The GERDA enterprise

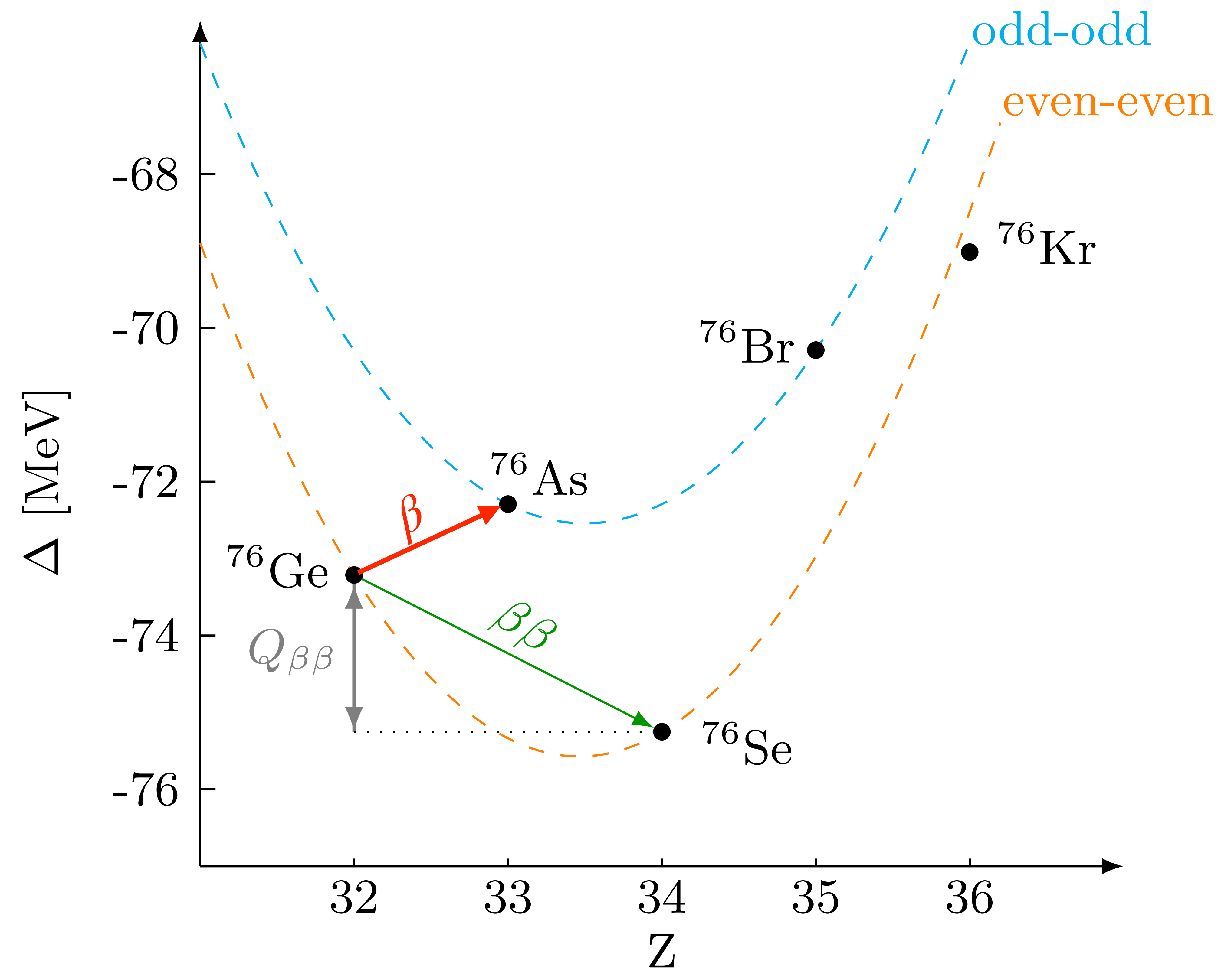
in the search for matter creation

Tommaso Comellato - Neutrino Oscillation Workshop 2022 - 09.09.2022

Double-beta decay

...occurs when single beta is forbidden

arXiv:2202.01787



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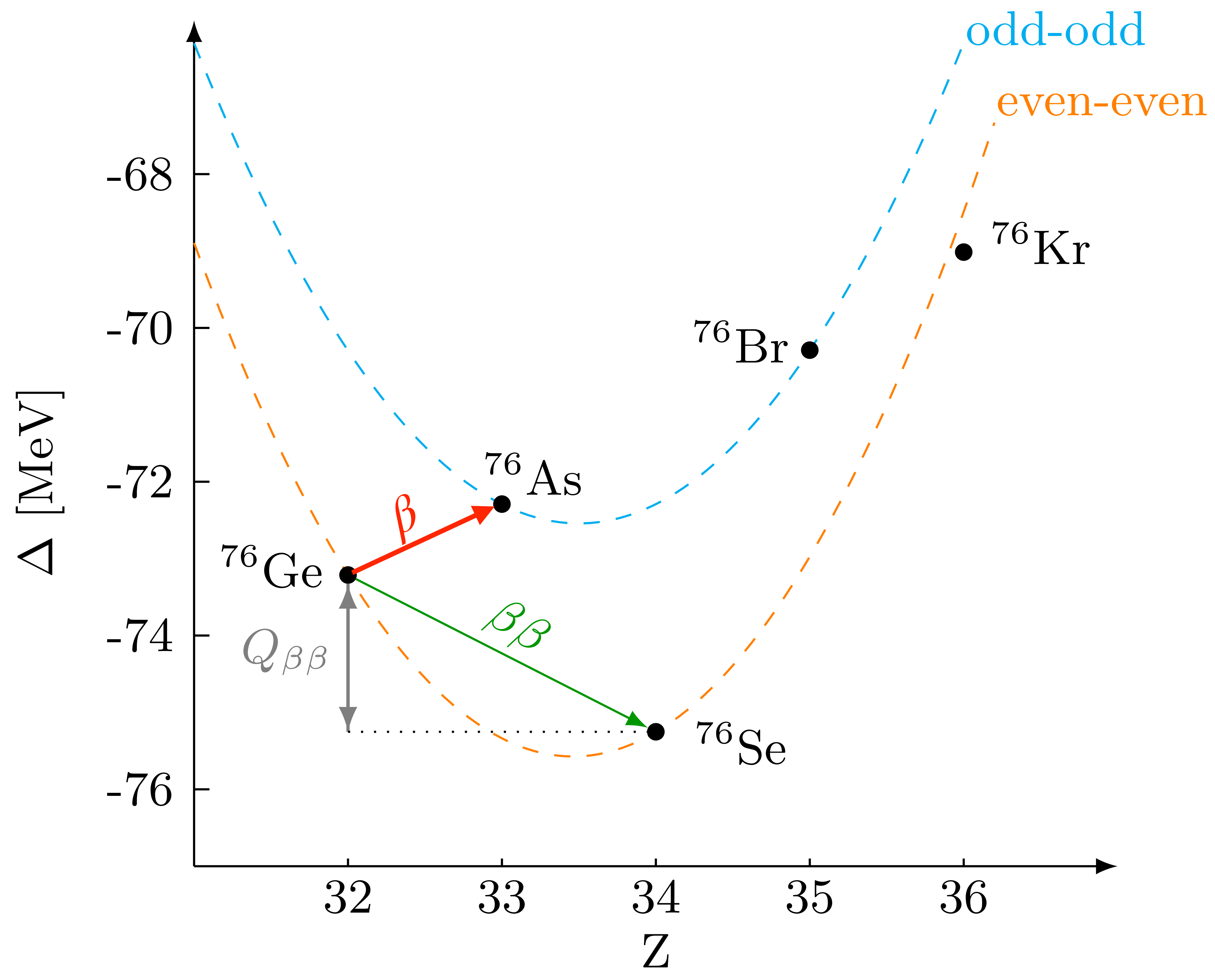

- β-decays move toward stability

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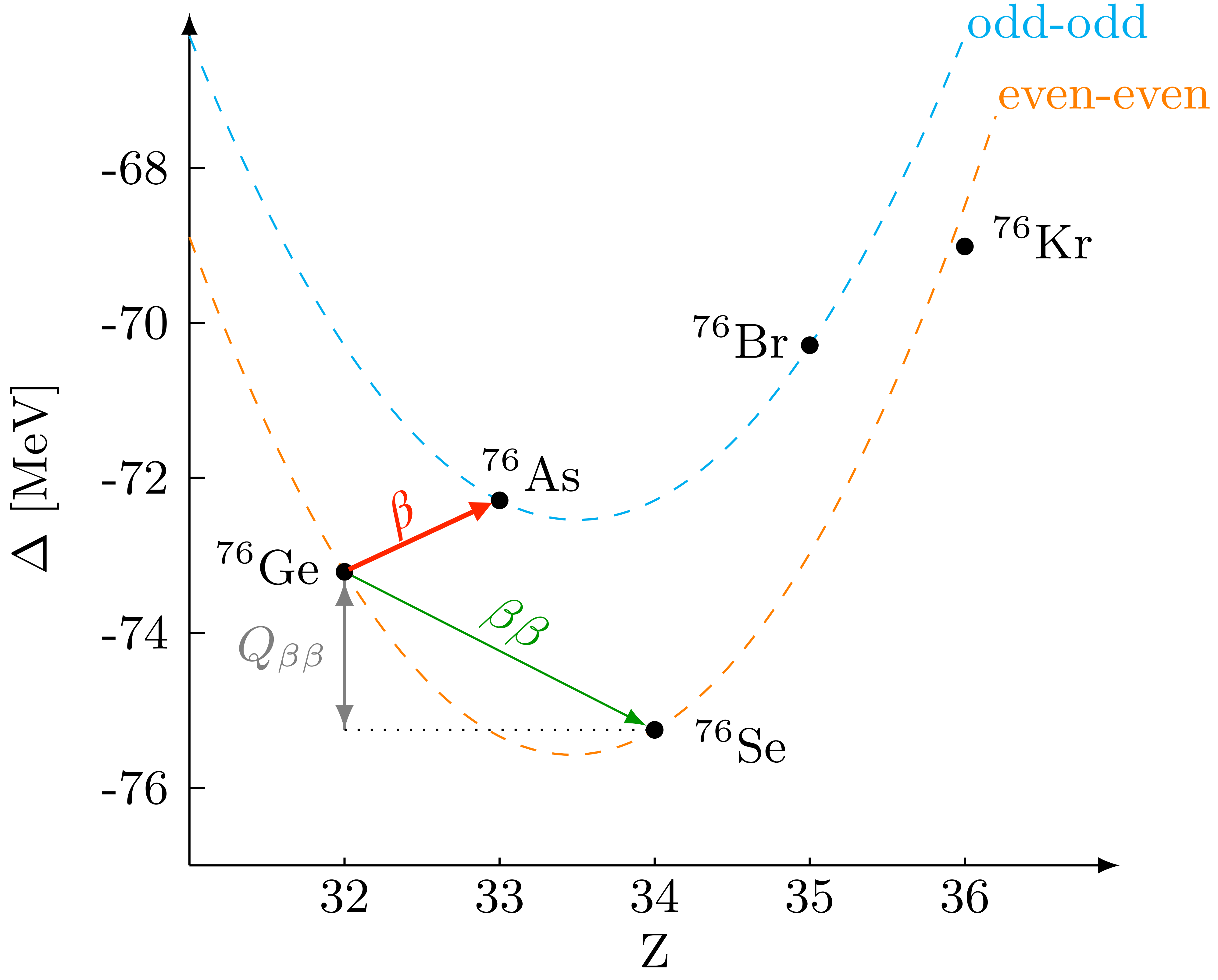

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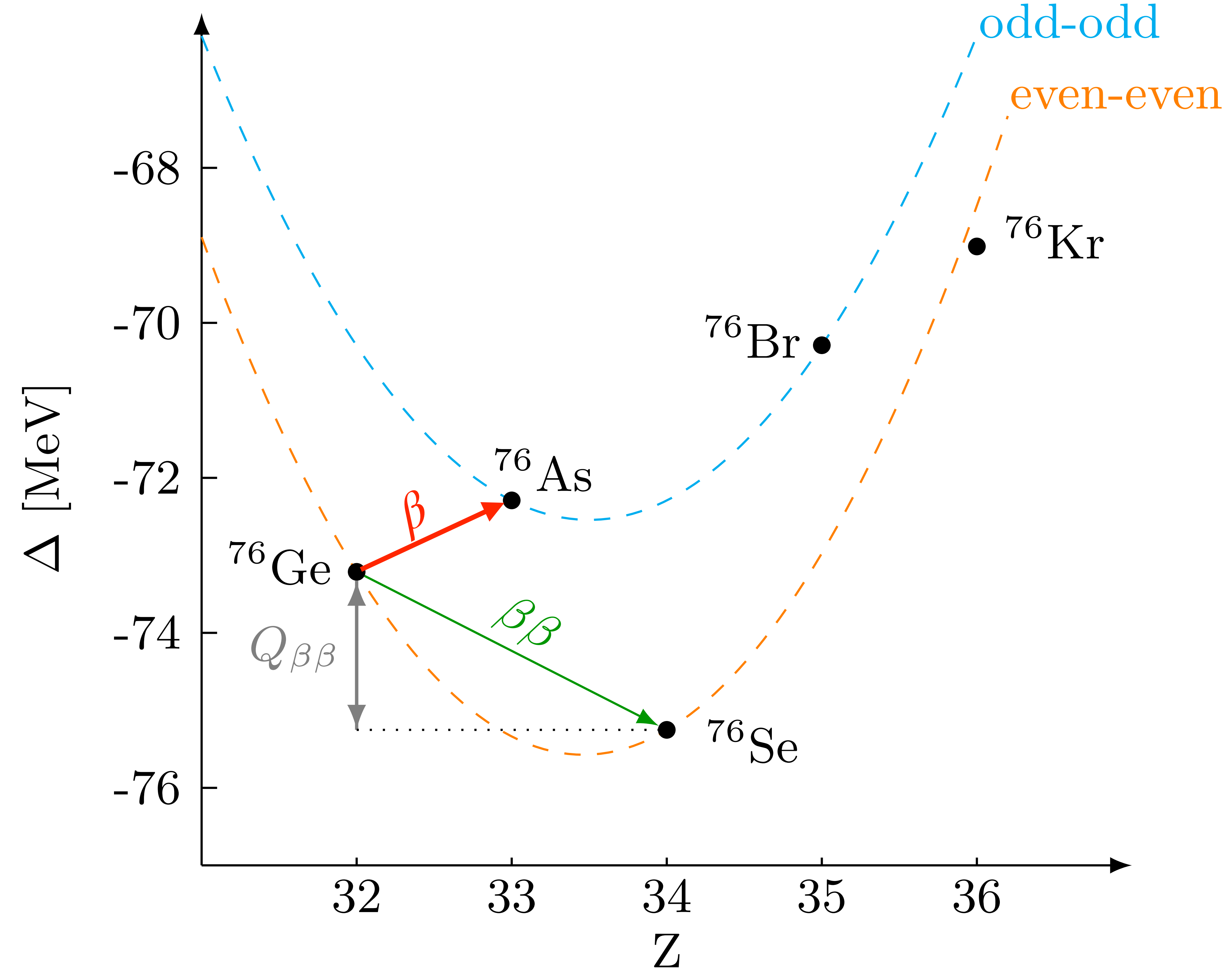

$$(A, Z) \rightarrow (A, Z+2) + 2e^{-} + 2\bar{\nu}_e$$

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- Path towards stability with a "double-jump"
  - Double β-decay

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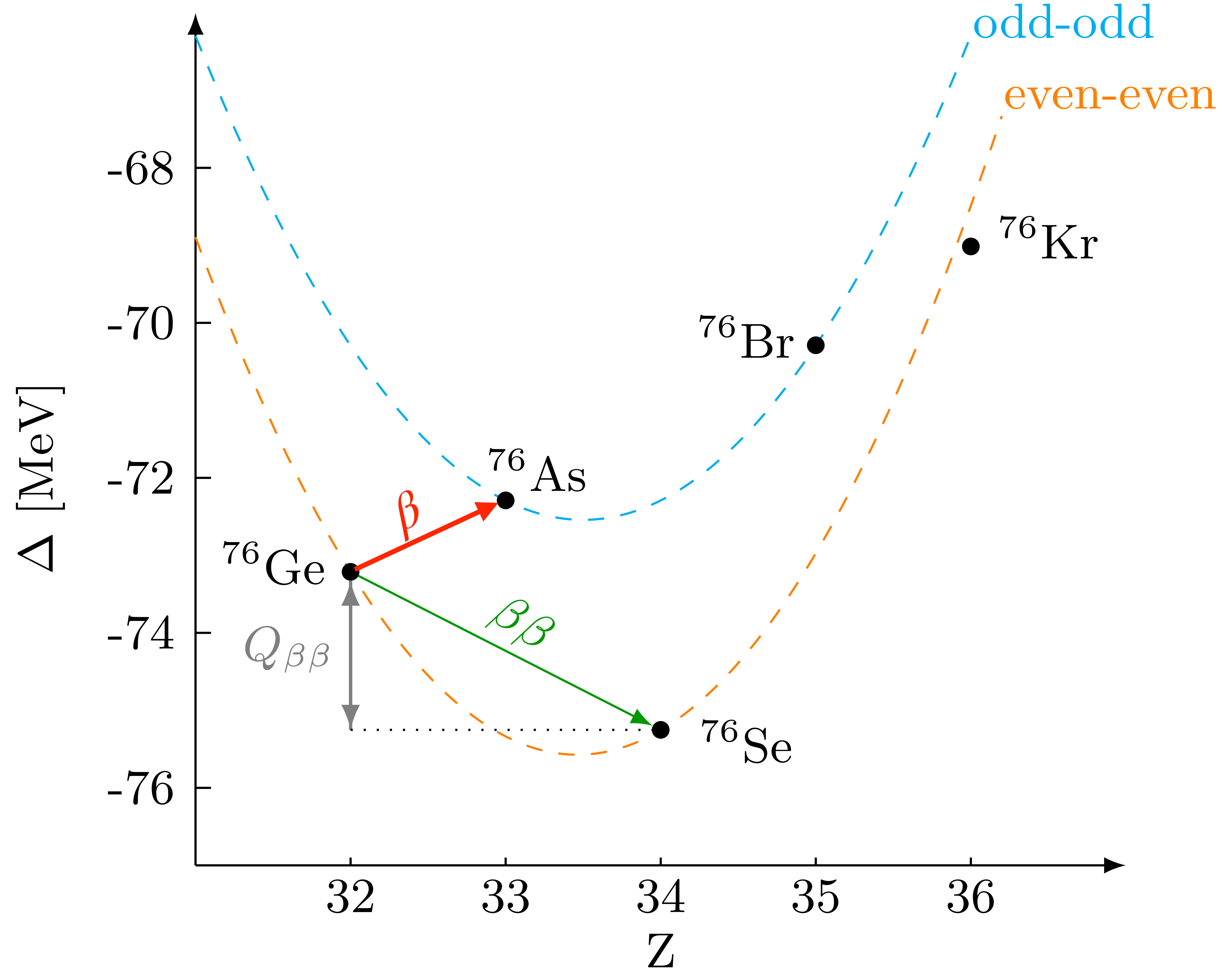

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  - $T_{1/2} > \mathcal{O}(10^{17})$ y [Goeppert-Mayer, M, *Phys Rev* 48 (1935), no. 6, 512–516]

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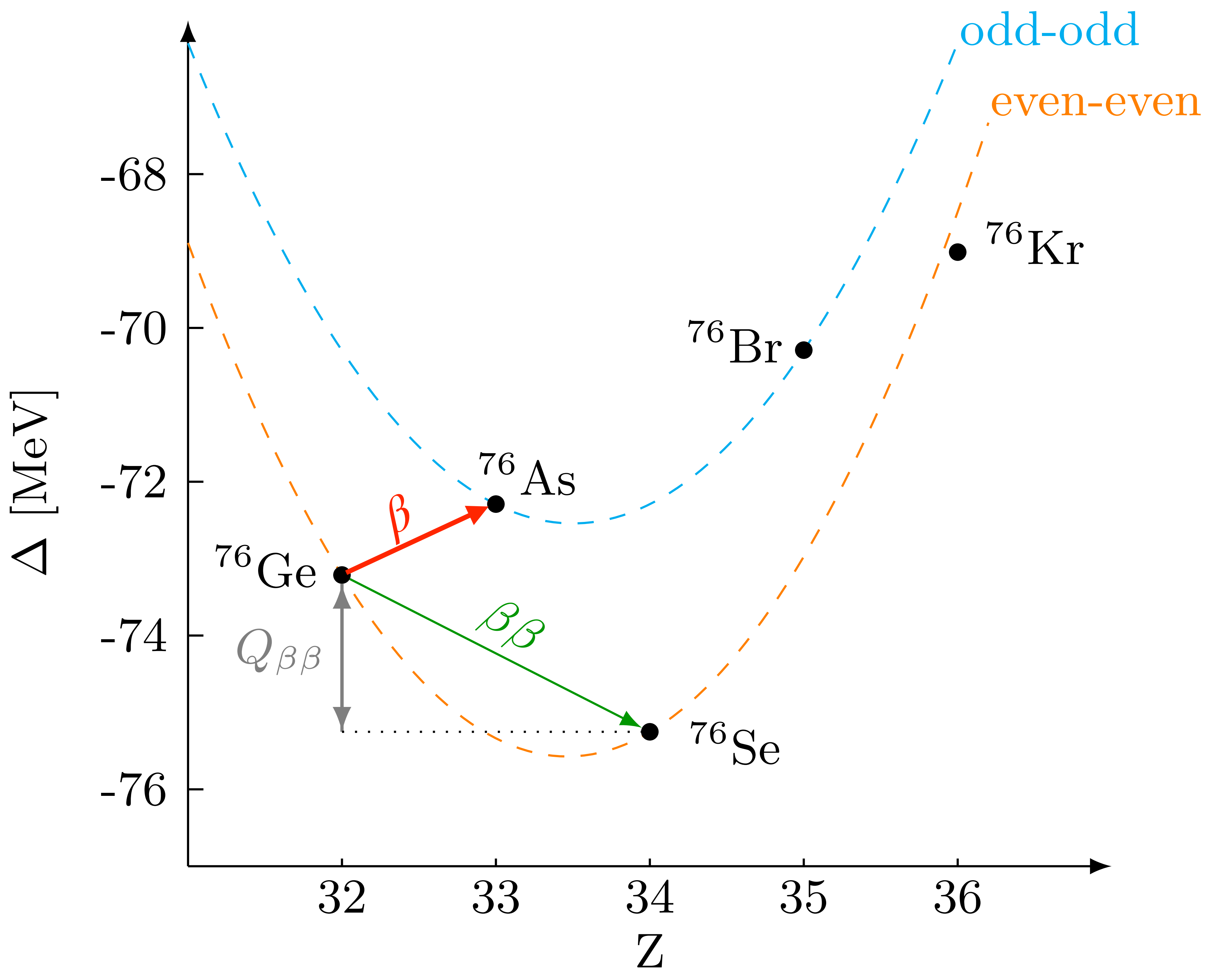

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  - $T_{1/2} > \mathcal{O}(10^{17})$ y [Goeppert-Mayer, M, *Phys Rev* 48 (1935), no. 6, 512–516]
- Measured in several isotopes (^{76}Ge, ^{82}Se, ^{100}Mo, ^{130}Te, ^{136}Xe...)
  - $T_{1/2} \approx \mathcal{O}(10^{18 \div 21})$ y

A particular double-beta decay creates matter

The neutrinoless double-beta decay

- Double-beta decay channel without emission of neutrinos
- Creation of matter without anti-matter
  - Lepton number not conserved $\Delta L = 2$
  - Not allowed in the Standard Model
- Portal to new physics

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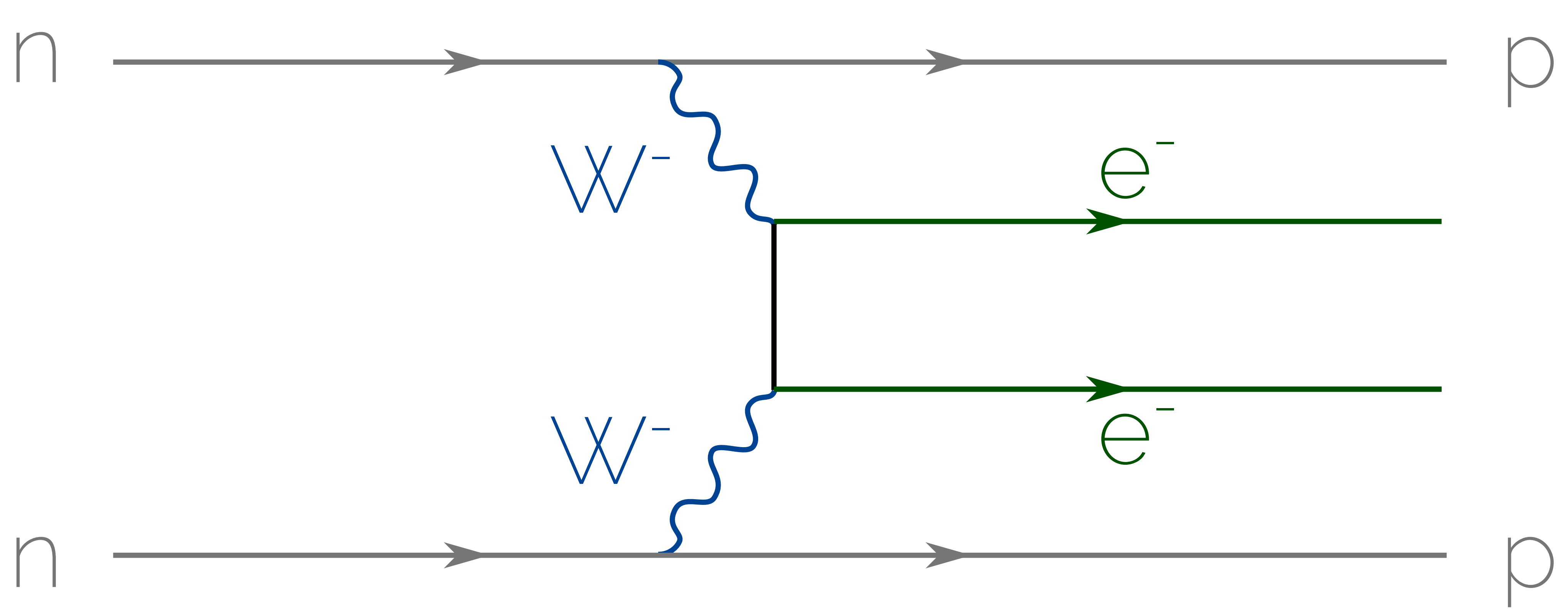
$$2n \rightarrow 2p \ + \ 2e^-$$



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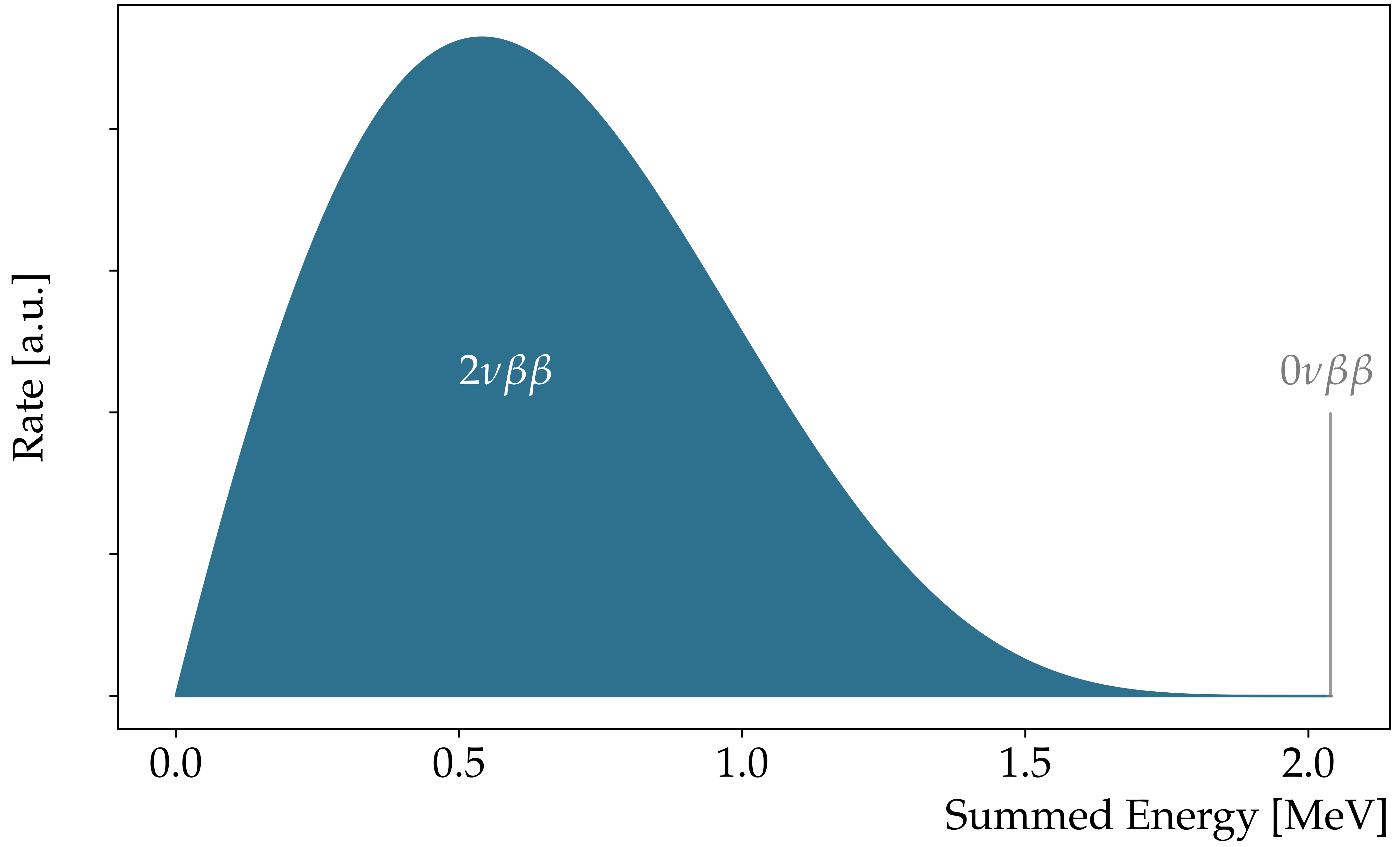
Detecting double-beta decay

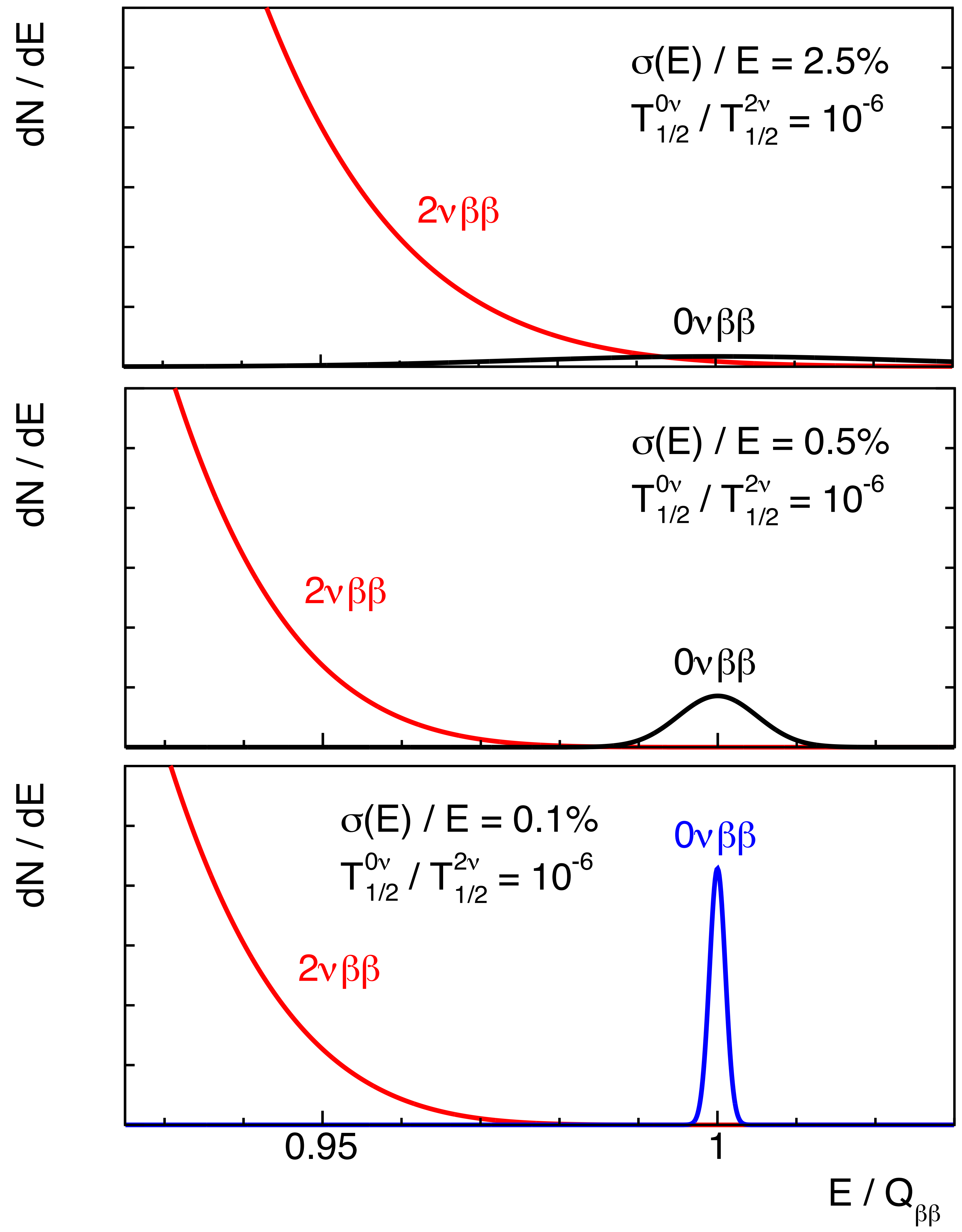
The experimental signature



- Signature:
  - $0\nu\beta\beta$: energy deposition of 2 electrons @ $Q_{\beta\beta}$ (= 2039 keV for ^{76}Ge)
  - $2\nu\beta\beta$: energy deposition of 2 electrons @ $E < Q_{\beta\beta}$
- Experimental challenge:
  - No background @$Q_{\beta\beta}$ for $\mathcal{O}(10)$ y

Detecting double-beta decay

...with the GERmanium Detector Array experiment



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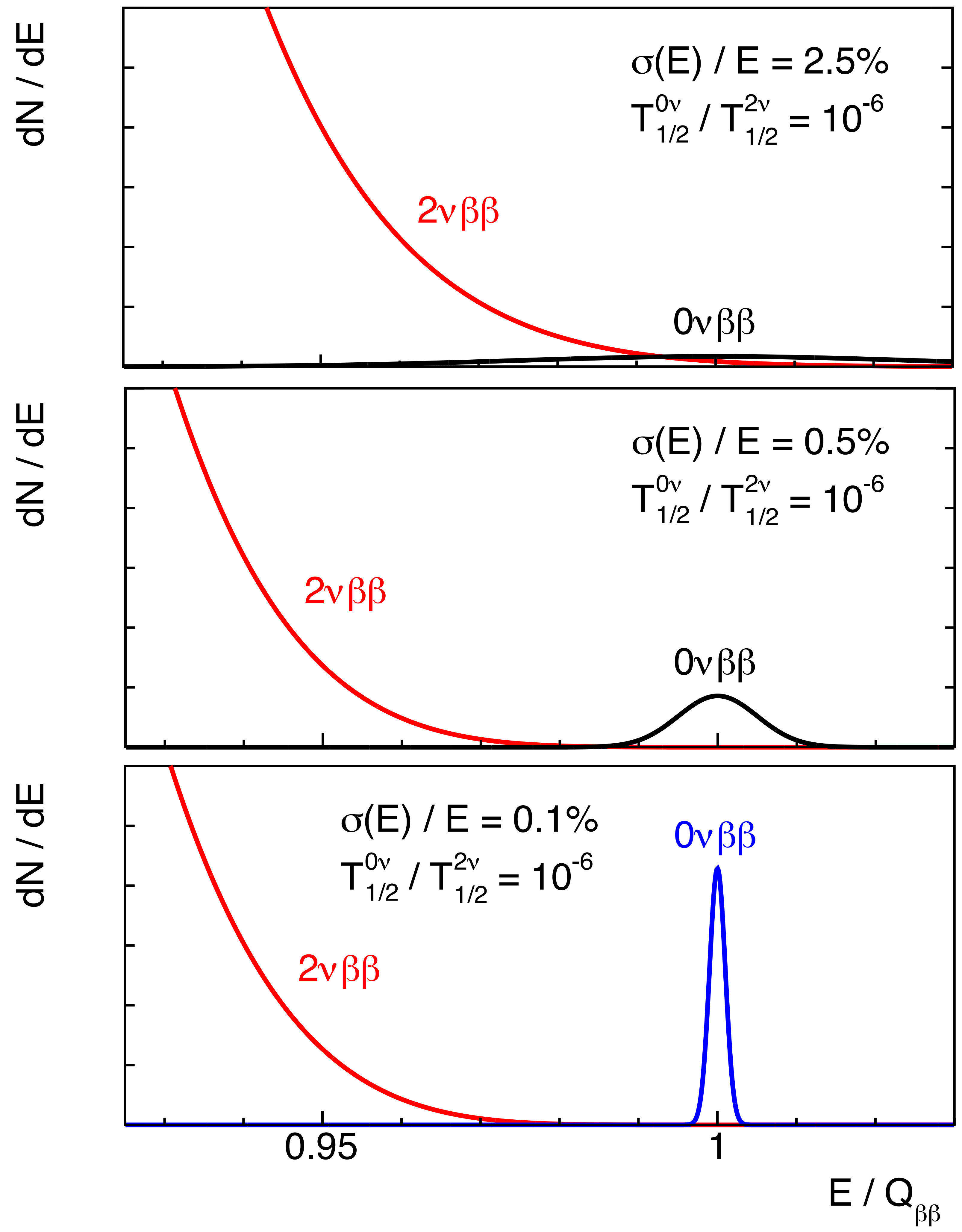

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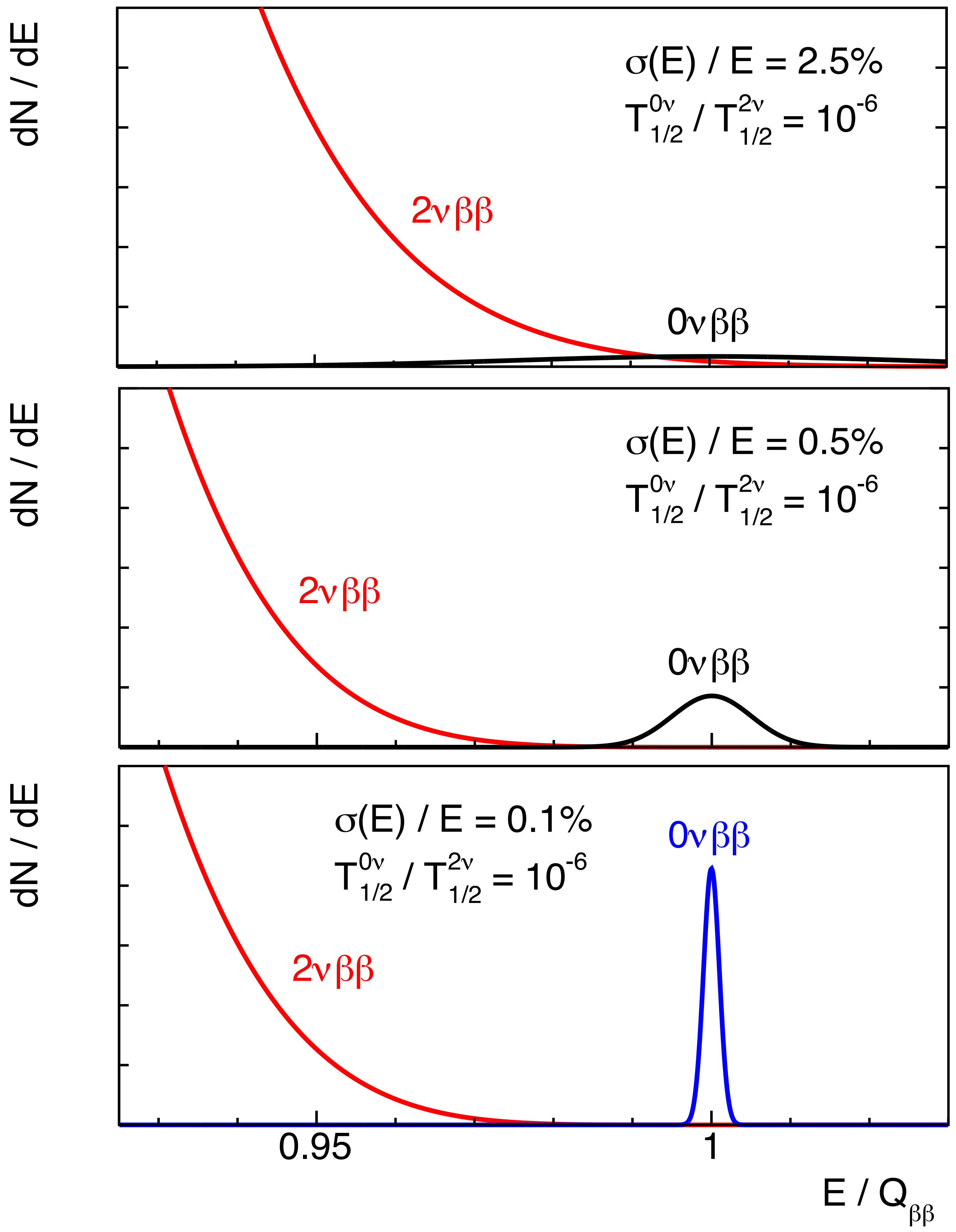

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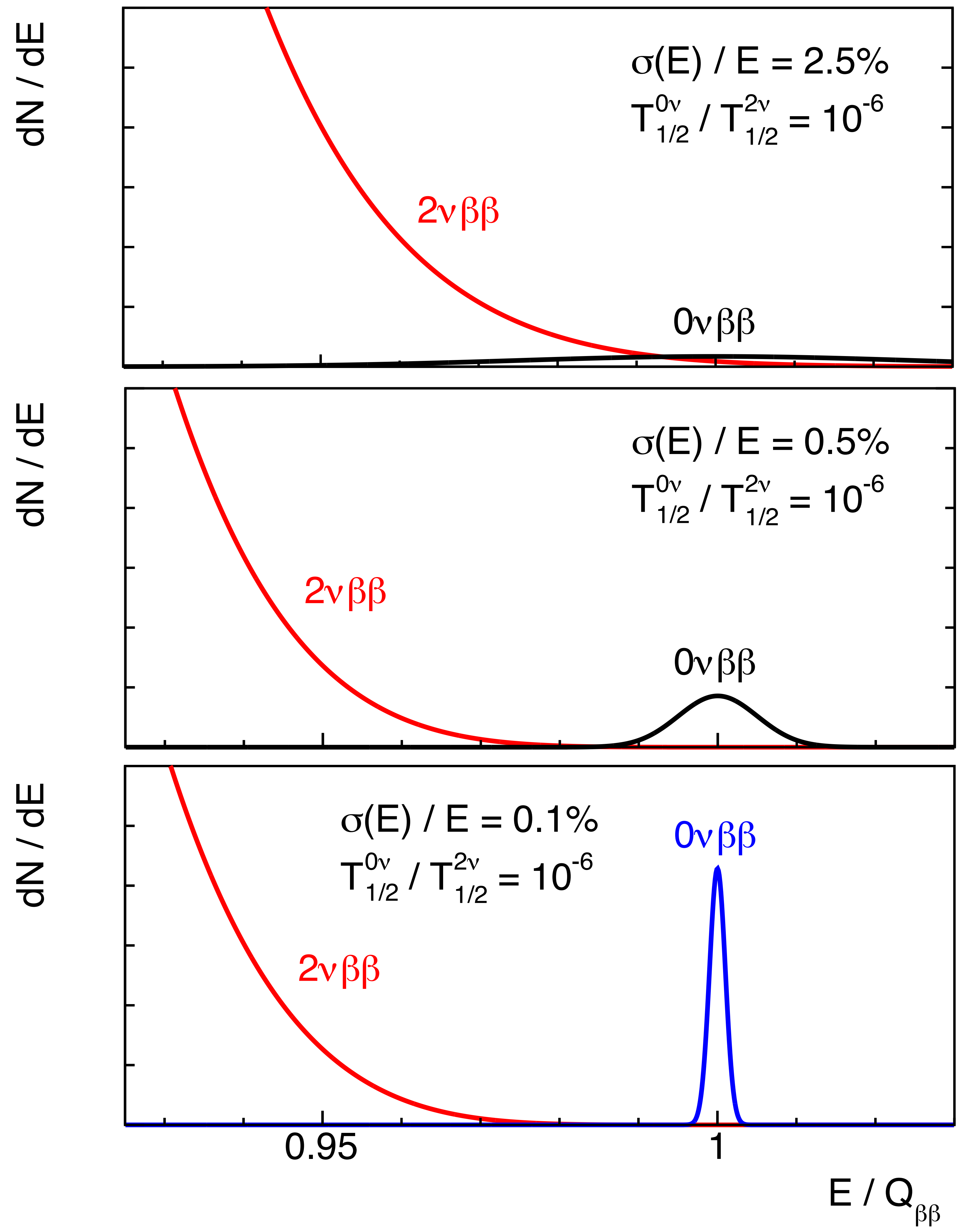

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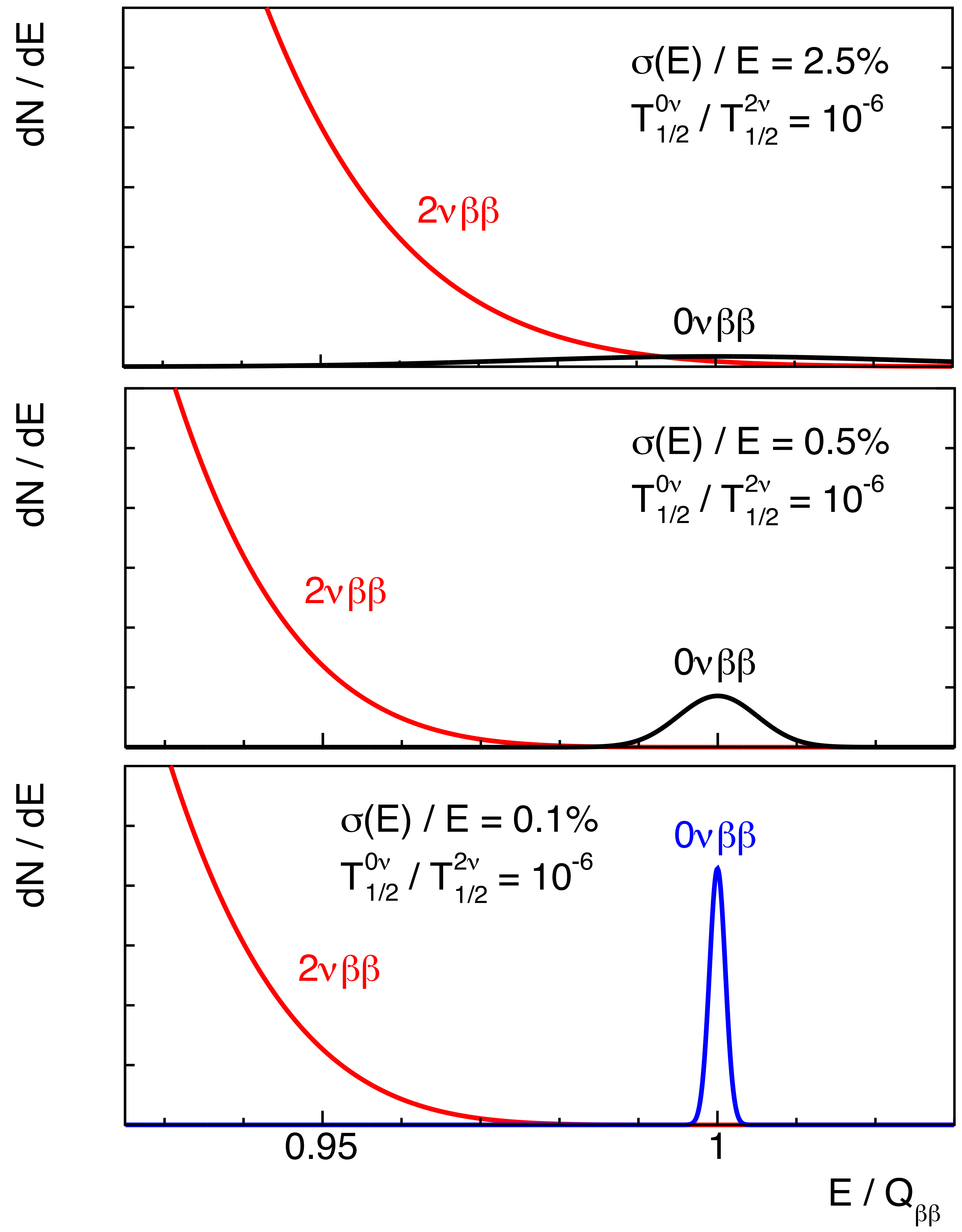

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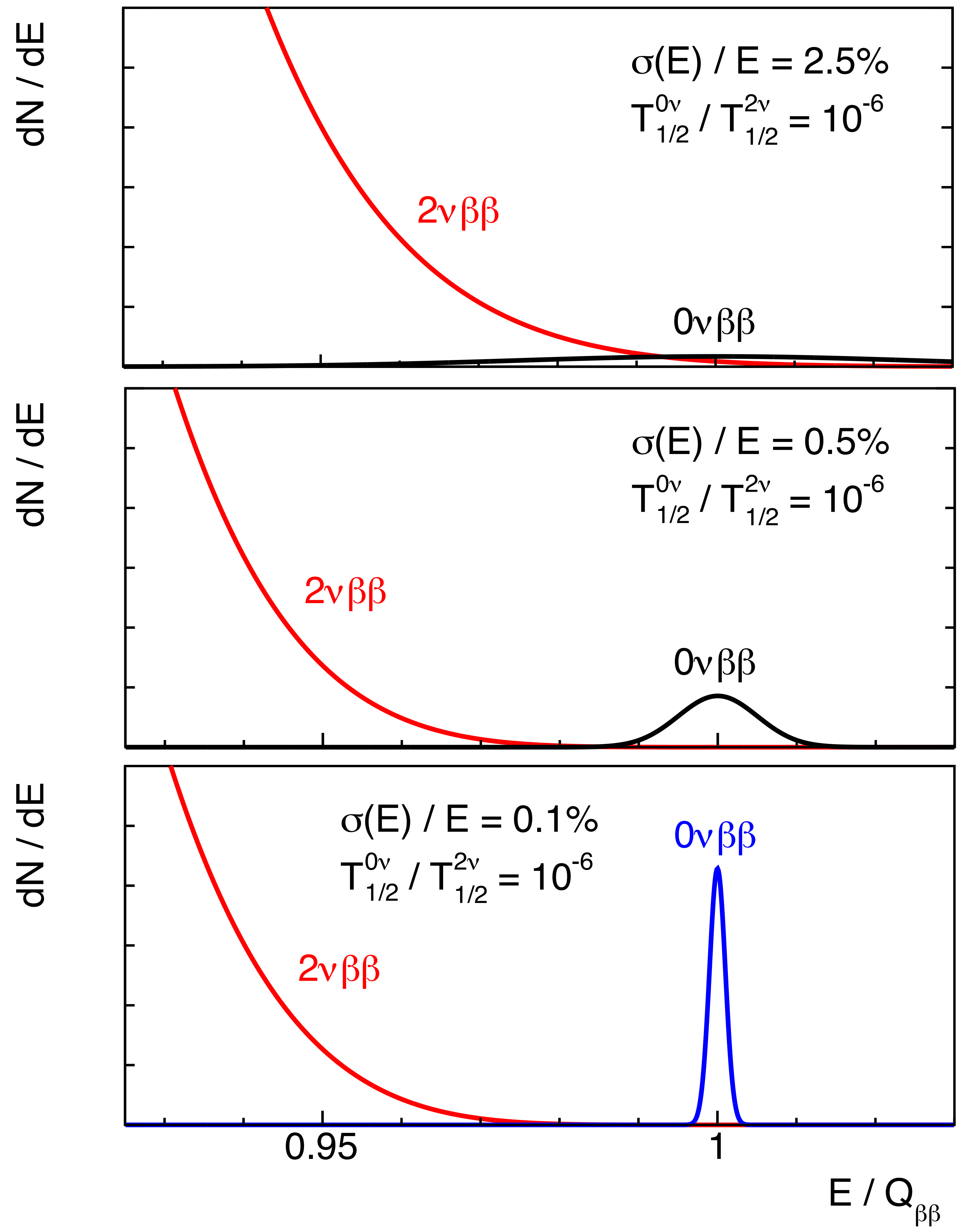

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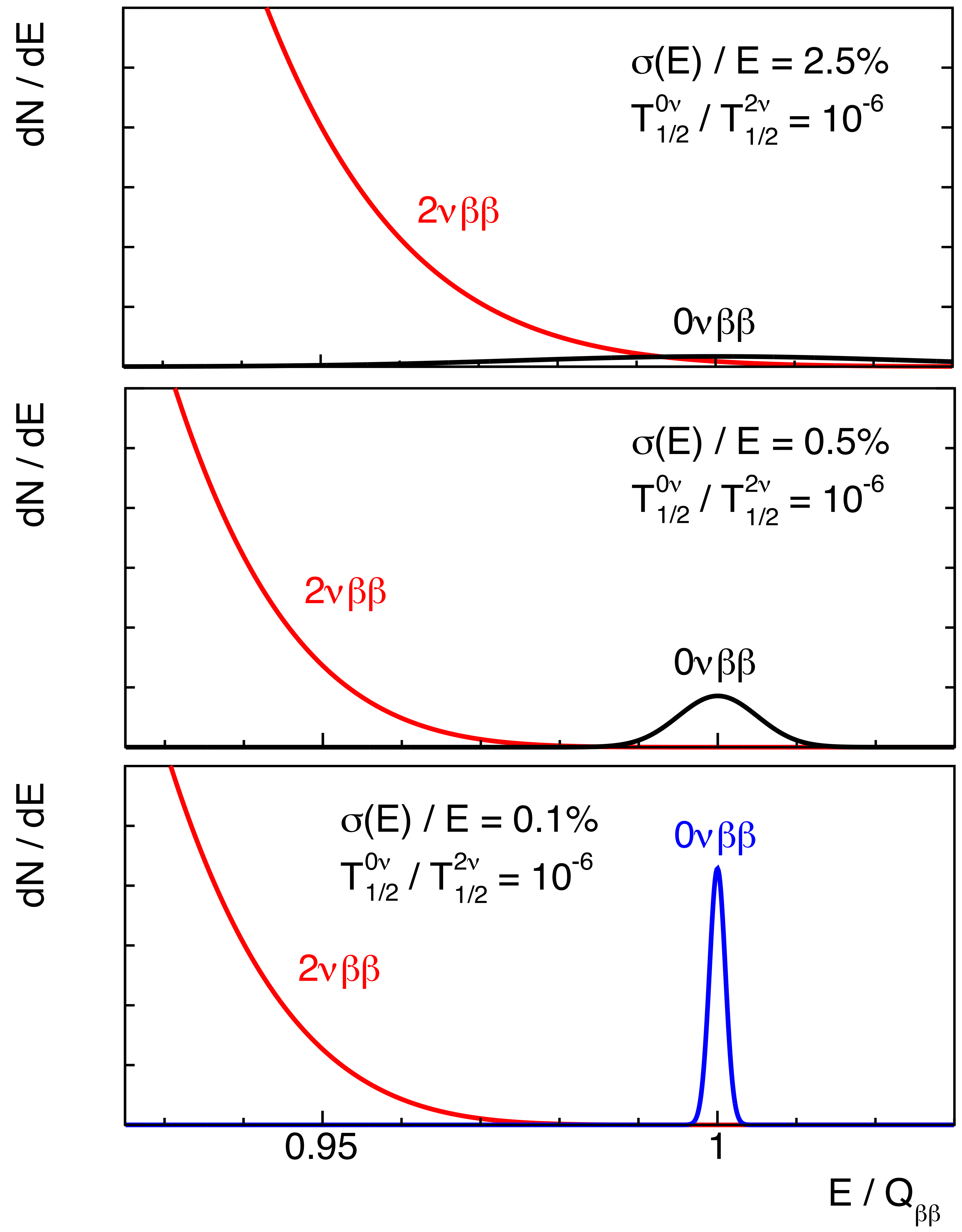

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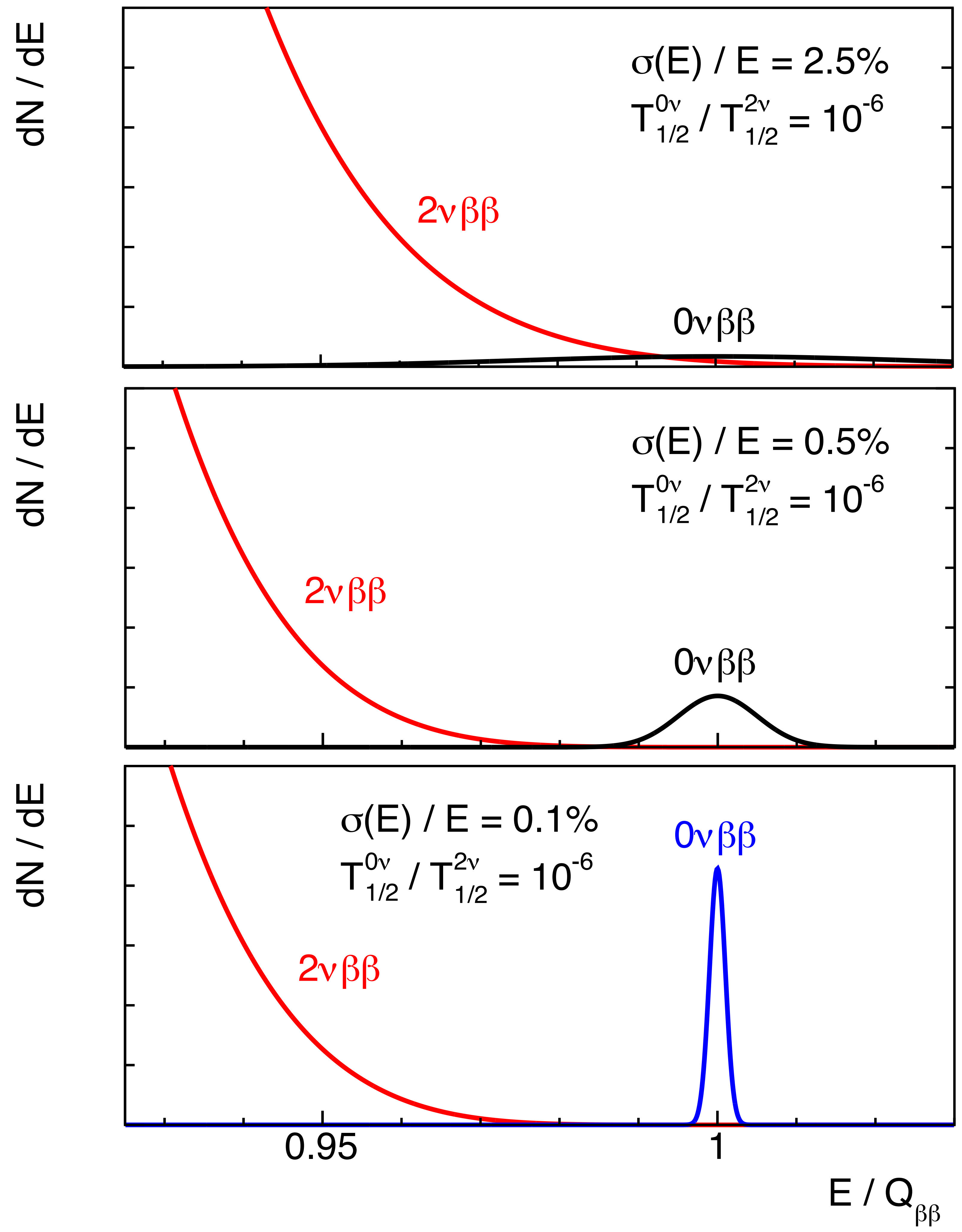

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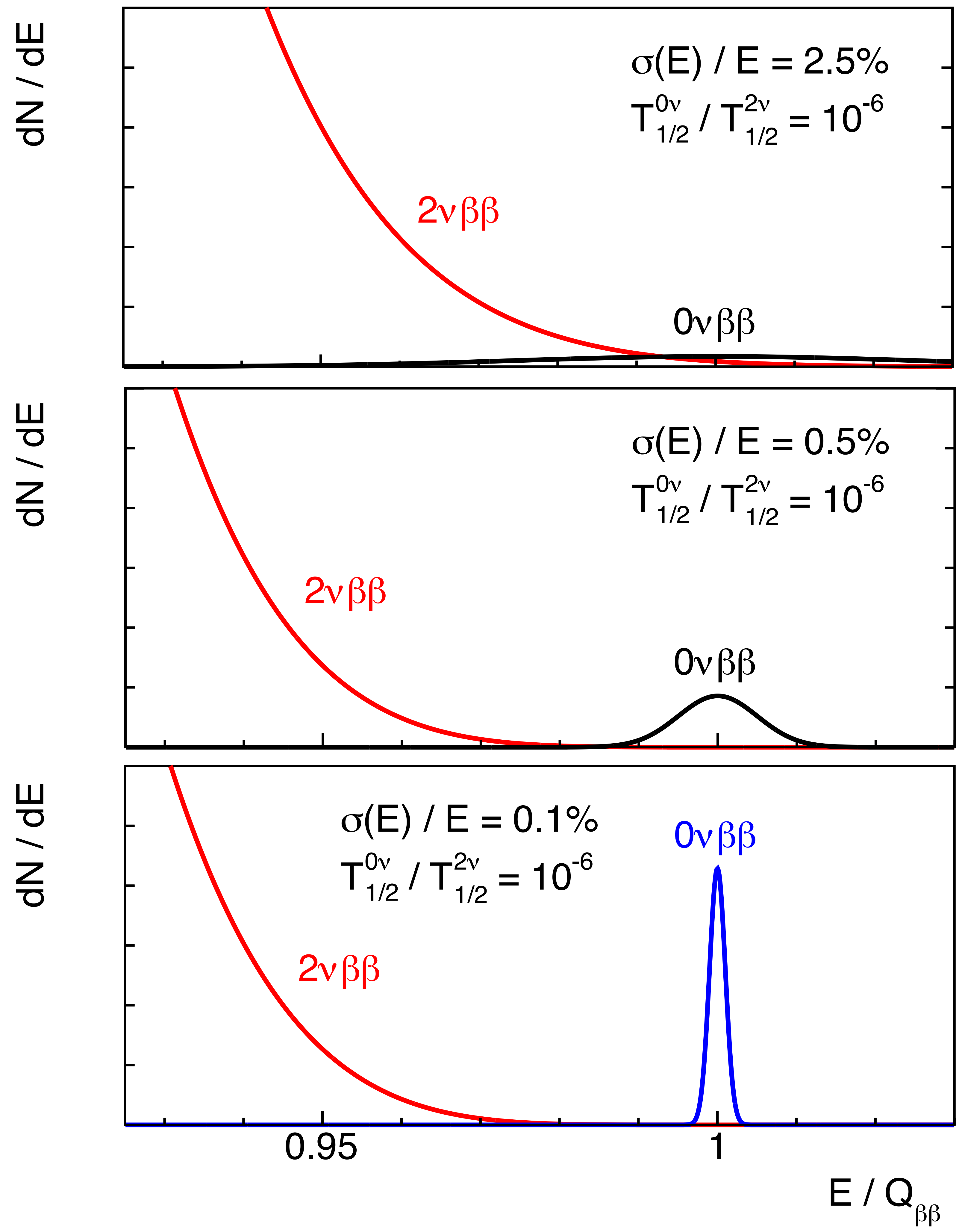

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  - Radio-purity [GERDA, Astropart.Phys. 91 (2017) 15-21]
  - Excellent energy resolution ($\mathcal{O}(0.1\%)$)
  - Event topology Discrimination - Pulse Shape Discrimination (PSD)

→ High detection efficiency

Detecting double-beta decay

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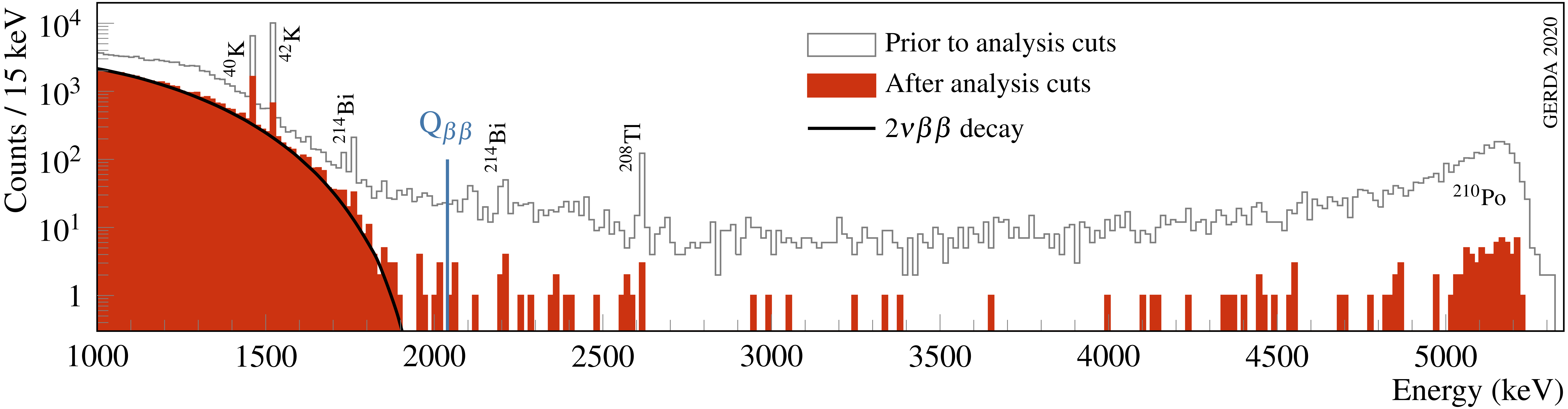
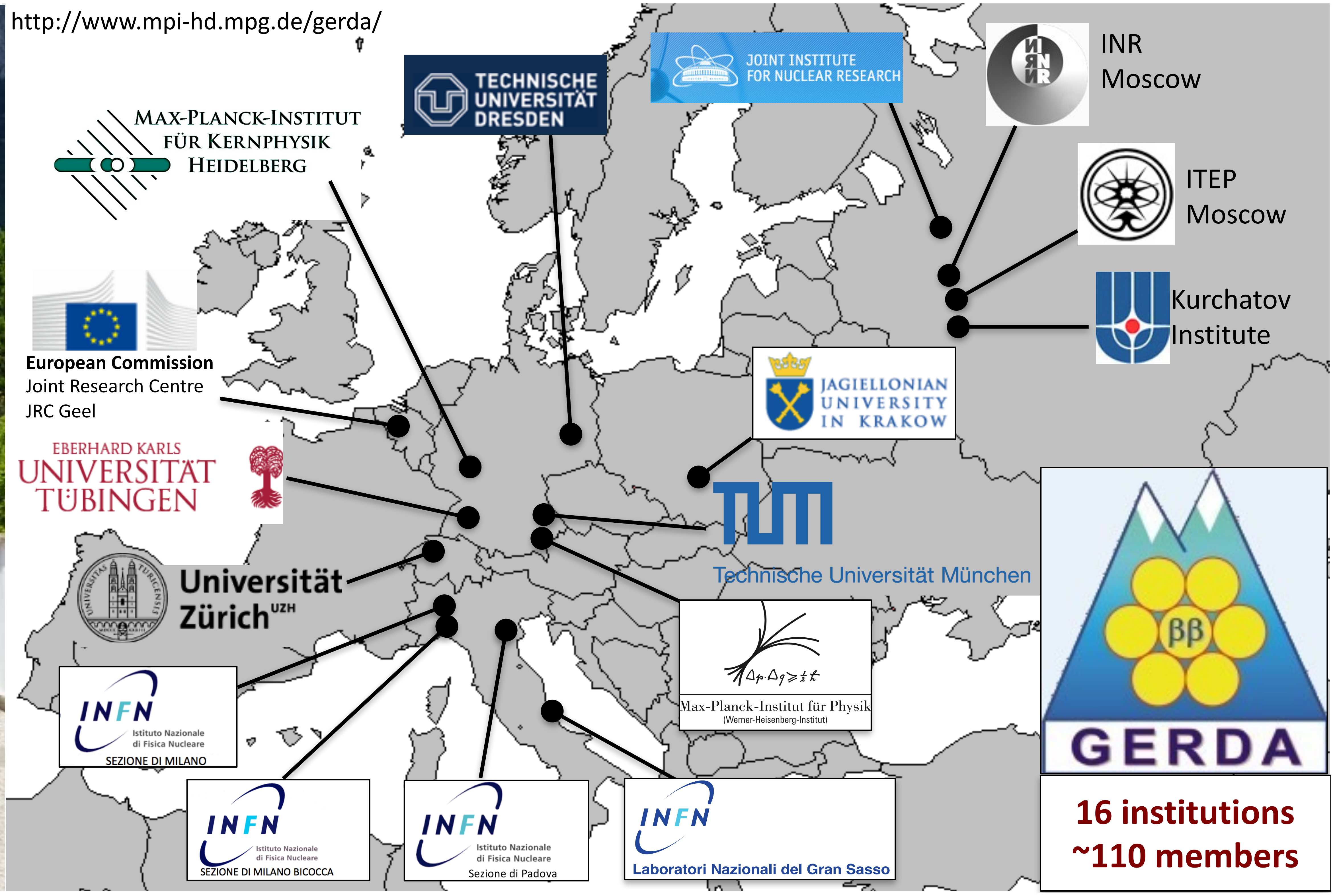


[GERDA, *Phys Rev Lett* **125** (2020), 252502]

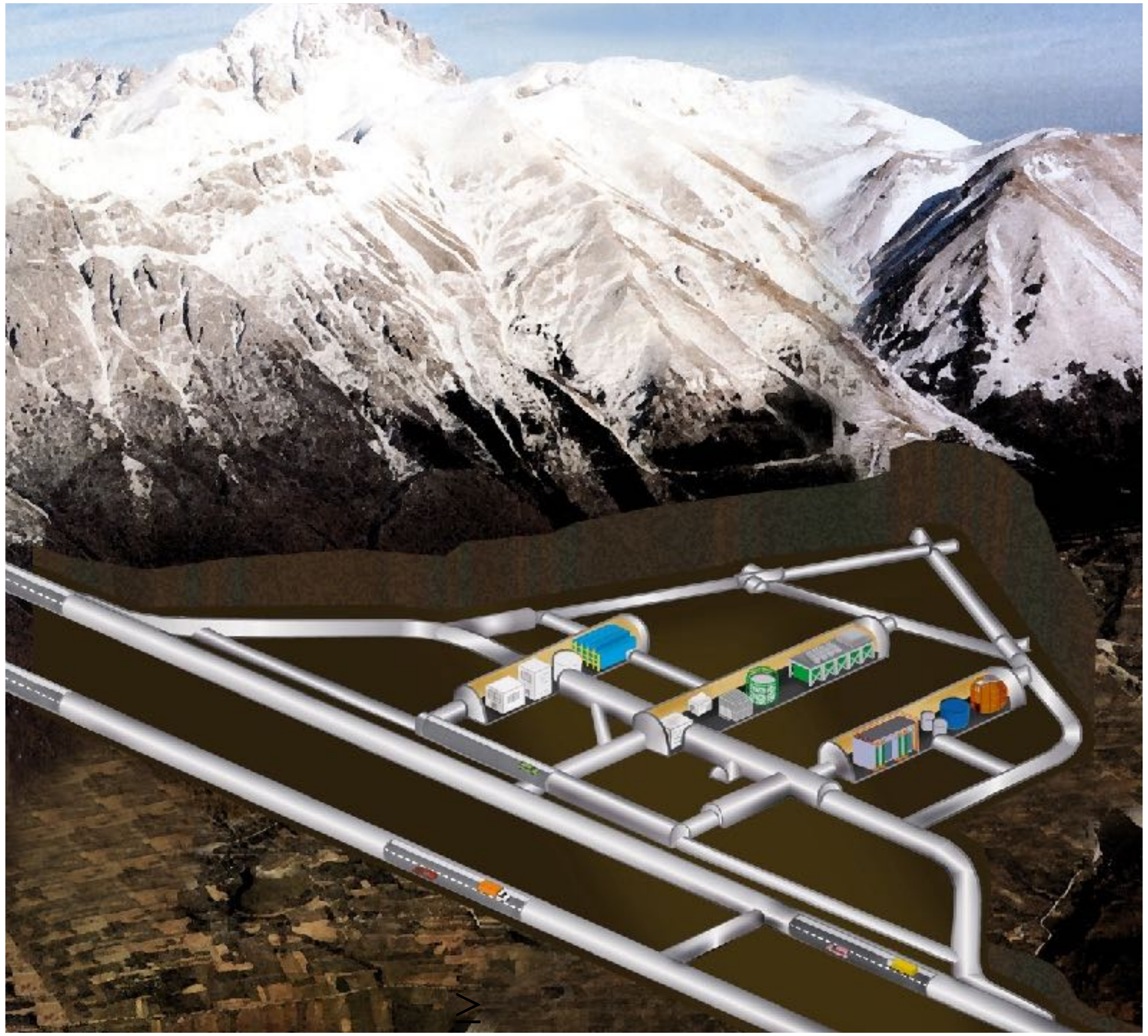
- Background expectations @$(Q_{\beta\beta} \pm 2\sigma)$ = 0.3 counts **after 103.7 kg yr exposure**

High resolution, background-free search of $0\nu\beta\beta$ decay

The GERDA collaboration



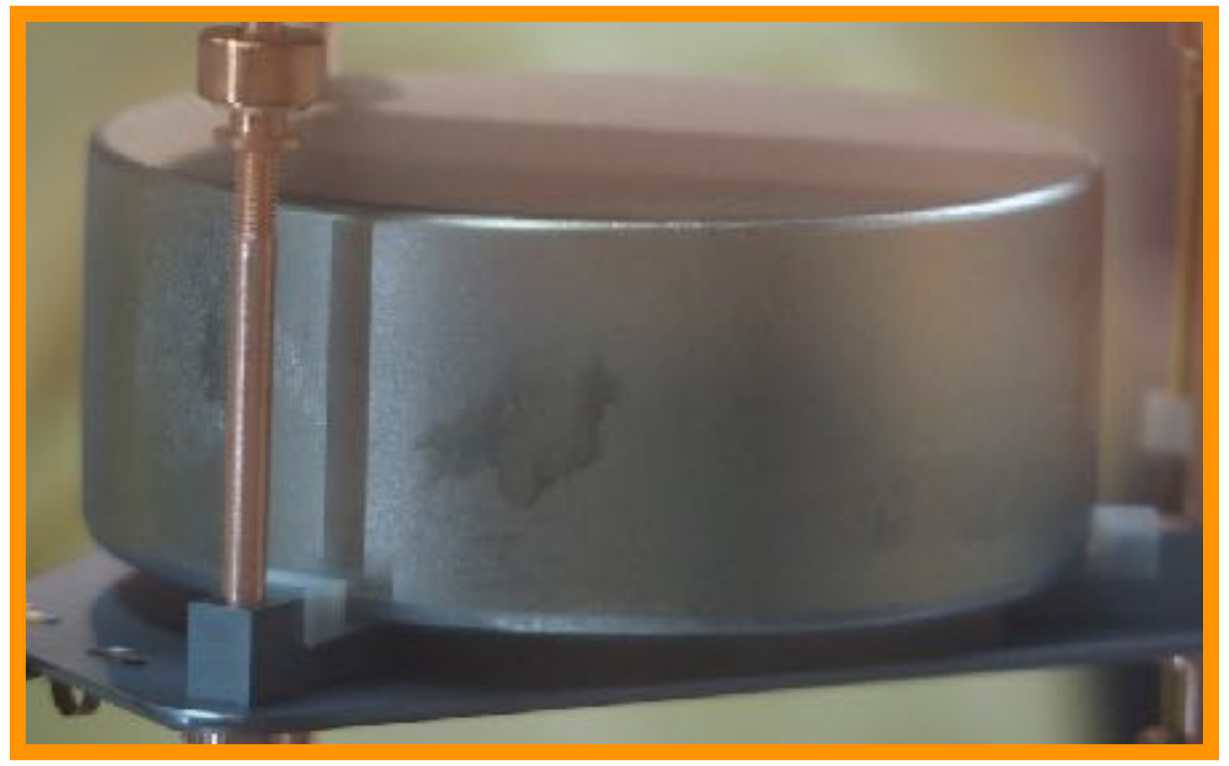
The GERDA experiment



- Located @ Laboratori Nazionali del Gran Sasso (Italy)
- Shielded by 3500 m.w.e.

	Goals
Background	10^{-3} cts/(keV kg yr)
Exposure	> 100 kg yr
Sensitivity	$T_{1/2}^{0\nu\beta\beta} \geq 10^{26}$ yr

The GERDA experiment



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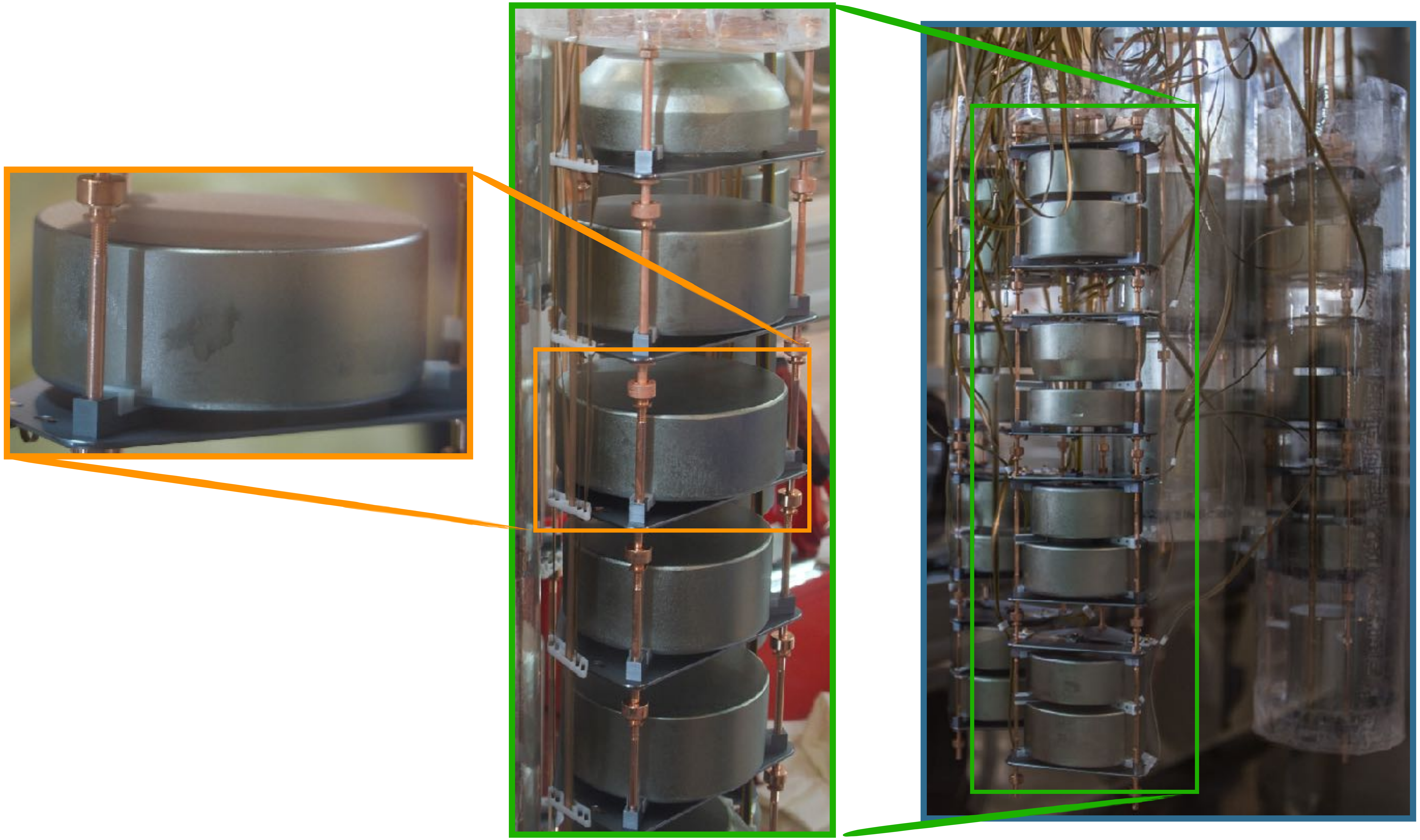
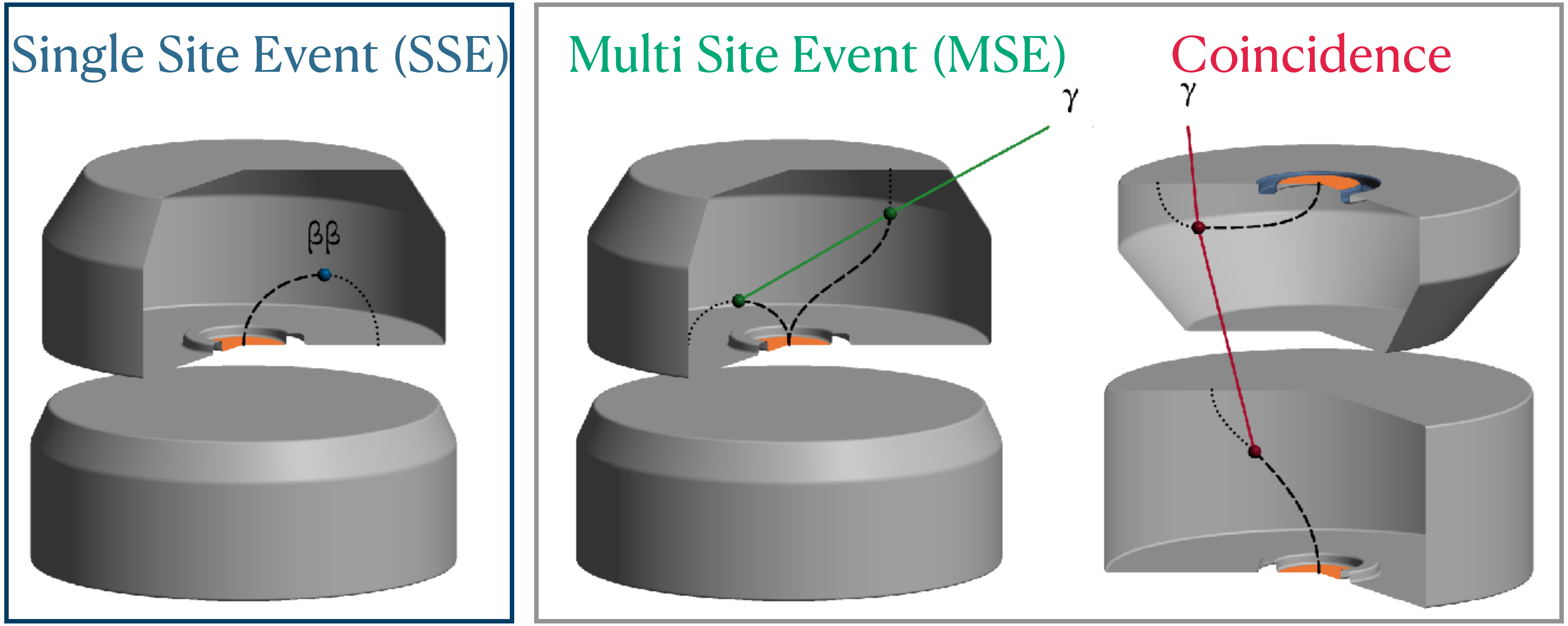


Image produced with: https://github.com/gipert/gedet-plots

Event discrimination in germanium

Signal and background



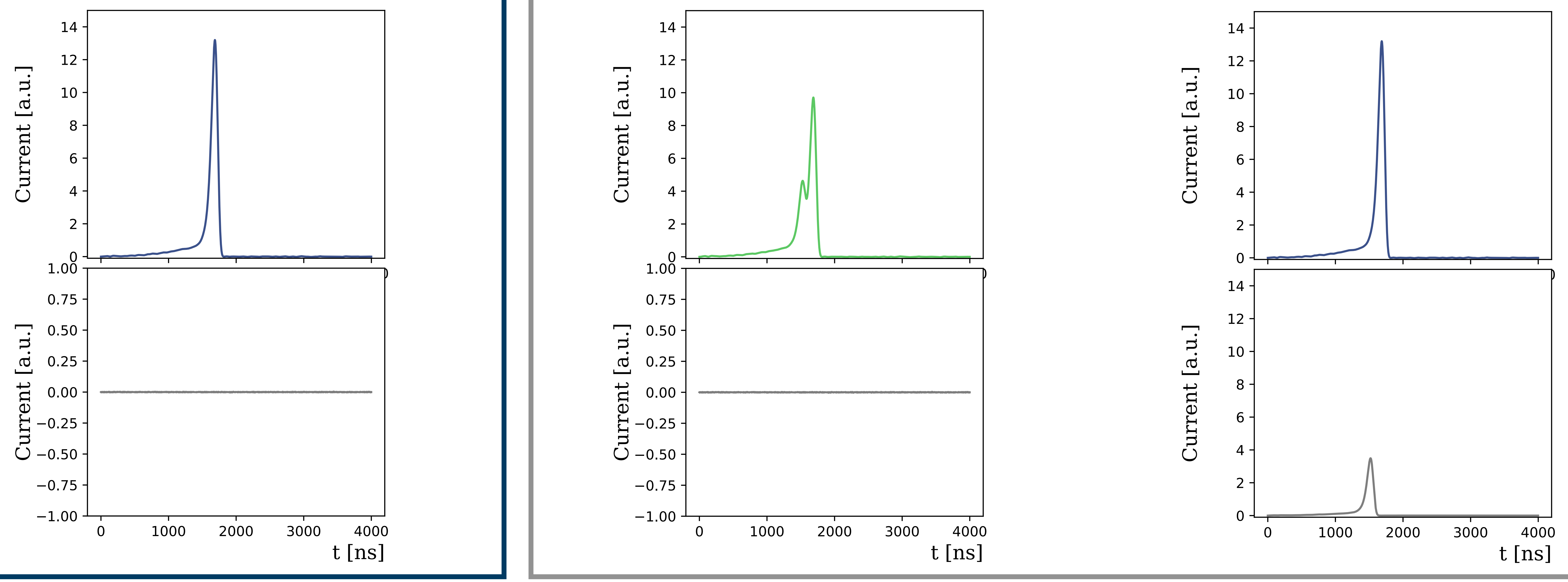
Signal

Background

Event discrimination in germanium

Signal and background

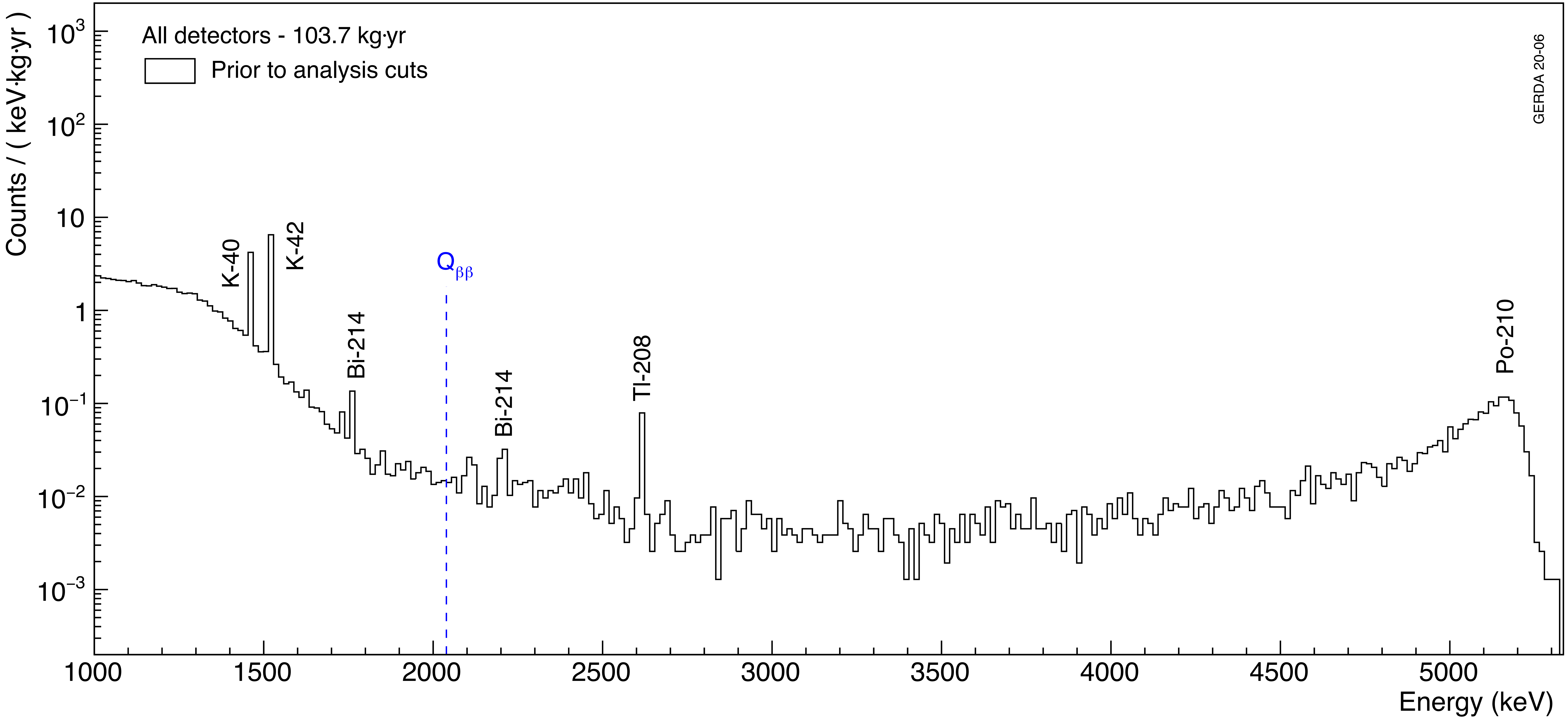
Single Site Event (SSE) | Multi Site Event (MSE) | Coincidence



Signal | Background

Active background suppression

Performance



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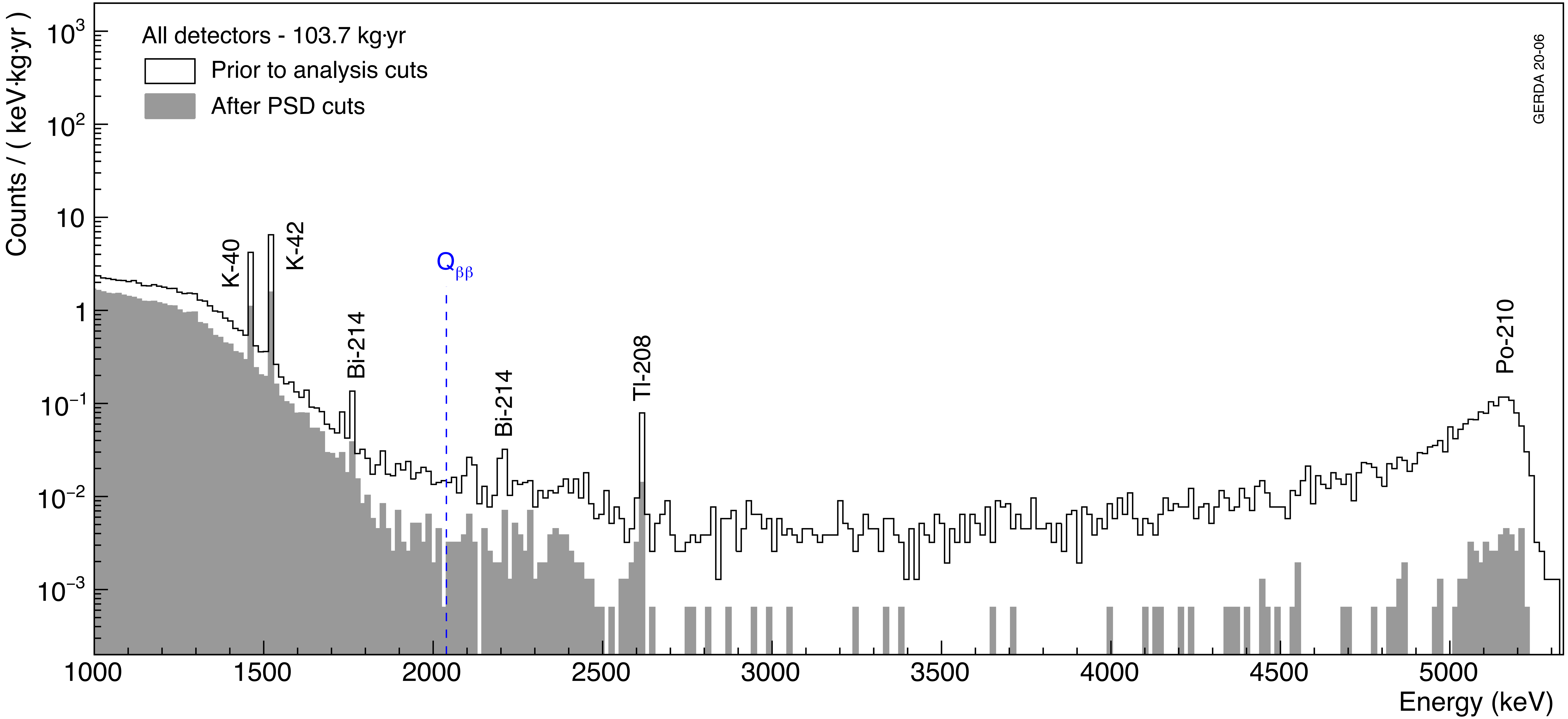

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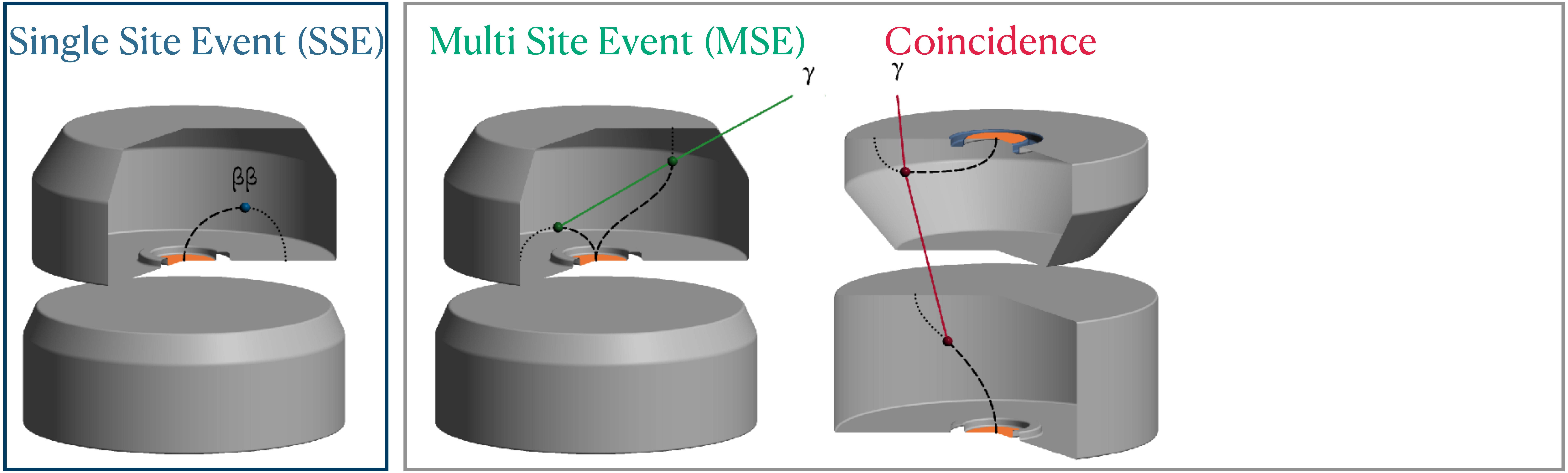
Pulse Shape Discrimination

Signal and background



Signal

Background

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Pulse Shape Discrimination

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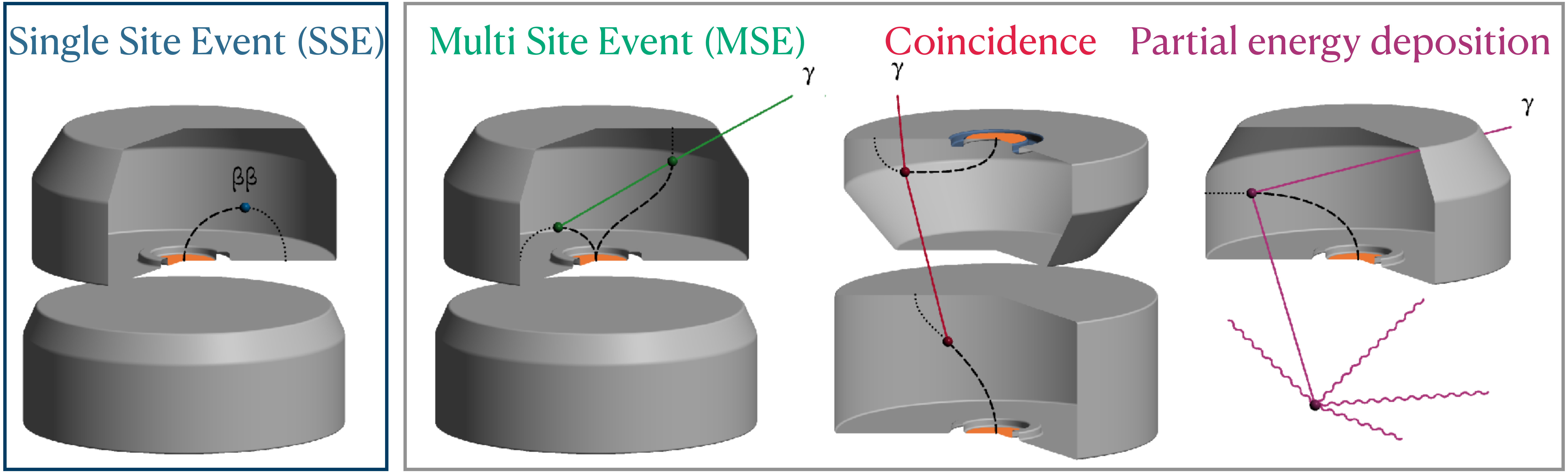


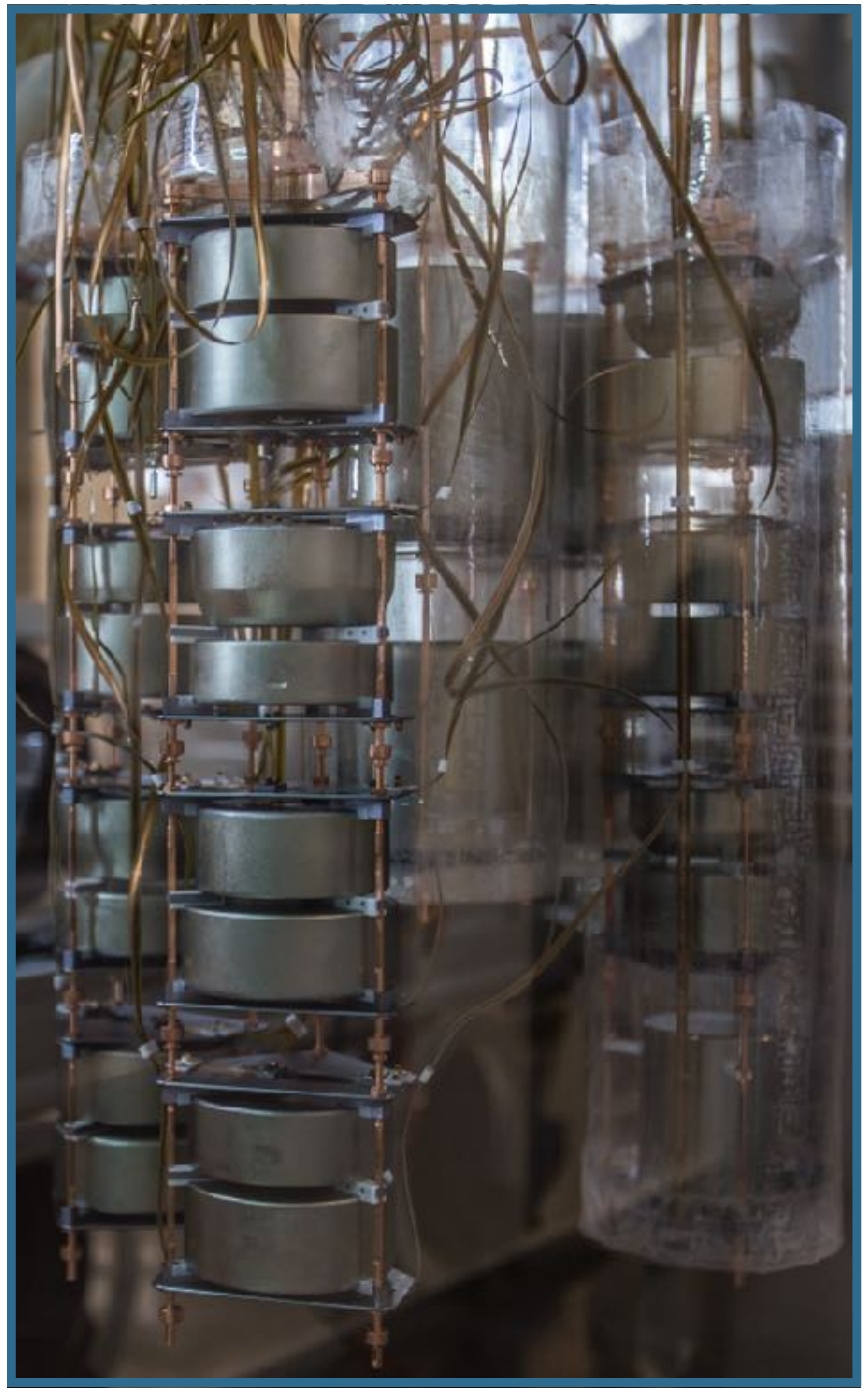
Signal

Background

Surrounding liquid argon (LAr) tags these events

[GERDA, *European Phys J C* **78** (2018), 388]

The LAr instrumentation



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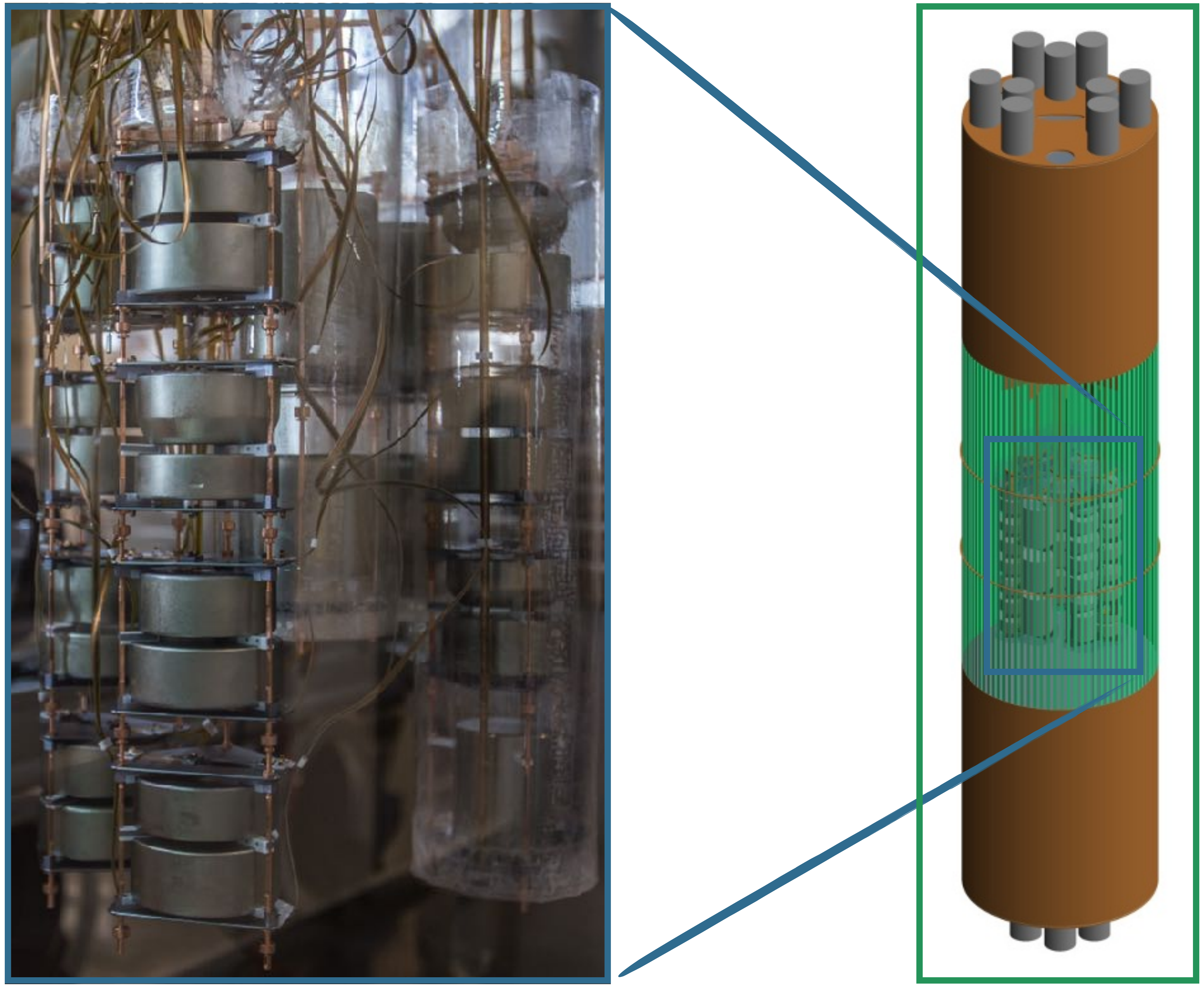

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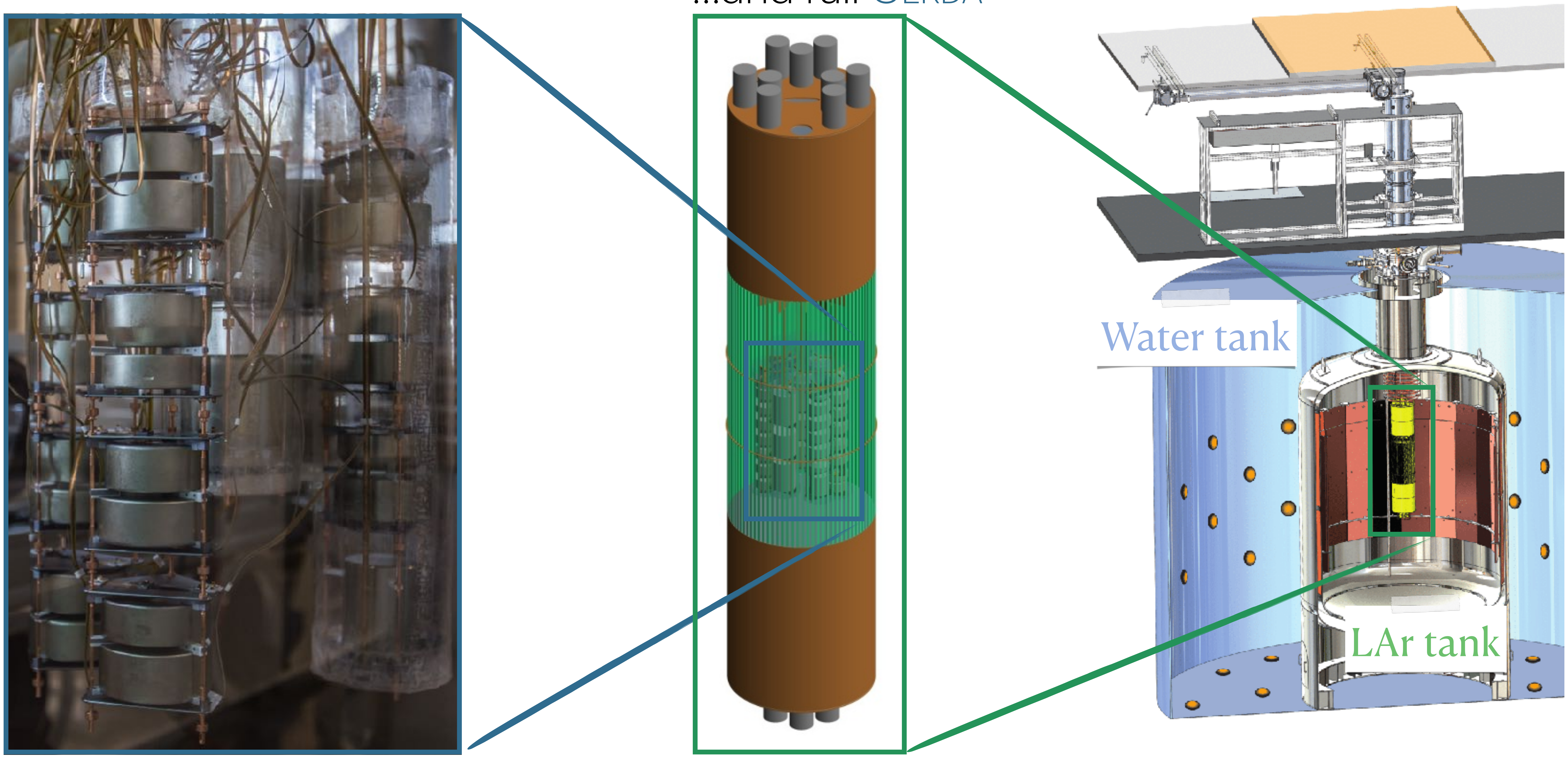
The LAr instrumentation

...and full GERDA



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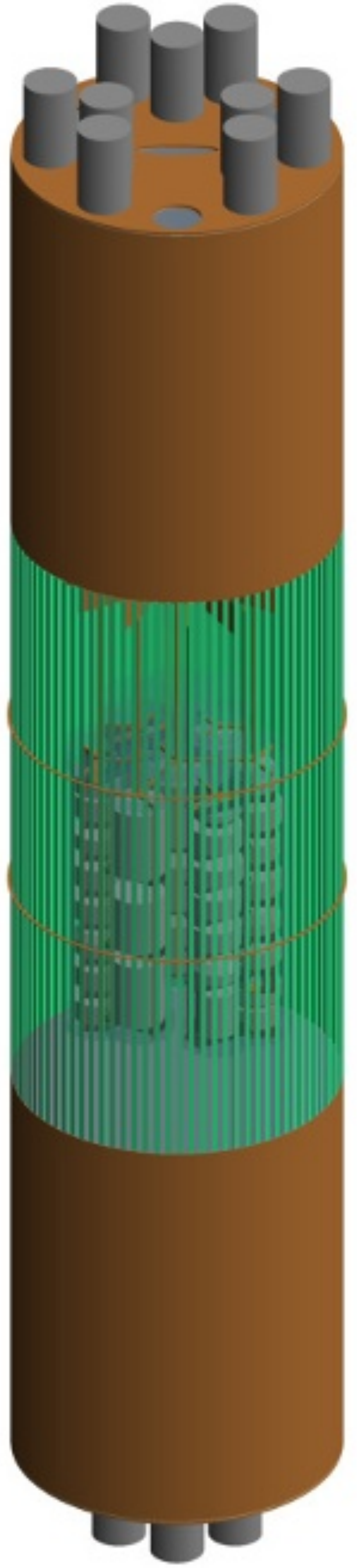
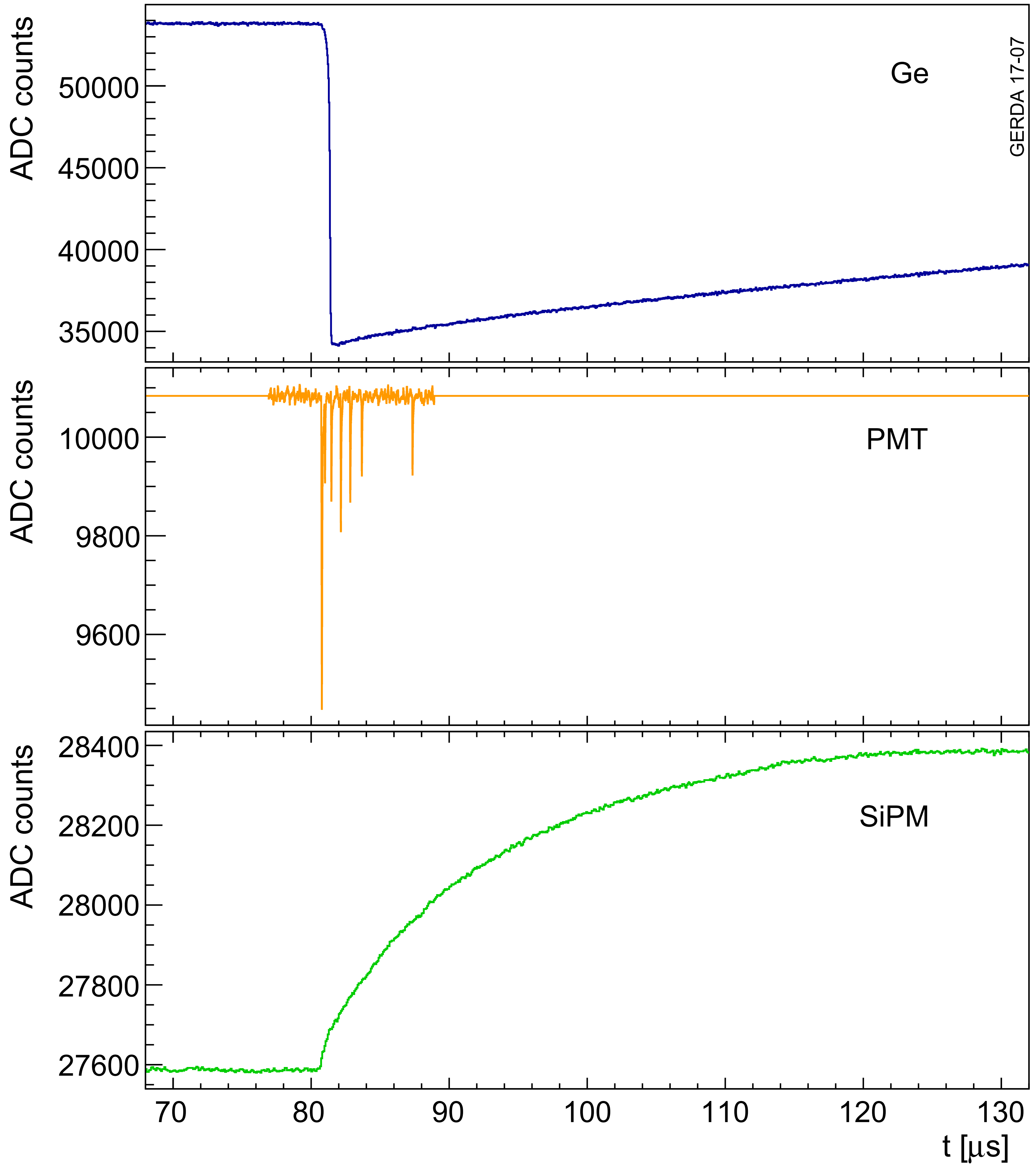


How it works

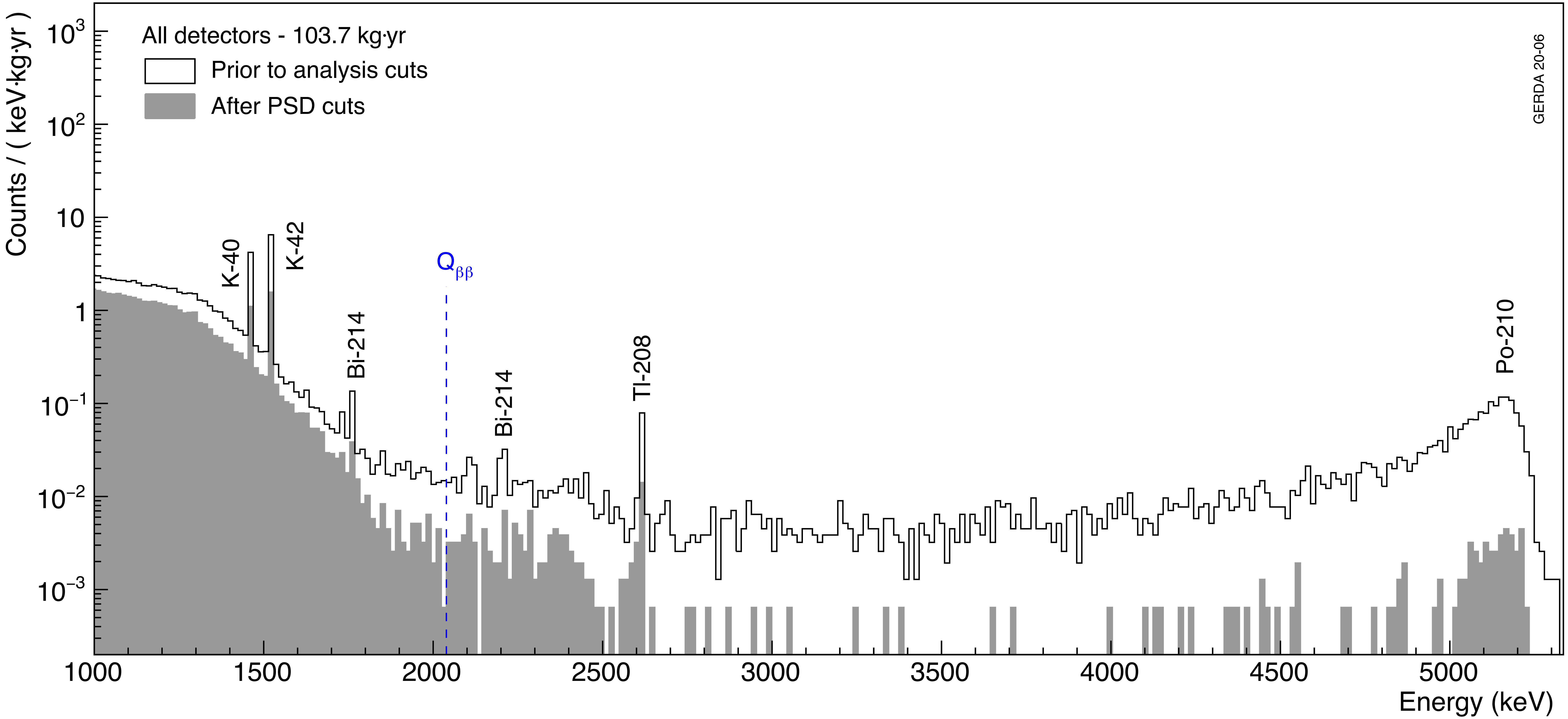
- 16 PMTs
- ~1.5 km light guiding fibers + SiPM readout
- Vetoes events in coincidence with Germanium
- Acceptance ($0\nu\beta\beta$) : ~98 %

[GERDA, *Phys Rev Lett* **125** (2020), 252502]



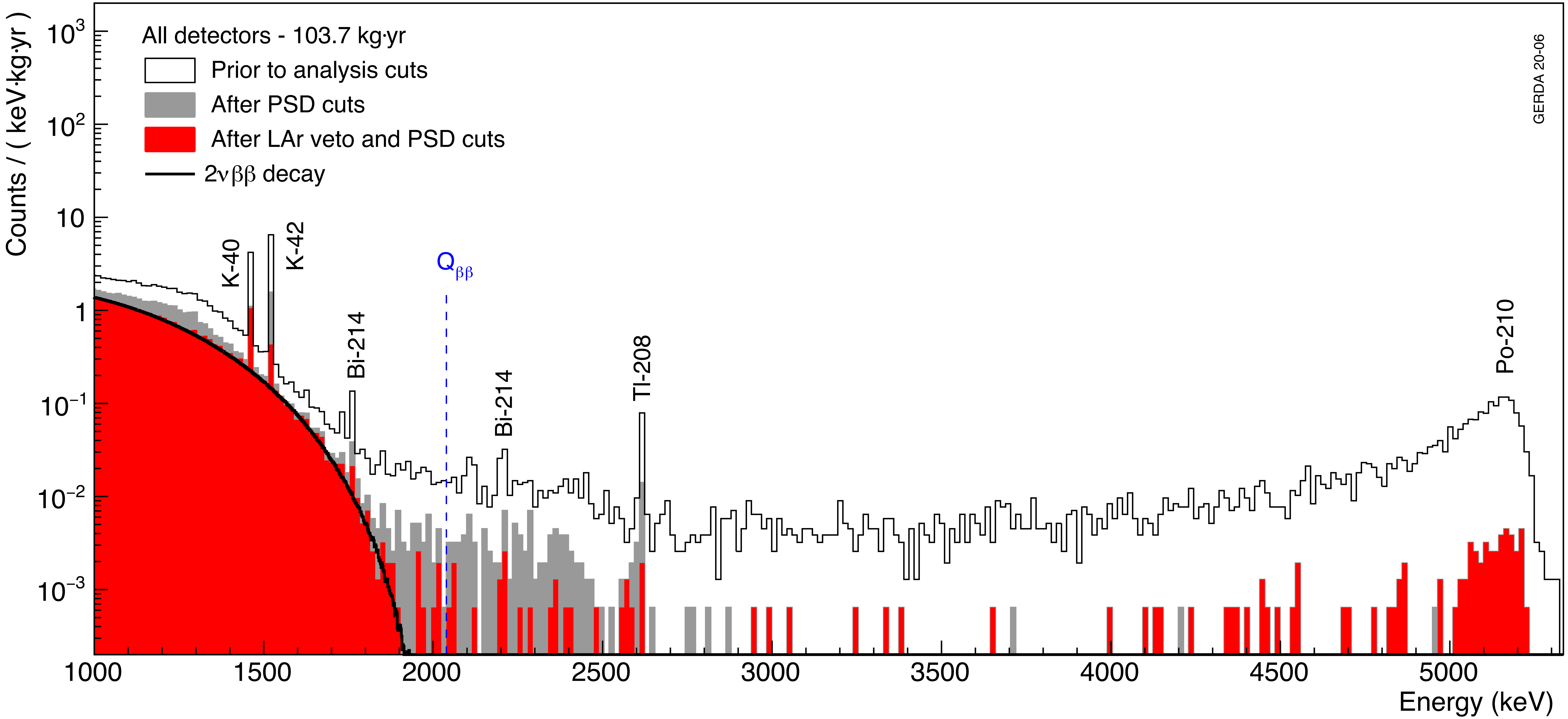
Active background suppression

Performance



Total active background suppression

Performance

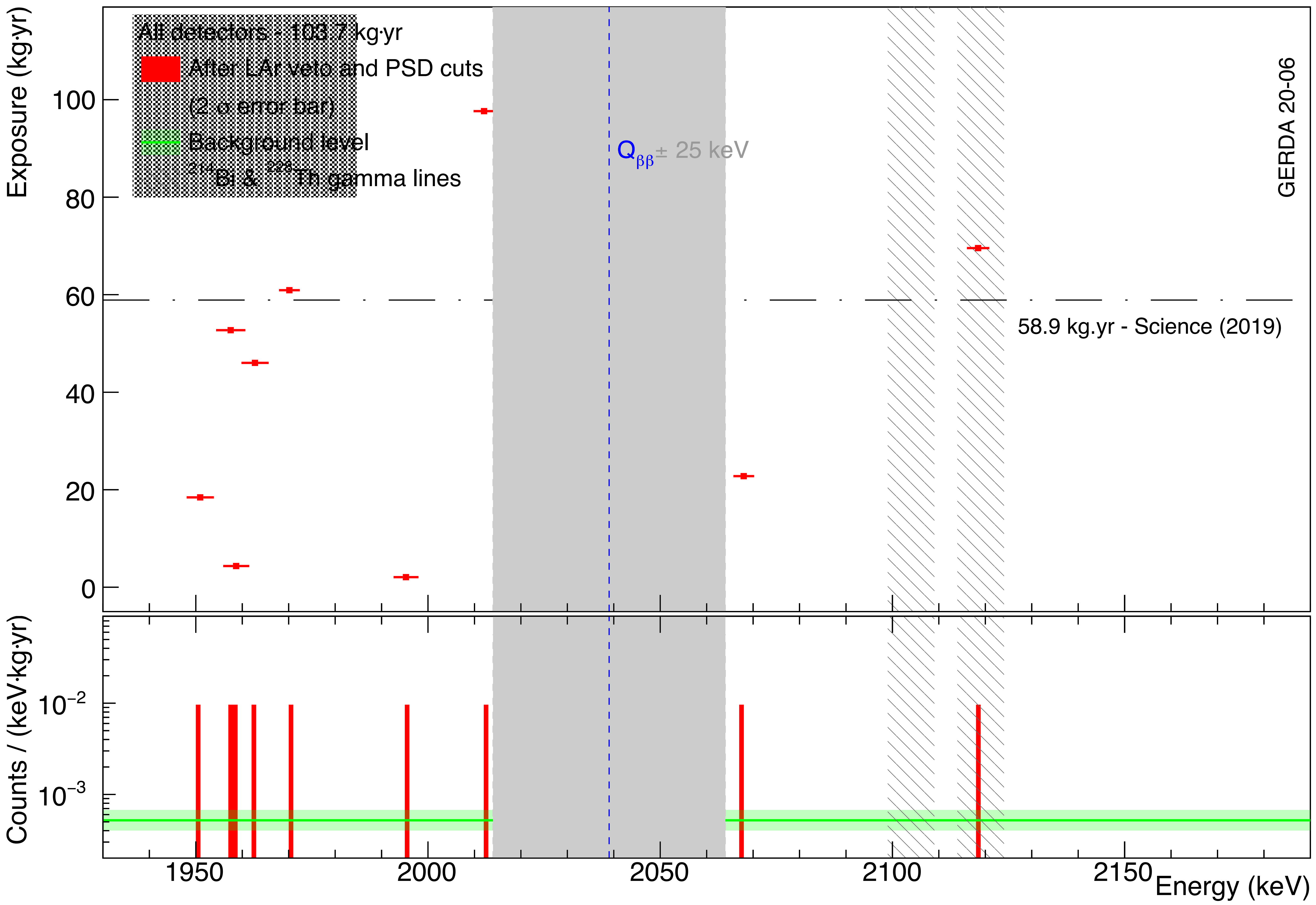


Final results @$Q_{\beta\beta}$

[GERDA, *Phys Rev Lett* **125** (2020), 252502]

Final Results of GERDA

...in the analysis window



- Blind analysis around $Q_{\beta\beta}$
- Latest unblinding in May 2020
- 2 new counts in $Q_{\beta\beta} \pm 25$ keV
- No new counts @$Q_{\beta\beta}$
- Background:
  - $5.2^{+1.6}_{-1.3} \cdot 10^{-4}$ cts/(keV kg yr)

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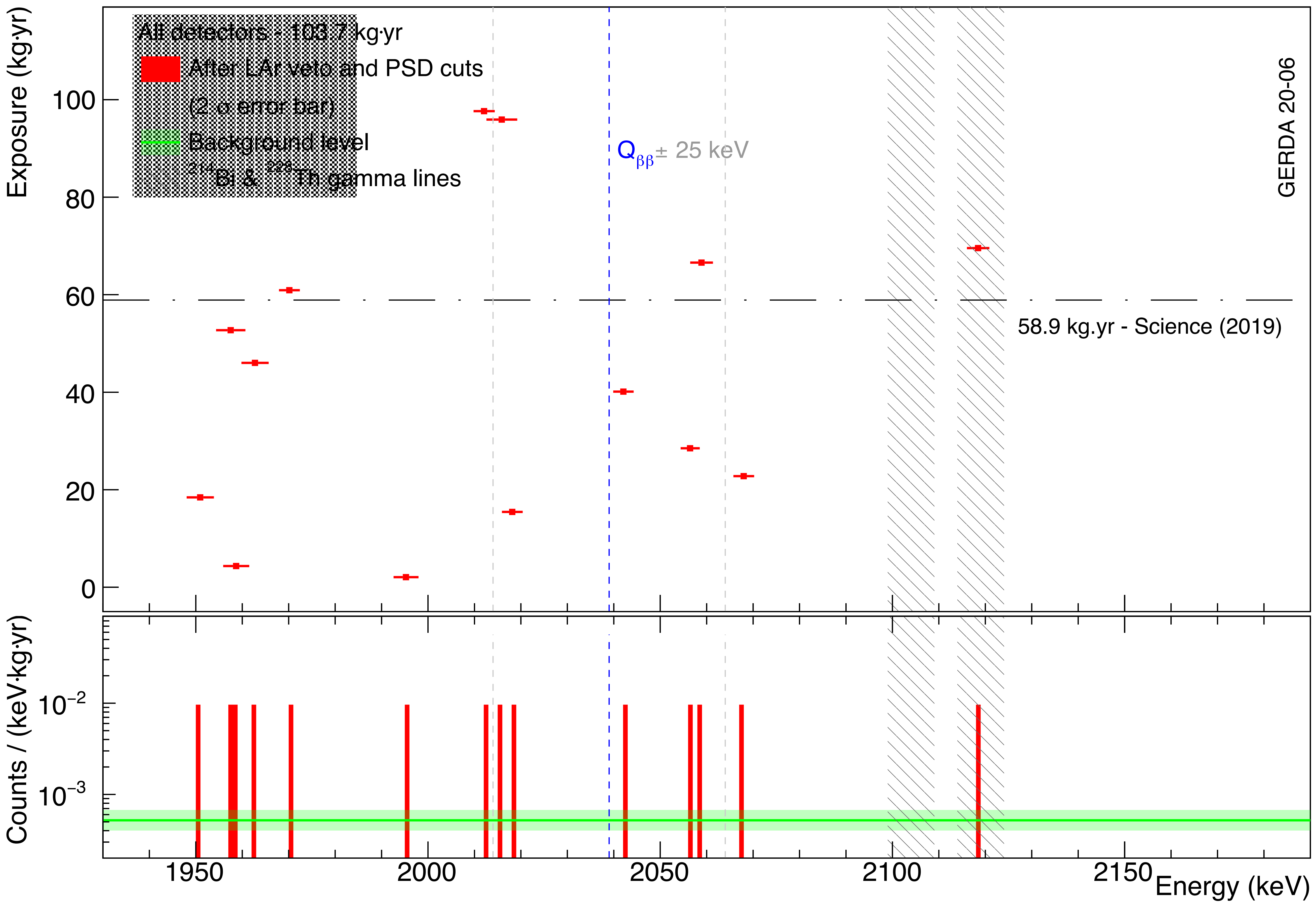

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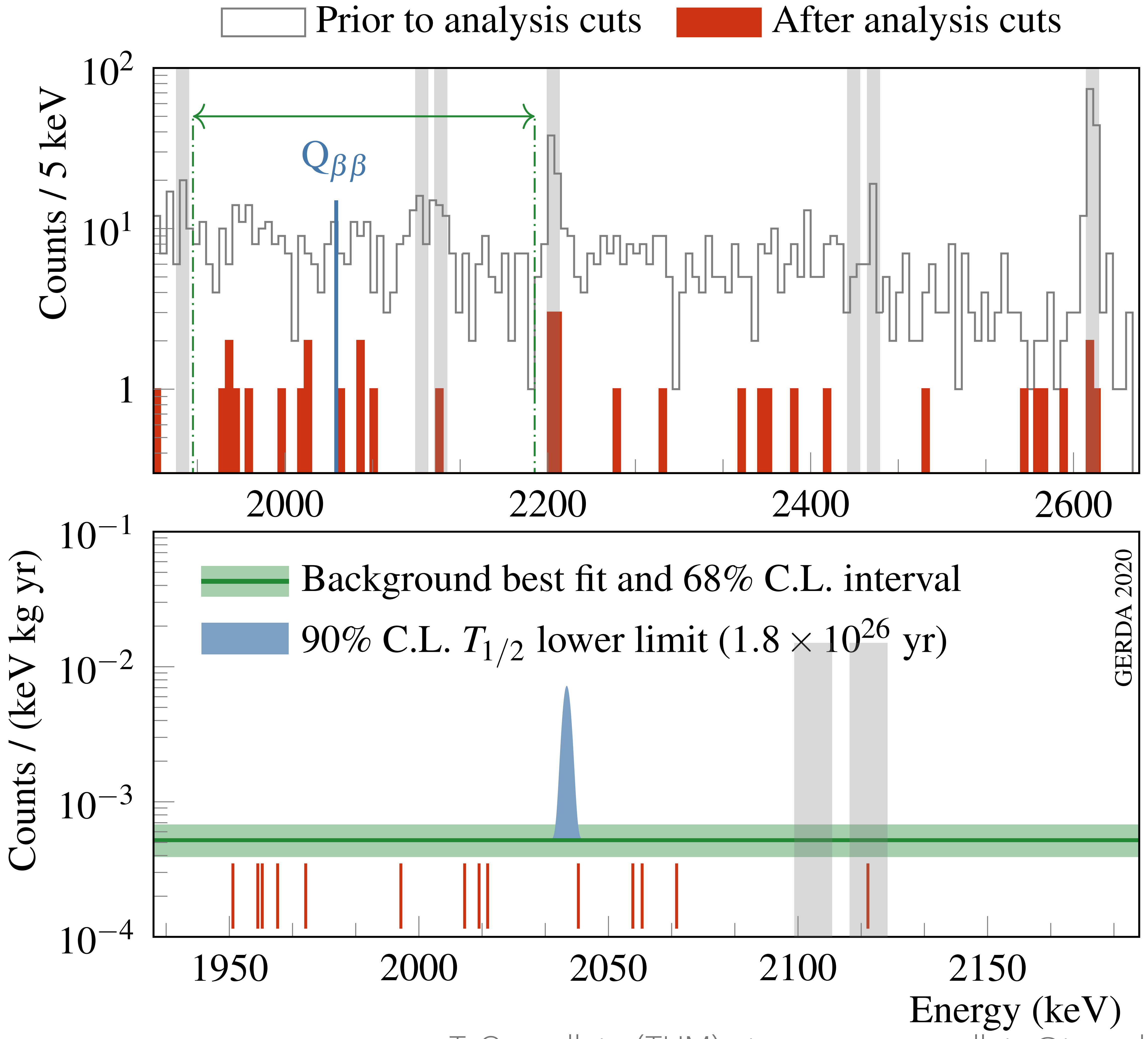
Final Results of GERDA

...limits on $0\nu\beta\beta$



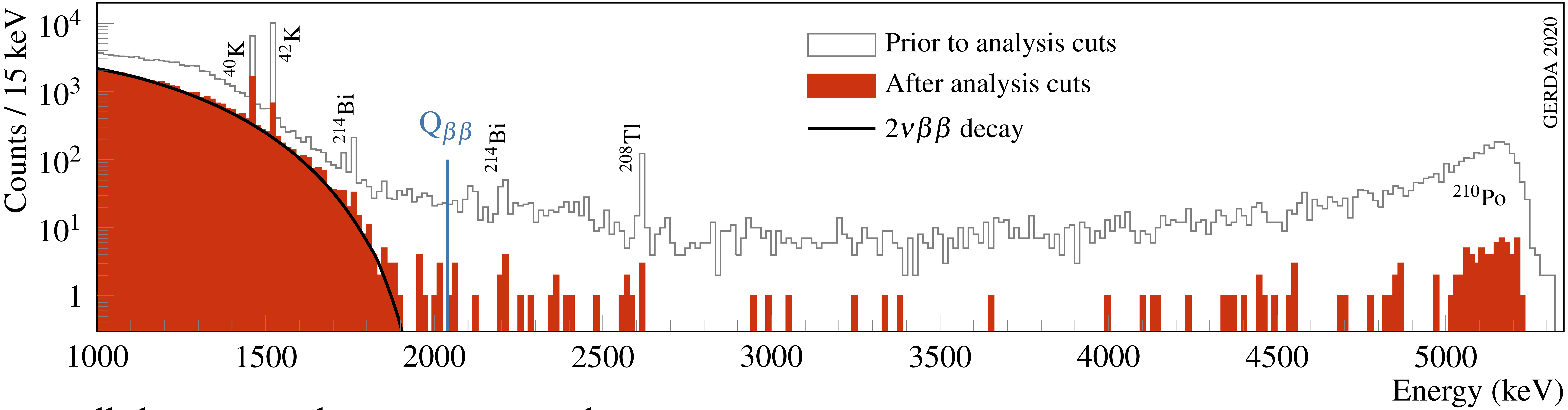
- Combined (data partitions, Phase I) unbinned maximum likelihood fit
  [GERDA, *Nature* **544** (2017), 47–52]
- Best fit for null signal strength
- Limit (and sensitivity) on $0\nu\beta\beta$ half-life:

$$T_{1/2}^{0\nu\beta\beta} > 1.8 \cdot 10^{26}\ \text{yr (90\% C.L.)}$$

- Limits on $m_{\beta\beta}$:

$$m_{\beta\beta} < [79 - 180]\ \text{meV}$$

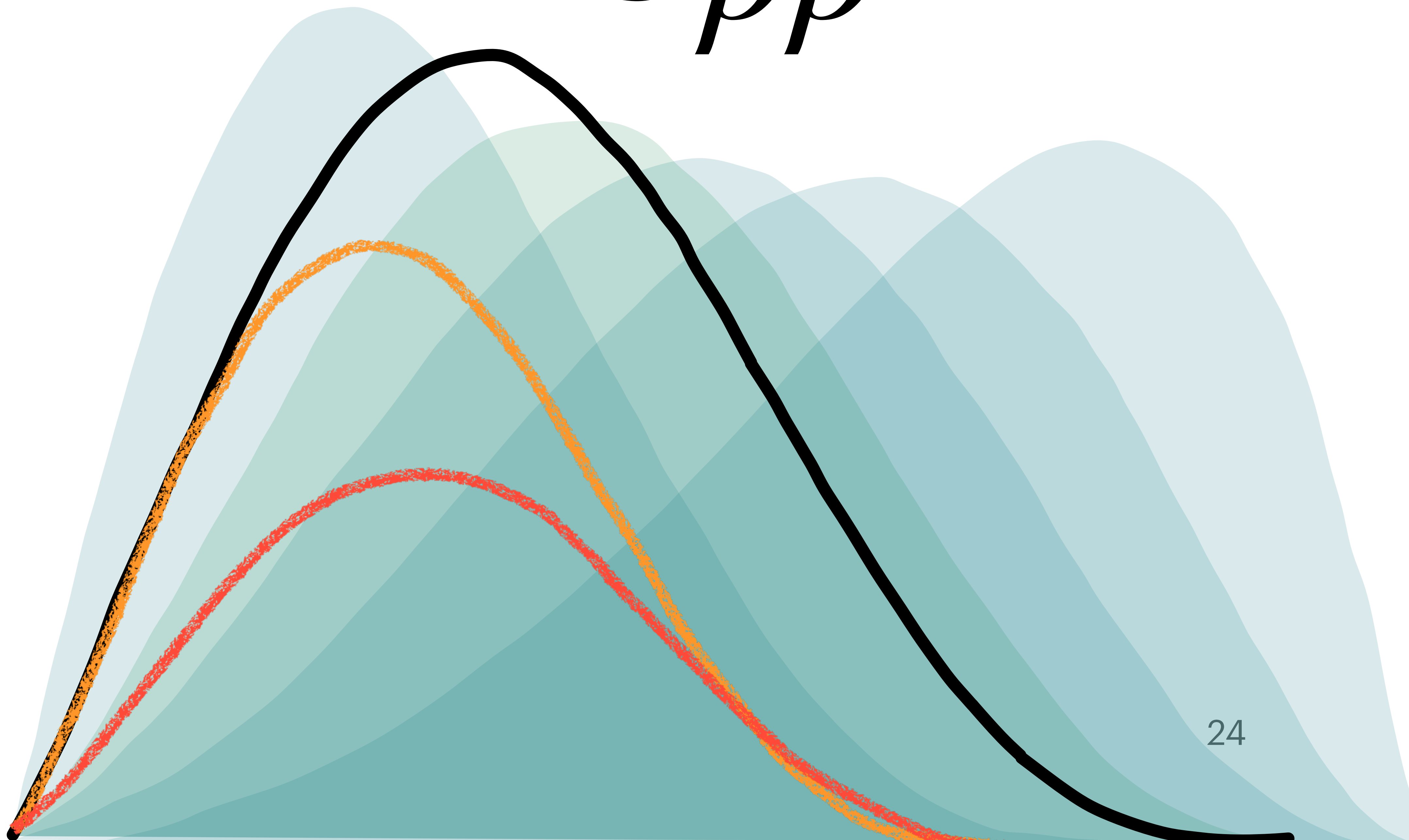
Final Results of GERDA



- All design goals are surpassed!

	Goals	Achievements
Background	10^{-3} cts/(keV kg yr)	$5.2^{+1.6}_{-1.3} \cdot 10^{-4}$ cts/(keV kg yr)
Exposure	≥100 kg yr	103.7 kg yr
Sensitivity	$T_{1/2}^{0\nu\beta\beta} \geq 10^{26}$ yr	$T_{1/2}^{0\nu\beta\beta} > 1.8 \cdot 10^{26}$ yr

Physics results below $Q_{\beta\beta}$



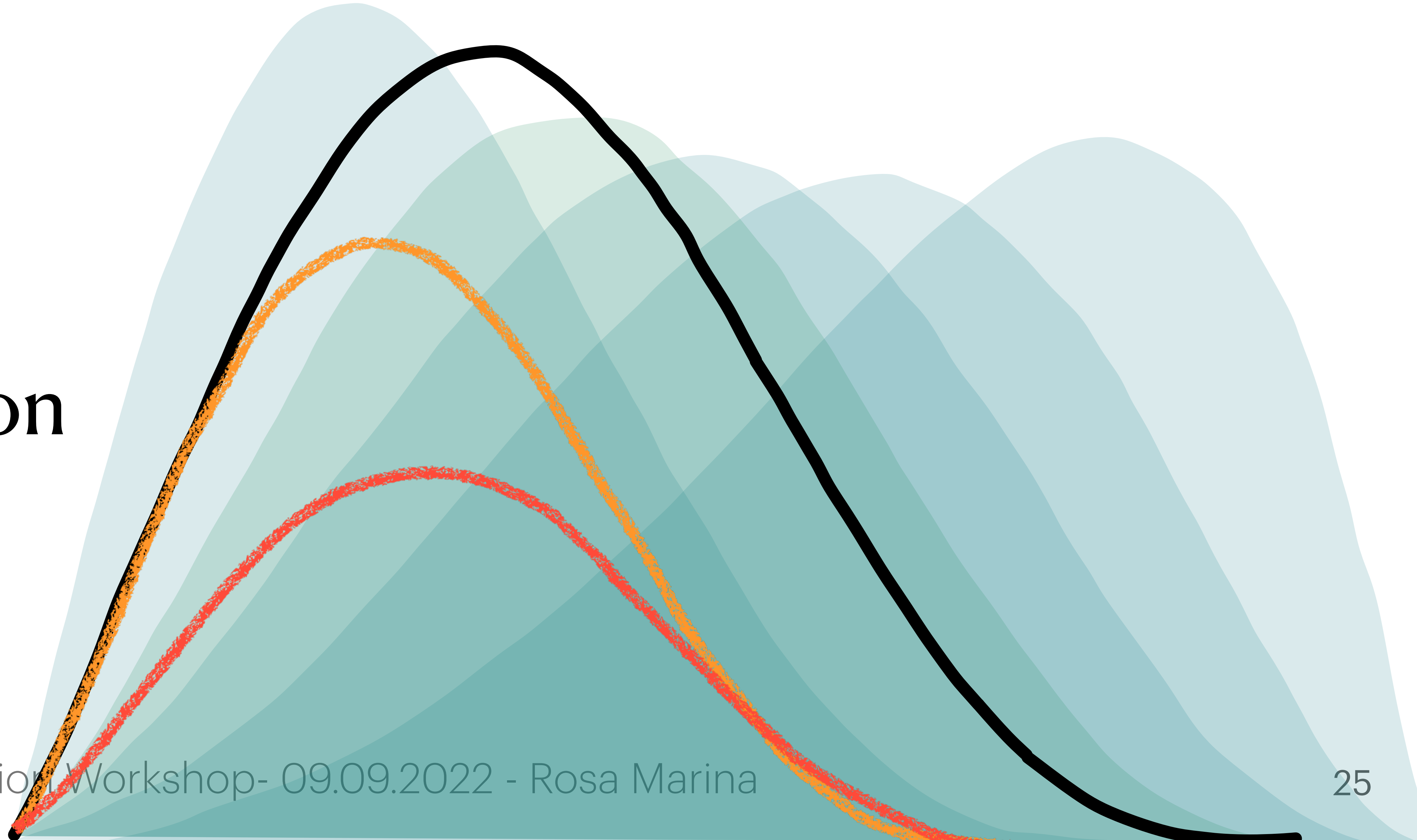
[arXiv:2209.01671]

GERDA's studies below $Q_{\beta\beta}$

A broad physics program

- Precise determination of the $2\nu\beta\beta$ half-life
- Updated limits on Majoron-involving decays
- First constraints with ^{76}Ge on Lorentz violation
- First experimental constraints on light exotic fermions
- Constraints on sterile neutrinos

- Competitive results thanks to LAr instrumentation

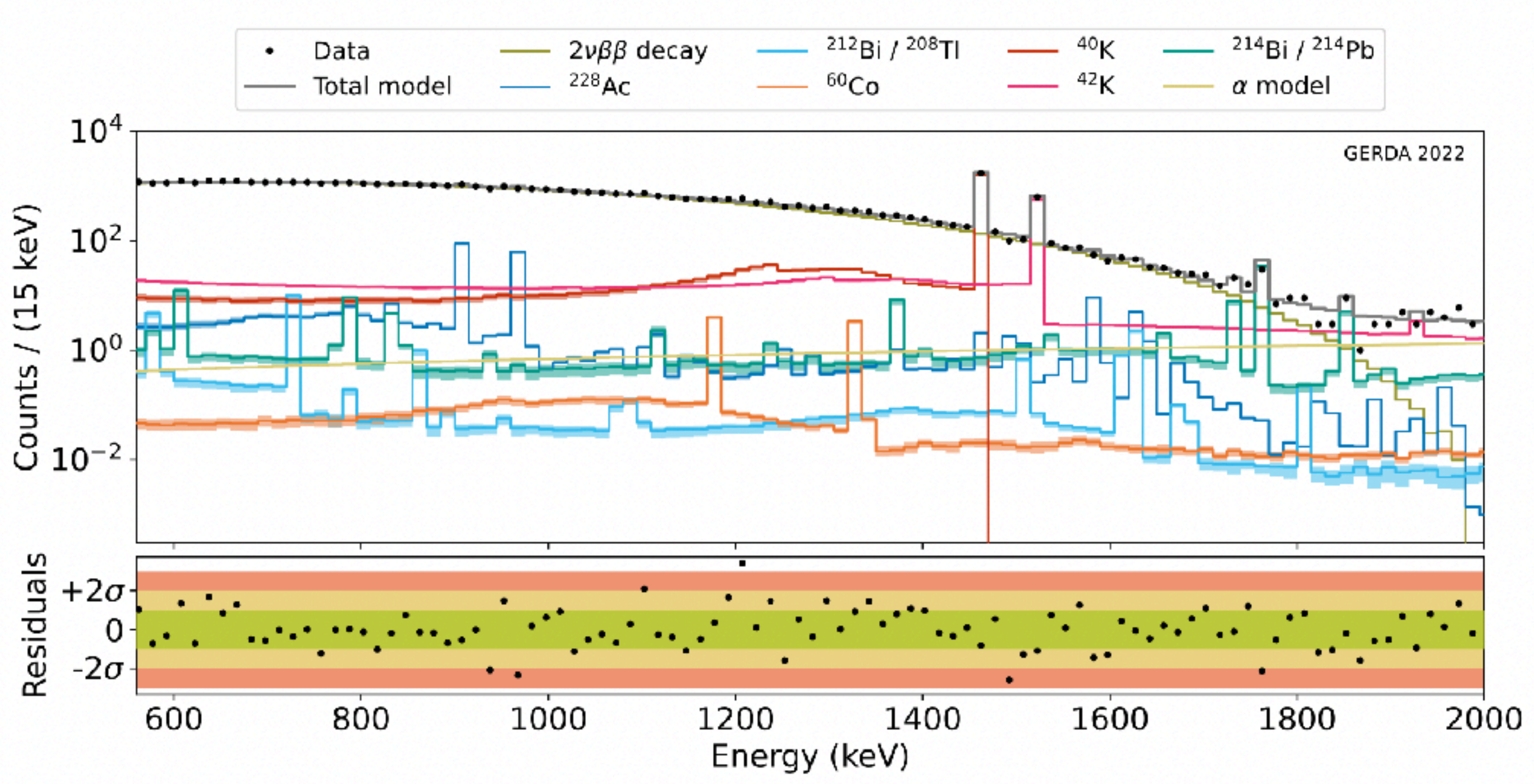


[arXiv:2209.01671]

LAr instrumentation provides clean $2\nu\beta\beta$ spectrum

...and its modeling gives knowledge on the background underneath

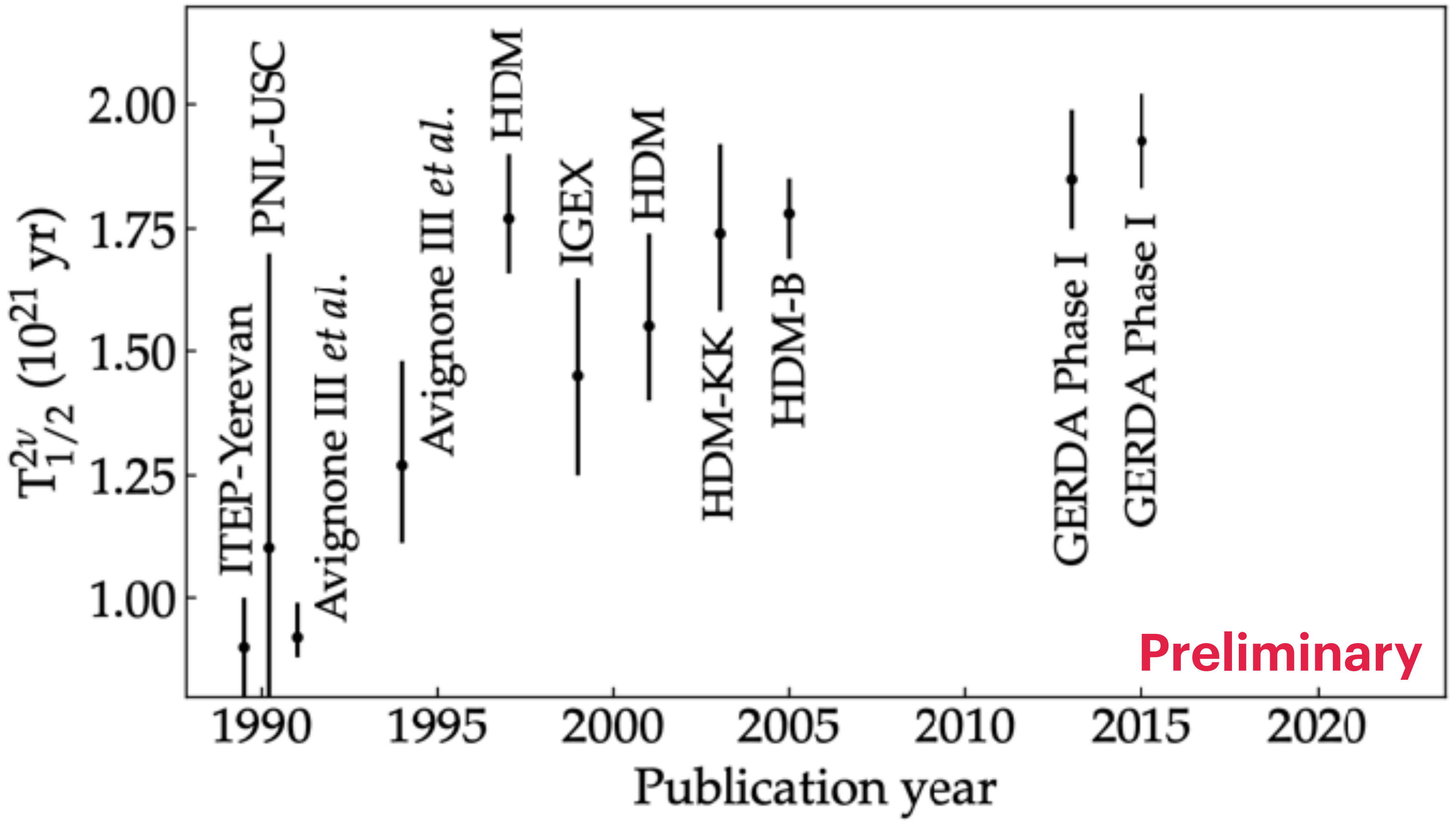
- LAr instrumentation reduces background by factor ~10 in the $2\nu\beta\beta$ region
- Synergy background model-LAr model reveals what background is underneath
- Almost pure $2\nu\beta\beta$ spectrum



Precision measurement of the $2\nu\beta\beta$ half-life

Precision measurement of the $2\nu\beta\beta$ half-life

- Result of GERDA Phase I:
  - w/o LAr instrumentation
  - Systematics dominated by uncertainty in the active volume
  - $T_{1/2}^{2\nu\beta\beta} = (1.926 \pm 0.094) \cdot 10^{21}$ yr



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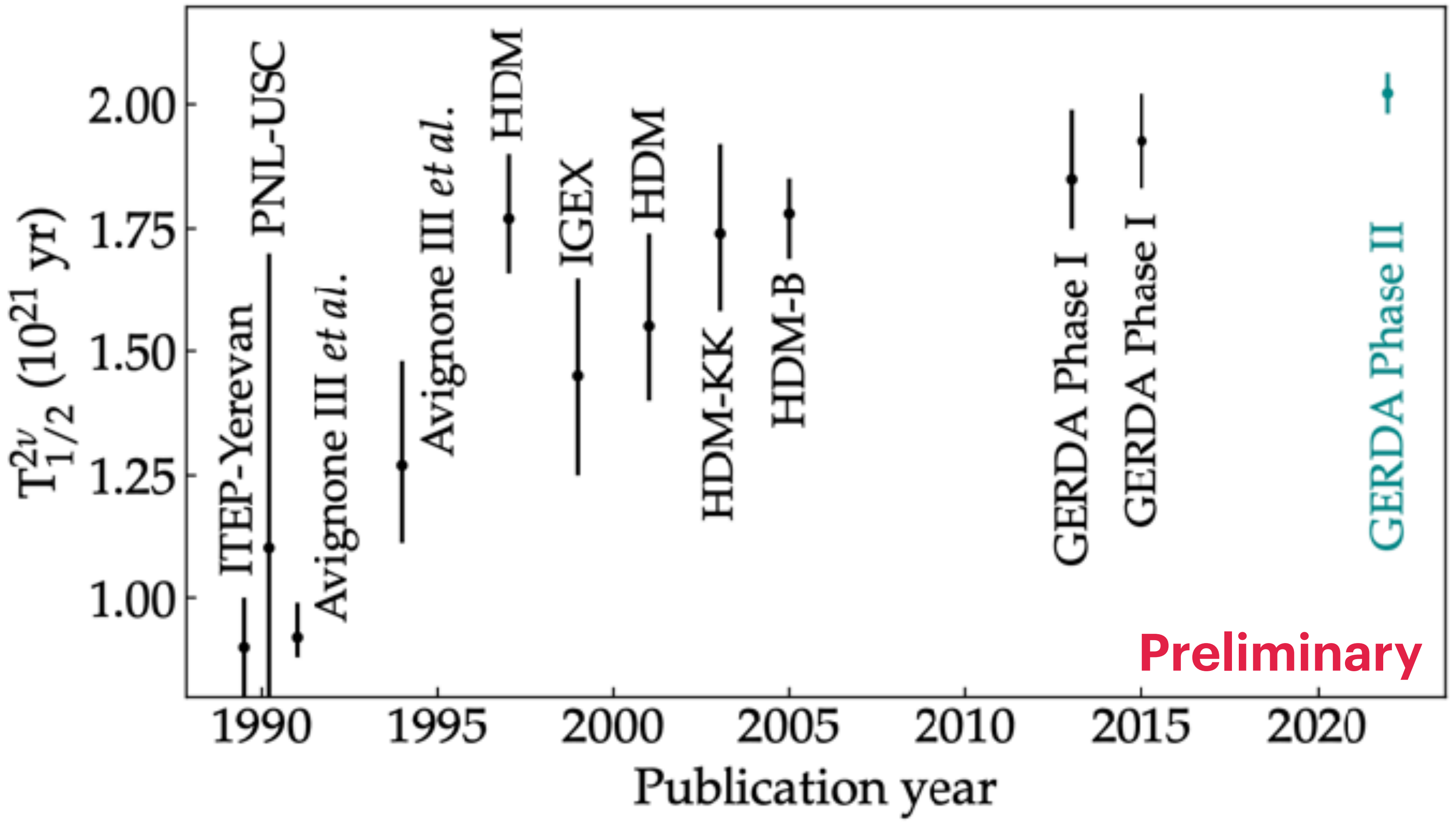
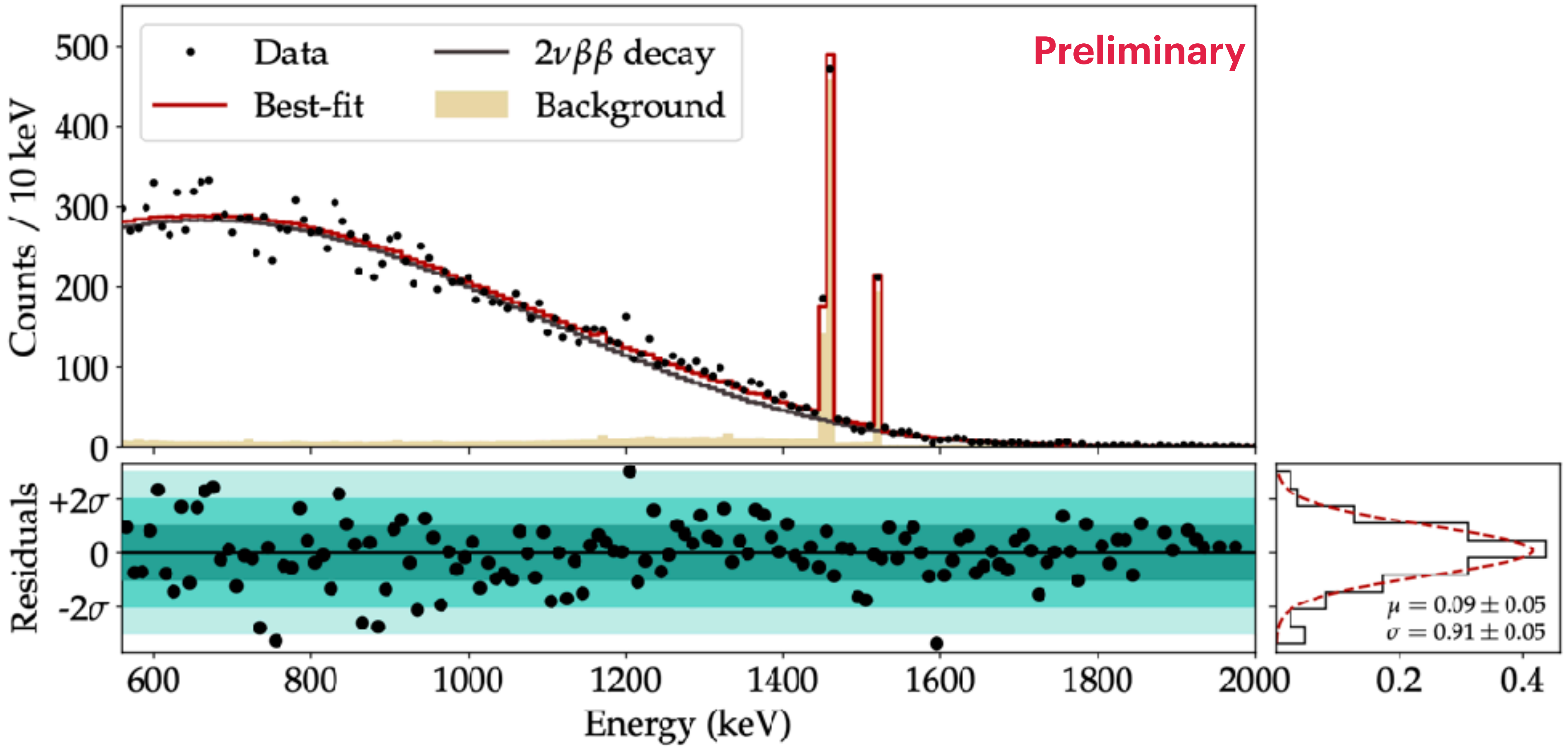
  - w/o LAr instrumentation
  - Systematics dominated by uncertainty in the active volume
  - $T_{1/2}^{2\nu\beta\beta} = (1.926 \pm 0.094) \cdot 10^{21}$ yr
- New result of GERDA Phase II:
  - w/ LAr instrumentation
  - Improved systematics
  - $T_{1/2}^{2\nu\beta\beta} = (2.022 \pm 0.041) \cdot 10^{21}$ yr **Preliminary**
  - Most precise determination of ^{76}Ge $2\nu\beta\beta$ half-life

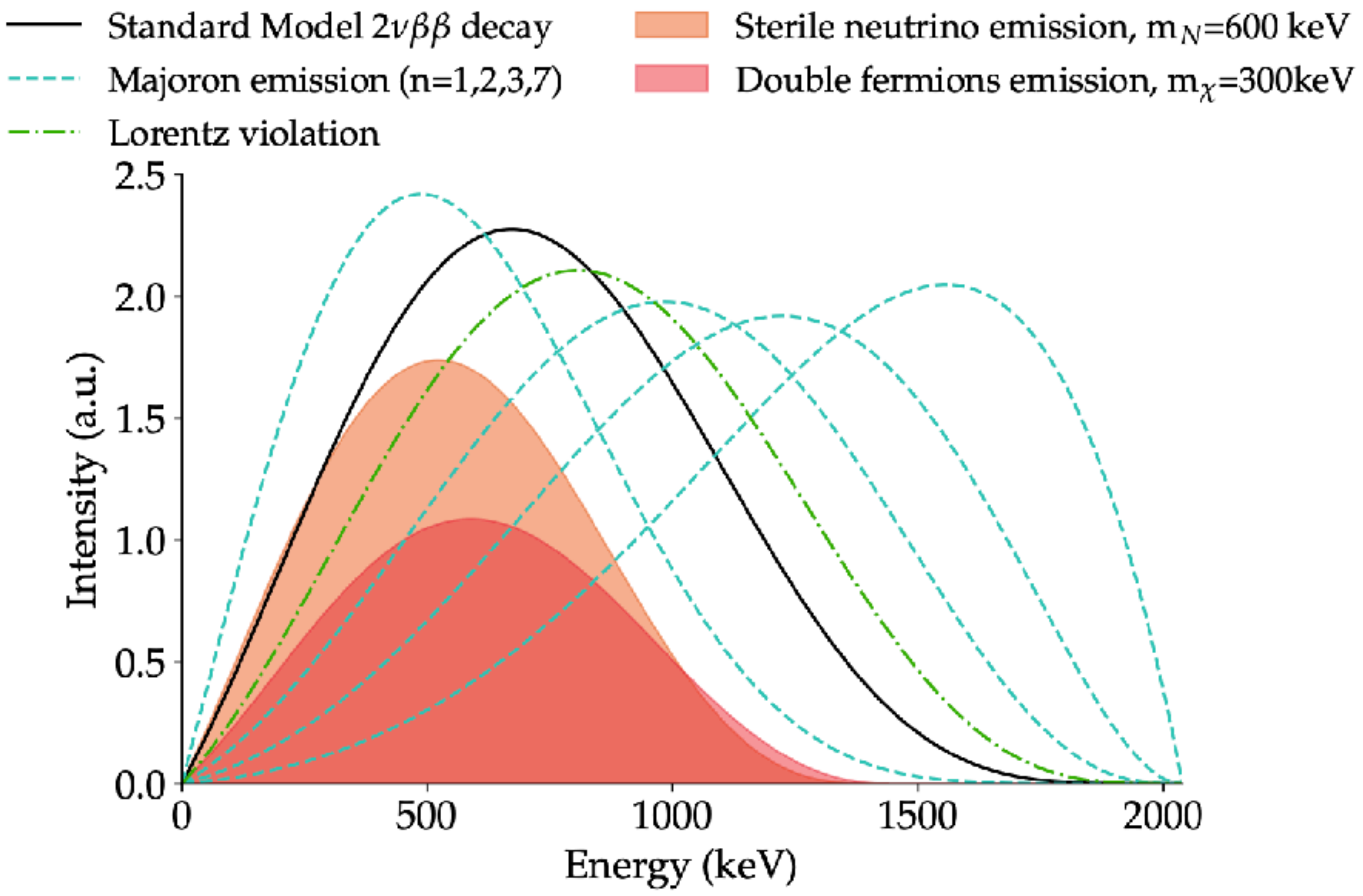




Exotic double-beta decay modes

Will show up as deformations on the $2\nu\beta\beta$ spectrum

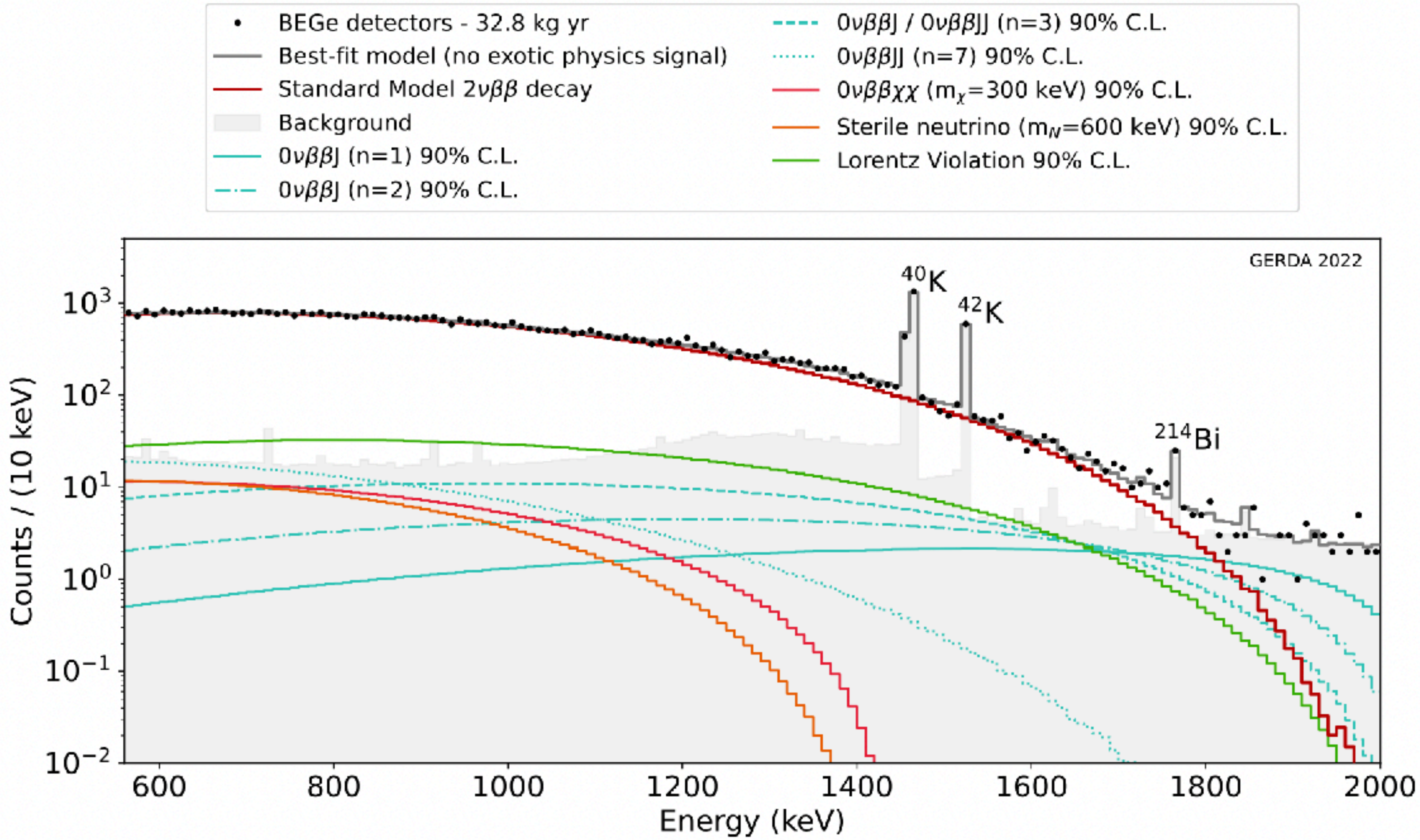
- Search for double-beta decays with emission of one or two exotic particles
  - Majorons
    - $(A,Z) \to (A,Z+2) + 2e^- + J(2J)$
    - Limits on the neutrino-Majoron coupling constant g_J
  - Sterile neutrinos N [Phys.Rev.D 103 (2021) 5, 055019, Phys. Lett. B 815 (2021)]
    - $(A,Z) \to (A,Z+2) + 2e^- + \bar{\nu}_e + N$
  - Light exotic fermions χ [Phys.Rev.D 103 (2021) 5, 055019, Phys. Lett. B 815 (2021)]
    - $(A,Z) \to (A,Z+2) + 2e^- + 2\bar{\chi}$
- Lorentz violation in the neutrino sector
  - $(A,Z) \to (A,Z+2) + 2e^- + 2\bar{\nu}_e^{LV}$



[arXiv:2209.01671]

Exotic double-beta decay modes

Results

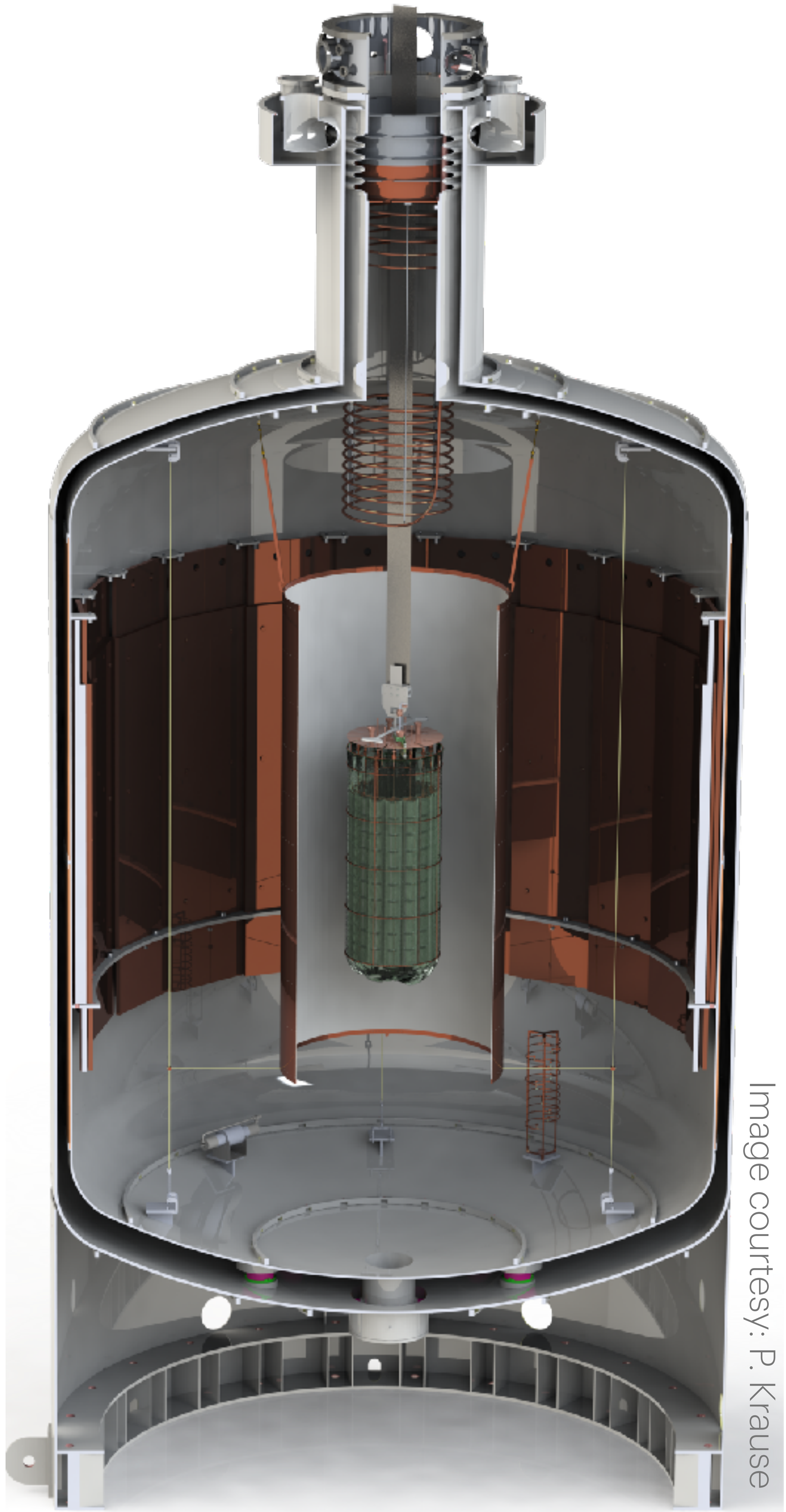


- No evidence of positive signals, but 90% C.L. limits are derived
- Details in backup

Exotic decay mode	Observed Limit
Decay with Majorons (n=1)	$T_{1/2}$>6.4 10^{23} yr
n=2	$T_{1/2}$>2.9 10^{23} yr
n=3	$T_{1/2}$>1.2 10^{23} yr
n=7	$T_{1/2}$>1.0 10^{23} yr
Lorentz Violation	(-2.7 < $a_{of}^{(3)}$ < 6.2) 10^{-6} GeV
Sterile Neutrinos (m_N=500-600 keV)	$\sin^2\vartheta$ < 0.013
Exotic fermions (m=300 keV)	$T_{1/2}$ > 1.6 10^{23} yr

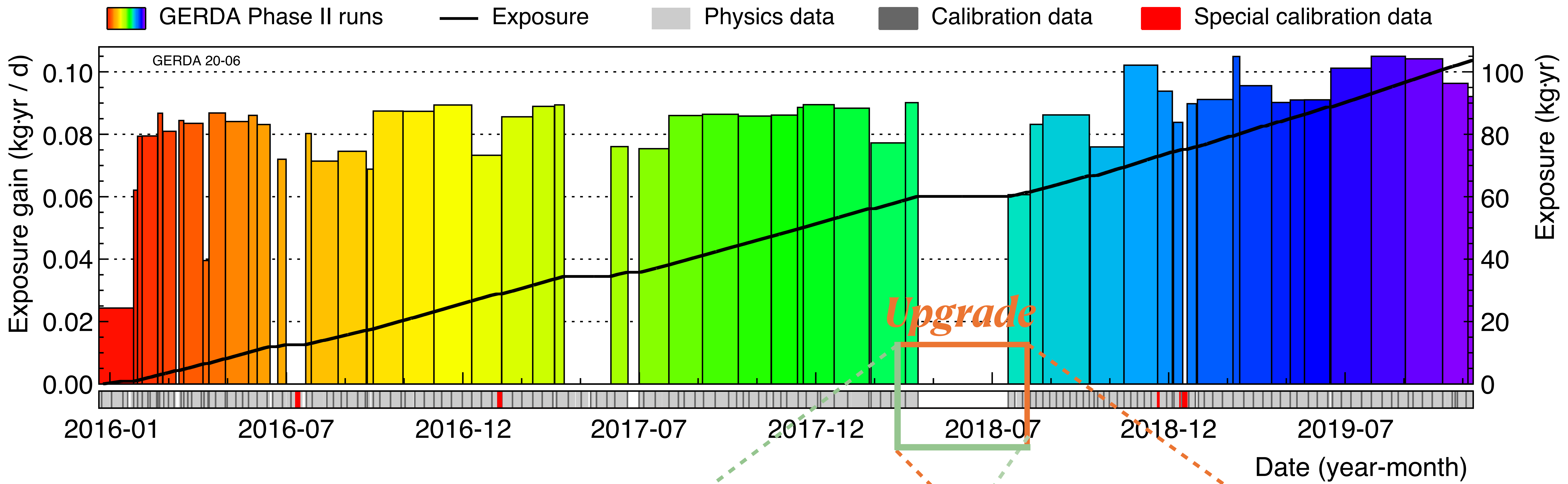
Conclusions

- GERDA has run in background-free regime for the entire duration of its data taking
- Provided among the most stringent constraints on the half-life of $0\nu\beta\beta$ decay
- Obtained a precise determination of the half-life of ^{76}Ge $2\nu\beta\beta$ decay
- Searched for a broad variety of BSM physics and obtained competitive limits
- Bright future ahead LEGEND
  - —>See R. Brugnera's talk tomorrow 16:25



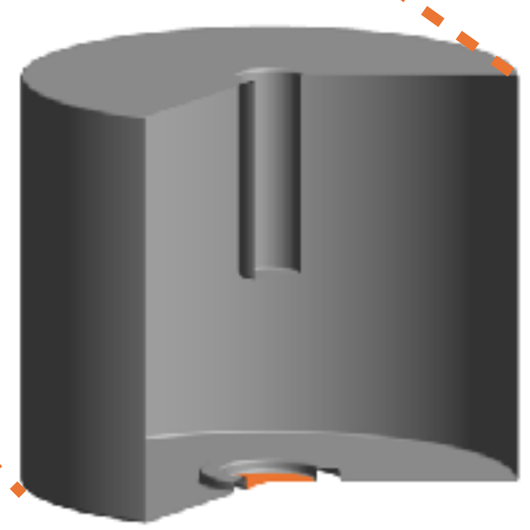
Backup

The data taking of GERDA phase II



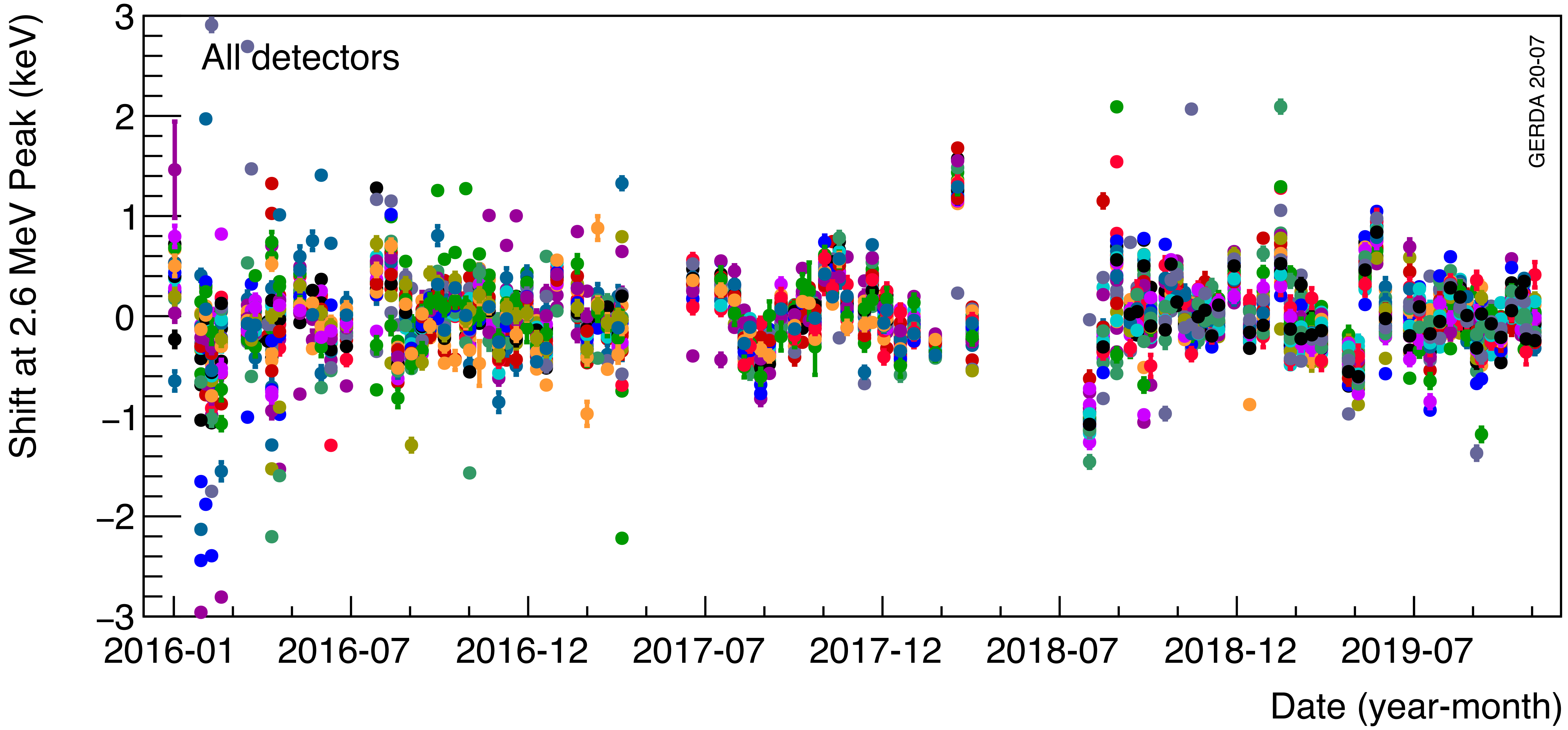
- Phase II duty cycle: 87.7%
- **103.7 kg yr** (127.2 kg yr with Phase I)
- Upgrade in 2018

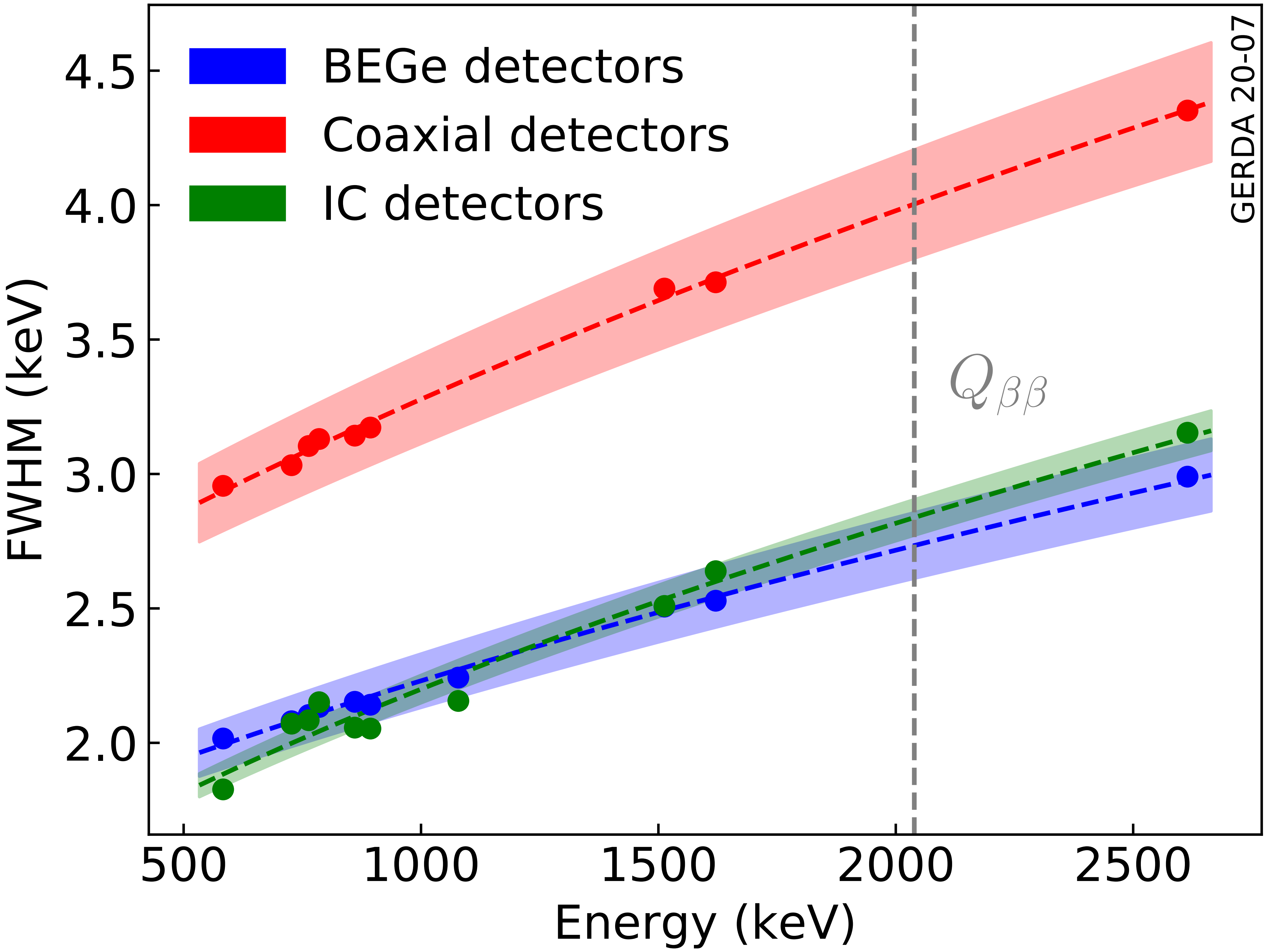
new fiber shroud



5 new inverted coaxial detectors

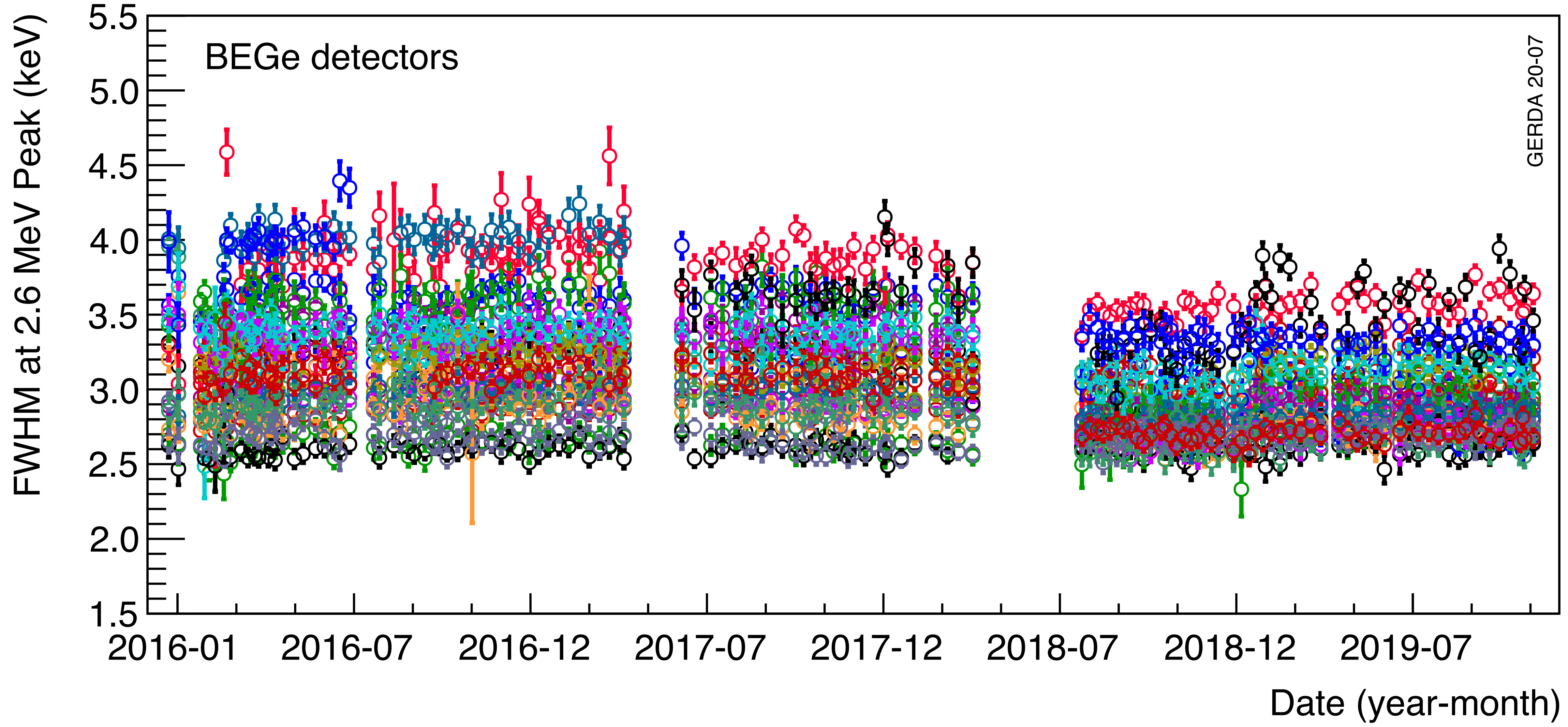
Performance on the energy scale

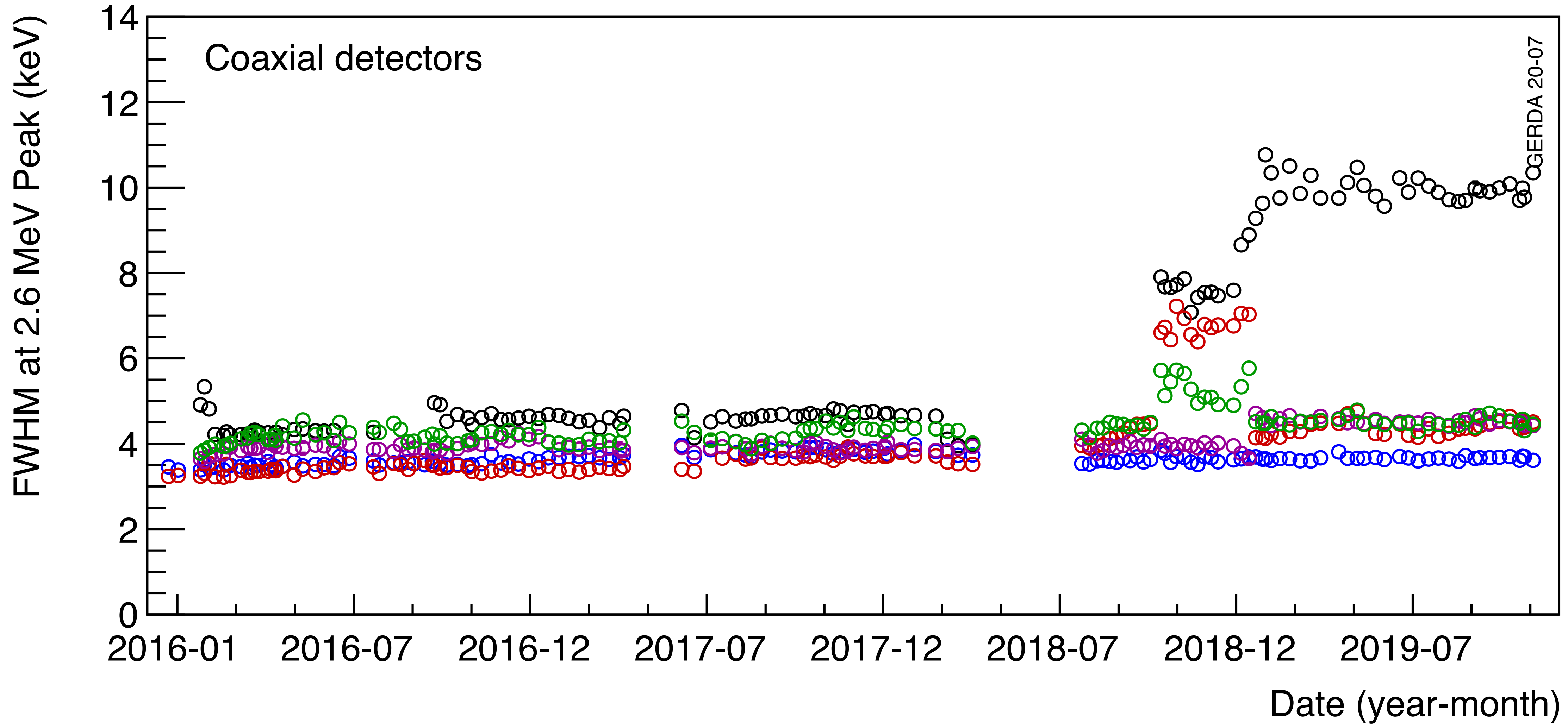


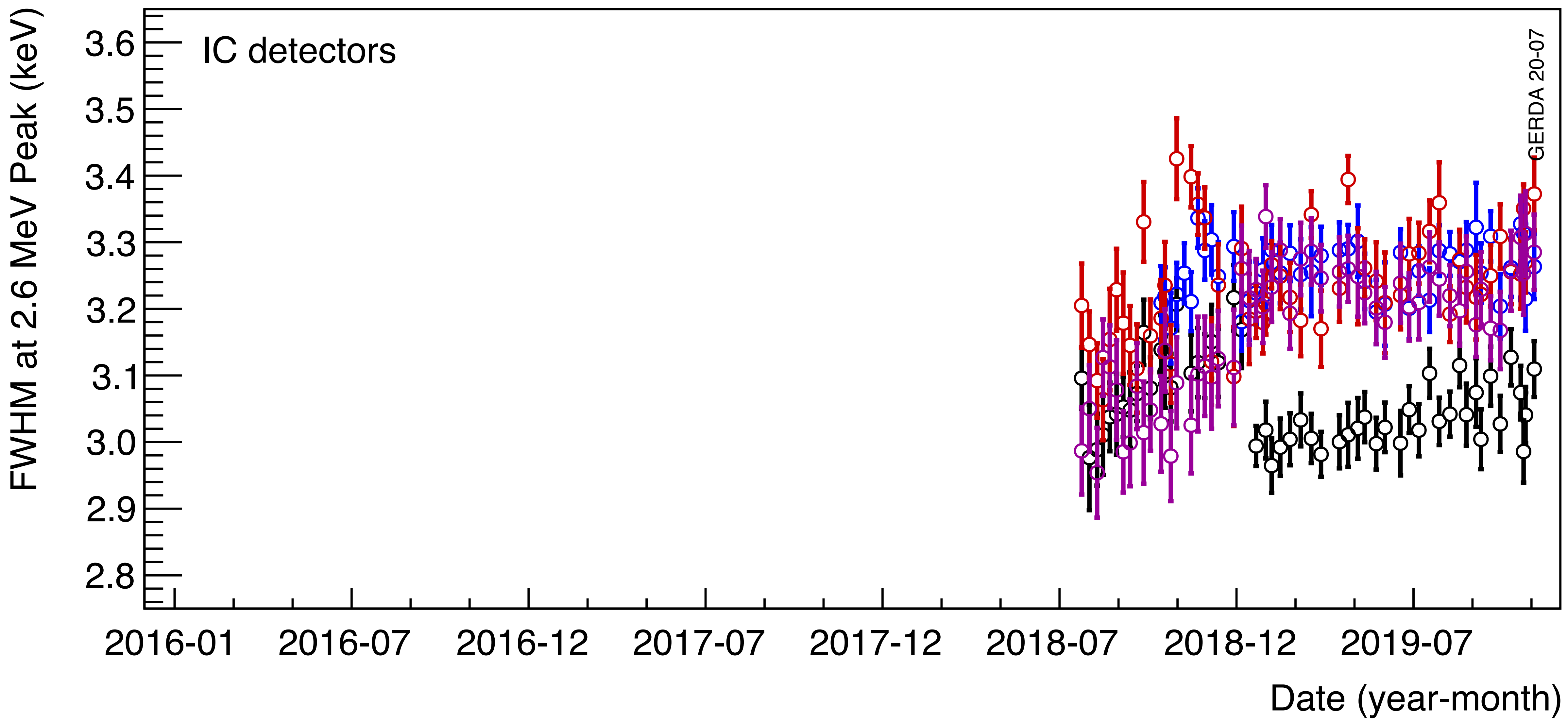


- Detectors calibrated weekly with ^{228}Th
- Energy shifts between calibrations < 1 keV
- Zero Area Cusp energy filter [*European Phys J C* 75 (2015), 255]

Resolution stability

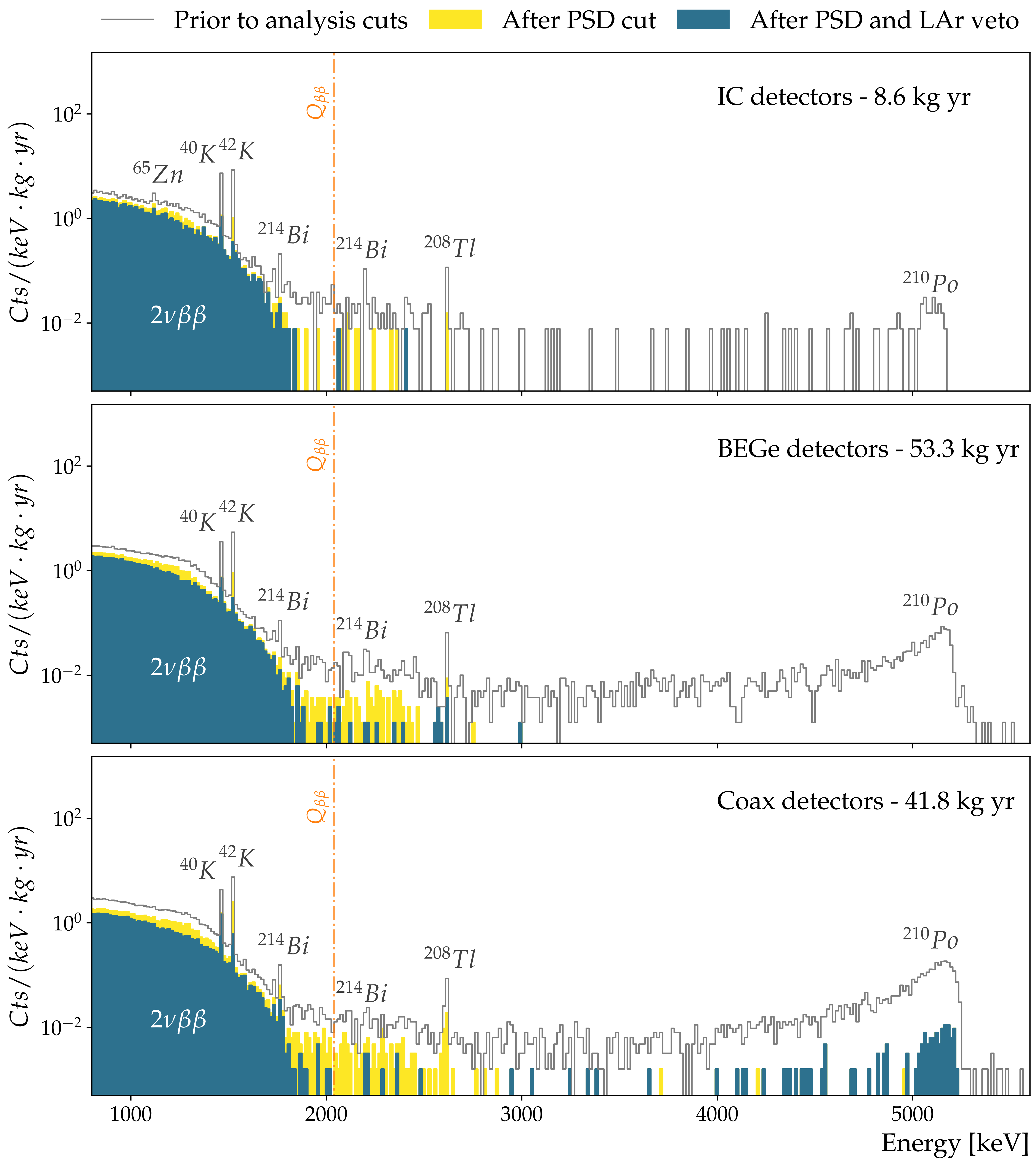






Total active background suppression

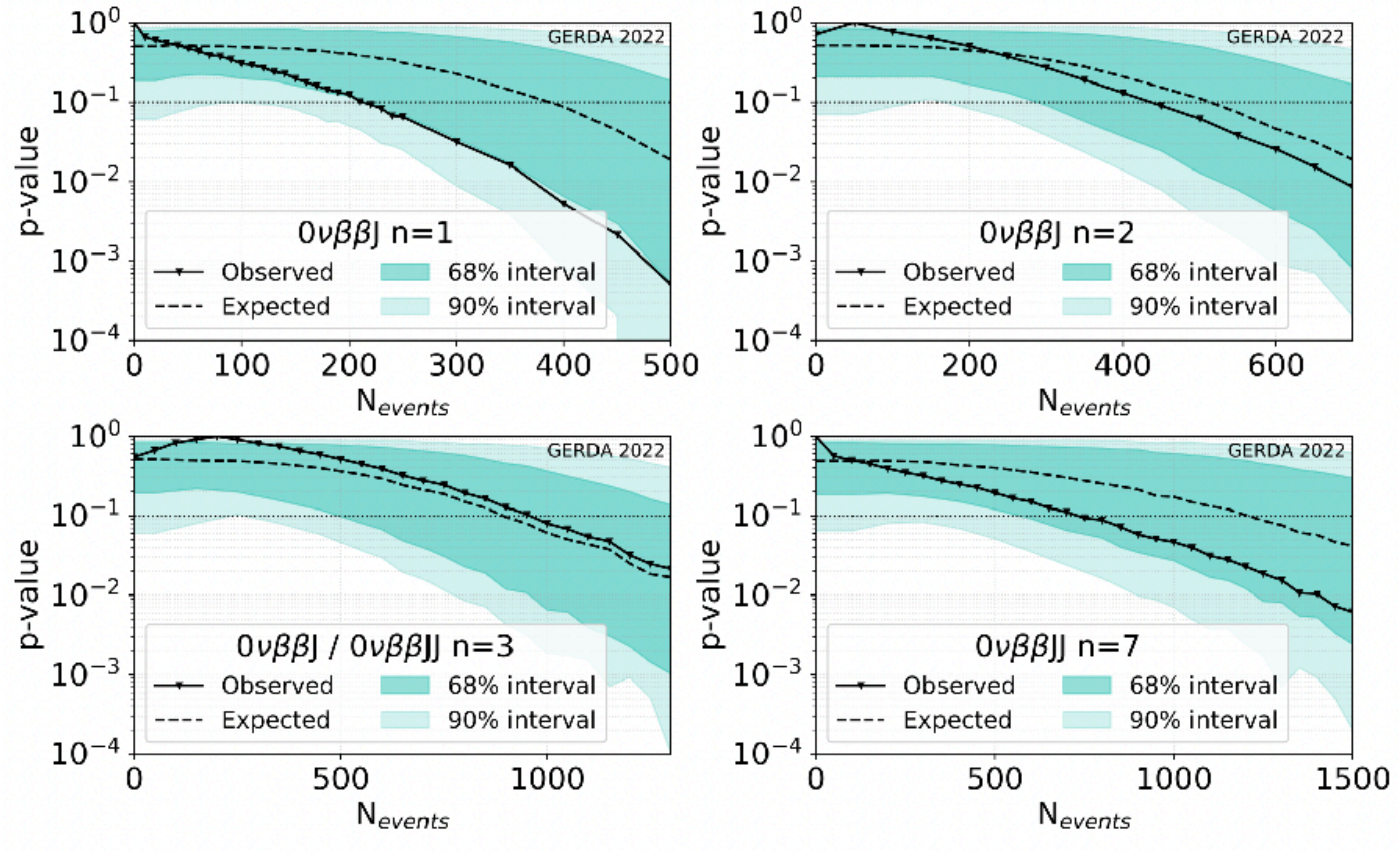
..per detector family



- ^{210}Po coming from coaxial detectors
- BI: $\mathcal{O}(10^{-4})$ cts/(keV kg yr) for all detector families

Majoron-involving decays

$$(A,Z) \rightarrow (A,Z+2) + 2e^- + J(2J)$$

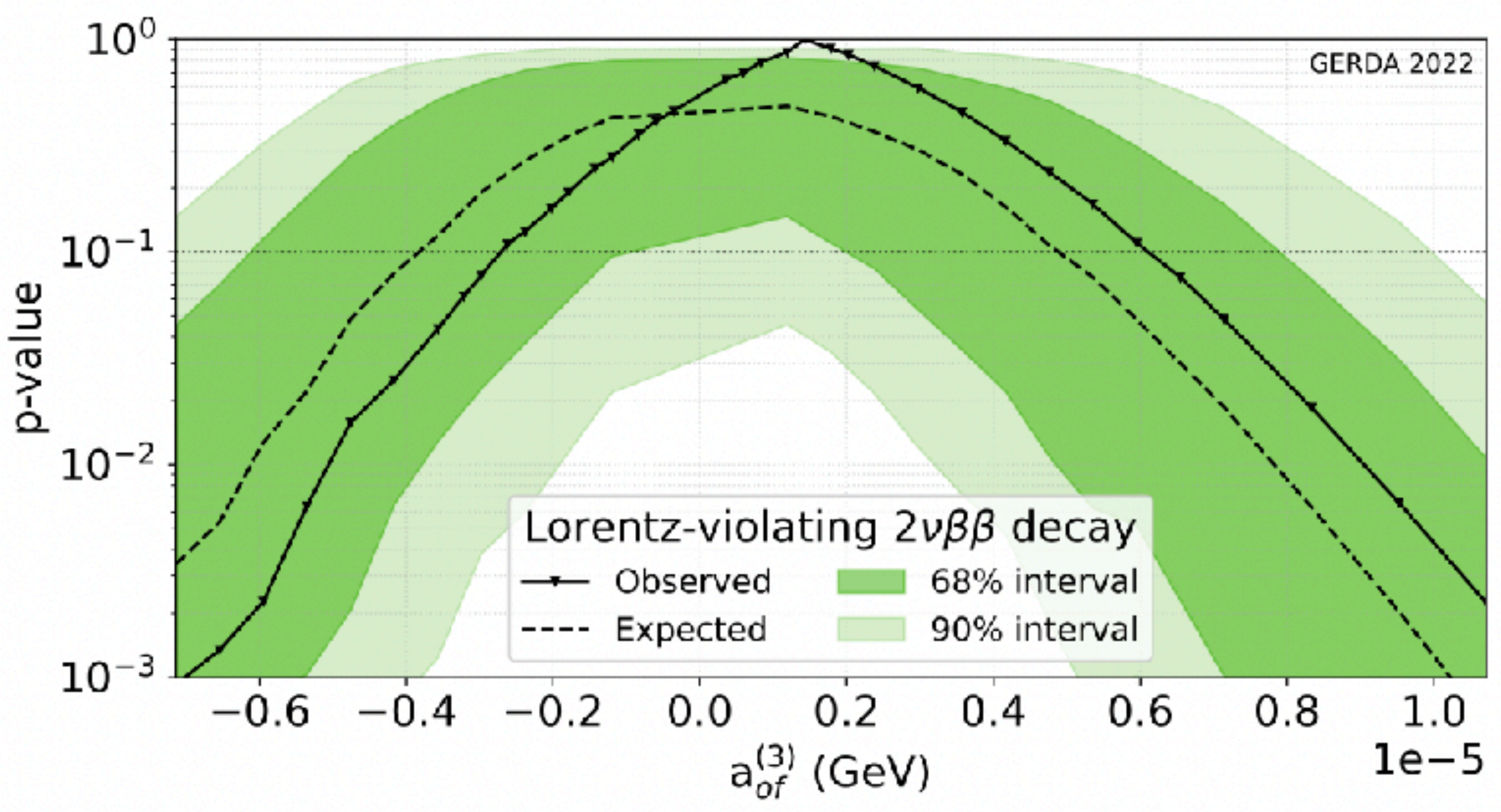


- Searched for double-beta decays with emission of two Majorons according to 4 different models (n=1,2,3,7)
- Limits can be converted into the Majoron-neutrino coupling constant g_J

Decay mode	$T_{1/2}$ (yr) Sensitivity	$T_{1/2}$ (yr) Observed limit	g_J
$0\nu\beta\beta J$ $(n=1)$	$3.5{\cdot}10^{23}$	$> 6.4{\cdot}10^{23}$	$< (1.8-4.4){\cdot}10^{-5}$
$0\nu\beta\beta J$ $(n=2)$	$2.5{\cdot}10^{23}$	$> 2.9{\cdot}10^{23}$	–
$0\nu\beta\beta J$ $(n=3)$	$1.3{\cdot}10^{23}$	$> 1.2{\cdot}10^{23}$	< 0.017
$0\nu\beta\beta JJ$ $(n=3)$	$1.3{\cdot}10^{23}$	$> 1.2{\cdot}10^{23}$	< 1.2
$0\nu\beta\beta JJ$ $(n=7)$	$5.8{\cdot}10^{22}$	$> 1.0{\cdot}10^{23}$	< 1.0

Lorentz violation

$$(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\bar{\nu}_e^{LV}$$



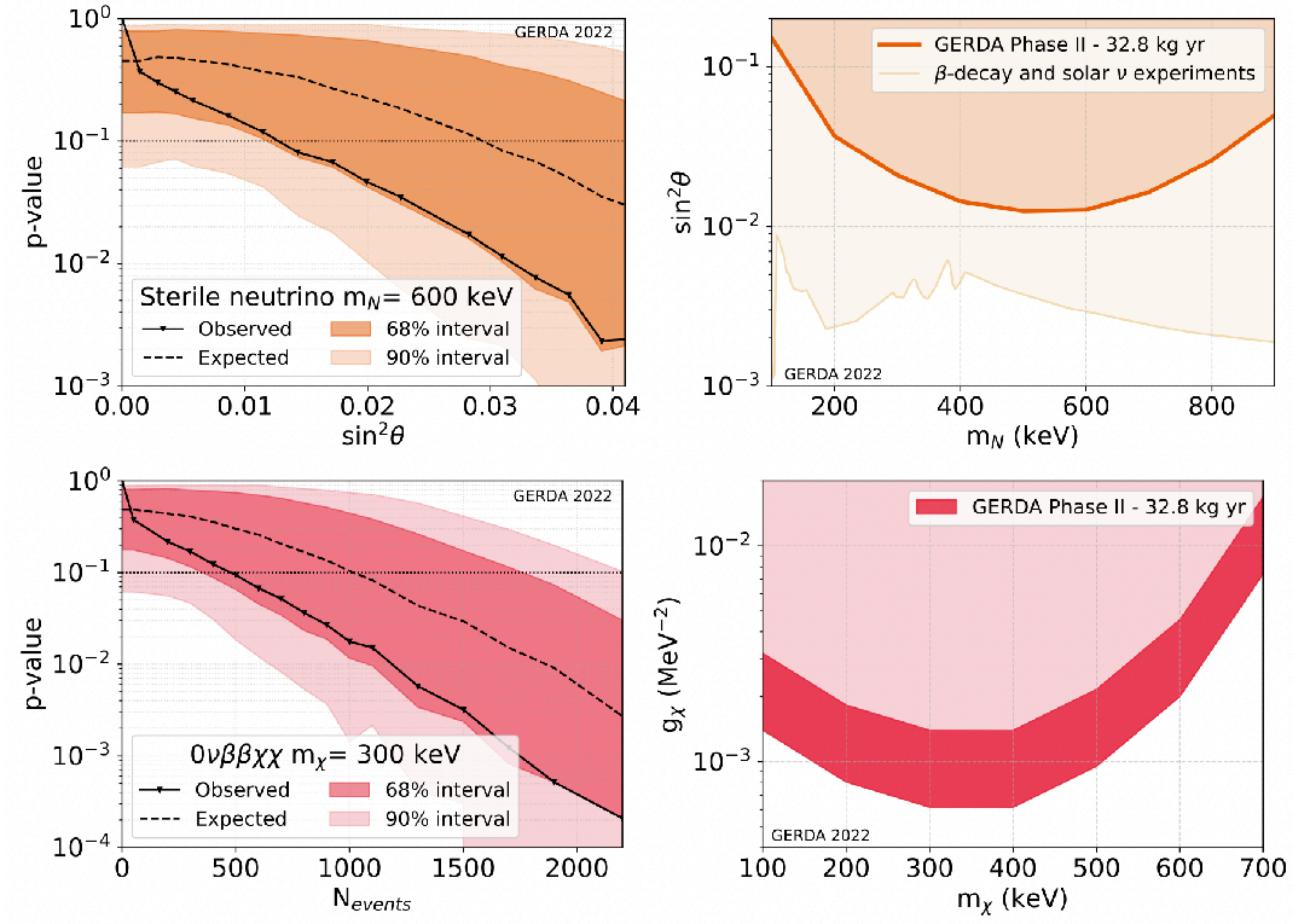
- Lorentz violation in the neutrino sector would affect the energy distribution of electrons through isotropic component $a_{of}^{(3)}$
- First constraints with ^{76}Ge
- Results comparable with other double-beta isotopes

Sensitivity	Observed Limit
$(-3.8 < a_{of}^{(3)} < 4.9)\ 10^{-6}$ GeV	$(-2.7 < a_{of}^{(3)} < 6.2)\ 10^{-6}$ GeV

Phase space ratio to combine SM distribution and LV perturbation from [Phys. Rev. D 103, L031701]

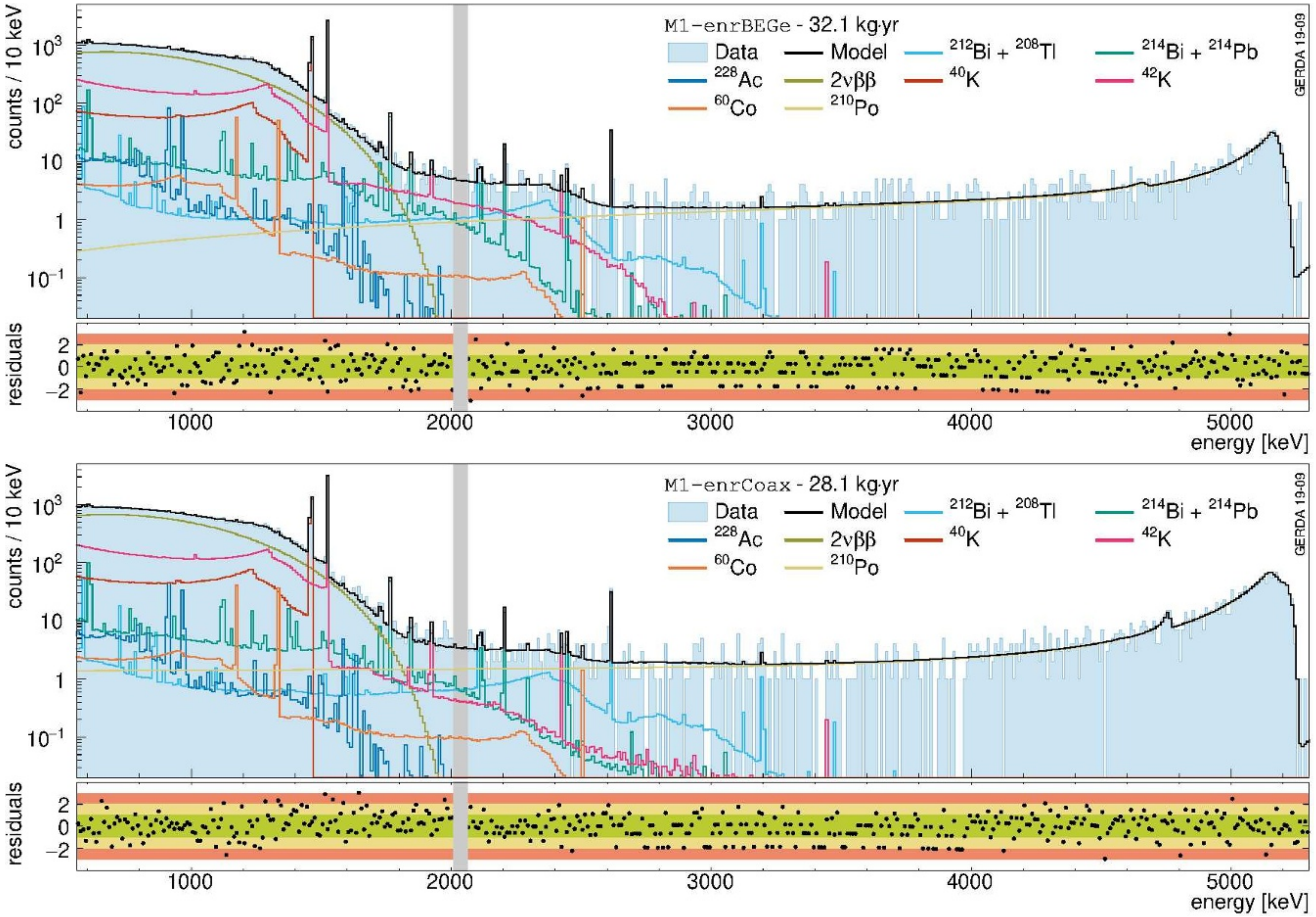
Search for light-exotic fermions

$(A,Z) \rightarrow (A,Z+2) + 2e^- + \bar{\nu}_e + N$ AND $(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\bar{\chi}$

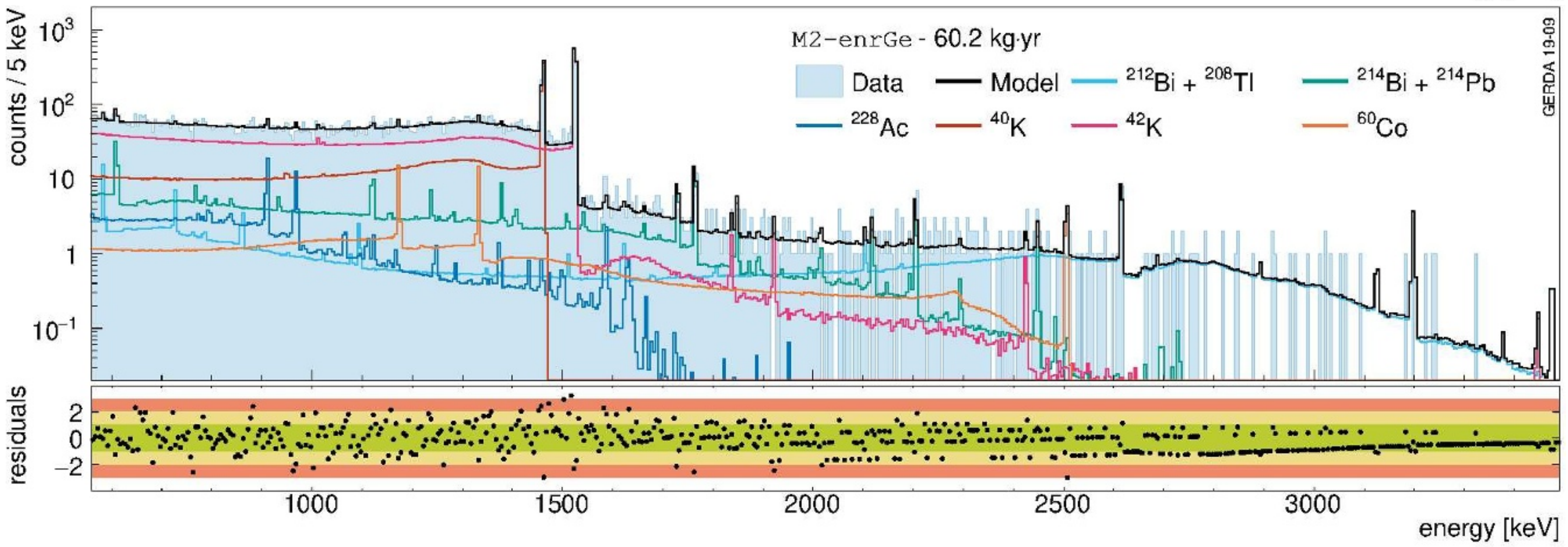


- Massive exotic fermions would shift the endpoint to lower values
- We searched for sterile neutrinos (N) and their Z_2-odd variant
- Limits for sterile neutrinos not competitive with single-beta decay experiments
- Pair production of exotic fermions can only be tested in double-beta decay

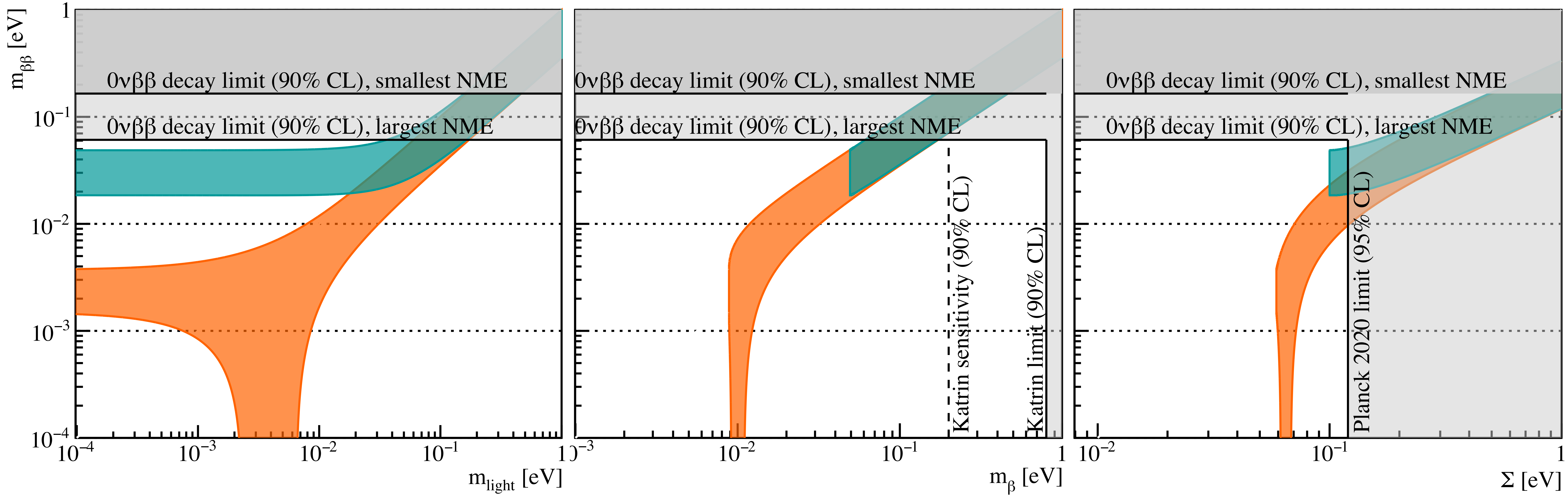
Background Model



[GERDA, *J High Energy Phys*, **2020** (2020), no. 3, 139]



Global picture of the neutrino mass



arXiv:2202.01787

On NMEs and discovery potential