Neutrinoless Double-Beta Decay and the MAJORANA Experiment

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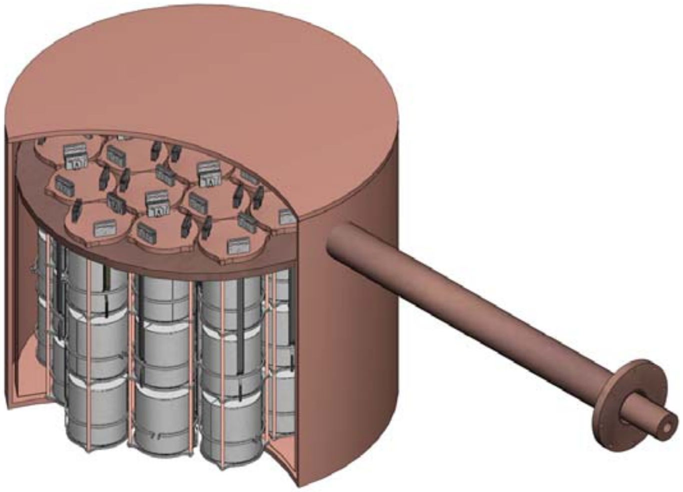
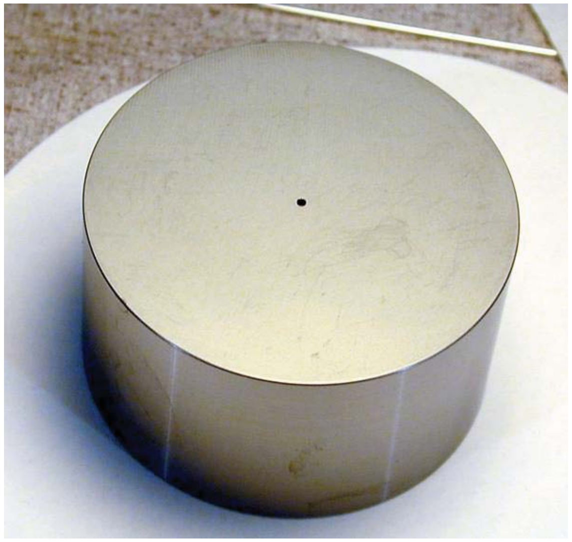
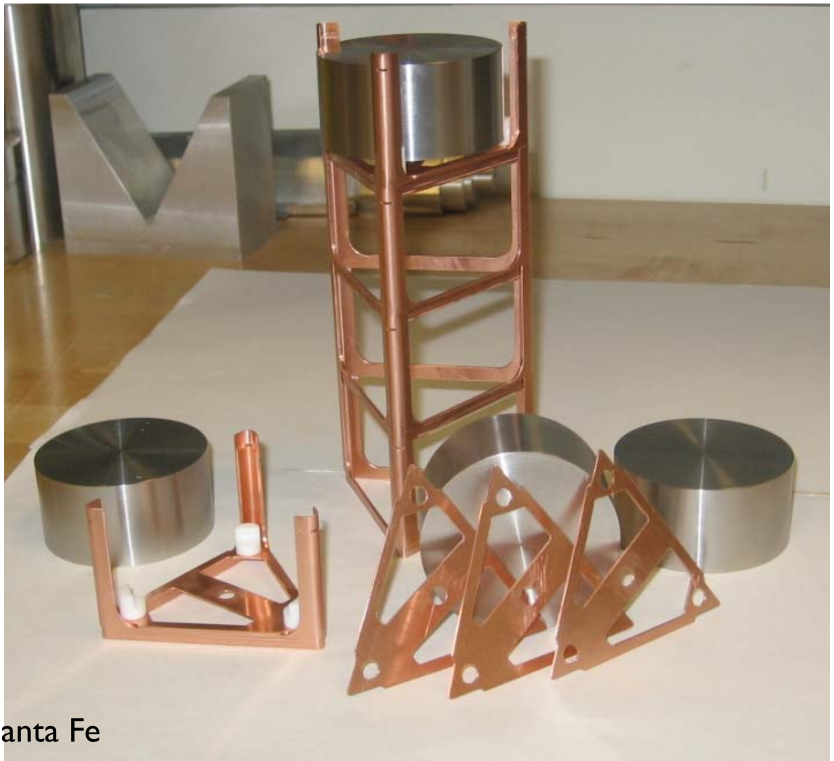
for the
MAJORANA Collaboration

Outline

- Double-Beta Decay
- The MAJORANA Experiment
- The Initial MAJORANA Module
- Backgrounds and Background Rejections
- Detectors
- Recent Progress and Plans

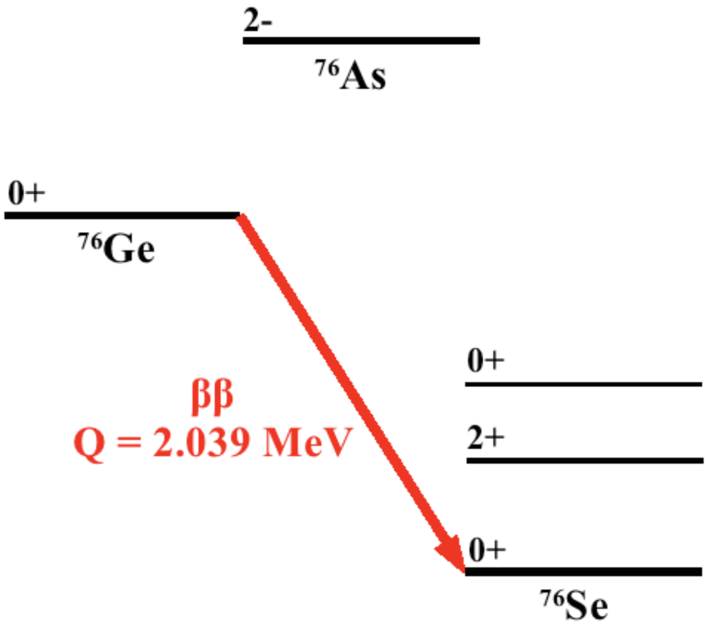






Two Neutrino Double-Beta Decay

- An allowed nuclear physics process
  - Can occur when single β decay not allowed
  - Lepton number is conserved
  - Observed in a number of isotopes



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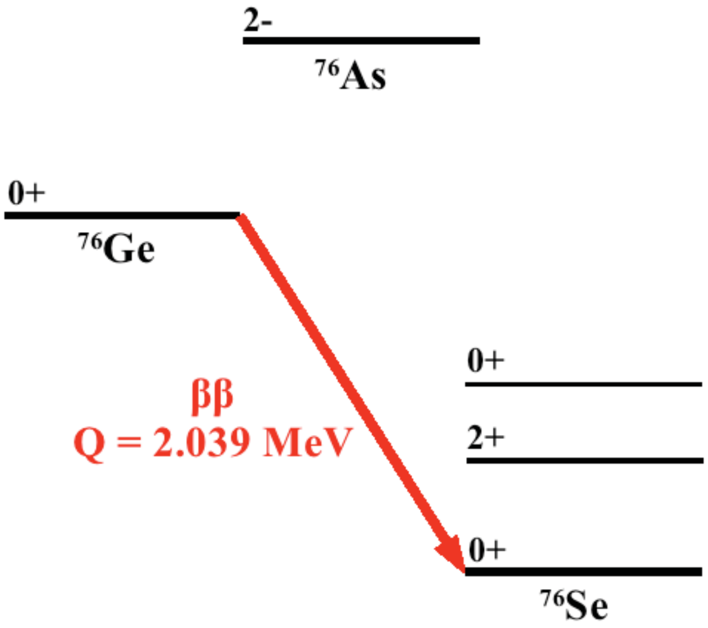
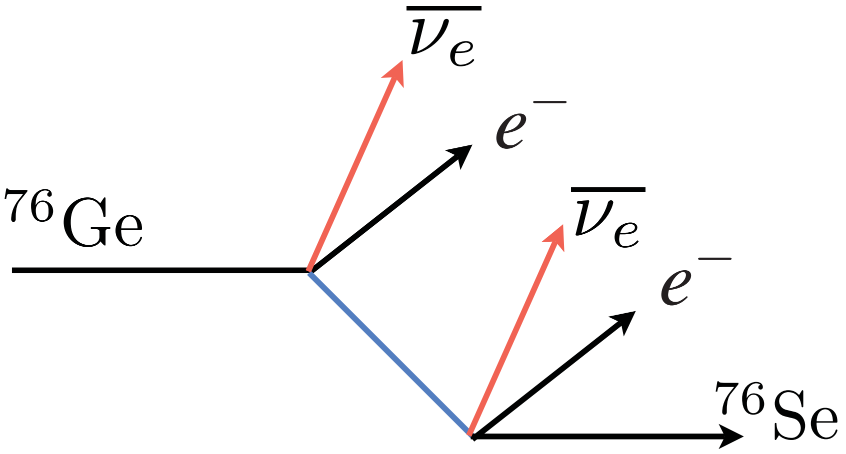


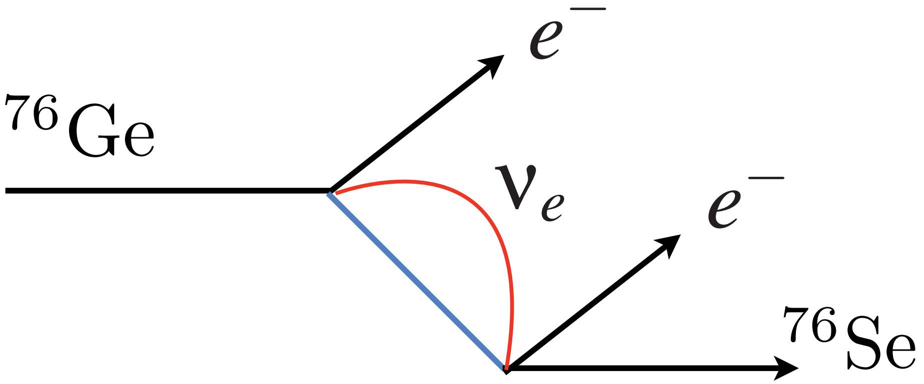
$$^{76}\mathrm{Ge} \Rightarrow {}^{76}\mathrm{Se} + 2e^- + 2\overline{\nu_e}$$



Neutrinoless Double-Beta Decay

- No neutrinos emitted
- Discovery provides:
  - Neutrino is own antiparticle (Majorana)
  - Lepton number violation
  - Neutrino mass

$$^{76}\mathrm{G}e \Rightarrow {}^{76}\ \mathrm{S}e + 2e^-$$



$$n \Rightarrow p + e^- + \overline{\nu}_e \quad (RH\ \overline{\nu}_e)$$

$$(LH\ \nu_e) \quad \nu_e + n \Rightarrow p + e^-$$

How to Measure ββ

Observe double-beta decay by collecting the energy of the 2 e^- in a detector

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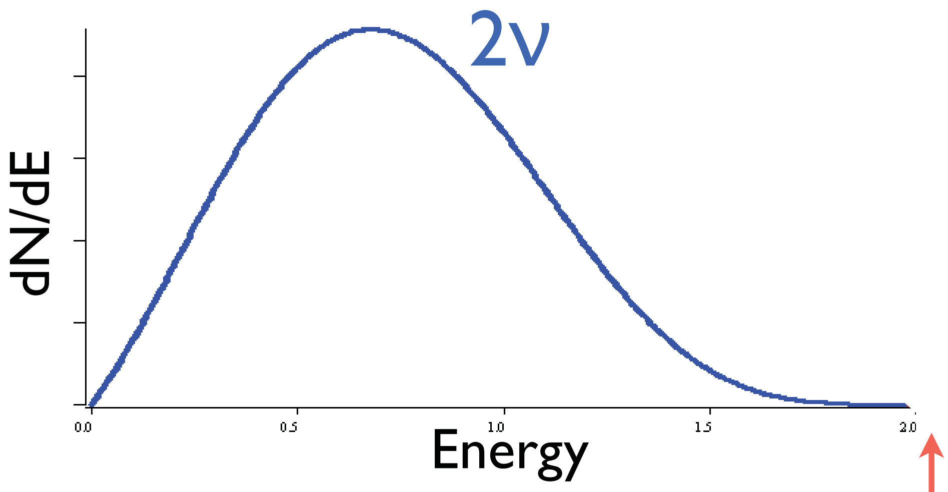
- With 2 neutrino double-beta decay, the electrons share the decay energy with the neutrinos



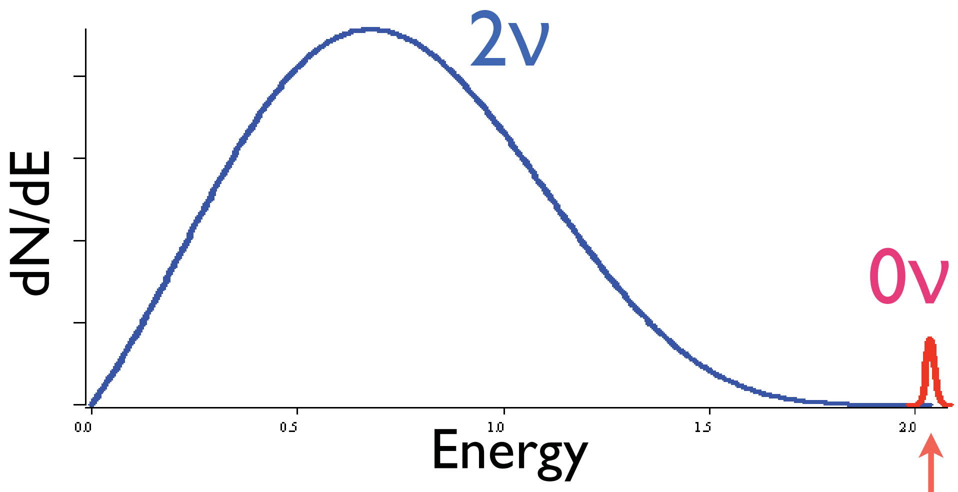
Endpoint Energy

Q=2.039 MeV

How to Measure ββ

Observe double-beta decay by collecting the energy of the 2 e^- in a detector

- With 2 neutrino double-beta decay, the electrons share the decay energy with the neutrinos
- With neutrinoless double-beta decay, the electrons carry the full decay energy



Endpoint Energy

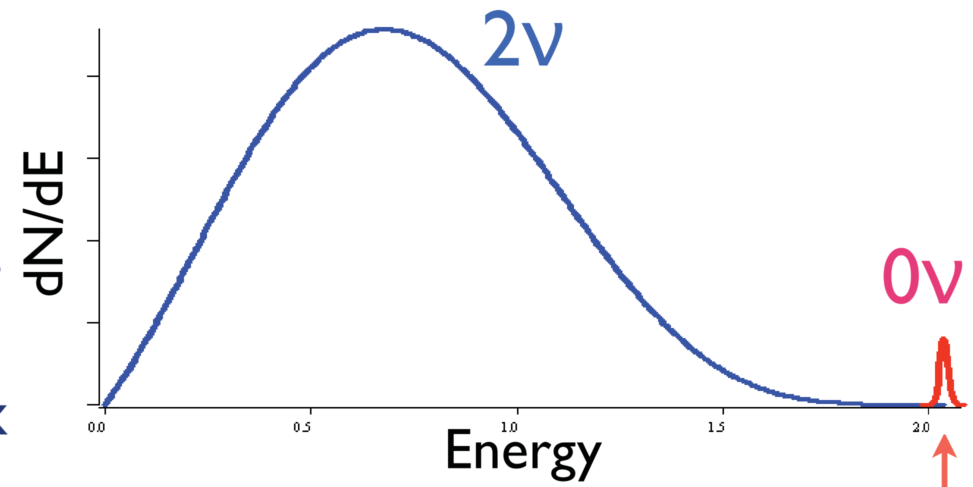
Q=2.039 MeV

How ββ Relates to the Neutrino

Measure decay rate of to get neutrino absolute mass scale

$$\Gamma_{0\nu} = G_{0\nu} \left|M_{o\nu}\right|^2 \langle m_\nu^2 \rangle$$

- G are calculable phase space factors
- M are nuclear physics matrix elements
  - Hard to calculate
- m_ν is the effective Majorana mass

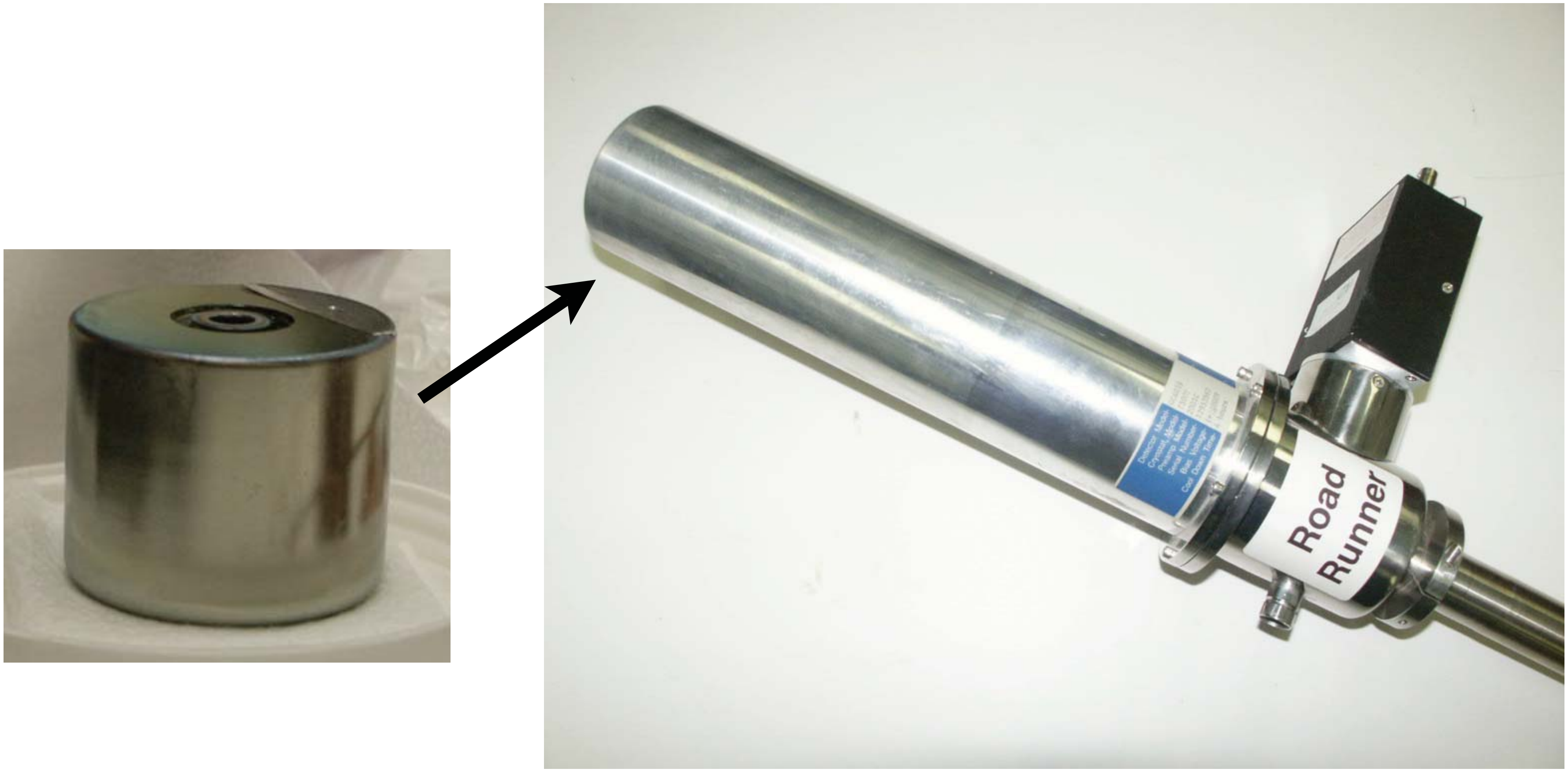


Endpoint Energy

Q=2.039 MeV

A Ge Detector Can Detect ββ

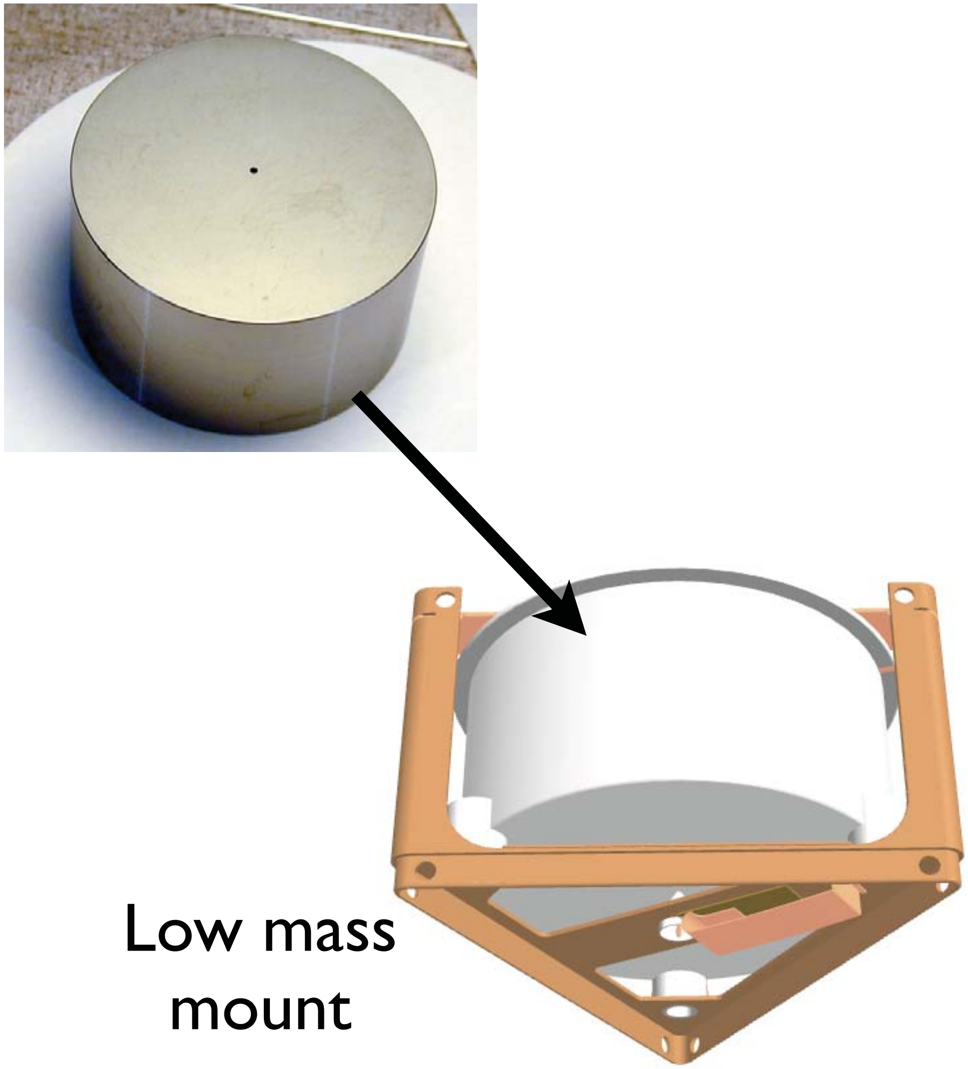
Ge detectors are commercially available radiation spectroscopy detectors



The MAJORANA Approach to ββ

Ge crystal

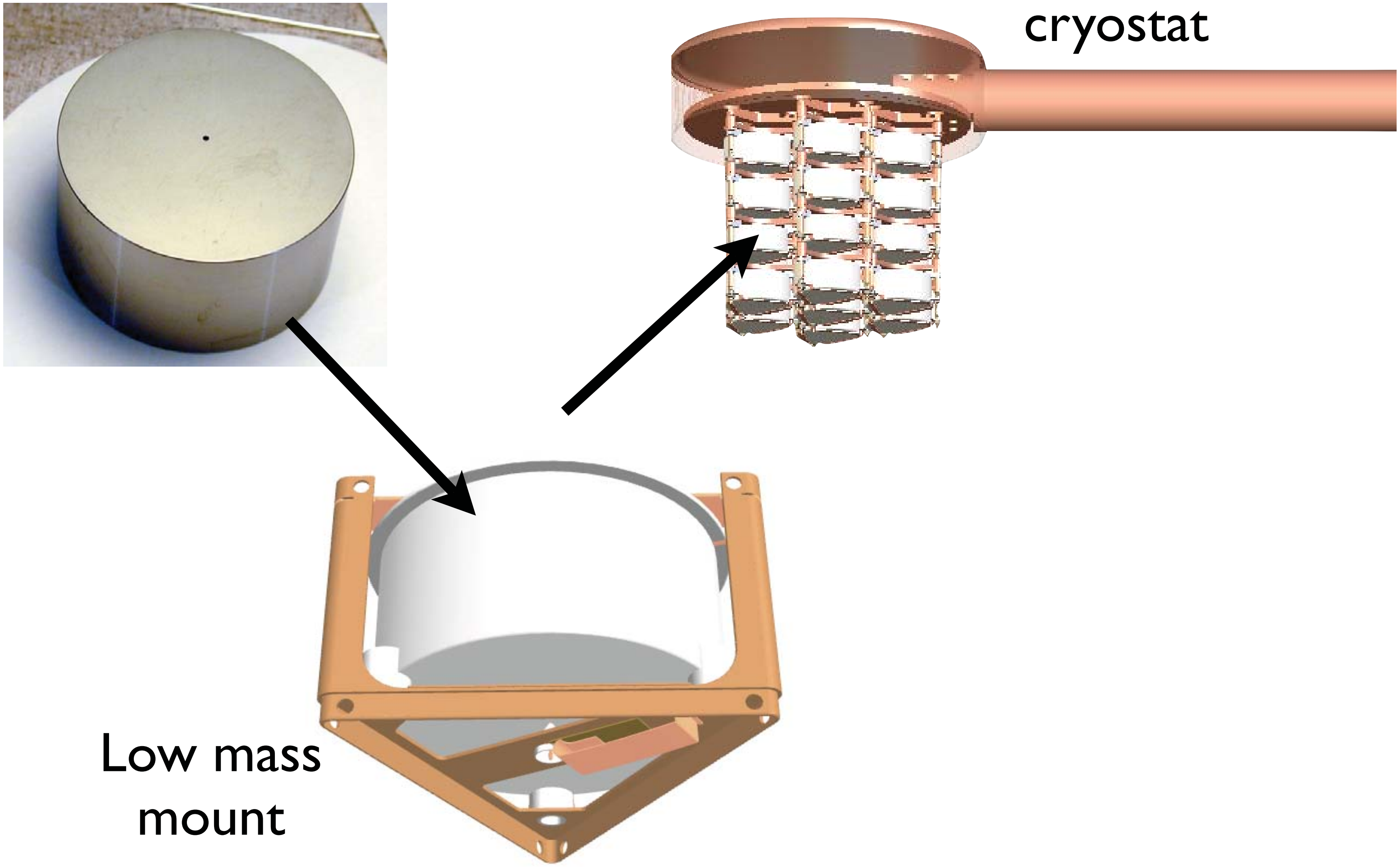
The MAJORANA Approach to ββ



Ge crystal

Low mass
mount

The MAJORANA Approach to ββ

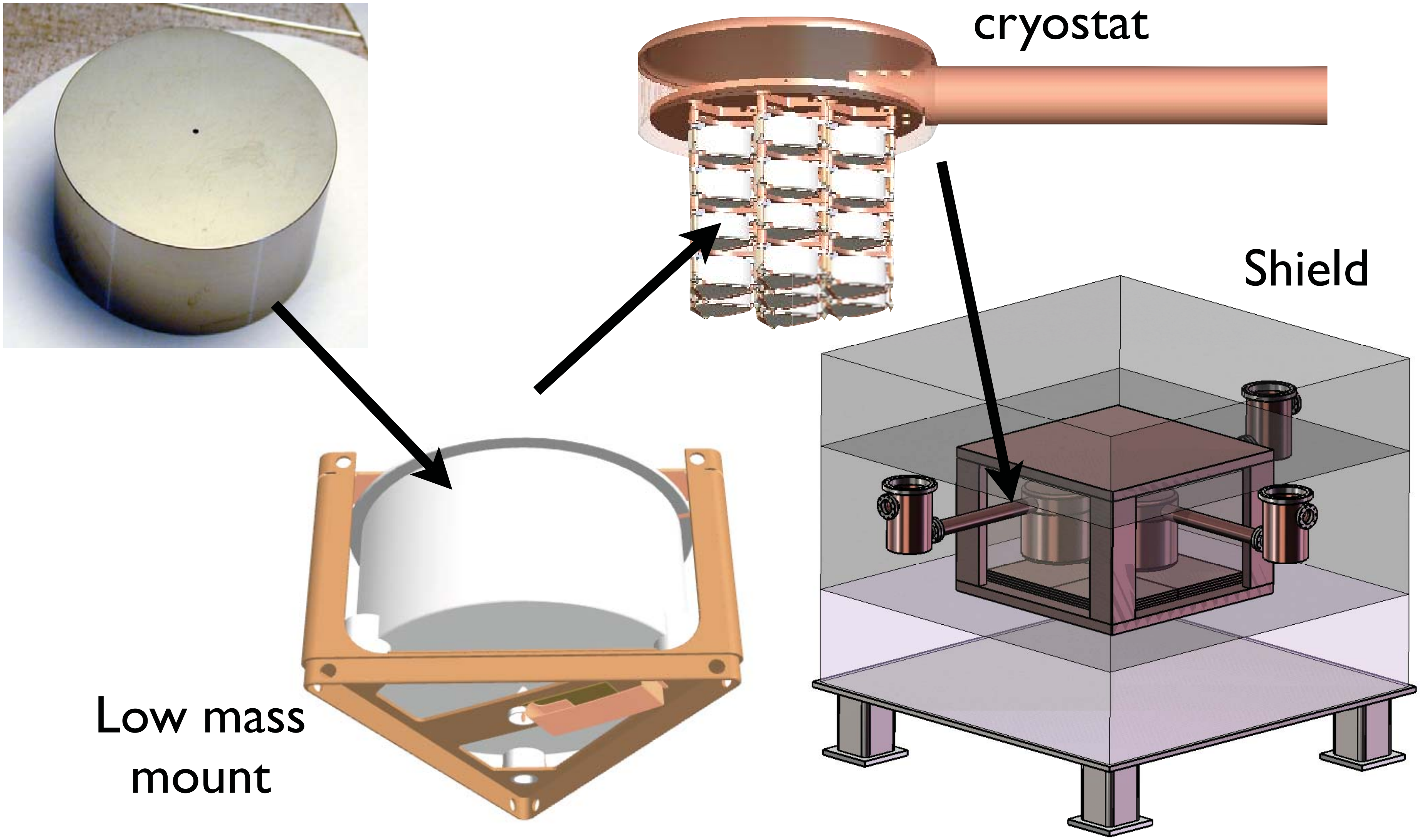


Ge crystal

Array inside cryostat

Low mass mount

The MAJORANA Approach to ββ



Ge crystal

Array inside cryostat

Shield

Low mass mount

MAJORANA Favors ^{76}Ge

^{76}Ge offers an excellent combination of capabilities & sensitivities.

- Ge is the source & detector
  - maximizes source to total mass ratio
  - Well-understood technologies
  - Excellent energy resolution: 0.16% at 2.039 MeV, 4-keV ROI
    - Advantage for improving signal to background
  - Existing, well-characterized large Ge arrays
- Demonstrated ability to enrich 7.44% to 86%
- Favorable nuclear matrix element
  - e.g. $\langle M_{0\nu} \rangle = 3.9$ [Rodin et al. 2005, erratum], 2.6 [Caurier et al. 2007]
- Slow $2\nu\beta\beta$ rate ($T_{1/2} = 1.4 \times 10^{21}$ y)
- Powerful background rejection technologies
  - Segmentation, granularity, timing, pulse shape discrimination
- Best current limit on $0\nu\beta\beta$ used Ge
    - IGEX & Heidelberg-Moscow $T_{1/2} > 1.9 \times 10^{25}$ y

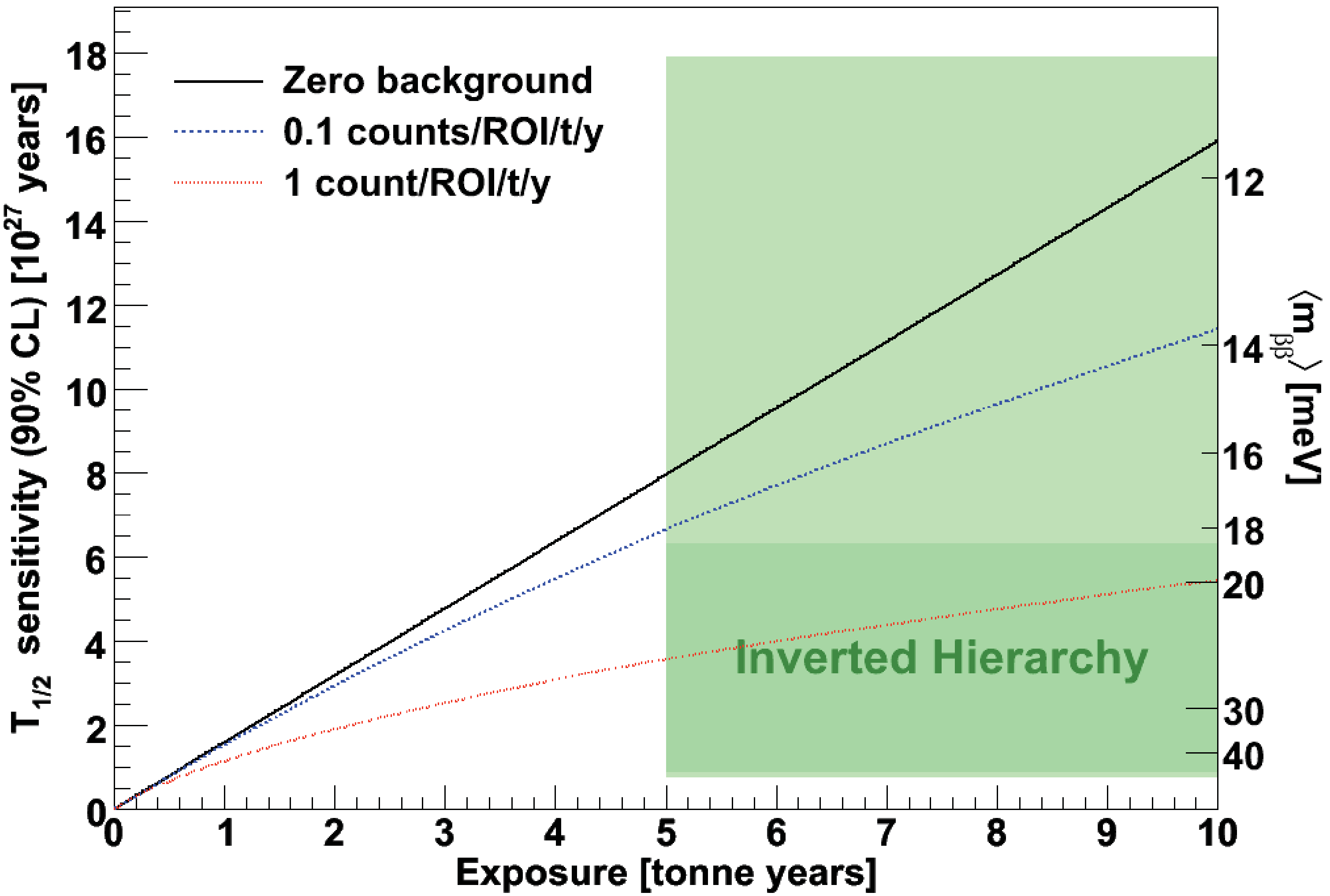
MAJORANA Collaboration Goals

Actively pursuing R&D aimed at a ~1 tonne scale
^{76}Ge 0νββ-decay experiment

- Technical Goal: Demonstrate background low enough to justify building a ton-scale experiment
- Science Goal: Build a prototype module to test the recent claim of an observation of 0νββ
- Work cooperatively with the GERDA Collaboration to prepare for a single international ton-scale Ge experiment that combines the best technical features of MAJORANA and GERDA
- Pursue longer term R&D to minimize costs and optimize the schedule for a ton-scale experiment

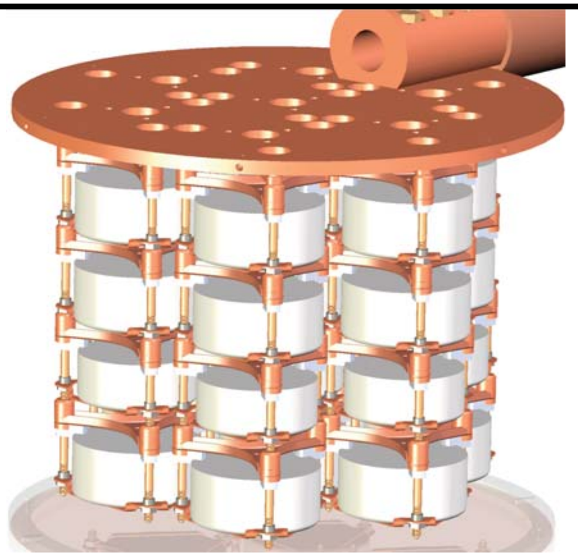
MAJORANA 1-tonne Will Reach 20 meV

Goal is to achieve ultra-low backgrounds of less than 1 count per ton of material per year in the Region of Interest (ROI) about the ββ(0ν) Q-value energy.



Evaluate MAJORANA Design with Initial Module

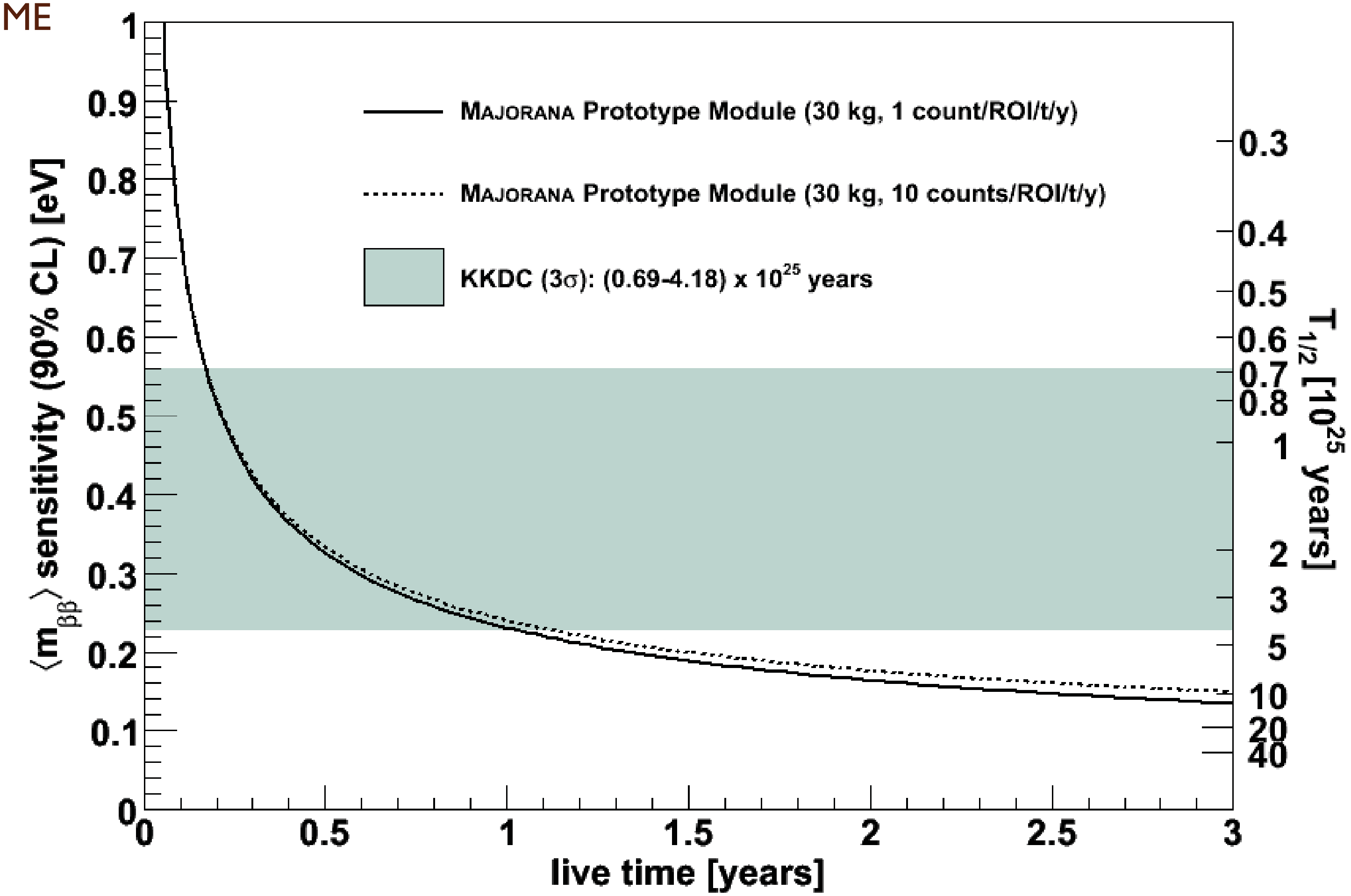
R&D Reference Design



- 60 kg of Ge crystals
  - 30 kg of 86% enriched ^{76}Ge crystals
    - to test claim of 0νββ
  - Additional 30 kg of natural Ge or depleted in ^{76}Ge
    - for background sensitivity
  - Examine detector technology options
    - Emphasis on p-type point-contact (PPC) detectors,
  - Additional physics with low-energy (~100 eV) threshold
- Low-background cryostat and shielding
  - Ultra-clean, electro-formed Cu cryostats
  - Early implementation with first (of 3) cryostat with nat-Ge PPC detectors
  - Compact low-background passive Cu and Pb shield with active muon veto
- Agreement to locate at 4850’ level (4200 m.w.e) at Sanford Lab/ (future home of DUSEL)

Prototype Module Probes to 200 meV

- Expected Sensitivity to 0νββ
  - for 30 kg enriched material, running 3 years, or 78 kg-y of ^{76}Ge exposure
  - $T_{1/2} \geq 1.0 \times 10^{26}$ y (90% CL) Sensitivity to $\langle m_\nu \rangle$ < 140 meV (90% CL) [Rod06 erratum] RQRPA NME



MAJORANA Must Achieve Low Background

The key of the MAJORANA design is the ability to reduce backgrounds to unprecedented levels

- Advanced Detector Design
  - allow greater signal processing
  - reduce sensitivity to backgrounds
  - allow multi-dimensional event reconstruction

- Controlling intrinsic and external backgrounds
  - Ultra-clean, electro-forming of cryostat and shield
  - Detector purity

MAJORANA Backgrounds

- Goal: ≤1 event / ton-year in 4 keV ROI
- Backgrounds:
  - Natural isotope chains: ^{232}Th, ^{235}U, ^{238}U, Rn
  - Cosmic Rays:
    - Activation at surface creates ^{68}Ge, ^{60}Co.
    - Hard neutrons from cosmic rays in rock and shield.
      - (n,n´γ) in Pb, Ge, Cu
  - 2νββ-decays.
- Need factor ~100 reduction over what has been demonstrated.
- Monte Carlo estimates of acceptable levels

Most backgrounds are multi-site. Signal is single-site

MAJORANA Materials

- 2009 campaign to further reduce limits on backgrounds in electroformed Cu (previous best: ~0.7 µBq/kg, addressing bath purity)

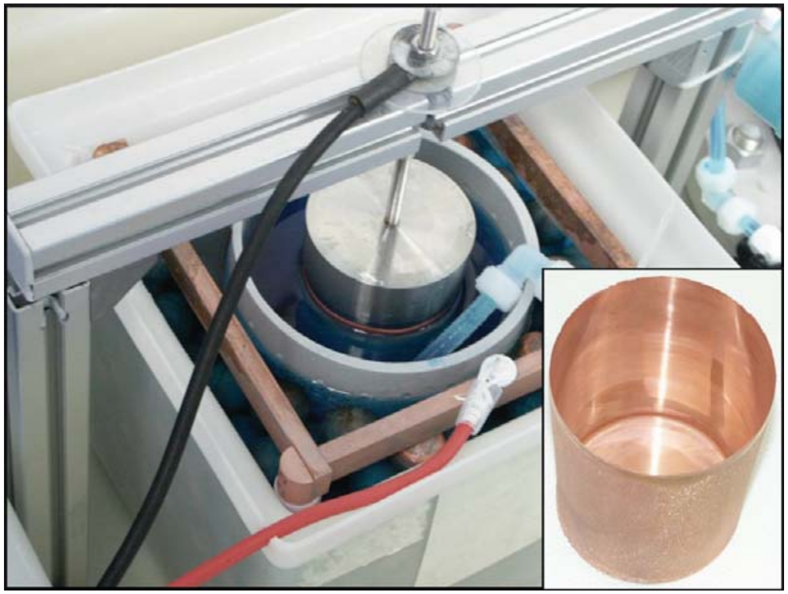
- Procuring enough plastic for detector supports, with NAA to follow

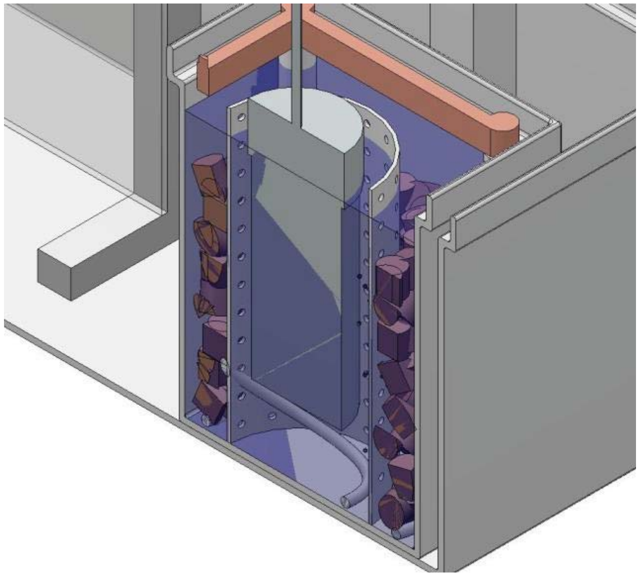
- Staged Pb procurement with ICPMS program for shield

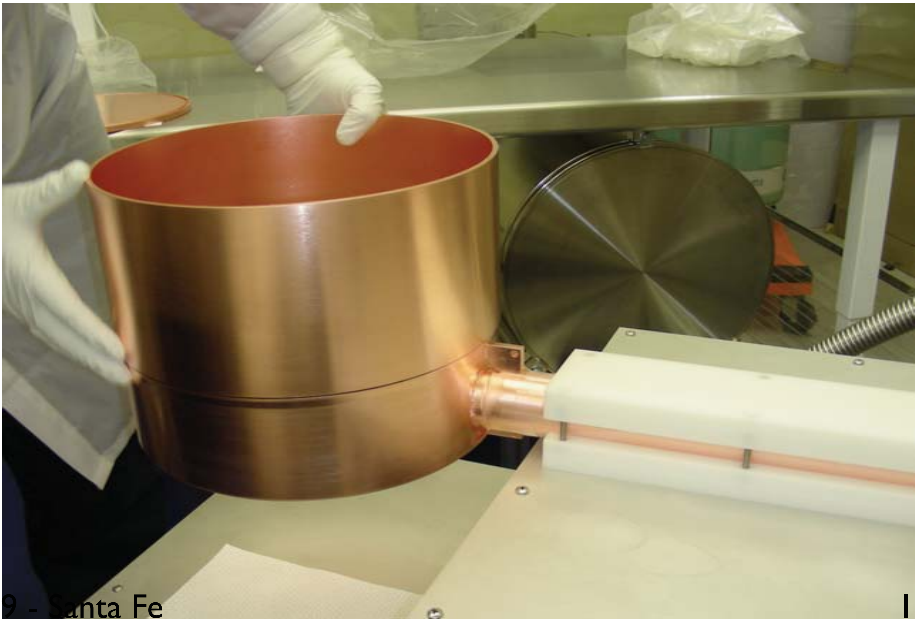
- Cables and electronics materials screening

- Enriched Ge
  - UMICORE not interested in processing enriched Ge
  - Fully costed plan to establish a small processing facility in Oak Ridge
  - Collaborator has funding to start an underground crystal pulling lab

Electroforming Cu

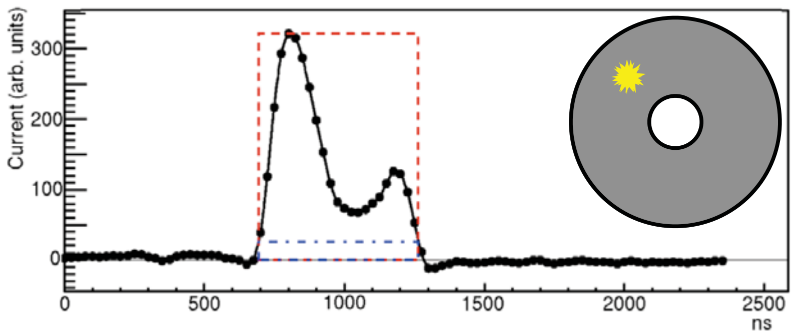




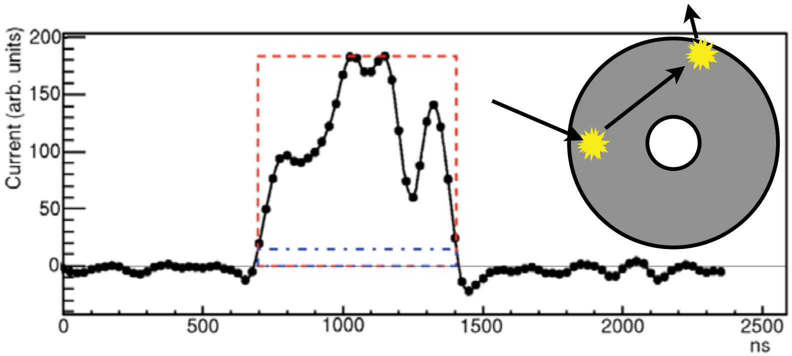


Background Rejection Techniques Exist

Pulse Shape Analysis



Single-site event



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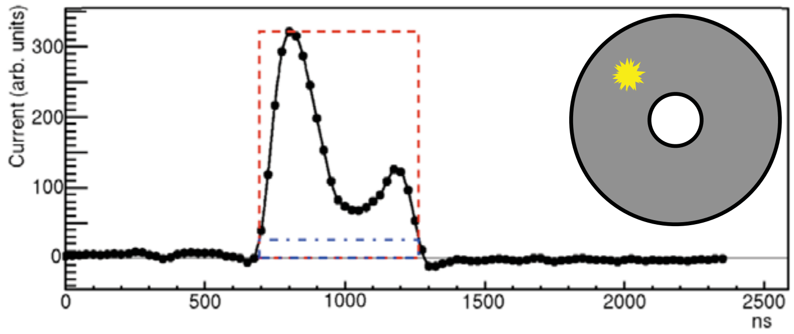

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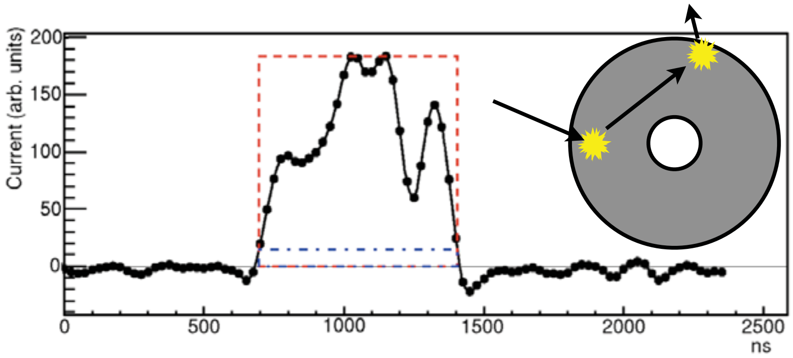
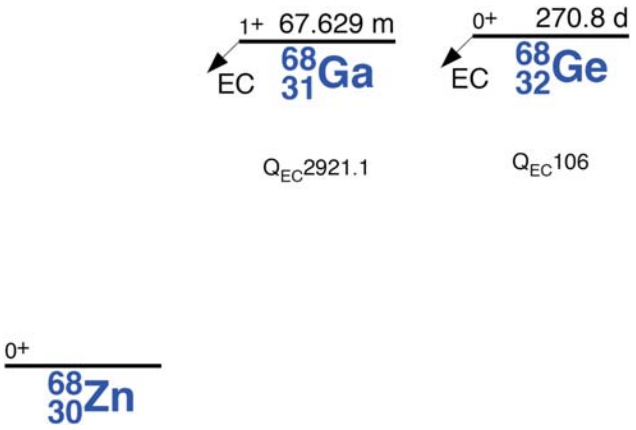


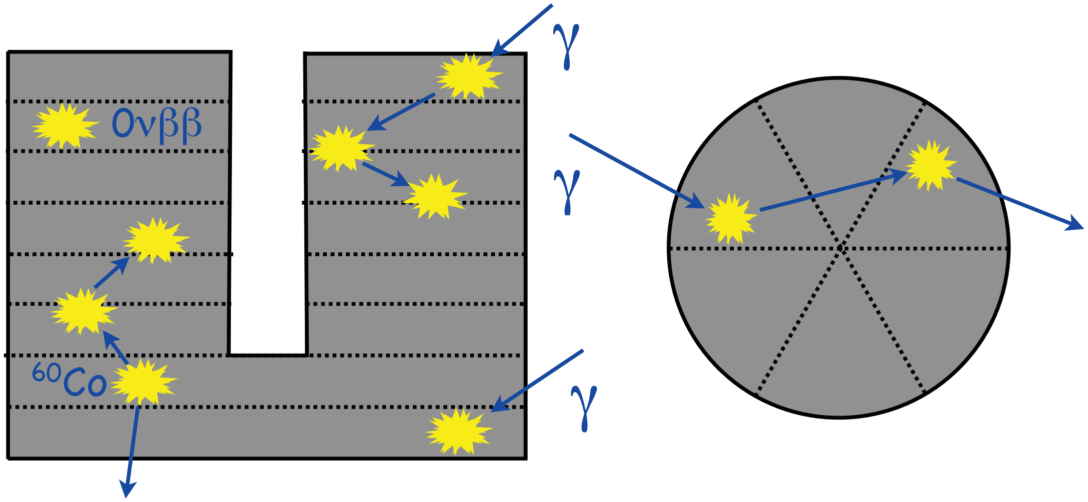
Multi-site event

Timing Analysis

- ^{68}Ga β^+ can deposit single-site at Q-value
- Look back in time for X-ray from ^{68}Ge



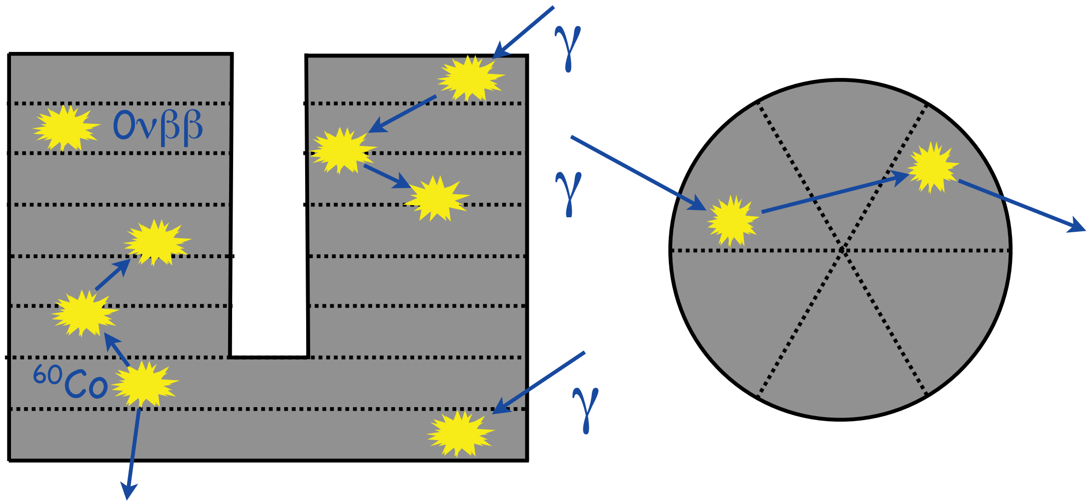
Detector Design Aids in Background Rejection



Segmentation Analysis

- Multi-site depositions occur over many segments
- Single-site deposition in one segment

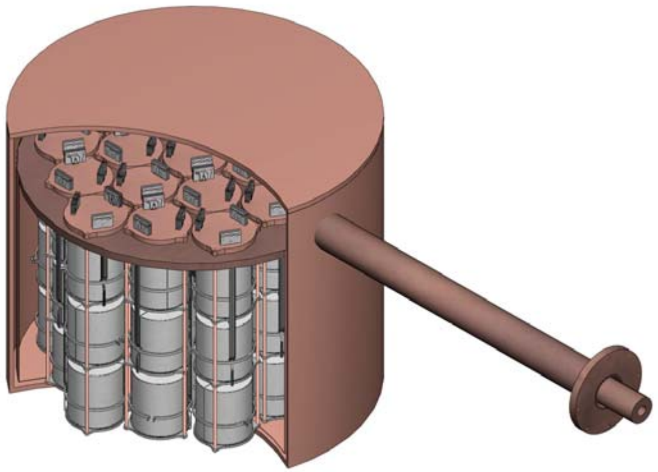
Detector Design Aids in Background Rejection



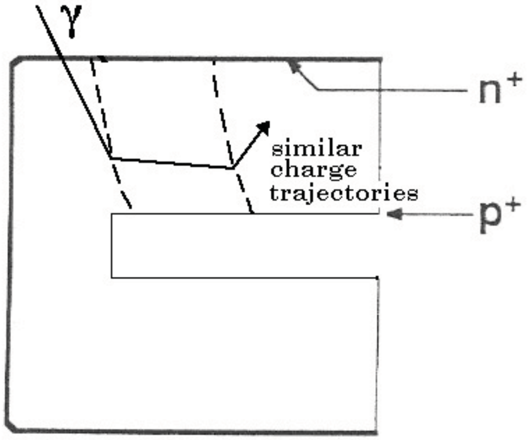
Segmentation Analysis

- Multi-site depositions occur over many segments
- Single-site deposition in one segment
- Proximity of additional detectors pick up escaping events

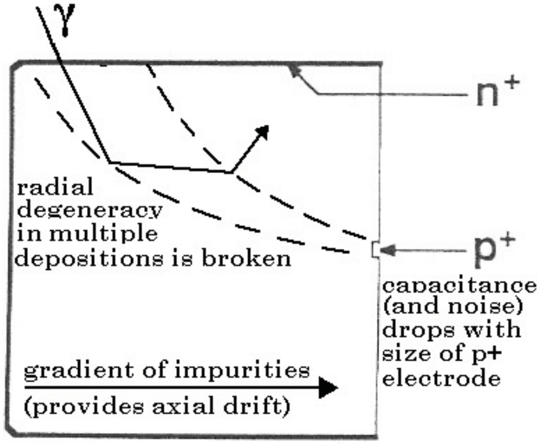
Granularity



P-type Point Contact Detectors

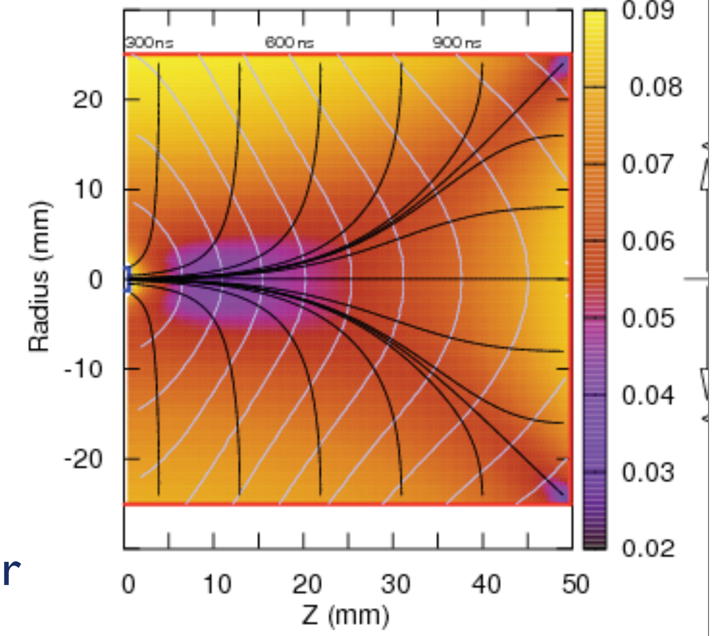


standard coaxial HPGe

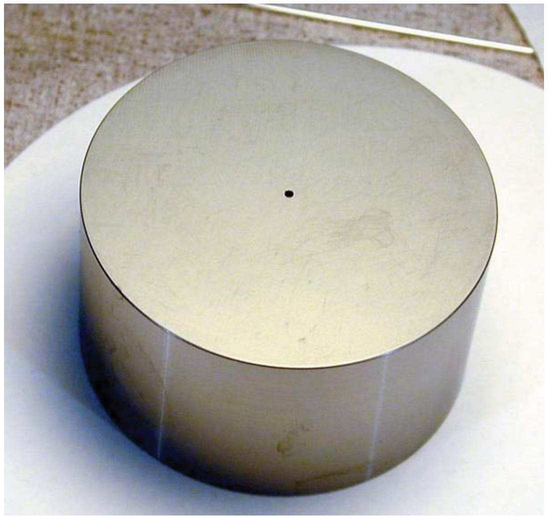


P-type modified electrode

Hole v_{drift} (mm/ns) w/ paths, isochrones



- An exciting novel P-type Ge detectors design.
- A solid p-type detector: simpler to fabricate, easier handle, instrument, very low capacitance.
- The longer drift distance in the PPC stretches the pulse leading to a clear indication of a multiple site event.
- Advantage of segmented detectors, without extra complexity and backgrounds.
- Low energy threshold permits additional physics applications: e.g. Dark Matter, Axions



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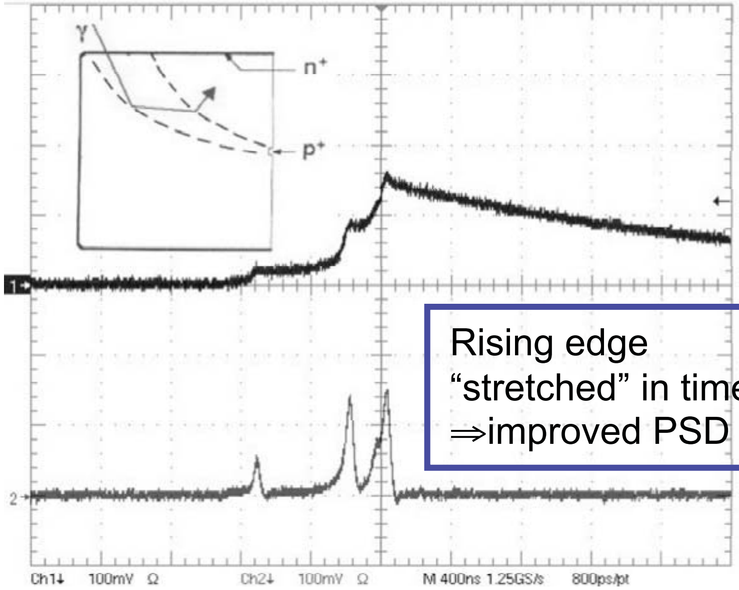
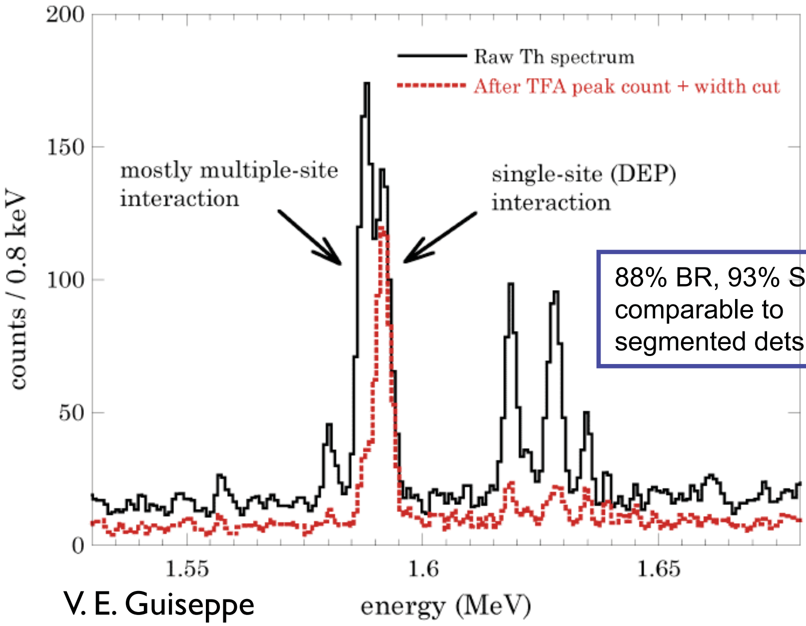
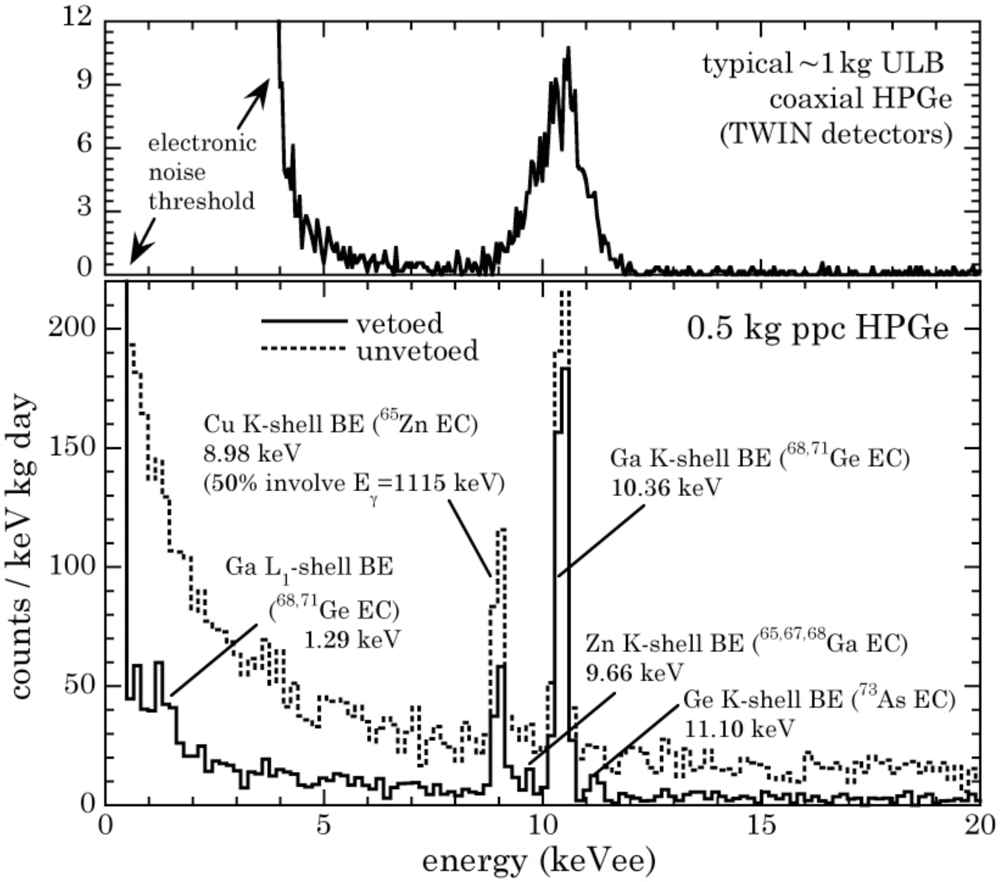


Rising edge "stretched" in time ⇒improved PSD

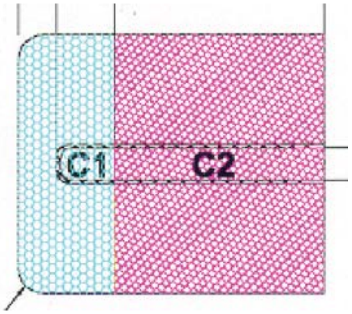


88% BR, 93% SA: comparable to segmented dets.



Luke et al., IEEE trans. Nucl. Sci. 36 , 926(1989)
Barbeau et al., JCAP 09 (2007) 009
arXiv:0807.0879v4 CoGeNT Collaboration

Segmented N-type Detectors



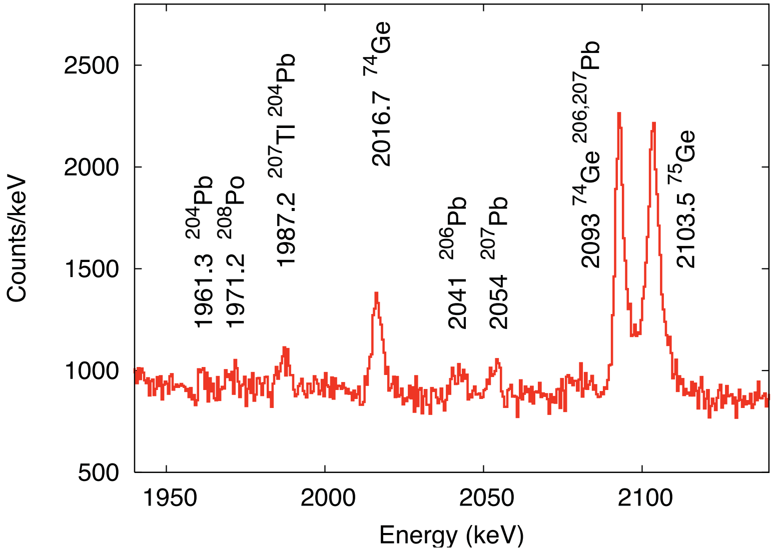
- Segmented Enriched Germanium Assembly detector
  - Crystal description
    - N-type ^{76}Ge detector (86%)
    - 12 segments - 6 outer X 2 inner
    - Currently in temporary cryostat
      - Segmentation studies
      - Pulse shape analysis techniques
  - Currently electro-forming detector mount components
  - Deploy at WIPP late 2009

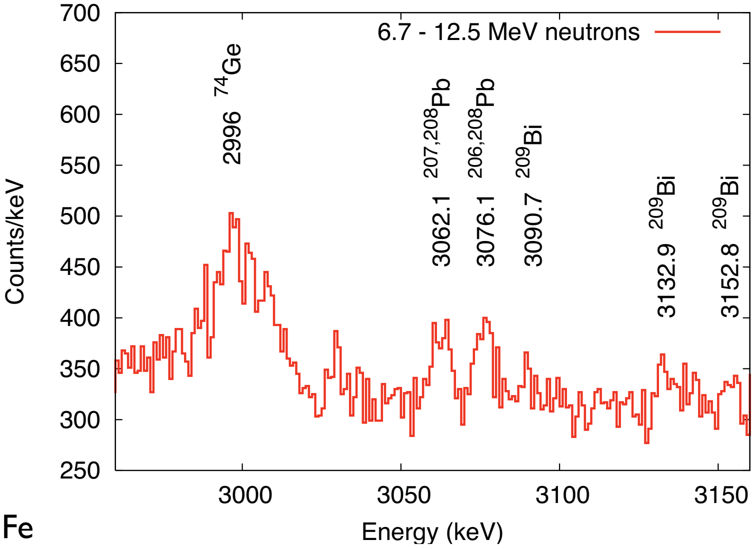
Lower Sensitivity - New Backgrounds

Pb excitations

- Specific Pb gamma rays are problematic backgrounds
    - ^{206}Pb has a 2041-keV γ ray
    - ^{207}Pb has a 3062-keV γ ray
    - ^{208}Pb has a 3060-kev γ ray
- The DEP of the ~3062 keV γ ray is a single site energy deposit at ββ Q-value
- Neutron interactions in Pb can excite these levels
- Cross sections unknown

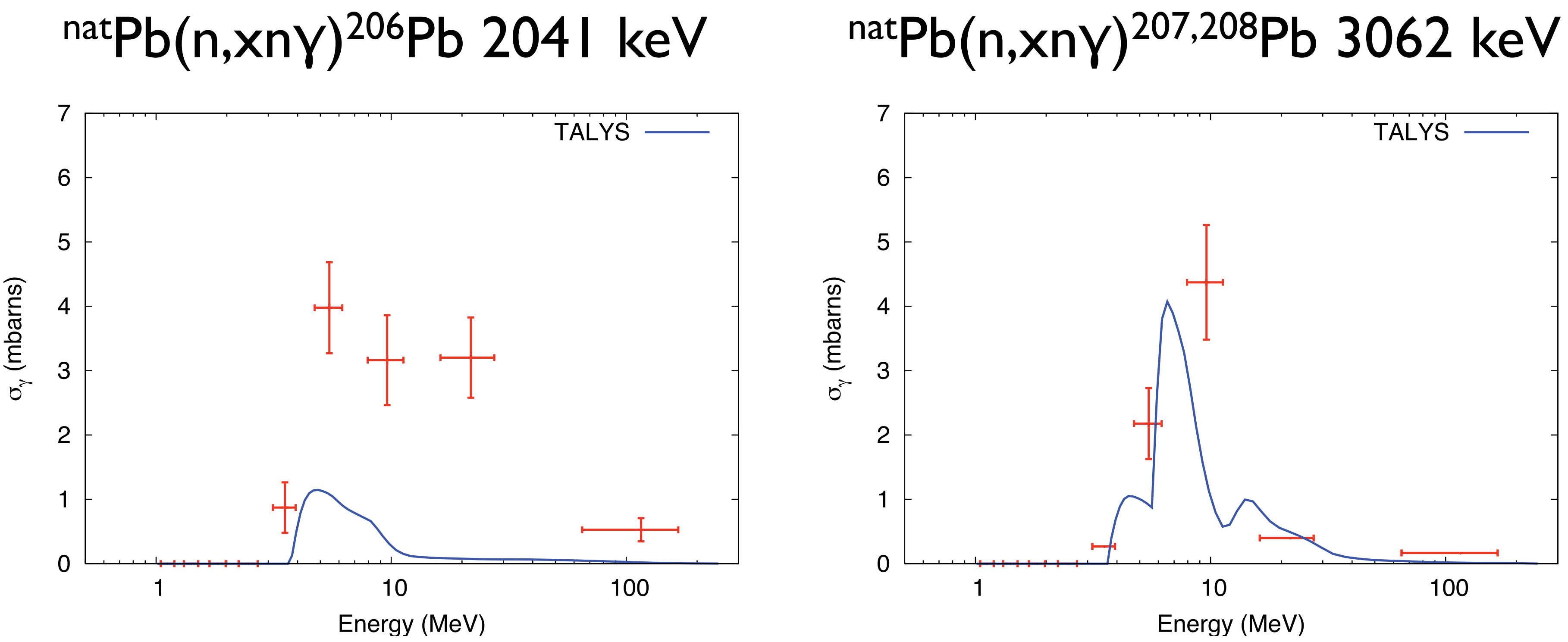
Pb target in a neutron beam





Neutron Inelastic Scattering Measured

Measured gamma-ray production cross sections from a Pb target in a neutron beam at LANSCE



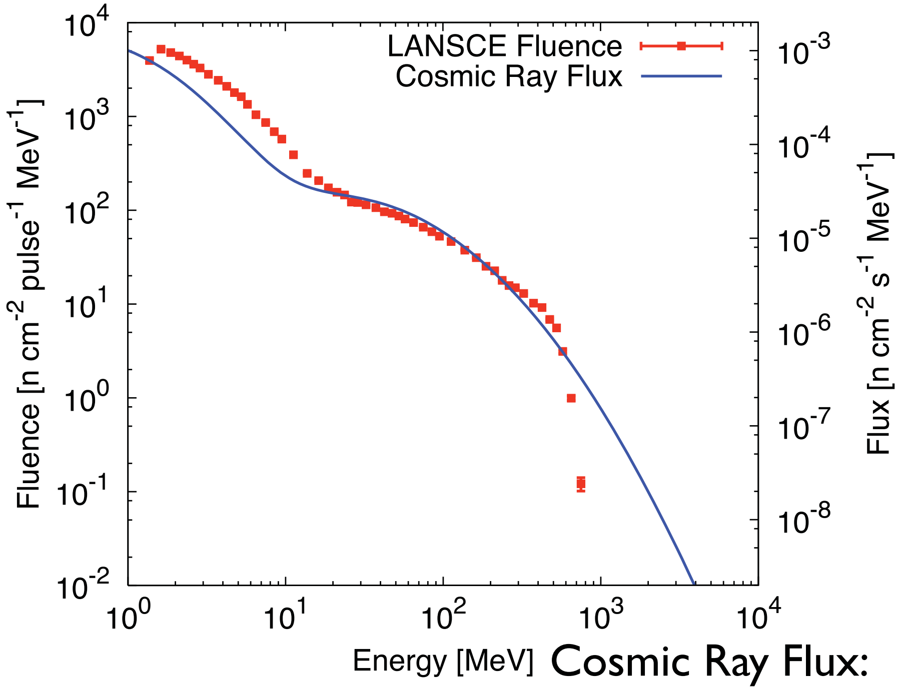
Other cross sections in Cu and Ge being measured

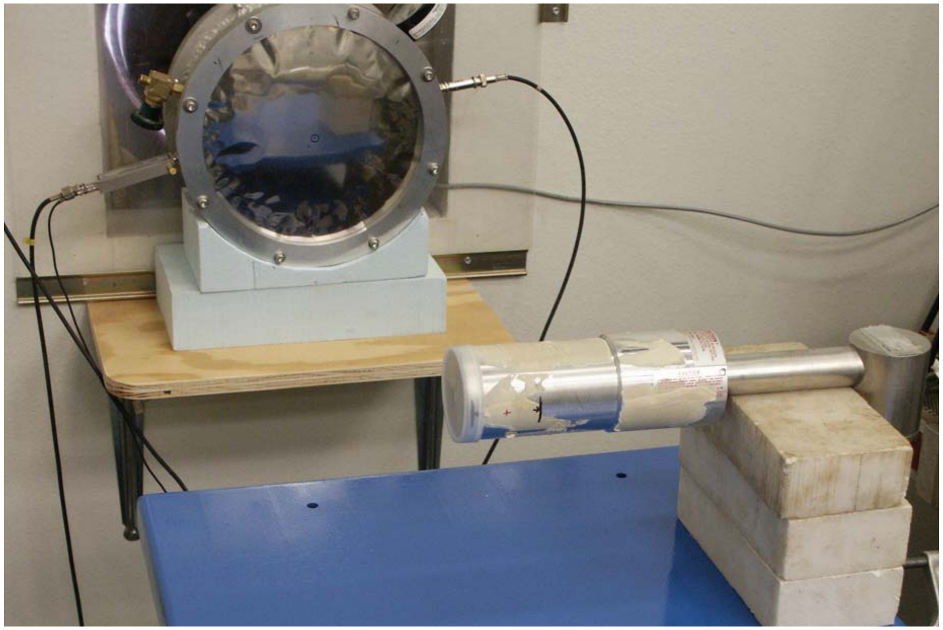
V.E. Guiseppe *et al.* (2009) PRC **79**, 054604

Cosmic Activation of Ge

- Some uncertainty in the cosmogenic activation rate of some radionuclides in ^{nat}Ge and ^{76}Ge
- ^{68}Ge and ^{60}Co are troublesome internal backgrounds

Activation rate measured by placing a working ^{nat}Ge detector in a high-intensity neutron beam (LANSCE)

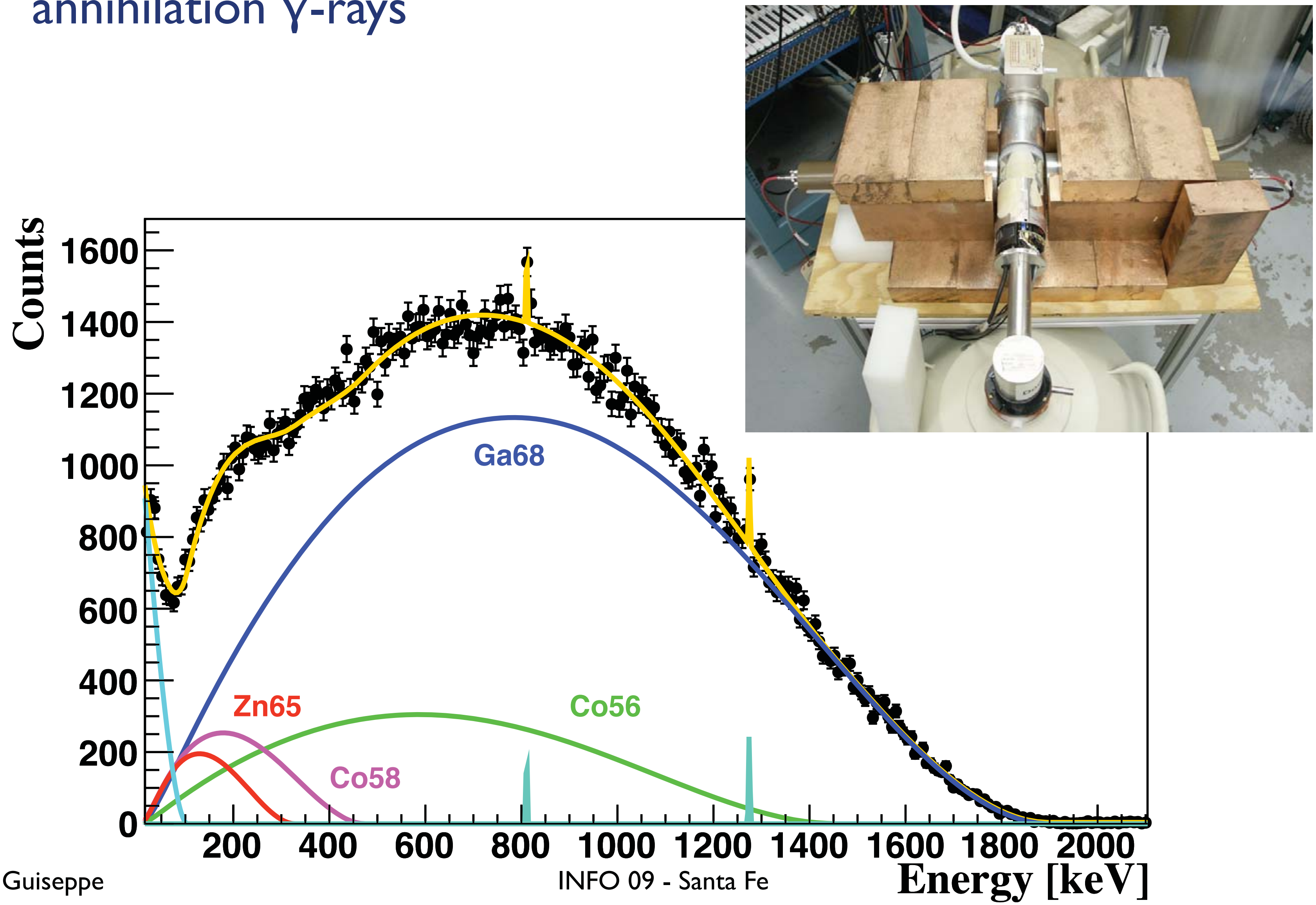




Cosmic Ray Flux: Gordon et al., IEEE TNS, **51**, 3427 (2004)

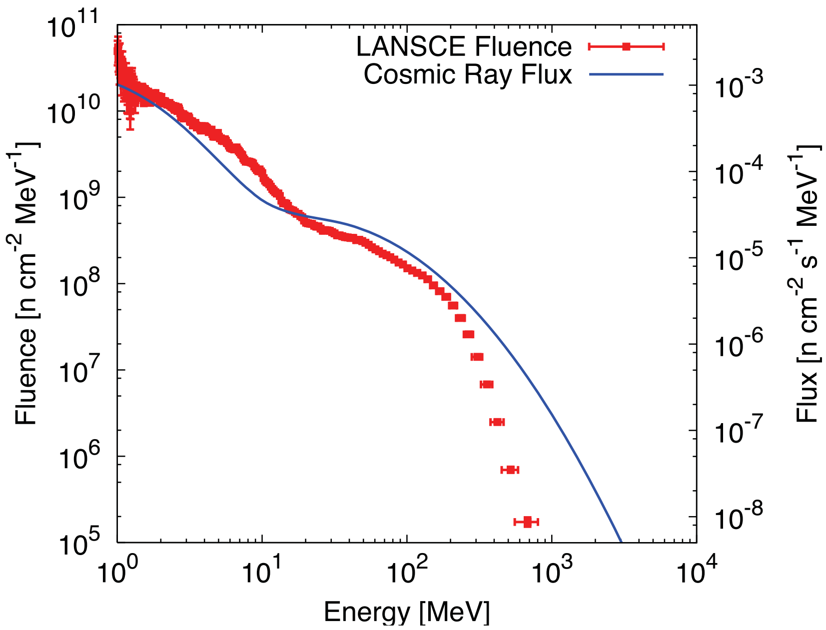
Cosmic Activation of ^{nat}Ge

- β+ spectrum constructed by tagging on external back-to-back annihilation γ-rays



Cosmic Activation of ^{76}Ge

Activation rate measured by placing a ^{76}Ge sample in a high-intensity neutron beam (LANSCE)



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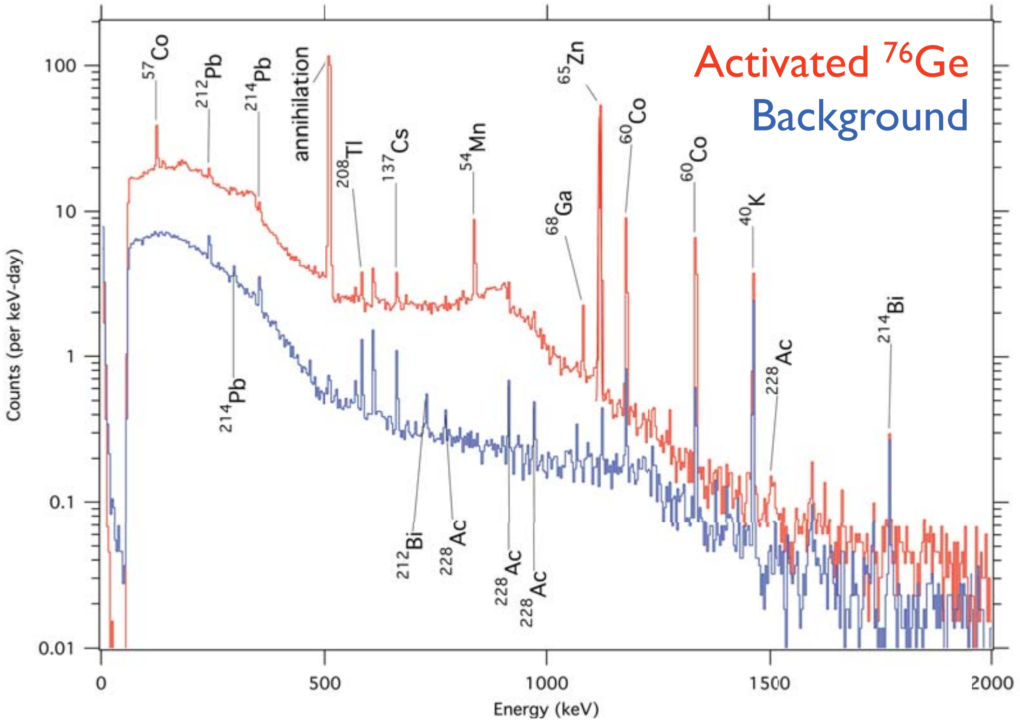
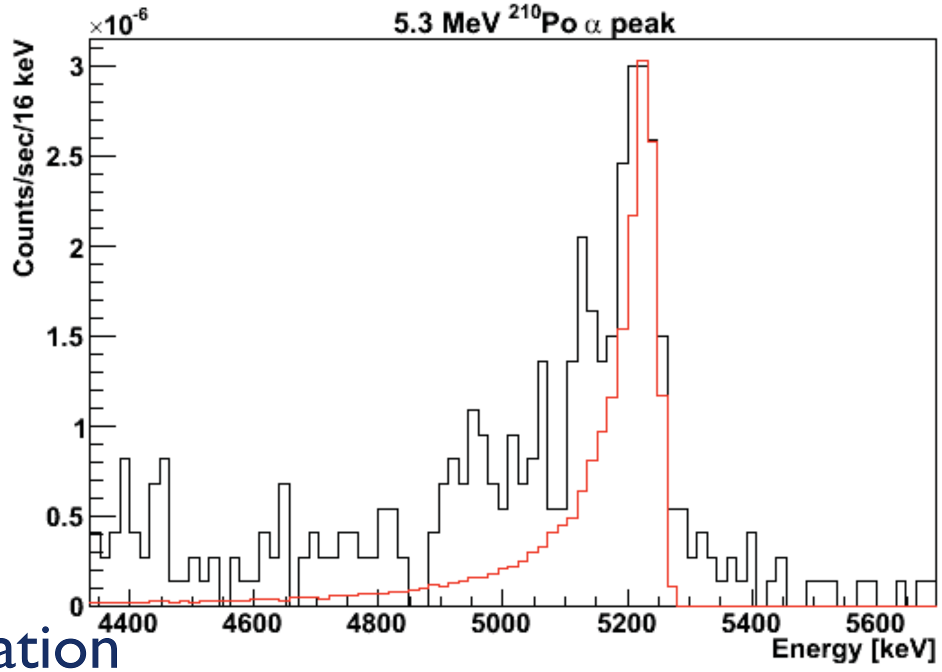
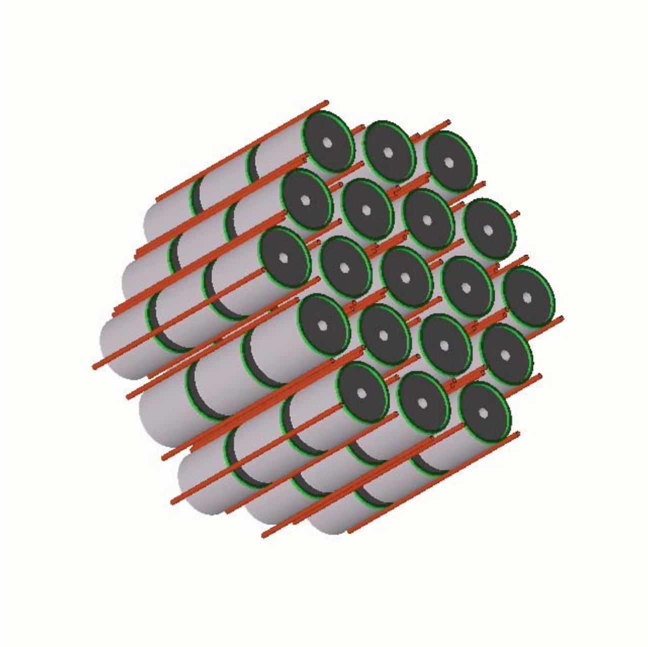


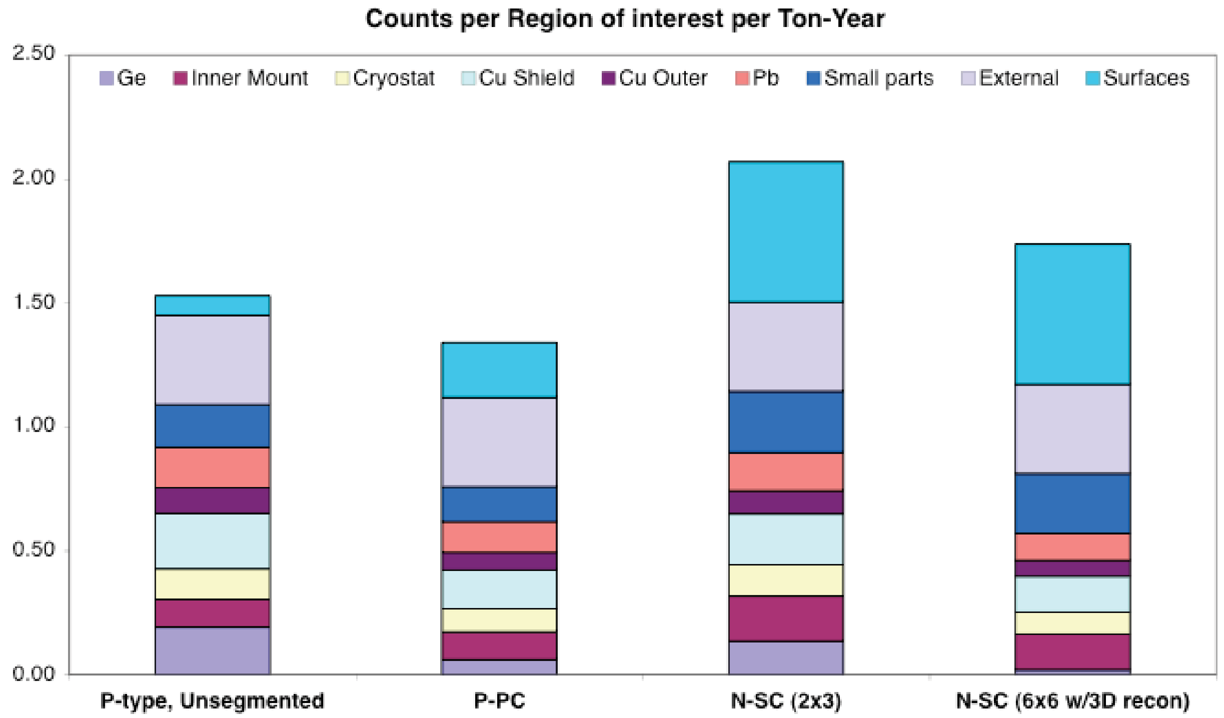
Recent R&D



- Design background simulations
  - Internal front-ends
  - Internal Cu
  - ^{40}K in plastics
  - New structural components
  - Detector contacts
- Neutron interaction simulations
- Low energy modeling and veification
- Detector characterization
- Rn deposition on crystal surfaces
- Surface alpha background characterization
- Spectral shape as a function of source position (see arxiv:0902.4370)

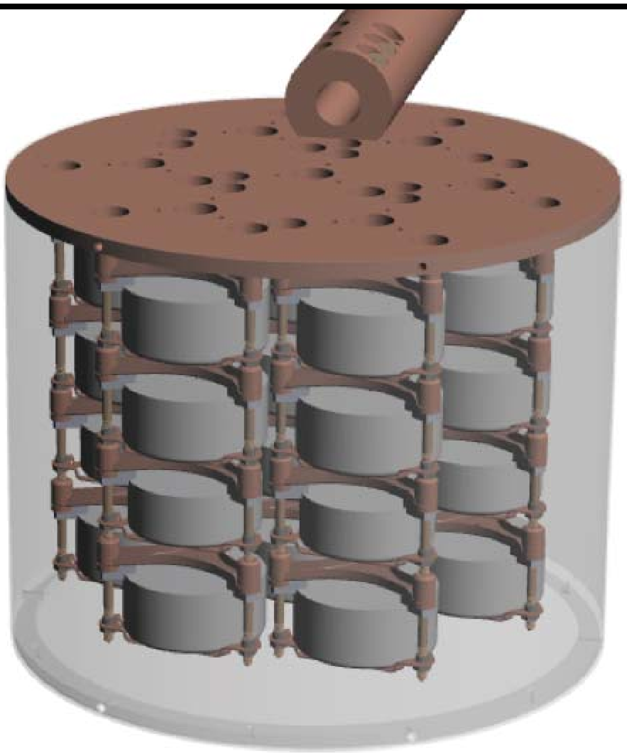
Background simulations





- Background modeling
  - Simulated major background sources for detector components using MaGe
  - Calculated total backgrounds individually for each detector technology under consideration
  - Cu purity of ~0.3 Bq/kg is required; sizeable contribution from ^{208}Tl in the cryostat and shield.
  - Higher rejection of segmented designs is roughly balanced by extra readout components.
  - P-PC appears to achieve the best backgrounds with minimal readout complexity.

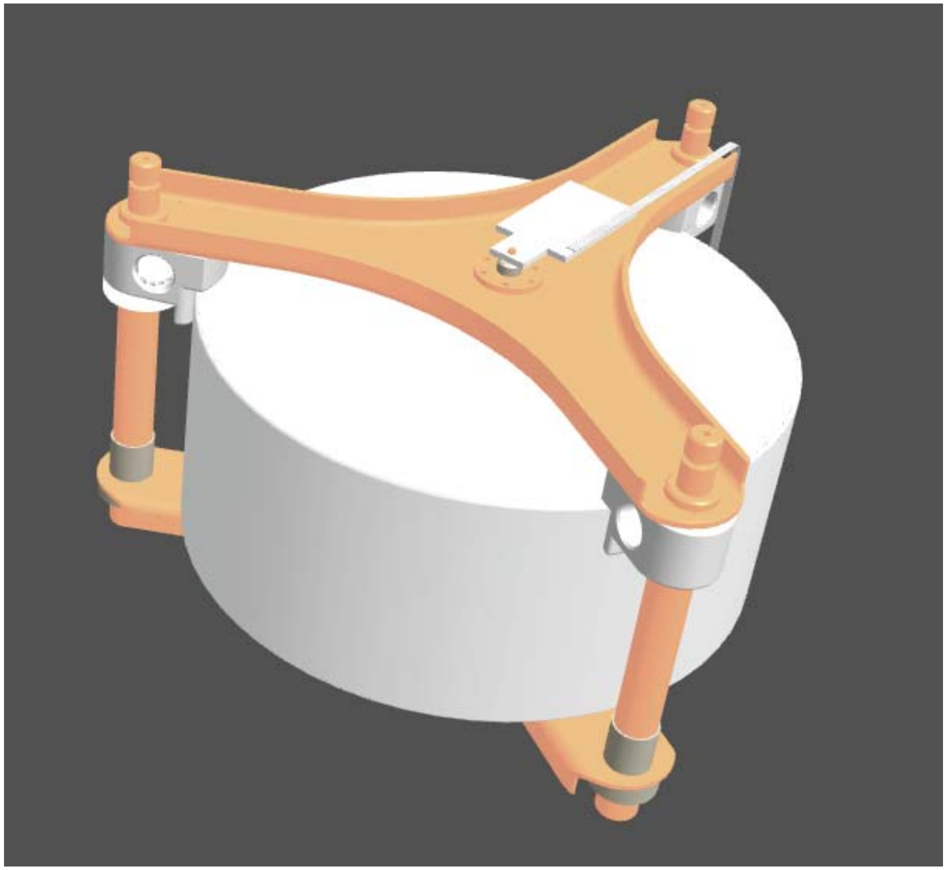
First Sub-Module



- 18 natural-Ge Canberra BEGe's now being delivered
  - ∅ = 70±2.5 mm, h = 30±2.5 mm
  - 579 g active mass
  - contact r < 6.5 mm (5 mm nom.)
  - Front surface metalized for HV
- 4 to 6 crystals per string
- Front-ends mounted next to the crystal
- Closed cold plate and beefier Cu in detector mounts for added strength

Detector Mounts

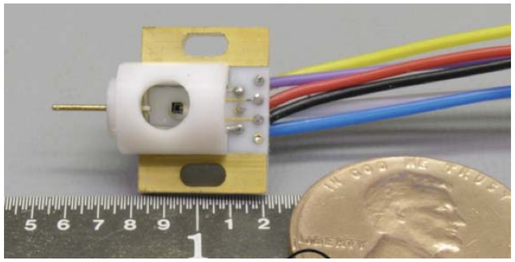
- Single detector units that attach to form strings
- HV on outer contact
- Mostly electro-formed Cu with minimal amount of plastics
- Front ends integrated into contact pin; encapsulate in electro-formed Cu for α, β shielding
- Currently iterating design and prototyping



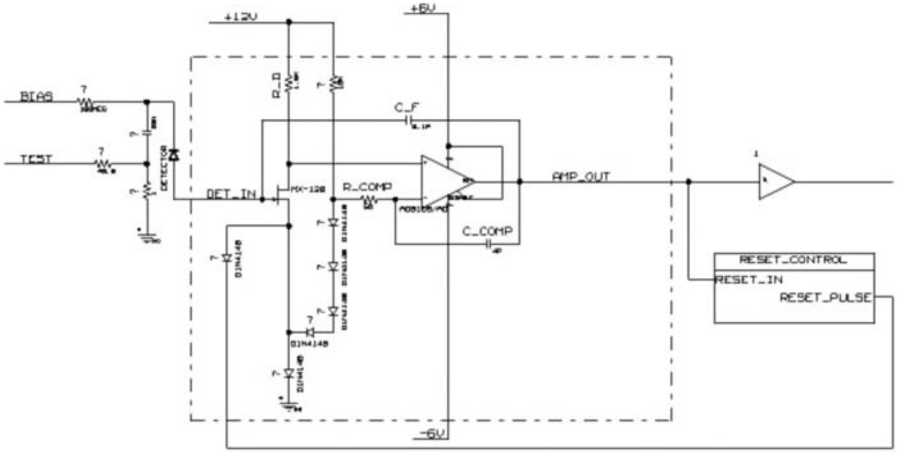
Front End Electronics

Pulse Reset

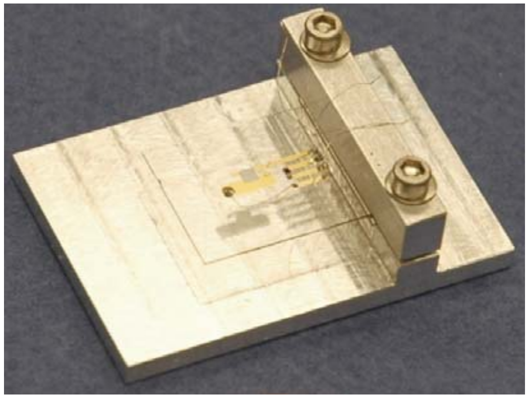
COGENT front ends
(U Chicago)



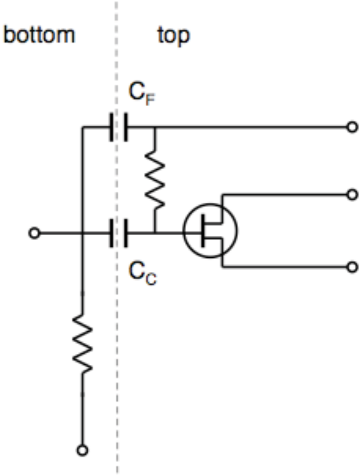
UW “Hybrid” Design



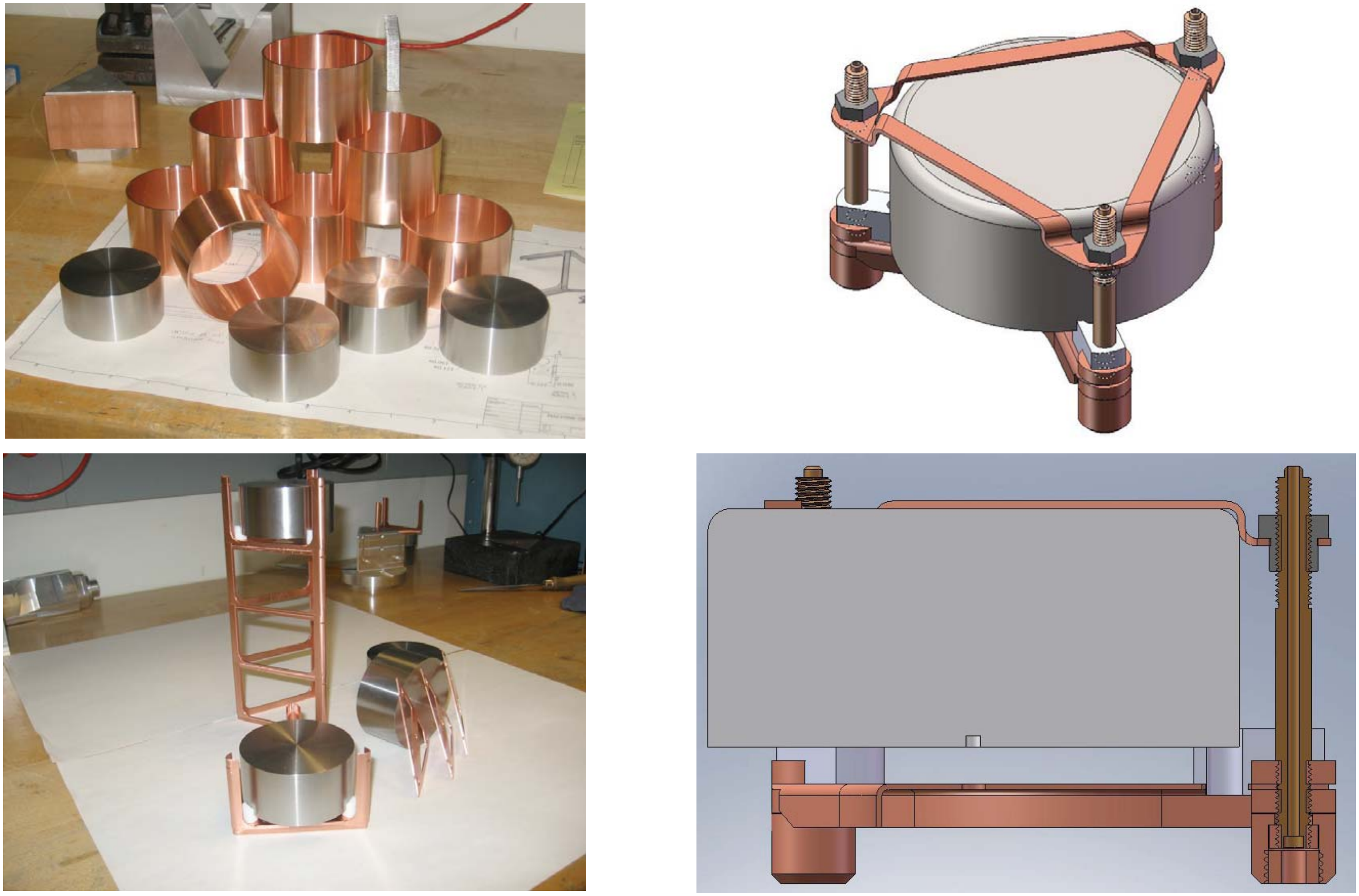
Resistive Feedback



LBNL Design

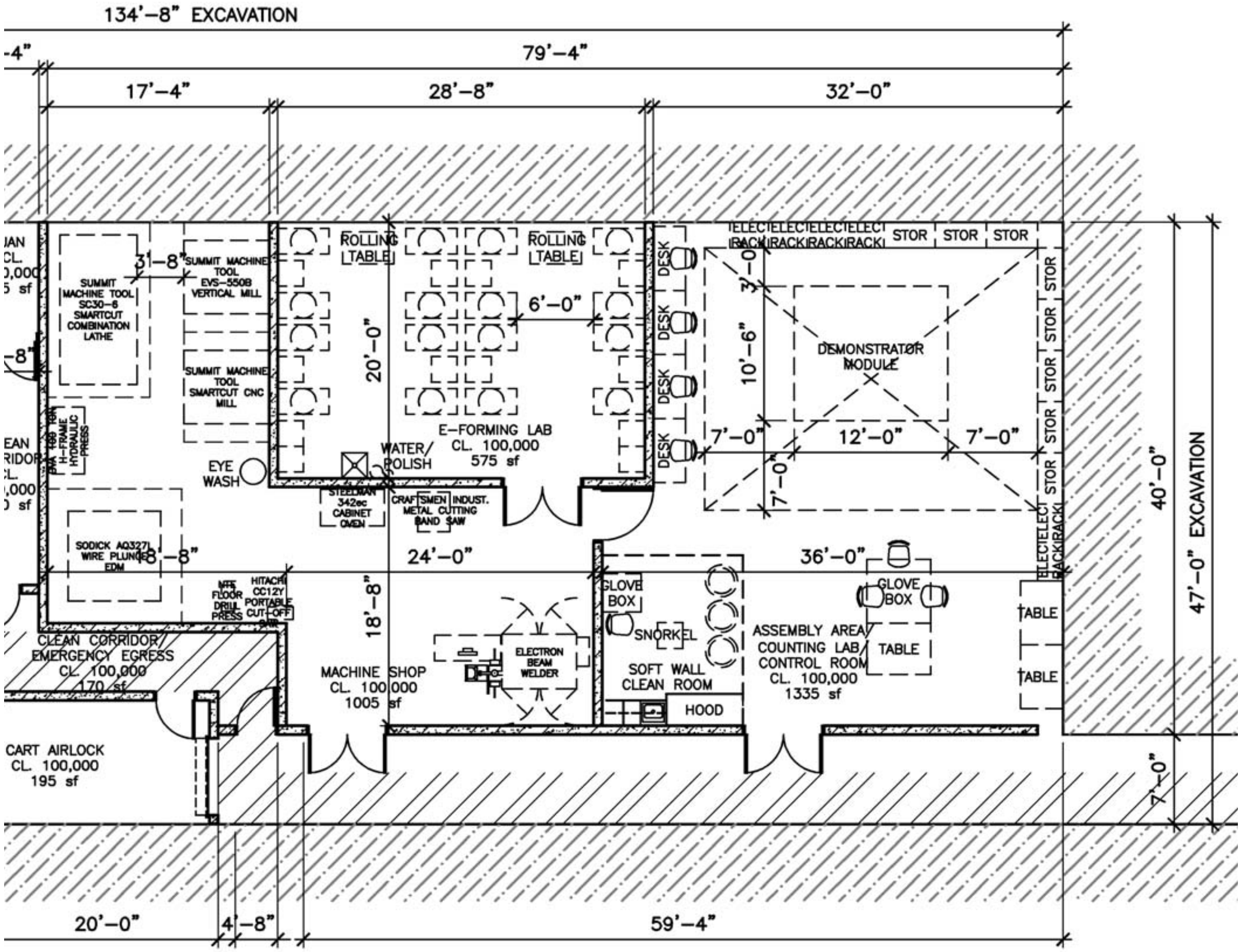


String Designs



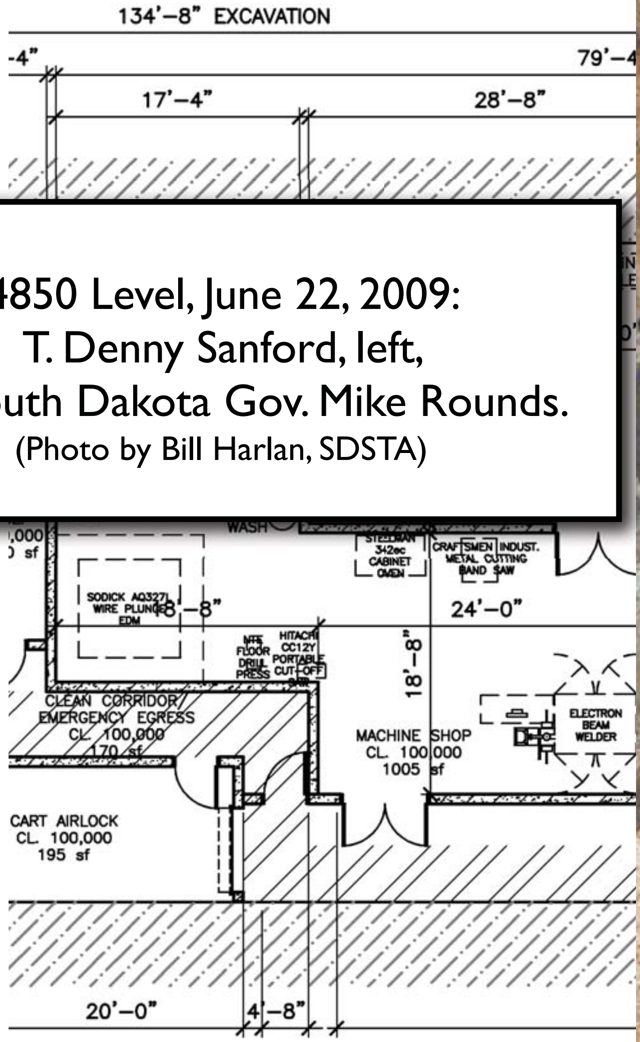
MAJORANA Lab Space

- Design of underground space at Sanford Lab 4850' level near Davis Cavity



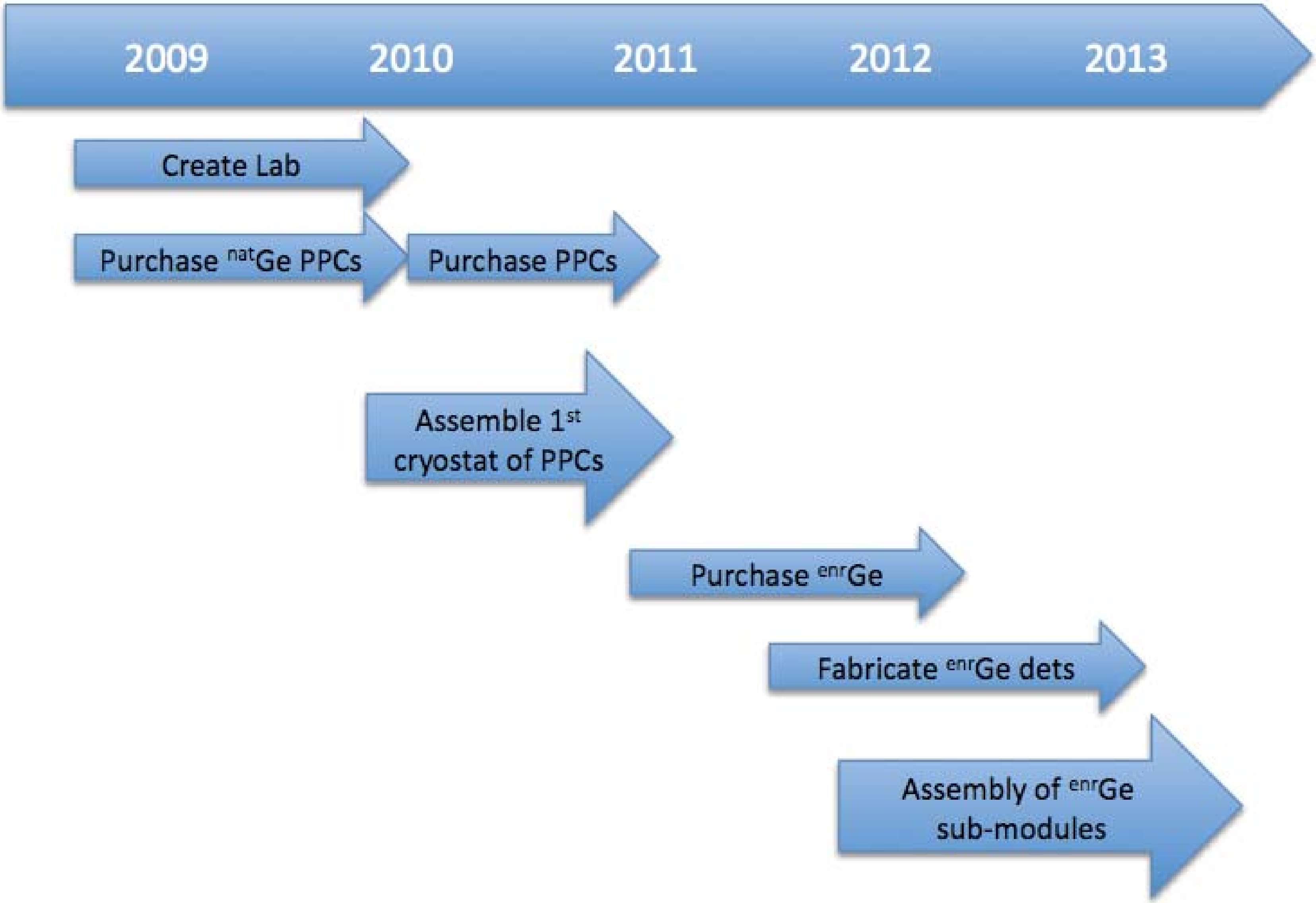
MAJORANA Lab Space

- Design of underground space level near Davis Cavity



4850 Level, June 22, 2009:
T. Denny Sanford, left,
and South Dakota Gov. Mike Rounds.
(Photo by Bill Harlan, SDSTA)

MAJORANA Demonstrator Schedule



Create Lab

Purchase ^{nat}Ge PPCs

Purchase PPCs

Assemble 1st cryostat of PPCs

Purchase ^{enr}Ge

Fabricate ^{enr}Ge dets

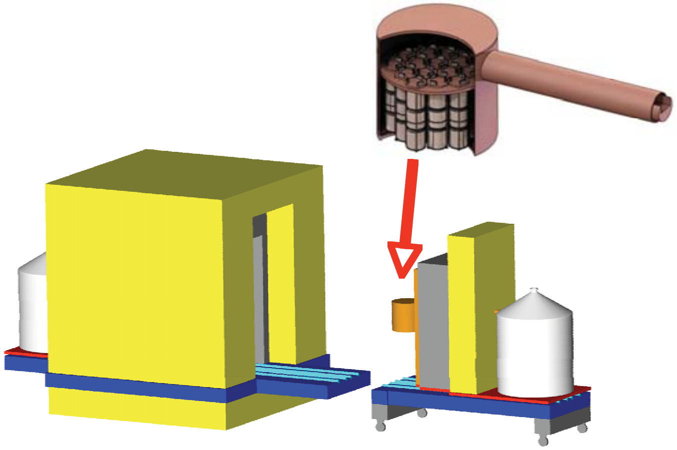
Assembly of ^{enr}Ge sub-modules

MAJORANA Status

- Support: As a R&D Project by DOE Nuclear Physics & NSF Particle and Nuclear Astrophysics
- Progress towards Demonstrator Module
  - Much design work and prototyping in progress
  - UG clean room laboratory space preparations are proceeding, initial installations in 2009/2010 at Sanford Laboratory (Homestake gold mine, Lead, SD).
  - UG Electroforming facility will be initial focus due to required time to prepare Cu parts of shield.
  - Primary focus on deployment of first demonstrator sub-module cryostat with point-contact detectors.
  - Working with industrial partner to develop Ge refinement process that could be located either near detector fabrication facility or UG.

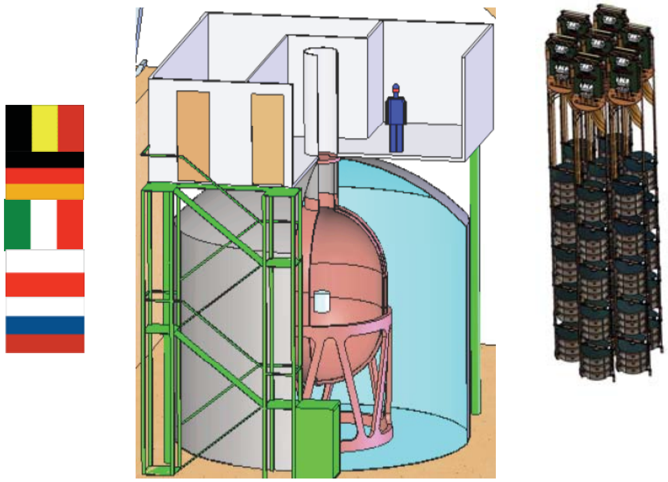
MAJORANA & GERDA

MAJORANA



- Modules of ^{enr}Ge housed in high-purity electroformed copper cryostat
- Shield: electroformed copper and lead
- Initial phase: R&D Demonstrator module - 60kg (30 kg enriched)

GERDA



- Bare ^{enr}Ge in liquid Argon
- Shield: high-purity Argon/H$_2$0
- Phase I: ~18 kg (HdM/IGEX crystals)
- Phase II: add ~20kg new detectors

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Note: Red text indicates students