The *Majorana* Neutrinoless Double-Beta Decay Experiment

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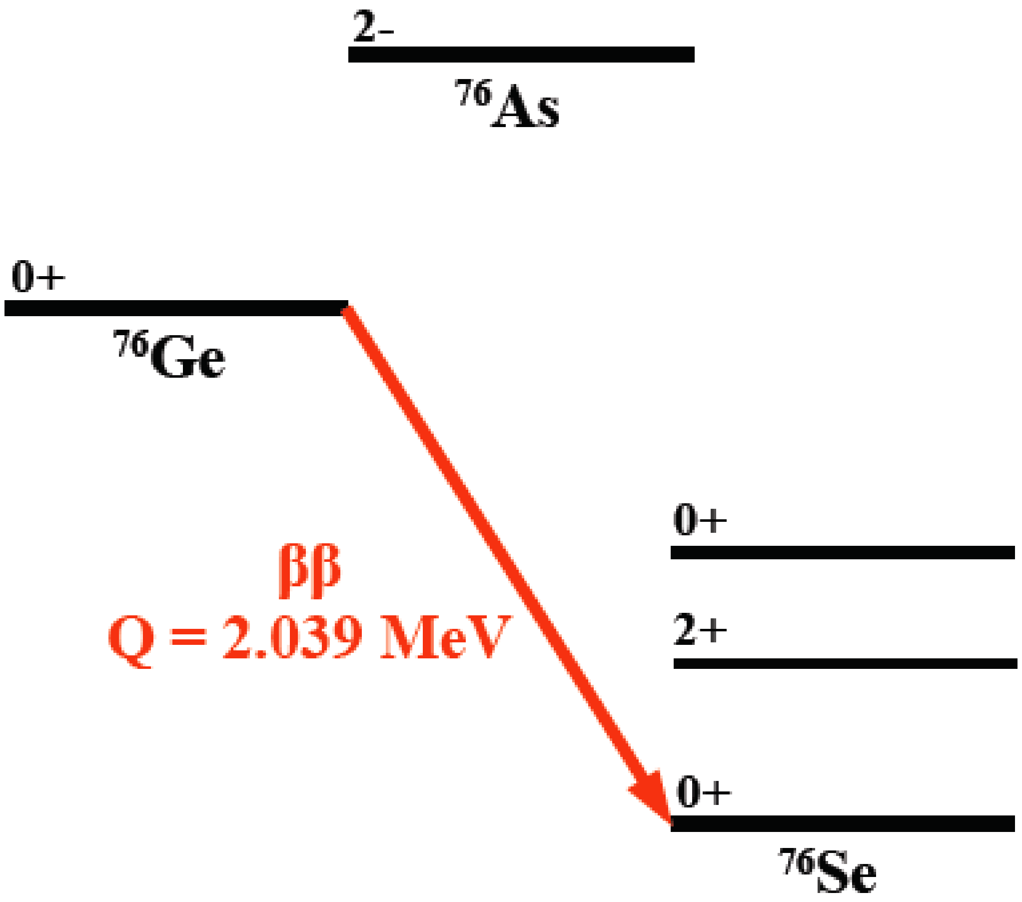
ββ Decay in ^{76}Ge



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

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

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

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

[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

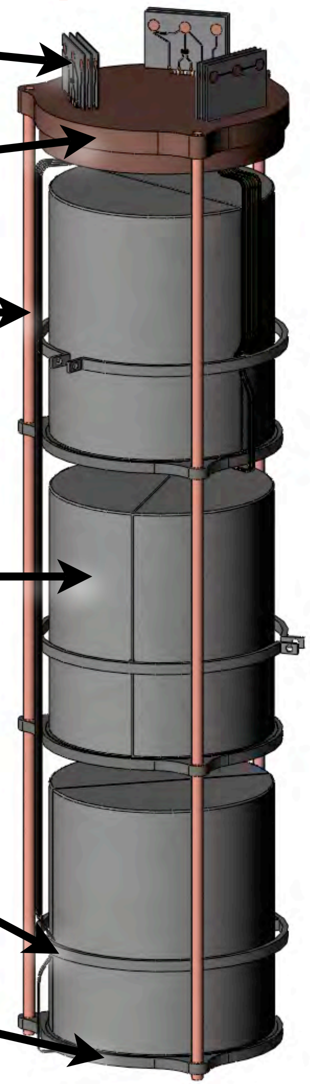
- Probe the quasi-degenerate neutrino mass region above 100 meV
- Demonstrate background levels that would justify scaling up to a 1 ton or larger experiment
- If the Klapdor-Kleingrothaus claimed observation of $0\nu\beta\beta$ in ^{76}Ge is confirmed, do a precision measurement of the decay rate (20%)

Majorana Overview

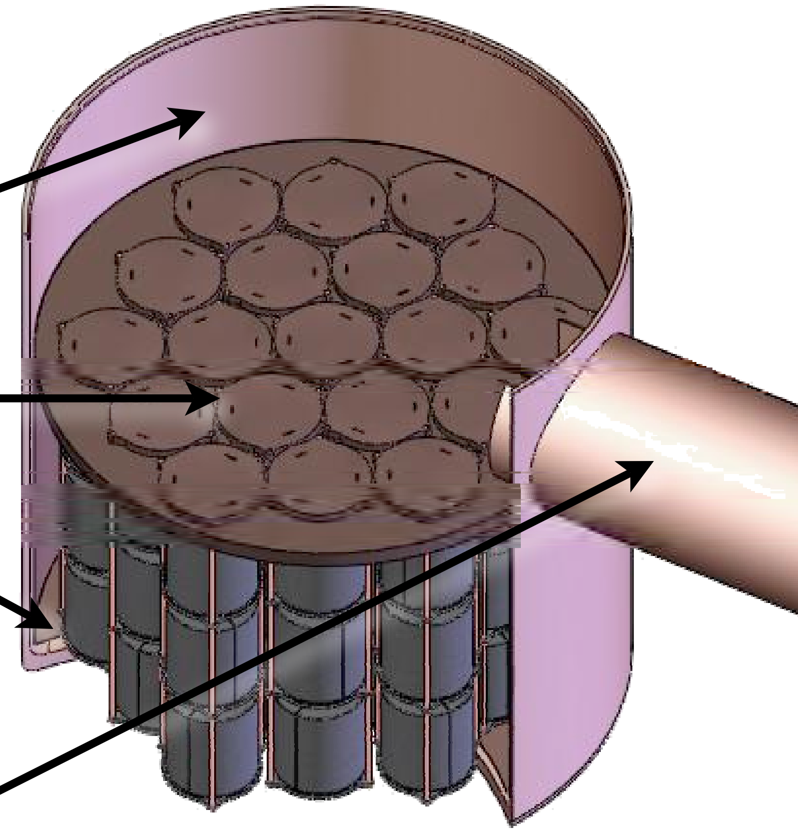
- Modules of 57 close-packed, 1.1 kg, segmented n-type HPGe detectors enriched to 86% ^{76}Ge
- Independent cryostats made of ultra-clean electroformed Cu
- Low background passive lead + electroformed Cu shield and 4π active veto
- Located deep underground (4500-6000 mwe)

60 kg Modules

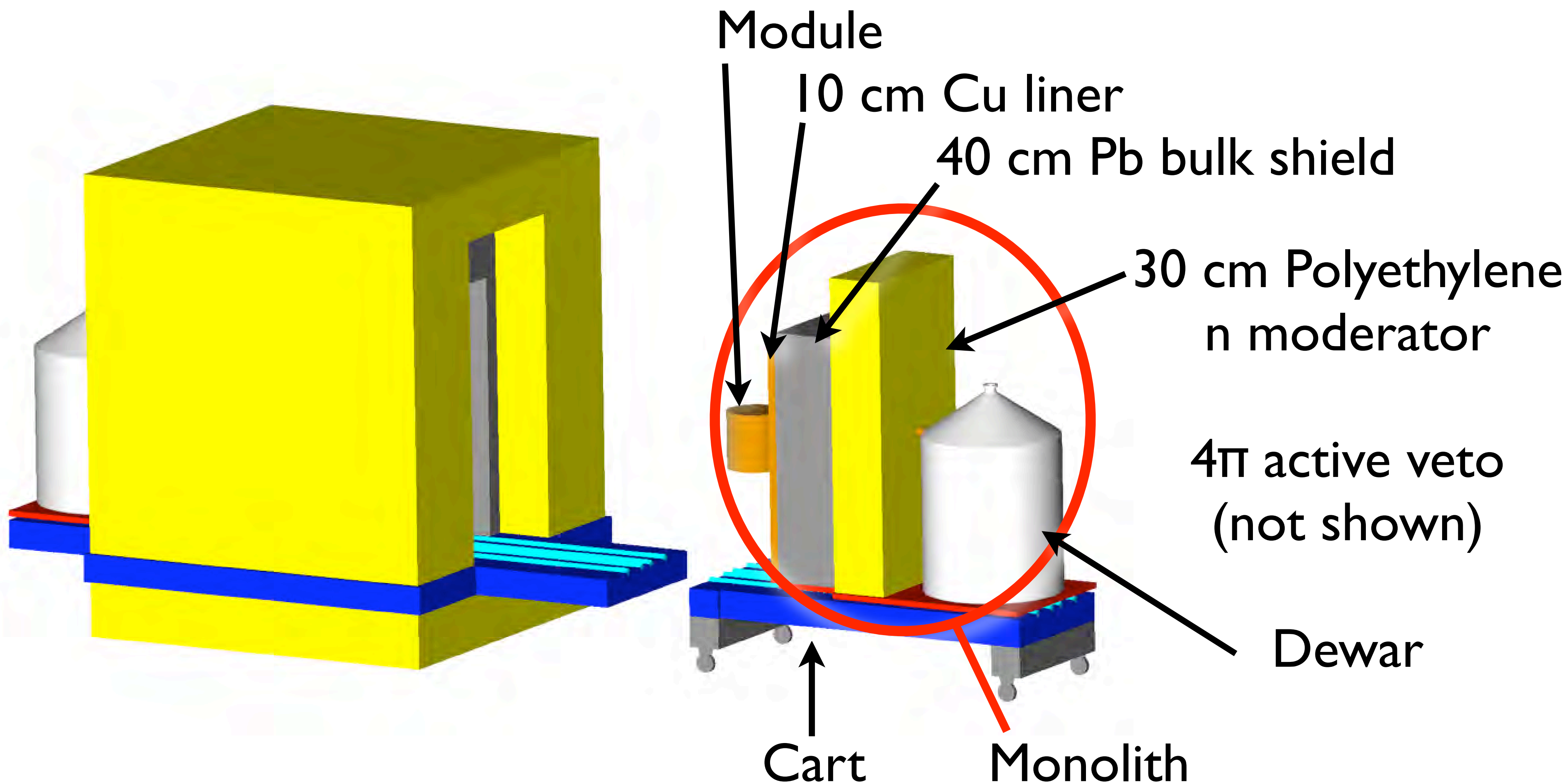
3-crystal string



57-crystal module



Passive and Active Shielding

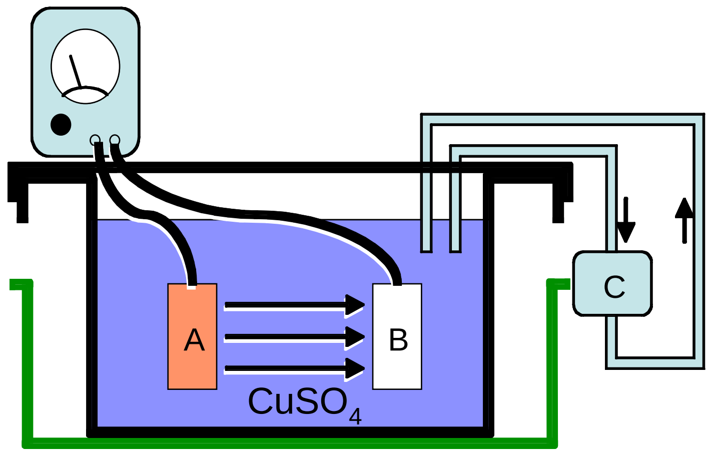


Backgrounds

- 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

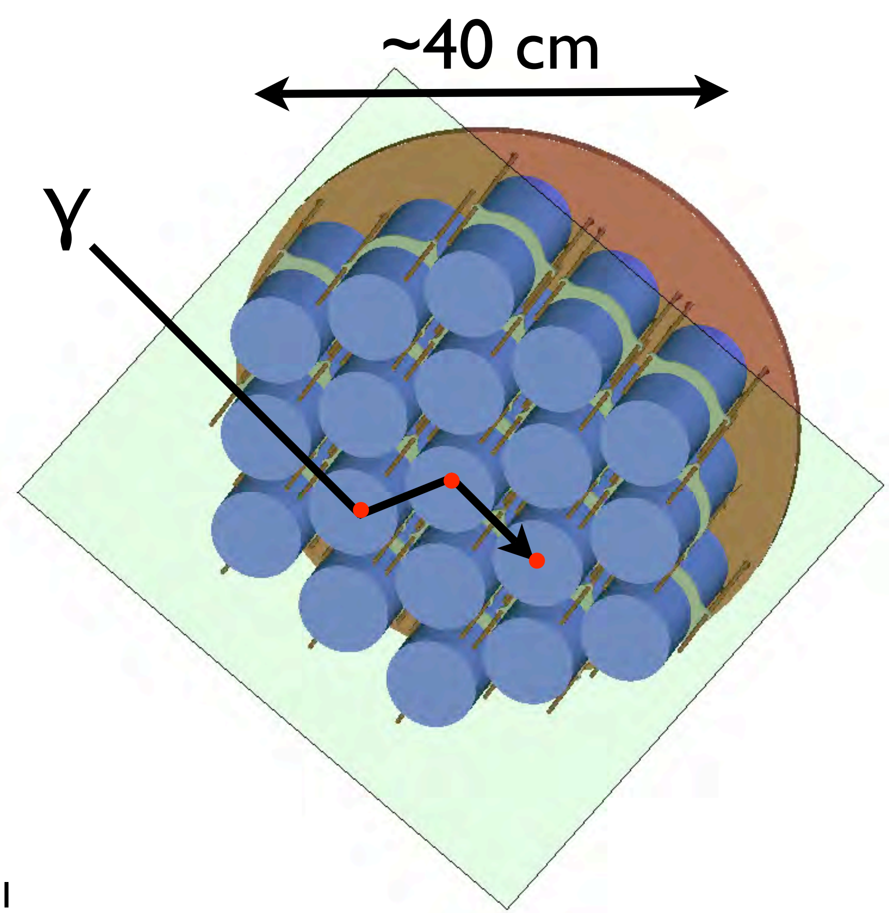
- ^{232}Th < 1 μBq/kg
- Recently improved bath chemistry: requires less surface finishing
- Improved starting stock quality and handling

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)



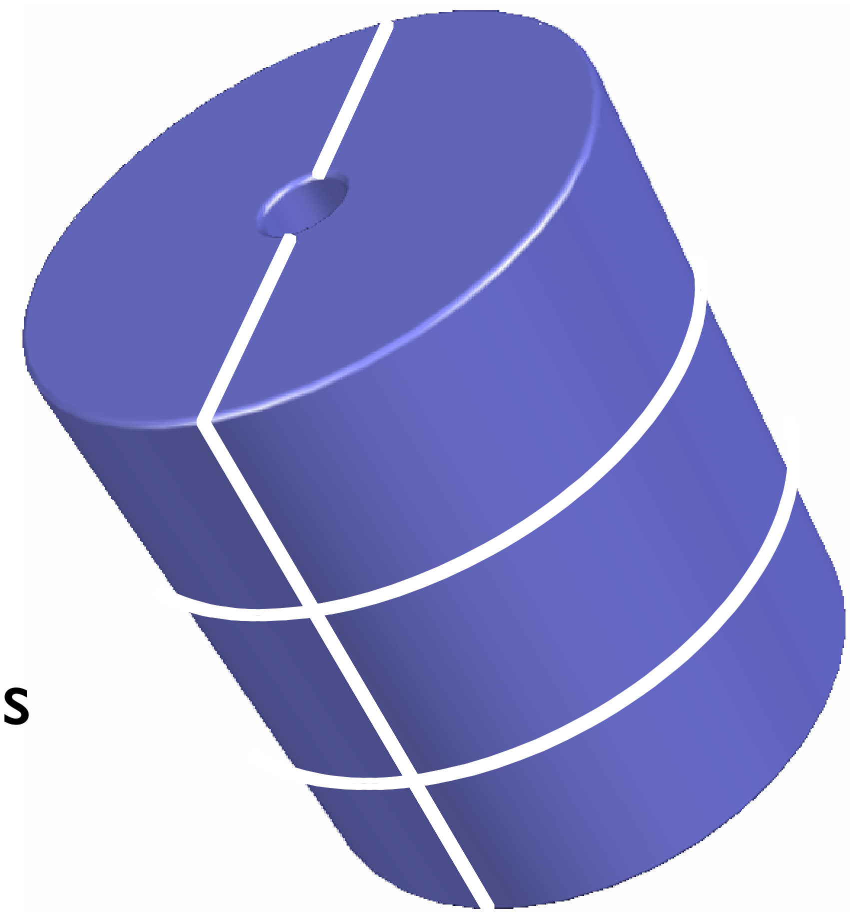
Background Rejection: Segmentation

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)

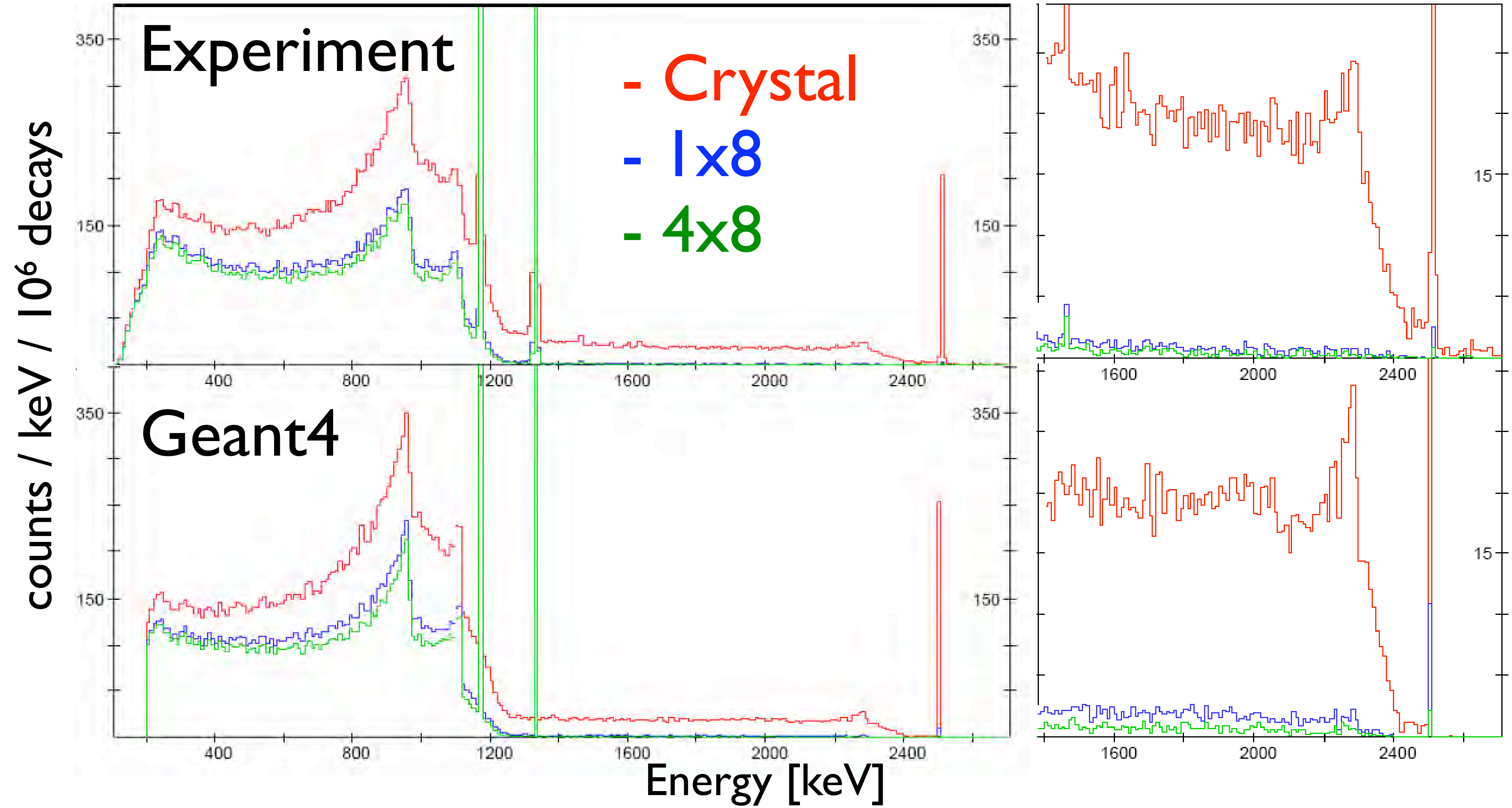
- Requires additional electronics and small parts



Background Rejection: Segmentation

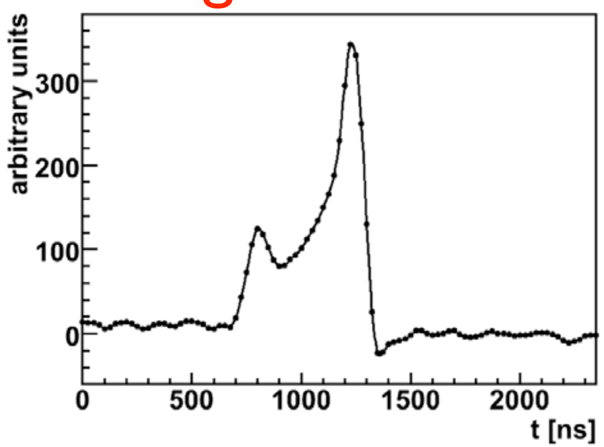
MSU/NSCL segmented Ge array, ^{60}Co source

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

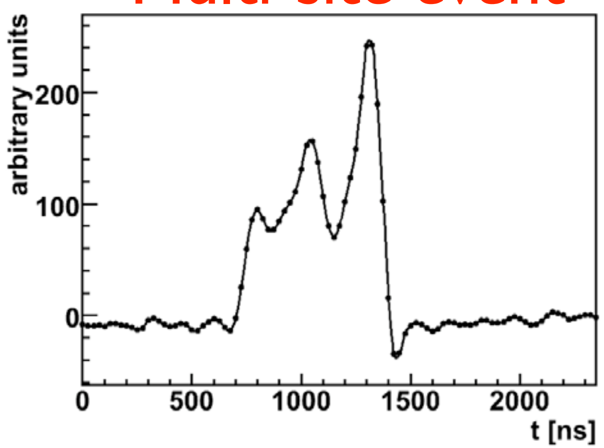


Background Rejection: Pulse Shape Discrimination

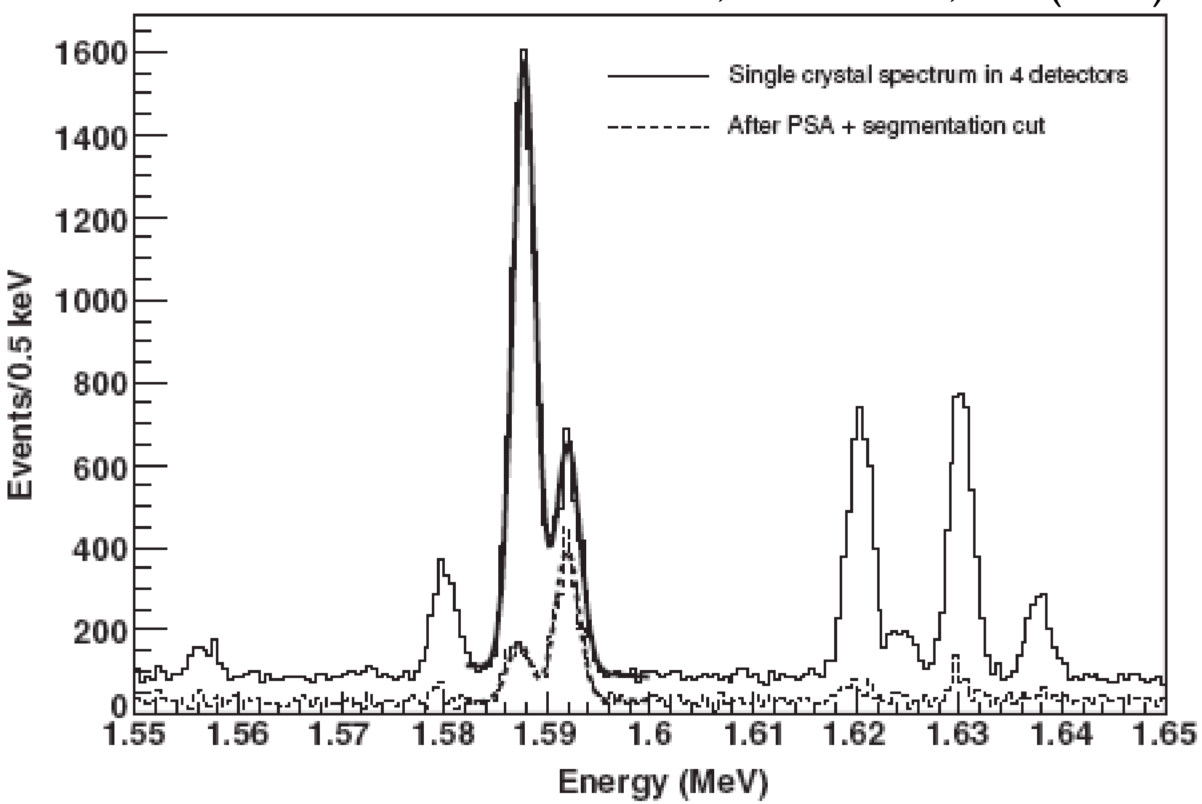
Single-site event



Multi-site event

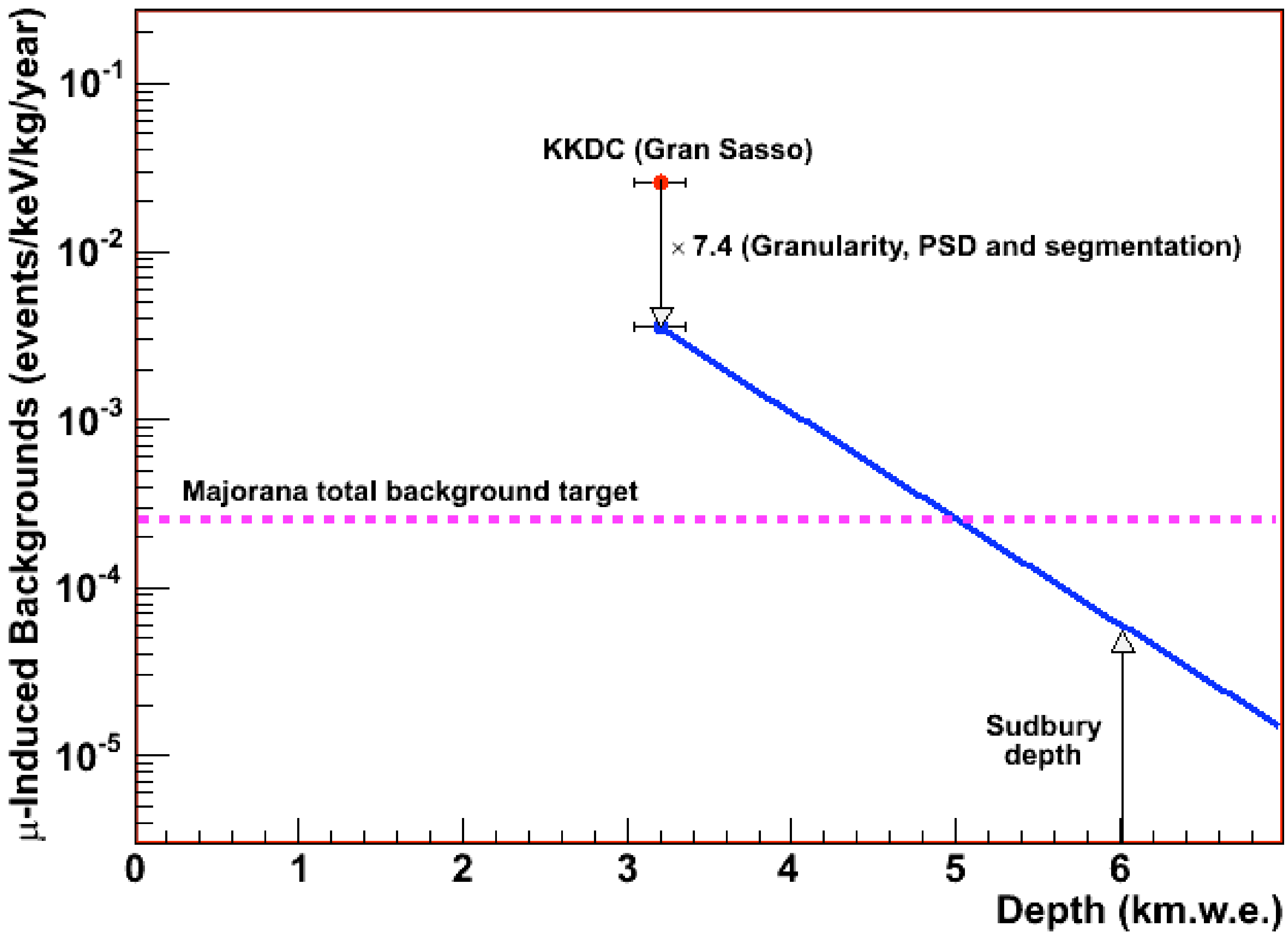


S.R. Elliott *et al.*, NIM A **558**, 504 (2006).



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

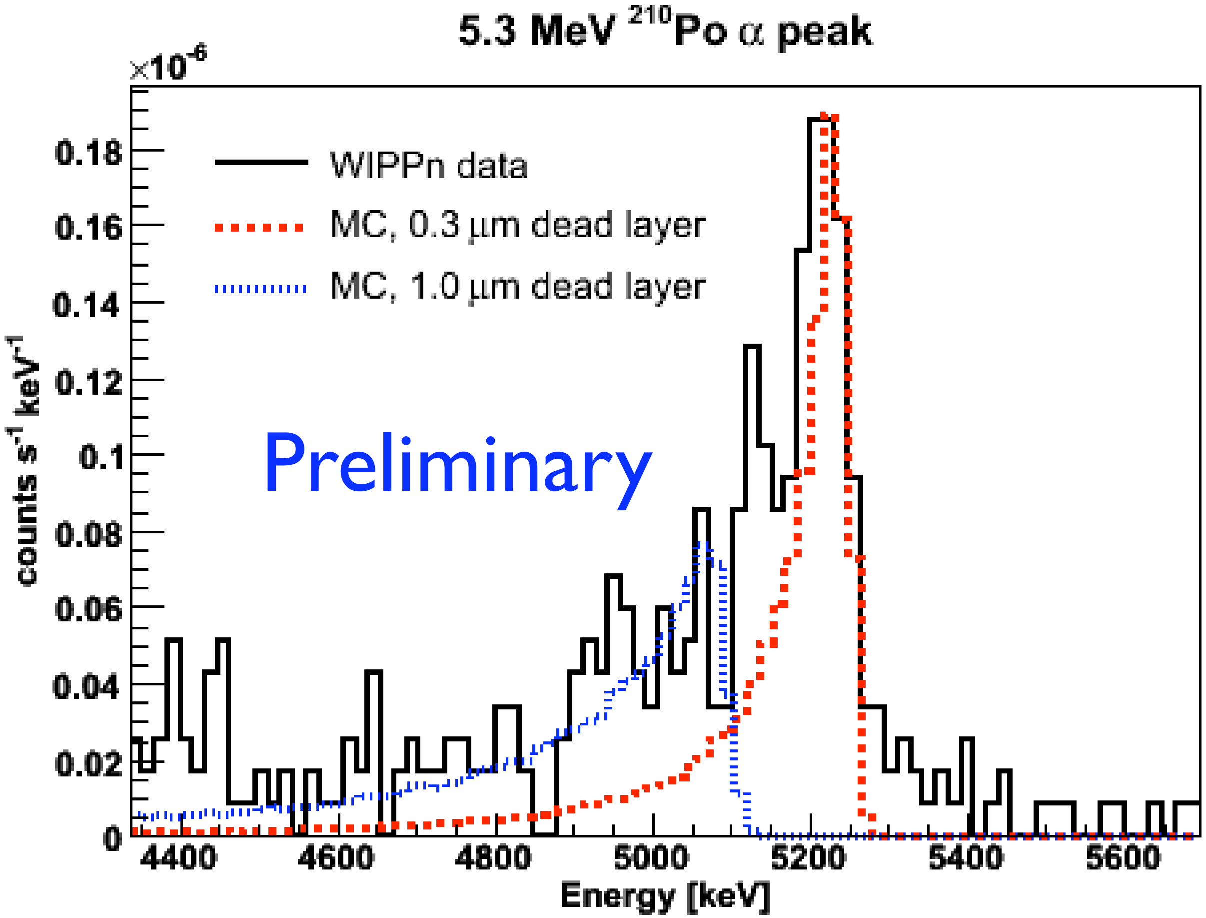
Cosmogenic Backgrounds

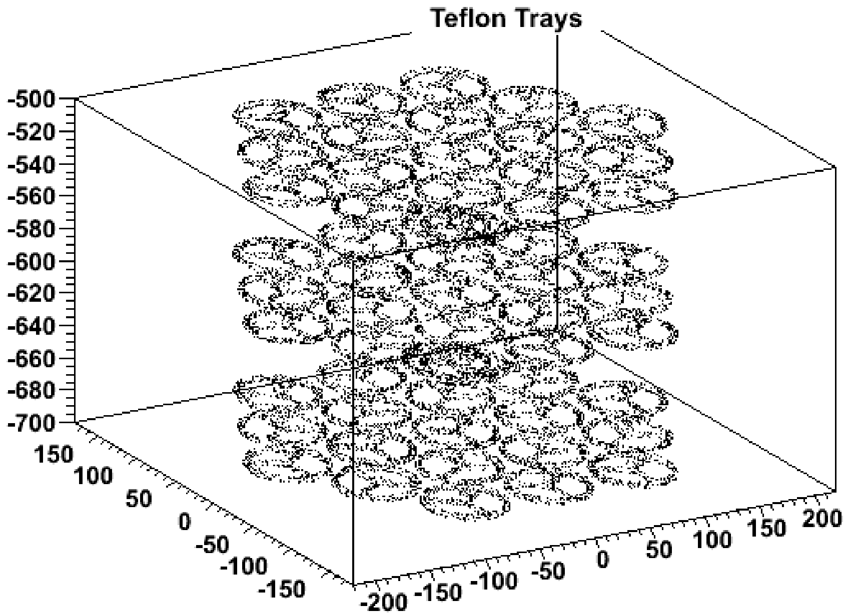


D.-M. Mei and A. Hime, Phys. Rev. D **73**, 053004 (2006).

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

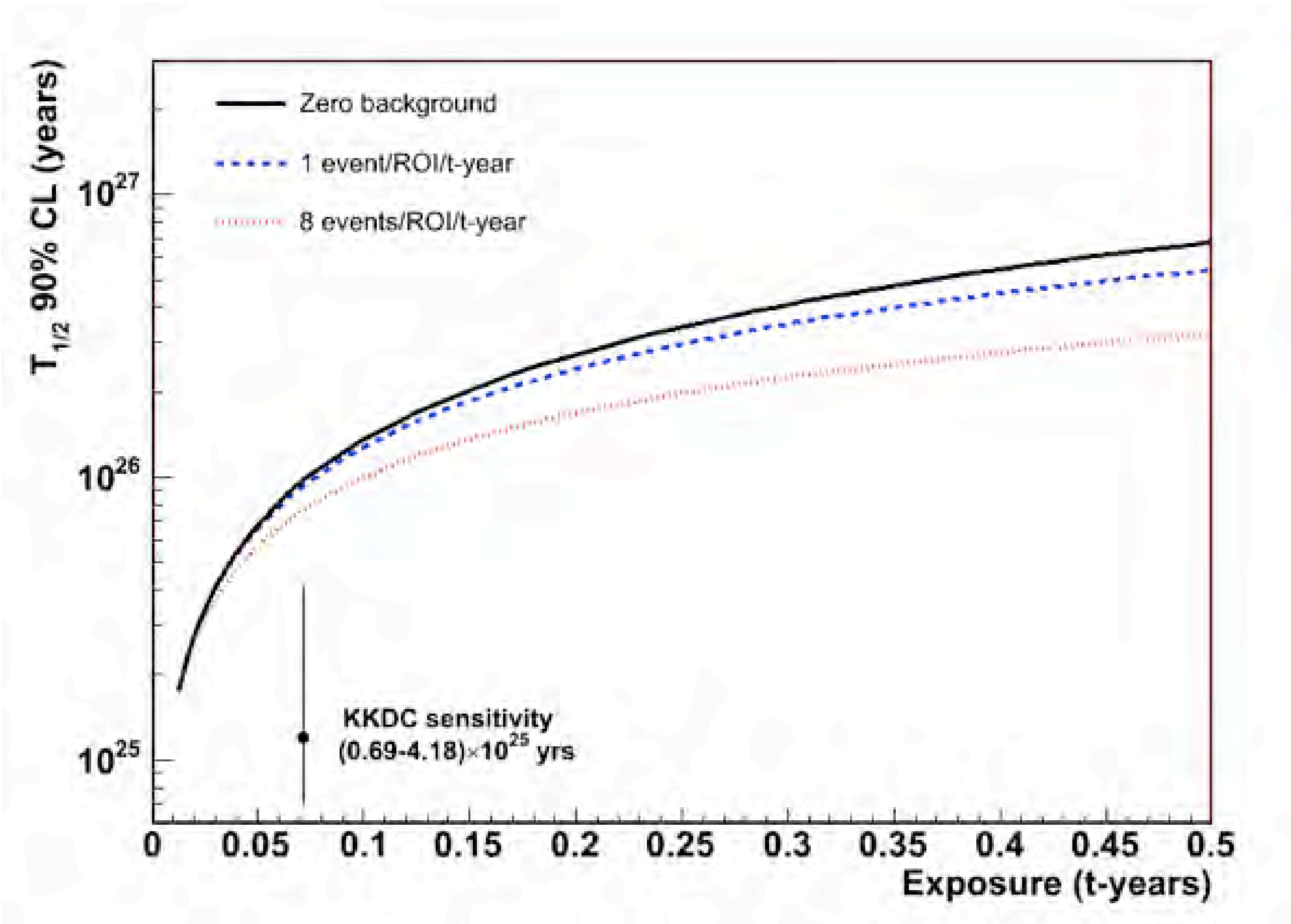
Crystals are clean

Dominated by ^{232}Th in Cu

Requires QC

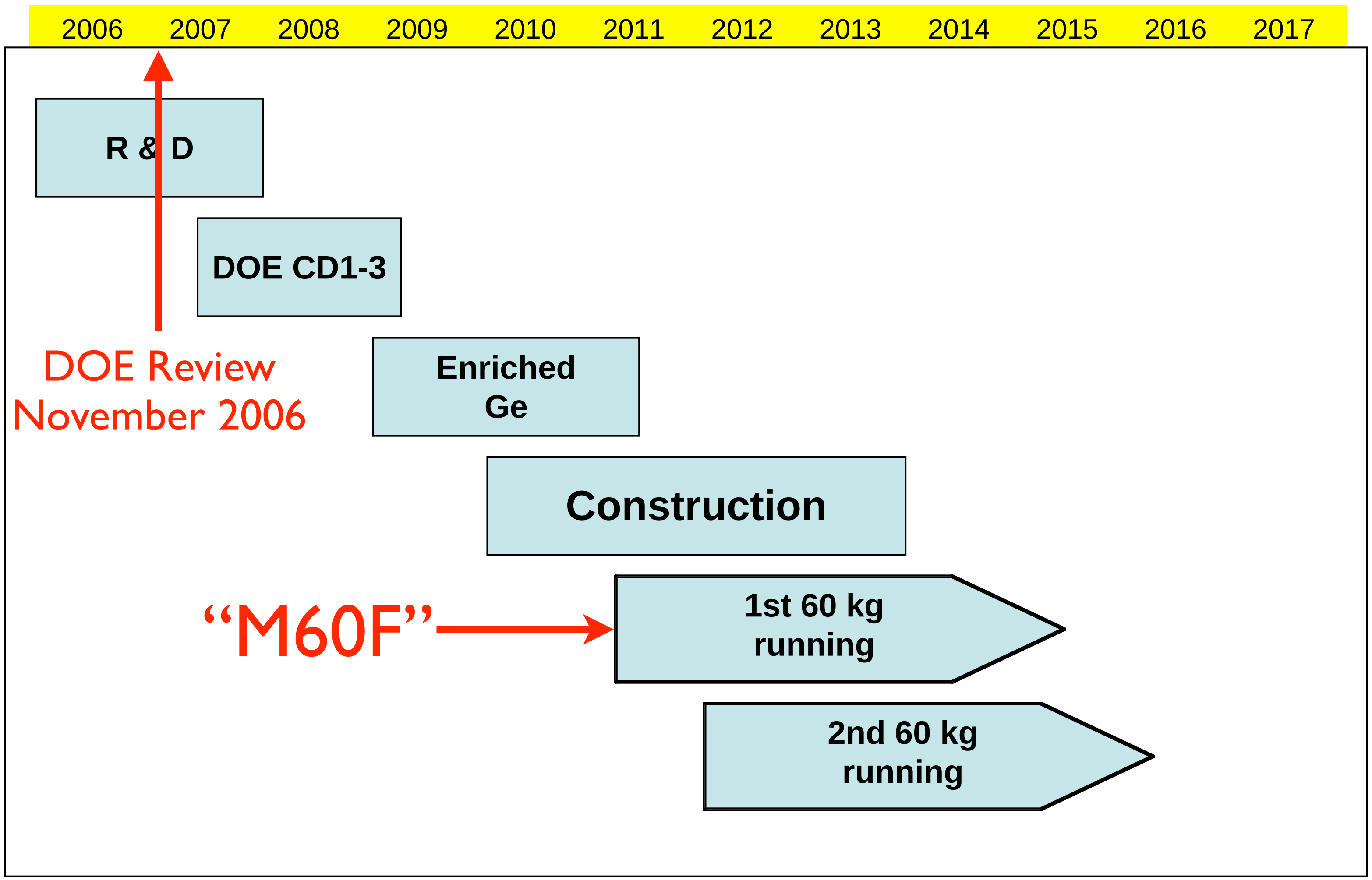
Must go deep

Majorana Sensitivity



Schedule

(assuming two modules)

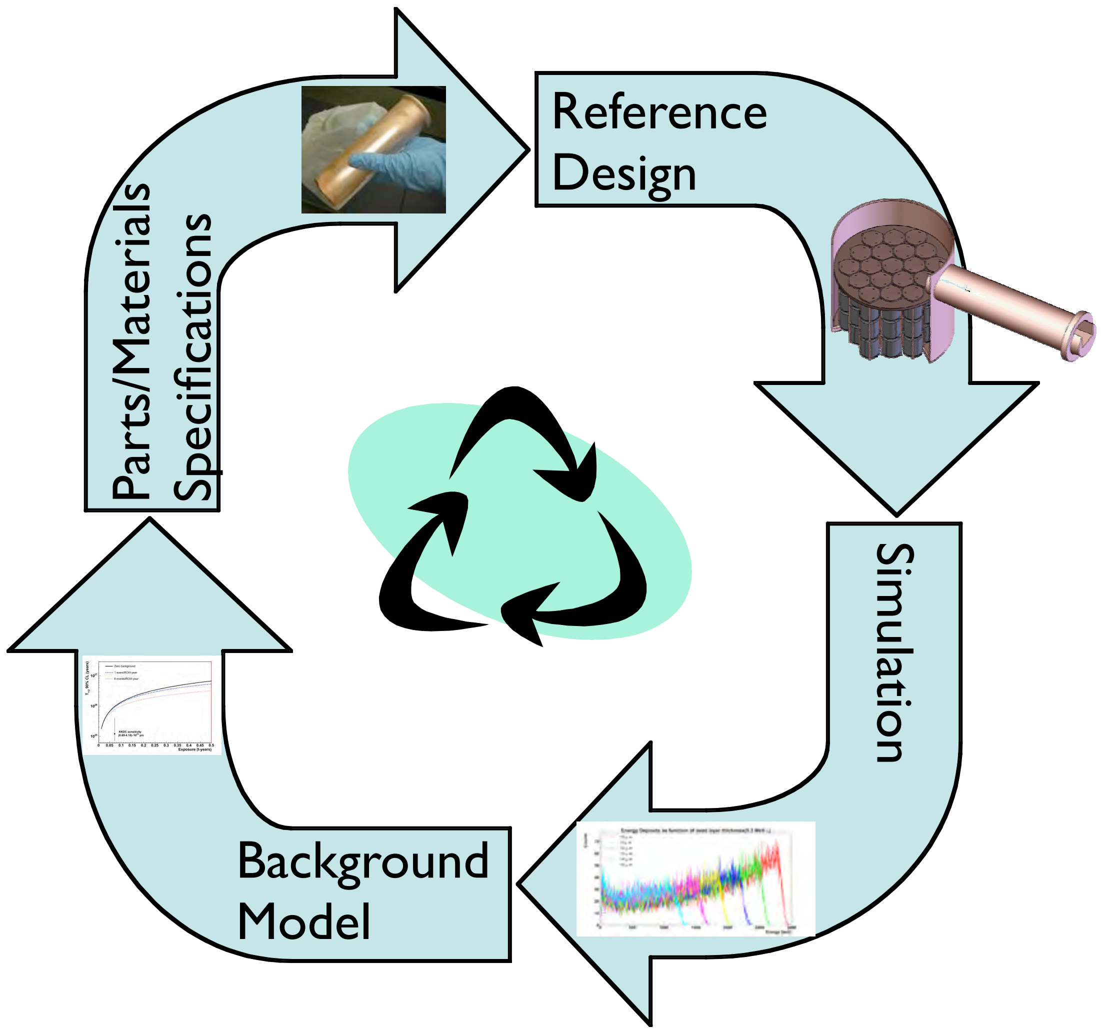


Our schedule is constrained by the requirement to follow the DOE "413" capital acquisition process.

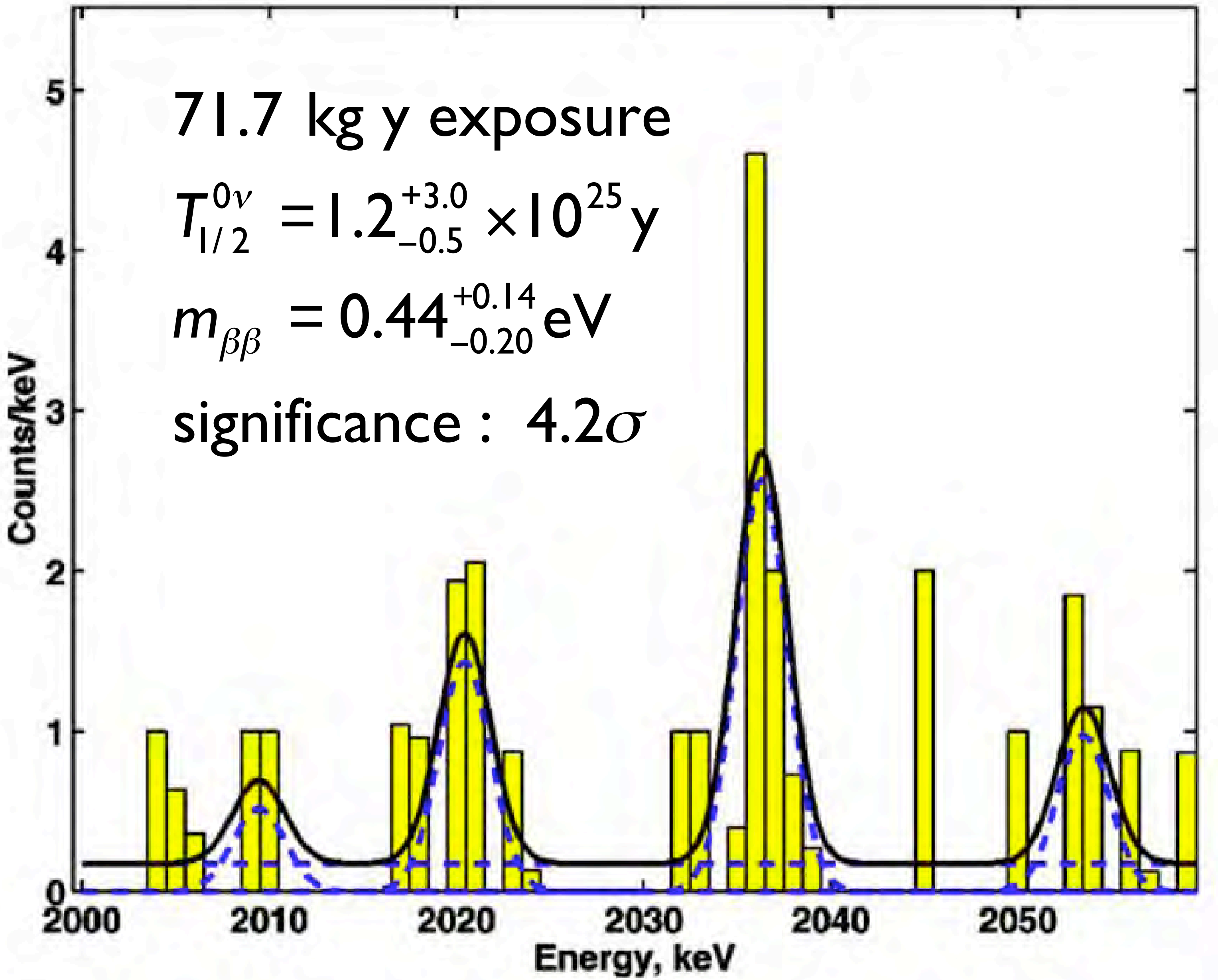
Summary

- 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 ($m_{\beta\beta}$ ~ 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 $\beta\beta$-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

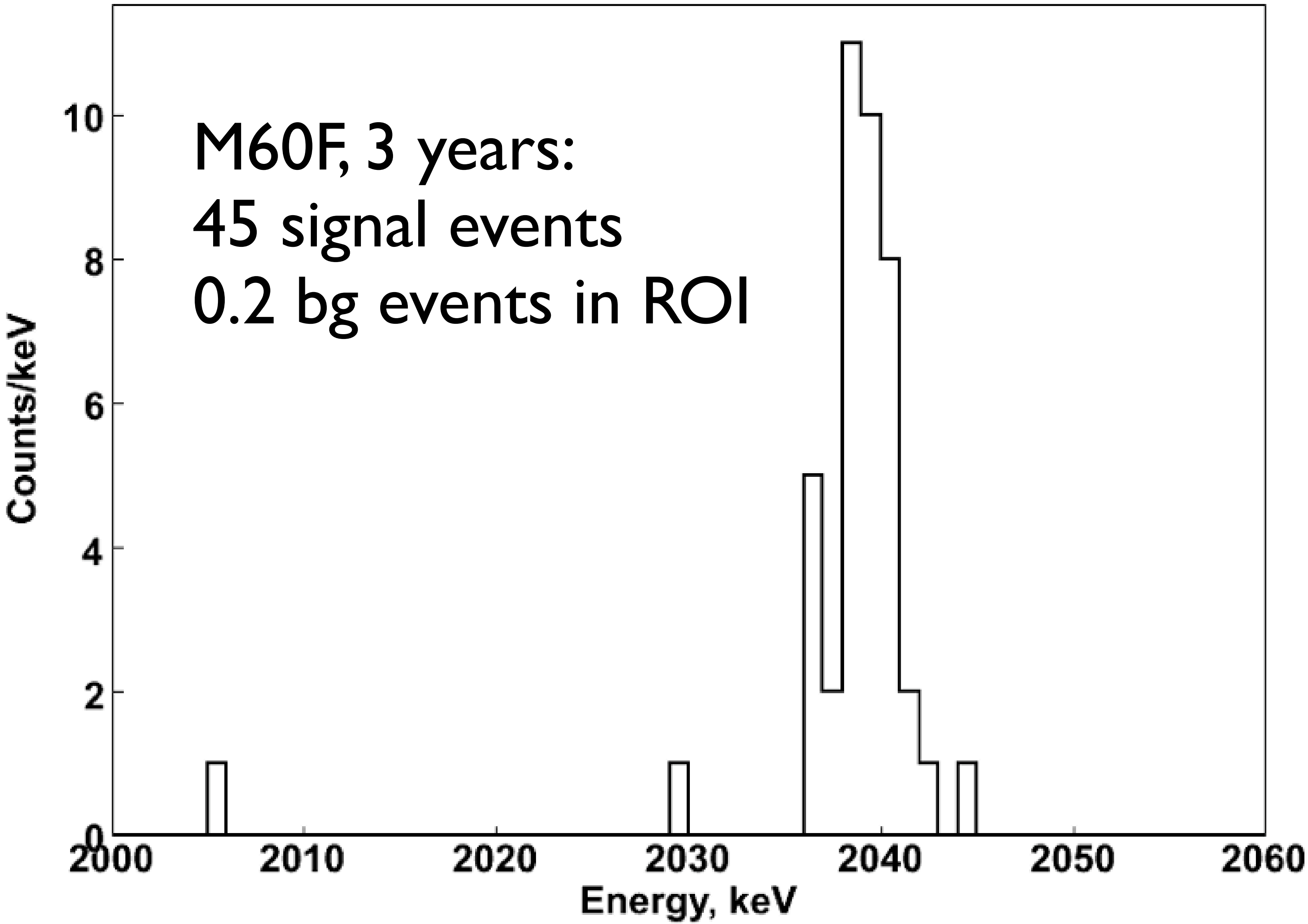


Sensitivity to KKDC Signal

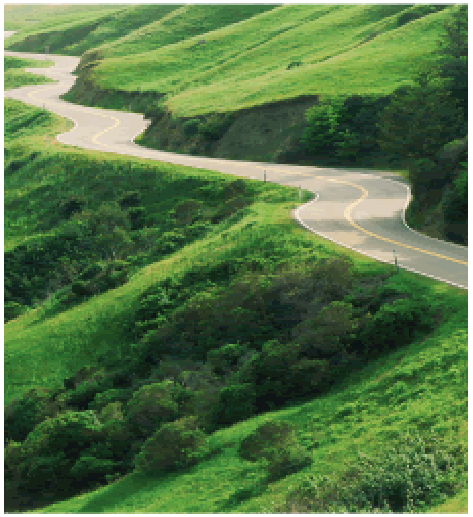


H.V. Klapdor-Kleingrothaus *et al.*, Phys. Lett. B **586**, p. 198 (2004).

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_ν> meV	Exposure in 2013	Expt. Start	90% CL <m_ν> 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