Probing neutrinoless double beta decay with LEGEND

University of Zurich[UZH]

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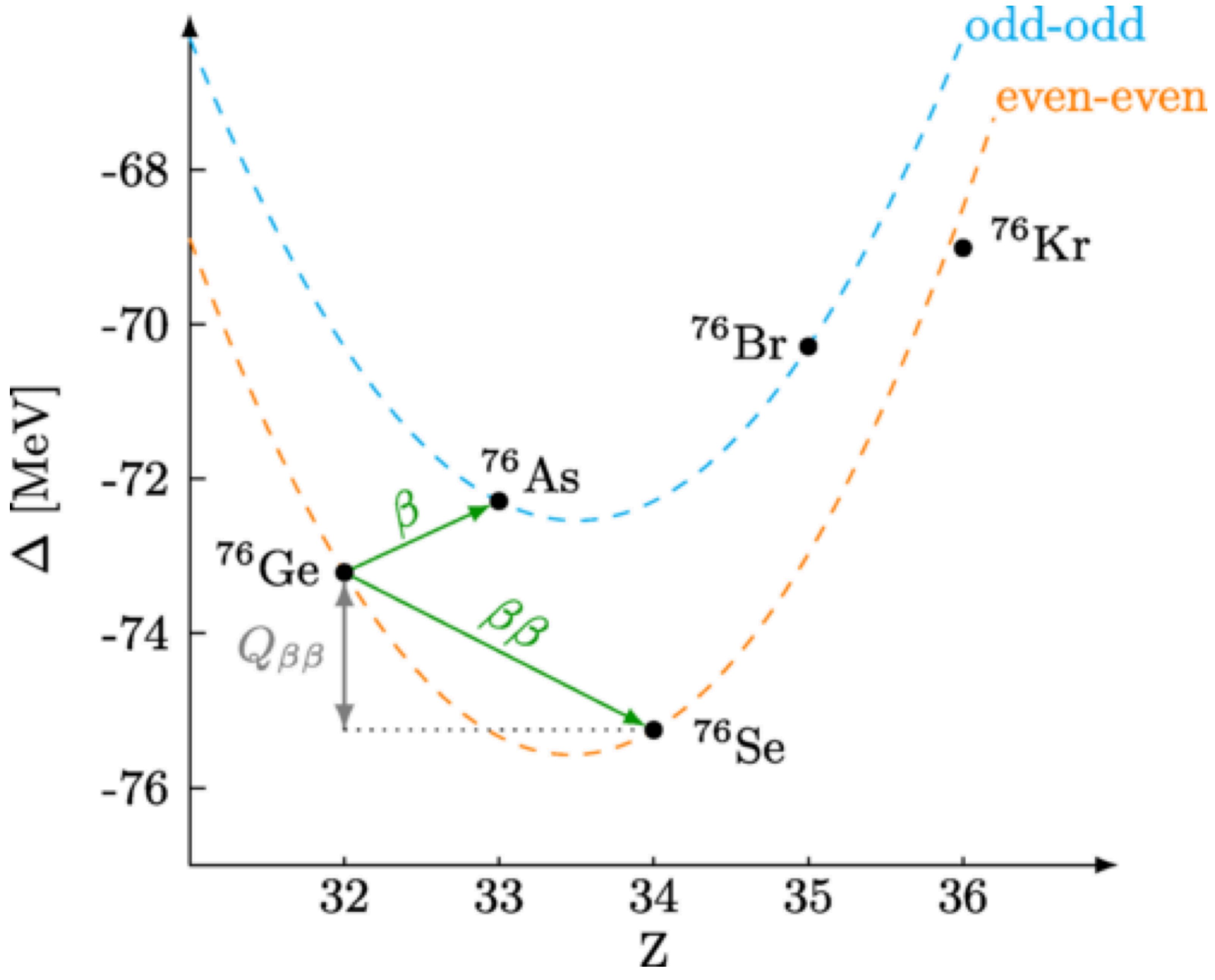
Aravind Remesan Sreekala on behalf of the LEGEND Collaboration
aravind.remesansreekala@physik.uzh.ch

Neutrinoless Double Beta ($0\nu\beta\beta$) Decay



- In some even-even isotopes, β-decay is energetically unfavourable —> they undergo two neutrino double beta ($2\nu\beta\beta$) decay.

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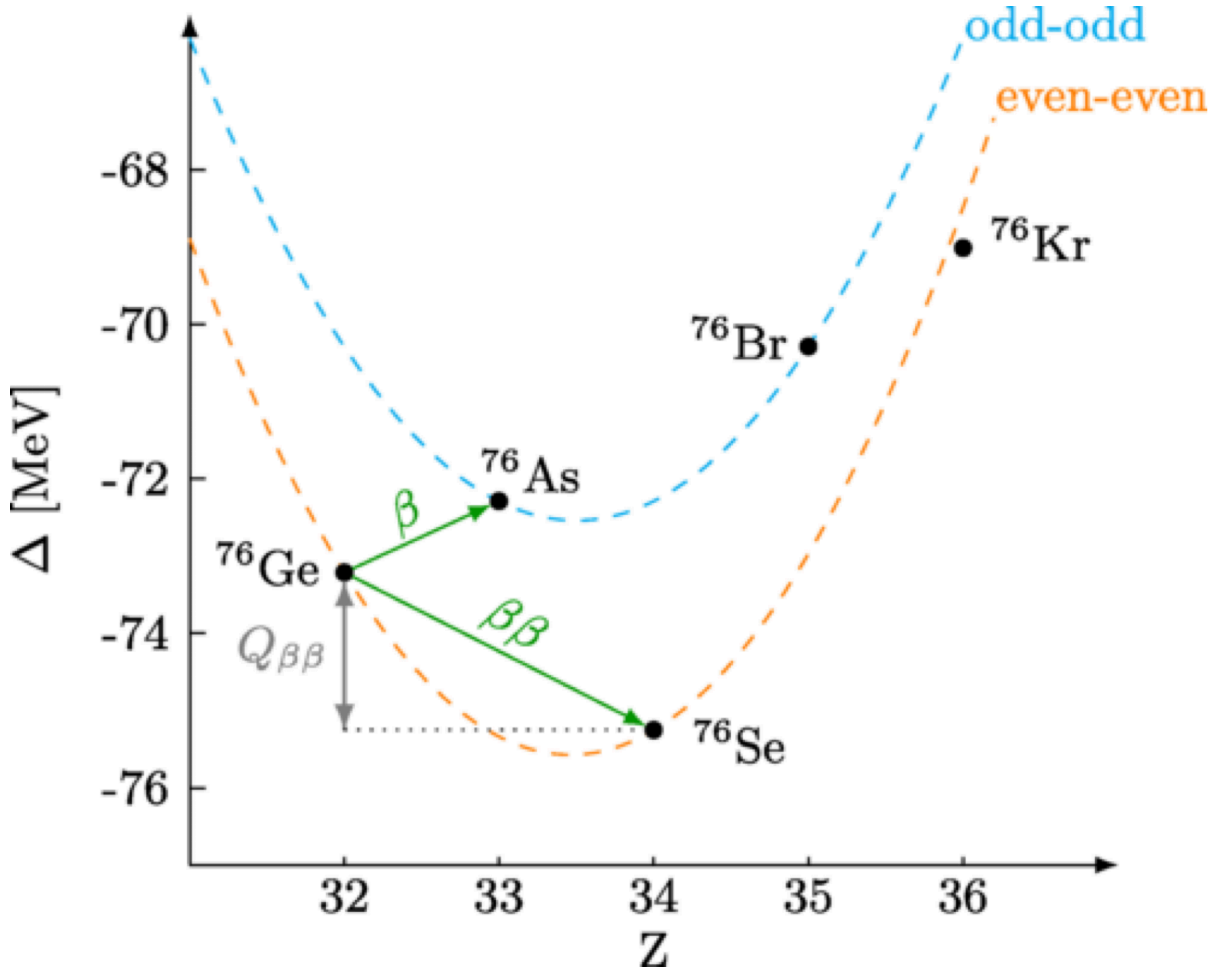
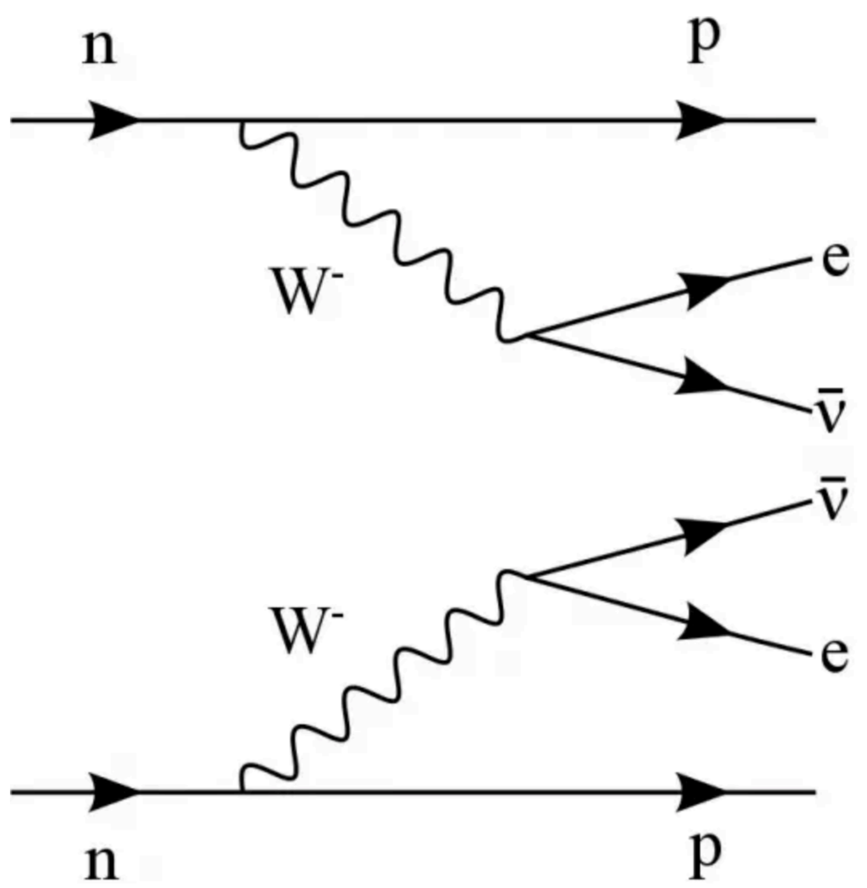


Double beta decay



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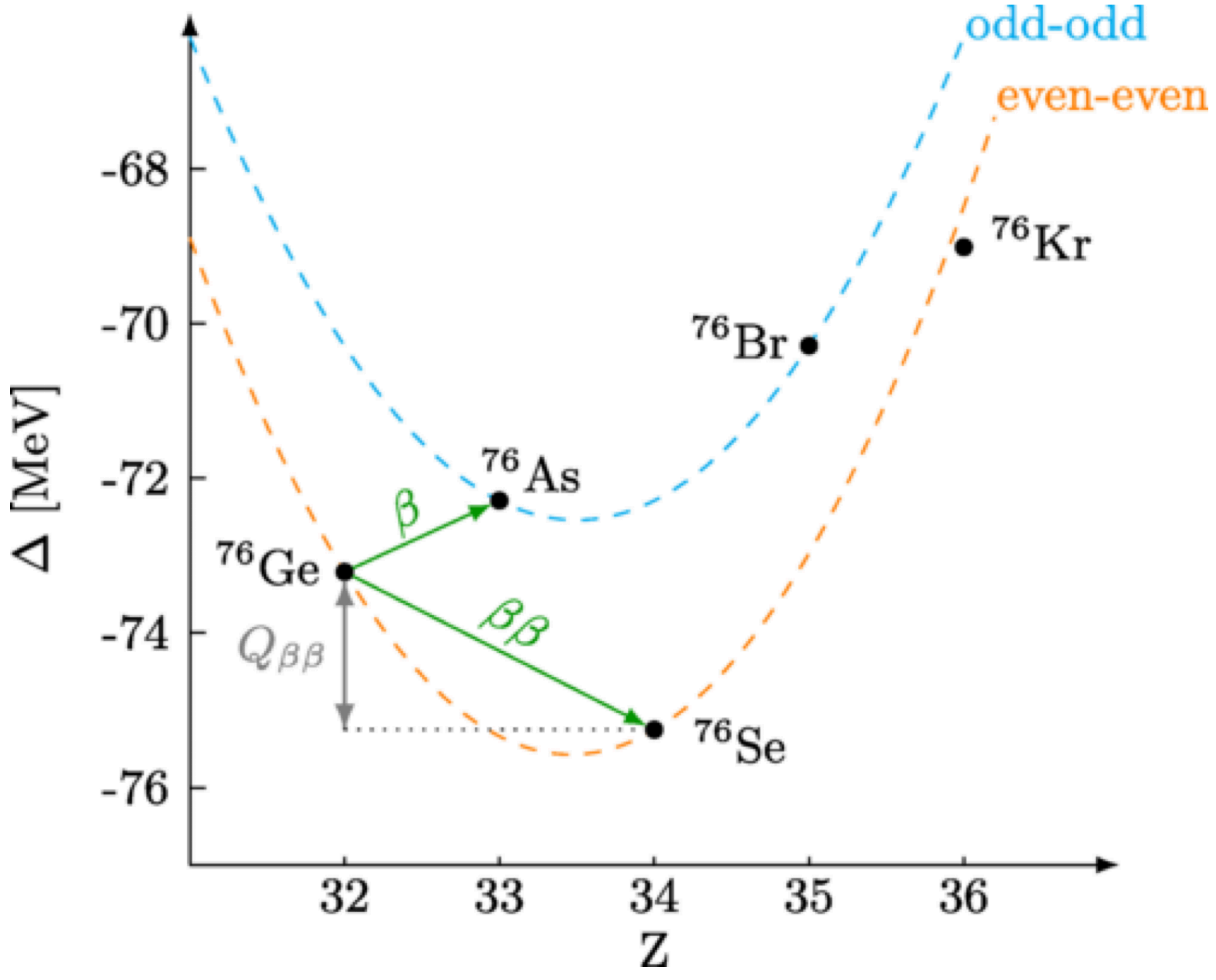

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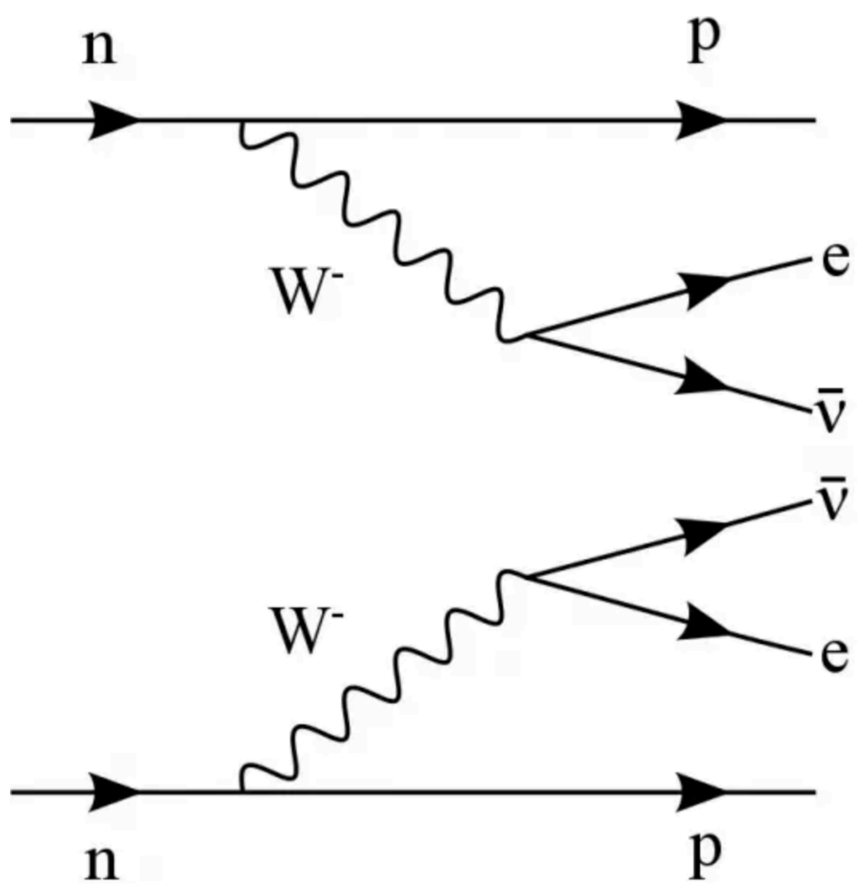

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- Lepton number conserved.
- Standard Model allowed process.
- $T^{2\nu}_{1/2} = 1.8^{+0.14}_{-0.10} \cdot 10^{21}$ yr (Age of the Universe is $< 1.4 \cdot 10^{10}$ yr!) [Phys. G: Nucl. Part. Phys. 40 035110]

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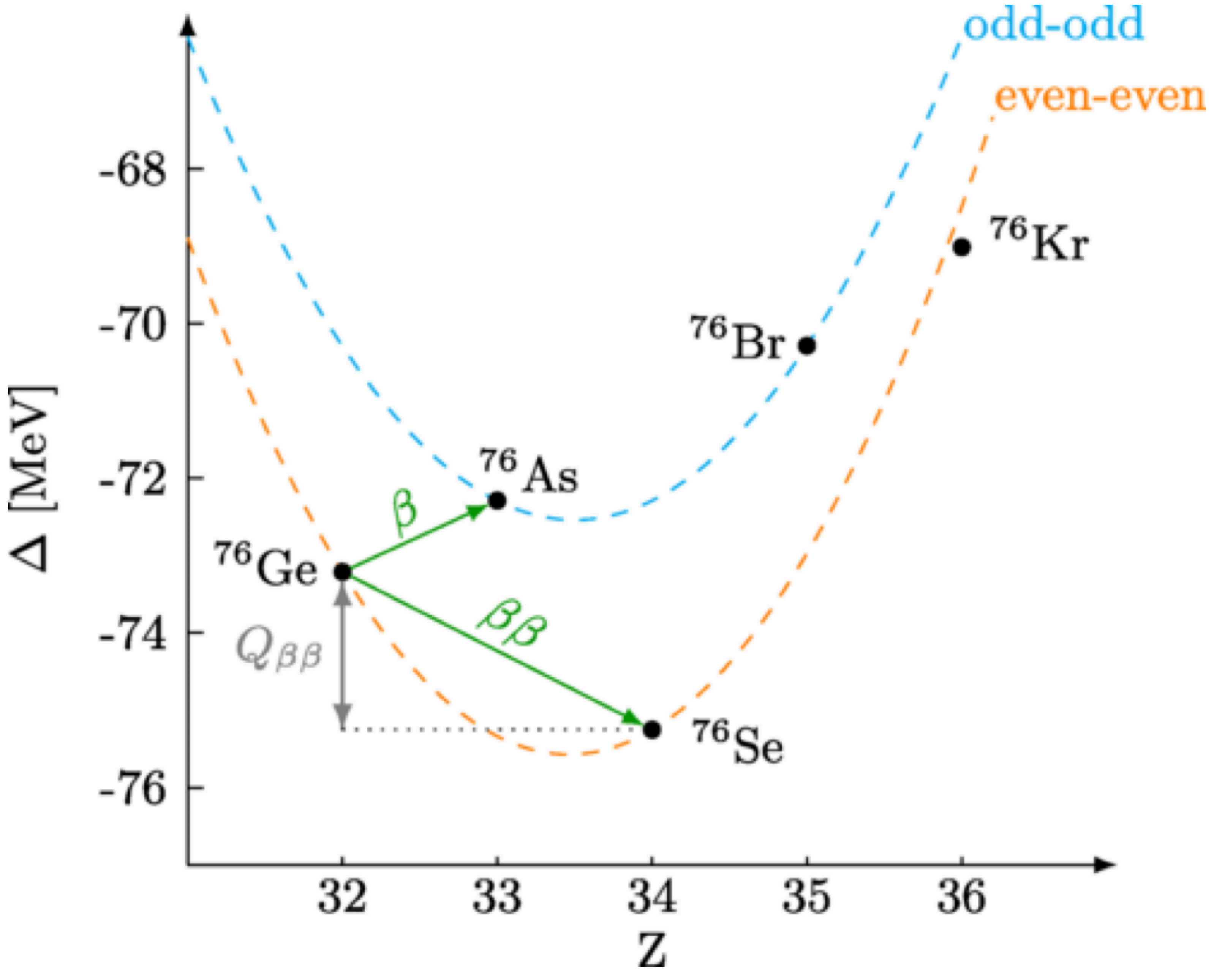

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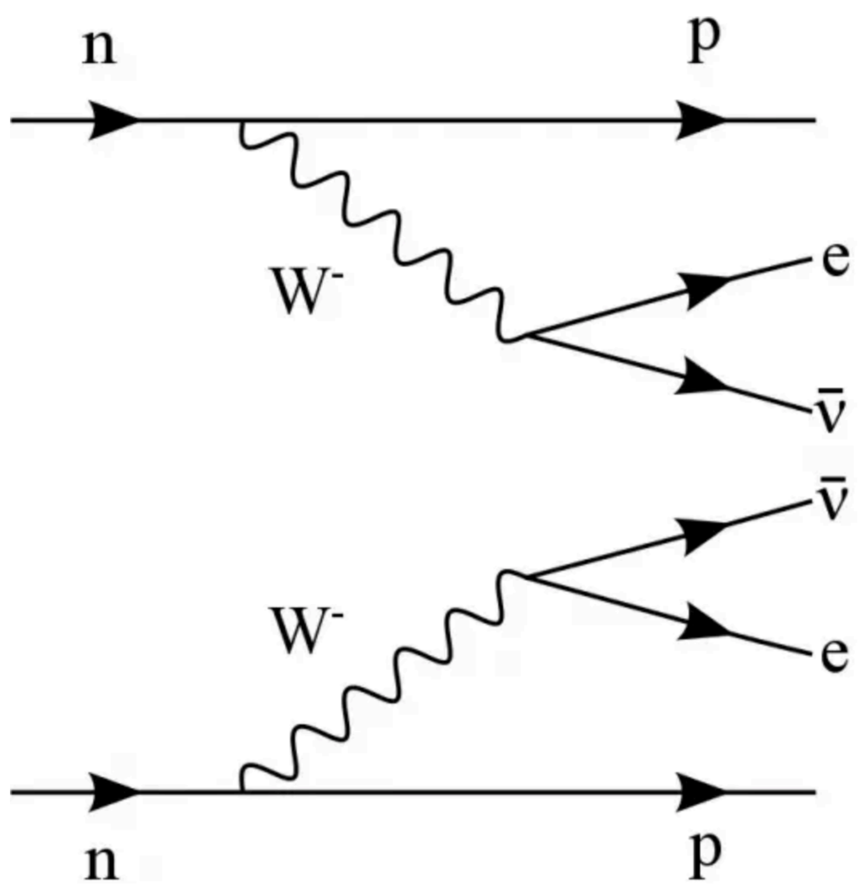

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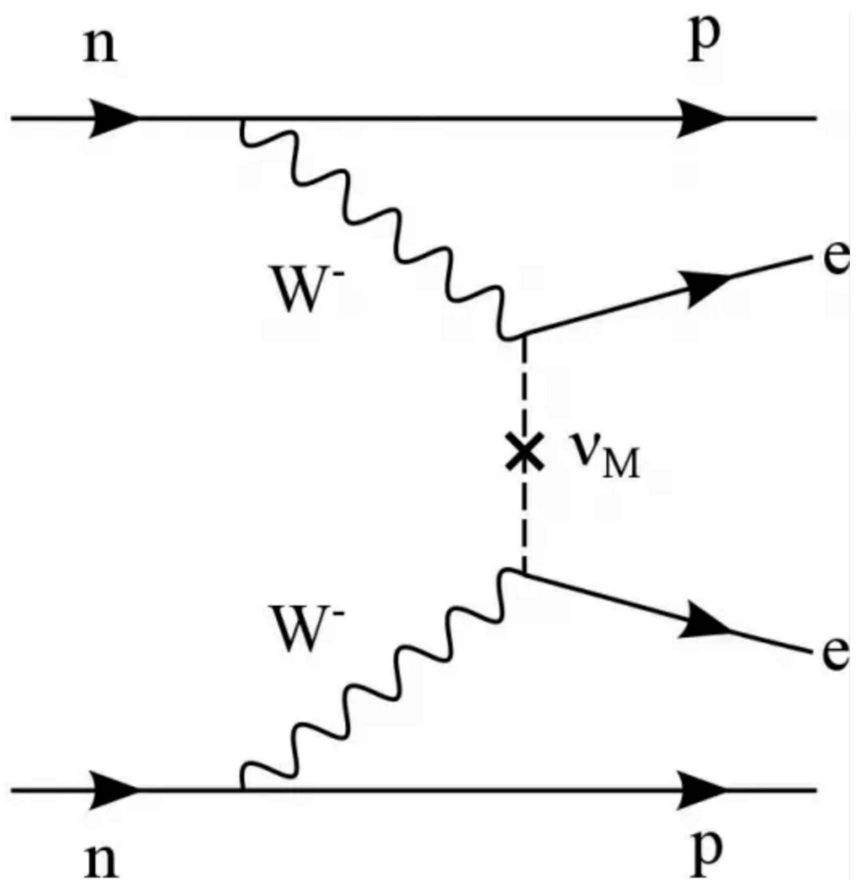
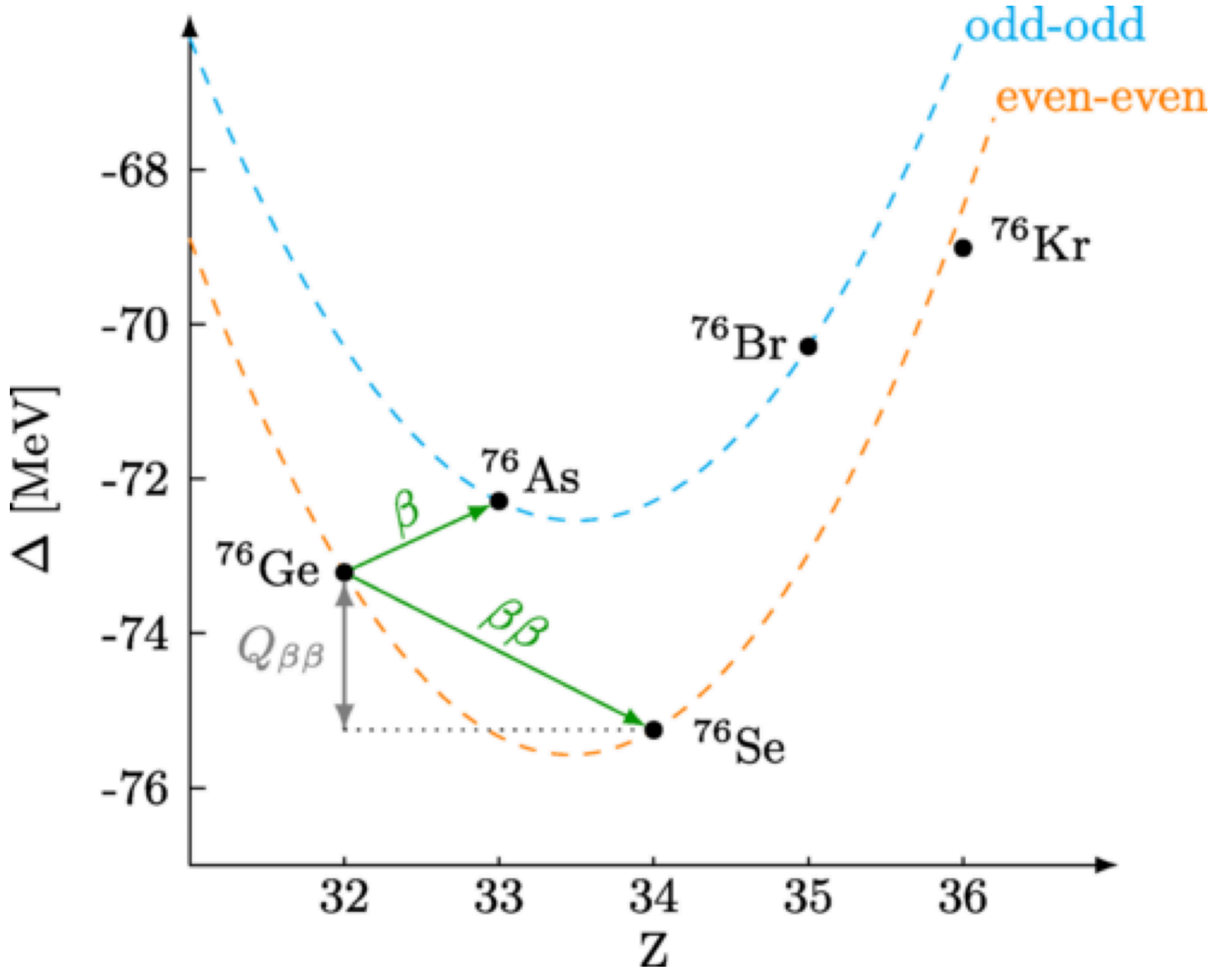
Neutrinoless double beta decay



^{76}Ge$\rightarrow$^{76}Se $+2e^-\,(\Delta L = 2)$

Neutrinoless Double Beta ($0\nu\beta\beta$) Decay



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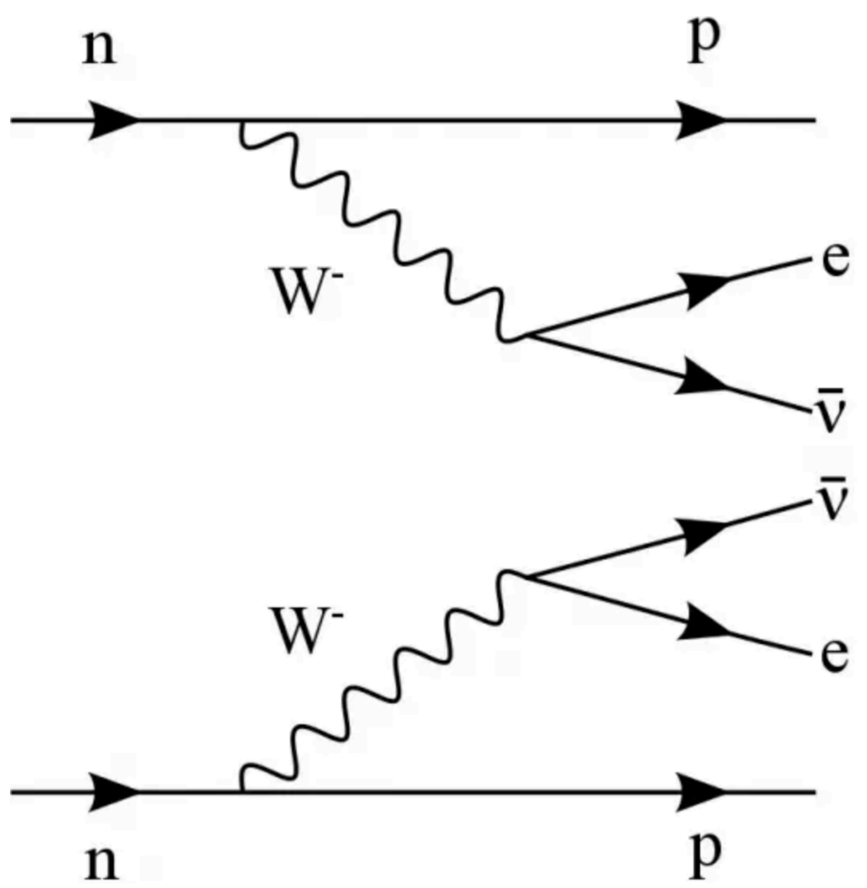

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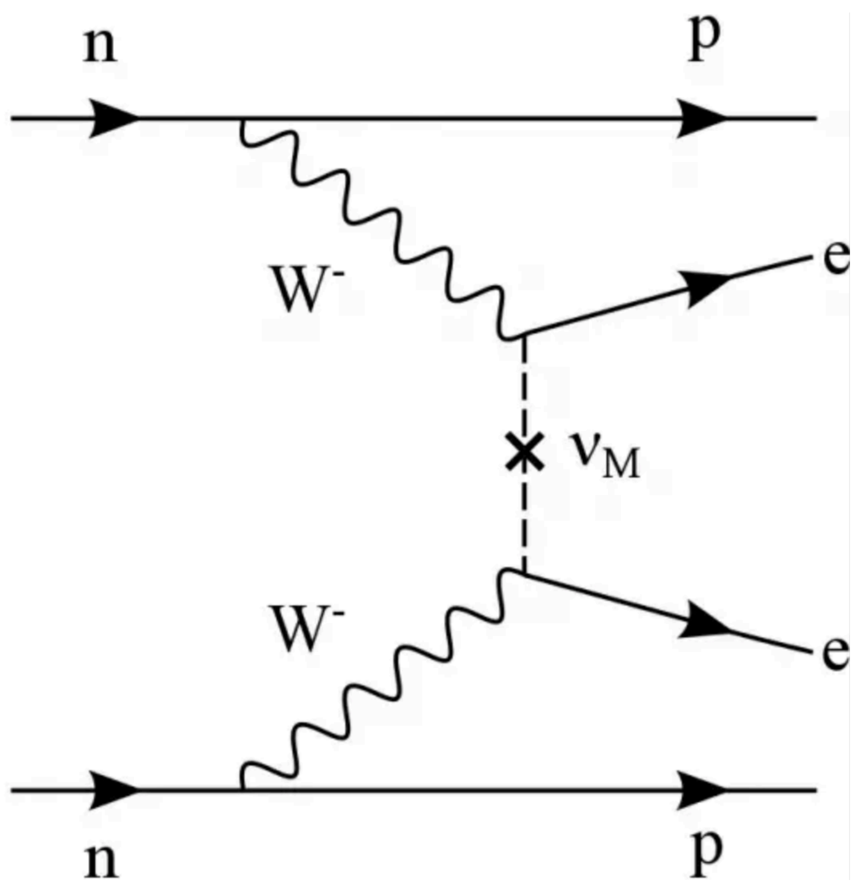
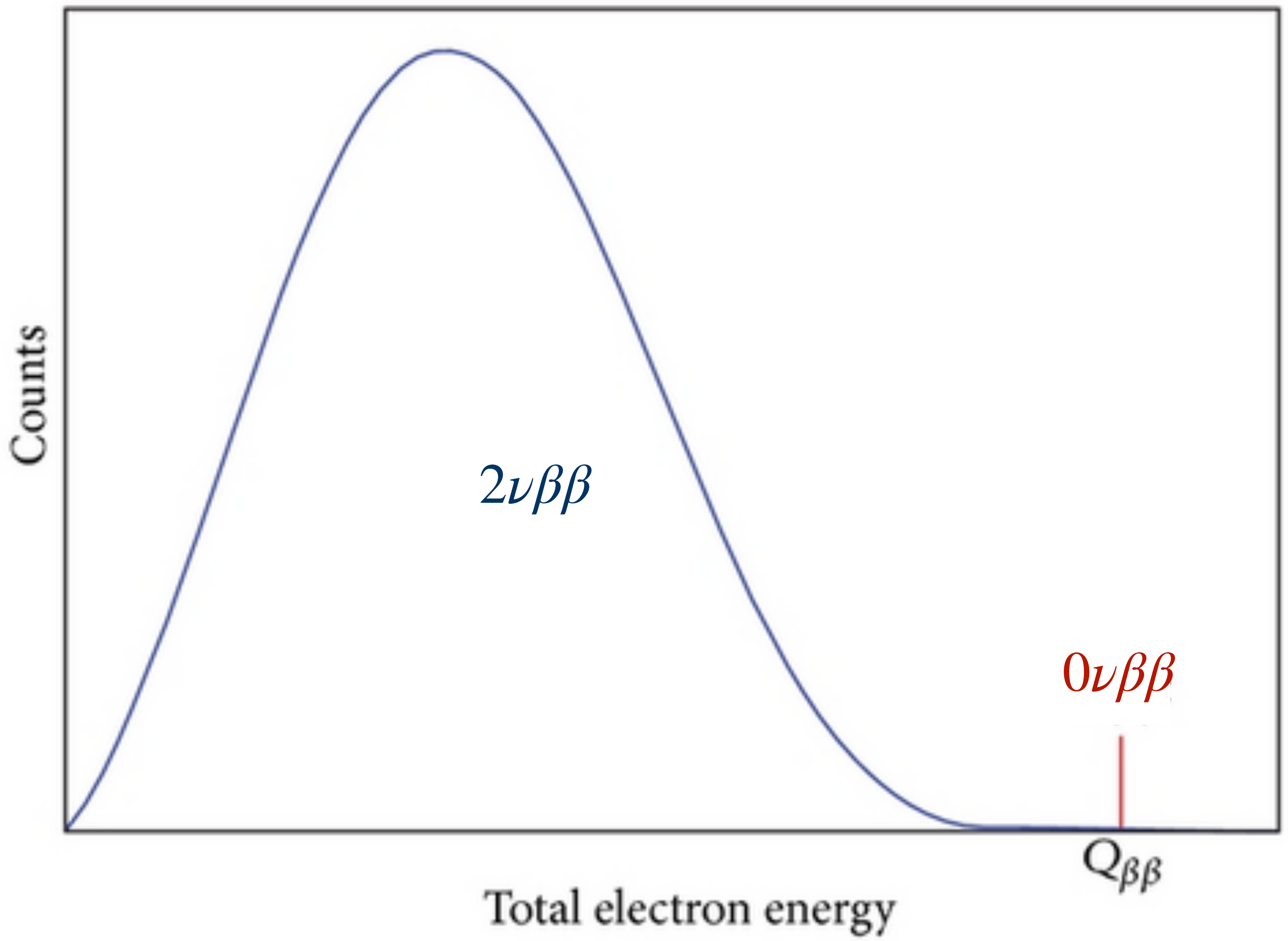


^{76}Ge$\rightarrow$^{76}Se$+2e^- \, (\Delta L = 2)$

- Lepton number violation (if observed).
- Hypothetical process.
- $T^{0\nu}_{1/2} > 1.8 \cdot 10^{26}$ yr [Phys. Rev. Lett. 125, 252502].
- Evidence of Majorana nature of neutrinos.
- Hint on matter-antimatter asymmetry and insight into neutrino mass ordering.

How is the signal measured?

- The total energy of the two emitted electrons is measured.
- For $2\nu\beta\beta$ decay, the energy distribution of the two electrons forms **a continuous spectrum.**
- For $0\nu\beta\beta$ decay, all the energy is carried by the electrons —> **Monoenergetic peak at** $Q_{\beta\beta}$.
- $Q_{\beta\beta}$ = 2039.061(7) keV for ^{76}Ge.



Neutrinoless Double Beta ($0\nu\beta\beta$) Decay - The Search

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$$T^{0\nu}_{1/2} \propto \epsilon \cdot \sqrt{\frac{(M_{^{76}Ge} \cdot t)}{BI \cdot \Delta E}}$$

Sensitivity ↑

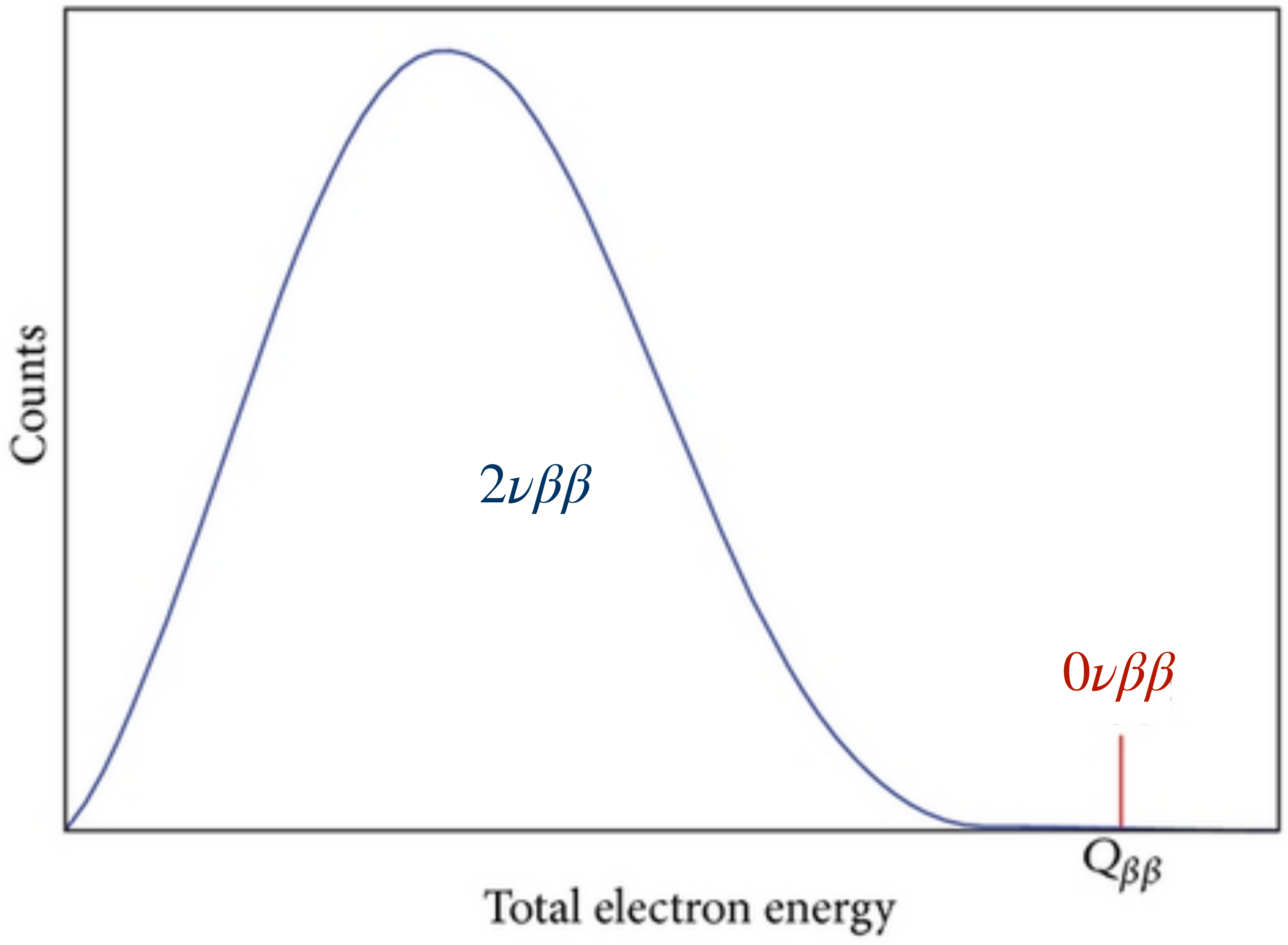
Detection efficiency ↑

Exposure ↑

Background Index ↓

Energy Resolution ↓

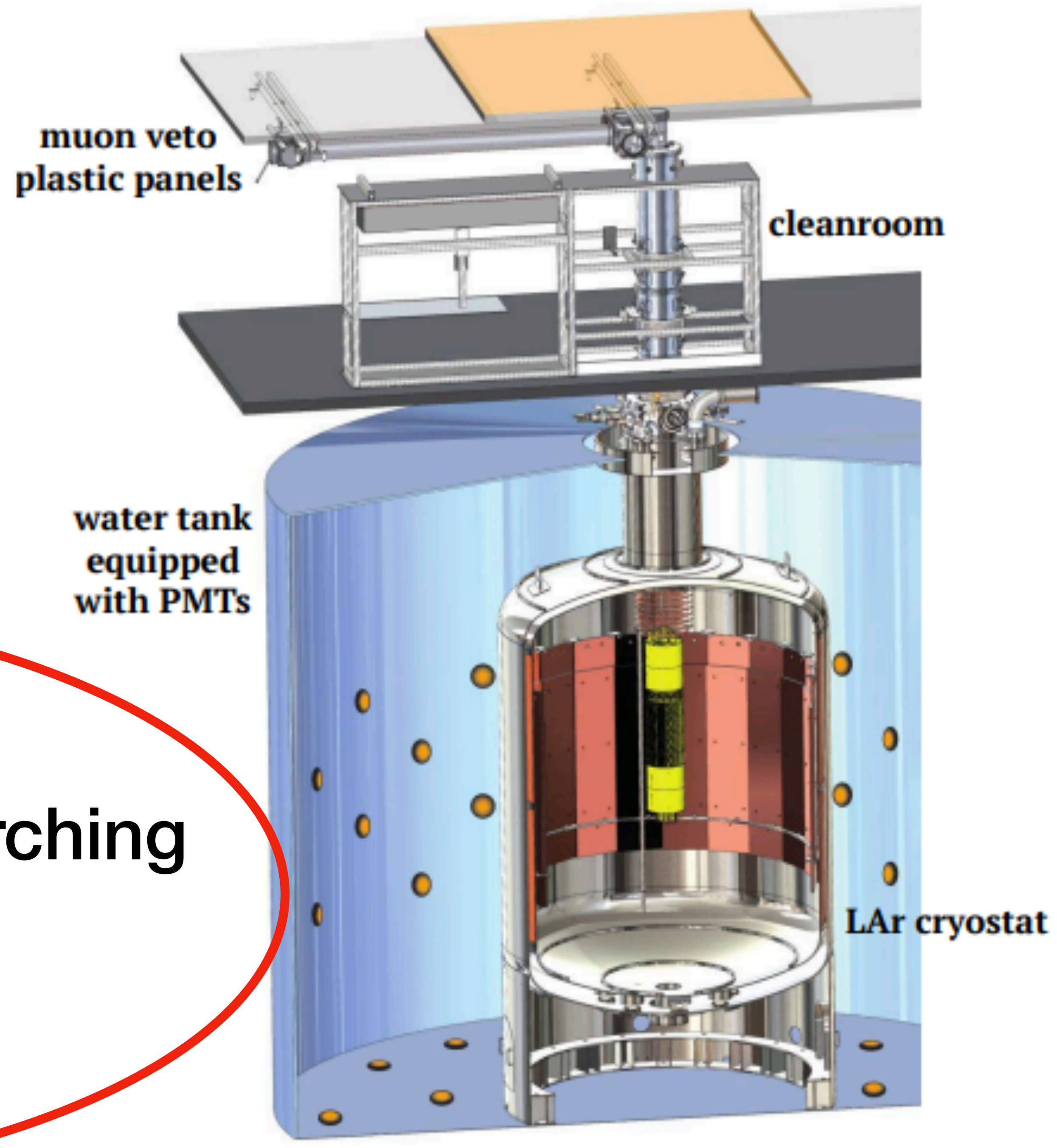
In GERDA/LEGEND experiments ➔ **Background Estimation window: 1930 - 2190 keV**

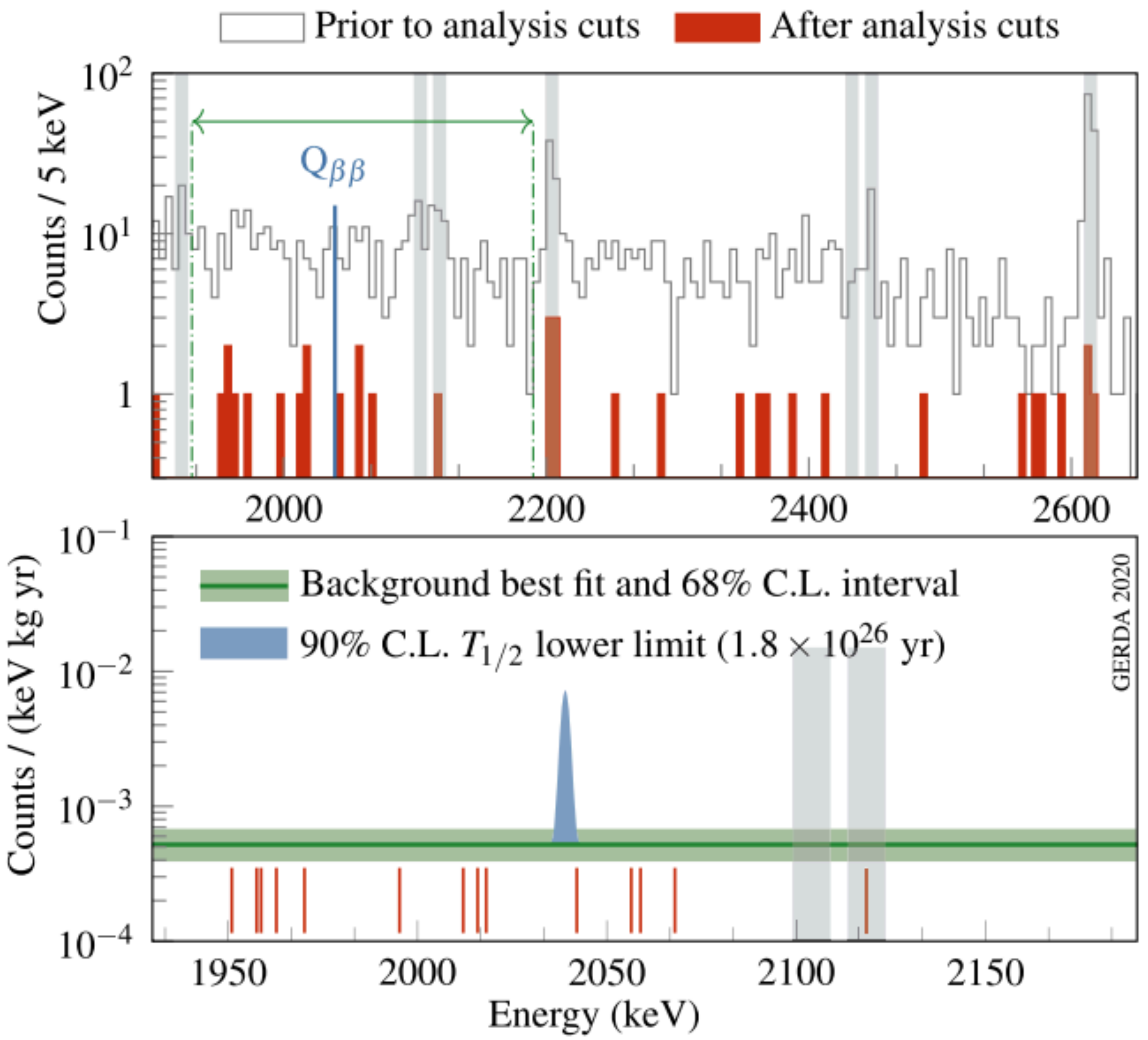


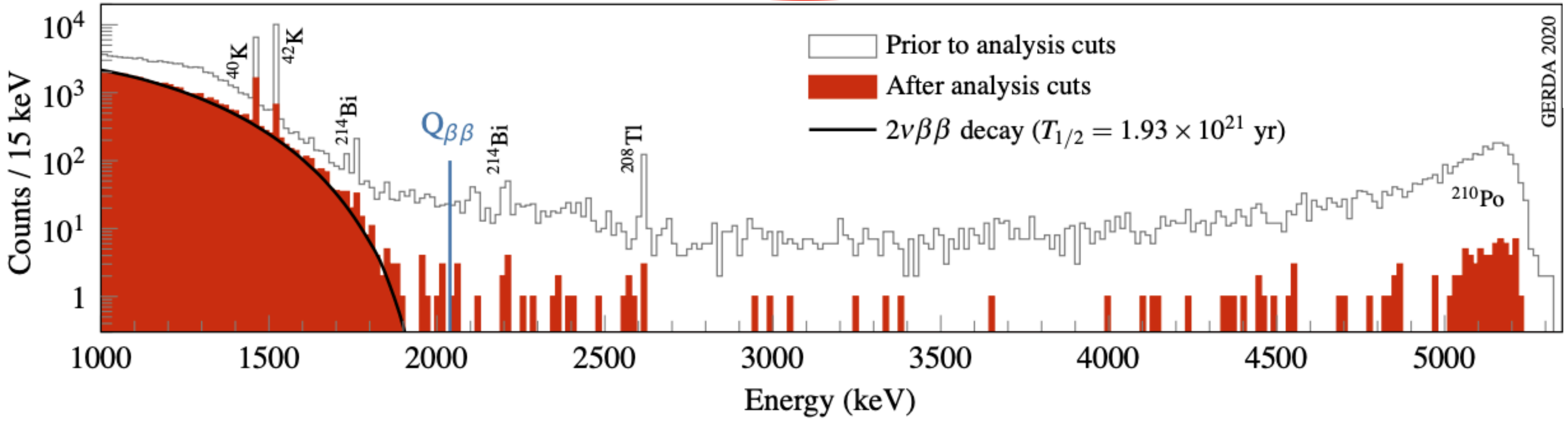
Prior search for $0\nu\beta\beta$ decay - GERmanium Detector Array (GERDA) results

- ^{76}Ge-based experiment to search for $0\nu\beta\beta$ decay.
- 100 kg yr of exposure.
- No $0\nu\beta\beta$ decay signal was observed.
- BI $= 5.2^{+1.6}_{-1.3} \cdot 10^{-4}$ counts/(keV kg yr).
- $T^{0\nu}_{1/2} > 1.8 \cdot 10^{26}$ yr.

Lowest BI achieved in ^{76}Ge-based experiments searching for $0\nu\beta\beta$ decay





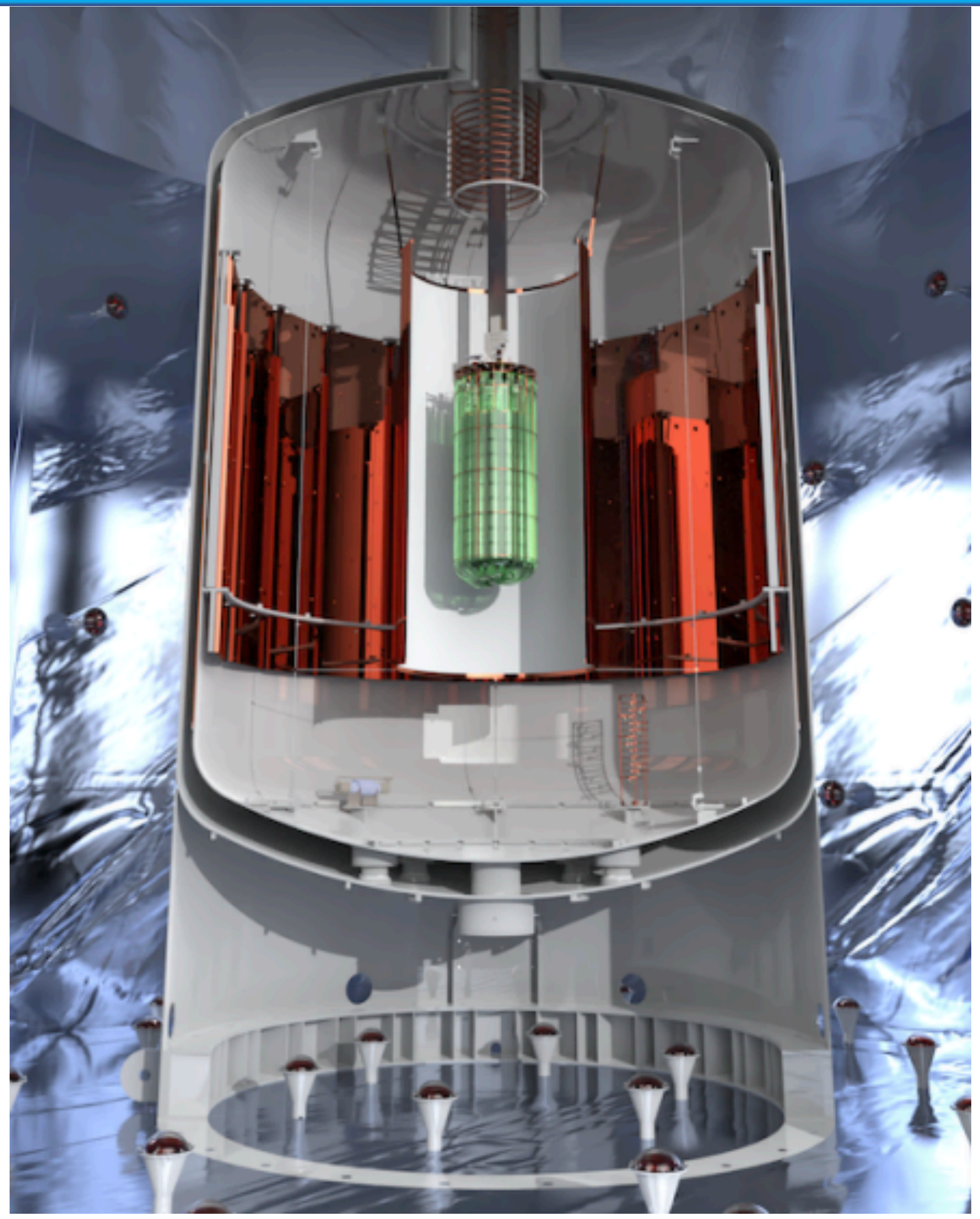


PhysRevLett.125.252502

LEGEND-200

- Aims to operate 200 kg of enriched ^{76}Ge; 5 years of data taking (1 tonne-year exposure).
- BI goal of $2 \cdot 10^{-4}$ counts/(keV kg yr); half-life sensitivity goal of $T^{0\nu}_{1/2} > 10^{27}$ yr.
- Data-taking since March 2023 with 142 kg of ^{76}Ge.

@LNGS



Large Enriched Germanium Experiment for Neutrinoless double beta Decay

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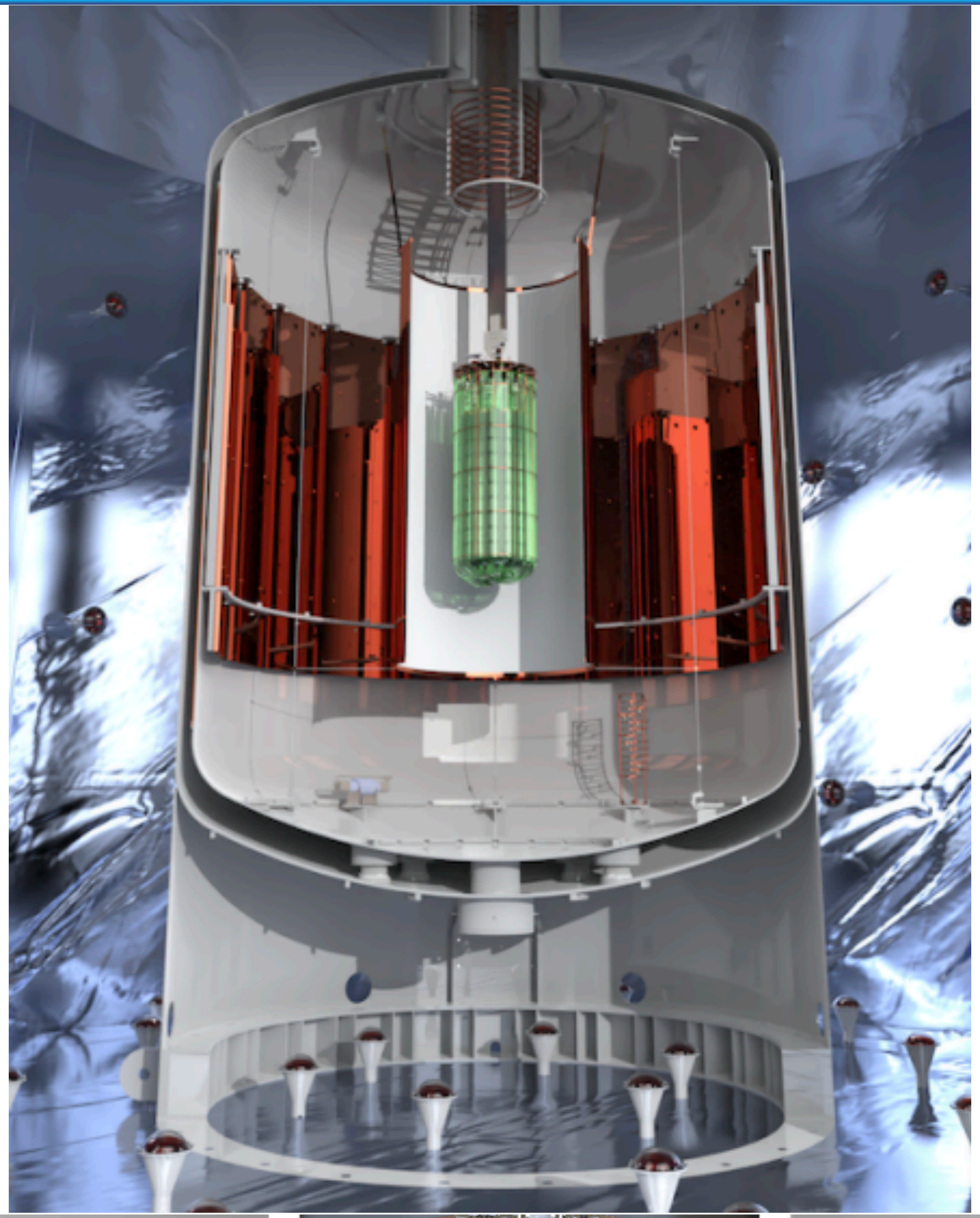
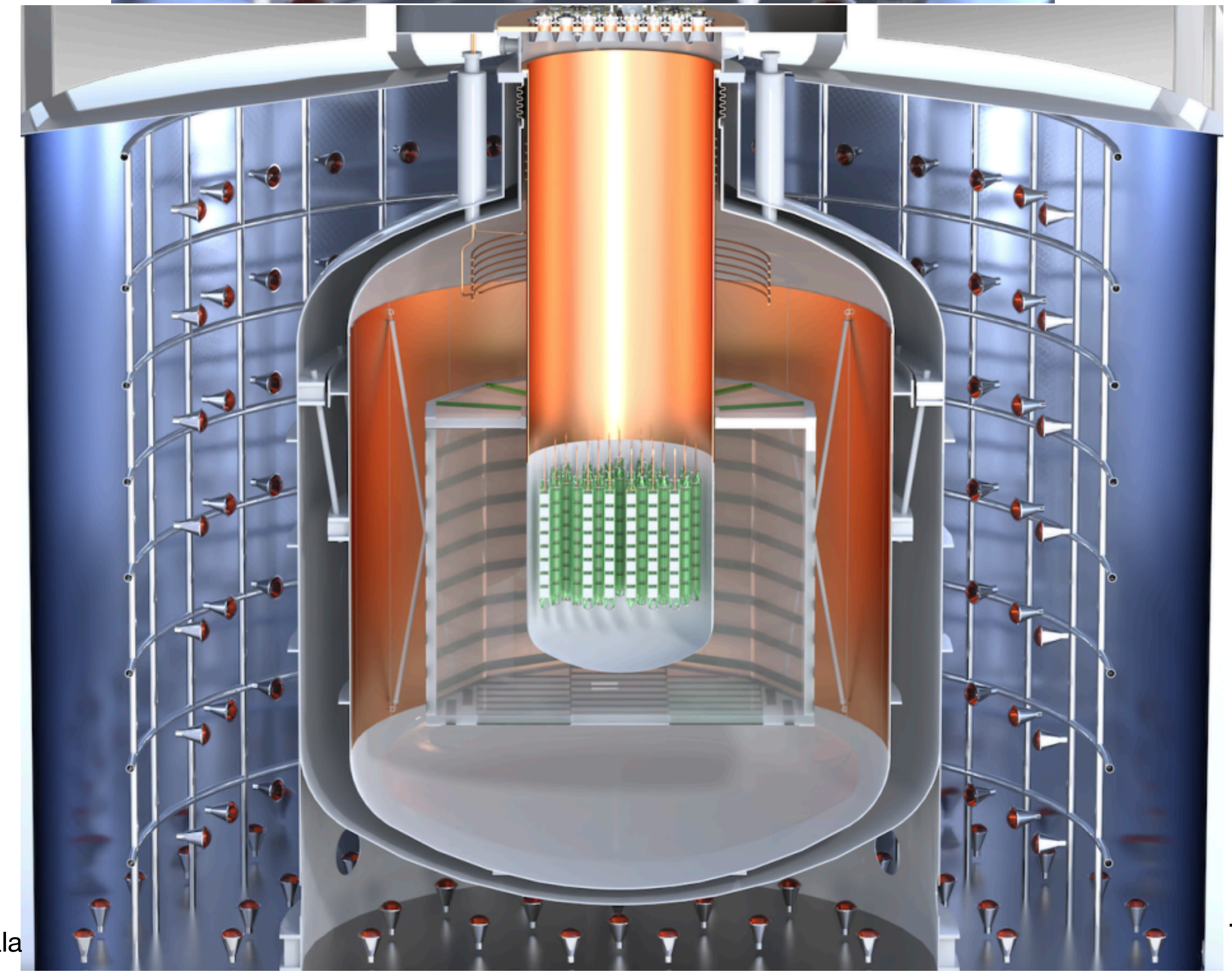


@LNGS

LEGEND-1000

- Aims to operate 1000 kg of enriched ^{76}Ge; 10 years of data taking (10 tonne-year exposure).
- BI goal of $1 \cdot 10^{-5}$ counts/(keV kg yr); half-life sensitivity goal of $T^{0\nu}_{1/2} > 10^{28}$ yr.
- Under construction; data-taking is planned to start by 2030.



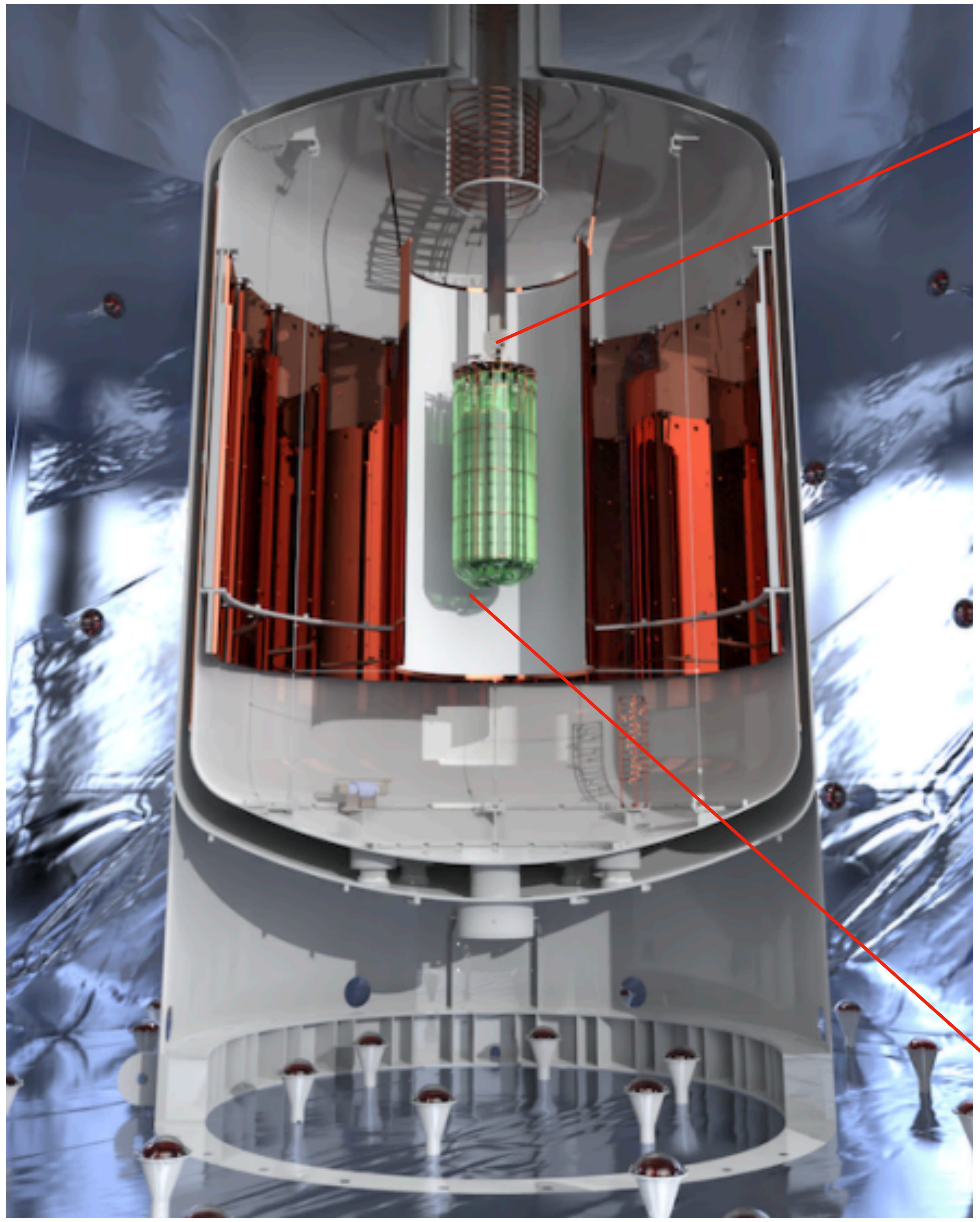
LEGEND-200

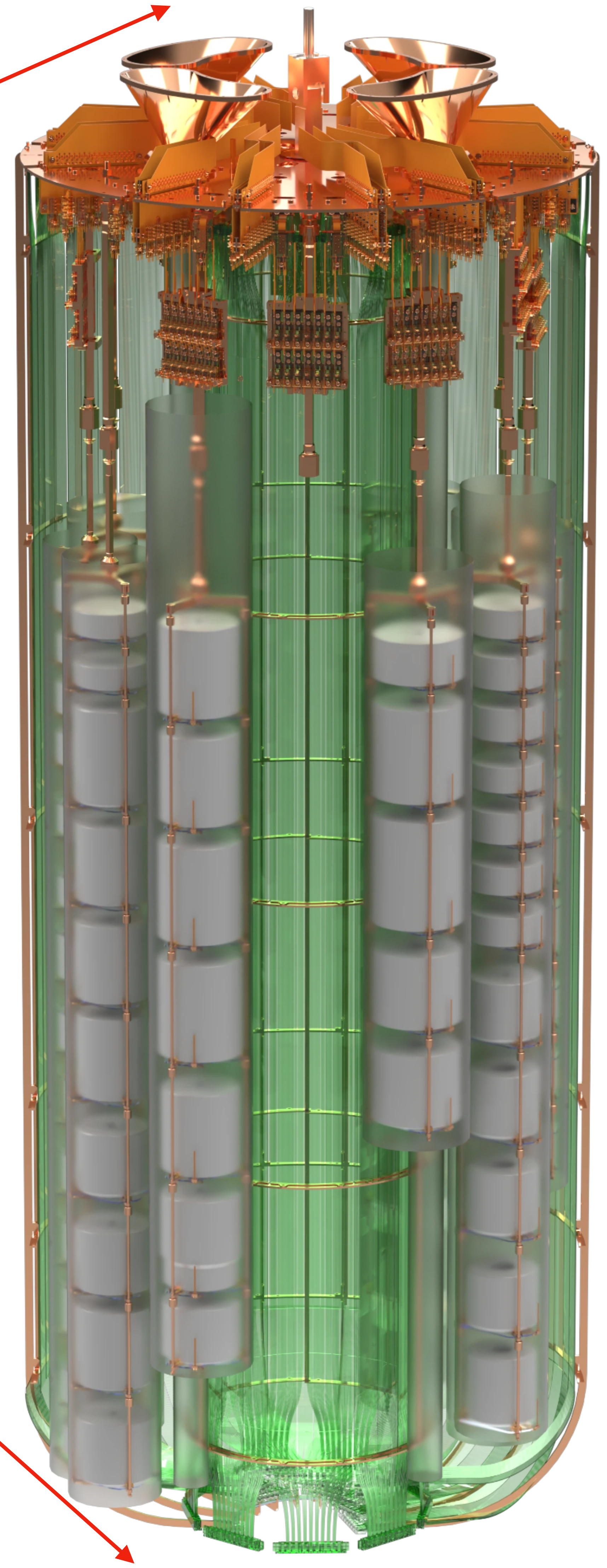
- **Detector array**: 101 High-purity Ge (HPGe) detectors on 10 strings, immersed in 64 m^3 of LAr.

- **Liquid Argon (LAr) cryostat:**
  - Stores LAr.
  - Coolant for the HPGe and passive shield.
  - Active veto by detecting LAr scintillation light to reject background.

  Wavelength shifting reflectors and fibres: Surrounds the detector array; converts VUV scintillation light to visible, which is detected by SiPMs.

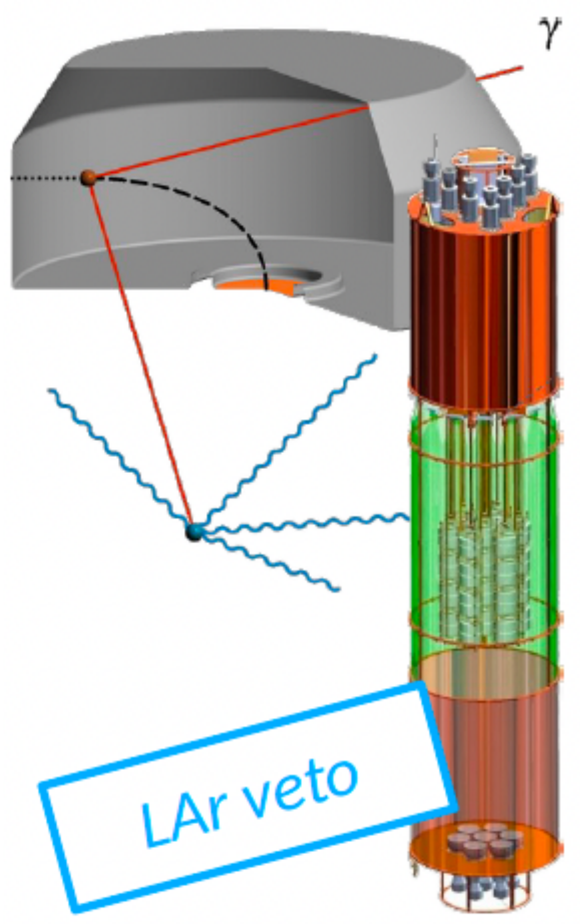
- **Water tank**: Stores 590 m^3 water; PMTs in the tank detect Cherenkov light from cosmic muons.





LEGEND-200: Background Rejection Methods

1. Liquid Argon Anti-Coincidence



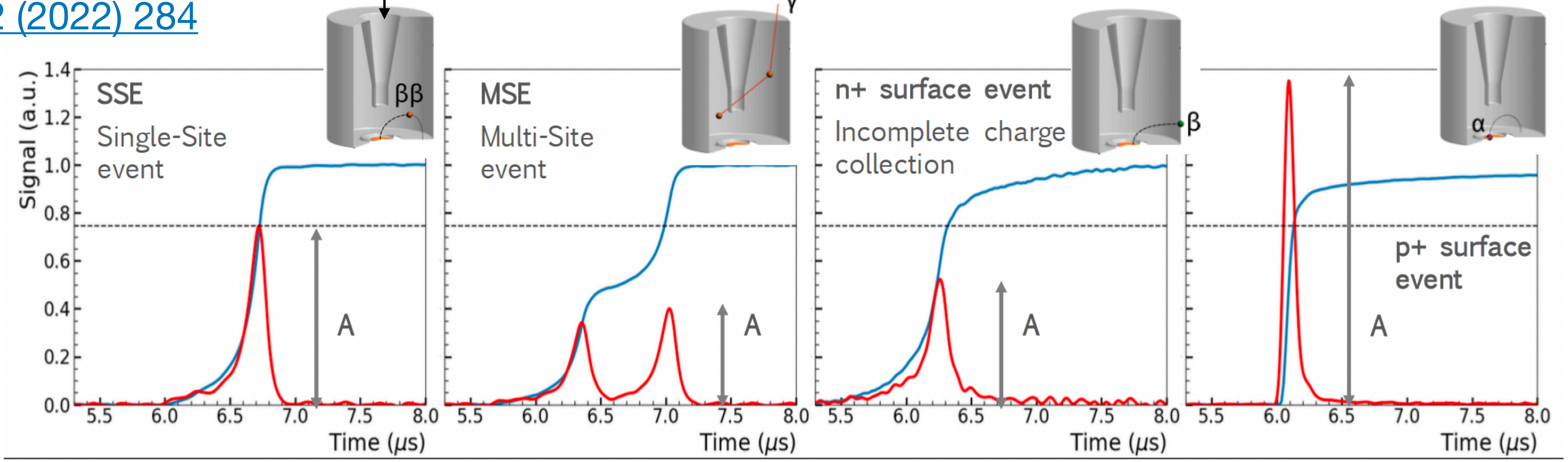
2. Detector Anti-Coincidence

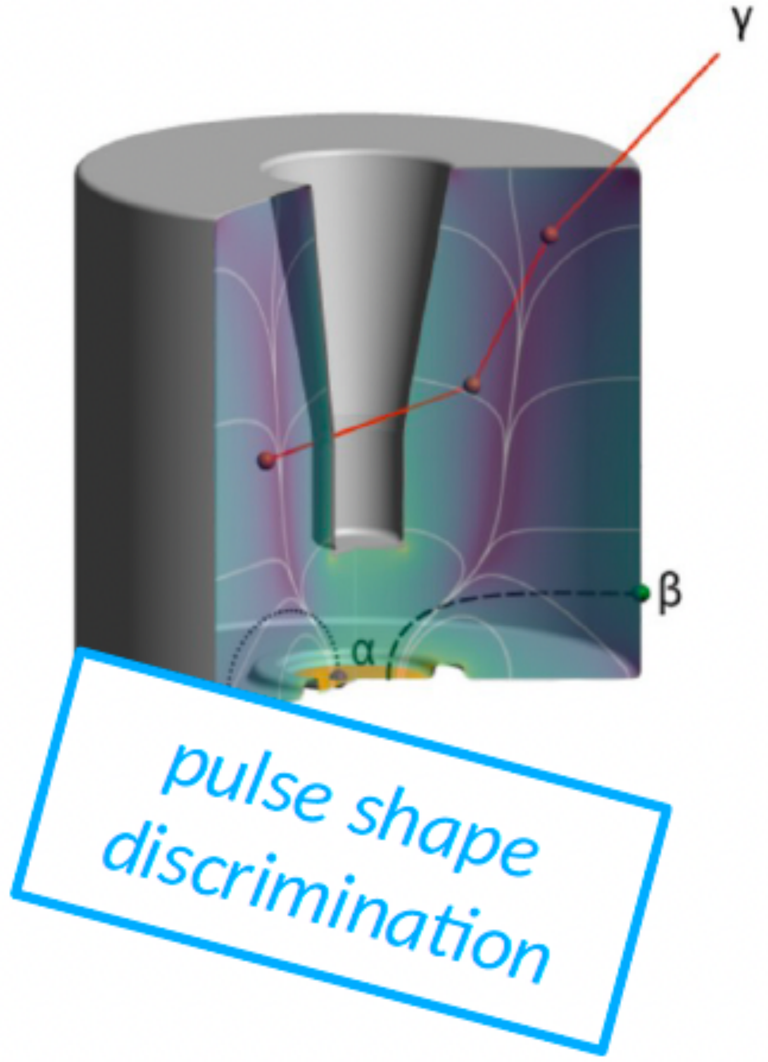
3. Muon Veto

4. Pulse Shape Discrimination

$\beta\beta$-decay signal: single-site event energy deposition in a 1 mm^3 volume.

[Eur. Phys. J. C 82 (2022) 284]

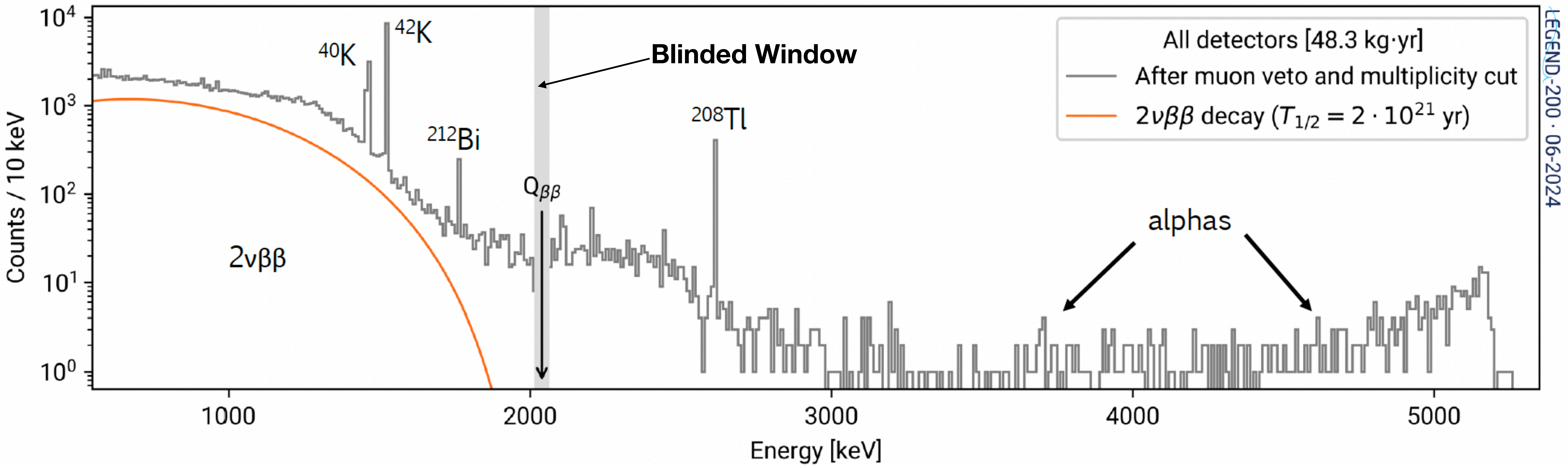




Dataset after Muon veto and Detector Anti-Coincidence Cuts

- Physics data taken from March 2023 - February 2024; 48.3 kg yr exposure.
- Blinding was applied to a 50 keV window around $Q_{\beta\beta}$.
- >95% of physics events survive after the cuts.

LEGEND talk at Nu24, Milan



Dataset after LAr Anti-Coincidence

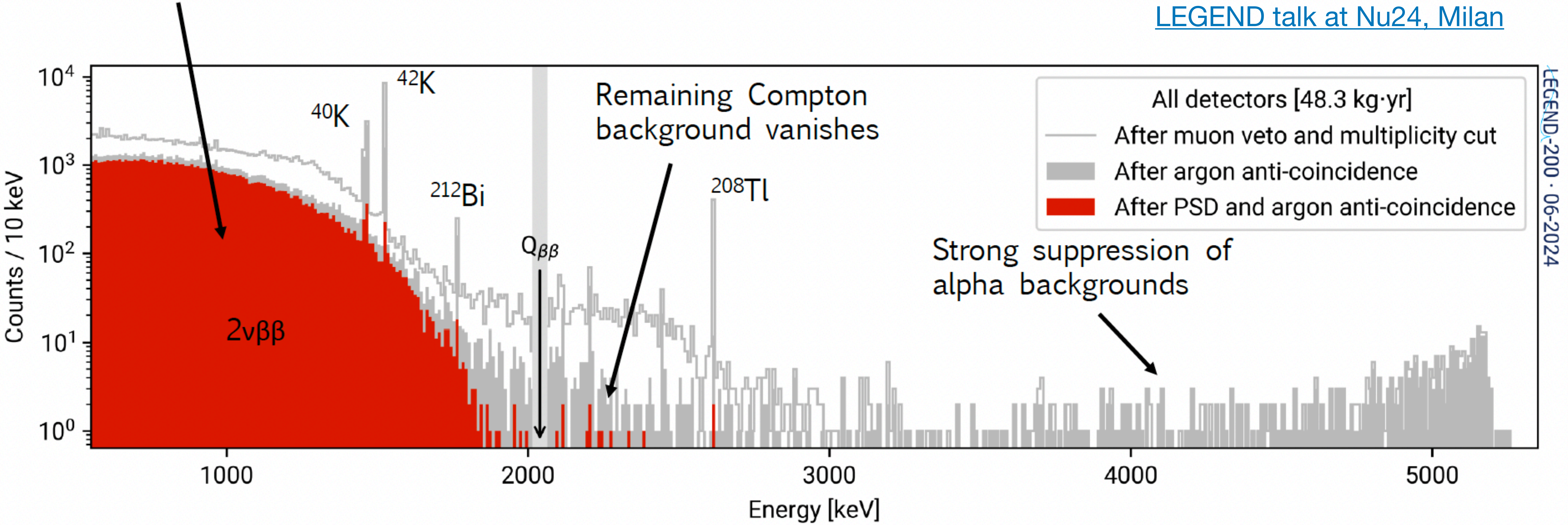
- Multi-site Compton events are effectively tagged.
- High survival fraction of alphas.

LEGEND talk at Nu24, Milan

Dataset after Pulse Shape Discrimination

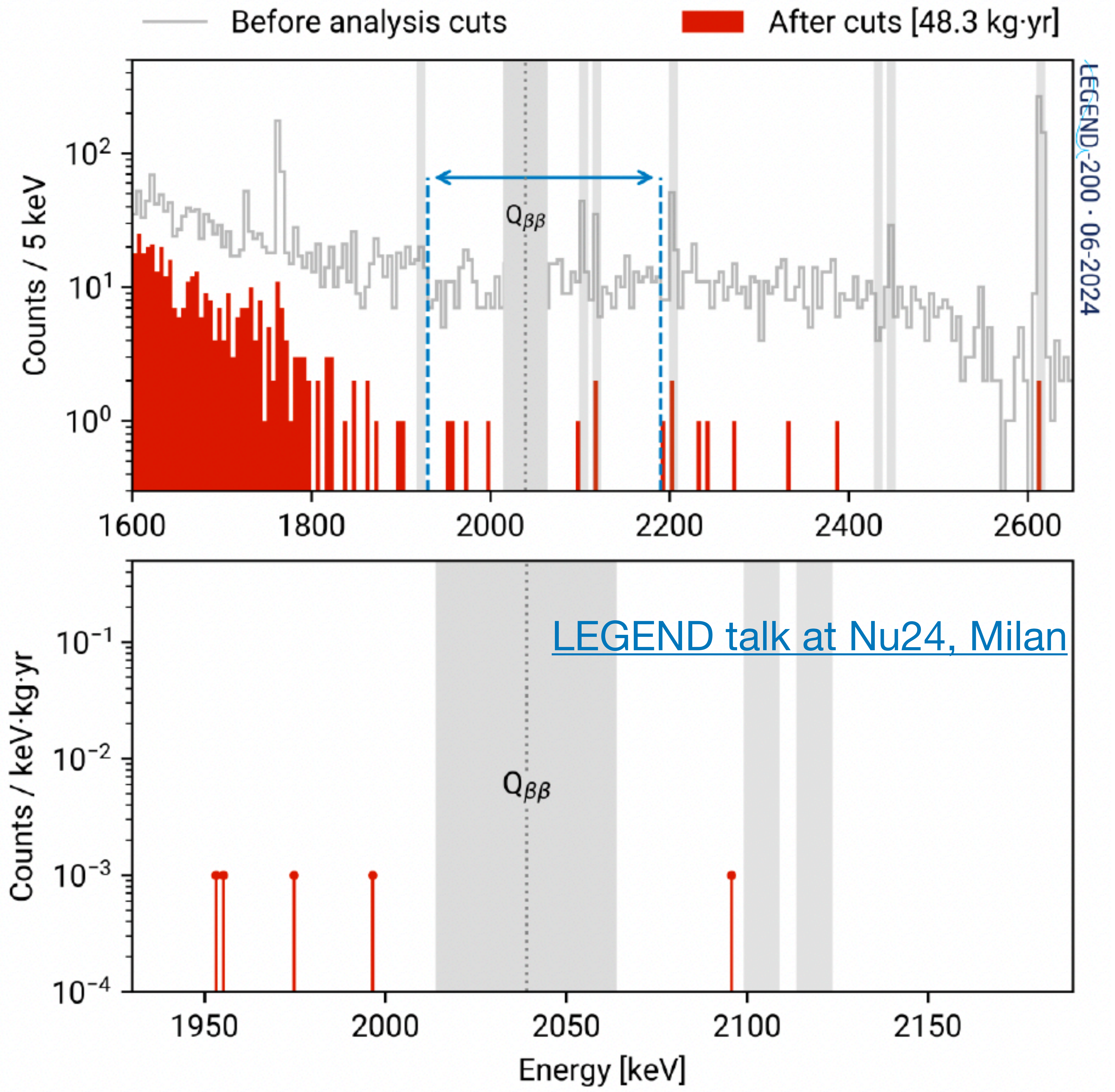
Pure $2\nu\beta\beta$ decay spectrum at lower energies

[LEGEND talk at Nu24, Milan]



BEFORE UNBLINDING

- 5 events in BI window after all analysis cuts.



LEGEND talk at Nu24, Milan

LEGEND-200: First results

AFTER UNBLINDING

- Unblinding on 13 June 2024.
- 7 events survive in the BI window after analysis cuts.

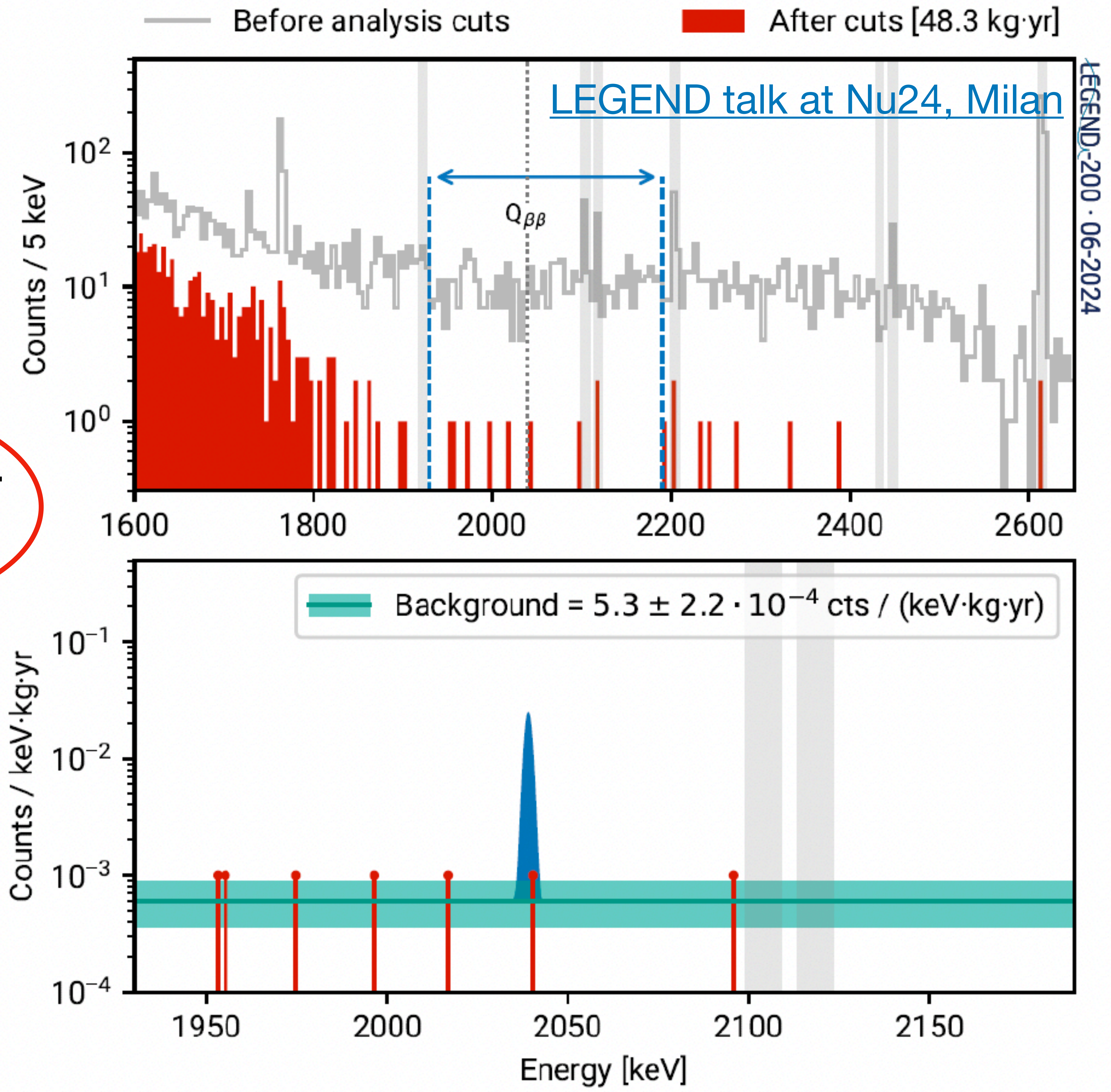
BI (at 90% C.L) $= (5.3 \pm 2.2) \cdot 10^{-4}$ **counts/(keV kg yr)**

~GERDA world-leading level

BI is higher than expected

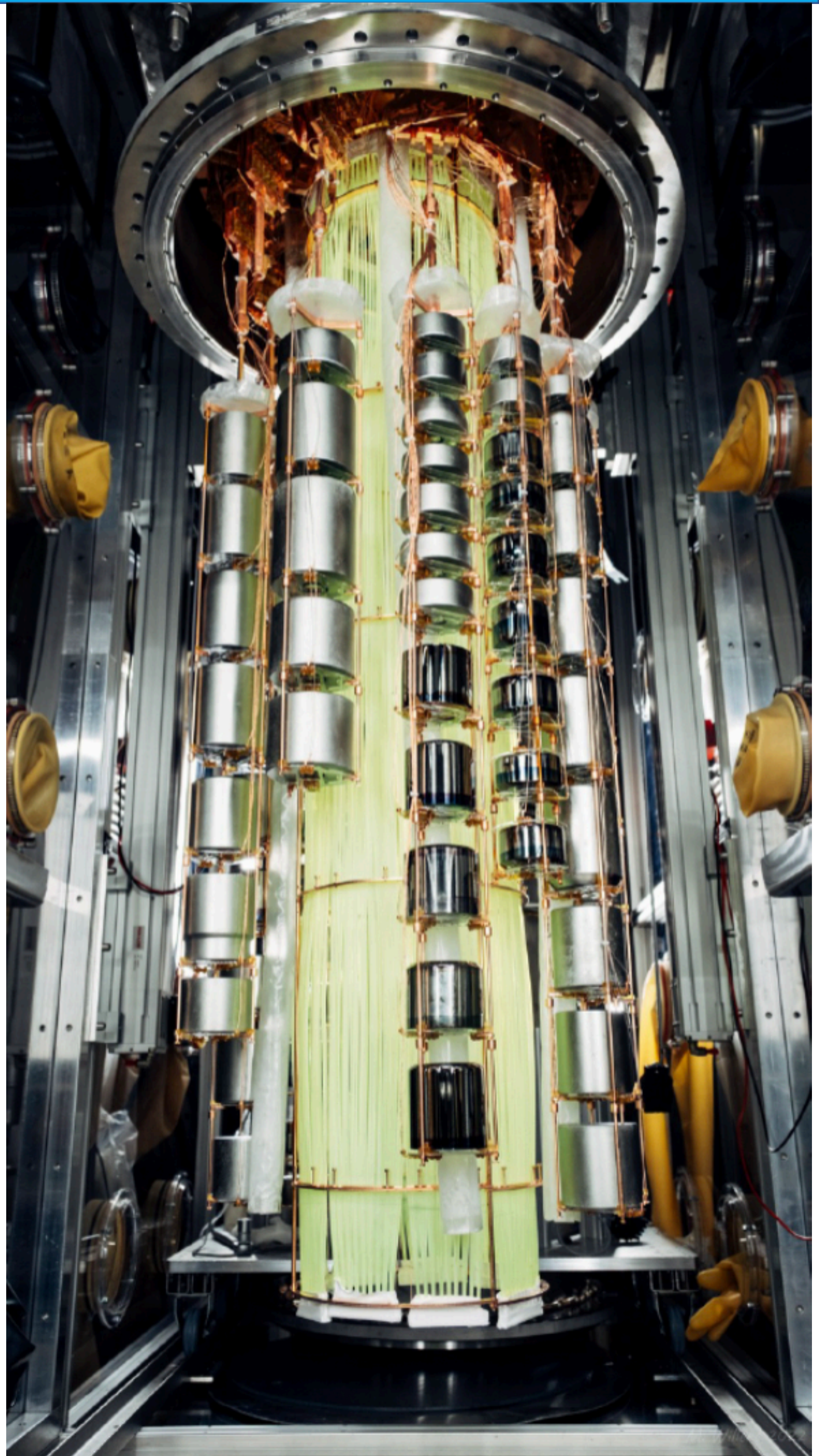
- Combined fit from GERDA, MAJORANA and LEGEND:

$$\mathbf{T}^{0\nu}_{1/2} > 1.9 \cdot 10^{26}\ \mathbf{yr}$$



LEGEND: What's next?

- Radioassays of materials are ongoing to understand the backgrounds.
- Appox. 35 kg of Ge detectors will be added, increasing the total mass to 177 kg.
- Publication of the first results is in progress.
- Physics data taking to resume in the Fall of 2024.



Summary

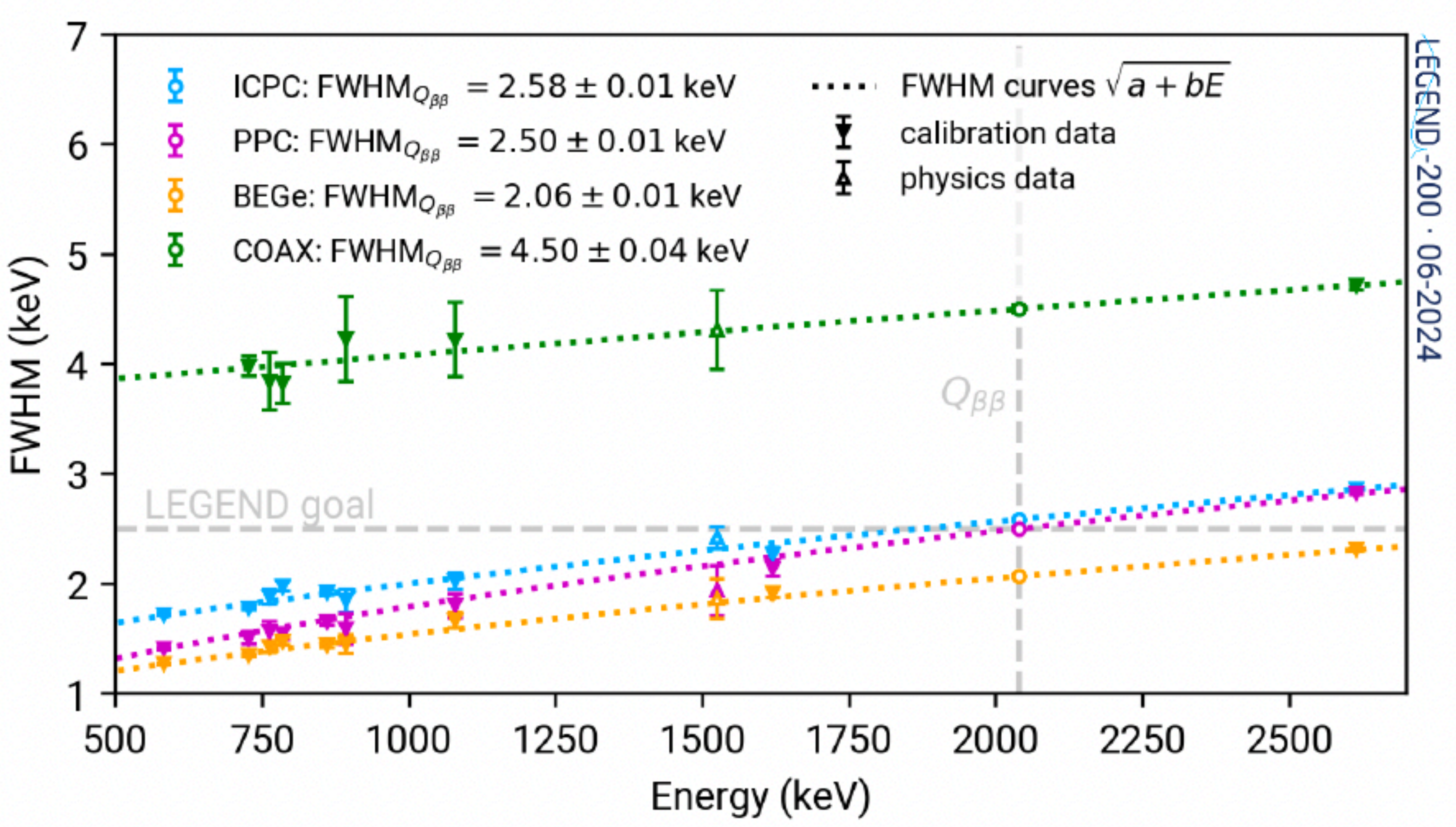
- LEGEND-200 completed one year of data-taking; the first results were unblinded in June 2024.
- 7 events in the Background Estimation window.
- BI $= (5.3 \pm 2.2) \cdot 10^{-4}$ counts/(keV kg yr) —> Higher than expected. Radioassay campaign ongoing to understand backgrounds.
- **GERDA + MAJORANA + LEGEND combined limit for half-life is** $T^{0\nu}_{1/2} > 1.9 \cdot 10^{26}$ yr.
- LEGEND-1000 under construction; data-taking from 2030 onwards.

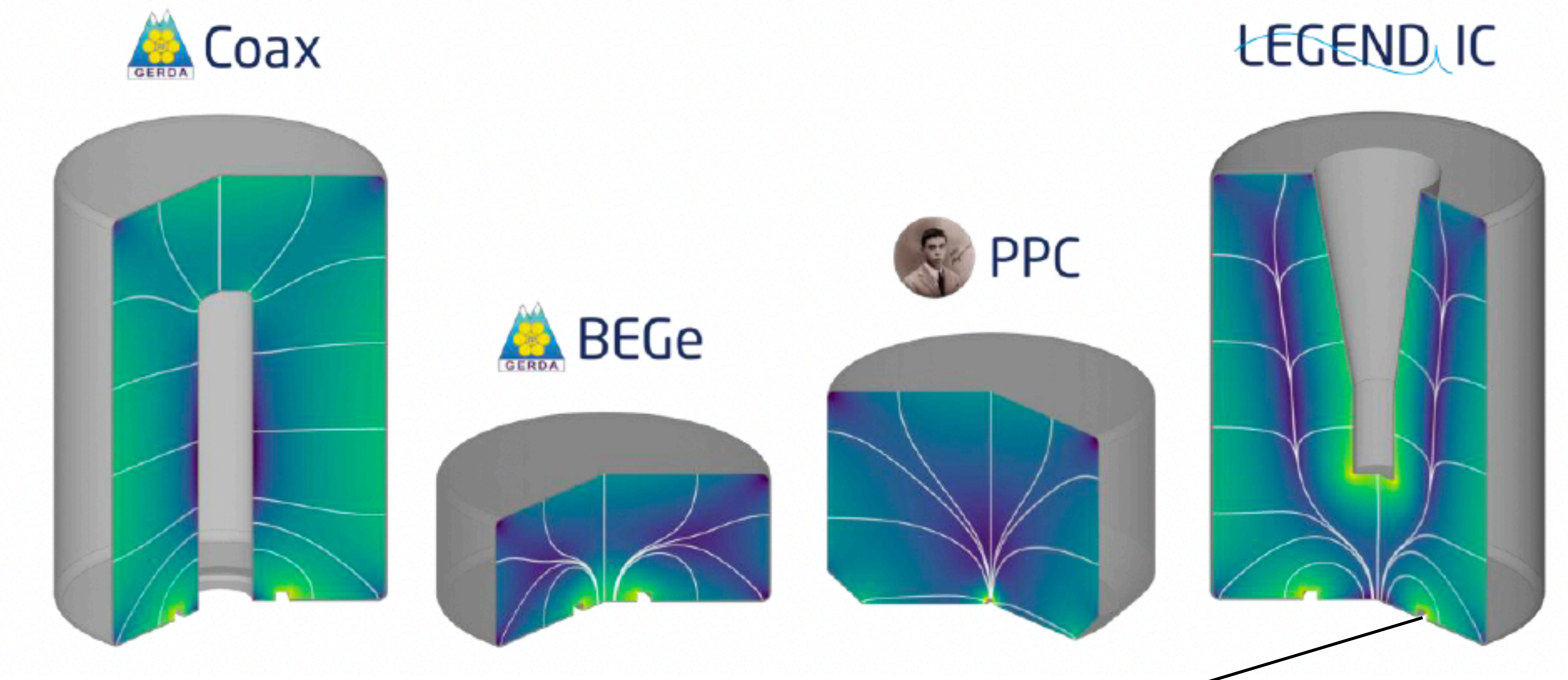
Backups

LEGEND-200 Detectors

Germanium is excellent for $0\nu\beta\beta$ searches

- Source and detector: high efficiency
- Offers excellent energy resolution (0.1% at $Q_{\beta\beta}$ - best in the field as of June 2024)
- Well-established technology
- Lowest background per FWHM energy resolution in the field





- Enriched 92% in ^{76}Ge
- Good energy resolution and PSD
- Larger than BEGe and PPC; fewer channels and lesser background
- The surface-volume ratio is better

LEGEND-200: First results

- Physics data taken from March 2023 - February 2024.
- SILVER Dataset: All detectors in ‘ON’. 76.2 kg yr exposure
- GOLDEN Dataset: PSD corrections applied. 48.3 kg yr exposure.