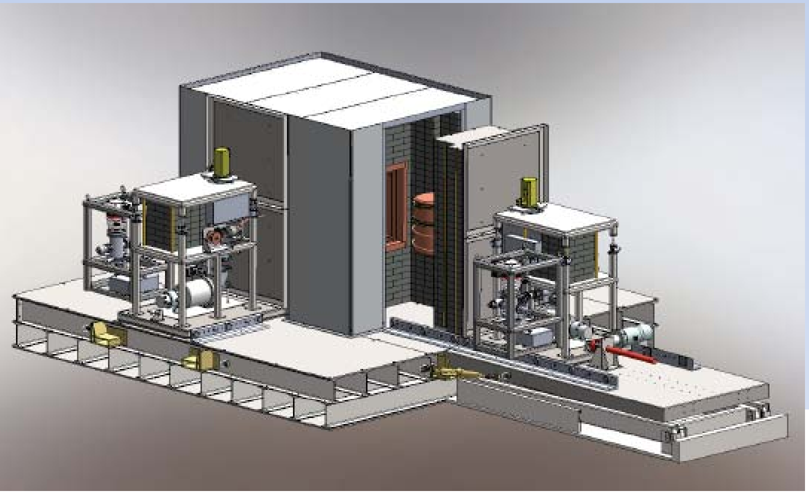
The MAJORANA DEMONSTRATOR



Ryan Martin, for the MAJORANA Collaboration
Lawrence Berkeley National Laboratory
DBD '11, Osaka, Japan, November 2011

Outline

- ^{76}Ge for neutrinoless double-beta decay
- MAJORANA goals and expected sensitivity
- Backgrounds and mitigation
- Technology choices and development status

Germanium for neutrinoless double-beta decay experiments

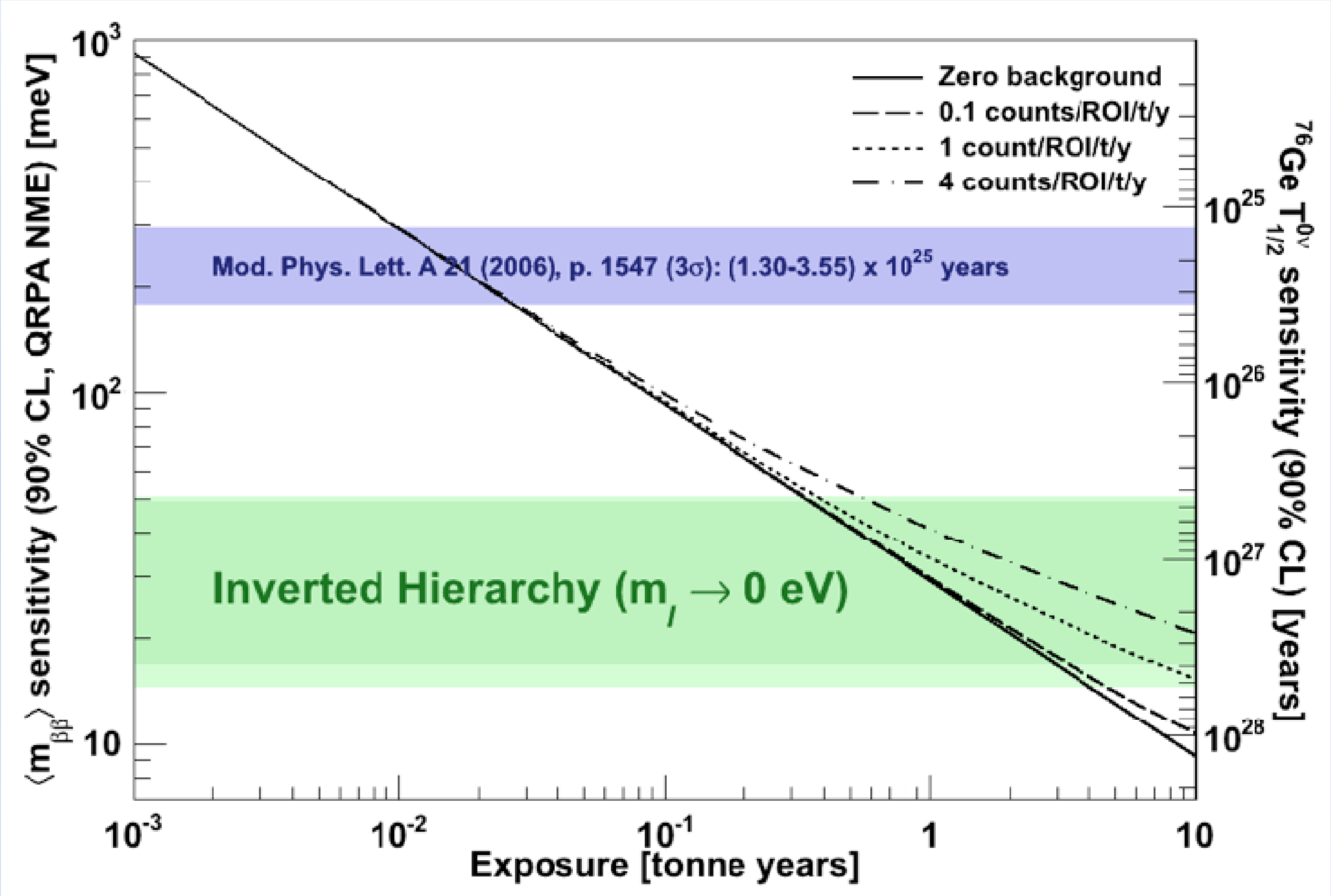
Germanium detectors

- Source is detector
- Good energy resolution
- Well established technology
- Intrinsically clean (high-purity germanium)

^{76}Ge isotope for $0\nu\beta\beta$

- Q-value of 2039keV above most backgrounds
- Can be enriched to >86% in ^{76}Ge (nat. abundance ~ 8%)
- Slow $2\nu\beta\beta$ rate (10^{21} yr)
- Best limit to date on $0\nu\beta\beta$

Tonne-scale sensitivity for Ge



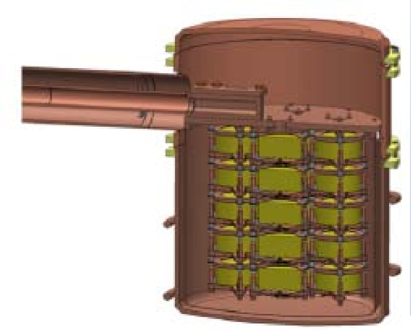
Need tonne-year exposure to probe inverted hierarchy, atmospheric neutrino mass scale

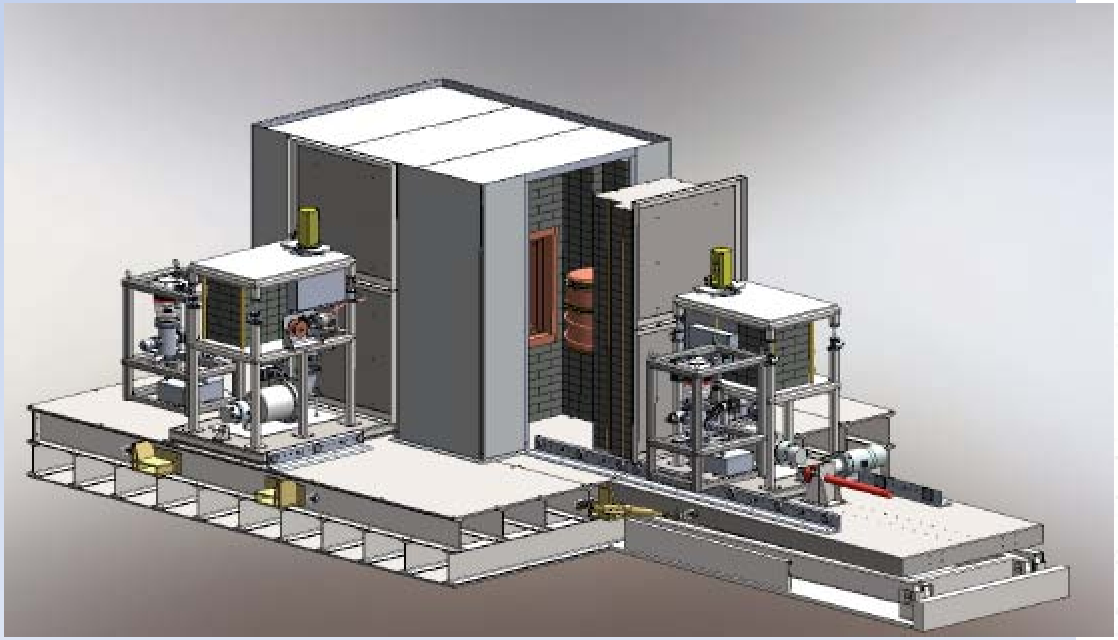
MAJORANA DEMONSTRATOR Goals

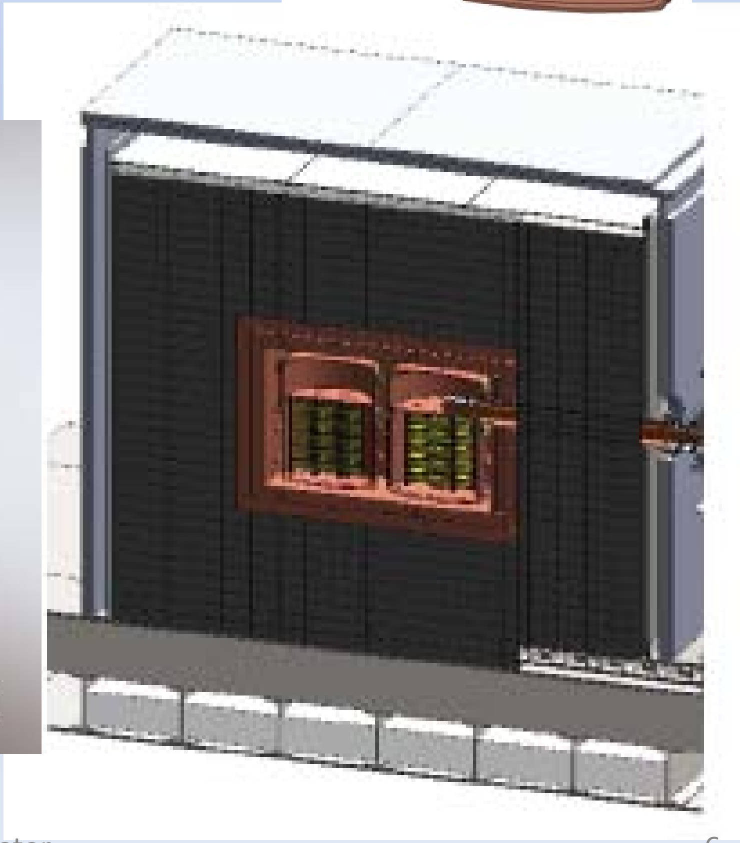
- An R&D project towards a tonne scale germanium experiment
- Demonstrate a design that can achieve a background rate of 1cnt/t/y/ROI when scaled to a 1 tonne detector (ROI = 4keV region around 2039keV)
- Test Klapdor-Kleingrothaus claim
- Agreement to work with GERDA to develop a design for a tonne scale experiment
- Potential for additional physics (eg. dark matter)

The MAJORANA DEMONSTRATOR

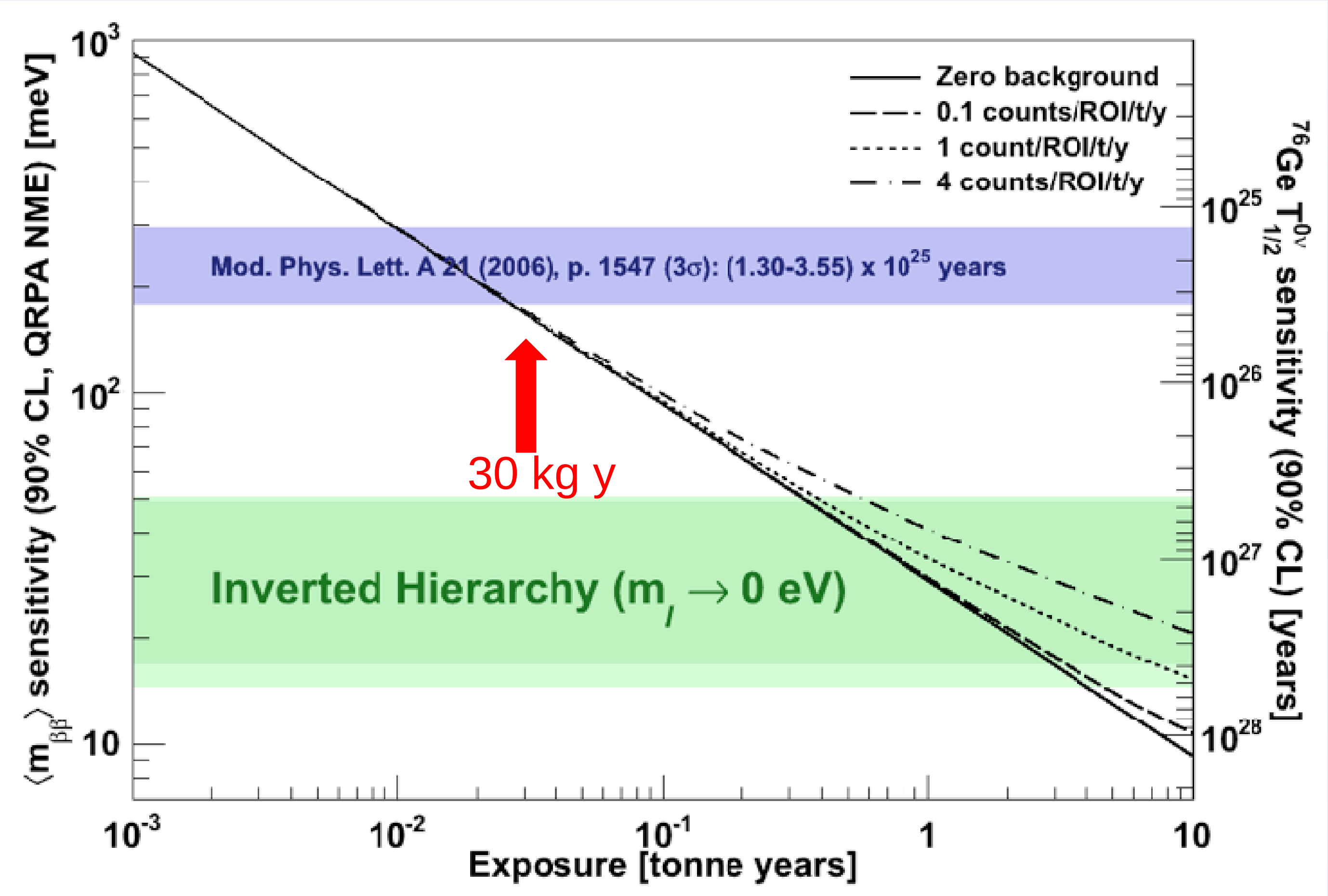
- 40kg of detectors, up to 30kg enriched to >86% ^{76}Ge
- 2 cryostats made of copper electroformed underground, 7 strings of 5 detectors per cryostat
- "Conventional" shielding (EfCu, Cu, Pb, poly),4π active muon veto, Rn exclusion box







MJD Sensitivity

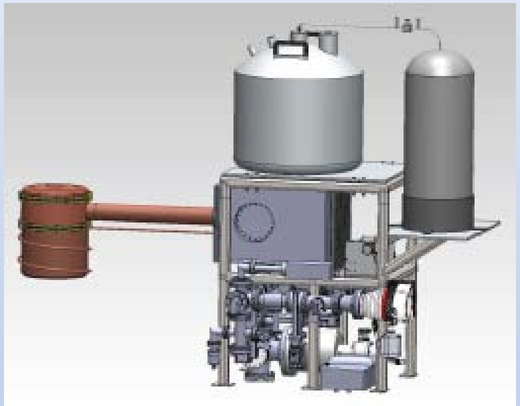


With 30kg of enriched germanium detectors, ~1 yr to test KKDC claim at 90%

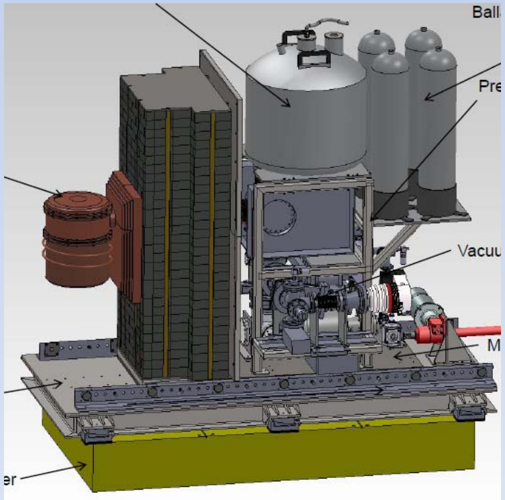
MJD Schedule

MJD will proceed in 3 phases

- **Prototype Module (summer 2012):**
  - o above ground, commercial copper, 2-3 strings ^{nat}Ge
  - ➢ Test mechanical design
  - ➢ Test detector performance in cryostat and Monte Carlo models (eg. granularity)
- **Cryostat 1 (spring 2013)**:
  - o underground, electroformed copper, 3 strings ^{enr}Ge, 4 strings ^{nat}Ge
- **Cryostat 2 (fall 2014)**:
  - o underground, electroformed copper, up to 7 strings ^{enr}Ge



Prototype cryostat

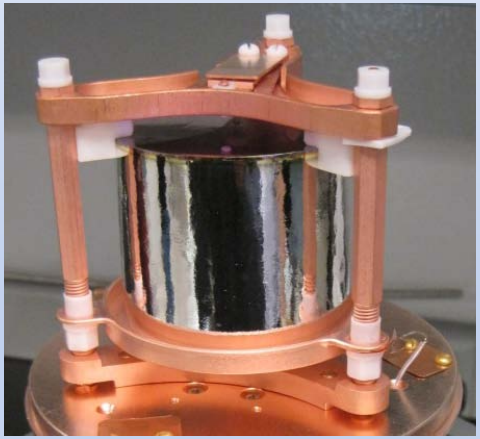


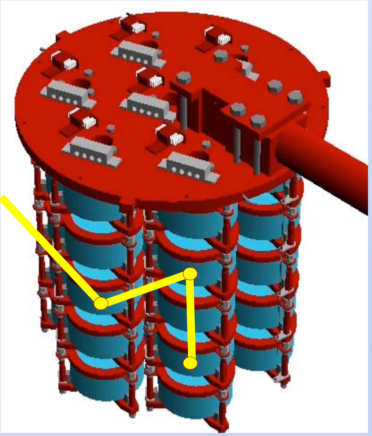
Underground cryostat and “monolith”

Backgrounds and mitigation

- **Natural radioactivity:**
  - **in components (U, Th)**
  - **surface contaminants (α, β)**
- Cosmogenic:
  - Activation (^{68}Ge, ^{60}Co)
  - Muons, fast neutrons
- Irreducible:
  - $2\nu\beta\beta$ decay
  - Neutrino scattering (reactor, solar, atm., geo, SN…)

Detector mount and Geant4 geometry:



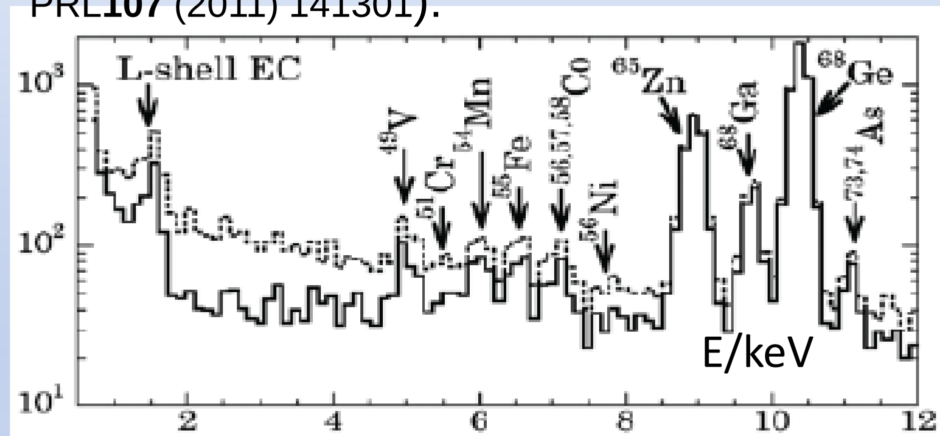


•Detailed MC simulations to understand background contributions
•Intensive assay campaign to identify clean materials
•Clean handling
•Special processes (electroforming)
•Analysis cuts ("PSA", "granularity")

Backgrounds and mitigation

- Natural radioactivity:
  - in components (U, Th)
  - surface contaminants (α, β)
- **Cosmogenic:**
  - **Activation (^{68}Ge, ^{60}Co)**
  - **Muons, fast neutrons**
- Irreducible:
  - $2\nu\beta\beta$ decay
  - Neutrino scattering (reactor, solar, atm., geo, SN…)

Cosmogenic lines at low energy (from CoGeNT, PRL**107** (2011) 141301):

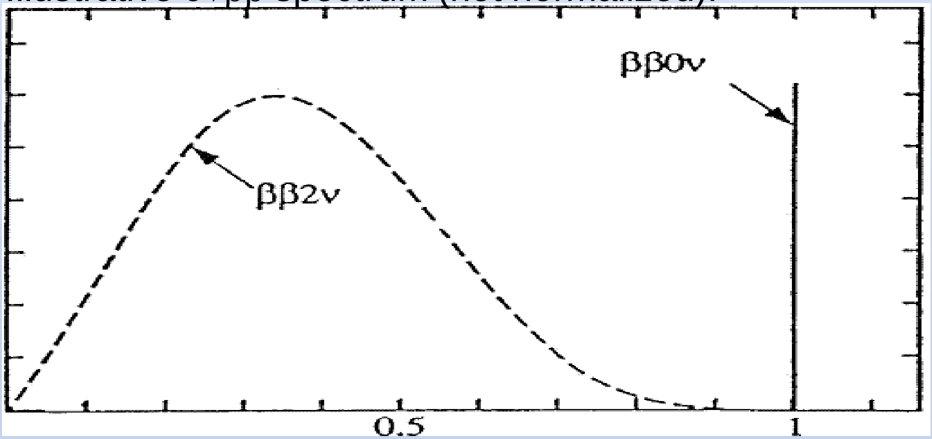


- Deep underground
- Muon veto
- Fabricate materials underground (copper)
- Limit surface exposure (germanium)
- Analysis cuts (^{68}Ge tag using low energy x-rays, Pulse Shape Analysis)

Backgrounds and mitigation

- Natural radioactivity:
  - in components (U, Th)
  - surface contaminants (α, β)
- Cosmogenic:
  - Activation (^{68}Ge, ^{60}Co)
  - Muons, fast neutrons
- **Irreducible:**
  - **2$\nu\beta\beta$ decay**
  - **Neutrino scattering (reactor, solar, atm., geo, SN…)**

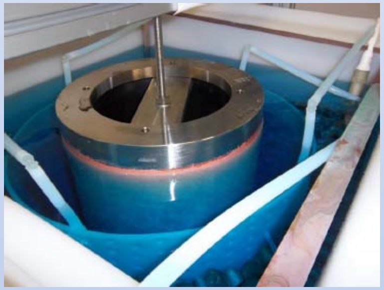
Illustrative 0$\nu\beta\beta$ spectrum (not normalized):

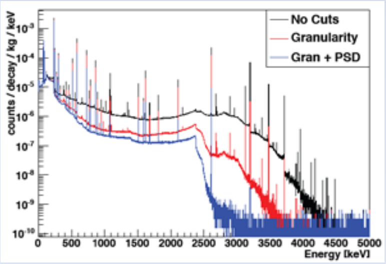


- Irreducible backgrounds
- Energy resolution of germanium is main mitigation

MJD status and technologies

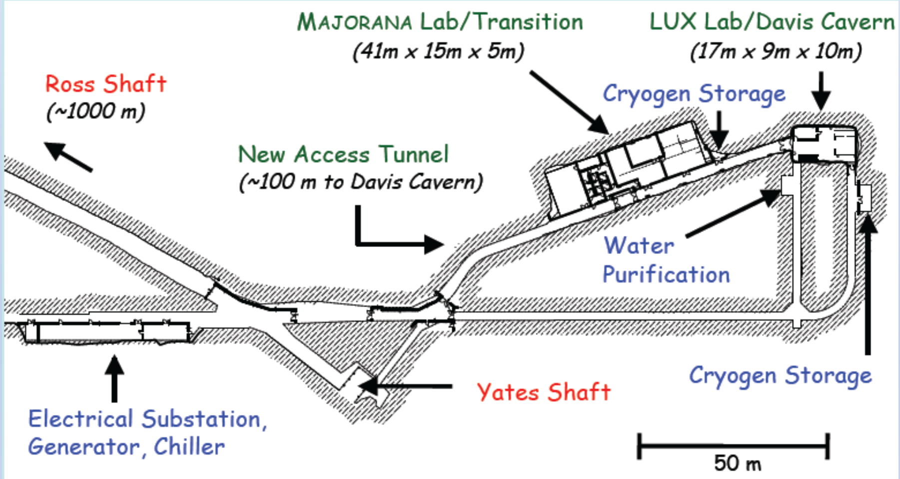
- Underground lab
- Electroformed copper
- Thermal tests
- Prototype cryostat fabrication
- MJD detectors and status
- Low noise/low background electronics
- Detector integration tests
- Detailed model and simulations
- Calibration





The Sanford Underground Lab

- MJD will be located at 4850' level of Sanford Underground Lab at the Homestake mine in Lead, South Dakota
- **Beneficial occupancy expected spring 2012**



Underground clean room

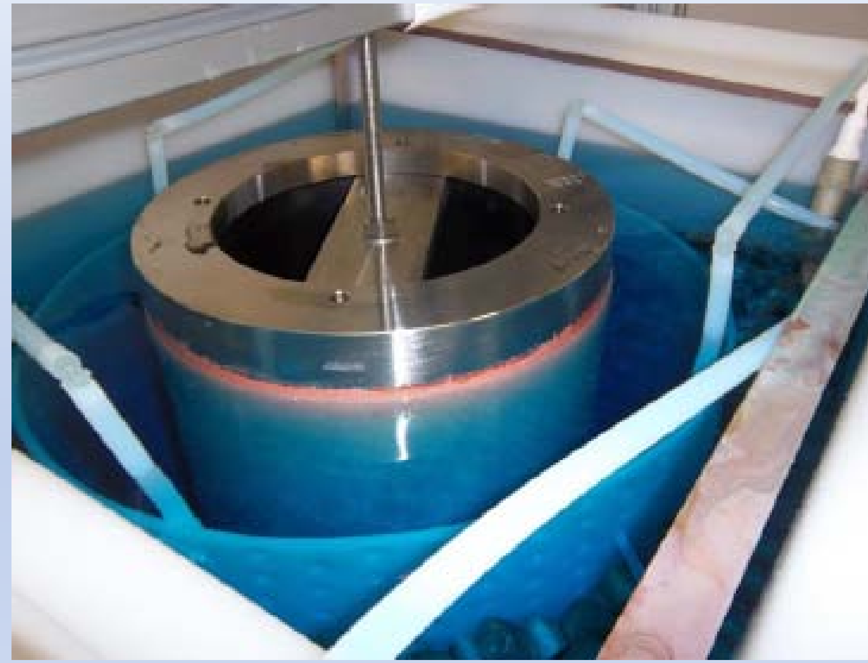
After de-watering

Clean room

- Underground clean room was completed in spring 2011
- Started storing natural detectors underground in winter 2010

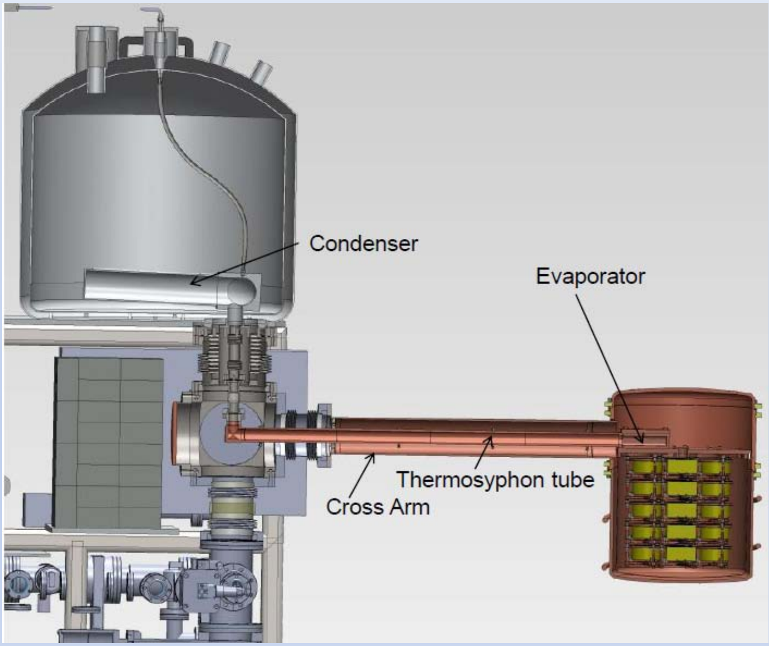
Underground detector storage

Electroformed copper



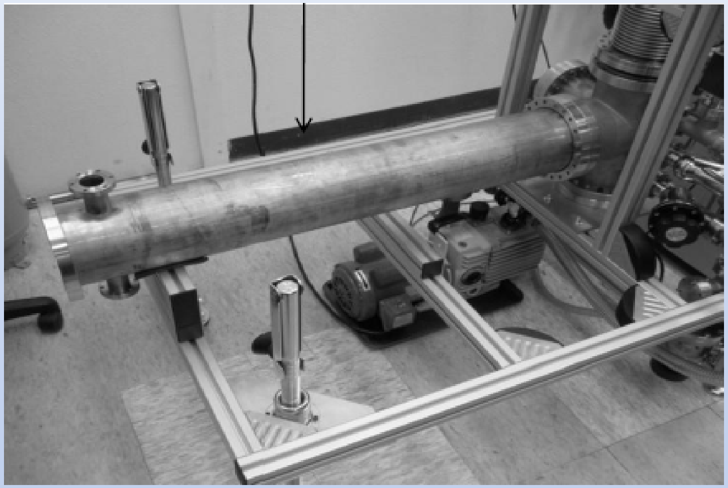
- Deployed 10 baths in underground clean room (4850ft) [also: 6 baths at PNNL (100ft), Sept.2010]
- Started underground electroforming 21 July 2011

MAJORANA detector cooling



Thermosiphon

Test string

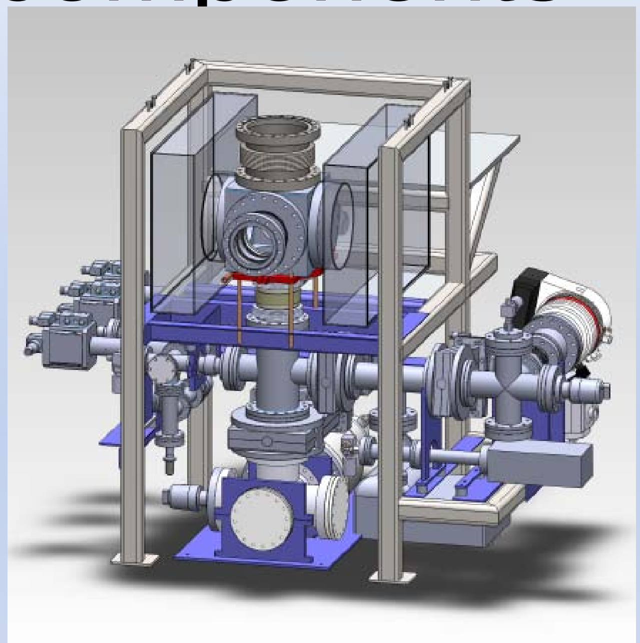


Prototype thermosiphon tested

- Cooling to the cold plate provided by a thermosiphon
- Detailed thermal model produced to understand cooling power and needs
- Cooling tests performed and design optimized (detector blanks < 95K)

MJD prototype cryostat components

Demonstrated e-beam weld for cryostat hoop



Vacuum system for prototype

Parts purchased!

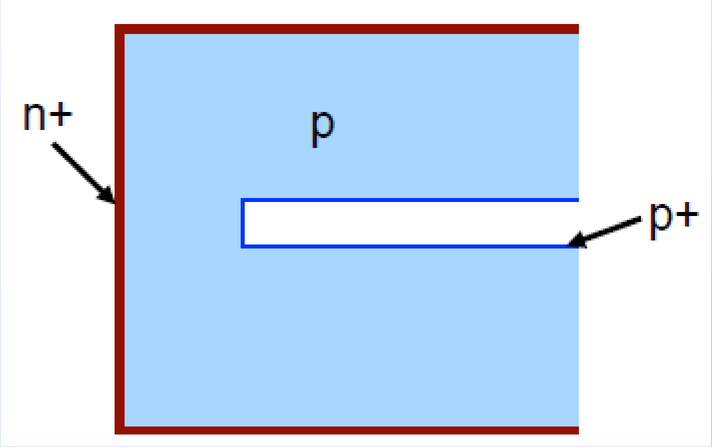
Purchased clean machining tools to be deployed in above ground clean room (then underground)

Most components for prototype in hand

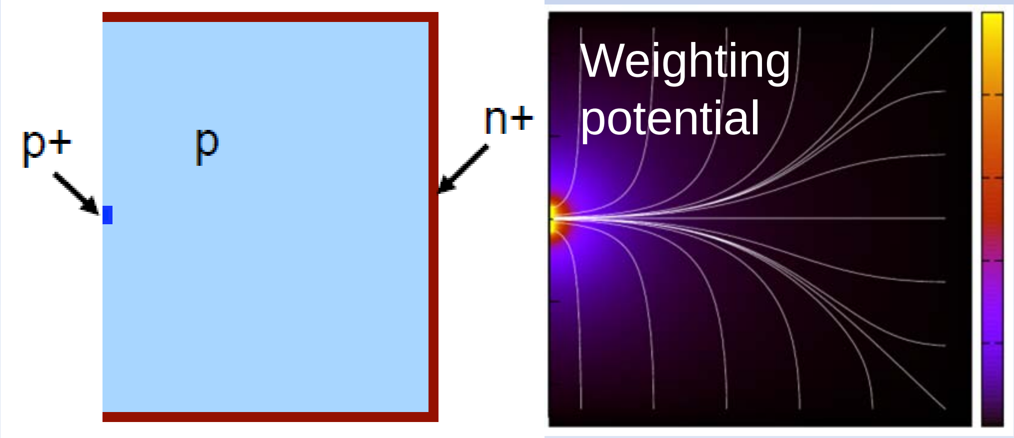
Parts for thermosiphon

"PPC" detectors

- P-type Point Contact HPGe detectors
- "Novel" technology
- Small point contact to readout charge, low capacitance
- Thick outer contact (n+, lithium diffused), strongly attenuates alphas



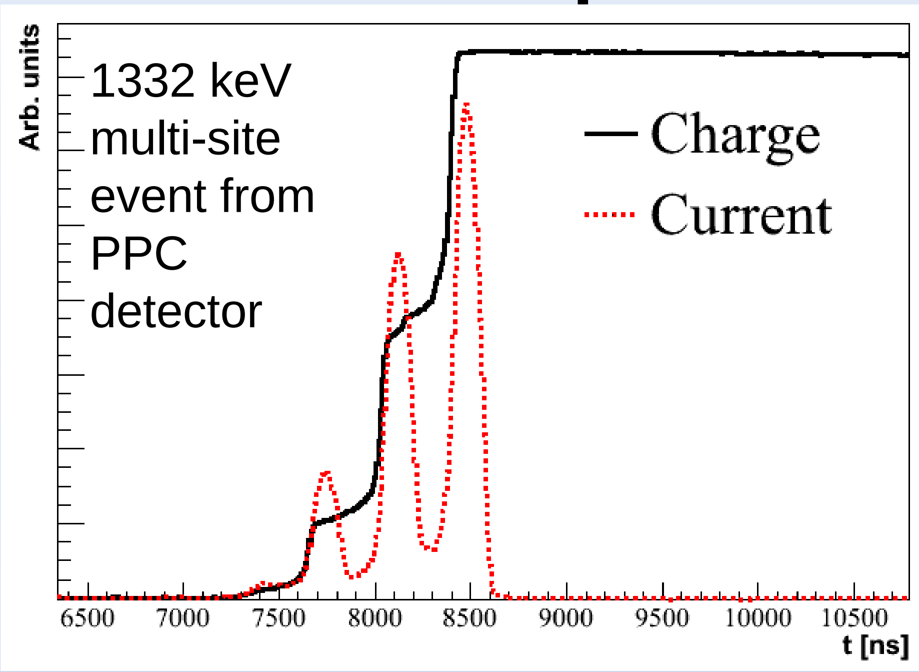
Semi coaxial detector



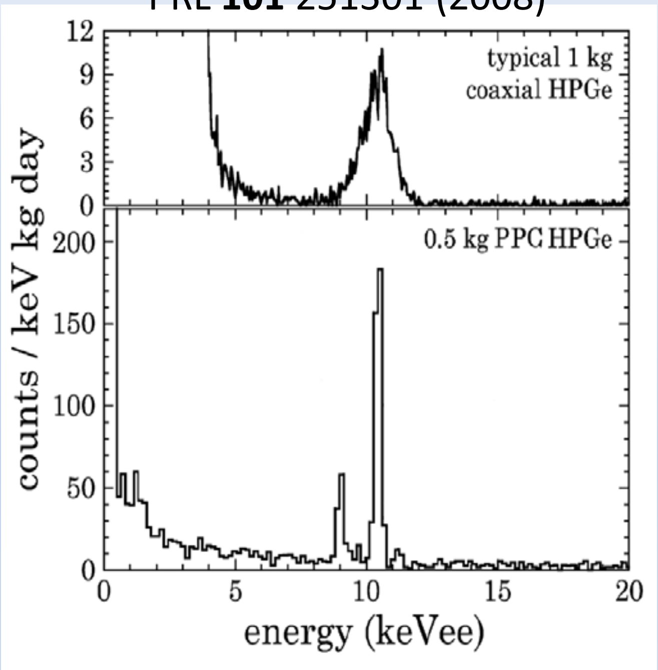
Point contact detector

•P. N. Luke, F. S. Goulding, N. W. Madden, R. H. Pehl, IEEE T. Nucl. Sci. **36** (1989) 926
•P. S. Barbeau, J. I. Collar, O. Tench, J. Cosmol. Astropart. Phys. **0709** (2007) 009.
•E. Aguayo et al. [The Majorana Collaboration], http://arxiv.org/abs/1109.6913 (2011)

Properties of PPCs



PRL **101** 251301 (2008)

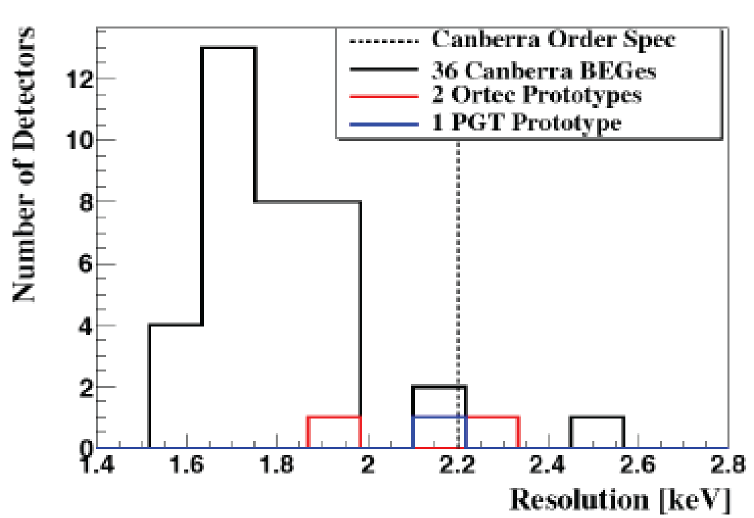


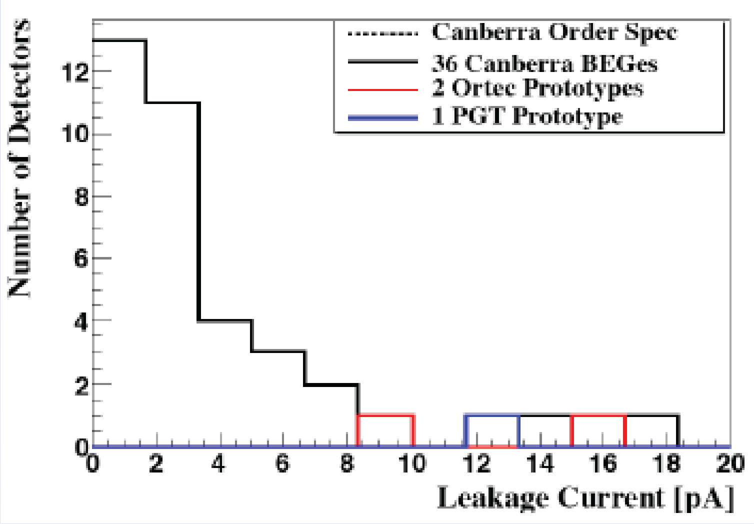
- Sharp weighting potential allows multi-site events to be identified
- Most backgrounds at 2MeV are multi-site

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

Natural detectors

- Have tested a large number of PPC detectors within the collaboration
- Have purchased all detectors required for non-enriched component
- “Modified – BEGe” detectors purchased from Canberra in FY11-12 received and characterized (20+kg)
- 19 BEGes now stored underground

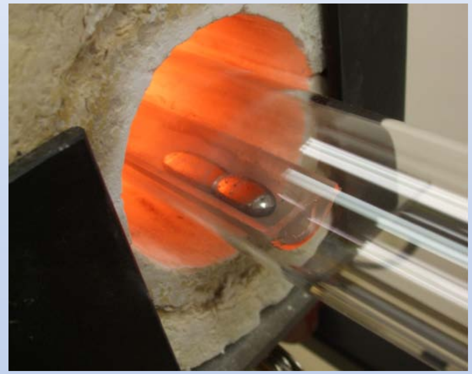




PPCs tested by MJD

Institution	Manufacturer	Dia. x length [mm x mm]	Type	Date
LBNL	Paul Luke	50 x 50	NPC	1987
		62 x 50	Segmented-PPC	2008
		20 x 10	Mini-PPCs (x3)	2009
		62 x 50	PPC	2009
	Canberra USA	70 x 30	Mod. BEGe	2011
Univ. Chicago	Canberra France	50 x 44	PPC	2005
	Canberra USA	60 x 30	Mod. BEGe (large)	2008
PNNL	Canberra France	50 x 50	PPC	2008
LANL	PHDs	72 x37	PPC	2008
	Canberra USA	70 x 30	Mod. BEGe (x39)	2009-11
	ORTEC	62 x 51	PPC	2009
		67 x 54	PPC	2010
	PGT	70 x 30	PPC	2010
UNC	Canberra USA	61 x 30	Mod. BEGe (low bgd)	2009
		61 x 32	Mod. BEGe	2010
		70 x 30	Mod. BEGe (x3)	2011

Enriched germanium processing



Enrichment to >86% at Electro-Chemical Plant (ECP) in Russia

Reduction to Ge metal at Electrochemical Systems Inc. (ESI)

Zone-refinement by commercial vendor

Pull crystal by commercial vendor

Detector fabrication by commercial detector vendor

Enriched germanium status

- Received first batch (29kg) of GeO_2 enriched in ^{76}Ge on 12th September 2011 from ECP (Russia)
- Verified to be 88% ^{76}Ge, meeting our specifications
- Material stored at shallow site (~100mwe)
- Have successfully processed ^{nat}Ge

Batch	Quantity
Batch 1	**20kg**
Batch 2	15.5kg
From Russian collaborators	10-14kg

Enriched Ge procurements (elemental weight)

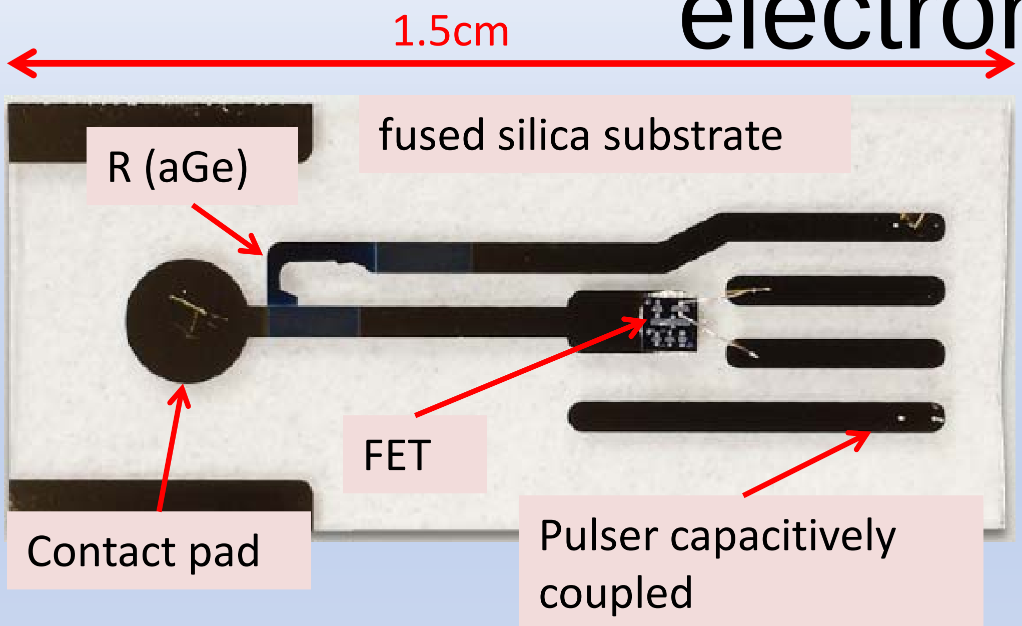
Shipping/storing shield

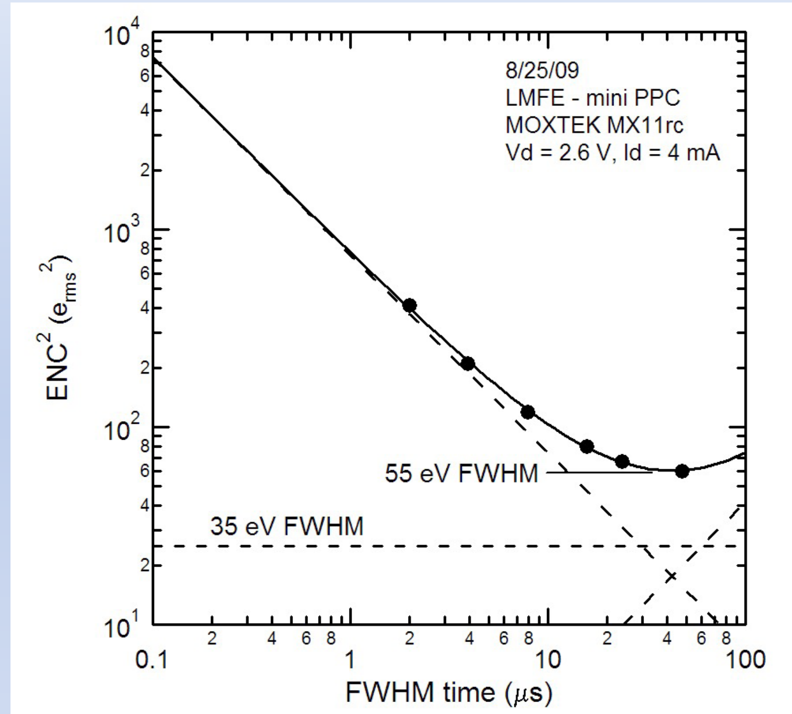
Samples to test isotopic purity

Oxide powder in storage contained

Shallow site storage safe

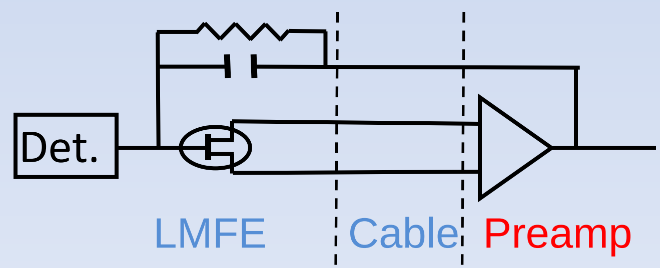
Low background front-end electronics



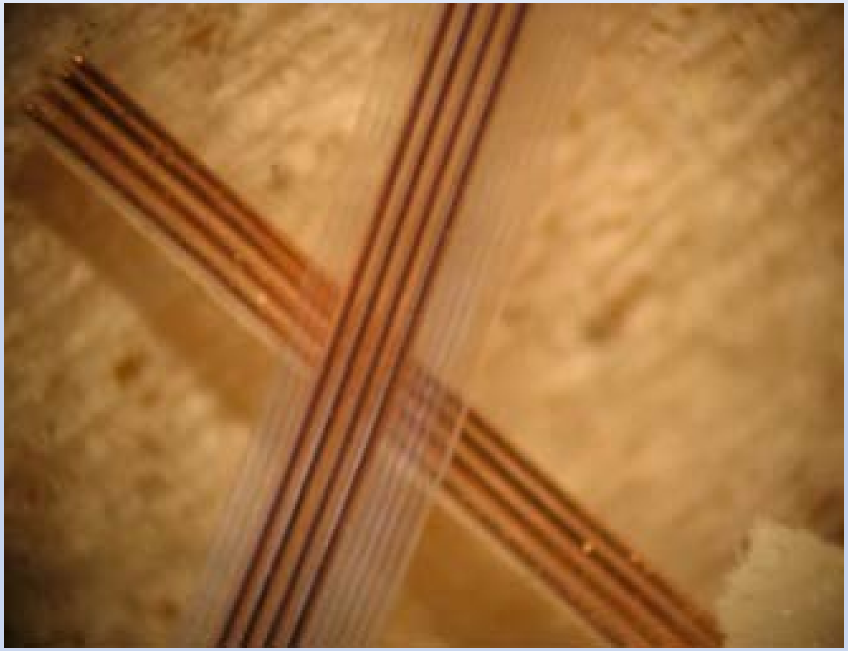


Low Mass Front End (LMFE):

- Fused silica substrate
- Au-Cr traces
- Amorphous-Ge resistor
- Low background
- Low noise

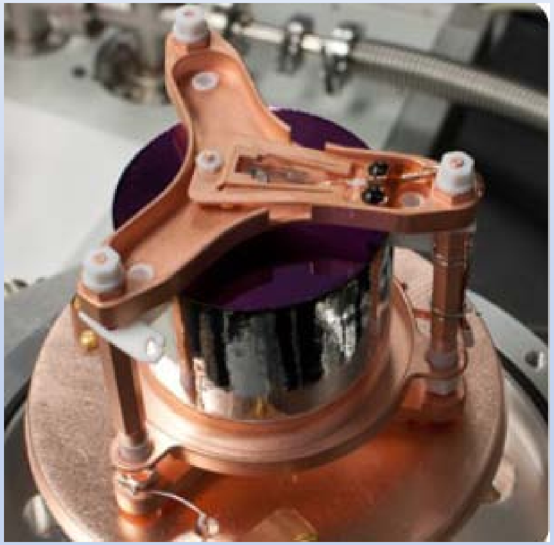


Low background cable



- Parylene coated copper
- Tested signal cable with a detector
- Components assayed clean, need to confirm for assembled cable
- Investigating commercial options in parallel

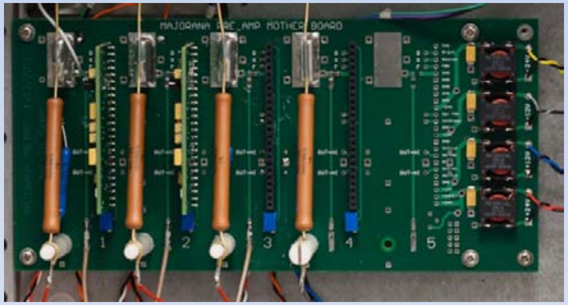
Detector integration tests



PPC detector integration test with LMFE, prototype cable, mount (2010-2011)

String integration tests (on going)

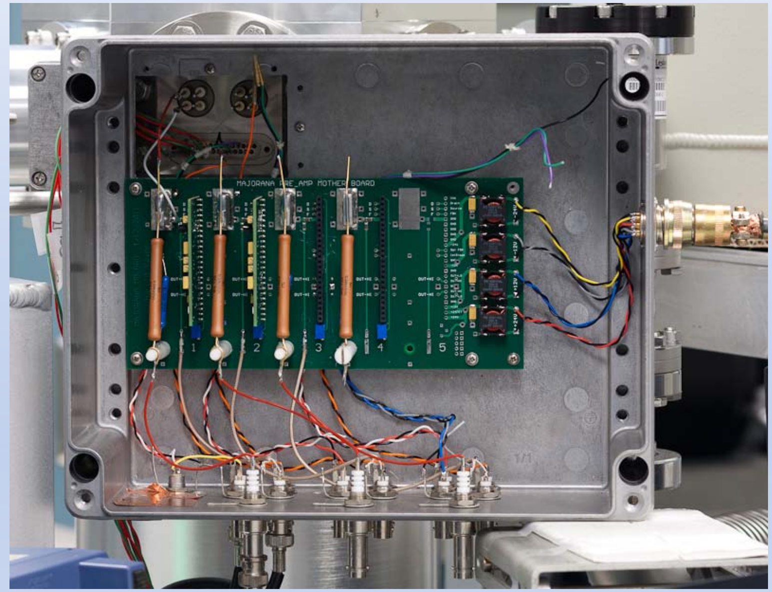
Preamplifier card (1 per detector)



Preamplifier mother board (for 5 detectors)

String test cryostat

String test cryostat and dewar



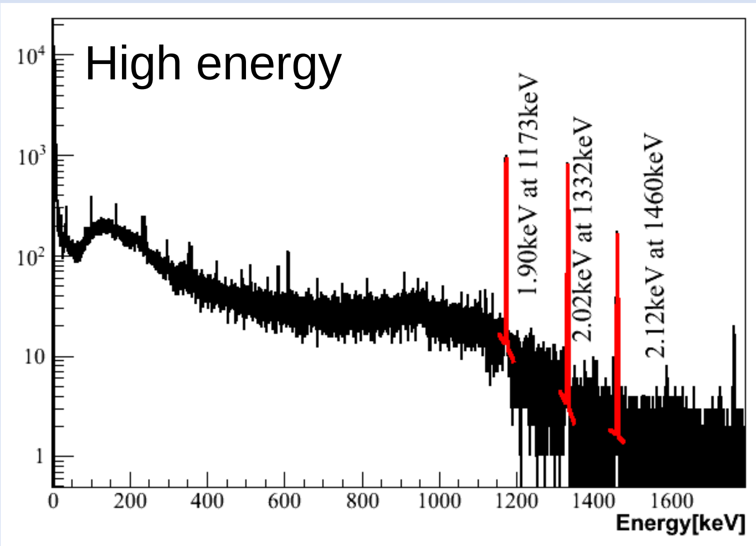
Preamplifier mother board on string test cryostat

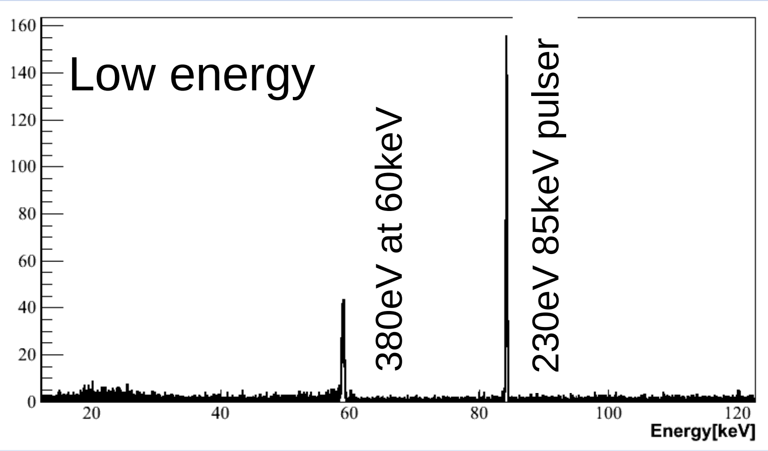
On-going tests to:

•Test electronic readout (grounding, cross-talk, etc.)

•Test operation of multiple detectors

Readout chain performance – Energy resolution



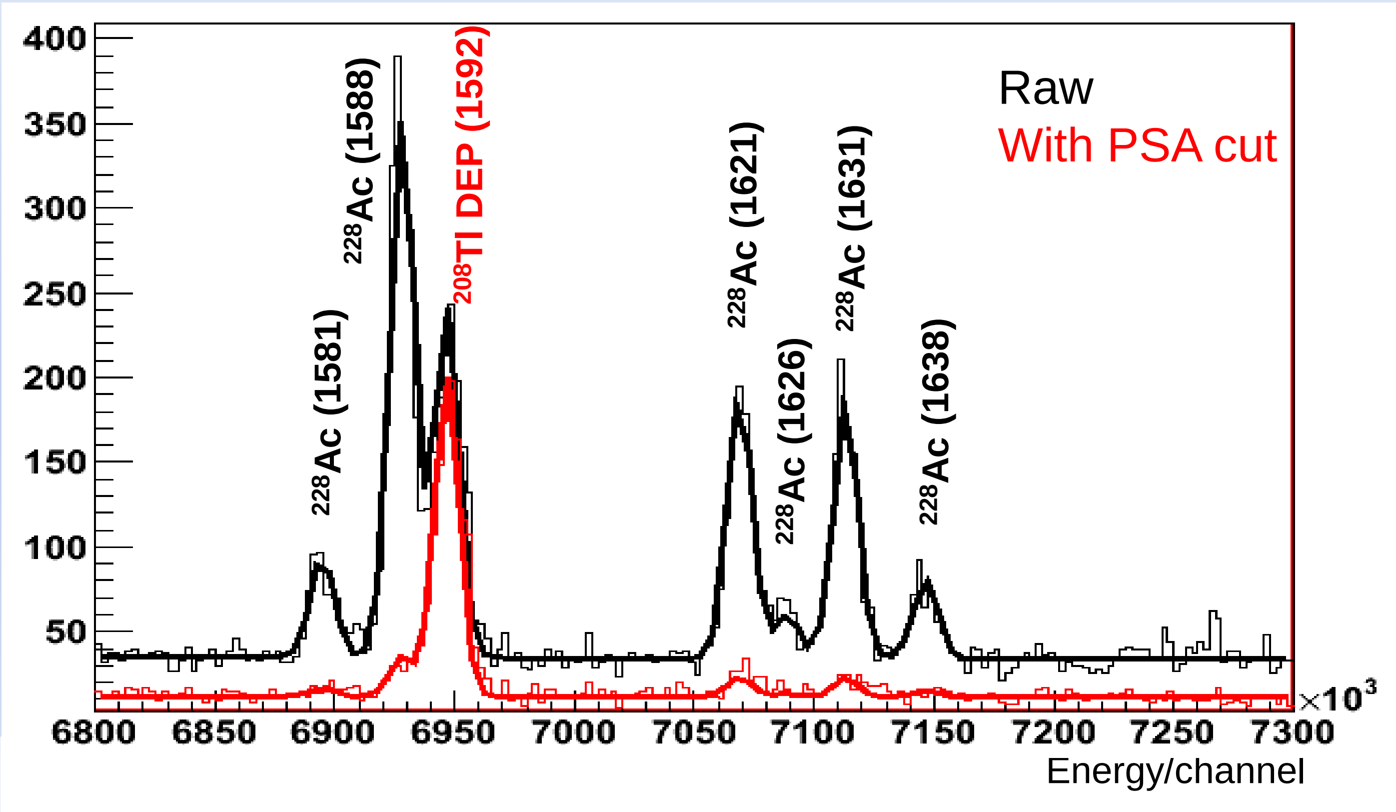


Energy resolution with readout chain meets specifications:

- high energy for $0\nu\beta\beta$
- low energy for ^{68}Ge tag

Energy	Specification	Measured
1332keV	<3.2keV	2.0keV
60keV	<0.5keV	0.38keV

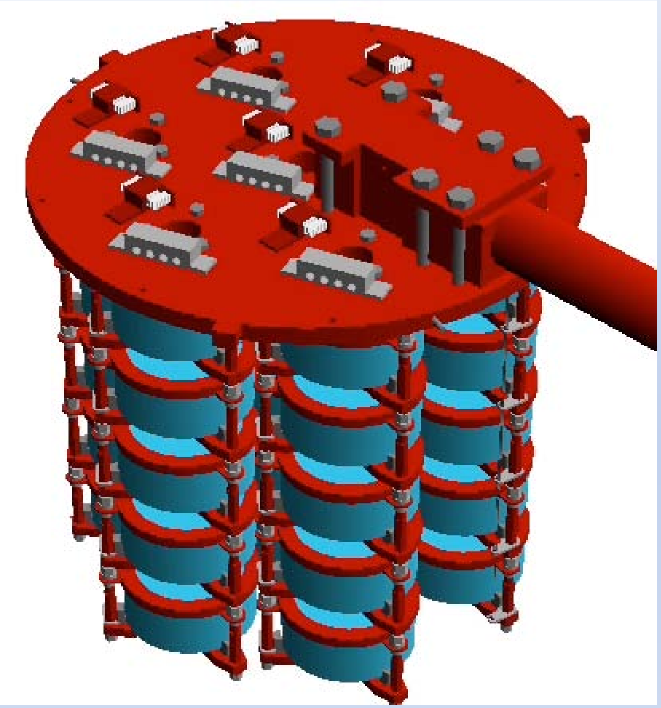
Readout chain performance – Pulse shape analysis

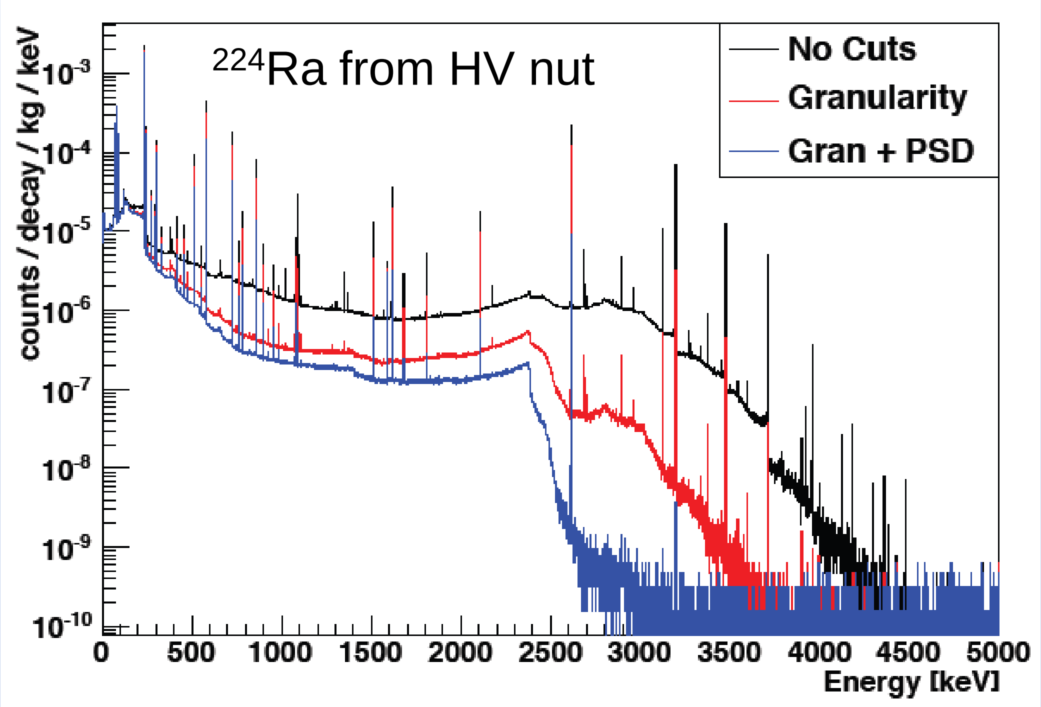


^{232}Th calibration data from prototype shows that with pulse shape analysis cut:

- Remove 93% of multi-site events (full energy peaks), background-like
- Retain 90% of single-site events (^{208}Tl double escape peak), $0\nu\beta\beta$-like

MJD Simulations

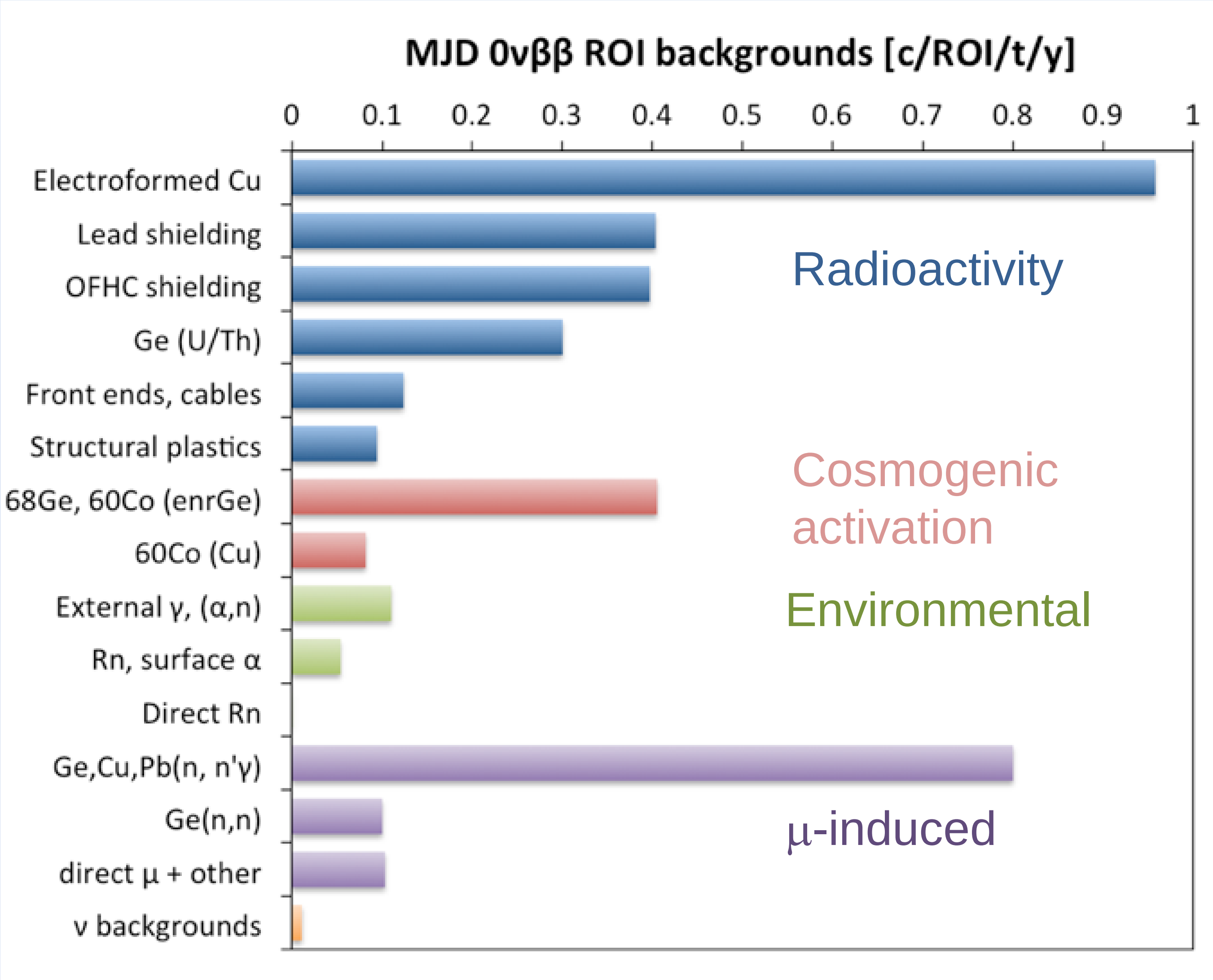




- Detailed Monte Carlo model to simulate backgrounds from 3800 components and detailed verification campaign
- So far ~60kCPU hours of simulations, analysis in progress
- U, Th, K chains for all components and ^{68}Ge, ^{60}Co for select components
- Dominant contribution at $Q_{\beta\beta}$ is from multi-site events from U and Th (^{214}Bi, ^{208}Tl)

MJD Background Model

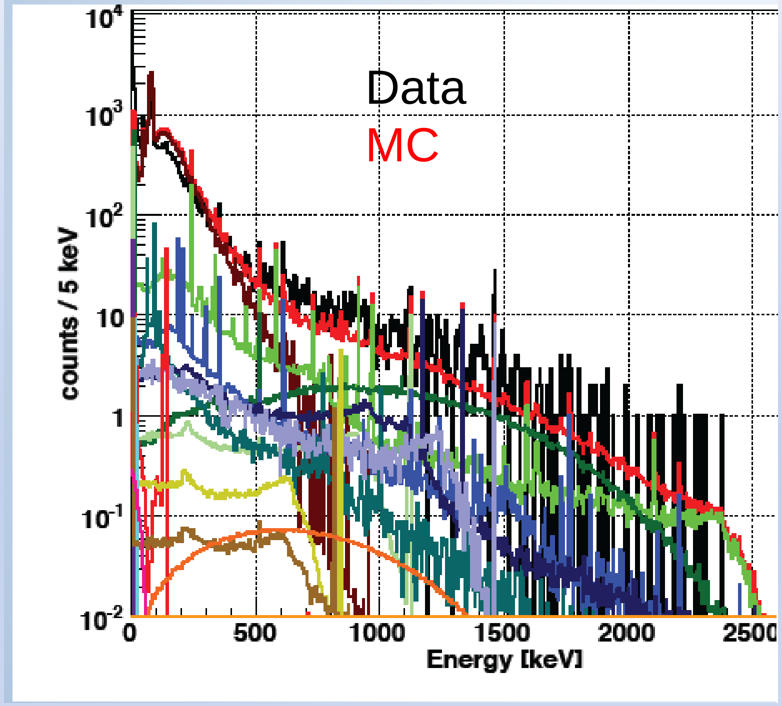
- Detailed background model produced
- Based on previous assays and reasonable expectations
- Expect 4c/t/y/ROI in MJD
- Translates to 1c/t/y/ROI for tonne-scale experiment:
  - More self-shielding
  - Longer cooldown for ^{68}Ge
  - Deeper (or improved shielding)



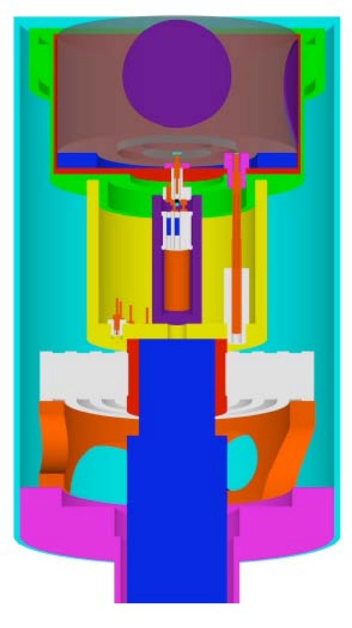
MALBEK

NIM A **652** (2011) 692

MALBEK detector



Simulated spectrum



Detailed MC geometry

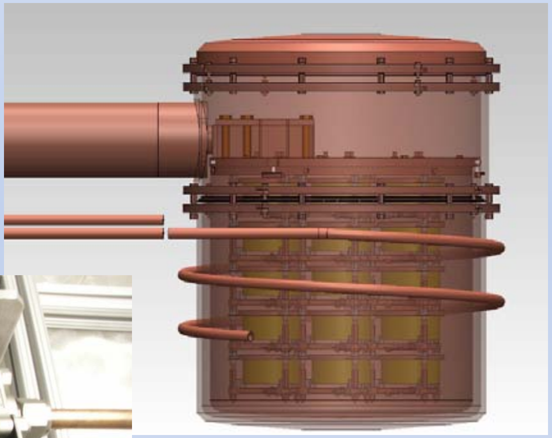
•450g modified BEGe detector in a low background mount deployed at the Kimballton Underground Research Facility (KURF) in Virginia (1450mwe)

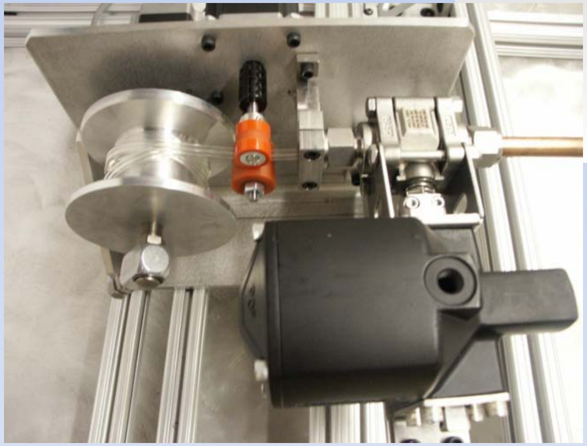
•Used to study low energy physics, understand backgrounds, test DAQ (including low energy triggering) and validate Monte Carlo simulation package

•Recently remounted detector removing Pb compononents, ^{210}Pb background down by x10

MJD calibration

- Electroformed copper calibration track, Rn exclusion, retractable line sources
- Internal cosmogenic lines for low energy
- Dedicated pulser distribution system
- PSA, granularity, efficiency, electronics response, energy, timing





Source drive motor

^{228}Th source

Summary

- The MAJORANA DEMONSTRATOR is a prototype to investigate the design for a tonne scale germanium $0\nu\beta\beta$ experiment
- Detailed simulations suggest that the MJD design will result in required level of backgrounds when scaled to a tonne scale experiment
- Will start to operate with enriched germanium in 2013
- Expected to test the KKDC claim with approximately one year of data (with 2 cryostats)

The MAJORANA Collaboration

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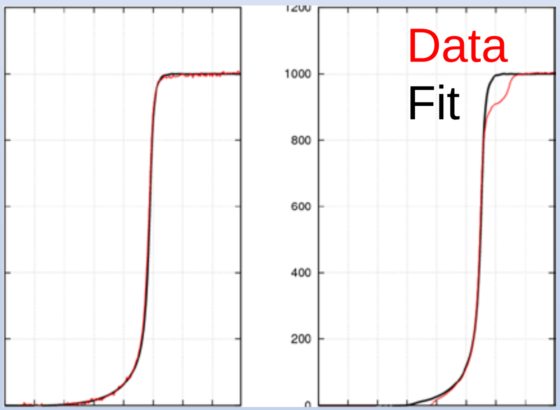
Students in red

Backup slides

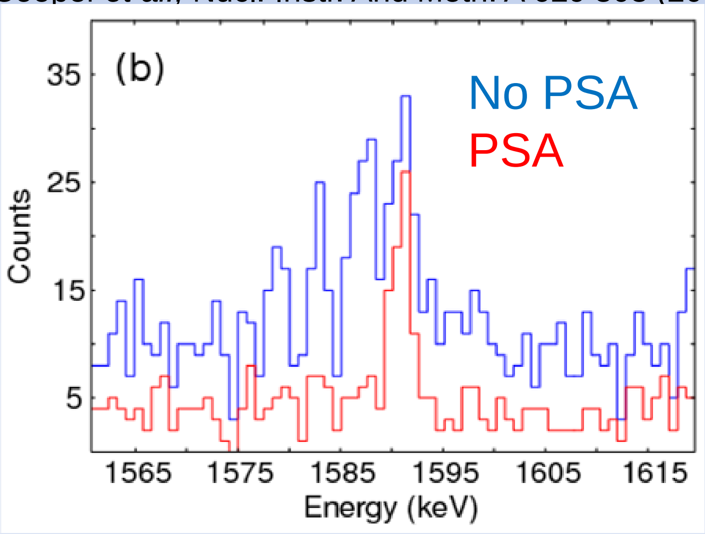
- Chi-squared PSA
- SSTC for ^{68}Ge
- Slow pulses (x2)
- MALBEK lead background
- Monolith
- Glove box
- S4 geometries
- Depth dependent backgrounds
- Background limits
- 1TGe down select schedule

Pulse shape analysis with PPCs

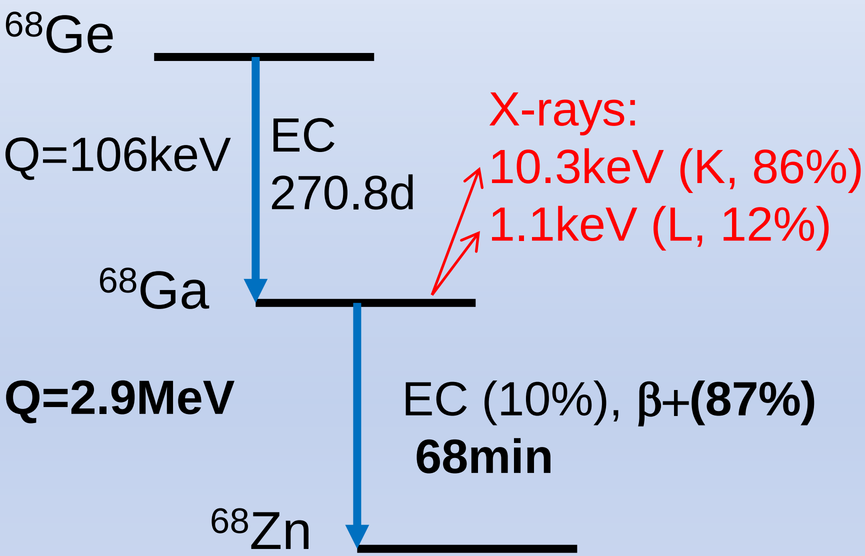
- Pulse fitting method to identify single-site events (0$\nu\beta\beta$-like)
- Based on a library of unique pulse shapes for each detector
- Retain 98% of single-site events (DEP) while only 1% of multi-site events (SEP)
- Rely on PSA to remove 'multi-site' backgrounds

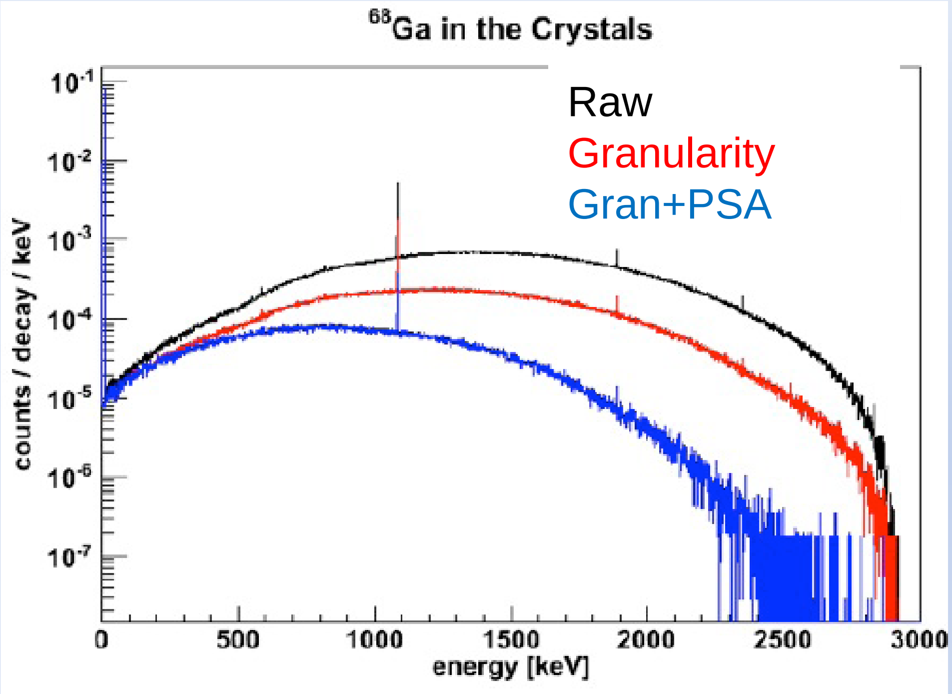


R.J. Cooper *et al.*, Nucl. Instr. And Meth. A 629 303 (2011)



Time correlation cut (^{68}Ge)

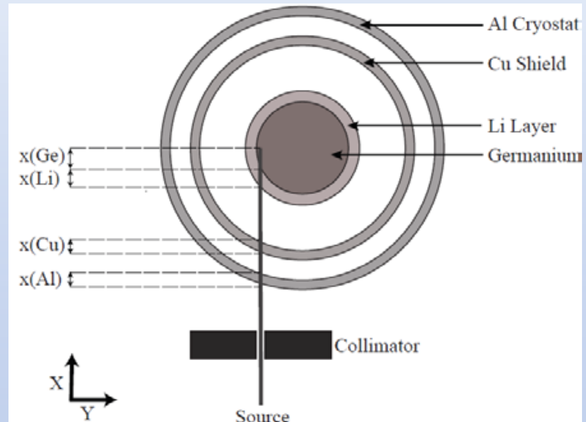




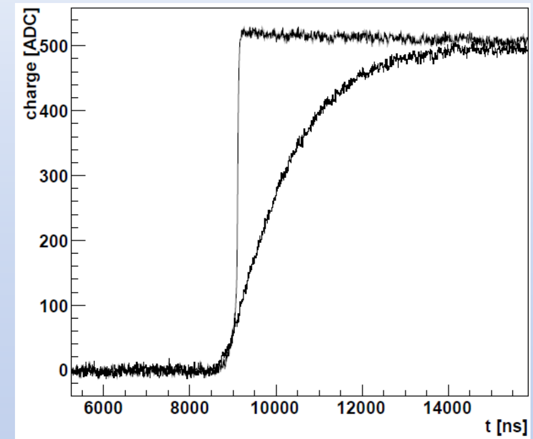
- ^{68}Ge produced by cosmogenic activation
- Sea-level activation rate 2.1 (30) atoms/kg/day for ^{enr}Ge (^{nat}Ge)
- Assume 100 day exposure for ^{enr}Ge, saturation for ^{nat}Ge
- Highly suppressed by granularity (x1/4) and PSA (1/25x)
- **Tag ^{68}Ge decays with 10.3keV and 1.1keV x-rays, then veto for ~5 x 68 minutes**
- **0.4 c/t/y/ROI (after analysis cuts)**

Detailed detector studies

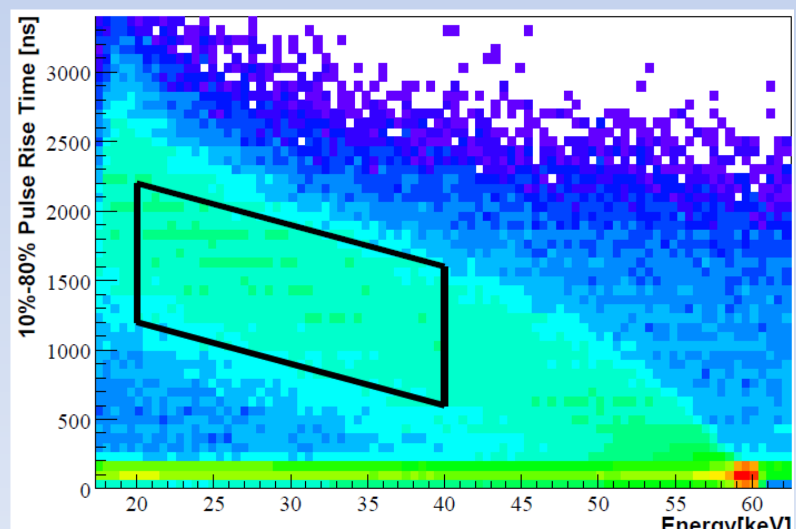
- Slow, energy-degraded pulses observed in CoGeNT
- From energy depositions near thick n+ contacts, where E-field is weak
- Important to understand for MJD low energy analysis
- Several detailed experiments performed
- Quantitative model produced



Detailed scanning of detectors



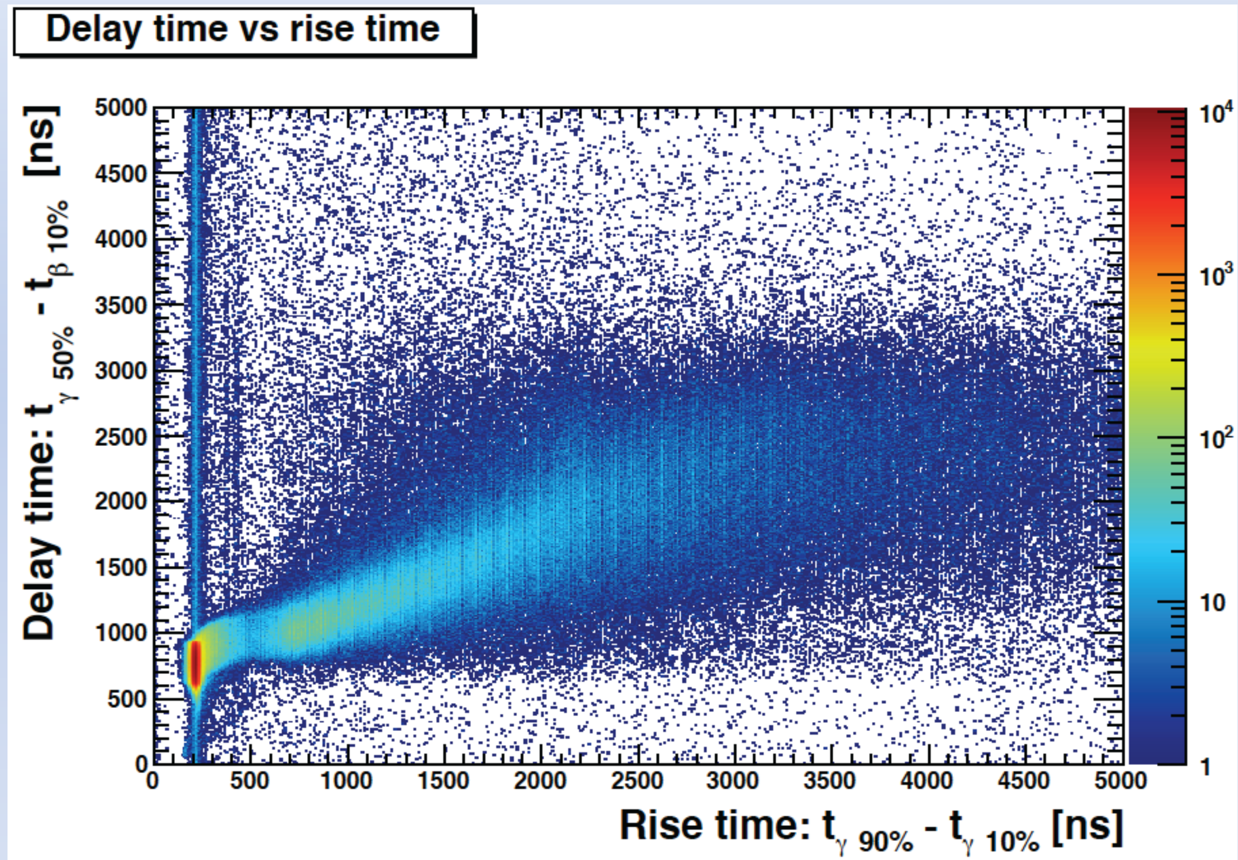
Slow pulses evident



Slow pulses “leaking out” from 60keV ^{241}Am peak

Detailed detector studies (2)

- β–γ coincidence studies showed that the slow pulses are also delayed
- Detailed model being developed to quantitatively understand

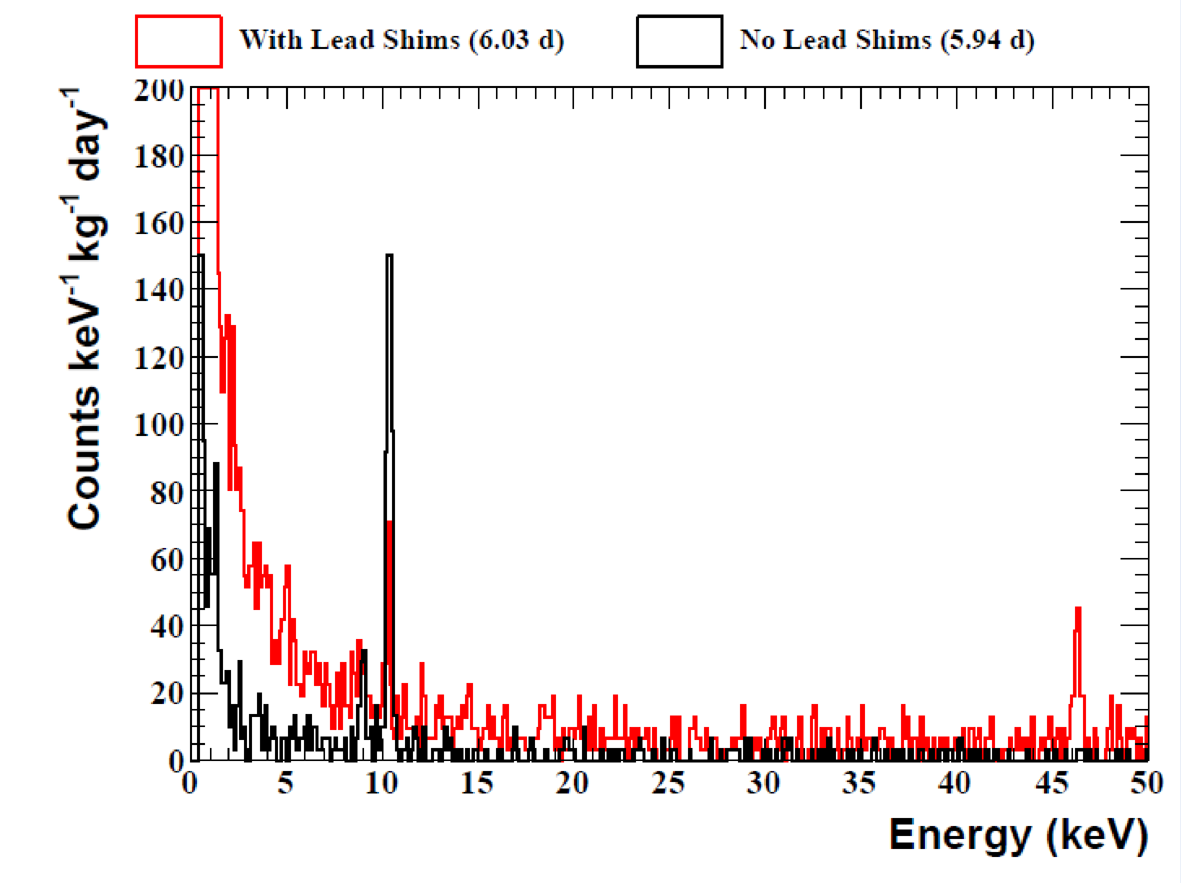


MALBEK Pb backgrouds

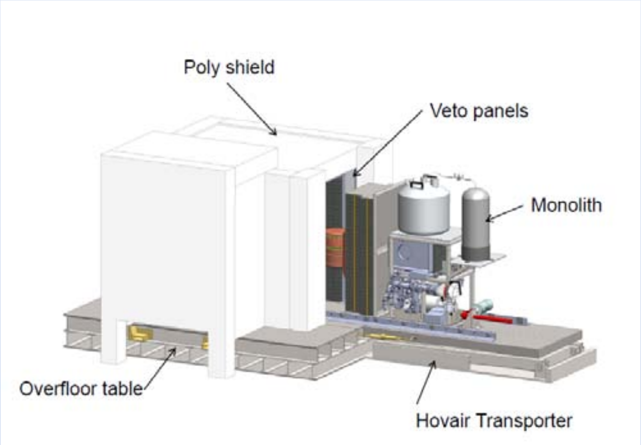
After removing Pb shims, backgrounds at low energy:

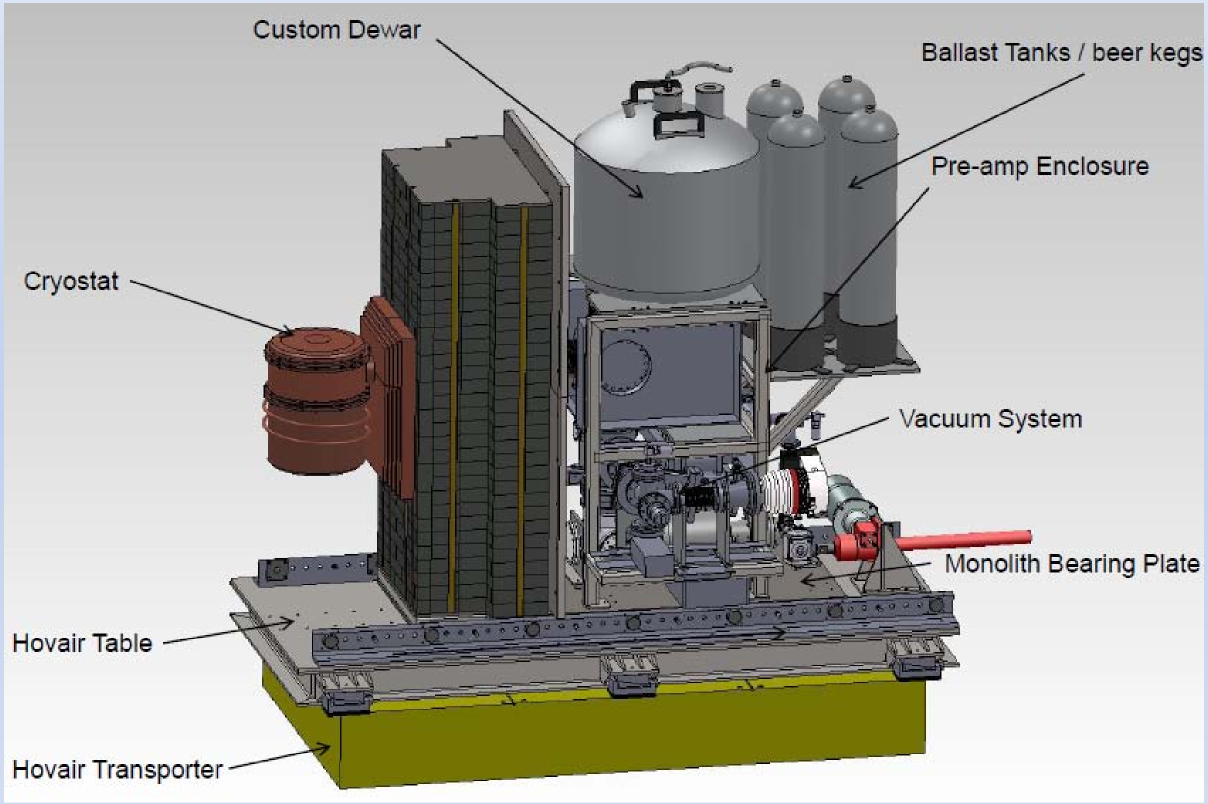
•16x improvement [thres. – 1keV]

•7x improvement [2keV-8keV]



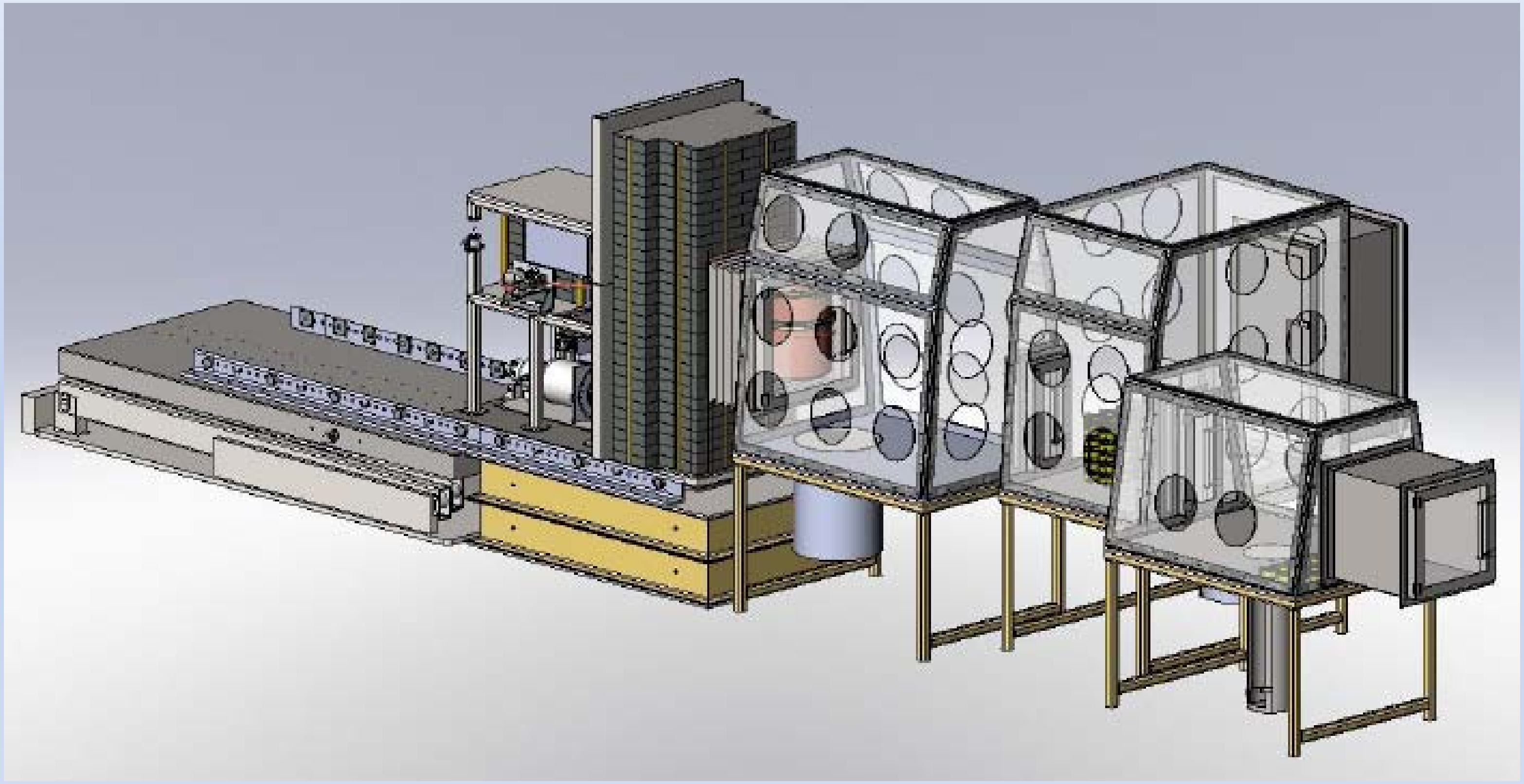
“Monolith”





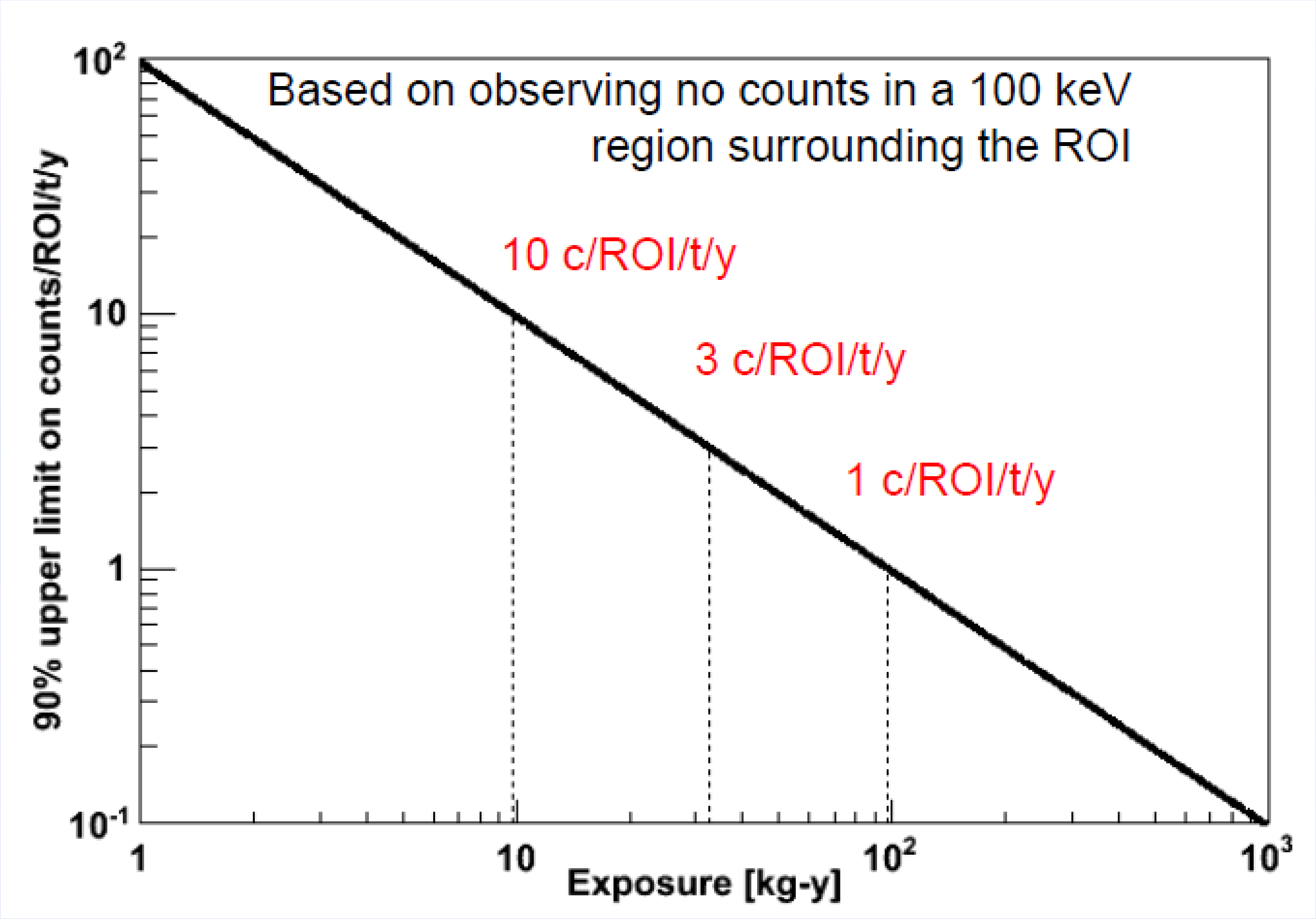
- Monolith allows detector and part of the shield to be removed for modular deployment
- Hovair purchased and delivered

Glove box

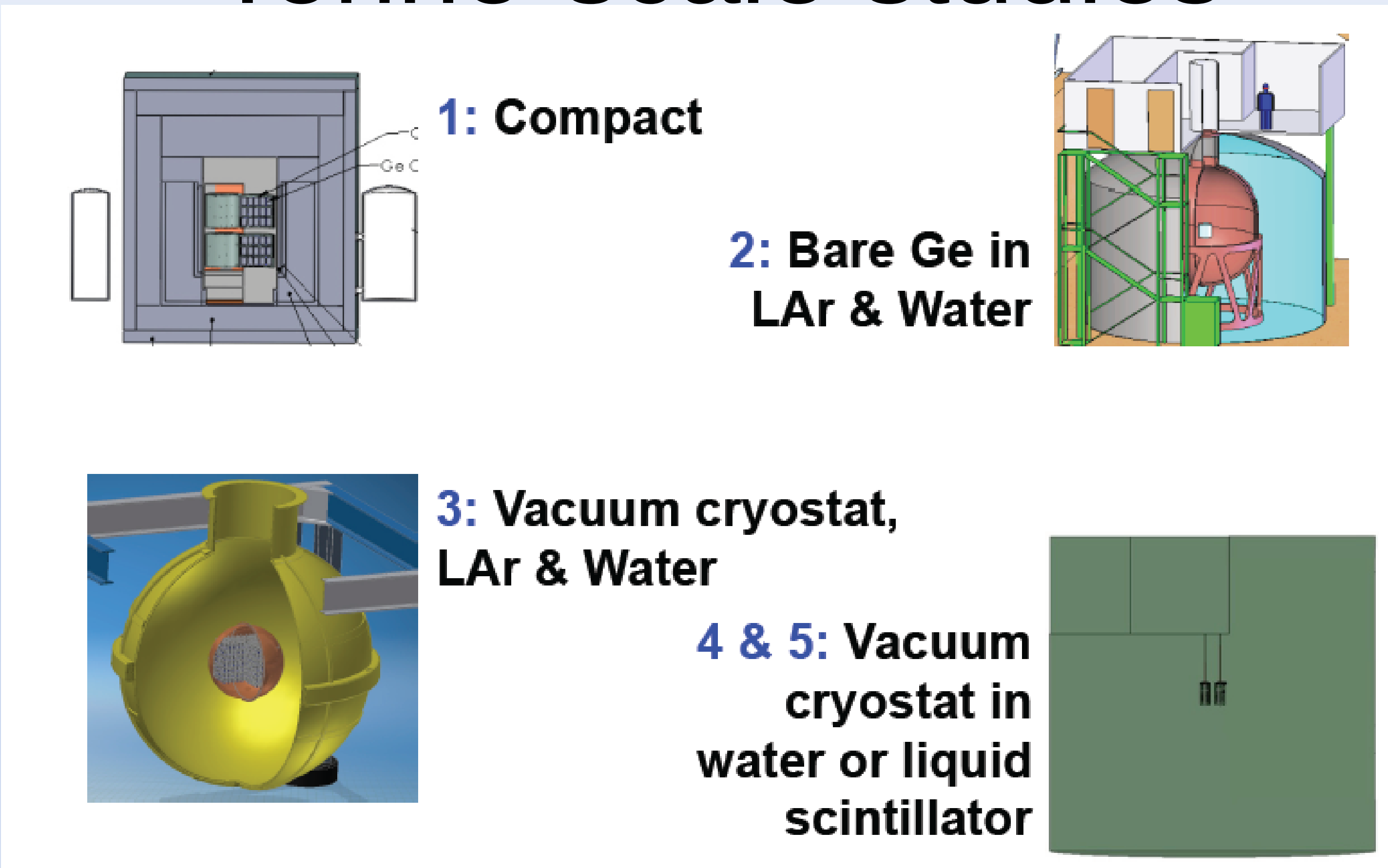


•Underground assembly will be performed in glove box (Rn mitigation)
•Design final

MJD background limit



Tonne-scale studies

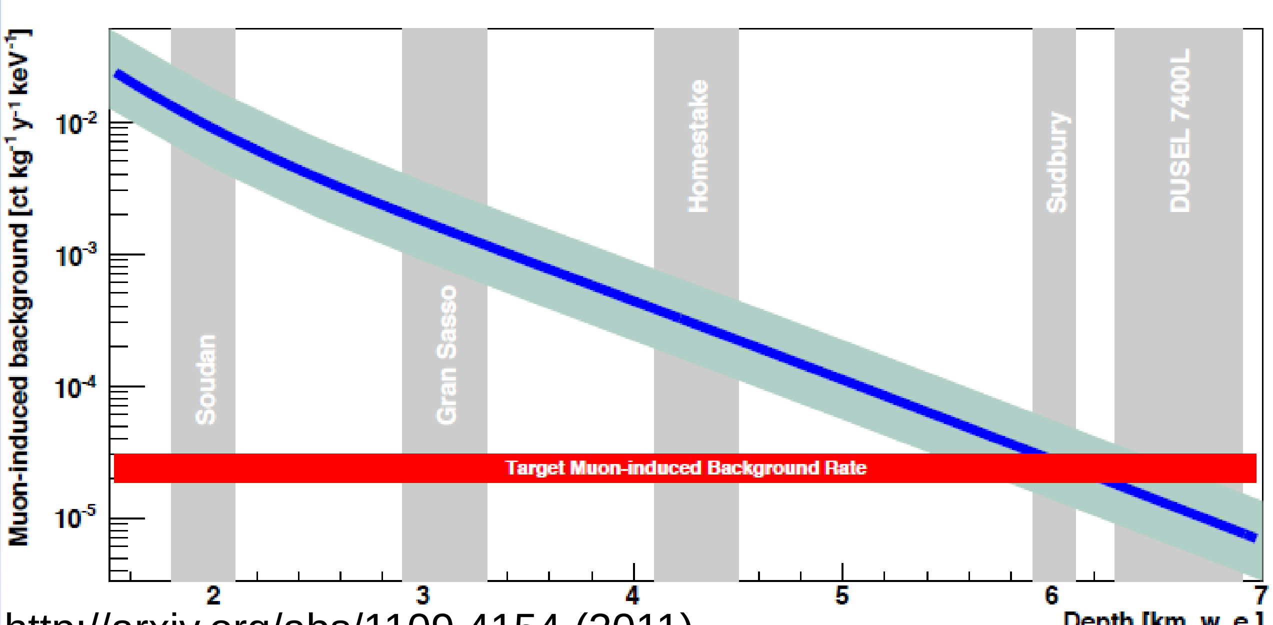


- Different geometries studied for tonne scale experiment, collaboration with some members of GERDA
- Engineering studies also performed
- Collaboration with DUSEL/SURF engineers

Depth-dependent backgrounds

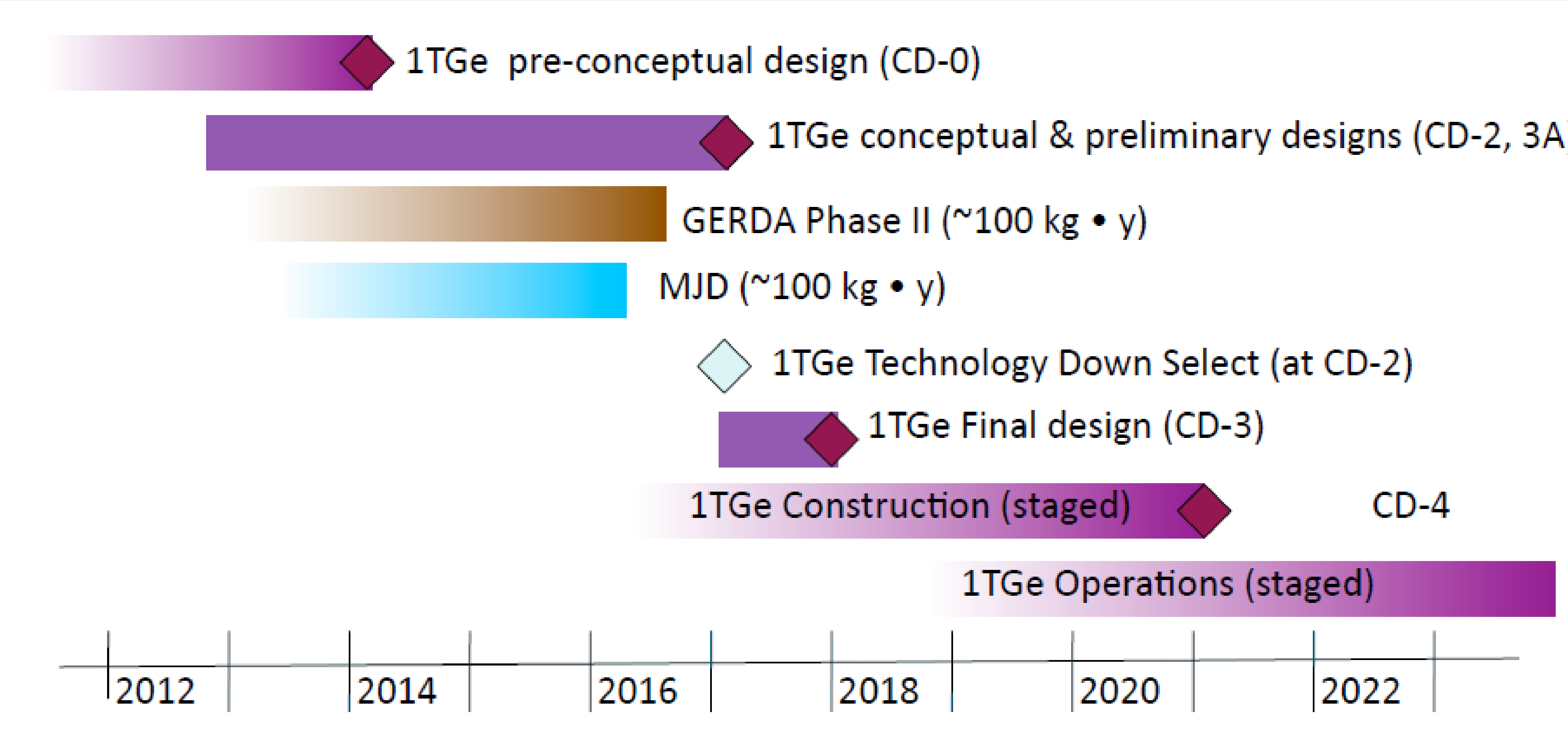
Reaction	Mei & Hime		Scaled
$^{76}Ge(n,n'\gamma)$	40		0.49
$^{74}Ge(n,n'\gamma)$	8.0		0.10
$Cu(n,n'\gamma)$	7.6		0.094
$^{208}Pb(n,n'\gamma)$	14		0.17
$Ge(n,n)$	14		0.17
μ hits	10		0.17
Others	9.6		0.13
Total	**100**	ct/ROI/t/y	**1.3**

- •Scaled backgrounds by assuming 4300mwe (vs 3100mwe), better veto, thicker poly
- •For tonne scale experiment, need to go to ~6000mwe for MJ-style design
- •Can go less deep with liquid shield



http://arxiv.org/abs/1109.4154 (2011)

Tonne-scale schedule



- Technology selection will be based on outcome of R&D and results from MJD and GERDA