Physik Institut
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GERmanium Detector Array : Status and Plans

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for the GERDA Collaboration

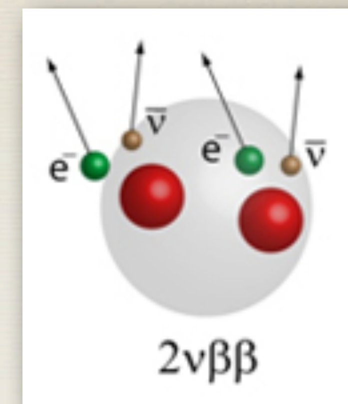
Outline

* Double Beta Decay
* Neutrino - Dirac or Majorana
* GERDA - Motivation & Goals
    - Experimental Setup
    - Preliminary results: Phase-I
* Phase - II - Perspectives
    - BEGe Detectors : Testing and Preparation
    - Liquid Argon (L.Ar) Instrumentation
* Conclusion

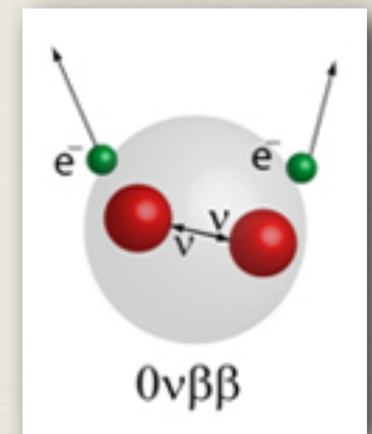
Double Beta Decay

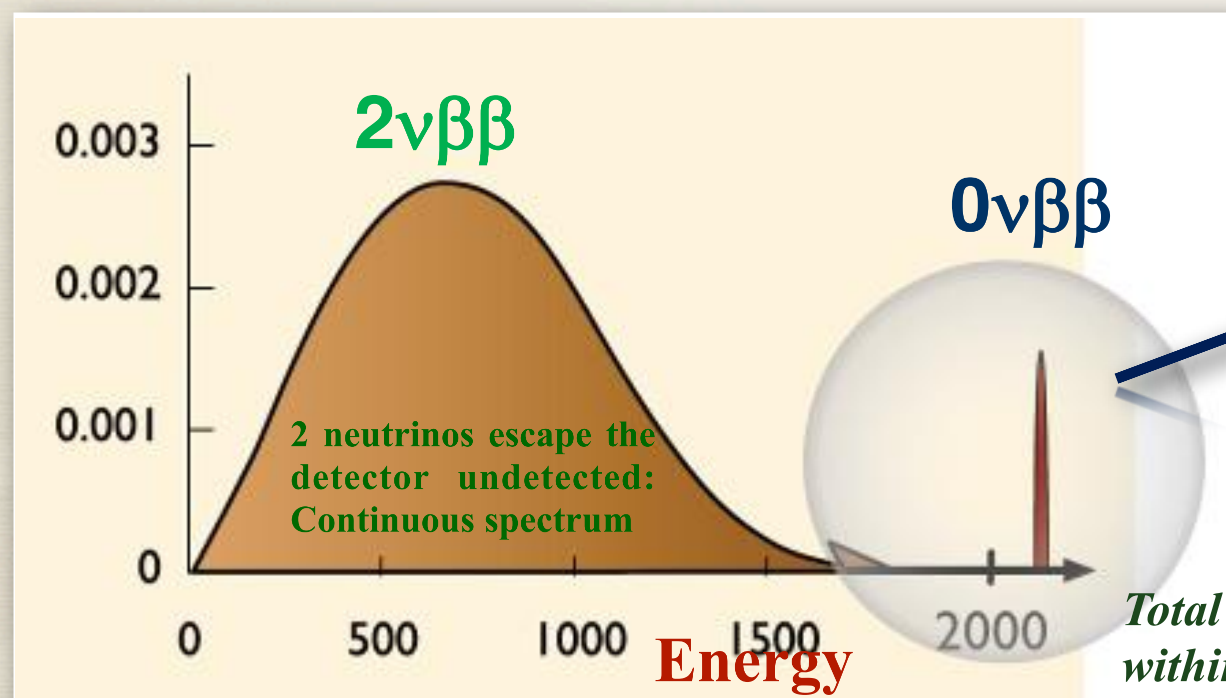
* Double beta decay is a radioactive decay process where a nucleus releases two beta_particles as a single process.
* Two beta decay is possible if the usual single beta decay is energetically forbidden.

* In double-beta decay, two neutrons ➟ protons, 2e and 2ν_e are emitted.
* β-decay is possible, if the final nucleus has larger binding energy than the original nucleus.



* If the neutrino is a Majorana particle (antineutrino and the neutrino are the same particle), and at least one type of neutrino has non-zero mass (established by the neutrino oscillation experiments), then it is possible for neutrinoless double-beta decay to occur.





0νββ-signal: Point-like energy deposition at 0νββ signatures in Ge:
Q = 2039 keV ⇒ single site event (SSE)

Total energy of decay is deposited within detector: sharp peak

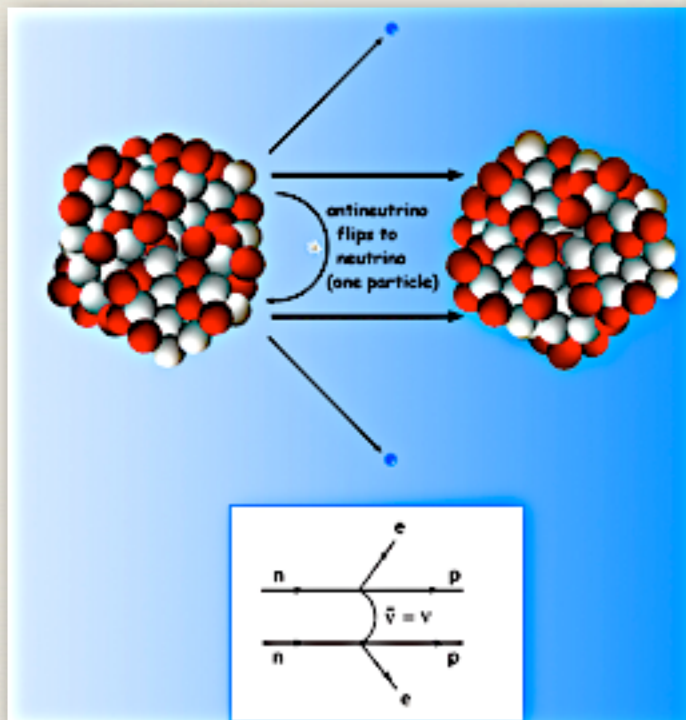
Neutrino - Dirac or Majorana

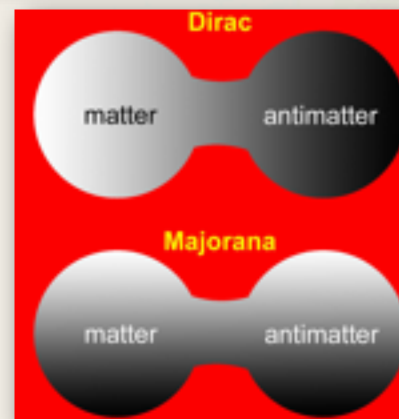
What is known
* Neutrinos have mass
* Mass difference between eigenstates

What is unknown?
* Mass Scale
* Mass Hierarchy
* Majorana vs Dirac

Majorana

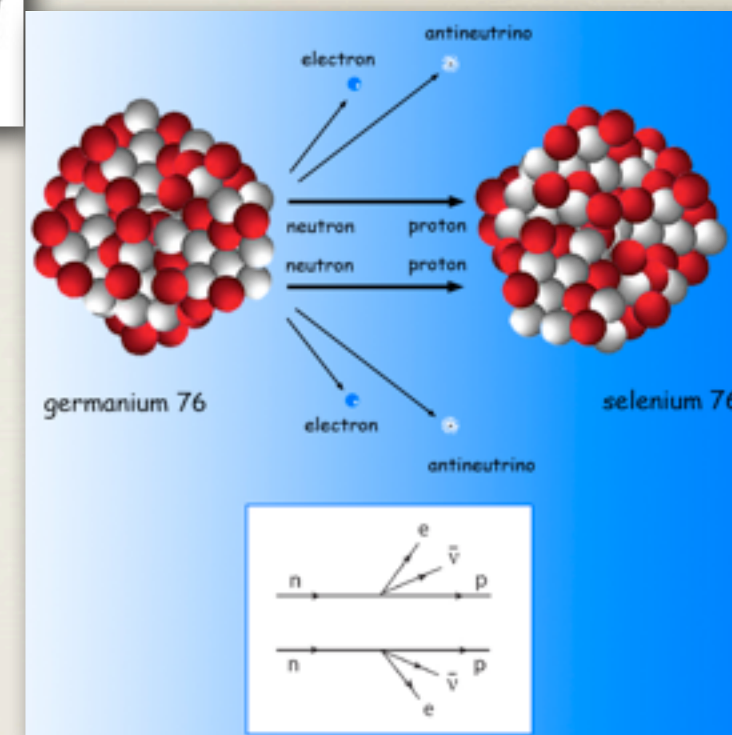
$\nu = \bar{\nu}$





Dirac

$\nu \neq \bar{\nu}$



$0\nu\beta\beta$ and $2\nu\beta\beta$

* Forbidden process in SM
* Lepton number violated $\Delta L = 2$
* $(T^{0\nu}_{1/2})^{-1} = G^{0\nu} \cdot |M^{0\nu}|^2 \cdot \langle m_{\beta\beta} \rangle^2$
* $(A, Z) \rightarrow (A, Z+2) + 2e^-$

* Allowed by SM
* Lepton number conserved $\Delta L = 0$
* Observed in many isotopes
* $T_{1/2} \sim 10^{19}\text{-}10^{21}$y
* $(A, Z) \rightarrow (A, Z+2) + 2e^- + 2\nu_e$

$G^{0\nu}$: Phase space integral

$M^{0\nu}$: Nuclear matrix elements

$\langle m_{\beta\beta} \rangle^2 = |\Sigma_i U^2_{ei} m_{\nu_i}|^2$

GERDA - Motivation & Goals

Heidelberg-Moscow Experiment--> The Claim

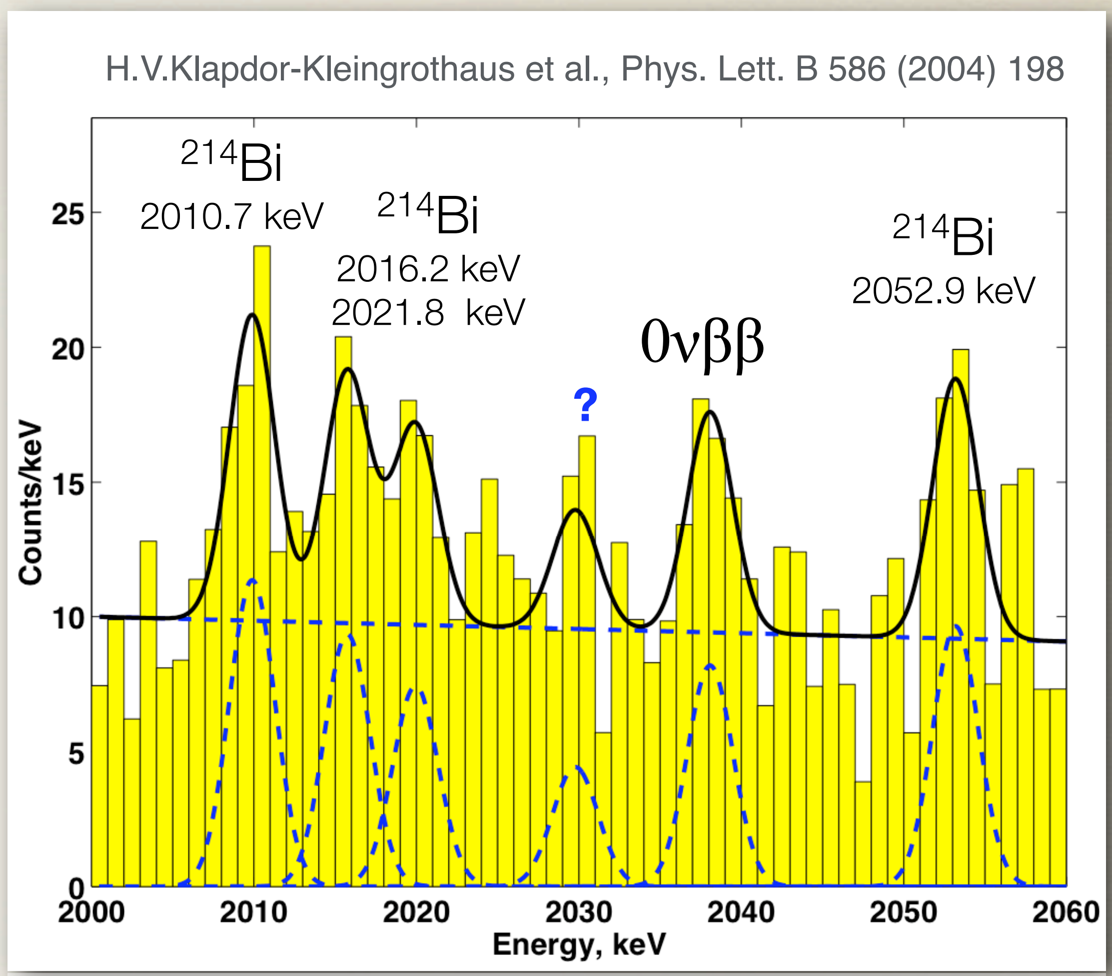
* 5 HPGe crystals with 71.7 kg y
* Peak at Q value:

$$T^{0\nu}_{1/2} = 1.2\ (0.7\text{-}4.2) \times 10^{25}\ \text{y}\ (3\sigma)$$

$$\langle m_{\beta\beta} \rangle = 0.44\ (0.24 - 0.58)\ \text{eV}\ (3\sigma)$$

Background index (BI) [cts/(keV·kg·yr)] ~ 0.1

*RevModPhys 80(08)481

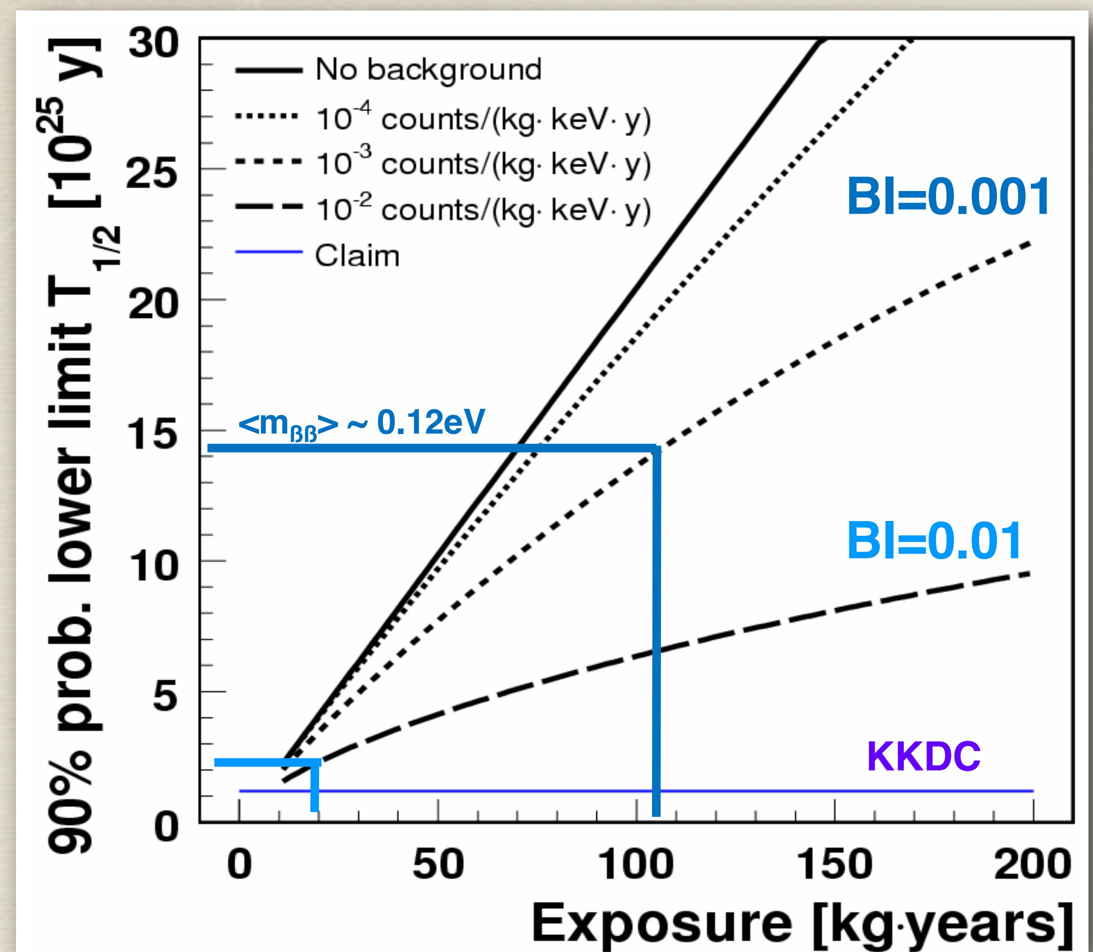


* Significance of the claim depend on the background model and energy region selected.

* Needs cross-check: Experiments with higher sensitivity

GERDA - Motivation & Goals

Reach background index (BI) at $Q_{\beta\beta}$ = 2039 keV of 0.01 / 0.001 cts / (keV·kg·yr)



Phase I :

* Use Ge-76 diodes of HD-Moscow & IGEX
* ~18 kg (enriched to 86% Ge) + 7.59 kg Natural.
* Reach BI ~ 0.01 cts / (keV·kg·yr) - check the claim of Klapdor-Kleingrothaus et al.
* Half-life $T_{1/2}$ > 2 × 10^{25} s
* Majorana mass m_{ee} < (0.23 - 0.39) eV (Phys. Rev. C 81 (2010) 028502)

Phase II:

* Add new enriched Ge-76 detectors, 20 kg
* Reach Background (BI) 10^{-3} cts/(keV kg y)
* Half-life $T^{1/2}$ > 1.5 × 10^{26} y
* Majorana mass m_{ee} < (0.09 - 0.15) eV (Phys. Rev. C 81 (2010) 028502)

Why Germanium?

Advantages of Germanium:

* High ε: Source = Detector

* High signal efficiency ~ 85-95%

* Ultrapure material, High Purity Ge

* Excellent ΔE: FWHM ~ (0.1-0.2)%

* Helps to reduce background from 2νββ and avoid γ's from the Compton continuum.

* Well-established technology.

Disadvantages of Germanium:

* $Q_{\beta\beta}$=2039 keV, still plenty of γ's

* Small phase space factor : needs a factor of ~3 times more mass to observe the same no of events - compared to ^{130}Te.

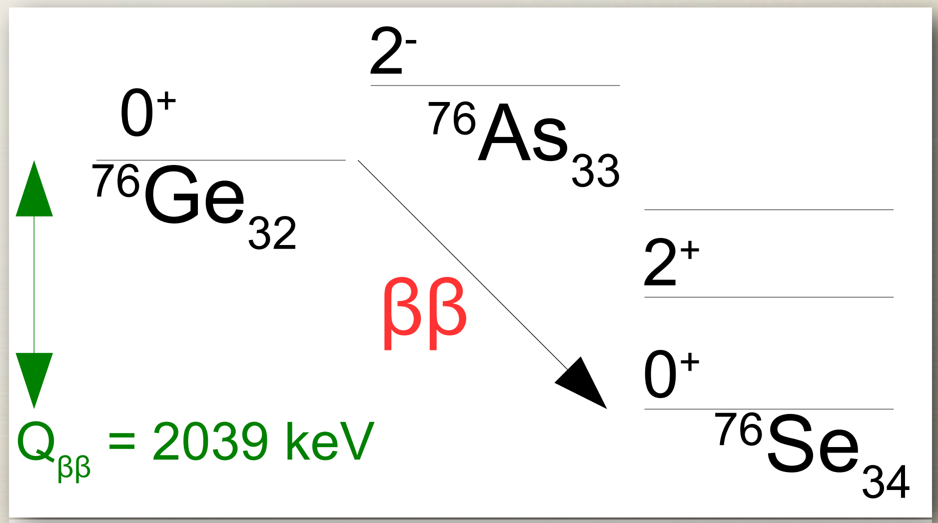
* Limited sources of crystal & detector manufacturers. Enrichment expensive.

* Low Q value below 2615 keV γ-line of ^{208}Tl

$$S \sim \varepsilon . a . \sqrt{\frac{M.t}{b\Delta E}}$$

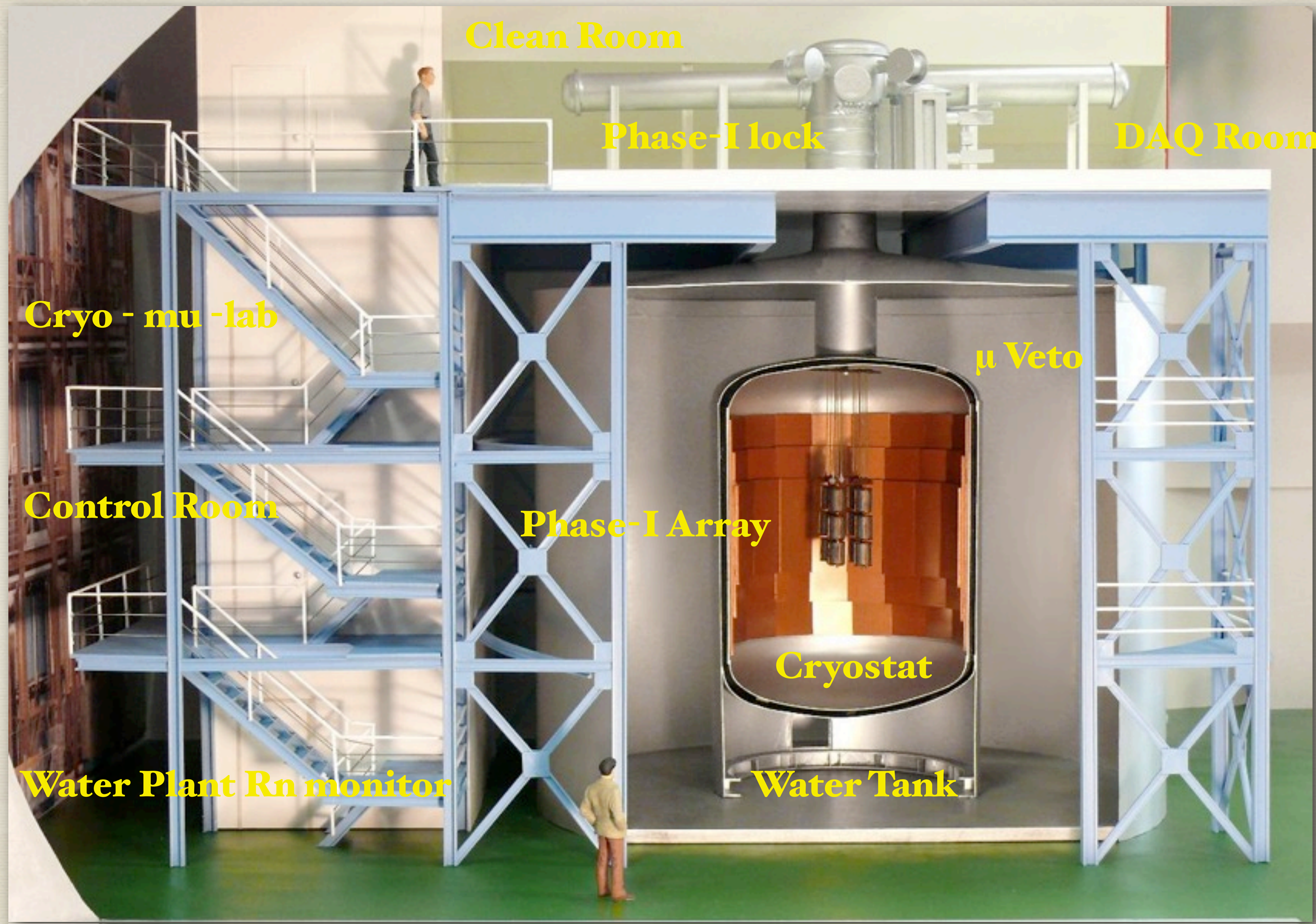
S: sensitivity
ε: efficiency
a: abundance of 2νββ isotope
M: detector mass

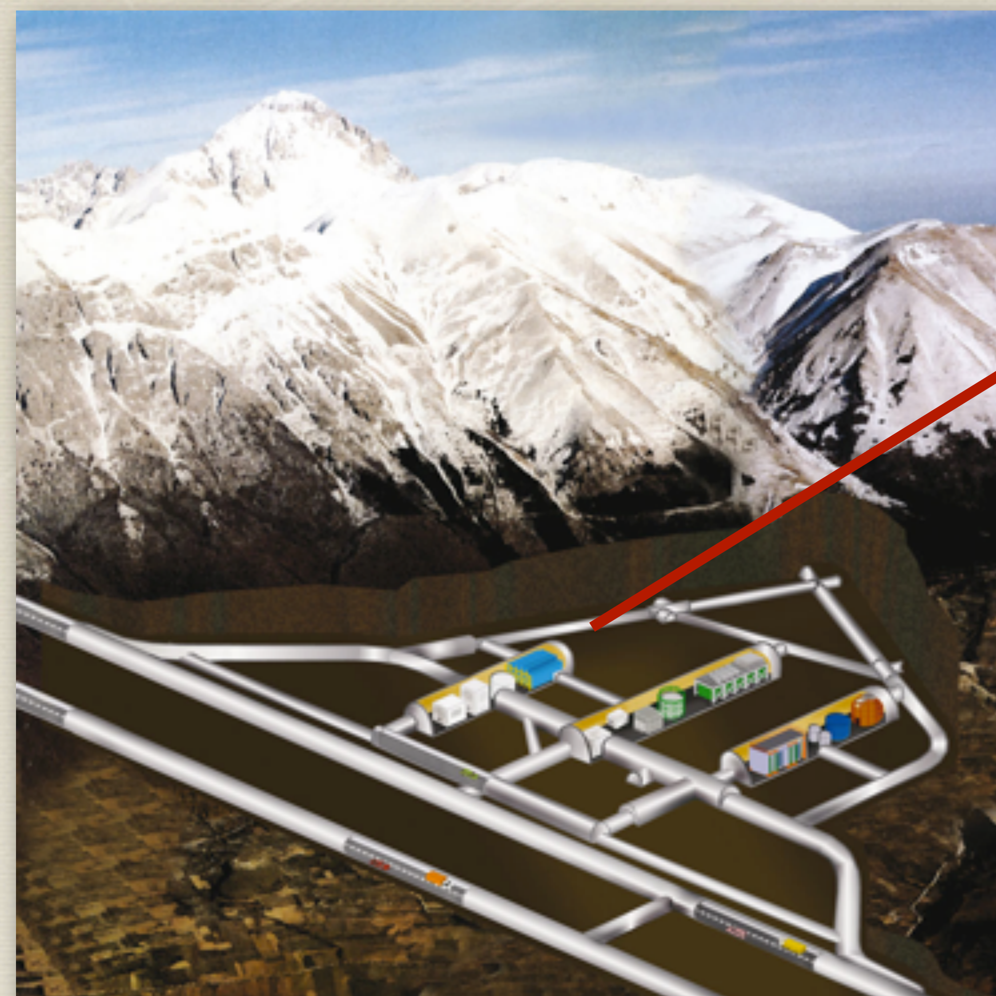
t: exposure
b: background index
ΔE: detector resolution



0νββ decay scheme of ^{76}Ge

GERDA -Experimental Setup

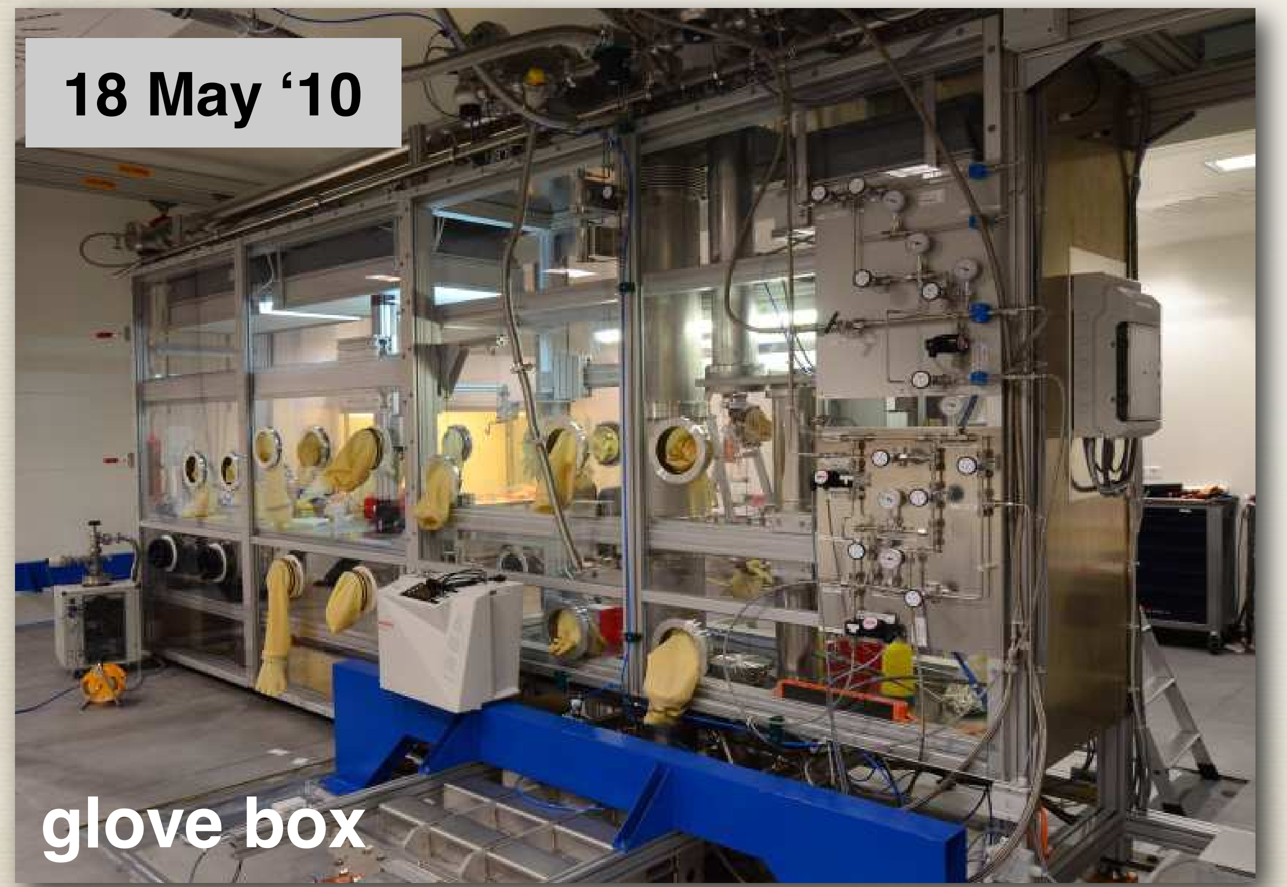




Location: Hall A of LNGS, Assergi, Italy
3500 mwe

GERDA -Experimental Setup

GERDA Underground Detector Laboratory (GDL):
Testing and preparation of Phase I detectors

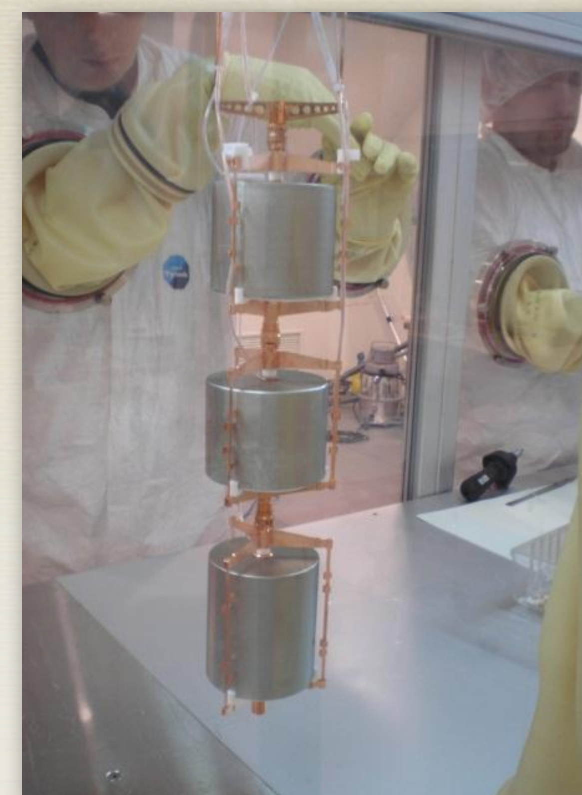


Mini Shroud

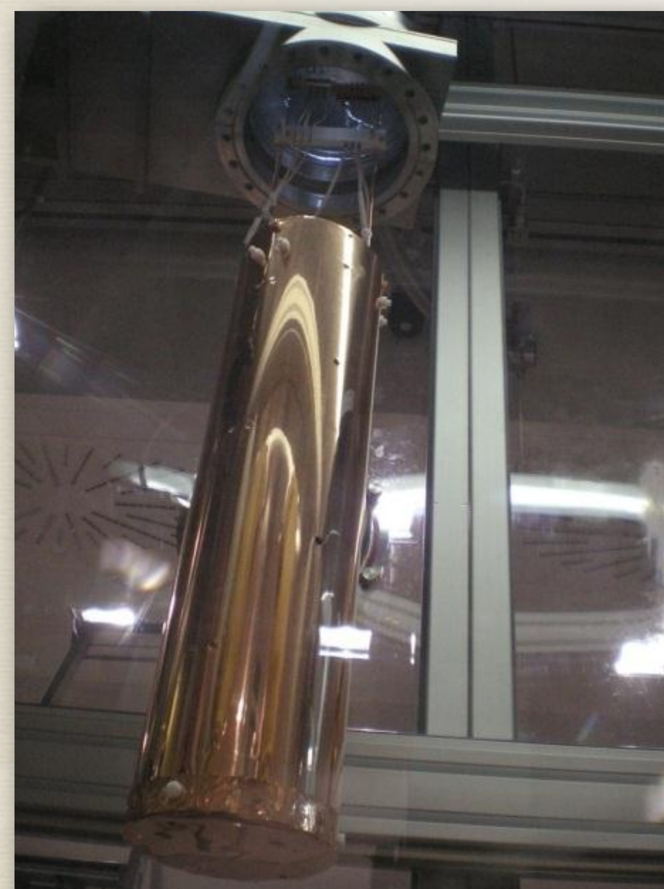
In IGEX and H-M experiments the detector's background was due to radioactive contamination of surrounding materials (including copper cryostat).

In GERDA we use "Bare" Ge detectors submerged into the High-Purity liquid Ar which shields from radiation and cools the Ge detectors.

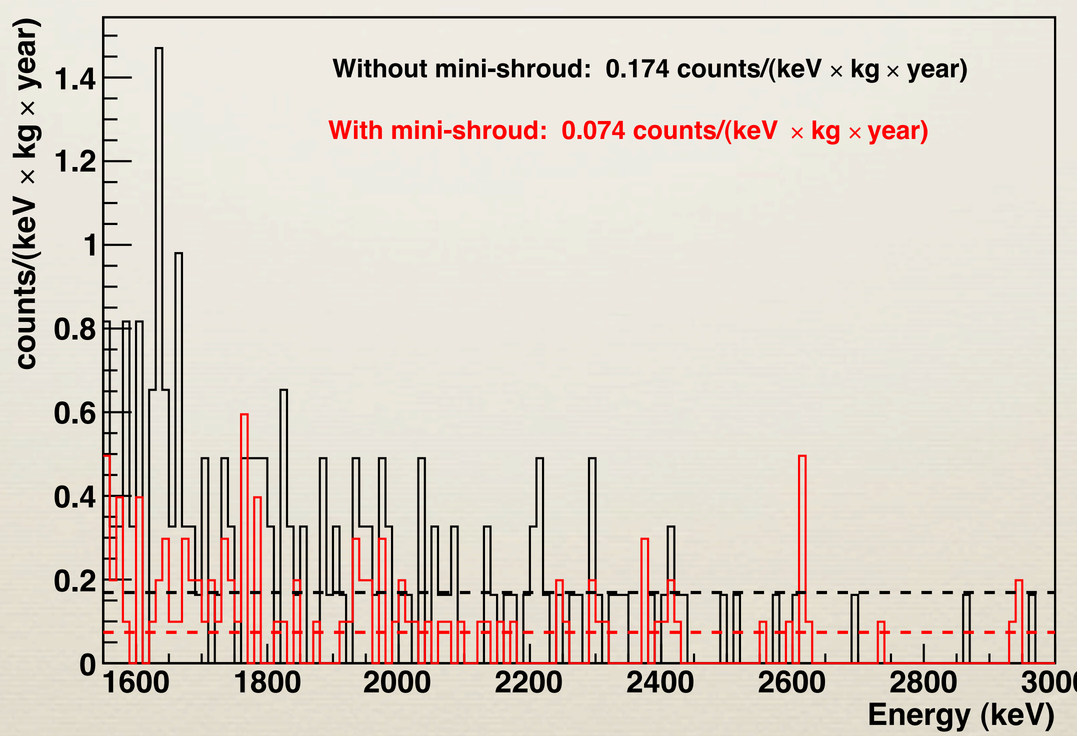
If positive or negative ions of ^{42}K are drifting in the liquid Ar they could be attracted by the E-field of the detectors or another electrodes. To check this different electrical fields have been organized by using shroud and mini-shroud.



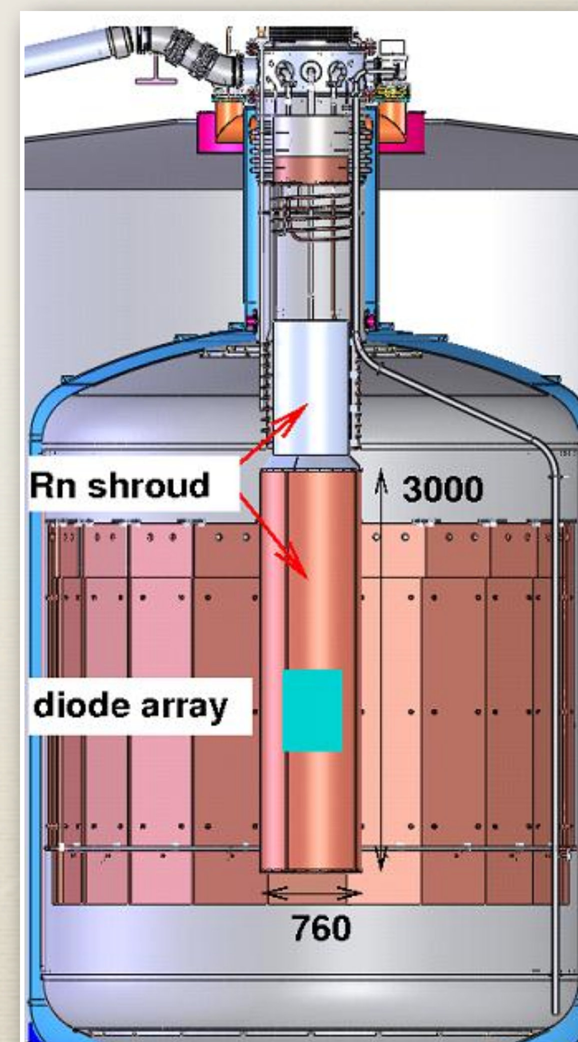
Detectors without mini-shroud



Detectors with mini-shroud



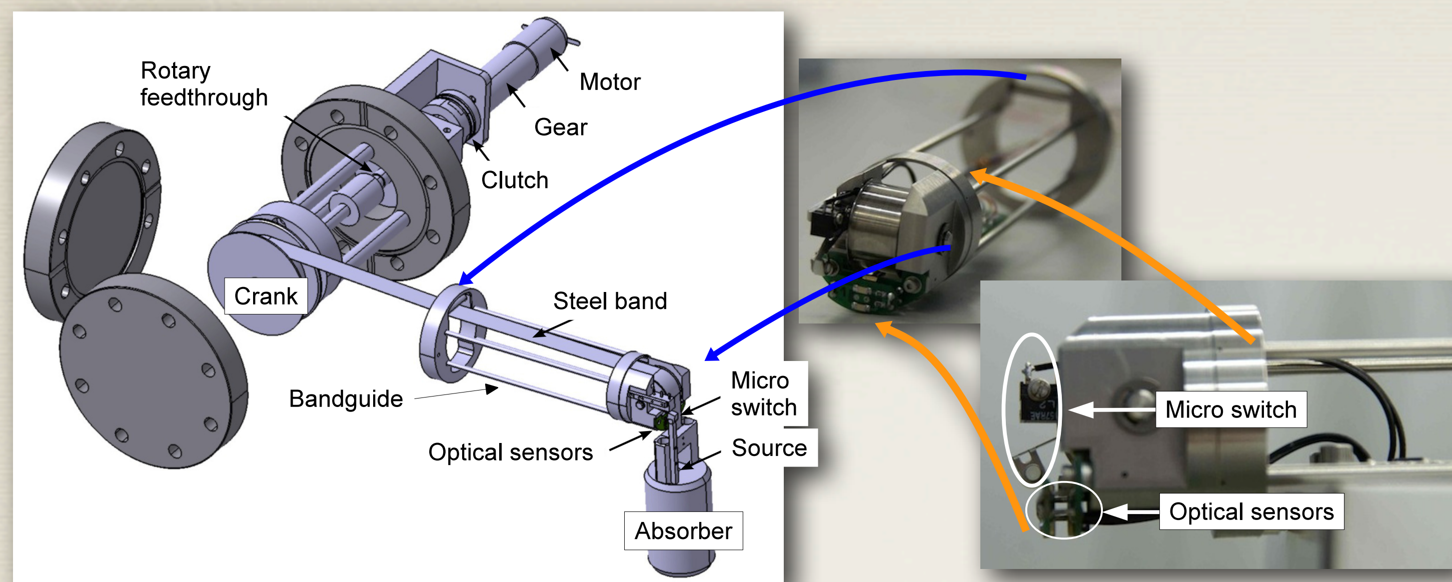
Spectra with and without Mini-shroud



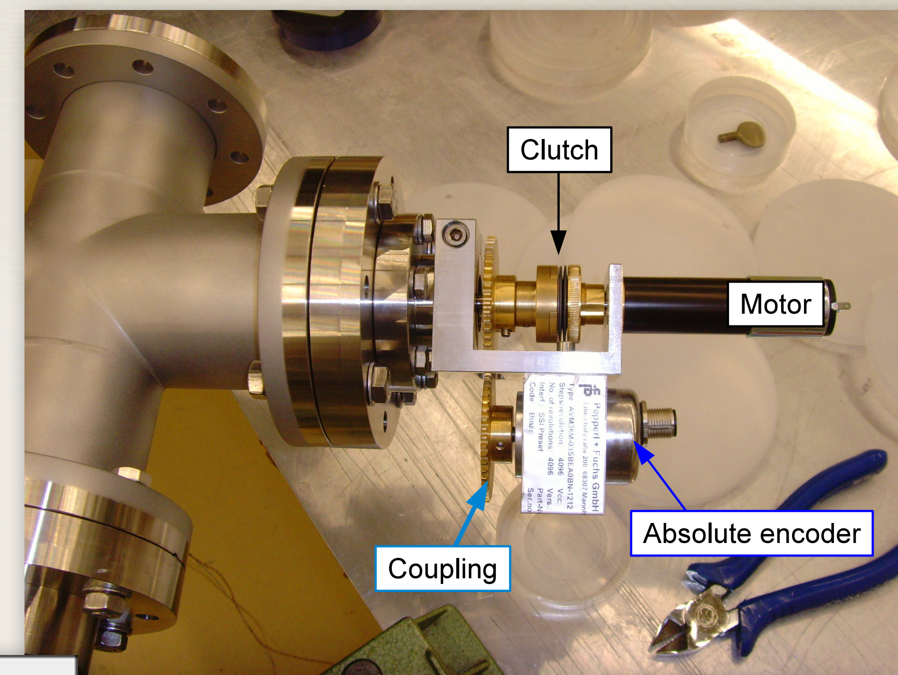
Source Insertion System (SIS)

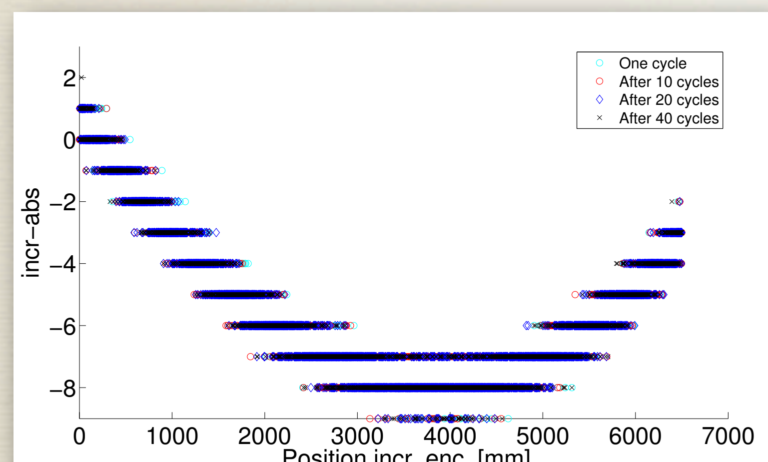
* 3 Source Insertion Systems (SIS) for calibration.

* Calibration system -- allows to lower 3 Th-228 sources, ~20 kBq each, close to the Ge array.

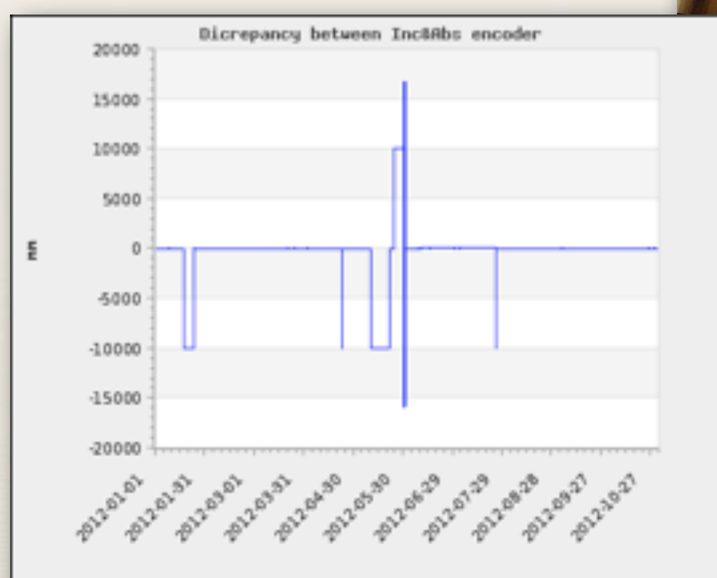


Schematics of the SIS, Inner parts





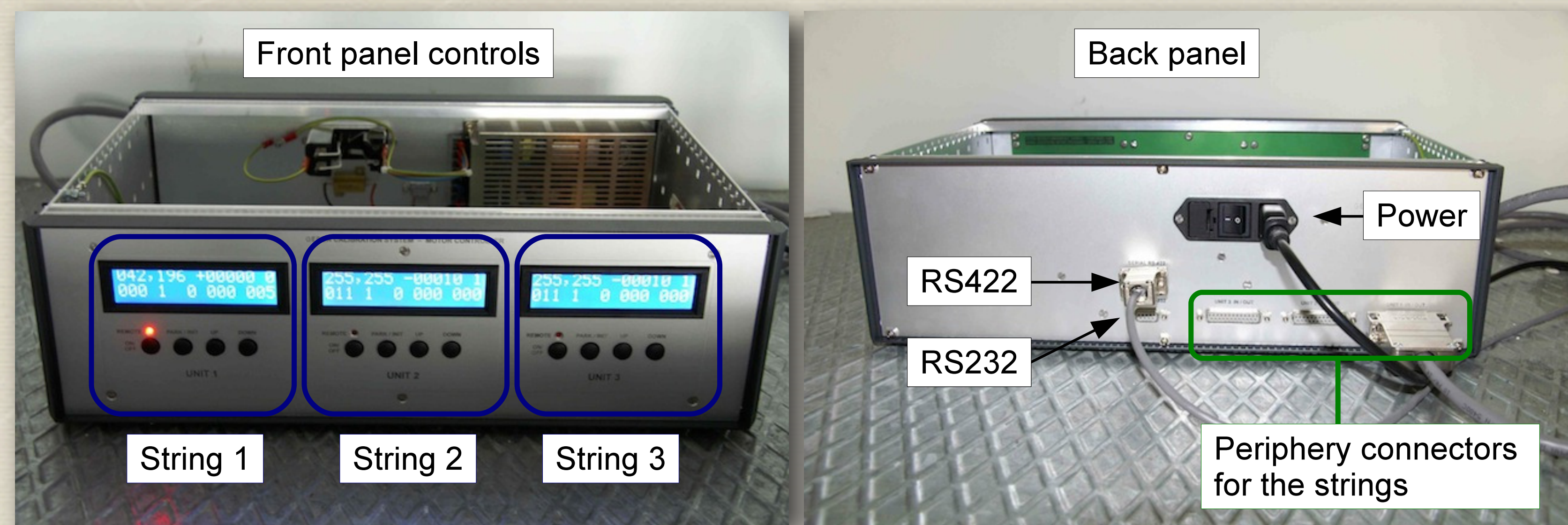
Difference between incremental and absolute encoders



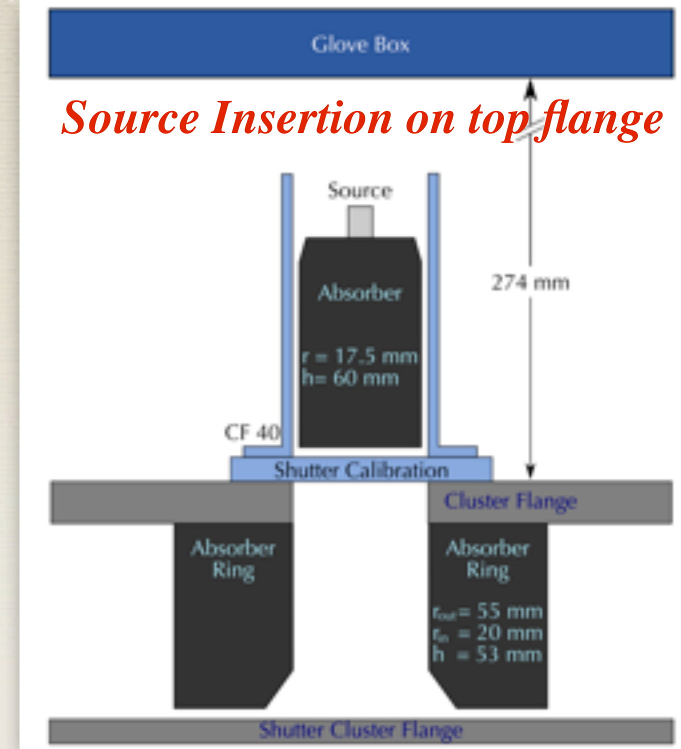
Difference between incremental absolute encoder over time

* Incremental Encoder: An optical system with an LED on one side of the steel band and two photosensors on the other side counts the holes in the steel band.

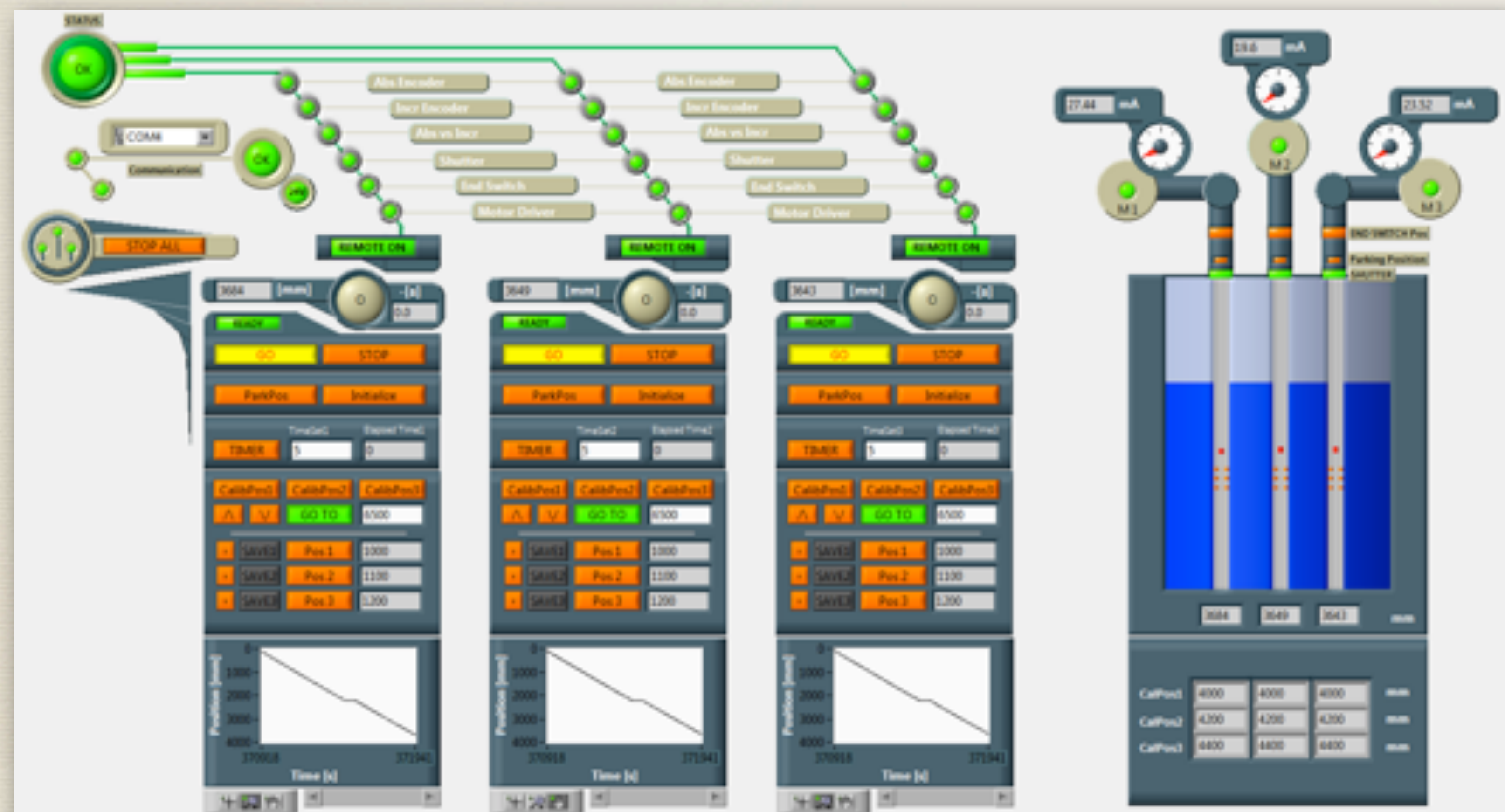
* Absolute Encoder: Connected via rank wheels, the system counts the turns of the crank.



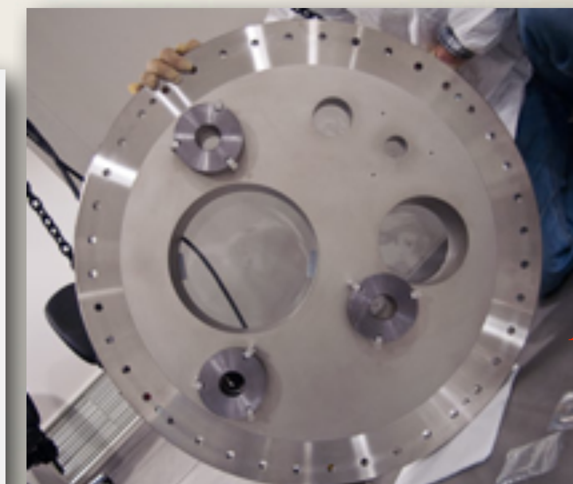
SIS Control Box



Source Insertion on top flange

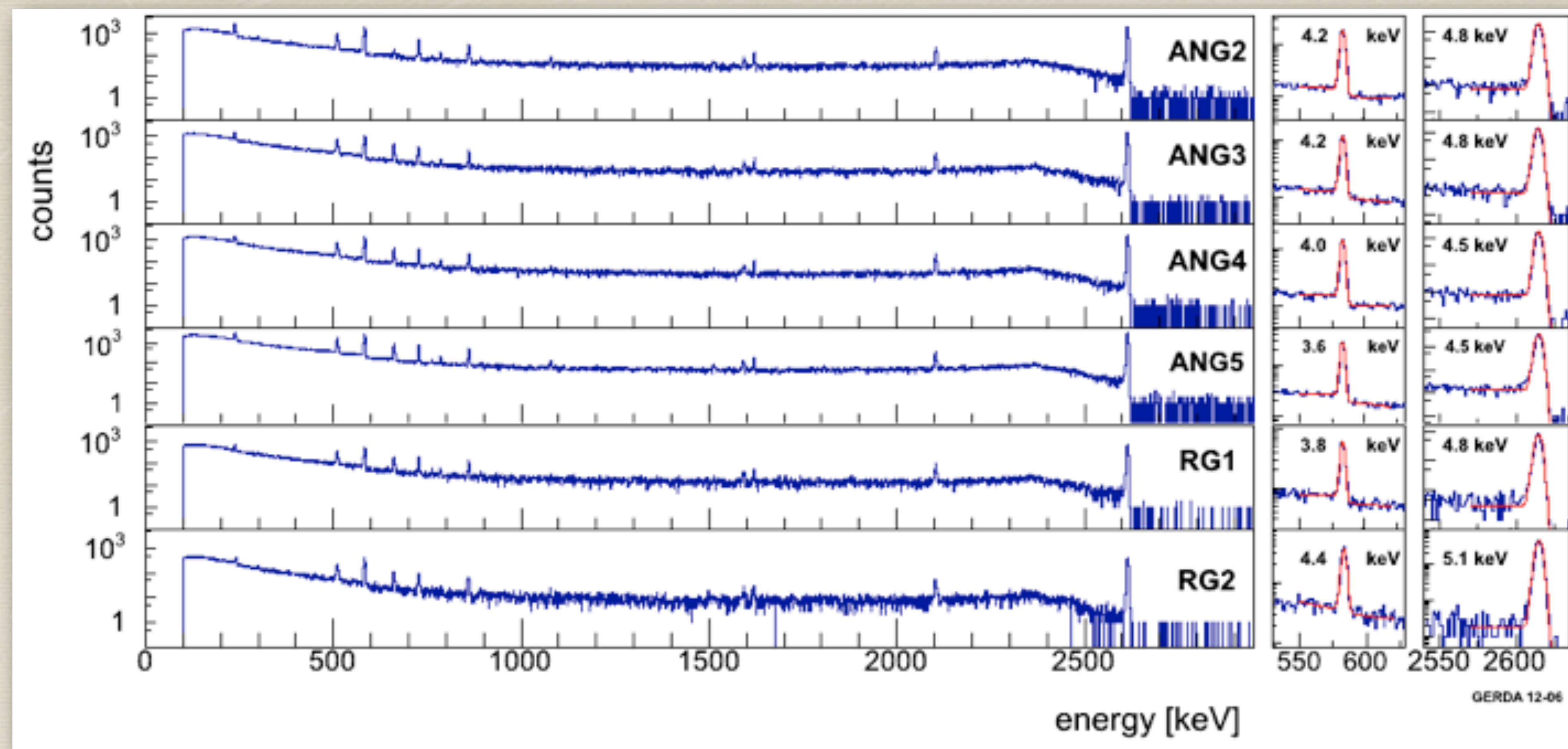


SIS LabView Interface



Phase - I Top Flange

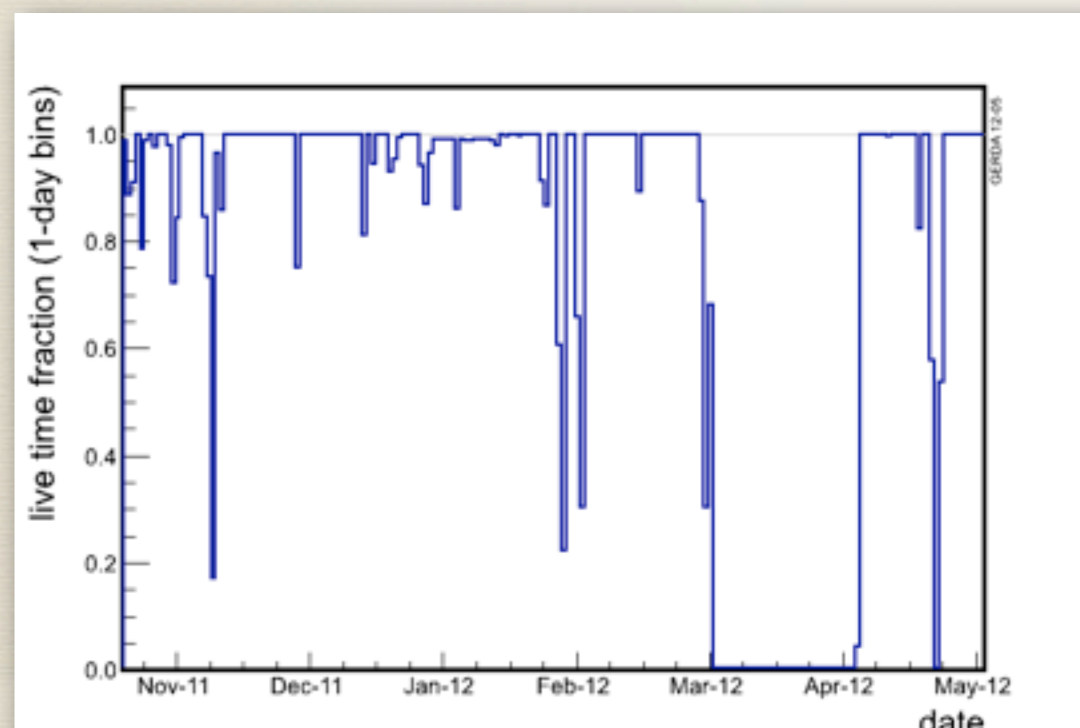
Source and Ta absorber



Phase I Data Taking

^{enr}Ge mass 14.63 kg

^{nat}Ge mass 7.59 kg



Nov. 2011 – May 2012

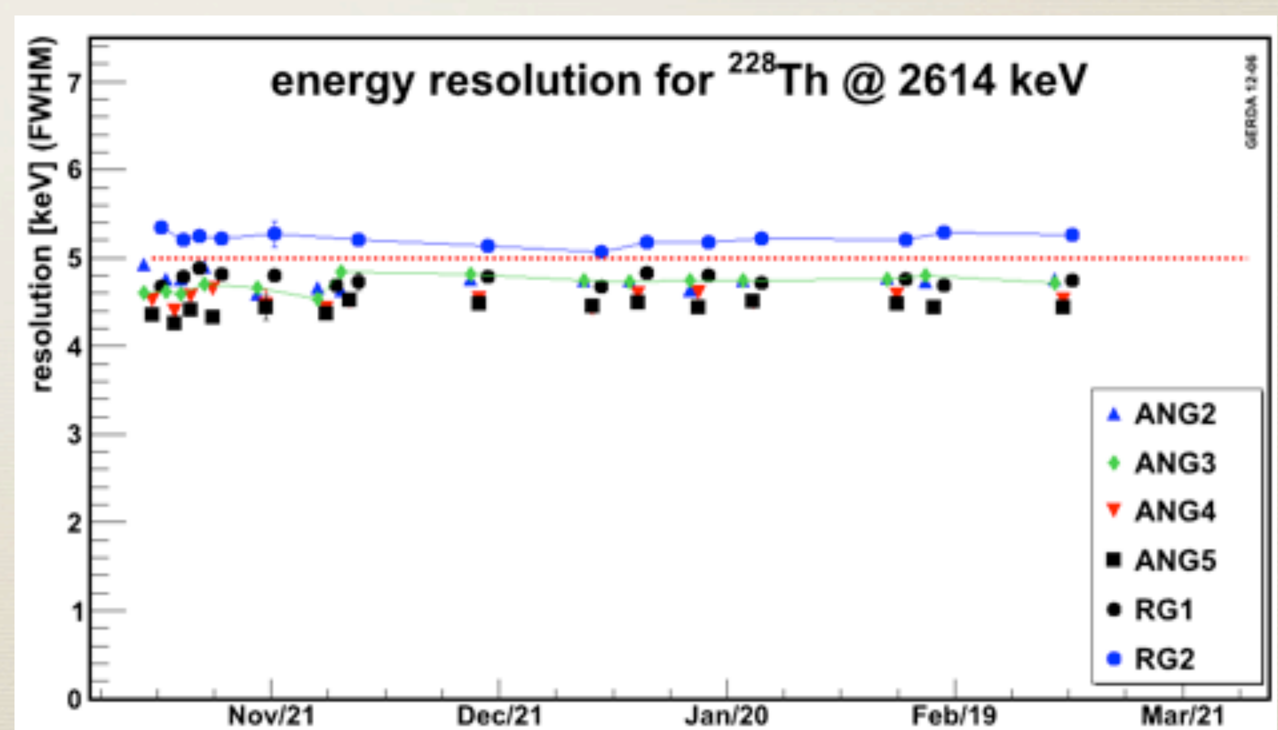
Live time = 152.49 days

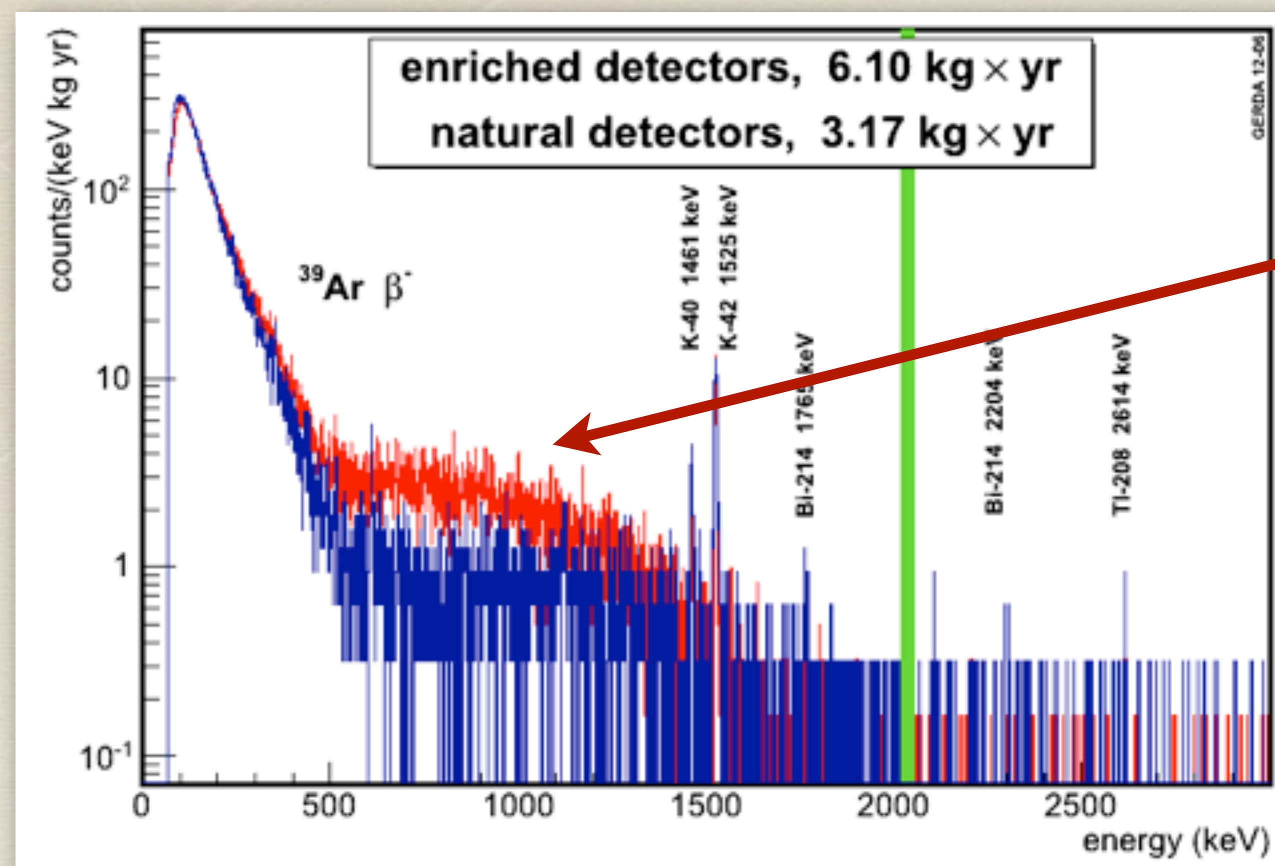
Duty cycle = 78.3%

Calibration and long term stability

4.5 to 5.1 keV (FWHM) at 2614 keV

@ $Q_{\beta\beta}$ = 2039 keV: 4.5 keV resolution (FWHM)





Excess counts in ^{enr}Ge due to 2νββ

Spectra (data) from Phase I Detectors

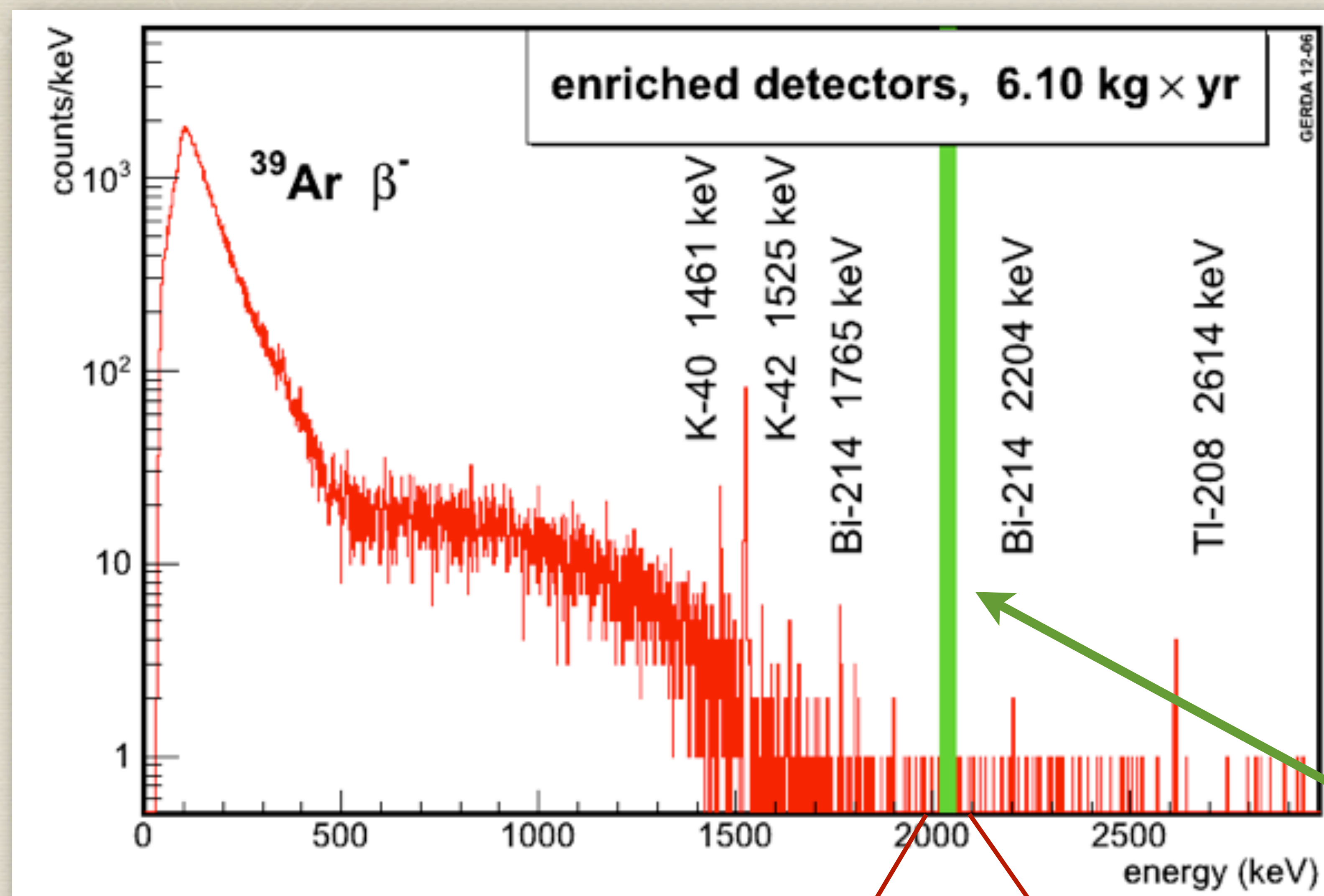
^{nat}Ge spec scaled by exposure to have the same rate as ^{enr}Ge in low energies

2νββ decay in Gerda Phase-I

Counts and rates of background lines for the enriched and natural detectors in Gerda in comparison to the enriched detectors of HdM

isotope	energy [keV]	^{nat}Ge (3.17 kg·yr) tot/bck [cts]	^{nat}Ge (3.17 kg·yr) rate [cts/(kg·yr)]	^{enr}Ge (6.10 kg·yr) tot/bck [cts]	^{enr}Ge (6.10 kg·yr) rate [cts/(kg·yr)]	HdM (71.7 kg·yr) rate [cts/(kg·yr)]
^{40}K	1460.8	85 / 15	$21.7^{+3.4}_{-3.0}$	125 / 42	$13.5^{+2.2}_{-2.1}$	181 ± 2
^{60}Co	1173.2	43 / 38	< 5.8	182 / 152	$4.8^{+2.8}_{-2.8}$	55 ± 1
	1332.3	31 / 33	< 3.8	93 / 101	< 3.1	51 ± 1
^{137}Cs	661.6	46 / 62	< 3.2	335 / 348	< 5.9	282 ± 2
^{228}Ac	910.8	54 / 38	$5.1^{+2.8}_{-2.9}$	294 / 303	< 5.8	29.8 ± 1.6
	968.9	64 / 42	$6.9^{+3.2}_{-3.2}$	247 / 230	$2.7^{+2.8}_{-2.5}$	17.6 ± 1.1
^{208}Tl	583.1	56 / 51	< 6.5	333 / 327	< 7.6	36 ± 3
	2614.5	9 / 2	$2.1^{+1.1}_{-1.1}$	10 / 0	$1.5^{+0.6}_{-0.5}$	16.5 ± 0.5
^{214}Pb	352	740 / 630	$34.1^{+12.4}_{-11.0}$	1770 / 1688	$12.5^{+9.5}_{-7.7}$	138.7 ± 4.8
^{214}Bi	609.3	99 / 51	$15.1^{+3.9}_{-3.9}$	351 / 311	$6.8^{+3.7}_{-4.1}$	105 ± 1
	1120.3	71 / 44	$8.4^{+3.5}_{-3.3}$	194 / 186	< 6.1	26.9 ± 1.2
	1764.5	23 / 5	$5.4^{+1.9}_{-1.5}$	24 / 1	$3.6^{+0.9}_{-0.8}$	30.7 ± 0.7
	2204.2	5 / 2	$0.8^{+0.8}_{-0.7}$	6 / 3	$0.4^{+0.4}_{-0.4}$	8.1 ± 0.5

Background Index of Gerda Phase-I



Background contribution at $Q_{\beta\beta}$:

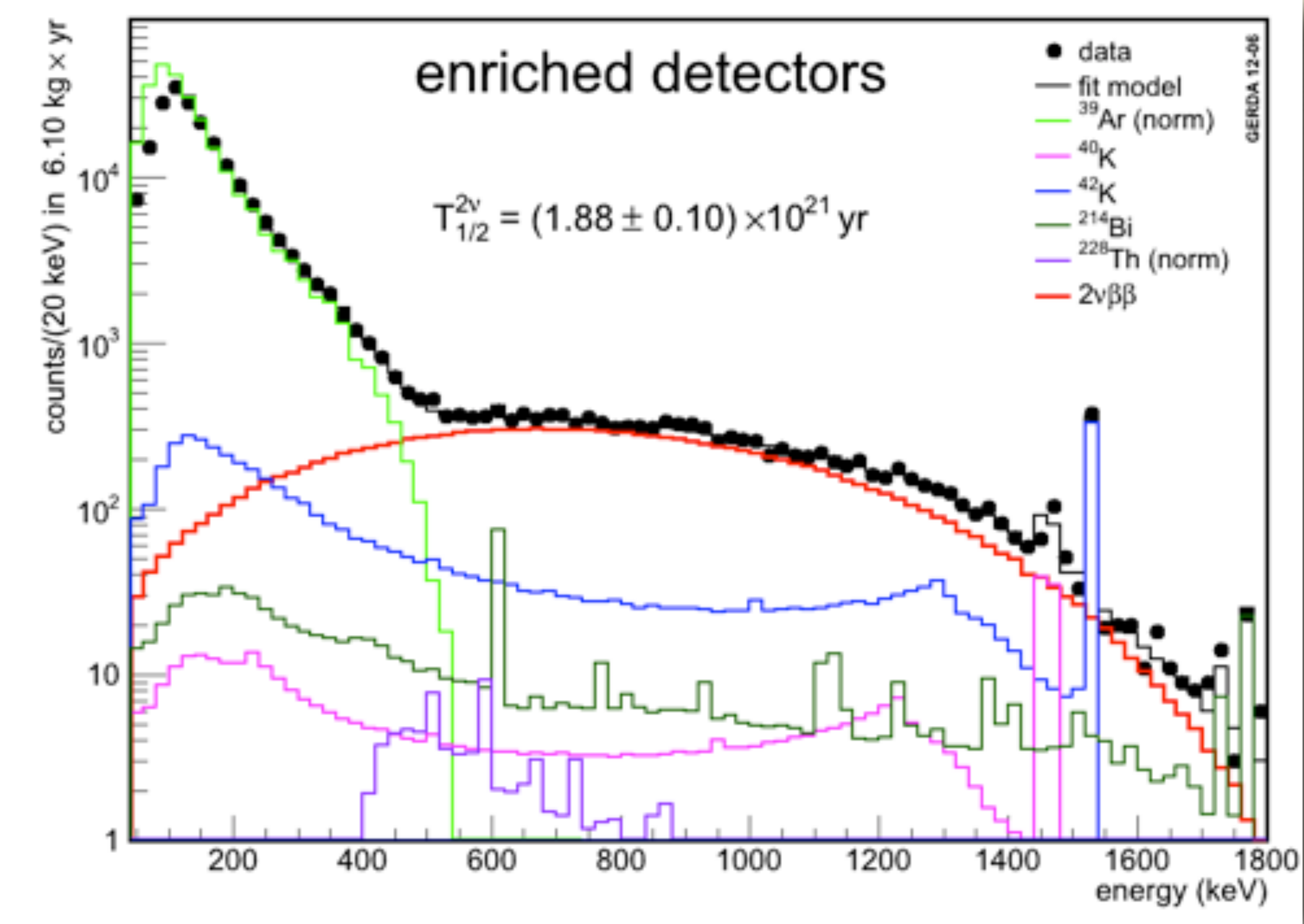
* γ rays from ^{214}Bi and ^{208}Tl
* degraded α from ^{210}Po
* β from ^{42}K
* internal contaminations such as ^{60}Co

40 keV blinded window FWHM @ $Q_{\beta\beta}$ = 4.5 keV

Background index in a 200 keV window
(- 40 keV blinded) centered on
$Q_{\beta\beta}$ = 0.020 + 0.006 - 0.004 counts/(keV. kg. yr)

No PSD Applied

Preliminary half-life of 2νββ decay of ^{76}Ge



The $T_{1/2}^{2\nu}$ prelimenary values from fit to data from 6 enriched diodes we achieved an half-life of

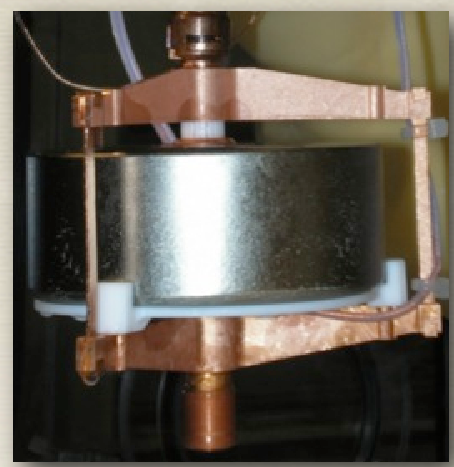
$$T^{2\nu}_{1/2} = (1.88 \pm 0.10) \cdot 10^{21} \text{ yr}$$

Compilation of results of the 2νββ of ^{76}Ge. The exposure is normalized to germanium isotopically enriched at 86% in 76Ge; the exposure of the PNL-USC used, natural germanium (7.44% in ^{76}Ge)

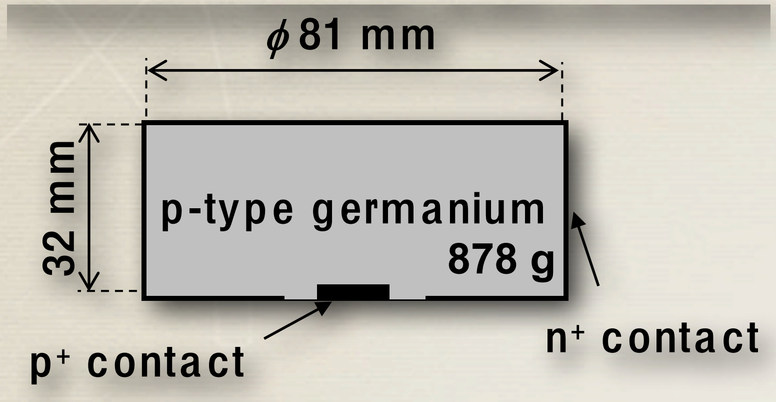
$T^{2\nu}_{1/2}$ [10^{21} yr]	Experiment	Exposure [kg·yr]	year
0.9 ± 0.1 †)	ITEP-YPI	0.83	1990
$1.1^{+0.6}_{-0.3}$ ⋆)	PNL-USC	0.17	1991
$0.92^{+0.07}_{-0.04}$ ⋆)	PNL-USC-ITEP-YPI	0.06	1991
$1.2^{+0.2}_{-0.1}$ †)	PNL-USC-ITEP-YPI	0.10	1994
$1.77 \pm 0.01(\text{stat})^{+0.13}_{-0.11}(\text{syst})$	Heidelberg-Moscow (HdM)	10.58	1997
1.45 ± 0.15 †)	Igex	5.7	1999
$1.55 \pm 0.01(\text{stat})^{+0.19}_{-0.15}(\text{syst})$	Heidelberg-Moscow (HdM)	47.7	2001
$1.74 \pm 0.01(\text{stat})^{+0.18}_{-0.16}(\text{syst})$	Klapdor-HdM	41.57	2003
$1.78 \pm 0.01(\text{stat})^{+0.07}_{-0.09}(\text{syst})$	Bakalyarov-HdM	50.5	2005

Phase-II: Preparation and Status

⇒ R & D of Phase-II detectors:



BEGe detectors were chosen for the Phase II of the GERDA experiment

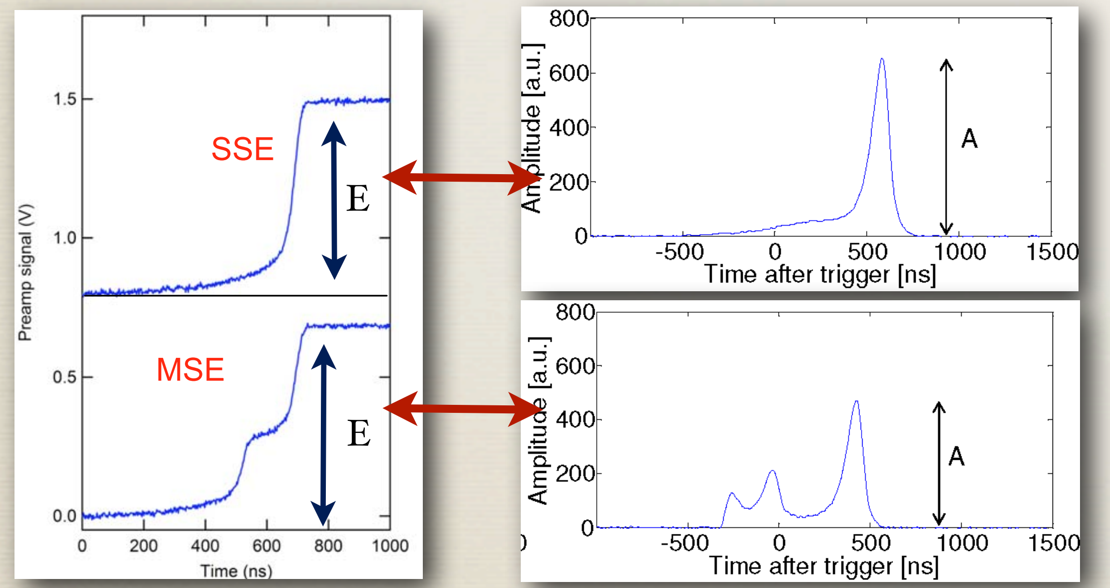


Schematic of a typical P-type BEGe

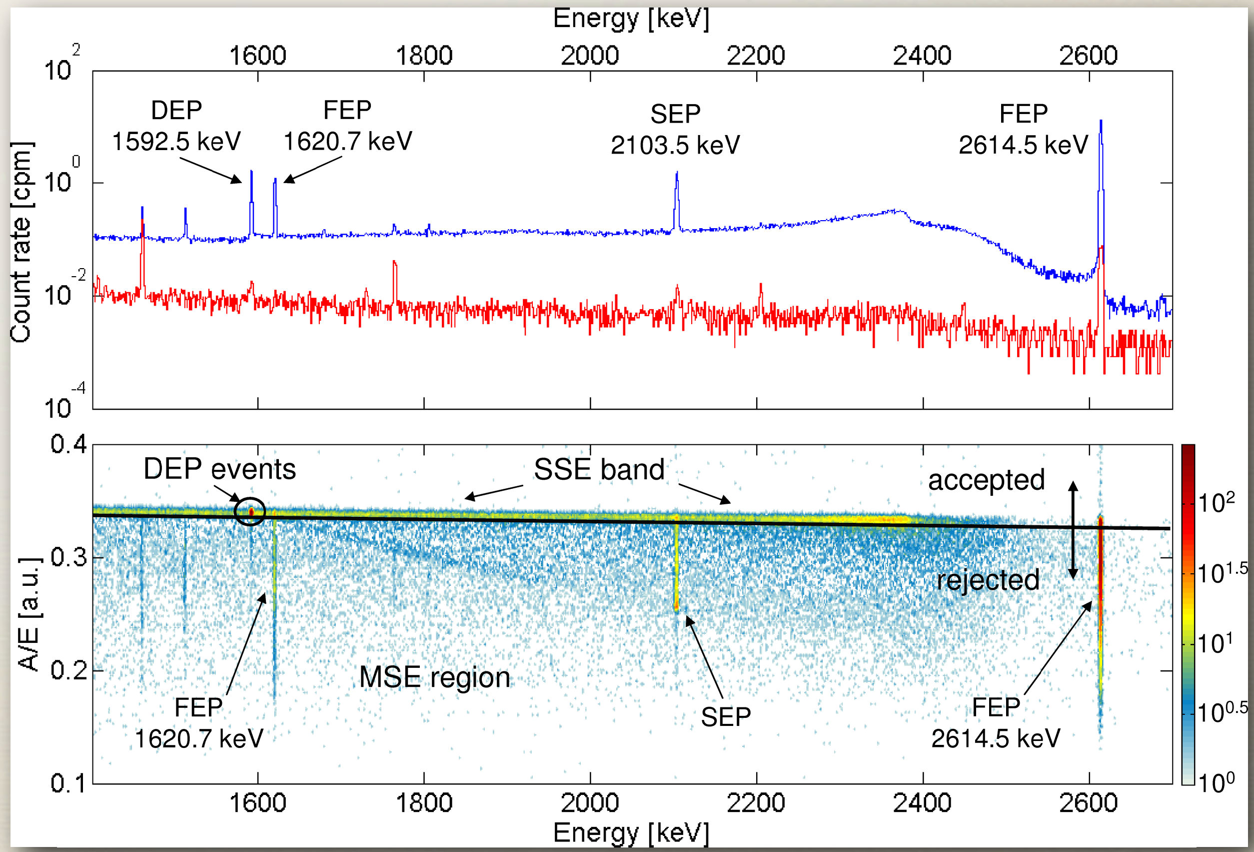
crystal pulling completed 9 crystals pulled
26+ enr. diodes (20+ kg)

* Pulse Shape Discrimination using A/E for BEGe detectors.
* SSE and MSE are identified using A/E.
* A/E for SSE is independent of the energy.
* A/E for MSE is smaller

Charge Pulse *Current Pulse*



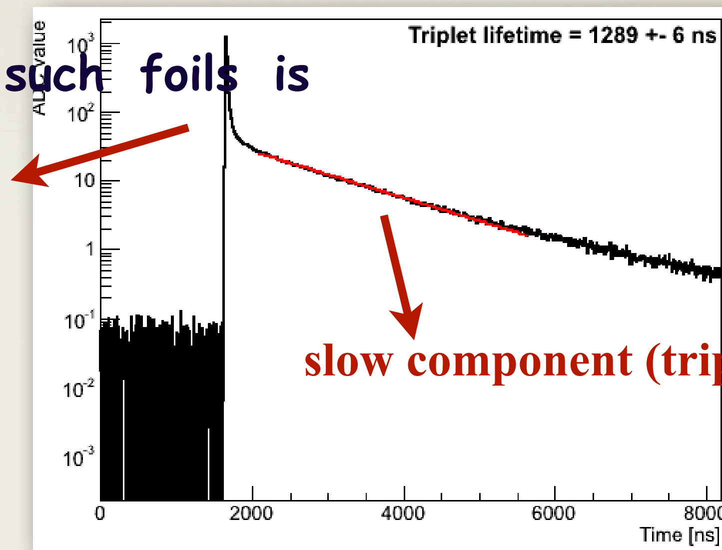
Candidate SSE (left) and MSE (right) current signals from the BEGe detector



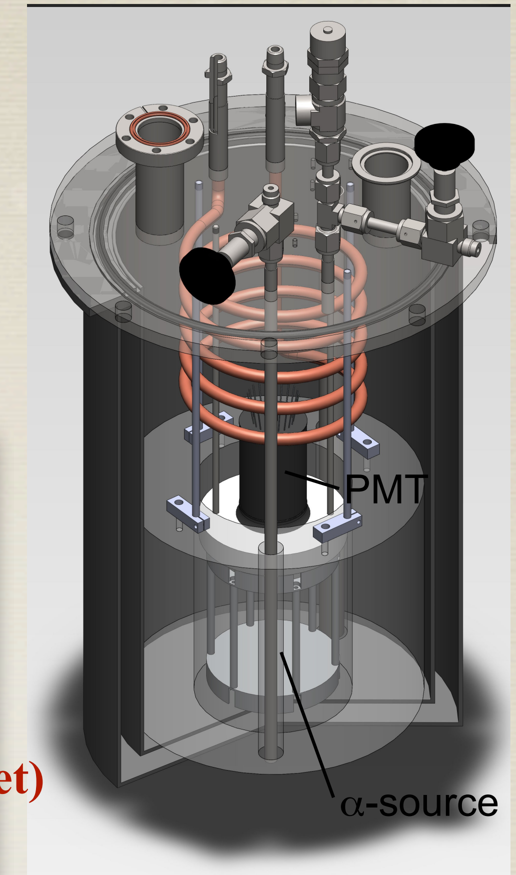
PSD cut – 90% of the ^{208}Tl 2614 keV DEP

LAr instrumentation - Wave Length Shifting foils

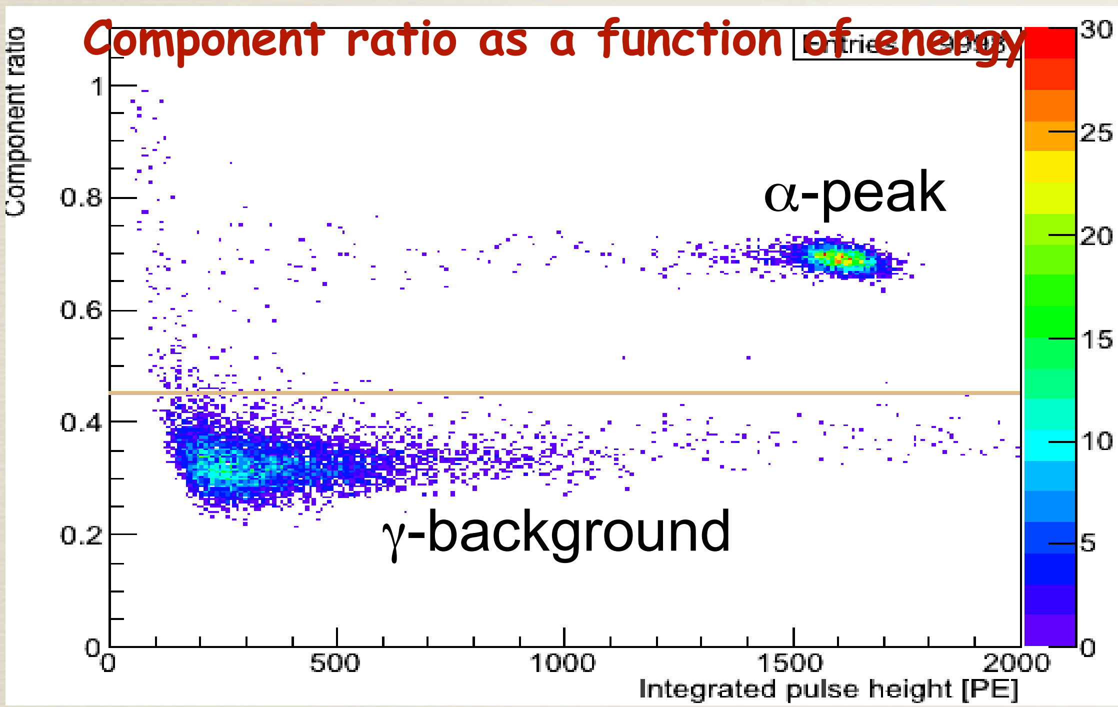
* Liquid argon is used as a coolant, shielding and will be instrumented to become an active veto in phase II.
* Scintillation light in LAr has a wave length of 128nm, it is converted to higher wave lengths to be detected by PMT's with glass window.
* The quantum efficiency and stability of various such foils is being tested



Mean Trace with exponential fit.



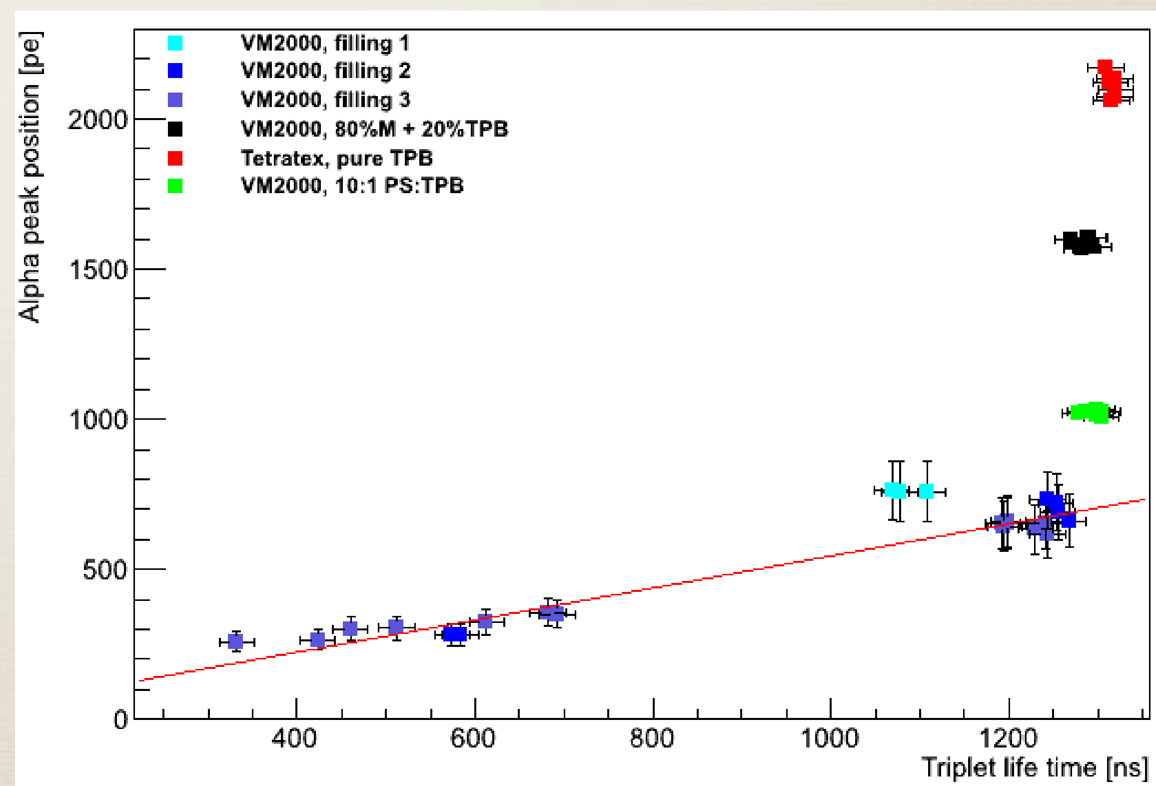
LAr Test Stand.



Component ratio: Is the integral in the fast component over the integral of whole trace.

L.Ar test stand

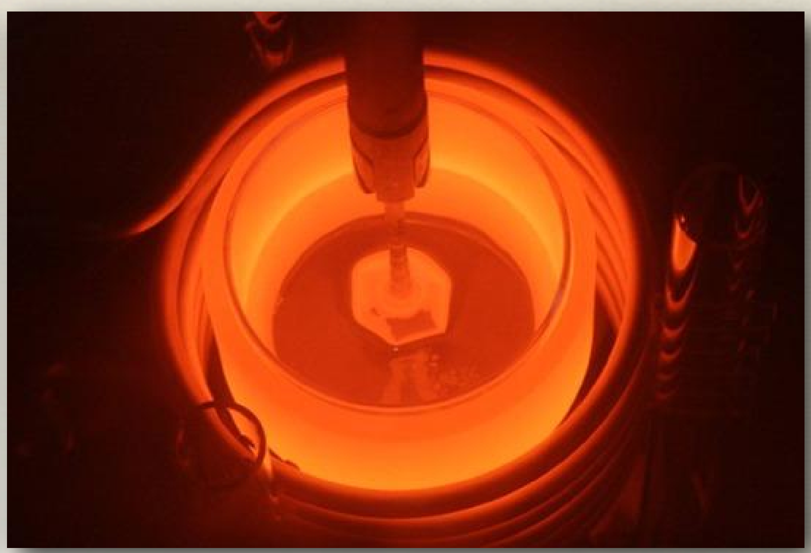
Scintillation light produced by an ^{241}Am α-source and shifted by a surrounding cylinder of WLS reflector foil.



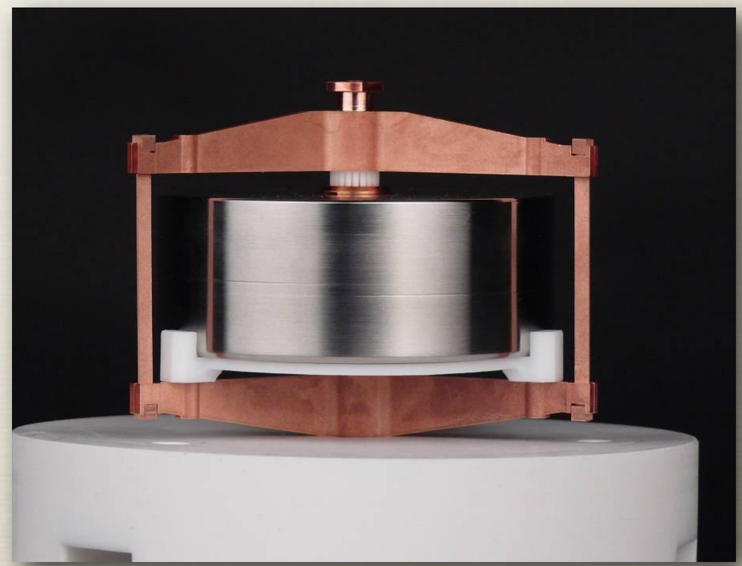
Efficiency of the various wls coatings

GERDA Phase II: Diode Production and Characterization

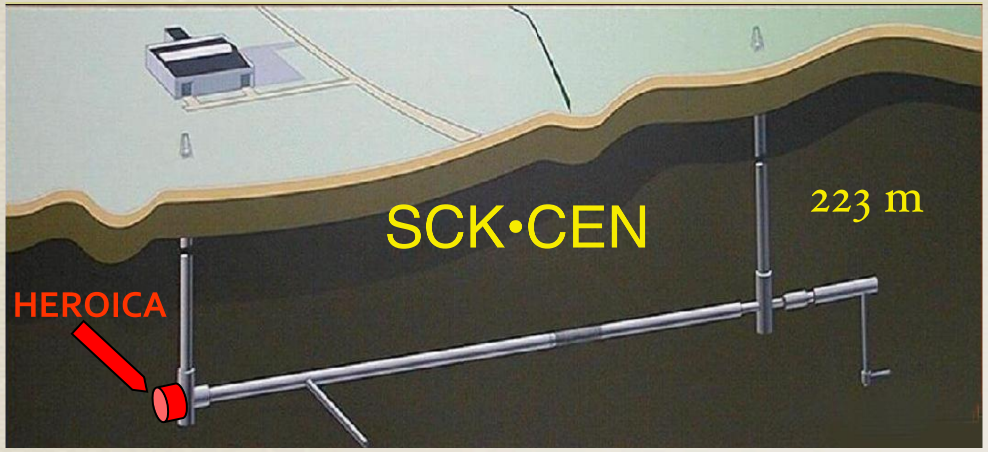




1. Purchase Enriched $^{76}GeO_2$: ECP Zelenogorsk, RU
2. Metal Reduction and Zone Refinement: Langelsheim, DE
3. Crystal Pulling at Canberra: Oakridge, TN, USA
4. BEGe Detector Diode Production: Olen, BE

Phase-II: Infrastructure in Hades

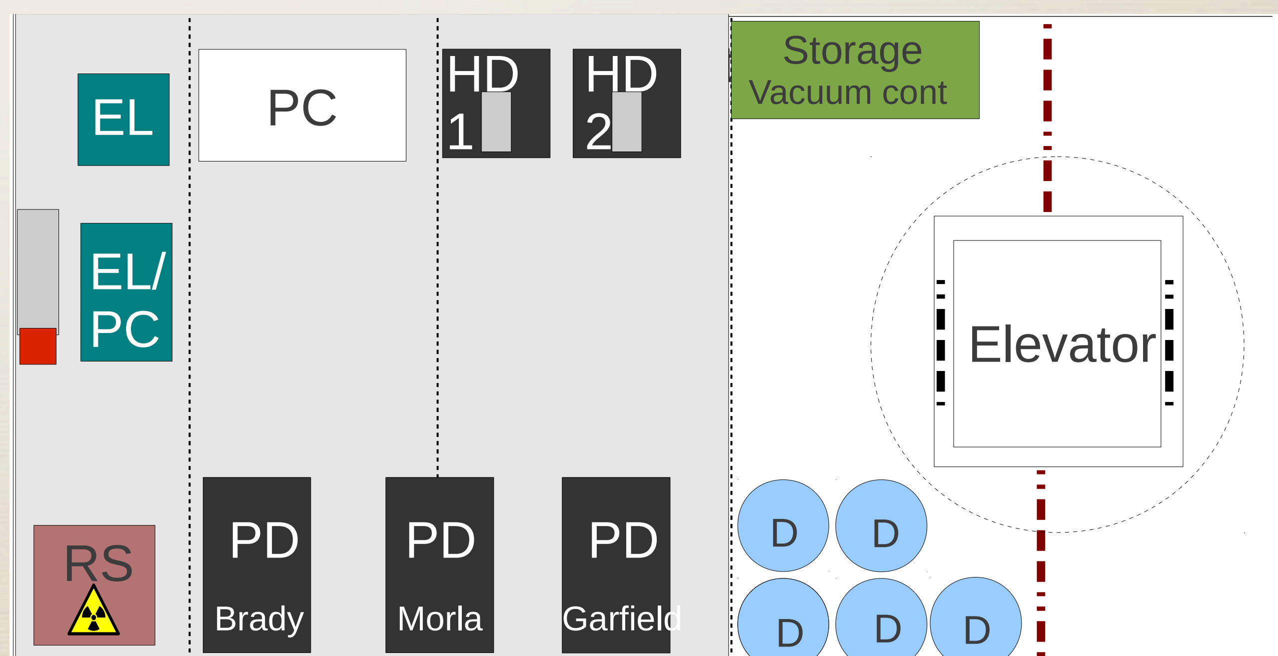


HEROICA
Hades **E**xperimental **R**esearch **O**f **I**ntrinsic **C**rystal **A**ppliances

Diodes are always placed in underground locations in the vicinity of the production and characterization centers to minimize cosmic activation (^{68}Ge, ^{60}Co).

Fixed Table

Scanning Table



Schematic of the lab in HADES

Phase-II: BEGe performance measurements

Diode Production in Canberra, Olen:

1. Groove + etching

2. Li diffusion for n^+ contact

3. 4h Annealing to get larger DL

4. B implantation for p^+ contact

5. Passivation layer (PL) for tests in LN2 and in vacuum.

7. Tests:- ^{60}Co, ^{57}Co, ^{55}Fe : E - resolution - in LN2: I/V, Leakage Currant.

(7b. If reprocessing needed: Etching, new PL, annealing)

8. Mounting to vacuum cryostats or in vac. containers

Next:

9. Al evaporation, Contacting

10. Remove PL, (tests in Olen),

Store in vac. containers → LNGS

Measurements done in Hades:

1. Resolution measurement at nominal voltage : Using ^{241}Am, ^{60}Co.

2. Active Volume measurement: Using ^{60}Co source

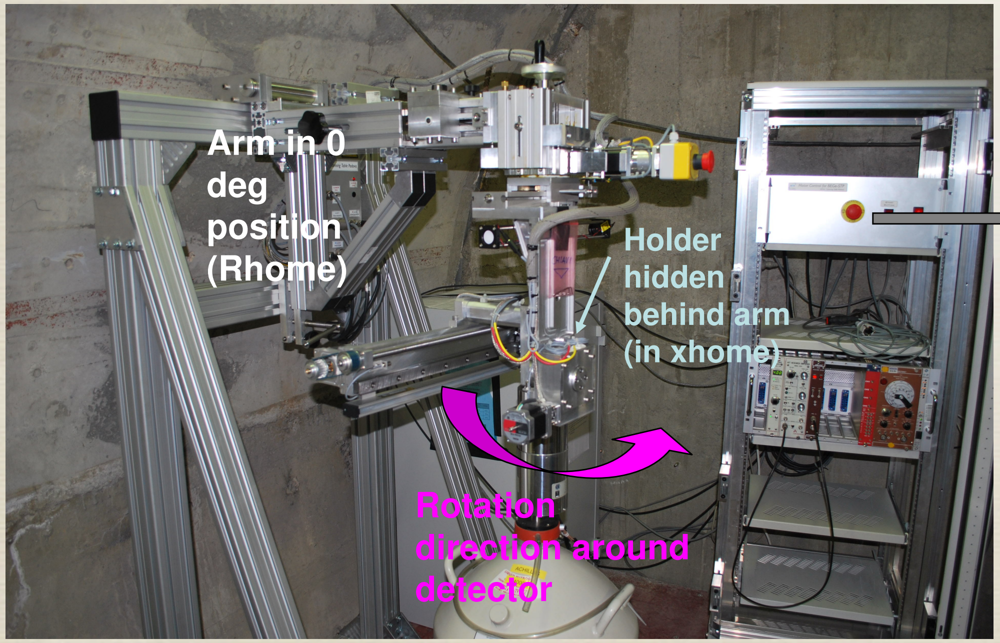
3. Precise measurement of Dead Layer: Using ^{133}Ba and ^{241}Am and comparing spectra with the Monte-Carlo simulations.

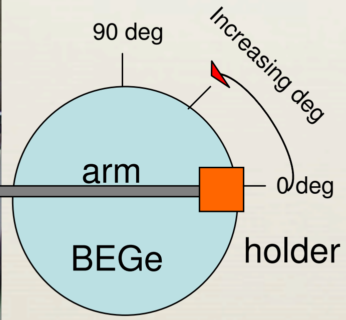
4. High Voltage Scan : From operational Voltage to 499V in -50V steps.

5. Pulse Shape Discrimination: Using ^{228}Th source. A/E studies to characterize the PSD performance.

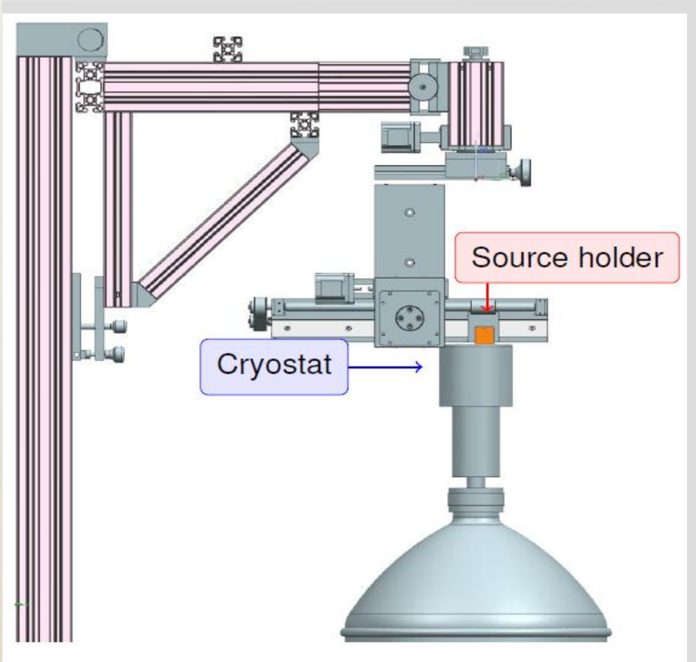
6. ^{241}Am Scanning: Two type of measurements are performed on the scanning tables:

- linear scanning on the TOP or LATeral surface;
- circular scanning on the TOP or LATeral surface.





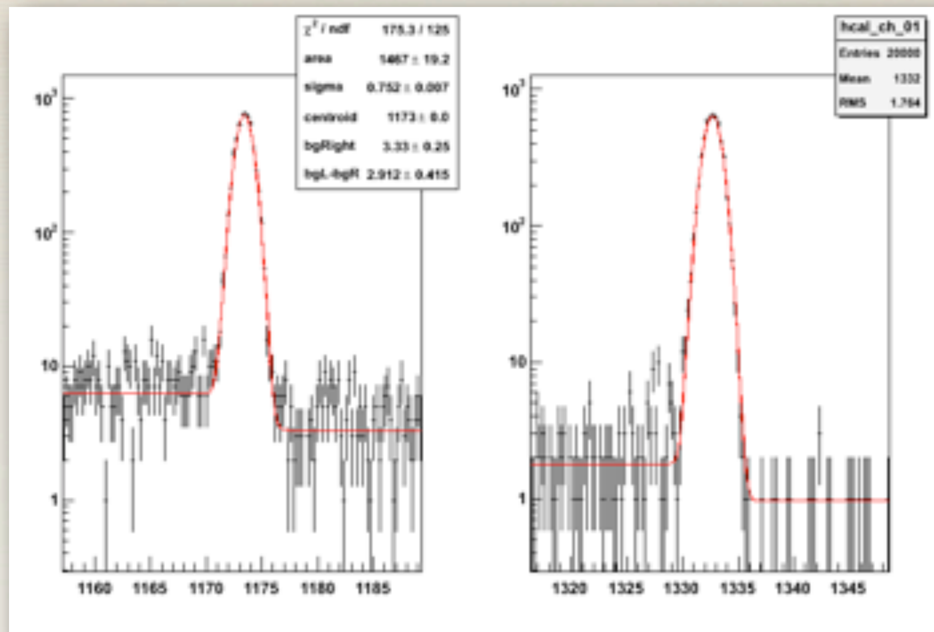
Top Circular Scan

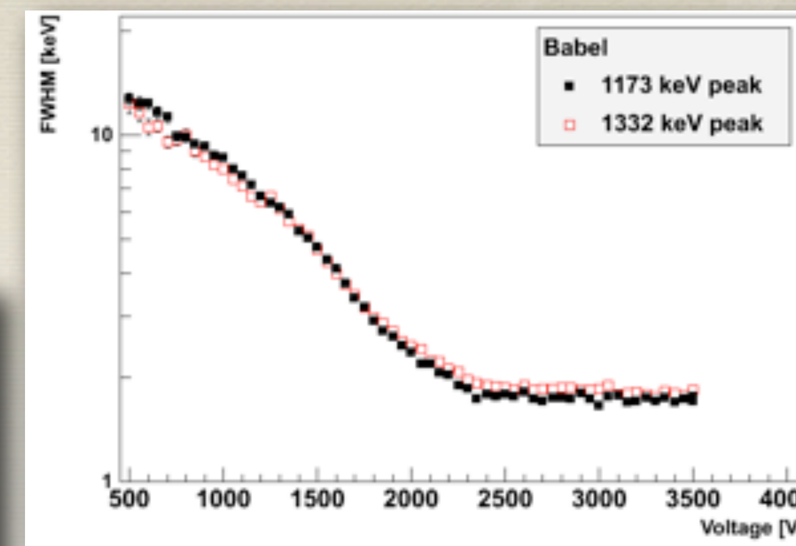


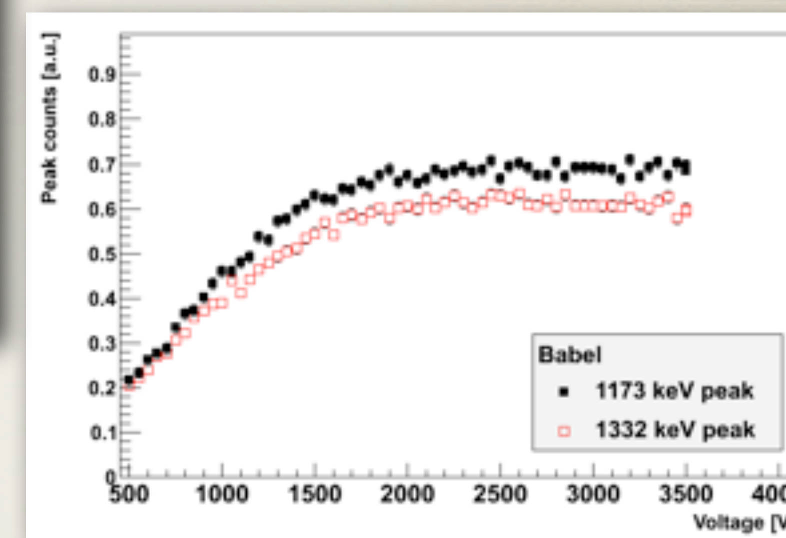
Schematic of the scanning table

Phase-II: BEGe performance: Results I

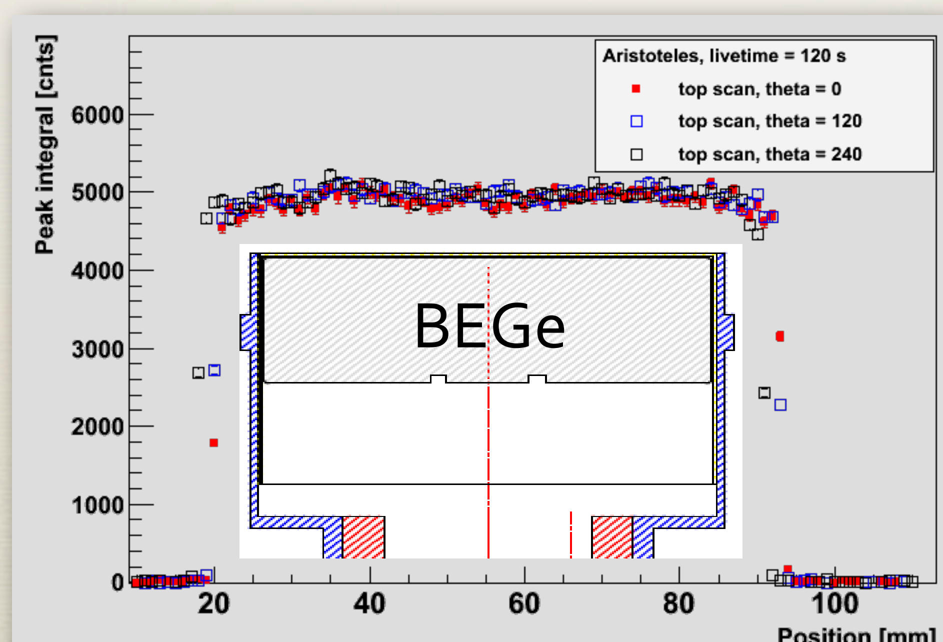
Energy resolution and high voltage scan up to the operational value (≤4kV) with ^{60}Co.



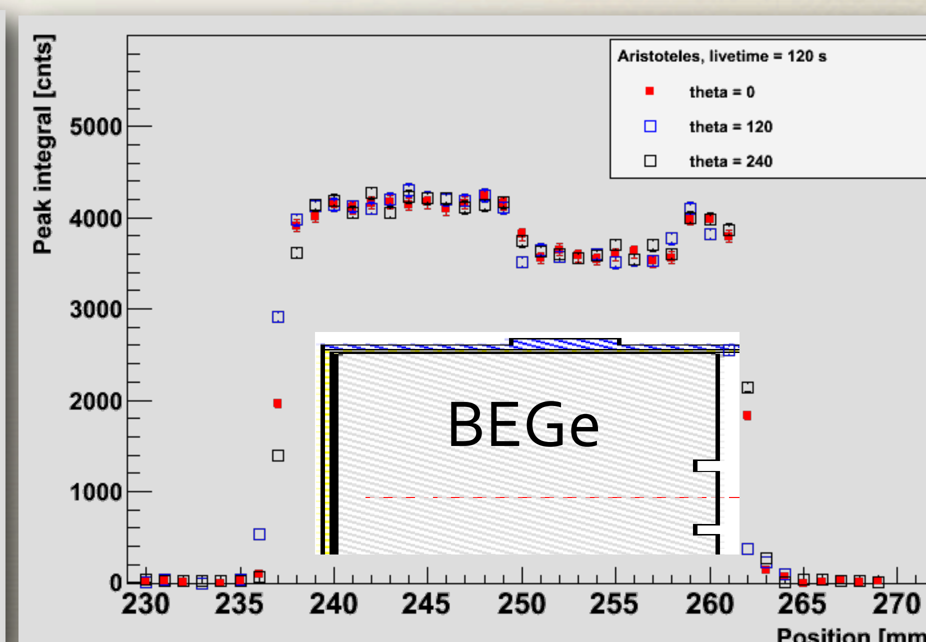




Automated surface scan of detector: count rate and FWHM @ 59 keV -precision ~ 2 mm



Top Scan



Side Scan

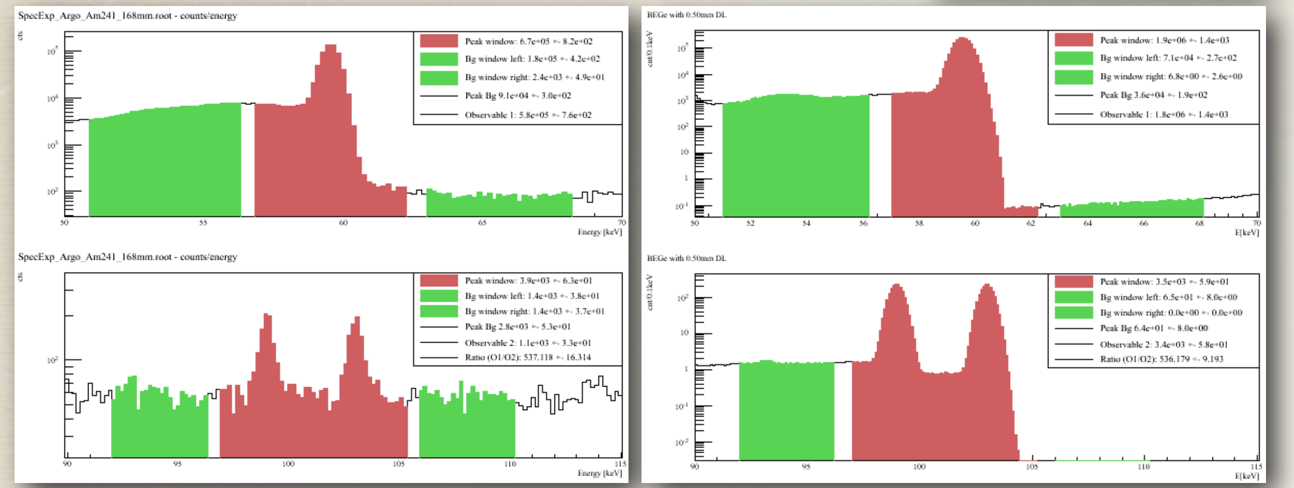
Phase-II: BEGe performance: Results II

Average top surface dead layer determination using ^{241}Am and ^{133}Ba: dead layer

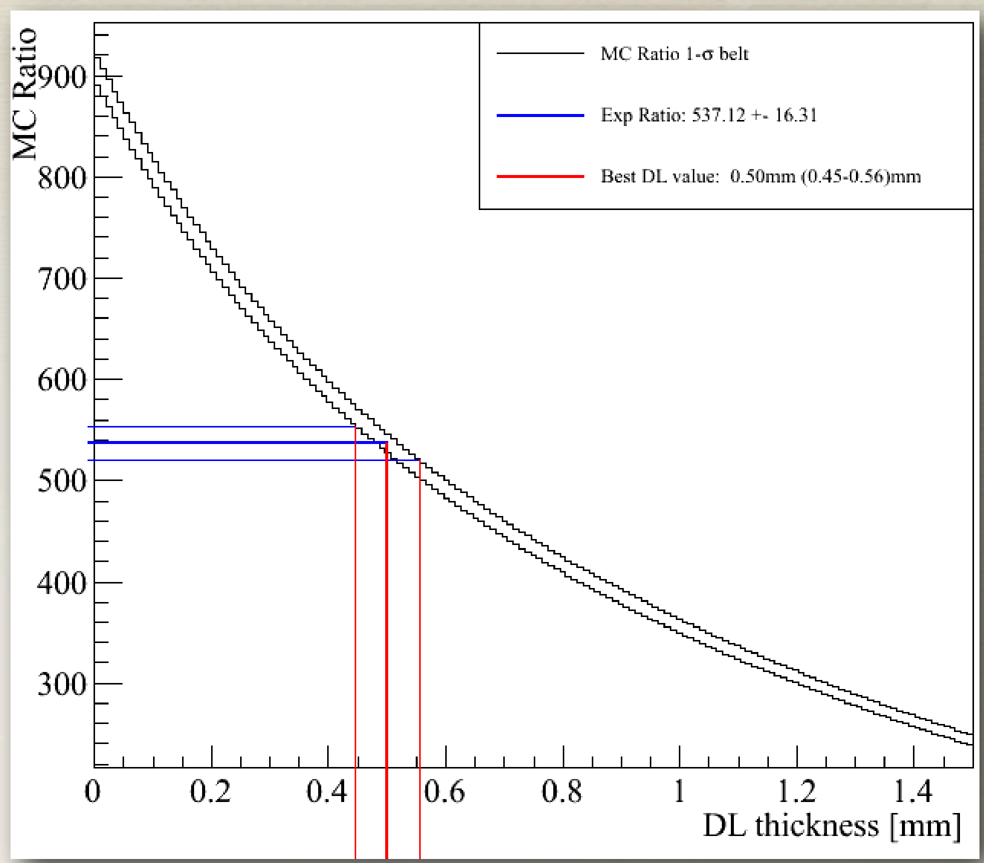
$$r_{Am241} = \frac{\varepsilon_{59.5keV}}{\varepsilon_{99keV} + \varepsilon_{103keV}}$$

$$r_{Ba133} = \frac{\varepsilon_{81keV}}{\varepsilon_{356keV}}$$

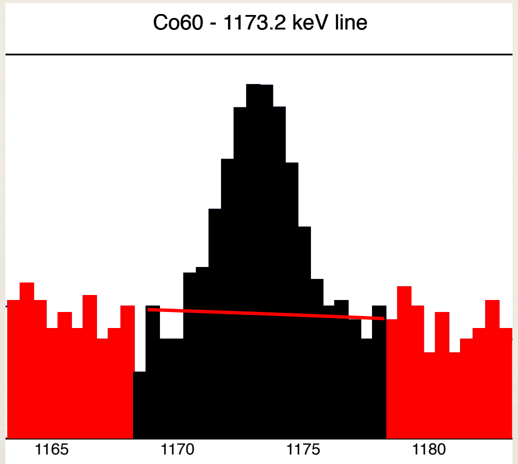
$\varepsilon =$ Experimental count rate under peak

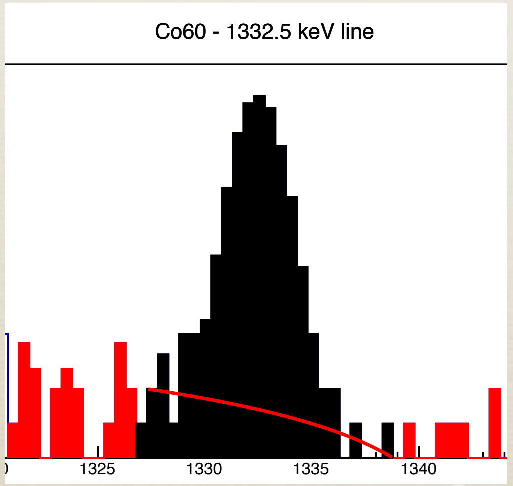


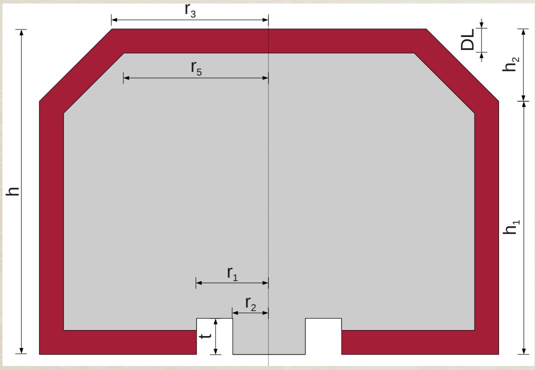
Dead Layer measurement



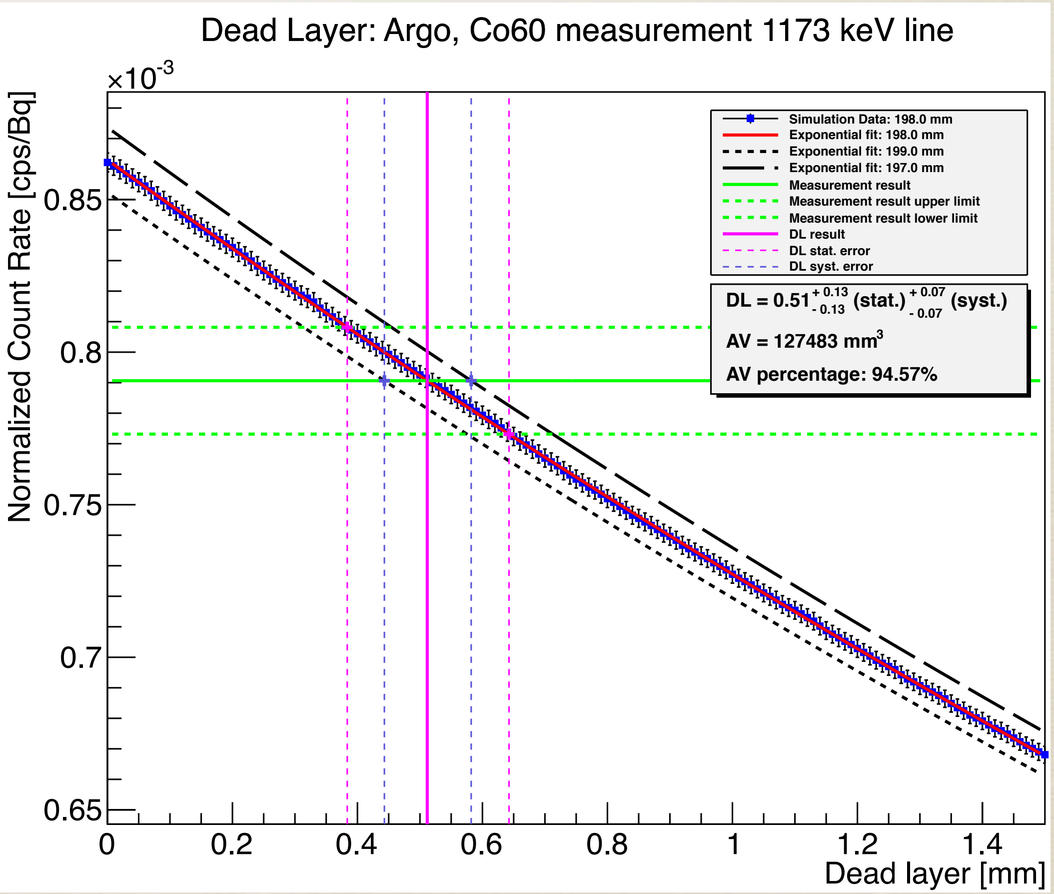
Active volume determination using ^{60}Co: count rate under the peaks @ 1173.2 keV and 1332.5 keV is compared to the simulated one.







Dimensions of a BEGe



Active Volume measurement

Summary and Outlook

Phase - I

GERDA Phase I started in November 2011 with 17.6 kg of ^{enr}Ge. Blinding 2019 – 2059 keV

- Signal/background ratio for 2nubb is 4. GERDA has the best value of all Ge-76 experiments.
- Phase I background index of 10^{-2} counts/(keV kg yr) is attainable when PSD applied. Present BI = 0.02 counts/(keV kg yr)
- Half-life of the 2νββ decay of ^{76}Ge measured with a remarkable signal-to-noise ratio.
- Accurate determination of the ^{42}Ar contaminant concentration. ^{42}Ar(^{42}K) activity determined: (93.0 ± 6.4) μBq/kg. (Preliminary)
- Minimized ^{42}Ar background through the use of polarized mini-shrouds.
- 5 ^{enr}BEGe added to Phase I to increase ^{enr}Ge mass to 18.1 kg.
- First 2νββ half-life results will be published soon. $T^{2\nu}_{1/2} = (1.88 \pm 0.10) \cdot 10^{21}$ yr

Phase - II

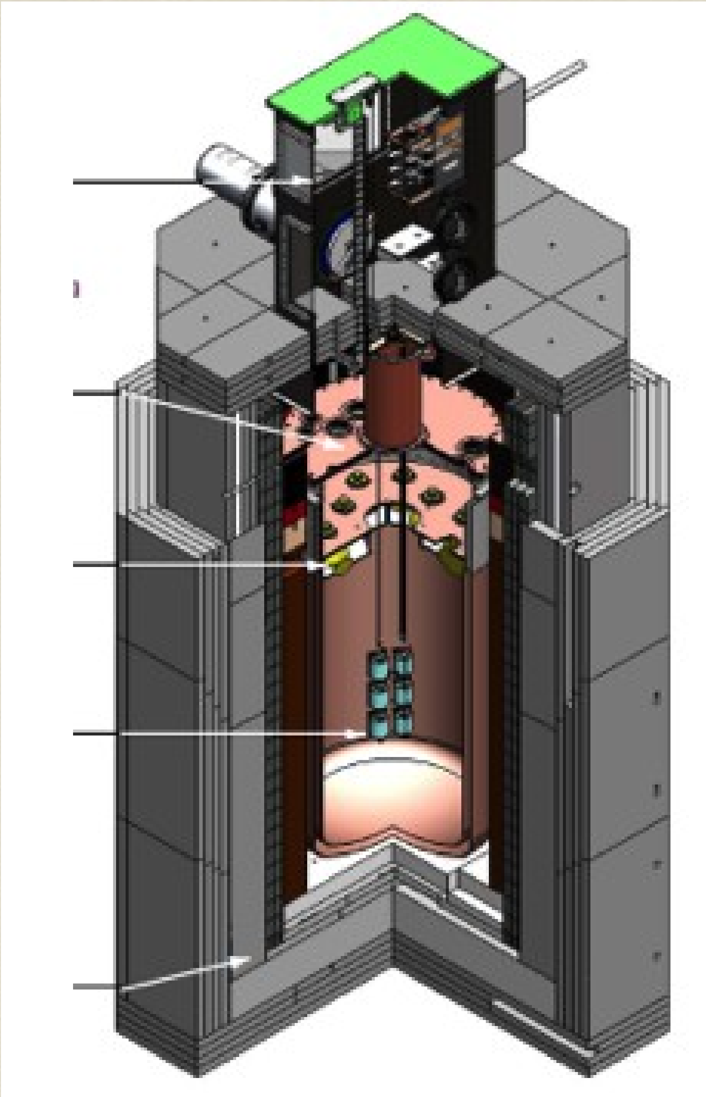
- Phase II ^{enr}BEGe detectors are under production (> 20 kg).
- Phase II R&D for LAr scintillation light read-out is going on.
- Phase II background index 10^{-3} counts/(keV kg yr) with LAr veto and PSD.
- Precise measurement of DL, AV, PSD performance of the new BEGe's.

Backup Slices & Pictures

Phase - I

* 8 ^{enr}Ge (HdM & IGEX) + 3 ^{nat}Ge p-type coaxial Ge detector refurbished
* ^{enr}Ge mass:1-3 kg (total 17.6 kg)
* Deployed in strings of 3 dets each.
* Mounted in low-mass Cu holders.
* HV contact: on Li surface by pressure.
* Readout contact: in borehole spring-loaded.
* All the detectors tested naked in L.Ar and they performed well (Resolution < 3 keV @ 1332 keV)

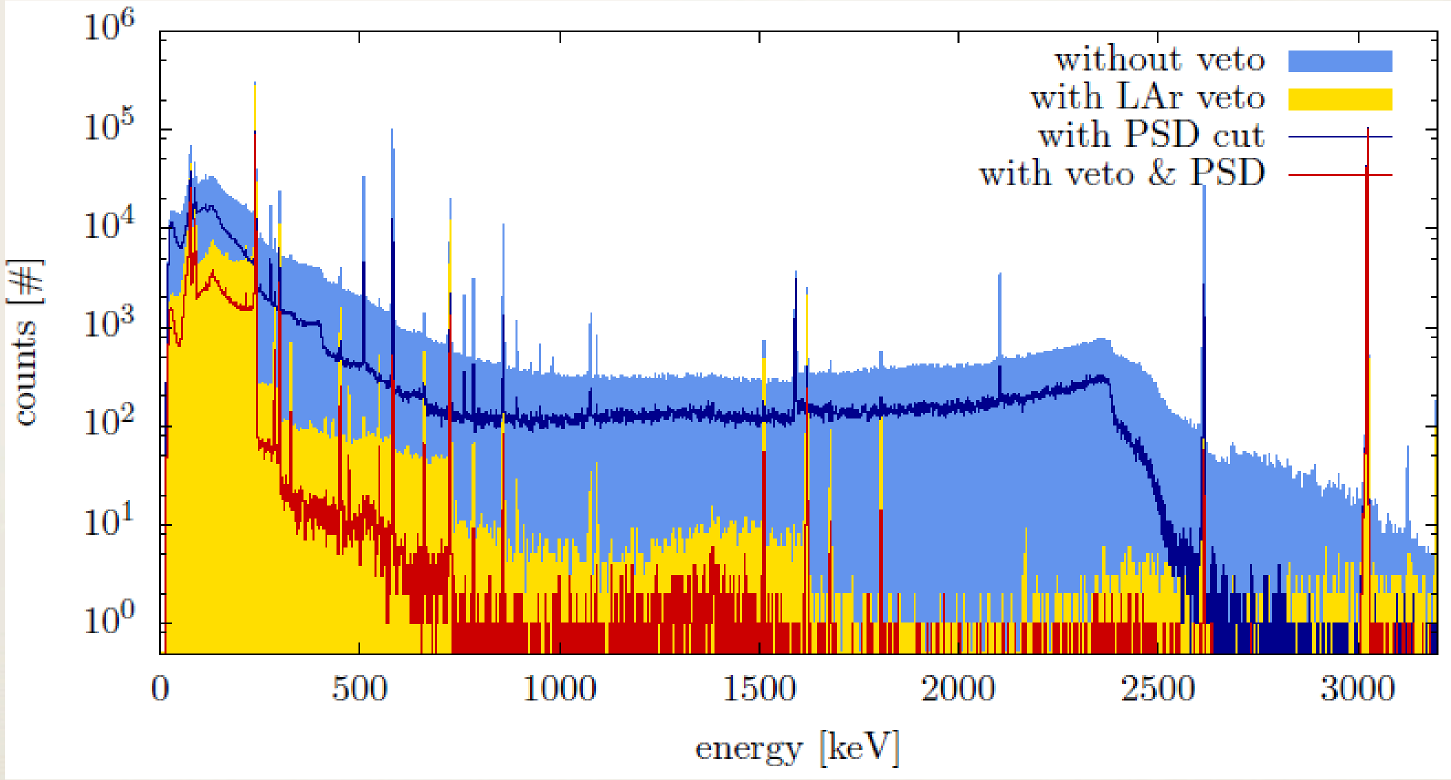
Low mass Cu holder



LArGe test facility

LAr scint. light read-out

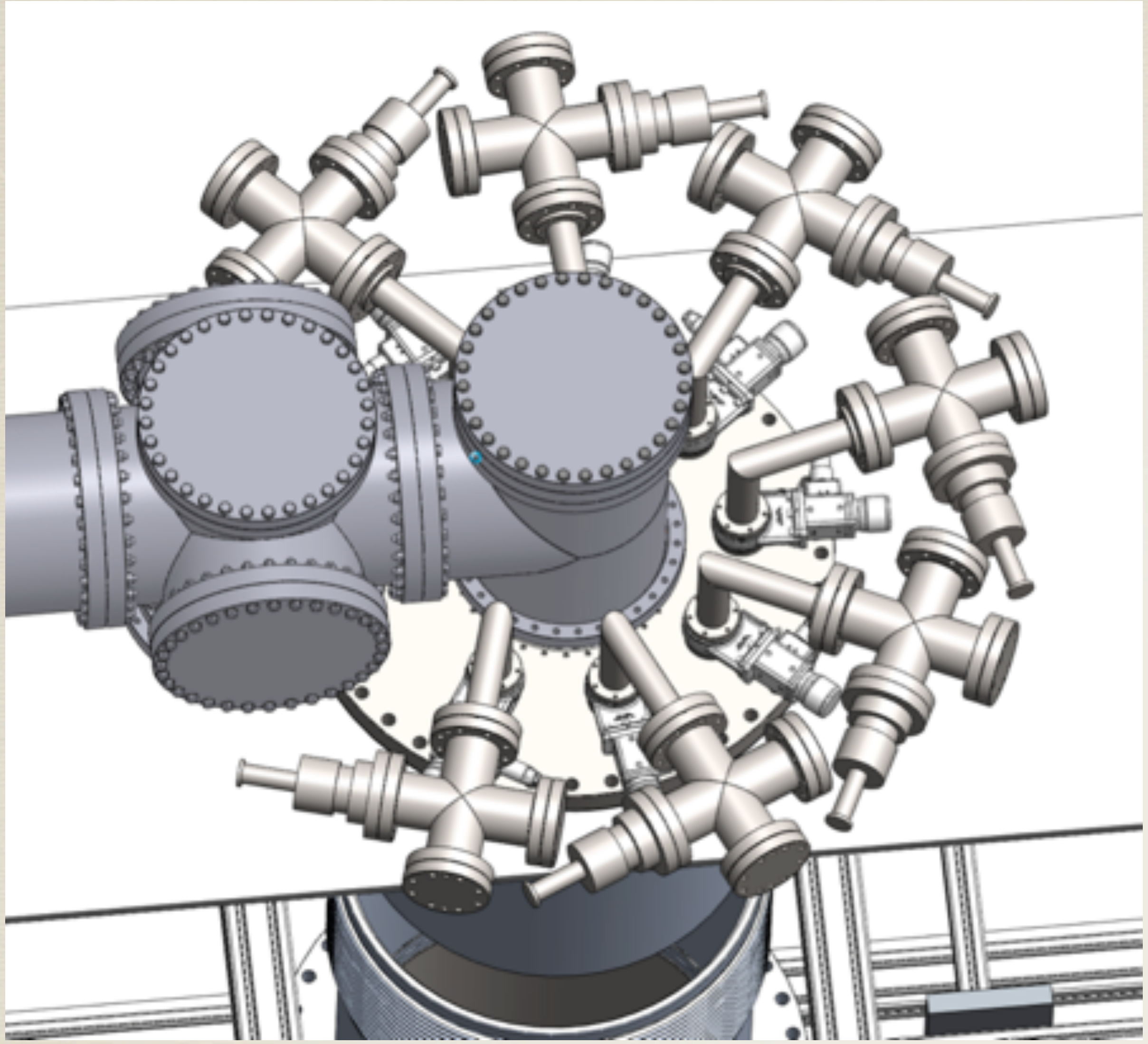
*SiPMs connected to fibers
* Low background PMTs



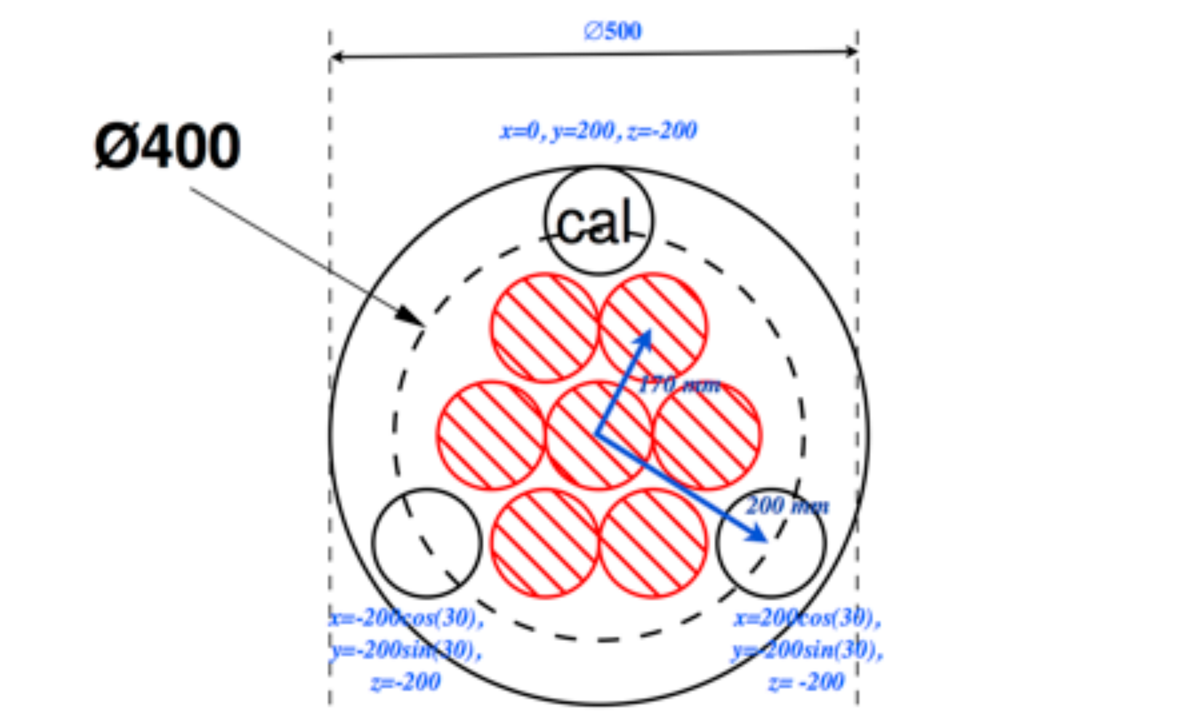
Operation of Phase II detector prototype in LArGe:

Measured suppression factor at $Q_{\beta\beta}$: ~$0.5 \cdot 10^4$ for a ^{228}Th calibration source

Also: successful read out scintillation light with fibers coupled to SiPMs

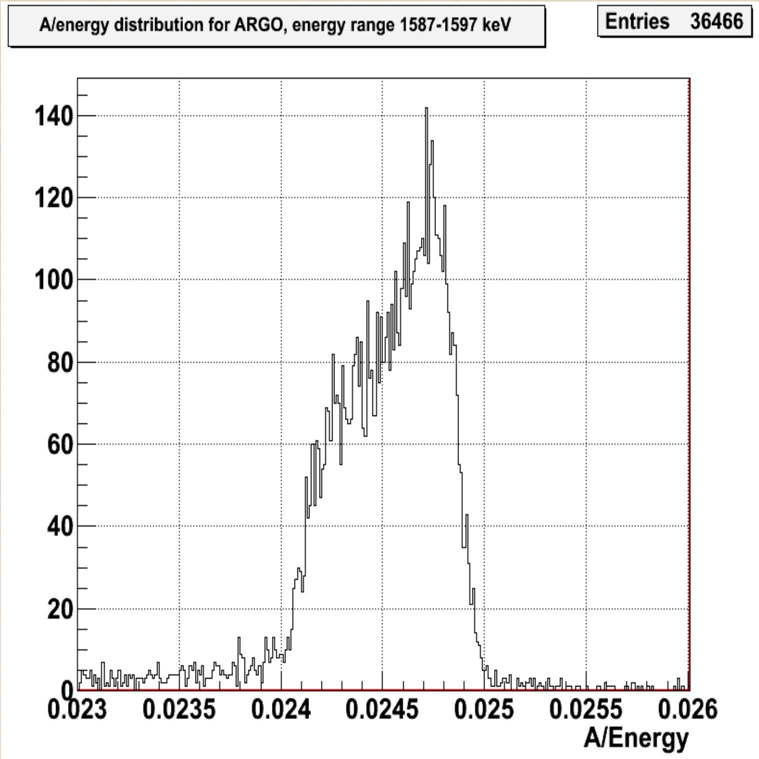


Phase-II Lock Design



String Alignment in DN500 - Phase II

PSA Measurement for ARGO



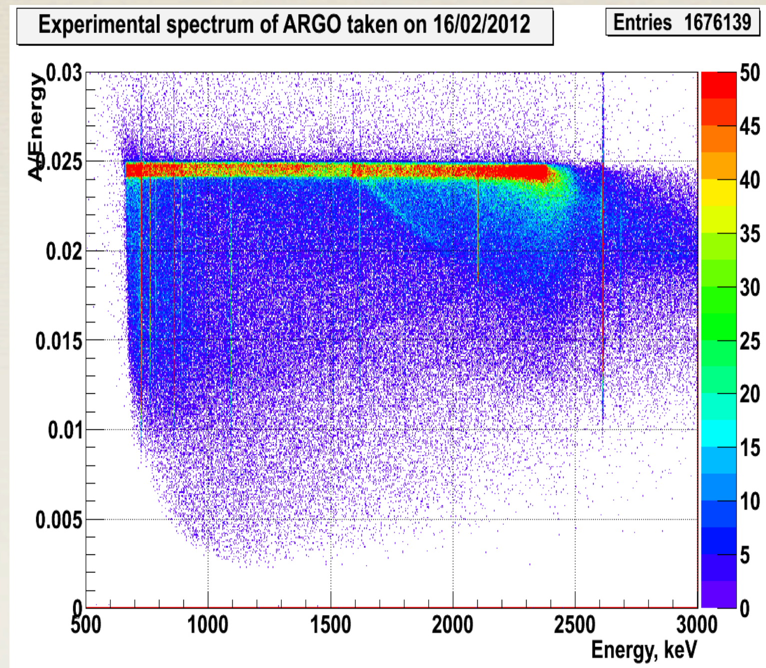


Figure 2: A/E Distribution of ARGO

List of 1st Batch BEGe PSA performance

	ARGO	ANDROMEDA	ARCHIMEDES	ANUBIS
DEP	0.900 ± 0.023	0.900 ± 0.0258	0.900 ± 0.013	0.900 ± 0.027
FEP 1.6MeV	0.128 ± 0.010	0.112 ± 0.014	0.180 ± 0.009	0.181 ± 0.014
SEP	0.078 ± 0.007	0.080 ± 0.009	0.121 ± 0.006	0.142 ± 0.010
FEP 2.6MeV	0.132 ± 0.002	0.117 ± 0.002	0.163 ± 0.001	0.217 ± 0.003
2004-2074keV	0.400 ± 0.005	0.403 ± 0.007	0.427 ± 0.004	0.464 ± 0.007
1989-2089keV	0.395 ± 0.004	0.404 ± 0.006	0.427 ± 0.003	0.466 ± 0.006
Measuring time	5 h	5 h	12 h	12 h (3h live)
	ARISTOTELES	ACHILLES	AGAMENNONE	Ge-9
DEP	0.900 ± 0.017	0.899 ± 0.018	0.900 ± 0.019	0.901 ± 0.029
FEP 1.6MeV	0.159 ± 0.009	0.104 ± 0.007	0.106 ± 0.007	0.099 ± 0.011
SEP	0.106 ± 0.007	0.056 ± 0.005	0.051 ± 0.006	0.057 ± 0.008
FEP 2.6MeV	0.157 ± 0.002	0.065 ± 0.001	0.082 ± 0.001	0.074 ± 0.002
2004-2074keV	0.404 ± 0.004	0.325 ± 0.004	0.323 ± 0.004	0.327 ± 0.006
1989-2089keV	0.405 ± 0.004	0.322 ± 0.003	0.323 ± 0.003	0.324 ± 0.005
Measuring time	8 h	8 h	7 h	6 h

Table 2: List of PSD acceptances for first 7 enriched BEGe detectors and depleted DD BEGe detector at nominal high voltage.

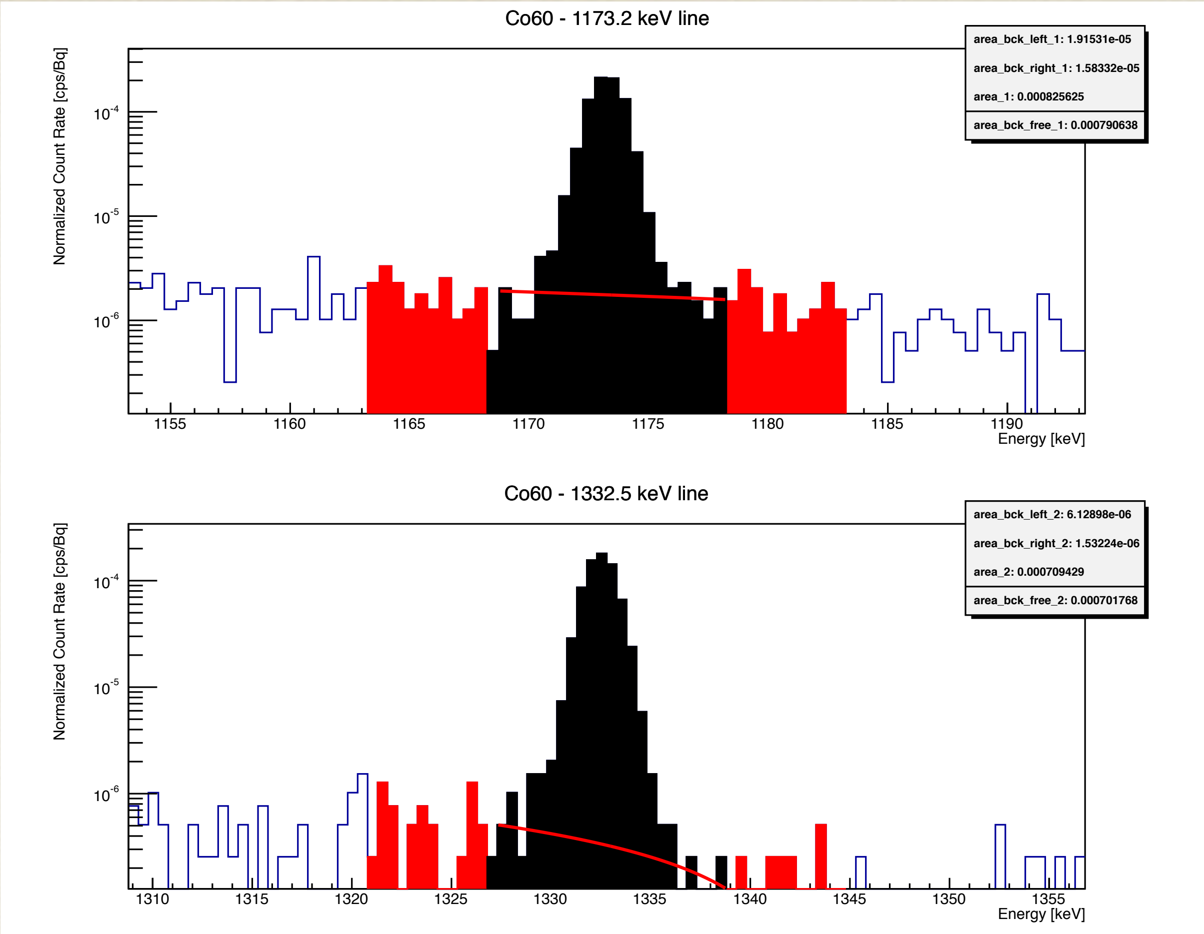
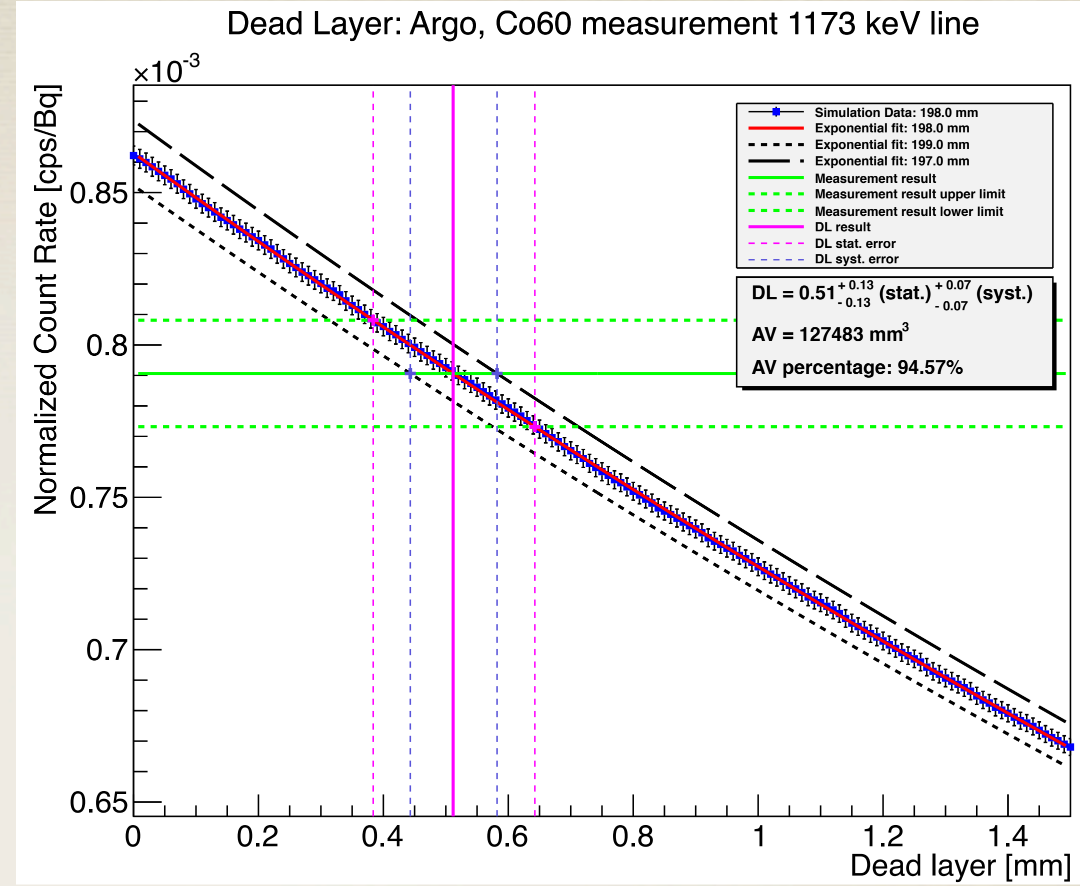
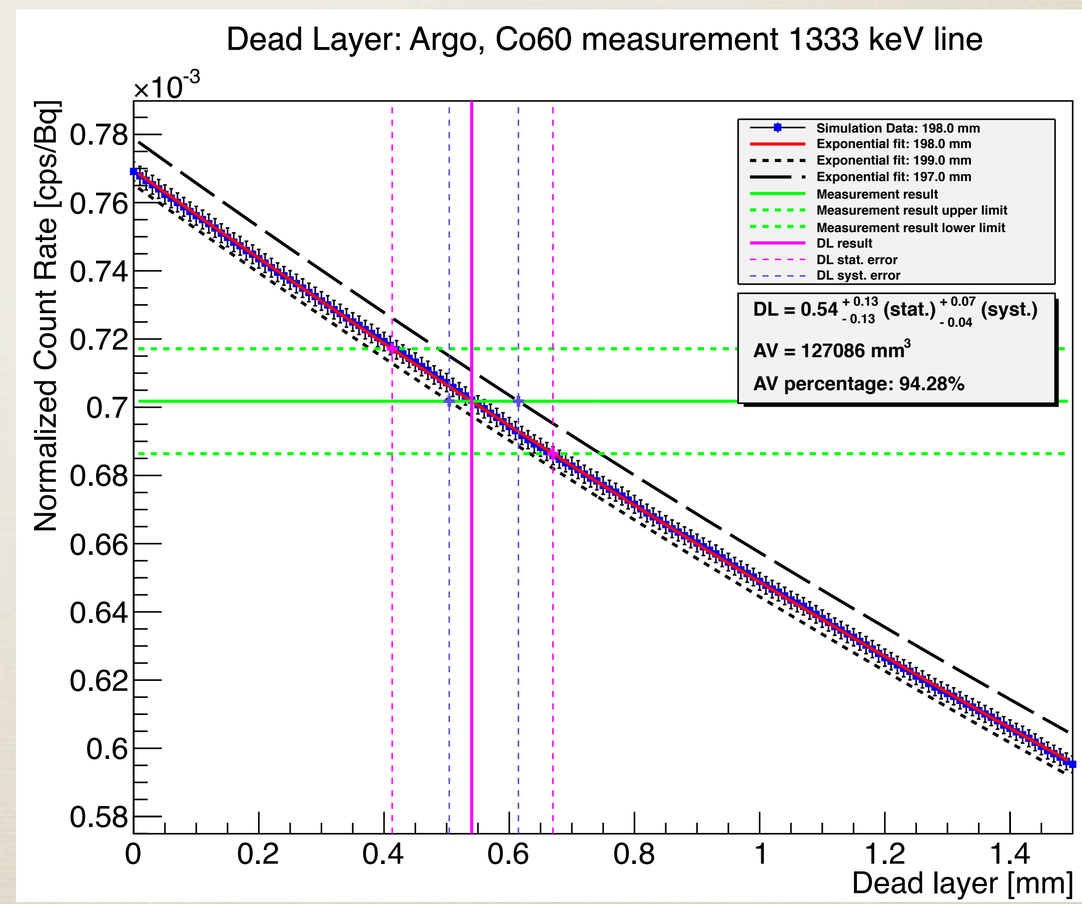
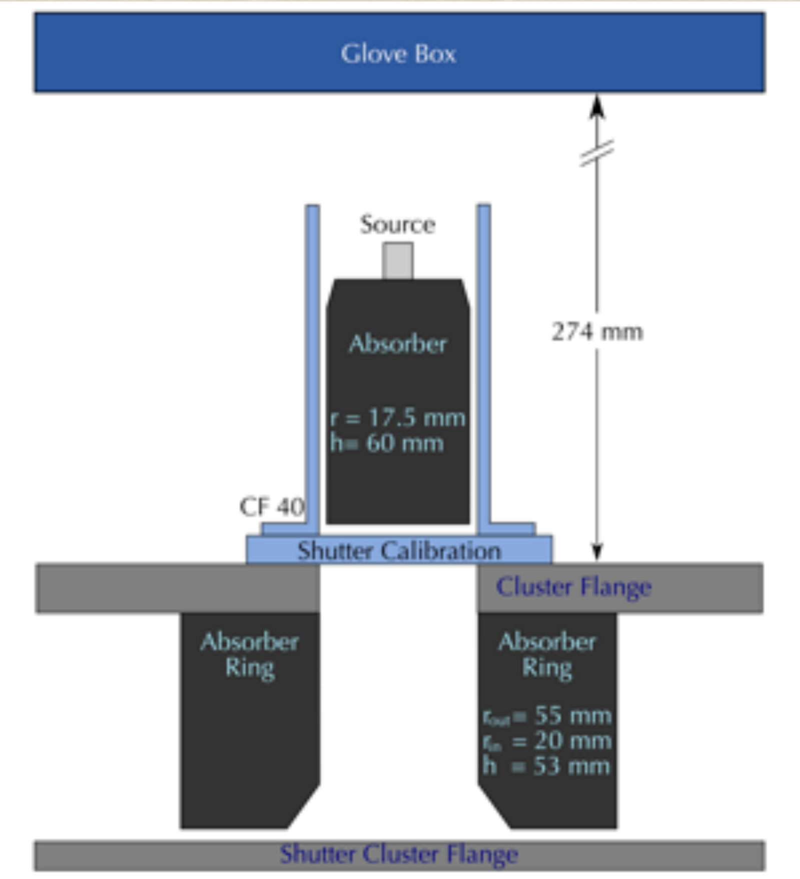


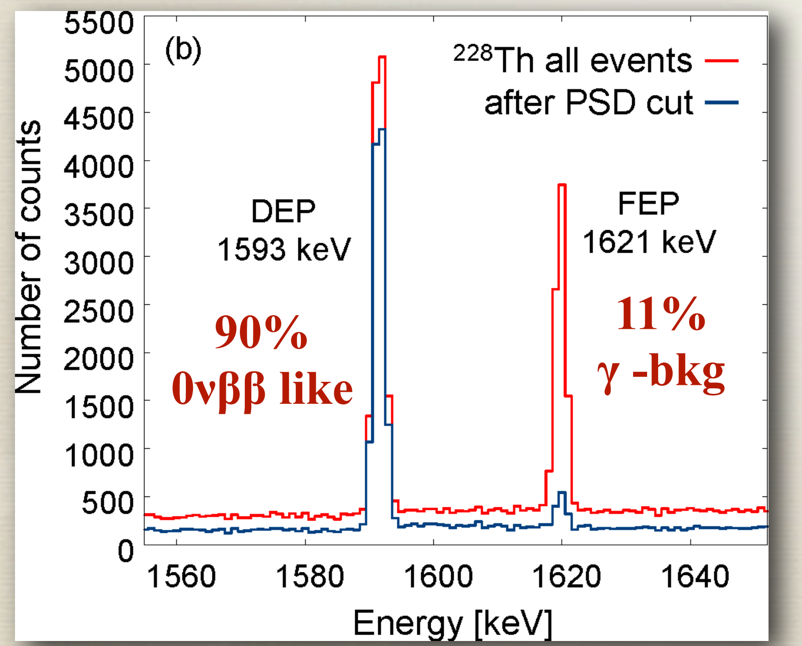
Figure 4: Peak and background regions for Argo. The normalized count rate is plotted as a function of the energy.

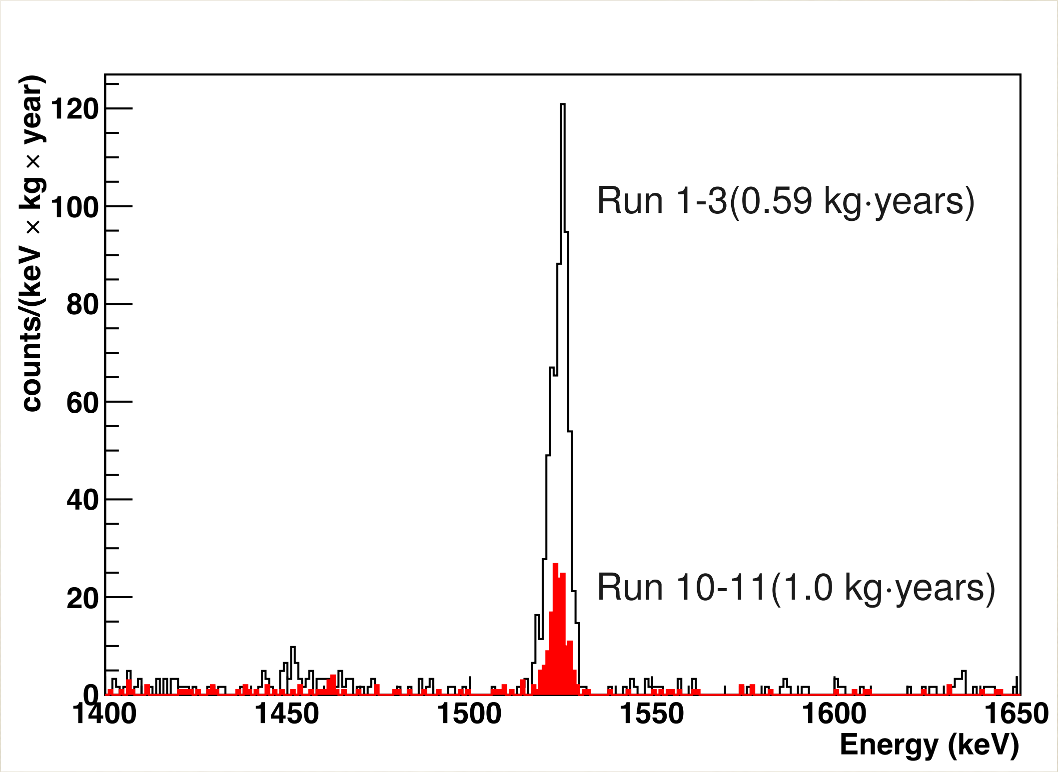


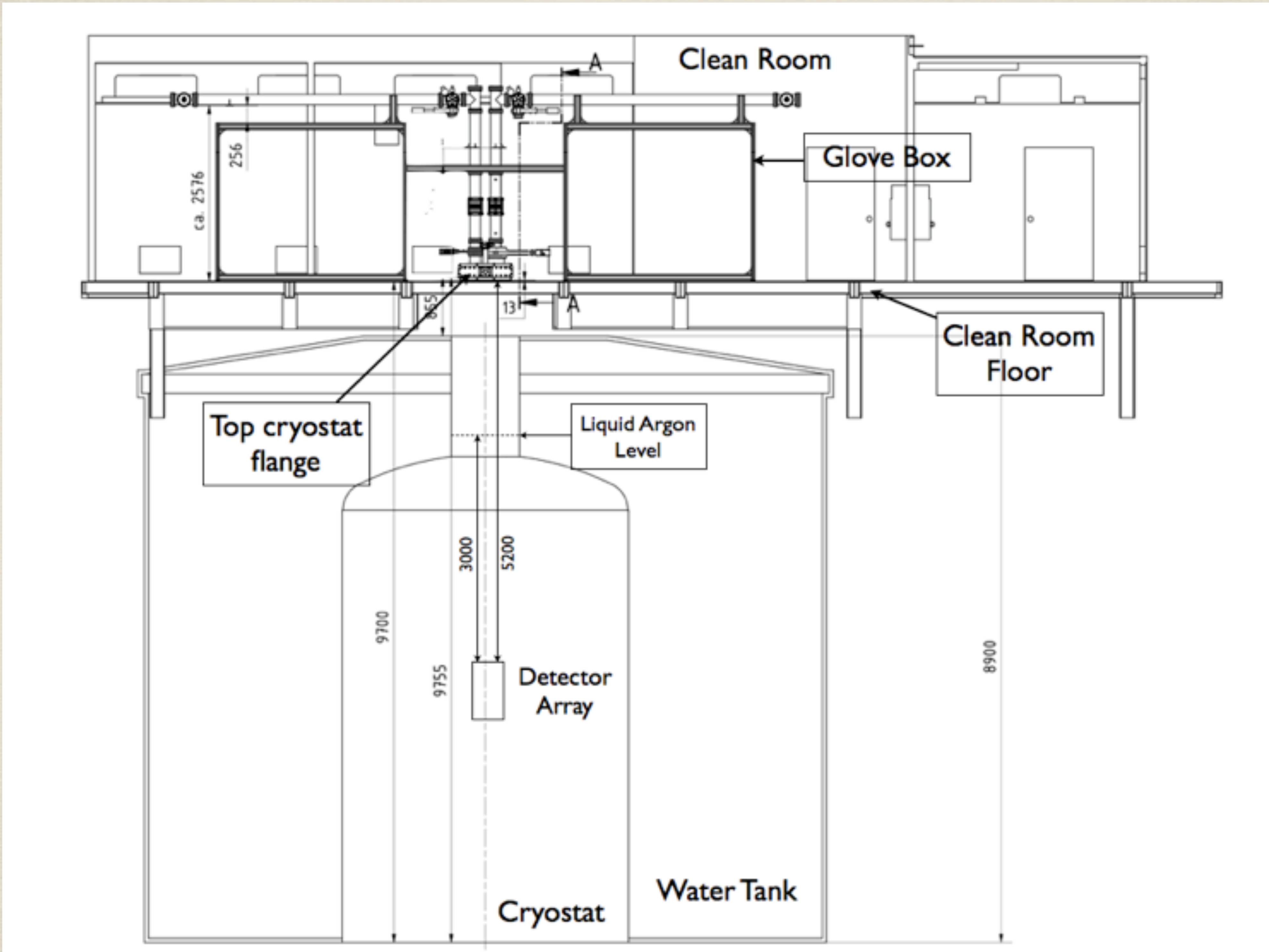


Active Volume Measurement for ARGO


Glove Box
Source
Absorber
r = 17.5 mm
h= 60 mm
274 mm
CF 40
Shutter Calibration
Cluster Flange
Absorber Ring
Absorber Ring
h = 53 mm
Shutter Cluster Flange


(b)
228Th all events
after PSD cut
DEP
1593 keV
FEP
1621 keV
90%
0νββ like
11%
γ -bkg
Number of counts
Energy [keV]


Run 1-3(0.59 kg·years)
Run 10-11(1.0 kg·years)
counts/(keV × kg × year)
Energy (keV)


Clean Room
A
Glove Box
256
ca. 2576
13
A
Clean Room Floor
Top cryostat flange
Liquid Argon Level
3000
5200
9700
9755
8900
Detector Array
Water Tank
Cryostat