A/E PSD for the GERDA experiment

Outline:

- Neutrinoless double beta decay
- The GERDA experiment
- Introduction to some GERDA Backgrounds
- PSD for GERDA Phase-I BEGes
- Outlook & Summary

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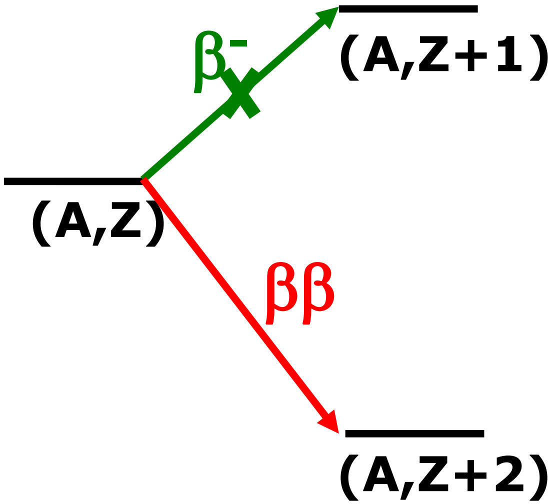
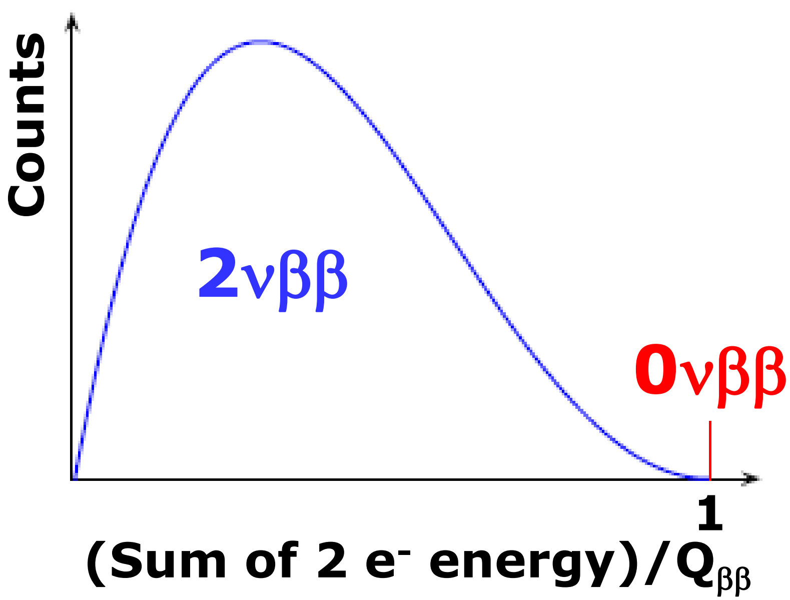
IMPRS @ Föhringer Ring 6, Munich, 17/01/2014

Neutrinoless Double Beta Decay



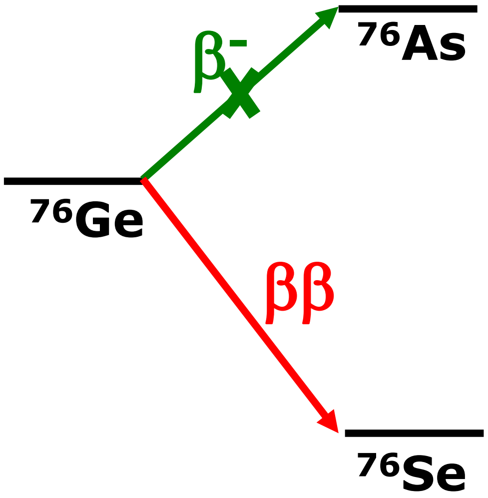
- **Single β decay is not allowed for some isotopes, only ββ decay**
- **2νββ decay:**
  (A,Z) → (A,Z+2) +2e$^-$+2$\bar{\nu}$
  SM allowed & observed
- **0νββ decay: (ν=$\bar{\nu}$)**
  (A,Z) → (A,Z+2) +2e$^-$
  if ν is Majorana particle



Study of 0νββ can:

- **Discover lepton number violation**
- **Determine nature of ν (Majorana or Dirac)**
- **Give information on absolute ν mass**
  ⟶ Mass hierarchy of ν

Neutrinoless Double Beta Decay



- Single β decay is not allowed for some isotopes, only ββ decay
- 2νββ decay:
  $^{76}Ge \rightarrow {}^{76}Se + 2e^{-} + 2\bar{\nu}$
  SM allowed & observed
- 0νββ decay: ($\nu = \bar{\nu}$)
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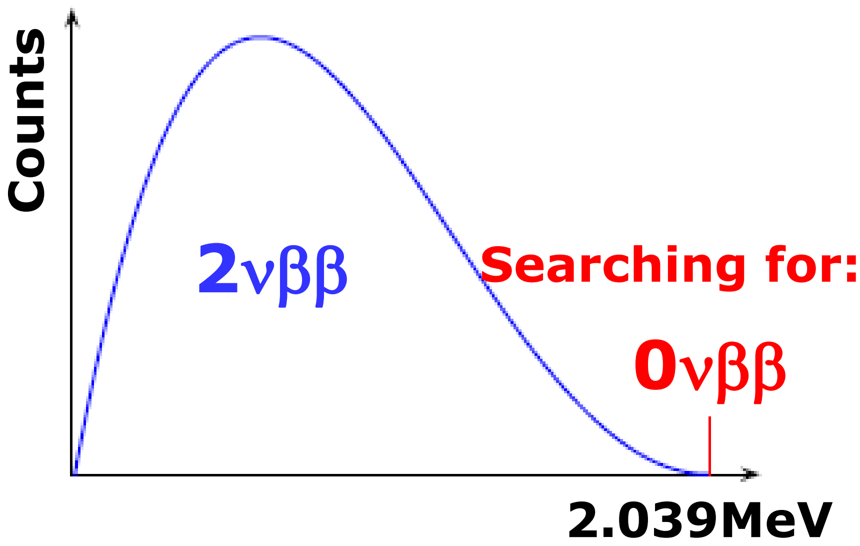
  if ν is Majorana particle



⇒ Use detector made of ββ emitting material:
HP ^{76}Ge detector

⇒ Experimental signature:
(1) A sharp peak at 2.039 MeV
(2) Single Site Events

Experimental Observable of 0νββ Decay

0νββ Decay rate

phase space integral

nuclear transition matrix element

Effective Majorana ν mass

$$\langle m_{ee} \rangle = \left| \sum_i U_{ei}^2 \, m_i \right|$$

$$\frac{1}{T_{1/2}^{0\nu\beta\beta}} = G(Q,Z) \, |M_{nucl}|^2 \, \langle m_{ee} \rangle^2$$

Measure quantity : Half-life of 0νββ

Parameter contains physics

➡ One measurement, lots of information

Experimental Challenges

- Experiments always have backgrounds that can mimic the signal
- To avoid backgrounds:
  - Compact shielding design
  - Radio pure materials close to the detector
    Typical activities ~ μBq/kg
    → careful choice of materials + screening tests
    + Minimizing the support structure
  - Go underground to reduce cosmic backgrounds
    (cosmogenic activation on detector materials, muons)
- Establish techniques able to distinguish signals from backgrounds
  → Use intelligent detectors

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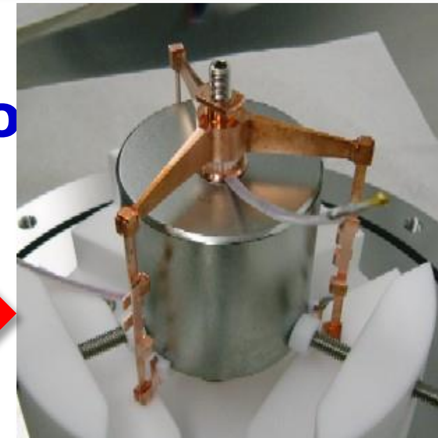
Experimental Challenges


Commerical Ge detector


GERDA Ge detector

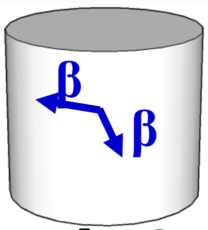
- Exp e **backgro** n mimic the
- To
  - (sign
  - close to t
    Bq/kg
    → careful choice of materials + screening tests + **Minimizing the support structure**
  - Go underground to reduce cosmic backgrounds (cosmogenic activation on detector materials, muons)
- Establish techniques able to distinguish signals from backgrounds
  → Use **intelligent detectors**

Experimental Challenges

There are ~ 35 candidates in nature, however …

- **Sensitivity of** $T_{1/2}^{0\nu\beta\beta} \propto \epsilon\, a \sqrt{\frac{M\,T}{B\,\Delta E}}$
  - **detection eff.** (ϵ)
  - **enrichment fraction** (a)
  - ***MT*: exposure (kg·yr)**
  - **background index (Cts/day·kg·keV)** (B)
  - **energy resolution** (ΔE)

- **Why HP ^{76}Ge detector ?**
  - **High detection efficiency**
  - **Very good energy resolution (~0.2% in ROI)**
  - **Intrinsically pure**



(source=detector)

- **Why enrichment ?**

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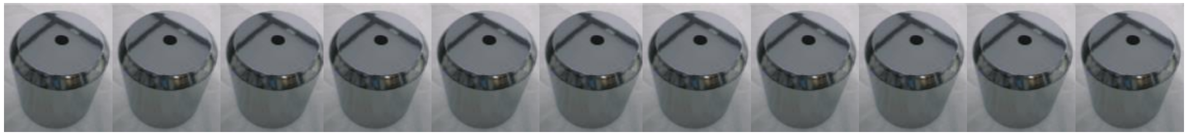
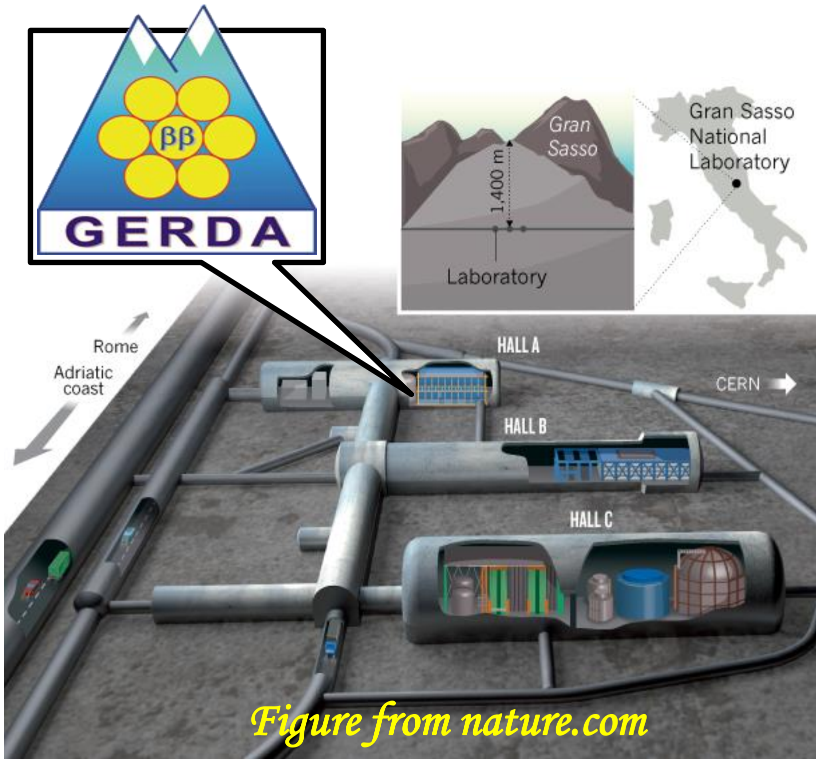


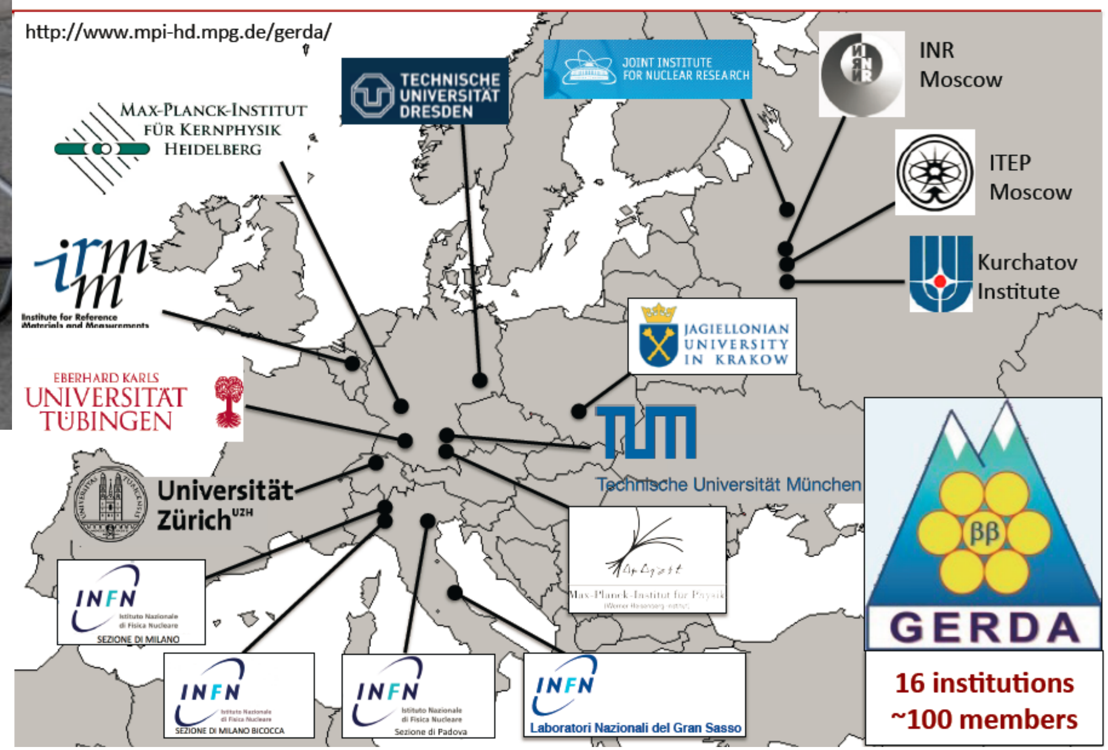
1 ^{76}Ge diode = **11x ^{nat}Ge diodes**

The GERDA Experiment



- **GERmanium Detector Array**
- **Search for 0νββ decay in ^{76}Ge @ $Q_{\beta\beta}$=2.039 MeV**
- **Location: Hall A, LNGS**
- **Overburden: 3500 m.w.e**

The GERDA Collaboration



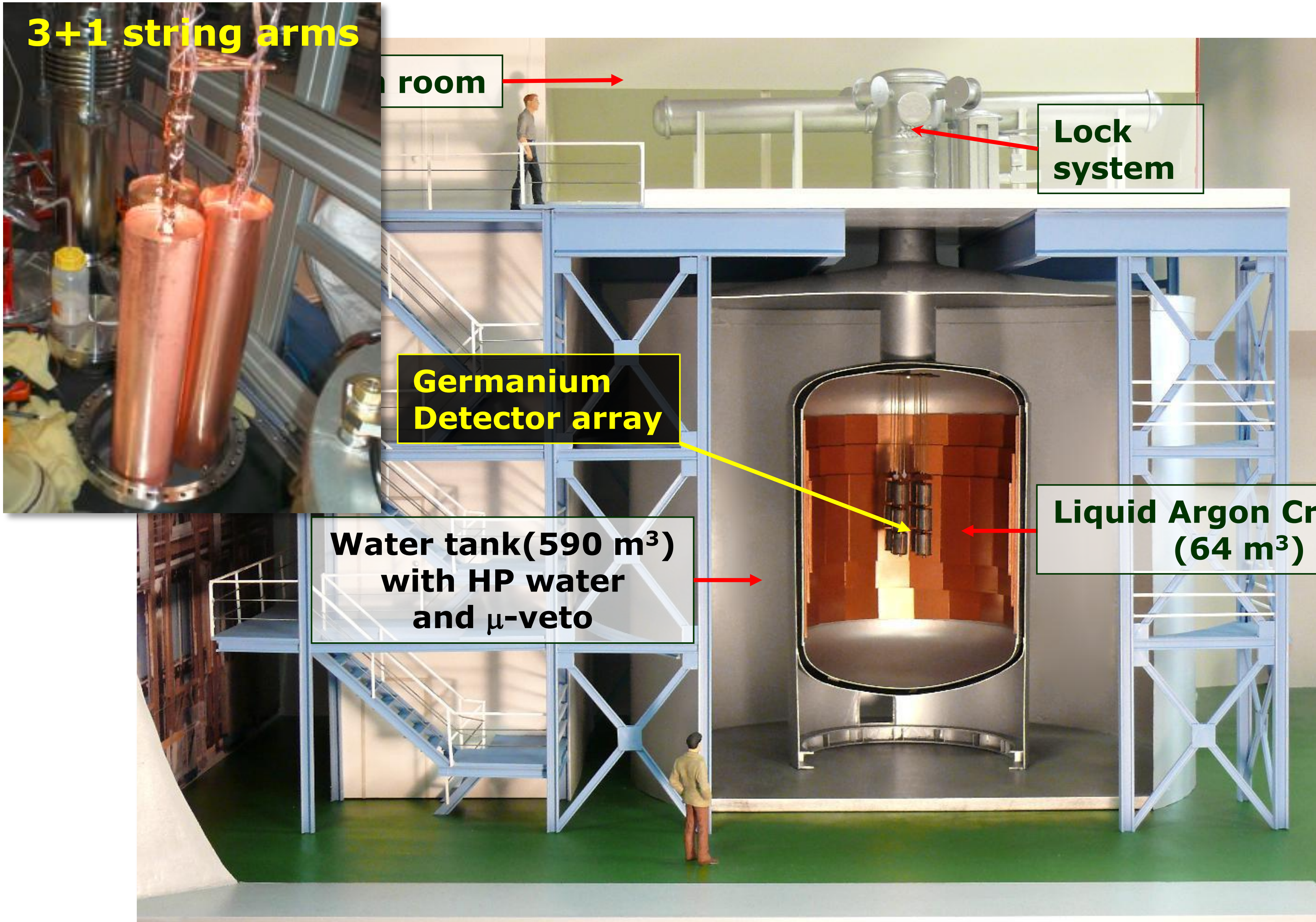
The GERDA Experiment

- **Previous results for ^{76}Ge 0νββ decay:**
  - **limit:** $T_{1/2}^{0\nu\beta\beta} > 1.9 \cdot 10^{25} yr$ @ 90% C.L. from HDM and IGEX [EPJ. A12 (2001)147-154]
  - **claim:** $T_{1/2}^{0\nu\beta\beta} > 1.2 \cdot 10^{25} yr$ Klapdor-Kleingrothaus et al., [PL B586 (2004) 198]

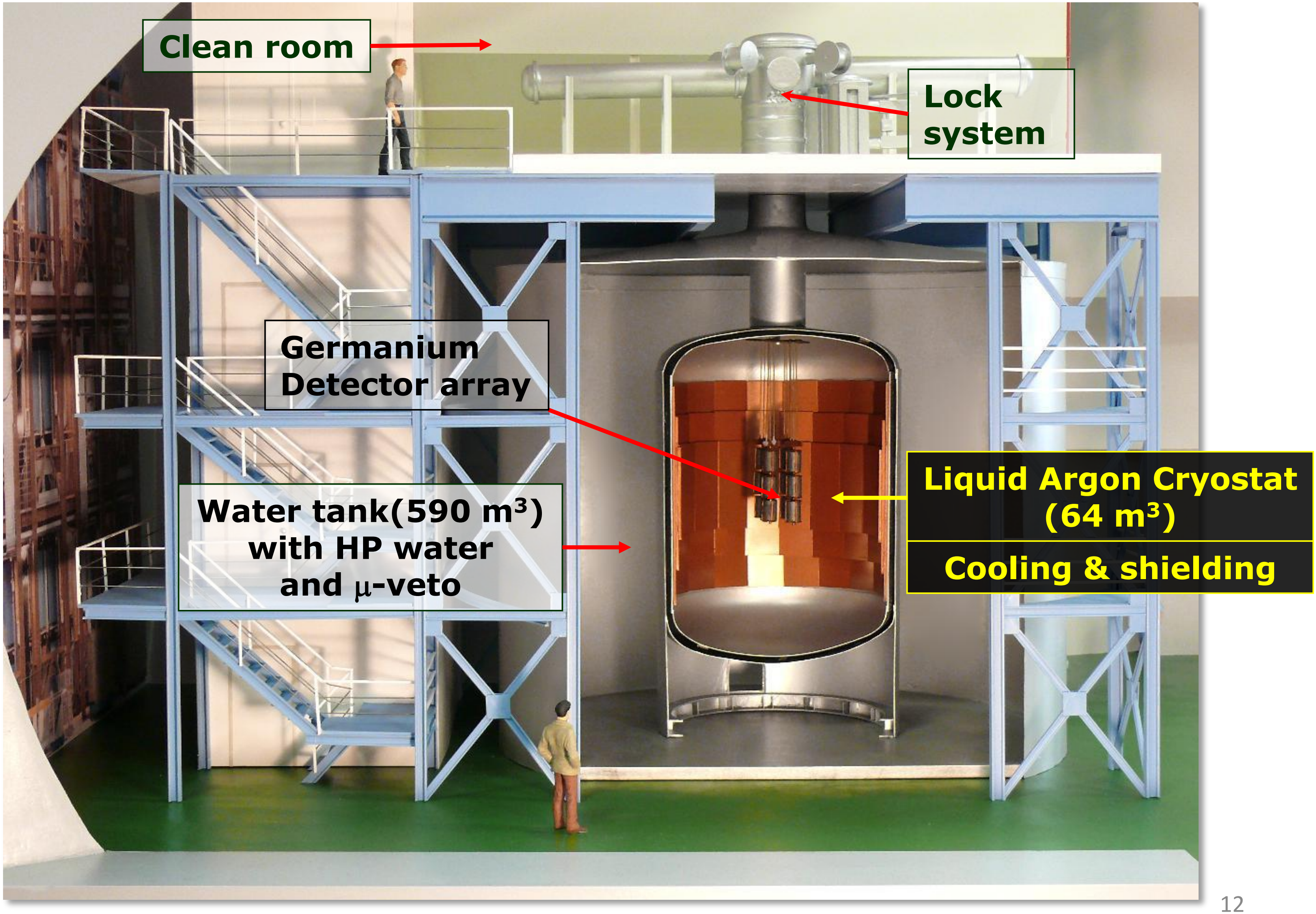
- **Phase-I:**
- Data taking: Nov. 2011 to Jun 2013, exposure: 21.6 kg·yr
- Detector:
  8 ^{enr}coax detectors(17.7 kg) from HDM & IGEX
  5 ^{enr}BEGe Phase-II detectors (3.6 kg) (started in May 2012)
  1 non-enriched coaxial detector (3.0 kg)
- BI: ~10^{-2} Cts/(keV·kg·yr)
- **Physics result:** $T_{1/2}^{0\nu\beta\beta} > 2.1 \cdot 10^{25} yr$ @ 90%C.L. [PRL 111 (2013) 122503]
  $T_{1/2}^{0\nu\beta\beta} > 3.0 \cdot 10^{25} yr$ in combine with HDM & IGEX results
- **Phase-I successfully completed, Klapdor claim strongly disfavored**

- **Phase-II:**
- Detector: +20 kg ^{enr}BEGe detectors
- Design goal: BI=10^{-3} Cts/(keV·kg·yr) + exposure: 100 kg·yr
- Expected sensitivity: ~10^{26} yr

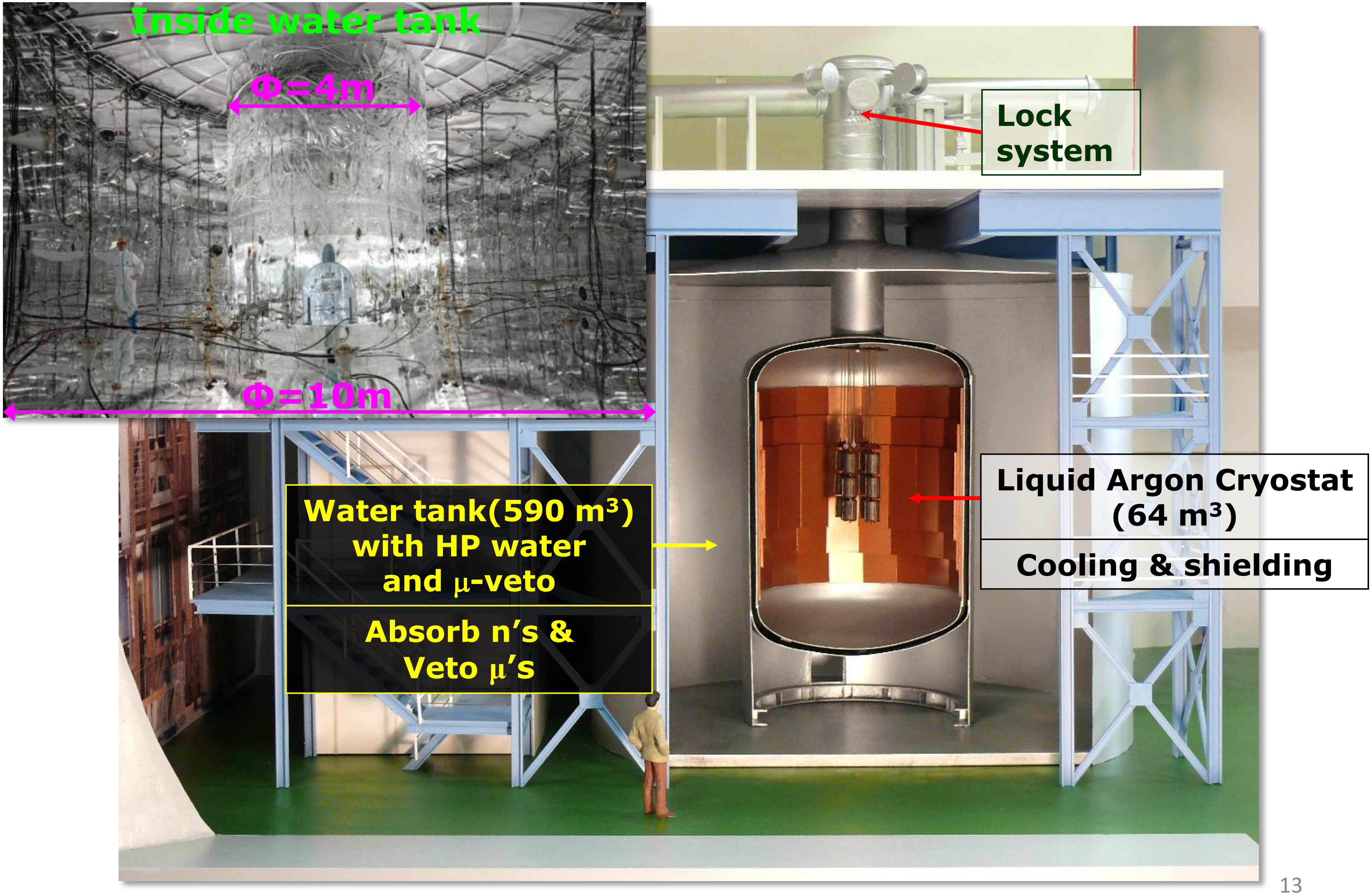
The GERDA Experiment



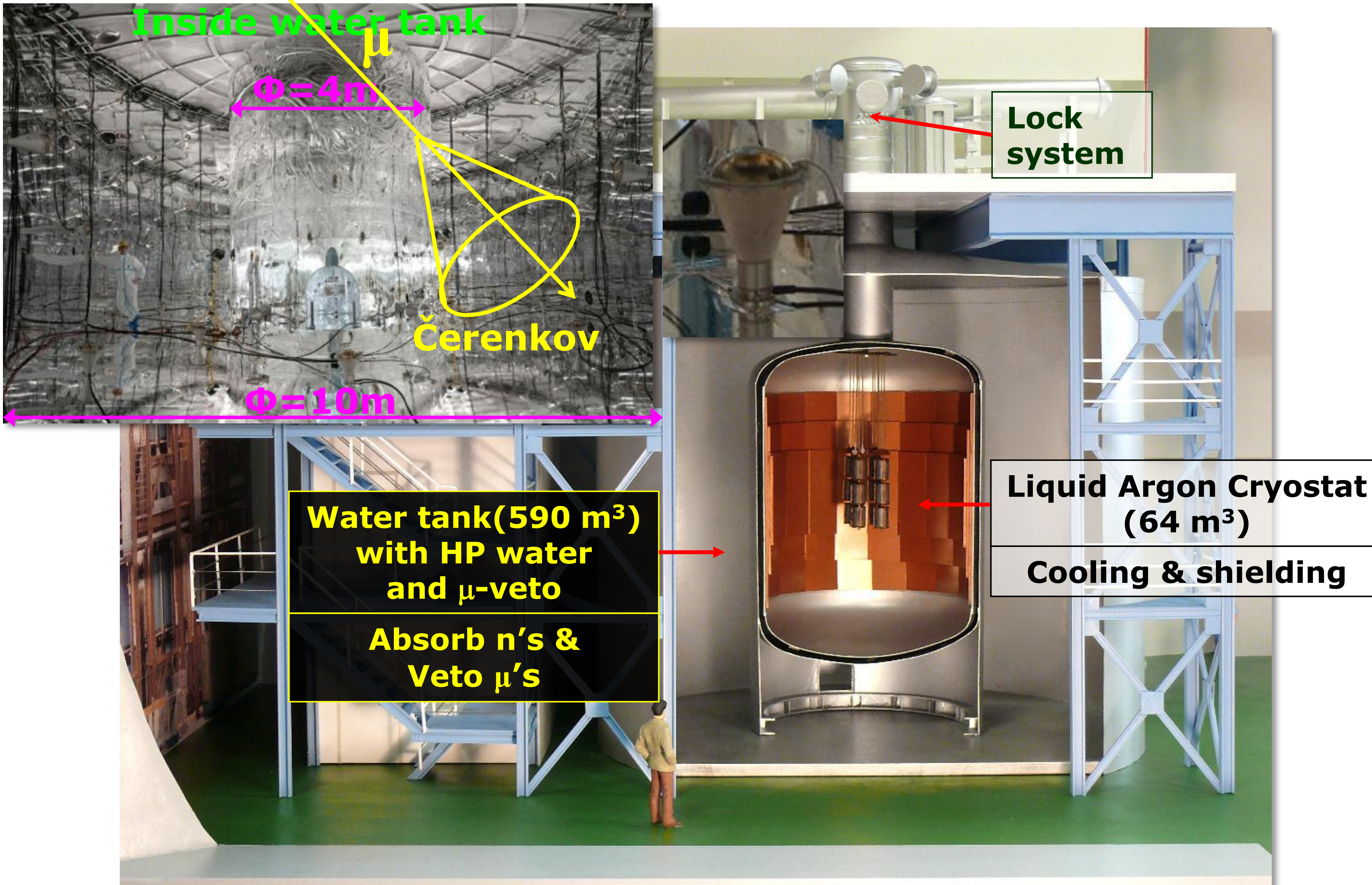
The GERDA Experiment



The GERDA Experiment



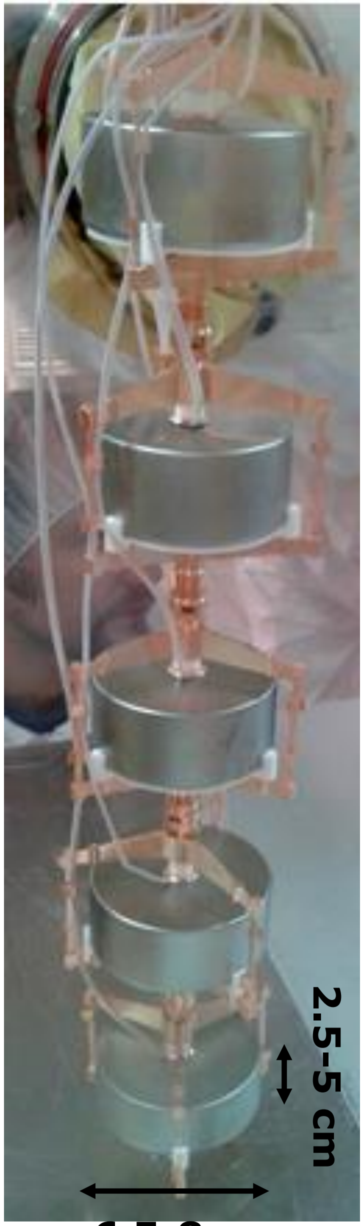
The GERDA Experiment



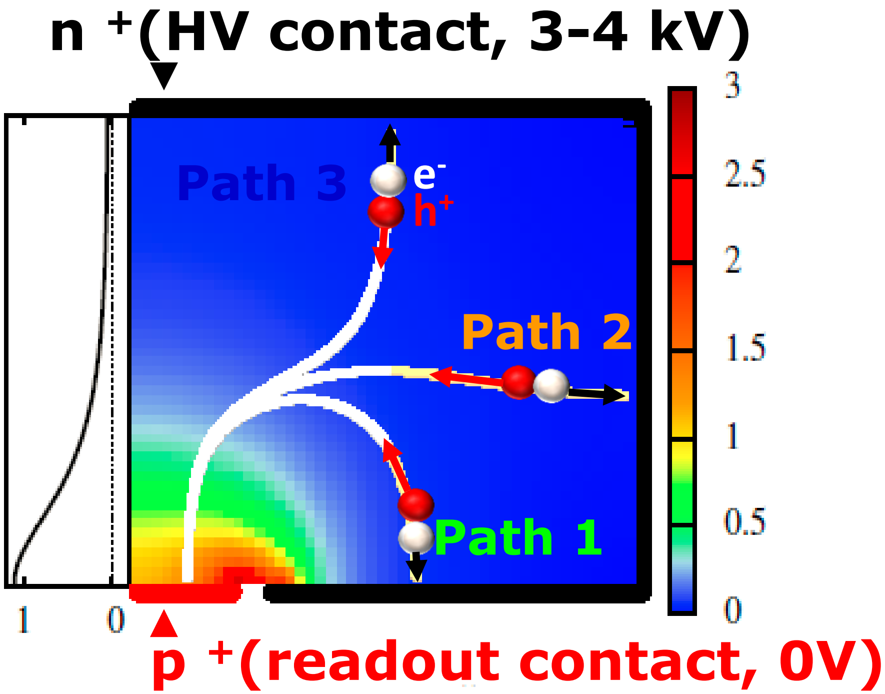
GERDA Phase-I BEGe Detectors

- **Broad Energy Germanium Detectors**
- **Advantages of BEGe detectors:**
  ✓**Low capacity → low noise**
  ✓**Very good energy resolution**
  @ 2.6 MeV:
  $\Delta E_{coaxial} \sim 4.5$ **keV**
  $\Delta E_{BEGe} \sim 3$ **keV**

  ✓**Powerful PSD to reject backgrounds:**
  → A/E parameter
- **Total exposure for BEGe detectors:**
  2.4 kg·yr



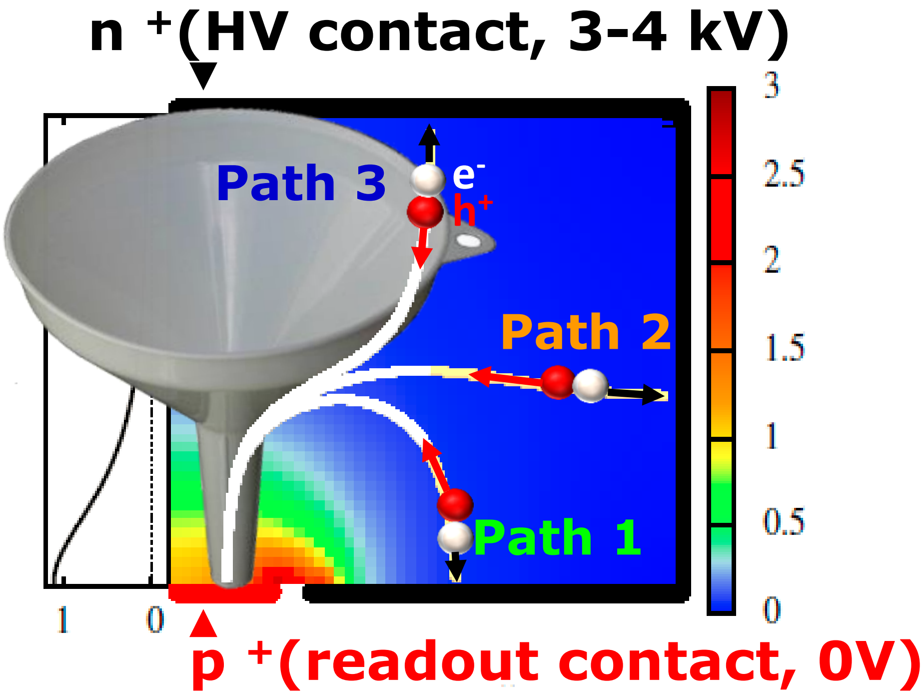
Pulse Shape Properties of BEGes



Properties of E-field of BEGe:

- h^+s are collected toward the readout electrode in the same path
- Different interaction positions

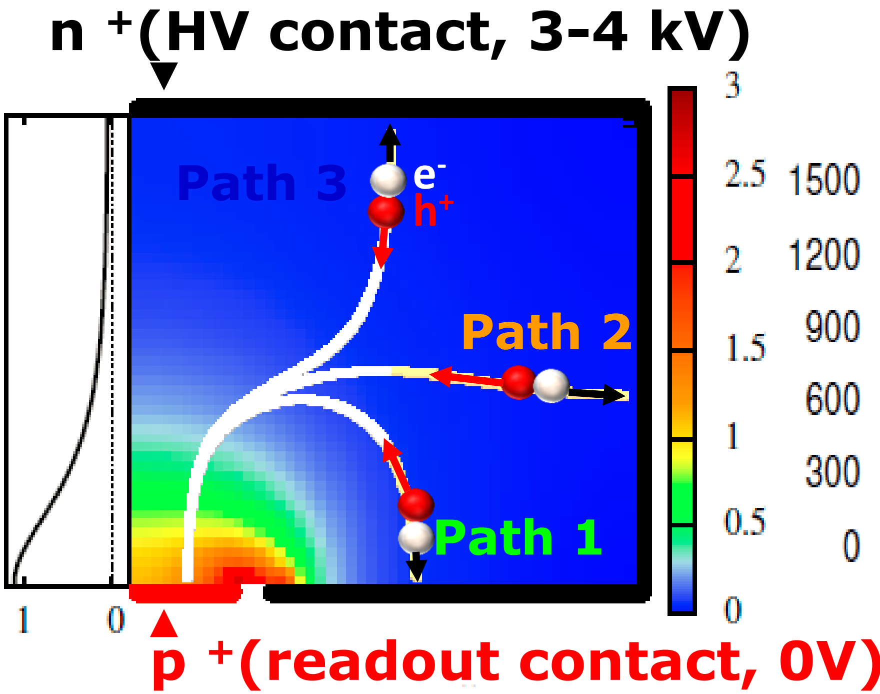
Pulse Shape Properties of BEGes

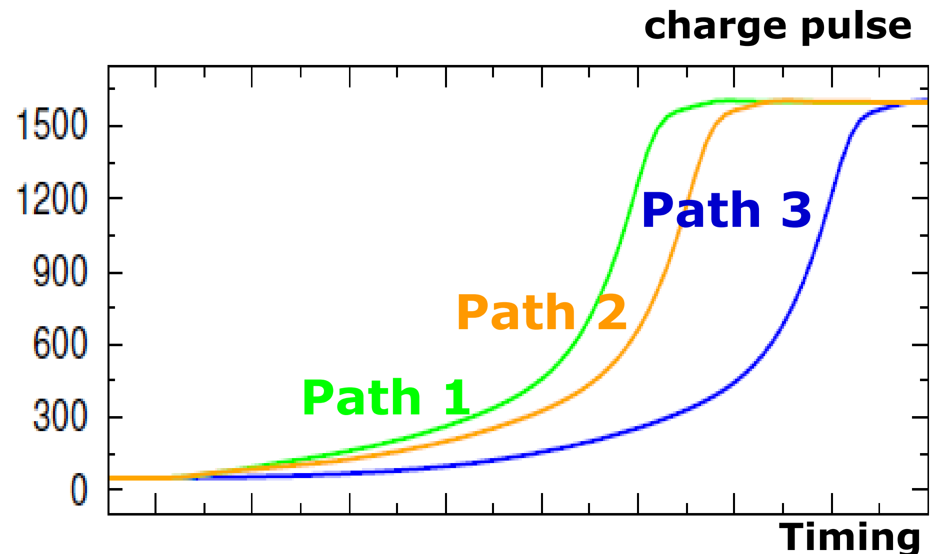


Properties of E-field of BEGe:

- h^{+}s are collected toward the readout electrode in the same path → **"Funneling effect"**
- Different interaction positions

Pulse Shape Properties of BEGes





Properties of E-field of BEGe:

- h^+s are collected toward the readout electrode in the same path → **"Funneling effect"**
- Different interaction positions → **the same pulse height**

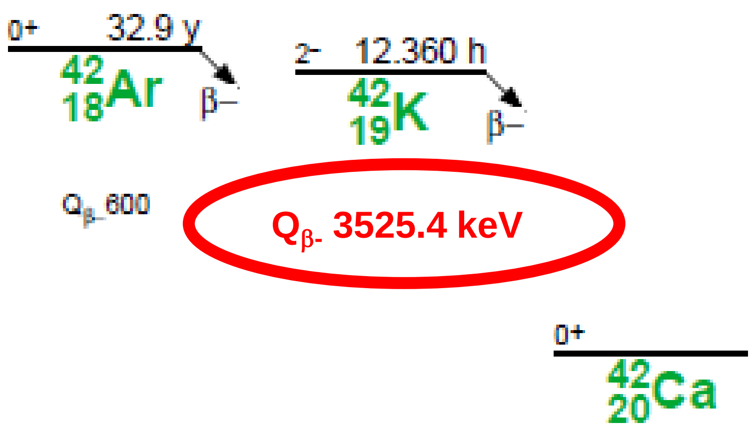
Ramo-Shockley theorem:

$$Q = -q \cdot \phi$$

Charge Signal — charge — W. potential

^{42}K Background in GERDA

- **^{42}Ar: Isotope of Ar created by cosmic-ray activation**
- **Decay chain:**
  $^{42}Ar \longrightarrow$ $^{42}K \longrightarrow$ ^{42}Ca



- **^{42}K ions get attracted by detector HV**
- **GERDA Phase I approach:**
  Installation of mini-shroud
  $\longrightarrow$ Keep ions away from detectors

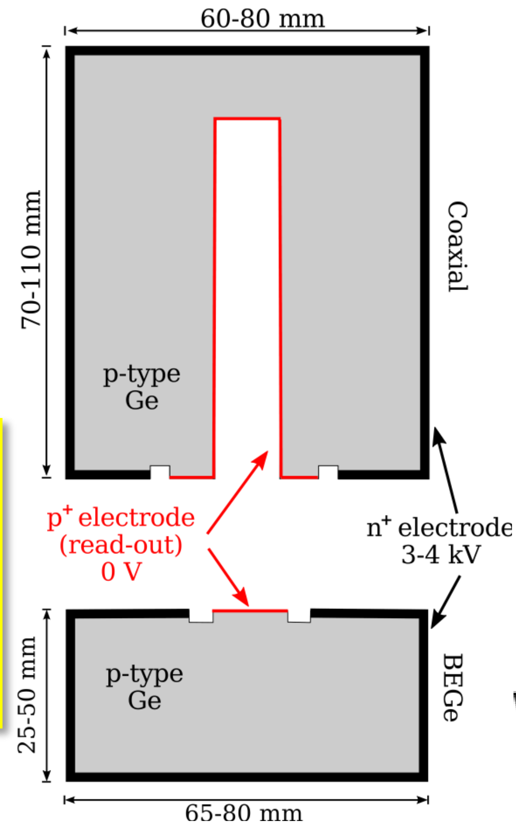
α-induced events in GERDA

- **Range of α particles(4MeV-9MeV):**
  34 μm - 113 μm in Lar
  14 μm - 41 μm in Ge

- **Thickness of surface is different for p^+ & n^+ contacts.**

p^+(B) < 1 μm
n^+(Li) ~ 2 mm for coax
n^+(Li) ~ 1 mm for BEGe

α contributes to bkg. only when the decays on the p+ surface or in LAr very close (<100 μm) to p+ surface



Ra-226 (E_α = 4.8 MeV, $T_{1/2}$ = 1600 y)

Rn-222 (E_α = 5.5 MeV, $T_{1/2}$ = 3.8 d)

Po-218 (E_α = 6.0 MeV, $T_{1/2}$ = 183 s)

Pb-214 ($T_{1/2}$ = 0.45 h)

Bi-214 ($T_{1/2}$ = 0.33 h)

Po-214 (E_α = 7.7 MeV, $T_{1/2}$ = 164 μs)

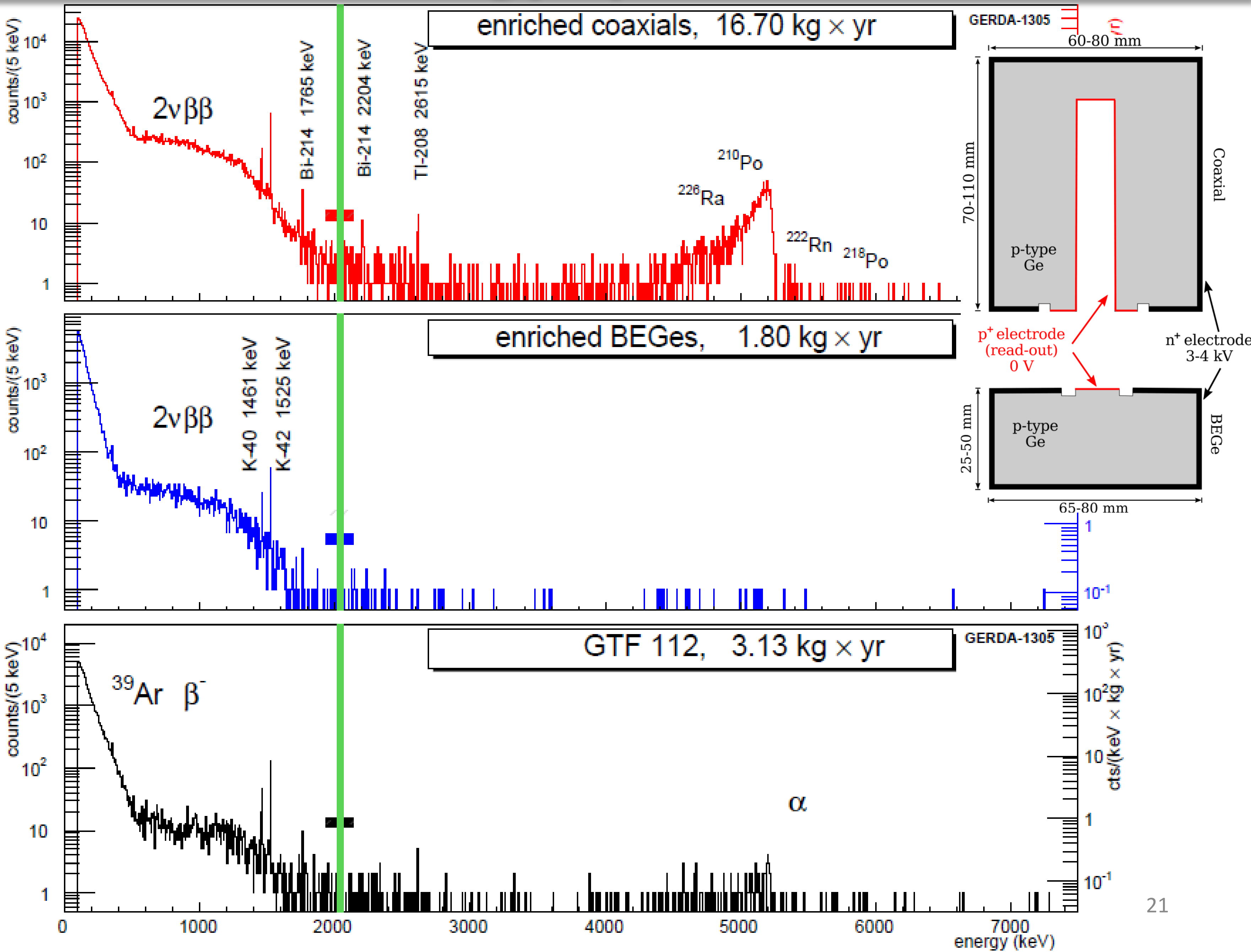
Pb-210 ($T_{1/2}$ = 22.3 y)

Bi-210 ($T_{1/2}$ = 5.01 d)

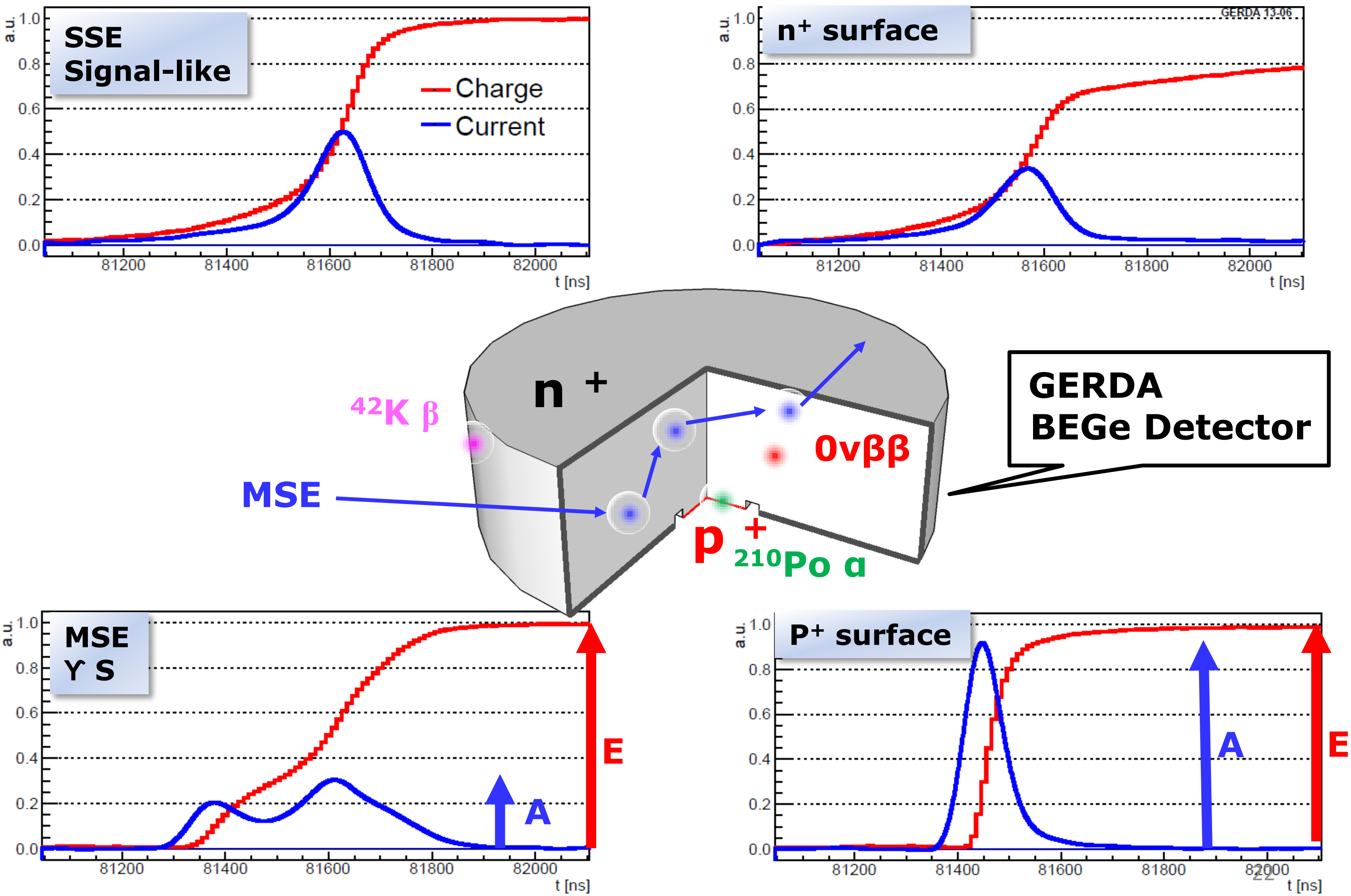
Po-210 (E_α = 5.3 MeV, $T_{1/2}$ = 138.4 d)

Pb-206 (stable)

Energy spectra



A/E Pulse Shape Discrimination Method

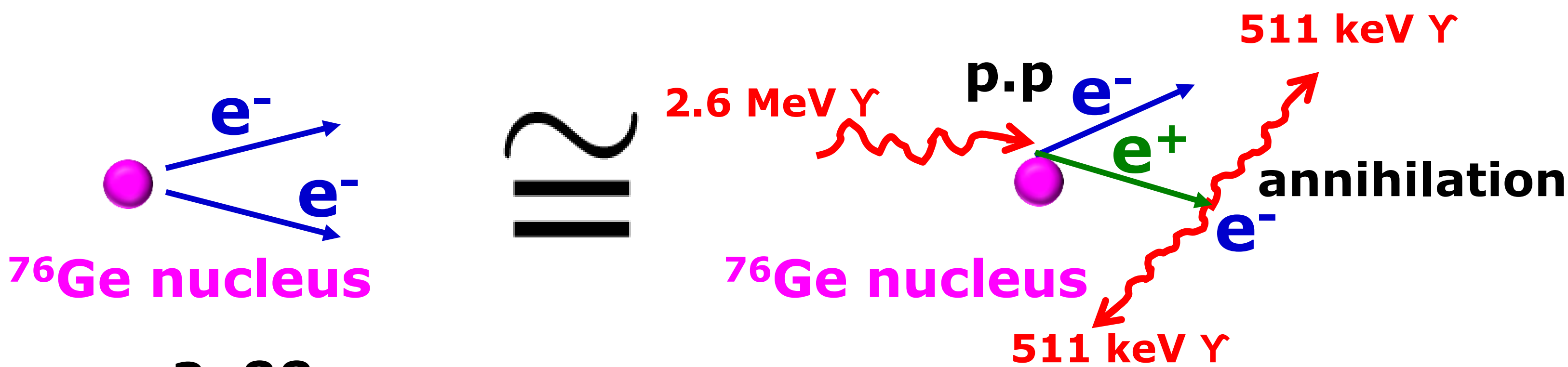


BEGe Pulse Shape Discrimination

BEGe PSD:

- Use A/E parameter
- Develop PSD method with ^{228}Th calibration data → apply it on physics data
- Double Escape Peak events from 2.6 MeV γ of ^{228}Th spectrum are SSEs → Proxy of 0νββ

Event topology



2νββ
(localized energy deposition)

DEP
(signal-like event)

BEGe Pulse Shape Discrimination

BEGe PSD:

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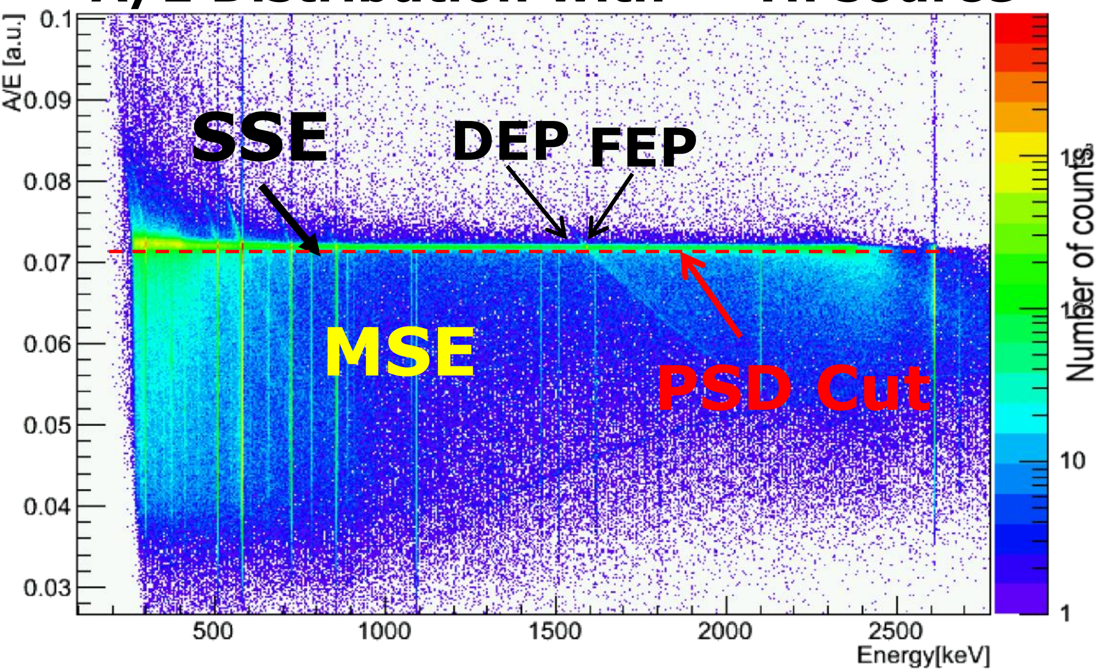
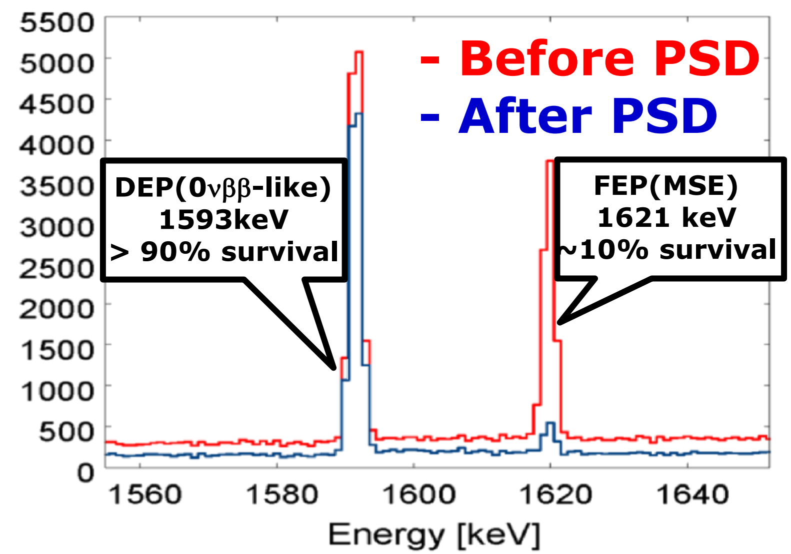
A/E Distribution with ^{228}Th source

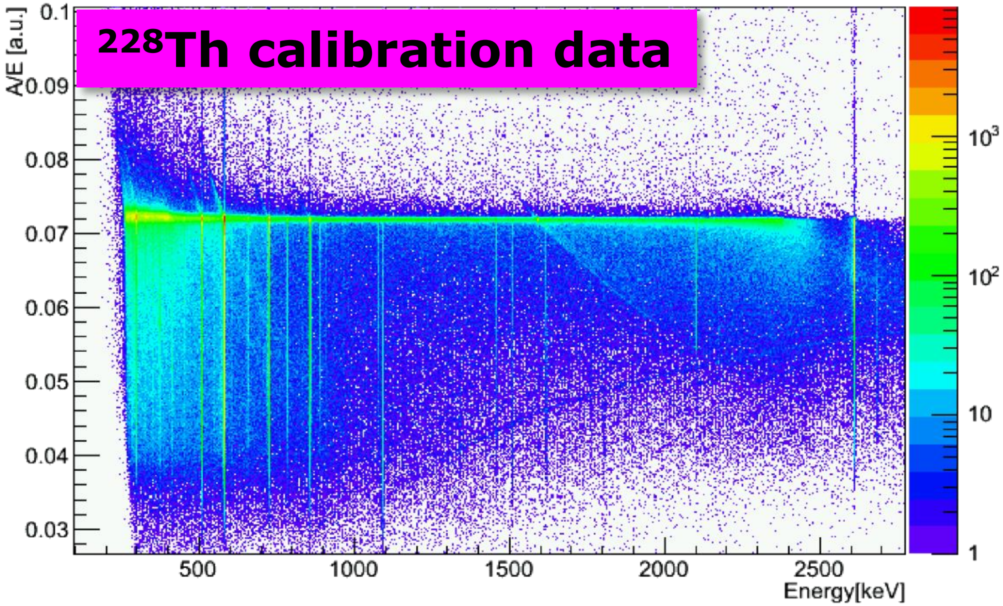


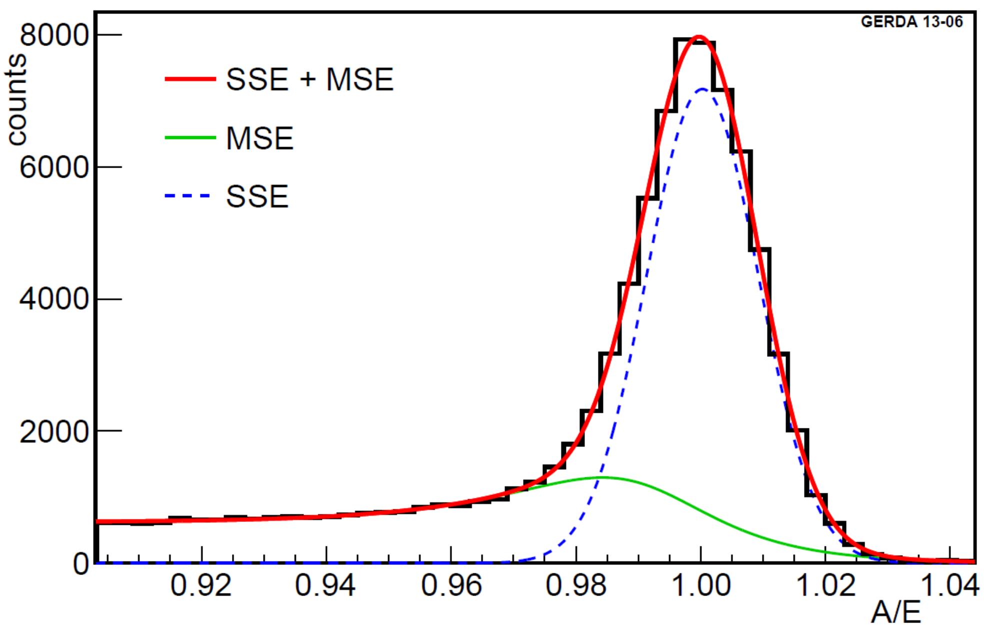
Energy spectrum with ^{228}Th source



Dušan Budjaš et al, JINST 4 P10007, 2009

A/E Modeling : Distributions





A/E Distribution:

- Decompose to: func. of SSE + MSE
- SSE: Gaussian

$$s(A/E) = \frac{\alpha}{\sigma\sqrt{2\pi}} e^{\frac{(E-\mu_{A/E})^2}{2\sigma^2_{A/E}}}$$

- MSE:

$$m(A/E) = \beta \cdot \frac{e^{\eta \cdot (E-\nu)} + \lambda}{e^{\frac{(E-\nu)}{\zeta}} + 1}$$

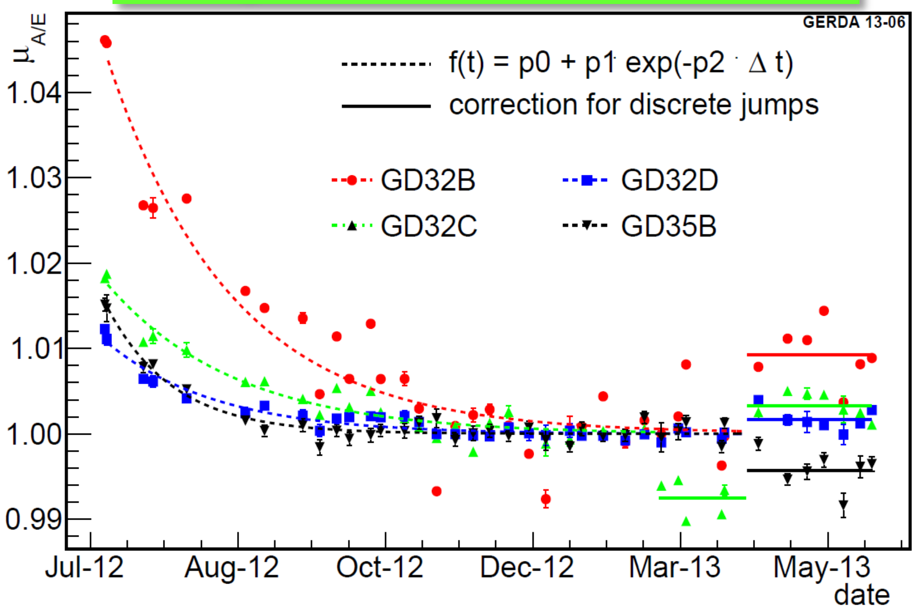
A/E PSD: Time Dependence Correction

A/E PSD:

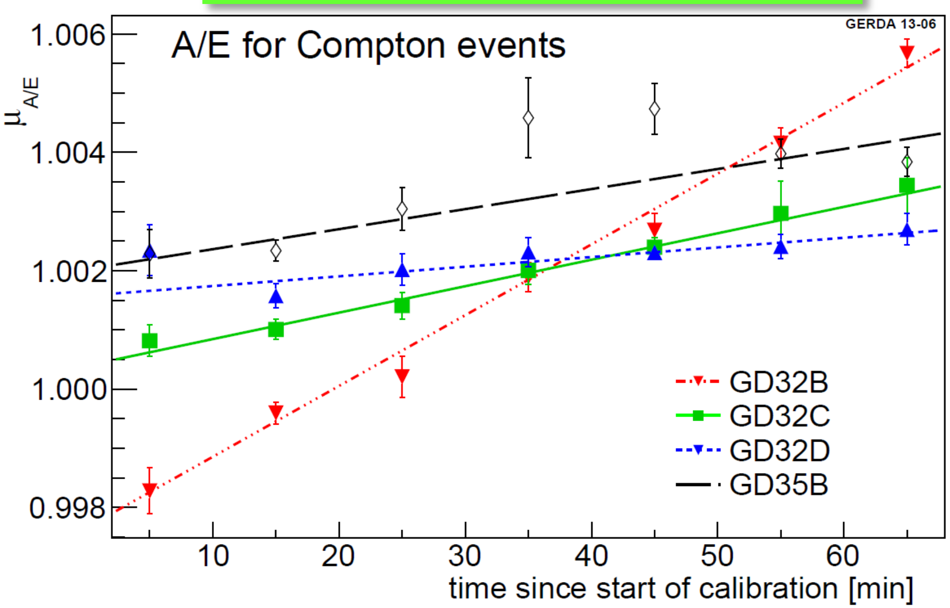
- **Sensitive to A performance**
- **Calibration using ^{228}Th external source for every one/two weeks**
  ➡ **Monitor PSD stability over time**

- **Optimization of PSD/Global PSD cut:**
  ➡ **Normalization schemes are investigated**

Long term drift correction



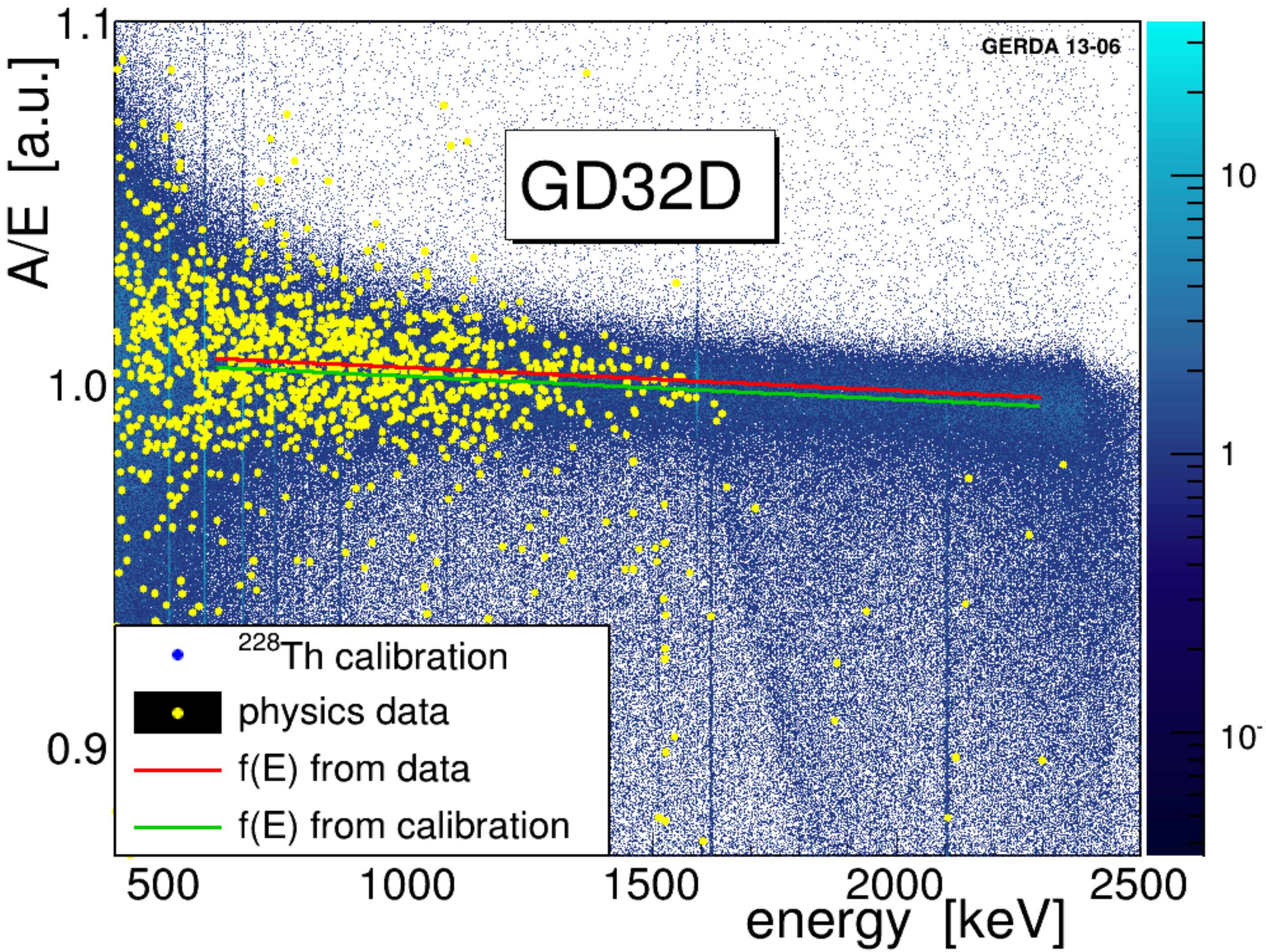
First 70 min correction



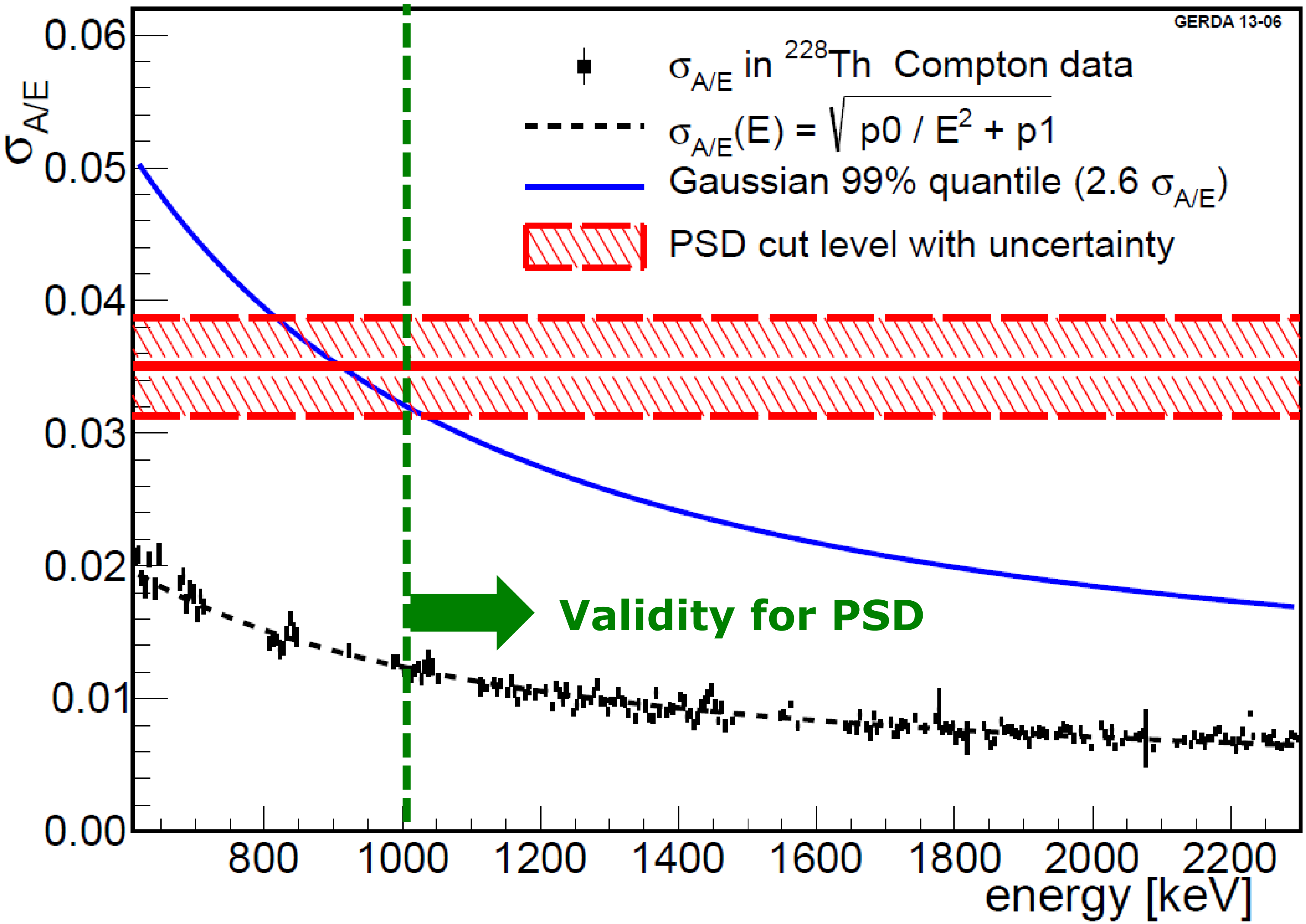
^{228}Th calibration data

A/E PSD: Energy Dependence Normalization

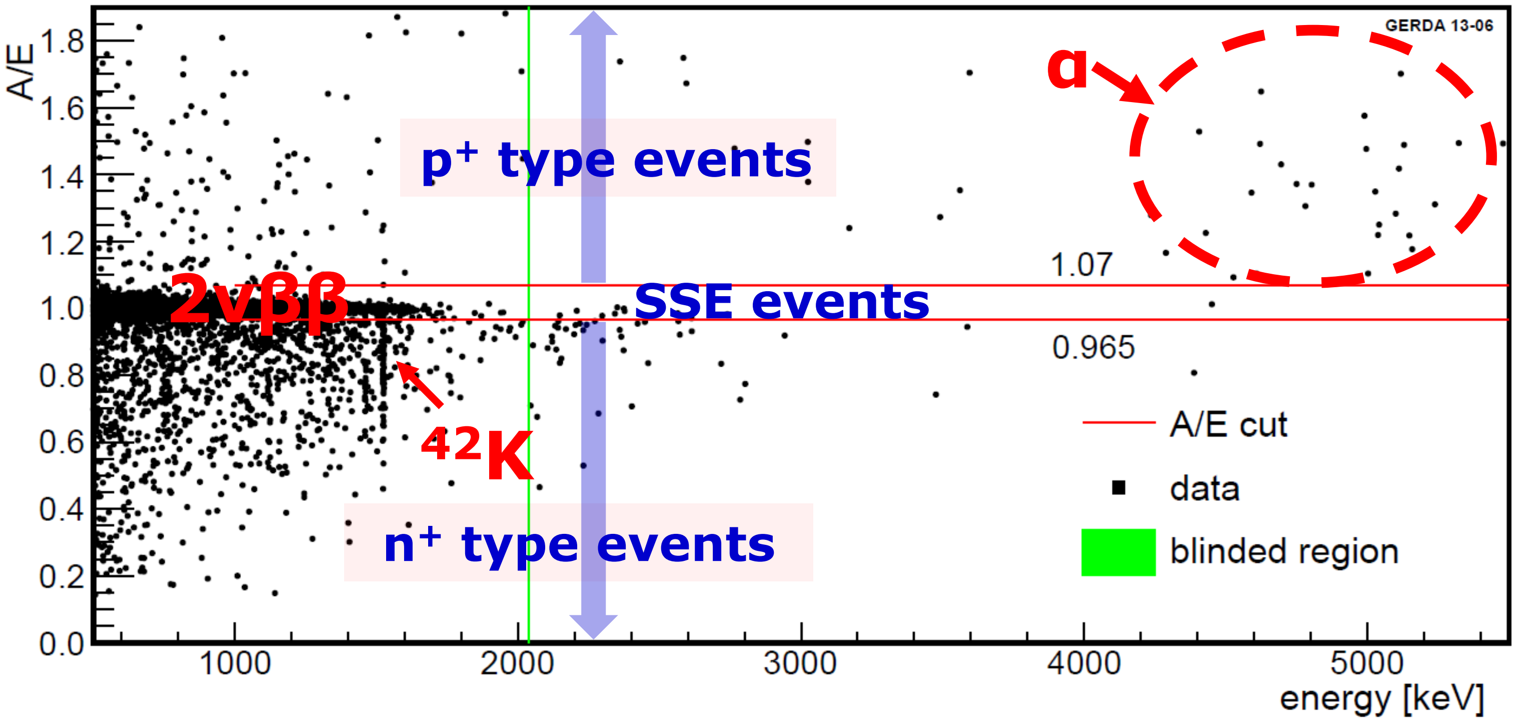
Energy dependence corr. → A/E w.r.t DEP peak norm.



Global PSD for the GERDA Phase-I BEGe



PSD for the GERDA Phase-I BEGe



region	low A/E cut $A/E < 0.965$	high A/E cut $A/E > 1.07$	surviving fraction $0.965 < A/E < 1.07$
^{228}Th calibration			
DEP 1592.5 keV	0.054 ± 0.003	0.015 ± 0.001	0.931 ± 0.003
FEP 1620.7 keV	0.771 ± 0.008	0.009 ± 0.002	0.220 ± 0.008
SEP 2103.5 keV	0.825 ± 0.005	0.011 ± 0.001	0.165 ± 0.005
physics data			
FEP 1524.7 keV	0.69 ± 0.05	0.027 ± 0.015	0.29 ± 0.05
1000 - 1450 keV	0.230 ± 0.011	0.022 ± 0.004	0.748 ± 0.011
1839 - 2239 keV	30/40	3/40	7/40 =0.175
> 4 MeV (α at $p+$)	1/35	33/35	1/35 =0.028

Proxy of 0νββ

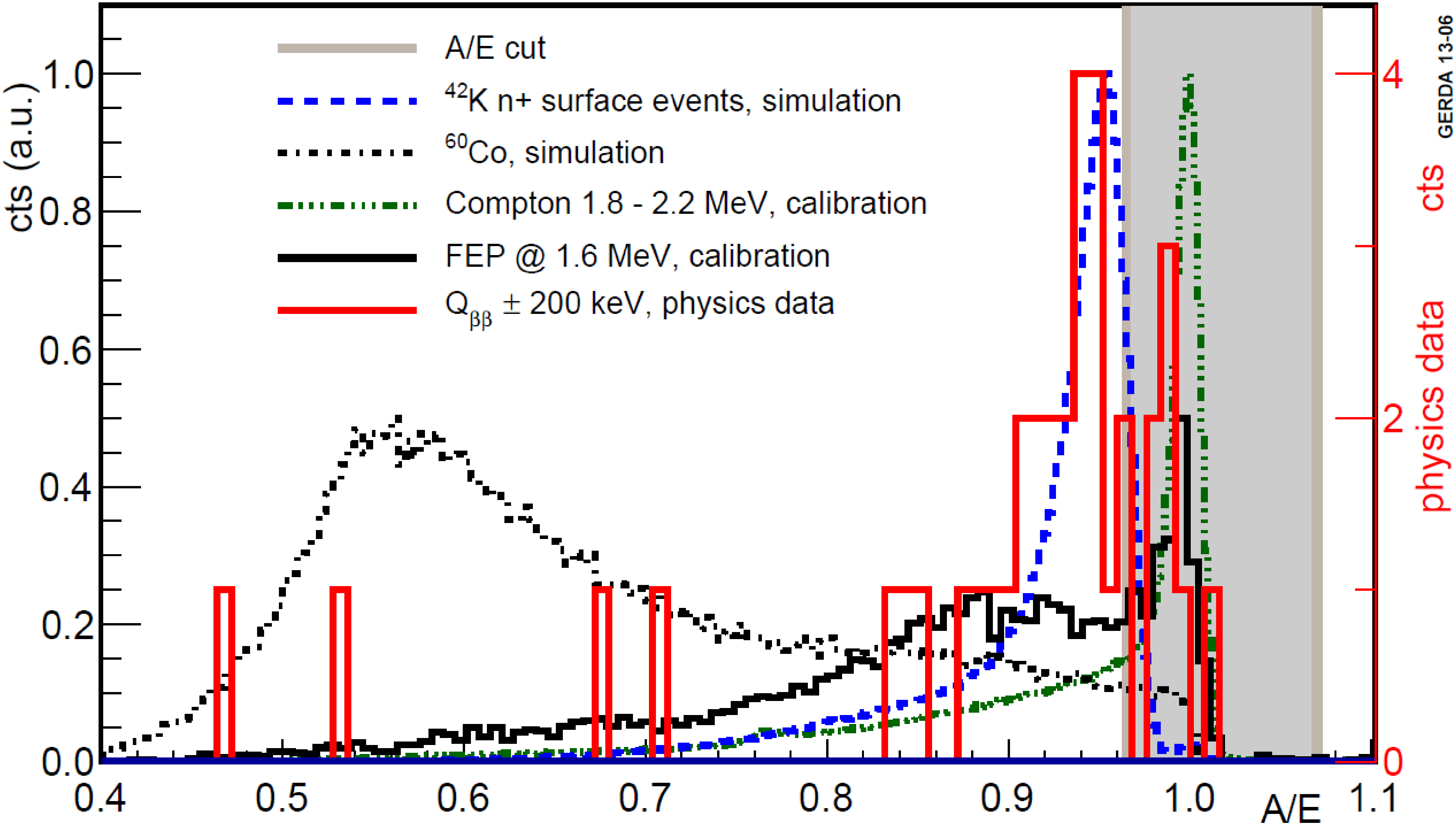
MSE

^{42}K

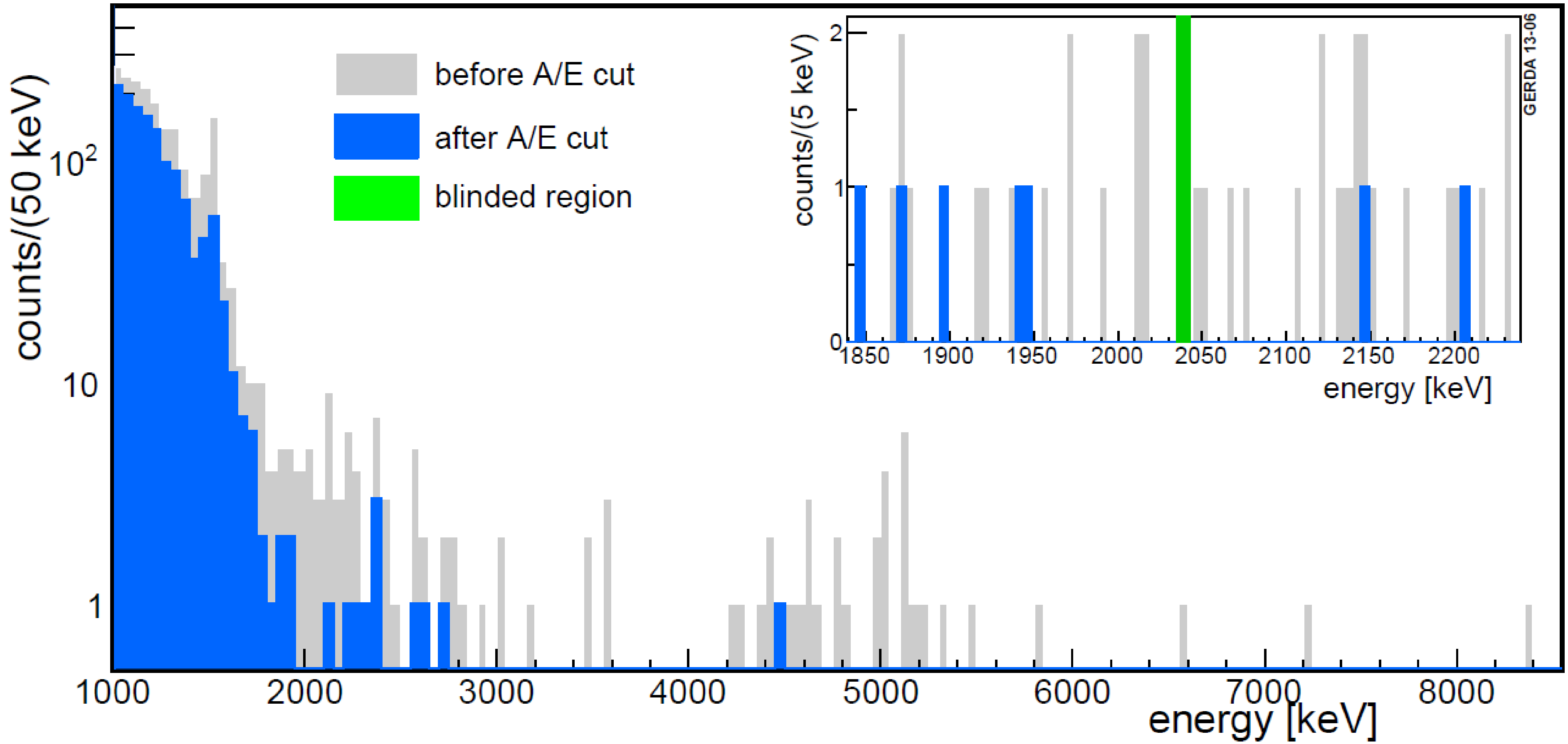
ROI

α

A/E: Background

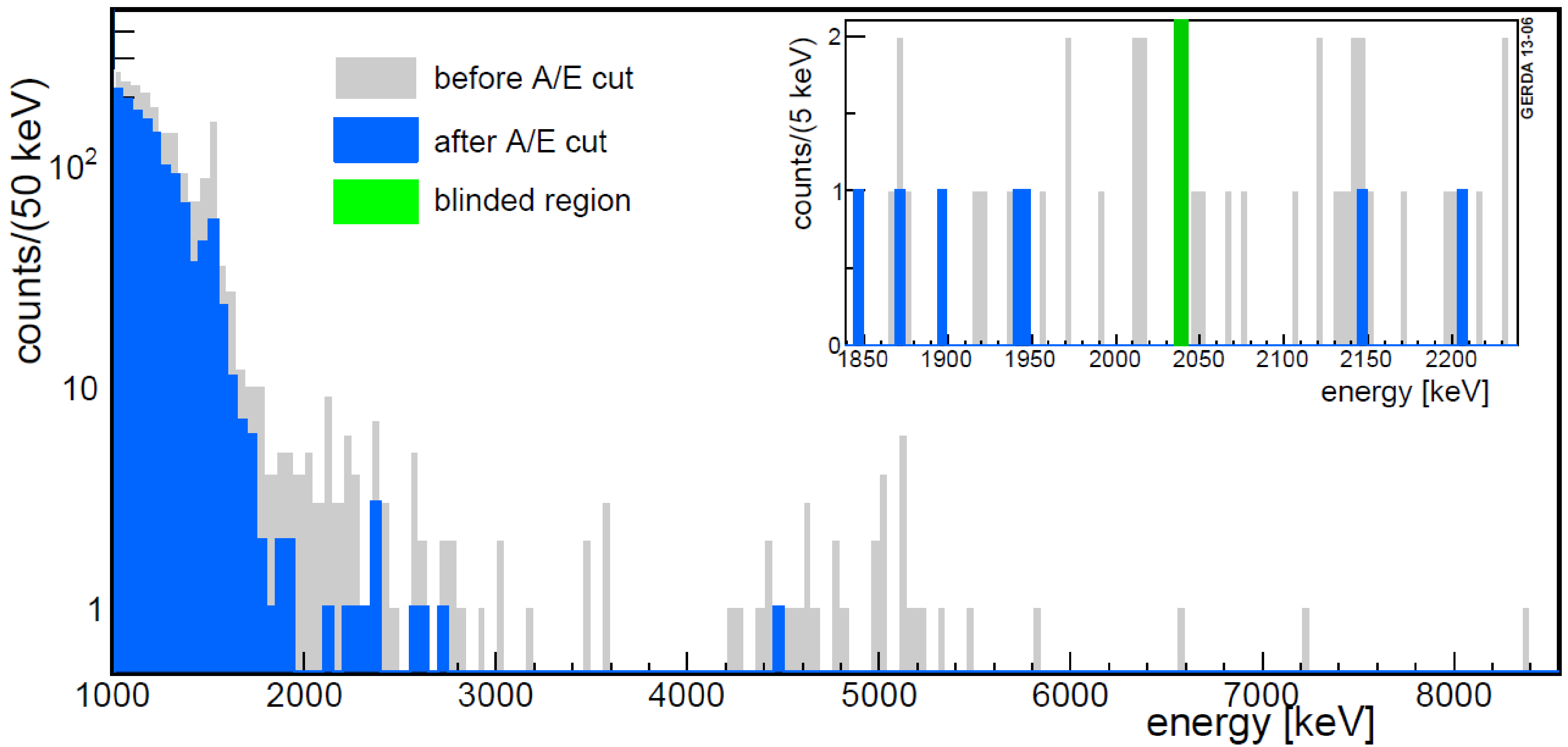


Global PSD for the GERDA Phase-I



- **BI in ROI :**
  Before/After PSD: 0.036/ 0.007 Cts/(kg·yr·keV)
  Suppression factor: > 80% of bkg events
  Signal efficiency: (92 ± 2) %

Global PSD for the GERDA Phase-I



- **After unblinding:**
  0/1 event after/before PSD cut

Outlook & Summary

- **Physics result for GERDA phase I:**
  $T_{1/2}^{0\nu\beta\beta} > 2.1 \cdot 10^{25} yr$ **@ 90% C.L.**
- **A/E PSD of BEGes demonstrates powerful SSE/MSE pulse shape recognition efficiency**
- **Physics result for GERDA phase I BEGes:**
  0/1 event after/before PSD cut with 92% efficiency
- **GERDA phase I successfully completed & decommissioned**
- **GERDA phase II will go beyond:**
  Increase total detector mass & lower background index