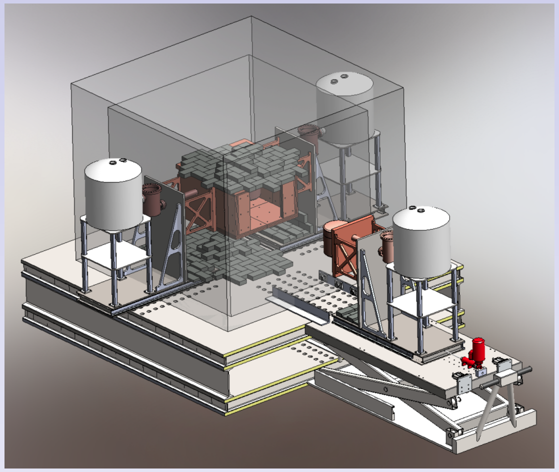
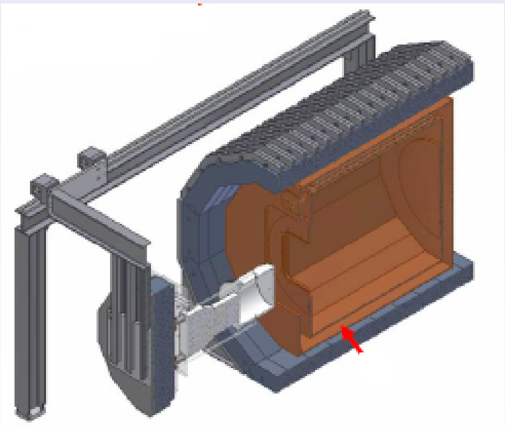
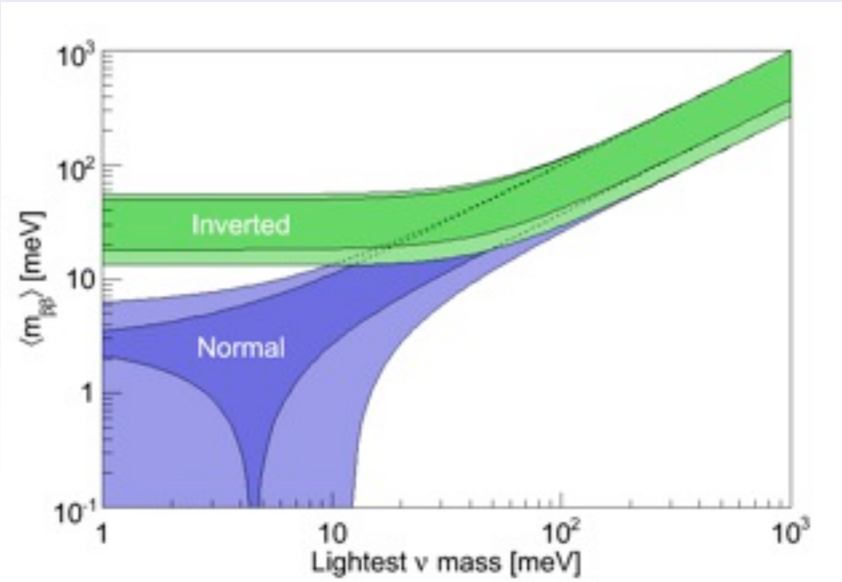
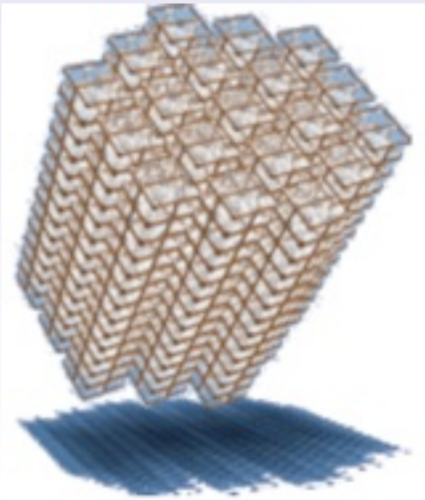
ν mass from double beta decay

- Extracting ν mass from 0νββ
- Experiments & Sensitivity
  - ^{76}Ge: GERDA and MAJORANA
- What would constitutes a discovery and mass measurement?









THE UNIVERSITY of NORTH CAROLINA at CHAPEL HILL

February 8, 2010
Seattle, WA

J.F. Wilkerson
INT Workshop on
The Future of ν mass measurements

0νββ decay

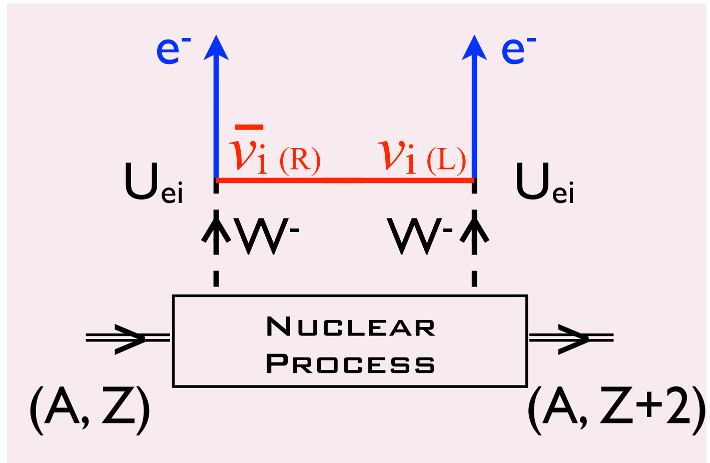
Requires:

- neutrino to have non-zero mass
  - "wrong-handed" helicity admixture ~ m_i/E_{ν_i}

Any process that allows 0νββ to occur requires Majorana neutrinos with non-zero mass.
Schechter and Valle, 1982

- Lepton number violation
  - No experimental evidence that Lepton number must be conserved

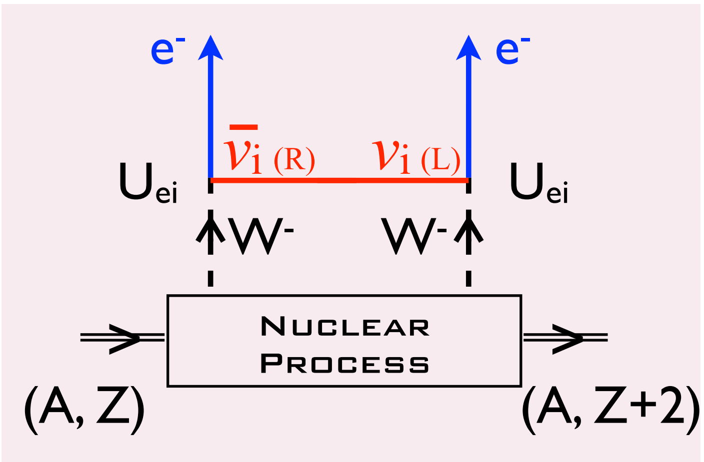
  (i.e. general SM principles, such as electroweak-isospin conservation and renormalizability)



If 0νββ decay is observed ⇒ neutrinos are Majorana particles
lepton number is violated

0νββ and ν mass

Observable (decay rate) depends on nuclear processes & nature of lepton number violating interactions (η).



$$\left[T_{1/2}^{0\nu}\right]^{-1} = G_{0\nu}\left|M_{0\nu}(\eta)\right|^2 \eta^2$$

$$\Downarrow$$

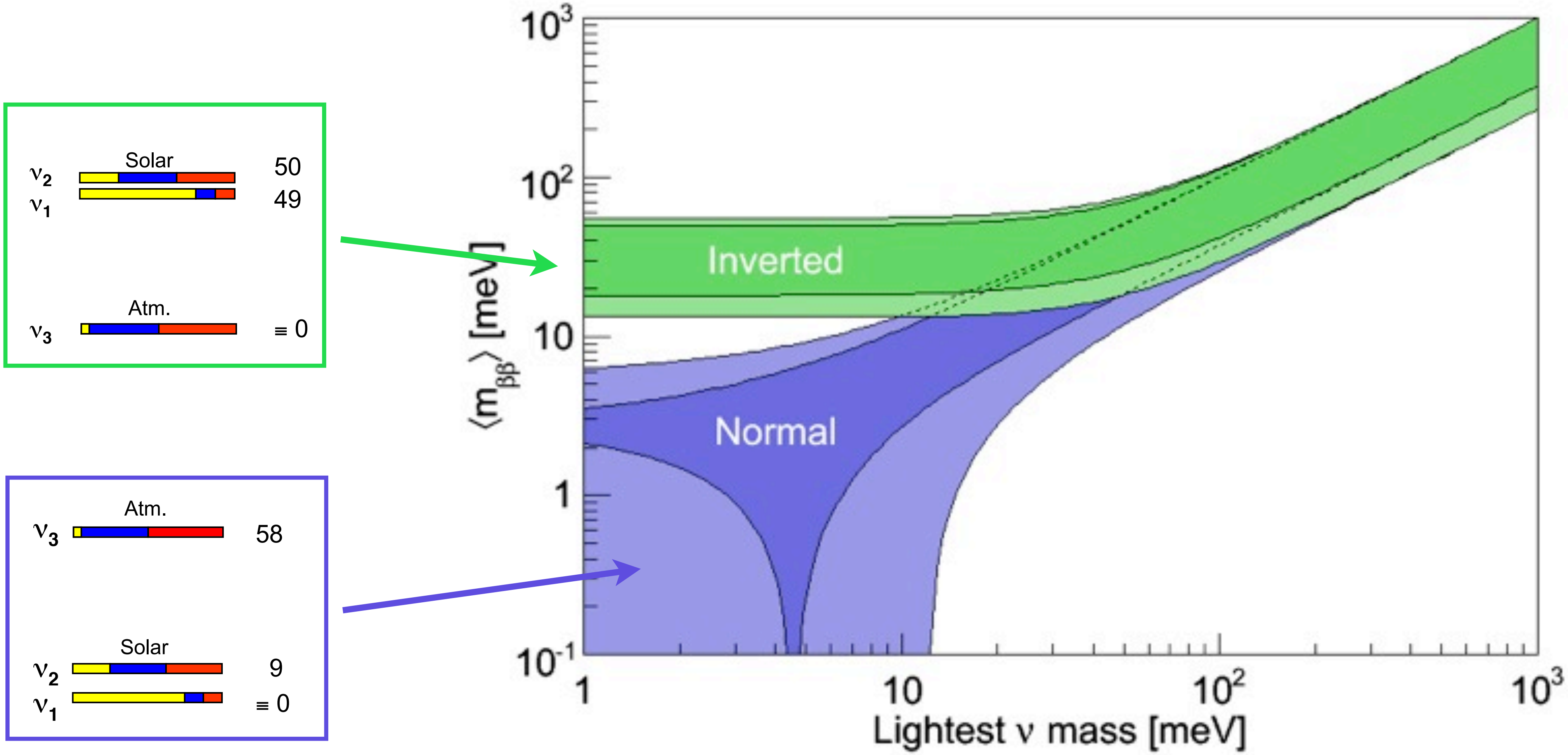
$$\left[T_{1/2}^{0\nu}\right]^{-1} = G_{0\nu}\left|M_{0\nu}\right|^2 \langle m_{\beta\beta}\rangle^2$$

- Phase space, $G_{0\nu}$ is calculable.
- Nuclear matrix elements (NME) via theory (Shell Model, Quasi-random phase approximation, interacting boson model).
- Effective neutrino mass, $<m_{\beta\beta}>$, depends directly on the assumed form of lepton number violating (LNV) interactions.

$0\nu\beta\beta$ Decay Sensitivity to $<m_{\beta\beta}>$

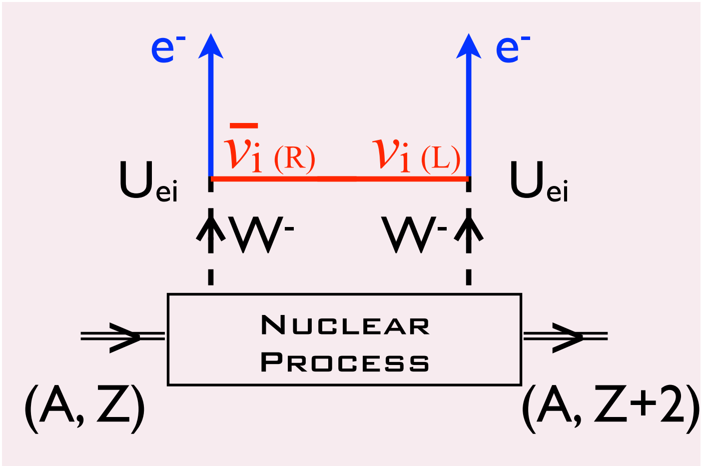
Assuming LNV mechanism is light Majorana neutrino exchange and SM interactions (W)

$$m_{\beta\beta} = \left|\sum_i U_{ei}^2 m_i\right| = \left|c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3}\right|$$



Extracting ν mass from 0νββ

- Requires calculation of reliable theoretical nuclear matrix elements.
- Requires an understanding of the lepton number violating (LNV) interaction mechanism – currently assume a model.



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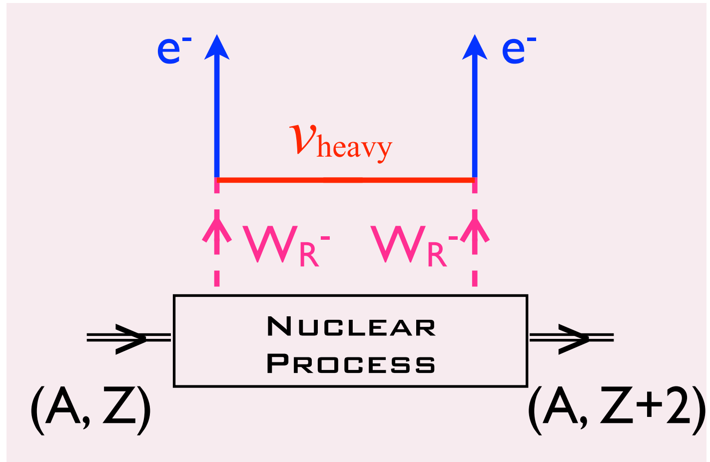

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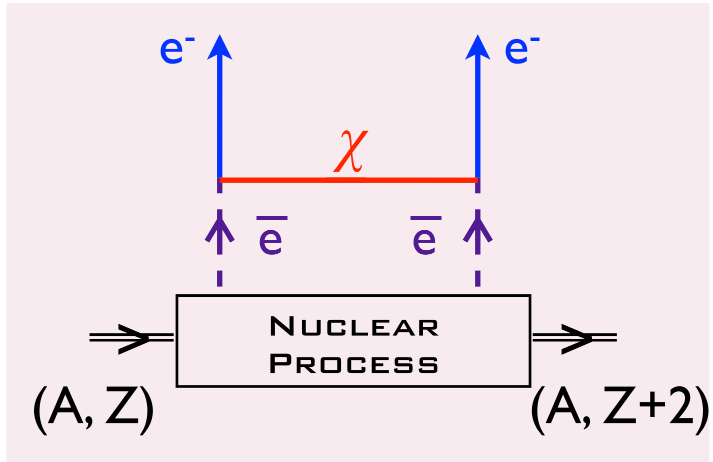

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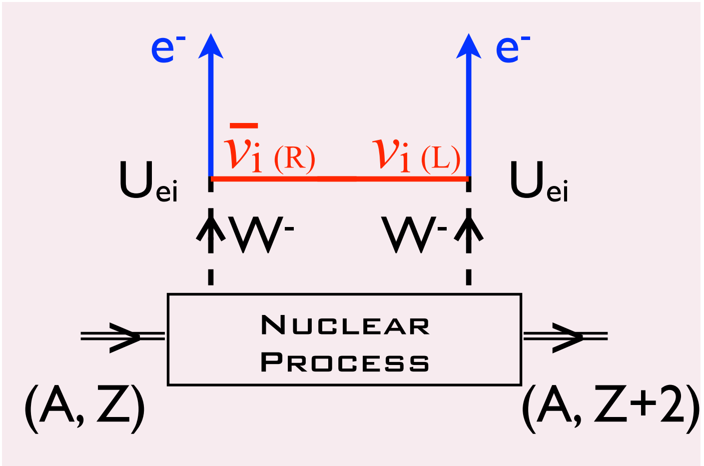


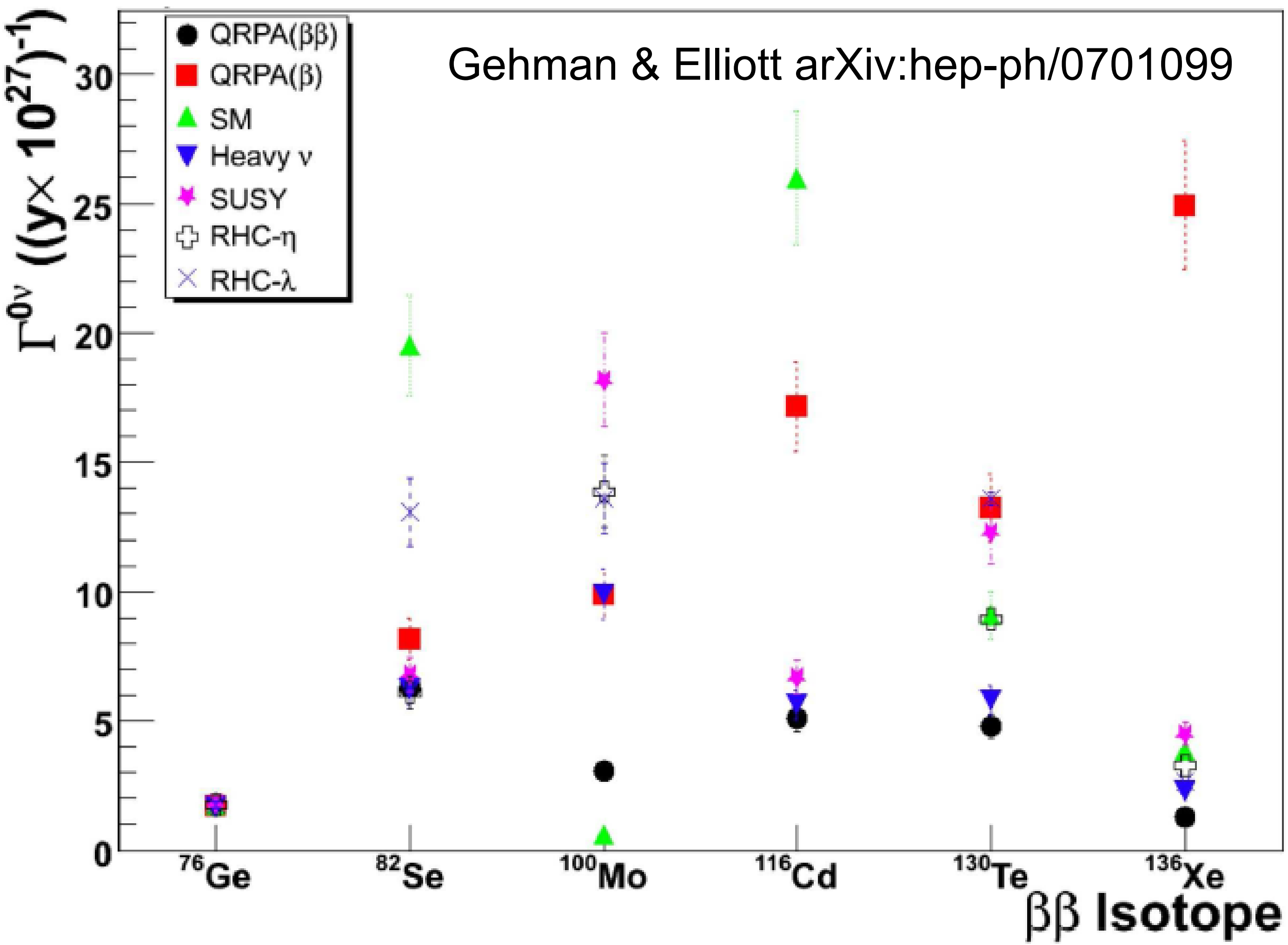
- In the "simplest" model – light Majorana neutrino and SM interactions – $\langle m_{\beta\beta}\rangle$ depends on mass hierarchy, lepton matrix mixing values, & Majorana phases.
  - for normal hierarchy, can have a cancelation resulting in no observable decay.

Key advantage: ^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr ^{100}Mo, ^{116}Cd ^{130}Te, ^{136}Xe, ^{150}Nd

Potential future advantage: additional excited state decays (NME)

0νββ-decay as a Probe of LNV Interactions

If 0νββ is observed, then measurements on 3-4 multiple isotopes might be able to distinguish potential physics mechanisms



Comparison assumes a single dominant mechanism.

Requires results from 3-4 isotopes & calculation of NME to ~20%

Also see
Deppisc & Päs
arXi:hep-ph/0612165

Experiments & sensitivity to 0νββ-decay

Most sensitive experiments to date (using ^{76}Ge and ^{130}Te) have attained $T_{1/2} > 10^{24}$ - 10^{25} years.

Best case, 0 background !	$\propto$ Source Mass • $time_{exp}$

Typical masses ~ 1-10 kg

Typical exposure times of 5-8 years

Question 1: What would convince one that 0νββ has been discovered?

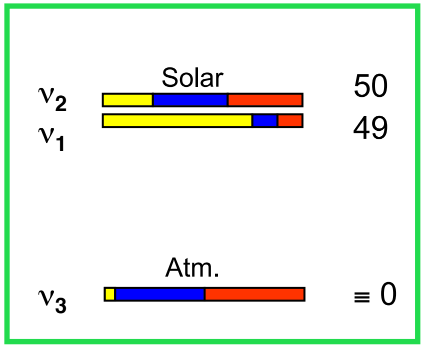
Question 2: What's needed to reach sensitivities of $T_{1/2}$ on the order of 10^{26} - 10^{27} y?

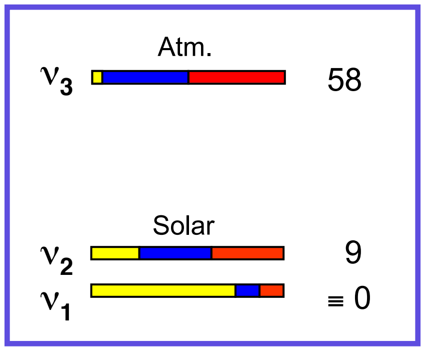
Current Sensitivity to <mββ>

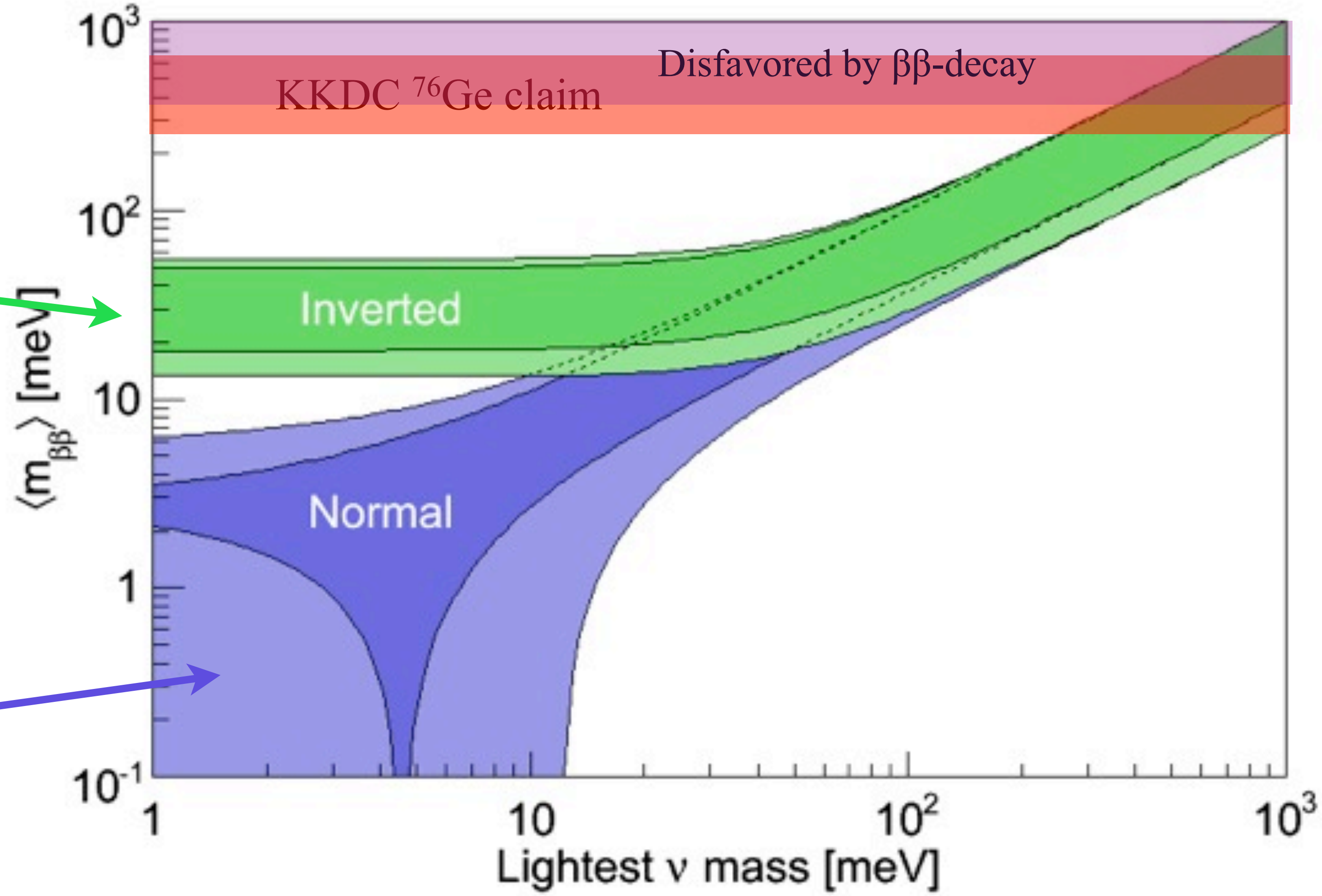
Assuming LNV mechanism is light Majorana neutrino exchange

$0\nu\beta\beta$ limits for: ^{48}Ca, ^{76}Ge, ^{82}Se, ^{100}Mo, ^{116}Cd ^{128}Te, ^{130}Te, ^{136}Xe, ^{150}Nd

$$m_{\beta\beta} = \left|\sum_i U_{ei}^2 m_i\right| = \left|c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3}\right|$$







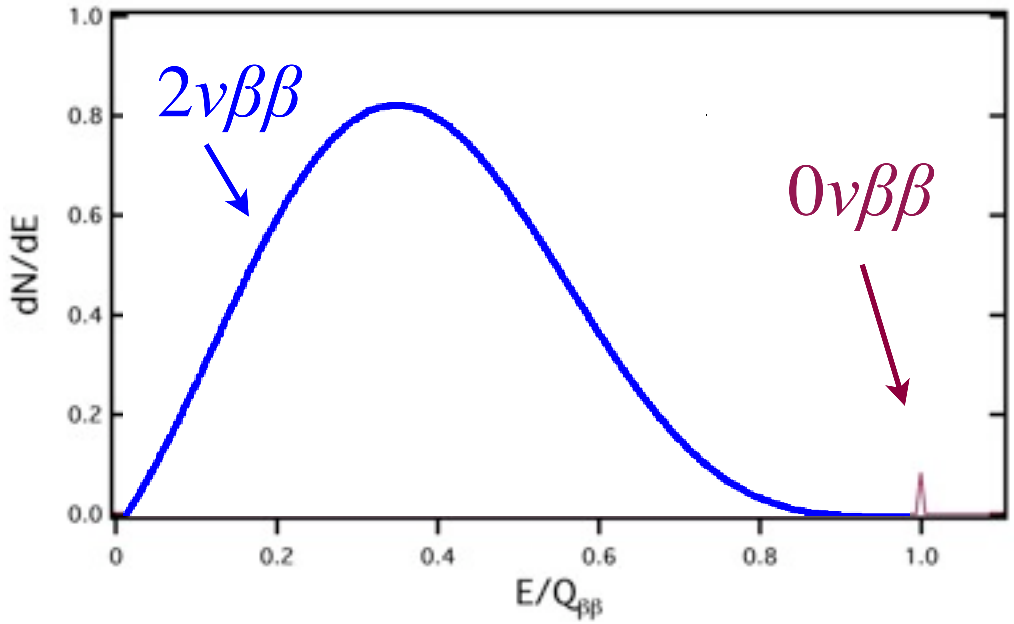
Experimental Considerations

*Searching for an **extremely** rare process*

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

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

Ideal (only $2\nu\beta\beta$ backgrounds)



Need large, highly efficient source mass

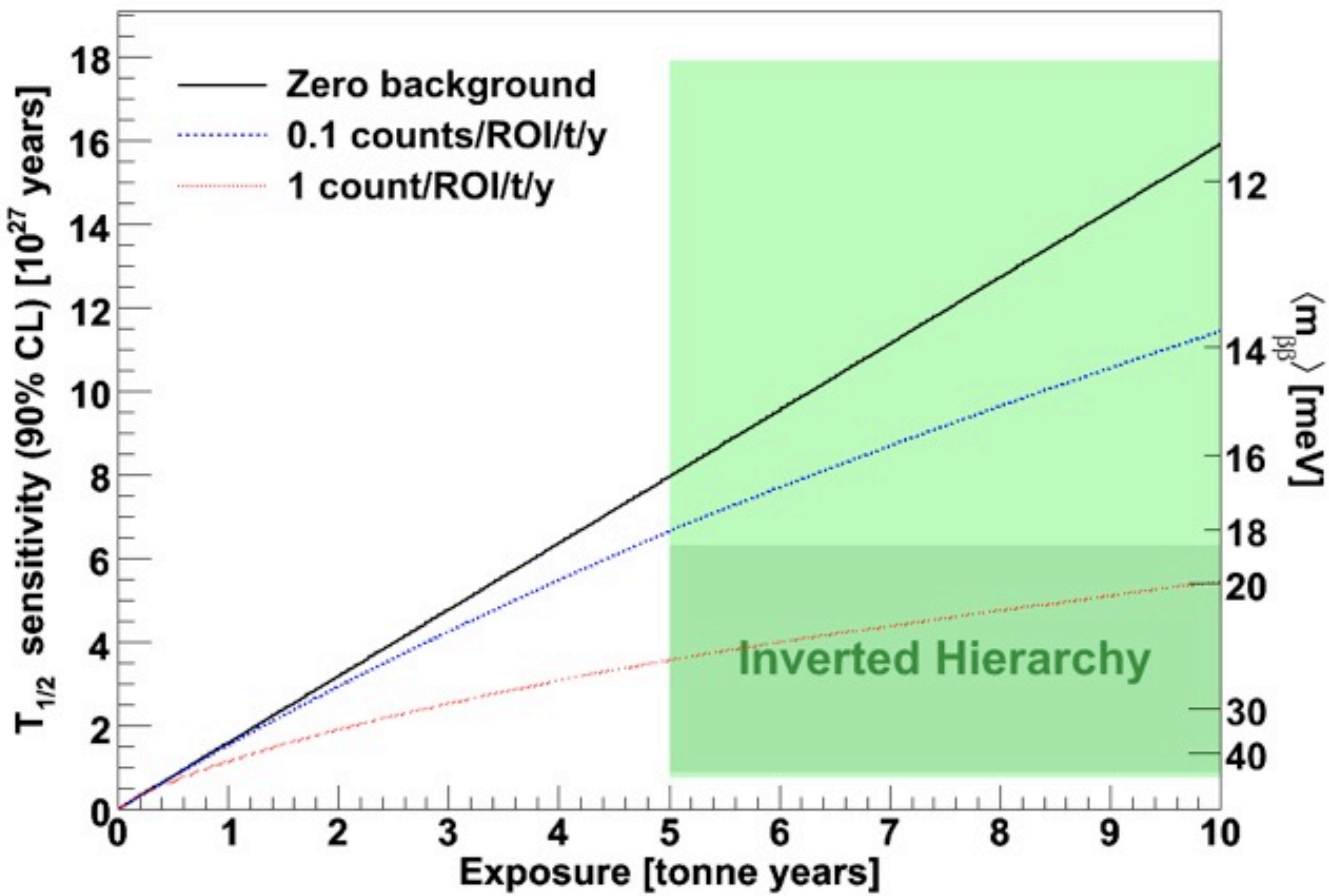
Want best possible energy resolution and/or kinematical method to discriminate $0\nu\beta\beta$ from $2\nu\beta\beta$

Desire extremely low (near-zero) backgrounds in the $0\nu\beta\beta$ peak region

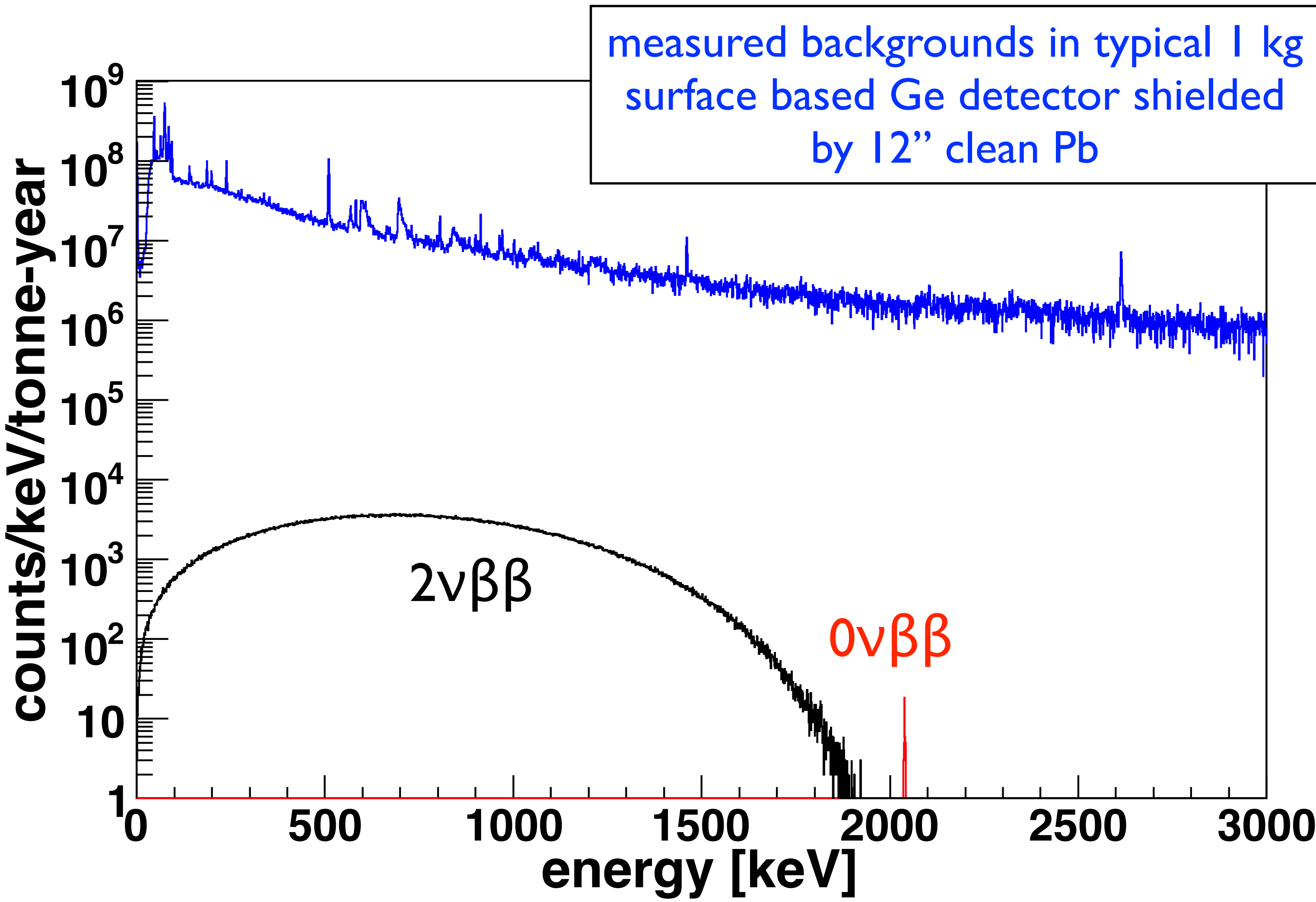
Sensitivity and backgrounds

1-tonne ^{76}Ge Example

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



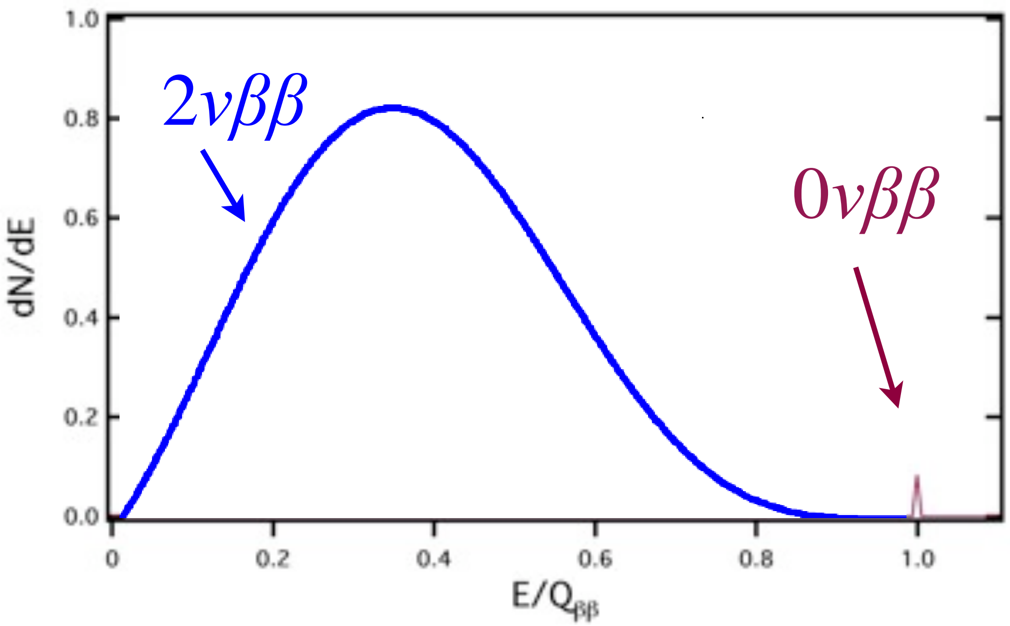
1ct/tonne-year in context - Ge example

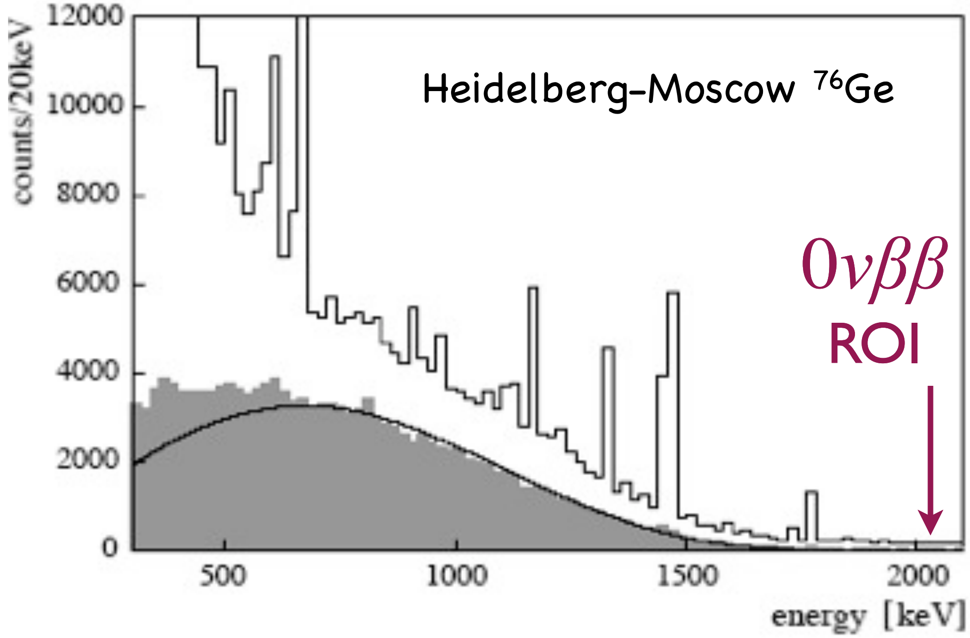


A. Schubert

For illustrative purposes 0νββ half-life chosen to be 10x current limit

Best to date - 100 cnts/tonne-year in ROI





Note ^{76}Ge has best resolution : 0.16%

Only $2\nu\beta\beta$

$2\nu\beta\beta$ (negligble)
Cosmogenic activity
Natural radioactivity
neutron induced activity

Klapdor-Kleingrothaus et al.,
Eur. Phys. J 12, 147 (2001)

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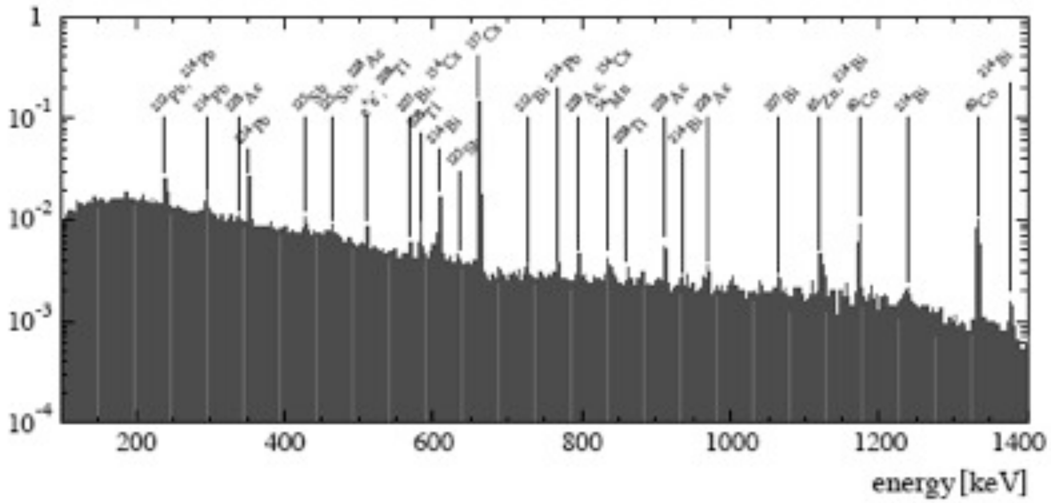

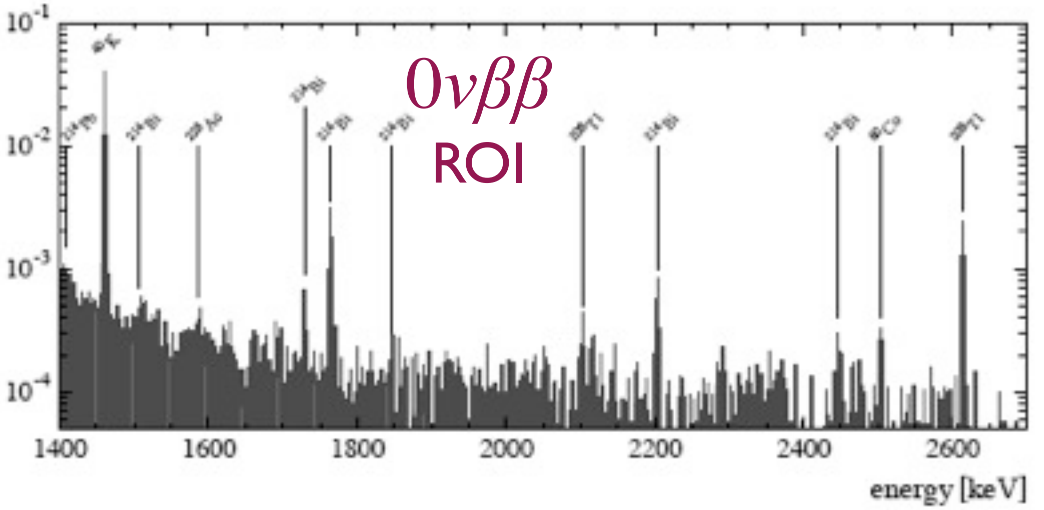

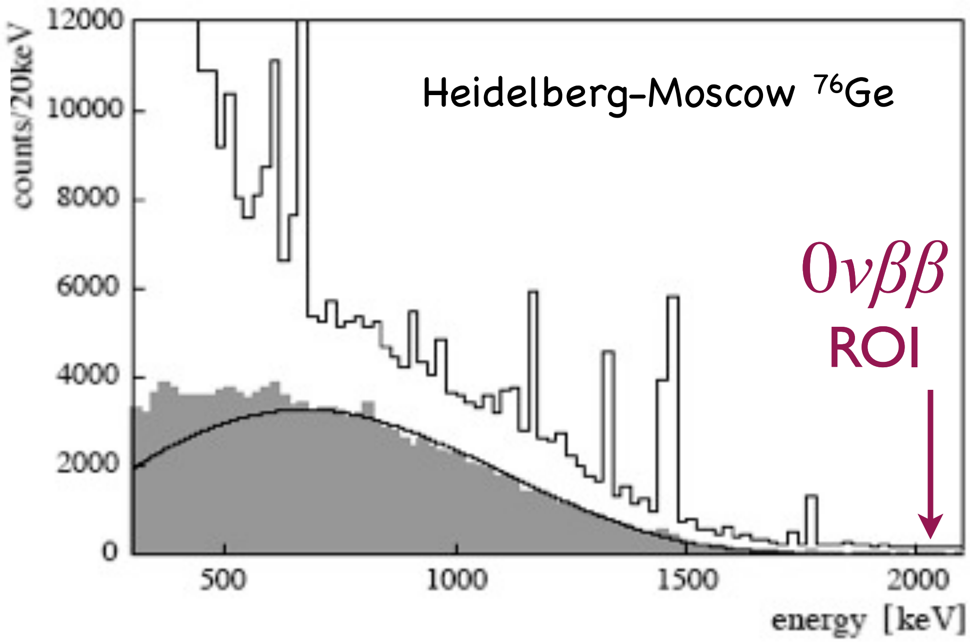

Note ^{76}Ge has best resolution : 0.16%

2νββ (negligble)
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Natural radioactivity
neutron induced activity

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Eur. Phys. J 12, 147 (2001)

The KKDC Result

Klapdor-Kleingrothaus, Krivosheina, Dietz and Chkvorets, *Phys. Lett.* B **586** 198 (2004).

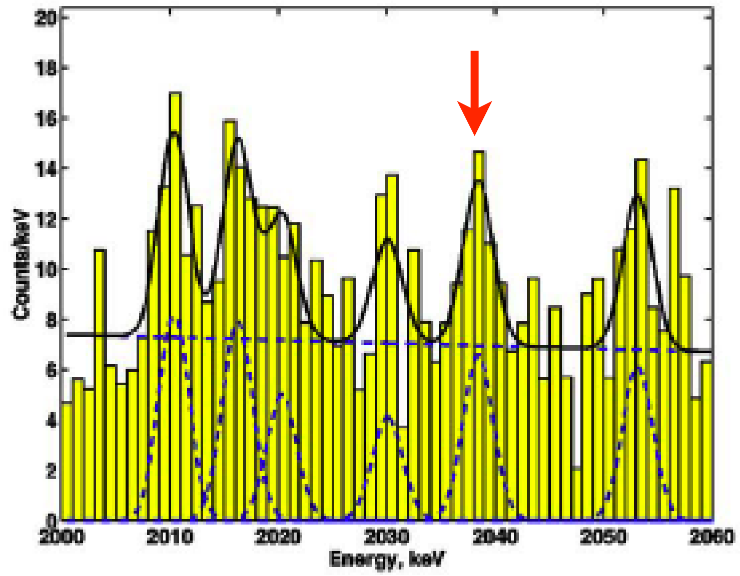
Result: Five ^{76}Ge crystals, 10.96 kg of total mass, 71 kg-years of data.

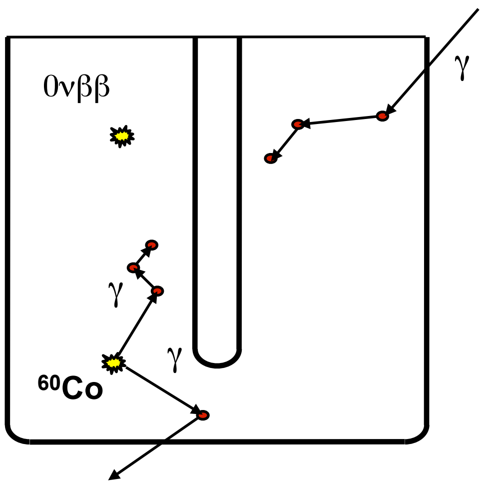
$T_{1/2} = (1.19 +2.99/-0.5) \times 10^{25}$ y

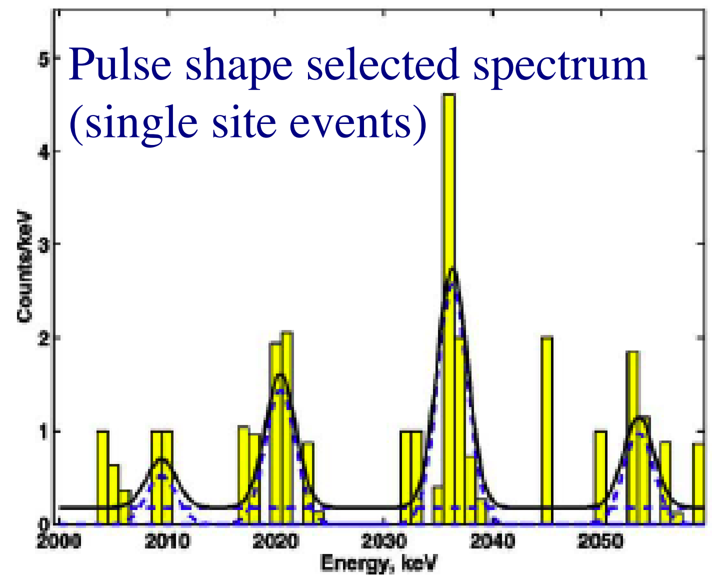
$0.24 < m_\nu < 0.58$ eV (3σ)

Plotted a subset of the data for four of five crystals, 51.4 kg-years of data.

$T_{1/2} = (1.25 +6.05/-0.57) \times 10^{25}$ y

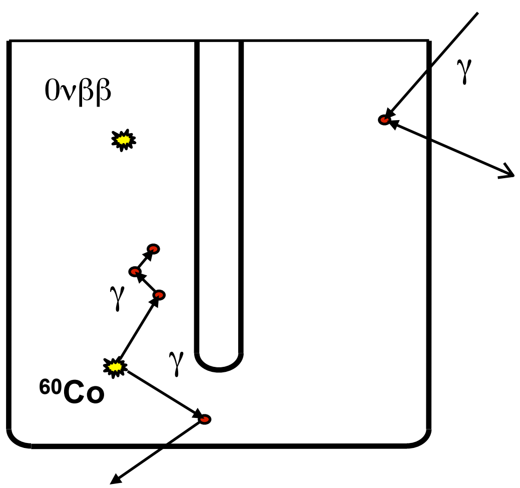




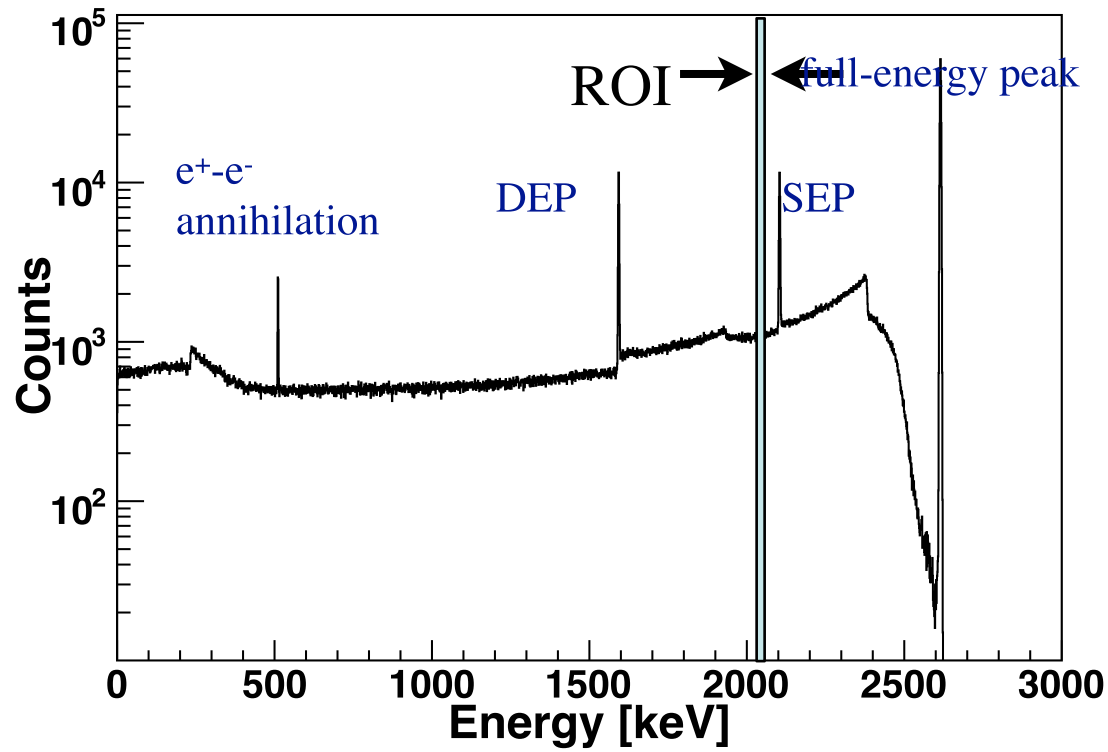


Backgrounds from ^{208}Tl

simulations and measurements show that some ^{208}Tl gammas from outside materials will interact in the detector, and then scatter back out, leaving a continuum of "point like" interactions



simulated response of Ge detector exposed to 2615-keV γs



80-mm diameter, 30-mm tall detector simulated with MaGe

Simulations by A. Schubert

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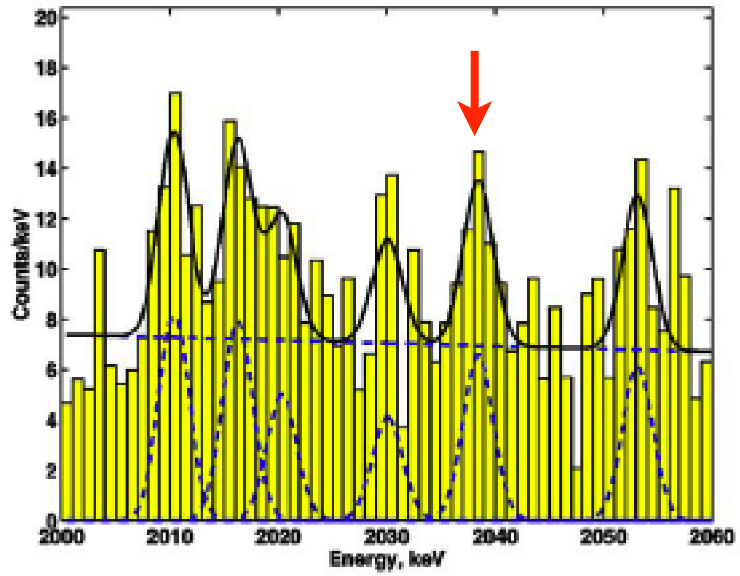
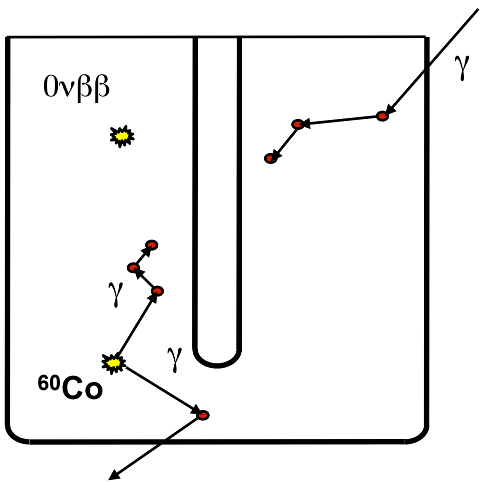
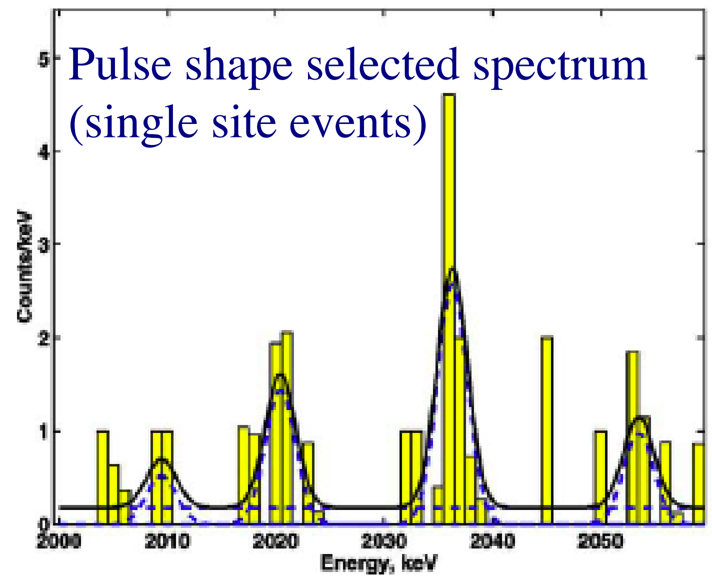






Backgrounds & Sensitivity to 0νββ

Next generation experiments are striving for backgrounds in the 0νββ region of **counts/tonne-year**.

Requires materials with sub μBq/kg level radioimpurities.

Very difficult to achieve this sensitivity with direct radioassays

Shielding from cosmogenic activation.

"New background regimes" -- background sources that could previously be ignored

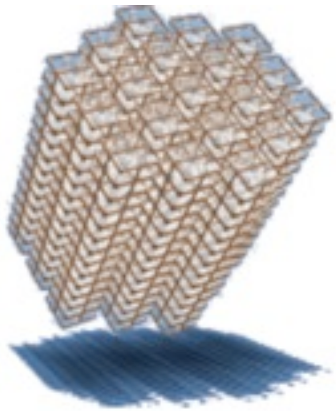
e.g. : very weak (n,n',gamma) lines

Each experiment's susceptibility to backgrounds depends on a number of factors:

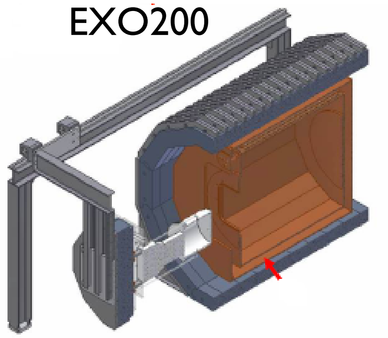
Detection technique (Solid state, TPC, bolometer, ...)
Detector resolution
Detector response function to backgrounds (γ, α, β, neutron, ...)
Construction materials and surrounding materials
Signal to background discrimination capabilities

0νββ decay Experiments - Efforts Underway

CUORE



EXO200

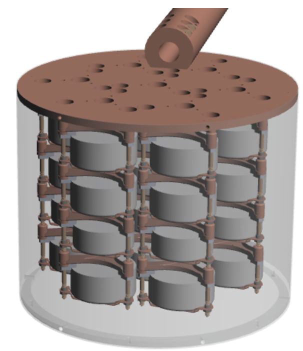


NEMO

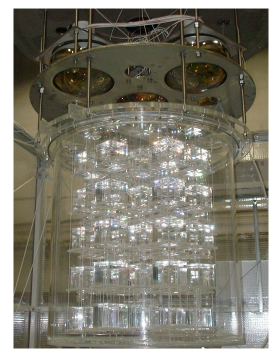
Collaboration	Isotope	Technique	Mass	Status
CAMEO	Cd-116	$CdWO_4$ crystals	1 t	
CANDLES	Ca-48	60 CaF_2 crystals in liq. scint	6 kg	Construction
CARVEL	Ca-48	$^{48}CaWO_4$ crystal scint.	100 kg	
COBRA	Cd-116, Te-130	CdZnTe detectors	10 kg	R&D
CUROICINO	Te-130	TeO_2 Bolometer	11 kg	Operating
CUORE			206 kg	Construction
DCBA	Nd-150	Nd foils & tracking chambers	20 kg	R&D
EXO200	Xe-136	Xe TPC	200 kg	Construction
EXO		Xe TPC with ion ID		Future
GEM	Ge-76	Ge diodes in LN	1 t	
GERDA	Ge-76	Seg. and UnSeg. Ge in LAr	35-40 kg 1 t	Construction Future
GSO	Gd-160	Gd_2SiO_5:Ce crystal scint. in liquid scint	2t	
MAJORANA	Ge-76	Point Contact Ge	60 kg 1 t	Construction Future
NEMO3	Mo-100 Se-82	Foils with tracking	6.9 kg 0.9 kg	Operating
SuperNEMO			100 kg	R&D
NEXT	Xe-136	High Pressure TPC	1t	R&D
MOON	Mo-100	Mo sheets	200 kg 1 t	R&D
SNO+	Nd-150	0.1% suspended in Scint.	56 kg	Construction
Xe	Xe-136	Xe in liq. Scint.	1.56 t	

GERDA

MAJORANA



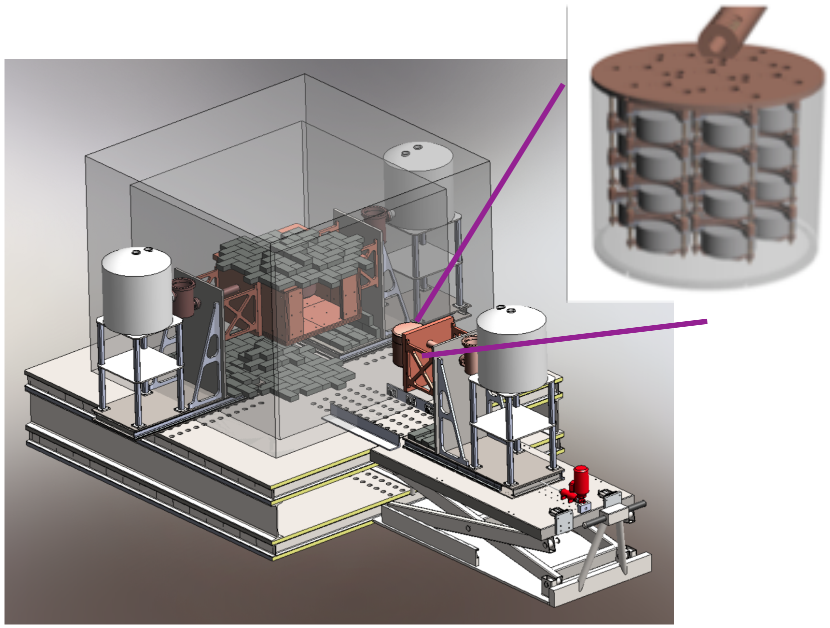
CANDLES

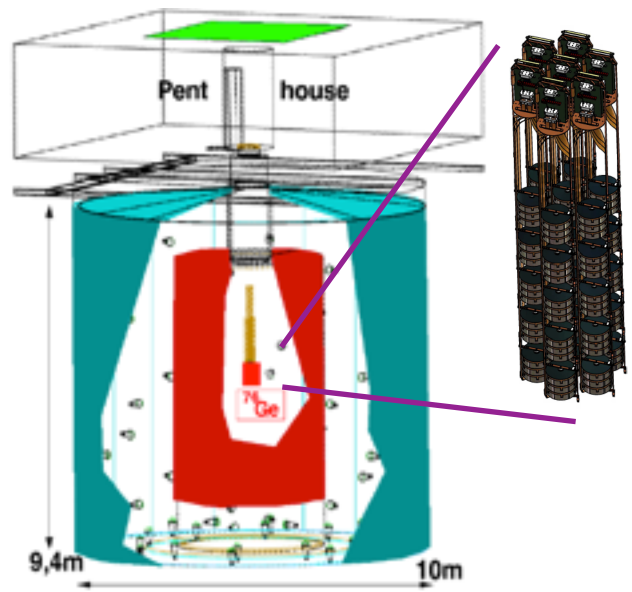


Operating Construction

^{76}Ge - GERDA and MAJORANA

- 86% enriched High purity ^{76}Ge crystals
- 0.16 % resolution
- best $0\nu\beta\beta$−decay sensitivity to date



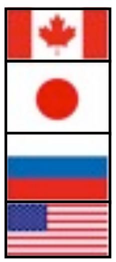


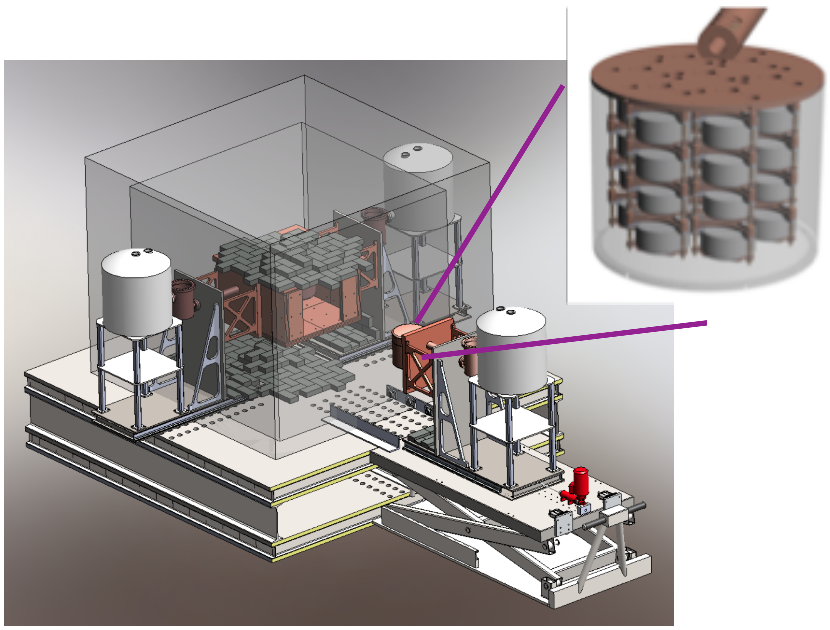
- ^{enr}Ge modules in electroformed Cu cryostat, Cu / Pb passive shield
- 4π plastic scintillator μ veto
- DEMONSTRATOR: 30 kg ^{enr}Ge/30 kg ^{nat}Ge

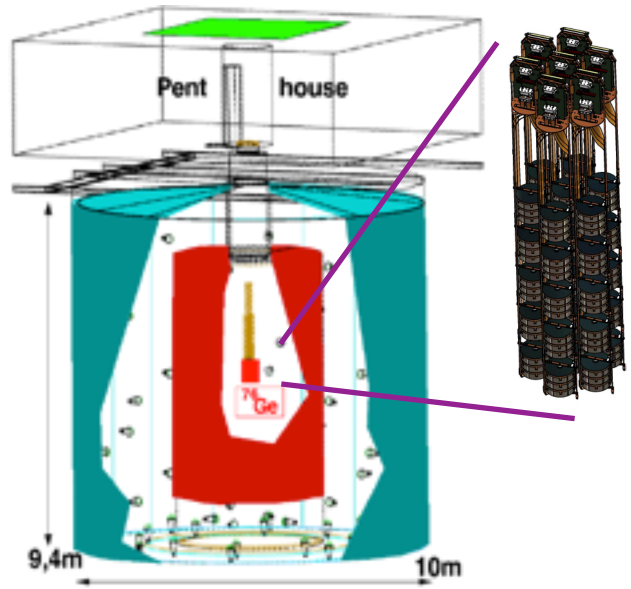
- ^{enr}Ge array submersed in LAr
- Water Cherenkov μ veto
- Phase I: ~18 kg (H-M/IGEX xtals)
- Phase II: +20 kg xtals

^{76}Ge - GERDA and MAJORANA

Joint Cooperative Agreement:
Open exchange of knowledge & technologies (e.g. MaGe, R&D)
Intention to merge for larger scale 1-tonne exp. (Talk by I. Abt, Session 7)
Select best techniques developed and tested in GERDA and MAJORANA







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- Phase I: ~18 kg (H-M/IGEX xtals)
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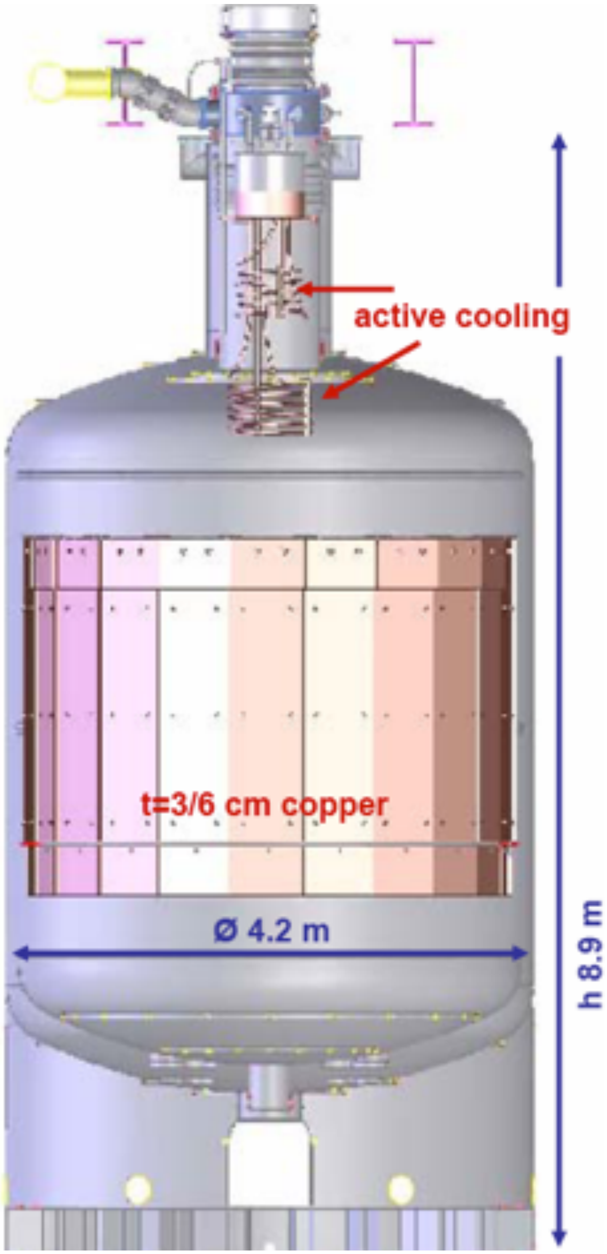
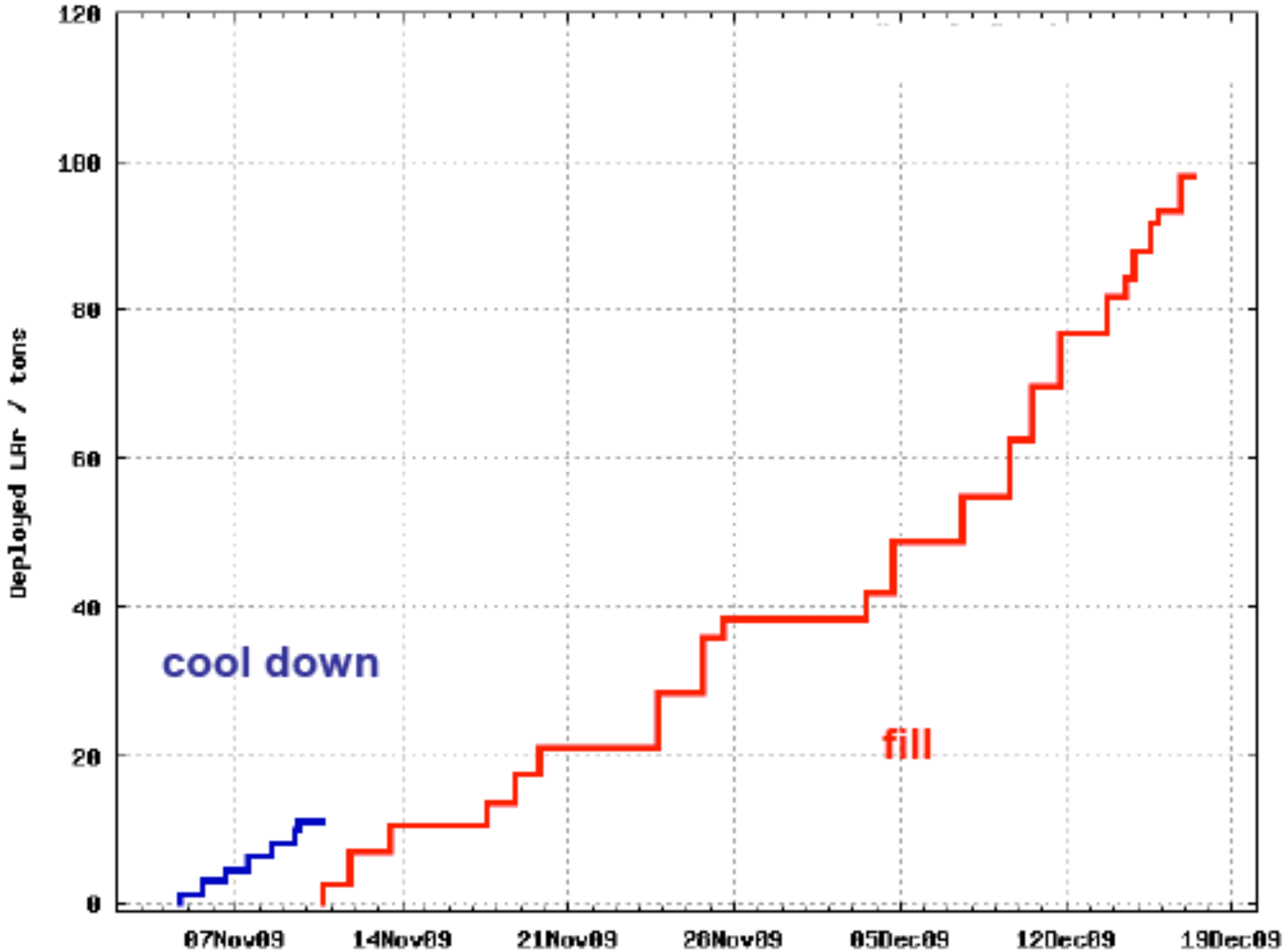
GERDA Status

- Commissioning of Phase 1 is underway
  - 18 kg of 86% enriched ^{76}Ge (8 p-type semi-coax detectors from H-M & IGEX).
  - 15 kg of ^{Nat}Ge (6 p-type semi-coax detectors from Genius Test Facility
  - Background goal: 0.01 cnts/(kg keV y)
    40 cnts/tonne/y in ROI
  - Goal: Check KKDC result.

GERDA LAr Fill

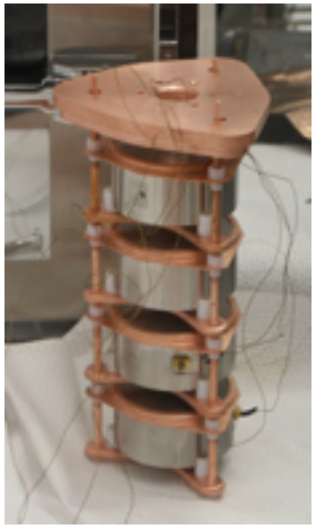




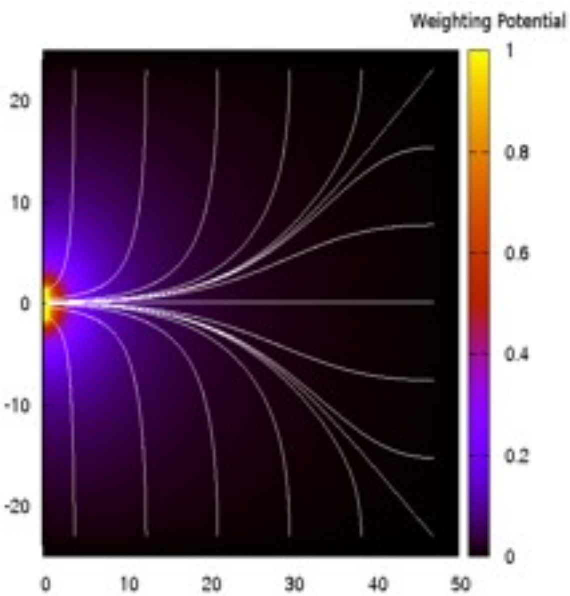
GERDA Status

- Commissioning of Phase I is underway
  - 18 kg of 86% enriched ^{76}Ge (8 p-type semi-coax detectors from H-M & IGEX).
  - 15 kg of ^{Nat}Ge (6 p-type semi-coax detectors from Genius Test Facility
  - Background goal: 0.01 cnts/(kg keV y)
40 cnts/ROI/t-y
  - Goal: Check KKDC result.
- Insertion of first detectors scheduled for this spring.
- Development work to fabricate and build Phase II enriched detectors is continuing.

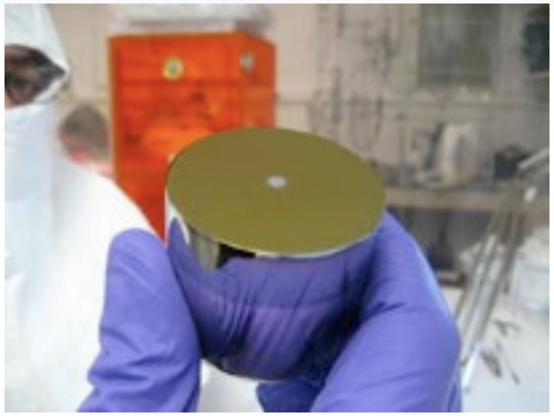
MAJORANA DEMONSTRATOR Status



- **Under construction.**
  - Detector Technology: P-type, point-contact.
  - 30-kg of ^{nat}Ge (10 kg (18 detectors) in-hand, additional 10 kg on order)
  - 30-kg of 86% enriched 76Ge crystals
  - Background Goal in the 0νββ peak region of interest (4 keV at 2039 keV)
    ~ 3 count/ROI/t-y (after analysis cuts)
- **Goals**
  - backgrounds low enough to justify building a tonne scale Ge experiment.
  - Establish feasibility to construct & field modular arrays of Ge detectors.
  - Test the KKDC claim
  - exploit the low-energy sensitivity to perform searches for dark matter, axions.

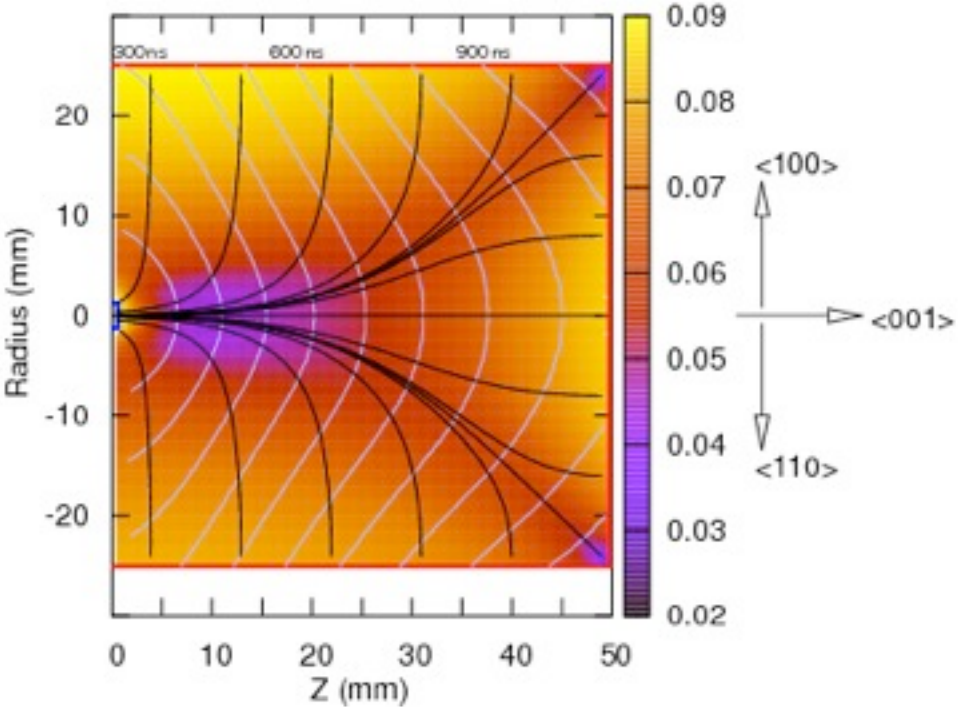


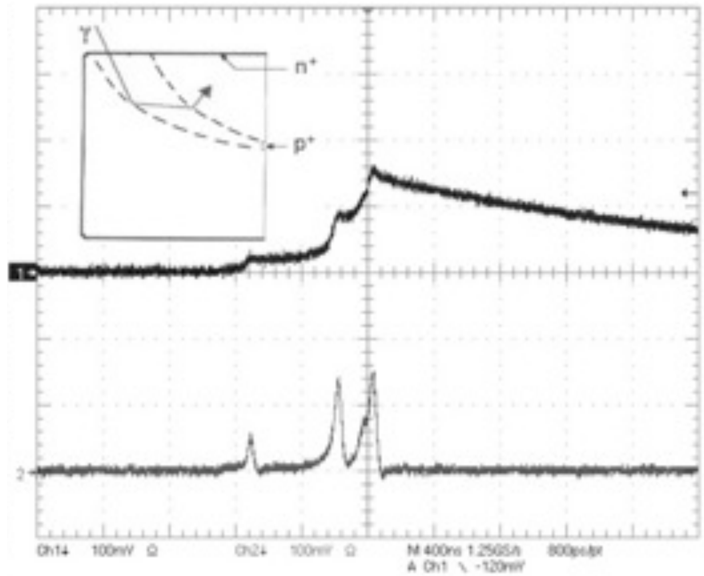
P-type Point Contact Detectors



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

Hole vdrift (mm/ns) w/ paths, isochrones





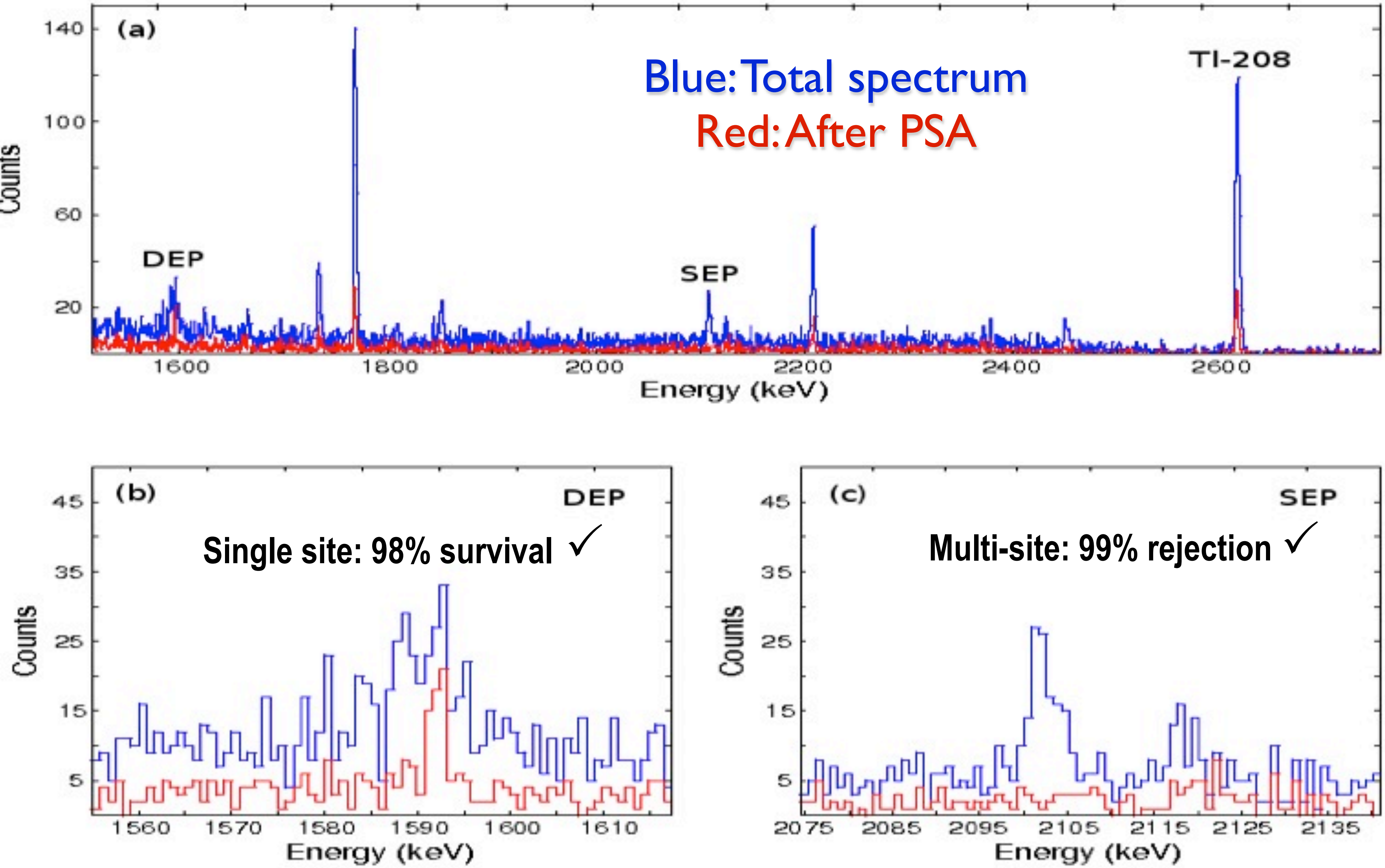
MAJORANA Point Contact Detectors

Institution	Manufacturer	Dimensions Dia. x length [mm x mm]	Type	Date
LBNL	Paul Luke	50 x 50 62 x 50 20 x 10 62 x 50	NPC S-PPC Mini-PPCs (3) PPC	1987 2008 2009 2009
Univ. Chicago	Canberra France Canberra USA	50 x 44 60 x 30	PPC (now BEGe)* BEGe	2005 2008
PNNL	Canberra France	50 x 50	PPC	2008
ORNL	PHDs Canberra USA	62 x 46 90 x 30	PPC BEGe (large)	2008 2009
LANL	PHDs Canberra USA ORTEC	72 x 37 70 x 30 65 x 50	PPC BEGe (x18) PPC	2008 2009 2009
UNC	Canberra USA	61 x 30	BEGe*	2009

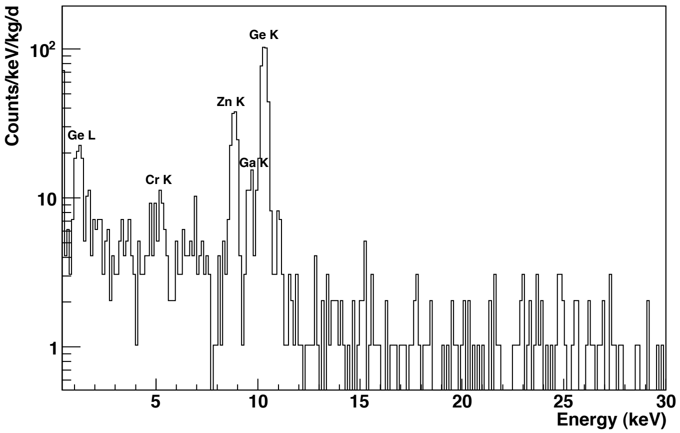
* ultra low background cryostat

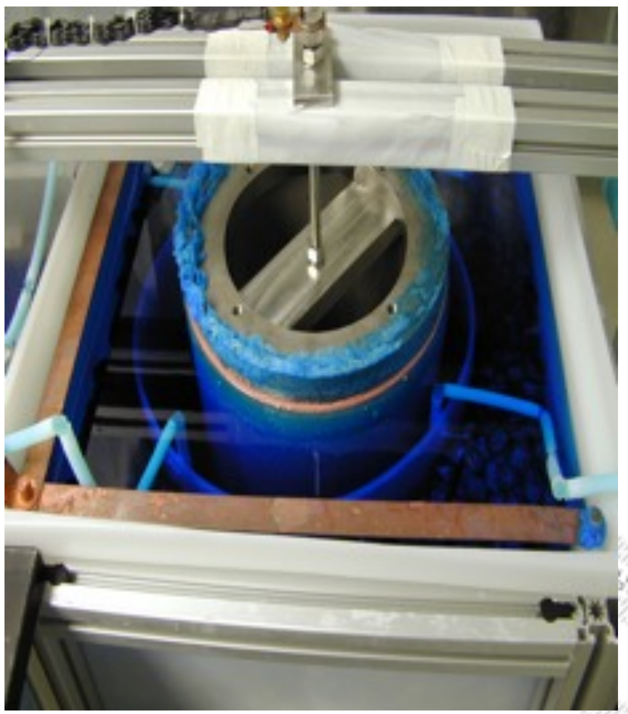
Pulse Shape Analysis

Large BEGe detector, loaned to ORNL from Canberra   *ORNL Pulse-Shape Analysis algorithm*

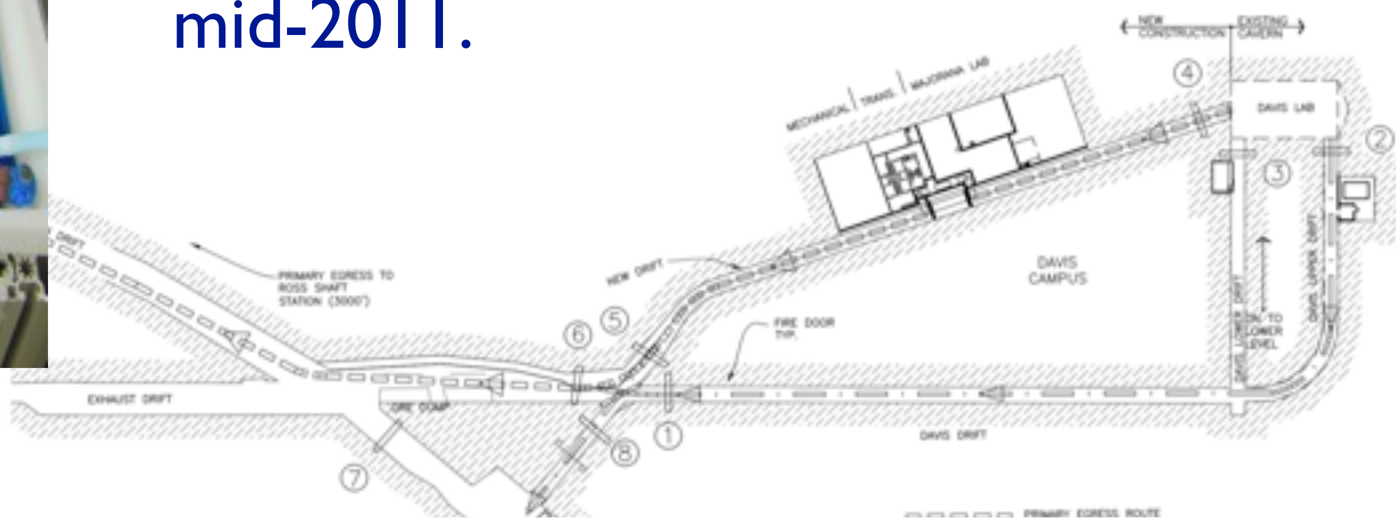


MAJORANA DEMONSTRATOR Status





- Under construction.
  - Detector Technology: P-type, point-contact.
  - 30-kg of ^{nat}Ge (10 kg (18 detectors) in-hand, additional 10 kg on order)
  - 30-kg of 86% enriched 76Ge crystals
  - Background Goal in the 0νββ peak region of interest (4 keV at 2039 keV)
    ~ 3 count/ROI/t-y (after analysis cuts)
- Preparing to start UG electroforming.
- Aim to commission first 20 kg module by mid-2011.



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.
- Further confirmation : more difficult
  - Observe the two-electron nature of the event
  - Measure kinematic dist. (energy sharing, opening angle)
  - Observe the daughter
  - Observe the excited state decay(s)
- Convincing
  - Observe 0νββ in several different isotopes, using a variety of experimental techniques

Determination of ν mass from $0\nu\beta\beta$

- Observe $0\nu\beta\beta$ in 3-4 different isotopes, using a variety of experimental techniques.
- Nuclear matrix elements "known" to the 20% level
  - Agreement between different calculation techniques?
  - Consistent with NME related predictions for other observables in the same and nearby nuclei (β-decay, EC, excited states).
- Consistent $0\nu\beta\beta$ results for the assumed LNV interaction and the NMEs.
  - Determination of LNV from independent measurements? (e.g. nEDM, exotic decays, ...)