GERDA: The search for Neutrinoless Double Beta Decay

Outline:

- Physics of 0νββ decay
- The GERDA experiment
- Phase-I Background
- Phase-I Pulse Shape Discrimination
- Phase-I Results
- Phase-II Status
- Summary & Outlook

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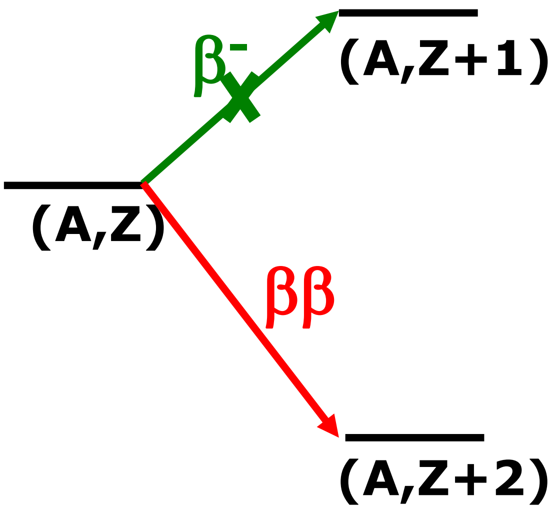
for the GERDA collaboration

Max-Planck-Institut für Physik

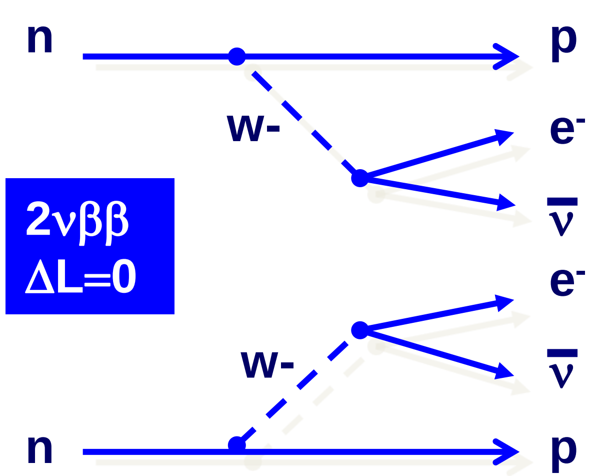
INFO 15 @ Santa Fe, 12/07/2015

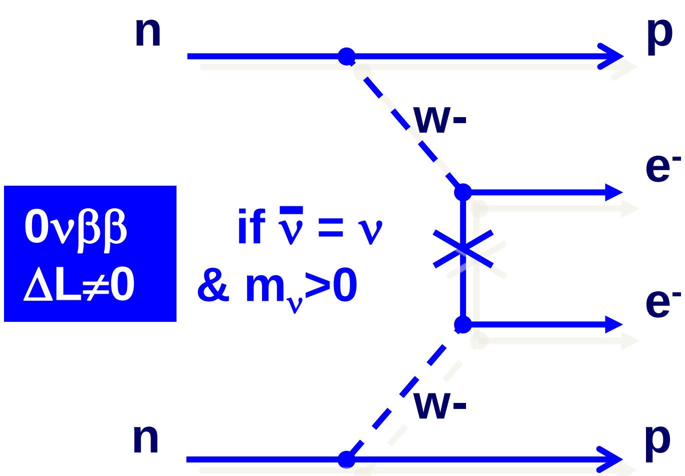
Neutrinoless Double Beta Decay



Level Scheme

- **Observable if 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: ($\nu=\bar{\nu}$)**
  (A,Z) → (A,Z+2) +2e⁻
  if ν is Majorana particle
  & Helicity flip is needed





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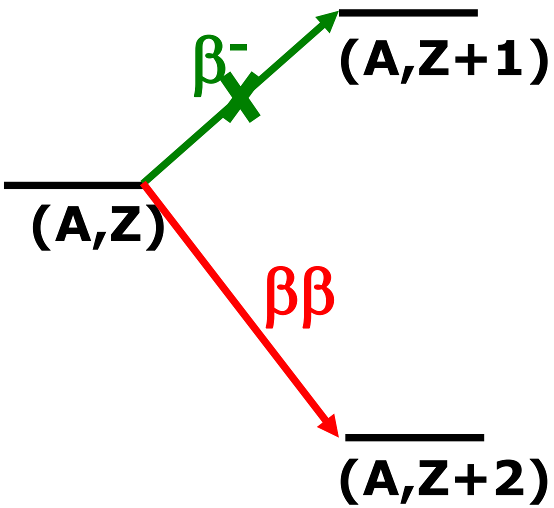
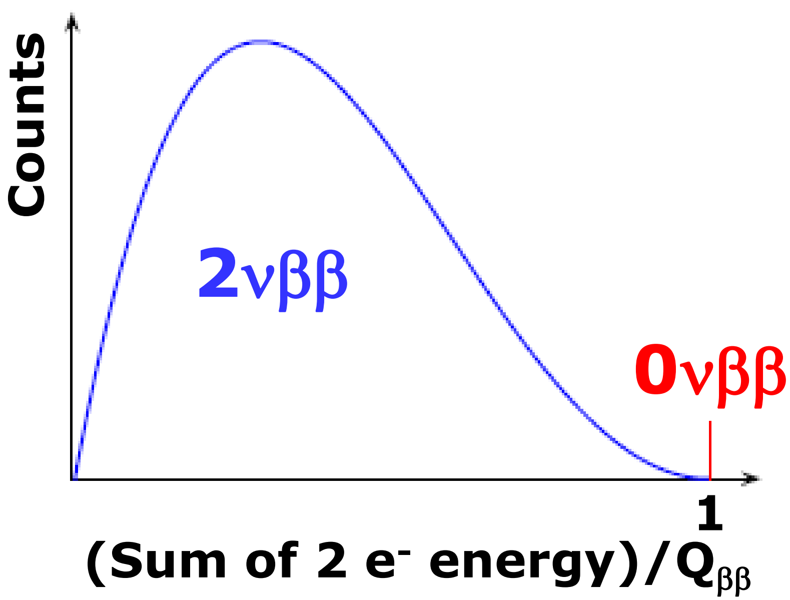


Level Scheme



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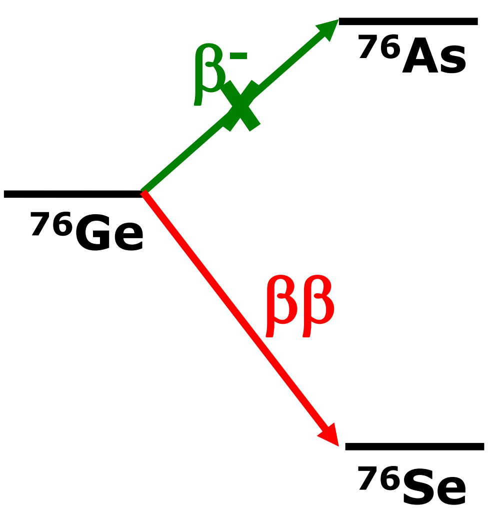
- 0νββ decay: ($\nu=\bar{\nu}$)
  (A,Z) → (A,Z+2) +2e$^-$
  if ν is Majorana particle
  & Helicity flip is needed

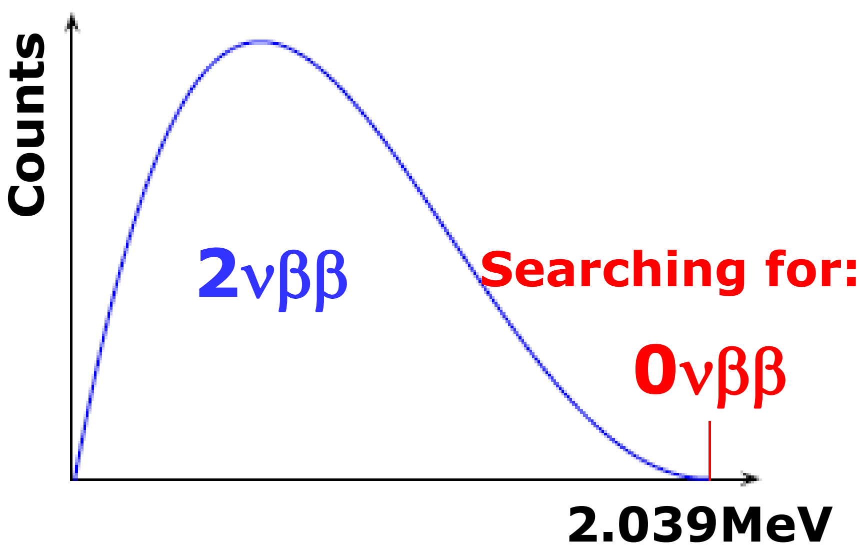
Study of 0νββ can:

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

^{76}Ge Neutrinoless Double Beta Decay



Level Scheme



- **Observable if single β decay is not allowed for some isotopes, only ββ decay**
- **2νββ decay: (measured $T_{1/2}$~10^{21} yr)**
  ^{76}Ge → ^{76}Se+2e^{-}+2$\bar{\nu}$
  SM allowed & observed
- **0νββ decay: ($\nu=\bar{\nu}$)**
  (measured $T_{1/2}$>10^{25} yr)
  ^{76}Ge → ^{76}Se+2e^{-}
  if ν is Majorana particle
  & Helicity flip is needed

⇒ Use detector made of ββ emitting material: HPGe detectors made from enriched ^{76}Ge

⇒ 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

Information on neutrino mass

One measurement, lots of information

Experimental Challenges

There are ~ 35 candidates in nature, however ...

- **Sensitivity of** $T_{1/2}^{0\nu\beta\beta} \propto \epsilon\, a \sqrt{\frac{M\,T}{B\,\Delta E}}$

  (if background is present)

  detection eff. (ϵ)

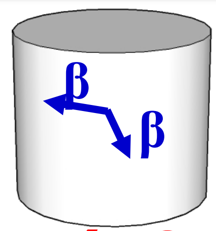
  enrichment fraction (a)

  ***MT*: exposure (kg·yr)**

  energy resolution (ΔE)

  background index (cts/day·kg·keV) (B)

- **Why Ge-76 detector ?**
  - **High detection efficiency**

    (source=detector)
  - **Very good energy resolution (~0.2% in ROI)**
  - **Intrinsically pure (important for low bkg. experiment)**
- **Why enrichment ? (abundance + bkg. scale with mass)**

1 ^{76}Ge diode

=

11x ^{nat}Ge diodes

Background Sources

- **Experiments always have backgrounds that can mimic the signal**
- **Background sources: Cosmic rays, natural radioactivity (in the environment & shielding), …**
- **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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Background Sources

- Exp… e backgro… mimic the…
- Bac… smic rays, rad… …
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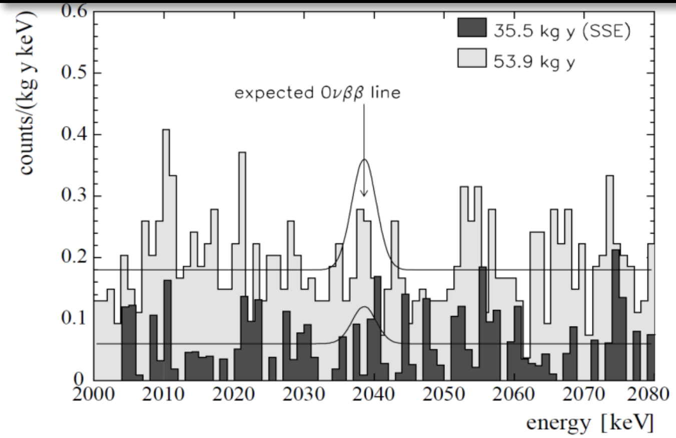
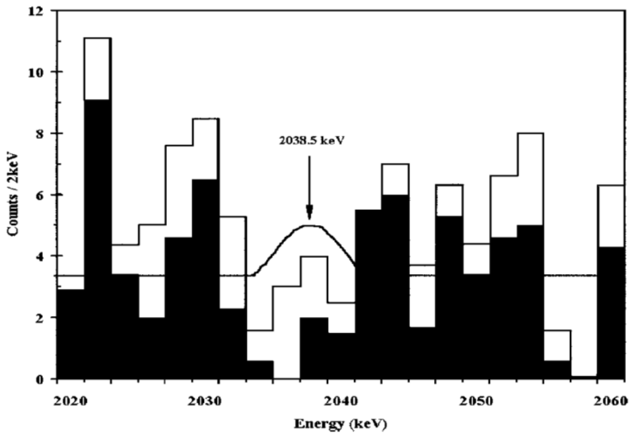
    → careful choice of materials + screening tests + Minimizing the support structure
  - □ Go underground to reduce cosmic backgrounds (cosmogenic activation on detector materials, muons)
- Establish techniques able to distinguish signals from backgrounds → Use intelligent detectors

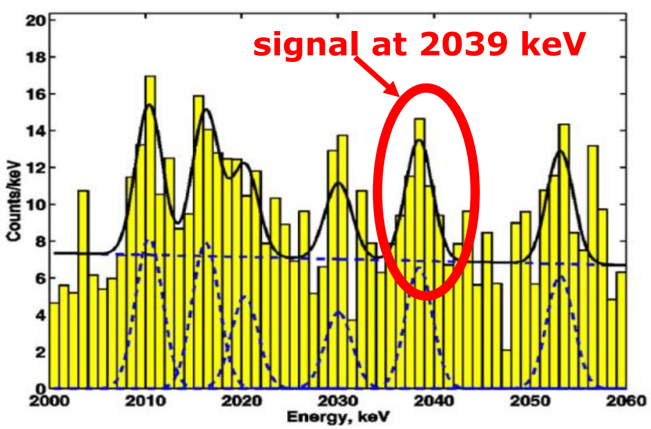
Commerical Ge detector

GERDA
Ge detector

Previous 0νββ Germanium Experiments







- **Previous limits for ^{76}Ge 0νββ decay:**
  - **Heidelberg-Moscow(HdM)**

    [EPJ. A 12 147-154 (2001)]

    $T_{1/2}^{0\nu\beta\beta}$ > 1.9·10^{25} yr (@ 90% C.L.)

    $T_{1/2}^{0\nu\beta\beta}$ > 1.3·10^{25} yr (w/o PSD)
  - **International Germanium Experiment (IGEX)**

    [PRD. 65 092007 (2002)]

    $T_{1/2}^{0\nu\beta\beta}$ > 1.6·10^{25} yr (@ 90% C.L.)
  - **Klapdor-Kleingrothaus et al.**

    [PL B586 (2004) 198]

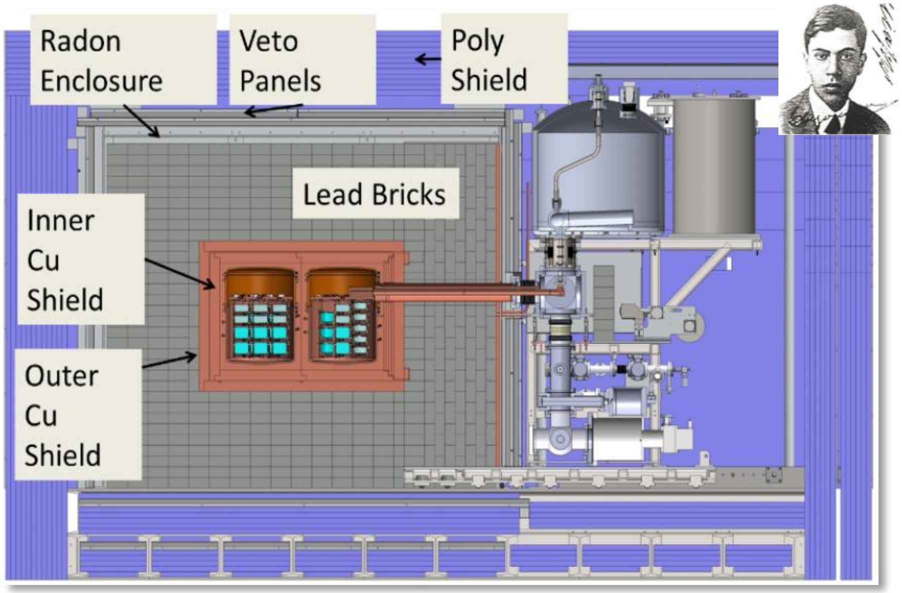
    $T_{1/2}^{0\nu\beta\beta} = \mathbf{1.19^{+0.37}_{-0.23}}$·10^{25} yr (@ 90% C.L.)

Current 0νββ Germanium Experiments

GERDA

- 'Bare' ^{enr}Ge array in liquid argon
- Shield: high-purity liquid Argon / H_2O
- Underground: LNGS, 3500 m.w.e
- Phase I (2011-2013): 21.6 kg·yr
- Phase II (2015-):
  +~20 kg new ^{enr}BEGe detectors; +LAr readout;
  10x lower BI compare to Phase I
  Total ~35 kg ^{enr}BEGe + 7 kg ^{nat}Ge

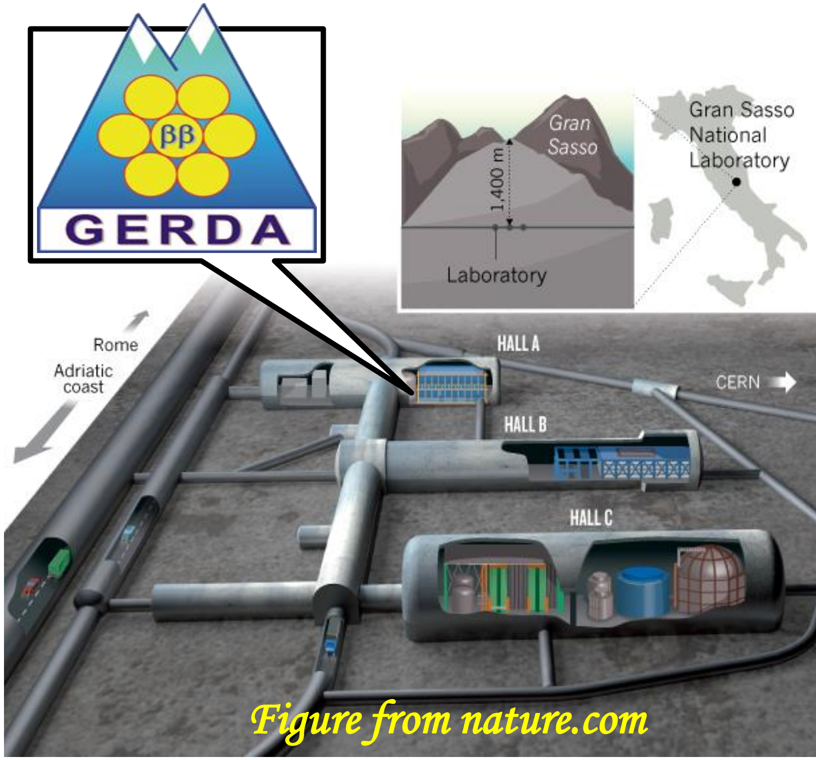
MAJORANA DEMONSTRATOR



- Arrays of ^{enr}Ge housed in high-purity electroformed copper cryostat
- Shield: electroformed copper / lead
- Underground: SURF, 4300 m.w.e
- Initial phase(2015-): R&D demonstrator module: Total ~40 kg (30 kg enr.)

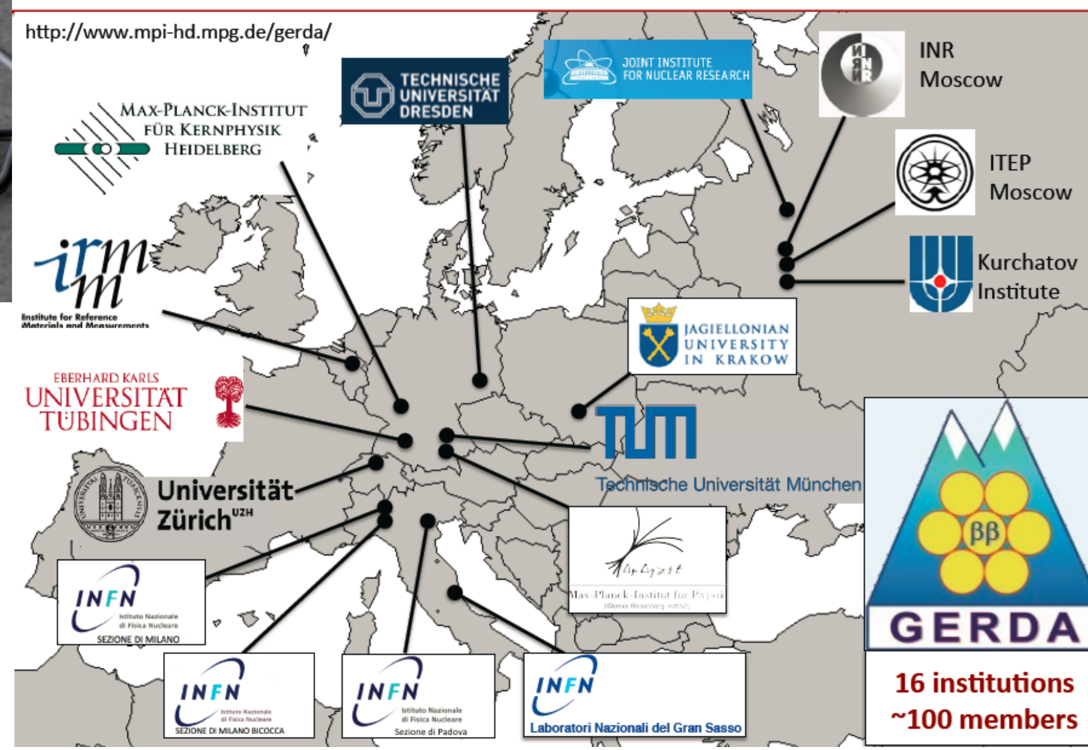
→ **Details in Brandon's talk**

The GERDA Experiment

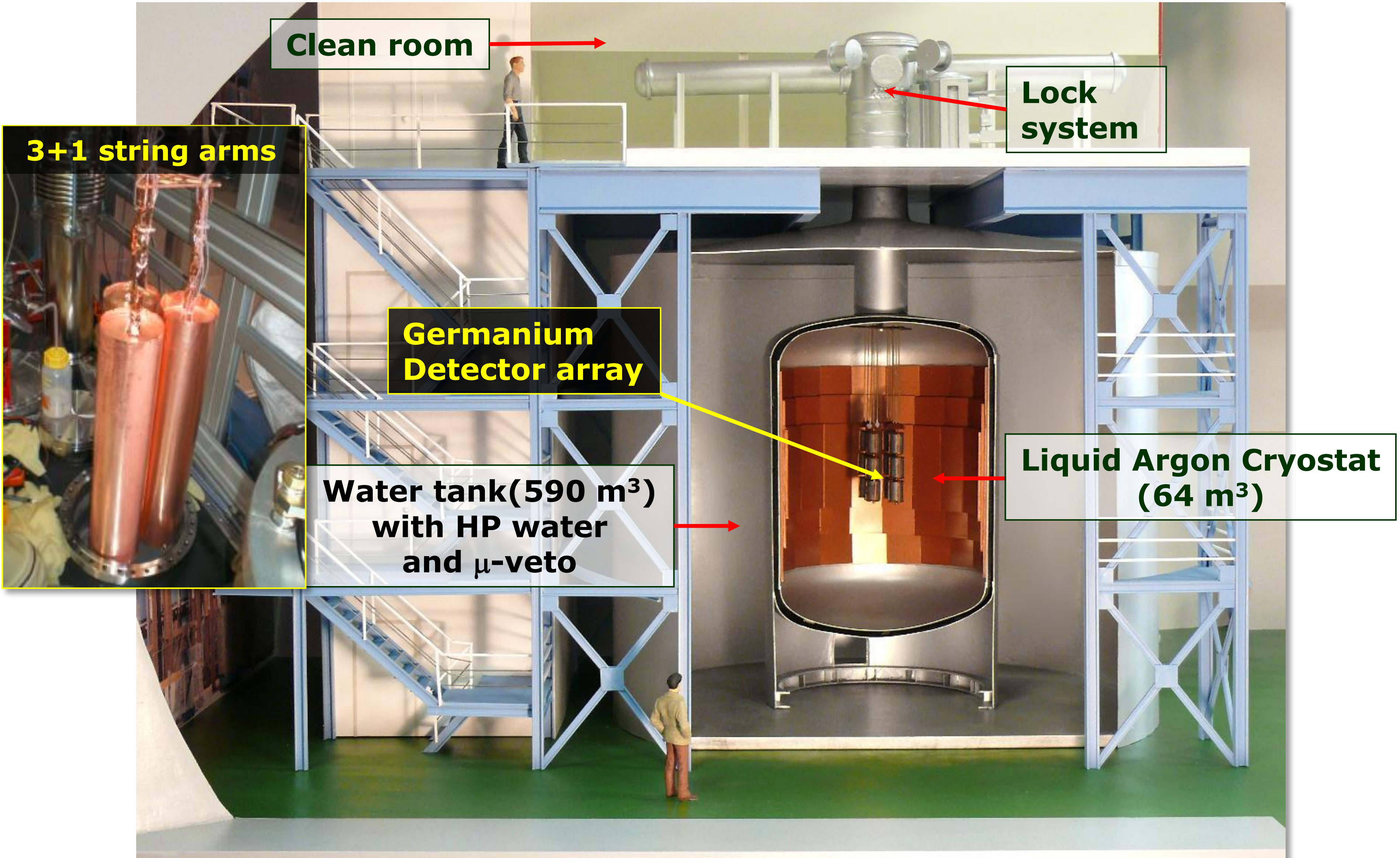


- **GERmanium Detector Array**
- **Search for 0νββ decay in ^{76}Ge @ $Q_{\beta\beta}$=2.039 MeV**
- **Location: Hall A, LNGS**
- **Overburden: 3500 m.w.e**

The GERDA Collaboration



The GERDA Experiment



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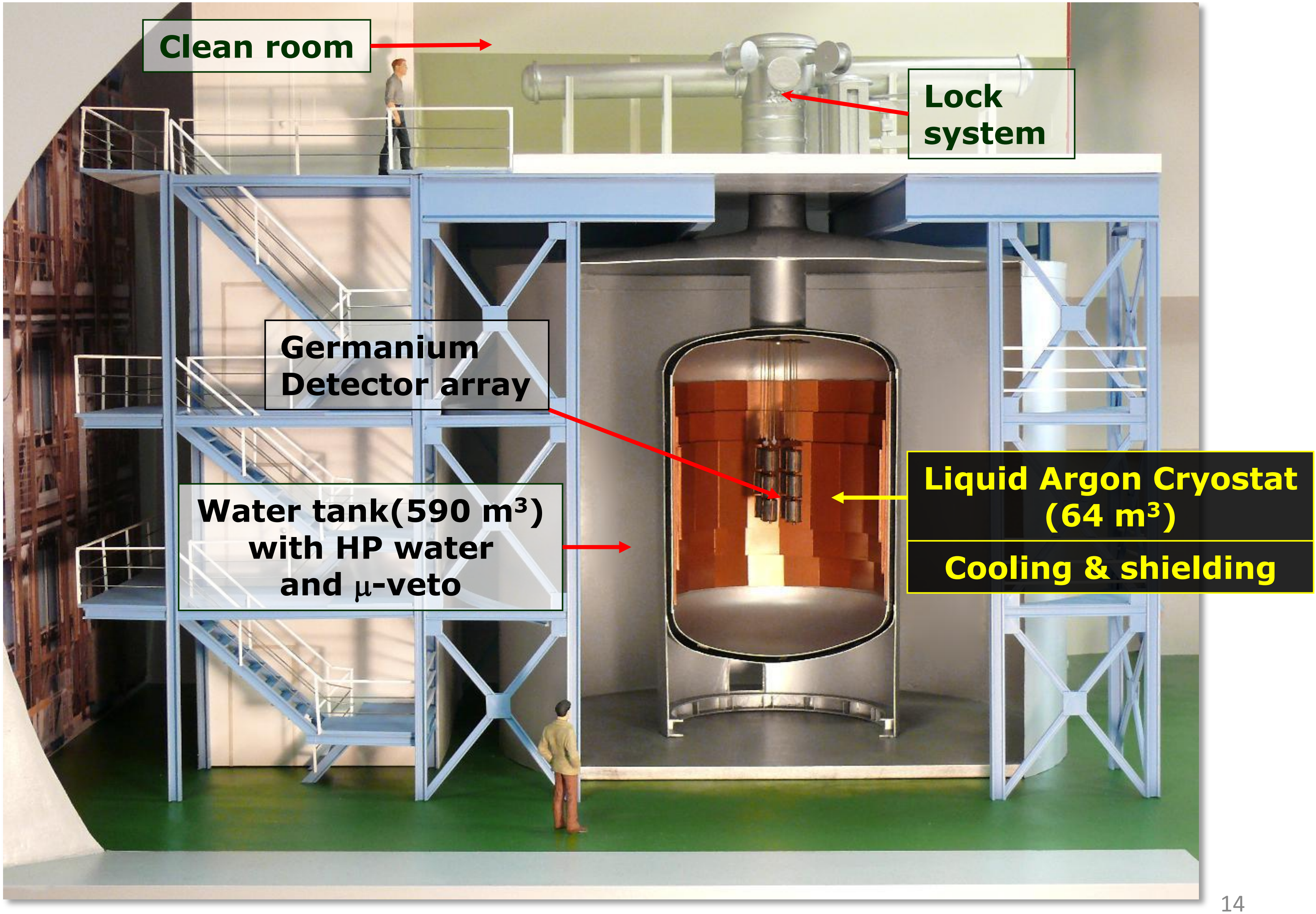

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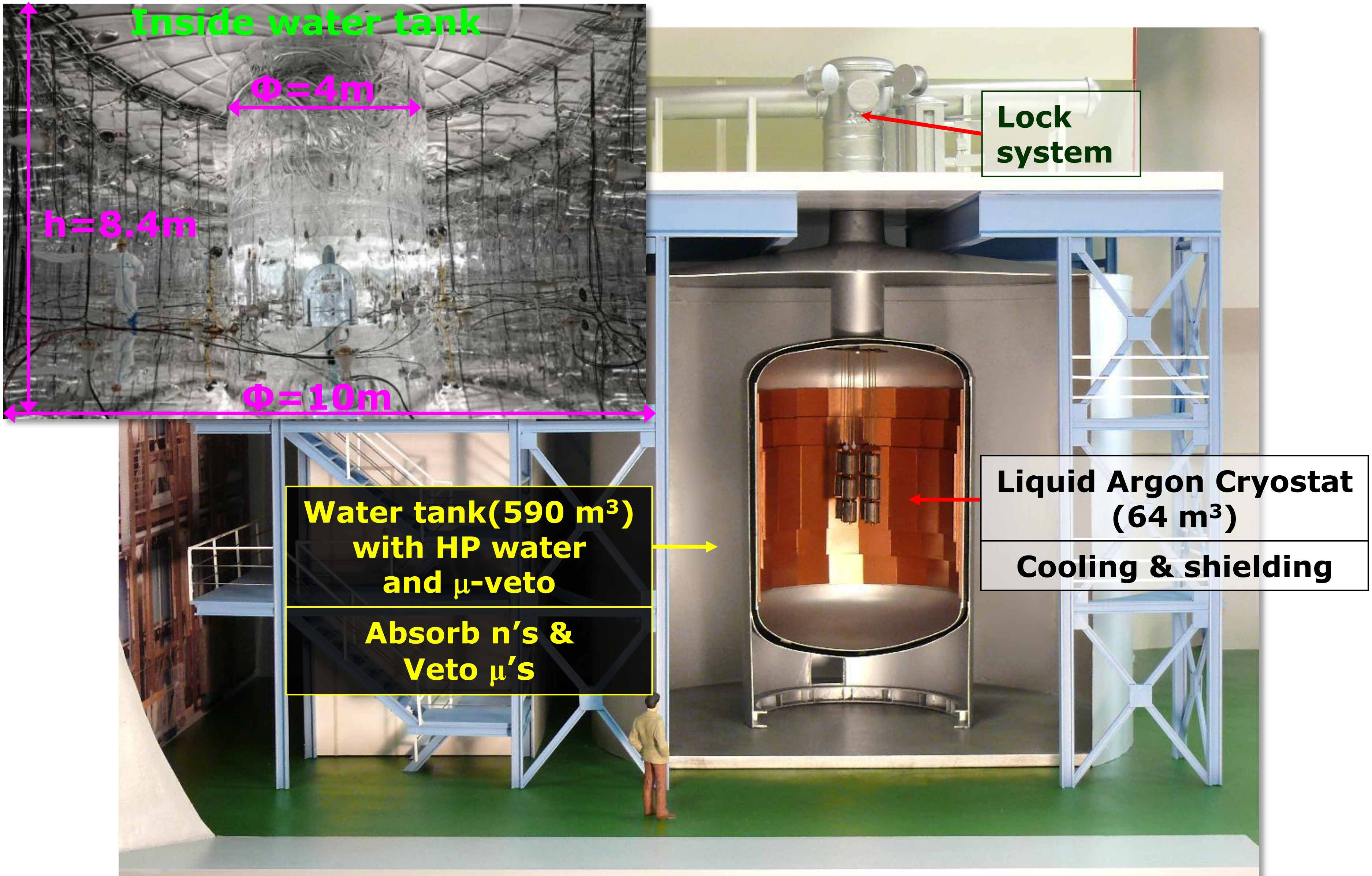

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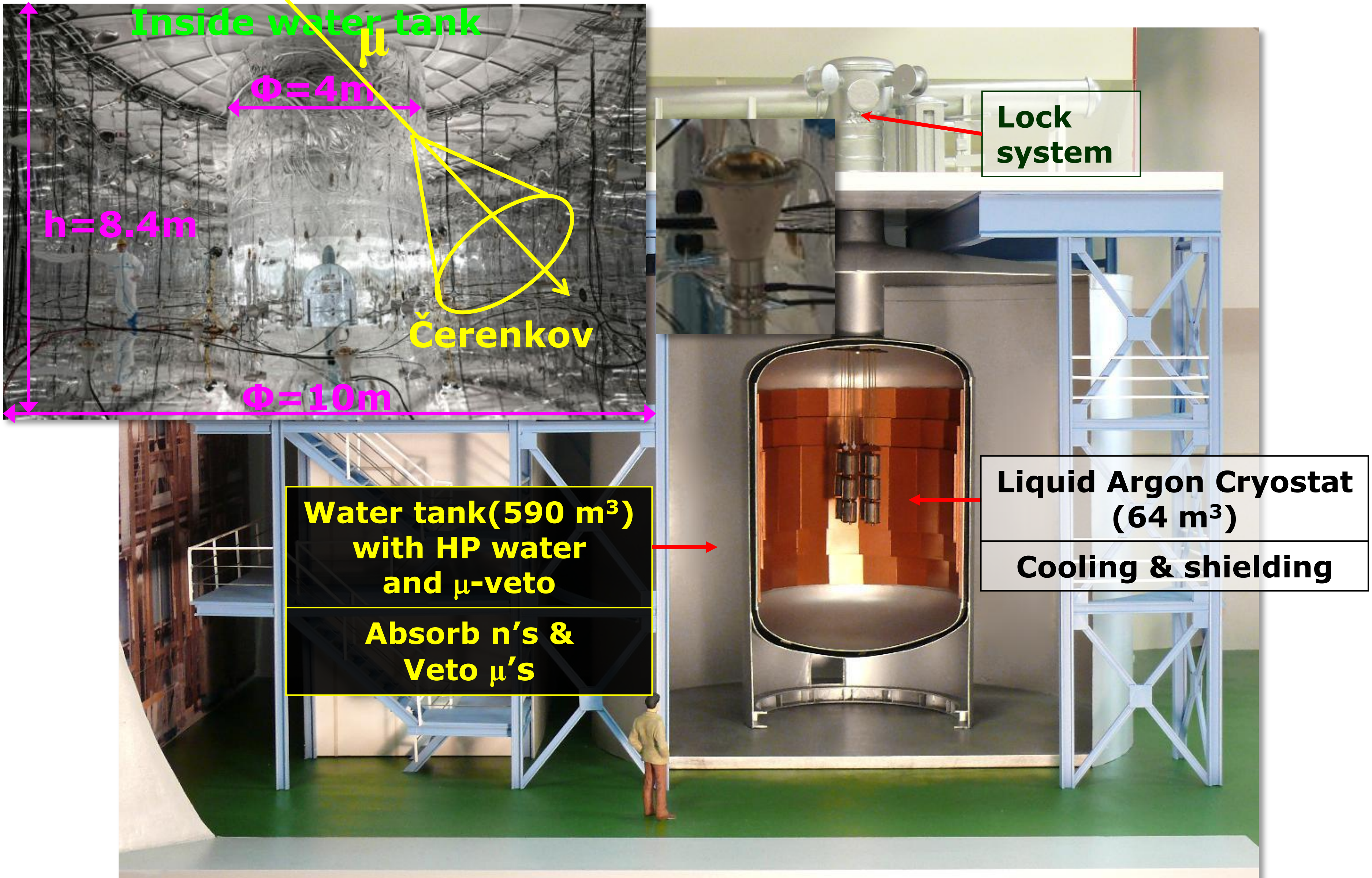
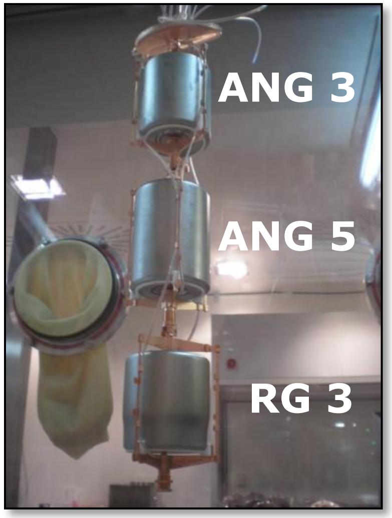
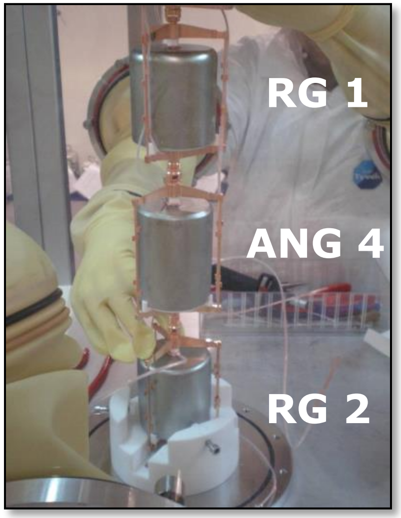


GERDA Phase I Detectors

- **9 coax detectors**
  ANG1-5: from HdM experiment
  RG1-3: from IGEX experiment
  ~86% enrichment fraction
  GTF112: natural Ge diode

Reprocessed by CANBERRA

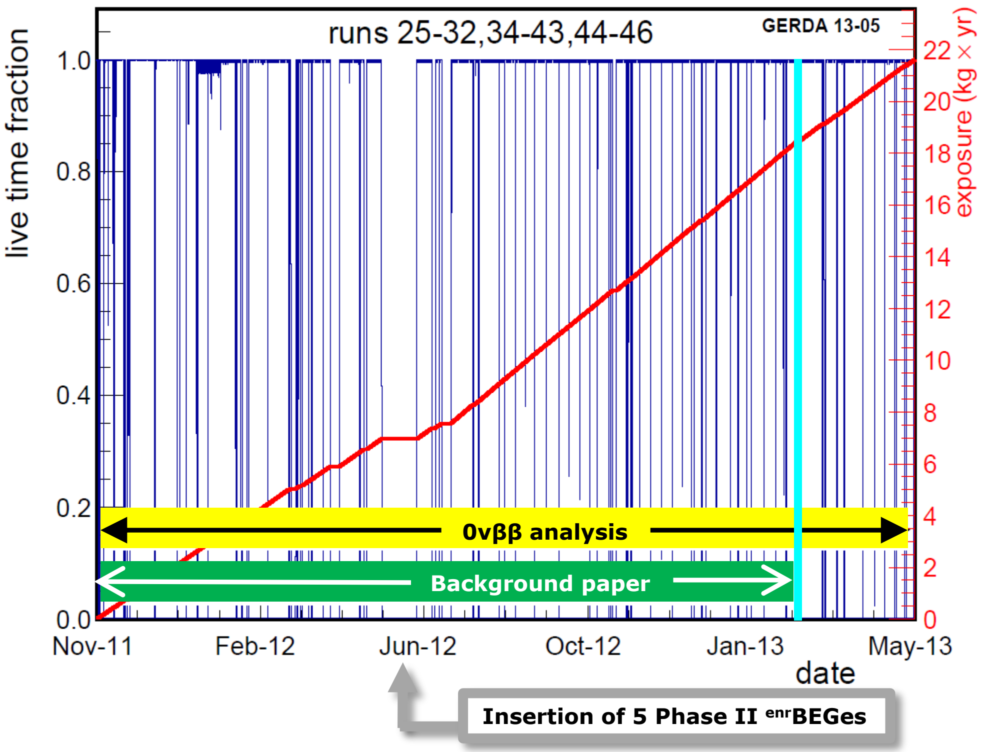


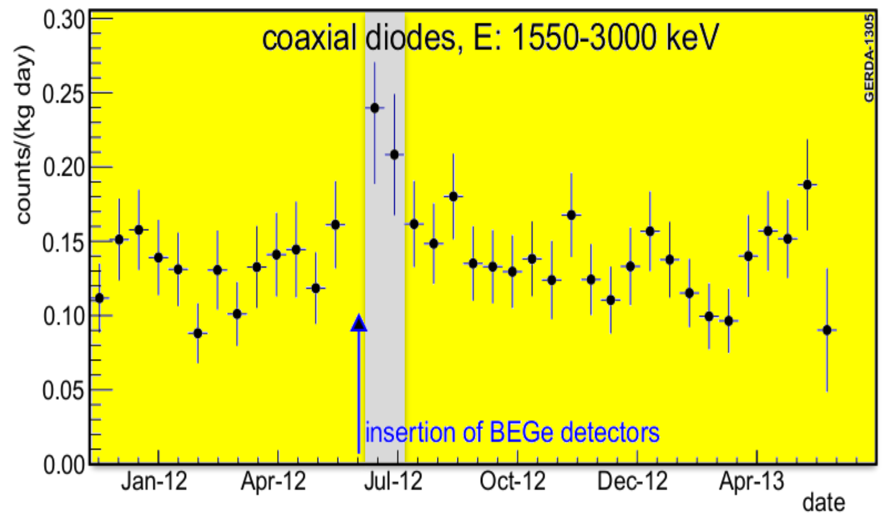


- **5 Phase II BEGe detectors**
  GD32B-35C: new, inserted later
  ~88% enrichment fraction
  Improved performance of pulse shape discrimination
- **Total mass of enriched detectors: 17.6 kg**

p.s. ANG1, RG3, GD35C → high leakage currents & instabilities

Phase I Data Taking: Overview

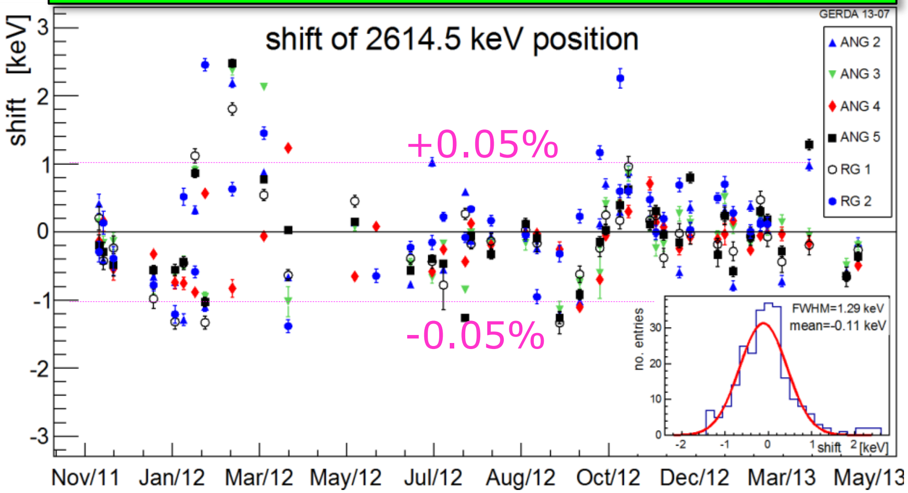




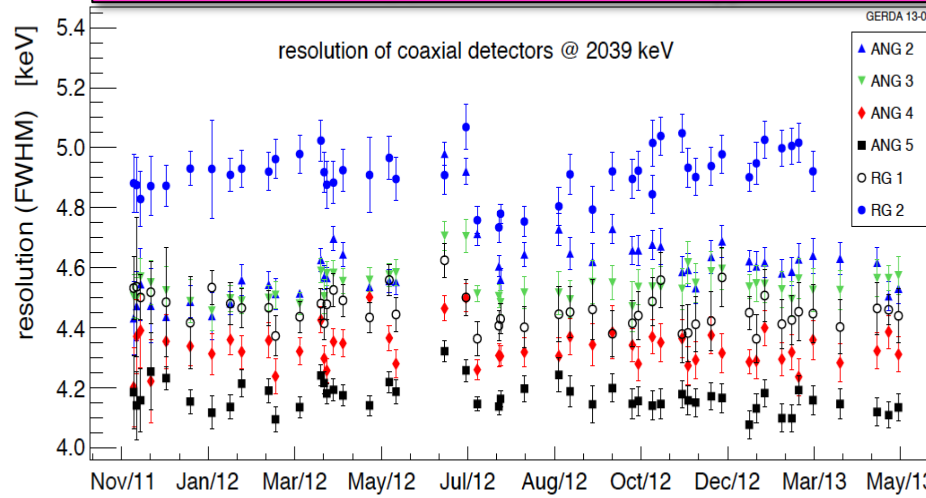
- **Stable data taking during most of the time**
  - Calibration run every 1-2 week(s): for energy & PSD
  - Physics run in between
- **Phase I data taking divided into 3 sets:**
  - *Gold-coax*: 17.9 kg·yr
  - *Silver-coax*: 1.3 kg·yr (30 days after BEGe insertion)
  - *BEGe*: 2.4 kg·yr
- **Total exposure for 0νββ analysis: 21.6 kg·yr**

Detector Performance: Stability & Energy Resolution

Calibration data: shift of 2614.5 keV peak

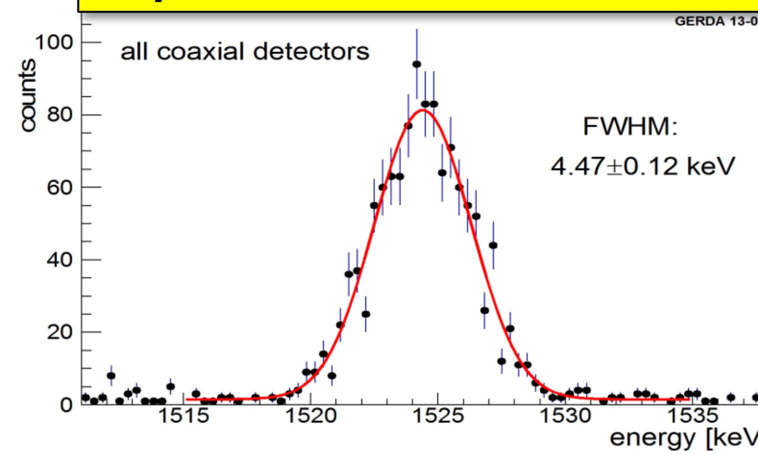


Energy Resolution at $Q_{\beta\beta}$

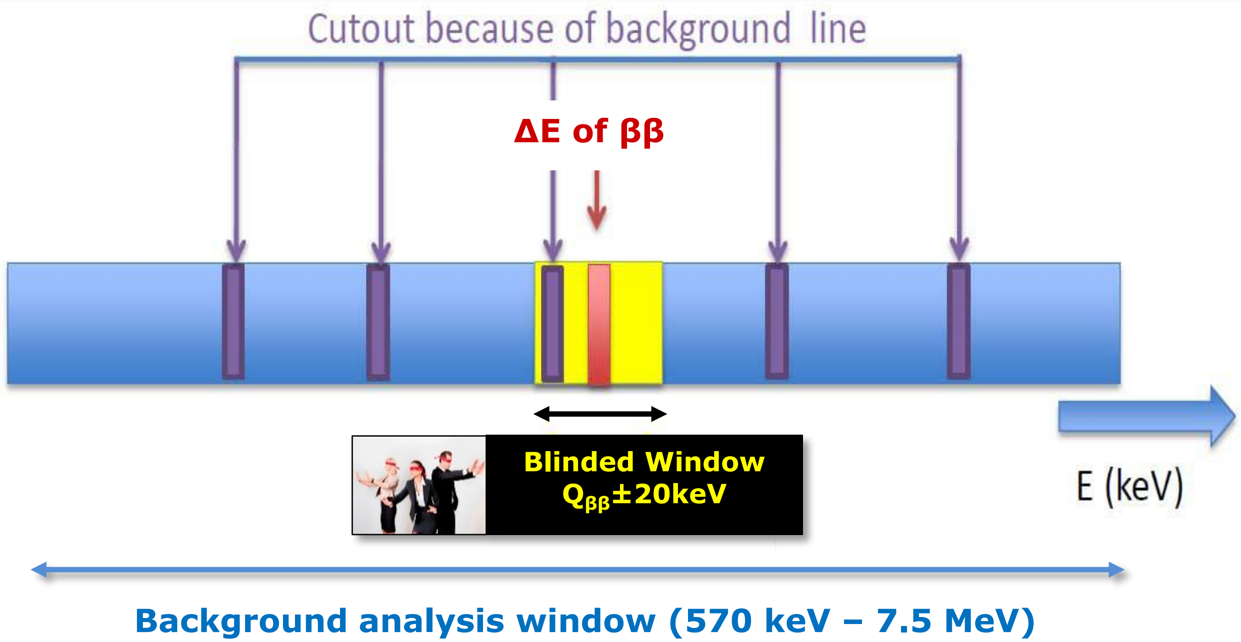


- **Monitor detector performance over time**
  pulser(0.05Hz) + ^{228}Th source
- **Peak position shifts:**
  small compared to FWHM ~ 0.2% $Q_{\beta\beta}$
- **Energy resolution stable**
- **Averaged FWHM of physica data @ $Q_{\beta\beta}$:**
  coax: 4.8±0.2 keV (~0.24%)
  BEGe: 3.2±0.2 keV (~0.16%)

Physics data: ^{42}K 1524.6 keV line

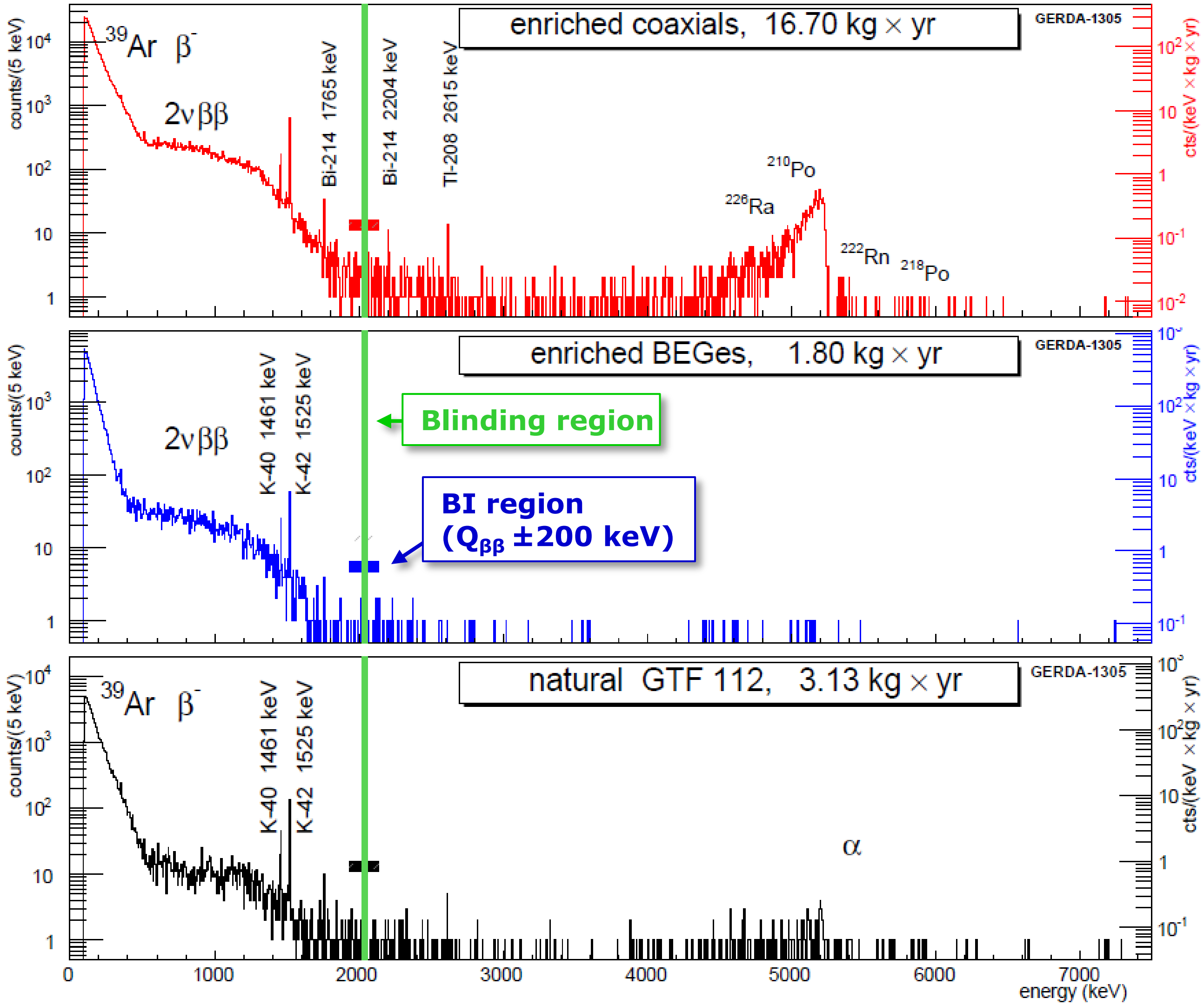


Blinding Procedure



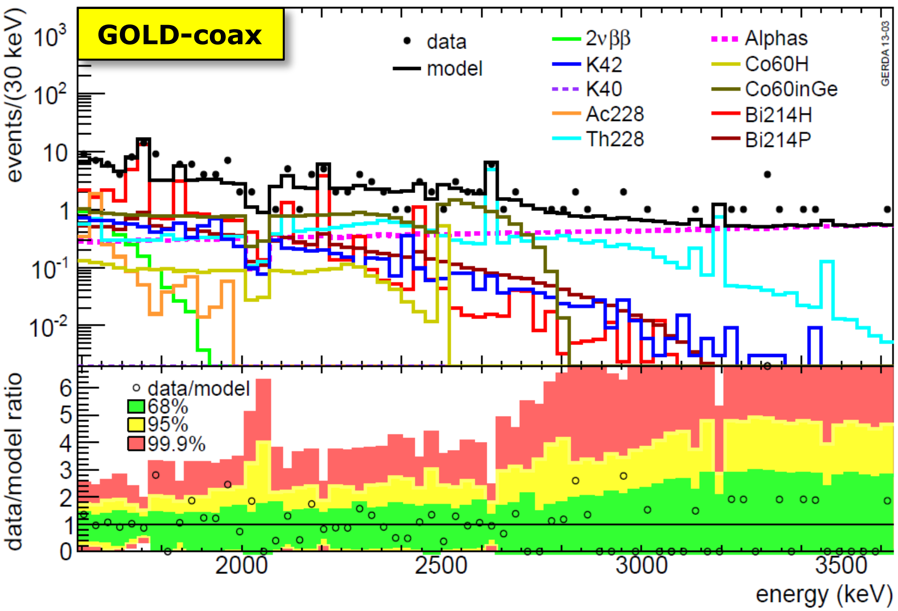
- **Data blinding:**
  Events in $Q_{\beta\beta}$±20 keV were saved but did not enter the data analysis pipe line before all parameters were fixed
- **Two steps unblinding:**
  - **[1] Evaluation of run parameters & bkg. model: $Q_{\beta\beta}$±20 keV**
  - **[2] Partial unblinding: Consistency check for the models**
    Fixing of pulse shape discrimination parameters:
    - **coax detectors: $Q_{\beta\beta}$±5 keV**
    - **BEGe detectors: $Q_{\beta\beta}$±4 keV**

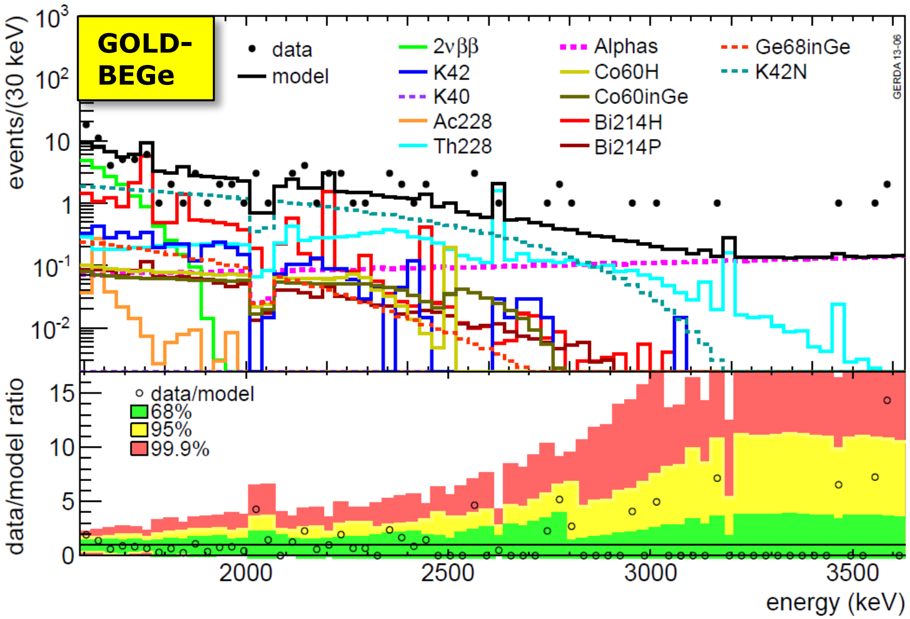
Energy spectra



- **Background decomposition:**
  - **Simulate known & observed background**
  - **MC spectra of different contributions fit to data (570 keV to 7.5 MeV, blinded at $Q_{\beta\beta}$±20 keV)**

Background Model



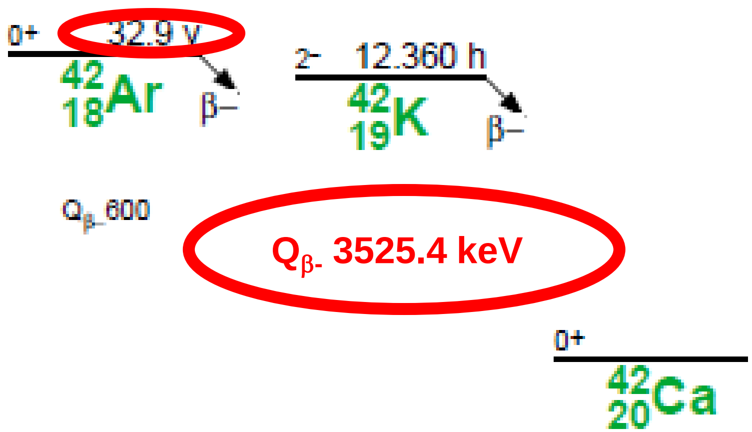


- **Close bkg. components dominate (<2cm from detectors)**
- **Contributions at $Q_{\beta\beta}$**
  - **Coax detectors:**
    No dominant source
    - β/γ induced events from:
      - ^{214}Bi (^{238}U) & ^{208}Tl (^{228}Th)
      - ^{42}K (Q = 3.5 MeV)
      - ^{60}Co (Q = 2.8 MeV)
    - α events from:
      - surface contamination
        ➡ confirmed by pulse shape analysis
      - degraded alphas in LAr
  - **BEGe detectors:**
    ^{42}K on the n+ surface dominate
    ➡ confirmed by pulse shape analysis

^{42}K Background in GERDA

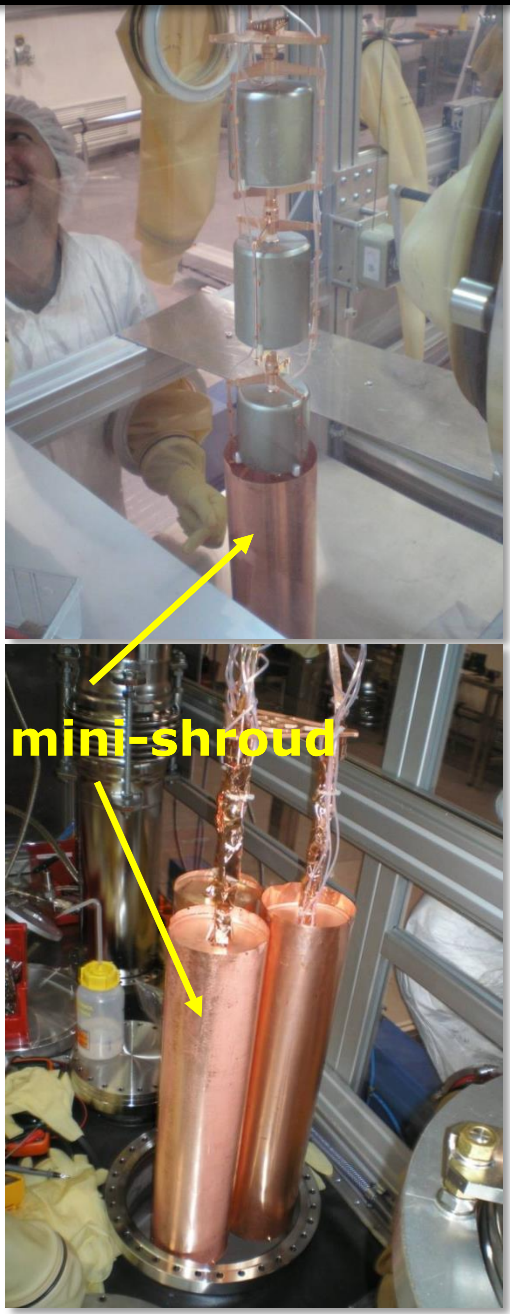
- **^{42}Ar: Isotope of Ar, created mostly in cosmic-ray induced spallation reactions**
- **Decay chain:**

^{42}Ar ⟶ ^{42}K ⟶ ^{42}Ca



- **^{42}K ions get attracted by detector HV**

- **GERDA Phase I approach:**
  - ✓ **Installation of mini-shroud**
    - ⟶ **Keep ions away from detectors**



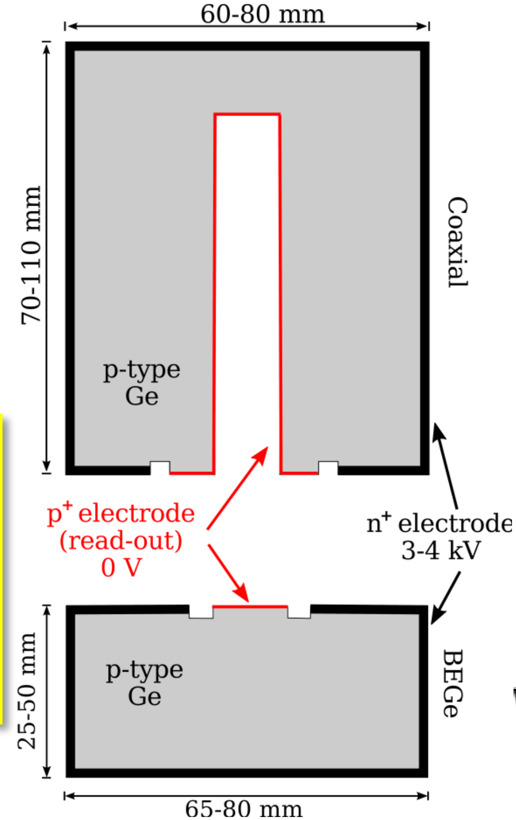
α-induced events in GERDA

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

- **Dead layer 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)

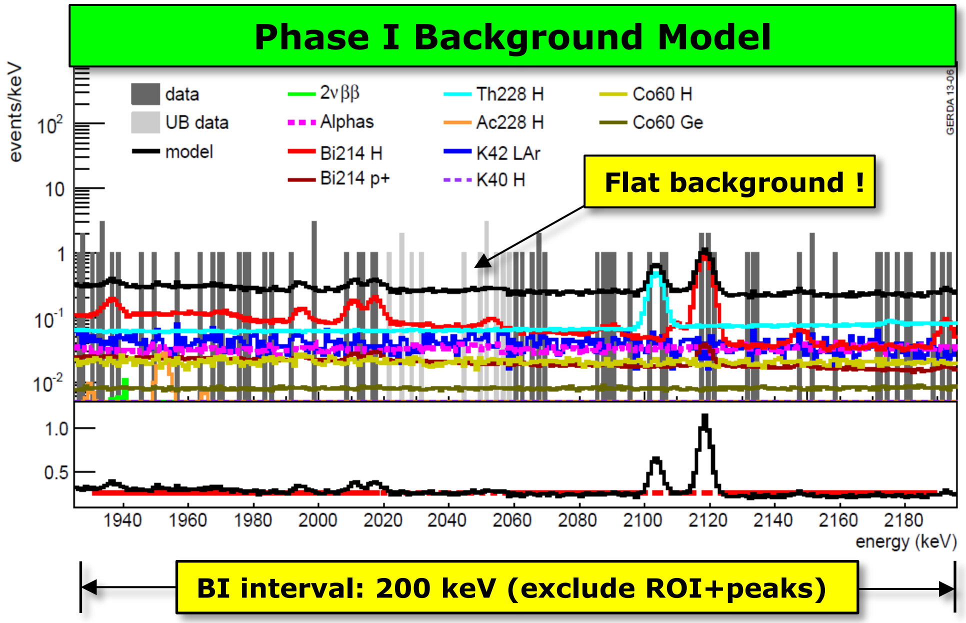
Pb-210 ($T_{1/2}$ = 22.3 y)

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

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

Pb-206 (stable)

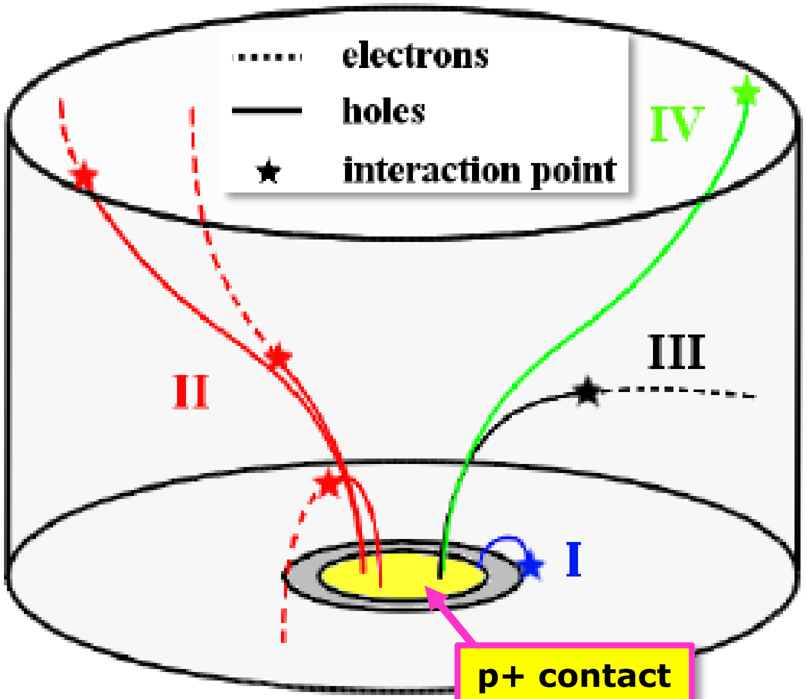
Prediction of Background Model

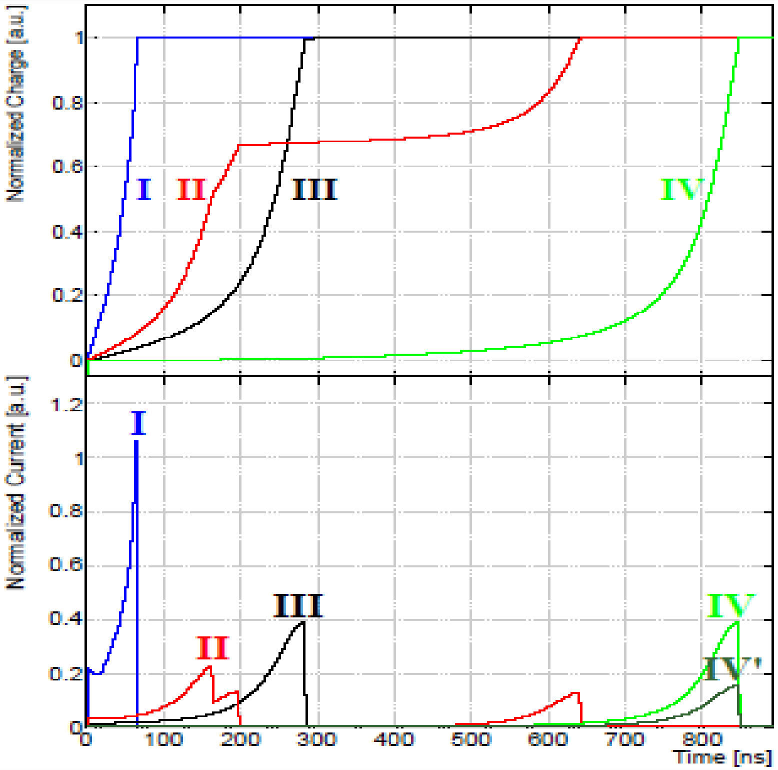


No surprise was found & analysis was applied with no changes

- **Background model:**
  - **Flat background in the ROI**
- **Expected entries around $Q_{\beta\beta}$:**
  - **coax: 8.6-10.3 evts**
    observed: 13 evts
  - **BEGes: 2.2 evts**
    observed: 2 evts
- **BI around $Q_{\beta\beta}$ (ΔE=200 keV):**
  using interpolation of the background by a const. excluding known bkg. peaks
  - **BI(coax):**
    $(1.75^{+0.26}_{-0.24})\cdot 10^{-2}$ **cts/(keV·kg·yr)**
  - **BI(BEGe):**
    $(3.6^{+1.3}_{-1.0})\cdot 10^{-2}$ **cts/(keV·kg·yr)**

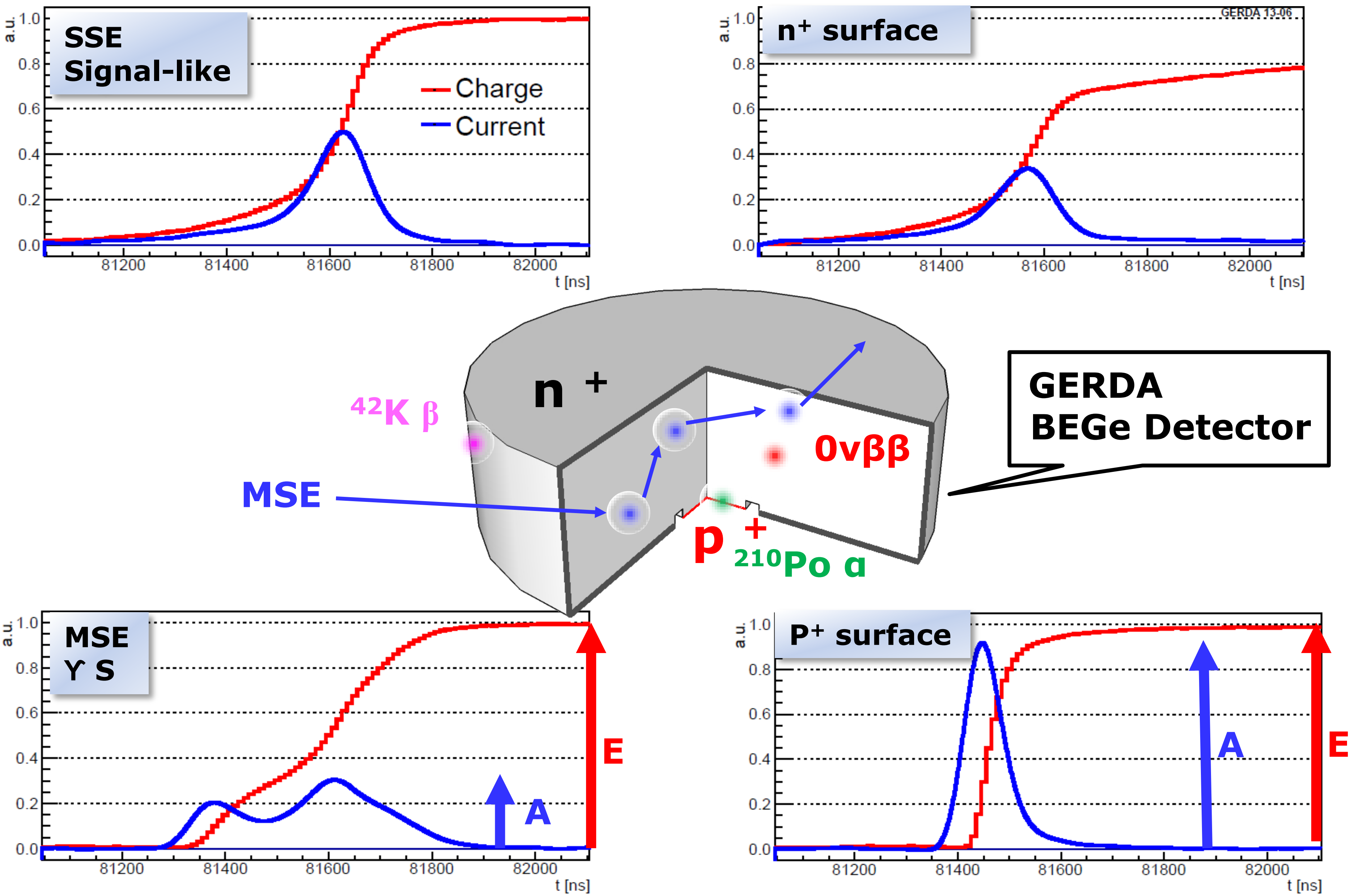
BEGe Pulse Shape Properties





- **Properties of E-field of BEGe:**
  - **Well pronounced weighting field near the read out electrode:**
    ⇨ **Uniform waveform at the end for SSE indept. of where the individual energy depositions happen**
  - **Pulse shape discrimination:**
    Keep signal-like events & reject background-like events

A/E Pulse Shape Discrimination Method

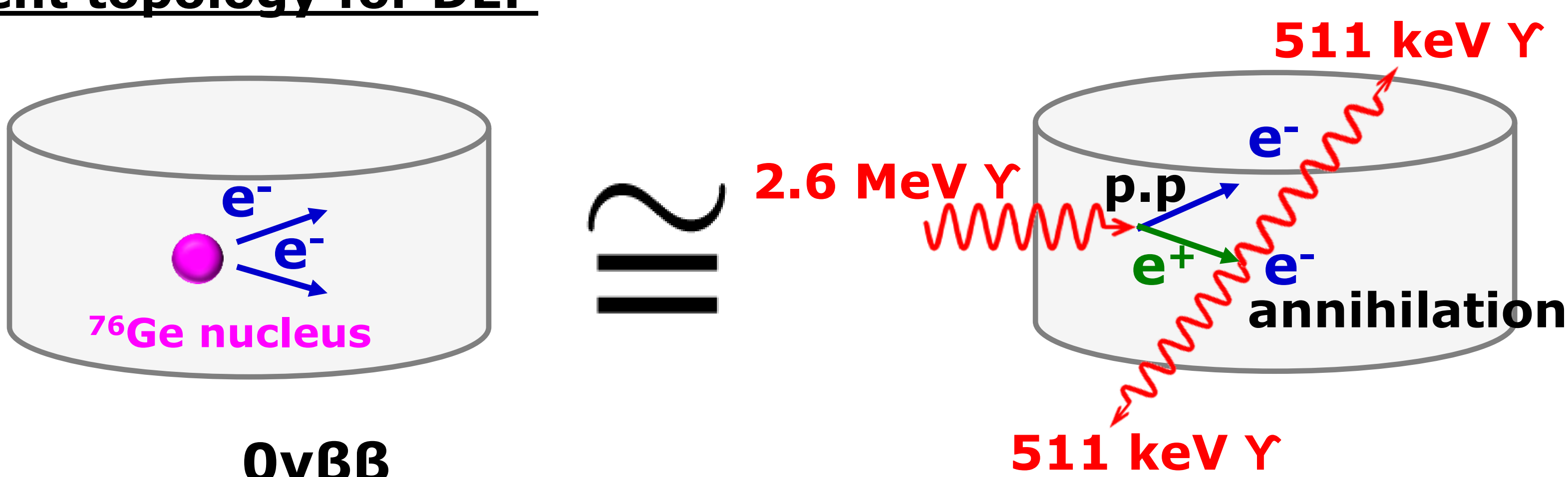


Proxies for Signal & Background

- Develop PSD method using external ^{228}Th source
  → Apply A/E cut value on physics data
- Proxies:
  - DEP: **D**ouble **E**scape **P**eak (1.59 MeV) from 2.6 MeV
    ➡ SSE (0νββ-like)
  - FEP: **F**ull **E**nergy **P**eak (1.62 MeV)
  - SEP: **S**ingle **E**scape **P**eak (2.10 MeV)

  } ➡ mostly ϒs ➡ MSE

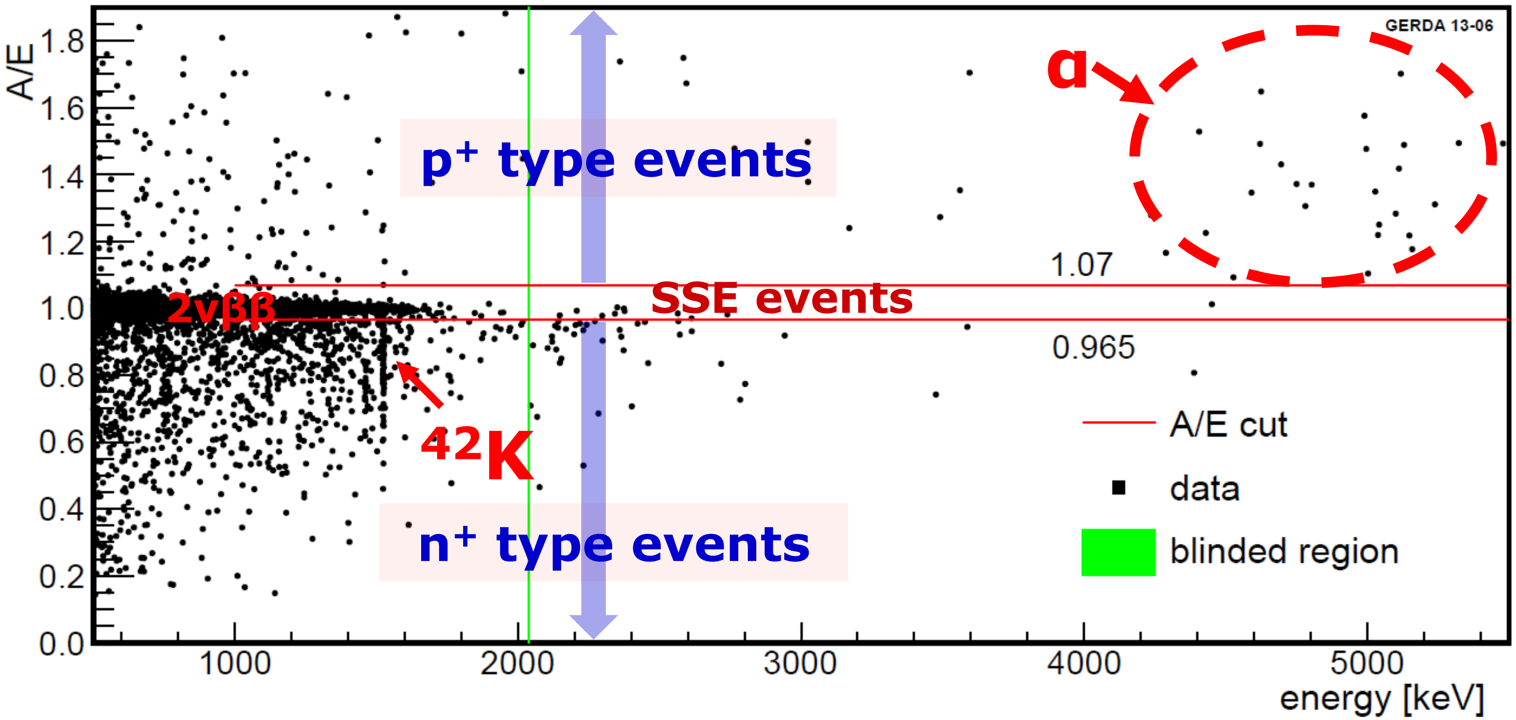
Event topology for DEP



0νββ
(localized energy deposition)
λ(e⁻) @ 2 MeV in Ge~ few mm

DEP
(signal-like event)

Physics Data of 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 (DEP 1592.5 keV)

MSE (FEP 1620.7 keV, SEP 2103.5 keV)

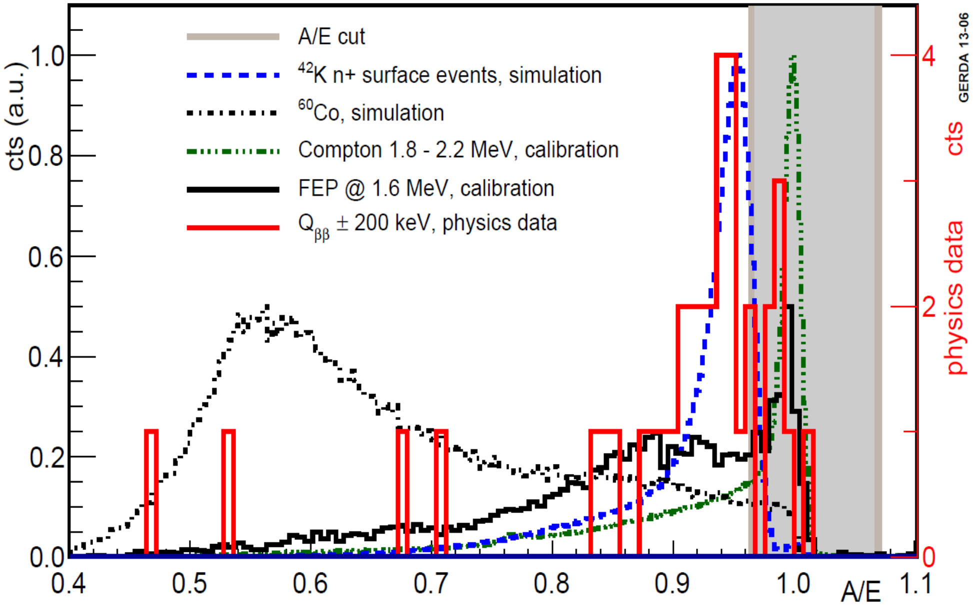
42K (FEP 1524.7 keV)

2νββ dominant (1000 - 1450 keV)

ROI (1839 - 2239 keV)

α (> 4 MeV)

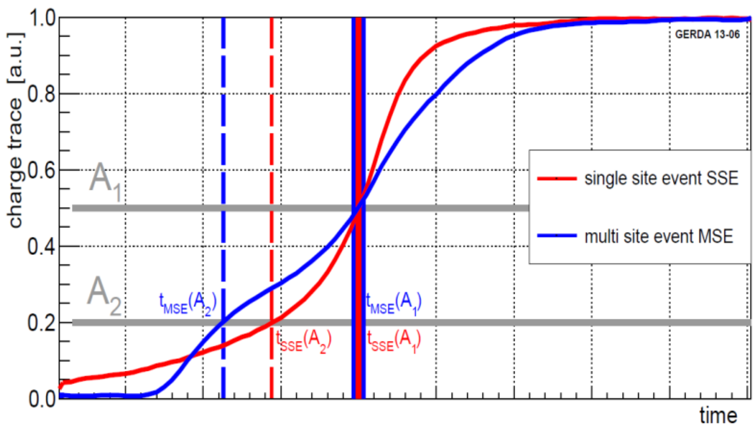
PSD Results for the GERDA Phase-I BEGe

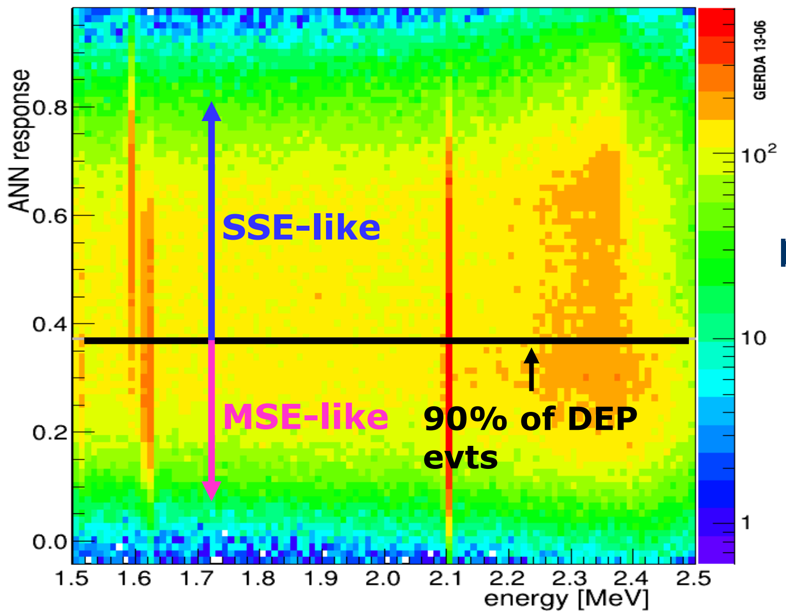


- **A/E PSD:**
  Supports the GERDA bkg. model : most of the BEGe background is from ^{42}K on n+ contact

- **BI at $Q_{\beta\beta}$:**
  - **Suppression factor:** **> 80% of bkg. events**
  - **Signal efficiency:** **(92 ± 2) %**
  - **2νββ efficiency:** **(91 ± 5) %**

PSD for Phase I Coaxial Detectors





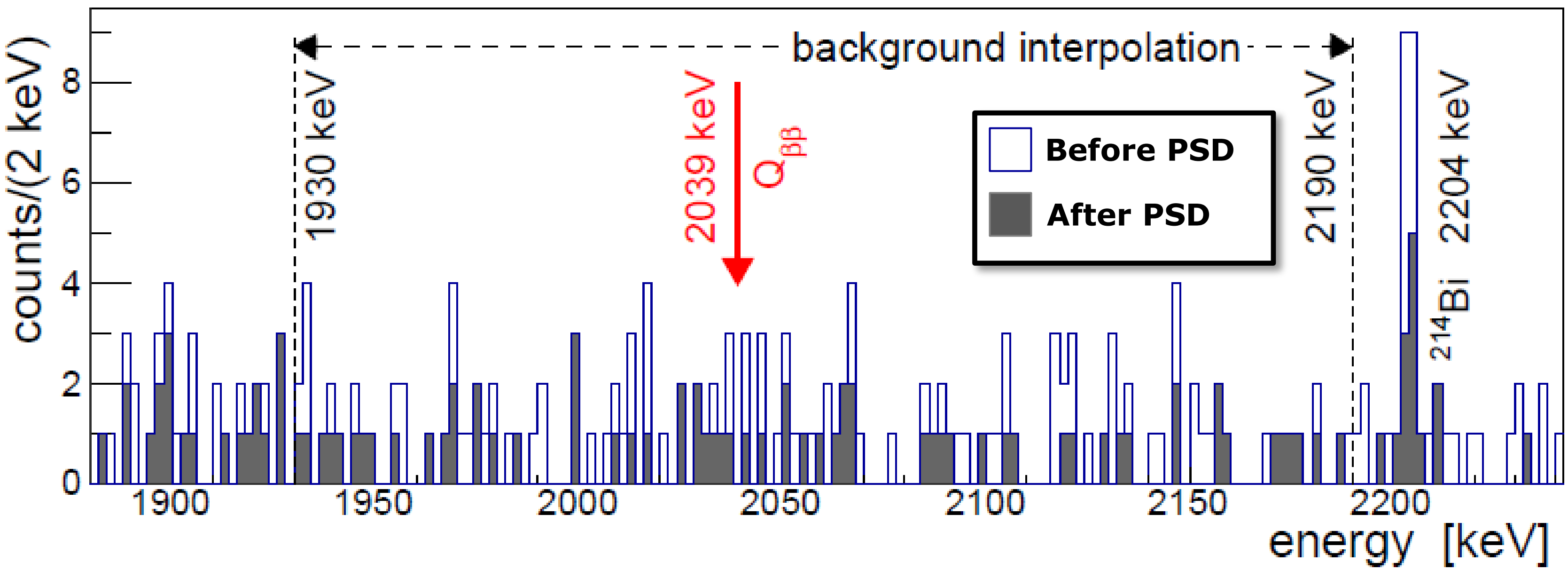
- **PSD using Artificial Neural Network**

  50 rise time info (1,3,5,…99%) as input neurons

- **Training with calibration data:**
  - **SSE Library:**
    DEP peak of ^{208}Tl 2615 keV
    gamma at 1593 keV
  - **MSE library:**
    FEP of ^{212}Bi at 1620 keV

- **BI at $Q_{\beta\beta}$:**
  - **Suppression factor:**
    ~ 45% of bkg. events
  - **Signal efficiency:**
    (90^{+5}_{-9}) %
  - **2νββ efficiency:**
    (85 ± 2) %

GERDA Phase I Results



Data Set	Exposure (kg·10yr)	BI 10^{-2} cts/(keV·kg·yr)		Expected Counts		Observed Counts	
		w/o PSD	w/ PSD	w/o PSD	w/ PSD	w/o PSD	w/ PSD
Gold	17.9	1.8	1.1	3.3	2.0	5	2
Silver	1.3	6.3	3.0	0.8	0.4	1	1
BEGe	2.4	4.2	0.5	1.0	0.1	1	0

↓ 5.1 ↓ 2.5 ↓ 7 ↓ 3

GERDA Phase I: Half-life Limits for 0νββ Decay

$$T_{1/2}^{0\nu\beta\beta} = \frac{(ln2)N_A}{m_{enr}N^{0\nu\beta\beta}}(M \cdot T)\epsilon$$

(background-free)

Bayes analysis:

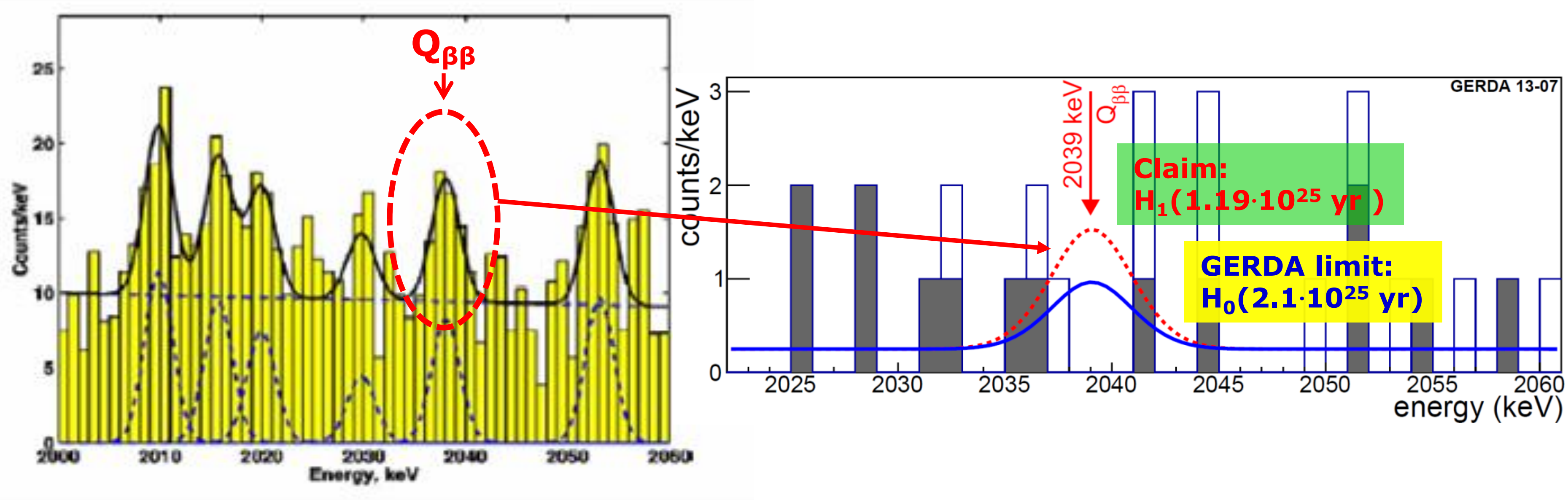
- Flat prior on $T_{1/2}^{0\nu\beta\beta}$ in 0-10^{24} yr
- Best fit $N^{0\nu\beta\beta}$ = 0 cts
- $N^{0\nu\beta\beta}$ < 4.0 cts (90% C.I.)
- $T_{1/2}^{0\nu\beta\beta}$ > 1.9·10^{25} yr (90%C.I.)
- Median sensitivity for no signal (MC):
  $T_{1/2}^{0\nu\beta\beta}$ > 2.0·10^{25} yr (90%C.I.)

Frequentist approach:

- Profile likelihood fit to 3 datasets with common $1/(T_{1/2}^{0\nu\beta\beta})$
- Best fit $N^{0\nu\beta\beta}$ = 0 cts
- $N^{0\nu\beta\beta}$ < 3.5 cts (90% C.L.)
- $T_{1/2}^{0\nu\beta\beta}$ > 2.1·10^{25} yr (90%C.L.)
- Median sensitivity for no signal (MC):
  $T_{1/2}^{0\nu\beta\beta}$ > 2.4·10^{25} yr (90%C.L.)
- Combined GERDA + IGEX + HdM:
  $T_{1/2}^{0\nu\beta\beta}$ > 3.0·10^{25} yr (90%C.L.)

➡ **Results have been published in:**
PRL 111, 122503 (2013)

Result compared with Previous Claim



- **Hypothesis test:**

Claimed signal
H_1 ($T_{1/2}^{0\nu\beta\beta}$=1.19·10^{25} yr + bkg)
expected signal cts: 5.9±1.4

v.s.

bkg. only
H_0 ($T_{1/2}^{0\nu\beta\beta}$=2.1·10^{25} yr)
expected bkg cts: 2.0±0.3
observed cts: 3

GERDA Only

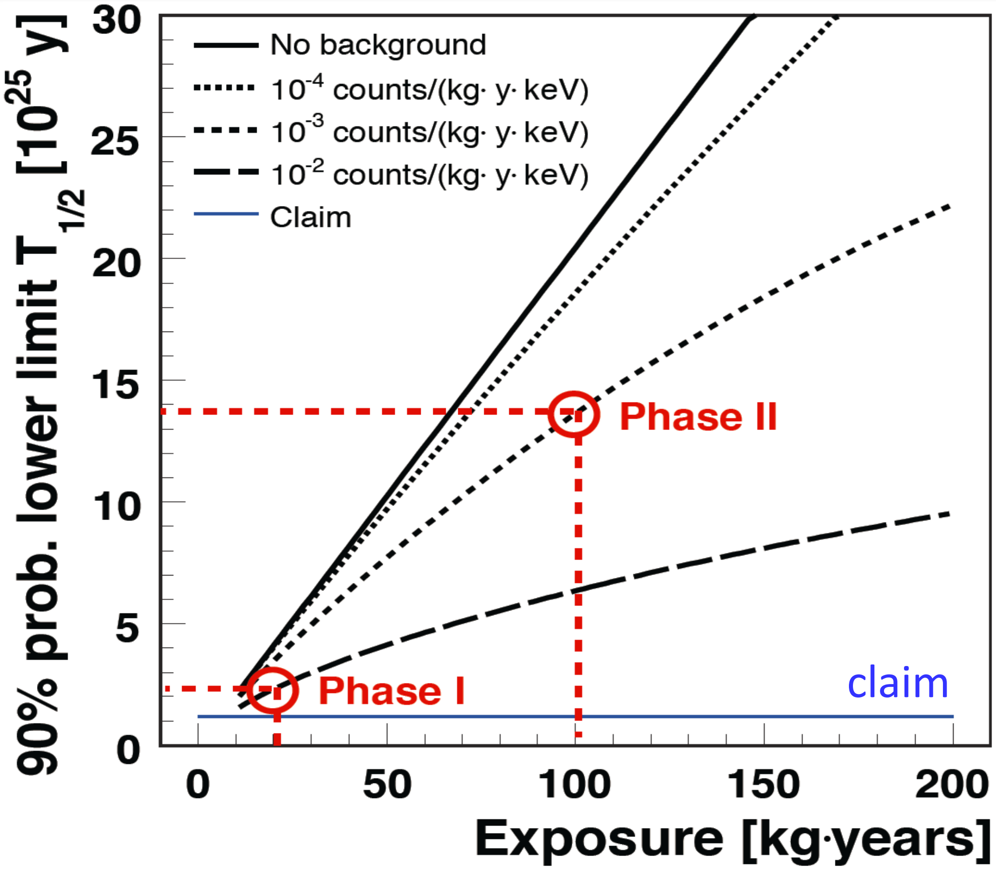
- **Frequentist p-value P($N^{0\nu\beta\beta}$ =0| H_1)=0.01**
- **Bayes factor P(H_1)/P(H_0) = 2.4·10^{-2}**

Combined GERDA + IGEX + HdM

- **Bayes factor P(H_1)/P(H_0) = 2.0·10^{-4}**

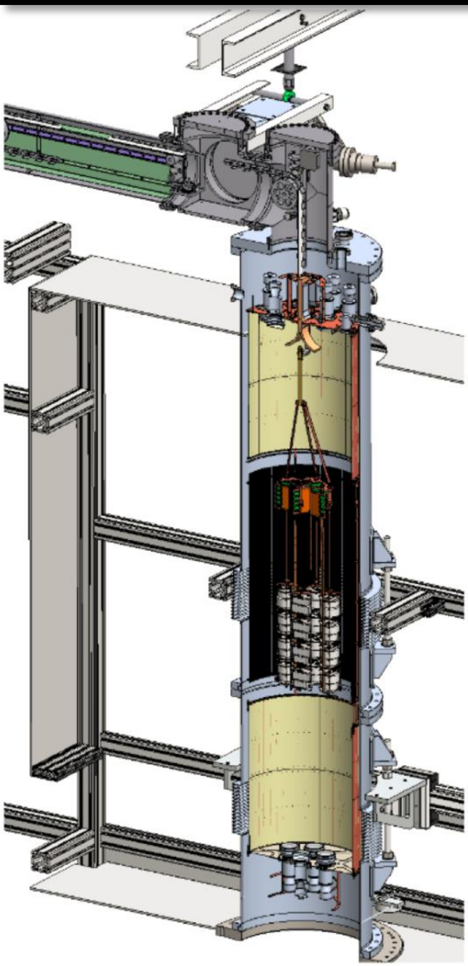
long standing claim disfavored!!

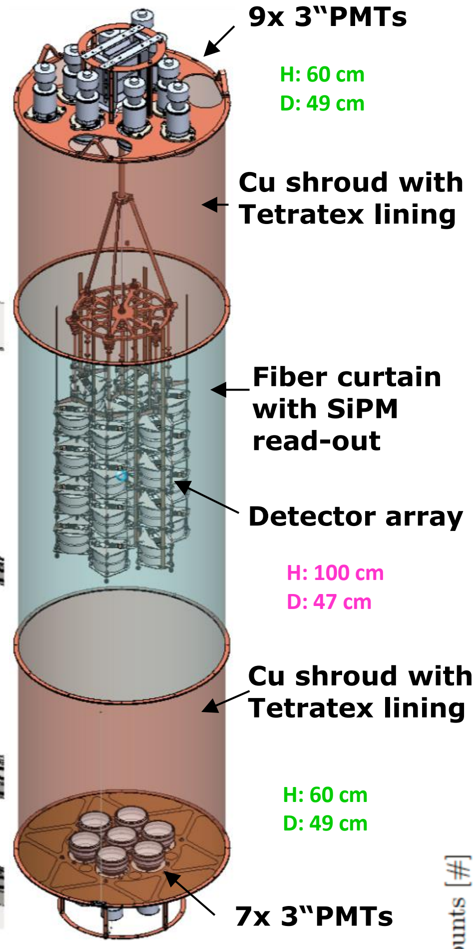
GERDA Phase-II Goal & Sensitivity



- **GERDA Phase-II:**
  - Improve limit on $T_{1/2}^{0\nu\beta\beta}$
  - Detector: **+20 kg** ^{enr}BEGe detectors
  - Design goal: **BI=10^{-3} Cts/(keV·kg·yr)**
    + **exposure: 100 kg·yr**
  - Expected sensitivity: **~$1.4\cdot10^{26}$ yr**

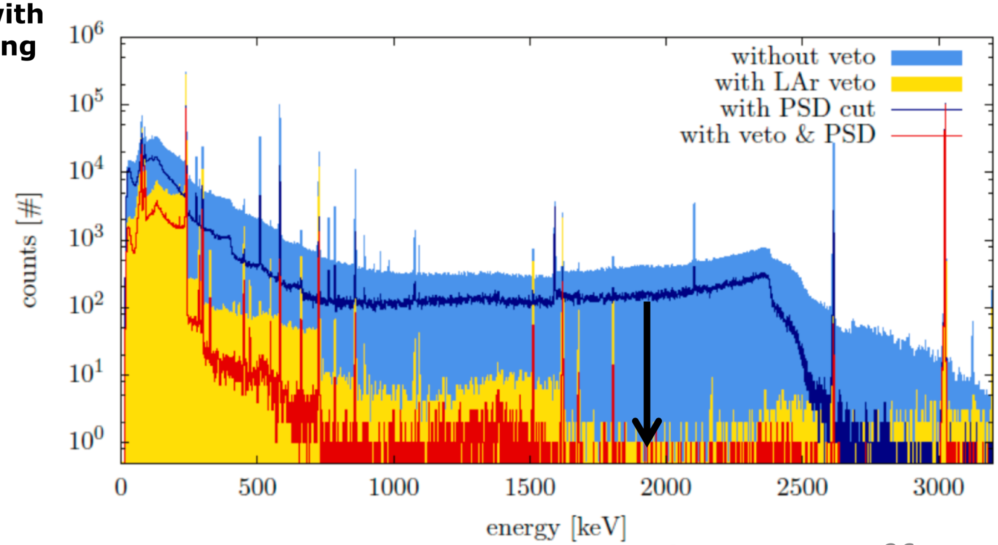
GERDA Phase-II Approach





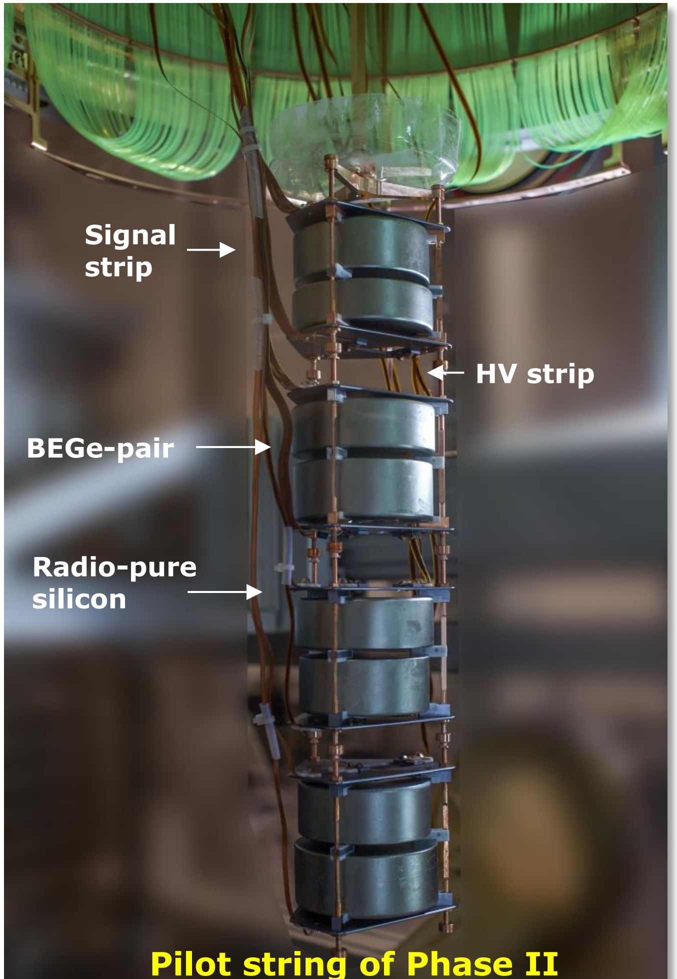
- **New lock system**
  - Size of array increased to 7 strings
  - LAr instrumentation surrounding the array
- **LAr scintillation light veto :**
  - PMT arrays on top and bottom
  - Si-PMTs coupled to wavelength-shifter fibers
  - LAr veto test in LArGe:

    A suppression factor of **>1000** @ $Q_{\beta\beta}$ after all cuts **for the ^{228}Th measurement**



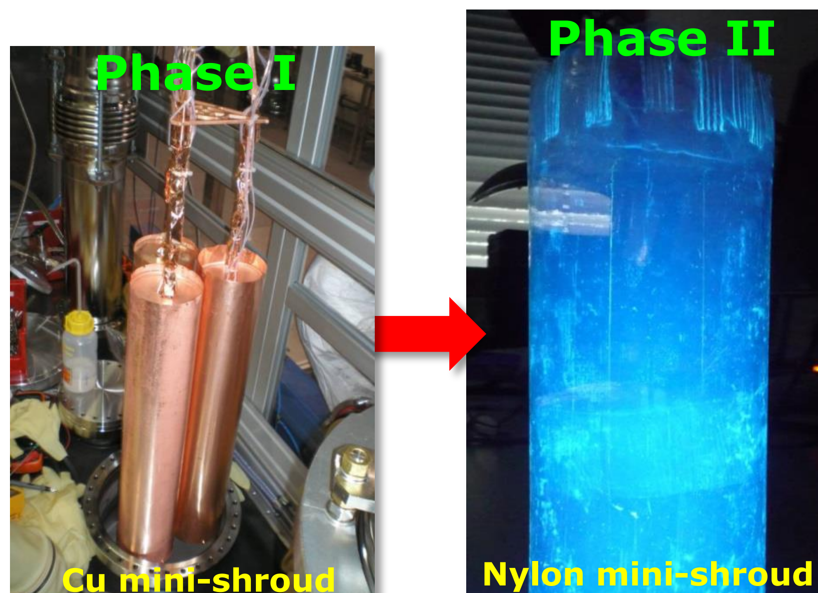
[arXiv: 1501.05762]

GERDA Phase-II Approach

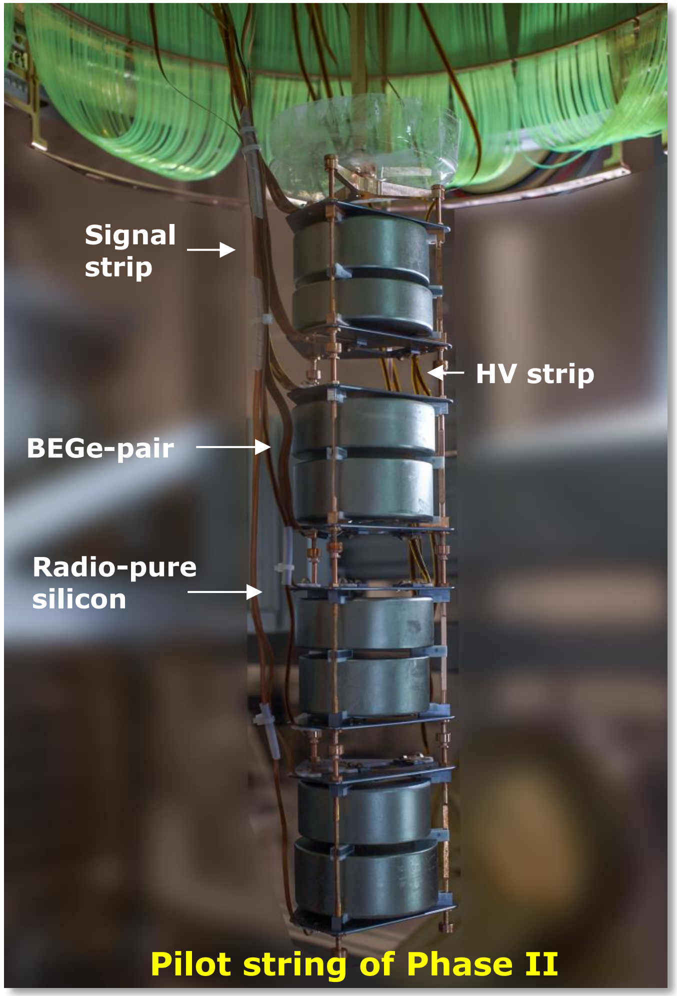


- **Reduction of bkg. sources close to detectors:**
  - Significant amount of copper and PTFE replaced by intrinsically radio-pure silicon
  - Reduce material for holders & use cleaner signal and HV cables
  - ^{42}K Background mitigation:
    Cu mini-shroud replaced by Nylon mini-shroud made from Borexino material

- **30 new Phase II BEGe detectors have been characterized & currently stored in LNGS**

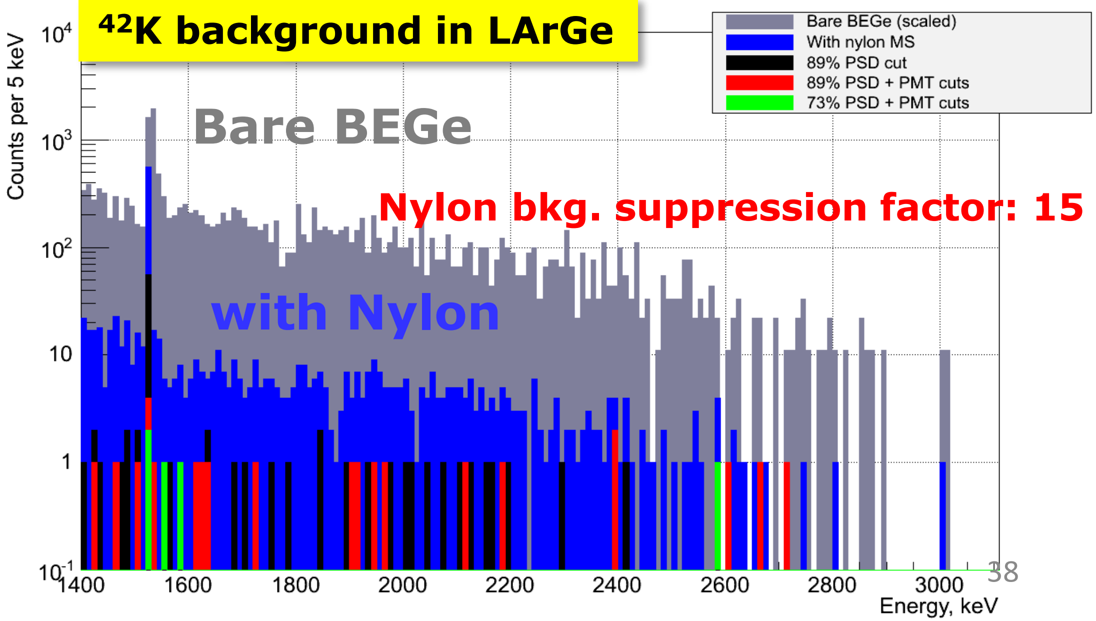


GERDA Phase-II Approach



- **Reduction of bkg. sources close to detectors:**
  - Significant amount of copper and PTFE replaced by intrinsically radio-pure silicon
  - Reduce material for holders & use cleaner signal and HV cables
  - ^{42}K Background mitigation: Cu mini-shroud replaced by Nylon mini-shroud made from Borexino material

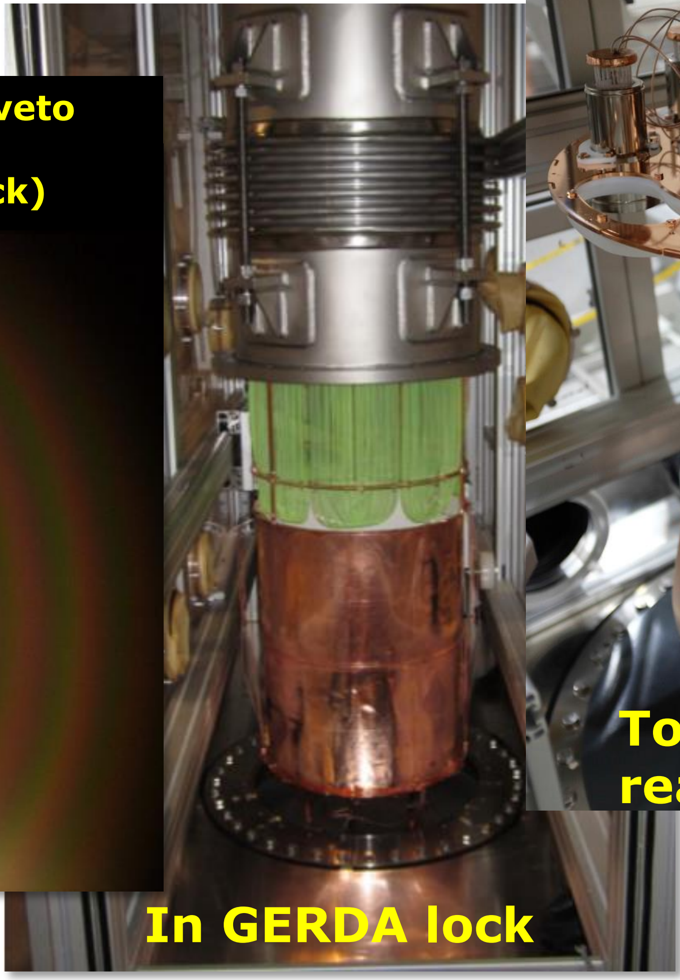
^{42}K background in LArGe

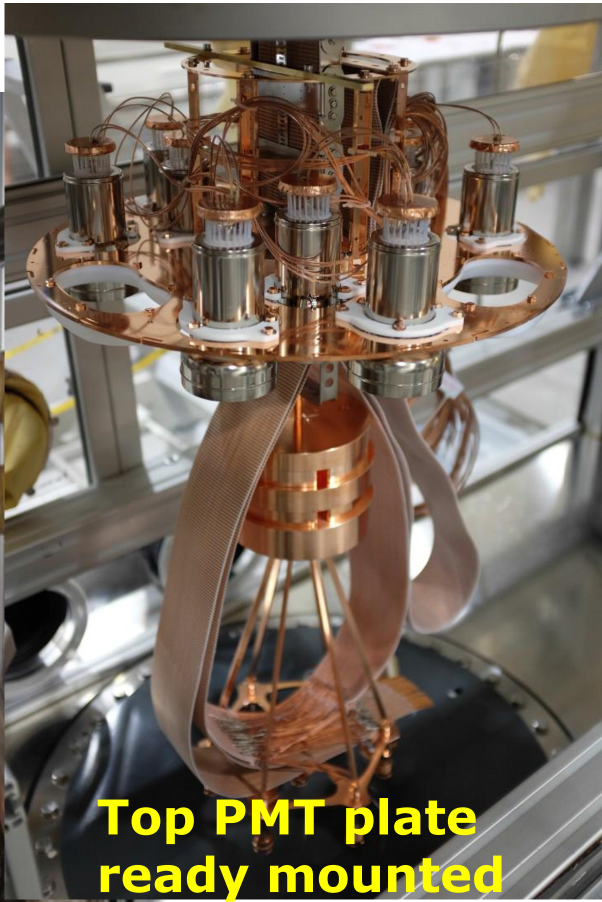


- **30 new Phase II BEGe detectors have been characterized & currently stored in LNGS**

LAr Light Instrumentation

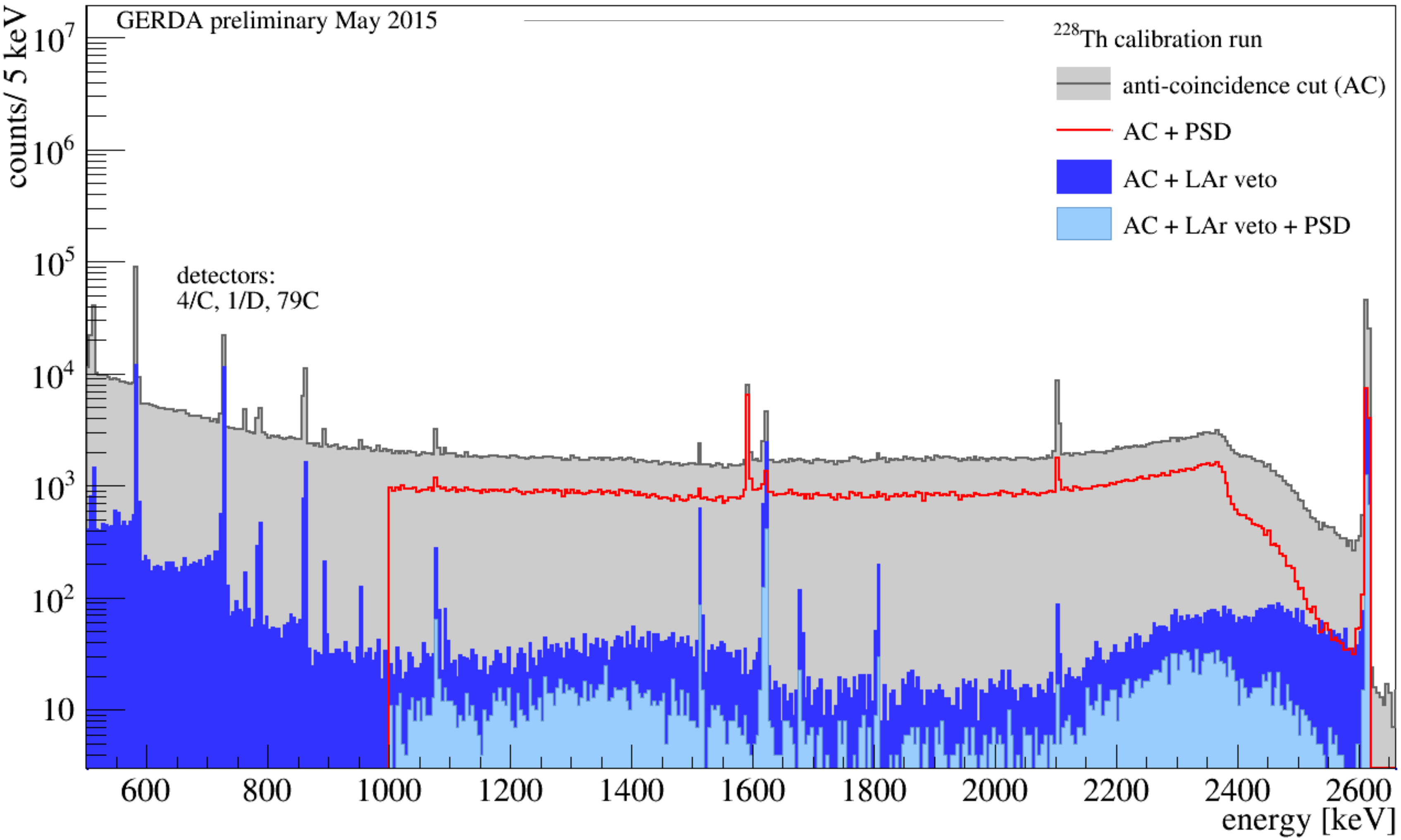
1st successful deployment of full LAr veto structure into GERDA cryostat (view from top through cryostat neck)





LAr light instrumentation was successfully installed in GERDA!

First Commissioning Tests



- **Spectrum taken in the Phase II commissioning run**
- **Suppression factor: >400 after all cuts @ $Q_{\beta\beta}$ measured by using ^{228}Th source**

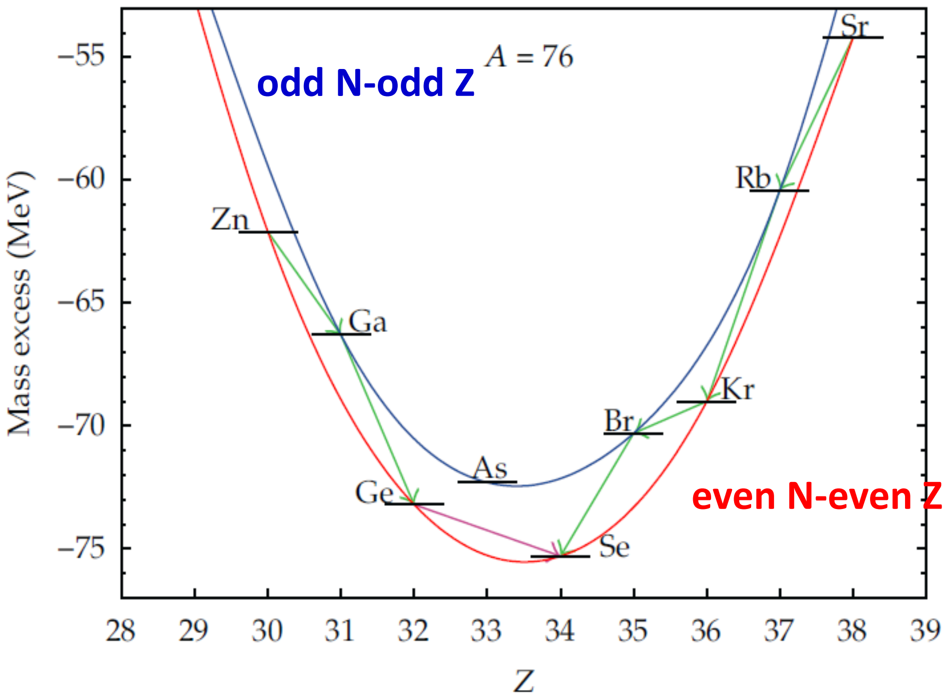
Summary & Outlook

- **GERDA Phase I design goals reached:**
  - Exposure of **21.6 kg·yr**
  - BI at $Q_{\beta\beta}$ after PSD : **~10^{-2} cts/(kg·keV·yr)**
  - **No observation for 0νββ signal**
    Long standing claim strongly disfavored
  - New limit on 0νββ half-life in Ge: $T_{1/2}^{0\nu\beta\beta}$ **>$2.1 \cdot 10^{25}$ yr (90% C.L.)**
  - GERDA+IGEX+HdM (Ge): $T_{1/2}^{0\nu\beta\beta}$ **>$3.0 \cdot 10^{25}$ yr (90% C.L.)**

- **Toward GERDA Phase II:**
  - New detectors available: **+20kg**, characterized → available
  - Major upgrade of infrastructure:
    lock system, calibration system, glove box → finished
  - Liquid Argon instrumentation → installed
  - First results of bkg. suppression by LAr veto are promising
  - Integration tests on going: new contacting, electronics
  - Background target **10^{-3} cts/(kg·keV·yr)**
  - Explore 0νββ half-life in the range of **10^{26} yr**

FREE BONUS!

^{76}Ge Double Beta Decay



- **Bethe-Weizaecker formula:**

***M* (*Z*, *A=const*.) ~a *Z* +b *Z* + δ_P**

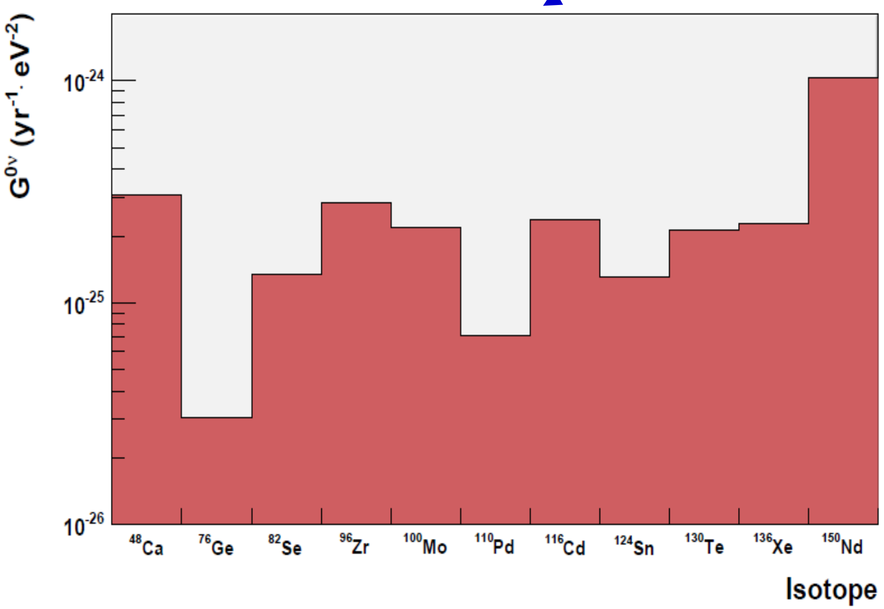
δ_{P}: pair energy term

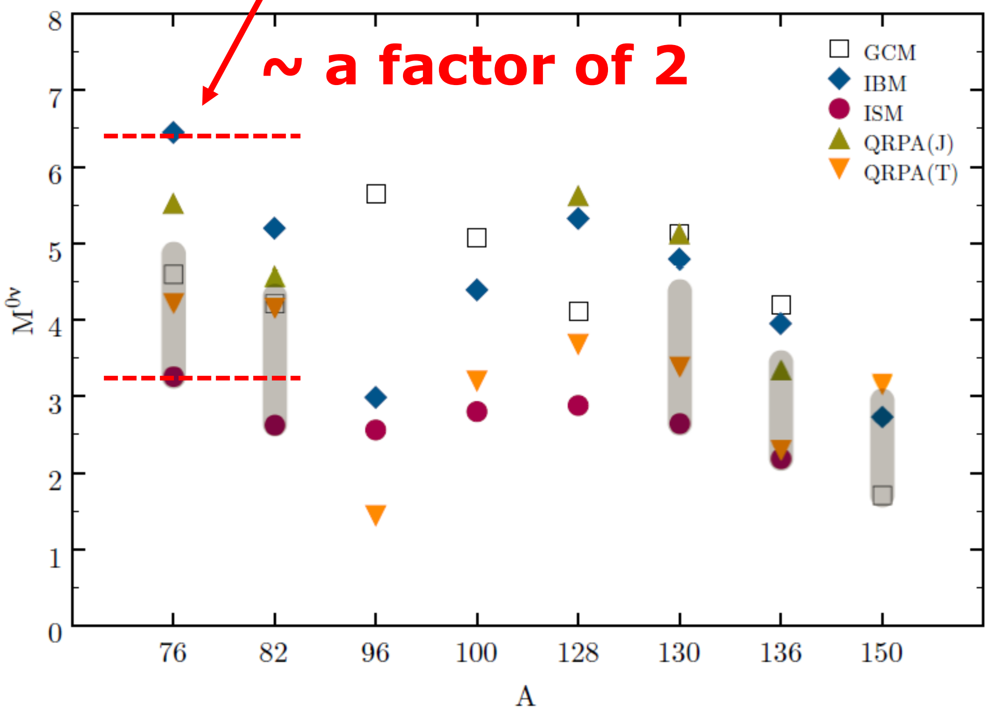
- **$\delta_P > 0$: odd/odd nuclei**
- **$\delta_P < 0$: *even/even nuclei***

The DBD exists due to nuclear pairing interaction that favors energetically the even-even isobars over the odd-odd ones.

Nuclear Matrix Element

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

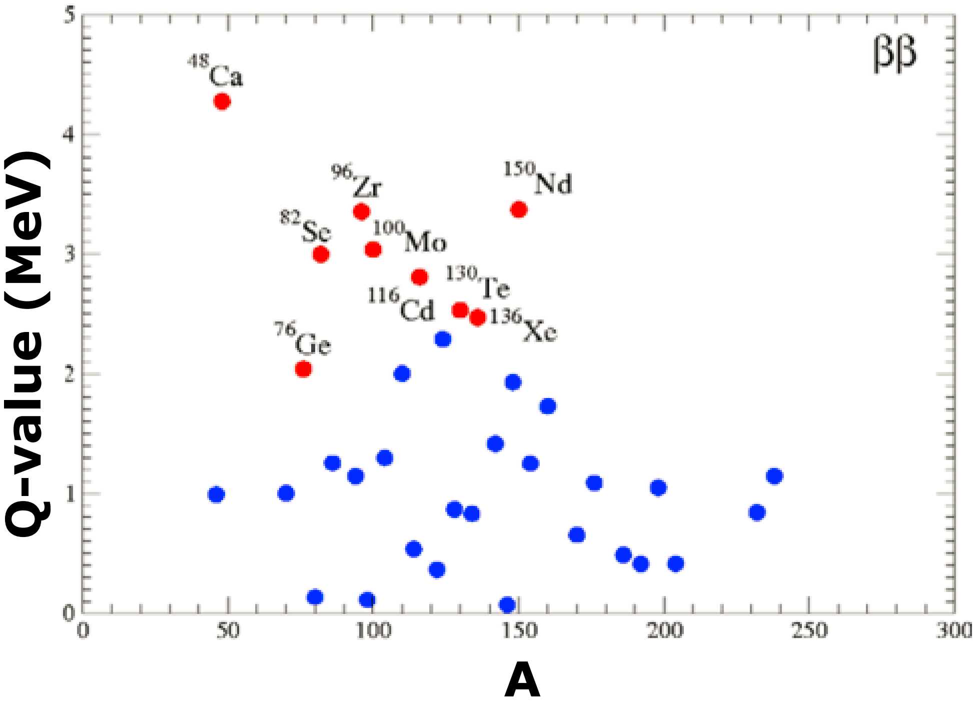




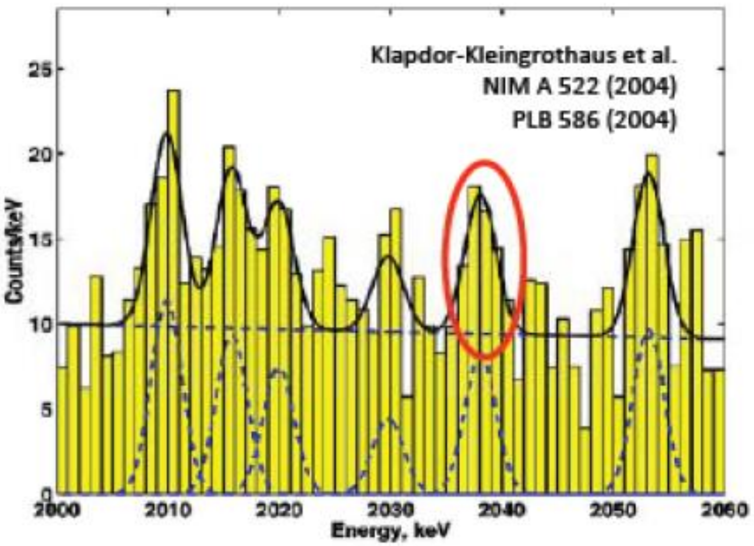
[arXiv: 1109.5515]

2νββ Isotopes

	Q(MeV)	Abund.(%)
$^{48}Ca \rightarrow ^{48}Ti$	4.271	0.187
$^{76}Ge \rightarrow ^{76}Se$	2.040	7.8
$^{82}Se \rightarrow ^{82}Kr$	2.995	9.2
$^{96}Zr \rightarrow ^{96}Mo$	3.350	2.8
$^{100}Mo \rightarrow ^{100}Ru$	3.034	9.6
$^{110}Pd \rightarrow ^{110}Cd$	2.013	11.8
$^{116}Cd \rightarrow ^{116}Sn$	2.802	7.5
$^{124}Sn \rightarrow ^{124}Te$	2.228	5.64
$^{130}Te \rightarrow ^{130}Xe$	2.533	34.5
$^{136}Xe \rightarrow ^{136}Ba$	2.479	8.9
$^{150}Nd \rightarrow ^{150}Sm$	3.367	5.6



Claim



Klapdor-Kleingrothaus et al., NIM A 522 (2004), PLB 586 (2004):

- 71.7 kg year - Bgd 0.17 / (kg yr keV)
- 28.75 ± 6.87 events (bgd:~60)
- Claim: 4.2σ evidence for $0\nu\beta\beta$
- reported $T_{1/2}^{0\nu} = 1.19 \times 10^{25}$ yr

N.B. Half-life $T_{1/2}^{0\nu} = 2.23 \times 10^{25}$ yr $T_{1/}$after PSD analysis (Mod. Phys. Lett. A 21, 1547 (2006).) is not considered because:

- reported half-life can be reconstructed only (Ref. 1) with $\varepsilon_{psd} = 1$ (previous similar analysis $\varepsilon_{psd} \approx 0.6$)
- $\varepsilon_{fep} = 1$ (also in NIM A 522, PLB 586 (2004) (GERDA value for same detectors: $\varepsilon_{fep} = 0.9$)

Ref: B. Schwingenheuer in Ann. Phys. 525, 269 (2013)

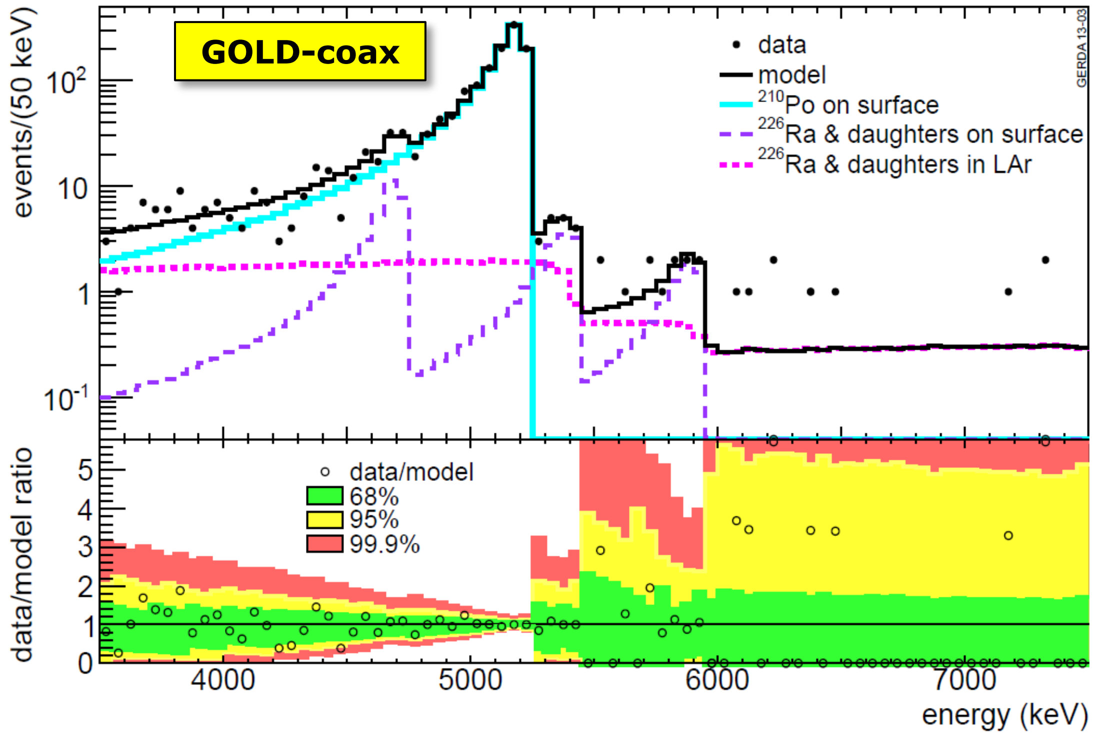
0νββ experiments

The name of the game ↓

Exp.	Mass [kg]	f_A	Bkg. $[\frac{10^{-3}\text{cnts}}{\text{keV}\cdot\text{kg}\cdot\text{yr}}]$	ΔE [keV]	Eff.	Enrich.	$f_A \cdot \epsilon \cdot \eta \cdot \sqrt{\frac{M}{B \cdot \Delta E}}$	$T^{0\nu}_{1/2}$ 10^{25} yr	$m_{\beta\beta}$ meV
Past experiments									
Hd–Moscow	11	0.35	120	7	1	0.86	1	1.9	170–530
Cuoricino	41	1	170	16	0.9	0.28	1	0.4	210–500
NEMO-3	6.9	2.1	1.2	400	0.06	0.9	0.3	0.1	310–900
Running experiments									
EXO-200	100	0.55	1.5	100	0.55	0.81	6	4.2	75–170
Kaml.-Zen	12800	0.55	0.05	250	0.31	0.023	4	2.6	90–220
Kaml.-Zen2	12800	0.55	0.01	250	0.31	0.06	22	15	40–90
GERDA-I	15	0.35	20	8	0.8	0.86	2	3.9	120–370
GERDA-II	35	0.35	1	6	0.85	0.88	20	18	60–170
Experiments under construction									
Major.-Dem.	30	0.35	1	6	0.9	0.9	20	17	60–170
CUORE	750	1	10	12	0.9	0.27	19	7.5	50–110
SNO+	780000	1.5	0.0002	230	0.33	5.6E-5	3	0.8	100–240
NEXT	100	0.55	0.8	25	0.25	0.9	9	5.2	70–160
Proposed experiments									
S.NEMO	100	1.1	0.1	200	0.2	0.9	14	6.9	55–140
Lucifer	100	1.1	1	10	0.9	0.5	50	19	33–85

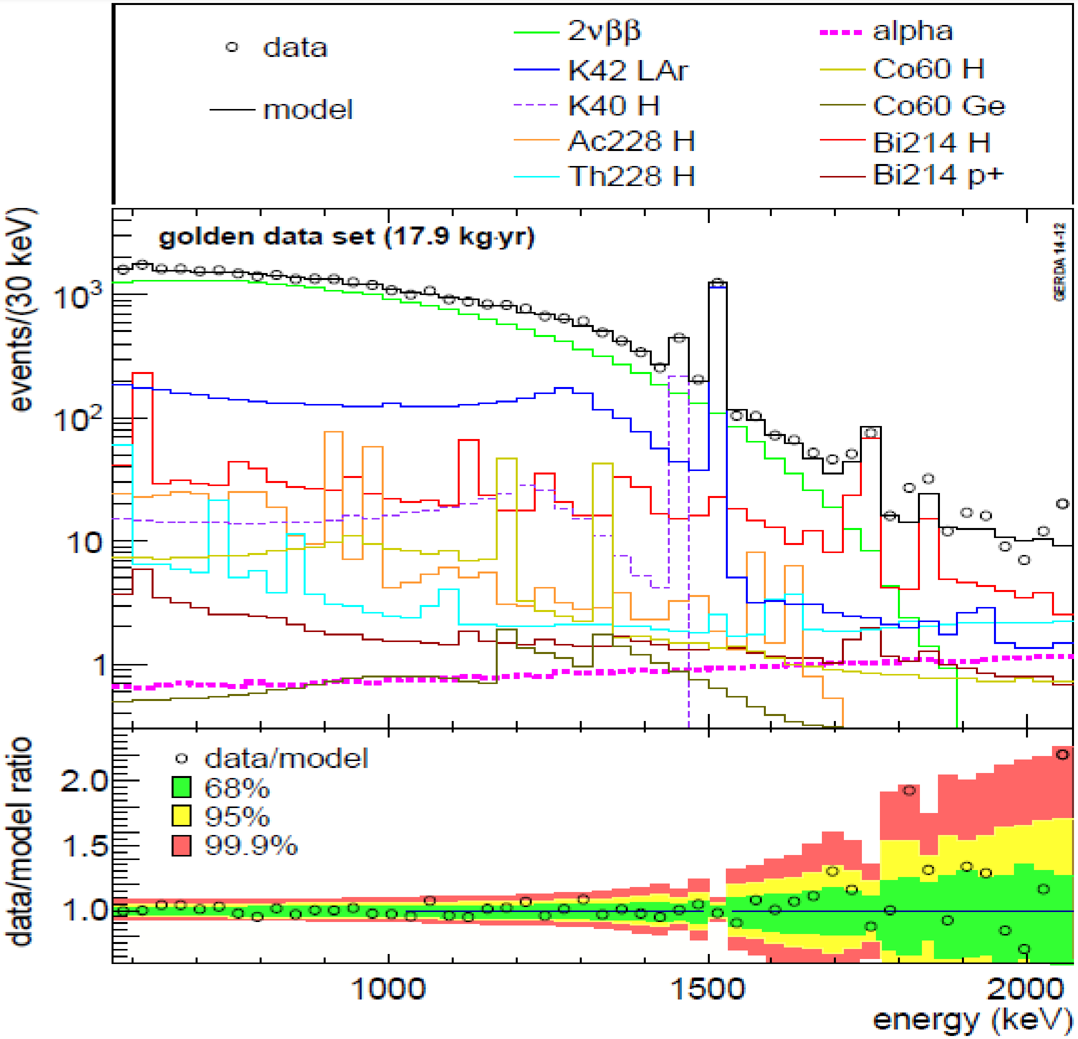
Ref: **Bernhard Schwingenheuer, Ann. Phys. (Berlin) 525, No. 4, 269–280 (2013)**

Background Decomposition & Model



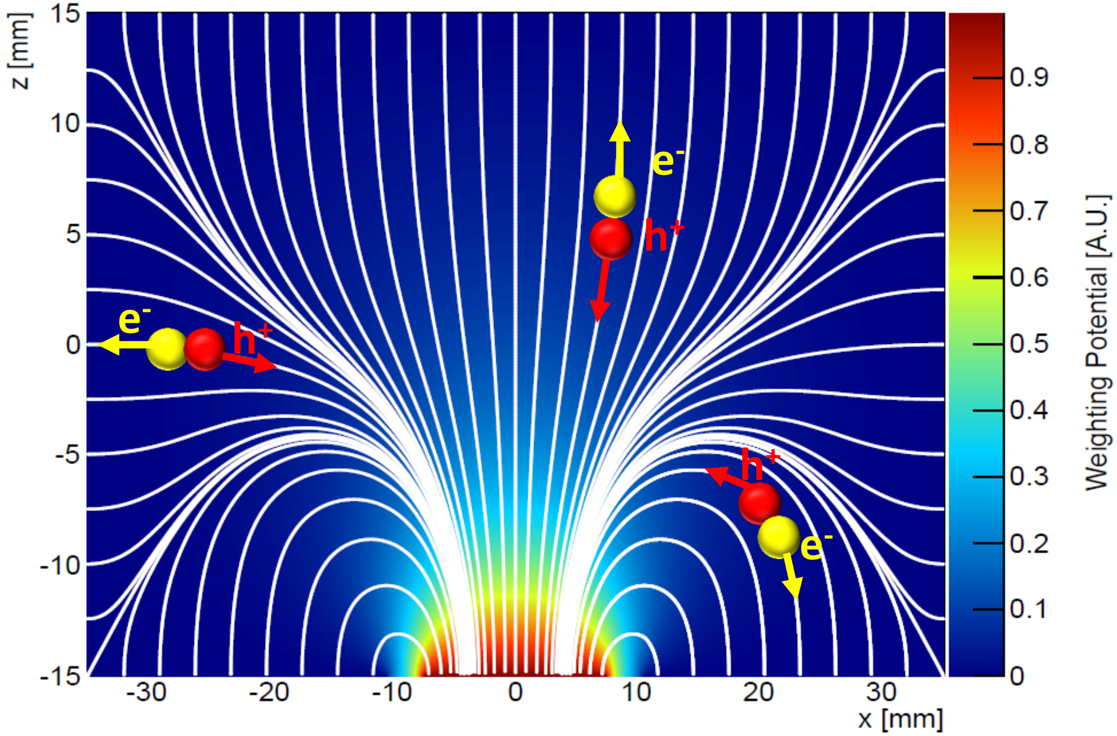
- **Background Models:**
  - **Minimum model: Use min. amount of sources to describe measured spectrum**
  - **Maximum model: Add more plausible sources (knowledge from screening measurements, activation history, etc.)**

2νββ Half-life



- **Updated 2νββ results:**
  - $T_{1/2}^{2\nu\beta\beta}$=(1.93±0.01)·10^{21} yr [arXiv: 1501.02345, submitted to EPJC]

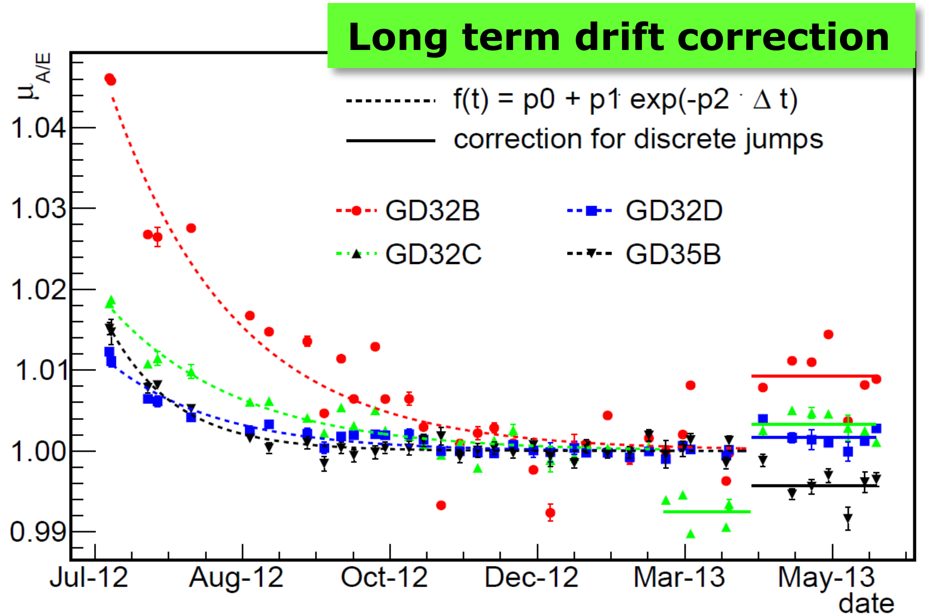
BEGe Pulse Shape Properties

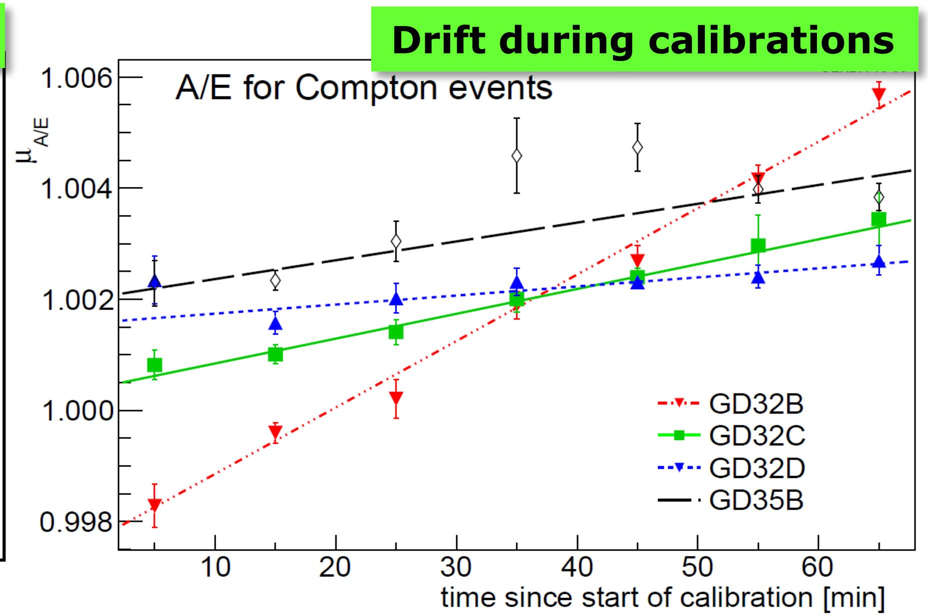


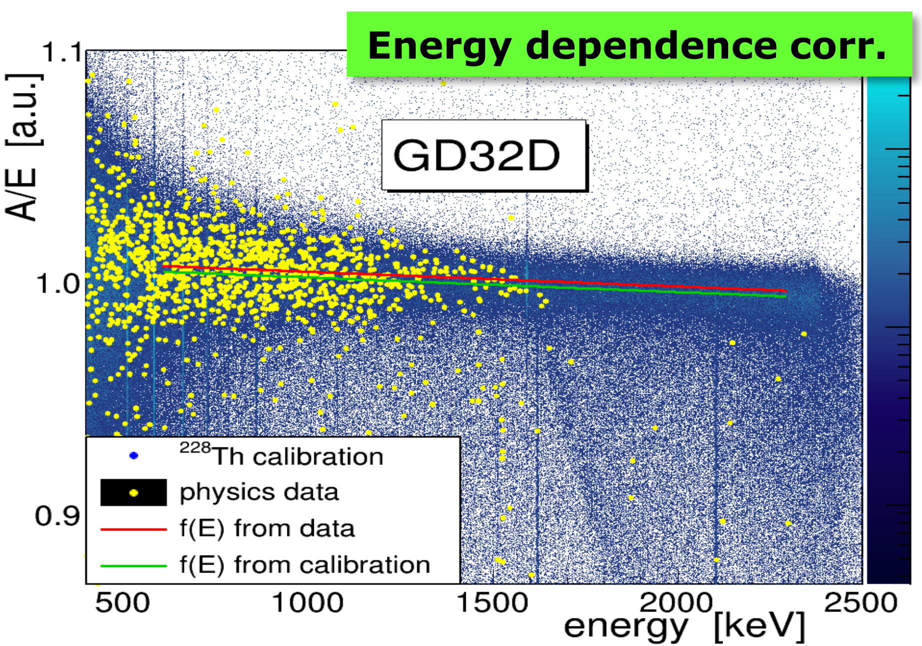
- **Properties of E-field of BEGe:**
  - **Well pronounced weighting field near the read out electrode:**

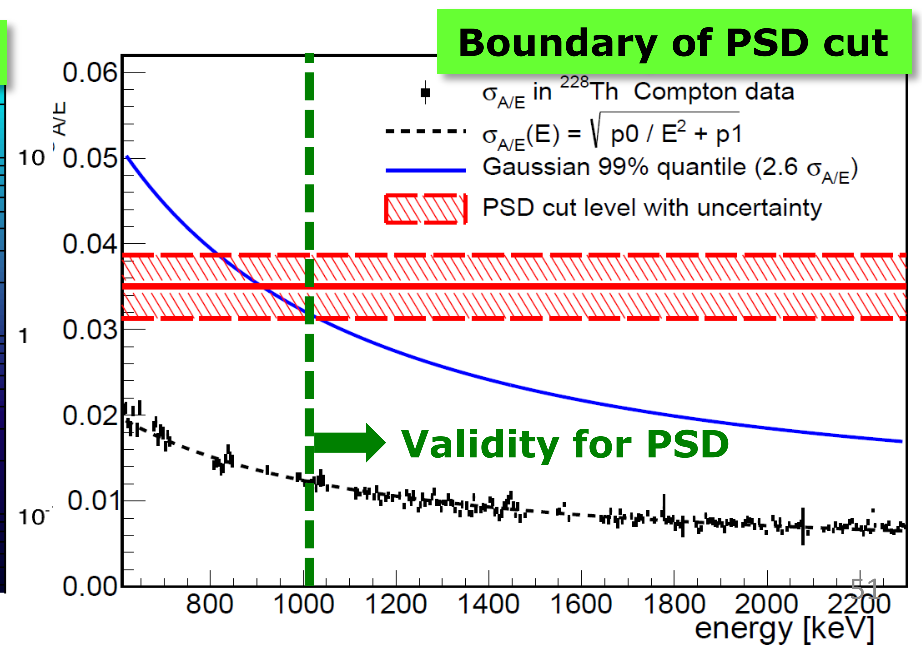
    ⇨ **Uniform waveform at the end for SSE indept. of where the individual energy depositions happen**

A/E PSD Normalization









GERDA Phase I: Half-life Limits for 0νββ Decay

$$T_{1/2}^{0\nu\beta\beta} = \frac{(ln2)N_A}{m_{enr}N^{0\nu\beta\beta}}(M \cdot T)\epsilon$$

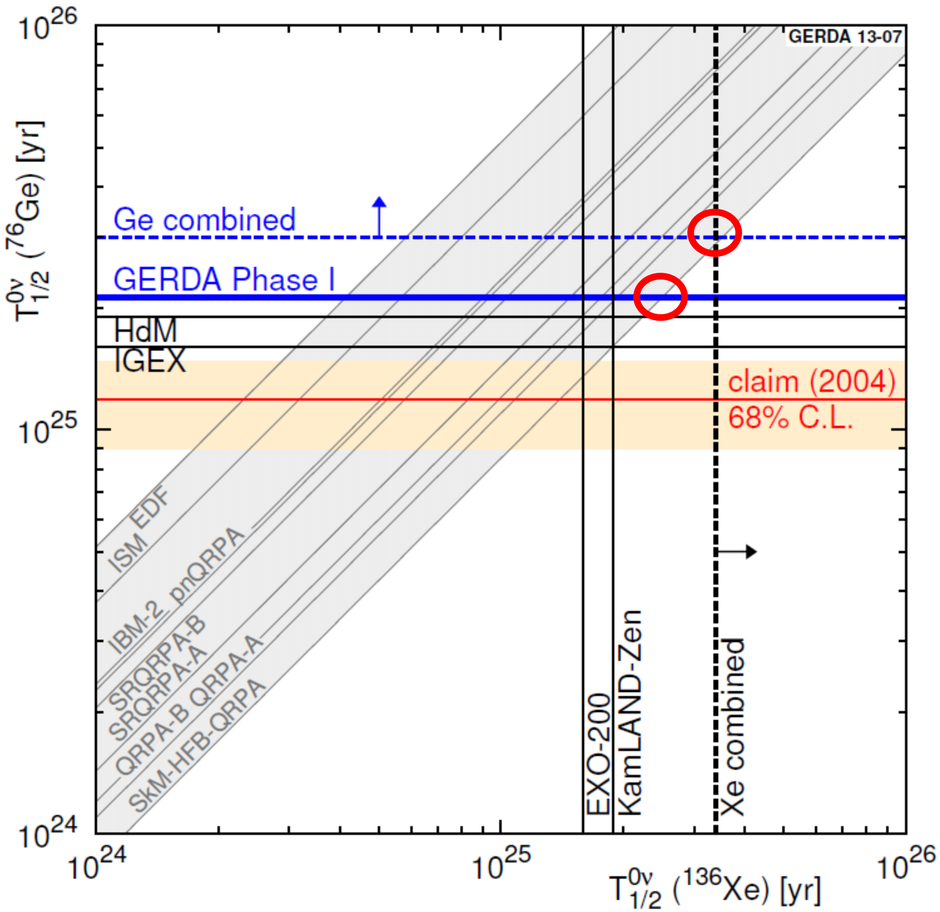
(background-free)

$$\epsilon = f_{76} f_{av} \varepsilon_{FEP} \varepsilon_{PSD}$$

N_A: Avogadro's const.
$M \cdot T$: Exposure (detector mass × live time)
m_{enr} : Molar mass of the enriched material
$N^{0\nu\beta\beta}$: Number of 0νββ signal
f_{76}: ^{76}Ge atoms fraction
f_{av}: Active volume fraction
ε_{FEP}: efficiency for total energy deposited in active volume
ε_{PSD} : Signal acceptance efficiency after PSD cut

Data Set	f_{76}	f_{av}	ε_{FEP}	ε_{PSD}
Gold	0.86	0.87	0.92	0.90
Silver	0.86	0.87	0.92	0.90
BEGe	0.88	0.92	0.90	0.92

Comparison with ^{136}Xe Experiments

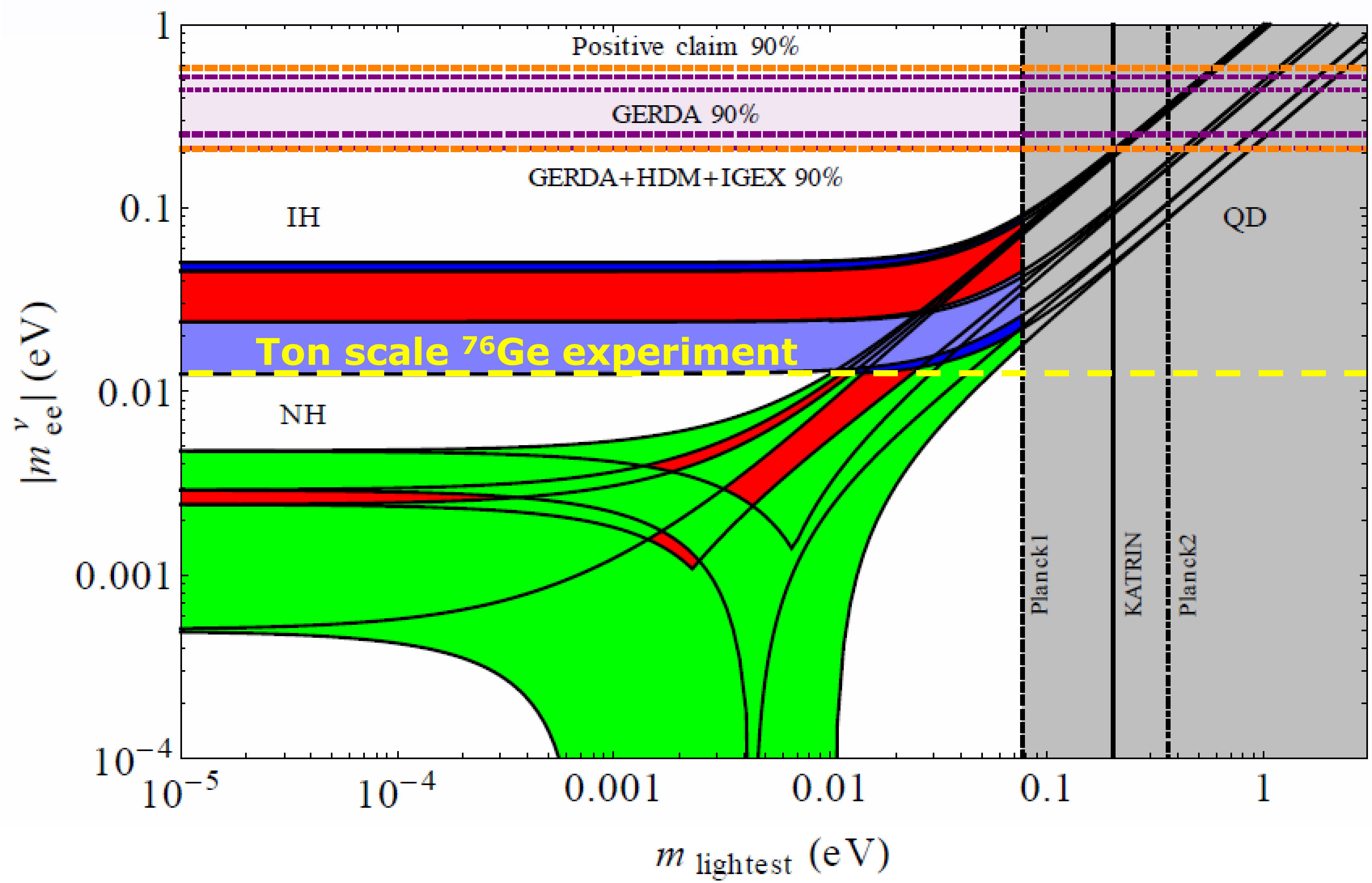


Ge combined limit:
$\langle m_{0\nu\beta\beta} \rangle < 0.2 - 0.4$ eV
[PRL 111, 122503 (2013)]

- **GERDA provides model-indept. test of the signal claim**
- **Comparison with ^{136}Xe experiments:**
  - **Assuming leading mechanism is exchange of light Majorana ν**
  - **Model dependent matrix element computations**
  - **The most conservative exclusion using smallest NME ratio:**
    $M_{0\nu}(^{136}Xe)/M_{0\nu}(^{76}Ge) \approx 0.4$
    [PRD 88, 091301 (2013)]

Experiment	Isotope	P(H1)/P(H0)
GERDA	^{76}Ge	0.024
GERDA+ HdM+IGEX	^{76}Ge	0.0002
KamLAND-Zen	^{136}Xe	0.40
EXO-200	^{136}Xe	0.23
GERDA+KLZ +EXO	^{76}Ge + ^{136}Xe	0.002

Disentangle IH/NH



Potential Backgrounds

- **Backgrounds NOT considered for the BKG model:**
  - ✓ **BI from n & μ:** ~10^{-5}, 10^{-4} cts/keV·kg·yr
  - ✓ **^{76}Ge:**

Physical process	Signature
Neutron capture	E_γ= 470, 861, 4008, 4192 keV
^{206}Pb (excited by inelastic n scattering)	E_γ= 898, 1705, 3062 keV
^{56}Co ($T_{1/2}$=77 d)	E_γ= 1771, 2598, 3253 keV

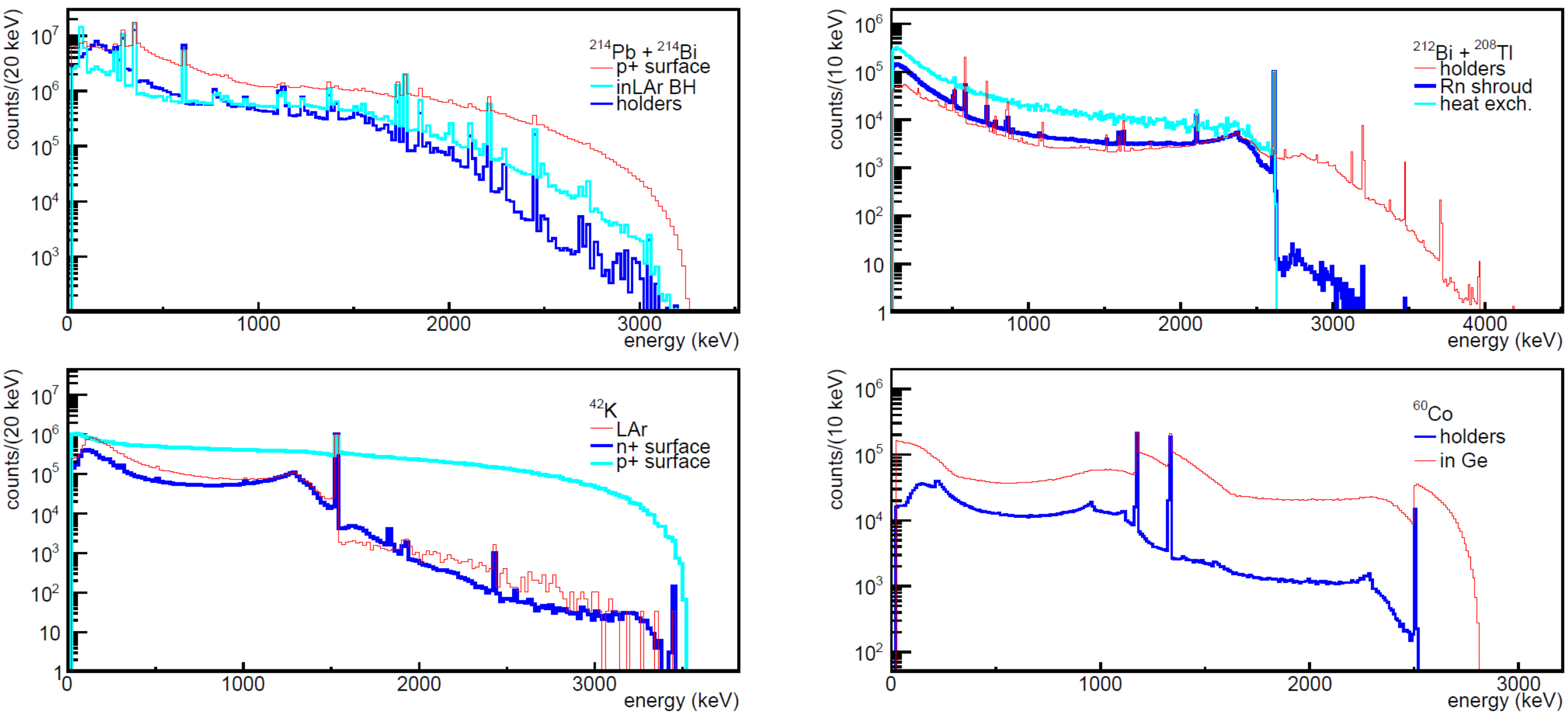
  - ✓ **BI from cryostat & water tank:** < 10^{-4} cts/keV·kg·yr
  - ✓ **^{39}Ar beta decay(<600 keV):**

    To avoid uncertainties due to n+ DL thickness & theoretical shape of beta decay spectrum

Background Model: MC Lists

source	location	simulation	events simulated
^{210}Po	p^+ surface	single det., $d_{dl_{p^+}}$	10^9
^{226}Ra chain	p^+ surface	single det., $d_{dl_{p^+}}$	10^9
^{222}Rn chain	LAr in bore hole	single det., $d_{dl_{p^+}}$	10^9
^{214}Bi and	n^+ surface	single det.	10^8
^{214}Pb	mini-shroud	array	10^9
	detector assembly	array	10^8
	p^+ surface	single det.	10^6
	radon shroud	array	10^9
	LAr close to p^+ surface	single det.	10^6
^{208}Tl and	detector assembly	array	10^8
^{212}Bi	radon shroud	array	10^9
	heat exchanger	array	10^{10}
^{228}Ac	detector assembly	array	10^8
	radon shroud	array	10^9
^{42}K	homogeneous in LAr	array	10^9
	n^+ surface	single det.	10^8
	p^+ surface	single det.	10^6
^{60}Co	detectors	array	$2.2 \cdot 10^7$
	detector assembly	array	10^7
$2\nu\beta\beta$	detectors	array	$2.2 \cdot 10^7$
^{40}K	detector assembly	array	10^8

MC spectra for different bkg contributions at different source locations



→ **Perform fit of binned distributions.**
Posterior probability given by Bayes

$$P(\boldsymbol{\lambda}|\mathbf{n}) = \frac{P(\mathbf{n}|\boldsymbol{\lambda})P_0(\boldsymbol{\lambda})}{\int P(\mathbf{n}|\boldsymbol{\lambda})P_0(\boldsymbol{\lambda})d\boldsymbol{\lambda}}$$

Prior probability of the parameters

with

$$P(\mathbf{n}|\boldsymbol{\lambda}) = \prod_i P(n_i|\lambda_i) = \prod_i \frac{e^{-\lambda_i}\lambda_i^{n_i}}{n_i!}$$

Likelihood of the parameters

Observed **Expected** **Number of events**

$$\lambda_i = \sum_M \lambda_{i,M} \qquad \lambda_{i,M} = N_M \int_{\Delta E_i} f_M(E)dE$$

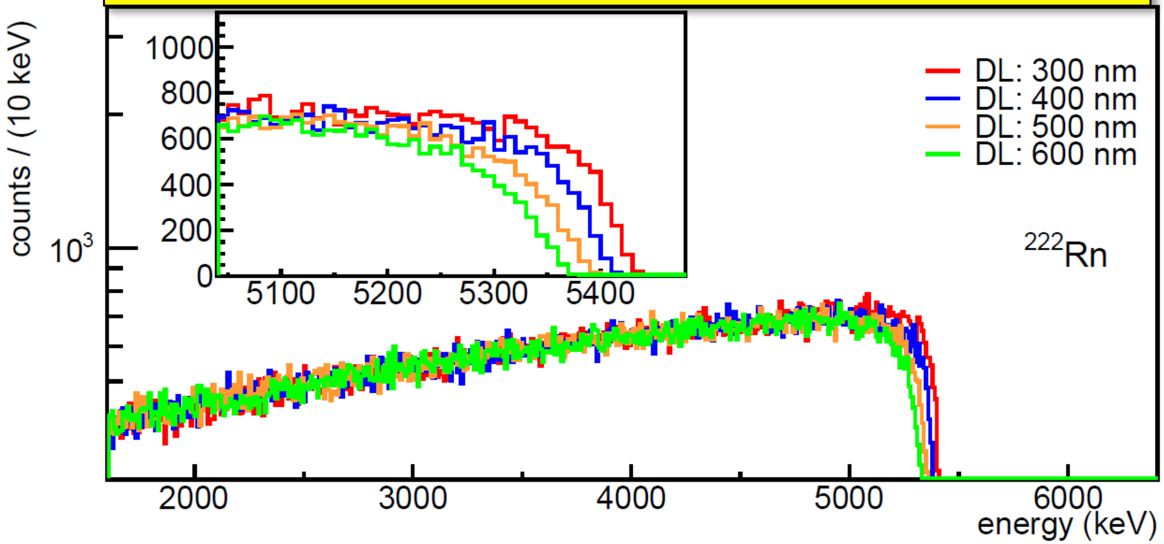
Expected Number of events in i-th bin

Sum over all components M

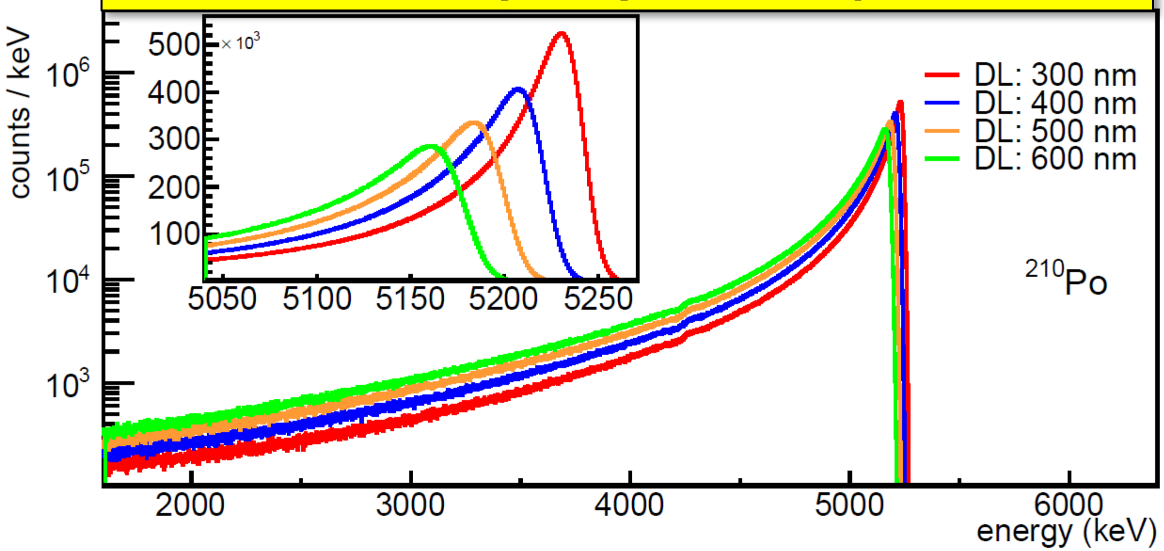
Normalized spectrum from component M

Alpha spectrum for different DLs

α-contribution (^{222}Rn) in LAr close to p+ surface

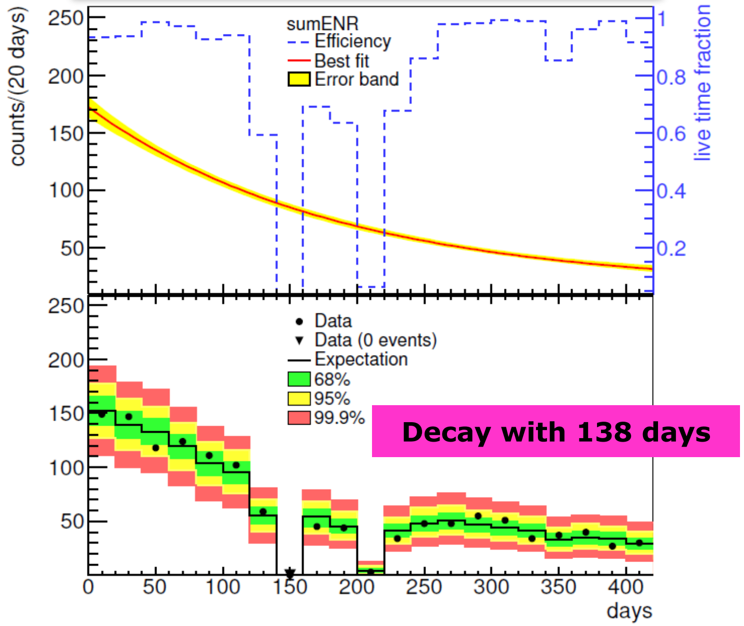


α-contribution (^{210}Po) in LAr on p+ surface

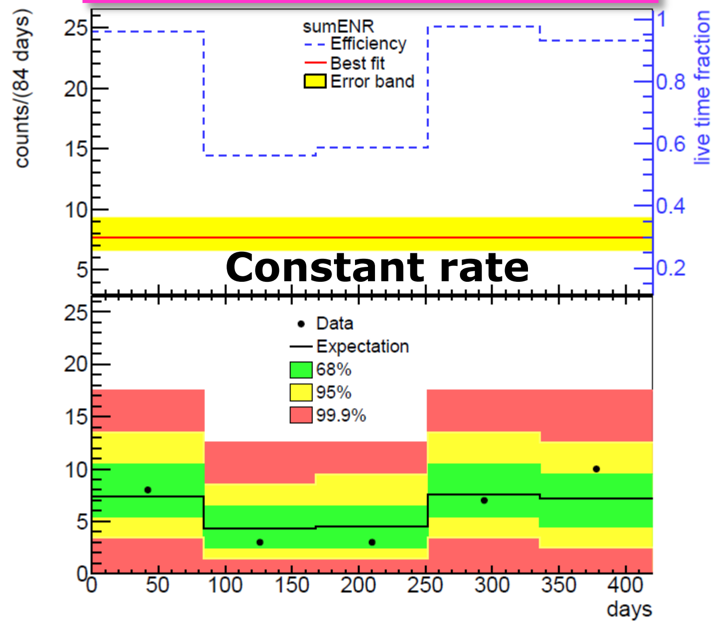


Time Distribution of Alpha Events

3.5 MeV < E < 5.3 MeV



E > 5.3 MeV



- ^{210}Po contamination of the surface of some of the detectors
- Alphas are mainly from ^{210}Po, confirmed by the time distribution

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)

Background Index

	GOLD-coax	*GOLD-nat*	*SUM-bege*
	BI in central region around $Q_{\beta\beta}$ (10 keV for coaxial, 8 keV for BEGe) 10^{-3} cts/(kg keV yr)		
interpolation	17.5 [15.1,20.1]	30.4 [23.7,38.4]	36.1 [26.4,49.3]
minimum	18.5 [17.6,19.3]	29.6 [27.1,32.7]	38.1 [37.5,38.7]
maximum	21.9 [20.7,23.8]	37.1 [32.2,39.2]	
	background counts in the previously blinded energy region		
	30 keV	40 keV	32 keV
data	13	5	2
minimum	8.6 [8.2,9.1]	3.5 [3.2,3.8]	2.2 [2.1,2.2]
maximum	10.3 [9.7,11.1]	4.2 [3.8,4.6]	