The Majorana Neutrinoless Double Beta Experiment

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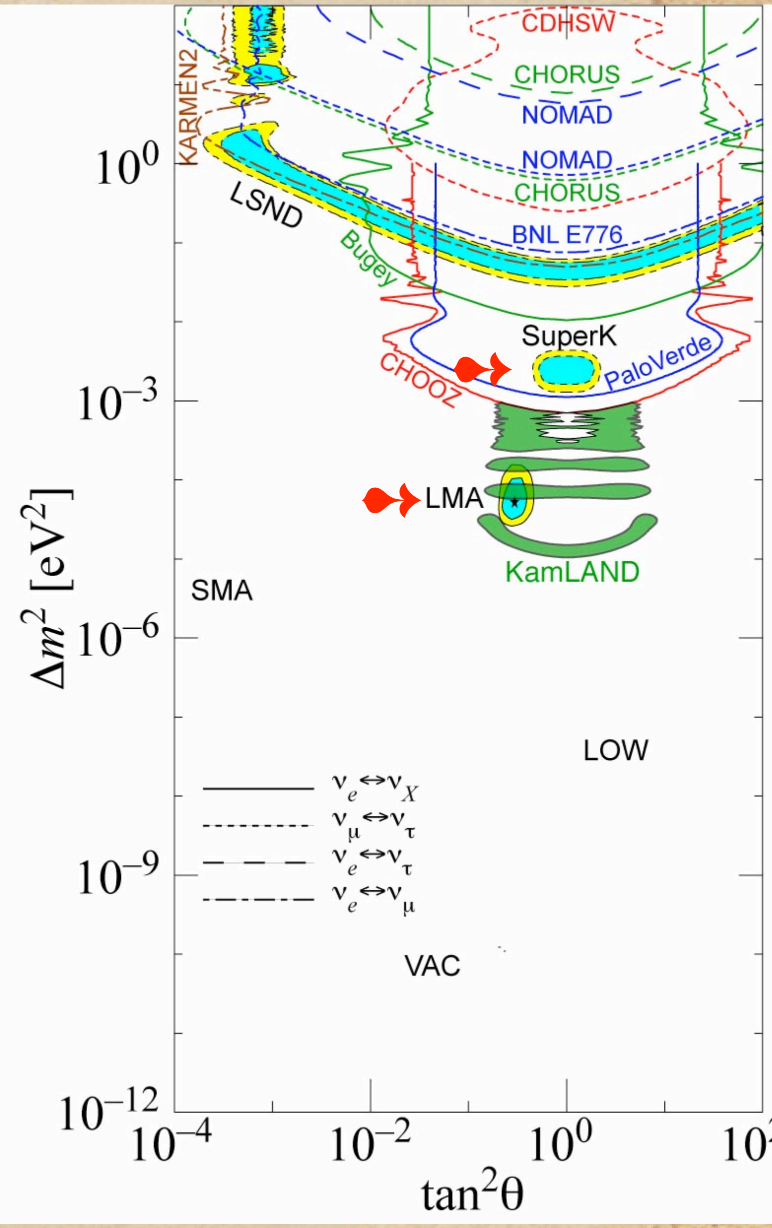
17 September 2005

Outline of Presentation

- Motivation and General Considerations for 0νDBD Experiments
- Majorana Approach and Goals
- Backgrounds and Mitigation Plans
- Current Status
- Conclusions

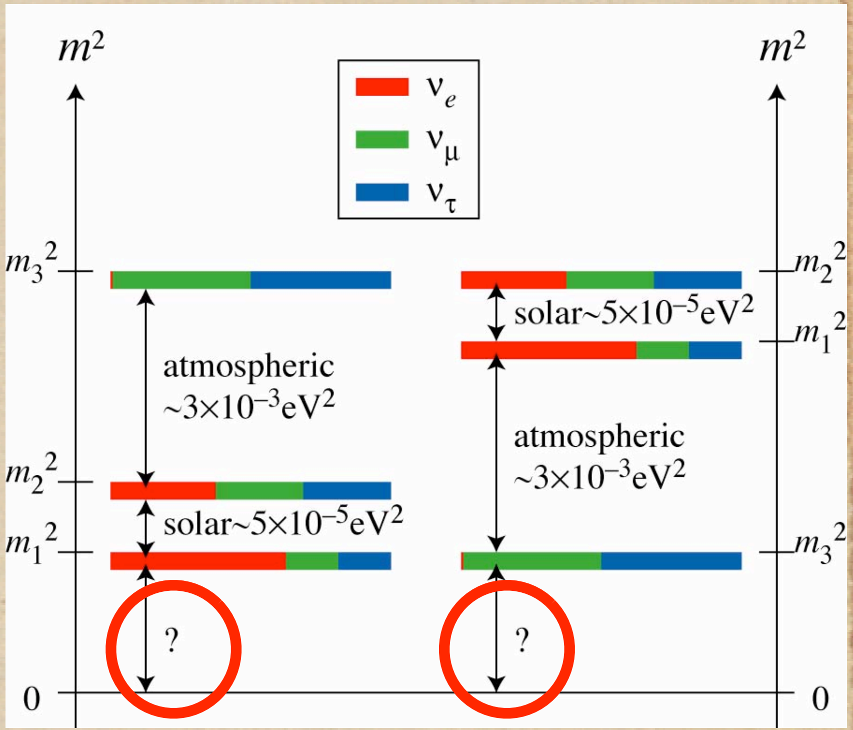
Recent Neutrino Successes

- Massive neutrinos
- Reduced Parameter space by 7 orders of magnitude, LMA confirmed for solar
- No dark side
- Strong evidence for MSW
- Evidence for Oscillations from Super-K and KamLAND
- Maximal Θ_{23}, Large but non-maximal Θ_{12}



Outstanding Problems for Neutrinos

- Neutrino Mass Scale
- MNSP Matrix Elements
  - θ_{13} - size of angle
  - θ_{12} - unitarity of matrix
  - Mass hierarchy
  - Verify Oscillations
- Sterile Neutrinos? LSND affect?
- CP Violation
- Neutrino Nature (Dirac or Majorana)



Neutrinoless Double Beta Decay

- Oscillation experiments indicate νs are massive, set relative mass scale, and minimum absolute mass.
- β decay + cosmology set maximum for the absolute mass scale.
- One ν has a mass in the range: $45\ \text{meV} < m_\nu < 2200\ \text{meV}$
- $0\nu\beta\beta$ experiments can determine the absolute mass scale and only way to establish if neutrinos are Dirac or Majorana
- $0\nu\beta\beta$ can establish mass hierarchy
- Even negative results are now interesting

Decay Rates, Signal, and Sensitivity

Decay Rate:

$$[T^{0\nu}_{1/2}]^{-1} = G^{0\nu}(E_0,Z)\ |\langle m_\nu\rangle|^2\ |M^{0\nu}_F - (g_A/g_V)^2 M^{0\nu}_{GT}|^2$$

$G^{0\nu}(E_0,Z)$ = 2-body phase factors

$M^{0\nu}_F$ = Fermi Matrix Elements

$M^{0\nu}_{GT}$ = Gamow-Teller Matrix Elements

$|\langle m_\nu\rangle|$ = Effective Majorana Electron Neutrino Mass

$$|\langle m_\nu\rangle| \equiv \left|\ |U^L_{e1}|^2 m_1 + |U^L_{e2}|^2 m_2\, e^{i\varphi 2} + |U^L_{e3}|^2 m_3\, e^{i\varphi 3}\right|$$

$$\ln 2\ [T^{0\nu}_{1/2}]^{-1} = N_{\beta\beta}/\epsilon N_{source} t_{exp}$$

$$\ln 2\,[T^{0\nu}_{1/2}]^{-1} = N_{\beta\beta}/\epsilon N_{source} t_{exp}$$

Two Limits to Experimental Reach

with Background

$$\langle m_{\beta\beta}\rangle \sim [A/ax\epsilon G^{0\nu}|M^{0\nu}|^2]^{1/2}\,[b\Delta E/Mt_{exp}]^{1/4}$$

without Background

$$\langle m_{\beta\beta}\rangle \sim [A/ax\epsilon G^{0\nu}|M^{0\nu}|^2]^{1/2}\,[1/Mt_{exp}]^{1/2}$$

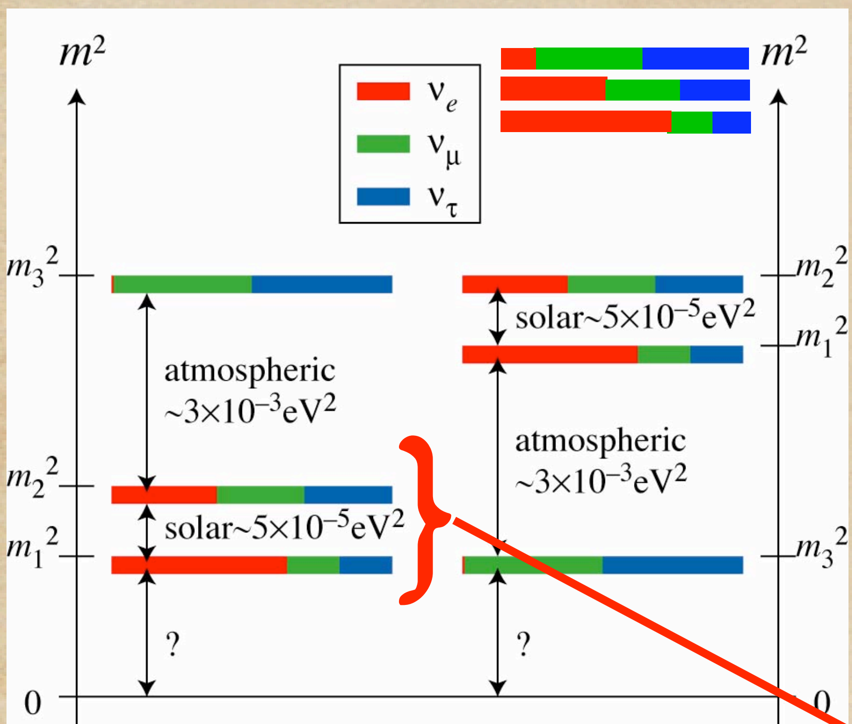
A = Molecular weight

a = isotopic abundance

x = # isotope nuclei per molecule

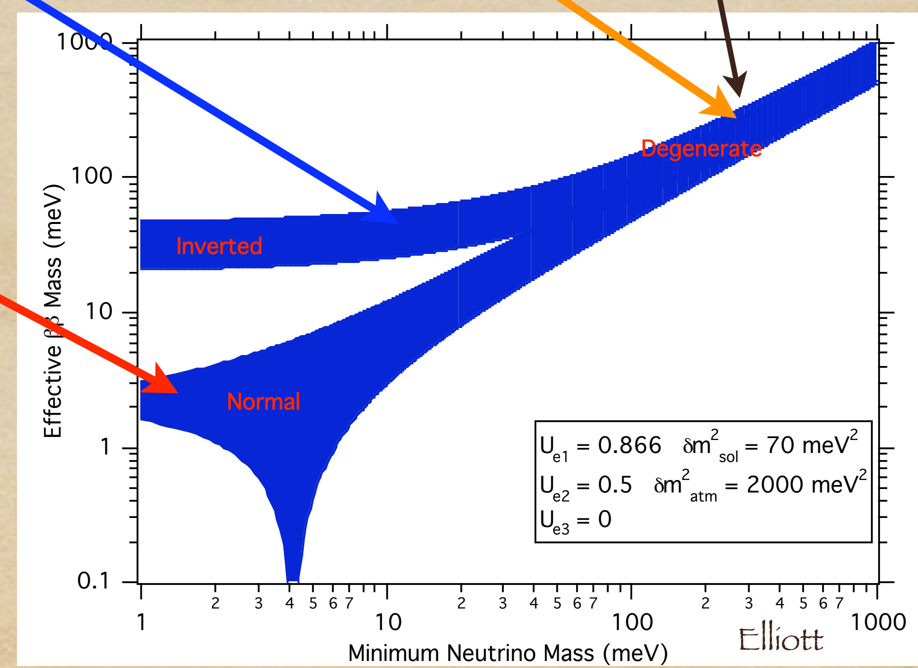
ϵ = efficiency

Masses Hierarchy and 0νββ



Cosmology &

Klapdor



With Background

$$\langle m_{\beta\beta}\rangle \sim [A/ax\epsilon G^{0\nu}|M^{0\nu}|^2]^{1/2}[b\Delta E/Mt_{exp}]^{1/4}$$

$$\langle m_{\beta\beta}\rangle \sim 1/[\,|M^{0\nu}|\,(G^{0\nu}T_{1/2})]$$

to get the scales right:

$\langle m_{\beta\beta}\rangle \sim$ 10 meV to 100 meV

$T_{1/2} \sim 10^{27}$ years

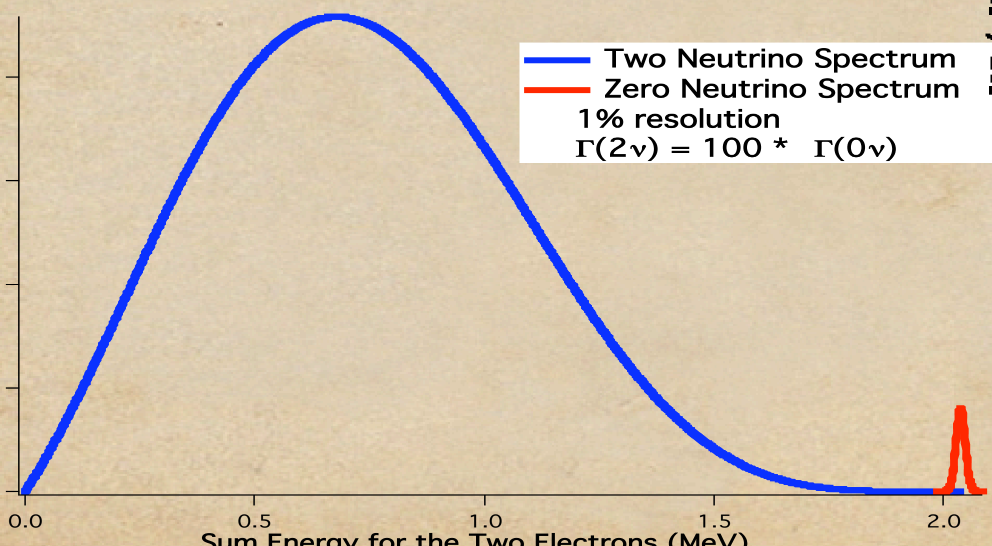
$t_{exp} \sim$ years & M ~ 100kg

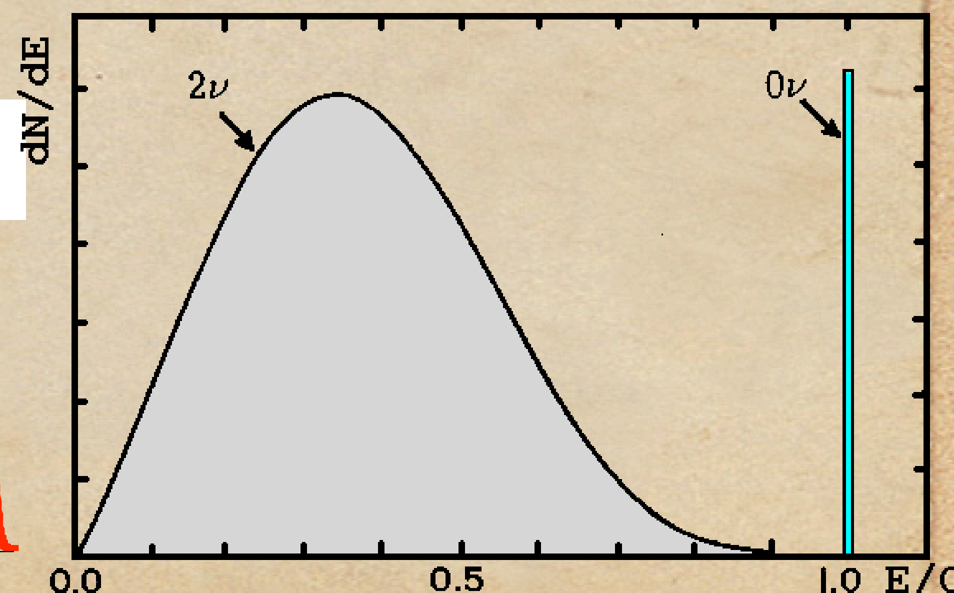
four factors to focus on: backgrounds, energy resolution, mass, and stability

Energy Resolution

- Radioactive backgrounds signals
- Instrumentation effects
- 2νββ backgrounds

Perfect Experiment





U. Zargosa

Detector Mass & Purity

- Isotopic enrichment, chemical purity, & inactive detector elements all effect experimental sensitivity
- added wrong mass ⇒ risk of additional backgrounds, hidden background sources, non-probeable (i.e. dead) detector elements
- Want experimental mass to be all the correct isotope and all to be "active" detector elements
- to probe degenerate mass range ~ 50 - 100 kg
- to probe inverted mass range ~ 500 - 1000 kg
- to probe normal mass range ~ multi-ton range

Backgrounds

- Internal Radioactive Contamination
- Isotopes of concern are a function of the Q-value: for ^{76}Ge 2039 keV, U, Th chains
- External Radioactive Contamination
- Neutrons (fission, CR-generated, reaction)
- Instrumental Issues (cross talk, noise, etc.)

Stability

- Need stable and dependable operation for years
- High live-time fraction
- Low maintenance

The Majorana Experiment

Majorana is scalable, permitting expansion to ~ 1000 kg scale

- Reference Design (180 kg) to address first goals
  - 171 segmented, n-type, 86% enriched ^{76}Ge crystals.
  - 3 independent, ultra-clean, electroformed Cu cryostat modules.
  - Enclosed in a low-activity passive shielding and active veto.
  - Located deep underground (~5000 mwe).
- Background Specification in the $0\nu\beta\beta$ ROI

  1 count/t-y

- Expected $0\nu\beta\beta$ Sensitivity (3 y or 0.46 t-y ^{76}Ge exposure)

  $T_{1/2} \geq 5.5 \times 10^{26}$ y (90% CL)

  $\langle m_\nu \rangle$ < 100 meV (90% CL) ([Rod05] RQRPA matrix elements)

  or a 10% measurement assuming a 400 meV value.

Why Germanium?

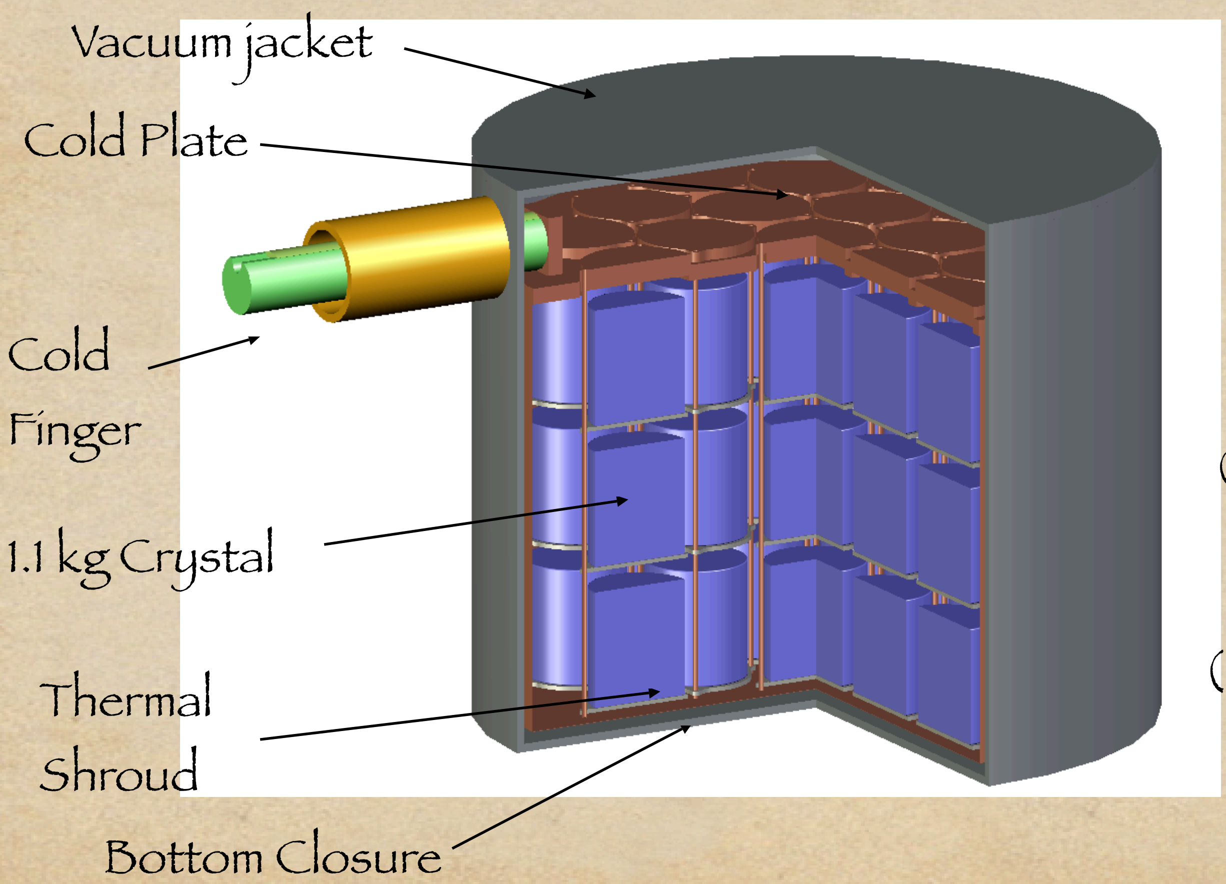
^{76}Ge offers an excellent combination of capabilities and sensitivities: ready to proceed with demonstrated technologies without proof-of-principle R&D.

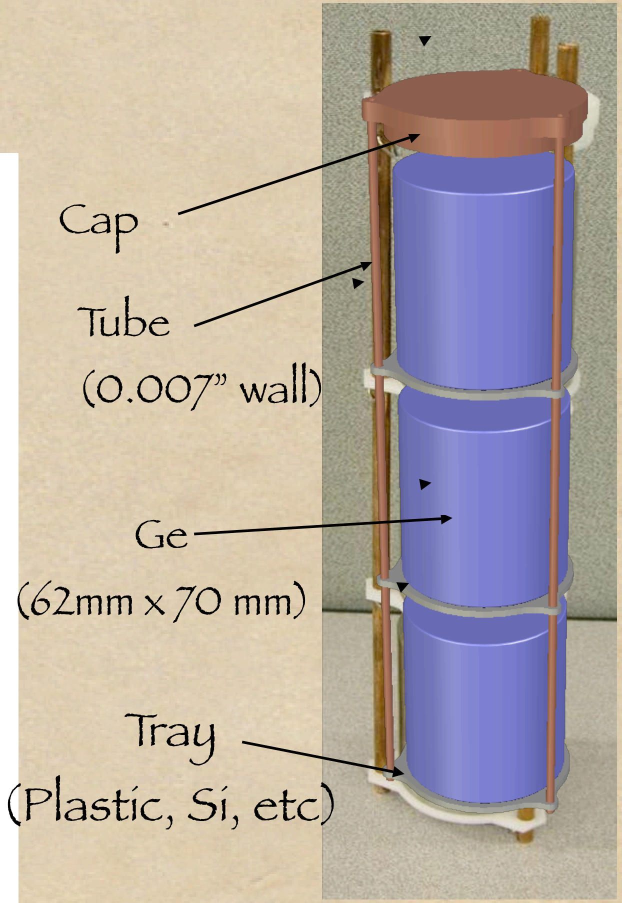
- Favorable nuclear matrix element $|M^{0\nu}| = 2.4$ [Rod05], 2.68 ± 0.06 (QRPA) ($G^{0\nu} = 0.30 \times 10^{-25} y^{-1} eV^{-2}$)
- Reasonably slow $2\nu\beta\beta$ rate ($T_{1/2} = 1.4 \times 10^{21}$ y)
- Demonstrated ability to enrich from 7.44 to 86%
- ∴ High fraction of Ge is both source & active detector
- Elemental Ge further maximizes the source-to-total mass ratio
- Excellent History of Intrinsic high-purity Ge diodes with high purity

- Excellent energy resolution — 0.16% at 2.039 MeV yielding ROI of ~ 4 keV
- Powerful background rejection.
  Segmentation, granularity, timing, pulse shape discrimination
- Well-understood technologies
  - Commercial Ge diodes
  - Existing, well-characterized large Ge arrays (Gammasphere, Gretina)
- Best limits on $0\nu\beta\beta$ used Ge
  $T_{1/2} > 1.9 \times 10^{25}$ y (90%CL)

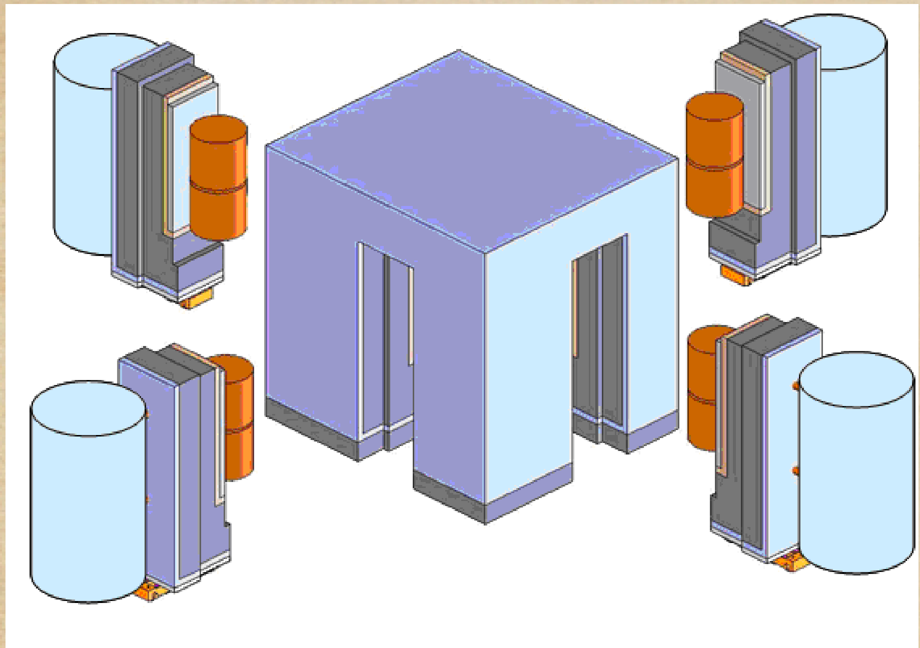
Detector Model

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

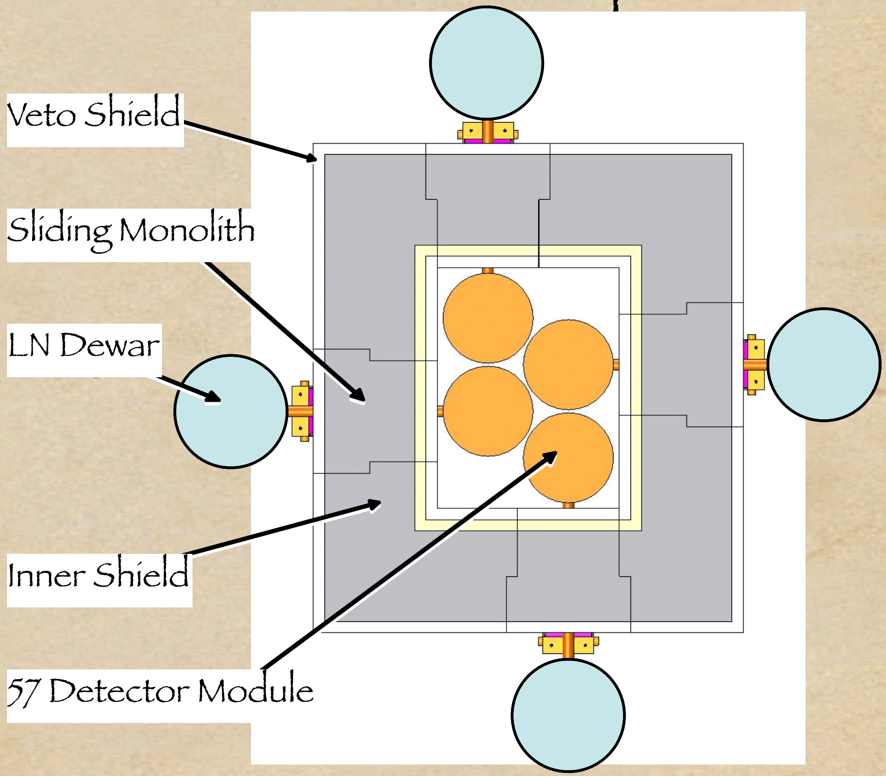




- Allows modular deployment and operation
  - contains up to eight 57-crystal modules (M180 populates 3 of the 8 modules)
  - 40 cm bulk Pb, 10 cm ultra-low background shield



Top view



- Sensitivity to 0νββ decay is ultimately limited by Signal-to-Background performance
- Our specification for backgrounds is 1 cnt/t-y in 0νββ ROI. The specification is based on existing assay limits plus demonstrated techniques for impurity reduction

Bkg Location	Purity Issue	Target Exposure	Activation Rate Spec.	Demonstrated Rate		Ref.
Ge Crystals	^{68}Ge & ^{60}Co	100 d	1 atom/kg/d	1 atom/kg/d		[Avi92]
		Target Mass	Target Purity Spec.		Achieved Assay	
Inner Mount	^{232}Th in Cu	2 kg	1 μBq/kg	<8 μBq/kg	2-4 μBq/kg	[Arp02] & ongoing work
Cryostat		38 kg				
Cu Shield		310 kg				
Small Parts		1 g/crystal	1 mBq/kg	1 mBq/kg	1 mBq/kg	[Mil92]

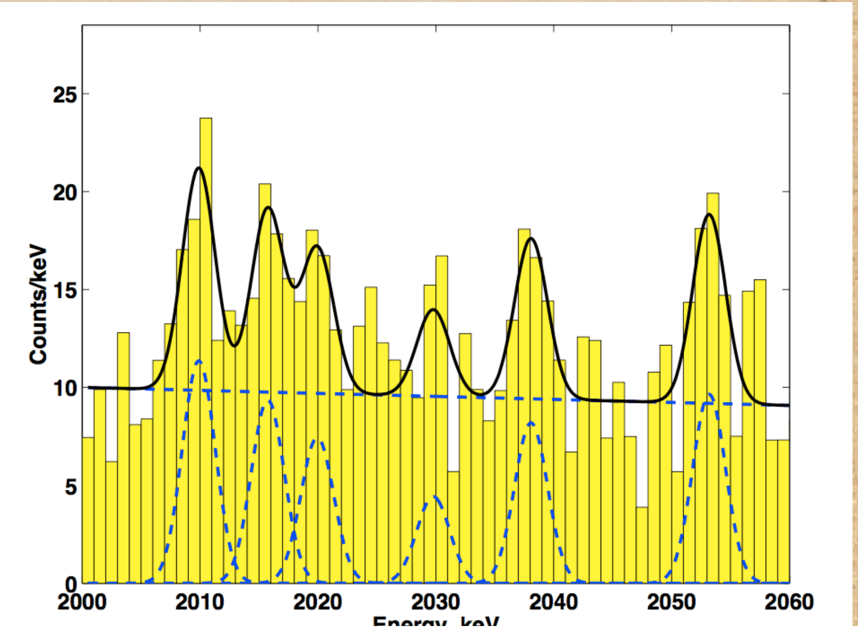
As discussed by John

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

KKDC: 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)



Expected signal in Majorana

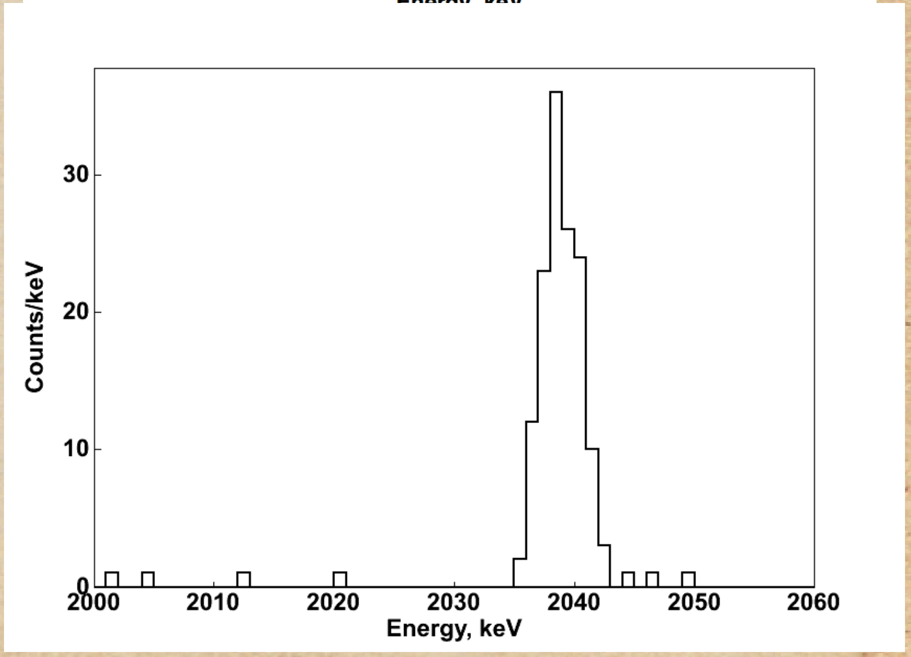
(for 0.46 t-y)

135 counts

With a background of

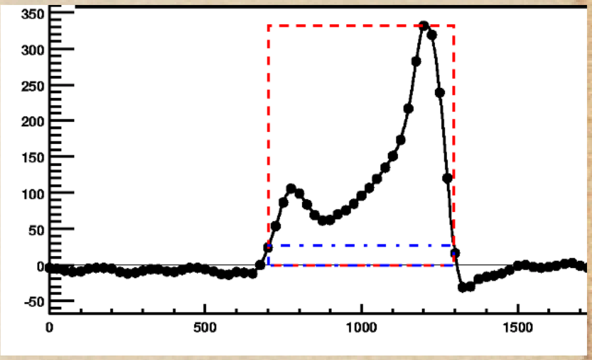
Specification: < 1 total count in the ROI

(Demonstrated < 8 counts in the ROI)



Reducing & Mitigating Backgrounds

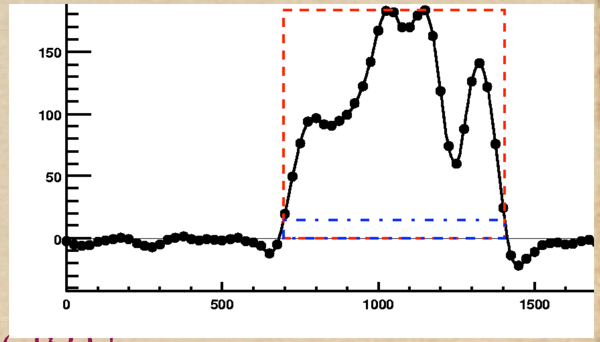
- Reduce internal, external, & cosmogenic-created activities
  - Minimize all non-source materials
  - Use of ultra-pure materials
  - Clean passive shield & active veto shield
  - Go deep — reduced μ induced activities



0νββ - a single site phenomenon

Many backgrounds - multiple site

- Invoke background rejection techniques
  - Use of discrete detectors to reject scattered background events
  - Single Site Time Correlated events (SSTC)
  - Energy resolution
  - Advanced signal processing
    - Single site event selection
      - Event Reconstruction 3-D
      - Segmented Detectors (finer multiplicity)
      - Pulse shape analysis

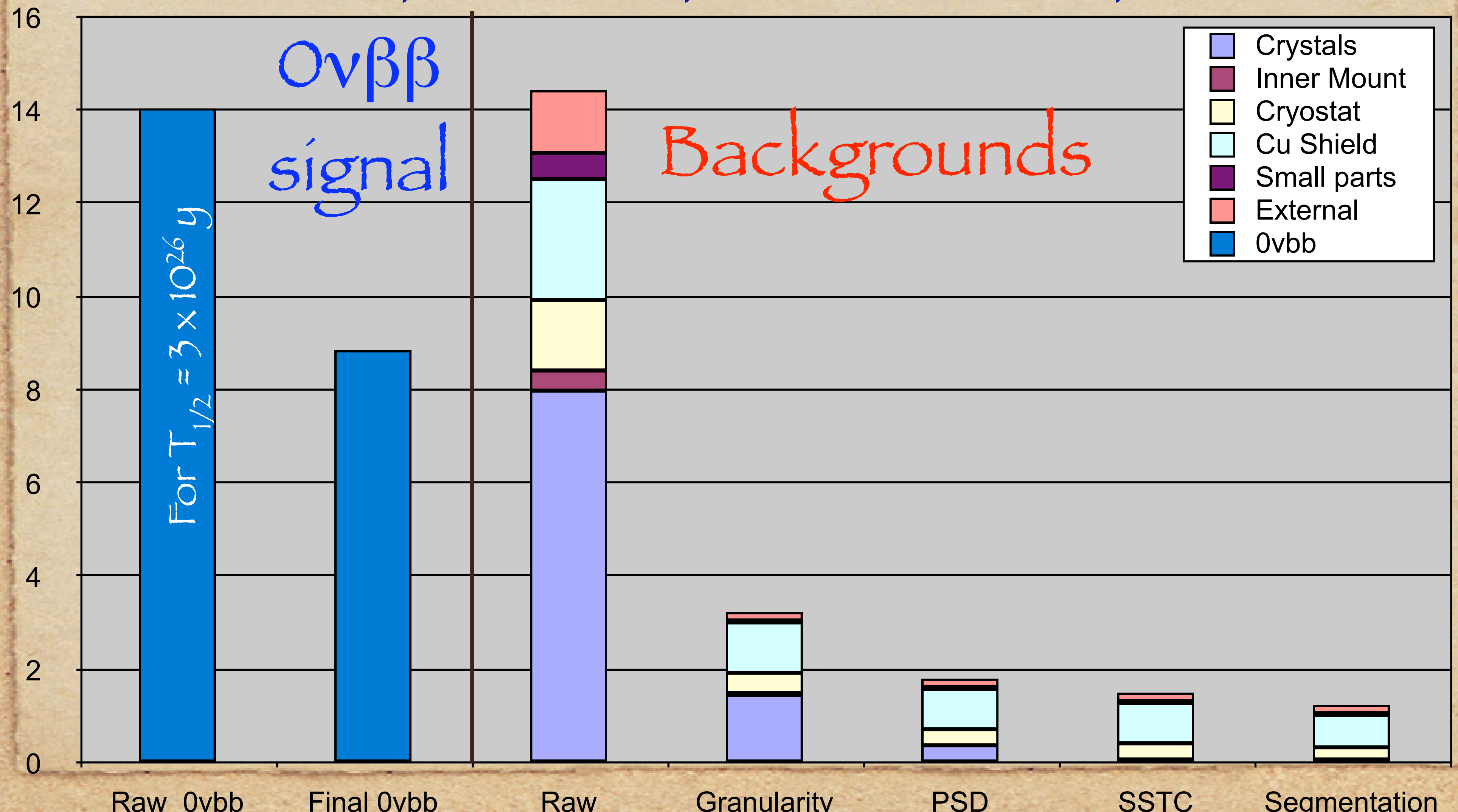


Cuts Efficiency & Background Estimates

2039 keV ROI + Analysis cuts discriminates $0\nu\beta\beta$ from backgrounds

Only known activities that occur ~ 2039 keV are from very weak branches,

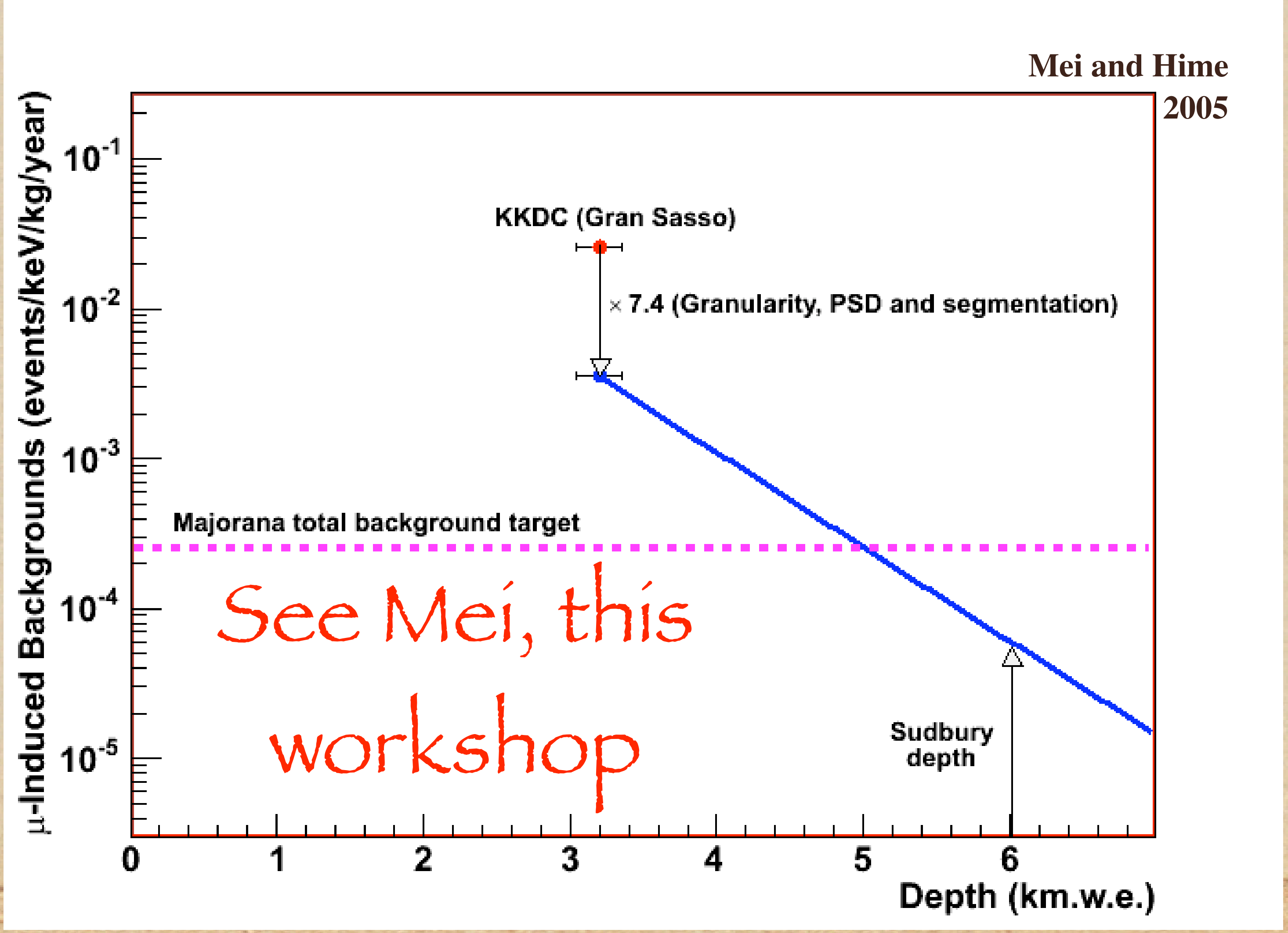
with corresponding strong peaks elsewhere in the spectrum



Influence of Depth on Backgrounds

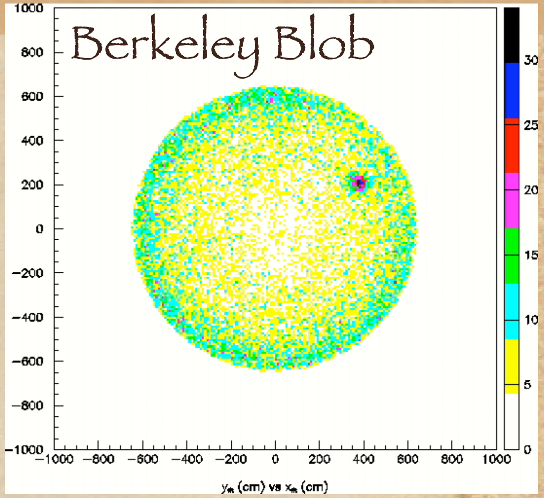
The total background target is met at ~5000 mwe, at 6000 mwe ~

15-20% of the expected background will be from μ-induced activities in Ge and the nearby cryostat materials (dominated by fast neutrons).

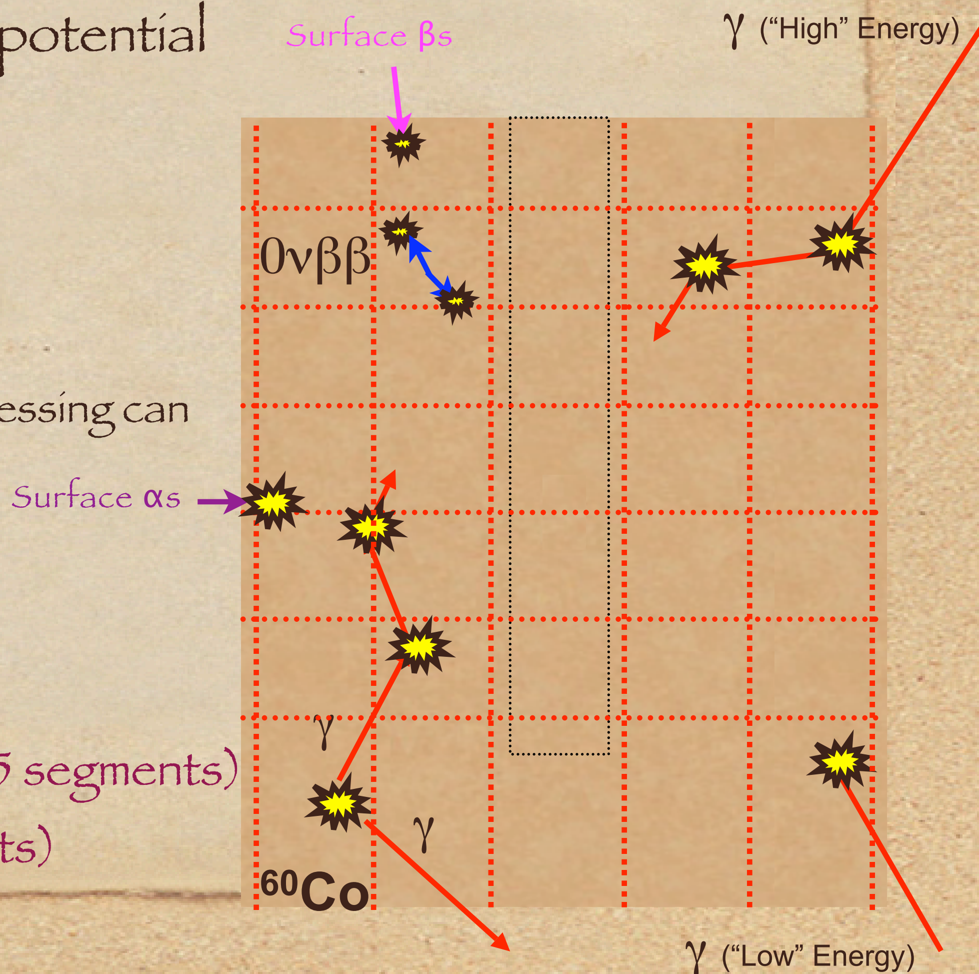


- Simulations — See Henning
  - MaGe — GEANT4 based development package with GERDA
  - Verified against a variety of Majorana low-background counting systems as well as others, e.g. MSU Segmented Ge, GERDA.
  - Fluka for μ-induced calculations, tested against UG lab data
- Assay — See Aalseth
  - Radiometric (Current sensitivity ~8 μBq/kg (2 pg/g) for ^{232}Th)
    - Counting facilities at PNNL, Oroville (LBNL), WIPP, Soudan, Sudbury
  - Mass Spect (Current sensitivity 2-4 μBq/kg (0.5-1 pg/g) for ^{232}Th)
    - Using Inductively Coupled Plasma Mass Spectrometry + tracers
    - ICPMS has the requisite sensitivity (fg/g)
    - Present limitations on reagent purity being addressed by sub-boiling distillation
    - ICPMS expected to reach needed 1 μBq/kg sensitivity
- Key specifications
  - Cu at 1 μBq/kg (currently obtained ≤ 8 μBq/kg)
  - cleanliness on a large scale (100 kg)

Crystal Segmentation & Event Reconstruction



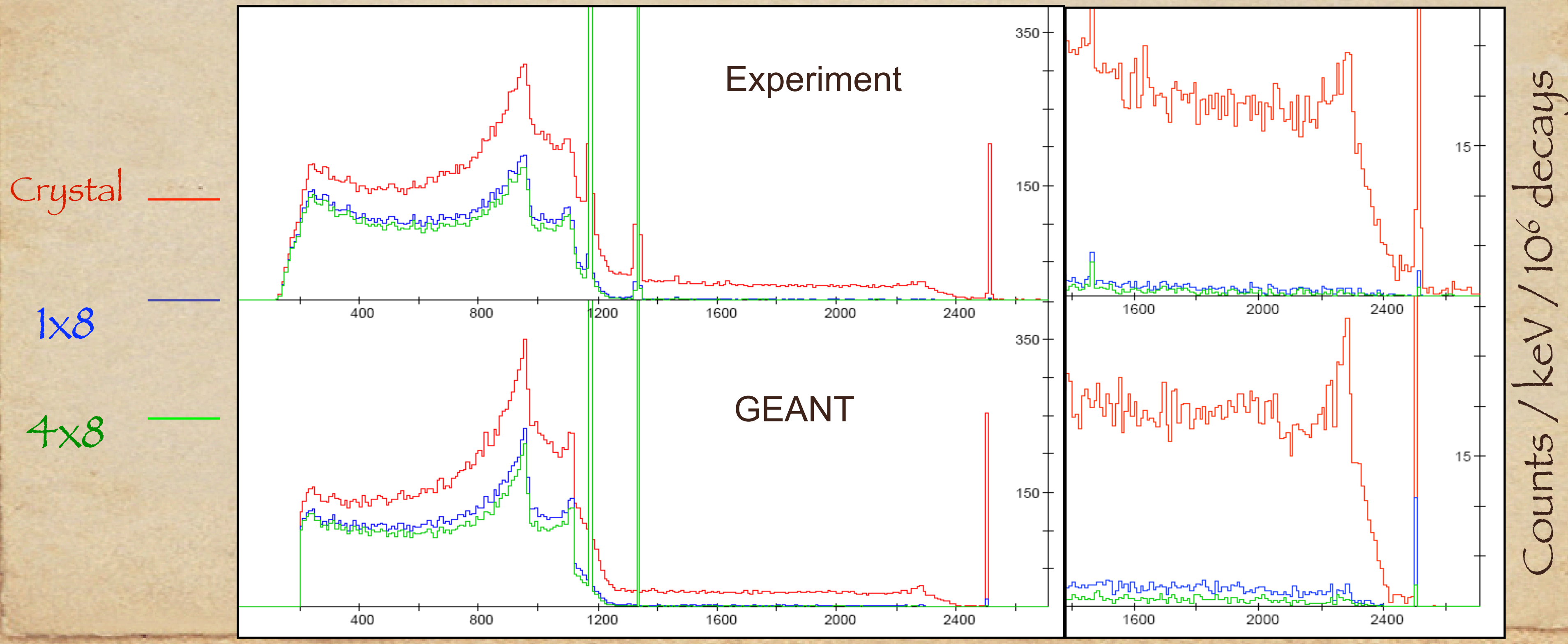
- Segmentation
  - Multiple conductive contacts
  - Additional electronics and small parts
  - Rejection greater with more segments
  - Permits multi-dimensional analysis and robust signal "tests", signal robustness
  - Analysis-based fiducial volumes and potential hot spot identification
- Background discrimination
  - Multi-site energy deposition
    - Simple two-segment rejection
    - Sophisticated multi-segment signal processing can provide ~ 2 mm events reconstruction
- Demonstrated and Verifiable
  - MSU experiment (4x8 segments)
  - LANL Clover detector (2 segments)
  - Underground LLNL+ LBNL detector (8x5 segments)
  - SEGA Isotopically enriched (2x6 segments)



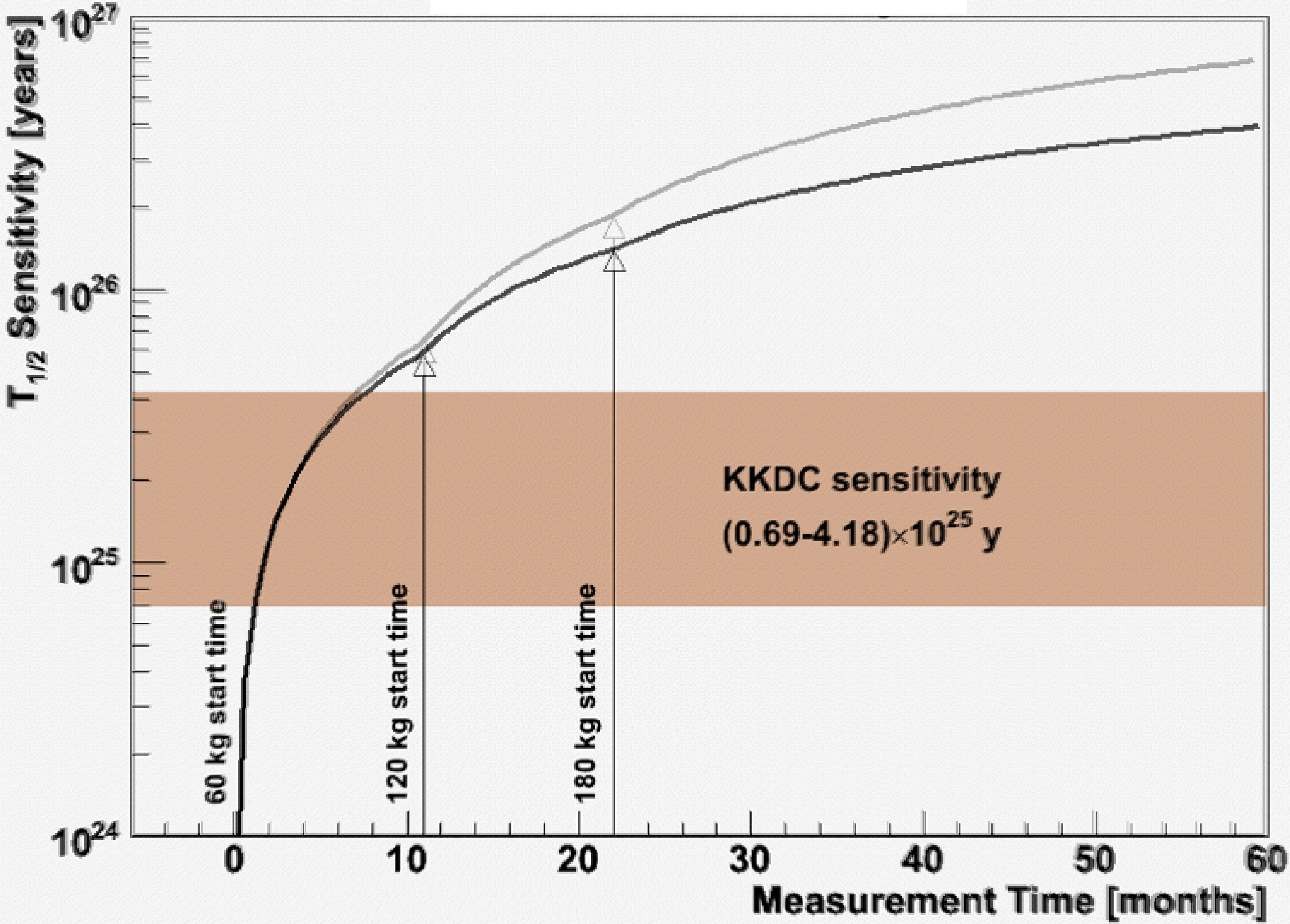
Segmentation experiment & simulation

Experiment with MSU/NSCL Segmented Ge Array

- N-type, 8 cm long, 7 cm diameter
- 4x8 segmentation scheme: 4 angular 90 degrees each, 8 longitudinal, 1 cm each
- ^{60}Co source
- Segmentation successfully rejects backgrounds.
- Data are in good agreement with the simulations



M180, 8 count/Ty



Summary

- Design is scalable to the 500-1000 kg size, once operation and backgrounds are confirmed
- Addresses $<m_\nu>$ goals in a phased approach
- Compared to best previous $0\nu\beta\beta$ experiments, M180
  - has 18 times more Ge
  - 8 times lower radioactivity
  - Improved design and detector technology should yield ~ 30 times better background rejection.
- Can reach a lifetime limit of 5.5×10^{26} y (90% CL) corresponding to a neutrino mass of 100 meV or perform a 10% measurement assuming a 400 meV value with 180 kg and 3 years
- Detector designs permit multi-dimensional background rejection and signal robustness tests - not just (E, t), anymore, (E, t, z ,r, φ)

The Majorana Collaboration

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