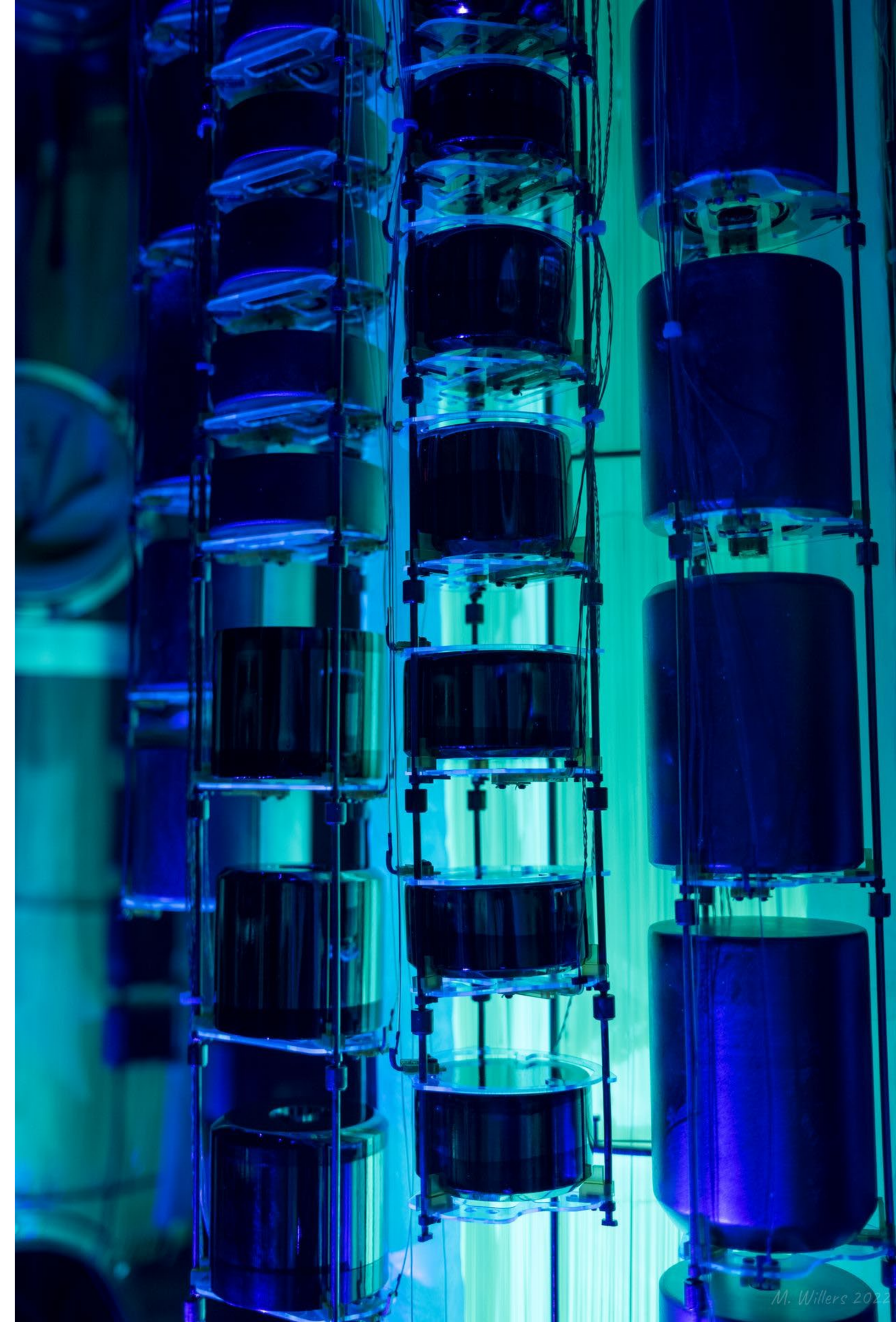


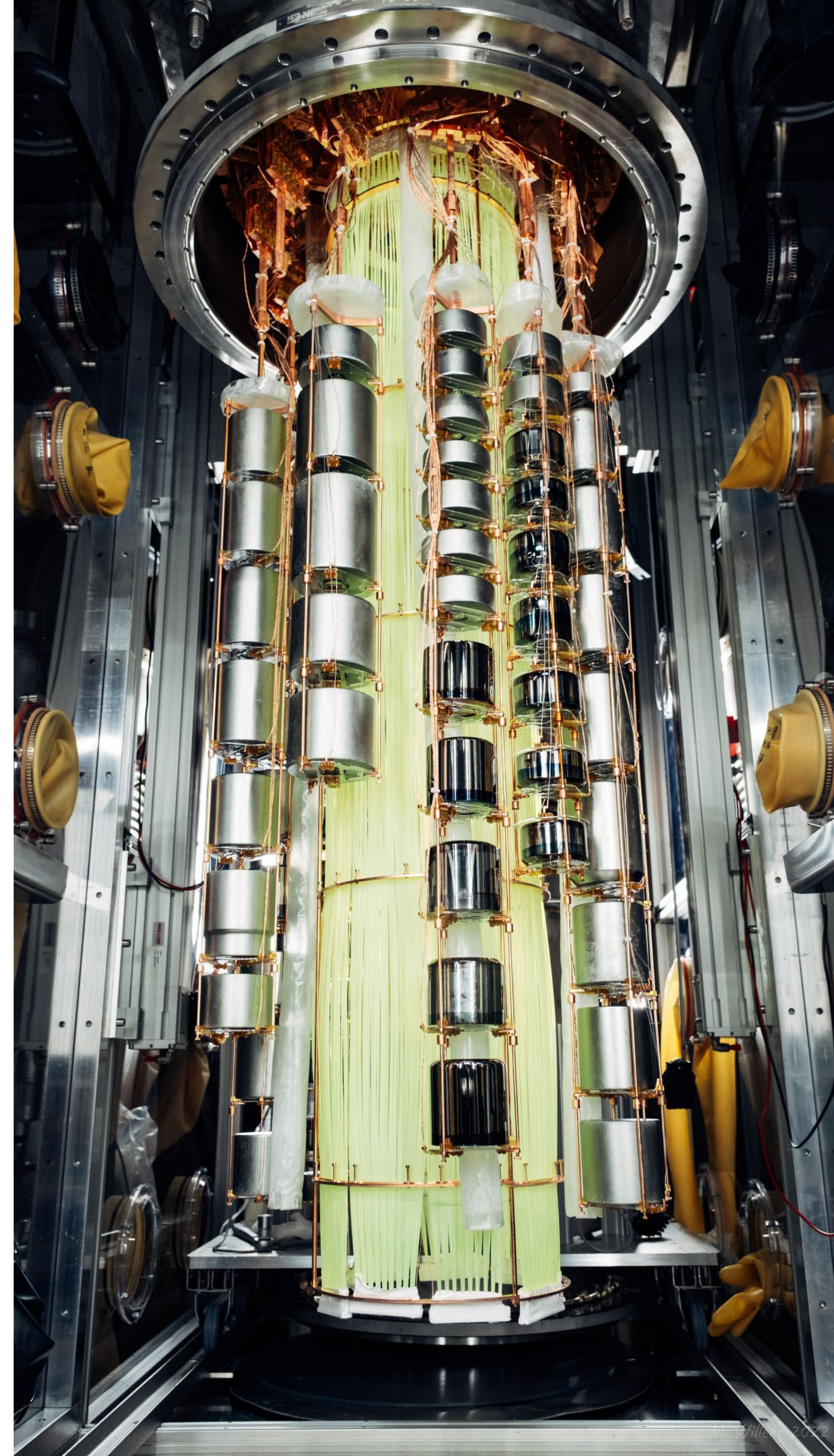
Latest LEGEND Results and Future Prospects

Jason Detwiler, U. of Washington
UGRP 2026, Institute of Science, Tokyo
28 September 2026



Outline

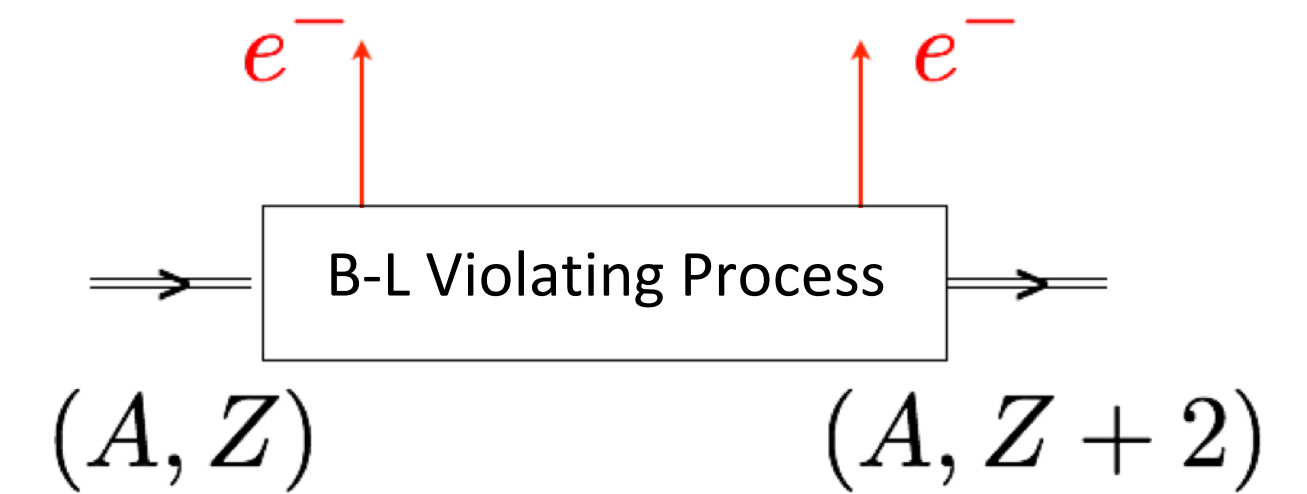
- Introduction
- Recent results from LEGEND-200
- LEGEND-1000 status and future prospects



Neutrinoless Double-Beta Decay

Creates two new particles of matter but no antimatter

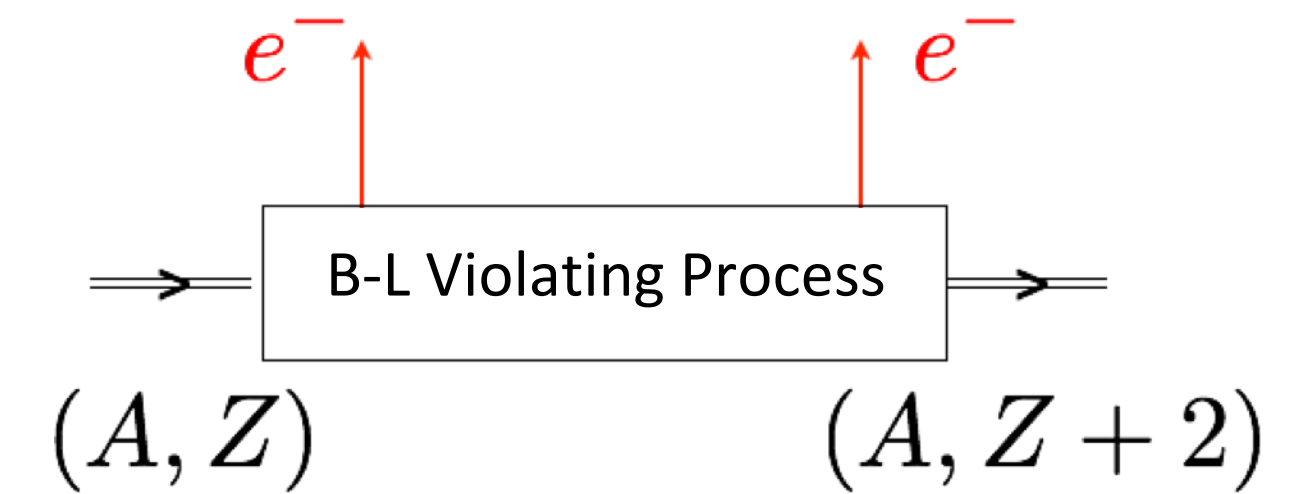
- Violates not just L but $B-L$: the last accidentally conserved quantity of the SM
 - Other accidental symmetries L_e, L_μ, L_τ all violated by m_ν ...
- An observation of this process would be important regardless of theoretical motivations



Neutrinoless Double-Beta Decay

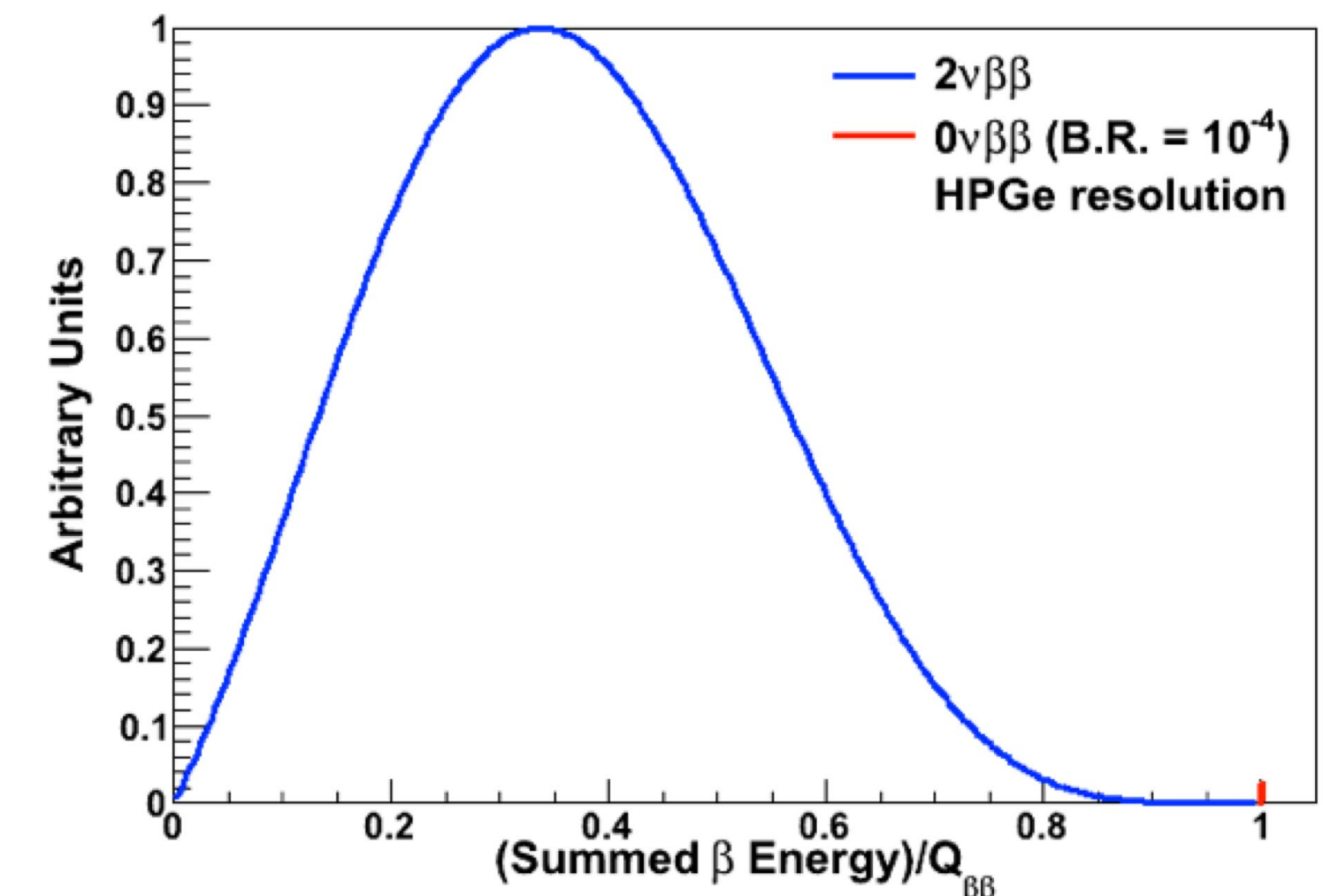
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- An observation of this process would be important regardless of theoretical motivations



Experimental Signature: δ peak at $Q_{\beta\beta}$

- Necessary and sufficient to measure $\Sigma T_{\beta i}$ (in multiple isotopes)
- Tracking $(\cos\theta, T_{\beta 1}:T_{\beta 2})$ and isotope dependence probes the decay mechanism
- Additional handles provide background rejection, statistical characterization

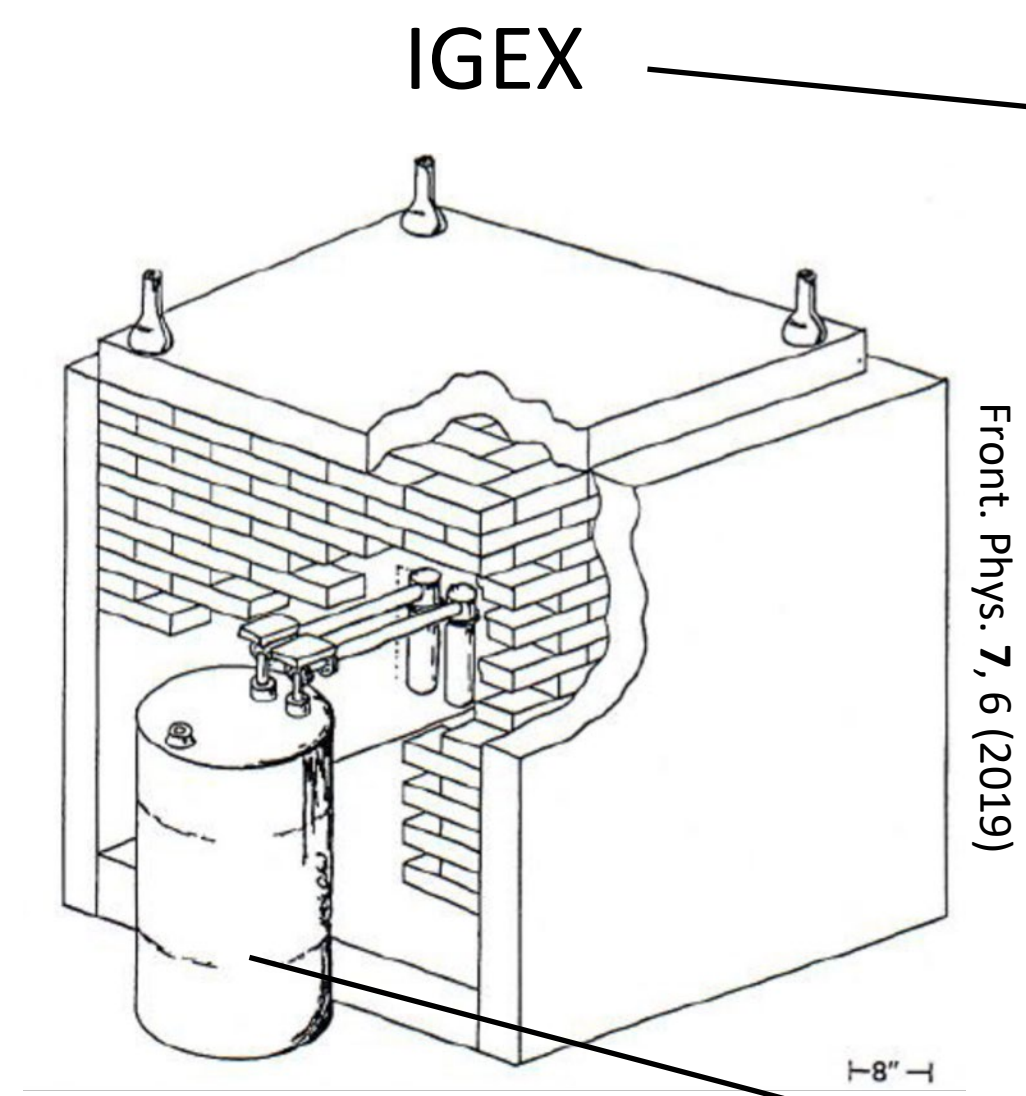
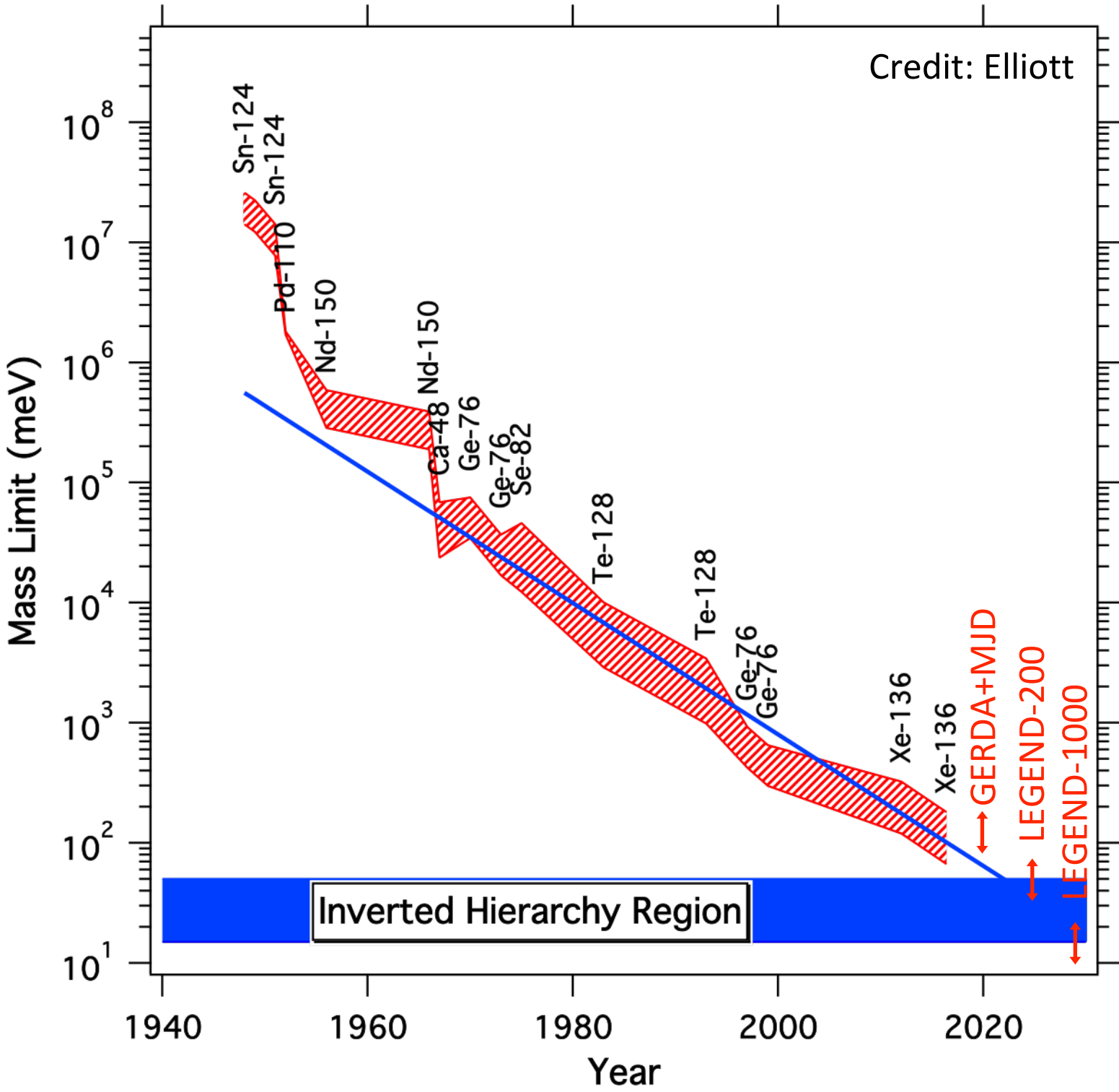


$0\nu\beta\beta$ Decay Searches with ^{76}Ge

- Able to enrich Ge from 7.75% to >90% in ^{76}Ge
 - Enrichment by ultracentrifuge of GeF_4
 - Costs stable; large, reliable global supply; market for depleted byproduct
- Single-crystal Ge detectors = source, intrinsically pure
 - High efficiency ($\sim 70\%$), effective use of all enriched material ($>90\%$)
 - Compact non-volatile solid, typical mass has increased x2-3 in last decade
 - No challenging operation requirements (<5 kV, ~ 77 K)
- Best energy resolution: $\sim 0.1\%$ at 2039 keV (~ 2.5 keV FWHM)
 - No prominent background lines within many σ of $Q_{\beta\beta}$, $2\nu\beta\beta$ background negligible
 - Energy scale linear to $\sim 0.01\%$, stable long-term operation with minimal maintenance
- Lowest achieved background levels (per FWHM): ~ 1 count/t-yr
 - Effectively a single-channel TPC: multiplicity, timing, pulse shape gives event topology information, providing powerful background suppression
 - Can be operated in scintillating liquid argon active veto



History of ^{76}Ge Double-Beta Decay



MAJORANA: ultra-pure materials, electronics, PPCs

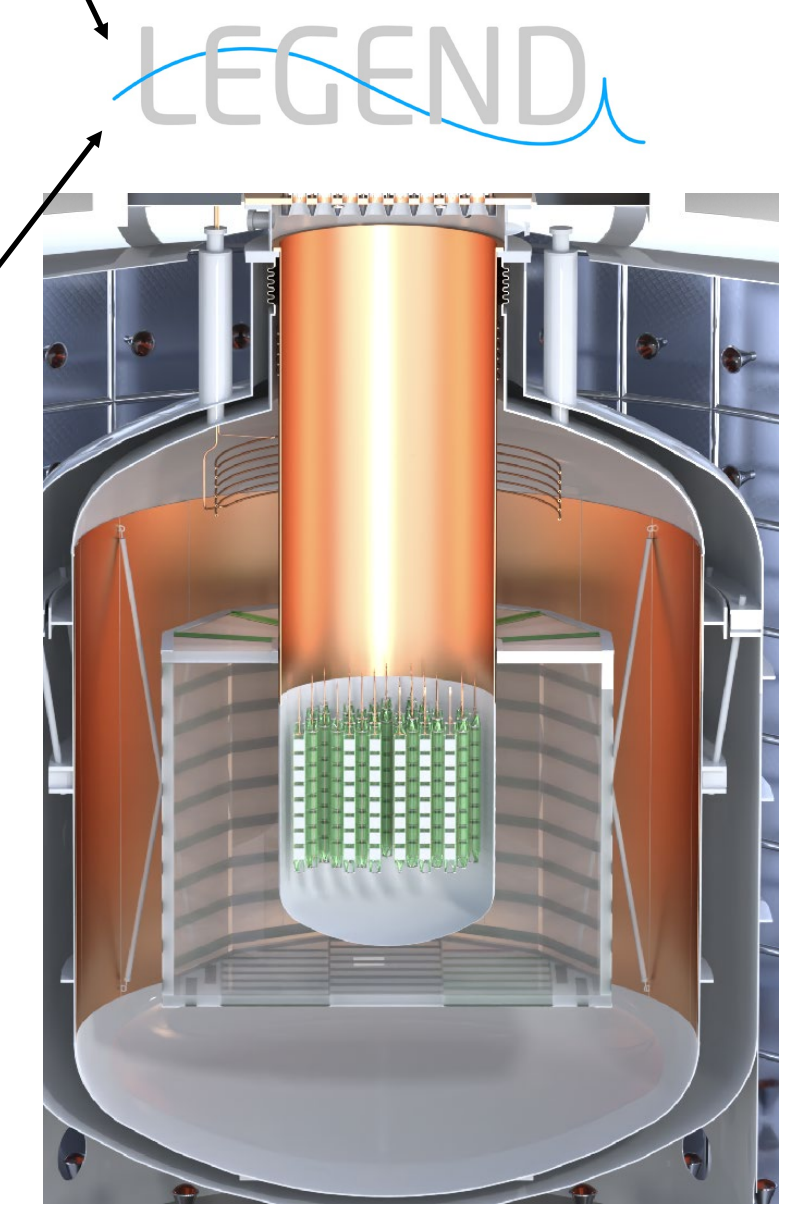
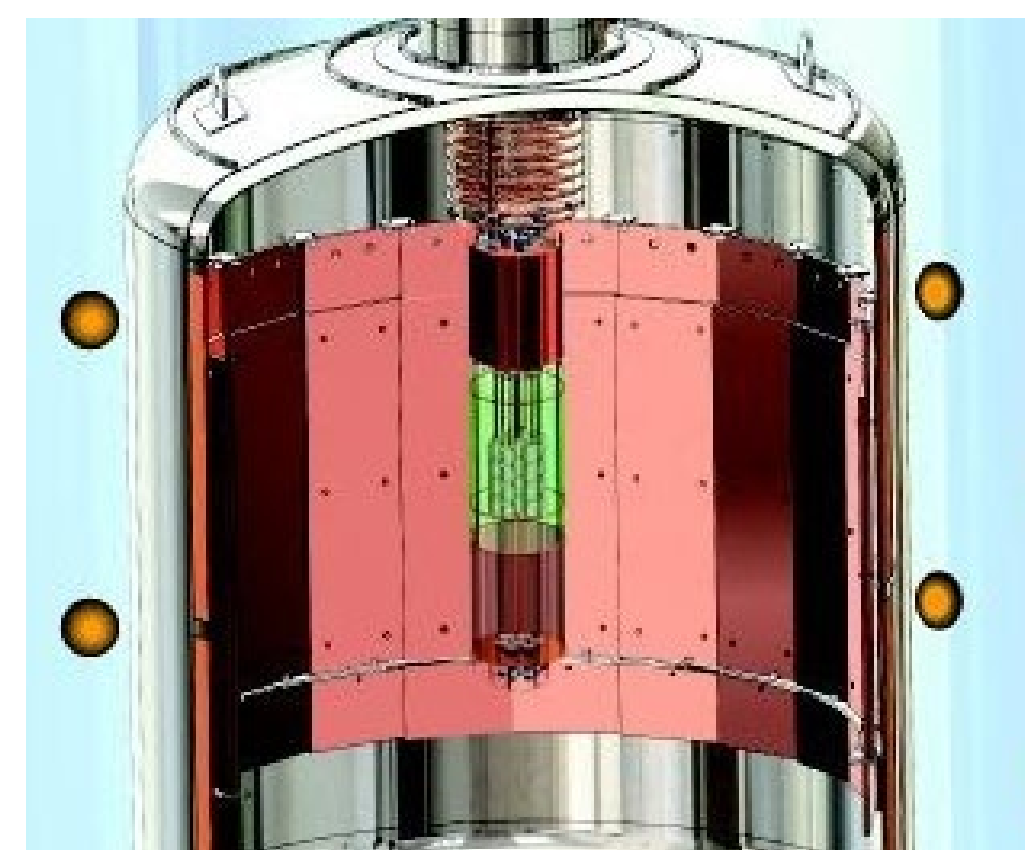


Heidelberg-Moscow

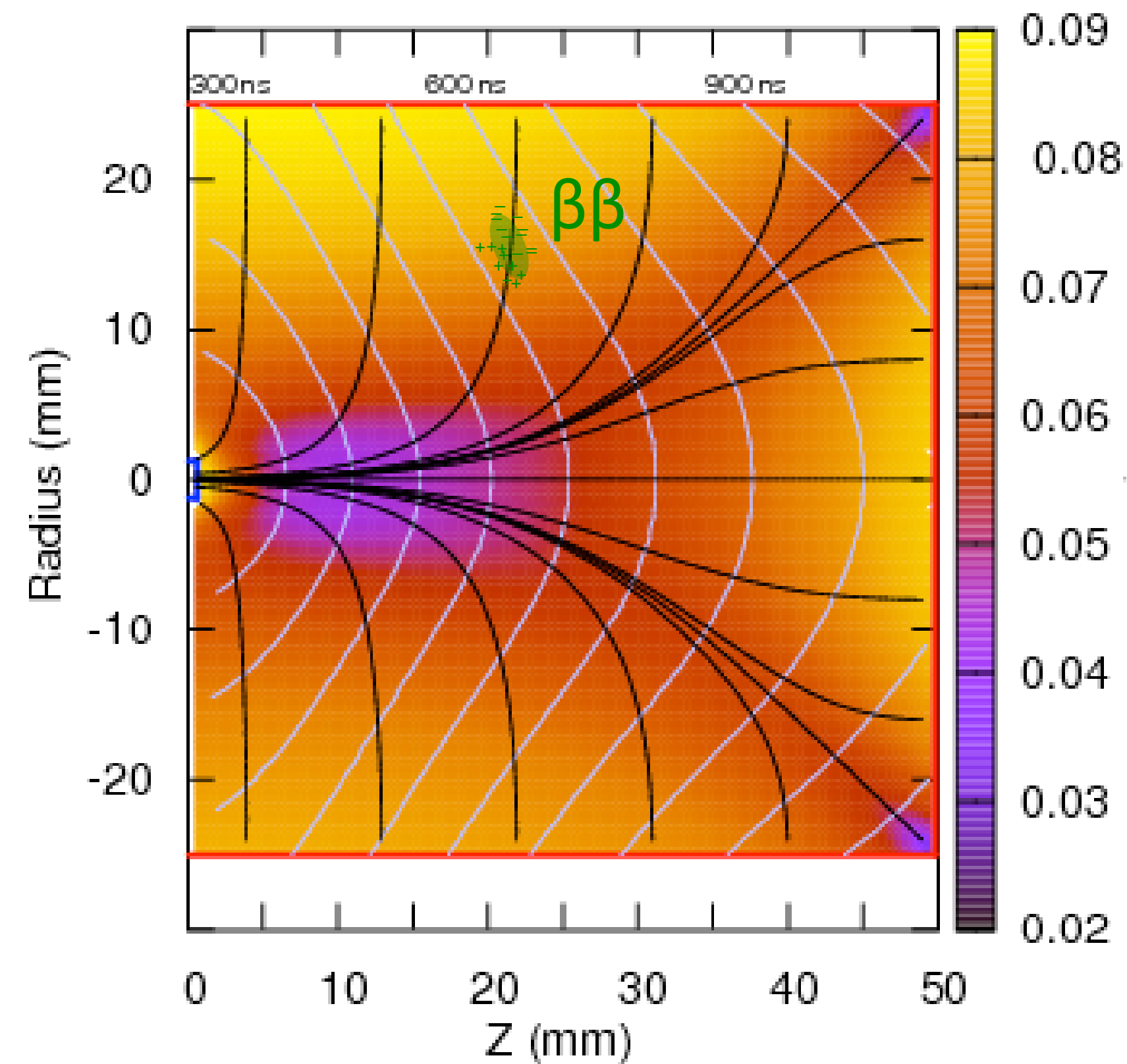
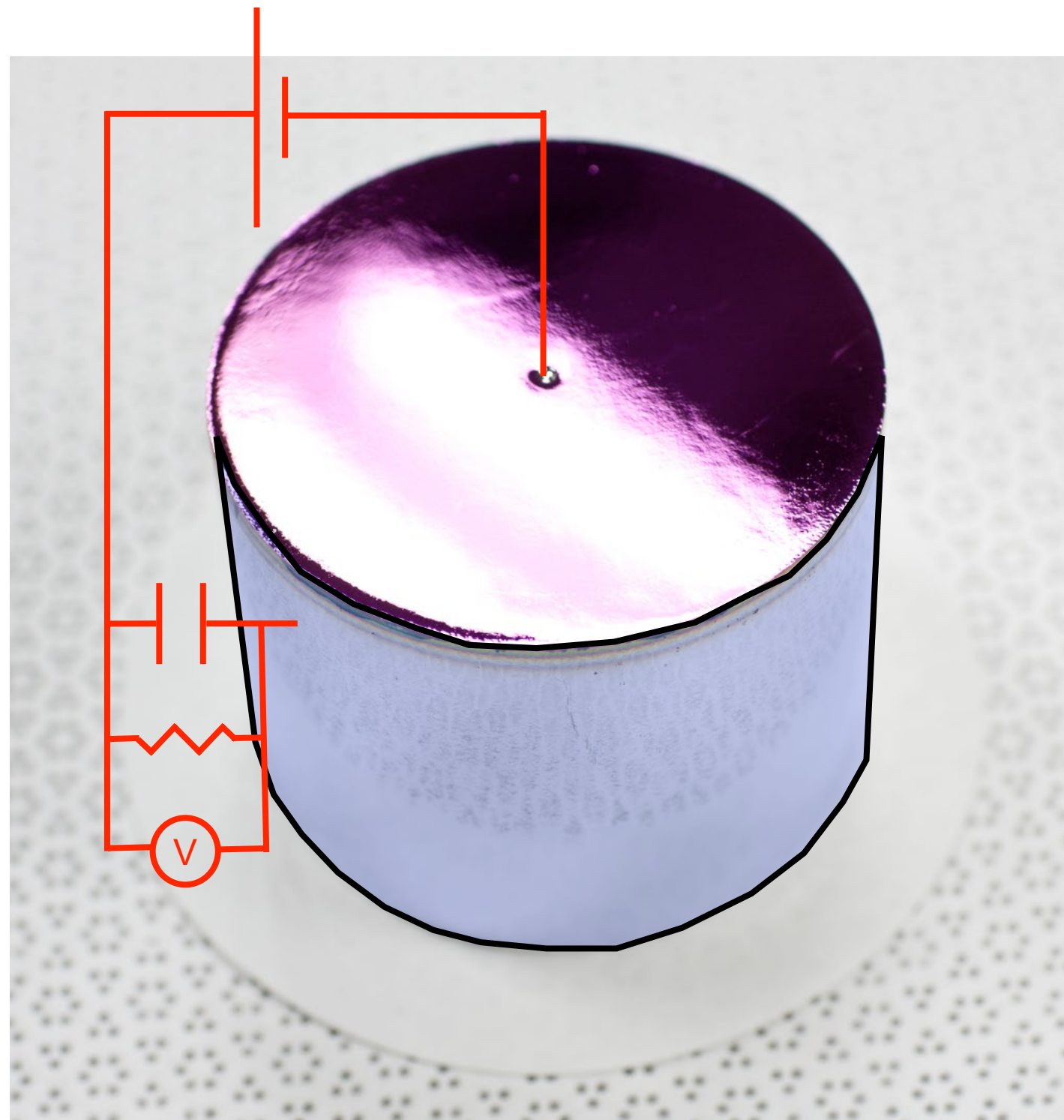


Prog. Part. Nucl. Phys. 32, 261 (1994)

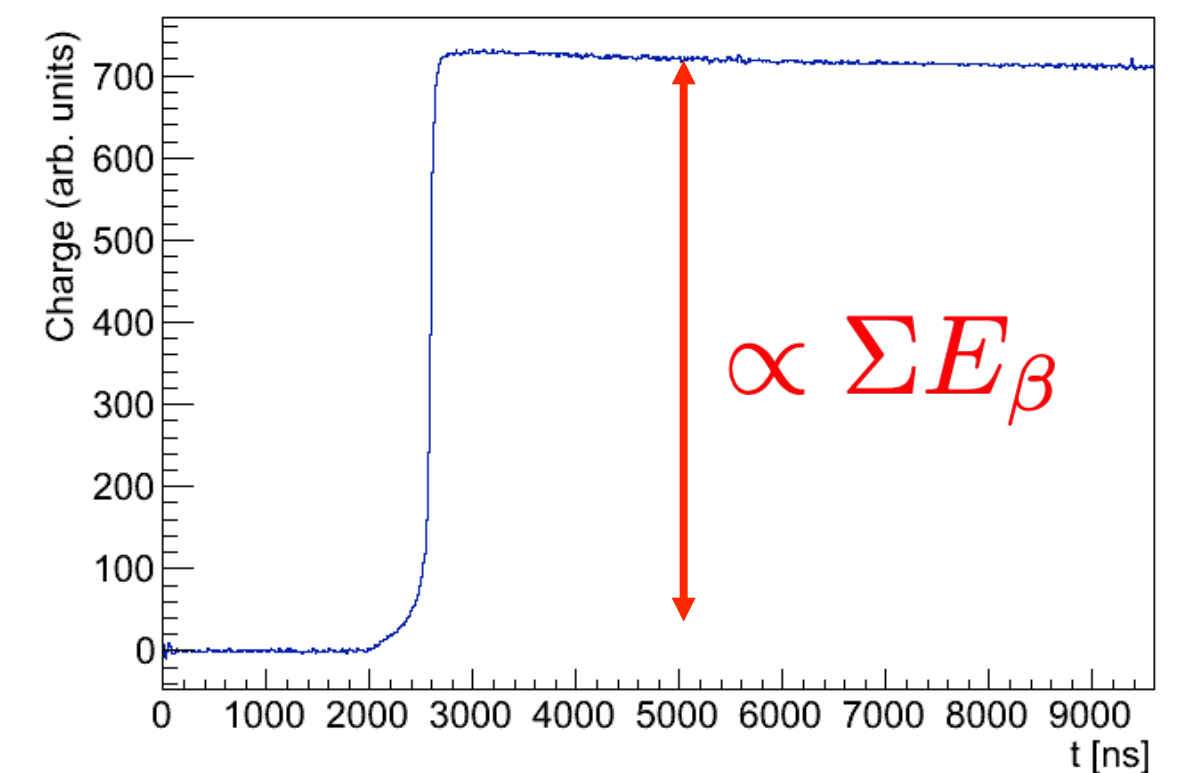
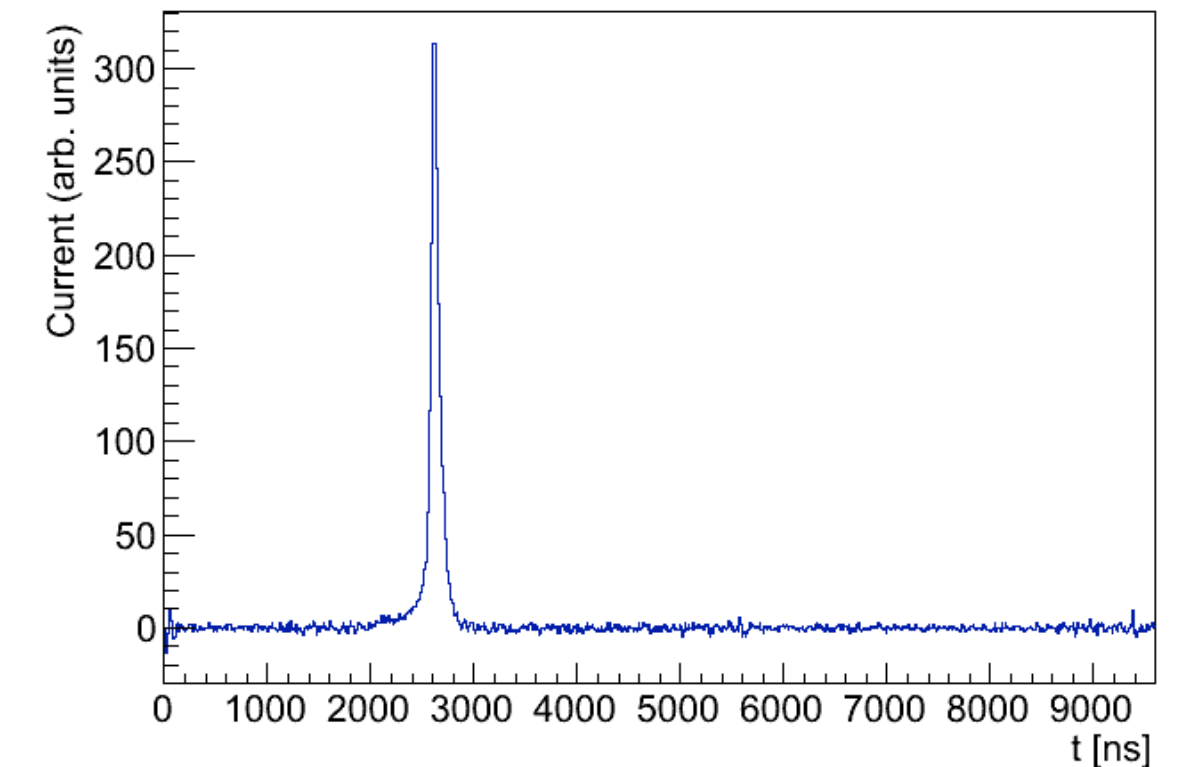
GERDA: LAr direct immersion
Coax + BEGes



$0\nu\beta\beta$ Decay Detection in HPGe



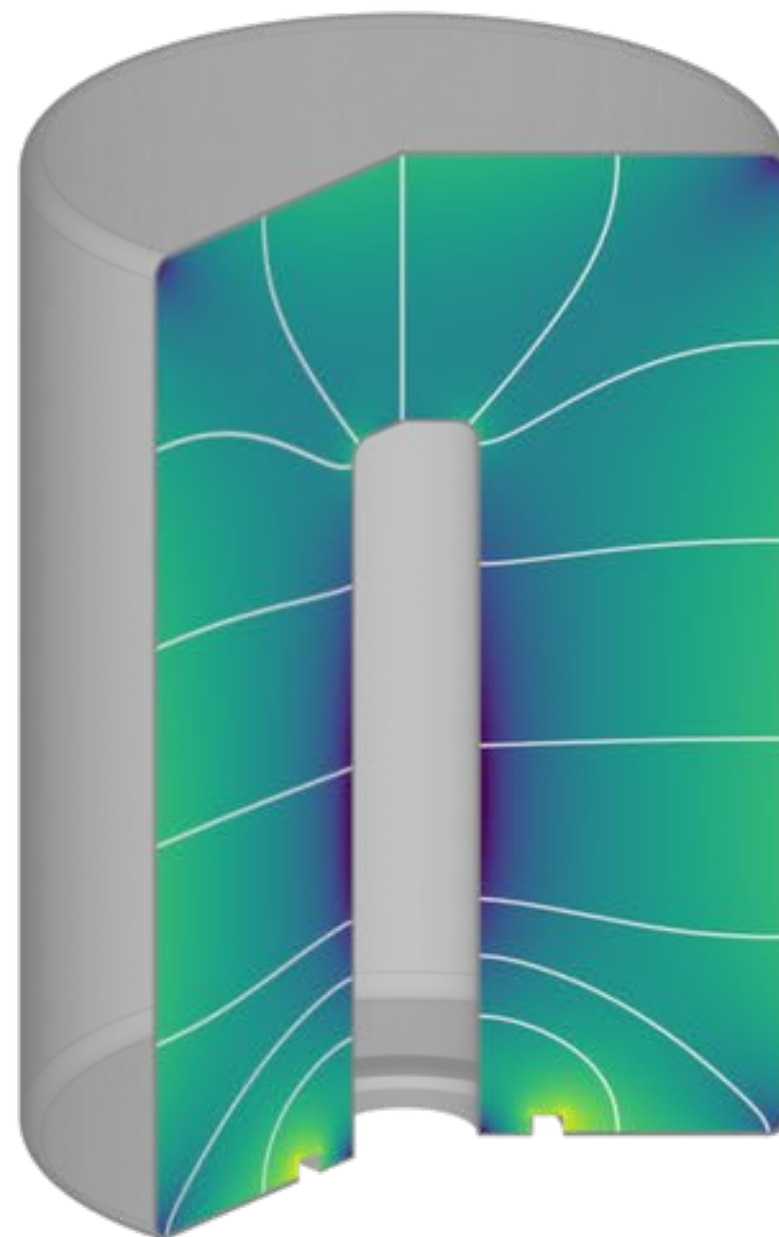
Hole v_{drift} (mm/ns) with drift paths, isochrones



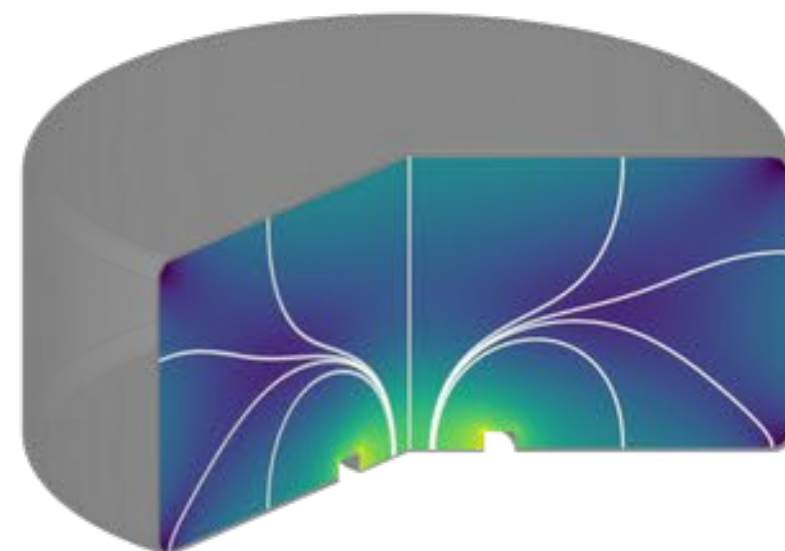
HPGe detector geometries for $0\nu\beta\beta$ Decay

- Larger detectors have lower background (instrumentation / kg; S:V ratio)
- Point-contact (PC) geometries offer ~optimal bulk multi-site discrimination
- LEGEND's Inverted-Coaxial PC: large mass (3-4 kg) with E resolution of ~ 2.5 keV FWHM @ $Q_{\beta\beta}$

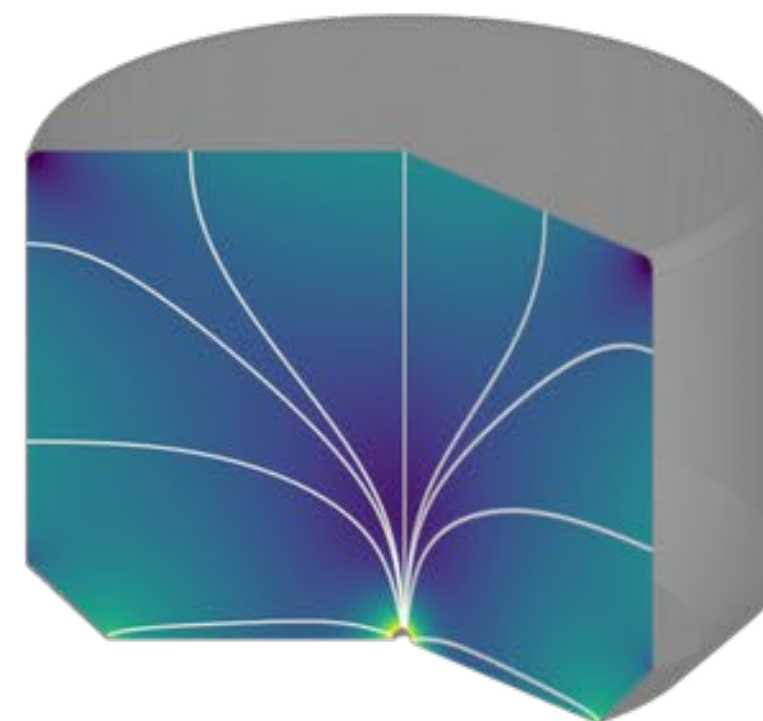
HM
IGEX  Coax



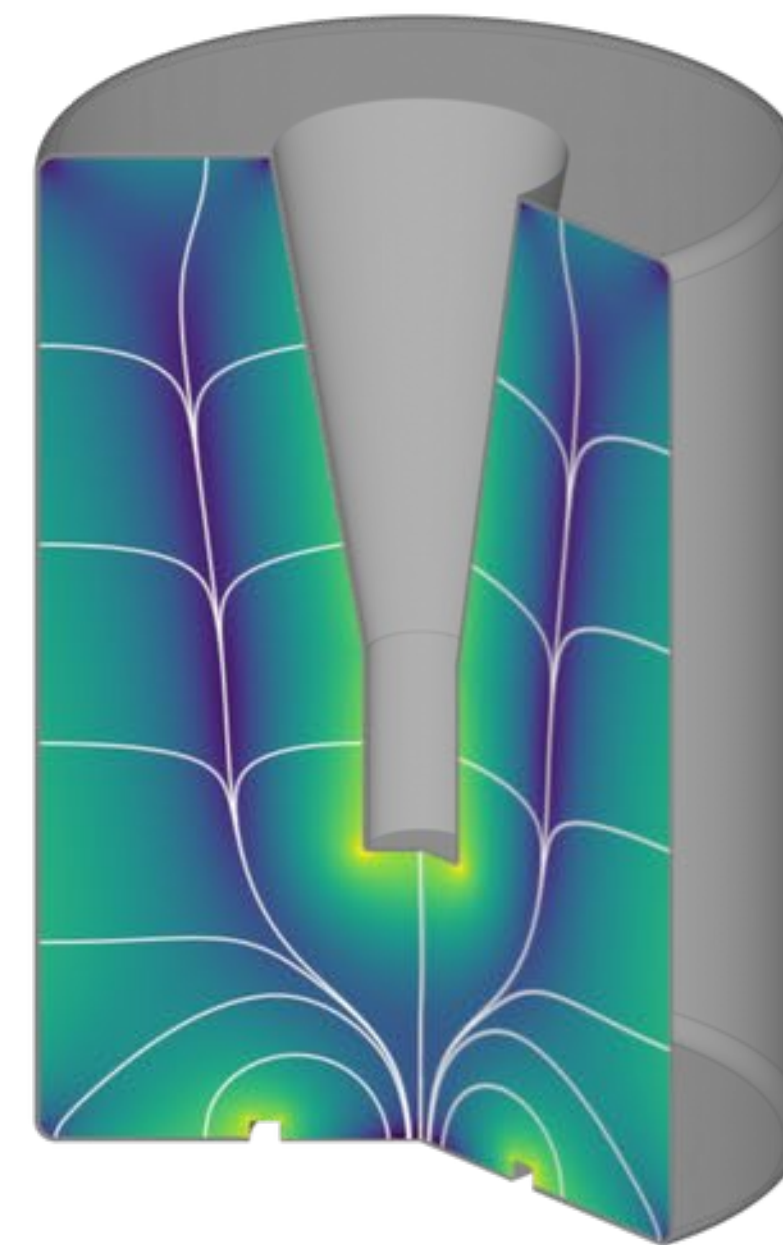
 BEGe



 PPC

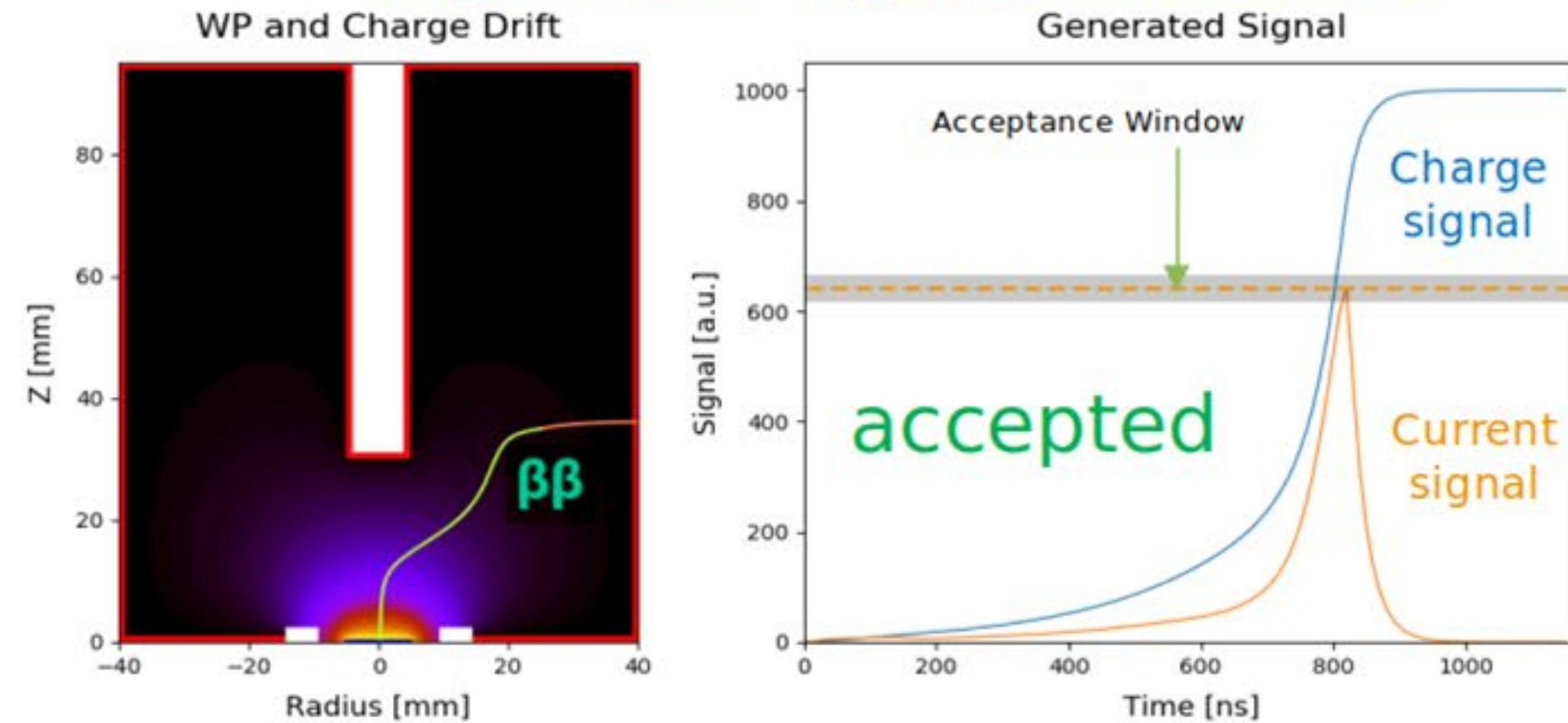


LEGEND IC

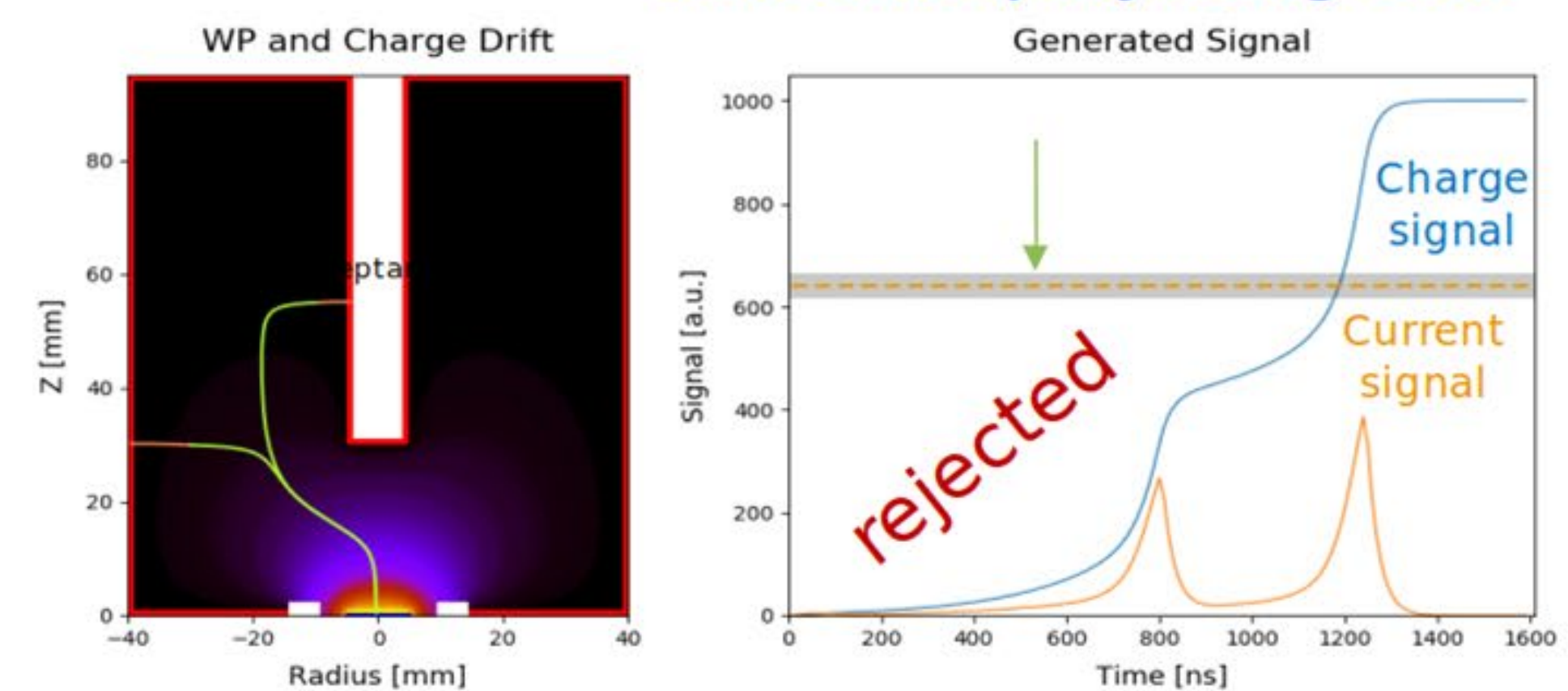


ICPC Pulse-Shape Discrimination (PSD)

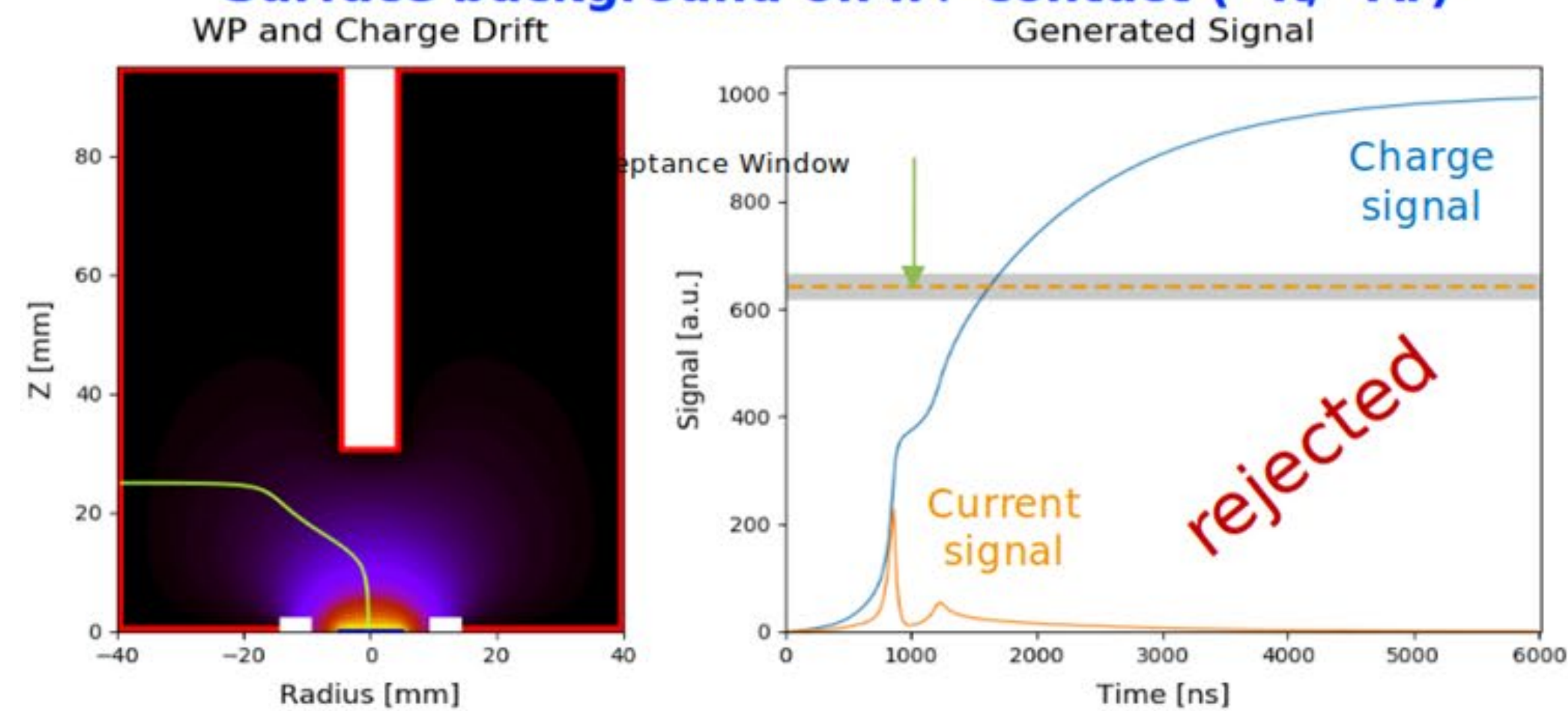
Single-sited - $0\nu\beta\beta$ event candidate



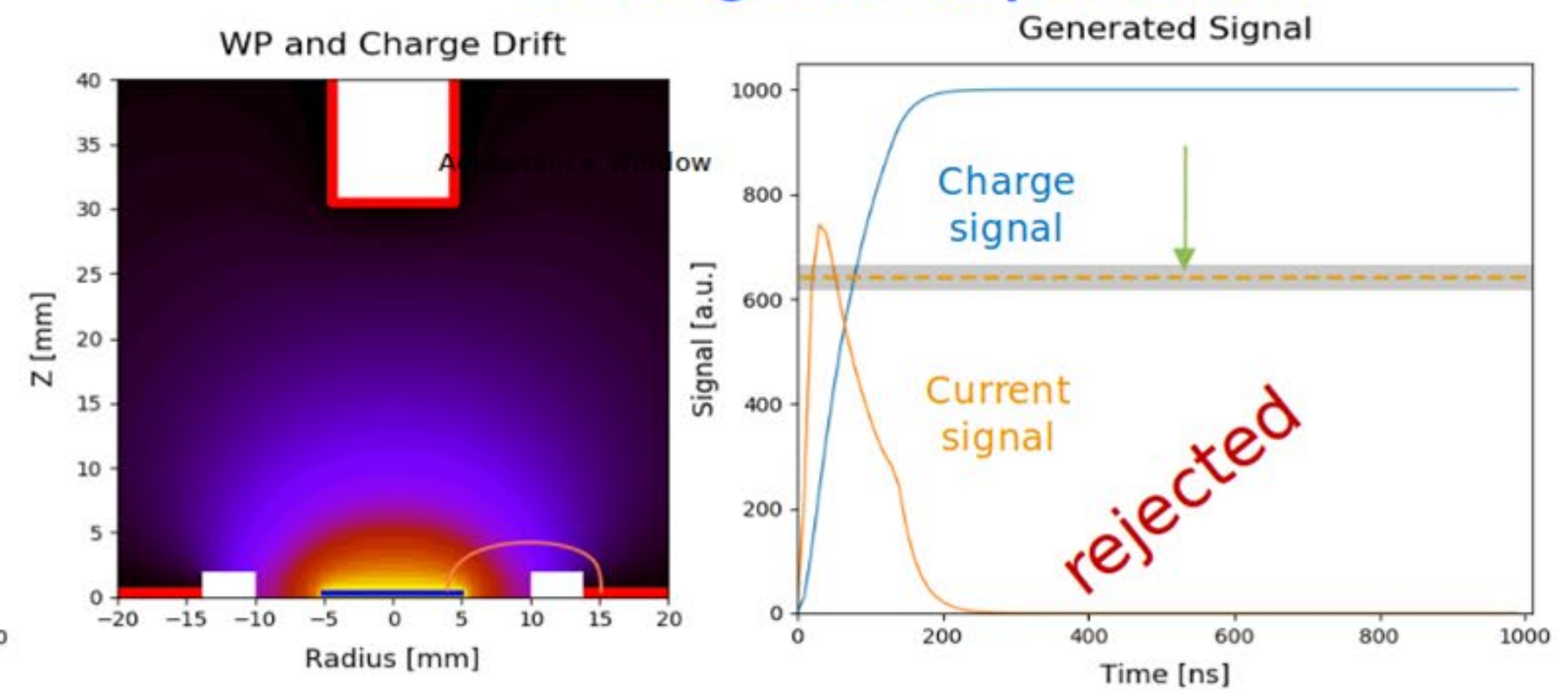
Multi-sited γ -ray background



Surface background on n+ contact ($^{42}\text{K}/^{42}\text{Ar}$)



α -background on p+ contact

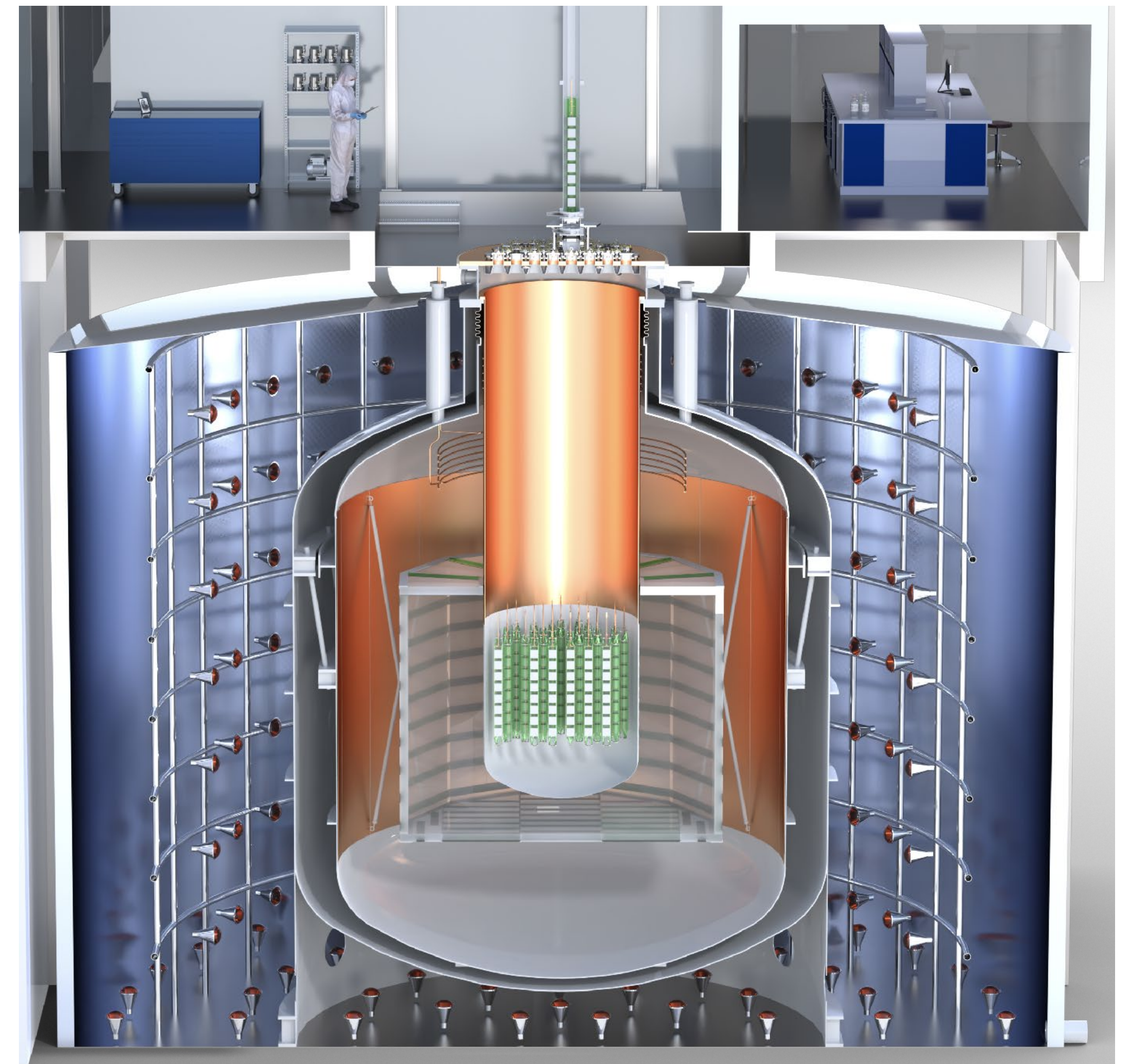


Use MAJORANA's ultraclean materials and low-noise electronics...

- Start with the lowest achievable backgrounds
- Narrow the region-of-interest near $Q_{\beta\beta}$ as much as possible

... and directly immerse detectors in GERDA's liquid argon active veto

- LAr stops most alphas and gammas before they can reach the detectors
- LAr scintillates, allowing for rejection of what does reach the detectors



12 countries
~60 institutions
~350 scientists



LEGEND Stages

• LEGEND-200

- Up to 200 kg of 90%-enriched Ge detectors deployed in an upgrade of the existing GERDA infrastructure at LNGS
- Reuses GERDA and MAJORANA enriched detectors (~60 kg) and adds new detectors (~140 kg, "ICPCs")
- Background goal: <0.2 cts/(keV t yr)
- Data taking is underway

• LEGEND-1000

- 1000 kg (staged) of 90%-enriched Ge detectors deployed in a new experimental infrastructure at LNGS
- Uses underground argon (eliminates ^{42}Ar and ^{39}Ar)
- Background goal: <0.01 cts/(keV t yr)
- Start of data taking with first detectors: early 2030's



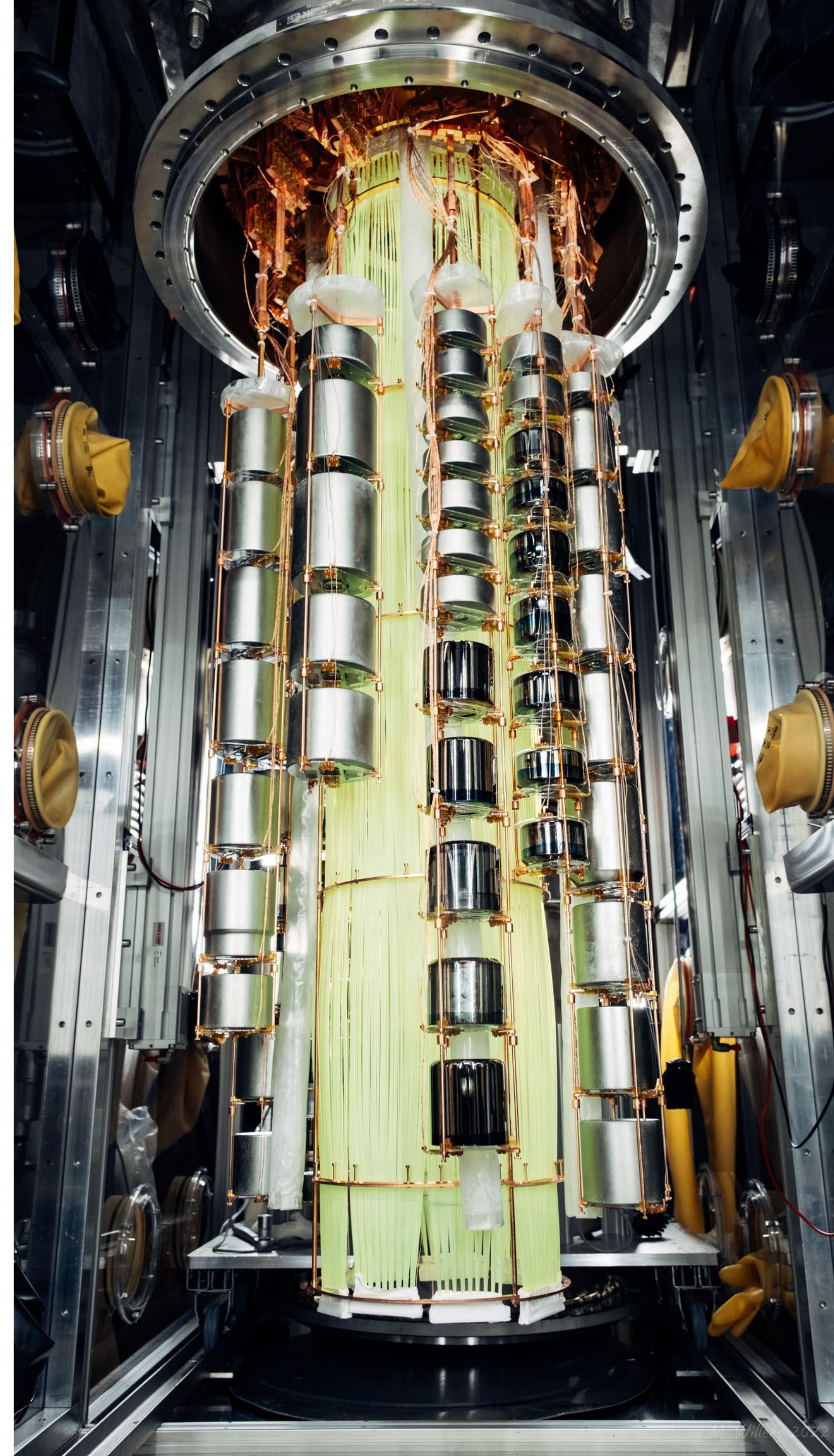
LEGEND-200



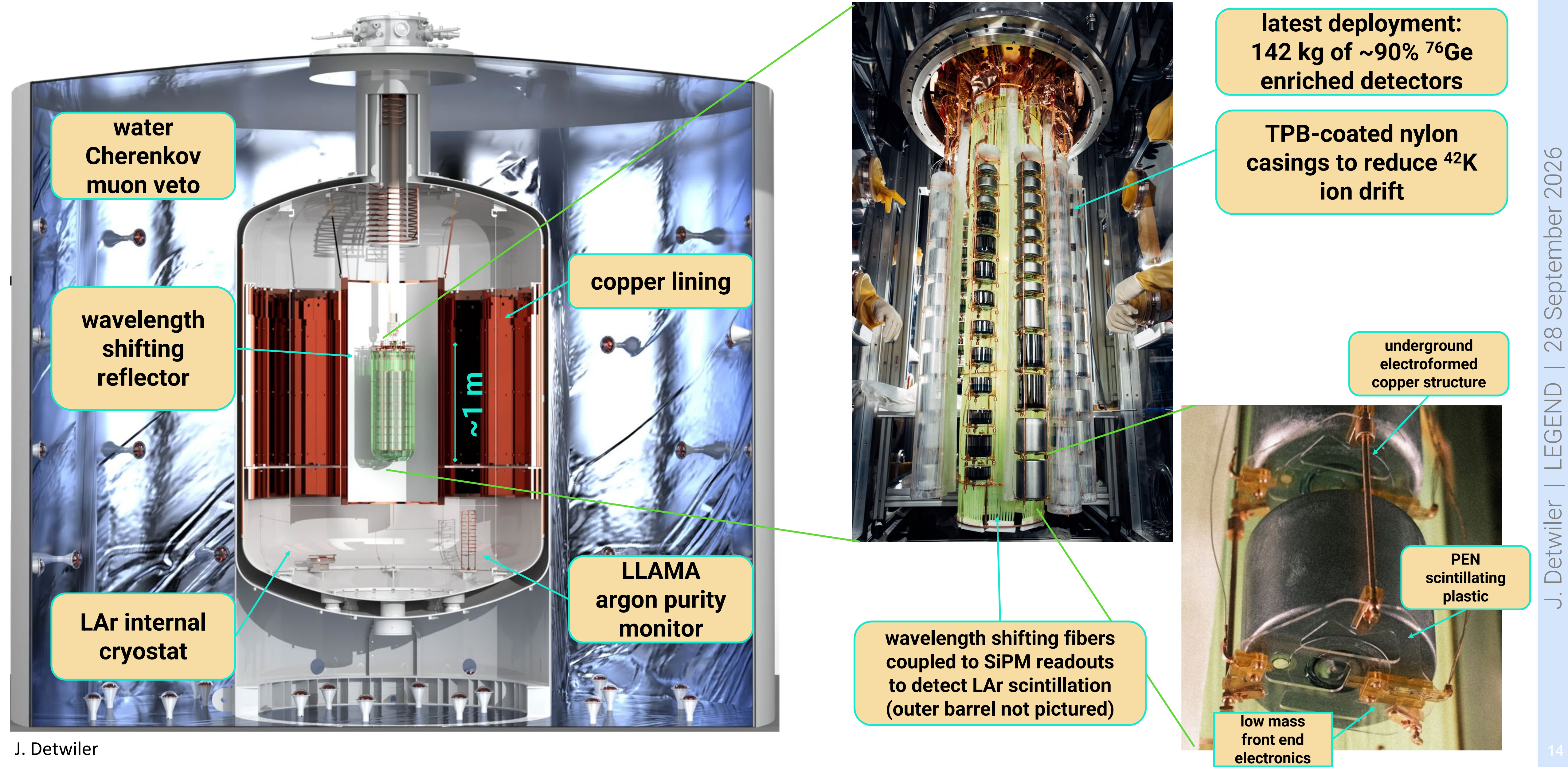
LEGEND-1000

Outline

- Introduction
- **Recent results from LEGEND-200**
- LEGEND-1000 status and future prospects

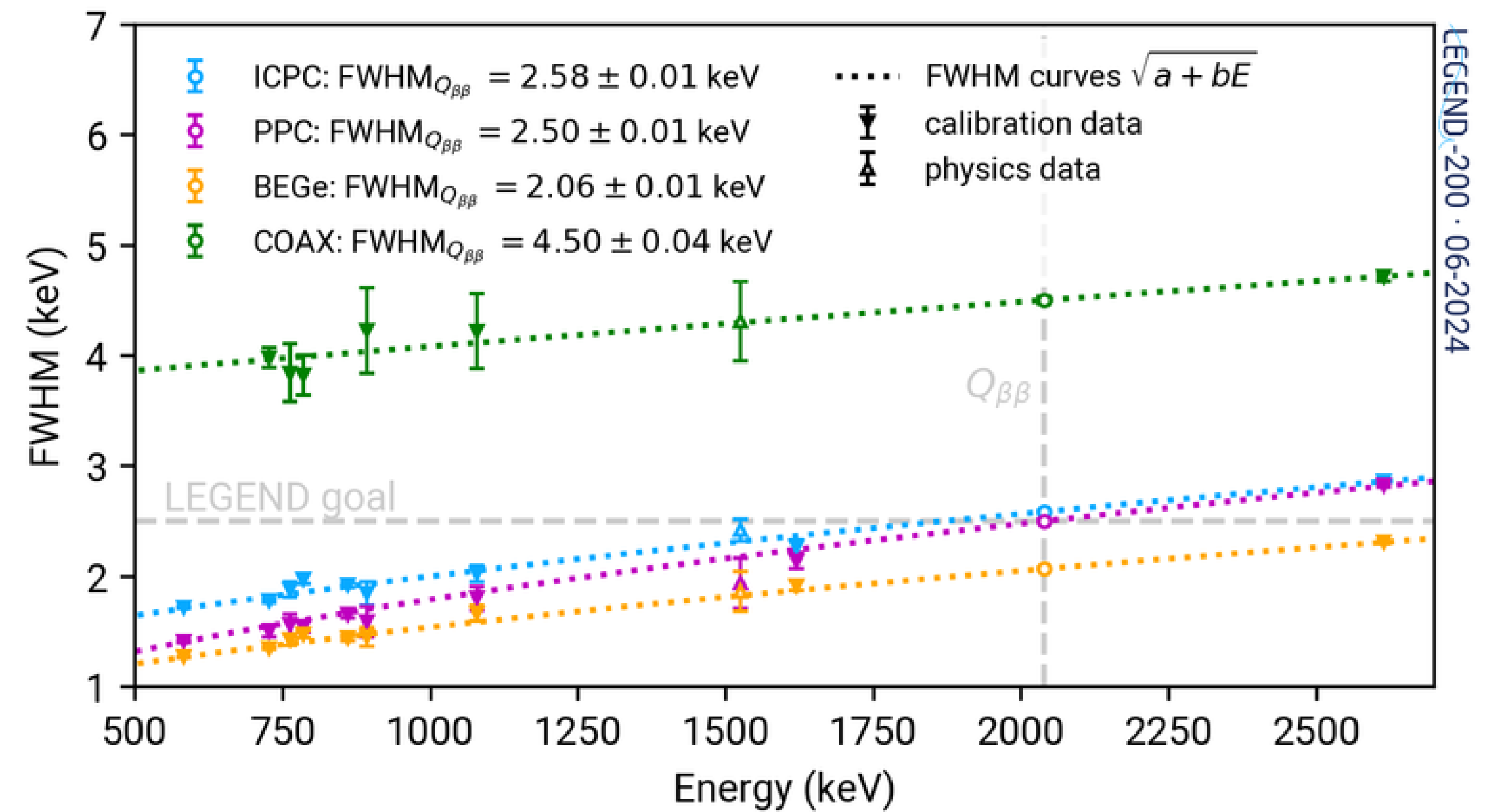
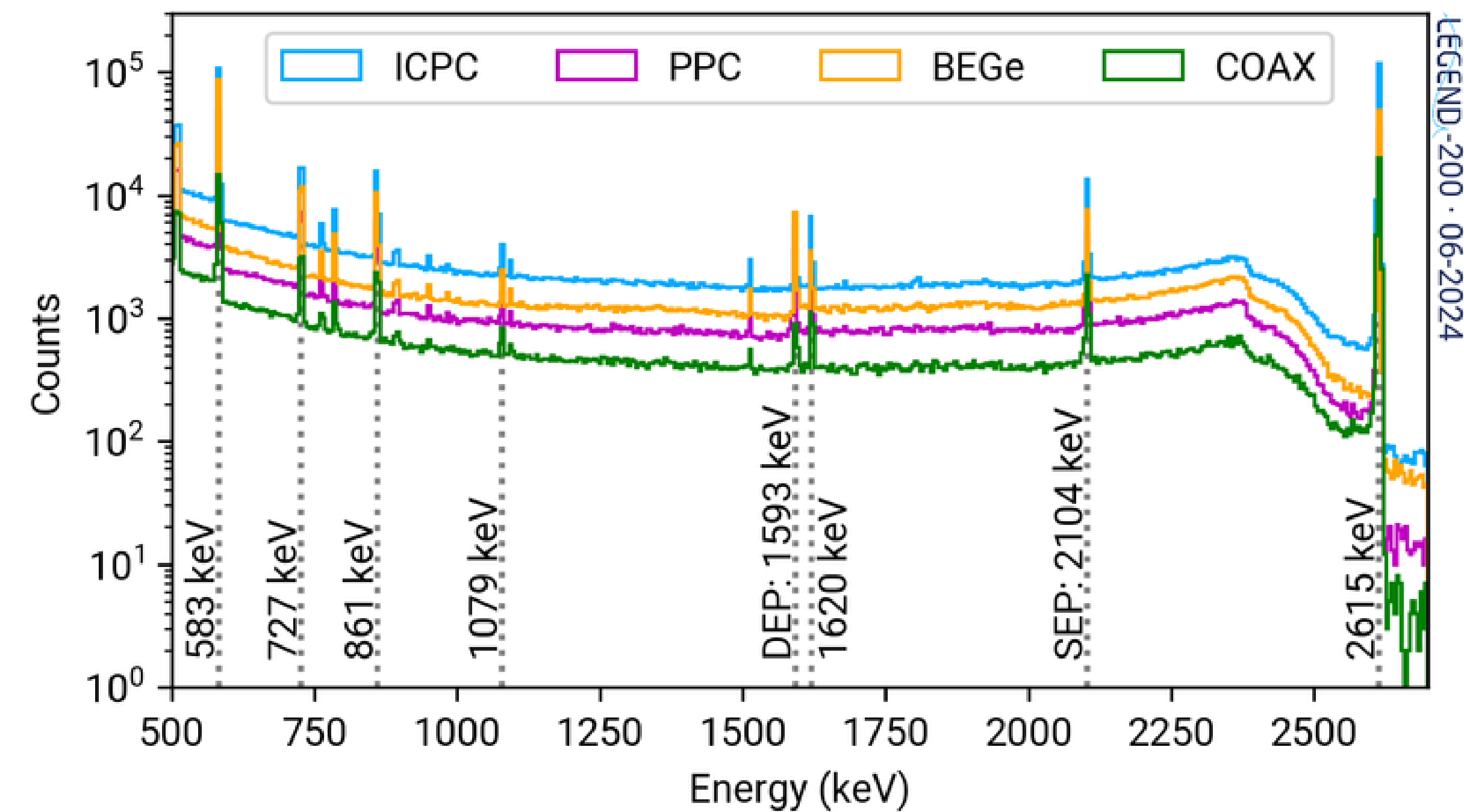
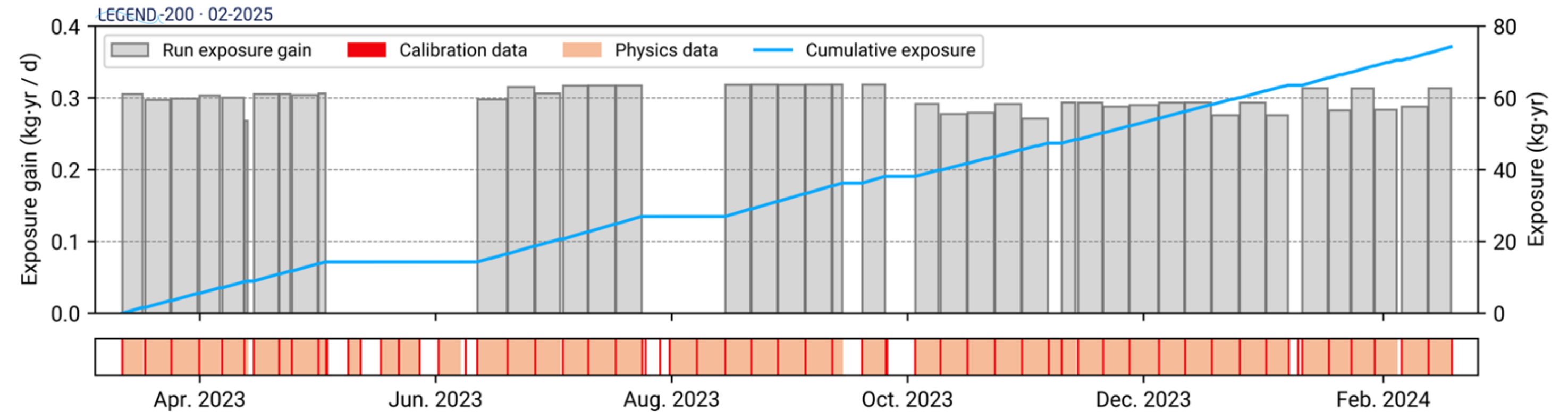


LEGEND-200 Overview



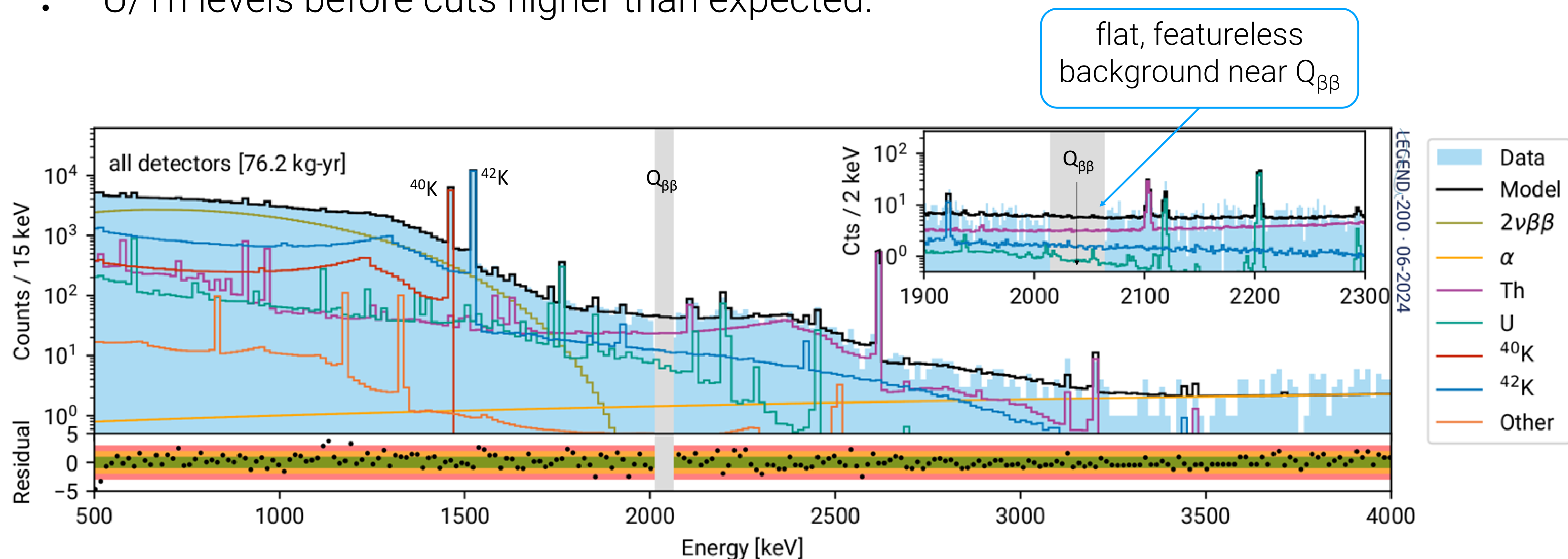
First dataset: March 2023 – February 2024

- Energy resolution of $\sim 0.1\%$ FWHM at $Q_{\beta\beta}$.
- Weekly calibrations with ^{228}Th source.



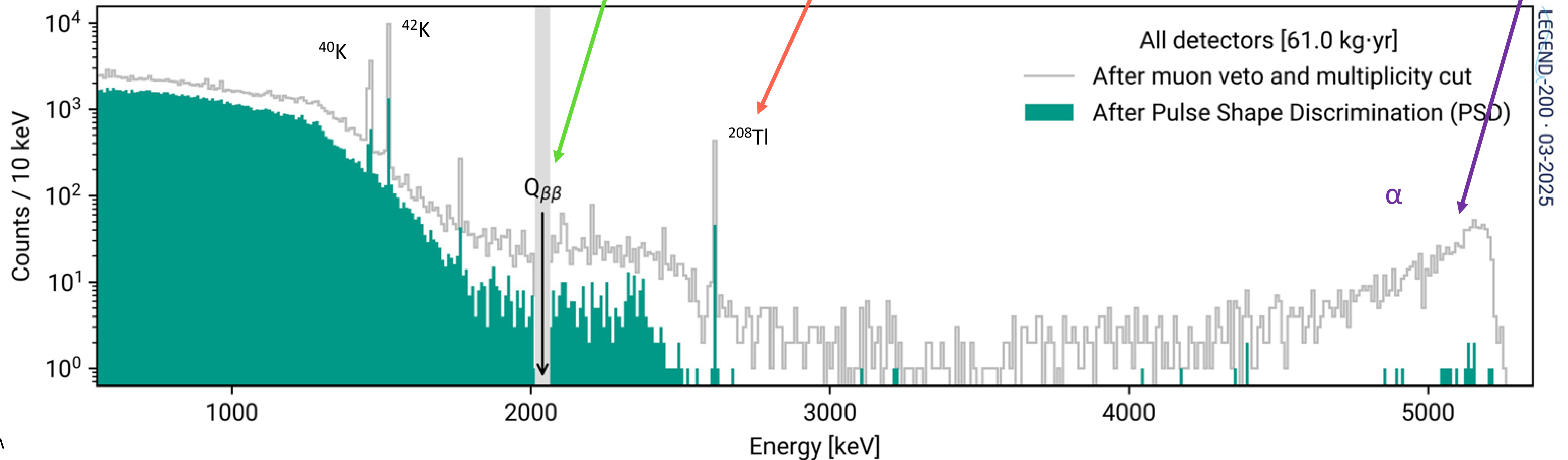
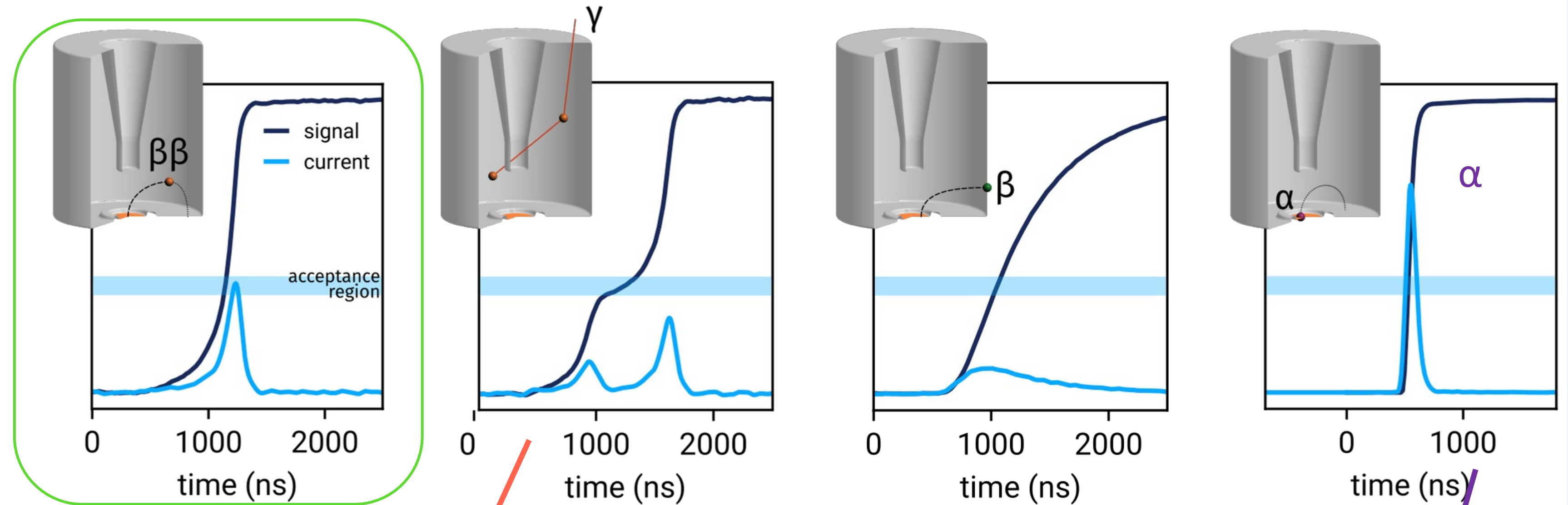
Data before analysis cuts

- Spectral shape matched well by fit to data.
- Backgrounds near $Q_{\beta\beta}$ highly suppressed by analysis cuts.
- U/Th levels before cuts higher than expected.



Pulse shape discrimination

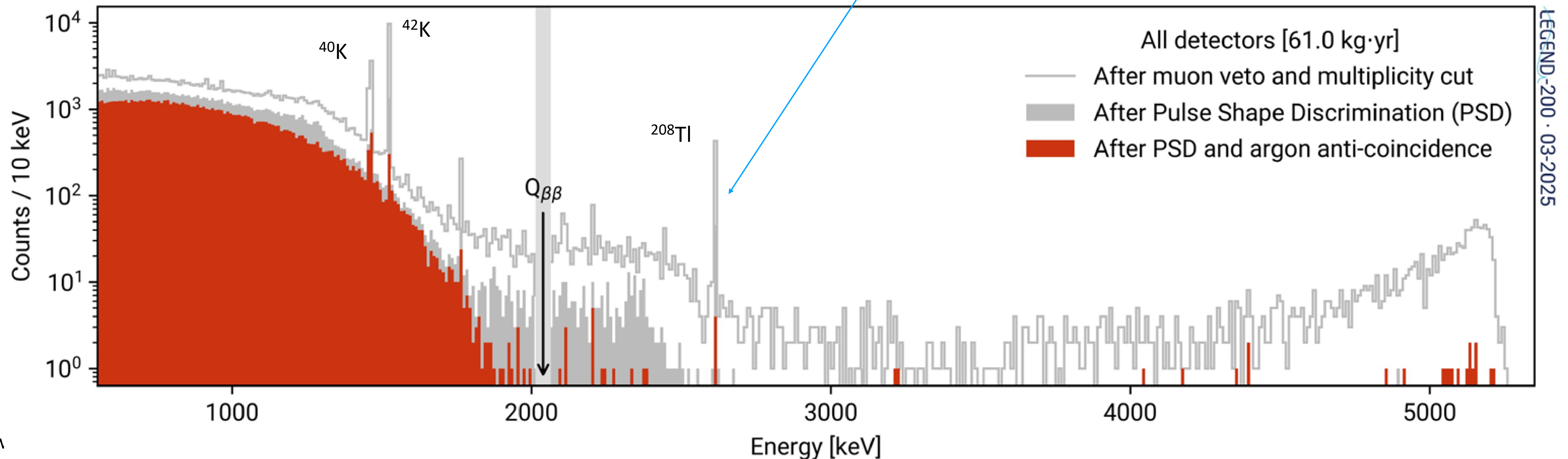
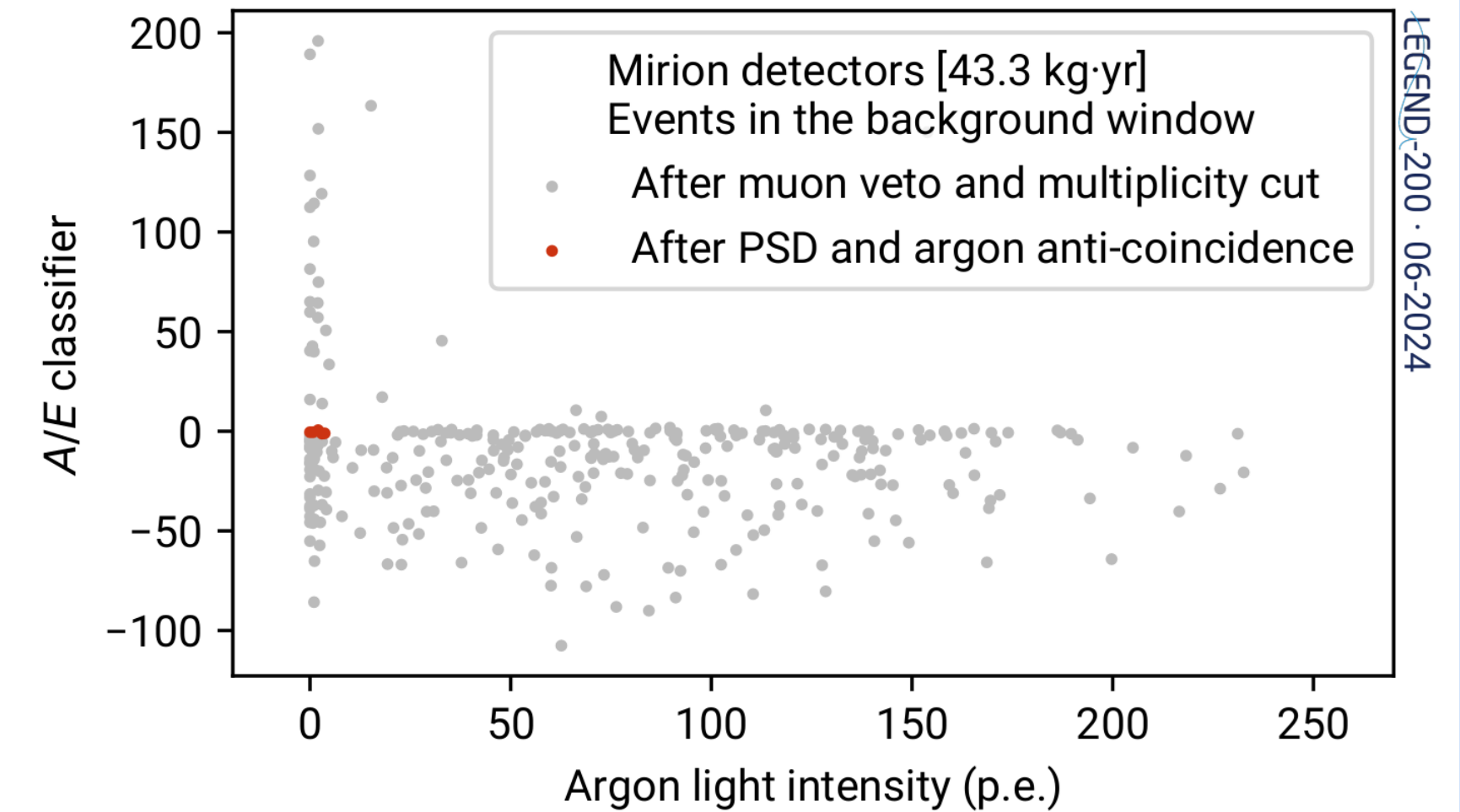
- Strongly suppresses α , β backgrounds
- $\sim 60\%$ suppression of Compton multi-site events at $Q_{\beta\beta}$



Liquid argon anti-coincidence

- LAr veto and PSD cuts are largely anti-correlated.
- Combination of cuts suppresses nearly all backgrounds.

effective at removing
 ^{208}Tl backgrounds
from γ coincidence



Limits on Majorana mass $m_{\beta\beta}$

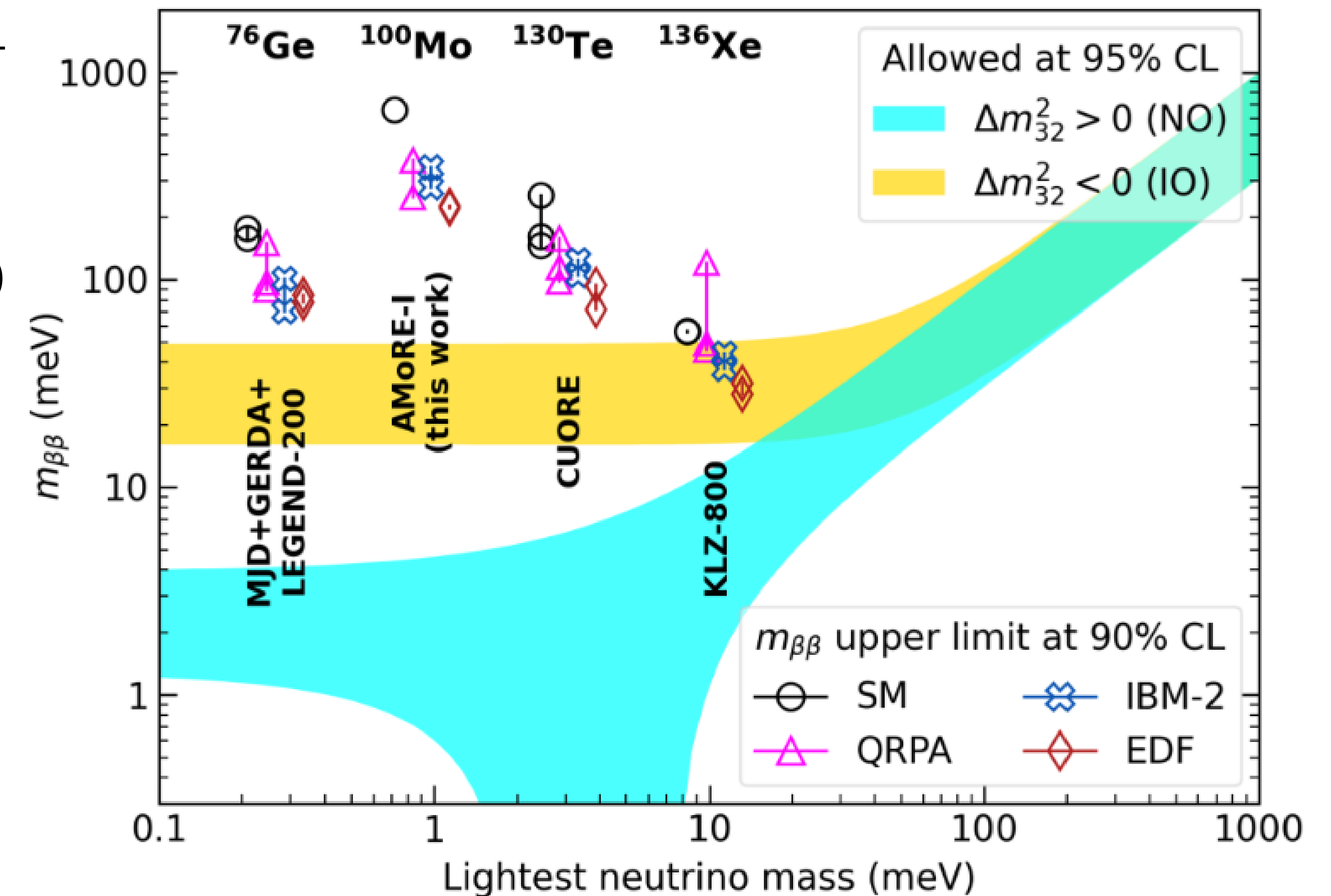
[A. Agrawal et al., Eur. Phys. J. C **85**, 9 \(2025\)](#)

- Using phenomenological NME: $M_{0\nu} = 2.35 - 6.34$
 $m_{\beta\beta} < 75 - 200$ meV (90% CI)

(Plot shows result prior to new unblinding but only minor difference.)

- LEGEND leading in $T_{1/2}$ sensitivity
- KLZ-800 leading charge into ν mass IO
- LEGEND-200's next result has good discovery probability!

→ other experiments to follow in next few years!



Uncertainty quantified NMEs

- Recent *ab initio* methods include quenching and short-range physics, as well uncertainty quantification for ^{76}Ge NME: $M_{0\nu} = 2.6^{+1.28}_{-1.36}$

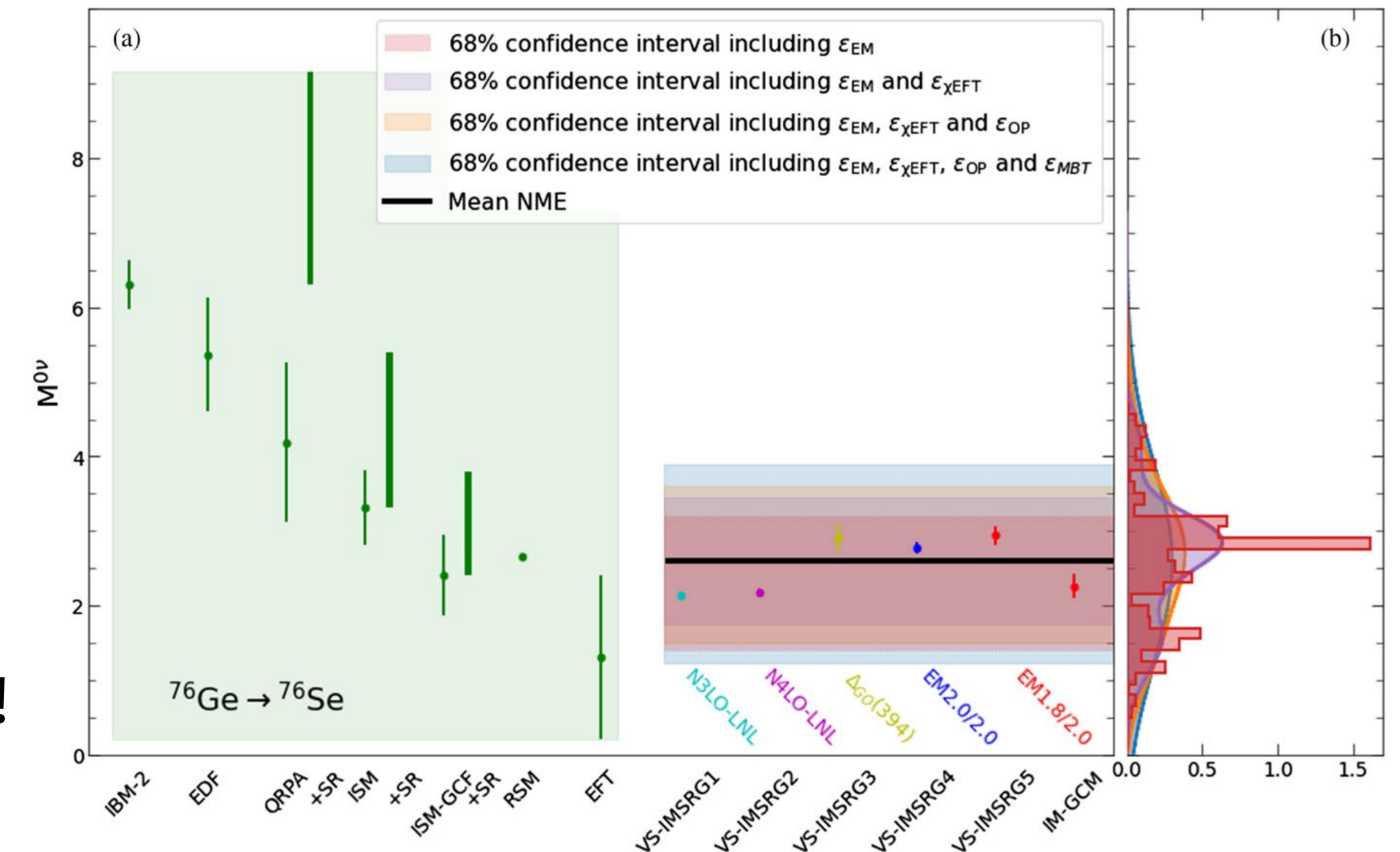
[A. Belley et al., PRL **132**, 182502 \(2024\)](#)

- Incorporate into ^{76}Ge limit with a Bayesian approach:

$$m_{\beta\beta} < 320 \text{ meV (90\% CI)}$$

- Nominal result with $\pm 1\sigma$ theory uncertainty for comparison: $m_{\beta\beta} < 180^{+190}_{-60} \text{ meV}$

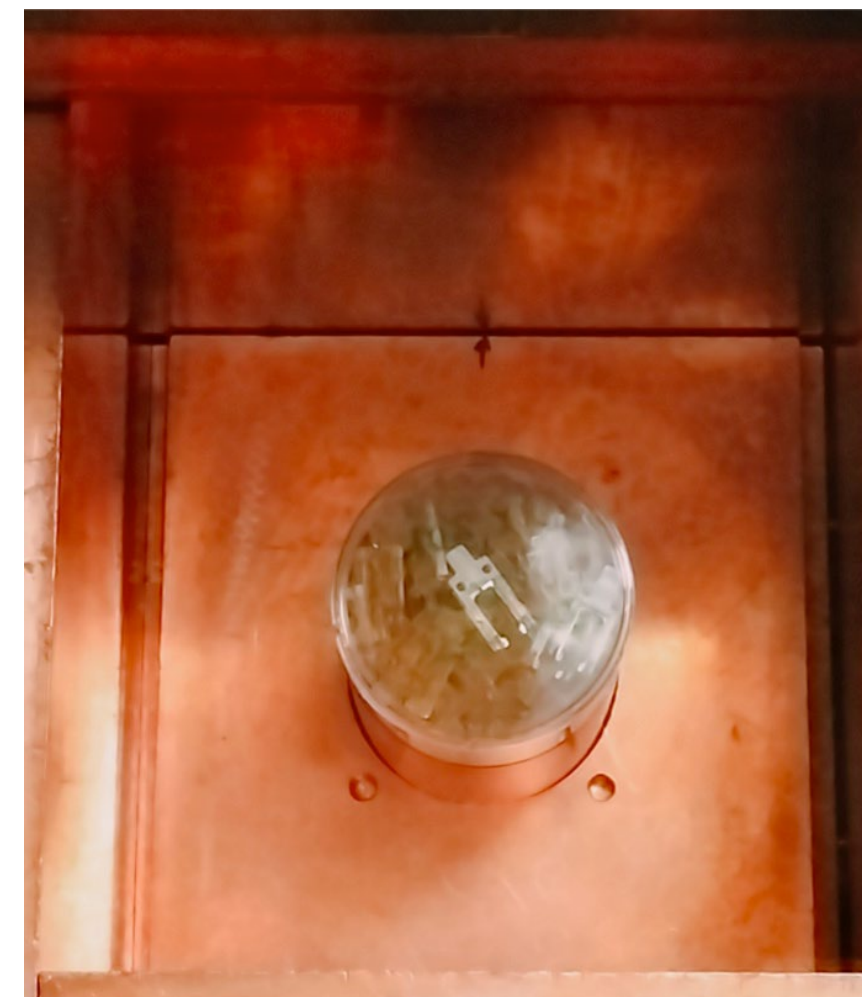
- We are entering the era of uncertainty-quantified NMEs!**
But: *the uncertainties are still large!*



- Ab initio* NME calculations with uncertainties exist for other nuclei, central values at low end of phenomenological ranges. [A. Belley, T. Miyagi, S. R. Stroberg, and J. D. Holt, arXiv:2307.15156](#)
- Combined limits on $m_{\beta\beta}$ require an understanding of correlations between theory predictions in different isotopes and improved uncertainty handling, similar to ^{76}Ge . [F. Capozzi et al., arXiv:2503.07752](#)

Background Investigations and Redeployment

- Final background index (BI) a factor of ~ 2.5 higher than desired
- Elevated U/Th in pre-cuts spectrum, embarked on forensic campaign:
 - Special runs: outer fiber shroud and nylon minishrouds removed
 - Array dismantled, all components sent for assay
 - Elevated U/Th in some components: hypothesized surface contamination, BI dominated by U
 - Follow-up assay underway



Ultem γ assay



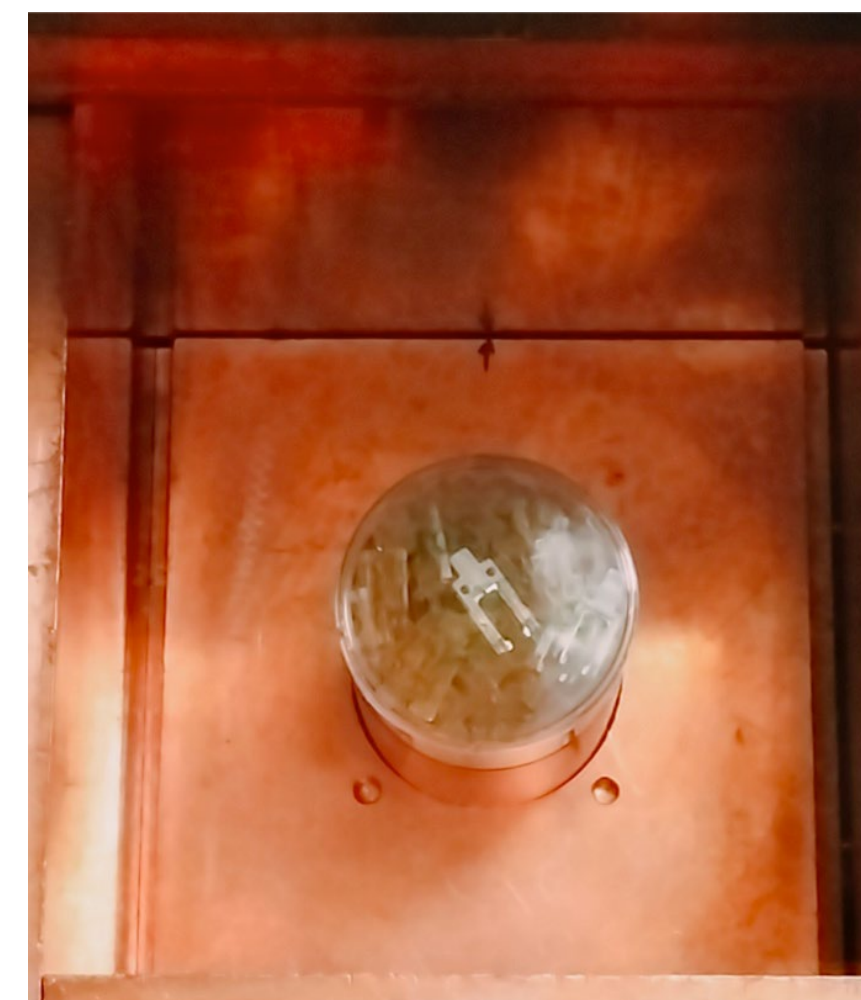
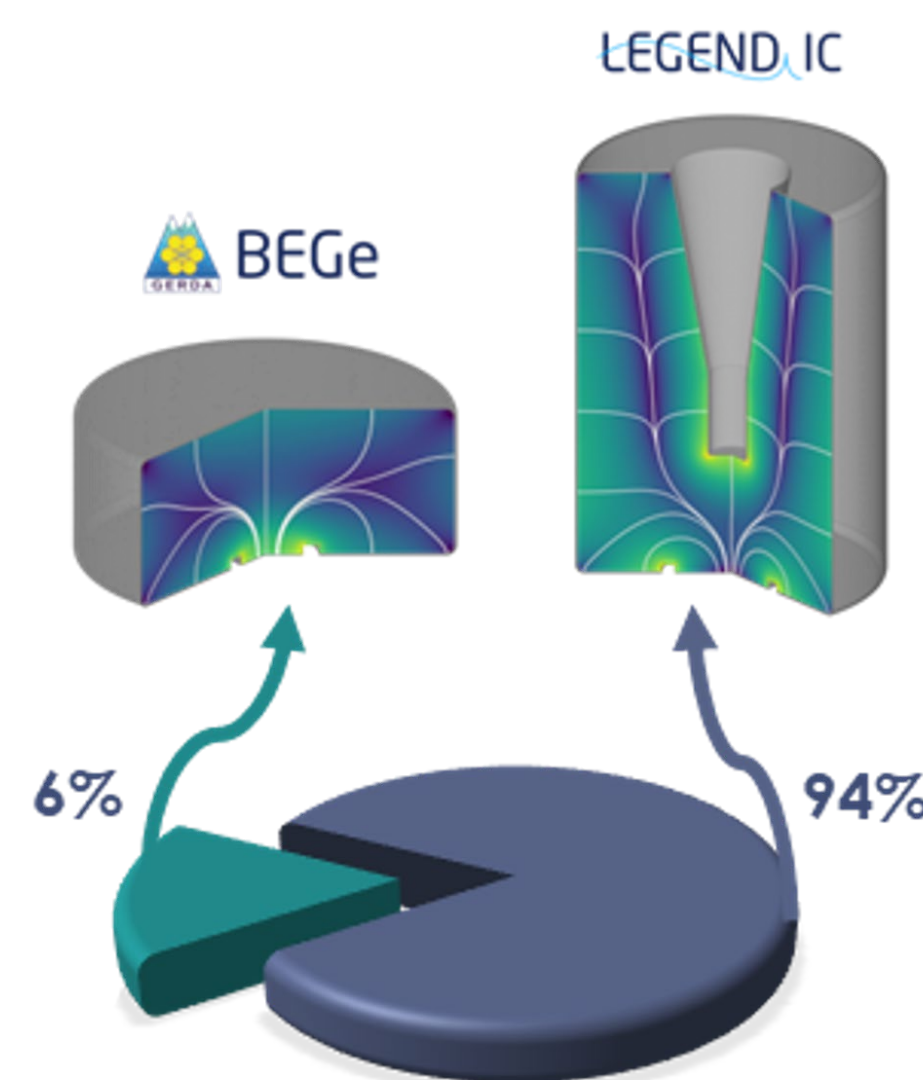
Cu pins Rn emanation assay

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• 2025 redeployment

- New components produced
- All components thoroughly cleaned with QC verification
- Coax, PPCs, poorly performing detectors sent for conversion to L1000-style ICs
- Add new detectors: 140 kg deployed



Ultem γ assay



Cu pins Rn emanation assay



Cu rods etching



Array reassembly

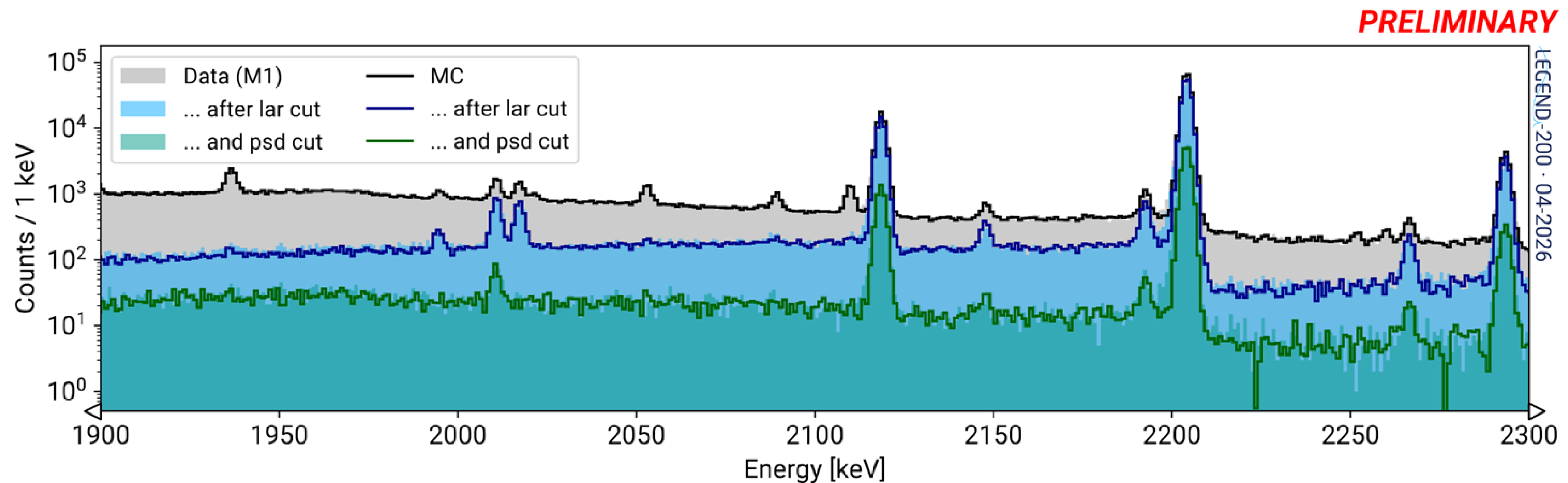
Special Characterization Data

Goal: develop and validate MC models, especially optics

Special runs:

- LAr instrumentation only
- Weak ^{228}Th source data
- ^{226}Ra source data

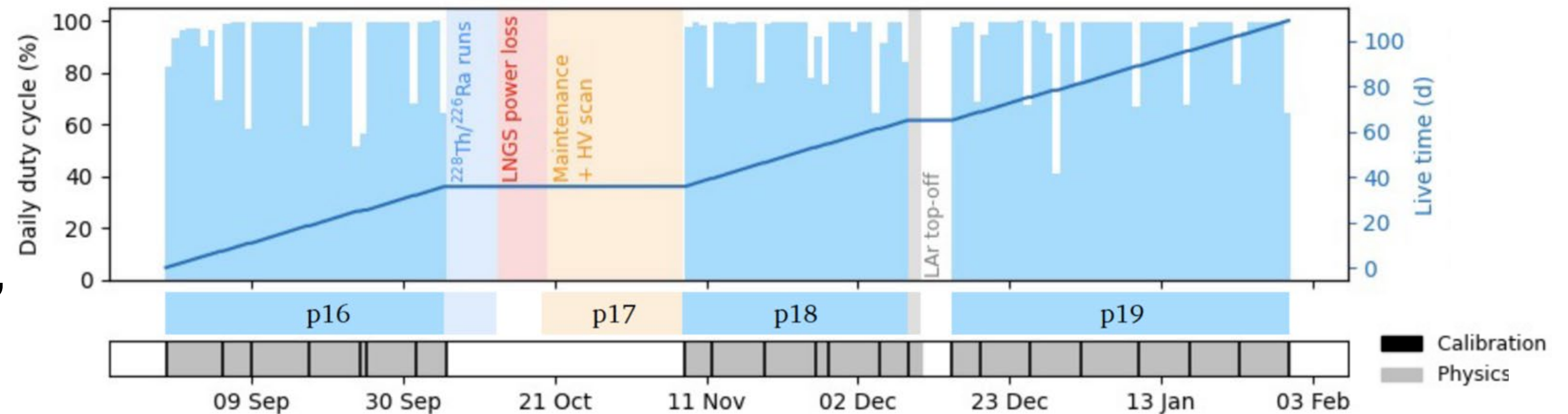
Excellent agreement achieved with minimal tuning, further modeling underway



Redeployment Operations and Performance

Data taking from
Fall 2025

- Downtimes for LNGS power loss + recovery, LAr top-off, special calibrations
- Duty cycle: 95% (70%) without/with downtimes
- Data shown here: 32.5 kg yr



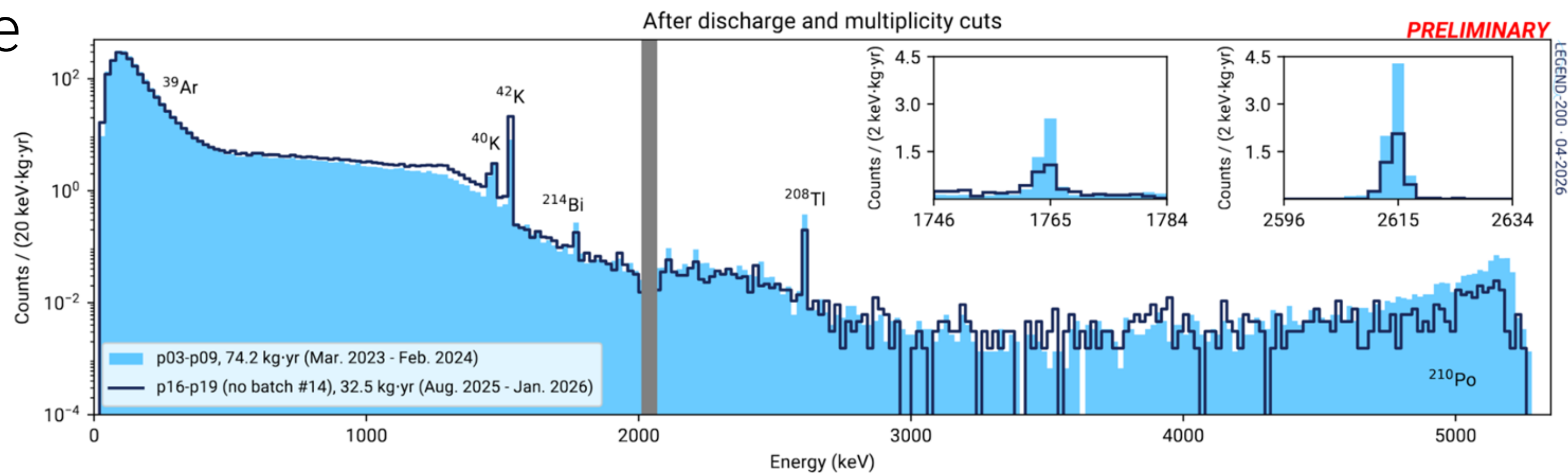
Detector performance is stable, but elevated leakage currents / degraded energy resolution

- electronics tuning / investigations underway

Redeployment Background Performance and Plans

U/Th lines suppressed by $\sim x2$ before cuts relative to PRL dataset

New “batch 14” detectors have elevated ^{68}Ge



Redeployment Background Performance and Plans

U/Th lines suppressed by $\sim x2$ before cuts relative to PRL dataset

New “batch 14” detectors have elevated ^{68}Ge

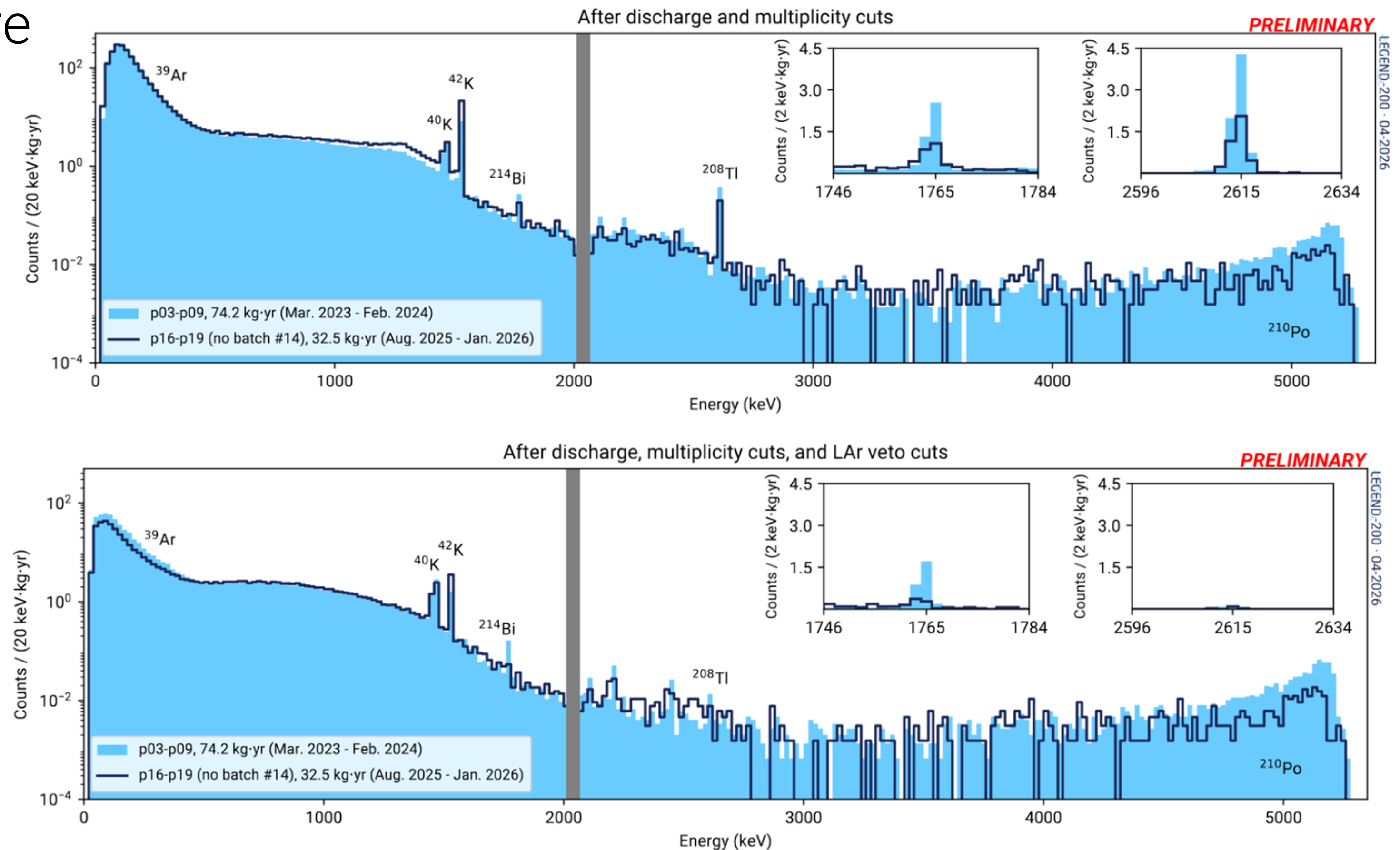
After LAr cuts:

- U suppressed by $\sim x3-5$!
- Th $\sim$ eliminated at current stats

→ Redeployment cleaning efforts were highly successful!

Final background index measurement in preparation

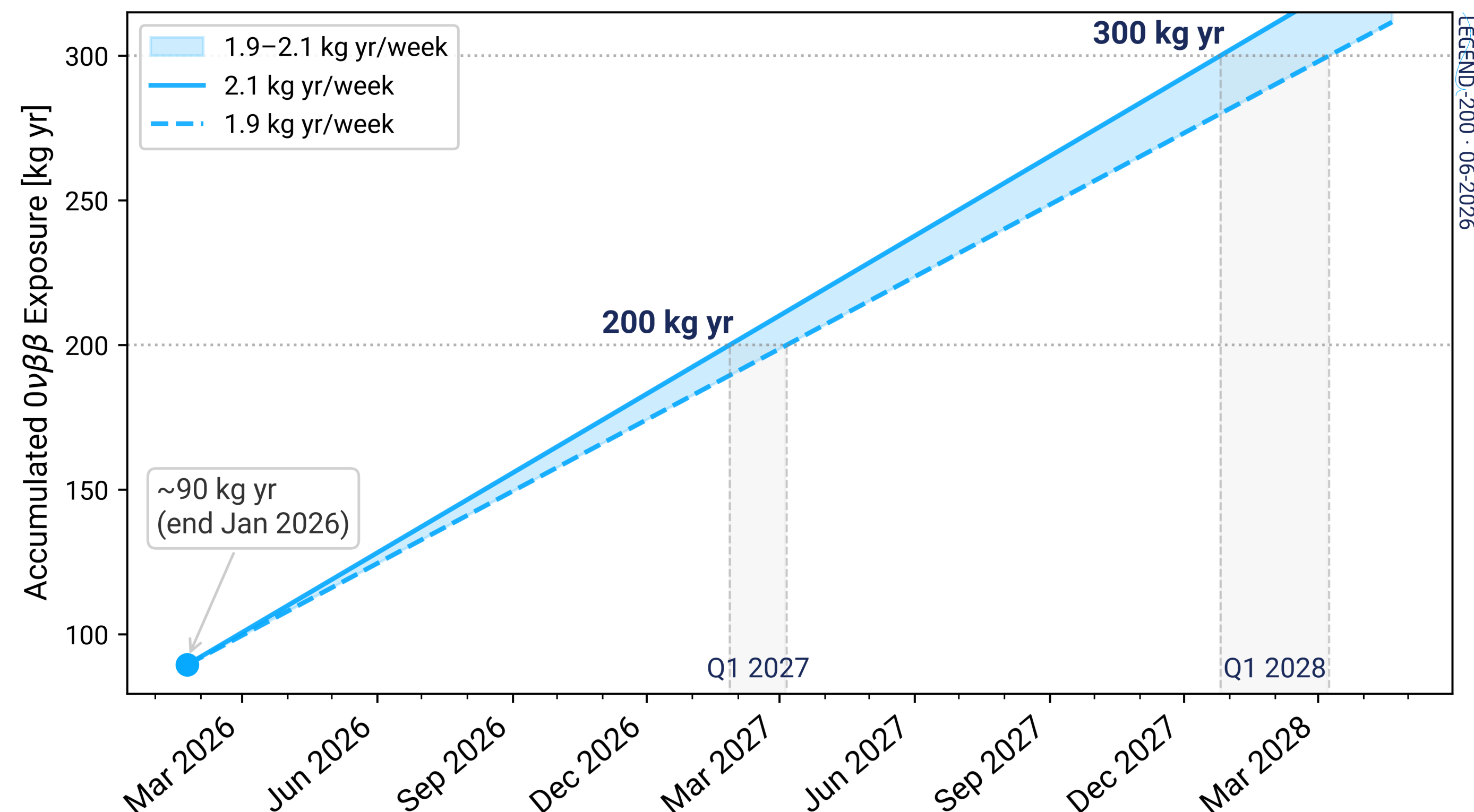
- Tuning PSD
- Collecting more stats



LEGEND-200 Plans

Near term: continue running with minimal interruption

- 100 kg-yr new exposure collected so far
→ $2\nu\beta\beta$ physics, exotic searches
- ~Triple the exposure for $0\nu\beta\beta$ by early 2028
→ good discovery probability!



LEGEND-200 Plans

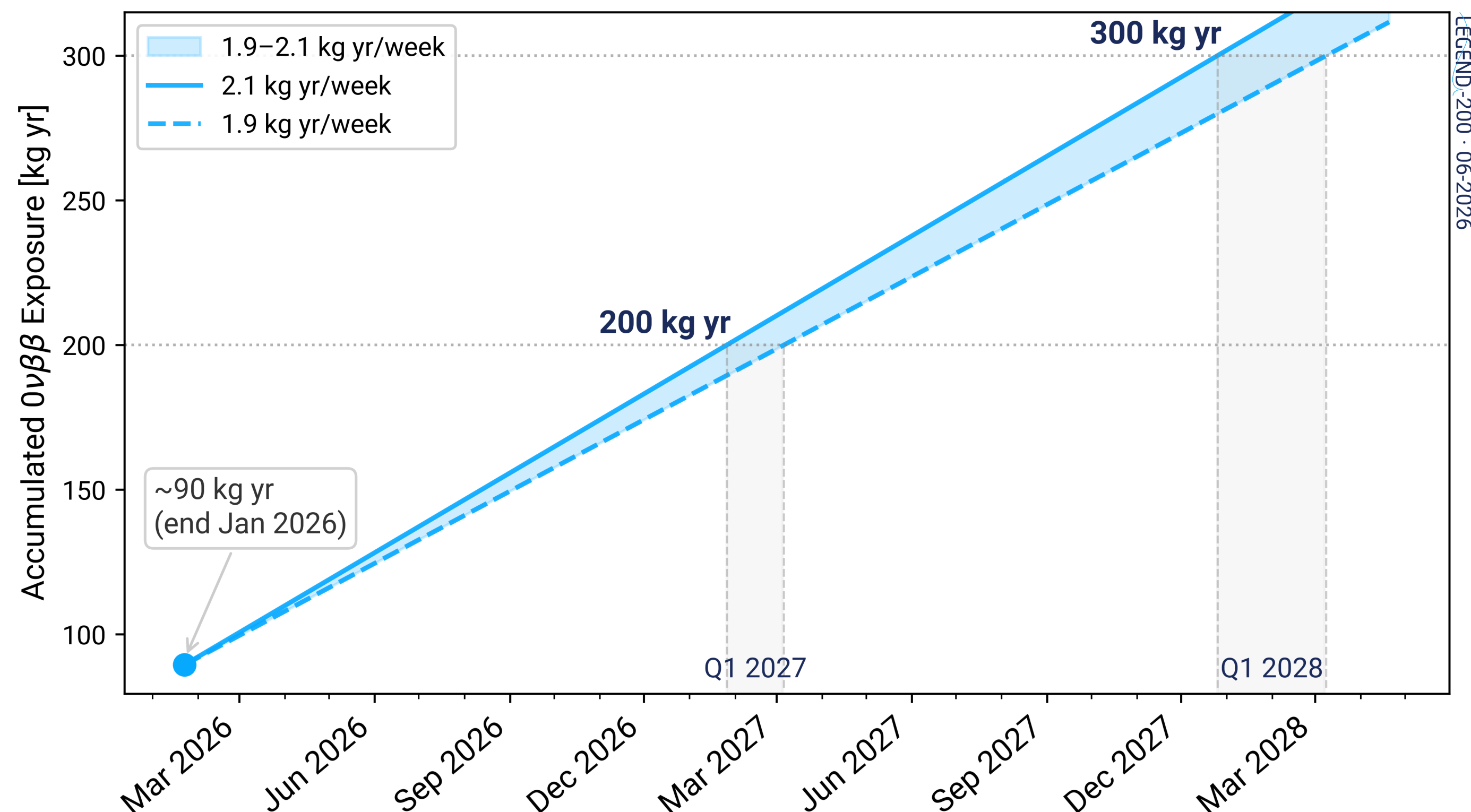
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Next detector deployment in 2028

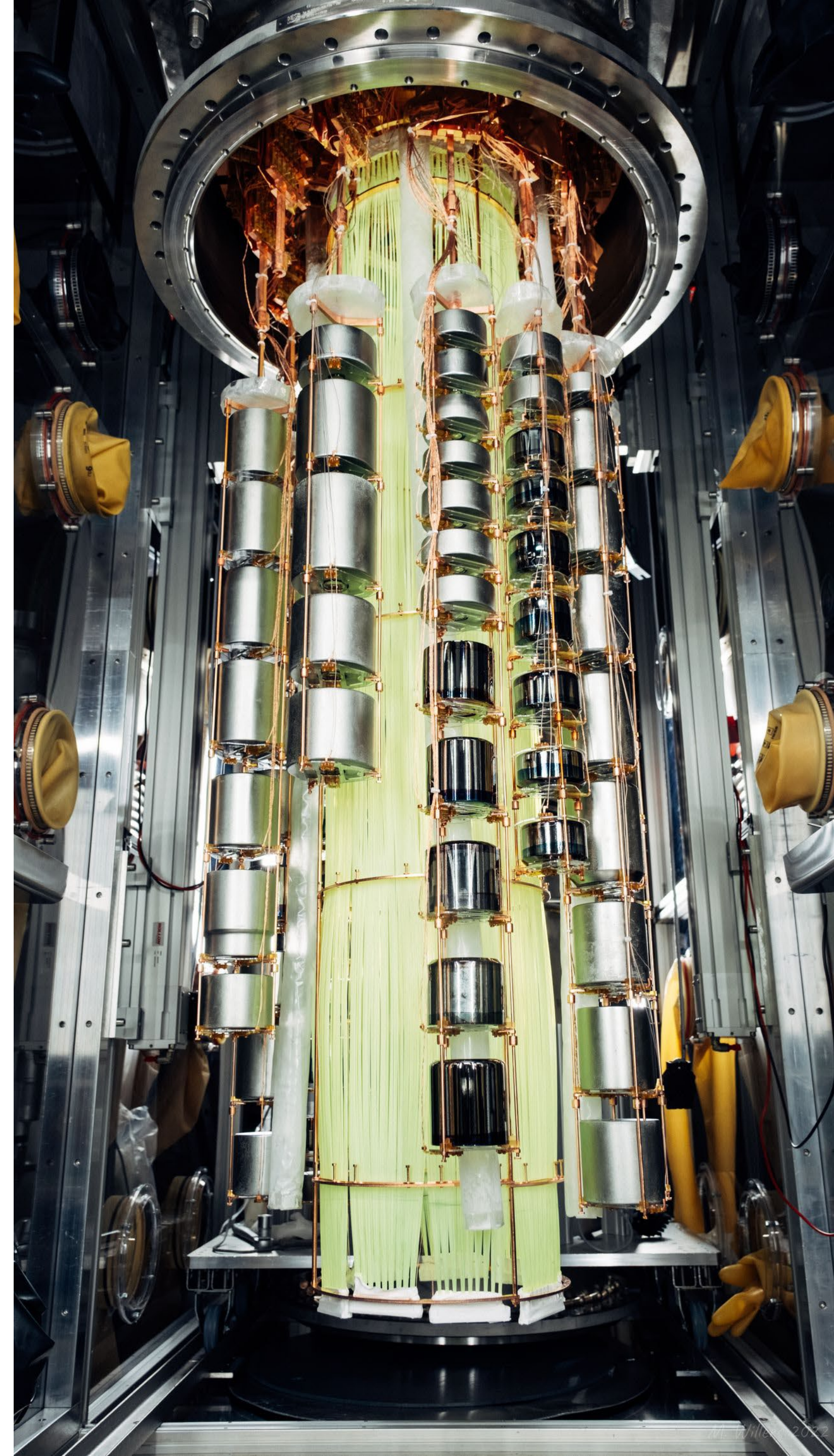
- Detector production underway
+ ~20 kg new detectors → ~160 kg total
- R&D for improvements: noise mitigation, PEN films to replace nylon minishrouds, updated baseplates

Then continue running until LEGEND-1000



Outline

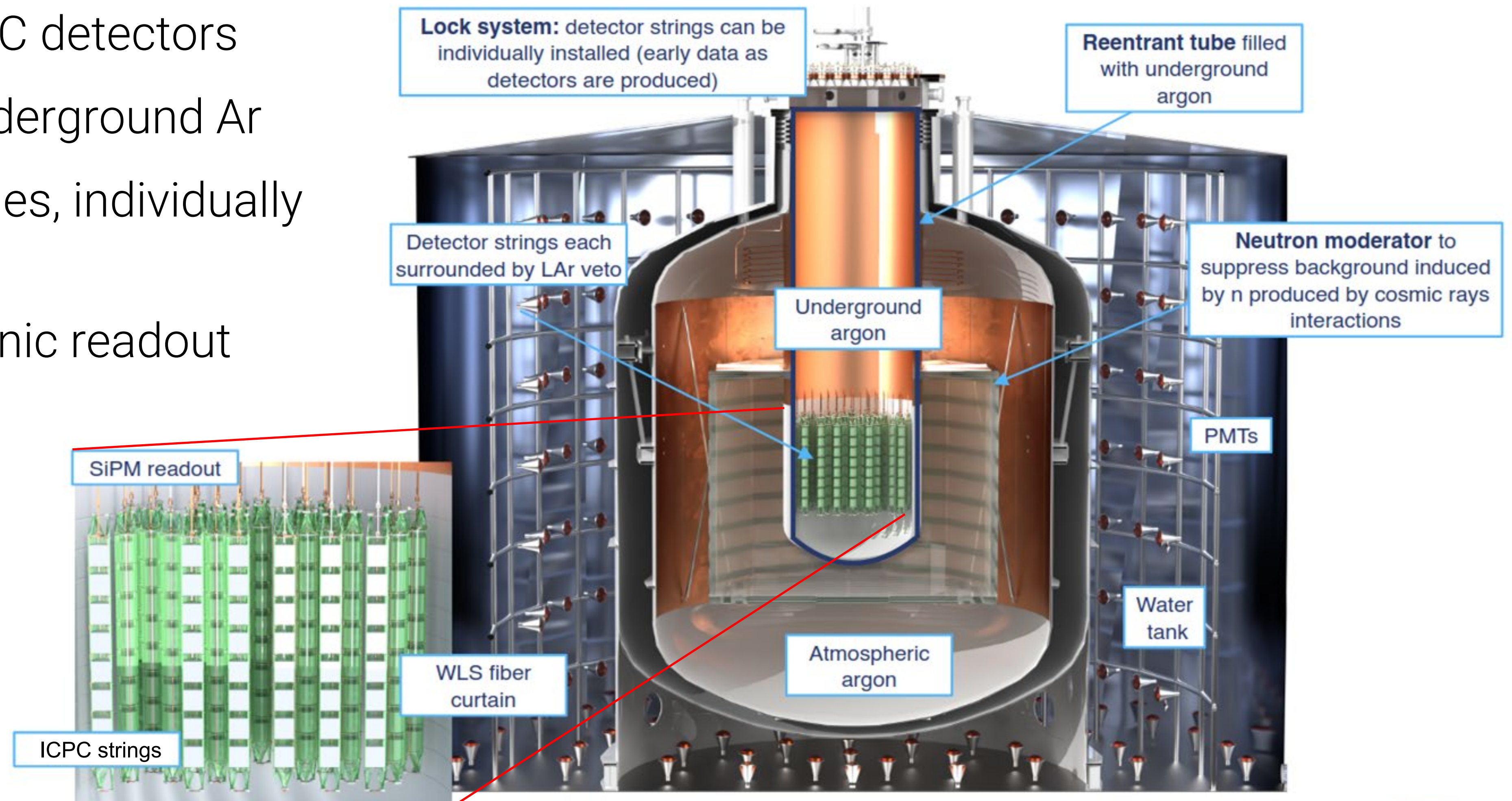
- Introduction
- Recent results from LEGEND-200
- **LEGEND-1000 status and future prospects**



LEGEND-1000 Overview

Ton-scale instrument with key improvements over LEGEND-200:

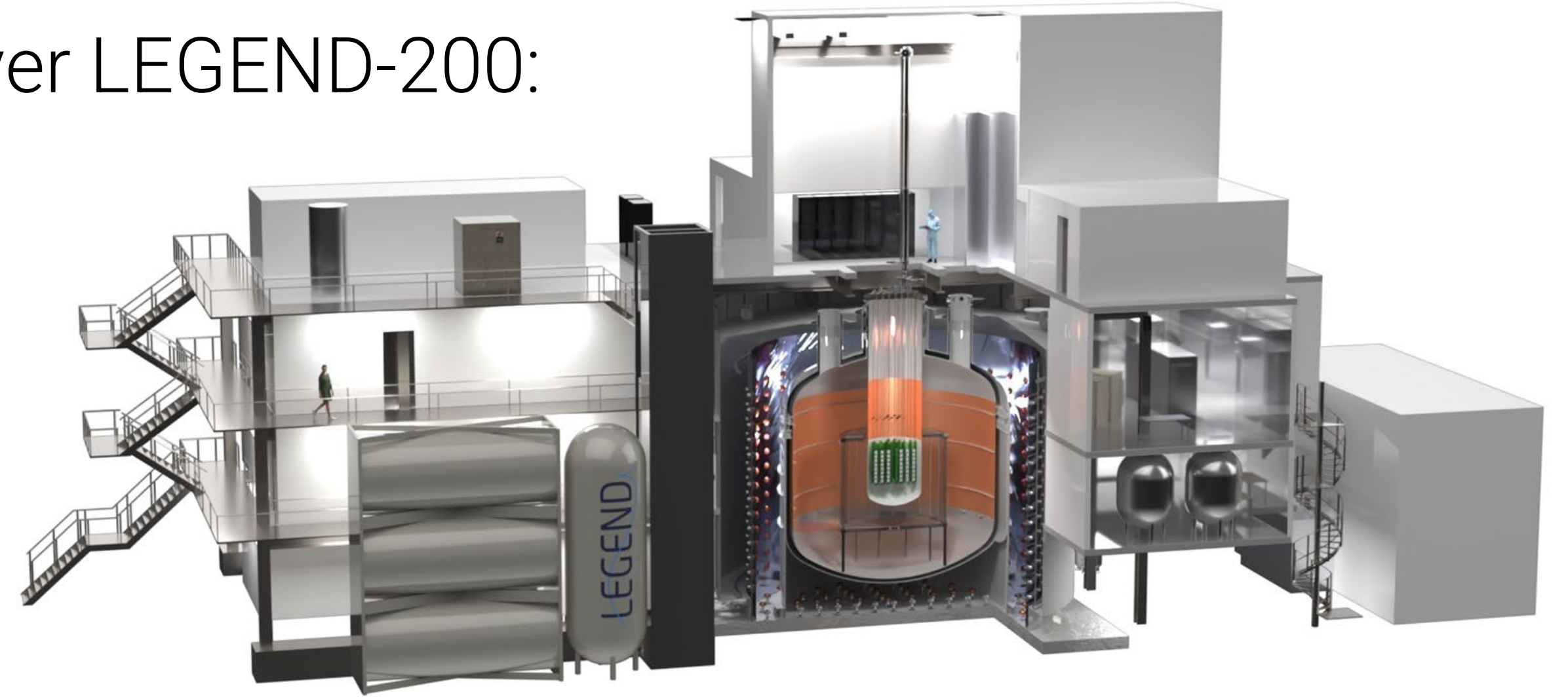
- 100% larger mass IC detectors
- Inner volume of underground Ar
- Single-string modules, individually deployable
- ASIC-based electronic readout



LEGEND-1000 Overview

Ton-scale instrument with key improvements over LEGEND-200:

- 100% larger mass IC detectors
- Inner volume of underground Ar
- Single-string modules, individually deployable
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Proposal / Funding / Support Status:

- **DOE** status: successful CD-1 review in Nov 2025, awaiting CD-1 approval, funding
- **NSF** MREFC proposal: design funds in-hand, Final Design Review in early 2027
- **BMFTR** prioritized LEGEND for FIS funding, Site Visit April 2026 -- recommended for funding
- LEGEND designated as a flagship **INFN** project
- Substantial contributions already from **DOE, NSF, INFN, MPG, DFG, SNSF, MNiSW**

LEGEND-1000 Expected Backgrounds



Highest Contributor: ^{42}K in the Ar

- Generated from ^{42}Ar
- LEGEND-200 rate a factor 10-20 too high
- Underground Ar reduces by >1400, can remove L200-style “minishrouds”

Natural Radioactivity

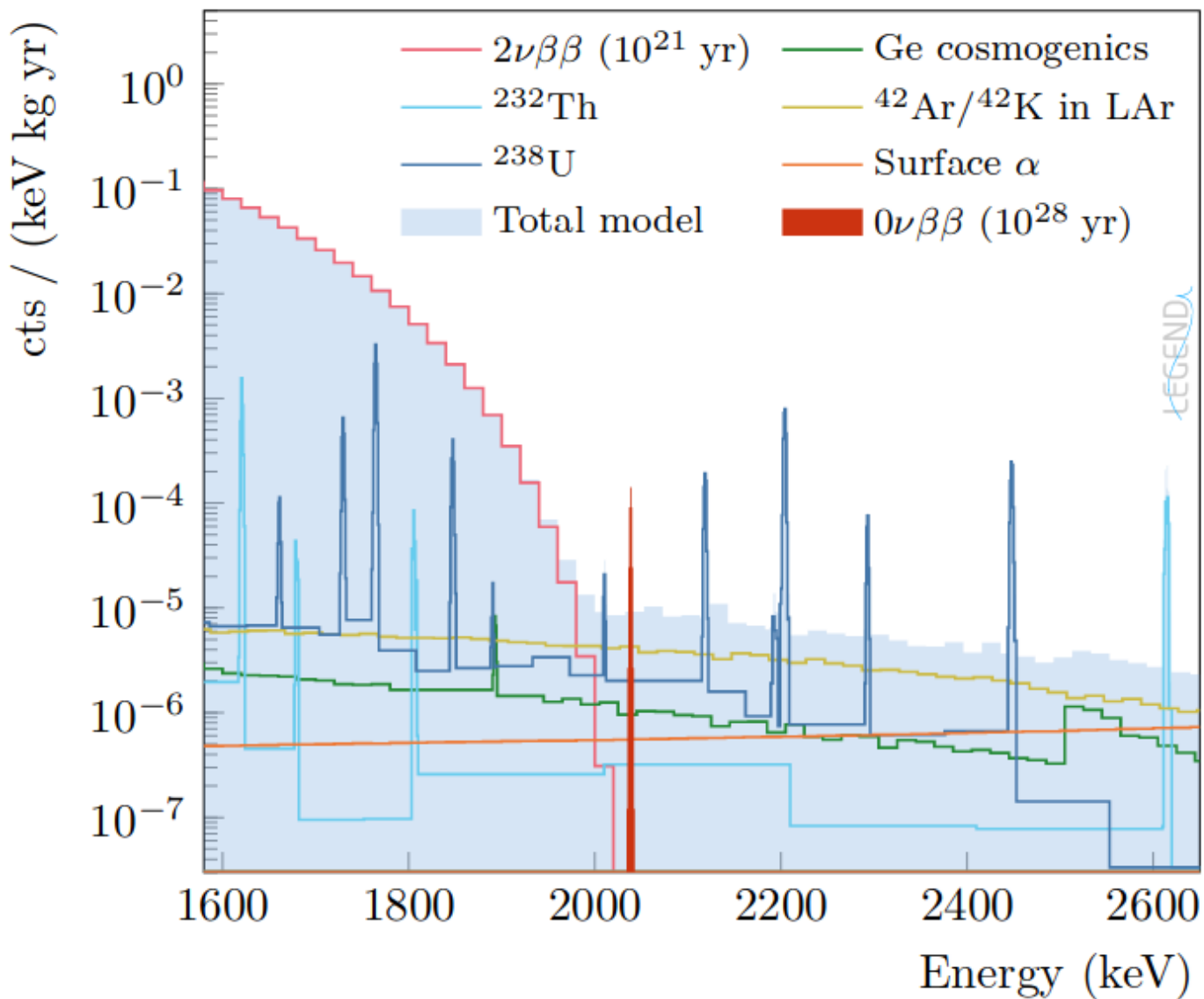
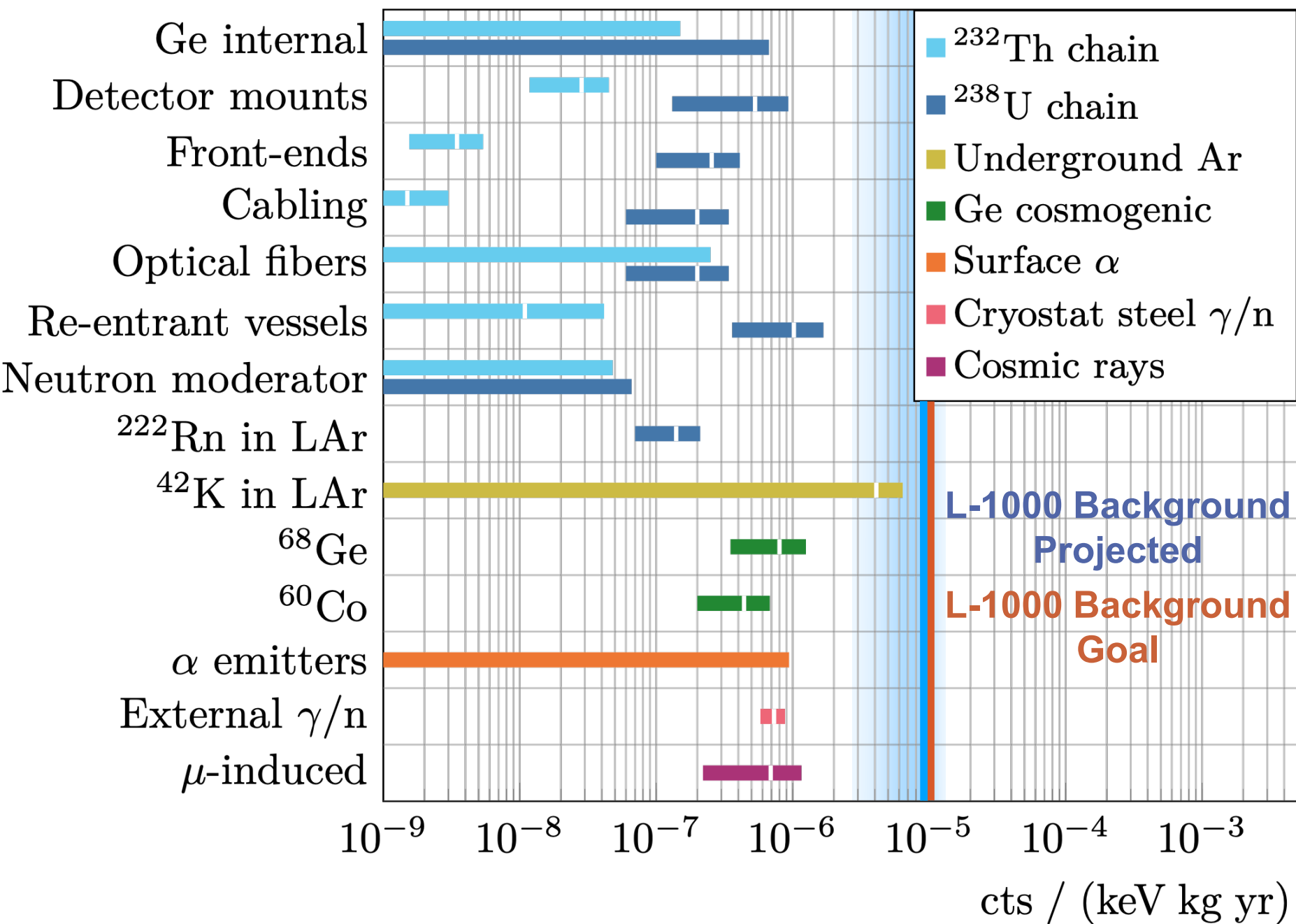
- Biggest contributor is lower U chain in nearby components and reentrant vessel
- Largely under control thanks to GERDA, MAJORANA, and LEGEND-200 developments

Cosmogenics

- Top contributor: ^{77}Ge from fast n, mitigated by n moderator in outer LAr so that they are captured in Ar instead of Ge

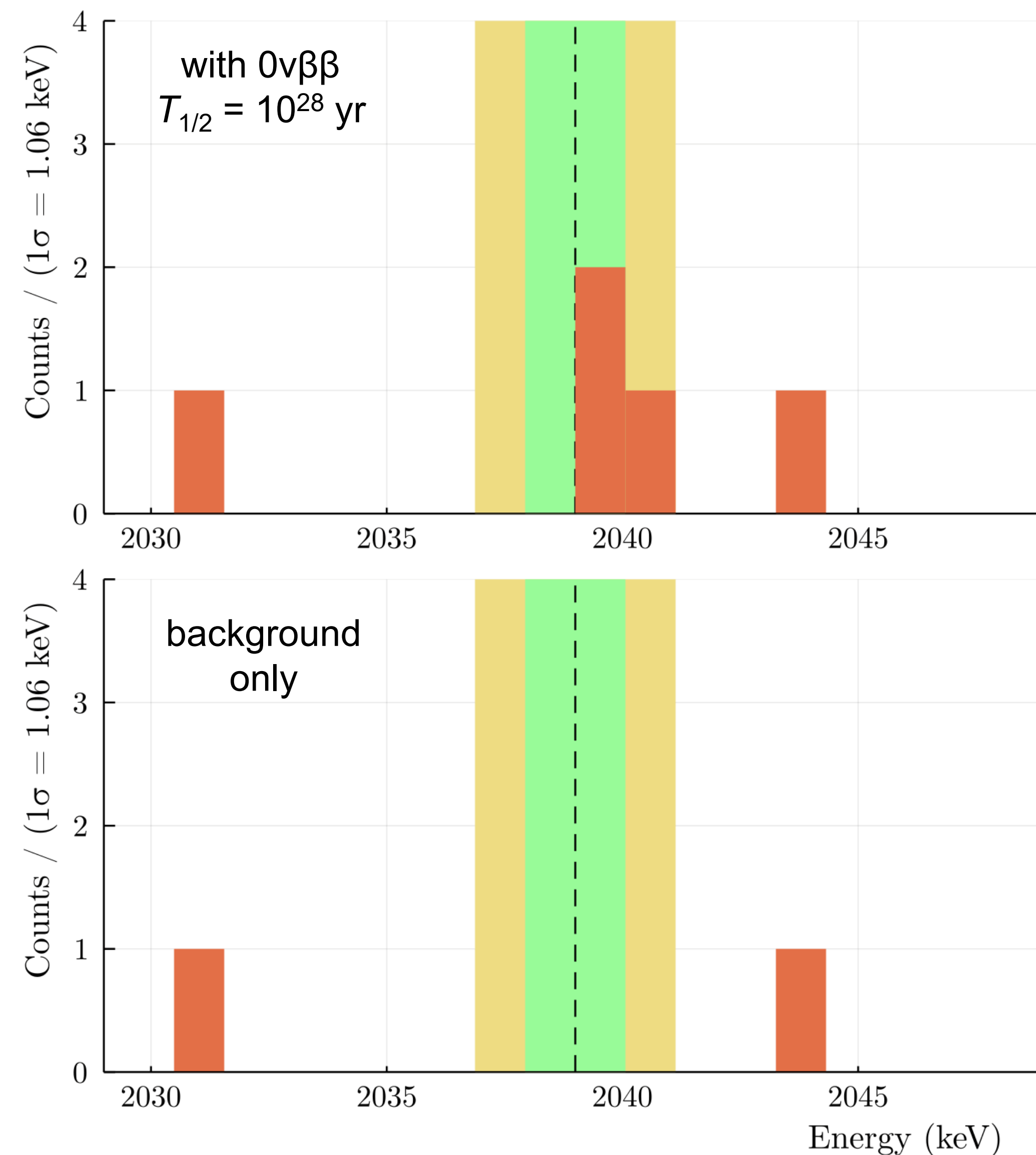
Other contributors

- Ge cosmogenic activation products mitigated by limiting surface exposure
- Solar neutrinos and long-lived cosmogenics are subdominant
- Alphas are an upper limit



LEGEND-1000 Sensitivity

- Expect a clear peak over a nearly background-free continuum near $Q_{\beta\beta}$
- LEGEND-1000 10-year 3σ discovery sensitivity:
 - $T_{1/2} > 10^{28}$ yr
 - $m_{\beta\beta} \sim 9 - 21$ meV (phenom. NME)



LEGEND-1000 Progress: Ge Detectors and Readout

Ge procurement

- Numerous discussions with vendors in anticipation of funding availability
- Recent price volatility for $^{\text{nat}}$ Ge: Investigating seed stock and depleted Ge recycling to alleviate bottlenecks associated with supply

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ASIC development

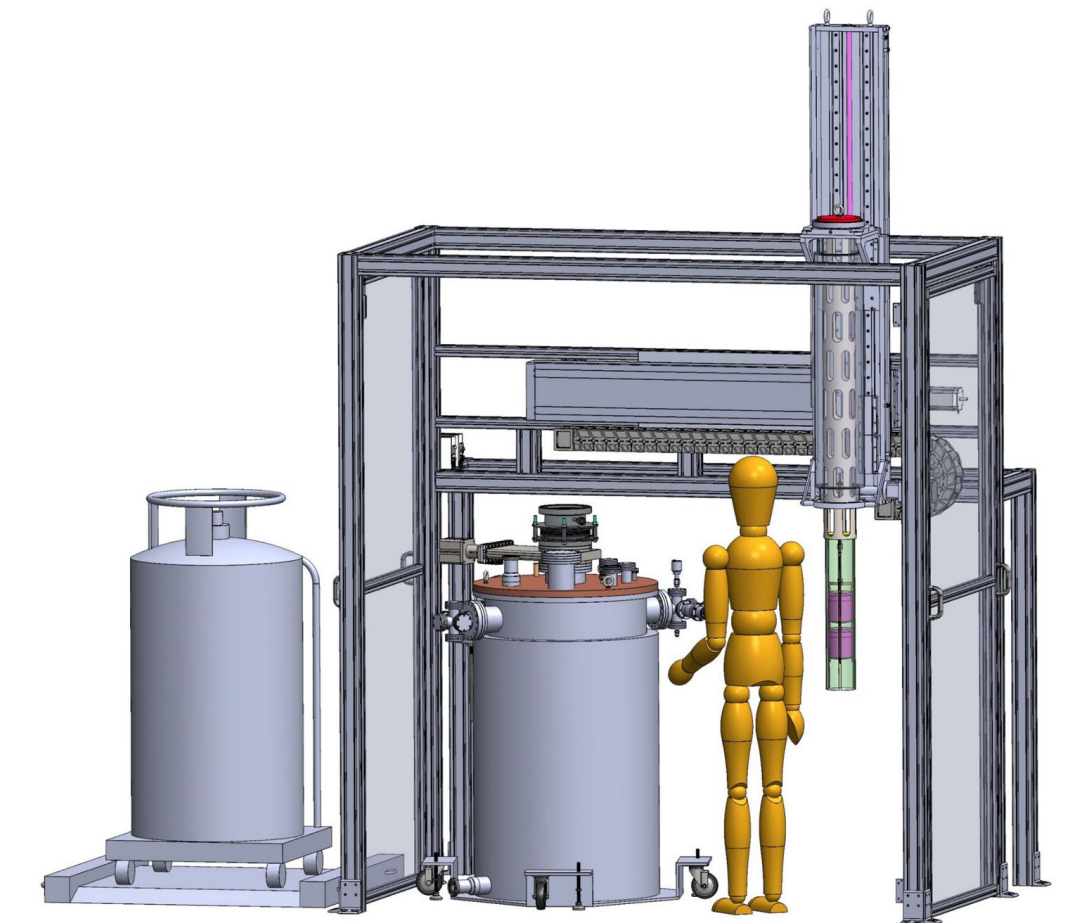
- Extensive prototyping, testing
- Integration with flex cables underway
- Alternative clean cable development

Readout integration test stand

- Preliminary design complete



LUIGI ASIC tests



Integrated test stand design



LEGEND-1000 Progress: Light Detection

Inner Ar instrumentation

- Prototyping, thermal / mechanical tests underway
- SiPM evaluation underway
- R&D on scintillating fibers

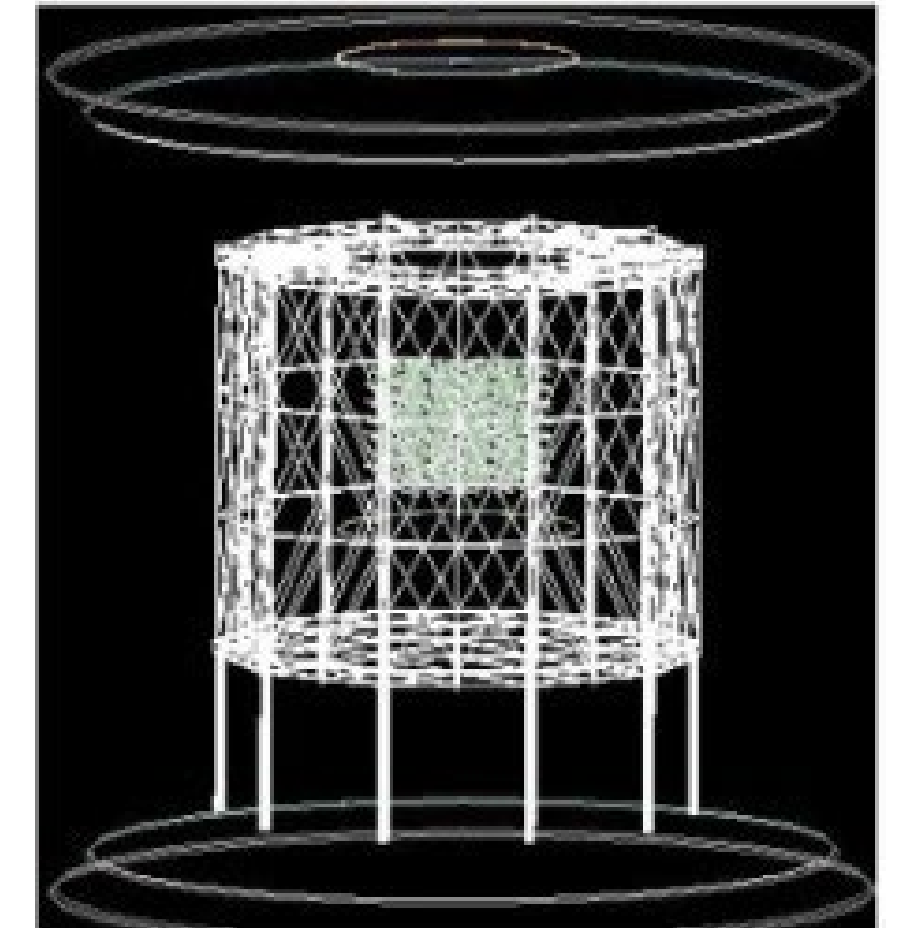
Outer Ar Instrumentation

- Simulation modeling and design optimization
- SiPM characterization and assay
- LEGENDArYno facility ready: testing of light-detection module prototypes in LAr started

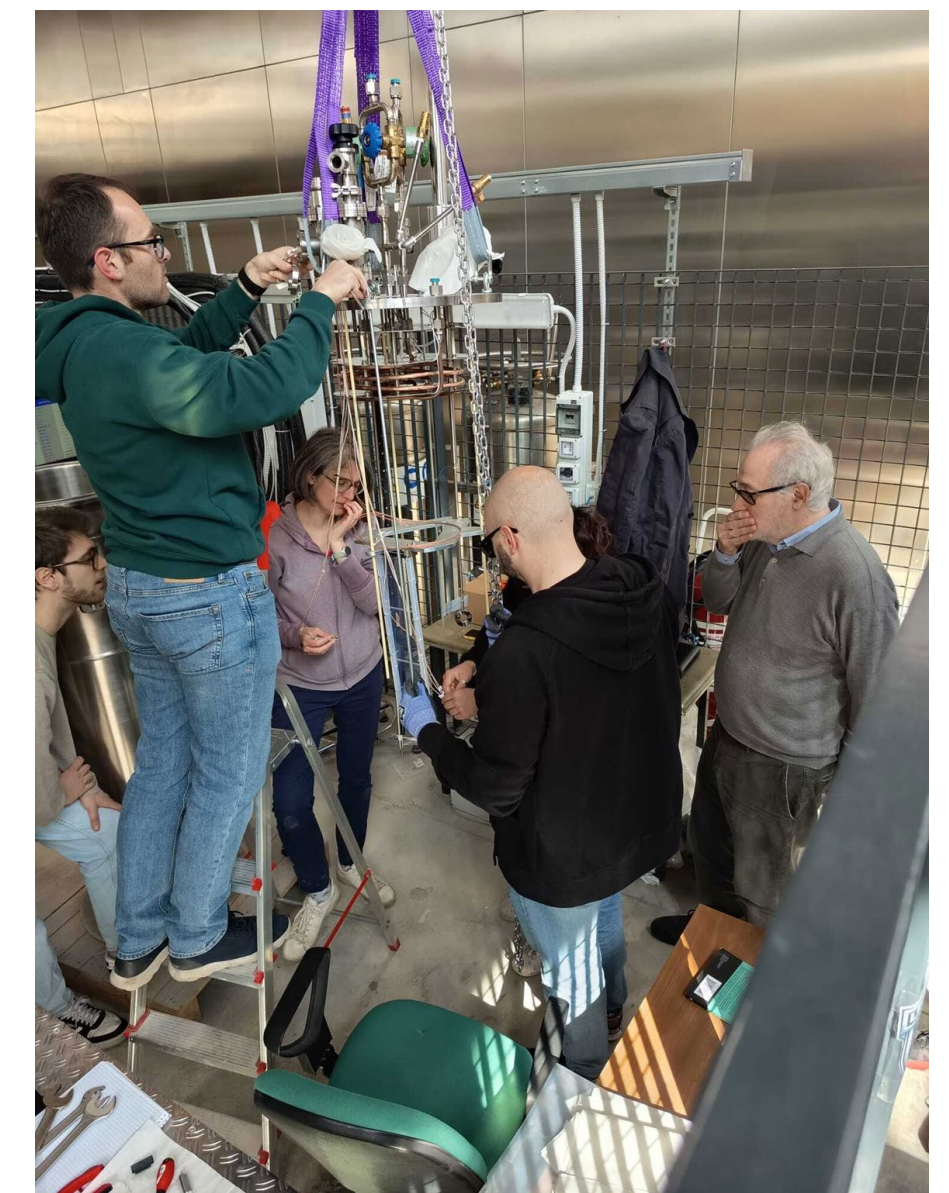
Water tank instrumentation optimization underway



Inner Ar readout prototype



n moderator
simulation model



test deployment in
LEGENDArYno at LNGS

Footprint and infrastructure interfaces maturing

- BOREXINO dismantling and site preparation has just started!
- Installation plan developed

Cryostat, water tank design advanced

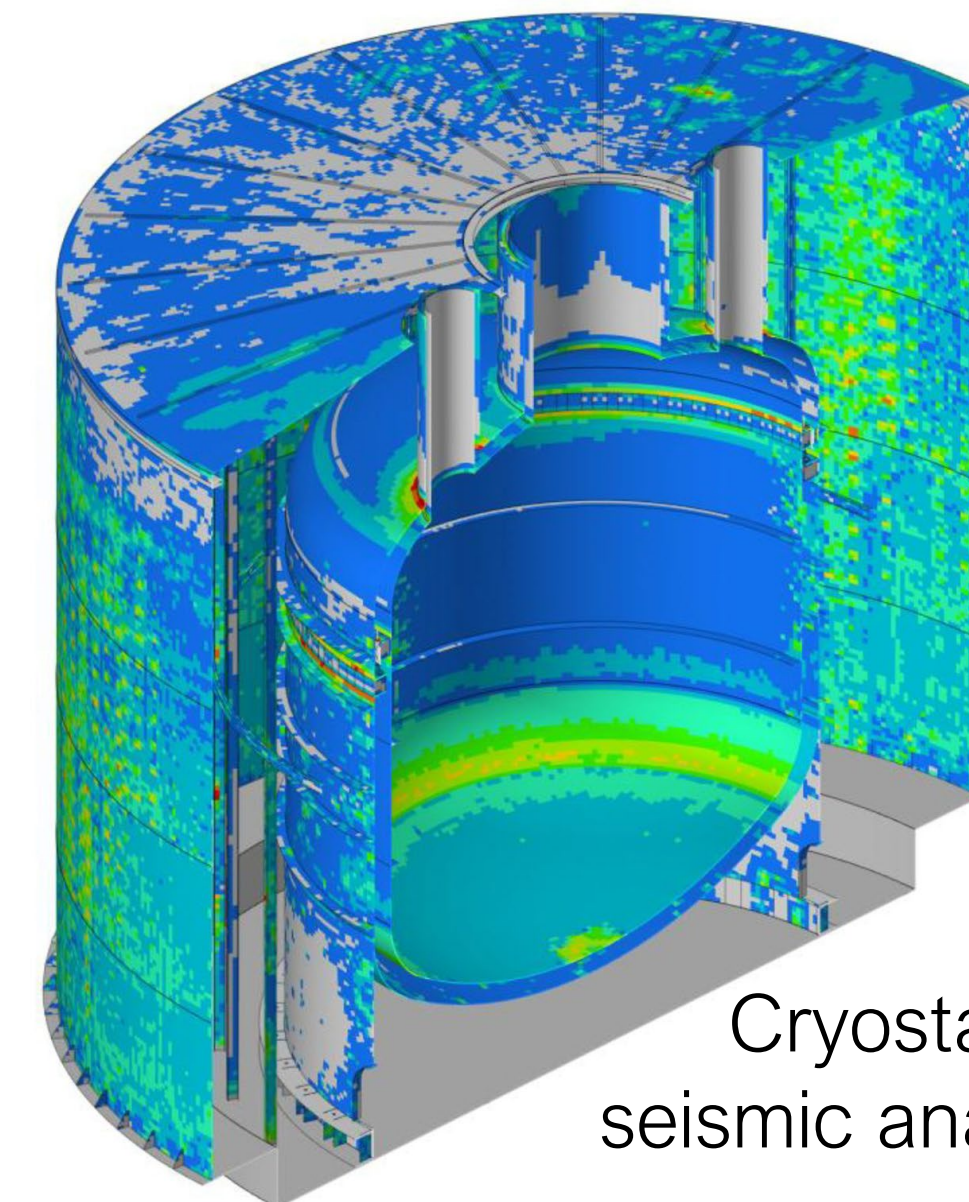
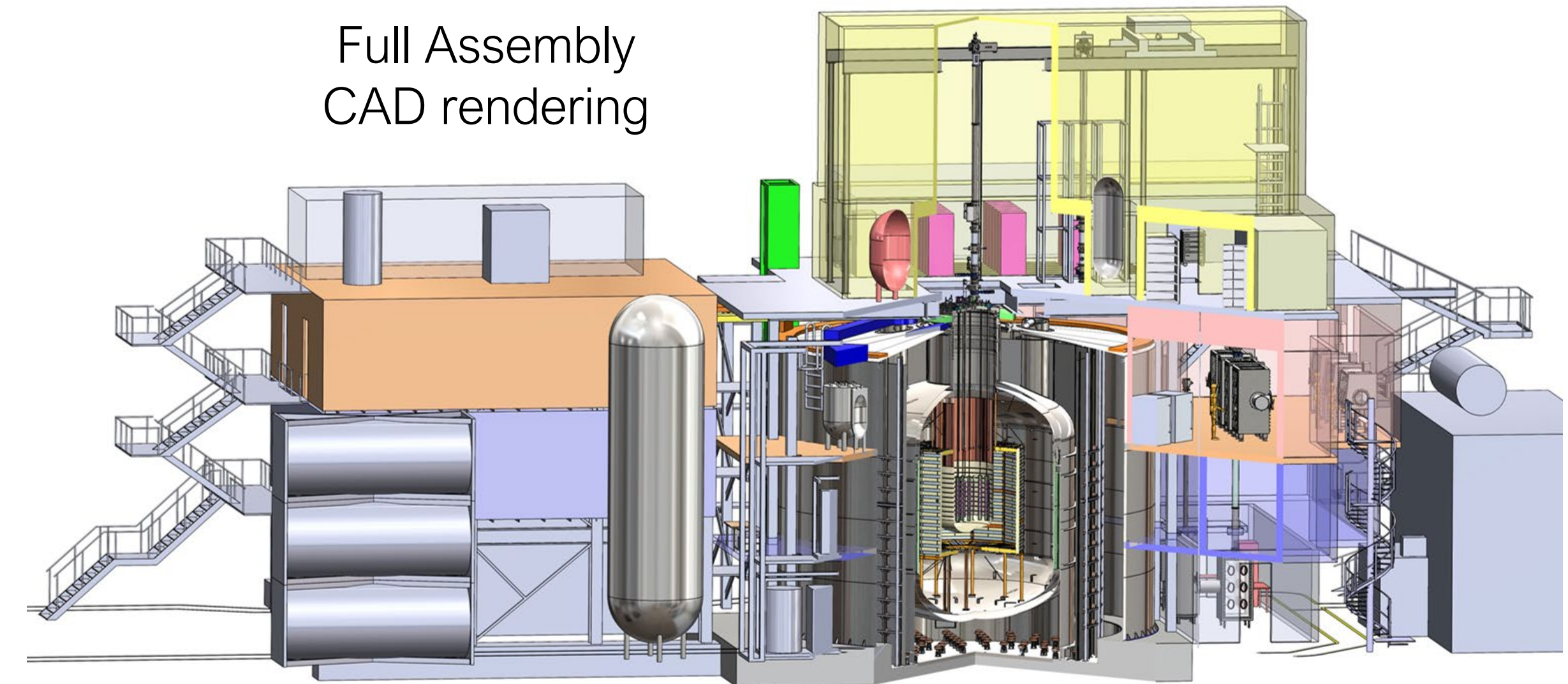
- Steel is purchased and assayed
- New P&ID developed for Ar handling

UAr procurement to follow DarkSide extraction

- Plant under commissioning in Colorado
- Transport tank design ready for internal review, then tender

Re-entrant tube design advancing

- Welding / burst tests underway



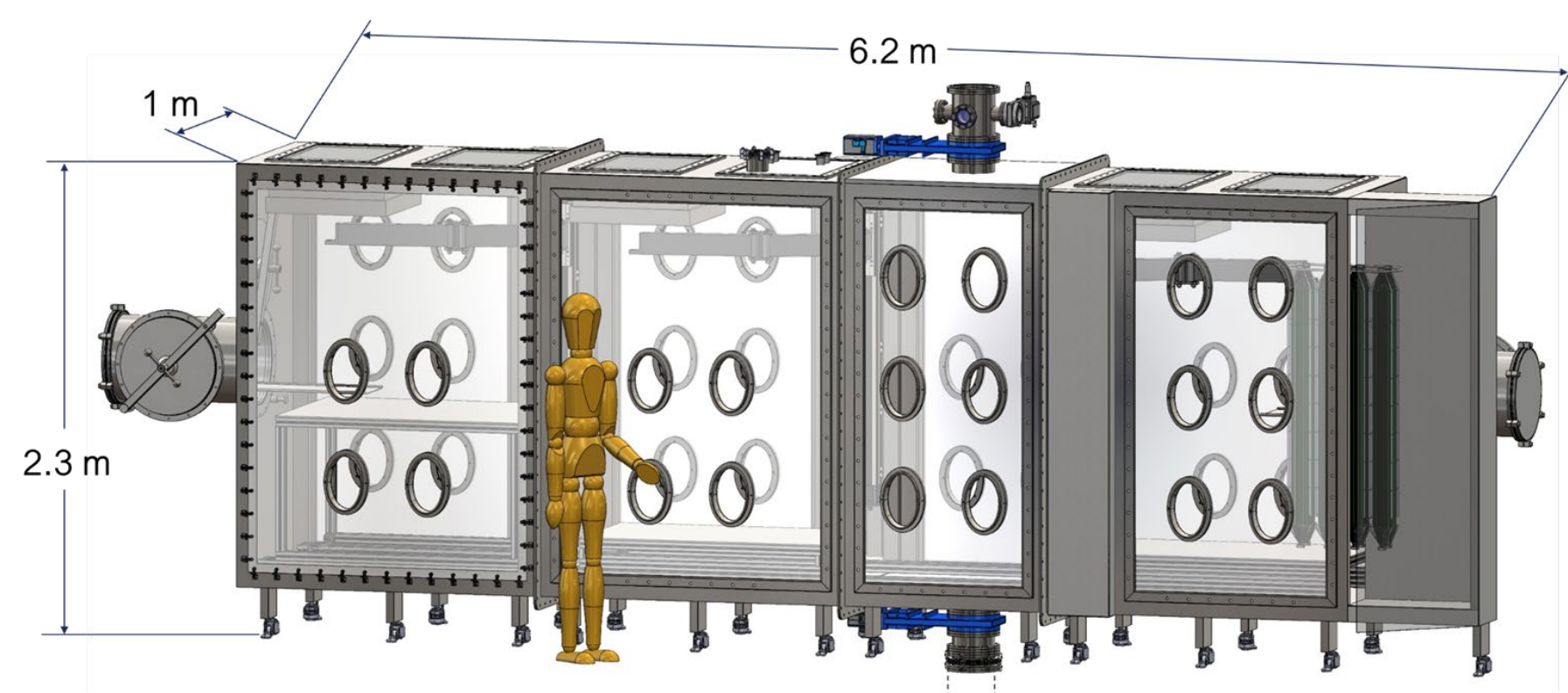
Cryostat
seismic analysis



Urania plant in
Colorado

Glove box / handling design maturing Lock Systems

- Sealing actuator, winch prototyped
- Test apparatus under construction



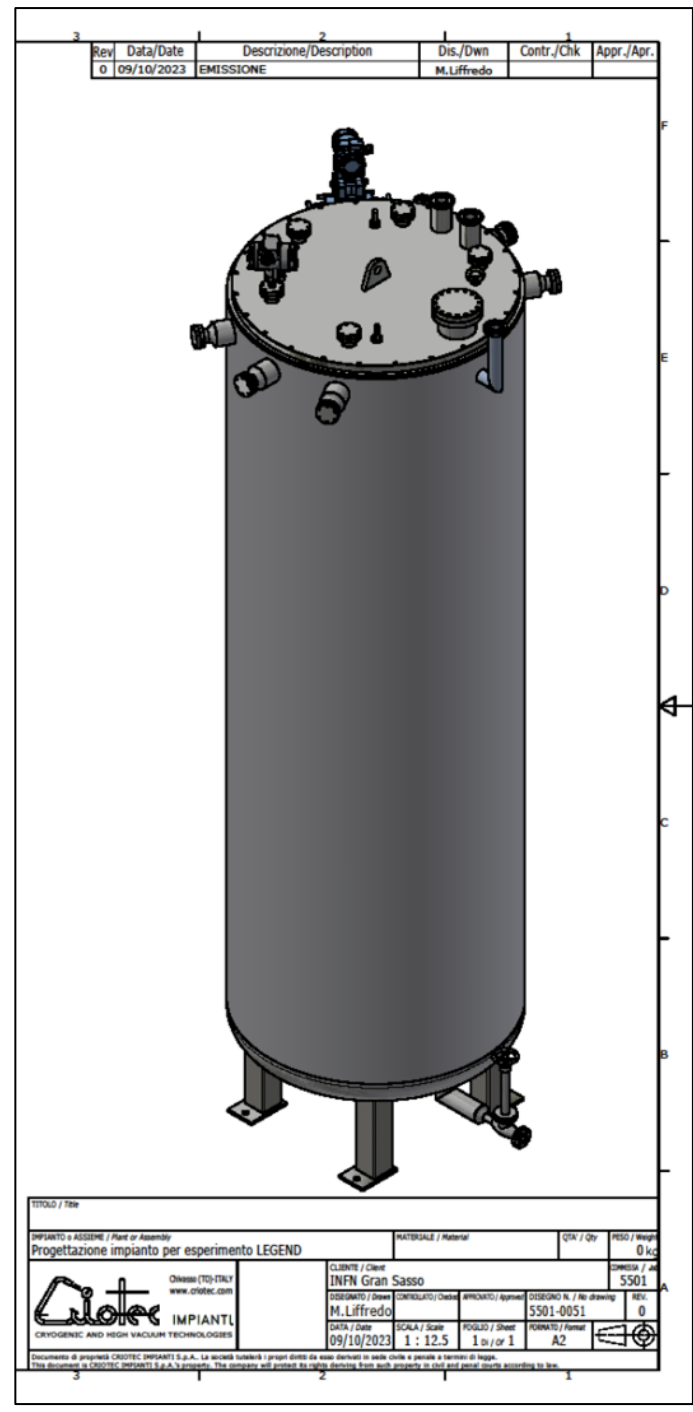
Glove box design

LEGENDArY test cryostat

- Incorporate LAr immersion tests during deployment
- Design maturing

Calibration Systems

- Design maturing

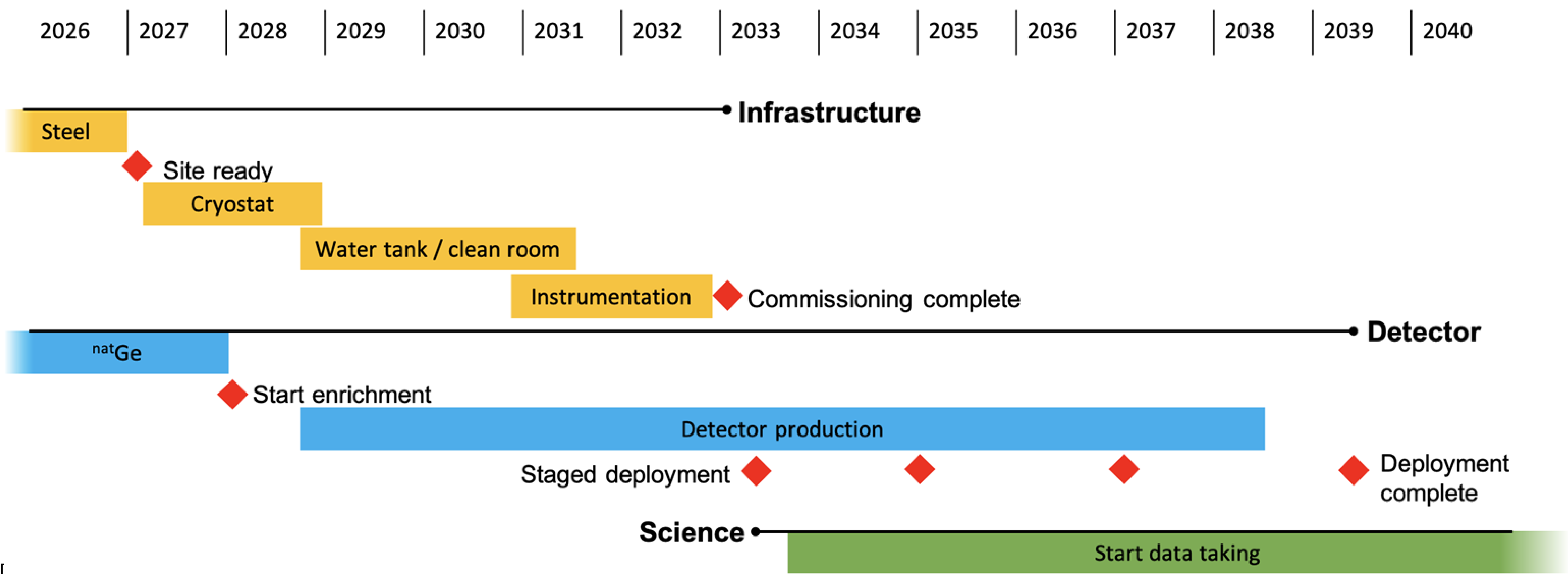


LEGENDArY design



Lock sealing mechanism testing

- Ultimate schedule limited by Ge / detector production rate
- First science limited by infrastructure construction and instrumentation deployment
- Aiming for first data in ~2033



Summary

- Discovery of neutrinoless double beta decay would be the first observation of matter creation (without antimatter) by humans, and is deeply important regardless of the theoretical motivation.
- The international experimental program in both experiment and theory is robust and aggressive, and LEGEND is playing a leading role.
 - LEGEND-200 is breaking new ground in the coming years.
 - Taking data smoothly after successful redeployment
 - Key background contributors reduced
 - LEGEND-1000 is on track to fully test the IO in the next decade.
 - Proceeding toward major funding from multiple agencies
 - Lots of technical progress
- A steady march in sensitivity improvement is expected for at least a decade. Discovery could come at any time!