MAJORANA

An Ultra-Low Background Enriched-Germanium Detector Array for Fundamental Physics Measurements

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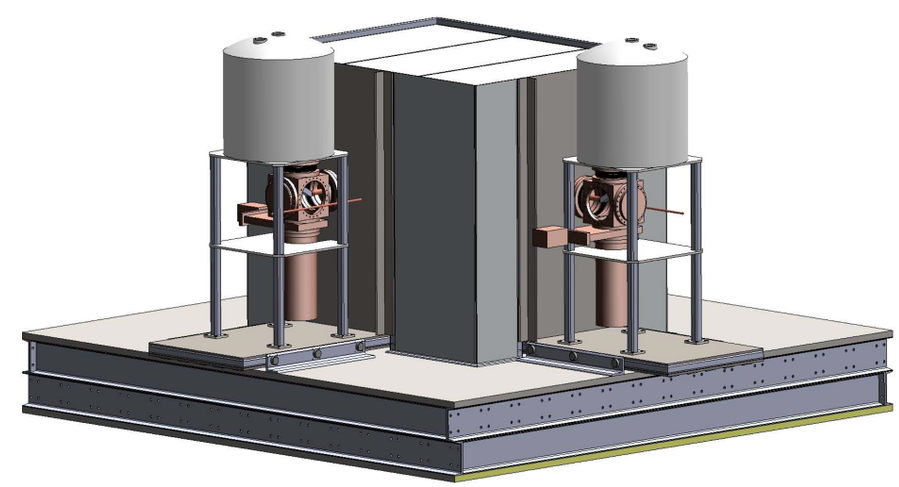
March 1, 2011



Outline

- Introduction to $0\nu\beta\beta$ decay
- $0\nu\beta\beta$ searches and other physics with ^{76}Ge
- MAJORANA status
- Backgrounds and sensitivity
- Summary

Majorana Neutrinos

$$\nu = \bar{\nu}$$

Majorana Neutrinos

$$L = \tfrac{1}{2}\,(\,\bar{\nu}_L^{\,c}\ \bar{\nu}_R\,)\begin{pmatrix} m_L^M & (m^D)^T \\ m^D & m_R^M \end{pmatrix}\begin{pmatrix} \nu_L \\ \nu_R^{\,c} \end{pmatrix} + \text{h.c.}$$

Two classes of eigen-ν:

$$\nu_1 \approx (\nu_L - \nu_L^{\,c}) + (m^D/m_R^M)(\nu_R - \nu_R^{\,c}) \qquad m_1 \approx m^D\,(m^D/\,m_R^M)$$

$$\nu_2 \approx (\nu_R + \nu_R^{\,c}) + (m^D/m_R^M)(\nu_L + \nu_L^{\,c}) \qquad m_2 \approx m_R^M$$

"Seesaw" mechanism

Majorana Neutrinos

$\nu = \bar{\nu} \leftrightarrow$ Lepton number violation $\rightarrow$ Leptogenesis

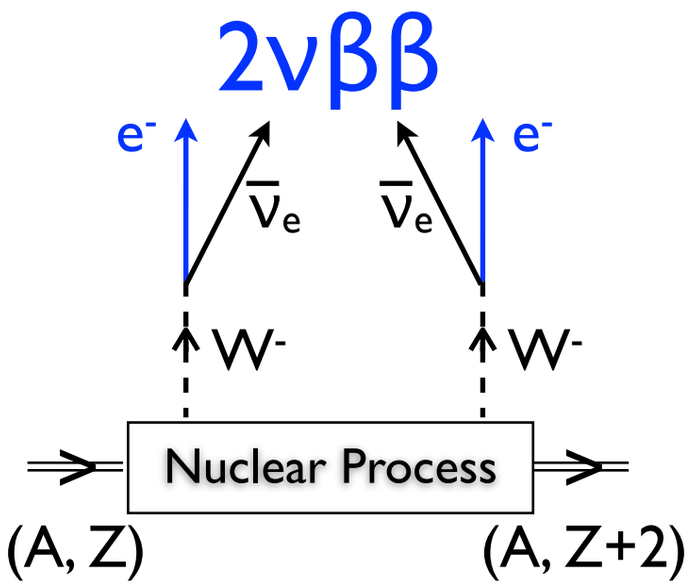
Matter-Antimatter Asymmetry: Sakharov conditions*

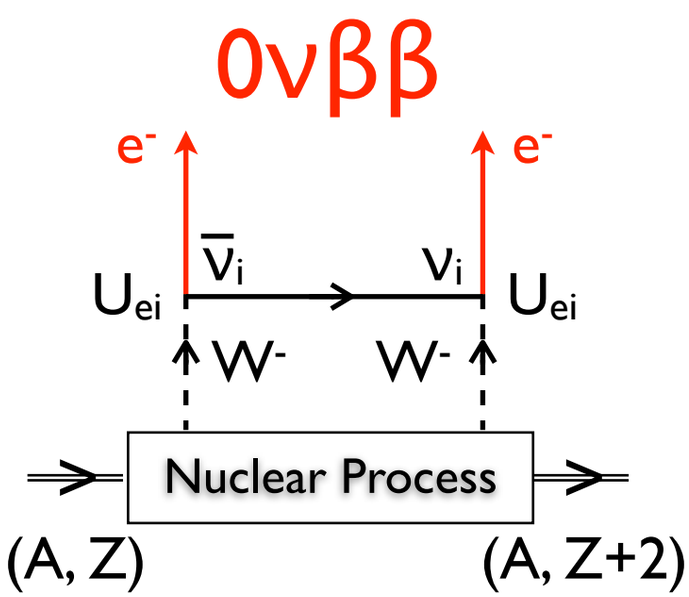
- Baryon number violation / baryogenesis
- C and CP violation
- Interactions out of thermal equilibrium

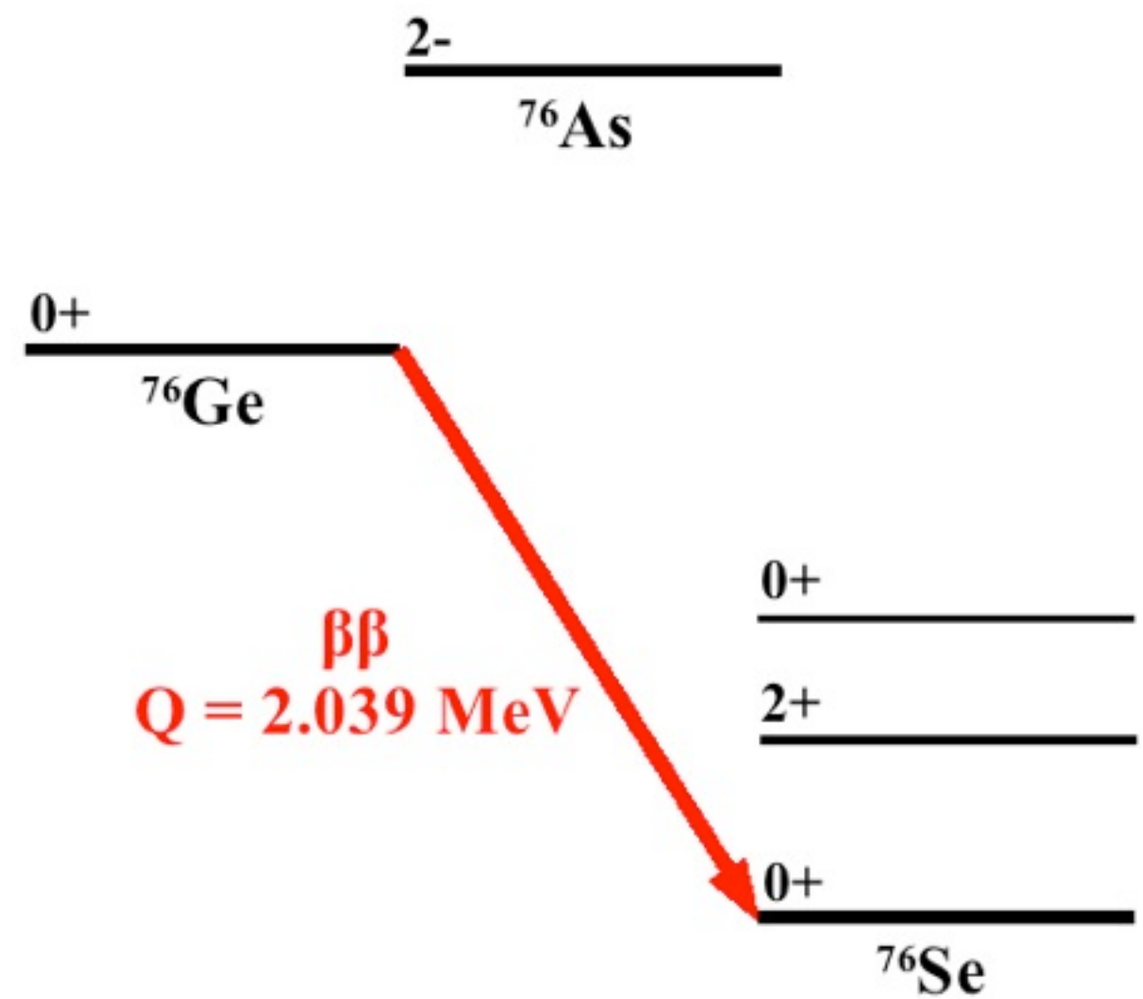
Double-beta decay is currently the only practical method of determining if ν are Majorana particles.

* A. D. Sakharov, JETP **5**, 24 (1967).

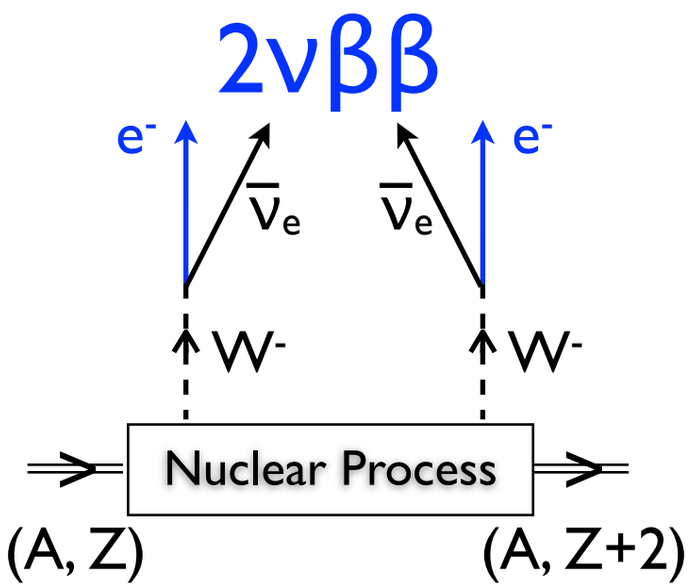
Double-Beta Decay

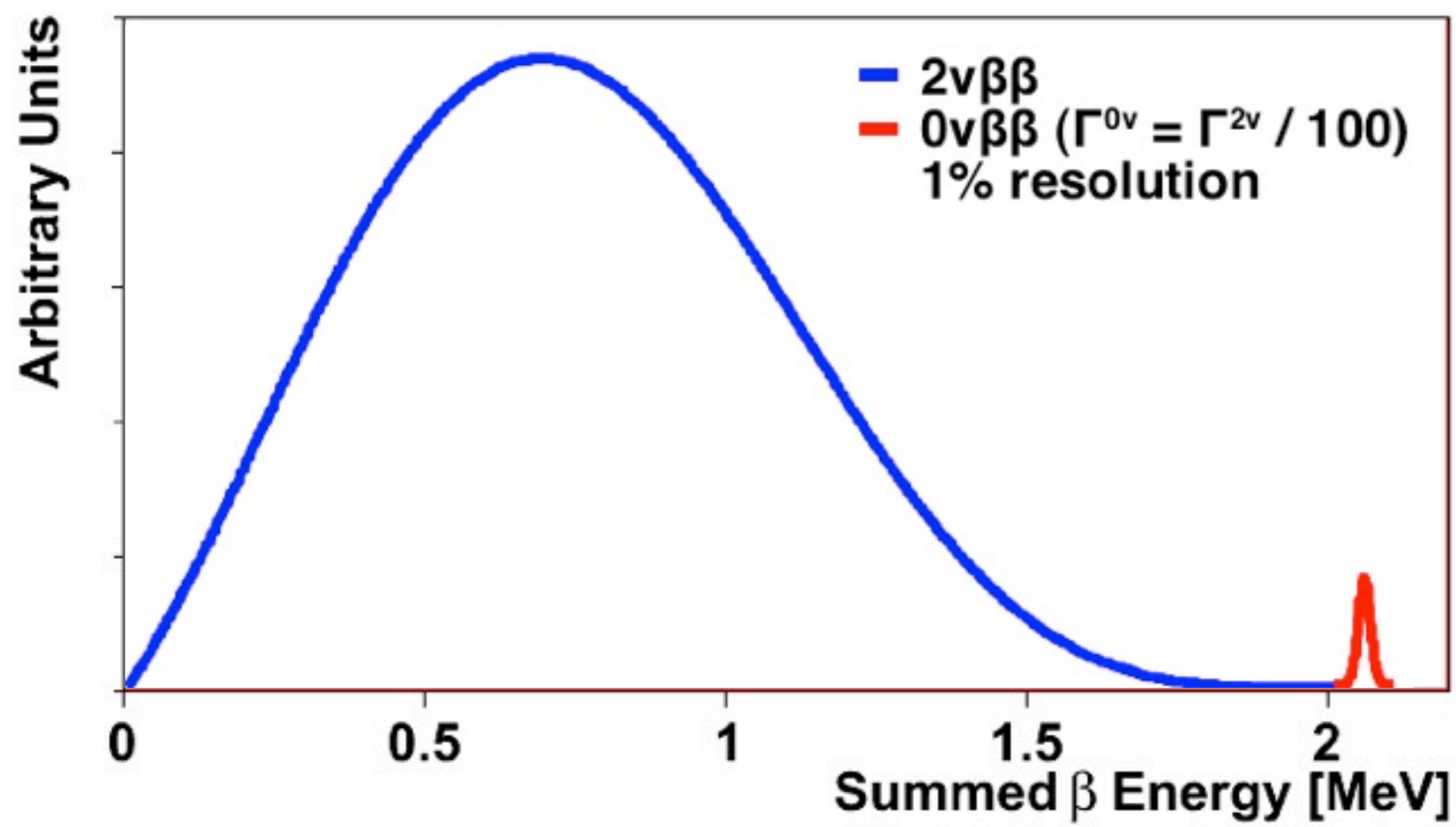


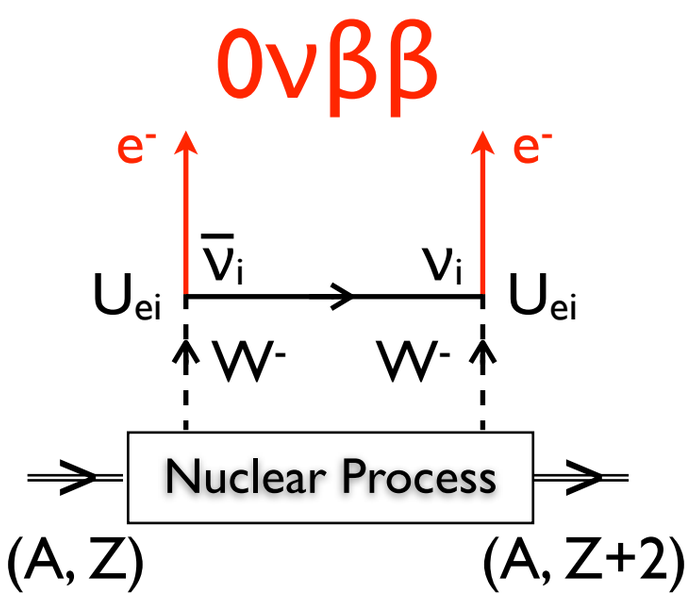




Double-Beta Decay



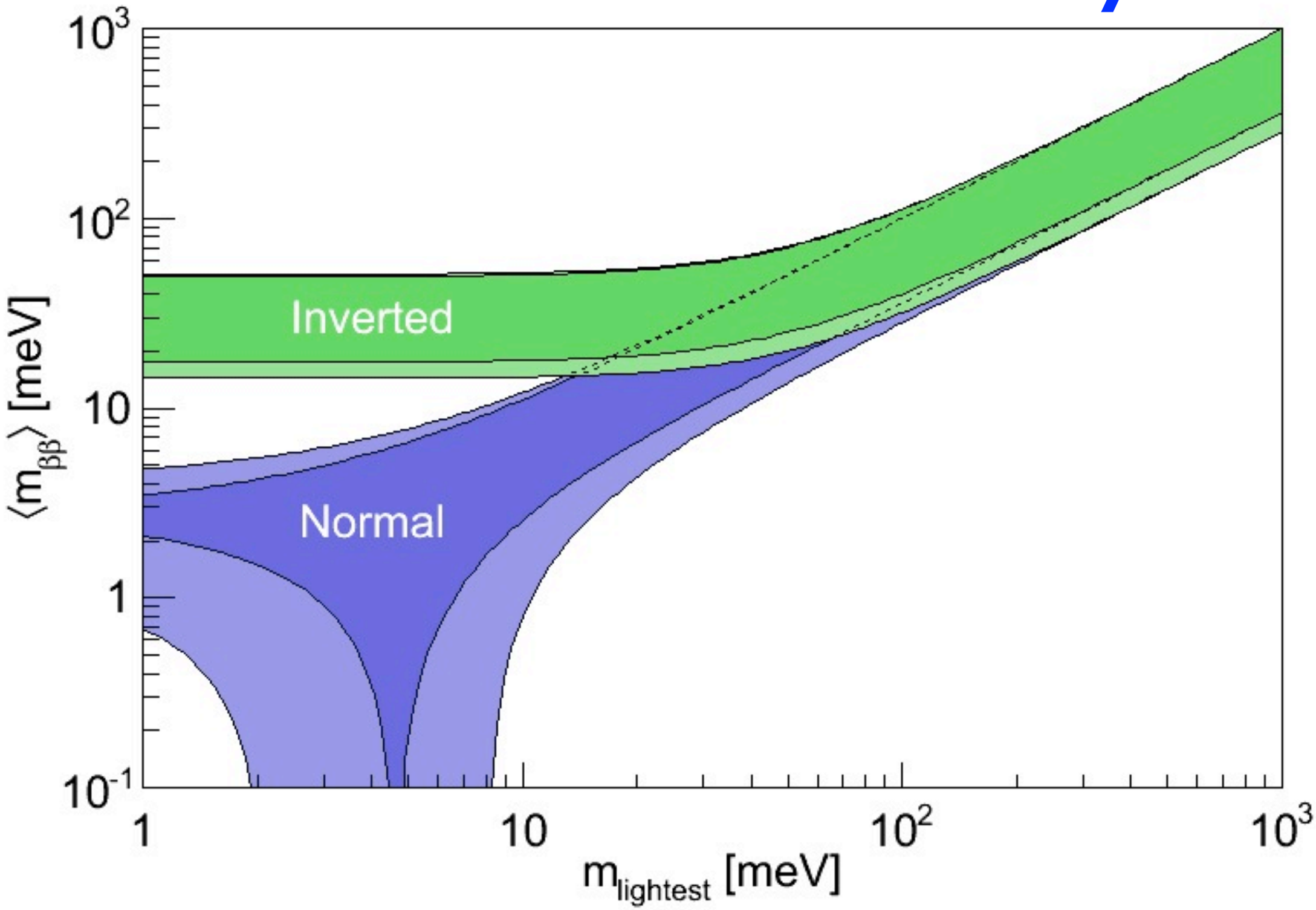




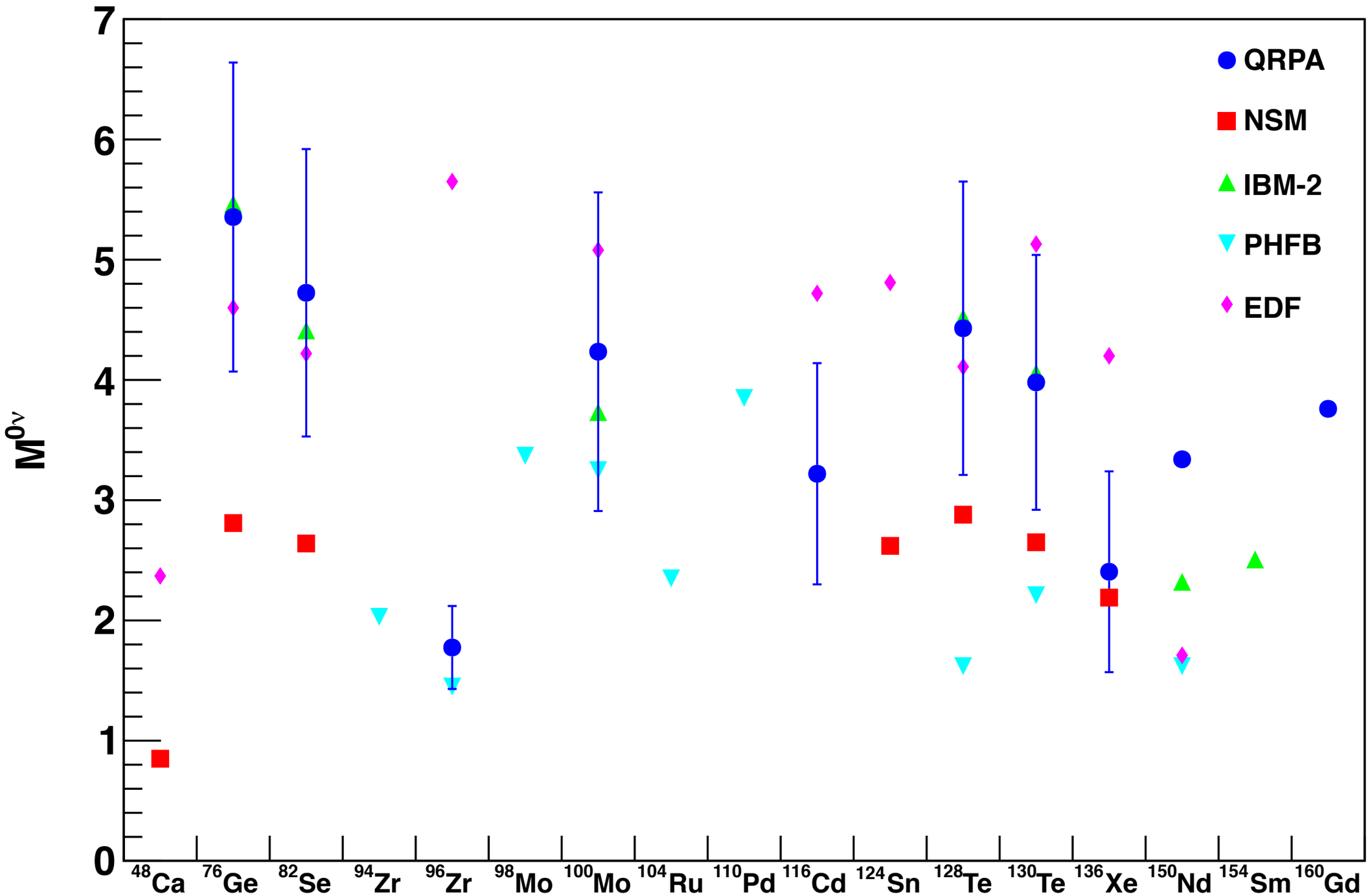
$$\Gamma_{1/2}^{0\nu} = G^{0\nu} \, |M^{0\nu}|^2 \, \langle m_{\beta\beta} \rangle^2$$

$$\langle m_{\beta\beta} \rangle \equiv \sum m_i \, U_{ei}^2 \square$$

Double-Beta Decay



Nuclear Matrix Elements

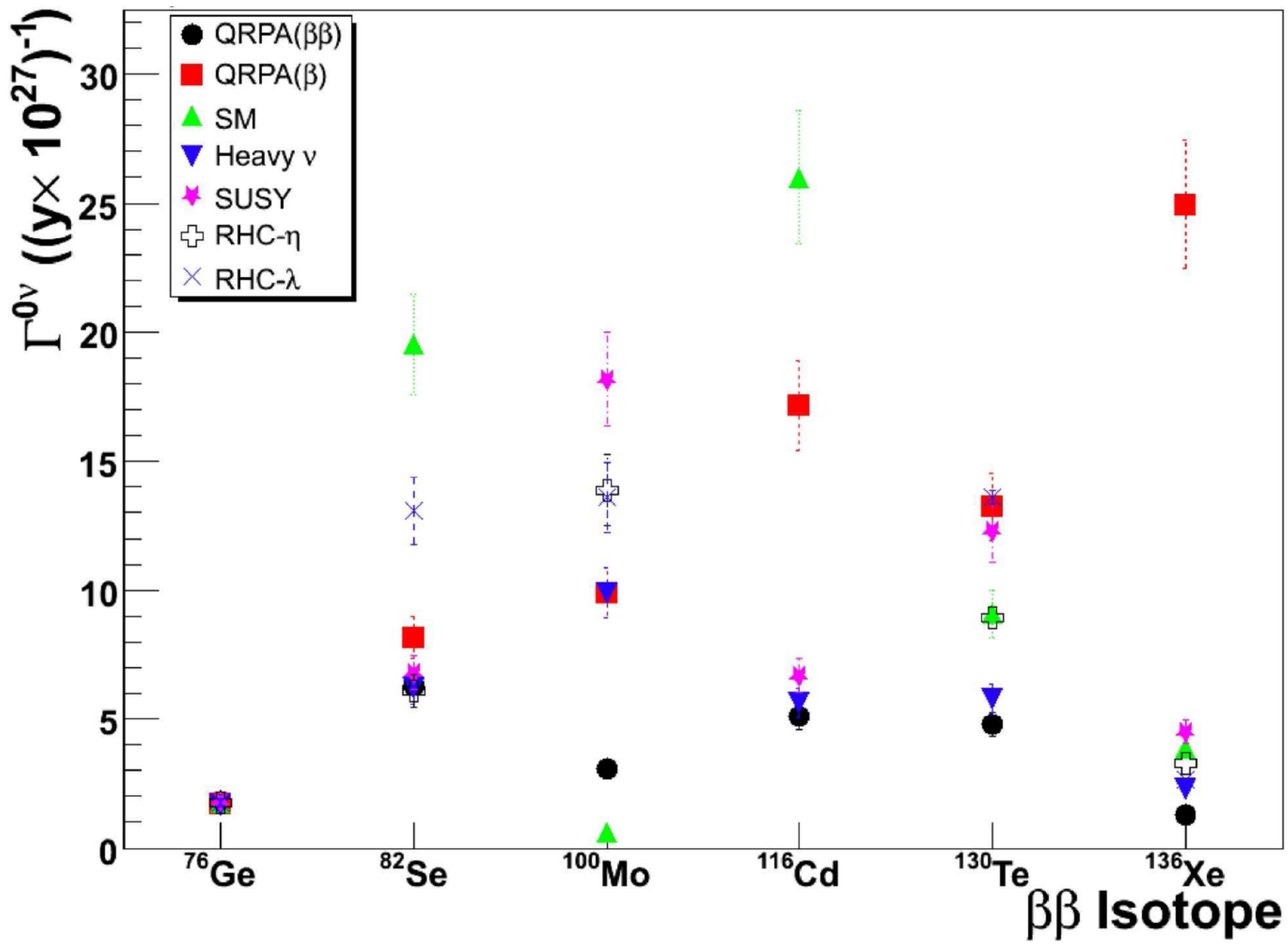


PRC **79**, 055501 (2009)
arXiv:1101.2149 (2011)
Nucl. Phys A **818**, 139 (2009)

PRC **79**, 044301 (2009)
Europhys. Lett. **86**, 32001 (2009)
arXiv:1008.5260v2 (2010)

Multiple Measurements

- Assumes a single dominant mechanism
- Requires NME calculated to 20%
- But correlations between NME must be considered (see, e.g., Fogli *et al.*, PRD **80**, 015024(2009))



V. M. Gehman and S. R. Elliott, J. Phys. G **34**, 667 (2007).

Outline

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- 0νββ searches and other physics with ^{76}Ge
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Advantages of ^{76}Ge

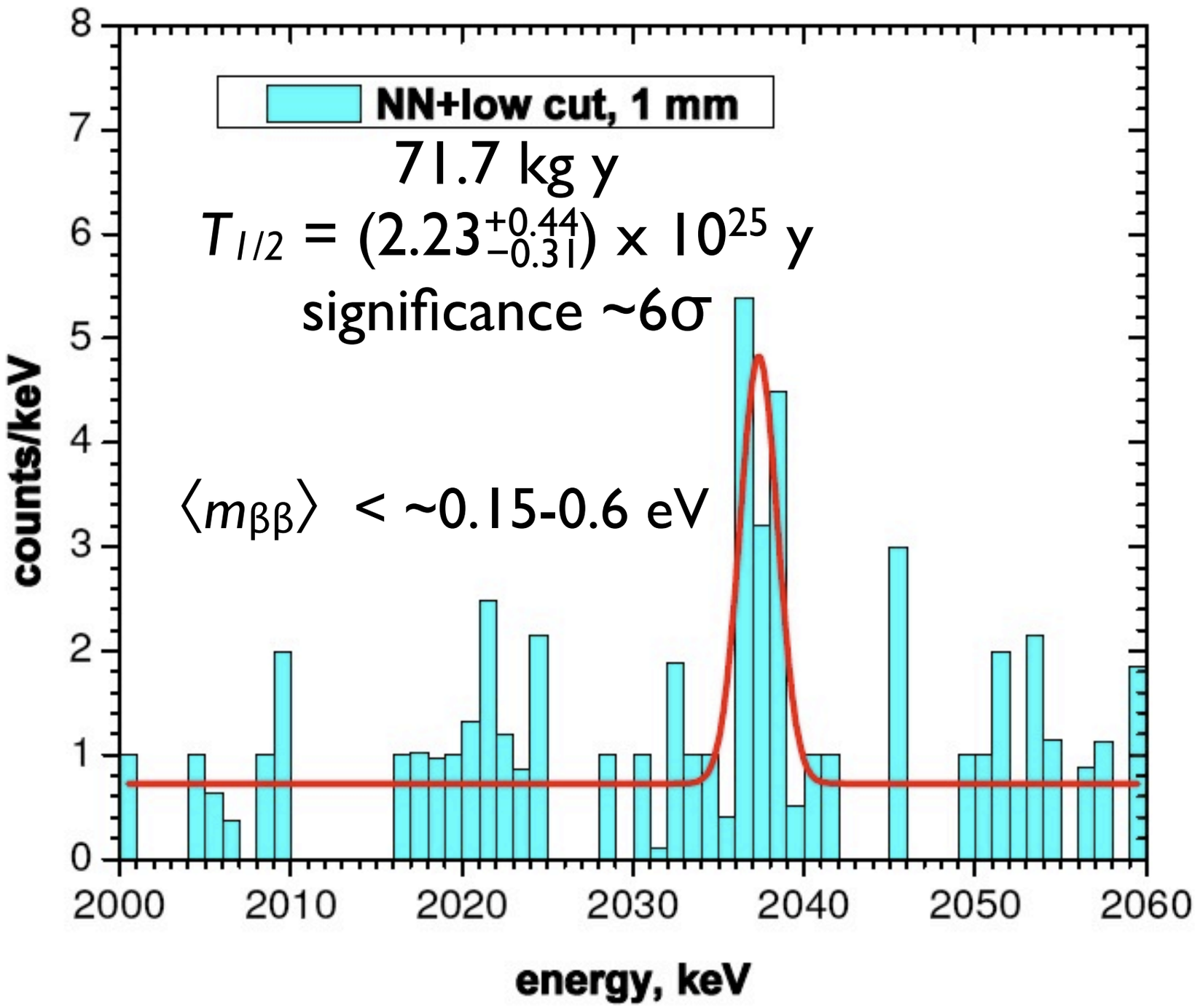
- Intrinsic high-purity Ge detectors = source
- Excellent energy resolution: 0.16% at 2039 keV (4 keV ROI)
- Powerful background rejection: segmentation, timing, pulse-shape discrimination
- Demonstrated ability to enrich from 7.44% to ≥86%
- ^{76}Ge has the current best half-life limit:

$$T_{1/2}^{0\nu} > 1.9 \times 10^{25}\ \text{y (90\% CL)}$$

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

Claimed Observation

Klapdor Kleingrothaus *et al.*, Mod. Phys. Lett. A **21** (2006) p 1547.



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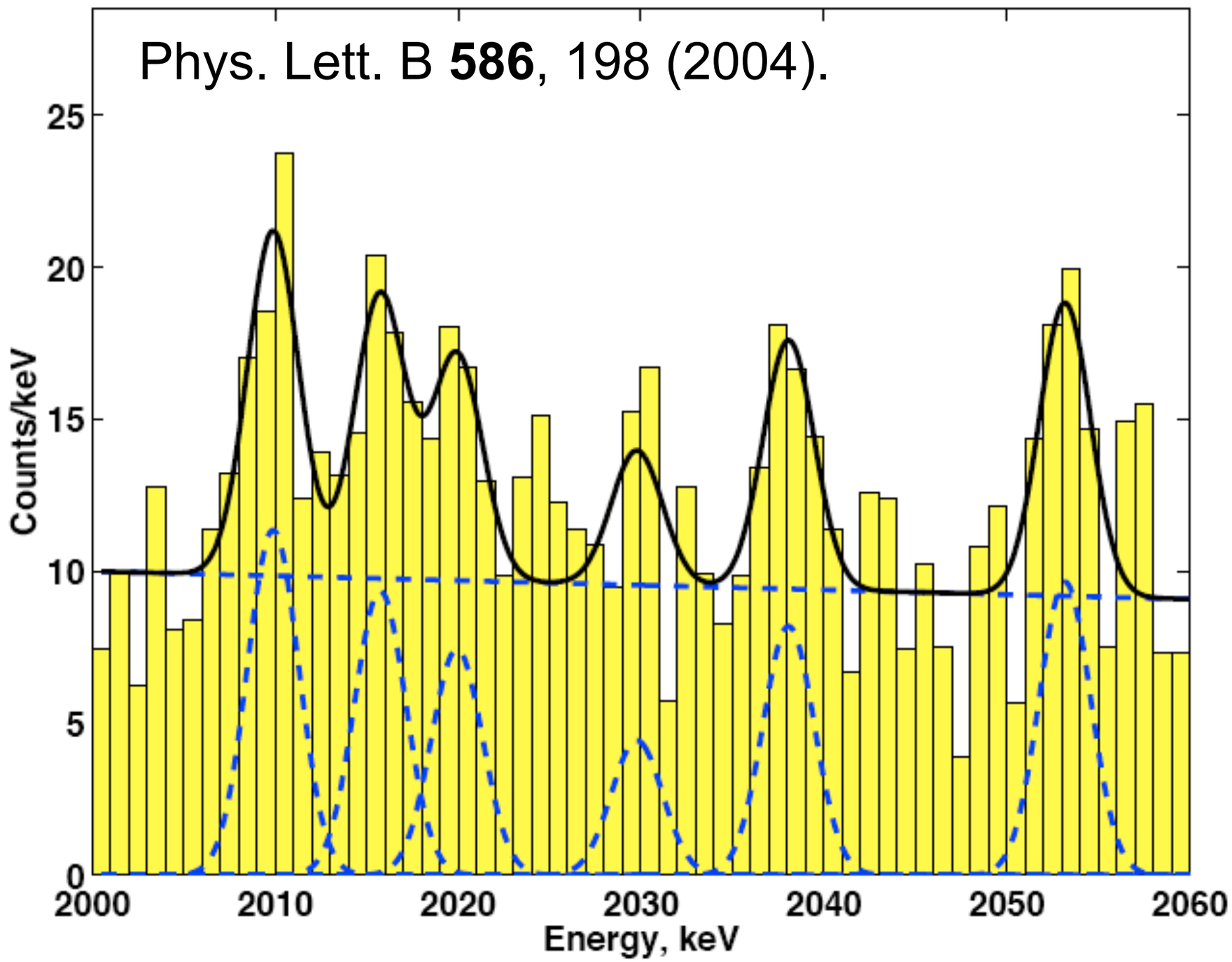
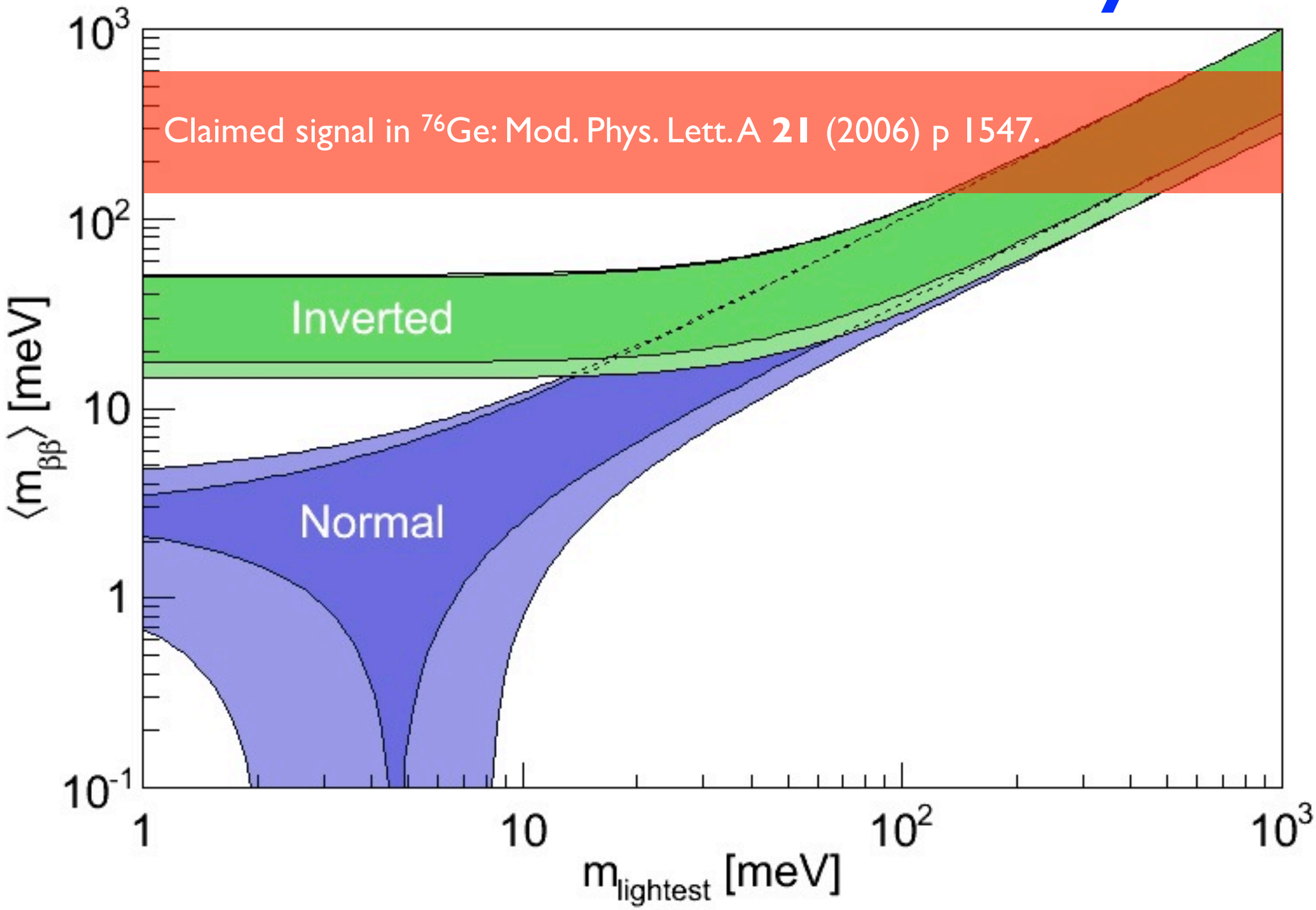


Double-Beta Decay



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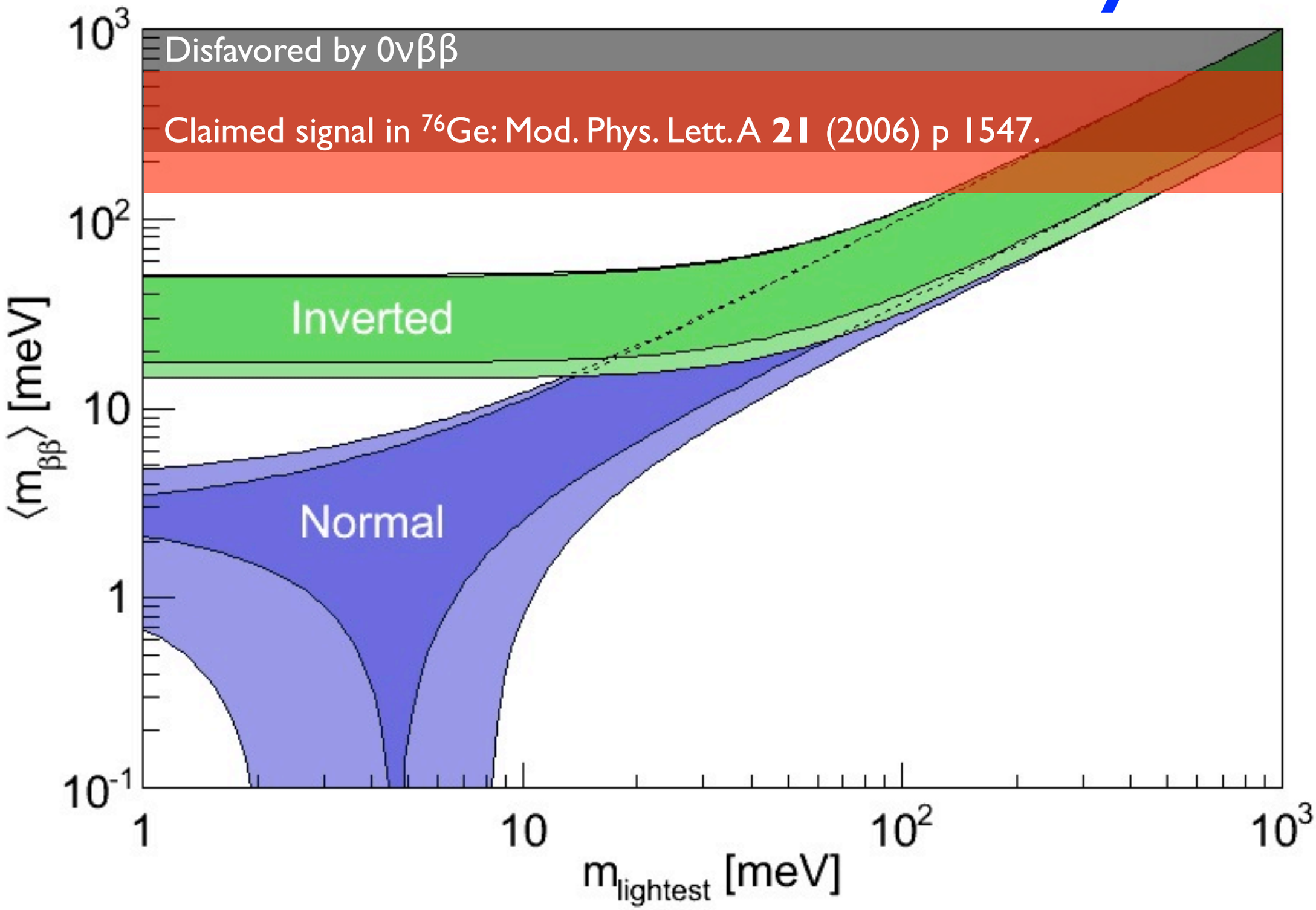

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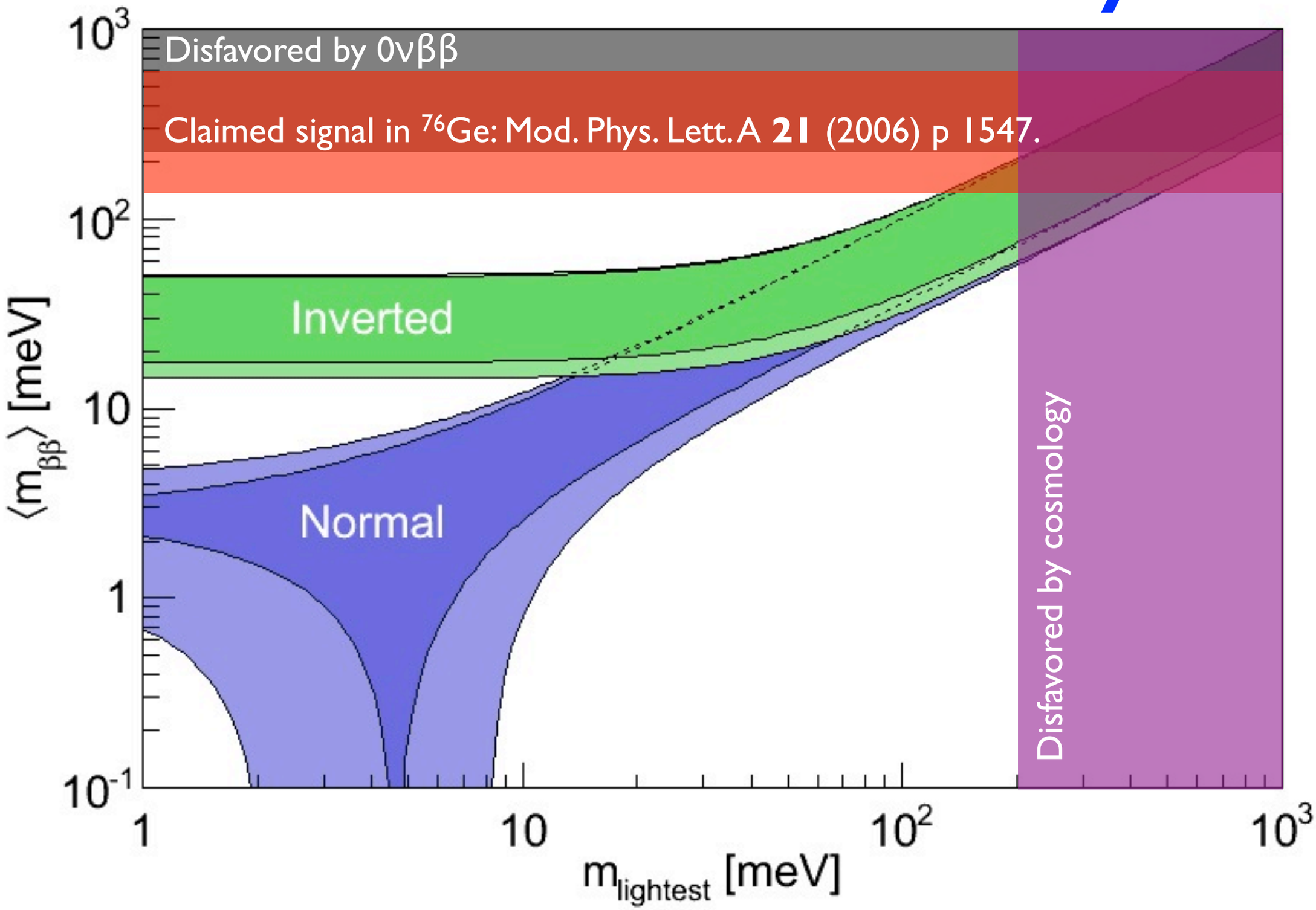

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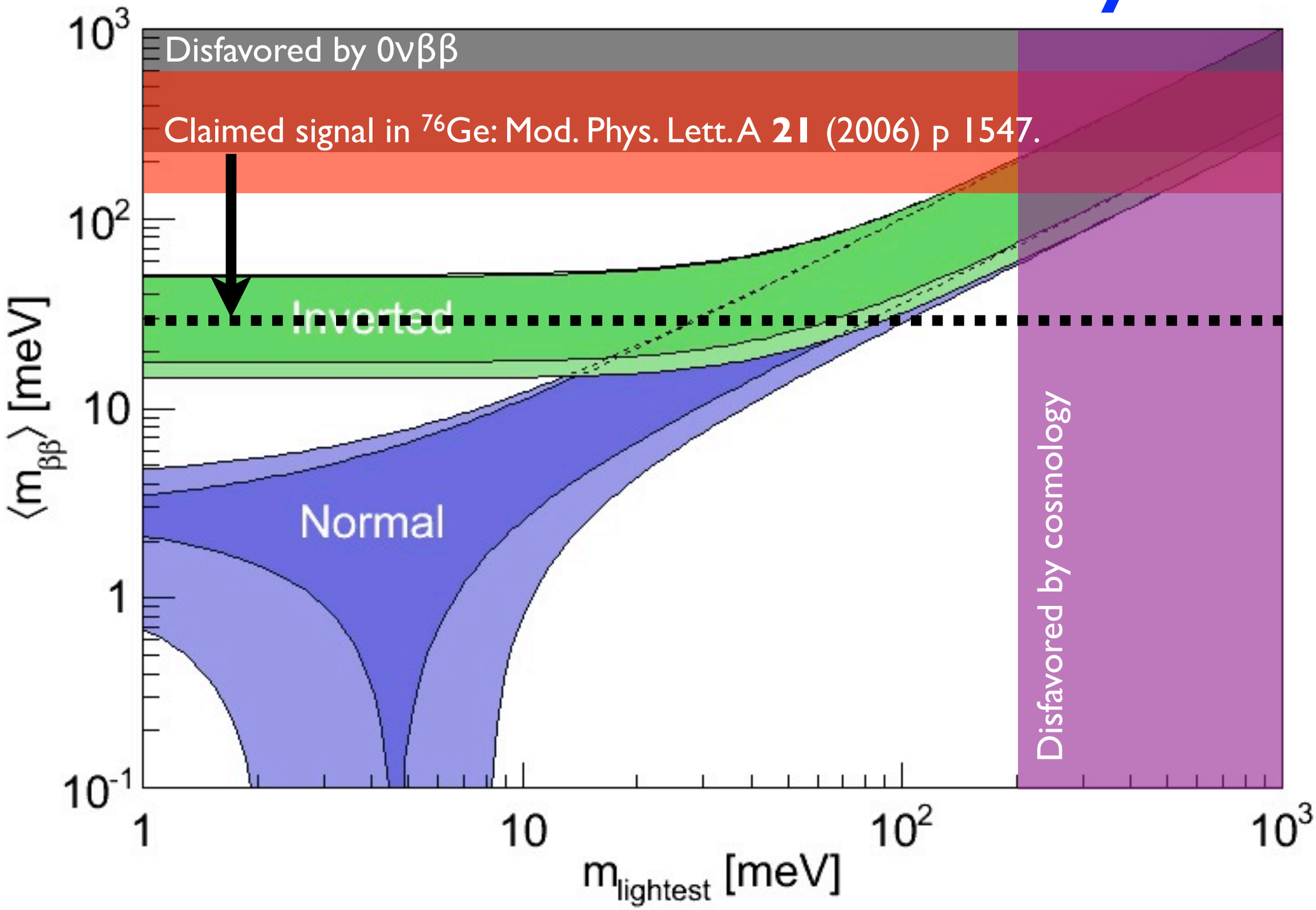

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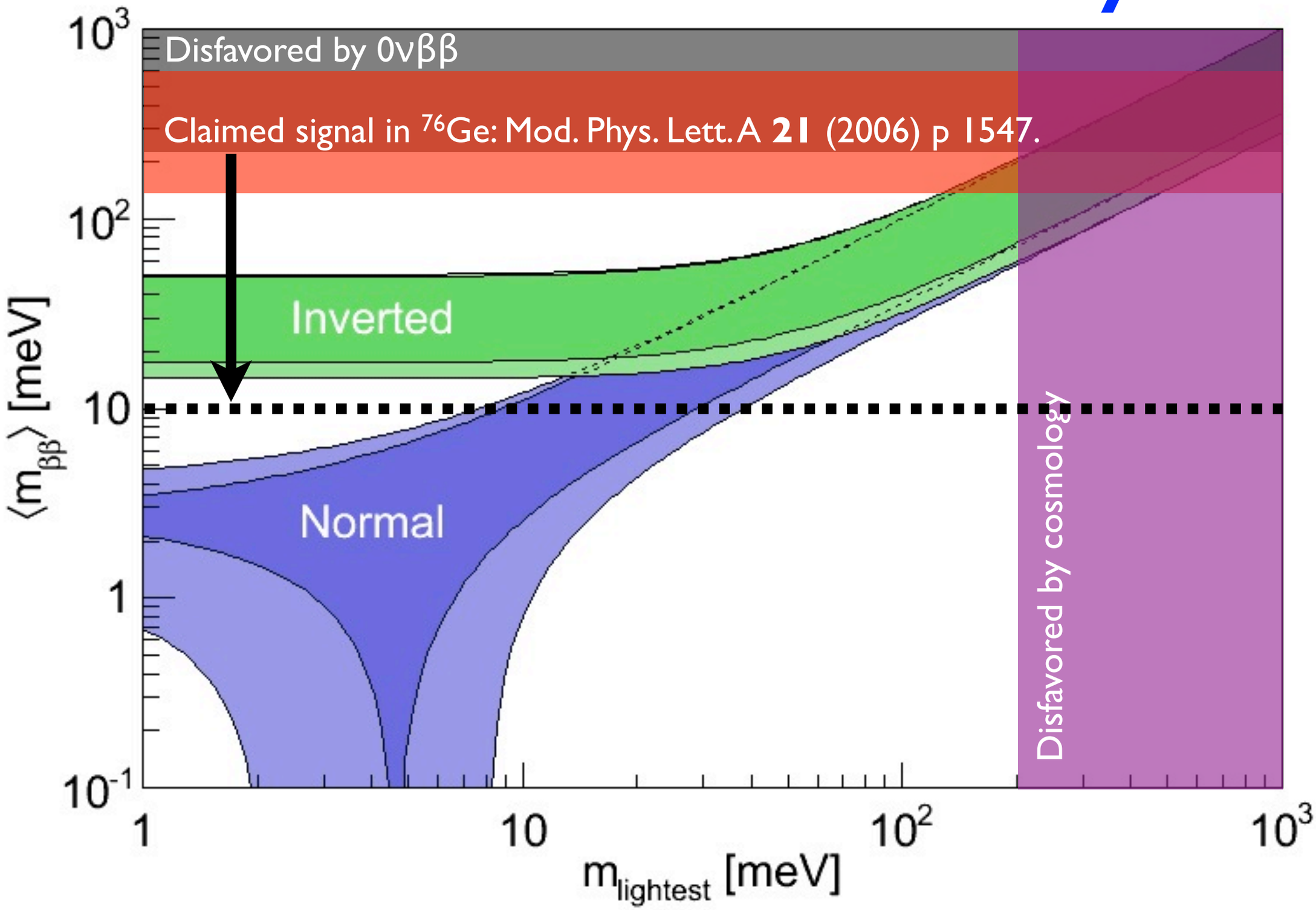
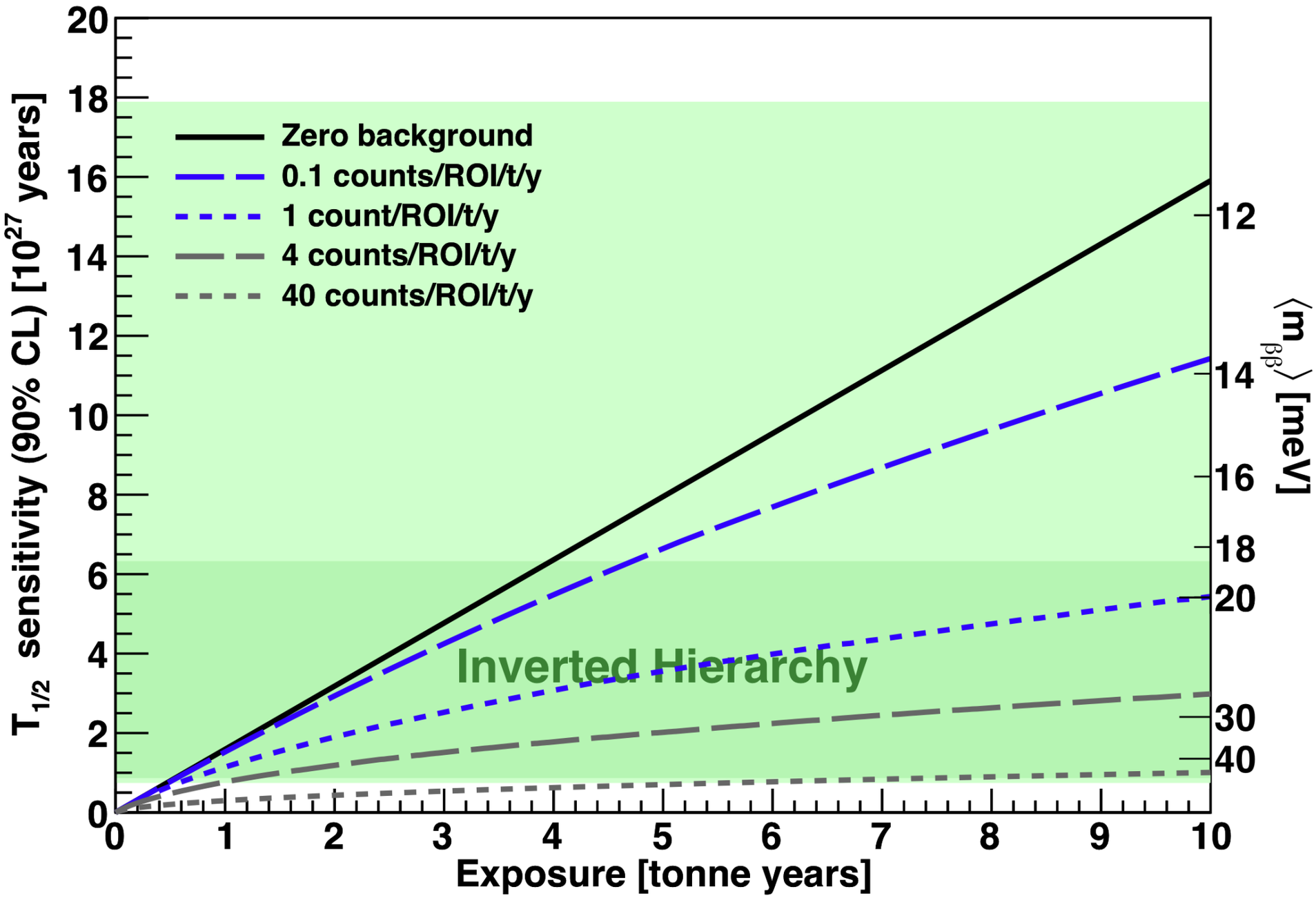
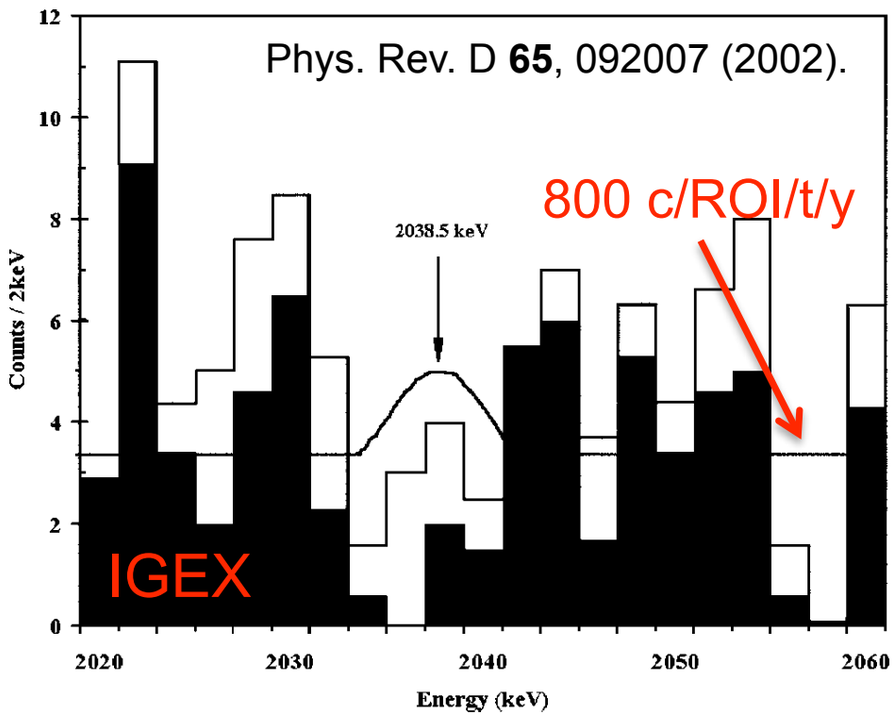
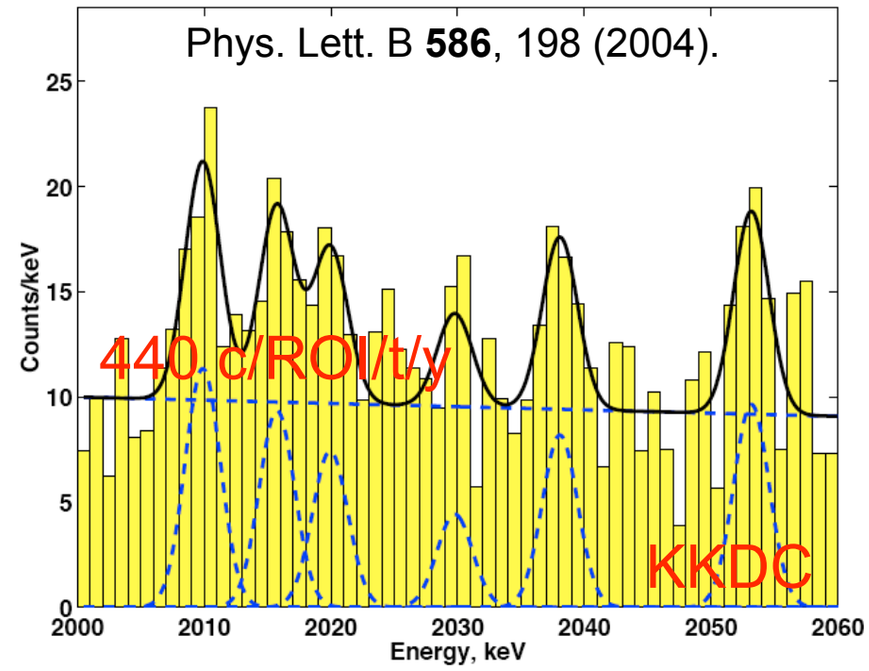


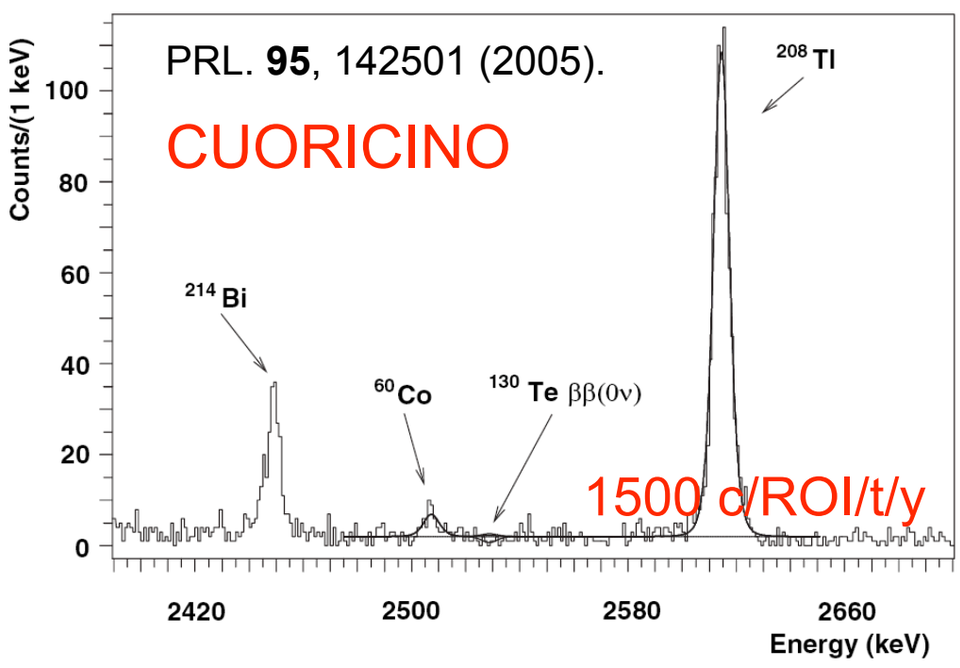
Ton-Scale Sensitivity

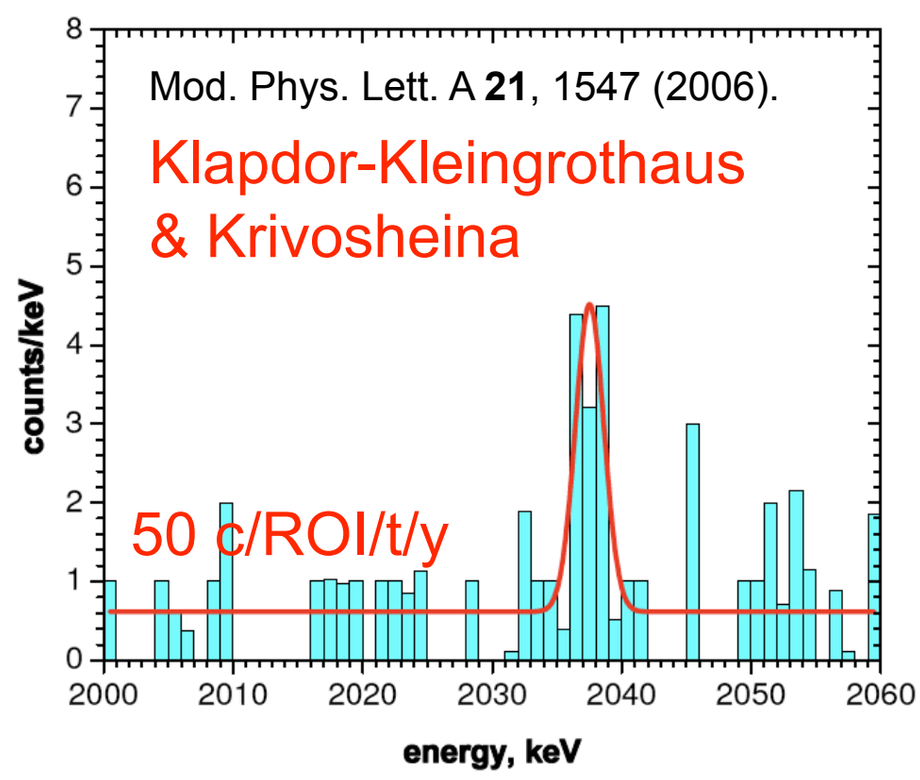


Recent Experiments

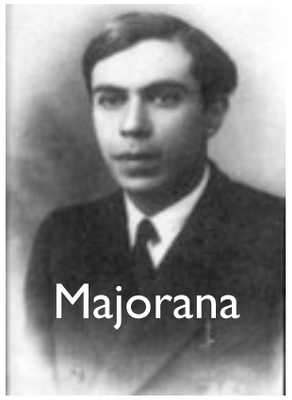


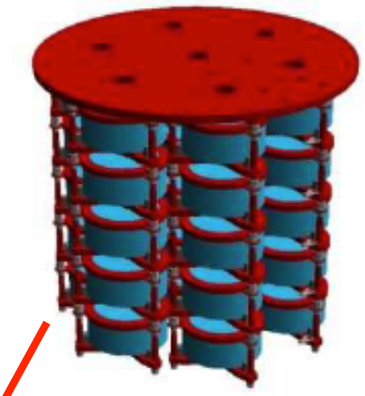




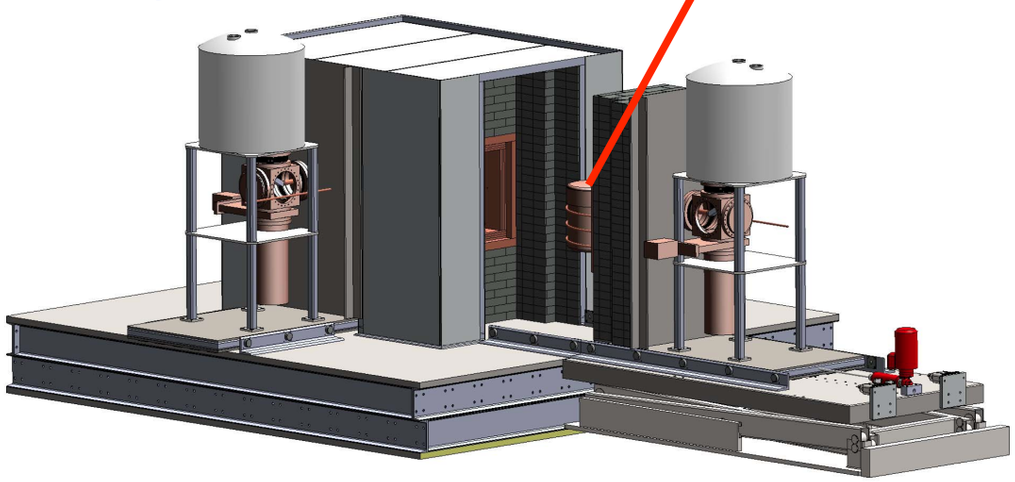


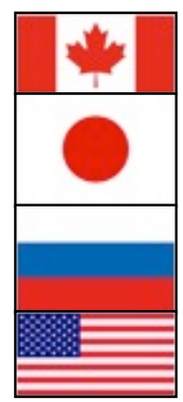
MAJORANA and GERDA

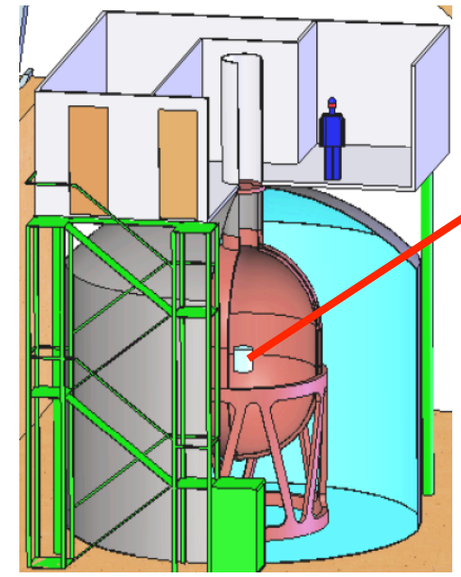


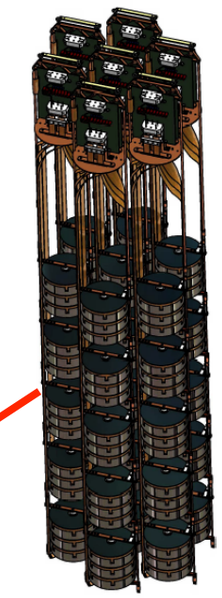


MAJORANA DEMONSTRATOR









- Modular ^{enr}Ge arrays in electroformed Cu cryostats
- E-formed Cu / Pb passive shielding
- 4π plastic scintillator μ veto

- ^{enr}Ge array submersed in LAr
- Water Cherenkov μ veto
- Phase I: ~18 kg (H-M/IGEX xtals)
- Phase II: +20 kg (BEGe)

- Open exchange of knowledge and ideas (e.g. MaGe MC)
- Intend to merge for ton-scale experiment using the best techniques

MAJORANA Collaboration

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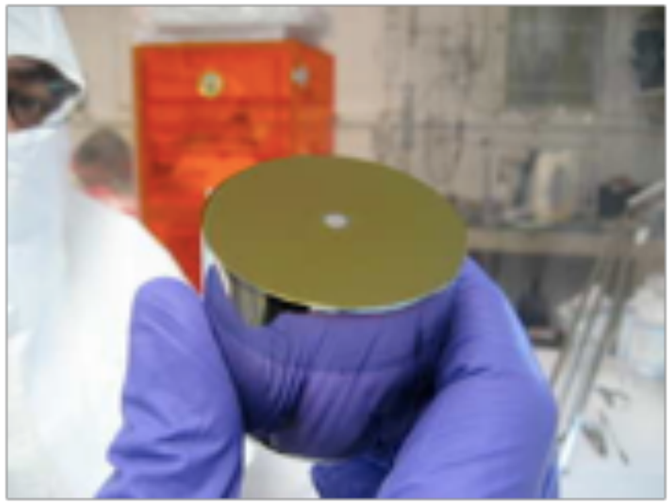
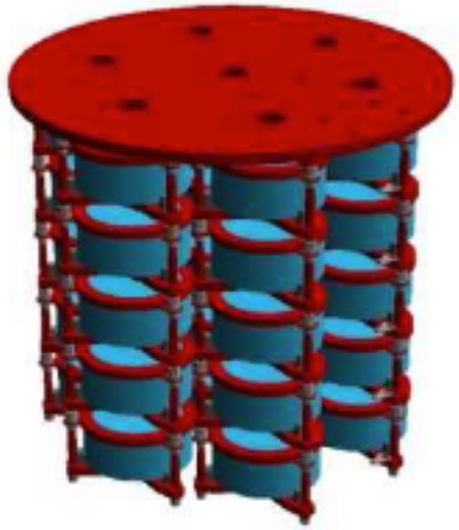
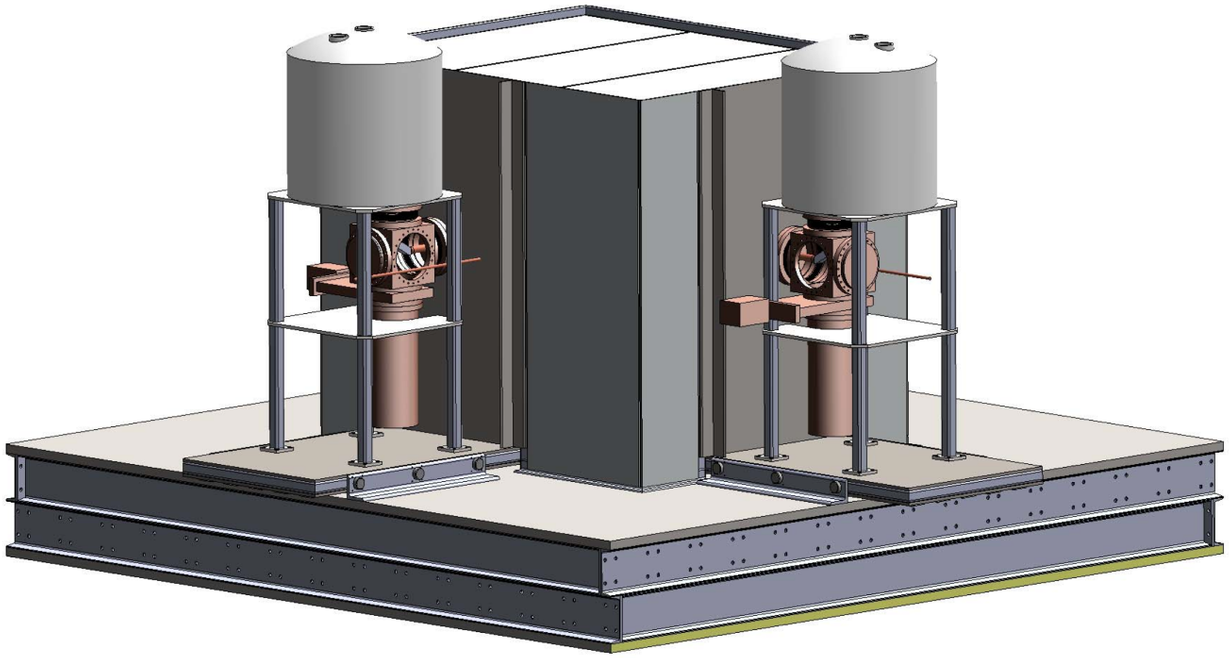
R. G. Hamish Robertson, Alexis Schubert, Tim Van Wechel, Brett Wolfe

The MAJORANA DEMONSTRATOR

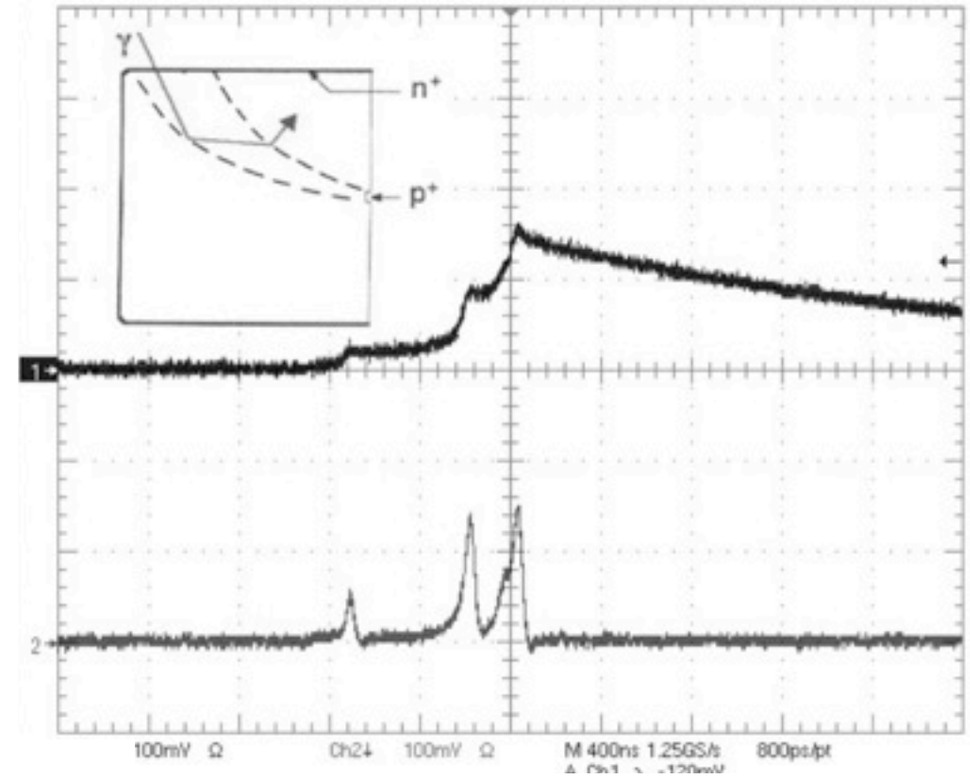
- 40 kg of Ge detectors, up to 30 kg enriched. Goal: demonstrate ton-scale background ≤1 c/ROI/t/y
- Detector technology:
  p-type point-contact detectors
- Agreement to locate at the 4850' level of Sanford Lab
- Modules:
  - Prototype: 3 strings ^{nat}Ge (2012)
  - Module 1: 3x^{nat}Ge + 4x^{enr}Ge (2013)
  - Module 2: up to 7 strings ^{enr}Ge (2014)



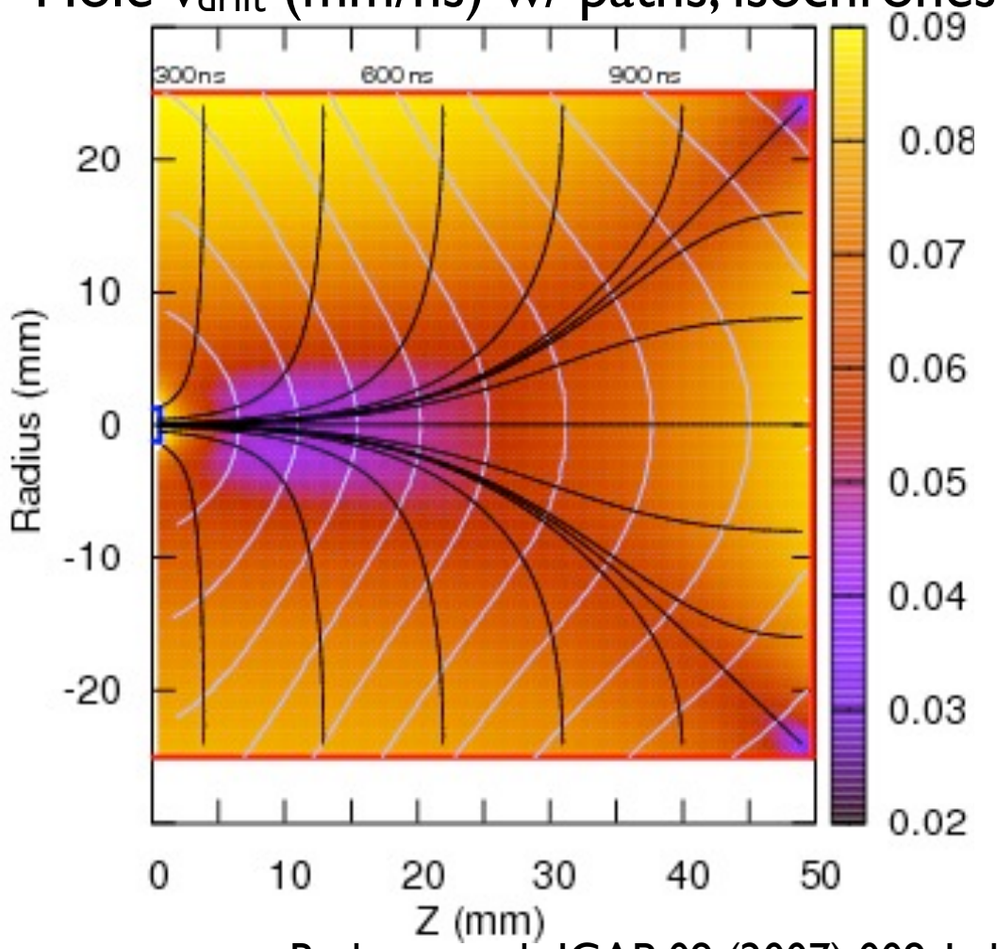


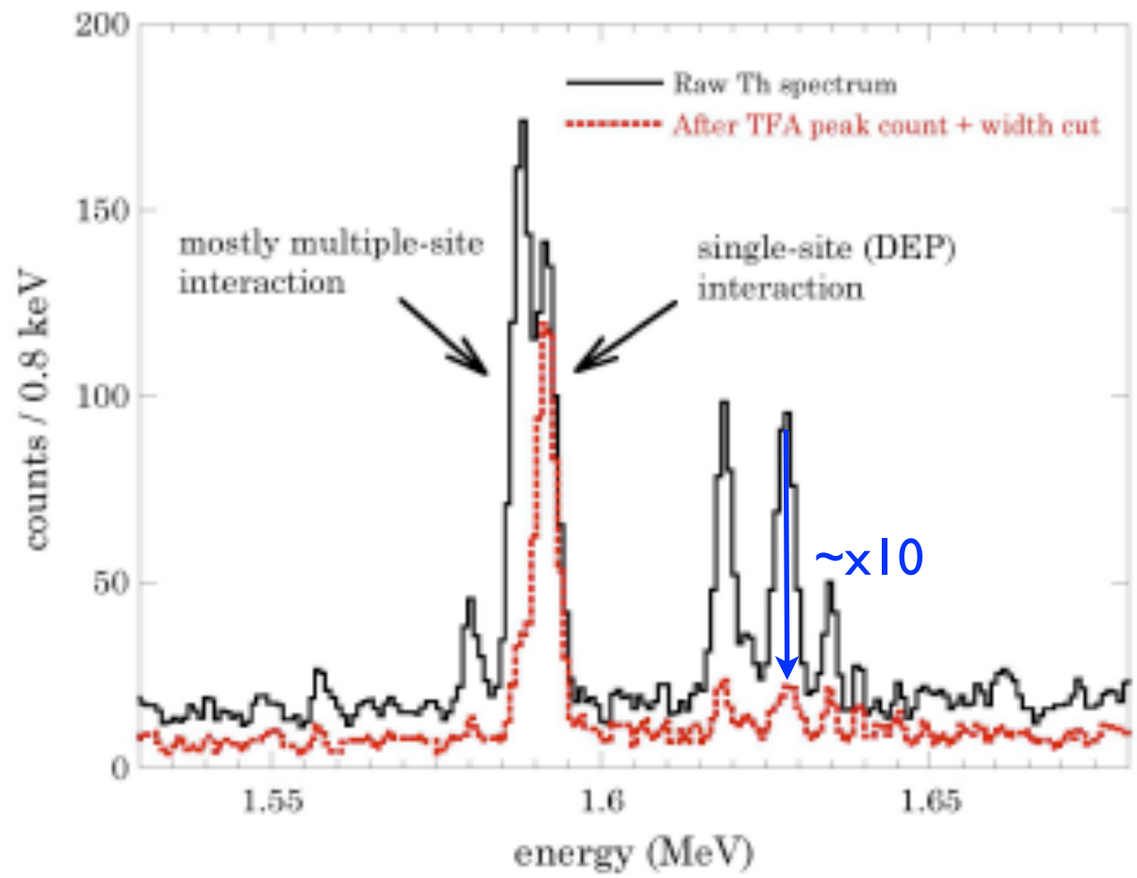


Point Contact Detectors



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

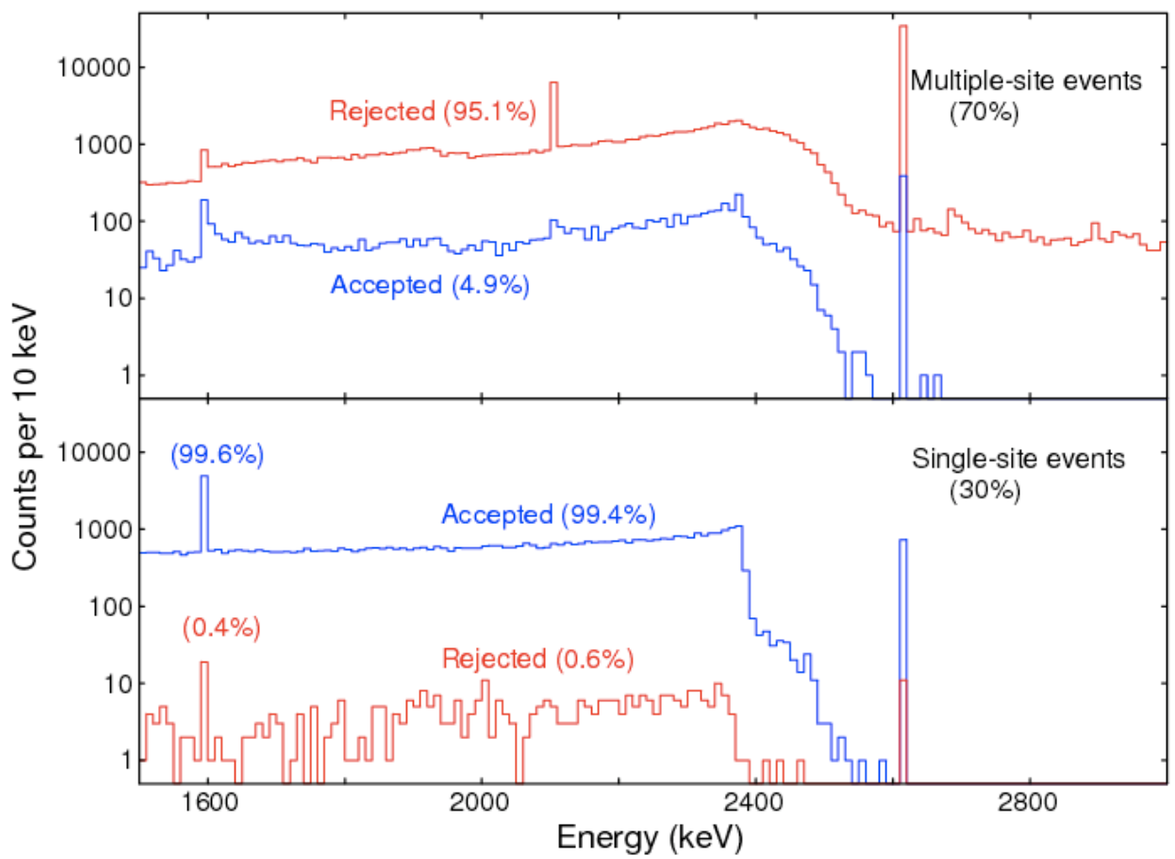


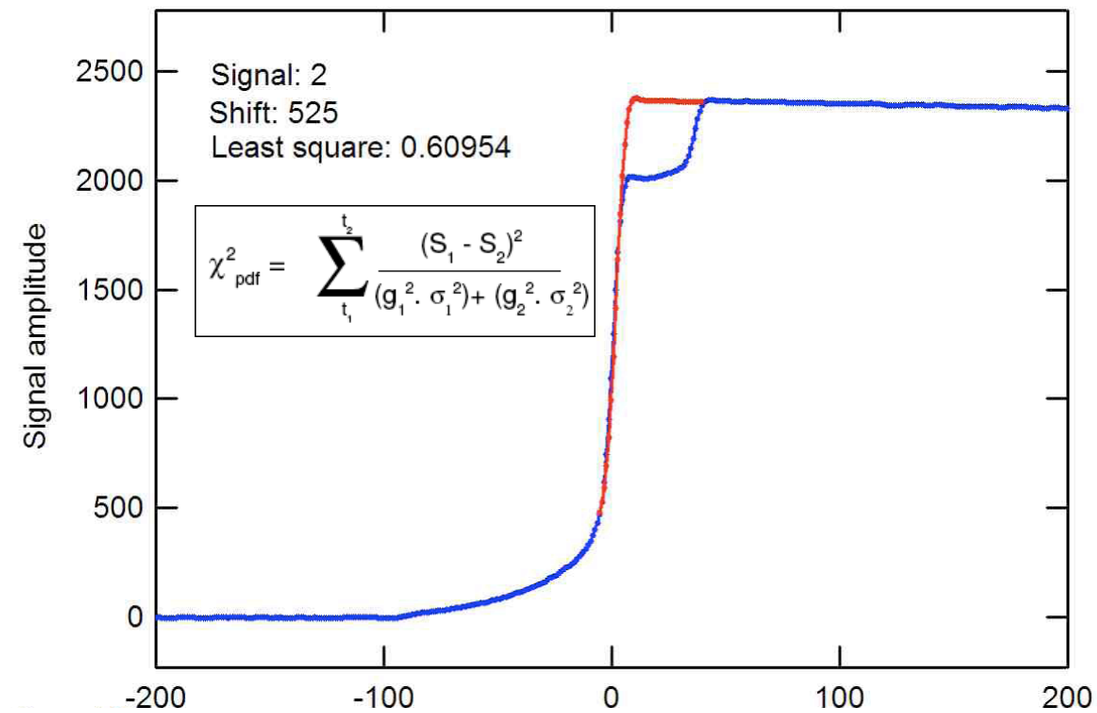


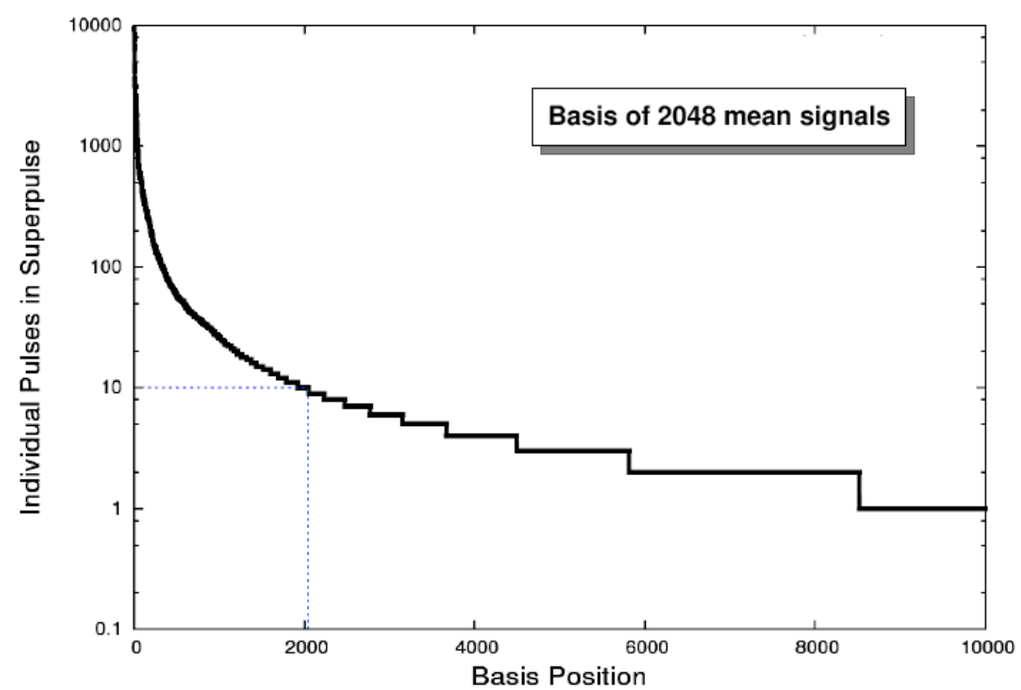
Barbeau et al., JCAP 09 (2007) 009; Luke et al., IEEE trans. Nucl. Sci. 36 , 926(1989).

χ^2-Based Pulse-Shape Analysis

- **Single-site event basis:**
  - **γ coincidence**
  - **cross-beam data**
  - **flood field data**
  - **simulation**

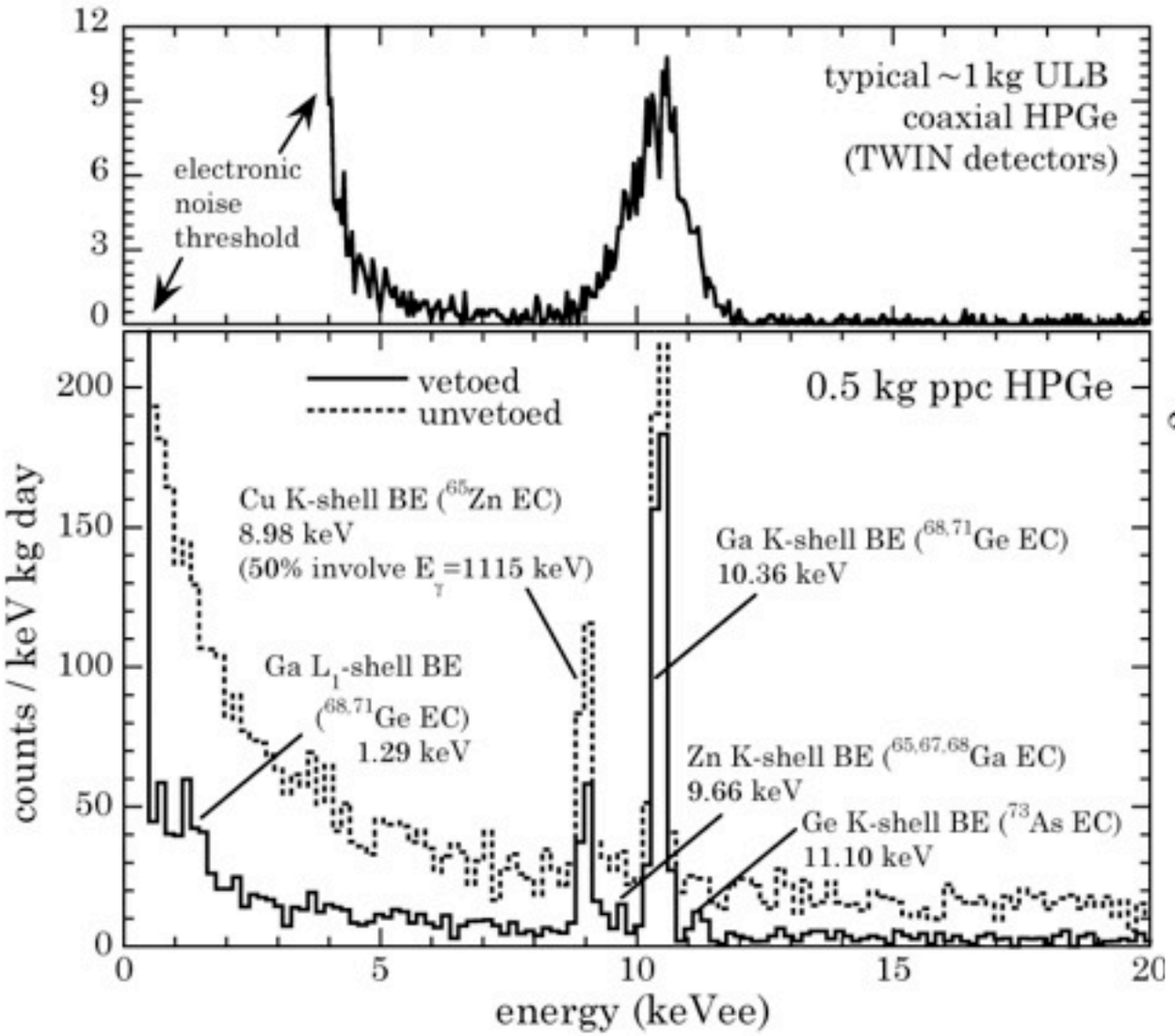


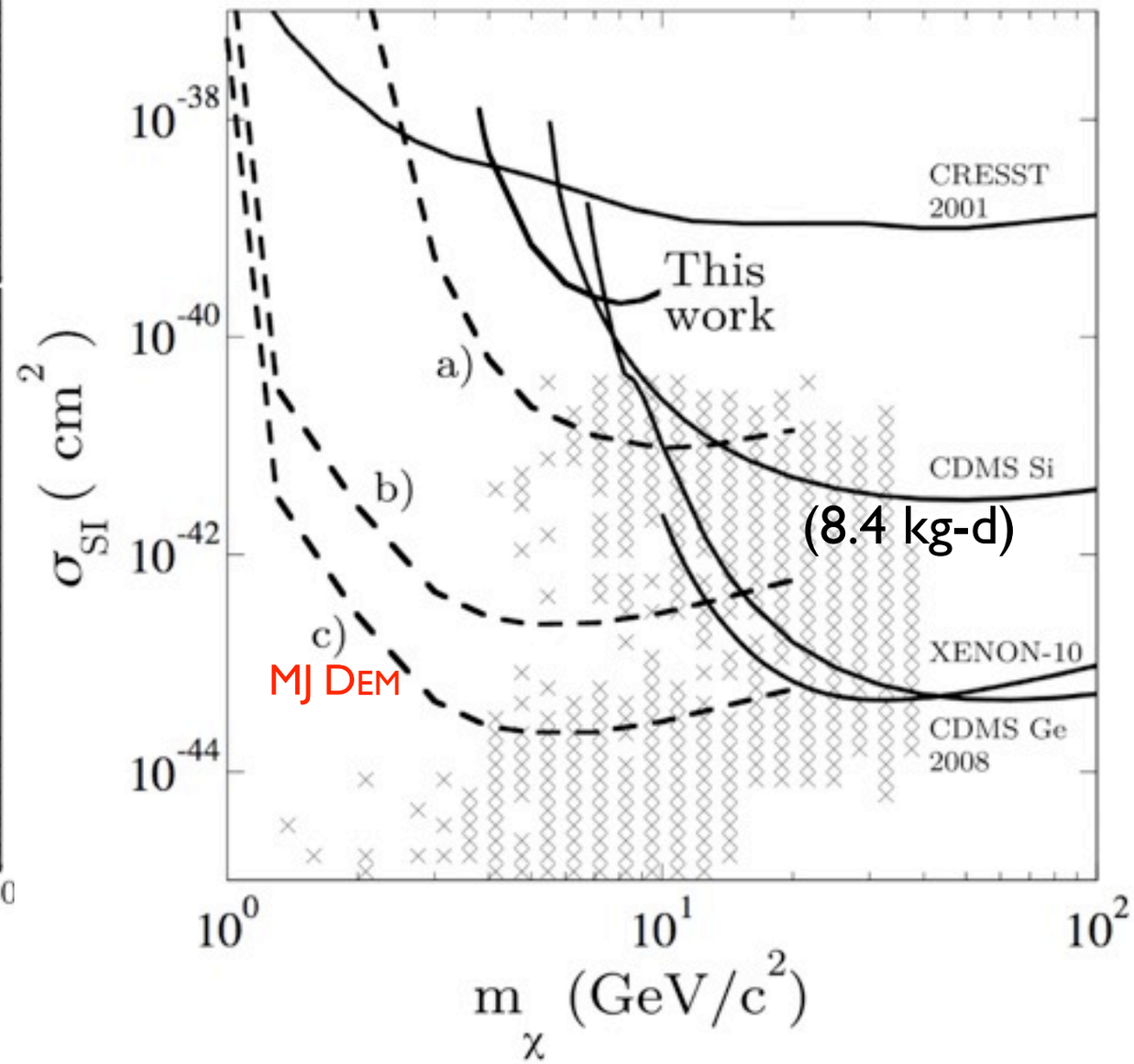




R.J.Cooper *et al.*, NIMA **629**, 303 (2011).

Point Contact Detectors

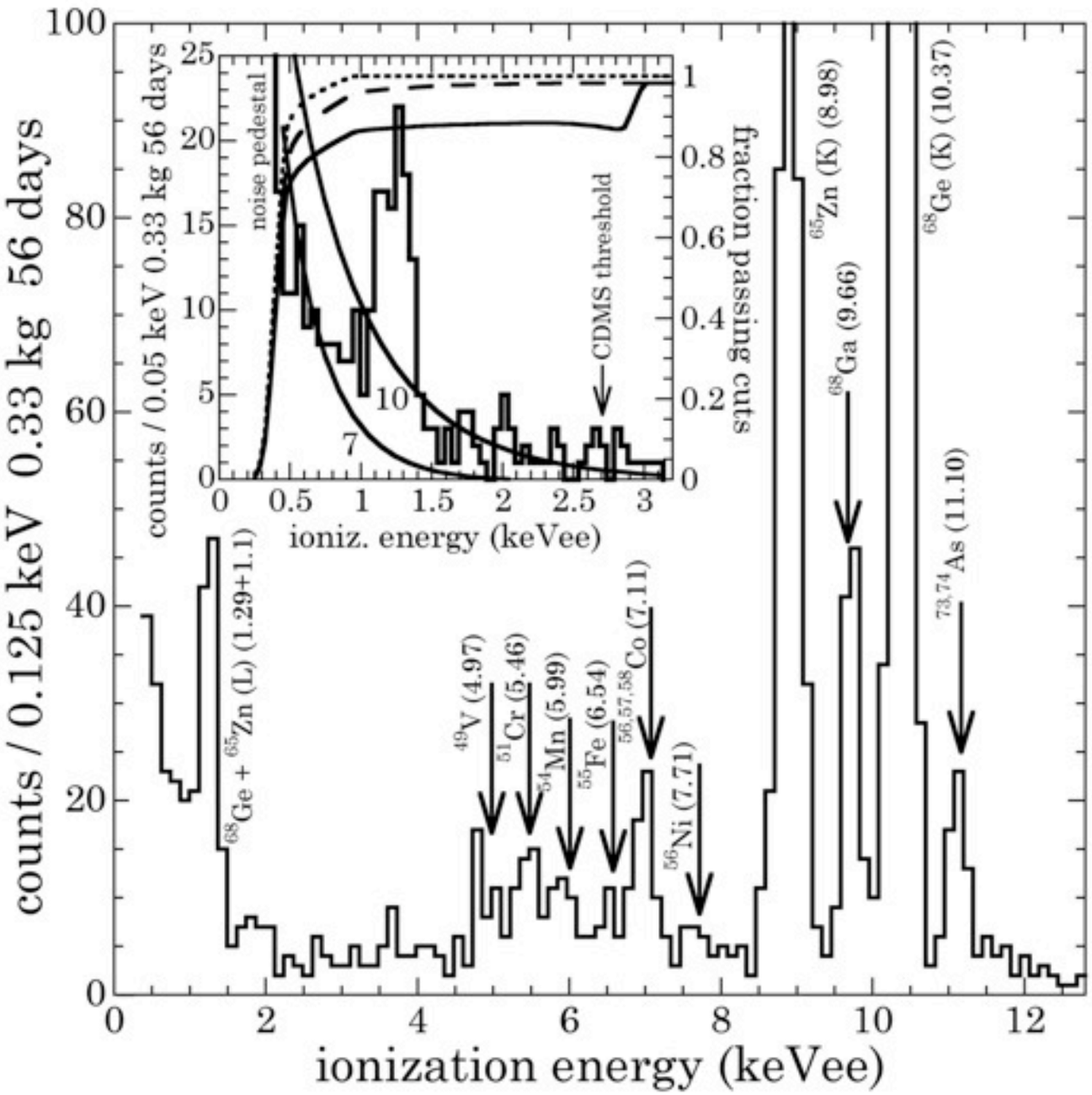


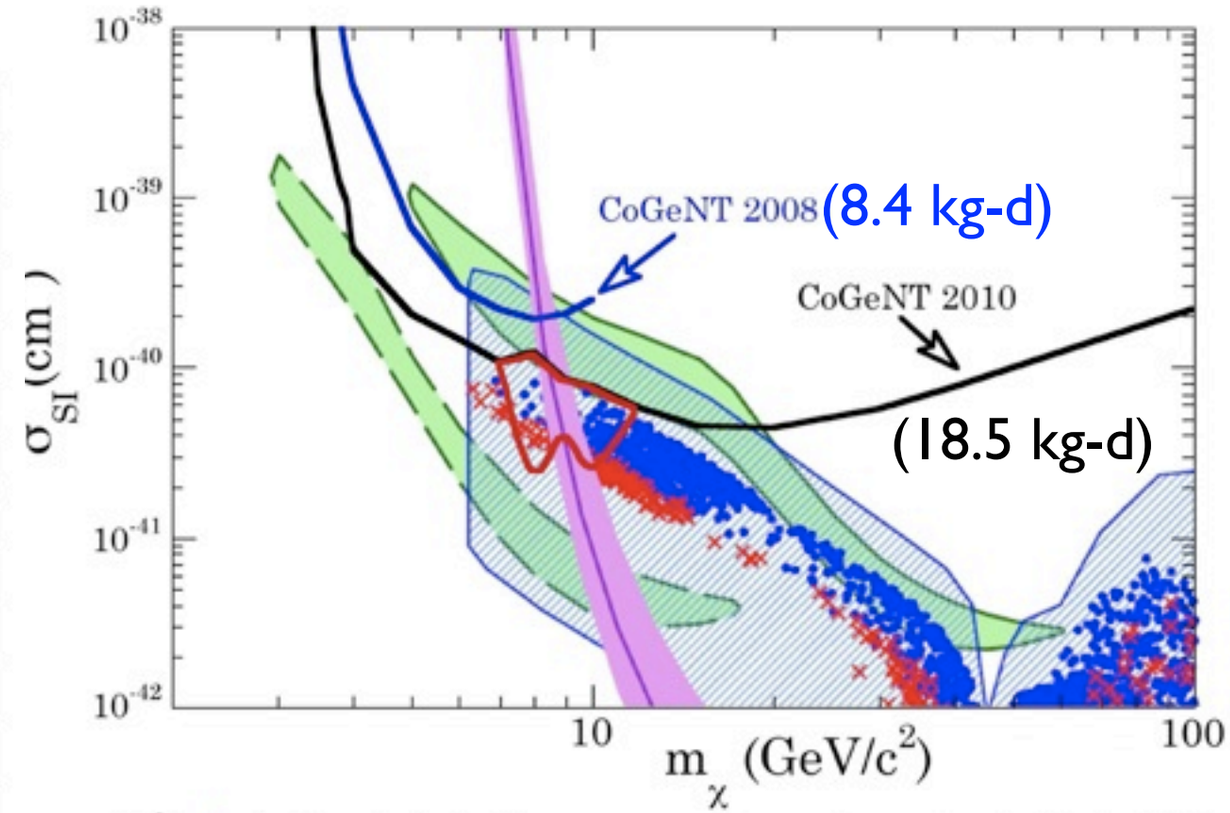


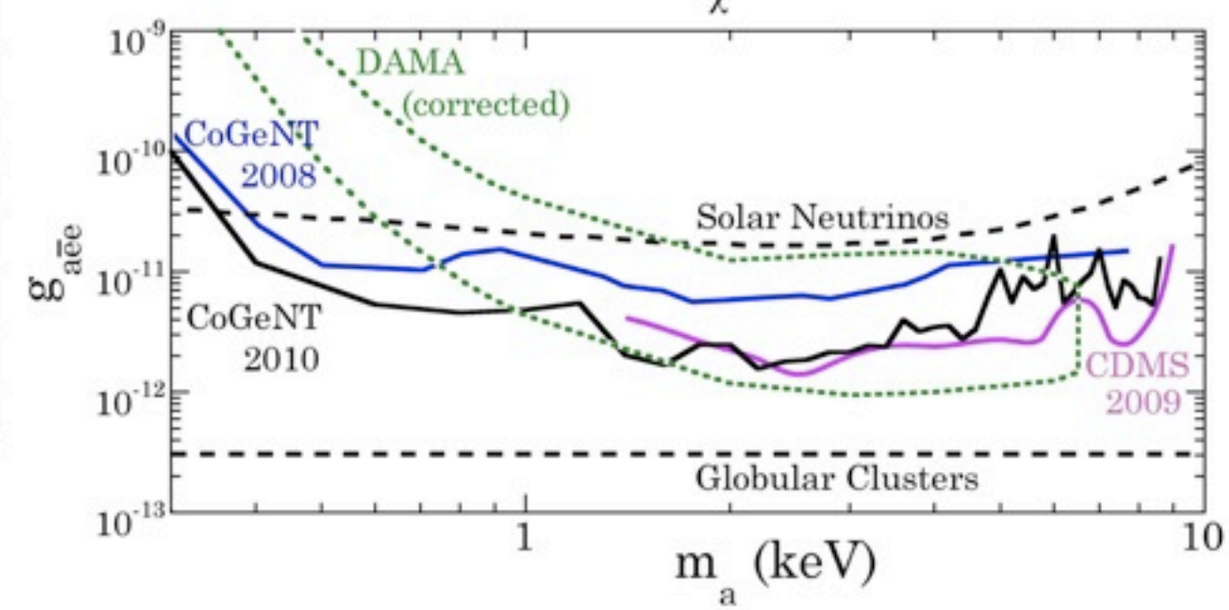
- DM (light/slow WIMPs, Q-balls)
- CνNS (Reactor, SN, solar ν...)
- Axions
- e^- decay, PEP-violation, ...

C. E. Aalseth *et al.*, Phys. Rev. Let. **101**, 251301 (2008);
Z. Ahmed *et al.*, arXiv:0902.4693 [hep-ex]

CoGeNT Results







C.E.Aalseth *et al.*, arXiv:1002.4703.

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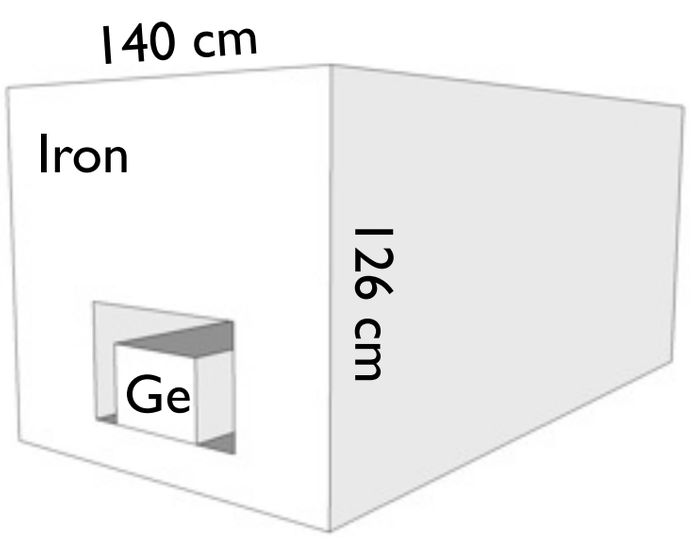
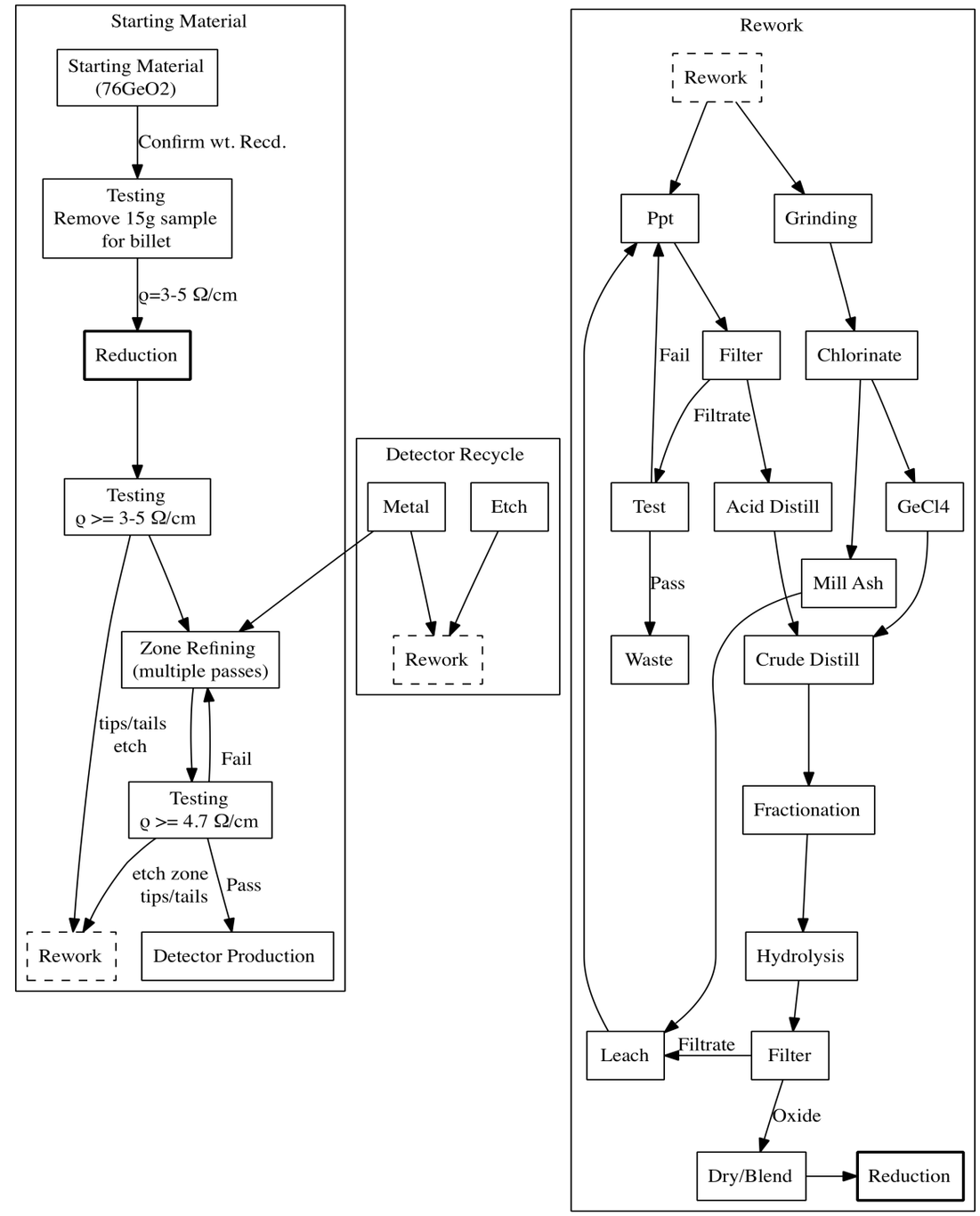
Enriched Germanium

- Centrifuge enrichment of GeF_4, convert to GeO_2 in Russia
- Establishing processing facility in Oak Ridge to convert enriched GeO_2 to metal (via NSF)
- 1st order of ^{enr}Ge placed!
- Studying shielding options for transport from Russia



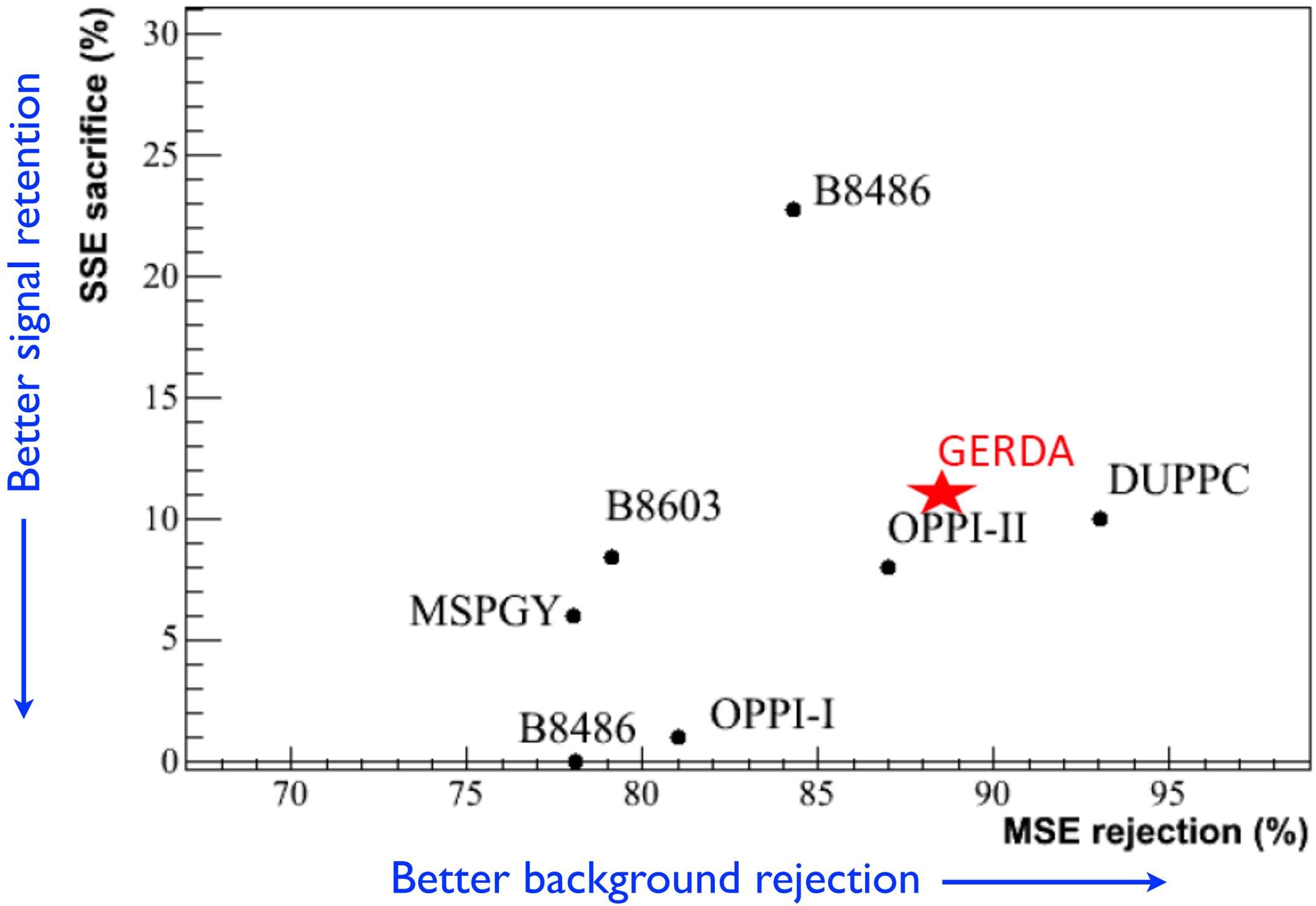


PPCs Studied / In Hand

Institution	Manufacturer	Dimensions ∅ x h [mm]	Type	Date
LBNL	Paul Luke	50x50	NPC	1987
		62x50	Segmented PPC	2008
		20x10	Mini-PPC (x3)	2009
		62x50	PPC	2009
	Canberra USA	70x30	Modified BEGe	2011
U. Chicago	Canberra Fr.	50x44	PPC (BEGe)	2005
	Canberra USA	60x30	BEGe	2008
PNNL	Canberra Fr.	50x50	PPC	2008
ORNL	PHDs	62x46	PPC	2008
	Canberra USA	90x30	BEGe (large)	2009
LANL	PHDs	72x37	PPC	2008
	Canberra USA	70x30	Mod. BEGe (33)	2009-2010
	ORTEC	62x51	PPC	2009
	ORTEC	67x54	PPC	2010
	PGT	70x30	PPC	2010
UNC	Canberra USA	61x30	M. BEGe (LBG)	2009
		61x32	Modified BEGe	2010
		70x30	Mod. BEGe (x3)	2010

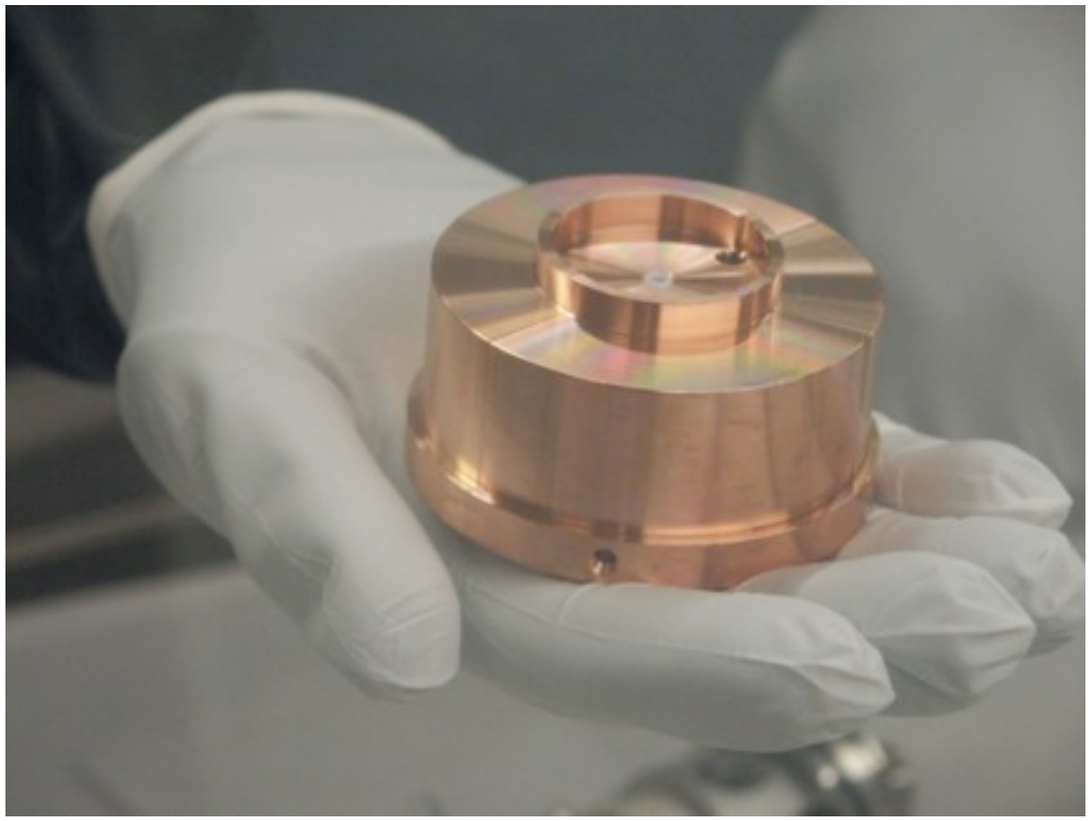
Prototype / Module 1

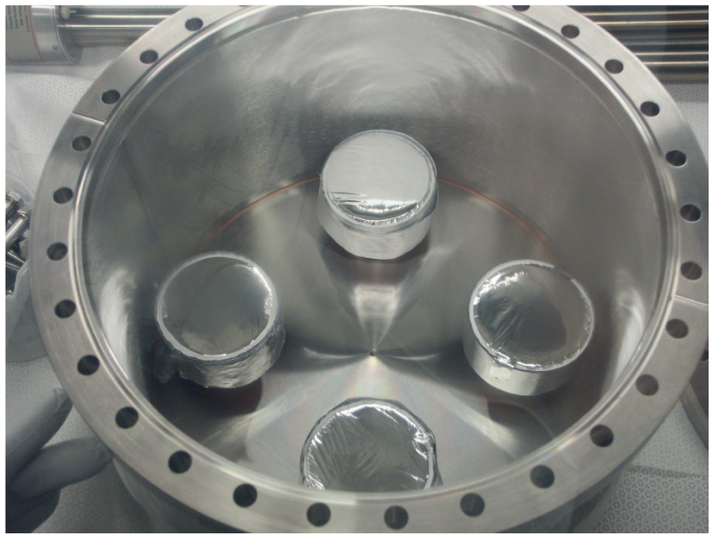
PPCs Studied / In Hand



First Module BEGes

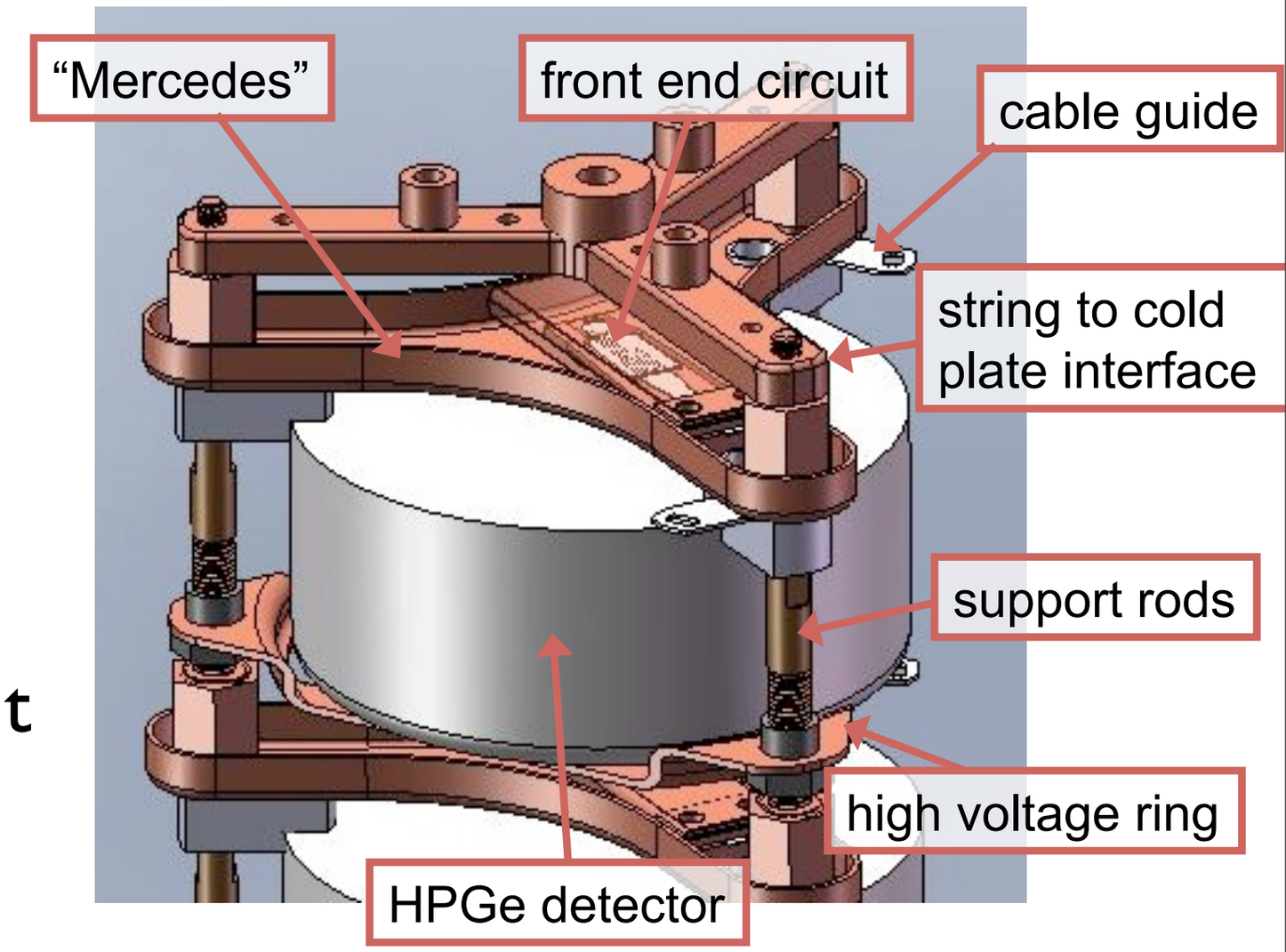
- 18 detectors delivered in 2009, 15+3 more in 2010
- 19 transferred underground to Sanford Lab late 2010





Detector Mounts

- EFCu and plastic, minimizing part count
- Thermally shorted to coldplate
- HV on outer contact
- Contact spring integrated into front end board mount
- Currently iterating design and prototyping



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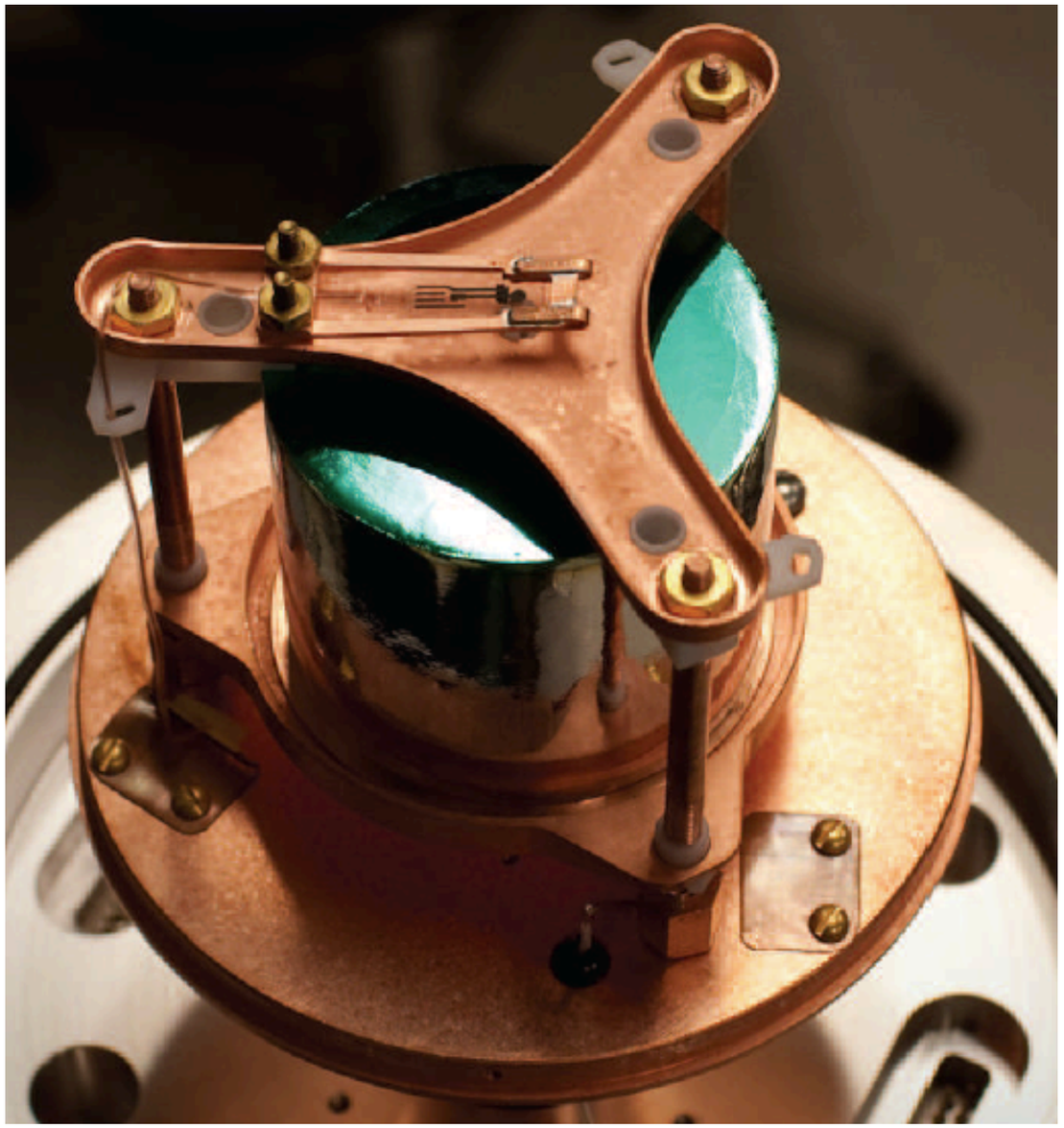

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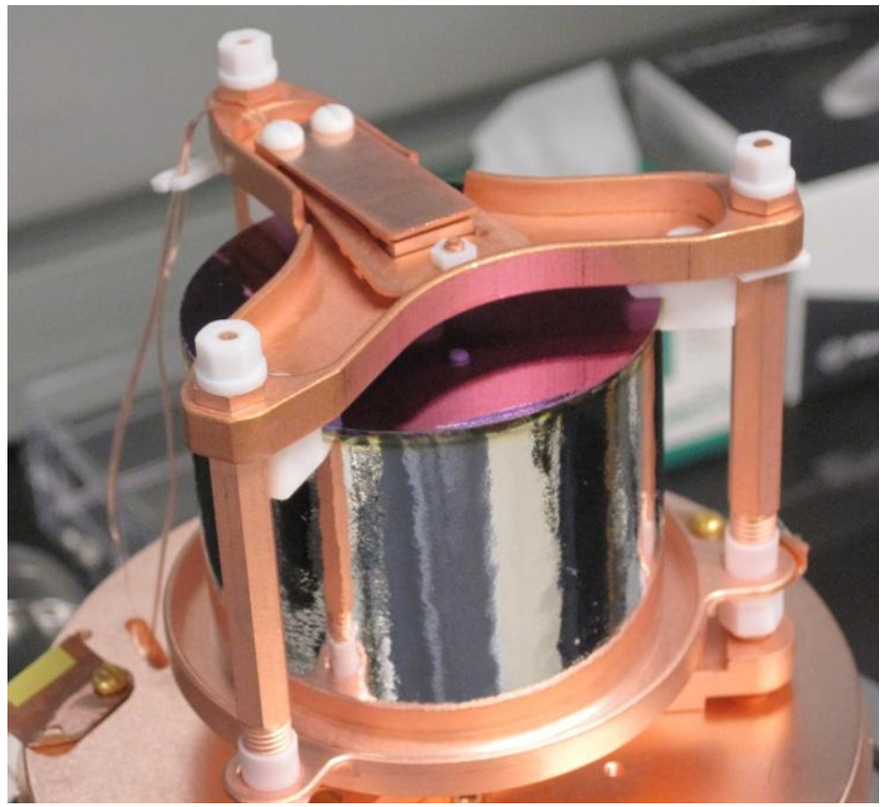
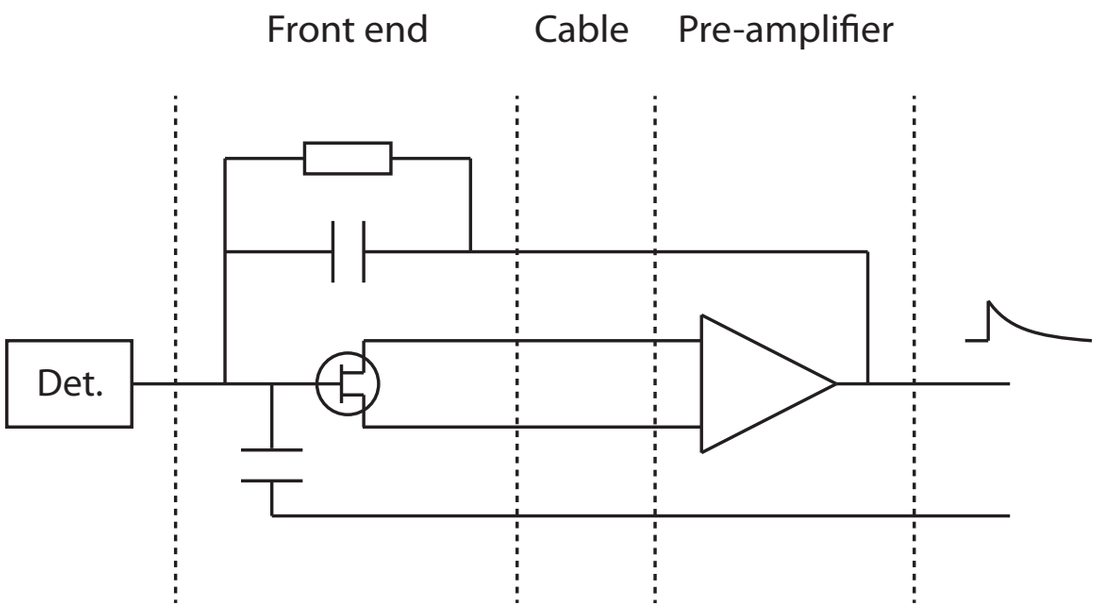
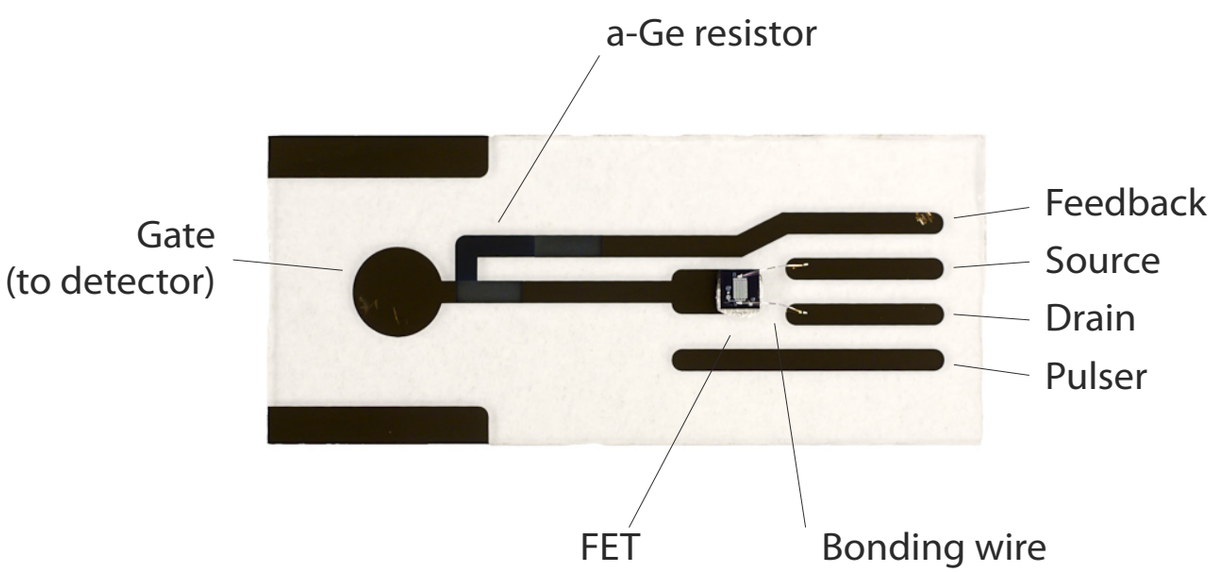


Front End Electronics





- Trace proximity provides ~1 pF capacitance
- Silica or sapphire substrate provides thermal control
- Amorphous Ge resistor: deposit in H environment gives proper R at low T
- MX-11 FET, custom low-noise preamp
- Have achieved possibly world record low-noise for this kind of circuit

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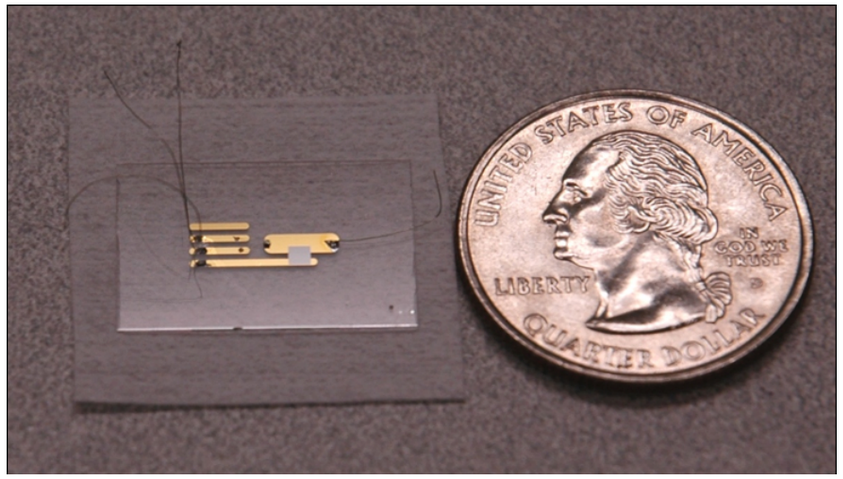

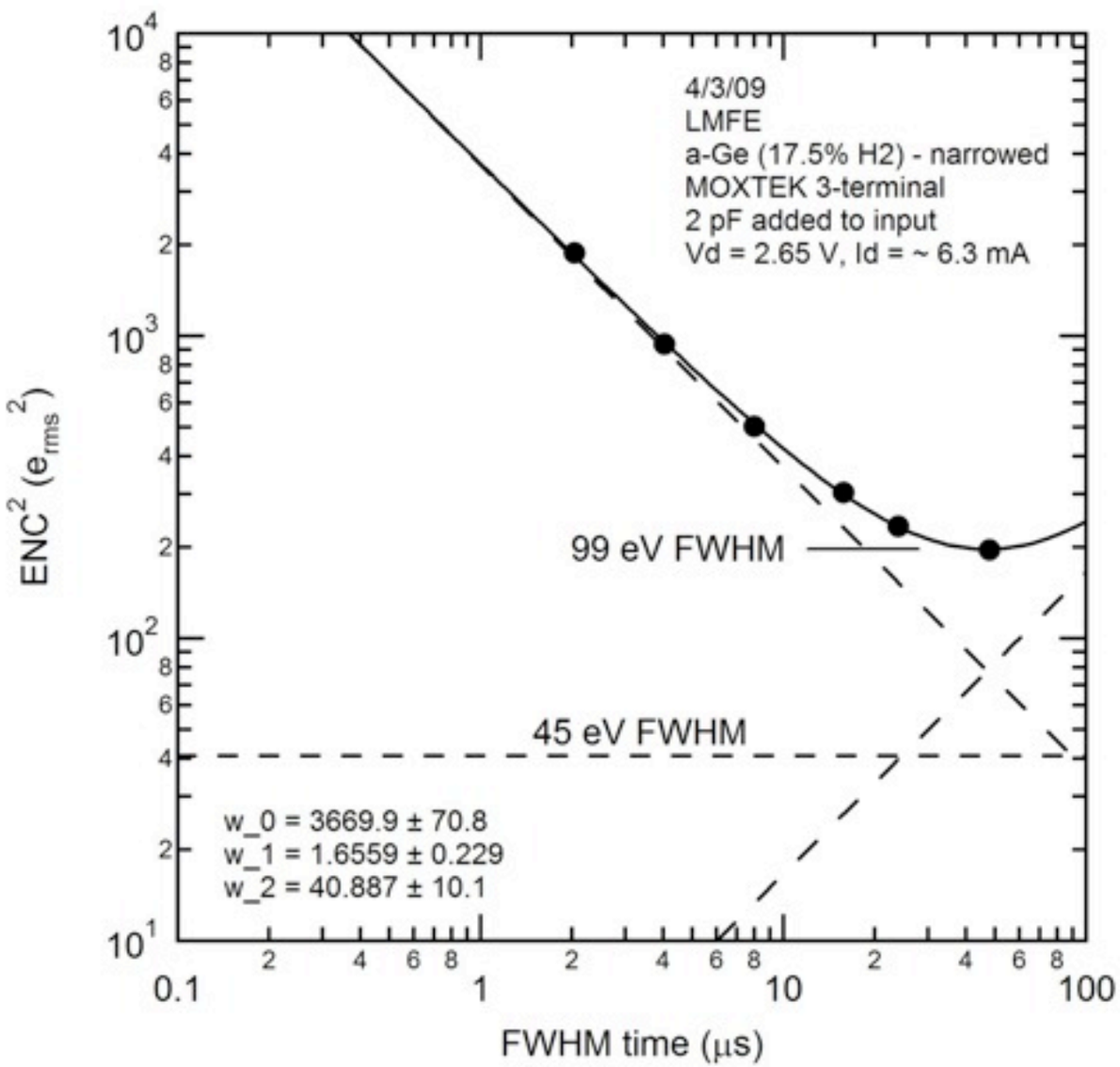

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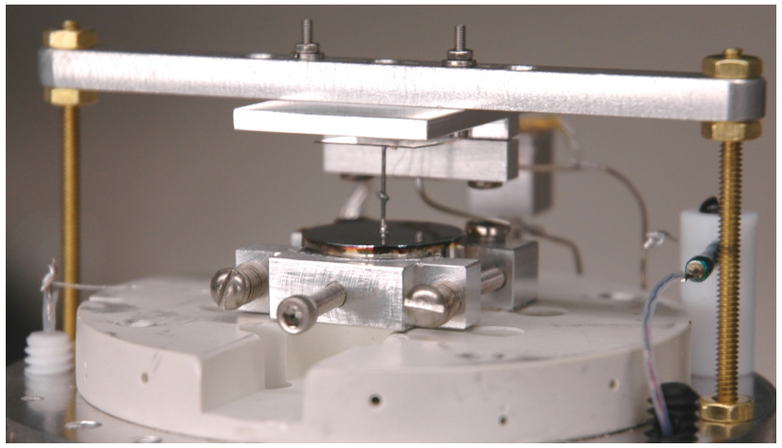

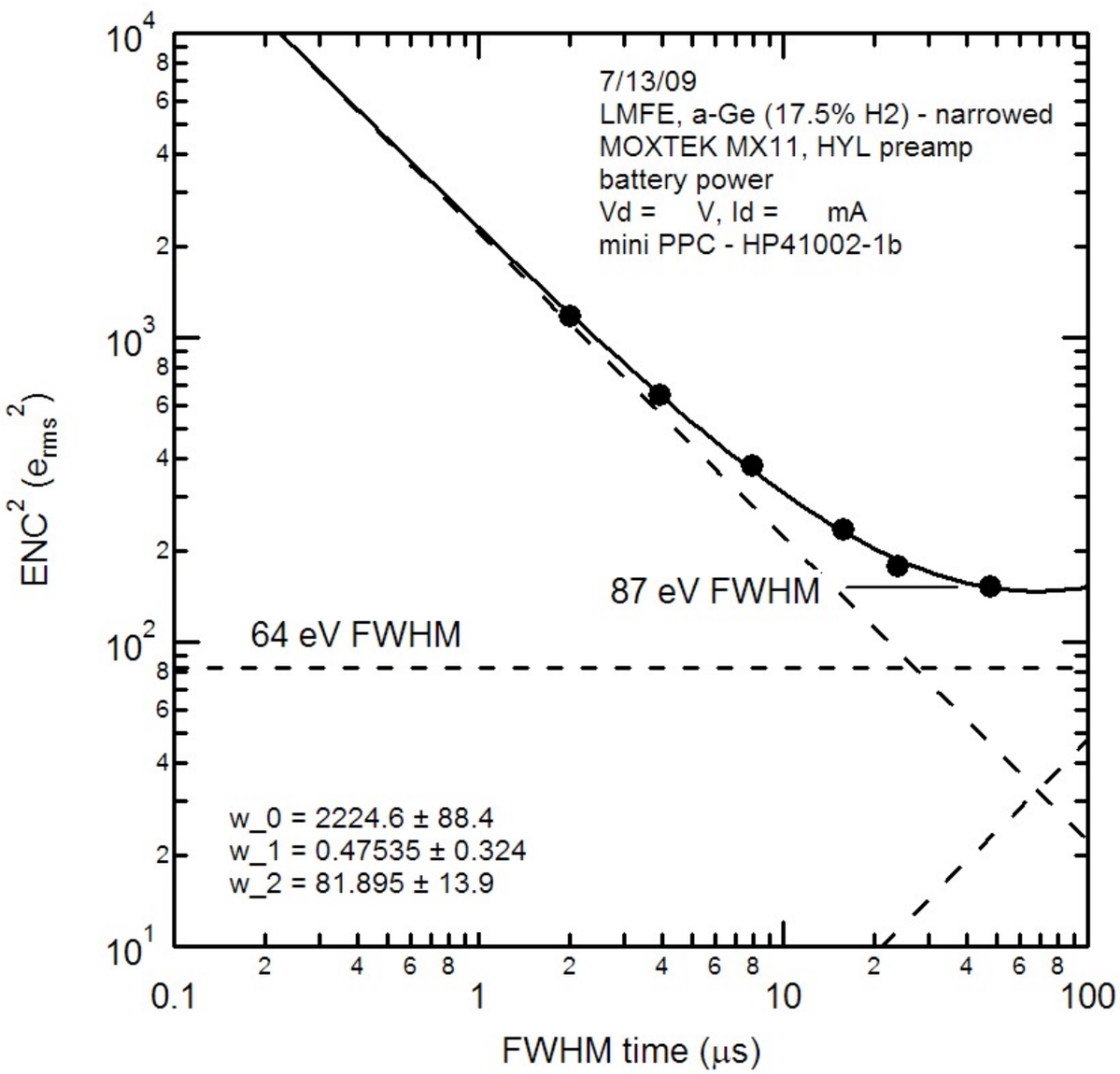

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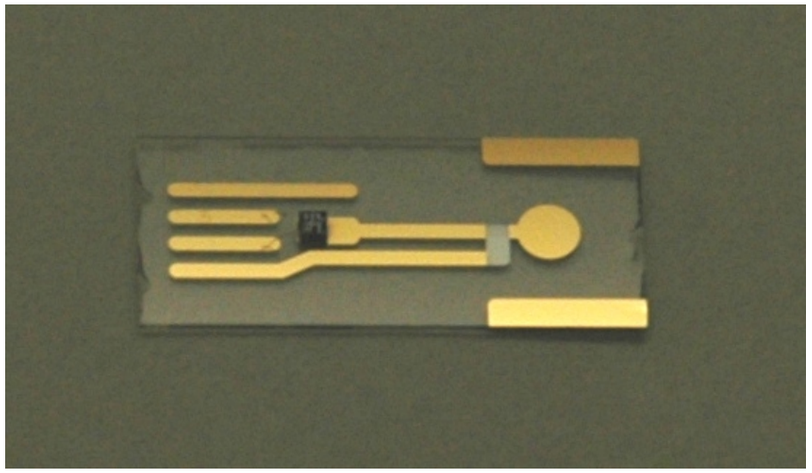

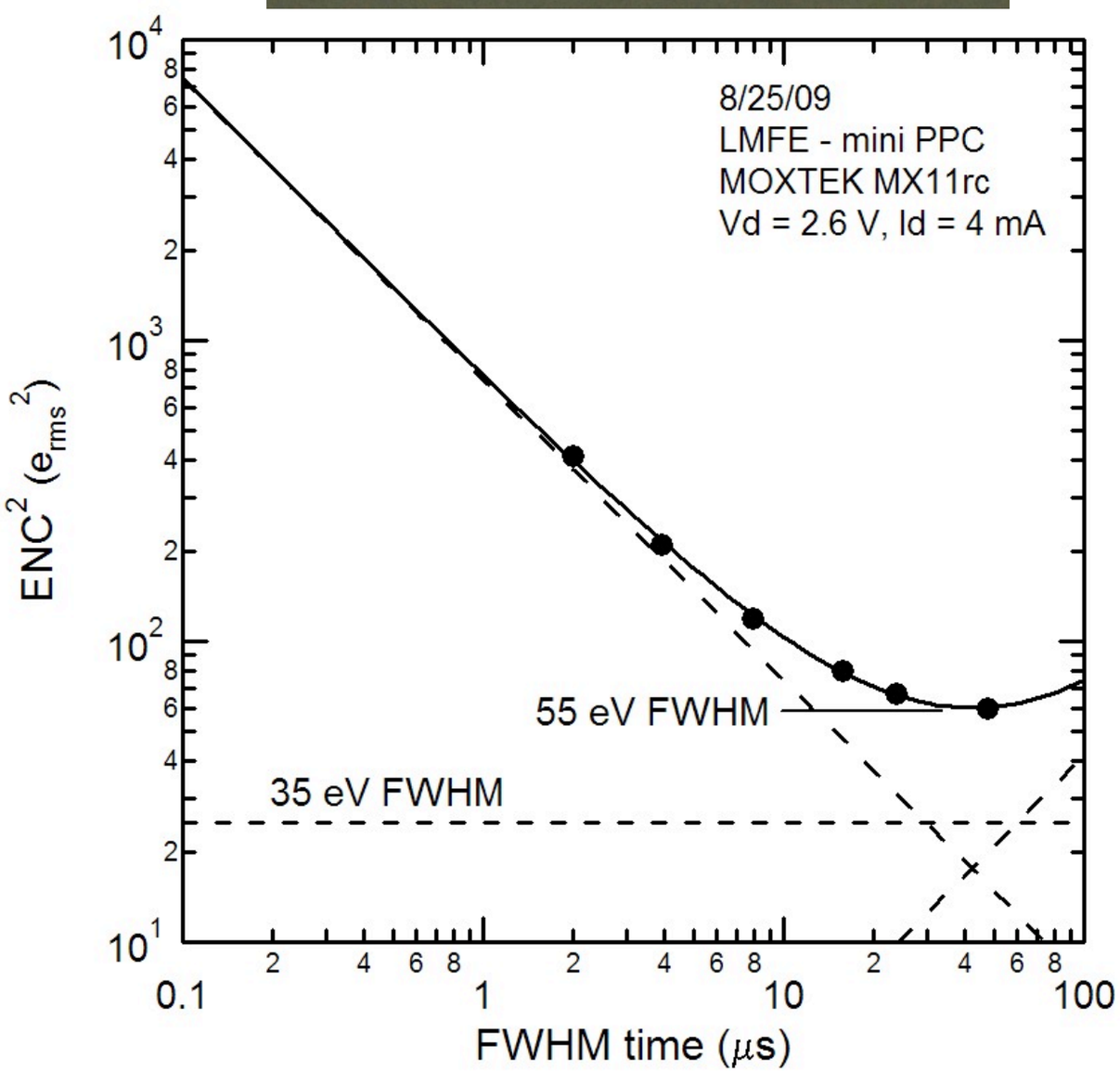

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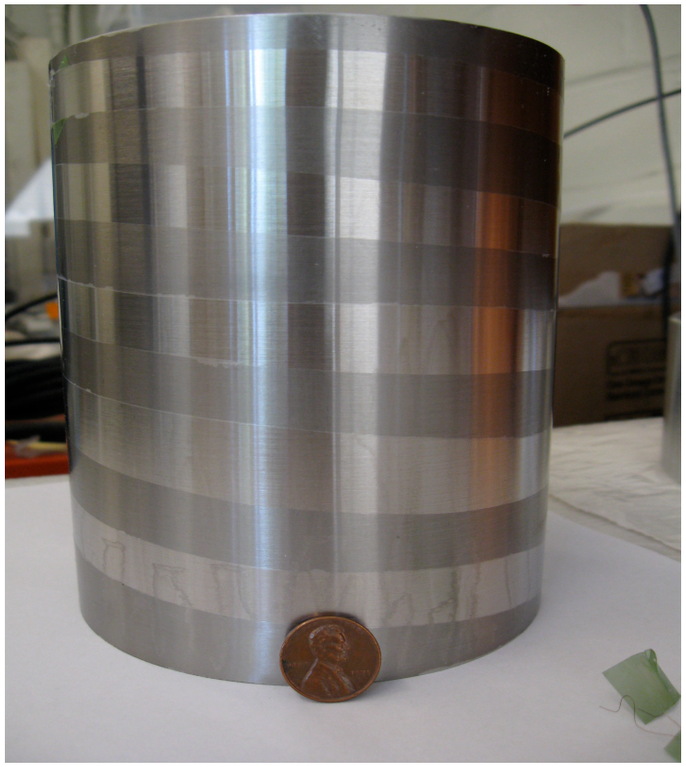
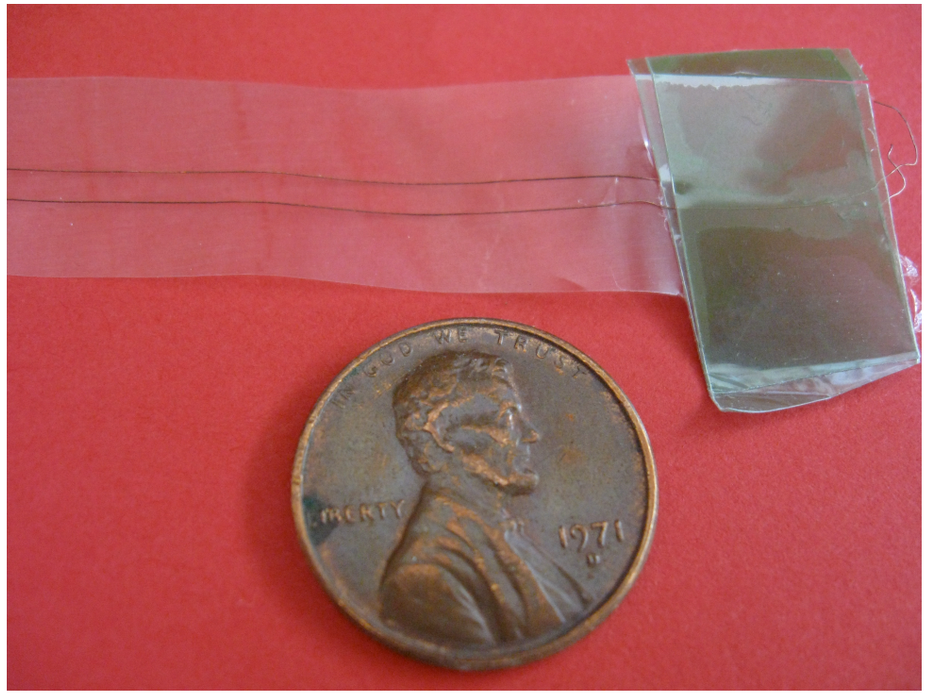
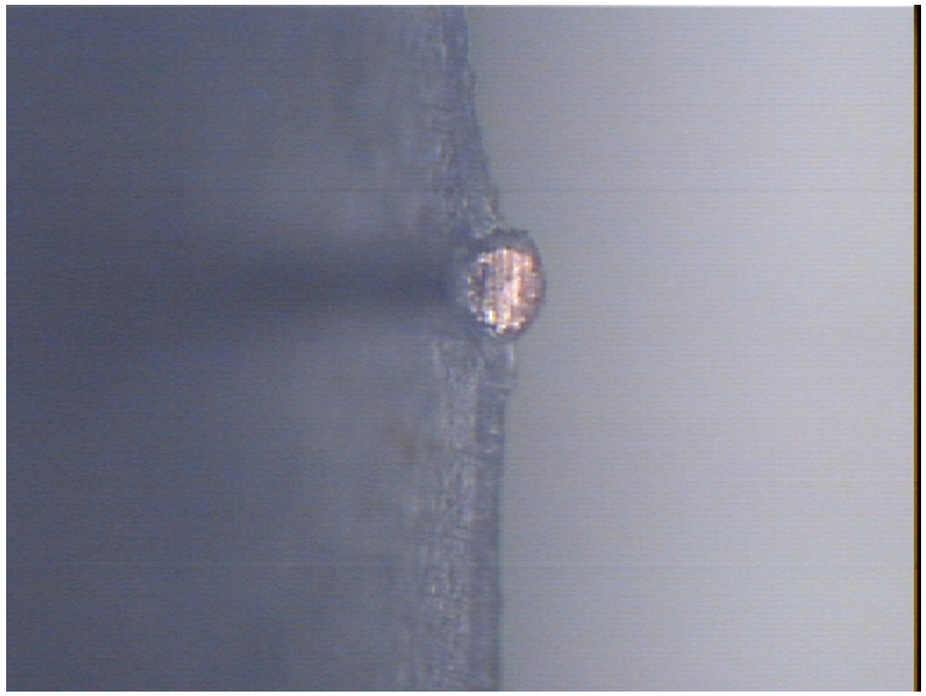
Cables

- 3-mil Cu wire
- Coated in parylene:
  U < 30 ppt, Th < 50 ppt
- Z = ~50 Ω
- M = ~4 mg/cm







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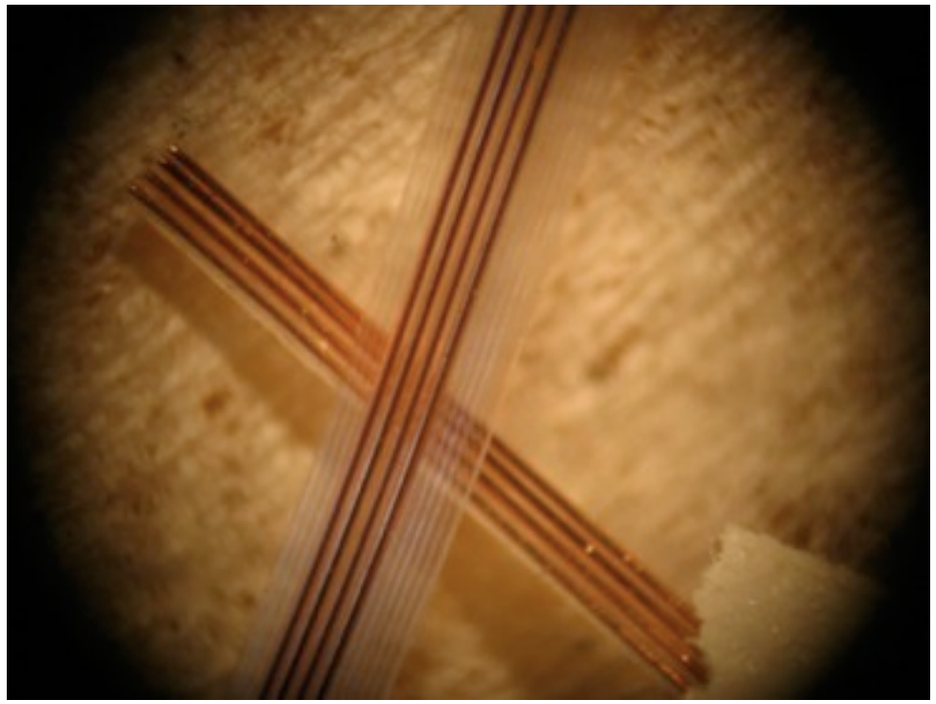

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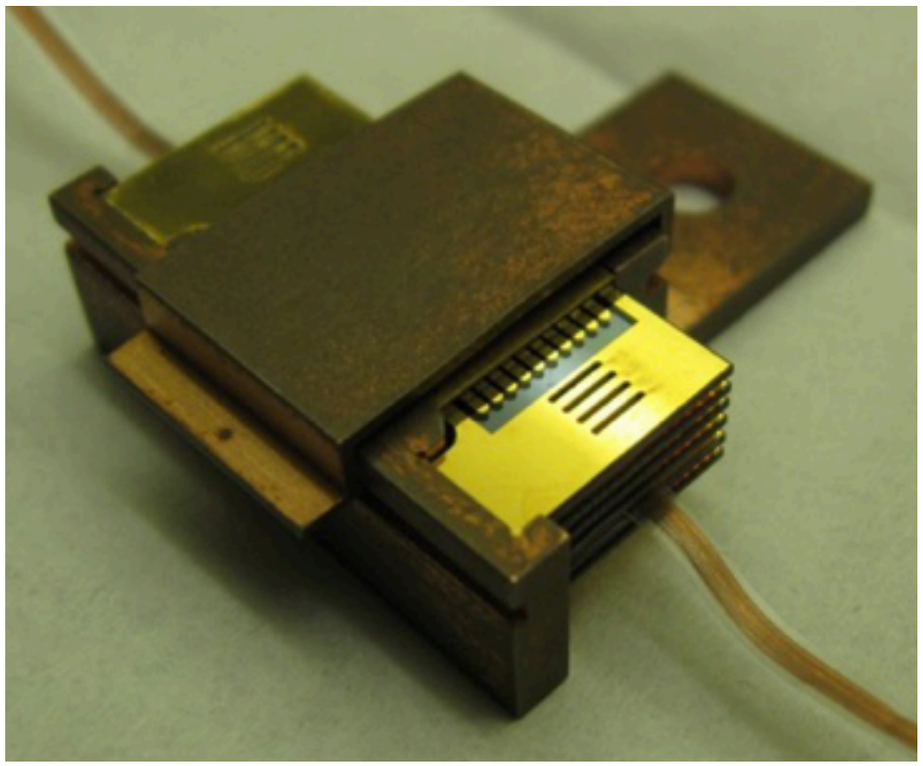
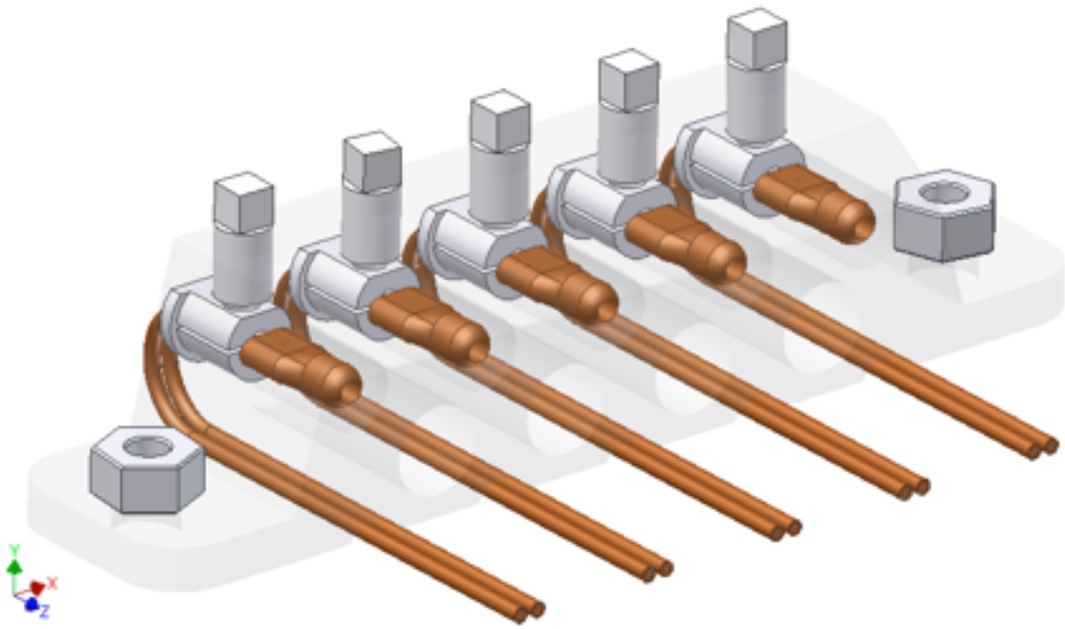
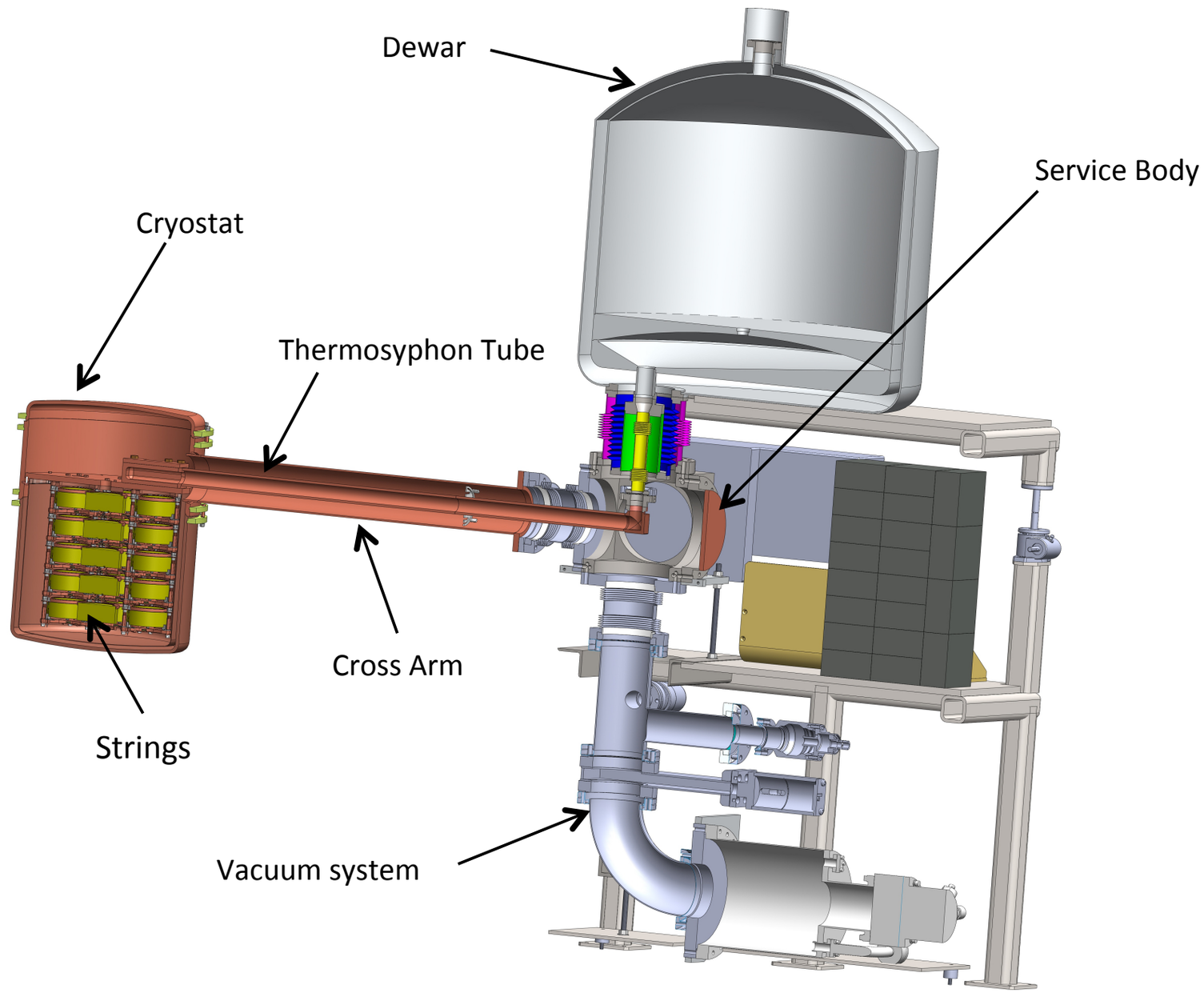
LBNL readout test





Thermosiphon and Cryostat

- Coldplate / cryostat / thermosiphon design and prototyping underway
- Thermal / mechanical testing and integration in the LANL Canary Cage



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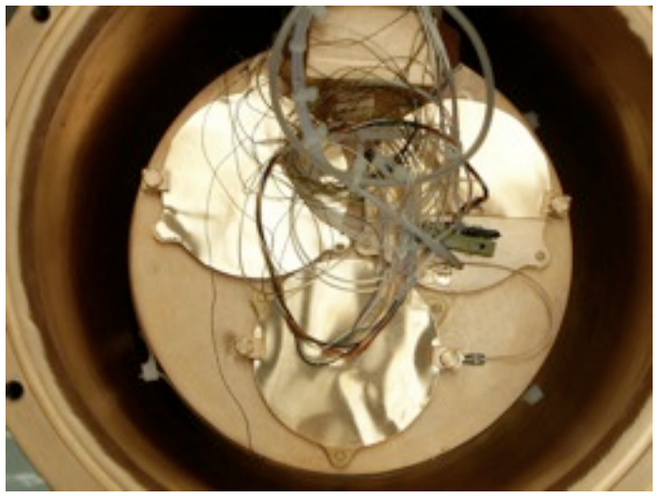
Canary Cage



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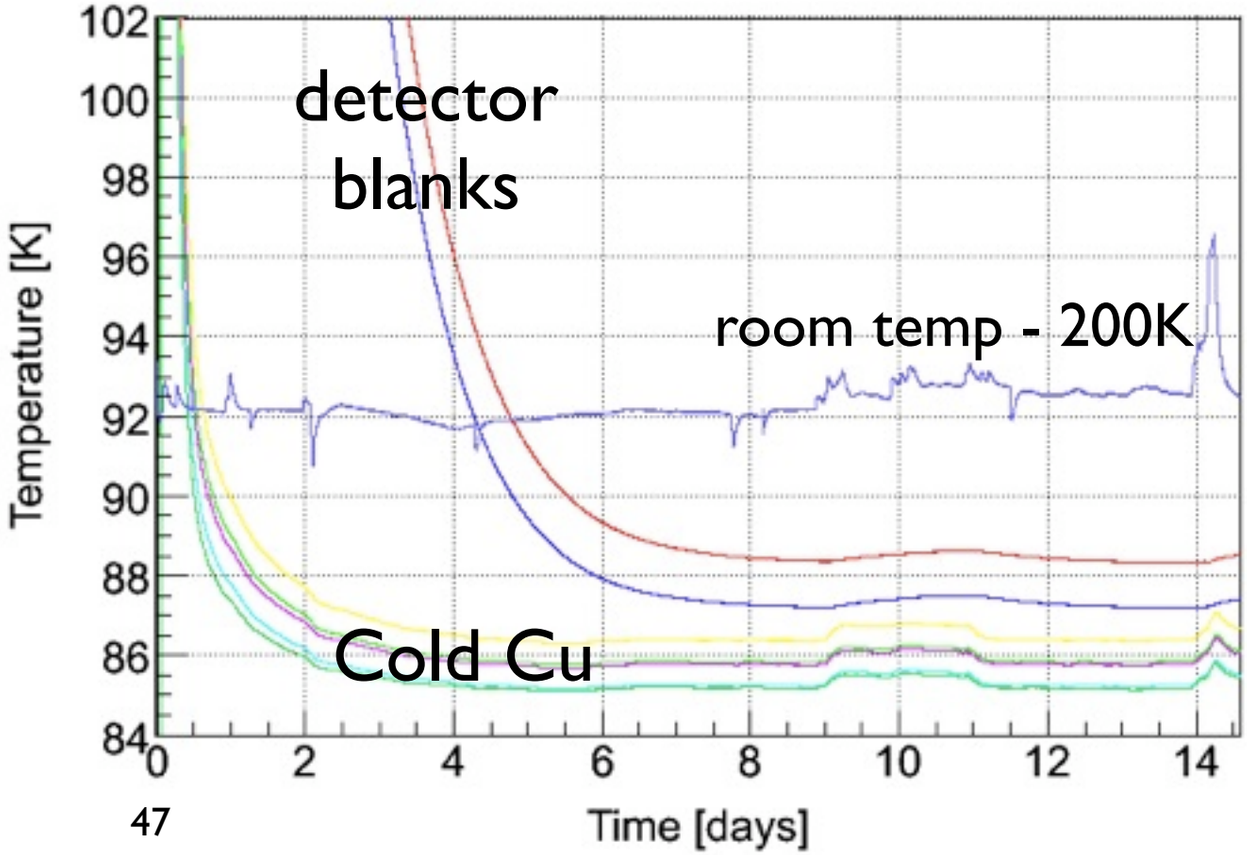
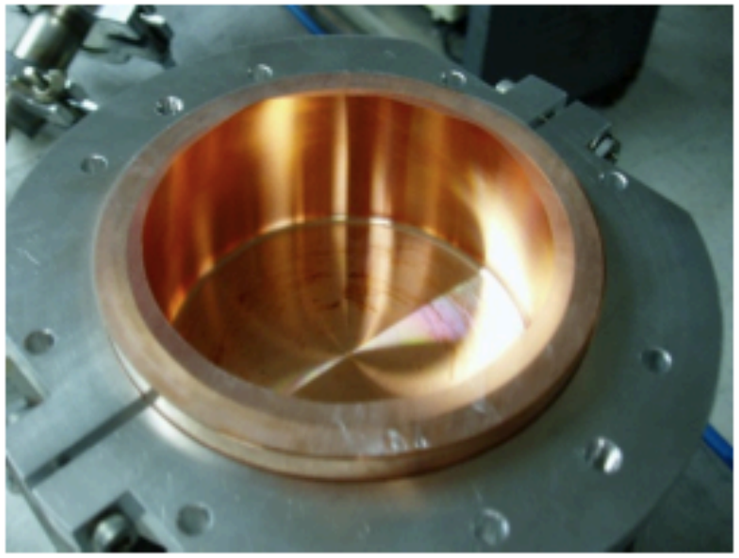
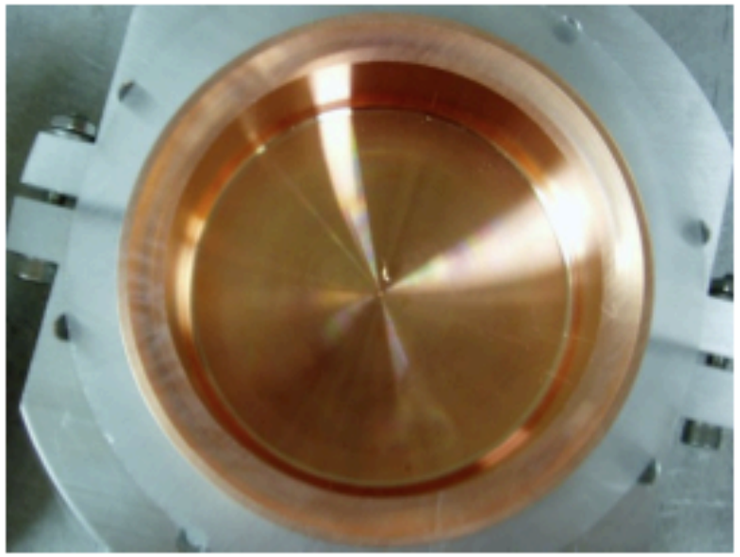


Thermosiphon and Cryostat

Parylene gasket R&D
(low-background substitute for In)

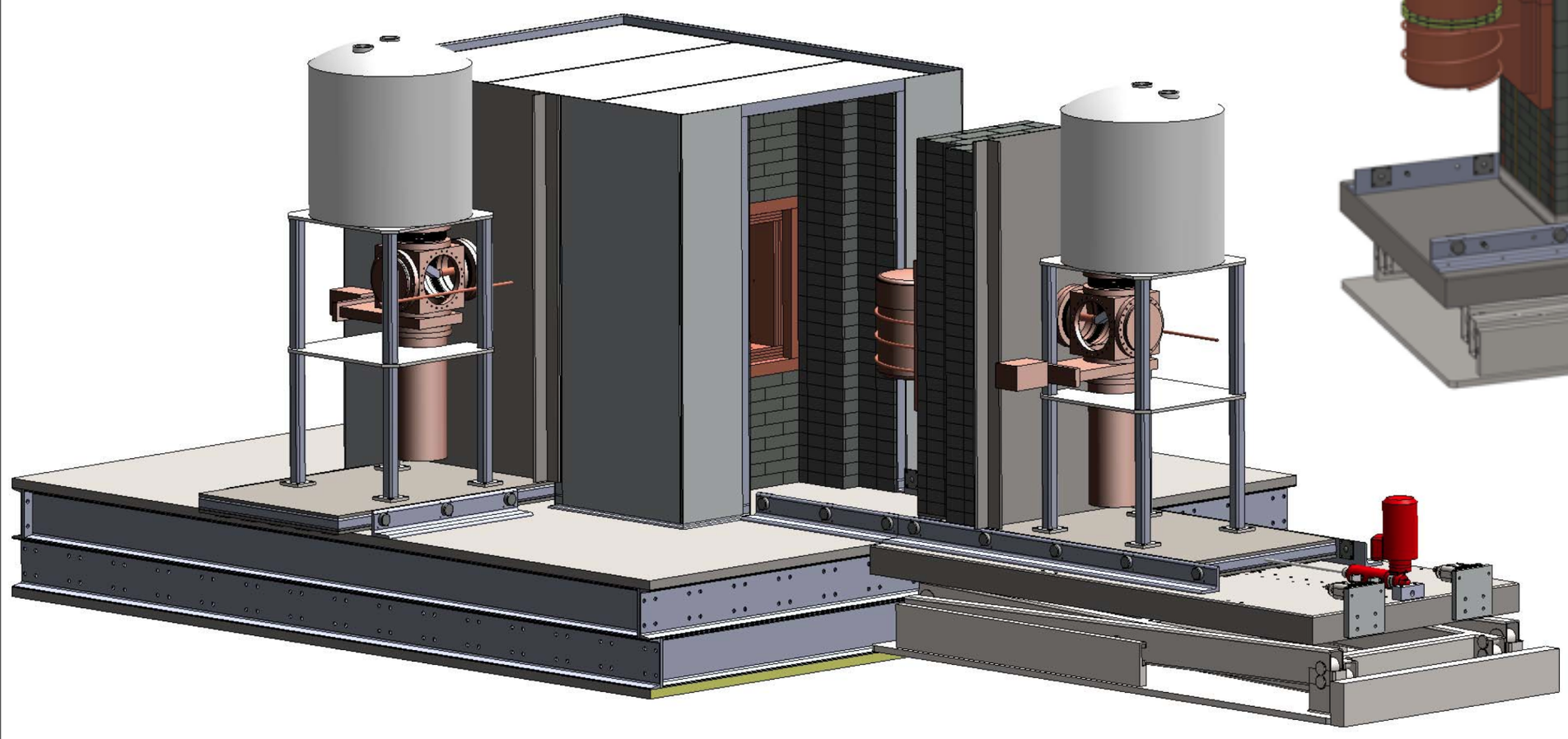


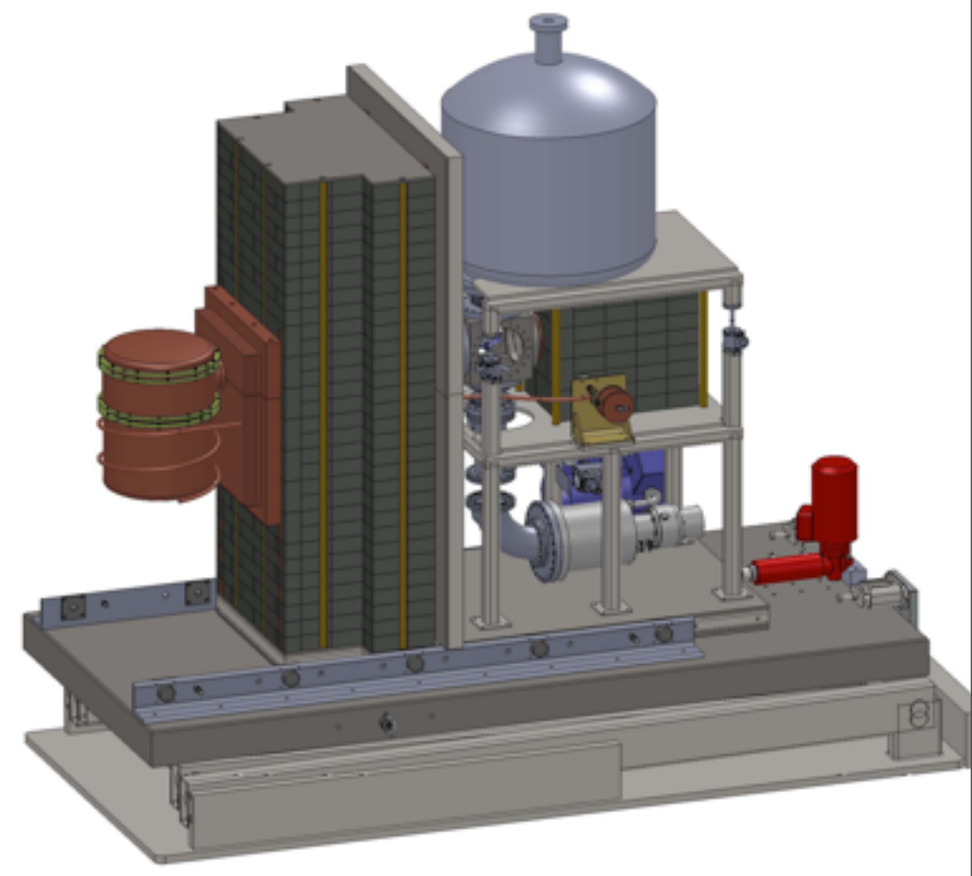


	Pressure [torr]	Helium [sccs]	
Round edge	2×10^{-6}	3×10^{-10}	seal looked very good after
45° edge	2×10^{-6}	3×10^{-7}	seated off-center, seal looked better on one side

Mechanical Systems

- Shield, monolith, calibration system engineering underway
- Most of the Pb is in hand





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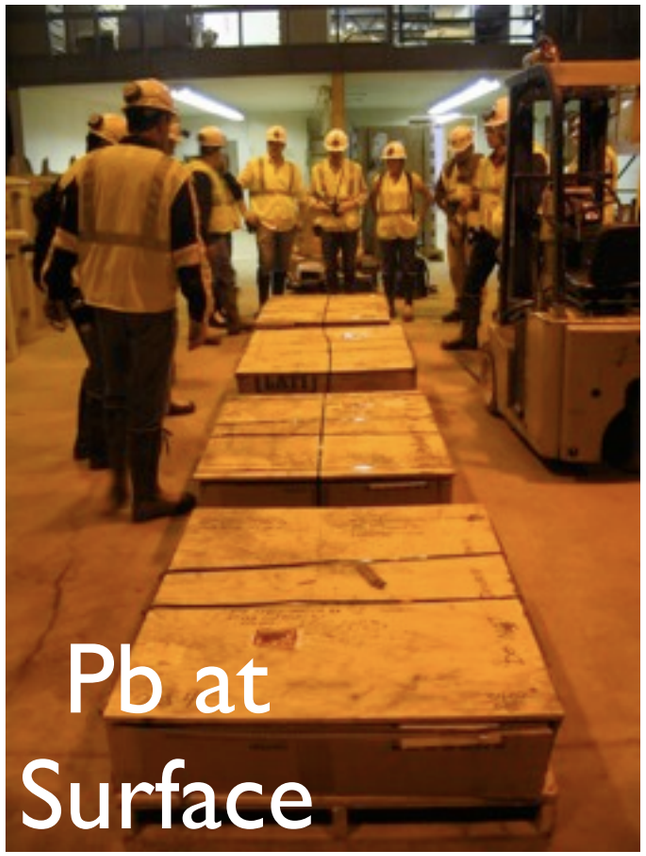
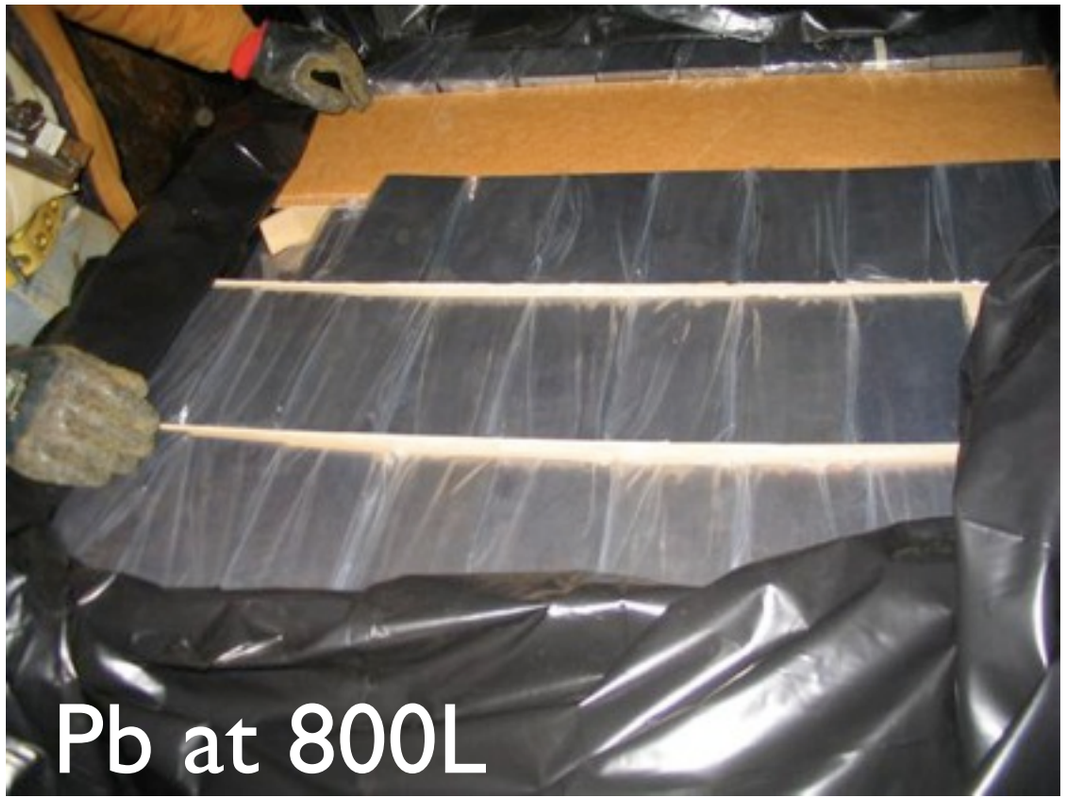




Site Facilities

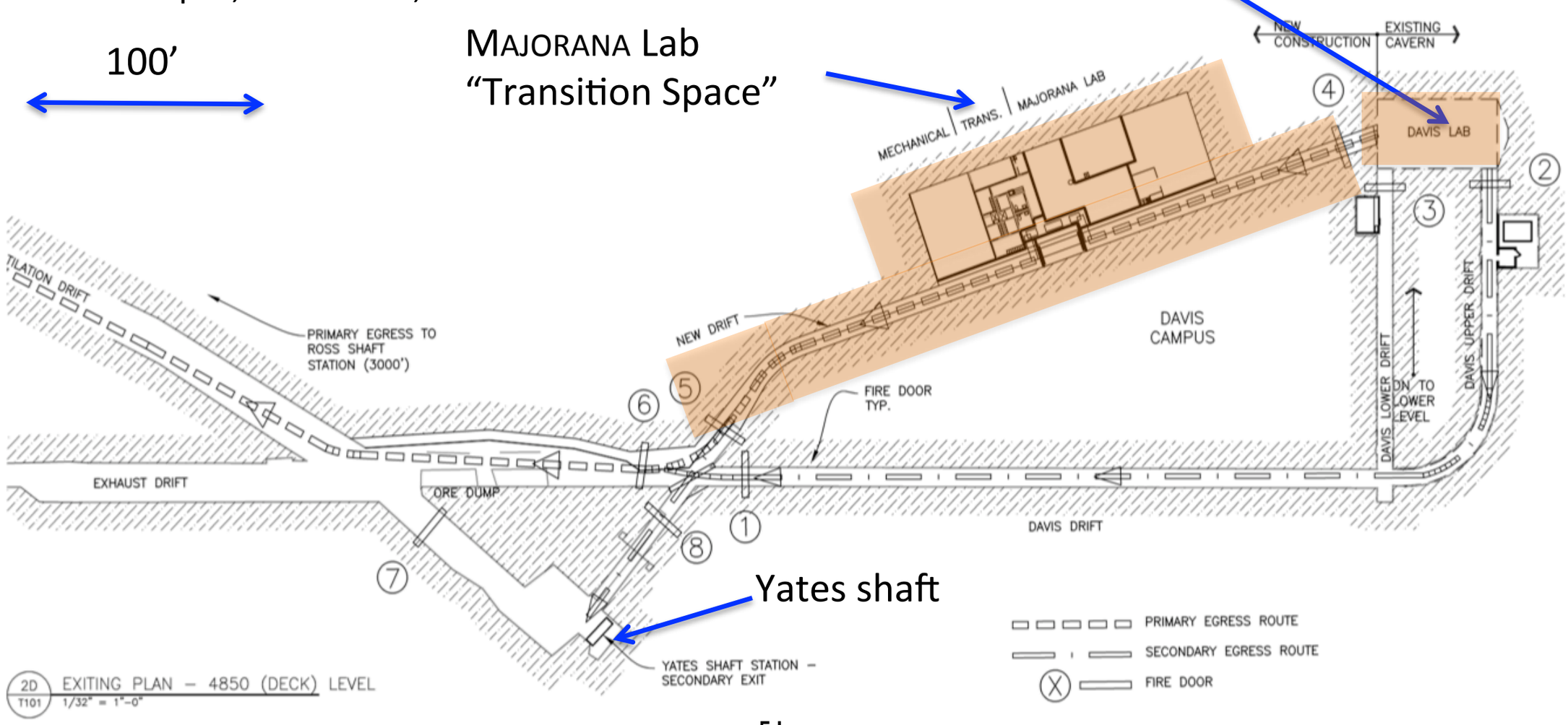
- EFCu, detector facilities, and machine shop at 4850' level in new drift to Davis cavity (LUX). Excavation complete.
- EFCu clean room ready; lab outfitting contract bids due this month!
- Beneficial occupancy anticipated mid-late 2011

Davis Campus, 4850' level, near Yates shaft

100'

MAJORANA Lab
"Transition Space"

LUX



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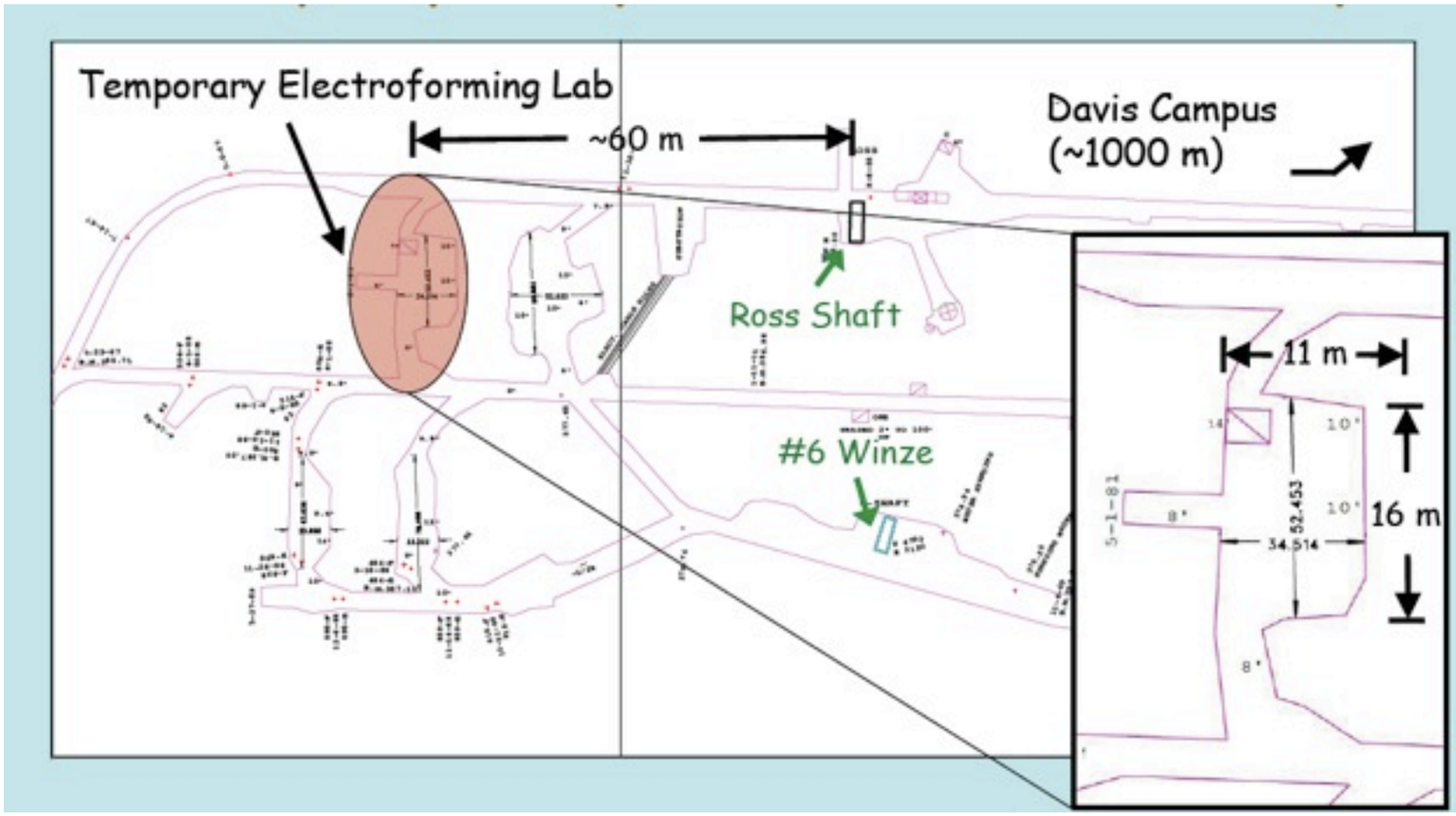
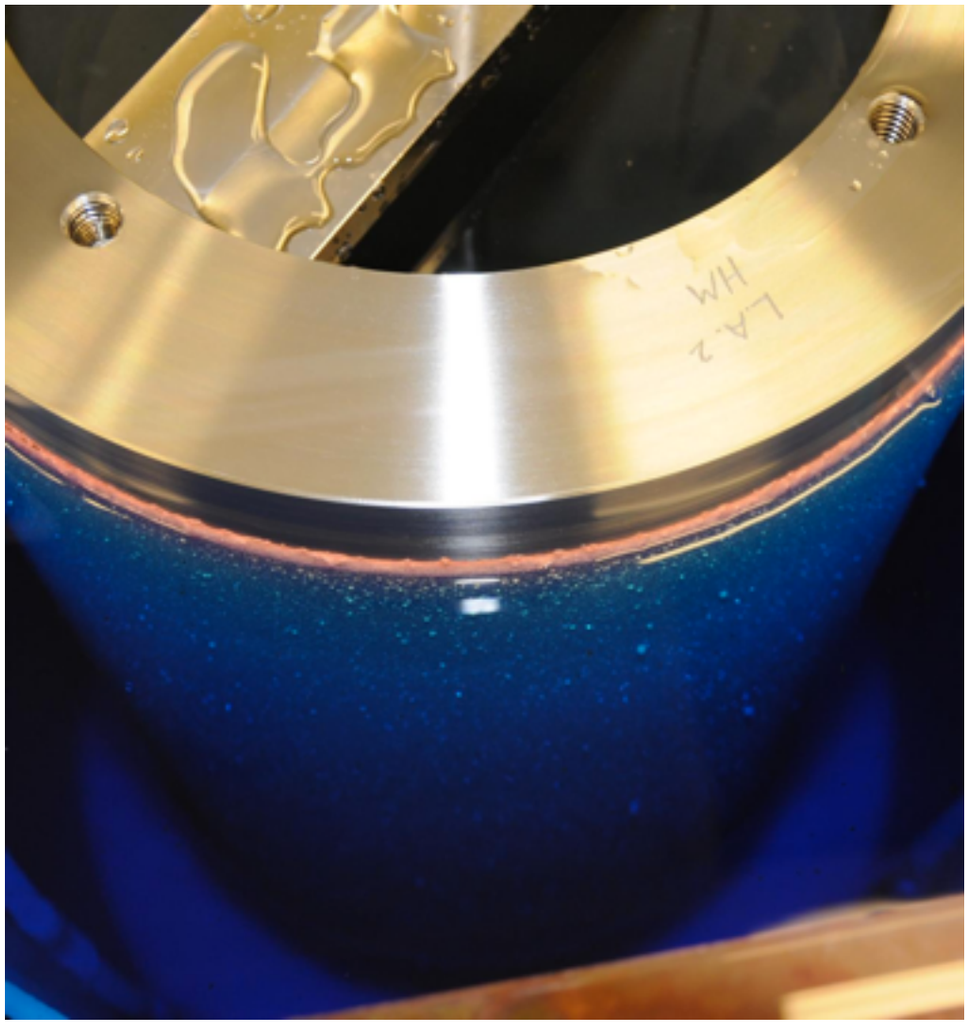


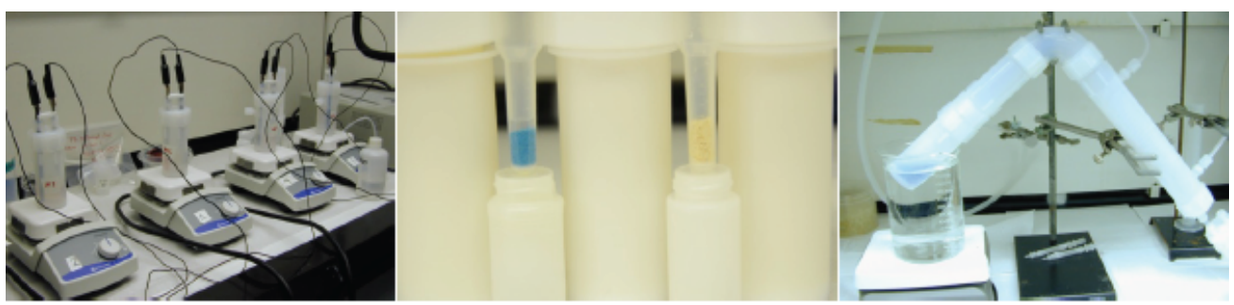
Outline

- Introduction to 0νββ decay
- 0νββ searches and other physics with ^{76}Ge
- MAJORANA status
- Backgrounds and sensitivity
- Summary

Materials and Assay

- EFCu lab at PNNL ready; Sanford lab coming soon
- Campaign to further reduce limits on backgrounds in EFCu (esp. U)
- Procured enough NXT-85 plastic for detector supports; verified purity via INAA
- Cables and electronics materials screening by ICPMS in Berkeley, Russia





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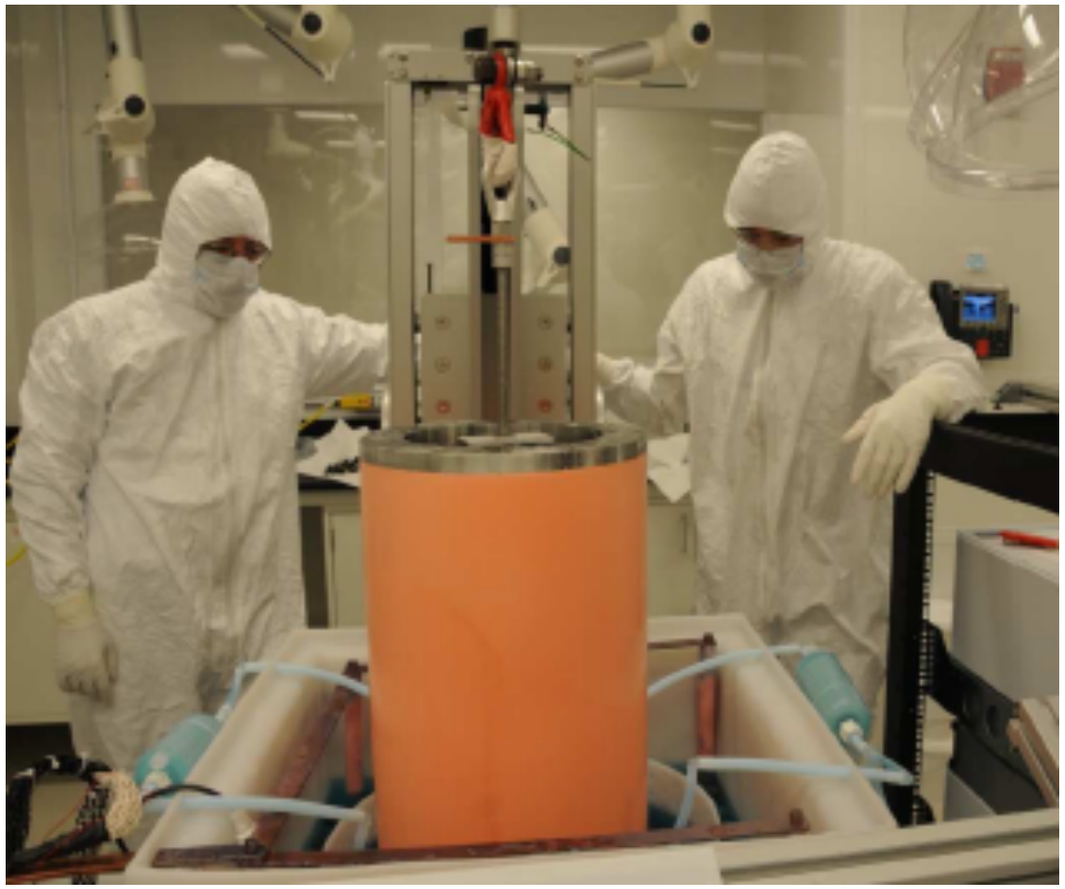

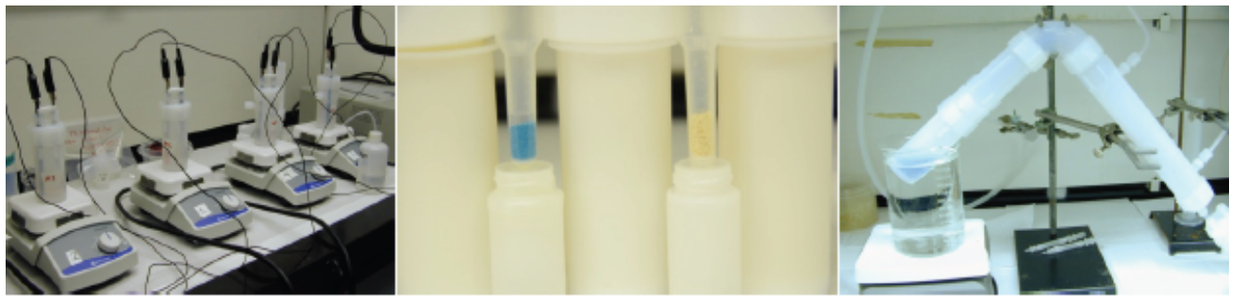

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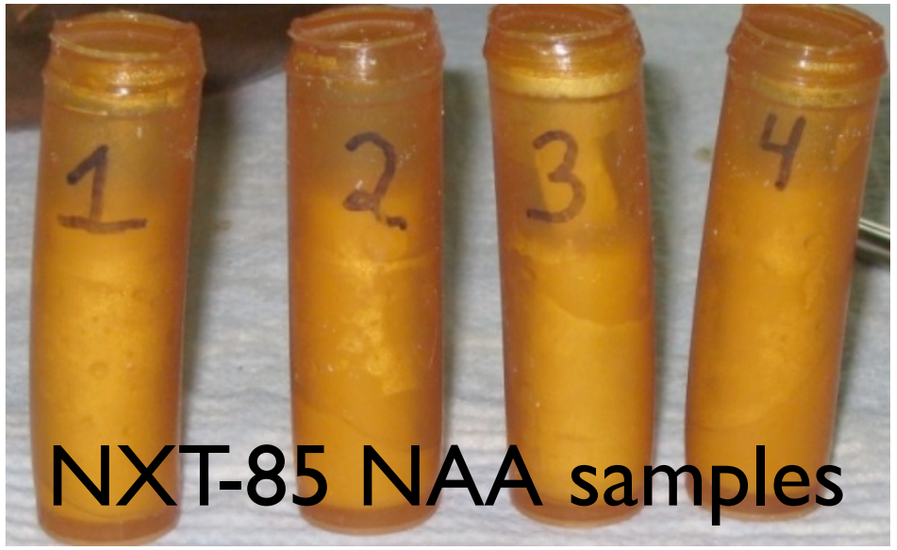
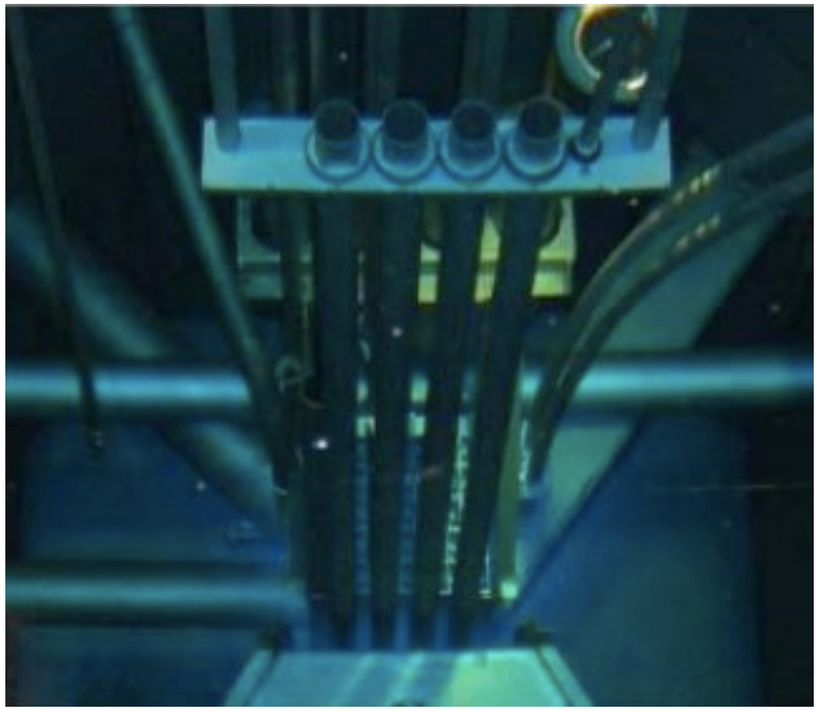


NXT-85 NAA samples



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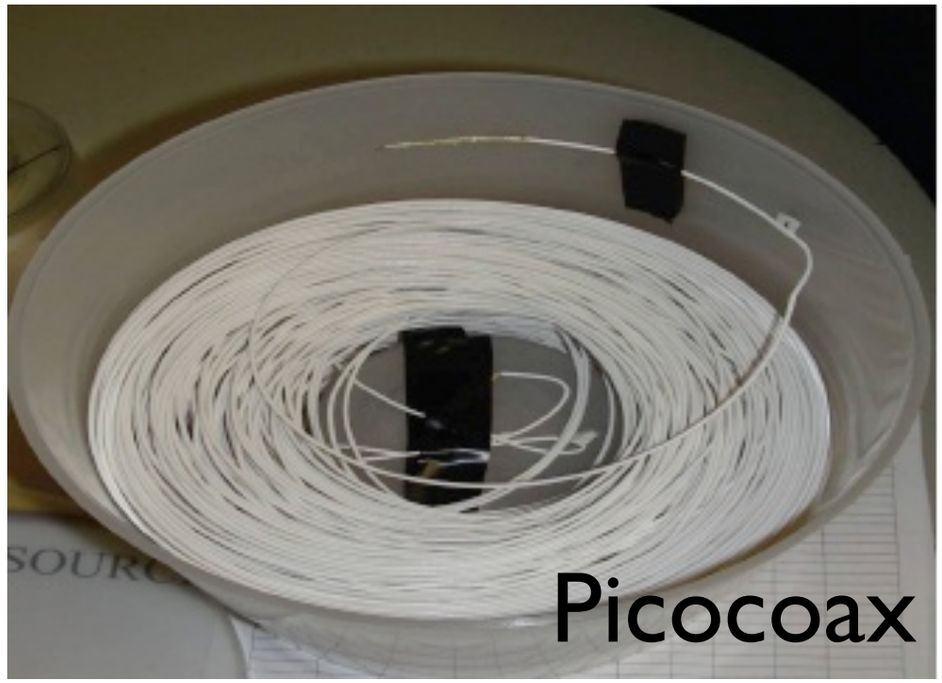
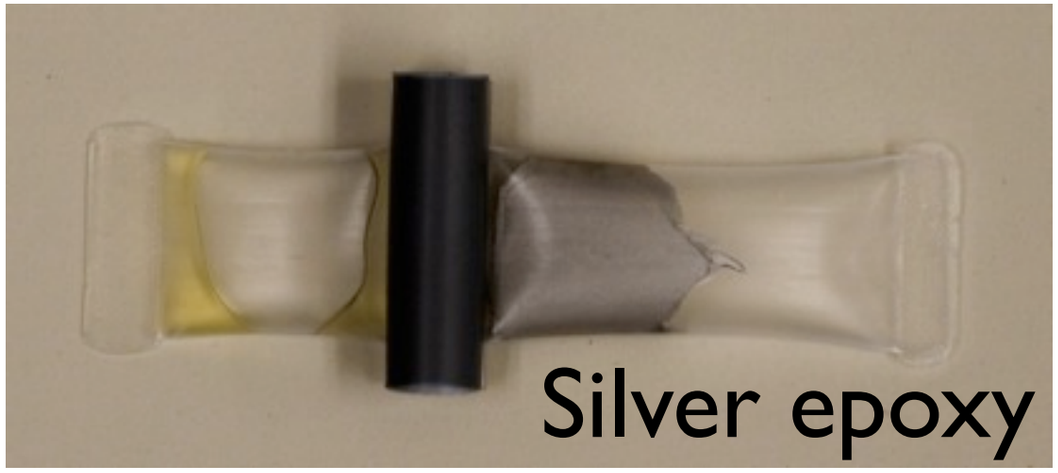


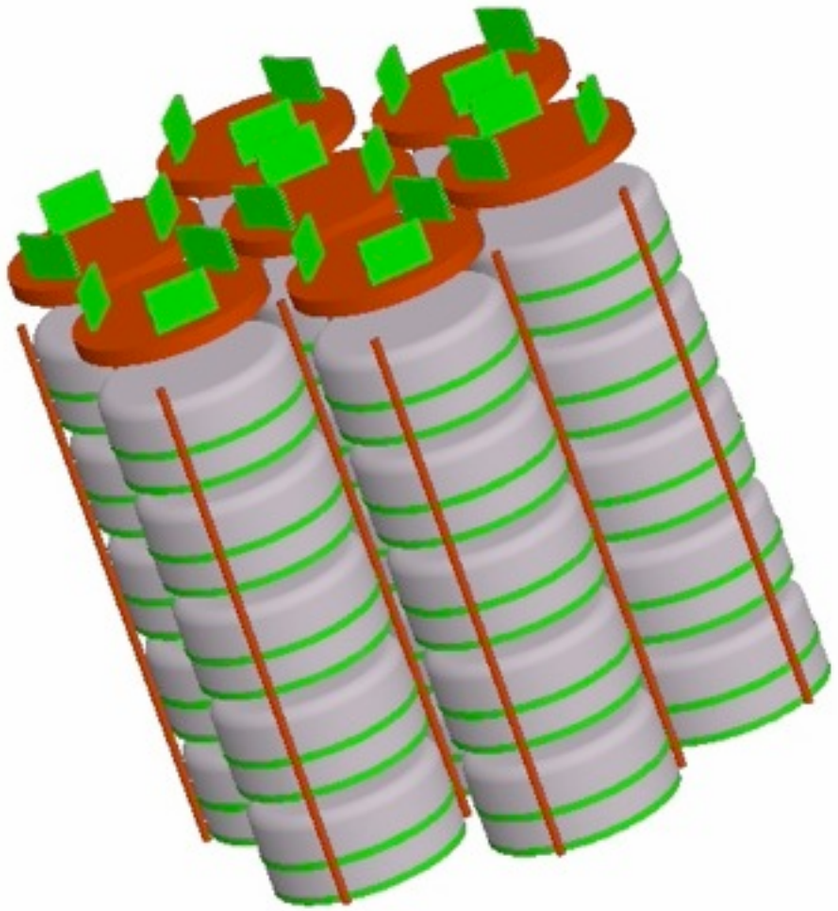


Materials Specifications

Material	Uses	Contaminant Goals	Equivalent Achieved Assay	Reference
Germanium	Detectors	<100 days ^{68}Ge exp. <30 days ^{60}Co exp.	N/A	[Avi92], [Ell10]
		<14 nBq/kg U/Th	<14 nBq/kg	[Det08b]
		<0.5 μBq/cm^2 surf. α	<0.5 μBq/cm^2	
Electroformed Copper	Detector Mounts, Cryostat, Inner Cu Shield	<0.1 μBq/kg ^{208}Tl <0.3 μBq/kg ^{214}Bi	0.2 ± 0.1 μBq/kg <40 μBq/kg	[Hop09]
Commercial Copper	Outer Cu Shield	<0.3 μBq/kg ^{208}Tl <3 μBq/kg ^{214}Bi	<3 μBq/kg <36 μBq/kg	[Leo08]
Lead	Lead Shield	<1 μBq/kg ^{208}Tl <10 μBq/kg ^{214}Bi	<1 μBq/kg <10 μBq/kg	[Leo08]
Plastic	Detector Mounts, Insulation	<0.4 μBq/kg ^{208}Tl <10 μBq/kg ^{214}Bi	<0.4 μBq/kg <10 μBq/kg	[Bac09], [Leo08]
Small Components	Front-End Electronics, Contacts	<6 nBq/chan. ^{208}Tl <24 nBq/chan. ^{214}Bi	<6 nBq/chan. <24 nBq/chan.	[Loa10], [Leo08]
Cables	Signal, High-Voltage	<40 μBq/kg ^{208}Tl <500 μBq/kg ^{214}Bi	<40 μBq/kg <500 μBq/kg	[Loa10], [Det08]
Polyethylene Shield	Neutron Modification	≥30 cm	N/A	[Bac08]
Rock	Overburden	≥4300 kmwe	N/A	[Mei06] Sanford Lab

Simulations and Analysis

- Developing simulation and data analysis software in cooperation with GERDA
- Background Simulation Campaign in progress:
  - Detailed DEMONSTRATOR geometry
  - Full-spectrum background model: $0/2\nu\beta\beta$, U/Th/K, α/β on surfaces, neutron backgrounds, cosmogenics ...
  - Estimate ~100k CPU-hours, ~10 TB data



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

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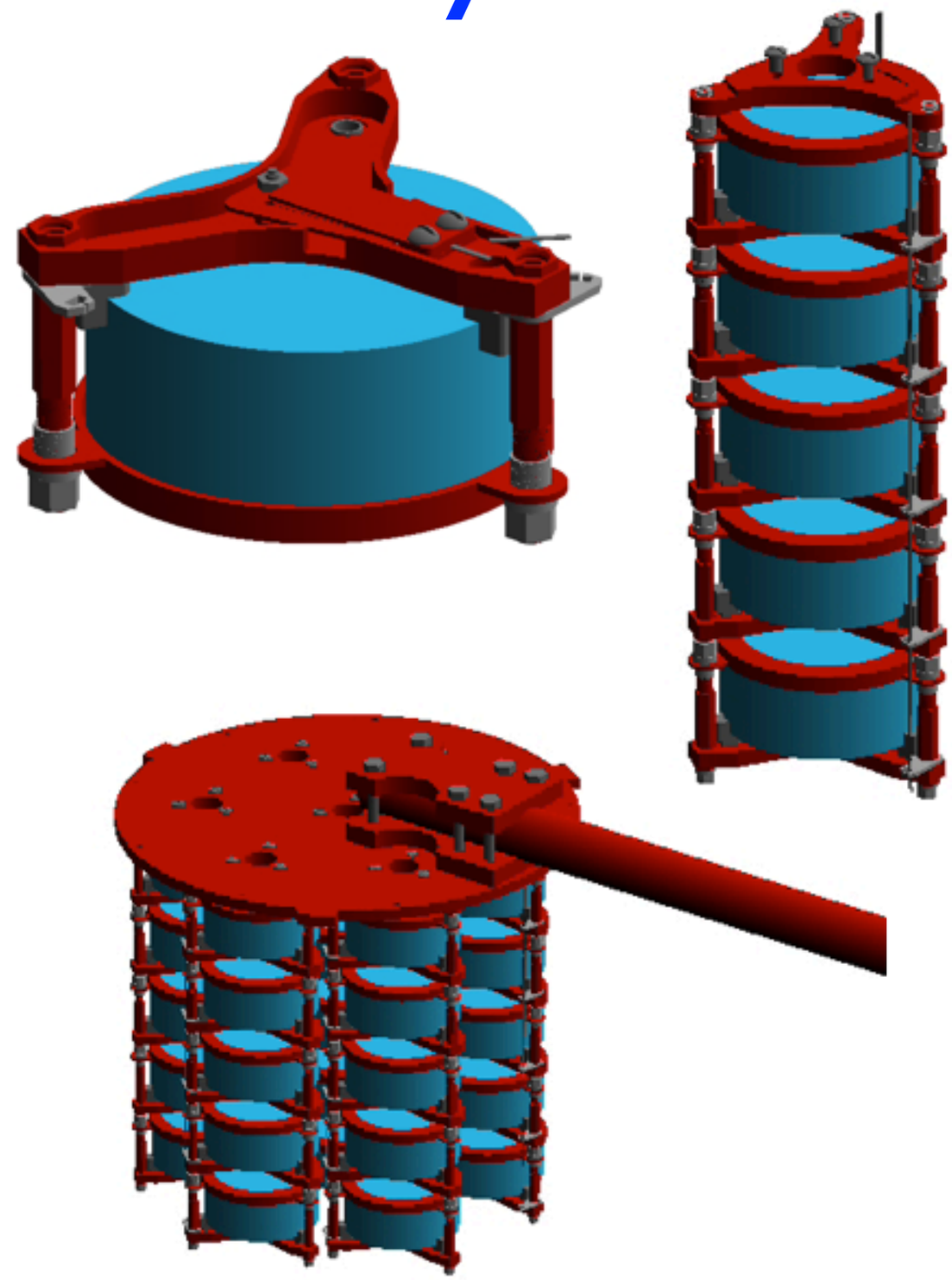
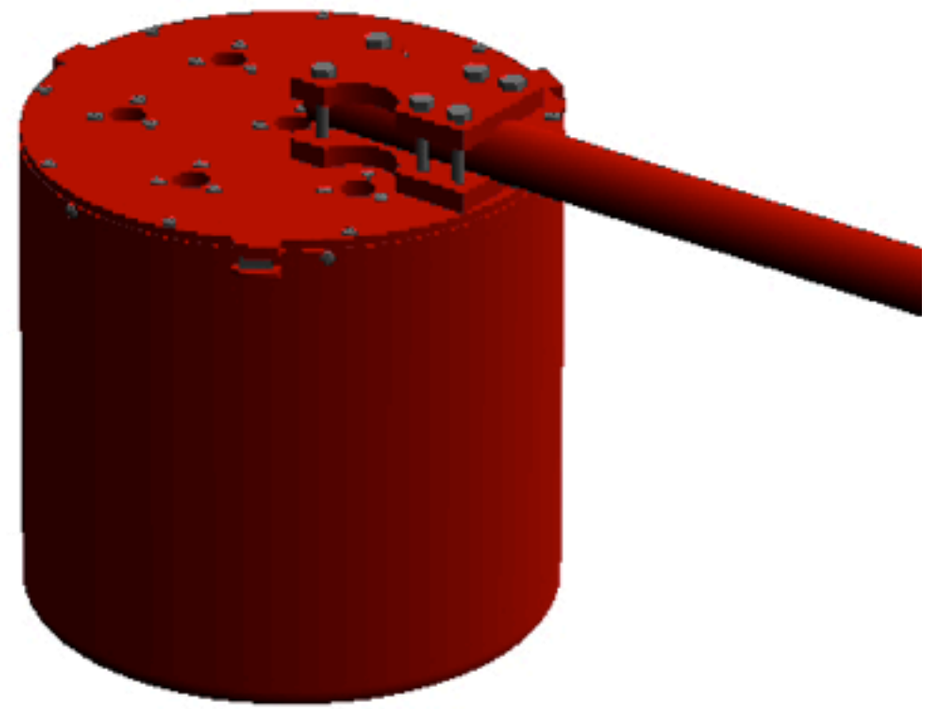


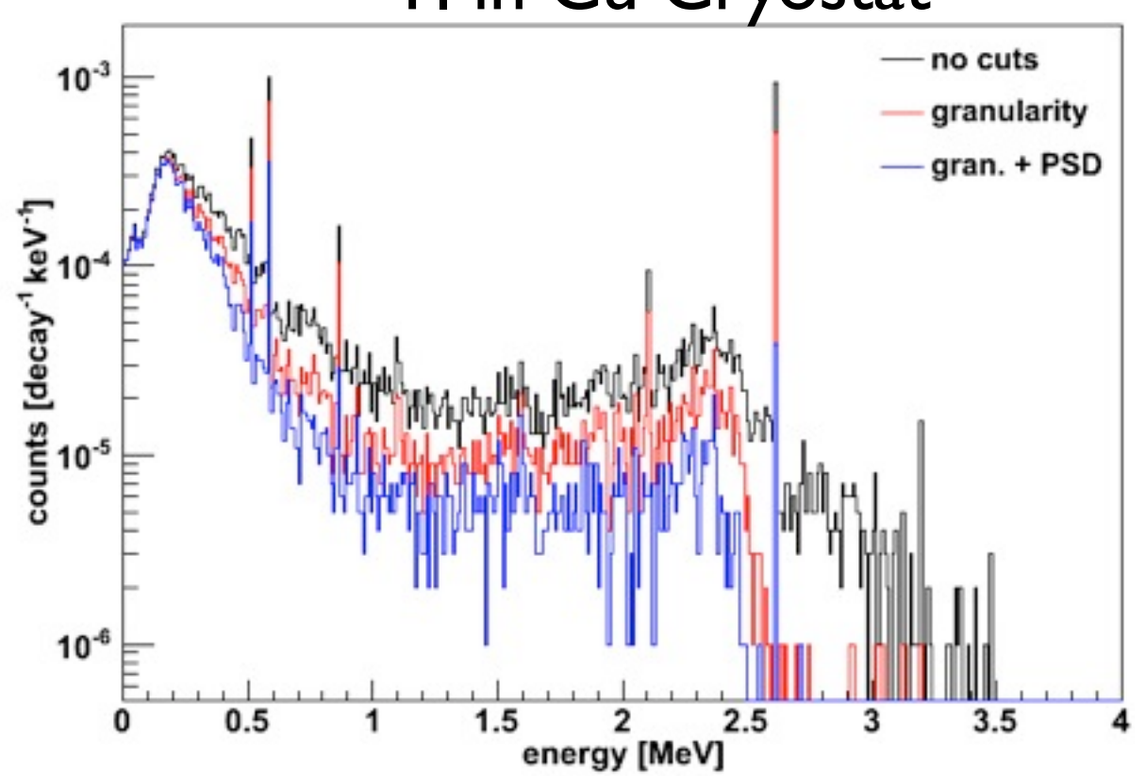
NATIONAL ENERGY RESEARCH SCIENTIFIC COMPUTING CENTER
NERSC
Advancing Computational Science of Scale—Producing Real Results

Simulations and Analysis

- Developing simulation and data analysis software in cooperation with GERDA
- Background Simulation Campaign in progress:
  - Detailed DEMONSTRATOR geometry
  - Full-spectrum background model: 0/2νββ, U/Th/K, α/β on surfaces, neutron backgrounds, cosmogenics ...
- Estimate ~100k CPU-hours, ~10 TB data



^{208}Tl in Cu Cryostat



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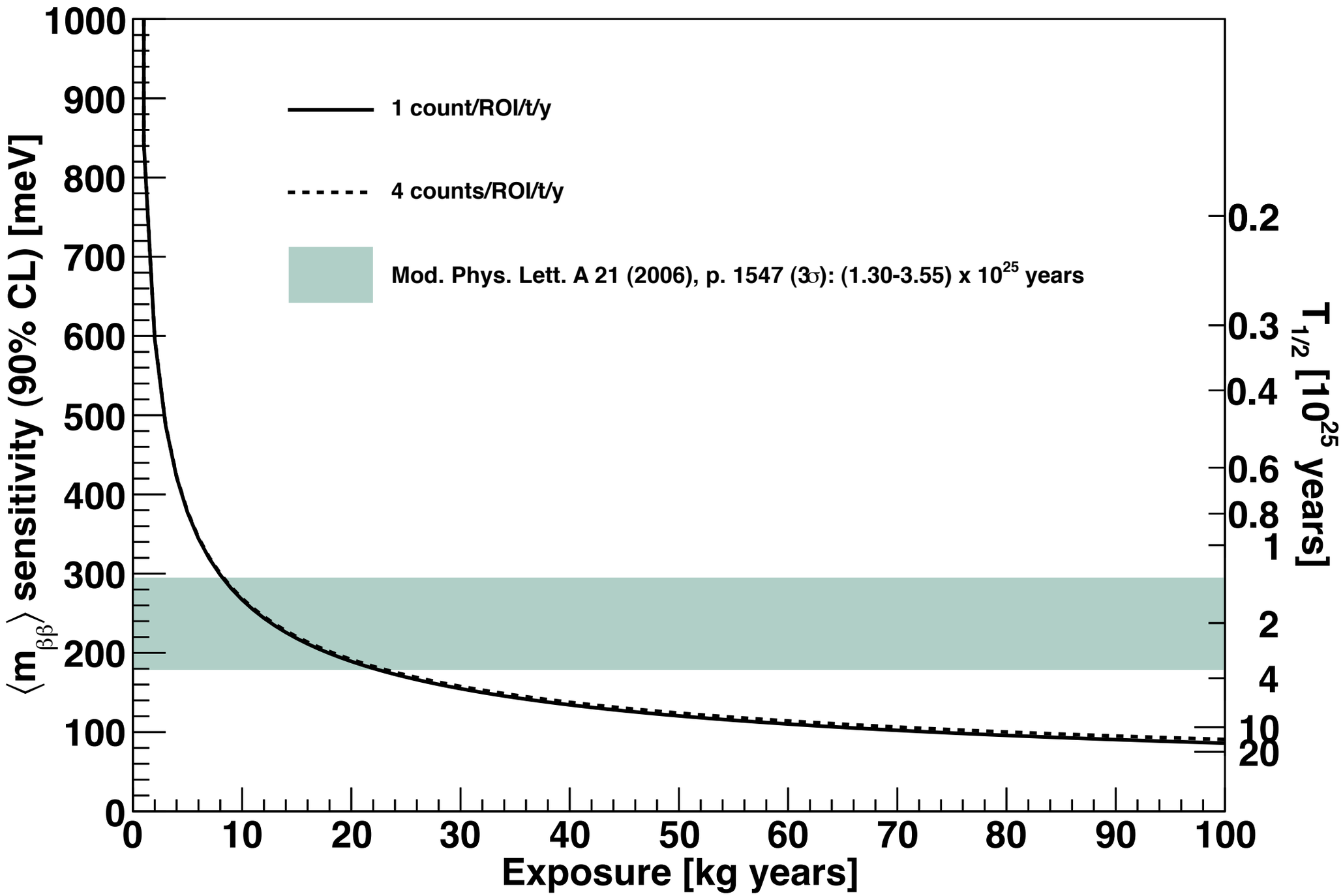
Background Summary

Component	Isotope	Gross Rate, 1.9-3 MeV [c/module/month]	ROI Background (DEMONSTRATOR) [c/ROI/t/y]	ROI Background (tonne scale) [c/ROI/t/y]
Germanium Crystals (enriched)	^{68}Ge	47 (7.6)	0.38	negligible
	^{60}Co	4.2	0.03	negligible
	U/Th	-	0.3	0.3
Cryostat, Inner Cu Shield (EFCu)	^{208}Tl, ^{214}Bi	2.1	0.91	0.48
Outer Cu Shield	^{208}Tl, ^{214}Bi	0.8	0.40	0.02
	^{60}Co	2.0	0.02	1×10^{-3}
Pb Shield	^{208}Tl, ^{214}Bi	0.5	0.40	negligible
Prompt Cosmogenics	(n,*)	-	~1	negligible
Other		1.2	0.38	0.27
	Totals:	57.8 (18.5)	3.81	1.07

DEMONSTRATOR Sensitivity



Summary

- Making rapid progress on technical designs, background goal
- It's fun being funded!
- Data for the early low-E physics program coming within the next 1-2 years, $0\nu\beta\beta$ physics to follow shortly thereafter

Extra Slides

The Neutrino

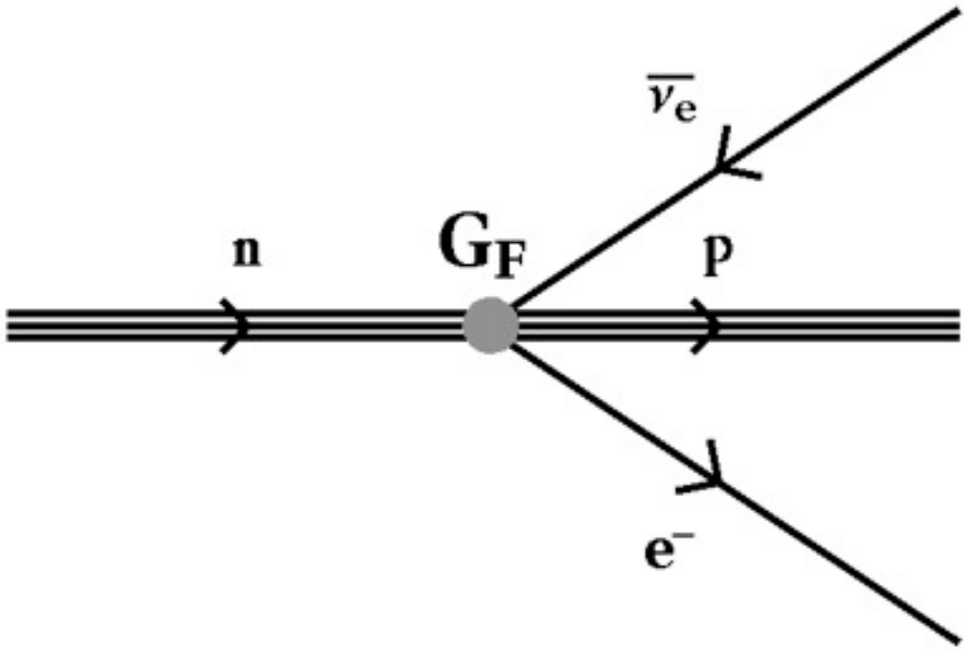
- "Invented" to save E, **P**, **L** conservation in β-decay

I have hit upon a desperate remedy...
-W. Pauli

Image from fnal.gov

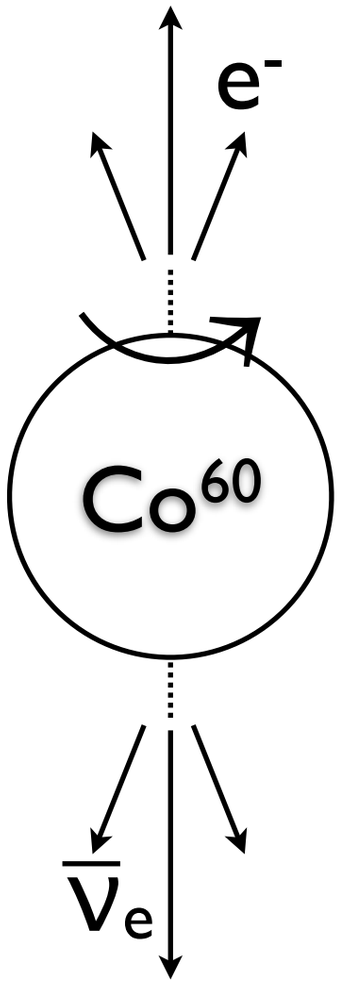
The Neutrino

- "Invented" to save E, **P**, **L** conservation in β-decay
- Fermi interaction → modern field theory



The Neutrino

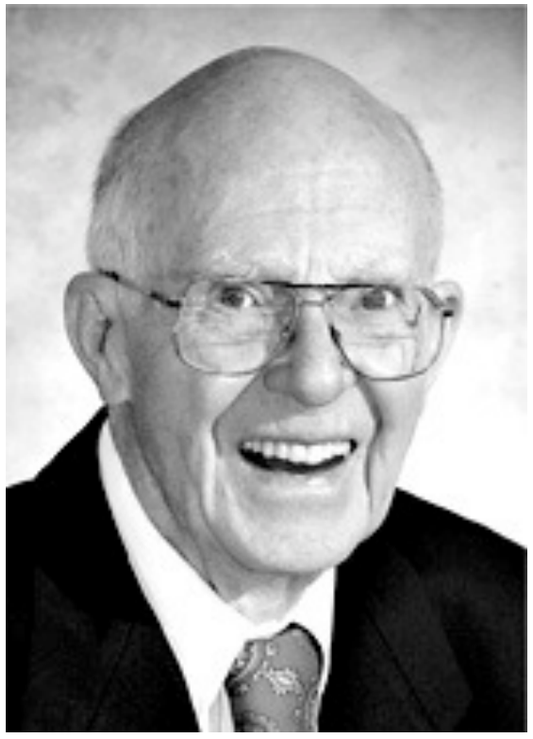
- "Invented" to save E, **P**, **L** conservation in β-decay
- Fermi interaction → modern field theory
- Parity violation first demonstrated in β-decay



The Neutrino

- "Invented" to save E, **P**, **L** conservation in β-decay
- Fermi interaction → modern field theory
- Parity violation first demonstrated in β-decay
- ν astrophysics (2002 Nobel Prize)

"For pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos."



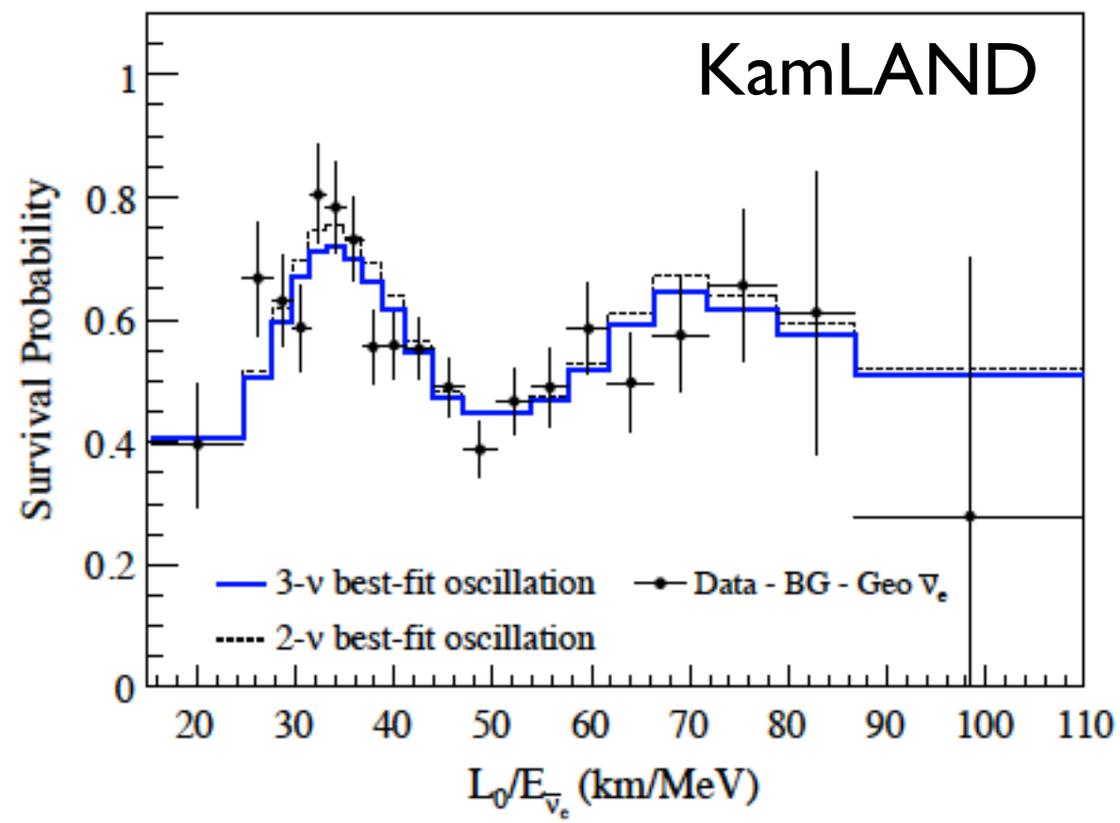
Raymond Davis Jr.

Masatoshi Koshiba

Images from nobelprize.org

The Neutrino

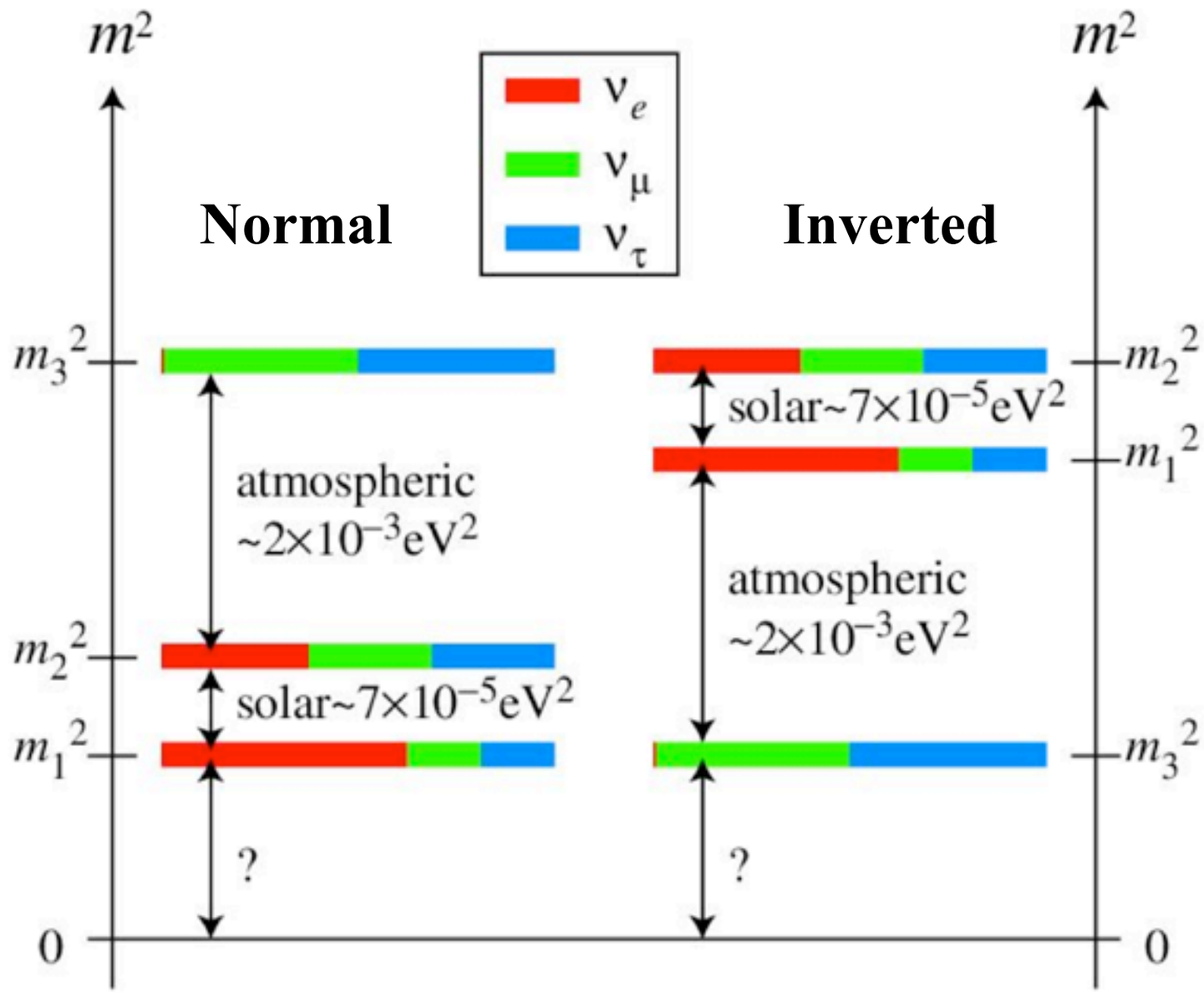
- "Invented" to save E, **P**, **L** conservation in β-decay
- Fermi interaction → modern field theory
- Parity violation first demonstrated in β-decay
- ν astrophysics (2002 Nobel Prize)
- $m_\nu > 0$: first "physics beyond the Standard Model"



A. Gando *et al.*, arXiv:1009.4771 (2010)

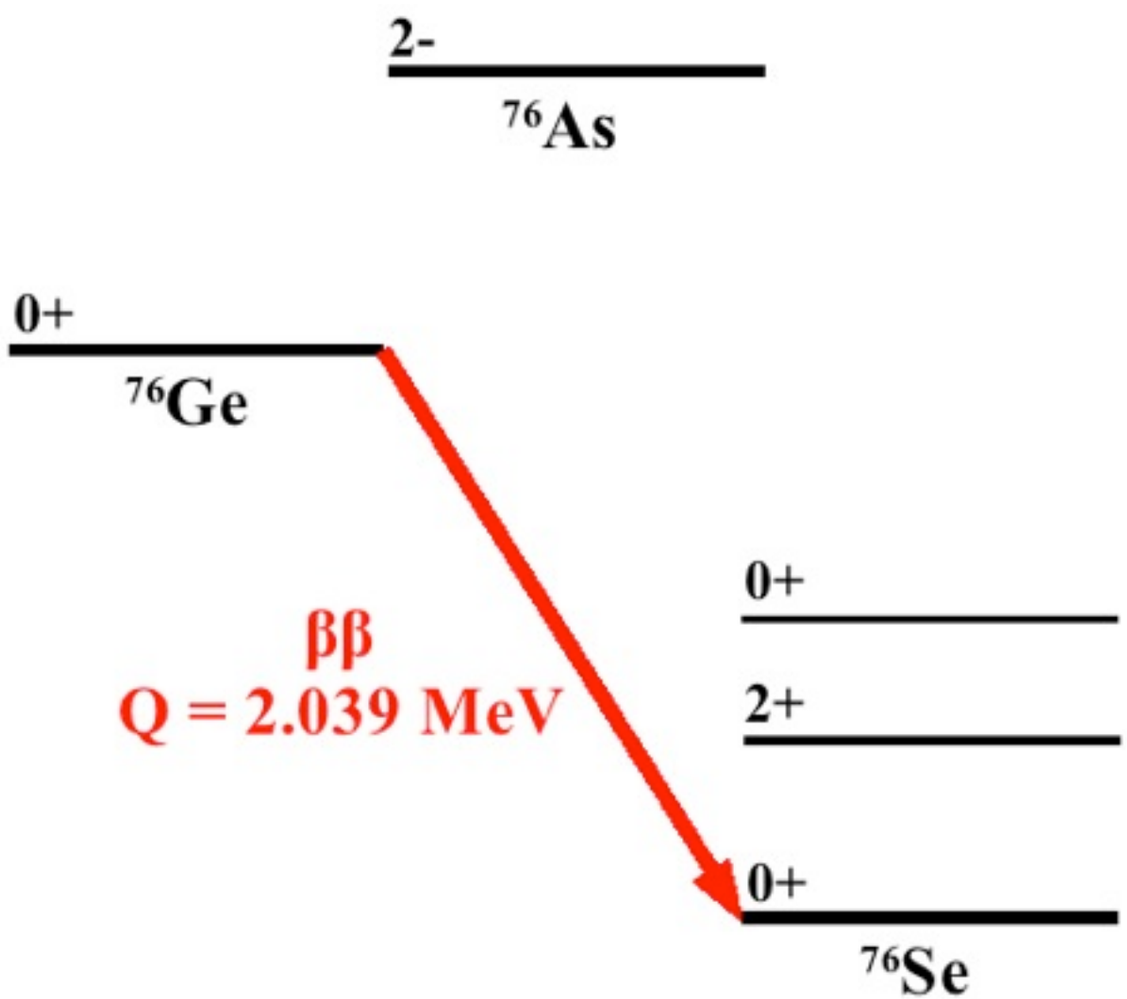
ν Questions

- What is the mass scale?
- What is the hierarchy?
- Does ν = $\bar{\nu}$?
- What are the precise oscillation parameters?
- Is $\theta_{13} > 0$?
- Is CP violated in the ν sector?
- Do sterile ν exist?
- What can ν tell us about the sun, Earth, SN, CνB, ...



From presentation by S. King at UKNF (Dec 2005), available at http://hepunx.rl.ac.uk/uknf/2005-05-04/uknf-sfk-pheno.ppt

^{76}Ge



$T_{1/2}^{2\nu} = (1.4 \pm 0.2) \times 10^{21}$ y [1]

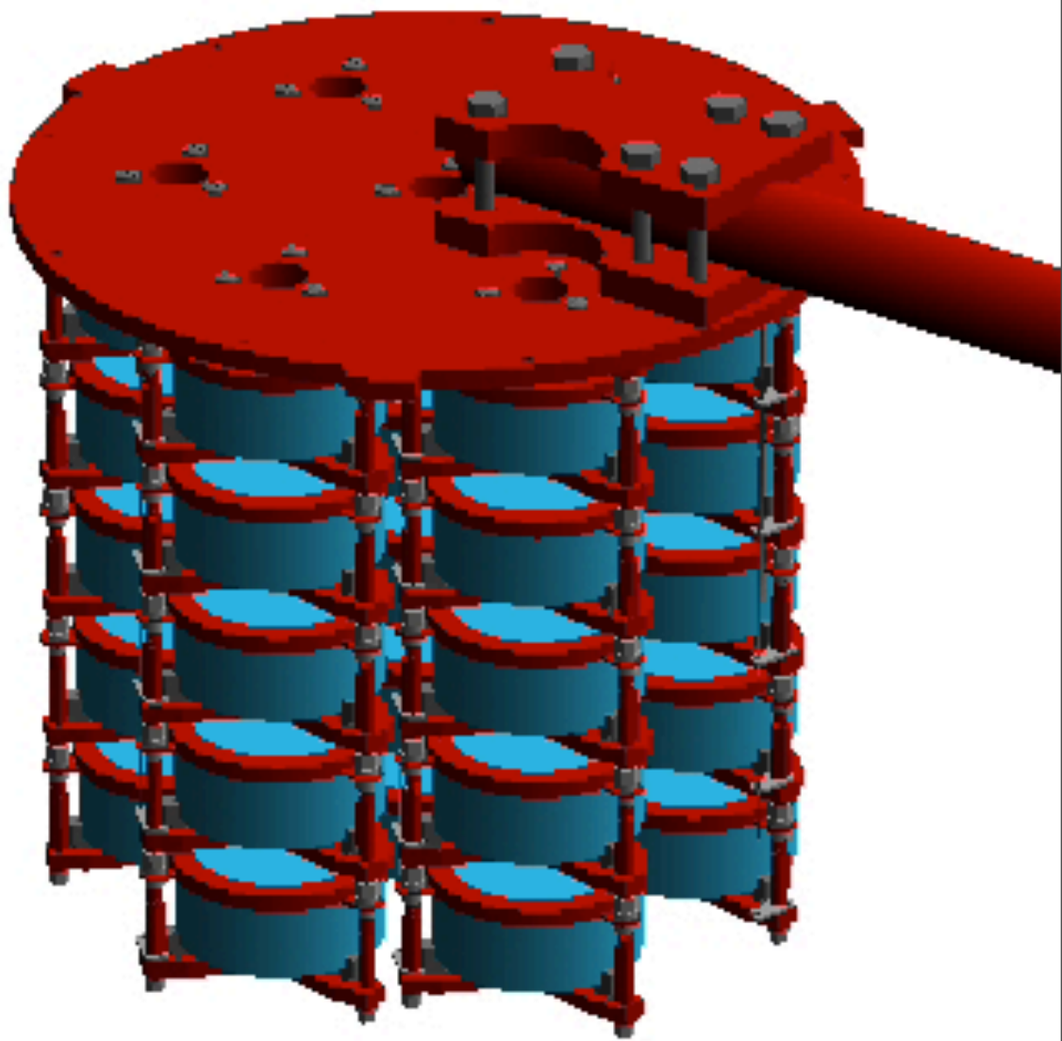
$G^{0\nu} = 0.30 \times 10^{-25}$ y^{-1} eV^{-2} [2]

$M^{0\nu} \approx 2.4$ [3]

[1] C. E. Aalseth *et al.*, Nucl. Phys. B. Proc. Suppl. **48**, 223 (1996); H.V. Klapdor-Kleingrothaus *et al.*, Eur. Phys. J. A **12**, 147 (2001); H.V. Klapdor-Kleingrothaus *et al.*, NIM A **513**, 596 (2003).
[2] F. Simkovic *et al.*, Phys. Rev. C **60**, 055502 (1999).
[3] V. A. Rodin *et al.*, Nucl. Phys. A **766**, 107 (2006); A. Poves, NDM06, Paris (2006), http://events.lal.in2p3.fr/conferences/NDM06.

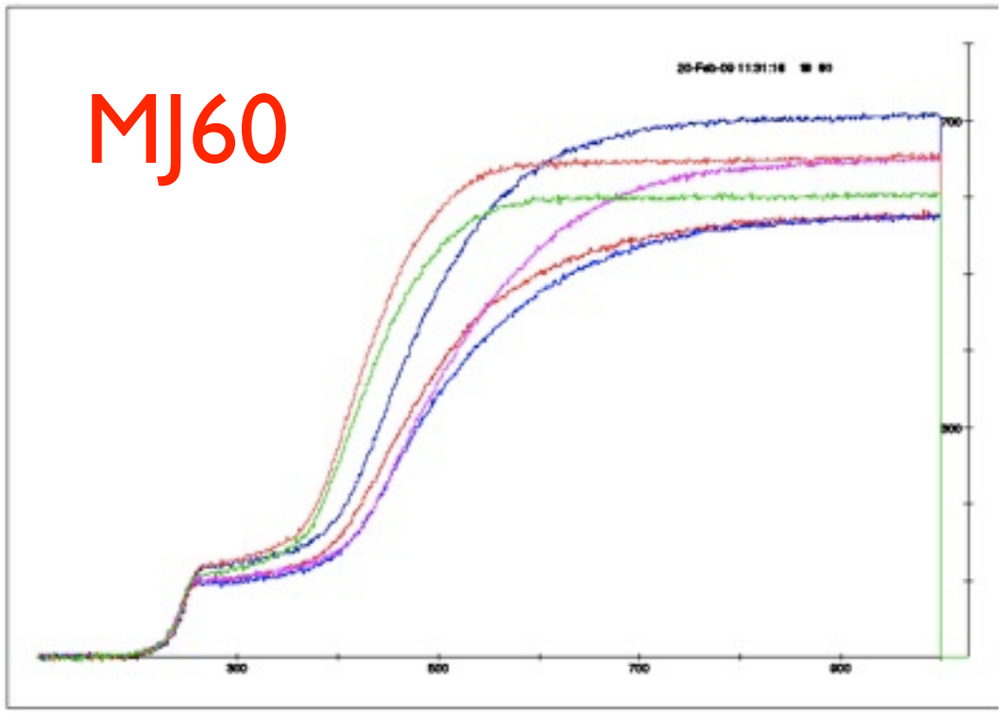
Prototype Module

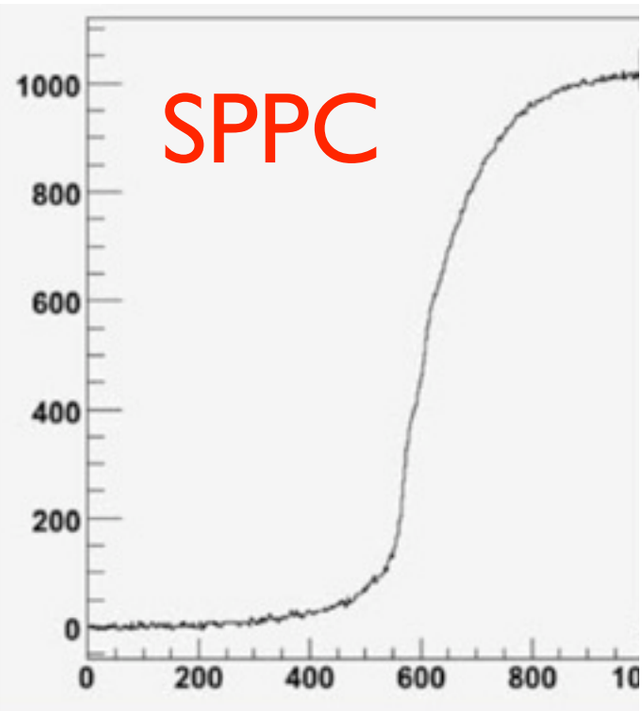
- 3-string array of natural-Ge Canberra Modified BEGe's
  - ∅ = 70±2.5 mm, h = 30±2.5 mm
  - 579 g active mass
  - contact r < 6.5 mm (5 mm nom.)
  - Front surface metalized for HV
  - 5 crystals per string
- Full scale demonstration of MAJORANA configuration
- Start counting 0νββ backgrounds
- Low-E physics

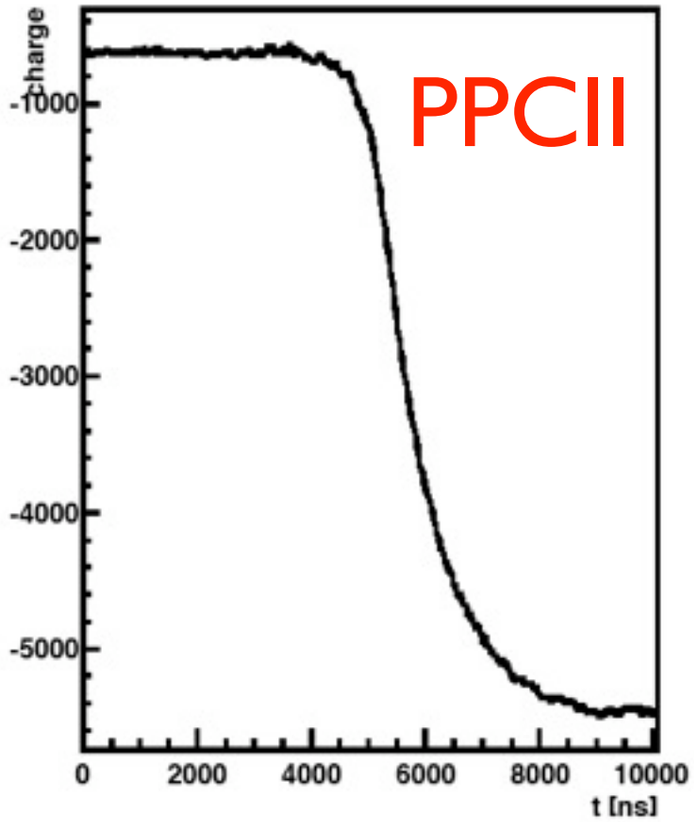


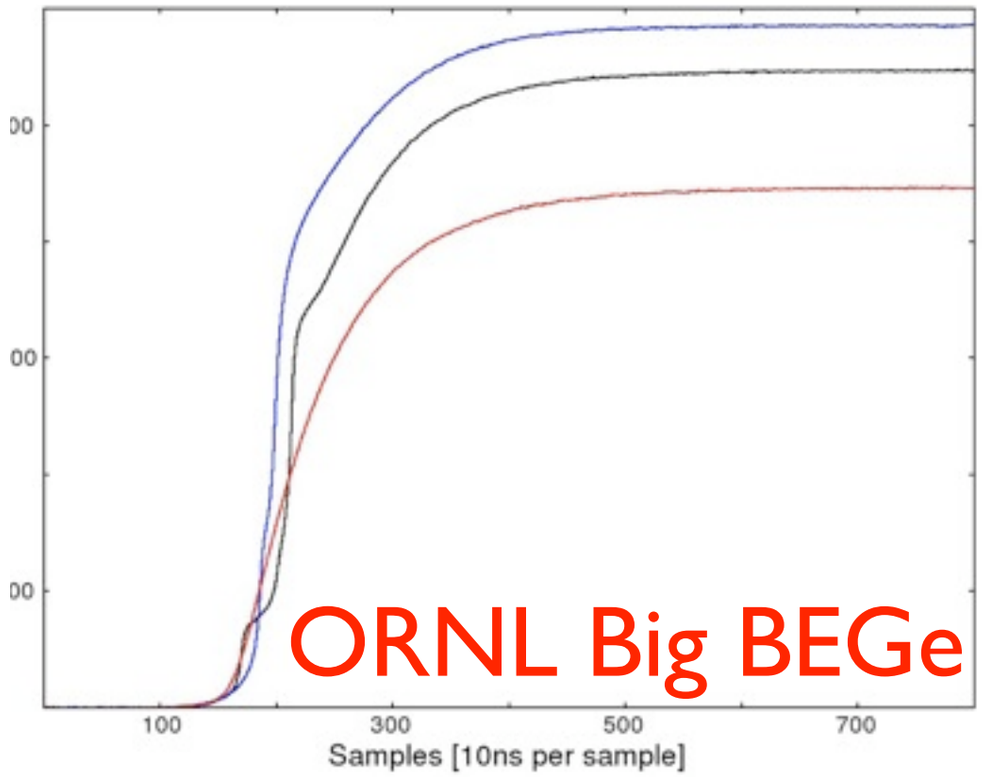
Slow-Rise Pulses

- Small percent of pulses with slow roll-up, possibly ubiquitous in PC detectors
- Kinked slow-roll pulses in MJ60 consistent with charged open surface with slower hole mobility
- Energy-, position-, surface-prep-dependence under investigation



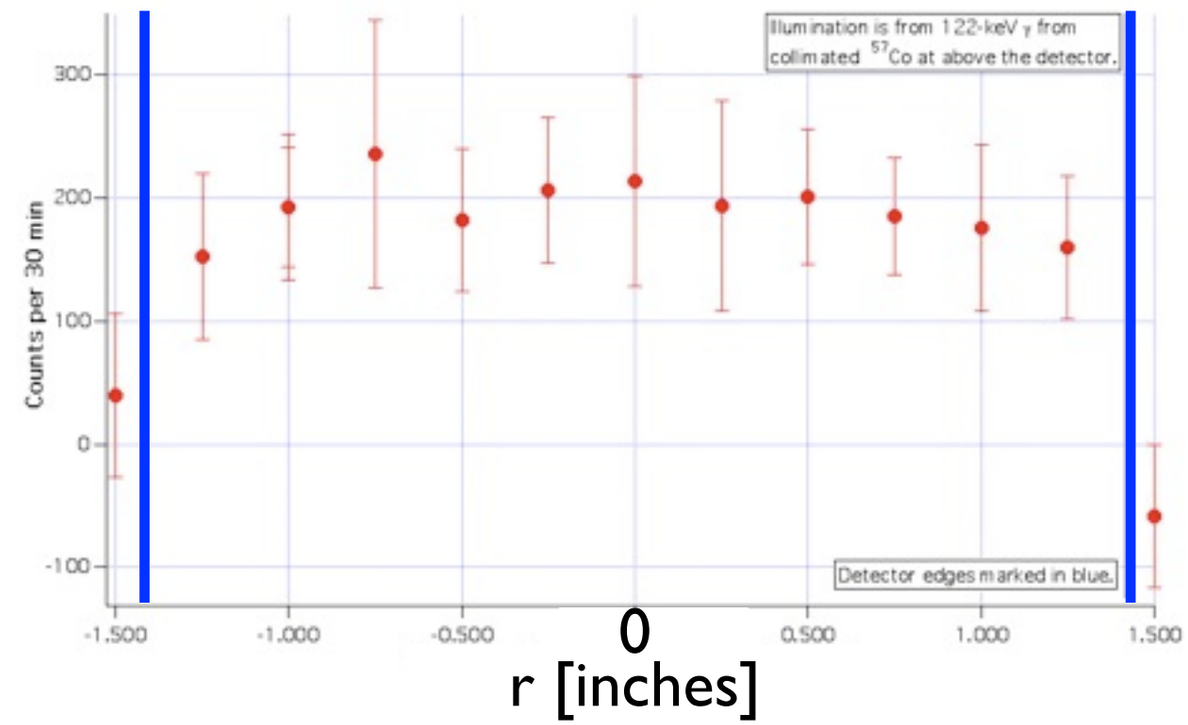


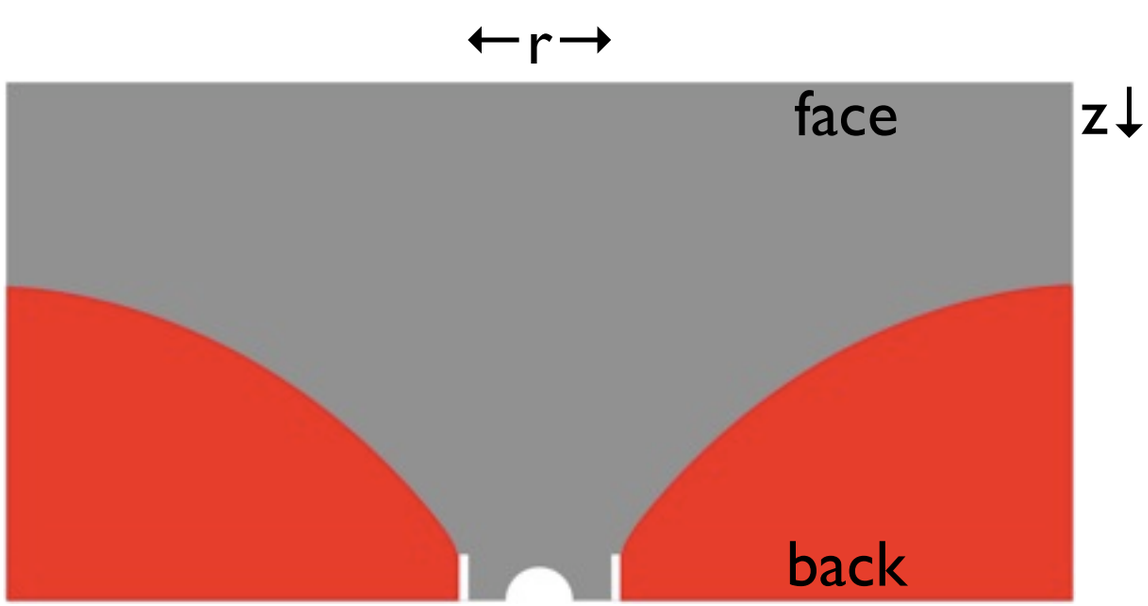


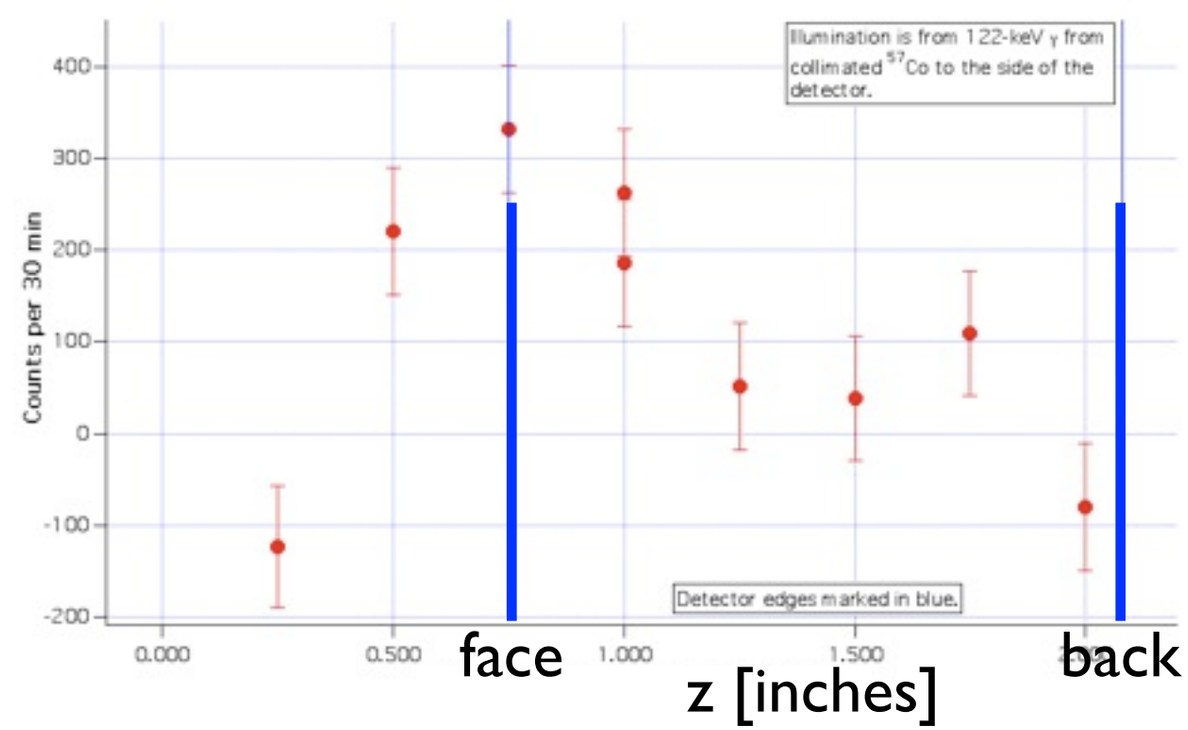


PPC Charge Collection R&D

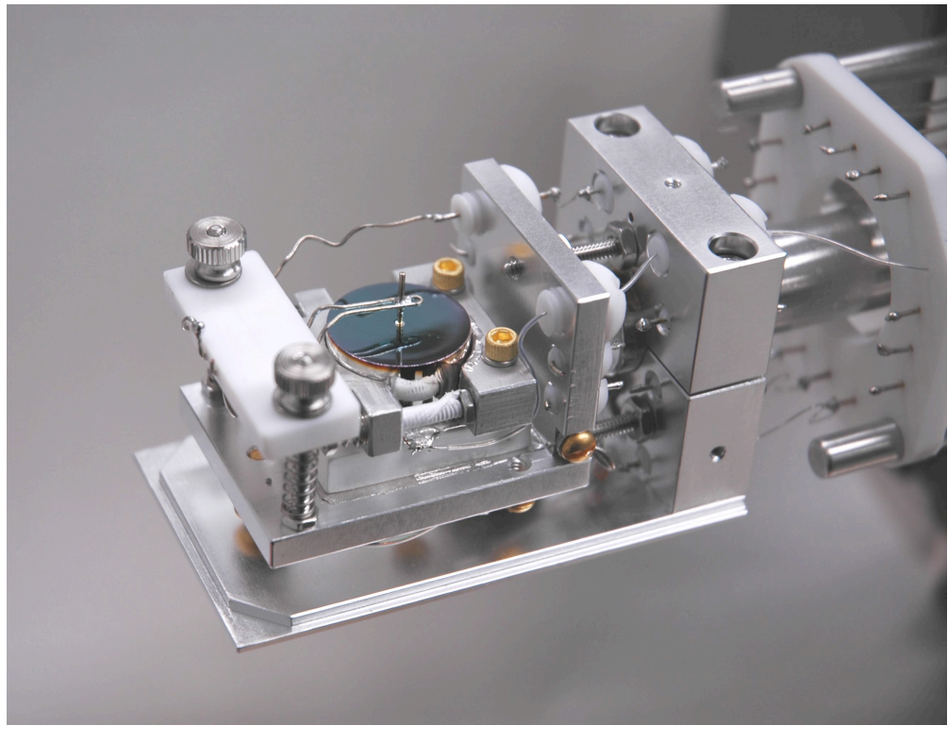
- ^{57}Co scan shows rapidly dropping efficiency near the detector back
- Consistent with drift trajectories being "blocked" by ditches

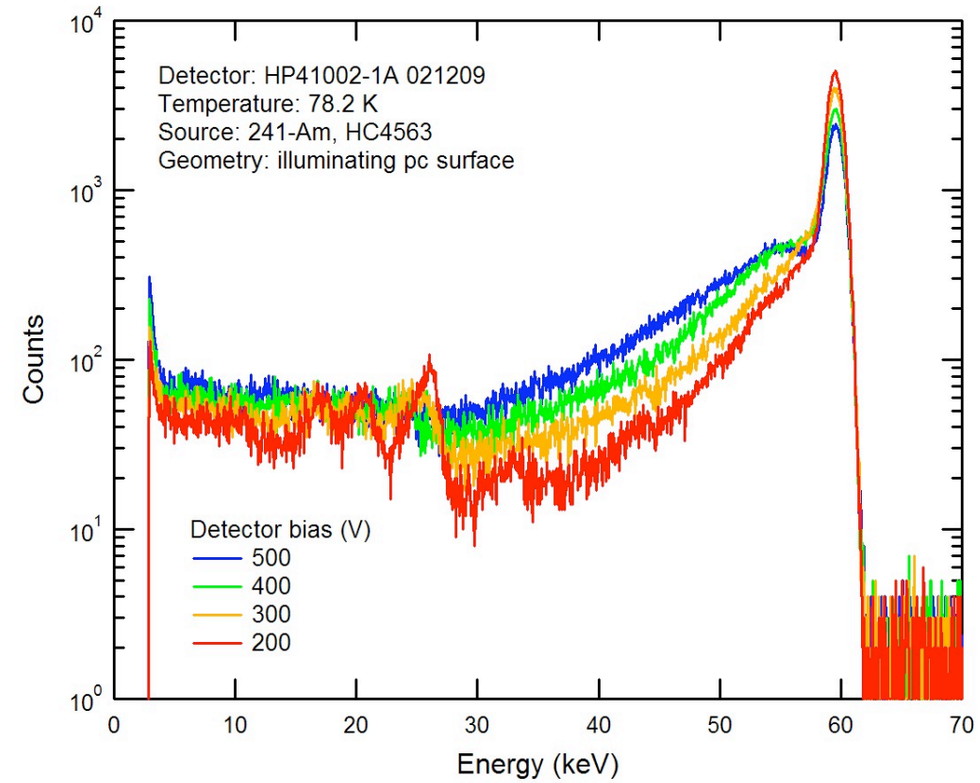




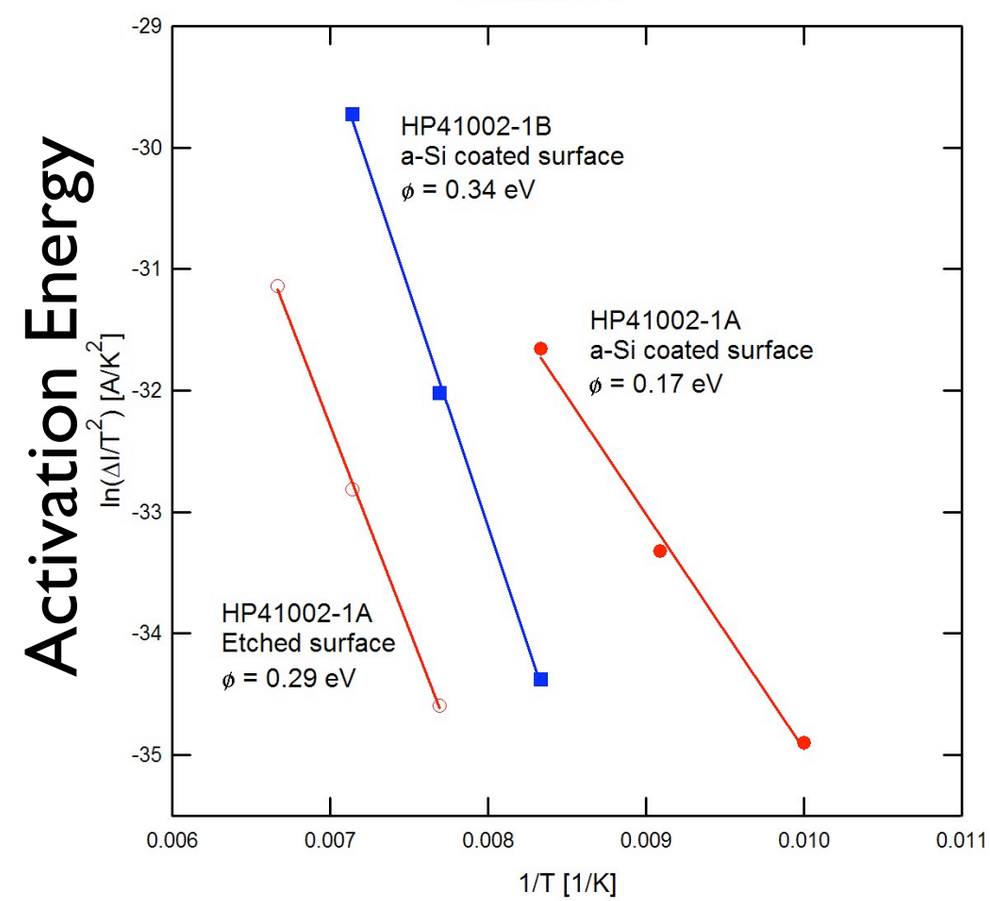


Surface Passivation R&D





- Mini-PPCs in T-variable cryostat
- Surface passivation recipe that didn't work for SPPC works for mini PPC, but gives different performance on identical mini PPCs
- Spectral variations consistent with charge trapping on passivated surface
- Investigate as a function of passivation recipe



Other R&D

- Neutron interaction simulations
- Cross-beam characterization
- Rn deposition on crystal surfaces
- Surface alpha background characterization
- Homestake backgrounds characterization

Chao's G4 bug report 1058

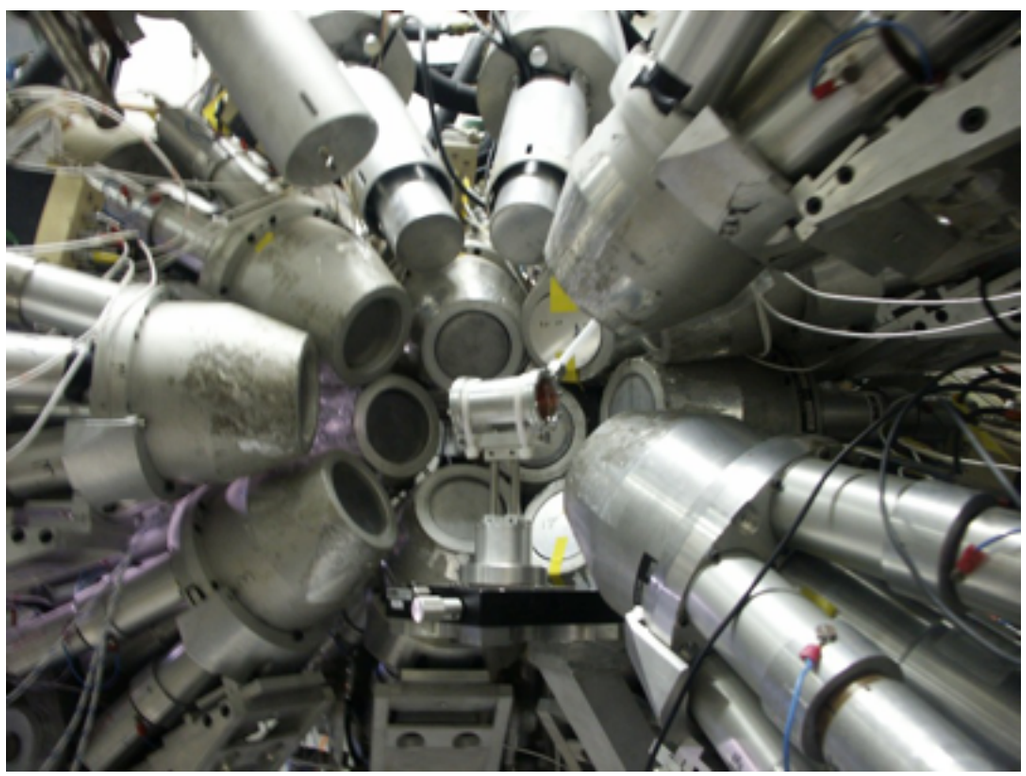
```
*******************************************************************************
* G4Track Information:   Particle = neutron,   Track ID = 1,   Parent ID = 0
*******************************************************************************

Step#    X       Y       Z      KineE   dEStep  StepLeng  TrakLeng   Volume     Process
   0   -10 cm   0 fm    0 fm    2 MeV   0 eV    0 fm      0 fm       Air    initStep
   1    -5 cm   0 fm    0 fm    2 MeV   0 eV    5 cm      5 cm       Air  Transportation
   2   8.01 mm  0 fm    0 fm    0 eV    0 eV    5.8 cm   10.8 cm   Germanium  NeutronInelastic
   :----- List of 2ndaries - #SpawnInStep=  6(Rest= 0,Along= 0,Post= 6), #SpawnTotal=  6 ----------
   :  8.01 mm   0 fm    0 fm   1.38 MeV   neutron
   :  8.01 mm   0 fm    0 fm   27.8 keV Ge74[0.0]
   :  8.01 mm   0 fm    0 fm   596 keV    gamma
   :  8.01 mm   0 fm    0 fm   370 eV     gamma
   :  8.01 mm   0 fm    0 fm   10.7 eV    gamma
   :  8.01 mm   0 fm    0 fm   10.7 eV    gamma
   :------------------------------------------------------------ EndOf2ndaries Info -------------
```

unexpected gamma lines

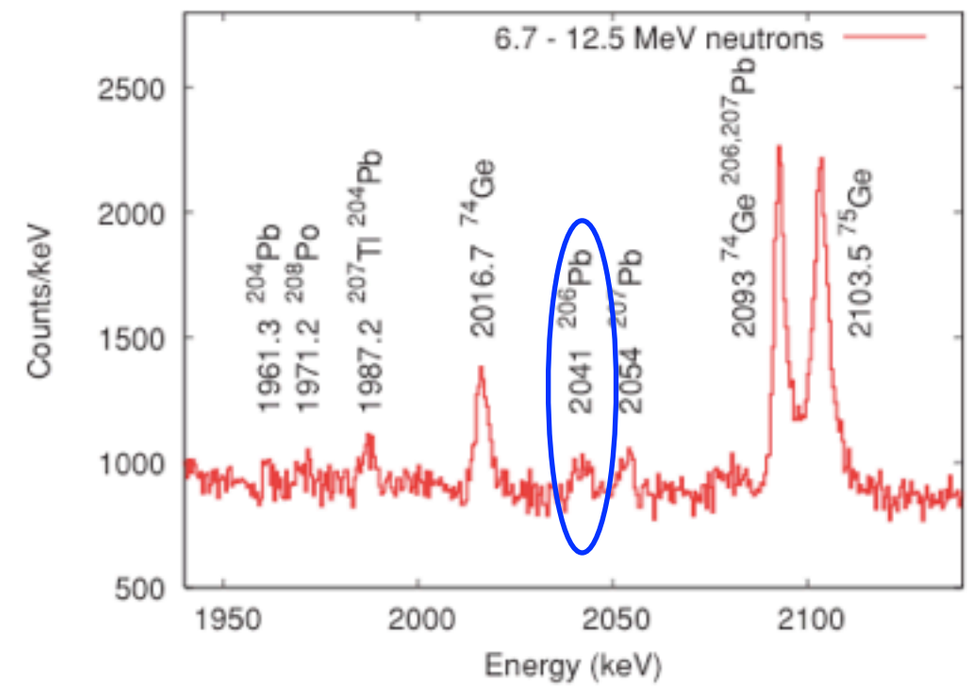
Other R&D

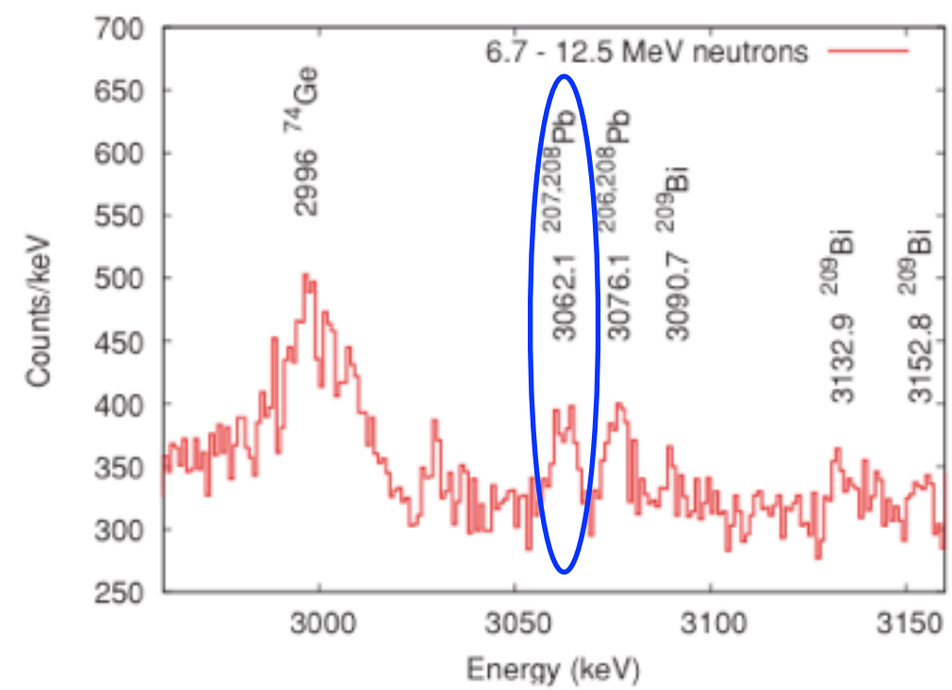
- (n,n'γ) measurements on Pb, Ge, Cu

LANSCE / GEANIE



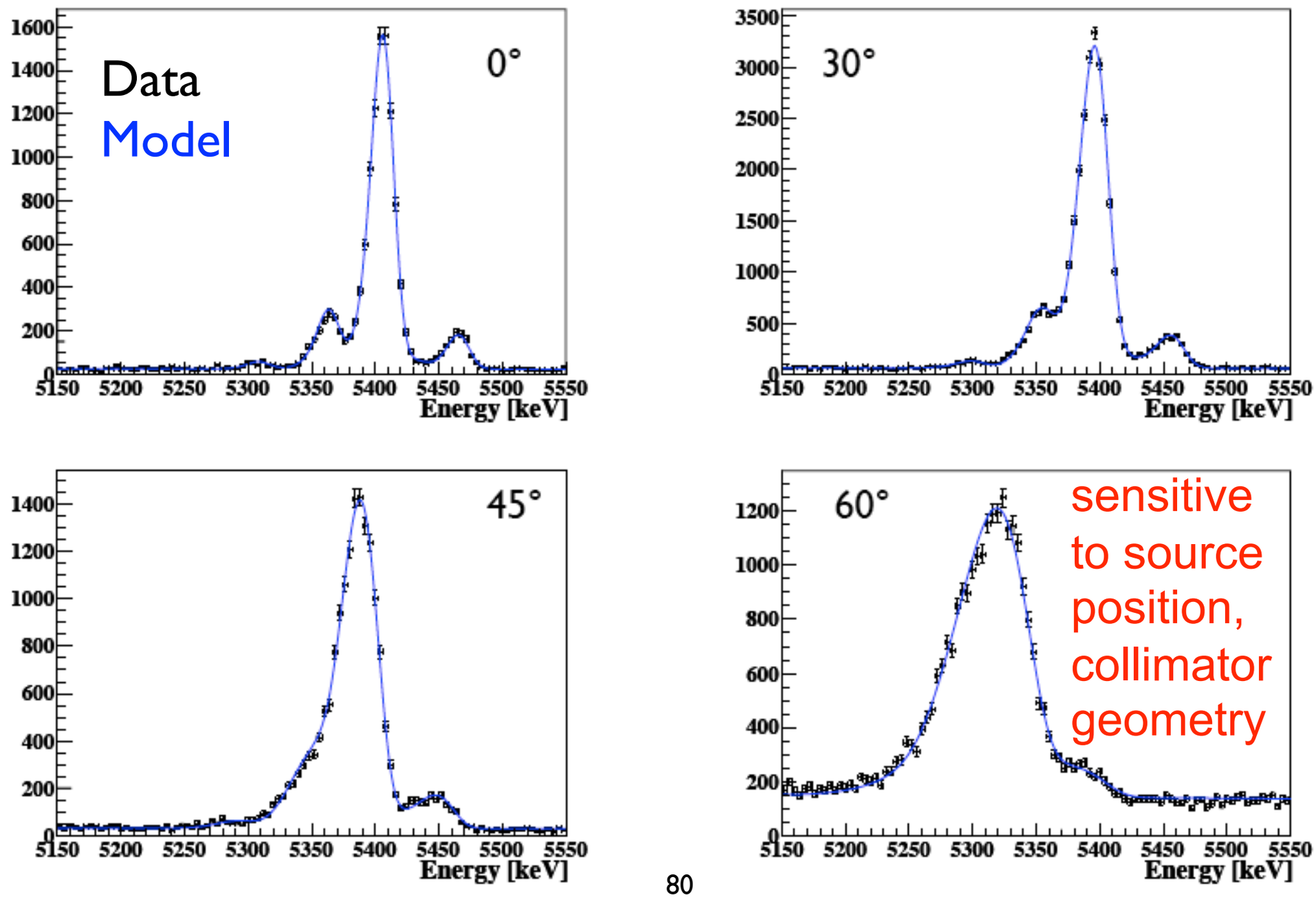
V.E.Guiseppe *et al.*, Phys. Rev. C **79**, 054604 (2009)





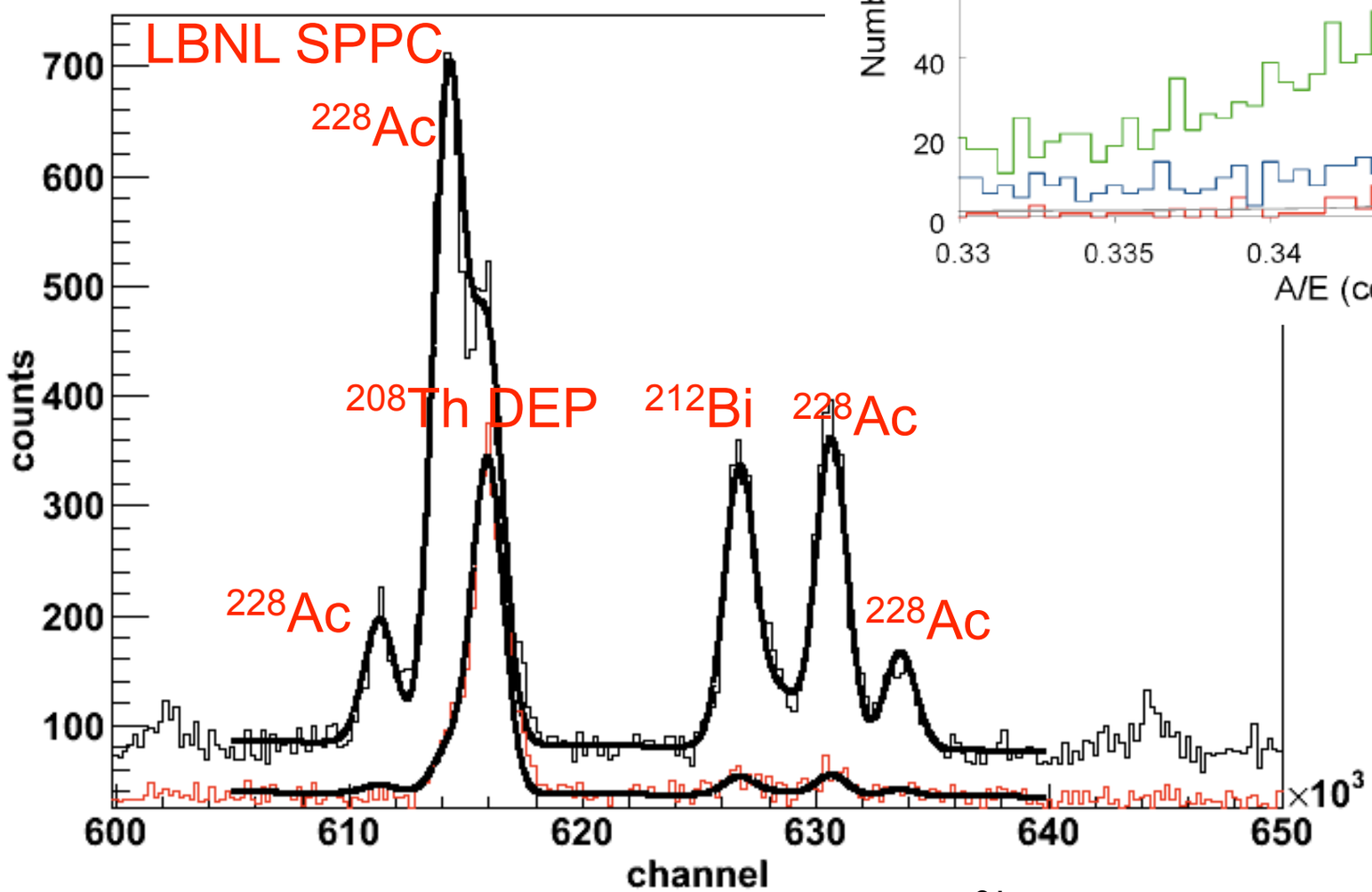
Surface Alphas

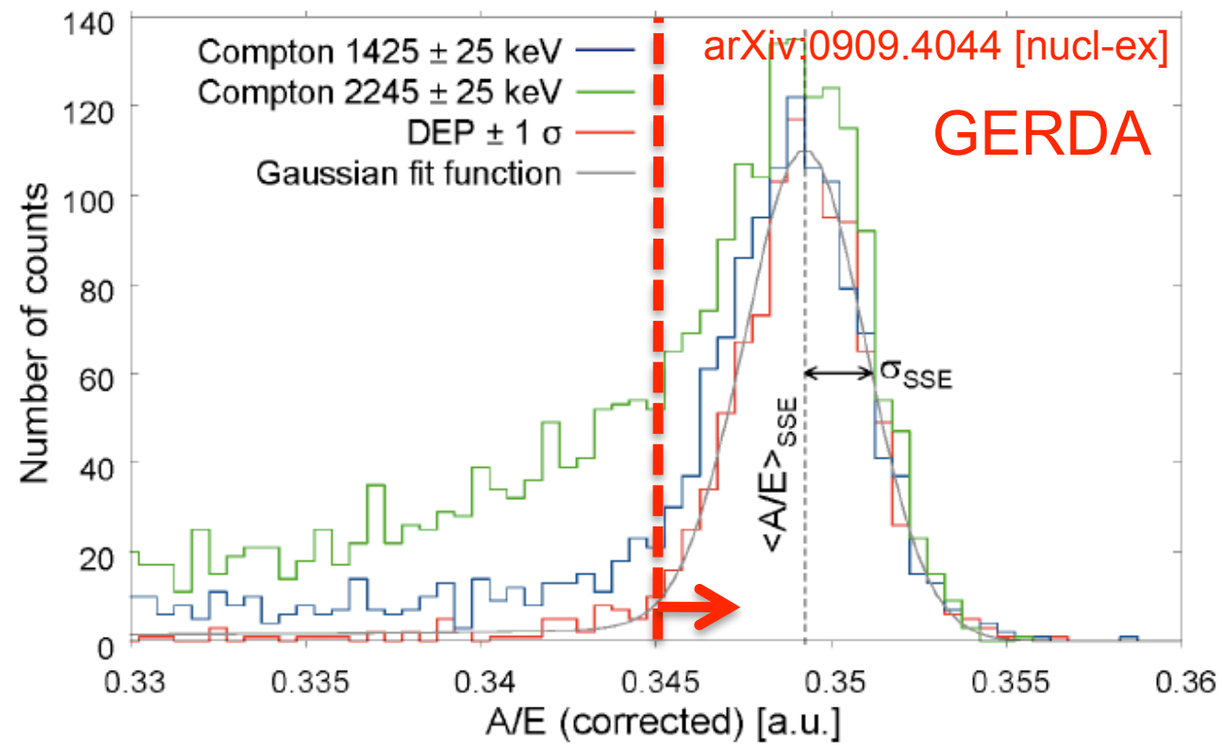
N-type detector, collimated ^{241}Am source data

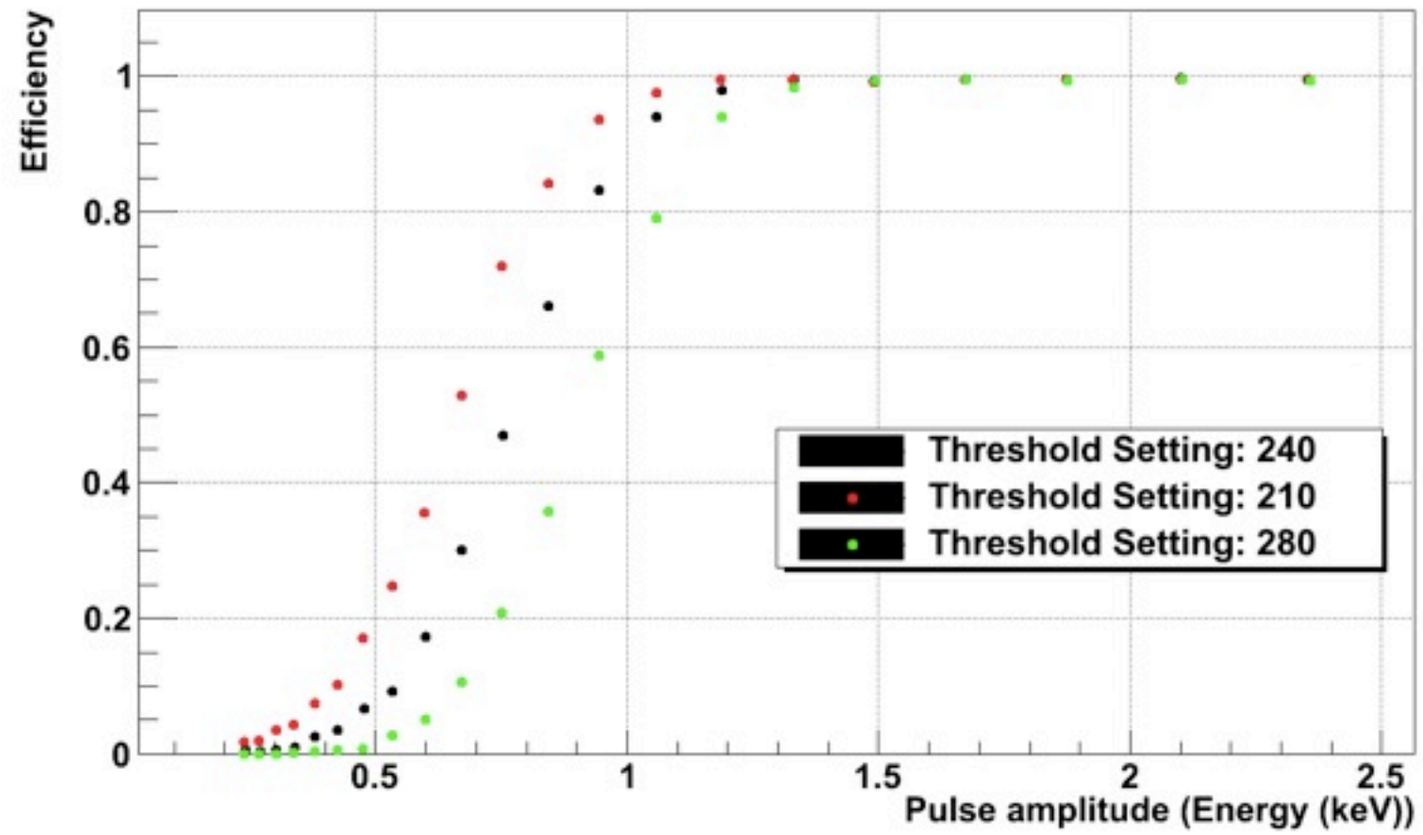
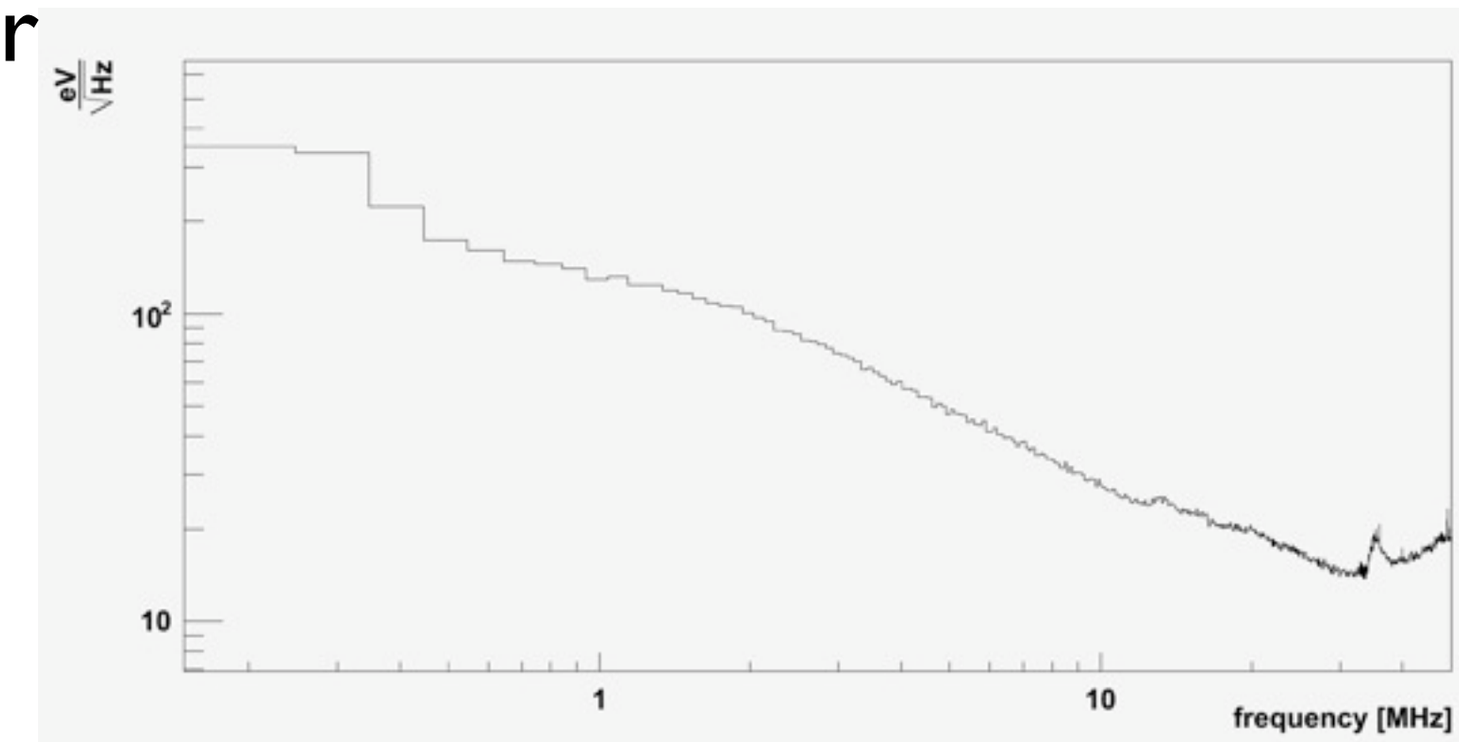


Pulse-Shape Analysis

- I_{max}/E PSD





DAQ

- Investigating noise / triggering at low-E
- Upgrade GRETINA card FPGA to increase integration time, trigger off of energy
- Exploring commercial alternatives (SIS)