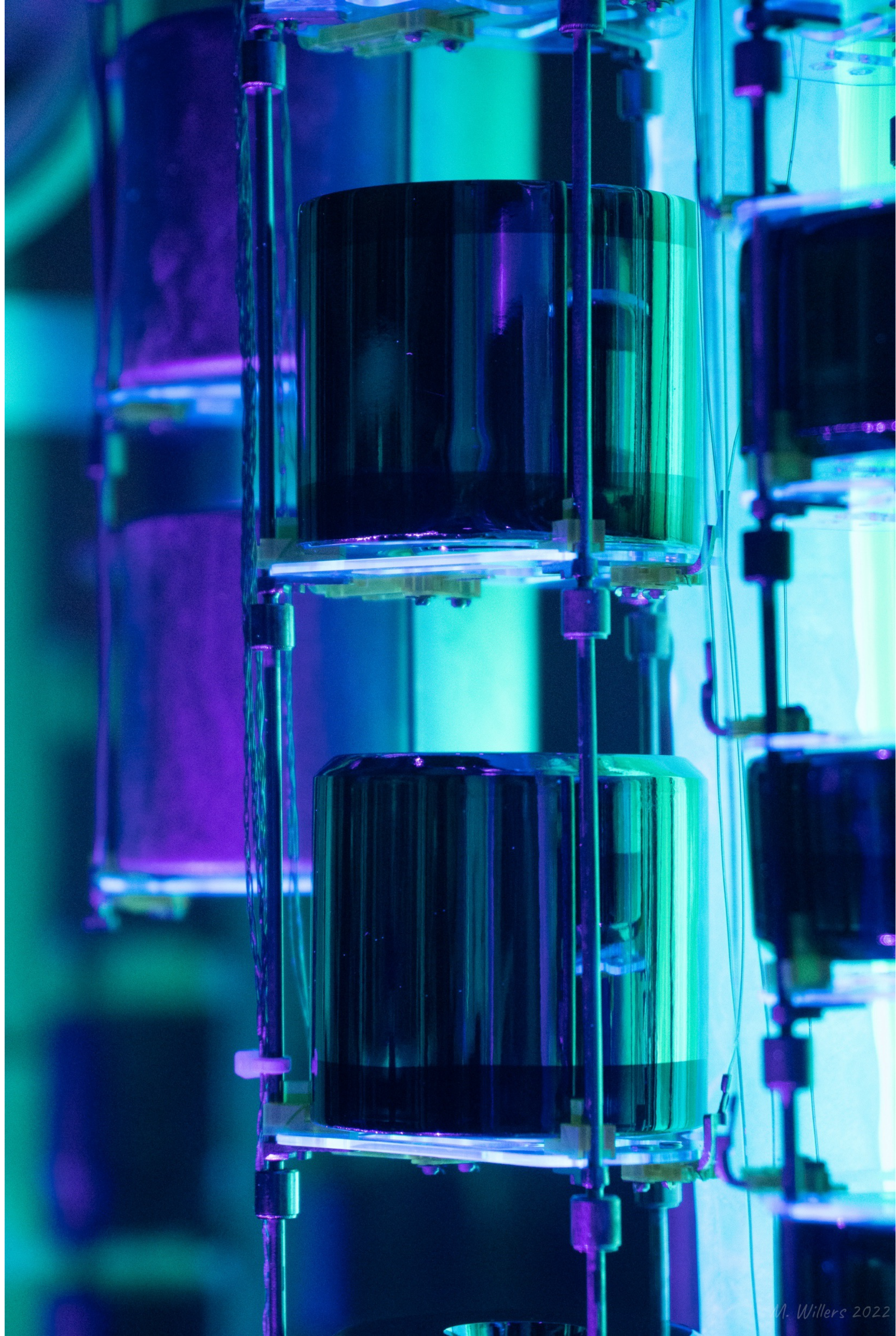
UNIVERSITÀ DEGLI STUDI DI PADOVA

INFN Istituto Nazionale di Fisica Nucleare

LEGEND

Large Enriched Germanium Experiment for Neutrinoless ββ Decay

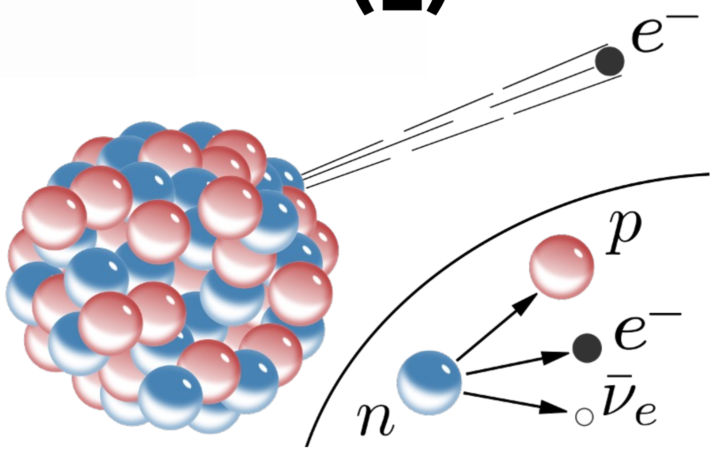
Search for 0νββ in ^{76}Ge with the LEGEND experiment at Gran Sasso



on behalf of the LEGEND Collaboration

Alberto Garfagnini, TAUP 2025, Aug 25, 2025, 西昌, China

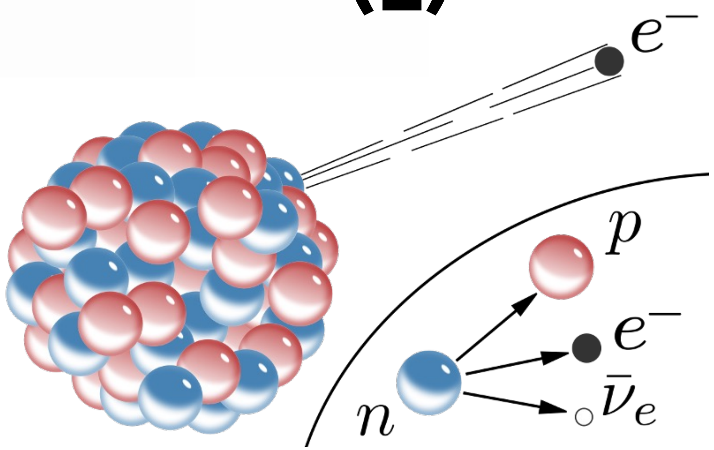
Double β decay (1)



- It's a nuclear transition, with 2 neutrons decaying into 2 protons

  (A,Z) → (A, Z+2) + 2 e^- + …

Double β decay (1)



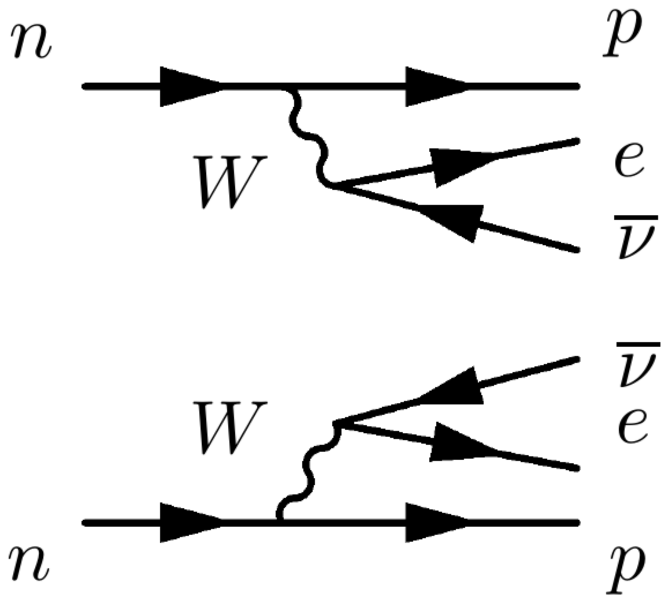
- It's a nuclear transition, with 2 neutrons decaying into 2 protons

  (A,Z) → (A, Z+2) + 2 e$^-$ + …

2 neutrino double-β decay (2νββ)

- it's a second order process, allowed in the Standard Model of Particle Physics
- first suggested by Goeppert-Mayer in 1935
  [M. Goeppert-Mayer, Phys. Rev. 48 (1935) 512]

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

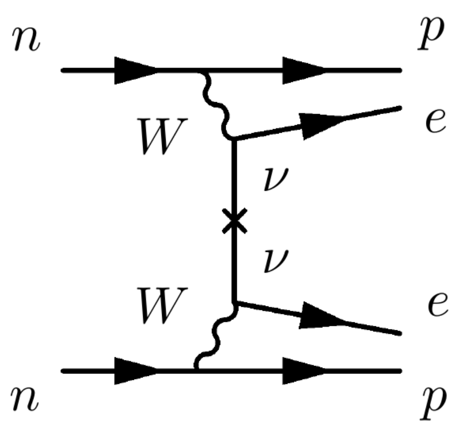


- Measured in several isotopes
- $T_{1/2}^{2\upsilon}$ in the range 10^{19} – 10^{24} yr

Double β decay (2)

- It's a nuclear transition, with 2 neutrons decaying into 2 protons

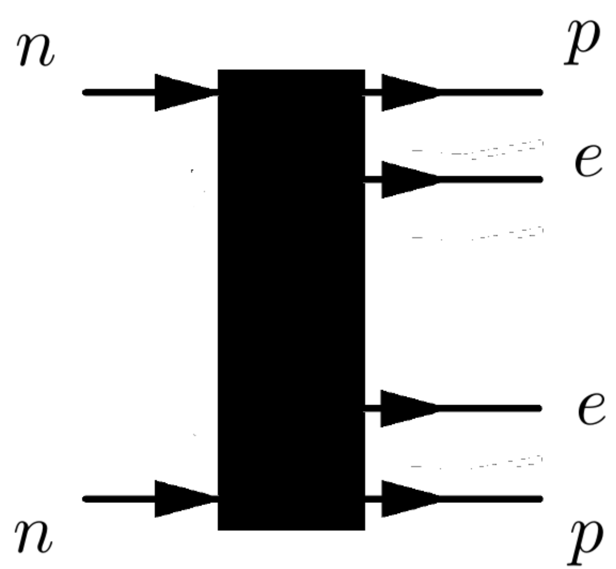
  (A,Z) → (A, Z+2) + 2 e^- + …



Neutrinoless double-β decay (2νββ)

- Foreseen by many extensions of the Standard Model of Particle Physics

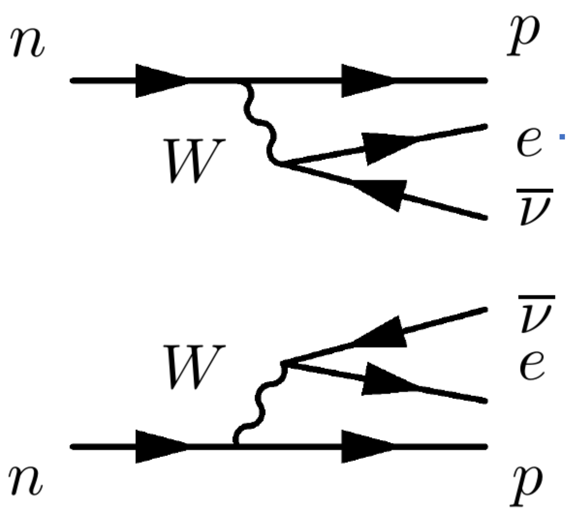
  (A,Z) → (A, Z+2) + 2 e^-

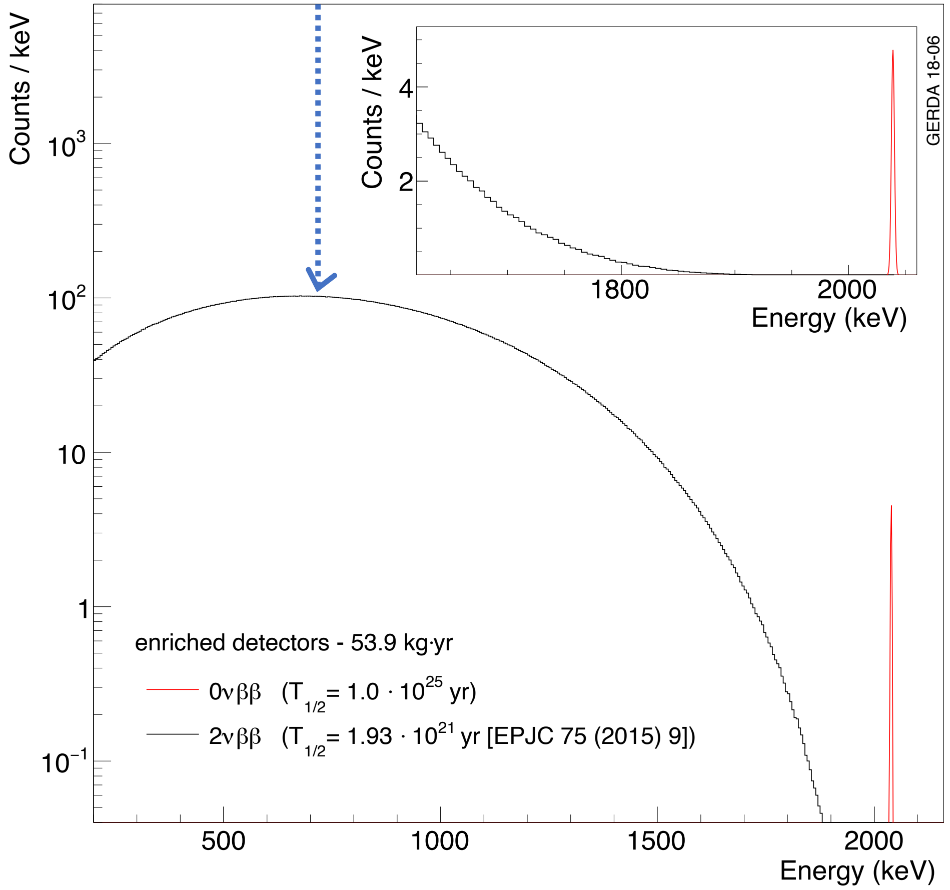


- Never observed so far, but allowed in several isotopes

→ $T_{1/2}^{0\nu}$ > O(10^{26}) yr

Double-β decay experimental signature



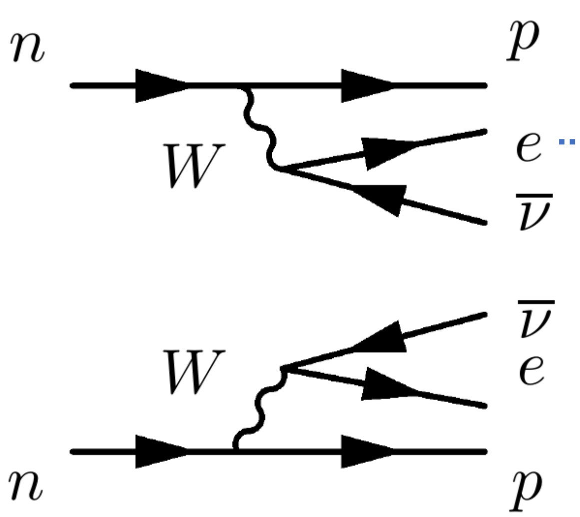


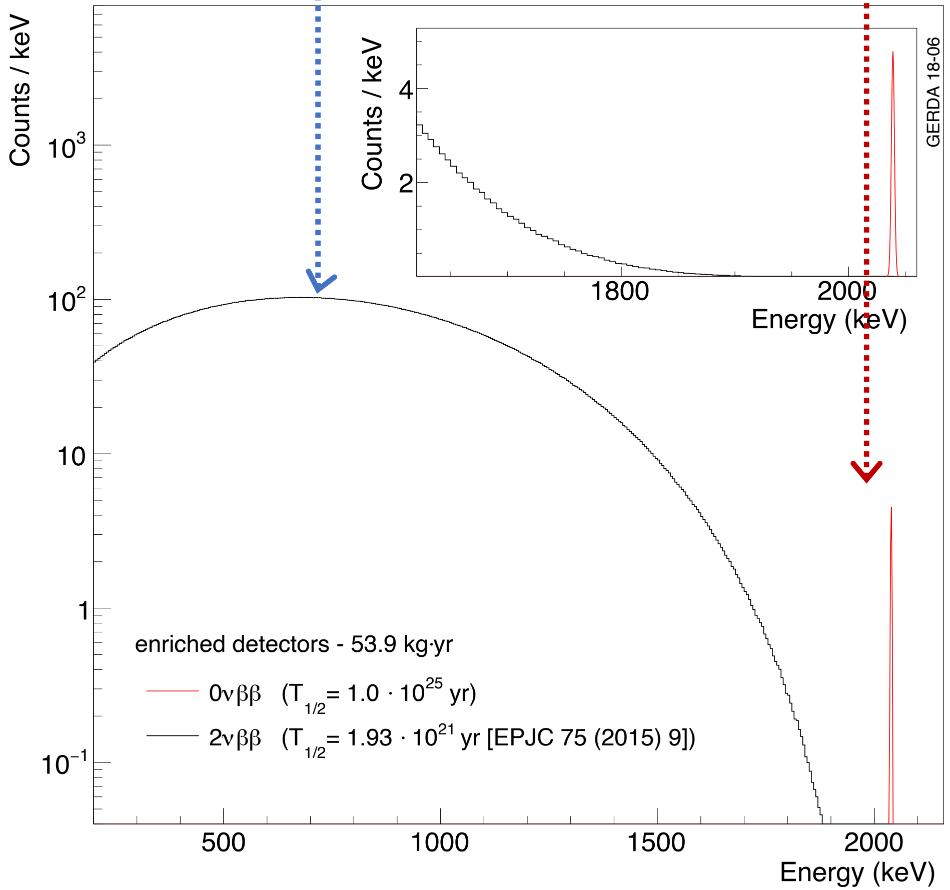
2νββ decay

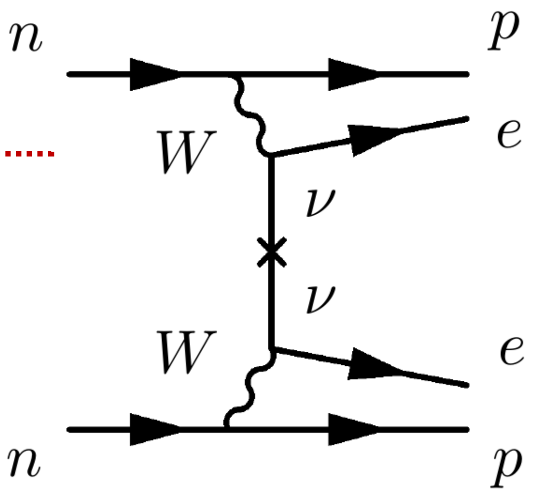
- energy continuum from 0 to $Q_{\beta\beta}$
- 2 electrons from vertex,

  2 vs undetected
- foreseen in the SM

Double-β decay experimental signature







2νββ decay

- energy continuum from 0 to $Q_{\beta\beta}$
- 2 electrons from vertex,

  2 νs undetected
- foreseen in the SM

0νββ decay

- Peak at $Q_{\beta\beta}$
- 2 electrons from vertex
- lepton number violation ΔL = 2

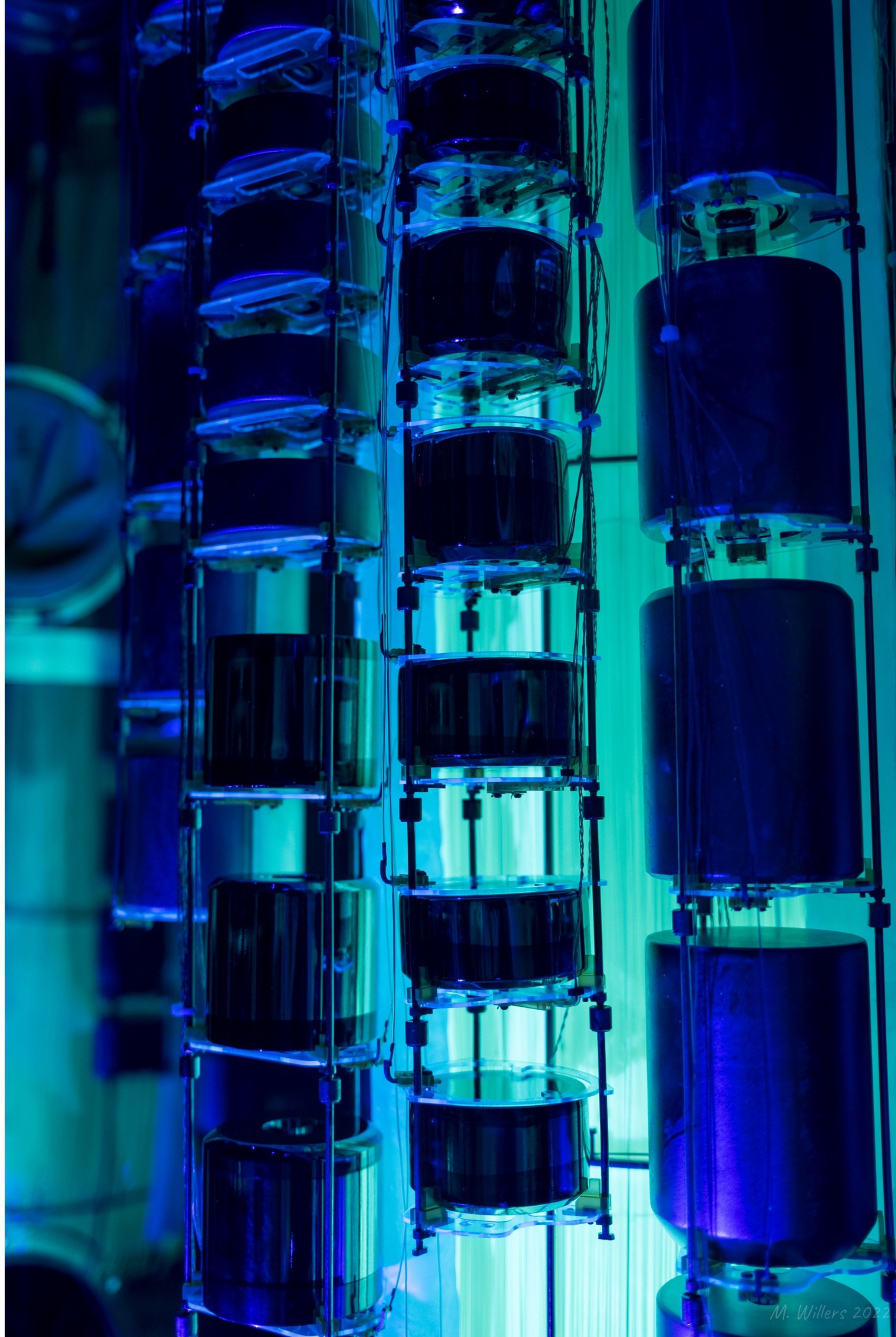
Why germanium?

- A “golden” isotope does not exist …
- … mix of theoretical & experimental preferences: costs, energy resolution, background level, scalability (liquids, gas, crystals)

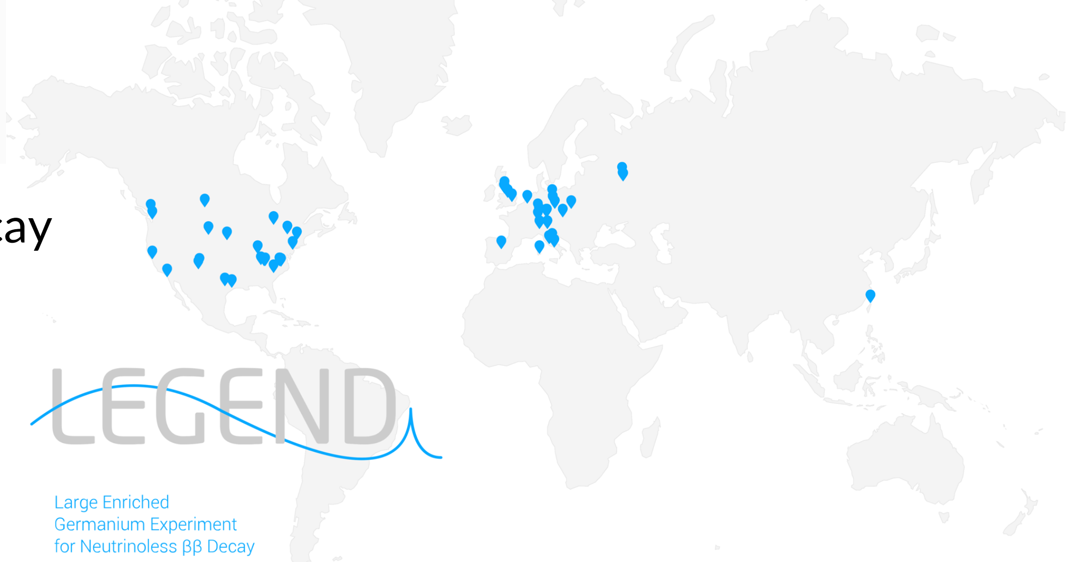
Already established technology → Detector ≡ source → High purity → Excellent energy resolution

- Detector ≡ source: High detection efficiency
- High purity: Low intrinsic background
- Excellent energy resolution: FWHM~ $\mathbf{0.1\%}$ @ $Q_{\beta\beta}$

- $Q_{\beta\beta}$ = 2039.06 keV: less processes can mimic the $0\nu\beta\beta$ signal
- Natural abundance is low (~8%): enrichment is required (and up to ~92% is achievable)



The LEGEND collaboration



Large Enriched Germanium Experiment for Neutrinoless ββ decay

- 13 countries, 60 institutions, ~ 300 members

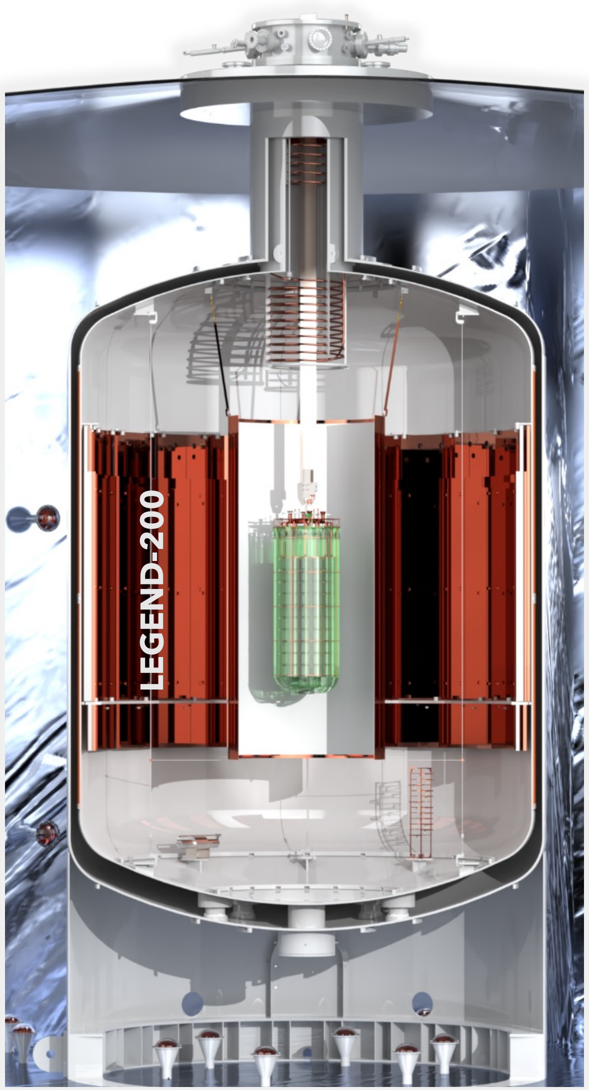
"The collaboration aims to develop a 76Ge-based 0νββ decay program with a discovery potential $T_{1/2} > 10^{28}$ yr using existing resources to expedite physics results"

N.Abgrall, et al., "LEGEND-1000 Preconceptual Design Report", arXiv 2107.11462

LEGEND: a phased approach

LEGEND-200

- Up to 200 kg of ^{enr}Ge detectors
- Uses GERDA infrastructure in Hall A, LNGS
- Operational since 2023
- **Goals:**
  - 1 ton*yr of exposure
  - Background ~ 2 x 10^{-4} cts / (keV*kg*yr)
  - $T^{0\nu}_{1/2} > 10^{27}$ yr $\mapsto$ $m_{\beta\beta} \sim 30 - 70$ meV



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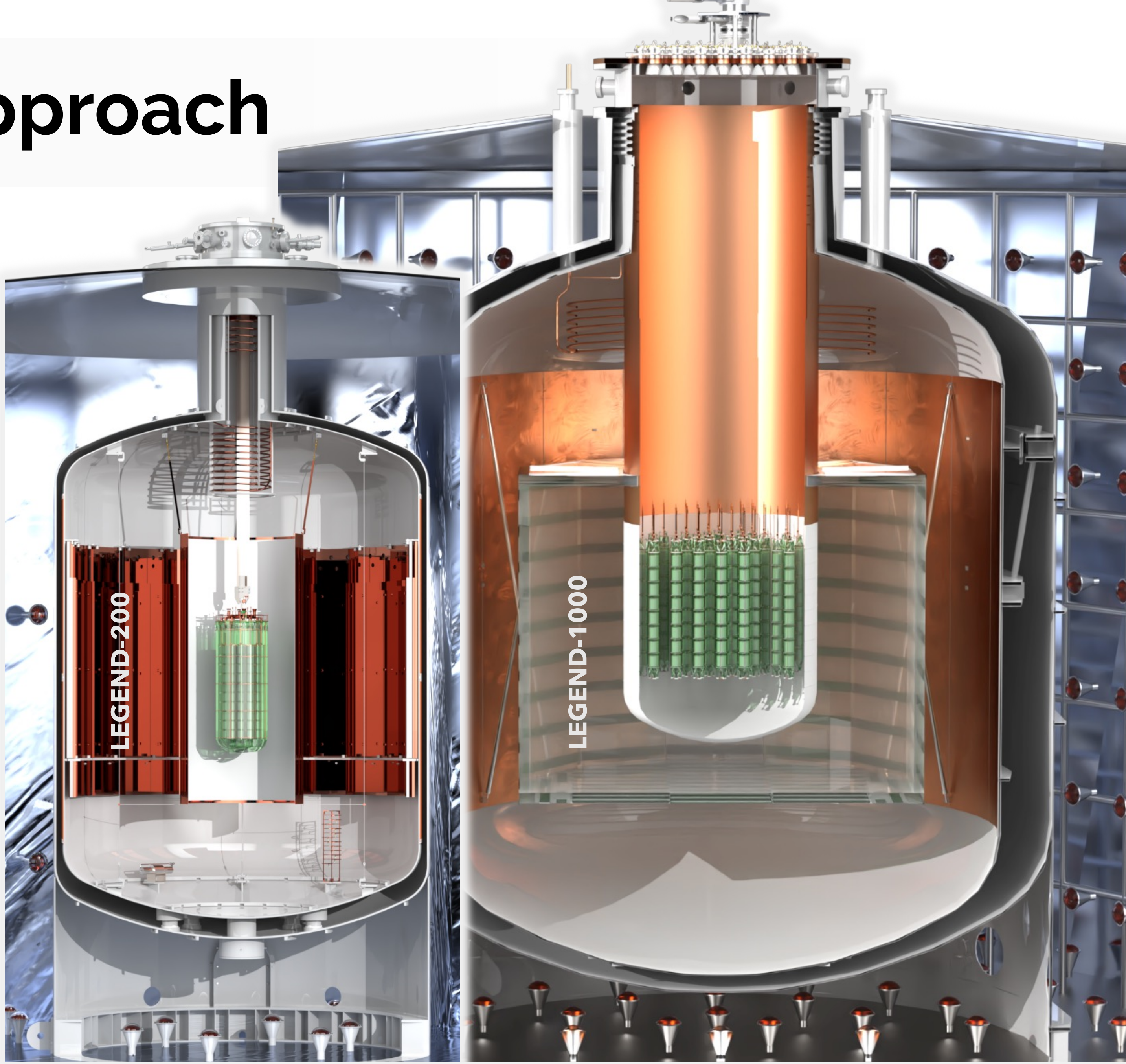
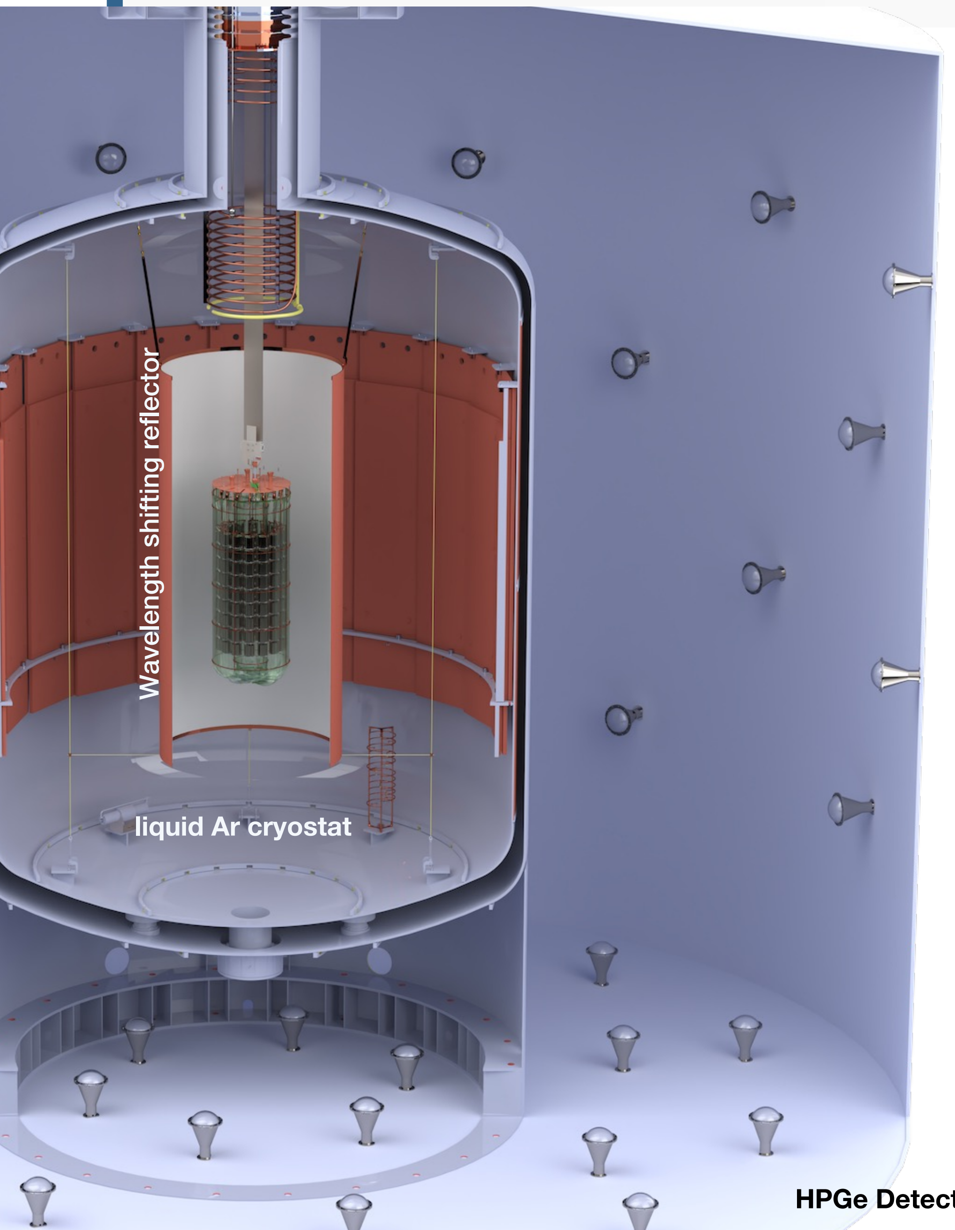
  - $T_{1/2}^{0\nu} > 10^{27}$ yr $\mapsto$ $m_{\beta\beta} \sim 30 - 70$ meV

LEGEND-1000

- 1000 kg of ^{enr}Ge detectors
- Uses new infrastructure in Hall C, LNGS
- **Goals:**
  - 10 ton*yr of exposure
  - Background ~ 10^{-5} cts / (keV*kg*yr)
  - $T_{1/2}^{0\nu} > 10^{28}$ yr $\mapsto$ $m_{\beta\beta} \sim 10 - 20$ meV

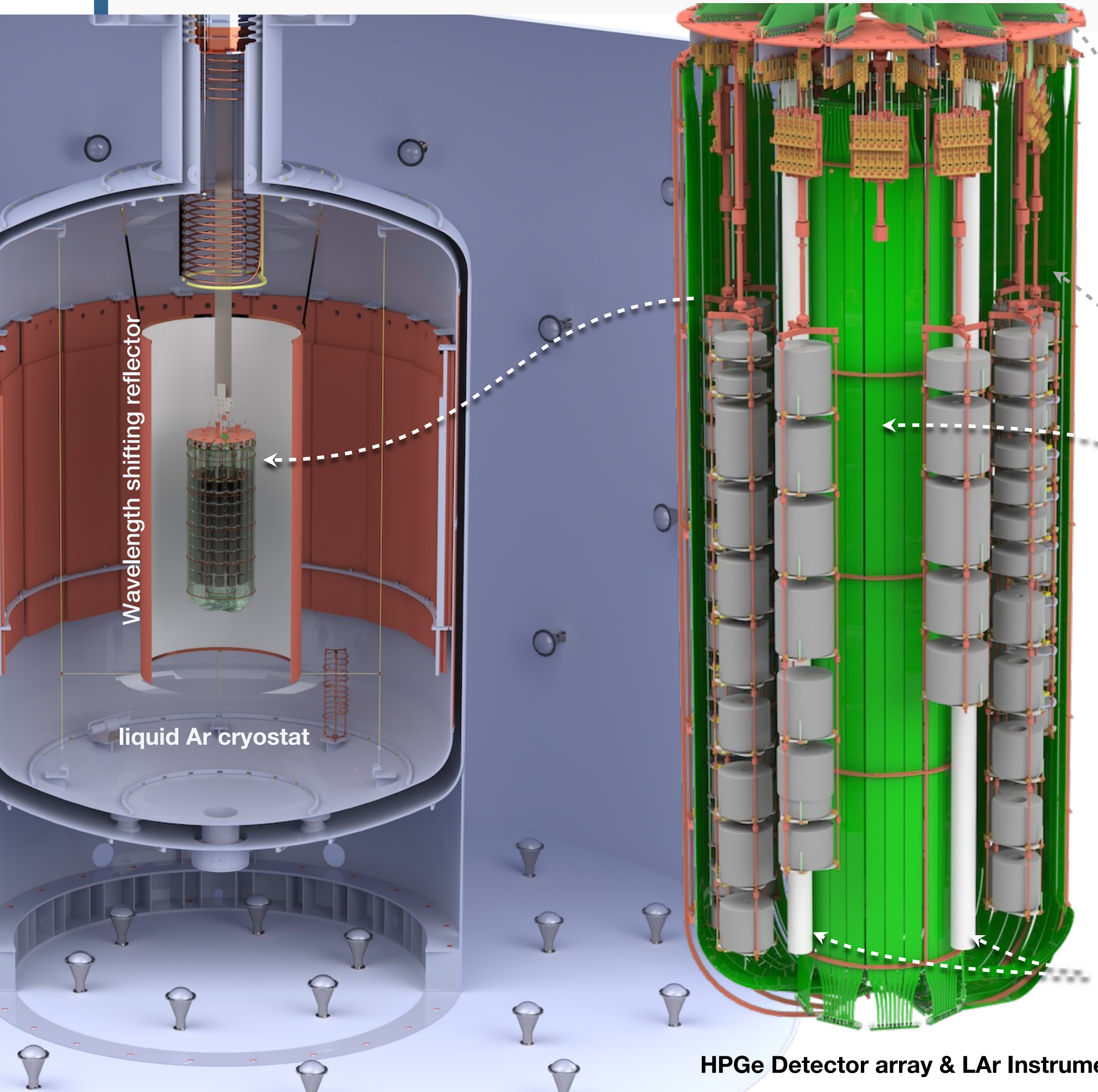


LEGEND-200 experimental setup



HPGe Detector array & LAr Instrumentation

LEGEND-200 experimental setup

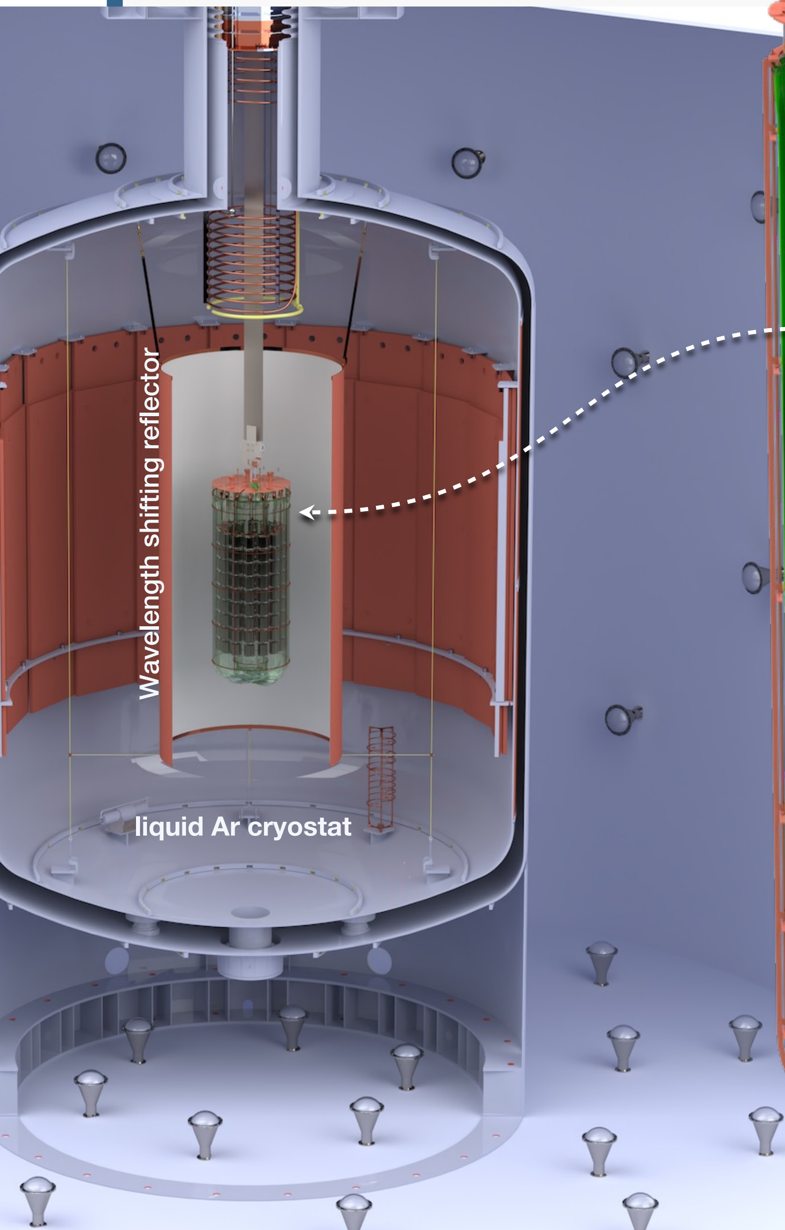


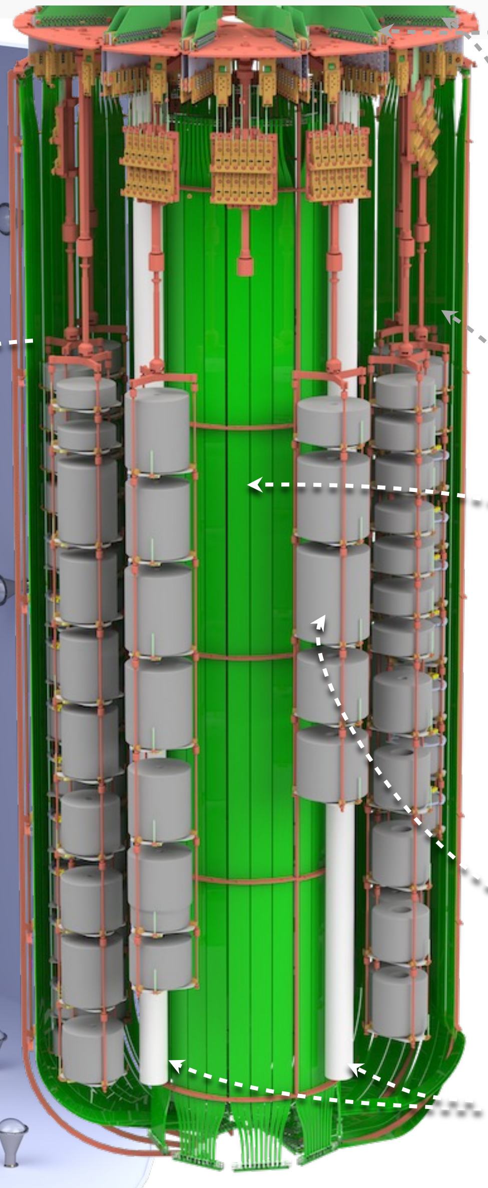
Liquid Argon instrumentation:
inner & outer fiber barrels with silicon photomultiplier (SiPM) readout at top & bottom

Source funnels for
^{228}Th calibration sources

HPGe Detector array & LAr Instrumentation

LEGEND-200 experimental setup





HPGe Detector array & LAr Instrumentation

HPGe readout electronics
based on MJD Low Mass Front-End
and GERDA charge sensitive amplifier (CC4)

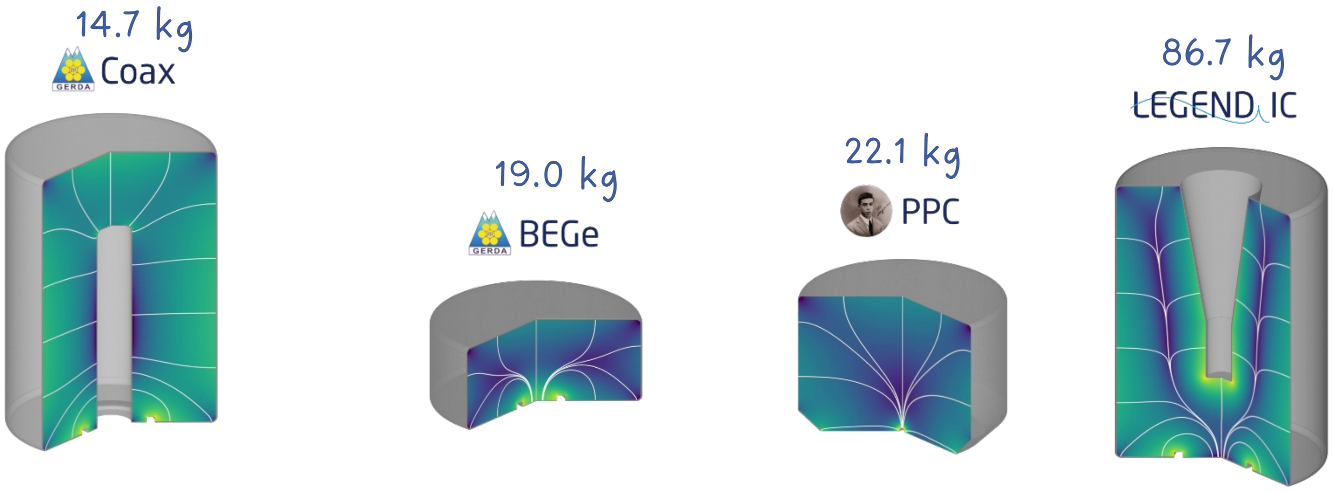
Detector mount: underground copper,
optically active PEN plates & radiopure PEI

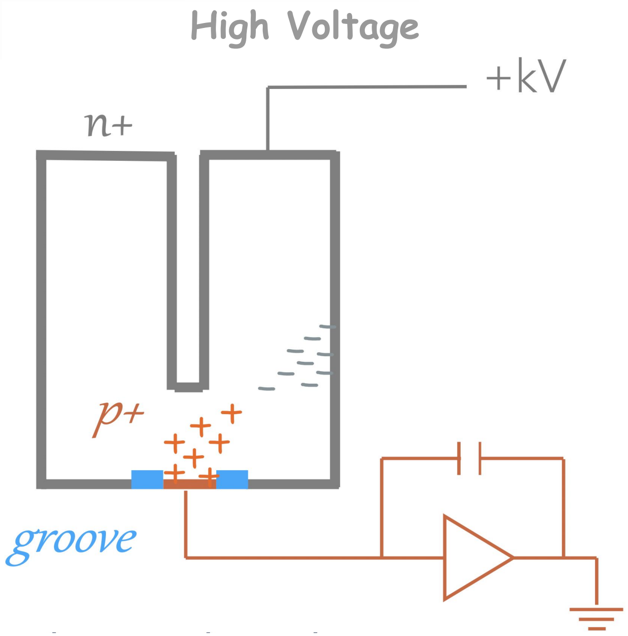
Liquid Argon instrumentation:
inner & outer fiber barrels with
silicon photomultiplier (SiPM)
readout at top & bottom

Larger mass (inverted coaxial)
HPGe **detectors** with up to 4 kg

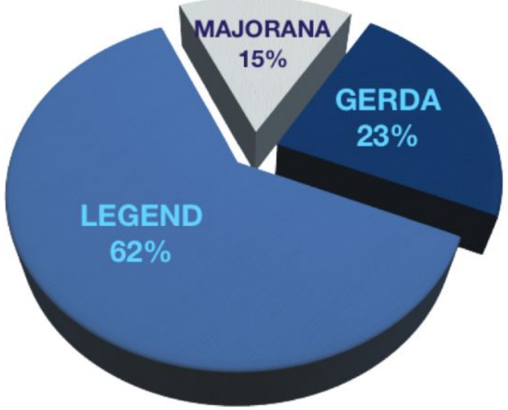
Source funnels for
^{228}Th calibration sources

LEGEND enrGe diodes

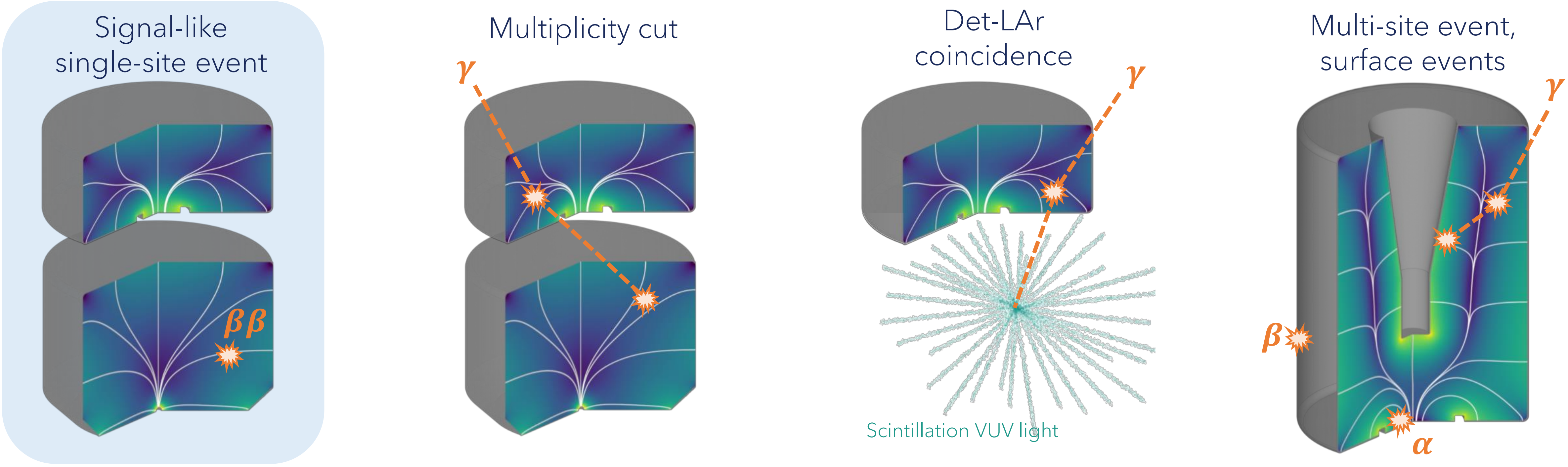




- Ge diodes: p+ (implanted B), n+ (diffused Li), passivated groove
- HPGe detectors have best energy resolution at $Q_{\beta\beta}$ (0.12% FWHM) and best background level in the field (10^{-4} cts/(keV kg yr))
- LEGEND-200 is currently using 4 HPGe detector types, from previous experiments and newly produced Inverted Coaxial (IC) geometry)
- Different geometries – single detector mass: 0.7 kg - 4 kg



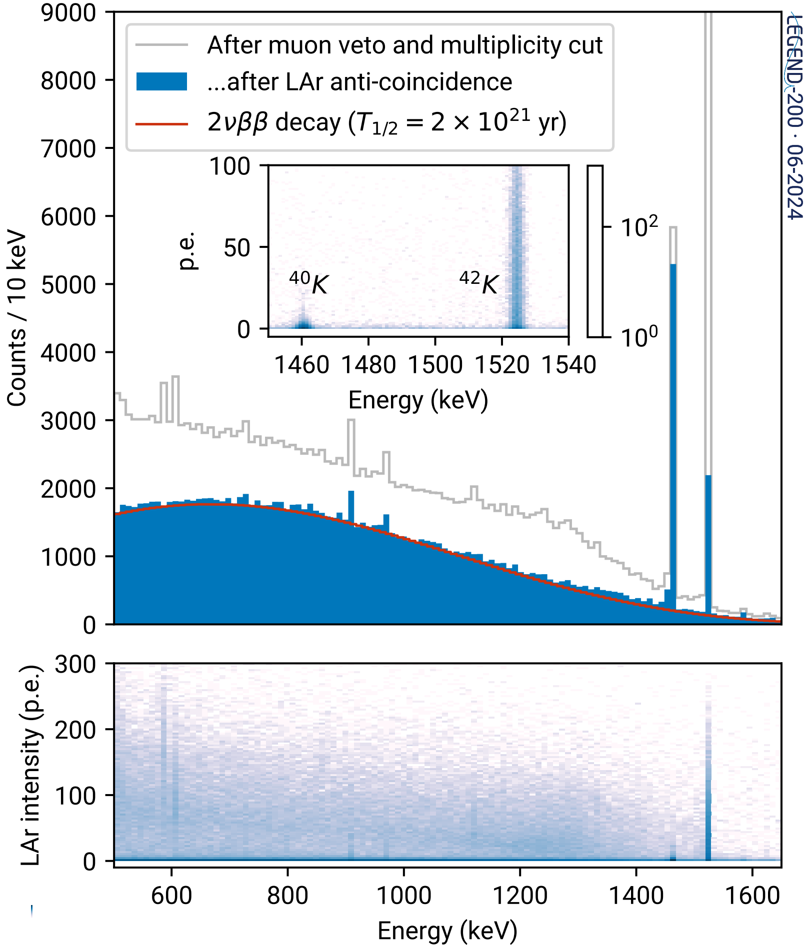
Background in LEGEND

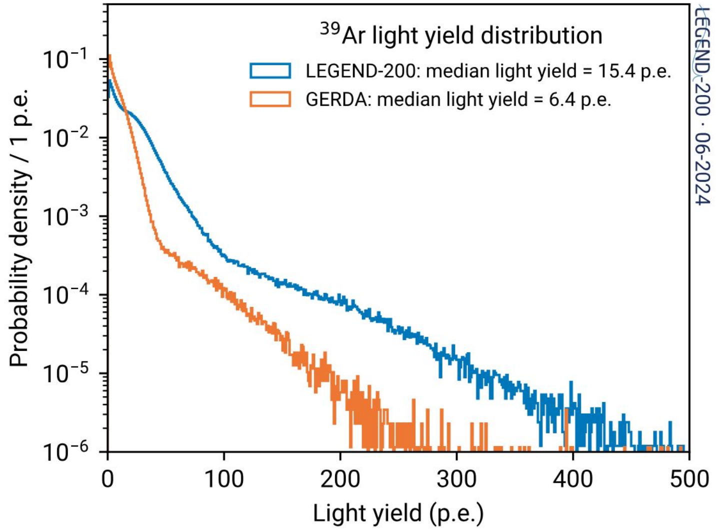


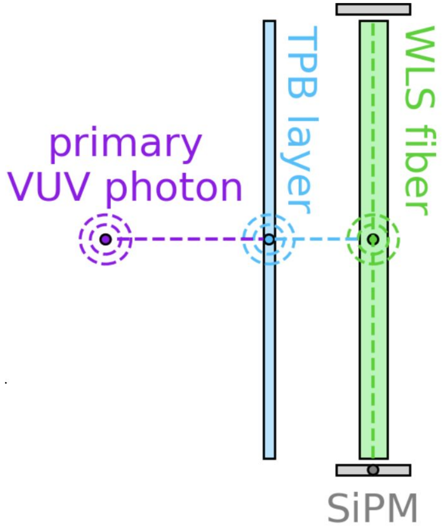
Background rejection : in addition to careful material selection and handling during installation, Liquid Argon instrumentation and Muon Veto + Pulse Shape Discrimination

Bkg reduction: LAr Instrumentation

Use LAr scintillation light
(128 nm VUV photons)
Captured by WLS fibers
and readout by SiPM
System successfully operated
in GERDA, now with higher light
yield and less shadowing

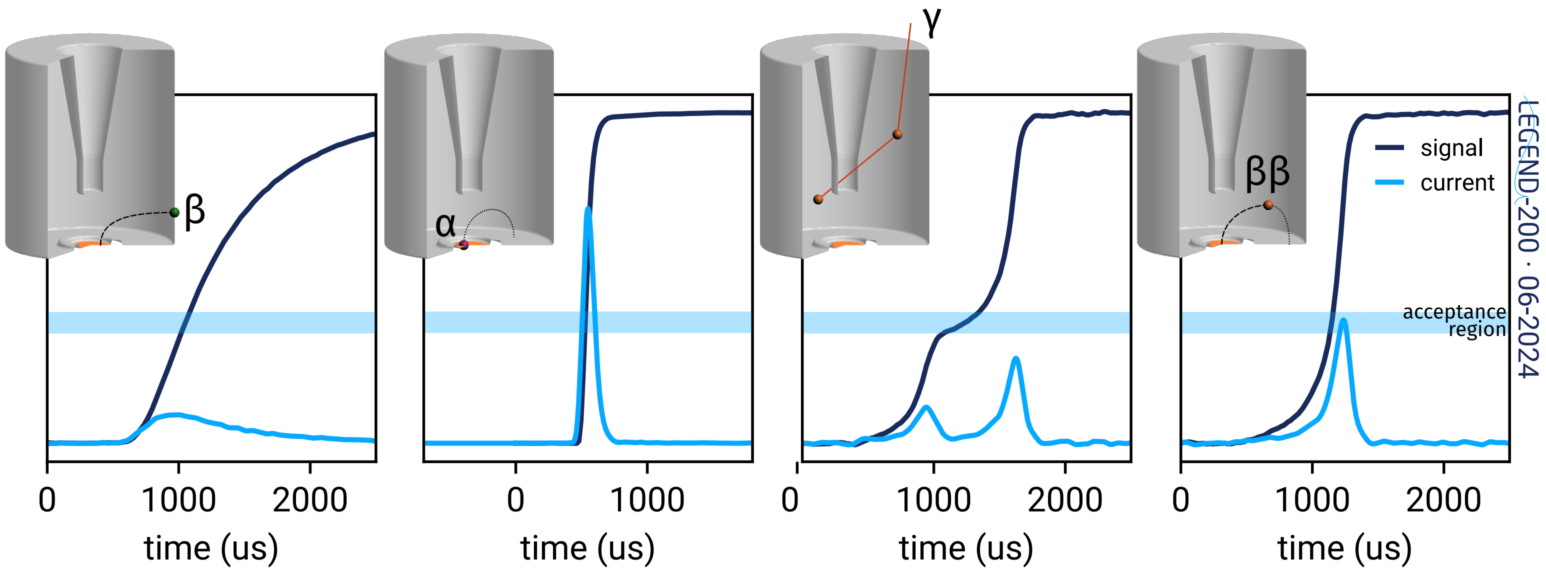






^{40}K EC process followed by gamma does not show coincidence with Lar → barely suppressed
^{42}K beta followed by 1525 keV gamma has LAr coincidence → strongly suppressed

Bkg reduction: Pulse Shape Analysis



n+ surface event ($^{42}K/^{42}Ar$)
REJECTED
Incomplete charge collection due to slow release of charges
Low A/E

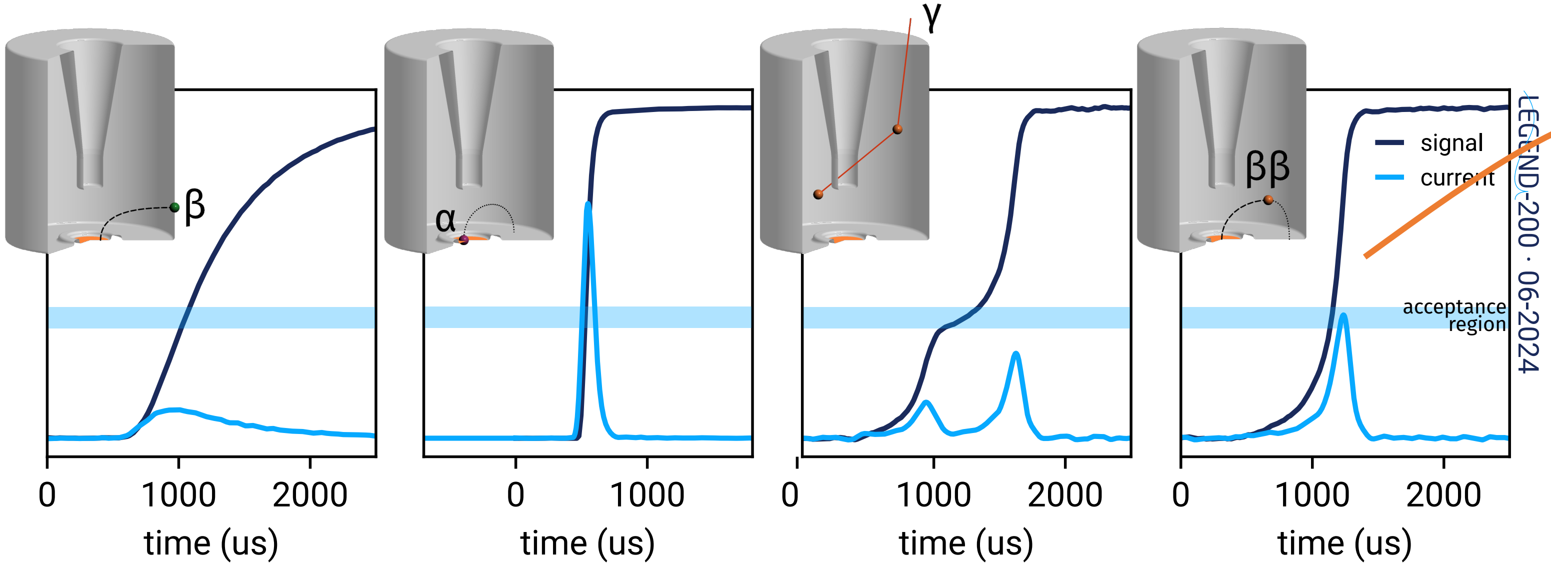
p+ surface event (α)
REJECTED
High A/E

Multi site event (γ)
REJECTED
Low A/E

Single site event (0νββ/2νββ)
ACCEPTED

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

Bkg reduction: Pulse Shape Analysis



n+ surface event ($^{42}K/^{42}Ar$)
REJECTED
Incomplete charge collection due to slow release of charges
Low A/E

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Single site event (0νββ/2νββ)
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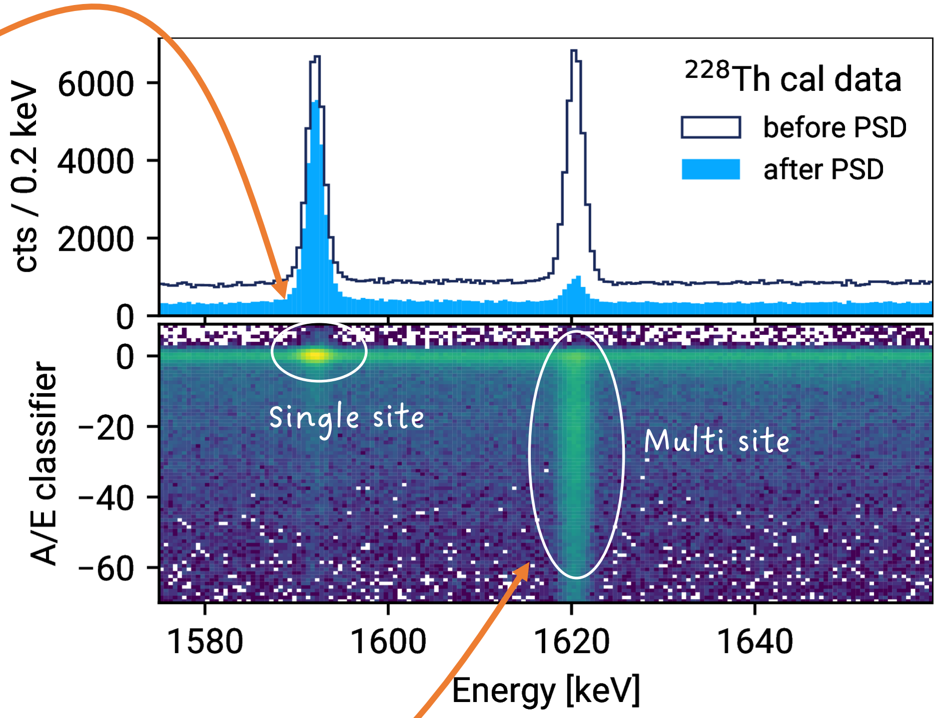
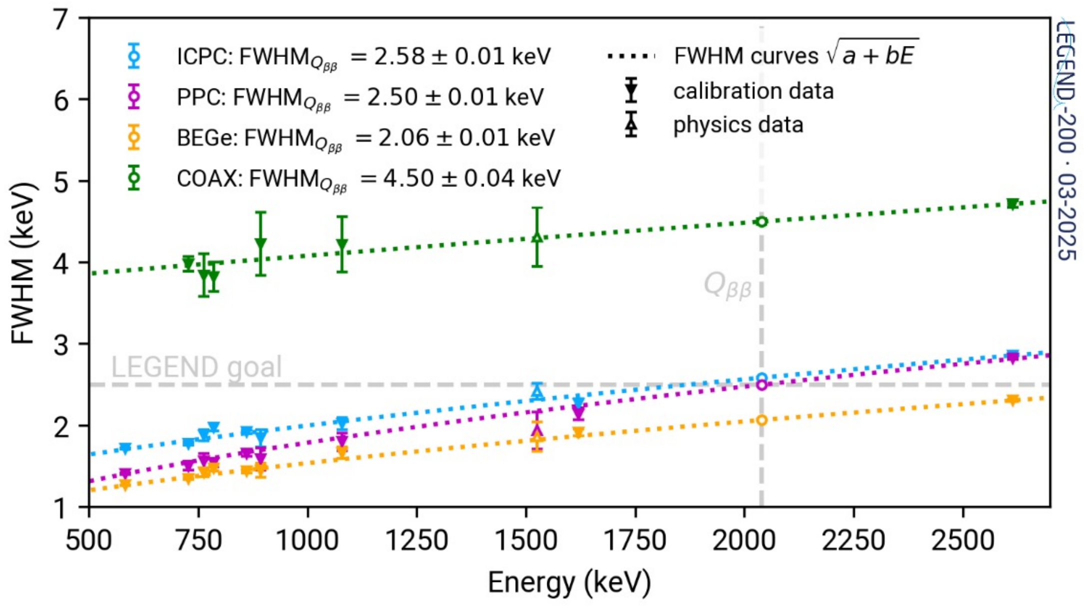
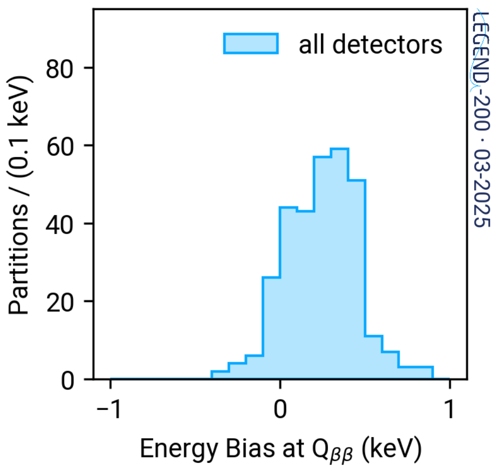


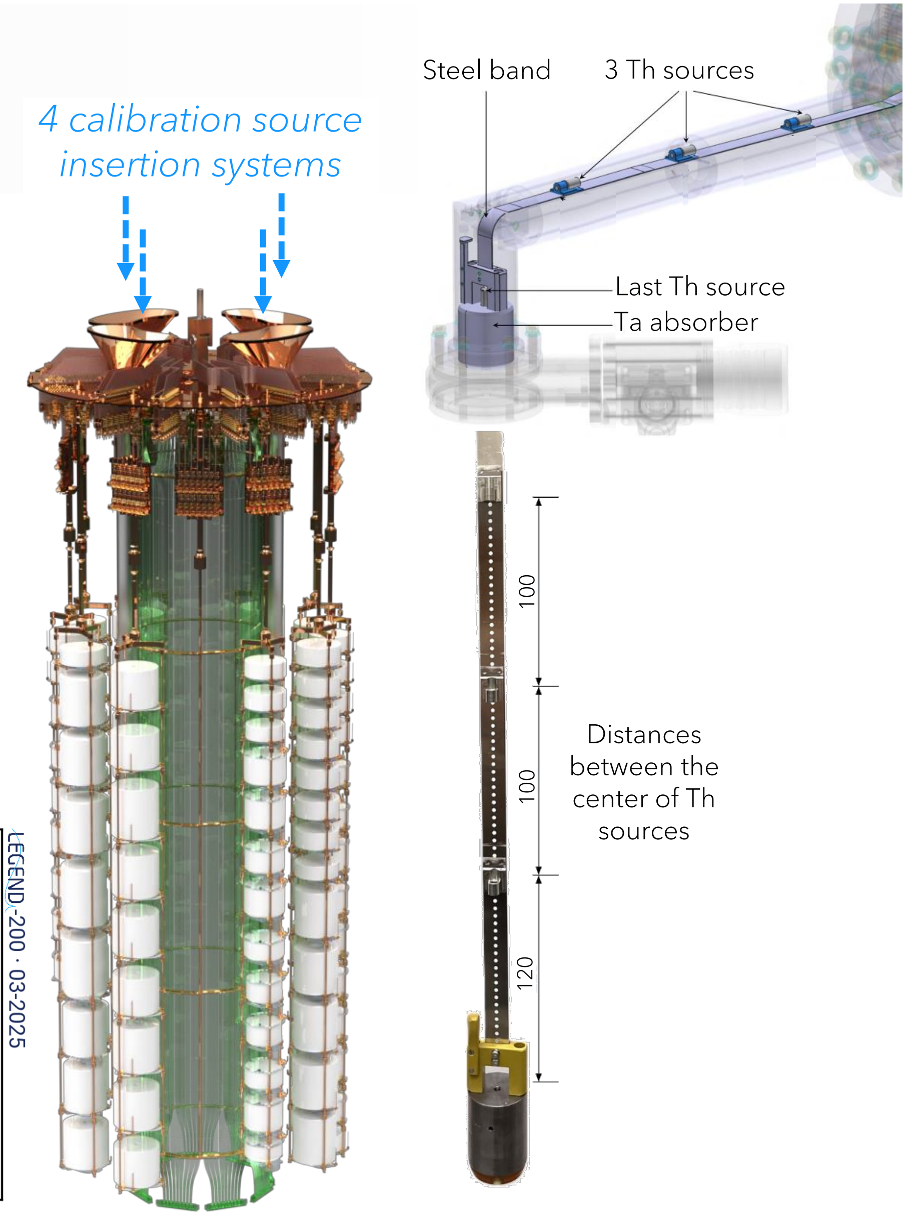
Pulse shape discrimination (PSD):
based on the signal risetime and amplitude

Energy scale and resolution

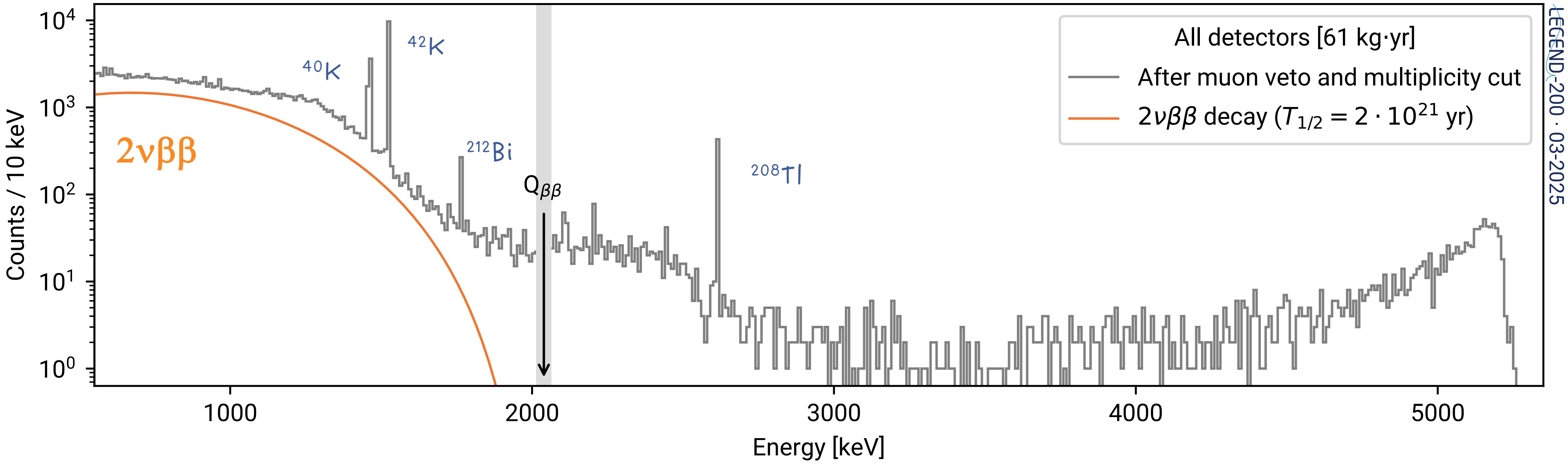
- Weekly energy calibrations using ^{228}Th sources
- Overall resolution of 0.1 - 0.2% FWHM at $Q_{\beta\beta}$
- Very stable energy scale - energy bias 0.2 ± 0.3 keV at $Q_{\beta\beta}$







LEGEND-200 energy spectrum

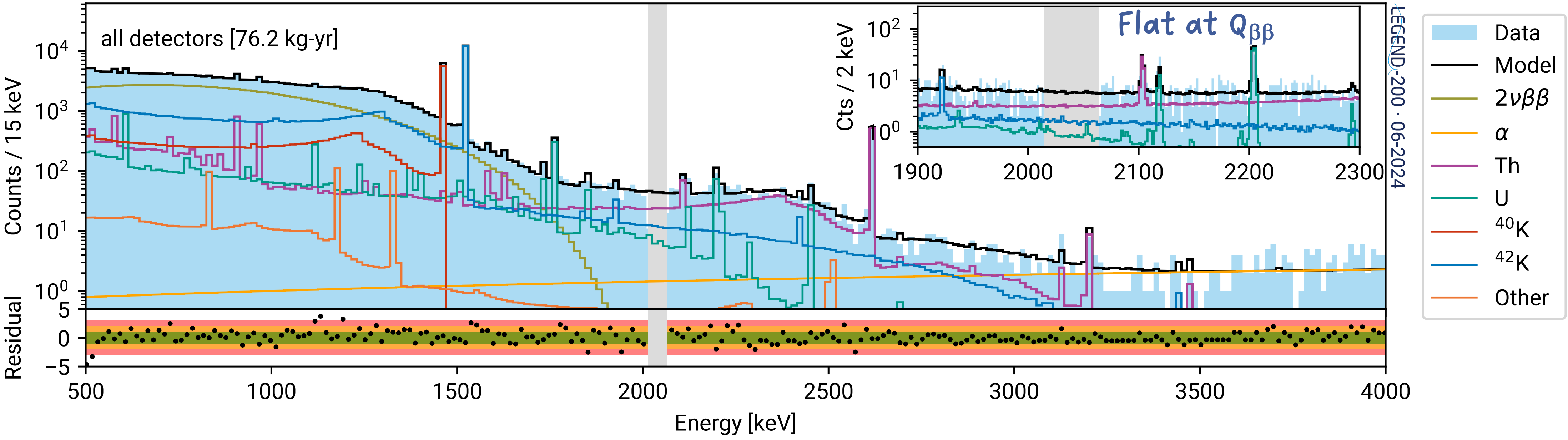


Blinded analysis in $Q_{\beta\beta}$±25 keV

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 $Q_{\beta\beta}$
- $T^{2\nu}_{1/2}$ = **(2.022 ± 0.018 stat ± 0.038 syst) × 10^{21} yr** [GERDA Collab., PRL 131, 142501 (2023)]

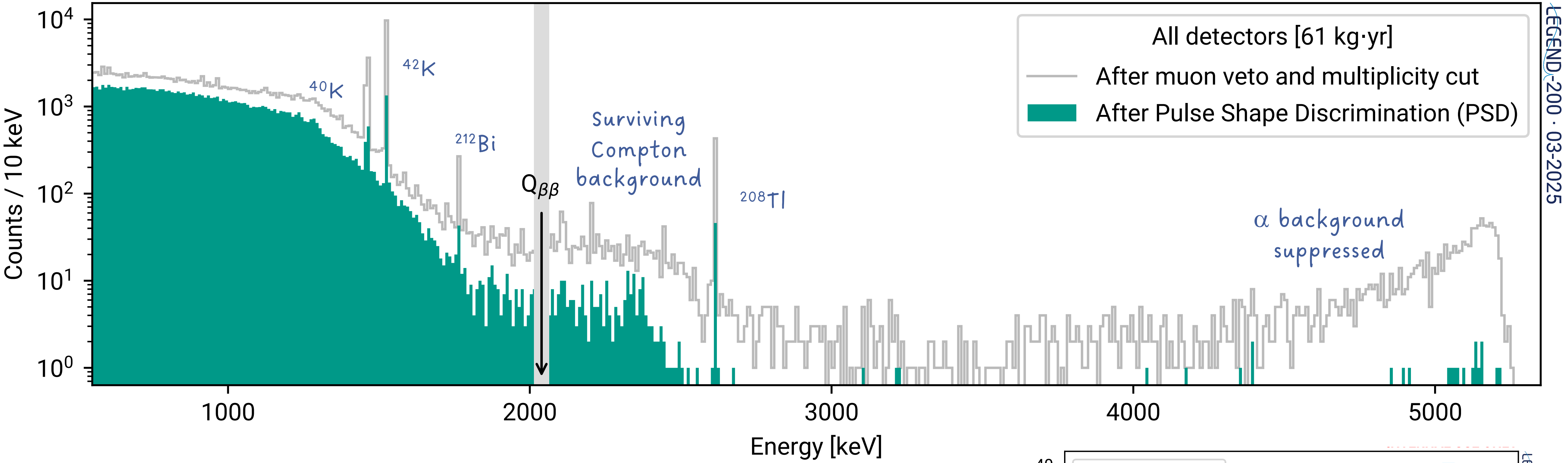
LEGEND-200 background model



- Bayesian background model using the full dataset + extra 10.2 kg·yr of special runs
- Decomposition of the full-range energy spectrum: no unexpected background components
- ^{228}Th underprediction in physics data compared to radioassay predictions
  - Tested different ^{228}Th locations via the background model: no hotspots or asymmetries
  - Ongoing screening campaign & re-evaluation of cleaning techniques

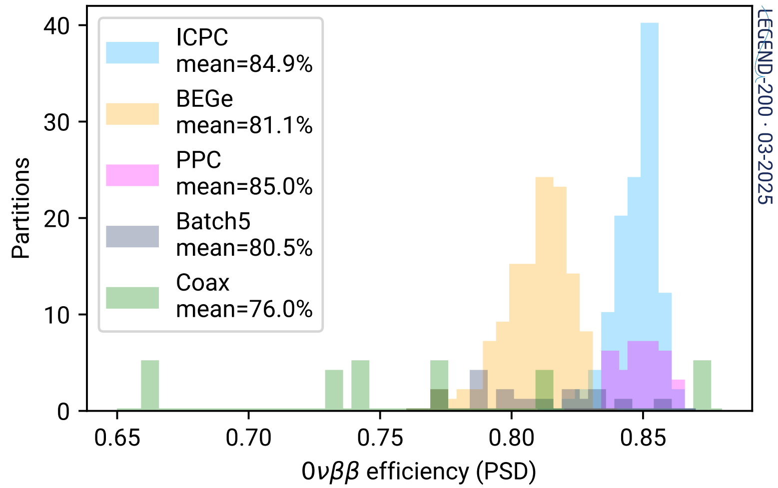
  → This background is efficiently suppressed by analysis cuts

Energy spectrum after PSD

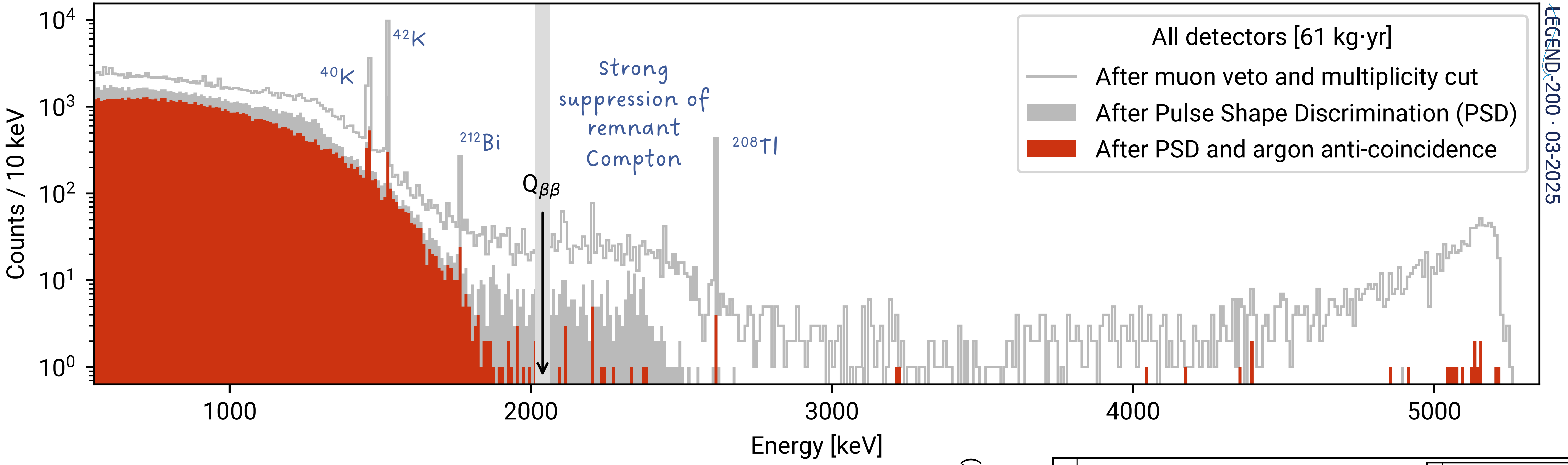


- Cut acting on A/E = max(current) / energy
- Late charge cut for PPC (large passivated surface)
- Neural-network methods developed for semi-coaxial

~60% suppression of Compton MSE at $Q_{\beta\beta}$

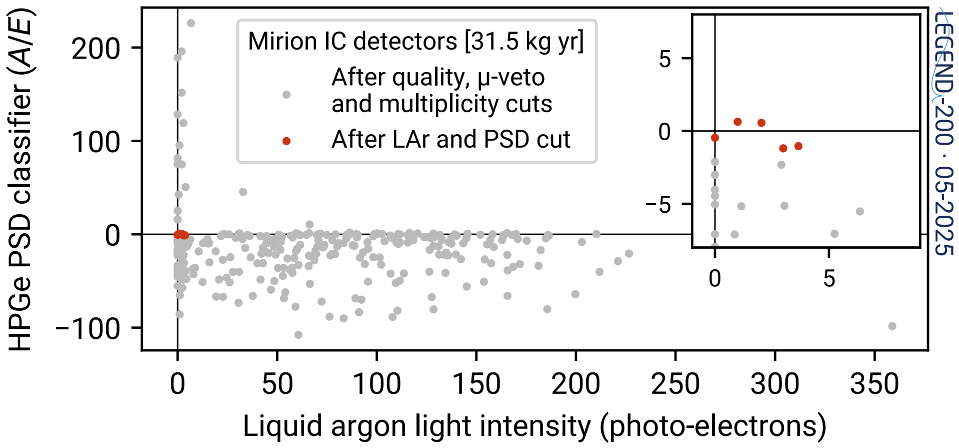


Energy spectrum after PSD & LAr cuts

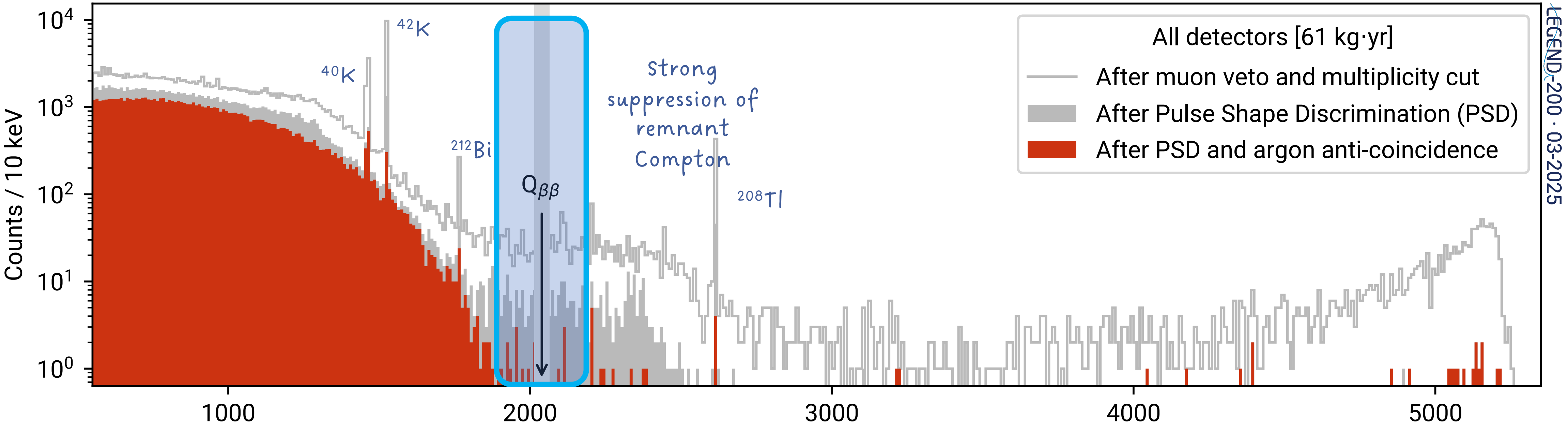


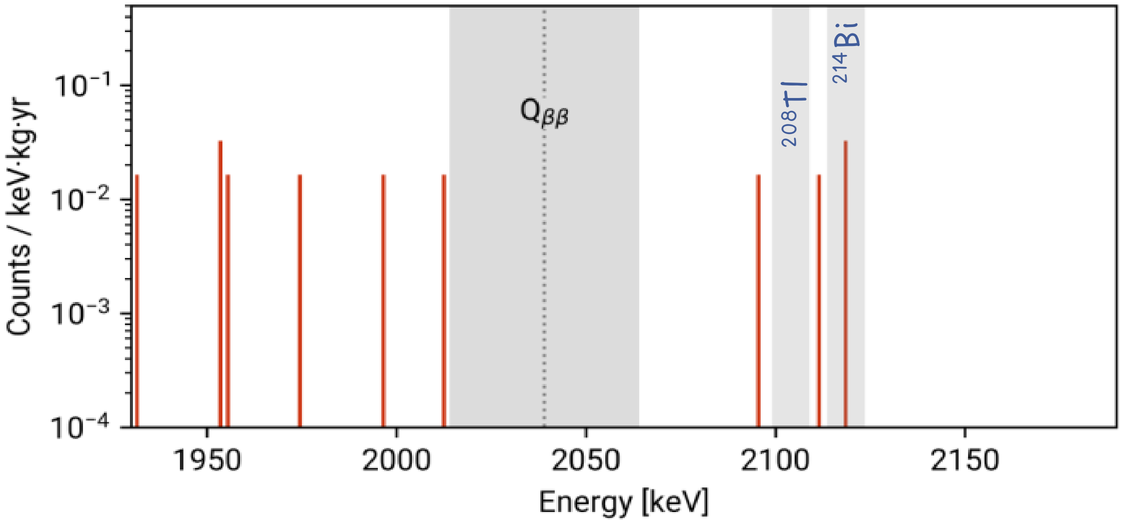
Cuts applied: *data cleaning + muon veto + multiplicity cut*

- *Pulse Shape Discrimination*
- LAr anti-coincidence:
- LAr ββ decay signal acceptance of ~93%
    - Strongly suppresses remnant Compton background
    - Pure "2νββ" behavior observed at lower energies



Energy spectrum after PSD & Lar cuts





Background estimation window:

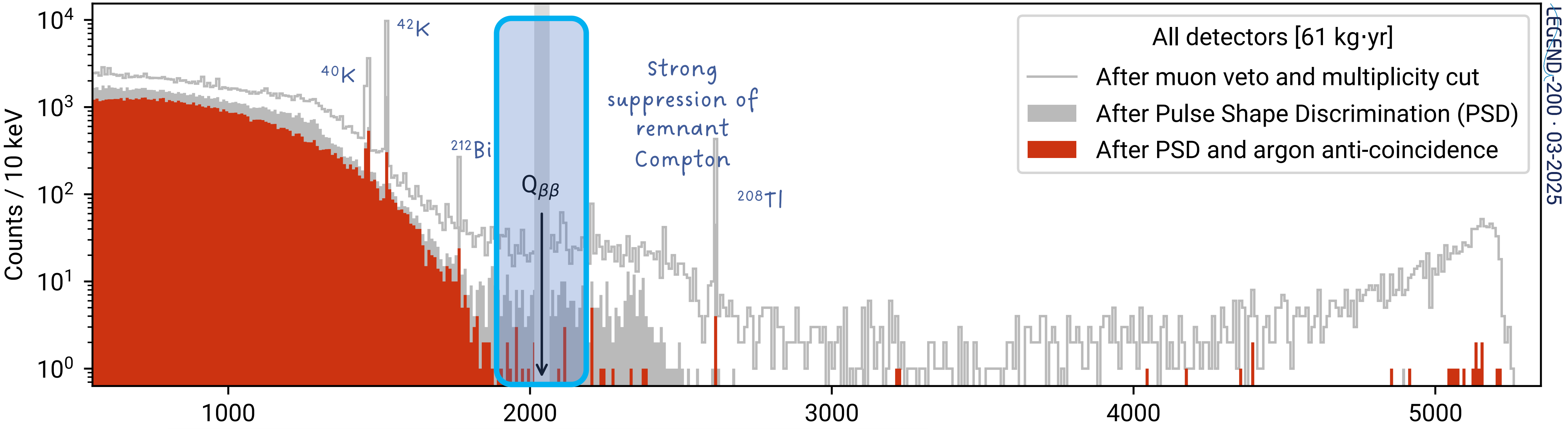
- 1930 – 2190 keV

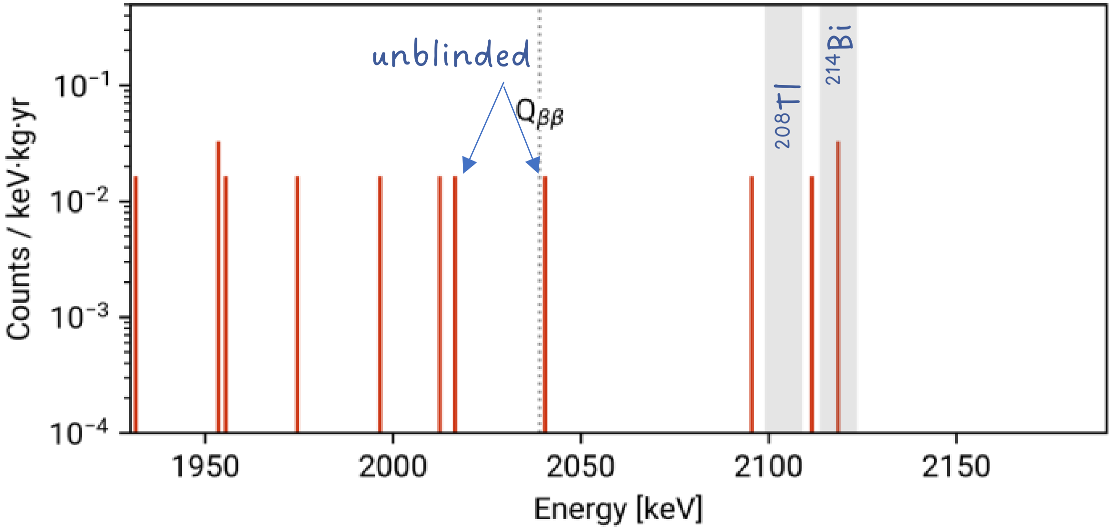
Excluded γ lines:

- ^{208}Tl at (2104 ±5) keV
- ^{214}Bi at (2119 ±5) keV

9 events BEFORE unblinding

Energy spectrum after PSD & Lar cuts





Background estimation window:

- 1930 – 2190 keV

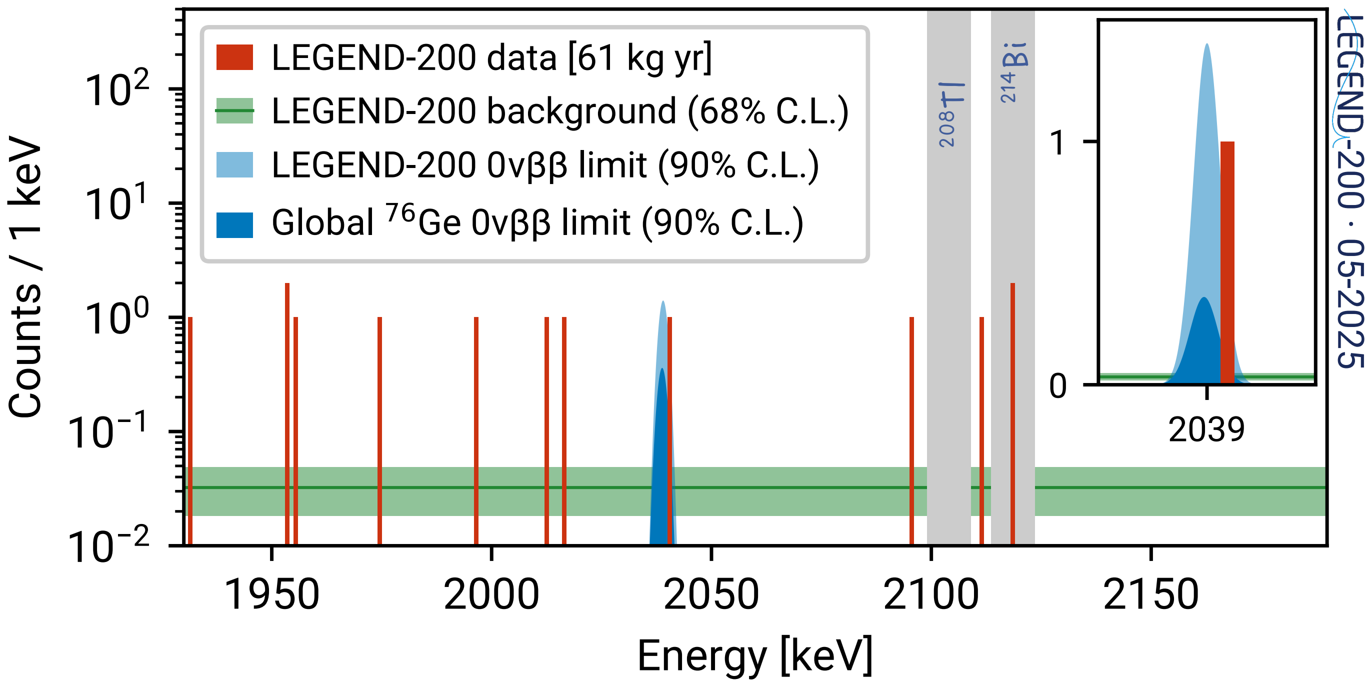
Excluded γ lines:

- ^{208}Tl at (2104 ±5) keV
- ^{214}Bi at (2119 ±5) keV

9 events BEFORE unblinding + 2 events AFTER
→ 11 surviving events

LEGEND 2νββ results

- Frequentist and Bayesian $0\nu\beta\beta$ analysis: no signal evidence
- BI: $0.5^{+0.3}_{-0.2}$ cts/(keV t yr)
- Observed $T_{1/2} > 0.5 \times 10^{26}$ yr @ 90% CL/CI
- Sensitivity $T_{1/2}$: 1.0×10^{26} yr
- 1 event at 1.4 σ from $Q_{\beta\beta}$ weakens the observed limit



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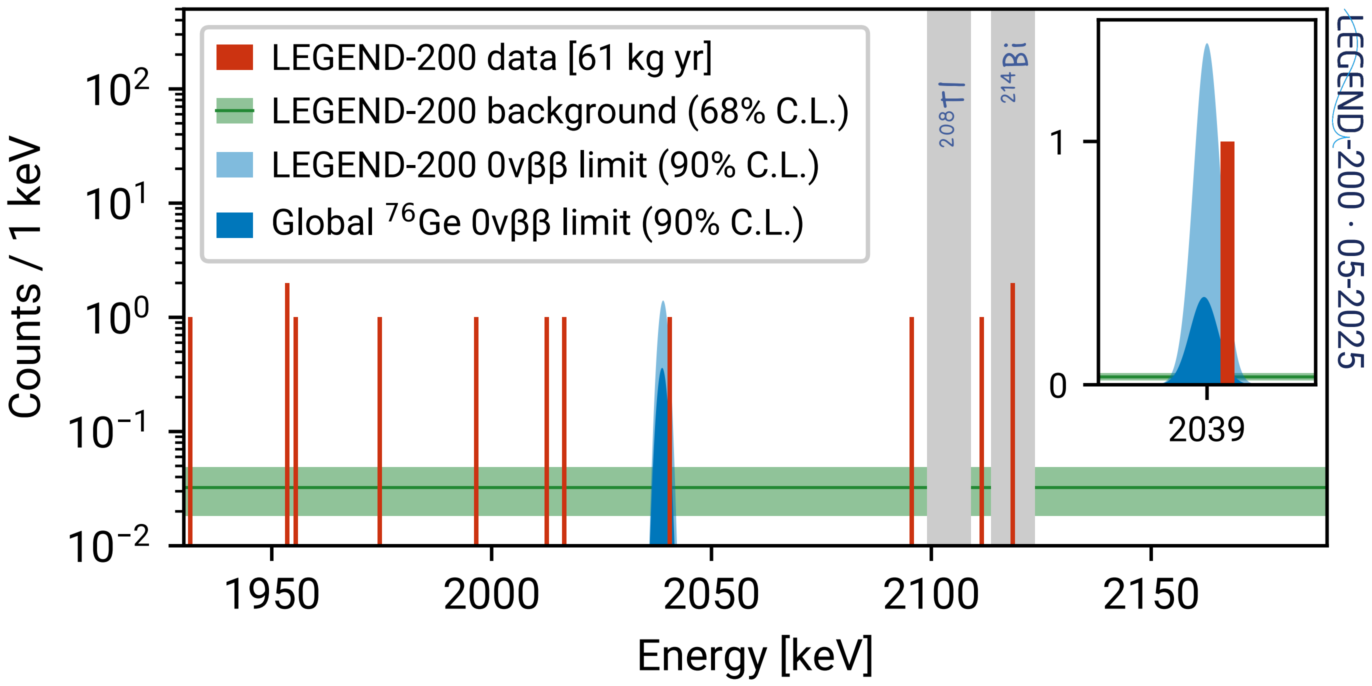


Combined fit of GERDA(*) + MJD (**) + LEGEND-200

- Frequentist and Bayesian $0\nu\beta\beta$ analysis: no signal evidence
- Observed $T_{1/2} > 1.9 \times 10^{26}$ yr @ 90% CL/CI
- World-leading sensitivity $T_{1/2} = 2.8 \times 10^{26}$ yr
- paper [arXiv:2505:10440] submitted to PRL

(*) GERDA, PRL 125 252502 (2020)
(**) MJD, PRL 130 062501 (2023)

Limits on $m_{\beta\beta}$

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

Nuclear Matrix Element

Effective Majorana neutrino mass

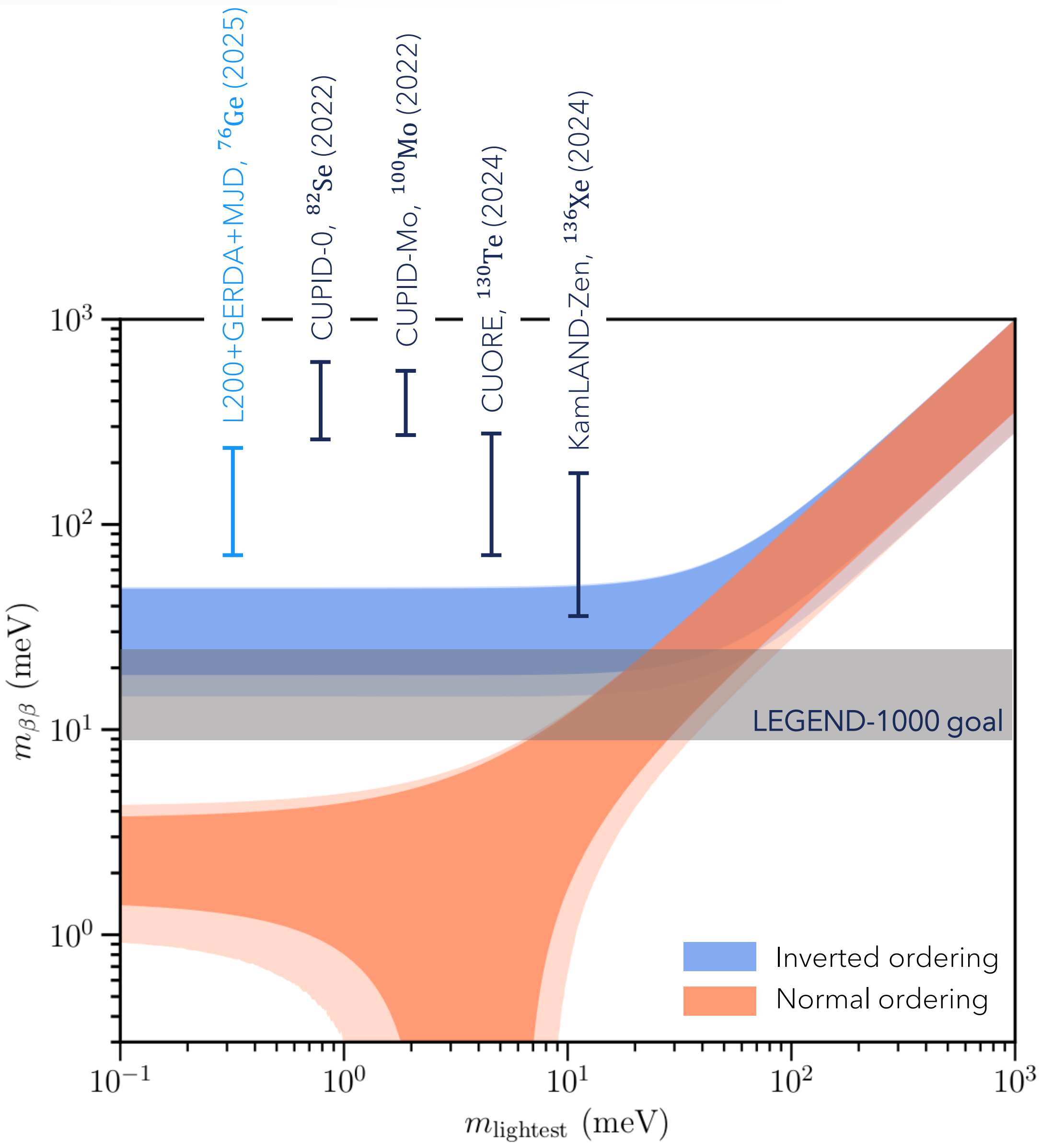
- Assumption: light Majorana neutrino exchange
- Range of phenomenological NME (^{76}Ge: 2.35 – 6.34)

  $m_{\beta\beta}$<75-200 meV @ 90% CL

- Uncertainty-quantified NME (^{76}Ge: $2.6_{-1.36}^{+1.28}$)
- Bayesian ab-initio calculation with quenching and short-range physics [Belley et al., PRL 132, 182502 (2024)]

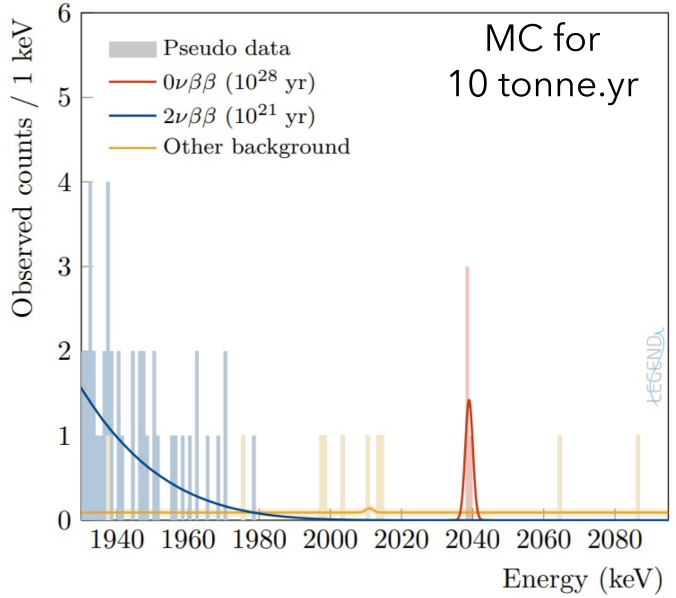
  $m_{\beta\beta}$<316 meV @ 90% CI

- A new era of uncertainty-quantified NME - however, uncertainties remain significant



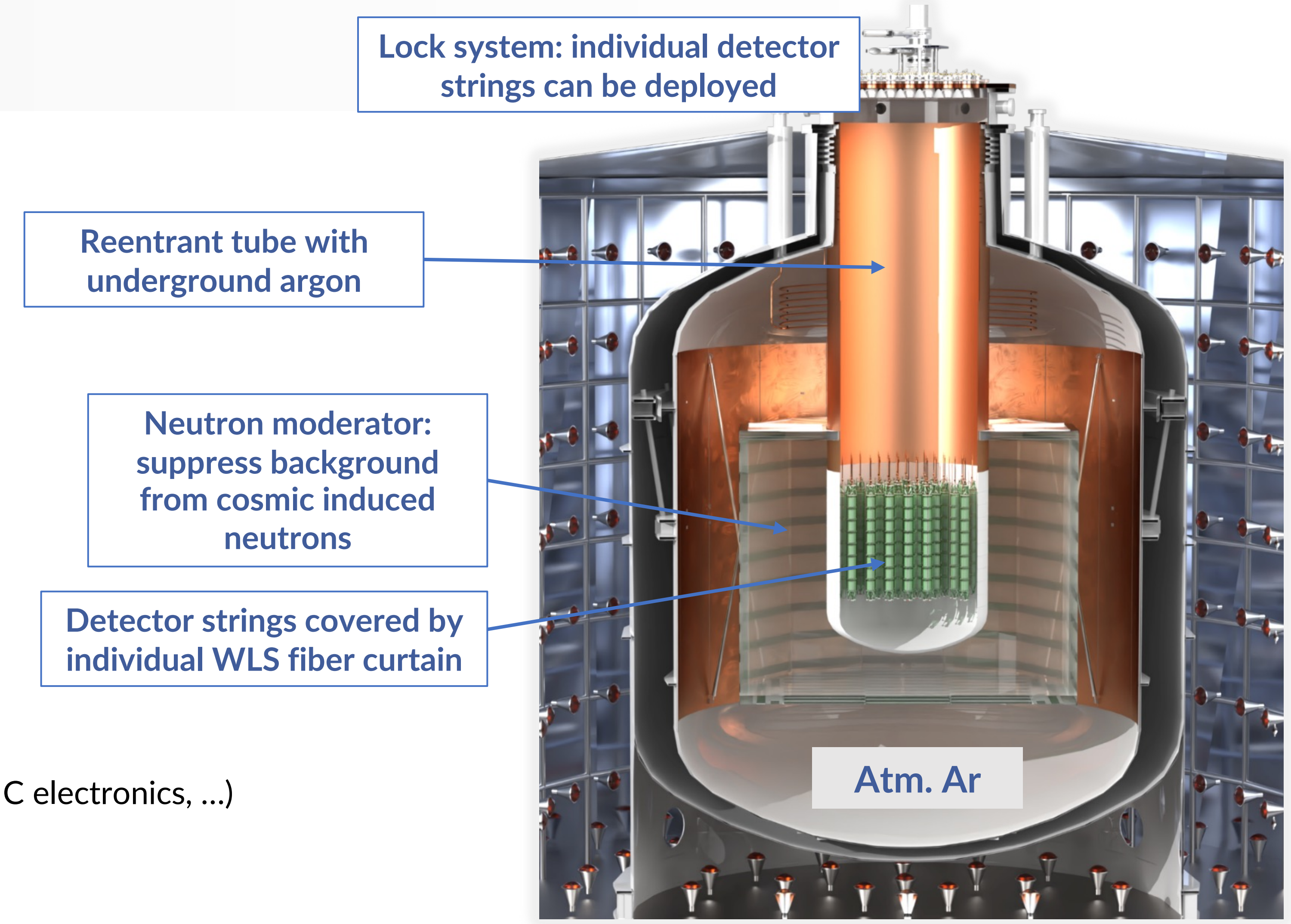
LEGEND-1000

Capable of unambiguous 0nbb discovery with just a handful of counts at $Q_{\beta\beta}$!



Reduce background x20 times from LEGEND-200:

- Lower background materials (underground Argon, ASIC electronics, …)
- Only IC detectors
- Improved material handling
- Improved light collection



L1000 pre-Conceptual Design Report

Funding request procedure for LEGEND-1000 has started both in US and Europe.

Summary and Outlook

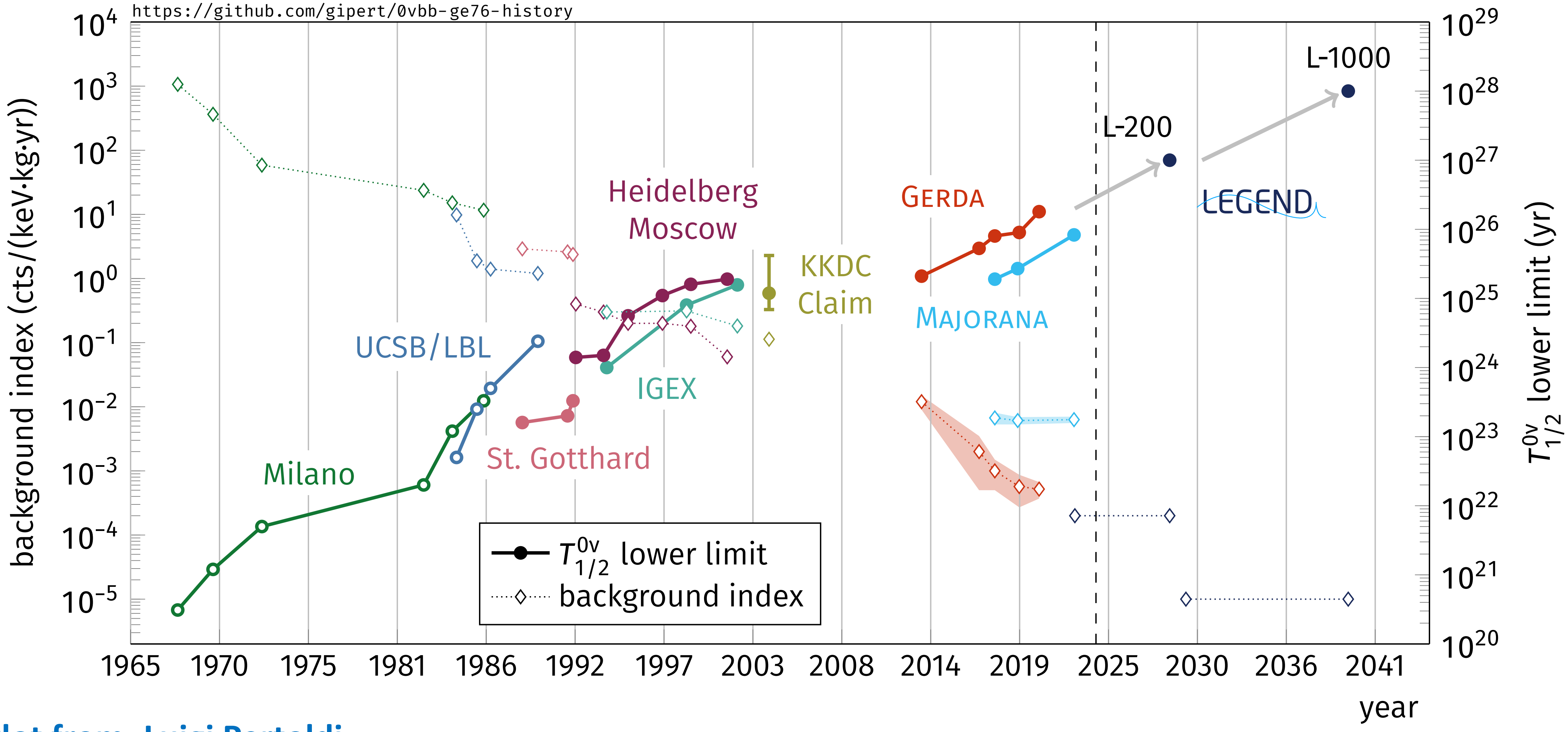
First LEGEND-200 results [arXiv2505.10440, submitted to PRL]

- Stable operations and excellent performance with 142 kg of ^{enr}Ge
- First LEGEND-200 0νββ results based on 61 kg·yr
- Combined fit with GERDA and MJD set $T_{1/2} > 1.9 \times 10^{26}$ yr @ 90% CL/CI
- World-leading sensitivity of 2.8×10^{26} yr
- New effective Majorana neutrino mass $m_{\beta\beta} < 75\text{-}200$ meV @ 90% CL

Current/Future steps

- Data taking will restart very soon
  →with enhanced detector array after deploying additional large-mass ICPC detectors
  →further background reduction by refining surface treatments of nearby components
- LEGEND-1000 preparations underway at LNGS

50+ years of ββ decay searches in ^{76}Ge



Plot from: Luigi Pertoldi

Backup

LEGEND-1000 funding status

Germany:

- ***MPG*** approved funding for cryostat
- ***BMFTR Research Infrastructure application*** submitted and ***prioritized in the*** [*BMFTR RI Roadmap*]

DOE:

- Review for the Critical Decision-1 ***(CD1)*** → Nov 2025
- CD3a phase → 2026

NSF: Two proposals.

- "Design of the NSF LEGEND-1000 Project", $2,744k submitted to NSF on Dec. 18, 2024 → **APPROVED**
- "Research Infrastructure: LEGEND-NSF Construction Proposal" MREFC proposal for $115 M submitted on Feb. 19, 2025. Proposed start date of MREFC construction FY 2027

Italy:

- ***CDR*** submitted in 2024
- ***TDR-Infrastructure*** (@LNGS) in preparation (to be submitted in October 2025).
- ***TDR-Detector*** → 2026

UK application in preparation

Poland received initial funding, additional funding expected

Switzerland received initial funding, additional funding expected