Next-generation ^{76}Ge neutrinoless double beta-decay experiments

GERDA


Majorana

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Acknowledgments:
Stefan Schönert, MPIK Heidelberg, Jason Detwiler, CENPA
The GERDA Collaboration, The Majorana Collaboration,

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NNN06, Sept. 21, 2006
Seattle, Washington

Using ^{76}Ge to search for $0\nu\beta\beta$

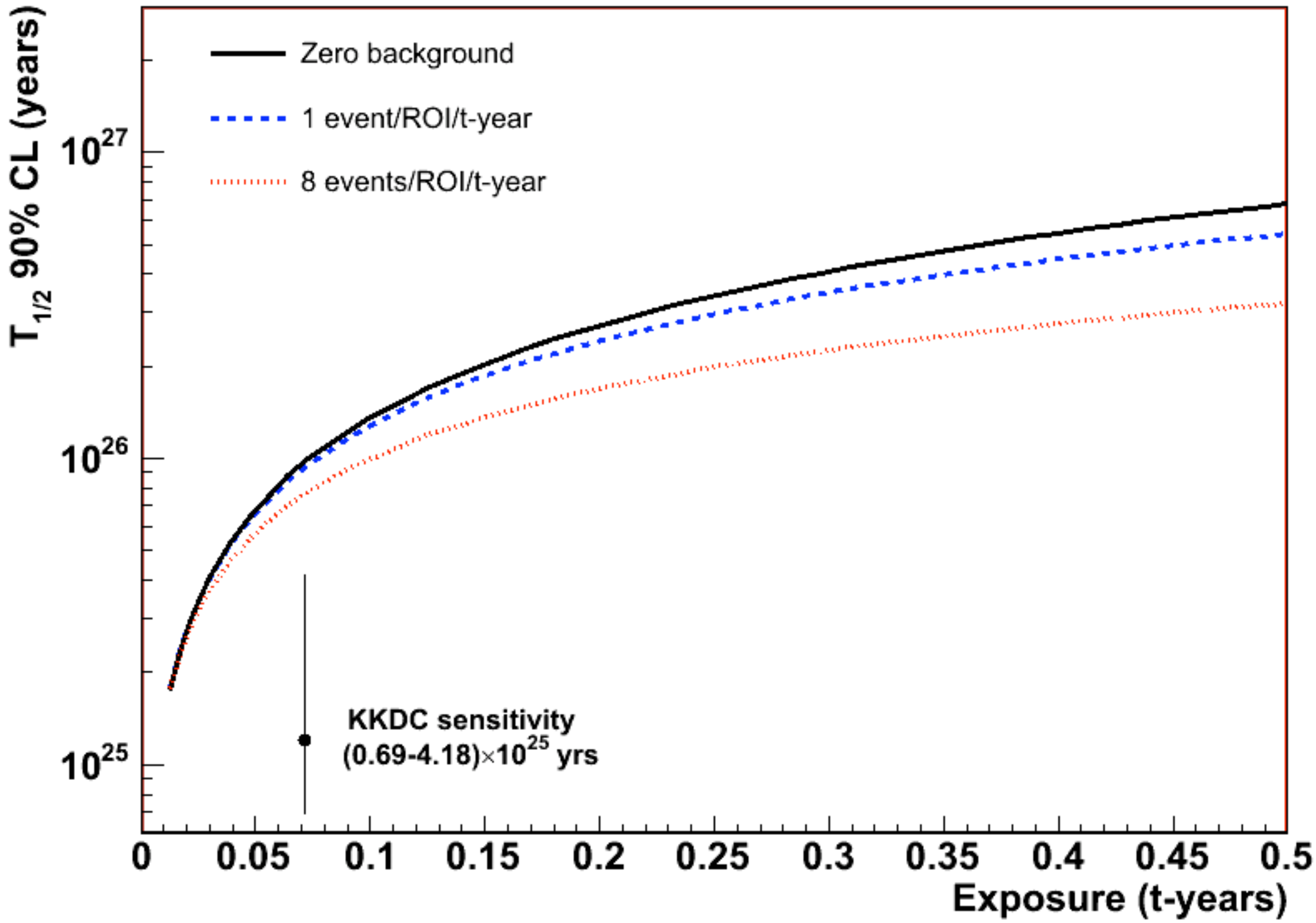
^{76}Ge offers an excellent combination of capabilities and sensitivities.

- Ge as source & detector.
- Elemental Ge maximizes the source-to-total mass ratio.
- Intrinsic high-purity Ge diodes.
- Favorable nuclear matrix element $|M^{0\nu}|=2.5$ [Rod06].
- Reasonably slow $2\nu\beta\beta$ rate ($T_{1/2} = 1.4 \times 10^{21}$ y).
- Demonstrated ability to enrich from 7.44% to ≥ 86%.
- Excellent energy resolution — 0.16% at 2.039 MeV, 4 keV ROI
- 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 (90%CL)
- Well-understood technologies
  - Commercial HPGe diodes
  - Large Ge arrays (Gammasphere, TIGRESS, AGATA, GRETINA)

^{76}Ge Sensitivity & Background Dependence

$$T_{1/2} = \frac{\ln(2)\cdot \varepsilon ff \cdot atoms \cdot time}{decays} \propto \frac{1}{< m_\nu >^2}$$

Limiting case of no obs. decays $T_{1/2} > \dfrac{\ln(2)\cdot \varepsilon ff \cdot atoms \cdot time}{\sqrt{\int B_i(t)\cdot dt}}$



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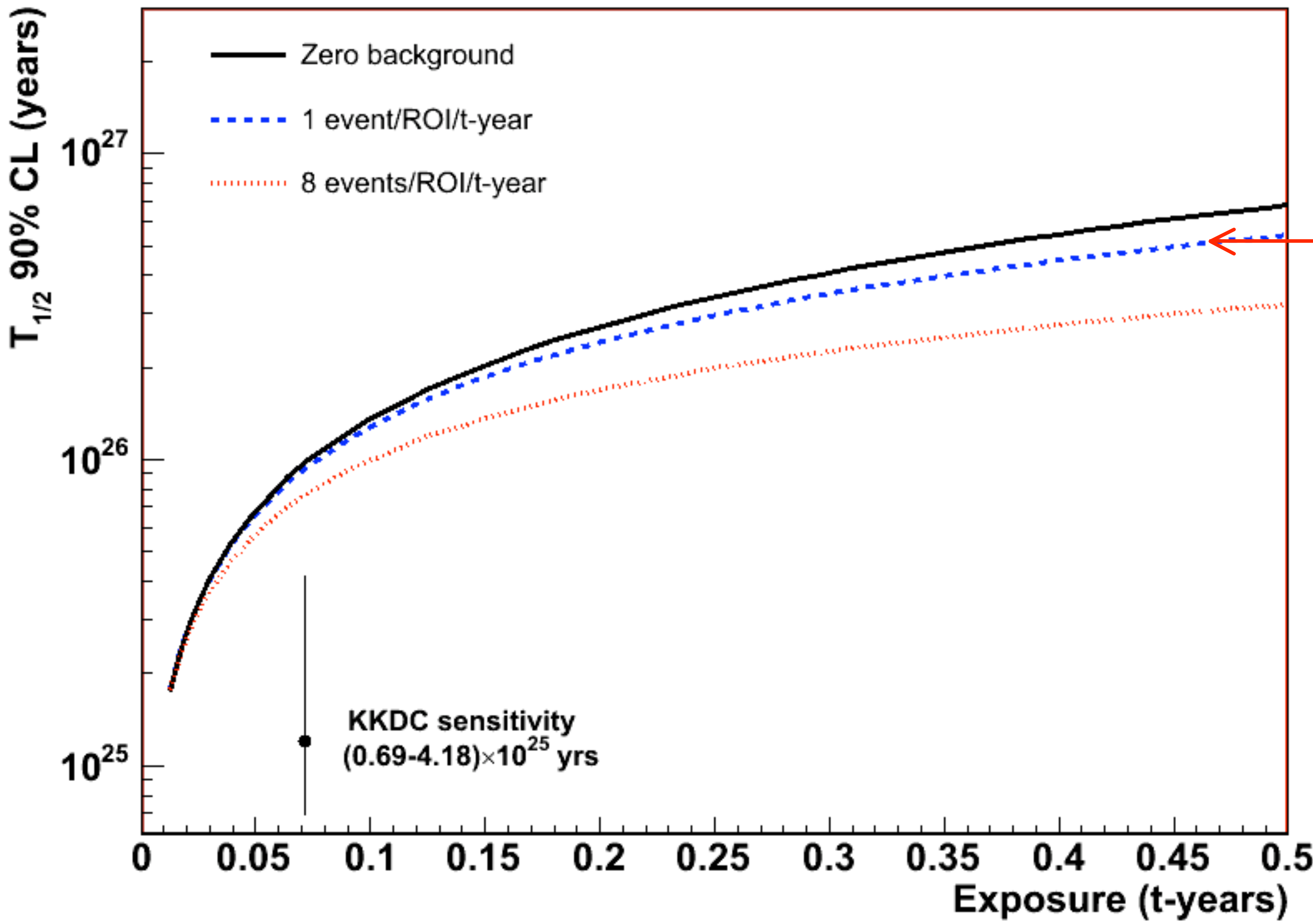


$<m_\nu>$ of 100 meV [Rod06]

Nuclear Matrix Elements and 0νββ-decay

$$\left[T_{1/2}^{0\nu}\right]^{-1} = G^{0\nu}(E_0, Z)\,|\langle m_\nu\rangle|^2 \left|M_f^{0\nu} - (g_A/g_V)^2 M_{GT}^{0\nu}\right|^2$$

- If neutrinos are Majorana particles, extracting the effective neutrino mass requires an understanding of the nuclear matrix elements (NME) at about the 20% theoretical uncertainty level.
  - For ^{76}Ge, a comparison of *previous* calculations yields a factor of 2-3 in predicted decay rates between Shell Model and RQRPA techniques or ~1.6 uncertainty in neutrino mass.
  - Using compilations or averages of previous sequential calculations should not be used to estimate theoretical uncertainties.

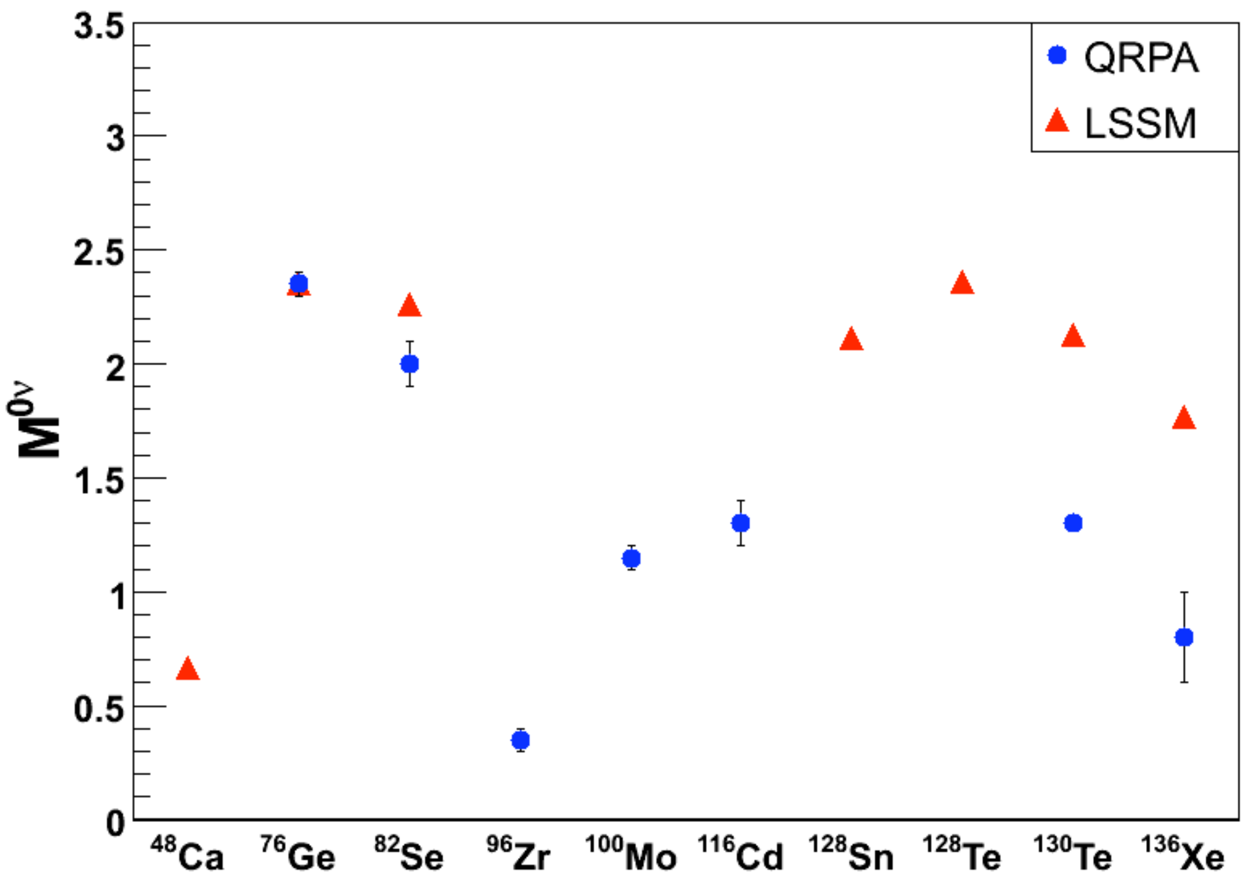
Recent Progress in NME Calculations

- QRPA
  - Rodin, Faessler, Simkovic, and Vogel used measured values of $2\nu\beta\beta$ to adjust g_{pp} resulting in “stable” $0\nu\beta\beta$ prediction.
    - Inclusion of short-range repulsion enhances NME by ~30%
    - Induced pseudeoscalar current reduces NME by ~30%
  - Have found that semi-magic nuclei (^{48}Ca, ^{116}Sn, ^{136}Xe) are very sensitive to pairing treatment.
  - Rodin has been investigating including more states and developing a Continuum-QRPA. This tends to quench the NME for $0\nu\beta\beta$ by 20-30%.

- Shell Model (Caurier, Nowacki, & Poves)
  - Advances with algorithms, “Large Scale Shell Model” (LSSM) can deal with a basis space containing 10^{11} Slater determinants.
  - Recent “hypothetical” studies indicate $0\nu\beta\beta$ is relatively insensitive spin-orbit partner effects when compared to $2\nu\beta\beta$.
  - Find a different multipole structure for 1+ contribution that is often the opposite sign from RQRPA.
  - Starting to investigate the 2p-2h excitations.

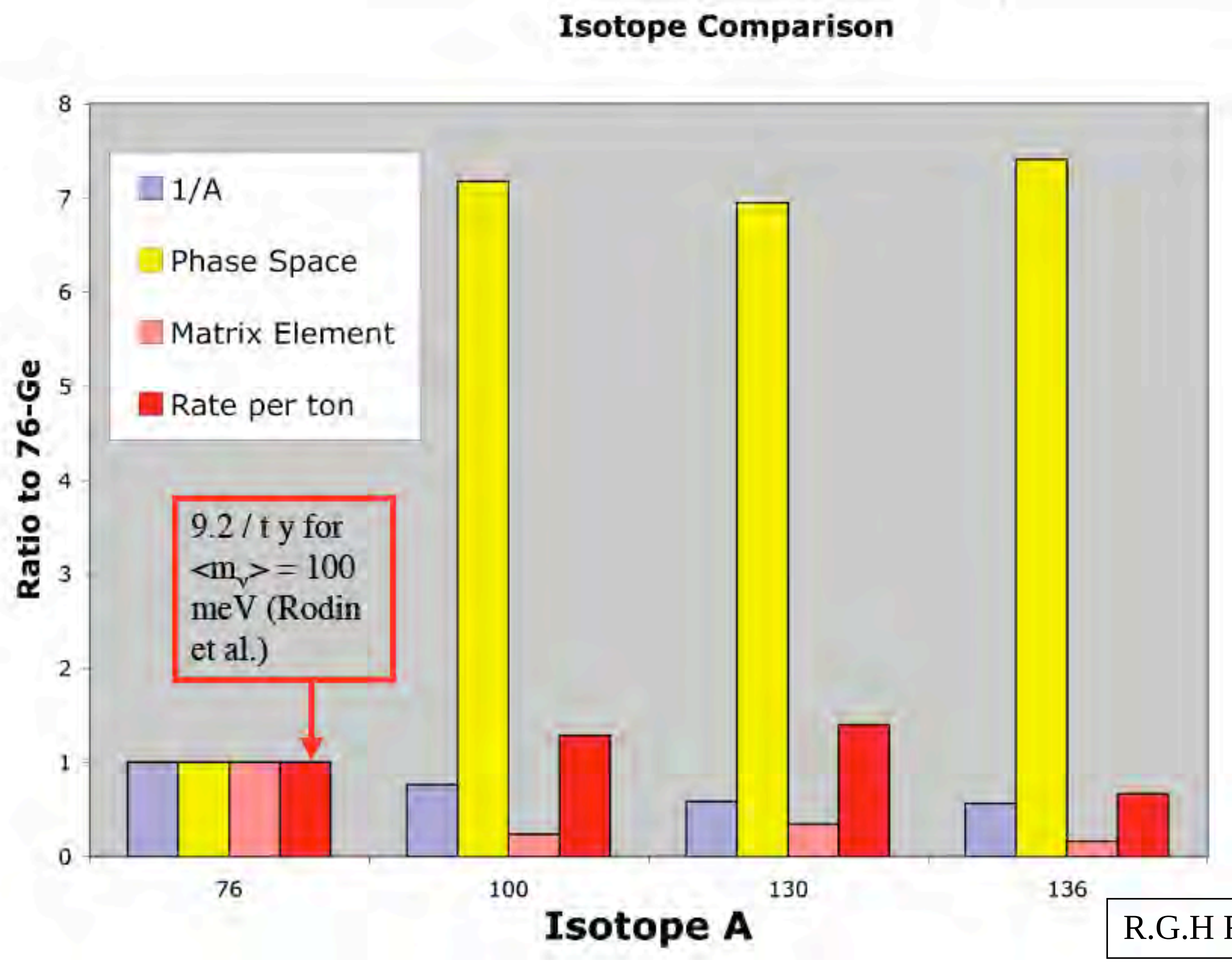
NME Comparison of QRPA and SM

QRPA: Nucl. Phys. A, **766** 107 (2006)
LSSM: From Poves NDM06 talk (Caurier, Nowacki, Poves),



"Relative" Sensitivities

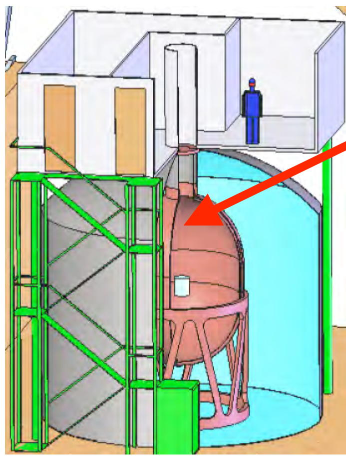
Using Rodin et al. Nucl. Matrix elements



R.G.H Robertson

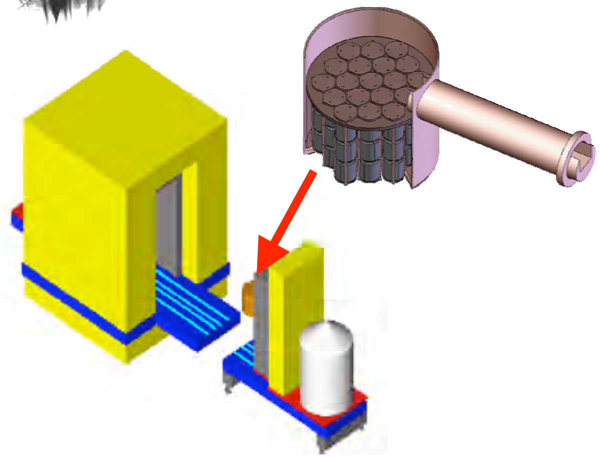
Next-generation ^{76}Ge Projects:

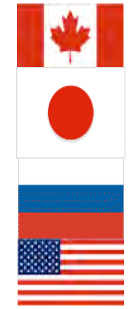
GERDA



- 'Bare' ^{enr}Ge array in liquid argon (nitrogen)
- Shield: high-purity liquid Argon (N) / H_2O
- Phase I: ~18 kg (HdM/IGEX diodes)
- Phase II: add ~20 kg new enr. detectors
  total ~40 kg

Majorana



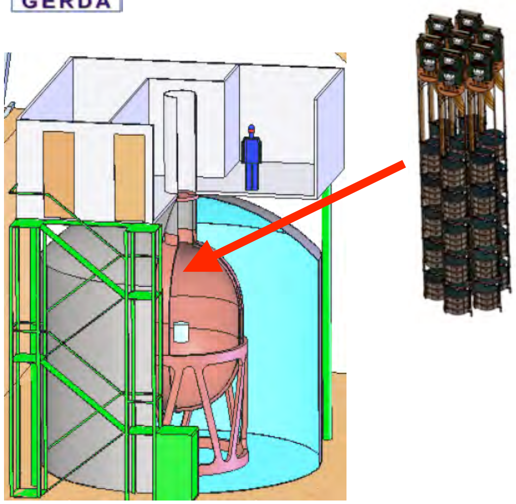


- Modules of ^{enr}Ge housed in high-purity electroformed copper cryostat
- Shield: electroformed copper / lead
- Staged approach based on ~20-60 kg modules (120 kg)

Physics goals:
- probe degenerate mass range;
- test KKDC result;
- study bgds. and exp. techniques required for large 1 ton scale experiment

Next-generation ^{76}Ge Projects:

GERDA



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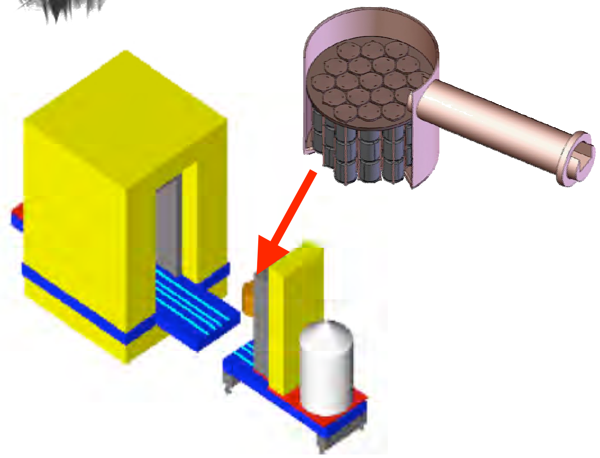
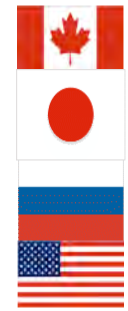




Physics goals:
- probe degenerate mass range;
- test KKDC result;
- study bgds. and exp. techniques required for large 1 ton scale experiment

Cooperative Agreement:
- open exchange of knowledge & technologies (e.g. MaGe MC)
- consider merging for O(1 ton) exp. (inv. Hierarchy) Select best techniques developed and tested in GERDA and Majorana

The KKDC Result

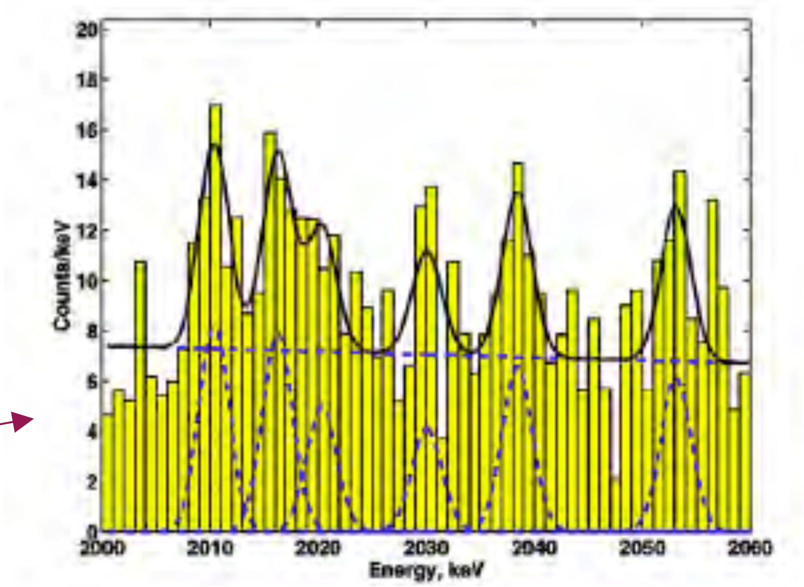
Klapdor-Kleingrothaus H V, Krivosheina I V, Dietz A and Chkvorets O, *Phys. Lett.* B **586** 198 (2004).

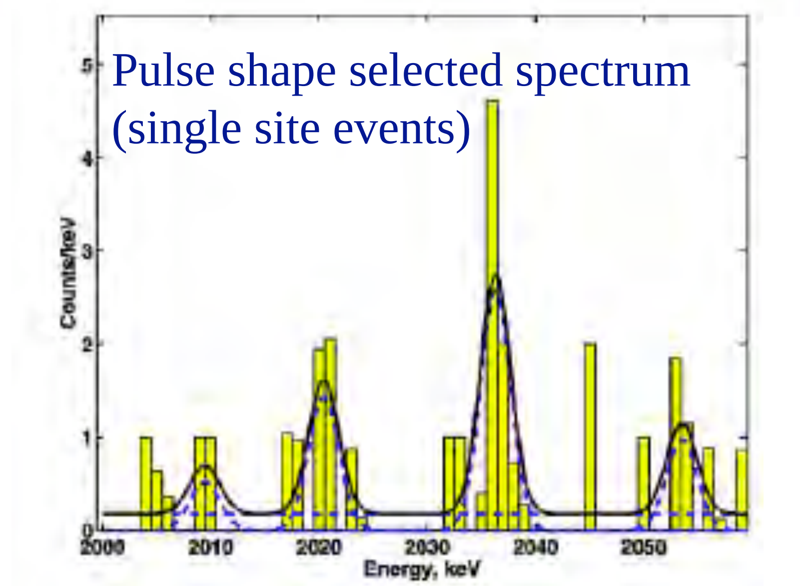
Best result - 5 ^{76}Ge crystals, 10.96 kg of mass, 71 kg-years of data.

$T_{1/2}$ = (1.19 +2.99/-0.5) x 10^{25} y
0.24 < m_ν < 0.58 eV (3 σ)

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) x 10^{25} y





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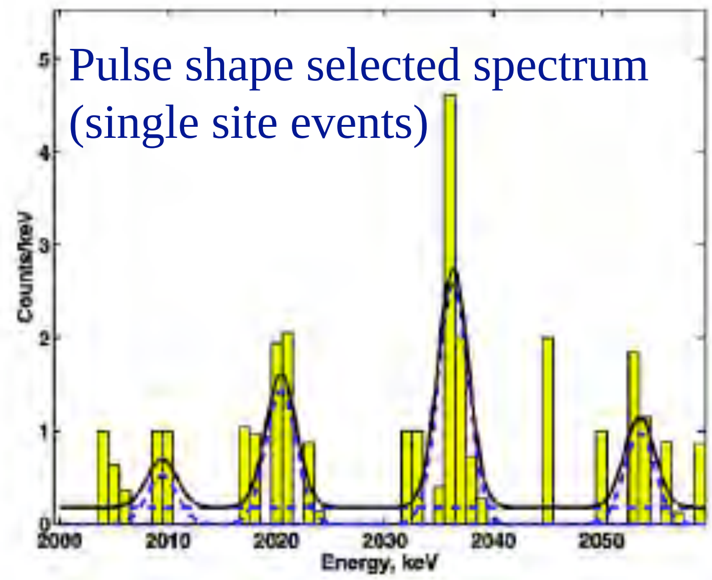
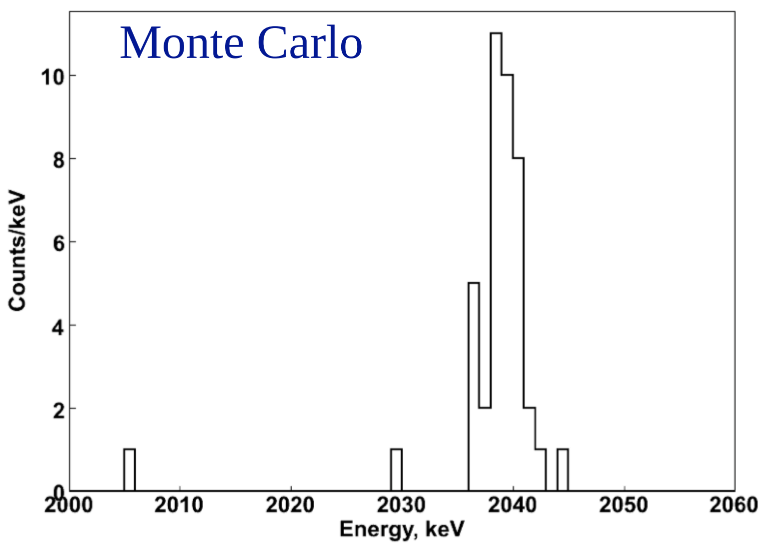


Projected signal in Majorana
After cuts (for 0.15 t-y)

45 counts

With a background of 0.2 events in ROI



Backgrounds!

- Sensitivity to $0\nu\beta\beta$ decay is ultimately limited by S-to-B.
  – Goal: ~ 60 - 150 times lower background (after analysis cuts) than previous ^{76}Ge experiments (H-M and IGEX).
- Approach
  – Optimize the detector energy resolution (HPGe)
  – Shield the detector from external natural and cosmogenic sources
  – Ultra-pure materials used in proximity to the crystals
    - electroformed Cu, LAr, clean low-mass support structures,
    - development of ultra-senstive ICPMS methods for materials assay
  – Discriminate between single site ($\beta\beta$-decay) vs. multi-site events
    - Granularity (close-packed crystal arrays)
    - Segmentation (segmented electrodes on individual crystals)
    - Pulse shape analysis
  – Time correlation analysis

Comparison of Background Goals

Expt	Isotope	Backgrounds (after cuts) cnt/kev/t-y	Backgrounds (after cuts) cnt/ROI/t-y	2.8s "ROI" width (keV)	Sigma (keV)	Eo (keV)	Res. At the peak (FWHM)
KKDC	^{76}Ge	60.00	240.00	4	1.386	2039	0.16%
EXO200	^{136}Xe	1.1	87.5	79.2	39.616	2476	3.77%
CUORE	^{130}Te	1	7	7	2.5	2533	0.20%
GERDA	^{76}Ge	1	4	4	1.386	2039	0.16%
Majorana	^{76}Ge	0.4	1.6	4	1.386	2039	0.16%

Notes:

KKDC - backgrounds BEFORE cuts is 113.00 cnt/kev/t-y from Physics Letters B 586 (2004) 198–212

KKDC - backgrounds after cuts come from Eur. Phys. J. **A 12**, 147–154 (2001). The data set included 35.5 kg y and the background index in the energy region between 2000– 2080 keV is (0.06±0.01) events/(kg y keV)

EXO gives resolution in sigma/E of 1.6%

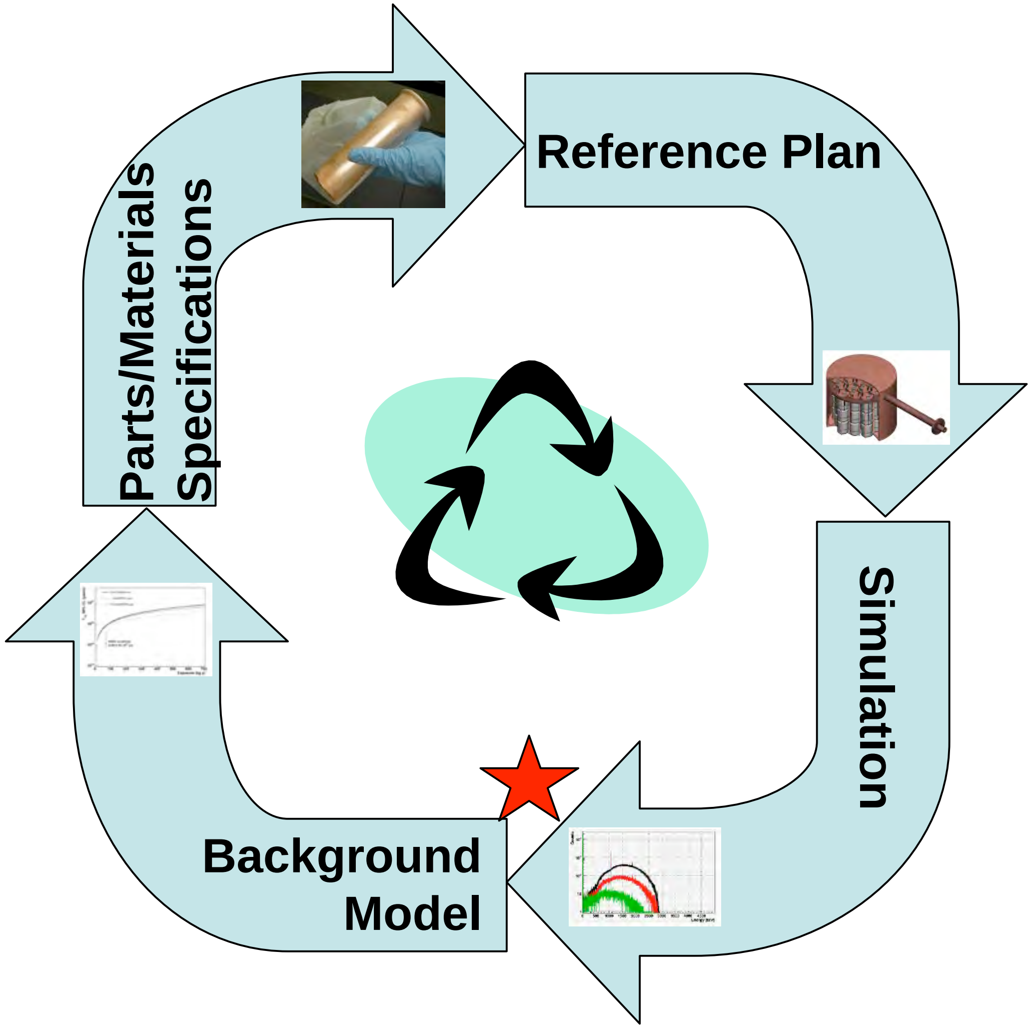
CUORE gives sigma value of 2.5 (larger than calculated from their typical resolution, 2.15)

Ultra-pure materials - Majorana Example

Table 4.1: Component material radioactivity goals for the major contributors to backgrounds in the $0\nu\beta\beta$ - decay region of interest. Note that the column Equivalent Achieved Assay specifies the goal for the component's activity in ^{208}Tl to the measured quantity of ^{232}Th. An activity of ^{208}Tl of 0.3 μBq/kg would correspond to an activity of ^{232}Th of 1.0 μBq/kg. We have focused on the Th contamination levels, since it has the more complex chemistry and hence is more difficult to remove.

Location	Purity Issue	Exposure	Activation Rate	Equiv. Achieved Assay	Reference
Germanium	^{68}Ge, ^{60}Co	100 d	1 atom/kg/day		[Avi92]
		Component Mass	**Target Purity**		
Inner Mount	^{208}Tl in Cu ^{214}Bi in Cu	2 kg	0.3 μBq/kg 1.0 μBq/kg	0.7-1.3 μBq/kg	Current work also [Arp02]
Cryostat	^{210}Tl in Cu ^{214}Bi in Cu	38 kg	0.1 μBq/kg 0.3 μBq/kg	0.7-1.3 μBq/kg	Current work also [Arp02]
Cu Shield	^{208}Tl in Cu ^{214}Bi in Cu	310 kg	0.1 μBq/kg 0.3 μBq/kg	0.7-1.3 μBq/kg	Current work also [Arp02]
Small Parts	^{208}Tl in Cu ^{214}Bi in Cu	1 g/crystal	30 μBq/kg 100 μBq/kg	1000 μBq/kg	

An iterative background model



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Background "budget" summary: Majorana Example

Background Source		Rates for Important Isotopes cnts/ROI/t-y				Total Est. Background cnts/ROI/t-y
		^{68}Ge	^{60}Co			
Germanium	Gross:	2.54	1.22			
	Net:	0.02	0.06			0.08
		^{208}Tl	^{214}Bi	^{60}Co		
Inner Mount	Gross:	0.12	0.03	0.26		
	Net:	0.01	0.00	0.00		0.01
Cryostat	Gross:	0.49	0.48	0.58		
	Net:	0.14	0.12	0.00		0.26
Copper Shield	Gross:	1.39	0.55	0.02		
	Net:	0.39	0.11	0.00		0.50
Small Parts	Gross:	0.45	0.68	0.34		
	Net:	0.05	0.17	0.00		0.22
Surface Alphas	All surfaces:					0.36
		muons	cosmic activity	gammas	(α, n)	
External Sources	Gross:	0.03	1.50	0.05	0.06	
	Net:	0.003	0.21	0.05	0.06	0.32
$2\nu\beta\beta$						<0.01
Solar ν						0.01
Atm. ν						0.02
		TOTAL SUM				1.75

Backgrounds!

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  - Goal: ~ 60 - 150 times lower background (after analysis cuts) than previous ^{76}Ge experiments (H-M and IGEX).
- Approach
  - Optimize the detector energy resolution (HPGe)
  - Shield the detector from external natural and cosmogenic sources
  - Ultra-pure materials used in proximity to the crystals
    - electroformed Cu, LAr, clean low-mass support structures,
    - development of ultra-senstive ICPMS methods for materials assay
  - Discriminate between single site ($\beta\beta$-decay) vs. multi-site events
    - Granularity (close-packed crystal arrays)
    - Segmentation (segmented electrodes on individual crystals)
    - Pulse shape analysis
  - Time correlation analysis

Techniques common to both GERDA & Majorana

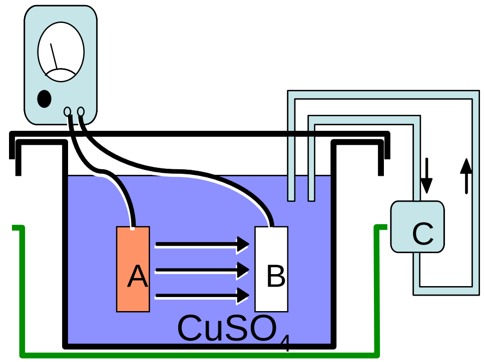
GERDA and Majorana Background Mitigation strategies

Source	Solution GERDA	Solution Majorana
γ's external to crystals from ^{208}Tl (^{232}Th), ^{214}Bi (^{226}Ra), ^{60}Co,…	Shield: high-purity liquid argon (nitrogen) / water shield	Shield: Electroformed copper, lead
Front-end electronics	ASIC (77/85° K)	Discrete low-level design
μ induced prompt signals	Underground location LNGS (3400 mwe); Water Cherenkov μ-veto	Underground location >4500 mwe; plastic scintillator μ-veto
μ induced delayed signals (e.g. n+^{76}Ge$\rightarrow$^{77}Ge $\xrightarrow[53s]{}$ ^{77}As	Low-Z material shield (Ar/water)	Combination low and high-Z shield: Deep underground location >4500 mwe
Internal to crystal: cosm. ^{60}Co ($t_{1/2}$= 5.27 y)	Minimize time above ground after crystal growing (30d$\rightarrow$ $2.5\cdot10^{-3}$ cts/(keV kg y)	same
Internal to crystal: cosm. ^{68}Ge ($t_{1/2}$= 270 d)	Minimize time after end of enrichment; shielded transportation container (180d$\rightarrow$$12\cdot10^{-3}$ cts/(keV kg y)	same

Materials in close vicinity of Ge diodes

GERDA: bare diodes submerged in **high-purity liquid Ar (N)**

Majorana: diodes housed in vacuum cryostat made of **electroformed cupper**



Main isotopes of concern in shielding materials:

Goal/achieved: <1µBq/m³ (STP) ^{226}Rn (^{214}Bi) in LN and LAr

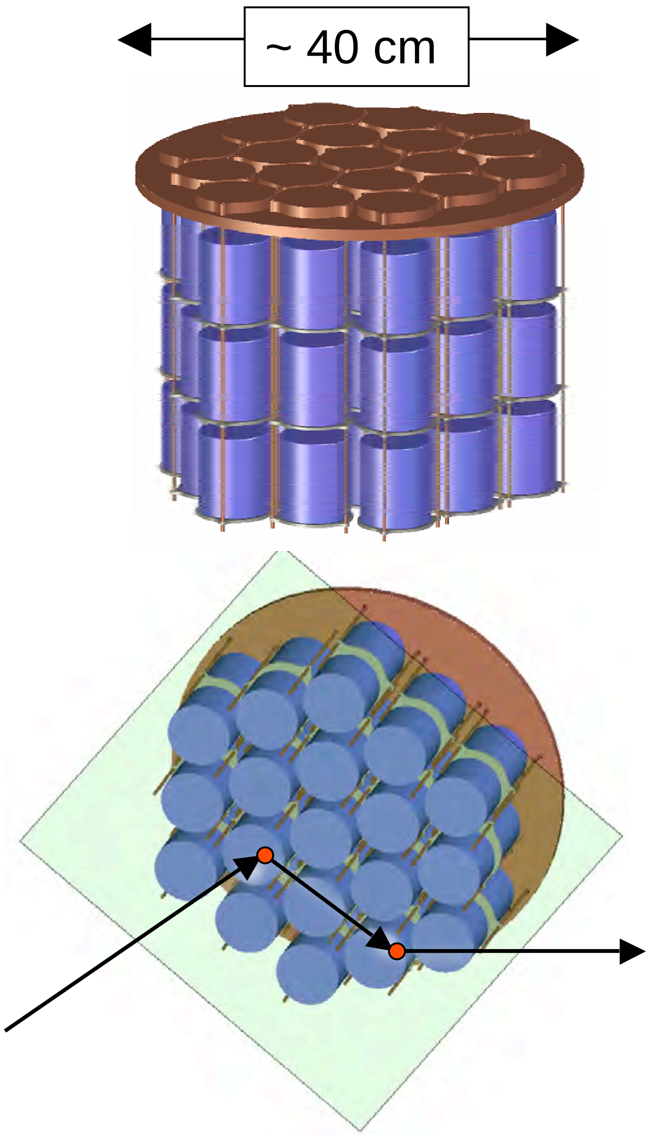
Goal: <0.3µBq/kg ^{208}Tl (<1 µBq/kg ^{232}Th)
Achieved: <2-4 µBq/kg ^{232}Th (ICPMS)

N.B.: shield design has impact on µ induced backgrounds

Low-Z shield ⇒LNGS 3400 mwe ok with water Cherenkov µ-veto

Low-Z/Pb/Cu shield & depth >4500 mwe ⇒ SNOlab or DUSEL

Background suppression: Granularity



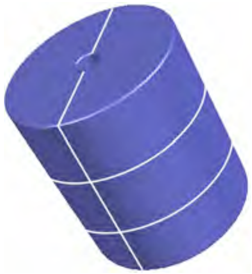
Granularity by close crystal packing

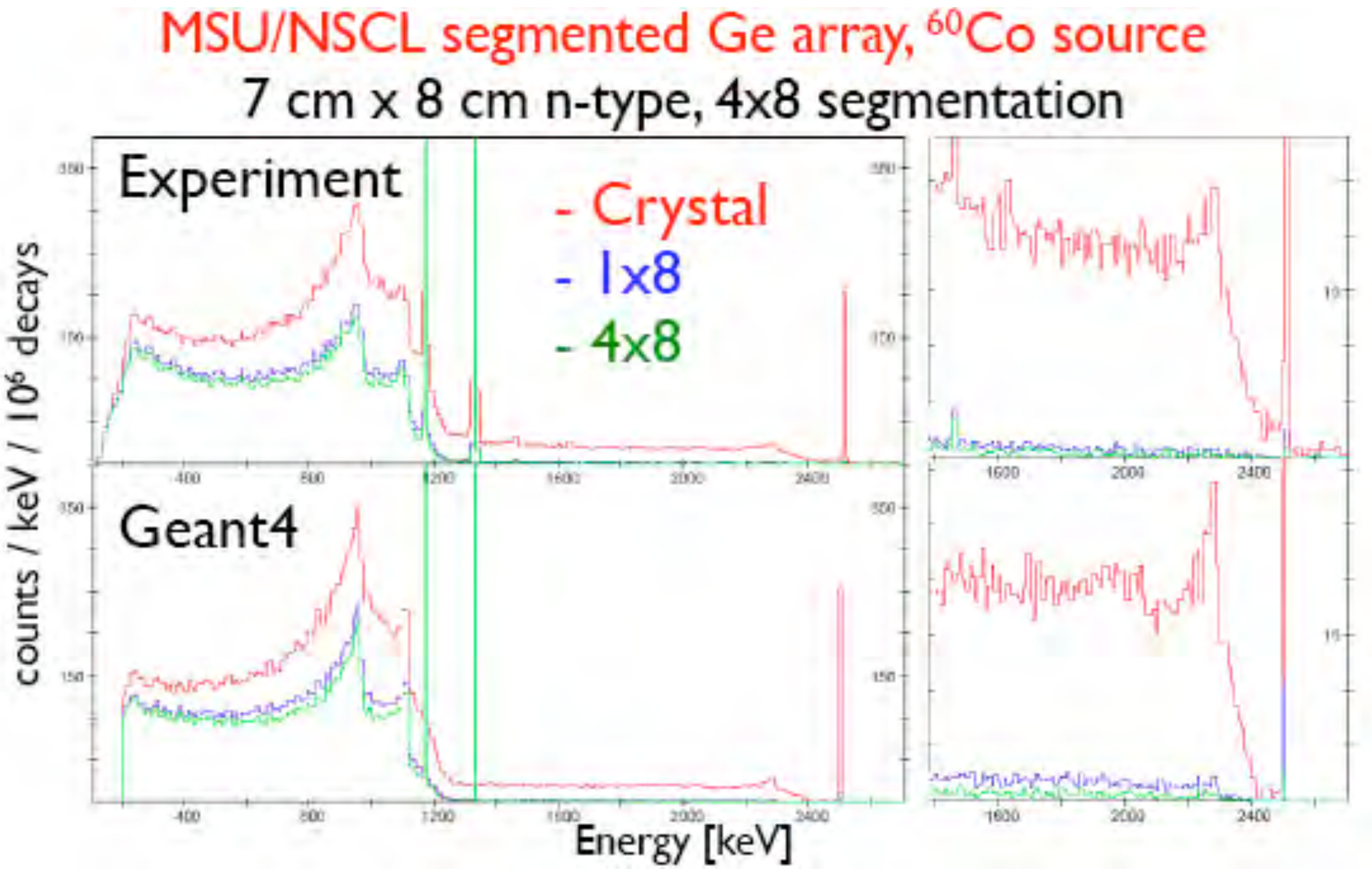
Simultaneous signals in two detectors cannot be $0\nu\beta\beta$

- Effective for:
  - High energy external γ's e.g. ^{208}Tl and ^{214}Bi
    - Supports/small parts (~5x)
    - Cryostat/shield (~2x)
  - Some neutrons
  - Muons (~10x)

Background suppression: Segmented Crystals

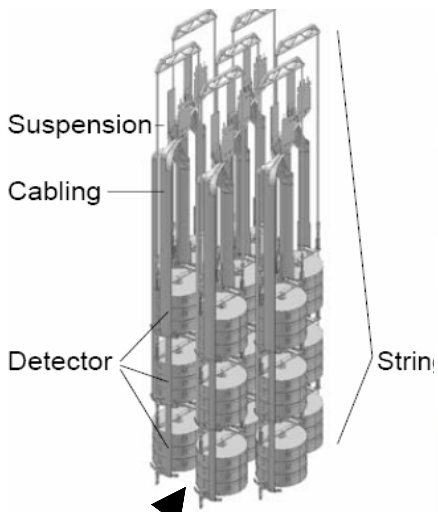
Discrimination of Multi Site Events (MSE) (e.g. Compton bgd.) from Single Site Events (SSE) (e.g. $0\nu\beta\beta$) by: **granularity of segmented crystals**

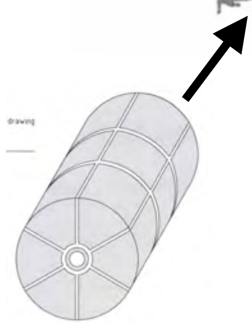




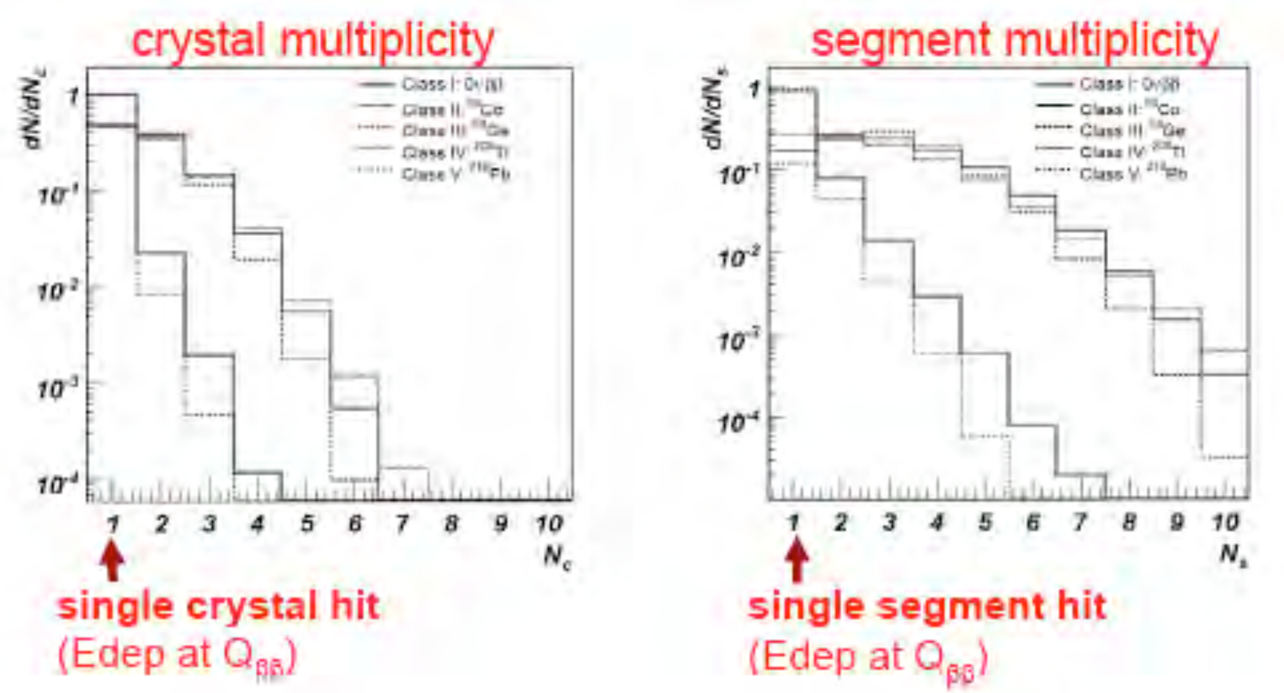
Background suppression: Granularity (crystals and segs.)

MC study (MaGe) of background suppression / $0\nu\beta\beta$ acceptance of GERDA array by **granularity cut**





GERDA array with 21 detectors with 6φ-3z segmentation

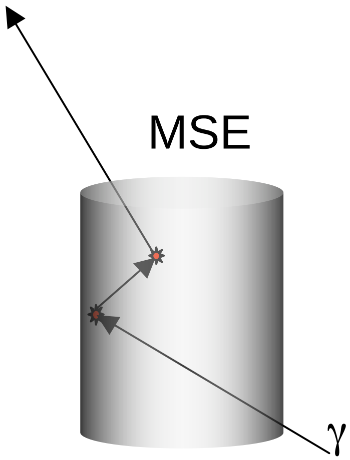


•$0\nu\beta\beta$ acceptance ~90% •Background suppression factors SF strongly dependent on: ⇒Isotope ⇒location	Range of suppression factors for single segment cut: ^{208}Tl: 3 – 13 ^{214}Bi: 6-13 ^{68}Ge: 18 (inside crystal) ^{60}Co: 38 - 157

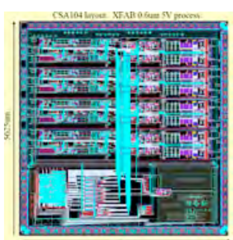
Similar results in Majorana study

Background suppression: PSA

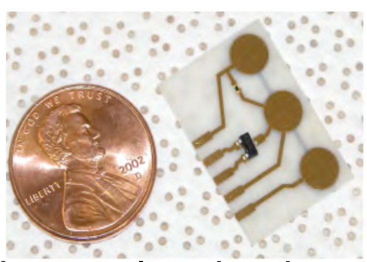
Discrimination of Multi Site Events (MSE) (e.g. Compton bgd.) from Single Site Events (SSE) (e.g. $0\nu\beta\beta$) by: **pulse shape analysis**



low-background FE electronics to be located close to diodes for high band width

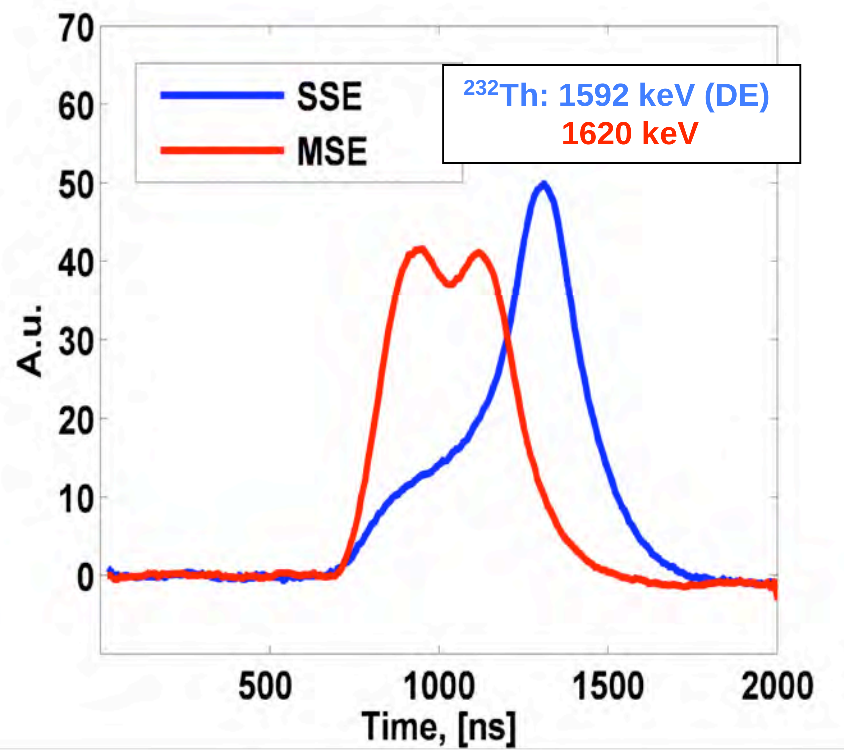


ASIC FE (GERDA); 'true co-axial' det.



Discrete low-background FE (Majorana)

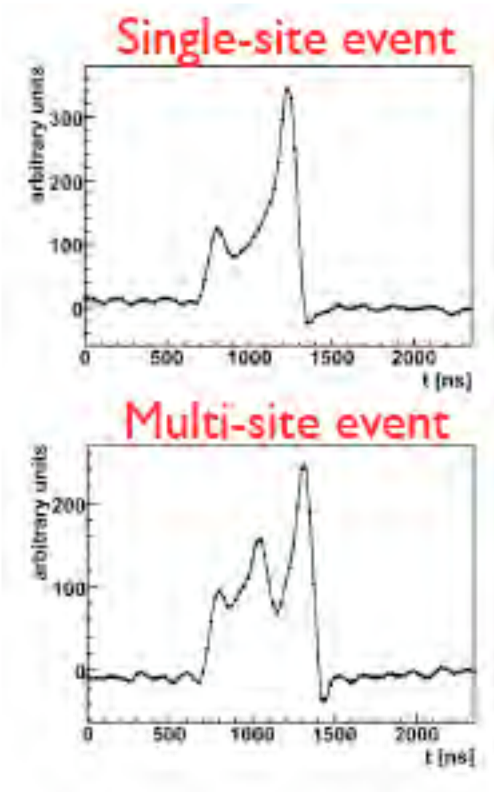
GERDA: ANG5 with old (slow) HdM FE



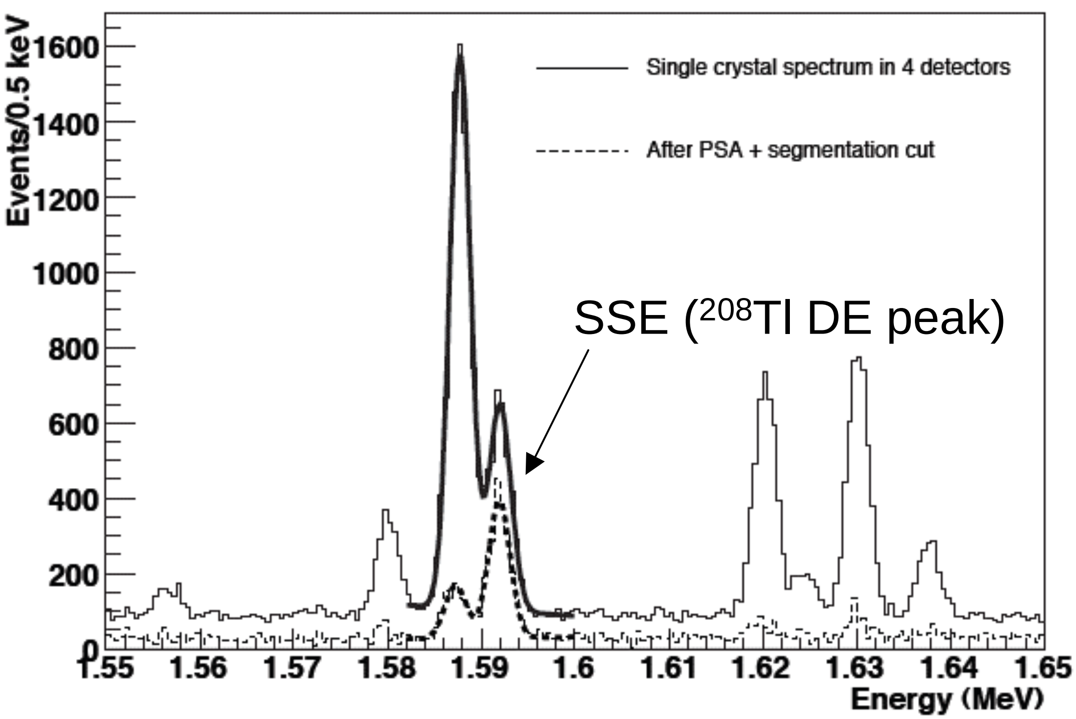
goal: effective MSE suppression with minimal loss of SSE's (i.e. $\beta\beta$ events)

Background suppression : Segmentation & PSA

Discrimination of Multi Site Events (MSE) (e.g. Compton bgd.) from Single Site Events (SSE) (e.g. $0\nu\beta\beta$) by: **segmented crystal AND pulse shape analysis**

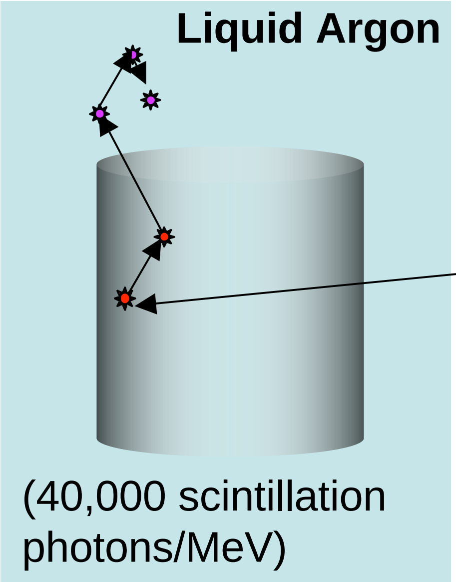


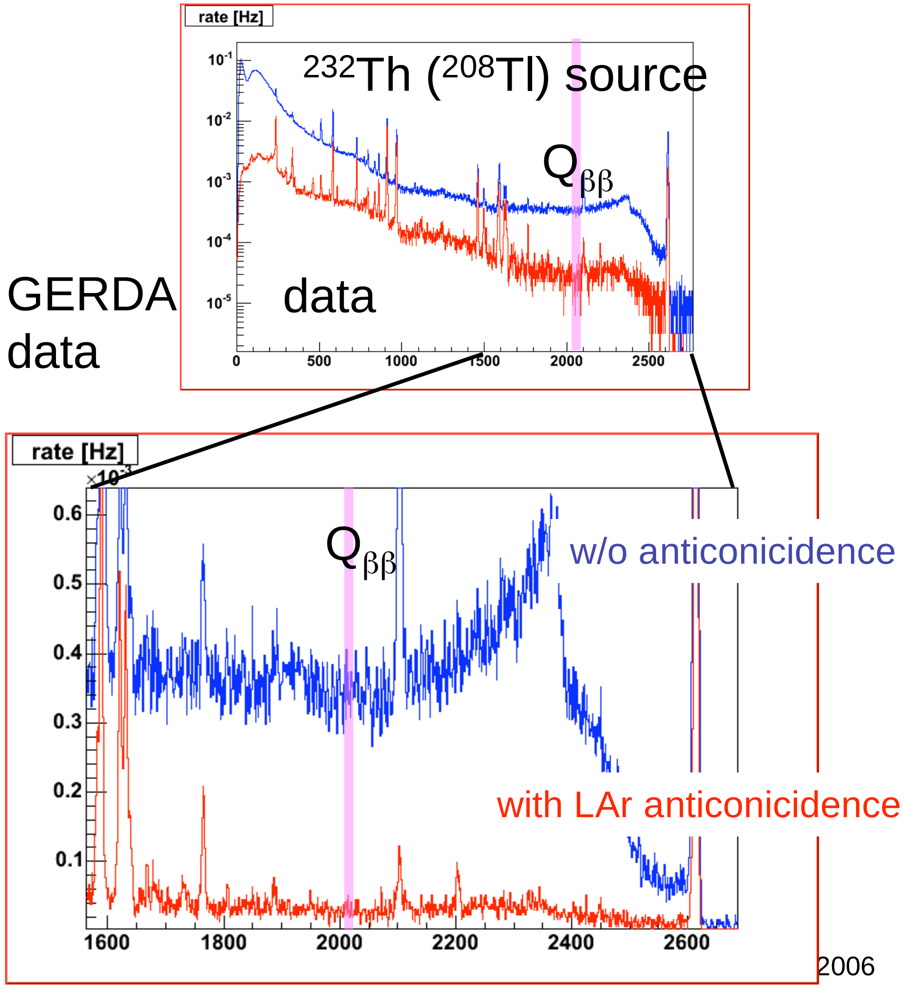
Majorana data:
Elliott et al. NIM A **558**, 504 (2006)



Background suppression: LAr (GERDA R&D)

Discrimination of Multi Site Events (MSE) (e.g. Compton bgd.) from Single Site Events (SSE) (e.g. $0\nu\beta\beta$) by: **liquid argon scintillation anti-coincidence (LArGe)**





- 20 cm diameter test setup
- Suppression factor (~20) limited by escape from setup

GERDA Progress and Status

- Approved by LNGS with location in Hall A
- Substantially funded by BMBF, INFN, MPG, and Russia in kind
- 18 kg of enriched detectors at LNGS – 37.5 kg of new enriched material stored underground
- Underground detector laboratory operational at LNGS
- Preparation for LNGS safety review of stainless steel cryostat
- LNGS Hall A under preparation for start of construction of main infrastructures in 2006

Majorana Progress and Status

- March 2006 external panel review of 120 kg detector
  - essentially ready for CD-1 review;
  - no major outstanding R&D issues
- Preparing for DOE NP Review that will be held in late Nov. or Dec. 2006
  - If successful will then be authorized to proceed through the DOE 413 CD-1 thru CD-3 process
- Exploring segmentation options
  - Highly segmented (6 by 6) or modest segmentation (2 x 3)
  - “modified electrode” detector (extremely good resolution)
- Will implement in a phased approach
  - Examining optimized cryostat module size 10 - 60 kg.
- Site: SNOlab or DUSEL (depth > 4500 mwe)

Summary

^{76}**Ge detector technology** provides intrinsic low-backgrounds, excellent resolution and powerful tools for background suppression and 0νββ event recognition

- GERDA & Majorana have different shield concepts, but common background reduction techniques
- **GERDA**
  - Funded; main infrastructure construction starting in 2006
  - **Phase I :** background 10 cts / (t·keV·y)
    - scrutinize KKDC result
  - **Phase II** : background 1 cts / (t·keV·y)
    - $T_{1/2} > 2 \cdot 10^{26}$ y , $<m_\nu> < 90 – 290$ meV
- **Majorana**
  - R&D funding; preparing for DOE Panel review
  - Staged approach based on 20-60 kg cryostat modules
    - background 0.4 cts / (t·keV·y)
  - 120 kg mss and 4.5 years, or 0.46 t-y of 76Ge exposure
    - $T_{1/2} >= 5.5 \times 10^{26}$ y (90% CL)
    - $<m_\nu> < 100$ meV (90% CL) ([Rod06] RQRPA matrix elements) or a 10-20% measurement assuming a 400 meV value.