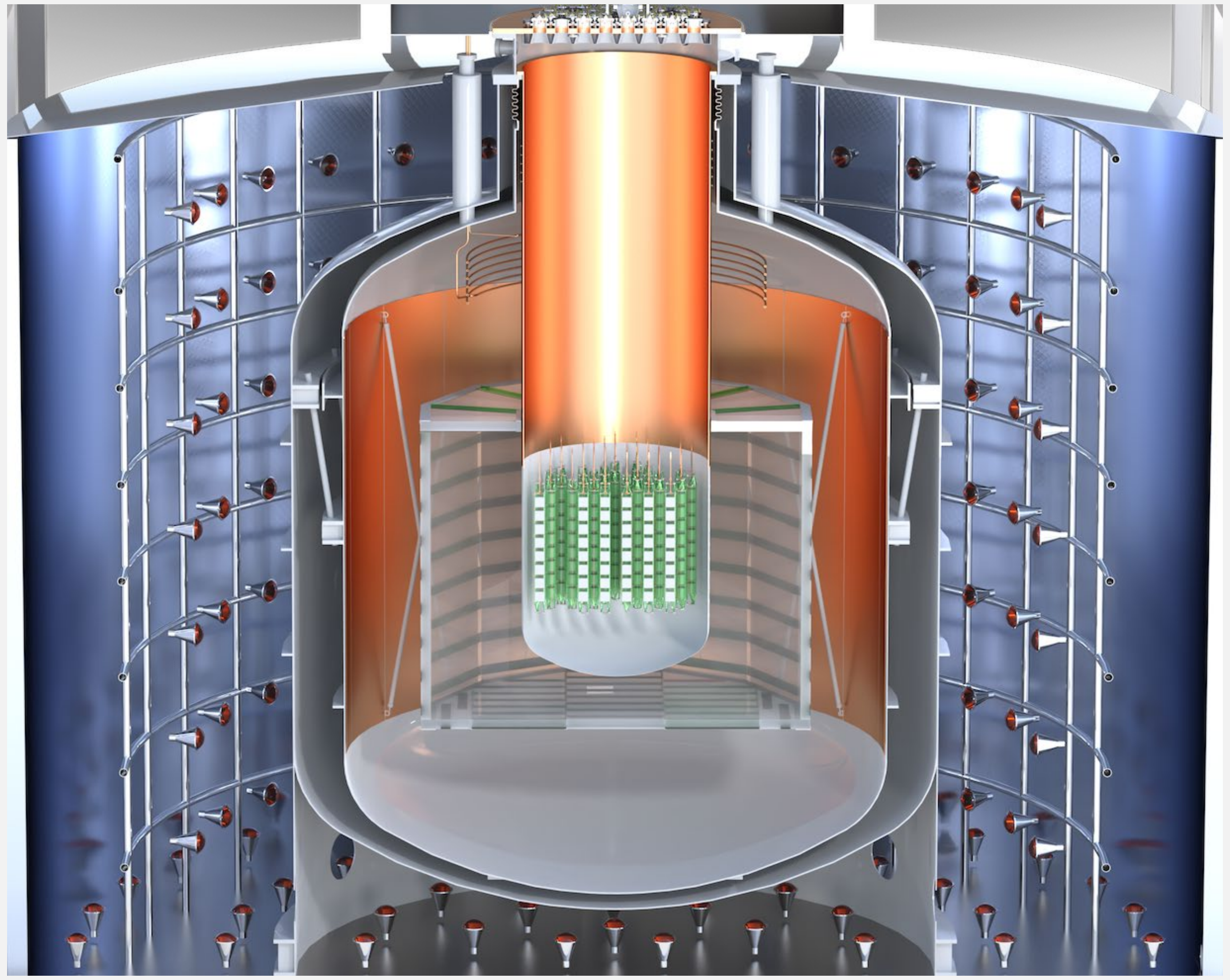
JINR

XXI Workshop on Neutrino Telescopes

LEGEND:
0νββ decay search with germanium detectors

LEGEND
Large Enriched Germanium Experiment for Neutrinoless ββ Decay



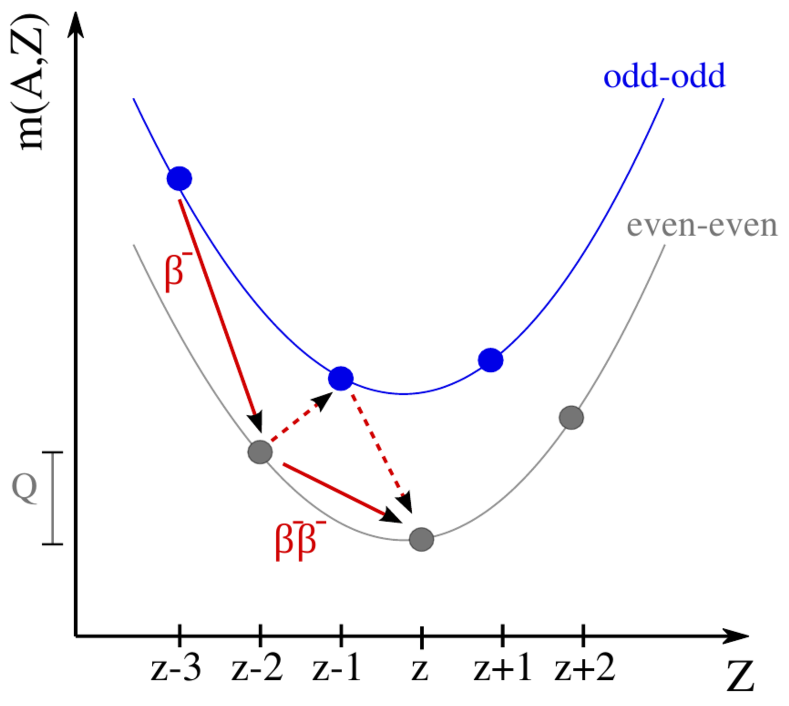
Konstantin Gusev

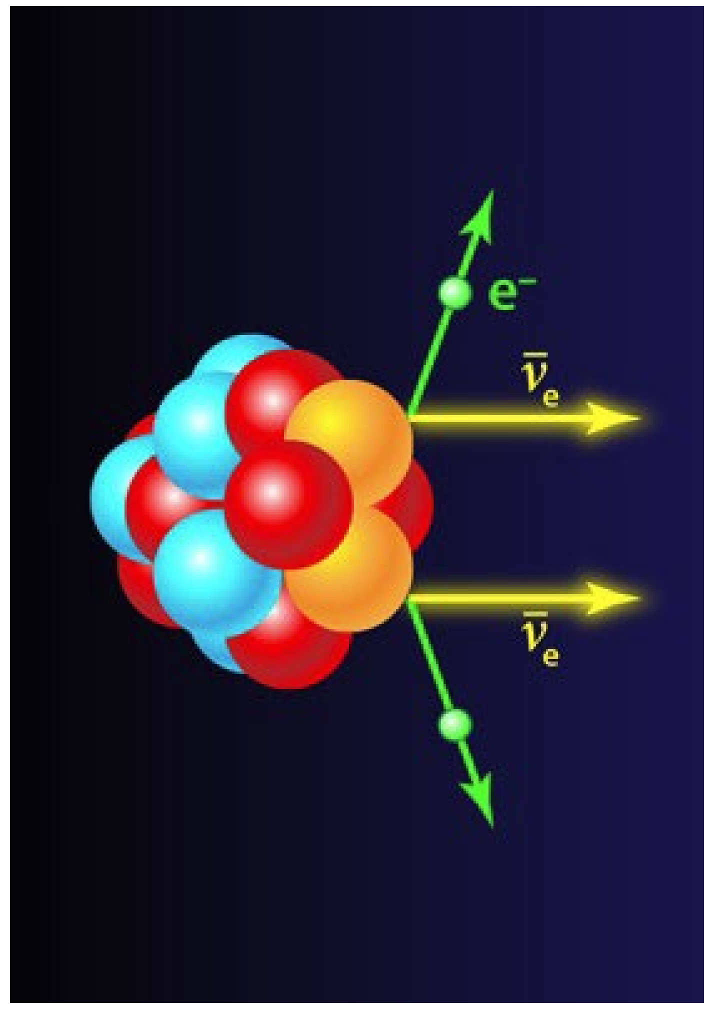
on behalf of LEGEND collaboration

30.09.2025

0νββ search: why?

Possible in 35 even-even nuclei
(β decay is energy/spin suppressed)





2νββ

- Rare process with half life is 10^{10} longer than the age of the universe, however already **observed** in 14 isotopes!
- Most precise measurement of 2νββ half-life in the world by **GERDA**:

$$T^{2\nu}_{1/2}(^{76}\mathrm{Ge}) = (2.043 \pm 0.033_{stat+sys}) \cdot 10^{21}\mathrm{yr}$$

0νββ search: why?

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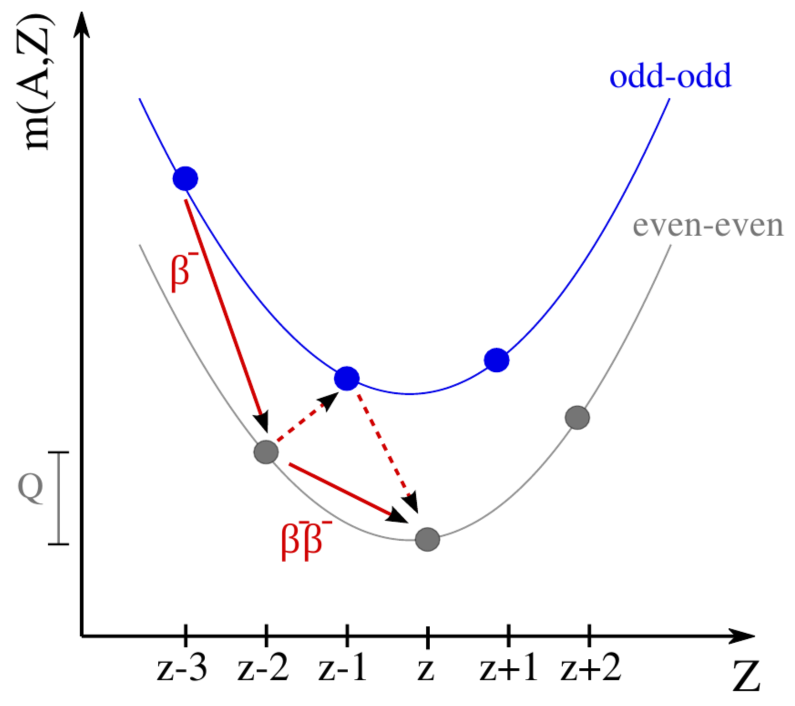

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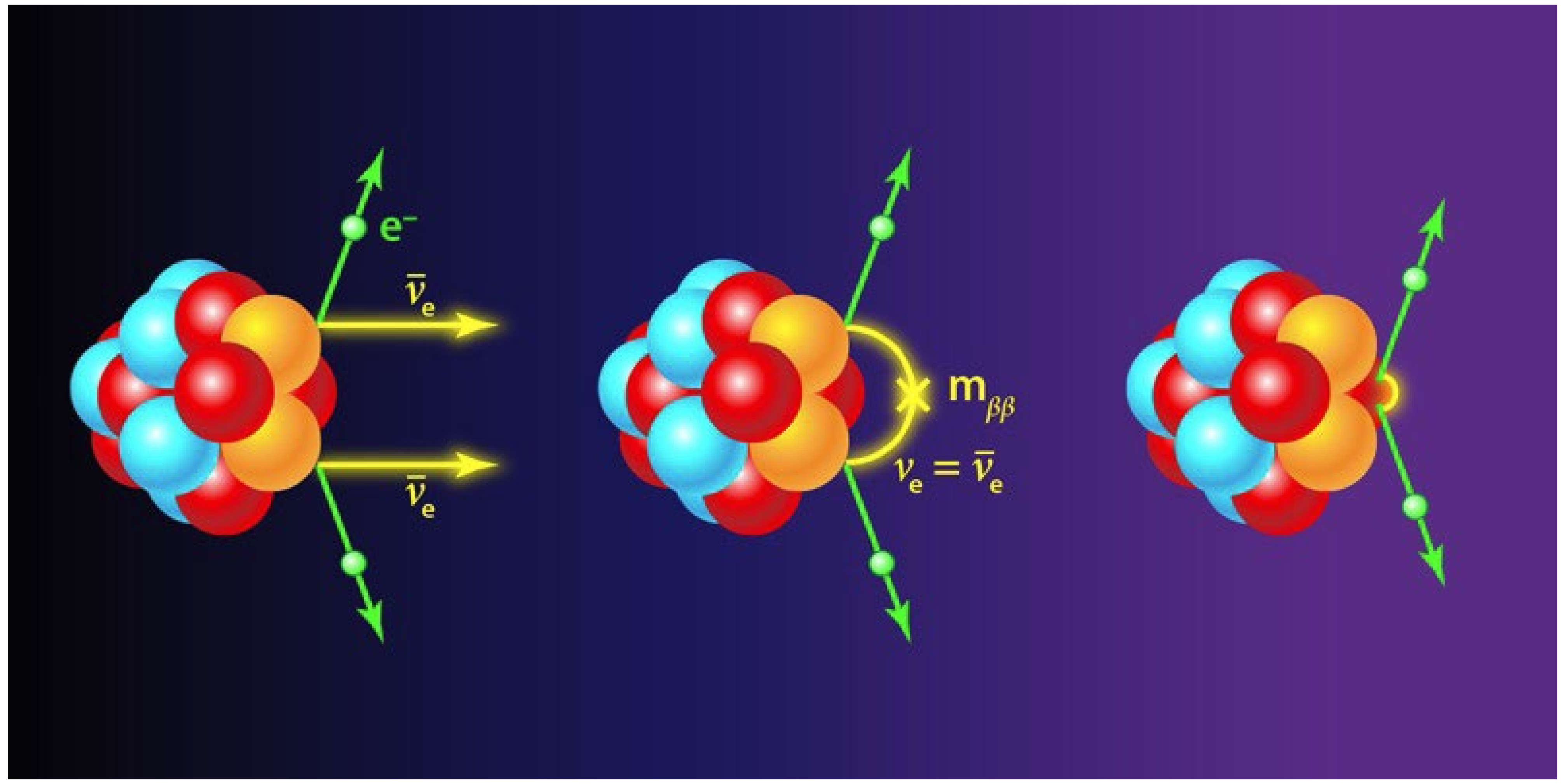


0νββ

- Violates lepton number
- Forbidden in Standard Model
  - New BSM physics
- Creates matter w/o antimatter
- Shows, that ν has Majorana mass component
- In case of light ν exchange
  - would give access to ν mass scale
  - would provide important input to cosmology

Link between 0νββ and ν-mass

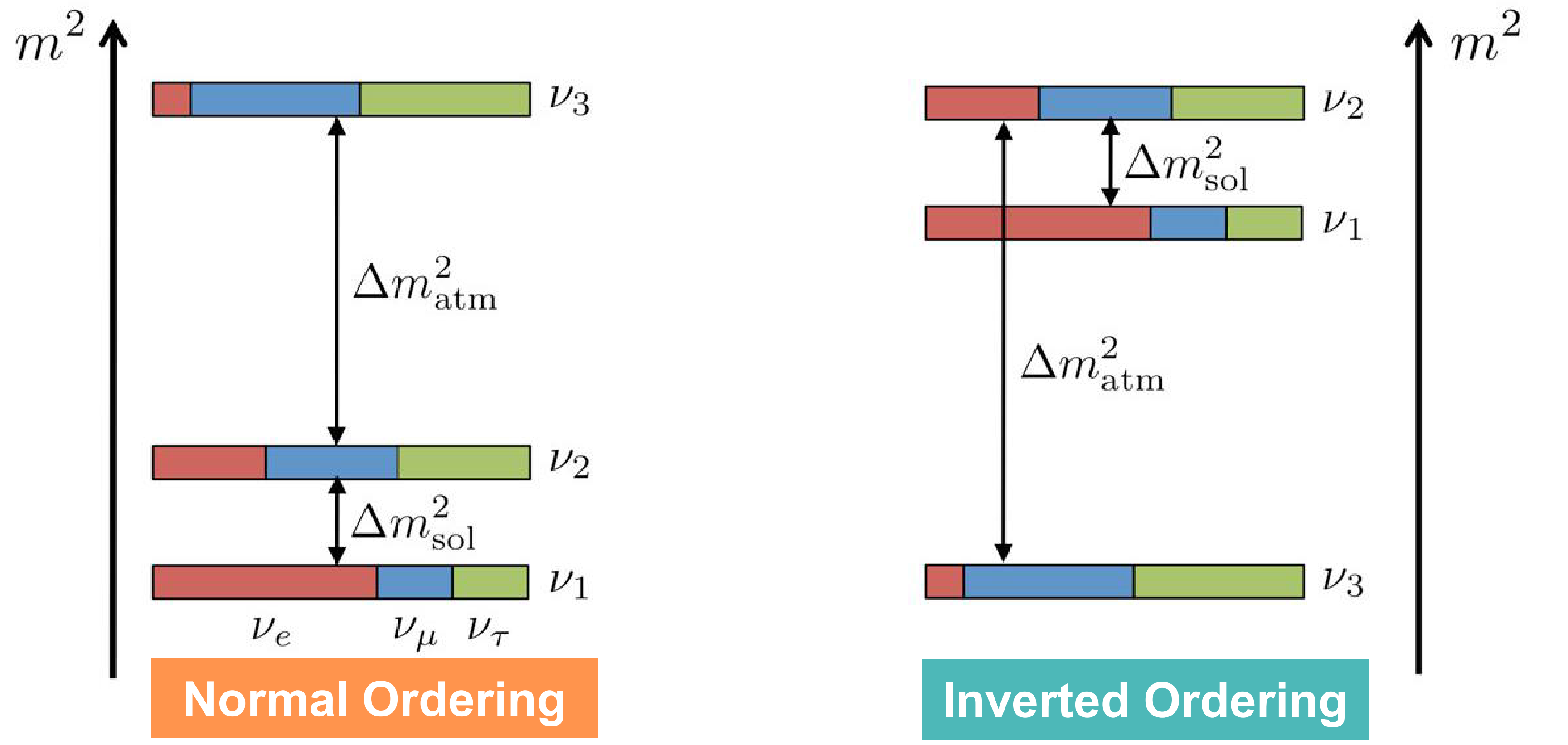
$$\frac{1}{T^{0\nu}_{1/2}} = G^{0\nu}(Q,Z)\, g_A^4\, |M^{0\nu}|^2 \left(\frac{m_{\beta\beta}}{m_e}\right)^2$$

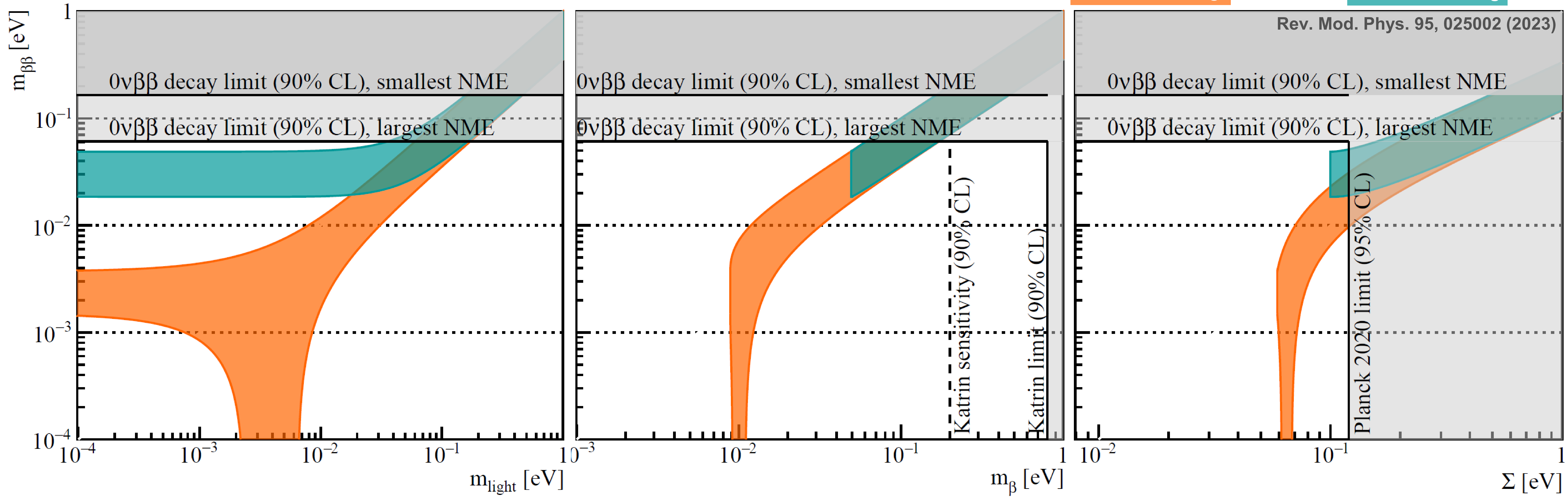
- $\frac{1}{T^{0\nu}_{1/2}}$: **0νββ decay rate**
- $G^{0\nu}(Q,Z)$: **Phase space factor**
- $|M^{0\nu}|^2$: **Nuclear Matrix Element**
- $m_{\beta\beta}$: **Effective Majorana neutrino mass**

$$m_{\beta\beta} = \left|\sum U_{ei}^2 m_i\right|$$

$$m_\beta = \sqrt{\sum m_i^2 |U_{ei}|^2}$$

$$\Sigma \text{ or } m_{cosm} = \sum m_i$$



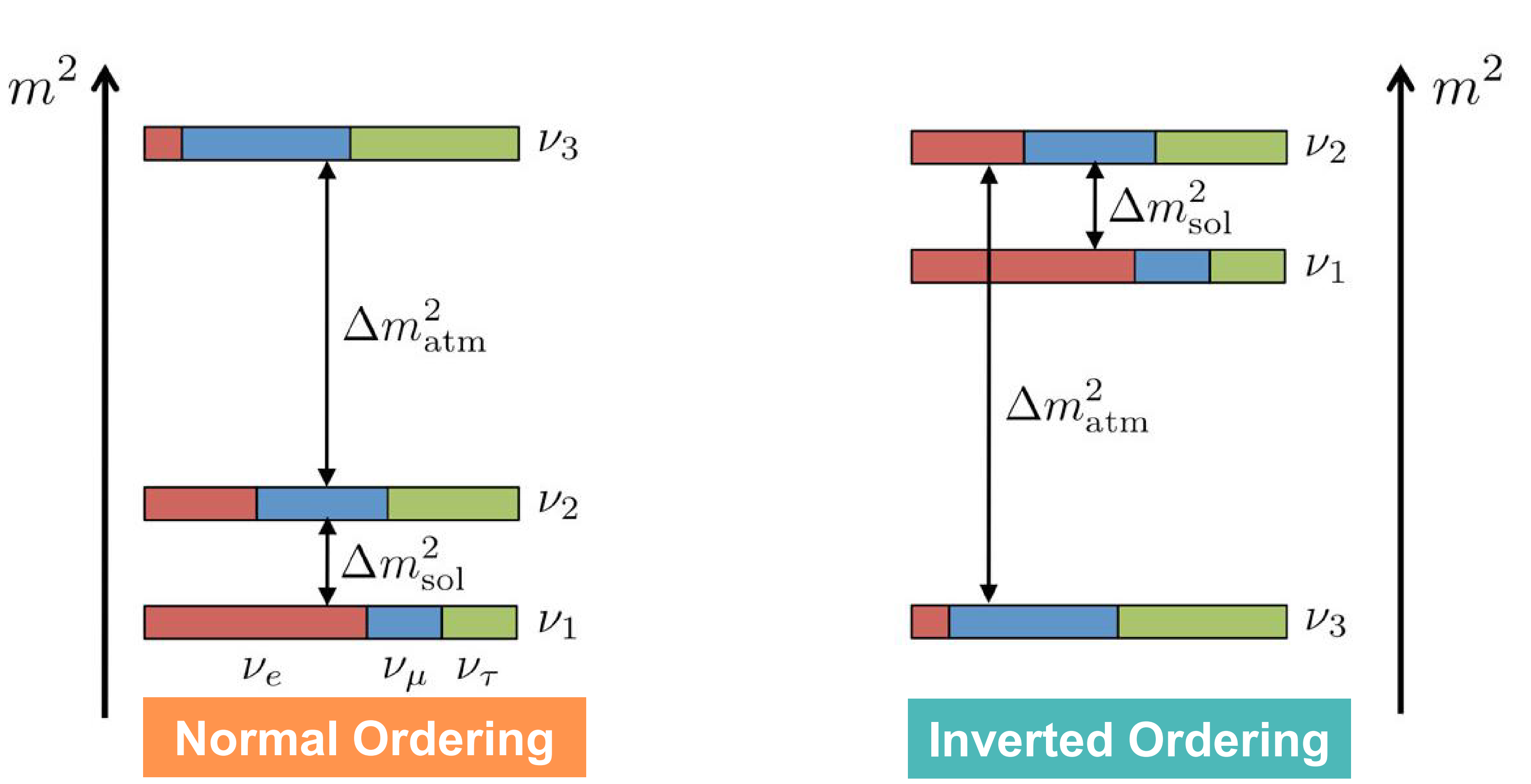


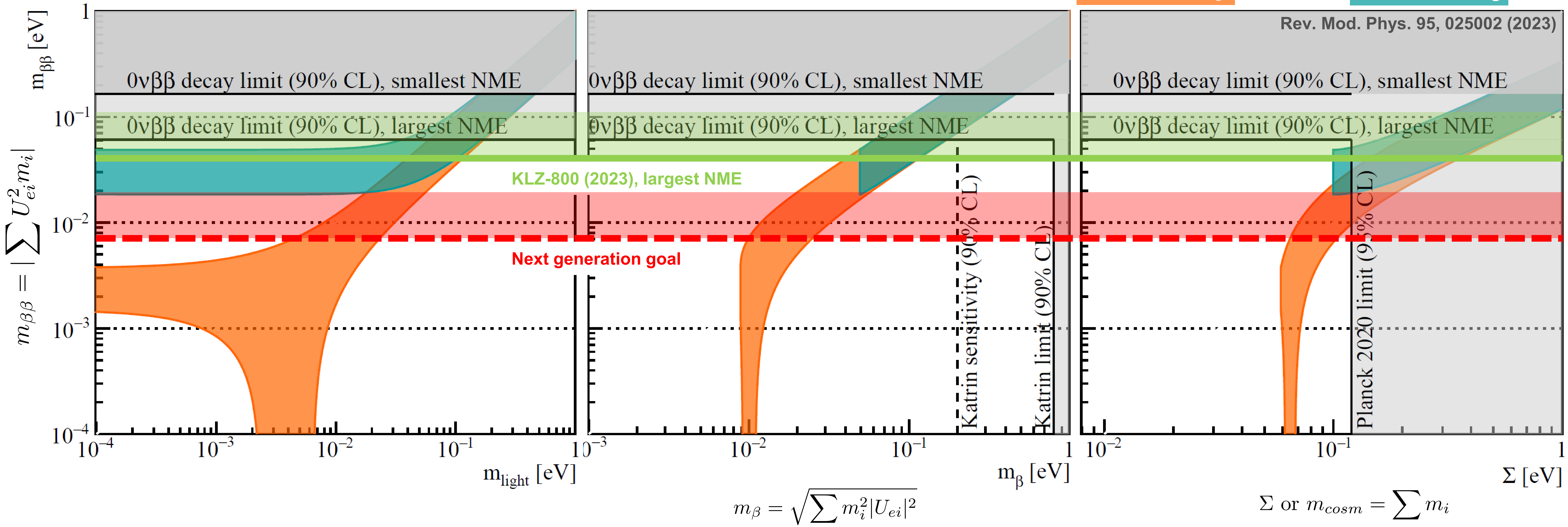
Link between 0νββ and ν-mass

Notes:

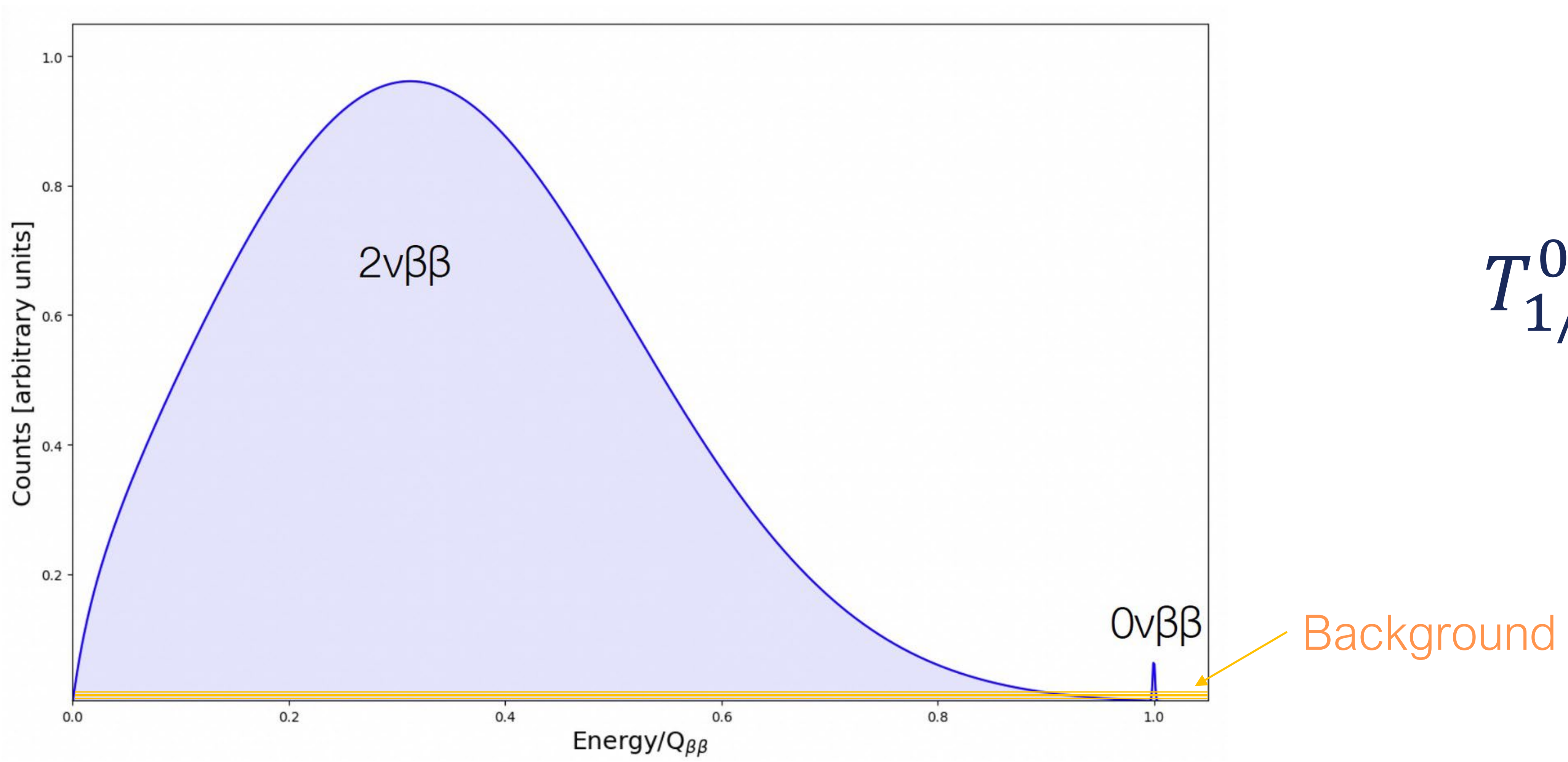
- **Recent KamLAND-Z 800** limit came to **IO** region
- Next generation projects fully cover **IO** and part of **NO**

$$\frac{1}{T_{1/2}^{0\nu}} = G^{0\nu}(Q,Z)g_A^4|M^{0\nu}|^2\left(\frac{m_{\beta\beta}}{m_e}\right)^2$$



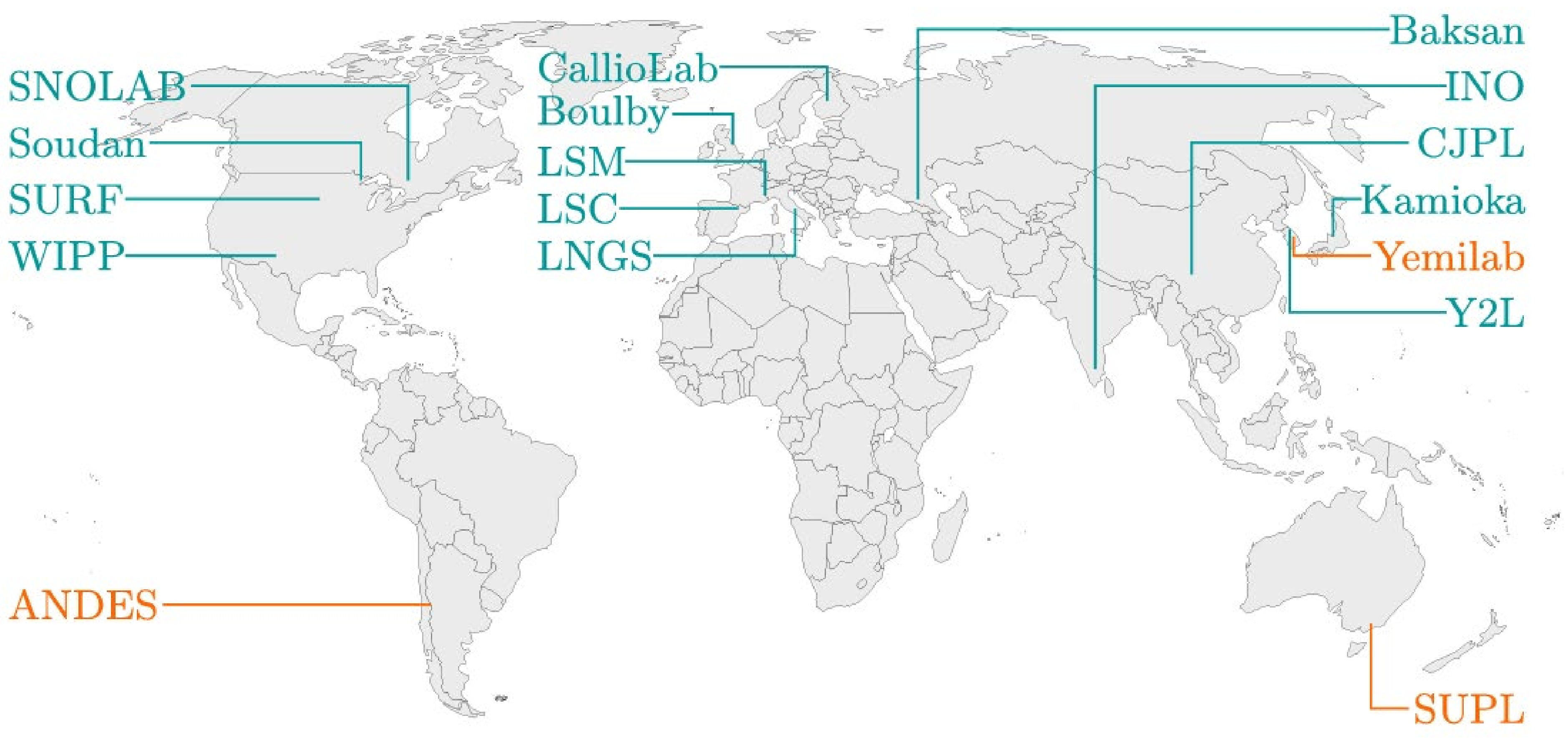


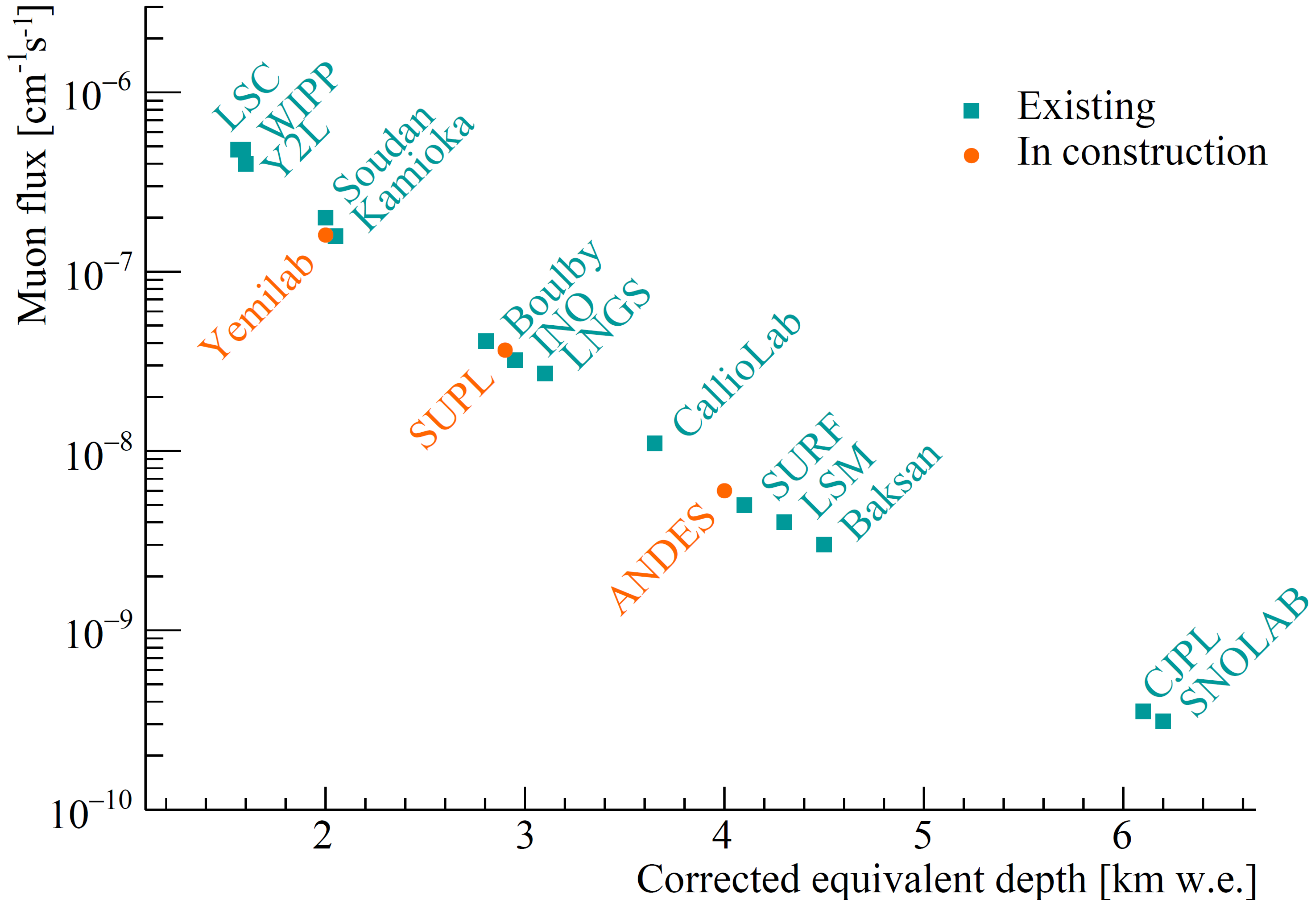
Experimental design considerations



$$T_{1/2}^{0\nu} \propto \epsilon \sqrt{\frac{M\,t}{\Delta E\,BI}}$$

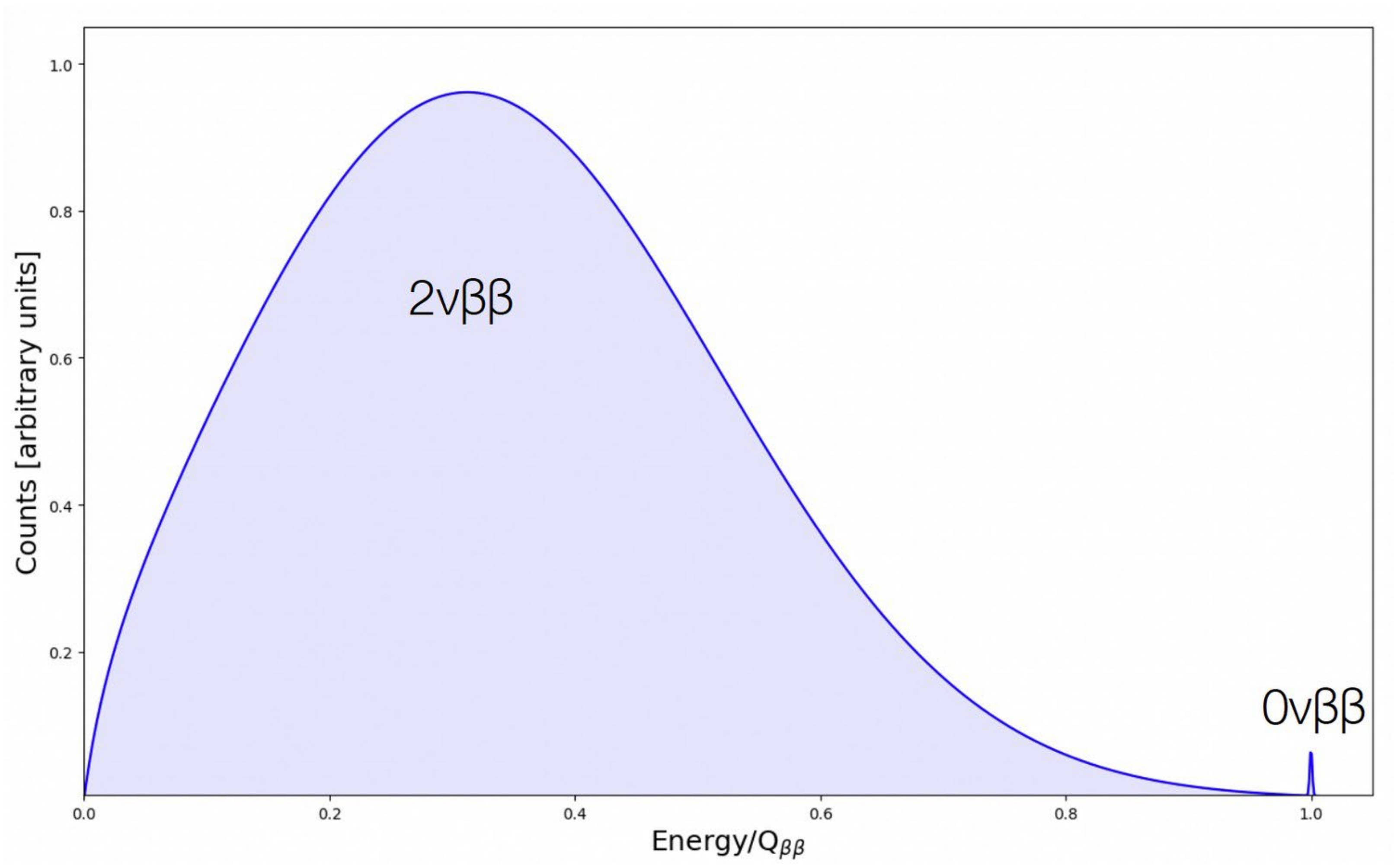
Background Index





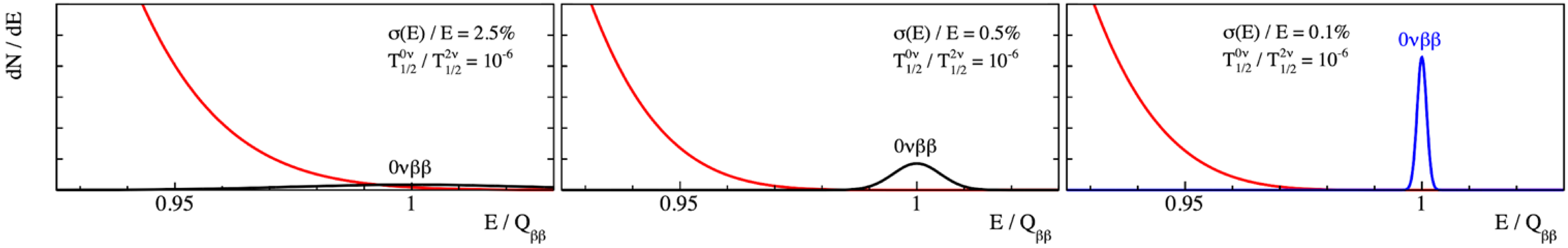
- Detector performance:
  - High mass and good long-term stability to increase exposure
  - High efficiency: source = detectors
  - Good energy resolution
  - Small background:
    - Underground labs to reduce the cosmogenic
    - Materials handling and cleanliness
    - Strict radiopurity constraints
    - Passive and active (!) shielding
    - Signal discrimination techniques

"Background free" experiment

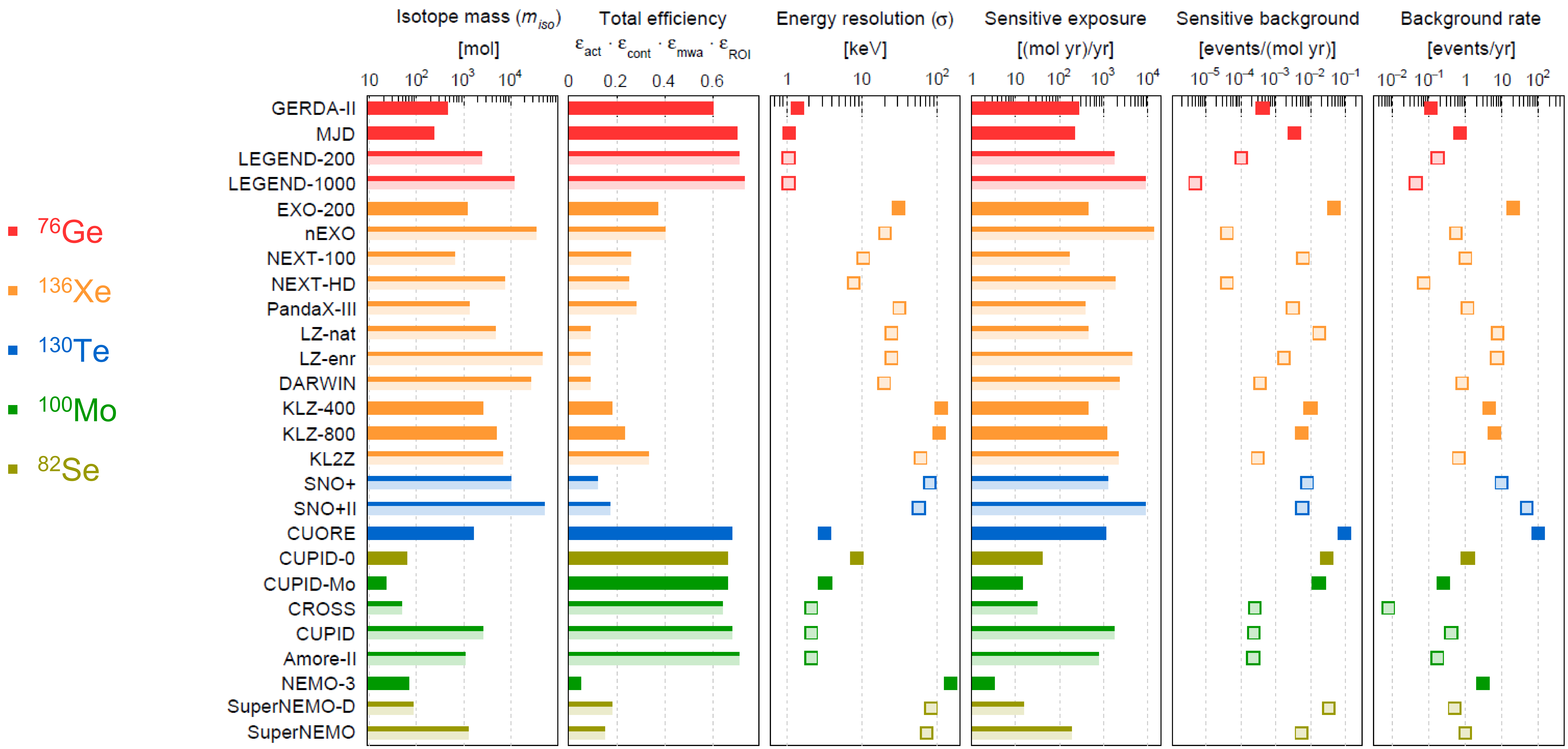


$$T_{1/2}^{0\nu} \propto \epsilon\, M\, t$$

- But energy resolution still essential!

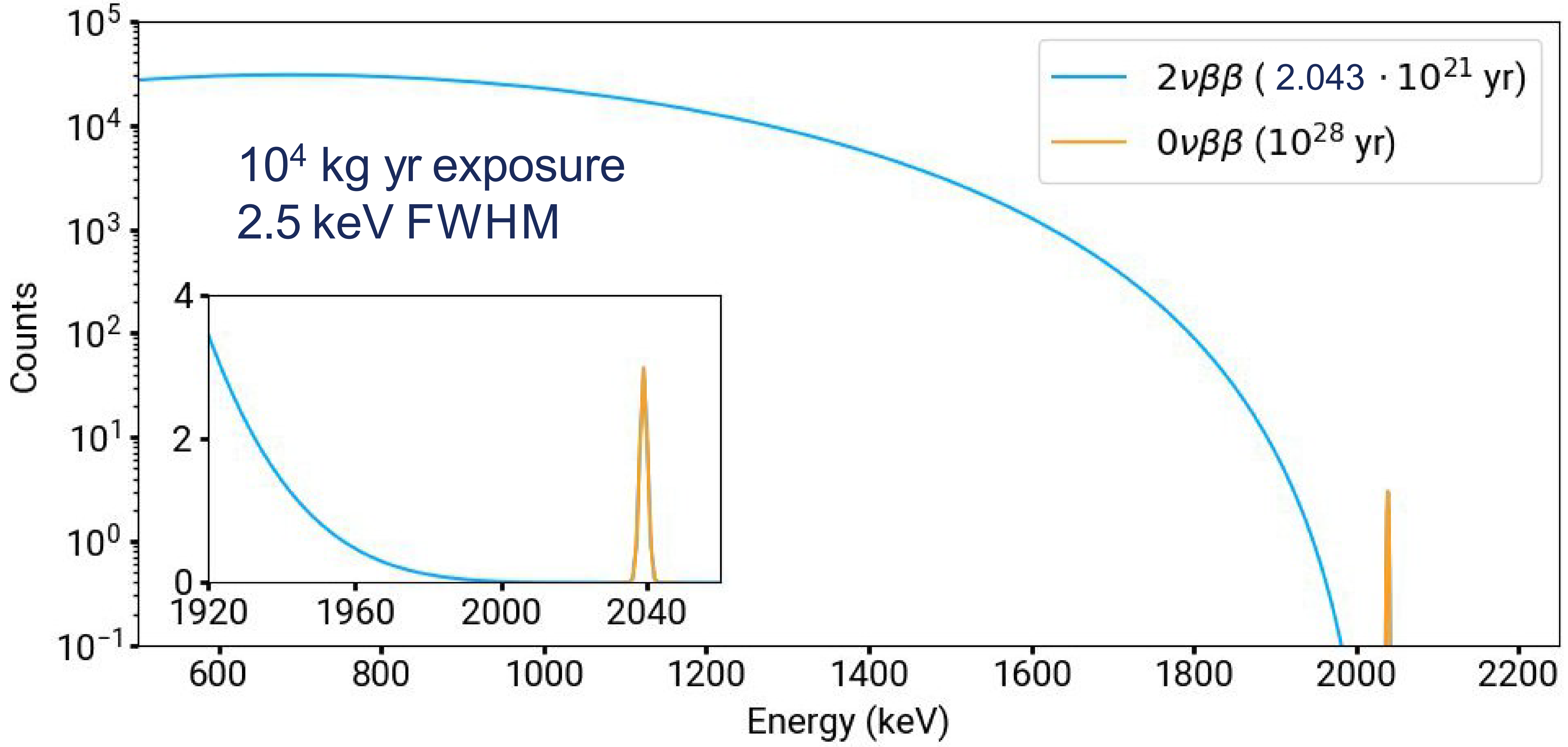


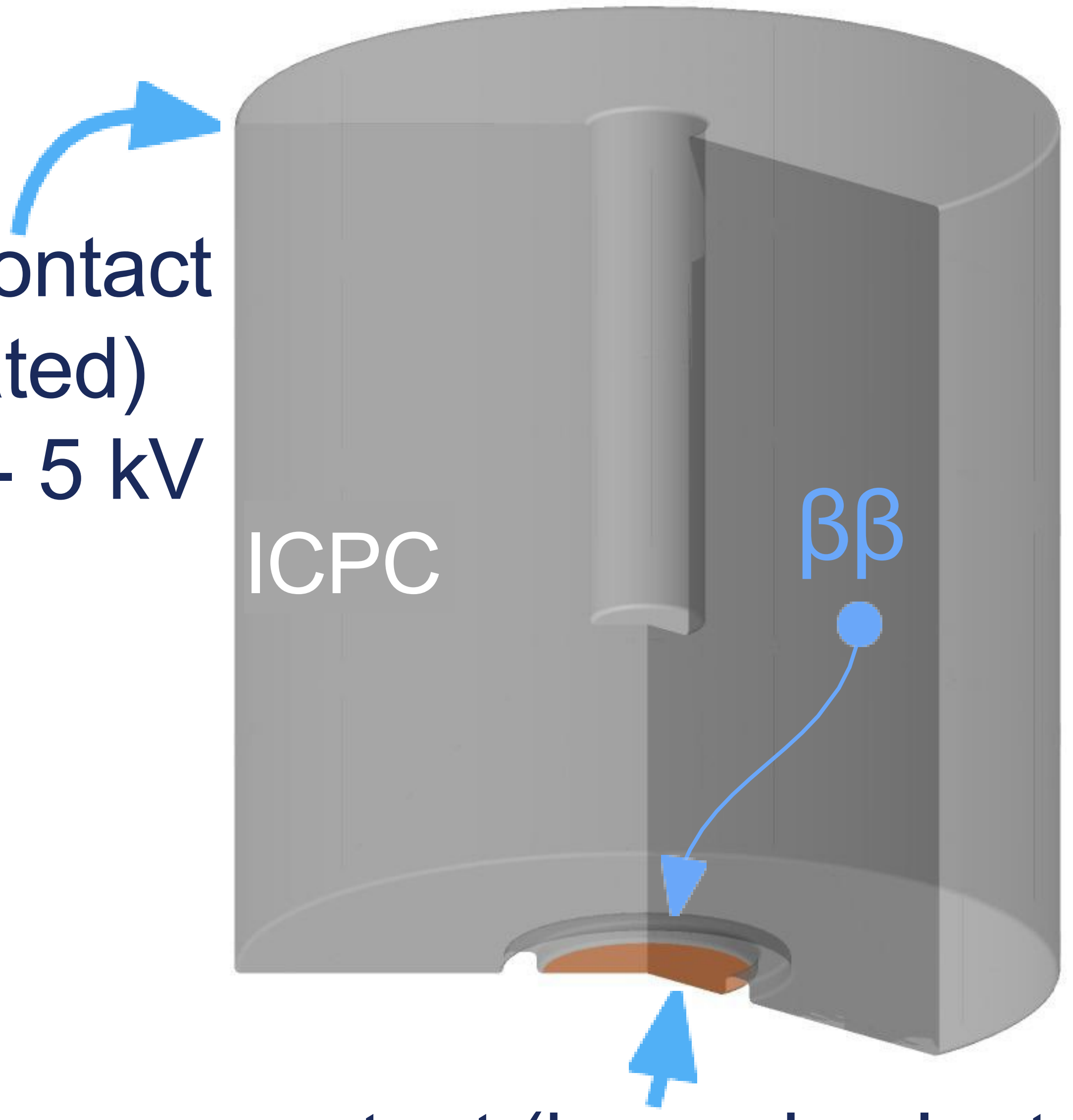
Experimental landscape



Rev. Mod. Phys. 95, 025002 (2023)

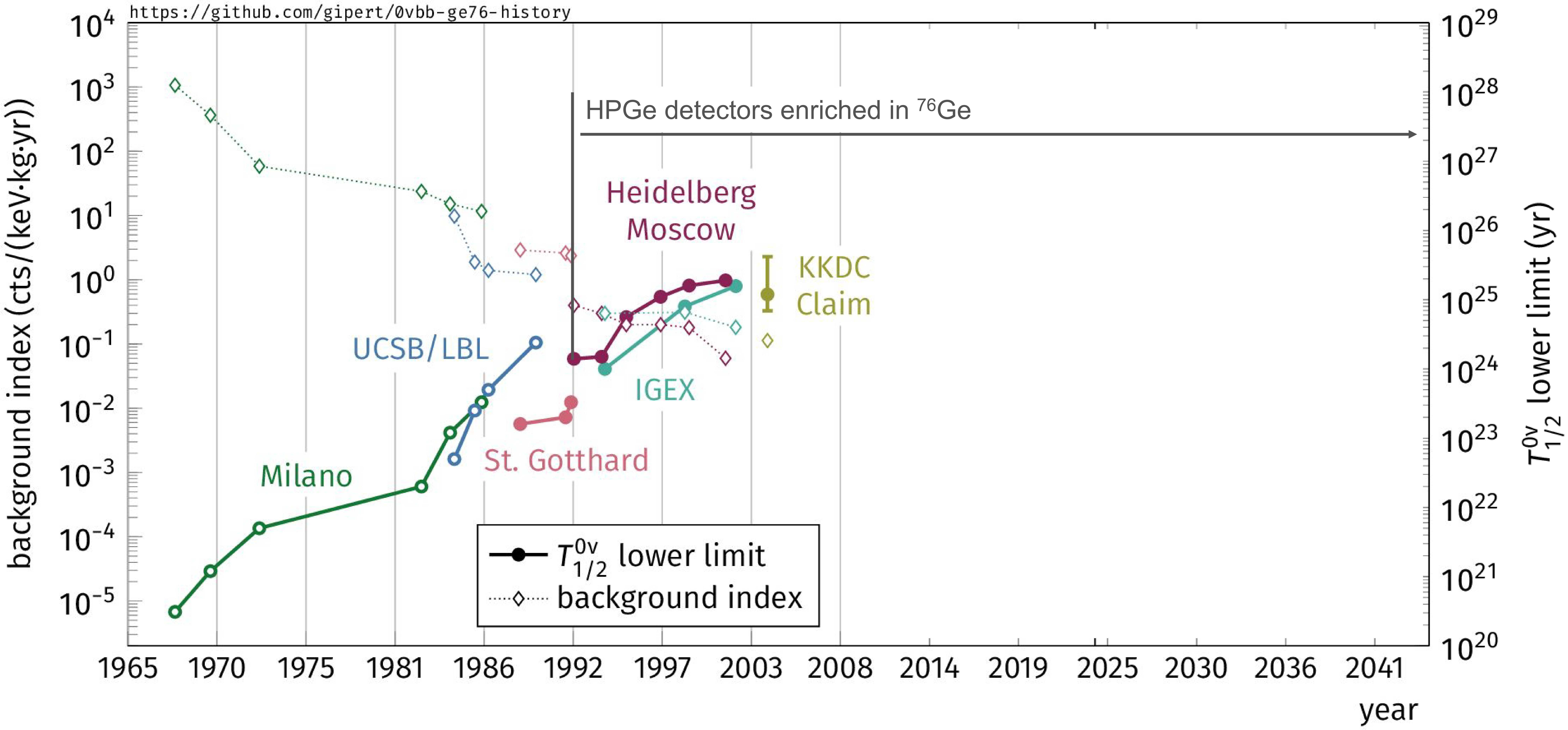
0νββ search with HPGe detectors enriched in ^{76}Ge



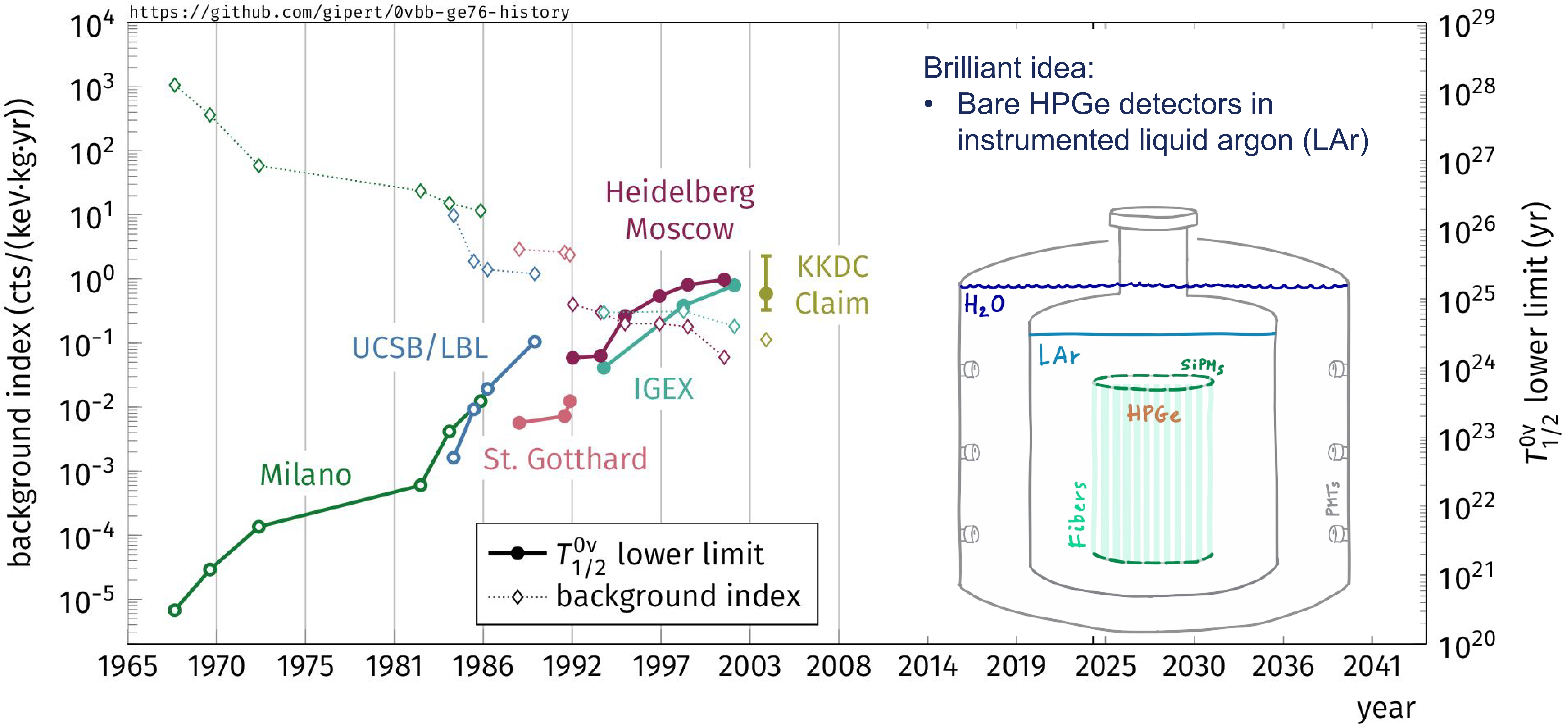


- High-Purity Germanium detectors enriched in ^{76}Ge
  - ββ source = detector → high efficiency
  - high purity → low intrinsic background
  - isotope enrichment → ≳ 90 % ^{76}Ge
  - excellent energy resolution → ~ 0.1 % FWHM @ $Q_{\beta\beta}$
  - topological discrimination → pulse shape discrimination (PSD)

History of 0νββ search with HPGe detectors



History of 0νββ search with HPGe detectors

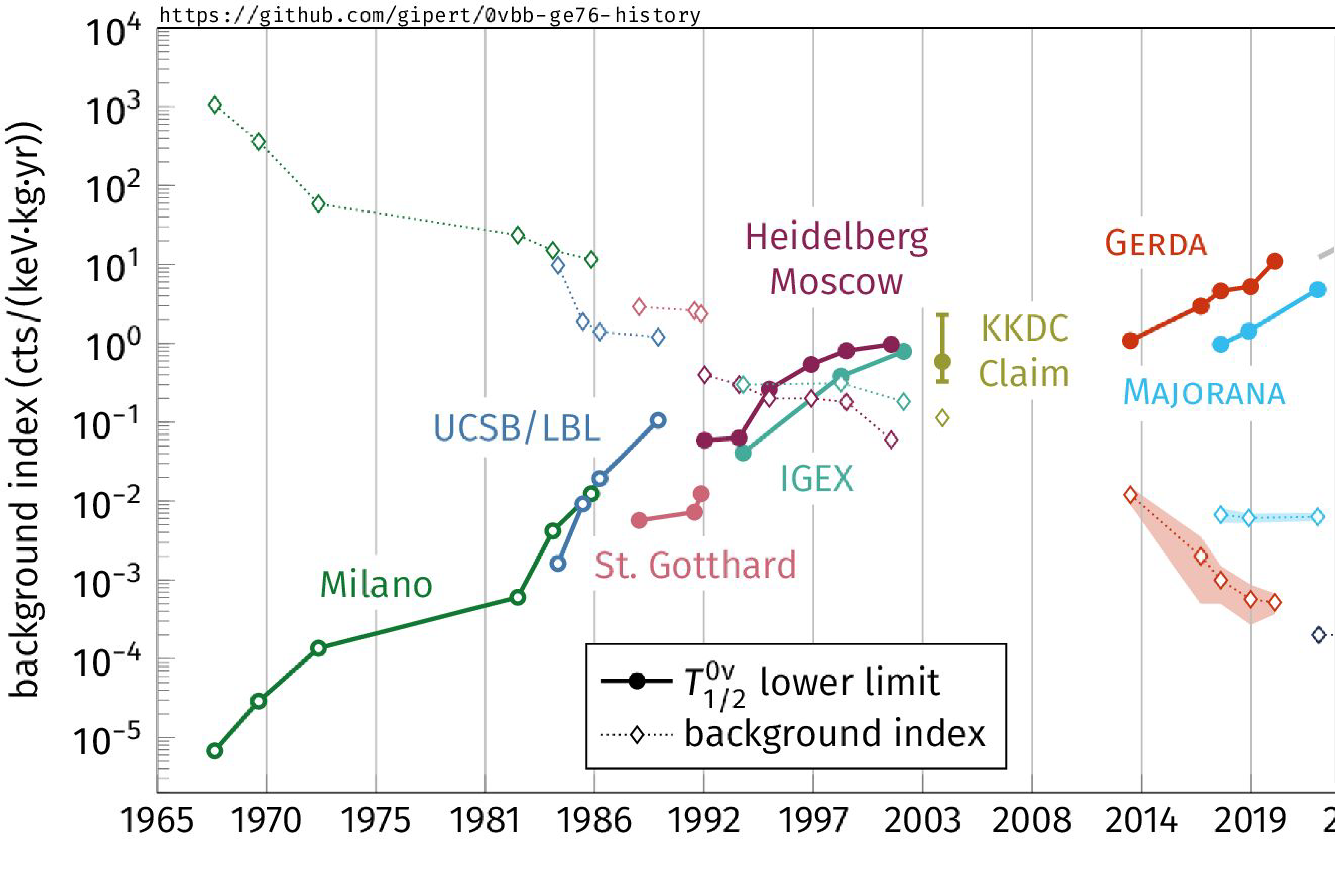


Brilliant idea:

- Bare HPGe detectors in instrumented liquid argon (LAr)

History of 0νββ search with HPGe detectors

LEGEND



GERDA

(127.3 kg yr)

Had the **best BI**:

5 × 10^{-4} cts/(keV kg yr)

Used both **PSD** and **LAr anti-coincidence**.

Majorana Demonstrator

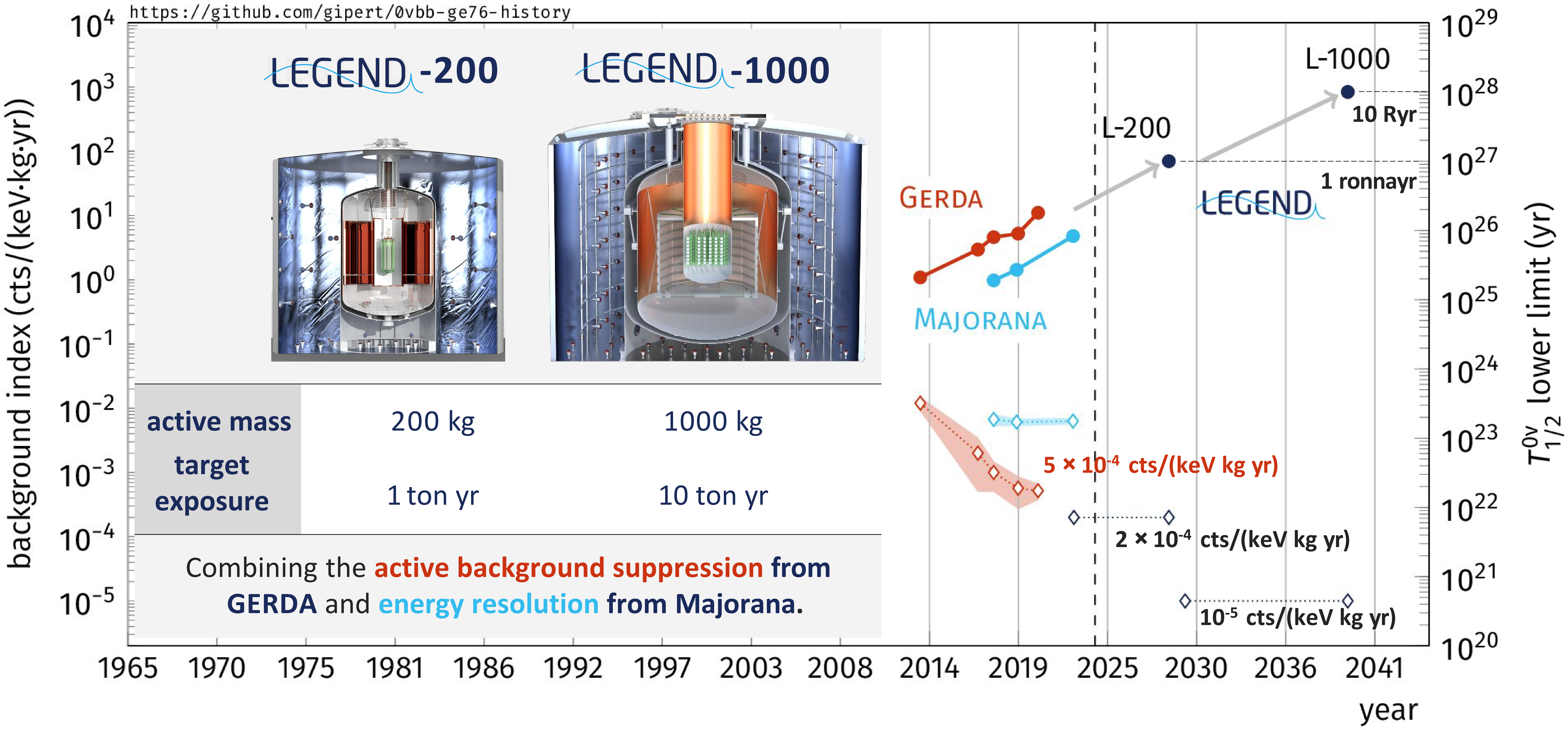
(64.5 kg yr)

Had the **best energy resolution:**

2.5 keV @ $Q_{\beta\beta}$

Used **PSD** to reduce BI.

New history of 0νββ search with HPGe detectors



	LEGEND-200	LEGEND-1000
active mass	200 kg	1000 kg
target exposure	1 ton yr	10 ton yr

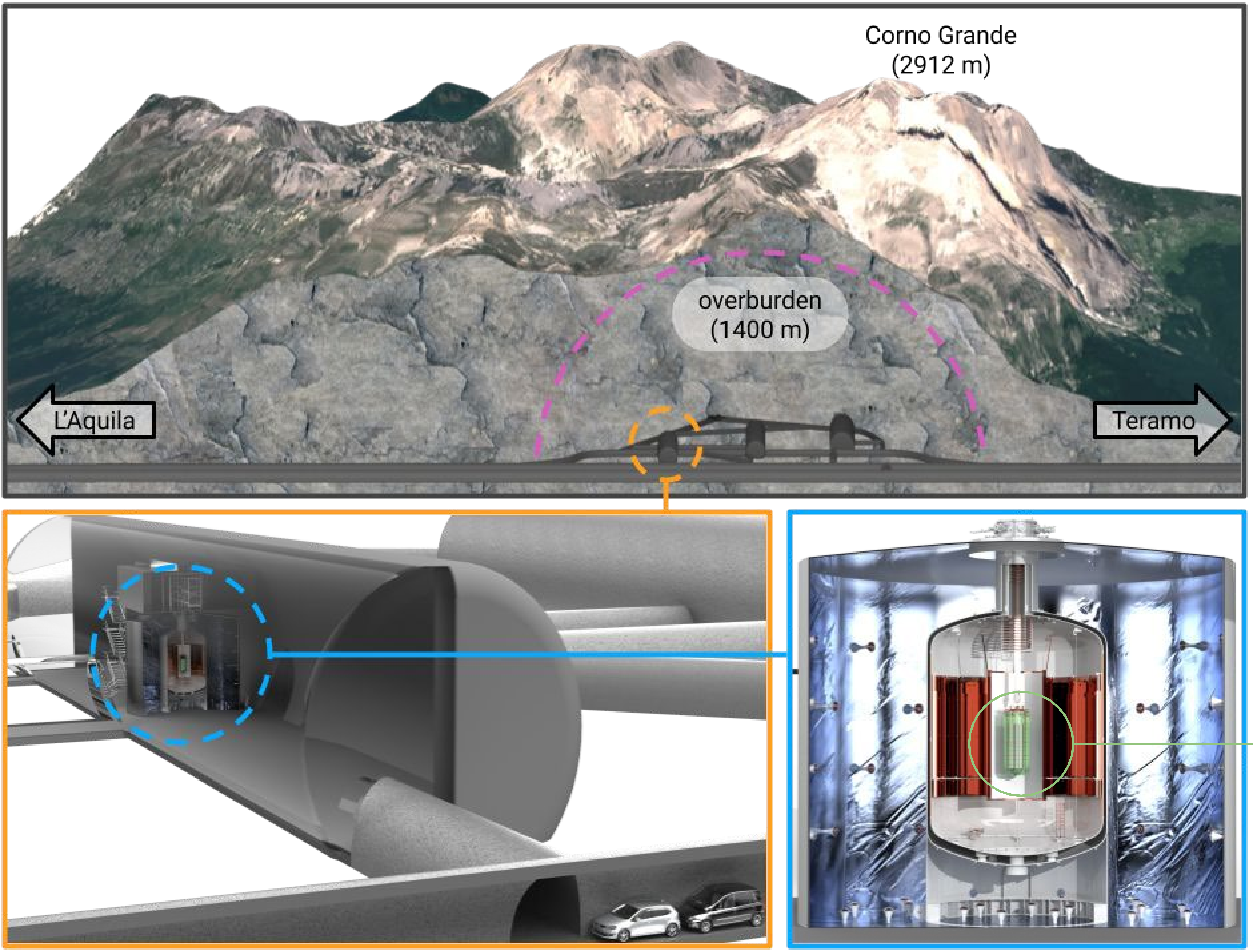
Combining the **active background suppression from GERDA** and **energy resolution from Majorana.**

LEGEND Collaboration

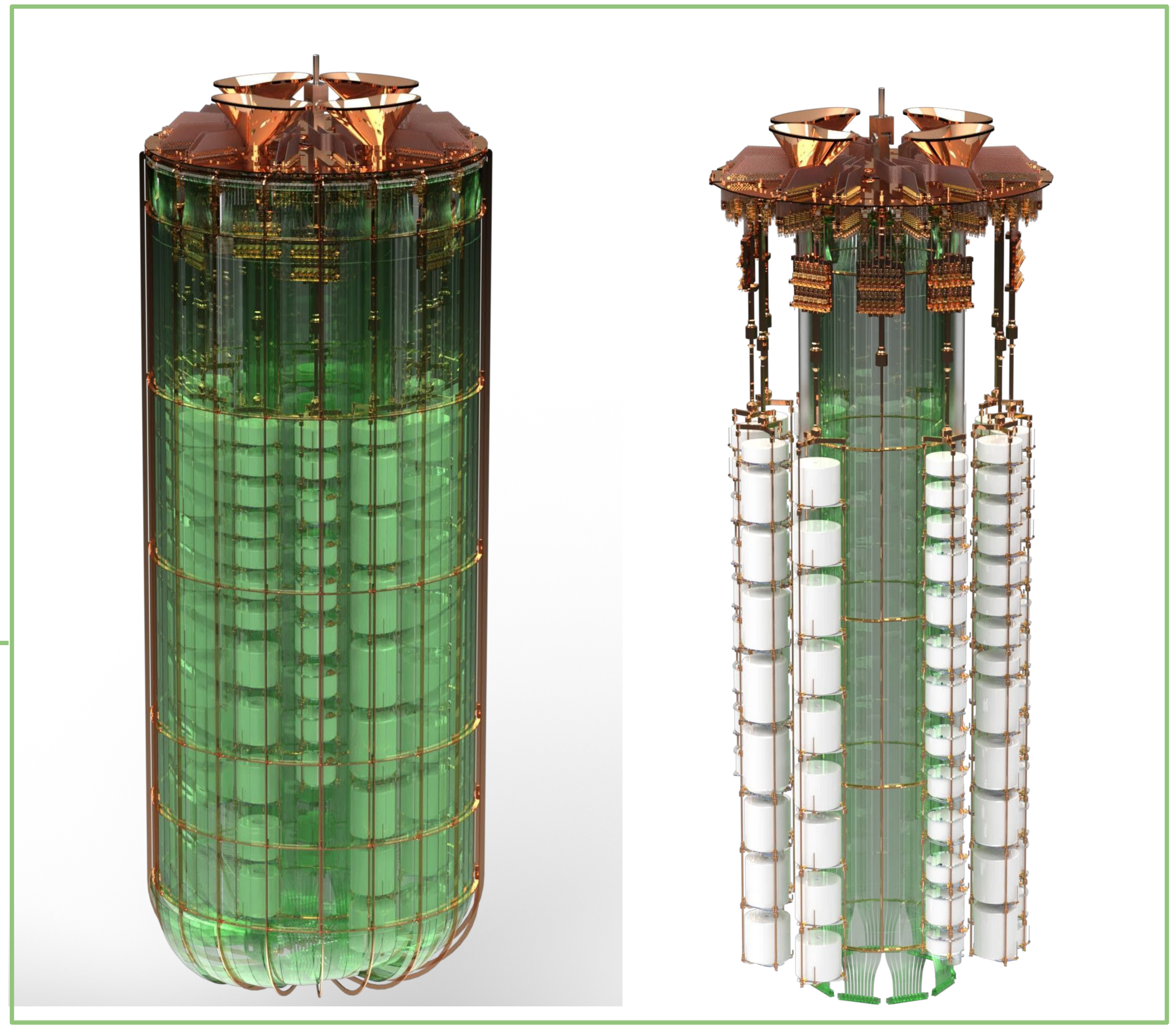
58 Institutions, 12 Countries, 1 Goal:

Develop a phased, ^{76}Ge based double-beta decay experimental program with discovery potential at a half-life beyond 10^{28} years

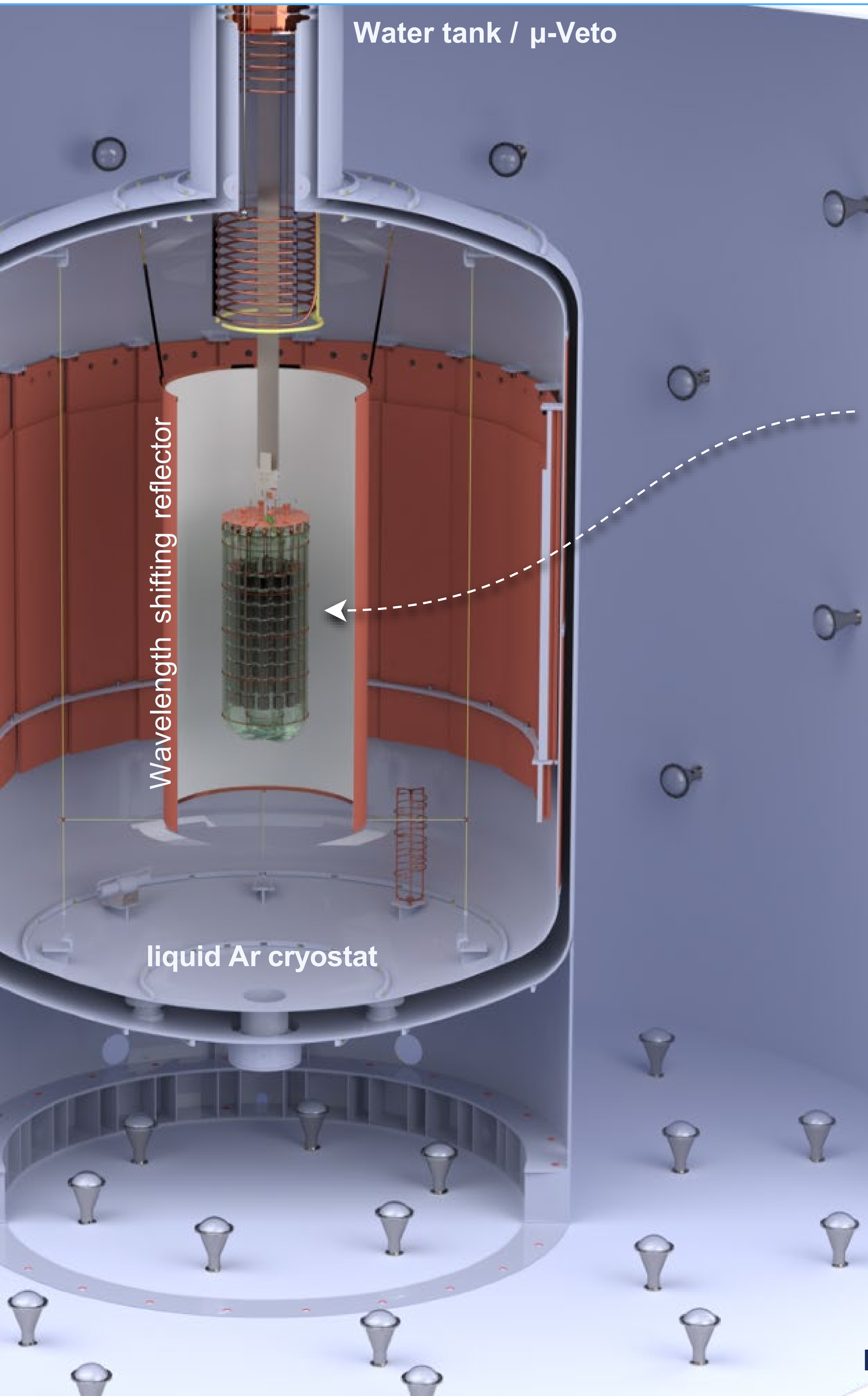
LEGEND-200: Location (LNGS Hall A) and design

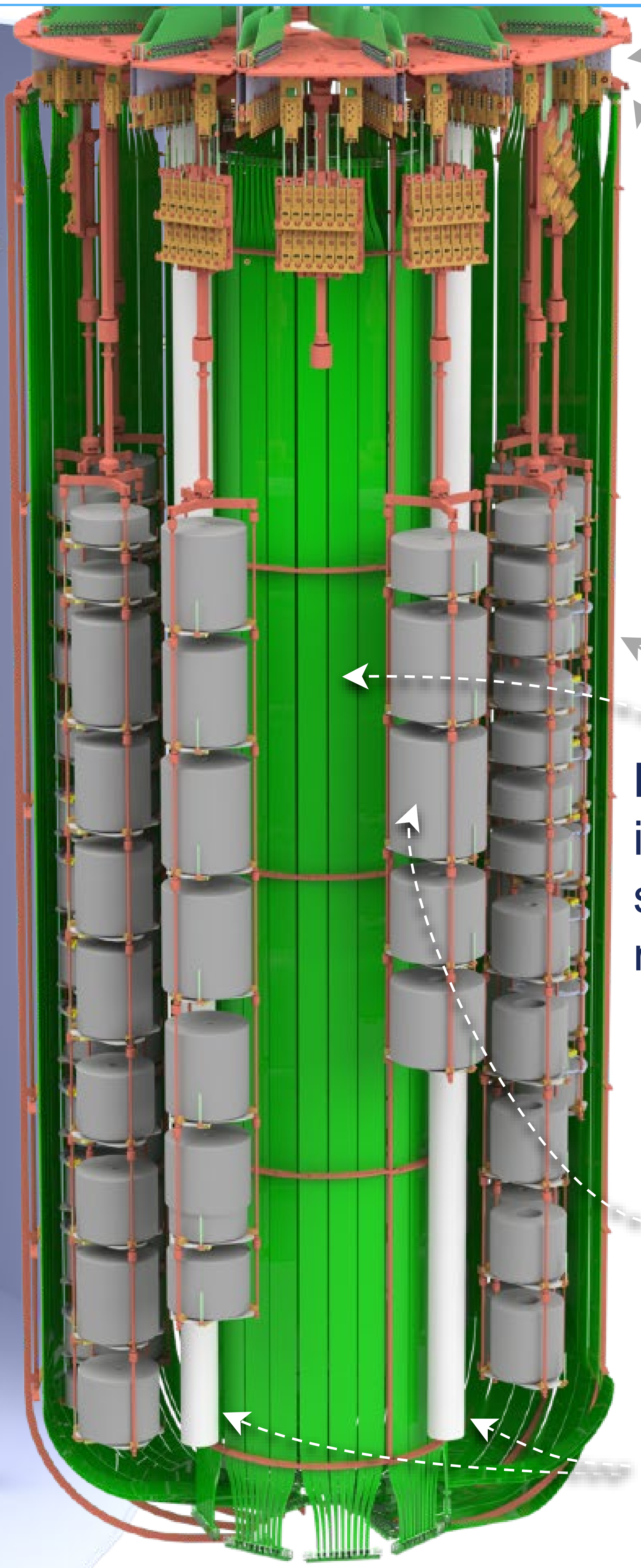


- Up to 200 kg HPGe Detectors
- LAr instrumentation (two fiber shrouds)
- Infrastructure of GERDA
- $T > 10^{27}$ yr
- $< 2 \cdot 10^{-4}$ cts/(keV kg yr)



LEGEND-200: the best from GERDA and Majorana





HPGe Detector array & LAr Instrumentation

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

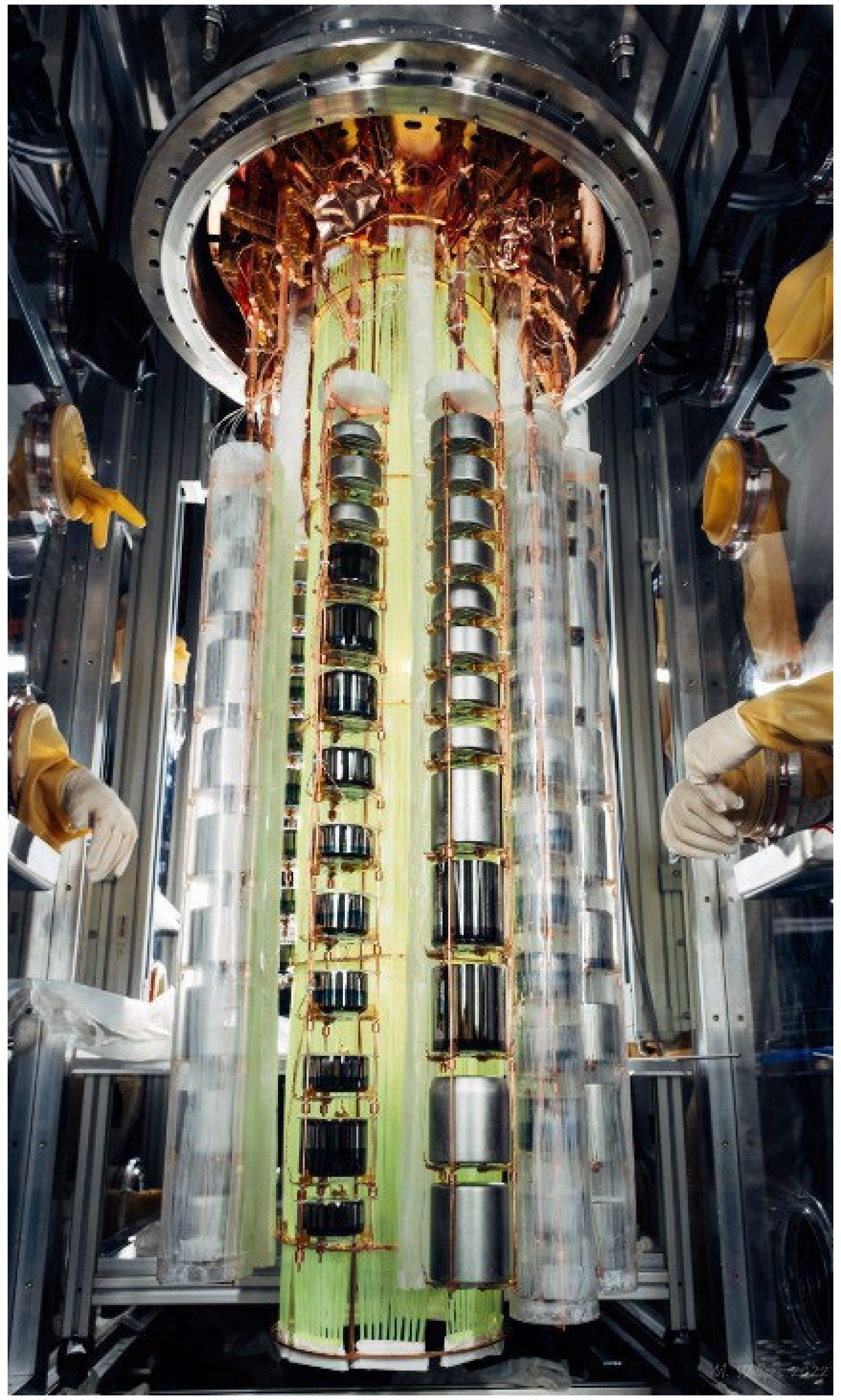
Detector mount: underground copper,
optically active PEN plates & radiopure plastics

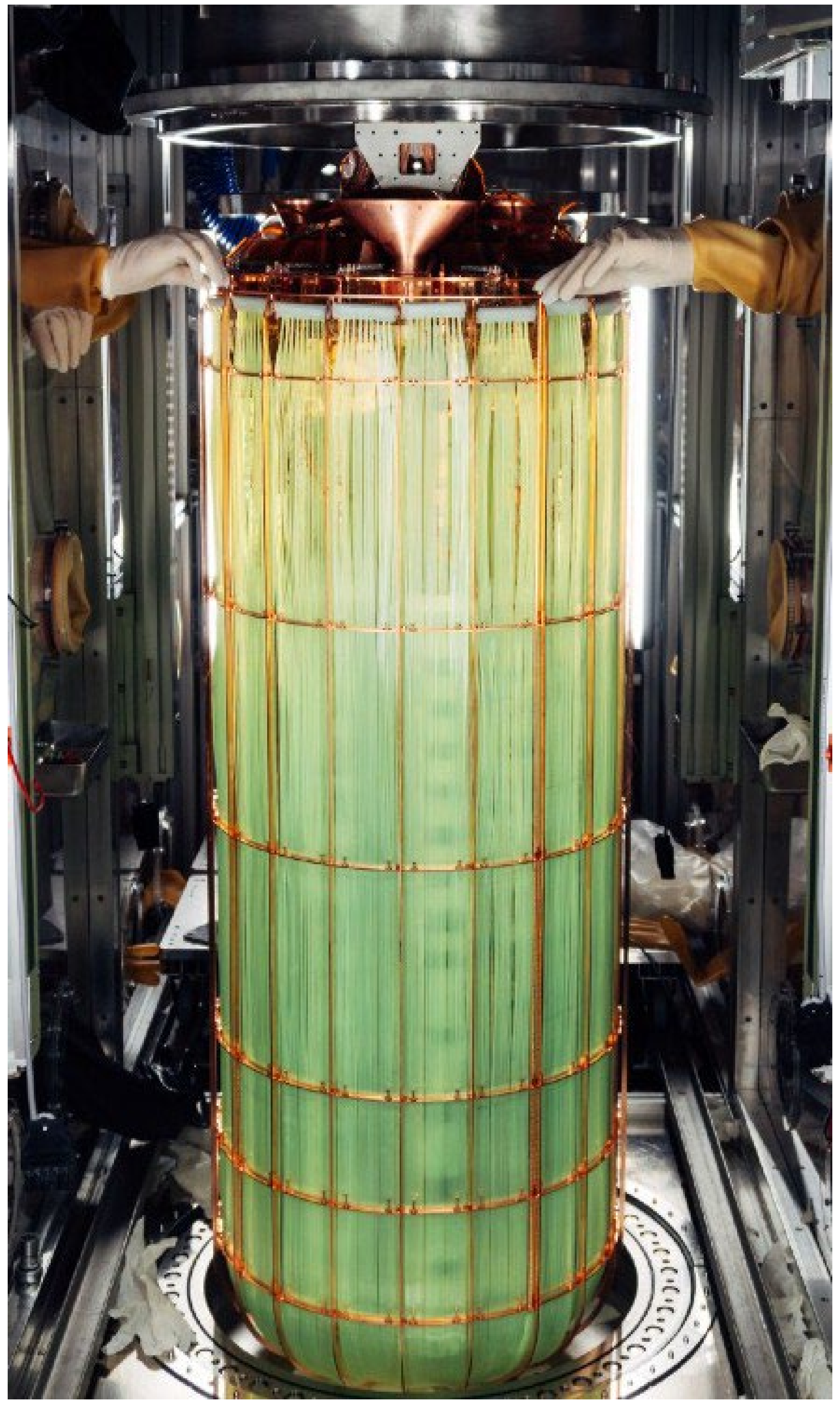
Liquid Argon instrumentation:
inner & outer fiber barrels with
silicon photomultiplier (SiPM)
readout at top & bottom

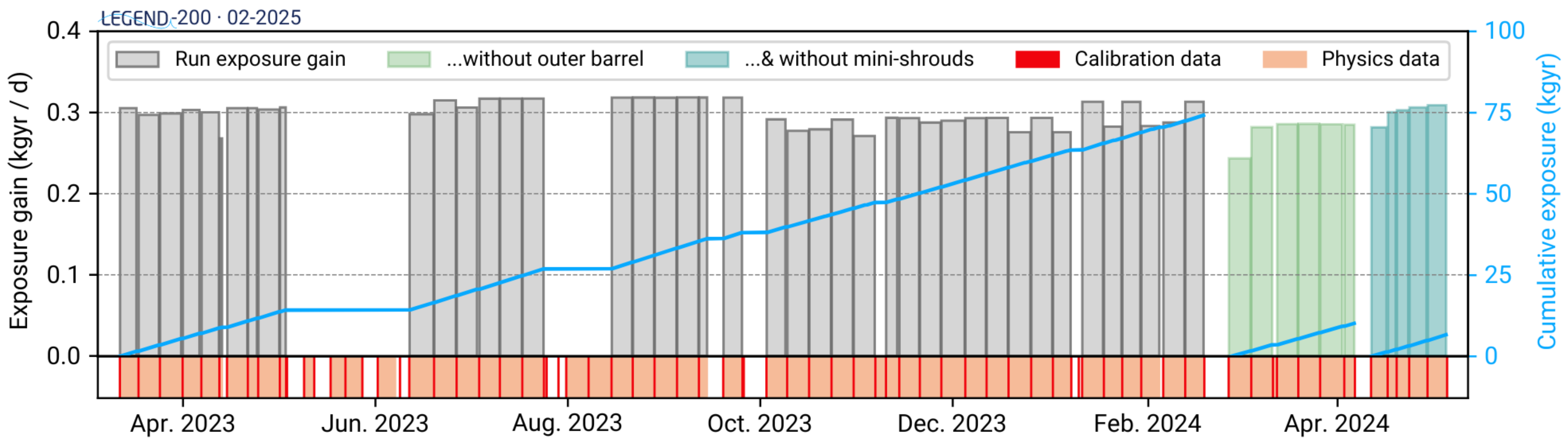
Larger mass (inverted coaxial)
HPGe detectors with up to 4 kg

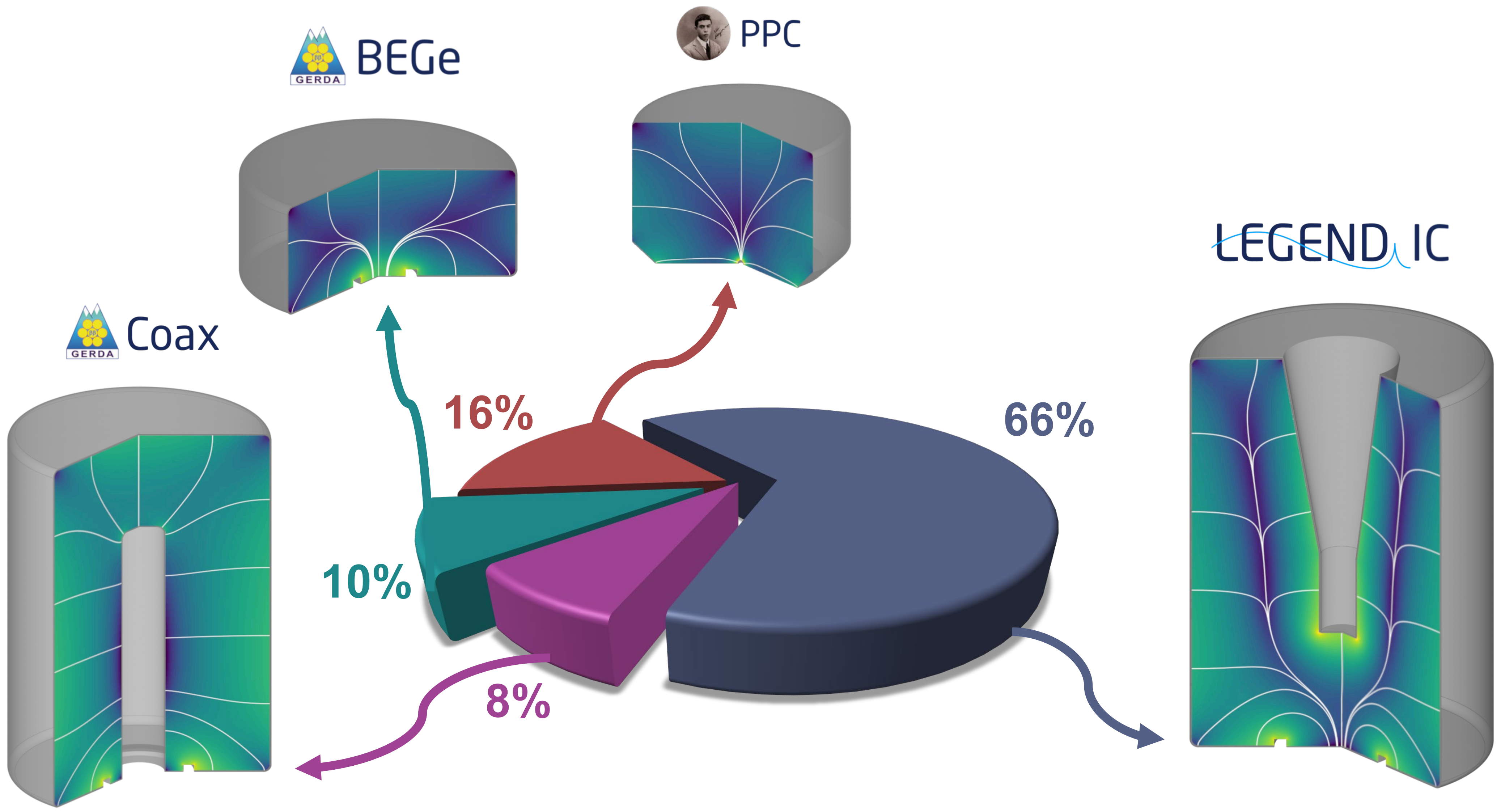
Source funnels for
^{228}Th calibration sources

LEGEND-200: Taking first data







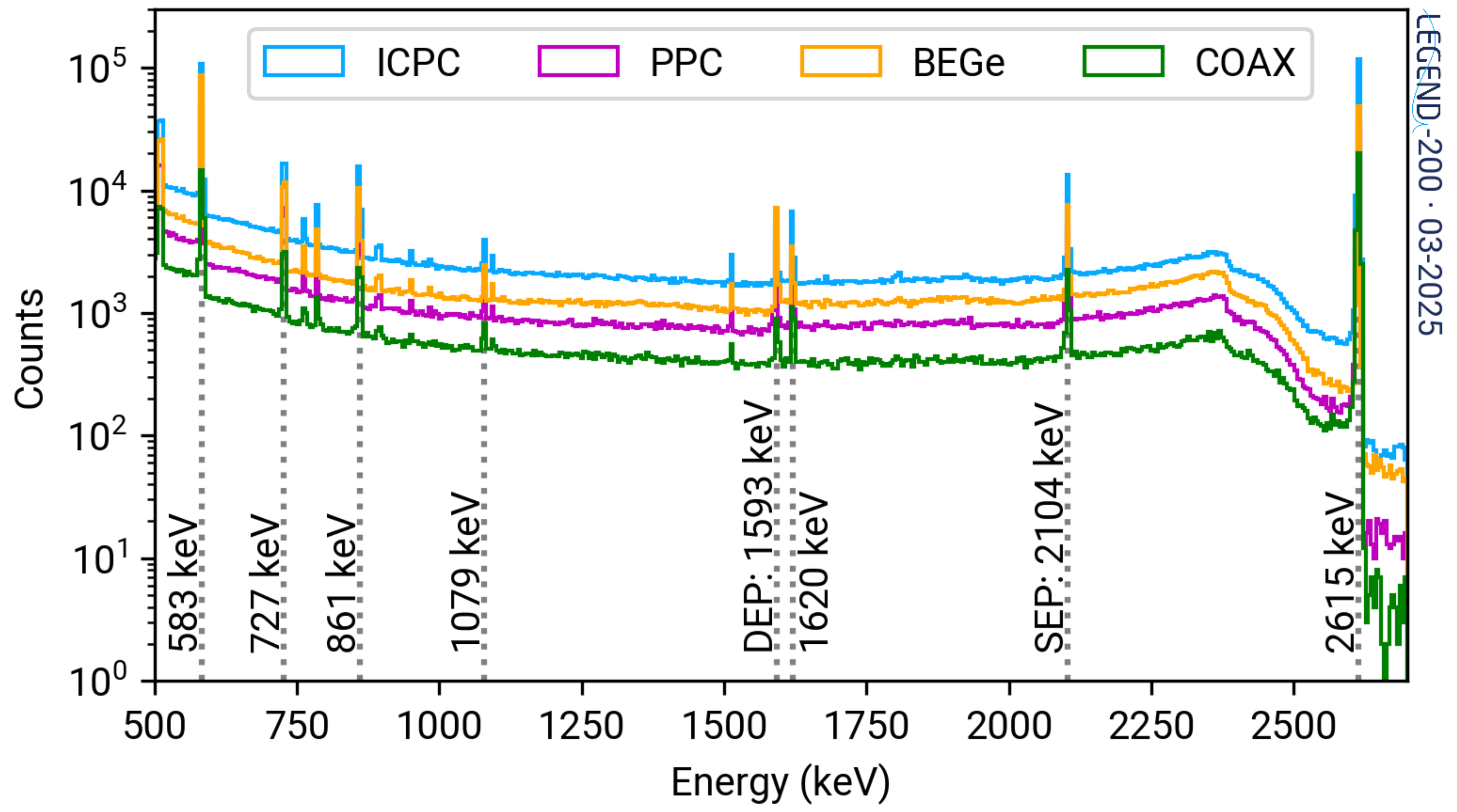


142 kg installation:

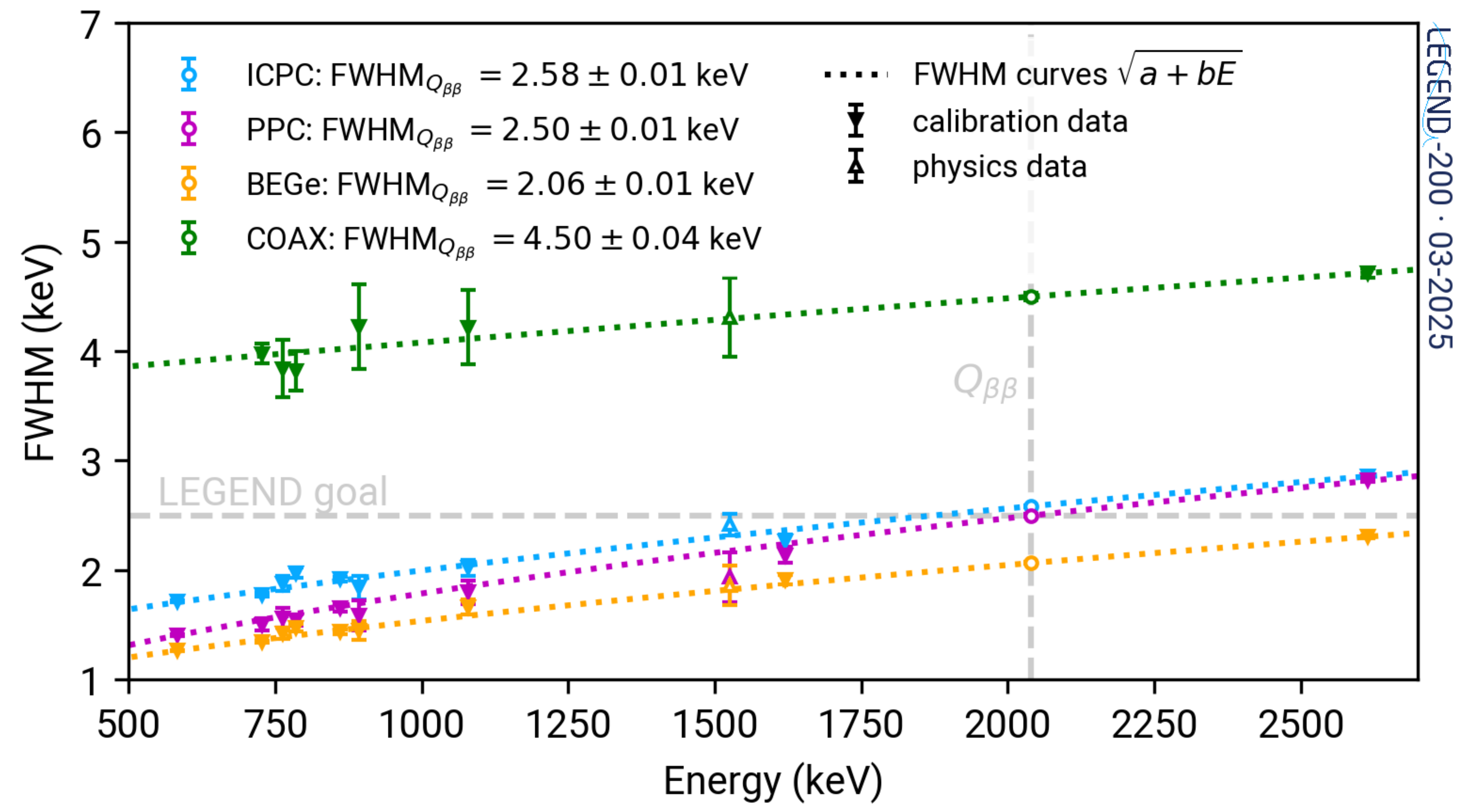
- Installation of all available HPGe detectors (101 detectors in 10 strings) as well as full LAr installation, DAQ, electronics (Oct'22)
- 130 kg operational (12 kg off due to hardware issues)
- LAr instrumentation operational
- About 1 year of data taking
- First results with 48 kg·yr exposure, updated with 61 kg·yr

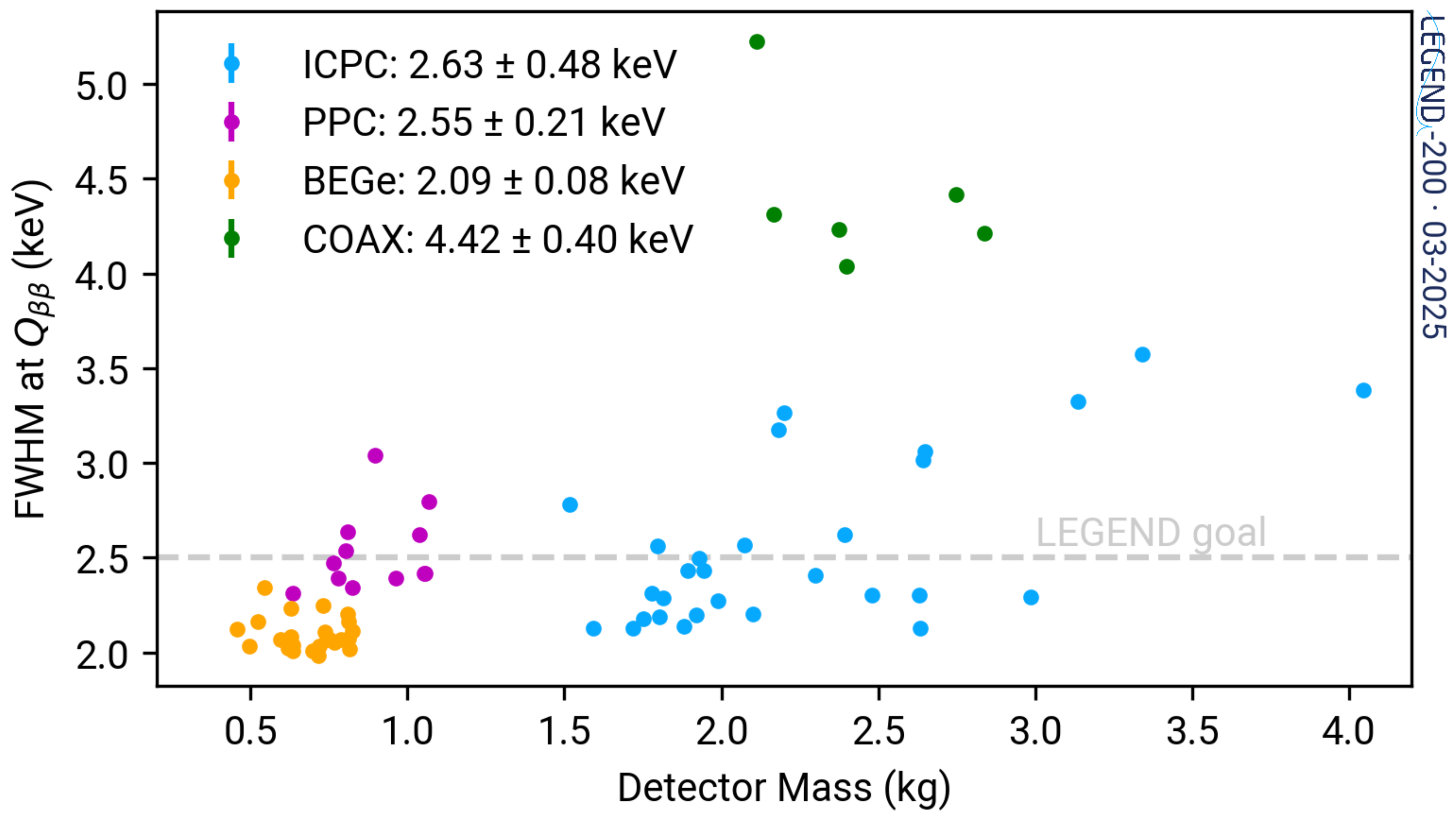
Maintenance work started in 2024 and finished recently

LEGEND-200: Energy Scale and Resolution

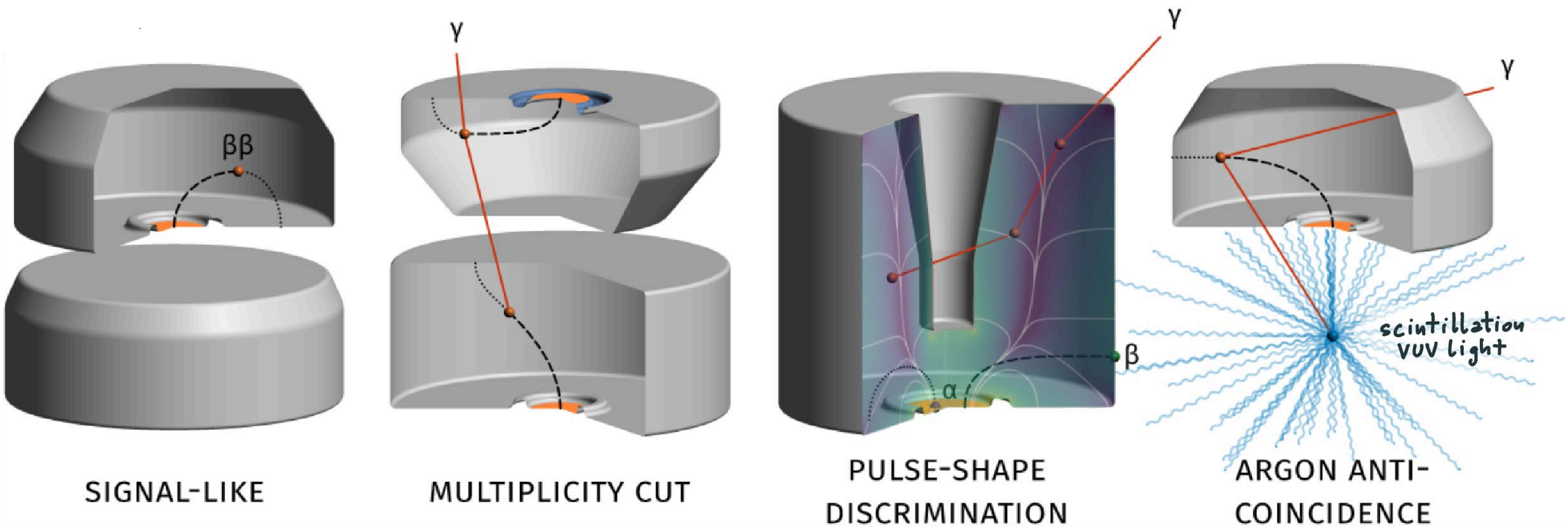


- Energy scale evaluated by weekly ^{228}Th calibration between physics runs
- Most detectors fulfill LEGEND energy resolution goal (0.12% at $Q_{\beta\beta}$)
- Stable energy scale among calibrations
- Data partitioned according to stability of energy observables

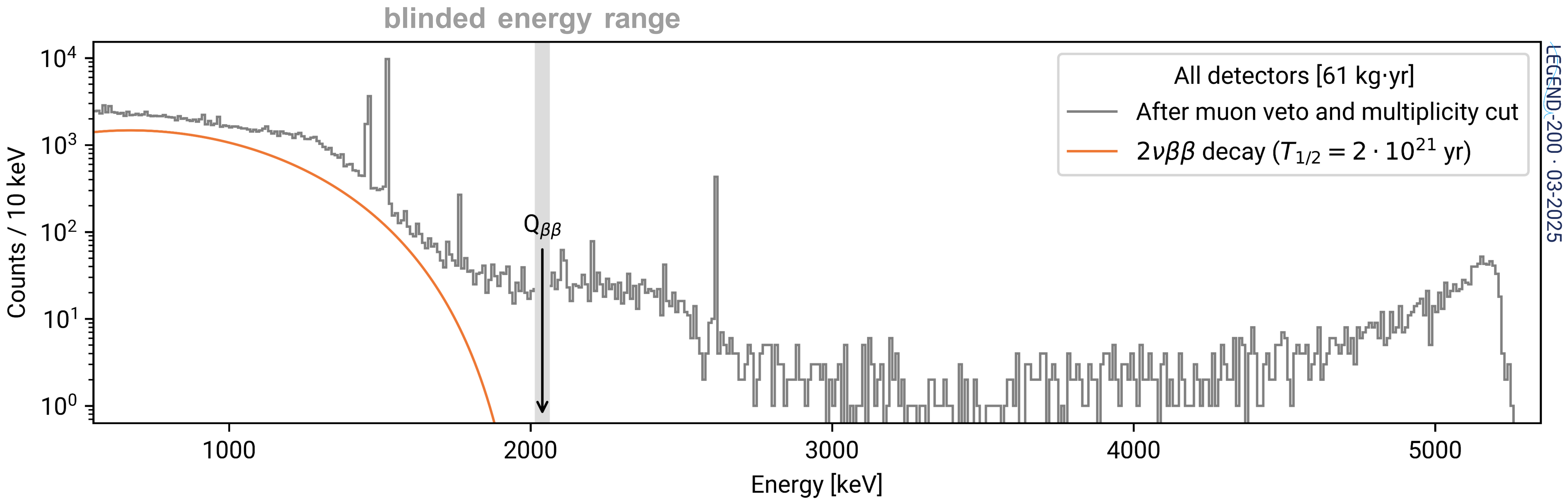




LEGEND-200: Signal and background discrimination



LEGEND-200: Quality, Muon Veto and Multiplicity

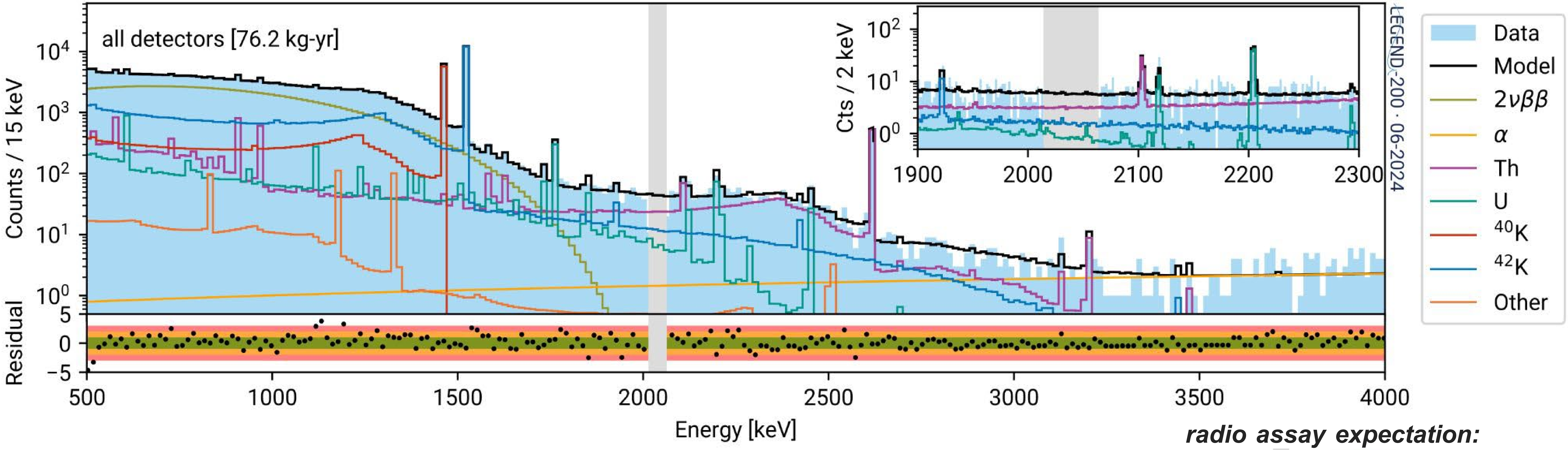


Blinding applied at $Q_{\beta\beta}$ = 2039 keV (50 keV window)

- Data cleaning: 95-99% survival after removal of unphysical events
- Muon veto: 2 events removed at $Q_{\beta\beta}$
- Multiplicity cut: 26% of events rejected near $Q_{\beta\beta}$

LEGEND-200: Modeling before Analysis Cuts

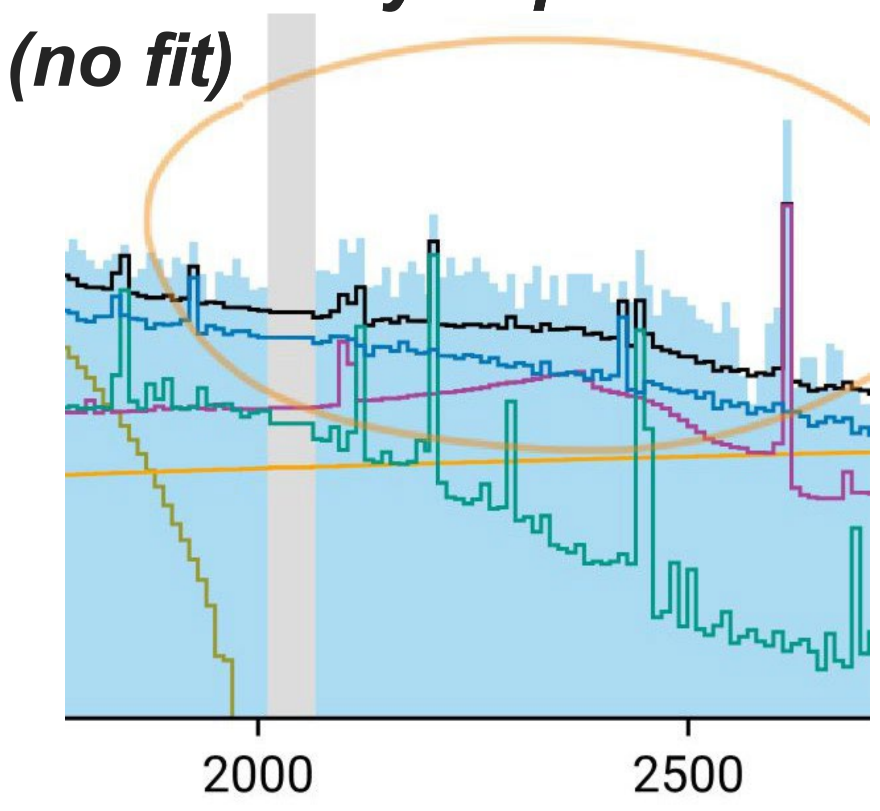
fit:



Bayesian background model using data before analysis cuts

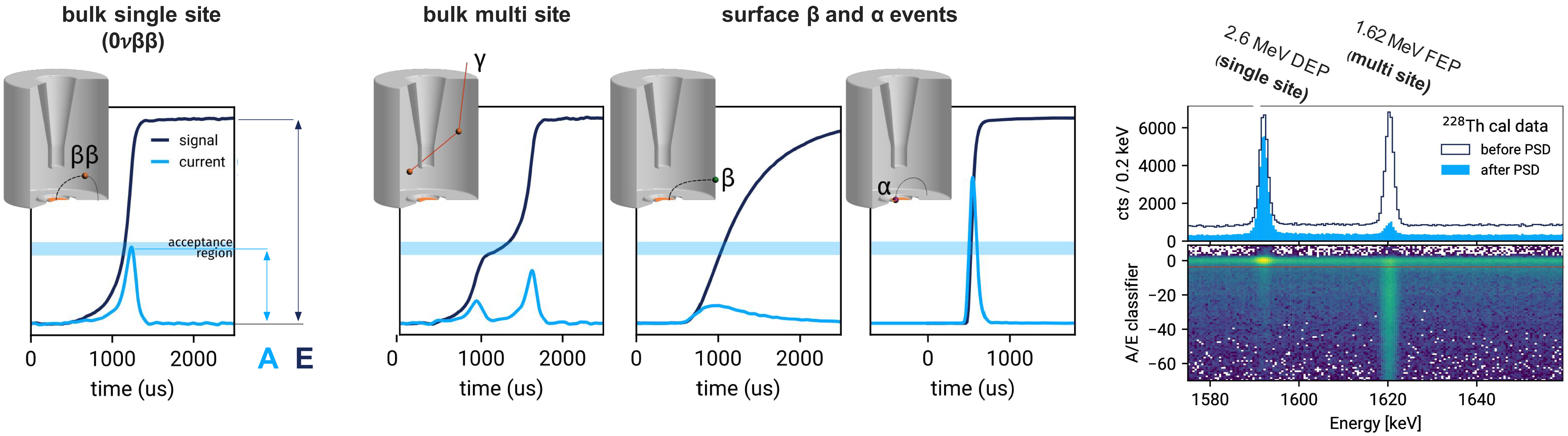
- fits reproduced data well
- estimates 2-3x higher ^{208}Tl / ^{214}Bi compared to radio assay expectation
- comprehensive screening campaign performed
- cleaning procedures re-evaluated for the new deployment

radio assay expectation: (no fit)

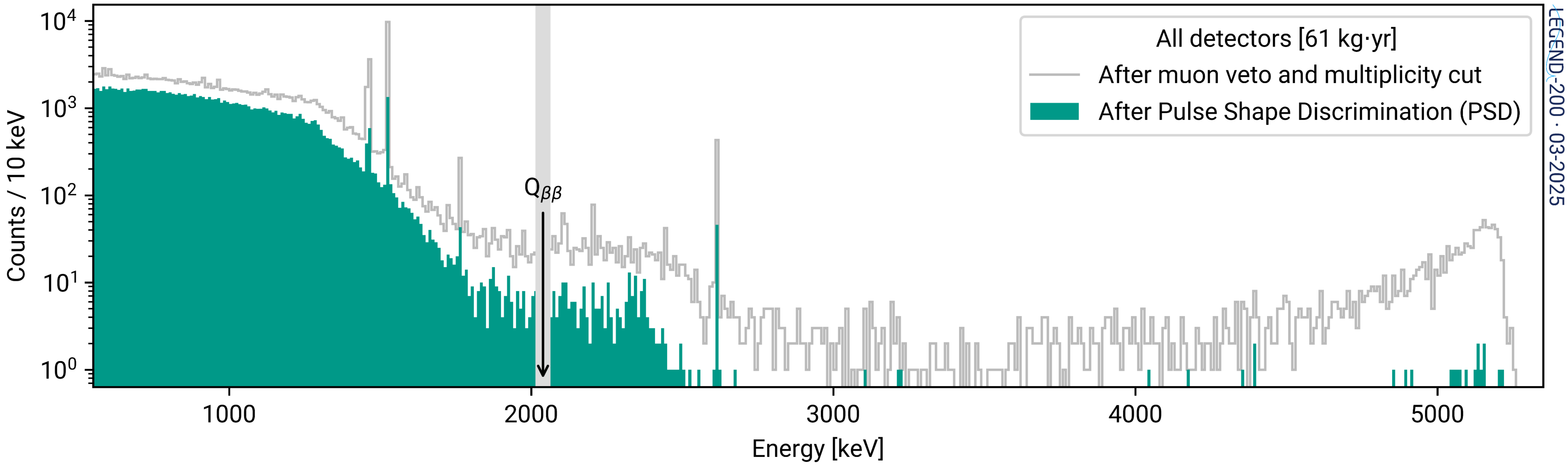


LEGEND-200: HPGe Pulse Shape Discrimination

- **Pulse shape classifier: A/E = max(current) / energy**

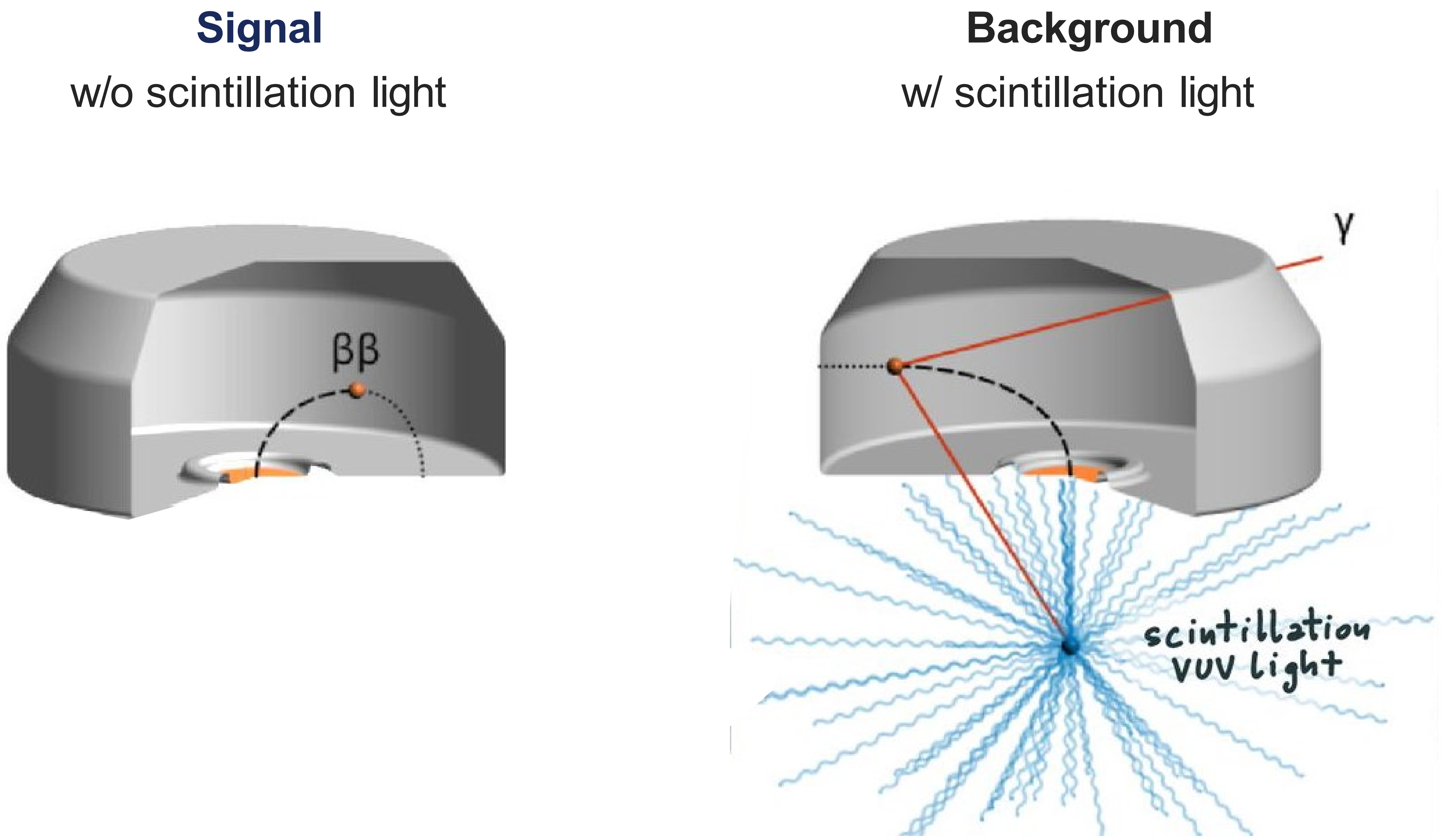


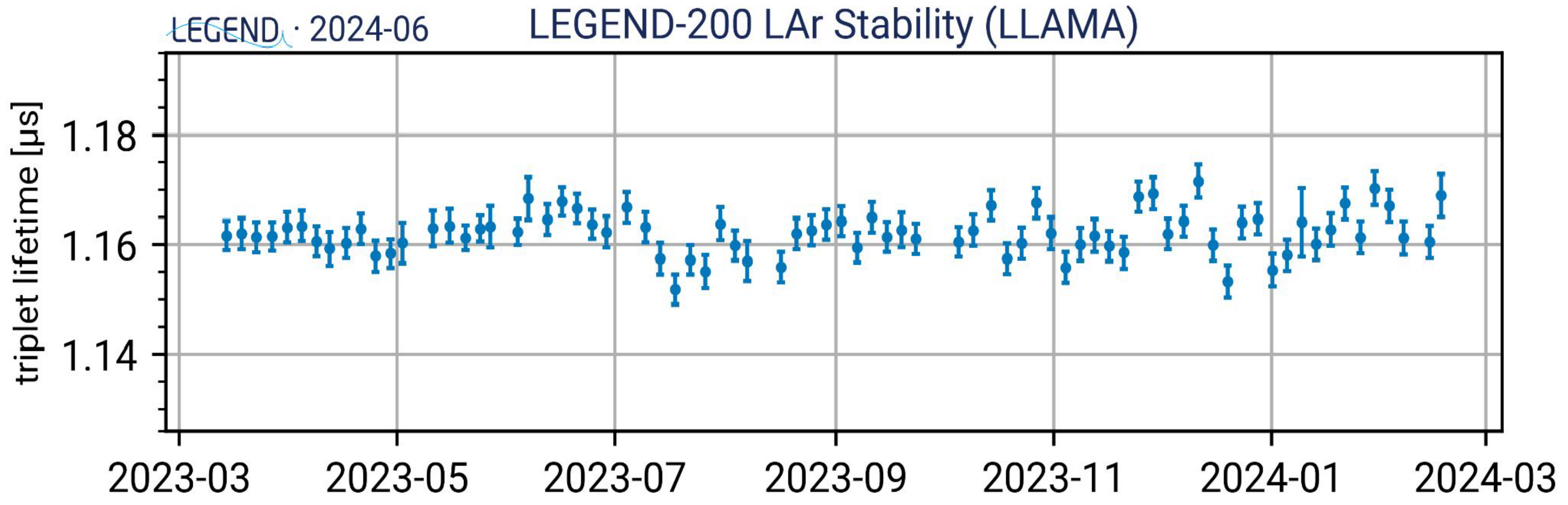
LEGEND-200: Spectrum after PSD

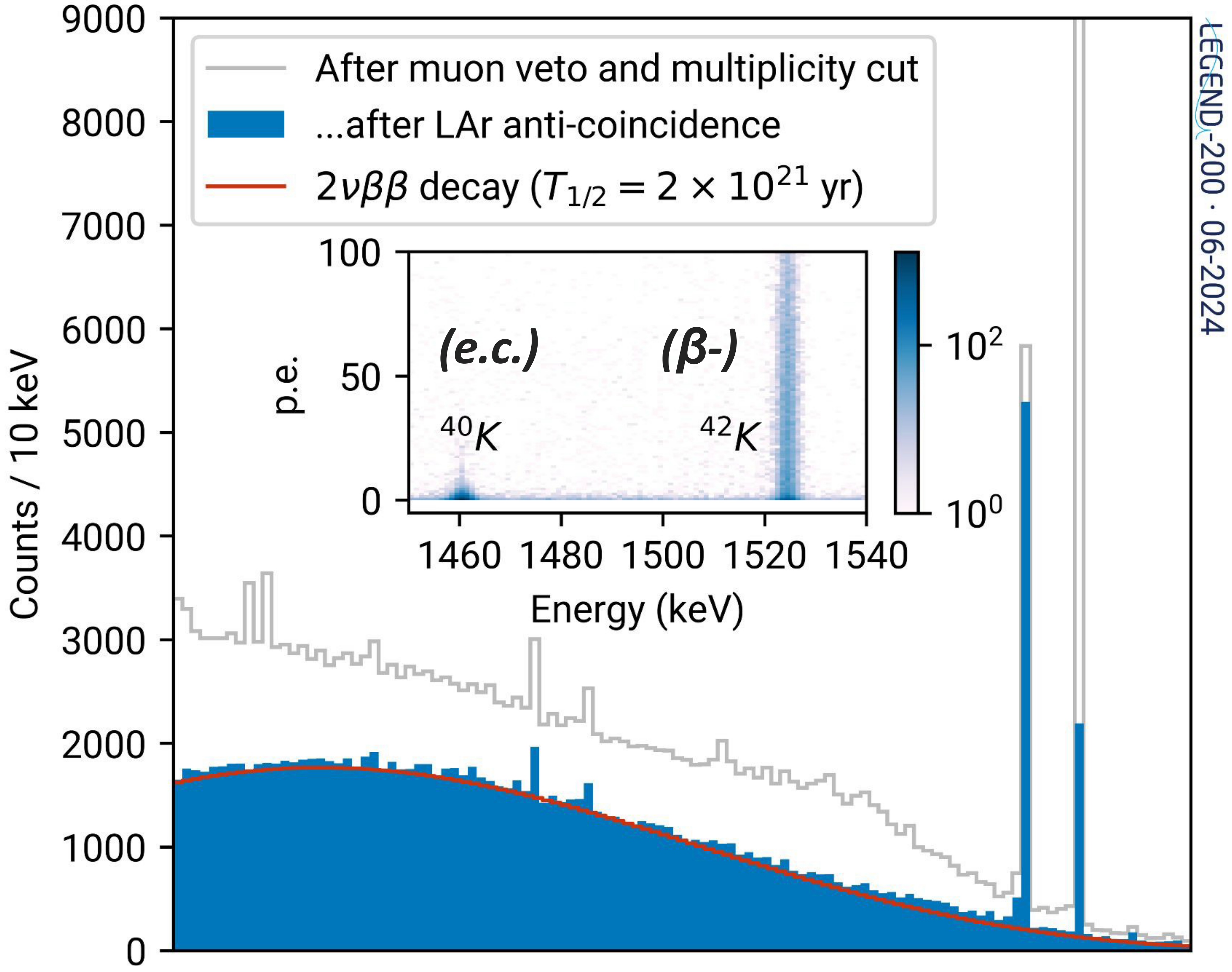


- Strong suppression of surface α and β (^{42}K) events
- ~60% suppression of Compton multi-site events at $Q_{\beta\beta}$
- 0νββ decay survival fraction of ~85%

LEGEND-200: Argon anti-coincidence

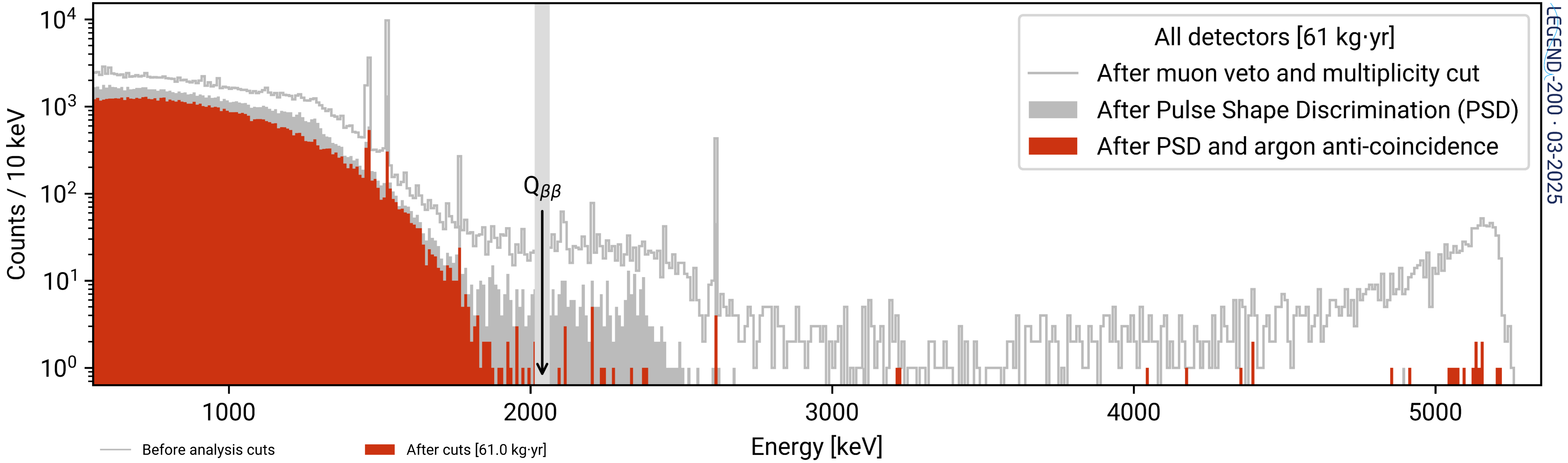


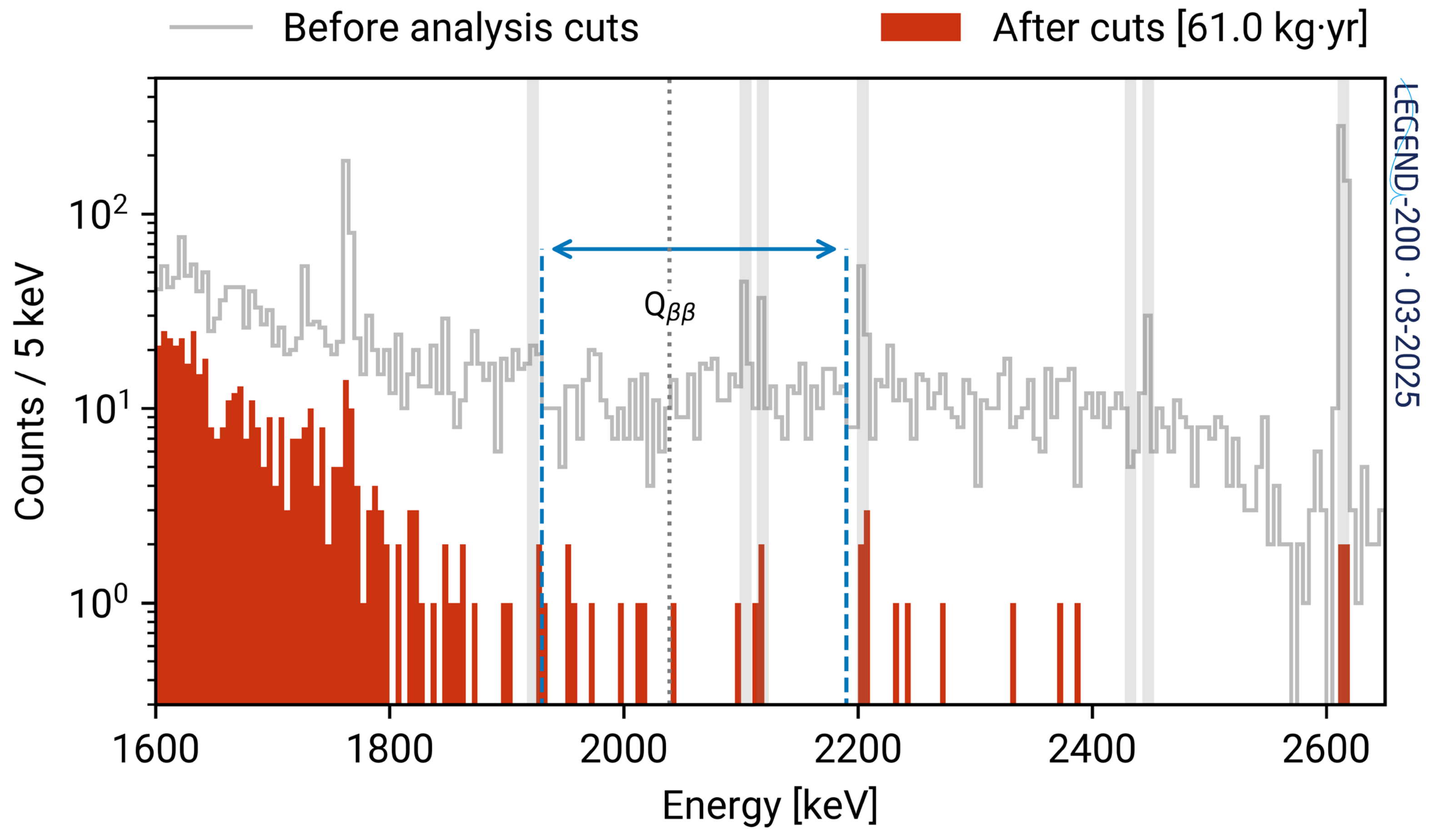




- Strong suppression of background above $2\nu\beta\beta$
- $\beta\beta$ decay signal acceptance of ~93%

LEGEND-200: Spectrum after all cats

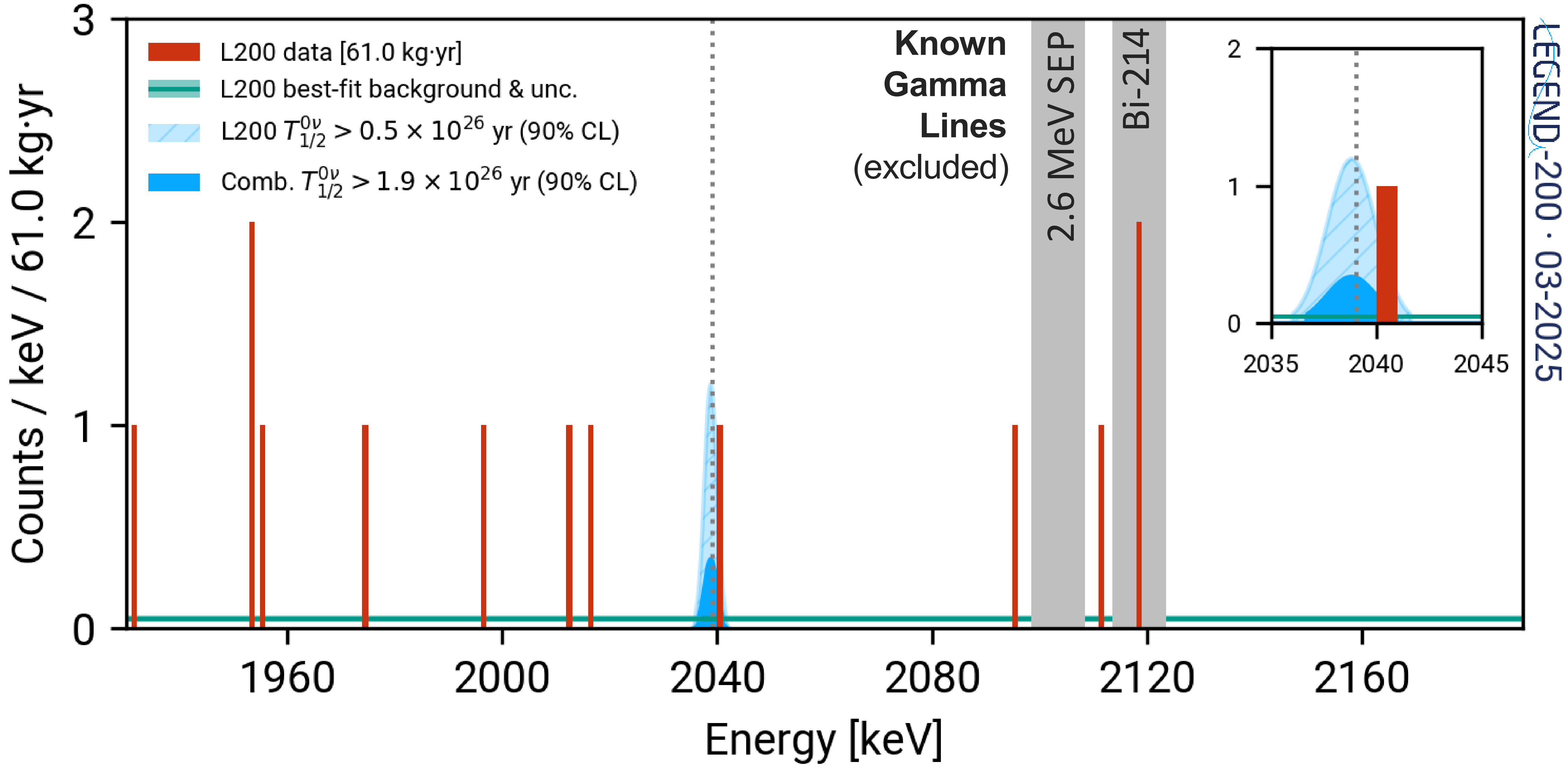




- PSD and argon cuts are complementary
- ^{232}Th strongly suppressed and remaining Compton background vanishes
- "Pure" 2νββ distribution at lower energies, 11 events surviving at $Q_{\beta\beta}$:
  9 before + 2 after unblinding

http://arxiv.org/abs/2505.10440

LEGEND-200: First results



- 11 events surviving
- background indices:

$$BI_{gold} = 5.4^{+2.7}_{-2.0} \times 10^{-4}\ cts/(keV \cdot kg \cdot yr)$$
$$BI_{silver} = 13^{+8.0}_{-5.4} \times 10^{-4}\ cts/(keV \cdot kg \cdot yr)$$

golden dataset: 48 kg·yr
silver dataset: 13 kg·yr (mainly coax)

GERDA, MAJORANA and LEGEND combined fit:

- $T^{0\nu}_{1/2}$ lower limits (90% frequentist C.L.)

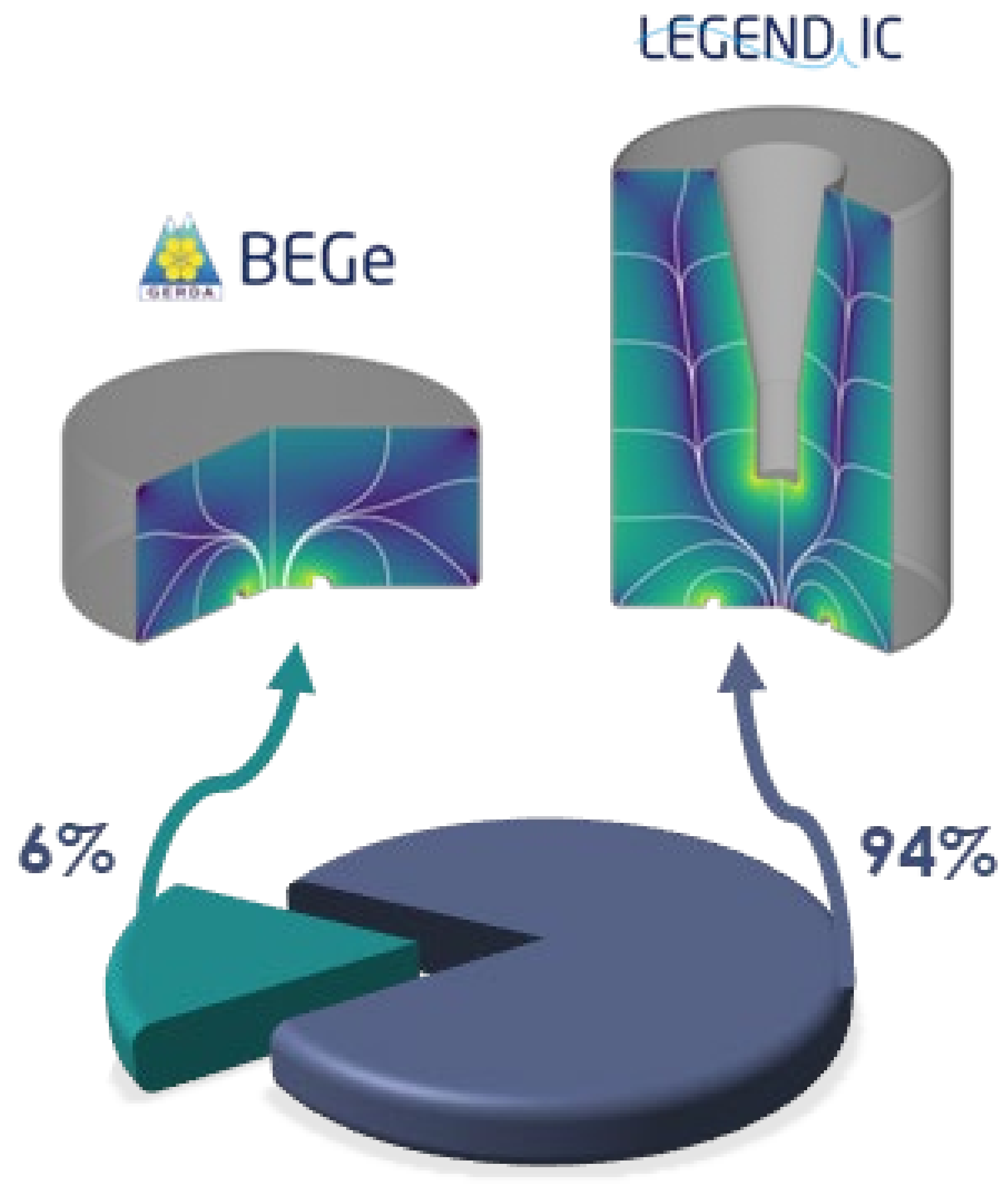
Sensitivity	Observed
2.8×10^{26} yr	$> 1.9 \times 10^{26}$ yr

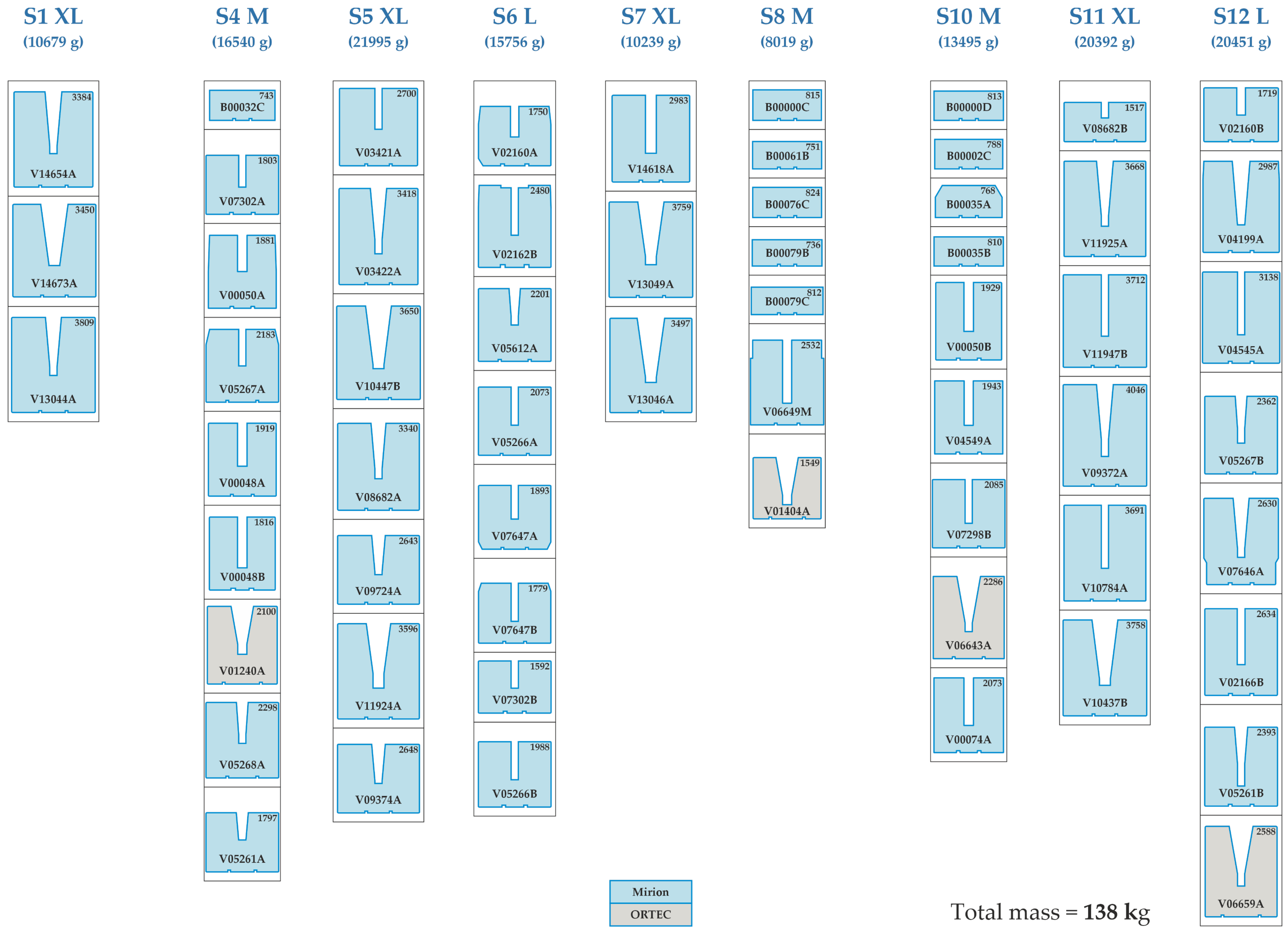
- Frequentist and Bayesian statistical analysis → no evidence of 0νββ signal
- World leading sensitivity, event at 1.4σ from $Q_{\beta\beta}$ weakens combined limit

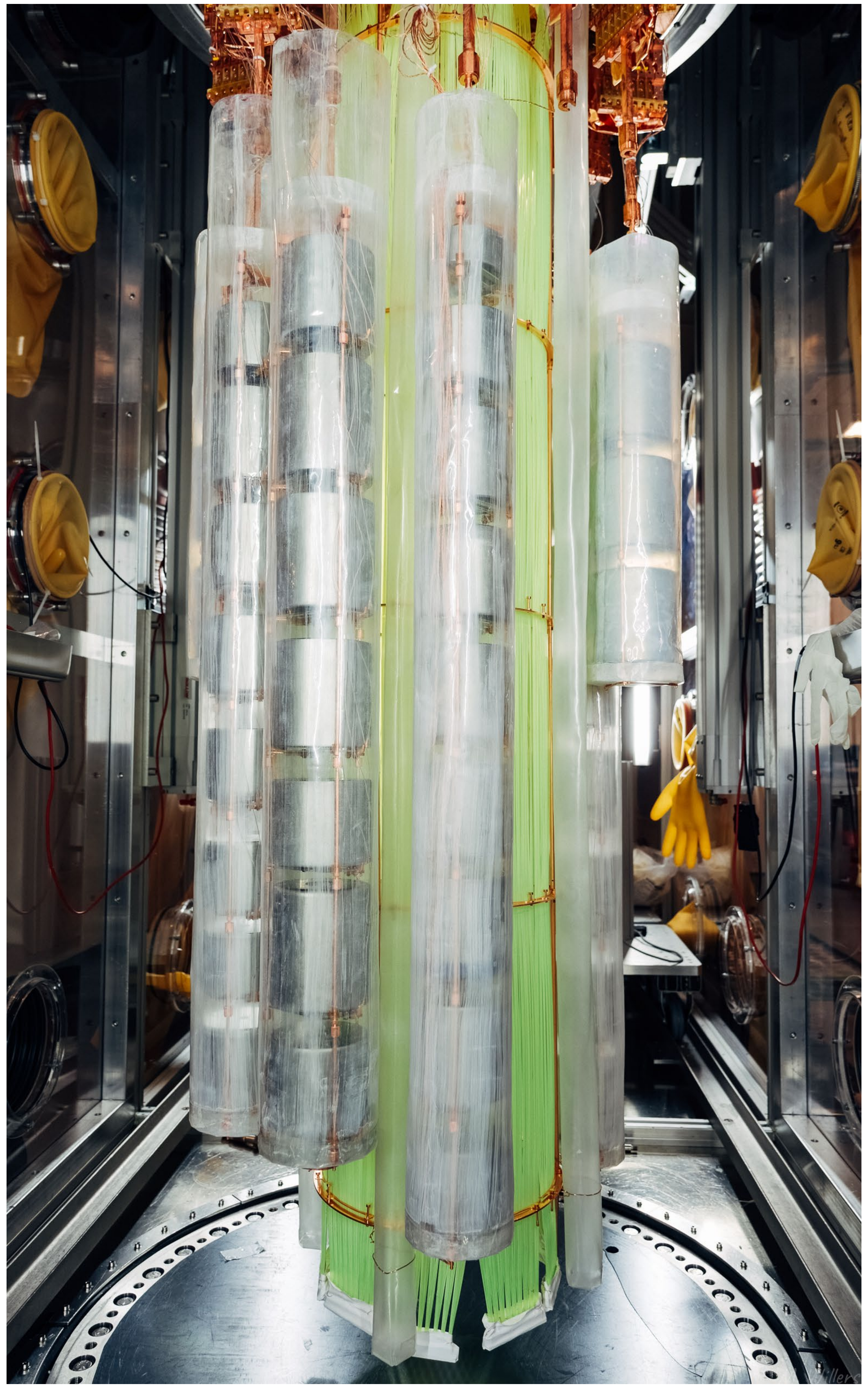
http://arxiv.org/abs/2505.10440

LEGEND-200: Status

- In July 2025 ~138 kg of HPGe detectors were redeployed (60 detectors in 9 strings) then data taking was restarted
- The operational strategy of LEGEND-200 has been modified to primarily utilize IC detectors, aligning more closely with the LEGEND-1000 concept (aims to employ exclusively ICs)
- The total deployed detector mass remained comparable to previous configuration; however, the number of channels was reduced by 40% (less materials close to detectors)

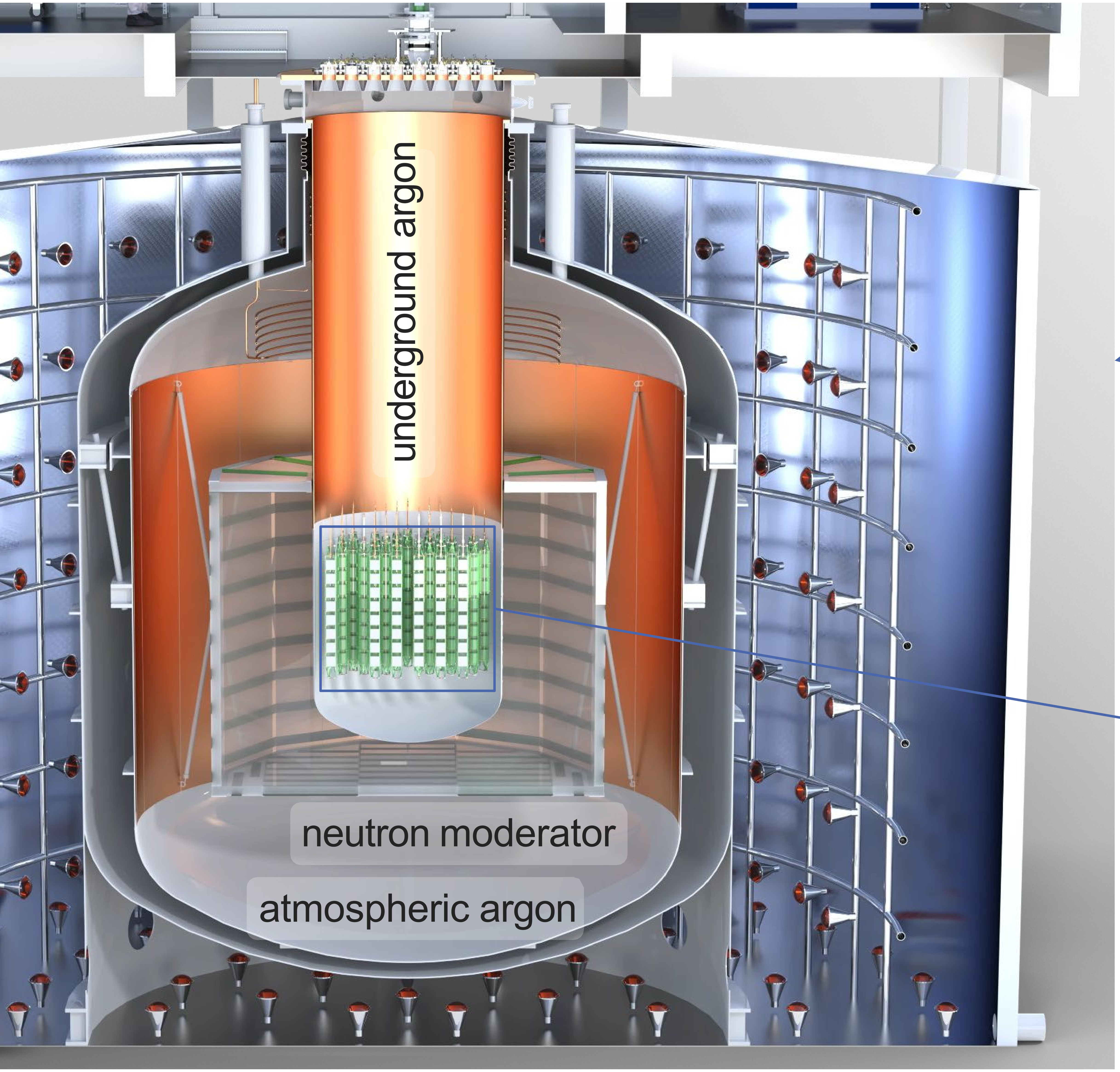


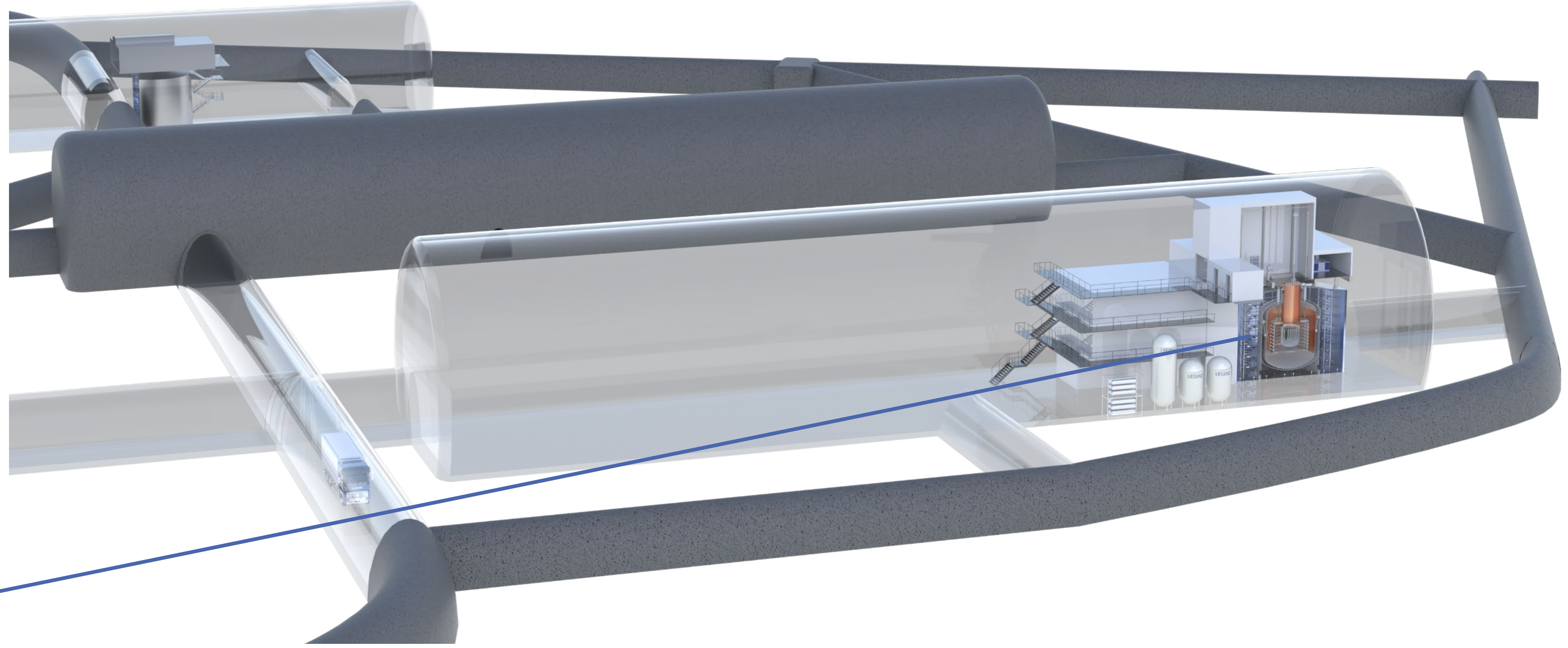


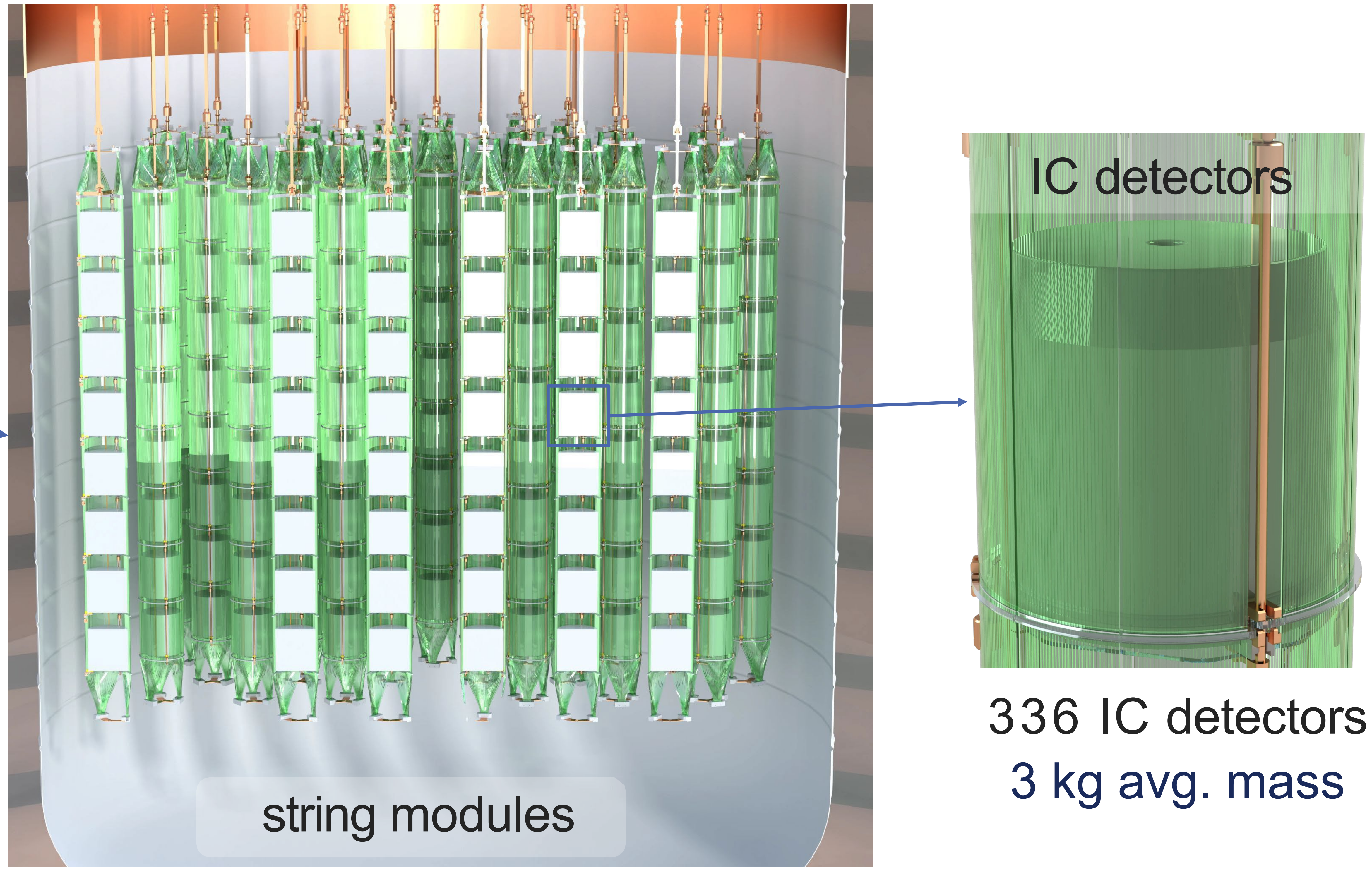


LEGEND. Episode 1000: A new hope

LEGEND-1000 @ LNGS Hall C

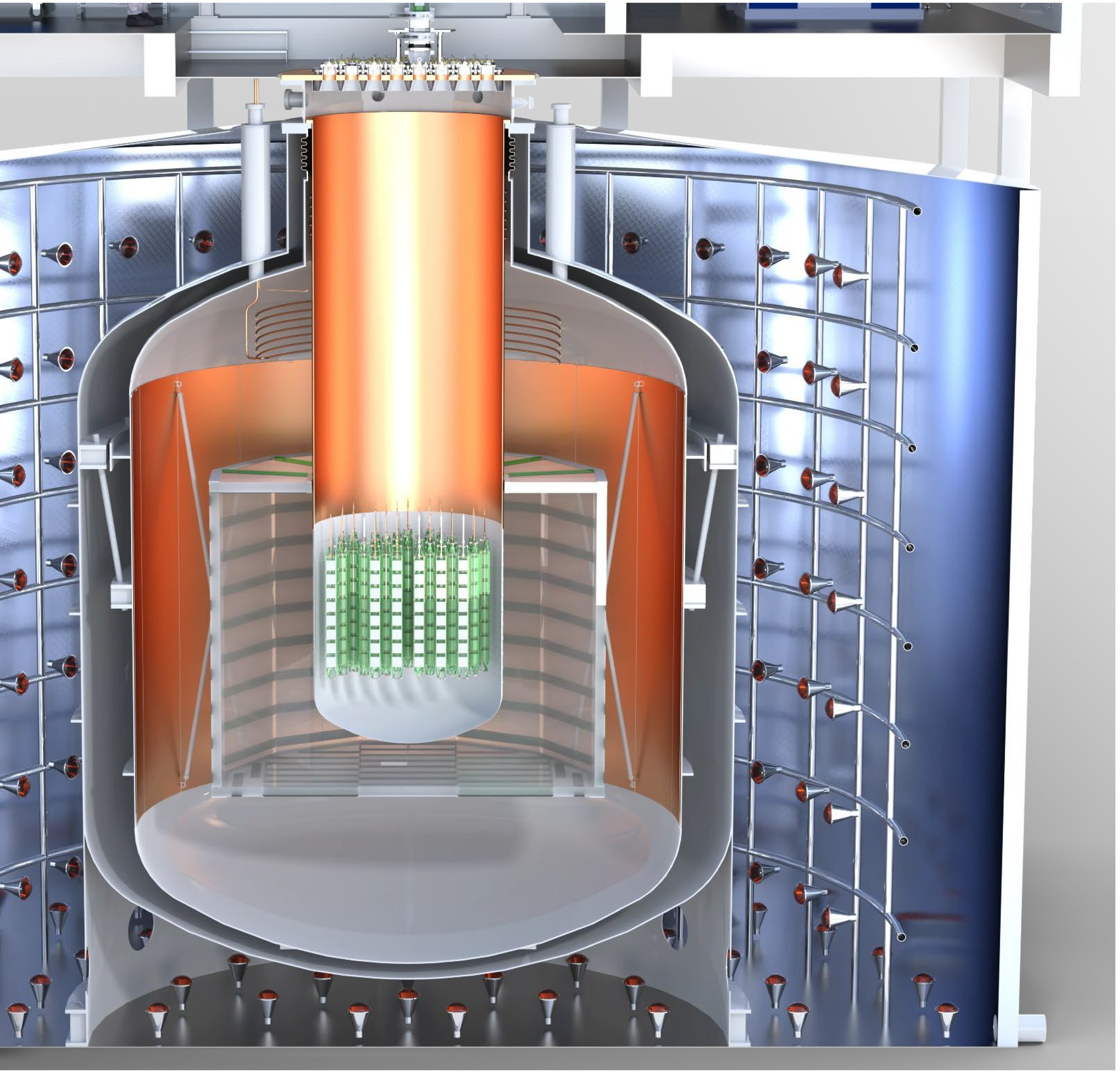






336 IC detectors
3 kg avg. mass

LEGEND-1000: Designed for an Unambiguous Discovery

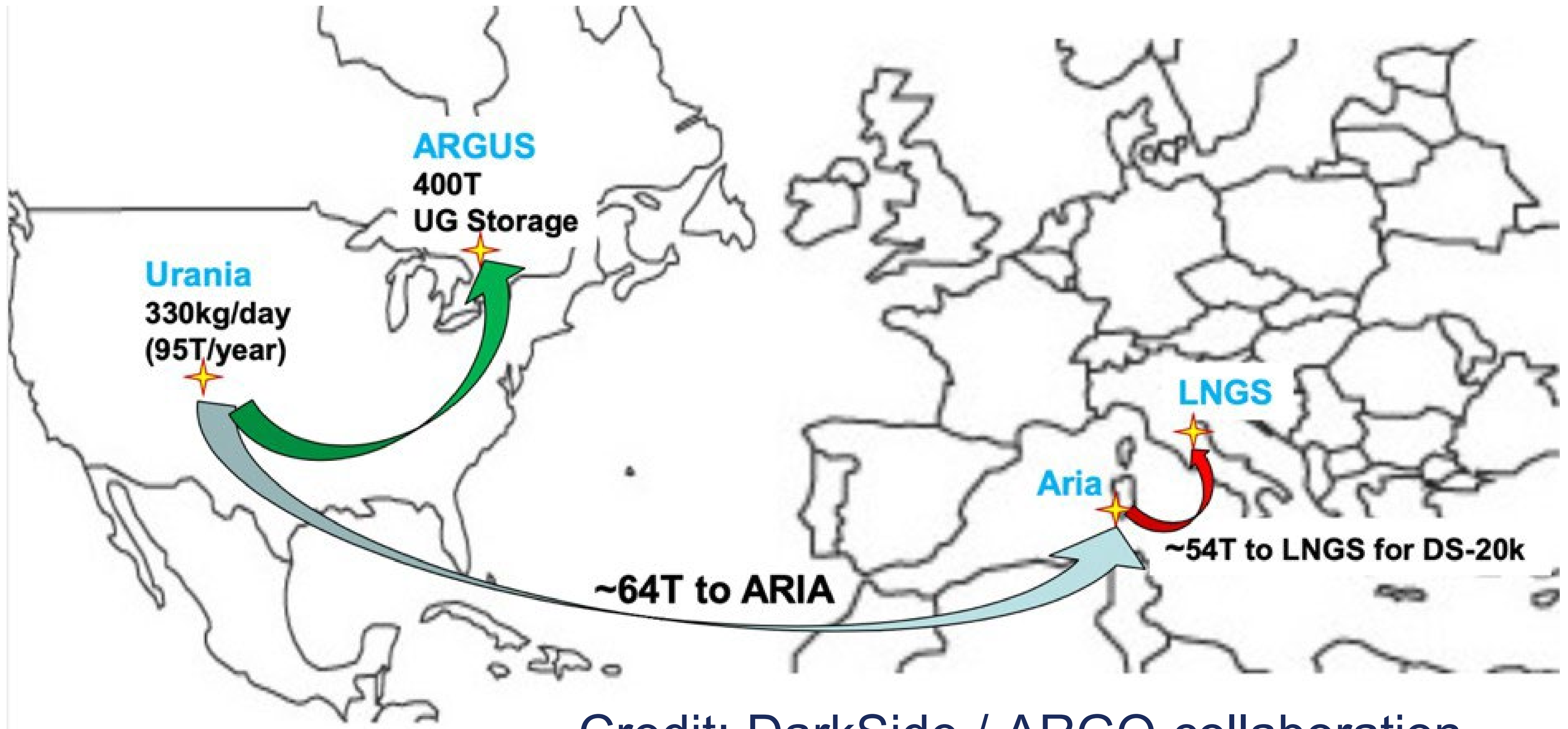


- Up to 1000 kg HPGe Inverted Coaxial Detectors
- New cryostat
- Large-mass IC detectors:
  - Excellent FWHM
  - Great PSD
  - Less cables and holder materials
- Underground LAr reentrant tube in an atmospheric LAr cryostat
- Single string design, modular approach
- Radiopure components
- $T^{0\nu}_{1/2} > 1{\cdot}10^{28}$ yr
- Background: $<1\times10^{-5}$ cts/(keV kg yr)

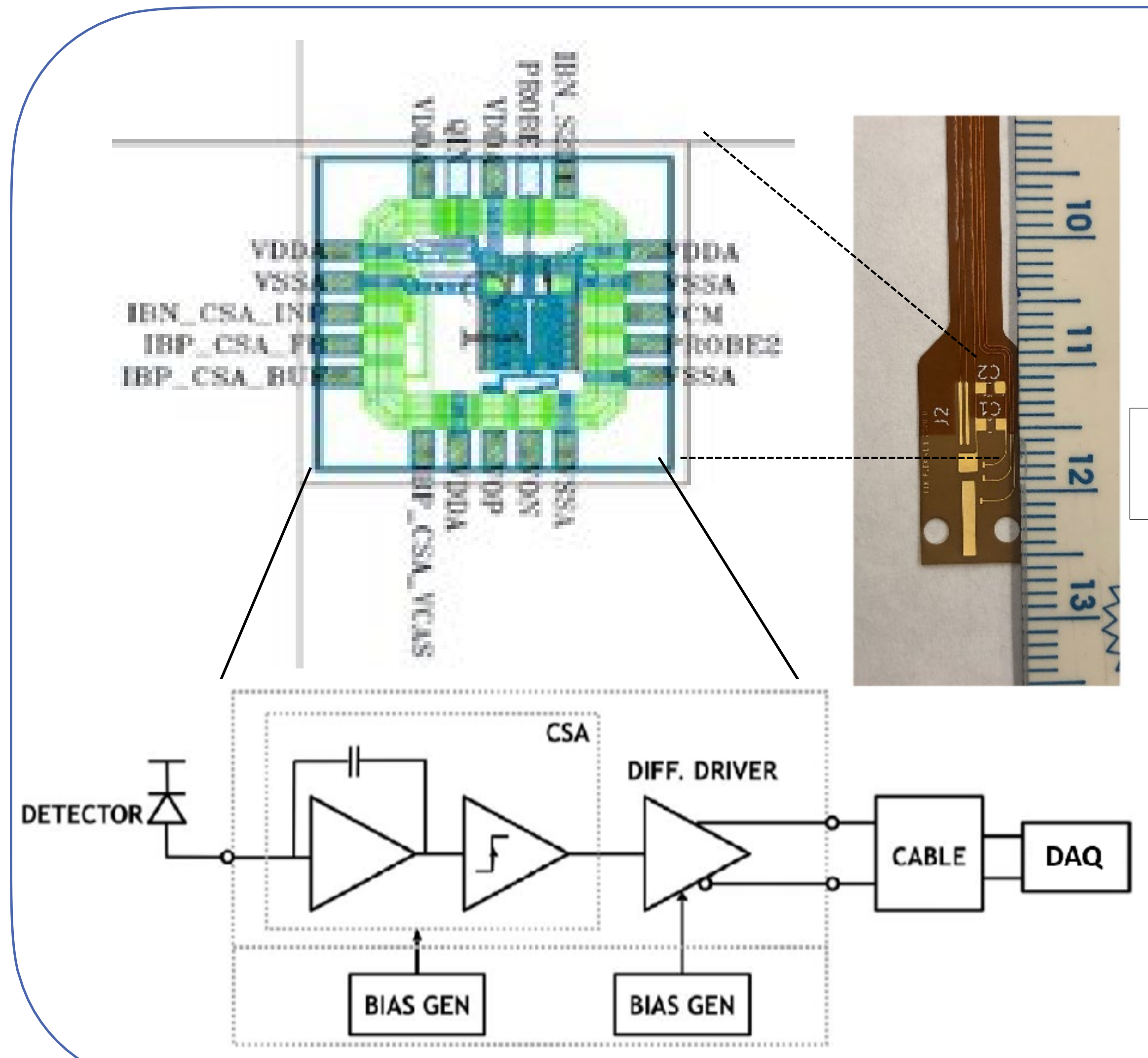
LEGEND-1000
Pre-Conceptual Design Report
arXiv:2107.11462

LEGEND-1000: Radiopure Components

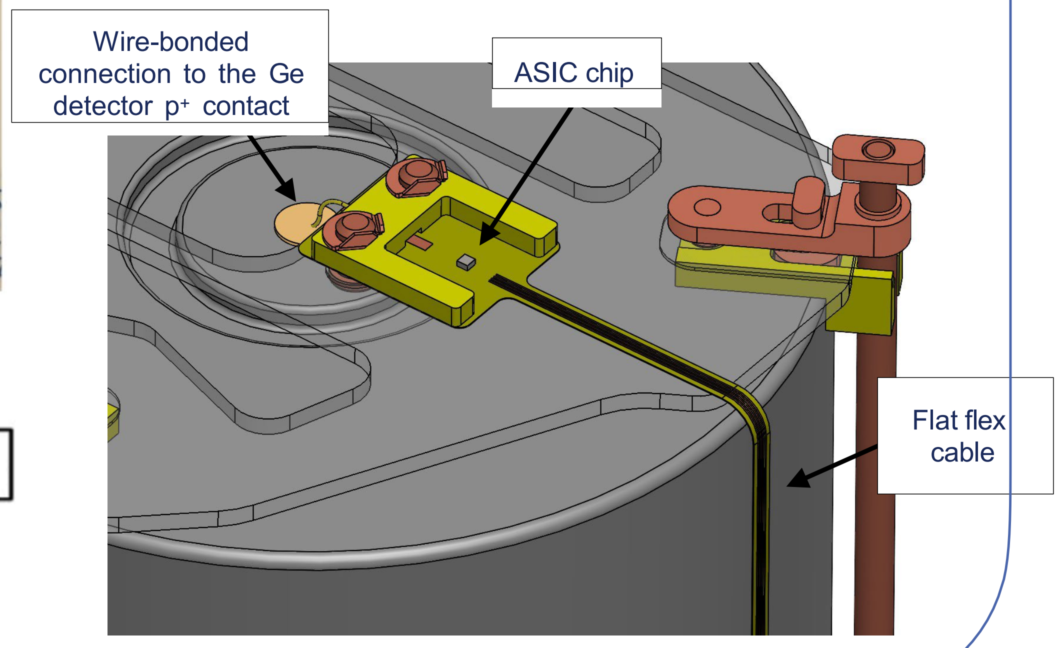
20-25 t of **underground-sourced LAr** reduced in ^{42}Ar
Acquisition builds on pioneering work of DarkSide collaboration



Credit: DarkSide / ARGO collaboration

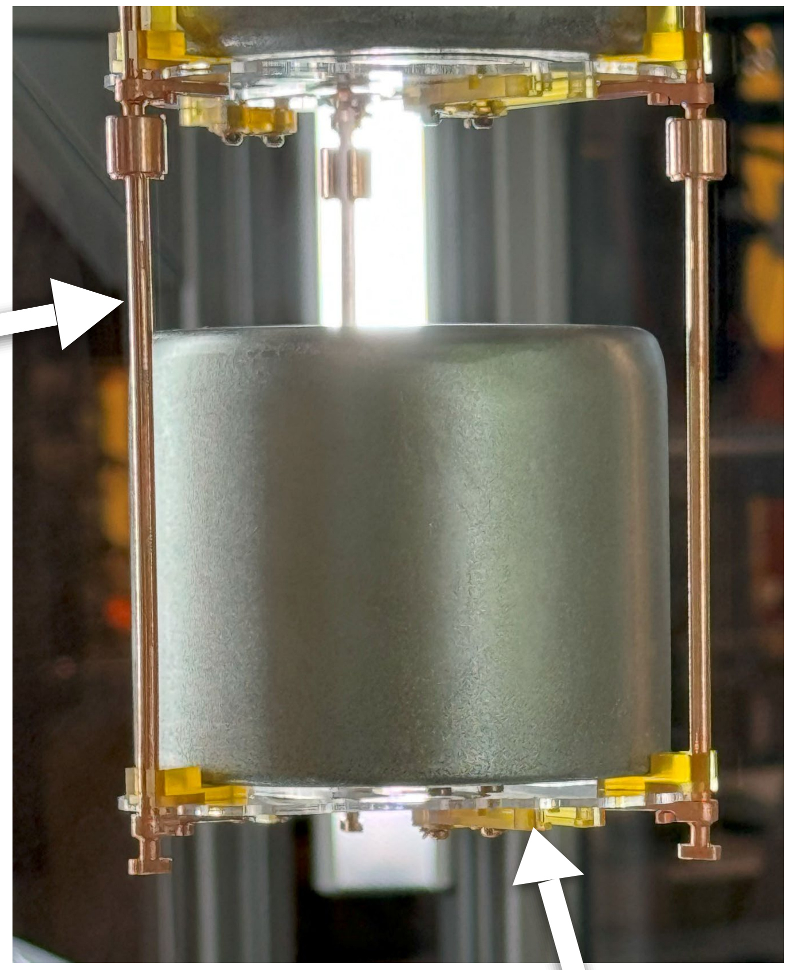


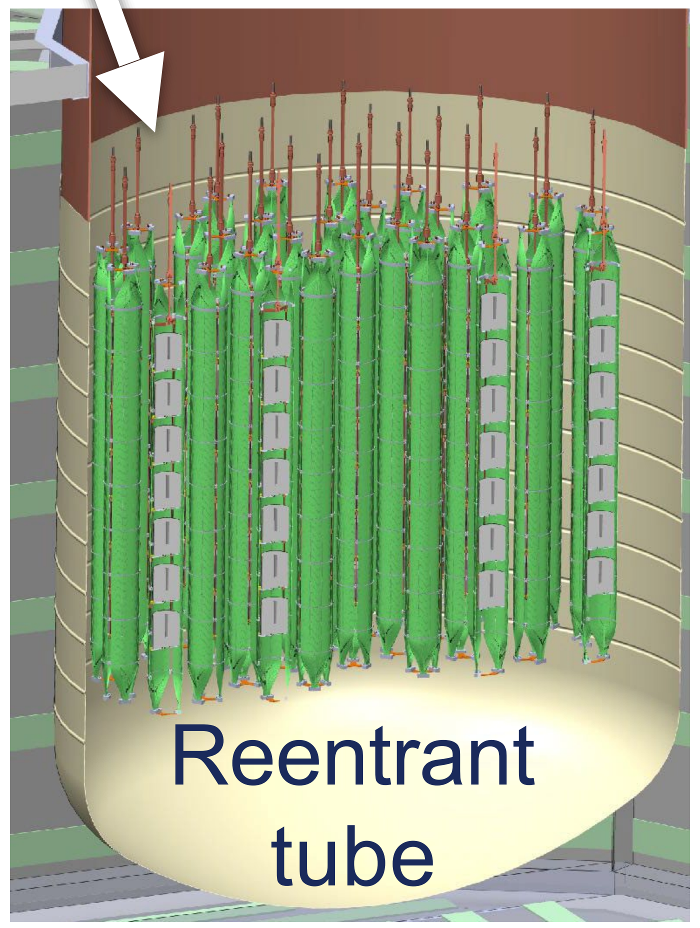
ASIC Front-End
Low noise / low threshold

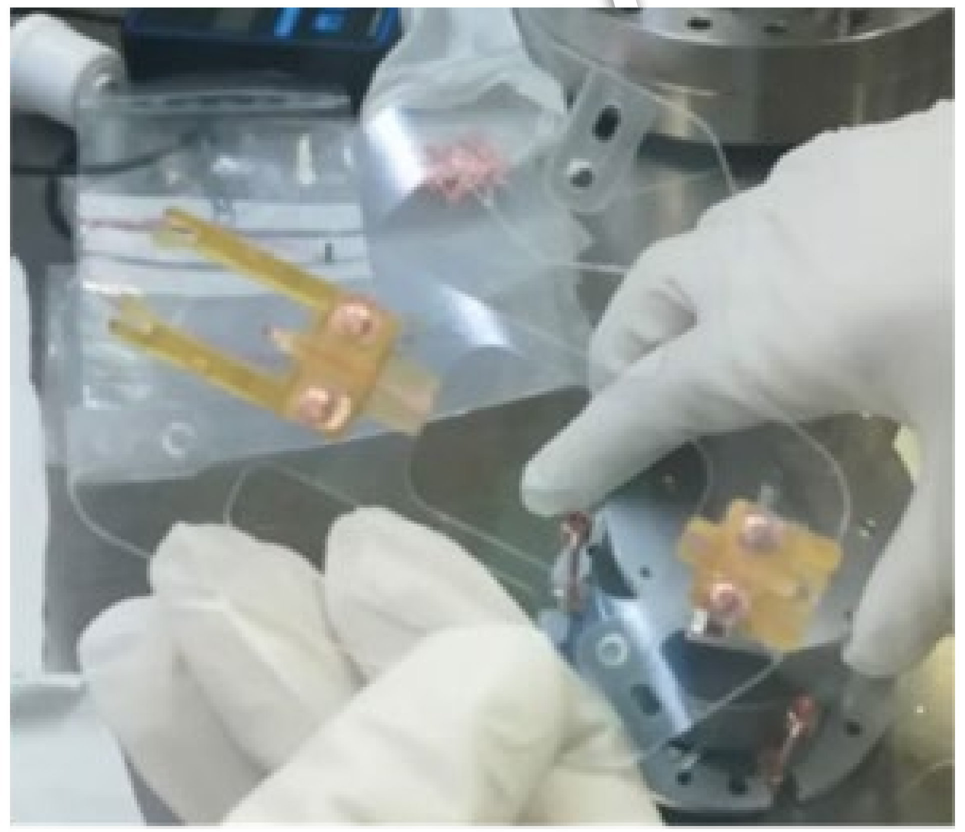


Underground electroformed Cu for detector holders and reentrant tube

Example: L200 Detector holder



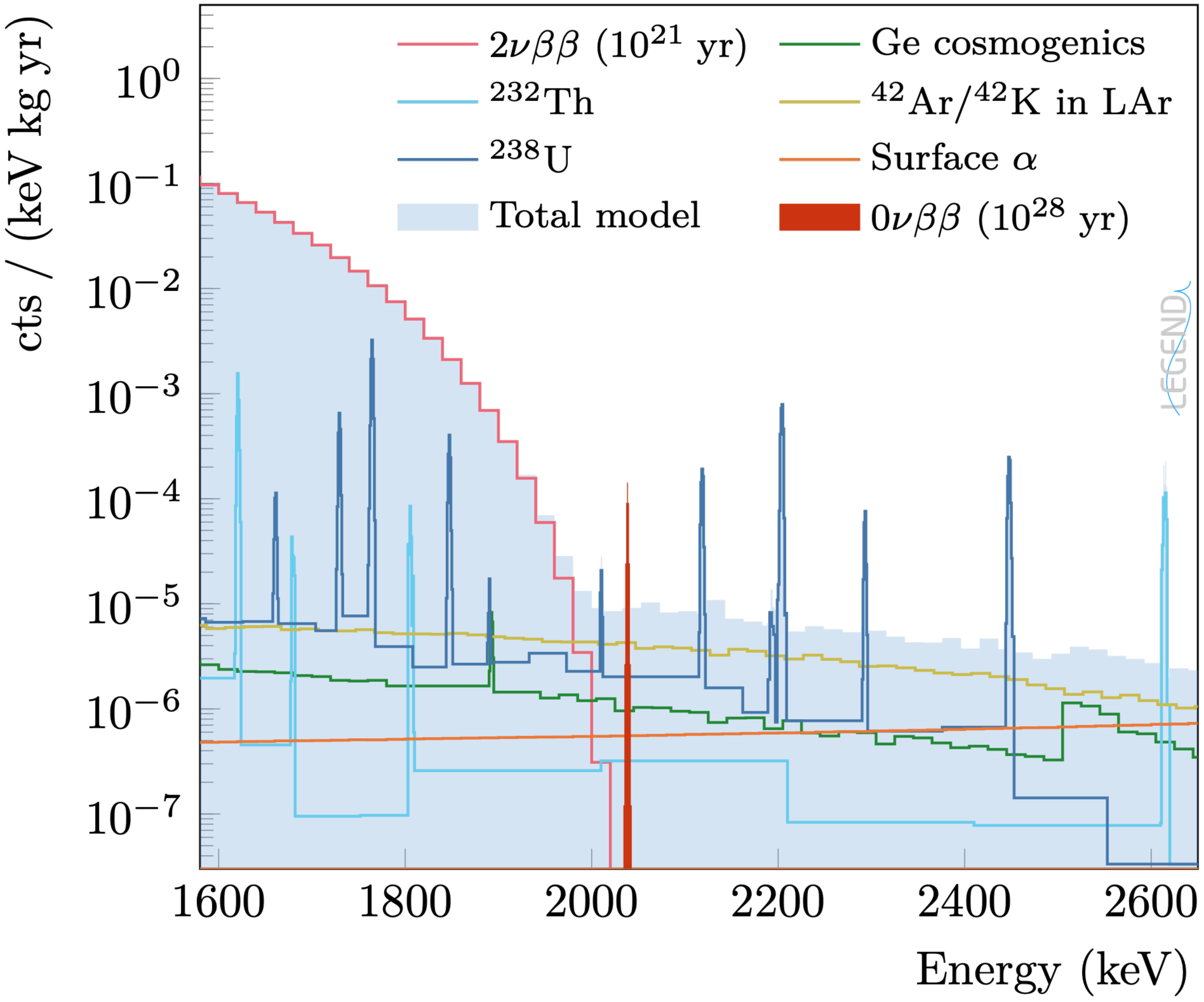




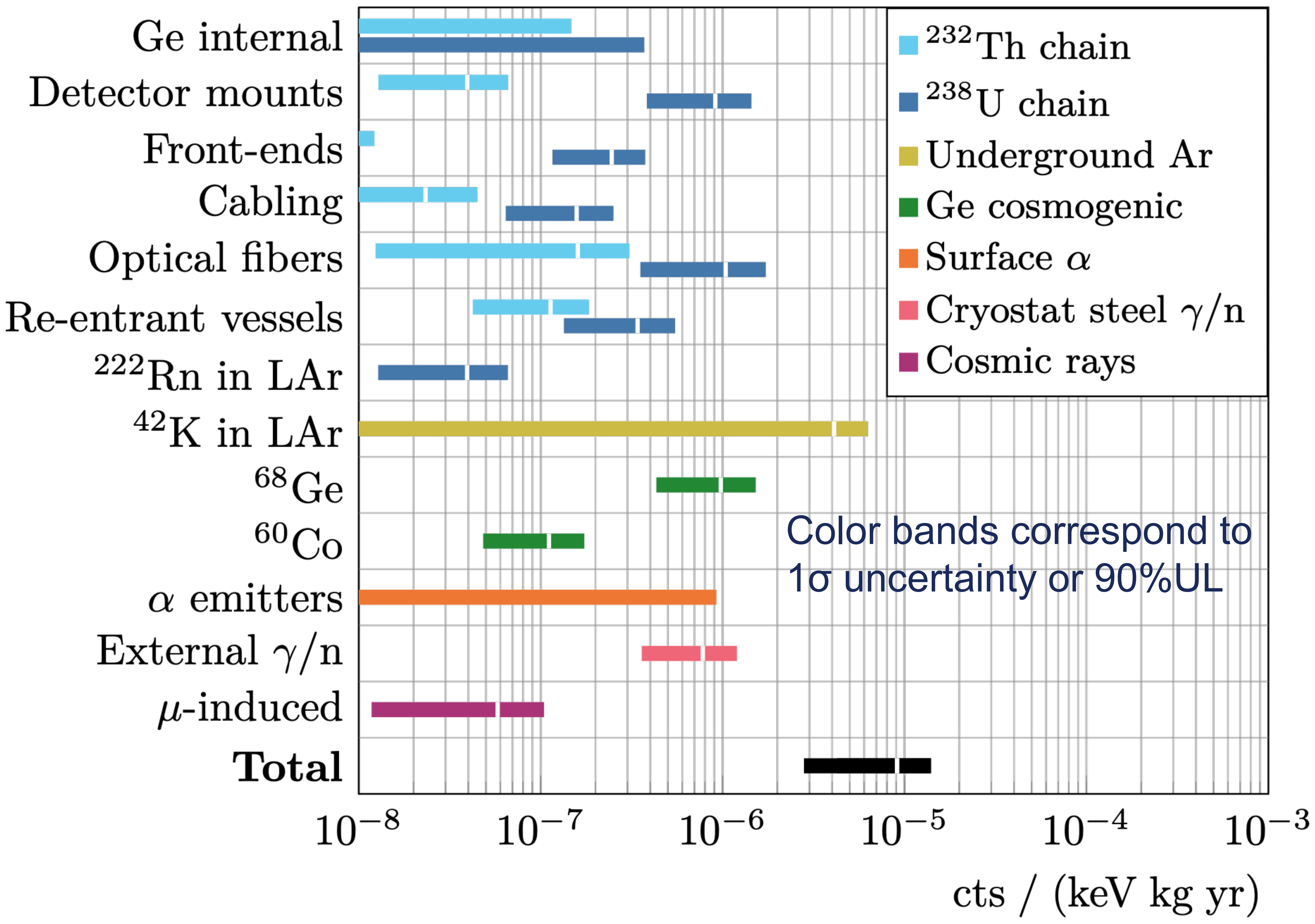
PEN: scintillating (self-vetoing) high-purity detector support

LEGEND-1000: Background Model

Simulated total background spectrum after cuts

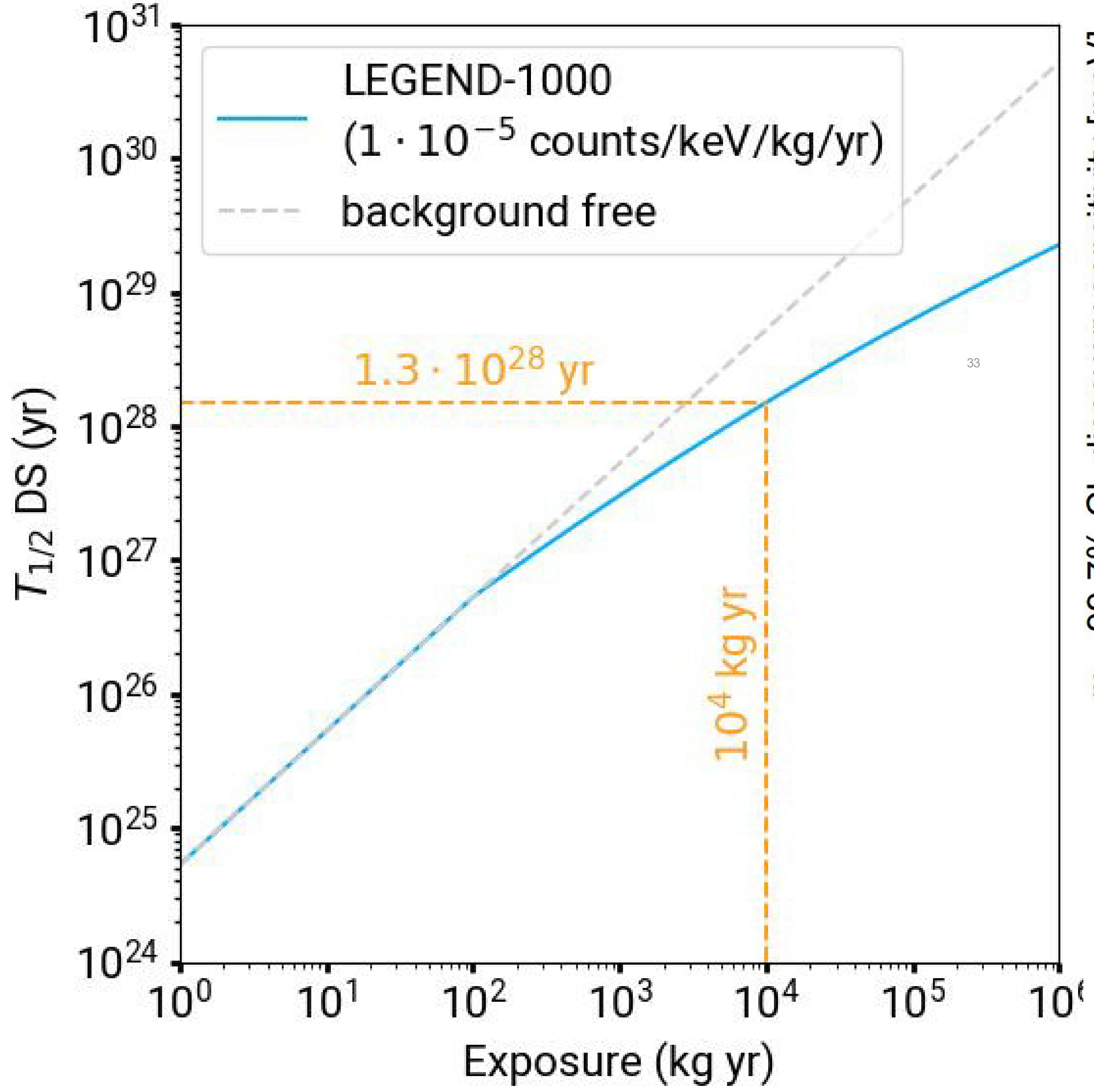


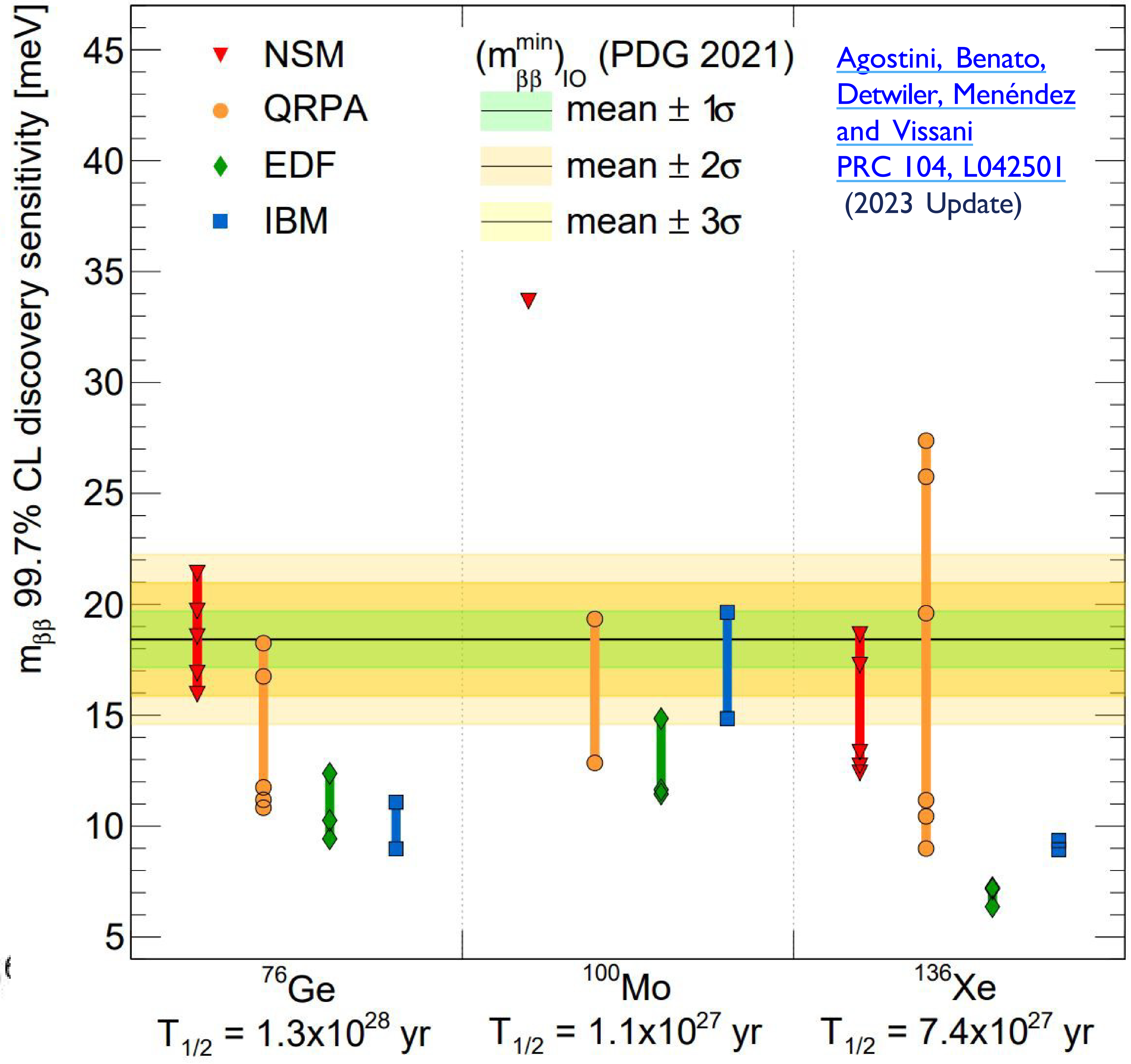
Expected background contributions (preliminary)



Projected background index ~ 10^{-5} cts/(keV kg yr)

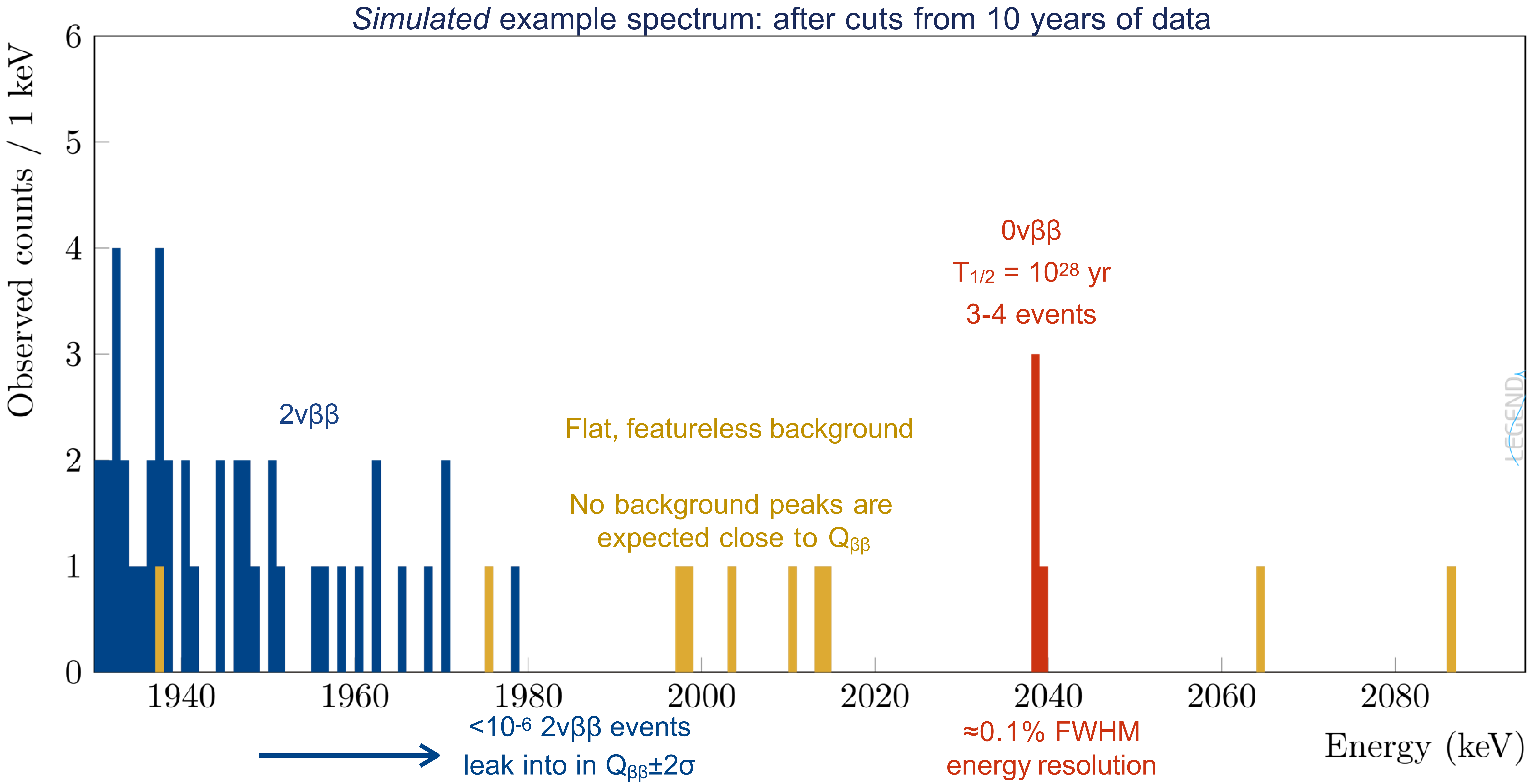
LEGEND-1000: Sensitivity





- LEGEND will span the inverted ordering and a large part of the normal ordering space
- Discovery sensitivity <18.4 meV for 12/15 calculations

LEGEND-1000: Designed for an Unambiguous Discovery



LEGEND-1000: Timeline & Outlook

2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036

Design & Reviews

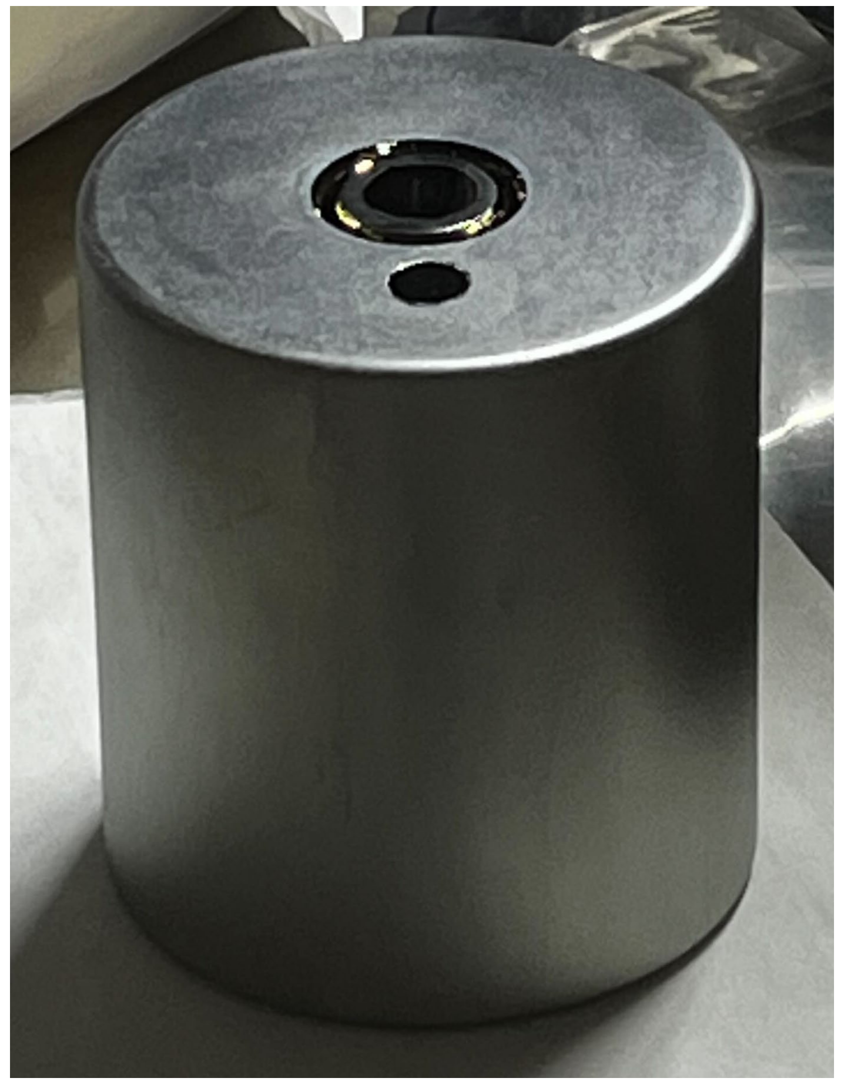
First Data

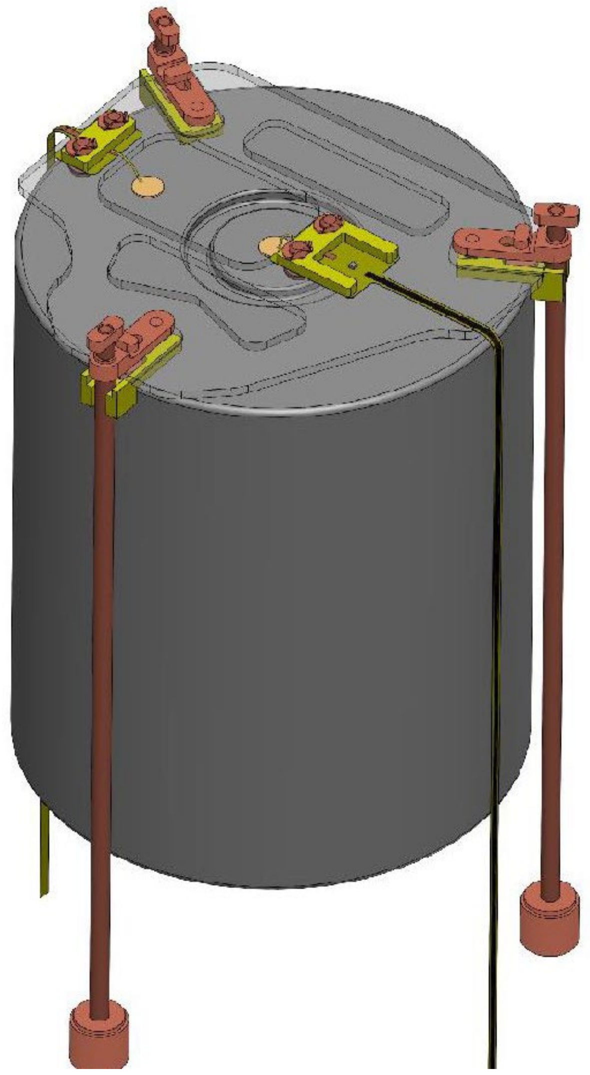
Full Data Taking

Construction, Detector Production & Installation

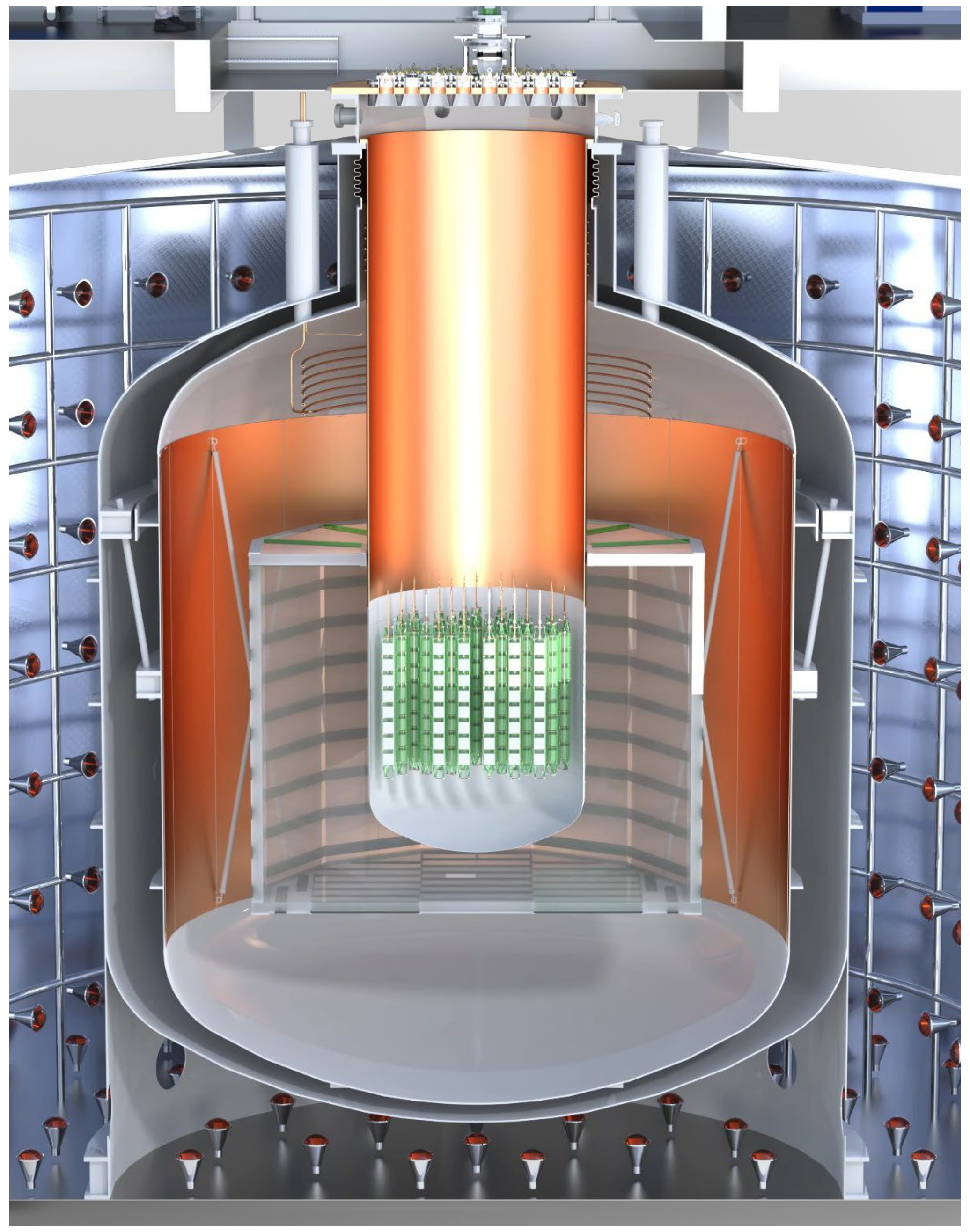
*Technically driven schedule

- LEGEND-1000 is optimized for a quasi-background-free 0νββ search
  - It builds on breakthrough developments by GERDA, MAJORANA, and LEGEND-200
  - LEGEND has a low-risk path to meeting its background goal of 10^{-5} counts/(keV kg yr)
  - Low backgrounds, excellent resolution, and event topology discrimination allow for an unambiguous discovery of 0νββ decay at $T_{1/2} = 10^{28}$ years





LEGEND Website
https://legend-exp.org/

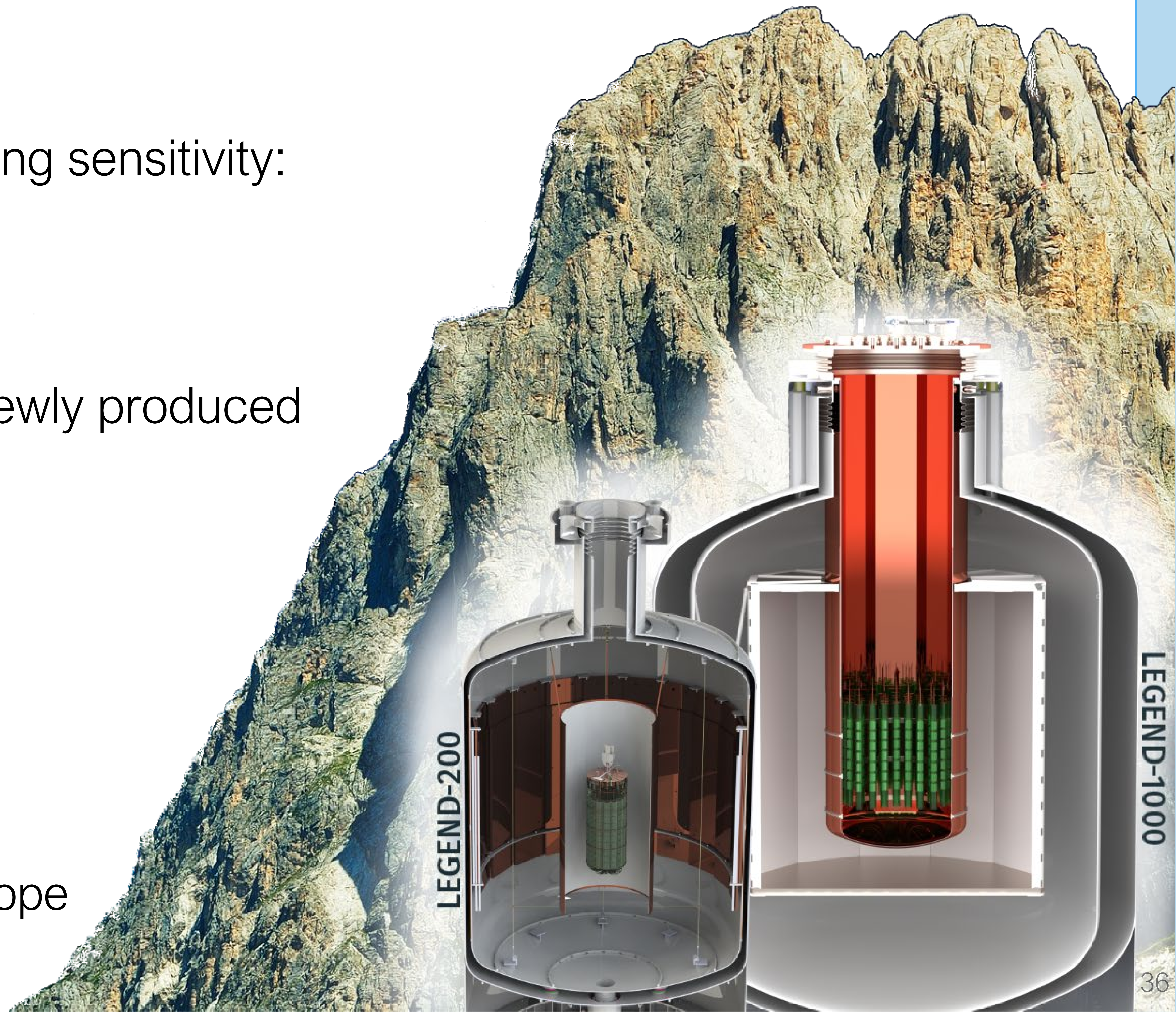


Summary

- LEGEND-200
  - collected over a year of exposure
  - first unblinding with combined world-leading sensitivity:

$$\mathbf{2.8 \times 10^{26}\ yr}$$

  - background studies completed
  - array redeployed in Summer 2025 with newly produced detectors
  - data taking restarted
- LEGEND-1000
  - design is well underway
  - technical preparations @ LNGS started
  - funding is being pursued in the US and Europe



Summary

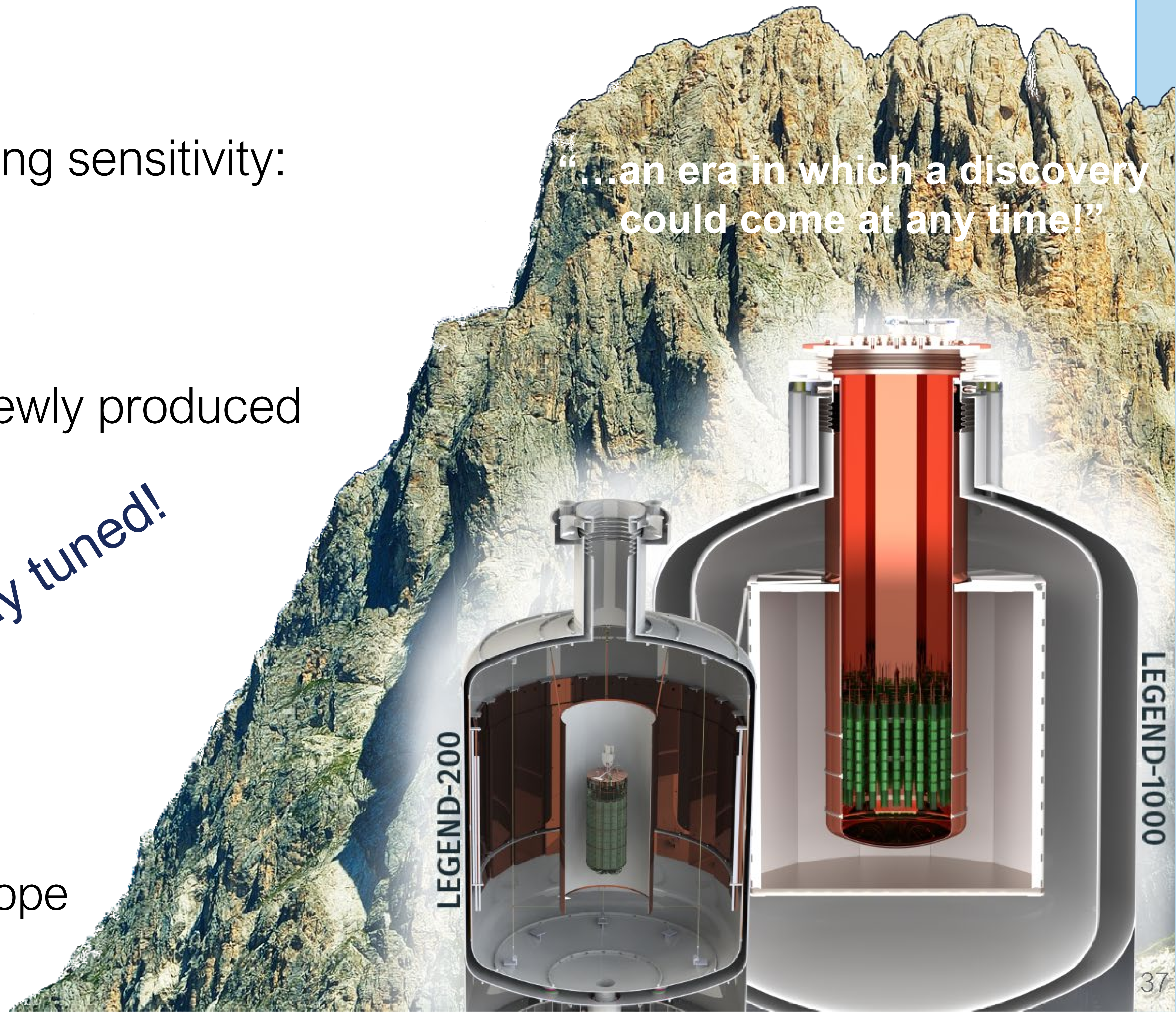
- LEGEND-200
  - collected over a year of exposure
  - first unblinding with combined world-leading sensitivity:

$$2.8 \times 10^{26}\ \text{yr}$$

  - background studies completed
  - array redeployed in Summer 2025 with newly produced detectors
  - data taking restarted

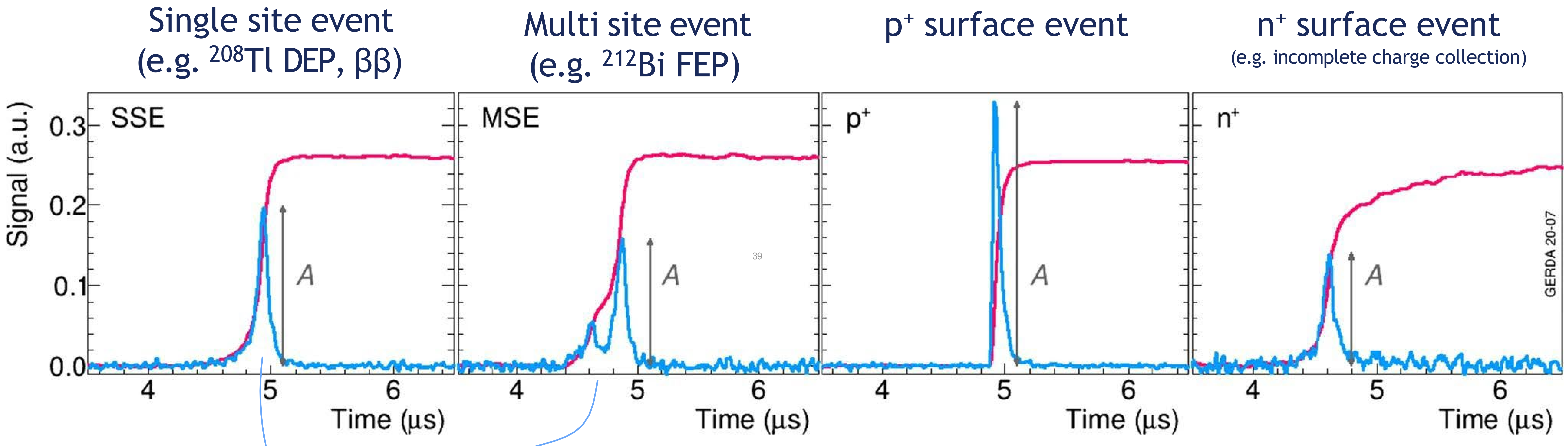
Stay tuned!

- LEGEND-1000
  - design is well underway
  - technical preparations @ LNGS started
  - funding is being pursued in the US and Europe

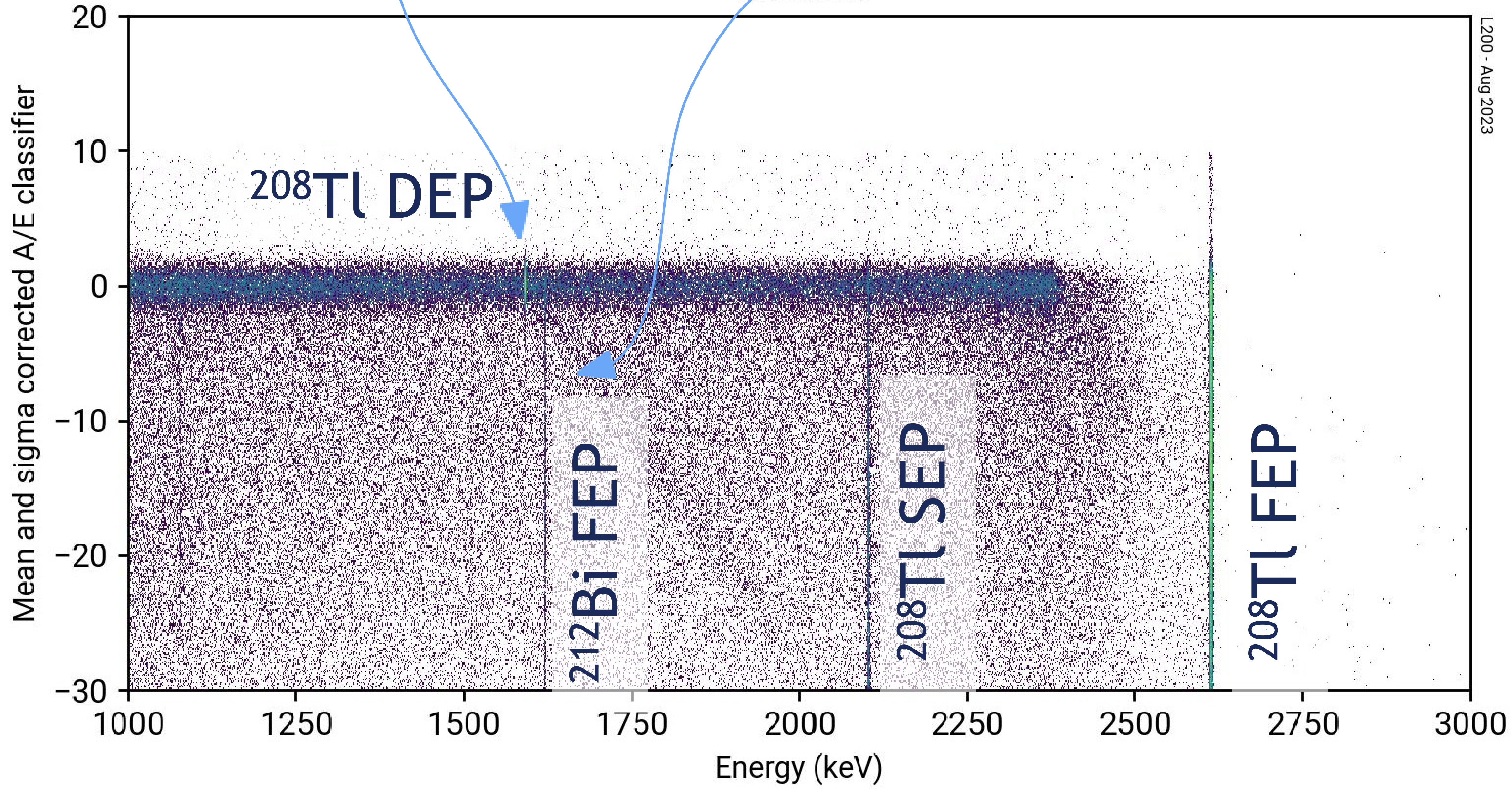


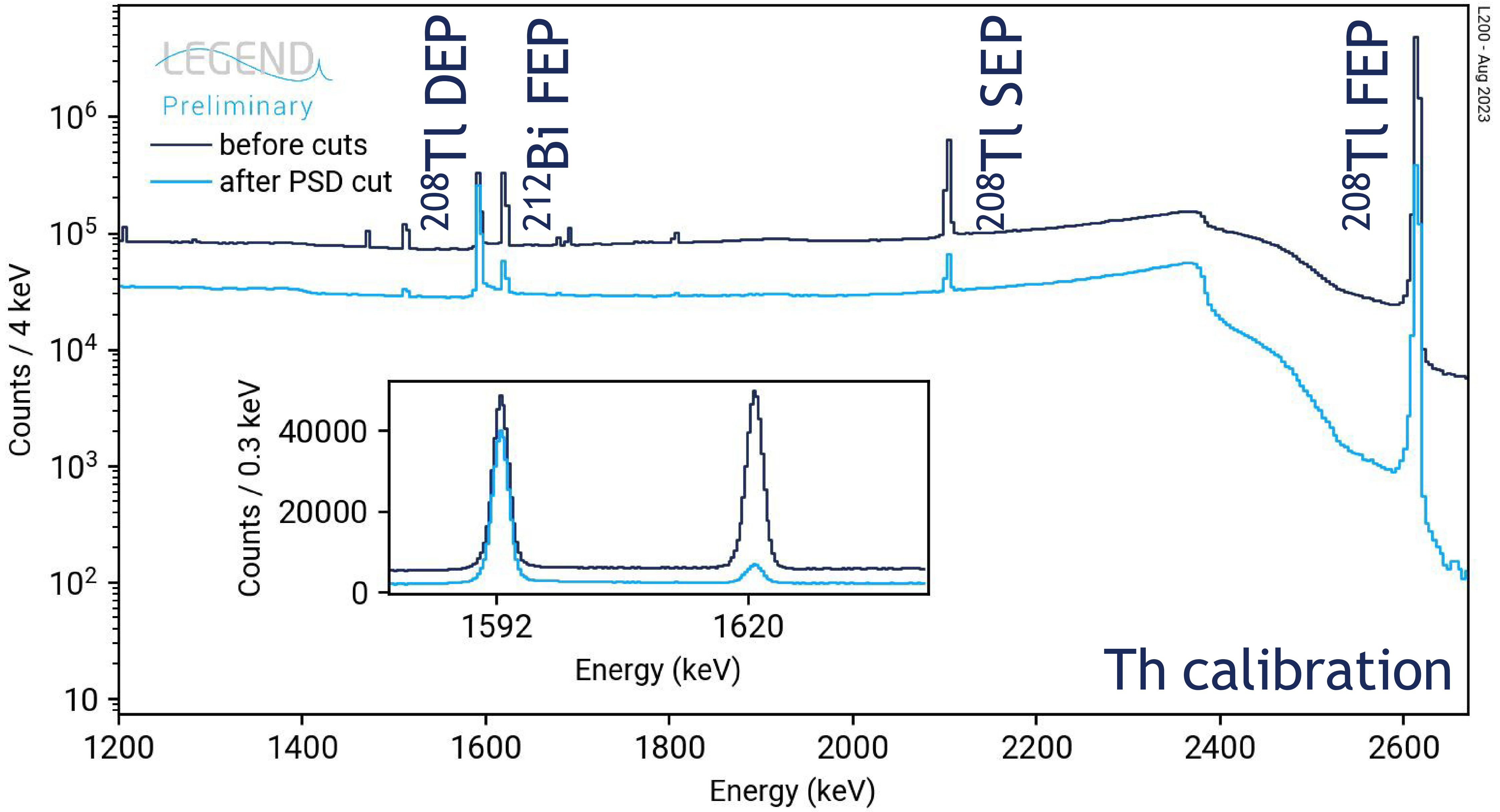
Backup slides

PSD in details

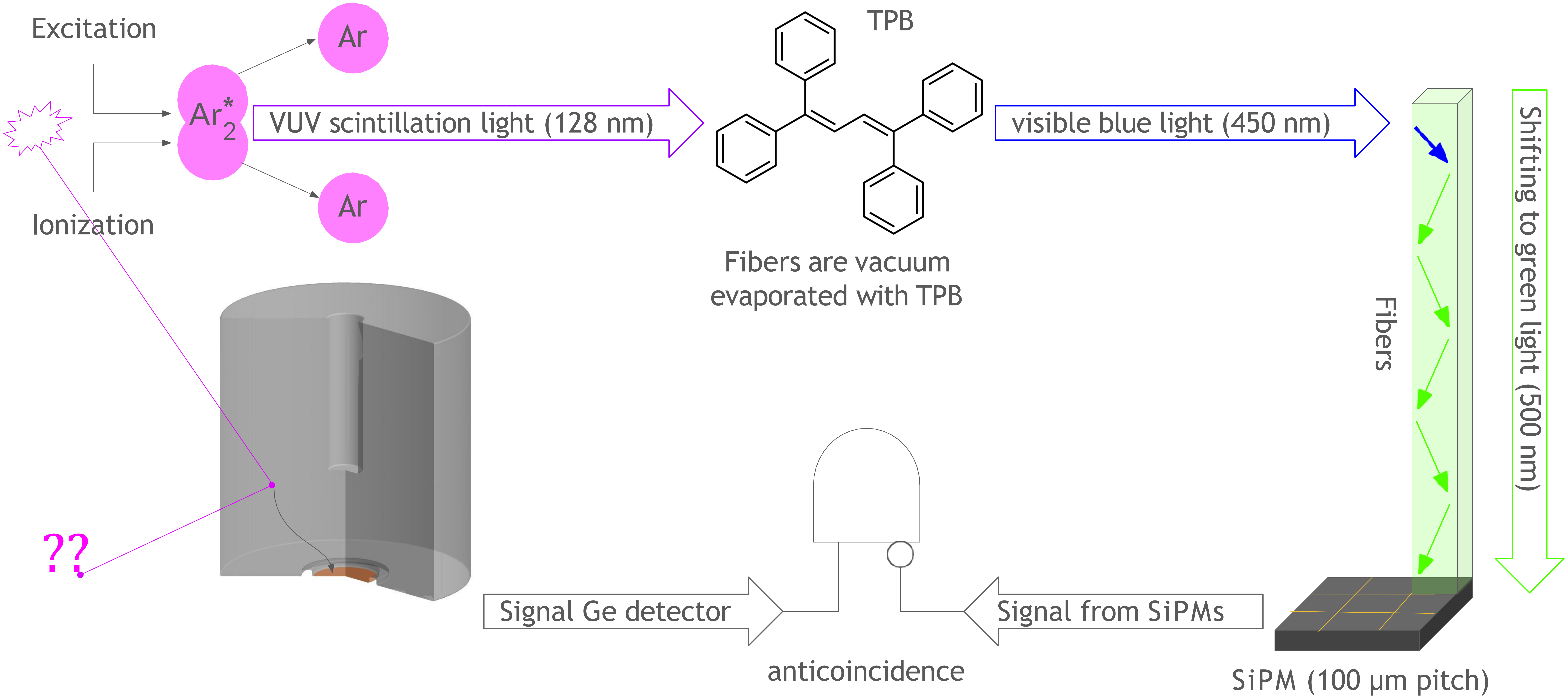


- Need to accept SSE (e.g. ββ)
- Reject the rest
- Optimize with calibration

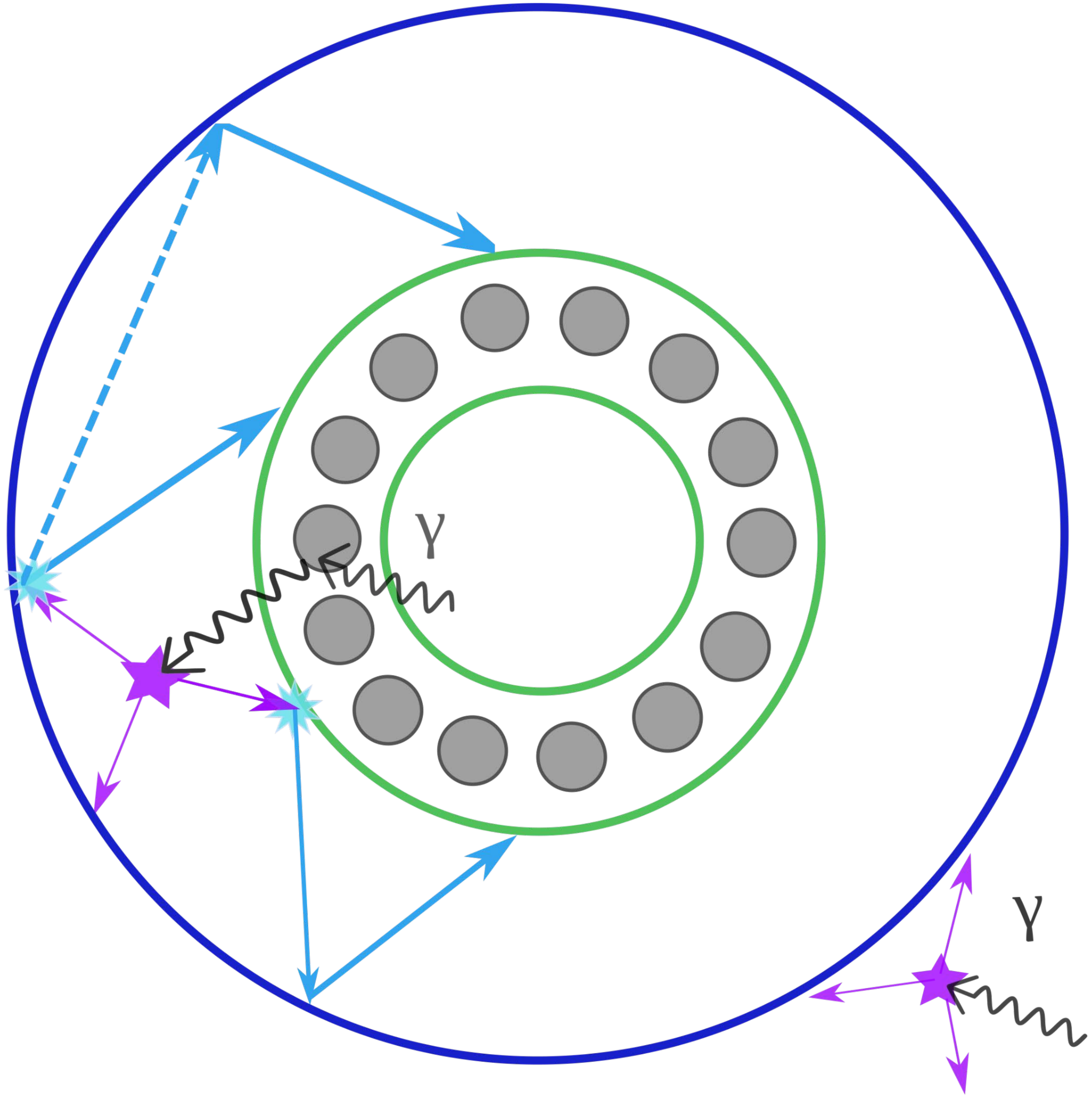




LAr scintillation principle



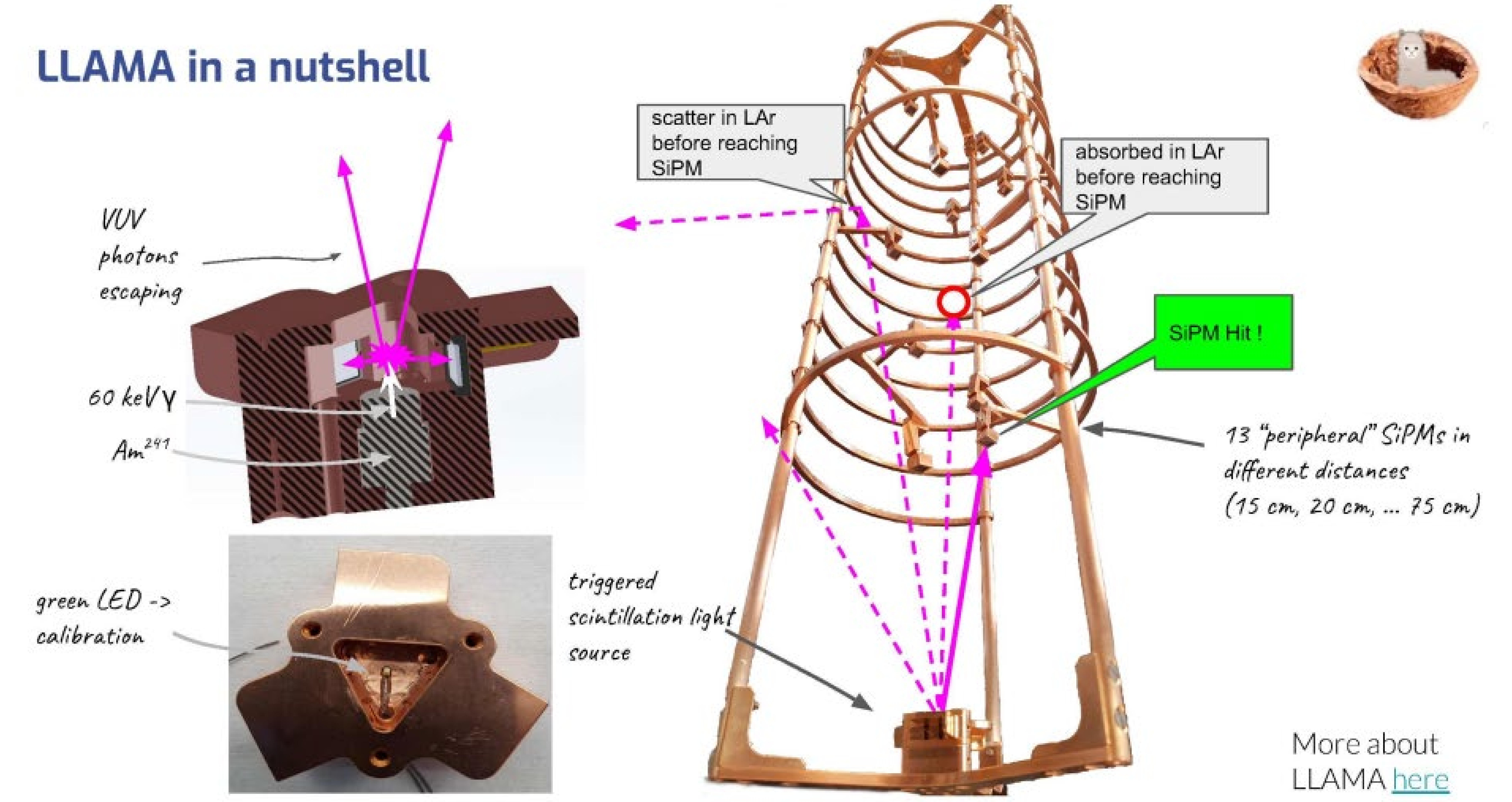
Wavelength Shifting Reflector



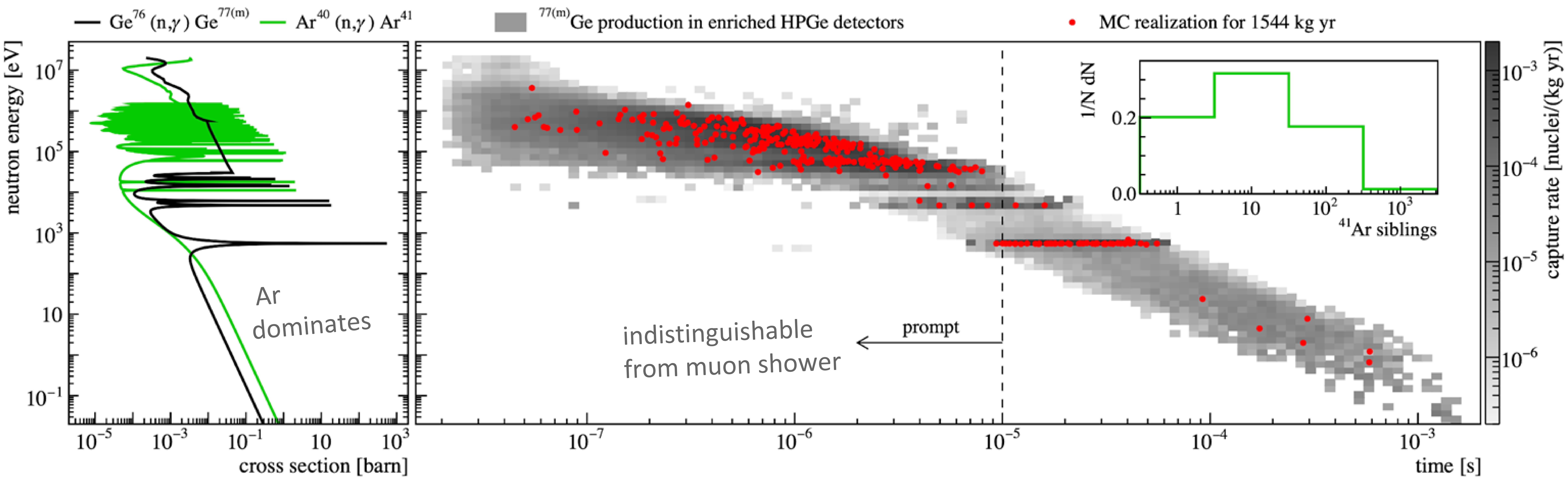
It restricts the LAr volume around the detectors.

Also shifts scintillation light to blue and reflects it back towards the LAr instrumentation

LEGEND LAr monitoring Apparatus



Virtual depth by active background rejection



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- **depth-dependent** in-situ production of $^{77(m)}$**Ge** by muon-induced neutron capture, **(0.21+-0.01) nuclei/(kg yr)** in GERDA at LNGS
- single-beta ^{77m}**Ge** background can be reduced by **delayed tagging cuts**, active reduction cuts place LNGS at ~**5000 m.w.e virtual overburden**