UNIVERSITY OF SOUTH DAKOTA

Rare-event searches with Germanium in South Dakota and The MAJORANA DEMONSTRATOR

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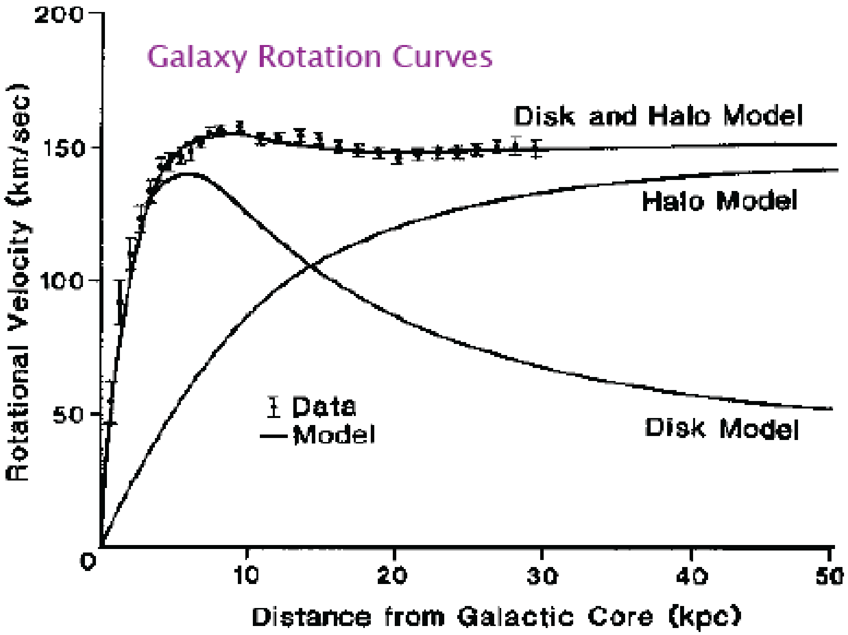
SLAC Seminar

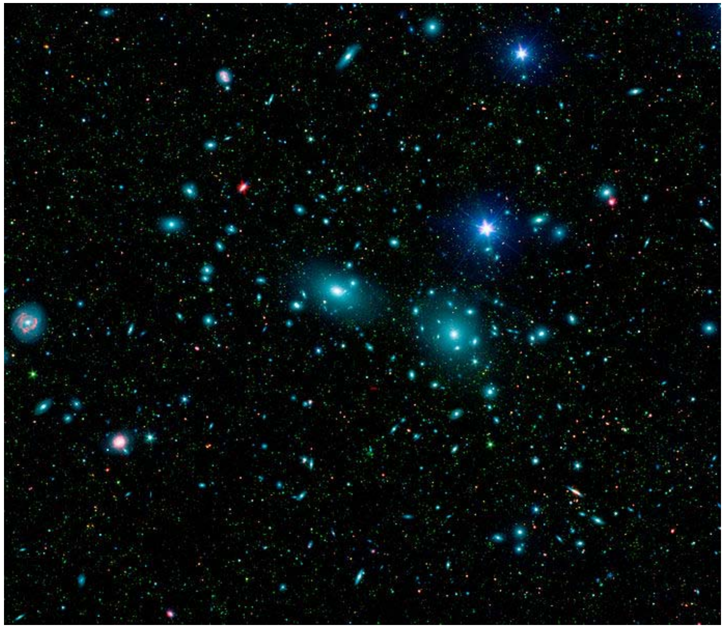
11th March 2014

Outline

- Rare-event searches:
  - Dark matter
  - Neutrinos and their mass
- Germanium detectors
- The MAJORANA DEMONSTRATOR experiment
- Future rare-event searches with Ge detectors

Dark Matter





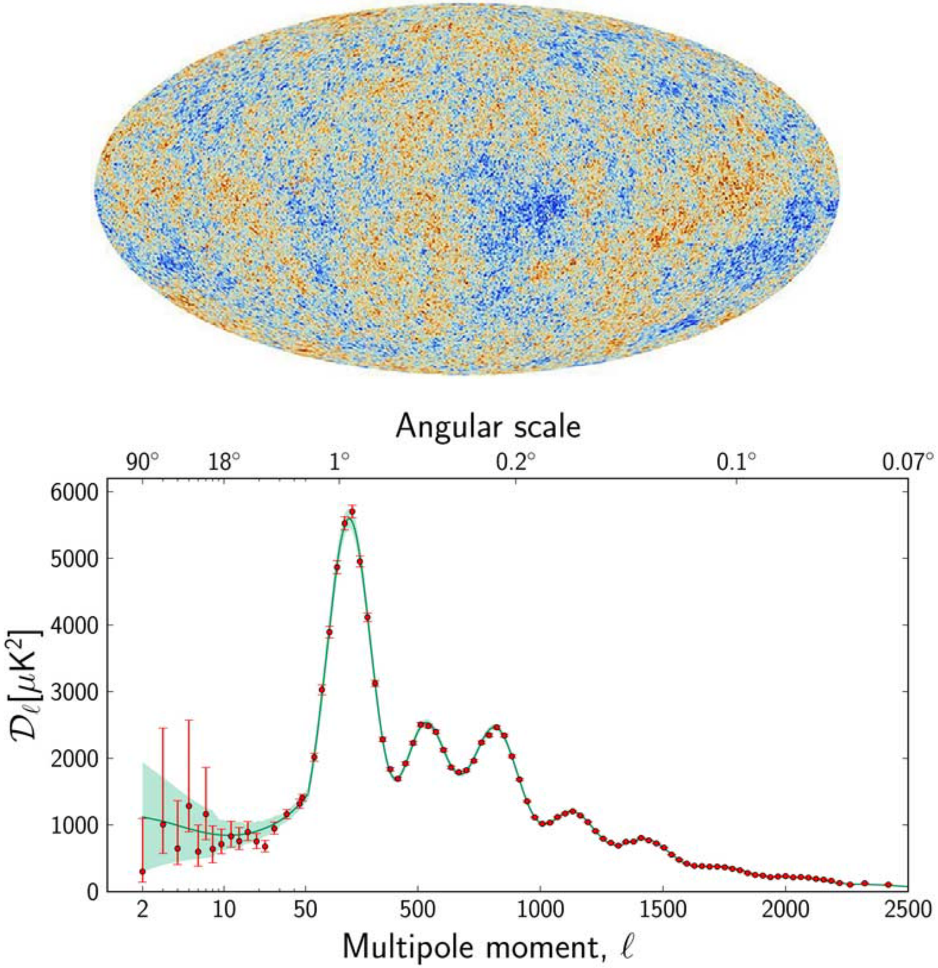
The Coma cluster (NASA SDSS+Spitzer)

- Jan Oort first discovered evidence in rotation curve for the Milky Way 1932
- Fritz Zwicky coined the term “Dark Matter” when looking at galaxies in the Coma cluster for missing matter

Evidence for dark matter is compelling

The bullet cluster (HST+Chandra)

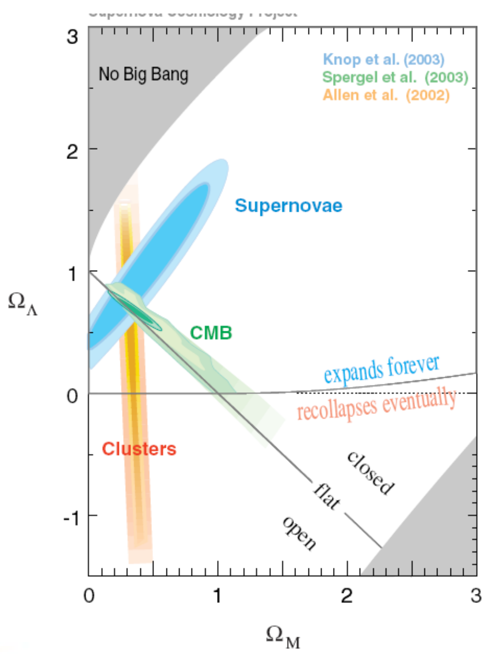
- A variety of instruments and methods agree that some matter is missing in the Universe

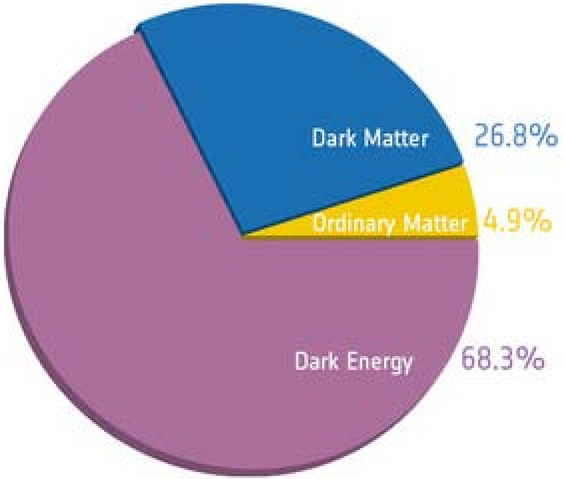


Cosmic microwave background from Planck

What is dark matter?

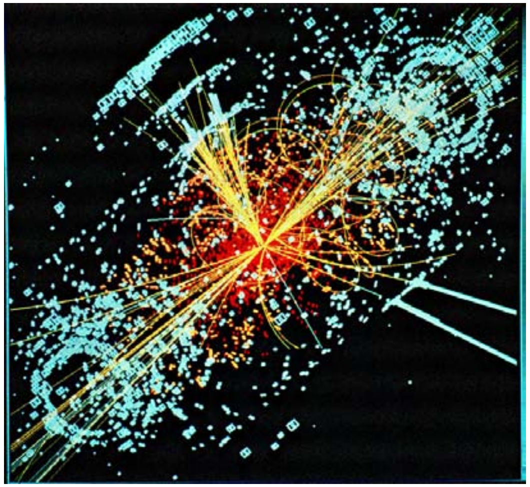
- Best fits to the data seem to indicate “Cold collision-less non-baryonic matter”
- Several candidates motivated by other needs in physics:
    - o Axions (solves some problems related to CP violation in the strong nuclear force)
    - o Lightest super-symmetric particle (if super-symmetry exists)
    - o Something else?
- **Weakly Interacting Massive Particle:**
    - Weak interaction would have the right order of magnitude to decouple and give the right density of particles





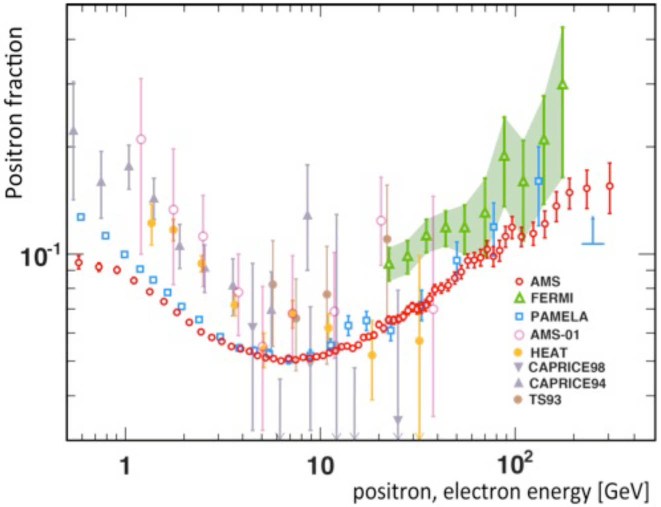
Energy density after Planck

Detecting dark matter



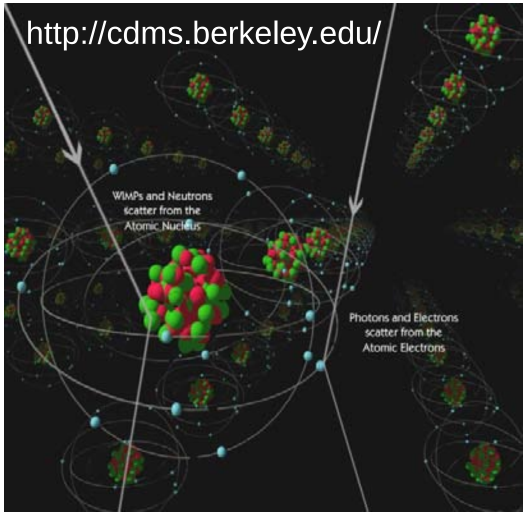
Simulated event in ATLAS

Production
in the lab



Positron fraction from AMS

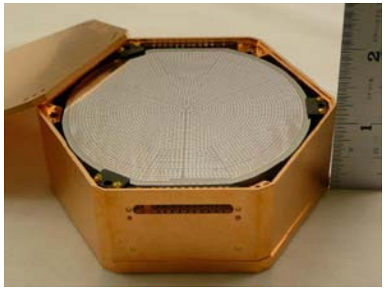
“Indirect”
detection


http://cdms.berkeley.edu/

Scattering off a nucleus

“Direct”
detection

Direct detection of dark matter



CDMS

Ionization

Scintillation

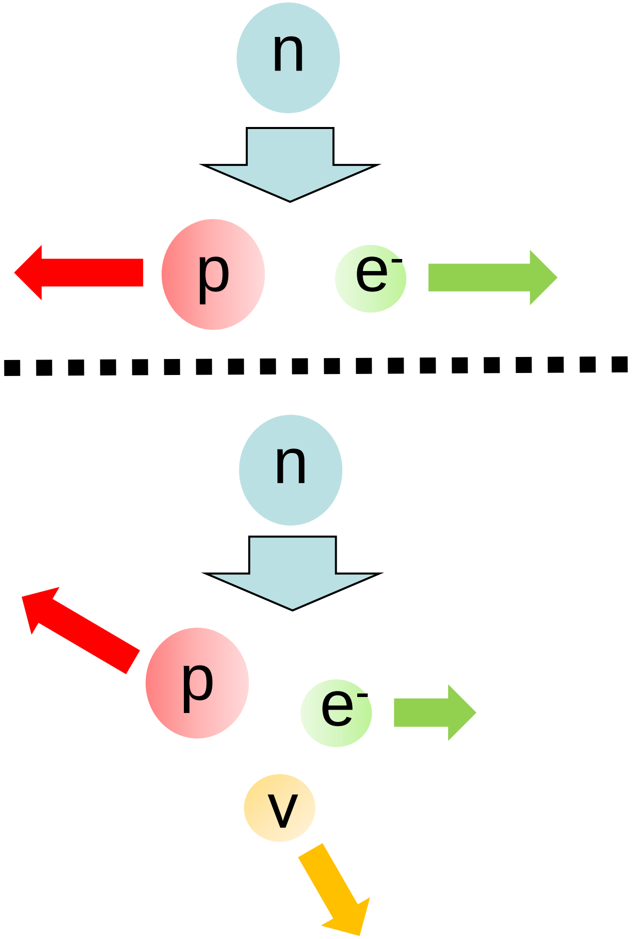
Heat

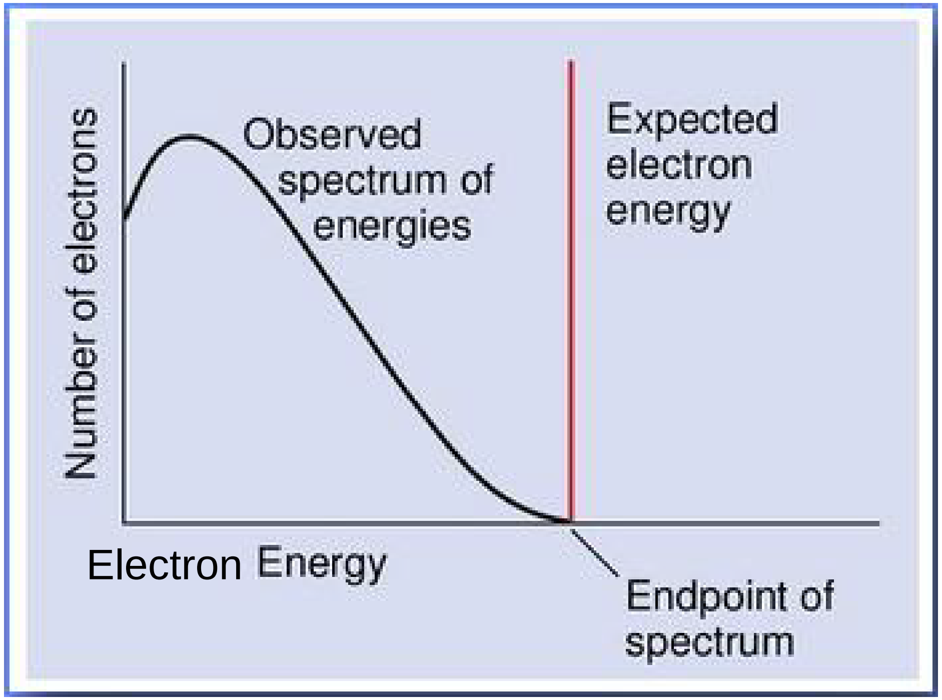
Challenges:

- Direct detection of a recoiling nucleus leaves **very little energy**
- **Backgrounds** can lead to false detection
- Low cross-section requires **large target masses**

Neutrinos to explain beta decay

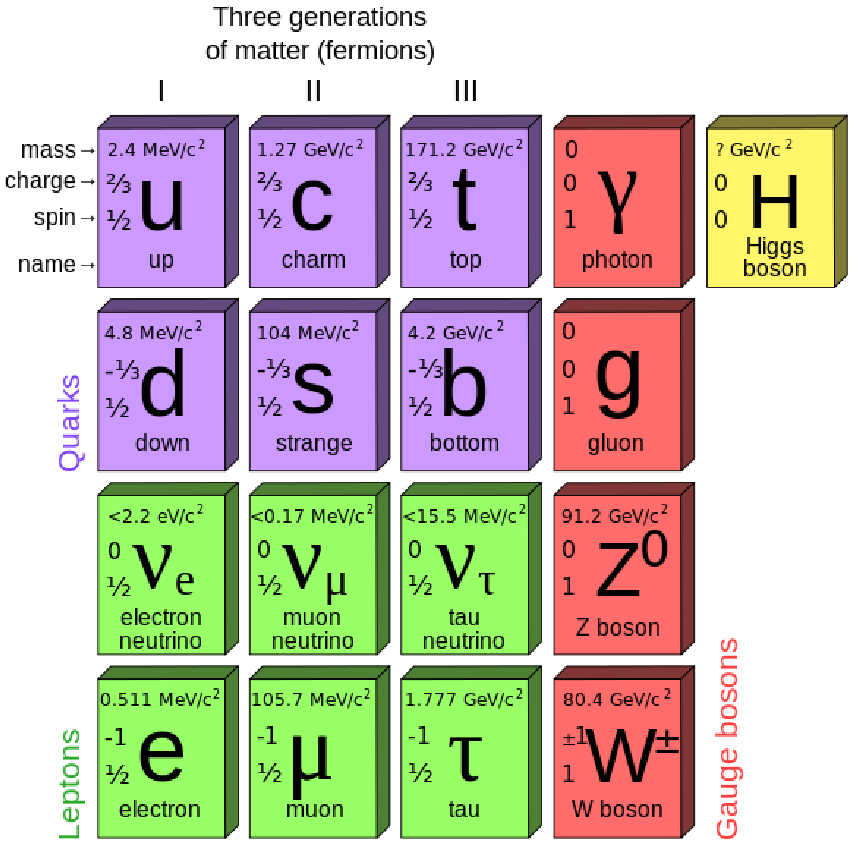
Beta decay:





- For a 2 body decay, expect a single line, but continuum observed
- In 1930, Pauli proposed the un-detectable neutrino to solve this problem

Neutrinos in the standard model



Three generations of matter (fermions)

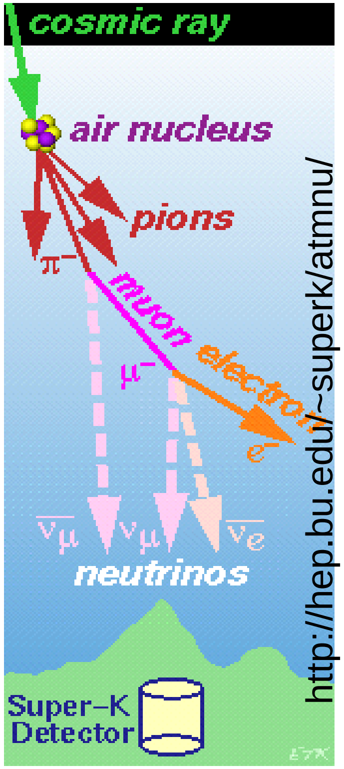
		I	II	III	Gauge bosons	
Quarks	mass→ charge→ spin→ name→	2.4 MeV/c^2 ⅔ ½ u up	1.27 GeV/c^2 ⅔ ½ c charm	171.2 GeV/c^2 ⅔ ½ t top	0 0 1 γ photon	? GeV/c^2 0 0 H Higgs boson
		4.8 MeV/c^2 -⅓ ½ d down	104 MeV/c^2 -⅓ ½ s strange	4.2 GeV/c^2 -⅓ ½ b bottom	0 0 1 g gluon	
Leptons		<2.2 eV/c^2 0 ½ ν_e electron neutrino	<0.17 MeV/c^2 0 ½ ν_μ muon neutrino	<15.5 MeV/c^2 0 ½ ν_τ tau neutrino	91.2 GeV/c^2 0 1 Z^0 Z boson	
		0.511 MeV/c^2 -1 ½ e electron	105.7 MeV/c^2 -1 ½ μ muon	1.777 GeV/c^2 -1 ½ τ tau	80.4 GeV/c^2 ±1 1 $W^\pm$ W boson	

- 3 “flavors” of neutrinos
- Interact only through the ***Weak*** interaction
- Lepton number to distinguish neutrinos and anti-neutrinos

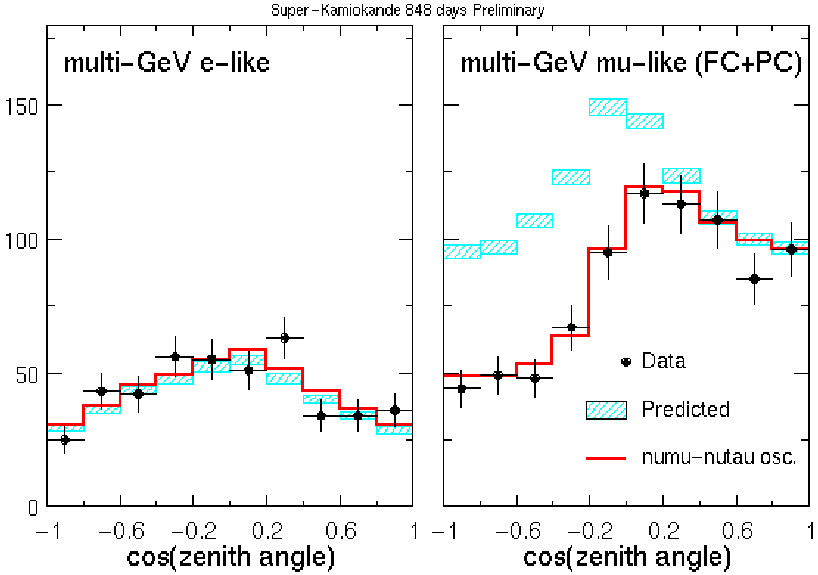
What we know about neutrinos

- There are 3 “active” flavors
- They can change flavor through “neutrino oscillations”
- They have mass
- We know quite precisely most of the parameters related to neutrino oscillations

$$P_{\nu_e\to\nu_e} = 1-\frac{1}{2}\sin^2(2\theta_{12})\left(1-\cos\left(\frac{\Delta m_{21}}{2E\hbar}t\right)\right)$$



http://hep.bu.edu/~superk/atmnu/

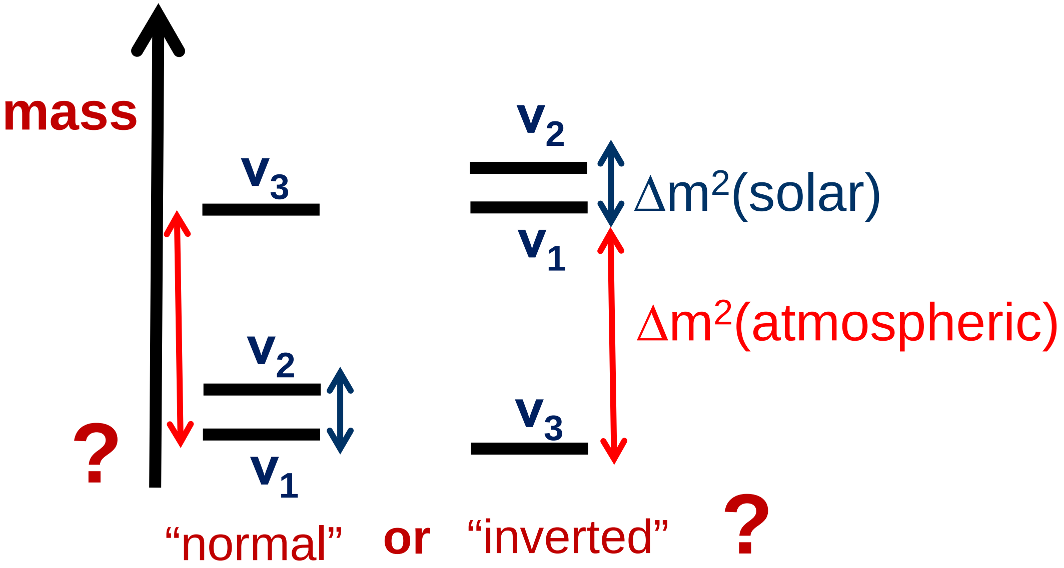


Super Kamiokande results, 1998

What we don’t know about neutrinos

- CP violating?
- Steriles?
- Mass (only differences are known)
- Hierarchy (which is heaviest?)
- Dirac or Majorana (are they their own anti-particle?)

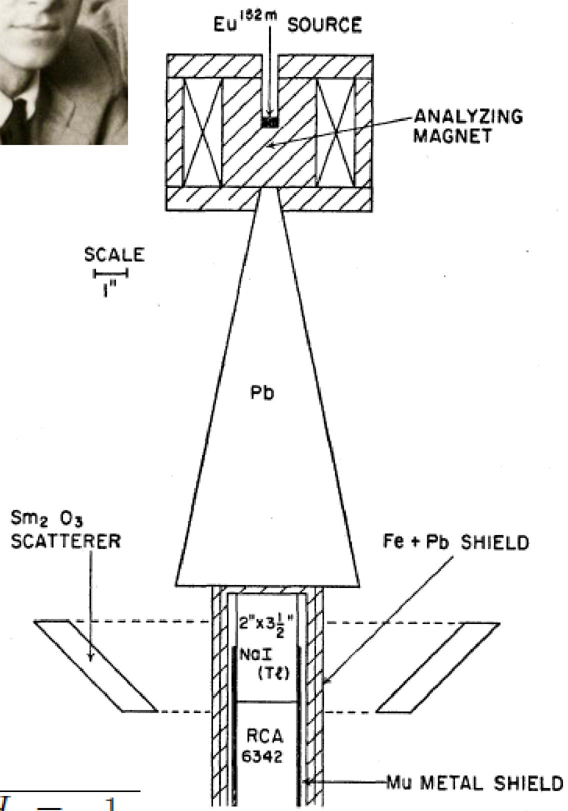
0νββ experiments can address!



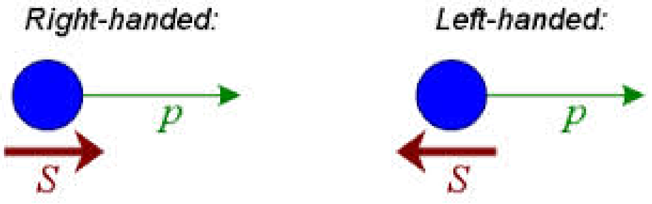
The Standard Model and neutrino mass

- Goldhaber's experiment showed that neutrinos are left-handed (PRC **109** p.1015 -1958)

    1. Neutrinos are massless
    2. Handedness is the only property to distinguish a neutrino from an "anti-neutrino" in the Weak interaction

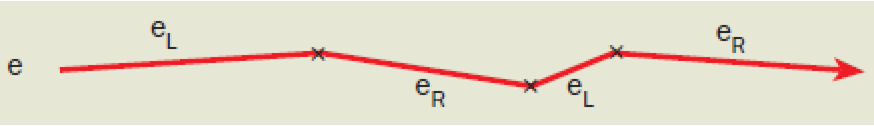


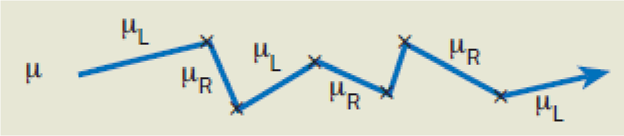
- But neutrinos are not massless, so what gives?



$^{152\mathrm{m}}\mathrm{Eu}$	$+$	e^-	$\longrightarrow$	$^{152}\mathrm{Sm}^*$	$+$	ν_e	$\longrightarrow$	$^{152}\mathrm{Sm}$	$+$	ν_e	$+$	γ	
0	$+$	$+\frac{1}{2}$	$\longrightarrow$	$+1$	$+$	$-\frac{1}{2}$	$\longrightarrow$	0	$+$	$-\frac{1}{2}$	$+$	$+1$	$\Rightarrow H_\nu = -1$
0	$+$	$-\frac{1}{2}$	$\longrightarrow$	-1	$+$	$+\frac{1}{2}$	$\longrightarrow$	0	$+$	$+\frac{1}{2}$	$+$	-1	$\Rightarrow H_\nu = +1$
				$\downarrow$		$\uparrow$			$\downarrow$	$\uparrow$		$(\downarrow)$	

Extending the Standard Model





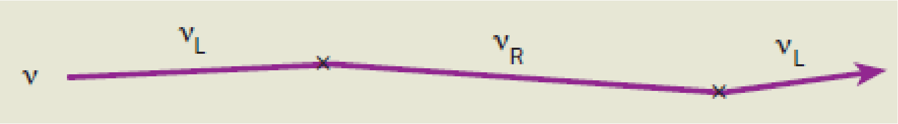
Interaction of particles with the Higgs field, makes them change helicity/chirality. Strength of coupling = mass.

Dirac mass option:

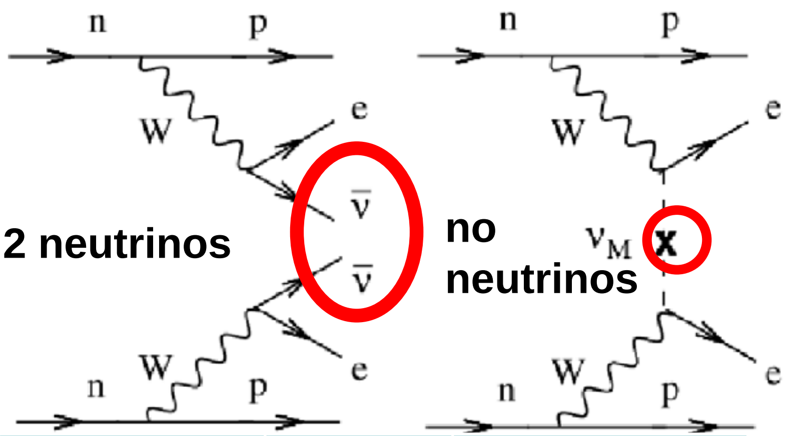
- 4 neutrino states (LHN, **RHN, LHAN**, RHAN)
- Distinguishable anti-neutrino (“Lepton charge/number”)
- 2 “sterile” neutrino states
- For some reason, neutrino coupling to Higgs is small

Majorana mass option:

- 2 neutrino states (LH, **RH**)
- technically, no “anti-neutrino”
- Lepton charge not conserved
- See-saw mechanism to explain low mass (RH is massive)
- Large mass consistent with some GUTs, leptogenesis



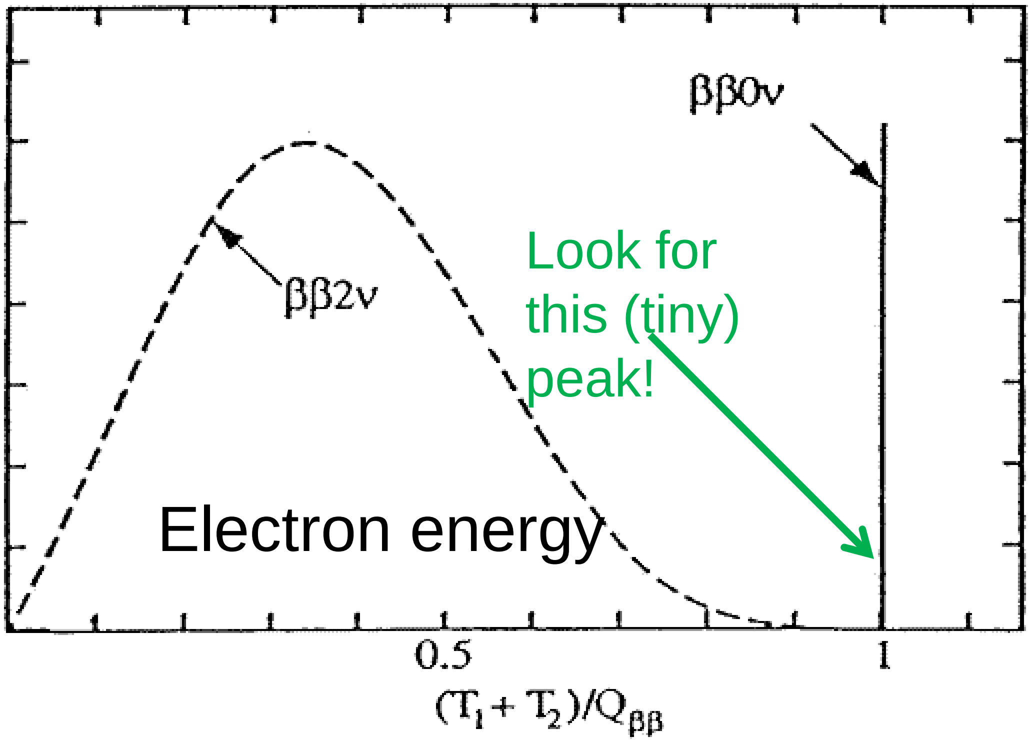
(Neutrinoless) double beta decay



2 neutrinos

no neutrinos

Isotope	Q (MeV)	Abundance (%)
^{48}Ca→^{48}Ti	4.3	0.2
^{76}Ge→^{76}Se	2.0	7.8
^{82}Se→^{82}Kr	3.0	9.2
^{96}Zr→^{96}Mo	3.4	2.8
^{100}Mo→^{100}Ru	3.0	9.6
^{110}Pd→^{110}Cd	2.0	11.8
^{116}Cd→^{116}Sn	2.8	7.5
^{124}Sn→^{124}Te	2.2	5.6
^{130}Te →^{130}Xe	2.5	34.5
^{136}Xe →^{136}Ba	2.5	8.9
^{150}Nd →^{150}Sm	3.4	5.6



Look for this (tiny) peak!

Electron energy

- Double-beta decay when normal beta decay energetically forbidden
- Energy of electrons can be detected

Experimental searches for neutrinoless double beta decay

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

$$T_{½}^{0\nu} = \left(G^{0\nu} |M^{0\nu}|^2 m_{\beta\beta}^{2} \right)^{-1} \geq 10^{25} \text{ years}$$

$$\langle m_{\beta\beta} \rangle \equiv U_{e1}^{2} m_1 + U_{e2}^{2} m_2 e^{i\phi 2} + U_{e3}^{2} m_3 e^{i\phi 3}$$

Sensitivity:

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

abundance

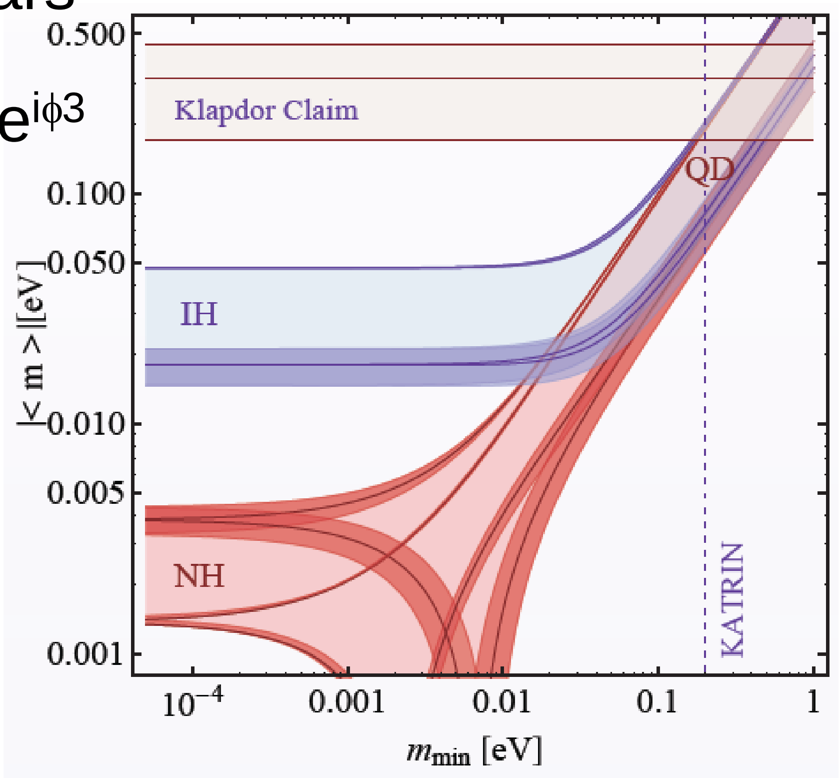
Detect eff.

mass

live-time

energy resolution

background rate

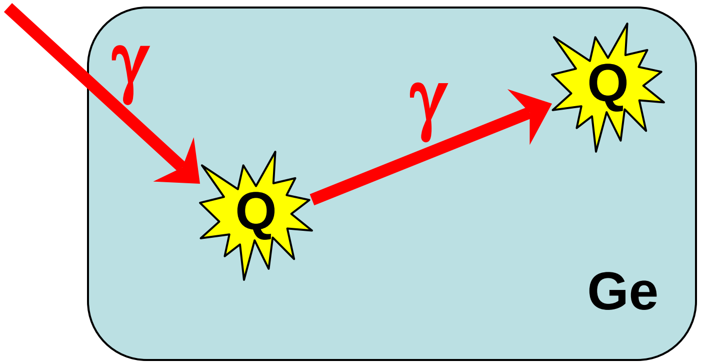


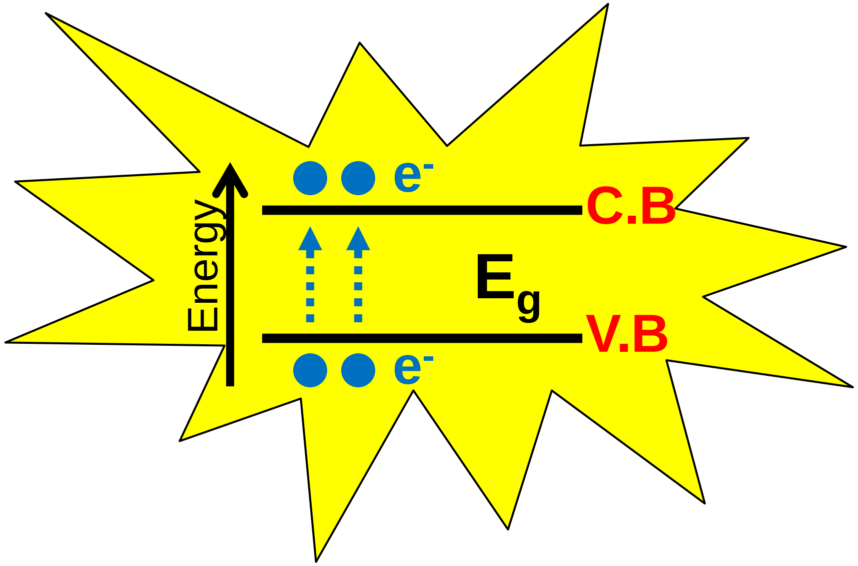
Needs for dark matter *and* neutrinos

- **Low background:**
    - Underground to shield from cosmic rays
    - Clean materials to limit internal radioactivity
- **Large target mass:**
    - More targets/more isotopes
- **Low energy threshold:**
    - Sensitivity to events that deposit little energy

→ Germanium Detectors!

Semiconductor detectors





Measure total Q to get Energy:

- Number of electron-hole pairs:

$$N = \frac{E_\gamma}{\varepsilon}$$

- Energy resolution:

$$\Delta E \propto \sqrt{FN}$$

For Ge:

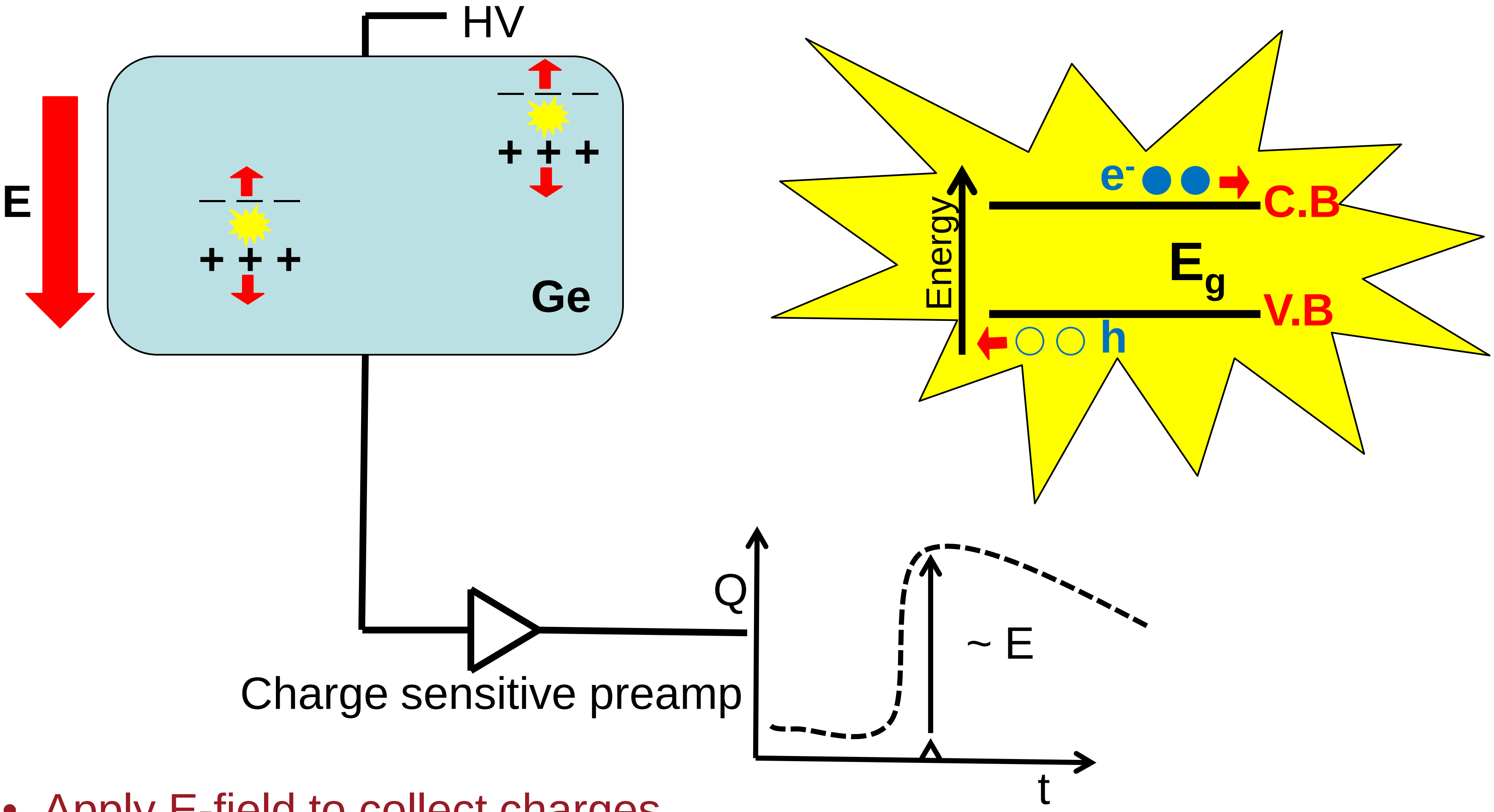
$$\varepsilon = 2.95eV, F \approx 0.1$$

- For 2MeV:

$$N \approx 700{,}000$$

$$\frac{\Delta E_{FWHM}}{E} \approx 0.1\%$$

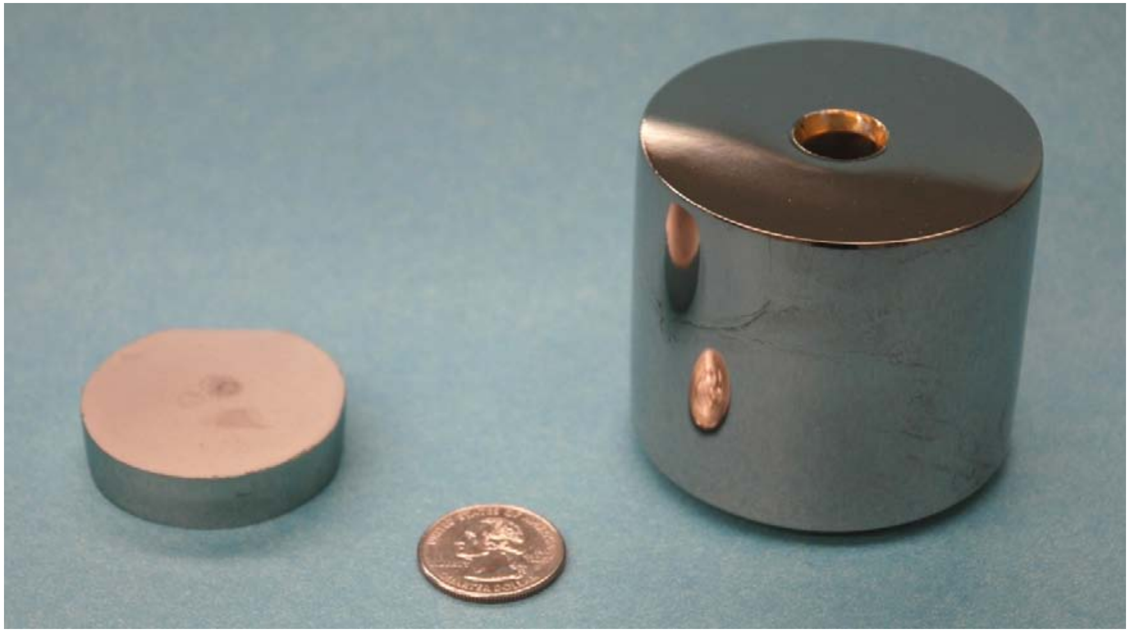
Semiconductor detectors



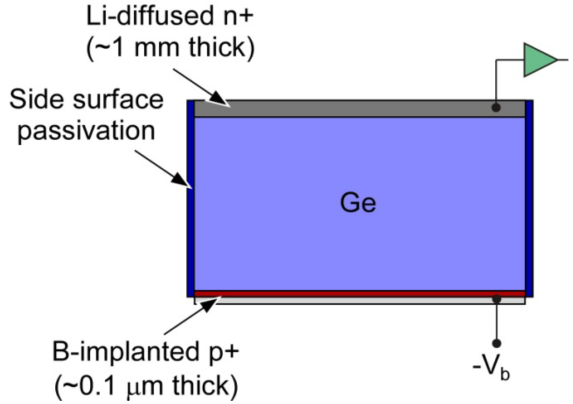
- Apply E-field to collect charges
- Low noise preamp to measure charge and obtain good energy resolution

“Classic” germanium detectors

planar



Coaxial



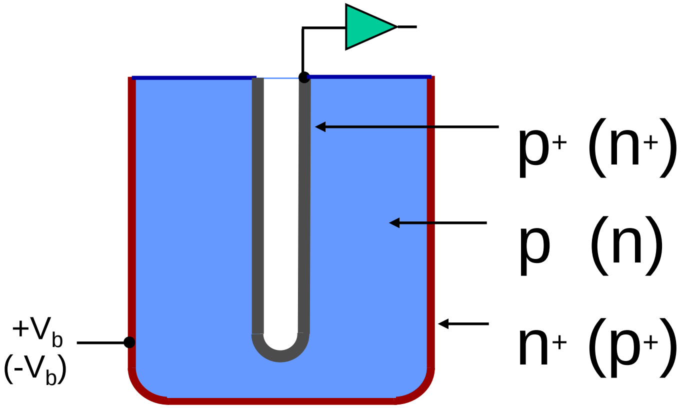
Li-diffused n+
(~1 mm thick)

Side surface
passivation

Ge

B-implanted p+
(~0.1 µm thick)

$-V_b$



$p^+ \ (n^+)$

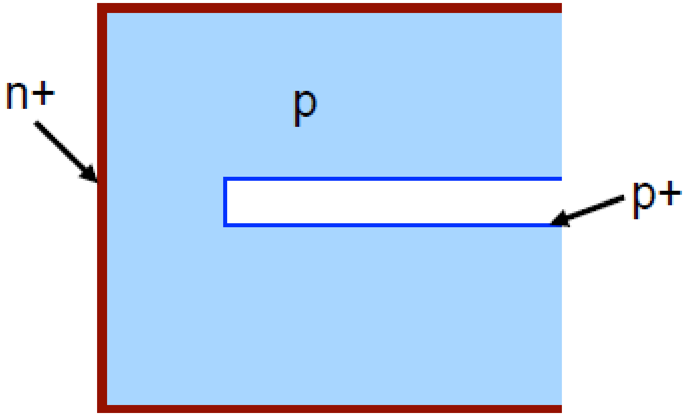
$p \ \ (n)$

$n^+ \ (p^+)$

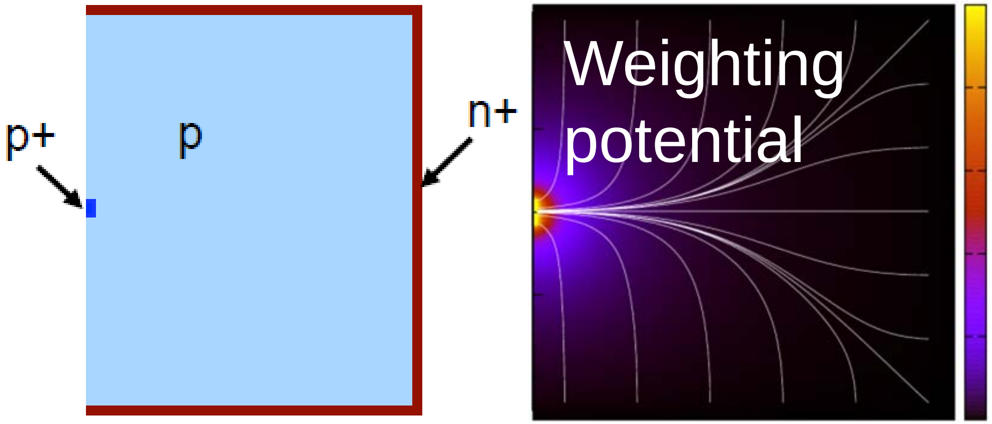
$+V_b$
$(-V_b)$

“PPC” detectors

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

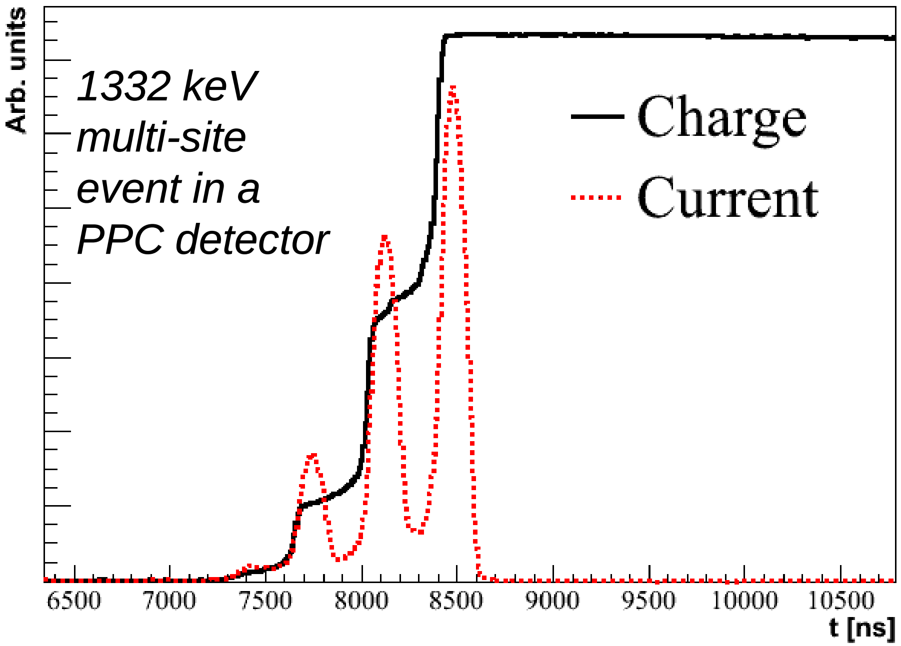


Semi coaxial detector

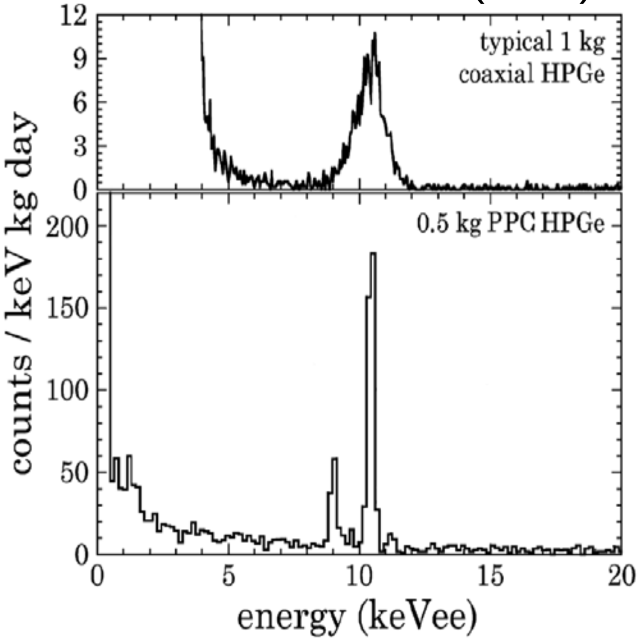


Point contact detector

Properties of PPCs



PRL **101** 251301 (2008)



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

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

Germanium for neutrinoless double-beta decay experiments

Germanium detectors

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

^{76}Ge isotope for 0nbb

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

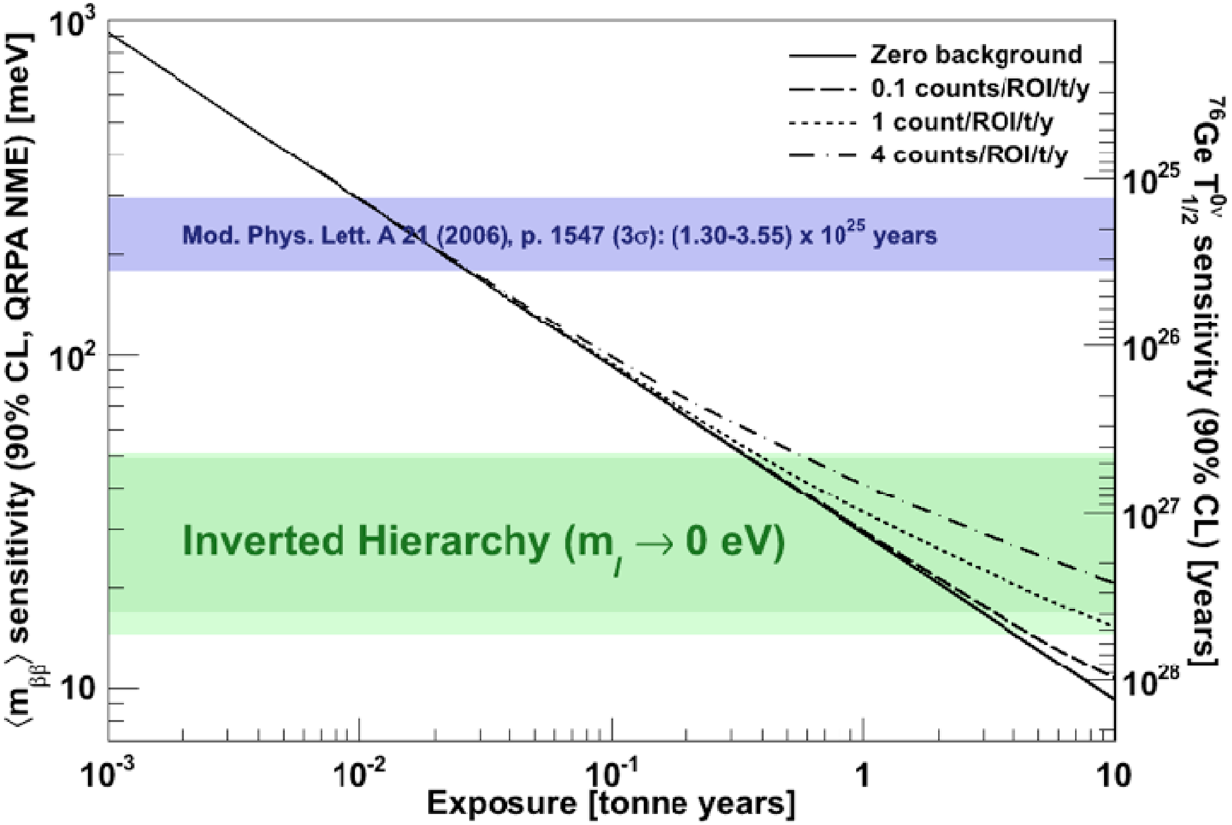
Sensitivity of germanium experiments

Background free:

$$T_{1/2}^{0\nu} \propto Mt$$

Background-limited:

$$T_{1/2}^{0\nu} \propto \sqrt{Mt}$$



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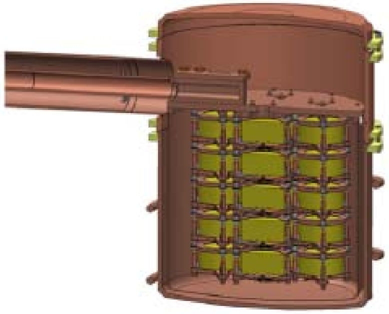
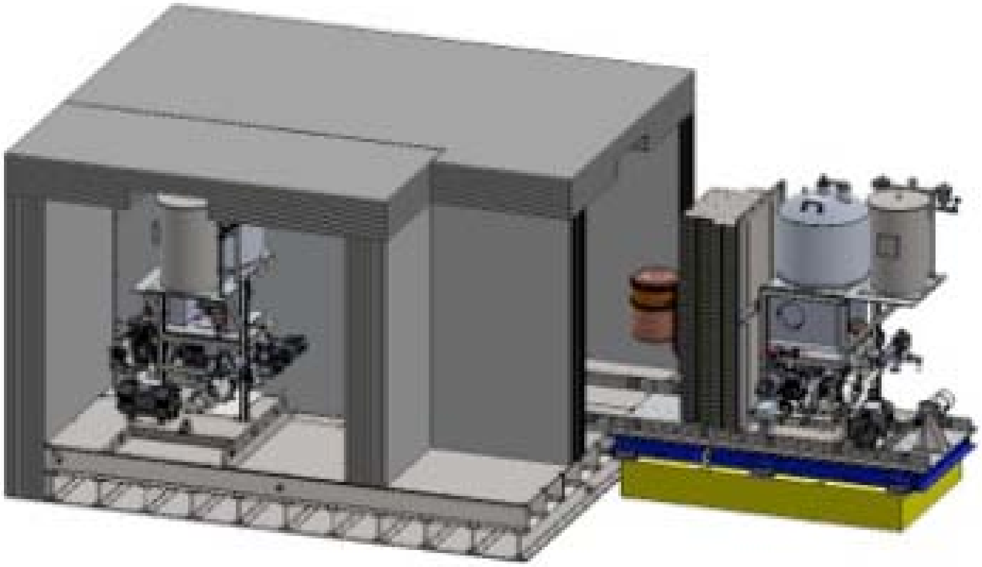
The MAJORANA DEMONSTRATOR

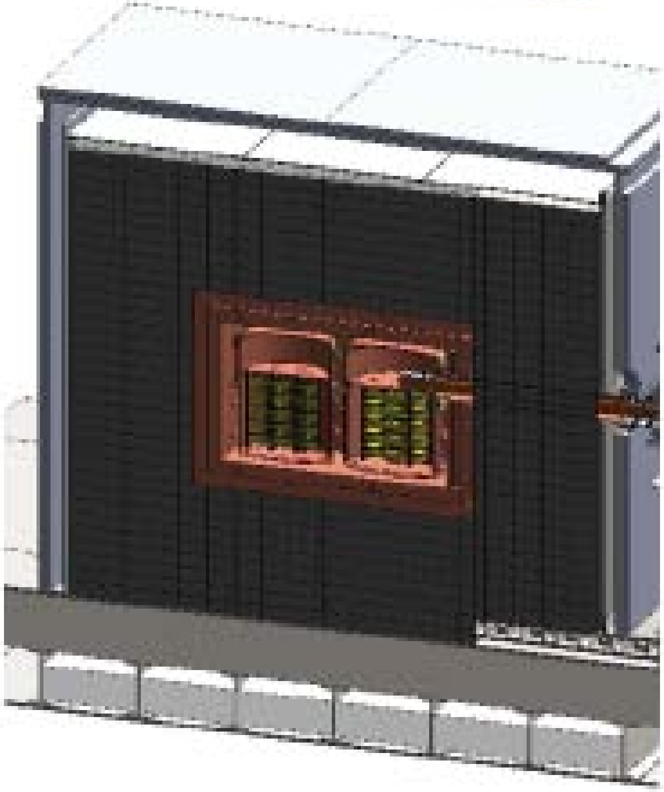
- An R&D project towards a tonne scale neutrinoless double-beta decay germanium experiment
- Demonstrate a design that can achieve a background rate of **1cnt/t/y/ROI** when scaled to a 1 tonne detector (ROI = 4keV region around 2039keV)
- Test Klapdor-Kleingrothaus claim
- Agreement to work with GERDA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

The MAJORANA DEMONSTRATOR

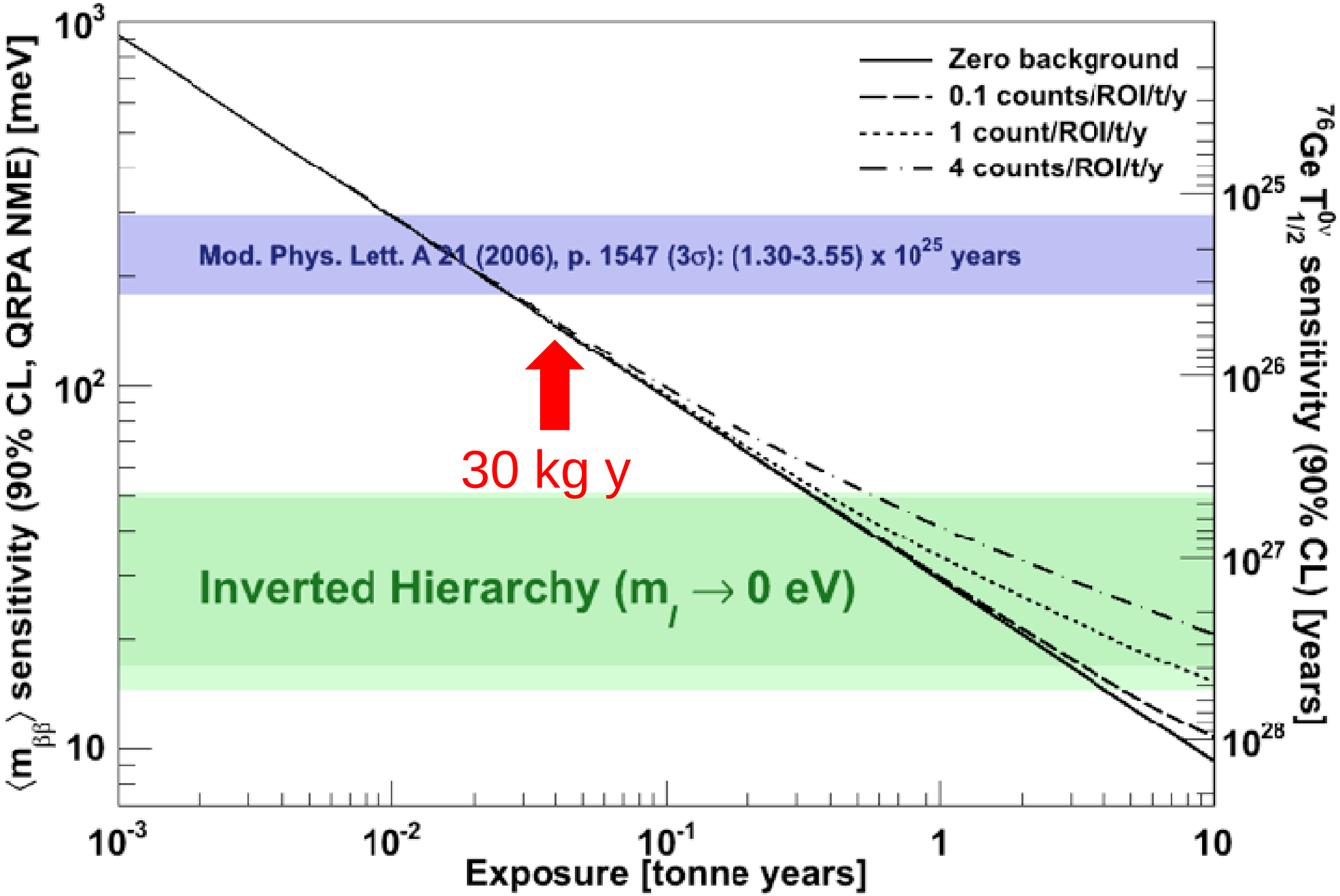
- 40kg of detectors, up to 30kg enriched to >86% ^{76}Ge
- 2 cryostats made of copper electroformed underground, 7 strings of 3-5 detectors per cryostat
- “Conventional” shielding (EfCu, Cu, Pb, poly),4π active muon veto, Rn exclusion box







MJD Sensitivity



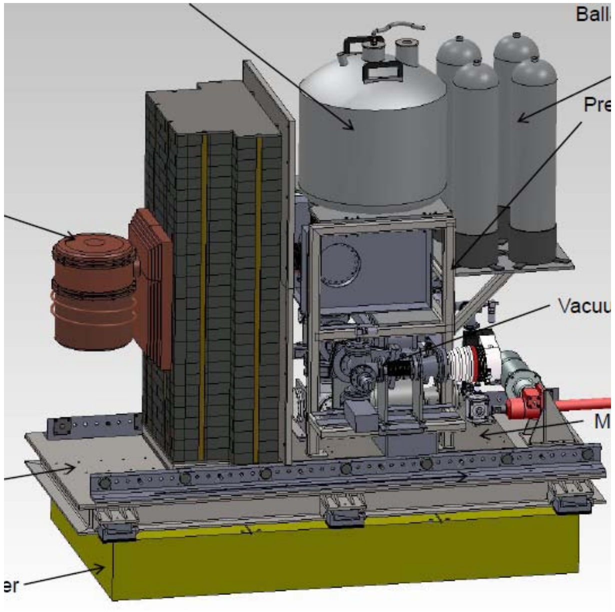
- With 30kg of enriched germanium detectors, ~1 yr to test KKDC claim at 90%

MJD Schedule

MJD will proceed in 3 phases

- **Prototype Module (now!):**
  - Commercial copper, 2 strings $^{\text{nat}}\text{Ge}$
    - Test mechanical design
    - Test detector performance
- **Module 1 (Spring 2014)**:
  - Electroformed copper, mix of $^{\text{enr}}\text{Ge}$ and $^{\text{nat}}\text{Ge}$
- **Module 2 (Fall 2014)**:
  - Electroformed copper , mix of $^{\text{enr}}\text{Ge}$ and $^{\text{nat}}\text{Ge}$

Prototype cryostat

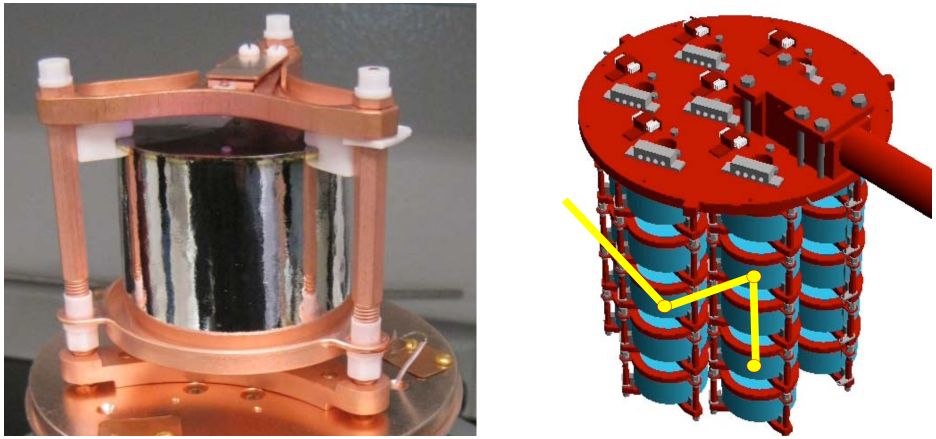


Cryostat 1 and 2

Backgrounds and mitigation

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

Detector mount and Geant4 geometry:

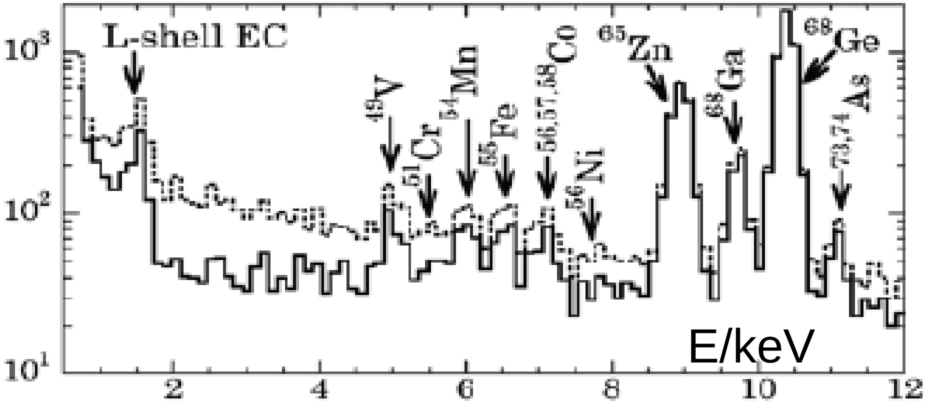


- Intensive assay campaign to identify clean materials
- Detailed MC simulations to understand background contributions
- Clean handling
- Special processes (electroforming)
- Analysis cuts (“PSA”, “granularity”)

Backgrounds and mitigation

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

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

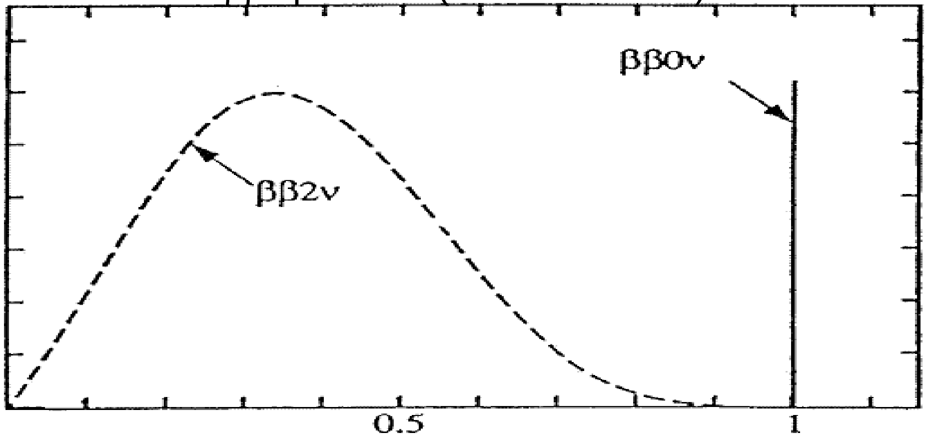


•Deep underground
•Muon veto
•Fabricate materials underground (copper)
•Limit surface exposure (germanium)
•Analysis cuts (^{68}Ge tag using low energy x-rays, Pulse Shape Analysis)

Backgrounds and mitigation

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

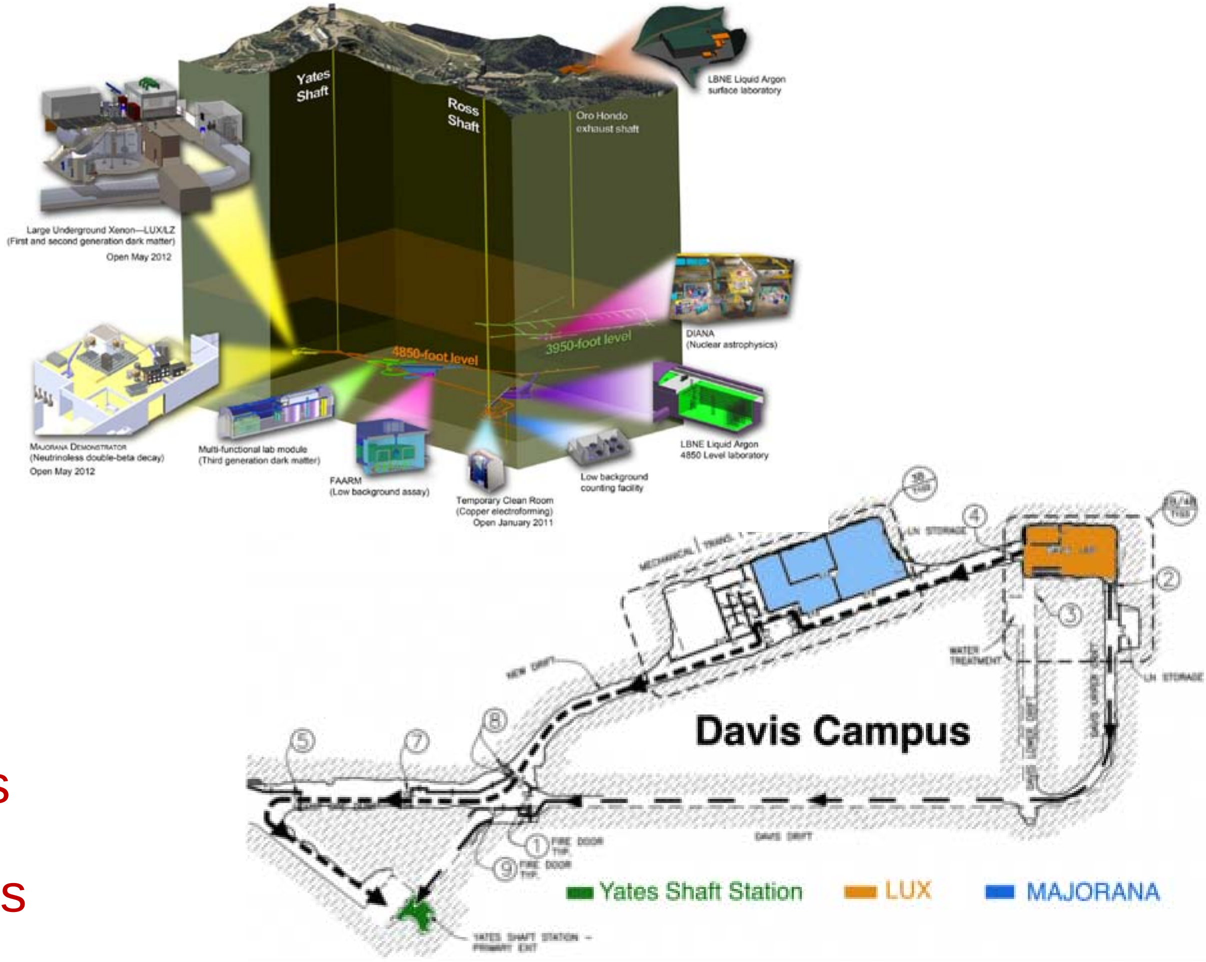
Illustrative $0\nu\beta\beta$ spectrum (not normalized):



•Irreducible backgrounds
•Energy resolution of germanium is main mitigation

MJD status and technologies

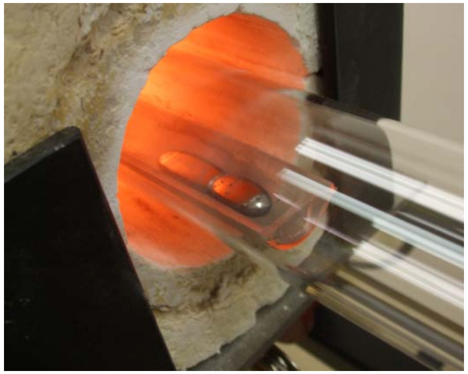
- Enriched detector processing
- Detector cooling
- Electroformed copper
- Low noise/low background electronics and tests at LBNL
- Underground lab and status
- Simulation and backgrounds



The Sanford Underground Research Facility, in Lead, SD

Enriched germanium processing

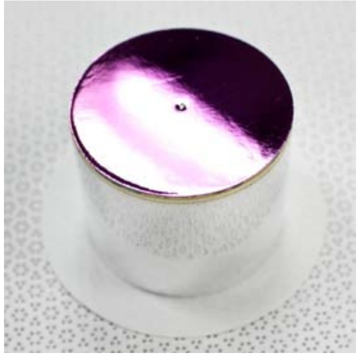
Enrichment to >86% at Electro-Chemical Plant (ECP) in Russia



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

Zone-refinement by commercial vendor

Pull crystal by commercial vendor

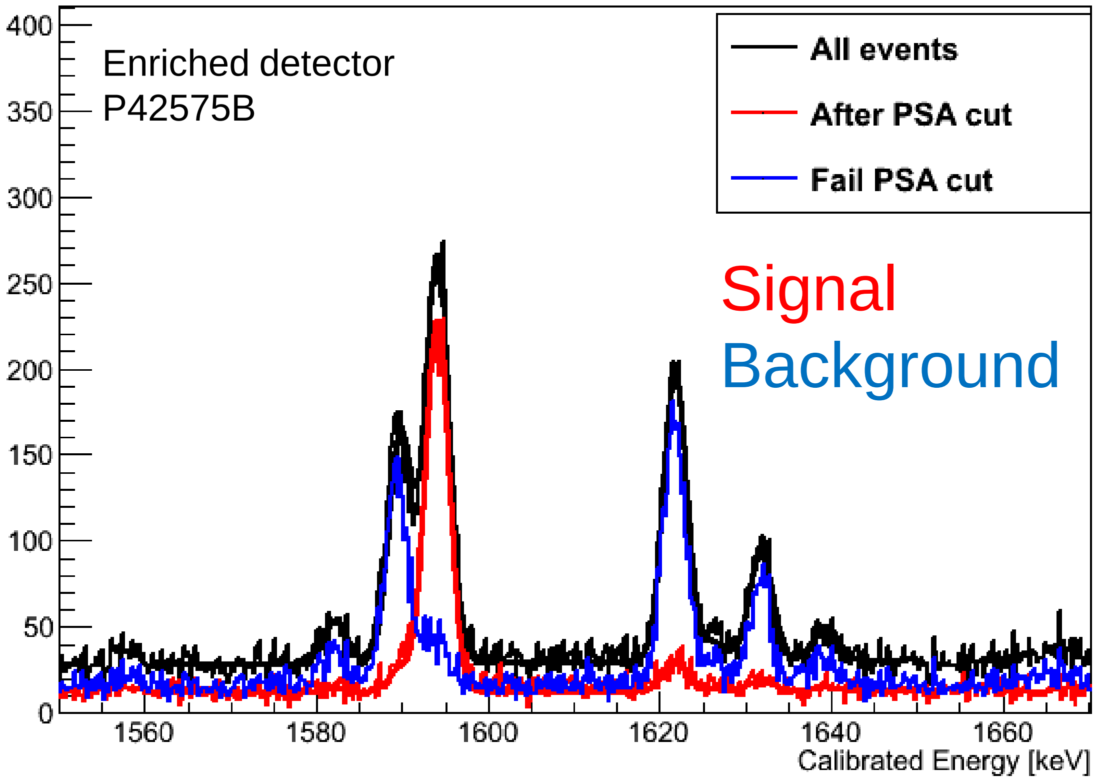


Detector fabrication

Status of enriched detectors

- Have produced 23 enriched detectors, 19.4kg.
- These are underground and have been tested
- Performance of detectors is excellent so far

Detector performance

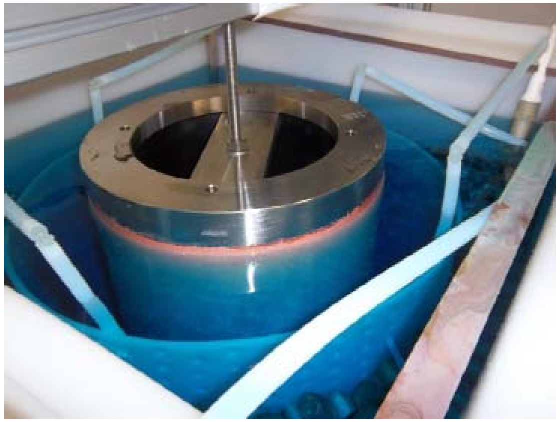


^{232}Th calibration data from enriched detector shows that with pulse shape analysis cut:

- Remove 90% 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

The cleanest copper in the world

The temporary clean room at SURF (4850)



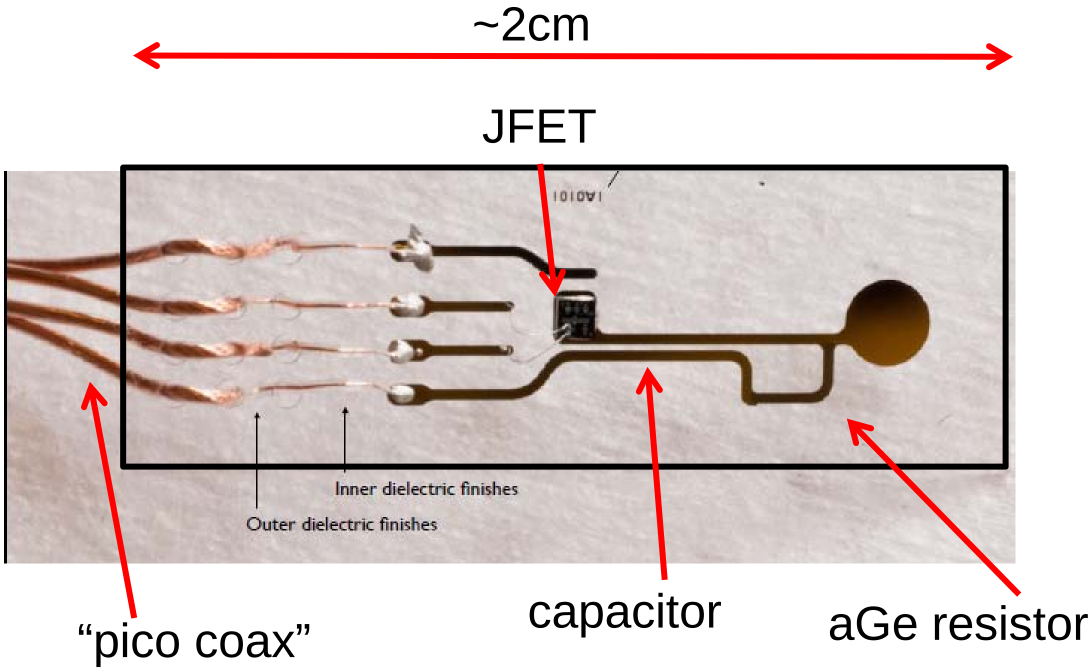
Copper being electroformed on a stainless steel mandrel

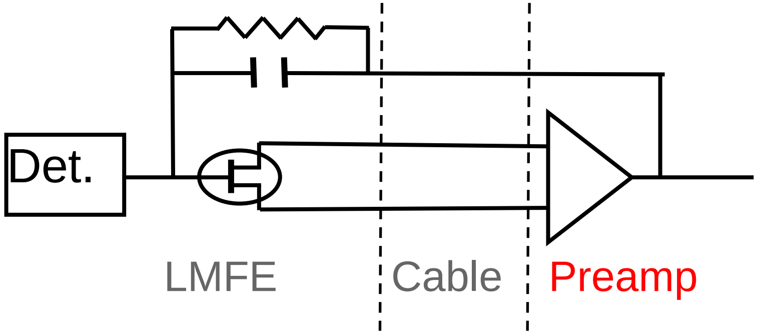
A clean machine shop underground

Instrumenting germanium detectors

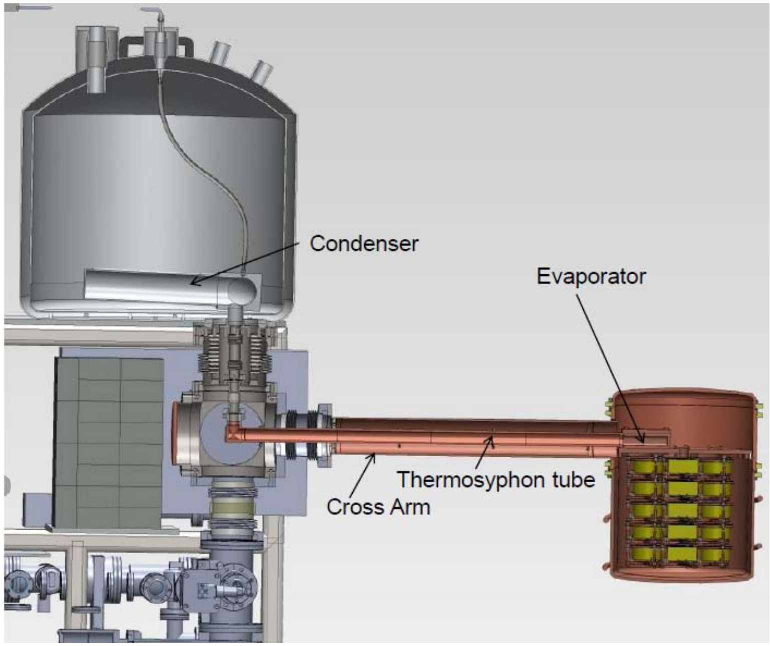
Detector unit from first underground string

- Developed ultra-low background low noise readout



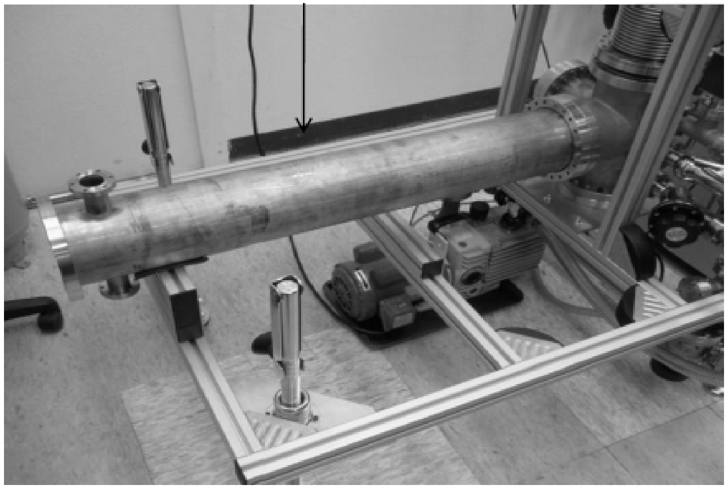


MAJORANA detector cooling



Thermosiphon

Test string

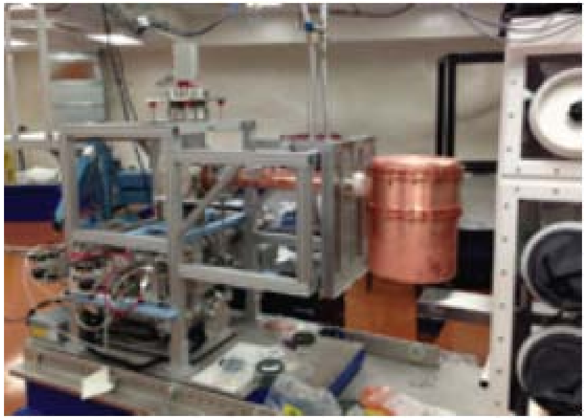


Prototype thermosiphon tested

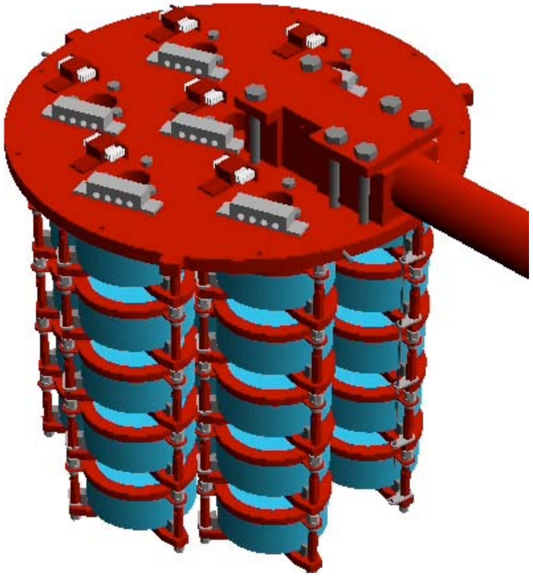
- Cooling to the cold plate provided by a thermosiphon
- Detailed thermal model produced to understand cooling power and needs
- Cooling tests performed and design optimized (detector blanks < 95K)

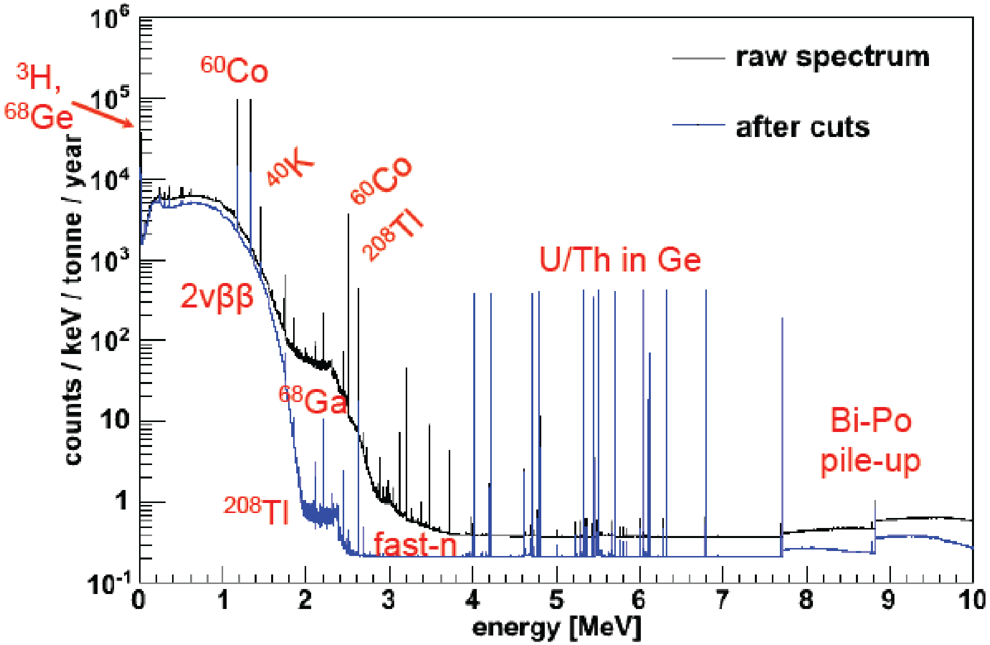
Current status of work underground

Dec. 2012



MJD Simulations

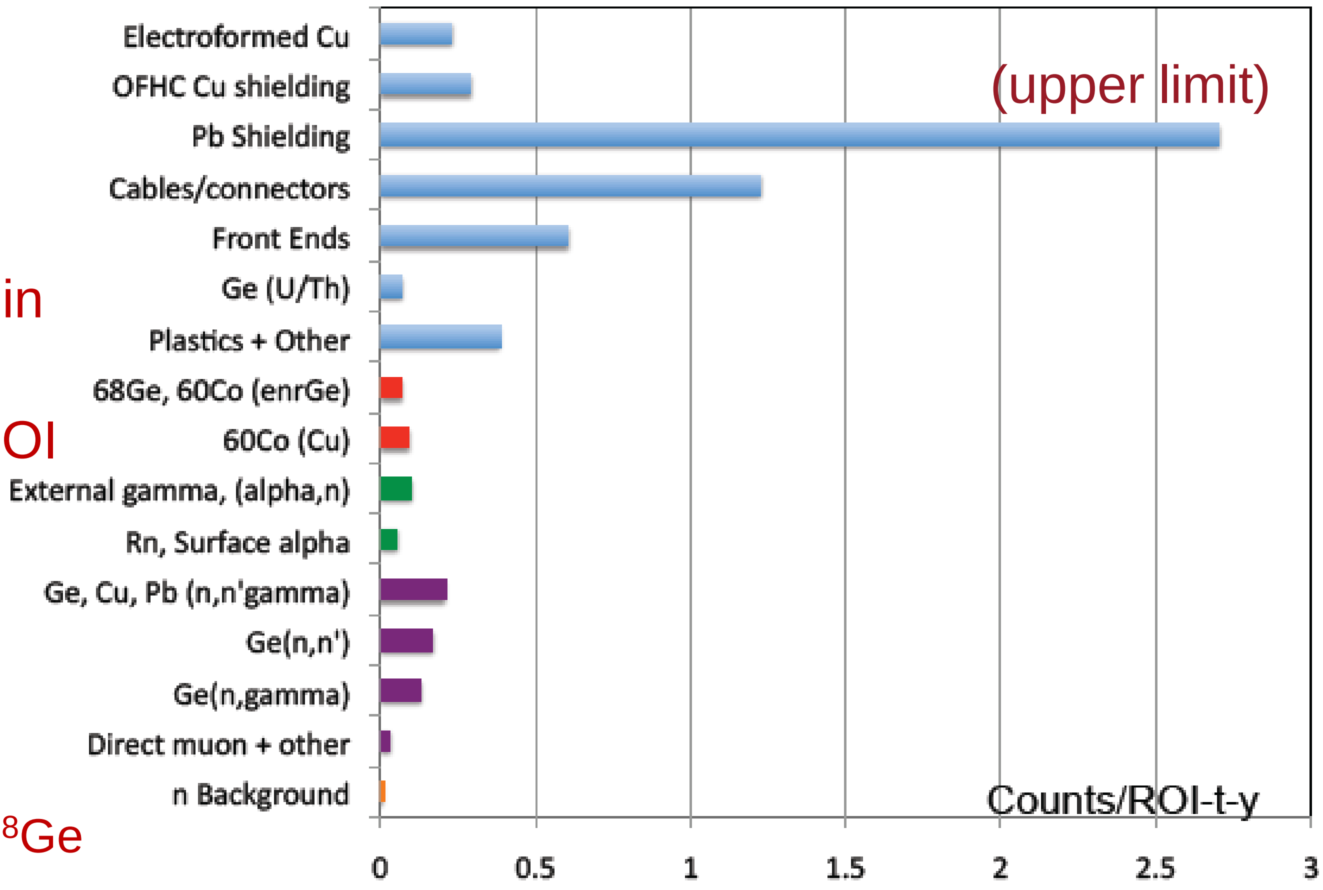




- Detailed Monte Carlo model to simulate backgrounds from 3800 components and detailed verification campaign
- ~60kCPU hours of simulations (PDSF)
- U, Th, K chains for all components and ^{68}Ge, ^{60}Co for select components
- Dominant contribution at $Q_{\beta\beta}$ is from multi-site events from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

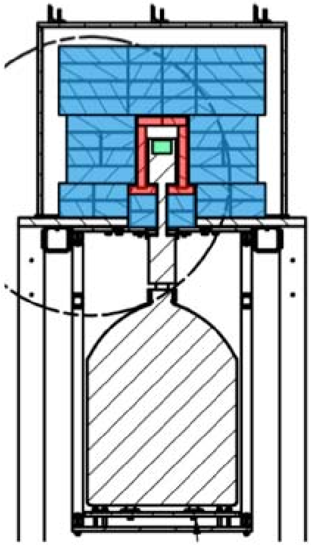
MJD Background budget

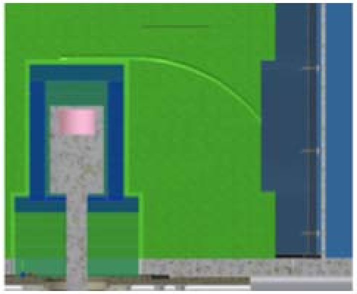
- Detailed background model produced
- Based on previous assays
- Expect <10 c/t/y/ROI in MJD
- Translates to 1c/t/y/ROI for tonne-scale experiment:
  - More self-shielding
  - Improve materials (cables/connectors)
  - Longer cooldown for ^{68}Ge
  - Deeper (or improved shielding)

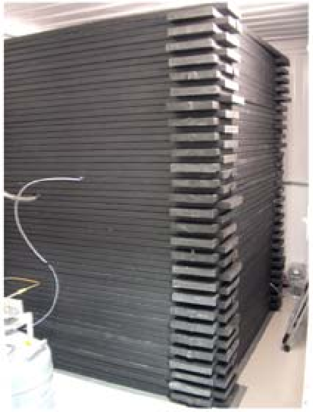


MJD Detector R&D - MALBEK

- Majorana Low Background BEGe at KURF
- 455g ^{nat}Ge
- **Customized CANBERRA Broad Energy Germanium Detector**
  - Crystal geometry optimized for charge collection and noise performance.
  - Low-background Cu cryostat (J.I. Collar -- UC)
- **R&D Goals**
  - Study optimized point-contact geometry
  - Test MJD DAQ
  - Backgrounds over broad energy range sub-keV to 3 MeV (surface events, noise, validate MJD background model)
  - Low-E sensitivity of MJD (^{68}Ge 0vββ background, Dark Matter, axions)

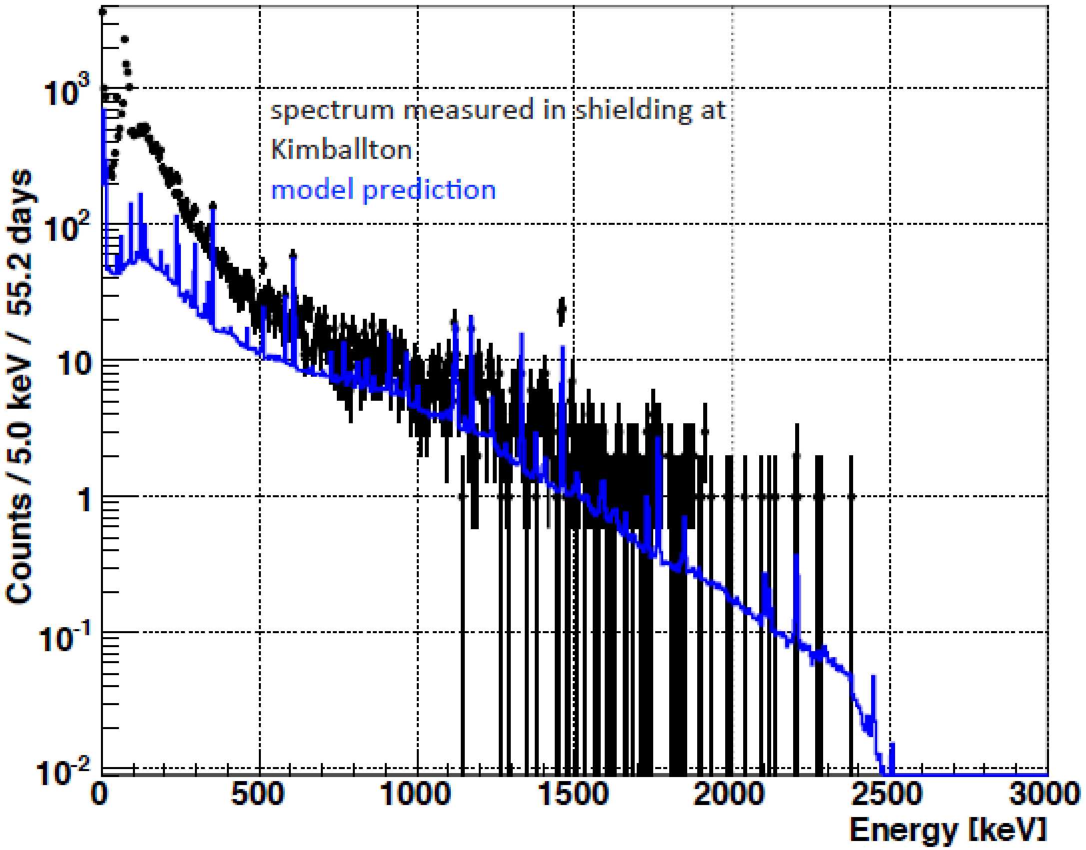






P. Finnerty et al., Nucl. Instr. and Meth. A 652, (2011) 692-695.
P. Finnerty et al. IEEE NSS-MIC, (2010) 671-673.

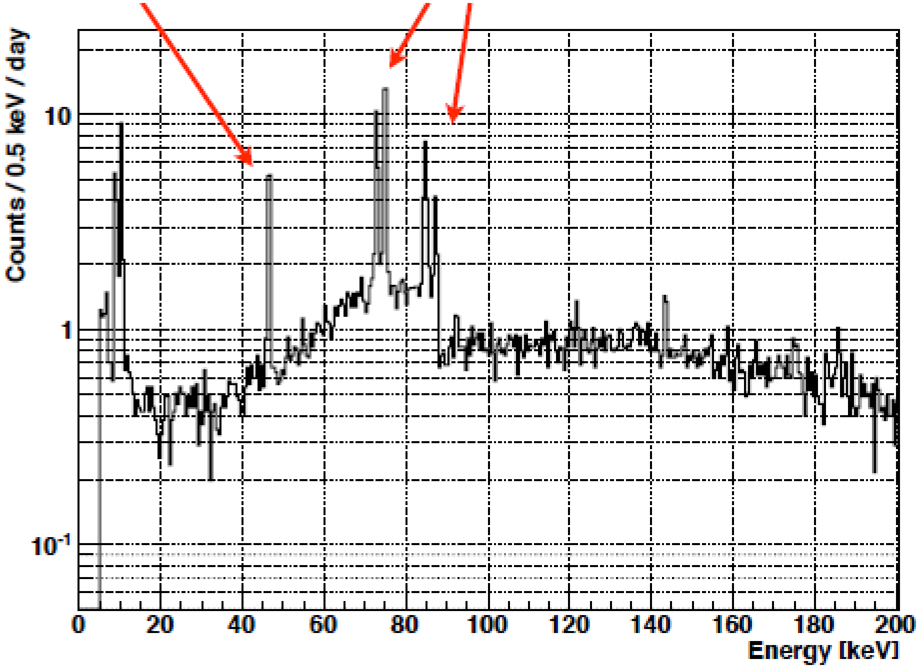
Background model for MALBEK

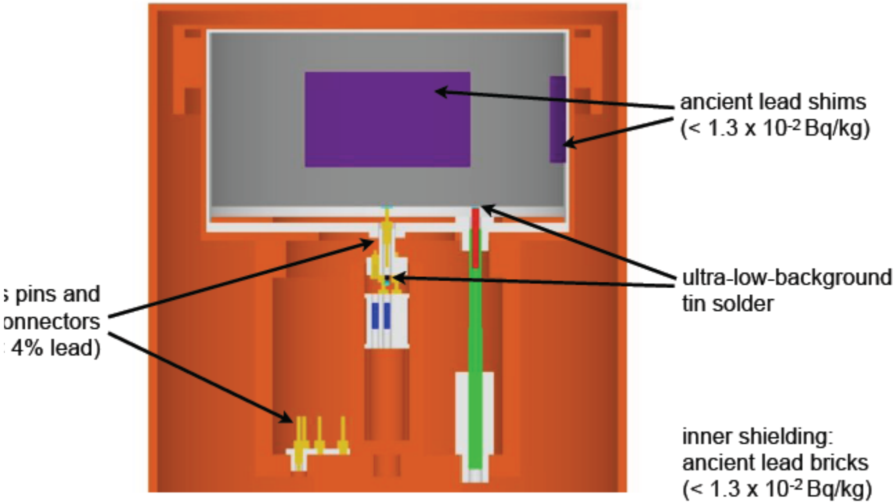


A. Schubert,
Univ. Washington,
Thesis 2012

- Agreement, initially not so great!

Background model for MALBEK

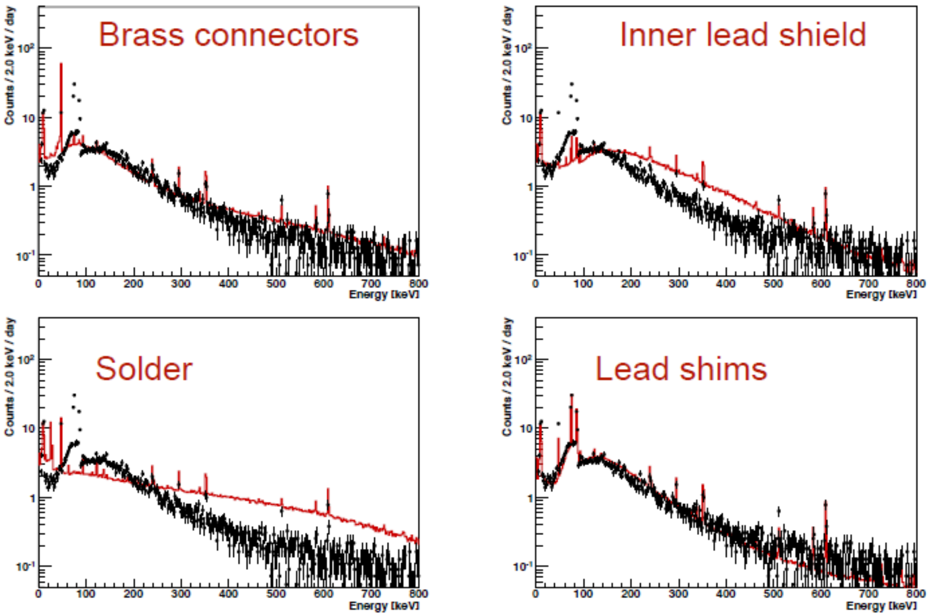


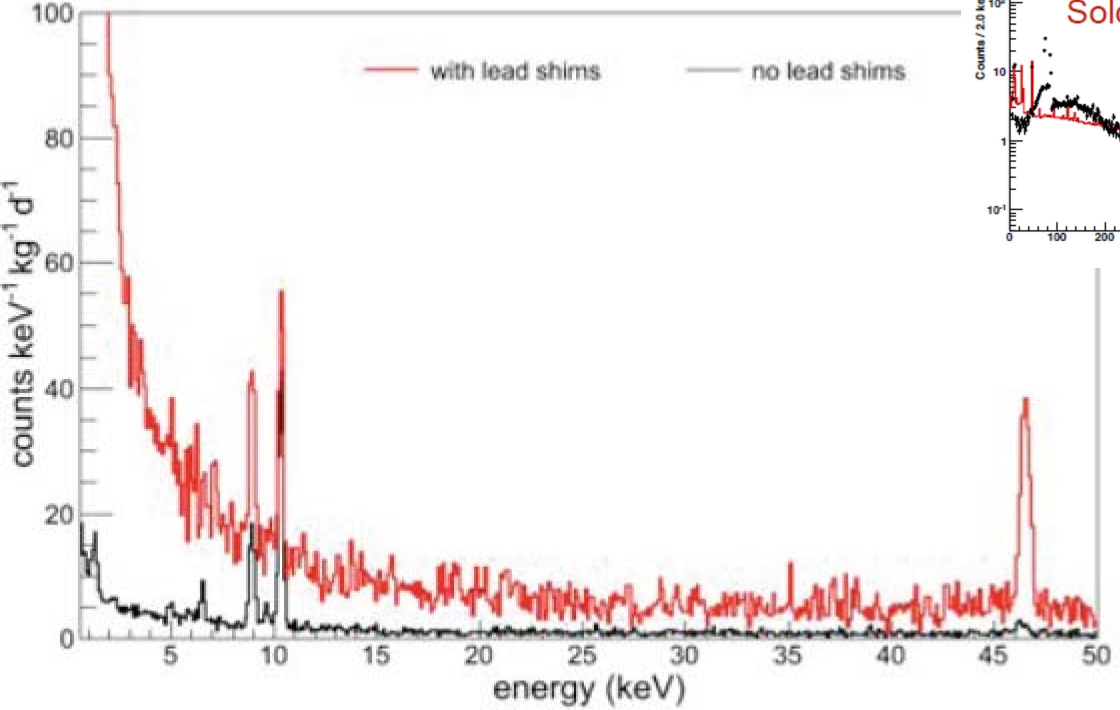


- Clear source of Pb in spectrum
- Modified MC simulation to try and understand source of Pb

Background model for MALBEK

- Able to use MC to identify shims as source of background

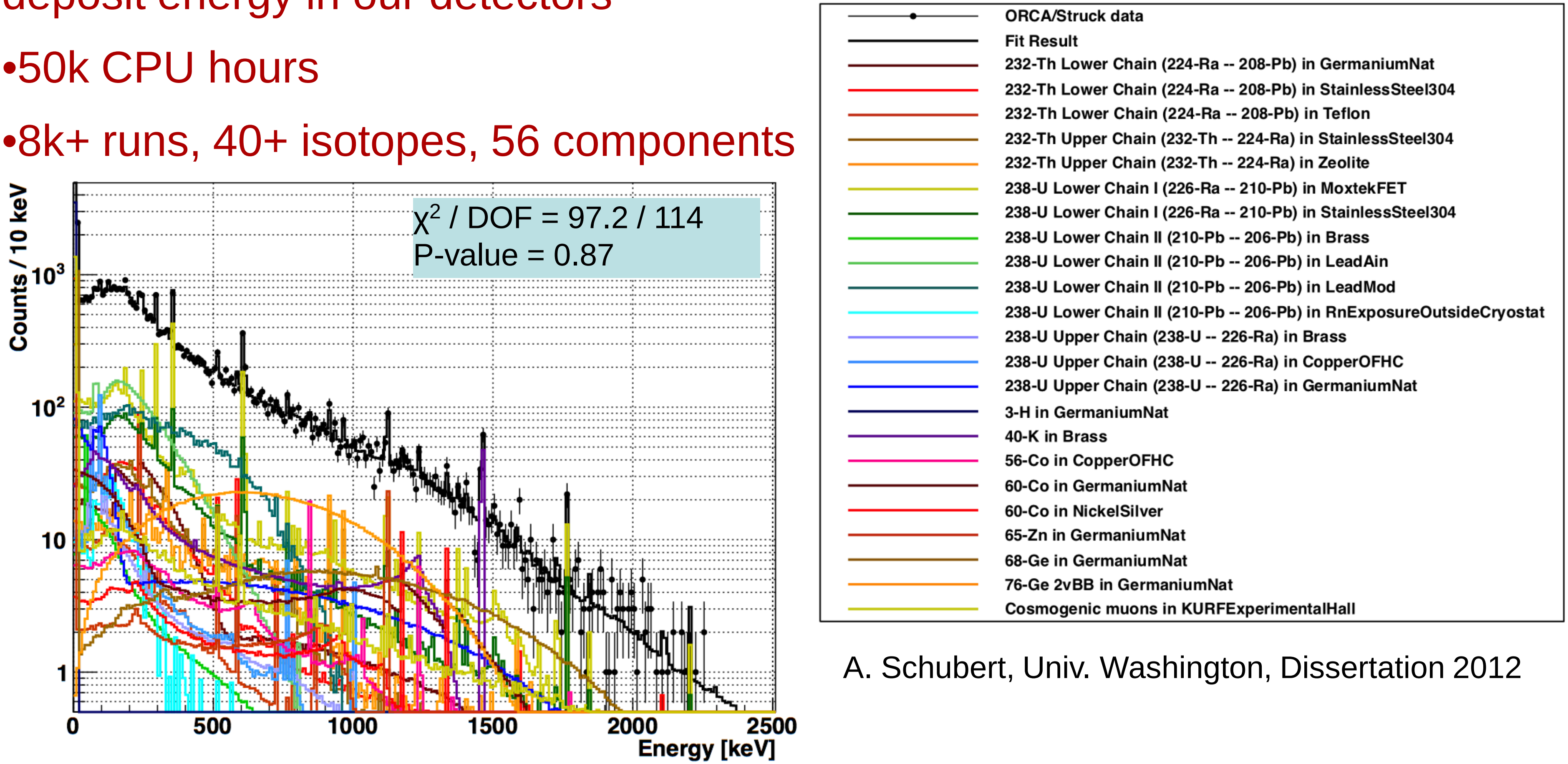




- After removing shims, dramatic reduction in background at low energies

Background model for MALBEK

- MaGe / Geant4 simulations to determine efficiencies for contamination to deposit energy in our detectors
- 50k CPU hours
- 8k+ runs, 40+ isotopes, 56 components



A. Schubert, Univ. Washington, Dissertation 2012

Dark matter with PPCs

The rate of interactions in the detector with a given recoil energy :

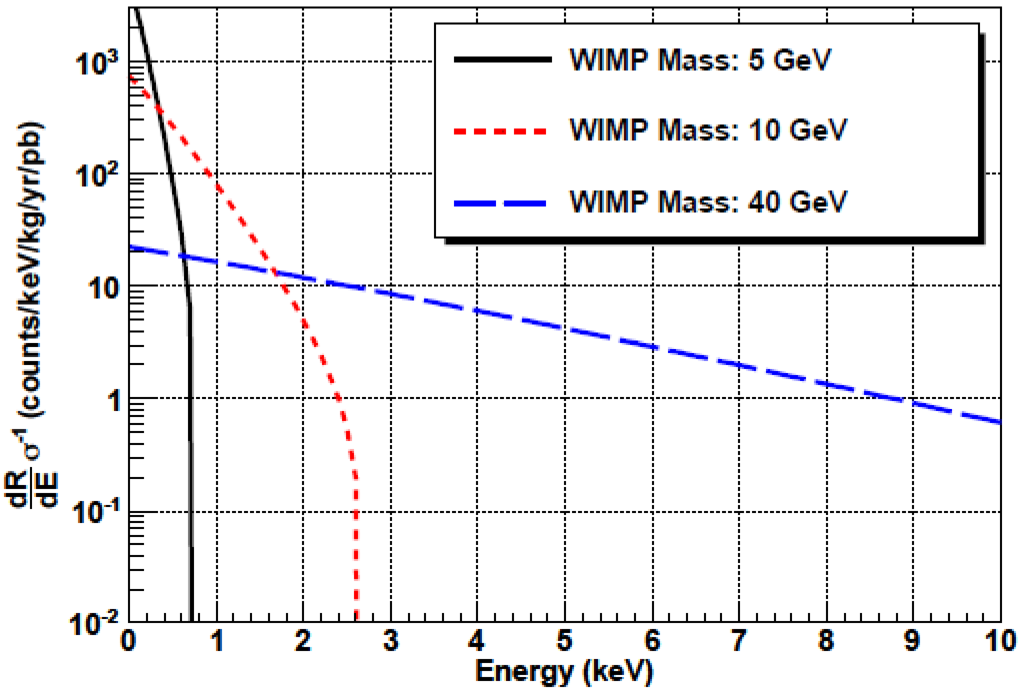
$$\frac{dR}{dE_{\mathrm{R}}} = N_T \frac{\rho_\odot}{M_{\mathrm{DM}}} \int_{|\vec{v}|>v_{\mathrm{min}}} d^3v\, v\, f_\oplus(v,t)\, \frac{d\sigma}{dE_{\mathrm{R}}}$$

The cross section for a certain nucleus and recoil

$$\frac{d\sigma}{dE_{\mathrm{R}}} = \frac{m_N \sigma_n}{2v^2\mu_n^2} \frac{[f_p Z + f_n(A-Z)]^2}{f_n^2} F_N^2(q) F_{\mathrm{DM}}^2(q,v)$$

Lindhard theory to convert recoil into ionization energy:

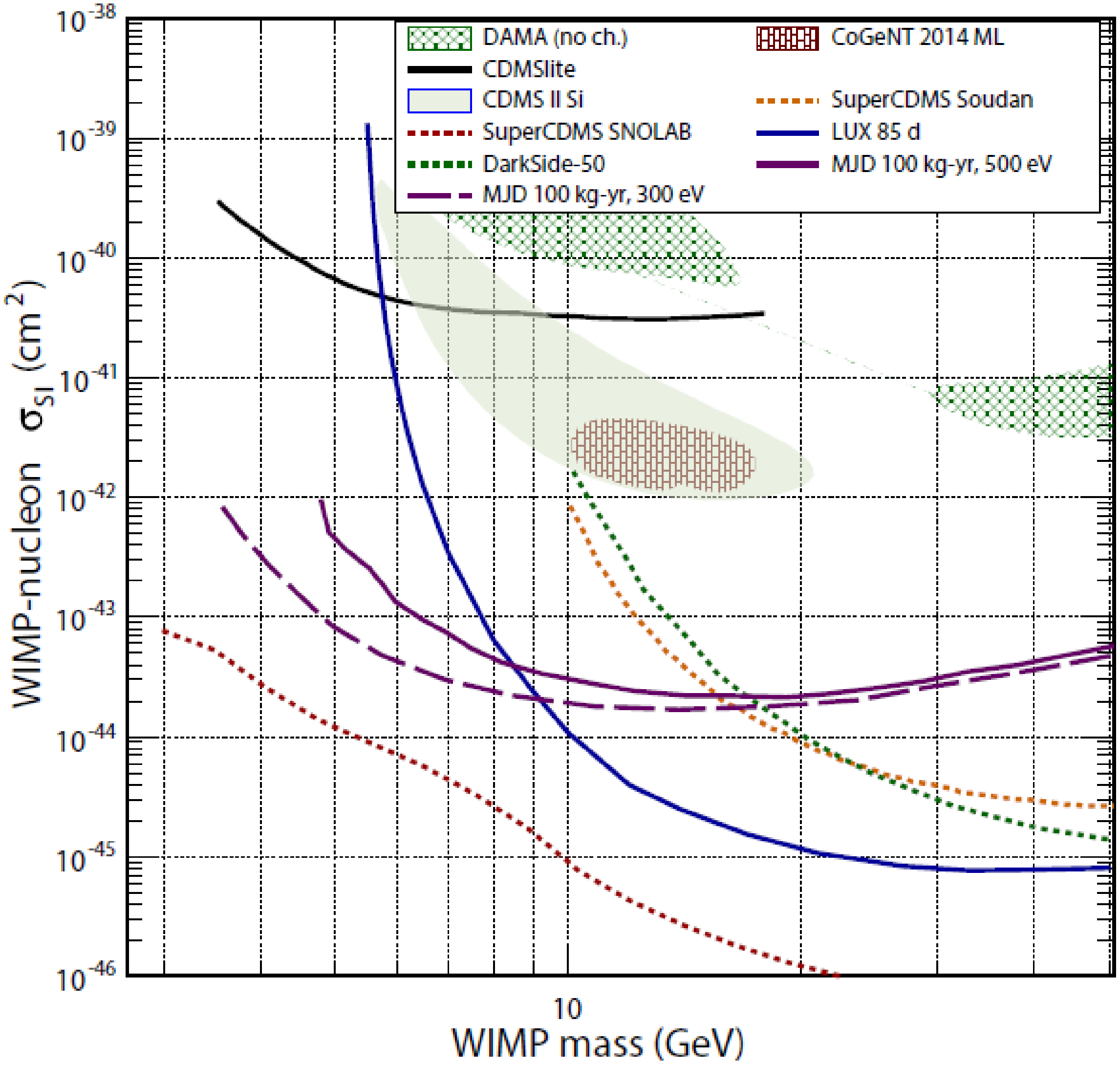
$$\frac{E}{\mathrm{keVee}} = 0.2 \left(\frac{E_R}{\mathrm{keV}}\right)^{1.12}$$



M.G. Marino, PhD Thesis (UW, 2010)

Low mass WIMP signal is an exponential at low energy (cut off by escape velocity of WIMPS) -> ***Can trade some mass for low threshold and preserve sensitivity (for light WIMPS)***

MAJORANA sensitivity to dark matter



Another interesting application for germanium detectors

Coherent neutrino-nucleus scattering:

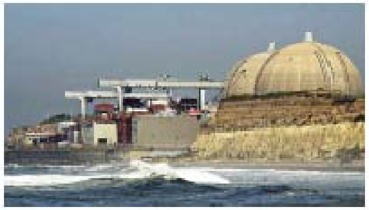
- Similar to dark matter nuclear recoils
- Never detected before
- Provides a way to detect all neutrinos flavours through neutral current interaction:
  - o Normalize neutrino oscillation experiments
  - o Search for “sterile” neutrinos
  - o Non-proliferation
  - o Nuclear structure

From D. Hogan (UCB/LBNL):

$$\frac{d\sigma}{dT} = \frac{G_F^2 Q_W^2}{4\pi} m_N \left(1 - \frac{m_N T}{2E_\nu^2}\right) F^2(Q)$$

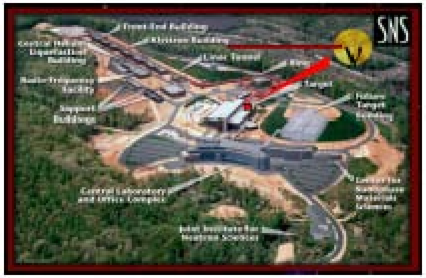
SONGS

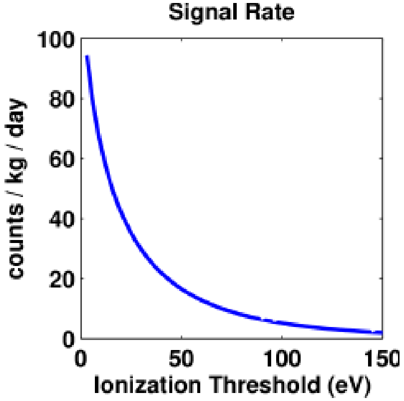
San Onofre Nuclear
Generating Station

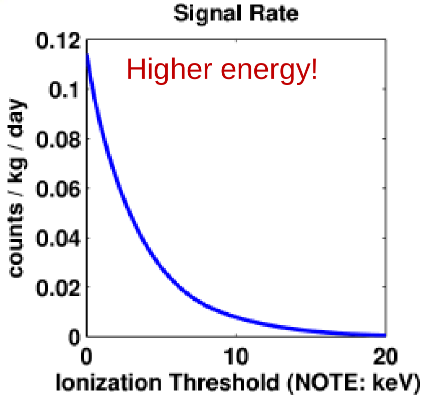


SNS

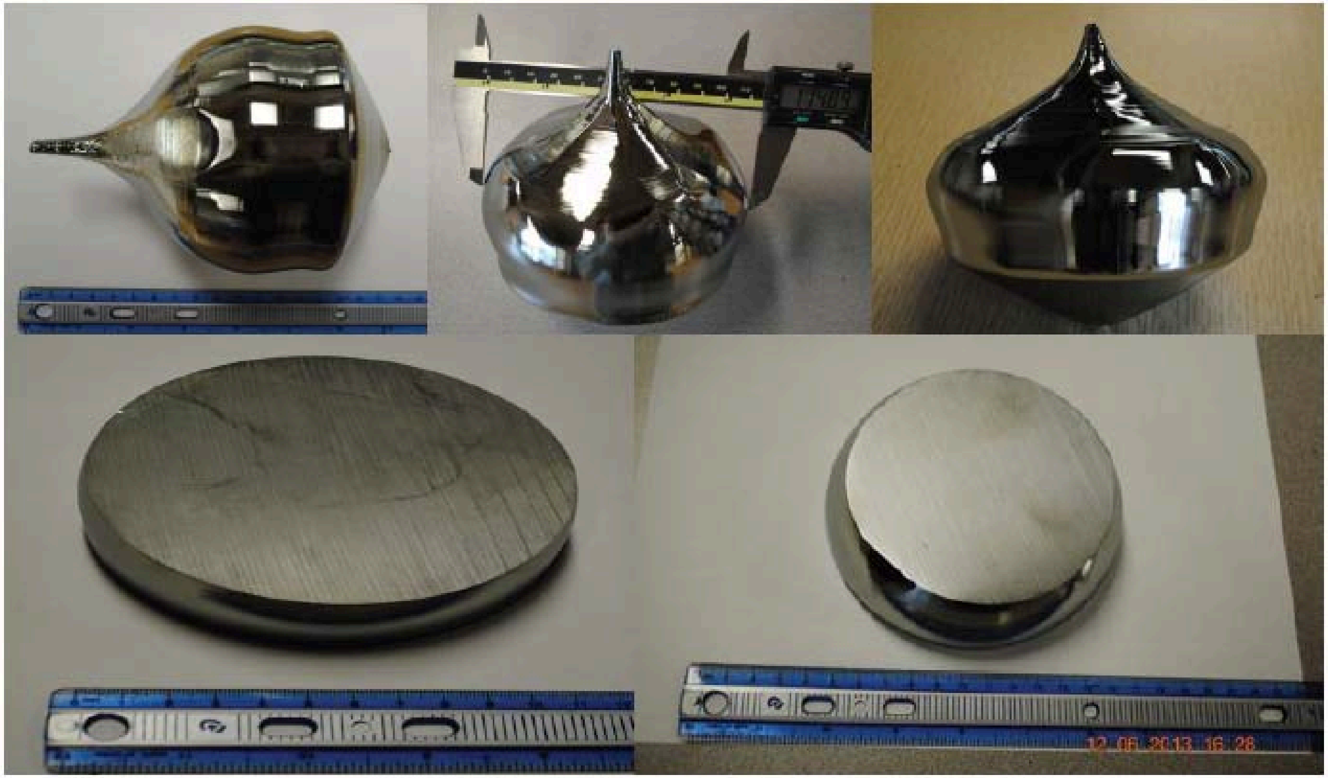
Spallation Neutron Source






Higher energy!

Large-Size Ge Crystal Growth at USD

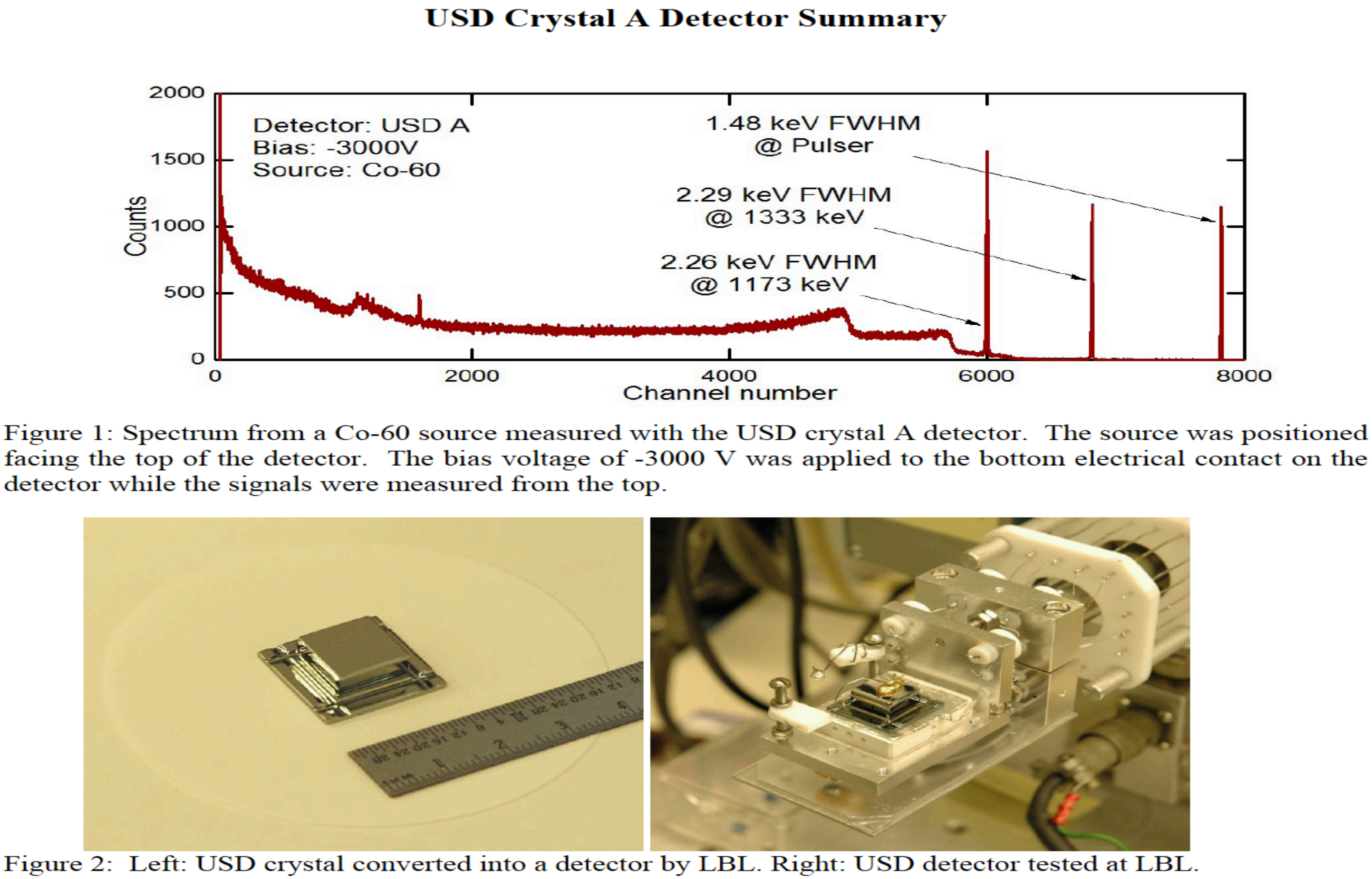


Mei 2014

- Upper: diameter: 11.5 cm; length: 17 cm; weight: 4809 g
- Lower: the useful detector portion: D >10 cm; thickness > 3.7 cm; weight > 2,000 g

(DE-FG02-10ER46709)

First Detector Fabricated at LBL



USD Crystal A Detector Summary

Figure 1: Spectrum from a Co-60 source measured with the USD crystal A detector. The source was positioned facing the top of the detector. The bias voltage of -3000 V was applied to the bottom electrical contact on the detector while the signals were measured from the top.

Figure 2: Left: USD crystal converted into a detector by LBL. Right: USD detector tested at LBL.

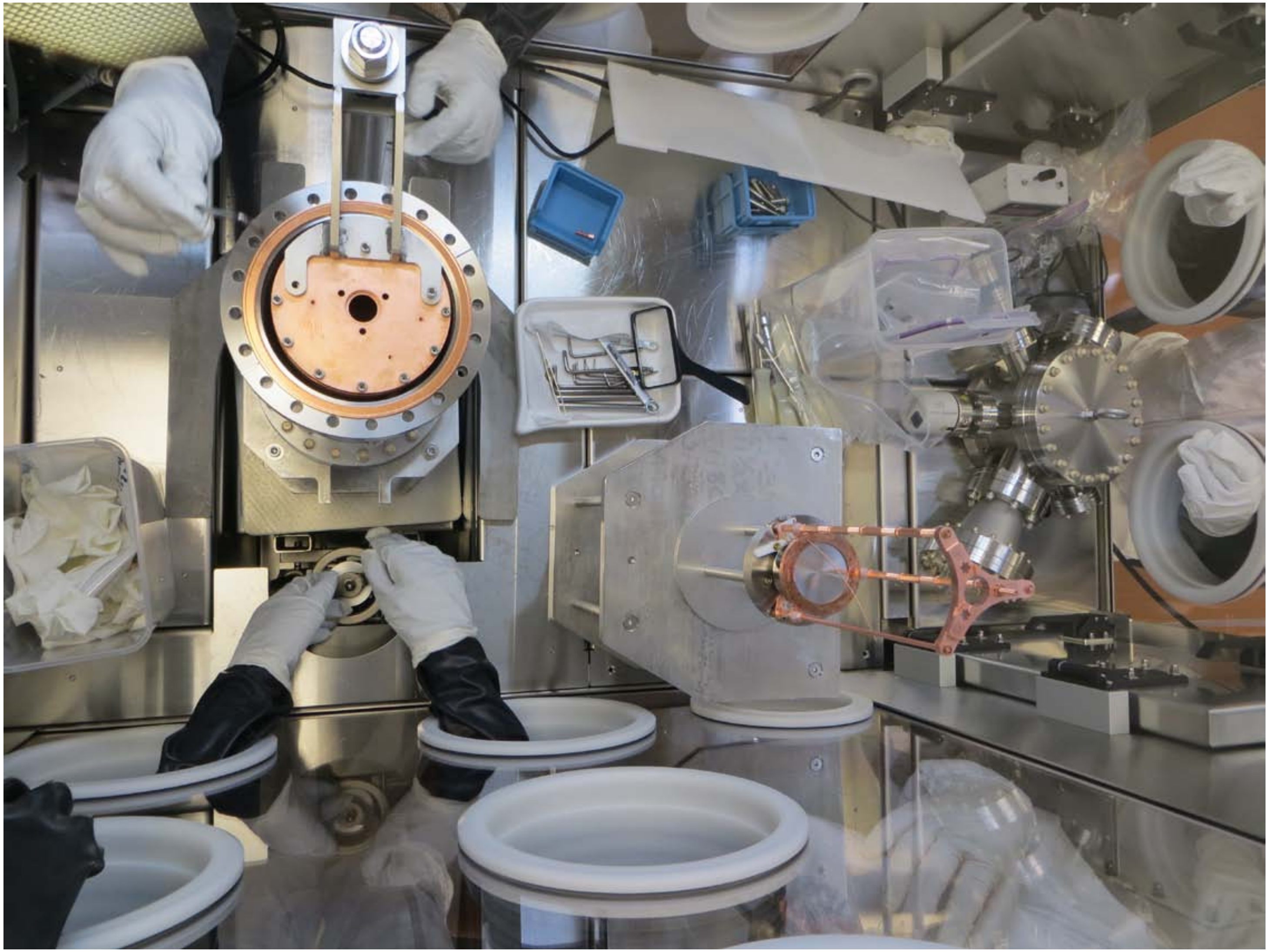
M. Amman (LBNL)

Summary

- Very exciting time!
- Started taking data underground
- Will start assembly of the enriched detector array soon
- Rich physics program with Ge detectors

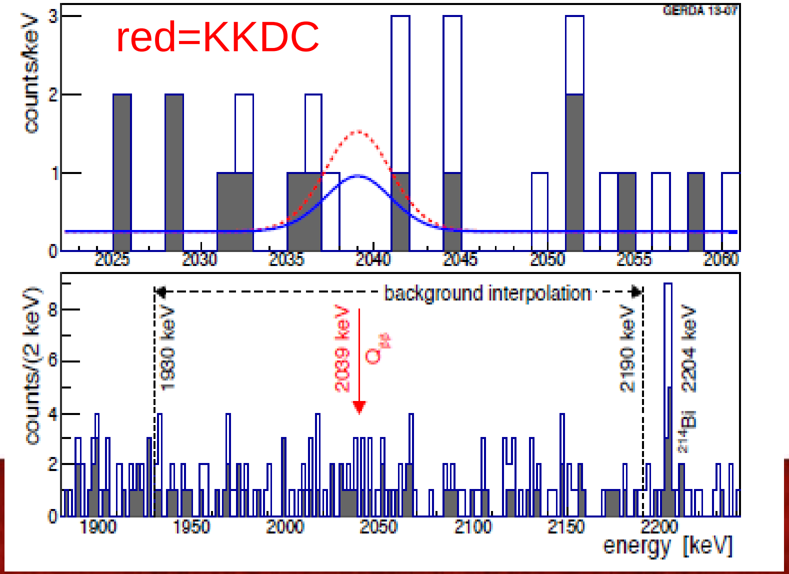
The MAJORANA Collaboration, April 2013 at SURF

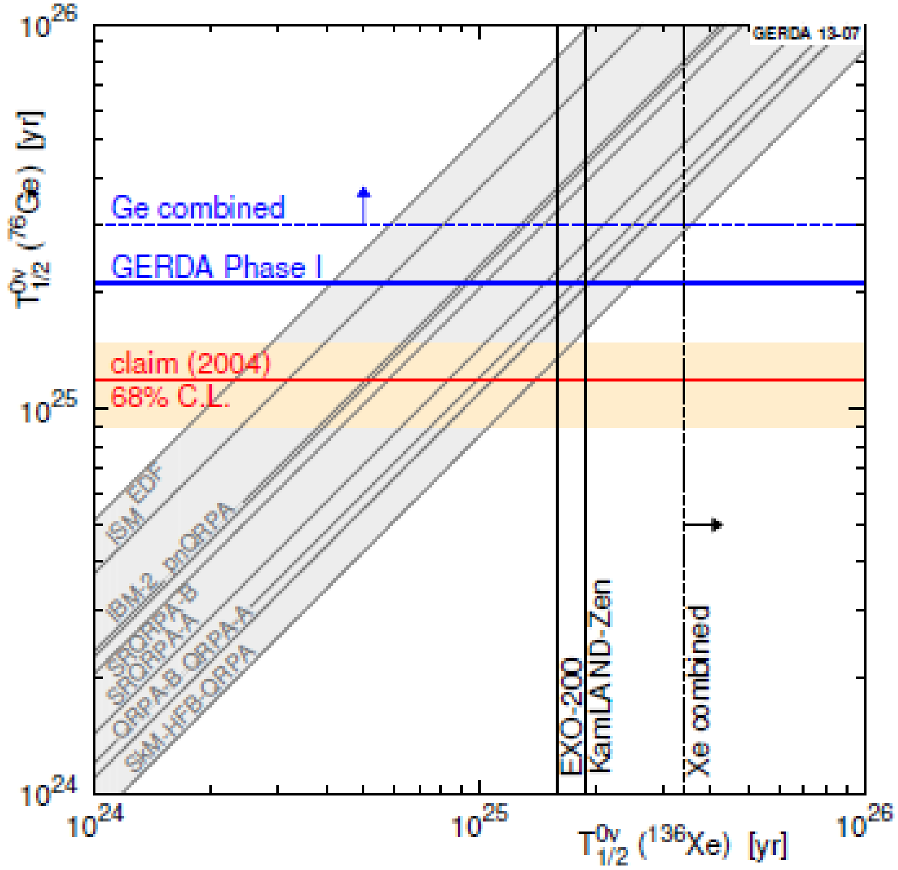
Thank you!



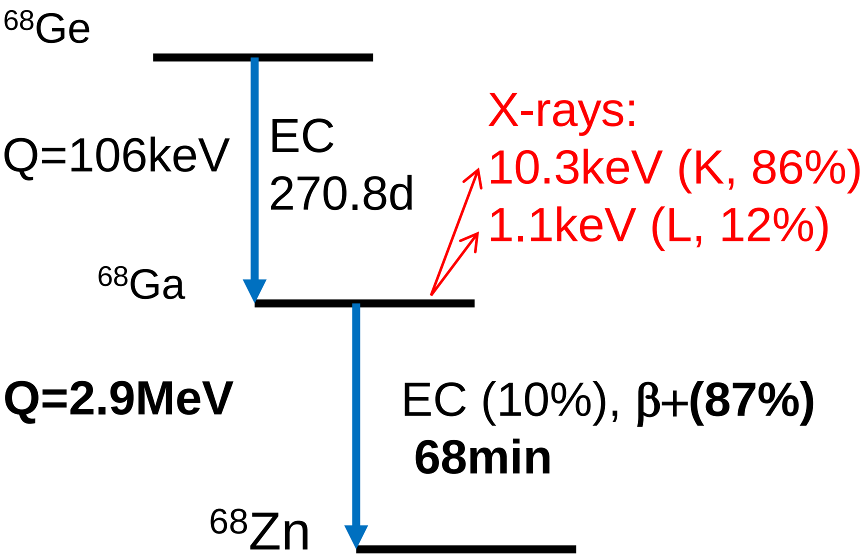
Backup slides

GERDA results


red=KKDC



Time correlation cut (^{68}Ge)



^{68}Ge

Q=106keV

EC
270.8d

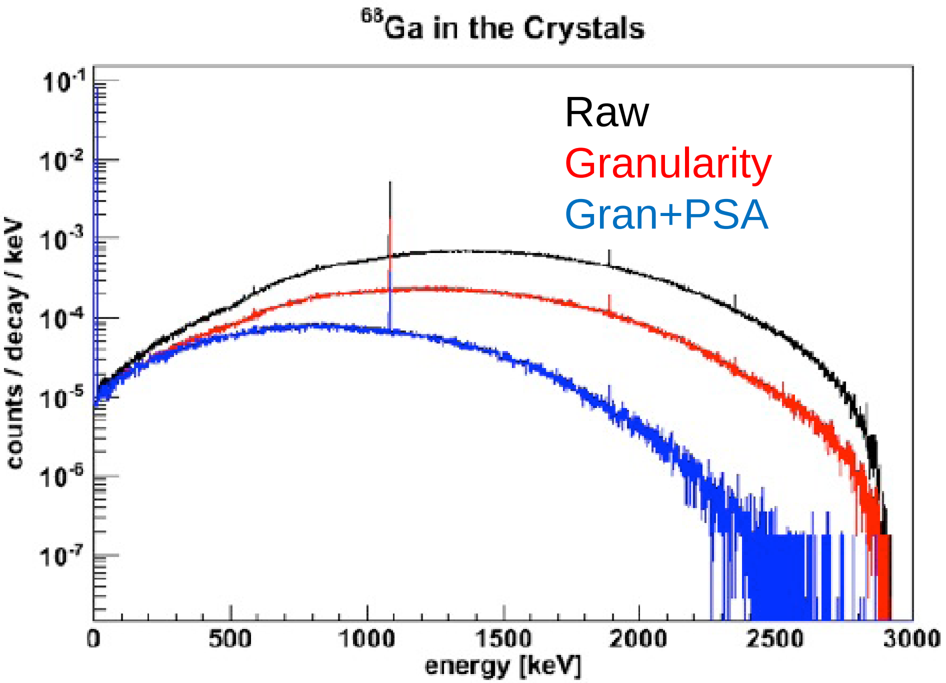
X-rays:
10.3keV (K, 86%)
1.1keV (L, 12%)

^{68}Ga

Q=2.9MeV

EC (10%), β+**(87%)**
68min

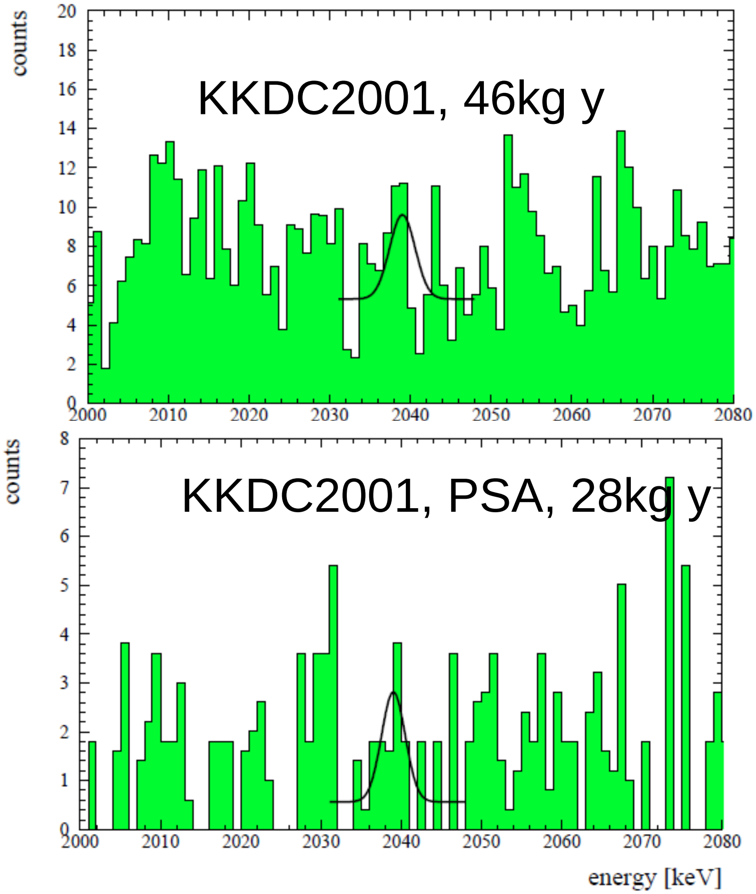
^{68}Zn

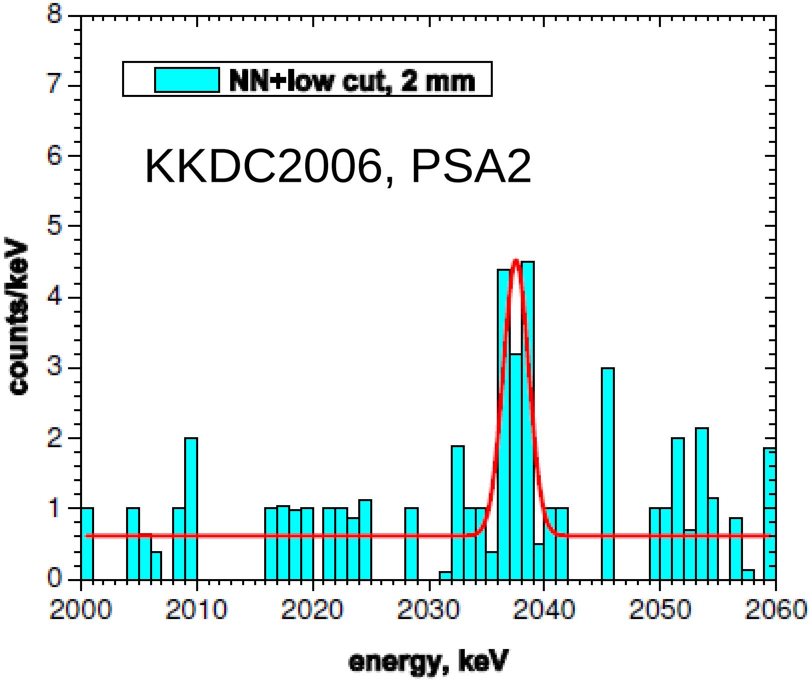


- ^{68}Ge produced by cosmogenic activation
- Sea-level activation rate 2.1 (30) atoms/kg/day for ^{enr}Ge (^{nat}Ge)
- Assume 100 day exposure for ^{enr}Ge, saturation for ^{nat}Ge
- Highly suppressed by granularity (x1/4) and PSA (1/25x)
- **Tag ^{68}Ge decays with 10.3keV and 1.1keV x-rays, then veto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

Klapdor-Kleingrothaus Claim

- Claim of a signal from operating 11kg of enriched (86% ^{76}Ge) from 1990-2003, from a subset of the Heidelberg-Moscow collaboration
- 2006 paper, with improved PSA, claims 6.8s significance





Making a claim on the spectrum from the 2001 paper has raised questions in the community about the rigor of the analysis.
The peak in the 2006 paper is more convincing.

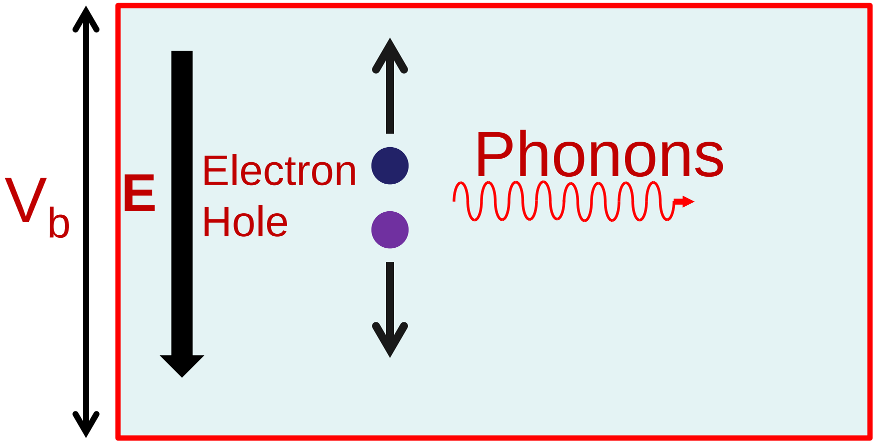
Lowering the energy threshold

Neganov-Luke phonons

- Drifting charge carriers loose energy through heat (phonons)

$E_T = Q * V_b$

- Can measure Q by measuring E_T
- Can increase V_b to increase gain in measuring E_T



Thermal energy:

$$E_T = (E_{rad}/\varepsilon_{Ge})e^*V_b + E_0$$

- Lower energy threshold in germanium and increase sensitivity to dark matter and neutrino-nucleus scattering!