Majorana Double Beta Decay Search Project
(Majorana Demonstrator)

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Outline

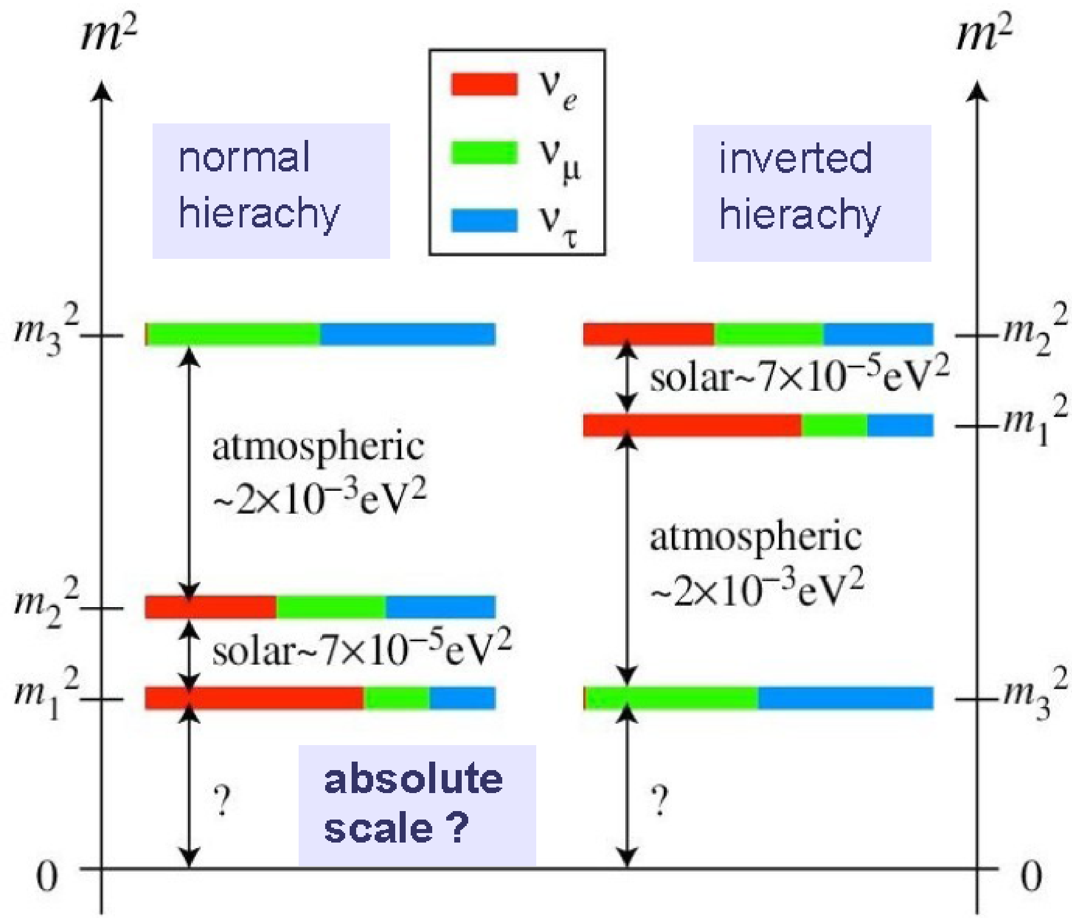
- Neutrino properties (short)
- Introduction to double-beta decay
- Majorana Demonstrator Project
- Summary

What we know (from ν oscillations):

- Neutrino flavour eigenstates differ from their mass eigenstates
- Neutrinos oscillate, hence they must have mass
- Mixing angles and Δm^2 values known (with varying accuracies)

What we don't know :

- Normal or inverted hierachy ?
- Dirac or Majorana particle ?
- CP violating phases in mixing matrix ?
- **No information about absolute mass scale !** (only upper limits)
- Existence of sterile neutrinos ?



Dirac or Majorana particle?

How test of Majorana nature of neutrinos ($\bar{\nu} \equiv \nu$)?

- The key test originally proposed by G.Racah (1937):

$$\mathbf{n \to p + e^- + \bar{\nu} \to (\bar{\nu} \equiv \nu) + n \to p + e^- + p + e^-}$$

Such a combination of events would violate the conservation of lepton number ($\Delta L=2$)

One way to study the Racah process is use real $\bar{\nu}$:

Ray Davis (1955) performed the famous $^{37}Cl \to {}^{37}Ar$ reaction using anti-neutrinos from reactor

($\nu + {}^{37}Cl \to {}^{37}Ar + e^-$ - reaction for famous experiment with neutrinos from the Sun)

Can produce $\bar{\nu}$ indeed ^{37}Ar nuclei in reaction above?

"Rumors of a positive result reached Bruno Pontecorvo in Moscow in 1957 and caused him to invent neutrino oscillations in direct analogy with the Gell-Mann-Pais analysis of neutral Kaon decay. The rumors eventually died out but the idea of oscillations is still alive and kicking." – S.P. Rosen (1992)

In 1957 with the discovery of parity nonconservation and the two-component neutrino, it was recognised that the two-step process of Racha is inhibited by helicity: the right-handed anti-neutrino emitted by the first neutron is in the wrong helicity state to be re-absorbed by another neutron.
In order to complete the second step of the Racah process, the anti-neutrino must be able to flip its helicity and turn itself into a neutrino.

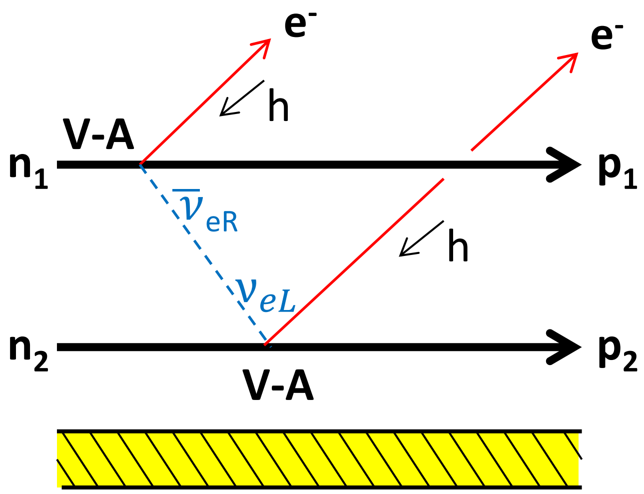
- A much more sensitive method is to study **double beta decay**

Table1. Emission and Absorption of Neutrinos in the Standard Model

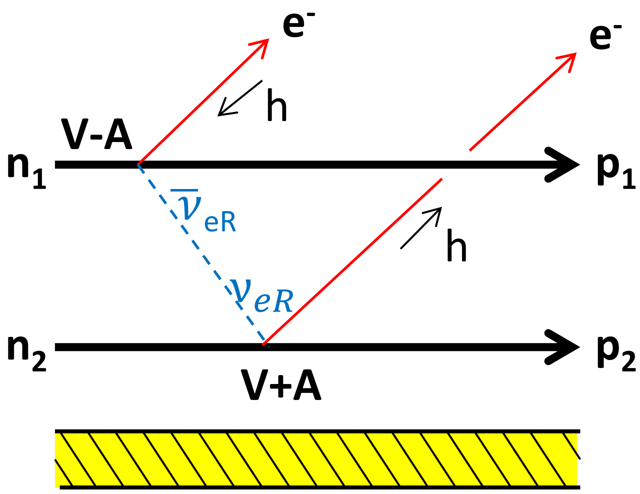
Process	Transition	Beta ray	Neutrino
Emission	n → p	e_L^-	$\overline{\nu}_{eR}$
Emission	p → n	e_R^+	ν_{eL}
Absorption	n → p	e_L^-	ν_{eL}
Absorption	p → n	e_R^+	$\overline{\nu}_{eR}$

Table2. Emission and Absorption of Neutrinos in a Modified Standard Model. The parameter η denotes small admixture of opposite helicities.

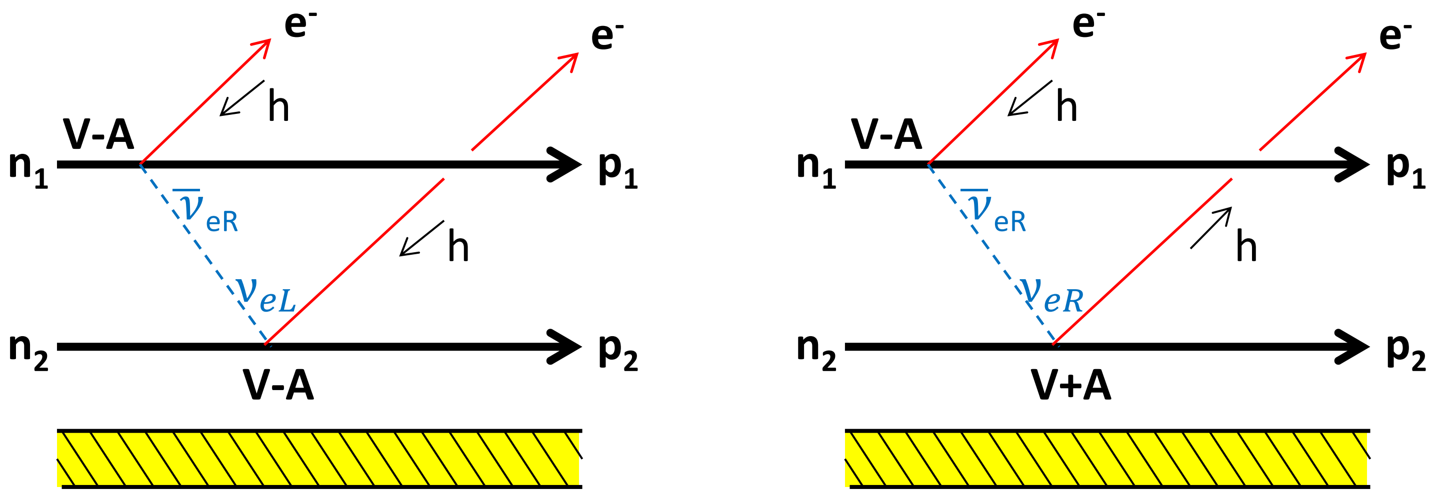
Process	Transition	Beta ray	Neutrino
Emission	n → p	e^-	$\overline{\nu}_{eR} + \eta\,\overline{\nu}_{eL}$
Absorption	n → p	e^-	$\nu_{eL} + \eta\,\nu_{eR}$



e-
e-
h
V-A
n_1
p_1
$\overline{\nu}_{eR}$
h
ν_{eL}
n_2
p_2
V-A



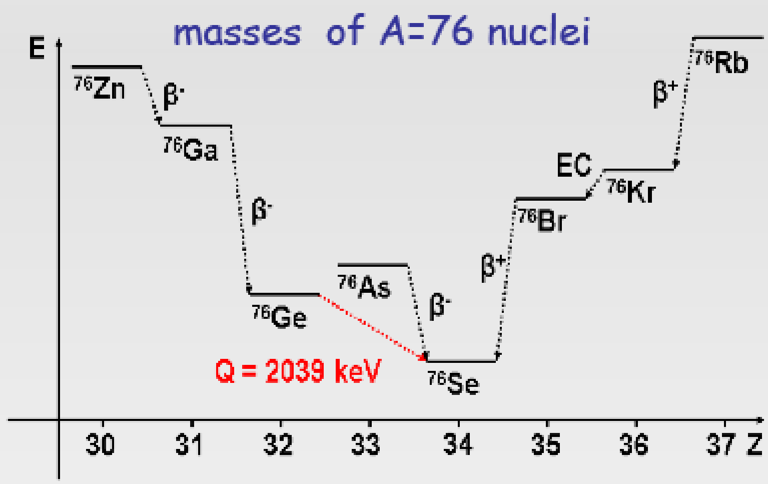
e-
e-
h
V-A
n_1
p_1
$\overline{\nu}_{eR}$
h
ν_{eR}
n_2
p_2
V+A



Important:

It can be treated the admixture of right-handed currents (RHC-mechanism) as a separate *phenomenological* mechanism for 0νββ decay. But it is not a separate *fundamental* mechanism. In gauge theories *the mass* is the fundamental mechanism for lepton number nonconserving processes: RHC- mechanism will not work unless there are mass term present in the neutrino mass matrix (J. Schechter-J.Valle theorem)

How to observe $\Delta L=2$



expected for 35 isotopes,
$2\nu\beta\beta$ found for 11 isotopes

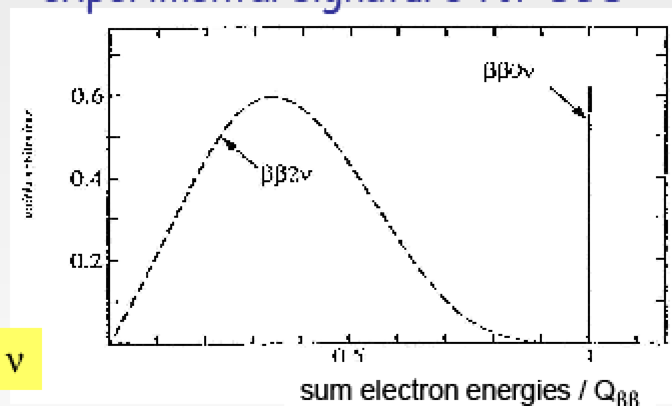
$\beta^+\beta^+$, β^+EC, ECEC rates smaller unless resonant enhancement
(e.g. for ^{152}Gd – ^{152}Sm ECEC Q=56 keV, Phys Rev Lett 106(2011) 052504)

"single" beta decay not allowed
$\longrightarrow$ only "double beta decay"

$(A,Z) \longrightarrow (A,Z+2) + 2\,e^- + 2\bar{\nu}$ $\Delta L=0$

$(A,Z) \longrightarrow (A,Z+2) + 2\,e^-$ $\Delta L=2$

experimental signature for DBD



Schechter Valle theorem: $0\nu\beta\beta \Longleftrightarrow$ Majorana ν

From $T_{1/2}$ to $\langle m_{ee} \rangle$

$$\frac{1}{T^{0\nu}_{1/2}} = G^{0\nu} \left| M^{0\nu} \right|^2 \frac{\langle m_{ee} \rangle^2}{m_e^2}$$

$T^{0\nu}_{1/2}$ = measured experimentally

$G^{0\nu}$ = phase space factor ~ Q^5

$M^{0\nu}$ = nuclear matrix element

m_e = electron mass

Experiment observes $N^{0\nu} = \ln 2 \frac{N_A}{A} \cdot a \cdot \epsilon \cdot M t \,/\, T_{1/2}$ and $N^{bkg} = Mt \cdot B \cdot \Delta E$

Experimental sensitivity

$$T_{1/2}(90\%CL) > \begin{cases} \frac{\ln 2}{2.3} \frac{N_A}{A} a \cdot \epsilon \cdot Mt & \text{for } N^{bkg} = 0 \\ \frac{\ln 2}{1.64} \frac{N_A}{A} a \cdot \epsilon \sqrt{\frac{Mt}{B \cdot \Delta E}} & \text{for large } N^{bkg} \end{cases}$$

M = mass of detector
t = measurement time
A = isotope mass per mole
N_A = Avogadro constant
a = fraction of $0\nu\beta\beta$ isotope
ε = detection efficiency
B = background index in units cnt/(keV kg y)
ΔE = energy resolution = energy window size

Focus on light neutrino exchange mode

Decay rate depends on an effective Majorana mass. Its calculation requires knowledge of nuclear physics quantities.

$$\left(T_{1/2}^{0\nu}\right)^{-1} = \underbrace{G^{0\nu}}_{\text{Phase space}} \cdot \underbrace{\left|M^{0\nu}\right|^{2}}_{\text{Nuclear matrix element}} \cdot \langle m_{\beta\beta} \rangle^{2}$$

Because of the imaginary phases cancellations may occur.

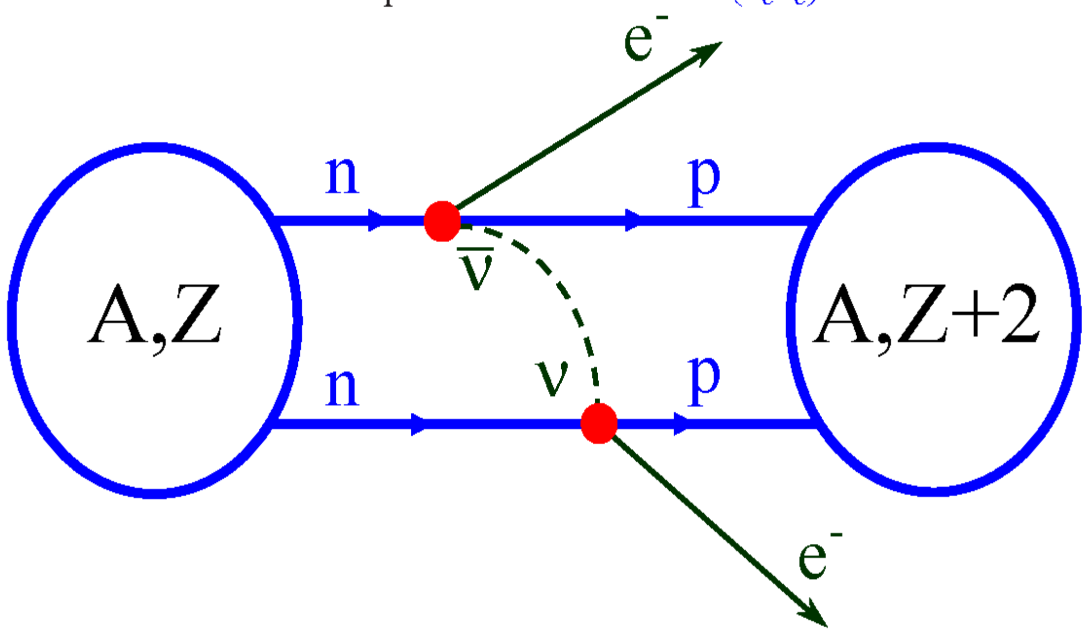
$$\langle m_{\beta\beta} \rangle = \left\| m_1 \right| \cdot U_{e1}^2 + \left| m_2 \right| \cdot U_{e2}^2 \cdot e^{2 \cdot i \cdot \Phi_{12}} + \left| m_3 \right| \cdot U_{e3}^2 \cdot e^{2 \cdot i \cdot \Phi_{13}} \right|$$

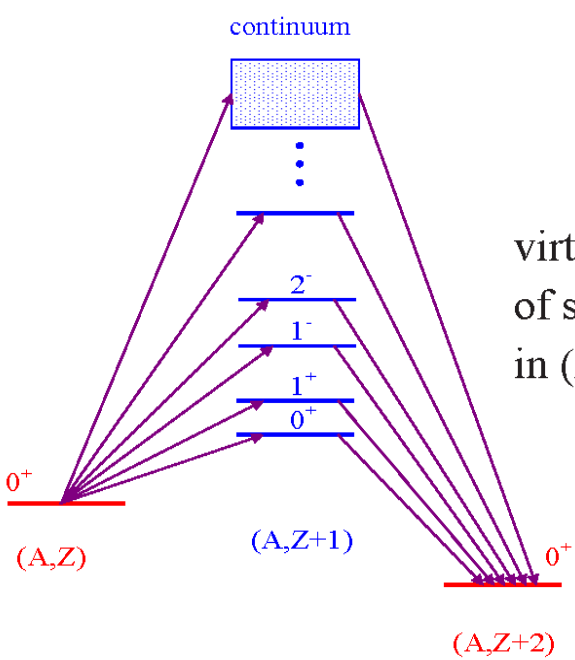
Assumes decay is driven by light neutrino exchange.

Nuclear $0\nu\beta\beta$-decay ($\bar{\nu} = \nu$)

strong in-medium modification of the basic process $dd \rightarrow uue^- e^- (\bar{\nu}_e \bar{\nu}_e)$

Light neutrino
exchange mechanism





virtual excitation
of states of all multipolarities
in (A,Z+1) nucleus

GT amplitudes to 1^+ states

— from charge-exchange reactions

(H. Ejiri, D. Frekers, H. Sakai, R. Zegers, et al.)

Nuclear Matrix Elements

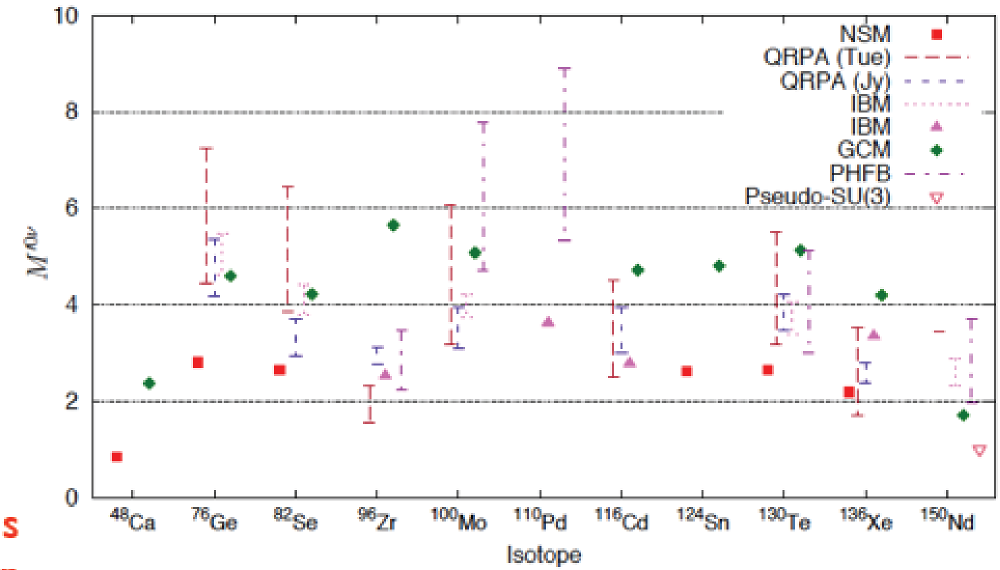
$$\left[T_{1/2}^{0\nu}\right]^{-1} = G_{0\nu}\left|M_{0\nu}\right|^{2}\langle m_{\beta\beta}\rangle^{2}$$

Extracting an effective neutrino mass requires an understanding of the nuclear matrix elements (NME) at about the 20% theoretical uncertainty level.

Recent progress NSM-QRPA:
2005 within x 5
2012 agree within x ~2

Agreement between methods doesn't necessarily provide an estimate of theoretical uncertainties or of actual values.

NME are calculated using different approximate methods: Nuclear Shell Model; Quasi-random phase approximation (QRPA); Interacting Boson Model; Projected Hartree-Fock-Bogoliubov; Generating co-ordinate method extension of PHFB; Pseudo-SU(3) deformed shell model.



Dueck, Rodejohann & Zuber Phys. Rev. D 63 054031 (2011)
with r_0 = 1.2 fm and g_A = 1.25

Germanium for neutrinoless double-beta decay experiments

Germanium detectors

- Source is detector
- Good energy resolution
- Well established technology
- Intrinsically clean (high-purity germanium)

^{76}Ge isotope for 0νββ

- Q-value of 2039keV above most backgrounds
- Can be enriched to >86% in ^{76}Ge (nat. abundance ~ 8%)
- Slow 2νββ rate (10^{21} yr)
- Best limit to date on 0νββ

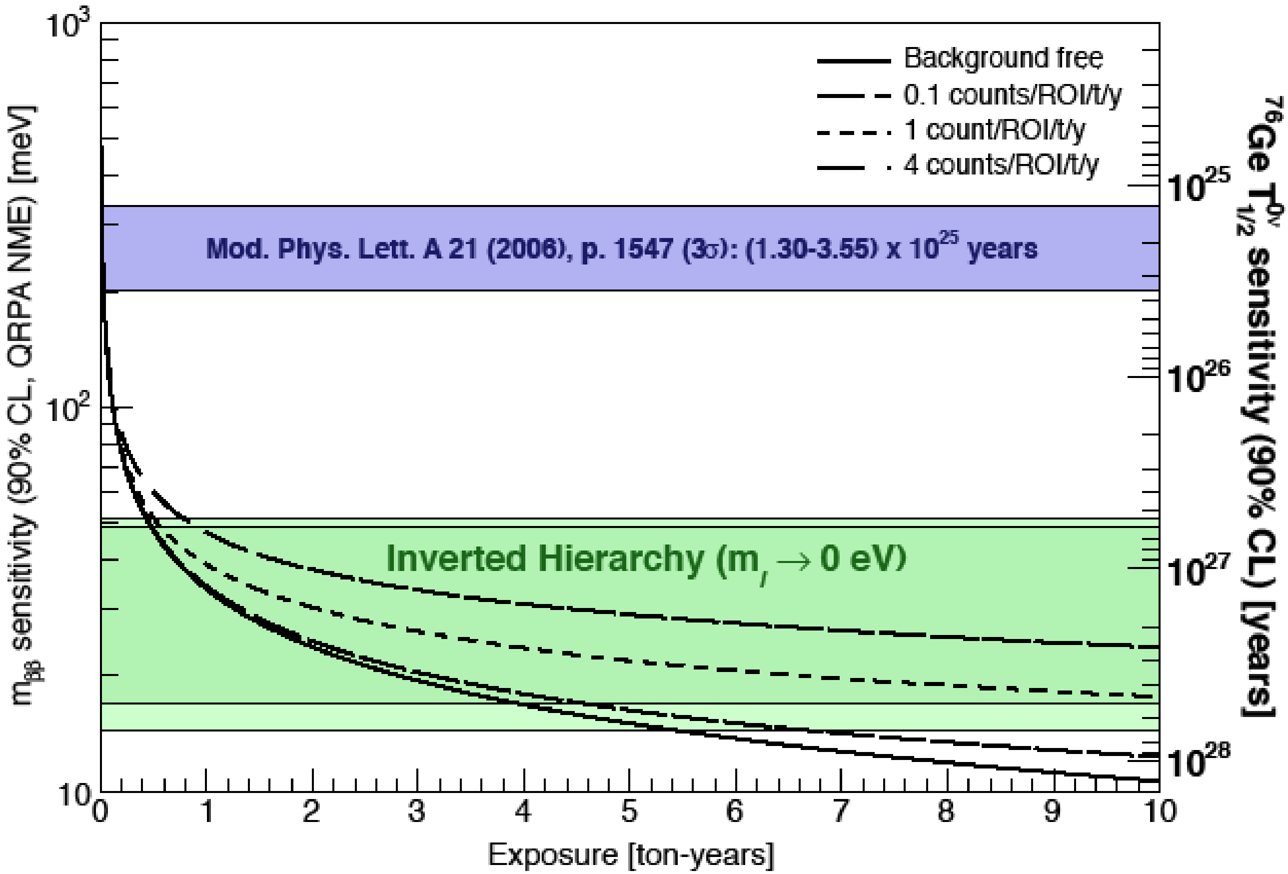
Sensitivity and backgrounds - ^{76}Ge

Background free

$$\left[T_{1/2}^{0\nu}\right]^{-1} \propto \varepsilon ff \cdot I_{abundance} \cdot Source\ Mass \cdot Time$$

Background limited

$$\left[T_{1/2}^{0\nu}\right]^{-1} \propto \varepsilon ff \cdot I_{abundance} \cdot \sqrt{\frac{Source\ Mass \cdot Time}{Bkg \cdot \Delta E}}$$



0νββ-decay

s, Feb. 6, 2013

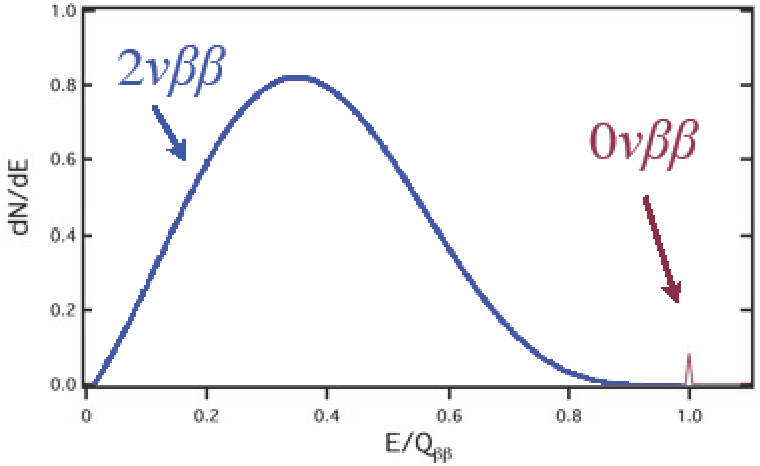
Wednesday, February 6, 13

Experiments & sensitivity to 0νββ-decay

To reach IH region requires sensitivities of

$0\nu\beta\beta$ $T_{1/2} \sim 10^{26} - 10^{27}$ years

($2\nu\beta\beta$ $T_{1/2} \sim 10^{19} - 10^{21}$ years)



Most sensitive experiments to date using ^{76}Ge, ^{130}Te, and ^{136}Xe have attained $T_{1/2} > 10^{25}$ years

Typical Source Mass · exposure times of 30 - 90 kg-years

$$\left[T_{1/2}^{0\nu}\right]^{-1} \propto \varepsilon ff \cdot I_{abundance} \cdot Source\ Mass \cdot Time$$

Background free

$$\left[T_{1/2}^{0\nu}\right]^{-1} \propto \varepsilon ff \cdot I_{abundance} \cdot \sqrt{\frac{Source\ Mass \cdot Time}{Bkg \cdot \Delta E}}$$

Background limited

The MAJORANA Collaboration

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Sanford Underground Research Facility

Sanford Underground Research Facility 2

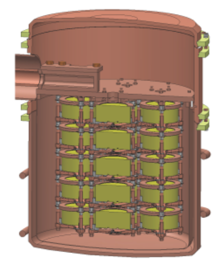
SURF Chronology: 2006-2013

2006	Homestake donates mine. T. Denny Sanford donates $70M.
2007	NSF selects Homestake to be the DUSEL.
2008	Ross Shaft reentry and underground dewatering begin.
2009	Yates Shaft reentry and construction on 4850 Level begin.
2010	Davis Campus excavation completed. NSB terminates DUSEL funding.
2011	Davis Campus outfitting begins. DOE funds operations at $15M / year.
2012	Davis Campus completed. LUX and MAJORANA experiments deploy underground for assembly. Ross Shaft refurbishment begins.
2013	LUX begins dark matter search. MAJORANA begins data collection. Designs advance for LBNE and LZ experiments. DIANA site selected.

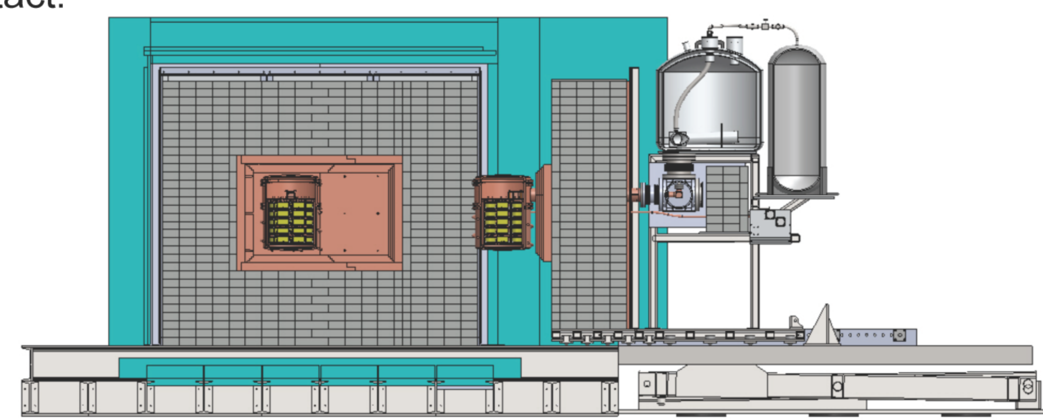
The MAJORANA DEMONSTRATOR

Funded by DOE Office of Nuclear Physics and NSF Particle and Nuclear Astrophysics,
with additional contributions from international collaborators.

Goals: - Demonstrate backgrounds low enough to justify building a tonne scale experiment.
- Establish feasibility to construct & field modular arrays of Ge detectors.
- Test Klapdor-Kleingrothaus claim.
- Low-energy dark matter (light WIMPs) search.



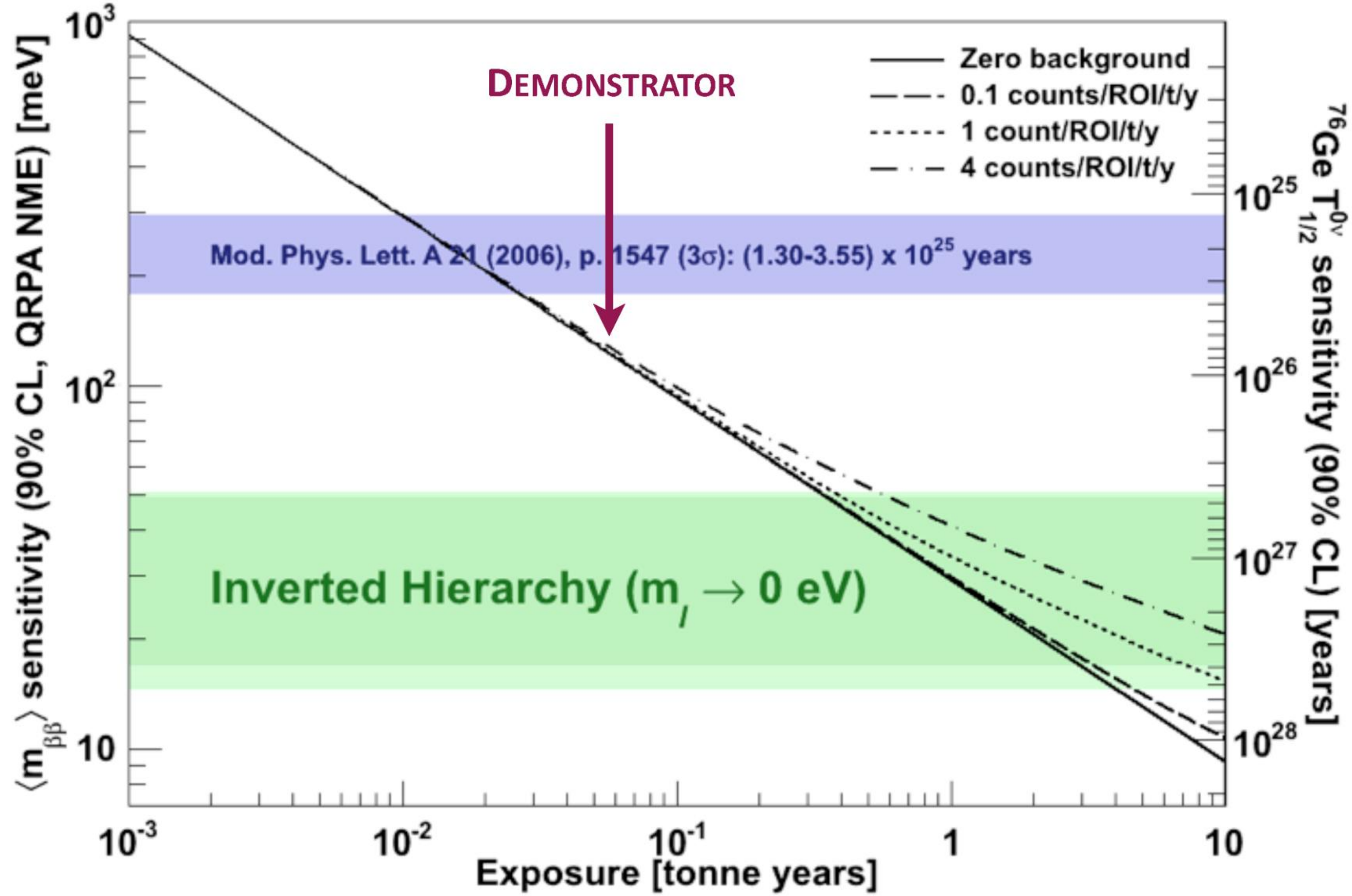
- **Located underground at 4850' Sanford Lab**
- **Background Goal in the 0νββ peak region of interest (4 keV at 2039 keV)**
  4 counts/ROI/t/y (after analysis cuts)
  scales to 1 count/ROI/t/y for a tonne experiment
- **40-kg of Ge detectors**
  – Baseline: 20-kg of 86% enriched ^{76}Ge crystals & 20-kg of ^{nat}Ge
  (up to 30-kg enriched ^{76}Ge)
  – Detector Technology: P-type, point-contact.
- **2 independent cryostats**
  – ultra-clean, electroformed Cu
  – 20 kg of detectors per cryostat
  – naturally scalable
- **Compact Shield**
  – low-background passive Cu and Pb shield with active muon veto



Sensitivity and backgrounds

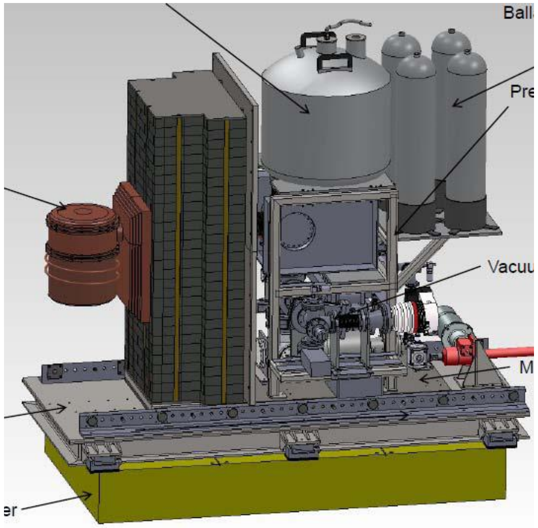
^{76}Ge Example

$T_{1/2}^{0\nu} = \ln(2) N \varepsilon t / UL(B)$



MJD Schedule

Prototype cryostat



Underground cryostat and "monolith"

MJD will proceed in 3 steps

Prototype Cryostat (Spring 2013): above ground, commercial copper, 2-3 strings **^{nat}Ge**
Test mechanical design
Test detector performance in cryostat and Monte Carlo models (eg. granularity)

Cryostat 1 (Early 2014): underground, electroformed copper, 3 strings **^{enr}Ge**, 4 strings **^{nat}Ge**

Cryostat 2 (Late 2014): underground, electroformed copper, up to 7 strings **^{enr}Ge**

Electroforming Copper

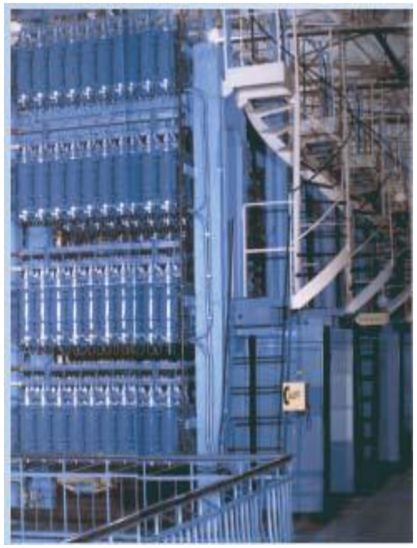
- <u>Status</u>

- For the past 18 months have been operating 16 baths, 10 at 4850L SURF and 6 at shallow UG site at PNNL.
- Mandrels with Cu pulled from baths at PNNL and TCR. Cu machined, removed, and flattened.
- Properties look good.
- Small parts fabricated from EF Cu.
- All cryostat 1 parts complete.
- Part of inner shield

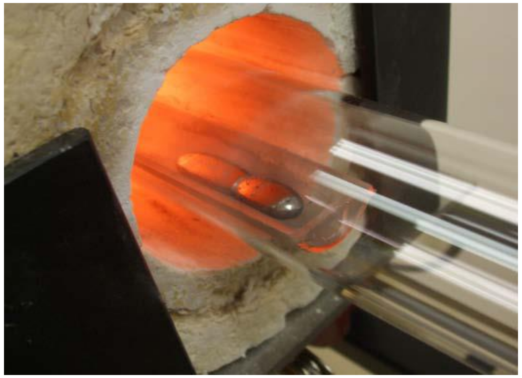
- Major remaining activities - 12 months of electroforming remain - cryo 2 parts, inner shield.

MJD Progress in FY13

Enriched germanium processing



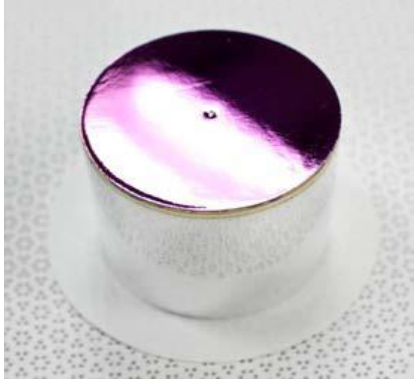
Enrichment to >86% at Electro-Chemical Plant (ECP) in Russia



Reduction to Ge metal at Electrochemical Systems Inc. (ESI)

Zone-refinement by commercial vendor

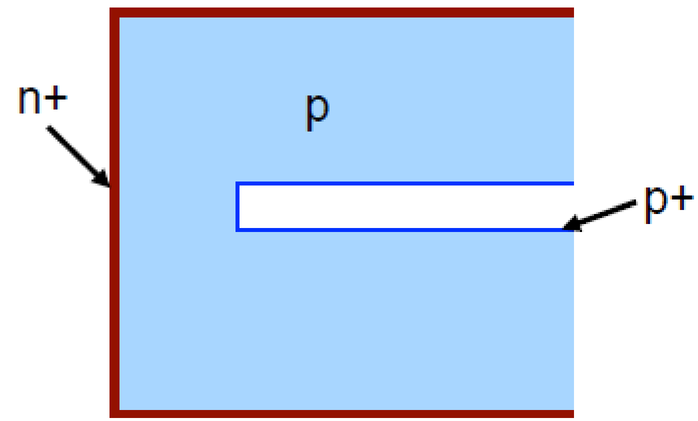
Pull crystal by commercial vendor



Detector fabrication by commercial detector vendor

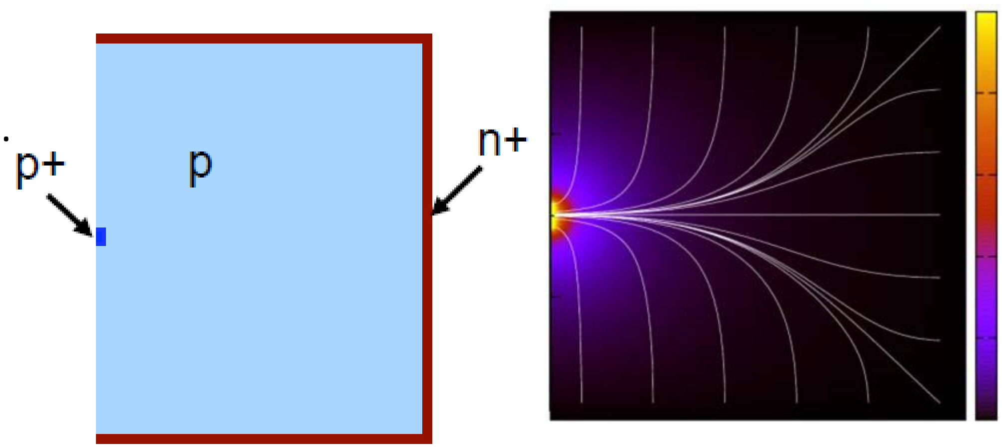
P-type Point Contact Detectors

- P-type Point Contact HPGe detectors
- “Novel” technology
- Small point contact to readout charge, low capacitance
- Thick outer contact (n+, lithium diffused), strongly attenuates alphas

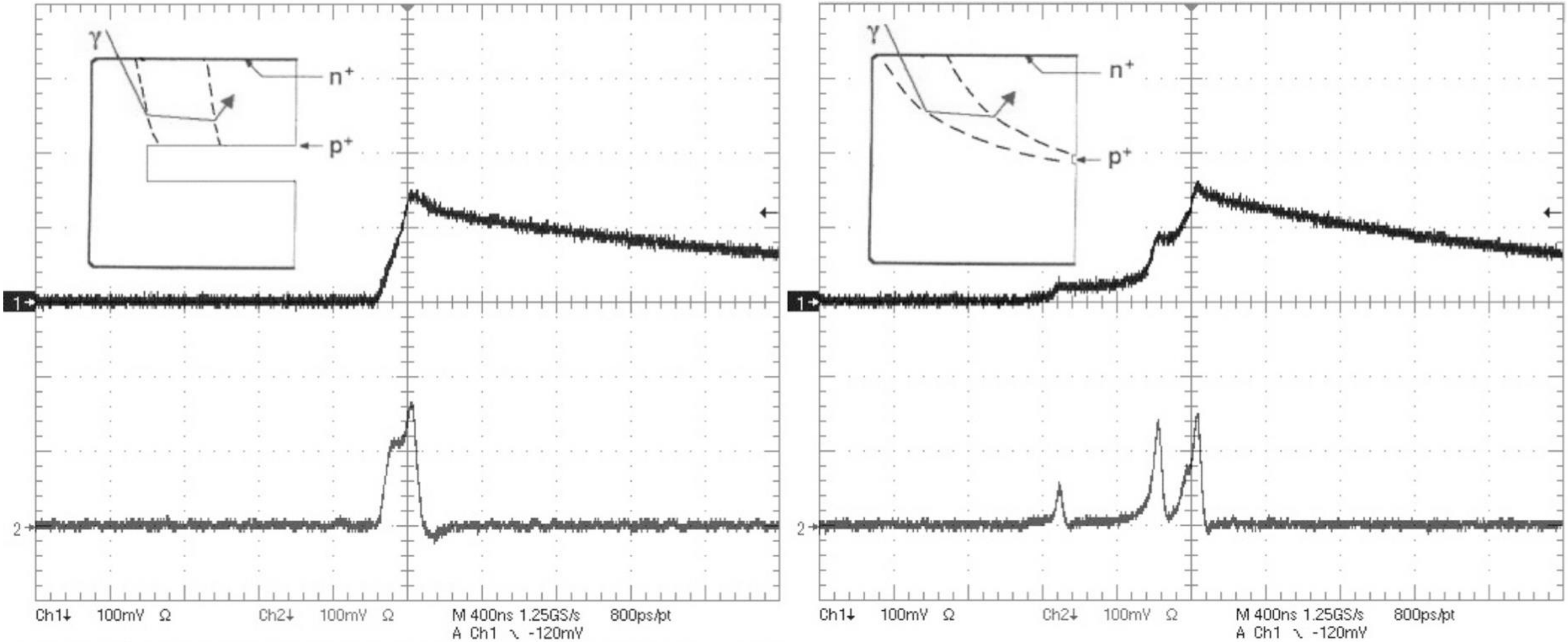


Semi coaxial detector

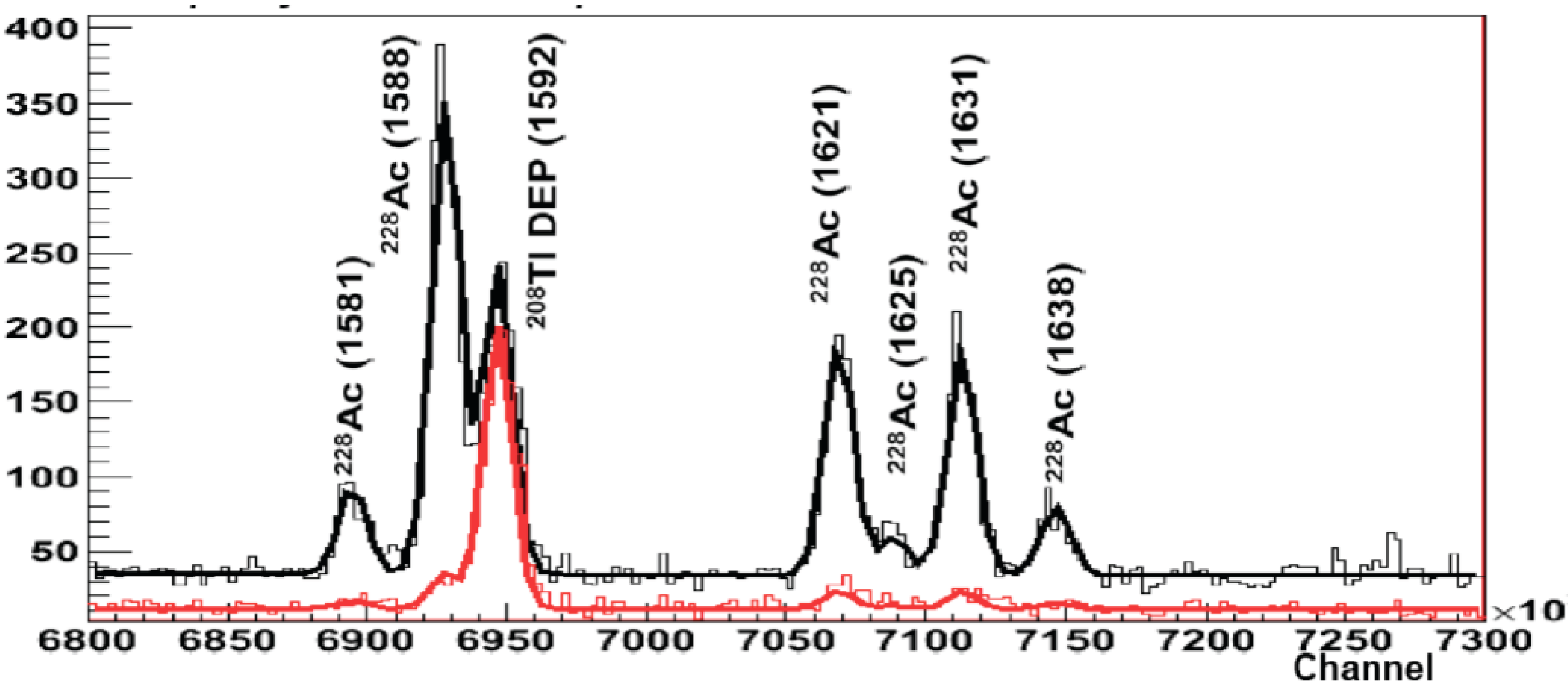
P. N. Luke, F. S. Goulding, N. W. Madden, R. H. Pehl, IEEE T. Nucl. Sci. **36** (1989) 926
P. S. Barbeau, J. I. Collar, O. Tench, J. Cosmol. Astropart. Phys. **0709** (2007) 009.
E. Aguayo et al. [The Majorana Collaboration], http://arxiv.org/abs/1109.6913 (2011)



Point contact detector



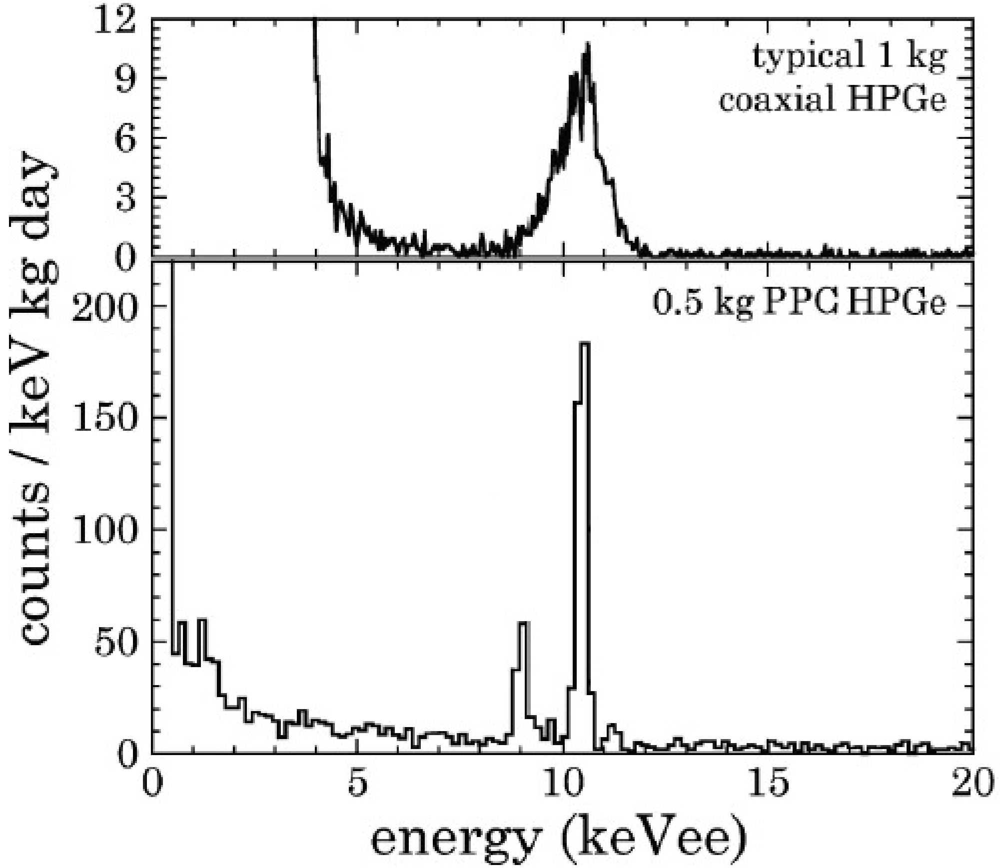
(Left top) A typical charge pulse of an ordinary semi-coaxial high-purity germanium detector.
(Left lower) The corresponding current pulse from differentiating the above pulse.
(Right upper) A typical charge pulse from a point contact detector.
(Right lower) the current pulse from differentiating the charging pulse above.



A gamma-ray spectrum taken with a point-contact detector using a 232Th calibration source (Black fitted line). The lines at 1581, 1588, 1621, 1625, 1631, and 1638 keV are full-energy peaks corresponding to gamma rays of those energies, and are dominantly multi-site.
The peak at 1592-keV is the double-escape peak from the 2615-keV line in the daughter 208Tl and serves as a proxy for the 0-decay signal.
The red spectrum shows the events remaining after the application of PSA cuts to remove multi-site events. A fit to the remnant peaks and background is also shown (red line).

P-type Point Contact Detectors

Low capacitance results in greatly reduced series noise
- opportunity for dark matter search



Discovery of 0νββ-decay

- Evidence : a combination of
  - Correct peak energy
  - Single-site energy deposit
  - Proper detector distributions (spatial, temporal)
  - Rate scales with isotope fraction
  - Good signal to background
  - Full energy spectrum (backgrounds) understood.

Reducing Backgrounds - Two Basic Strategies

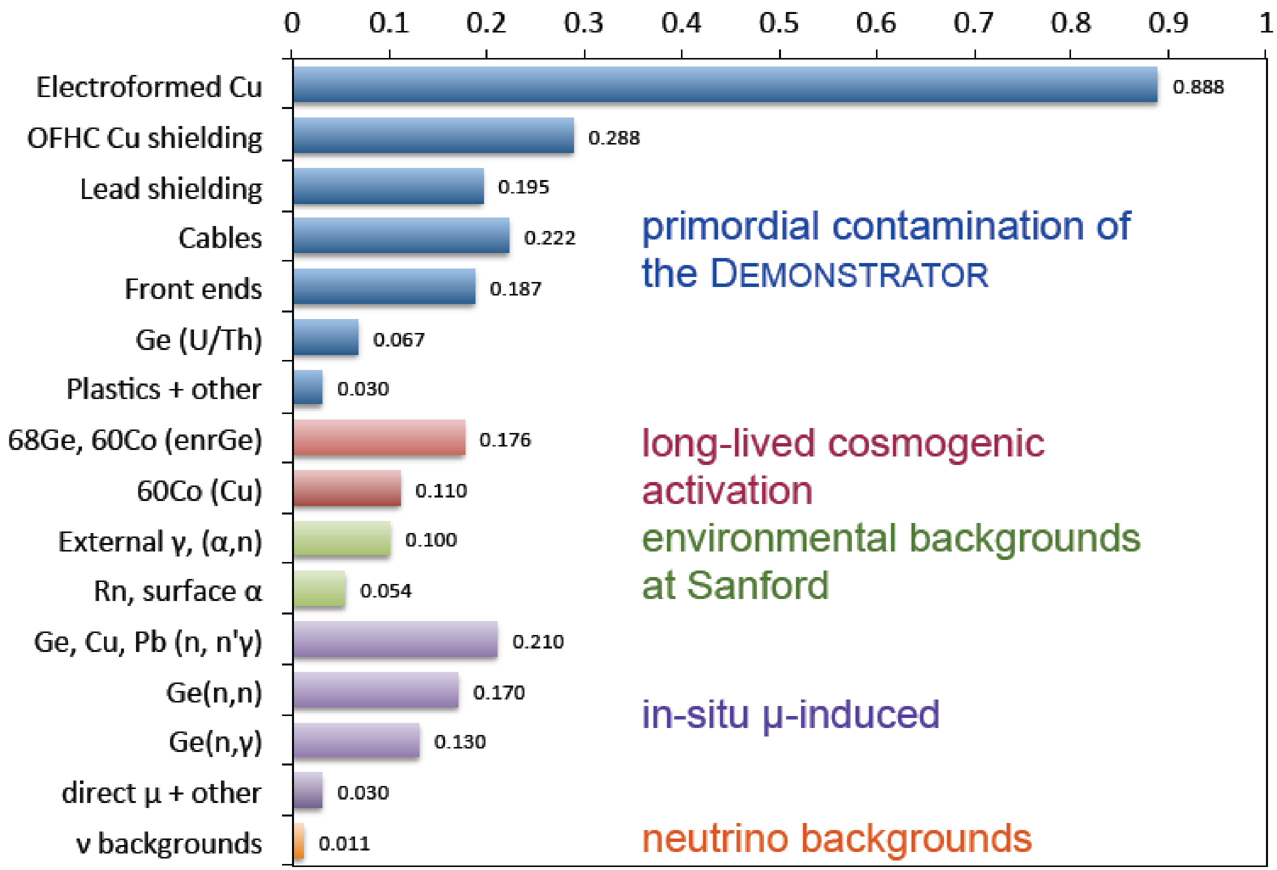
- Directly reduce intrinsic, extrinsic, & cosmogenic activities
  - Select and use ultra-pure materials
  - Minimize all non "source" materials
  - Clean passive shield
  - Fabricate ultra-clean materials underground
  - Go deep — reduced μ's & related induced activities
- Utilize background rejection techniques

$0\nu\beta\beta$ is a single site phenomenon, many backgrounds have multiple site interactions

- Energy resolution
- Active veto detector
- Tracking
- Energy & Angular correlations
- Ion Identification
- Granularity [multiple detectors]
- Pulse shape discrimination (PSD)
- Segmentation
- Single Site Time Correlated events (SSTC)

DEMONSTRATOR background budget

counts in the 0νββ region of interest
[counts / 4 keV / tonne-year]



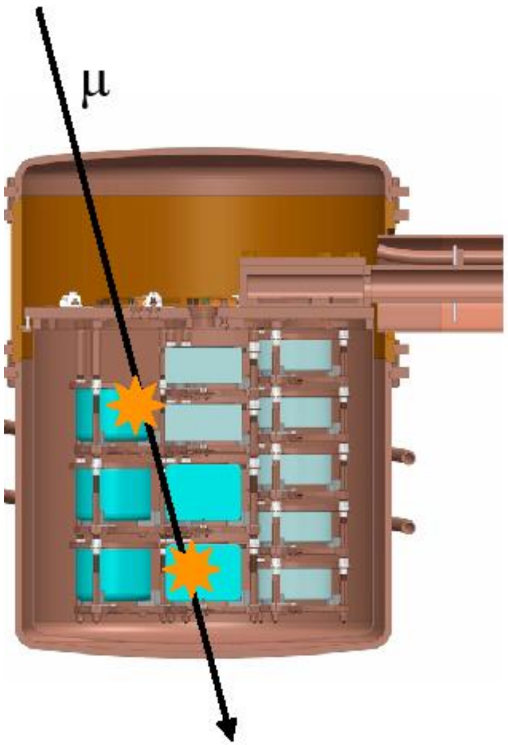
Total:
2.9 cts / 4 keV / t-y

22

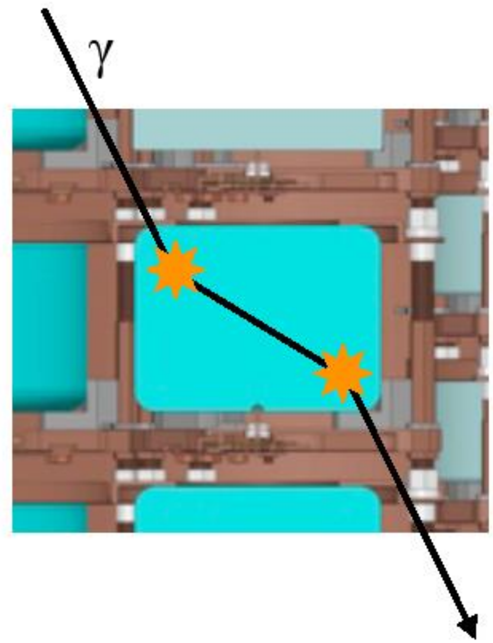
J. Detwiler, MJ CD4 Background Criteria Report

Background mitigation techniques

Granularity



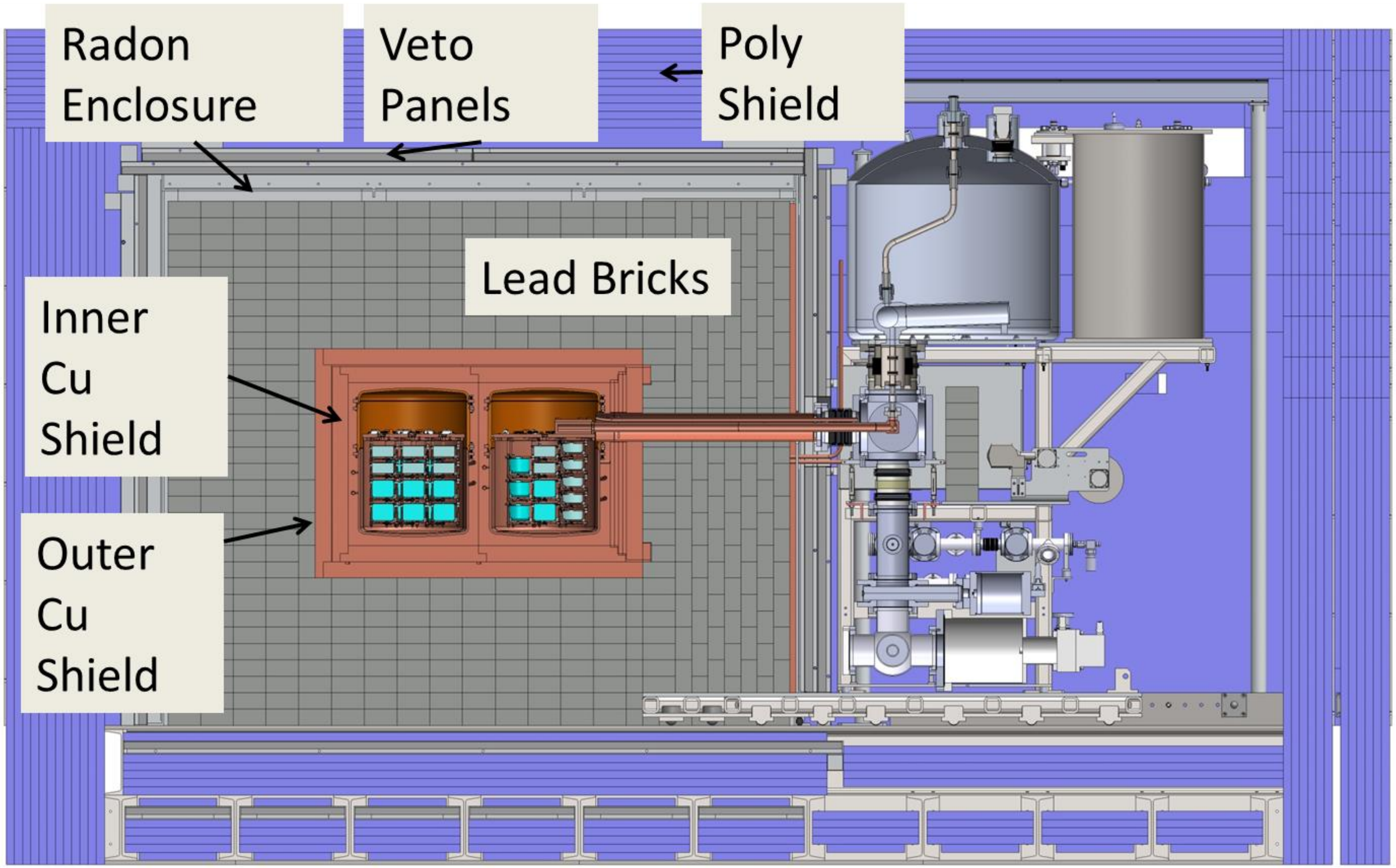
Pulse-shape analysis



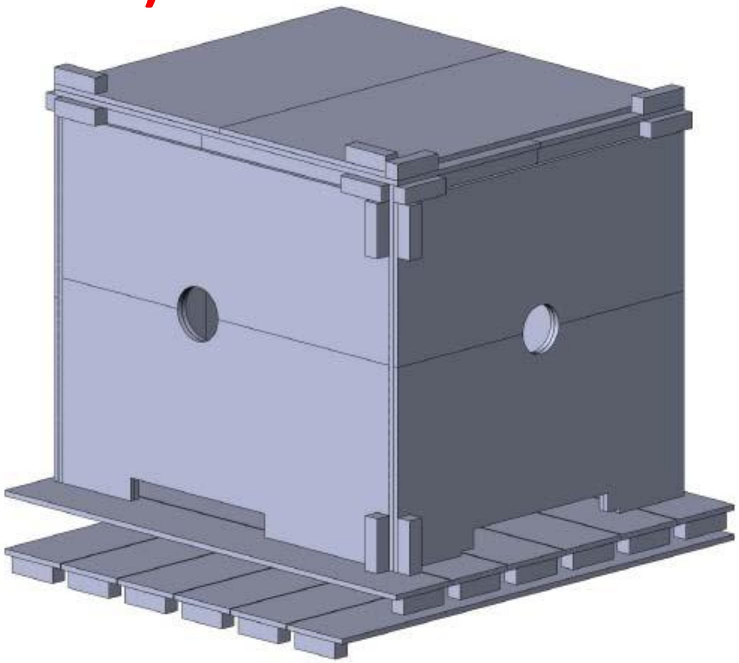
Time correlation

21

Shield Overview

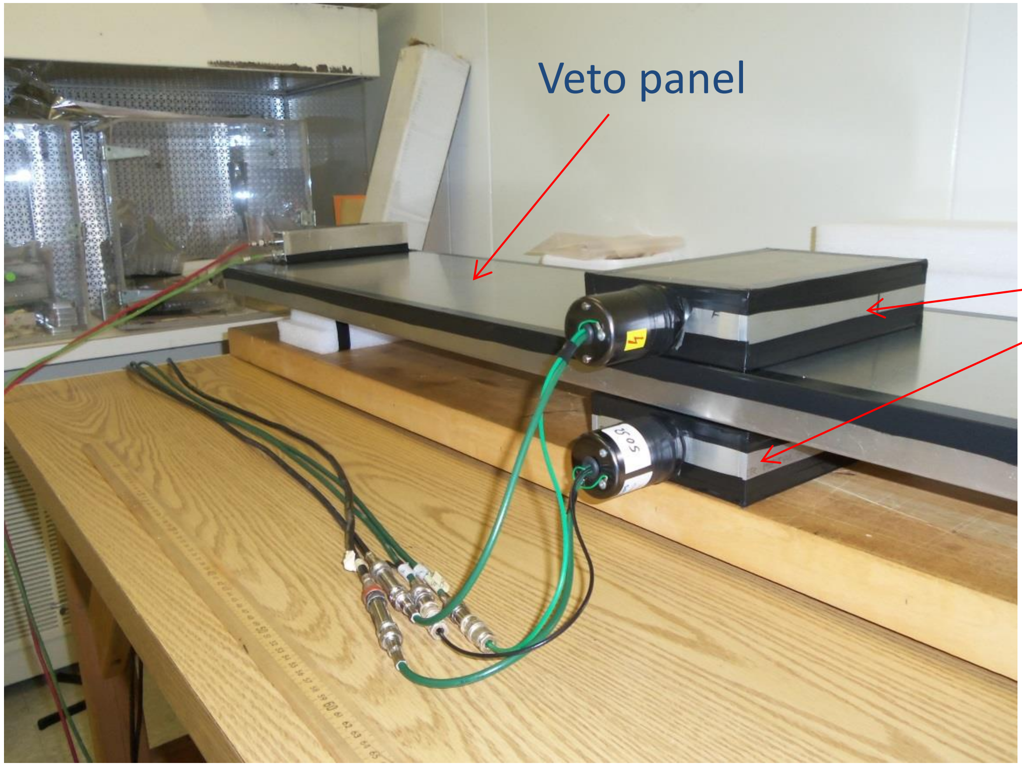


Majorana Active Veto System (Contribution part from UT)



32 veto panels

- **Dimensions of individual panels from 0.6 m^2 to 2.0 m^2 .**
- **Veto should be 99% hermetic**
- **Panels should be highly efficient for muons (>99%) and other penetrating particles but blind for gammas**
- **False veto signals should not introduce large dead time.**



- **All 32 Veto Panels were assembled and tested at SERF (UT, Knoxville)**
- **All 32 Veto panels are shipped to SD**
- **12 Veto panels are operated permanently at SURF in Davis campus since October 2013.**

International Program in 0νββ

Previous Expts.
~ 1 eV
~kg scale

Quasi-degenerate
~100's meV
30 - 200 kg
~8 -10 expts

Inverted hierarchy
~30 - 40 meV
1 tonne (phased/scaled)
~3 expts (?)

Normal hierarchy
~5 meV
≥10's ton scale

1980 - Present | 2007 - 2015 | 2016 - 2025

0νββ-decay Summary

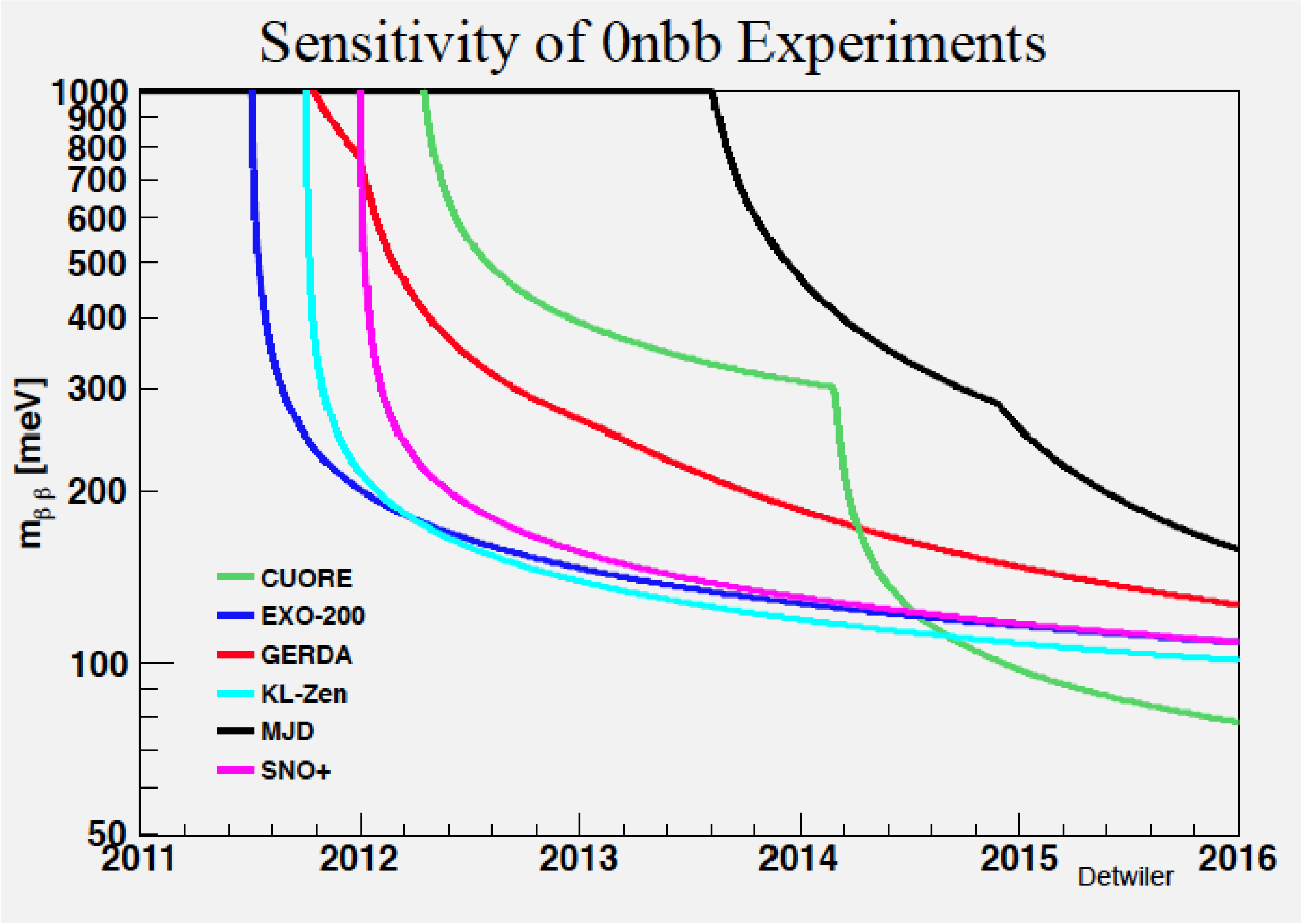
- The observation of 0νββ-decay would demonstrate Lepton number violation and indicate that neutrinos are Majorana particles - constituting a major discovery.
  - Needs to be confirmed from *independent experiments using different isotopes* and measurement techniques.

- If 0νββ-decay is observed then it opens an exquisitely sensitive window to search for physics beyond the Standard model.
  - *Measurements in different isotopes* may provide insights into the underlying physics process(es) (η).
  - Extraction of $\langle m_{\beta\beta} \rangle$ will be challenging.

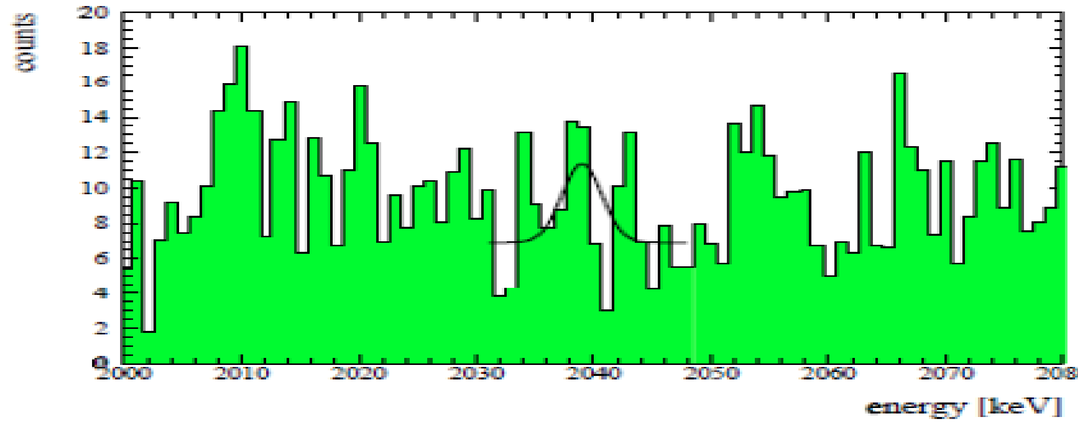
Thanks for your attention!

Backup slides

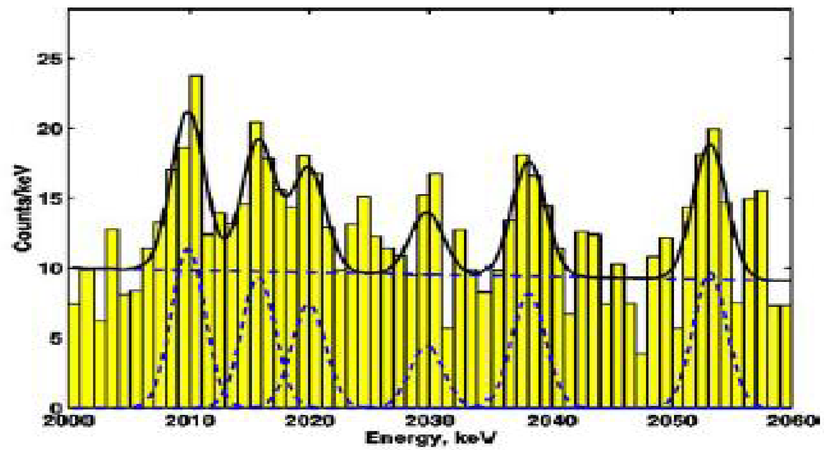
Sensitivity from now onwards



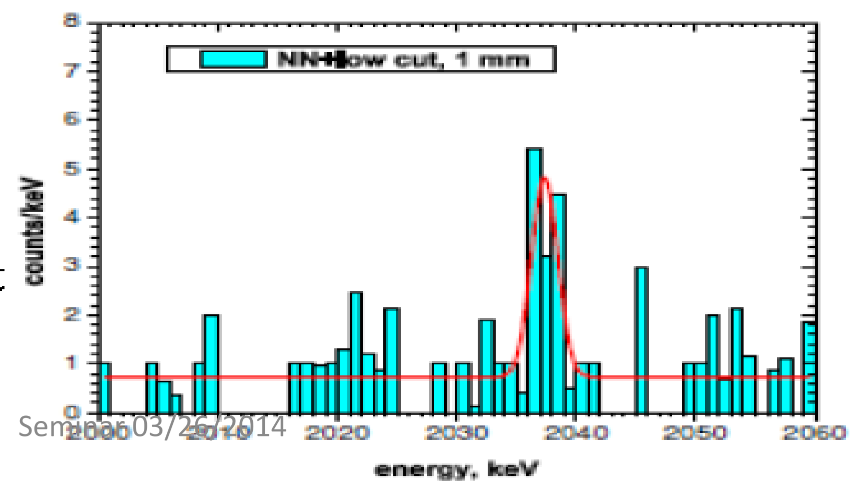
MPL A 16(2001)2409:
5 HP Ge, 1990.08-2000.05,
55.0 kg×y, no PSA, 2.2-3.1σ effect



PLB 586(2004)198:
5 HP Ge, 1990.08-2003.05,
71.7 kg×y, no PSA, 4.2σ effect



MPL A 21(2006) 1547:
4 HP Ge, 1995-2003,
? kg×y, PSA – 2 methods, 6.2σ effect



$2\beta0\nu$ decay of ^{76}Ge in the H-M experiment

Heidelberg-Moscow experiment:
5 HP Ge detectors (11 kg), 86-88% enriched in ^{76}Ge, Gran Sasso Underground Laboratory (3600 m w.e.), passive shielding, many years of measurements (start in 1990)

There are few articles on this subject:

0) H.V. Klapdor-Kleingrothaus et al. (HM collaboration, 14 persons),
Eur. Phys. J. A 12 (2001) 147 (received 2001.08.22)
53.9 kg×y full statistics (35.5 kg×y with PSA for single site events):
$T_{1/2}(0\nu) > 1.3(1.9)\times10^{25}$ yr at 90% C.L.

1) H.V. Klapdor-Kleingrothaus, A. Dietz, H.L. Harney, I.V. Krivosheina,
Mod. Phys. Lett. A 16 (2001) 2409 (received 2001.12.05)
55.0 kg×y full statistics (no PSA), $T_{1/2}(0\nu) = 1.6\times10^{25}$ yr [$(0.8\text{-}35.1)\times10^{25}$ yr at 95% C.L.]
46.5 kg×y part of statistics (no PSA), $T_{1/2}(0\nu) = 1.5\times10^{25}$ yr [$(0.8\text{-}18.3)\times10^{25}$ yr]
2.2-3.1σ effect

Criticized in number of works:

F. Feruglio et al., Nucl. Phys. B 637 (2002) 345	
C.E. Aalseth et al., Mod. Phys. Lett. A 17 (2002) 1475	
Yu.G. Zdesenko et al., Phys. Lett. B 546 (2002) 206	no effect or ~1.5σ effect
A. Ianni, Nucl. Instrum. Meth. A 516 (2004) 184	

Also, Moscow part of the H-M collaboration derived only limit:
$T_{1/2}(0\nu) > 1.6\times10^{25}$ yr at 90% C.L.
A.M. Bakalyarov et al., Phys. Part. Nucl. Lett. 2 (2005) 21

2) H.V. Klapdor-Kleingrothaus, I.V. Krivosheina, A. Dietz, O. Chkvorets,
Phys. Lett. B 586 (2004) 198
71.7 kg×y full statistics (no PSA), $T_{1/2}(0\nu) = 1.2\times10^{25}$ yr [(0.7-4.2)×10^{25} yr at 95% C.L.]
4.2σ effect

Not only statistics was bigger; also summing procedure was improved:
Final spectrum = sum of 9570 individual spectra
360 calibration spectra for each of 5 detectors, FWHM(2615 keV)=3.27 keV for sum of 1800 calibration spectra

3) H.V. Klapdor-Kleingrothaus, I.V. Krivosheina, Mod. Phys. Lett. A 21 (2006) 1547
? kg×y, PSA – 2 methods (pulse shapes were written since 1995)
$T_{1/2}(0\nu) = 2.23^{+0.44}_{-0.31}\times10^{25}$ yr – final result
6.2σ effect