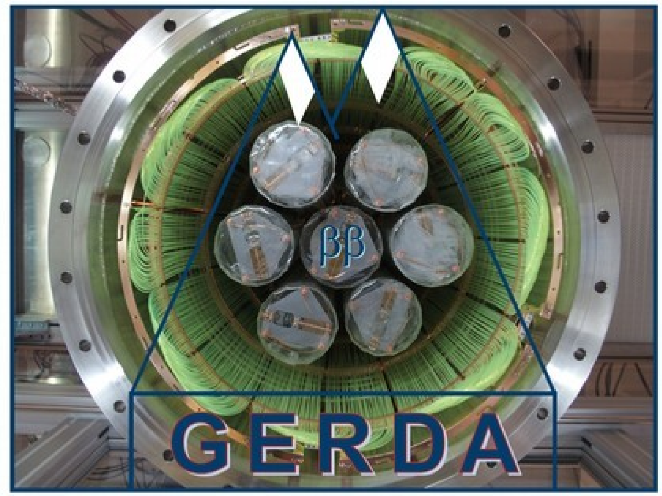
Search for 0νββ Decay: New Results from GERDA Phase II



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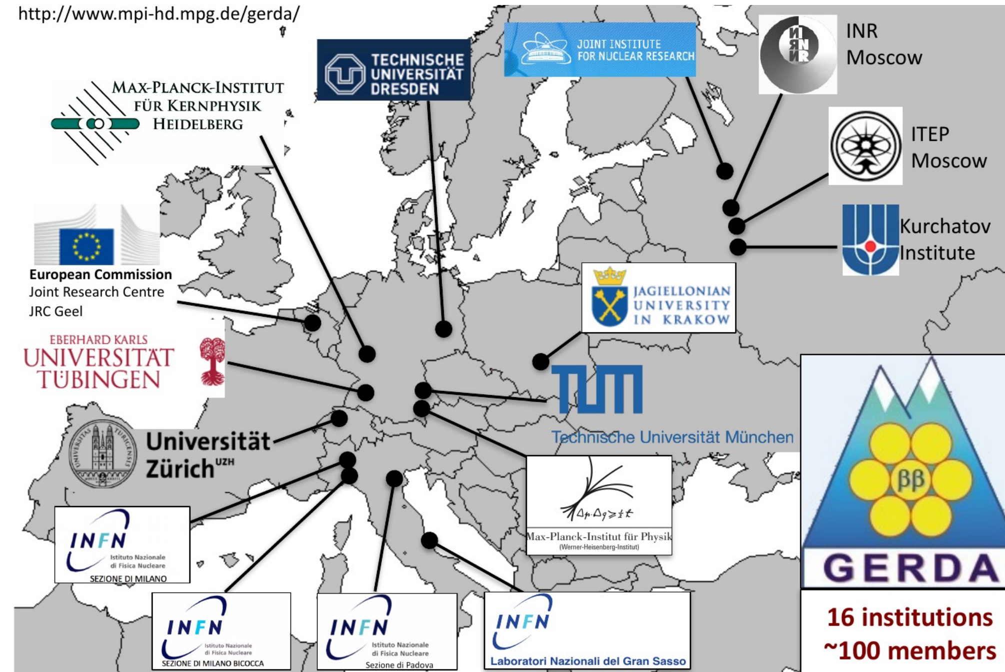
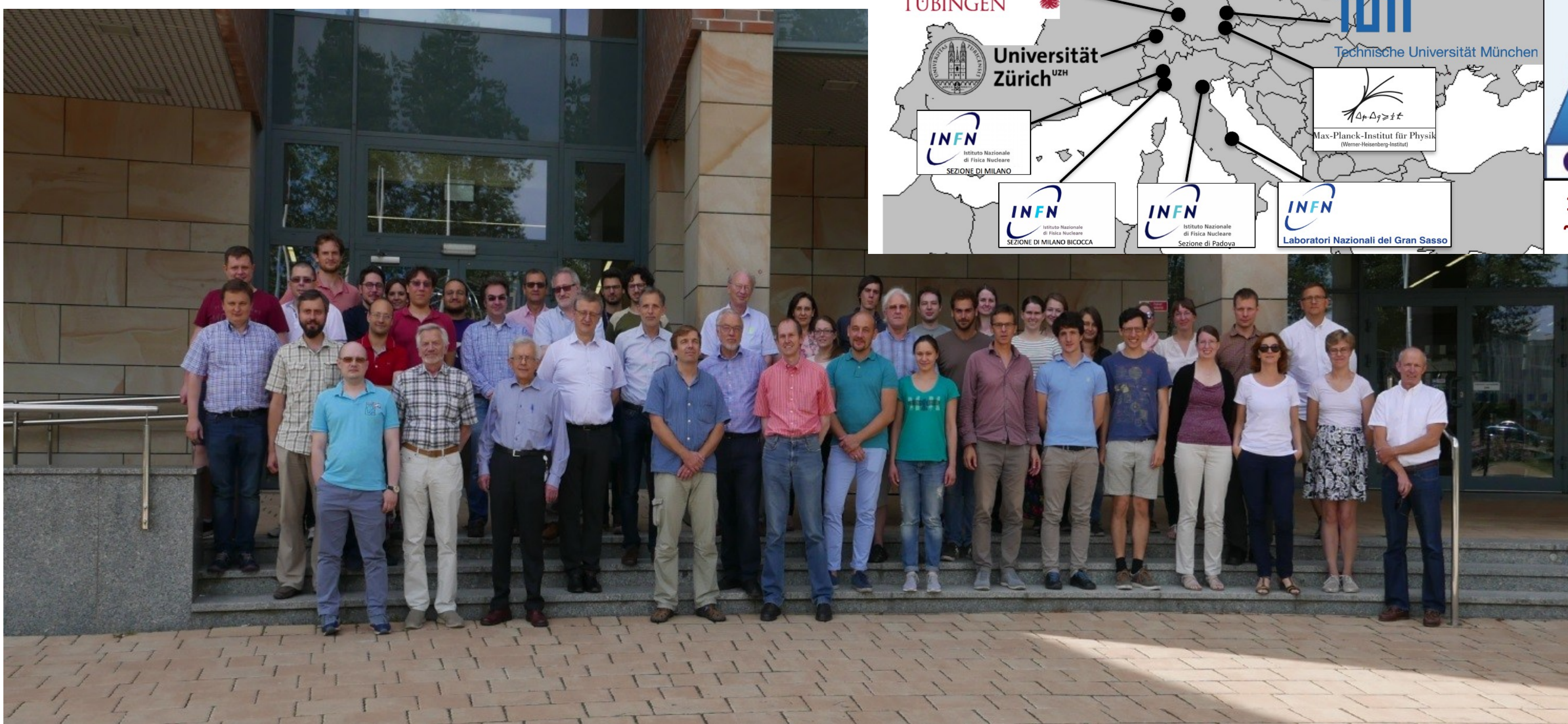
cea
DE LA RECHERCHE À L'INDUSTRIE
Irfu - CEA Saclay
Institut de recherche sur les lois fondamentales de l'Univers

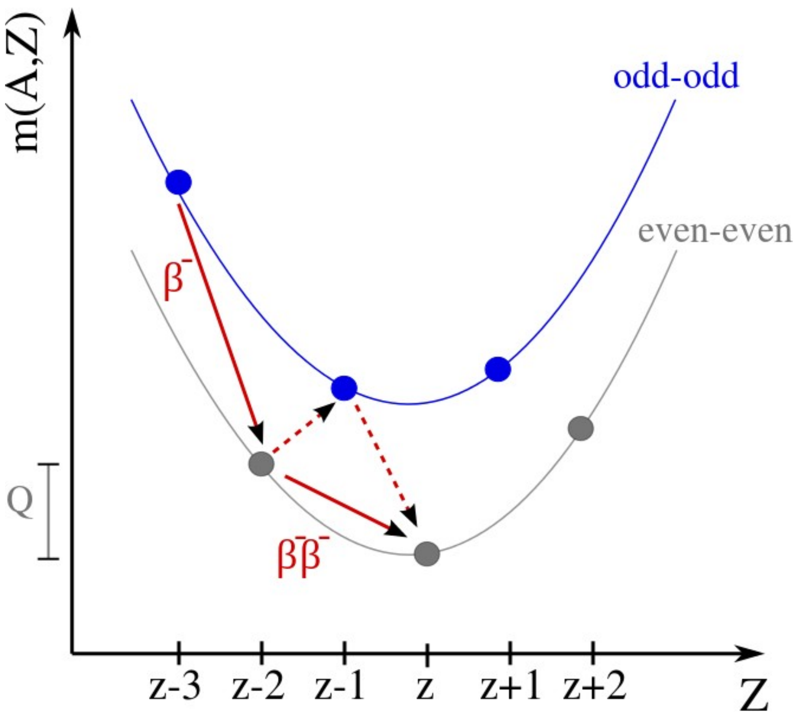
Laboratoire APC, Paris,
October, 23 2017

The GERDA Collaboration: searching for 0νββ decay of ^{76}Ge





Double Beta Decay



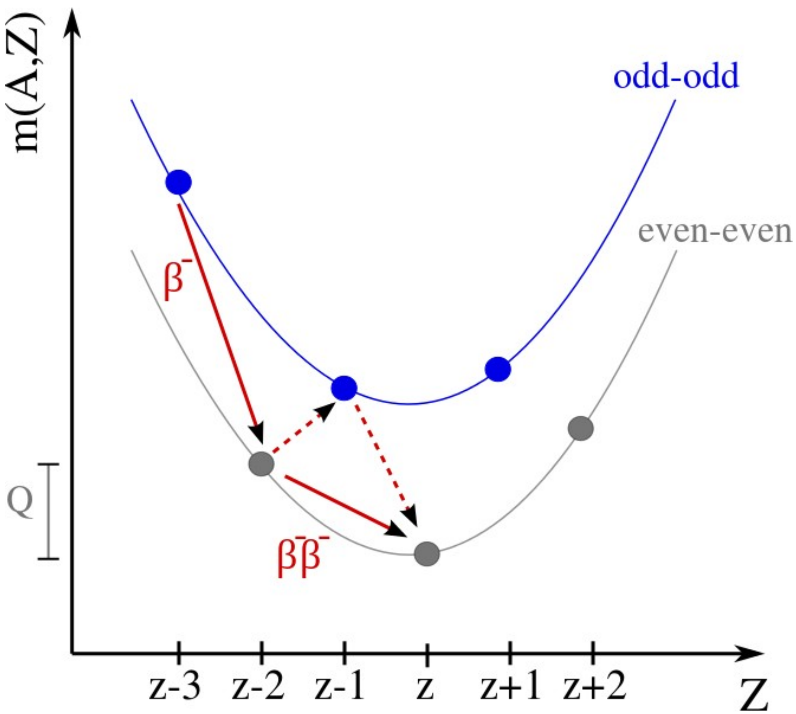
Double beta decay (2νββ)

- single β decay energetically forbidden
- (A,Z) → (A,Z+2) + 2e⁻ + 2ν̄
- e.g. ^{76}Ge, ^{136}Xe, ^{130}Te, ^{116}Cd
- half-life of 2νββ decay of ^{76}Ge measured by GERDA (most recent and precise measurement):

$$T_{1/2}^{2\nu} = (1.926 \pm 0.095) \cdot 10^{21}\ \text{yr}$$

arXiv:1501.02345v1

Double Beta Decay



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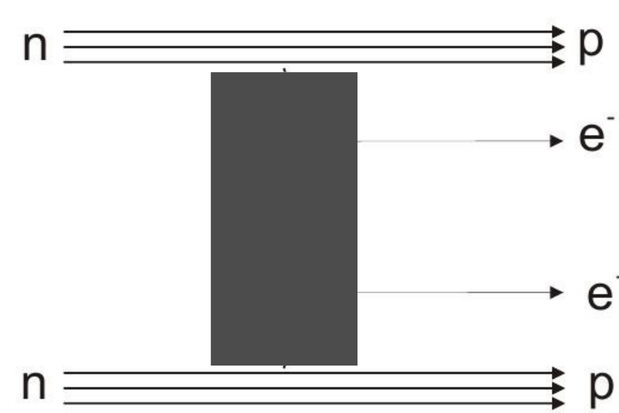
Neutrinoless double beta decay (0νββ)

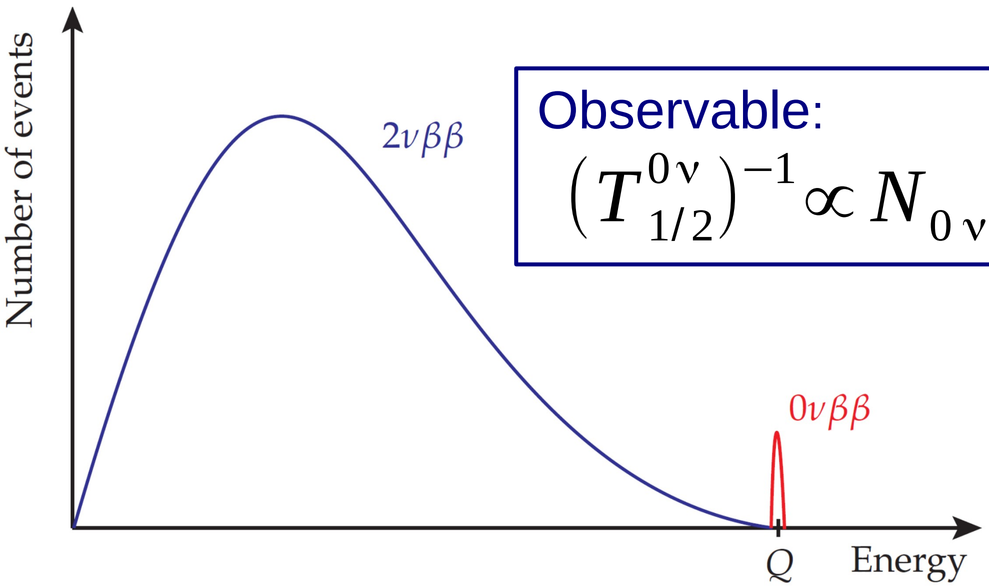
- (A,Z) → (A,Z+2) + 2e$^-$
- lepton number violated by **ΔL = 2**

  → **physics beyond SM**
- proof of Majorana mass component of neutrinos



0νββ Observable

- Measure sum energy of electrons

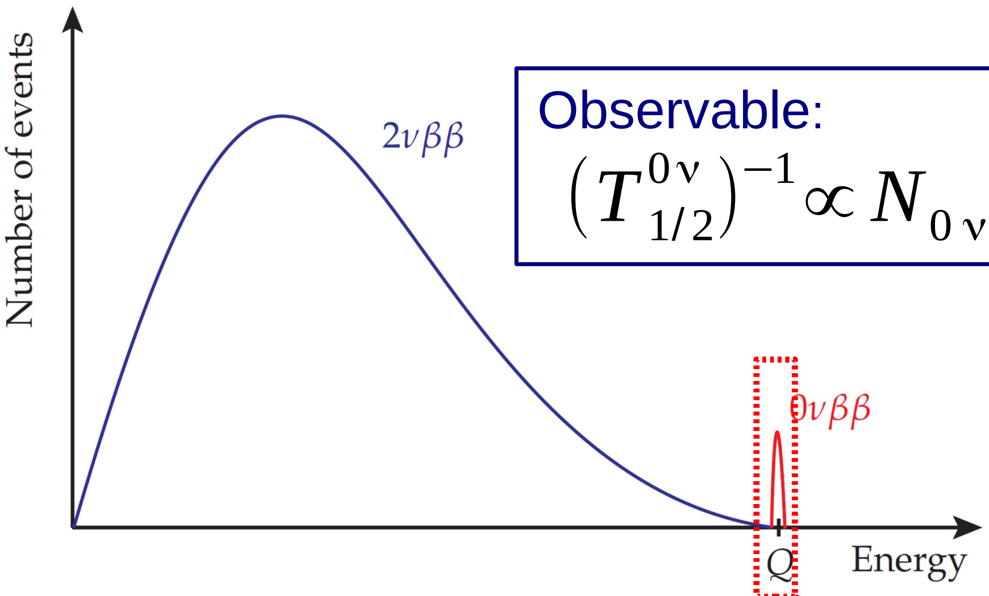


Observable:

$$\left(T^{0\nu}_{1/2}\right)^{-1} \propto N_{0\nu}$$

0νββ Observable

Measure sum energy of electrons



Observable:

$$\left(T_{1/2}^{0\nu}\right)^{-1} \propto N_{0\nu}$$

- zero background regime

$$T_{1/2}^{0\nu} \propto M \cdot t$$

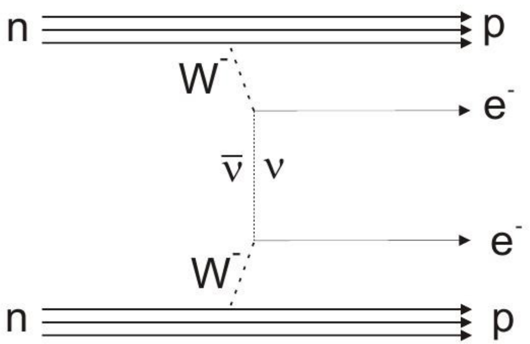
- background, i.e. statistical fluctuation limited scenario

$$T_{1/2}^{0\nu} \propto \sqrt{\frac{M \cdot t}{\Delta E \cdot BI}}$$

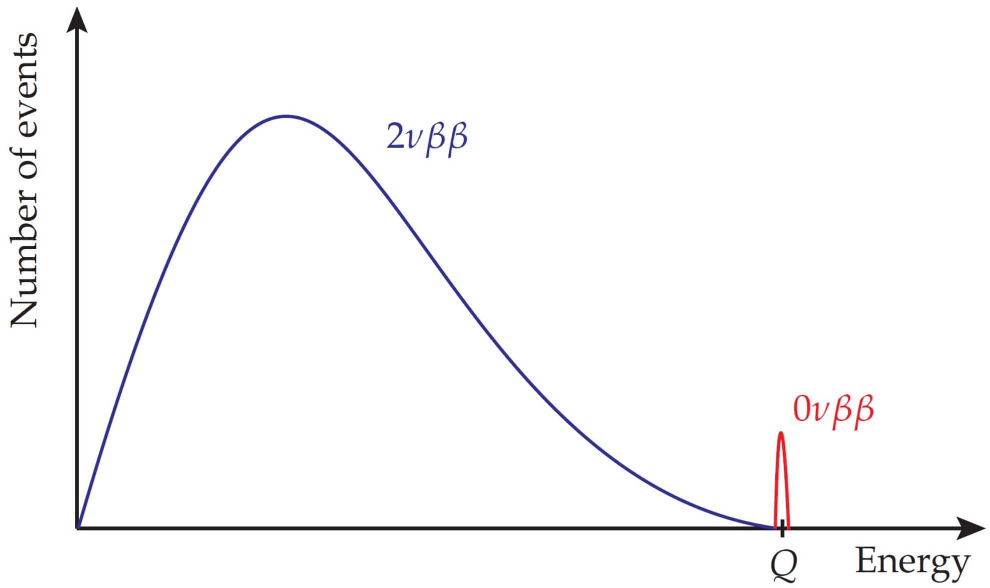
M·t: exposure [kg yr], ΔE: energy resolution,
BI: background index [counts/(keV kg yr)]

Need to achieve
- < 1 bck event in ROI
- excellent energy resolution

Effective Majorana Neutrino Mass

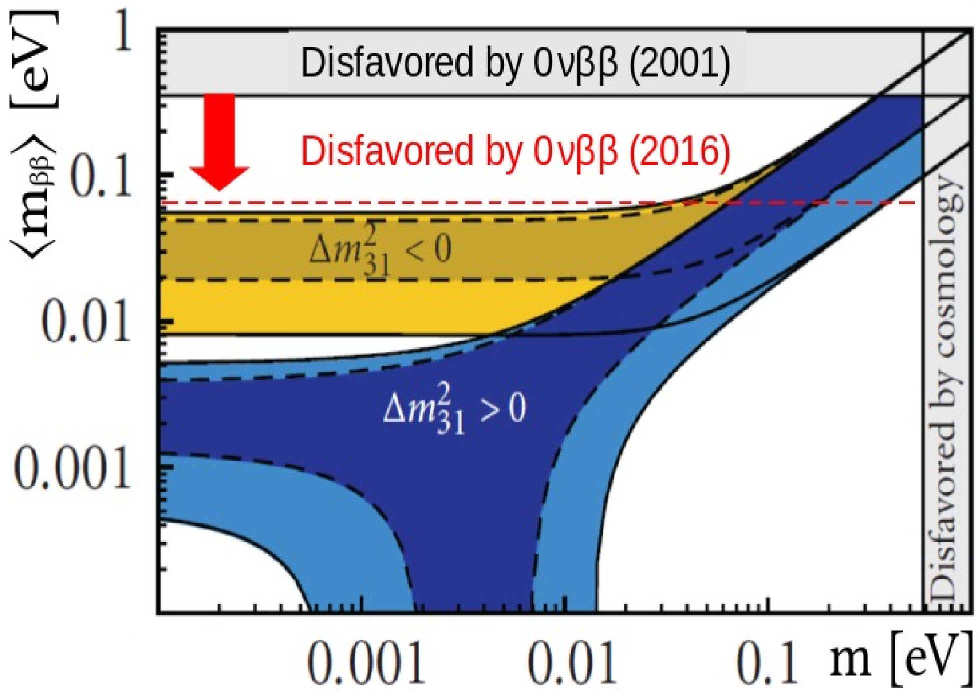


Measure sum energy of electrons



- Assuming light Majorana neutrino exchange

$$\left(T_{1/2}^{0\nu}\right)^{-1} \propto \left|m_{\beta\beta}\right|^2 \equiv \left|\sum_i U_{ei}^2 m_i\right|^2$$



Access to

- absolute neutrino mass scale
- mass hierarchy

0νββ Candidates

- no favored 0νββ isotope
- experimental considerations more important
- many different approaches to 0νββ search

  - multi-layer
  - scintillators
  - time projection chambers
  - (scintillating) bolometers
  - semi-conductors

$$\frac{1}{T_{1/2}^{0\nu}} = G^{0\nu}(Q,Z)\cdot\left|M^{0\nu}\right|^2\cdot\left(\frac{m_{\beta\beta}}{m_e}\right)^2$$

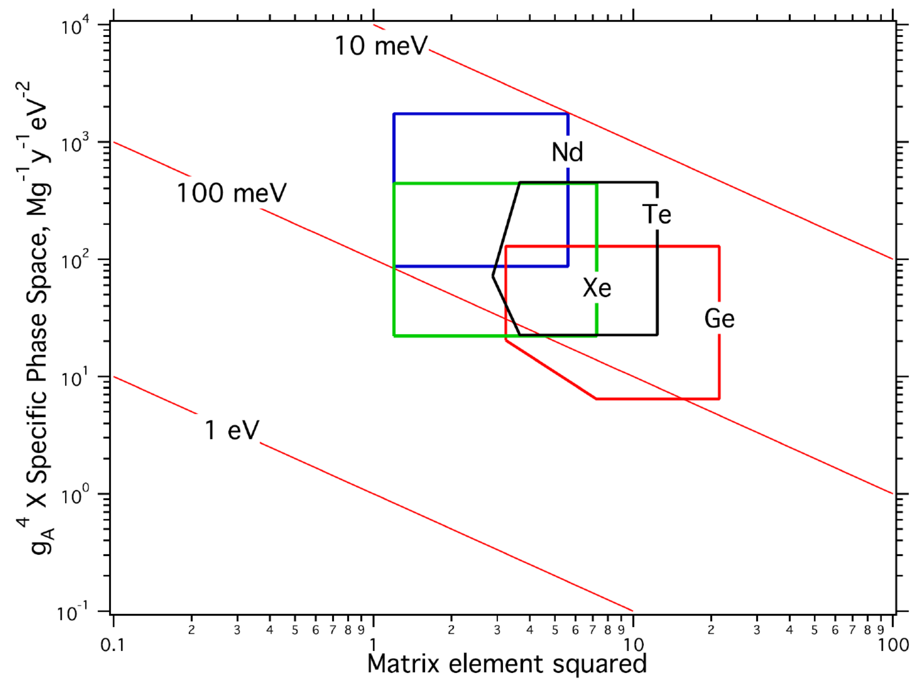
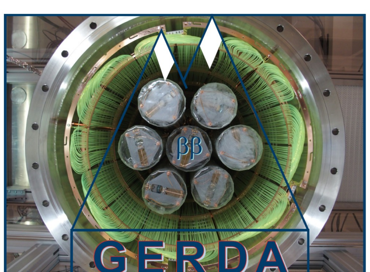
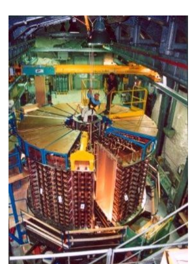
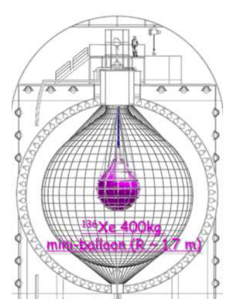
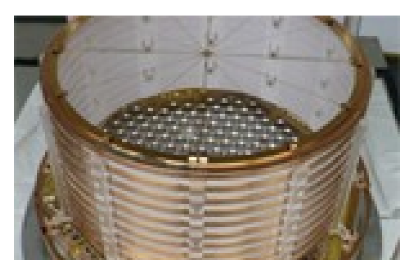
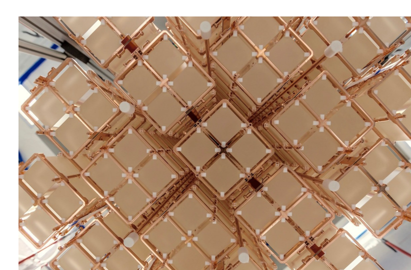


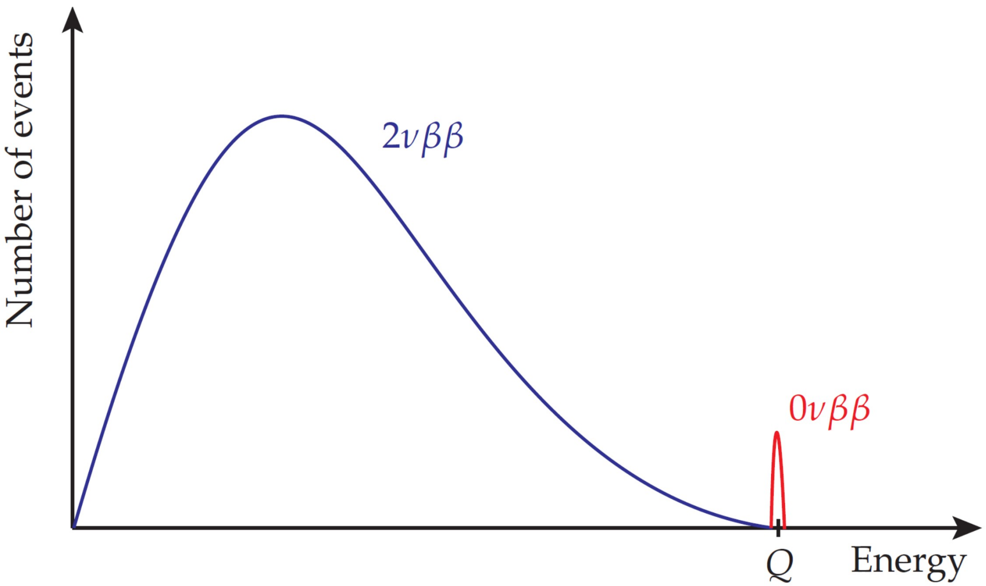
figure taken from Mod. Phys. Lett., A28:1350021, 2013

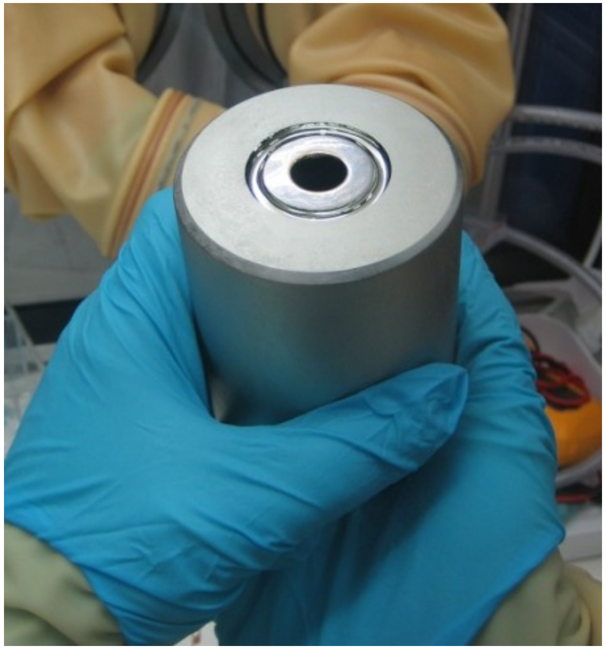


Germanium Detectors

Measure sum energy of electrons





High Purity Germanium (HPGe) Detectors

- 3-4 keV FWHM at $Q_{\beta\beta}$ = 2039 keV (0.2%)
- HPGe detectors isotopically **enriched** in ^{76}Ge (~87%)
- high detection efficiency of ββ: source = detector
- “no” intrinsic background [Astropart.Phys. 91 (2017) 15-21]
- discrimination of signal- from background like events using pulse shape analysis

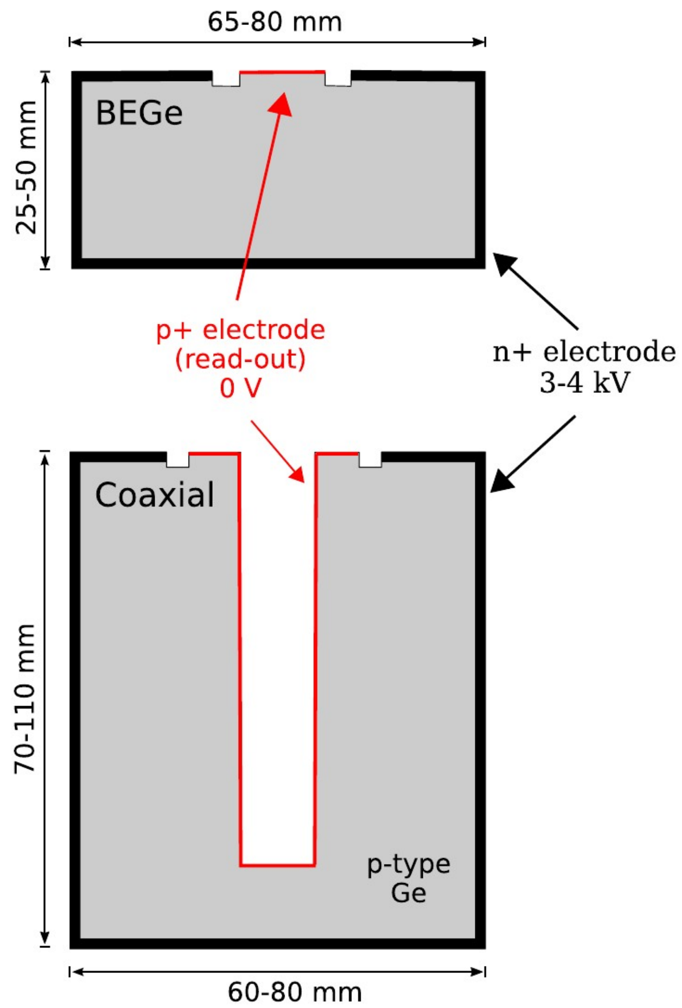
The GERDA HPGe

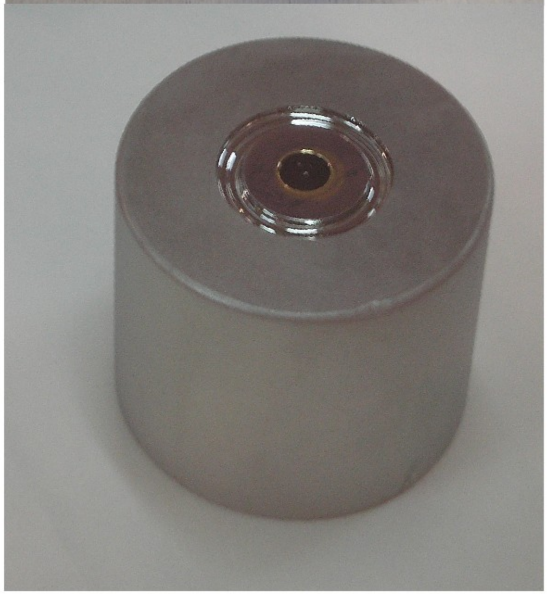
BEGe Detectors

- enhanced energy resolution and pulse shape discrimination
- low mass (~700 g)

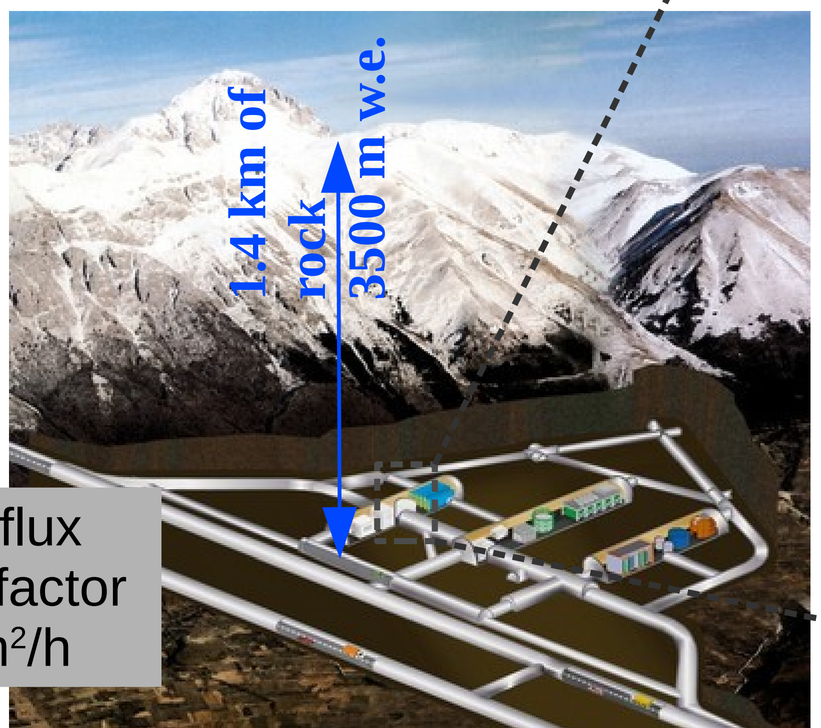
Semi-coaxial Detectors

- former HdM and IGEX experiment
- high mass (2-3 kg)





GERDA @ LNGS



cosmic muon flux
reduced by a factor
$\sim 10^6 \rightarrow 1\ \mu/m^2/h$

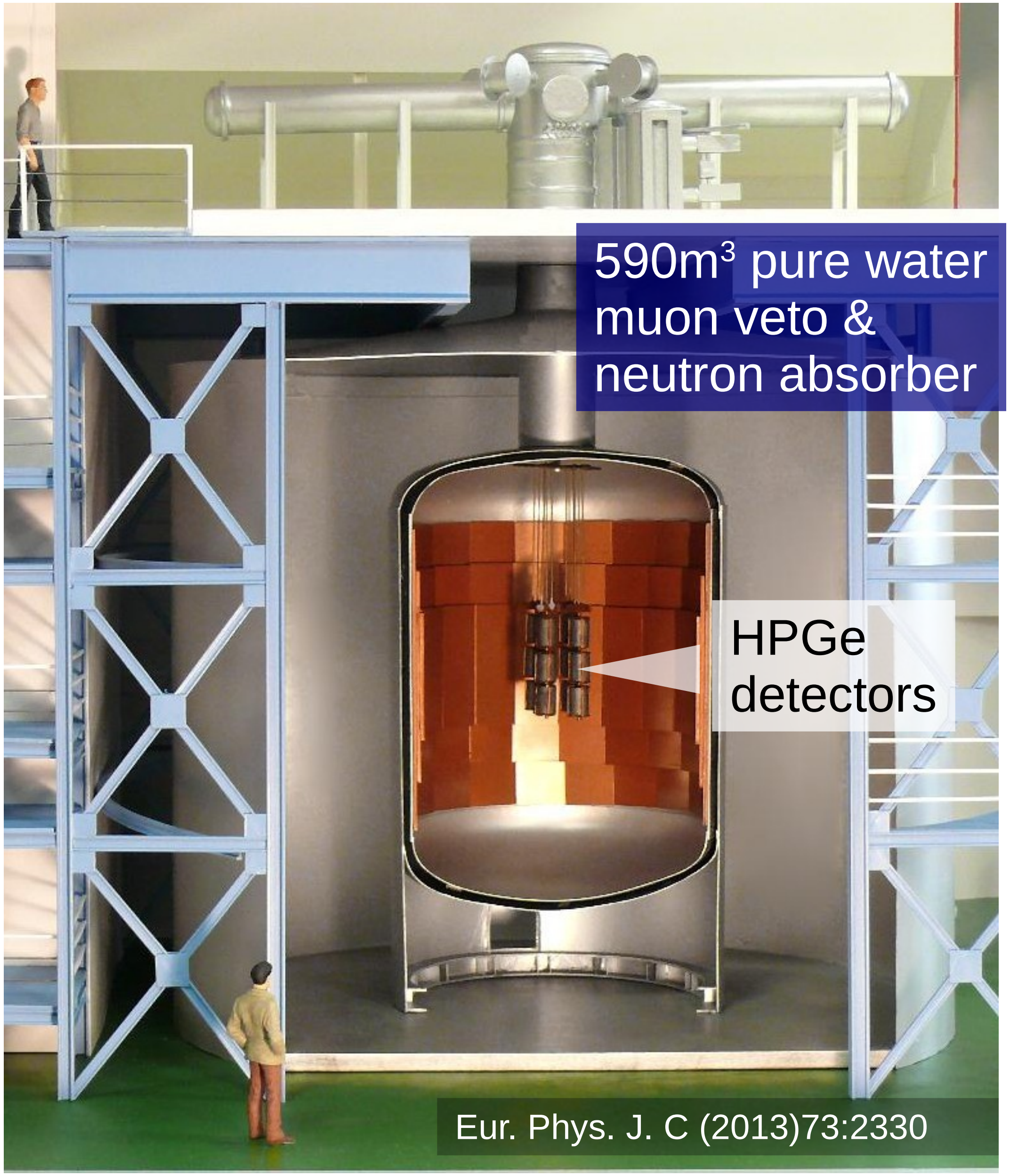
The **Germanium Detector Array**

concept:
operate bare HPGe detectors in LAr which serves as coolant & (active) shielding

GERDA Phase I (Nov 2011- May 2013)
- **17.8 kg** enriched semi-coaxial + **3.6 kg** enriched BEGe
- exposure 21.6 kg·yr
- BI ~ 10^{-2} counts/(keV·kg·yr)
- $T^{0\nu}_{1/2} > 2.1 \cdot 10^{25}$ yr (90% C.L.)

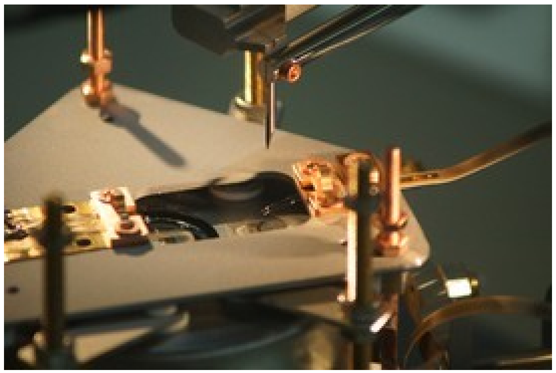
PRL 111, 122503 (2013)

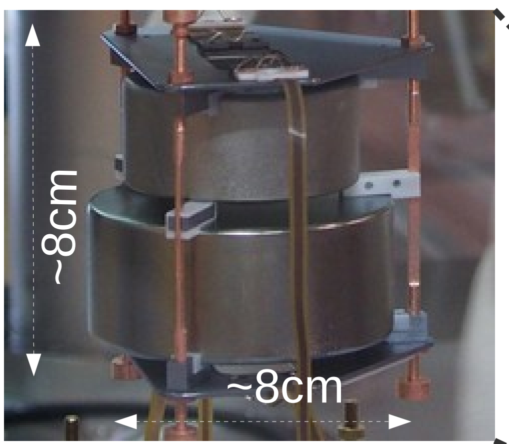
GERDA Phase II (Dec 2015 - ongoing)
- **30** enriched **BEGe** (= **20.0 kg**) + 7 enriched semi-coaxial (= **15.6 kg**)
- **LAr instrumentation**
- goal: BI ~ 10^{-3} counts/(keV·kg·yr)



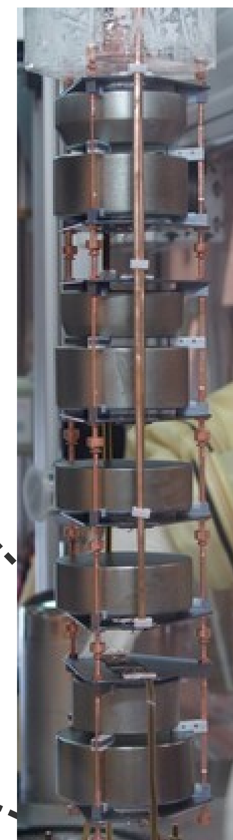
GERDA Phase II Array

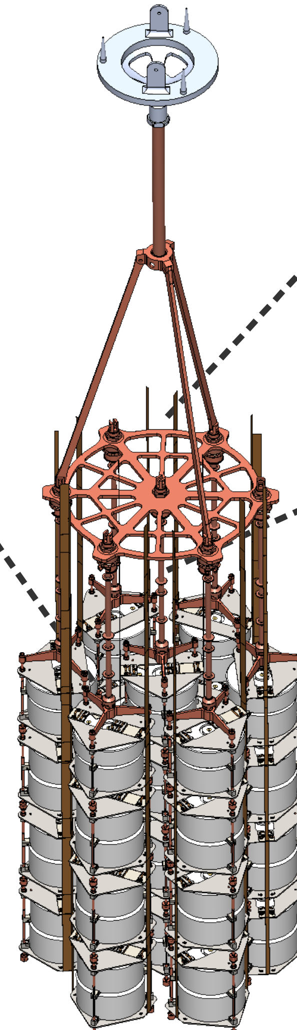
wire bonding for contacting

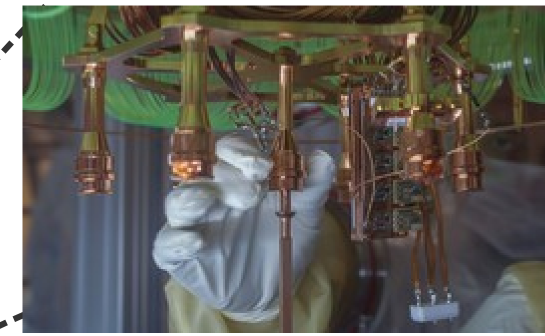




new low mass holders
with reduced mass
and Cu → Si







low radioactivity
electronics

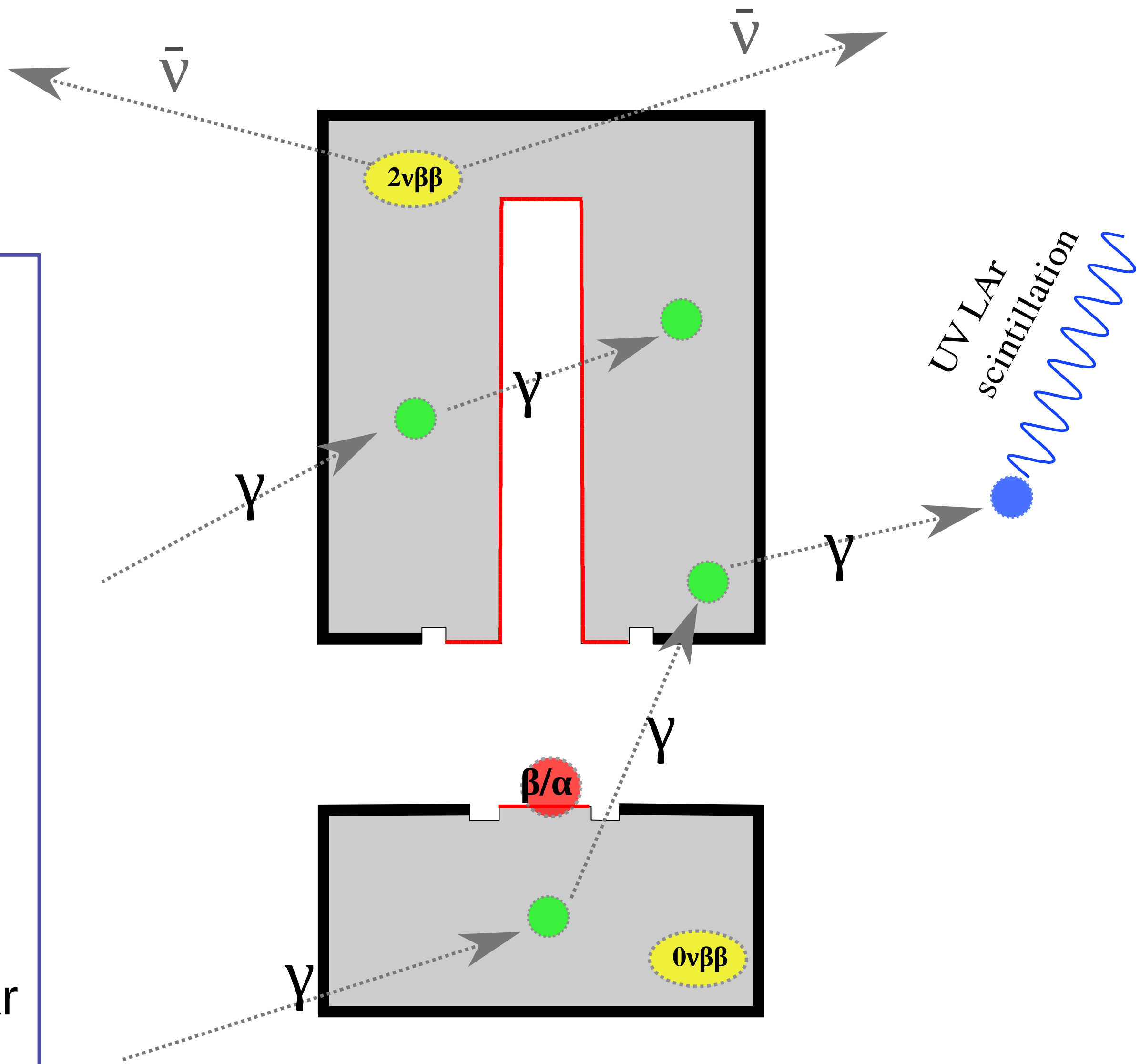
Discriminating Signal from Background Events

ββ event

- local energy deposition (SSE) in single detector

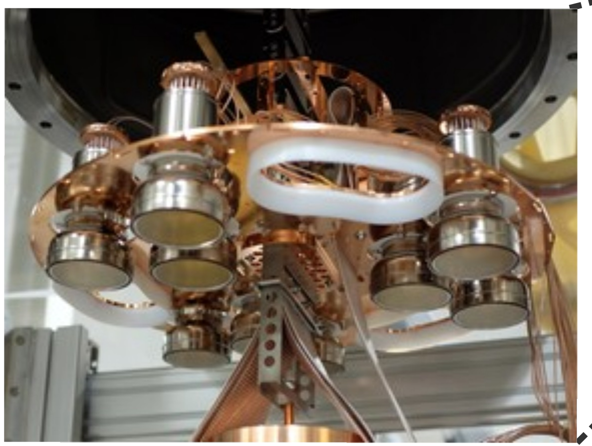
background event

- energy deposition in multiple locations (MSE) in single detector or on detector surface (α/β)
  → **pulse shape discrimination**
- coincident energy deposition in more than one detector
  → **detector anti-coincidence**
- additional energy deposition in LAr
  → **LAr veto**

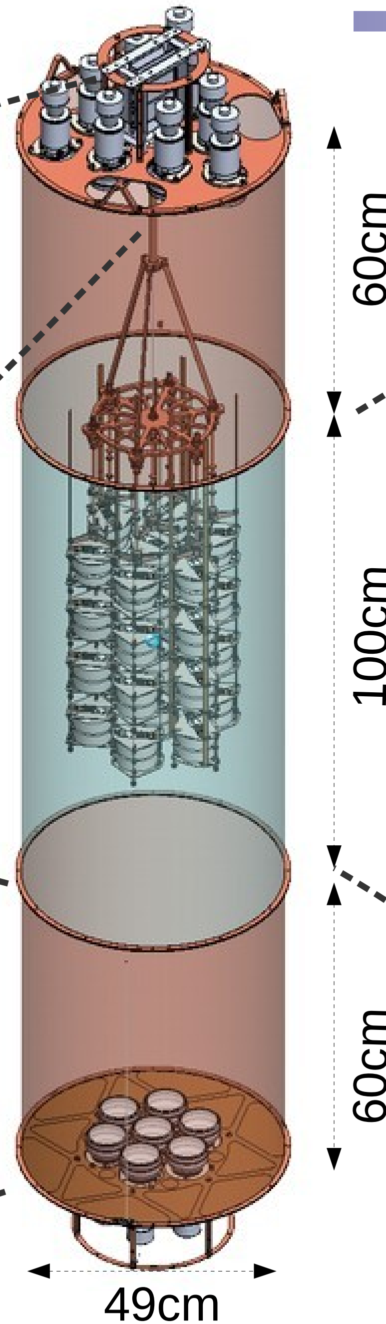


LAr Instrumentation – Hybrid Design

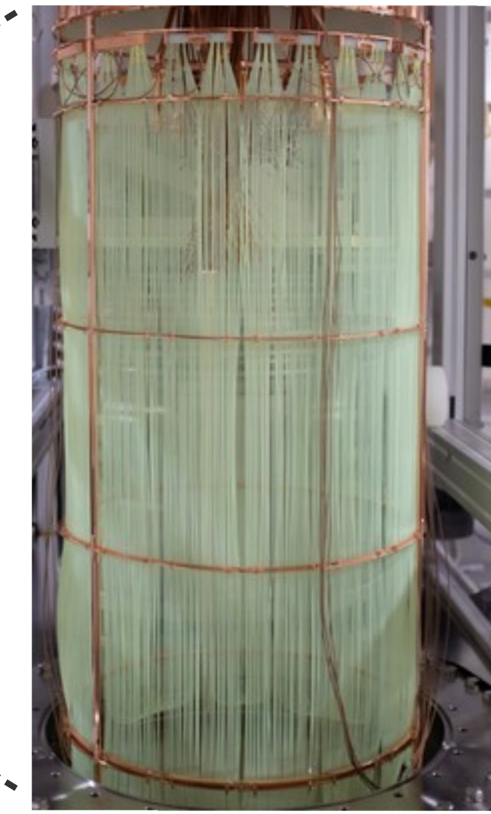
16 photomultiplier tubes (PMTs)



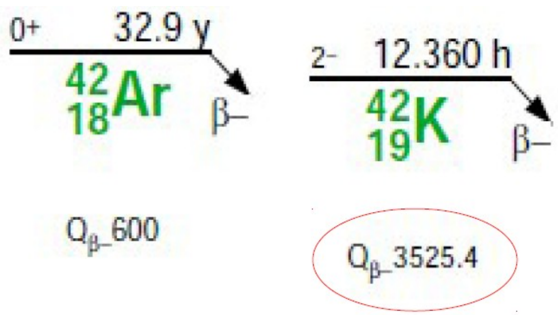
Cu cylinder with wavelength shifting reflector foil



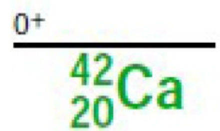
810 wavelength shifting fibers coupled to SiPMs



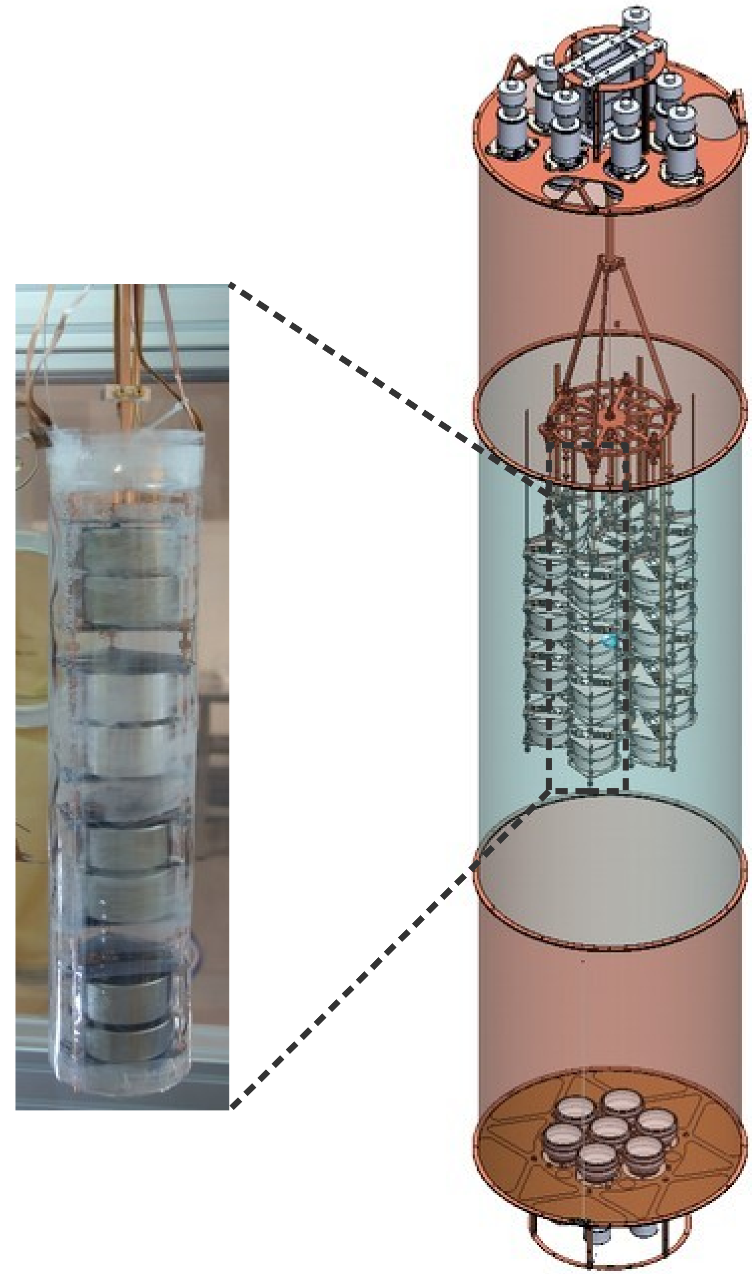
^{42}K Background



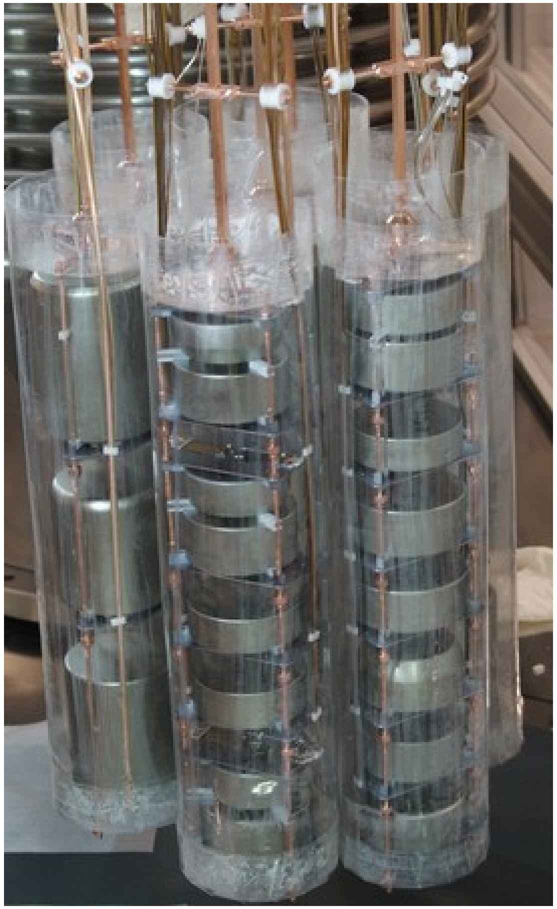
(charged) ^{42}K drift in field of Ge detectors



- solution:
  transparent nylon cylinder coated with wave length shifter
- tested in test cryostat LArGe
- nylon from BOREXINO



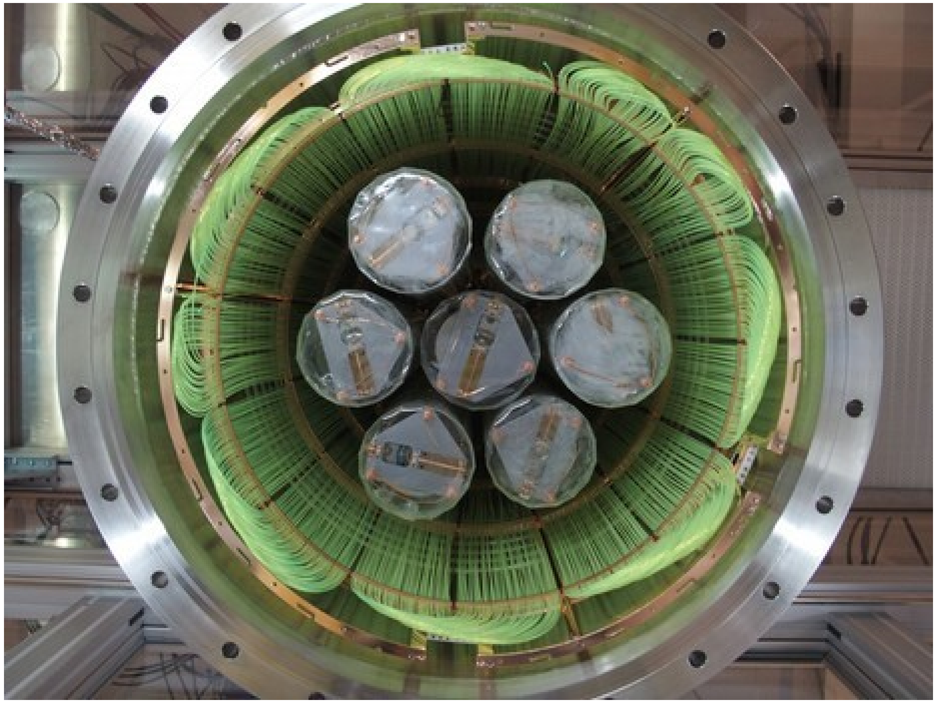
Start of GERDA Phase II



Full Integration of Phase II Array

finished in December 2015

- all Ge and LAr detector channels working



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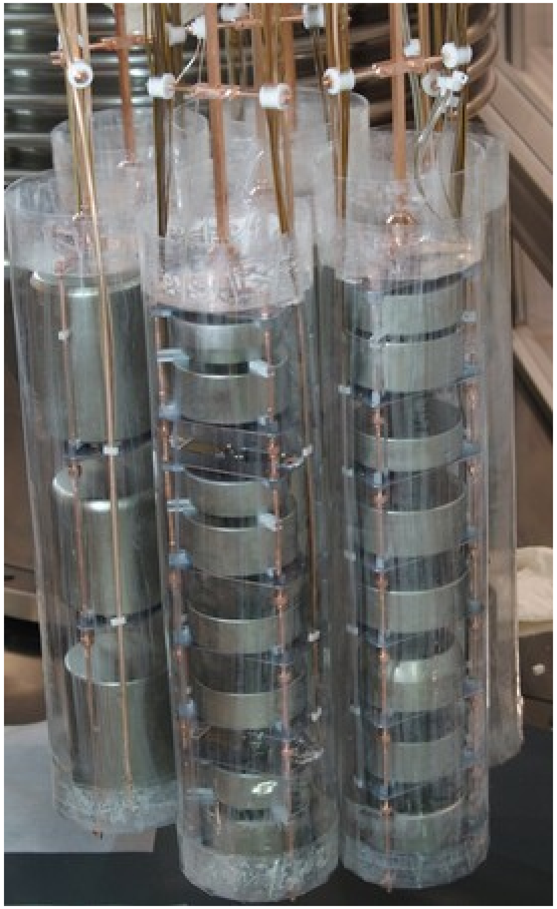
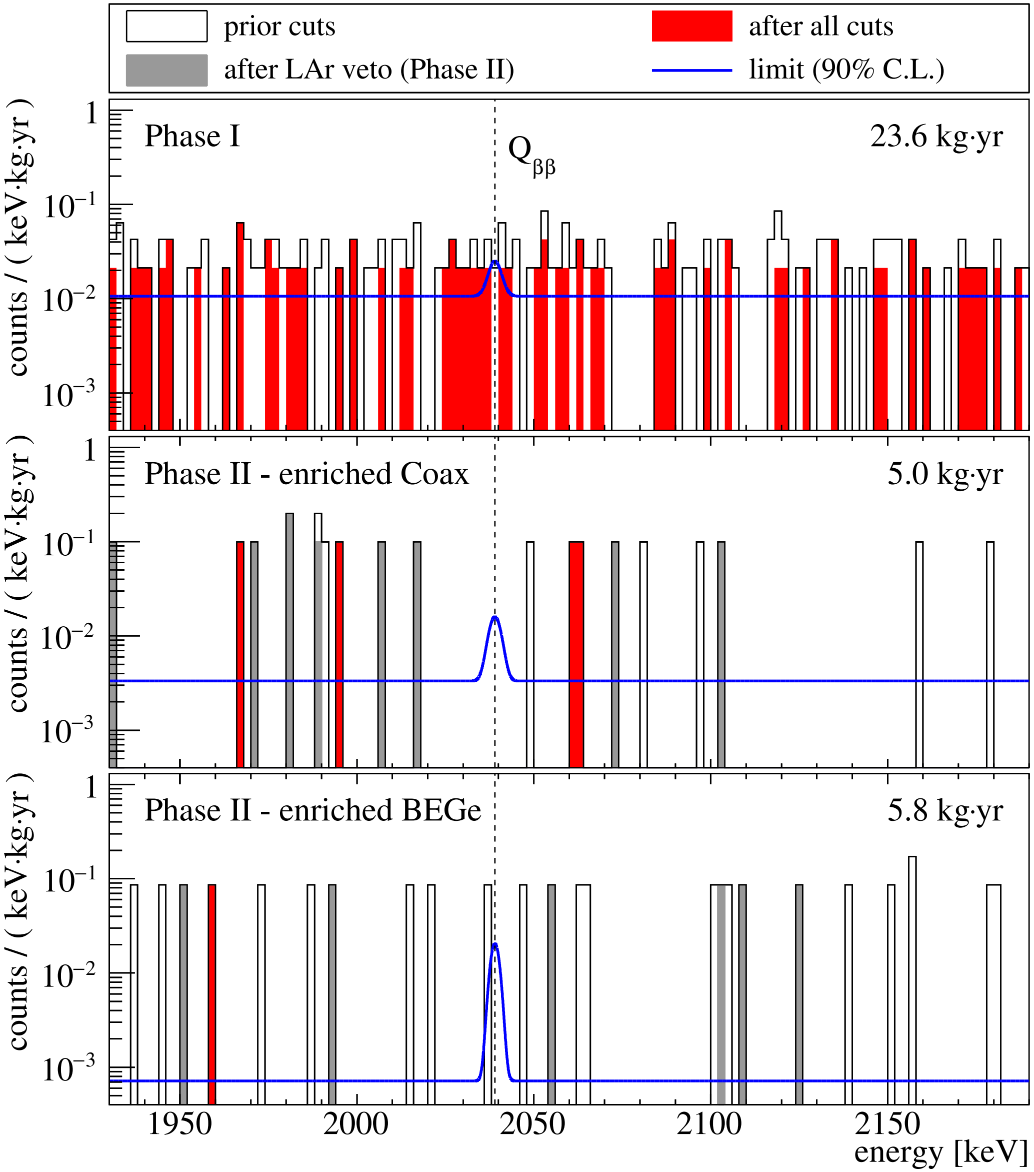



Full Integration of Phase II Array finished in December 2015

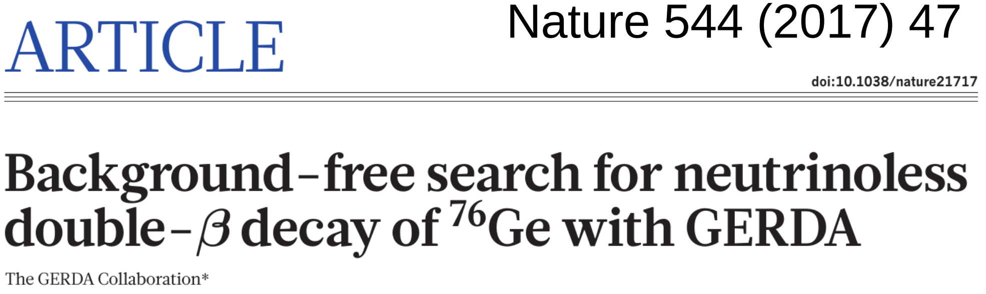
- all Ge and LAr detector channels working

- 35 out of 37 detectors used for analysis
- **blinded region: $Q_{\beta\beta}$ ± 25 keV**
- quality cuts (phys. acc. > 99.9%)
- events in coincidence with muon veto (phys. Acc.~ 99.9 %)
- **first data release in June 2016**
- 2nd data release in June 2017

First Phase II Data Release



Nature 544 (2017) 47



Background:

- coax: **3.5 · 10^{-3}** counts/(keV·kg·yr)
- BEGe: **7 · 10^{-4}** counts/(keV·kg·yr)

  → expect < 1 bck count in ROI during full exposure of 100 kg·yr

New limit on ^{76}Ge

$T^{0\nu}_{1/2} > 5.3 \cdot 10^{25}$ yr

with median sensitivity of

$4.0 \cdot 10^{25}$ yr (90 % C.L.)

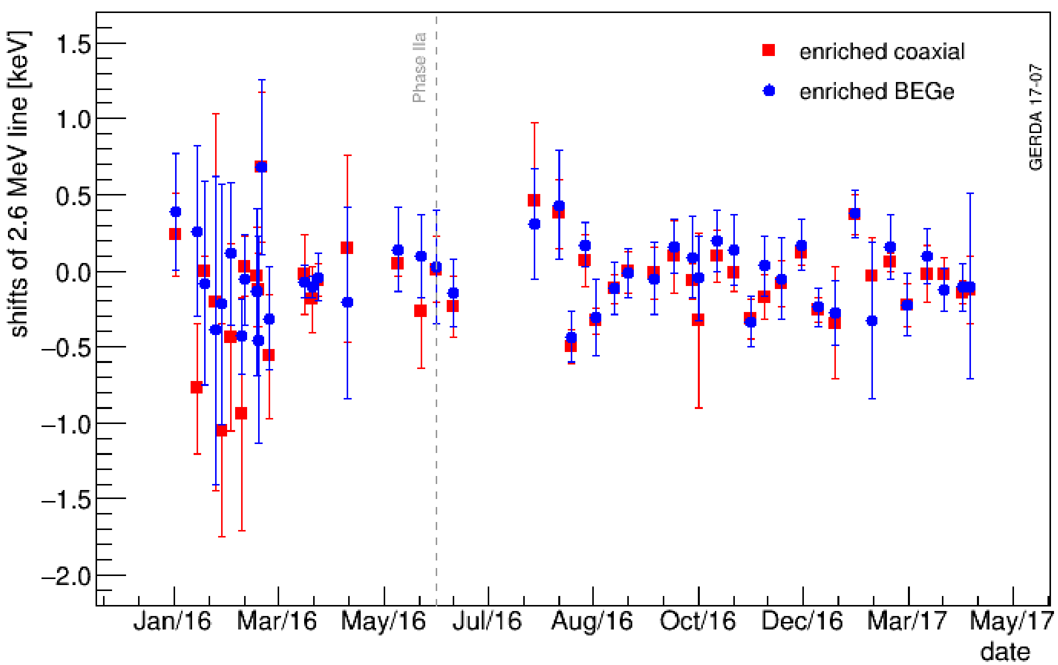
Second Phase II Data Release

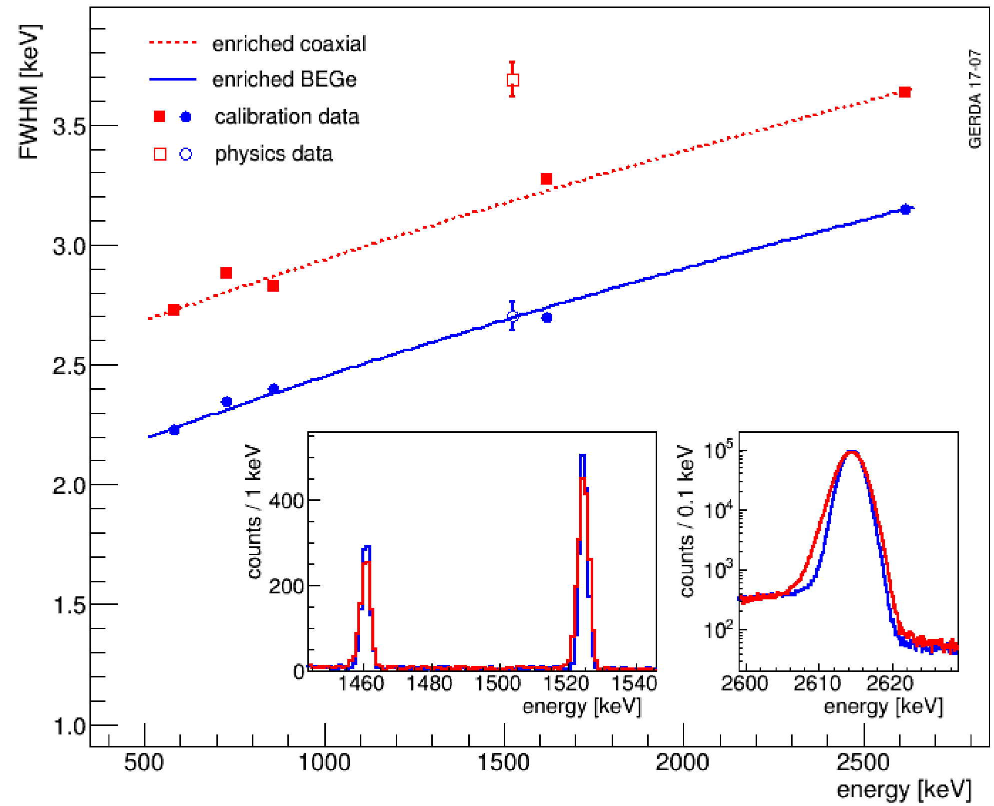
- Phase II exposure until April 2017: **34.4 kg·yr**

  → additional **12.4 kg·yr** (11.2 kg·yr) in **BEGe** (coax) data set with respect to Nature publication

FWHM @ $Q_{\beta\beta}$:

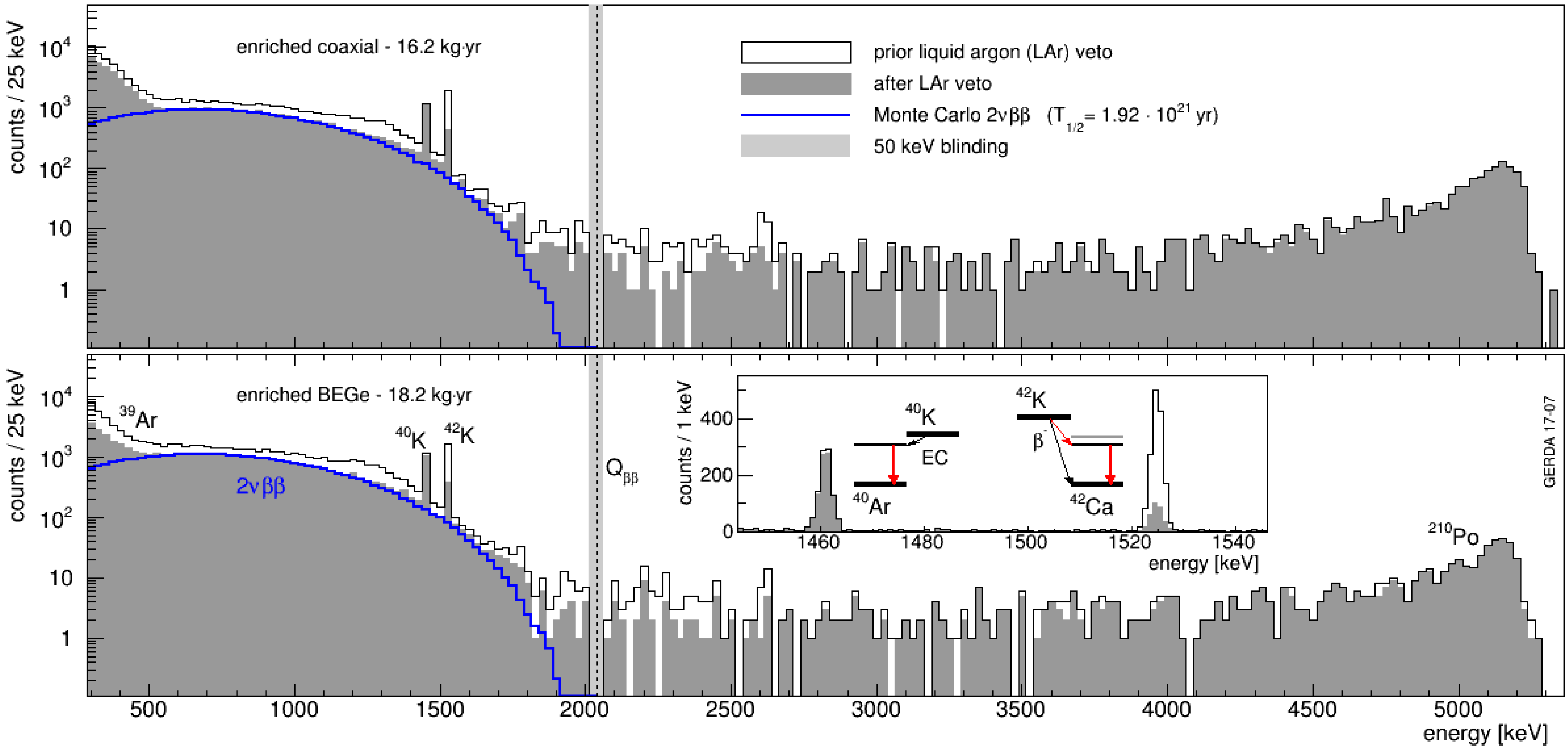
- BEGe's: 2.93(6) keV
- Coax: 3.90(7) keV





Performance of the LAr Veto

- $2\nu\beta\beta$:bck = 96:4 (1.0-1.3 MeV)

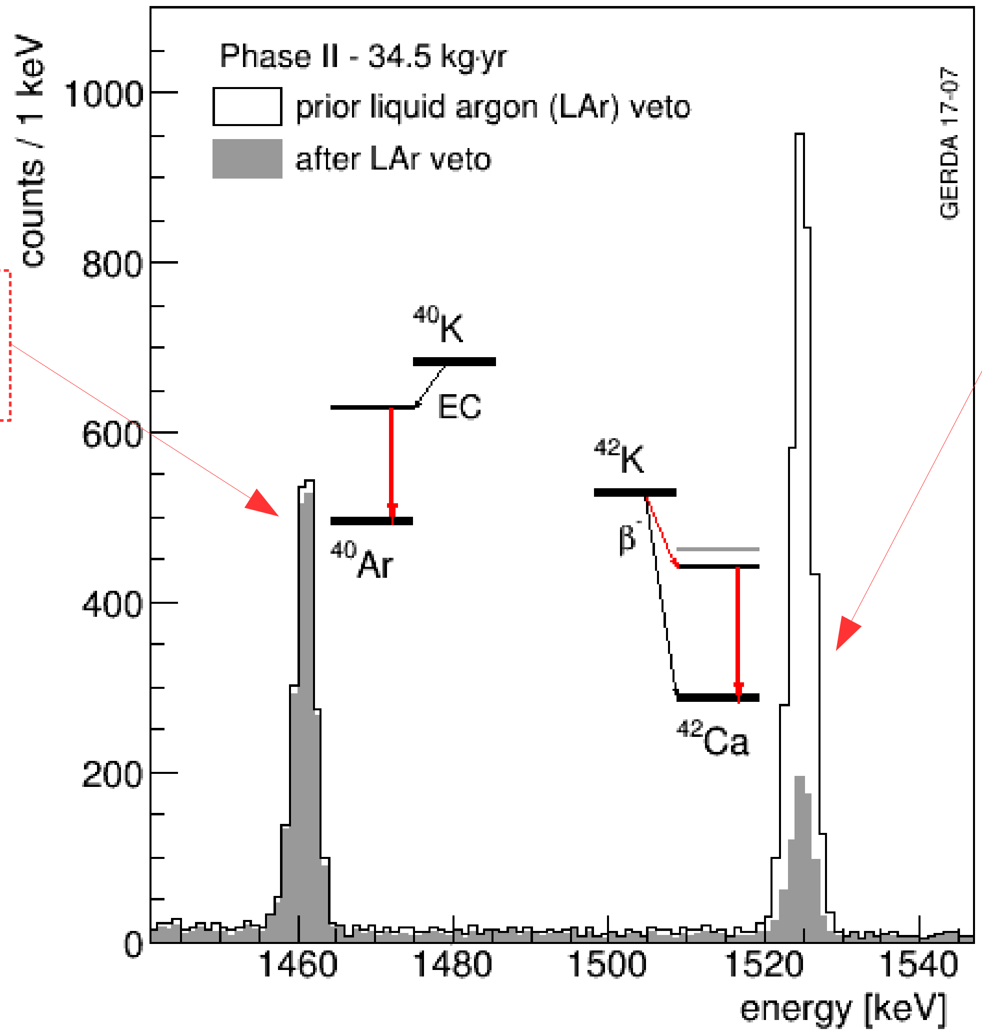


$2\nu\beta\beta$ MC with $T_{1/2} = 1.9 \cdot 10^{21}$ yr from Phase I EPJC 75 (2015) 416

Performance of the LAr Veto

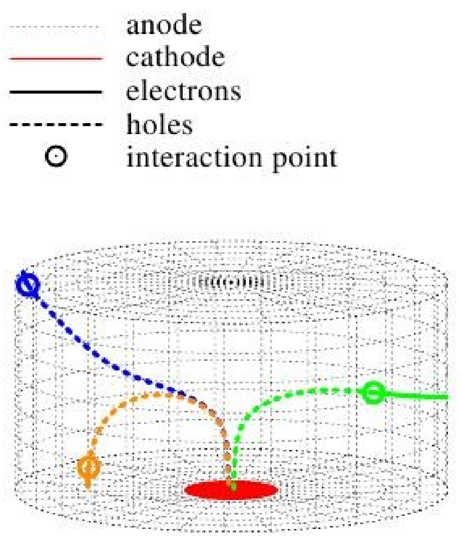
- random coincidences: 2.3%
- ^{42}K line suppressed by factor 5-6

^{40}K → ^{40}Ar (EC)
no energy in LAr



^{42}K → ^{42}Ca
+ γ (1.5 MeV) in Ge
+ β$^-$ (≤ 2 MeV) in LAr

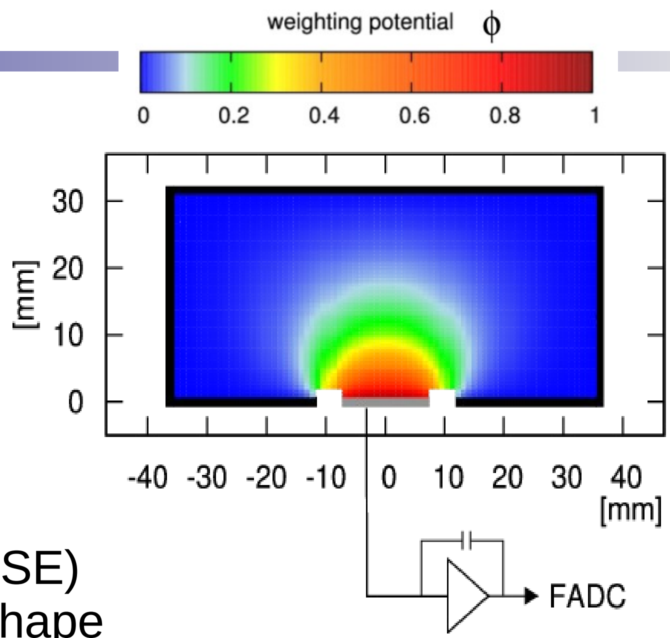
Signals of BEGe's



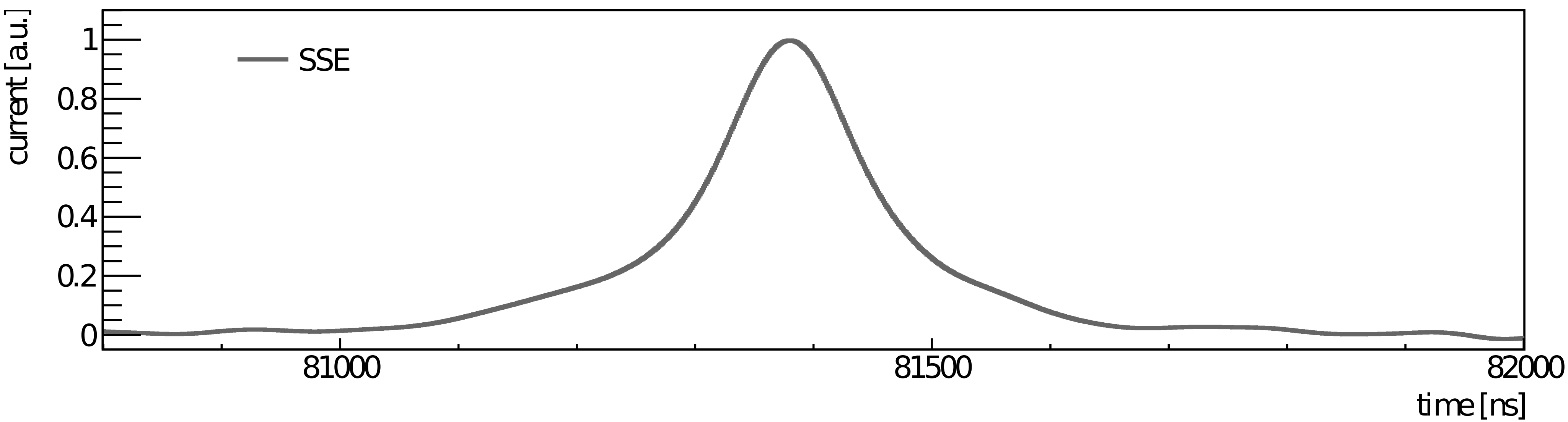
figures taken from JINST 6 P03005, 2011

- final drift paths of holes nearly independent of interaction point
- high gradient of weighting potential

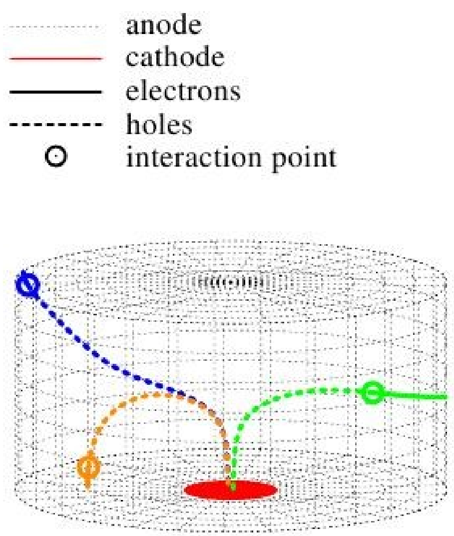
→ single site events (SSE) have similar pulse shape



current signal = $q \cdot v \cdot \nabla\phi$
q: charge, v: velocity



Signals of BEGe's



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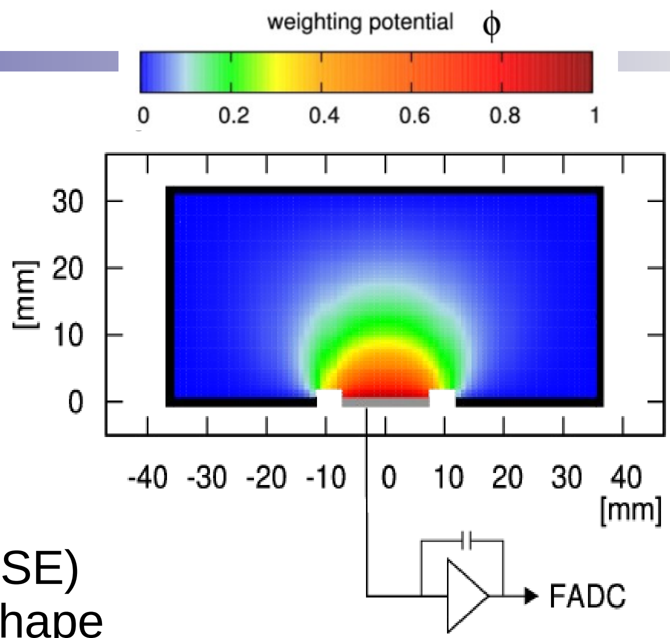

current signal = q · v · ∇ϕ
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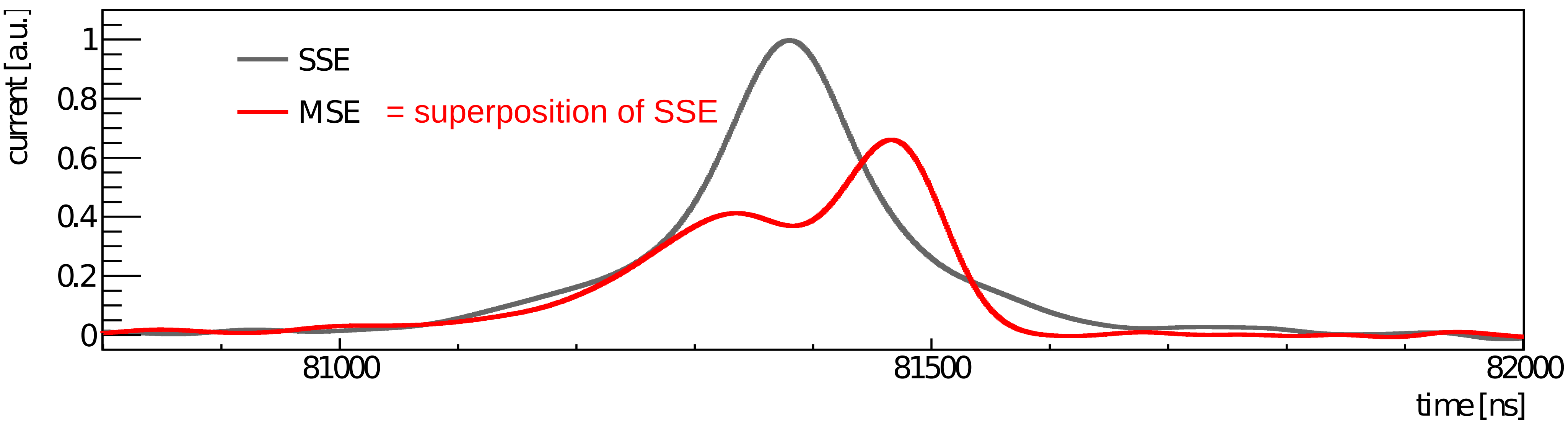
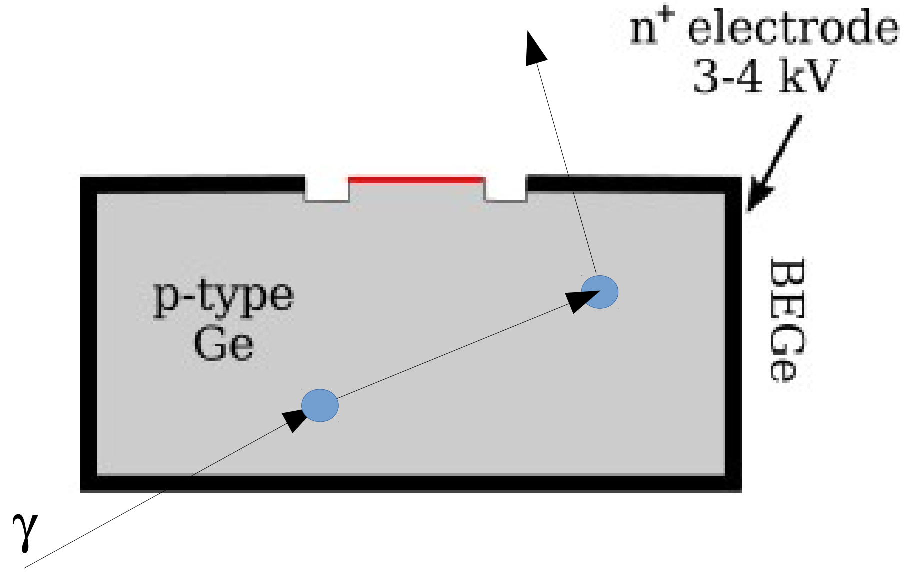
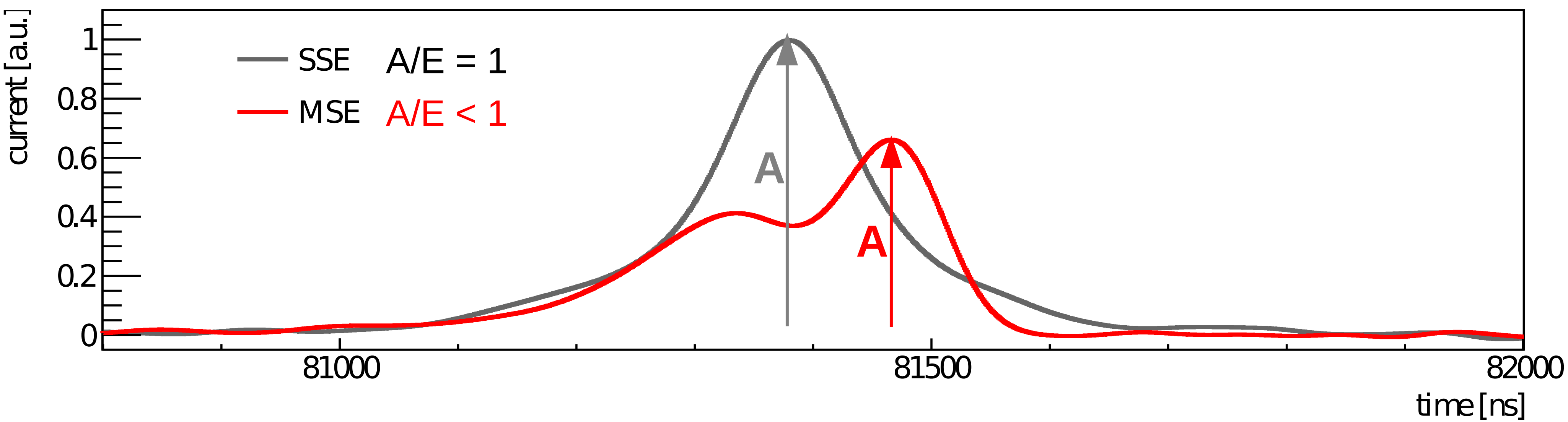


SSE vs MSE

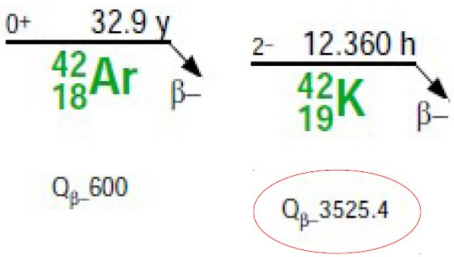
- A/E = maximum amplitude of current signal over deposited energy

- A/E to suppress external γ-rays of ^{214}Bi, ^{208}Tl and ^{60}Co (detector assembly)

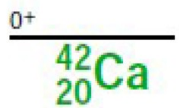


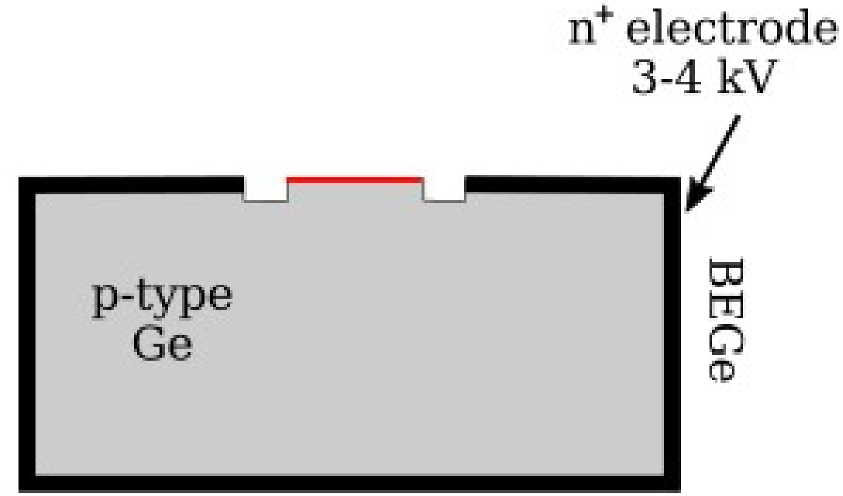


Surface Events: β-Decays

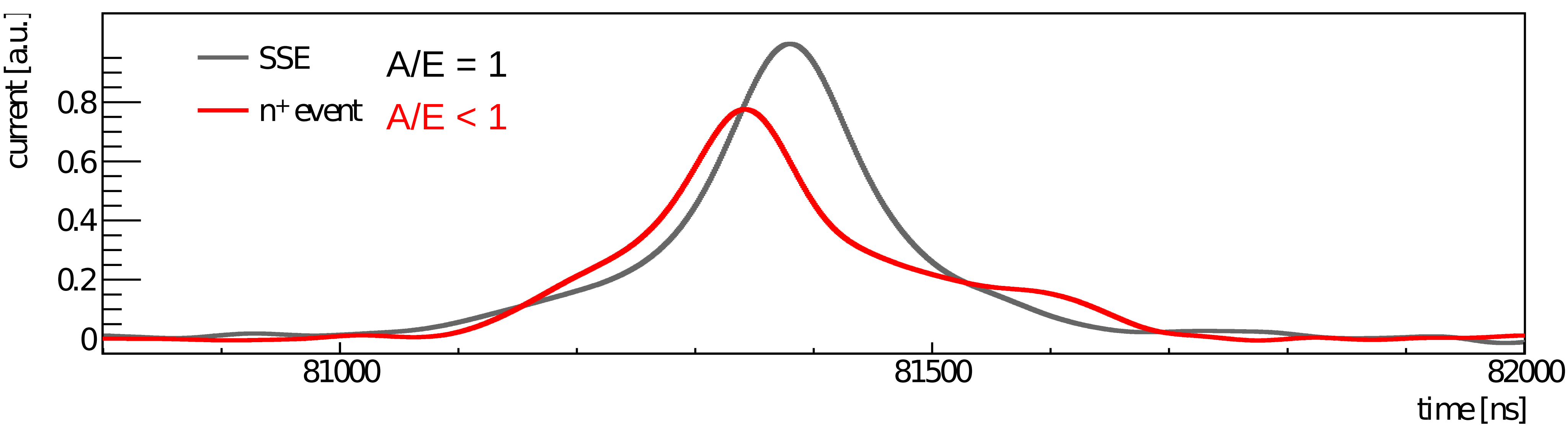
- 

(charged) ^{42}K drift in field of Ge detectors



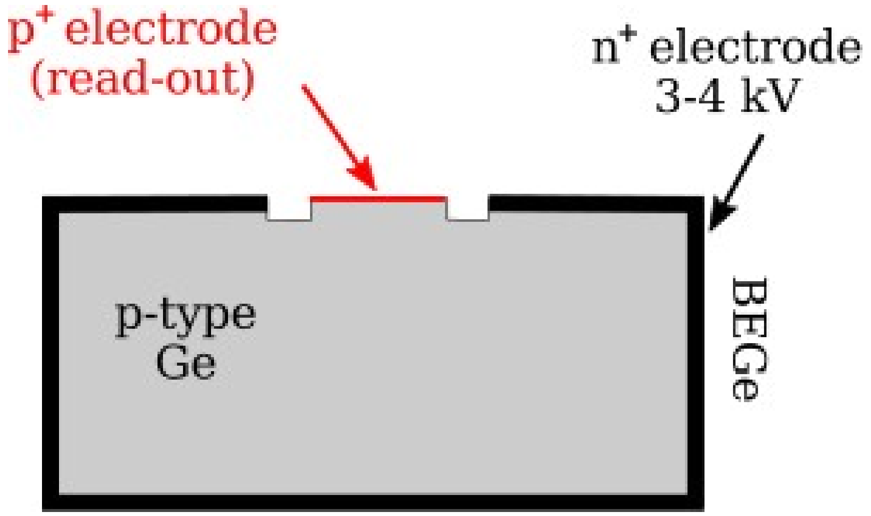


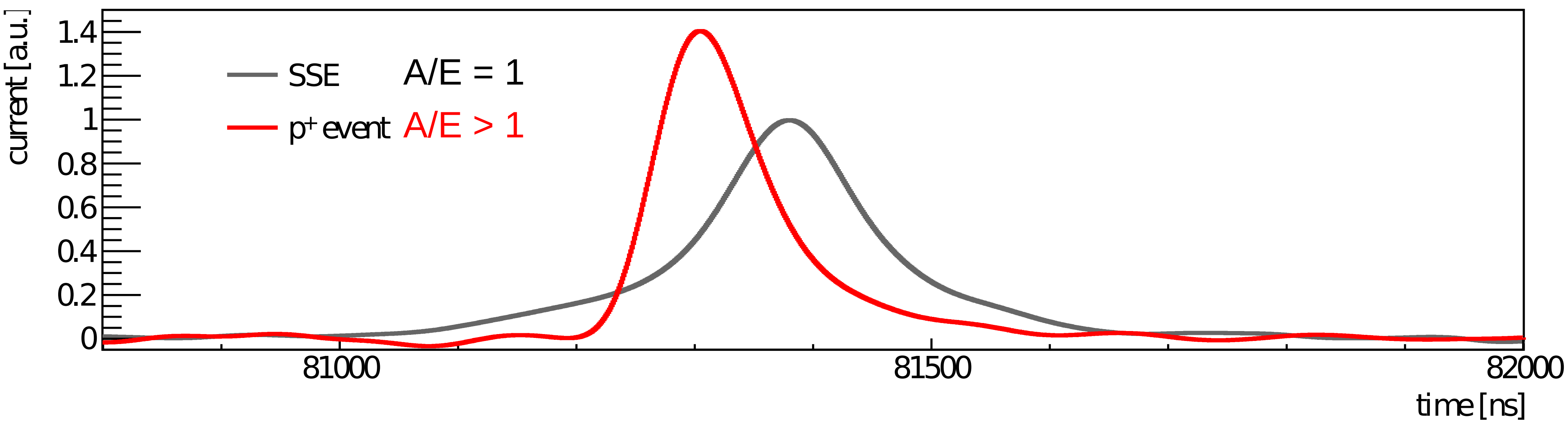
- decays on the detector surface (n+) typically produce slow pulses with low A/E



Surface Events: α-Decays

- α's cannot penetrate n^+, only p^+ contact
- decays on the detector p^+-contact and groove typically produce fast pulses with high A/E

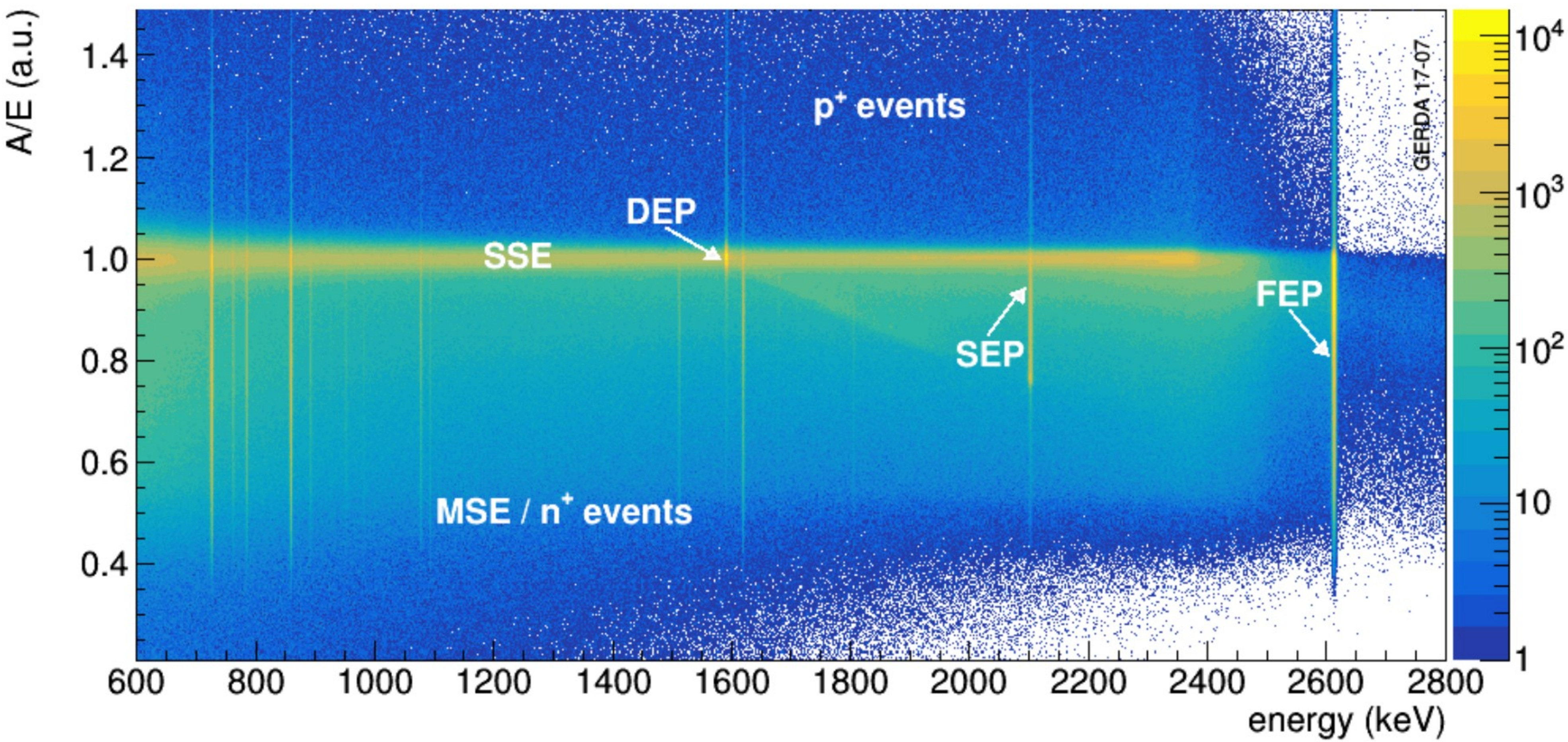




^{228}Th Calibrations

Regular ^{228}Th calibrations:

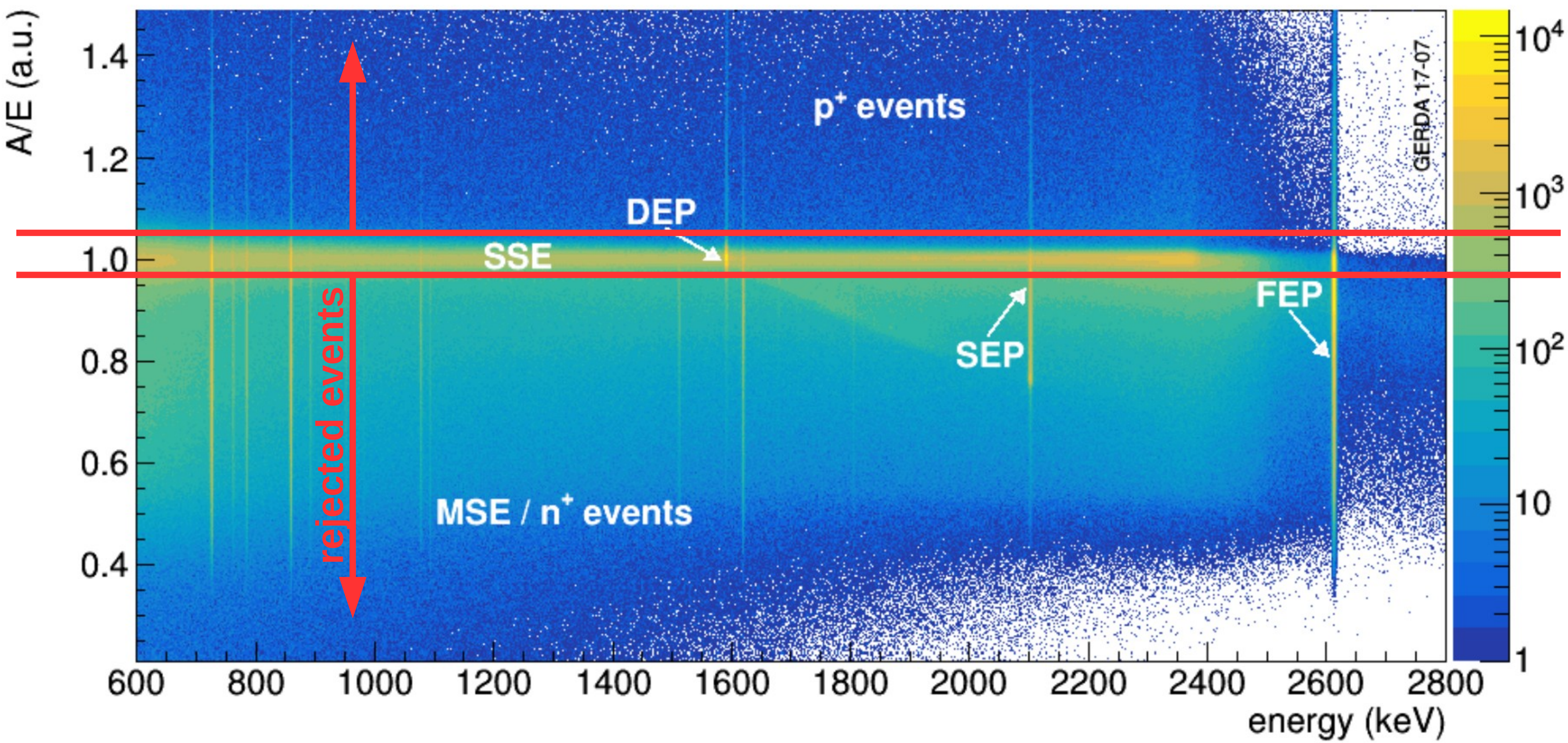
- single Compton events = SSE band
- prominent DEP **= signal proxy**



^{228}Th Calibrations

Regular ^{228}Th calibrations:

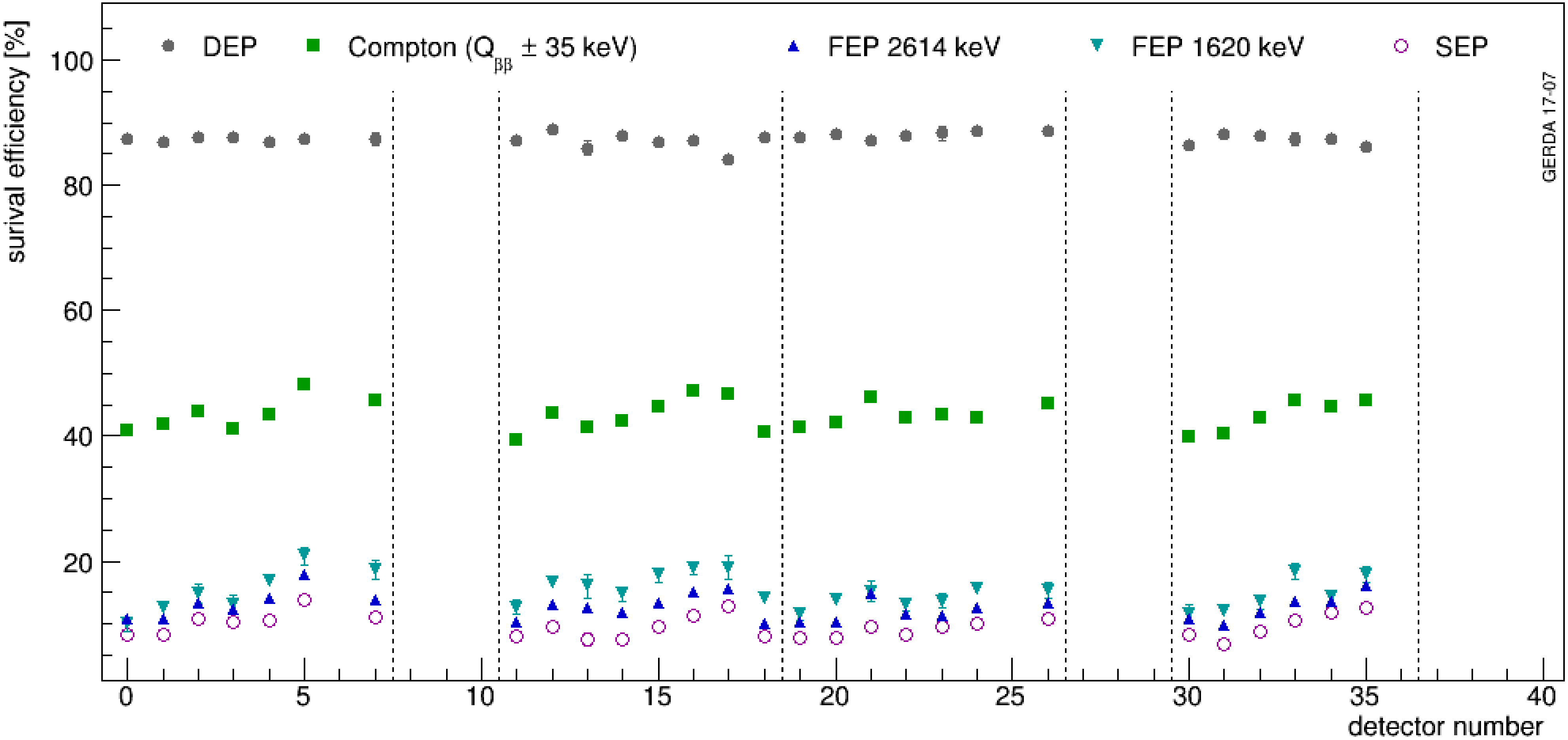
- adjust 2-sided cut
  - MSE/n^{+} cut at 90% DEP acceptance
  - p^{+} cut twice the distance to SSE band



$0\nu\beta\beta$ Signal Efficiency

- signal efficiency given by DEP acceptance:

$$\varepsilon_{PSD} = (87.4 \pm 0.2(stat) \pm 2.6\,(sys))\%$$



A/E in Physics Data

- $2\nu\beta\beta$ survival fraction[1]:

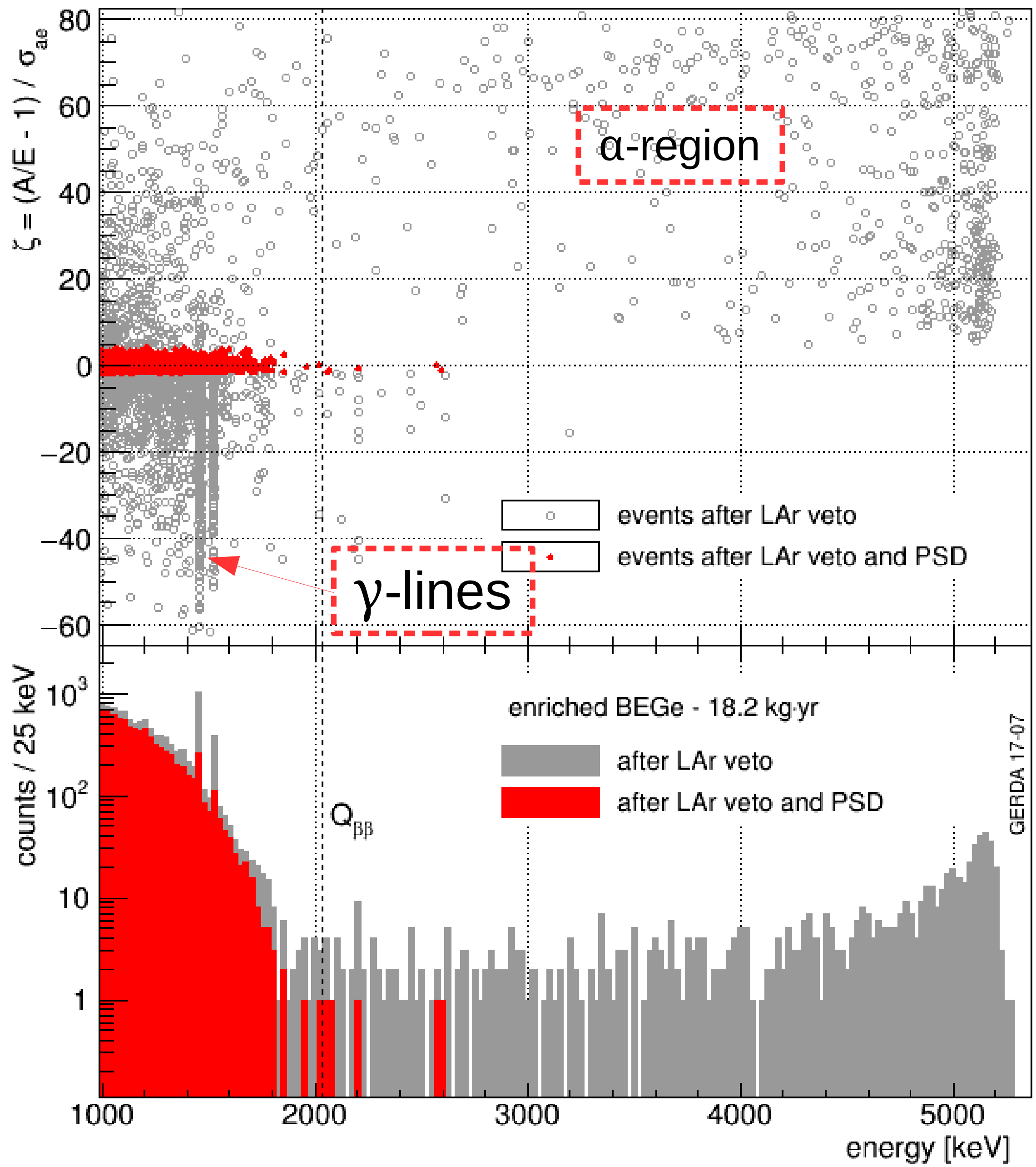
  (85.4 ± 0.4 (stat) + 1.4 (sys))%

- good agreement with signal efficiency

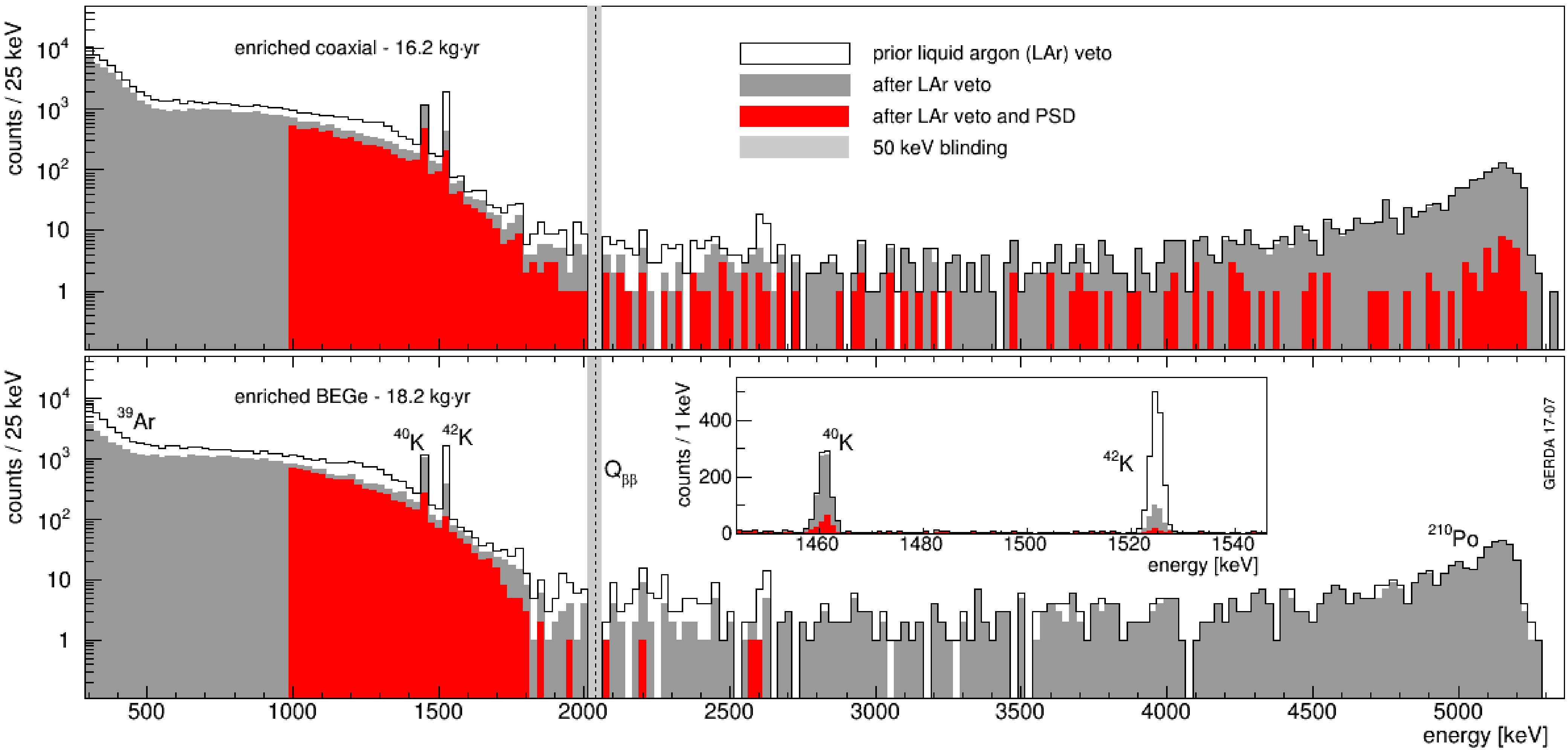
- FEP highly suppressed

- all events at high energies rejected by high A/E cut

- ~80% of bck-events rejected by PSD



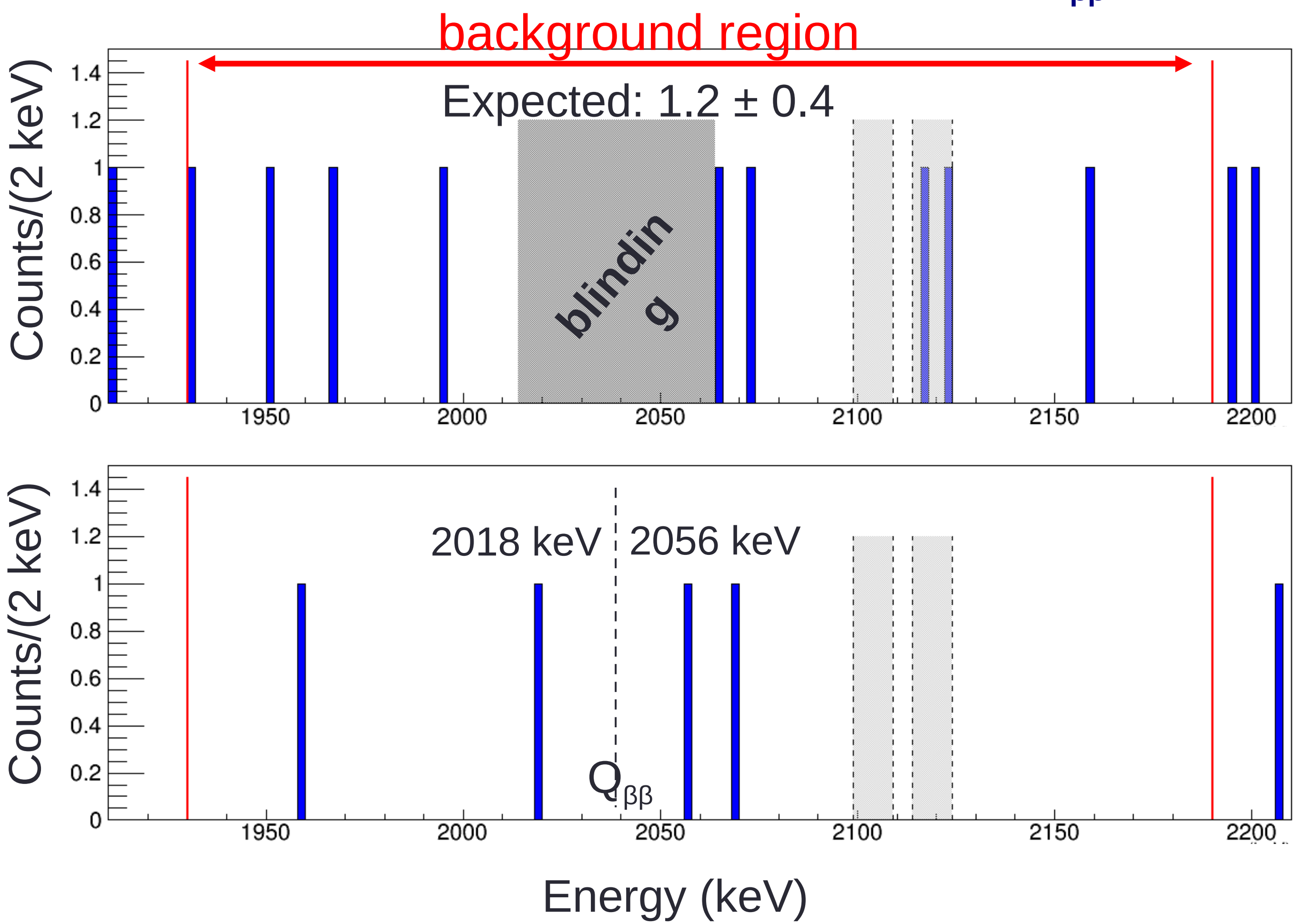
Phase II Spectra



- PSD for coaxial detectors to be further optimized to reject α-decays on detector groove
- PSD for BEGe cuts all α-events

Opening the Box

Spectra after LAr veto and PSD around $Q_{\beta\beta}$



- coax data set:
  5 kg·yr unblinded +
  11.2 kg·yr still blinded

Coax

$$BI = 2.7^{+1.0}_{-0.8} \cdot 10^{-3} \frac{counts}{keV \cdot kg \cdot yr}$$

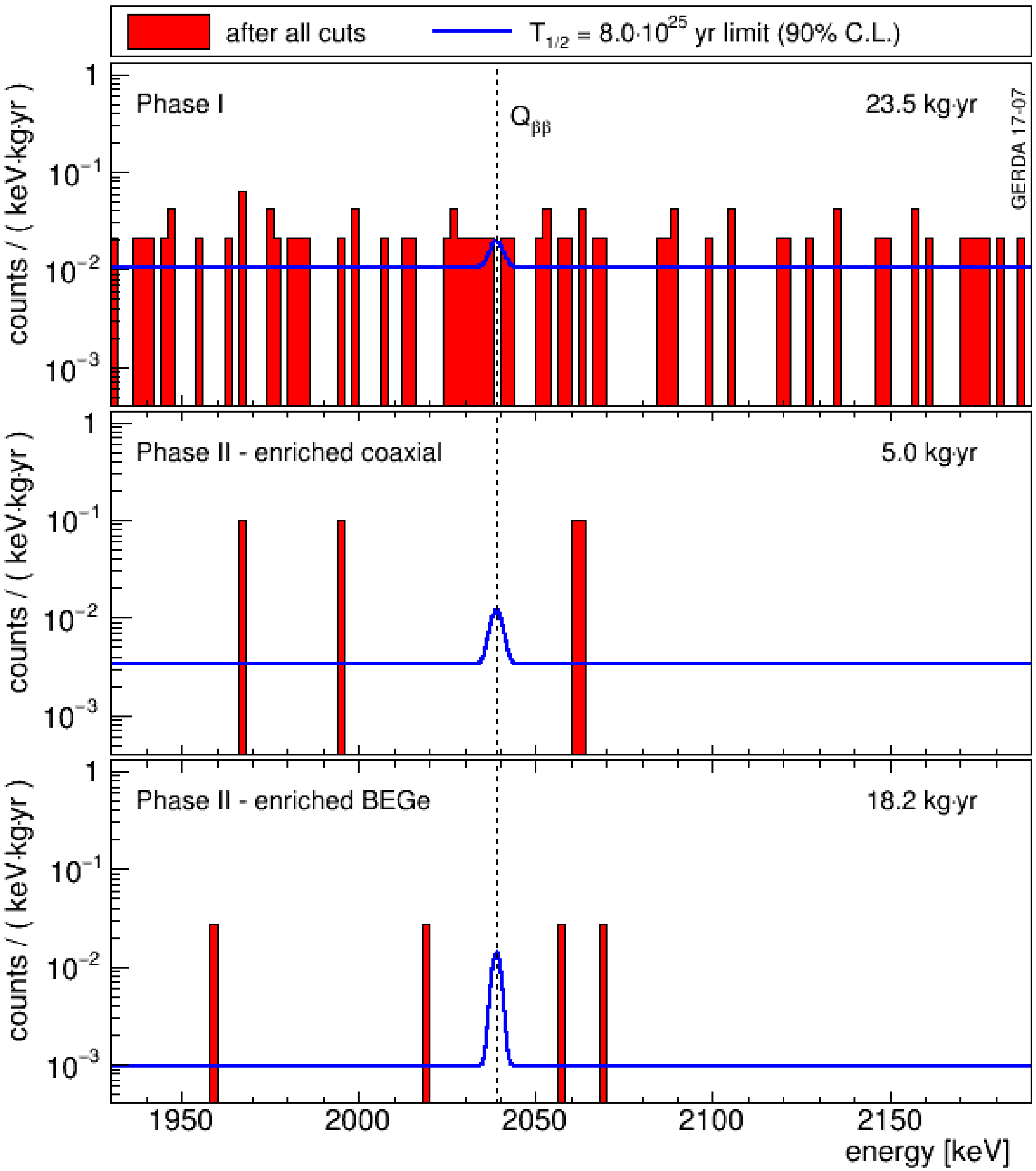
- BEGe data set:
  5.8 + **12.4 kg·yr unblinded**

BEGe

$$BI = 1.0^{+0.6}_{-0.4} \cdot 10^{-3} \frac{counts}{keV \cdot kg \cdot yr}$$

- PSD for coaxial detectors to be further optimized to reject α-decays on detector groove
- PSD for BEGe cuts all α-events

Statistical Analysis



6 data sets in total according to BI and FWHM:

→ Phase I (4 sets)
23.5 kg ·yr

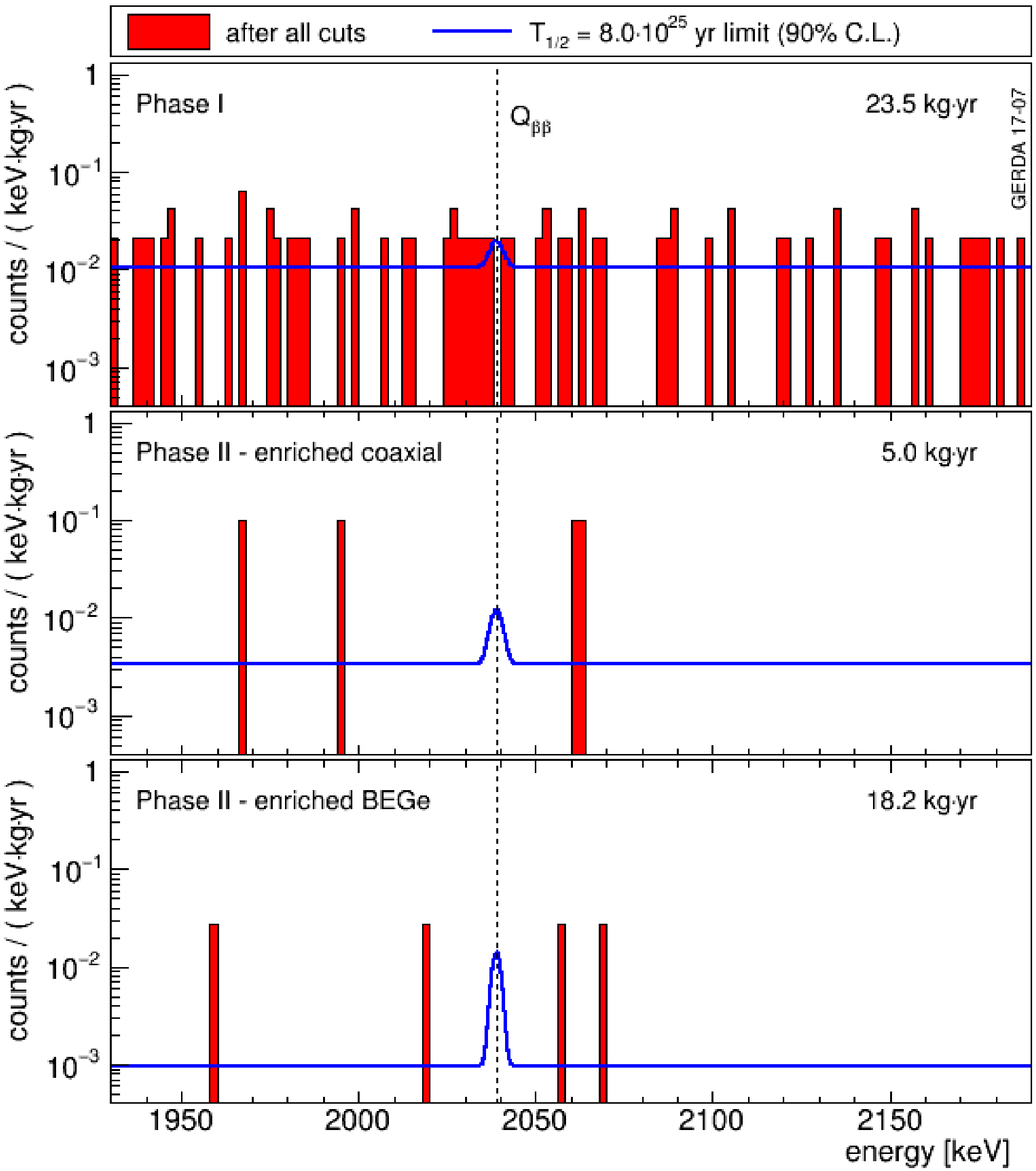
→ Phase II - coax
5.0 kg ·yr

} **same as Nature**

→ Phase II – BEGe
(5.8 + **12.4**) kg ·yr

+Frequentist approach after Cowan et al., EPJC 71 (2011) 1554

Statistical Analysis



Extended unbinned profile likehood:

- flat background in 1930-2190 keV
- signal = Gaussian with mean at $Q_{\beta\beta}$ and standard deviation σ_E
- 7 parameters: 6 BI + common $T_{1/2}$
- systematics folded in by pull terms

Preliminary

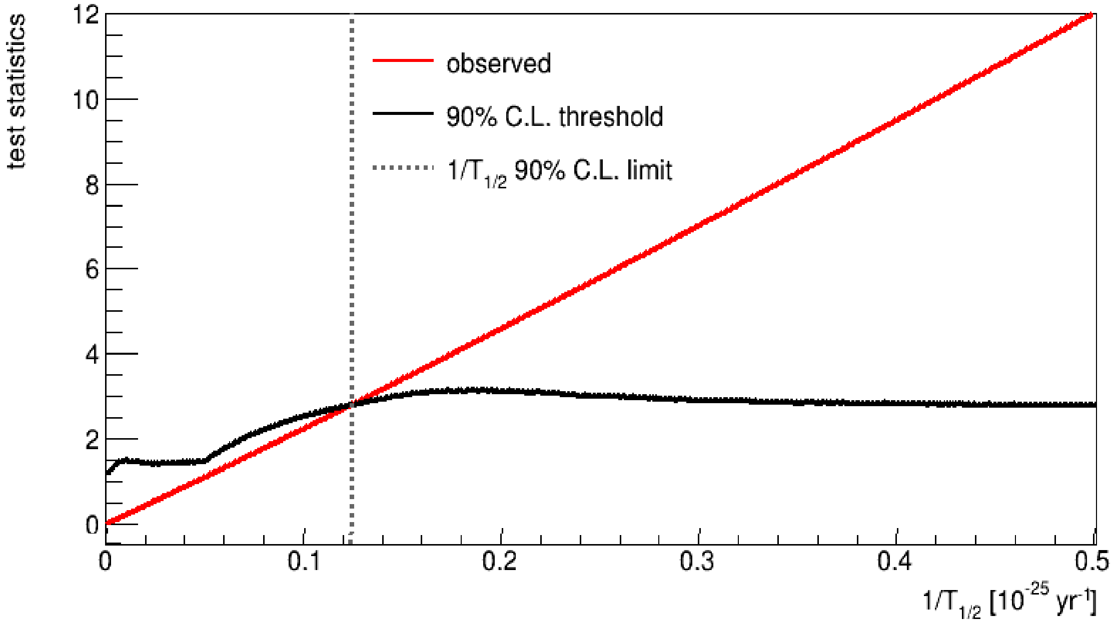
- best fit for $N_{0\nu} = 0$
- lower limit $T_{1/2} > 8.0 \cdot 10^{25}$ yr

  $m_{\beta\beta} < (120 – 270)$ meV

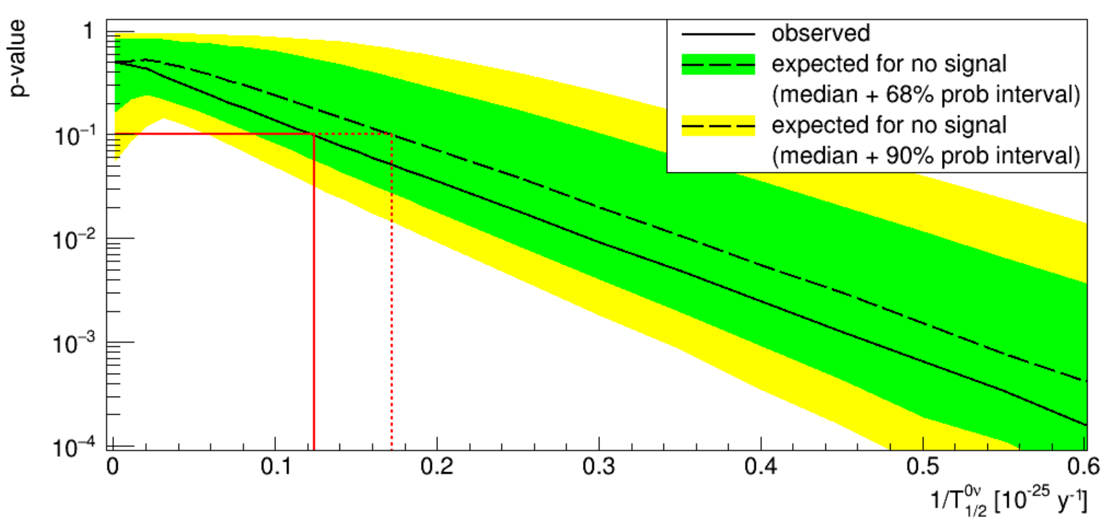
  with $T_{1/2}$ sensitivity $5.8 \cdot 10^{25}$ yr

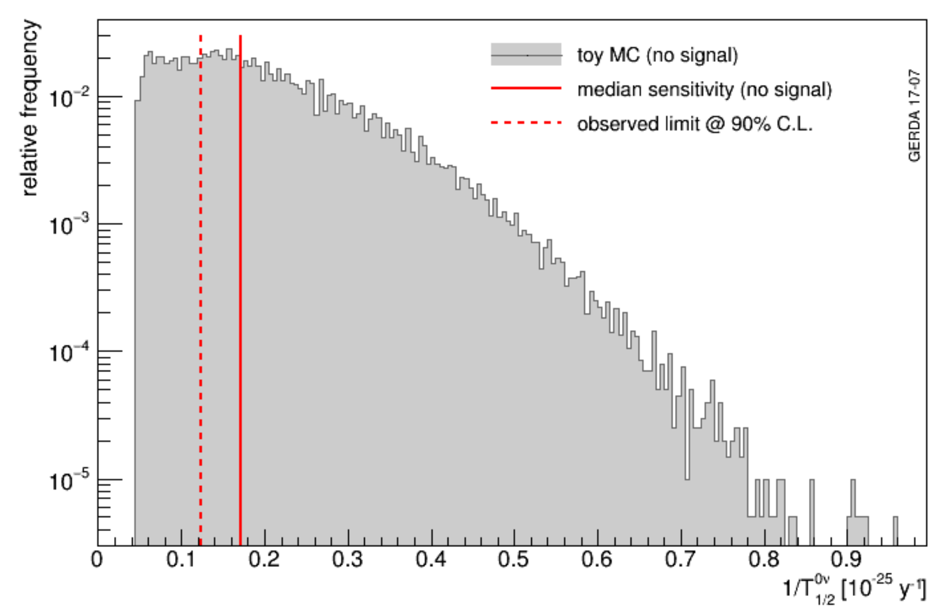
  (90 % C.L.)

The Frequentist Method



- recipe according to Cowan et al., EPJC 71 (2011) 1554
- see also Nature 544 (2017) 47, Extended "Methods" Section
- threshold for 90% CL coverage calculated by toy MC
- actual limit **stronger** than median sensitivity (30% chance)





GERDA within 0νββ Field

- KamLAND-Zen sets current best limit on 0νββ decay of ^{136}Xe:

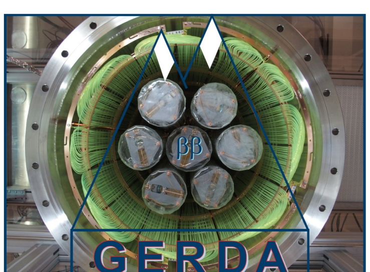
$$T^{0\nu}_{1/2} > 10.7 \cdot 10^{25}\ yr @ 90\ C.L.$$
$$m_{\beta\beta} < 165\ meV$$

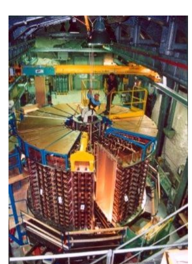
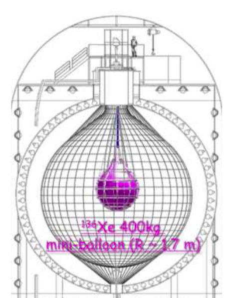
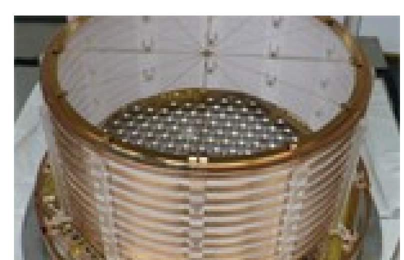
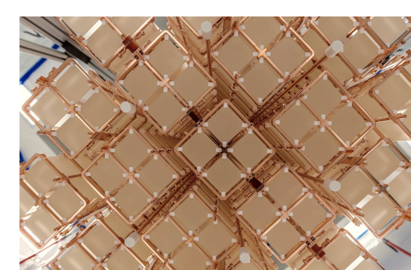
  - median sensitivity 5.6 · 10^{25} yr
  - exposure: 504 kg · yr

- GERDA sets current best limit on 0νββ decay of ^{76}Ge:

$$T^{0\nu}_{1/2} > 8.0 \cdot 10^{25}\ yr @ 90\ C.L.$$
$$m_{\beta\beta} < 270\ meV$$

  - median sensitivity 5.8 · 10^{25} yr
  - exposure: 47 kg · yr



Next Steps

- mid 2018 a sensitivity on $T_{1/2}$ of 10^{26} yr will be reached
- all ingredients for discovery:

  - excellent energy resolution (FWHM) of 2.9 keV (3.9 keV) BEGe (Coax) at $Q_{\beta\beta}$

  - flat background in ROI

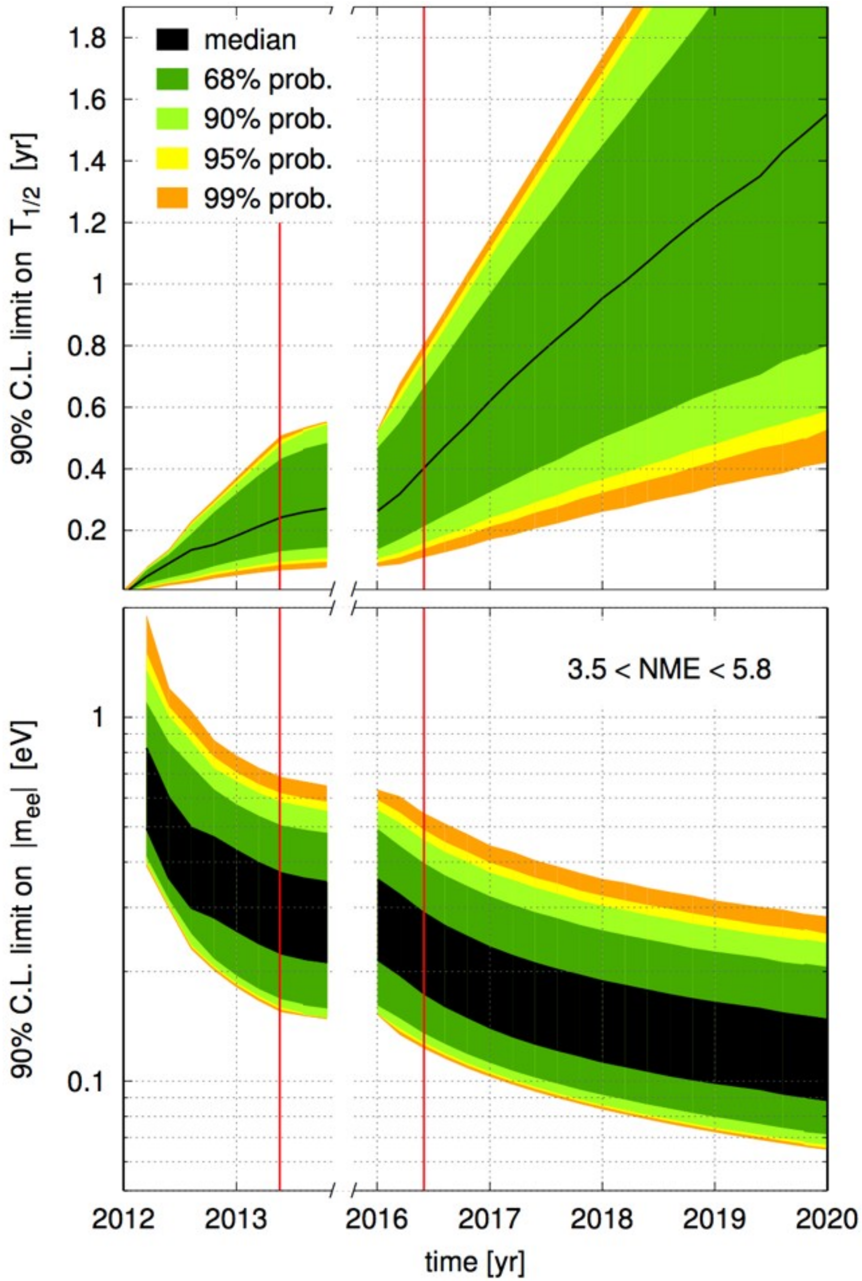
  - lowest background at $Q_{\beta\beta}$ (within FWHM): **10^{-3} counts/ (keV·kg·yr)**

- final sensitivity at design exposure 100 kg yr:

  - will stay **background-free**

  - 1.3 $\cdot 10^{26}$ yr (for **limit**)

  - 0.8 $\cdot 10^{26}$ yr (**50% for 3σ discovery**)



Beyond GERDA

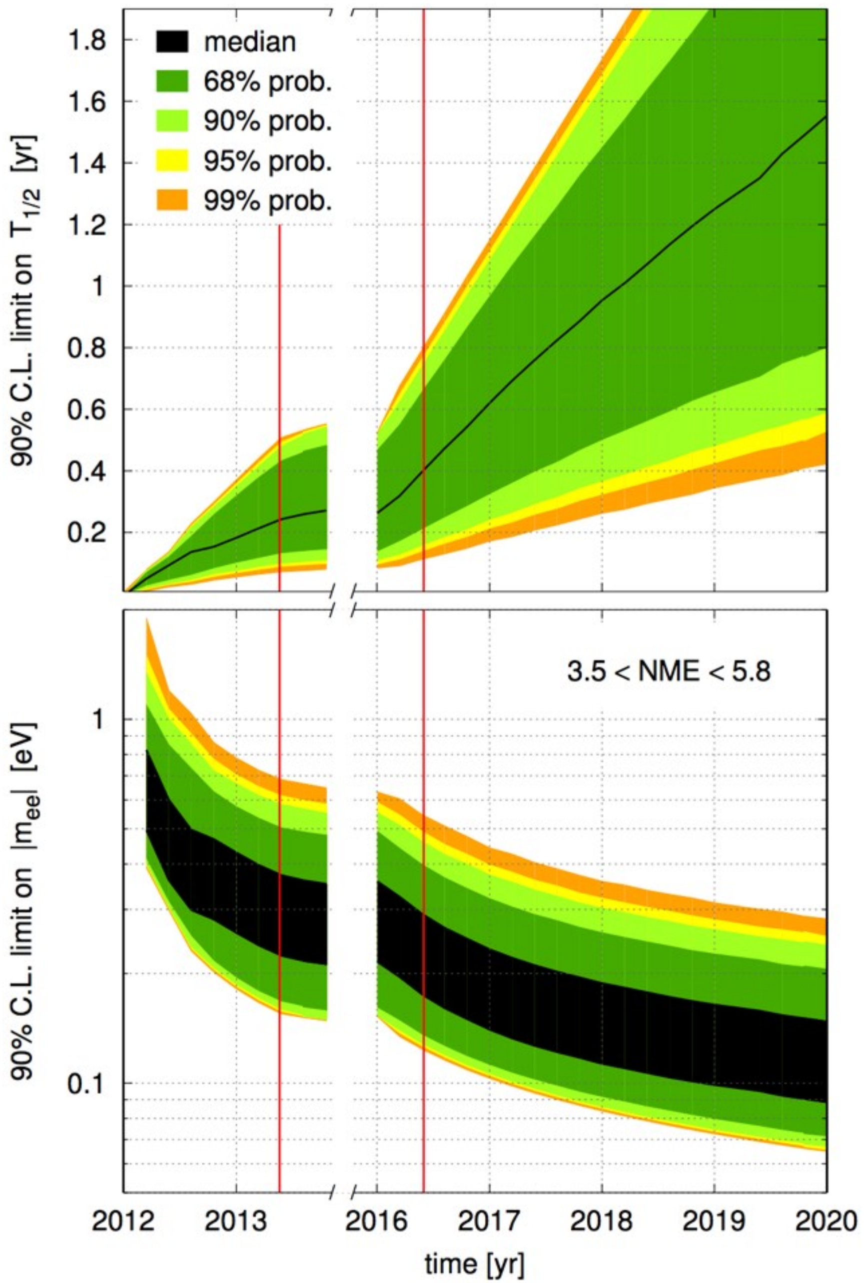
- LEGEND (Large Enriched Germanium Experiment for Neutrinoless Double Beta Decay)
- new collaboration formed in Oct 2016
  (=GERDA+Majorana+new groups)
- goals:

  - 1 t enriched Ge

  - first phase: 200 kg in existing infrastructure @ LNGS

  - reduce background with respect to GERDA → remain background-free

→ best discovery potential

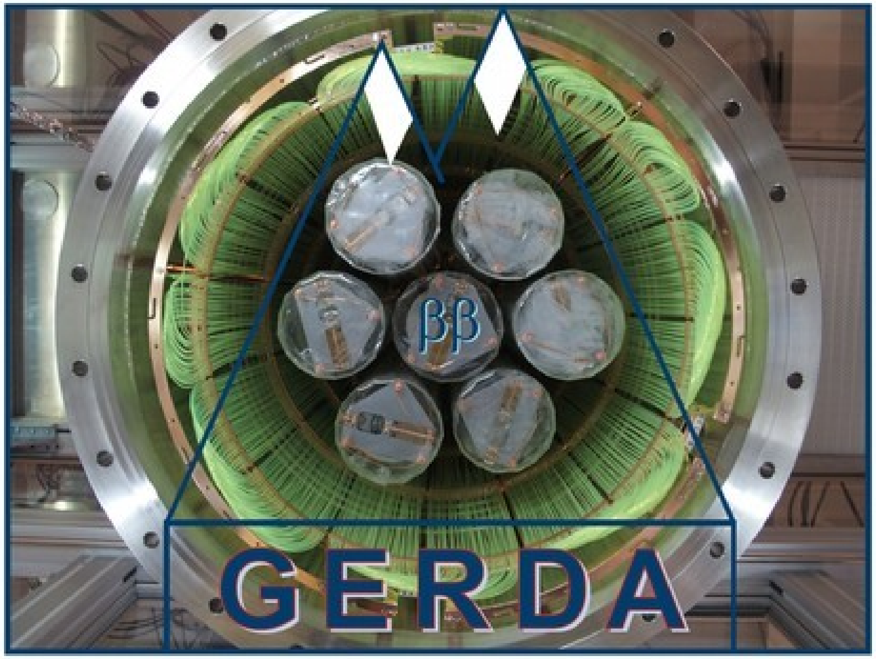


Conclusions

- GERDA proved to be a true high resolution and background free experiment
- sets a new limit on the half-life of $0\nu\beta\beta$ decay of ^{76}Ge

$$T^{0\nu}_{1/2} > 8.0 \cdot 10^{25}\, yr\ @90\ C.L.$$
$$m_{\beta\beta} < 270\, meV$$

- next generation Ge experiment **LEGEND** has best discovery potential



Bonus Slides

GERDA Spectra

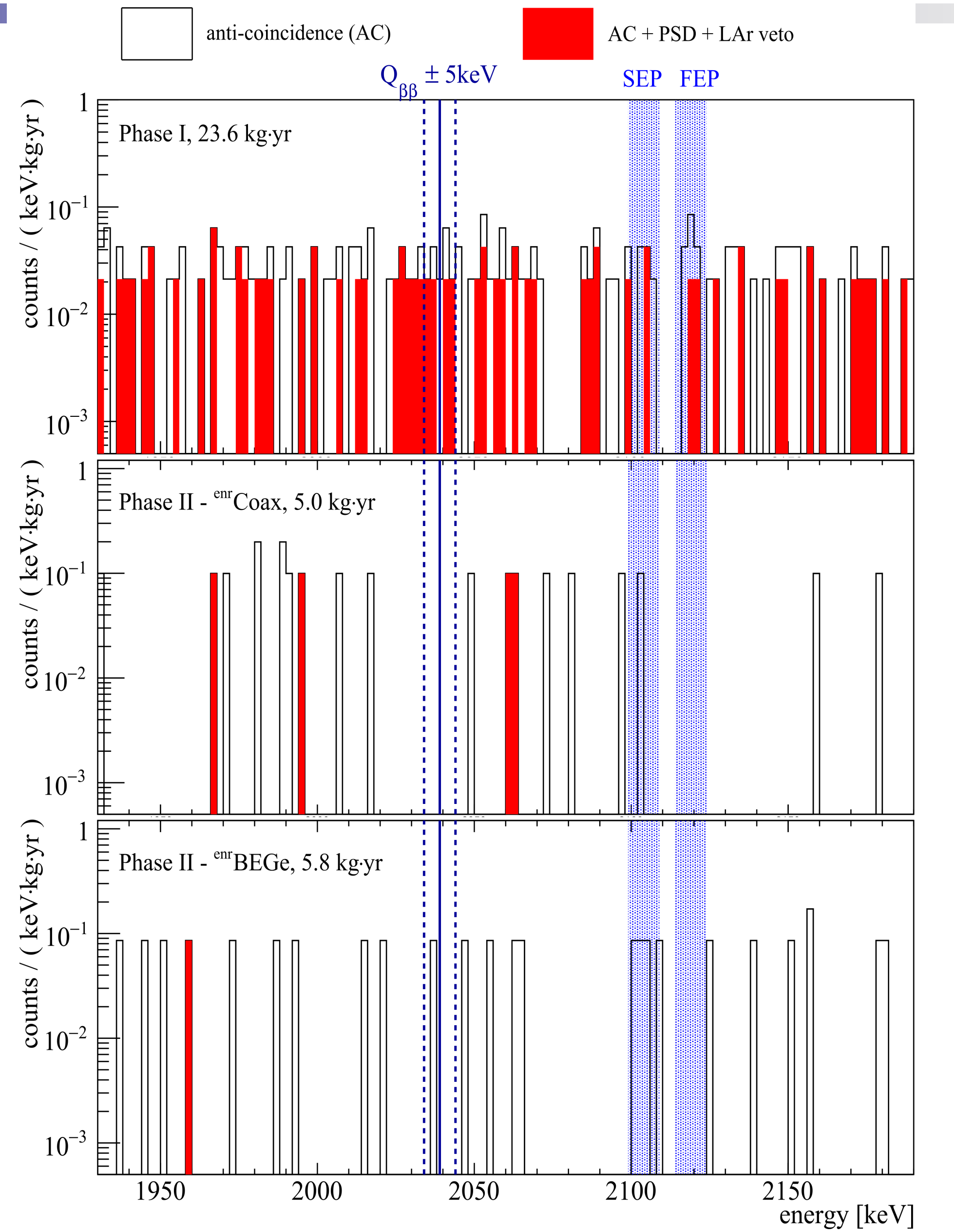
- background in ROI assumed to be flat
- + Gaussian signal centered at $Q_{\beta\beta}$
- pdf for single data set:

$$f(E|b,\frac{1}{T^{0\nu}_{1/2}})=\frac{1}{240\,keV\cdot b+N_{0\nu}}\left(b+\frac{N^{0\nu}}{\sqrt{2\pi}\cdot\sigma}\exp\frac{-(E-Q_{\beta\beta})^2}{2\sigma^2}\right)$$

- extended unbinned likelihood function

$$L(b,\frac{1}{T^{0\nu}_{1/2}})=\prod_k\frac{\mu^{N_k}\cdot e^{-\mu_k}}{N_k!}\prod_{i=0}^{N}f(E_i|b_k,\frac{1}{T^{0\nu}_{1/2}})$$

b_k: BI for given data set,
σ: energy resolution in given data set,
μ_k = b· 240 keV + $N_{0\nu}$ number of expected events



Phase I + II Data Sets (June 2016)

$$\left(T_{1/2}^{0\nu}\right)^{-1} \propto N_{0\nu} = \frac{\ln 2 \cdot N_A}{m_{76}} \frac{M \cdot t}{T_{1/2}^{0\nu}} \cdot \epsilon \cdot \epsilon_{PSD} \cdot \epsilon_{LAr}$$

N_A: Avogadro's constant, m_{76}: molar mass of ^{76}Ge
$M \cdot t$: exposure [kg yr], $T_{1/2}$: half-life of $0\nu\beta\beta$ decay,
ε_{LAr}: LAr efficiency, ε_{PSD}: PSD efficiency,
ε: exposure averaged efficiency incl. active volume, enrichement, FEP

data set	exposure [kg yr]	signal eff	Energy resolution (keV, FWHM)	Background index 0.001 cnts/(keV kg yr)
Phase I gold	17.9	0.57 (3)	4.3 (1)	11 ± 2
Phase I silver	1.3	0.57 (3)	4.3 (1)	30 ± 10
Phase I BEGe	2.4	0.66 (2)	2.7 (2)	5^{+4}_{-3}
Phase I extra	1.9	0.58 (4)	4.2 (2)	5^{+4}_{-2}
Phase II coax	**5.0**	**0.53 (4)**	**4.0 (2)**	$\mathbf{3^{+3}_{-1}}$
Phase II BEGe	**5.8**	**0.60 (1)**	**3.0 (2)**	$\mathbf{0.7^{+1.3}_{-0.5}}$

Comparison of Searches

$$\frac{1}{T_{1/2}^{0\nu}} = G^{0\nu}(Q,Z)\cdot|M^{0\nu}|^2\cdot\left(\frac{m_{\beta\beta}}{m_e}\right)^2$$

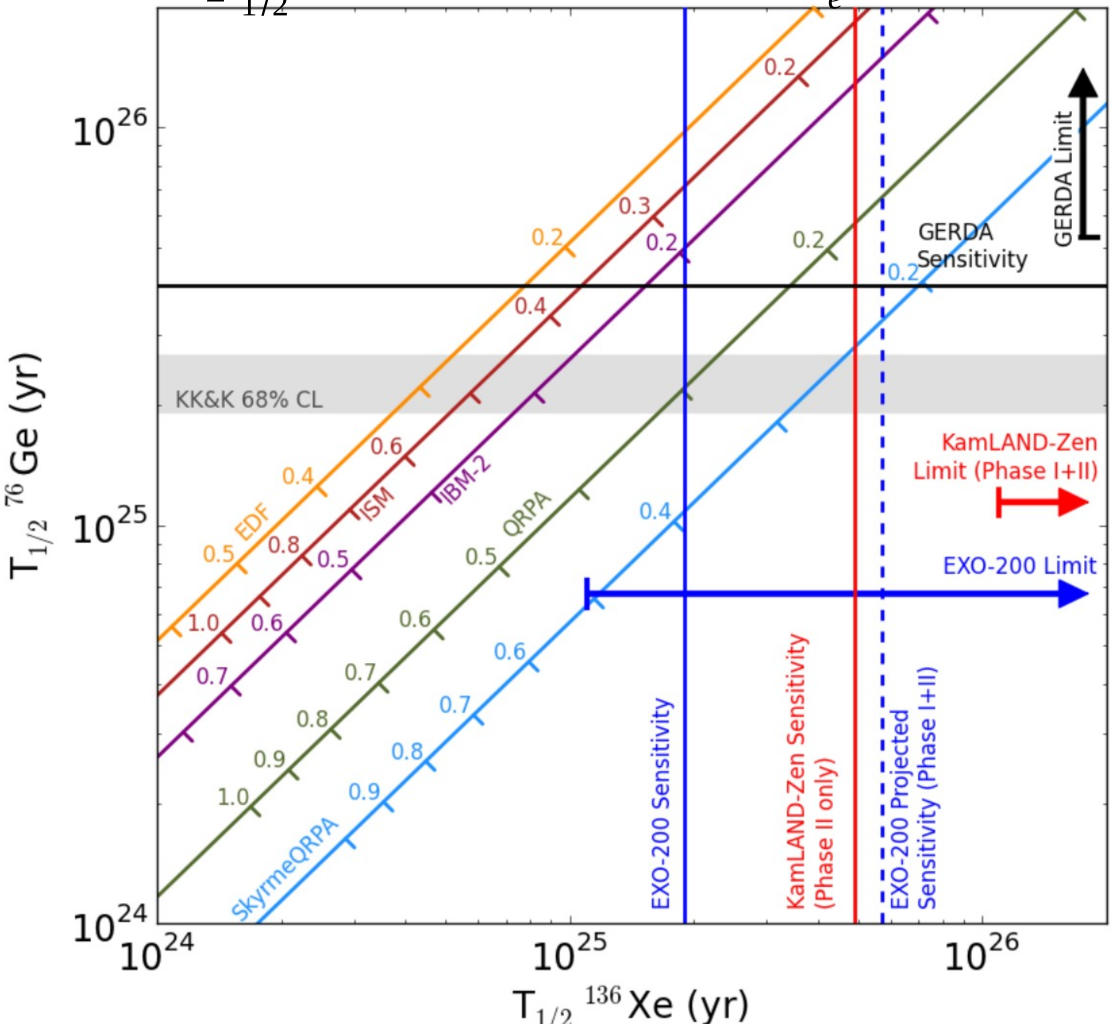
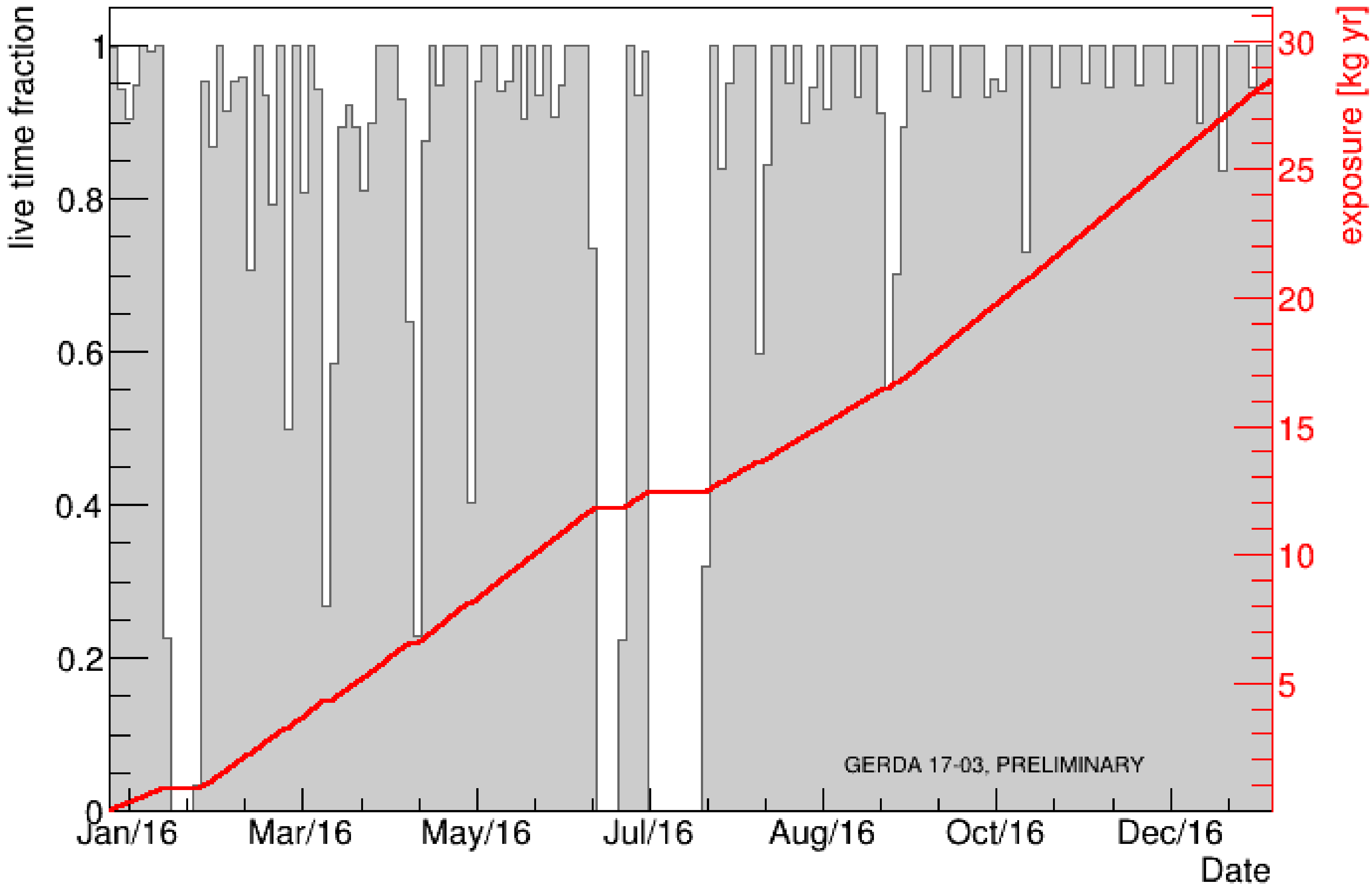


figure taken from L. Yang, talk at Neutrino 2016, London

Duty Cycle

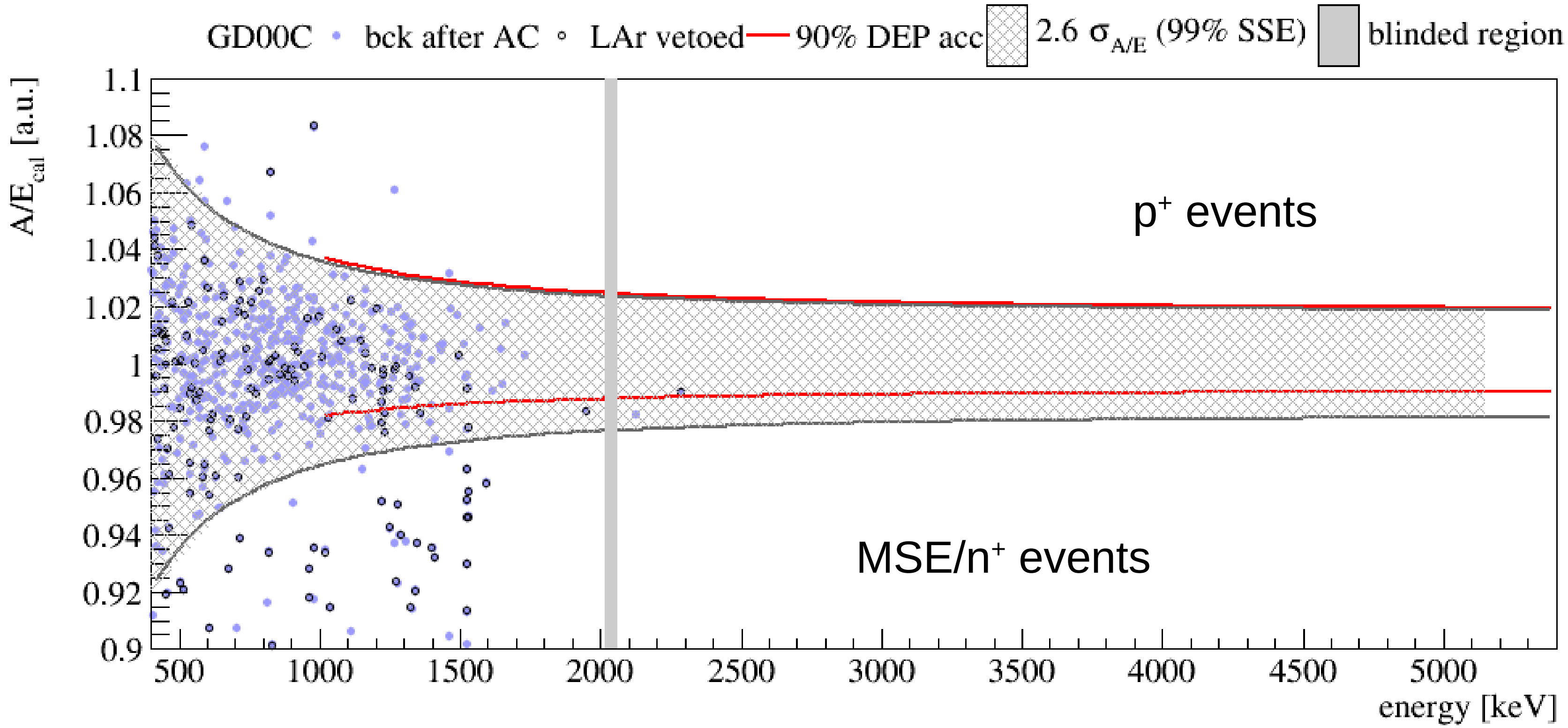


live time fraction
exposure [kg yr]
GERDA 17-03, PRELIMINARY
0
0.2
0.4
0.6
0.8
1
5
10
15
20
25
30
Jan/16
Mar/16
May/16
Jul/16
Aug/16
Oct/16
Dec/16
Date

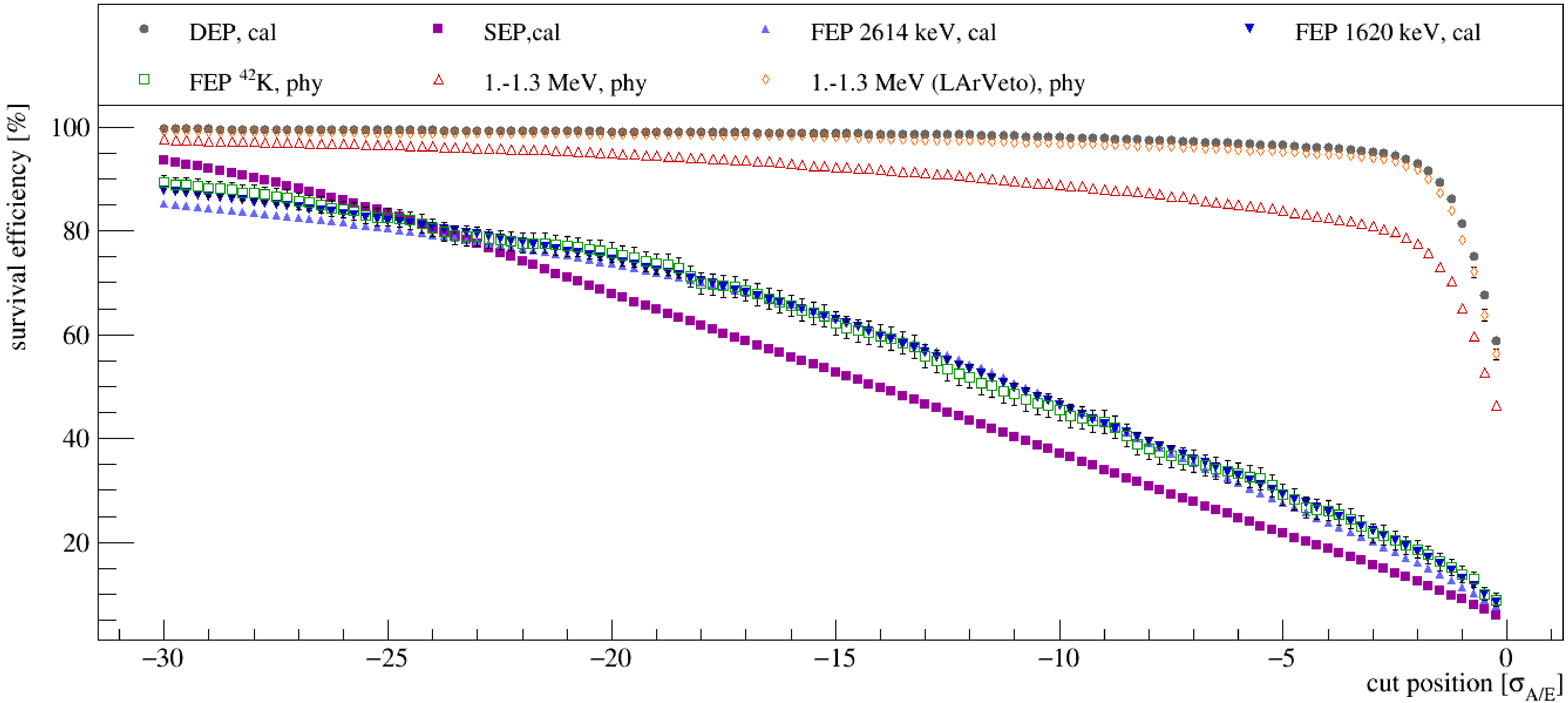
A/E Cut

Detector based A/E cut

- energy dependent cut following A/E broadening
- MSE/ n^+ cut set to 90% acceptance in DEP
- p^+ cut twice the distance to A/E = 1



Survival Efficiencies vs Cut Position



$0\nu\beta\beta$ Signal Efficiency

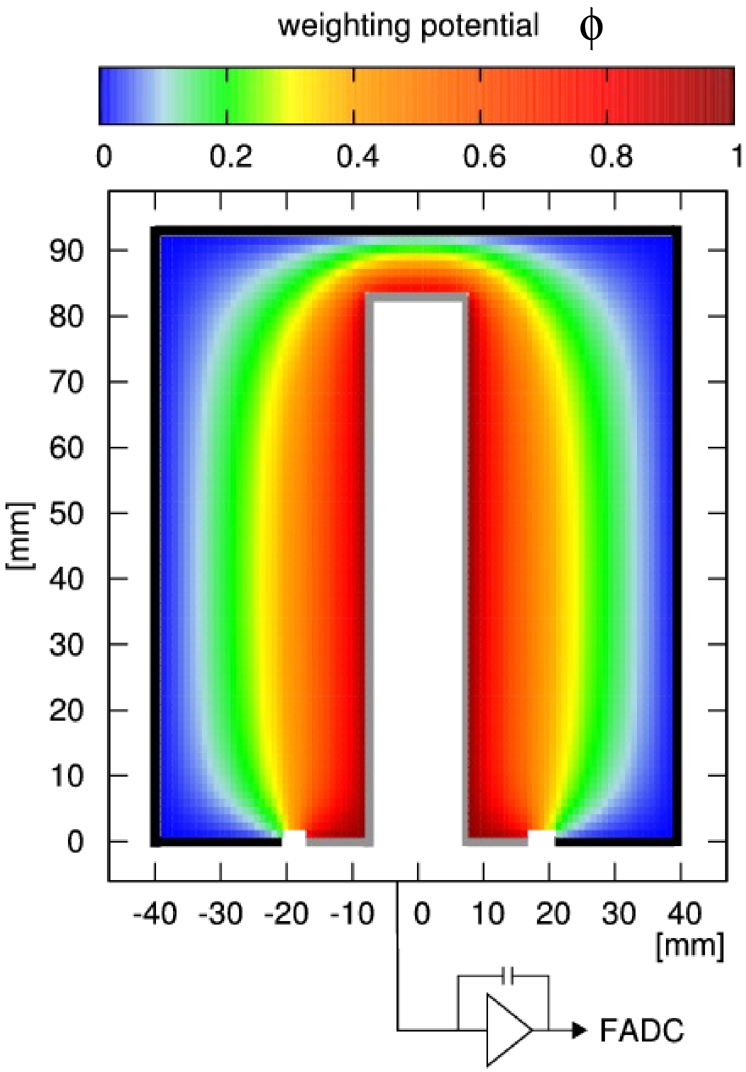
- signal efficiency given by DEP acceptance
- final signal efficiency:

$$(87.4 \pm 0.2(\text{stat}) \pm 2.6\ (\text{sys}))\%$$

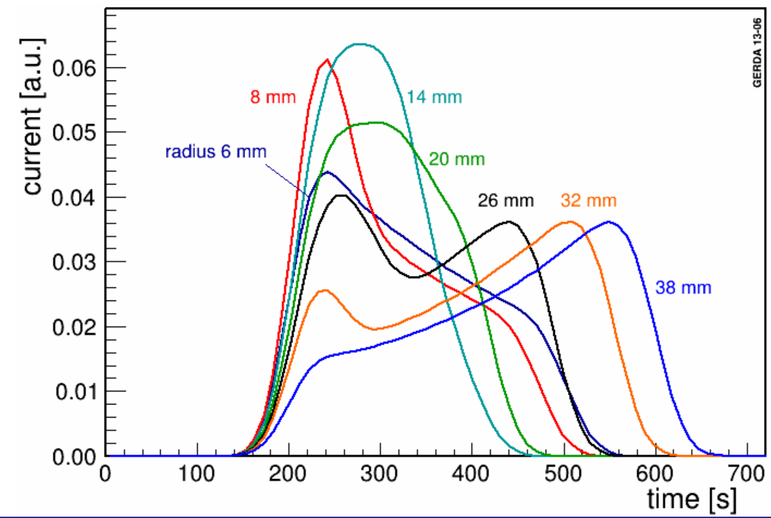
uncertainty	[%]
statistics	0.21
diff. phy and cal	0.80
energy dep. cut	0.24
energy scale of A/E	0.06
geometrical distribution	1.03
Instability A/E scale	1.0
topology of $0\nu\beta\beta$ events	2.03

PSD with Coaxial HPGe

more detail in Eur.Phys.J C73 (2013) 2583



current signal = $q \cdot v \cdot \Delta\phi$
q: charge, v: velocity

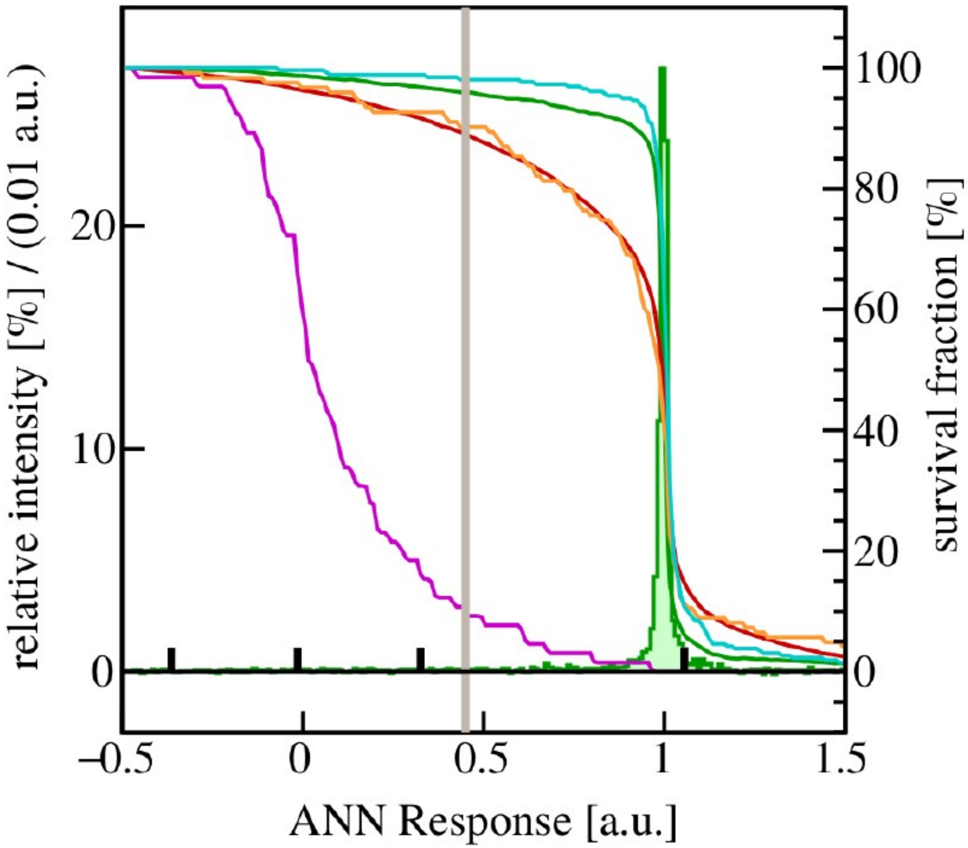


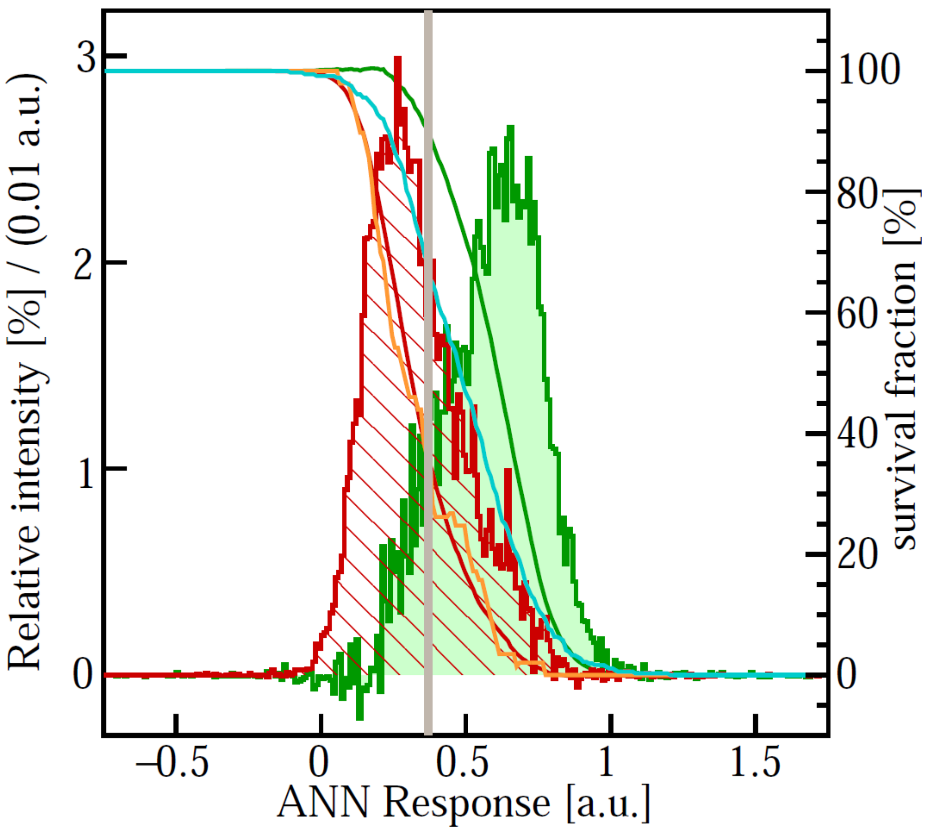
- To identify signal like events artificial neural network algorithm TMlpANN from TMVA is used
- Input variables: times when charge pulse reach 1%, 3%, … , 99% of maximum amplitude
- DEP events of at 1503 keV serve as signal sample
- FEP events at 1621 keV as multi site event sample

- second training on $2\nu\beta\beta$ and α events

- **combined $0\nu\beta\beta$ signal efficiency is (79±5) %**

Coax PSD





— $2\nu\beta\beta$ [1000 keV,1300 keV]

— α [3500 keV,4500 keV]

□ ^{208}Tl DEP

— ^{212}Bi FEP

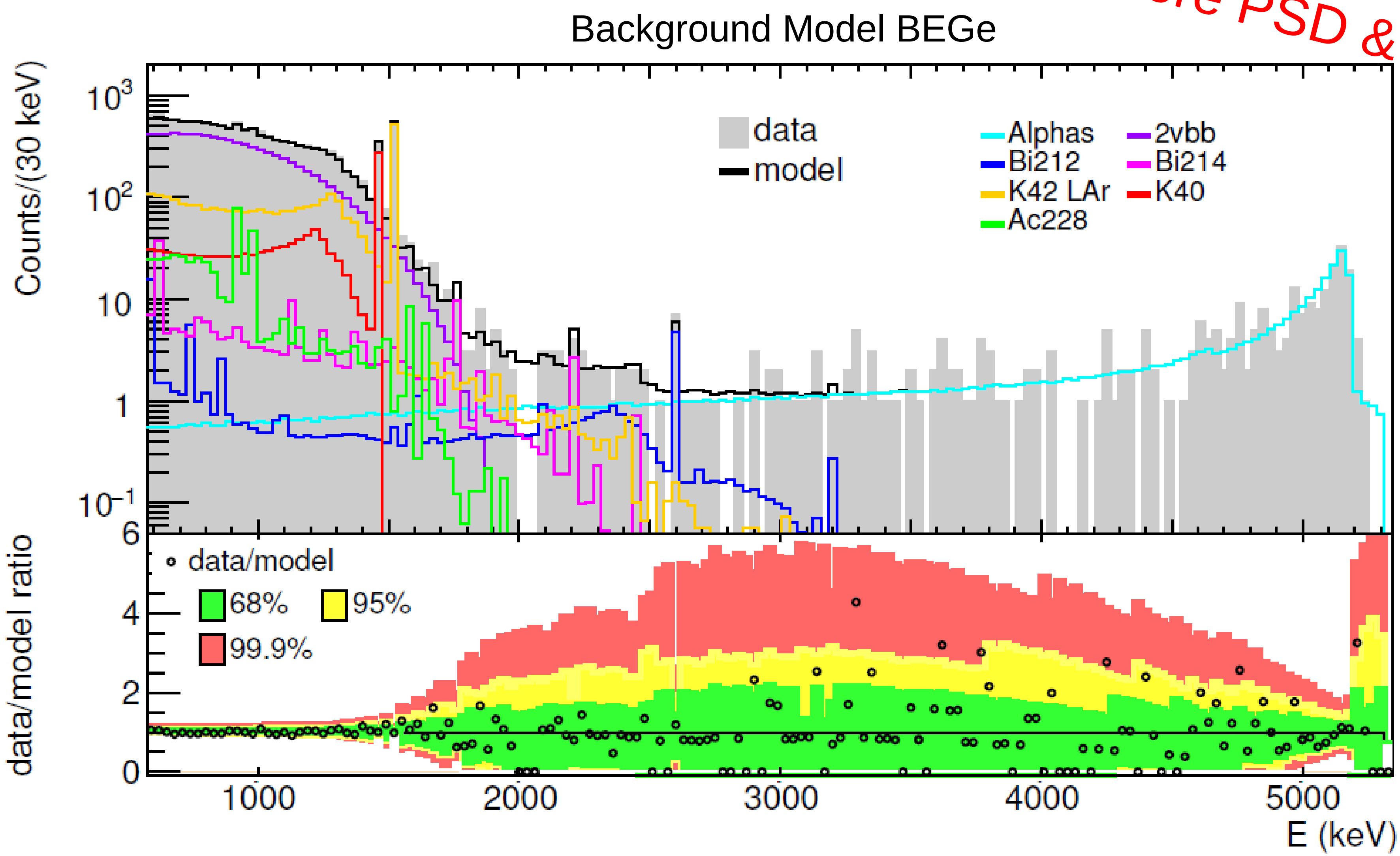
— ^{42}K FEP

□ ^{208}Tl DEP

▨ ^{208}Tl SEP

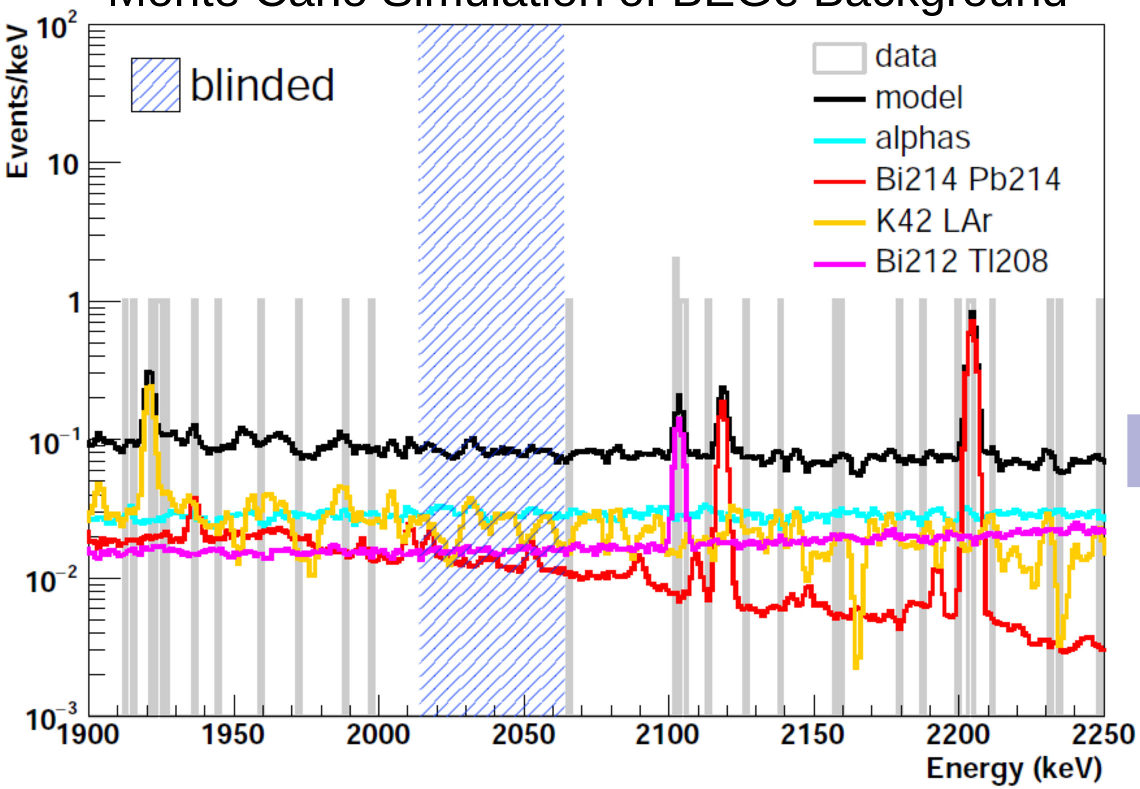
Background Model

Preliminary results
before PSD & LAr veto



Background Composition at $Q_{\beta\beta}$

Monte Carlo Simulation of BEGe Background



Preliminary results before PSD & LAr veto

expect flat background in ROI

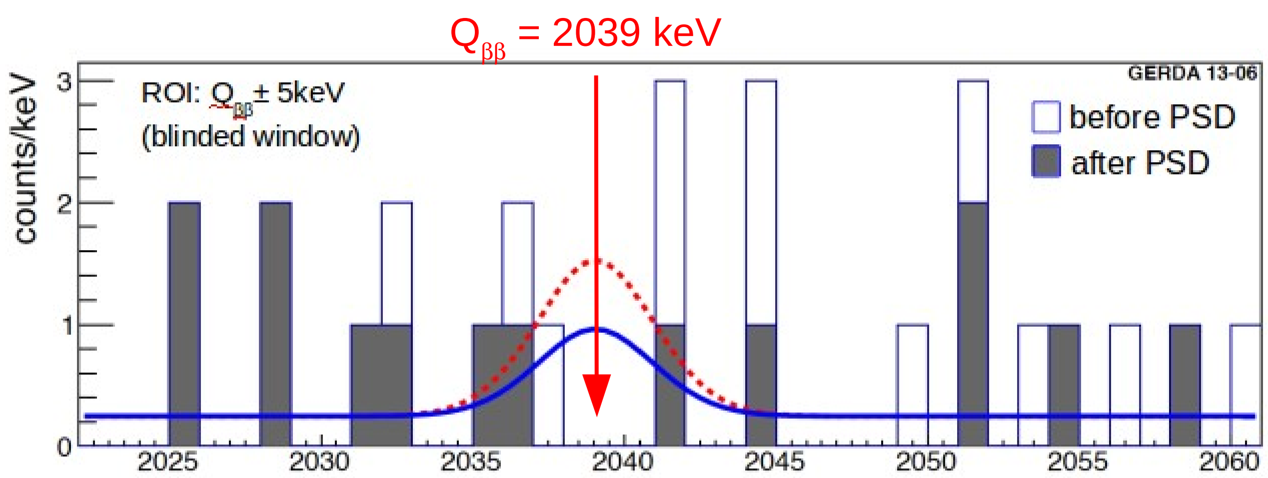
	^{enr}BEGe	^{enr}Coax
α	~ 1/3	~ 1/3
^{214}Bi and ^{208}Tl	~ 1/3	~ 1/3
^{42}K LAr	~ 1/3	~ 1/3
BI counts/(keV kg yr)	0.014	0.015

Results from GERDA Phase I

- 21.6 kg · y exposure
- blind analysis: events in ROI not available for analysis
- background index (BI) after pulse shape discrimination

$$BI = 1.0(1) \cdot 10^{-2} \frac{\text{counts}}{\text{keV kg yr}}$$

- 10 times better BI than previous experiments



number of events in $Q_{\beta\beta} \pm 2\sigma_E$ after cuts (gray):

- 2.0 ± 0.3 expected from background
- 3 observed

no signal observed at $Q_{\beta\beta}$

profile likelihood: best fit for $N_{0\nu\beta\beta} = 0$

→ limit on the half-life

$$T^{0\nu}_{1/2} > 2.1 \cdot 10^{25}\ \text{yr}$$

(90% C.L.)

→ claim rejected with 99% probability

GERDA: 90% lower limit ($T^{0\nu}_{1/2}$) [Phys. Rev. Lett. 111 (2013) 122503]

Claim: $T^{0\nu}_{1/2} = 1.19 \times 10^{25}$ yr [Phys. Lett. B 586 198(2004)]