
# Overview and Status of the Majorana Experiment


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# Introduction

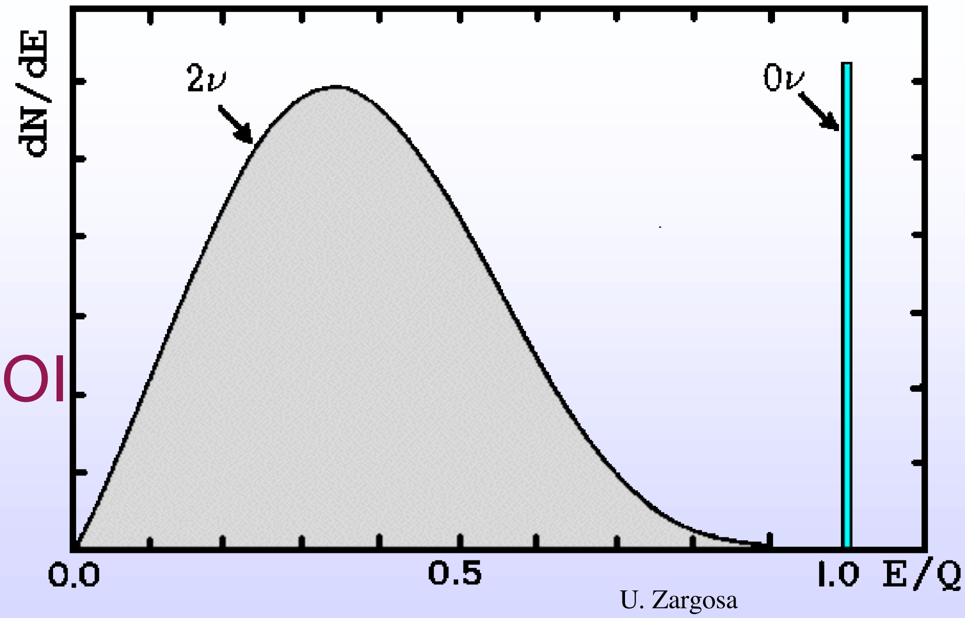
- Majorana proposes to search for neutrinoless double-beta decay of $^{76}Ge$.
  - Review Ge detection Scheme
  - Majorana Principle and Background Mitigation
  - Majorana Status

# Experimental Considerations

- Measure ***extremely*** rare decay rates :

  $T_{1/2} \sim 10^{26}$ - $10^{27}$ years ($\sim 10^{13}$x age of universe!)
- Large, highly efficient source mass.
- Extremely low (near-zero) backgrounds in the $0\nu\beta\beta$ peak region-of-interest (ROI) (1 count/t-y)

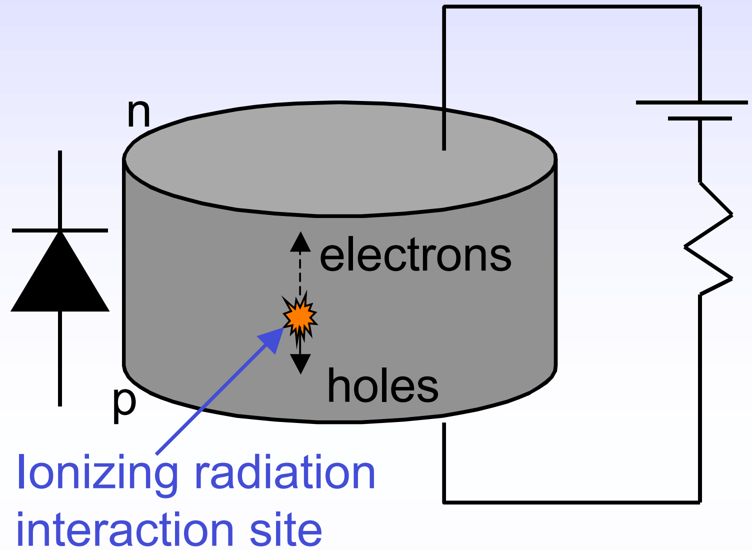
1. High Q value
2. Best possible energy resolution
   - Minimize $0\nu\beta\beta$ peak ROI to maximize S/B
   - Separate $2\nu\beta\beta/0\nu\beta\beta$



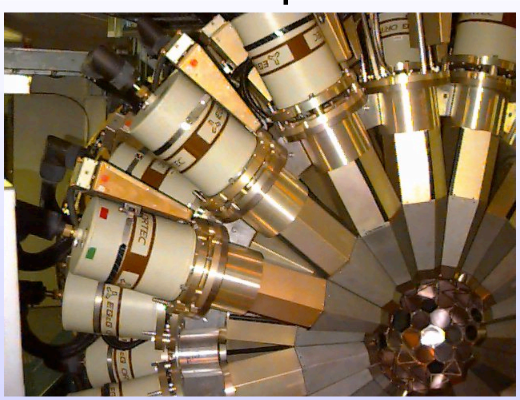
# Ge Detection Principle

- >40 years of experience
- Ge is semiconductor -- Diode.
- Ionizing radiation creates electron-hole pairs.
- Signal generated by collecting electrons and holes.
- Gamma-ray spectroscopy

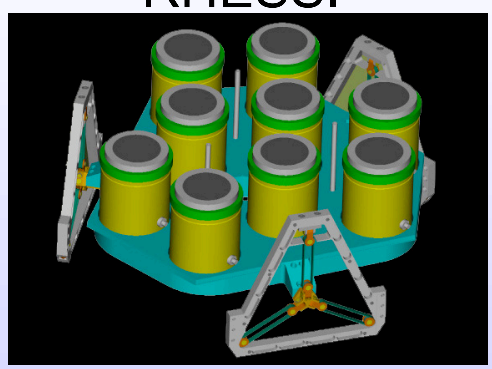
**Mature Technology**




Gammasphere



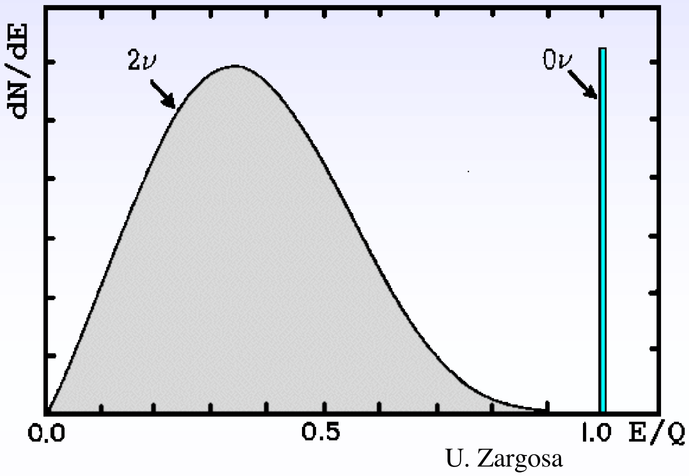
RHESSI



Eurisys
(Commercial)

# Majorana DBD Detection Principle

- Enriched HPGe Diodes -- Detector is Source.
- Excess at Q = 2039 keV
- Demonstrated in IGEX, Heidelberg Moscow.




$$W_D = 2.35\sqrt{F\varepsilon E}$$

$W_D$: FWHM

$F$: Fano factor: ~ 0.1

$\varepsilon$: Energy per e-h pair: 2.96eV

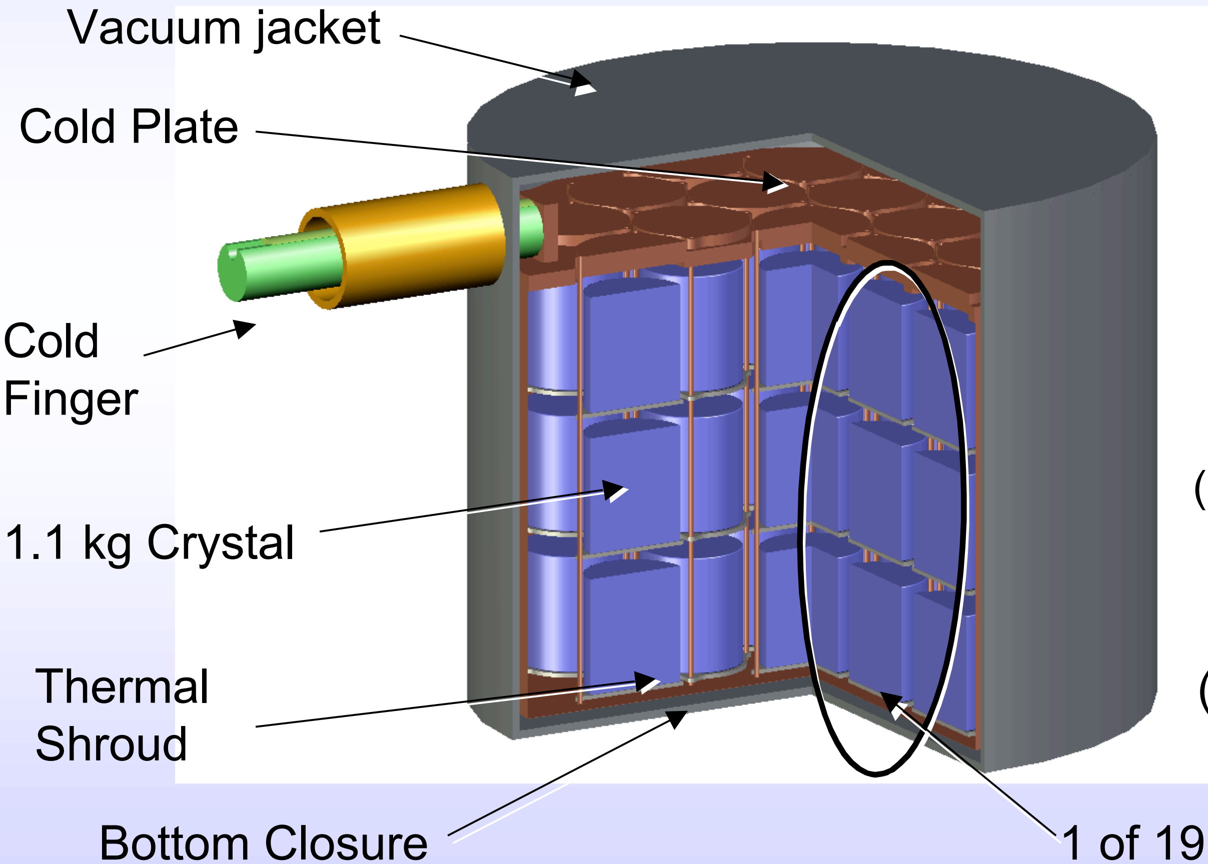
$E$: Energy

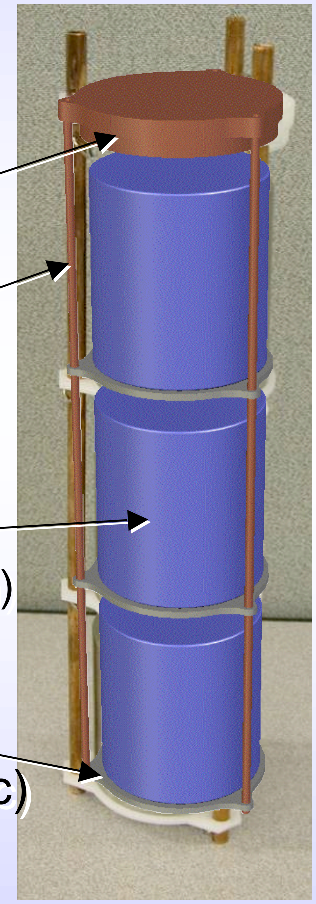
- ☞ **HPGe Detectors have excellent energy resolution**
- ☞ **0.16% at ROI for Majorana**

# The Majorana Modular Approach

## One concept: 57 crystal modules

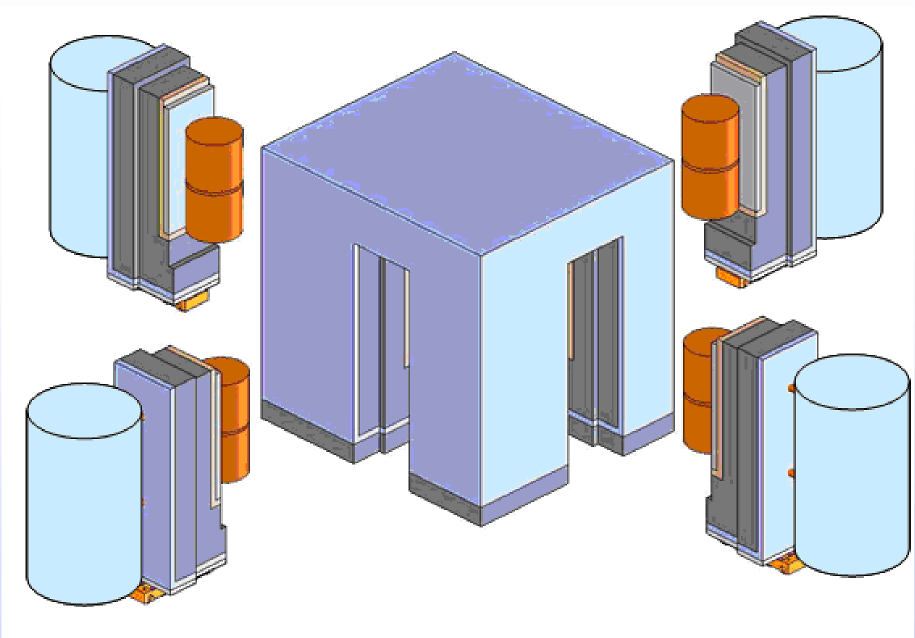
- Conventional vacuum cryostat made with electroformed Cu.
- Three-crystal stack are individually removable.



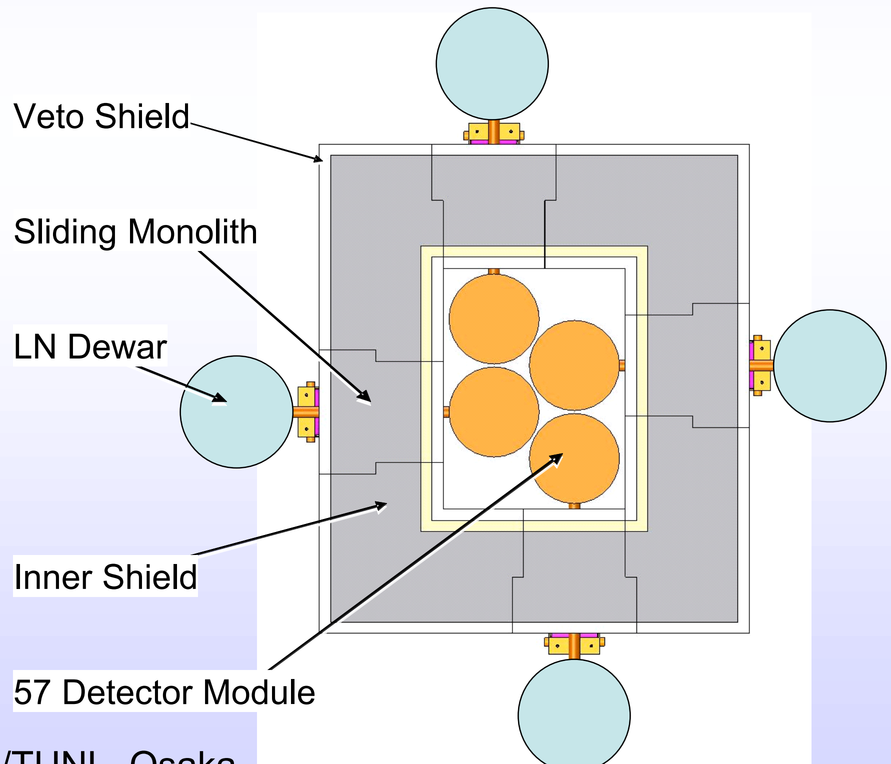



# The Majorana Shield - Conceptual Design

- Deep underground: >5000’
- Allows modular deployment, early operation
- Contains up to eight 57-crystal modules
- 40 cm bulk Pb, 10 cm ultra-low background shield
- Active 4$\pi$ veto detector



Top view



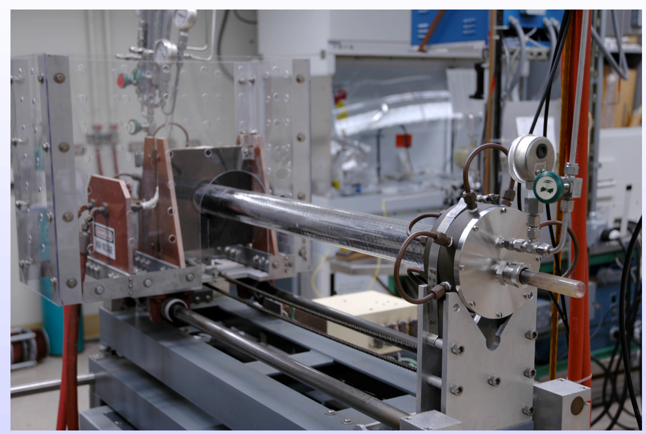
# Crystal Production

Enrichment (86% $^{76}$Ge)

E.E Haller Crystal growth

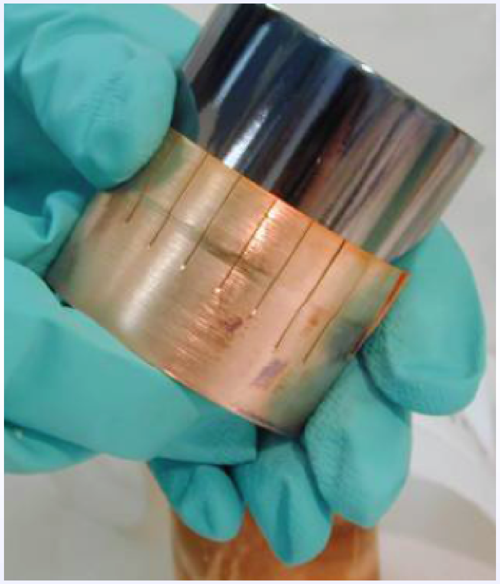

Polycrystalline bars

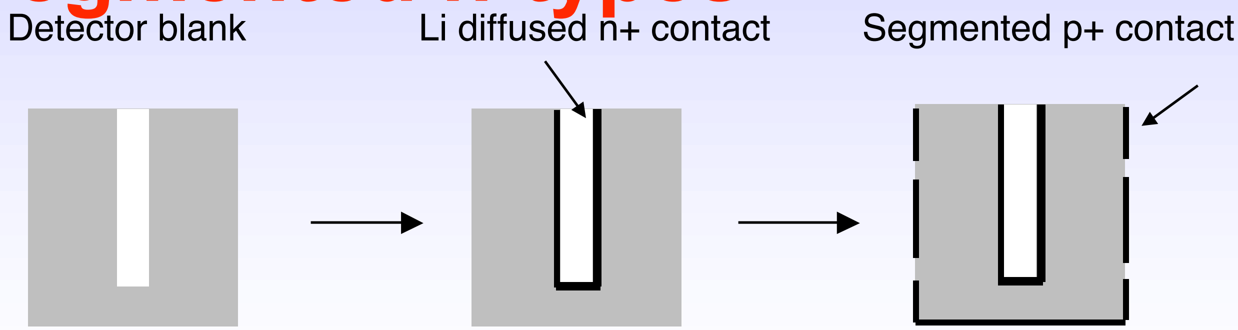
Zone refinement

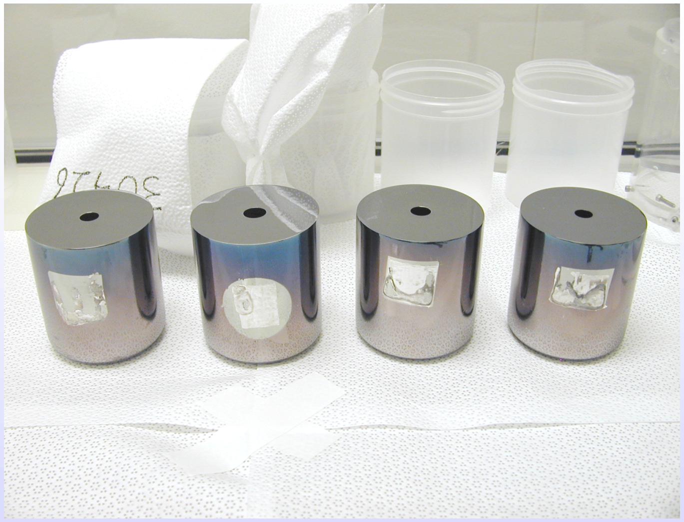


# Detector Fabrication

## Segmented n-types





Other designs under consideration:

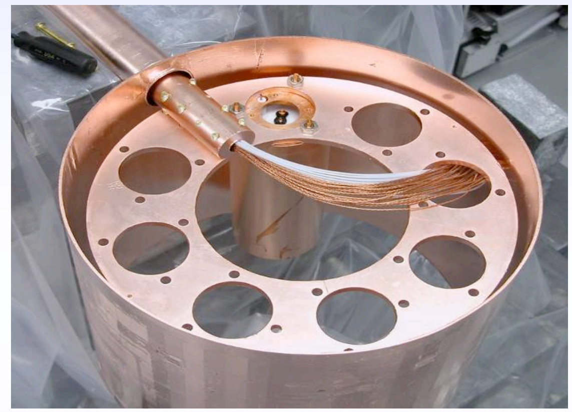
- Modified Electrode
- Unsegmented p-type

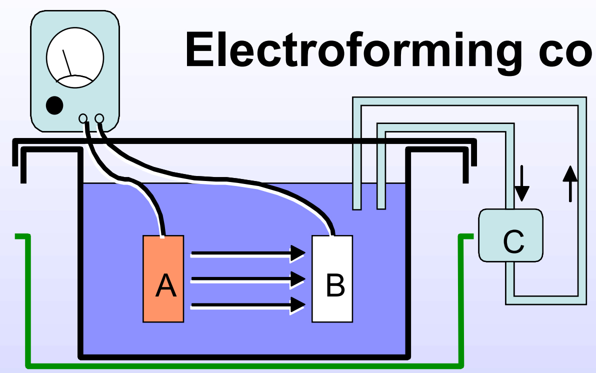
# Background Identification

- Majorana is background limited.
- Goal: 1 event / ton-year in 4 keV ROI
- Backgrounds:
  - Compton scattered gammas, surface alphas.
  - 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.
  - $2\nu\beta\beta$-decays.
- Need factor ~100 reduction over what has been demonstrated.
- Monte Carlo estimates of acceptable levels

# Ultra-Pure Cu

- Ultra-radioclean materials required
- Electroformed Cu is example
- Th chain purity in Cu is key
  - Ra and Th must be eliminated
  - Remove Ra, Th by ion exchange during electroforming
- We expect to achieve the 1 μBq/kg $^{232}$Th specification

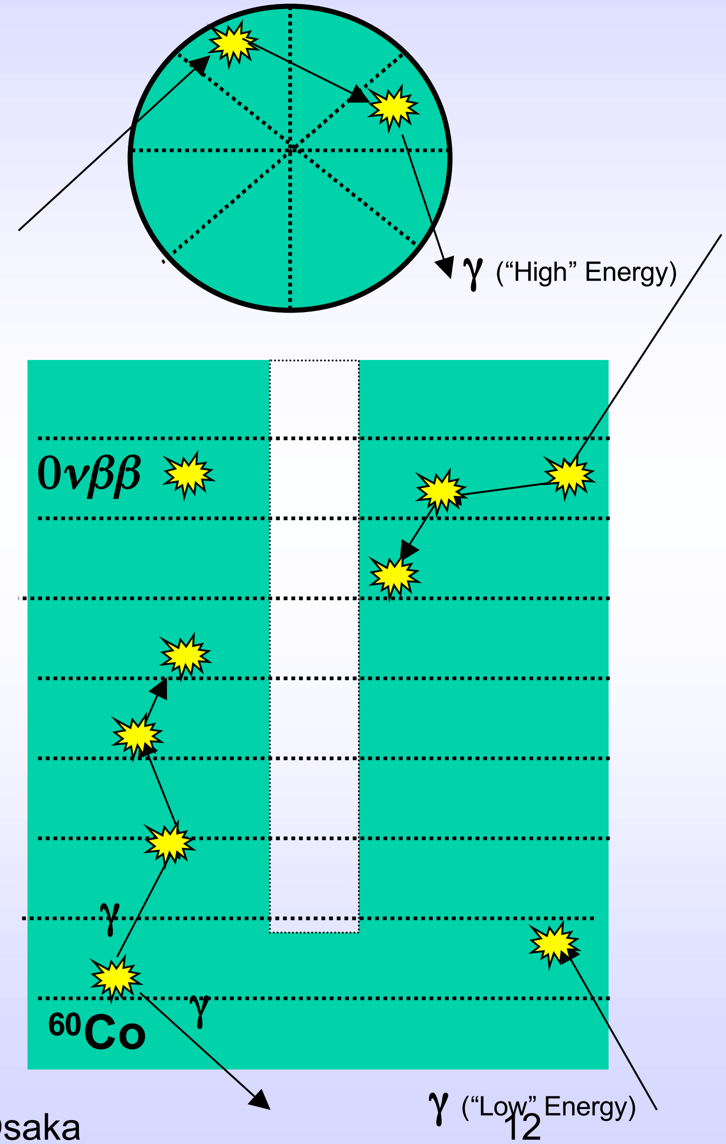




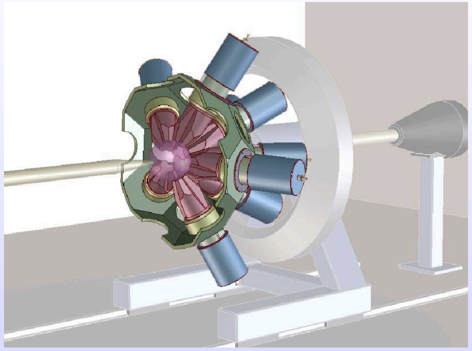

**Electroforming copper**

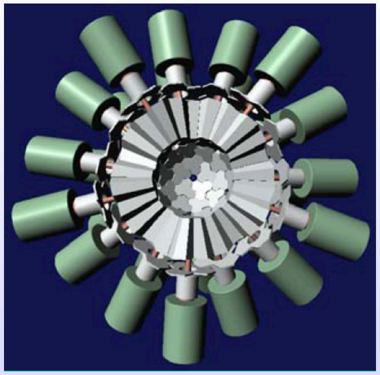
# Crystal Segmentation

- Multiple conductive contacts on crystal
- Discriminates against gammas
- Additional electronics and small parts



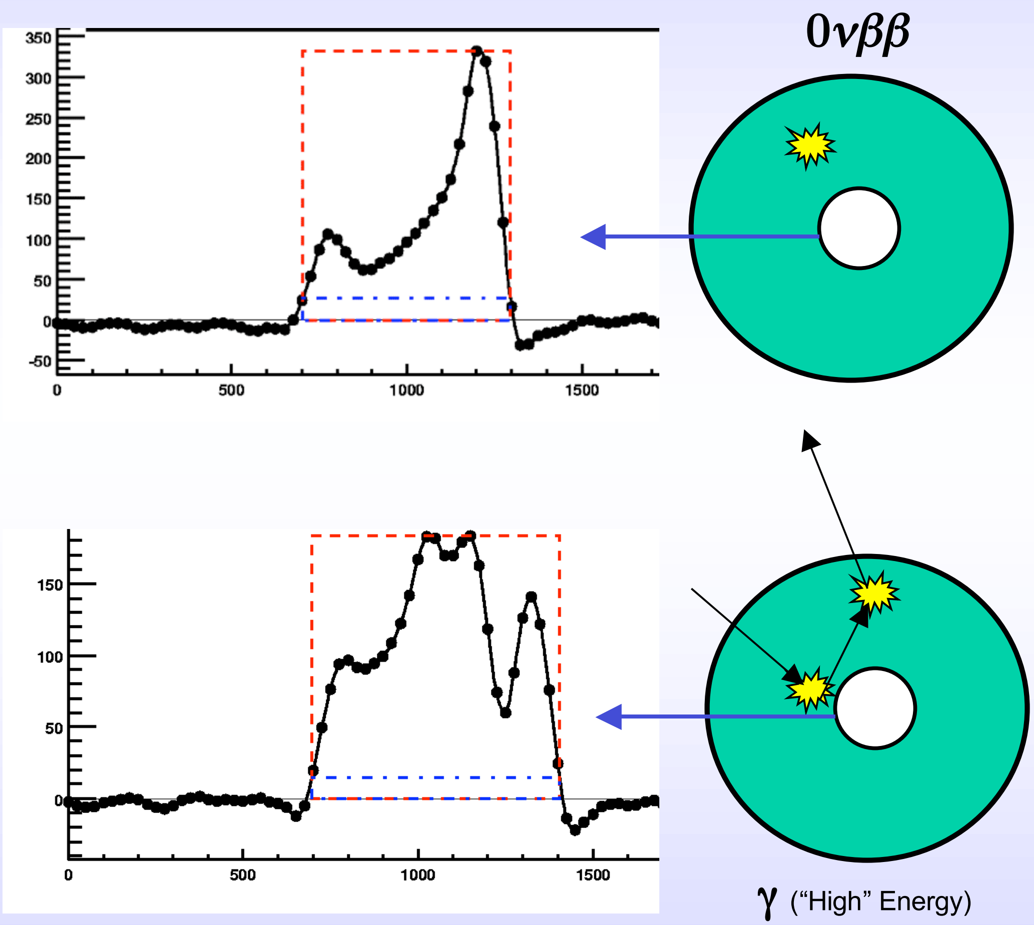

Example: Gretina and AGATA





# Pulse Shape Discrimination (PSD)

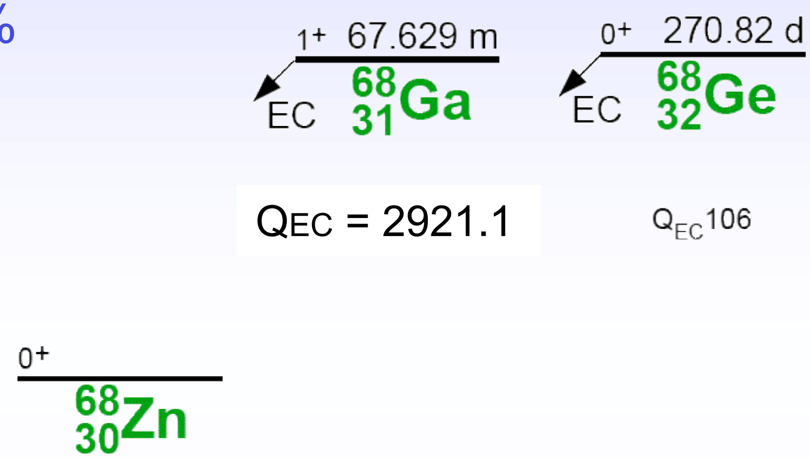
Central contact (radial) PSD

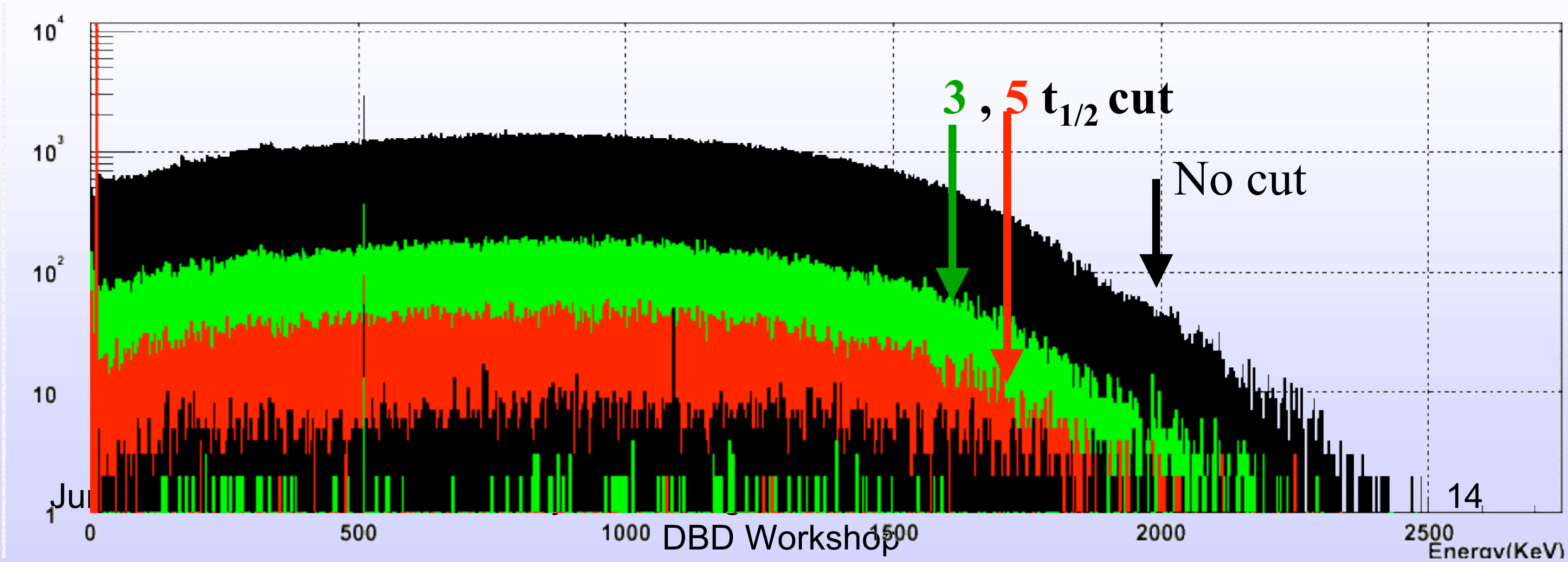



- Excellent rejection for internal $^{68}Ge$ and $^{60}Co$ (x4)
- Shown to work well with segmentation. Allows sophisticated techniques.

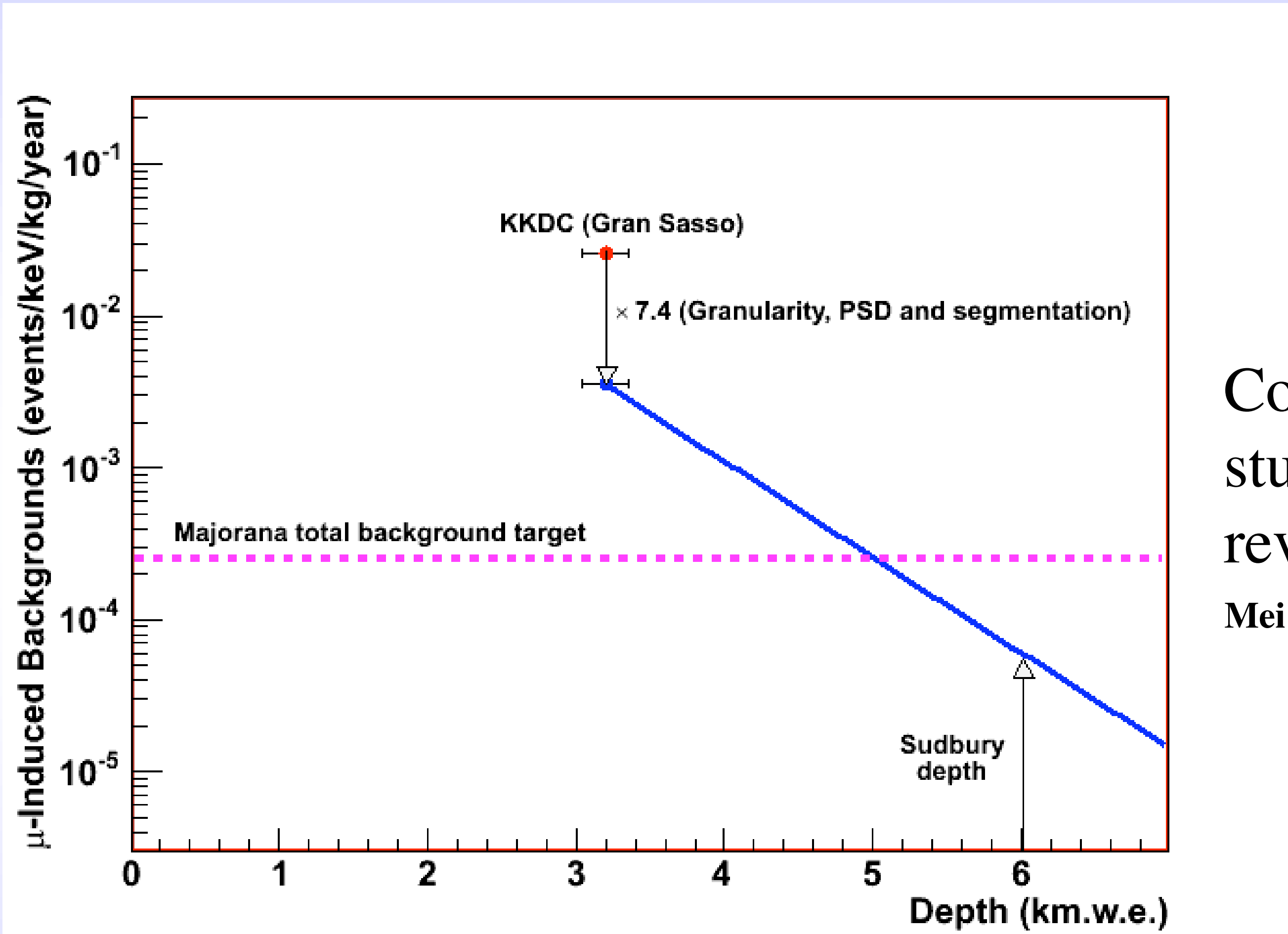
# Time Correlations

- $^{68}$Ge is worst initial raw background
  - $^{68}$Ge -> 10.367 keV x-ray, 95% eff
  - $^{68}$Ga -> 2.9 MeV beta
- Cut for 3-5 half-lives after signals in the 11 keV X-ray window reduces $^{68}$Ga β spectrum substantially



# Cosmic Ray Background



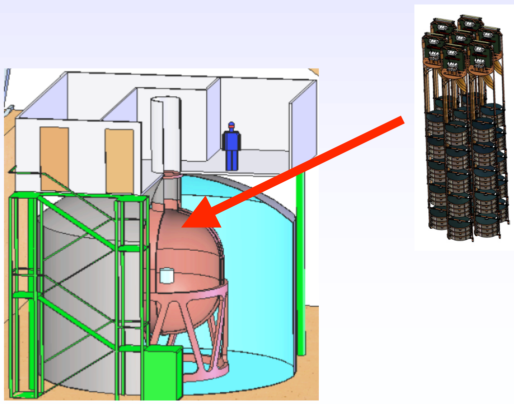

Comprehensive study (under review)

**Mei and Hime 2005**

## Require Deep Site > 5000 mwe

# GERDA - Majorana

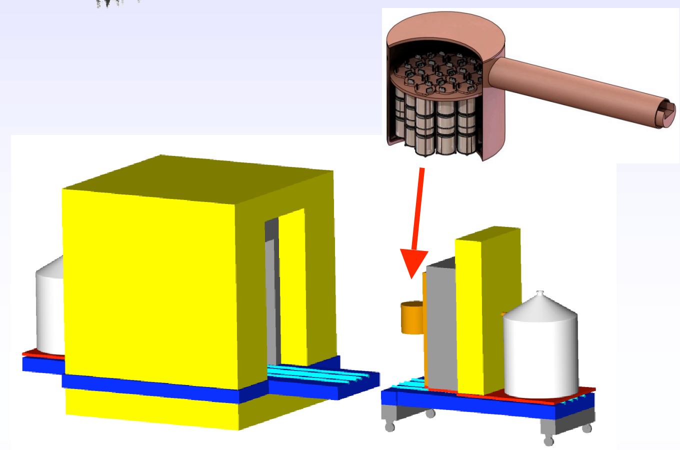
## GERDA



- ‘Bare’ $^{enr}$Ge array in liquid argon
- Shield: high-purity liquid Argon / $H_2O$
- Phase I (mid 2008): ~18 kg (HdM/IGEX diodes)
- Phase II (mid 2009): add ~20 kg new detectors

Total ~40 kg

## Majorana



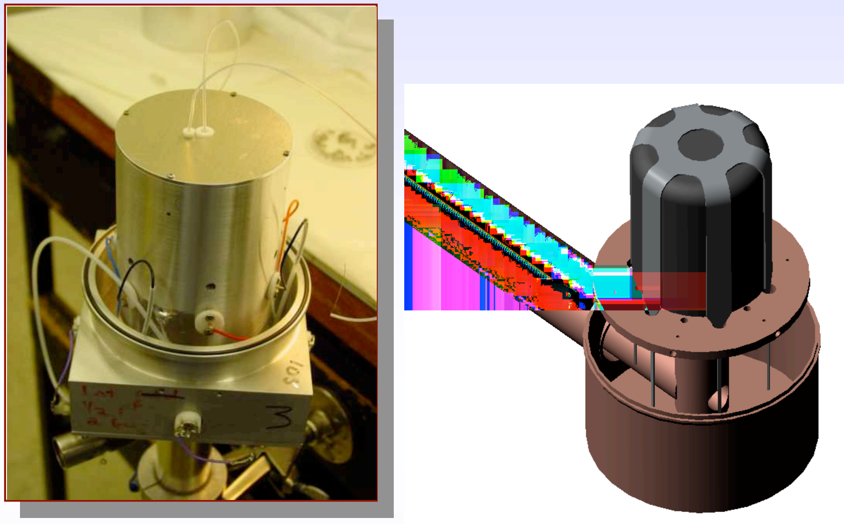
- Modules of $^{enr}$Ge housed in high-purity electroformed copper cryostat
- Shield: electroformed copper / lead
- Initial phase: R&D prototype module

Total 60 kg

**Joint Cooperative Agreement:**

- Open exchange of knowledge & technologies (e.g. MaGe, R&D)
- Intention to merge for 1 ton exp. Select best techniques developed and tested in GERDA and Majorana

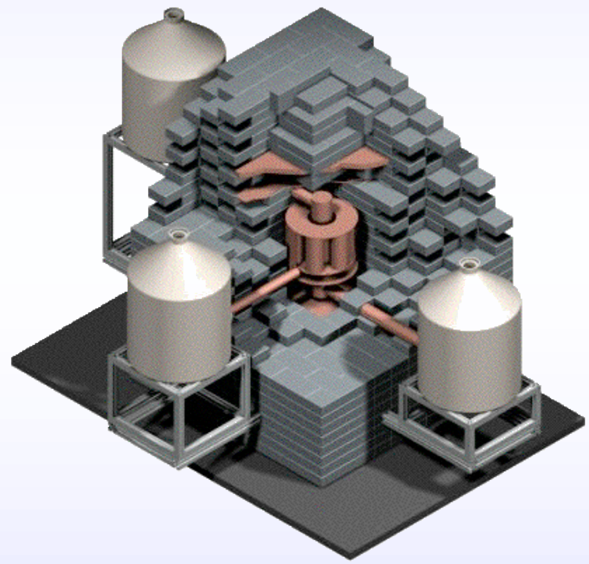
# Prototypes and R&D



**SEGA:**
**Segmented Ge**

TUNL FEL

**MEGA:**
**16+2 natural Ge at WIPP**



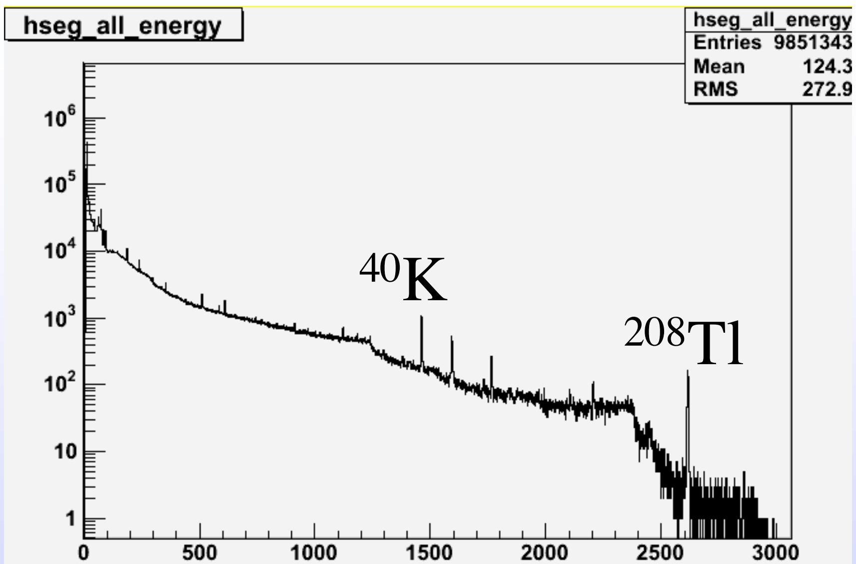
Low background counting

Crystal-to-crystal veto

# LLNL Detector at Oroville

- First highly segmented detector with pulse digitization in low background environment.
- Determine background rejection for natural radioactivity for a detector in the field.

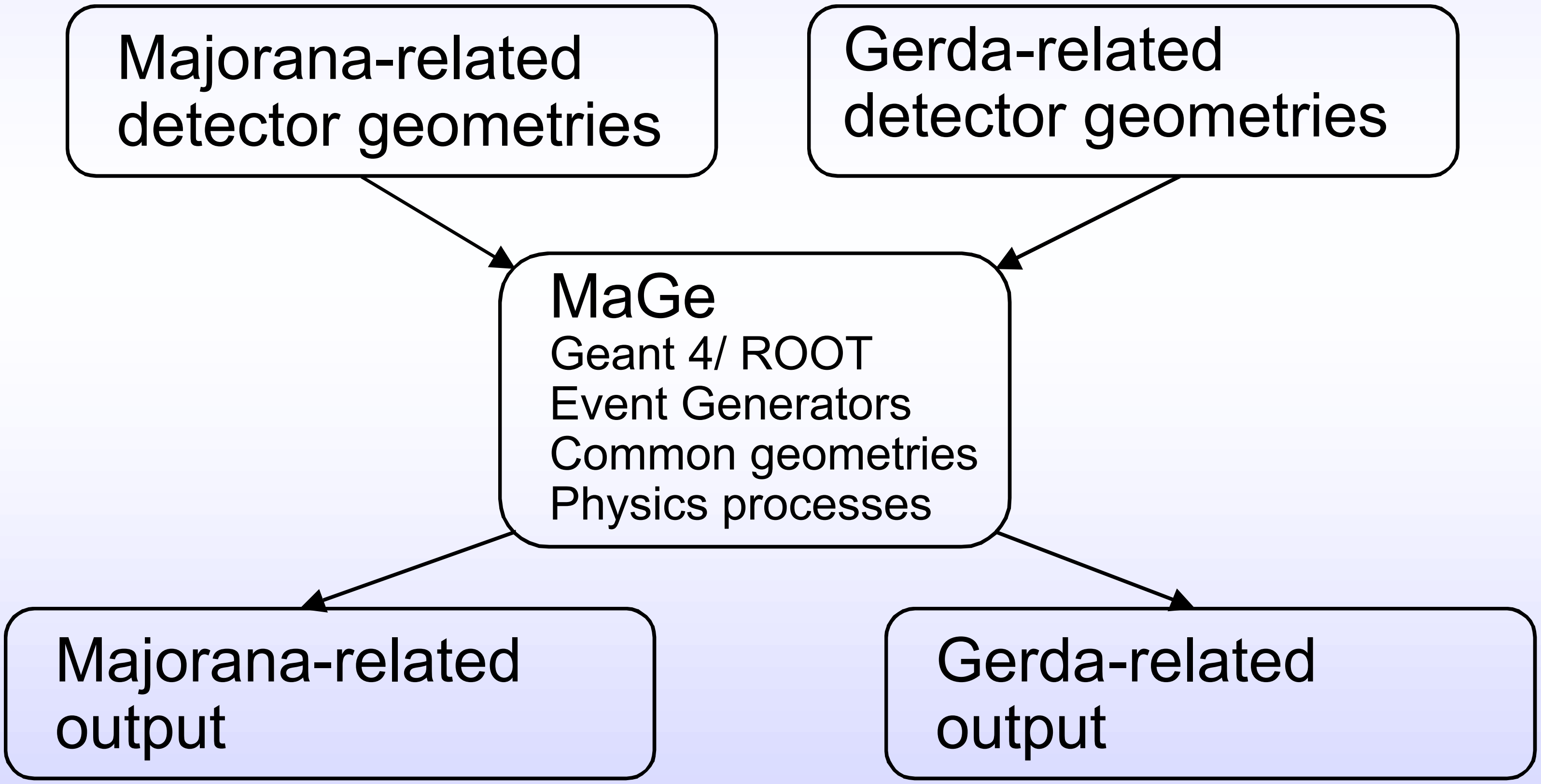
50 day spectra




Pulses from segments

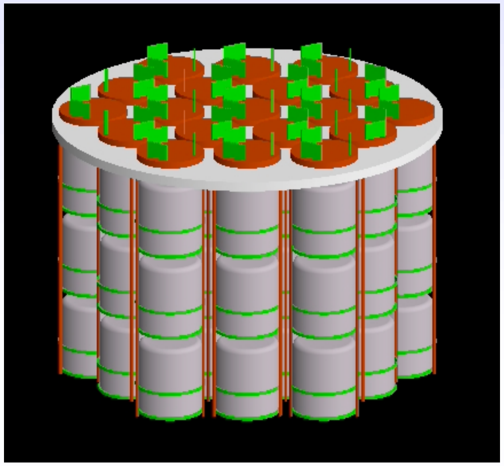
# “MaGe” Simulation Package.

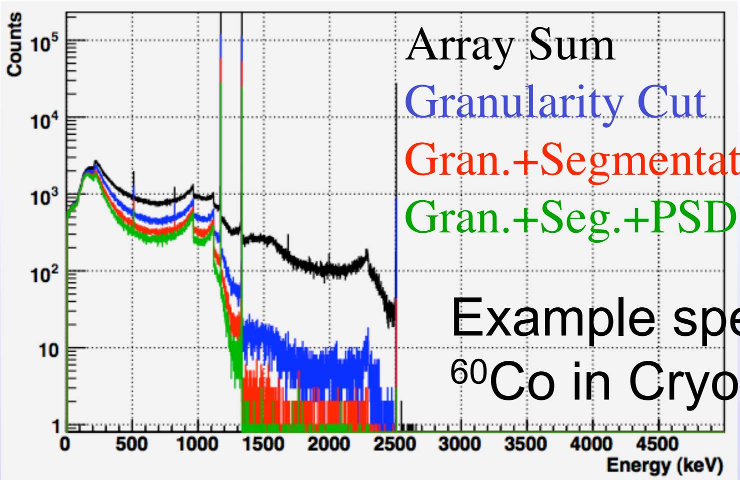
Framework uses powerful object-oriented and abstraction capabilities of C++ and STL for flexibility



# Majorana Simulation

Simulated Geometry
Shields & Cryostat Removed






Example spectra:
$^{60}$Co in Cryostat

**Simulation Includes:**

- 57 Enriched crystal w/ deadlayers.
- LFEPs
- Support Rods
- Ge Trays
- Contact Rings
- Cryostat
- Surface Alphas
- Shields:
  - Inner, Outer Cu
  - Inner, Outer Pb
  - Neutron shield.
  - Room, rock wall.
- 45,000 CPU hours, 12,000 jobs.

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

# Other Majorana technical progress

- Effectiveness of background cuts using a Clover detector (Elliott *et al.*)
- Multiple studies of segmented detectors and background reduction methods.
- Studies of effectiveness of background reduction using SEGA and the TUNL HIGs facility (paper in preparation).
- Constructed large prototype electroformed cryostat (MEGA) and operated with multiple crystals.
- Improved techniques to electroform large, ultra-clean Cu cryostats (Hoppe *et al.*).
- Pushing ICP-MS assay sensitivities to the sub $\mu$Bq/kg level (Hoppe et al. paper).
- Exploration of modified electrode Ge detector (Collar *et al.* papers submitted).
- Study of sensitivity of two neutrino and neutrinoless double-beta decay to excited states in $^{76}$Ge (Kazkaz dissertation and paper in preparation)
- Support of Gretina digitizing card in ORCA
- …

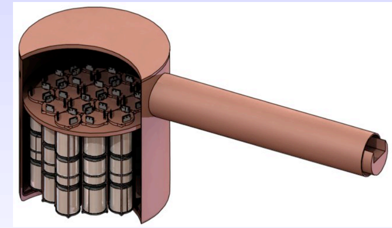
# Majorana Collaboration Current Status

Actively pursuing the development of R&D aimed at a ~1 ton scale $^{76}Ge$ neutrinoless ββ-decay experiment.

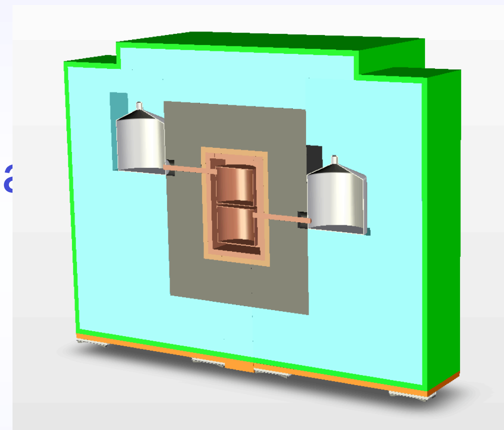
- Immediate thrust is to build a 60 kg prototype module to demonstrate backgrounds needed in a future experiment capable of reaching a sensitivity to the “inverted hierarchy” neutrino mass scale (30-40 meV).
- Using this prototype, expect to make a down-select between Majorana and GERDA technologies, picking the best method.
- Also exploring longer term R&D to minimize costs and optimize the schedule for a 1 ton experiment.

Our plan has been guided by advice from NuSAG, an independent external panel review (March 06), and a DOE ββ-decay Pre-conceptual design review panel (Nov. 06)

# The Majorana Prototype Module (WIP)

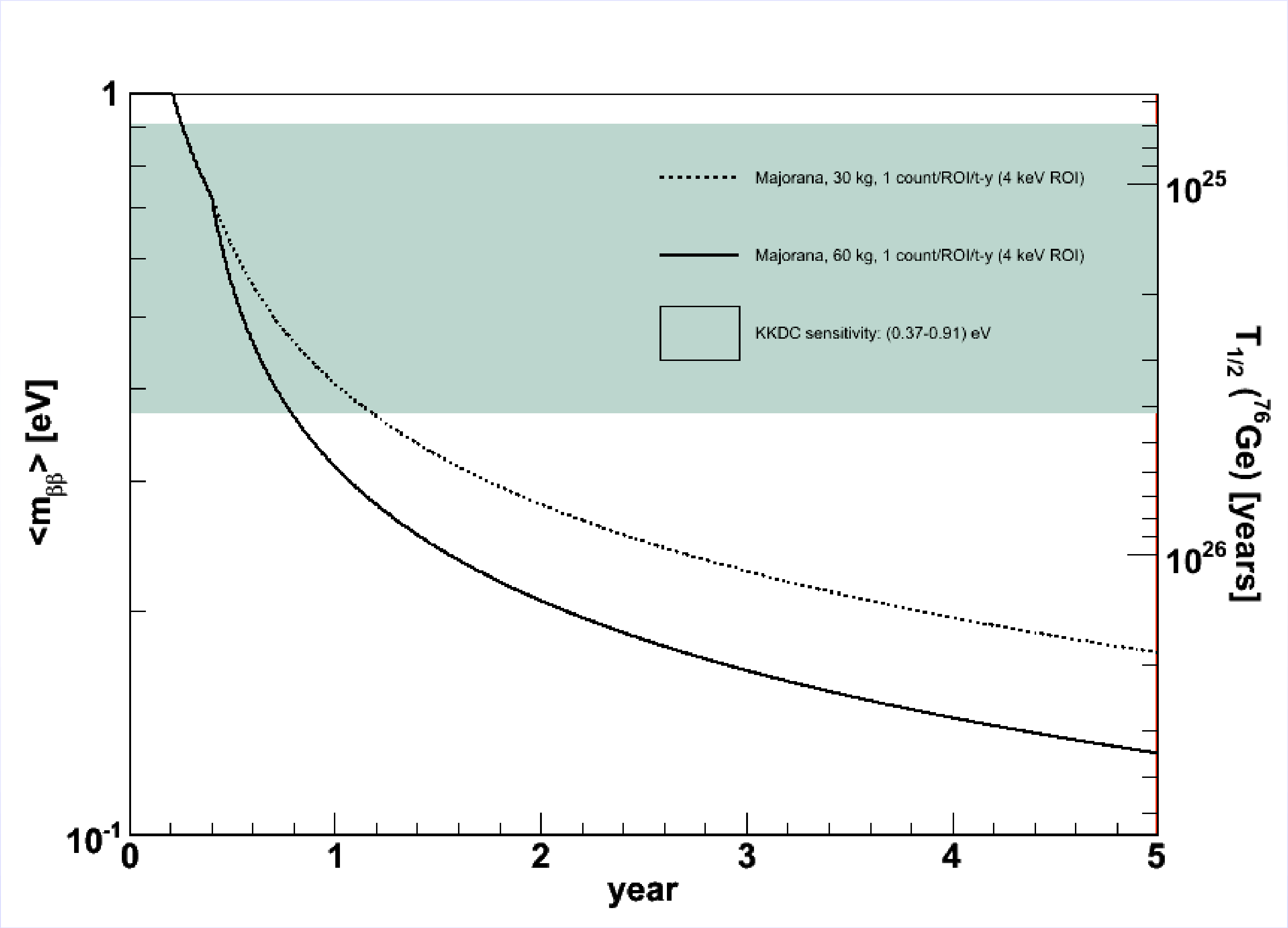


- 60 kg module, ~60-100 crystals.
- Different designs and levels of enrichment

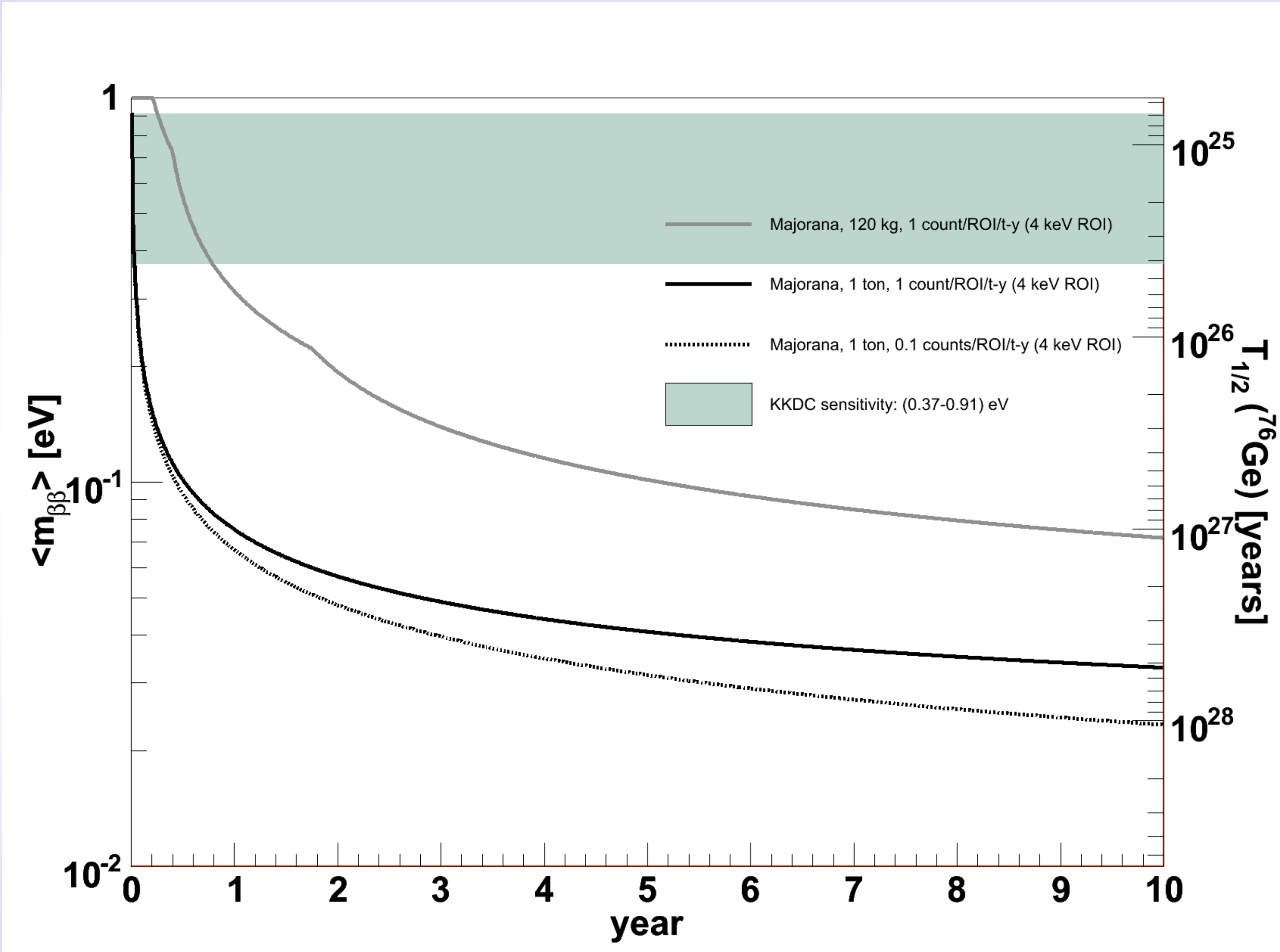


- ≥ 4500 mwe
- Background Specification Goal in the $0\nu\beta\beta$ pea region of interest (4 keV at 2039 keV)
  - **~ ≤1 count/ROI/t-y** (after analysis cuts)
- Expected Sensitivity to $0\nu\beta\beta$ (for 60 kg enriched material, running 2 years, or 0.12 t-y of $^{76}$Ge exposure)
  - **$T_{1/2} \geq 1.6 \times 10^{26}$ y (90% CL)**
  - **Sensitivity to $\langle m_\nu \rangle$ < 190 meV (90% CL) ([Rod06] RQRPA NME)**
  - **Able to confirm/refute KKDC 400 meV value (20% measurement).**

# Majorana Prototype Module Sensitivity



# 1-ton $^{76}$Ge Sensitivity vs. Background

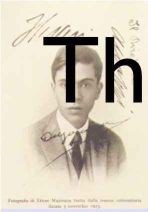


# Conclusion

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

- Ge as source & detector.
- Intrinsic high-purity Ge diodes.
- Favorable nuclear matrix element $\langle M'^{0\nu} \rangle = 2.4$ [Rod06].
- Reasonably slow $2\nu\beta\beta$ rate ($T_{1/2} = 1.4 \times 10^{21}$ y).
- Demonstrated ability to enrich from 7.8% to 86%.

- Excellent energy resolution — 0.16% at 2.039 MeV
- Powerful background rejection.
  Segmentation, granularity, timing, pulse shape discrimination
- Best limits on $0\nu\beta\beta$ - decay used Ge (IGEX & Heidelberg-Moscow)
  $T_{1/2} > 1.9 \times 10^{25}$ y (90%CL)
- Well-understood technologies
  - Commercial Ge diodes
  - Large Ge arrays (GRETINA, Gammasphere)



# The Majorana Collaboration

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# Backup Slides

# Majorana funding status and plans

- Pursuing immediate “R&D” funding to build a prototype $^{76}Ge$ detector module (~60 kg) as part of a long-term program to develop a 1-ton ββ-decay experiment.
  - The prototype $^{76}Ge$ demonstration module will allow a technology comparison between Majorana and GERDA.
  - Have received word that the collaboration’s DOE DUSEL R&D proposal will be funded (Don’t yet know the funding amount.)
  - Summer 2007 - Will submit a R&D proposal covering the full development of the prototype module. (Estimated total cost of $20M with most of the R&D module funding requested in FY09-11.)

# A Recent Claim

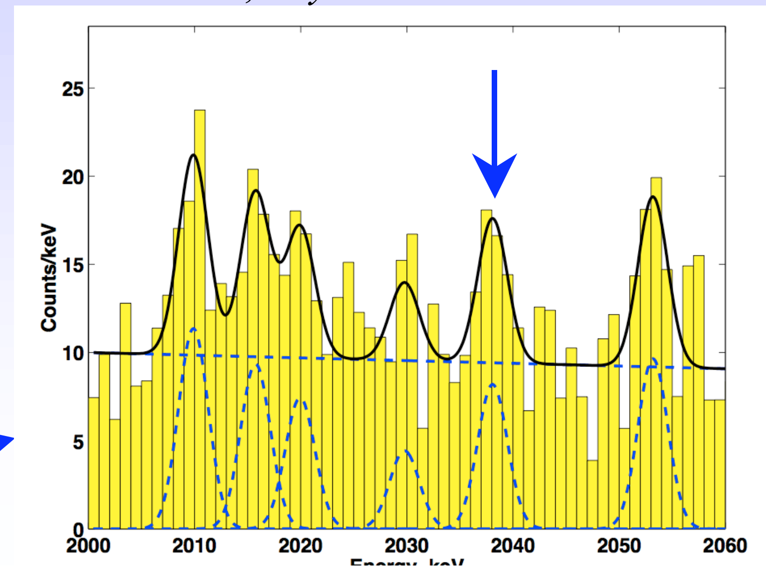
Klapdor-Kleingrothaus H V, Krivosheina I V, Dietz A and Chkvorets O, *Phys. Lett.* B **586** 198 (2004).

KKDC used five $^{76}Ge$ crystals, with a total of 10.96 kg of mass, and 71 kg-years of data.

$T_{1/2} = 1.2 \times 10^{25}$ y

$0.24 < m_\nu < 0.58$ eV (3 sigma)

Background level depends on intensity fit to other peaks.




Expected signal in Majorana

**With Analysis Cuts**

(for 0.46 t-y)

135 counts

With a background of

Specification: < 1 total count in the ROI