Double-Beta Decay and the Neutrino

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Outline

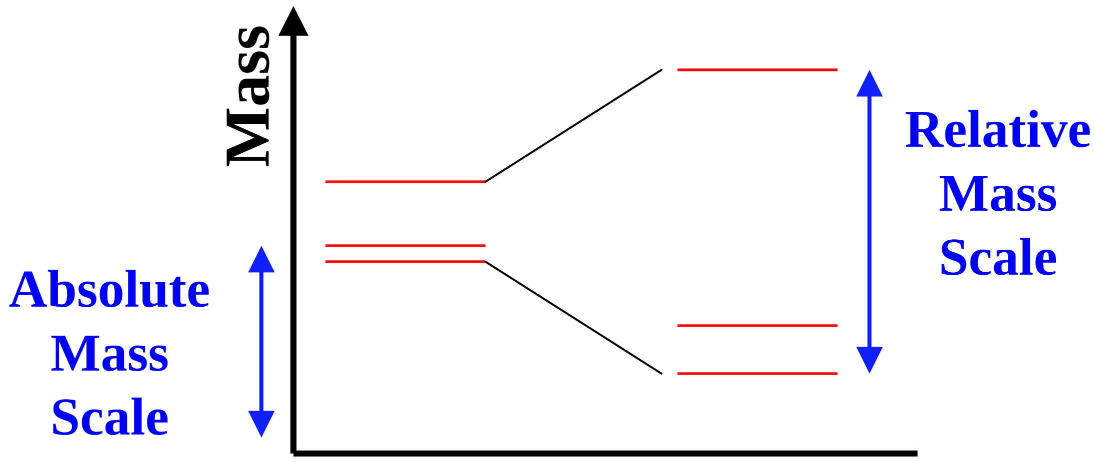
- **Double-Beta Decay and its relationship to the neutrino**
- **The experimental context**
  - **Where we're at and where we need to go**
- **Proposed future work**
  - **A focus on the Majorana Project**

Why Neutrinos?

ν properties are critical input to many physics questions

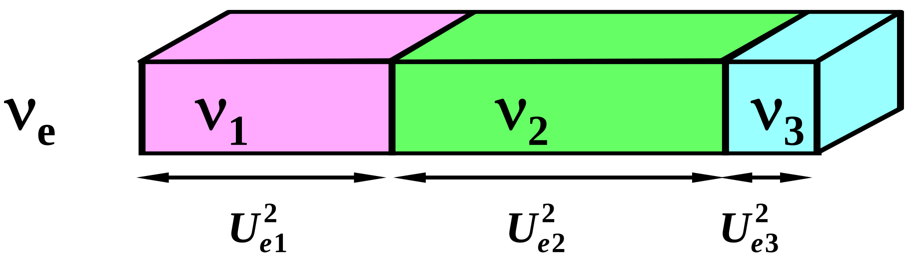
- **Particle/Nuclear Physics**
- **Cosmology**
- **Astrophysics**

Neutrinos: What do we want to know?



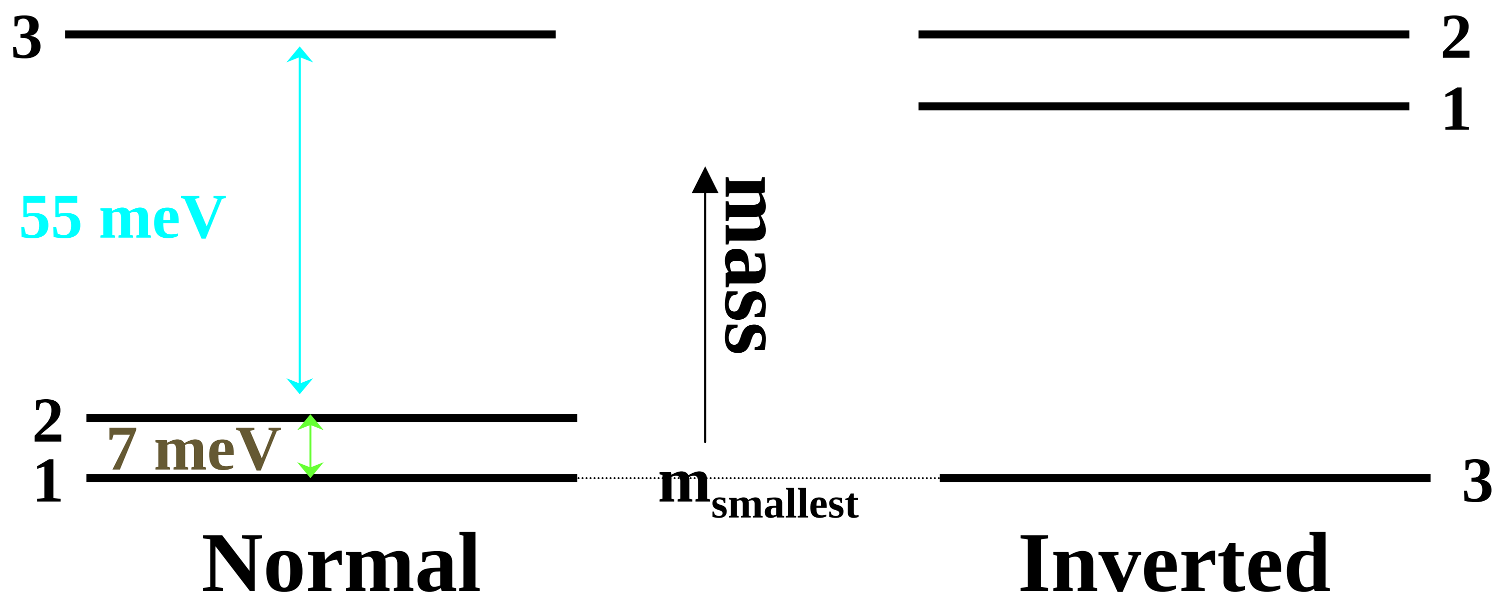
Dirac or Majorana

$$\begin{pmatrix}\nu_\uparrow\\ \nu_\downarrow\\ \bar{\nu}_\downarrow\\ \bar{\nu}_\uparrow\end{pmatrix} \text{ or } \begin{pmatrix}\nu_\uparrow\\ \nu_\downarrow\end{pmatrix}$$



Mixing

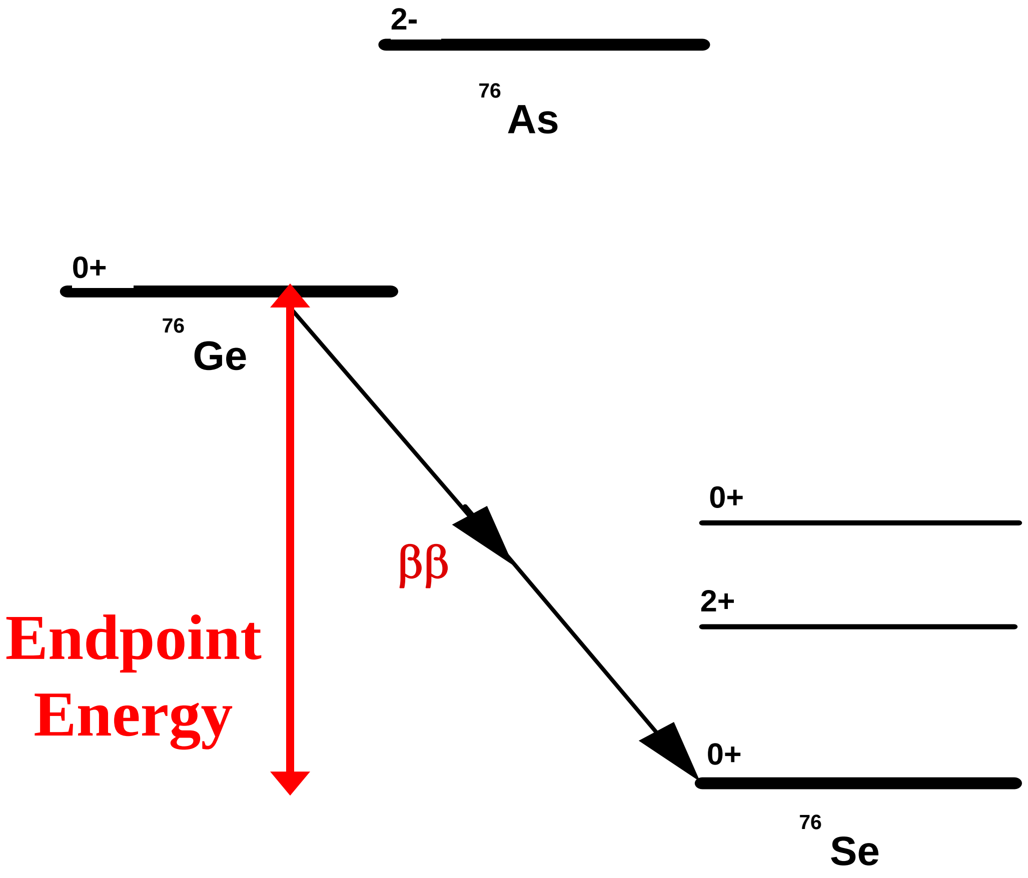
Oscillations and Hierarchy Possibilities



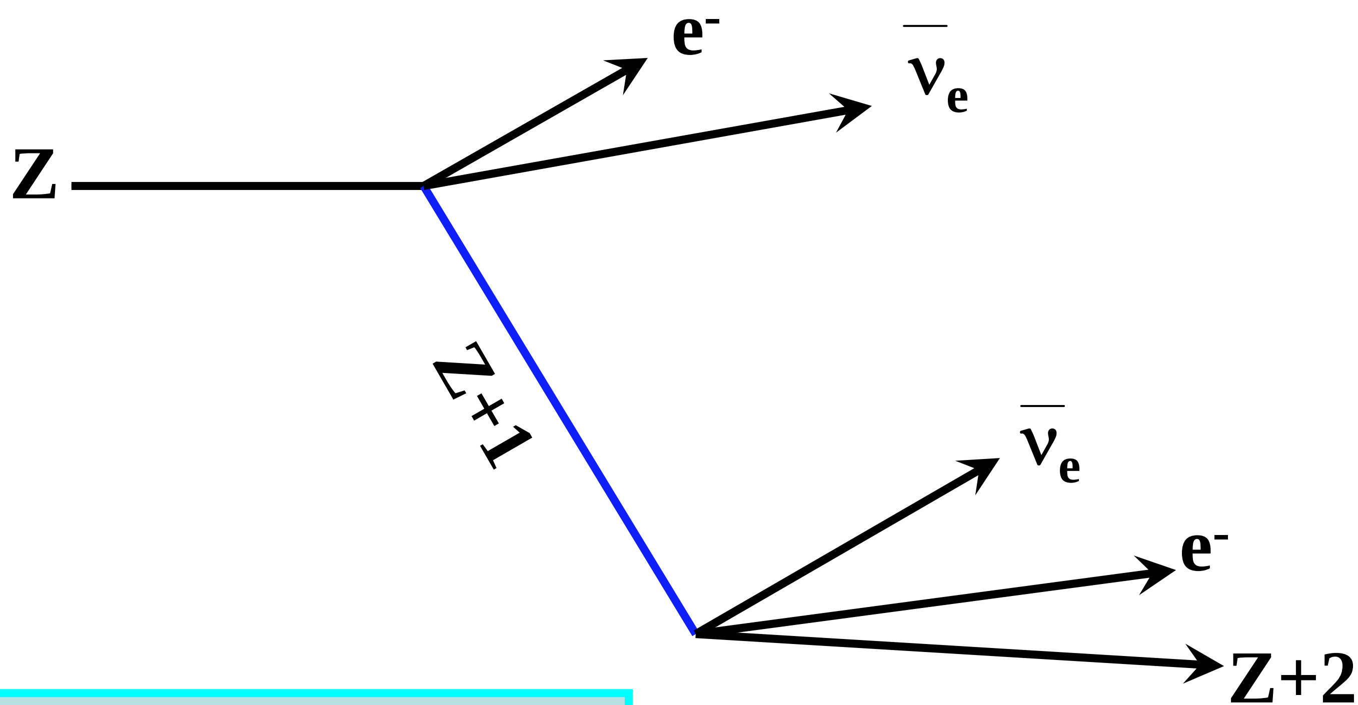
ν_e is composed of a large fraction of ν_1.

Example ββ Decay Scheme

In many even-even nuclei, β decay is energetically forbidden. This leaves ββ as the allowed decay mode.

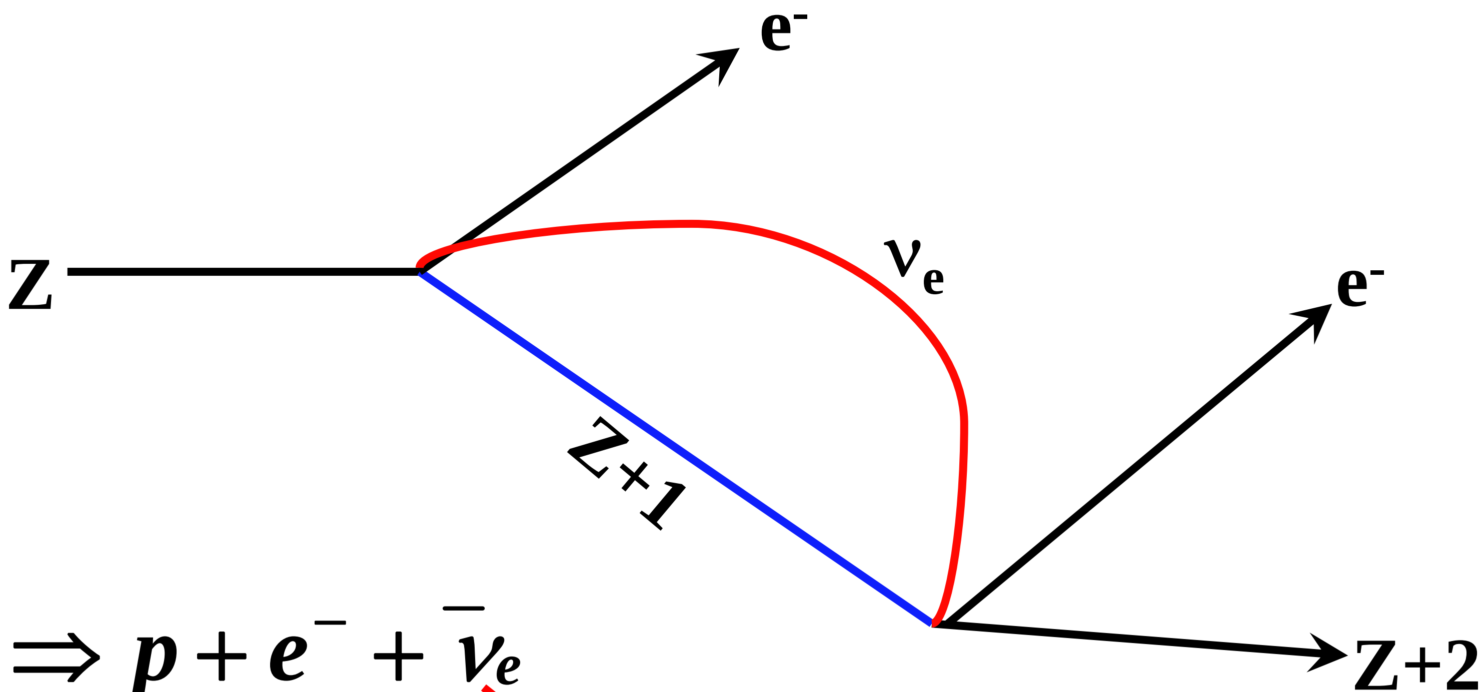


$\beta\beta(2\nu)$: Allowed weak decay



$$2n \Rightarrow 2p + 2e^{-} + 2\bar{\nu}_e$$

$\beta\beta(0\nu)$: requires massive Majorana ν

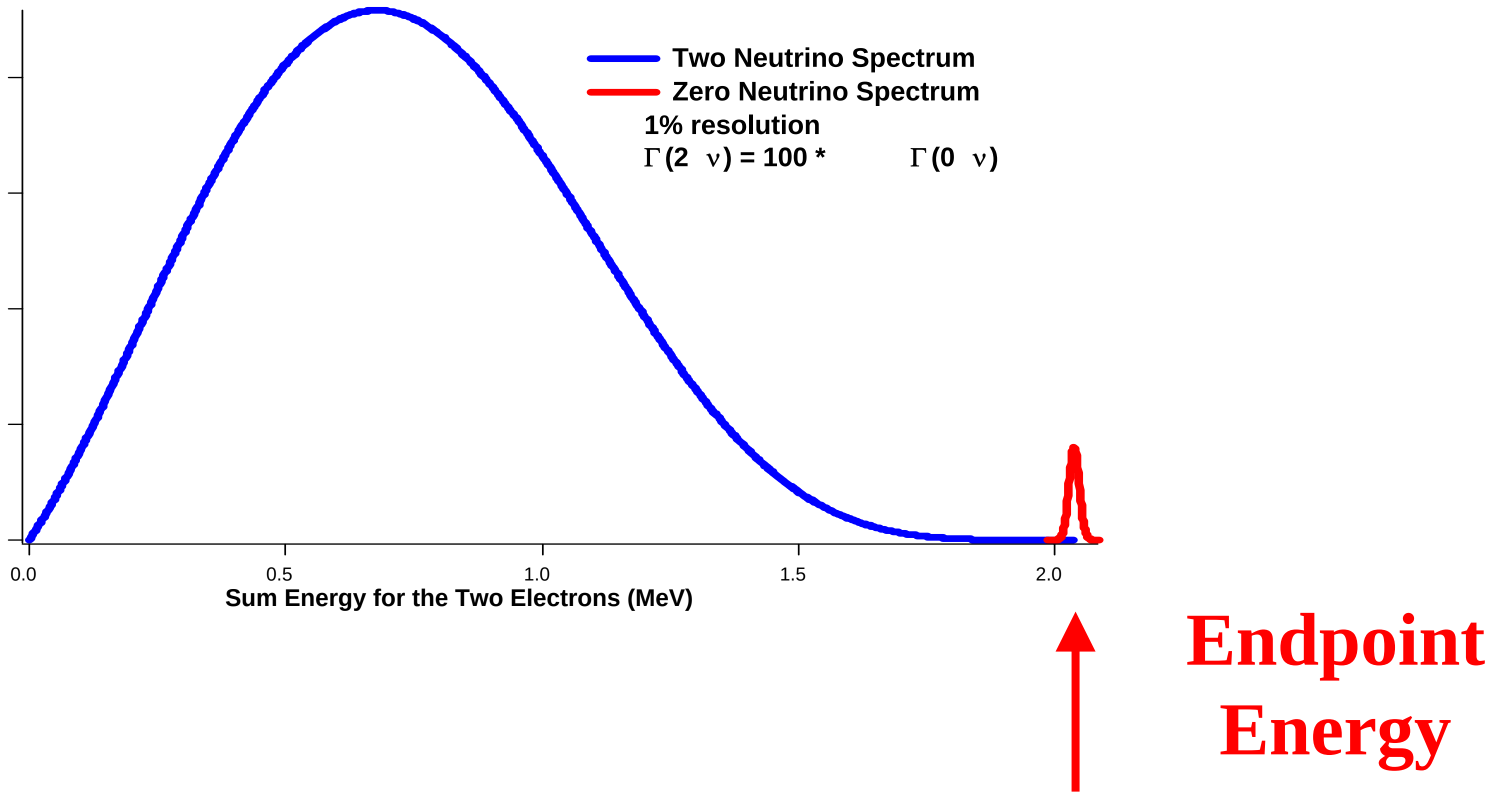


$$n \Rightarrow p + e^{-} + \overline{\nu}_e$$

(RH $\overline{\nu}_e$) (LH ν_e)

$$\nu_e + n \Rightarrow p + e^{-}$$

Energy Spectrum for the 2 e^-



ββ Decay Rates

$$\Gamma_{2\nu} = G_{2\nu}\left|M_{2\nu}\right|^2$$

$$\Gamma_{0\nu} = G_{0\nu}\left|M_{0\nu}\right|^2 m_\nu^2$$

G are calculable phase space factors.

$G_{0\nu} \sim Q^5$

|M| are nuclear physics matrix elements.

Hard to calculate.

m_ν is where the interesting physics lies.

What about mixing, m_ν & $\beta\beta(0\nu)$?

No mixing: $\langle m_{\beta\beta} \rangle = m_{\nu_e} = m_1$

$$\langle m_{\beta\beta} \rangle = \sum_{i=1}^{3} |U_{ei}|^2 m_i \, \varepsilon_i$$

virtual ν exchange

ε = ±1, CP cons.

Compare to β decay result:

$$\langle m_\beta \rangle = \sqrt{\sum_{i=1}^{3} |U_{ei}|^2 m_i^2}$$

real ν emission

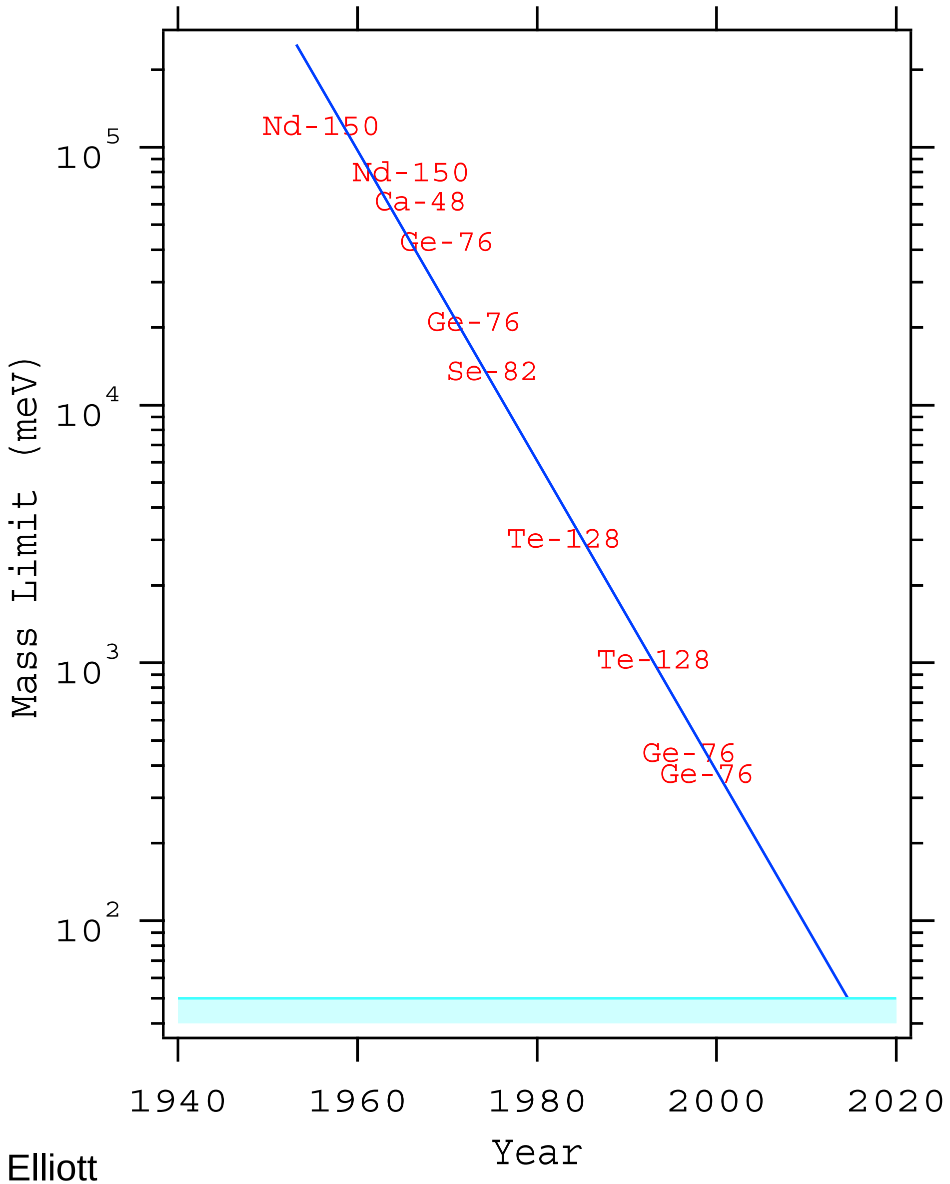
Compare to cosmology:

$$\Sigma = \sum m_i$$

Double Beta Decay

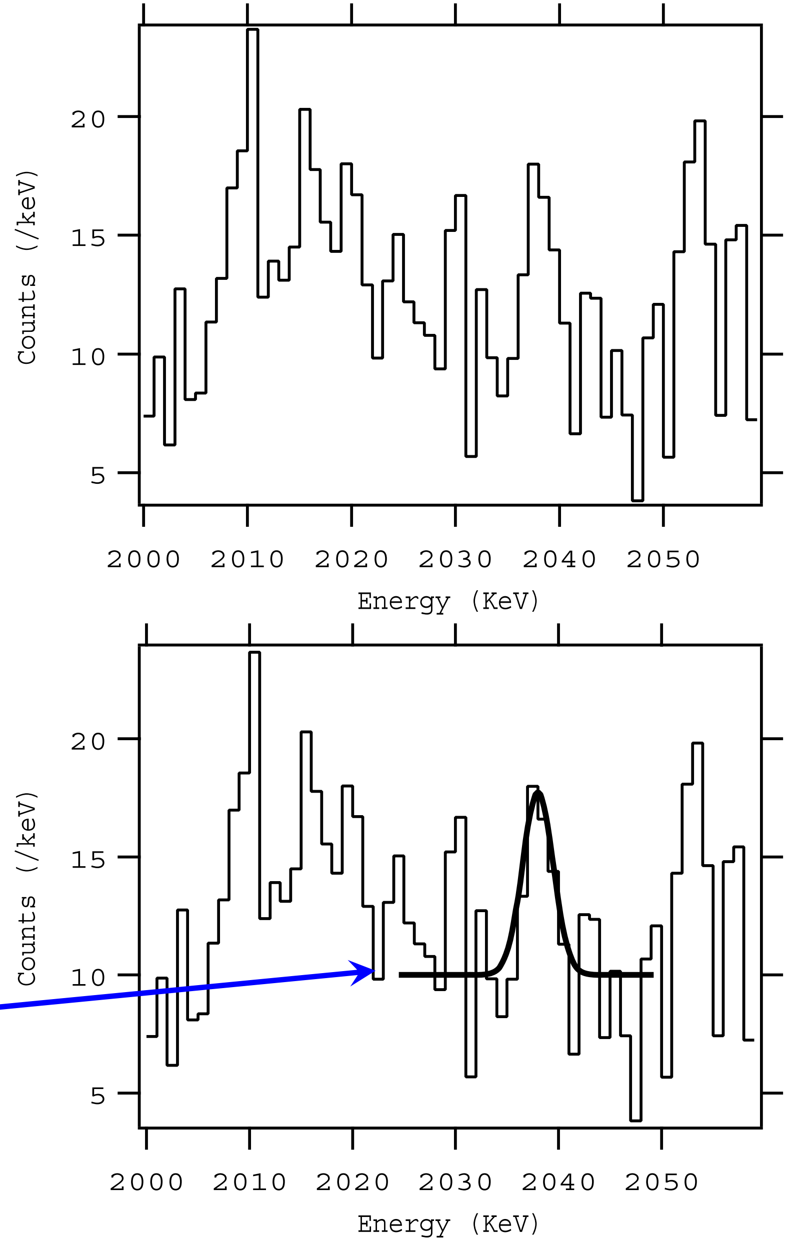
^{48}Ca	>1.4x10^{22} y	<(7.2-44.7) eV
^{76}Ge	>1.9x10^{25} y	<0.35 eV
^{76}Ge	>1.6x10^{25} y	<(0.33-1.35) eV
^{76}Ge	=1.2x10^{25} y	=0.44 eV
^{82}Se	>1.9x10^{23} y	<(1.3-3.2) eV
^{100}Mo	>3.5x10^{23} y	<(0.7-1.2) eV
^{116}Cd	>1.7x10^{23} y	<1.7 eV
^{128}Te	>7.7x10^{24} y	<(1.1-1.5) eV
^{130}Te	>5.5x10^{23} y	<(0.37-1.9) eV
^{136}Xe	>4.4x10^{23} y	<(1.8-5.2) eV
^{150}Nd	>1.2x10^{21} y	<3.0 eV

Elliott & Vogel
Annu. Rev. Part. Sci. 2002 52:115

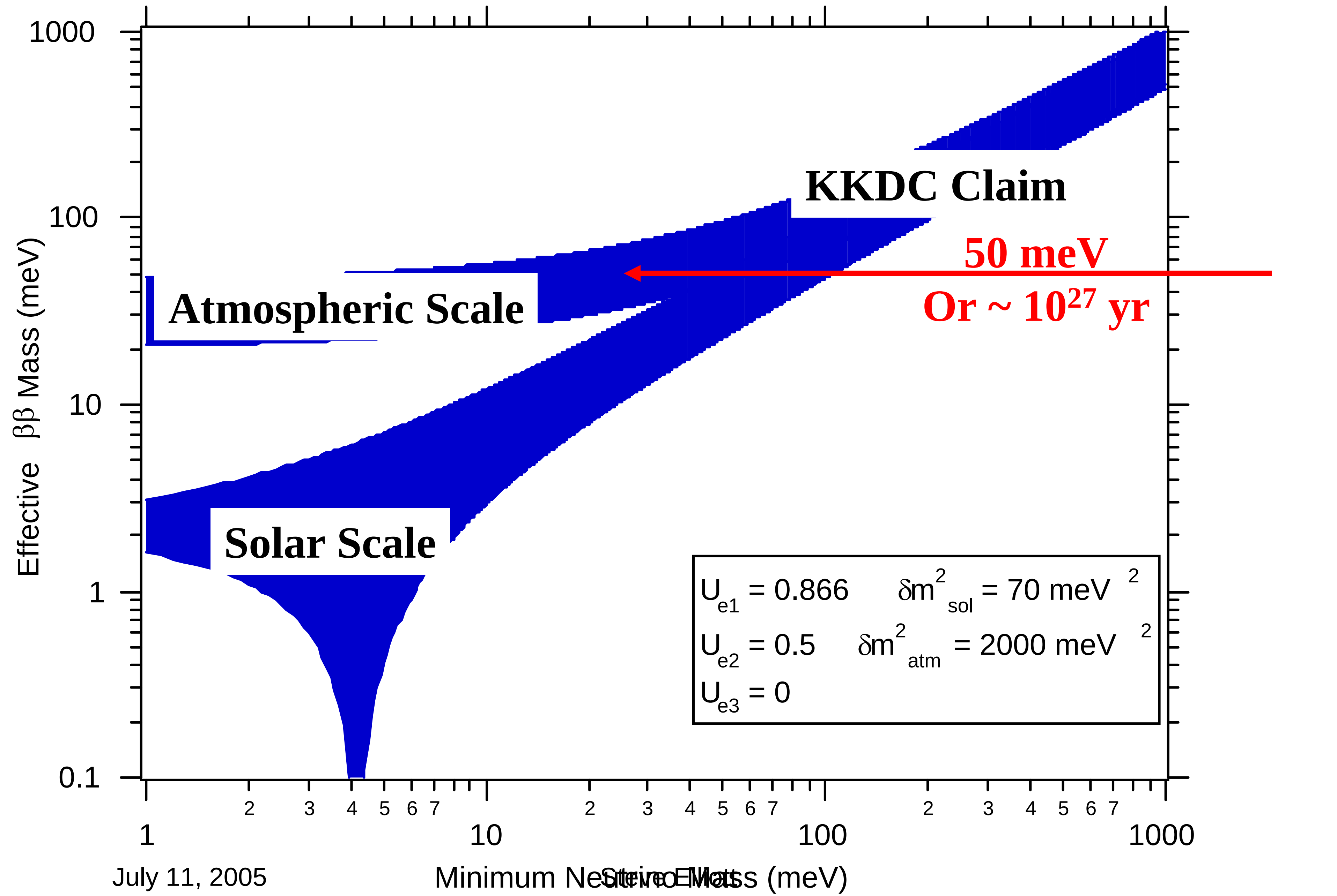


A Recent Claim

The "feature" at 2038 keV is arguably present. This will probably require experimental testing.



Background level depends on intensity fit to other peaks.



KKDC Claim
50 meV
Or ~ 10^27 yr
Atmospheric Scale
Solar Scale
U_e1 = 0.866 δm²_sol = 70 meV²
U_e2 = 0.5 δm²_atm = 2000 meV²
U_e3 = 0
Effective ββ Mass (meV)
1000
100
10
1
0.1
1
10
100
1000
Minimum Neutrino Mass (meV)
July 11, 2005
Steve Elliott

The UCI ^{82}Se Experiment

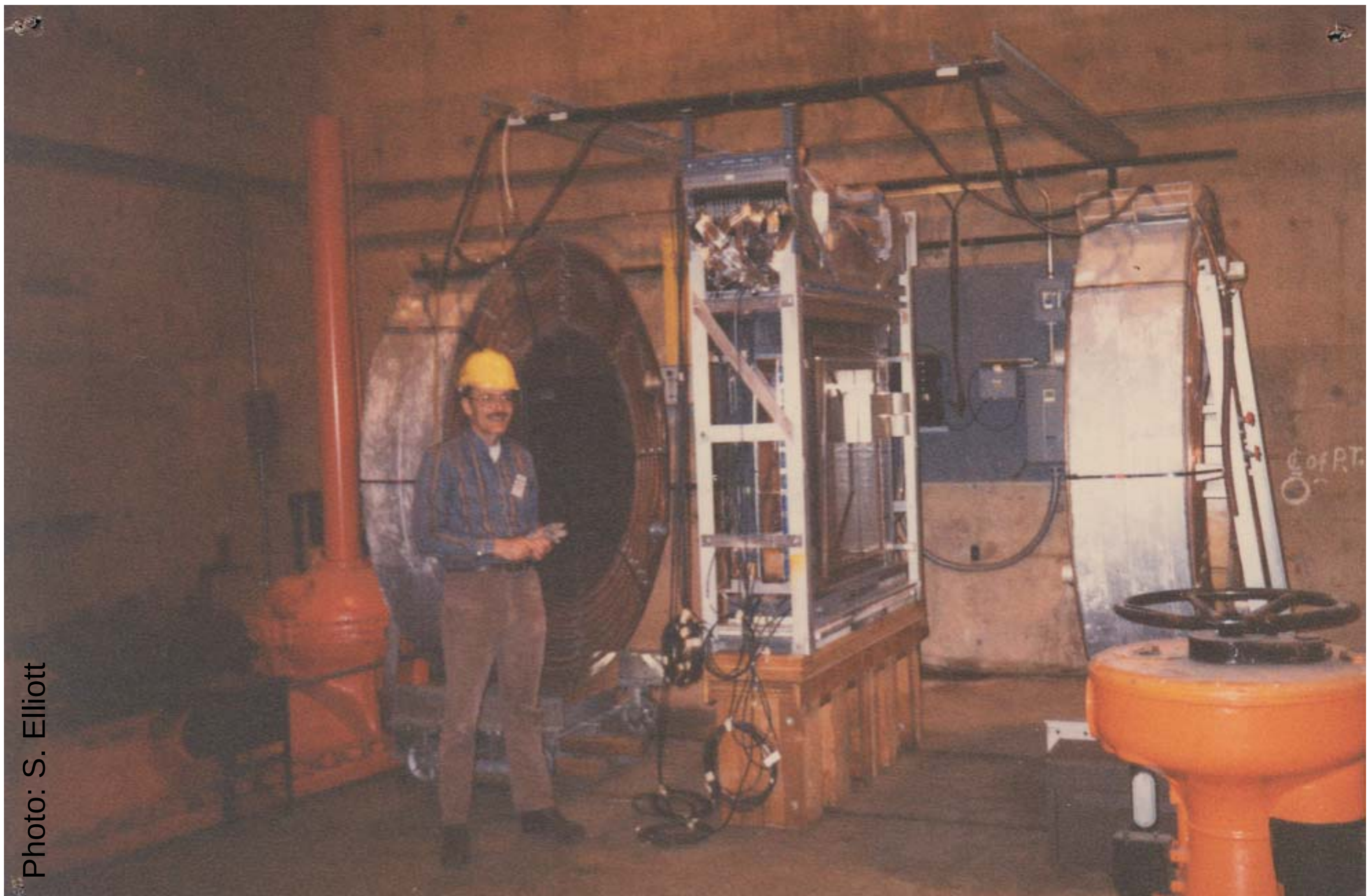
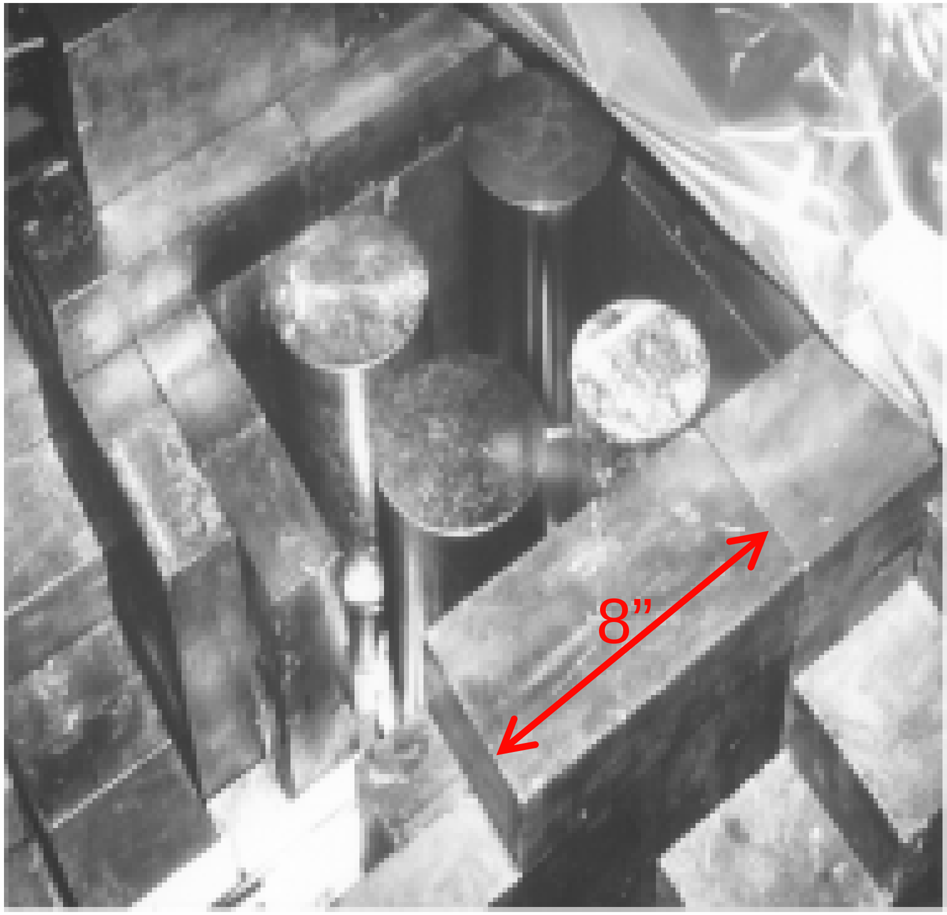


Photo: S. Elliott

The Heidelberg-Moscow Experiment

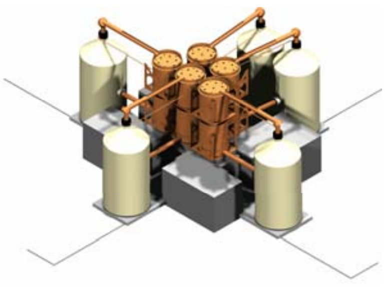


Foundations of Physics, 32, (2002)

A Great Number of Proposed Experiments

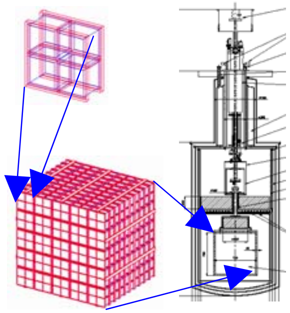
CARVEL	Ca-48	100 kg $^{48}CaWO_4$ crystal scintillators
COBRA	Te-130	10 kg CdTe semiconductors
DCBA	Nd-150	20 kg Nd layers between tracking chambers
NEMO	Mo-100, Various	10 kg of $\beta\beta$ isotopes (7 kg of Mo), expand to superNEMO
CAMEO	Cd-114	1 t $CdWO_4$ crystals
CANDLES	Ca-48	Several tons CaF_2 crystals in liquid scint.
CUORE	Te-130	750 kg TeO_2 bolometers
EXO	Xe-136	1 ton Xe TPC (gas or liquid)
GEM	Ge-76	1 ton Ge diodes in liquid nitrogen
GENIUS	Ge-76	1 ton Ge diodes in liquid nitrogen
GERDA	Ge-76	~30-40 kg Ge diodes in LN, expand to larger masses
GSO	Gd-160	2 t Gd_2SiO_5:Ce crystal scint. in liquid scint.
Majorana	Ge-76	~180 kg Ge diodes, expand to larger masses
MOON	Mo-100	Mo sheets between plastic scint., or liq. scint.
Xe	Xe-136	1.56 t of Xe in liq. Scint.
XMASS	Xe-136	10 t of liquid Xe

“Selected” Projects



Majorana

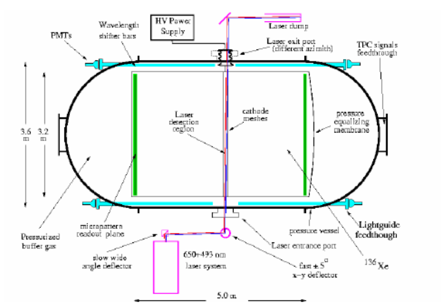
CUORE	TeO_2 Crystal bolometers
EXO	Liquid Xe TPC, daughter tag
GERDA	Bare Ge detectors in LN
Majorana	Ge det. in traditional cryostat
MOON	Scint. sandwiching Mo foils
SuperNEMO	Foils, tracking and scint.



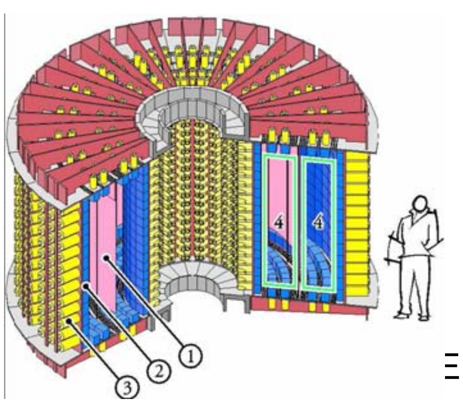
CUORE

EXO

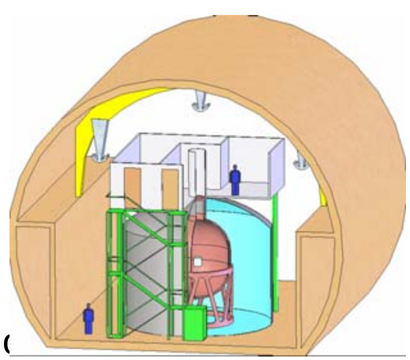
MOON

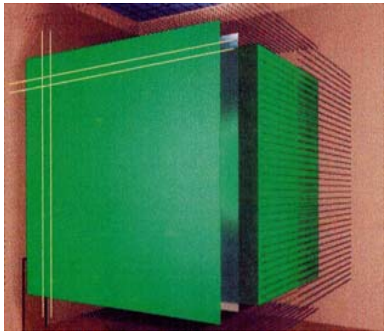


NEMO



GERDA





An exciting time for ββ!

For at least one neutrino:

$$m_i > \sqrt{\delta m^2_{atmos}} \approx 50\,meV$$

For the next experiments:

$$\langle m_{\beta\beta} \rangle \leq 50\,meV$$

< $m_{\beta\beta}$ > in the range near 50 meV is very interesting.

APS Study and M-180

The APS neutrino study on the future US Neutrino Program made a few things clear.
(http://www.aps.org/neutrino/)

- **Double-beta decay as one of the highest priorities.**
- **It recommends a staged approach beginning with 100-200 kg scaling later to 1 ton.**
  - **Precision measurement at degenerate scale**
  - **Followed by discovery potential at atmospheric scale**

Majorana has responded by developing a proposal for a 180-kg detector.

Why a precision measurement?

If <$m_{\beta\beta}$> is near the degenerate scale:

- **We will want to compare results from several isotopes to fully understand the underlying physics.**
- **A 10-20% decay rate measurement will allow effective comparisons between isotopes, when the matrix element uncertainty nears ~50%.**

Observation of ββ(0ν) implies massive Majorana neutrinos, but:

- **Relative rates between isotopes might discern light neutrino exchange and heavy particle exchange as the ββ mechanism.**
- **Relative rates between the ground and excited states might discern light neutrino exchange and right handed current mechanisms.**

Effective comparisons require experimental uncertainties to be small wrt theoretical uncertainties.

An Ideal Experiment

Maximize Rate/Minimize Background

$$\langle m_{\beta\beta} \rangle \propto \left(\frac{b \Delta E}{M t_{live}} \right)^{\frac{1}{4}}$$

Large Mass (~ 1 ton)
Good source radiopurity
Demonstrated technology
Natural isotope
Small volume, source = detector
Good energy resolution
Ease of operation
Large Q value, fast ββ(0ν)
Slow ββ(2ν) rate
Identify daughter
Event reconstruction
Nuclear theory

Ge Basics

Large Mass (~ 1 ton):	120-500 kg of ^{enr}Ge
Good source radiopurity:	Intrinsic Ge, well understood
Demonstrated technology:	“Ready to Go”
Natural isotope	
Small volume, source = det:	Fiorini “internal source method
Good energy resolution:	3-4 keV at 2039 keV, 0.2%
Ease of operation	High duty cycle operation
Large Q value, fast $\beta\beta(0\nu)$	2039 keV, above most radioactivities
Slow $\beta\beta(2\nu)$ rate	10^{21} yrs
Identify daughter	
Event reconstruction	segmentation, modularity, PSD
Nuclear theory	Low A - Shell Model and QRPA

Advantages for Majorana

^{76}Ge offers the best combination of capabilities and sensitivities. Majorana is ready to proceed, with demonstrated technologies.

- Favorable nuclear matrix element $<M^{0\nu}>$=2.4 [Rod05].
- Reasonably slow $2\nu\beta\beta$ rate ($T_{1/2}$ = 1.4×10^{21} y).
- Demonstrated ability to enrich from 7.44% to 86%.
- Ge as source & detectors.
- Elemental Ge maximizes the source-to-total mass ratio.
- Intrinsic high-purity Ge diodes.
- Excellent energy resolution — 0.16% at 2.039 MeV, for a ROI of 4 keV.
- 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
- Well-understood technologies
  - Commercial Ge diodes
  - Existing, well-characterized large Ge arrays (Gammasphere)

The Majorana 180 kg Experiment Overview

Majorana is scalable, allowing expansion to 1000 kg.

The 180 kg Experiment (M180)

- **Reference Design**
  - **171 segmented, n-type, 86% enriched ^{76}Ge crystals.**
  - **3 independent, ultra-clean, electroformed Cu cryostat modules.**
  - **Surrounded by a low-background passive shield and active veto.**
  - **Located deep underground (6000 mwe).**
- **Background Specification in the $0\nu\beta\beta$ peak ROI**

  1 count/t-y
- **Expected Sensitivity to $0\nu\beta\beta$**
  (for 3 years, or 0.46 t-y of ^{76}Ge exposure)

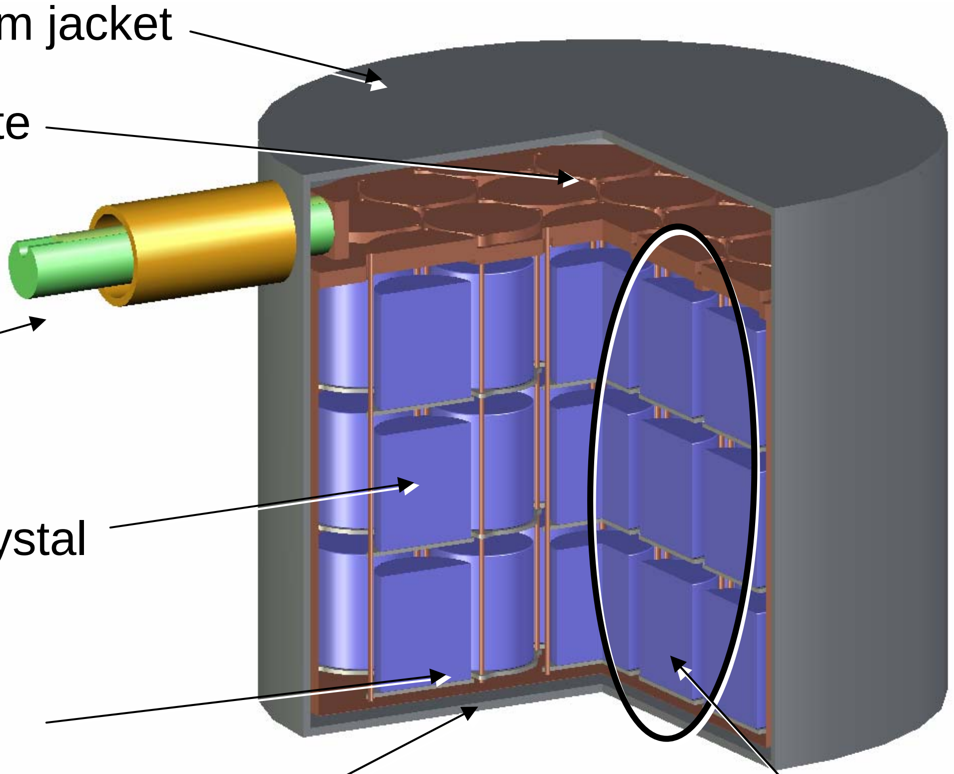
  $T_{1/2} >= 5.5 \times 10^{26}$ y (90% CL)

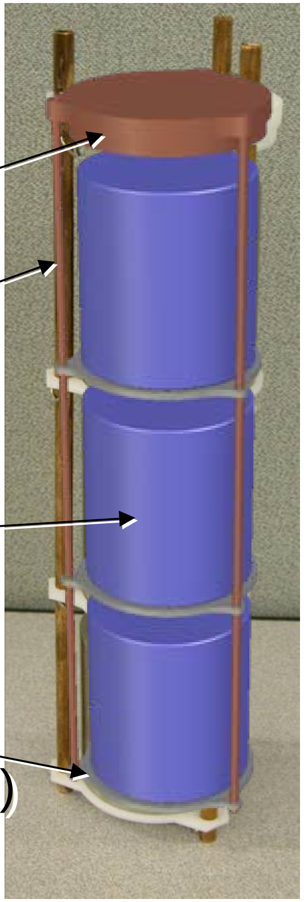
  $<m_\nu> < 100$ meV (90% CL) ([Rod05] RQRPA matrix elements)

  or a 10% measurement assuming a 400 meV value.

The Majorana Modular Approach

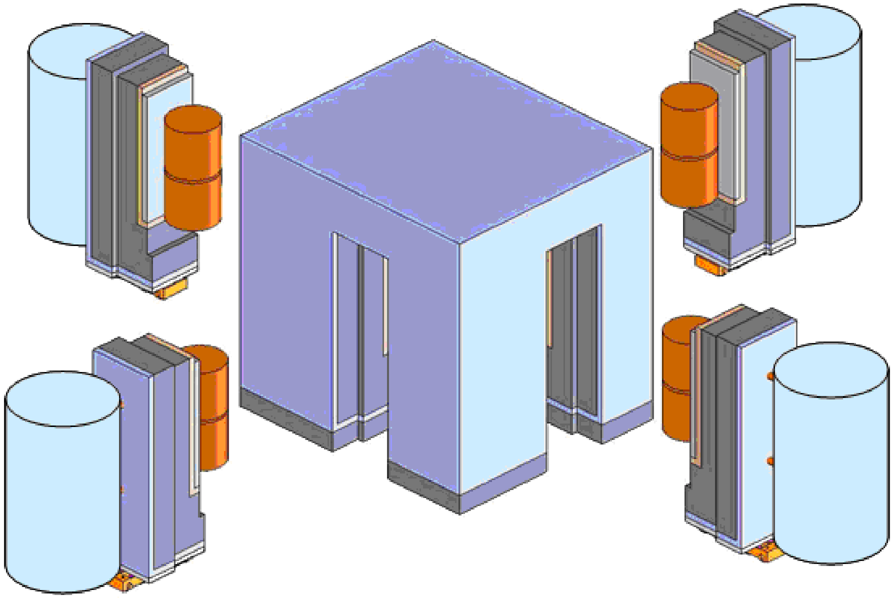
- **57 crystal module**
  - **Conventional vacuum cryostat made with electroformed Cu.**
  - **Three-crystal stack are individually removable.**

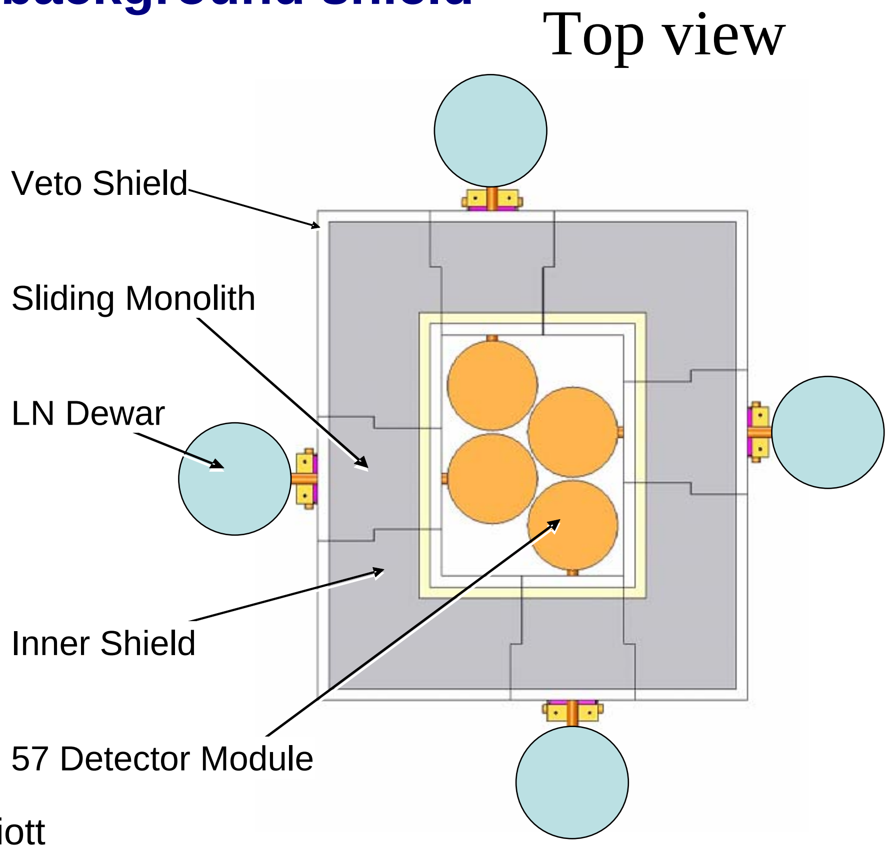




The Majorana Shield - Conceptual Design

- **Allows modular deployment, early operation**
- **contains up to eight 57-crystal modules (M180 populates 3 of the 8 modules)**
- **four independent, sliding units**
- **40 cm bulk Pb, 10 cm ultra-low background shield**
- **active 4π veto detector**





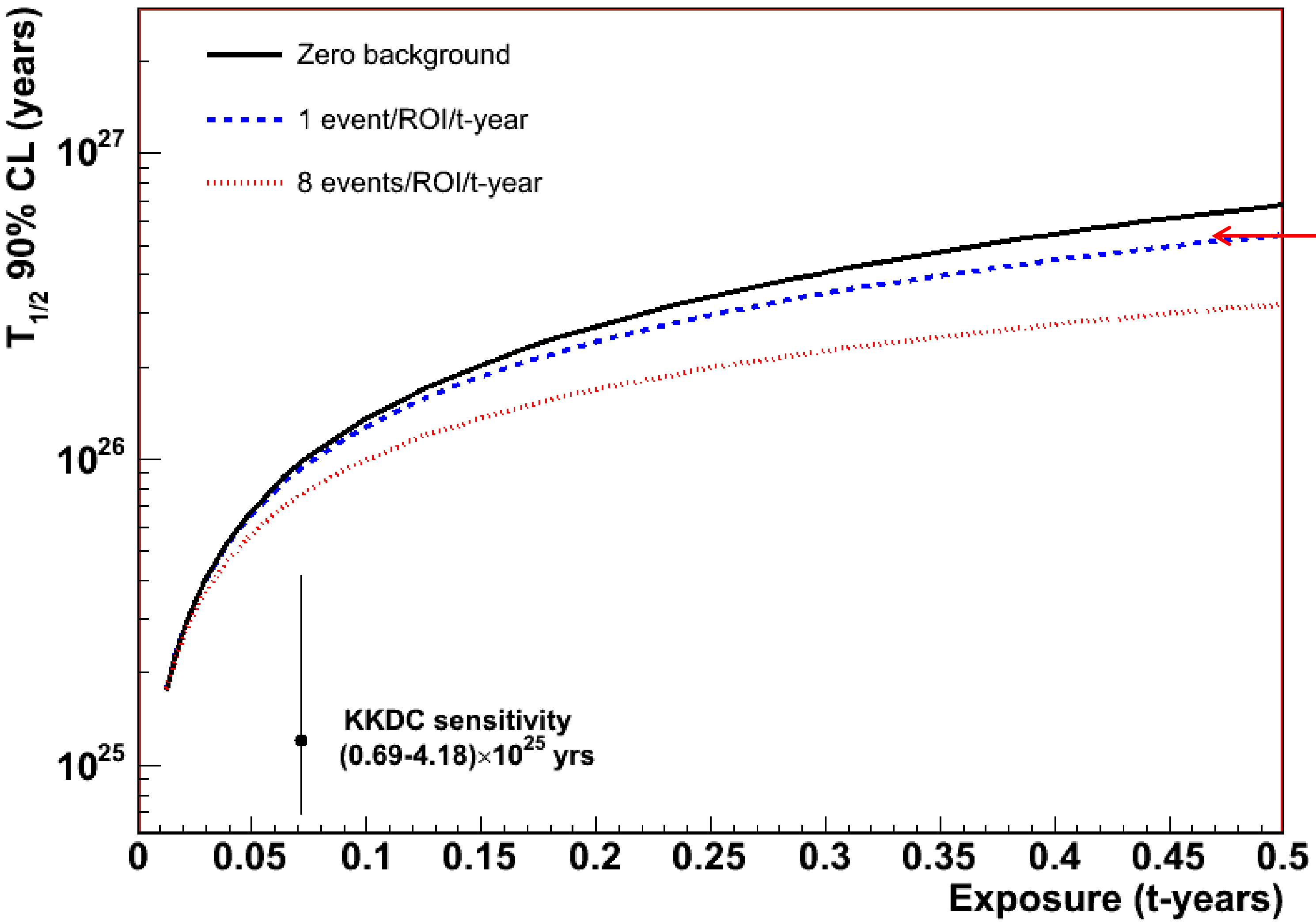
The Majorana Reference Plan

- Enrichment: **Ge ~200 kg of intrinsic Ge metal, enriched to 86% in ^{76}Ge, from the ECP in Russia**
- Transport: **surface ship this Ge to a detector manufacturing company in North America to produce Ge crystals, suitable for detector fabrication**
- Crystals: **produce approximately 180 1.1-kg, n-type, segmented Ge detectors with each segmentation geometry consisting of 2 segments**
- Module Assembly: **install detectors into Cu cryostats that have been electroformed underground**
- Module Installation: **install modules into an ultra-pure graded shield**
- Shielding: **incorporate an active, neutron and cosmic ray anti-coincidence detector (a veto system) into the Pb shield, deep underground**
- Front End Signals: **electronically read out the Ge detector signals with one high-bandwidth electronic channel per crystal and one low-bandwidth electronic channel per segment**
- Acquisition: **use commercial electronics technology for the data acquisition electronics**

Majorana Sensitivity vs. Background

$$T_{1/2} = \frac{\ln(2)}{\sqrt{B}} \times \varepsilon N t = \frac{\ln(2)}{\sqrt{B}} \times \varepsilon \alpha \frac{A_0}{W} M \times t$$

$$\langle m_\nu \rangle \propto (T_{1/2})^{-1/2} \propto B^{1/4}$$



$\langle m_\nu \rangle$ of 100 meV [Rod05]

Reducing Backgrounds - Two Basic Strategies

- **Directly reduce intrinsic, extrinsic, & cosmogenic activities**
  - **Select and use ultra-pure materials**
  - **Minimize all non "source" materials**
  - **Clean passive shield**
  - **Go deep — reduced μ's & related induced activities**
- **Utilize background rejection techniques**
  - **Energy resolution**
    - **$0\nu\beta\beta$ is a single site phenomenon**
    - **Many backgrounds have multiple site interactions**
  - **Granularity [multiple detectors]**
  - **Single Site Time Correlated events (SSTC)**
  - Active veto detector
  - Pulse shape discrimination (PSD)
  - Segmentation

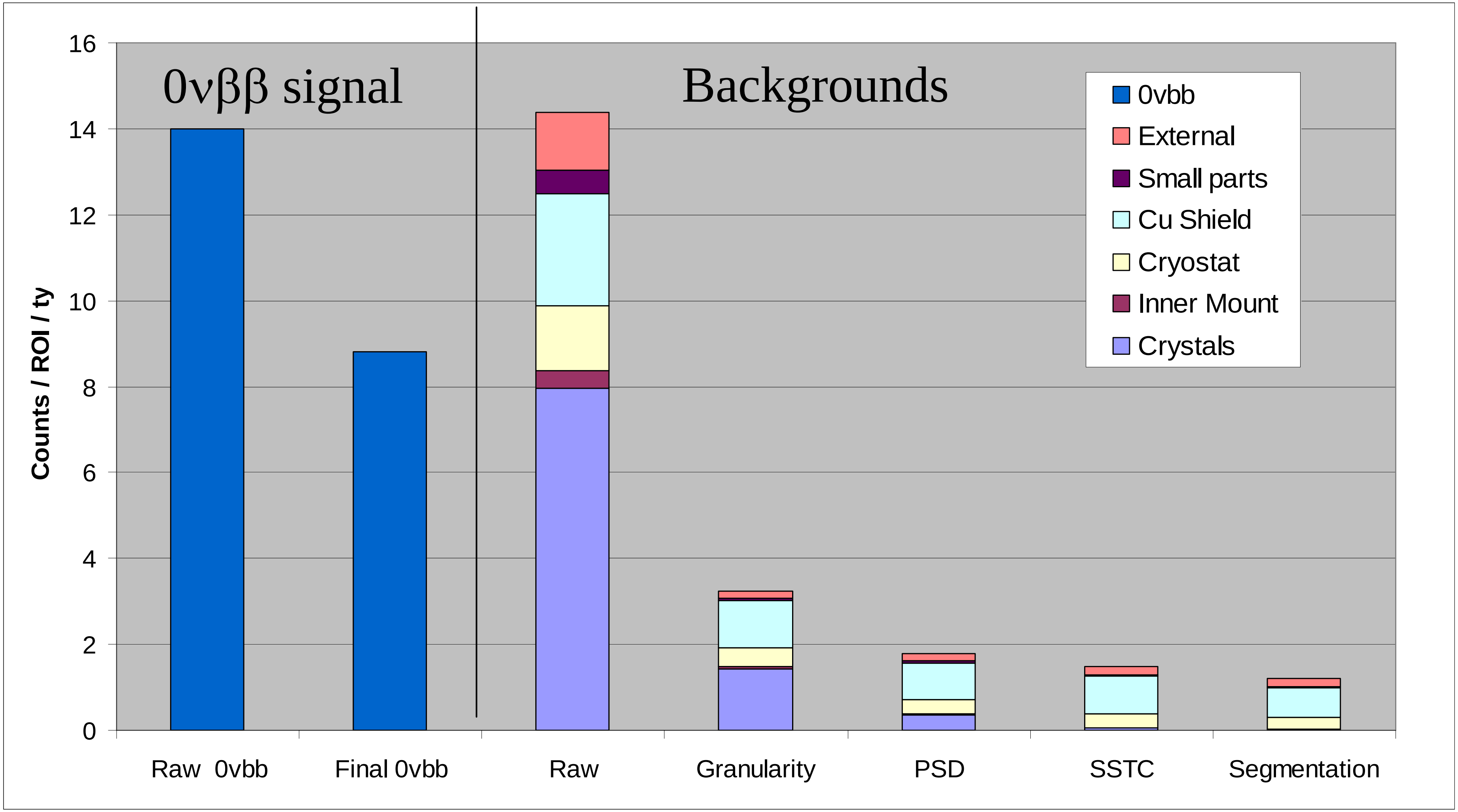
Demonstrating backgrounds requires:

- Sensitive assay capabilities
- Reliable and verified simulations

Cuts vs. Background Estimates

2039 keV peak plus cuts discriminates 0νββ-decay from backgrounds

Only known activities that occur at 2039 keV are very weak branches, with corresponding strong peaks that will appear elsewhere in the spectrum



Estimated backgrounds in the $0\nu\beta\beta$-decay ROI

Background Source		Gross and Net Rates for Important Isotopes Counts in ROI per t-y			Total Est. Background (per t-y) Counts in ROI
		^{68}Ge	^{60}Co		
Germanium (100 day exp)	Gross	2.54	1.22		
	Net	0.01	0.02		0.03
		^{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	0.77	0.16	0.58	
	Net	0.22	0.04	0.00	0.26
Copper Shield	Gross	2.28	0.30	0.02	
	Net	0.64	0.06	0.00	0.70
Small Parts	Gross	0.18	0.04	0.34	
	Net	0.02	0.01	0.00	0.03
External Sources (6000 mwe)		**muons**	**cosmic activity**	**(α,n)**	
	Gross	0.03	1.33	0.003	
	Net	0.003	0.18	0.003	0.18
$2\nu\beta\beta$ -decay					< 0.01
	TOTAL SUM				**1.21**

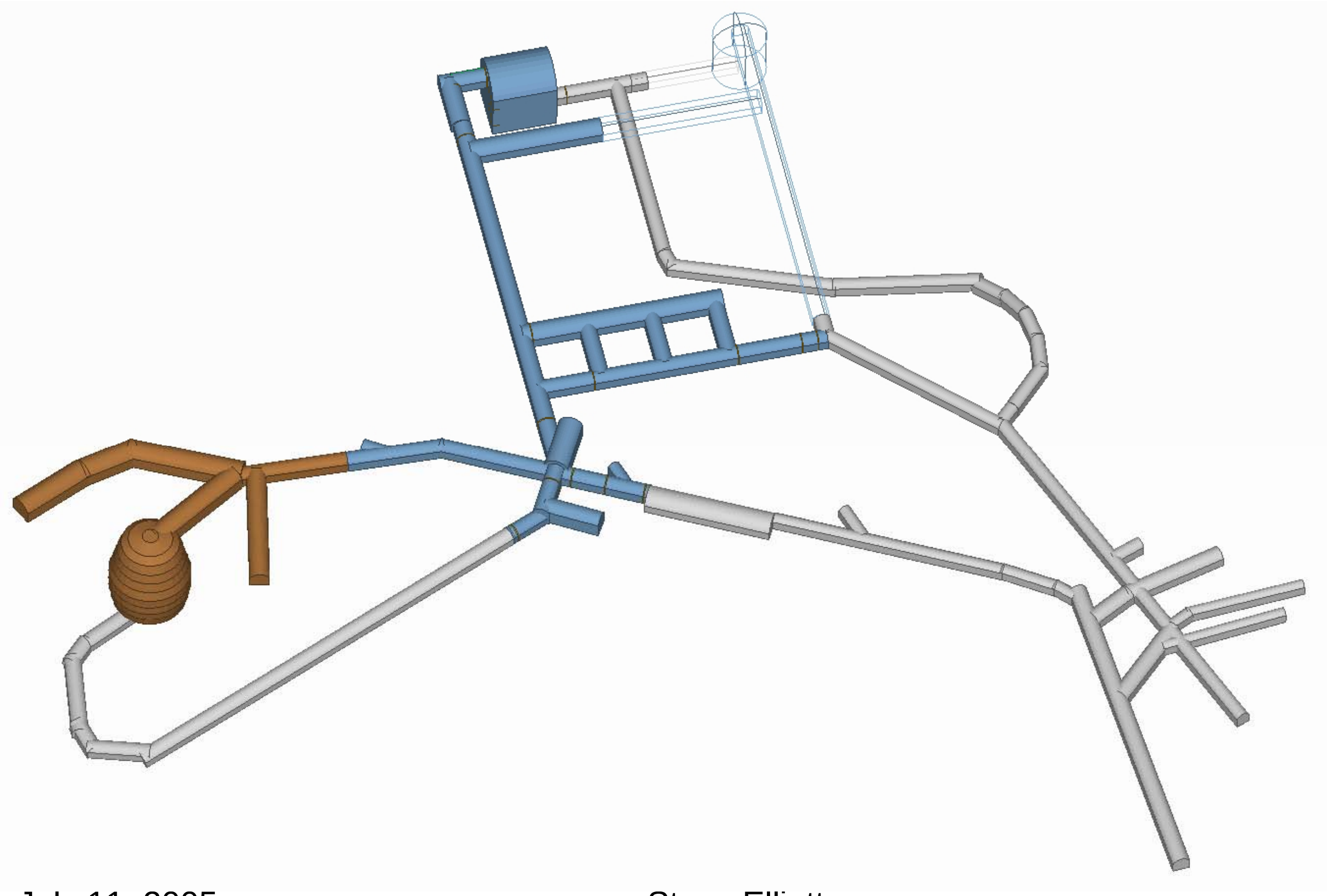
Crystals are clean

Dominated by ^{232}Th in Cu

Must go deep

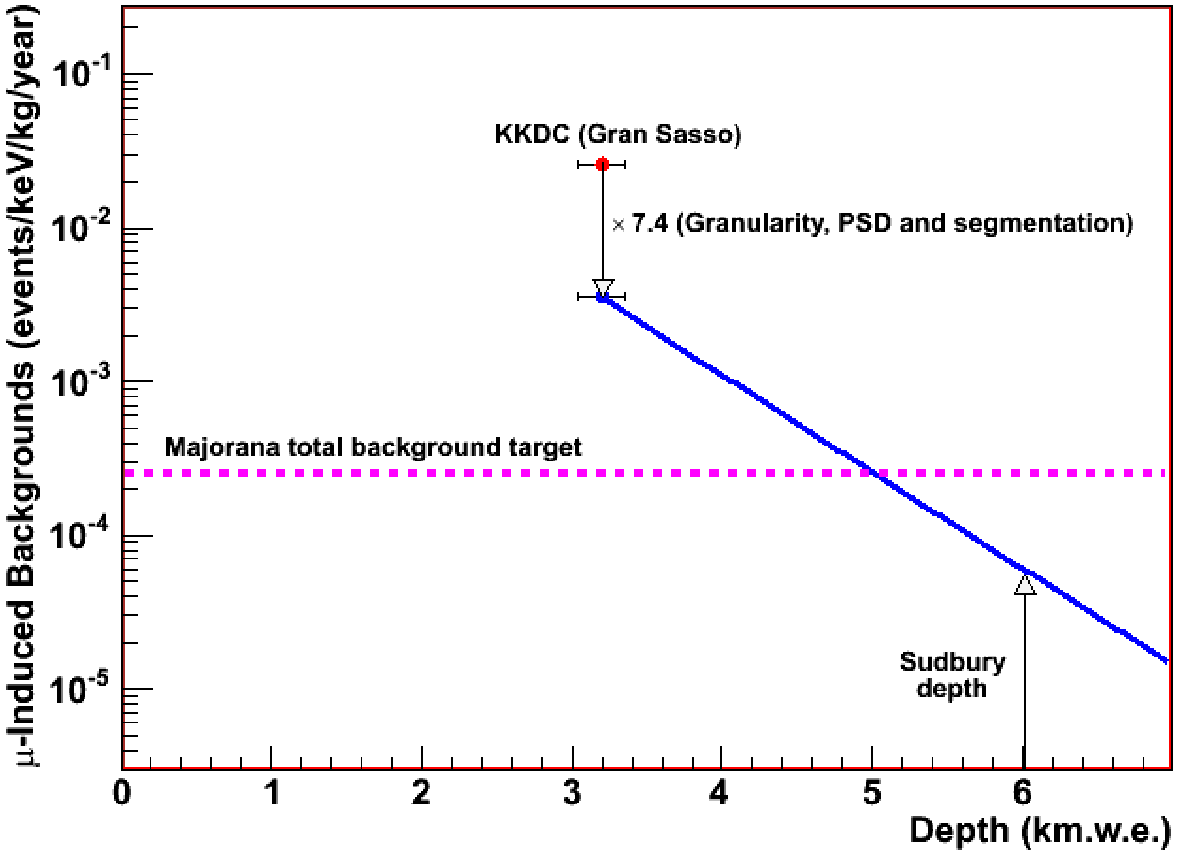
- **"Gross" indicates level of activity before any analysis cuts are applied.**
- **"Net" indicates level of activity after cuts have been applied.**

Maybe we'll go to SNOLab



Backgrounds for Majorana vs. Depth

At Sudbury depth, 6000 mwe, calculate that about 15-20% of the expected background in ROI will be from μ induced activities in Ge and the nearby cryostat materials (dominated by fast neutrons).



Mei and Hime 2005

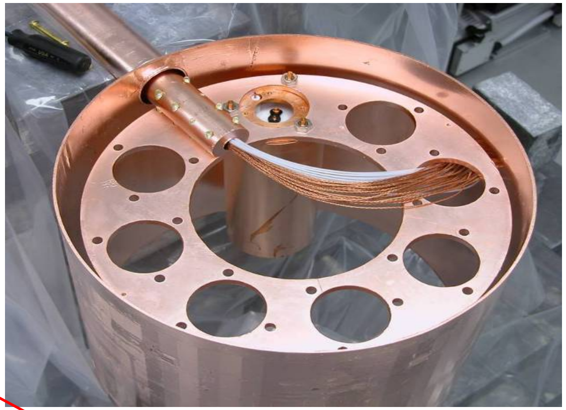
Readiness - Backgrounds

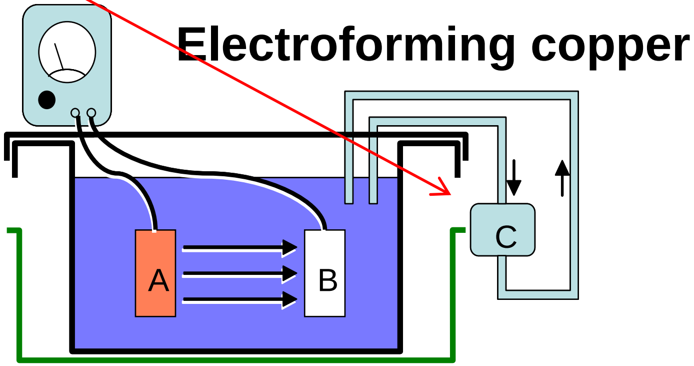
- Simulations
  - **MaGe — GEANT4 based development package**
    - **being developed in cooperation with GERDA**
  - **Verified against a variety of Majorana low-background counting systems as well as others, e.g. MSU Segmented Ge, GERDA.**
  - **Fluka for μ-induced calculations, tested against UG lab data.**
- Assay
  - **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, have made recent progress on using ^{229}Th tracer.**
    - **ICPMS has the requisite sensitivity (fg/g).**
    - **Present limitations on reagents being addressed by sub-boiling distillation.**
    - **ICPMS expected to reach needed 1 μBq/kg sensitivity.**

- **Key specifications**
  - Cu at 1 μBq/kg (current ≤ 8 μBq/kg)
  - cleanliness on a large scale (100 kg)

Readiness - Ultra-Pure Cu

- **Constructed electroformed Cu cryostat**
  - **30 cm dia x 30 cm high**
  - **Vacuum tested**
- **Th chain purity in Cu is key**
  - **Ra and Th must be eliminated**
  - **Remove Ra, Th by ion exchange during electroforming**
  - **Starting stock <9 μBq/kg ^{232}Th**
- **Using ^{229}Th tracer, demonstrated a factor of > 8000 Th rejection via electroforming**

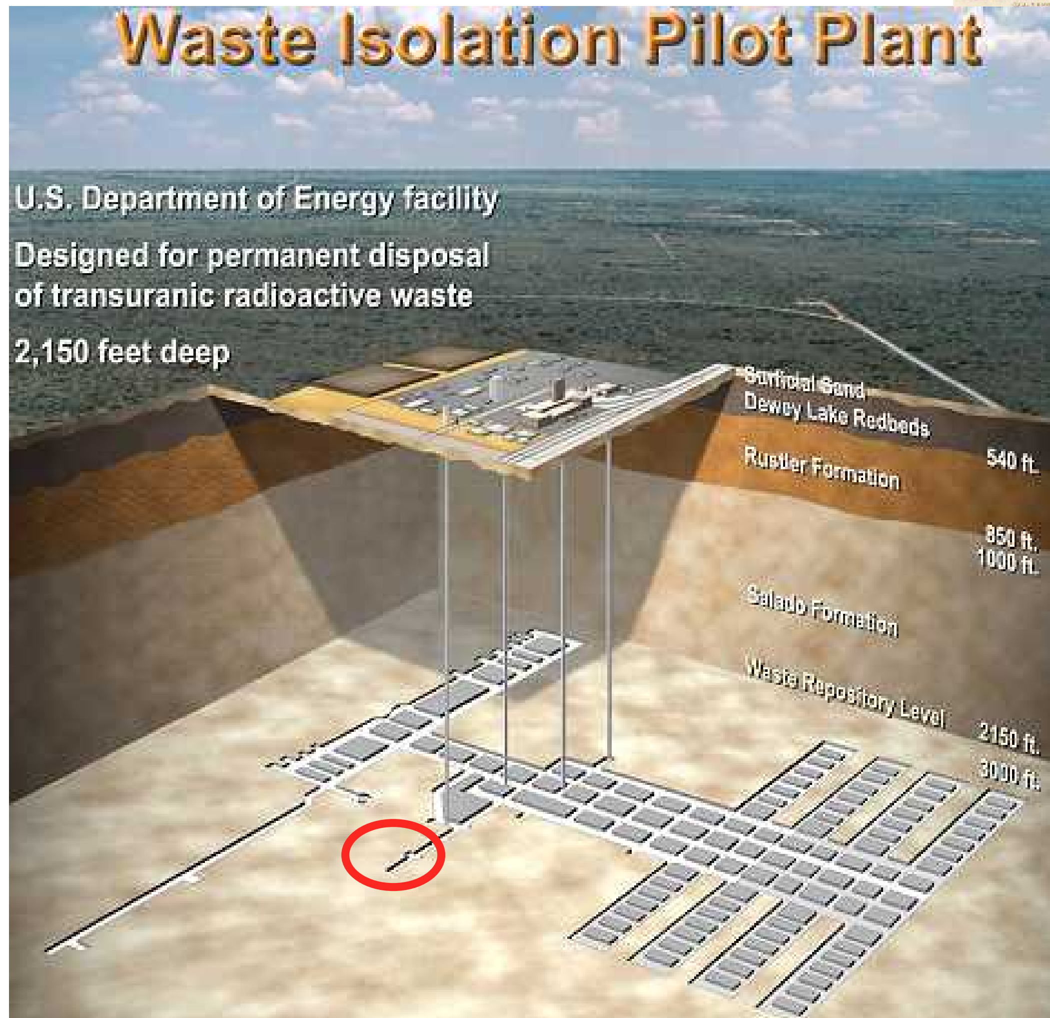




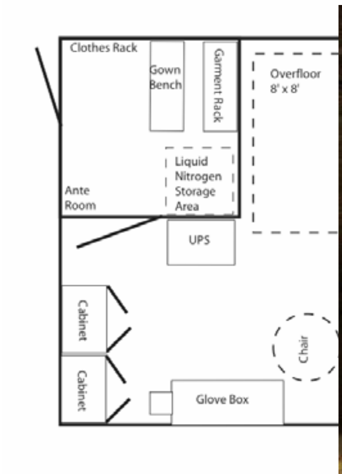
We expect to achieve the 1 μBq/kg ^{232}Th specification

WIPP

- DOE Facility
- Impressive infrastructure
- Modest depth (1600 mwe)
- Science as add-on to primary mission
- Low background counting lab being built MEGA-SEGA



WIPP Construction



Assembling MEGA at WIPP

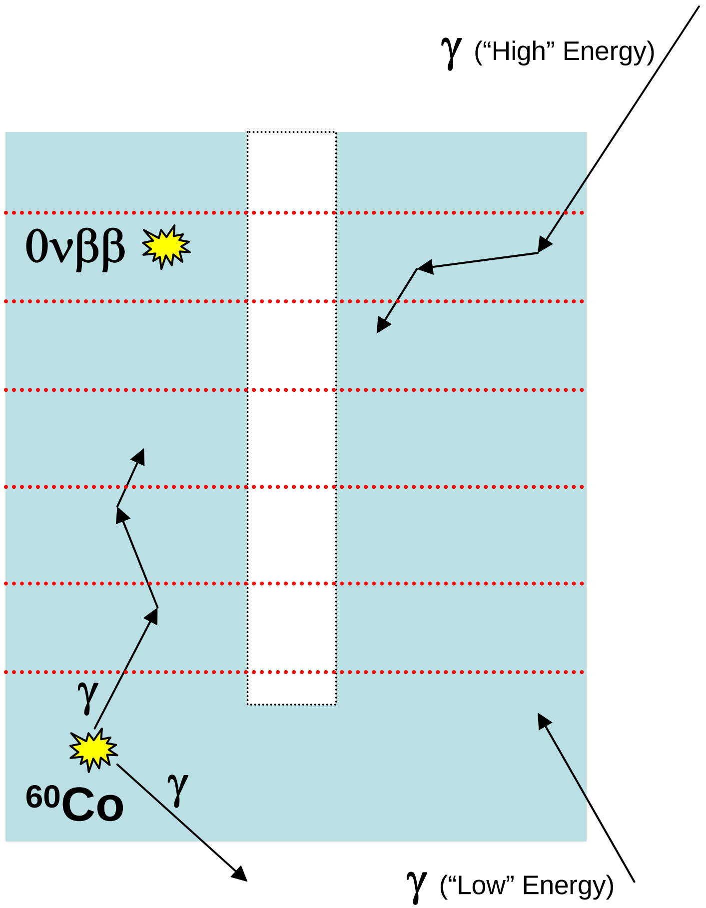
Readiness - Crystal Segmentation

- **Segmentation**
  - **Multiple conductive contacts**
  - **Additional electronics and small parts**
  - **Rejection greater for more segments**

- **Background discrimination**
  - **Multi-site energy deposition**
    - **Simple two-segment rejection**
    - **Sophisticated multi-segment signal processing can provide 2 mm reconstruction of events**

- **Demonstrated**

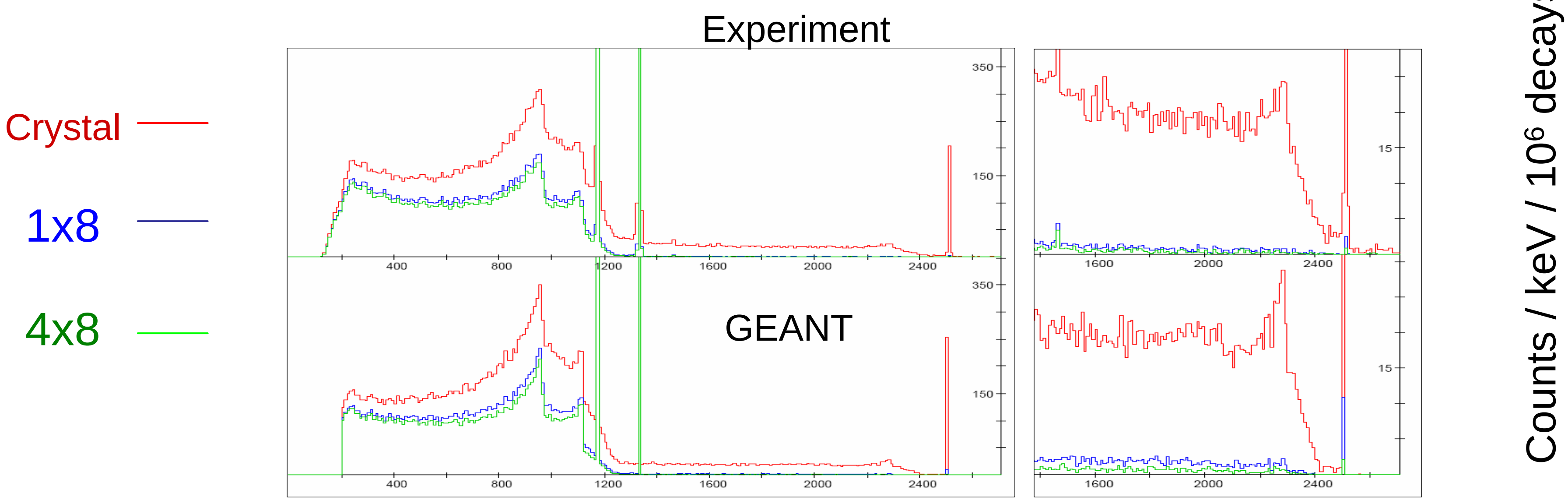
  (Note: reference plan has 2 segments)
  - **MSU experiment (4x8 segments)**
  - **LANL Clover detector (2 segments)**
  - **LLNL+LBNL detector (8x5 segments)**



Segmentation test & simulation comparison

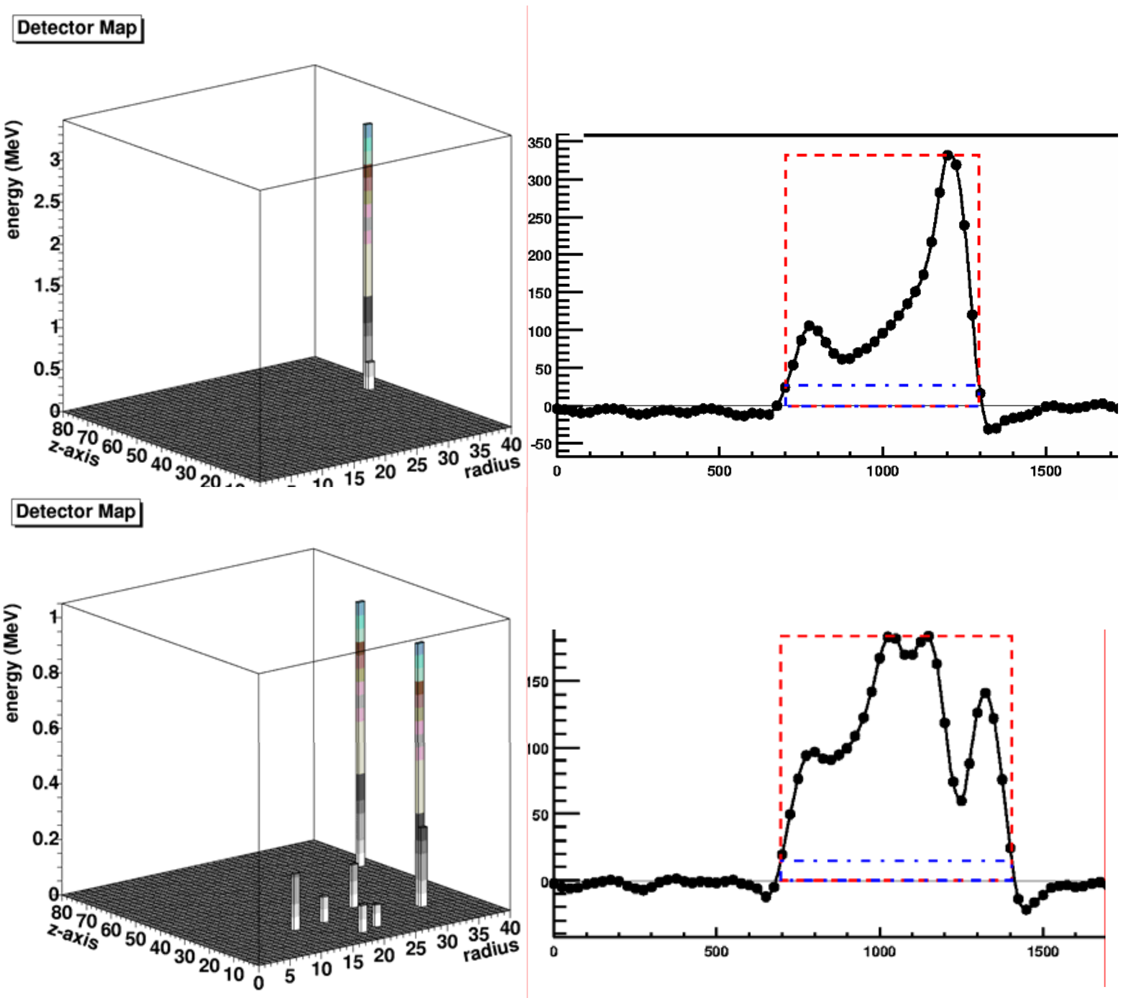
Experiment with MSU/NSCL Segmented Ge Array

- **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.**
- **In good agreement with the simulations**



Readiness - Pulse Shape Discrimination (PSD)

Central contact (radial) PSD



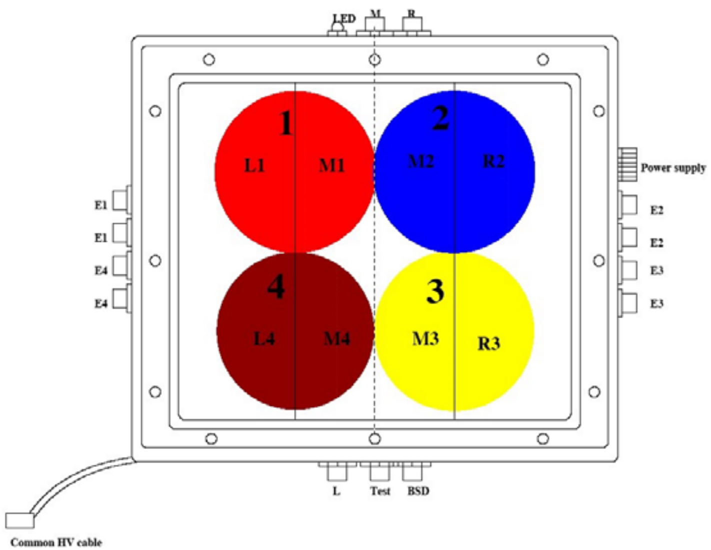
- **Excellent rejection for internal ^{68}Ge and ^{60}Co (x4)**
- **Moderate rejection of external 2615 keV (x0.8)**
- **Shown to work well with segmentation**
- **Demonstrated capability**
  - **central contact**
  - **outer contacts**

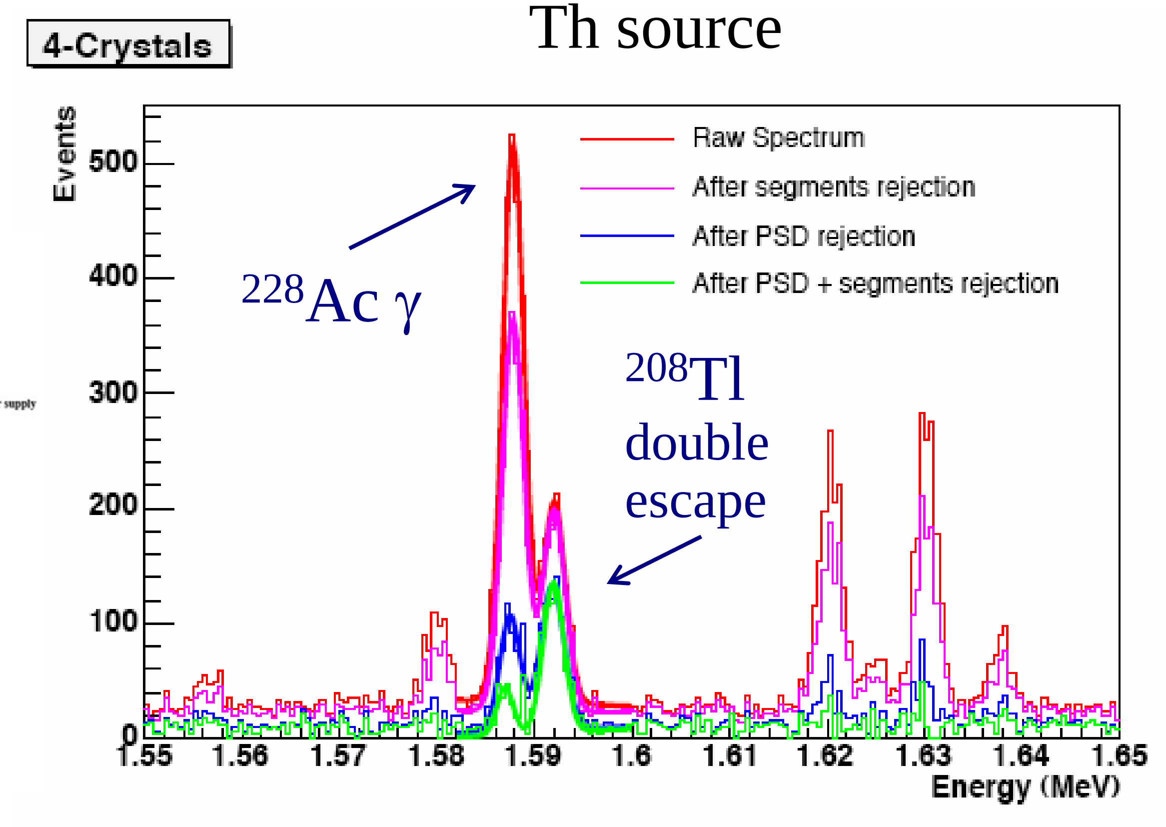
PSD uses off-the-shelf waveform digitizers

Demonstration of Segmentation & PSD

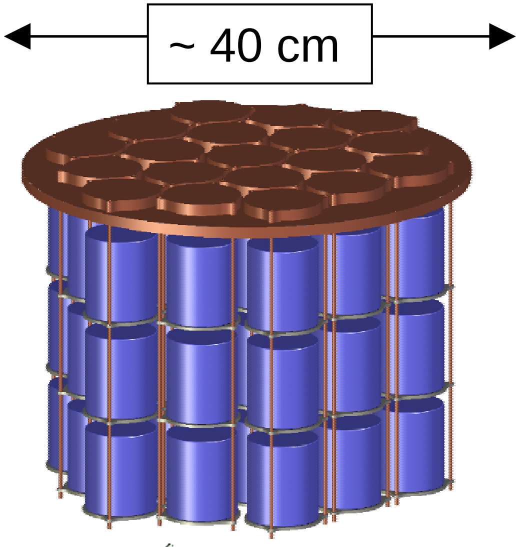
We have data that demonstrates the hypothesis that the PSD and segmentation cuts are independent.

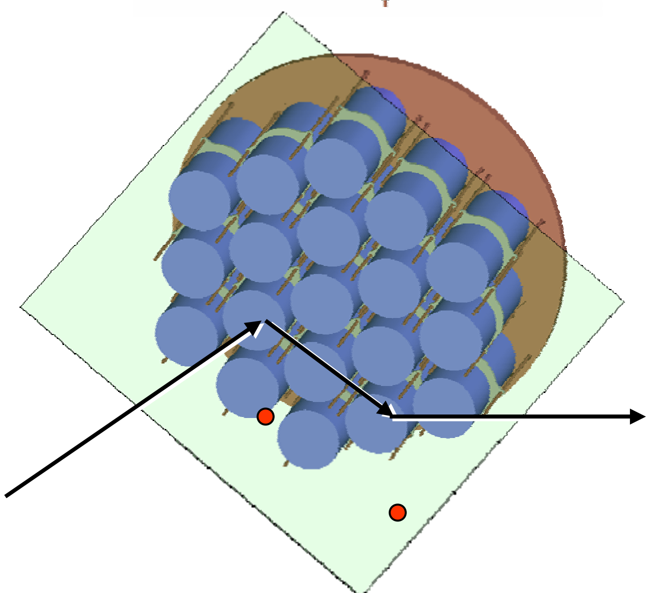
Clover detector





Array Granularity *detector-to-detector rejection*



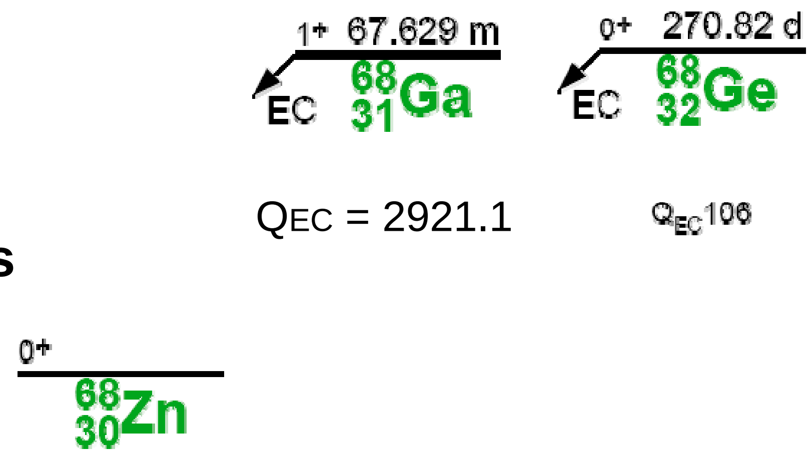


- Simultaneous signals in two detectors cannot be 0νββ
- Requires tightly packed Ge
- Successful against:
  - ^{208}Tl and ^{214}Bi
    - Supports/small parts (~5x)
    - Cryostat/shield (~2x)
  - Some neutrons
  - Muons (~10x)
- Simulation and validation with Clover

Granularity is basically free and a powerful background suppressor.

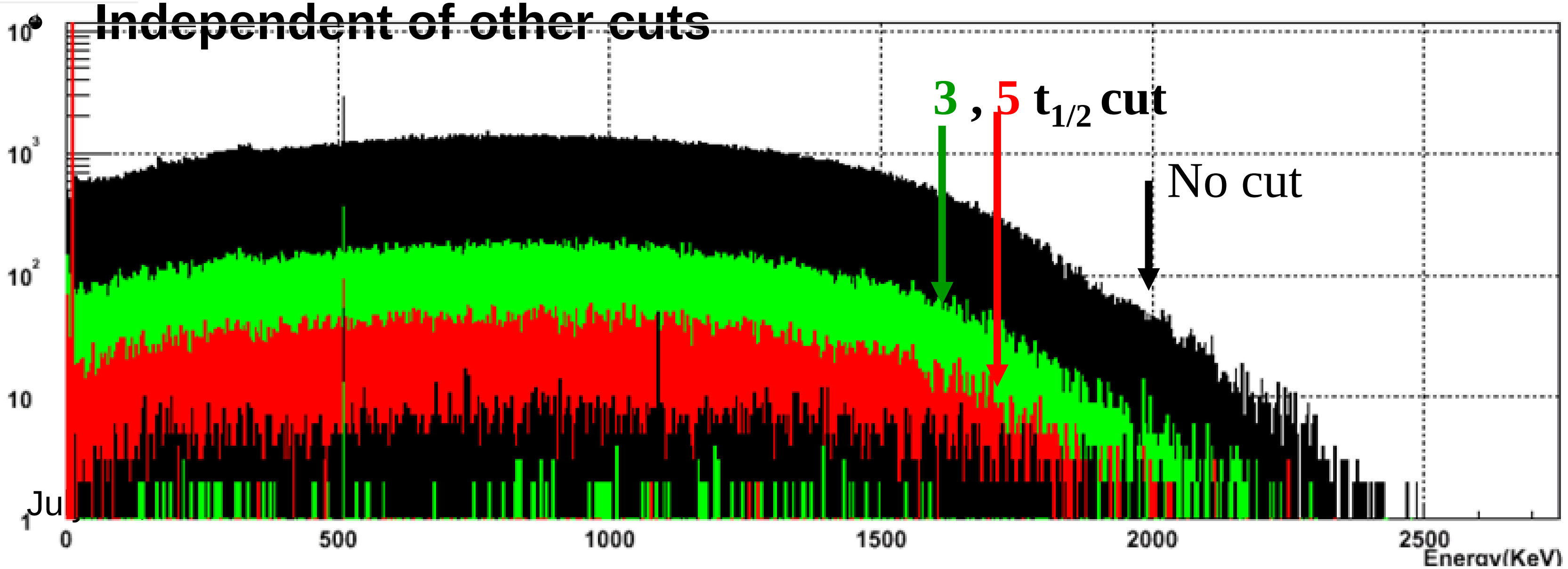
Readiness - Time Correlations

- ^{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

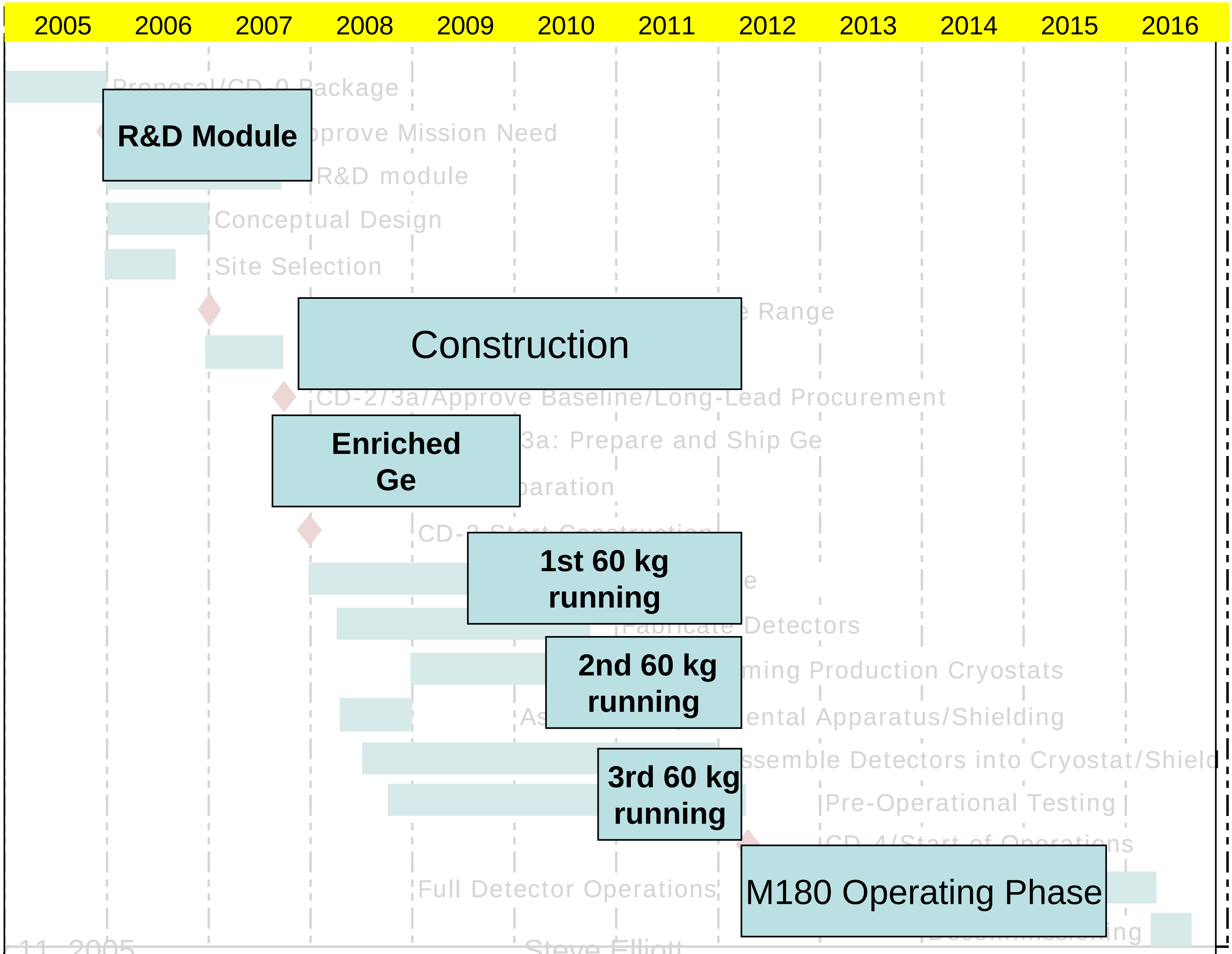


SSTC is powerful against our largest raw background, ^{68}Ge.

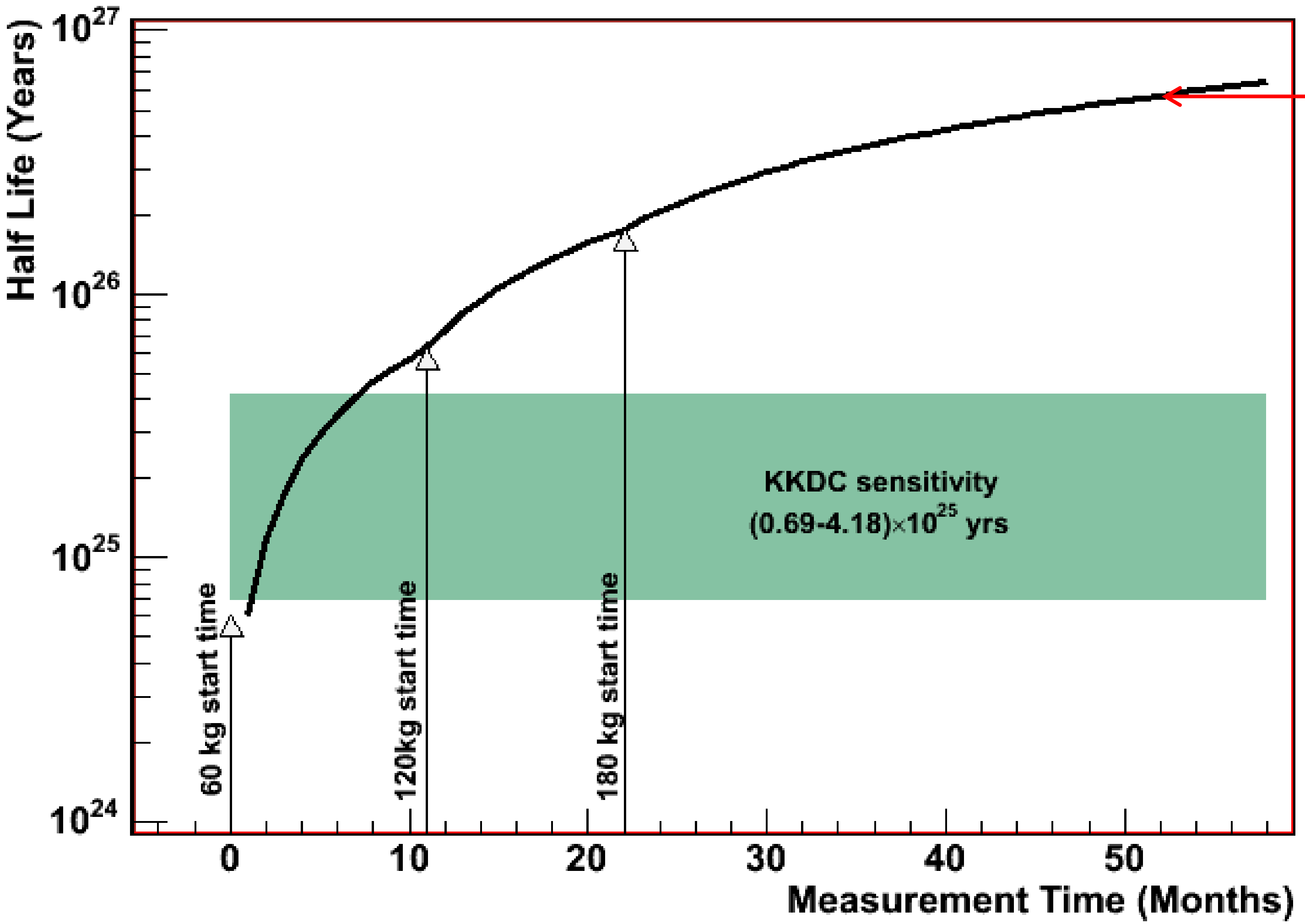
- Independent of other cuts



Schedule


2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
R&D Module
R&D module
Conceptual Design
Site Selection
Construction
CD-2/3a/Approve Baseline/Long-Lead Procurement
Enriched Ge
1st 60 kg running
Fabricate Detectors
2nd 60 kg running
3rd 60 kg running
Pre-Operational Testing
M180 Operating Phase
Full Detector Operations

Majorana Sensitivity: Realistic runtime



<m_ν> of 100 meV [Rod05]

To deduce $m_{\beta\beta}$ from τ, one needs Matrix Elements

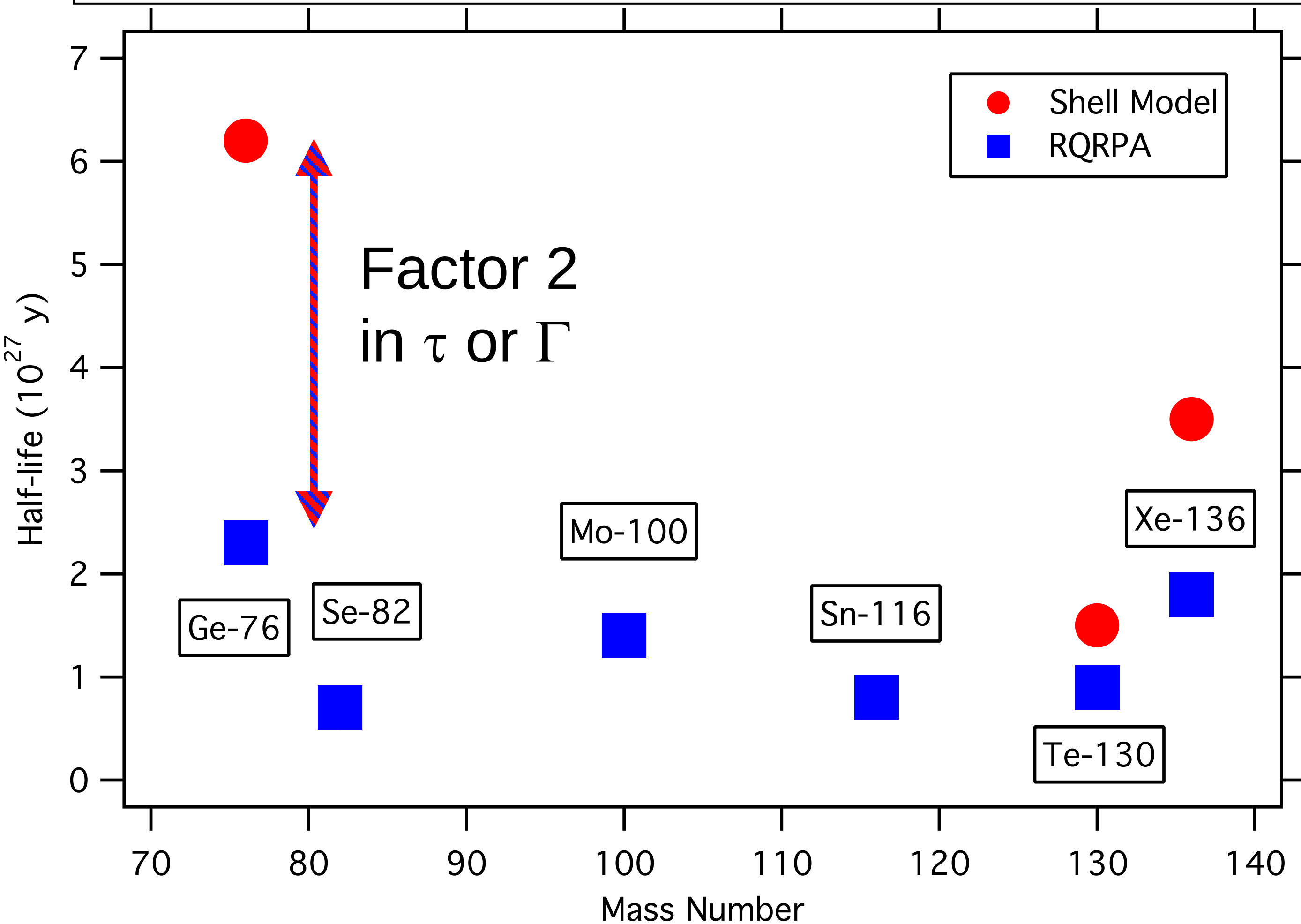
$$\frac{1}{\tau_{0\nu}} = G_{0\nu} \left| M_{0\nu} \right|^2 \left\langle m_{\beta\beta} \right\rangle^2$$

- **If $\beta\beta$ is observed, the qualitative physics conclusions are profound regardless of |M|.**
- **There are many calculations of |M|. Which should be used to deduce $m_{\beta\beta}$?**
- **How do we interpret the uncertainty associated with the nuclear physics?**

Progress in Understanding the Matrix Element Uncertainty

- **Previous spread is mostly due to the various implementations of QRPA.**
- **Rodin et al. show that QRPA results tighten up (typically to ~20% uncertainty in half life):**
  - **When implementation differences are accounted for**
  - **One uses $\beta\beta(2\nu)$ to set the free parameter**
- **Recent shell model numbers are comparable (differ < factor of 2). But these calculations are still evolving.**

RQRPA* and Shell Model Predictions



$$m_{\beta\beta} \approx \sqrt{\Gamma}$$

$$\delta m_{\beta\beta} \approx \frac{1}{2}\delta\Gamma$$

*renormalized quasiparticle random phase approximation

Progress in testing the matrix elements

- **Rodin *et al*. used $\beta\beta(2\nu)$ to set free parameter in QRPA. They found that this removed most of the spread in the $\beta\beta(0\nu)$ QRPA values.** **(nucl-th/0503063)**
- **Suhonen showed that this technique for setting g_{pp} predicted poor β and β^+ rates. He advocates using those measurements to set the parameter.** **(nucl-th/0412064)**
- **We'll be watching this productive debate closely.**

Summary

- **Science:**
  - ***Neutrino mass interest***
  - ***Potential for discovery***
  - ***Even null results will be interesting***
- **Infrastructure:**
  - ***Enrichment availability/Underground facility development***
- **Moderate-sized apparatus:**
  - ***Modest footprint***
  - ***No need for large underground cavity***
- **Low Risk:**
  - ***Proven technology/ Modular instrument / Re-configurable***
- **Experienced and Substantial Collaboration**
  - ***Long neutrino science track record, many technical resources***

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July 11, 2005 Steve Elliott

Note: Red text indicates students