The MAJORANA DEMONSTRATOR: Ge for $0\nu\beta\beta$ and Dark Matter

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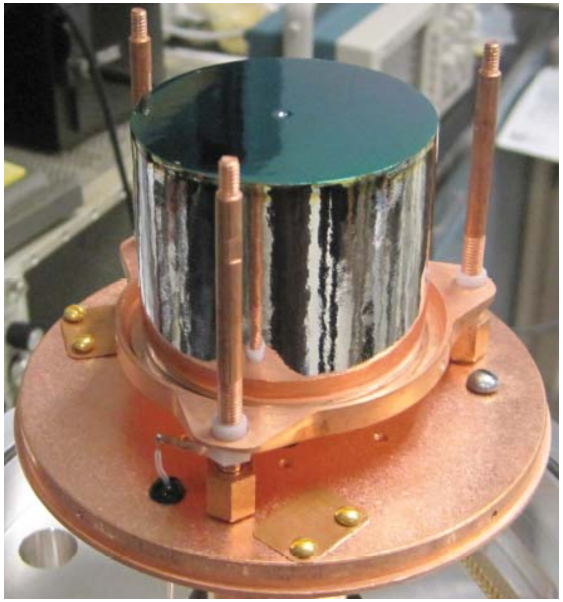
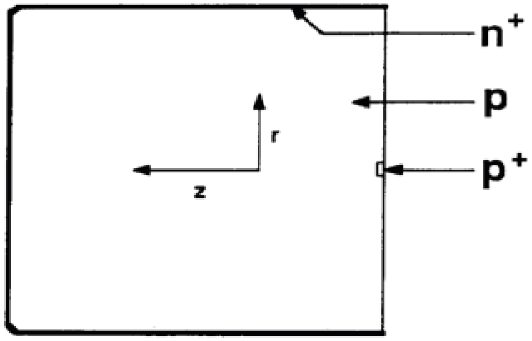
For the Majorana Collaboration

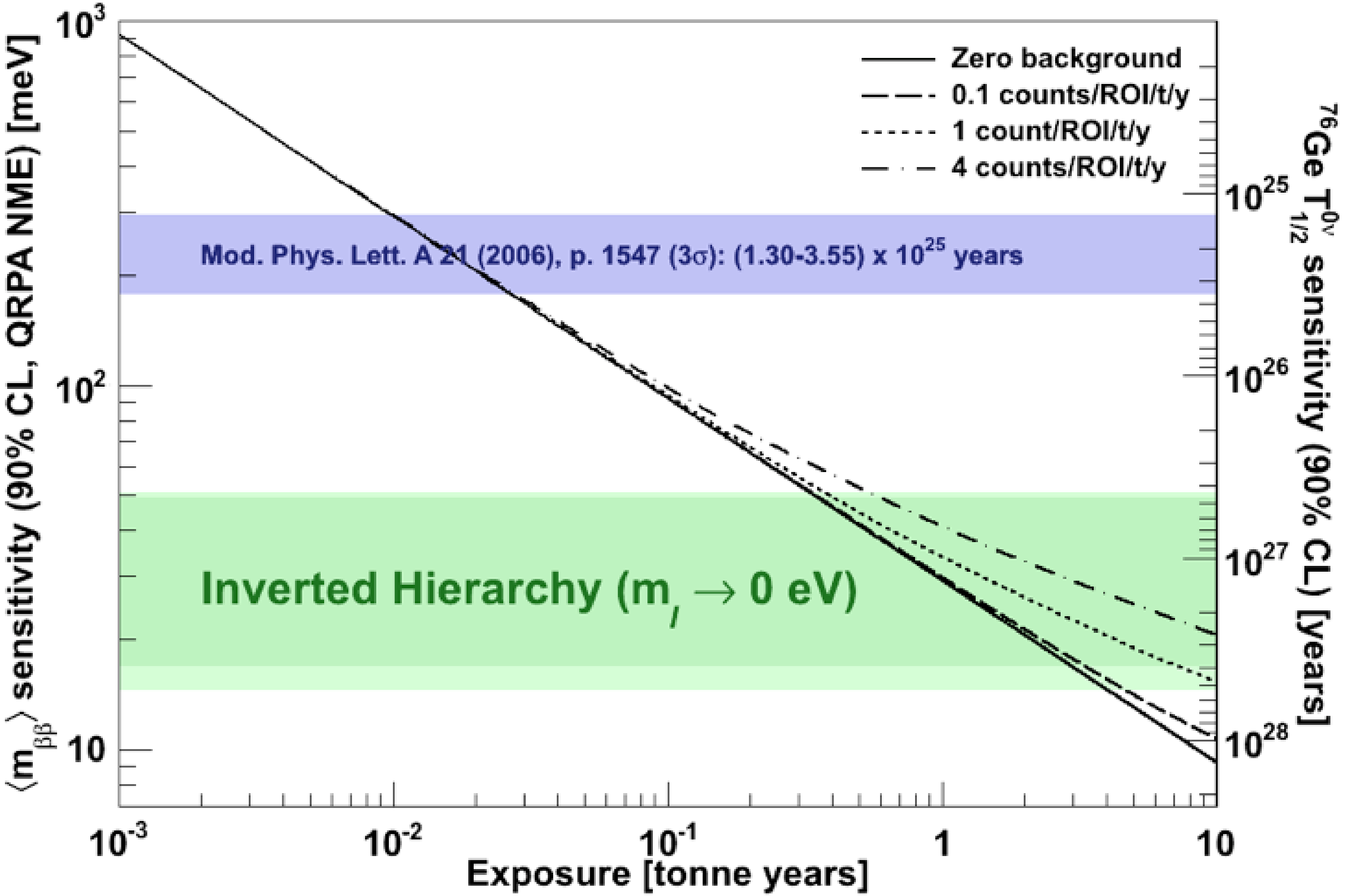
Germanium for 0νββ

- ^{76}Ge is an excellent candidate 0νββ source:
  - Ge detectors are a proven technology
  - Excellent energy resolution: 0.16% at 2039keV
  - Favorable Nuclear Matrix Element
  - Demonstrated background rejection techniques:
    - Granularity
    - Pulse-shape discrimination
- P-Type Point Contact detectors (PPCs)
  - Low-noise -> sub-keV energy thresholds
  - Excellent timing discrimination





0νββ sensitivity

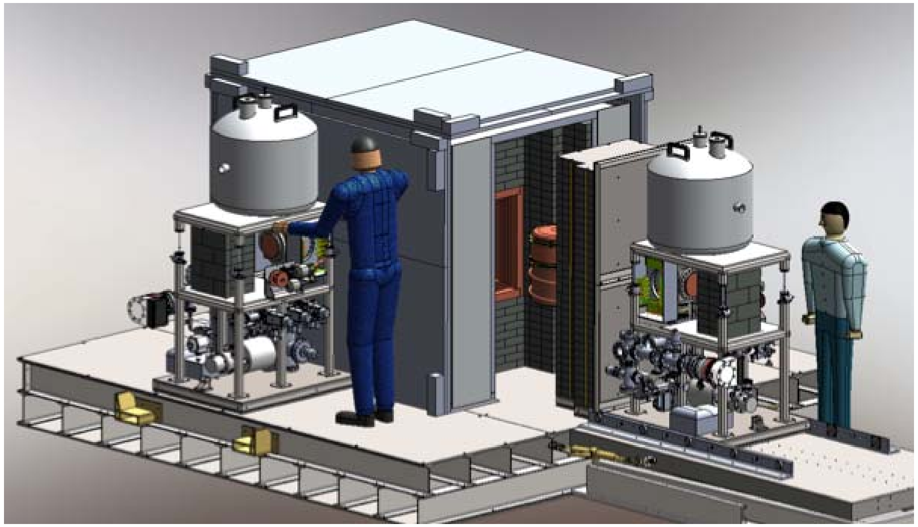


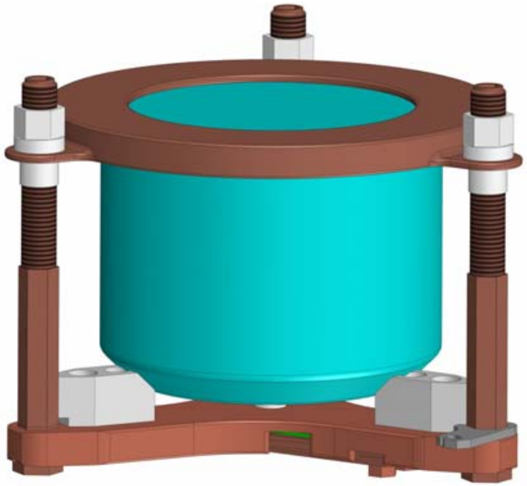
MAJORANA DEMONSTRATOR R&D Goals

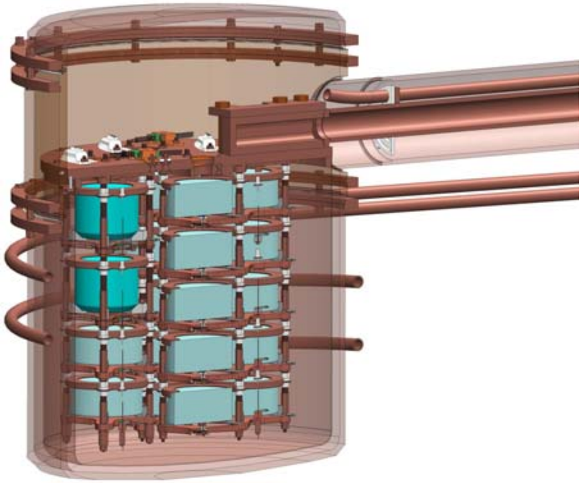
- Technical goals:
  - **Demonstrate backgrounds low enough to justify building a tonne-scale Ge experiment.**
  - Establish feasibility to construct & field modular arrays of Ge detectors.
  - Minimize costs, optimize the schedule, and retire risks for a future 1-tonne experiment.
- Science goals:
  - Although we are driven by technical goals, we also aim to extract the maximum science from the DEMONSTRATOR prototype,
    - (Directly) Test the recent claim of an observation of $0\nu\beta\beta$ in ^{76}Ge.
    - Exploit the low-energy sensitivity to perform searches for dark matter, axions.
- Work cooperatively with GERDA Collaboration toward a single international tonne-scale Ge experiment that combines the best features of MAJORANA and GERDA.

The MAJORANA DEMONSTRATOR

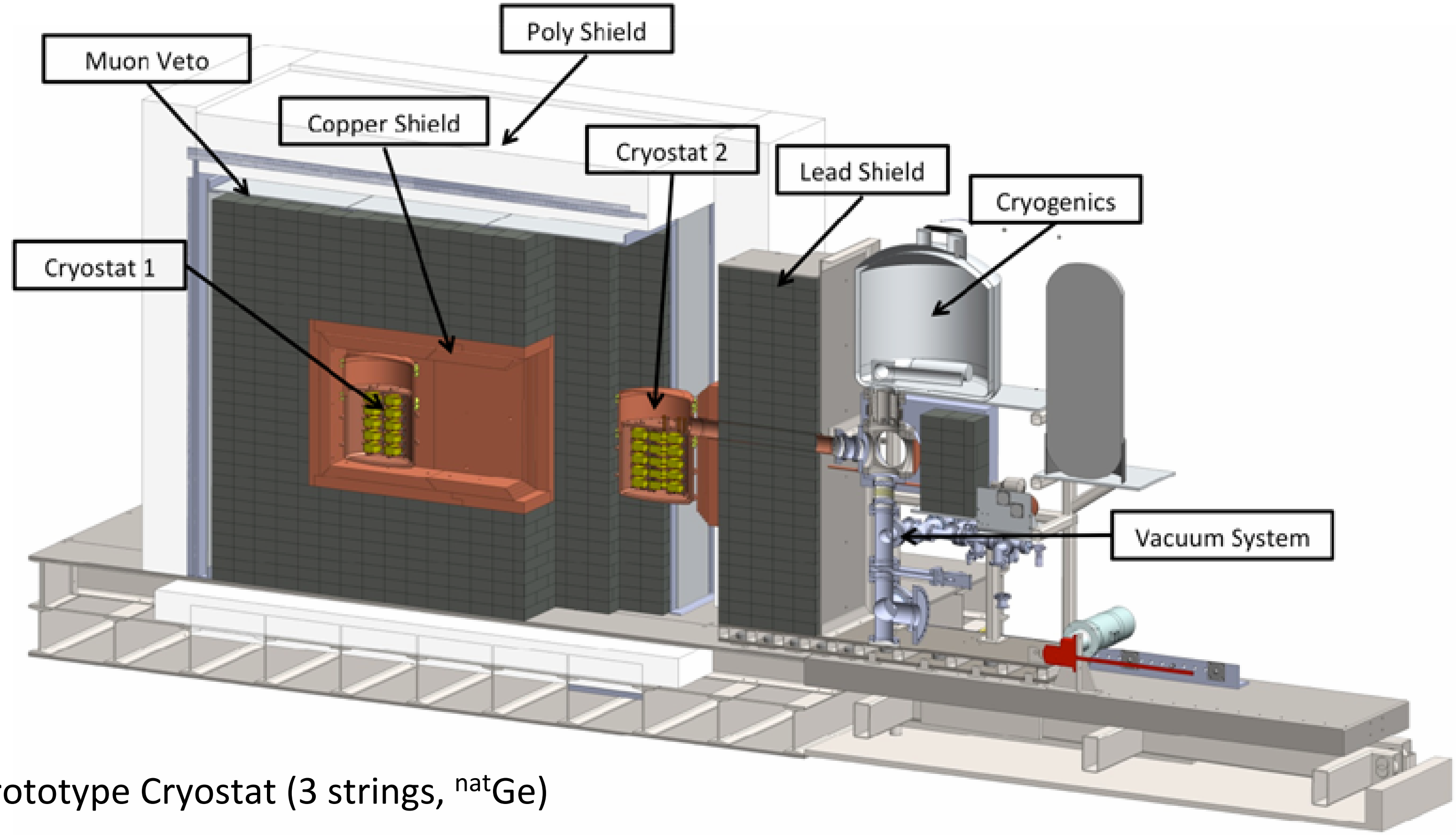
- Background Goal in the $0\nu\beta\beta$ peak region of interest (4 keV at 2039 keV)
  3 counts/ROI/t/y (after analysis cuts)
  scales to 1 count/ROI/t/y for a tonne experiment
- 40-kg of Ge detectors
  - Baseline: 20-kg of 86% enriched ^{76}Ge crystals & 20-kg of ^{nat}Ge (up to 30-kg enriched ^{76}Ge)
  - 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
- Located underground at 4850' Sanford Lab







The MAJORANA DEMONSTRATOR

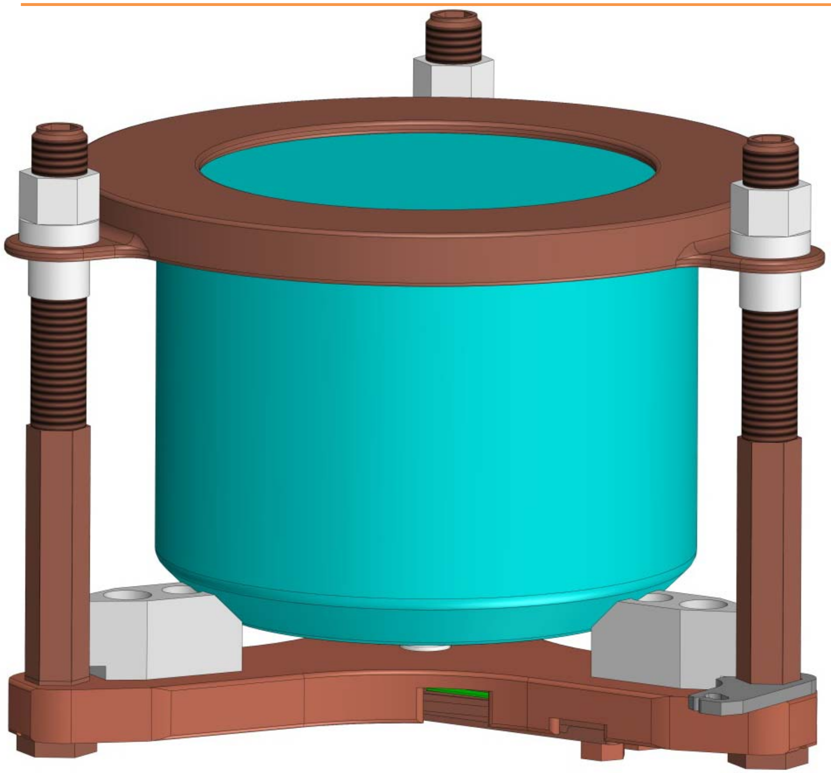


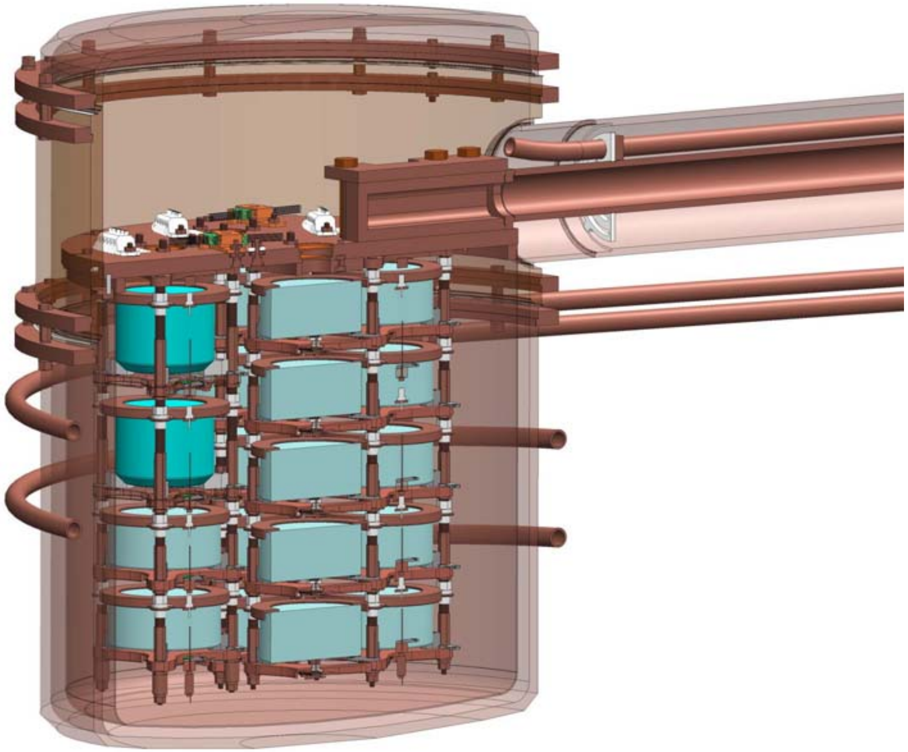
2012 - Prototype Cryostat (3 strings, ^{nat}Ge)

2013 - Cryostat 1 (3 strings ^{enr}Ge & 4 strings ^{nat}Ge)

2014 - Cryostat 2 (up to 7 strings ^{enr}Ge)

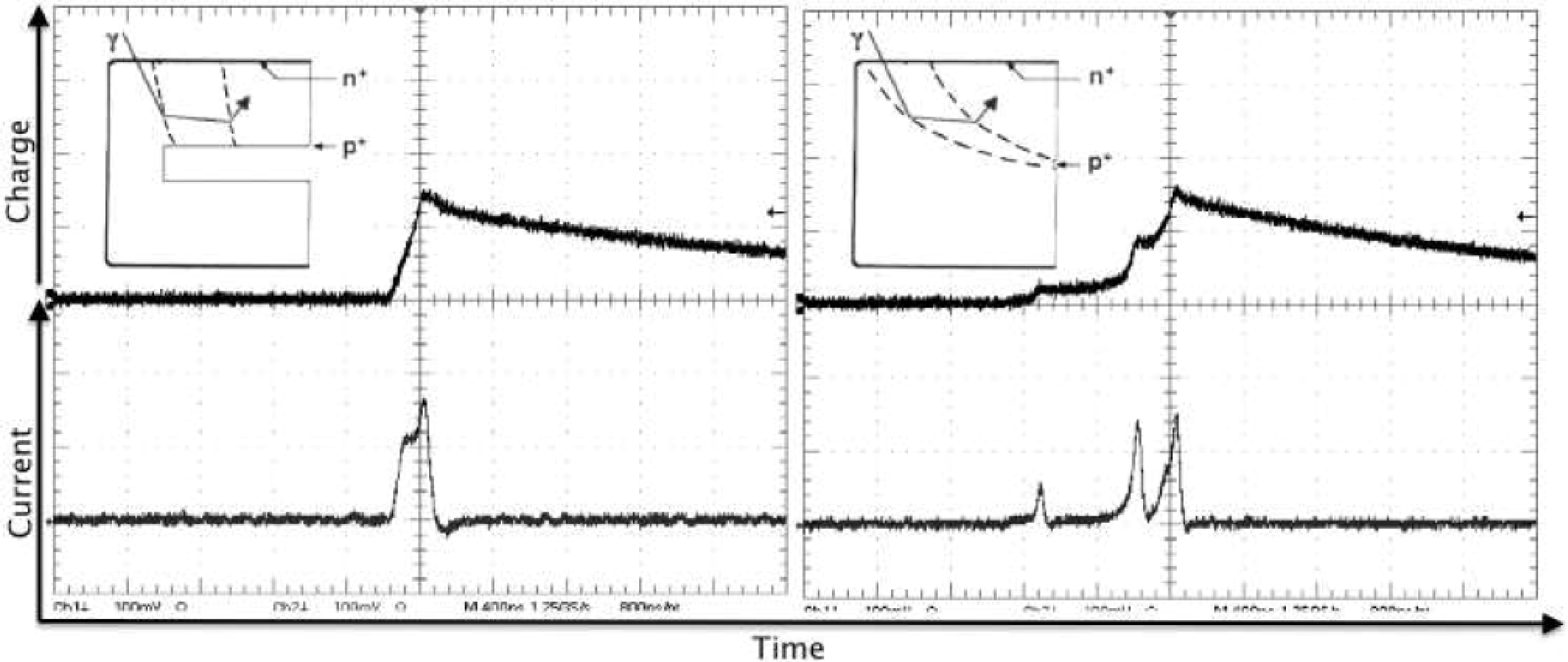
MJD Detector Arrays





- Ge detectors mounted in custom, low-mass mounts, fabricated from EFCu, PTFE
- Mounts compatible with range of detector form factors
- Detector units stacked in strings. Strings mechanically rigid; good thermal conductivity

PPCs: Timing Capabilites



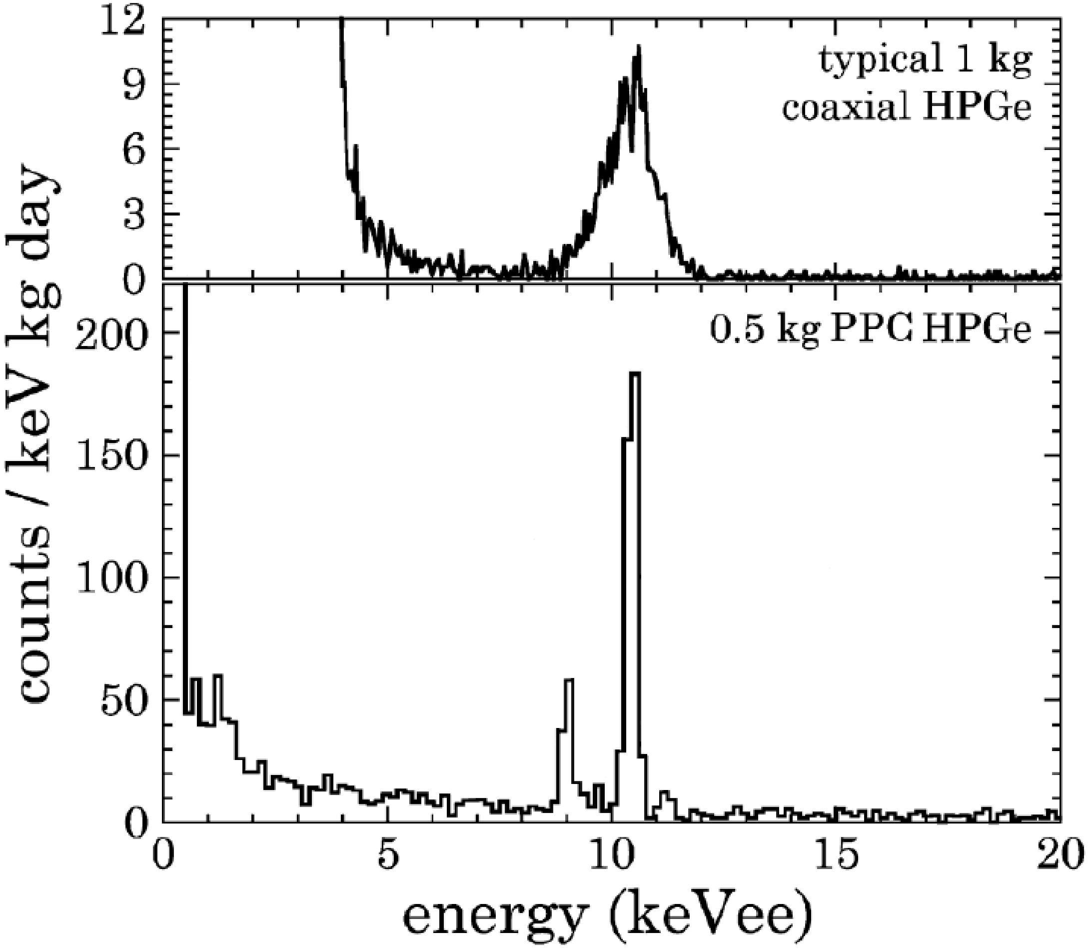
P. Barbeau, J. I. Collar, and O. Tench, Journal of Cosmology and Astroparticle Physics, 2007.

P. N. Luke et al, IEEE Transactions on Nuclear Science, Vol. 36, No. 1, February 1989

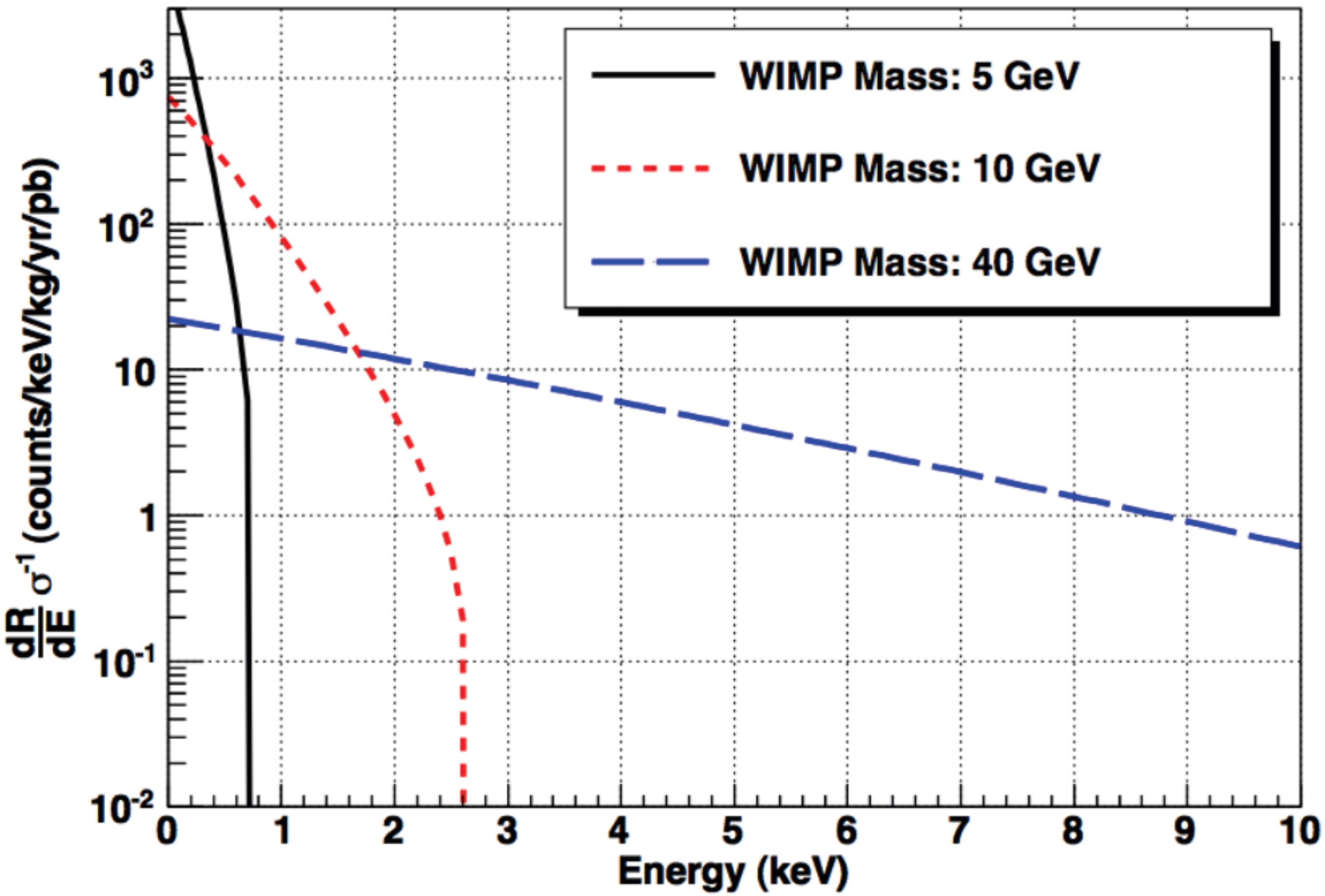
PPCs: Low-Energy Performance

- Point-contact reduces detector capacitance.
- PPCs capable of sub-keV energy thresholds.
- This presents an interesting opportunity for an array of PPC-type Ge detectors…

C. Aalseth et al., Physical Review Letters 101, 251301 (2008).



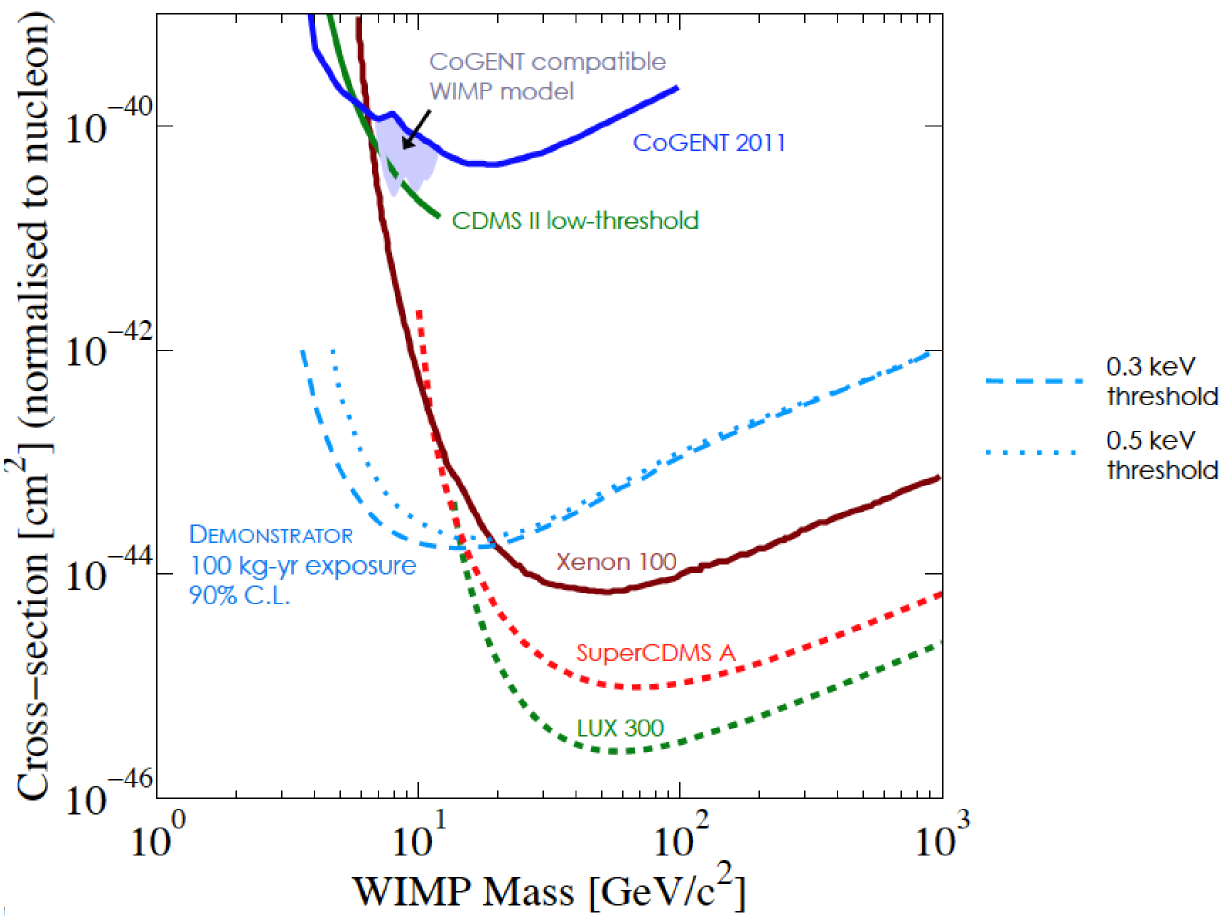
Sensitivity of PPCs to WIMPs



M.G. Marino, Ph.D. Disseration, Univ. of Washington (2010)

MAJORANA DEMONSTRATOR in the Dark Matter Picture

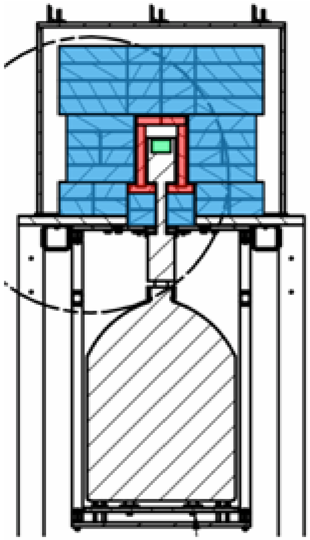
- PPC detectors provide a unique opportunity to probe an open region of WIMP detection space!
- Assumptions:
  - 20kg of detectors
  - Spin-independent WIMPS
  - ^3H: 15 days surface exposure
  - 0-10keV: .001 cnts/kg/keV/day
  - n: << ^3H, based on IGEX



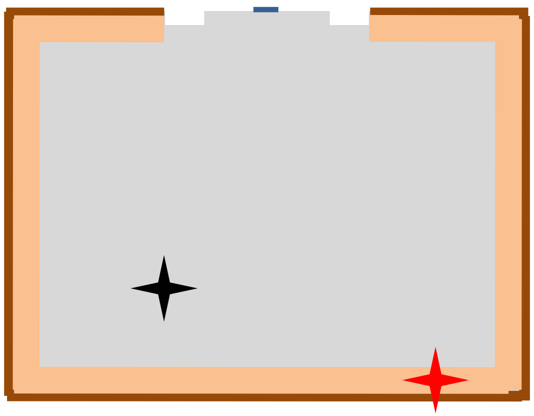
Xenon 100: arxiv:1104.2549v2
CDMS: Phys.Rev.Lett.106:131302, 2011
CoGENT: Phys.Rev.Lett.106:131301, 2011

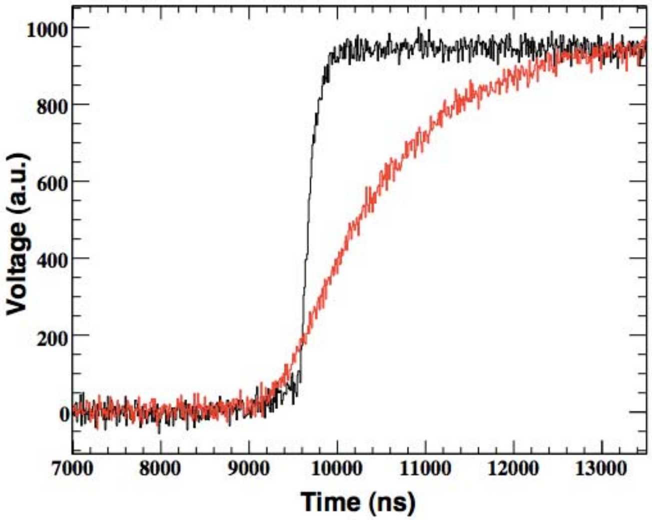
Dark Matter with PPCs: MALBEK

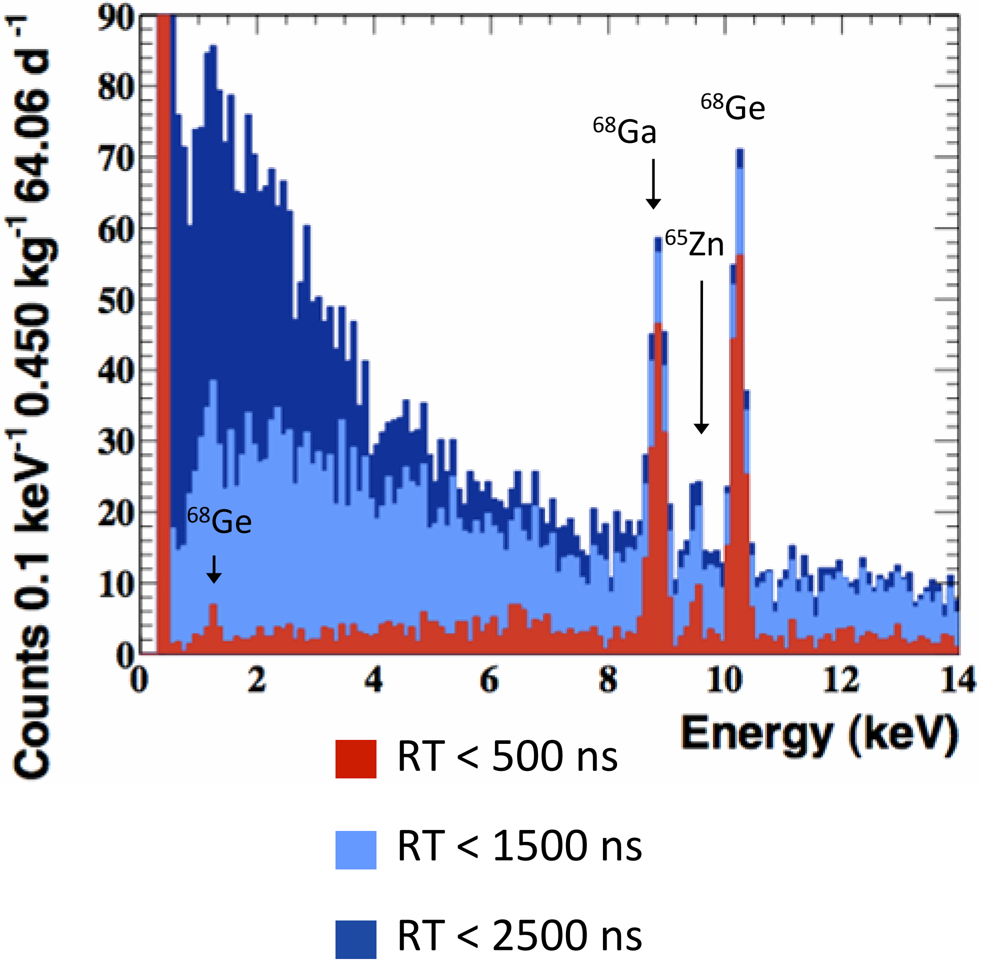
- MAJORANA Low-Background BEGe at KURF
- PPC detector
- Low-background cryostat
- Layered shielding
  - 1” ancient lead
  - 8” low-background lead
  - 2” plastic scintillator μ veto
  - 10” polyethylene
- Testbed for MAJORANA detector electronics, DAQ, simulations.



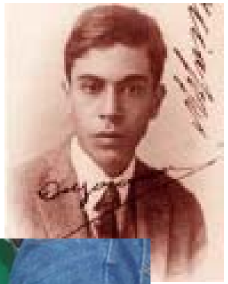
Rise Time Cuts: Removing Degraded Pulses







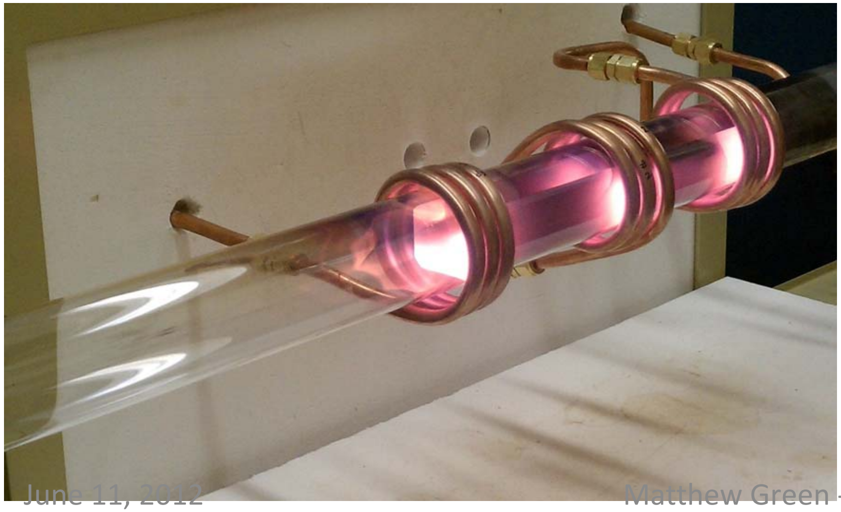
Producing ^{enr}Ge Detectors



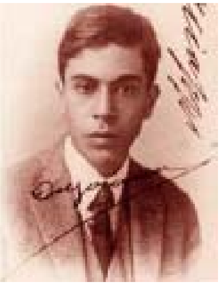
- MAJORANA received first shipment of ^{enr}Ge Sept. 2011.
- 28.5kg GeO_2 enriched at ECP, Krasnoyarsk, Russia (~20kg ^{76}Ge)
- Stored underground at Cherokee Caverns, Knoxville TN

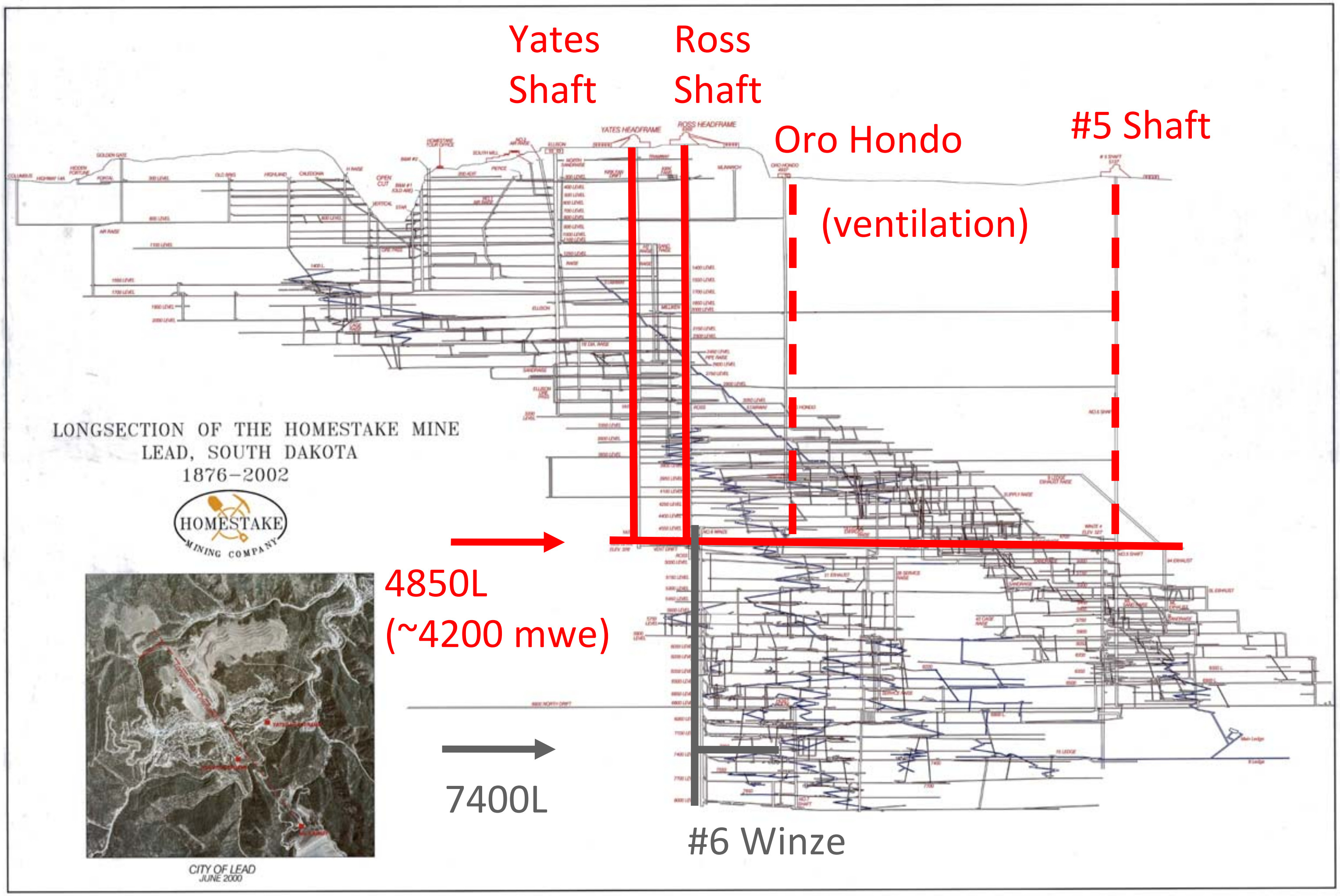
Ge Detector Production

- Reduction & Refinement
  - ESI, Oak Ridge, TN (SBIR)
- Crystal-pulling, machining, contact deposition
  - Commercial vendor selected.
- 19 commercial ^{nat}Ge detectors already on hand at SUL



Sanford Underground Laboratory





MJD Lab @ SURF

Background Simulations

- MaGe: a GEANT4-based application jointly developed by MAJORANA / Gerda
  - Geometries
  - Physics lists
  - Identical output to DAQ-unified analysis code
- MaGe is well-validated
  - MALBEK full background spectrum modeled accurately
  - Extensive suite of validation tests to ensure GEANT4 accuracy in $0\nu\beta\beta$ & light WIMP regimes

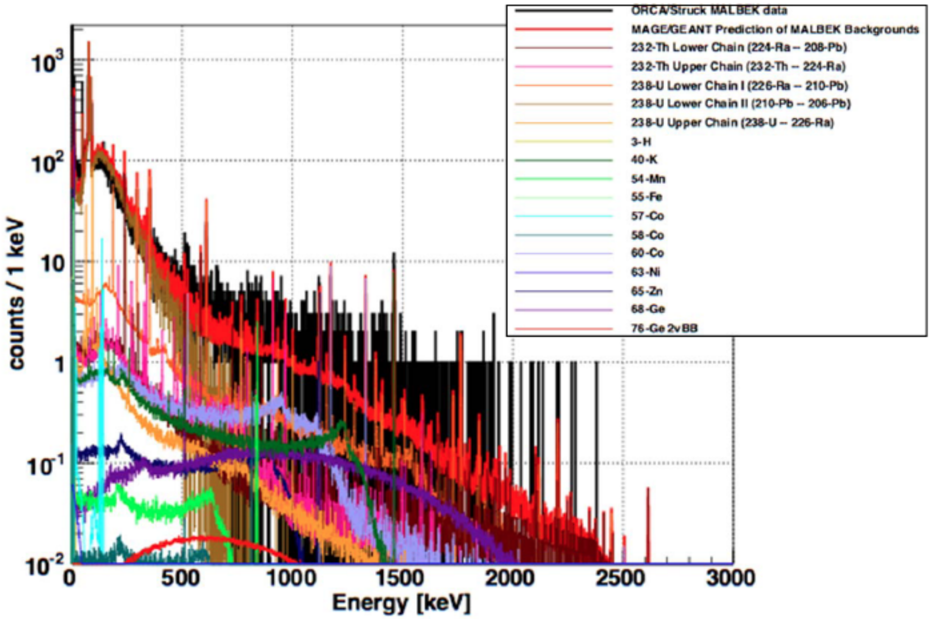
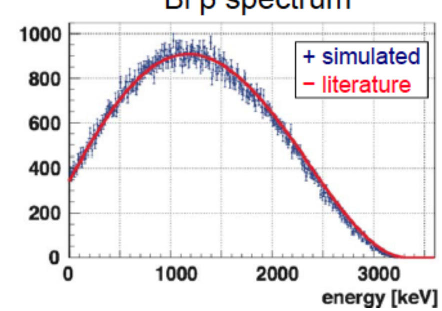


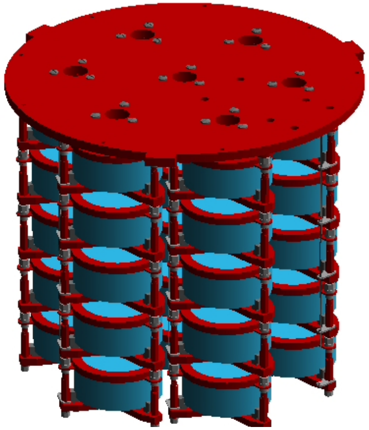
Table 60: ^{214}Bi branching ratios and β-decay energies

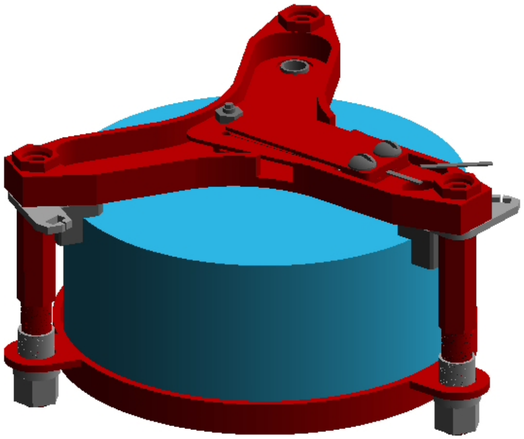
$E_{lit.}$ [keV]	$E_{sim.}$ [keV]	diff. [keV]	$I_{lit.}$ [%]	$I_{sim.}$ [%]	diff. [%]
1122 ± 11	1124.2	2.2	0.444 ± 0.018	0.425 ± 0.0065	-0.019
1151 ± 11	1153.5	2.5	4.345 ± 0.02	4.27 ± 0.021	-0.074
1182 ± 11	1183.6	1.6	0.102 ± 0.012	0.0944 ± 0.0031	-0.0076
1253 ± 11	1254.7	1.7	2.45 ± 0.009	2.21 ± 0.015	-0.24
1259 ± 11	1261.2	2.2	1.431 ± 0.008	1.38 ± 0.012	-0.051
1275 ± 11	1277.4	2.4	1.177 ± 0.017	1.13 ± 0.011	-0.042
1380 ± 11	1381.7	1.7	1.588 ± 0.013	1.59 ± 0.013	0.006
1423 ± 11	1424.6	1.6	8.14 ± 0.03	8.16 ± 0.029	0.016
1505 ± 11	1507.5	2.5	16.96 ± 0.05	17 ± 0.041	0.085
1527 ± 11	1529	2	0.125 ± 0.011	0.117 ± 0.0034	-0.0085
1540 ± 11	1542.4	2.4	17.57 ± 0.04	17.8 ± 0.042	0.24
1609 ± 11	1610.7	1.7	0.61 ± 0.05	0.721 ± 0.0085	0.11
1727 ± 11	1728.6	1.6	3.12 ± 0.03	2.95 ± 0.017	-0.17
1855 ± 11	1856.5	1.5	0.89 ± 0.03	0.824 ± 0.0091	-0.066
1892 ± 11	1894.3	2.3	7.35 ± 0.05	7.41 ± 0.027	0.061
3270 ± 11	3272	2	19.1 ± 0.17	18.3 ± 0.043	-0.83

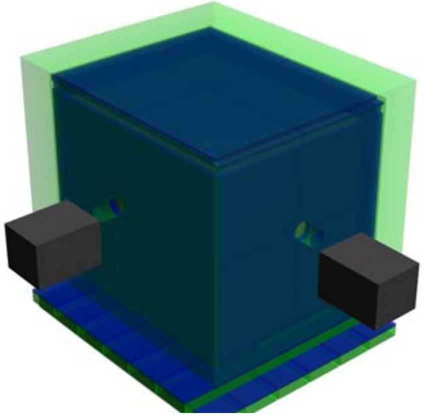
^{214}Bi β spectrum

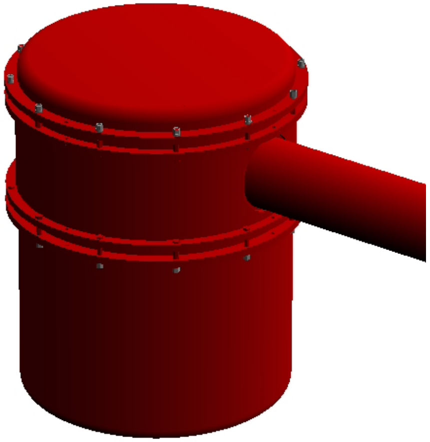


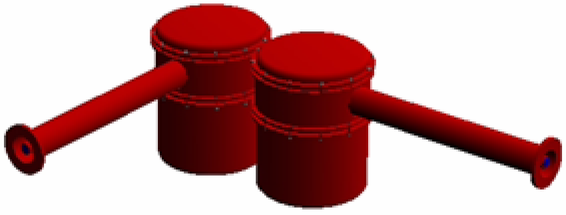
Background Simulations

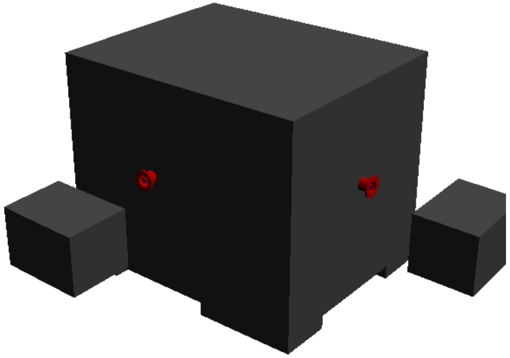






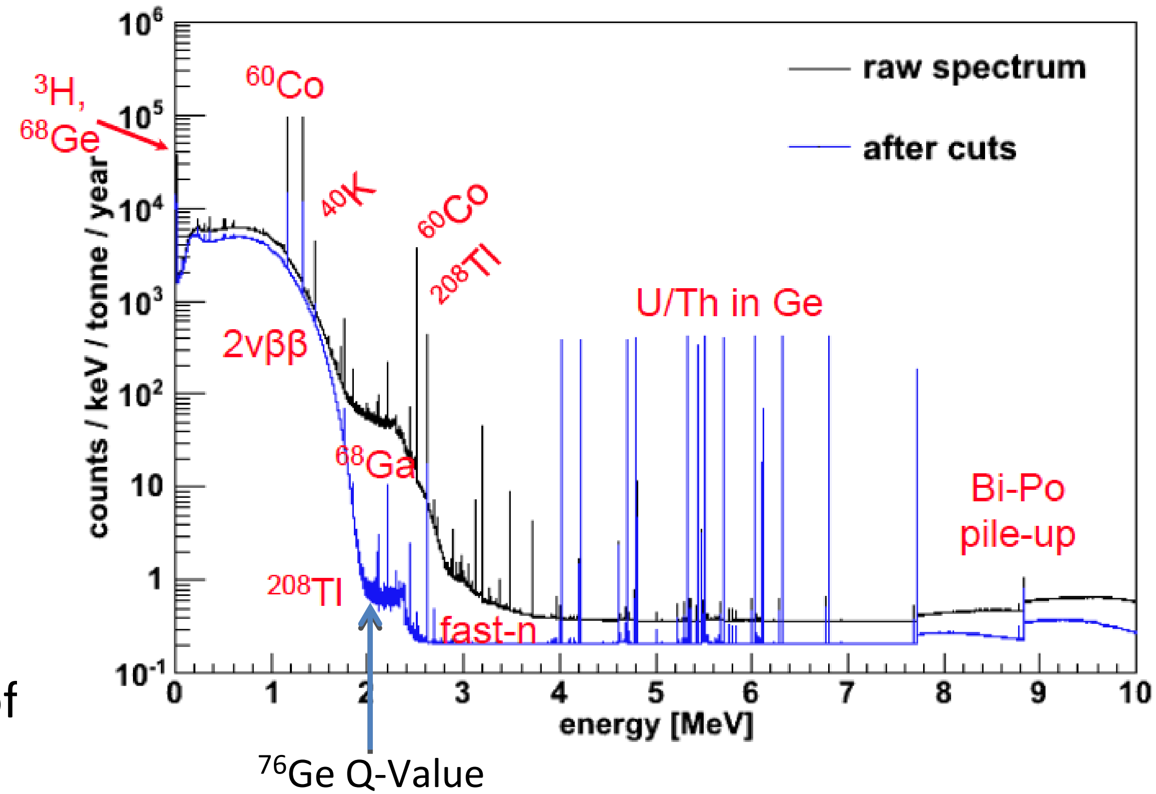






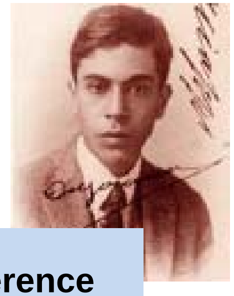
Background Simulations

- Full-spectrum background model:
  - Uranium / Thorium decay chains
  - ^{40}K / ^{60}Co / ^{68}Ge
  - α / β emitting surface contaminants
  - Neutron backgrounds
- Engineering design support
  - Shielding / veto efficiencies
  - Materials qualifications
  - Calibration system design
- Estimation of effectiveness of analysis cuts
- ~60k CPU hrs, 15Tb data on NERSC clusters



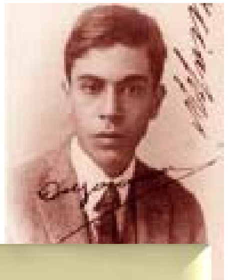
NATIONAL ENERGY RESEARCH SCIENTIFIC COMPUTING CENTER
Advancing Computational Science of Scale—Producing Real Results

Material Assay

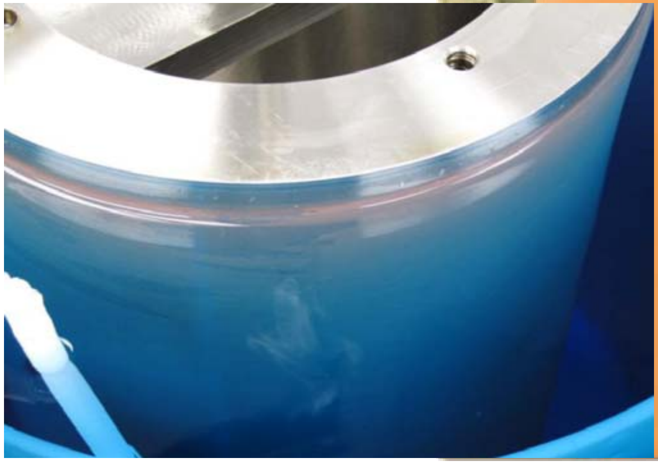


Material	Uses	Contaminant Goals	Equivalent Achieved Assay	Reference
Germanium	Detectors	<100 days ^{68}Ge exp. <30 days ^{60}Co exp.	N/A	[Avi92], [Ell10]
		<14 nBq/kg U/Th	<14 nBq/kg	[Det08b]
		<0.5 μBq/cm^2 surf. α	<0.5 μBq/cm^2	
Electroformed Copper	Detector Mounts, Cryostat Inner Cu Shield	<0.1 μBq/kg ^{208}Tl <0.3 μBq/kg ^{214}Bi <<20 μBq/kg ^{60}Co	0.2 ± 0.1 μBq/kg <1.3 μBq/kg rej. fac. ≤100	[Hop09], [Hop11]
Commercial Copper	Outer Cu Shield	<0.3 μBq/kg ^{208}Tl <3 μBq/kg ^{214}Bi ≤saturation ^{60}Co	0.3 ± 0.1 μBq/kg <36 μBq/kg <saturation	[Hop09], [Leo08]
Lead	Lead Shield	<1 μBq/kg ^{208}Tl <10 μBq/kg ^{214}Bi	<1 μBq/kg <10 μBq/kg	[Leo08]
Plastic	Detector Mounts, Insulation	<0.4 μBq/kg ^{208}Tl <10 μBq/kg ^{214}Bi	36 ± 3 nBq/kg <10 μBq/kg	[Efr10], [Leo08]
Small Components	Front-End Electronics, Contacts	<6 nBq/chan. ^{208}Tl <24 nBq/chan. ^{214}Bi	<6 nBq/chan. <24 nBq/chan.	[Leo08], [Loa10]
Cables	Signal, High-Voltage	<40 μBq/kg ^{208}Tl <500 μBq/kg ^{214}Bi	<40 μBq/kg <500 μBq/kg	[Det08], [Loa10]
Polyethylene Shield	Neutron Modification	≥30 cm	N/A	[Bac08]
Rock	Overburden	≥4300 mwe	N/A	[Ste10]

Electroformed Cu



- Cryostats 1&2, their detector components, shielding to be fabricated from underground e-formed Cu
- Baths operational at SUL, PNNL shallow underground facility
- Electroforming process inherently high-purity
- Assays of produced Cu show < 1ppt U^{238}
- 75 μm/day growth rate

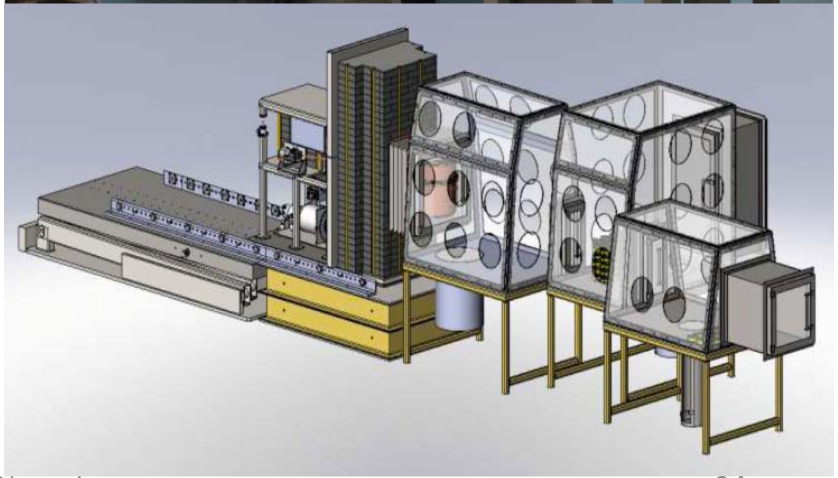


Cryostat and Component Fabrication

- Underground cleanroom machine shop being installed in MJD lab
- Most copper components will have no surface exposure
- Only clean, water-soluble lubricant
- All components acid-etched, surface-passivated
- Parts-tracking DB in use

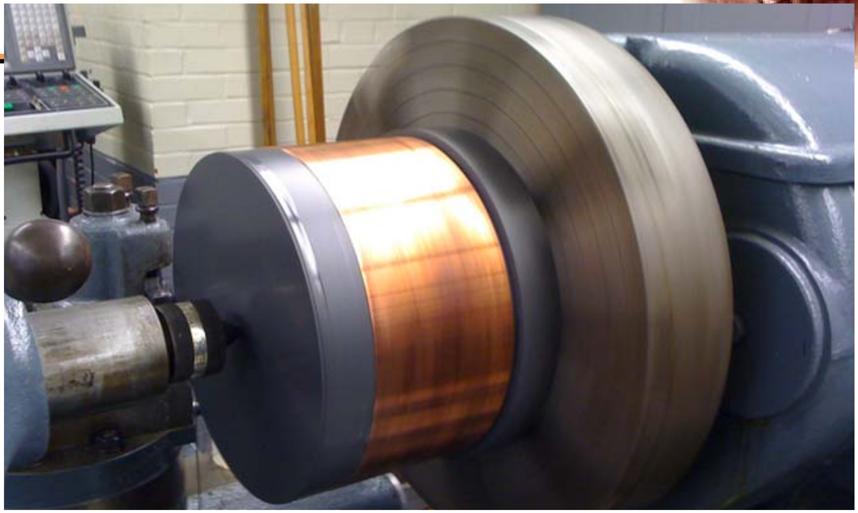
Glovebox Assembly

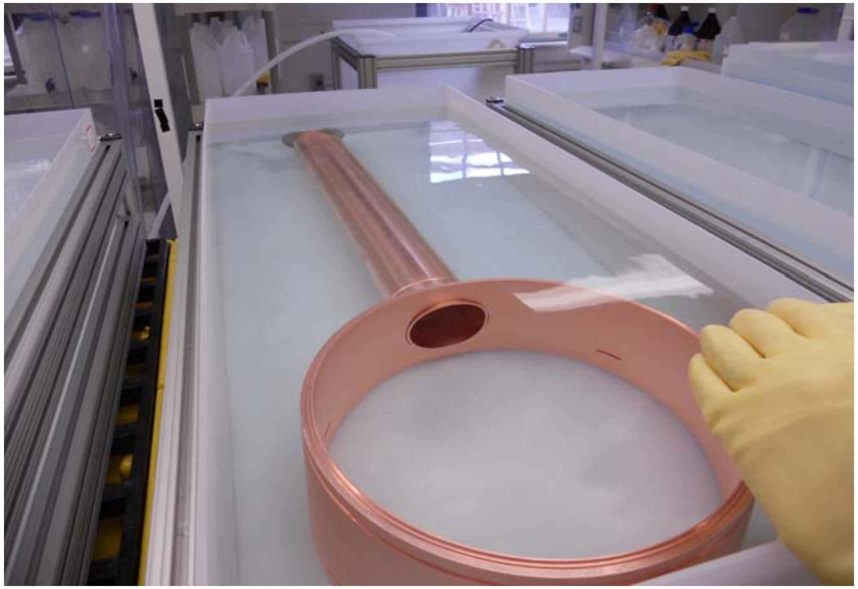
Detectors handled in
Rn-mitigated glovebox.



The Prototype Cryostat

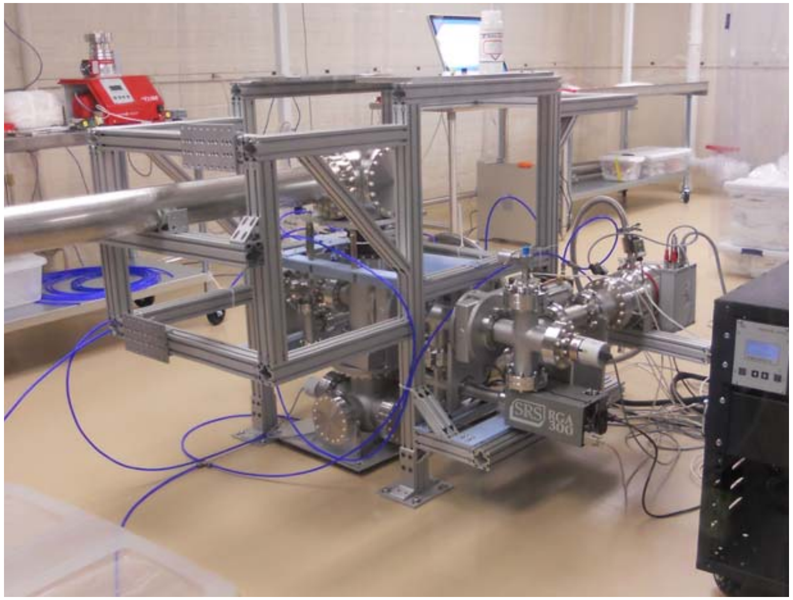
- Commercial Cu Cryostat
- Test of fabrication and assembly techniques / procedures
- Test of mechanical design

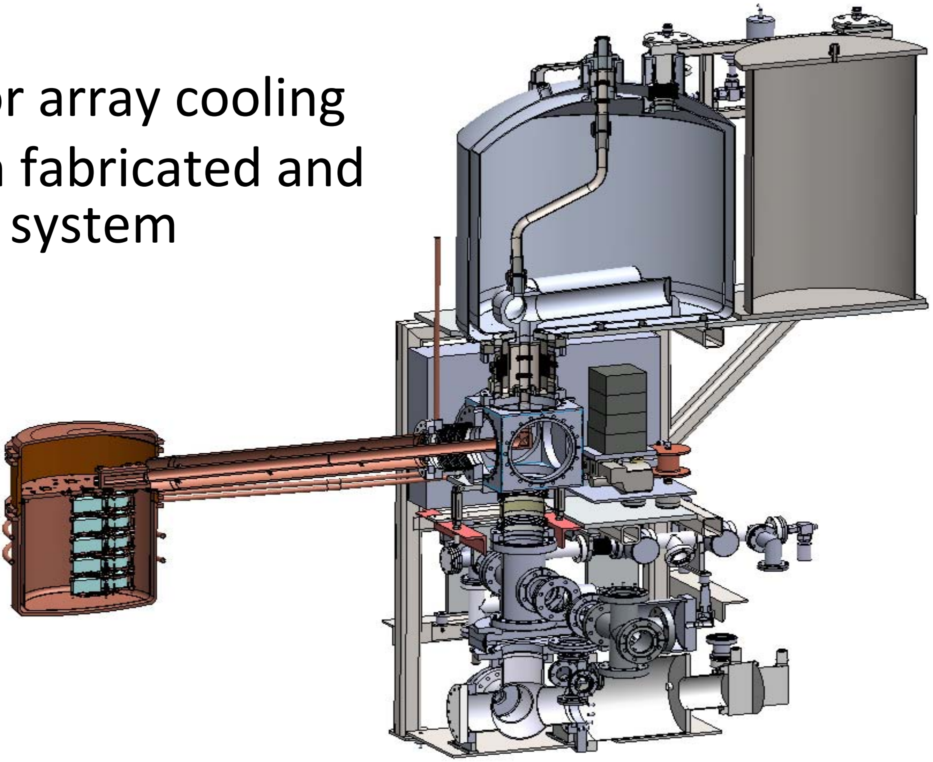




Vacuum & Cryogenic Systems

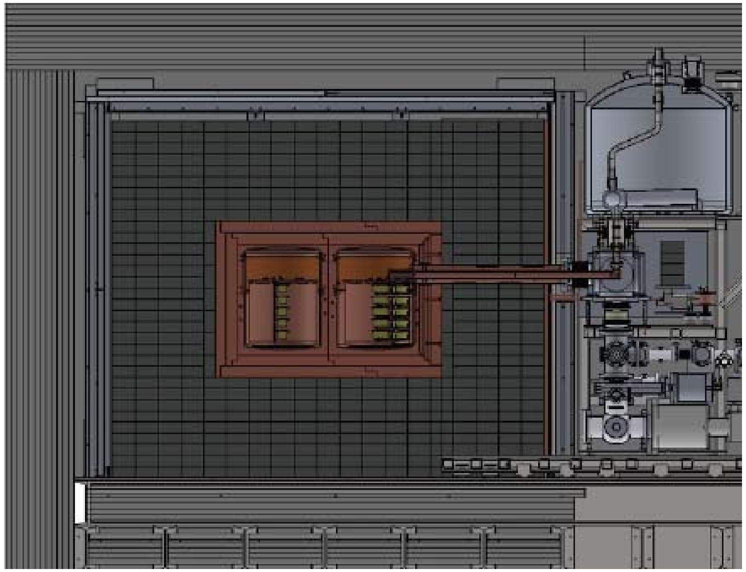
- Remotely-operated UHV vacuum system
- Prototype Cryostat vacuum system commissioning underway
- Thermosyphon system for detector array cooling
- Prototype Cryostat Thermosyphon fabricated and ready for integration with vacuum system

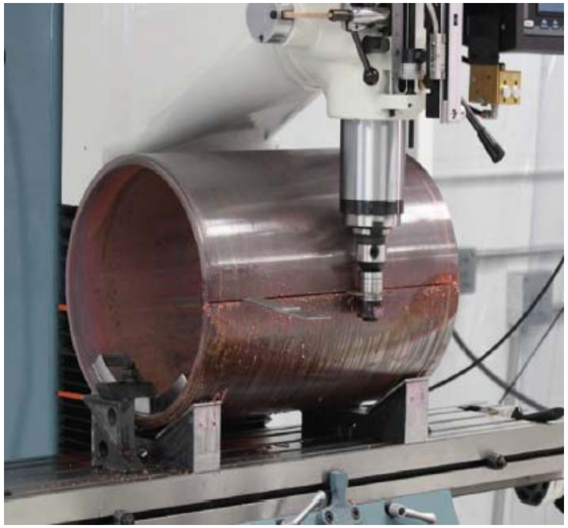


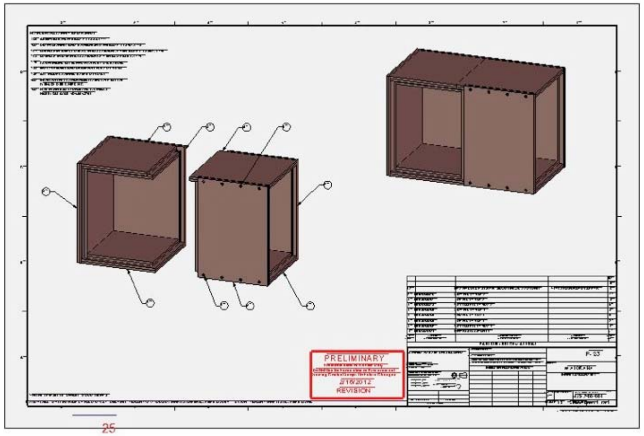


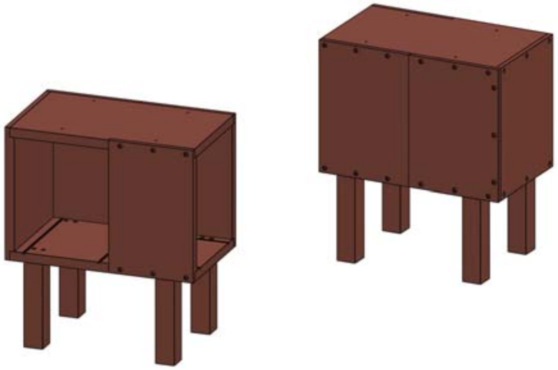
Passive Shielding: Copper

- 5cm ultra-pure EFCu inner shield
- 5cm low-background commercial copper outer shield
- Design complete, fabrication begun.
- Inner shield EFCu in production



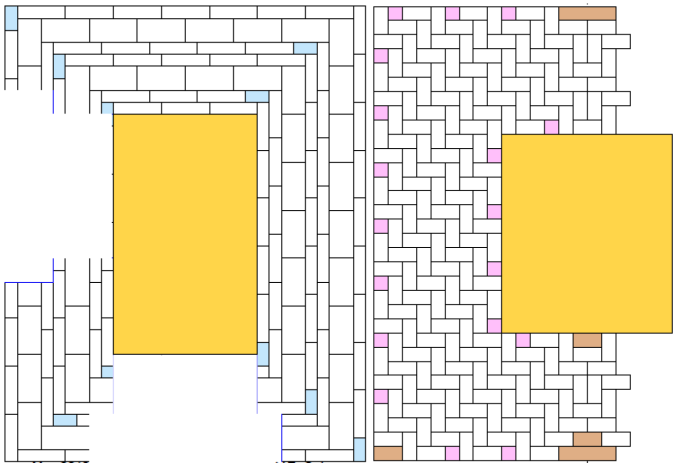






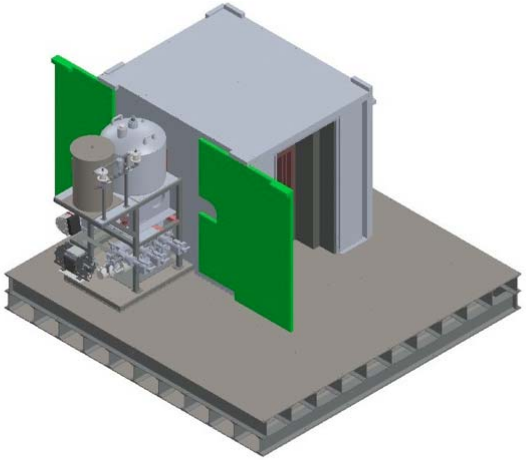
Passive Shielding: Lead

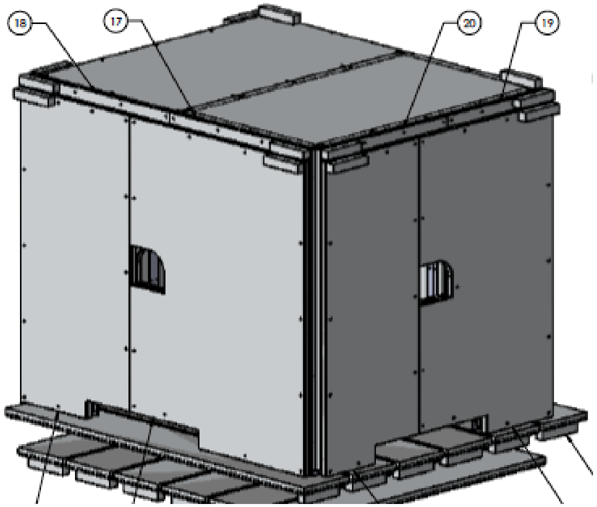
- 45cm Pb shielding
- 3500 5cm x 10cm x 20cm bricks purchased from Sullivan Lead, virgin Doe Run Source
- ~3000 bricks donated from University of Washington
- Cleaning facilities constructed
- Stacking pattern designed



Active Muon Veto

- Near-complete 4π coverage
- Monte Carlo studies: >99% efficiency
- Scintillator parts being procured



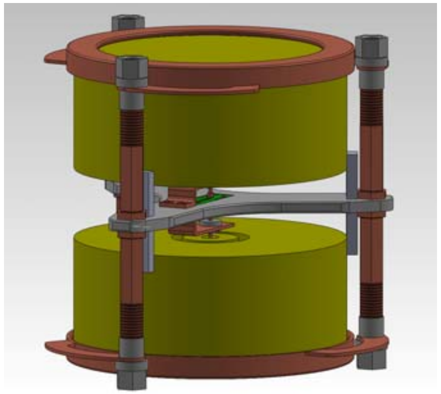


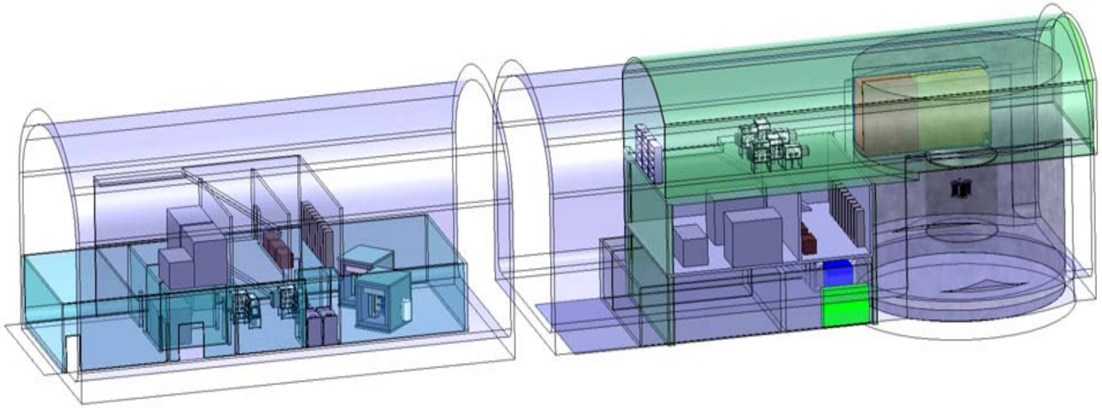
Potential DEMONSTRATOR Physics Reach

- The Demonstrator is an ultra-low background, low-threshold, high-resolution detector.
- Possible searches for new physics include:
  - $0\nu\beta\beta$
  - Dark Matter WIMPs
  - Axions
  - Sterile neutrinos
  - Pauli Exclusion Principle violation, other exotic things

Toward Tonne-Scale

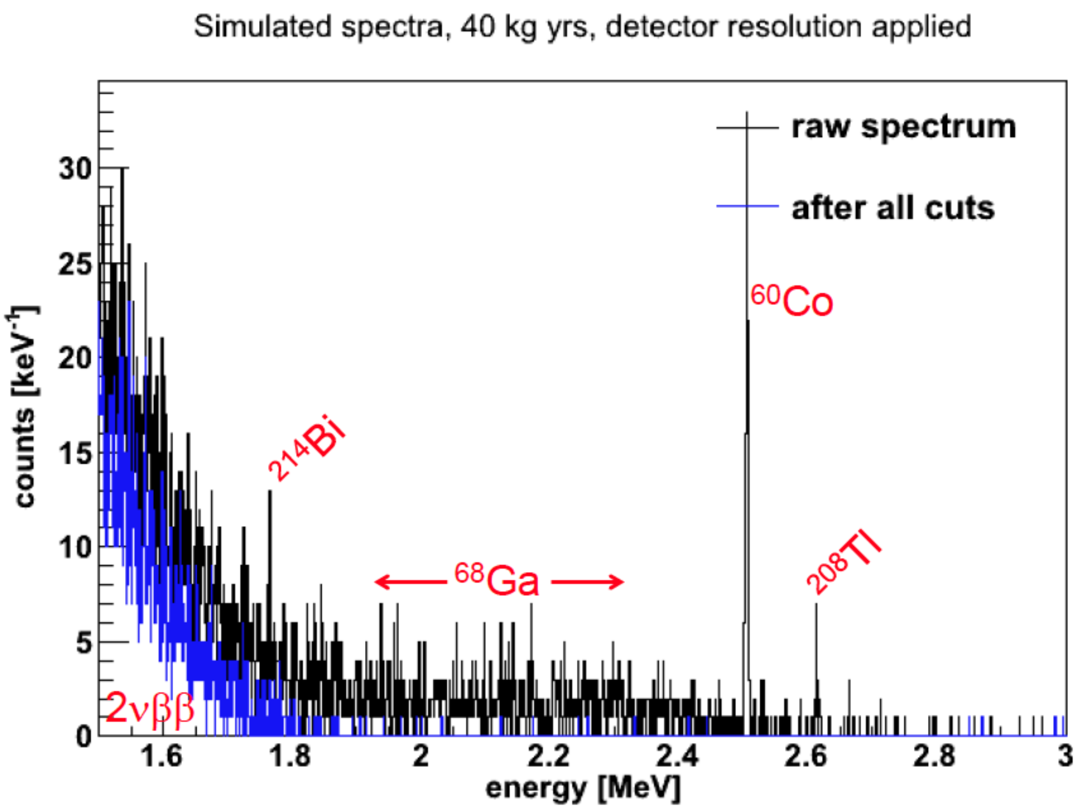
- Utilizes and builds on major R&D activities of GERDA and MAJORANA Collaborations.
- Pursuing a range of shield designs between the compact and the GERDA-like. Ultimate design will be based on results from GERDA Phases I & II and the MAJORANA DEMONSTRATOR.
- Should have preliminary information from both GERDA Phase II and MJD Cryo 1, aim to reach agreement on the down-select process during 2014.
- Various site options:
  - SNOLAB 6800L
  - China Jinping Underground Laboratory 8240’
  - Homestake 4850L - compact shield looks very risky based on current knowledge of background requirements. LAr also faces risks.





Summary

- The MAJORANA DEMONSTRATOR will probe $0\nu\beta\beta$ and dark matter with an ultra-low background detector.
- Phased deployment over the next 3 years, with data from enriched detectors as soon as 2013.
- The MAJORANA & Gerda Collaborations will combine efforts on a tonne-scale $0\nu\beta\beta$ experiment that will have the sensitivity to probe $0\nu\beta\beta$ lifetimes in ^{76}Ge ~10^{27}-10^{28} years.



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