First results on $0\nu\beta\beta$ decay with the LEGEND experiment

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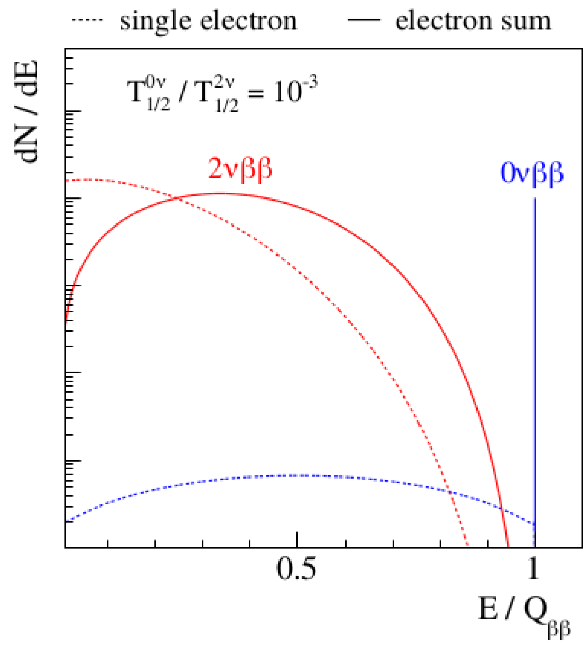
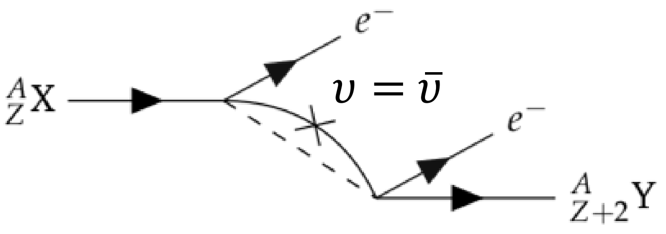
35th Rencontres de Blois

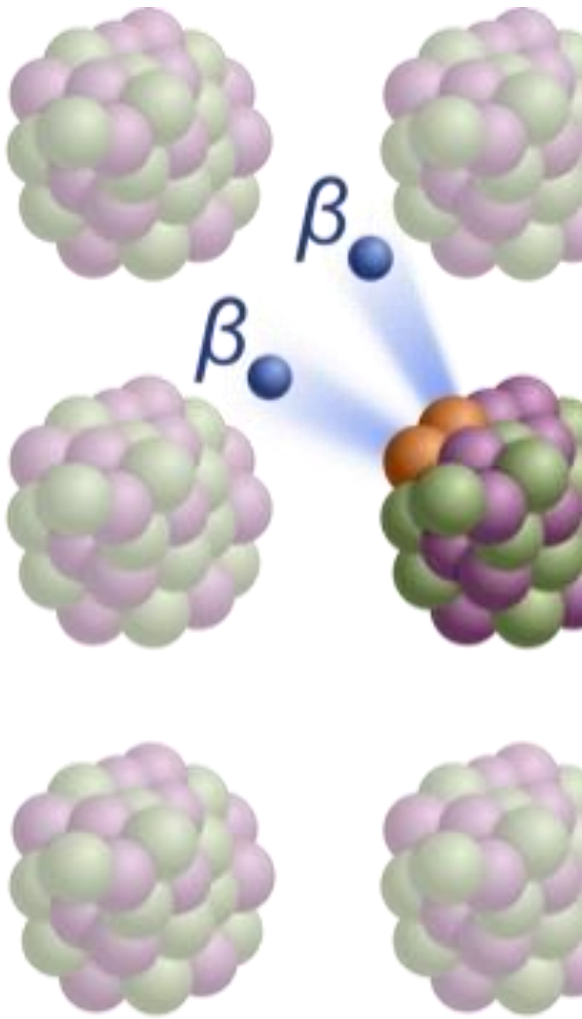
Searching for $0\nu 2\beta$

Signature

- $2\nu 2\beta$ (SM): continuous, broad spectrum → observed ($10^{18\text{-}21}$ yr)
- $0\nu 2\beta$ (BSM): peak at $Q_{\beta\beta}$ (electrons energy) → not observed ($>10^{21\text{-}26}$ yr)







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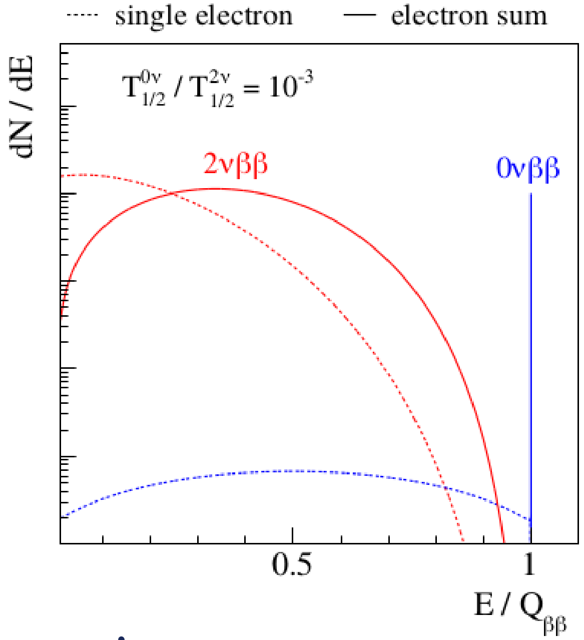

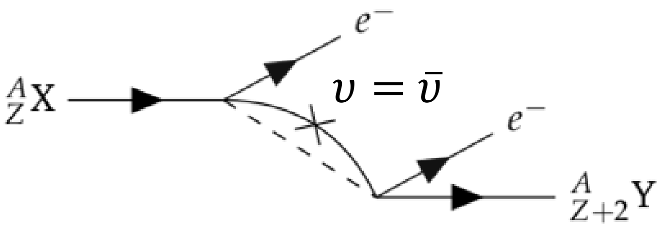

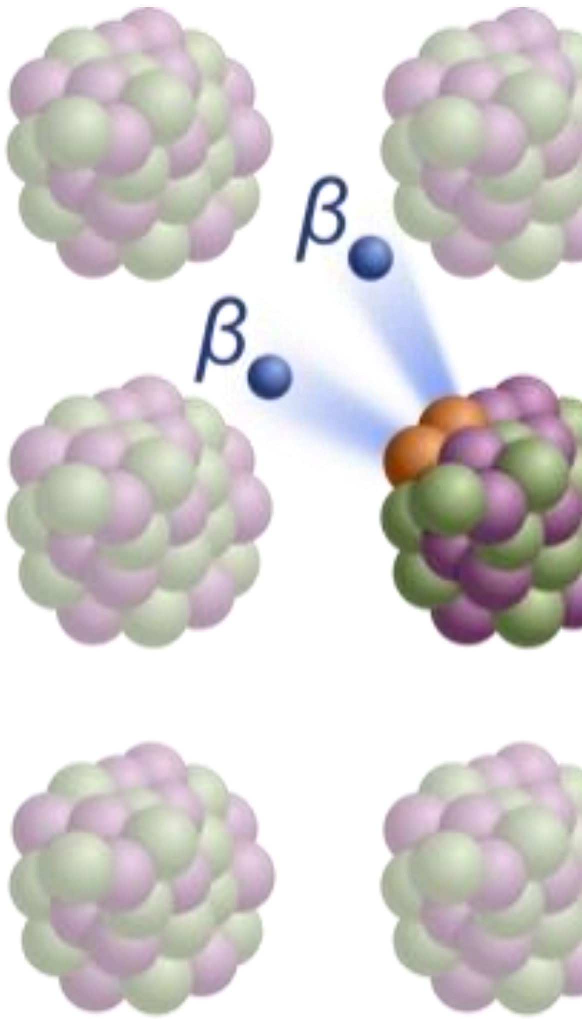

Physics Implications

- Nature of neutrinos (Dirac/Majorana) – *golden channel*
- Matter-antimatter asymmetry in the Universe
- Neutrino mass scale & ordering

Half-life

Phase-space integral

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

Nuclear Matrix Element (NME)

$m_{\beta\beta} = \left|\sum_i U_{ei}^2 m_i\right|$ → to compare results obtained with different isotopes: ^{76}Ge, ^{136}Xe, ^{130}Te, ^{100}Mo, ^{82}Se

Effective Majorana neutrino mass

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LEGEND

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Effective Majorana neutrino mass

Sensitivity

$$T_{1/2}^{0\nu} \propto \begin{cases} \epsilon \cdot f \cdot \sqrt{\frac{\varepsilon}{BI \cdot \Delta E}} & \text{with bkg} \\ \epsilon \cdot f \cdot \varepsilon & \text{without bkg} \end{cases}$$

ϵ: efficiency

f: isotopic fraction

$\varepsilon = mass \cdot time$: exposure

ΔE: energetic resolution at $Q_{\beta\beta}$

BI: background index

The LEGEND Project

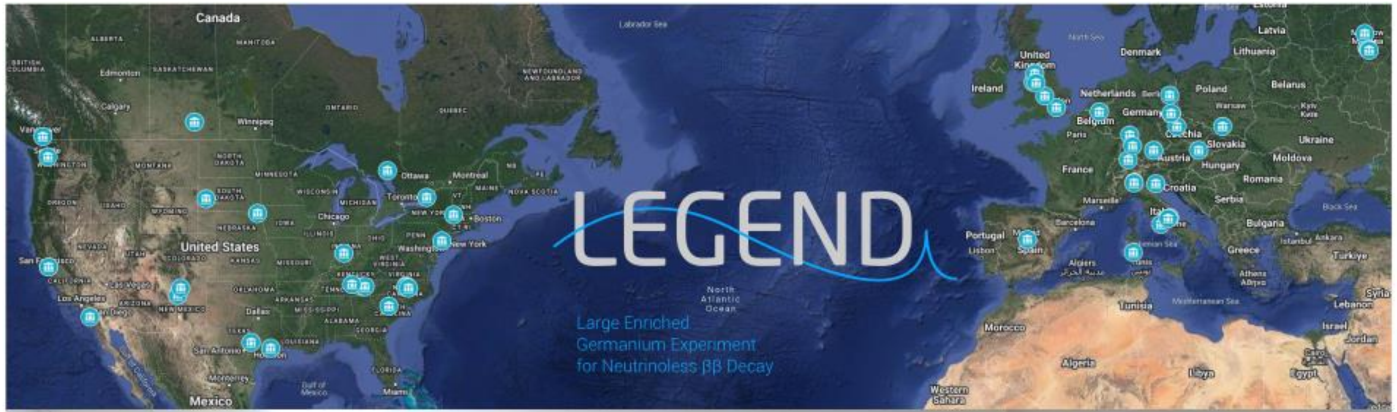
https://legend-exp.org/ https://github.com/legend-exp/

LEGEND

Large Enriched Germanium Experiment for Neutrinoless ββ Decay

GERDA +  + new groups

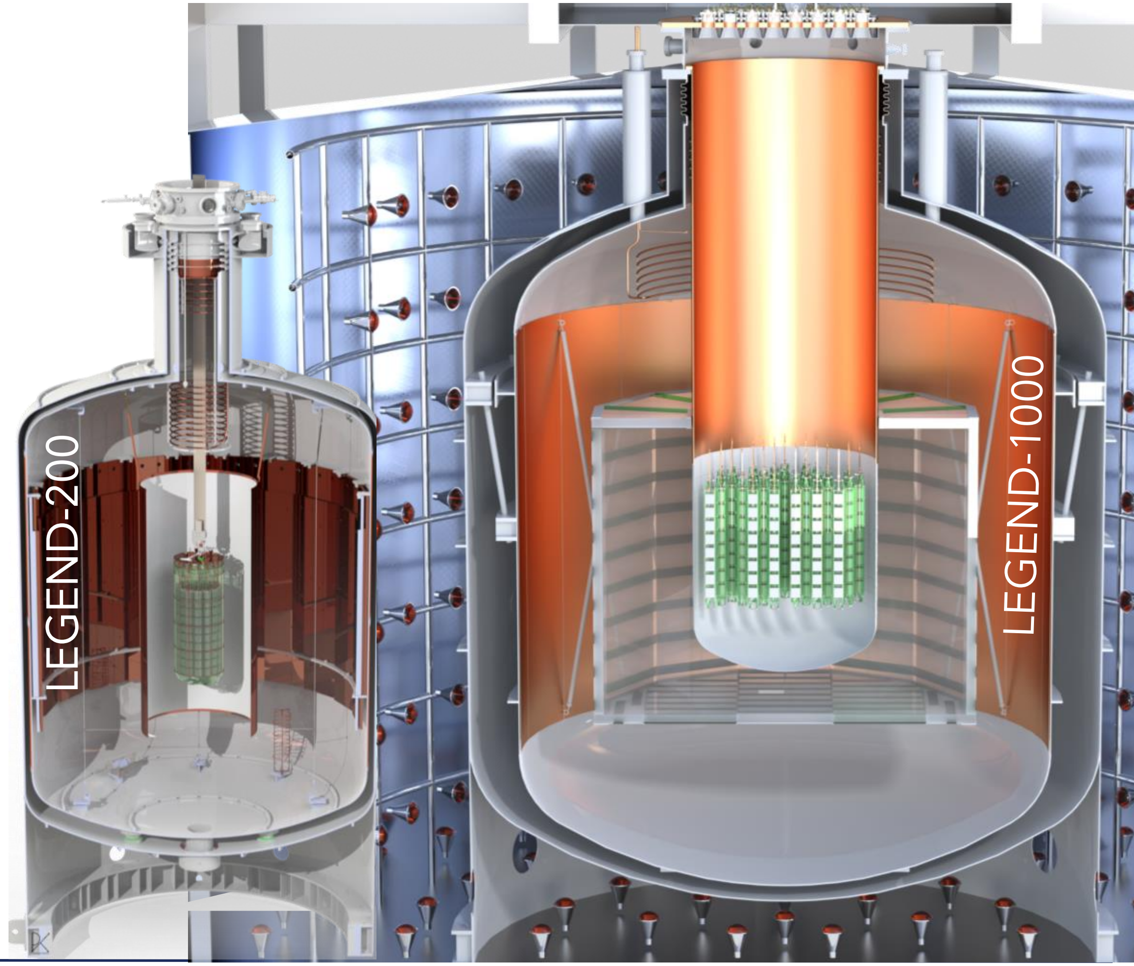
GERDA and MAJORANA DEMONSTRATOR set most stringent constraints for $0\nu\beta\beta$ Ge-76



The LEGEND Project

Pre-conceptual Desgin Report [2107:11462]

"The collaboration aims to develop a phased, ^{76}Ge-based 0νββ decay experimental program with ***discovery potential at a half-life beyond 10^{28} yr,*** *using existing resources as appropriate to expedite physics results"*



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LEGEND-200 [5 yr]

ε=1 t · yr

BI=2×10^{-4} cts/(keV · kg · yr)

$T^{0\nu}_{1/2} > 10^{27}$ yr

$m_{\beta\beta} < 34 - 78$ meV

LEGEND-1000 [10 yr]

ε=10 t · yr

BI=10^{-5} cts/(keV · kg · yr)

$T^{0\nu}_{1/2} > 1.3 \times 10^{28}$ yr

$m_{\beta\beta} < 9.4 - 21.4$ meV

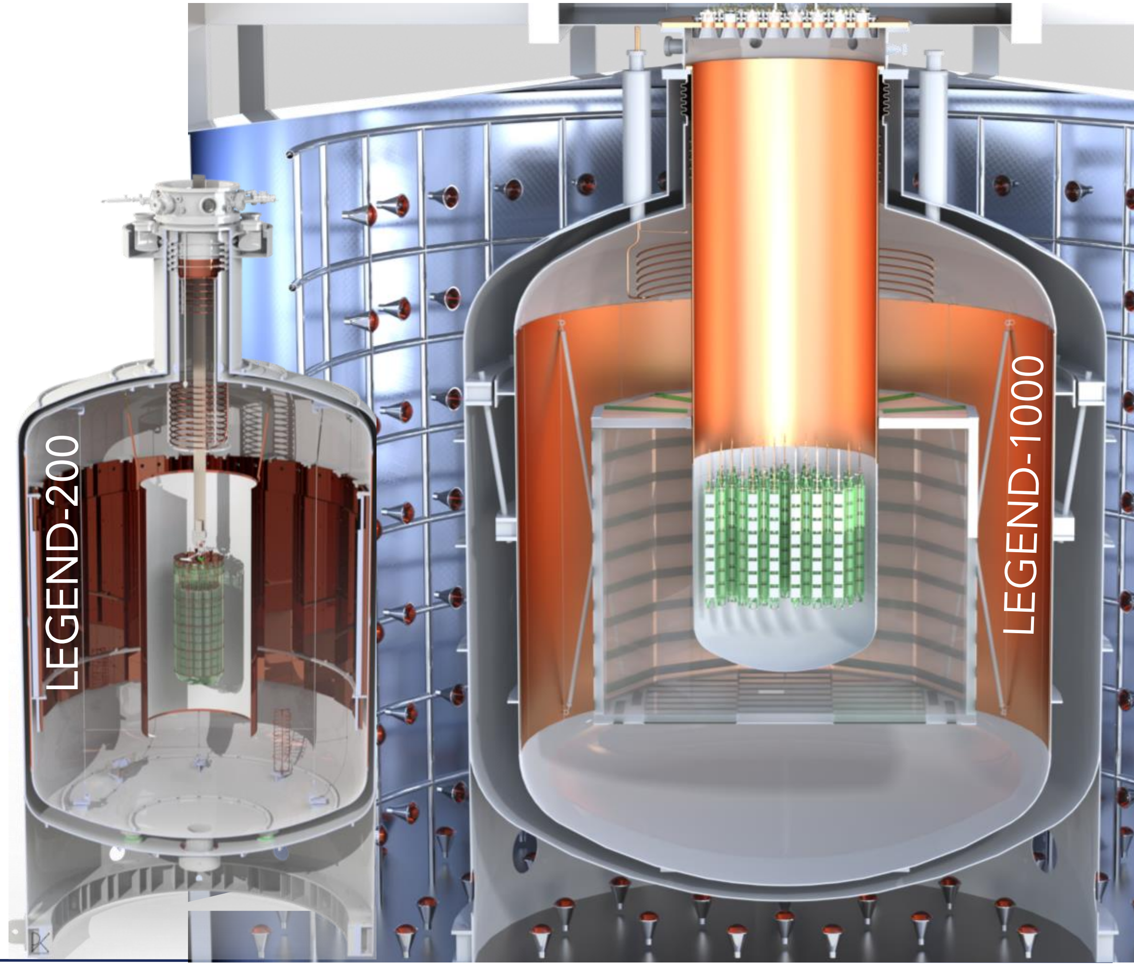
GERDA (PRL 125 252502, 2020)

ε=127.2 kg· yr

BI=5.2×10^{-4} cts/(keV · kg · yr)

$T^{0\nu}_{1/2} > 1.8 \times 10^{26}$ yr

$m_{\beta\beta} < 79 - 180$ meV



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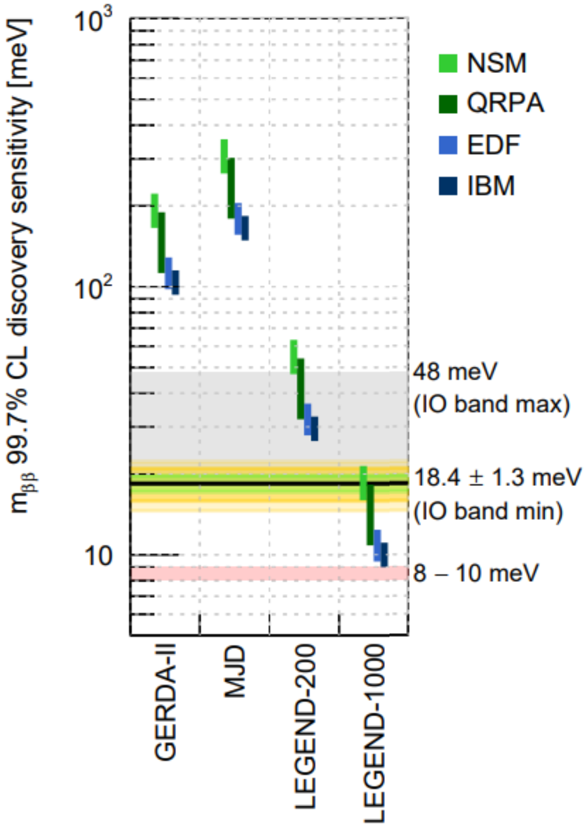

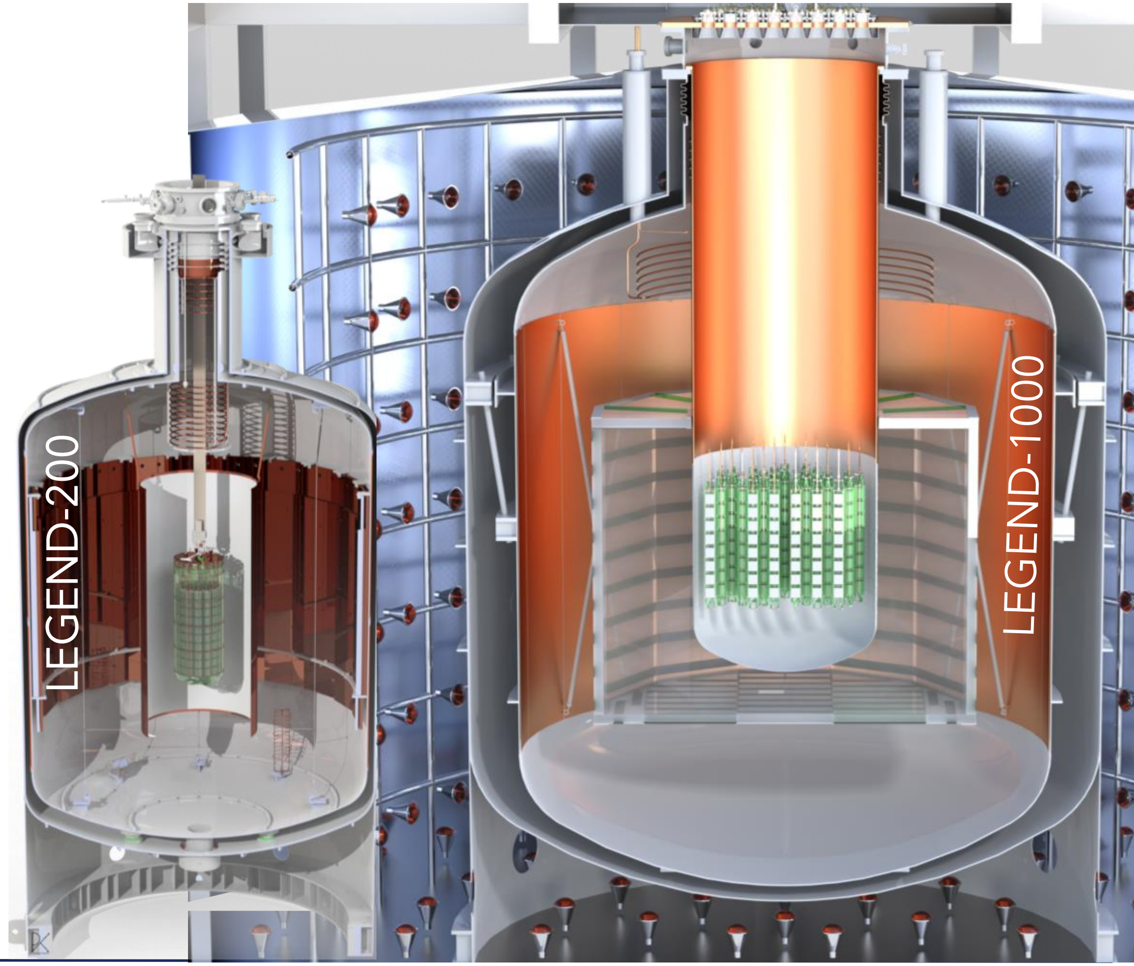

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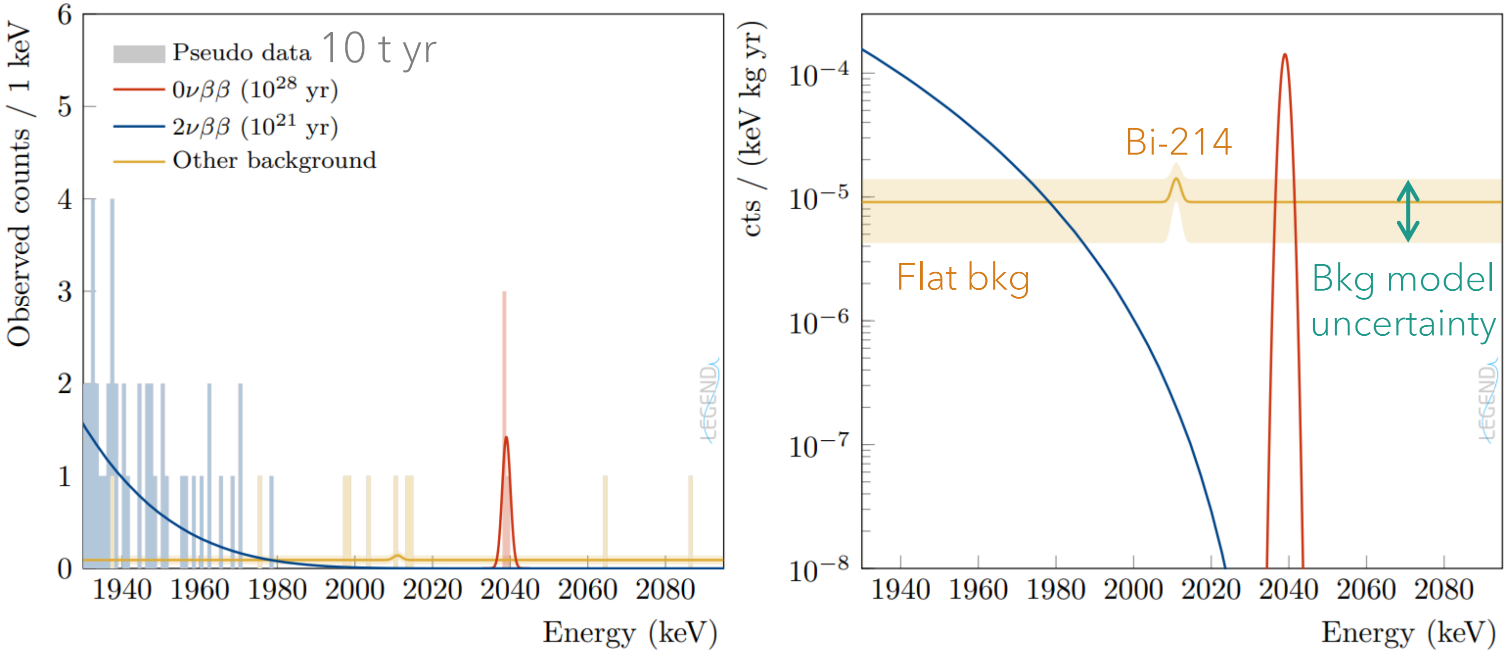
"By combining the lowest background levels and the best energy resolution in the field, LEGEND-1000 will perform a quasi-background-free search and can make an ***unambiguous discovery with just a handful of counts*** *at the $Q_{\beta\beta}$"*



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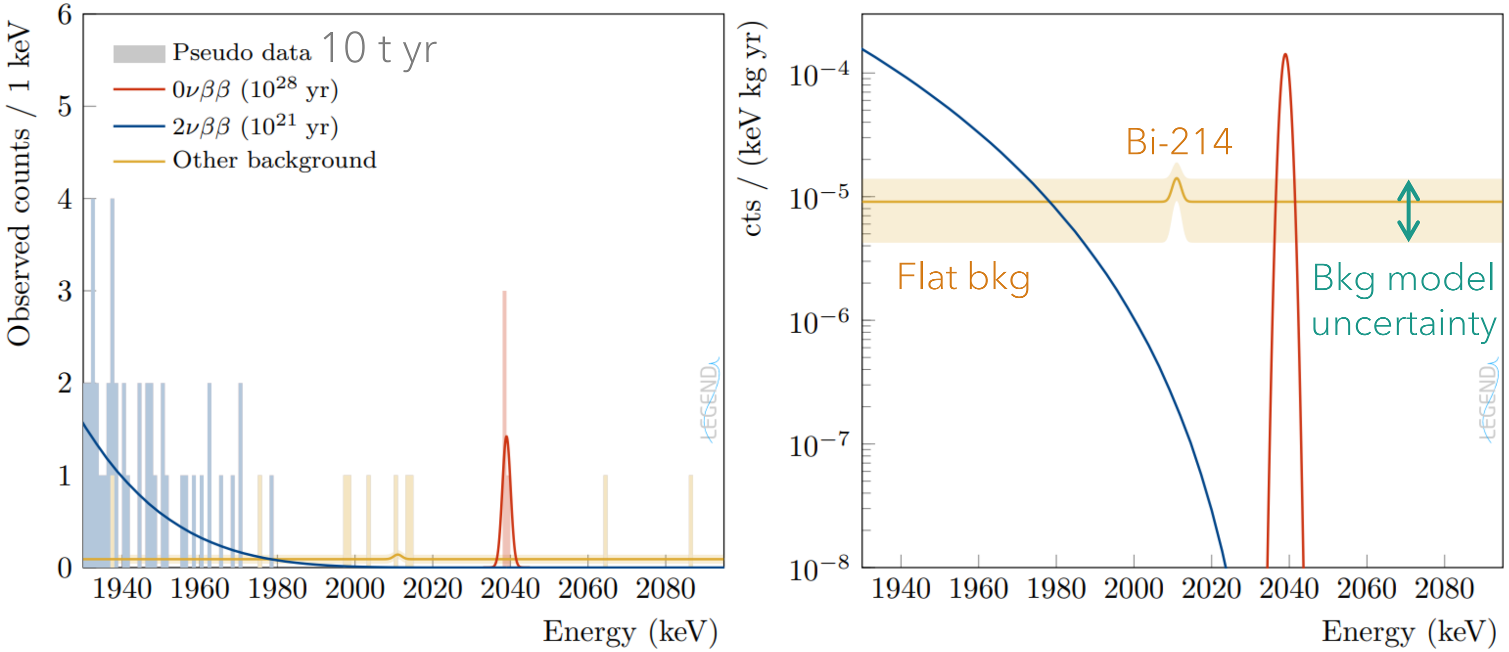

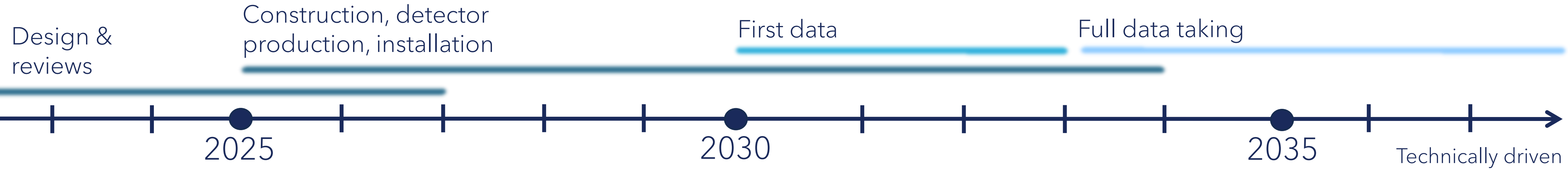

Technically driven schedule

Why Germanium?

- No theoretical preferences
- Experimental preferences
    - costs
    - energy resolution
    - background level
    - scalability (liquids, gas, crystals)

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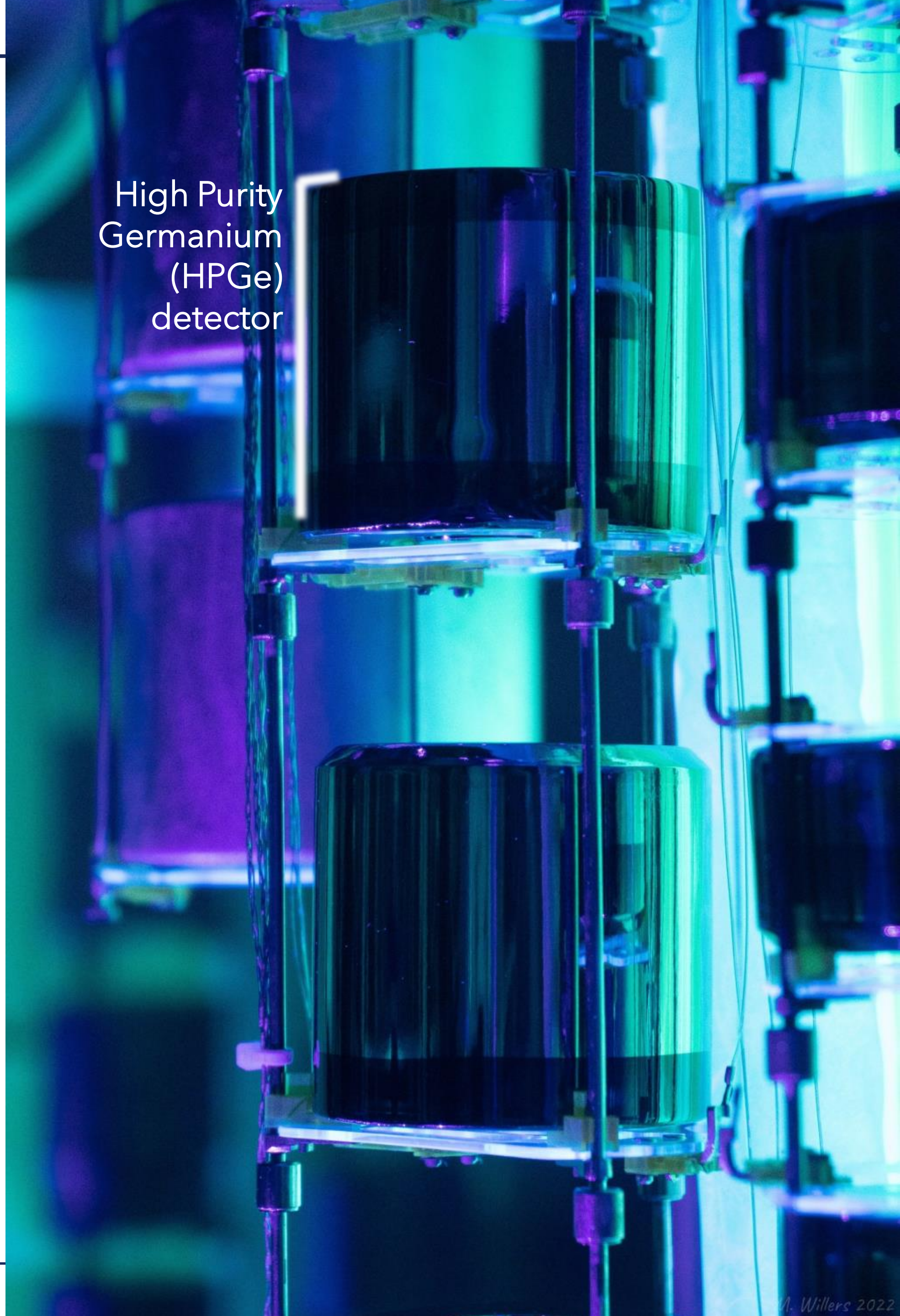
- ${}^{76}_{32}\mathrm{Ge} \rightarrow {}^{76}_{34}\mathrm{Se} + 2\mathrm{e}^- \ (+2\bar{\nu}_\mathrm{e})$ with $Q_{\beta\beta}$=2039.06 (7) keV
- $Q_{\beta\beta}$>2 MeV: less processes can mimic the $0\nu2\beta$ signal
- Natural abundance is low (~8%): enrichment up to ~92% is possible



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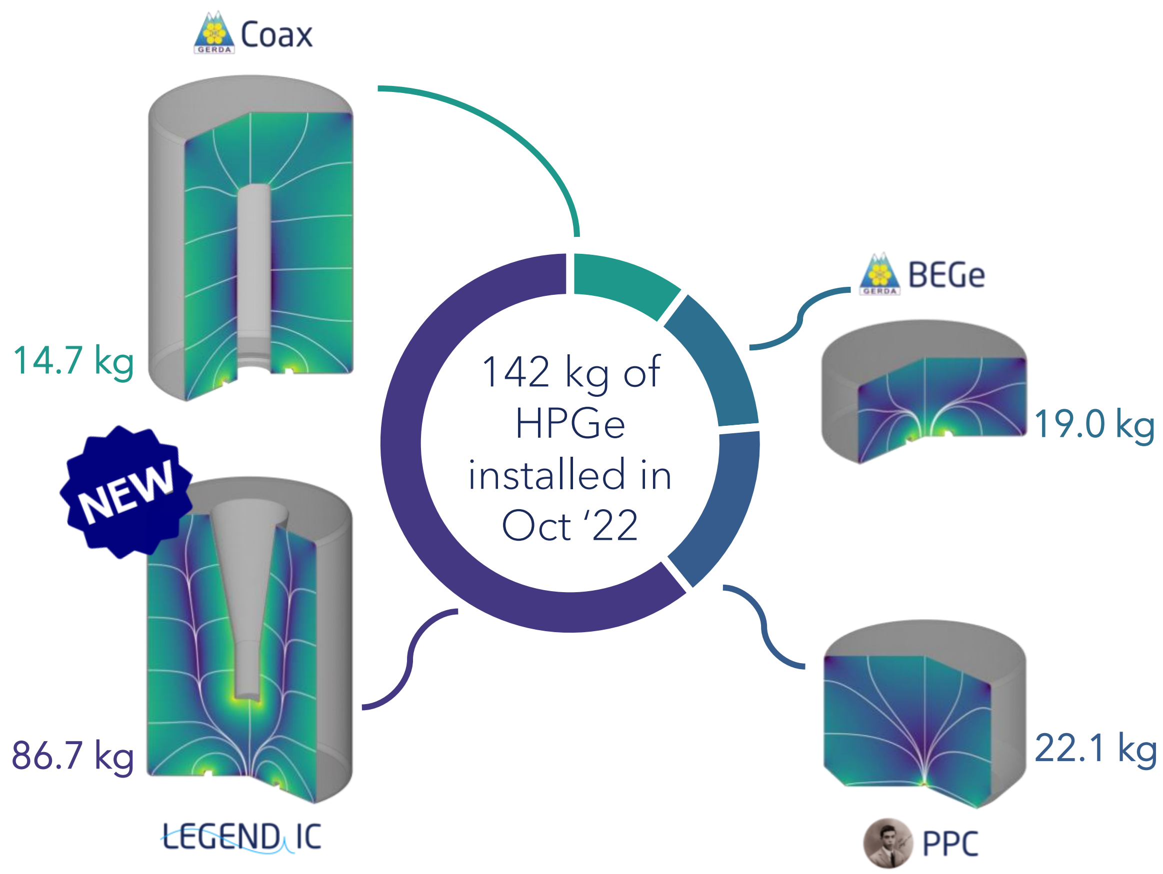
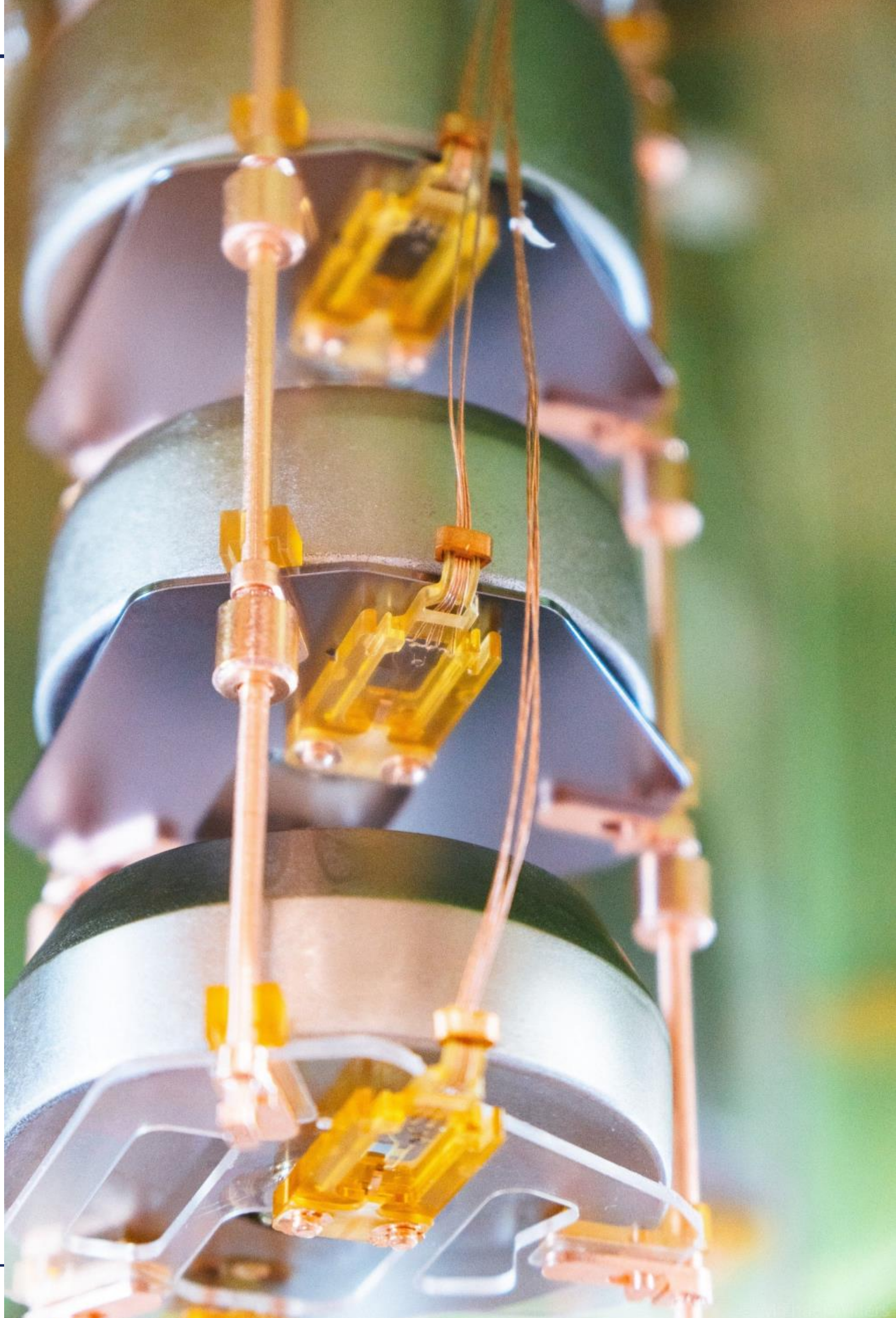
Already established technology → Source ≡ detector → Ge: high purity → Excellent energy resolution

High detection efficiency | Low intrinsic background | FWHM~ **0.1%** @ $Q_{\beta\beta}$

LEGEND-200 HPGe diodes

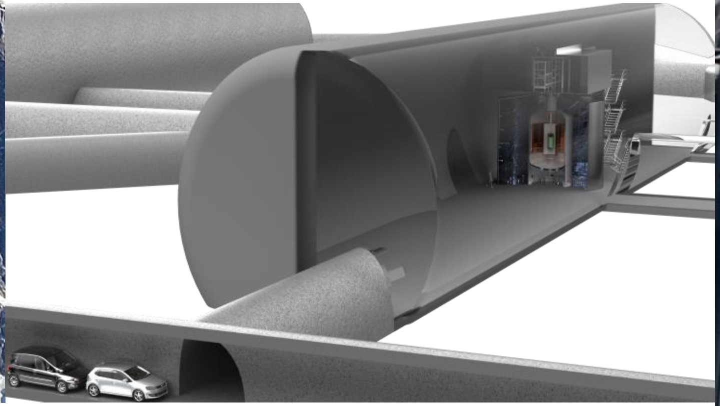


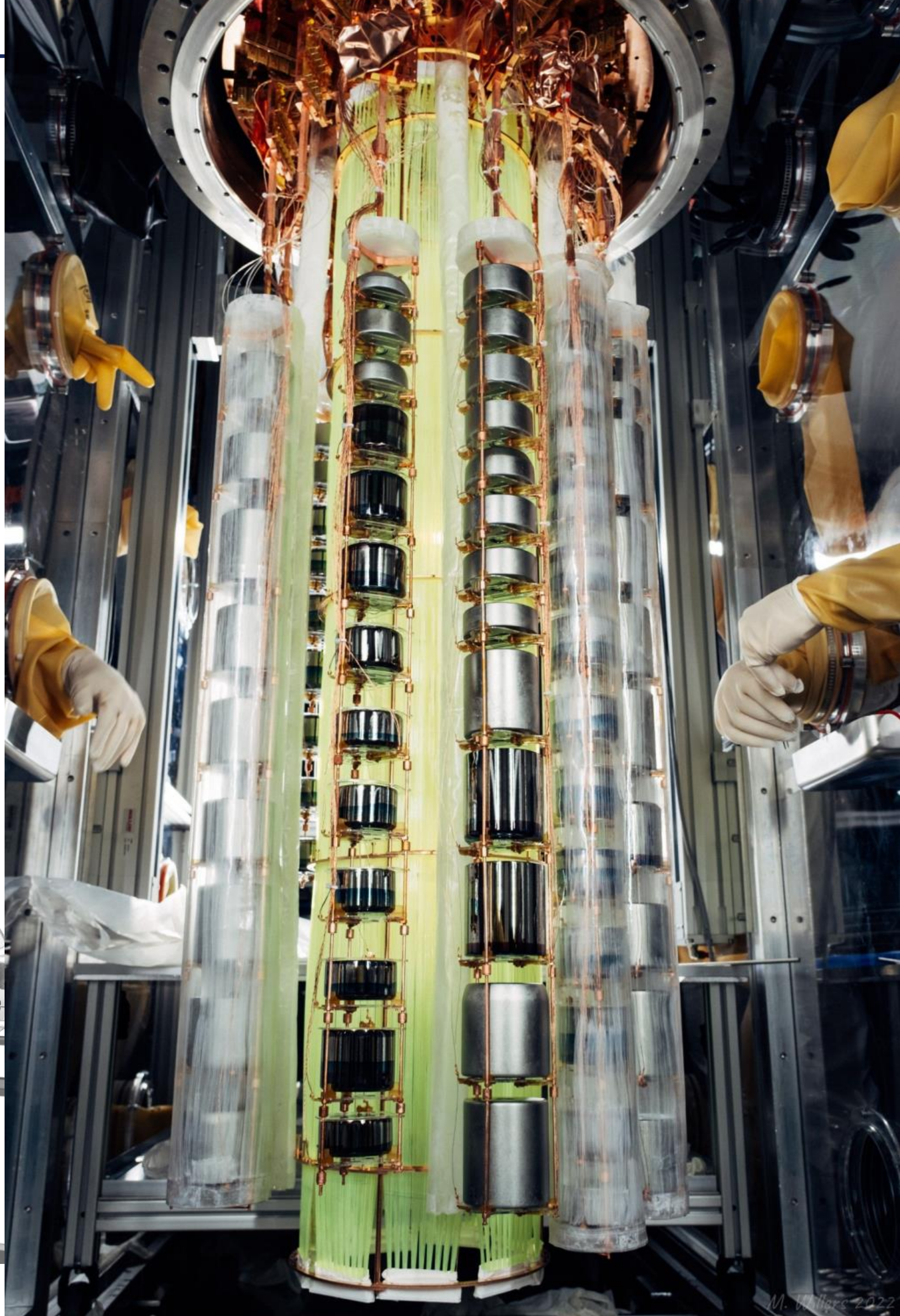


- p+ (implanted B), n+ (diffused Li), passivated groove
- Fully depleted crystals
- Different geometries - mass: 0.7-4 kg
- 130 kg operational (12 kg OFF for hardware issues)

LEGEND-200

- @ Hall A of *Laboratori Nazionali del Gran Sasso* (LNGS), Italy
- Same infrastructure of GERDA
- Rock overburden of 3500 m.w.e.
- Muon flux reduced to 1.25 / (m^2h) – reduction factor: $\mathcal{O}(10^6)$





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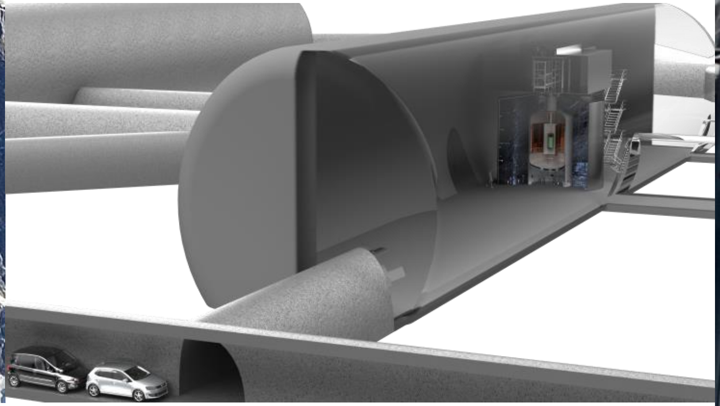
142 kg commissioning — Stable physics data taking — Background characterization, new HPGe mass, … — Start of physics data taking

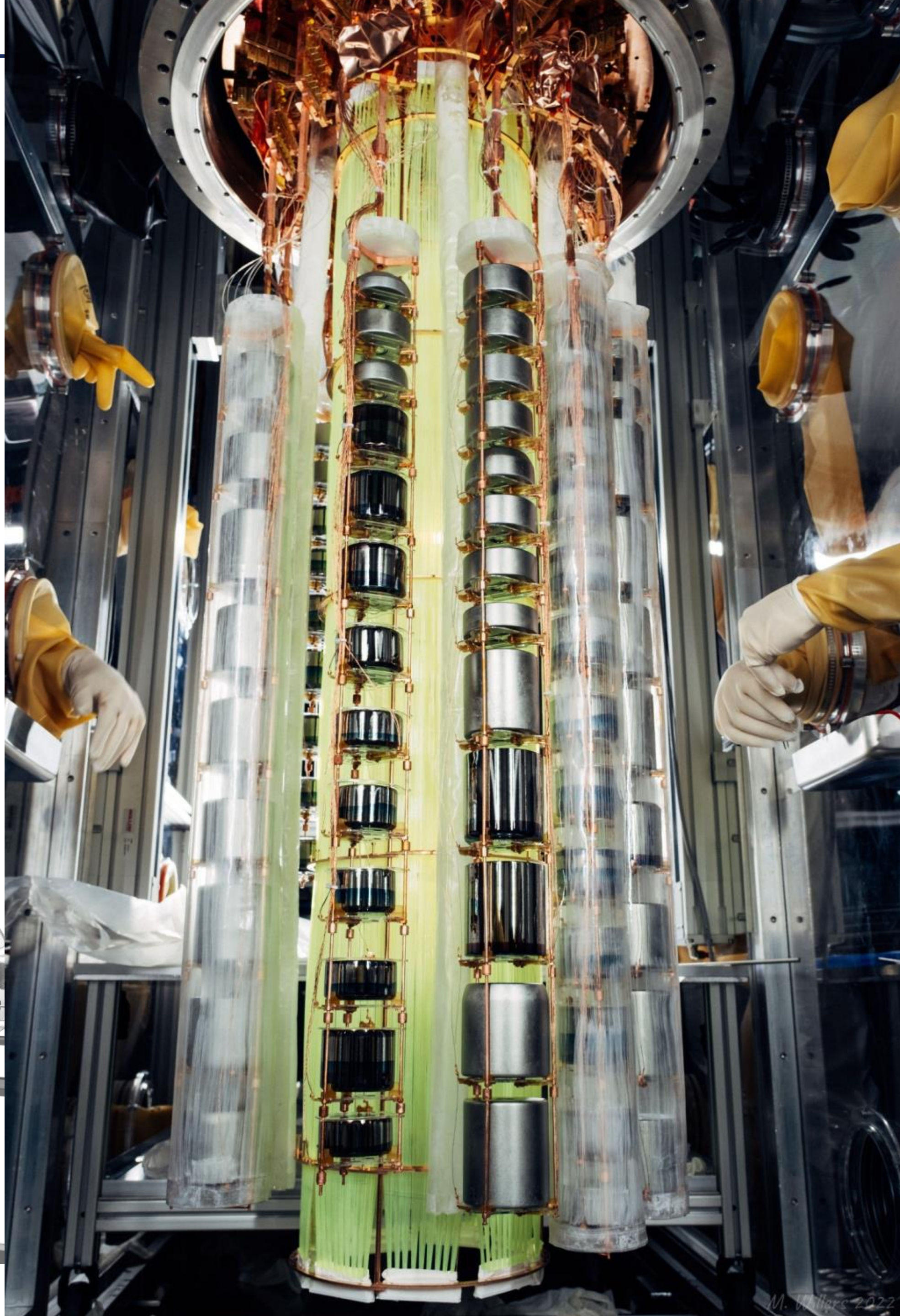
2023 — 2024 — 2025

TAUP'23
M. Willers talk
K. von Sturm talk

NU'24
L. Pertoldi talk

LRT'24
T. Dixon talk
L. Varriano talk





Experimental Setup

Array
of HPGe diodes

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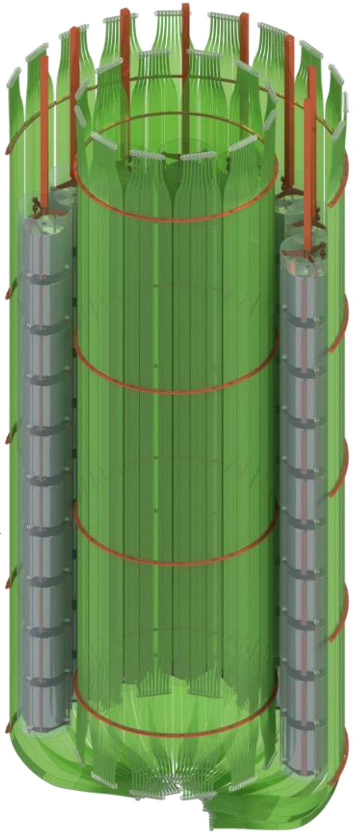
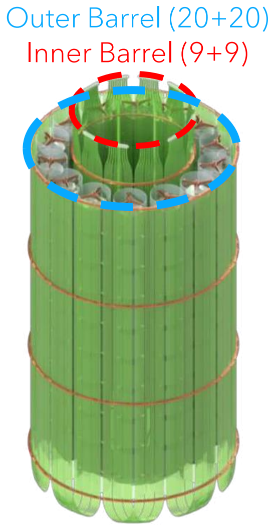
Liquid argon (LAr) system

- 58 read-out modules of **SiPMs** coupled to WLS fibers





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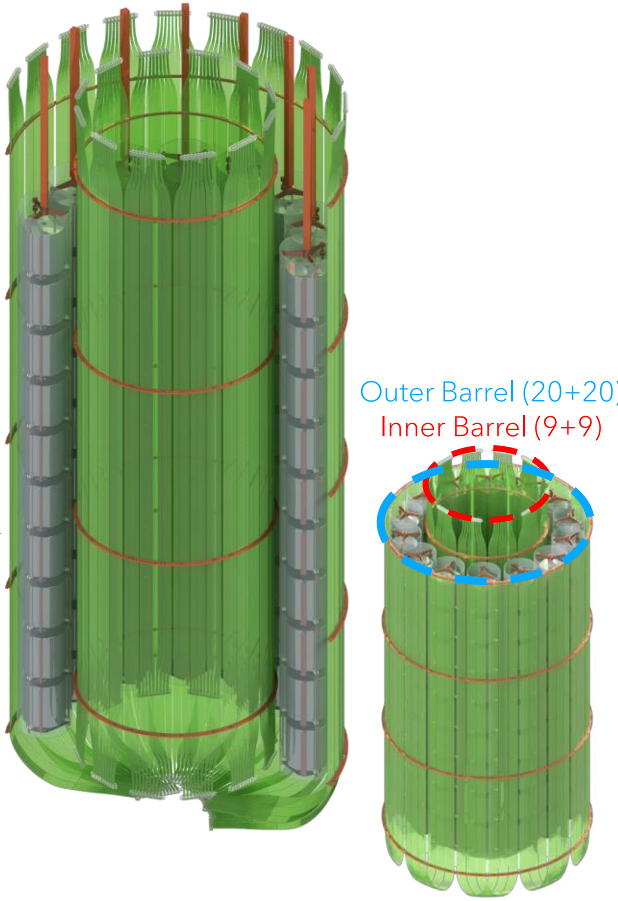

Cryostat
- Ø 4m, H 5.88m
- LAr: 64 m^3
- LLAMA for monitoring LAr properties

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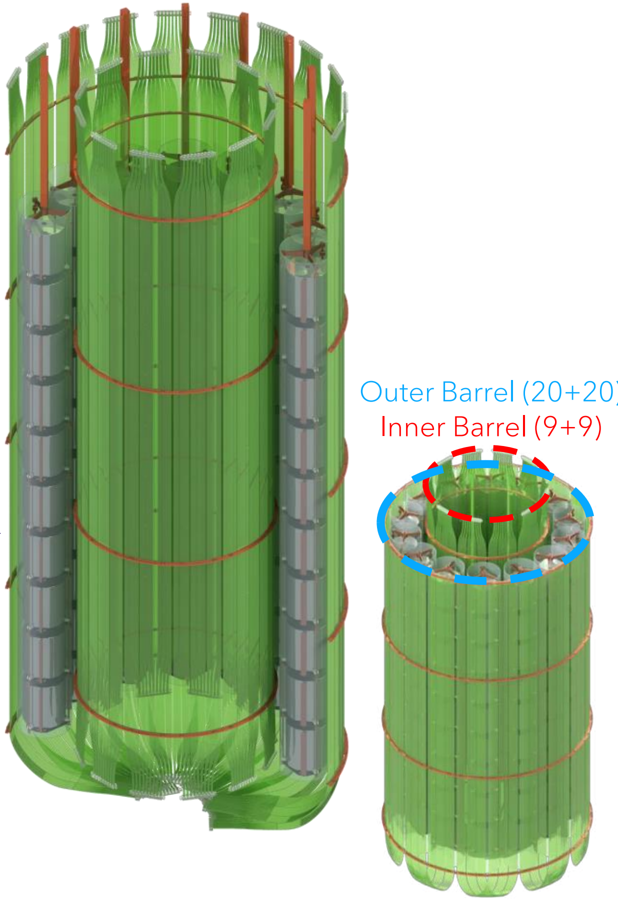

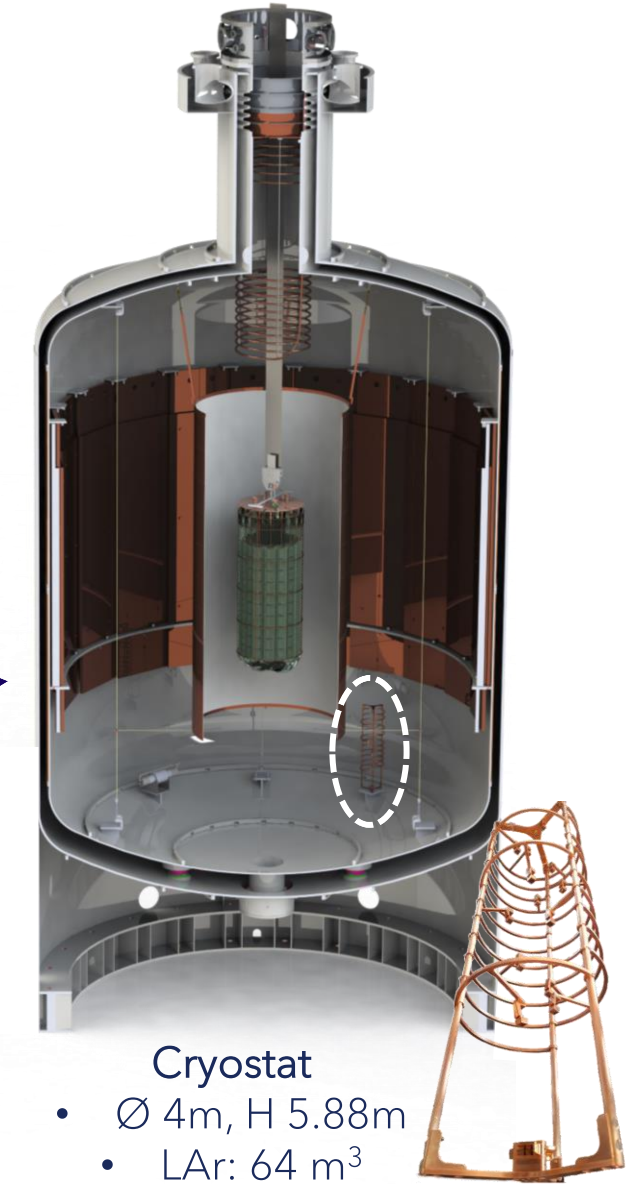

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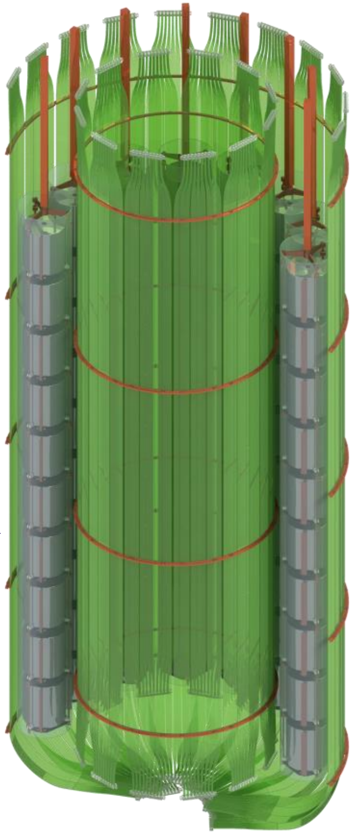

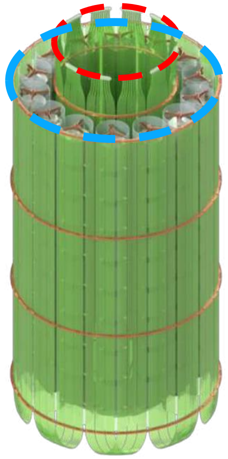

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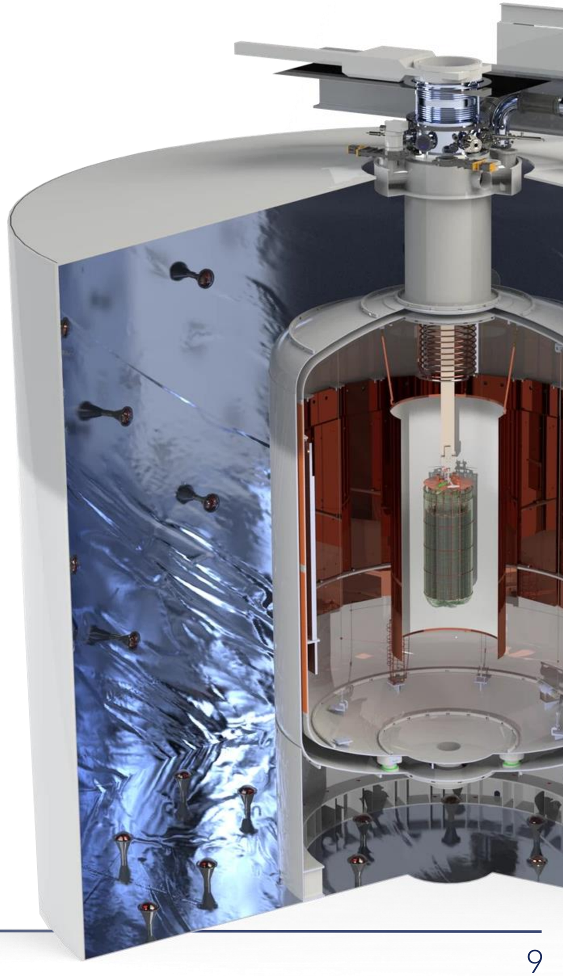
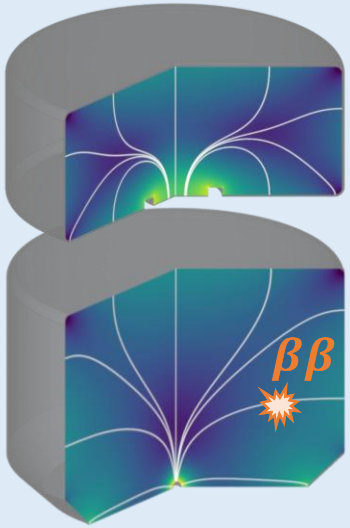
Ultrapure water tank
- Shields n, γ
- 66 PMTs (Cherenkov) + plastic scintillators for μ
- Ø 10m, H 8.5 m, V 590 m^3
- Clean room at 9.7 m



Background Reduction

Signal-like
single-site event



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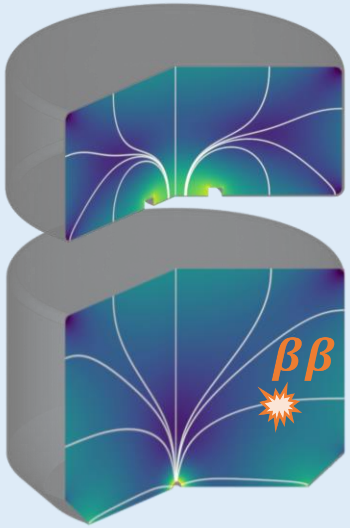
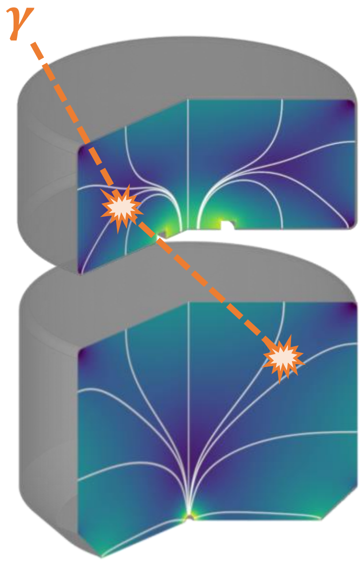
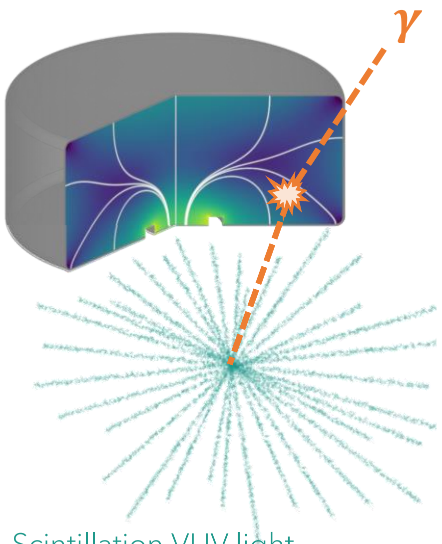


Multiplicity cut



Det-LAr
coincidence



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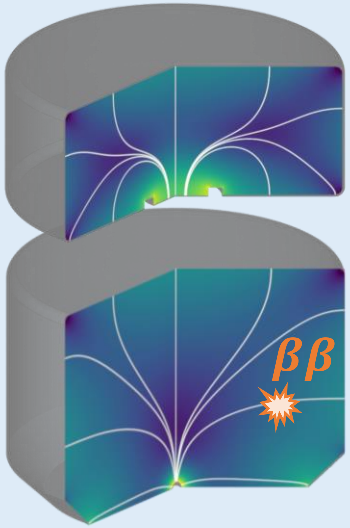

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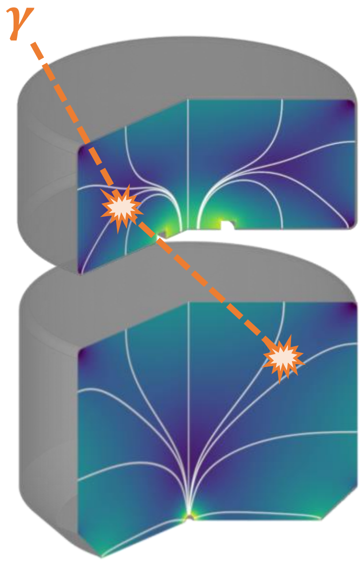
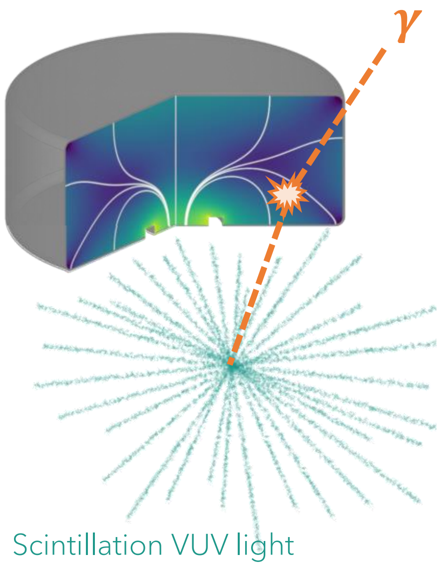
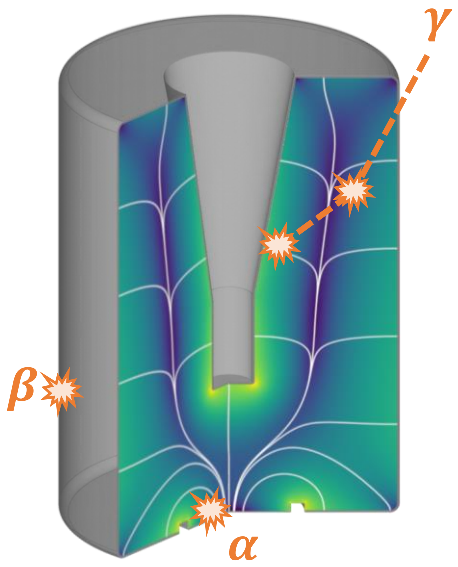
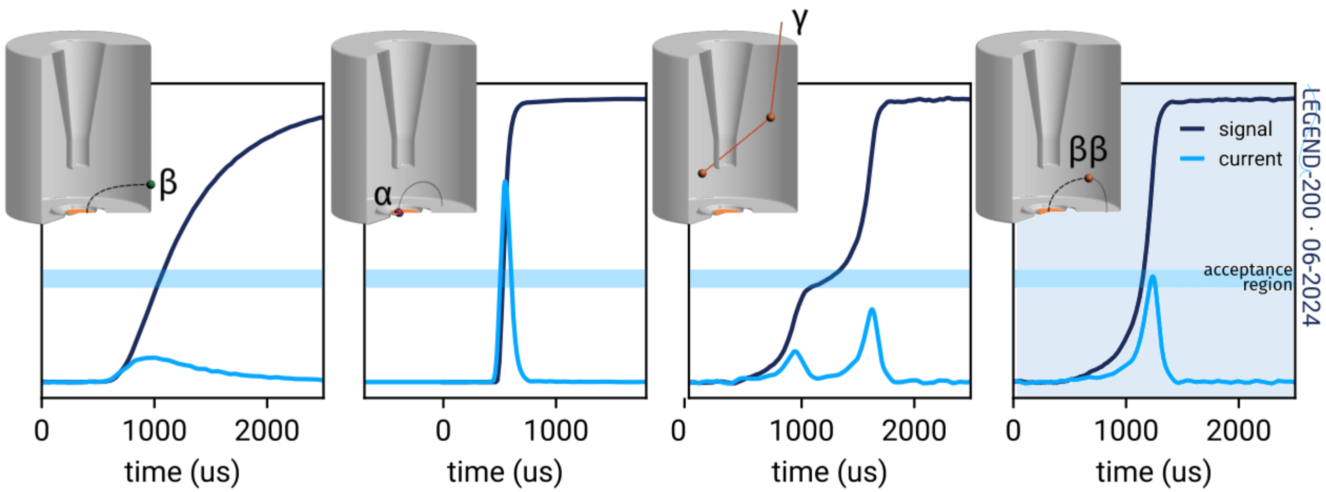


Det-LAr coincidence



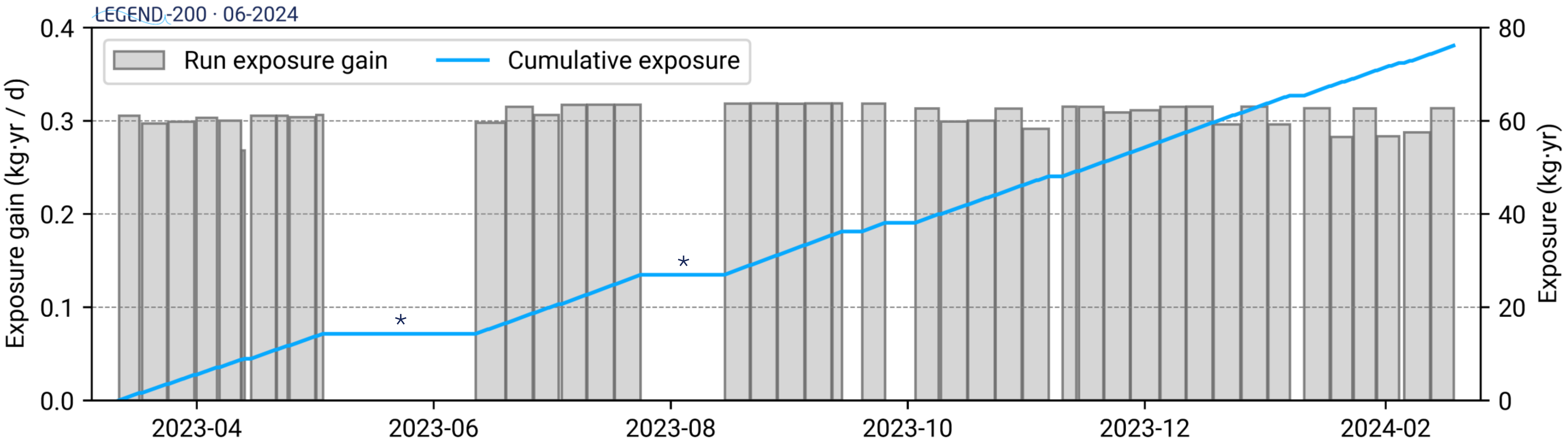
Multi-site event, surface events





Pulse shape discrimination (PSD): signal discrimination based on the signal risetime and amplitude

LEGEND-200 Data Sets



(*) Test or HV scan runs – duty cycle of 91.4% (242 days in total)

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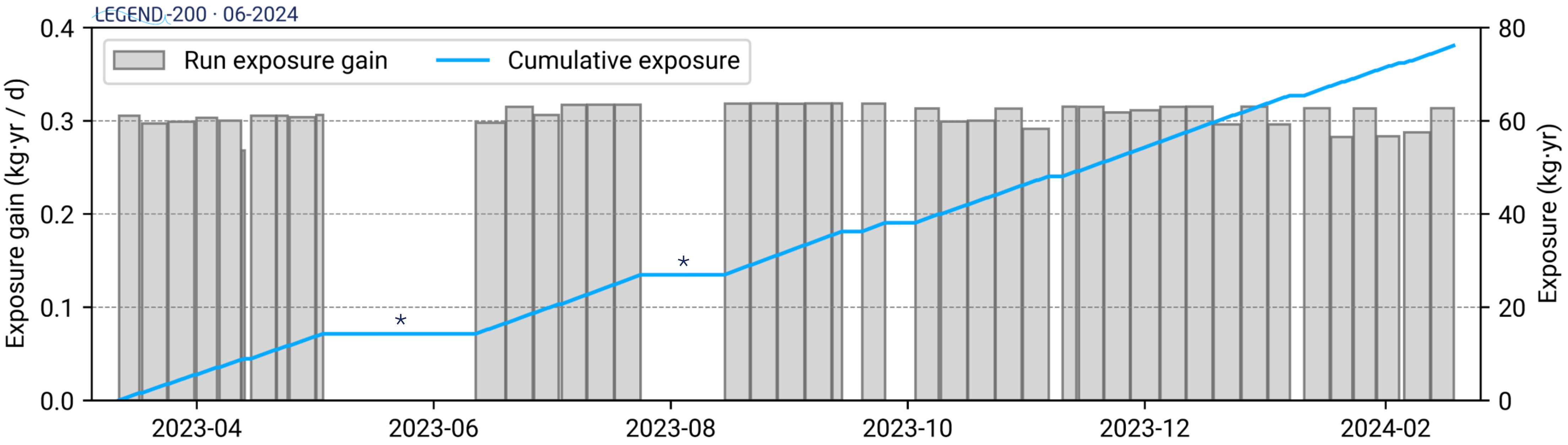

SILVER DATA SET – 76.2 kg·yr

- Background characterization
- All active detectors
- Extra 10.2/5.9 kg·yr of special background characterization runs without outer barrel/mini-shrouds

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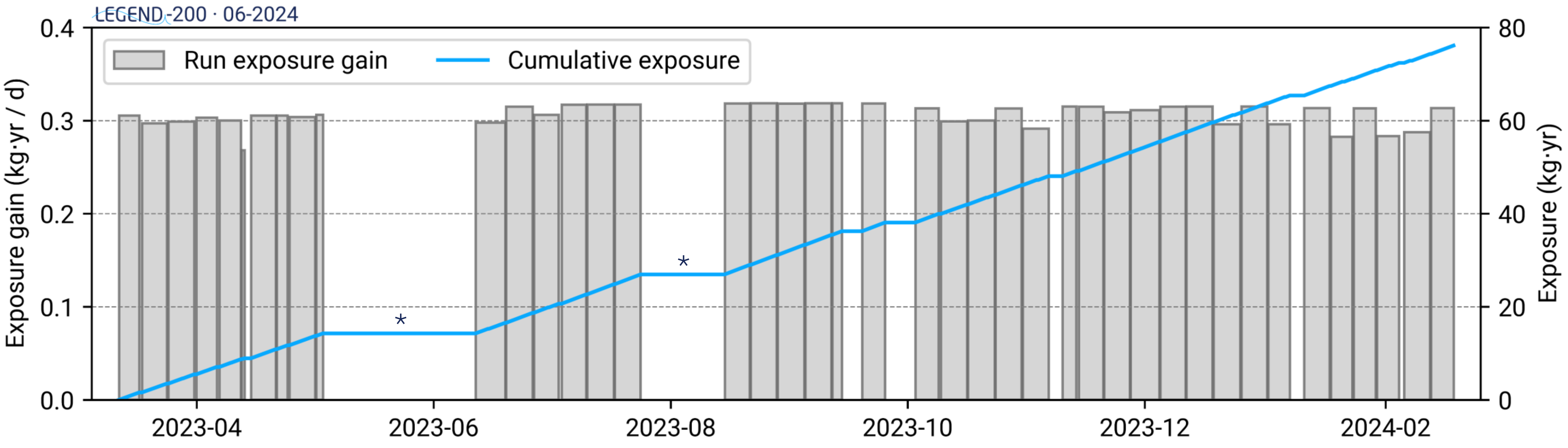

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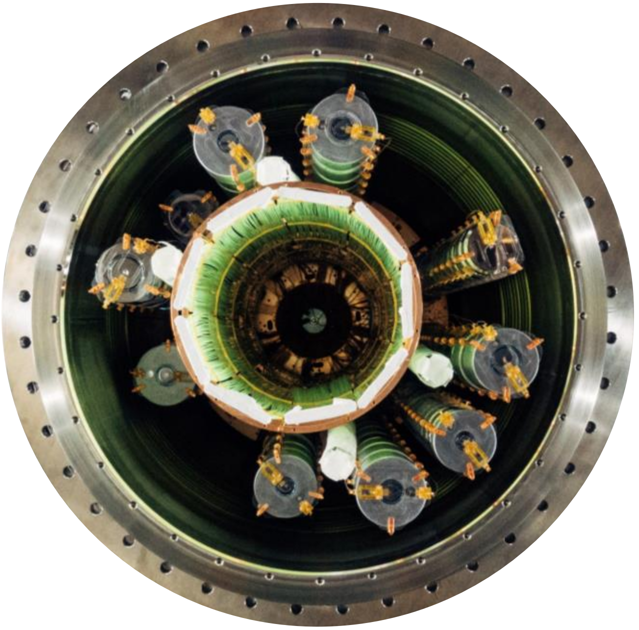
GOLDEN DATA SET – 48.3 kg·yr

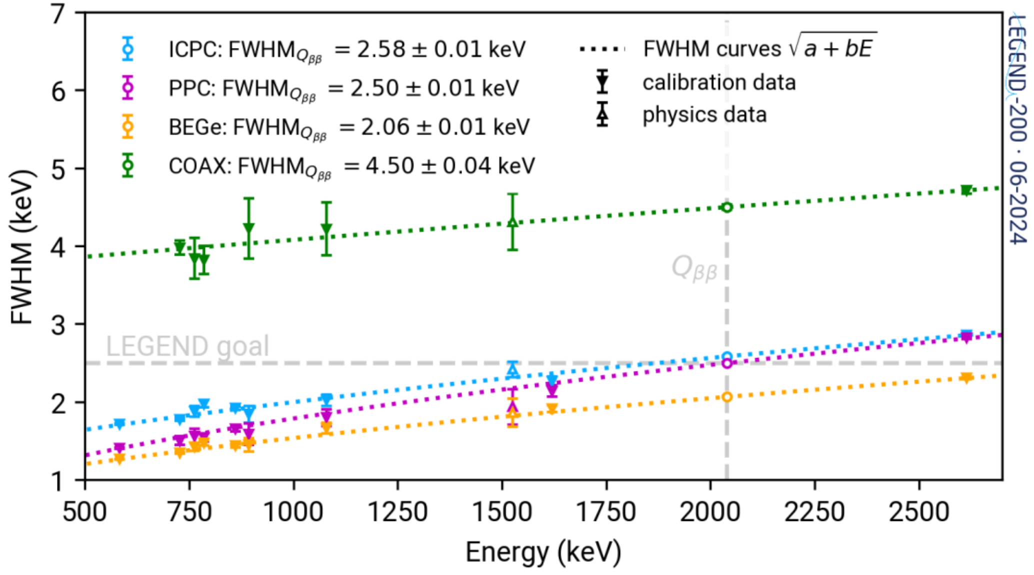
- Final neutrinoless double-beta decay data set
- All active detectors excluding those for which additional PSD cut studies are ongoing

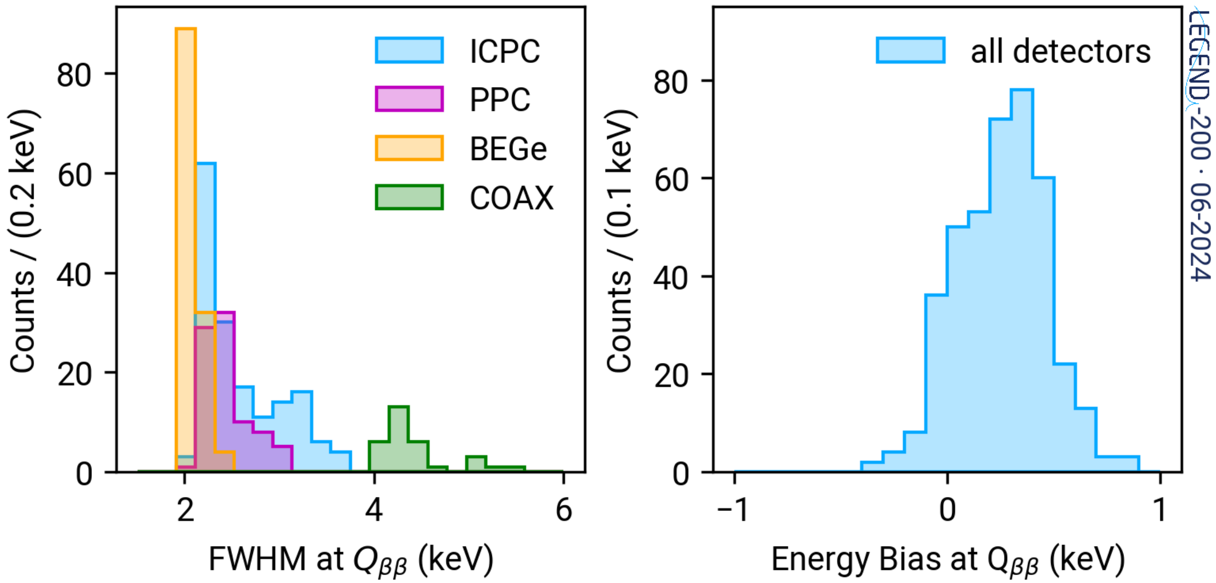
(*) Test or HV scan runs – duty cycle of 91.4% (242 days in total)

Energy Scale and Resolution

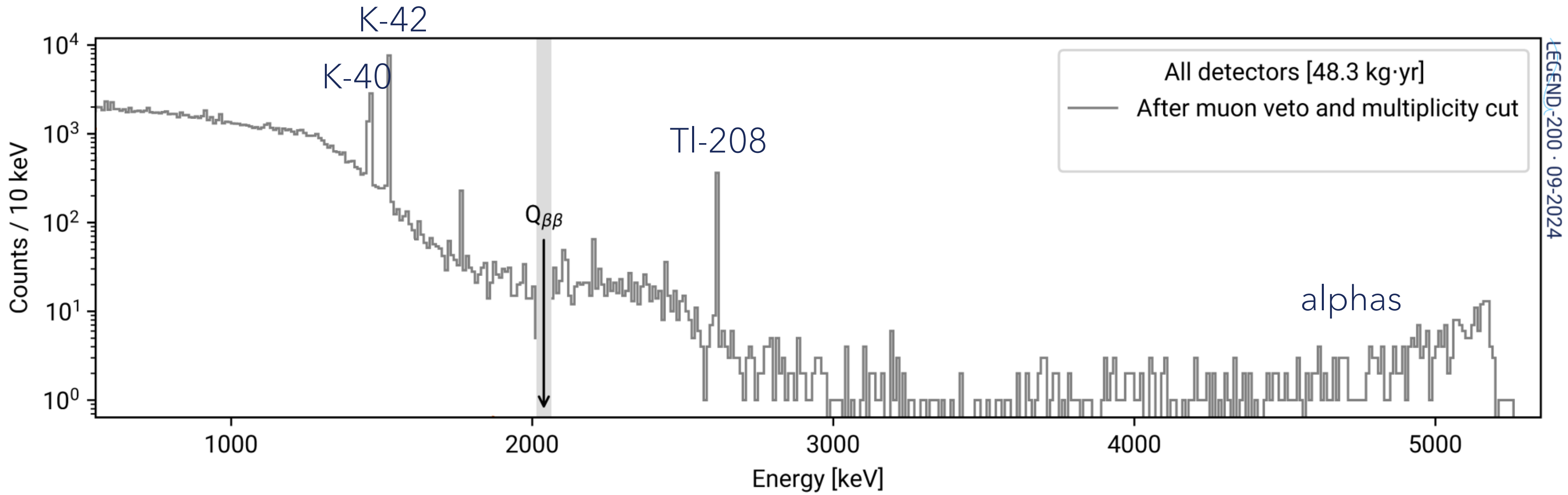
- Weekly energy calibrations between physics runs using Th-228 sources
- Overall resolution of 0.1% FWHM at $Q_{\beta\beta}$ (including large IC detectors)
- Very stable energy scale - energy bias 0.3±0.2 keV at $Q_{\beta\beta}$
- Data partitioned according to stability of energy observables





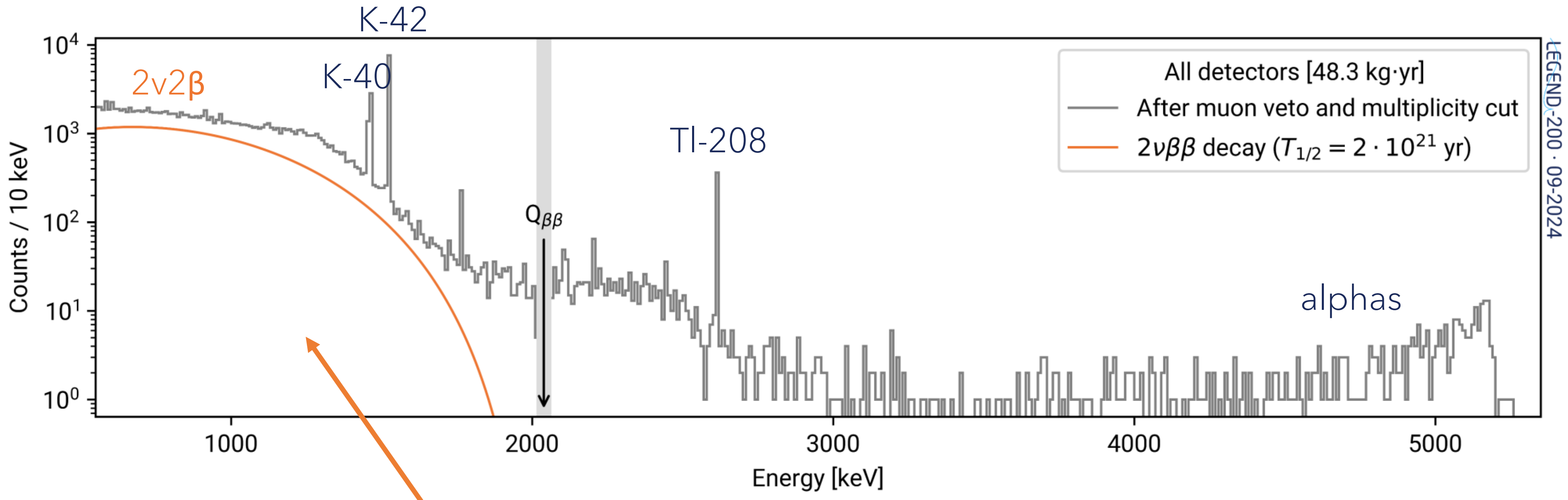


Energy Spectrum - *golden*



- Blinded analysis in $Q_{\beta\beta}\pm25$ keV
- Spectrum after:
  - **data cleaning** → 95-99% survival after removal of unphysical events
  - **muon veto** → 2 events removed at $Q_{\beta\beta}$
  - **multiplicity cut** → 26% events removed at $Q_{\beta\beta}$

Energy Spectrum - *golden*

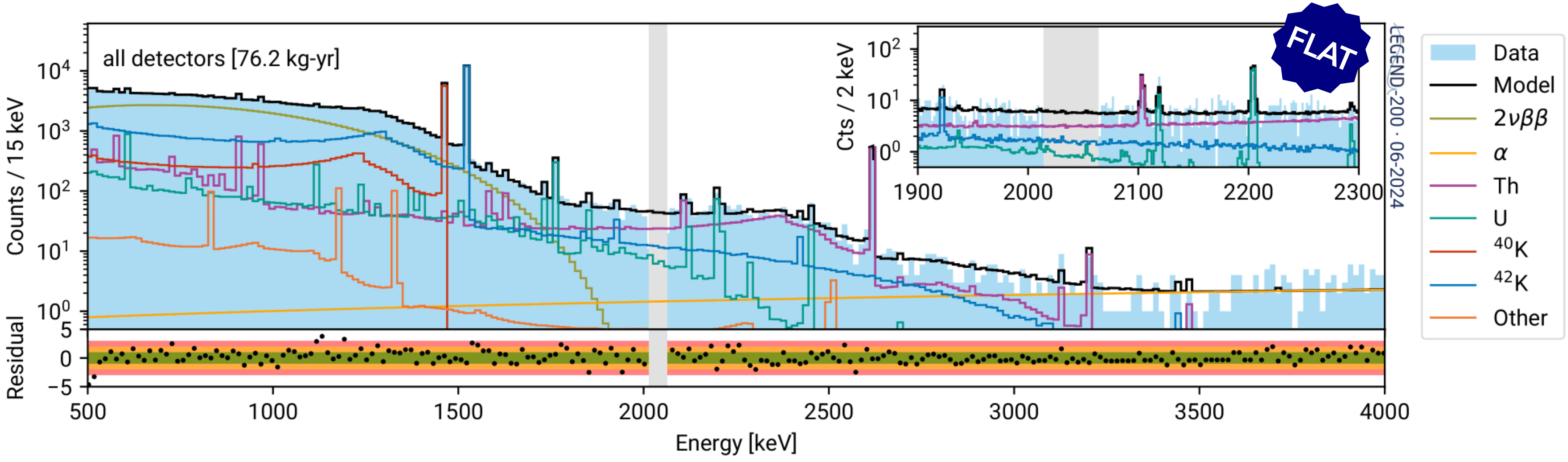


GERDA

PRL 131, 142501 (2023)

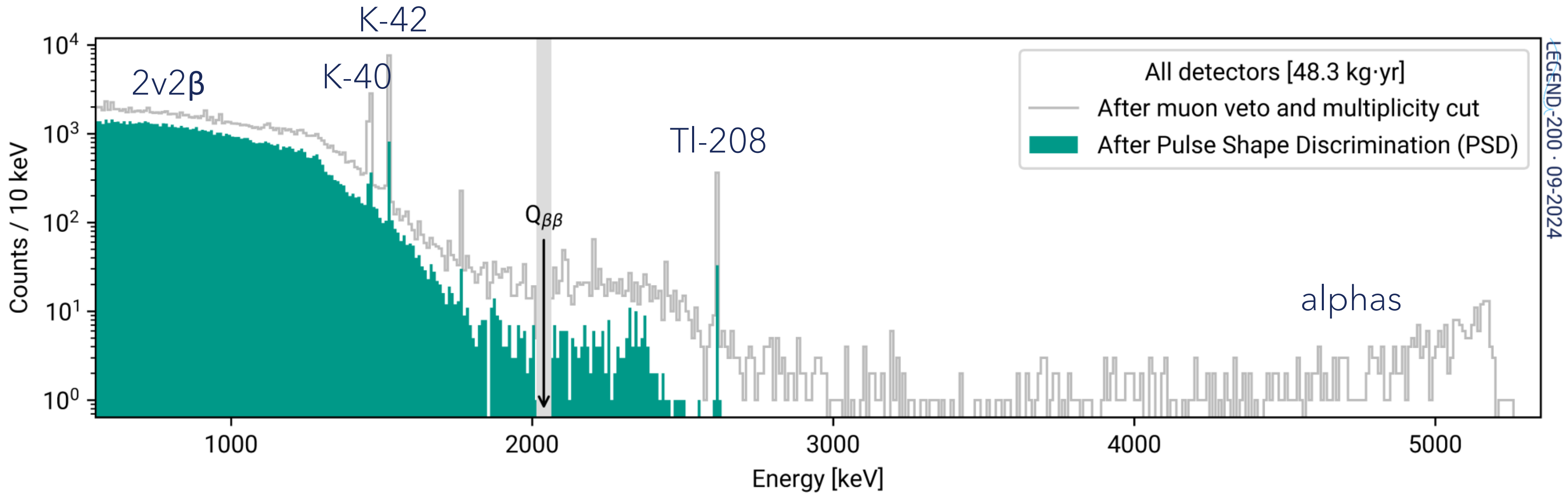
$$T_{1/2}^{2\nu} = 2.022 \pm 0.018_{stat} \pm 0.038_{syst} \times 10^{21}\ \mathrm{yr}$$

Background Model - *silver*

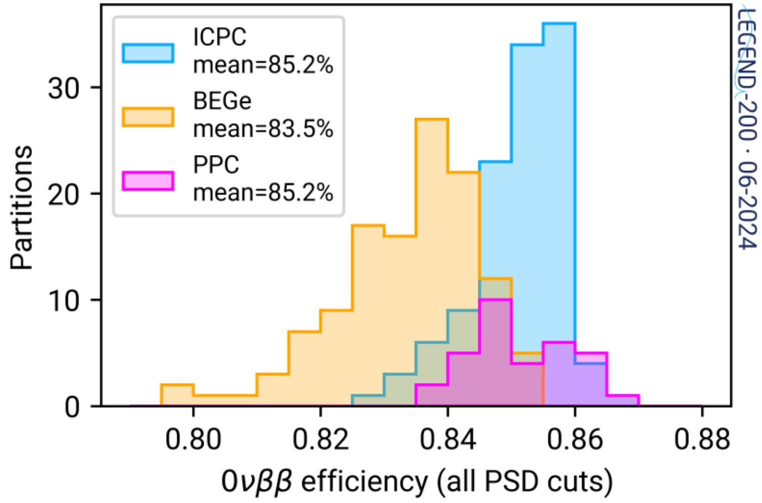


- Decomposition of the full-range energy spectrum
- Bayesian background model using silver data set + 10.2 kg·yr of special runs
- Silver data .vs. simulations and material radioassay: Th-228 underprediction in physics data
  - this background is efficiently suppressed by analysis cuts
  - tested different Th-228 locations via the background model: no hotspots or asymmetries

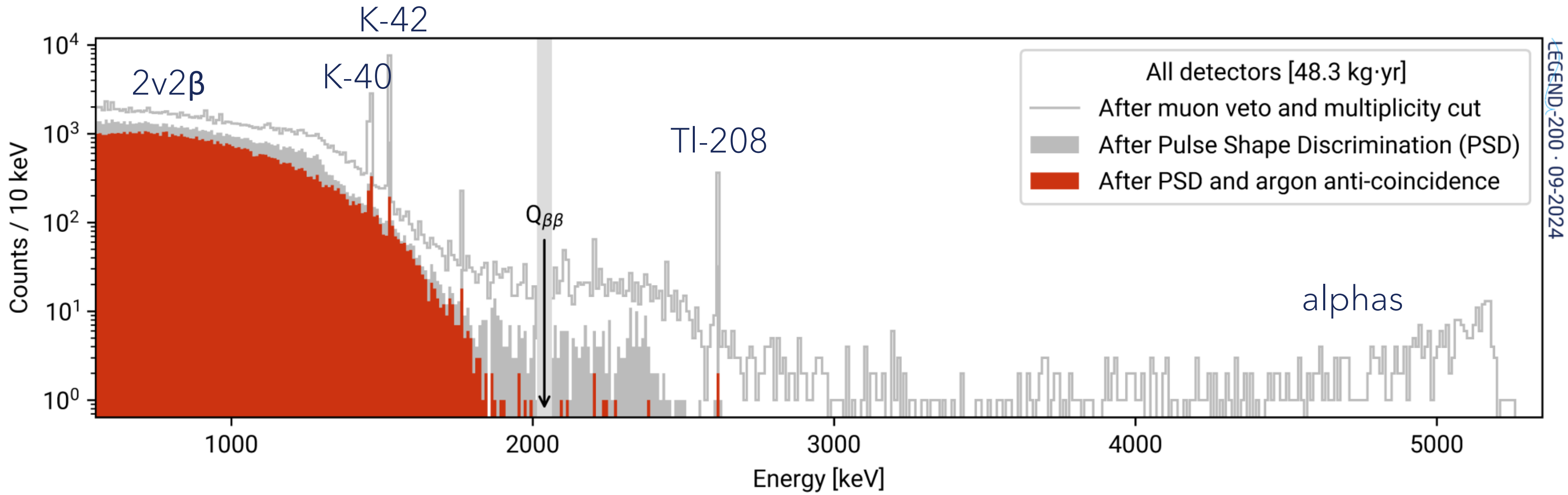
Pulse Shape Discrimination Cut - *golden*



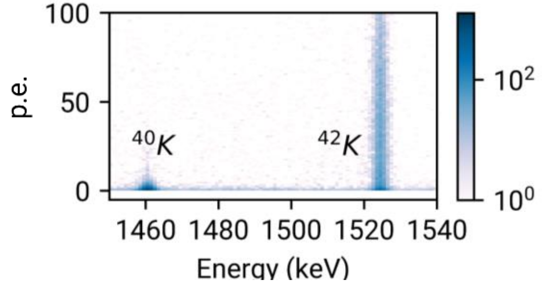
- 60% suppression of Compton MSE at $Q_{\beta\beta}$
- Cut acting on A/E = max(current) / energy
  - Late charge cut for PPC (large passivated surface)
  - Neural-network methods under development for Coaxial
- Data partitioned according to stability of PSD observables

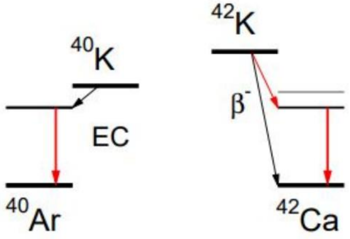


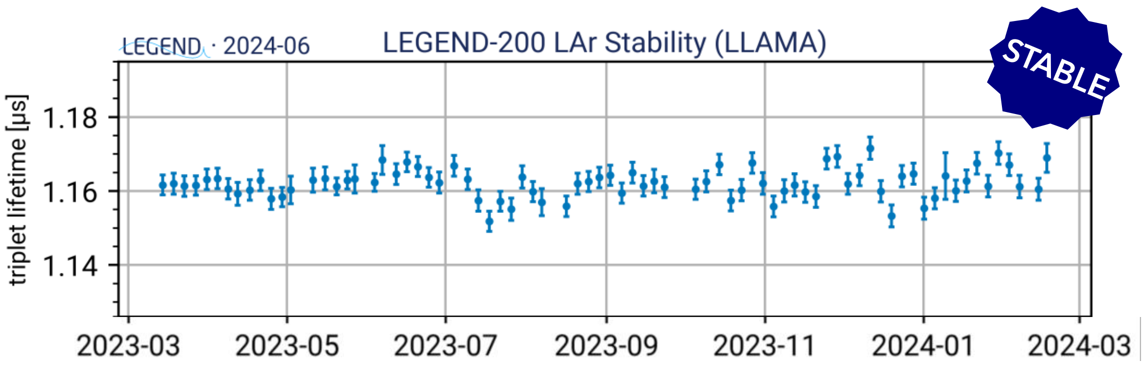
Liquid Argon (LAr) Cut - *golden*



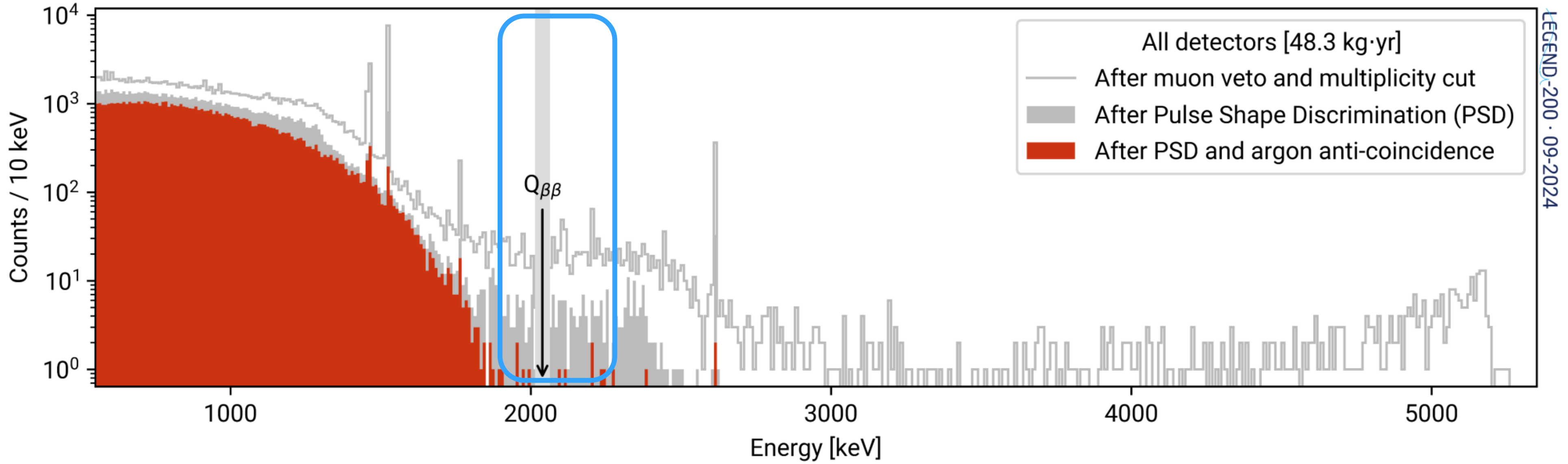
- Strong anti-correlation of PSD & LAr cuts
- Characterized via special runs: 1 p.e. per 10 keV
- ββ decay signal acceptance of ~93%

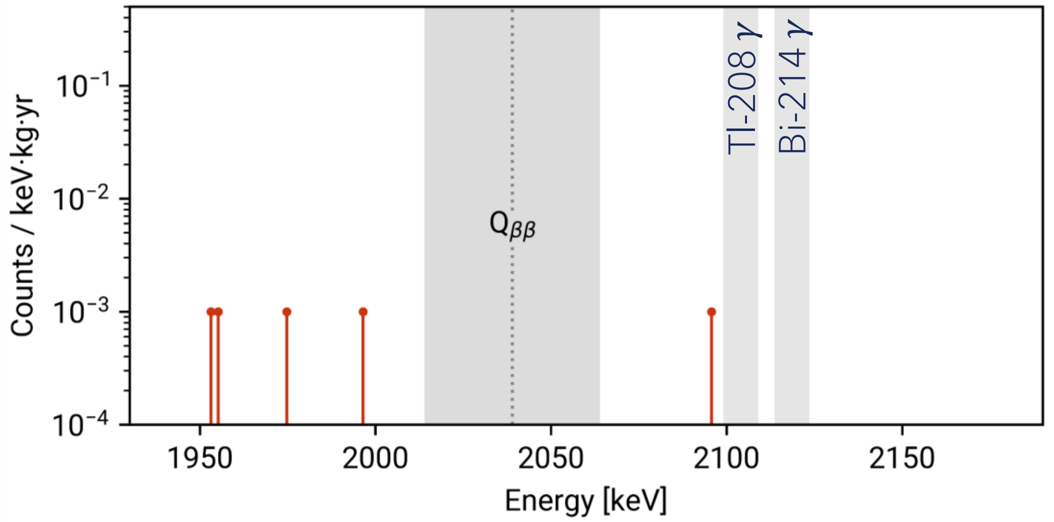






Results Before Unblinding - *golden*

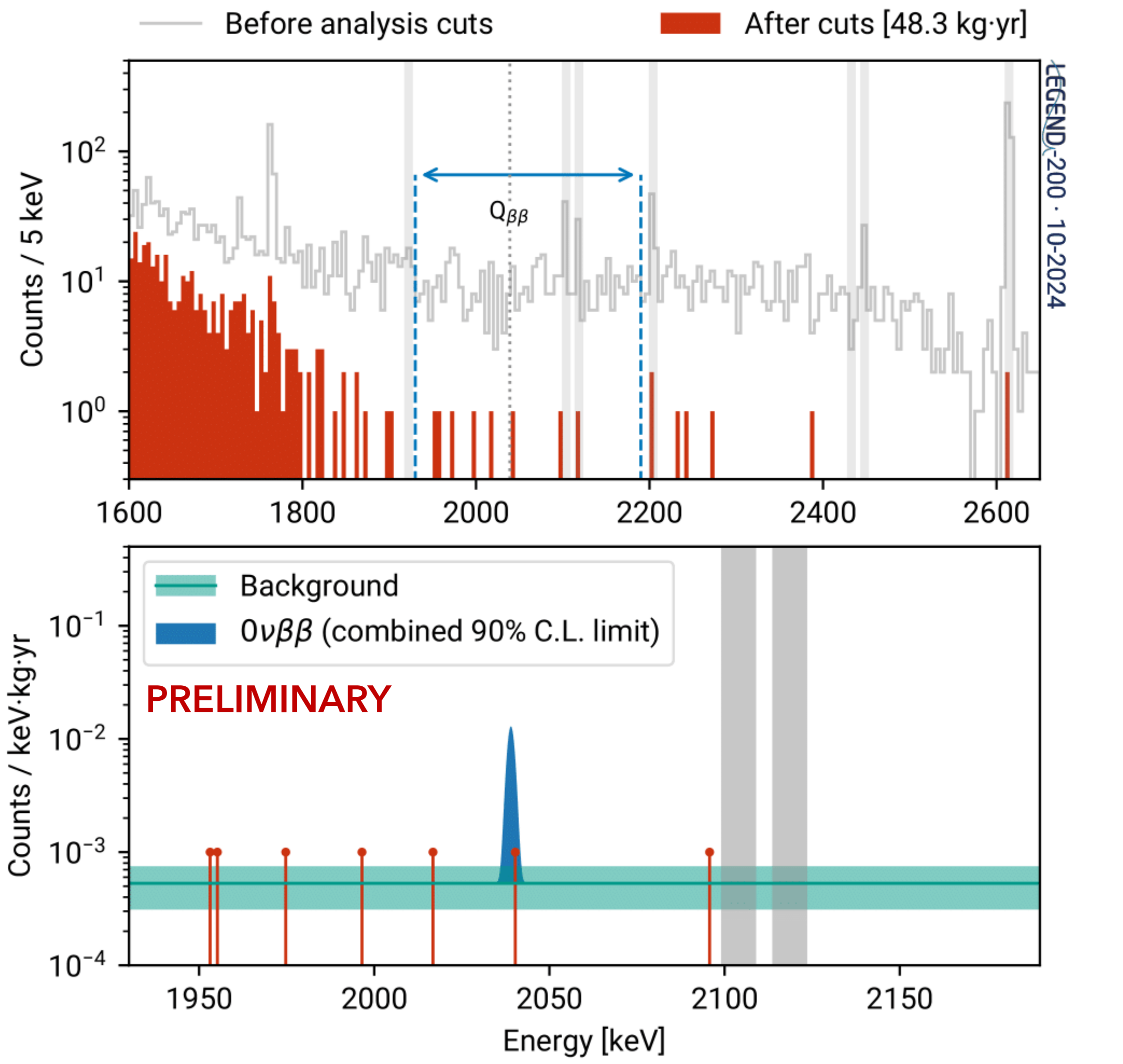




5 surviving events in the analysis window (1930-2190 keV) before unblinding

Results After Unblinding - *golden*

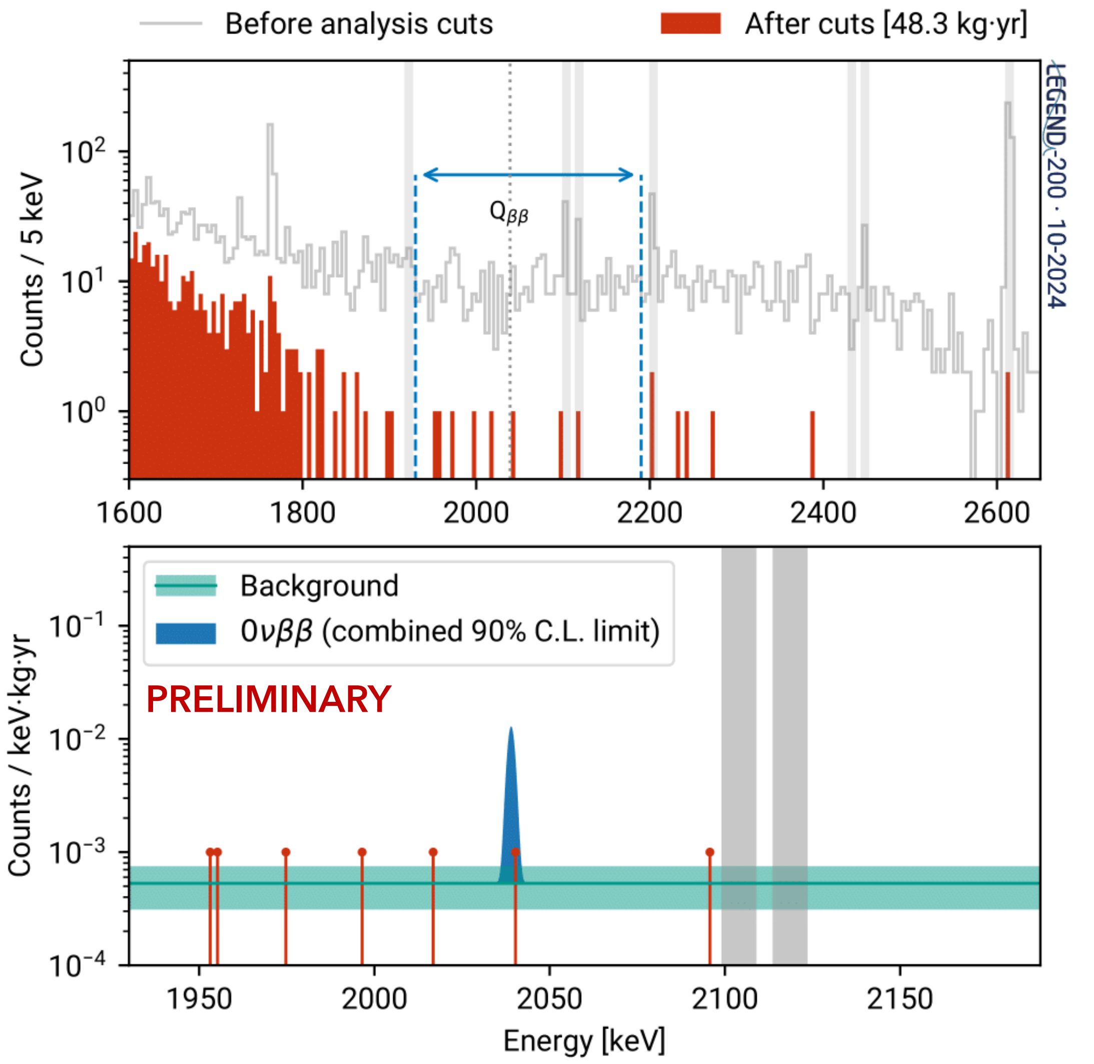
- 7 events after unblinding (1 event at 1.4σ from $Q_{\beta\beta}$)



(*) PRL 125 252502 (2020) (**) PRL 130 062501 (2023)

Results After Unblinding - *golden*

- 7 events after unblinding (1 event at 1.4σ from $Q_{\beta\beta}$)
- BI = 5.3 ± 2.2 × 10^{-4} cts/(keV·kg·yr)
  - world-leading result
  - goal: 2 × 10^{-4} cts/(keV·kg·yr)

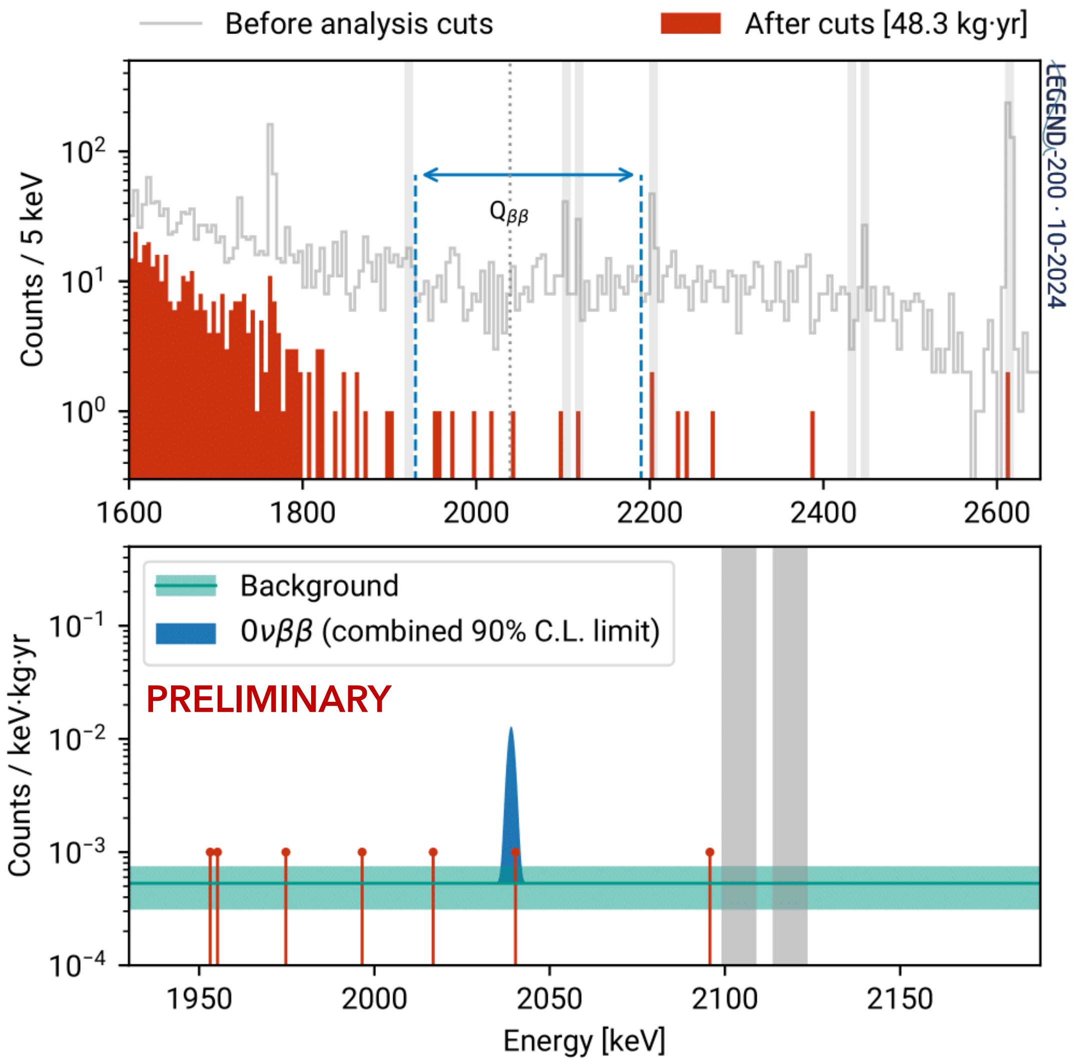


(*) PRL 125 252502 (2020) (**) PRL 130 062501 (2023)

Results After Unblinding - *golden*

- 7 events after unblinding (1 event at 1.4σ from $Q_{\beta\beta}$)
- BI = $5.3 \pm 2.2 \times 10^{-4}$ cts/(keV·kg·yr)
  - world-leading result
  - goal: 2×10^{-4} cts/(keV · kg · yr)
- Unbinned fit of GERDA(*) + MJD (**) + LEGEND-200
  - p-value of background-only = 26%
  - Observed $T_{1/2} > 1.9 \times 10^{26}$ yr @ 90% CL
  - Sensitivity $T_{1/2} = 2.8 \times 10^{26}$ yr @ 90% CL

    +30% thanks to LEGEND-200

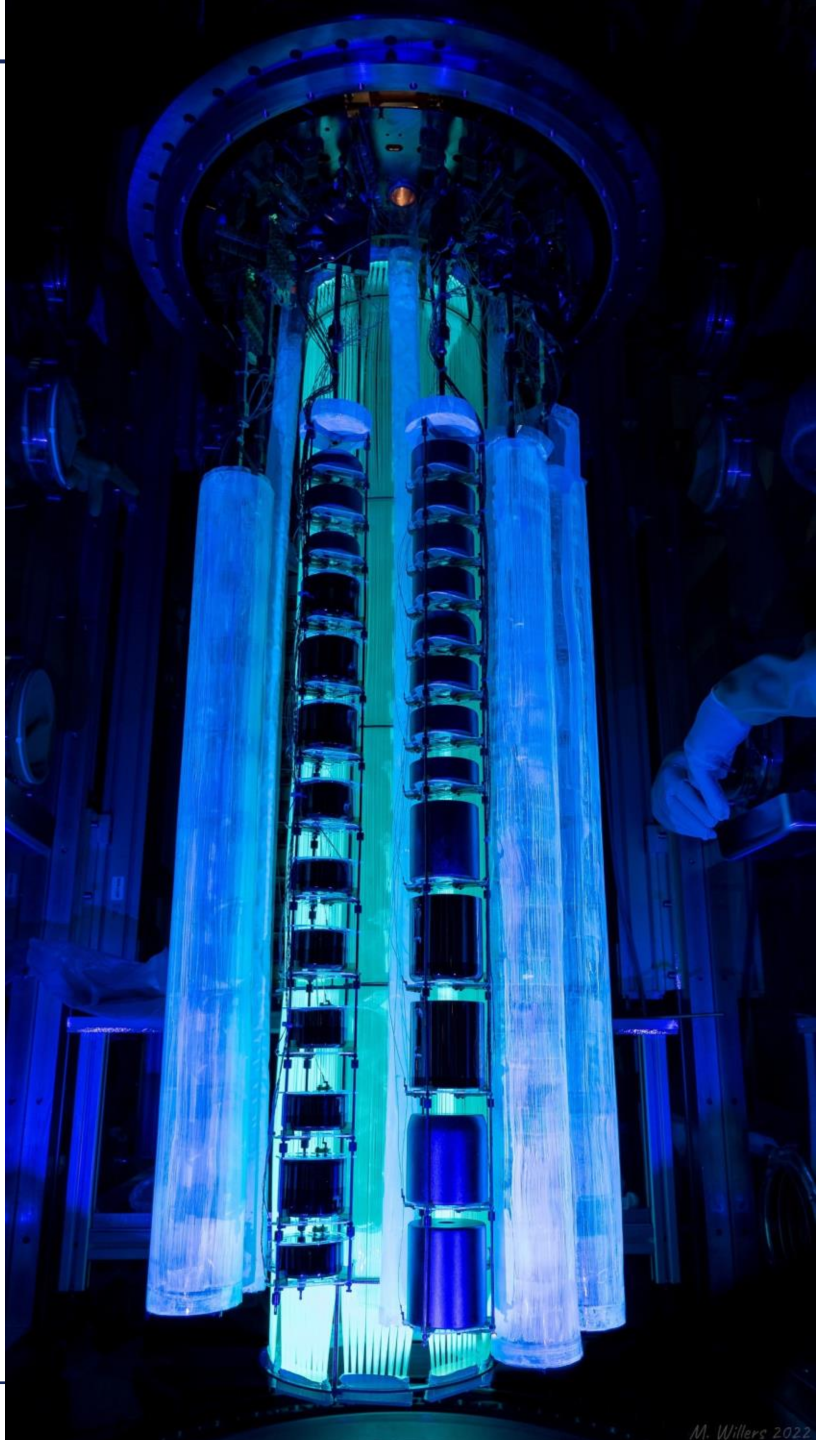


(*) PRL 125 252502 (2020) (**) PRL 130 062501 (2023)

Summary

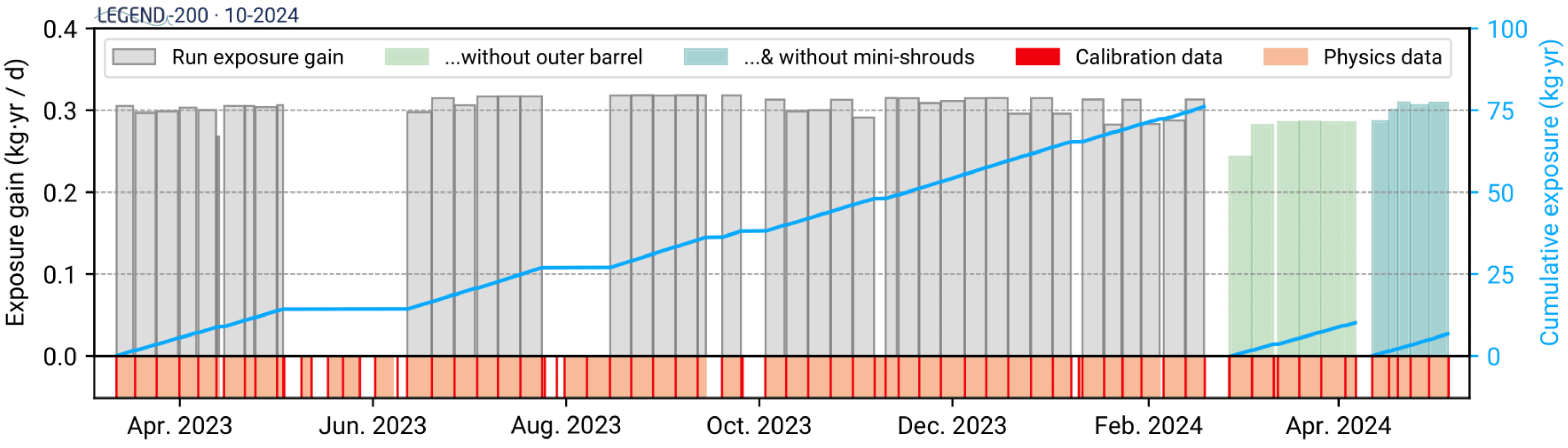
- LEGEND-200
  - fully operative at LNGS
  - first unblinded results over 1 yr of data taking
  - +30% in $0\nu2\beta$ median sensitivity
  - allows for a prompt investigation of issues
  - powerful LEGEND-1000 test-bench
  - ongoing analysis for testing background hypotheses with different setups
  - ongoing radioassay campaign
  - maintenance work (gain in background rejection)
  - install new 35 kg of enr-Ge + restart data taking at the end of 2024
- LEGEND-1000
  - preparations underway at LNGS following Borexino decommissioning
  - funding sought from U.S. (DOE and NSF) and EU
  - funding already in hand from several EU institutions
  - data taking will start in the next decade

Thank you for your attention!



BACKUP

Full LEGEND-200 Exposure



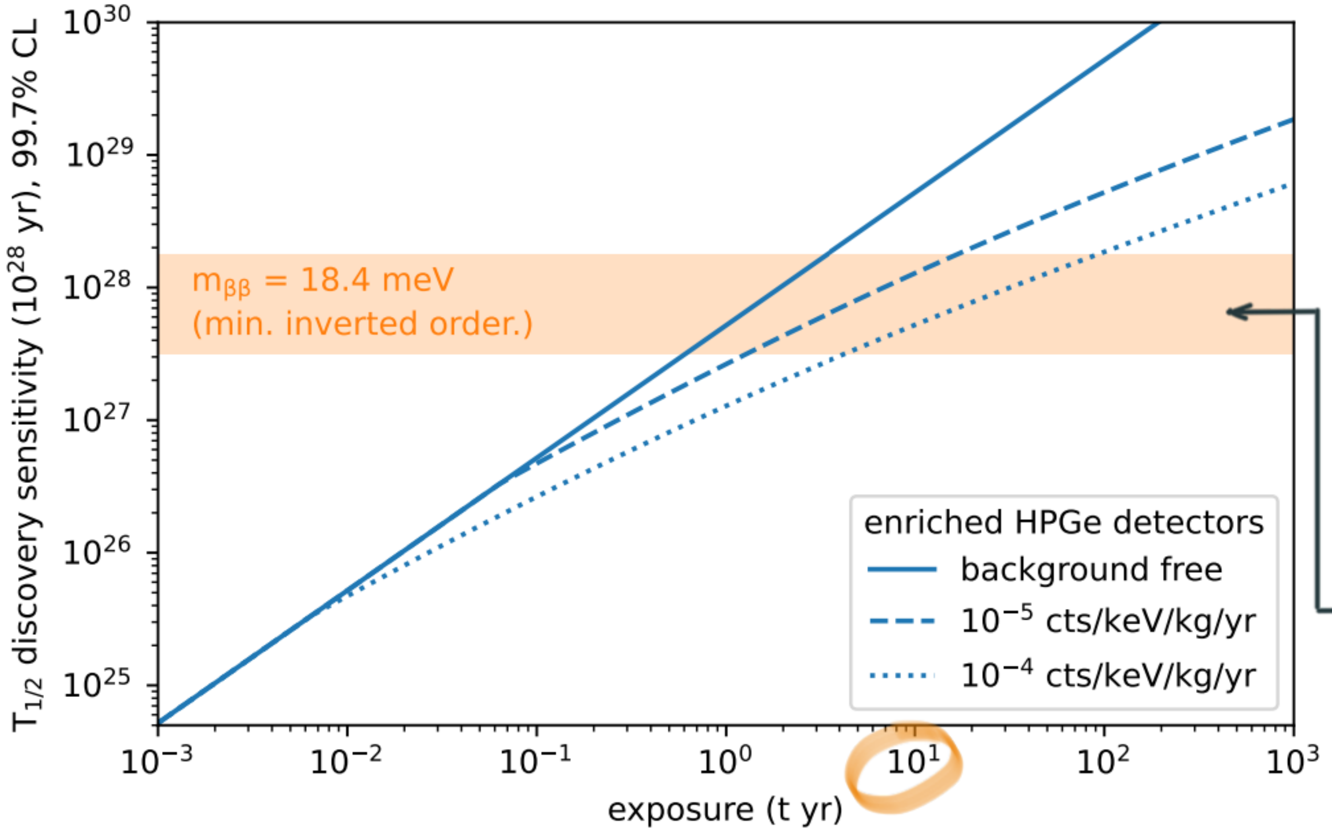
Silver dataset: 76.2 kg·yr
Golden dataset: 48.3 kg·yr

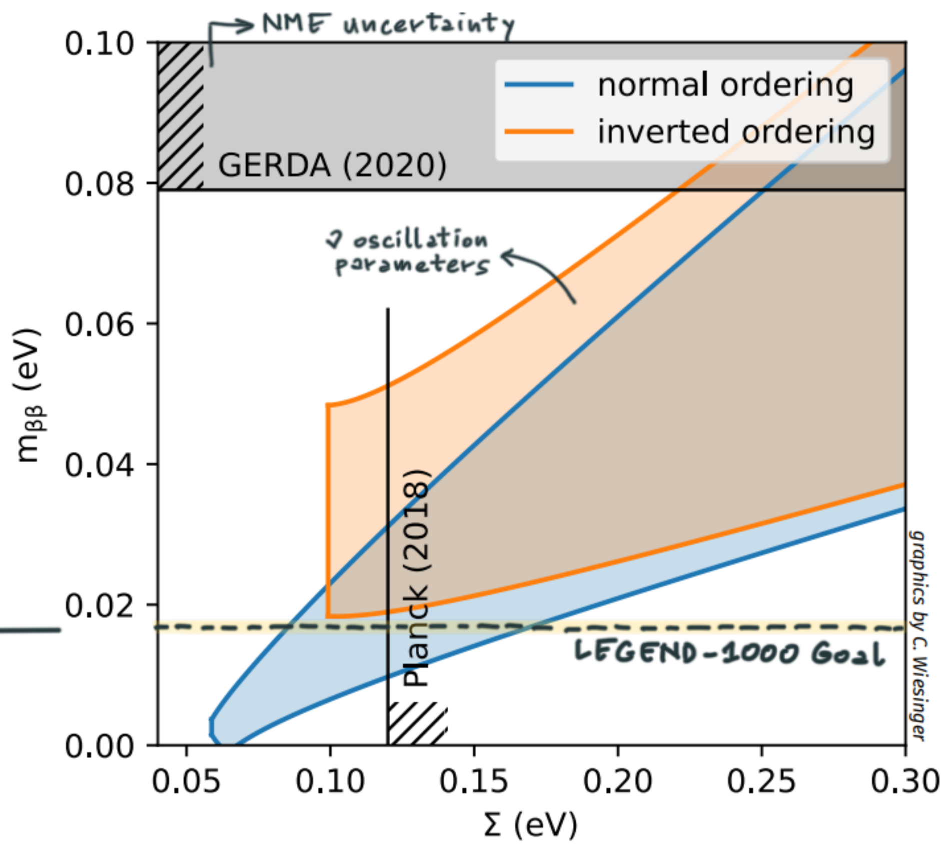
10.2 kg·yr

5.9 kg·yr

Special background characterization runs

LEGEND Sensitivity



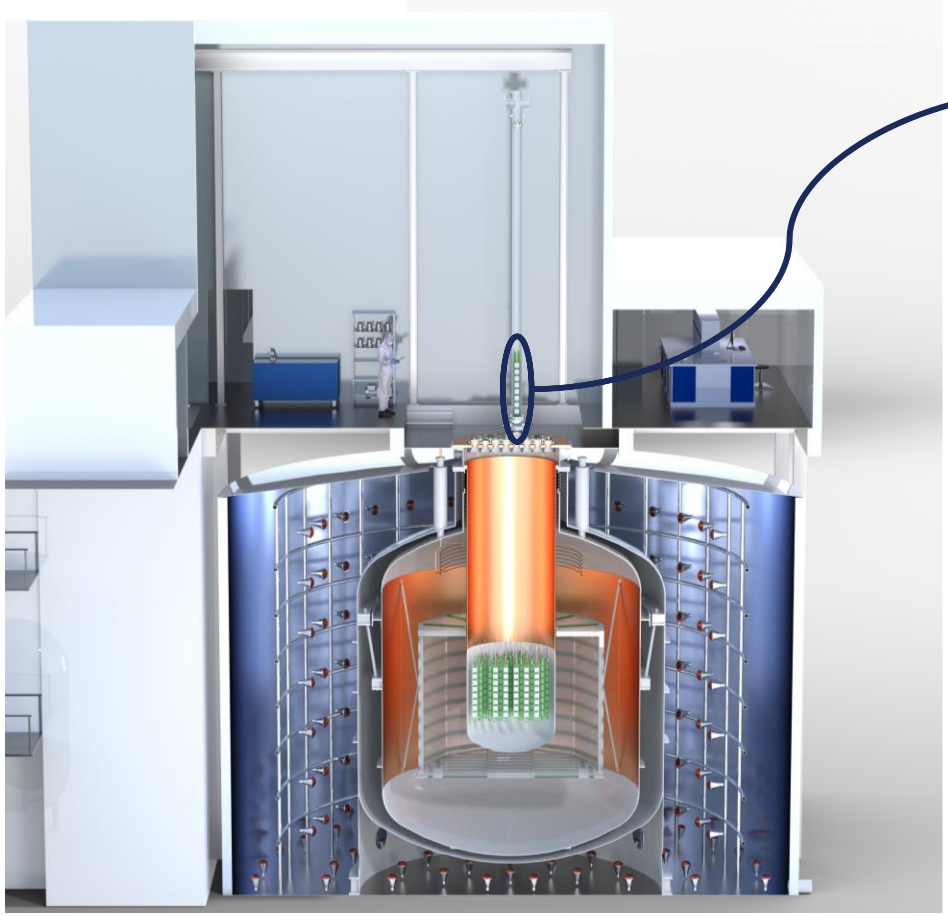


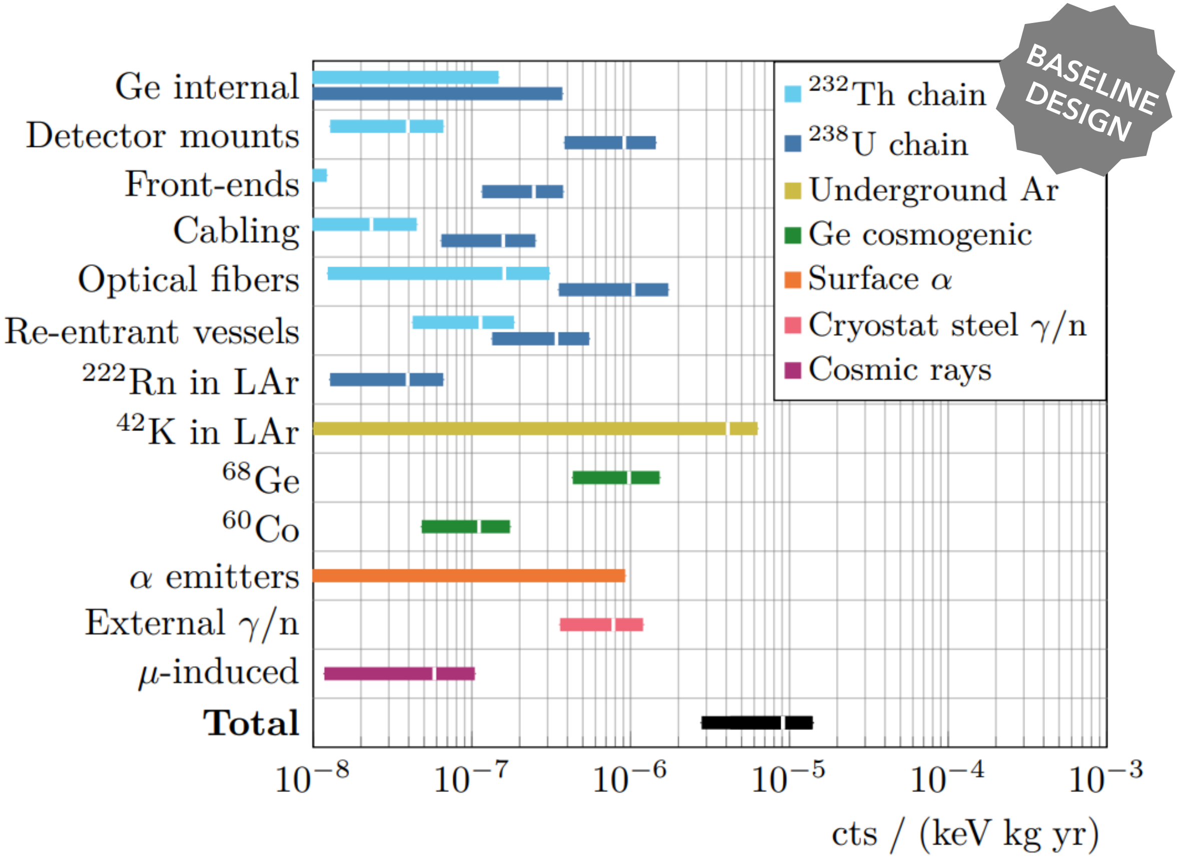
LEGEND-200: $T_{1/2}^{0\nu} > 10^{27}$ yr @ 90% CL
LEGEND-1000: $T_{1/2}^{0\nu} > 1.6 \cdot 10^{28}$ yr @ 90% CL

LEGEND-200: $m_{\beta\beta} < 34 - 78$ meV
LEGEND-1000: $m_{\beta\beta} < 8.5 - 19.4$ meV

LEGEND-1000

Rev. Mod. Phys. 95 (2023) 025002 [2202.01787]

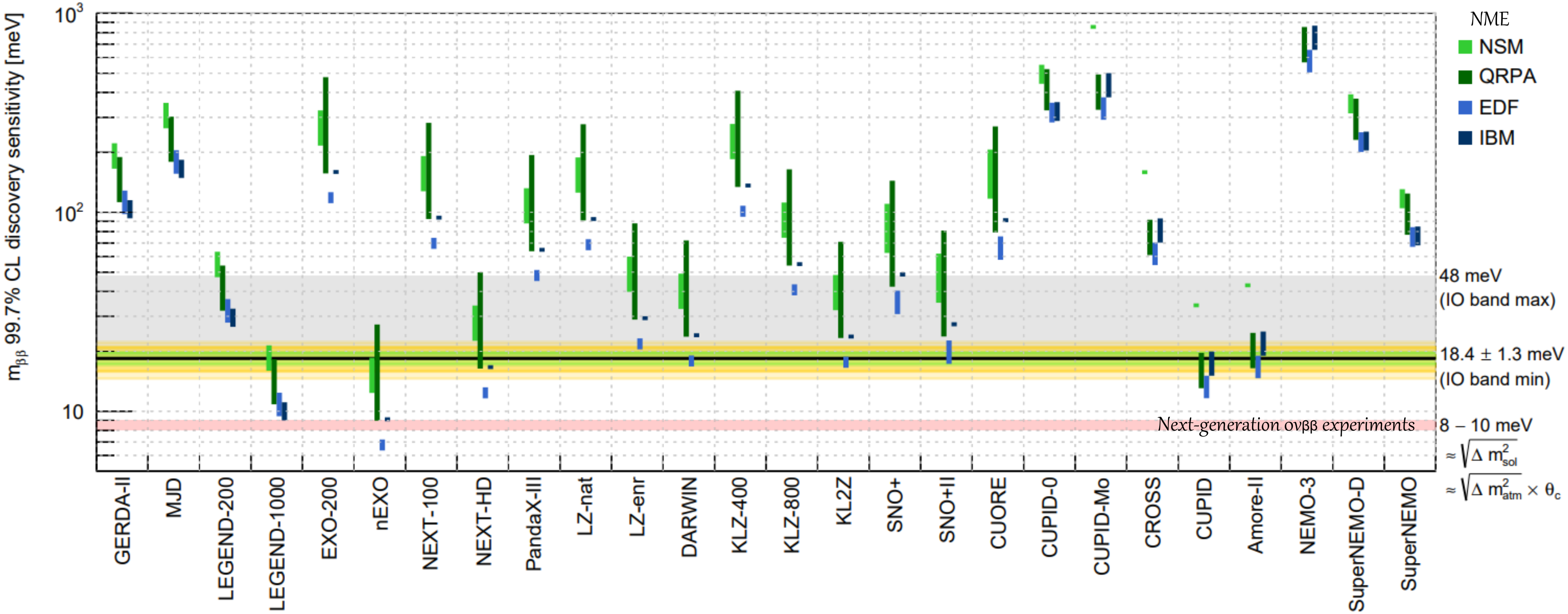




- 48 string modules instrumented with their own LAr system and lock
- Strings are immersed in a re-entrant tube filled with underground LAr (^{42}Ar reduced by a factor 1400)
- H-rich PMMA panels in LAr to moderate neutrons

Discovery Sensitivities

Rev. Mod. Phys. 95 (2023) 025002 [2202.01787]



LEGEND-200: $m_{\beta\beta} < 34 - 78$ meV
LEGEND-1000: $m_{\beta\beta} < 8.5 - 19.4$ meV

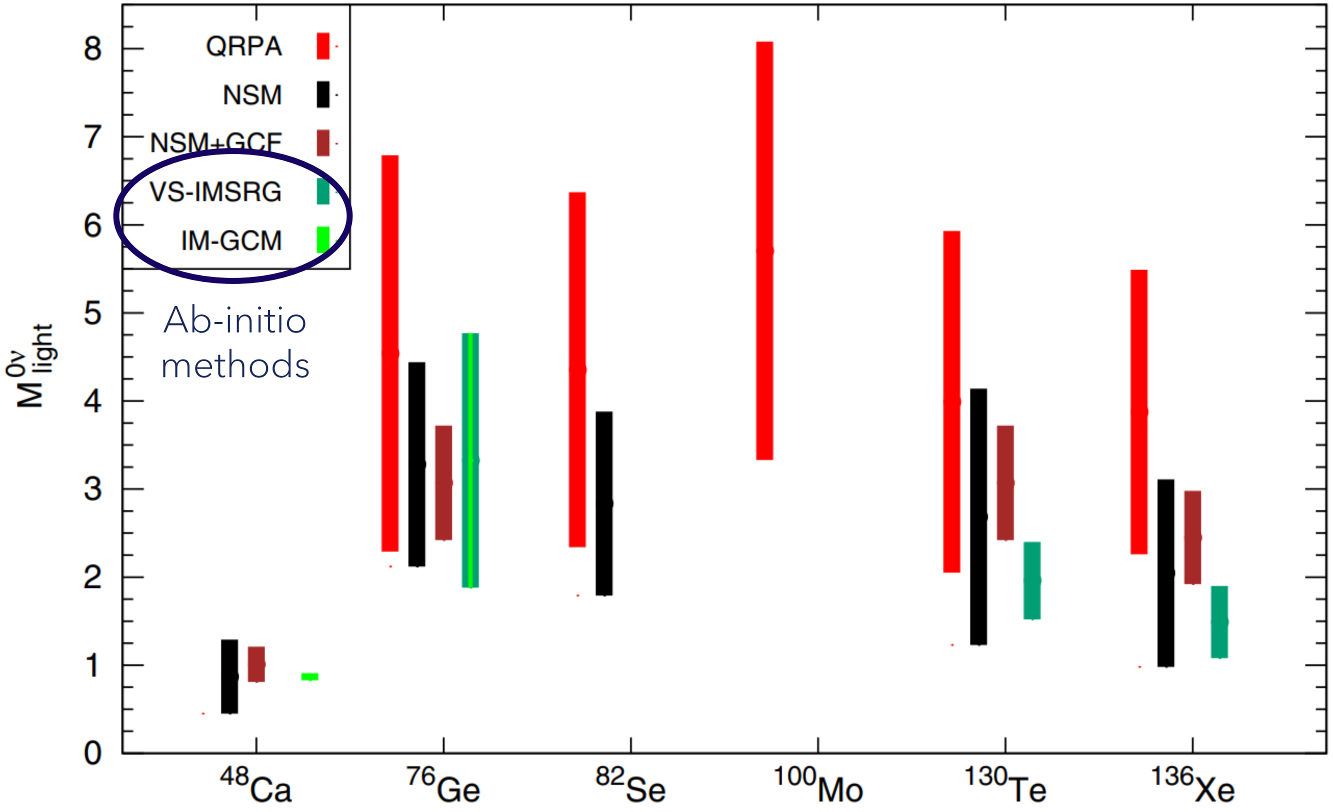
- Gray band: range of values $m_{\beta\beta}$ for the inverse hierarchy and $m_{light} \rightarrow 0$
- $m_{\beta\beta}$=18.4 meV: minimum allowed value for the IO
- 1σ, 2σ, 3σ uncertainty bands for $m_{\beta\beta}$=18.4 meV are shown in green, orange and yellow, respectively
- Red band at 8-10 meV: future aim for 0νββ next-generation experiments

Nuclear Matrix Elements

- NME are extracted for each ββ isotope
- **Many-body models** are dominating the landscape of NME calculations
  - Pros: "easier" than *ab initio* methods
  - Cons: introduce large uncertainties, especially for nuclei with complex nuclear structures

  → quenching factor: Gamow-Teller NMEs are systematically overestimated (unknown origin)
- ***Ab initio* and first principles methods** experienced an exponential boost in the last decade
  - Pros: all nucleons are included in the computation, and interactions between them are treated via realistic nuclear forces
  - Cons: more complex & computationally expensive than many-body models

J.J. Gómez-Cadenas, J. Martín-Albo, J. Menéndez, M. Mezzetto, F. Monrabal and M. Sorel, Riv. Nuovo Cim. 46 (2023) 619



$$\frac{1}{T^{0\nu}_{1/2}} = \mathcal{G}^{0\nu} g_A^4 \left(\mathcal{M}^{0\nu}_{\text{light}}\right)^2 \left(\frac{m_{\beta\beta}}{m_e}\right)^2$$

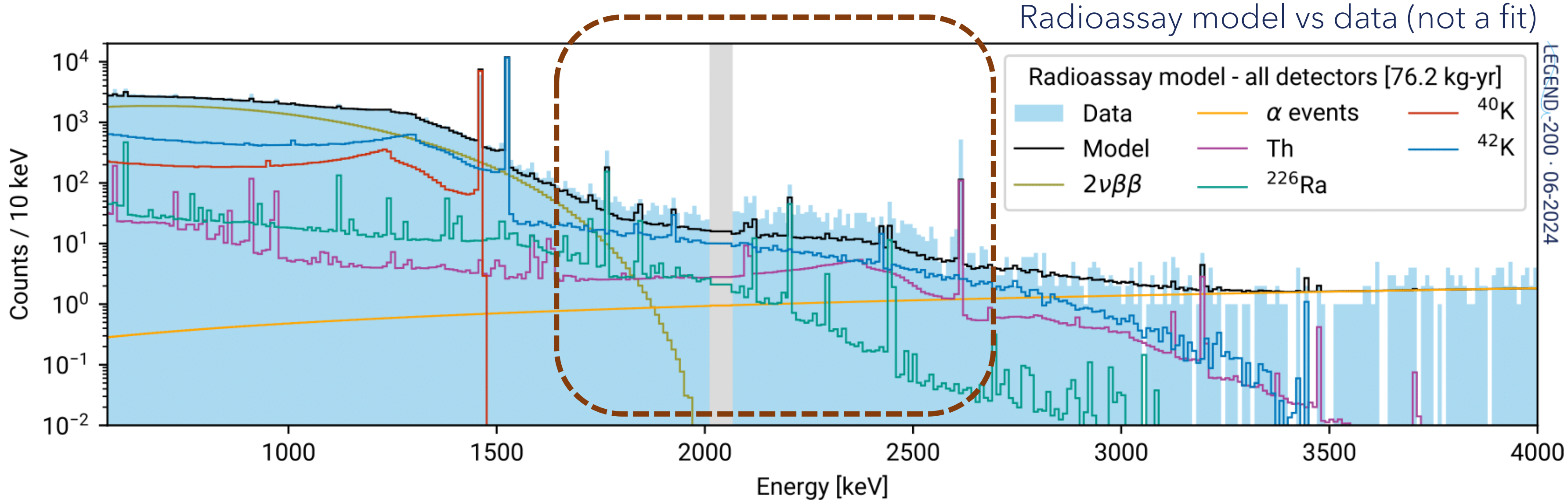
$$\mathcal{M}^{0\nu}_{\text{light}} = \mathcal{M}^{0\nu}_{\text{short}} + \mathcal{M}^{0\nu}_{\text{long}}$$

QRPA = quasiparticle random-phase approximation
NSM = nuclear shell model
GCF = generalized contact formalism
VS-IMSRG = valence-space in-medium similarity renormalization group
IM-GCM = in-medium generalized coordinate method

Radioassay Model - *silver*

Silver data .vs. material radioassay: **Th-228 underprediction in physics data**

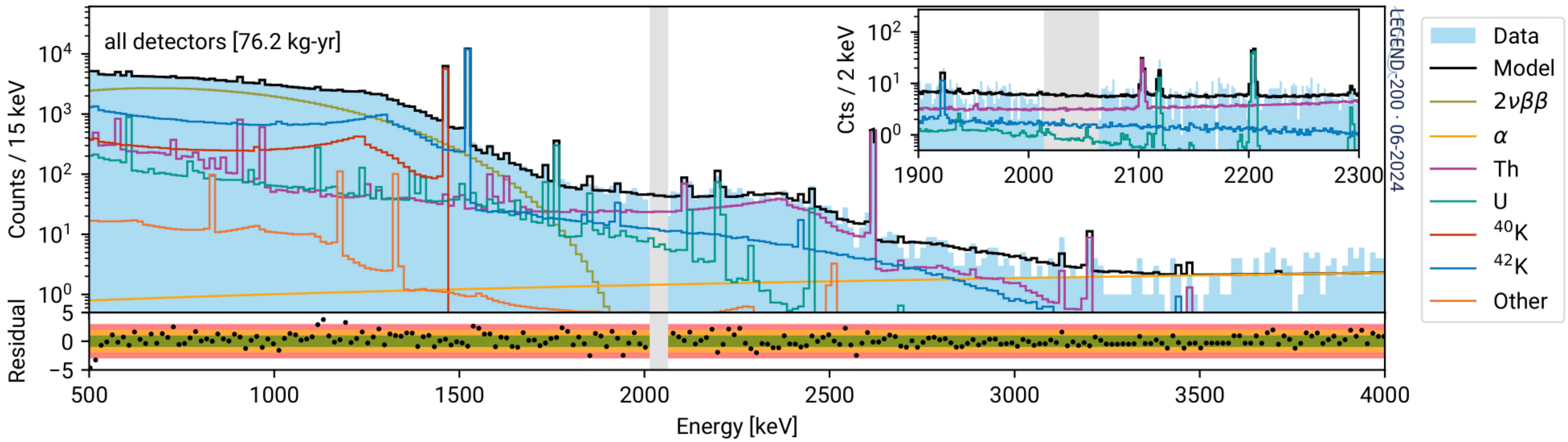
Radioassay model vs data (not a fit)



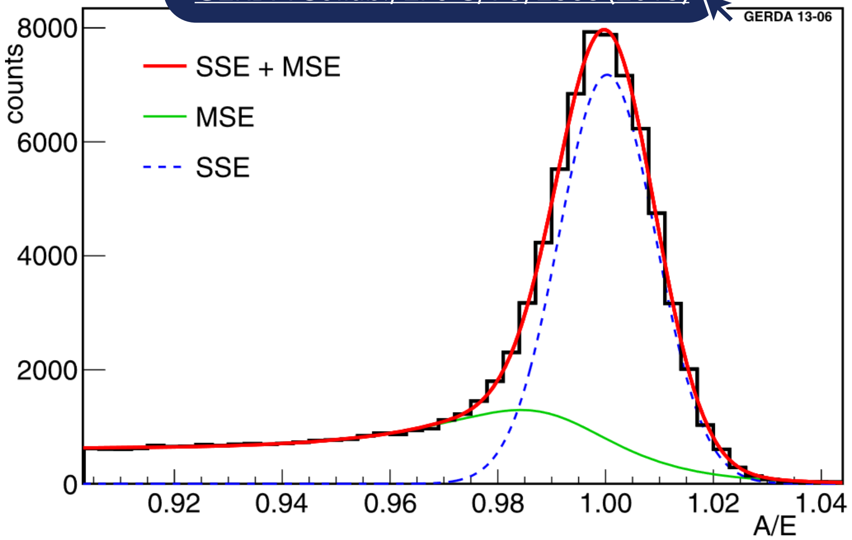
Background model fundamental for

- predicting the shape/composition of events in the $Q_{\beta\beta}$ region
- identifying residual impurities and their location
- finding alternative strategies to further reduce the background

Background model vs data (fit)



Pulse Shape Discrimination (PSD) Analysis



- A/E: gaussian (SSE) + tail at low energies (MSE):

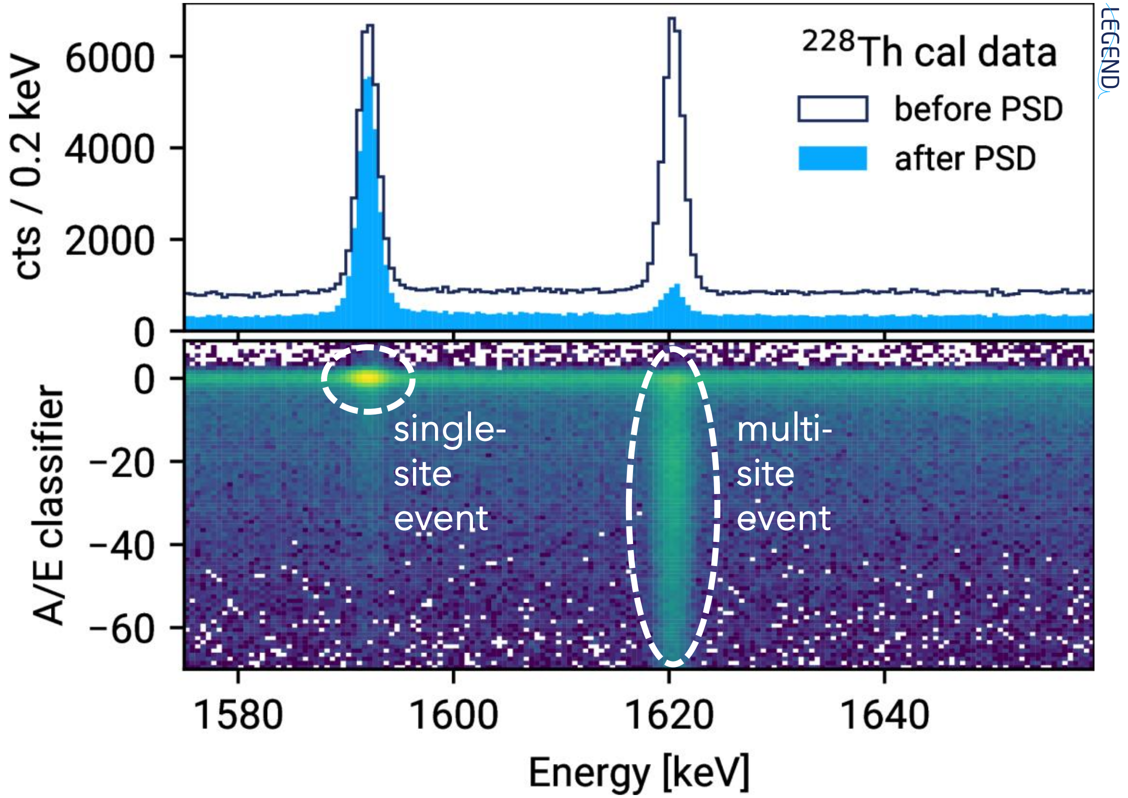
$$f(x = A/E) = \frac{n}{\sigma_{A/E} \cdot \sqrt{2\pi}} \cdot e^{-\frac{(x-\mu_{A/E})^2}{2\sigma^2_{A/E}}}$$

$$+ m \cdot \frac{e^{f\cdot(x-l)} + d}{e^{(x-l)/t} + l}$$

- Cuts over A/E are performed for each detector separately
- "A/E classifier": energy independent,

$$\zeta = ([A/E] / \mu_{A/E}(E) - 1) / \sigma_{A/E}$$

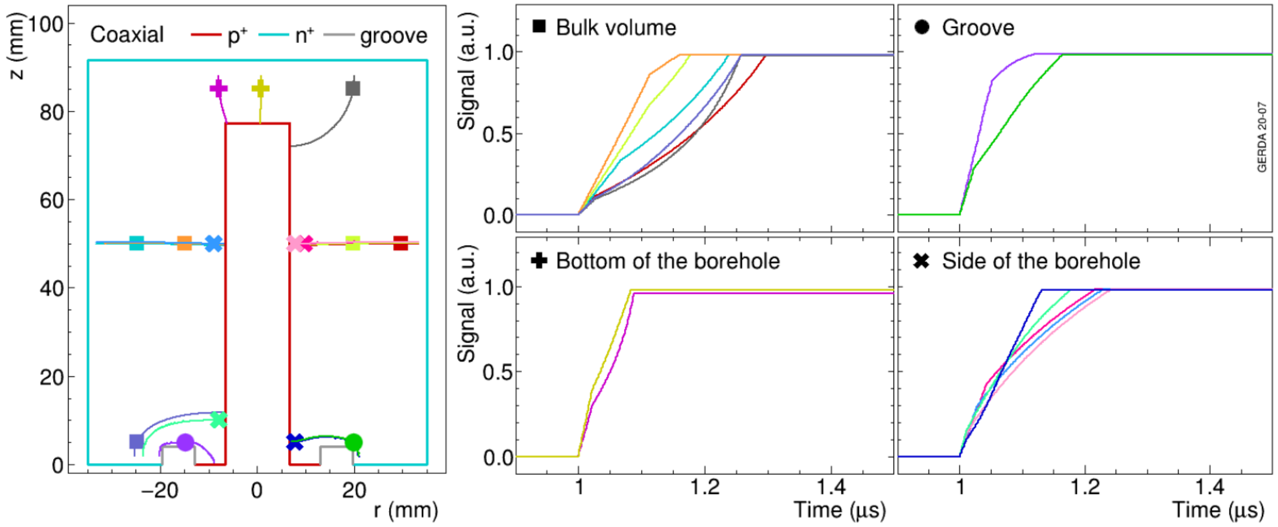
- ζ distribuited around 0, with std=1 for SSEs



Additional PSD cuts

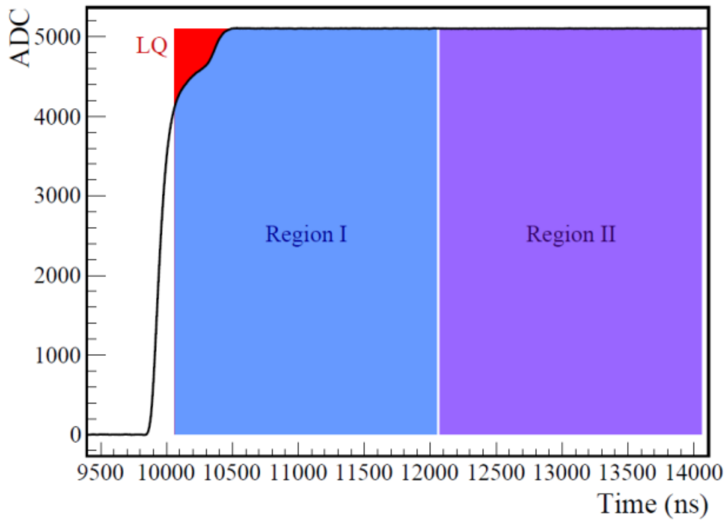
COAX detectors

GERDA Collab., EPJ C, 82, 284 (2022)



- Due to the geometry of COAX detectors, the pulse formation is affected by the drift of e-e+
  - different pulse shapes throughout the bulk of the diode

PPC detectors



- Late charge (LQ) cut is defined as integrated drift time for charge carrier after the waveform reaches 80% of its maximum
- Sensitive to events with slow components or kinks

0ν2β Experiments

Rev. Mod. Phys. 95 (2023) 025002 [2202.01787]

HPGe Diodes
Excellent resolution and efficiency, low bkg level

Xenon *Time Projection Chambers*
High m_{iso}, tracking of particles

Liquid Scintillators
High m_{iso}

Cryogenic Calorimeters
Excellent resolution and efficiency, high granularity

Tracking Calorimeters
Tracking of particles, decay kinematics