Segmented HPGe Detectors for the Search of 0νββ Decay

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OUTLINE:

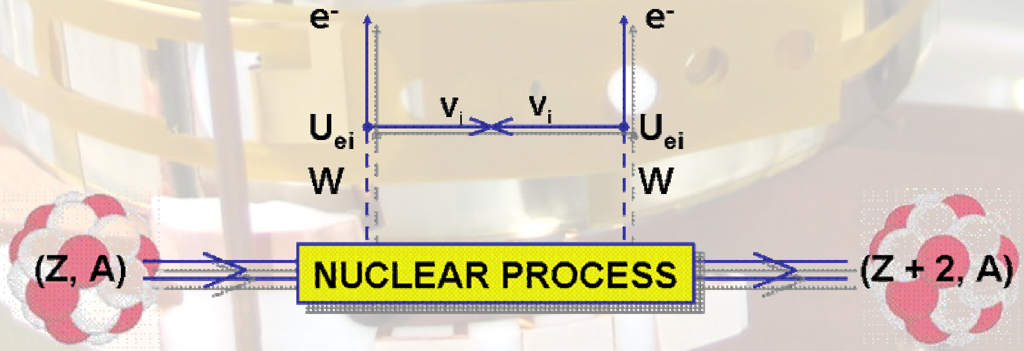
Motivation: Neutrino properties

Neutrinoless double beta-decay

0νββ with HPGe – present and future

Background reduction using event topologies

Segemented HPGe detectors



Motivation: Neutrino Properties

Massive neutrinos can mix just as quarks do if mass and flavor eigenstates are not identical:

Standard Model flavor states

Neutrino mass eigenstates

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Neutrino-oscillation experiments have taught us:

Neutrinos must have a mass!

But we have only measurements on the mass differences between the mass eigenstates.

Motivation: Neutrino Properties

We do not know the sign of Δm_{32}

→ Mass hierarchy is still unknown

We only have information on the squared mass difference between the eigenstates

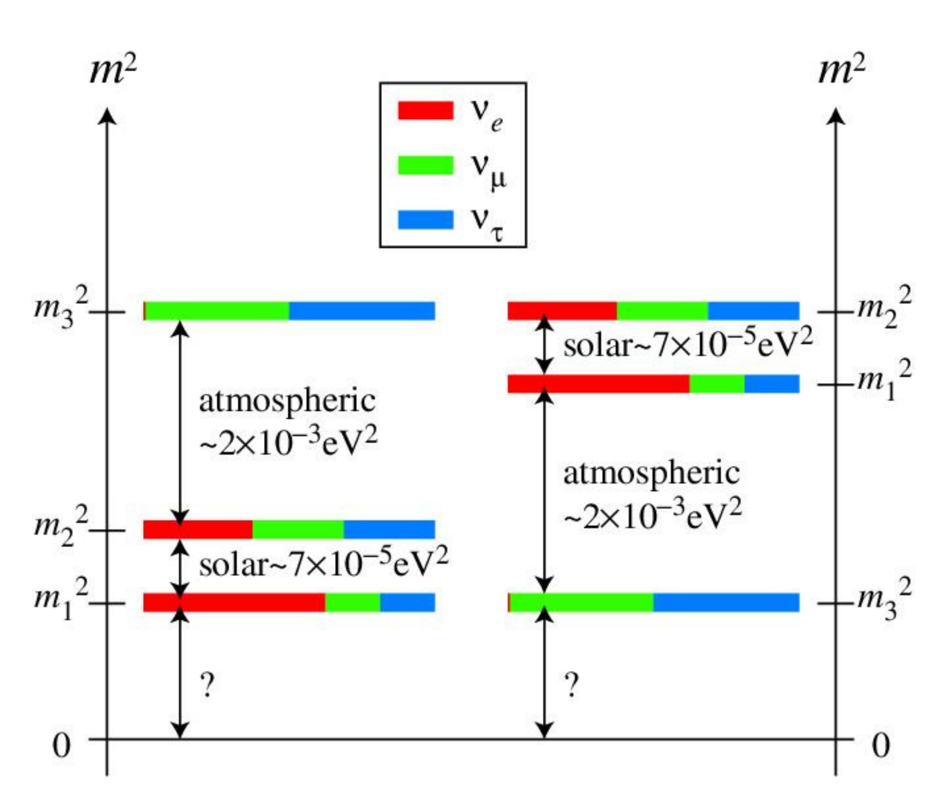
→Absolute mass scale still unknown

What kind of particle is the Neutrino?

→Majorana or Dirac?

Normal hierarchy $\Delta m_{32} > 0$ eV

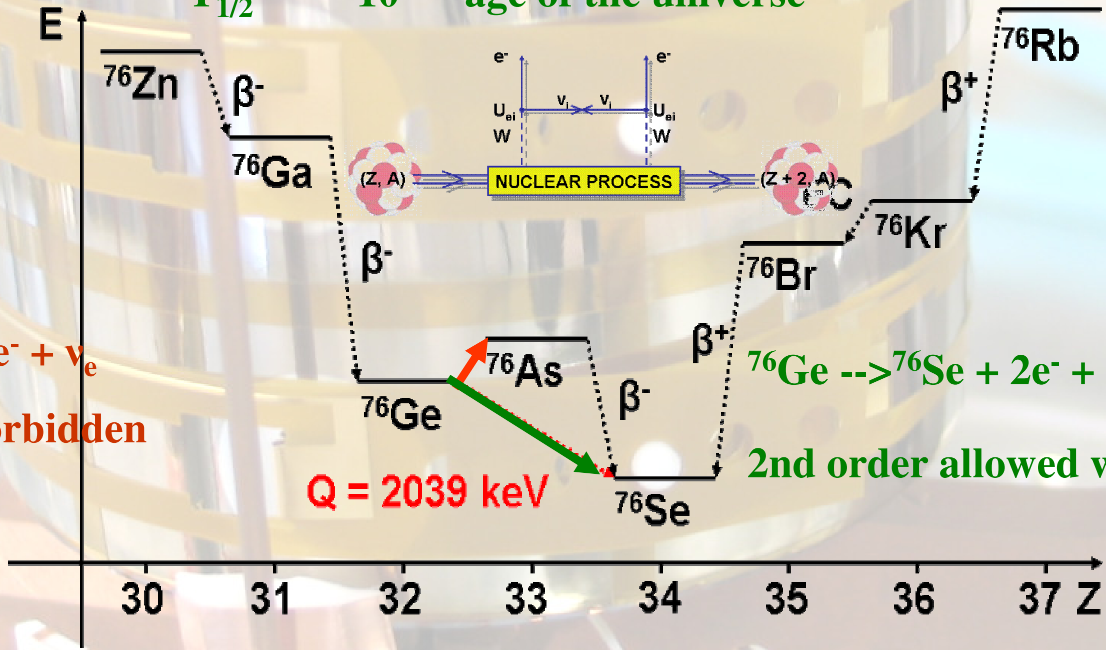
Inverted hierarchy $\Delta m_{32} < 0$ eV



Neutrinoless Double Beta-Decay

1. Initial state nucleus has to be bound less than final state nucleus, but stronger than intermediate.
2. Only possible in even-even nuclei.
3. 35 isotopes decay via 2νββ to stable nuclei.

$T_{1/2}^{2\nu\beta\beta} \sim 10^{10}$ • age of the universe



$^{76}Ge \rightarrow {}^{76}As + e^- + \nu_e$

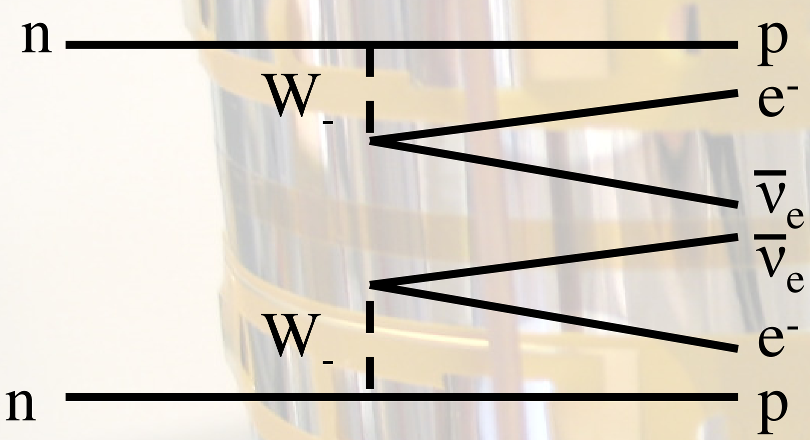
energetically forbidden

$^{76}Ge \rightarrow {}^{76}Se + 2e^- + 2\nu_e$

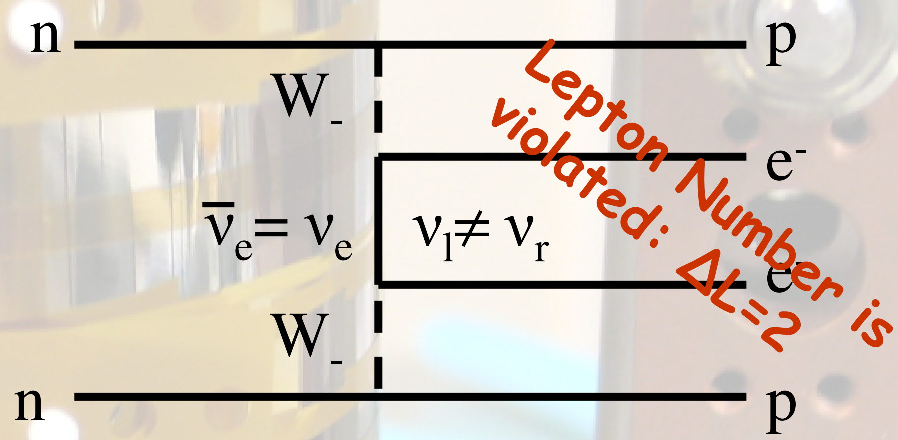
2nd order allowed weak process

Neutrinoless Double Beta-Decay

Neutrino accompanied Doubel-Beta Decay:



Neutrinoless Doubel-Beta Decay:



Neutrinoless mode of double beta decay can only occur if:

1. **Neutrino is identical with its antiparticle (Majorana particle)**
2. **Neutrino is massive (helicity flip required)**

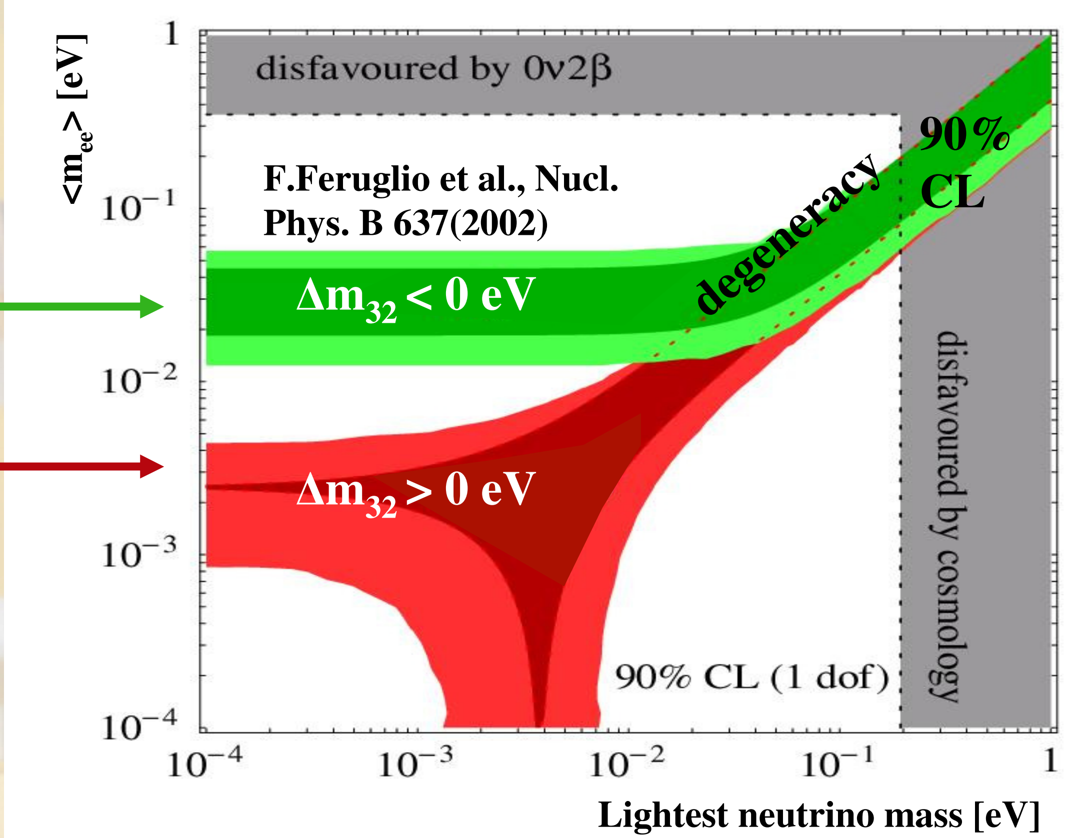
$$1/\tau = G(Q,Z)\,|M_{nucl}|^2\,\langle m_{ee}\rangle^2$$

0νββ Decay rate	**Phase space factor (~Q^5)**	**Matrix element**	**Effective Majorana Neutrino mass**

Neutrinoless Double Beta-Decay

Inverted hierarchy

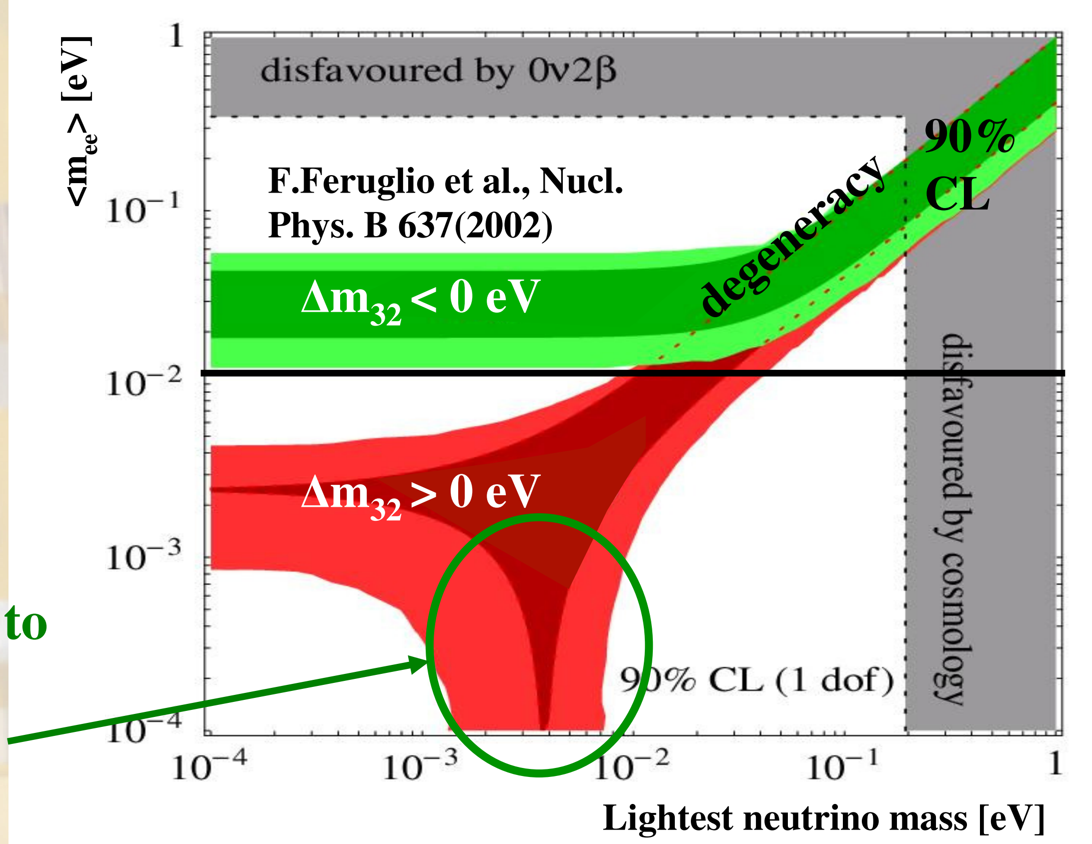
Normal hierarchy



Neutrinoless double-beta decay could solve the questions about hierarchy, absolute mass scale and nature (Dirac, Majorana) of neutrinos

Neutrinoless Double Beta-Decay

In order to discriminate between normal and inverted hierarchy, we need an experiment with sensitivity down to 10 meV !



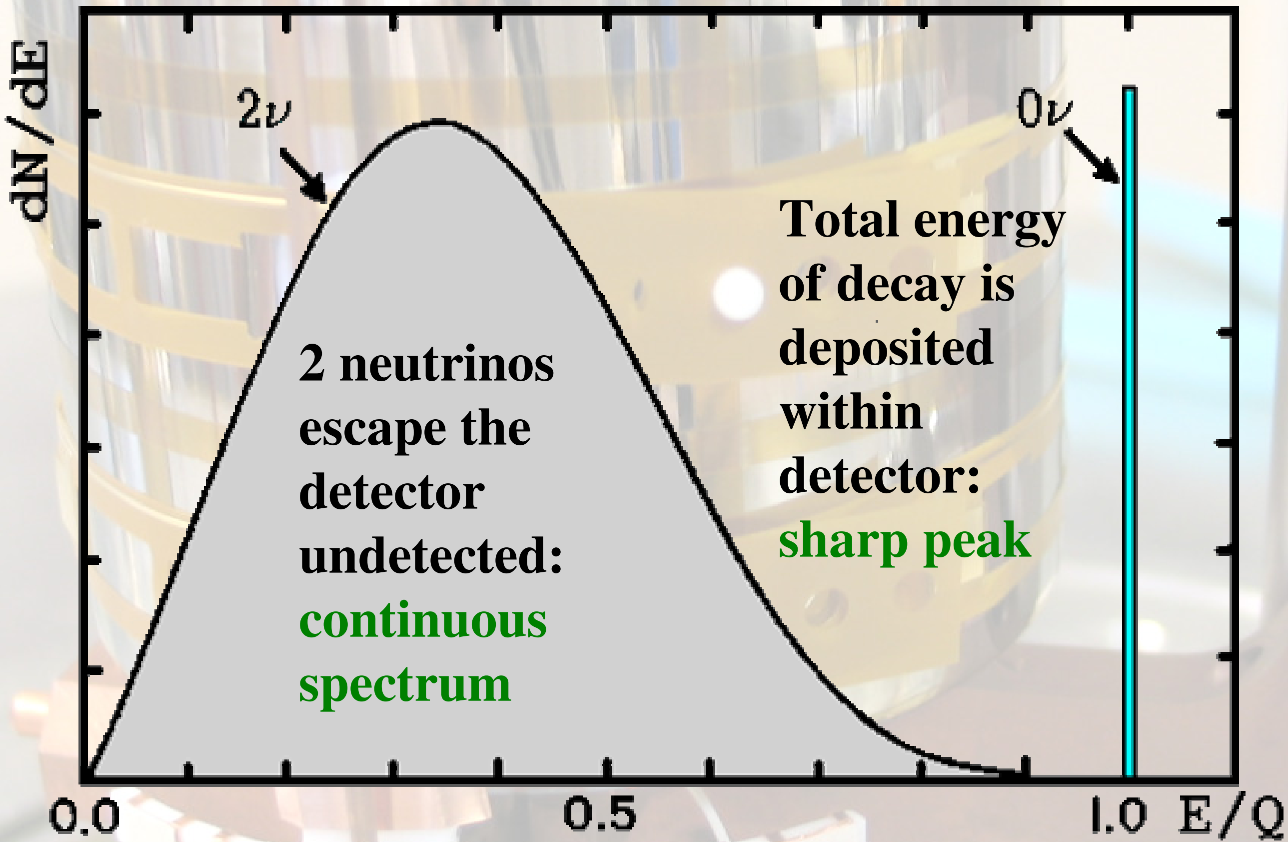
Complex phases can lead to cancellation of effective majorana neutrino mass

Neutrinoless double-beta decay could solve the questions about hierarchy, absolute mass scale and nature (Dirac, Majorana) of neutrinos

Neutrinoless Double Beta-Decay

Signature: Sharp peak at Q-value of the decay

(2039 *keV* for ^{76}Ge)



Neutrinoless Double Beta-Decay

The observable of neutrinoless double beta decay experiments is its half-life. $T_{1/2}^{0\nu\beta\beta} > 10^{15}$ • age of the universe

Figure of merit for a limit sensitivity:

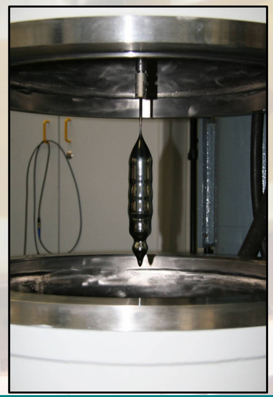
b>0 : $T_{1/2} \propto M_{nucl}\, a\, \varepsilon \sqrt{\frac{m\, t}{b\, \delta E}}$

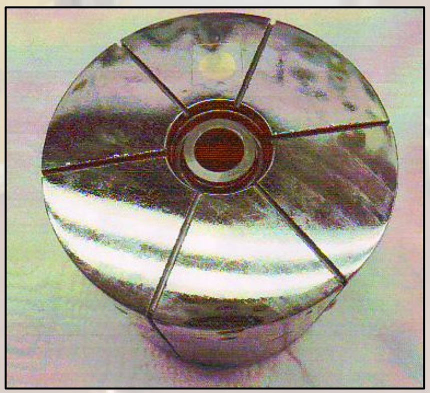
b=0 : $T_{1/2} \propto M_{nucl}\, a\, \varepsilon\, m\, t$

M_{nucl}	Nuclear matrix element	Select Isotope
b	background rate of the experiment	Minimize and select material
a	enrichment of isotope under consideration (< 1.0)	Use isotope with high natural abundance or enrich material
m	active target mass of the experiment	Increase target mass
ε	signal detection efficiency (<1.0)	Source =! Detector
δE	Energy resolution	Use high resolution spectroscopy
t	Measuring time (< 20y)	

0νββ with HPGe

Very good energy resolution	Background due to 2νββ decay negligible
Source = Detector	High signal detection efficiency (95%)
Very high purity of detector material (zone refinement)	Very low intrinsic background
Considerable experience	Well known and reliable, improvements possible
Natural abundance of ^{76}Ge 7,44%	Enrichment necessary



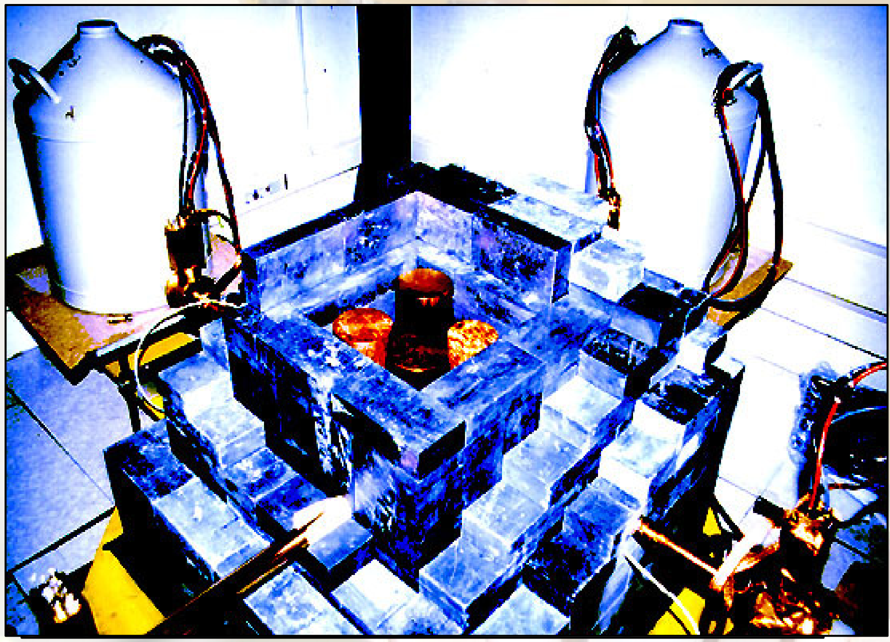


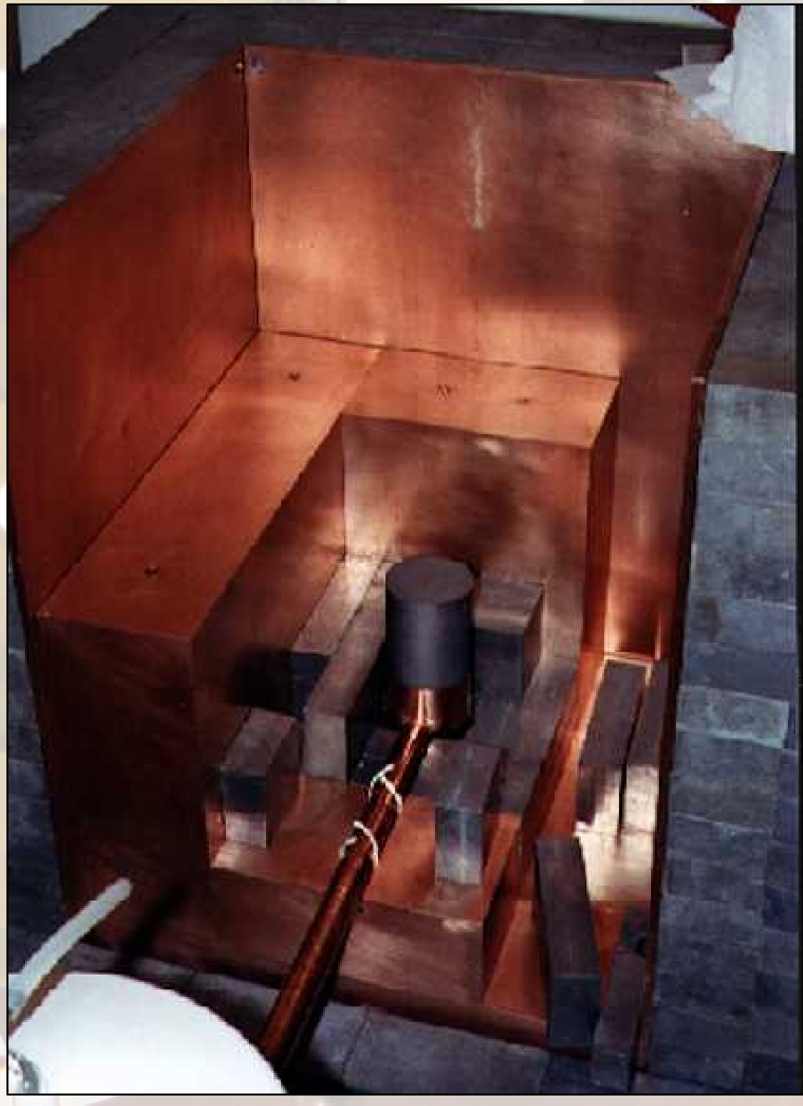
0νββ with HPGe

Five HPGe-detectors, enriched to 86%-88% in ^{76}Ge in conventional low background copper cryostat.

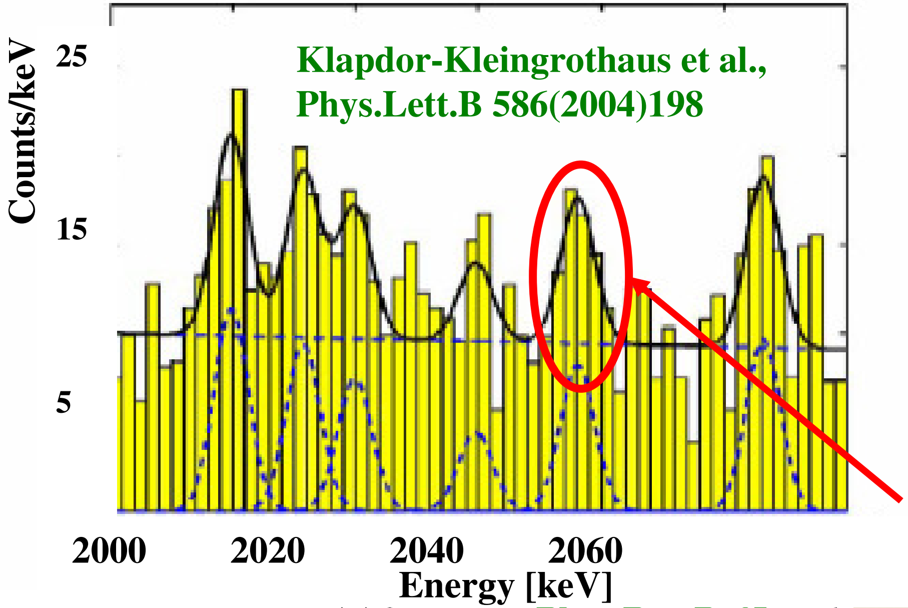
Detectors were surrounded by Cu/Pb shield, neutron shield and equipped with μ-veto

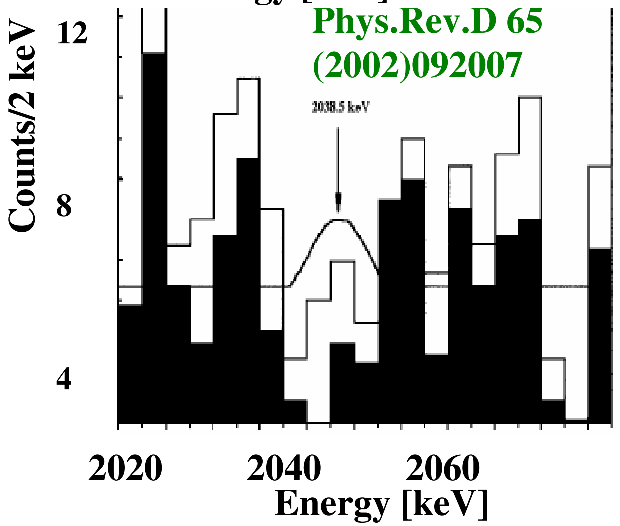
Data taking: 1990 - 2003





0νββ with HPGe





Heidelberg-Moscow Experiment:

11.5 kg of enriched Ge detectors

71.7 kg yrs of data

0.11 Counts/(kg keV y) around 2040 keV

→ Upper limit:

$T_{1/2} \geq 1.9 * 10^{25}$ years (90% C.L.)

4.2 σ claim: $T_{1/2} = 1.19 * 10^{25}$ years

→ $<m_{ee}>$ = 440 *meV* (KK matrix el.)

IGEX Experiment:

6.8 kg of enriched Ge detectors

8.5 kg yrs of data

0.17 Counts/(kg keV y) around 2040 keV

→ Upper limit:

$T_{1/2} \geq 1.6 * 10^{25}$ years (90% C.L.)

$0\nu\beta\beta$ with HPGe: Future Experiments

Main strategy to improve the sensitivity of future HPGe experiments:

Enlarge target mass and reduce background

Avoid Background:

Strategies for background reduction:

Go deep underground (cosmics)

Minimize materials close to detectors

Improve shielding of detectors:

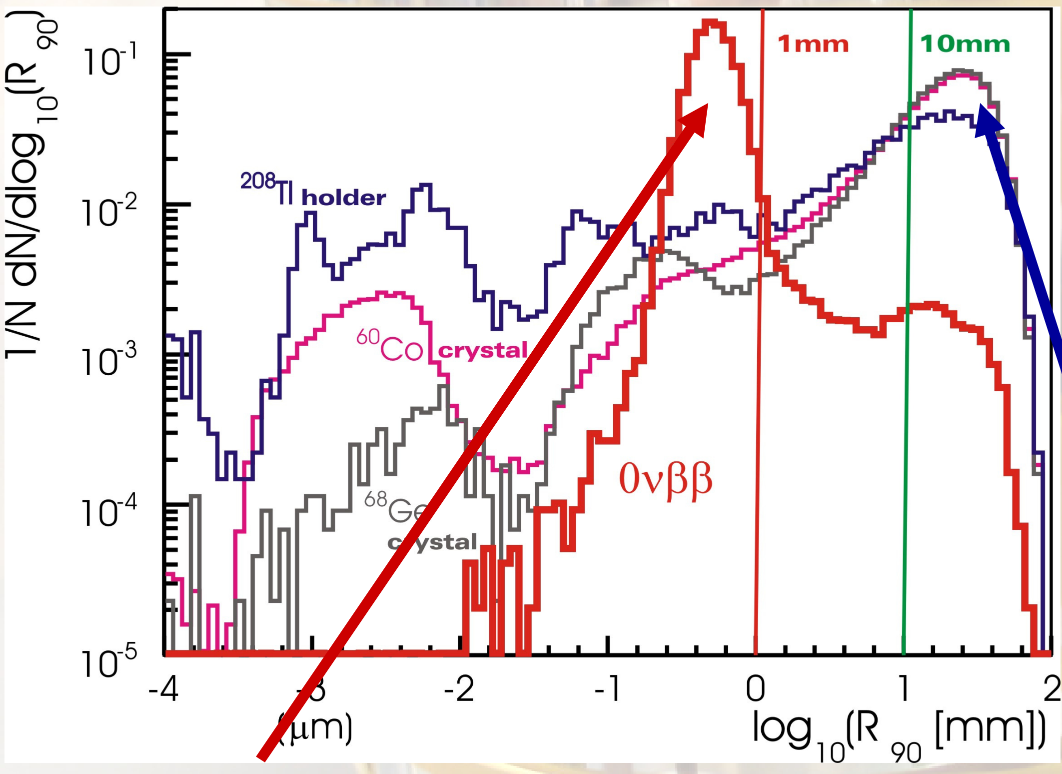
- **Ultra pure copper → MAJORANA (F. Avignone)**
- **Cryoliquid → GERDA (J. Jochum)**

Recognize Background:

Build "intelligent" detectors: Use event topologies

- **Segmented detectors**
- **Detectors with improved pulse shape properties**
- **Combination of the two?**

Event Topologies



Single Site Events (SSE):
Local energy deposition confined to within few mm of the crystal

Multi Site Events (MSE):
Energy depositions at multiple points of the detector. Location of depositions > 1cm apart.

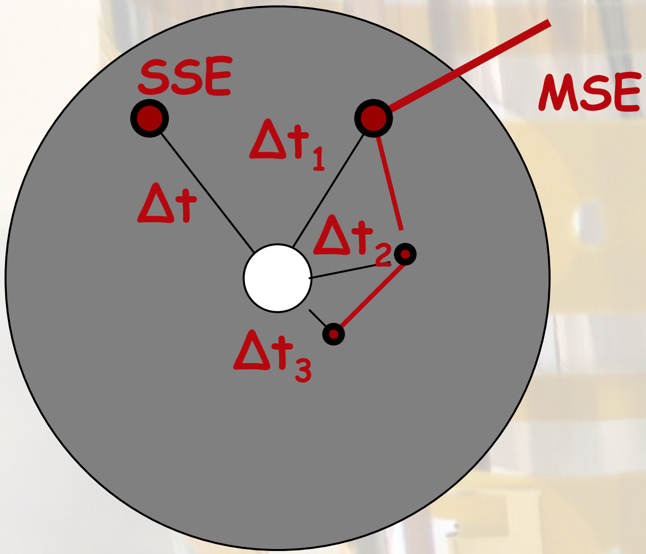
0νββ decays are mostly SSE: 2 electrons deposit energy within roughly one mm.

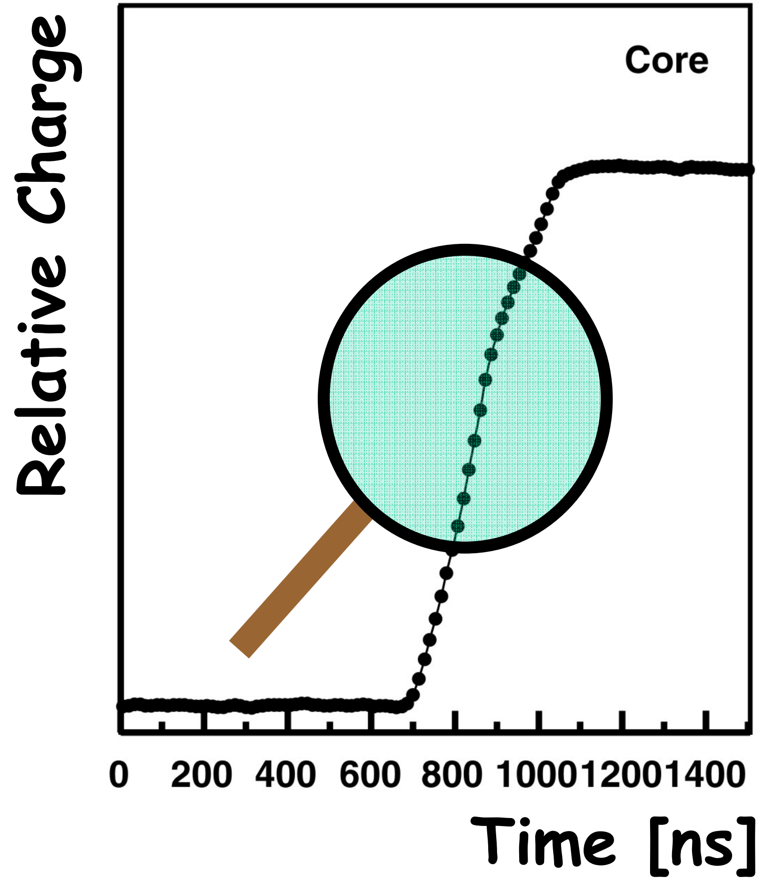
High energetic background gammas (E > 2 MeV) mostly multiple Compton scatter (mean free path ~cm) and thus mostly lead to MSEs.

→ If SSE can be efficiently separated from MSE, background can reduced considerably (efficiency dependent on type and location of background)!

Event Topologies: Pulse Shapes

Arrival distribution of electron-hole pairs, i.e. current at electrodes depend on locations of energy deposit within detector:





"The Wider the spread, the broader the current pulse"

→Background reduction up to factor ~three

→Required bandwidth: ~ 10MHz

Exploited by Heidelberg Moscow and IGEX collaborations

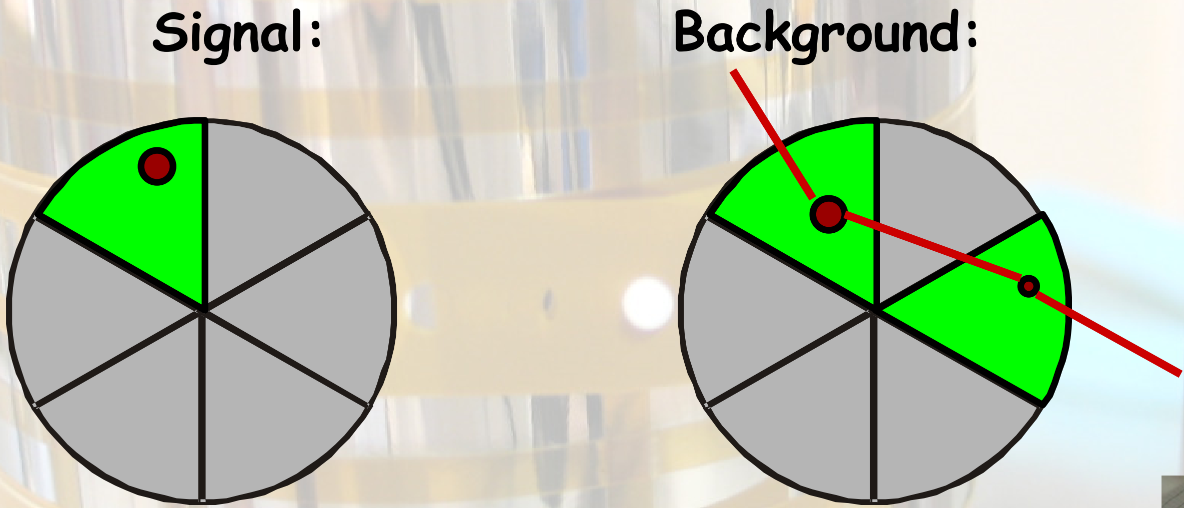
B. Majorovits and HVKK, EPJA 6(1999)463

D. Gonzales et al., NIM A 515(2003)634

Event Topologies: Segmentation

Germanium (and other) detectors can be segmented

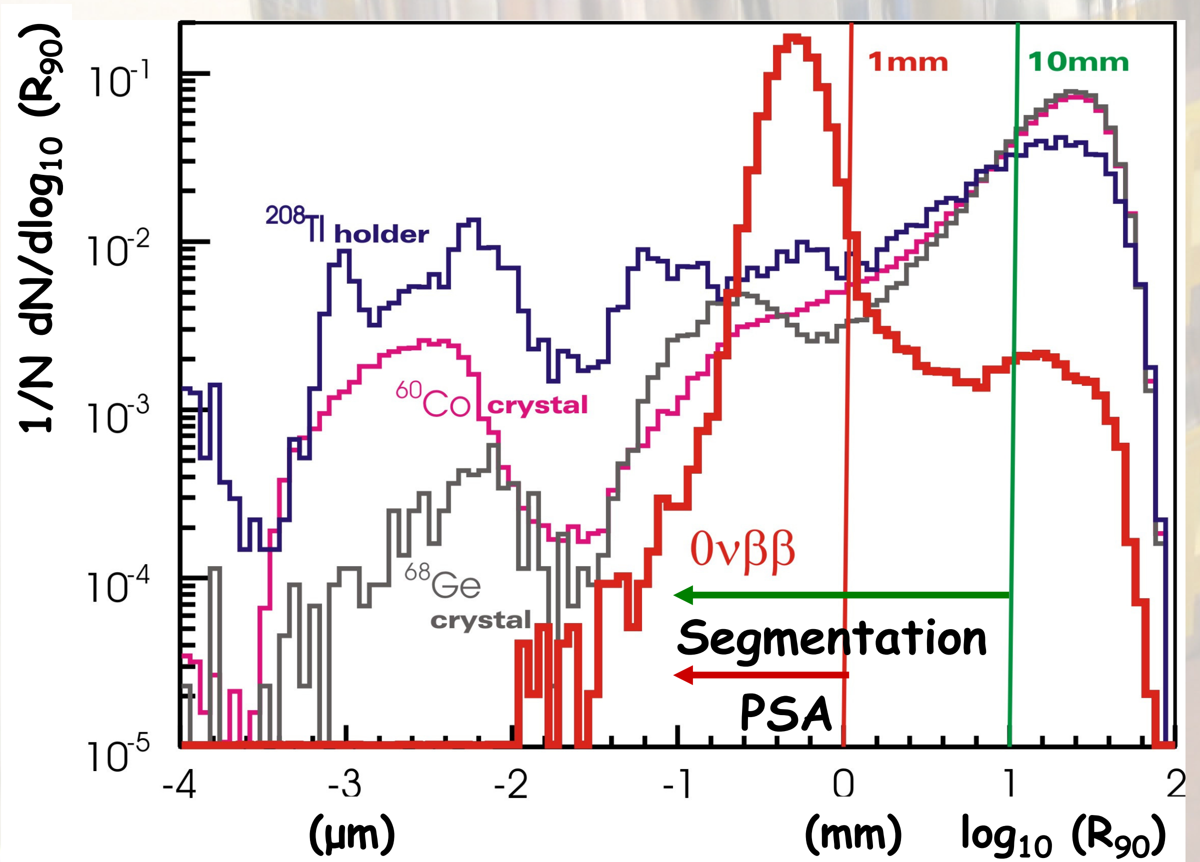
→ Background identification through identification of multiply Compton-scattered photons by coincidences



→Robust technique based on "counting" events
→ It can be easily simulated
→ No pulse data require, ie no bandwidth restrictions (no fiddling with electronics, cables…)
→ Needs extra cables however (one per segment)

Segemented HPGe detectors

A good fraction of MSE events can be identified with a spatial resolution ~1cm → For typical HPGe detector size 18-fold segmentation will do.



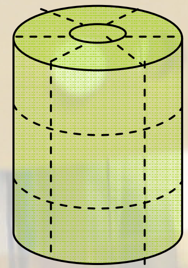
Reduction factors for GERDA (MC):

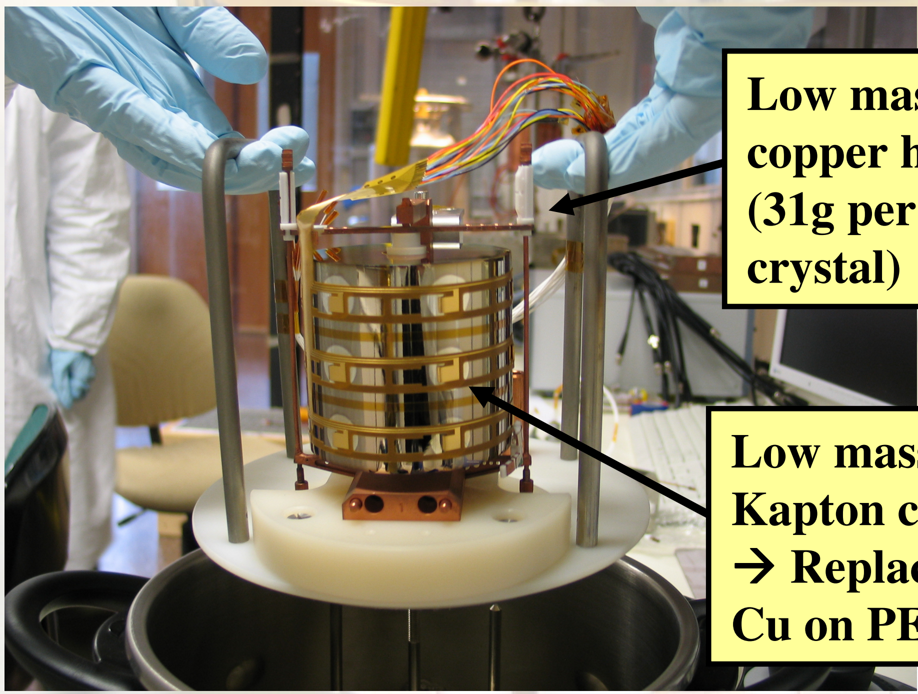
Source	Red.
^{208}Tl (in Ge)	13
^{60}Co (in Ge)	38
^{68}Ge (in Ge)	18
^{210}Pb (α on Ge surface)	1
^{208}Tl (in holder)	5
^{60}Co (in holder)	157
^{208}Tl (in cable)	5

Reduction factors depend on source and location!

Segemented HPGe detectors

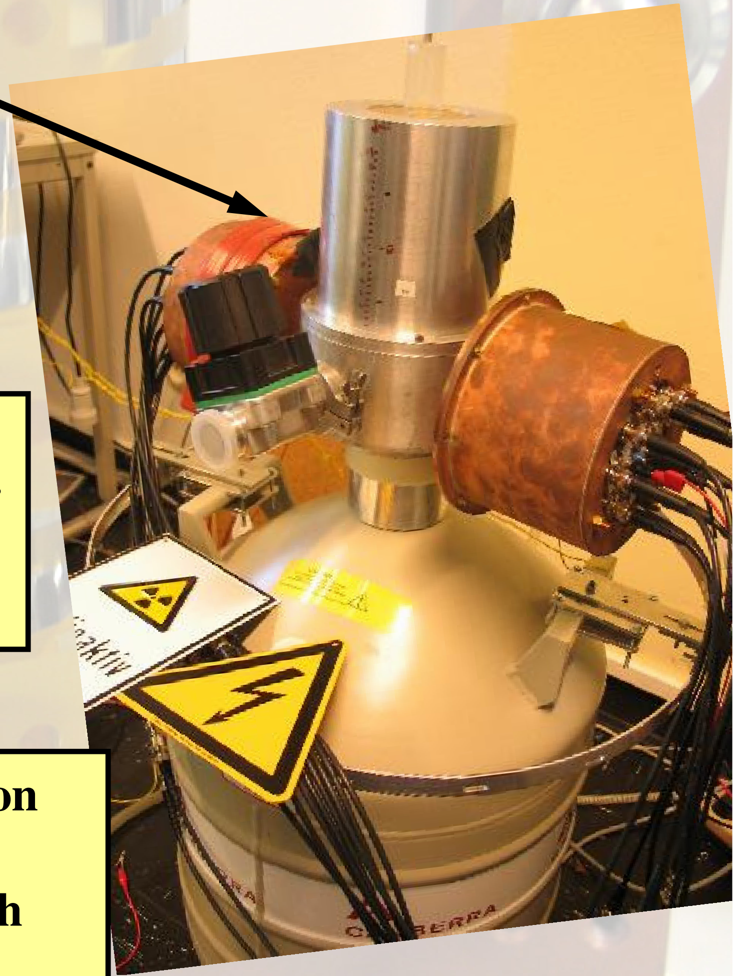
18 fold segmented (3 in Z, 6 in φ) prototype HPGe detector (75mm diameter, 70cm height) has been contacted with low mass novel contacting scheme. The detector was operated in standard vacuum cryostat.





Low mass Cu copper holder (31g per crystal)

Low mass Cu on Kapton cable.
→ Replace with Cu on PEN



I. Abt. et al, NIM A 577(2007)574, nucl-ex/0701004

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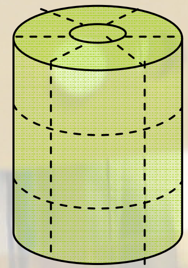

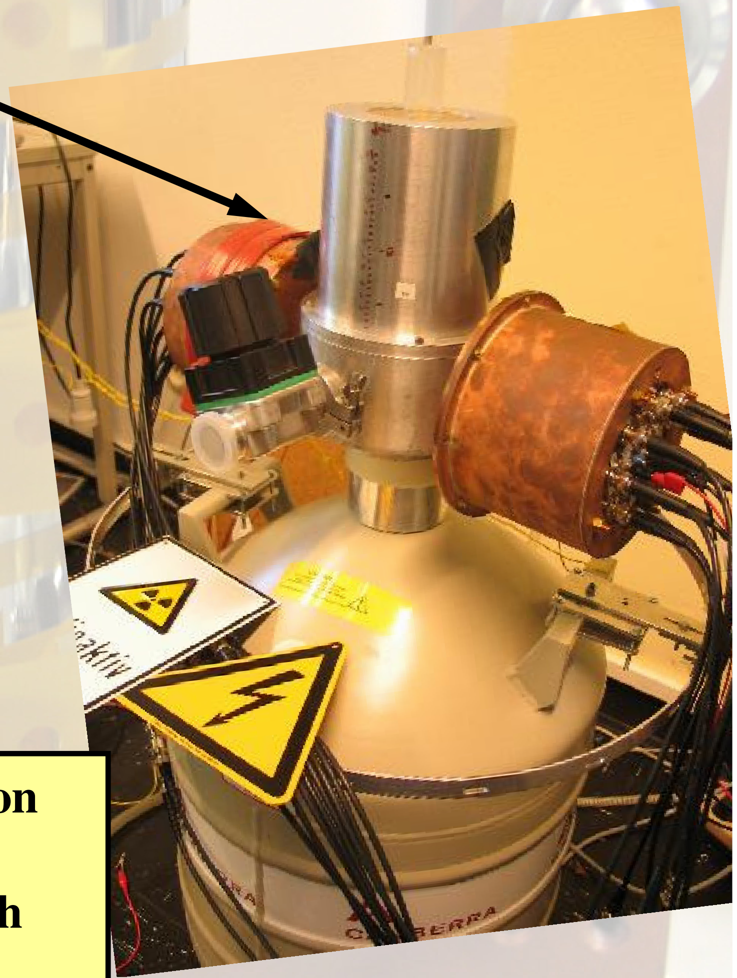

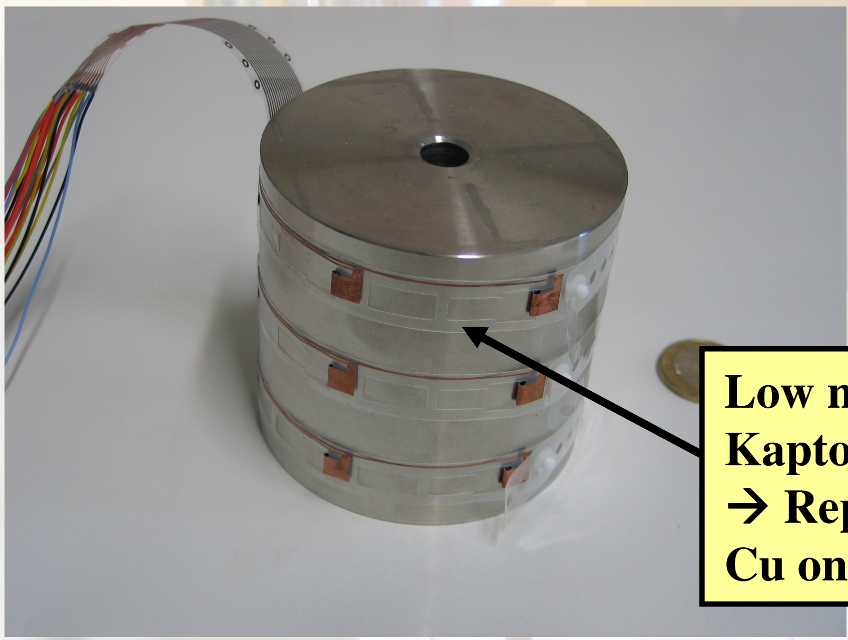

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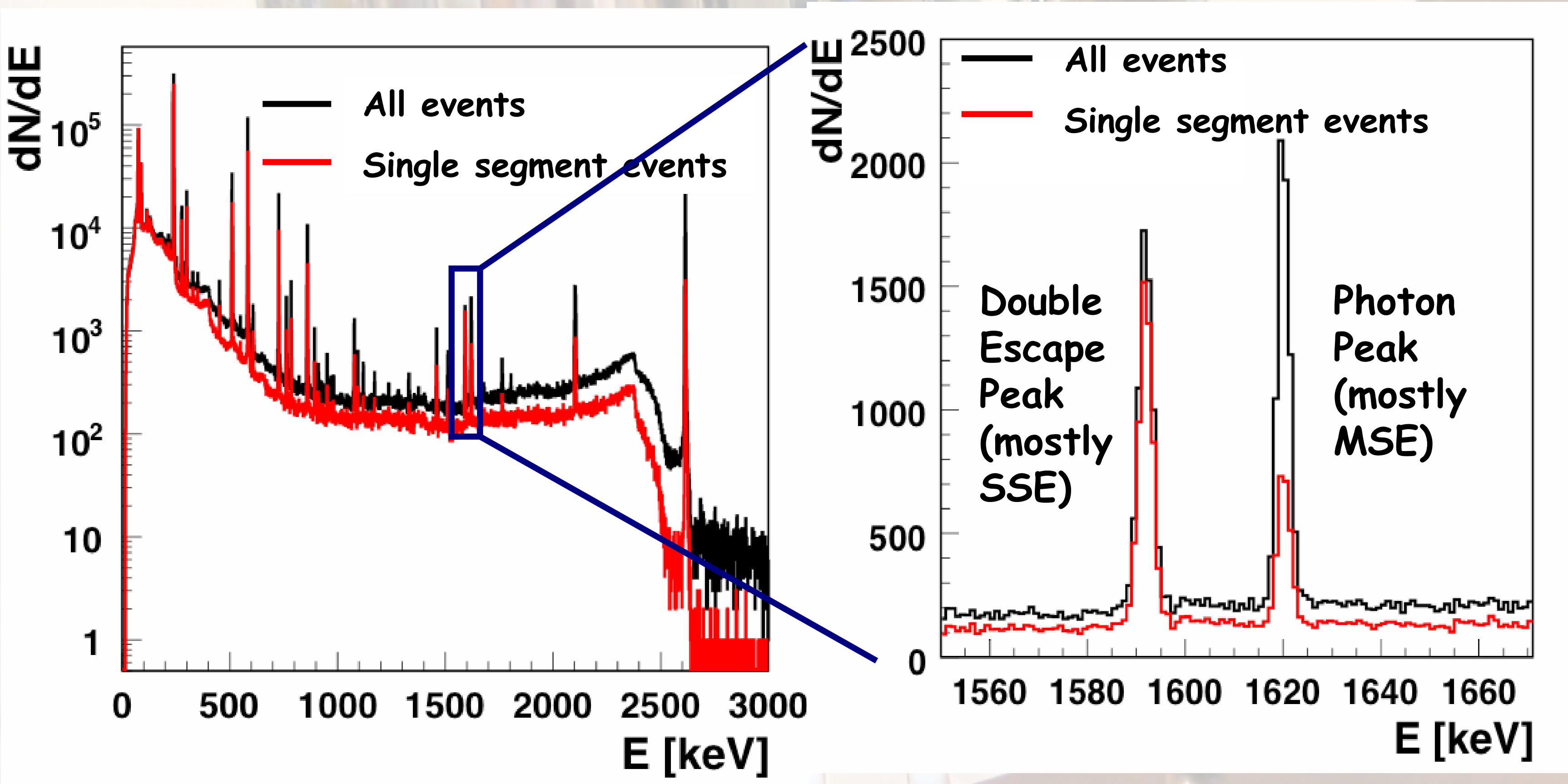
Segemented HPGe detectors

Compton Background recognition works as expected:

Photon Peak is reduced in single segment spectrum, whereas Double Escape Peak remains

Suppression factors (SF) as expected from MC



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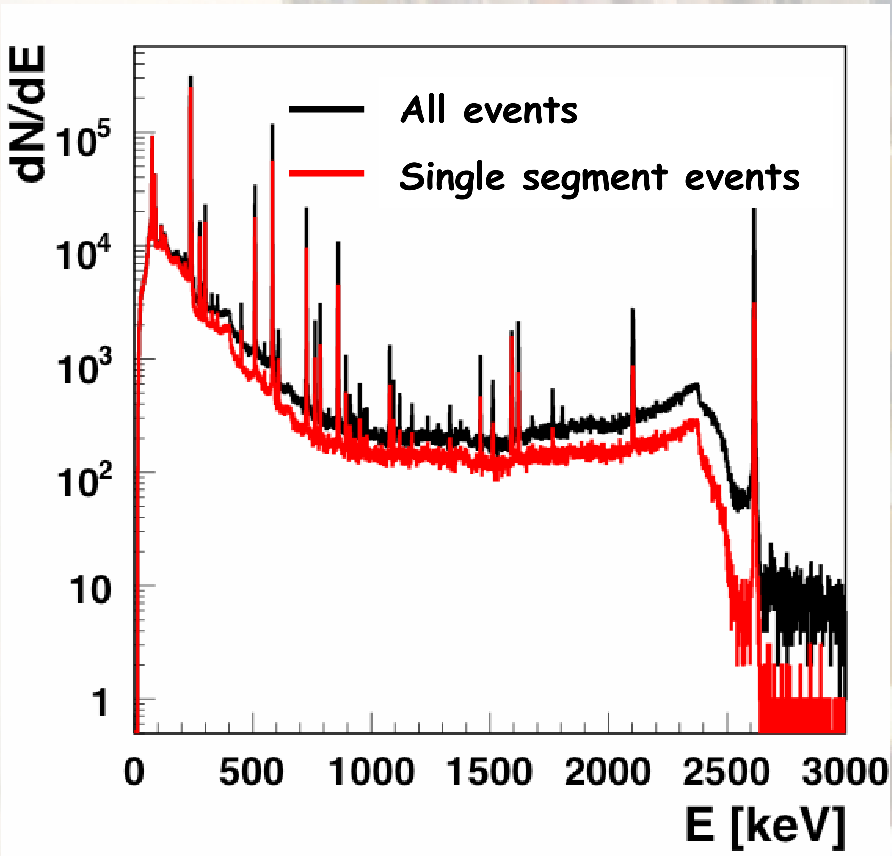
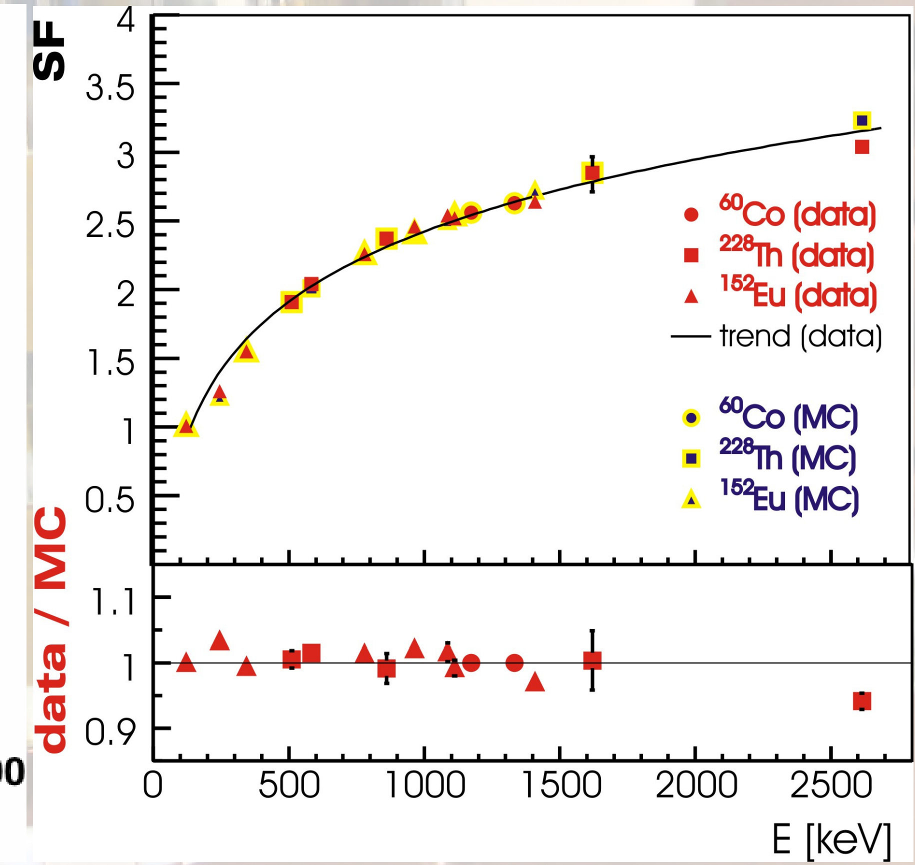
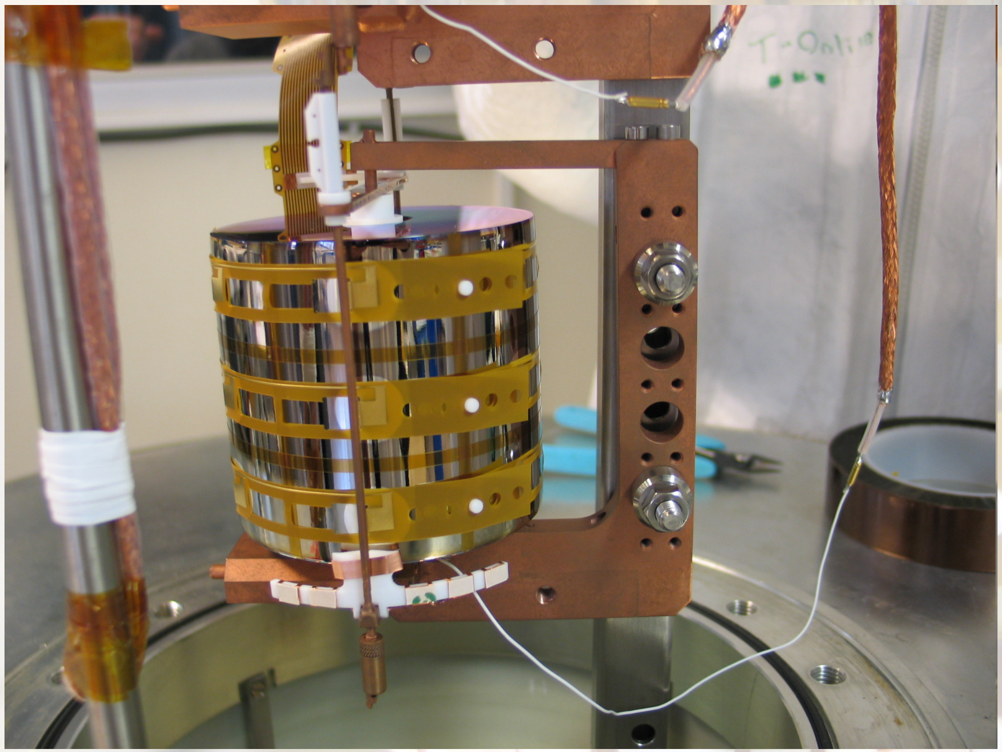


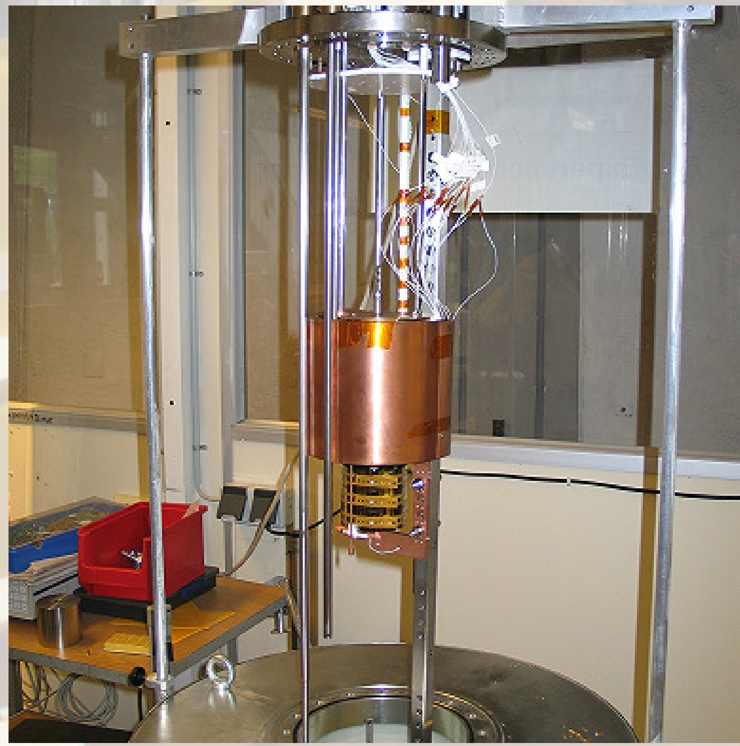


Segemented HPGe detectors

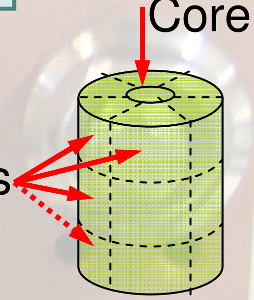
Segmented detectors are discussed for phase II of the GERDA experiment → operation of detectors directly in cryo-liquid.

Test stand at MPI Physik in Munich:

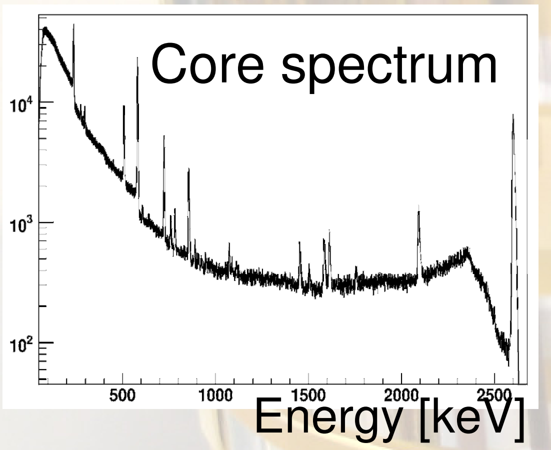


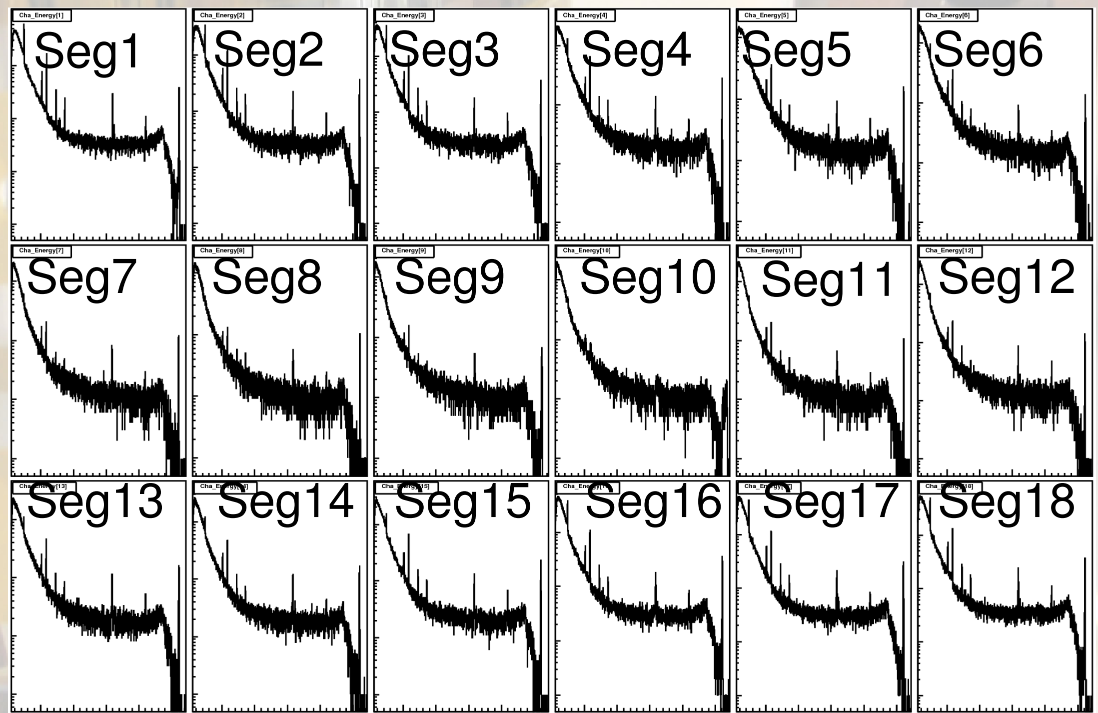


Prototype Detector in Cryoliquid:



1st time: operation of segmented n-type detector in LN
Constant leakage current: 35pA over 5 months period
Calibration Spectrum Th-228,
19 spectra taken at the same time
(under realistic conditions, FET 50cm from detector):



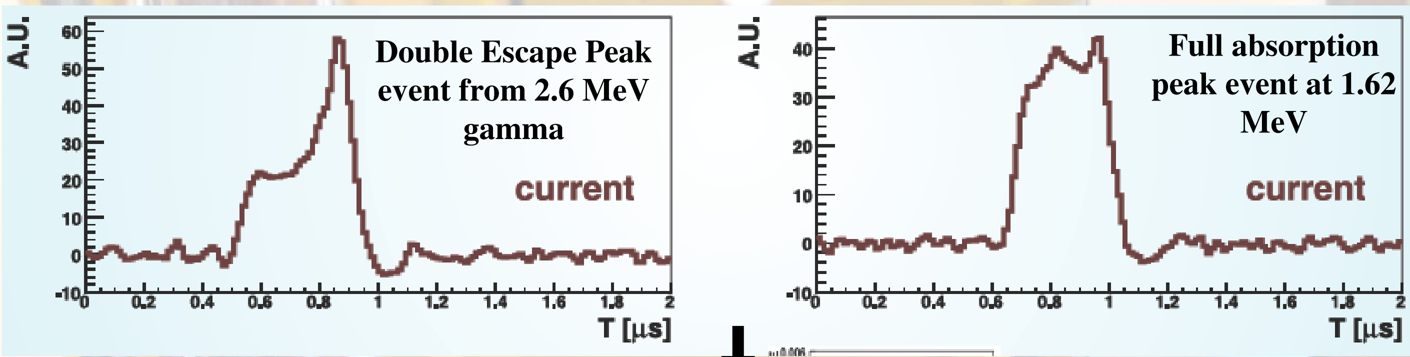


Energy measured in a single segment

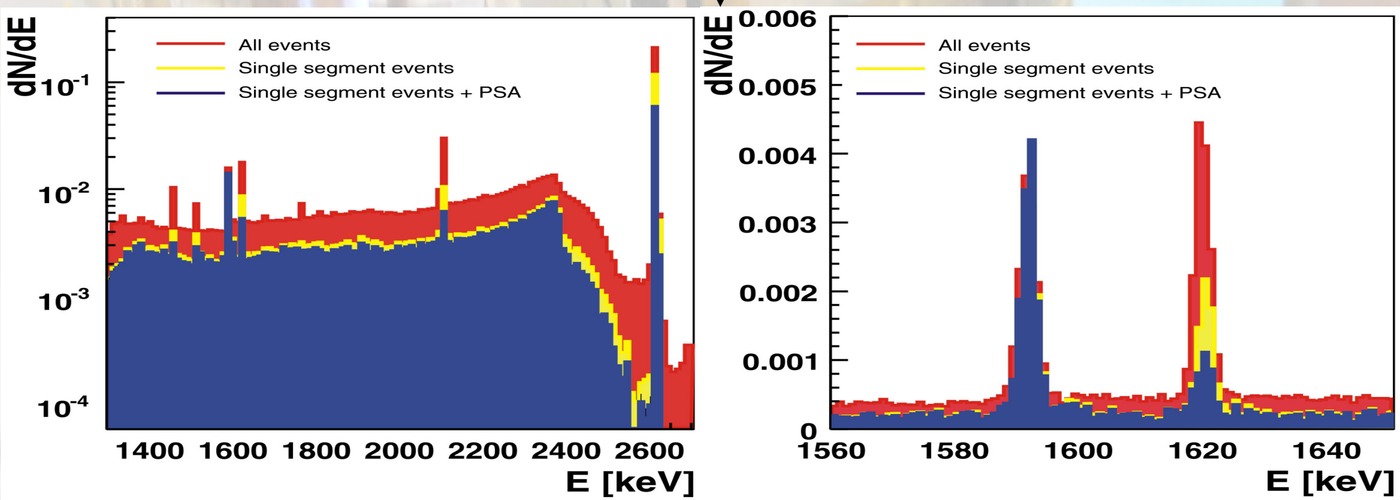
Energy resolution
(FWHM at 1.3 MeV):
Core: 4keV to 5 keV
Segements: 3 keV to 7 keV
→$\delta E/E \sim 3 \cdot 10^{-3}$

Segmented HPGe detectors: PSA

Additional (complementary) information can be achieved by analysis of core (and segment) pulses



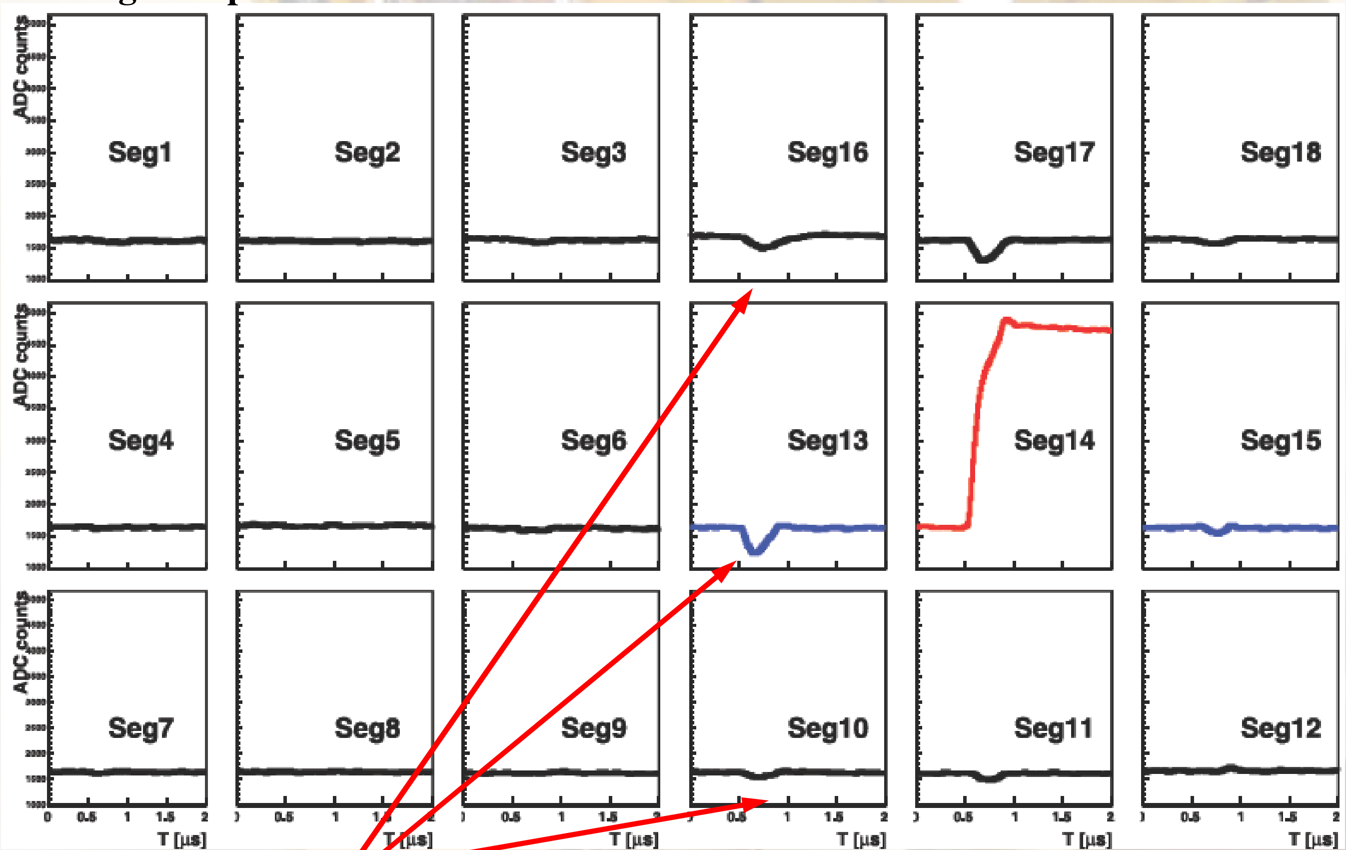
PSA by neural network, library, etc.



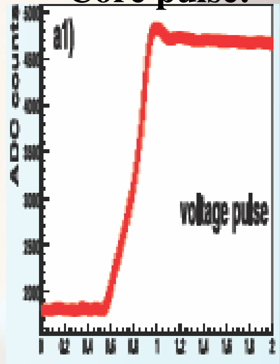
Segmented HPGe detectors: PSA

Pulses of core signal and all segments can be taken:

Segment pulses:



Core pulse:



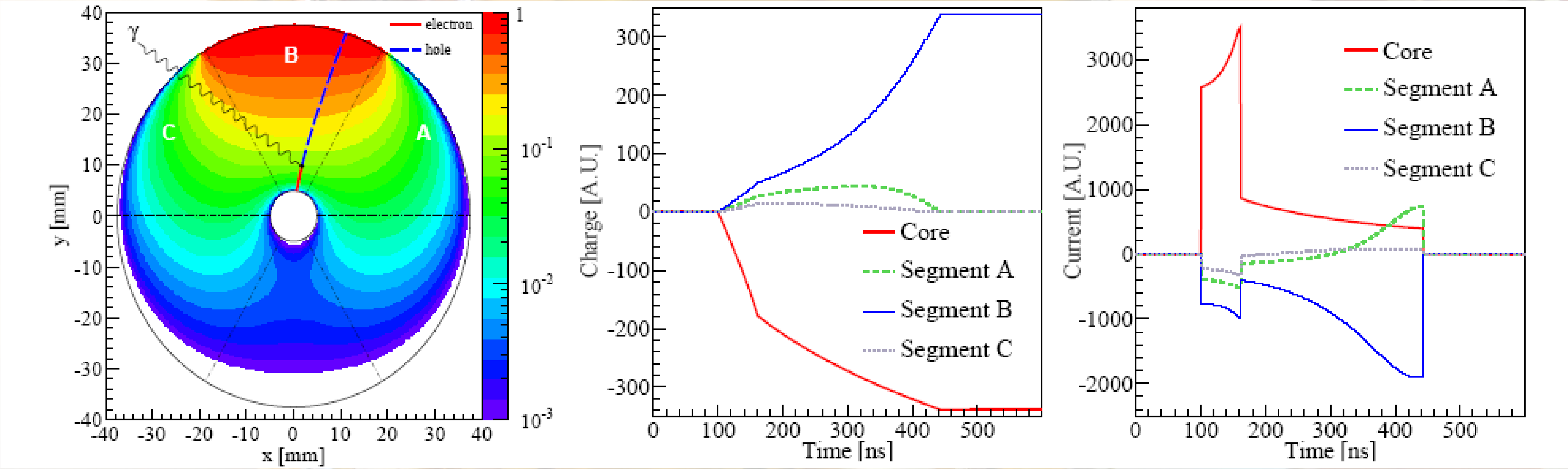
Single segment multi site event induced mirror pulses have different structure

→ Additional recognition efficiency

Mirror Pulses in neighbouring segments give information on location of interaction within segment.

Segmented HPGe detectors: PSA

Pulses shapes are helpful to understand your detector.
Compare measurement with expectations:



Simulation of pulse shapes:
- → Calculation of fields (Electrical field and weighting field)
- → Calculation of trajectories including crystal axis effects
- → Extraction of pulse shapes in core and hit segment
- → Calculation of induced signal in neighbouring segments (mirror charges)

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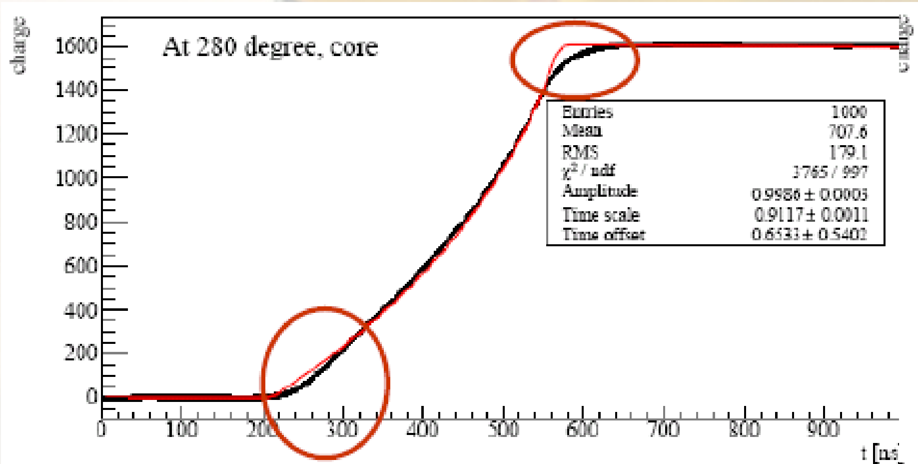

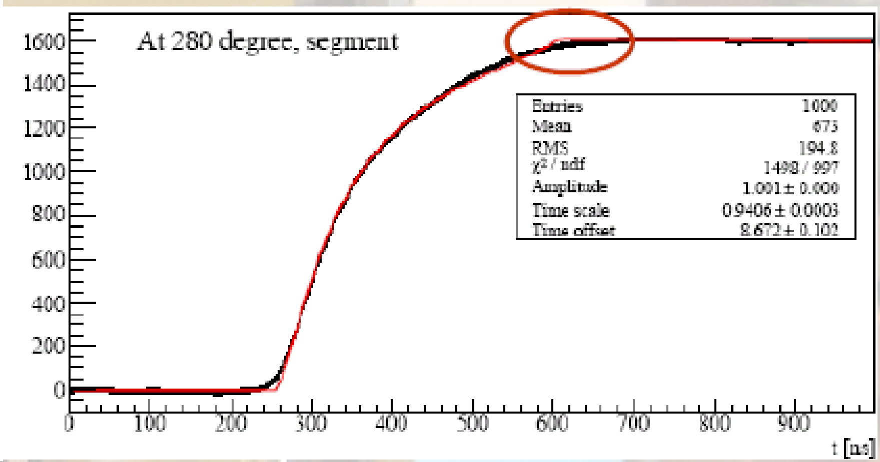

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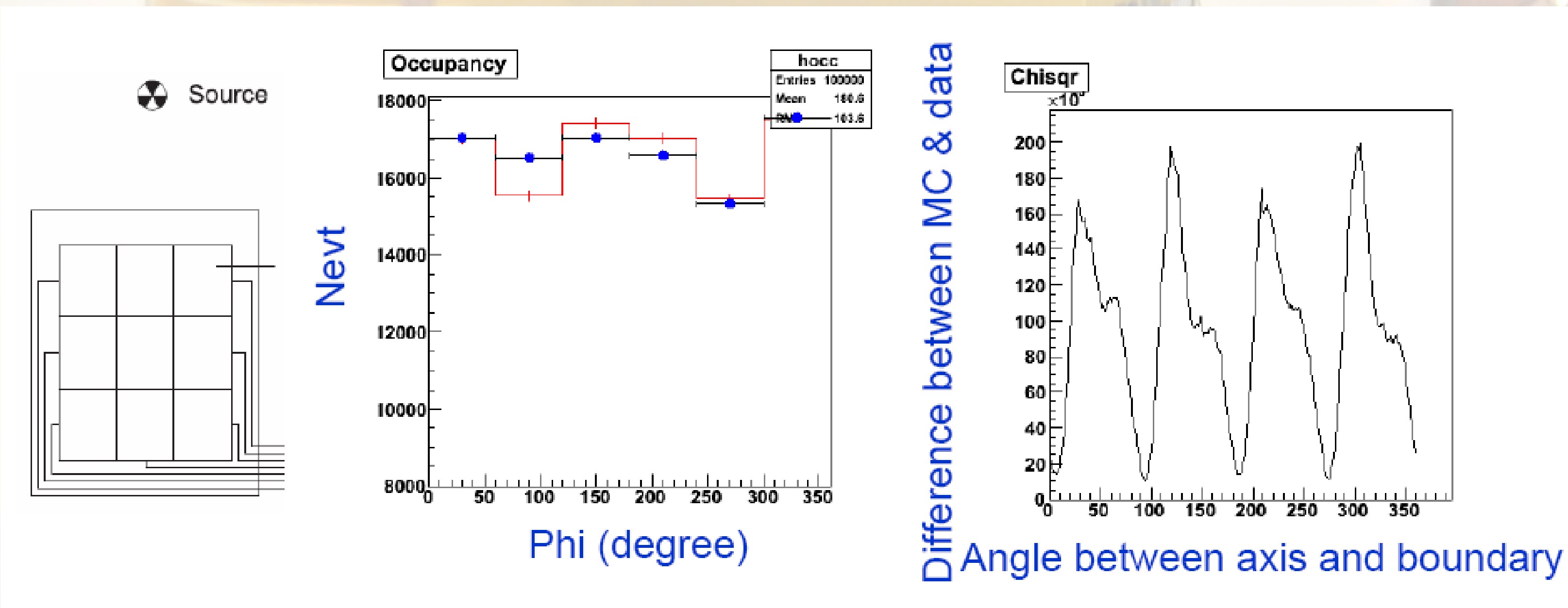
Segmented HPGe detectors: PSA



→Determination of crystal axis by occupancy distribution
→ Reconstruction of charge carrier density within individual layers/segments (use capacity of segments AND occupancy distribution)
→ Extra info on event location by understanding mirror pulses
→ Distinguish between MSE and SSE

Conclusions:

Neutrinoless double beta-decay is one of the key processes to understand neutrino properties

The search for 0νββ with HPGe detectors is very competitive

Background can be reduced using event Topologies

Segemented HPGe detectors have capability to increase sensitivity of HPGe experiments

GERDA sensitivity

1. GERDA will confirm or rule out the Klapdor-Kleingrothaus et al. claim (Phase I)
2. If not confirmed and background reduction to the level 10^{-3}/(kg yr keV) demonstrated (Phase II), go for
3. 1 ton expeiment (20 meV level) for distinction of hierarchies!