24.03.2009

Development of segmented germanium detectors

for neutrinoless double beta decay experiment GERDA

Jing Liu* and GERDA group at Max-Planck-Institut für Physik in Munich

* Jing Liu @ Kamioka

Outline

- Neutrino mass and its origin (5 min)
- Neutrinoless double beta decay (5 min)

- GERDA (GERmanium Detector Array) (5 min)

- Test stands for segmented germanium detectors (5 min)

- Event identification power of segmentation
  - Photon induced background (5 min)
  - Neutron induced background (10 min)

- Pulse shape simulation (5 min)
- Validation of pulse shape simulation (10 min)

Neutrino mass and its origin…

Neutrinos in Standard Model

- Created with definite helicity in weak interactions
- No mass => no way to change its helicity

- Neutrino (1) and anti-neutrino (-1)
  - neutrino + n → p + e^- V
  - anti-neutrino + n → p + e^- X (Raymond Davis, 1955)

- Left-handed neutrino & right-handed anti-neutrino (Goldhaber, 1957)

Neutrino oscillations

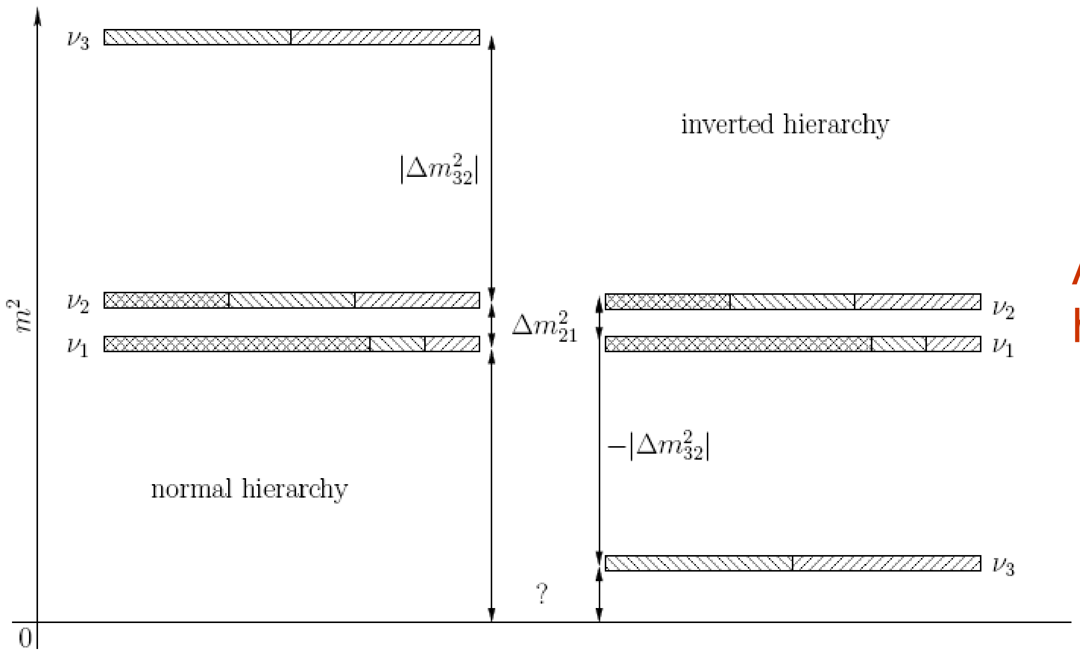
flavor eigenstates **mass eigenstates**

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

$$P_{\alpha\to\beta} = \delta_{\alpha\beta} - 4\sum_{i>j} Re(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin^2\left(\frac{\Delta m^2_{ij}L}{4E}\right) + 2\sum_{i>j} Im(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin\left(\frac{\Delta m^2_{ij}L}{2E}\right)$$

$$\Delta m^2_{ij} \equiv m^2_i - m^2_j$$

Neutrino mass spectrum



At least two neutrinos have non-zero mass!

Right-handed neutrino?

Neutrino has mass

$\Rightarrow$ left-handed neutrino is right-handed as seen in a faster system

=> why we didn't see right-handed neutrino?

- Right-handed neutrino doesn't interact !
- neutrino = anti-neutrino !

Neutrino = anti-neutrino ?

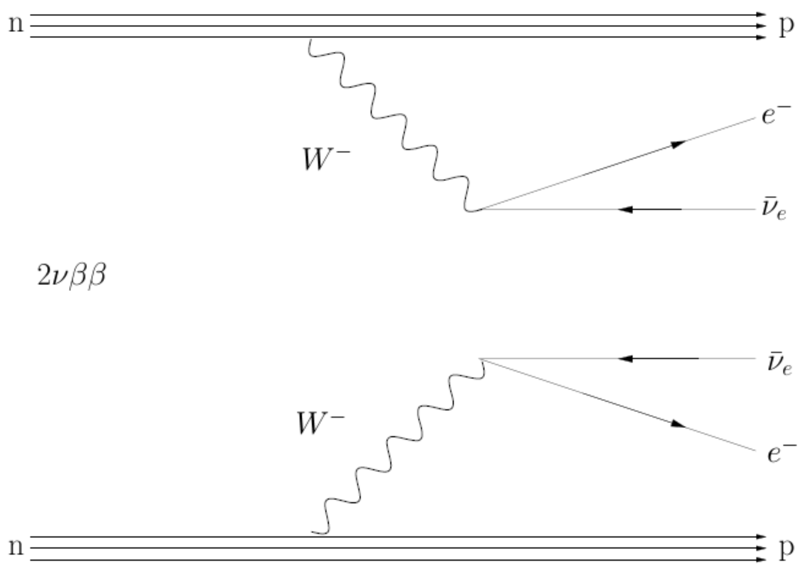
- Neutrino (1) and anti-neutrino (-1)
    - neutrino + n → p + e^- V
    - anti-neutrino + n → p + e^- X (Raymond Davis, 1955)

  – Weak interactions have chirality (Li & Yang, 1956)
  – Neutrino has no charge nor magnetic moment

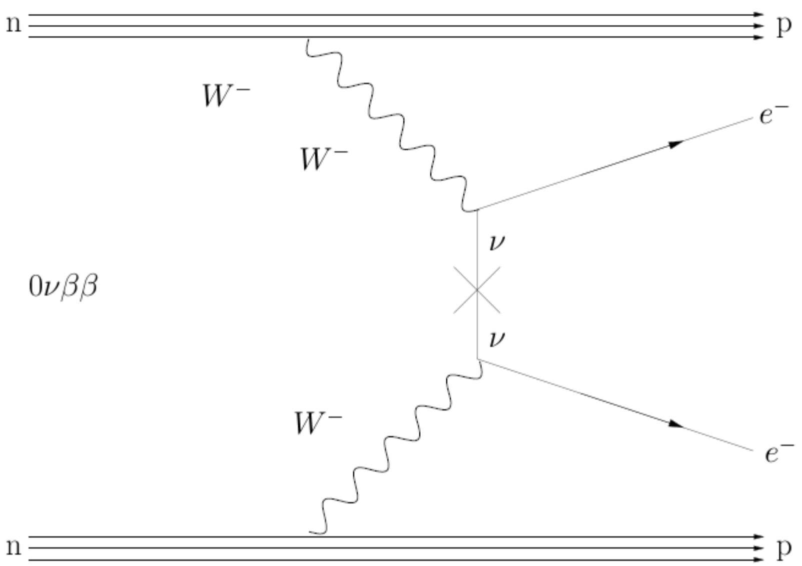
Neutrinoless double beta decay…

What is it

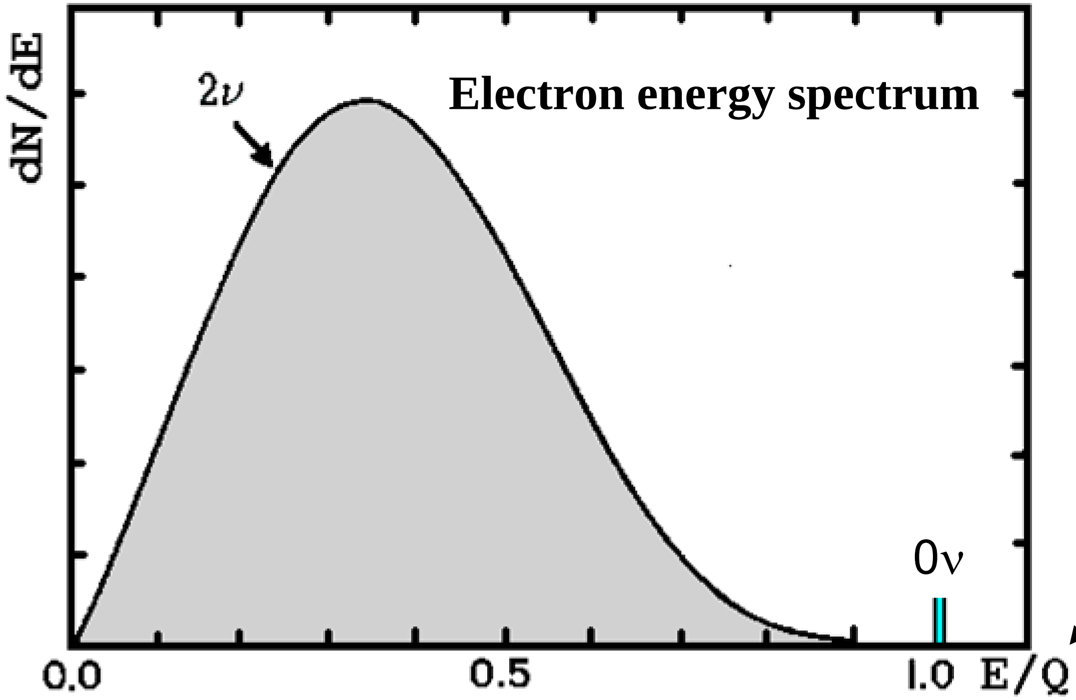
Double beta decay



Neutrinoless double beta decay



What is the signal

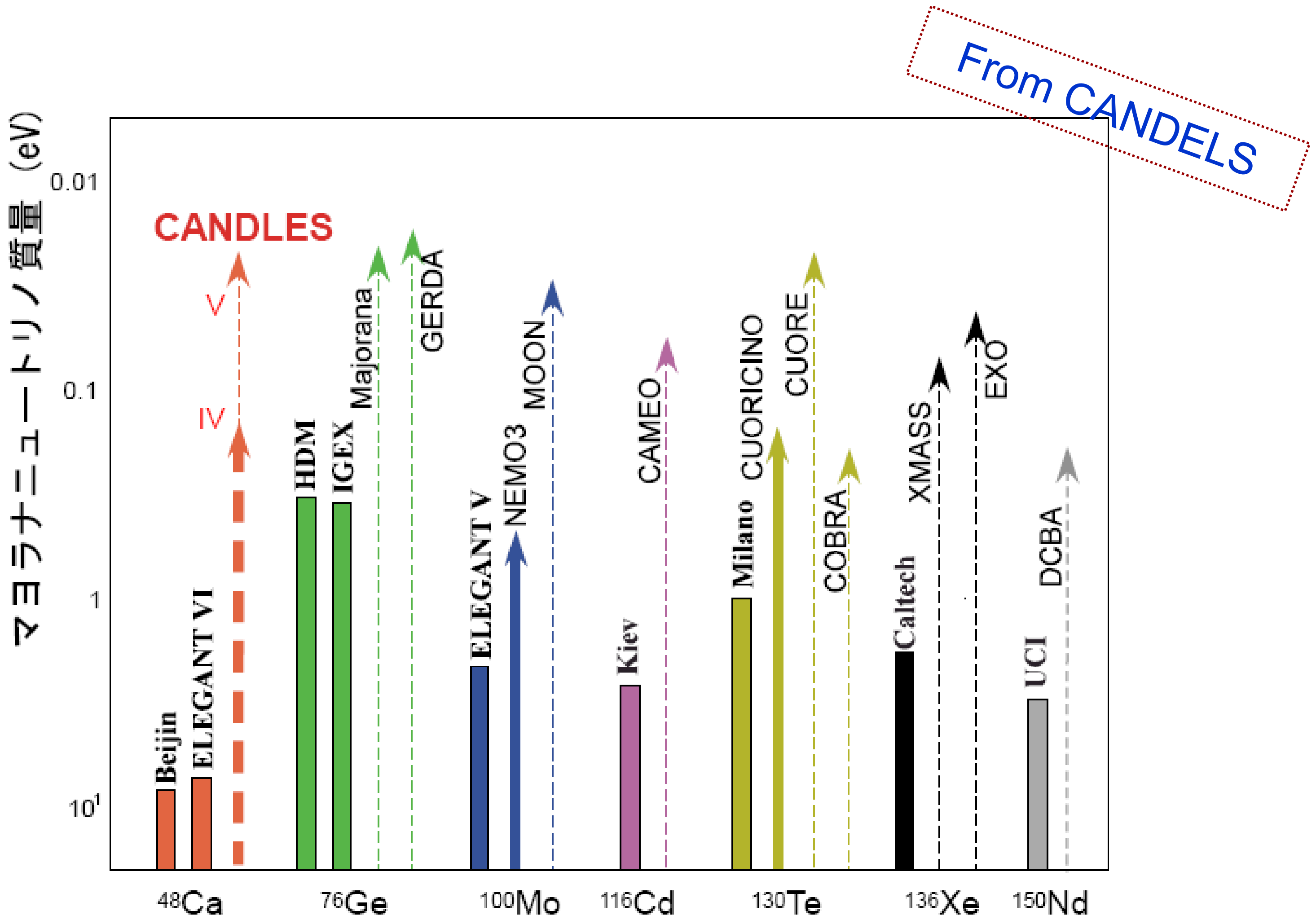


Q: mass difference of the nucleus before and after the decay

Candidates

Isotope	Q [MeV]	$\mathcal{M}_{0\nu}$	κ [%]	Properties
^{48}Ca	4.271	0.67^a	0.19	CaF_2 & $CaWO_4$ is a scintillator
^{76}Ge	2.039	4.51 ± 0.17	7.8	semiconductor
^{82}Se	2.995	4.02 ± 0.15	9.2	-
^{96}Zr	3.350	1.12 ± 0.03	2.8	-
^{100}Mo	3.034	3.34 ± 0.19	9.6	-
^{116}Cd	2.809	2.74 ± 0.19	7.5	$CdZnTe^b$ is a semiconductor; $CdWO_4$ is a scintillator
^{124}Sn	2.287	2.11^a	5.8	semiconductor
^{130}Te	2.530	3.26 ± 0.12	35	TeO_2 can be used as bolometer
^{136}Xe	2.480	2.11 ± 0.11	8.9	active material for time projection chambers
^{150}Nd	3.367	4.74 ± 0.20	5.6	could be dissolved in liquid scintillator

Battle field of neutrinoless double beta decay experiments



Common considerations

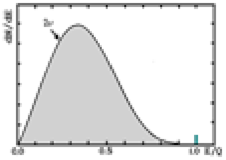
The source:

- The mass of the source material should be large
- The abundance of the isotope under study should be high

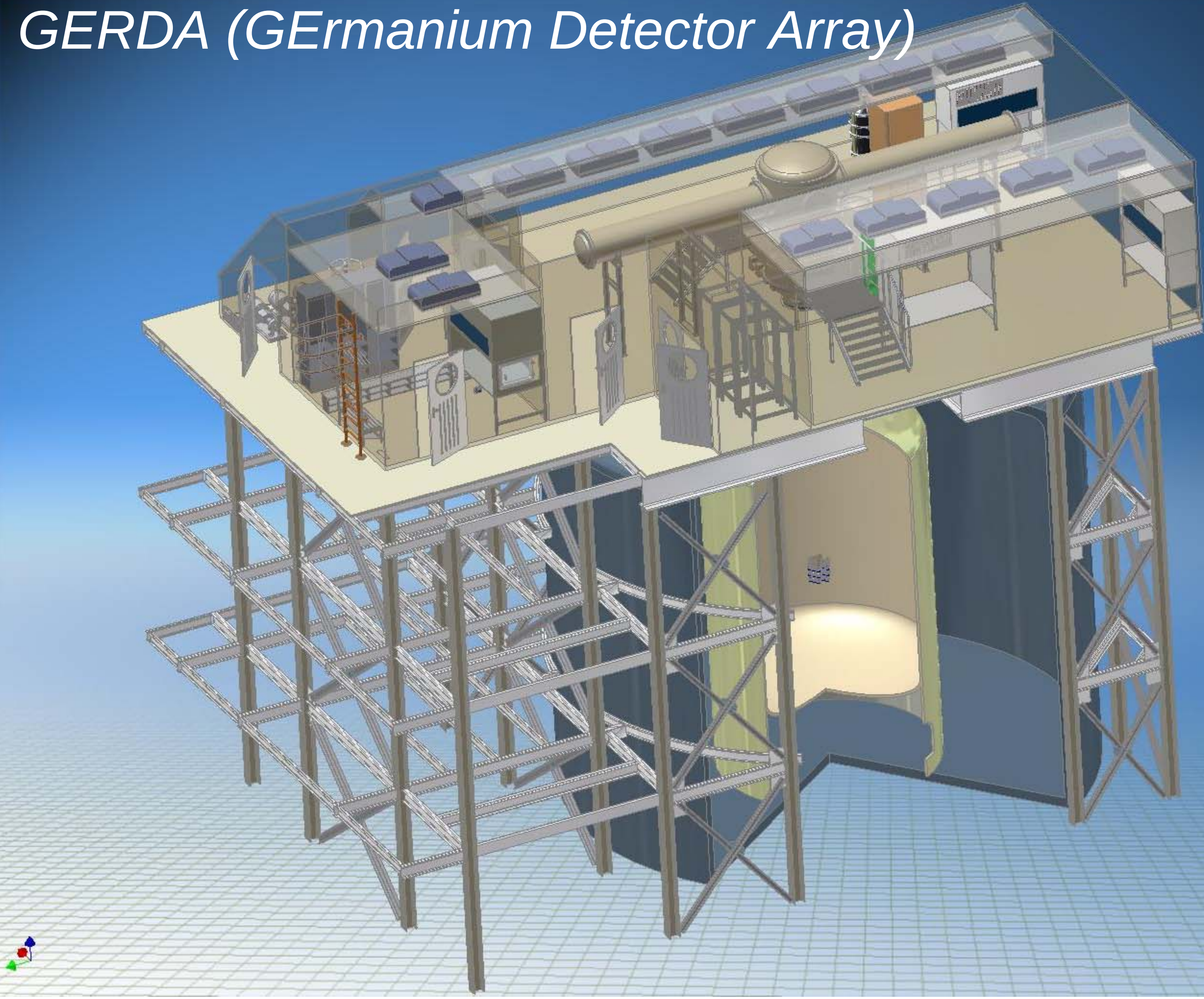
- The Q-value should be large
  - Higher decay rate
  - Less natural radioactive background

The detector:

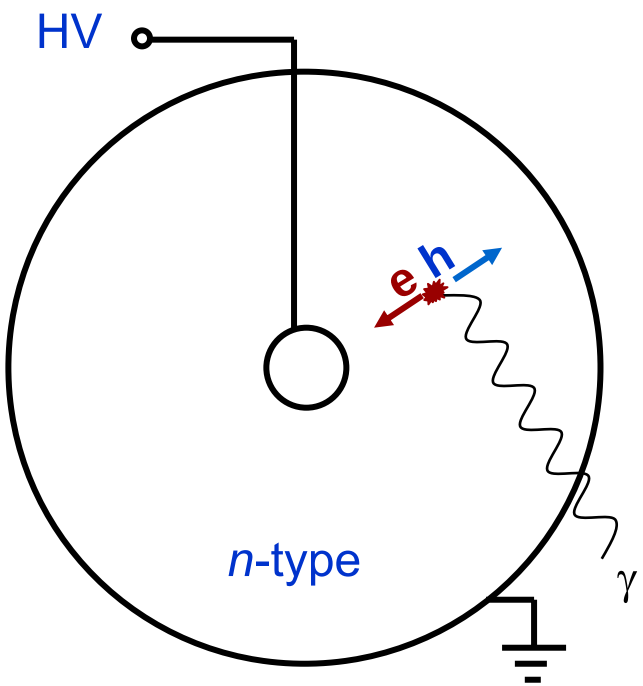
- The detecting efficiency should be large
- The energy resolution should be good
- The background level should be as low as possible

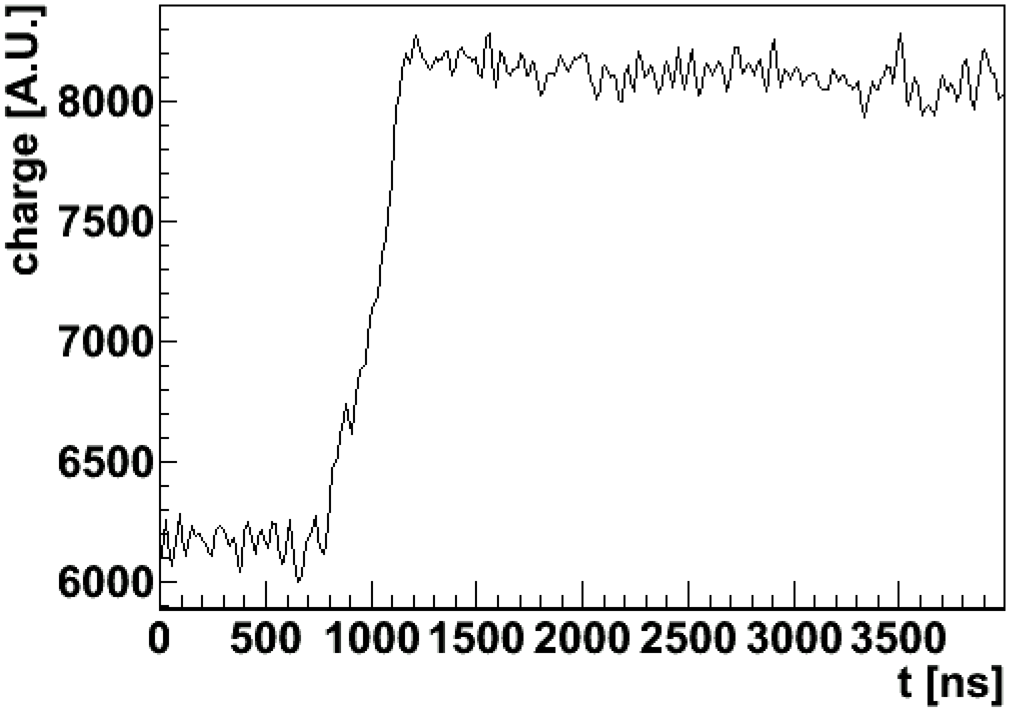


GERDA (GErmanium Detector Array)



Germanium detector





Pros and Cons of germanium

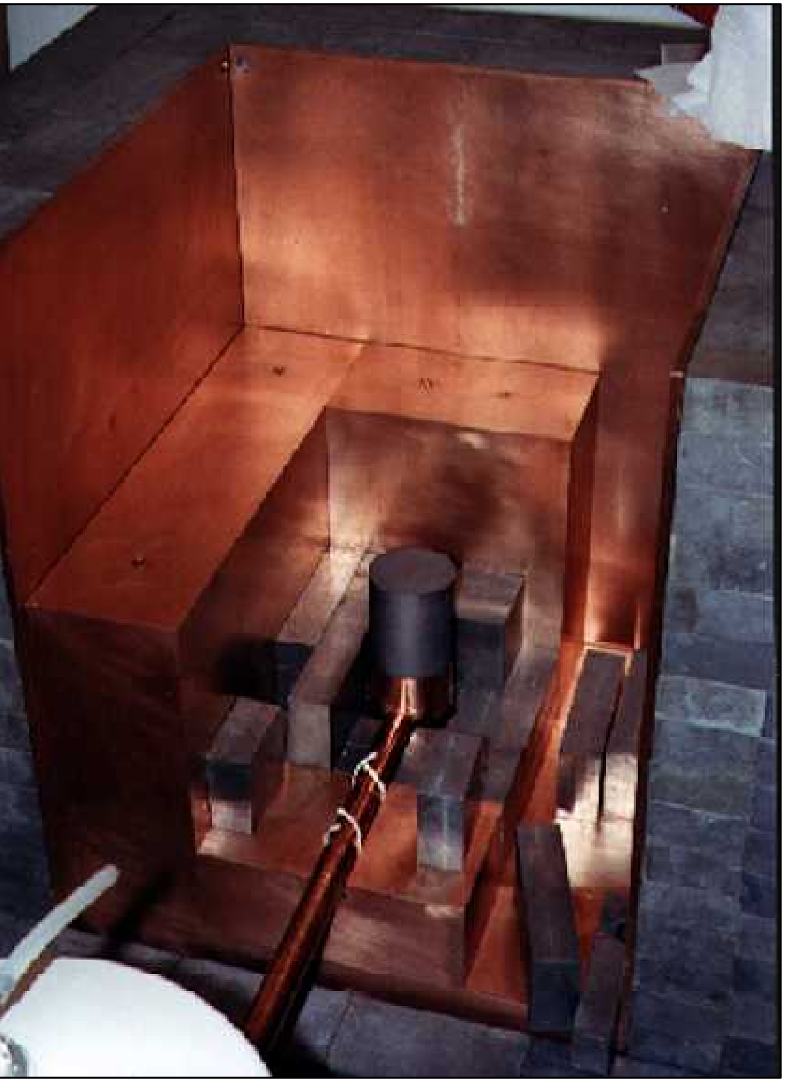
Isotope	Q [MeV]	$\mathcal{M}_{0\nu}$	κ [%]
^{48}Ca	4.271	0.67^{a}	0.19
^{76}Ge	2.039	4.51 ± 0.17	7.8
^{82}Se	2.995	4.02 ± 0.15	9.2
^{96}Zr	3.350	1.12 ± 0.03	2.8
^{100}Mo	3.034	3.34 ± 0.19	9.6
^{116}Cd	2.809	2.74 ± 0.19	7.5
^{124}Sn	2.287	2.11^{a}	5.8
^{130}Te	2.530	3.26 ± 0.12	35
^{136}Xe	2.480	2.11 ± 0.11	8.9
^{150}Nd	3.367	4.74 ± 0.20	5.6

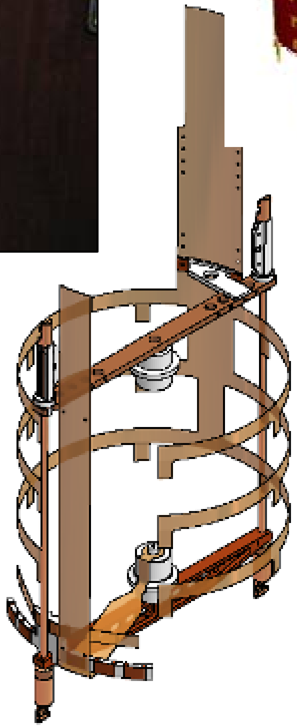
- Best resolution: 3-4 keV @ 2 MeV
- Enrichable: up to 86%
- High detect efficiency
- purest material in the world!

- Can only measure energy
- Low Q:
  - suffer from background
  - low rate
- Operated in low T: 78 K

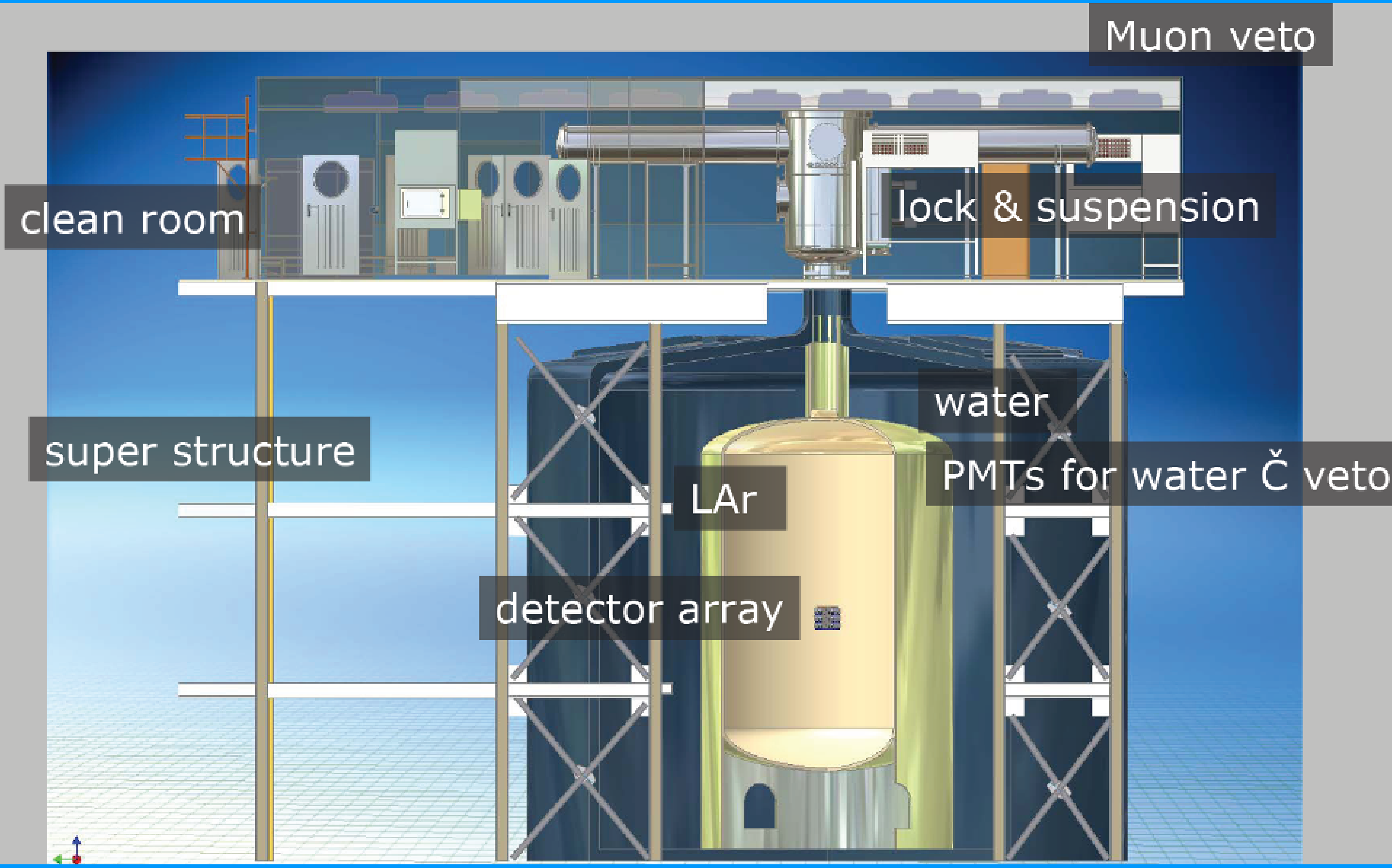
To reduce the background is the key for GERDA to success!

Operate germanium detector directly in cryogenic liquids

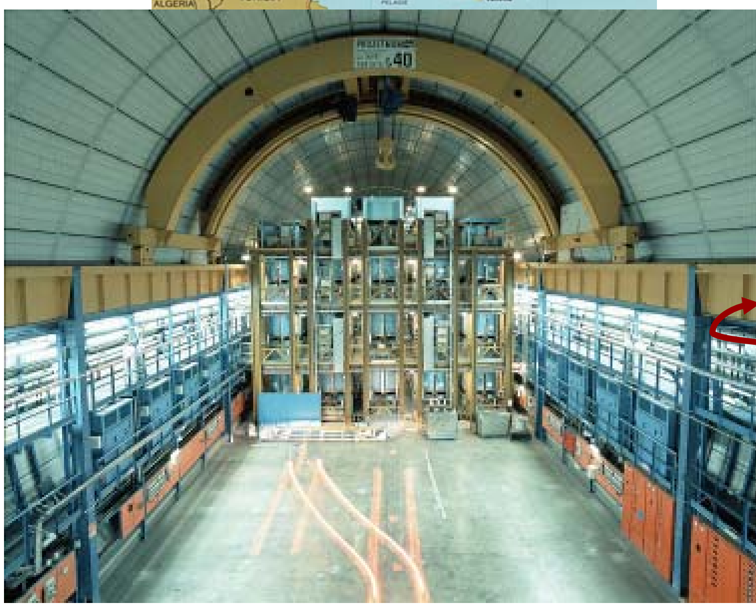




GERDA setup


Muon veto
clean room
lock & suspension
water
super structure
LAr
PMTs for water Č veto
detector array

GERDA location



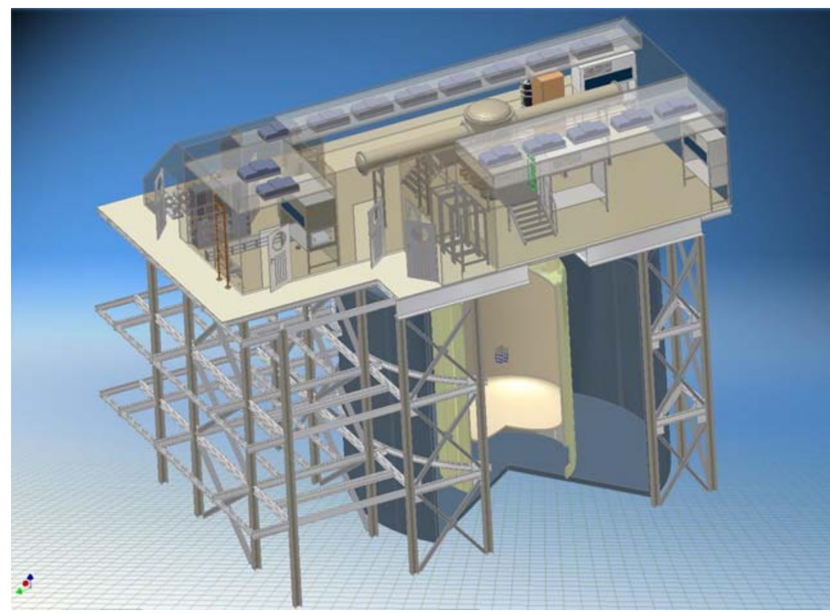
Comparison of different underground laboratories

TABLE I. Summary of the total muon flux measured at the underground sites and the equivalent vertical depth relative to a flat overburden.

Site	Total flux $cm^{-2}sec^{-1}$	Depth km.w.e.
WIPP	$(4.77 \pm 0.09) \times 10^{-7}$ [4]	1.585 ± 0.011
Soudan	$(2.0 \pm 0.2) \times 10^{-7}$ [5]	1.95 ± 0.15
Kamioka	$(1.58 \pm 0.21) \times 10^{-7}$ [12]	2.05 ± 0.15[a]
Boulby	$(4.09 \pm 0.15) \times 10^{-8}$ [6]	2.805 ± 0.015
Gran Sasso	$(2.58 \pm 0.3) \times 10^{-8}$ (this work)	3.1 ± 0.2[a]
	$(2.78 \pm 0.2) \times 10^{-8}$ [9]	3.05 ± 0.2[a]
	$(3.22 \pm 0.2) \times 10^{-8}$ [10]	2.96 ± 0.2[a]
Fréjus	$(5.47 \pm 0.1) \times 10^{-9}$ [11]	4.15 ± 0.2[a]
	$(4.83 \pm 0.5) \times 10^{-9}$ (this work)	4.2 ± 0.2[a]
Homestake	$(4.4 \pm 0.1 \times 10^{-9})$ (this work)	4.3 ± 0.2
Sudbury	$(3.77 \pm 0.41) \times 10^{-10}$ [7]	6.011 ± 0.1

[a]Equivalent vertical depth with a flat overburden determined by the measured total muon flux.

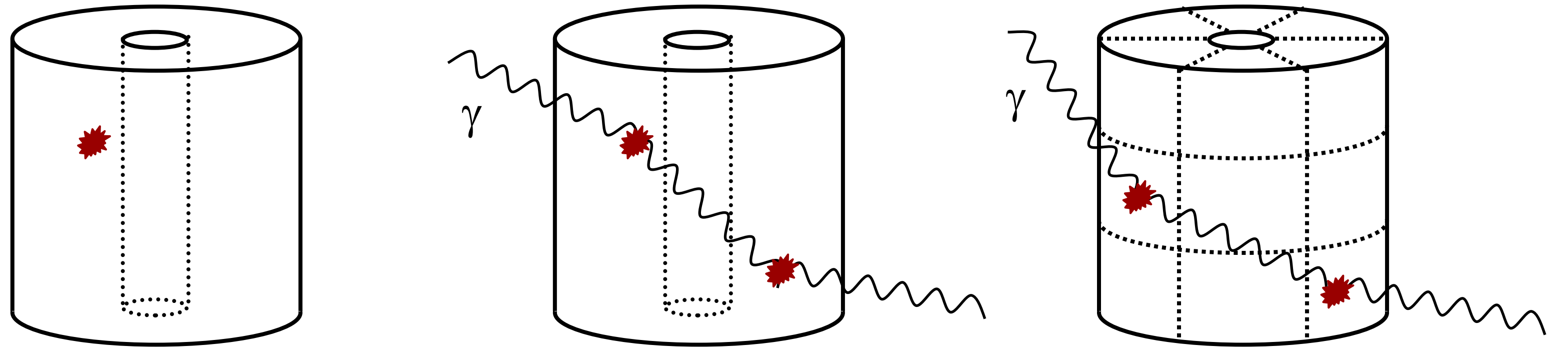
GERDA current status



Segmented germanium detector

Signal, E=2.039 MeV

Typical background



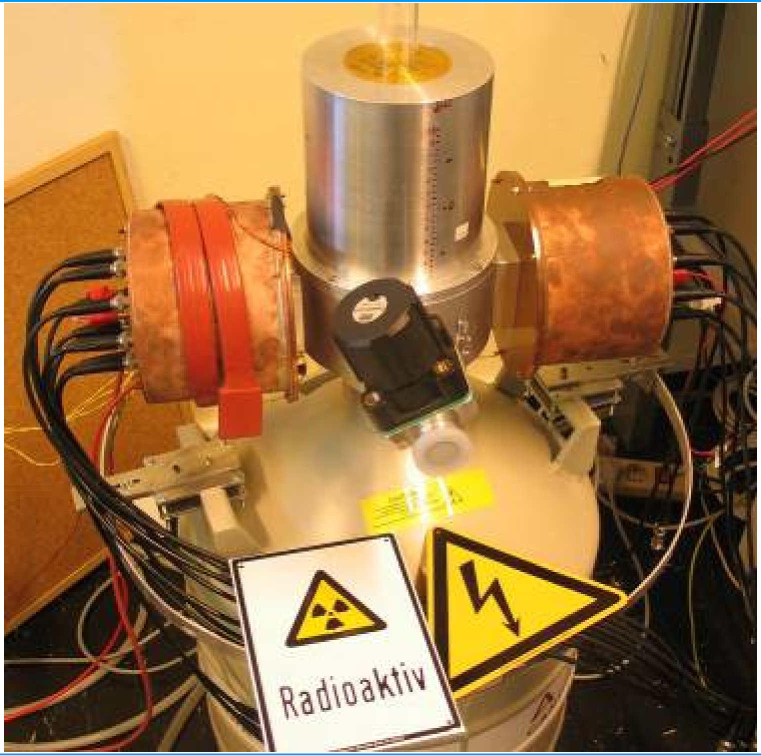
Single-site event

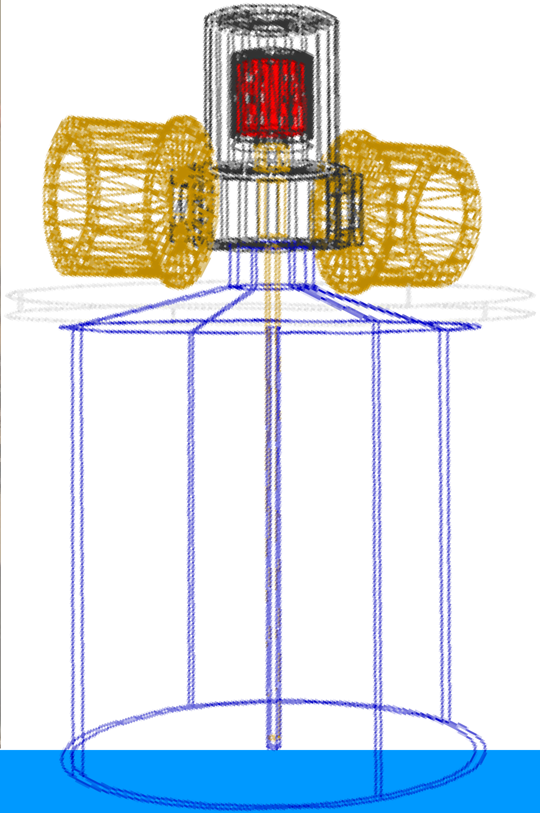
Multi-site event

Multi-segment event

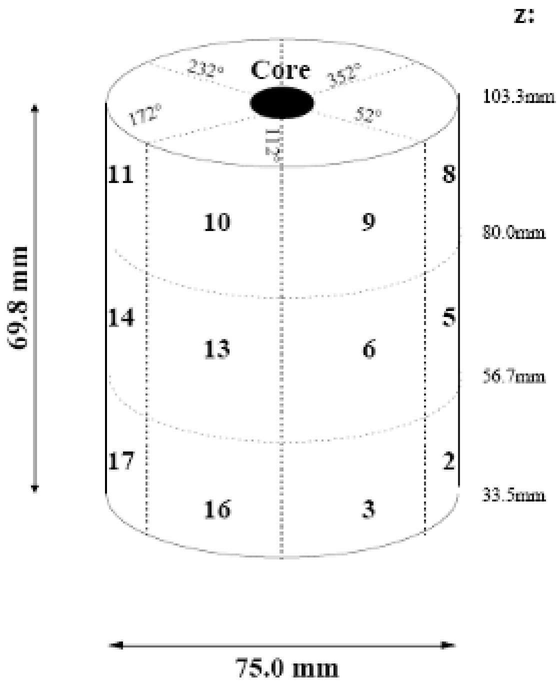
Segmented germanium detector test stands…

Test stand for the first GERDA Phase II prototype detector





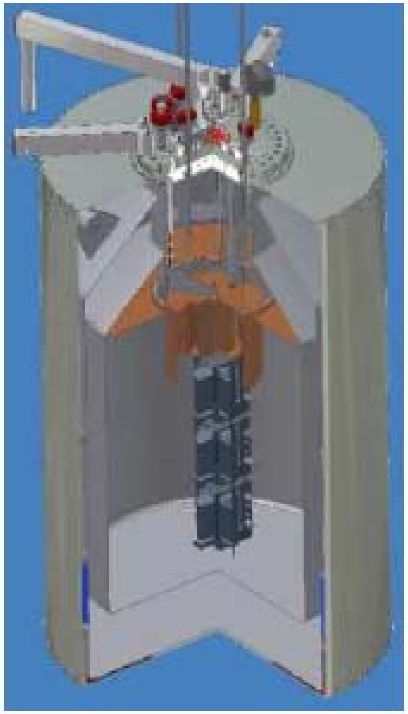
Siegfried I – first 18-fold segmented true co-axial detector



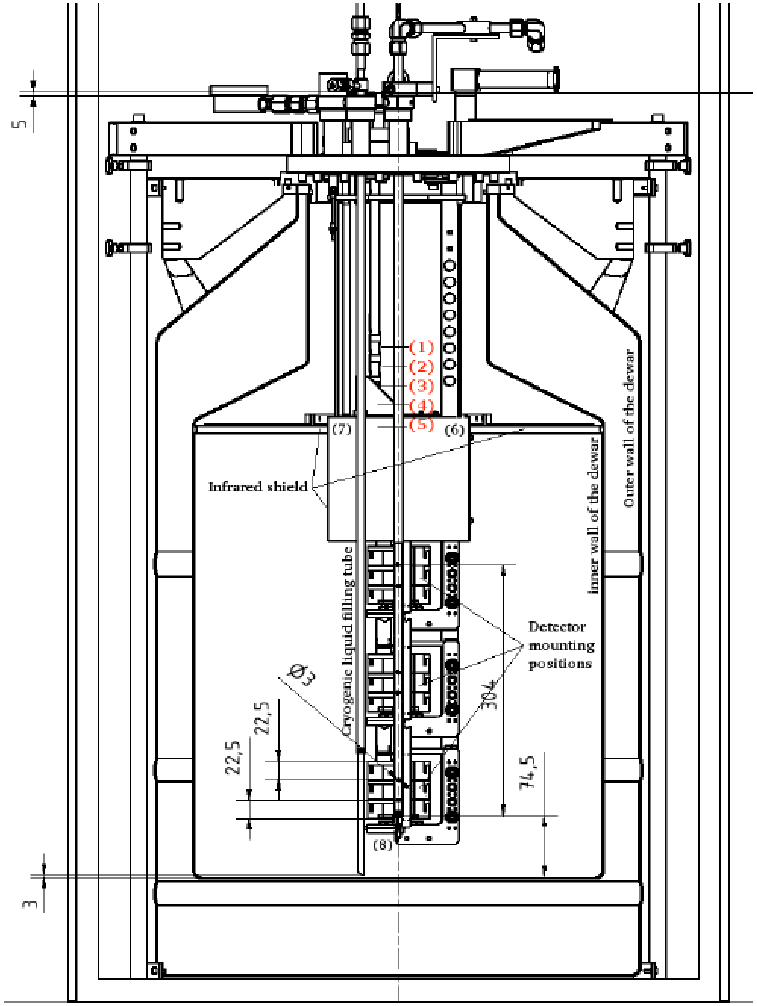
Detector:

- Natural germanium
- n-type
- True coaxial
- Segmented: 3(z) x 6(ϕ)
- Resolution ~3keV@1.3MeV

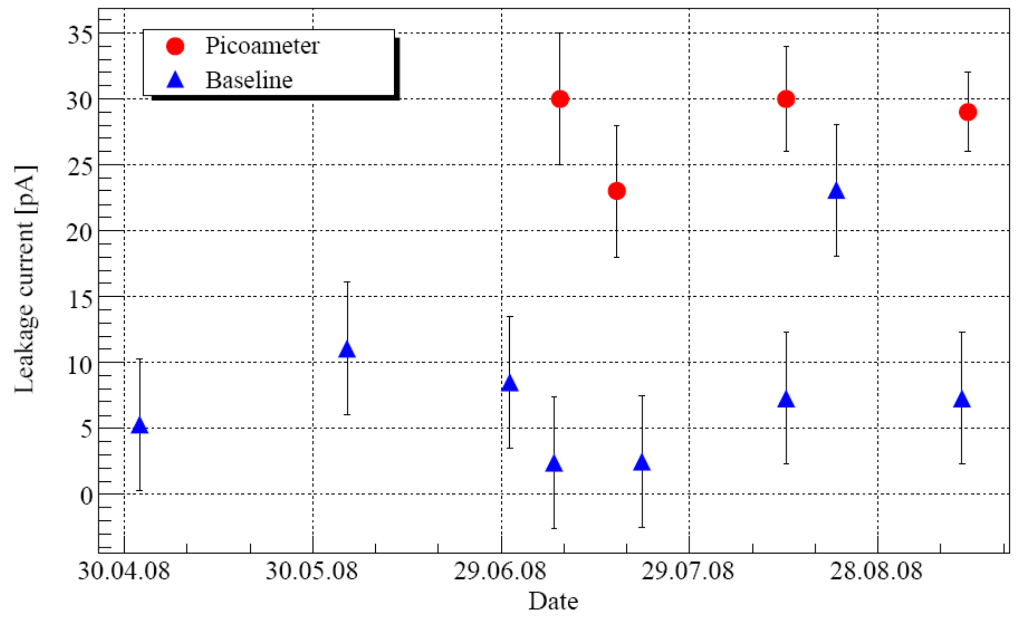
Gerdalinchen II – little GERDA



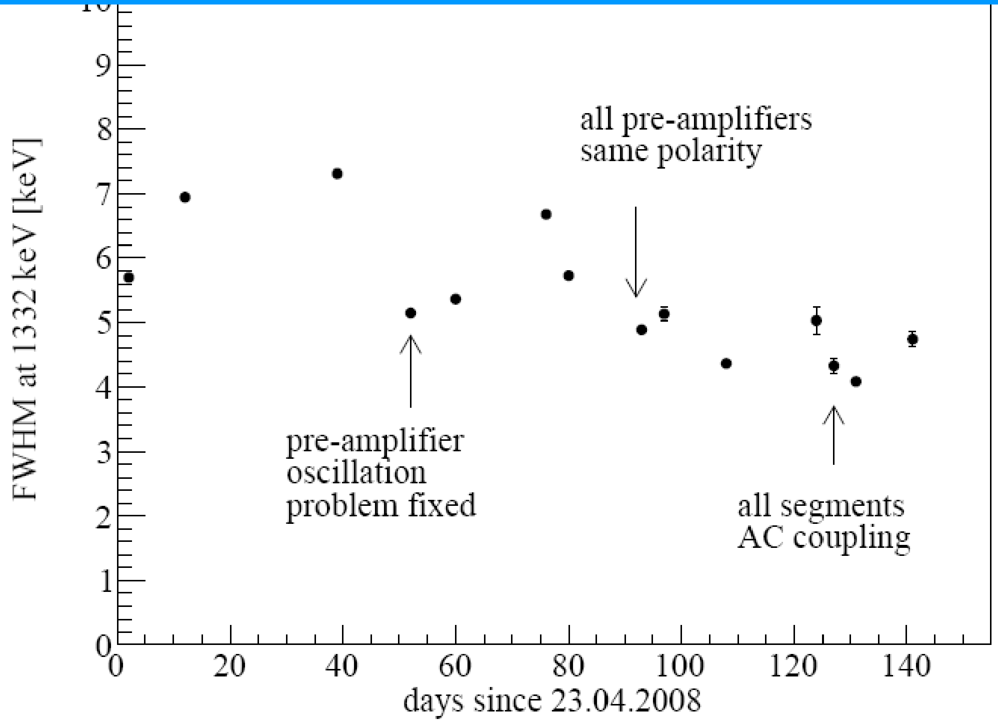

Leakage current measurement



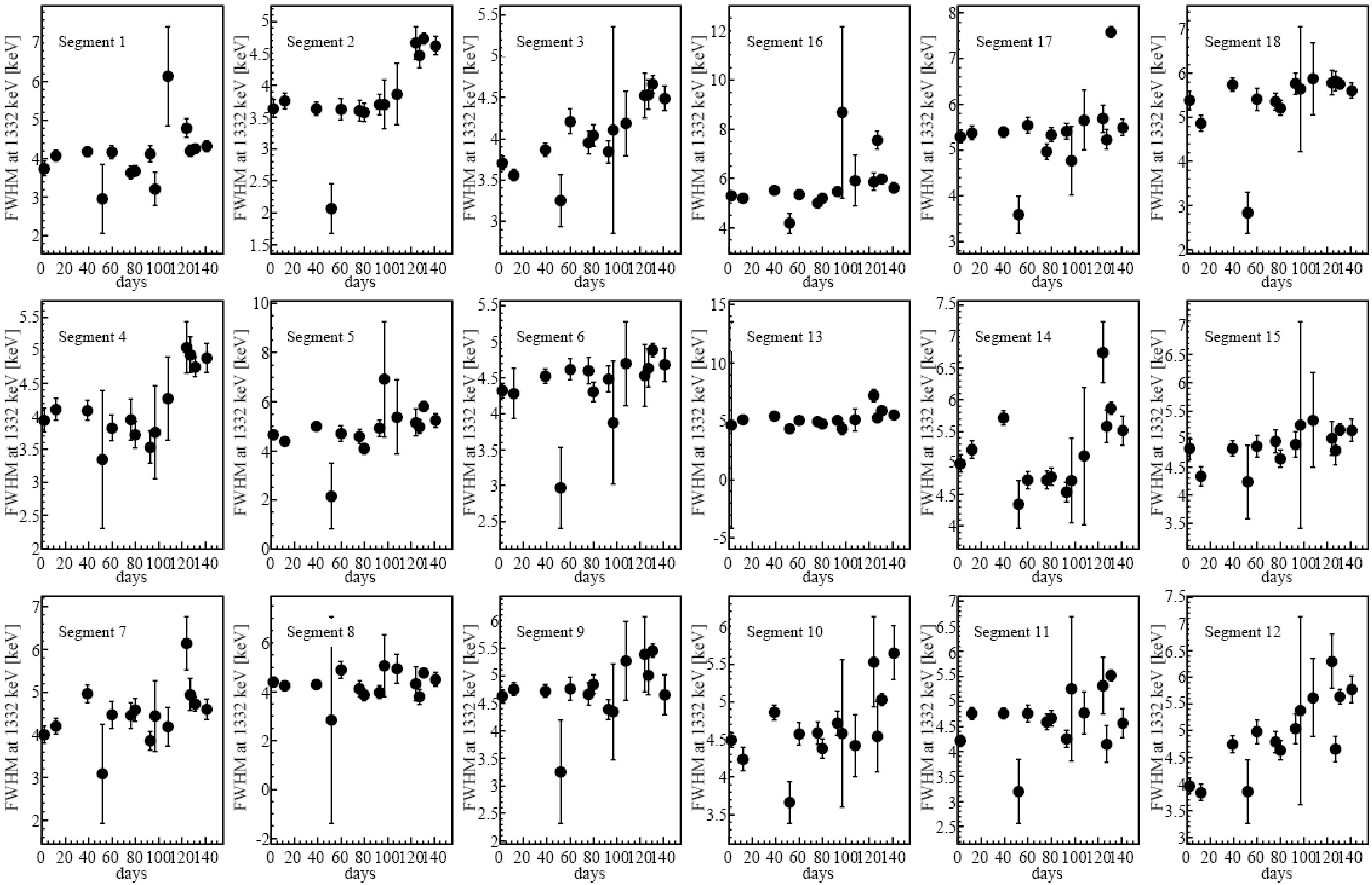
Four months of operation in LN_2



Core resolution

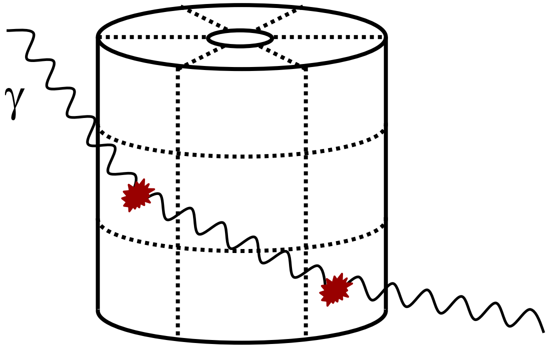


Segment resolution



Photon induced background…

Typical behavior of photon induced event

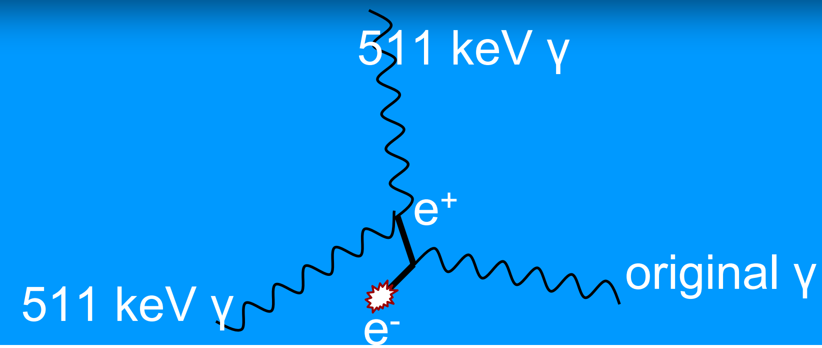


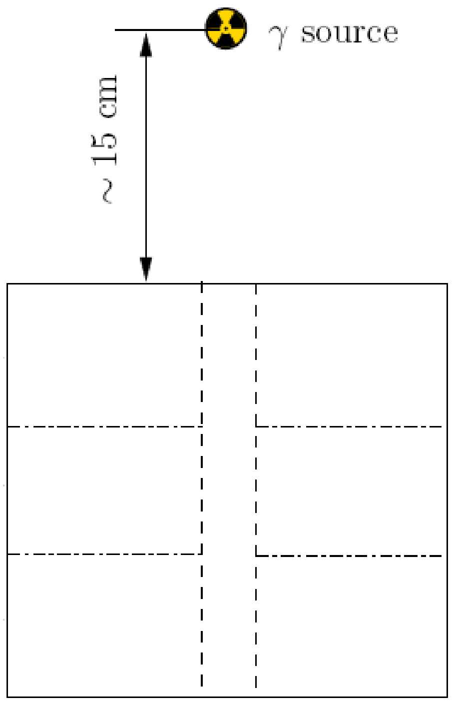
MeV range photons dominantly undergo multi Compton scattering

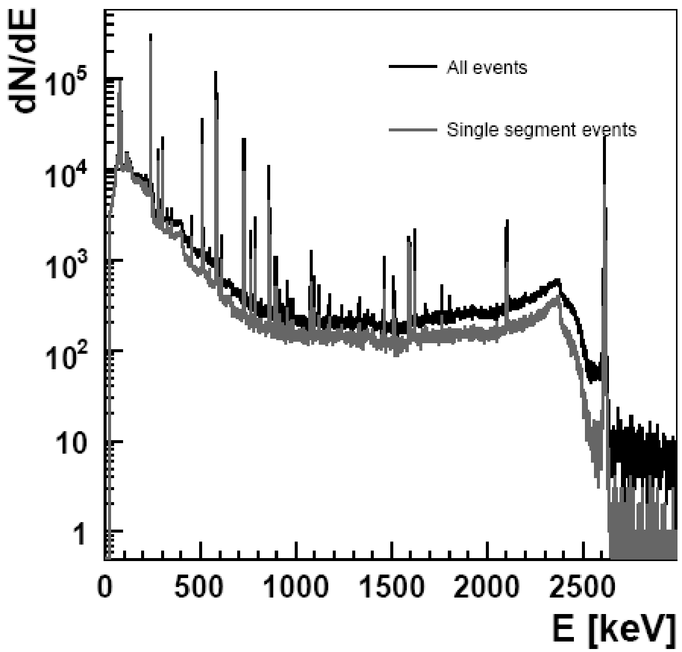
Mean free path ~ several cm

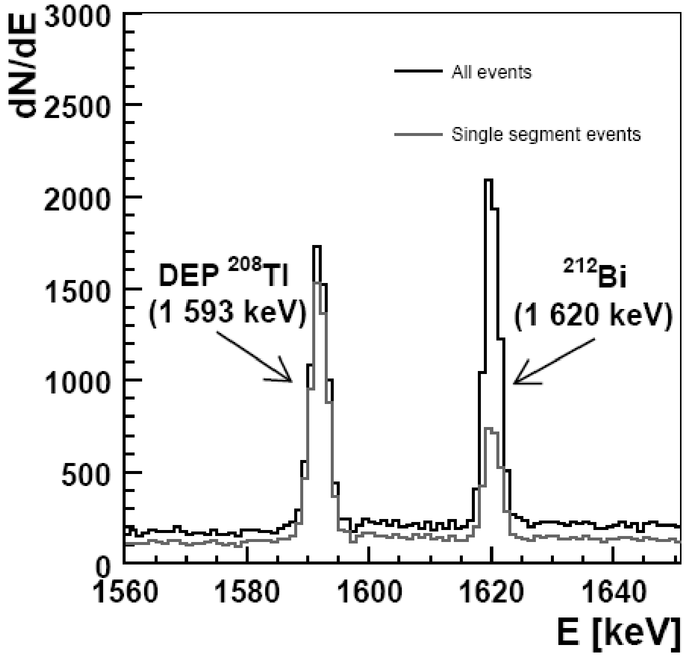
Segment size optimized accordingly

Discrimination power







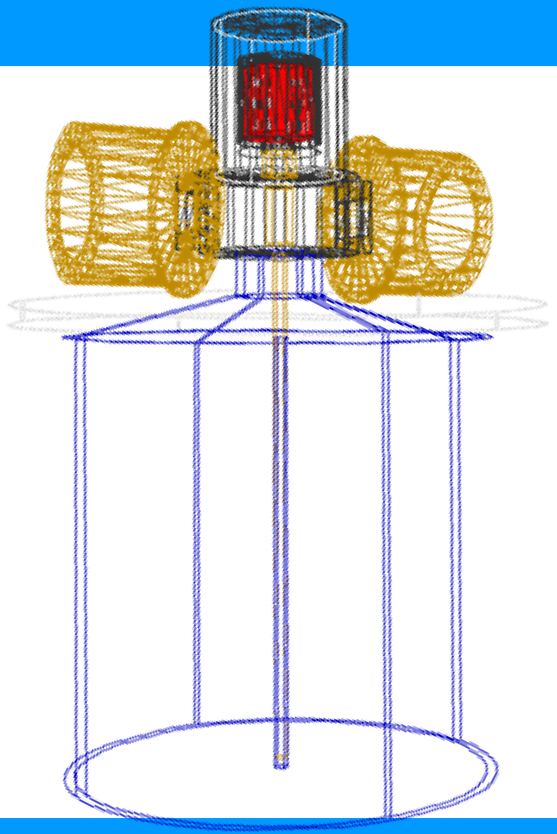


Simulation

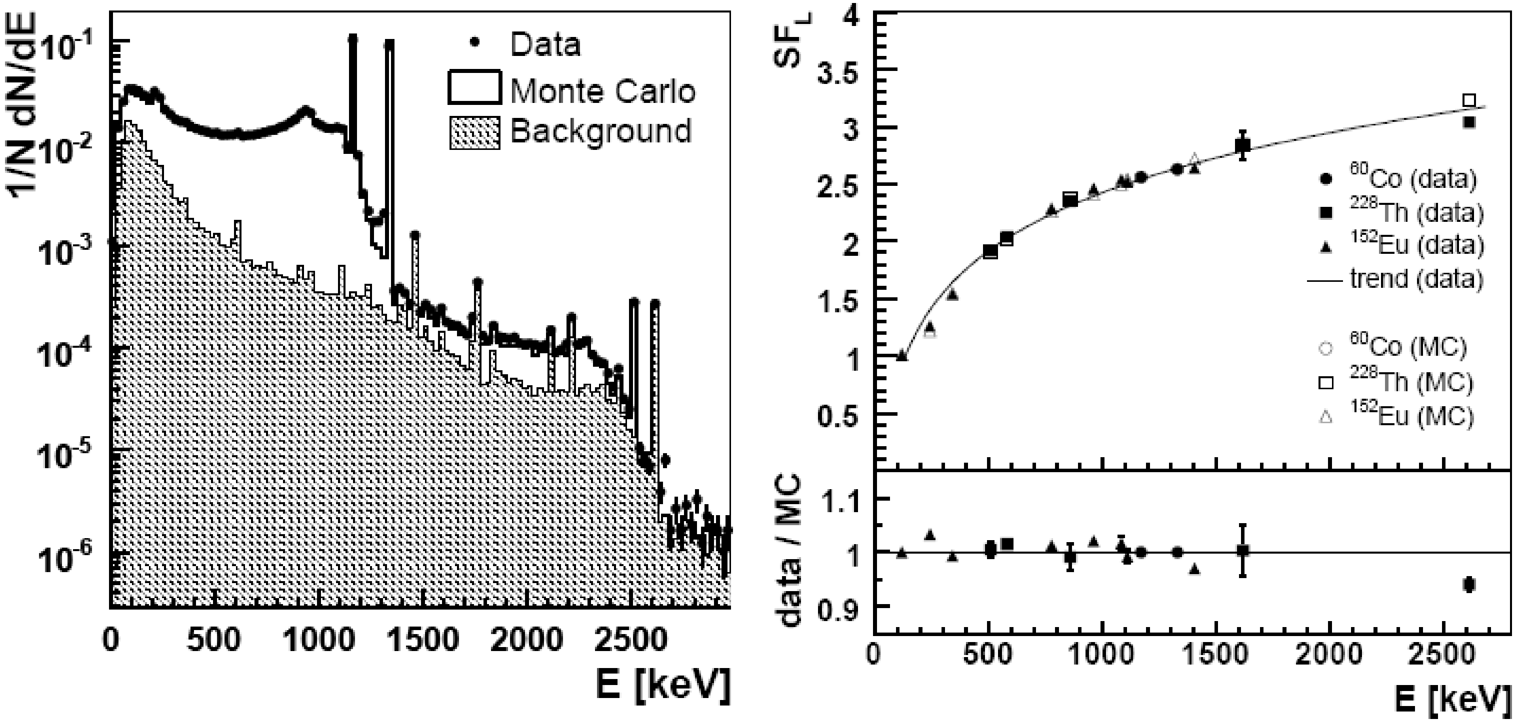
MaGe:

- a C++ simulation package developed by the MC groups of the Majorana and Gerda collaborations

- based on Geant4

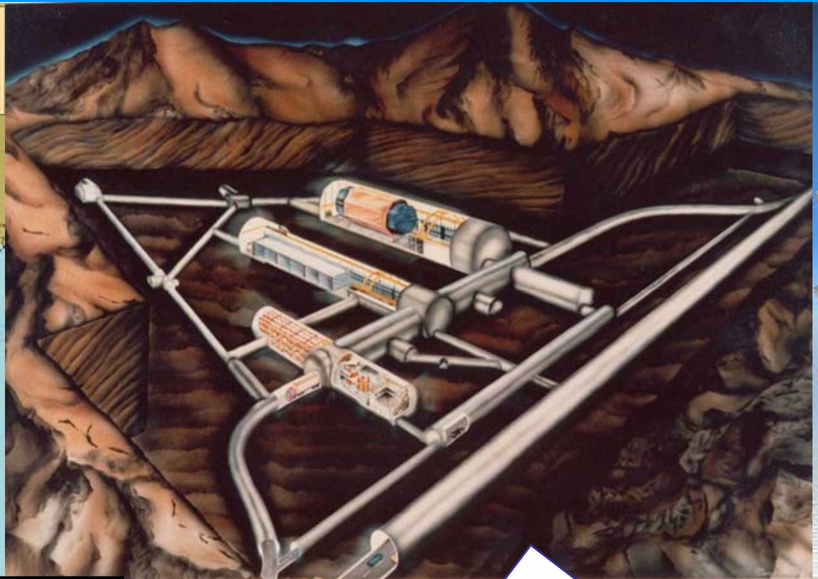


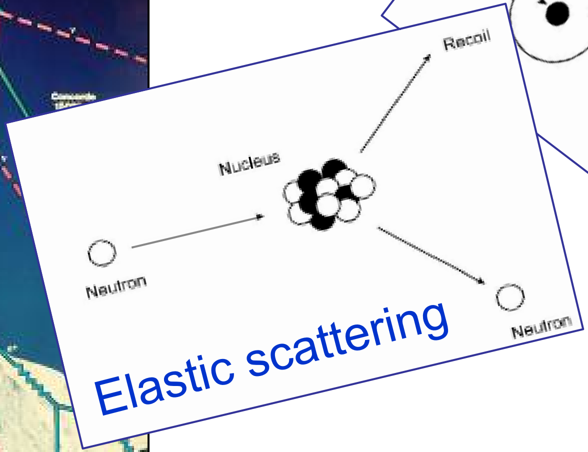
Verify the simulation

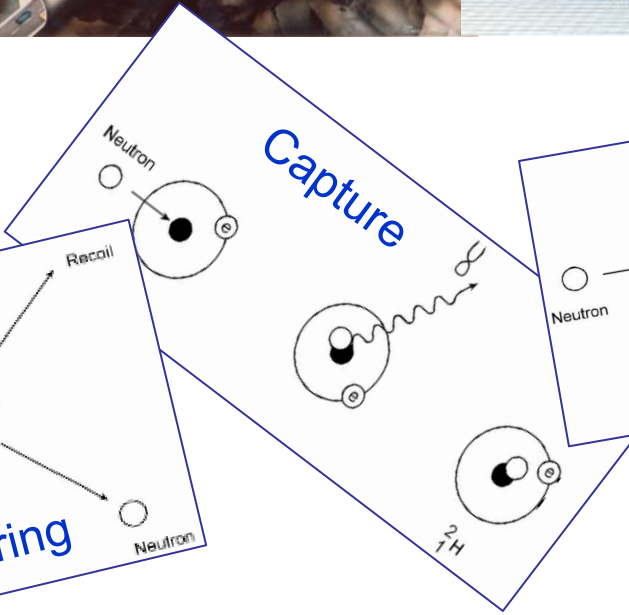


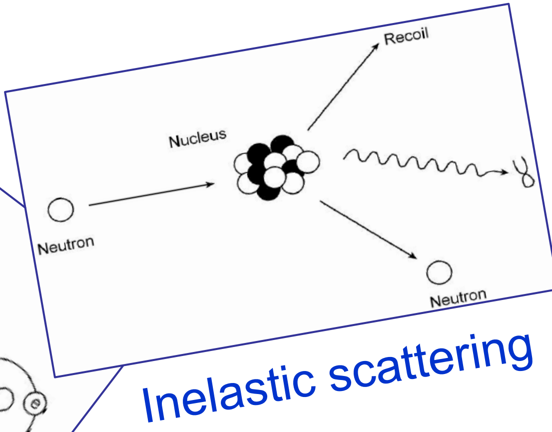
Identification of neutrino interactions with germanium detector…

Neutron as background for GERDA

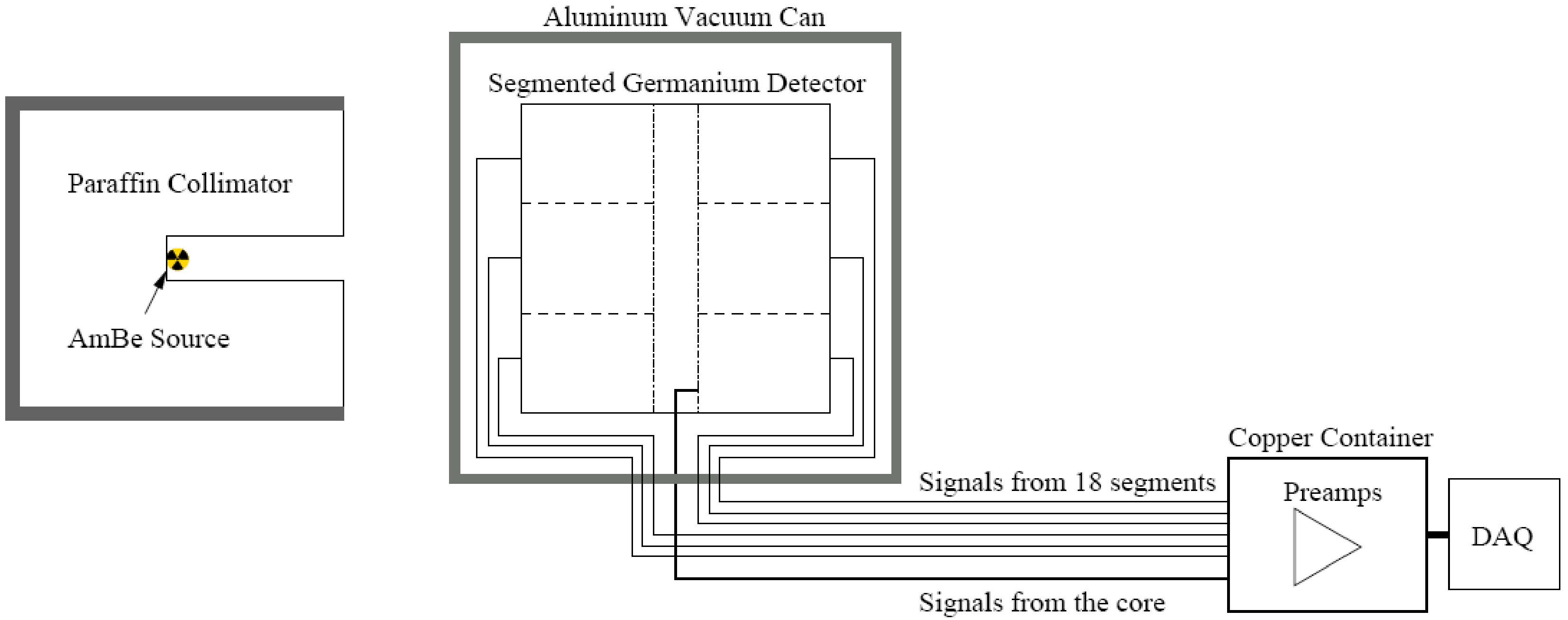








Experimental setup

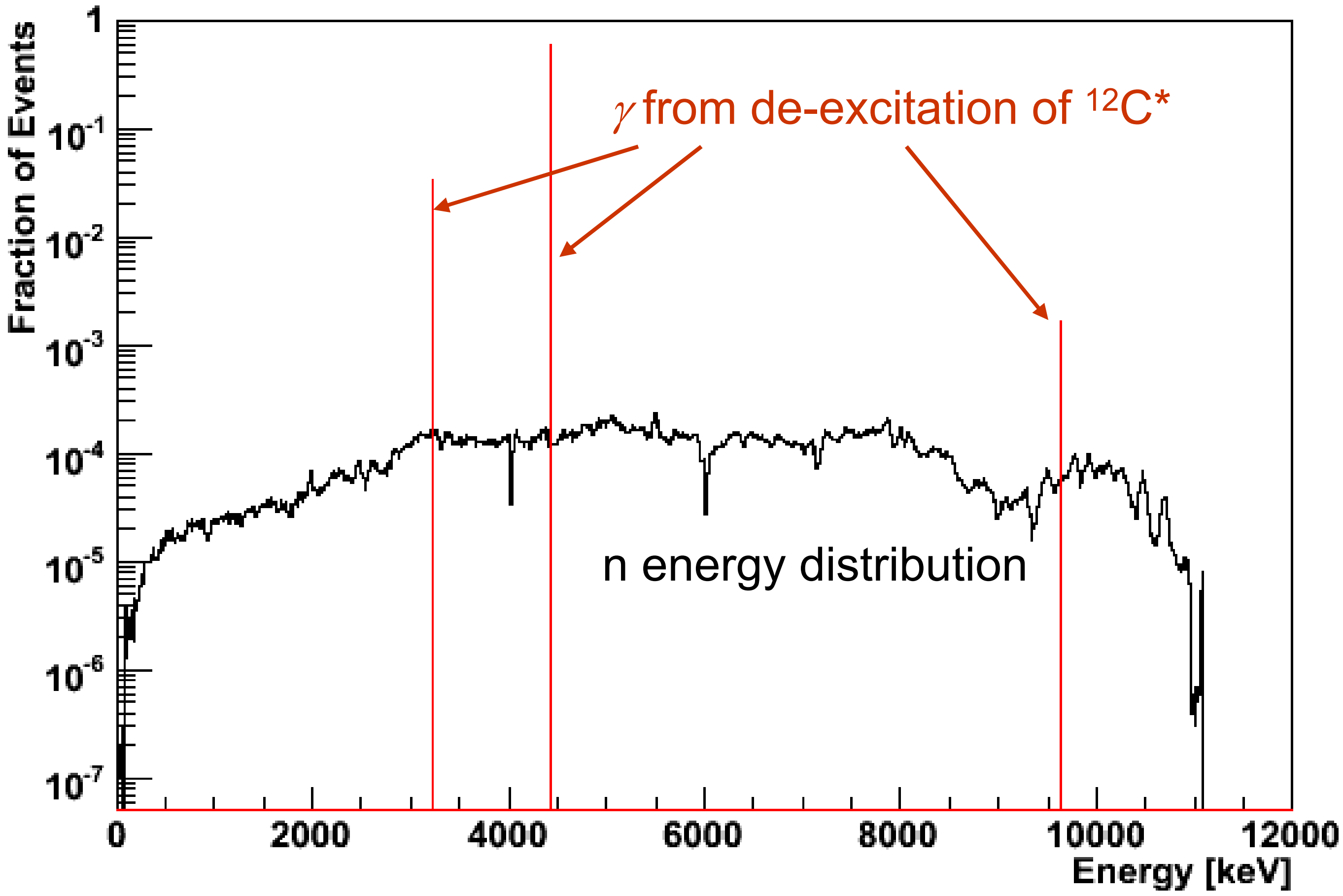


Schematic experimental setup (not to scale).

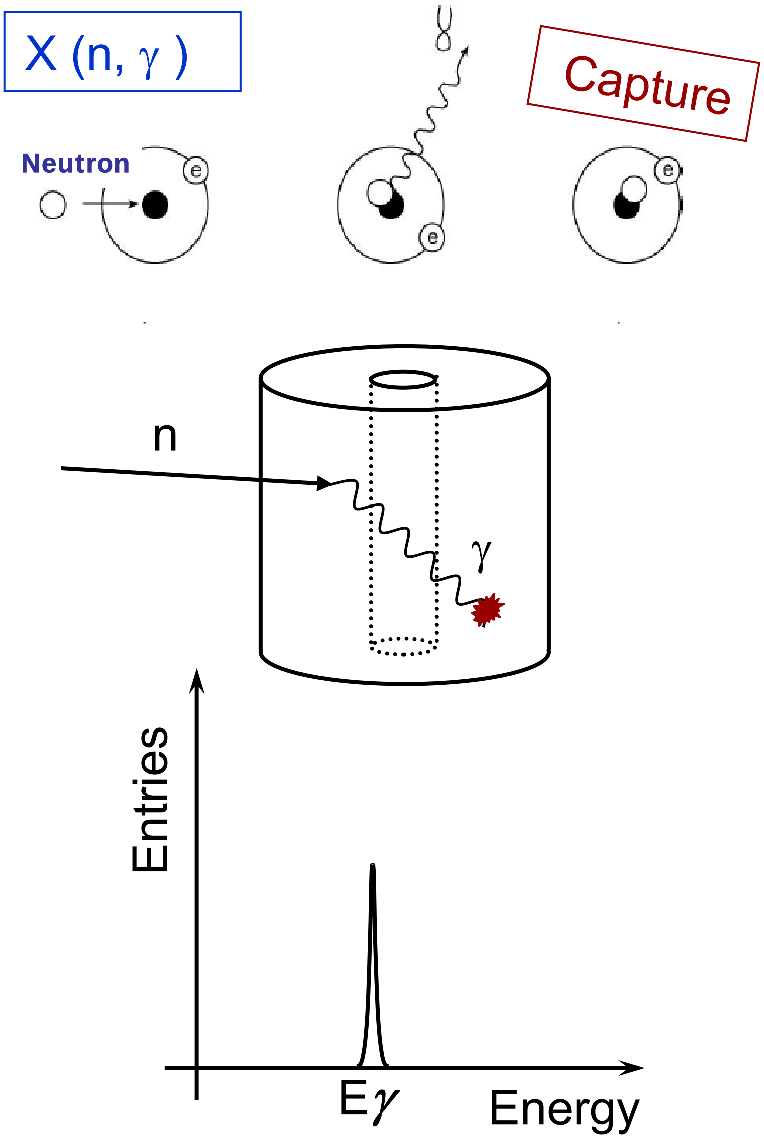
Am-Be neutron source

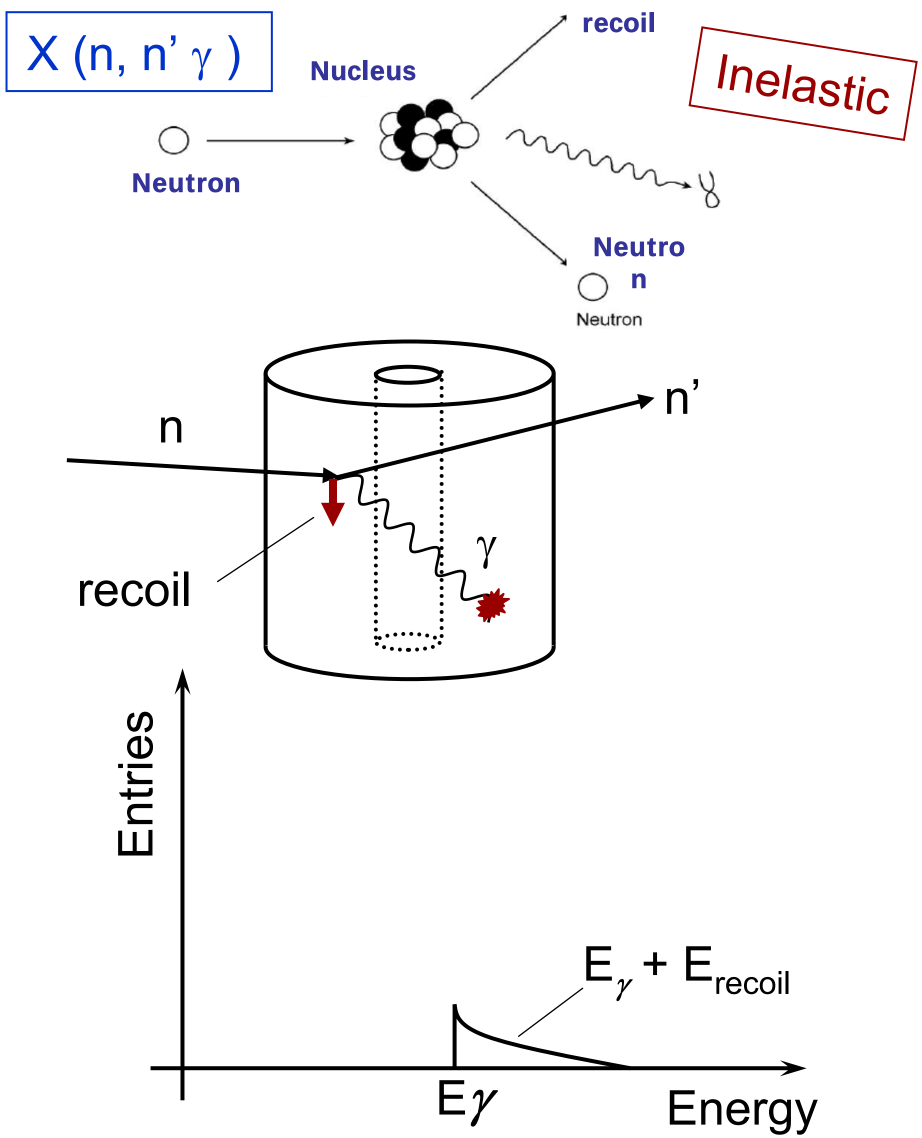
$$^{9}\mathrm{Be}(\alpha, n)^{12}\mathrm{C}^{*}$$

~ 500 neutrons / second

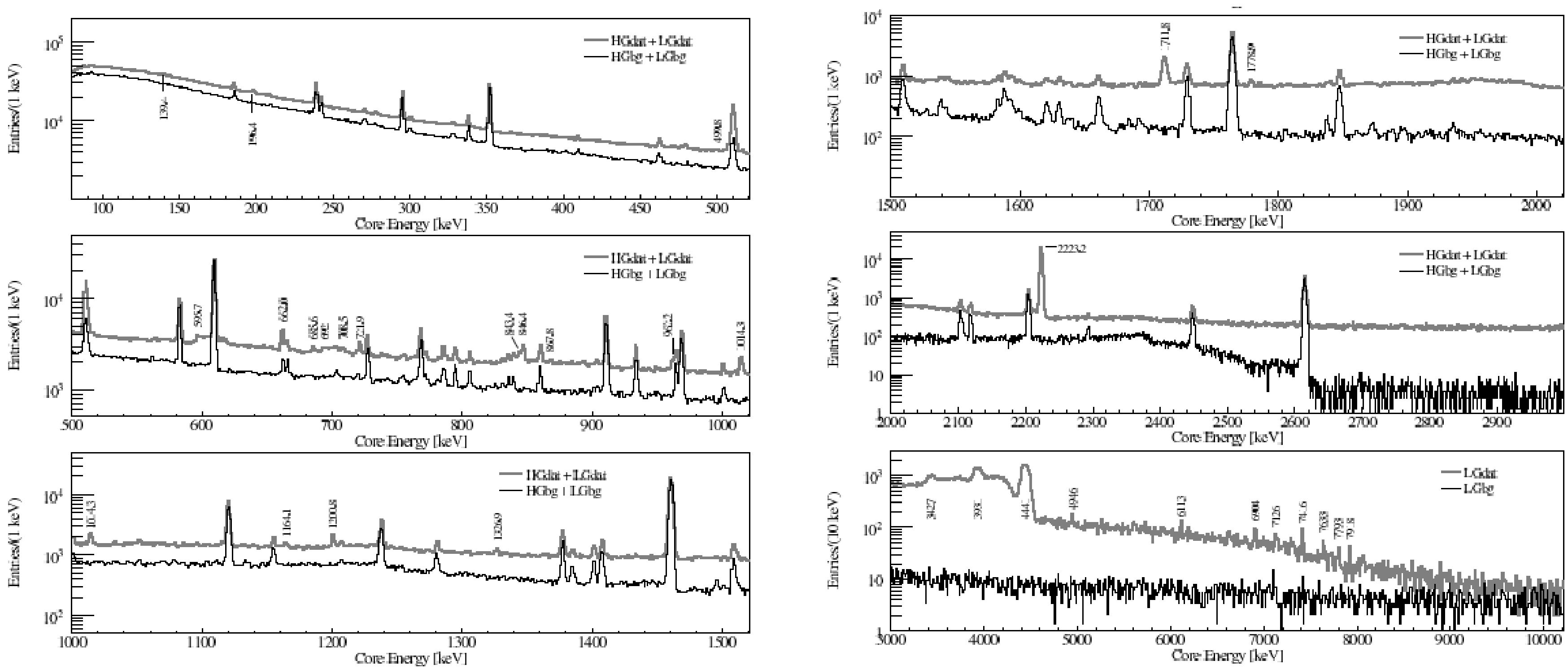


Neutron interactions that can be identified





Core energy spectra

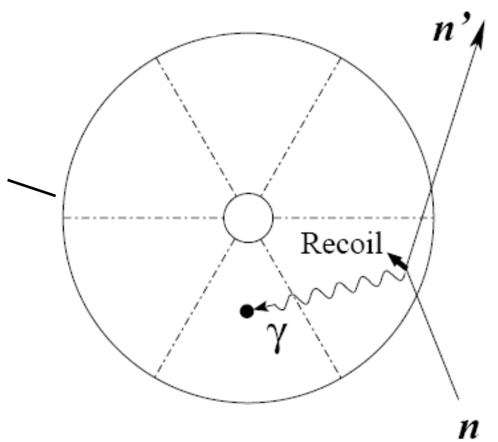


Peaks induced by AmBe neutron source

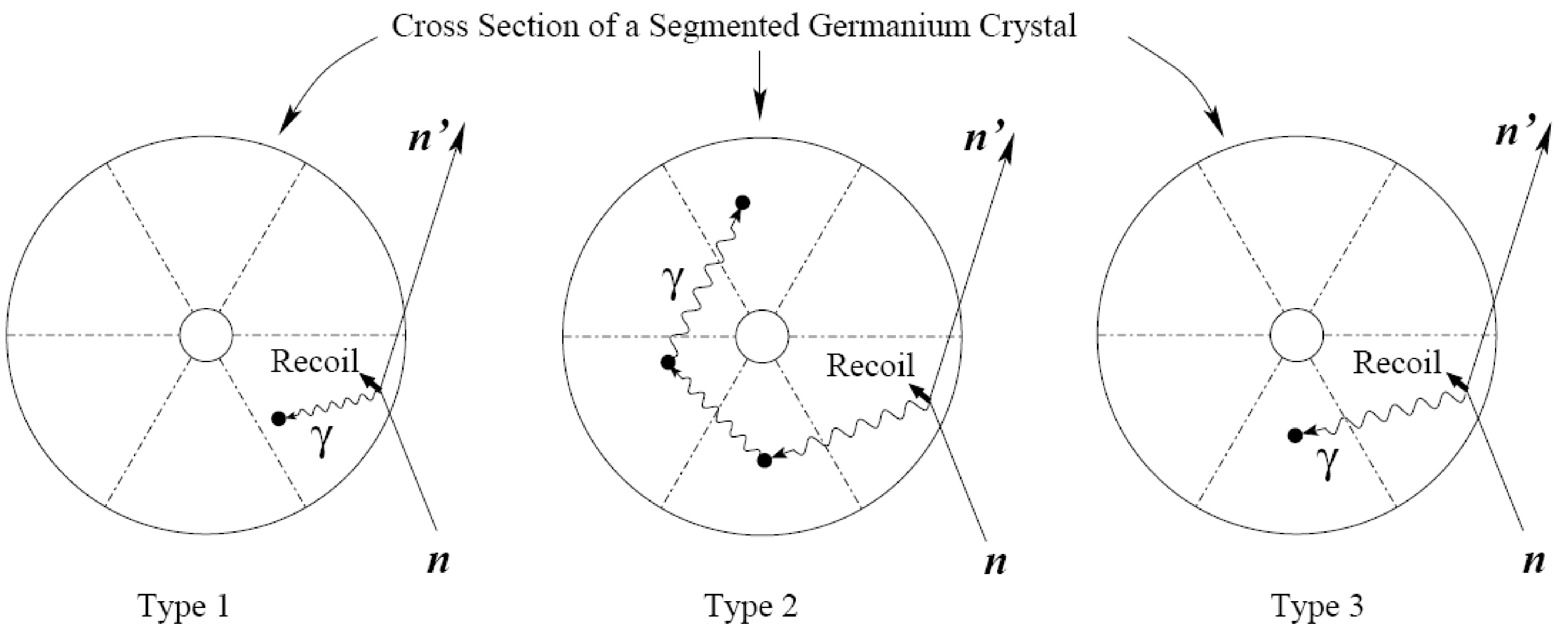
Fitted Energy [keV]	Fitted FWHM [keV]	Interaction Type	Number of Events
139.4	1.6 ± 0.2	^{74}Ge(n, γ^m)	3377 ± 520
197.9	1.9 ± 0.2	^{70}Ge(n, γ^m)	3306 ± 503
499.8	1.9 ± 0.7	^{70}Ge(n, γ)	503 ± 186
595.7^a	-	^{74}Ge$(n, n'\gamma)$	$(18.4 \pm 2.5) \times 10^3$
662.0^b	1.9 ± 0.1	^{140}Ce(n, γ)	2802 ± 188
685.6	1.4 ± 0.2	?^{c}	628 ± 111
692^d	-	^{72}Ge$(n, n'e)$	$\sim 7000^e$
708.5	2.4 ± 0.5	^{35}Cl(n, γ), ^{36}Cl$\rightarrow$^{36}Ar	782 ± 197
721.9	1.9 ± 0.2	?^{c}	3502 ± 148
843.4	2.4 ± 0.5	^{27}Al$(n, n'\gamma)$	1558 ± 202
846.6	2.4 ± 0.2	^{56}Fe$(n, n'\gamma)$	2802 ± 196
867.8	1.9 ± 0.5	^{73}Ge(n, γ)	425 ± 129
962.2	2.4 ± 0.2	^{63}Cu$(n, n'\gamma)$	1041 ± 129
1014.3	2.4 ± 0.2	^{27}Al$(n, n'\gamma)$	1958 ± 123
1164.1	2.6 ± 0.5	^{35}Cl(n, γ)	646 ± 140
1200.8	2.8 ± 0.2	DEP^f of 2223	2318 ± 122
1326.9	2.4 ± 0.2	^{63}Cu$(n, n'\gamma)$	711 ± 91
1711.8	3.8 ± 0.1	SEP^f of 2223	5555 ± 133
1778.9	2.6 ± 0.2	^{27}Al(n, γ), ^{28}Al$\rightarrow$^{28}Si	469 ± 73
2223.2	3.8 ± 0.1	^{1}H(n, γ)	79349 ± 300

Fitted Energy [keV]	Fitted FWHM [keV]	Interaction Type	Number of Events
3427	85 ± 7	DEP^a of 4441	2354 ± 263
3931	87 ± 5	SEP^a of 4441	5873 ± 368
4441	92 ± 2	^{9}Be$(\alpha, n)^{12}$C*	14672 ± 297
4946	4.9 ± 1.4	^{12}C(n, γ)	68 ± 15
6113	7^b	^{35}Cl(n, γ)	75 ± 12
6904	7^b	SEP^a of 7416	60 ± 10
7126	7^b	?^{c}	38 ± 9
7416	7^b	^{35}Cl(n, γ)	70 ± 10
7633	7^b	^{56}Fe(n, γ)	18 ± 10
7793	7.1 ± 2.1	^{35}Cl(n, γ)	21 ± 8
7918	6.8 ± 1.4	^{63}Cu(n, γ)	29 ± 8

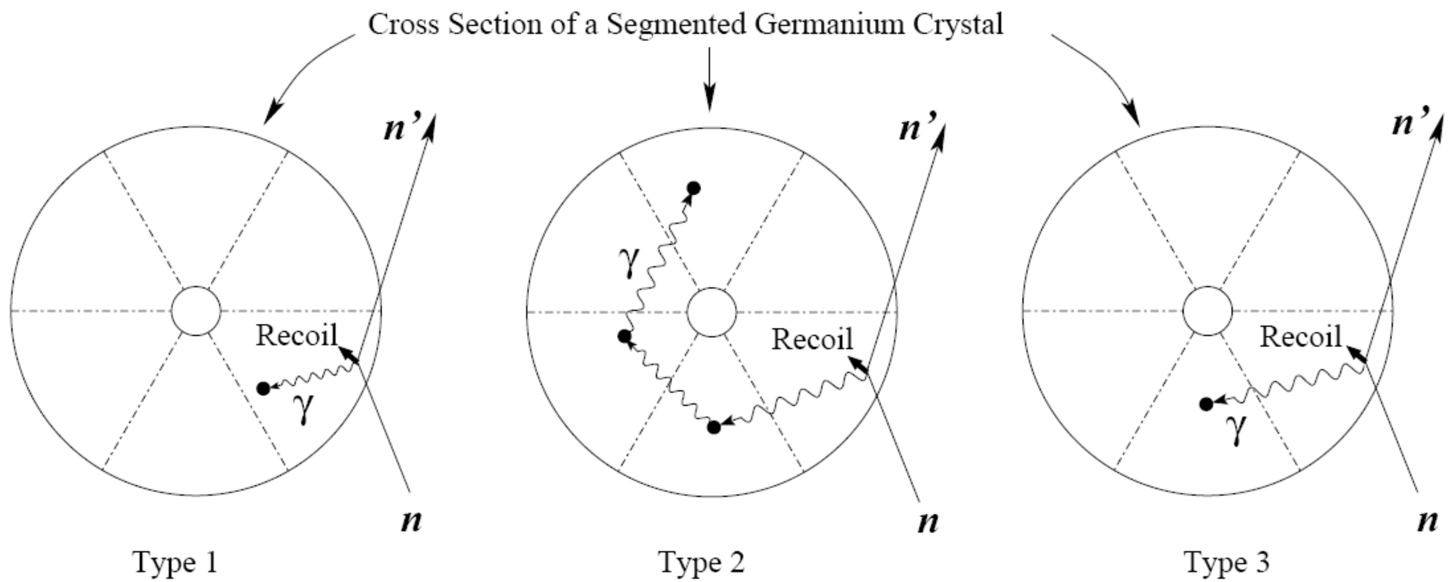
Cross section of the detector

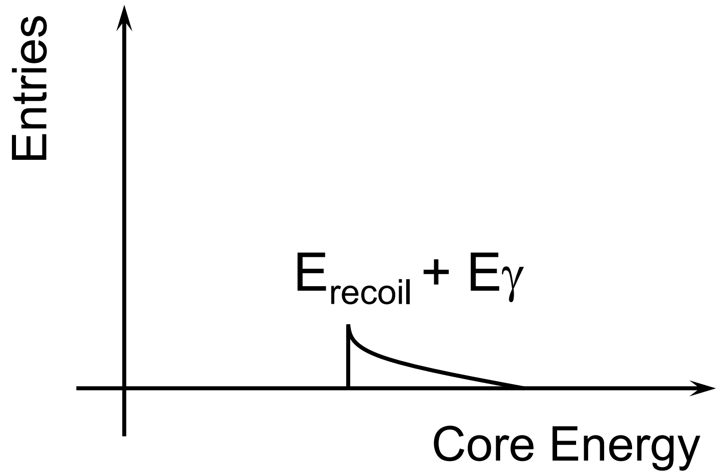


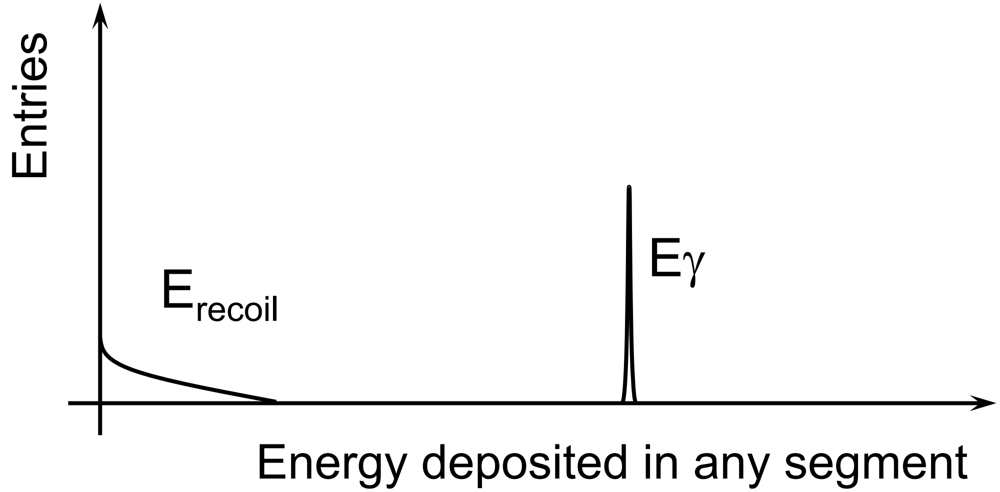
Interaction topologies of events in 595.7 keV peak from ^{74}Ge(n,n'γ)



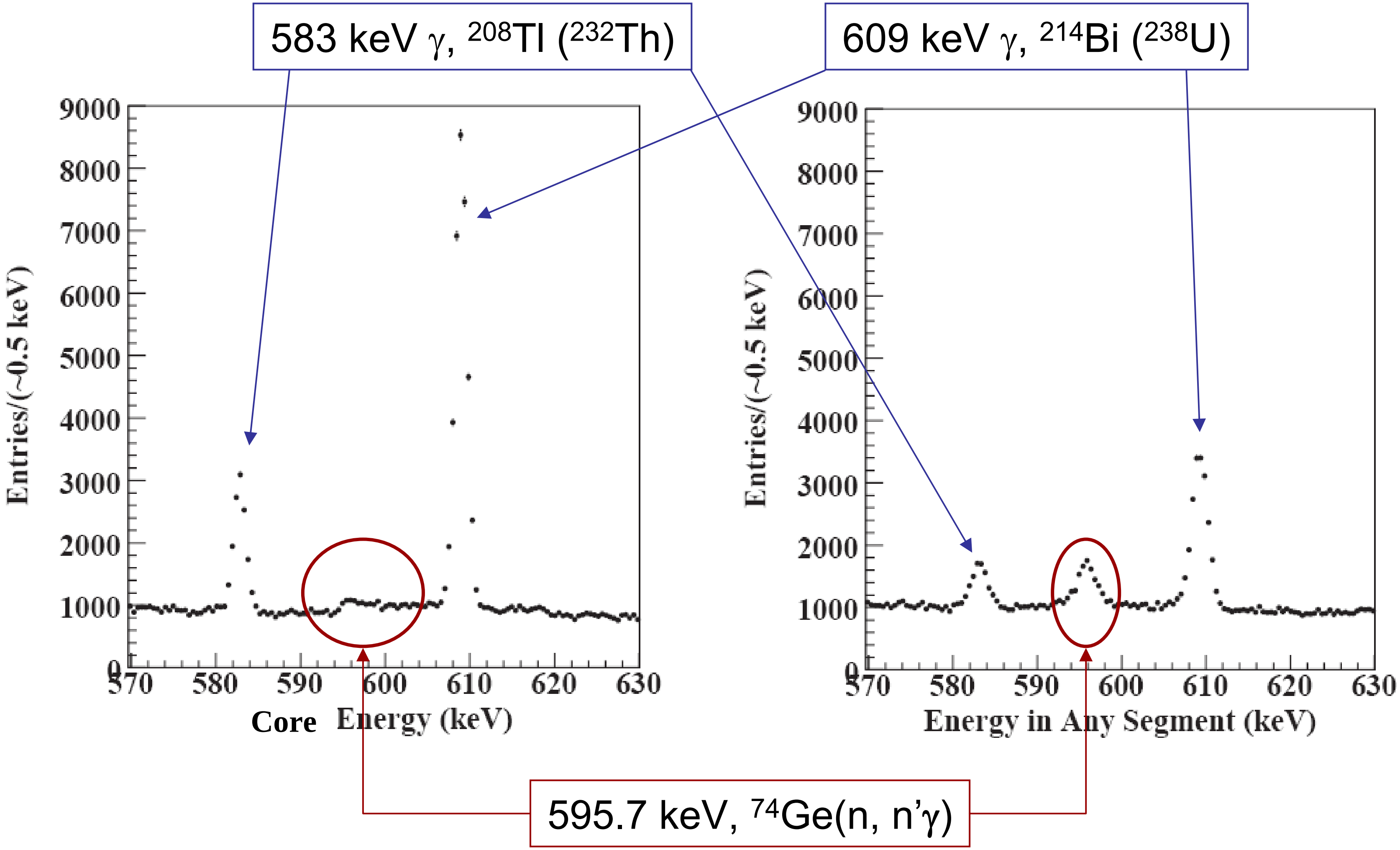
Interactions as seen by core & segments



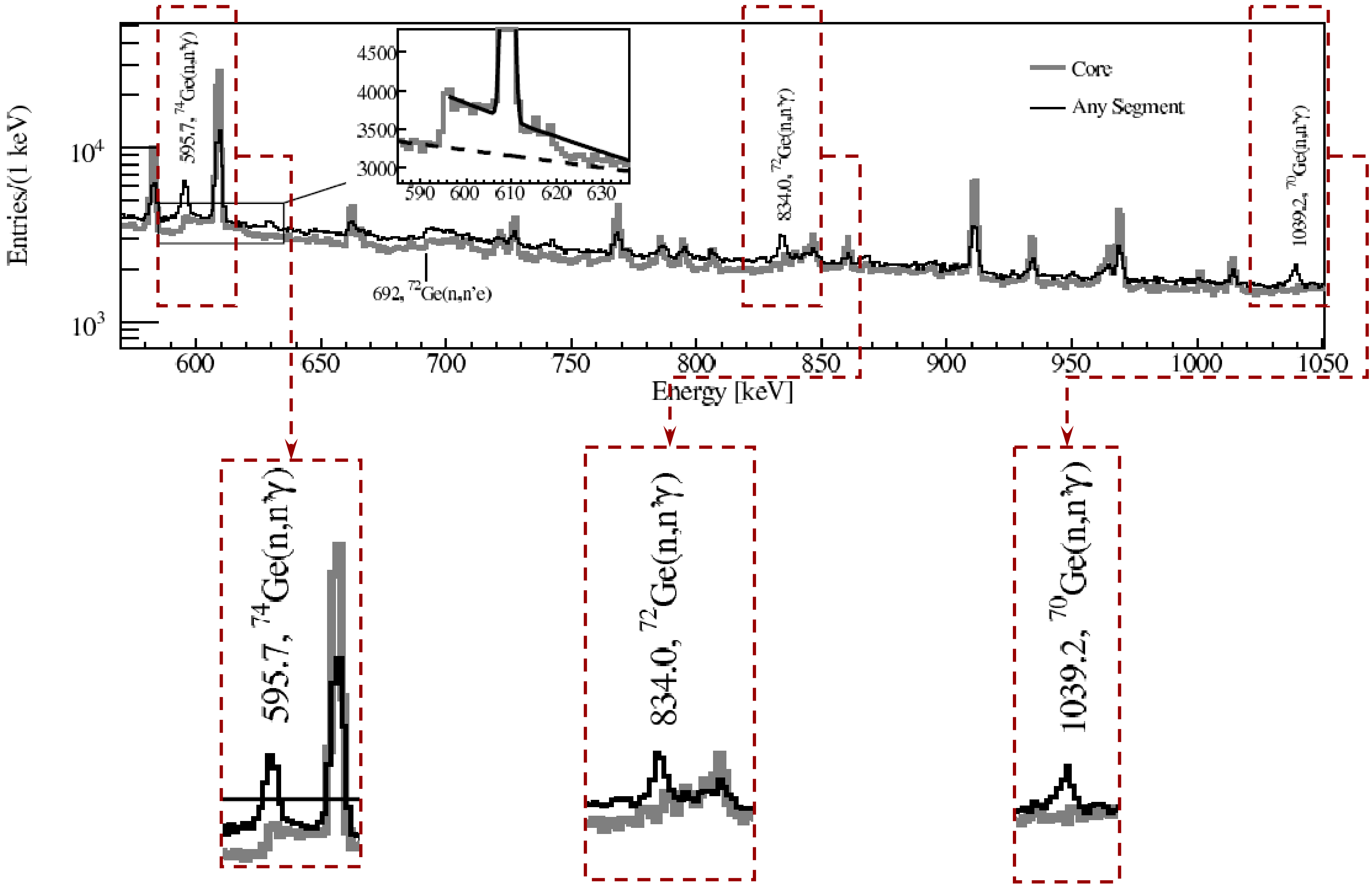




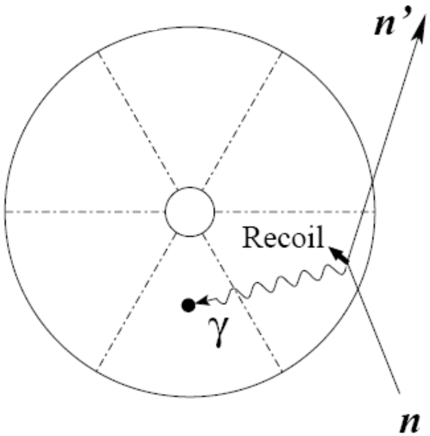
595.7 keV peak from $^{74}Ge(n, n'\gamma)$



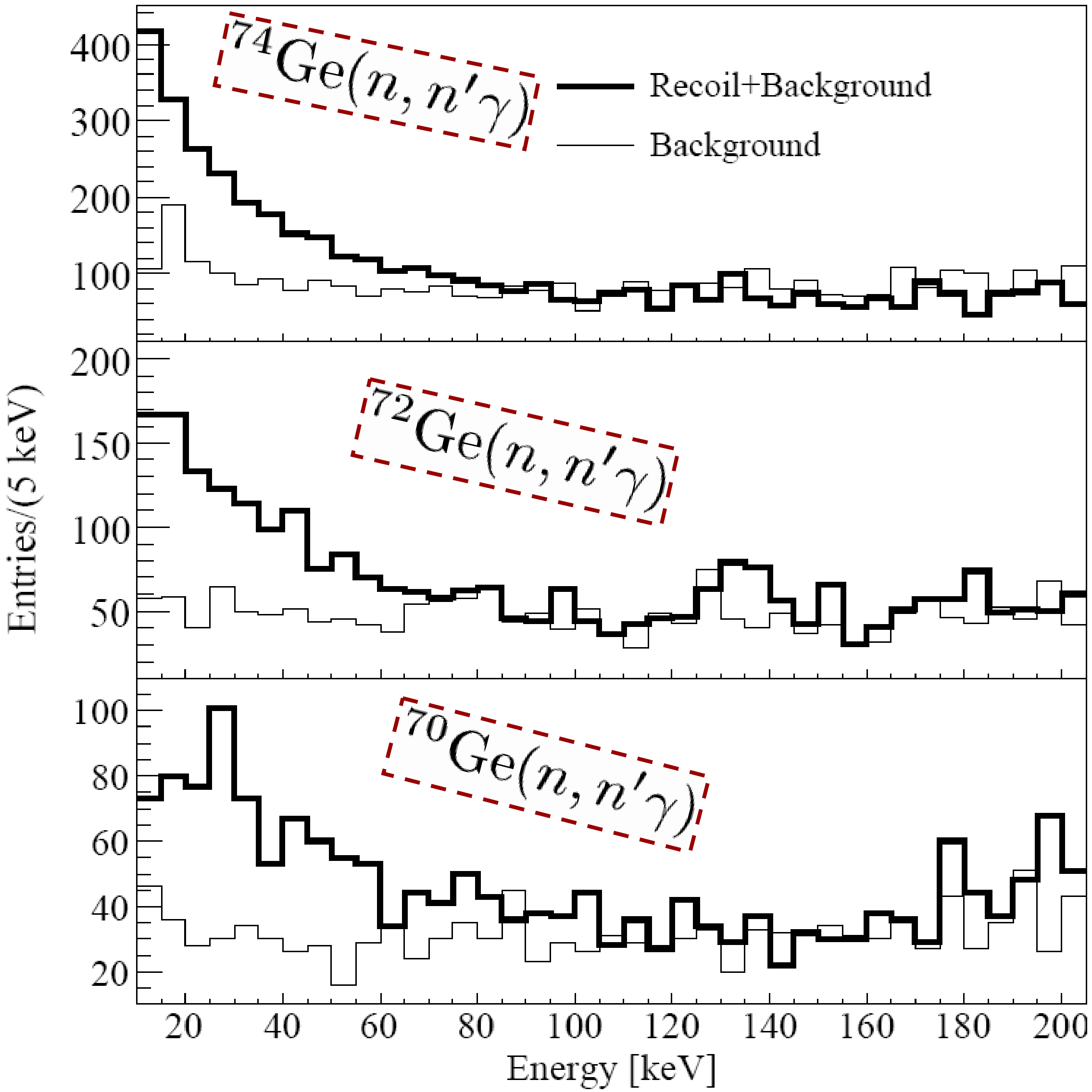
Two more peaks from neutron inelastic scattering



Recoil energy spectra

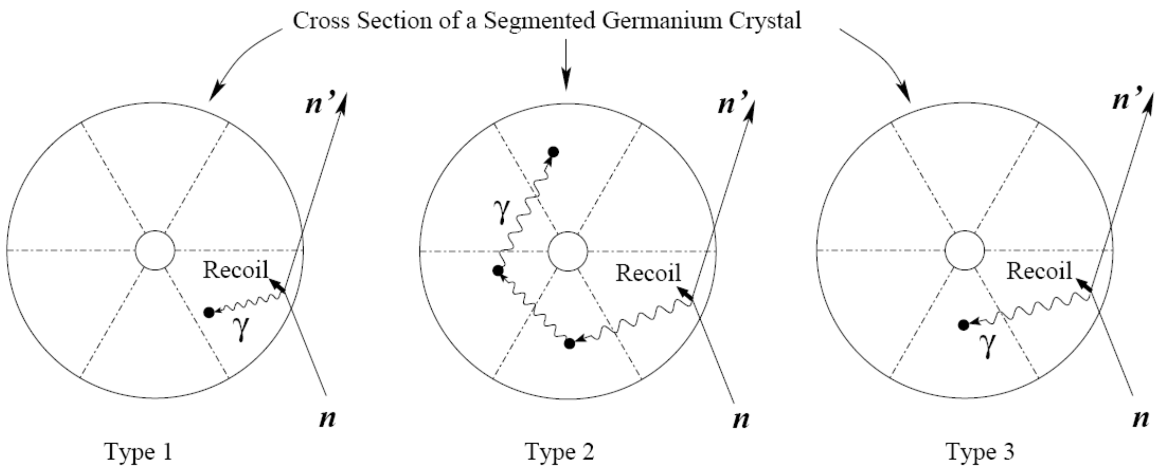


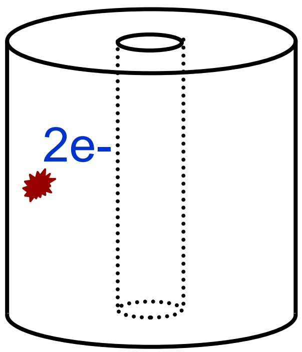
Type 3



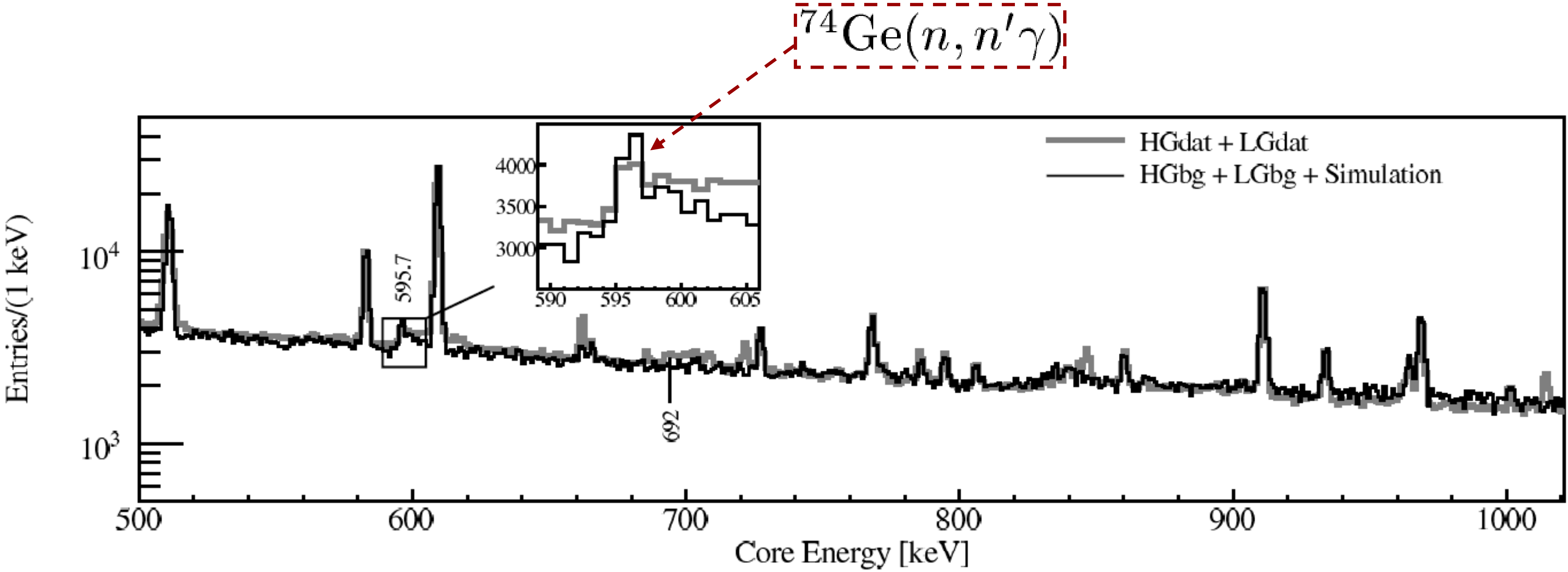
Number of events belonging to different types

E [keV]	N_{type1}	N_{type2}	N_{type3}	N_{total}
595.8	$(1 \pm 1) \times 10^3 *$	$(10 \pm 3) \times 10^3$	7285 ± 218	$(18.4 \pm 2.5) \times 10^3$
834.0	[0, 380]	[4100, 4700]	2592 ± 186	[6700, 7700]
1039.2	[0, 240]	[2700, 3100]	1429 ± 182	[4100, 4800]





Nuclear recoil is not simulated by Geant4



Bugzilla/Geant4 – Problem 675: No boost from CM->Lab for G4NeutronHPInelastic

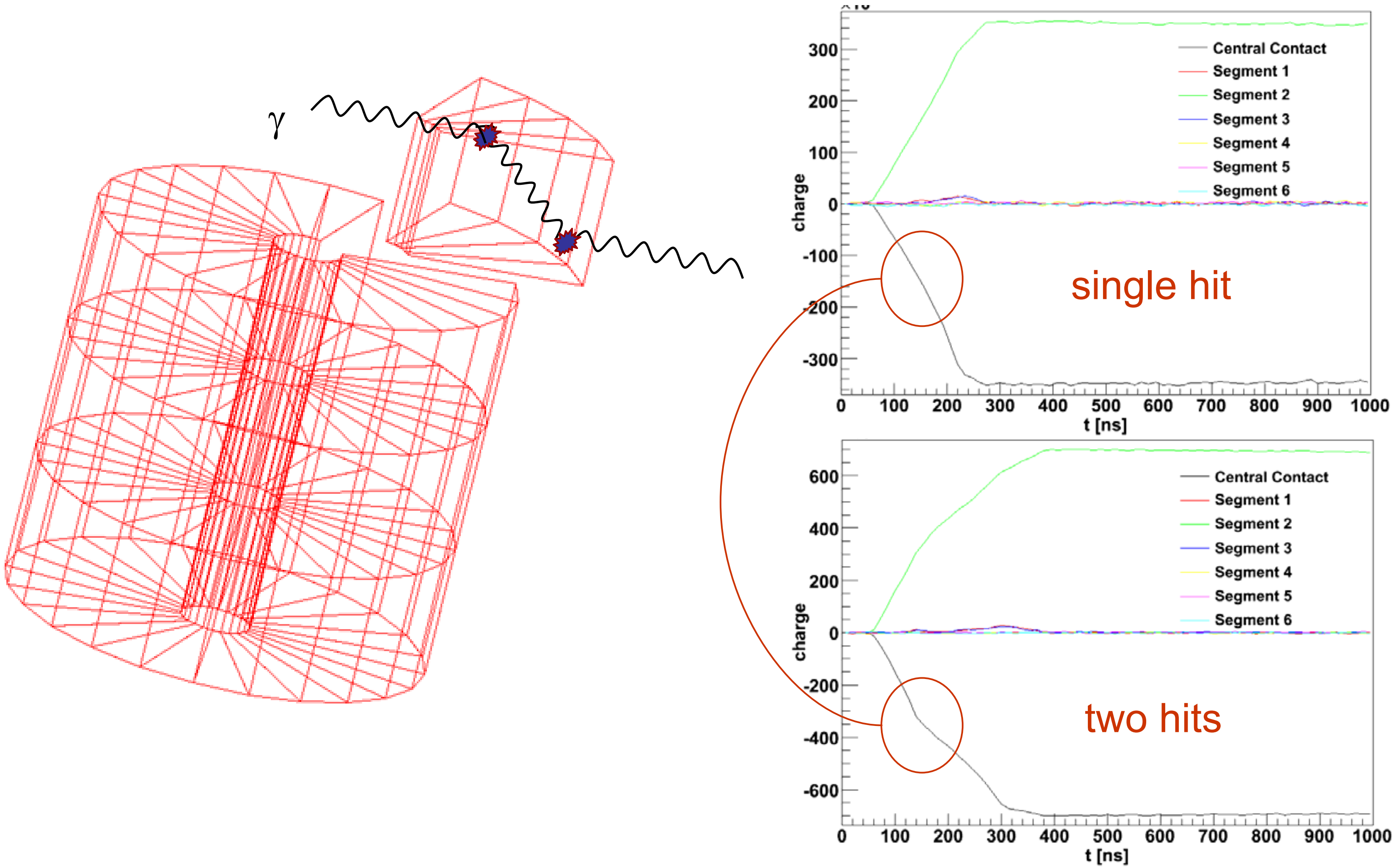
Other Geant4 bugs

- Meta stable states are missing [fixed]
- Internal conversion is missing [fixed]
- Energy of a photon from H(n,γ) is wrong [fixed]

Geant4.8.2-patch01
with G4NDL3.10

Pulse shape simulation…

Pulse shape analysis: last step to reach extreme low background



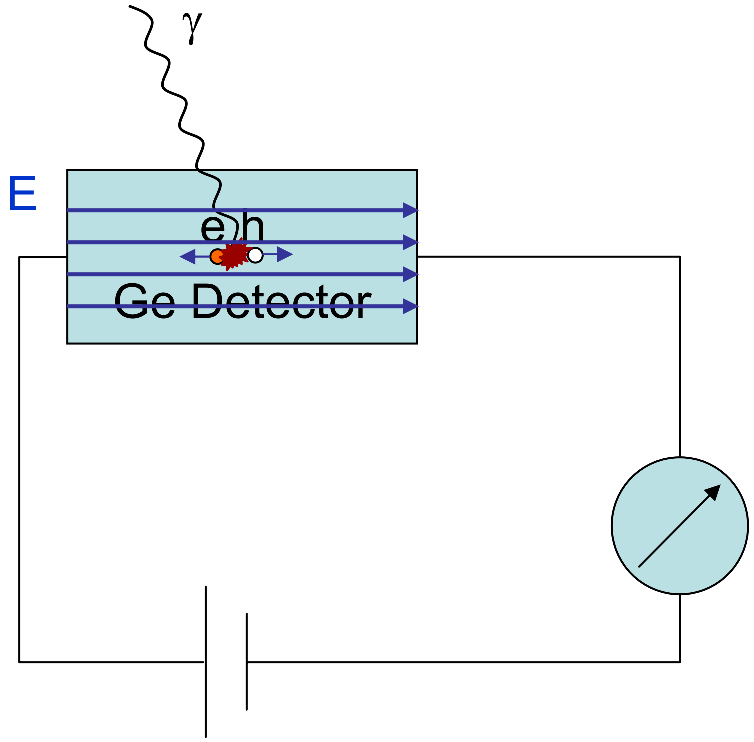
Why pulse shape simulation

- Pulse shape simulation (PSS):
  - Estimate the efficiency of pulse shape analysis
  - understand the detector meanwhile

Simulate the drift of charge carriers in germanium crystal

Poisson's Equation:

$$\nabla \cdot E = \frac{\rho}{\varepsilon}$$



Germanium has the same crystalline structure as silicon and diamond, namely, a face-centered cubic (FCC) structure, in which each atom lies at the center of a regular tetrahedron, and is surrounded at its apices by four atoms as shown in Fig. 1

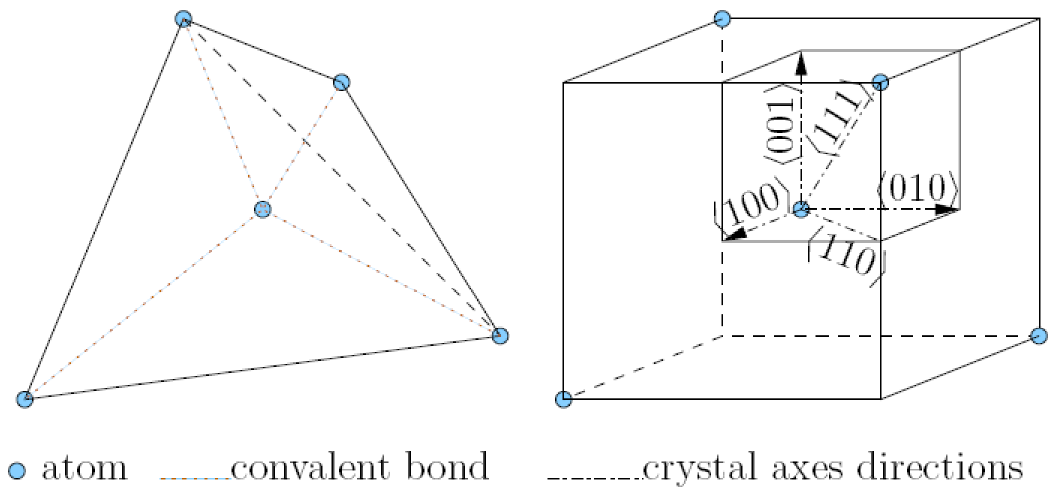


Figure 1: Structure of germanium crystal.

Due to the crystal lattice symmetry in germanium, in three directions, the crystallographic ⟨100⟩, ⟨110⟩ and ⟨111⟩, the mobility is always aligned with the electrical field.

Drift trajectories

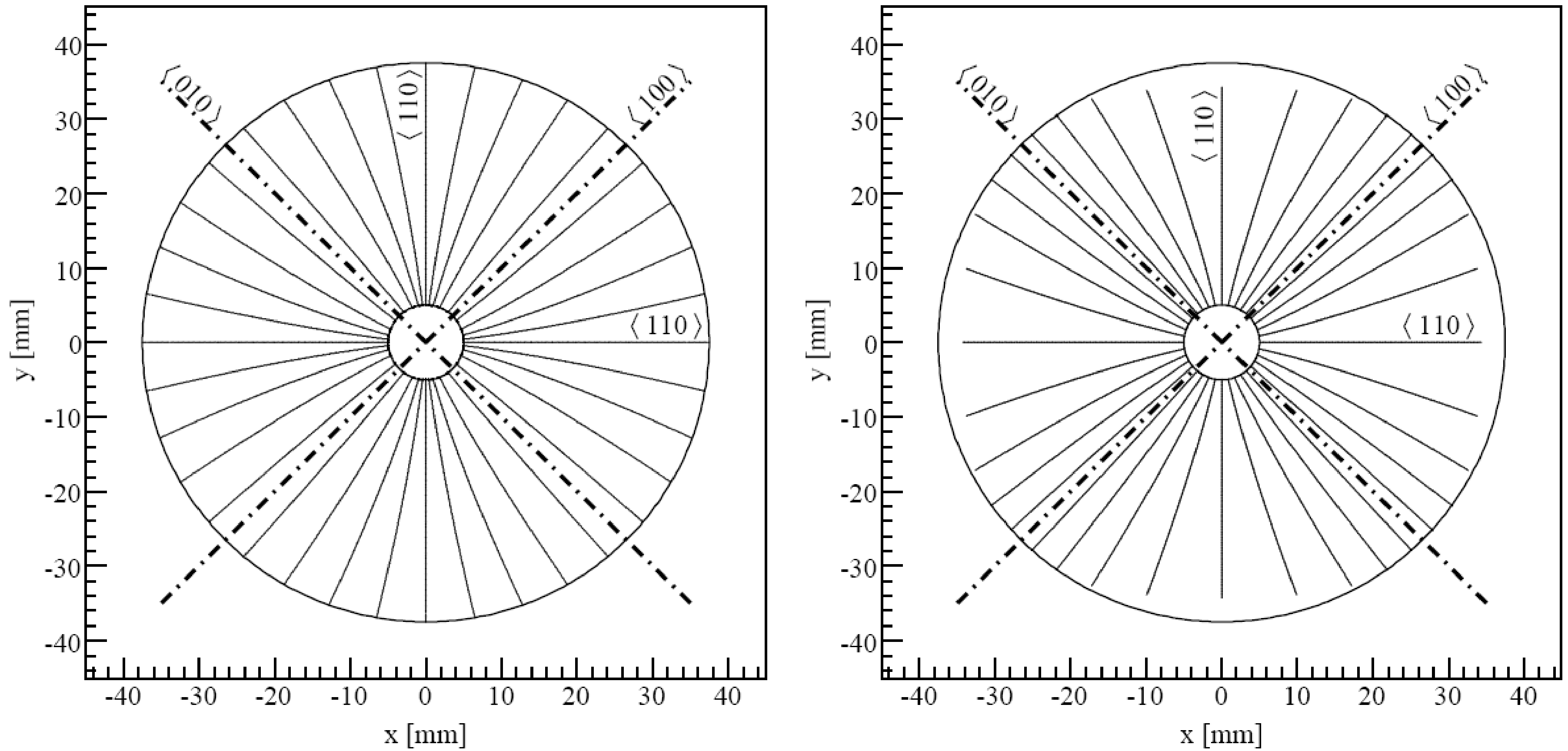
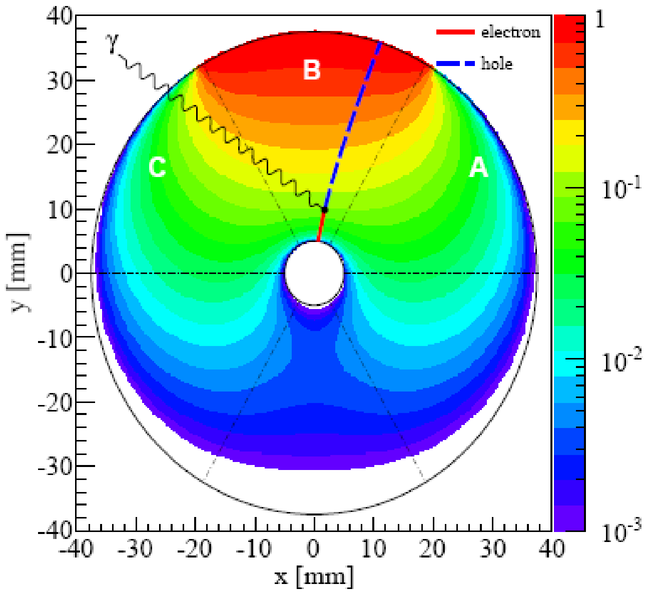
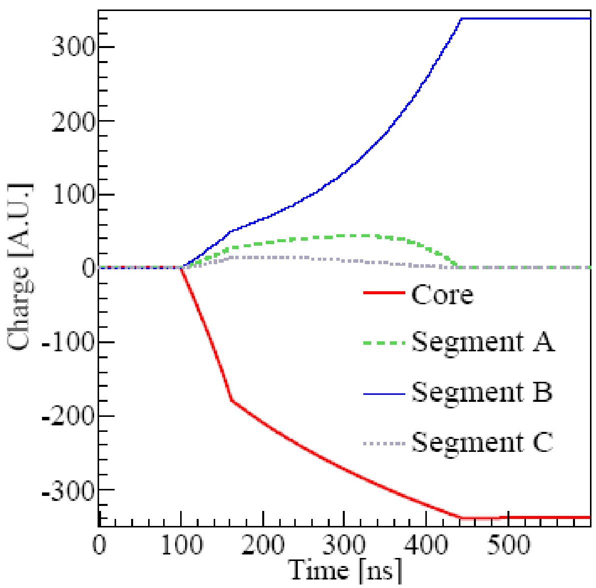
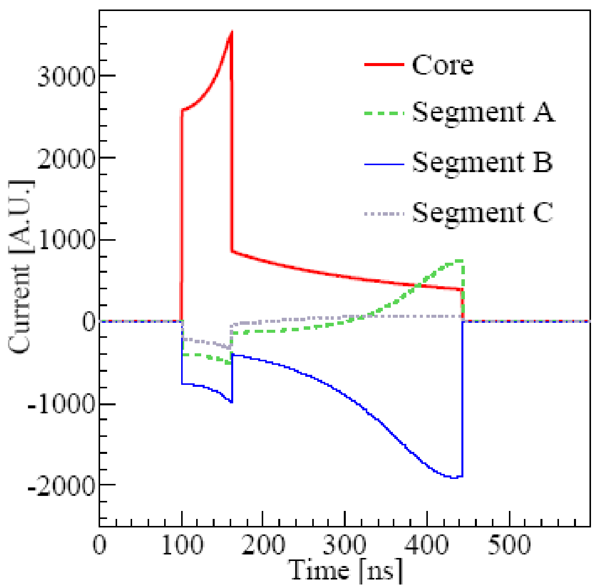


Figure 9: Charge carrier drift trajectories on X-Y plane. The transverse anisotropy causes the bend of the trajectories. Also shown are the cross section of a true coaxial cylindrical germanium detector with inner radius of 5 mm and outer radius of 37.5 mm. The crystal axes are indicated with the signs ⟨100⟩, ⟨110⟩ and ⟨010⟩.

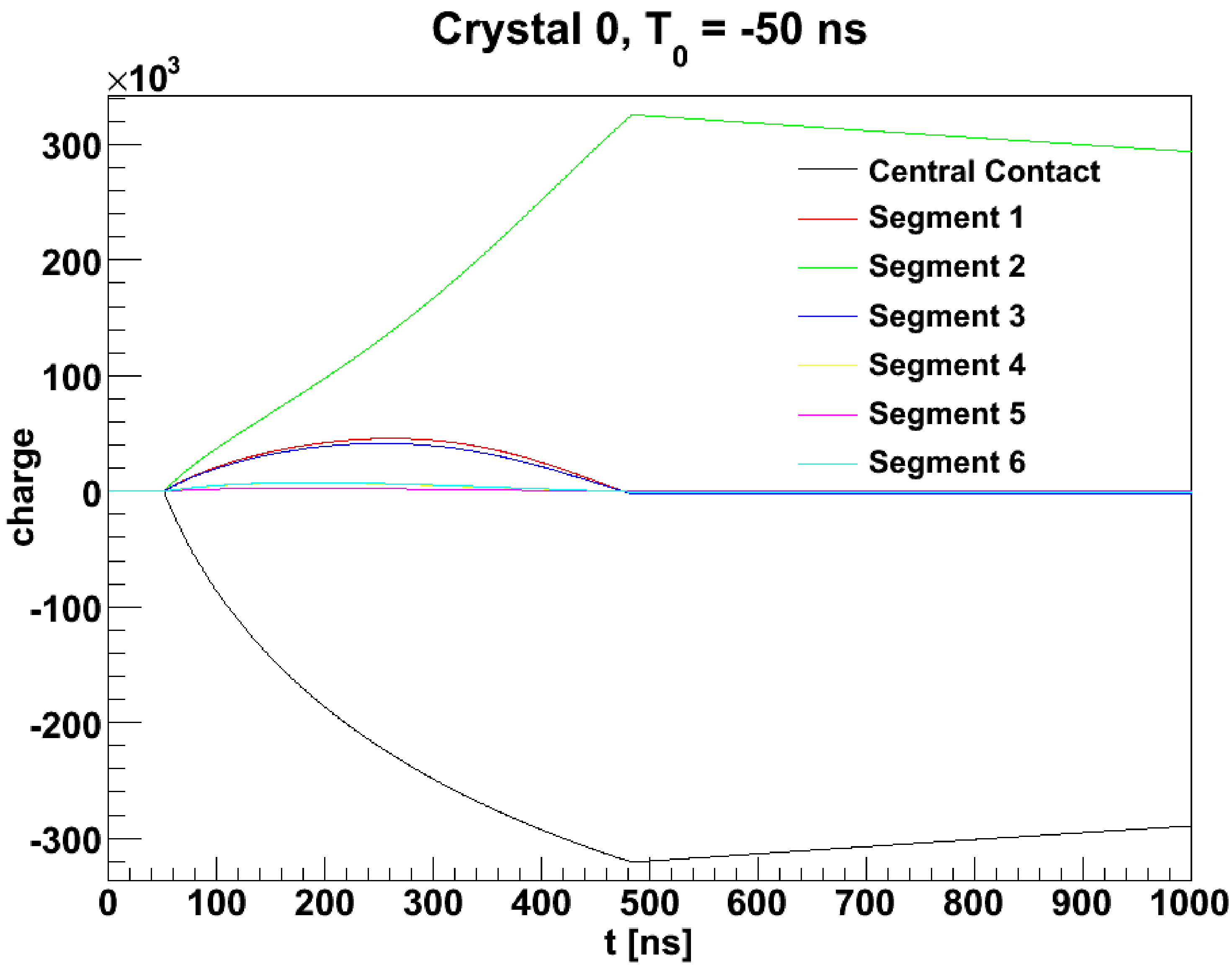
Pulse induced in electrodes



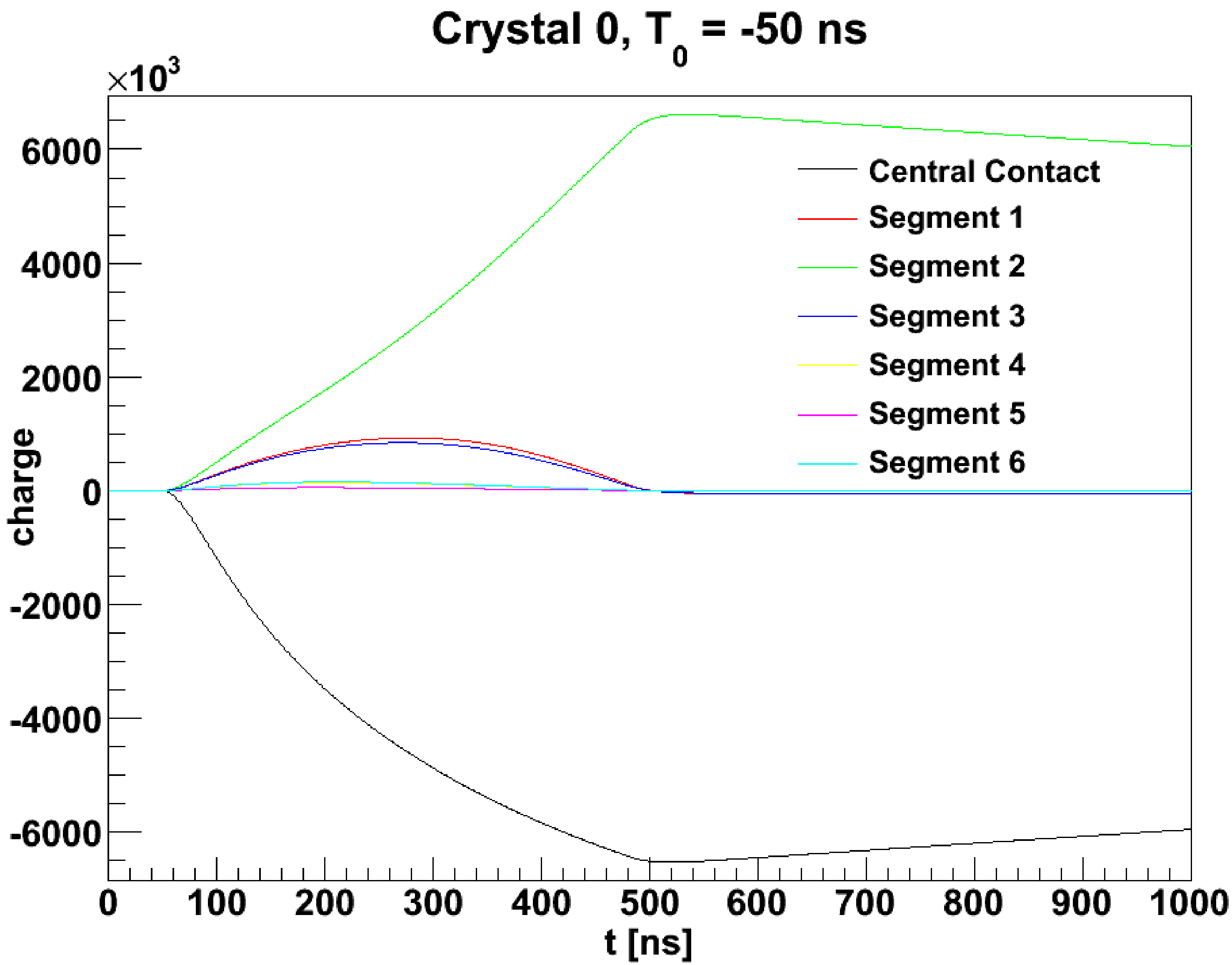




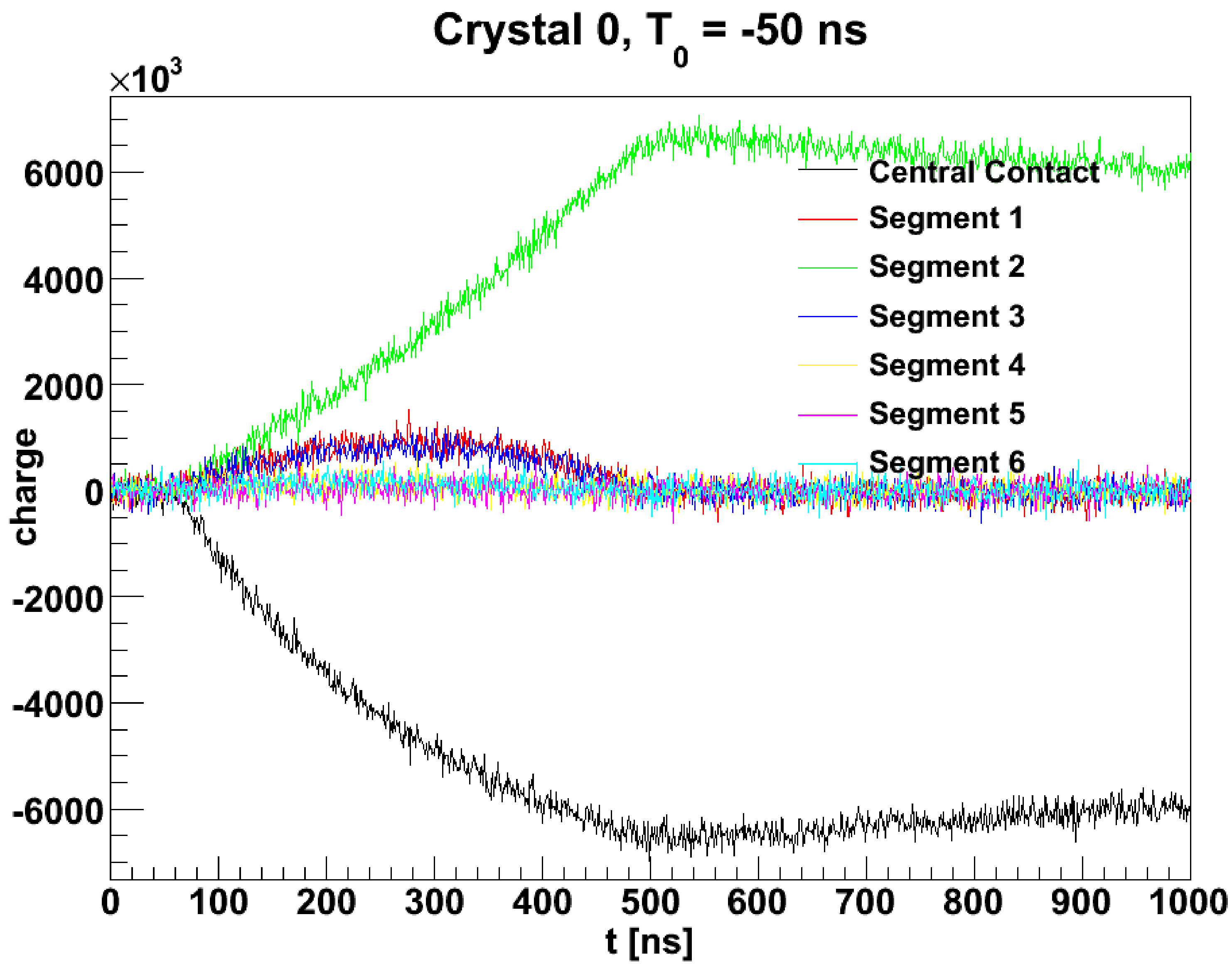
Simulation of decay time



Fold in bandwidth

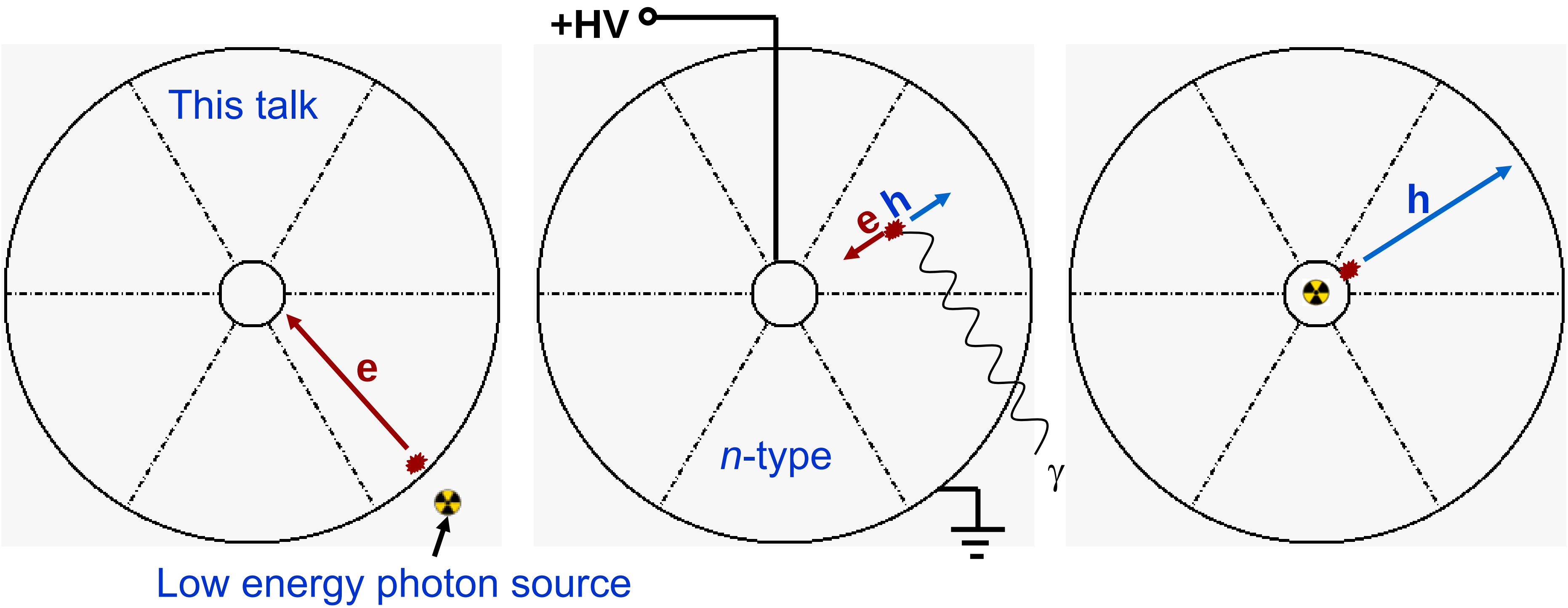


Let’s add some noise

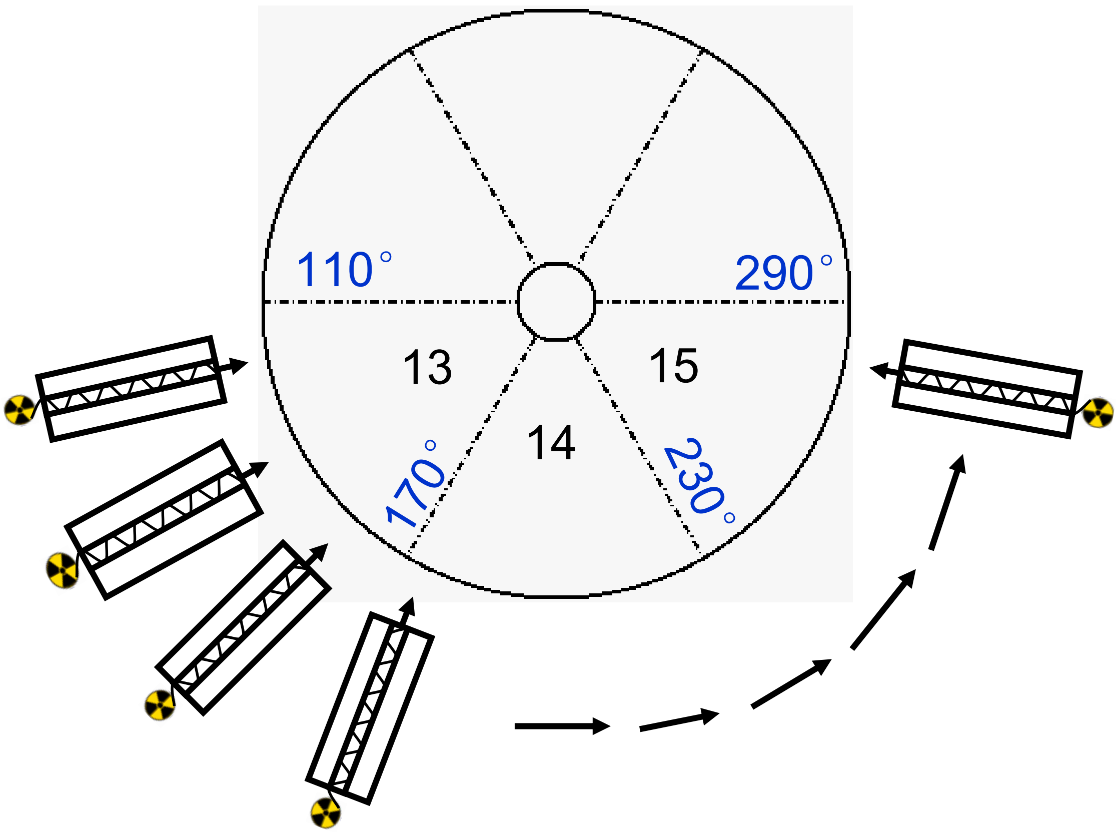


Validation of the pulse shape simulation…

How to make life easier



Surface scanning

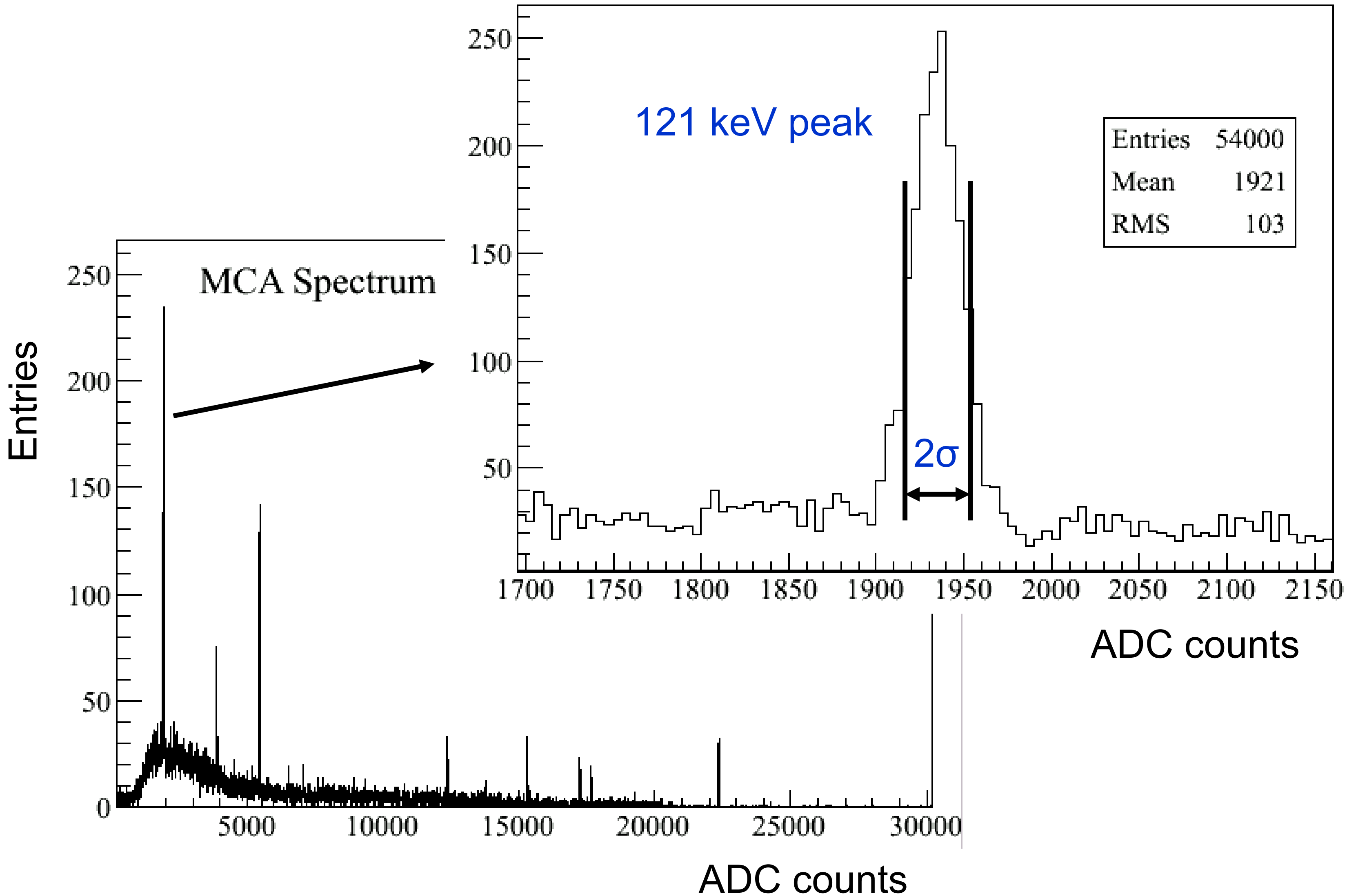


Start point: 120°
Stop point: 280°

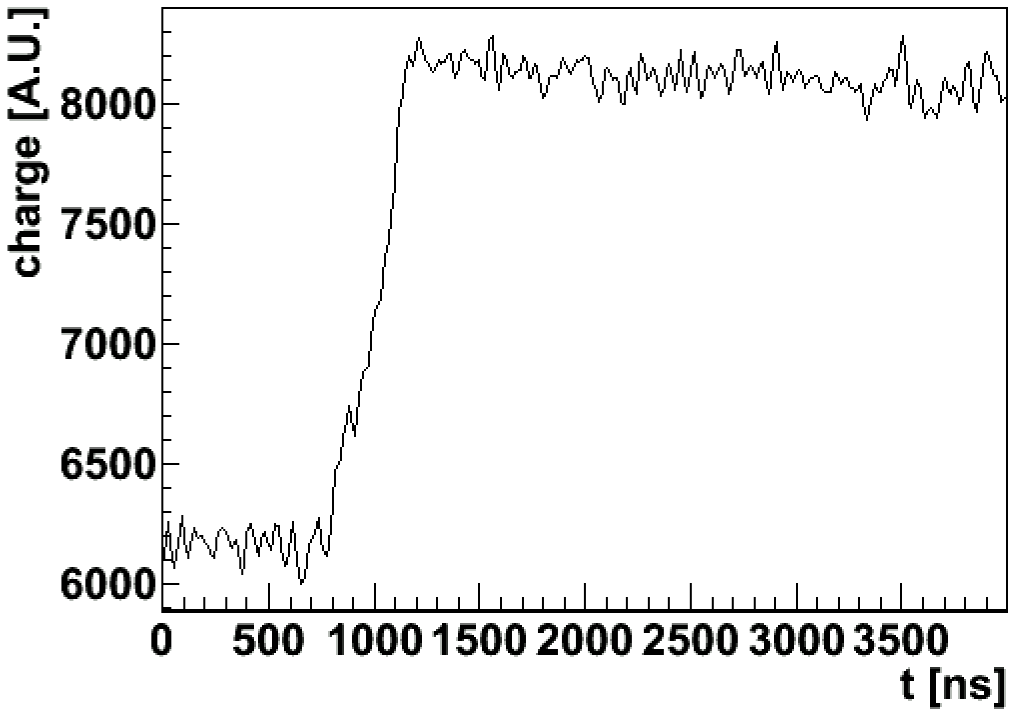
Step:

- 10° in segment 13, 15
- 5° in segment 14

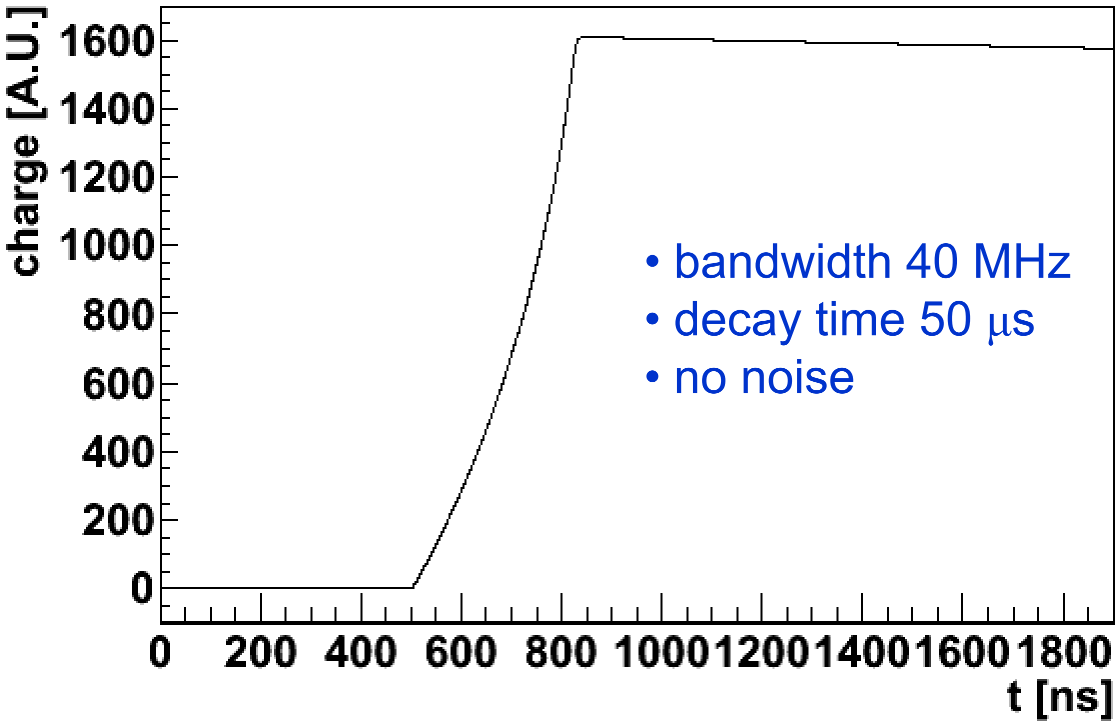
Event selection (taking 140° scanning data as an example)



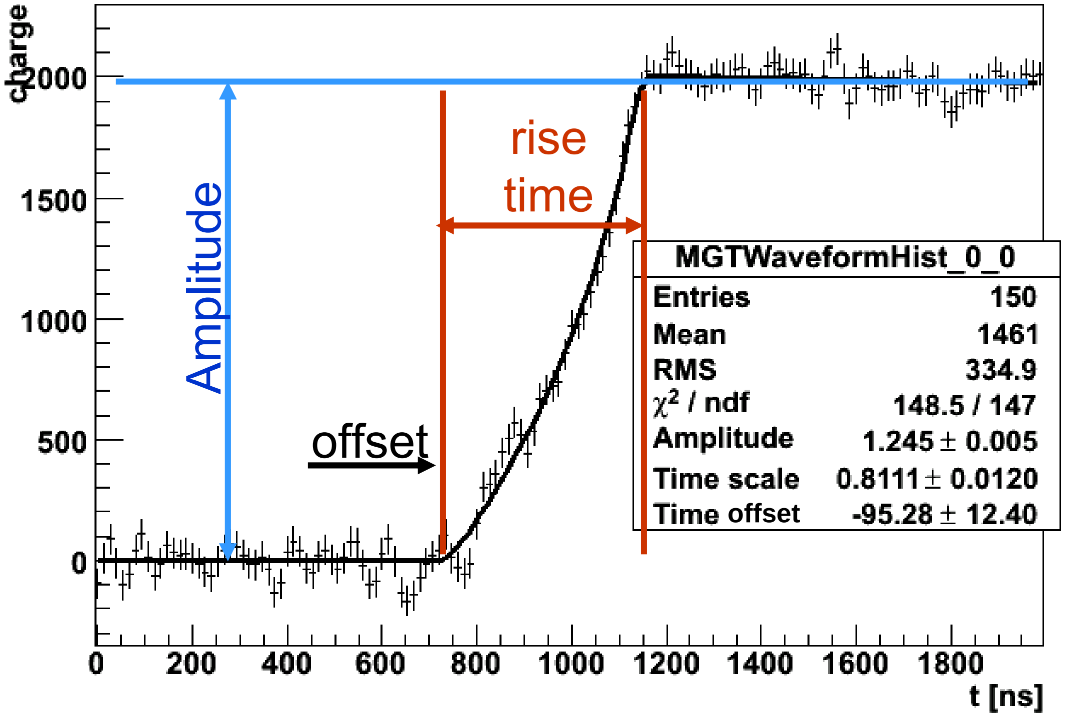
A real pulse seen by the core of the detector



A simulated core pulse

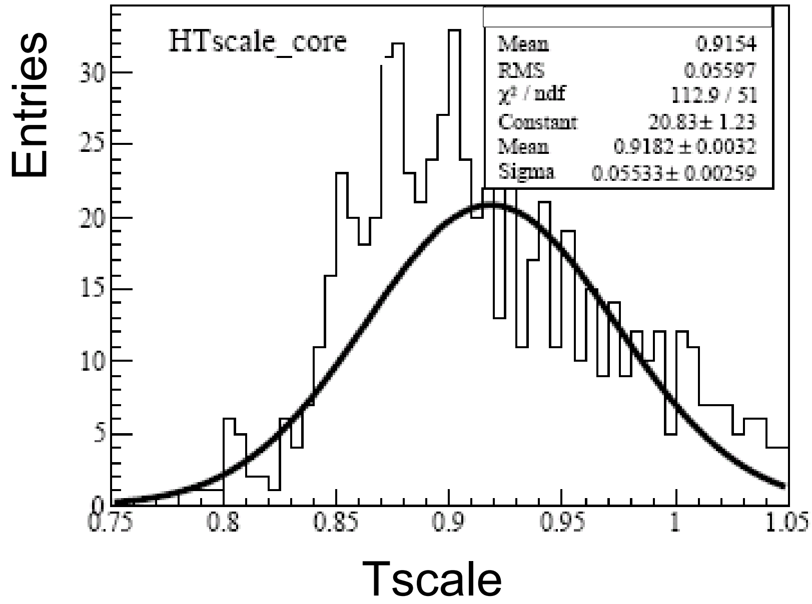


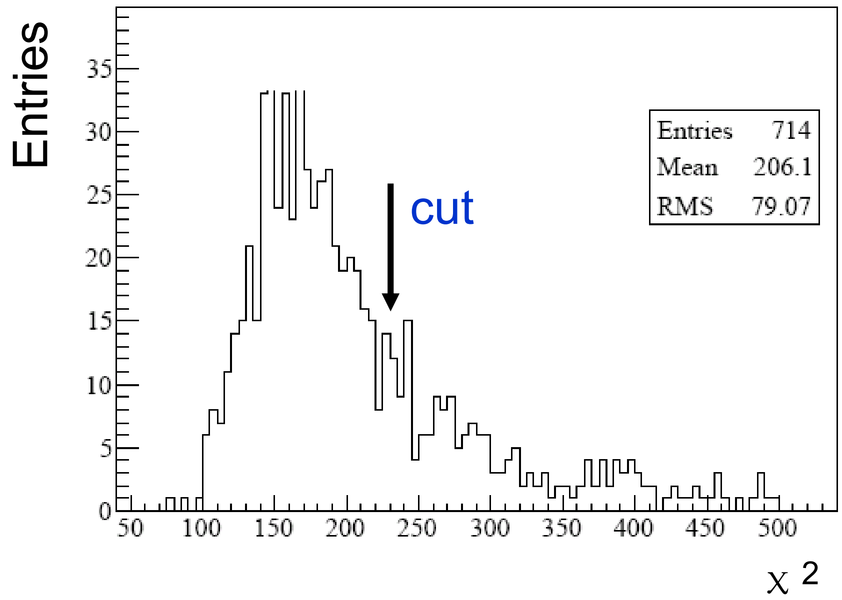
Fit simulated pulse to a real one



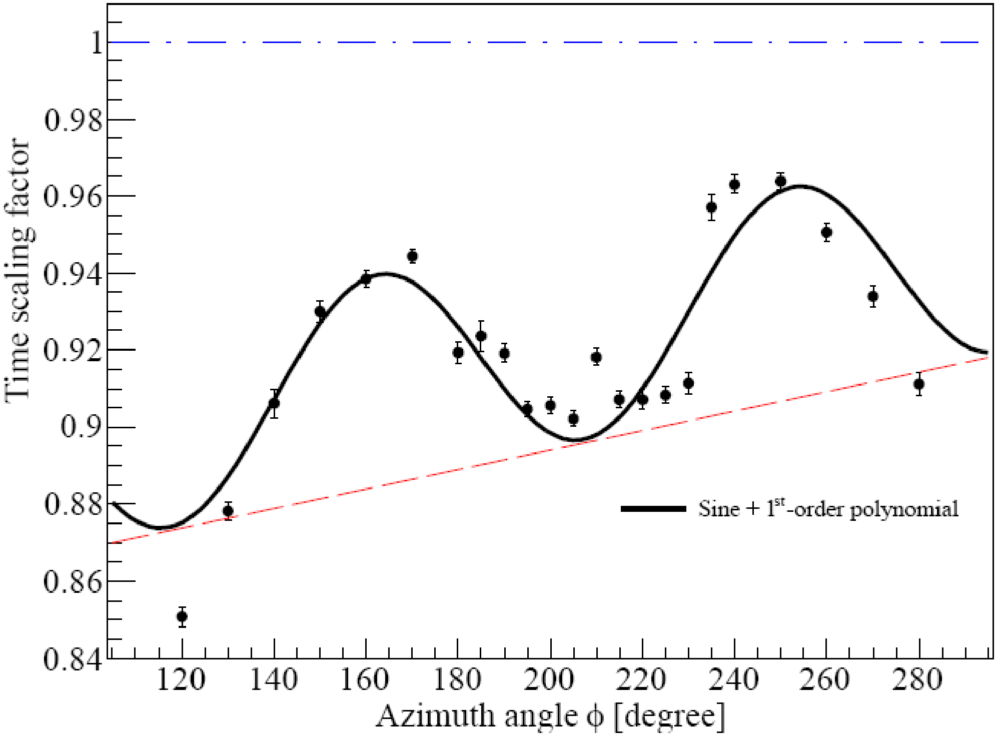
- real pulse:
  - dots with error bars
  - error is set according to noise
- simulated pulse:
  - smooth line
  - three free parameters:
    - Amplitude
    - Time scale
    - Time offset

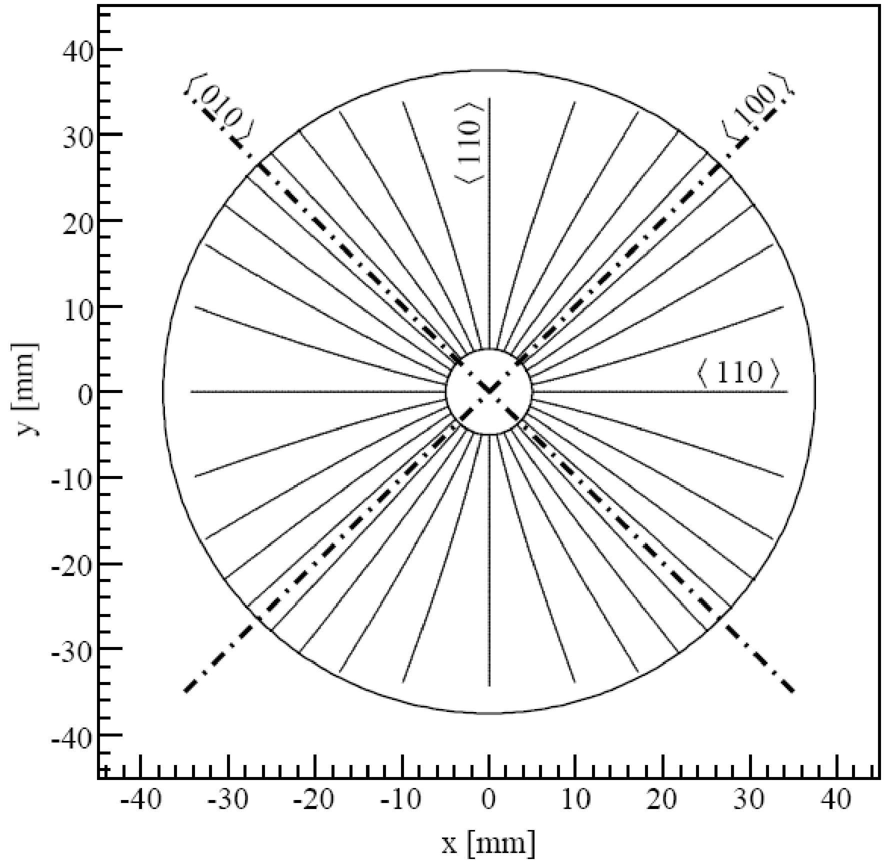
Time scale distribution





Mean time scale distribution along azimuth angle

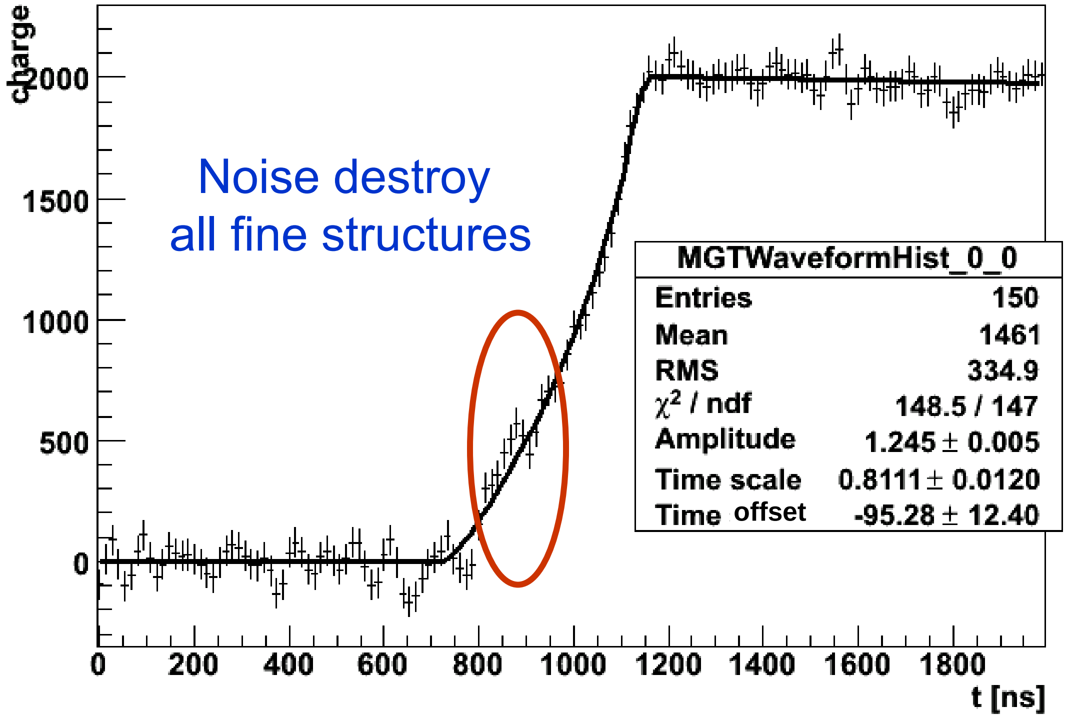




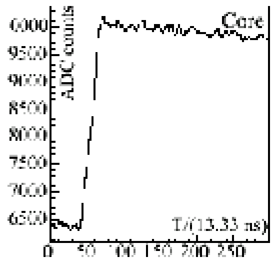
Possible explanation of the time scale distribution

- Input parameters for physics models
  - Shouldn't change from detector to detector
  - Checked by AGATA collaboration
- impurity density distribution, geometry
  - Change from detector to detector
  - Geometry is simple in our case
  - Inhomogeneous impurity distribution inside detector

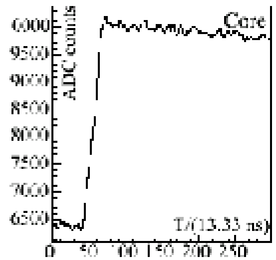
How to compare the fine structures



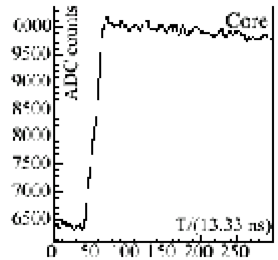
Average out the noise



+



+



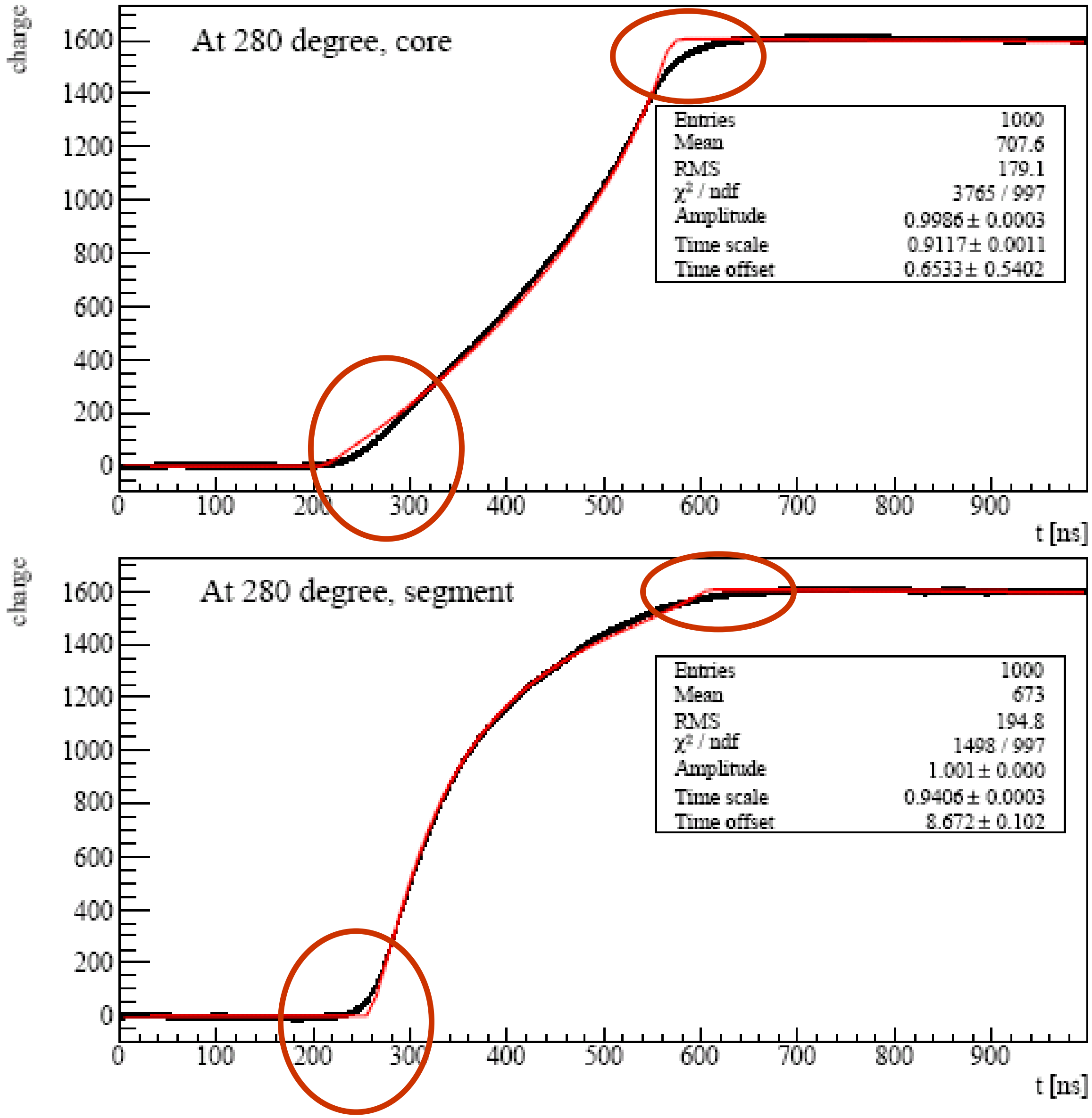
+ …

Total number of pulses

= averaged pulse

(noise averaged out!)

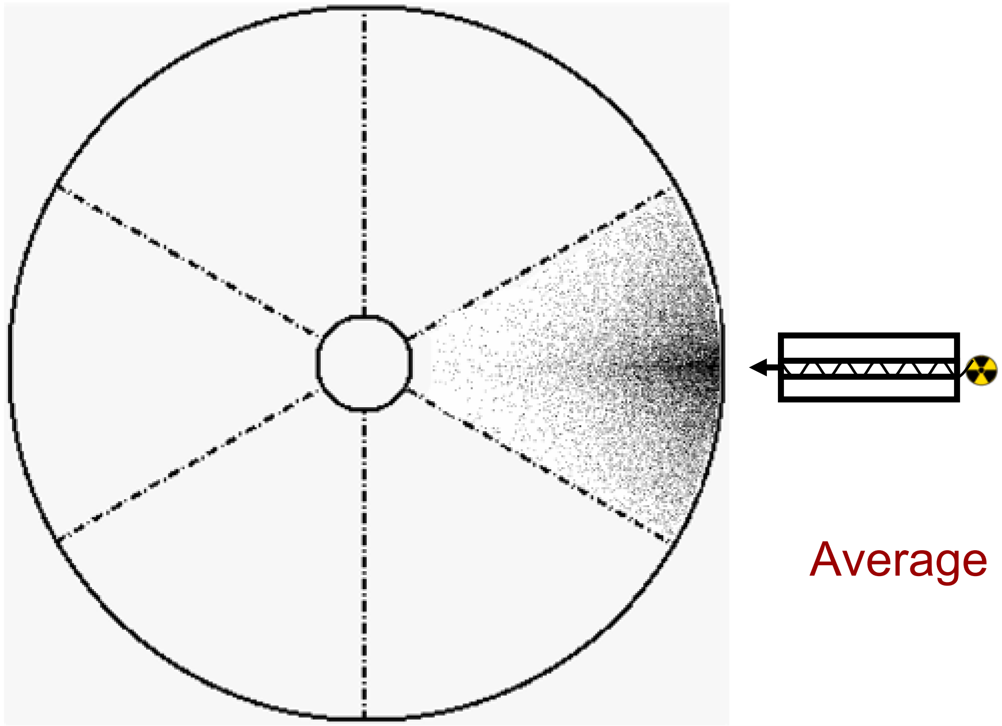
Fit simulated pulses to averaged pulses



Red: simulated

Black: data

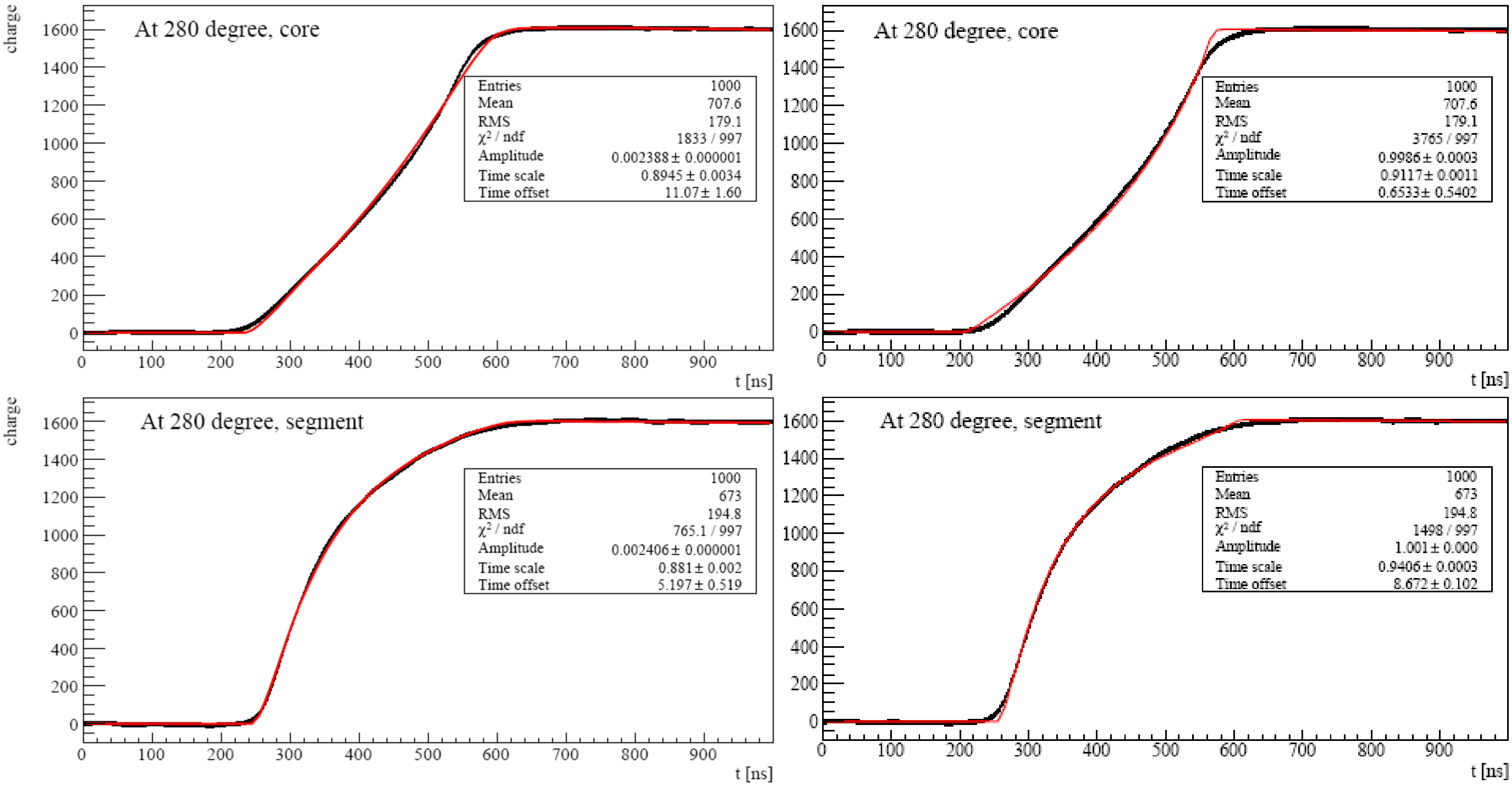
Distribution of hits from 121 keV photons



Hits have a distribution!

Average the simulated pulses as well!

A nearly perfect result



After averaging | Before averaging

Summary

- GERDA is trying to answer a very fundamental physcis problem: whether neutrino and antineutrino are the same

- Several new techniques are going to be used in GERDA

- We systematically investigate the performance and the background discrimination power of segmented detectors in cryogenic liquid for the first time.

- A fully functional pulse shape simulation package has been developed and verified in many aspects. – lays a stable basis for the pulse shape analysis

ありがとう