Searching for neutrinoless double-beta decay with GERDA

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Laboratori Nazionali del Gran Sasso - INFN

Searching for 0νββ of ^{76}Ge

^{76}Ge → ^{76}Se + 2e$^-$

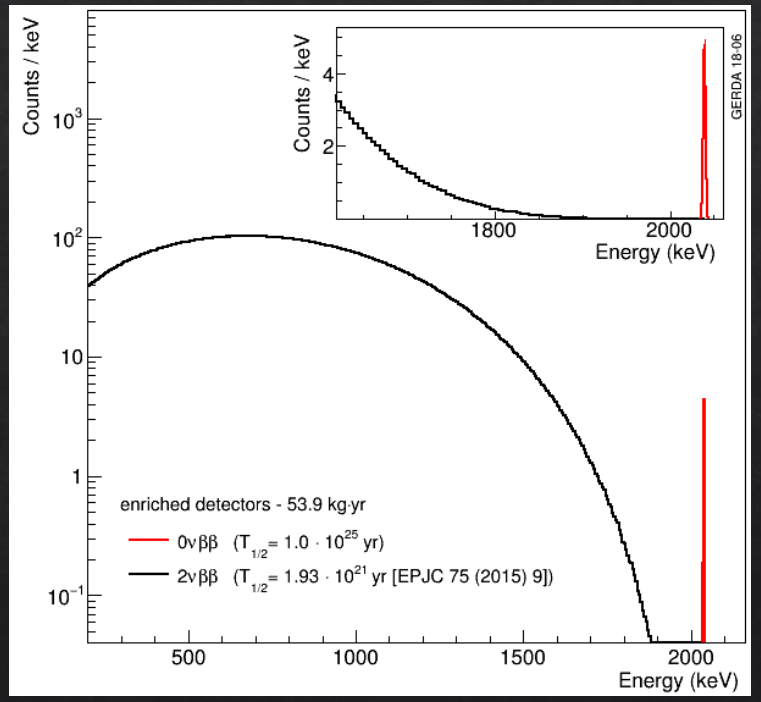
- ΔL = 2 → beyond Standard Model physics
- determines the nature of neutrinos: **Majorana particle $\nu = \nu$**;
- gives information on the ν mass via $m_{\beta\beta}$ (light neutrino exchange scenario)

Why high purity Ge detectors?

- source = detector → high efficiency
- radio-pure → no intrinsic background
- high density → e$^-$ absorbed in 1-2 mm
- semiconductor → ΔE < 0.1% at $Q_{\beta\beta}$
- enrichment up to 87% in ^{76}Ge

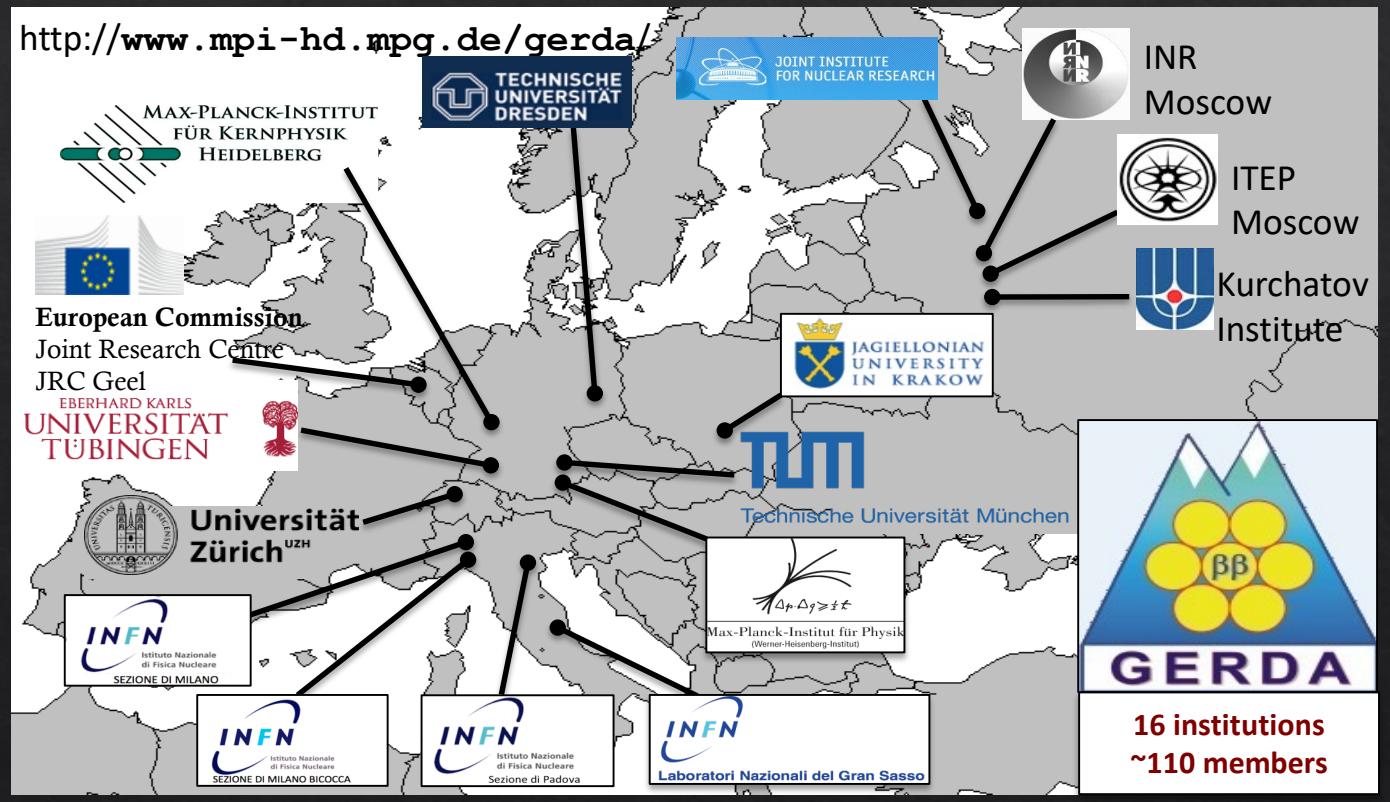
0νββ signature:

- point-like energy deposition in detector bulk volume
- sharp energy peak at 2039 keV (FWHM = 3-4 keV)

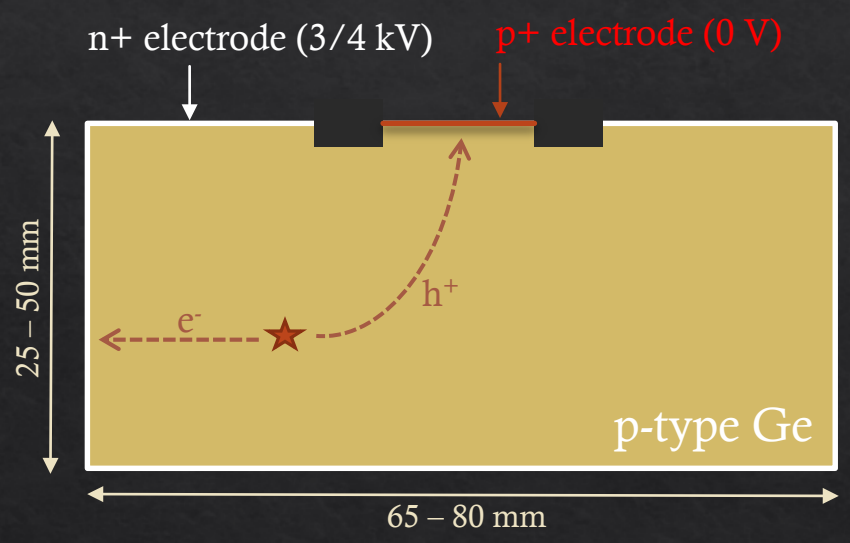


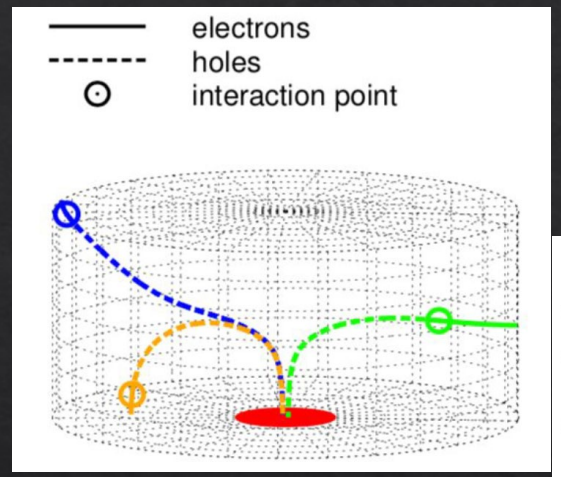
The GERDA experiment

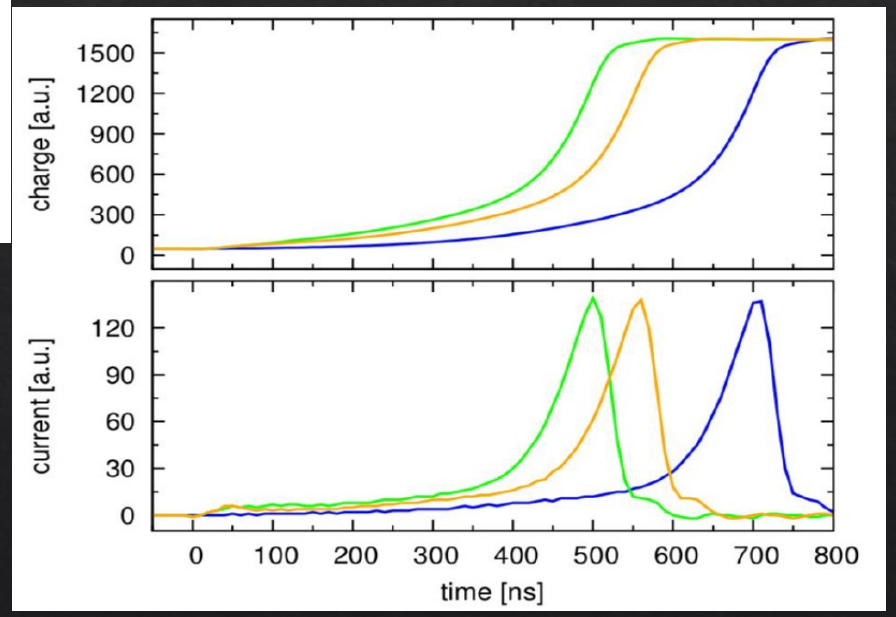
LNGS site: 3600 w.m.e



Germanium detectors







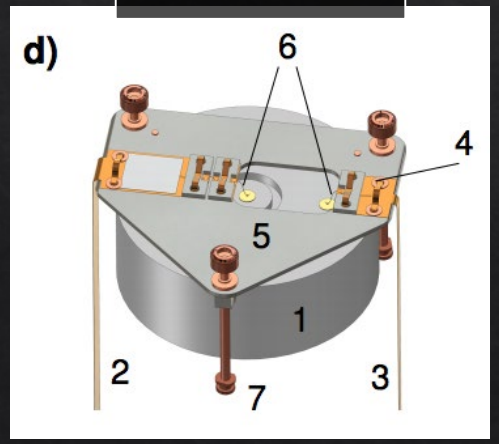
HPGe detector signals:

- ➢ signal induced by drift of electron-hole clusters
- ➢ identification of events with multiple energy depositions
- ➢ identification of events on the surface

GERDA phase II setup

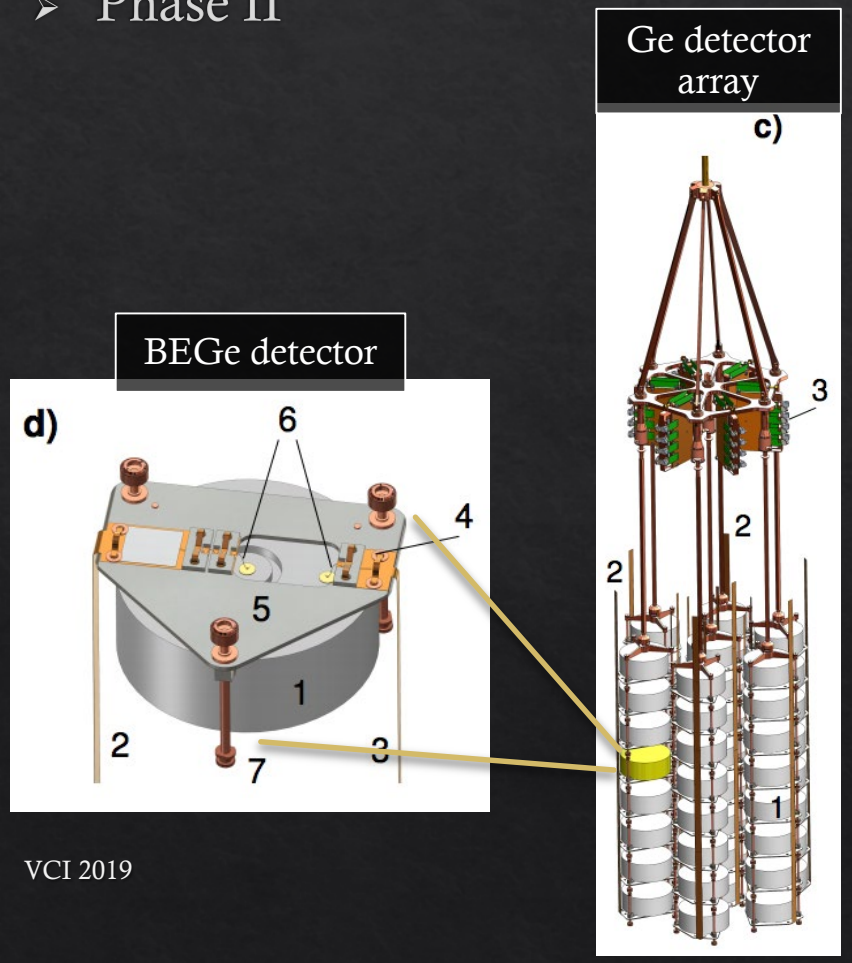
- Phase II

BEGe detector



GERDA phase II setup

- Phase II



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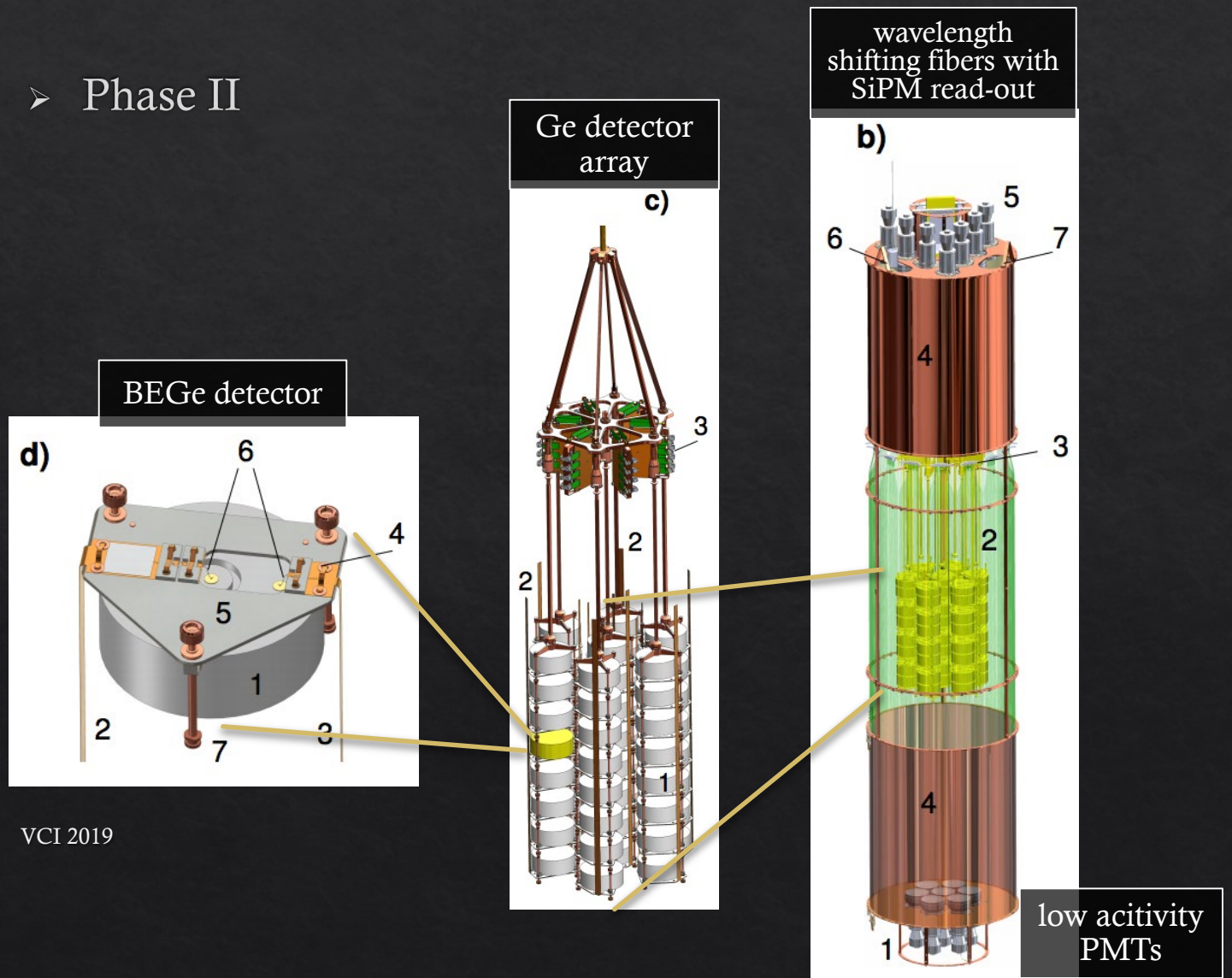

GERDA phase II setup

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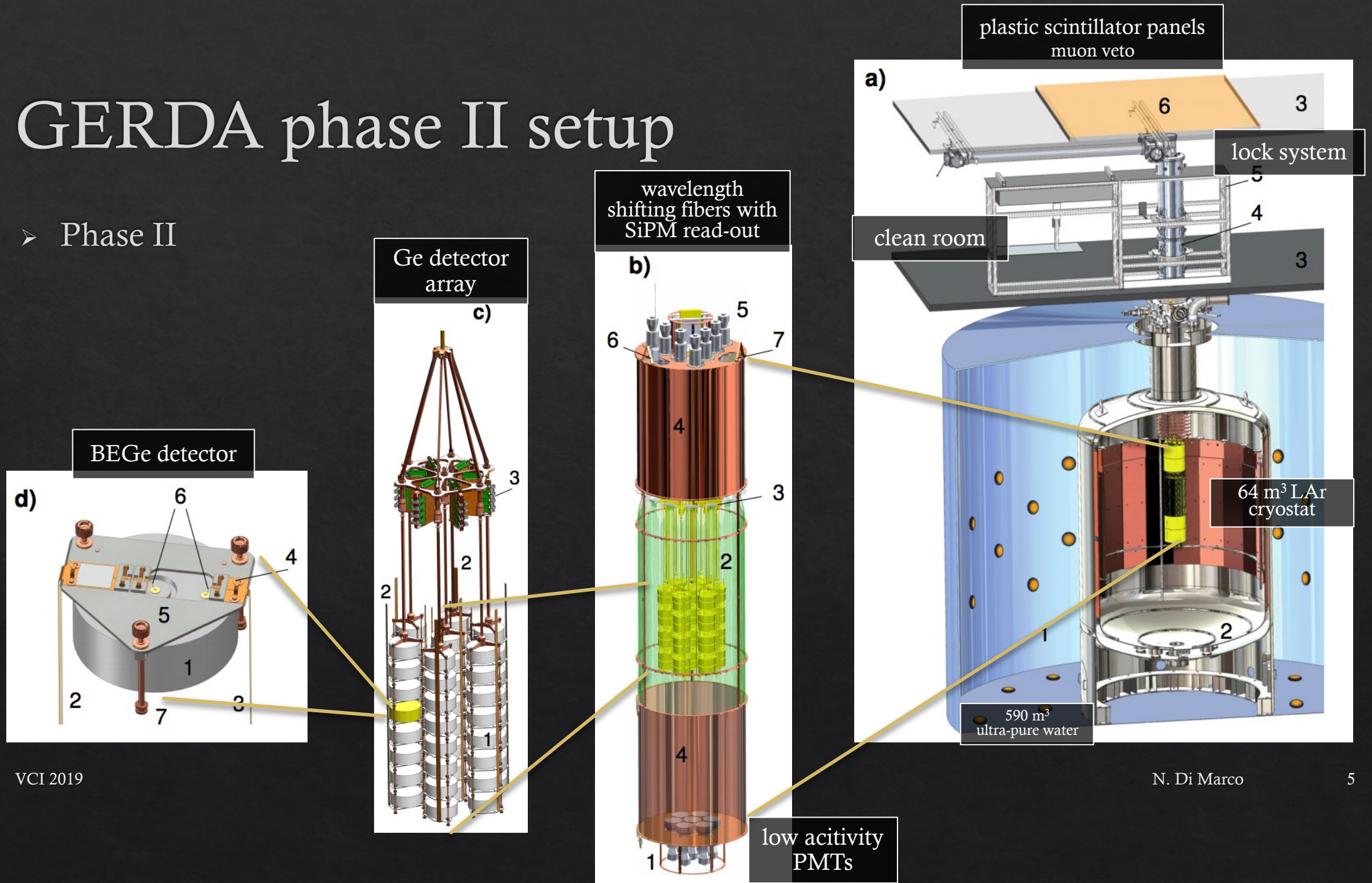
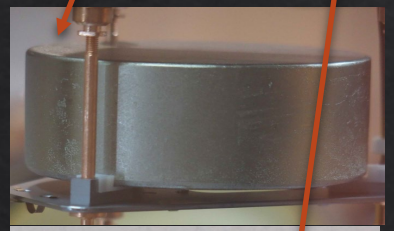
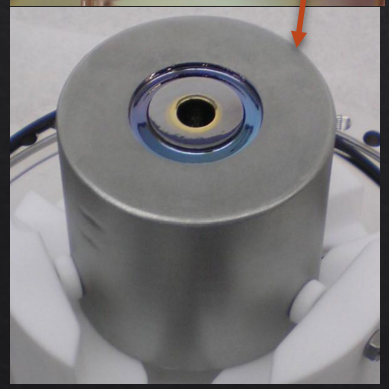


GERDA phase II setup

30 ^{enr}**BEGe** (20 kg)
7 ^{enr}**Coax** (16 kg)
3 ^{nat}**Coax** (8 kg)





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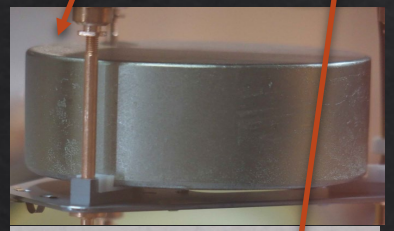

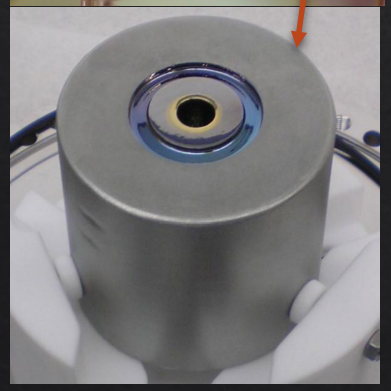

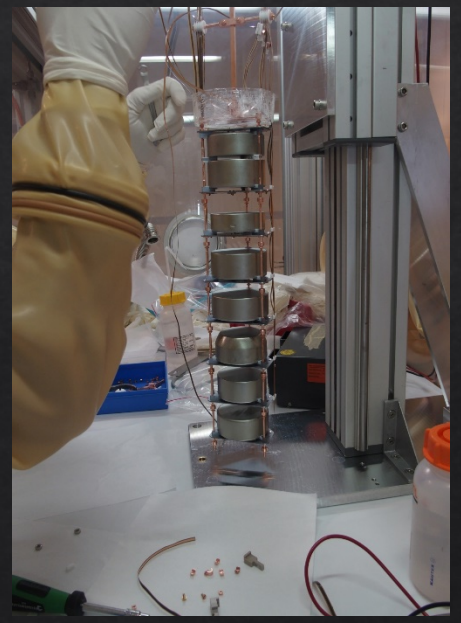

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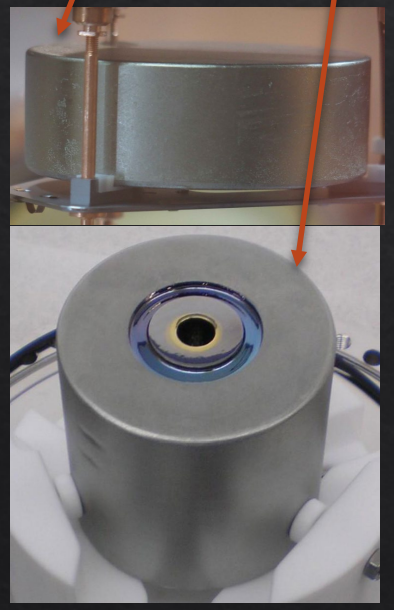

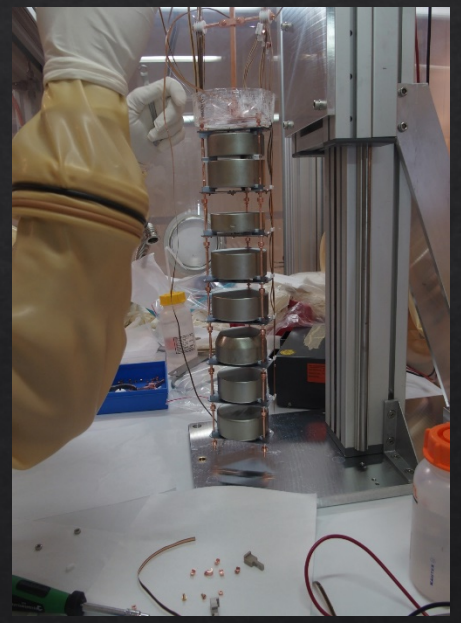

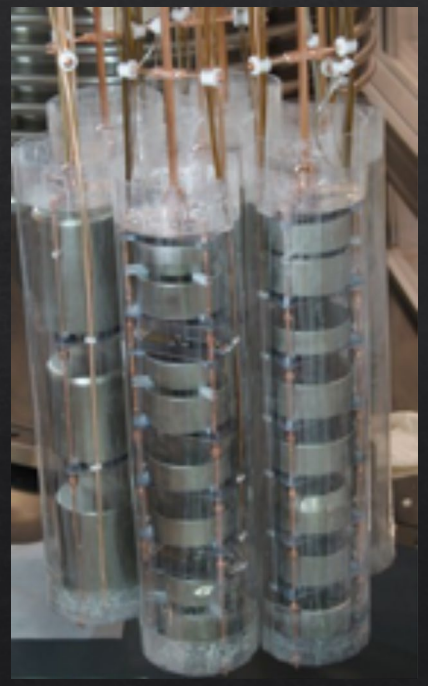

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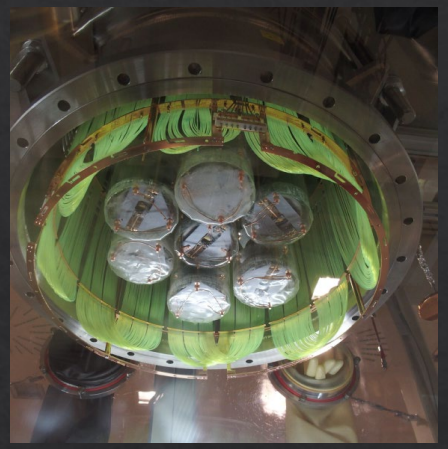

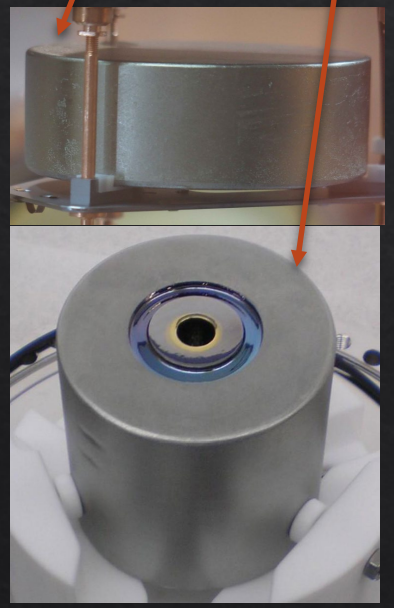

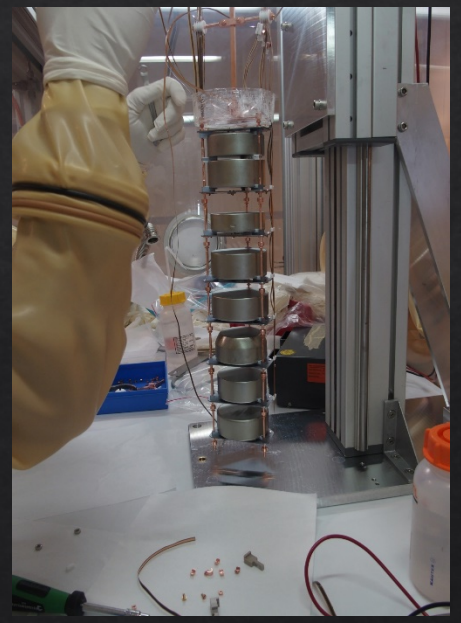

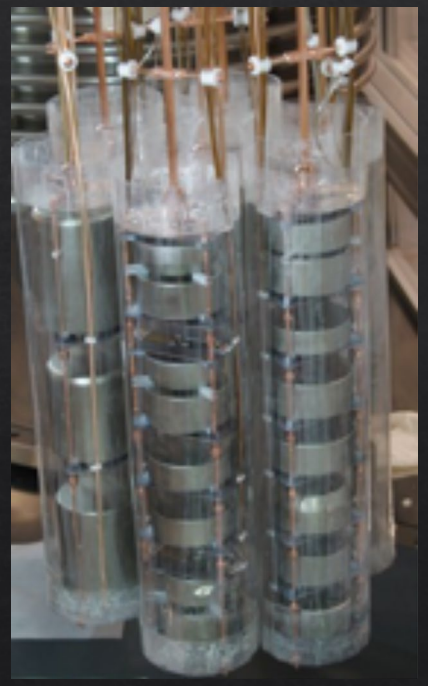

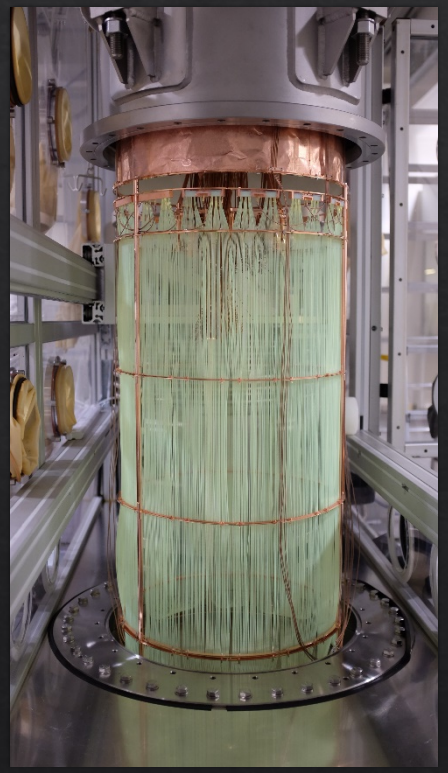

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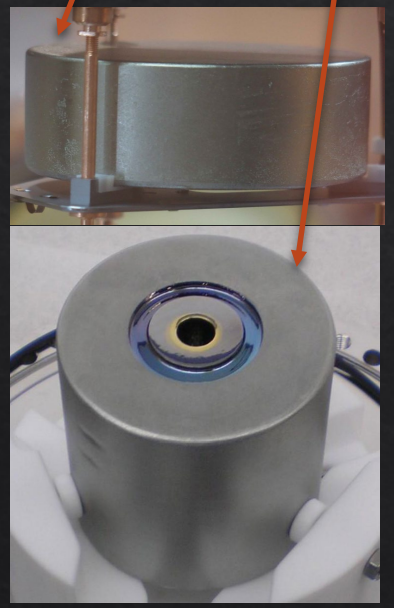

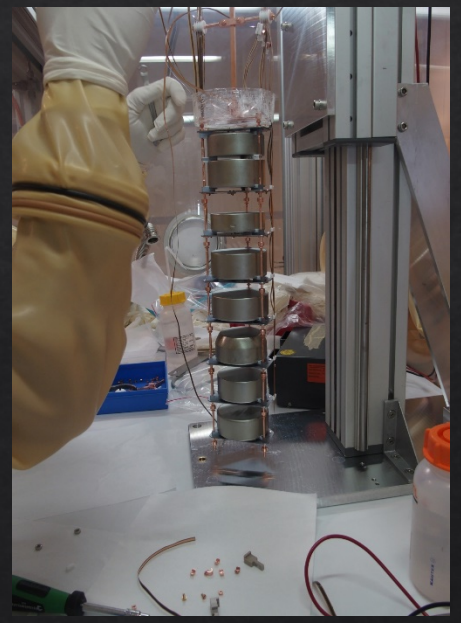

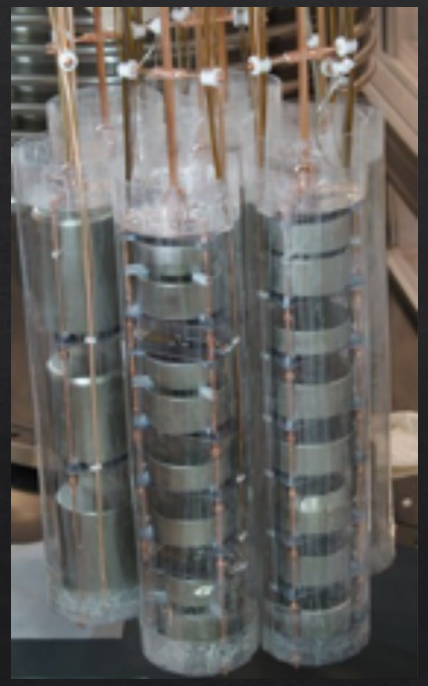

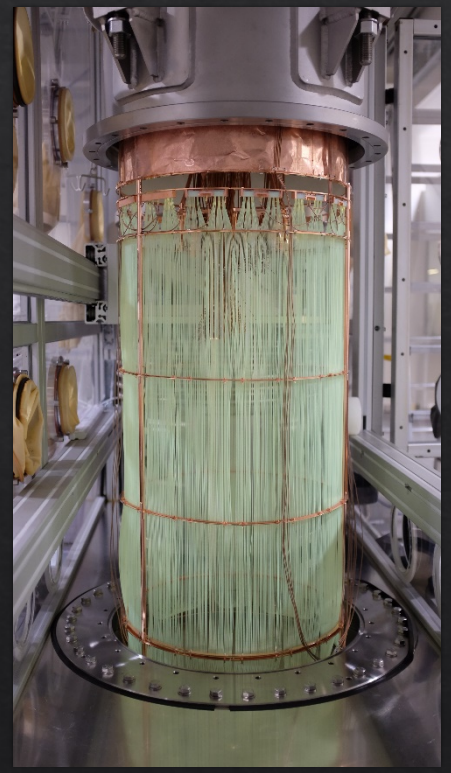

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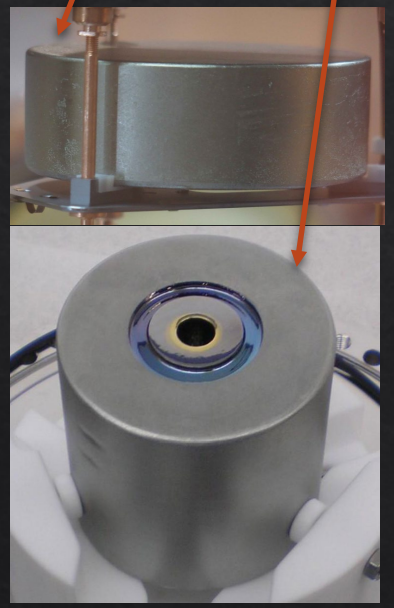
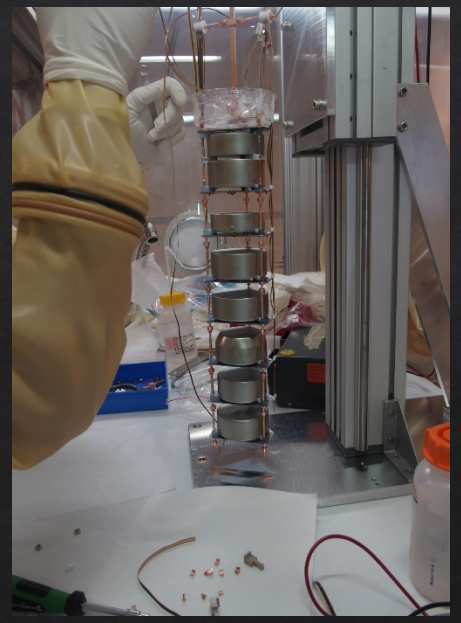
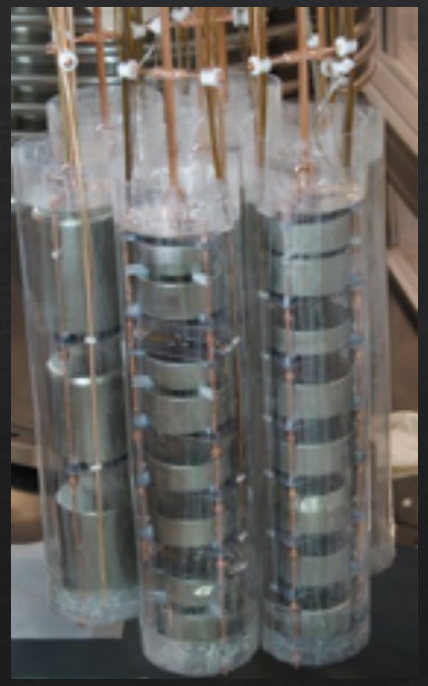
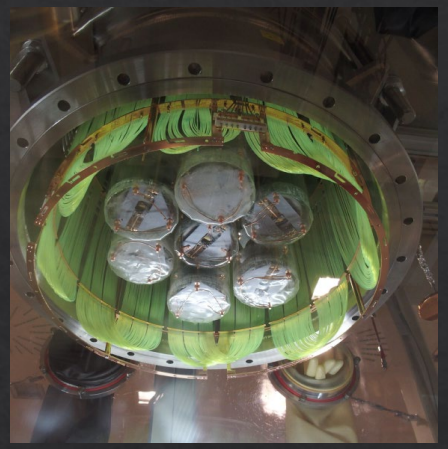
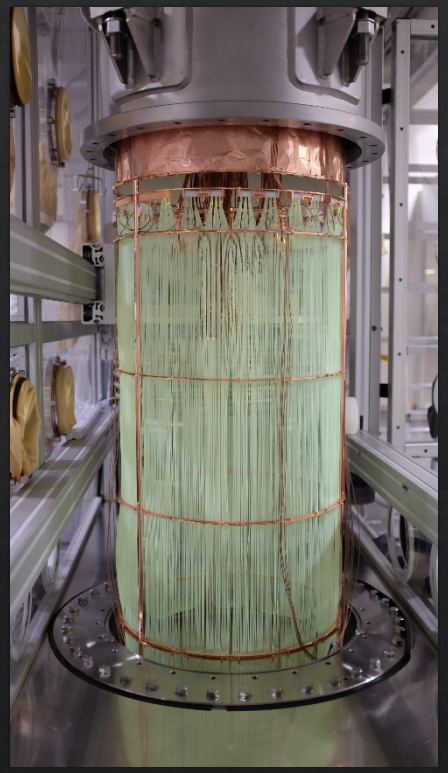










GERDA phase II - UPGRADE

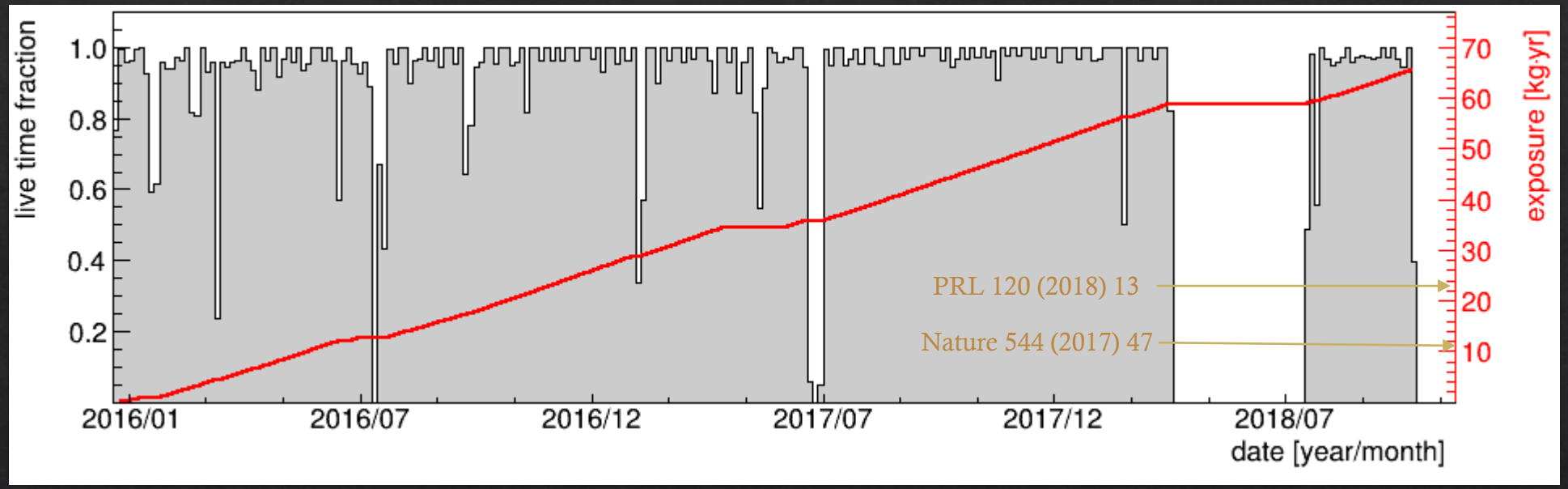
@ May 2018

- Improved electronics noise
- Increased LAr light collection

  (new fibers + new central module)
- Increased the enriched mass by 9.5 kg

  (remove nat. detectors → add inverted coax "IC")

Data taking / Duty cycle



Phase II: Dec 2015 → Apr 2018

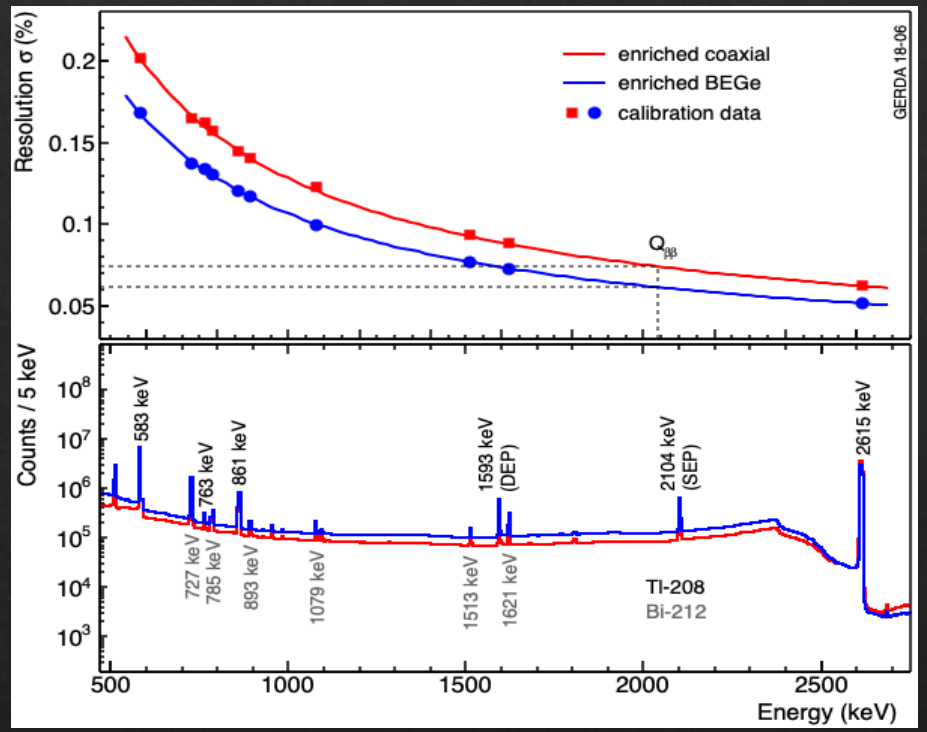
- live time → 835 d
- duty cycle → 93%
- Exposure → 59 kg yr
  (82 kg yr considering Phase I + Phase II)

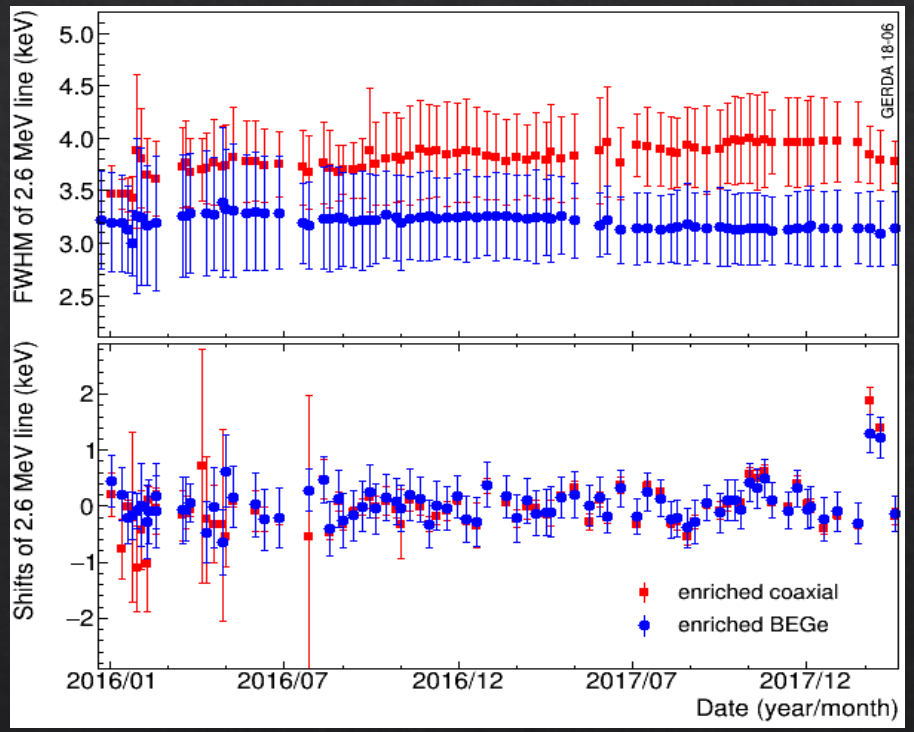
Phase II+: July2018 → ongoing

- 6.6 kg.yr exposure validated

GOAL: exposure 100 kg yr

Energy reconstruction / resolution



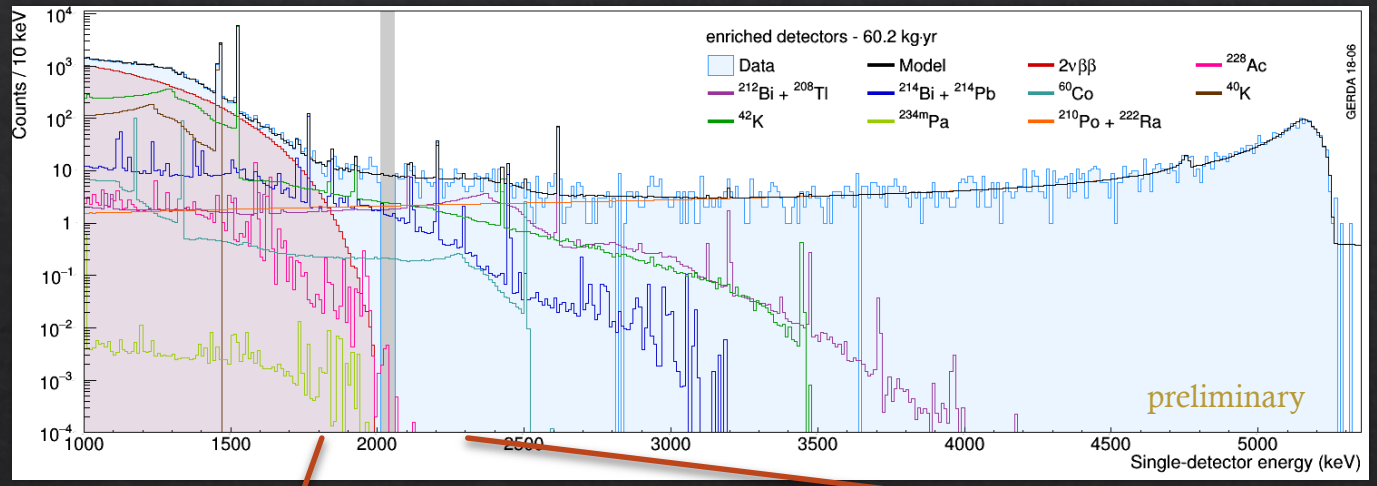


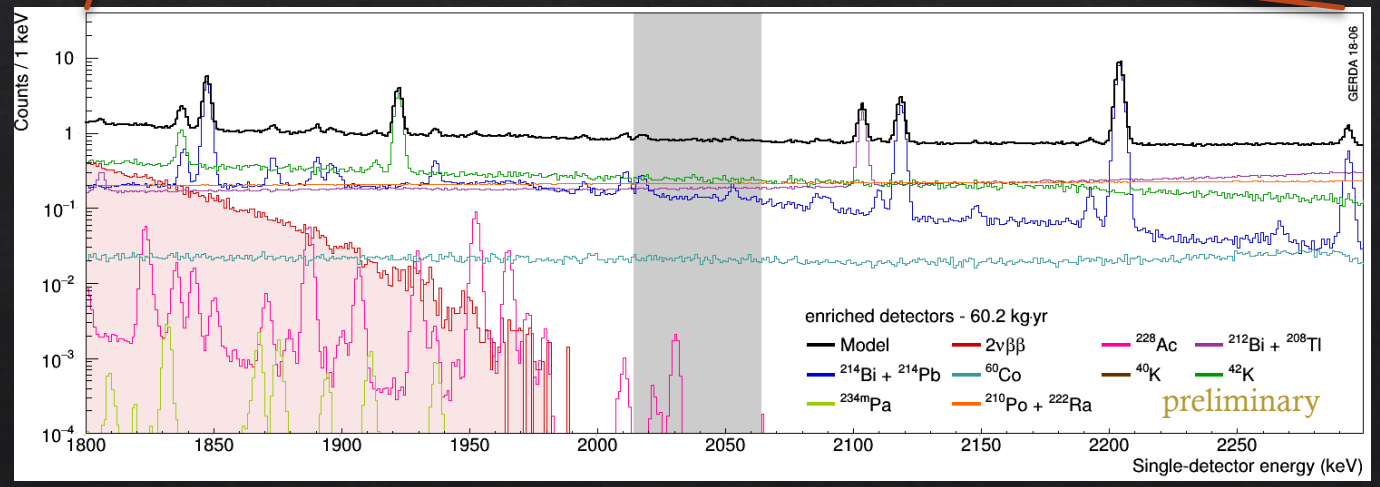
- Weekly calibrations with ^{228}Th sources
- Optimized ZAC filter (Eur. Phys. J. C 75 (2015) 255)
- Stability monitored online with Test Pulses, injected every 20 s

- Fluctuations between calibrations <1 keV
- Resolution at $Q_{\beta\beta}$ better than 0.1%

  (FWHM@$Q_{\beta\beta}$: 3.0(1) keV (BEGe), 3.6(1) keV (Coax))

Background modeling before analysis cuts





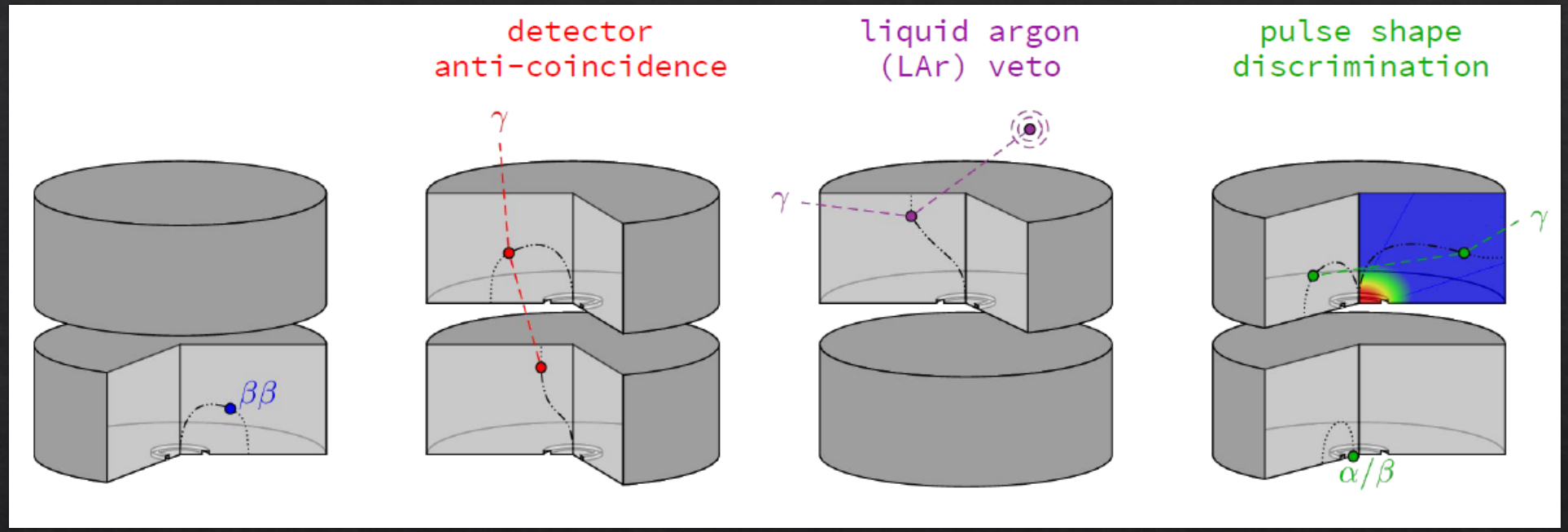
Full GERDA setup is reproduced in GEANT4

Bayesian fit of multiple datasets (BEGe, coaxial, multiplicity=2, $^{40}K/^{42}K$ tracking) with Monte Carlo PDFs, **screening measurements** as priors

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

α from **$^{210}Po/(^{222}Ra)$**
β from **^{42}K**
γ from **$^{208}Tl/^{214}Bi$**

Active background suppression

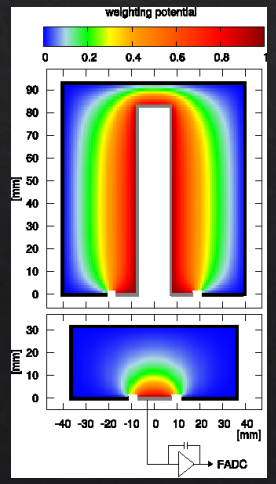


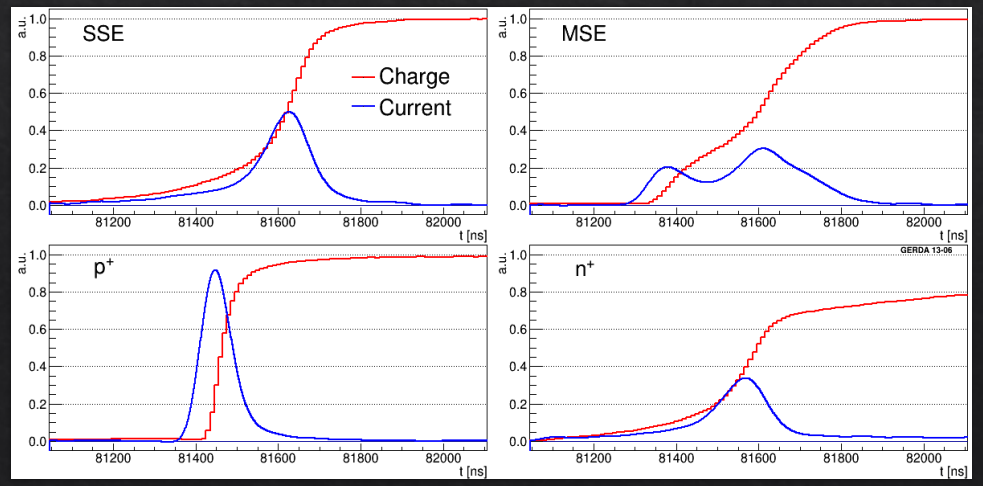
Discriminate **point like** (single site) **ββ** topology from:

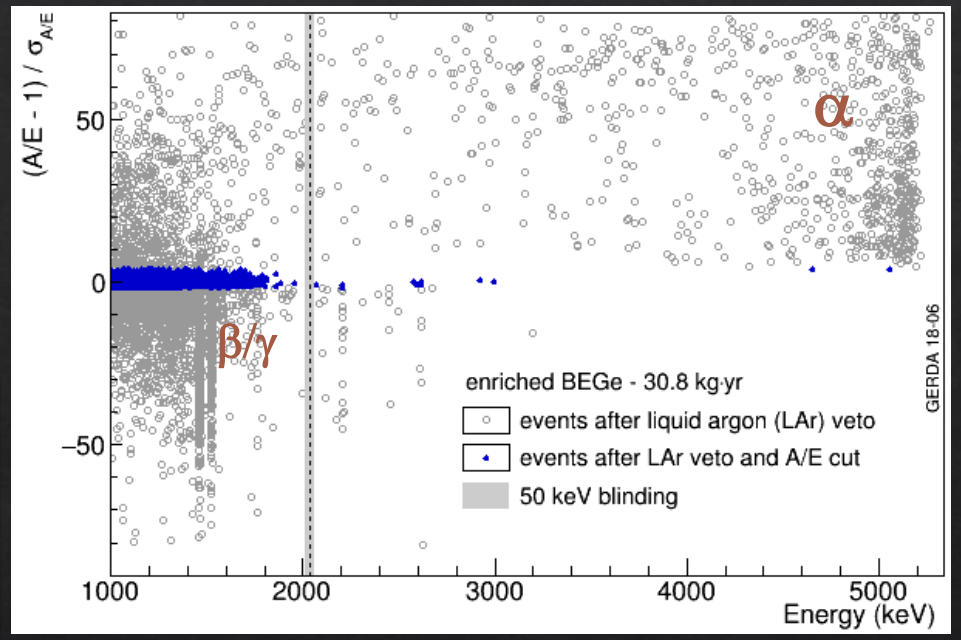
- **multi-detector** interactions
- interactions with **coincident energy deposition** in surroundings
- **multi-site/surface** interactions

Pulse shape discrimination for BEGe's

- Mono-parametric cut based on current pulse amplitude A and total energy E **(A/E)** [Eur. Phys. J. C73 (2013) 2583]
- normalized to single-site events
- cut value determined from **calibration data** (low cut @ 90% DEP acceptance, high cut @ 4σ)



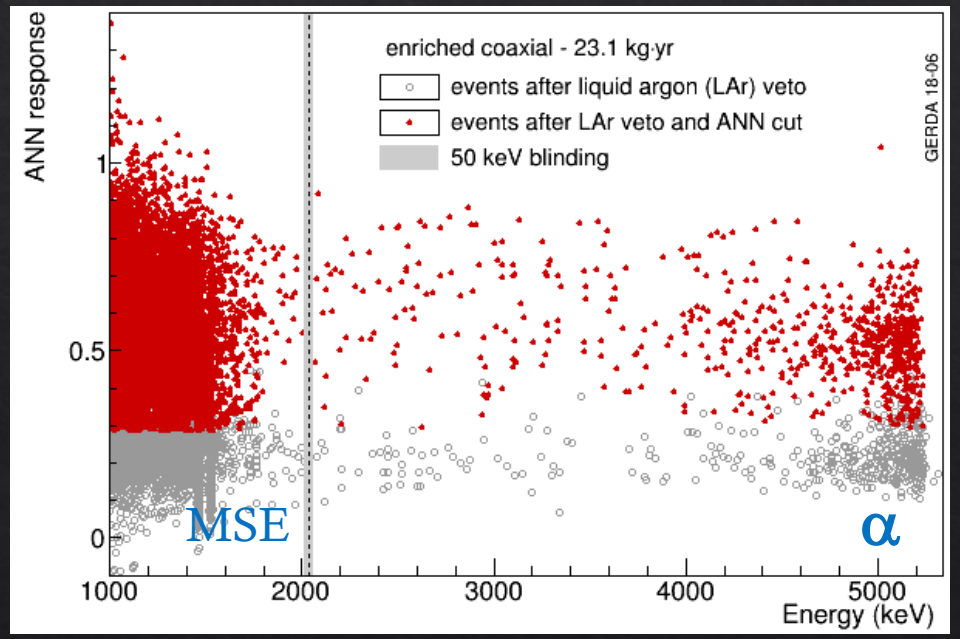


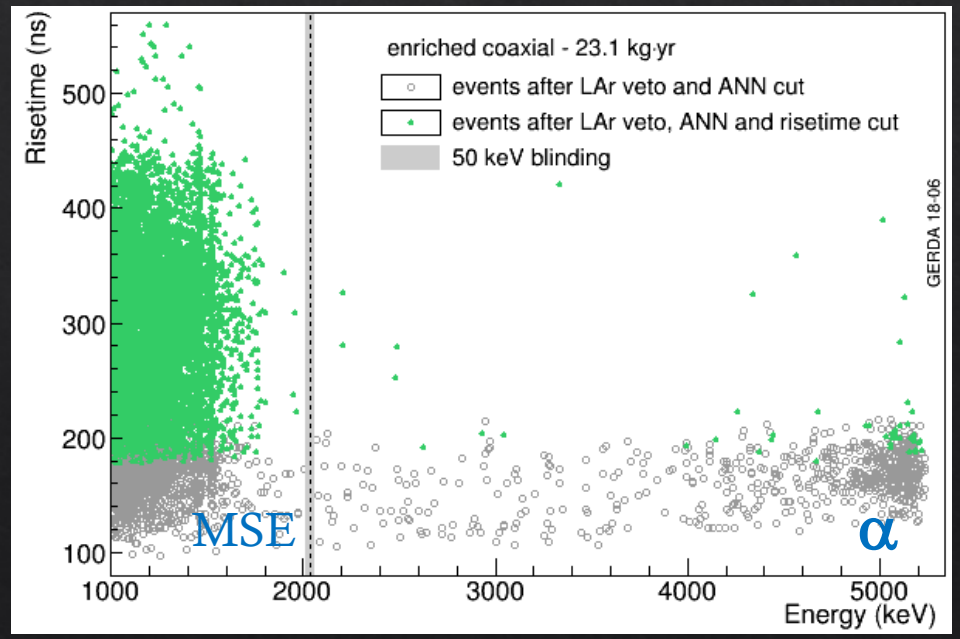


$0\nu\beta\beta$ acceptance BEGe **(87.6±2.5)%**

Pulse shape discrimination for Coaxials

- Artificial neural network (ANN) trained on ^{208}Tl DEP (signal) and ^{212}Bi SEP (background)
- acceptance from pulse shape simulations, cross-checked with 2νββ events
- additional α rejection based on (fast) signal rise time, tuned after ANN MSE rejection



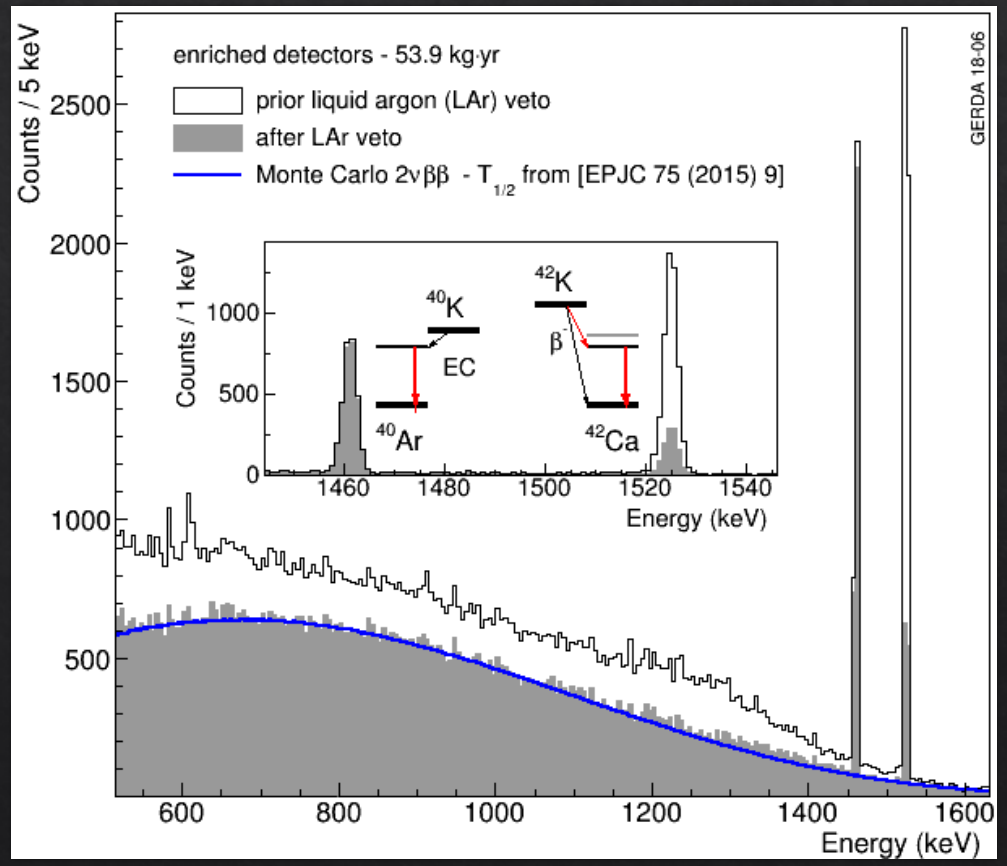


0νββ acceptance Coaxial

(84±5)% x (85±1)%

Liquid Argon Veto

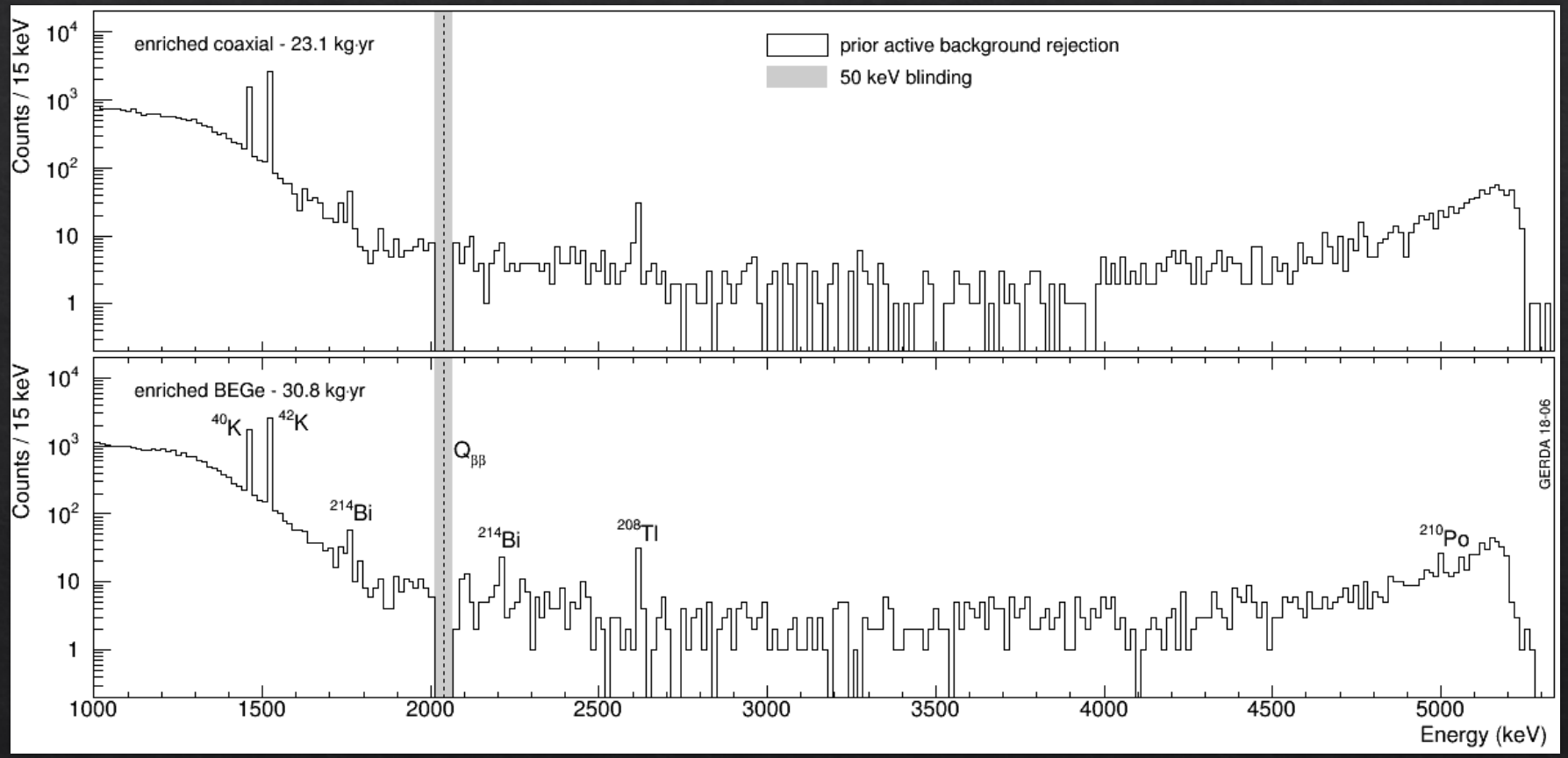
- Channelwise (**PMT/SiPM**) **anti-coincidence** condition
- Thresholds at ~0.5 P.E.
- **Compton suppression** by LAr veto -> almost pure **2νββ continuum**



$0\nu\beta\beta$ acceptance BEGe **97.7(1)%**

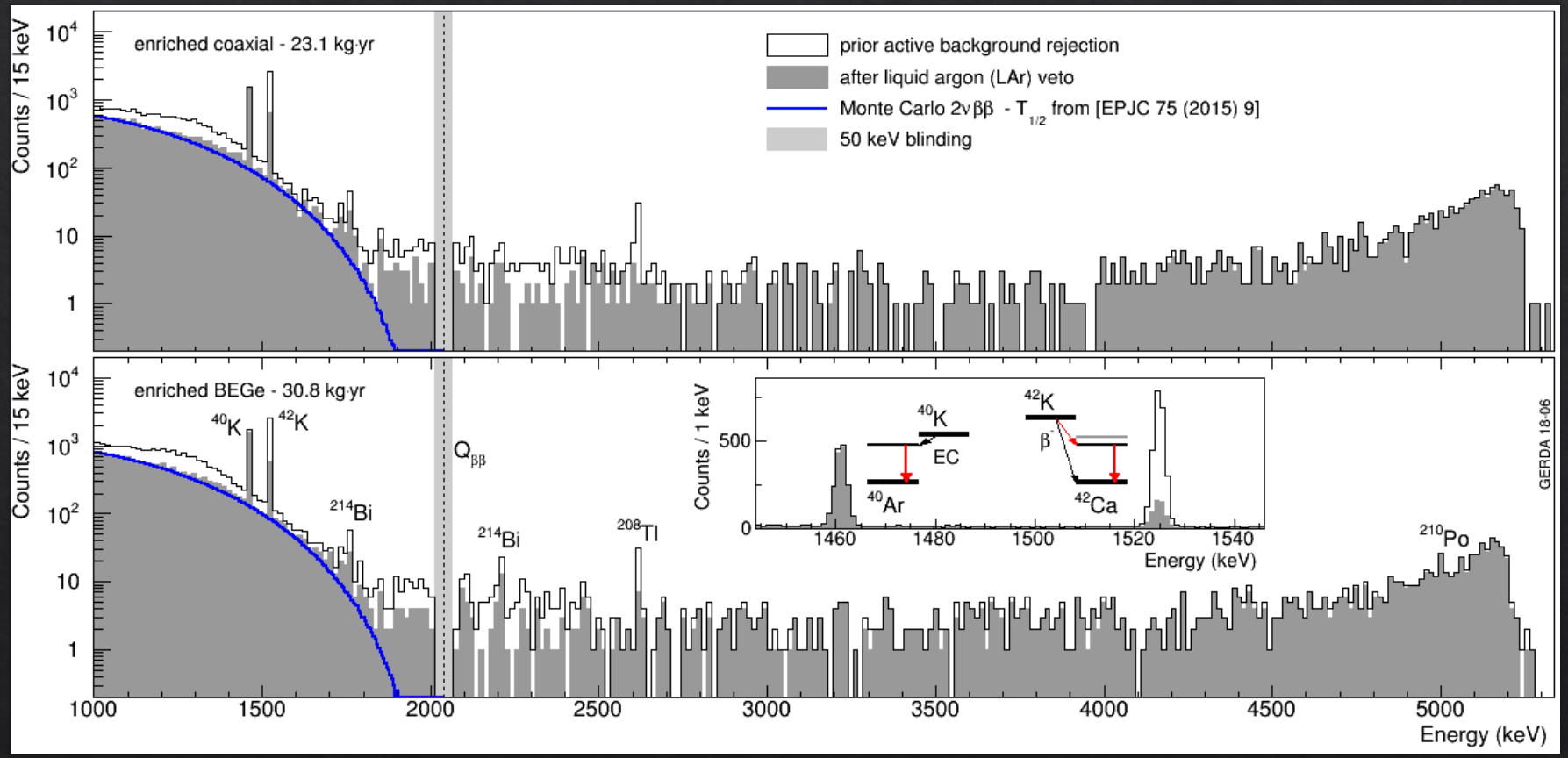
Dead Time 2%

Active background suppression

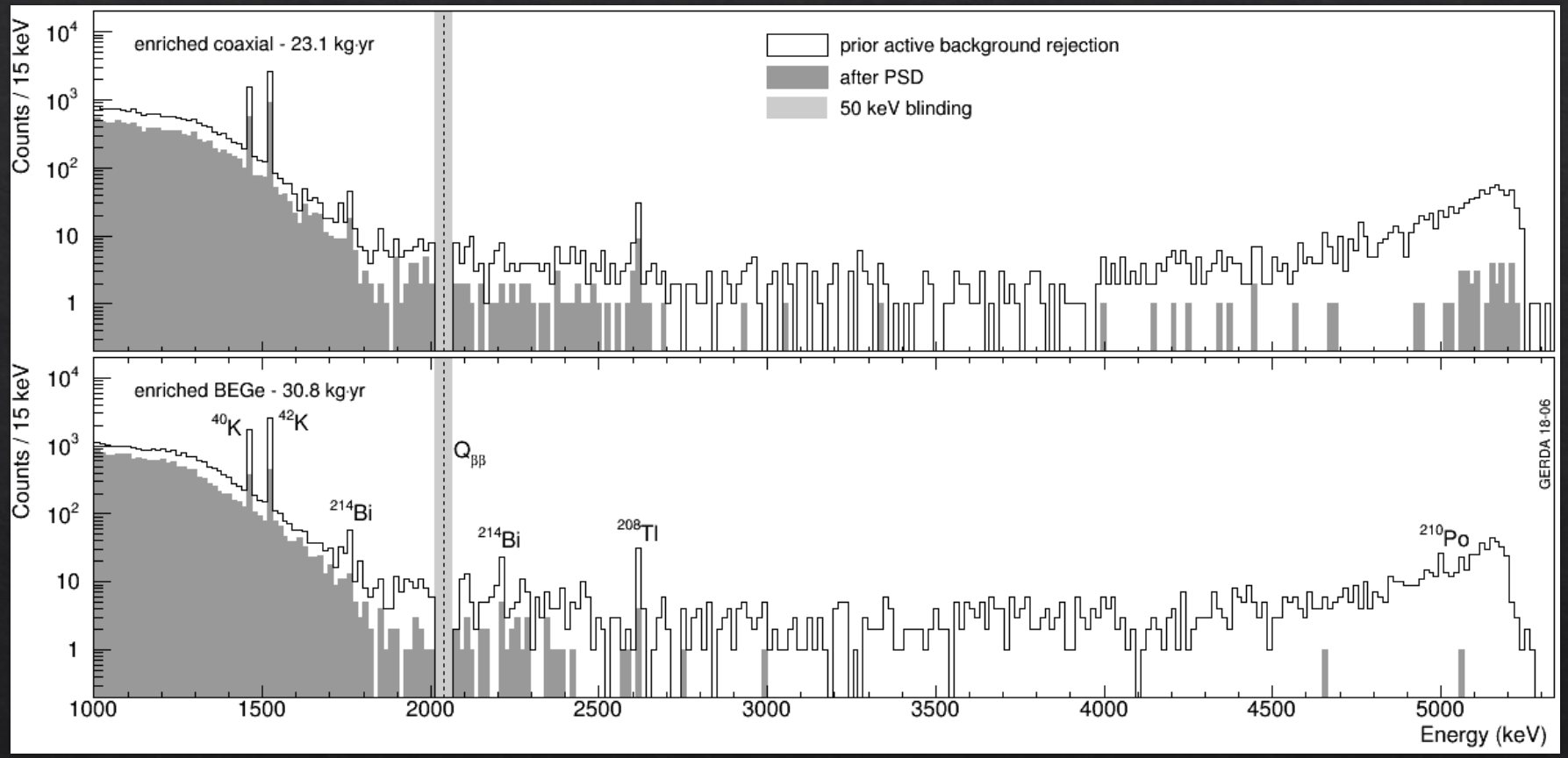


Blinded region ±25 keV @ $Q_{\beta\beta}$

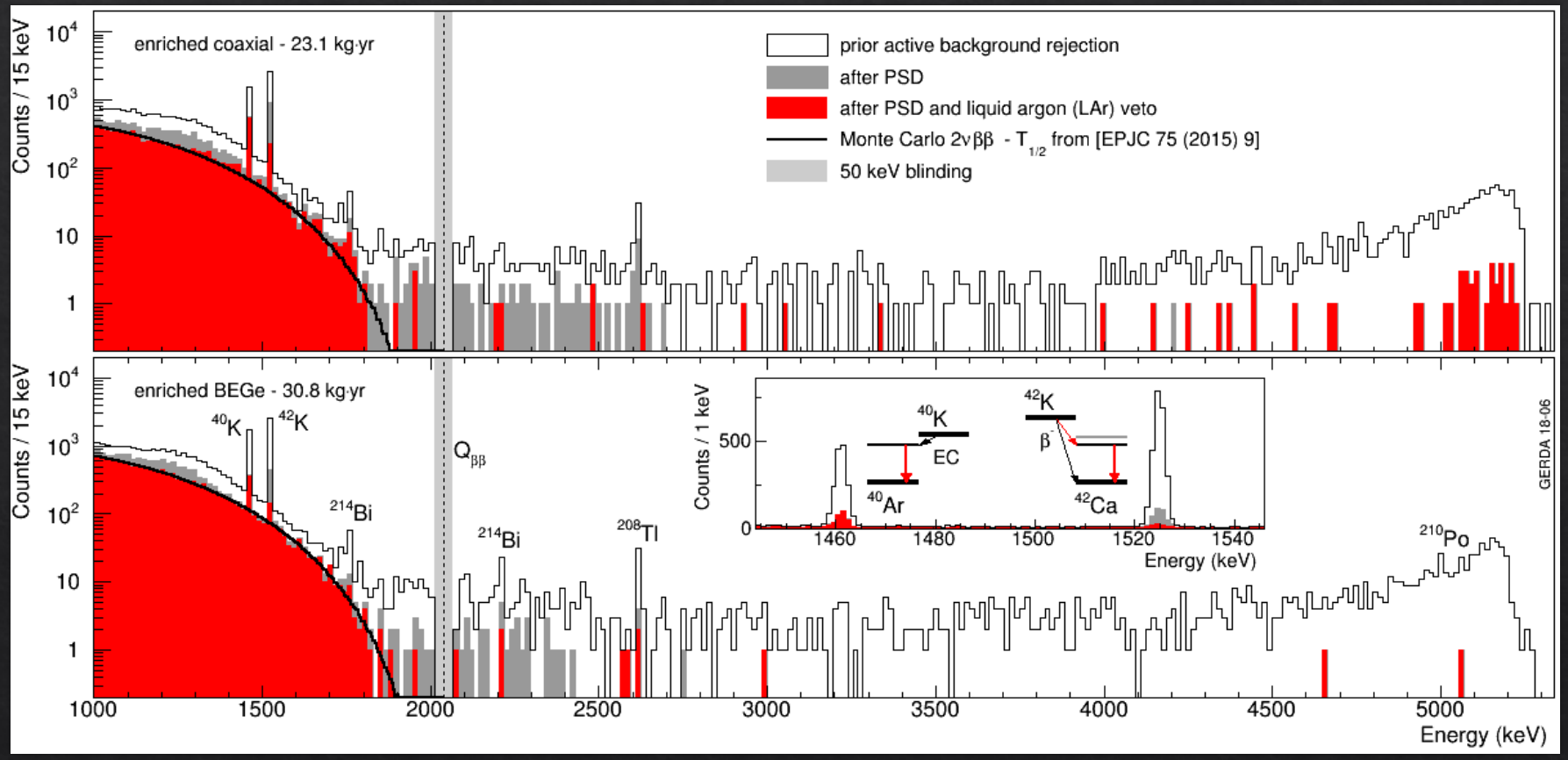
Active background suppression – LAr veto



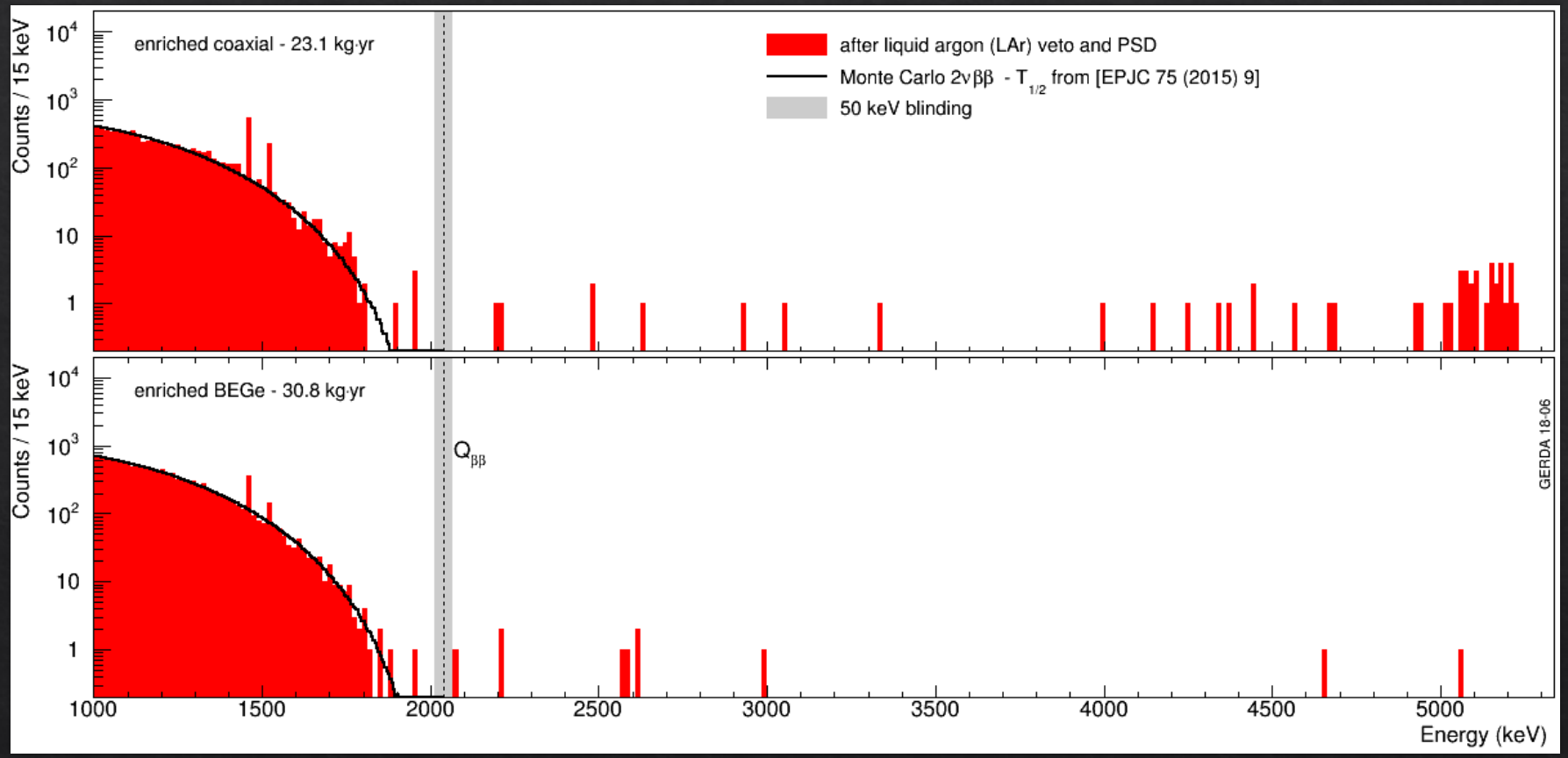
Active background suppression – PSD



Active background suppression – PSD&LAr veto



Active background suppression – PSD&LAr veto

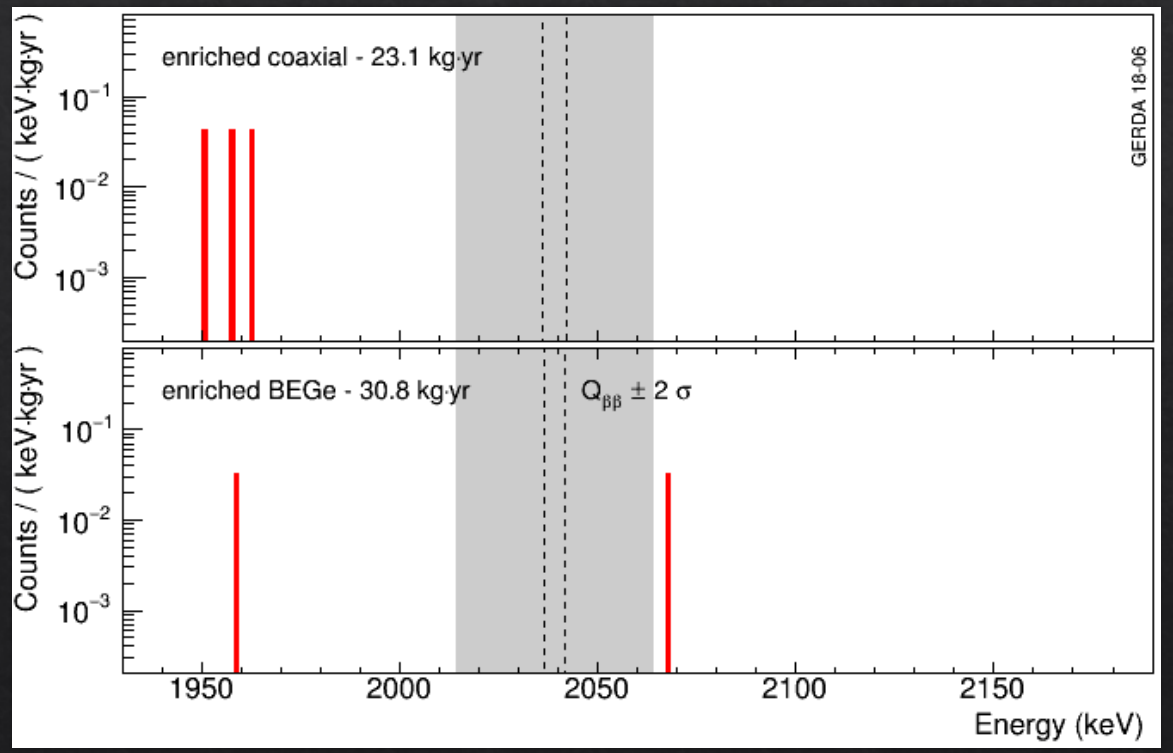


Background index

ROI:
[1930,2190] keV, excl. ±5 keV around
^{208}Tl (SEP), ^{214}Bi (FEP) and $Q_{\beta\beta}$

Enriched coaxial: $5.7^{+4.1}_{-2.6} \cdot 10^{-4}$ cts/(keV·kg·yr)

Enriched BEGe: $5.6^{+3.4}_{-2.4} \cdot 10^{-4}$ cts/(keV·kg·yr)



Statistical analysis

Frequentist:

Best fit $N^{0\nu} = 0$

$T^{0\nu}_{1/2} > 0.9 \cdot 10^{26}$ yr @ 90% C.L

Median Sensitivity

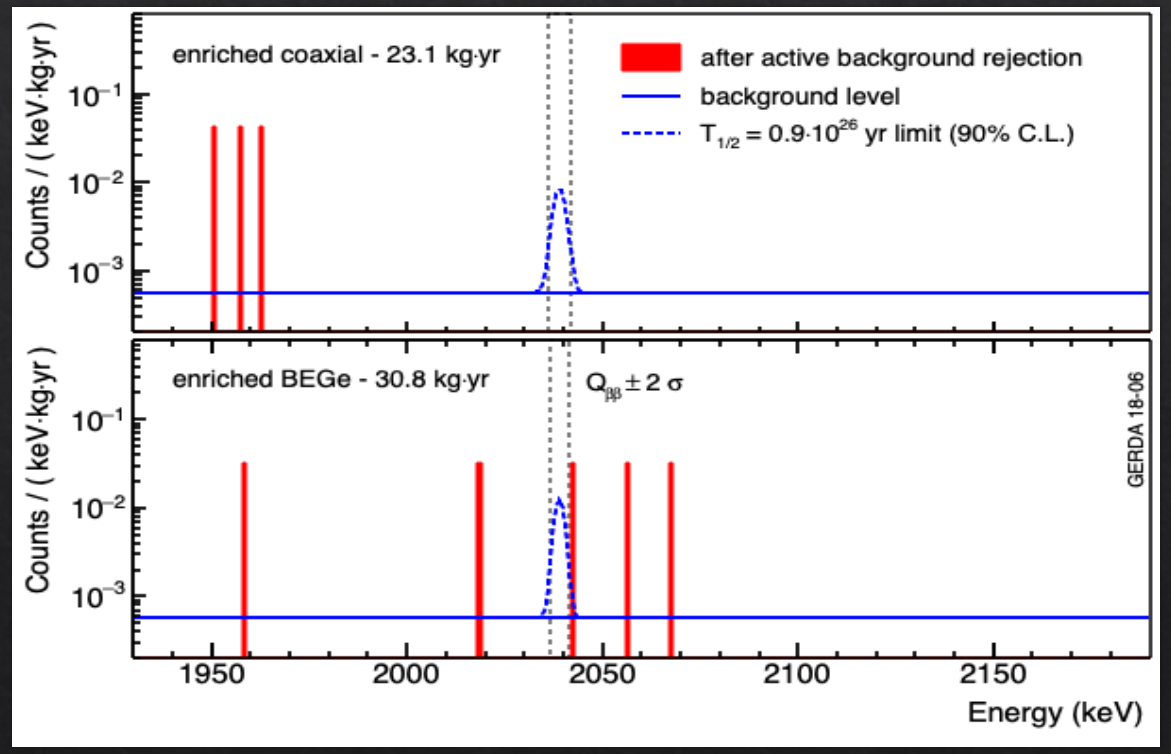
$T^{0\nu}_{1/2} > 1.1 \cdot 10^{26}$ yr @ 90% C.L.

Bayesian:

$T^{0\nu}_{1/2} > 0.8 \cdot 10^{26}$ yr @ 90% C.I.

Median Sensitivity:

$T^{0\nu}_{1/2} > 0.8 \cdot 10^{26}$ yr @ 90% C.I.



Background expectation in $Q_{\beta\beta} \pm 2\sigma \rightarrow$ <0.2 counts

Conclusion and outlook

- GERDA Phase II goals

  background ~10^{-3} cts/(keV·kg·yr) ✔

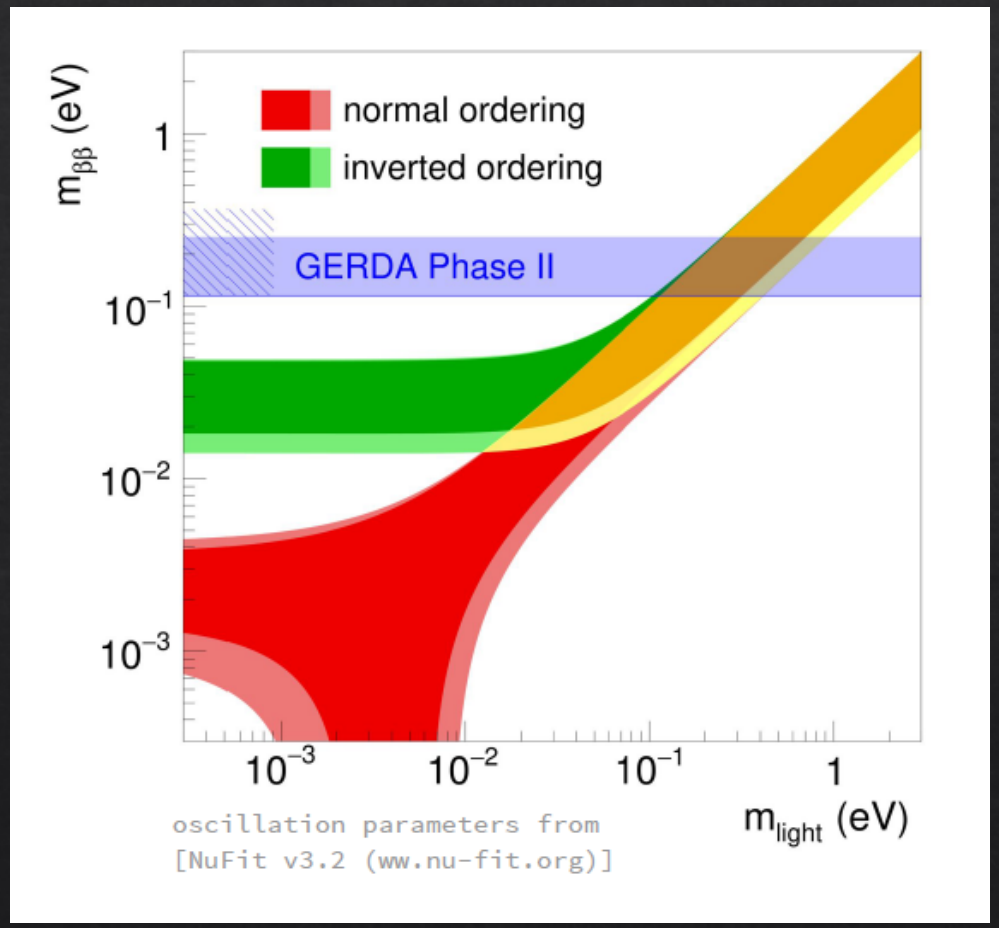
  sensitivity $T^{0\nu}_{1/2} \gtrsim 10^{26}$ yr ✔

  exposure ≳100 kg·yr → data taking still on-going after last upgrade (May 2018)

- GERDA performs a high resolution background-free $0\nu\beta\beta$ decay search approaching $T^{0\nu}_{1/2}$ beyond 10^{26} yr

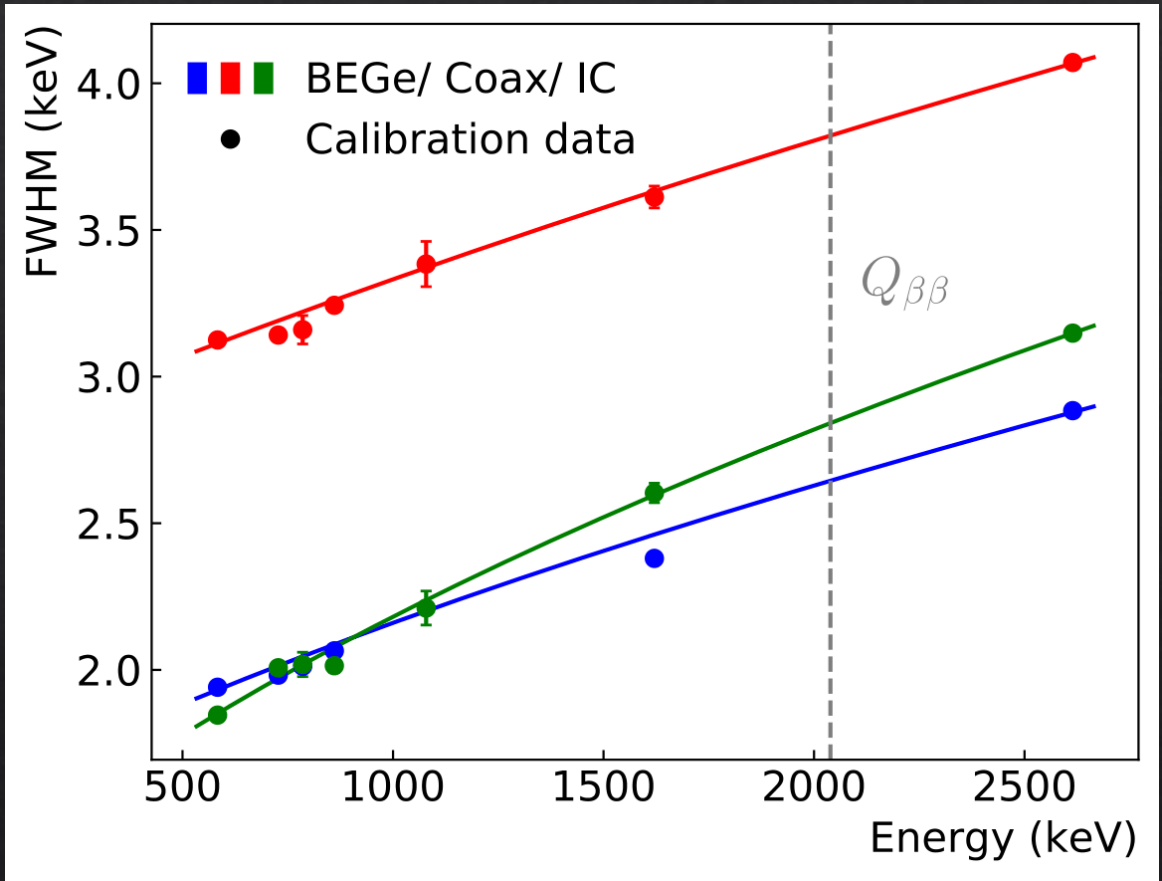
- Upper limit on $m_{\beta\beta}$ < (0.11-0.26) eV [NME range from [Rept.Prog.Phys. 80 (2017) no.4, 046301]

- **LEGEND-200** is in preparation to reach $T^{0\nu}_{1/2}$ above 10^{27} yr



BACKUP

Calibration Phase II+



Summary

	exposure [kg*yr]	FWHM [keV]	total efficiency	background index [cts/(keV*kg*yr)]
Phase I golden	17.9	4.3(1)	0.57(3)	$(1.1\pm0.2)*10^{-2}$
Phase I silver	1.3	4.3(1)	0.57(3)	$(3.0\pm1.0)*10^{-2}$
Phase I BEGe	2.4	2.7(2)	0.66(2)	$(5.4^{+4.0}_{-2.5})*10^{-3}$
Phase I extra	1.9	4.2(2)	0.58(4)	$(4.6^{+4.3}_{-2.5})*10^{-3}$
Phase II EnrCoax	5.0	3.57(1)	0.52(4)	$(3.5^{+2.1}_{-1.5})*10^{-3}$
Phase II EnrCoax_2	23.1	3.57(1)	0.48(4)	$\mathbf{(5.7^{+4.1}_{-2.6})*10^{-4}}$
Phase II EnrBEGe	30.8	2.96(1)	0.60(2)	$\mathbf{(5.6^{+3.4}_{-2.4})*10^{-4}}$
total	**82.4**			

combined unbinned maximum likelihood fit (flat background + gaussian signal)

- **Frequentist:** test statistics and method à la [Nature 544, 47 (2017)]
- **Bayesian:** flat prior on $1/T^{0\nu}_{1/2}$ between 0 and 10^{-24} yr^{-1}
- systematic uncertainties folded as pull terms by Monte Carlo