The *Majorana* Neutrinoless Double-Beta Decay Experiment

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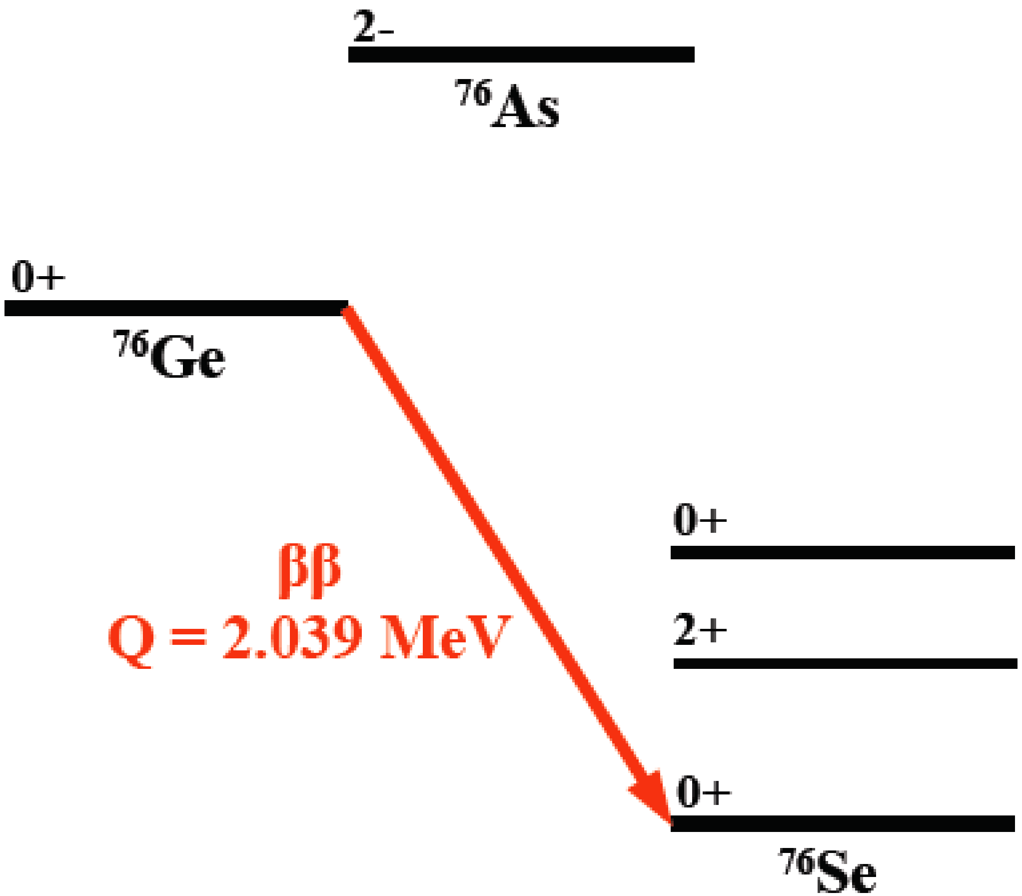
ββ Decay in ^{76}Ge



$$\Gamma^{0\nu} = G^{0\nu} \left| M^{0\nu} \right|^2 \langle m_\nu \rangle^2$$

$$G^{0\nu} = 0.30 \times 10^{-25}\ \mathrm{y}^{-1}\,\mathrm{eV}^{-2} \quad [1]$$

$$M^{0\nu} = 1.5 - 2.4 \quad [2]$$

$$T_{1/2}^{2\nu} = (1.3 \pm 0.1) \times 10^{21}\ \mathrm{y} \quad [3]$$

[1] F. Simkovic *et al*., Phys. Rev. C **60**, 055502 (1999).
[2] V.A. Rodin *et al.*, Nucl. Phys. A **766**, p. 107 (2006).
[3] C.E. Aalseth *et al.*, Nucl. Phys. B Proc. Supp. **48**, 223 (1996); F.T. Avignone *et al.*, Phys. Lett. B **256**, 559 (1991); H.V. Klapdor-Kleingrothaus *et al.*, Eur. Phys. J. A **12**, 147 (2001).

Germanium Detectors

- Source = Detector
- Intrinsically high purity, elemental Ge
- Demonstrated ability to enrich to 86% ^{76}Ge
- 0.16% energy resolution at 2039 keV
- Well-understood technologies
  - Commercial Ge diodes
  - Large Ge arrays (GRETINA, Gammasphere)
- Powerful background rejection
- Best limits on 0νββ: $T_{1/2}^{0\nu} > 1.9 \times 10^{25}$ y (90% CL) [1]

[1] H.V. Klapdor-Kleingrothaus *et al.*, Eur. Phys. J. A **12**, p. 147 (2001).

Majorana Science Goals

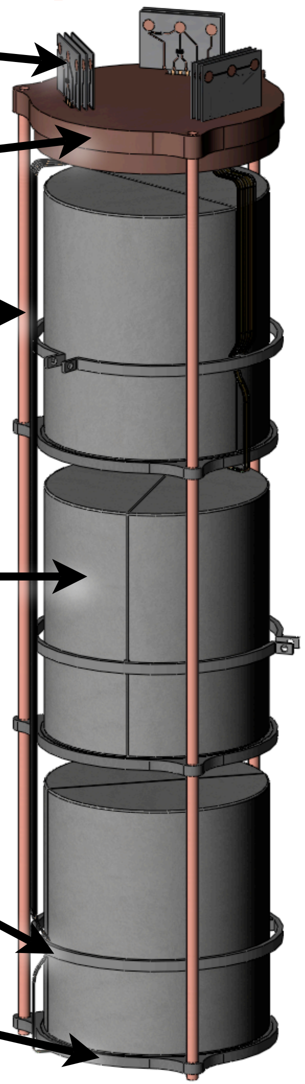
- Probe the quasi-degenerate neutrino mass region above 100 meV
- Demonstrate background levels that would justify scaling up to a 1 ton or larger experiment
- If the Klapdor-Kleingrothaus claimed observation of $0\nu\beta\beta$ in ^{76}Ge is confirmed, do a precision measurement of the decay rate (20%)

Majorana Overview

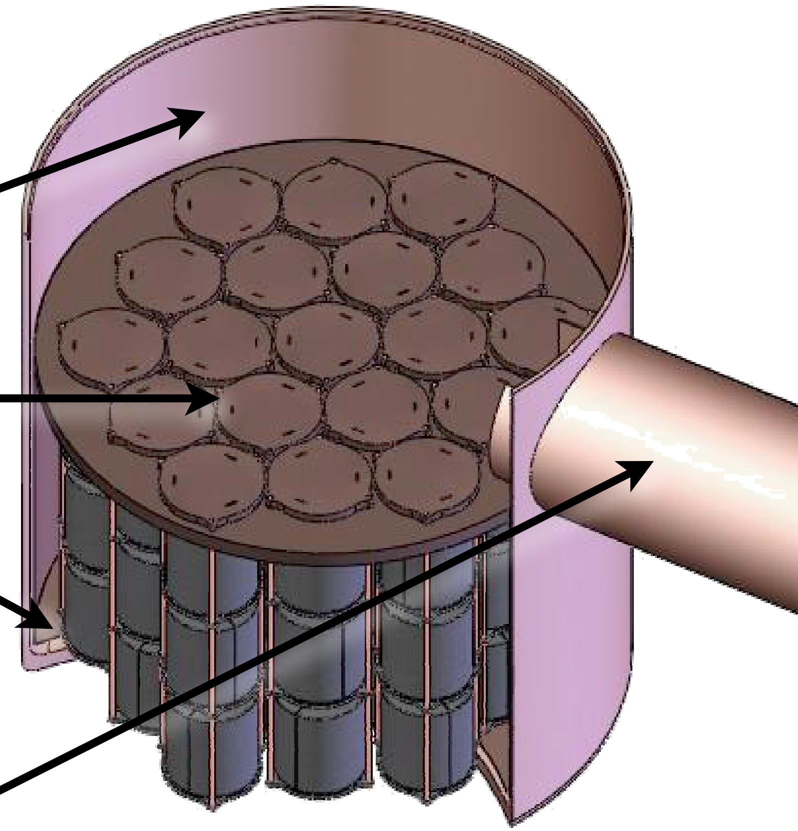
- Modules of 57 close-packed, 1.1 kg, segmented n-type HPGe detectors enriched to 86% ^{76}Ge
- Independent cryostats made of ultra-clean electroformed Cu
- Low background passive lead + electroformed Cu shield and 4π active veto
- Located deep underground (4500-6000 mwe)

60 kg Modules

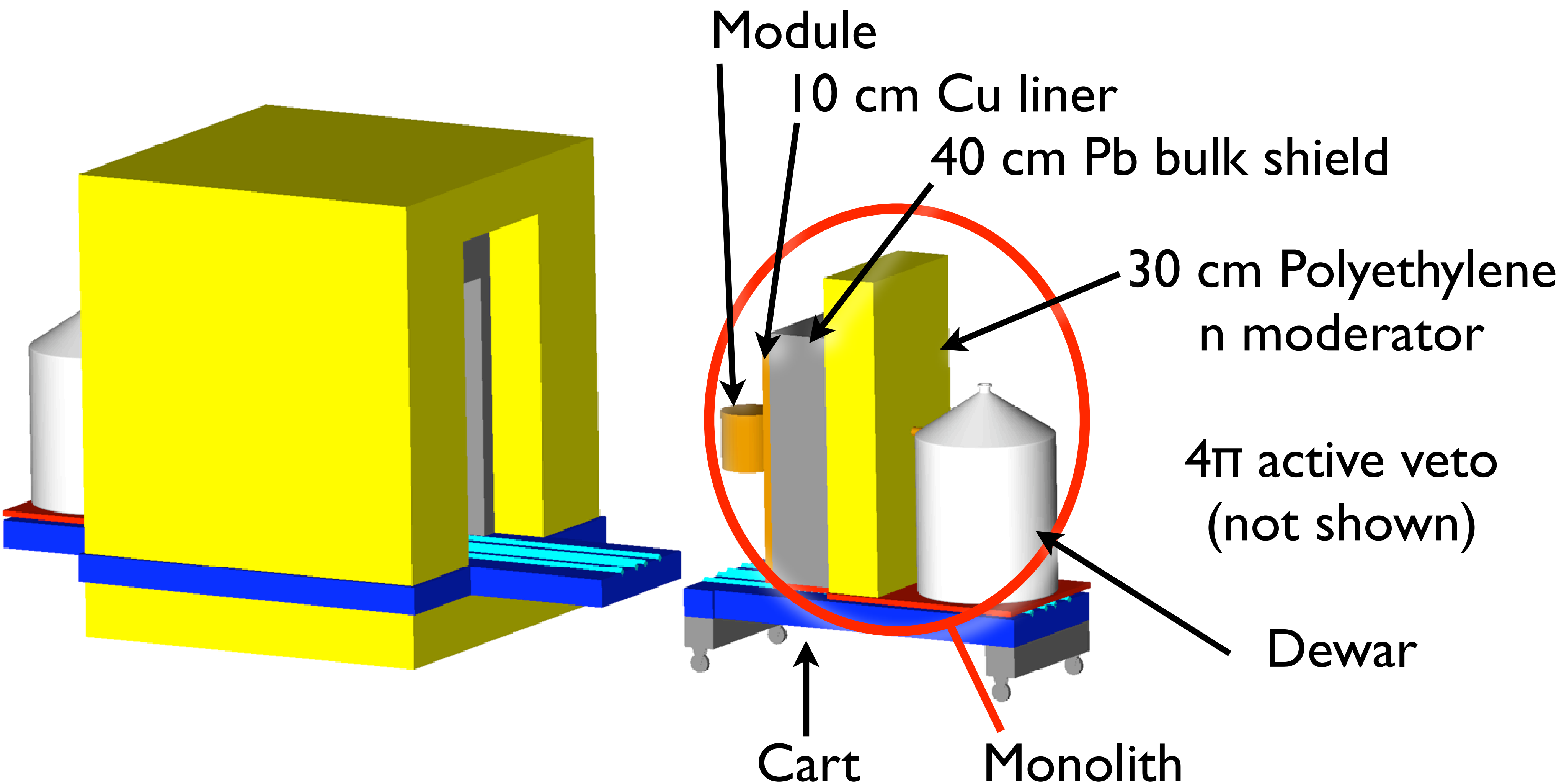
3-crystal string



57-crystal module



Passive and Active Shielding

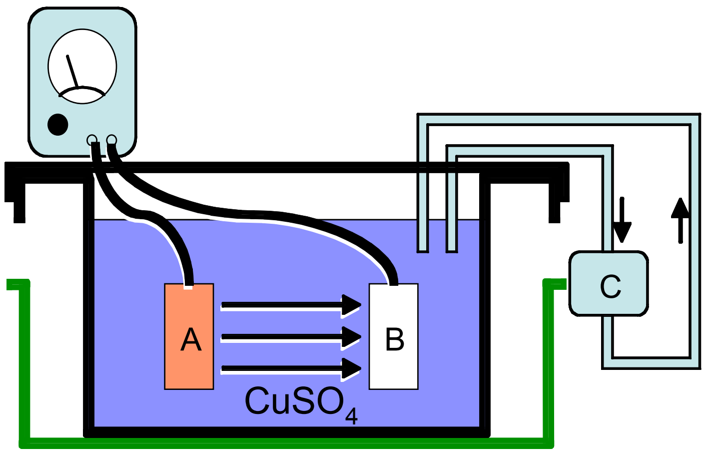


Backgrounds

- Intrinsic
  - Natural radioactivity (U, Th, Rn)
  - Anthropogenic (esp. surface contamination)
  - $2\nu\beta\beta$ (high resolution → negligible)
- Cosmogenic
  - Primary cosmic rays
  - Spallation neutrons
  - Cosmogenic radioisotopes

Background Goal: 1 event / ton-year in 4 keV ROI

Ultrapure Materials: Electroformed Copper



- Semiconductor-grade acids, recrystallized $CuSO_4$, high-purity copper stock
- Baths circulated with microfiltration, barium scavenge; cover gas
- Active plating manipulation, surface machining, cleaning, and passivation

- ^{232}Th < 1 μBq/kg
- Recently improved bath chemistry: requires less surface finishing
- Improved starting stock quality and handling

Background Rejection: Granularity

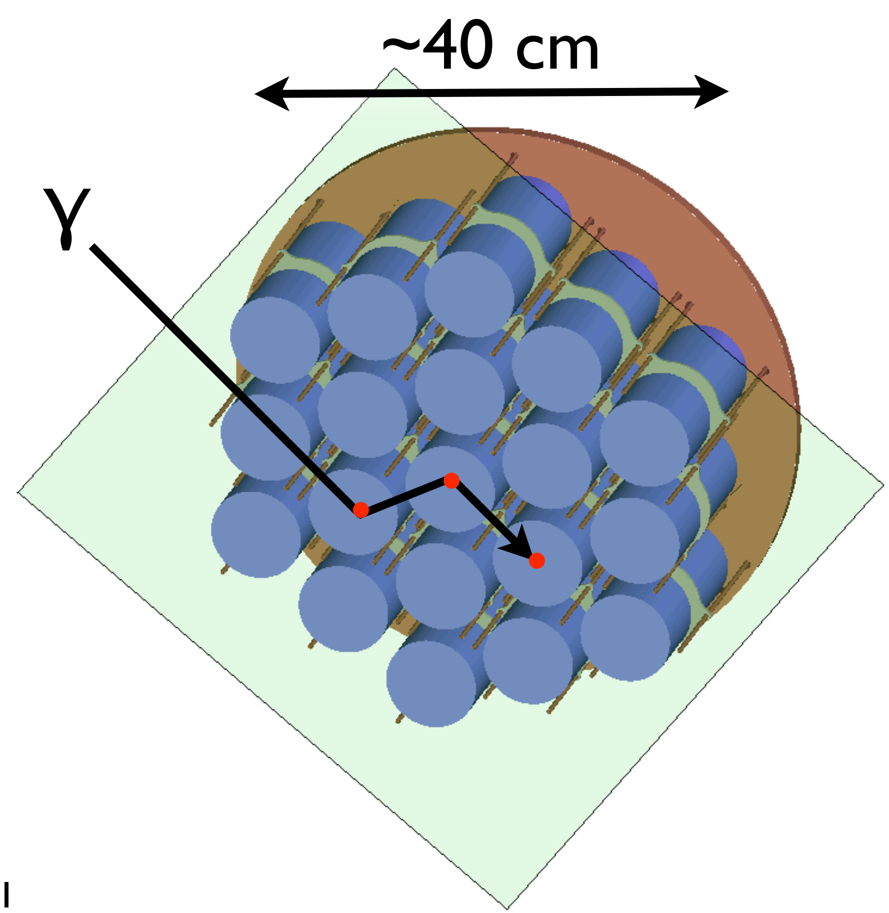
Simultaneous hits in >1 detector cannot be $0\nu\beta\beta$

Effective for:

- High energy external γ's, e.g. ^{208}Tl and ^{214}Bi (2x-5x reduction)

- Some neutrons

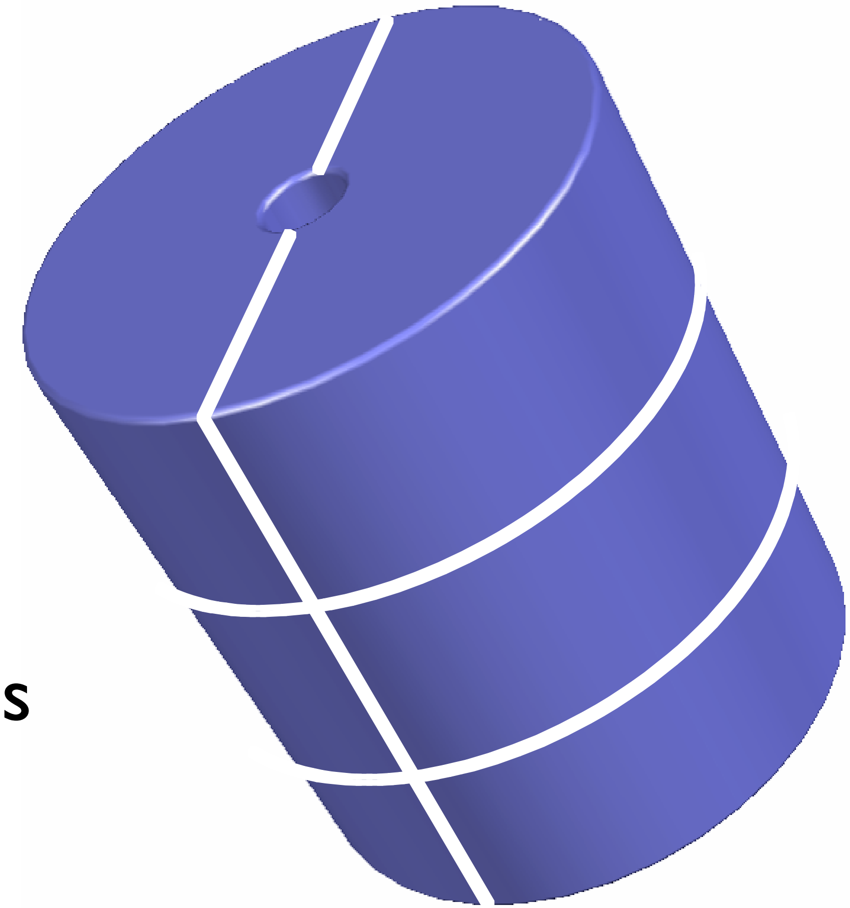
- Muons (10x)



Background Rejection: Segmentation

Simultaneous hits in >1 segment cannot be $0\nu\beta\beta$

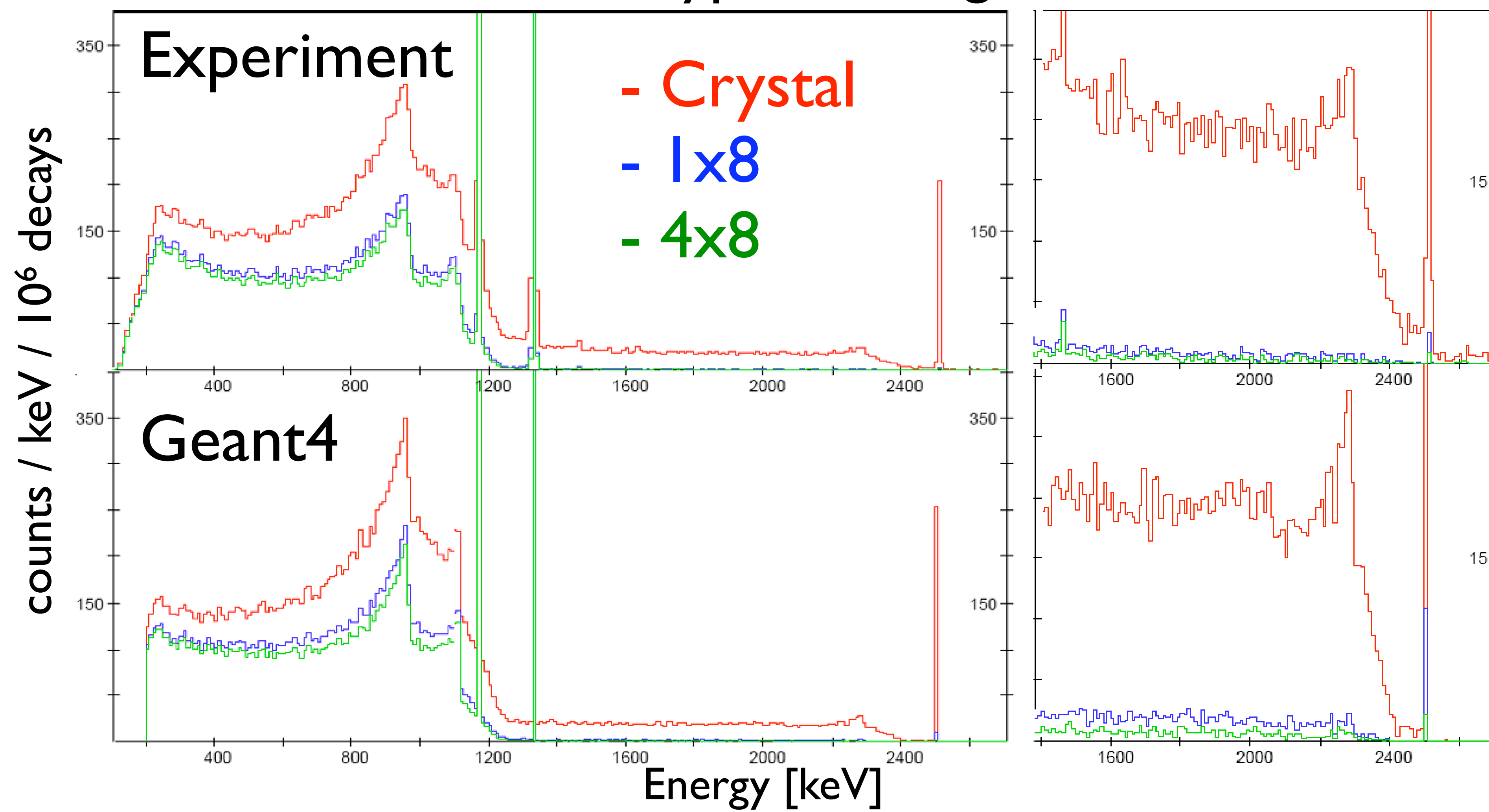
- Rejects multi-site events distributed in z and φ
- Effective against internal γ's (2x-5x reduction)
- Requires additional electronics and small parts



Background Rejection: Segmentation

MSU/NSCL segmented Ge array, ^{60}Co source

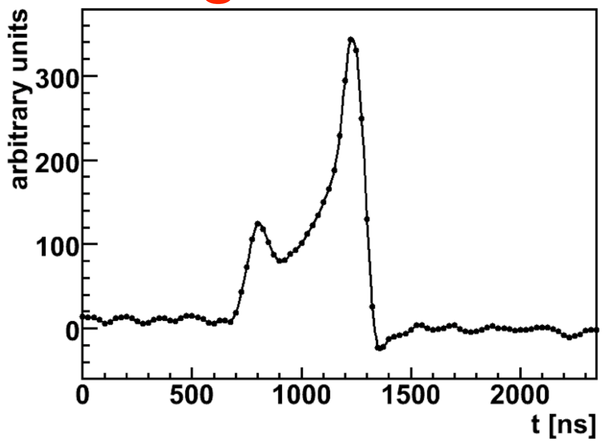
7 cm x 8 cm n-type, 4x8 segmentation



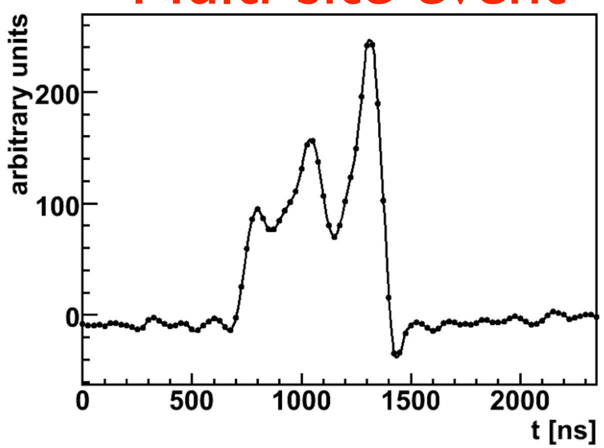
Background Rejection: Pulse Shape Discrimination

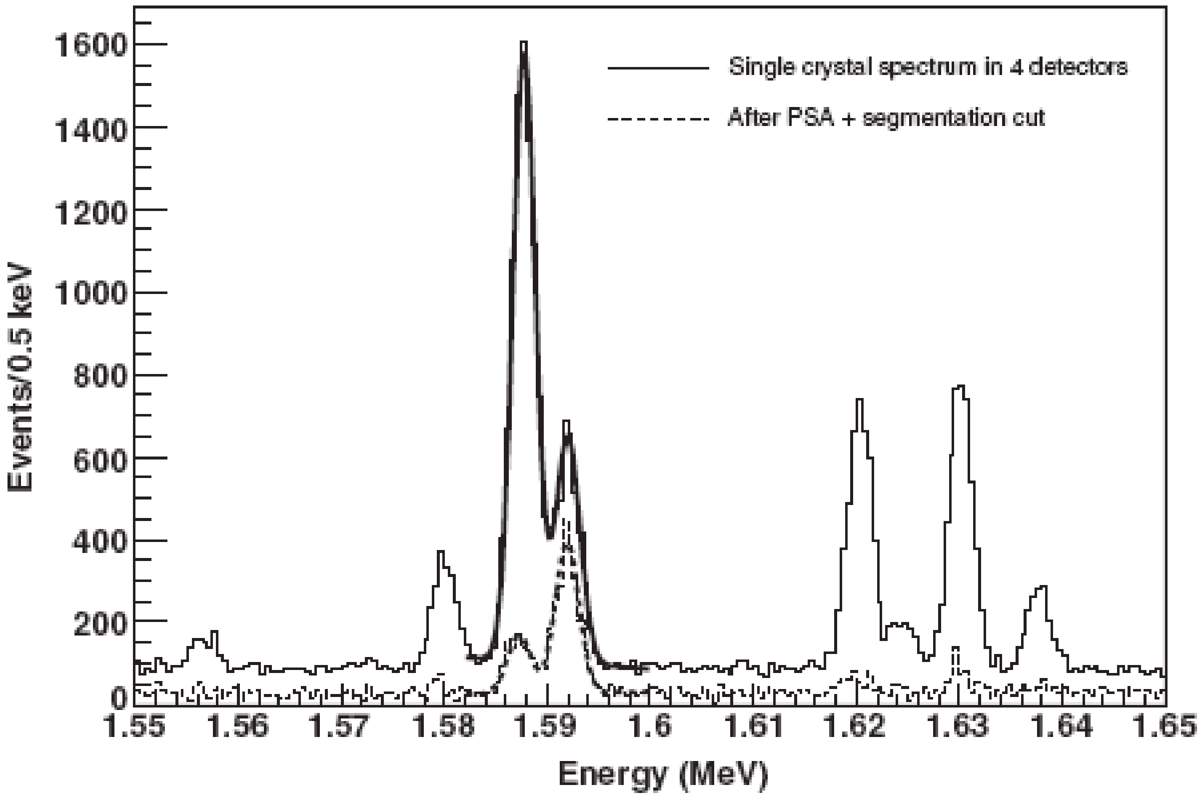
S.R. Elliott *et al.*, NIM A **558**, 504 (2006).

Single-site event



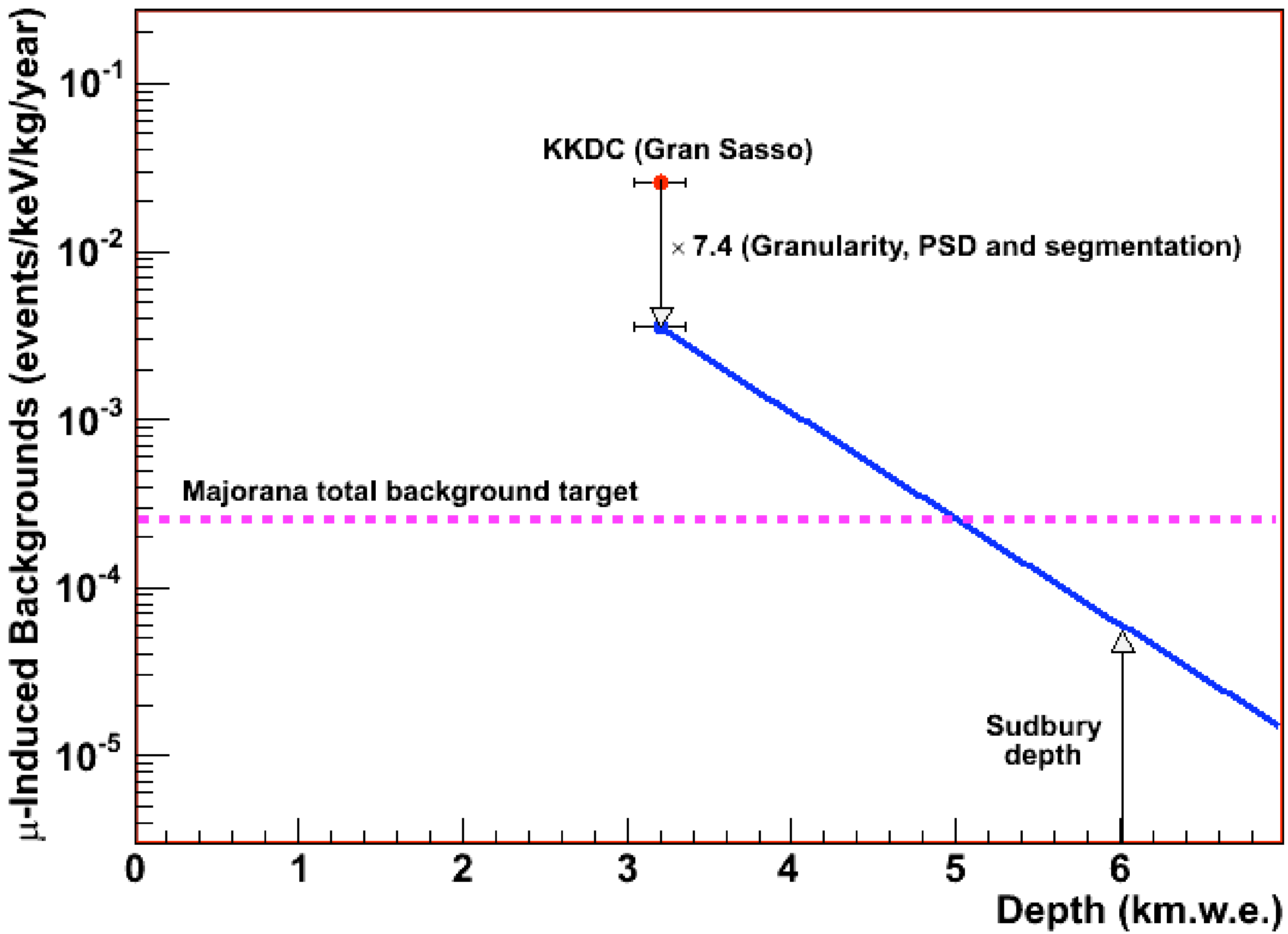
Multi-site event





- Rejects multi-site events distributed in *r*
- Effective against internal γ's (2x-5x reduction)
- Requires high bandwidth digitization

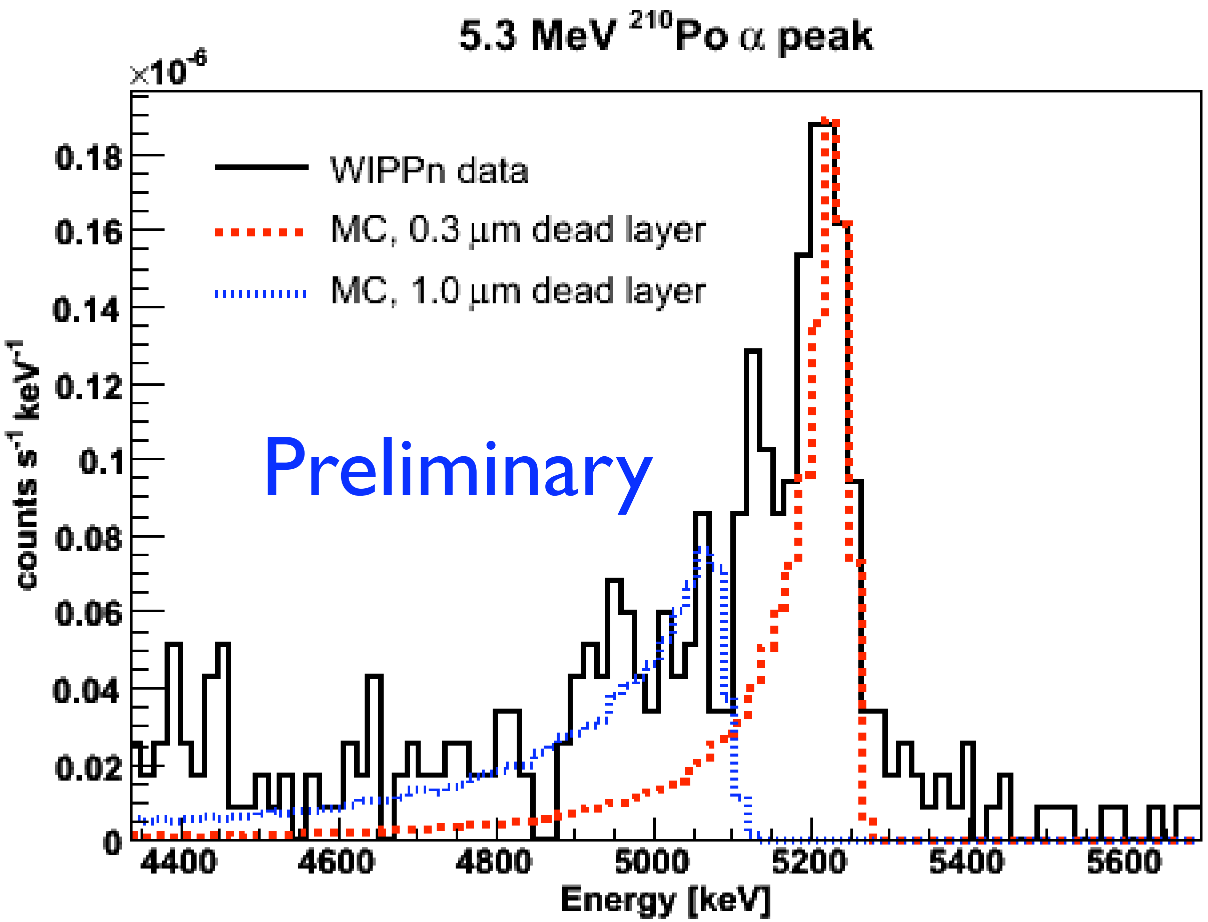
Cosmogenic Backgrounds

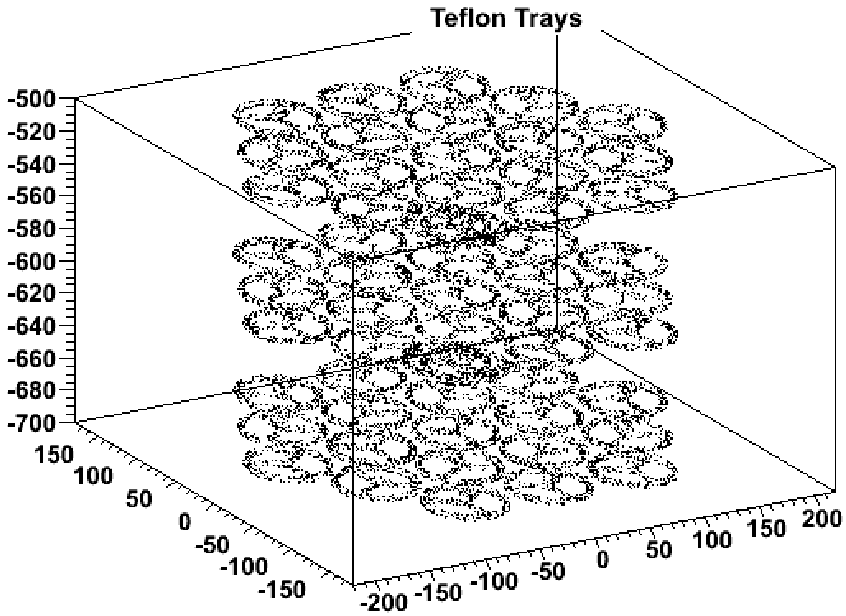


D.-M. Mei and A. Hime, Phys. Rev. D **73**, 053004 (2006).

Surface Contamination Simulations

- Generate decays uniformly on all component surfaces
- Extract cleanliness / QC requirements, feedback into design considerations





Materials Specifications

Location	Purity Issue	Exposure	Activation Rate	Equiv. Achieved Assay	Reference
Germanium	^{68}Ge, ^{60}Co	100 d	1 atom/kg/day		[Avi92]
		Component Mass	Target Purity		
Inner Mount	^{208}Tl in Cu ^{214}Bi in Cu	2 kg	0.3 μBq/kg 1.0 μBq/kg	0.7-1.3 μBq/kg	Current work also [Arp02]
Cryostat	^{210}Tl in Cu ^{214}Bi in Cu	38 kg	0.1 μBq/kg 0.3 μBq/kg	0.7-1.3 μBq/kg	Current work also [Arp02]
Cu Shield	^{208}Tl in Cu ^{214}Bi in Cu	310 kg	0.1 μBq/kg 0.3 μBq/kg	0.7-1.3 μBq/kg	Current work also [Arp02]
Small Parts	^{208}Tl in Cu ^{214}Bi in Cu	1 g/crystal	30 μBq/kg 100 μBq/kg	1000 μBq/kg	

Background Summary

Background Source		Rates for Important Isotopes cnts/ROI/t-y				Total Est. Background cnts/ROI/t-y
		^{68}Ge	^{60}Co			
Germanium	Gross: Net:	2.54 0.02	1.22 0.06			0.08
		^{208}Tl	^{214}Bi	^{60}Co		
Inner Mount	Gross: Net:	0.12 0.01	0.03 0.00	0.26 0.00		0.01
Cryostat	Gross: Net:	0.49 0.14	0.48 0.12	0.58 0.00		0.26
Copper Shield	Gross: Net:	1.39 0.39	0.55 0.11	0.02 0.00		0.50
Small Parts	Gross: Net:	0.45 0.05	0.68 0.17	0.34 0.00		0.22
Surface Alphas	All surfaces:					0.36
		muons	cosmic activity	gammas	(α, n)	
External Sources	Gross: Net:	0.03 0.003	1.50 0.21	0.05 0.05	0.06 0.06	0.32
$2\nu\beta\beta$						<0.01
Solar ν						0.01
Atm. ν						0.02
		TOTAL SUM				1.75

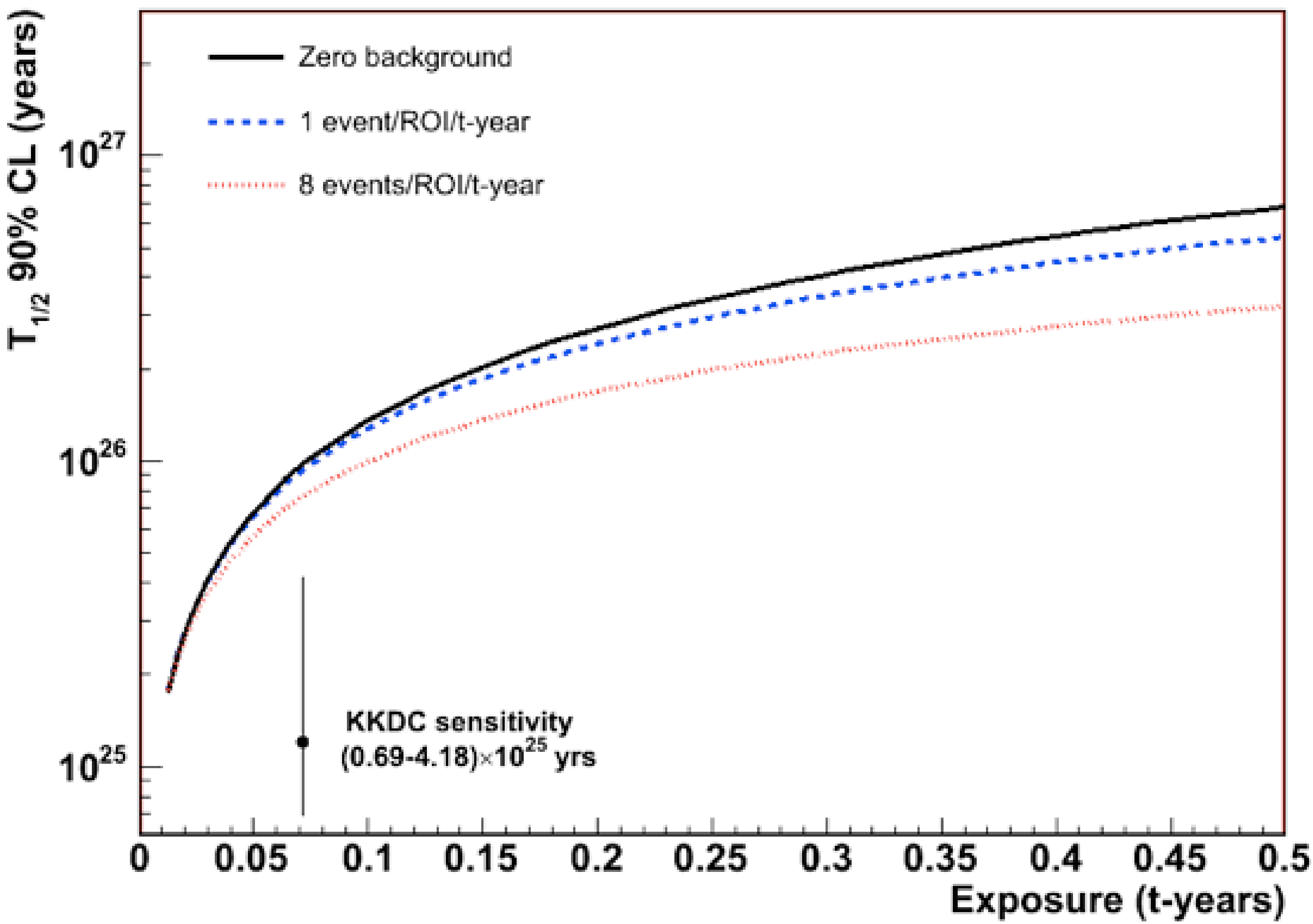
Crystals are clean (Germanium)

Dominated by ^{232}Th in Cu (Cryostat, Copper Shield)

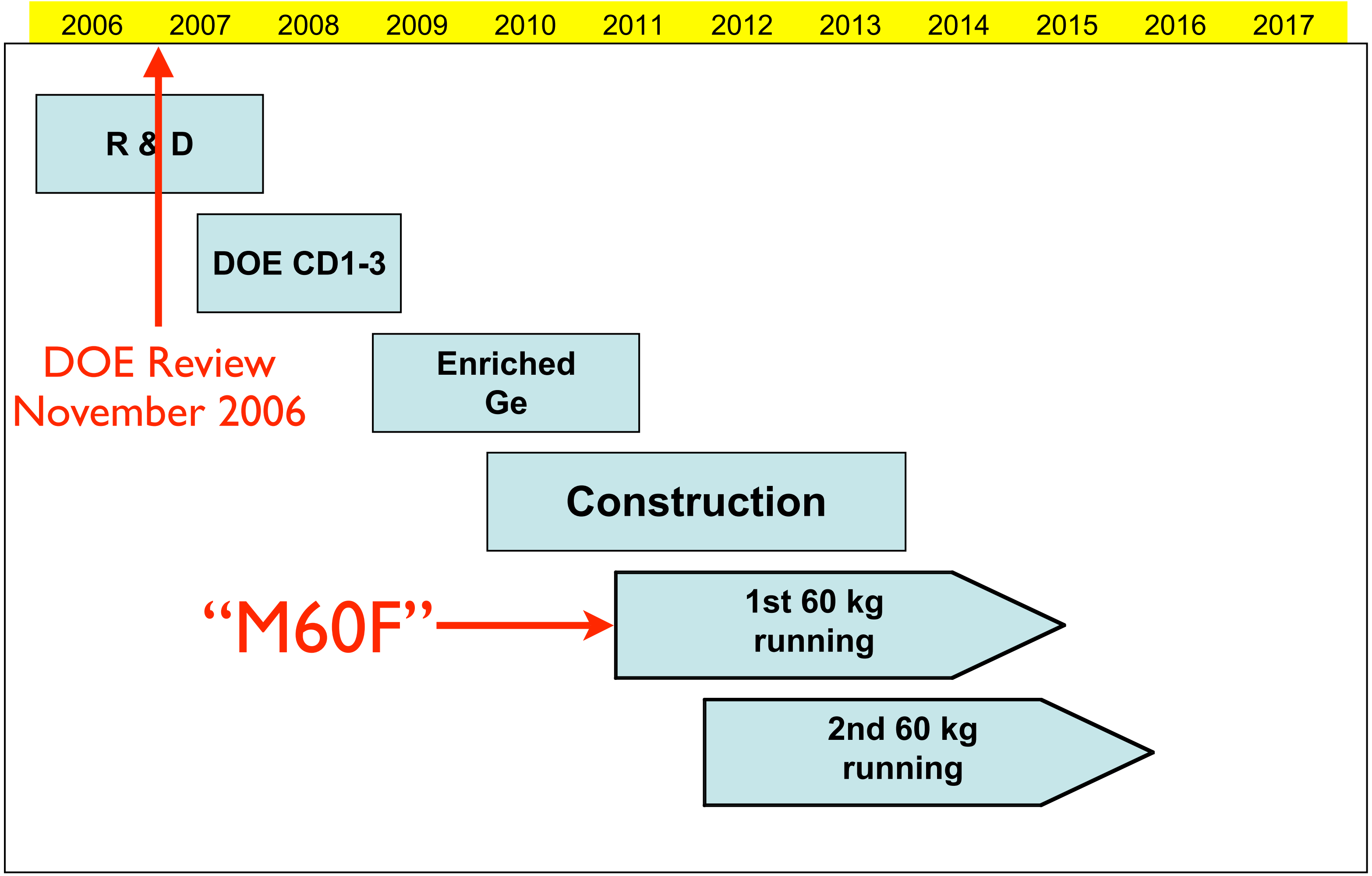
Requires QC (Surface Alphas)

Must go deep (External Sources)

Majorana Sensitivity



Schedule
(assuming two modules)

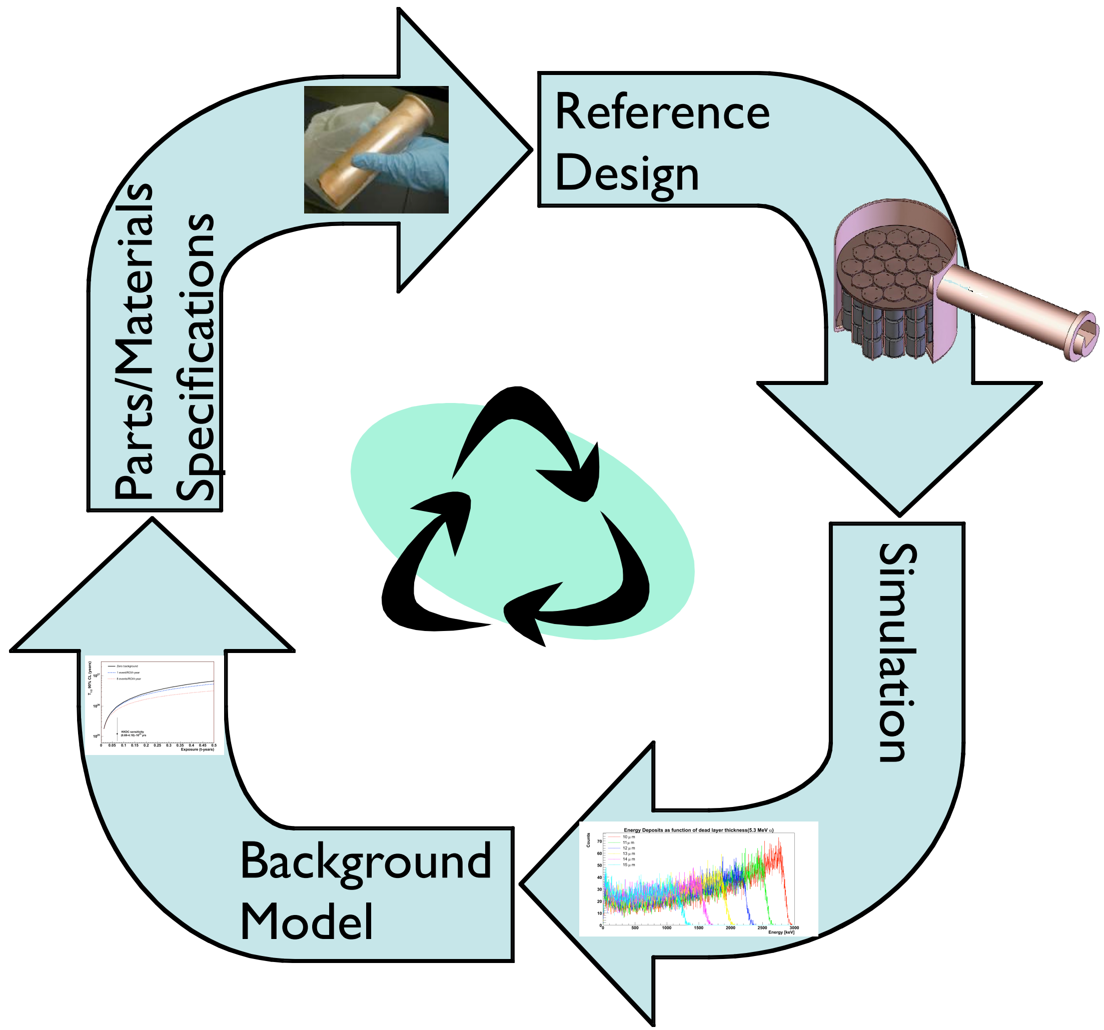


Our schedule is constrained by the requirement to follow the DOE "413" capital acquisition process.

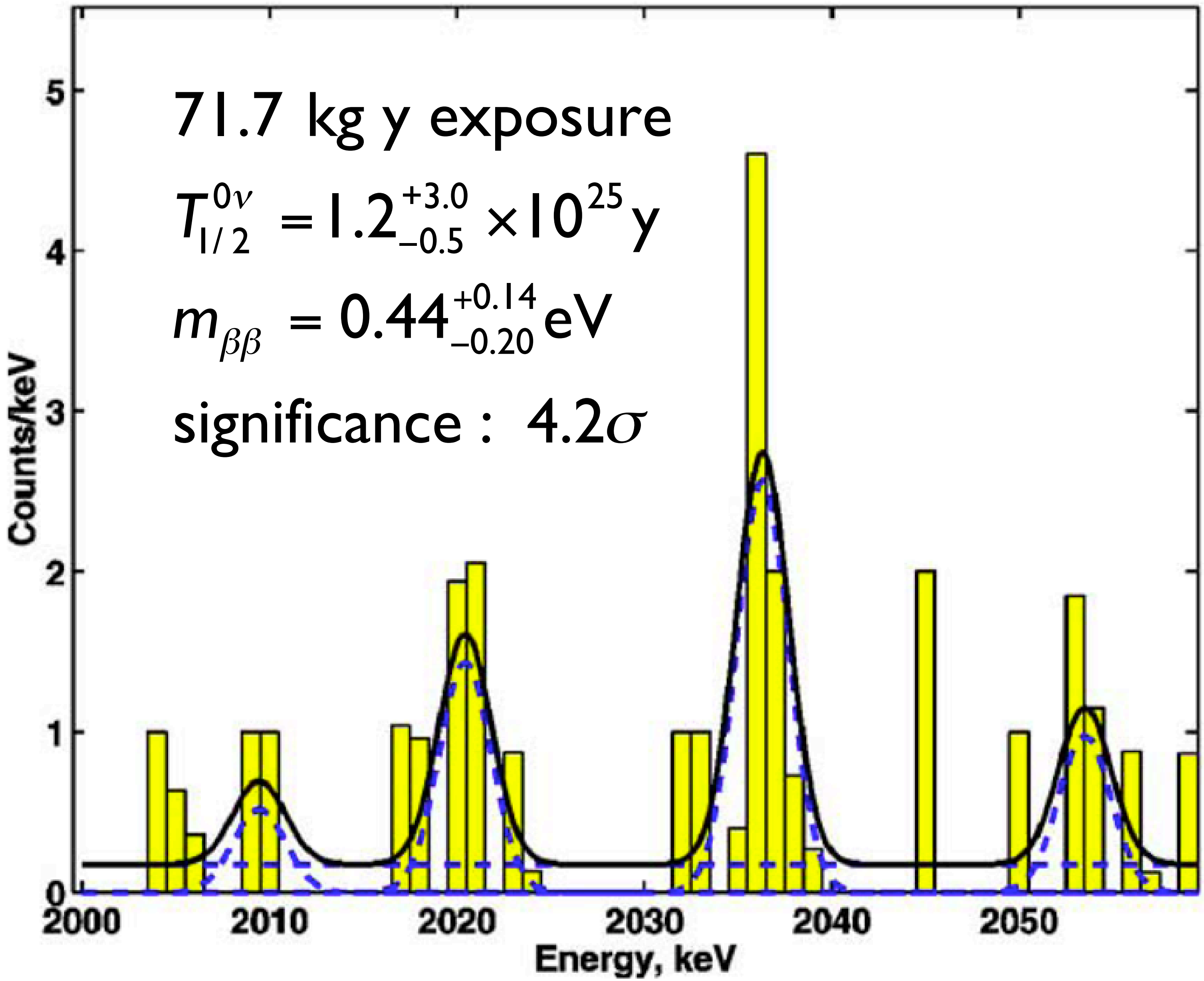
Summary

- Reference design based on demonstrated, scalable technology
- Modular approach, emphasis on fast deployment of first 60 kg module
- Goal: ~150 times lower background (after analysis cuts) compared to previous ^{76}Ge experiments
- 3 years with M60F can achieve 90% CL sensitivity to a $0\nu\beta\beta$ lifetime of 2.1×10^{26} y ($m_{\beta\beta} \sim 200$ meV)
- Received NuSAG recommendation in 2005
- In November 2005 approved by DOE NP to proceed with R&D and Conceptual Design activities (tied to DOE CD-0 for double-beta decay)
- Extensive collaboration experience with ββ-decay experiments and low background, large neutrino detectors
- Good communication and cooperation with GERDA (esp. joint simulation effort "MaGe"); LoI to combine for a future 1 ton scale experiment

Iterative Design Process

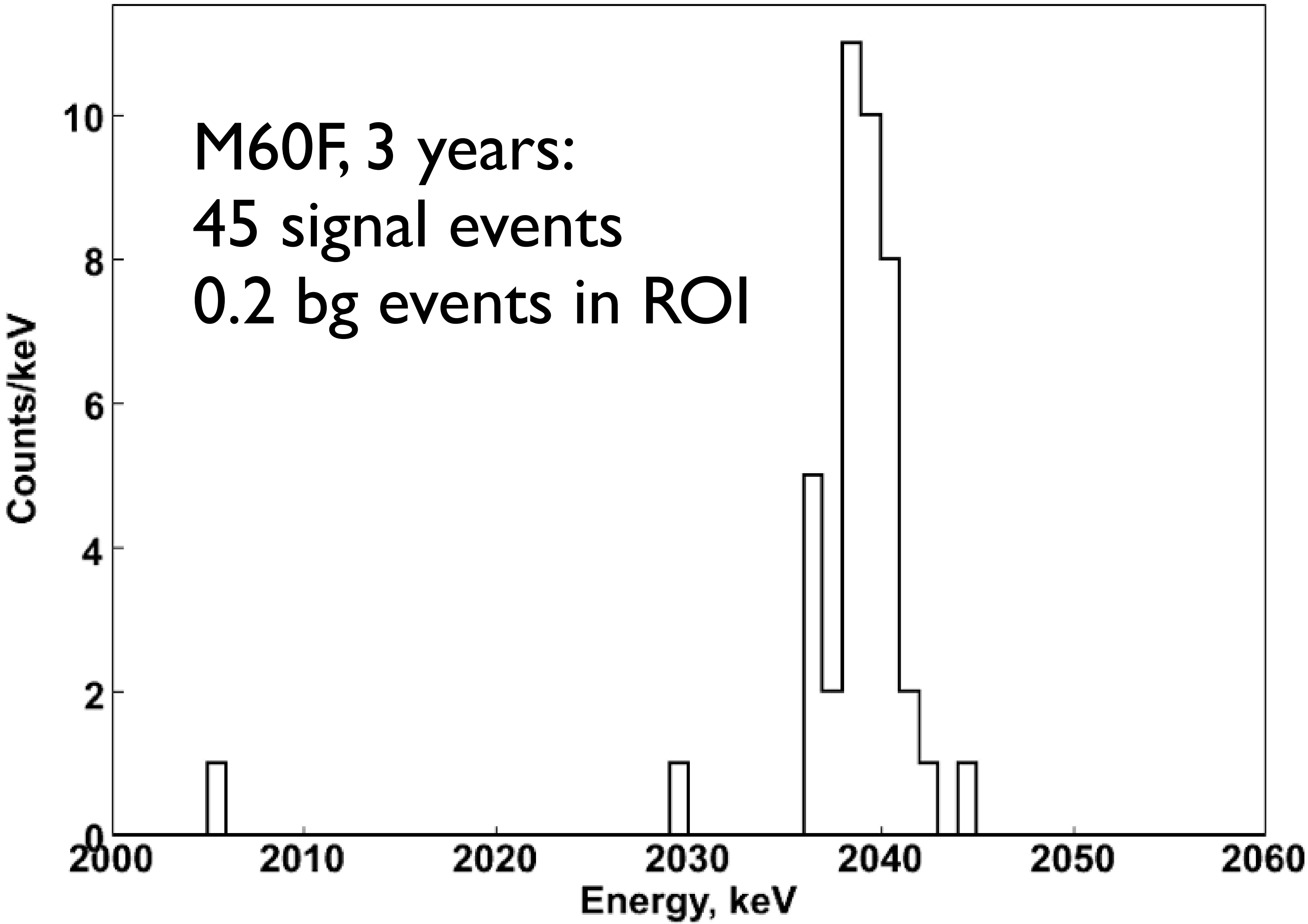


Sensitivity to KKDC Signal

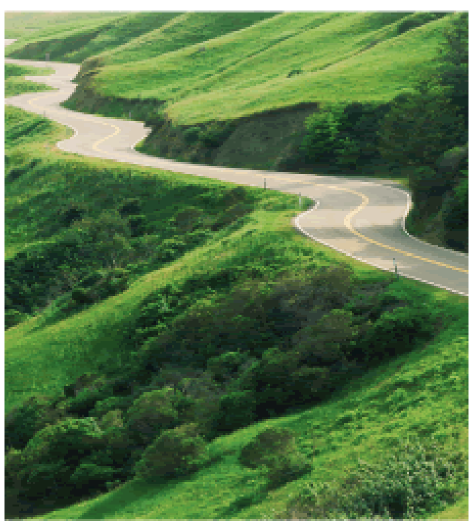


H.V. Klapdor-Kleingrothaus *et al.*, Phys. Lett. B **586**, p. 198 (2004).

Sensitivity to KKDC Signal



Where Are We in the Process?



- 2000-2001 NP Long-range plan
- Sept. 2001 - Majorana Charter (7 institutions)
- Mar. 2002 - Majorana Discussions with DOE NP
- Sept. 2003 - White Paper & DOE NP discussions
- Nov. 2003 - Office of Science 20 year Future Facilities
- Nov. 2004 - APS Multidivisional Neutrino Study
- May 2005 - NSAC NuSAG Review
- Sept. 2005 - NuSAG Report "high-priority for funding
- Nov. 2005 DOE CD-0 for generic bb-decay
  - Permission to redirect DOE funds to R&D
- Mar. 2006 - Successful External Panel Review
- Nov. 2006 - DOE NP ββ-decay Review

Backgrounds Compared to Other Experiments

Expt	Isotope	Active Mass (kg)	Backgrounds (after cuts) cnt/kev/t-y	Backgrounds (after cuts) cnt/ROI/t-y	2.8s "ROI" width (keV)	Sigma (keV)	Eo (keV)	Res. At the peak (FWHM)	Backgrounds before cuts cnt/kev/t-y
EXO200	^{136}Xe	160	1.1	87.5	79.2	39.616	2476	3.77%	
CUORE	^{130}Te	206	1	7	7	2.5	2533	0.20%	
GERDA	^{76}Ge	34.3	2	8	4	1.386	2039	0.16%	
Majorana	^{76}Ge	51.6	0.4	1.6	4	1.386	2039	0.16%	
KKDC	^{76}Ge	11	60.00	240.00	4	1.386	2039	0.16%	113.00

Notes:

KKDC - backgrounds BEFORE cuts is 113.00 cnt/kev/t-y from Physics Letters B 586 (2004) 198–212
KKDC - backgrounds after cuts come from Eur. Phys. J. **A 12**, 147–154 (2001). The data set included 35.5 kg y and the background index in the energy region between 2000– 2080 keV is (0.06±0.01) events/(kg y keV)

EXO gives resolution in sigma/E of 1.6%

CUORE gives sigma value of 2.5 (larger than calculated from their typical resolution, 2.15)

Comparison of Sensitivity and Timescales

Expt	Isotope	Active Mass (kg)	Detector Mass	2013 3 sigma $<m_\nu>$ meV	Exposure in 2013	Expt. Start	90% CL $<m_\nu>$ meV	Backgrounds (after cuts) cnt/kev/t-y
EXO200	^{136}Xe	160	200 Kg (80% enriched)	260	800	2008	220	1.1
CUORE	^{130}Te	206	750 kg (34.1% nat)	240	618	2010		1
GERDA	^{76}Ge	34.3	40 kg (86% enriched)	330	171.5	2008	230	2
Majorana	^{76}Ge	51.6	60 kg (86% enriched)	300	154.8	2010	200	0.4
KKDC	^{76}Ge		60 kg (86% enriched)					60.00