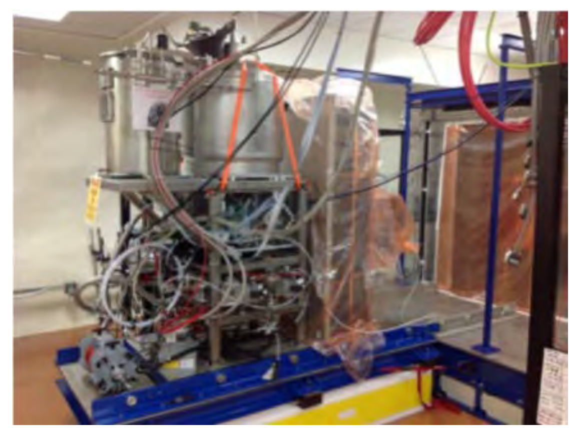
# DEMONSTRATOR background model




- Based on achieved assay or upper limit and simulations

# Module 1 status

- May 2015
  - Prior to cool-down 28 of 29 detectors showed good baselines
  - Efforts to seal with low-background parylene gaskets unsuccessful, switch to Kalrez® o-rings for initialcommissioning. Investigating additional alternate low-background seals
- June 2015
  - In shield, with 23 of 29 detectors operating. Non working detectors — signal connector (3), HV connection (1), leakage current (1), HV or front end (1)
  - Inner electroformed copper shield not installed (machining underway), outer poly shield, partially installed
  - Commissioning (completed in July), calibration, background runs.

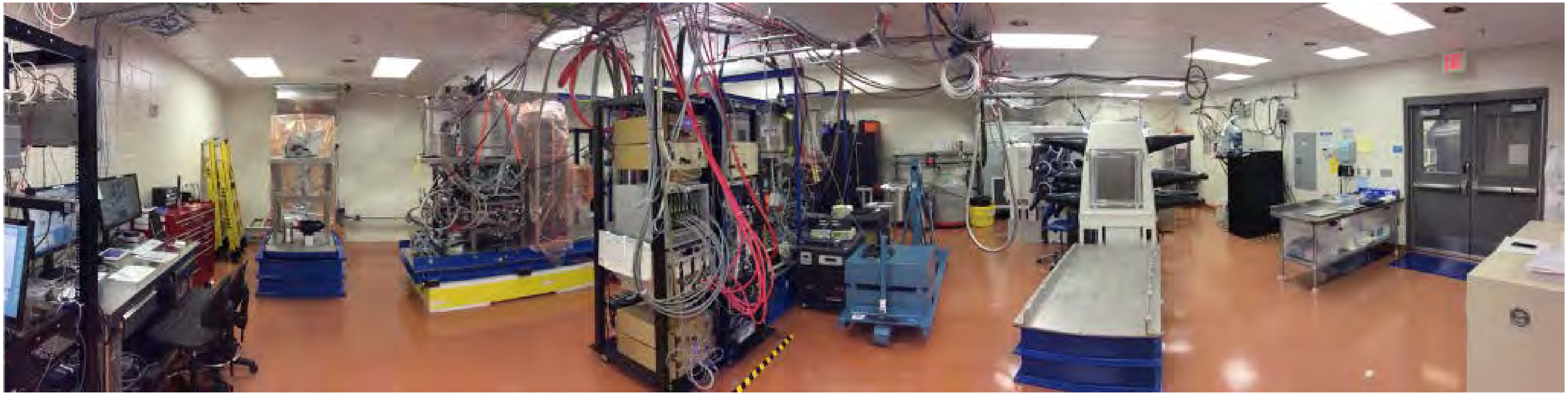


# Module 1 Improvements - Fall 2015

- During Oct.-Nov. we are performing planned improvements to Module 1.
- **Install inner Cu shield**: Will decrease background contribution from outer Cu shield and Pb by factor of about 10.
- **Replace Kalrez O-rings in cryostat**: These o-rings would contribute to our background. Replacement will be either parylene or PTFE.
  - Kalrez: Th ~ 2000-4000 ppt. Expect about 80 c/ROI t y.
  - Parylene: Th ~ 200 ppt, and uses much less mass. Requires a custom form for fabrication that is being fabricated. Expect about 0.3 c/ROI t y.
  - PTFE: very effective seal, gasket material being assayed.
- **Crossarm Shielding**: Being added to decrease background contributions from electronics-breakout box region.
- **Repair non-operating detectors and upgrade cables**:
  - Repairing non-operating detectors (cable connection, HV connection, LMFE replacement, …)
  - Will replace all cube-to-cold plate signal cables with cables having improved connectors.
  - Vacuum feedthroughs are difficult to connect/disconnect; internal connections are fragile and easy to miss-wire. Have improved D-sub connectors.

# Summary

- Assembly and construction proceeding at Sanford Davis Campus laboratory.
- Based on assays, material backgrounds projected to meet cleanliness goals.
- Successful reduction and refinement of $^{enr}$Ge with 98% yield.
- Electrofomed copper completed at SURF and PNNL.
- AMTEK (ORTEC) produced 35 detectors, 29.7 kg, from the $^{enr}$Ge. All are underground at SURF.
- Shield nearly complete.
- Module 1, in-shield running from June – Sept. 2015. Improvements underway. Scheduled for shield reinstallation in Dec. 2015
- Module 2 construction and assembly proceeding. Scheduled to start commissioning in 2016.



# The MAJORANA Collaboration

*Black Hills State University, Spearfish, SD*
Kara Keeter

*Duke University, Durham, North Carolina , and TUNL*
Matthew Busch

*Institute for Theoretical and Experimental Physics, Moscow, Russia*
Alexander Barabash, Sergey Konovalov, Vladimir Yumatov

*Joint Institute for Nuclear Research, Dubna, Russia*
Viktor Brudanin, M. Shirchenko, Sergey Vasilyev, E. Yakushev, I. Zhitnikov

*Lawrence Berkeley National Laboratory, Berkeley, California and the University of California - Berkeley*
Nicolas Abgrall, Mark Amman, Paul Barton, Adam Bradley, Yuen-Dat Chan, Paul Luke, Susanne Mertens, Alan Poon, Kai Vetter, Harold Yaver

*Los Alamos National Laboratory, Los Alamos, New Mexico*
Pinghan Chu, Steven Elliott, Johnny Goett, Ralph Massarczyk, Keith Rielage, Larry Rodriguez, Harry Salazar, Wenqin Xu

*North Carolina State University*
Matthew P. Green

*Oak Ridge National Laboratory*
Fred Bertrand, Kathy Carney, Alfredo Galindo-Uribarri, Monty Middlebrook, David Radford, Elisa Romero-Romero, Robert Varner, Brandon White, Chang-Hong Yu

*Osaka University, Osaka, Japan*
Hiroyasu Ejiri

*Pacific Northwest National Laboratory, Richland, Washington*
Isaac Arnquist, Eric Hoppe, Richard T. Kouzes, Brian LaFerriere, John Orrell

*Queen's University, Kingston, Canada*
Ryan Martin

South Dakota School of Mines and Technology, Rapid City, South Dakota
Adam Caldwell, Colter Dunagan, Cabot-Ann Christofferson, Stanley Howard, Anne-Marie Suriano, Jared Thompson

*Tennessee Tech University, Cookeville, Tennessee*
Mary Kidd

*University of North Carolina, Chapel Hill, North Carolina and TUNL*
Thomas Gilliss, Graham K. Giovanetti, Reyco Henning, Mark Howe, Jacqueline MacMullin, Samuel J. Meijer, Benjamin Shanks, Christopher O'Shaughnessy, Jamin Rager, James Trimble, Kris Vorren, John F. Wilkerson

*University of South Carolina, Columbia, South Carolina*
Frank Avignone, Vince Guiseppe, David Tedeschi, Clint Wiseman

*University of South Dakota, Vermillion, South Dakota*
Dana Byram, Ben Jasinski

*University of Tennessee, Knoxville, Tennessee*
Yuri Efremenko, Andrew Lopez

*University of Washington, Seattle, Washington*
Tom Burritt, Micah Buuck, Clara Cuesta, Jason Detwiler, Julieta Gruszko, Ian Guinn, Jonathan Leon, David Peterson, R. G. Hamish Robertson, Tim Van Wechel