A Background-Free Search for the Neutrinoless Double Beta Decay with GERDA

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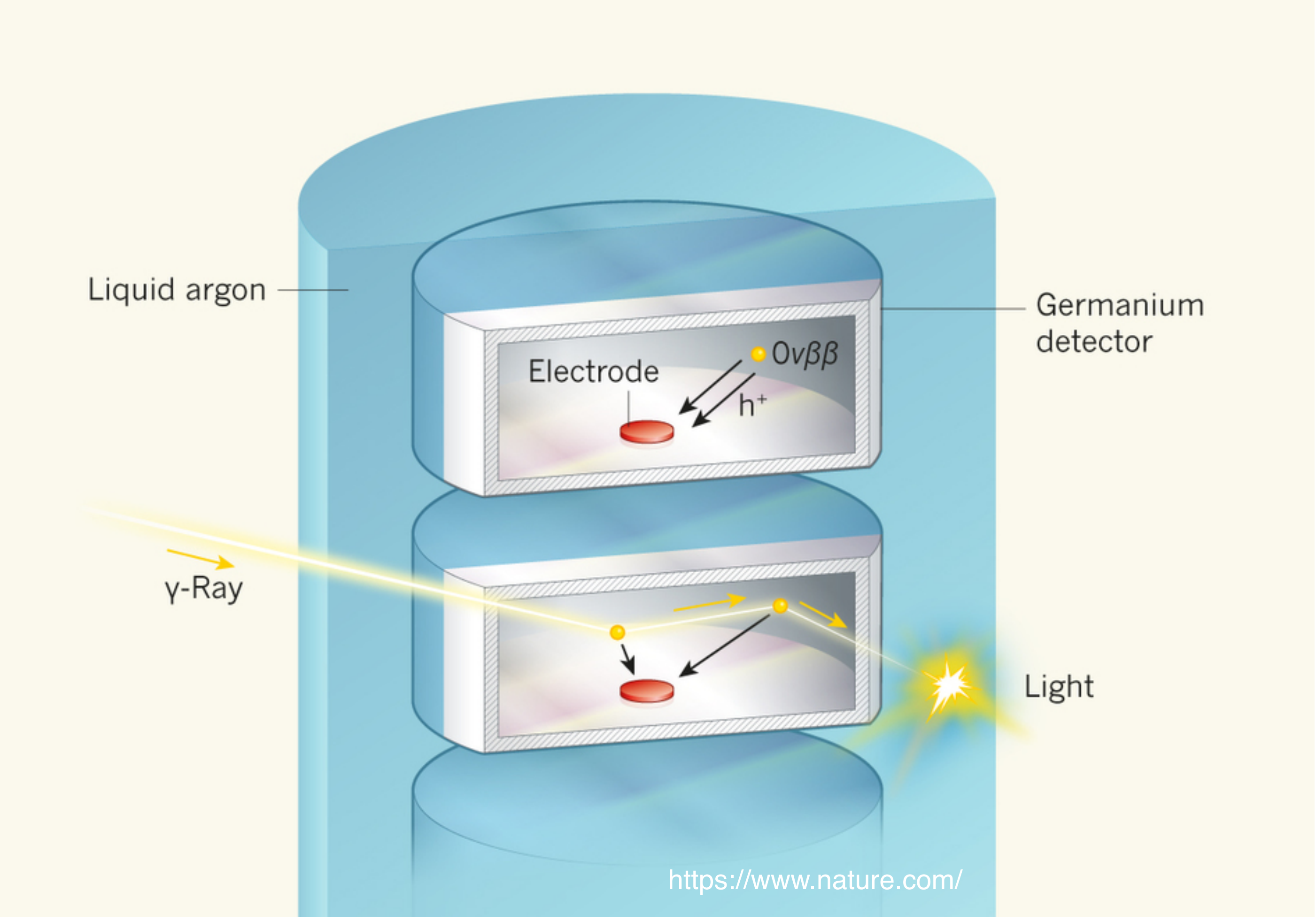
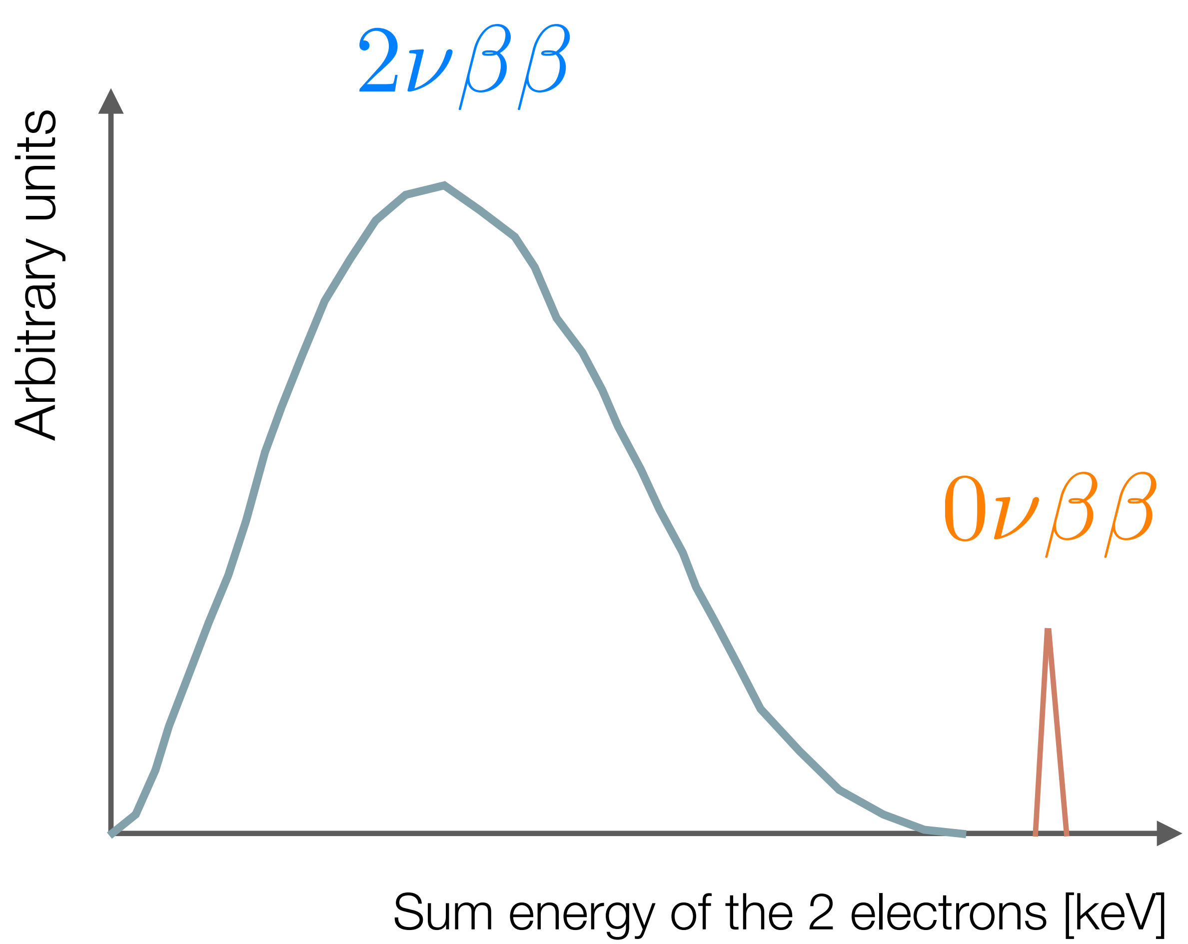
13th Patras Workshop on Axions, WIMPs and WISPs

Thessaloniki, May 18, 2017



Physics goal of GERDA

- Search for the neutrinoless double beta decay (0νββ) of ^{76}Ge
- Observe the 2 final-state e^-, expect sharp "peak" at the Q-value
- Excellent energy resolutions and ultra-low background: *essential for a discovery*



$$^{76}\mathrm{Ge} \rightarrow {}^{76}\mathrm{Se} + 2e^-$$

$$\Delta L = 2$$

$$Q_{\beta\beta} = E_{e1} + E_{e2} - 2m_e = 2039\,\mathrm{keV}$$

What is the observable decay rate?

Phase space factor | Axial-vector cc | NME

$$\Gamma^{0\nu} = \frac{1}{T^{0\nu}_{1/2}} = G^{0\nu} g_A^4 |M^{0\nu}|^2 \frac{|\langle m_{eff} \rangle|^2}{m_e^2}$$

Can be calculated: ~ Q^5 | **Difficult: factor 2-3**

- with the *effective Majorana neutrino mass:*

$$|\langle m_{eff} \rangle| = |U_{e1}^2 m_1 + U_{e2}^2 m_2 e^{i(\alpha_1 - \alpha_2)} + U_{e3}^2 m_3 e^{i(-\alpha_1 - 2\delta)}|$$

➡a coherent sum over mass eigenstates with potentially CP violating phases

➡a mixture of m_1, m_2, m_3, proportional to the U_{ei}^2, with α_1,α_2 = Majorana CPV phases

One Slide Current Status of the Field

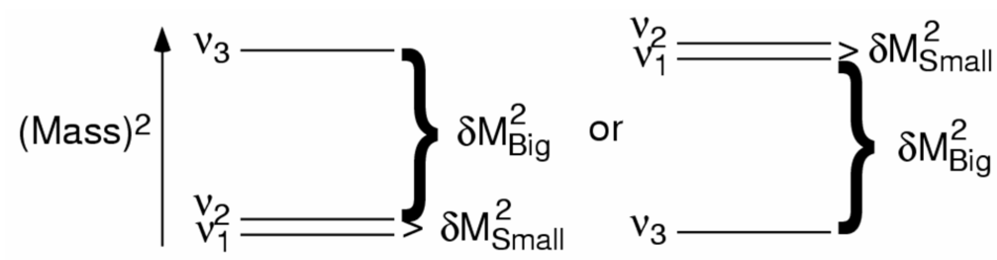
- No observation of this extremely rare nuclear decay *(so far)*
- Best lower limits on $T_{1/2}$: 1.07×10^{26} y (^{136}Xe), 5.3×10^{25} y (^{76}Ge), 2.7×10^{24} y (^{130}Te)

$$|\langle m_{eff} \rangle| = |\Sigma_i U_{ei}^2 m_i| \leq 0.06 - 0.4\,\mathrm{eV}$$

- Running and upcoming experiments (a selection):
  - ^{130}Te: CUORE, SNO+
  - ^{136}Xe: KAMLAND-Zen, KAMLAND2-Zen, EXO-200, nEXO, NEXT, DARWIN
  - ^{76}Ge: GERDA Phase-II, Majorana, LEGEND (GERDA & Majorana + new groups)
  - ^{100}Mo AMoRE, LUMINEU; ^{82}Se: LUCIFER, CUPID = CUORE with light read-out
  - ^{82}Se (^{150}Nd, ^{48}Ca): SuperNEMO

Effective Majorana neutrino mass

normal

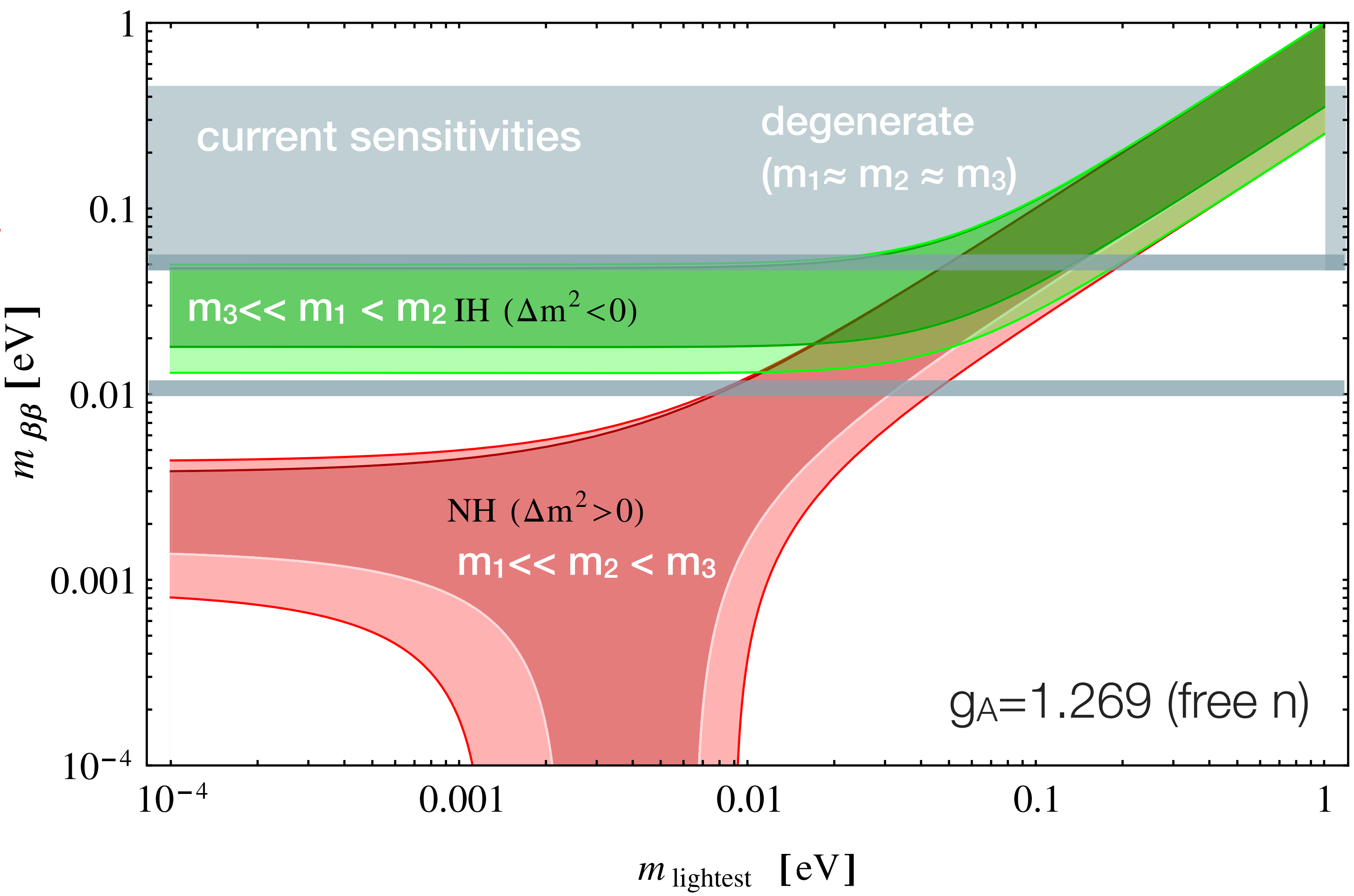


inverted

Del'Oro, Marocci, Vissani, PRD 90, 2014

$T_{1/2} \sim 10^{26} y$

$T_{1/2} \sim 10^{27} y$



0.1- 1 counts/(y kg)

0.5 - 5 counts/(y t)

0.1-1 counts/(y 100 t)

The GERDA Experiment: Overview

HPGe detectors, enriched to ~86% in ^{76}Ge

Liquid argon as cooling medium and shielding

(U/Th in LAr < 7×10^{-4} μBq/kg)

A minimal amount of surrounding materials

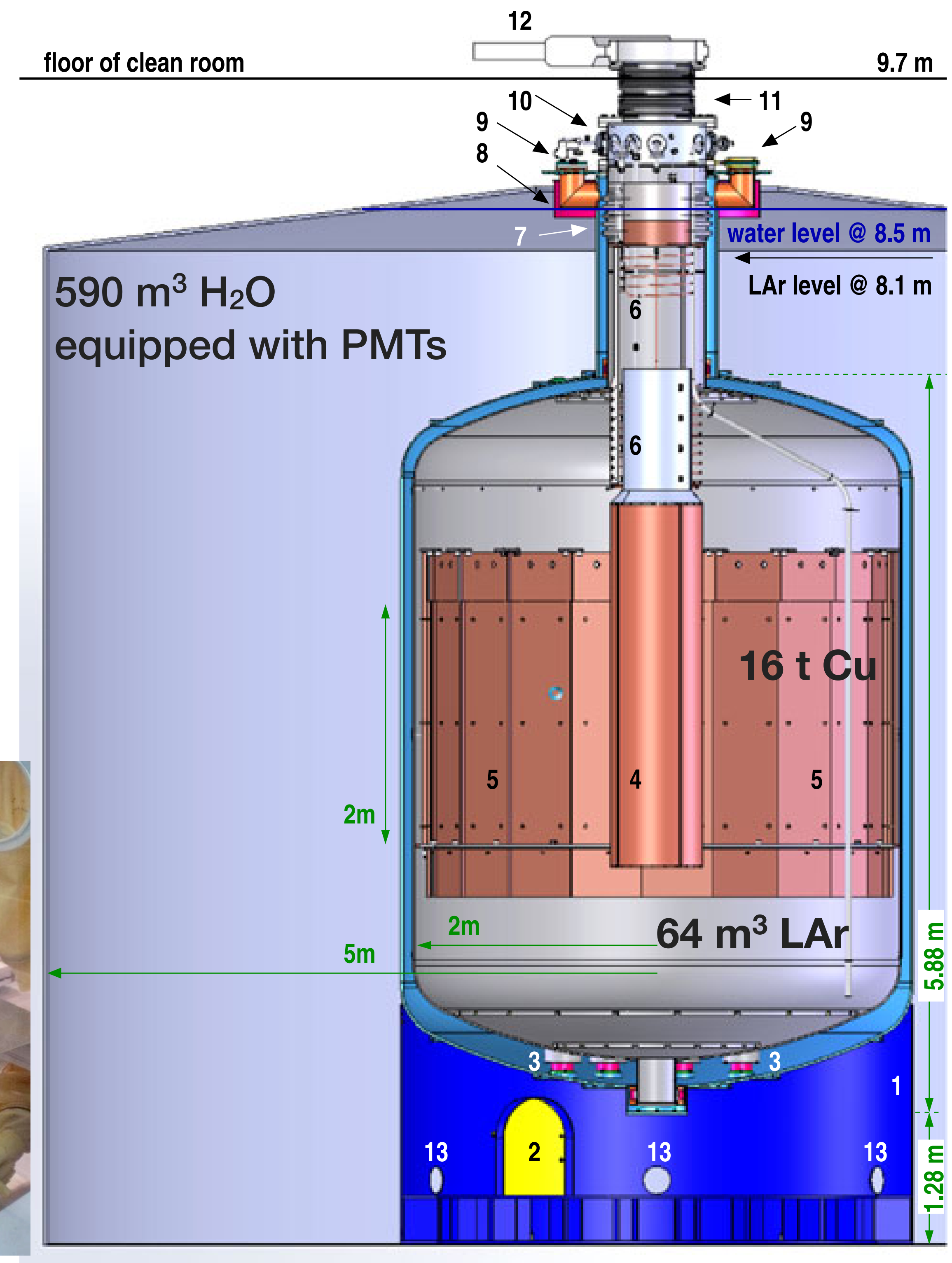
Phase I (2011-2014)

~18 kg HPGe detectors

Phase II (2015-2018)

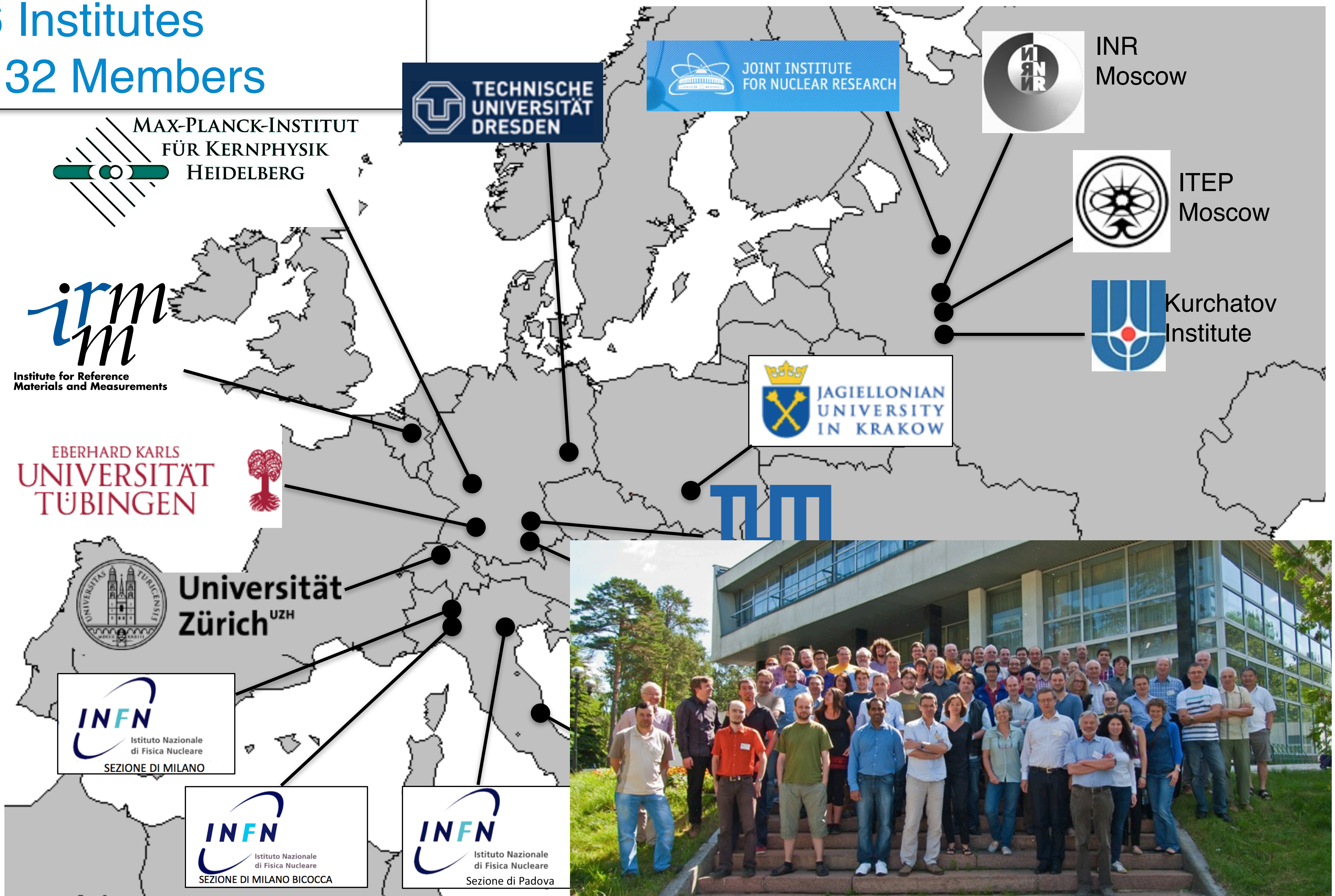
~ 36 kg HPGe detectors

Eur. Phys. J. C (2013) 73:2330

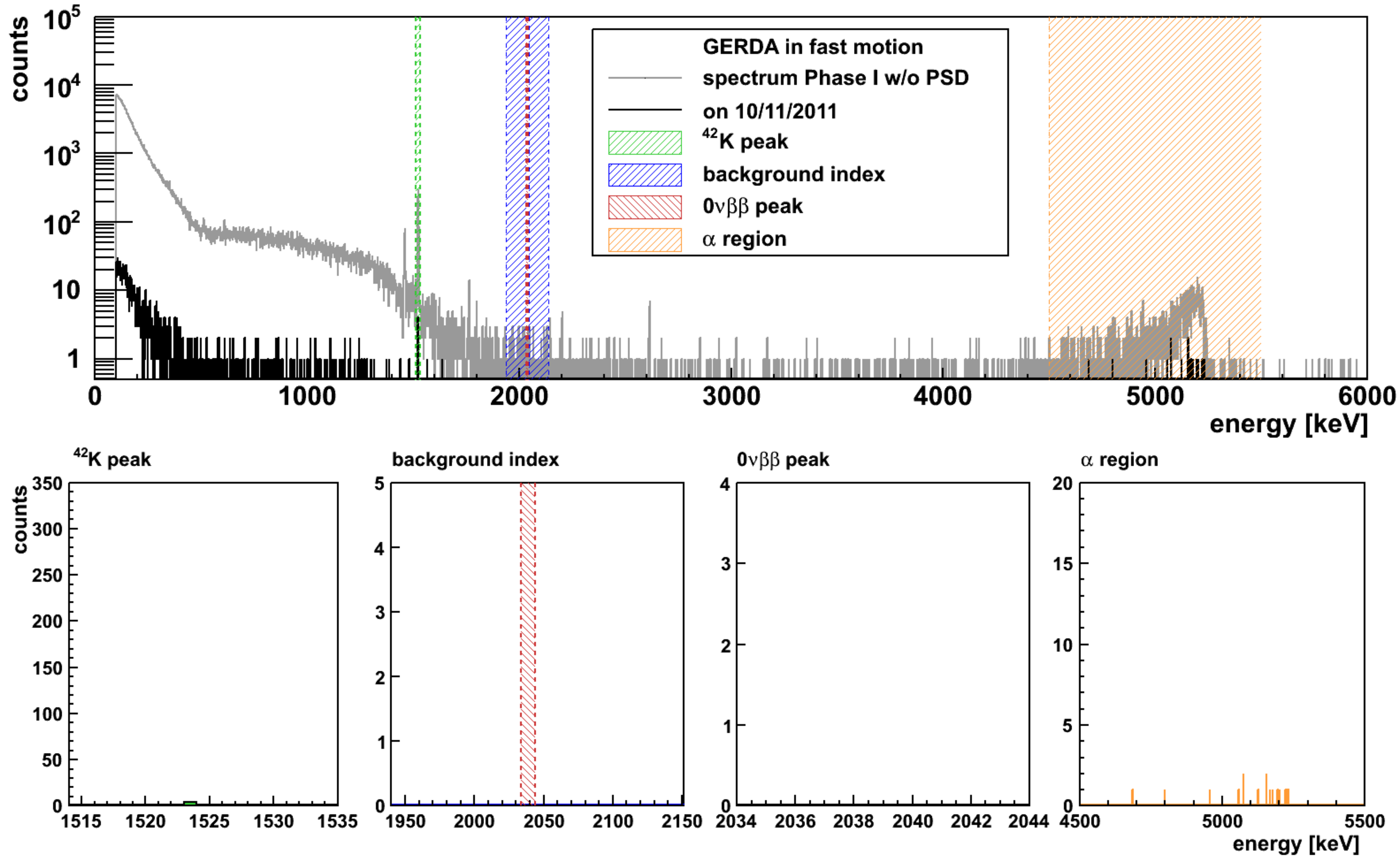


The GERDA Collaboration

16 Institutes
~132 Members



Reminder: GERDA Phase I



Total exposure used in neutrinoless double beta analysis: 21.6 kg yr

Background level: 0.011(2) events/(keV kg y)

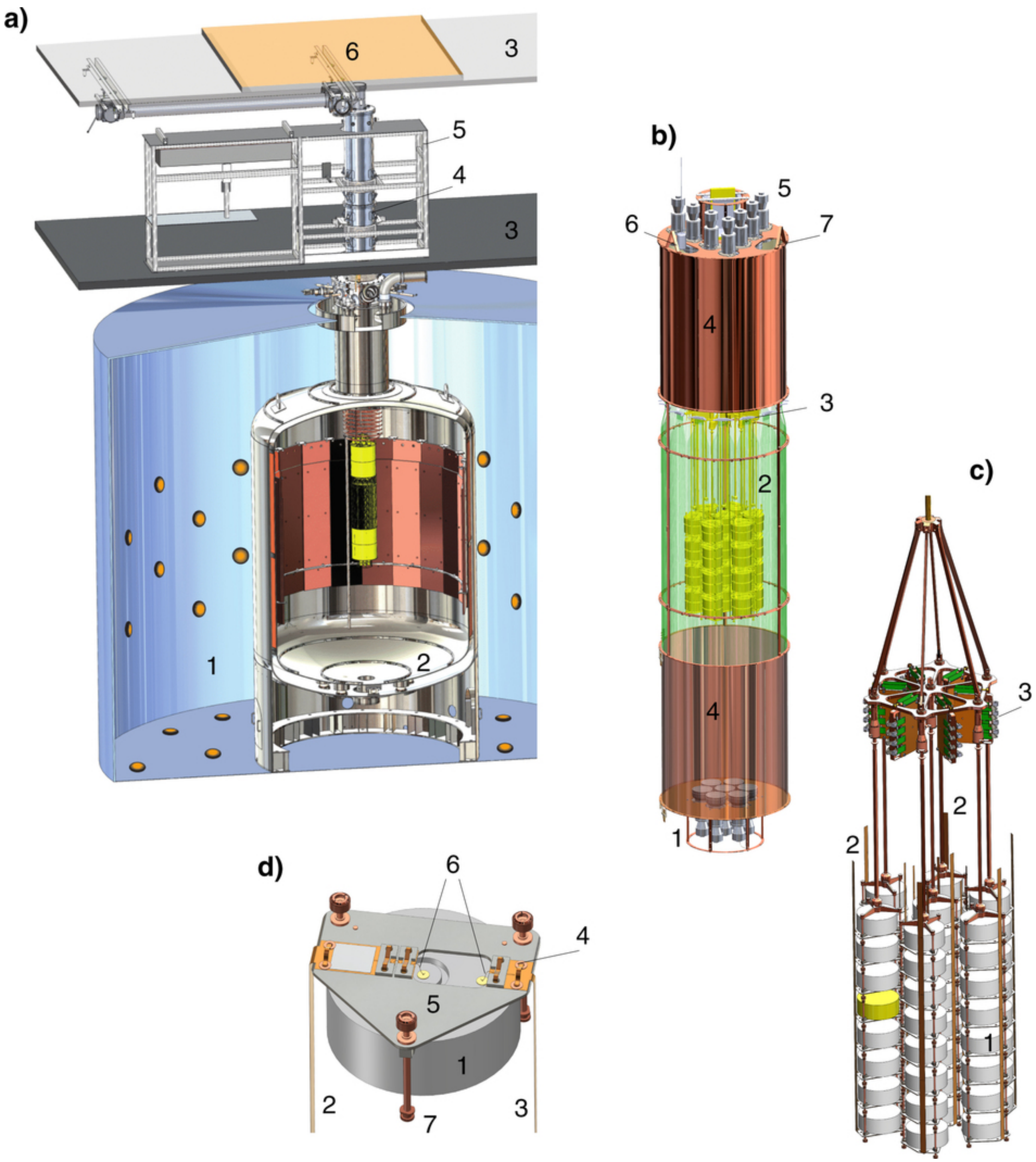
PRL 111, 2013

$$T_{1/2}^{0\nu} > \ 2.1 \times 10^{25}\,\mathrm{yr}\ (90\%\,\mathrm{C.L.})$$

Background model: EPJC 74, 2014

GERDA Phase II

- **Start science run in December 2015**
- 37 detectors (35.6 kg) enriched in ^{76}Ge
- Improve phase I sensitivity by factor 10:
  - 100 kg y exposure
  - background: 0.001 events/(kg y keV)
- LAr veto: 0.5 m diameter, 2 m high
- Viewed by optical fibres + SiPMs and 16 (7 + 9) 3-inch PMTs (R11065-10/20)
- **7 detector strings (one out of ^{nat}Ge detectors) fully operational**



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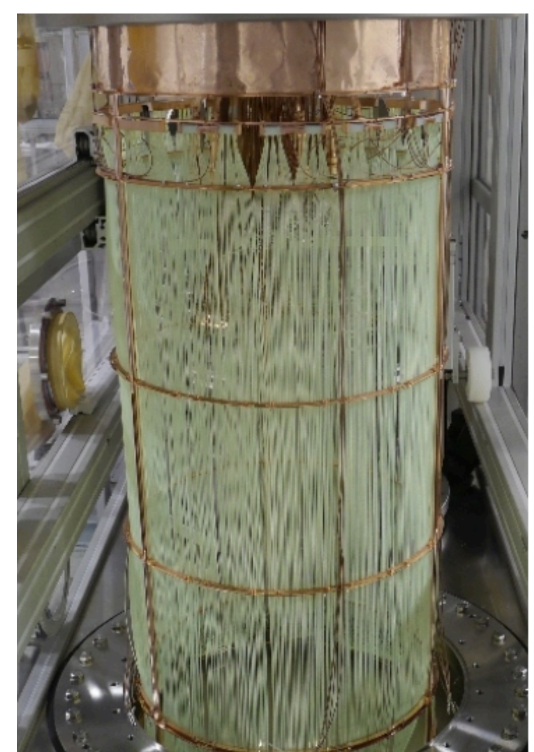
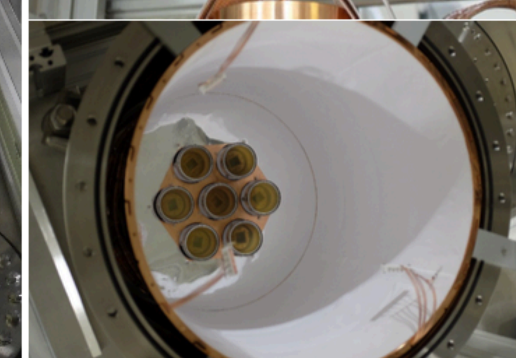
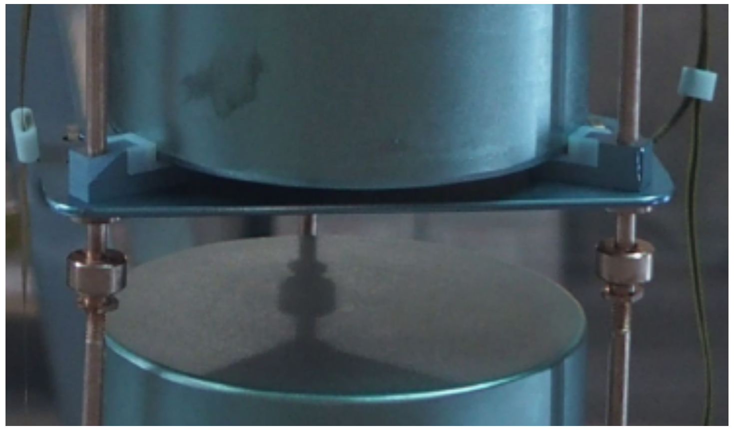
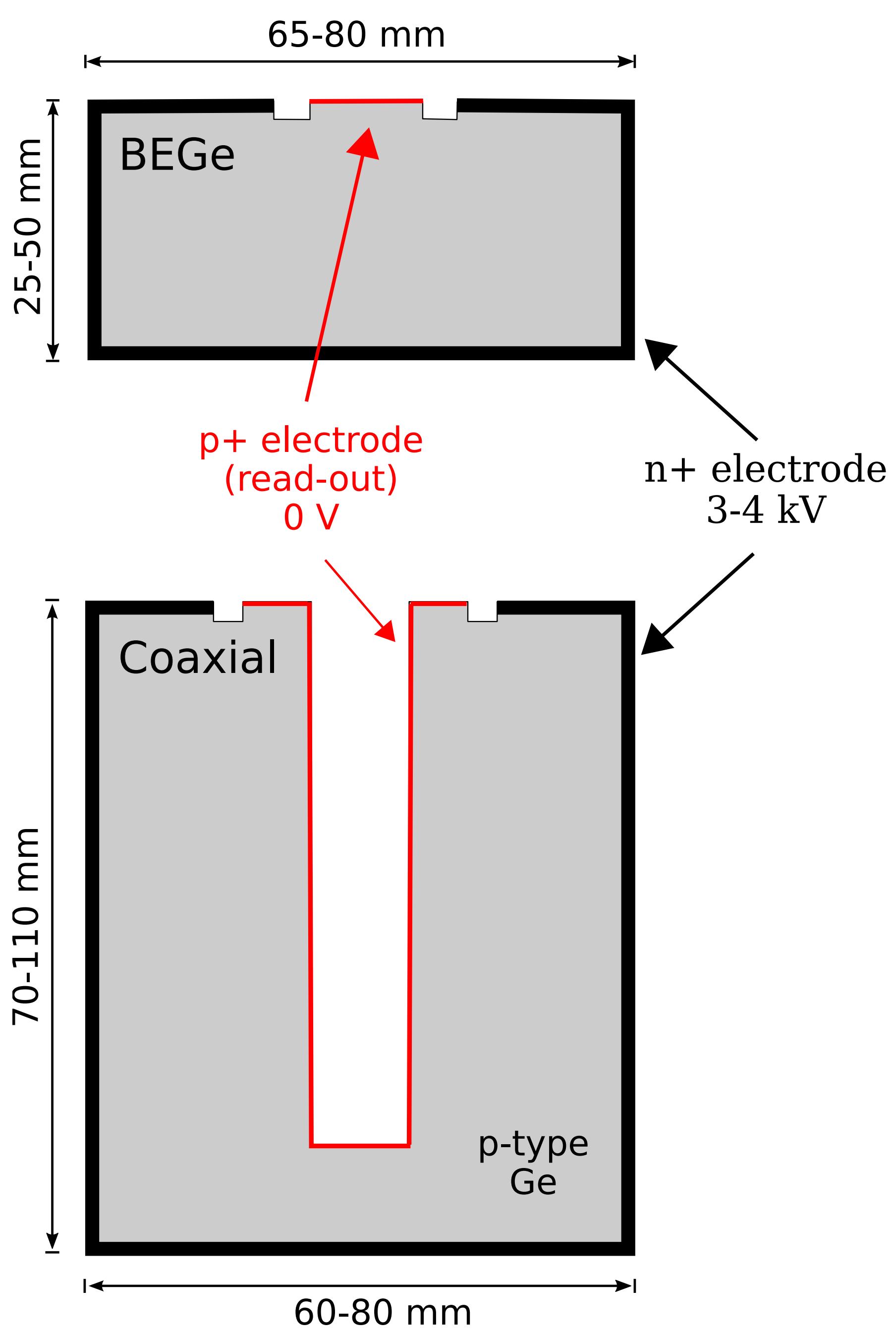


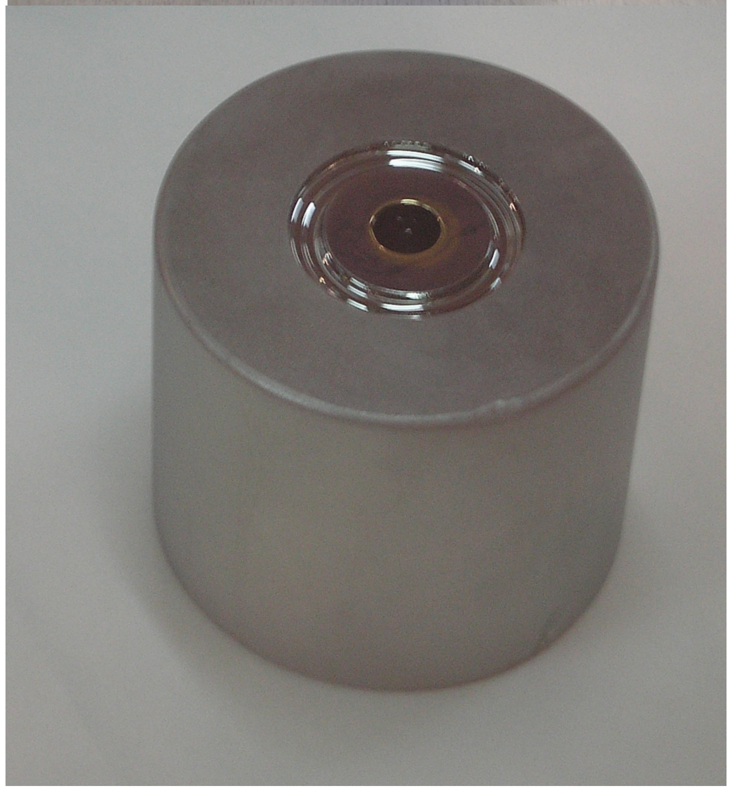


GERDA Detectors

- BEGe and coaxial
- p+ electrodes:
  - 0.3 μm boron implantation
- n+ electrodes:
  - 1-2 mm lithium layer (biased up to +4.5 kV)
- Low-mass detector holders (Si, Cu, PTFE)

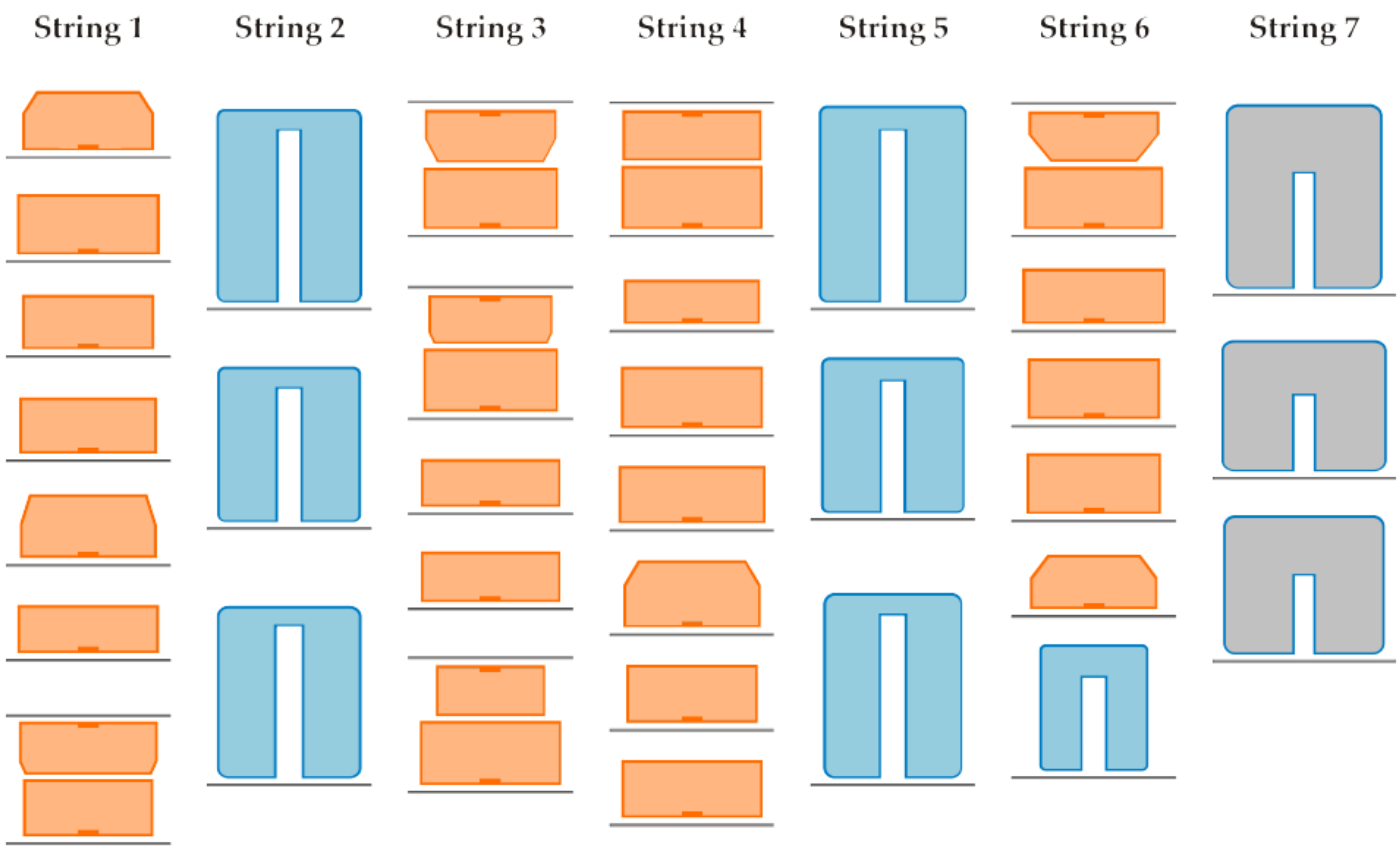






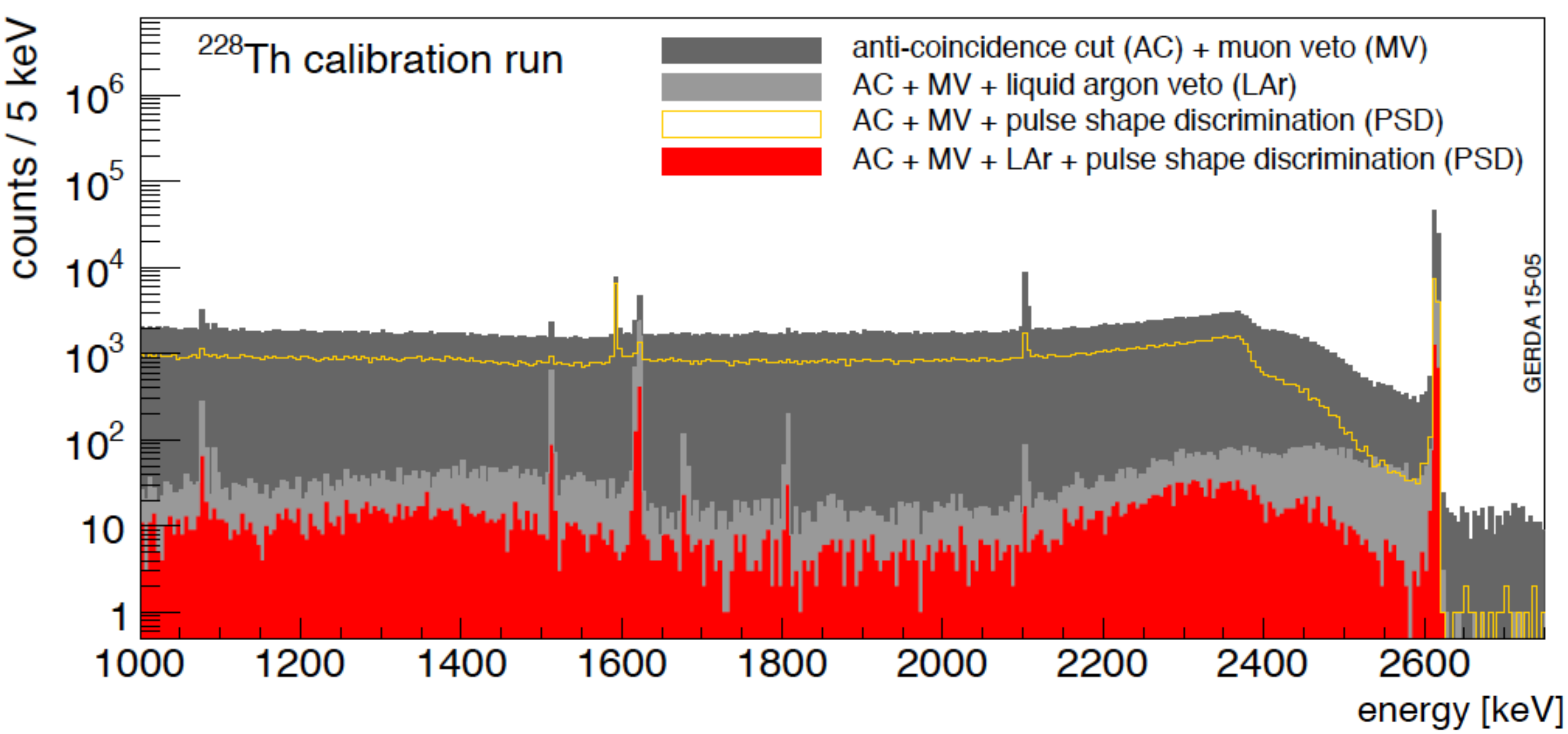
GERDA Detector Strings

- 7 strings, 40 detectors in total:
- 7 semi-coax (15.8 kg), 30 BEGe (20 kg), 3 nat semi-coax (7.6 kg)

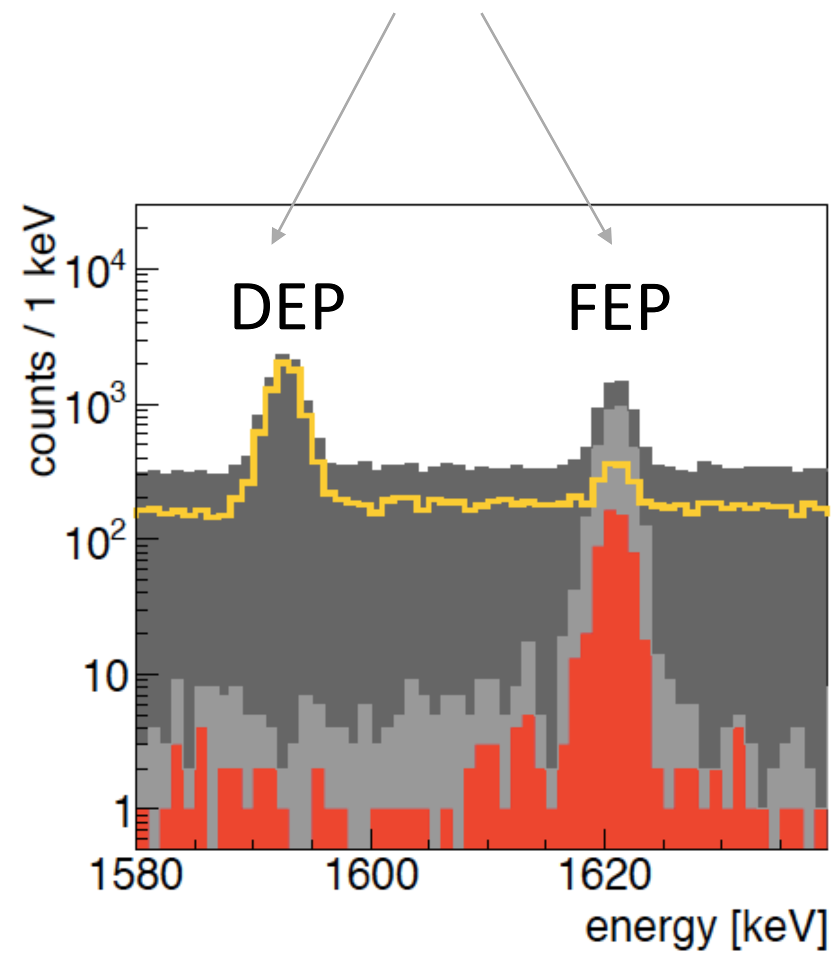


Background Suppression Methods

- Example: calibration data with ^{228}Th sources, background rejection via:
  - ➡Muon Veto (MV)
  - ➡Anti-coincidence detector array (AC)
  - ➡Anti-coincidence liquid argon veto (LAr)
  - ➡Pulse shape discrimination (PSD)

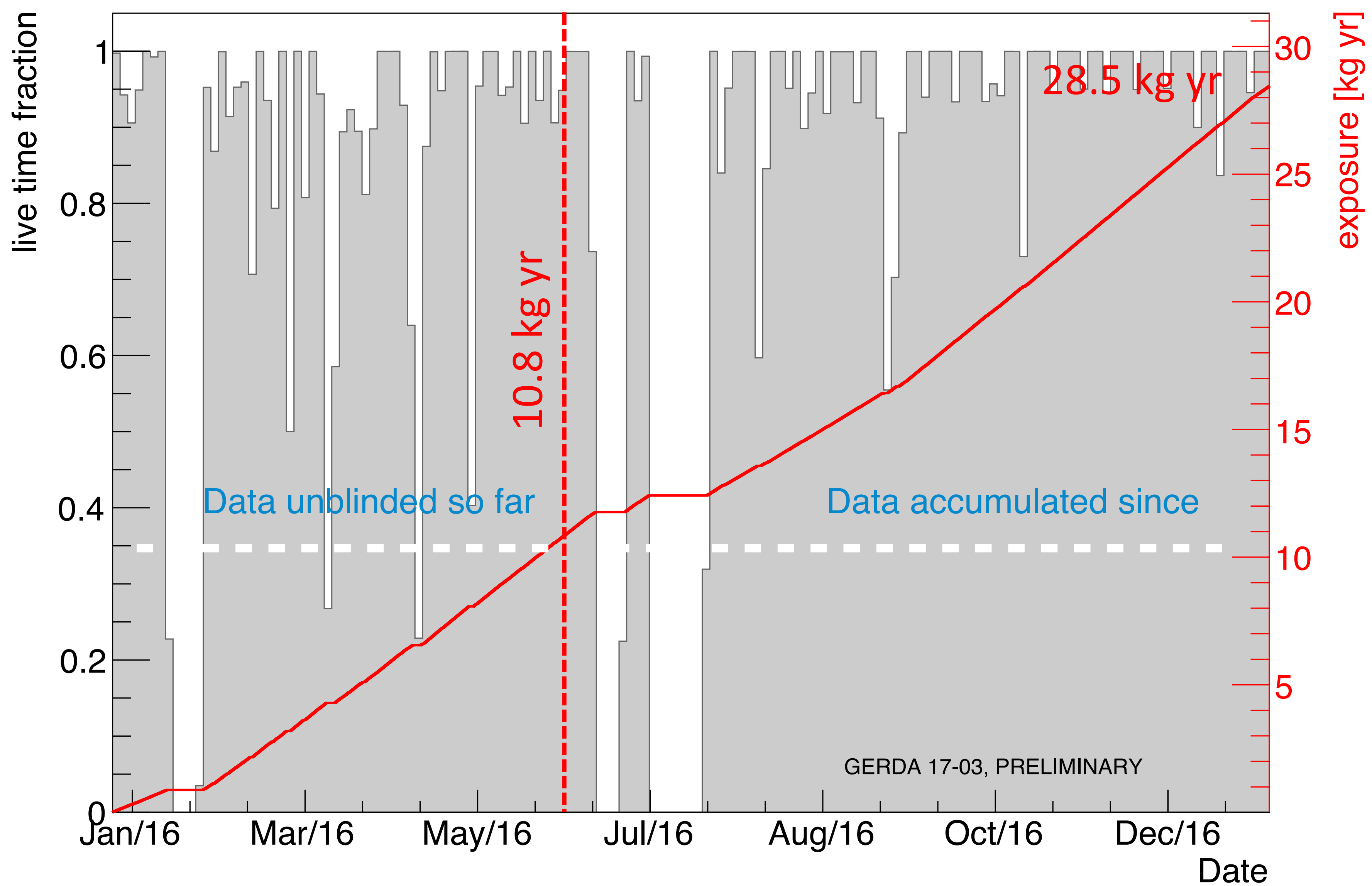


Peaks from ^{208}Tl line

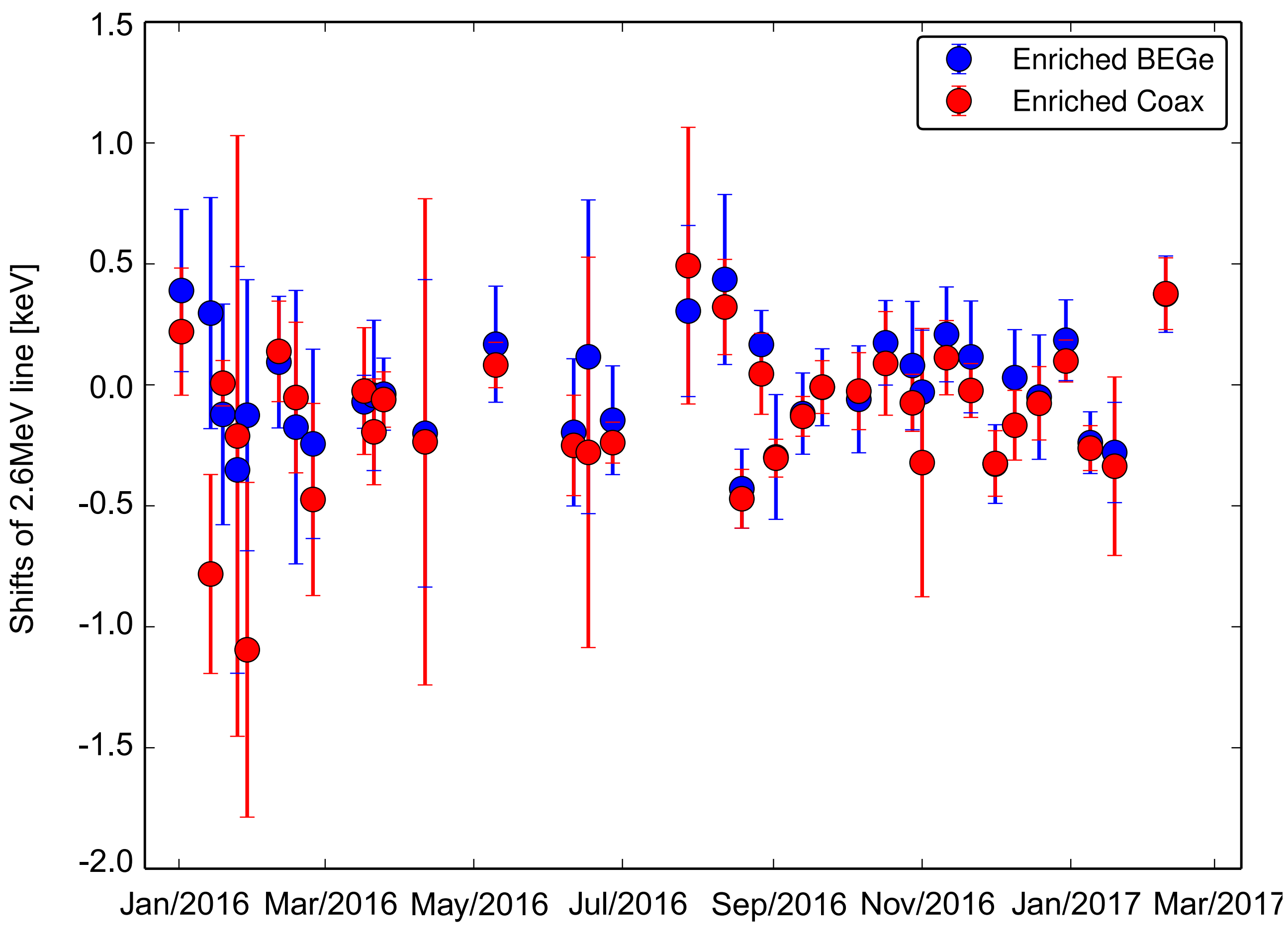


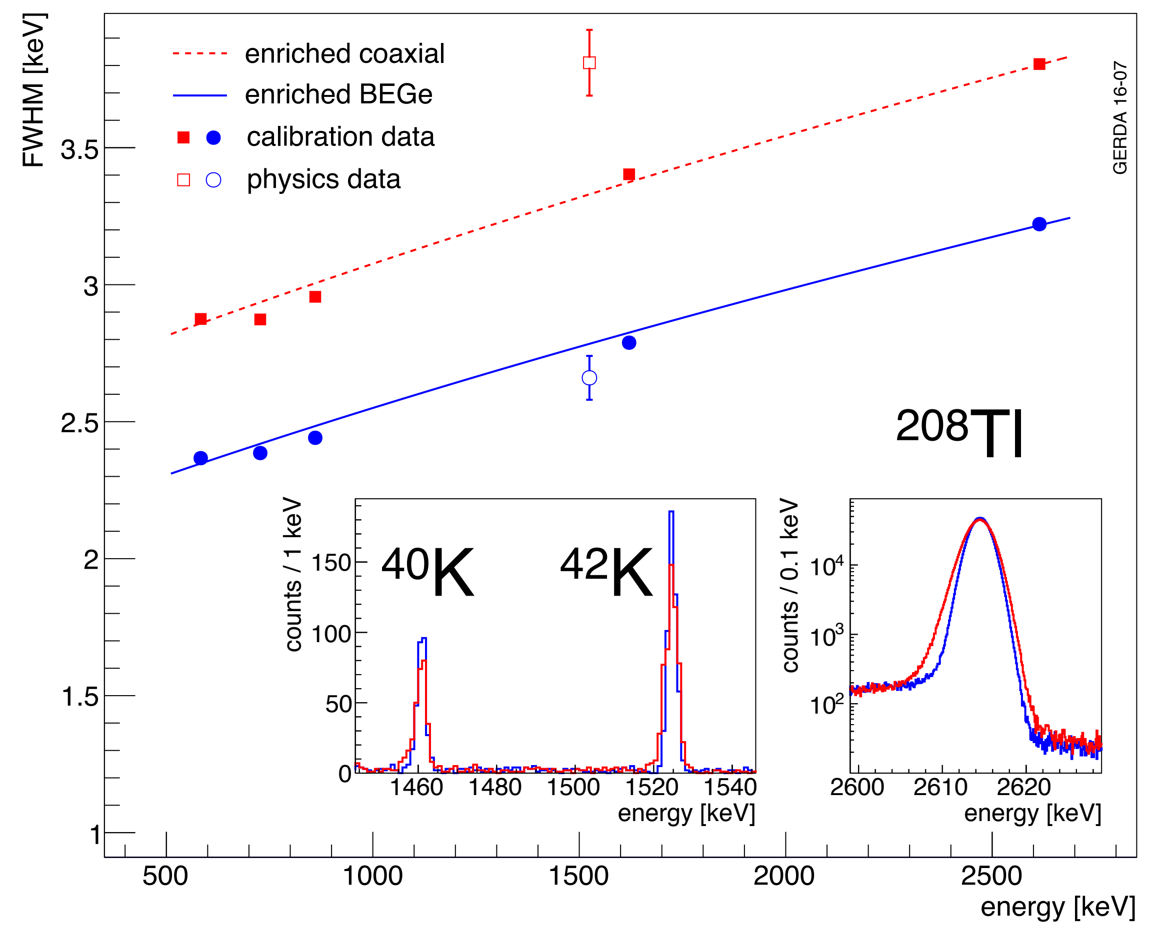
Phase II Data Taking and Exposure

- 30 enriched BEGe detectors: 20.0 kg, 7 enriched coaxial detector: 15.6 kg
- Dec 2015 - May 2016: 85% duty cycle, 10.8 ky y exposure
- 1st unblinding Neutrino2016 (published in Nature, Vol. 544, April 2017)



Calibration: Stability and Energy Resolution

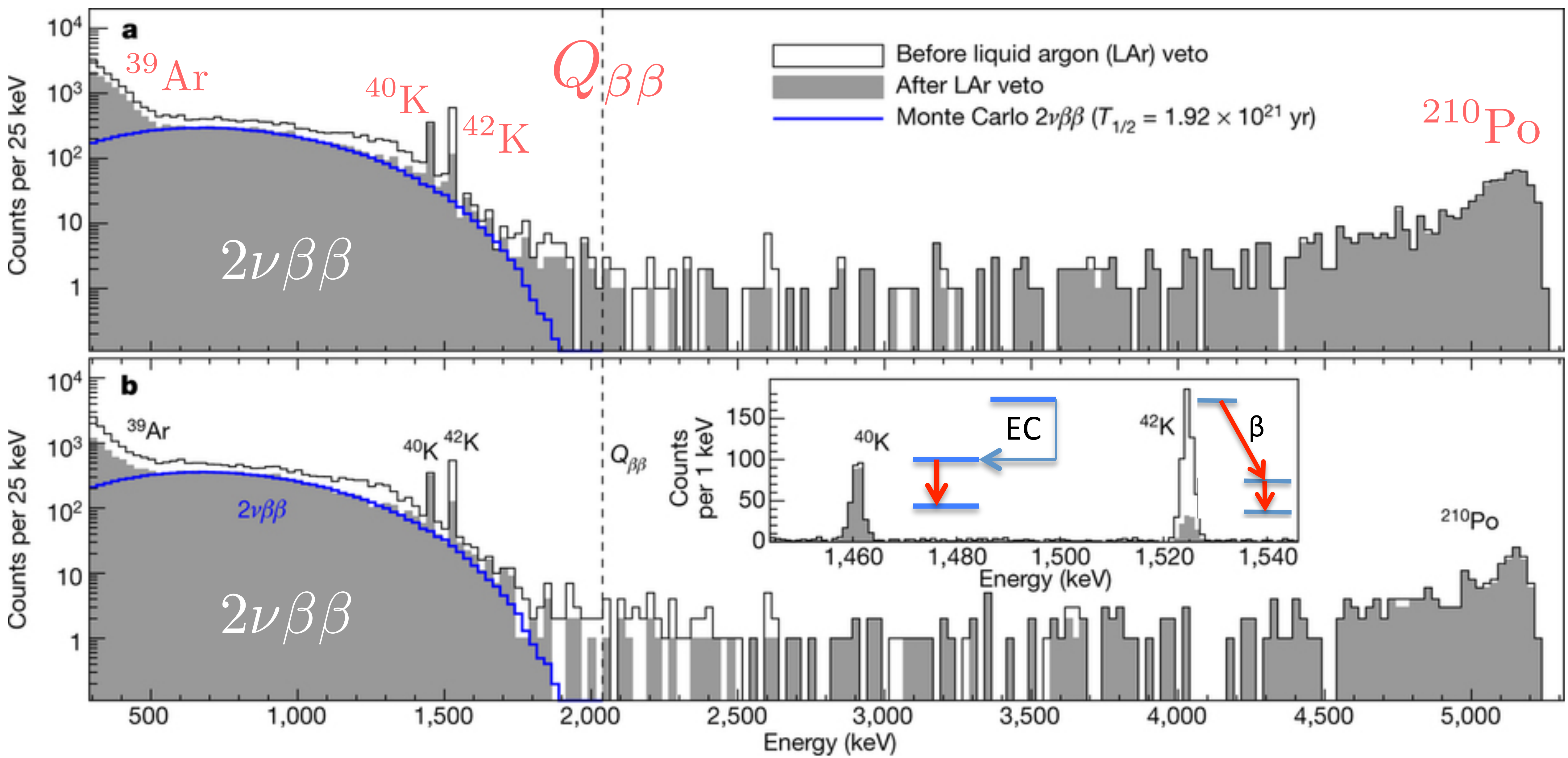




- Weekly calibration with three ^{228}Th sources
- FWHM at $Q_{\beta\beta}$: (3.0 ± 0.2) keV for BEGe, (4.0 ± 0.2) keV for coaxial

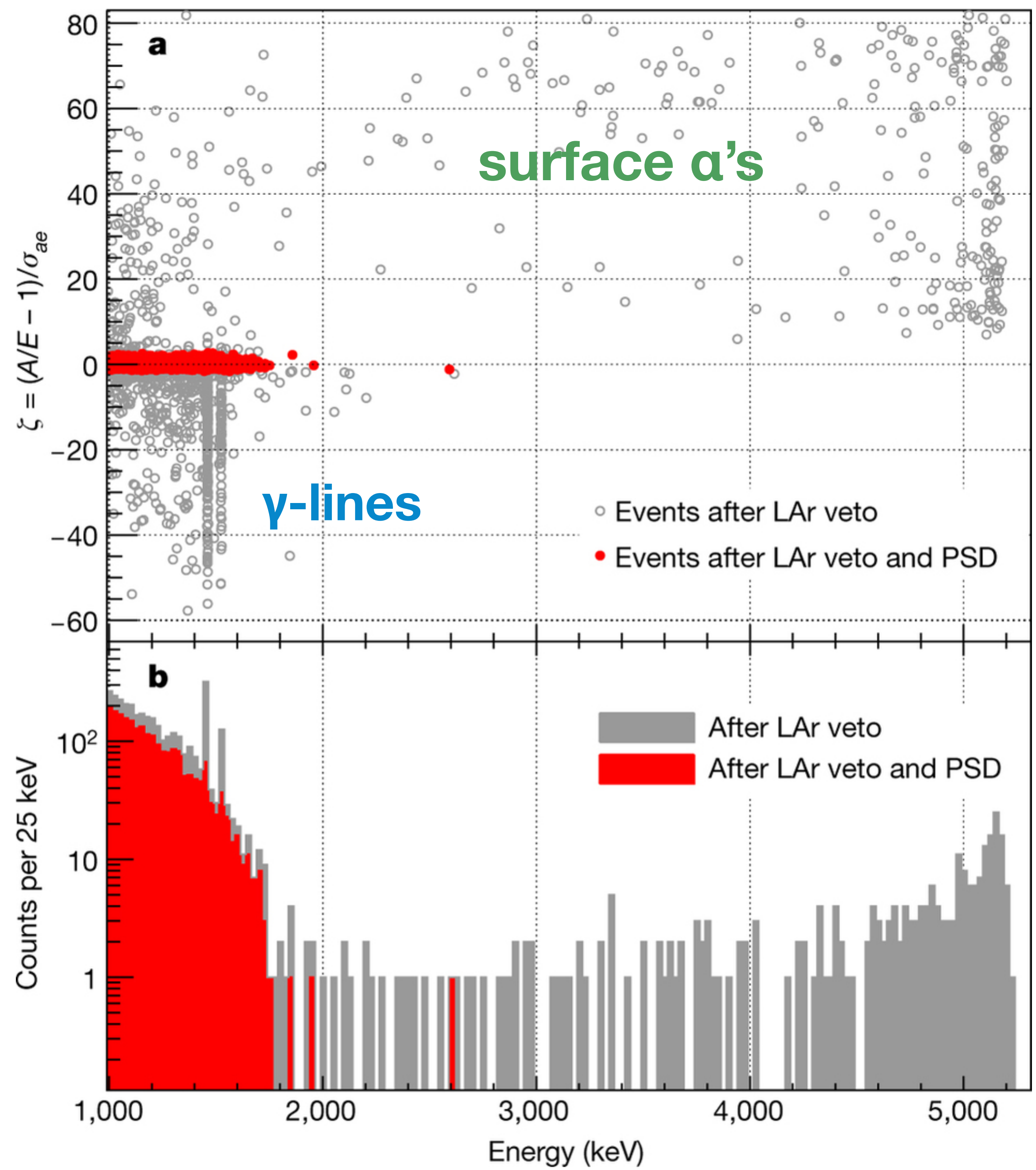
Energy Spectra in Phase II: 10.8 kg y

- Measured and expected for the $2\nu\beta\beta$ - decay (blue)
- LAr veto effect: ~ factor 5 background suppression at 1525 keV (^{42}K)

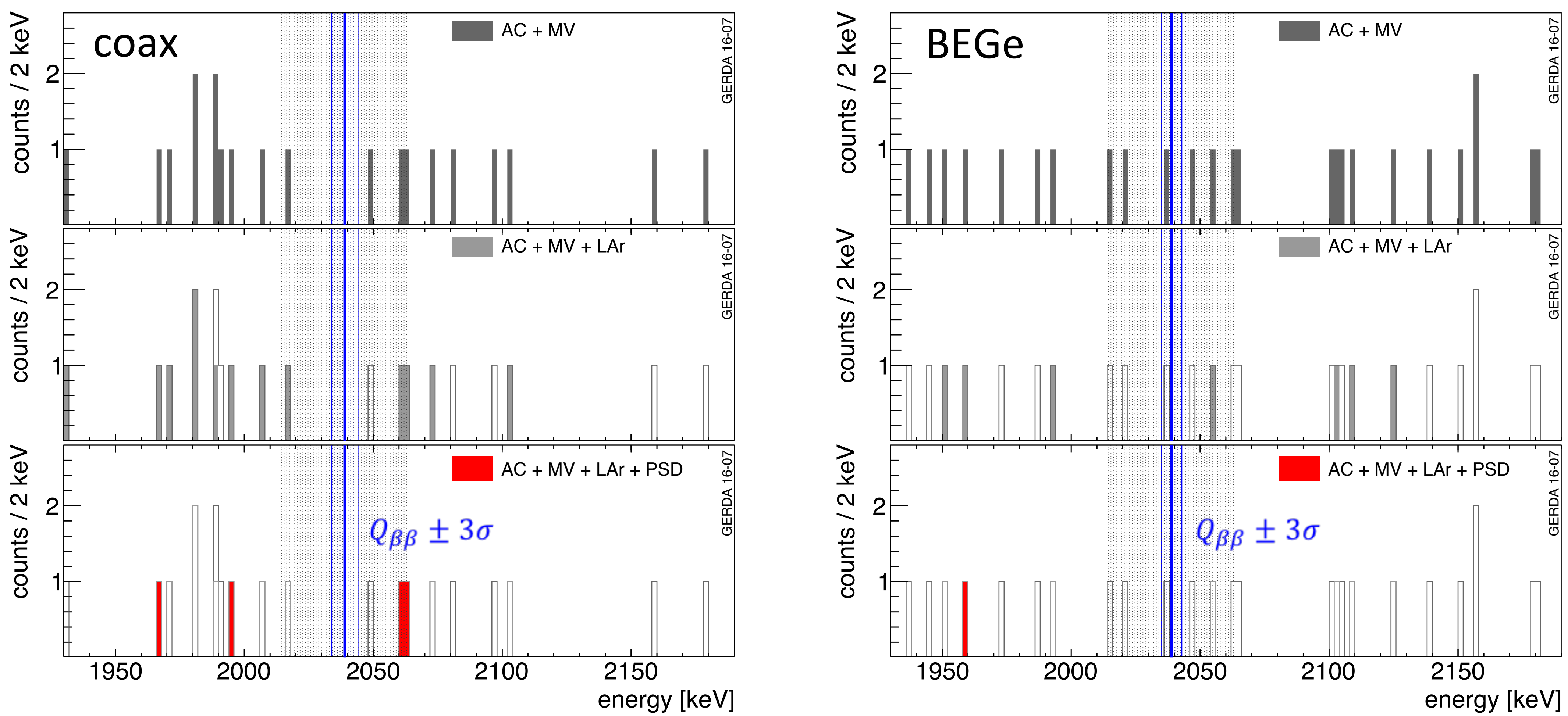


BEGe Pulse Shape Spectra

- Mono-parametric event selection based on A/E:
    - ➡current pulse amplitude *A*
    - ➡total energy *E*
- Tuned by calibration data (DEP from 2615 keV)
- Efficiencies:
    - ➡DEP: ~87%
    - ➡2νββ: ~85%
- **All surface α's removed**
- **γ-lines: factor 6 lower**



GERDA Phase II Initial Unblinding



	exposure $[\mathrm{kg \cdot yr}]$	BI* $\left[10^{-3} \cdot \frac{\mathrm{cts}}{\mathrm{keV \cdot kg \cdot yr}}\right]$	…after LAr veto	…after PSD	…after LAr veto + PSD
coaxial	5.0	$16.5^{+4.2}_{-3.5}$	$10.4^{+3.5}_{-2.7}$	$6.9^{+2.8}_{-2.2}$	$\mathbf{3.5^{+2.1}_{-1.5}}$
BEGe	5.8	$15.7^{+3.8}_{-3.1}$	$4.5^{+2.2}_{-1.6}$	$3.7^{+1.9}_{-1.5}$	$\mathbf{0.7^{+1.1}_{-0.5}}$

Background goal reached

Analysis range: 1930 keV - 2190 keV: 4 events in coax, 1 event in BEGe

GERDA Phase II + Phase I Data

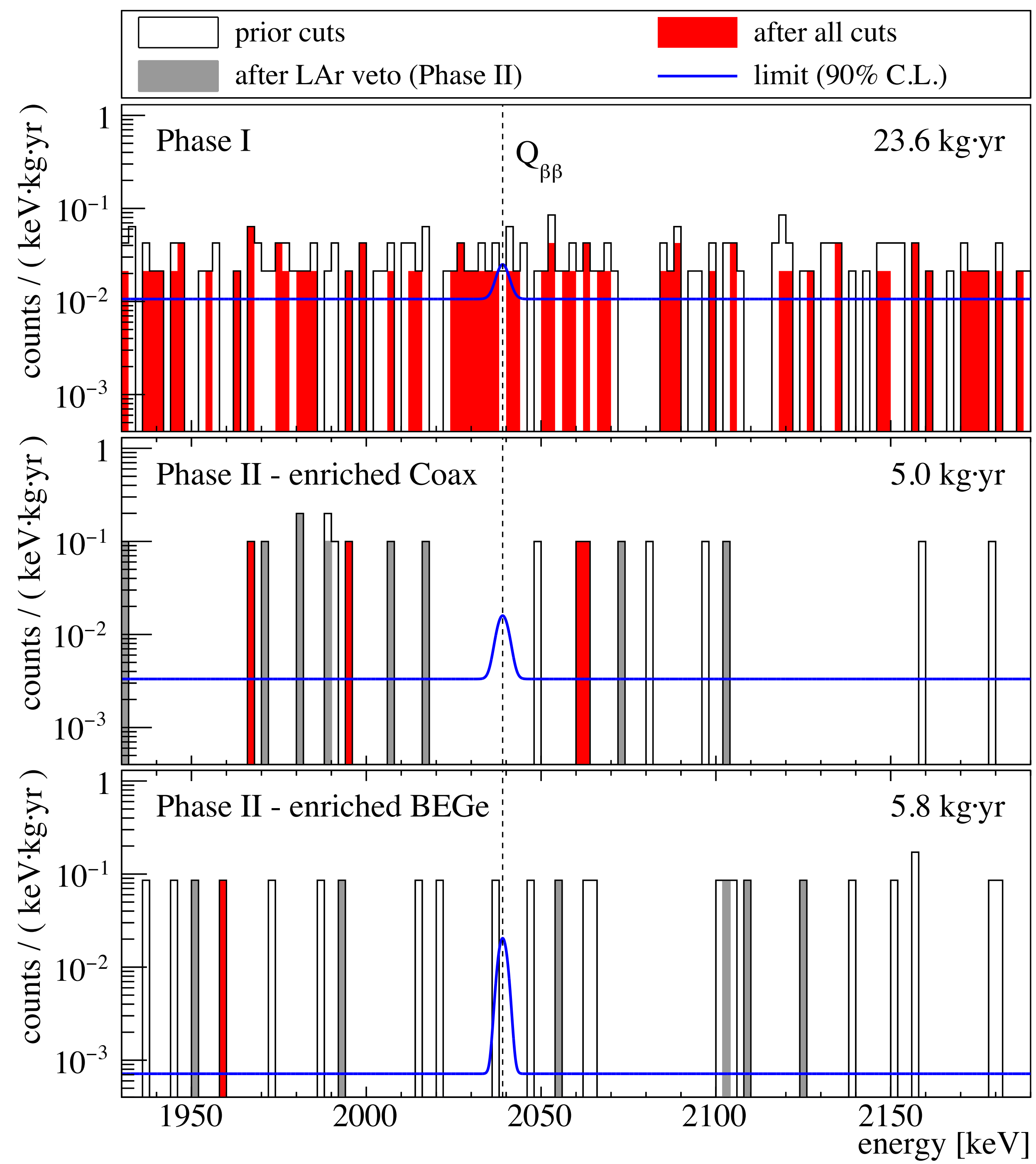
- No hint for a signal, and:

$$T^{0\nu}_{1/2} > 5.3 \times 10^{25}\,\mathrm{y}\ (90\%\mathrm{CL})$$

$$m_{\beta\beta} < 0.15 - 0.33\,\mathrm{eV}\ (90\%\mathrm{CL})$$

NME: 2.8 - 6.1

dataset	exposure $[\mathrm{kg \cdot yr}]$	FWHM $[\mathrm{keV}]$	efficiency*	BI $\left[10^{-3} \frac{\mathrm{cts}}{\mathrm{keV \cdot kg \cdot yr}}\right]$
PI golden	17.9	4.3(1)	0.57(3)	11 ± 2
PI solver	1.3	4.3(1)	0.57(3)	30 ± 10
PI BEGe	2.4	2.7(2)	0.66(2)	5^{+4}_{-3}
PI extra	1.9	4.2(2)	0.58(4)	5^{+4}_{-3}
PIIa coaxial	5.0	4.0(2)	0.53(5)	$3.5^{+2.1}_{-1.5}$
PIIa BEGe	5.8	3.0(2)	0.60(2)	$0.7^{+1.1}_{-0.5}$



- Phase I: improved energy reconstruction, extra data
- unbinned profile likelihood: flat background, Gaussian signal

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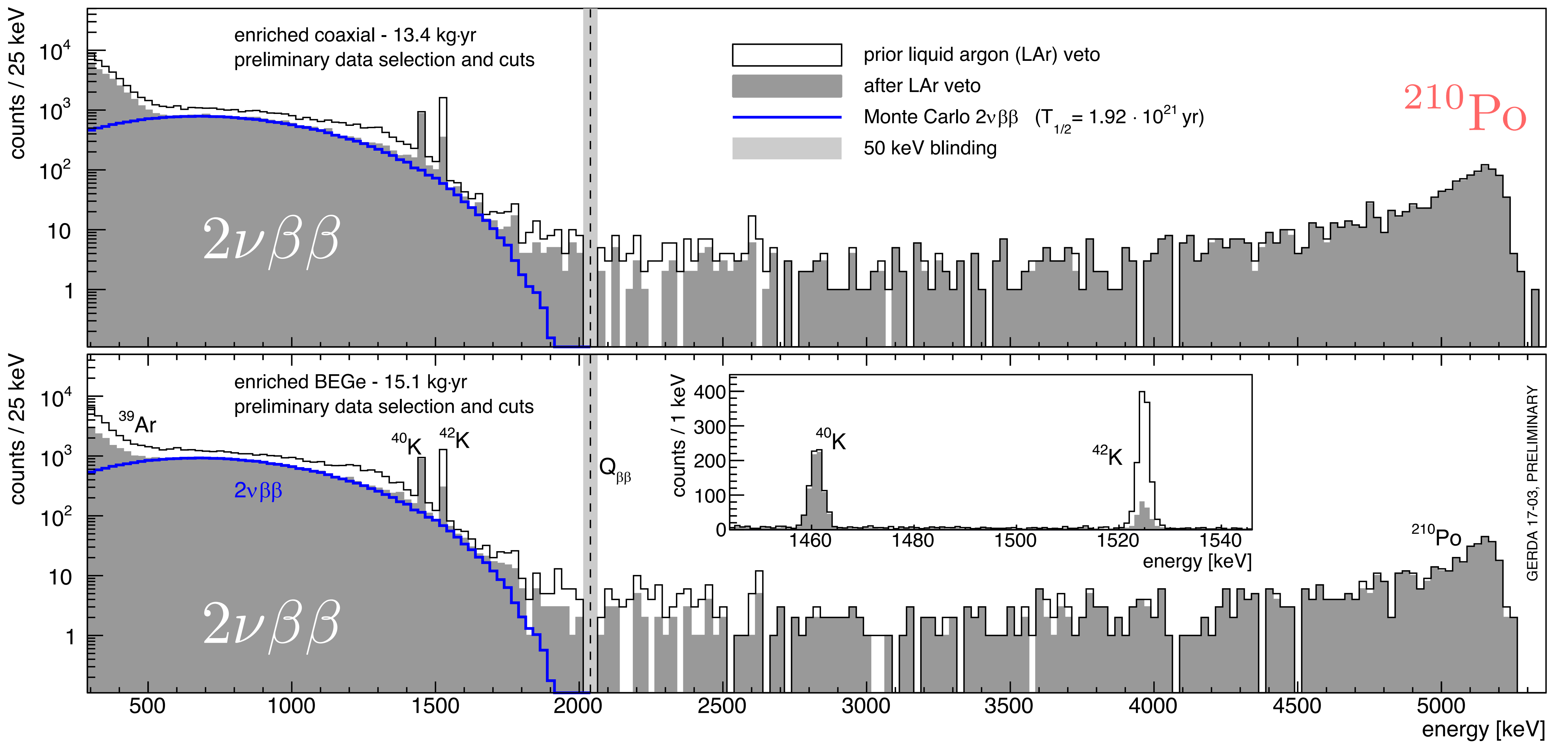
Science Run in Progress

- New background spectra; signal region blinded; unblinding in late June 2017



$$T_{1/2}^{2\nu} = (1.926 \pm 0.094) \times 10^{21}\ \mathrm{y}$$

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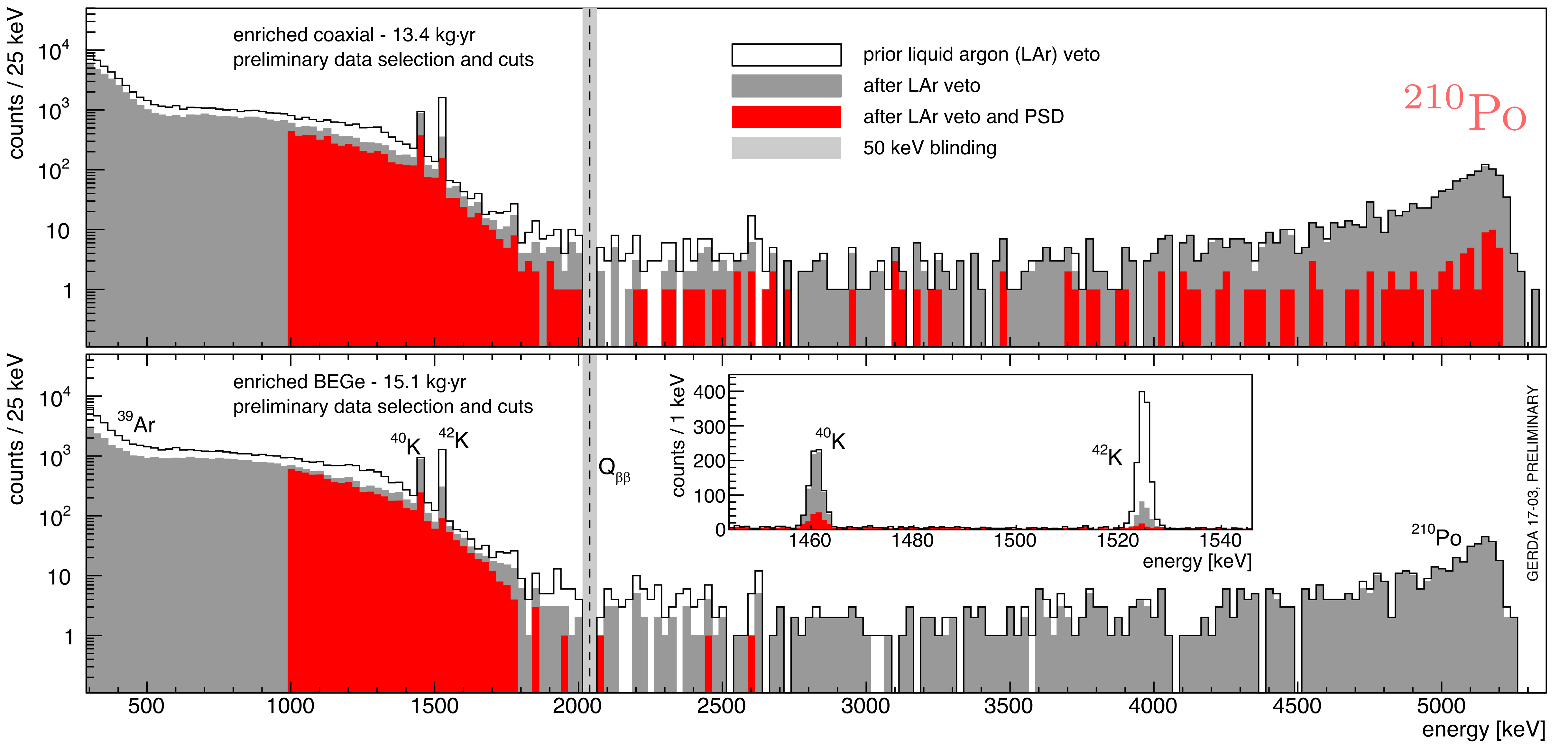


$$T_{1/2}^{2\nu} = (1.926 \pm 0.094) \times 10^{21}\ \mathrm{y}$$

Summary & Outlook

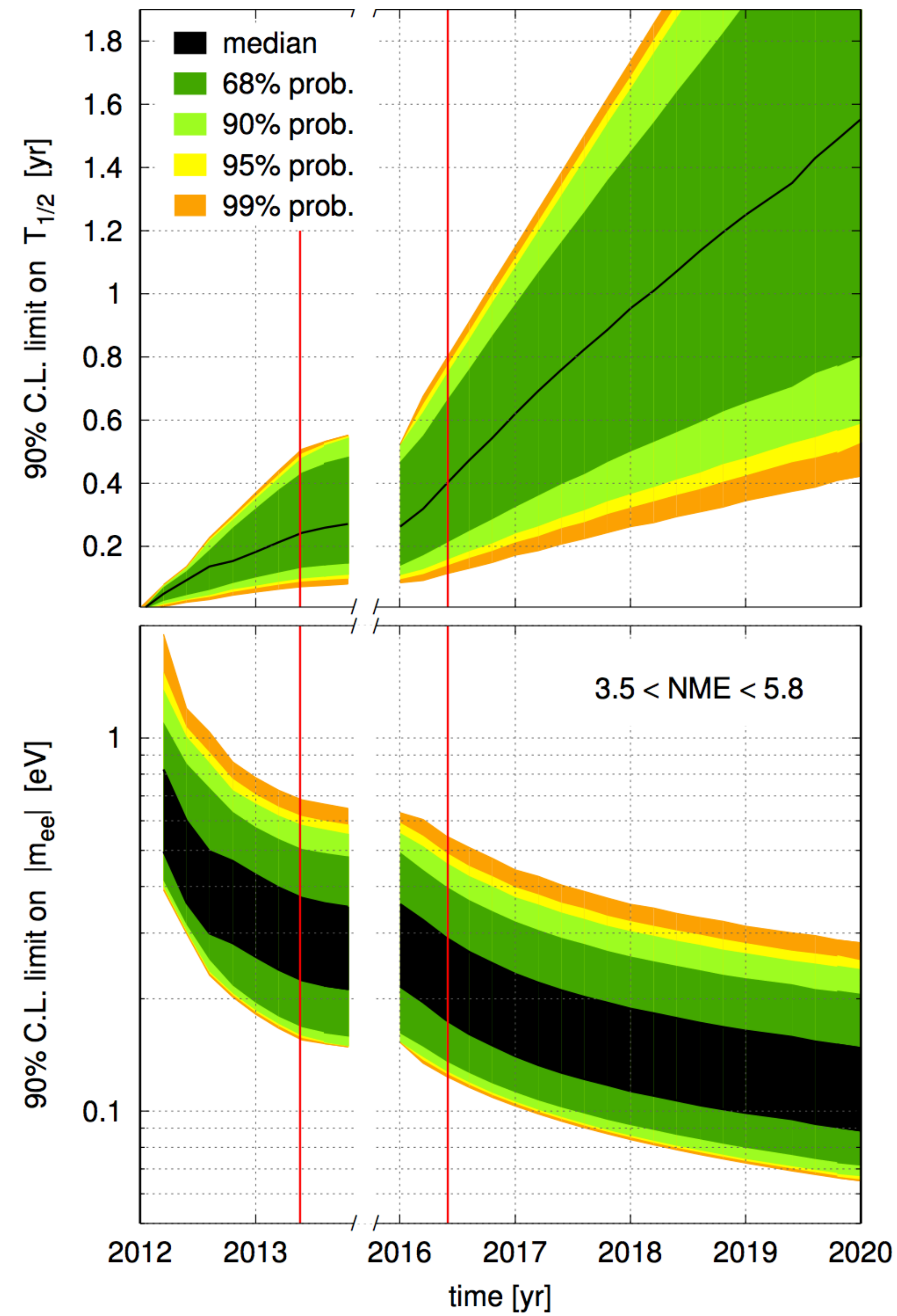
- Blind analysis: 10.8 kg y of phase II data
- New limit on the 0νββ-decay of ^{76}Ge

$$T^{0\nu}_{1/2} > 5.3 \times 10^{25}\,\mathrm{y}\ (90\%\mathrm{CL})$$

$$m_{\beta\beta} < 0.15 - 0.33\,\mathrm{eV}\ (90\%\mathrm{CL})$$

- **Exposure increased to 28.5 kg y**
- **New background index:**
  - BEGe: 0.6 (+0.6 - 0.4) x 10^{-3} events/(keV kg y)
  - Coaxial: 2.2 (+1.1 - 0.8) x 10^{-3} events/(keV kg y)
- *GERDA will stay "background-free"*
- **Sensitivity 100 kg y:**

$$T^{0\nu}_{1/2} \geq 1 \times 10^{26}\,\mathrm{y}\ (90\%\mathrm{CL})$$



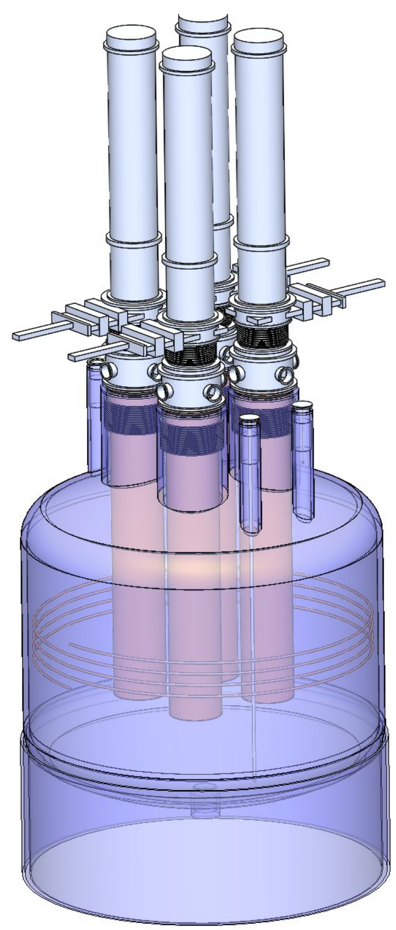
Beyond GERDA: LEGEND

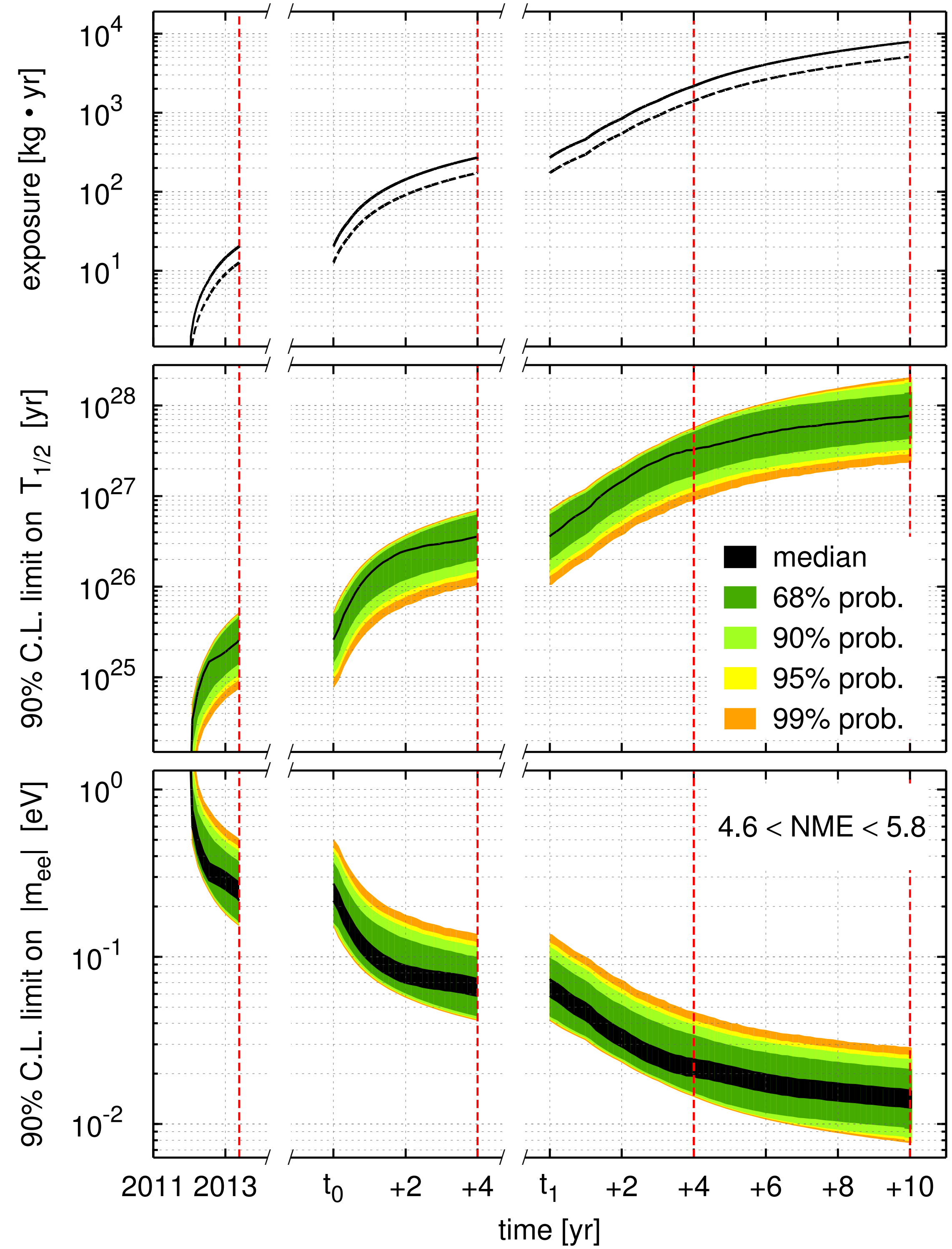
- *Large Enriched Germanium Experiment for Neutrinoless Double Beta Decay*
- Collaboration formed in October 2016
- 219 members, 48 institutions, 16 countries (legend-exp.org)
- Background goal:

$$\sim 10^{-4}\,\mathrm{events/(kg\,y\,keV)}$$

- Detector mass: 200 kg -> 1 t
- Discovery potential:

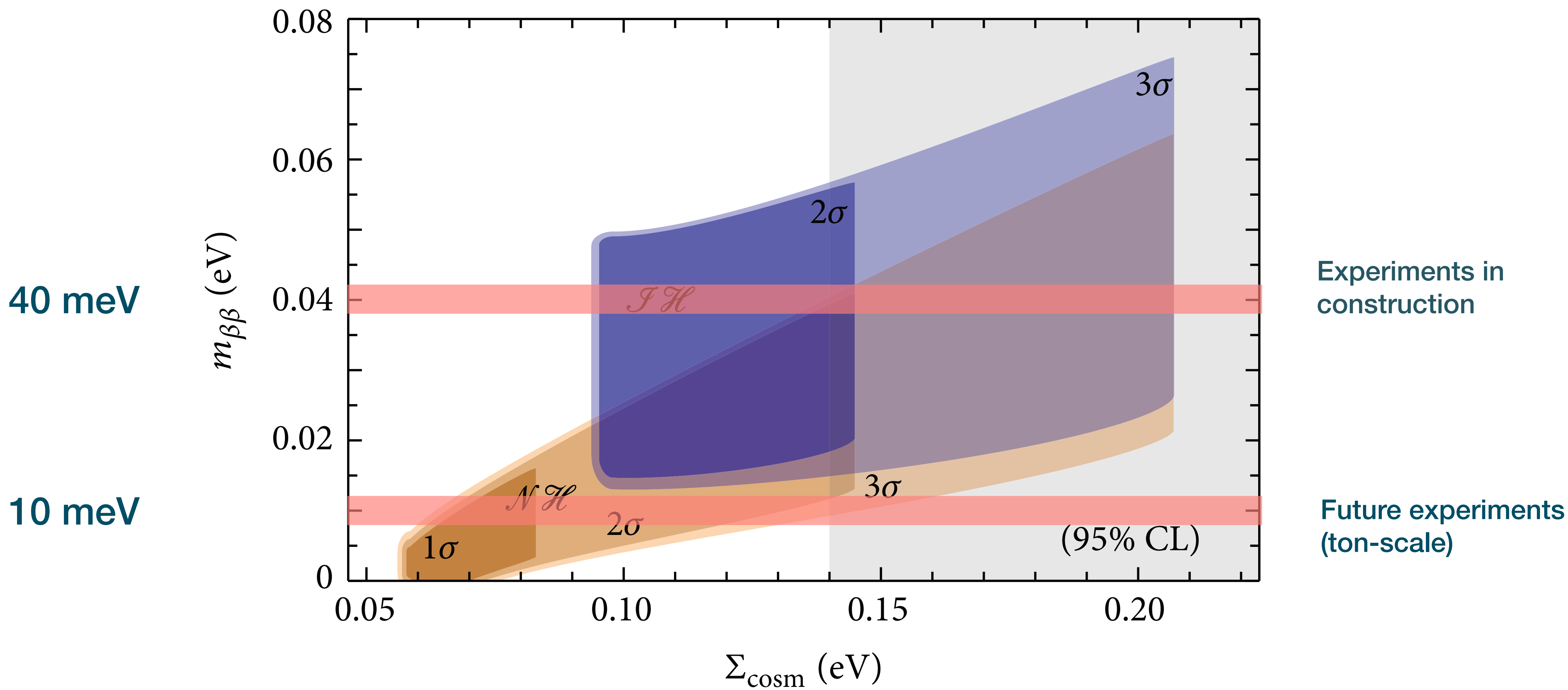
$$T_{1/2}^{0\nu} > 10^{27}\,\mathrm{y}$$





LEGEND: Physics Reach

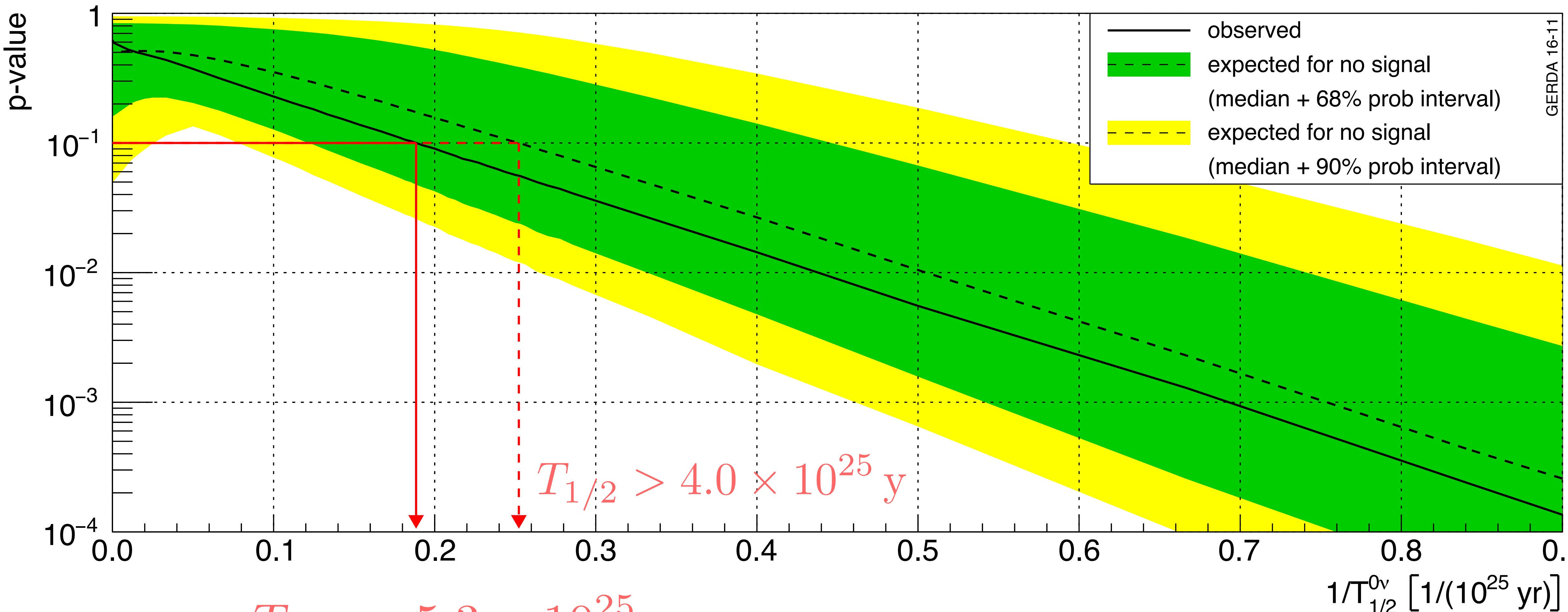
- Ton-scale experiments are indeed required to explore the inverted mass hierarchy scale
- Several other technologies also move into this direction
- ^{76}Ge experiments: the advantage of an excellent energy resolution coupled to ultra-low backgrounds



The end

GERDA phase II result

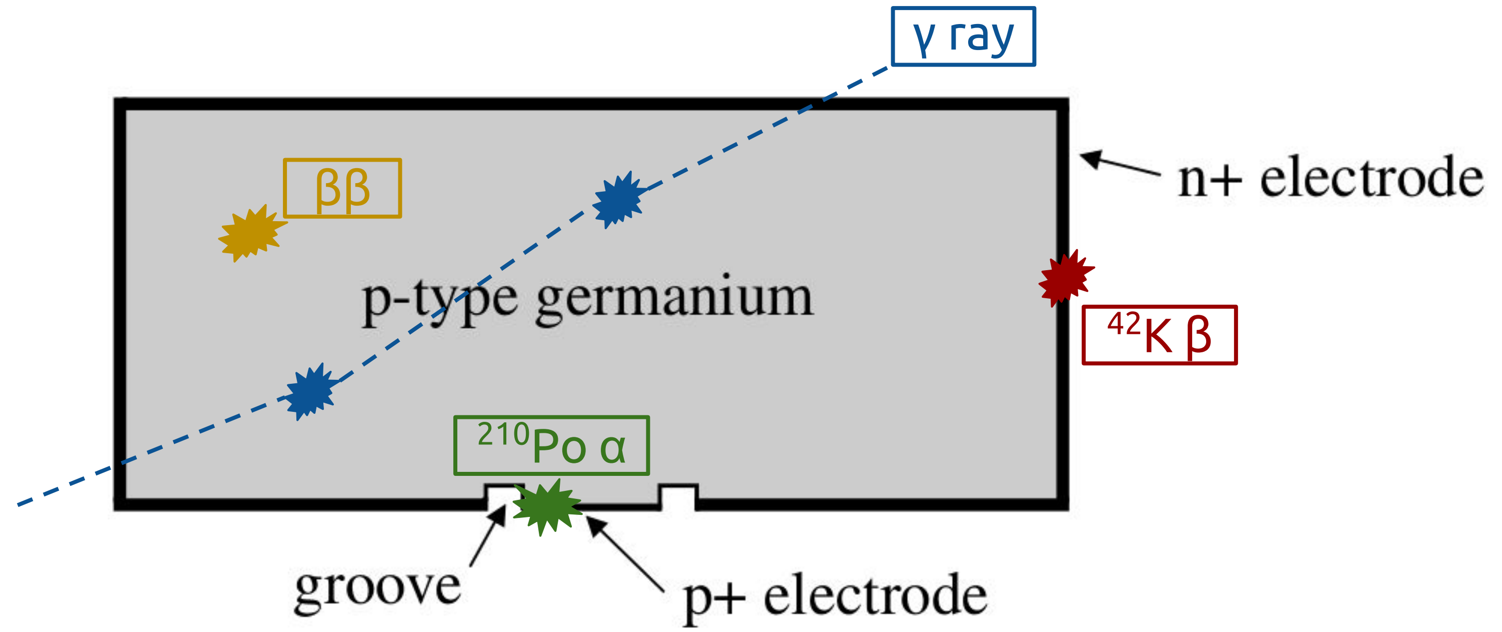
- p-value for the hypothesis test as a function of the inverse $T_{1/2}$ for the data and the median sensitivity

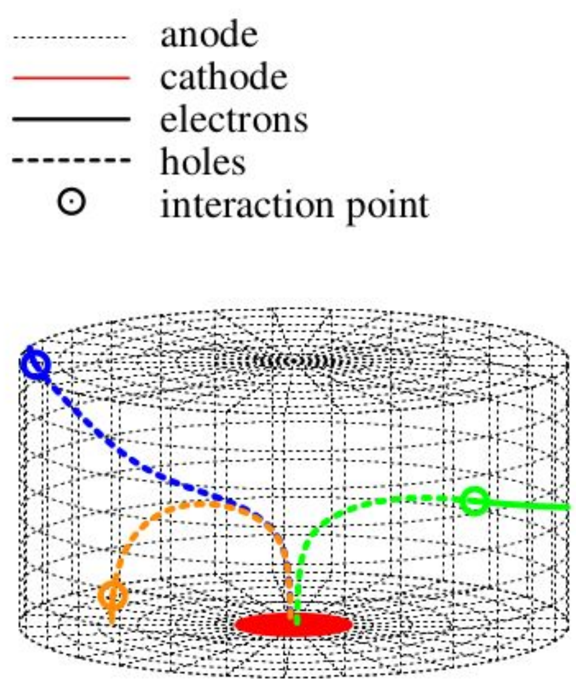


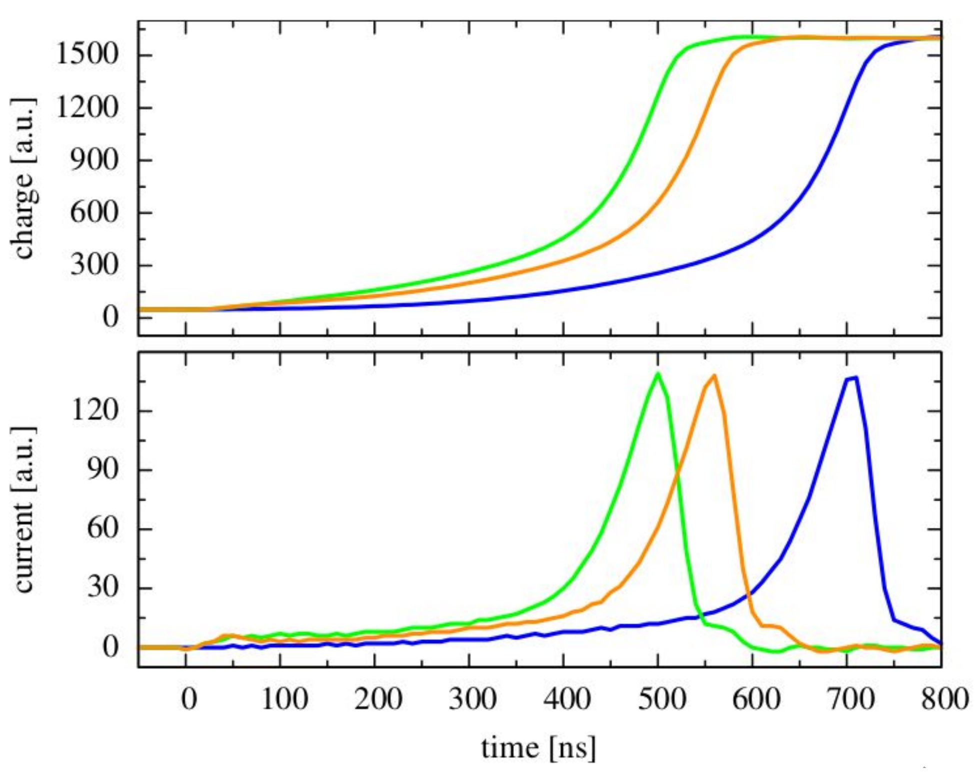
$T_{1/2} > 5.3 \times 10^{25}$ y

GERDA Pulse Shape Discrimination

- Signal-like: Single Site Events (SSE)
- Background-like: Multiple Site Events (MSE)
- BEGe detectors: E-field and weighting potential has special shape: pulse-height nearly independent of position

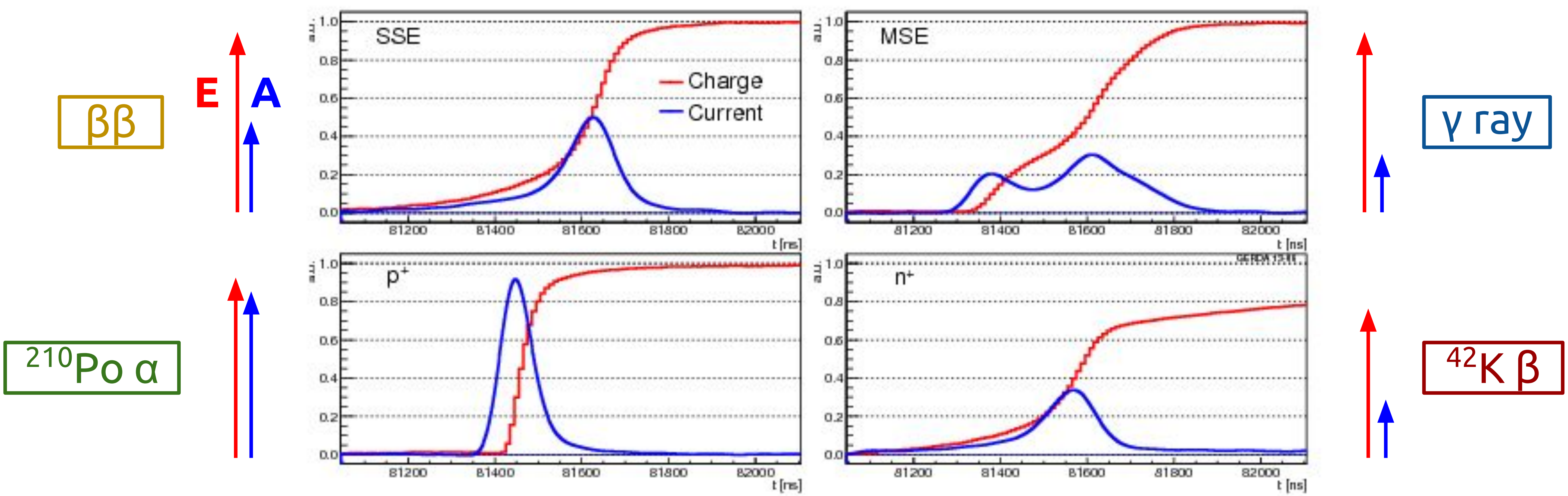






GERDA Pulse Shape Discrimination

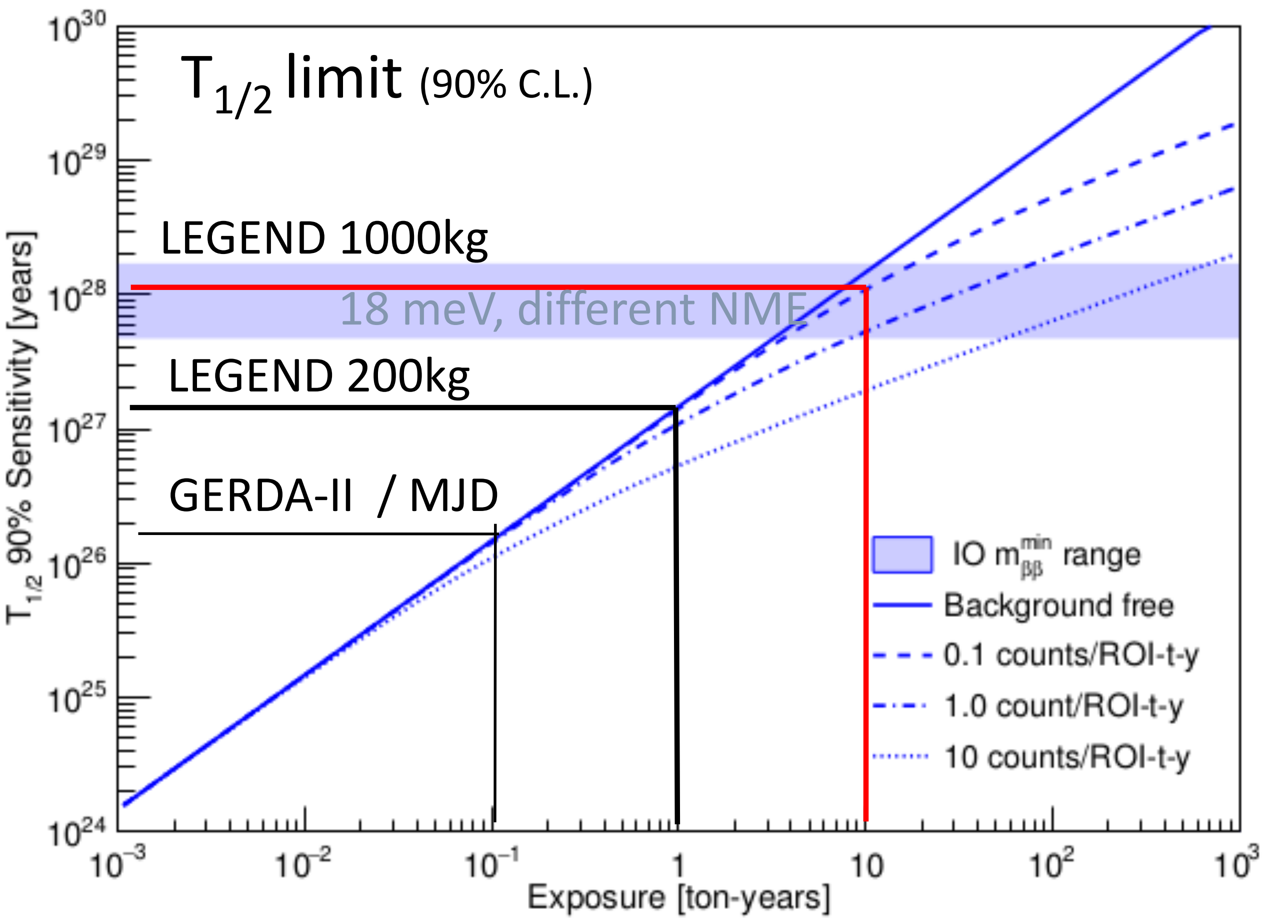
- A/E: amplitude of the current pulse over energy
- Multiple energy depositions: multiple peaks in current pulse => decreasing A/E
- p+ surface events: shorter signals => higher A/E

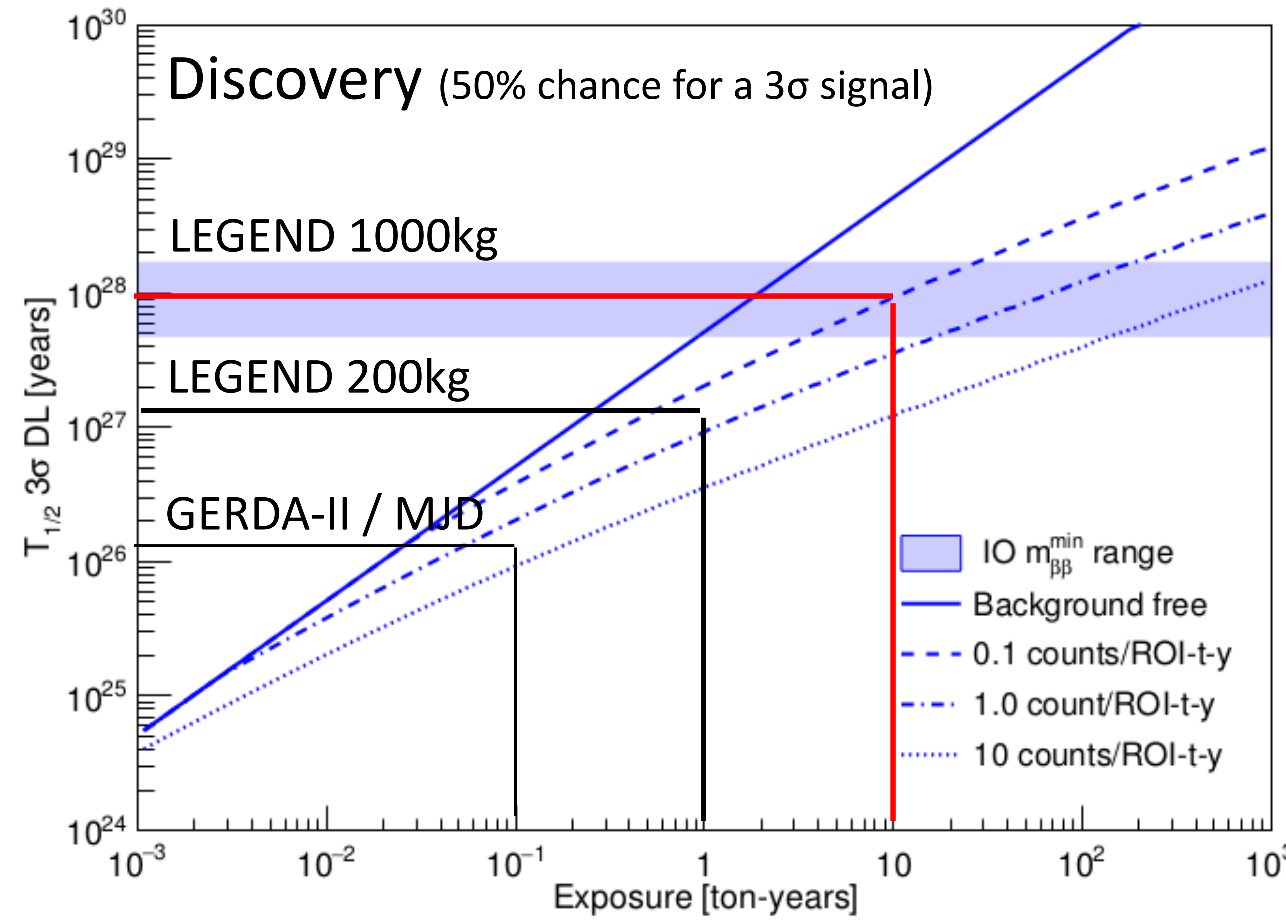


EPJC 73 (2013) 2583

LEGEND Physics Reach

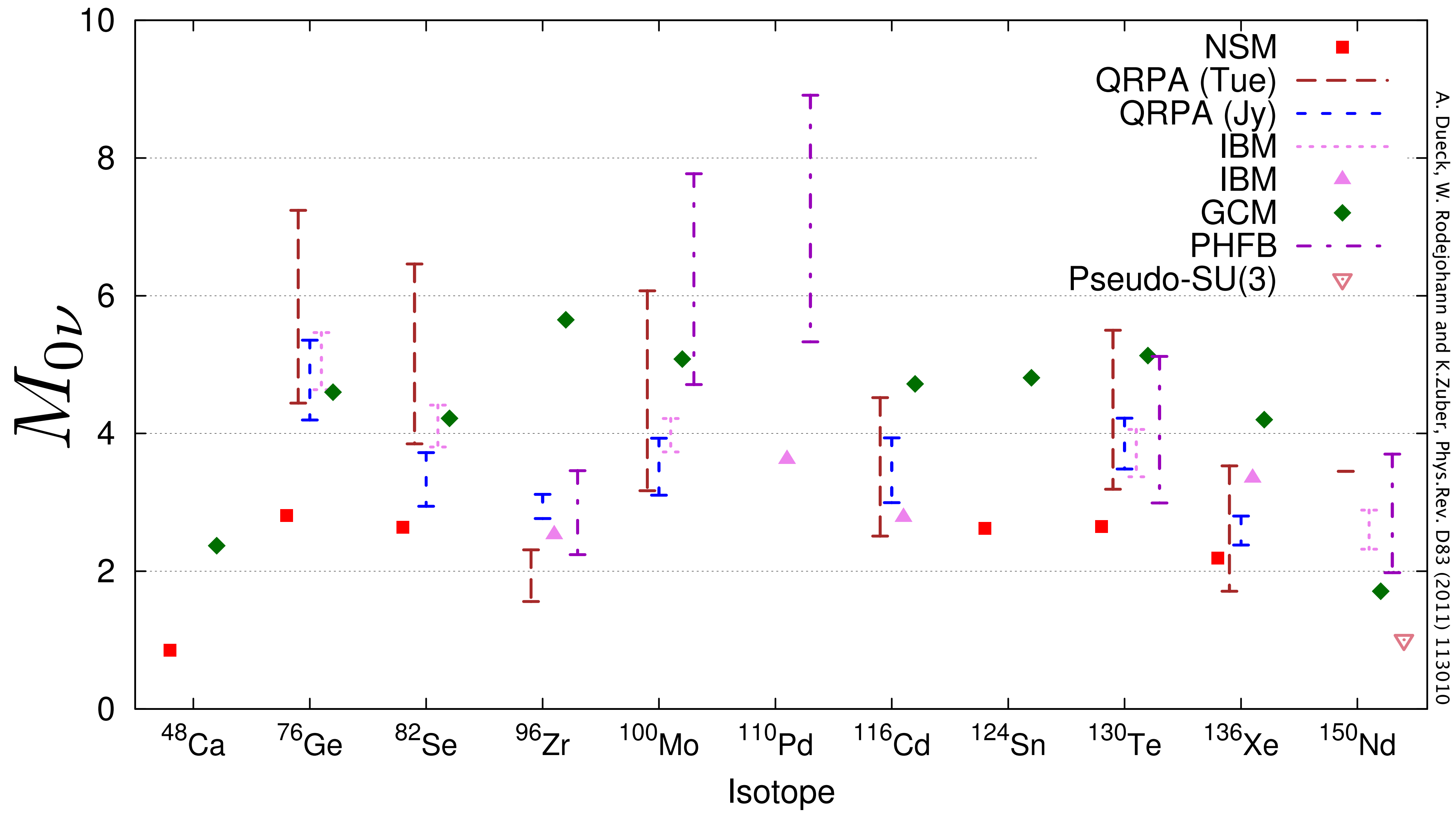
- 60% efficiency, including isotope fraction, active volume fraction, analysis cuts
- GERDA-II/MJD: 3 events/(ROI t y)
- LEGEND-200 (LEGEND-1000): 0.6 events/(ROI t y) (0.1 events/(ROI t y))





Matrix elements for $0\nu\beta\beta$

- Past years: improved agreement among the various methods
- Still spread by a factor 2-3 => **uncertainty of ~ 4 - 10 in $T_{1/2}$**



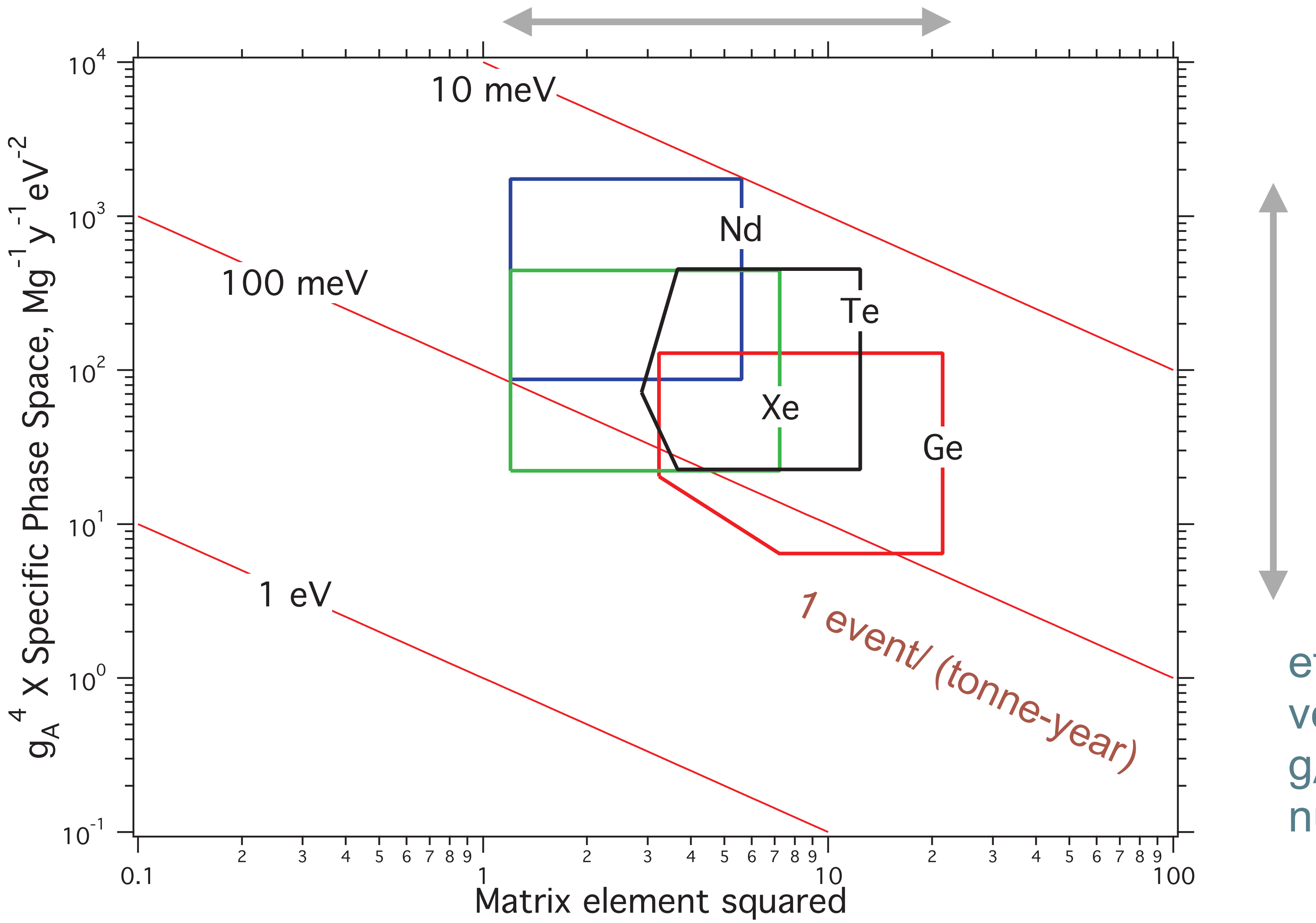
Isotopes and sensitivity to $0\nu\beta\beta$

Isotopes have comparable sensitivities in terms of rates per unit mass

$$\frac{1}{T^{0\nu}_{1/2}} = G^{0\nu} g_A^4 |M^{0\nu}|^2 \frac{|m\beta\beta|^2}{m_e^2}$$

$|M|^2$ uncertainty

$$g_A^4 \ln(2) \frac{N_A}{Am_e^2} G^{0\nu}$$



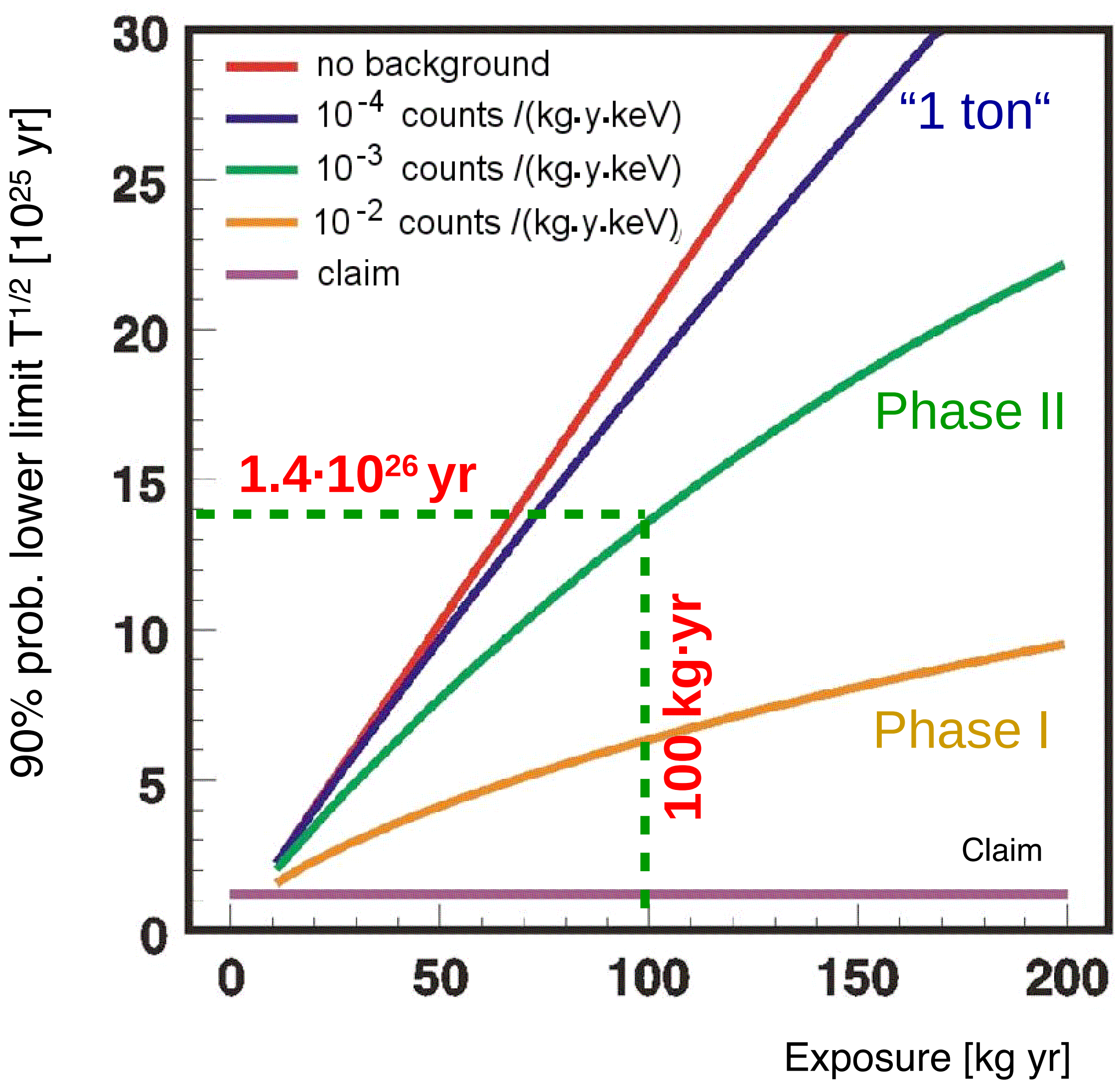
g_A^4 uncertainty

effective value for the axial vector coupling constant g_A: ~ 0.6 - 1.269 (free nucleon value)

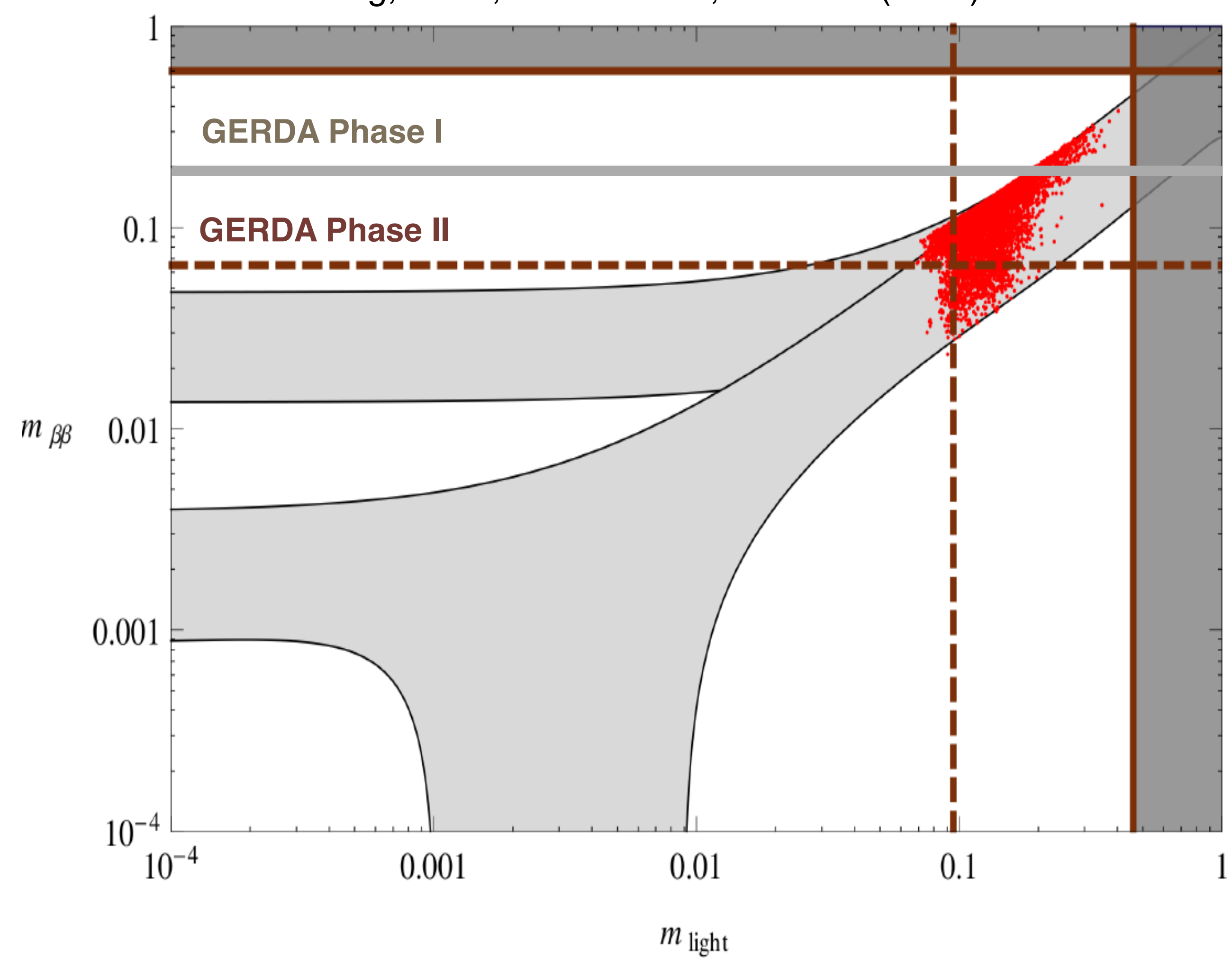
R. G. H. Robertson, Mod. Phys. Lett. A28 (2013) 1350021

GERDA phase II and beyond

- Demonstrated that a background of ≤ 10^{-3} events/(keV kg yr) is feasible
- Will explore $T_{1/2}$ values in the 10^{26} yr range, probing the degenerate mass region
- LEGEND, a ton-scale experiment (in collaboration with Majorana) is in design phase



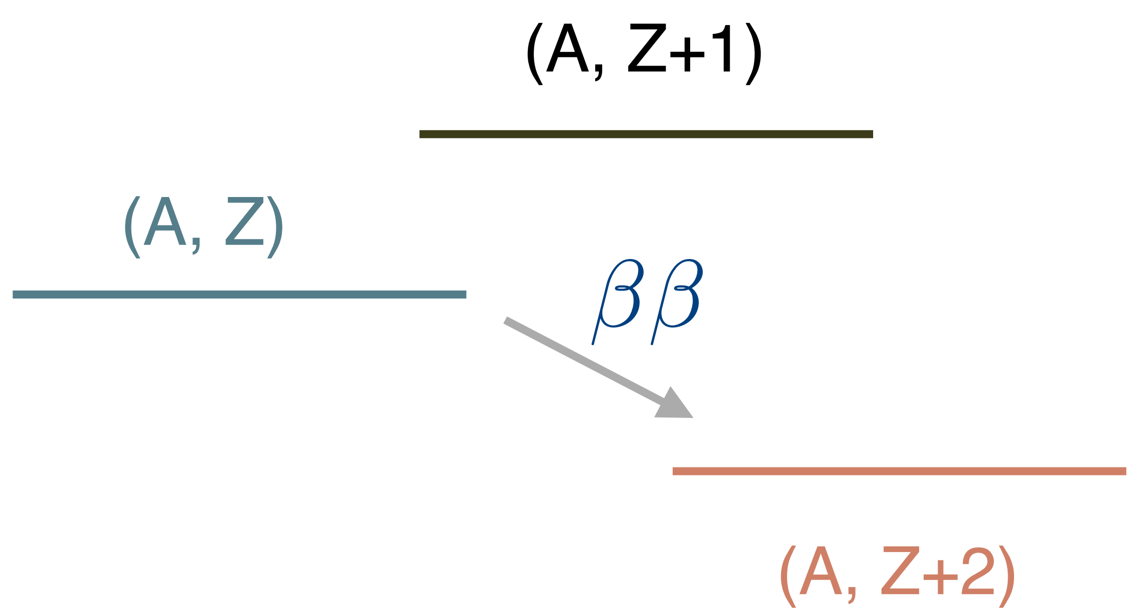
Alonso, Gavela, Isidori,Maiani, JHEP 1311 (2013) 187
Blankenburg,Isidori, Jones-Perez, EPJC 72 (2012) 2126



Theory: neutrino mixing and masses from a minimum principle

Which nuclei can decay via $0\nu\beta\beta$?

- Even-even nuclei
- Natural abundance is low (except ^{130}Te)
- Must use enriched material



Candidate*	Q [MeV]	Abund [%]
^{48}Ca -> ^{48}Ti	4.271	0.187
^{76}Ge -> ^{76}Se	2.040	7.8
^{82}Se -> ^{82}Kr	2.995	9.2
^{96}Zr -> ^{96}Mo	3.350	2.8
^{100}Mo -> ^{100}Ru	3.034	9.6
^{110}Pd -> ^{110}Cd	2.013	11.8
^{116}Cd -> ^{116}Sn	2.802	7.5
^{124}Sn -> ^{124}Te	2.228	5.64
^{130}Te -> ^{130}Xe	2.530	34.5
^{136}Xe -> ^{136}Ba	2.479	8.9
^{150}Nd -> ^{150}Sm	3.367	5.6

* Q-value > 2 MeV

Experimental requirements

- Experiments measure the half life of the decay, $T_{1/2}$ with a sensitivity **(for non-zero background)**

$$T^{0\nu}_{1/2} \propto a \cdot \epsilon \cdot \sqrt{\frac{M \cdot t}{B \cdot \Delta E}}$$

$$\langle m_{\beta\beta} \rangle \propto \frac{1}{\sqrt{T^{0\nu}_{1/2}}}$$

Minimal requirements:

large detector masses
high isotopic abundance
ultra-low background noise
good energy resolution

Additional tools to distinguish signal from background:

event topology
pulse shape discrimination
particle identification