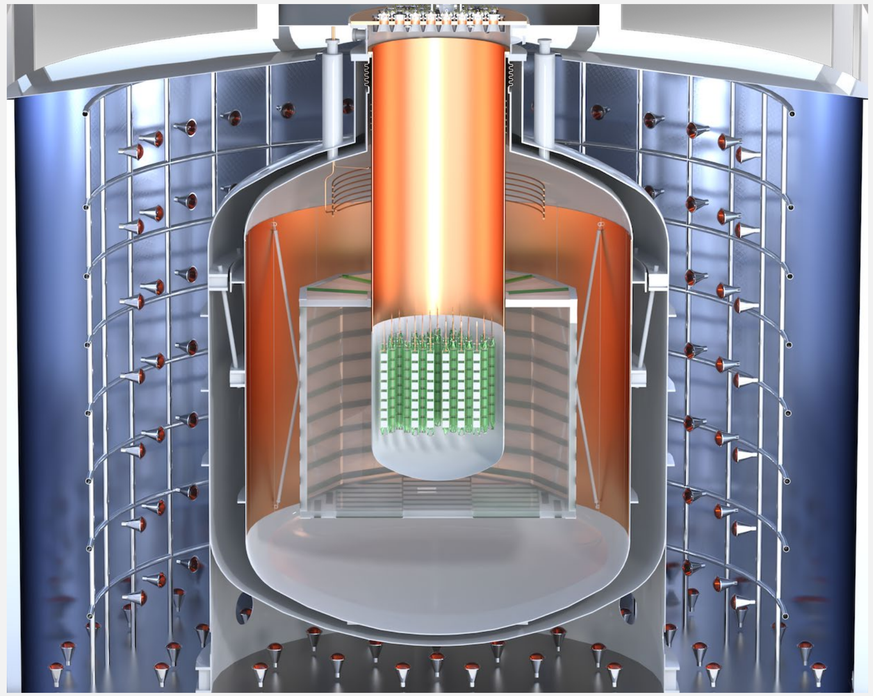
LEGEND:
текущий статус поиска 0νββ-распада ^{76}Ge

LEGEND
Large Enriched
Germanium Experiment
for Neutrinoless ββ Decay



Konstantin Gusev
ЛЯП ОИЯИ

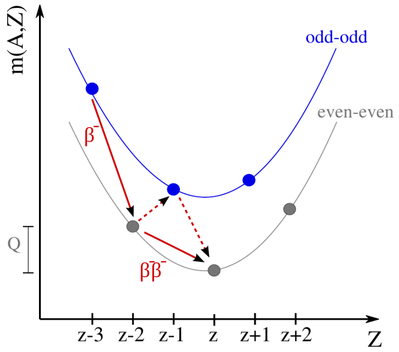
Общелабораторный семинар
22 июня 2026

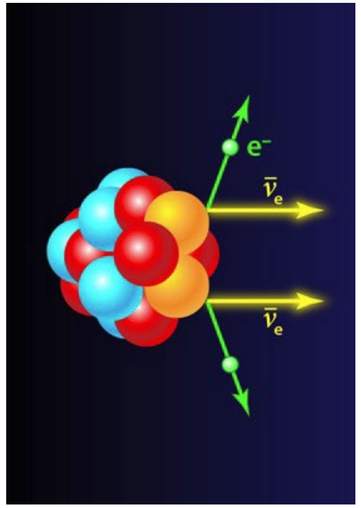
Vocabulary

- Experiments:
  - LEGEND – Large Enriched Germanium Experiment for Neutrinoless ββ Decay
  - GERDA – GERmanium Detector Array
  - MJD – Majorana Demonstrator
- HPGe detector types:
  - Coax – semi-coaxial
  - BEGe – Broad Energy Germanium
  - PPC – p-type Point Contact
  - IC or ICPC – Inverted Coaxial or Inverted Coaxial Point Contact
- LAr – Liquid Argon
  - AAr – atmospheric Ar, usual LAr that one can easily procure
  - UAr – underground LAr, produced and stored underground to avoid ^{39}Ar and ^{42}Ar contamination
- NMS – Nylon Mini-Shroud
- CC4 – low background cryogenic amplifier developed by GERDA
- LMFE – Low Mass Front End developed by MJD
- ASIC – Application Specific Integrated Circuit
- Sensitivity – expected number of signal events that an experiment has 50% chance of excluding at 90% CL
- Discovery sensitivity – expected number of signal events for which an experiment has 50% chance to observe an excess of events over the background at 99.73%

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**:

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

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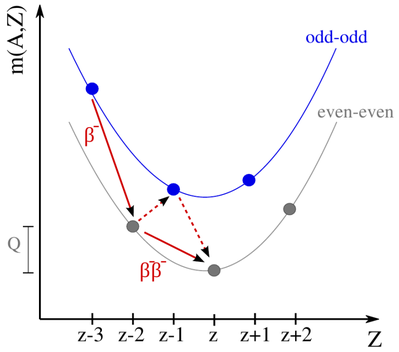

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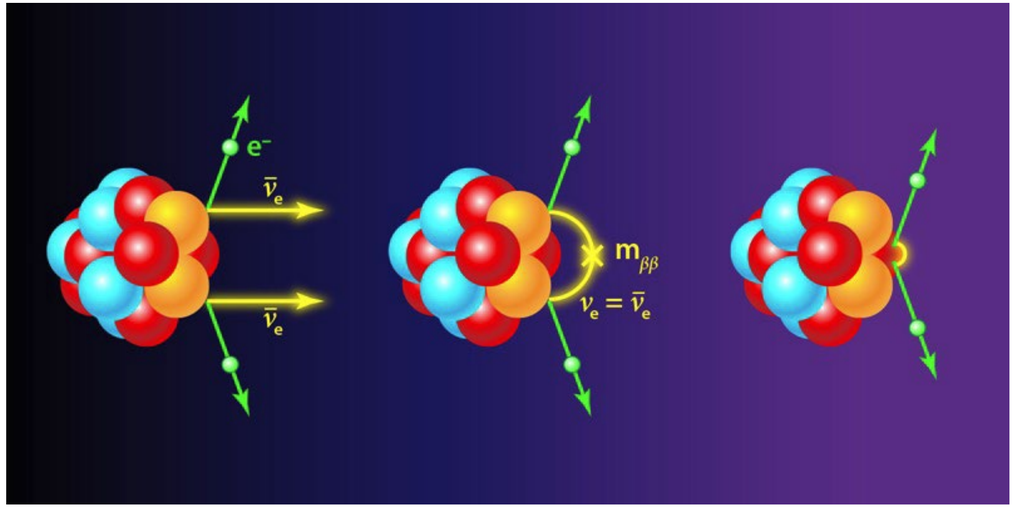


0νββ

- 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

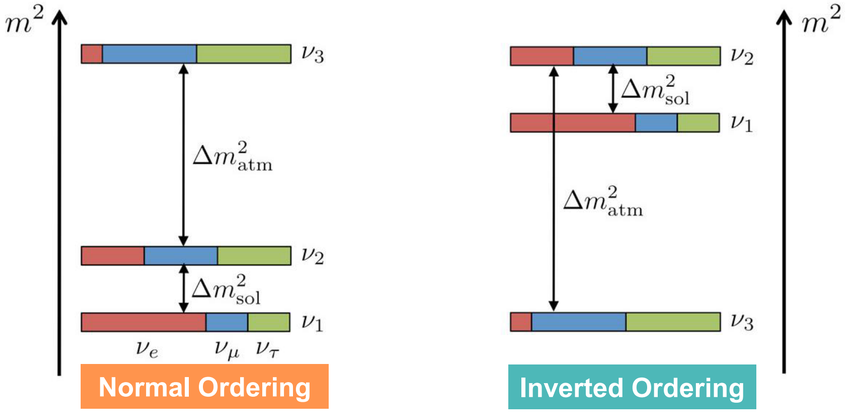
$$\frac{1}{T^{0\nu}_{1/2}} = G^{0\nu}(Q,Z)\, g_A^4\, |M^{0\nu}|^2 \left(\frac{m_{\beta\beta}}{m_e}\right)^2$$

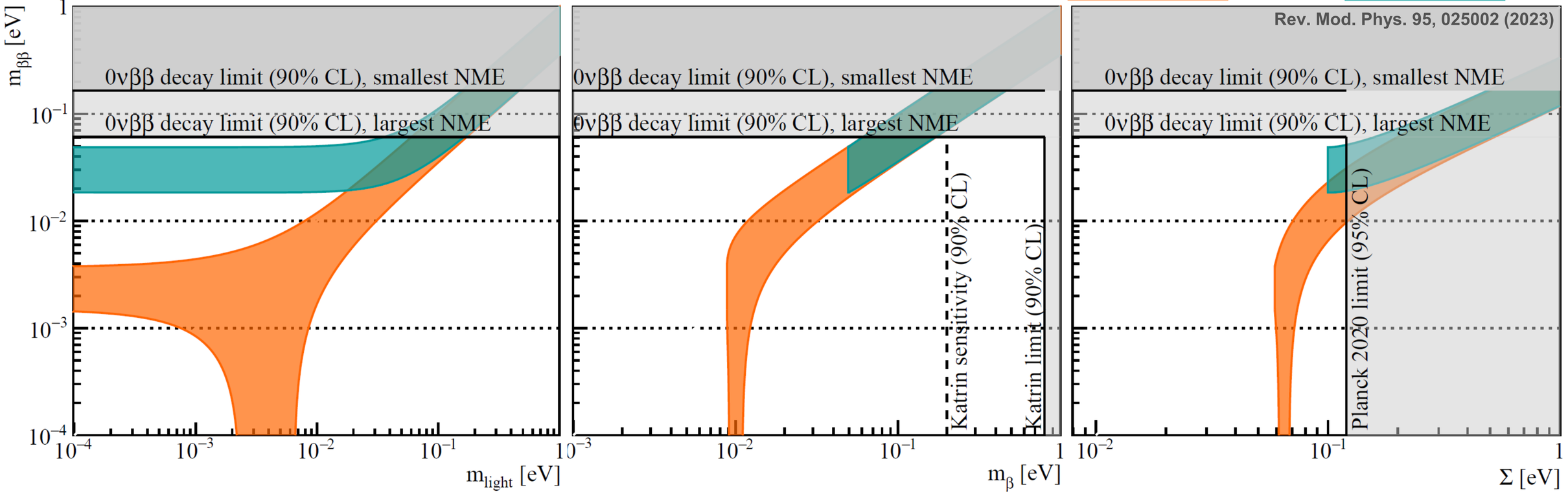
- $T^{0\nu}_{1/2}$: 0νββ decay rate
- $G^{0\nu}(Q,Z)$: Phase space factor
- $|M^{0\nu}|^2$: Nuclear Matrix Element
- $m_{\beta\beta}$: Effective Majorana neutrino mass

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

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

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



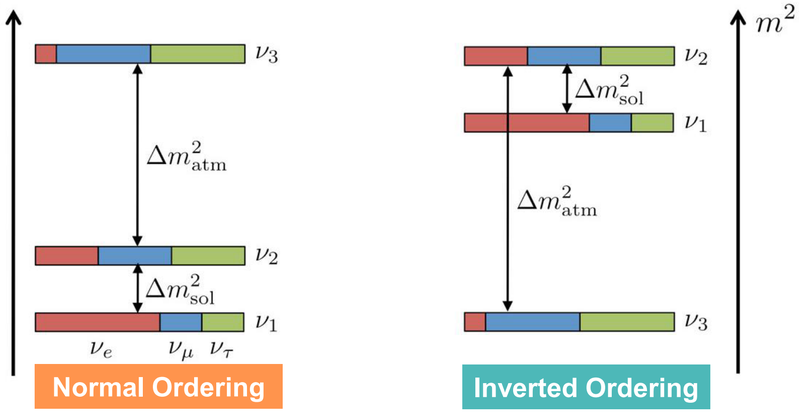


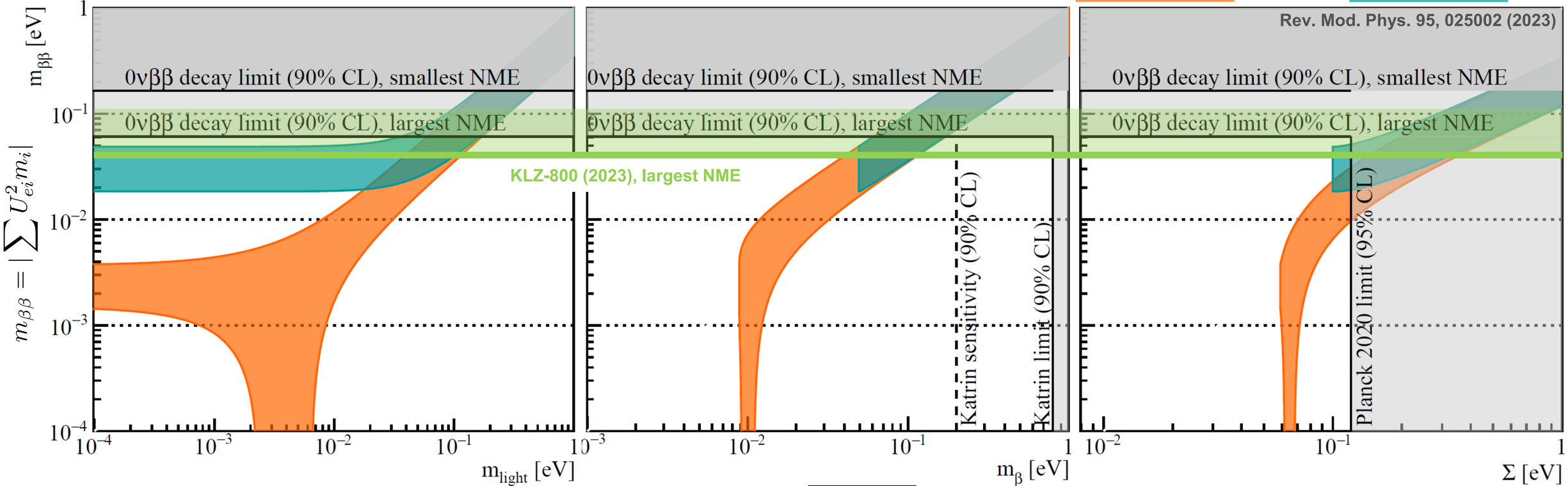
Link between 0νββ and ν-mass

Notes:

- **Recent KamLAND-Z 800** limit came to **IO** region

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





Link between 0νββ and ν-mass

Notes:

- **Recent KamLAND-Z 800** limit came to **IO** region *(maybe not – see next pages)*
- Next generation projects fully cover **IO** and part of **NO**

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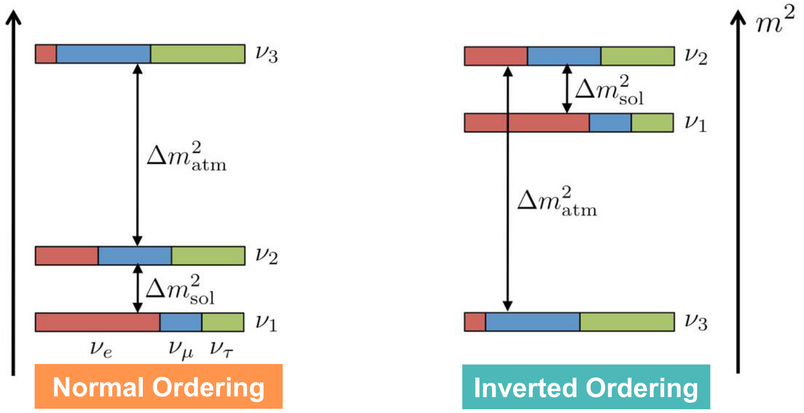
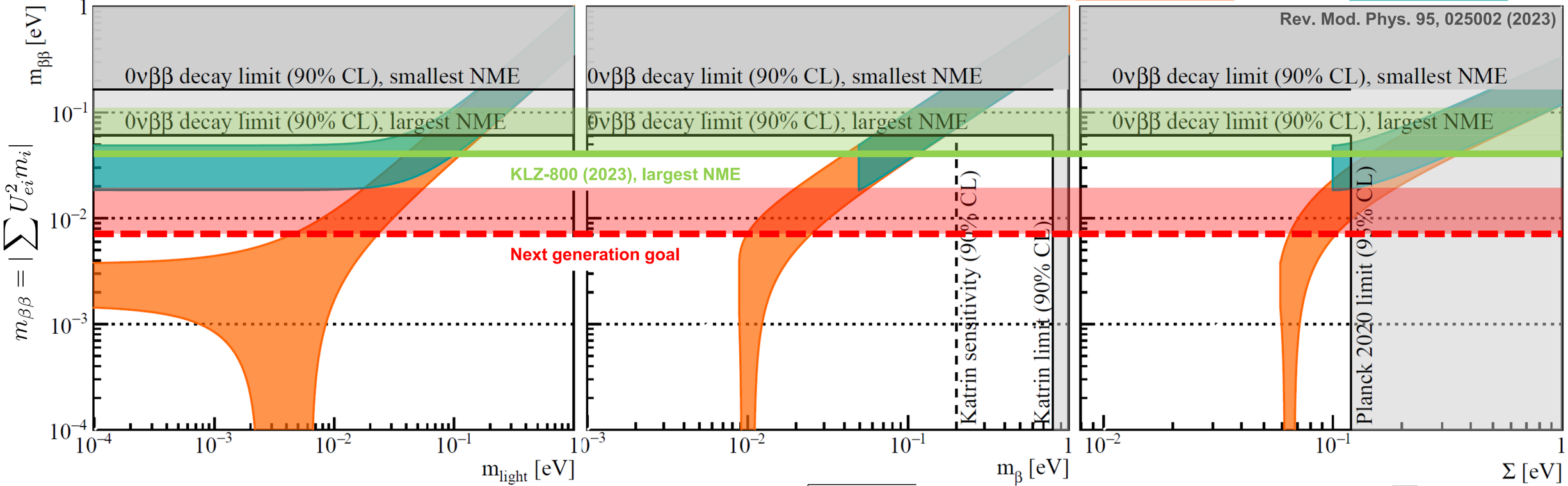




$$m_\beta = \sqrt{\sum m_i^2 |U_{ei}|^2}$$

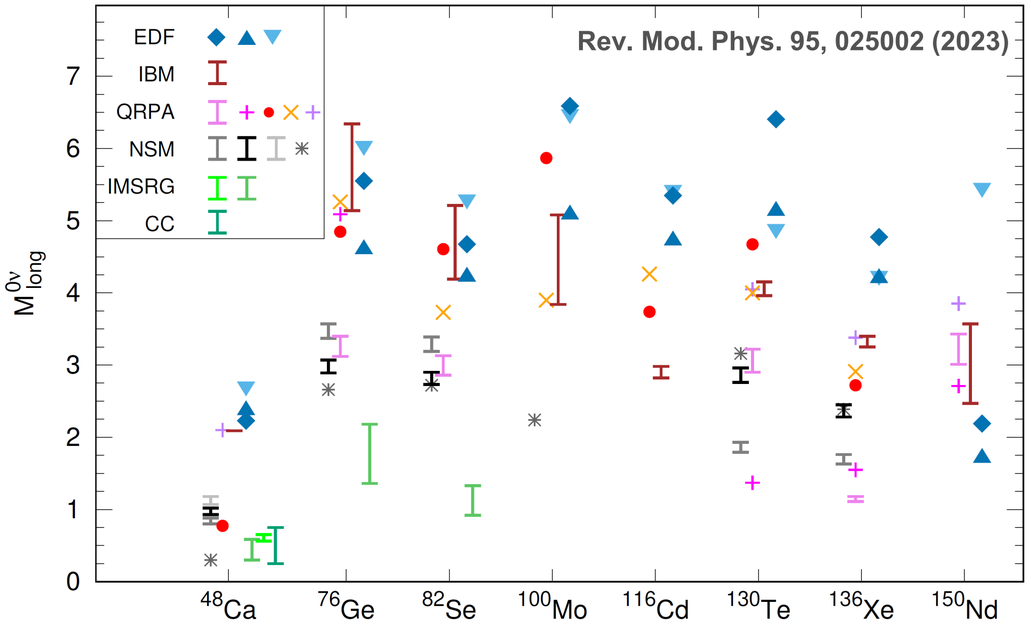
$$\Sigma \text{ or } m_{cosm} = \sum m_i$$

Nuclear Matrix Elements

Notes:

- Nuclear Matrix Element (NME) is a model dependent input to the result
- NME has large uncertainty depends on different models
- A lot of recent progress on the theoretical front to better constrain the value

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



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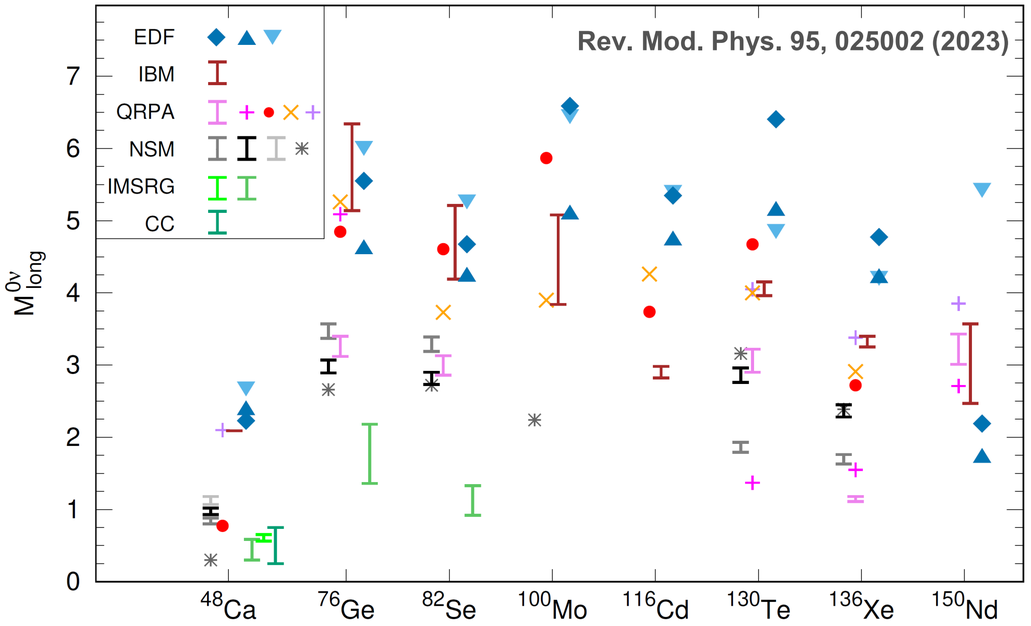
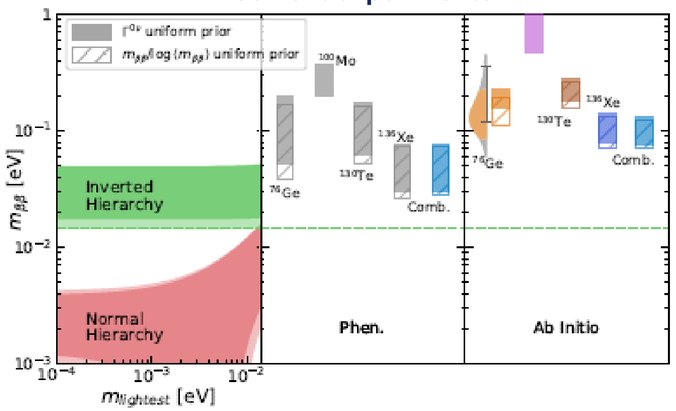
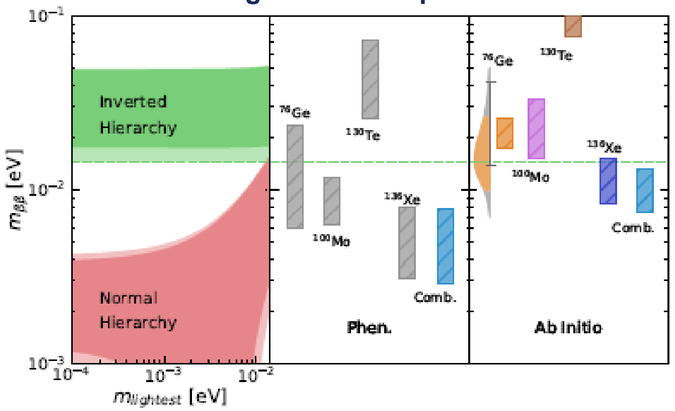


Current experiments



Next-generation experiments



Newest *ab initio* calculations

- push KLZ-800 limit up
- suggest that only combined limit from four key isotopes (^{76}Ge, ^{100}Mo, ^{130}Te, and ^{136}Xe) will cover full IO for the next generation experiments

https://arxiv.org/abs/2606.09288

Phase Space, Q-value, Abundance

Phase space factor

- Higher – better

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

Q-value

- Better > 2614.5 kev
- Above natural radioactivity

Natural abundance

- Enrichment is pretty expensive
- Influence the cost of an experiment

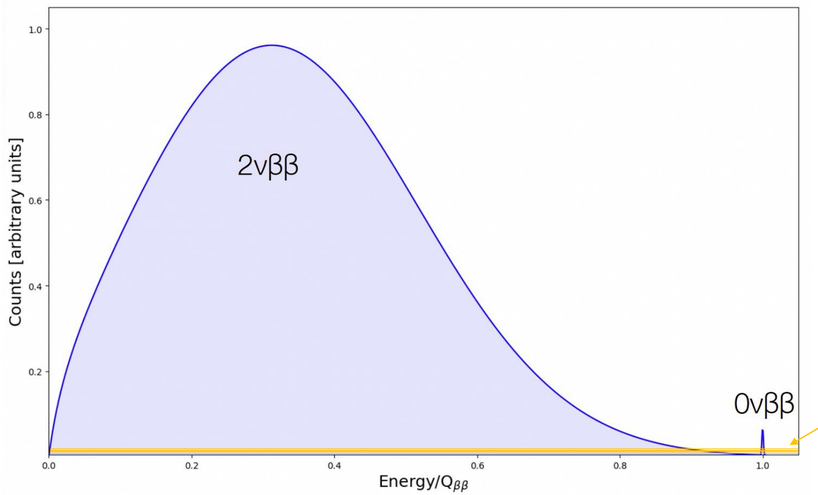
Isotope	$G^{0\nu}$ (10^{-14}yr)	Q(keV)	Nat. ab. (%)
^{48}Ca	6.3	4273.7	0.187
^{76}Ge	0.63	2039.1	7.8
^{82}Se	2.7	2995.5	9.2
^{100}Mo	4.4	3035.0	9.6
^{130}Te	4.1	2530.3	34.5
^{136}Xe	4.3	2461.9	8.9
^{150}Nd	19.2	3367.3	5.6

*enrichment required except for ^{130}Te, not (yet) possible for all, costs differ

- *Probably few needed to cover the IO in next generation experiments*

Experimental design considerations

Signature: sharp peak at the end of 2νββ spectrum on some background

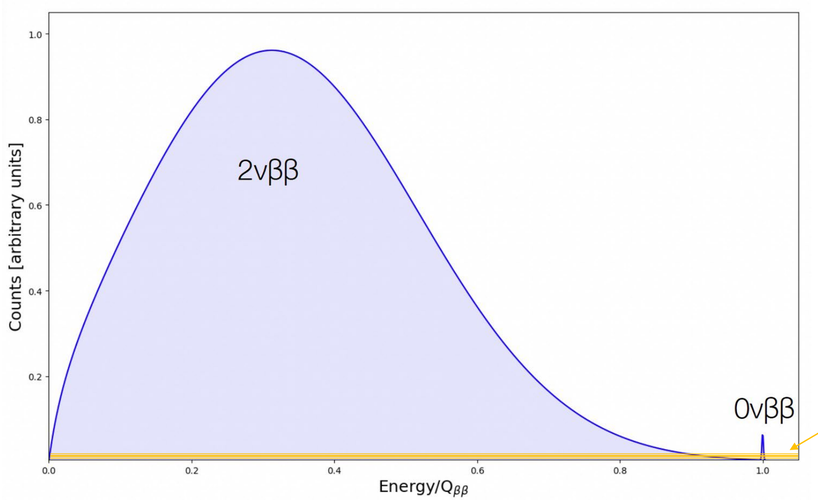


Exposure

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

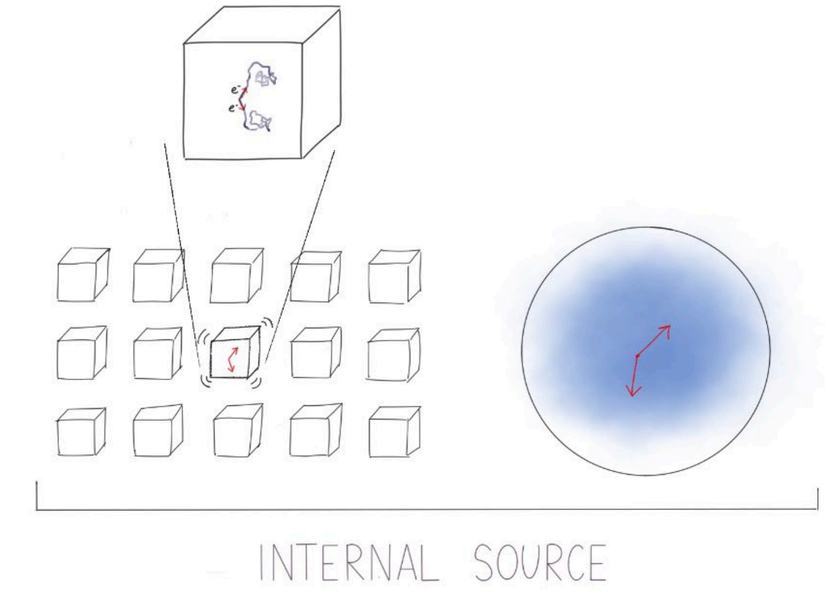
- Detector performance:
  - High mass and good long-term stability to increase exposure

Experimental design considerations

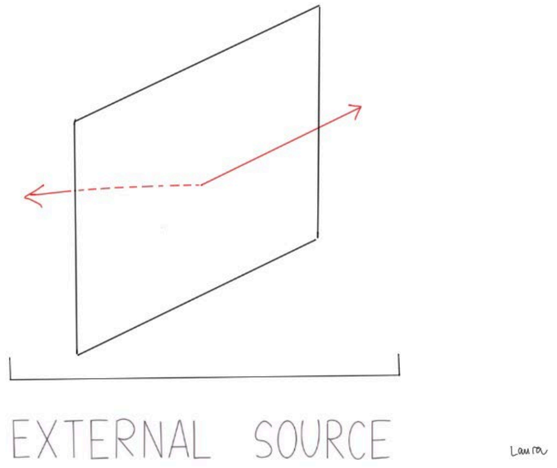


$$T_{1/2}^{0\nu} \propto \epsilon \sqrt{\frac{M\,t}{\Delta E\;BI}}$$

Efficiency

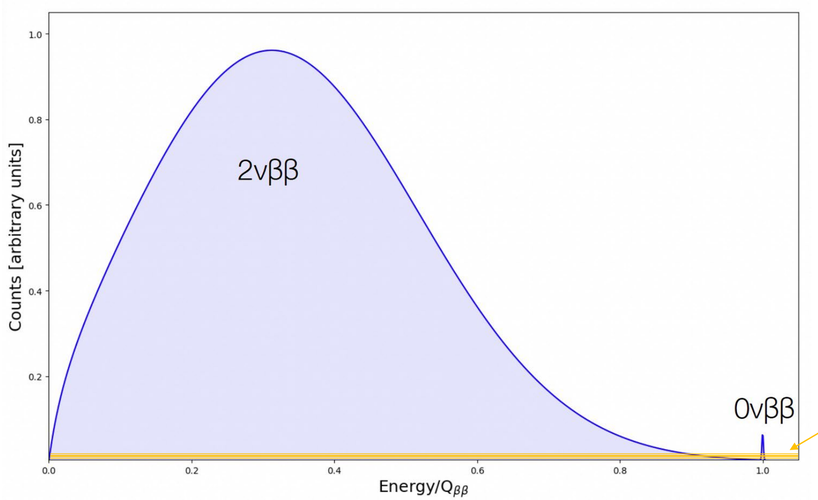


- Detector performance:
  - High mass and good long-term stability to increase exposure
  - High efficiency: source = detectors



Picture: Laura Manenti

Experimental design considerations



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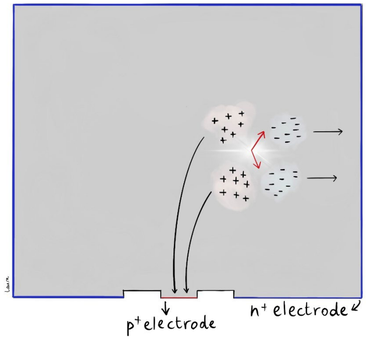
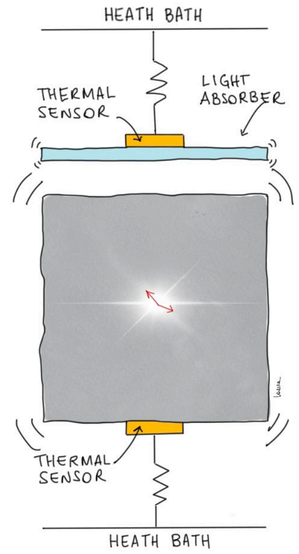
Energy resolution

HPGe detector



Bolometer



- Detector performance:
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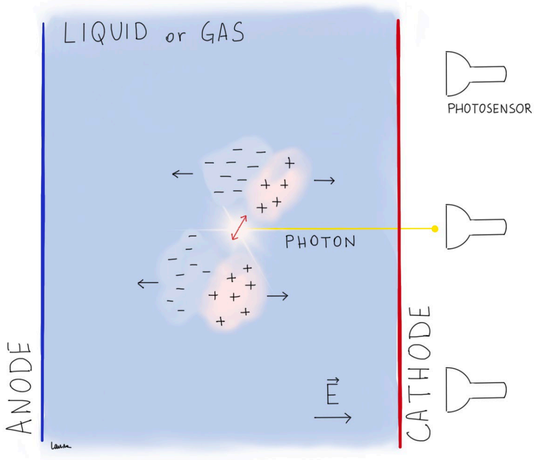
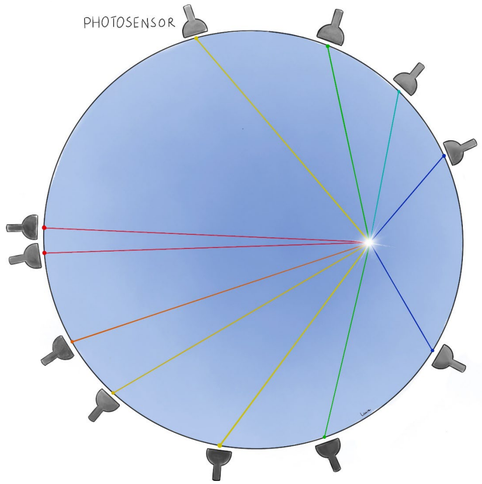
  - High efficiency: source = detectors
  - Good energy resolution

TPC

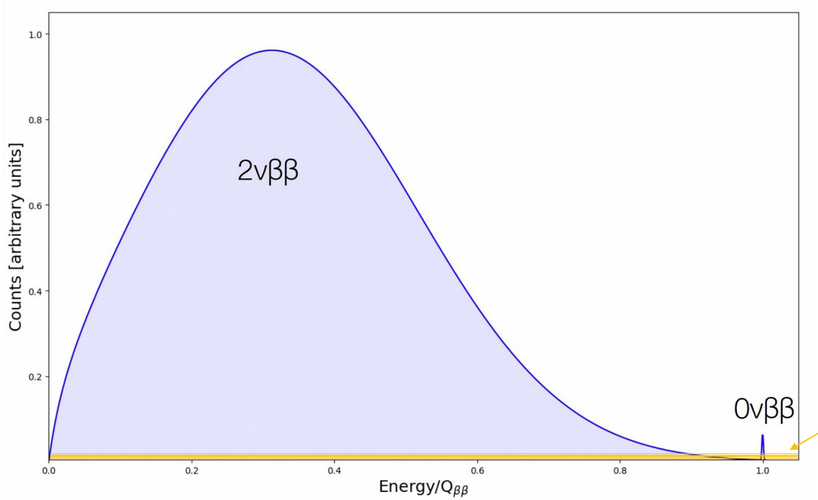


Liquid scintillator



Pictures: Laura Manenti

Experimental design considerations



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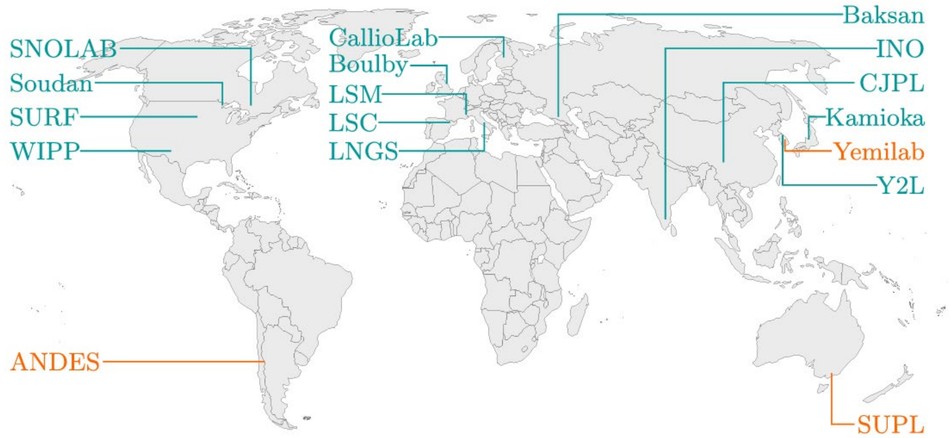
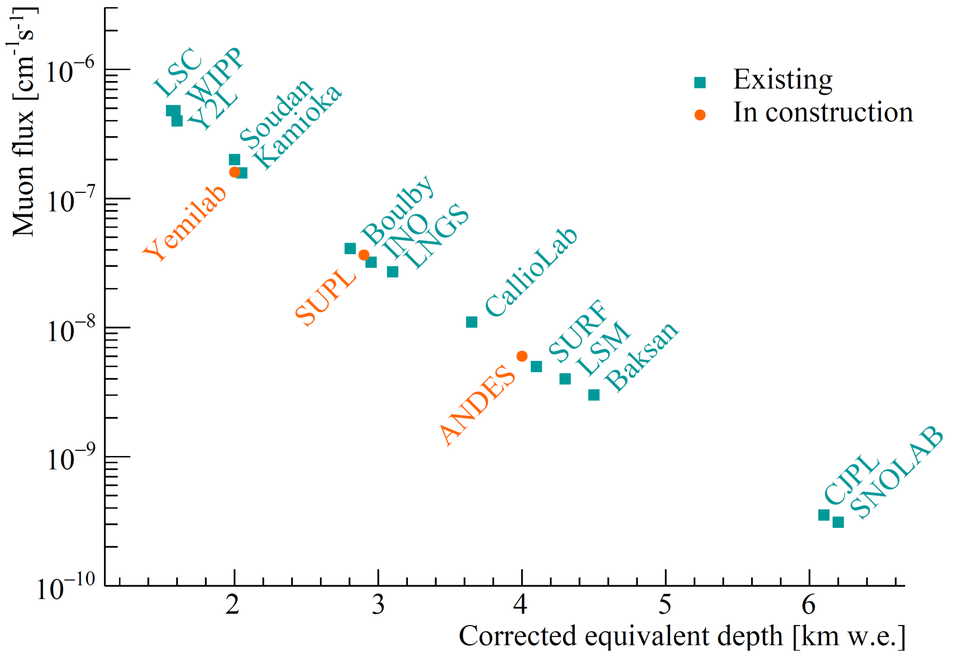
Background Index



- 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 technics



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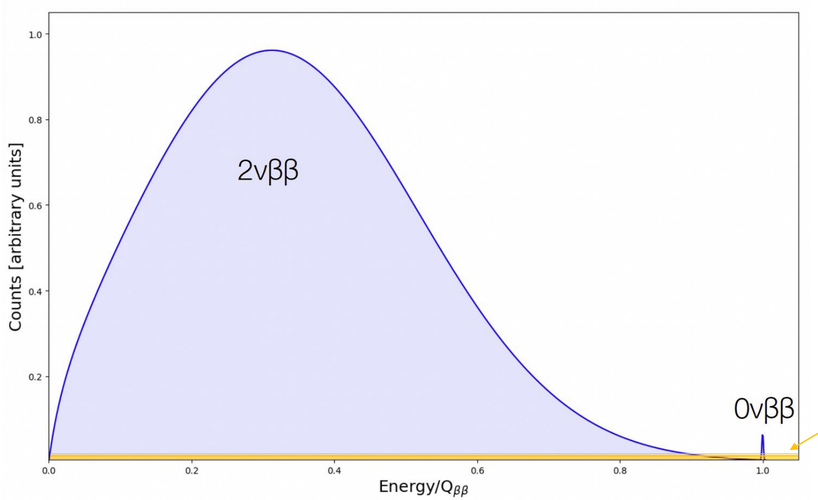

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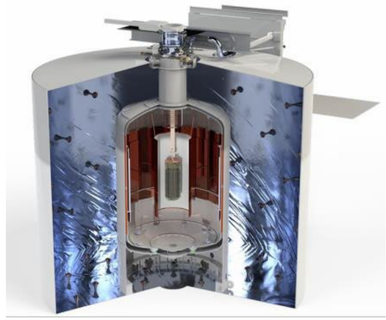
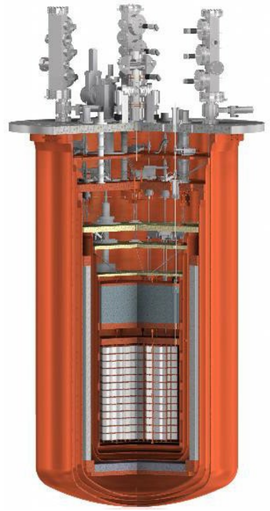
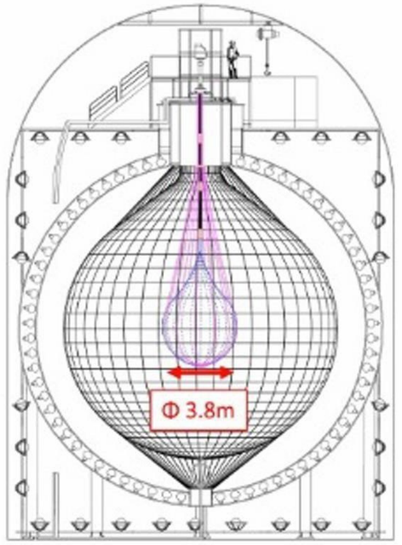


LAr (high Z, active)

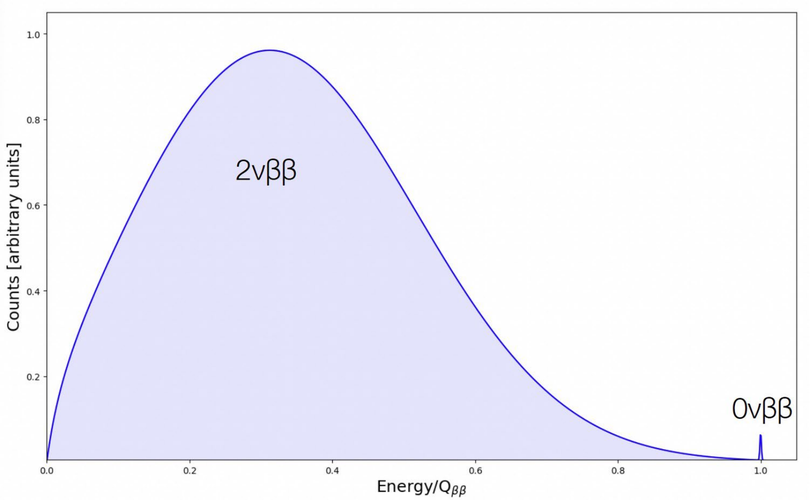


Pb (high Z)



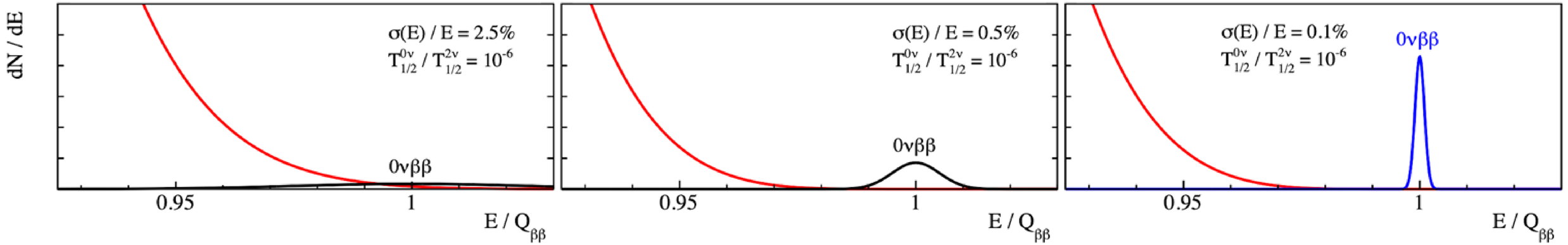
Fiducialization

“Background free” experiment

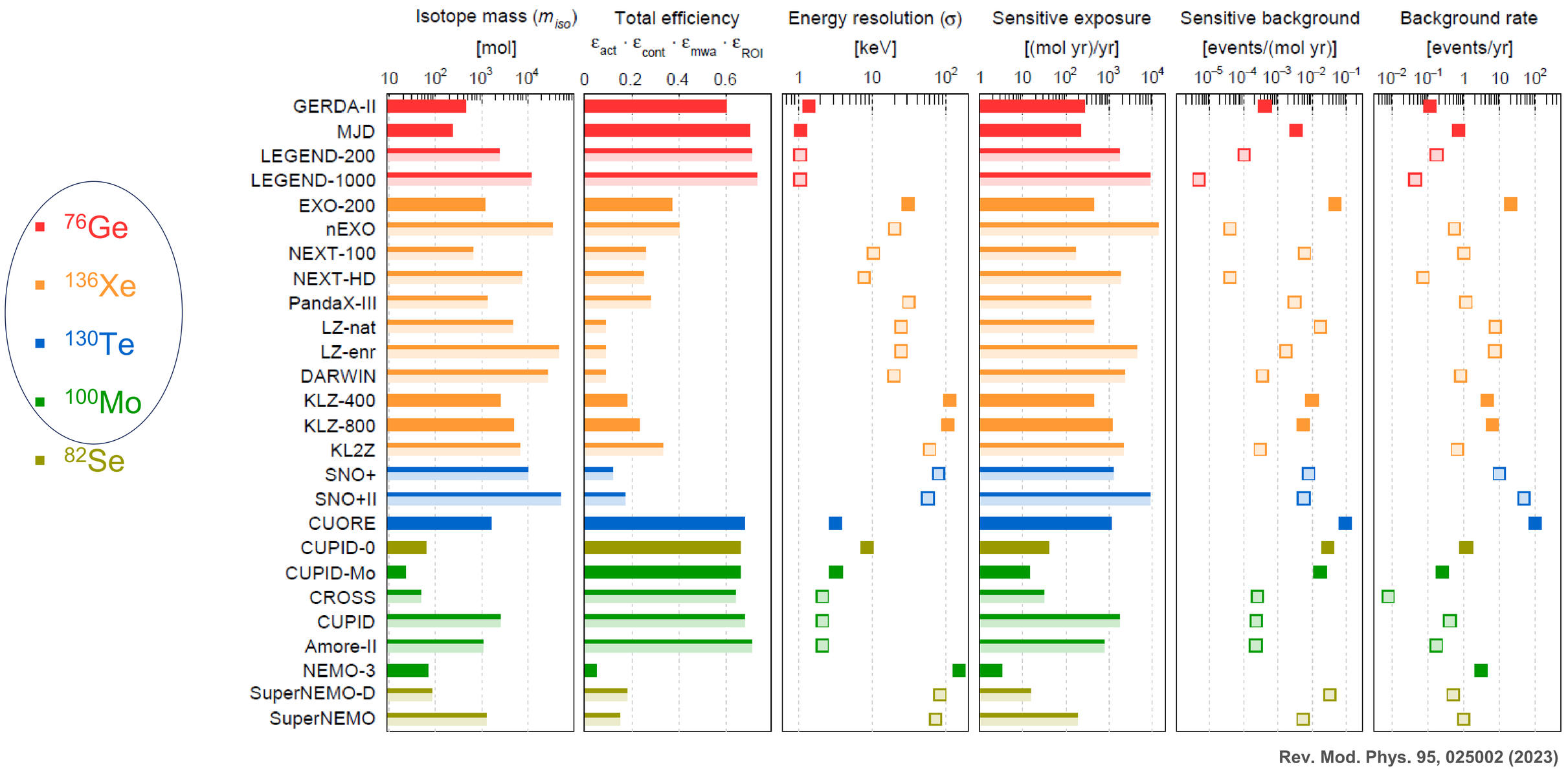


$$T_{1/2}^{0\nu} \propto \epsilon\, M\, t$$

- But energy resolution still essential!



Experimental landscape



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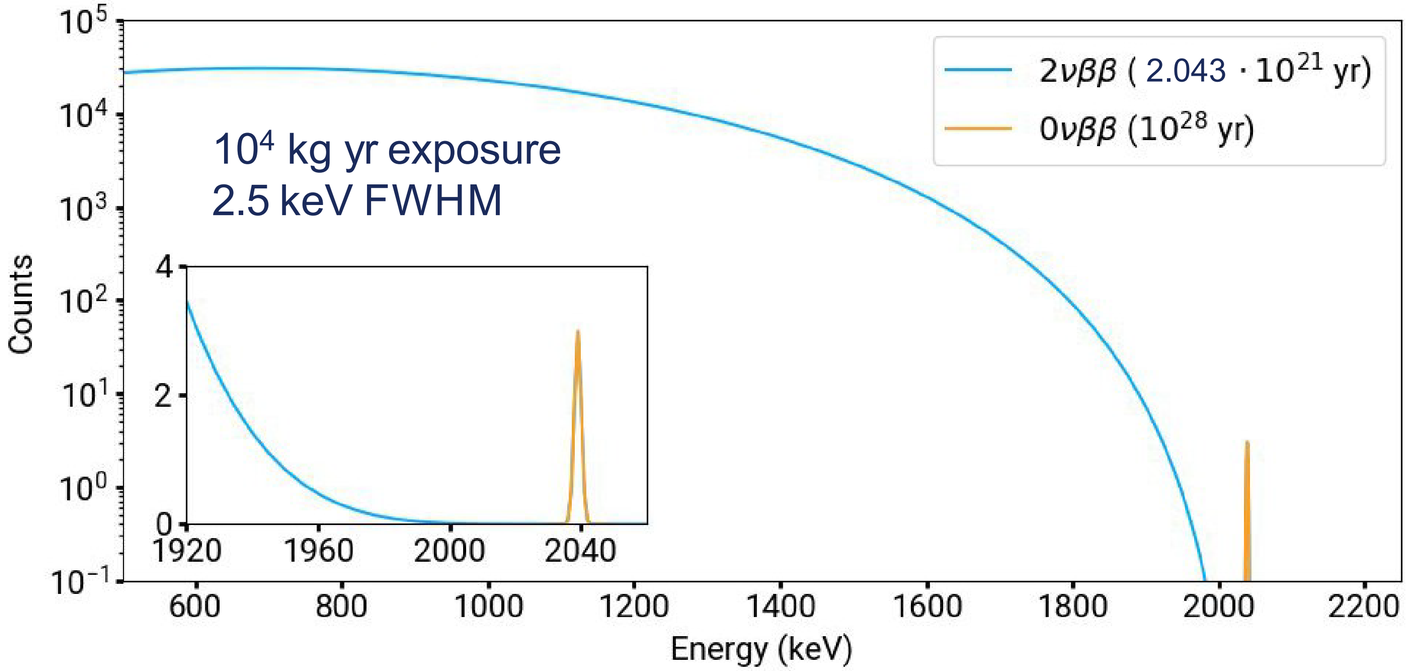
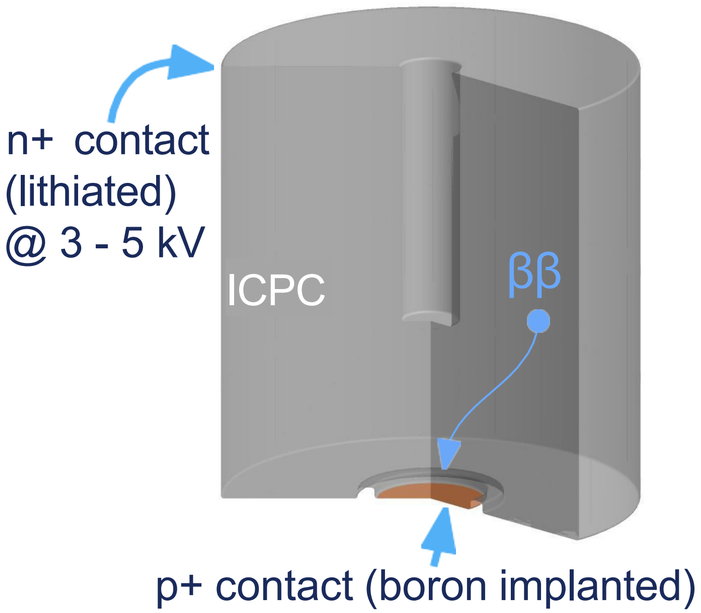
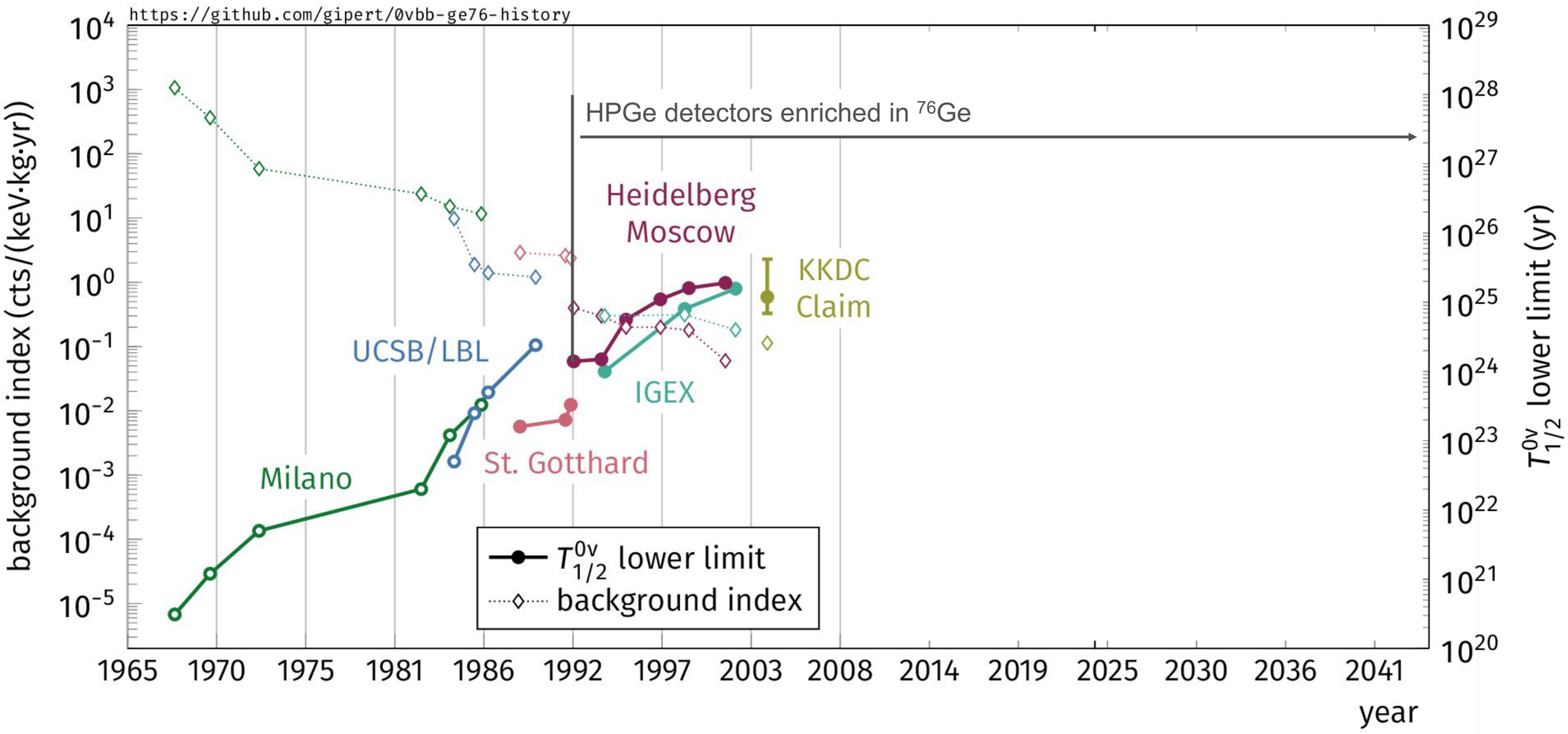
0νββ search with HPGe detectors enriched in ^{76}Ge





- 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



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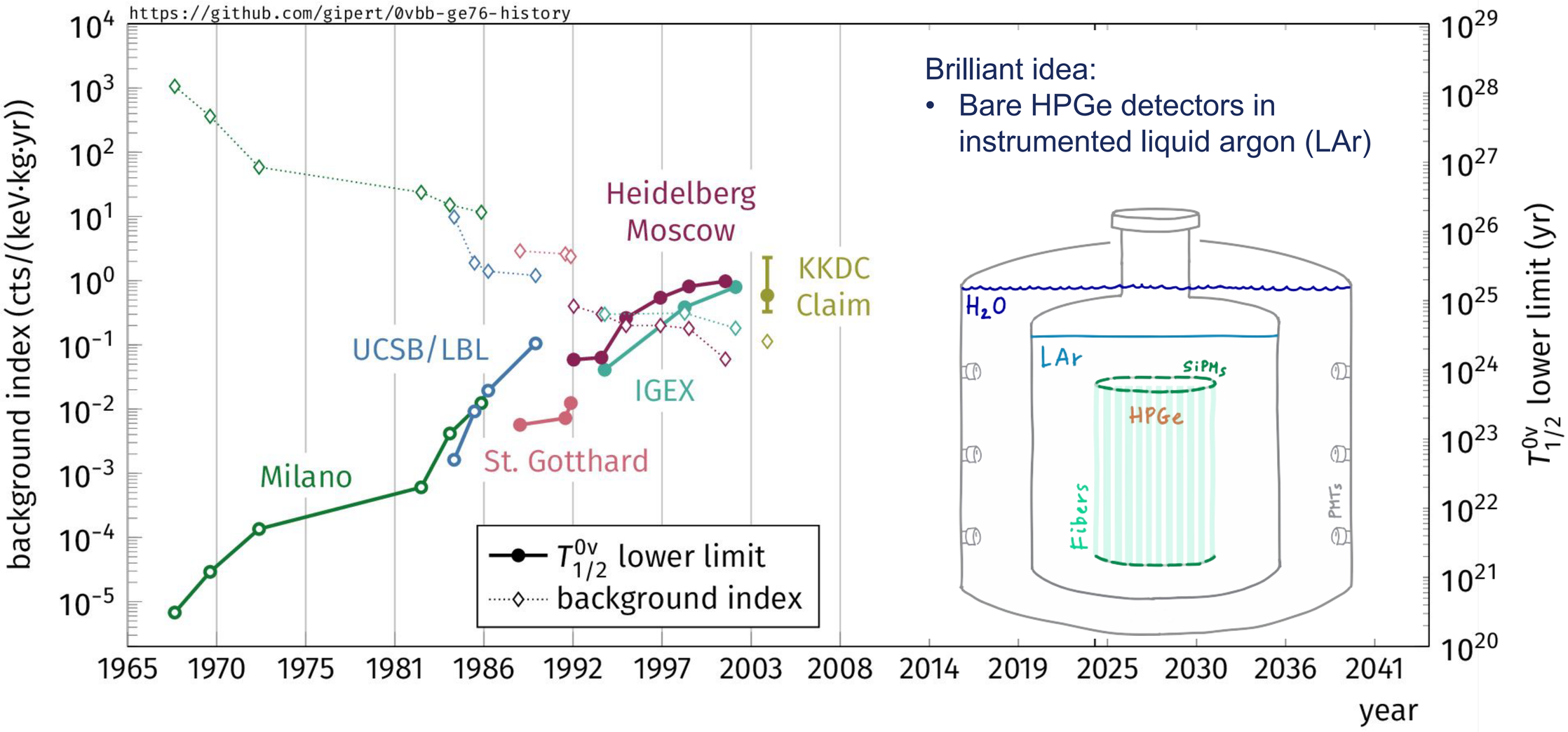

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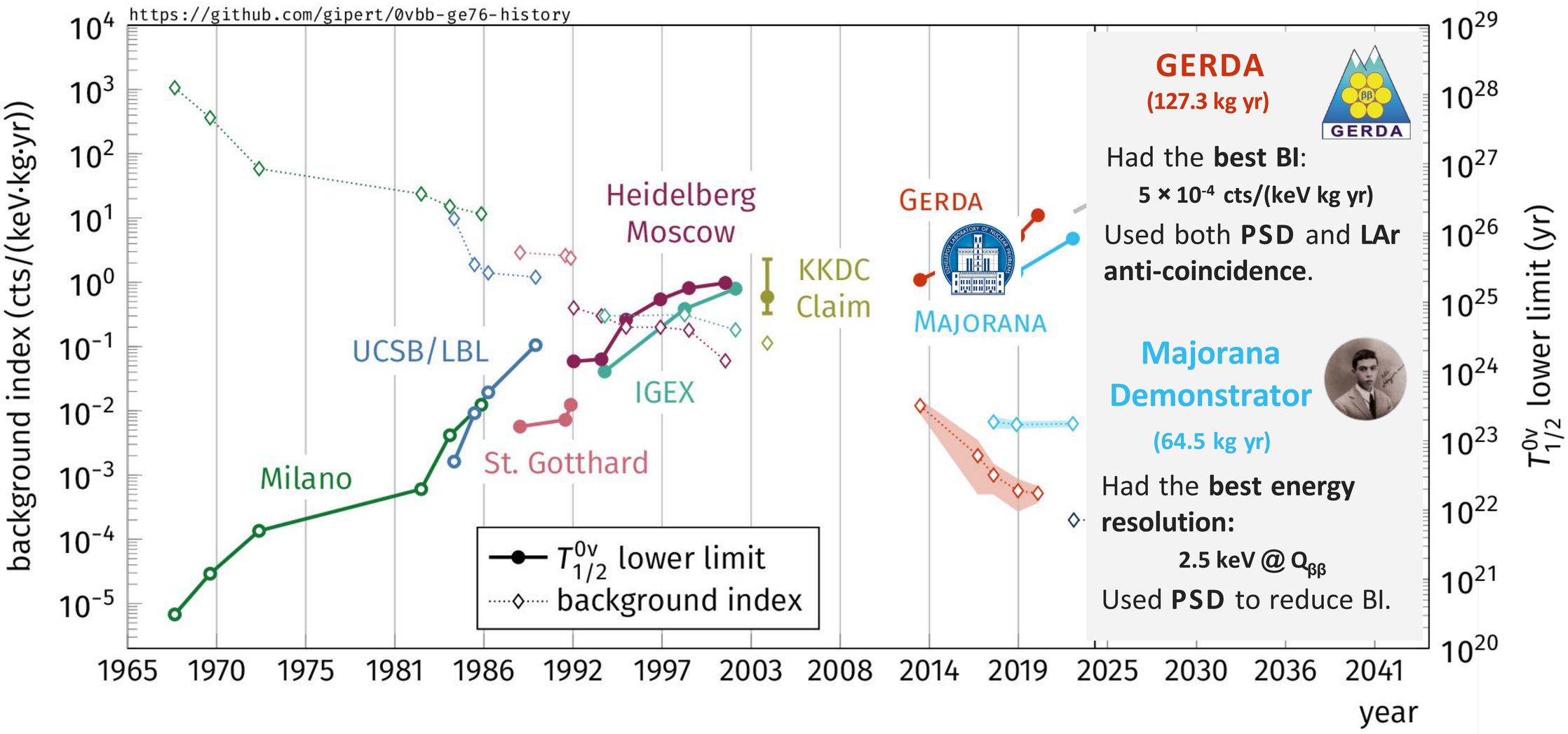
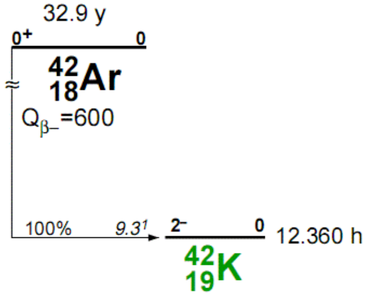
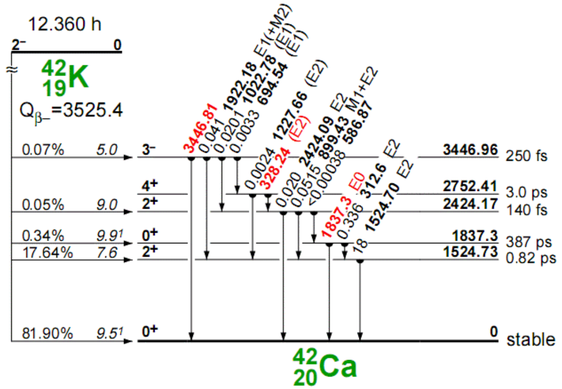


^{42}Ar problem

- In the first phase of GERDA elevated background from ^{42}K was found; ^{42}K (daughter of ^{42}Ar) – beta decay isotope with end point of 3.5 МэВ. Estimated activity in LAr ~ **(40-90) uBq/kg.**
- **Very dangerous background!**





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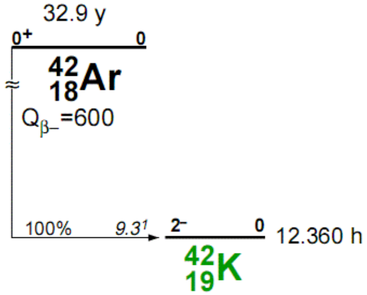
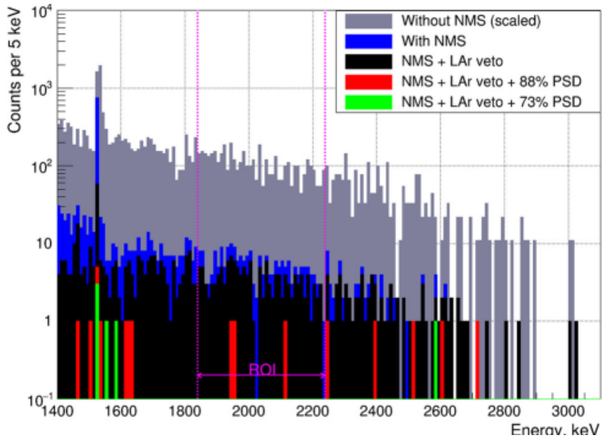
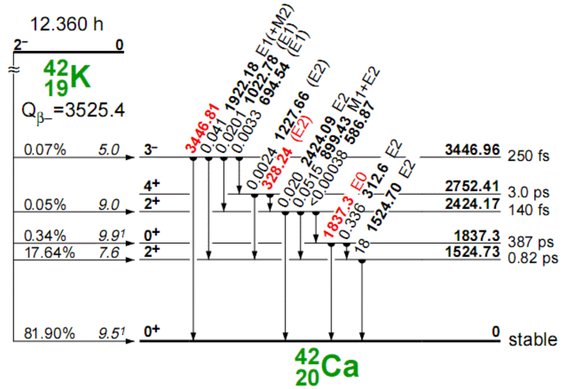
- In the first phase of GERDA elevated background from ^{42}K was found; ^{42}K (daughter of ^{42}Ar) – beta decay isotope with end point of 3.5 МэВ. Estimated activity in LAr ~ **(40-90) uBq/kg.**
- **Very dangerous background!**





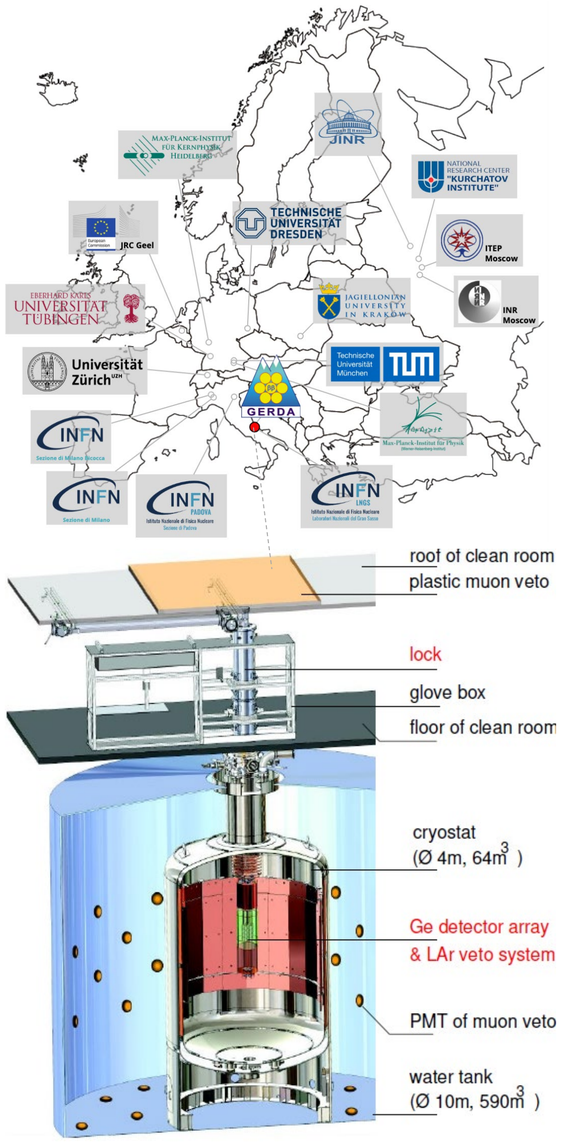




- Widely investigated
- Solution for GERDA Phase II found: nylon mini-shroud!

- Used in LEGEND-200 as well!

GERDA – first “background free” 0νββ search



- ✓ GERDA successfully finished data taking in Dec 2019
- ✓ Full data set analyzed in 2020

- ✓ **103.7 kg yr** of ^{76}Ge exposure collected in **Phase II** (**127.3** kg yr with Phase I)

- ✓ All design goals **surpassed!**

GERDA Phase II	goals	achievements
background	~ 10^{-3} cts/(keV kg yr)	$\mathbf{5.2^{+1.6}_{-1.3} \times 10^{-4}}$ cts/(keV kg yr)
exposure	≥ 100 kg yr	**103.7** kg yr
sensitivity	$T^{0\nu}_{1/2} \geq 10^{26}$ yr	$\boldsymbol{T^{0\nu}_{1/2} > 1.8 \times 10^{26}}$ **yr**

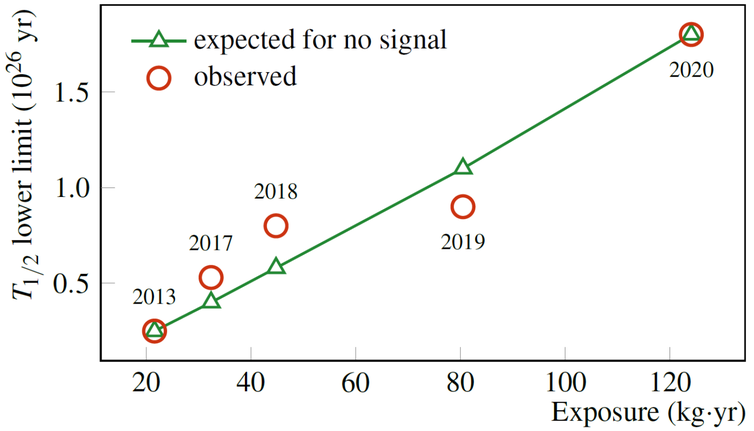
- ✓ GERDA achieved world best half-life limit!

$$T^{0\nu}_{1/2} > 1.8 \times 10^{26} \text{ yr (90\% CL)}$$

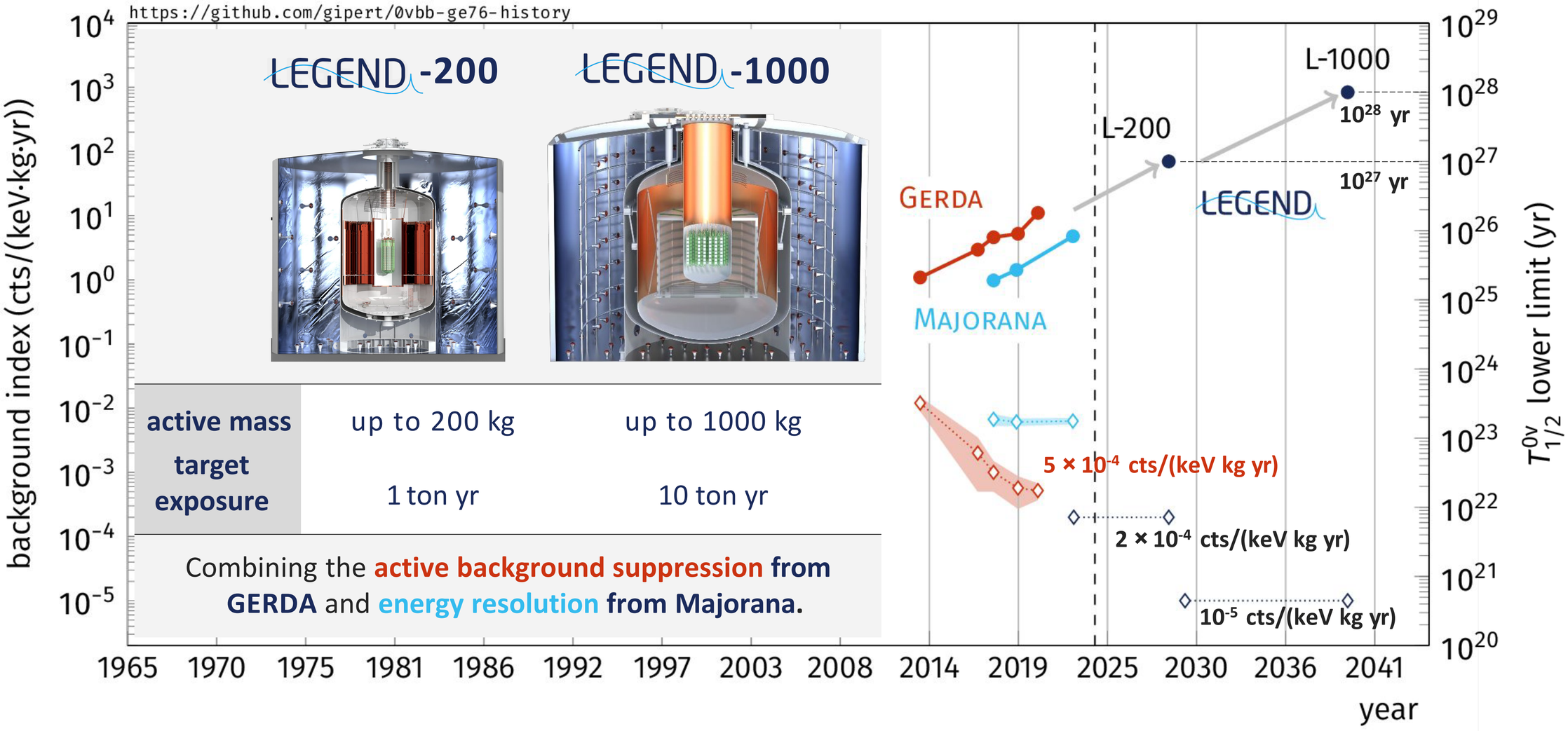
- ✓ Linear increase of sensitivity vs exposure is proven!
- ✓ Opened bright future for the next step:



LEGEND



New history of 0νββ search with HPGe detectors



LEGEND Collaboration





LEGEND

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

Ciemat · Comenius University Bratislava · Czech Technical University in Prague · Duke University · GSSI Gran Sasso Science Institute · Indiana University Bloomington · INFN · Jagiellonian University in Kraków · JINR · European Commission Joint Research Centre · INFN Laboratori Nazionali del Gran Sasso · Lancaster University · INFN LNF Istituto Nazionale di Fisica Nucleare · Laurentian University / Université Laurentienne · Berkeley Lab · ikz · ipf Leibniz-Institut für Polymerforschung Dresden · Los Alamos National Laboratory · Max-Planck-Institut für Kernphysik Heidelberg · Max-Planck-Institut für Physik · National Research Center "Kurchatov Institute" · National Taiwan University · NC State University · Oak Ridge National Laboratory · Politecnico Milano 1863 · Princeton University · Queens University · Science & Technology Facilities Council Daresbury Laboratory · SNOLAB · South Dakota Mines · Technische Universität Dresden · Tennessee Tech · TUNL Triangle Universities Nuclear Laboratory · Università degli Studi dell'Aquila · Università degli Studi di Milano · Università degli Studi di Milano-Bicocca · Università degli Studi di Padova · Roma Tre Università degli Studi · UCL · University of Houston · University of Liverpool · The University of New Mexico · The University of North Carolina at Chapel Hill · University of South Carolina · University of South Dakota · The University of Tennessee Knoxville · Texas The University of Texas at Austin · Warwick The University of Warwick · University of Washington · Universität Zürich[UZH] · Eberhard Karls Universität Tübingen

^{76}Ge Enrichment and Detector Production

Commercial Enrichment

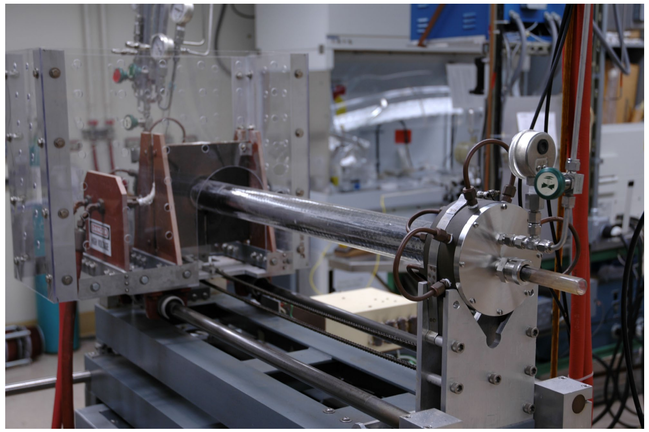
Germanium Oxide



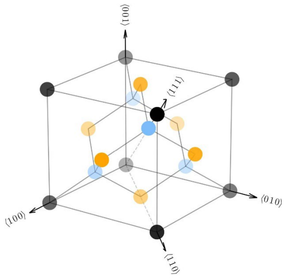
Germanium Metal



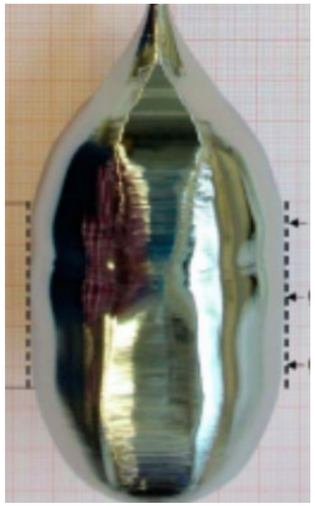
Zone Refining

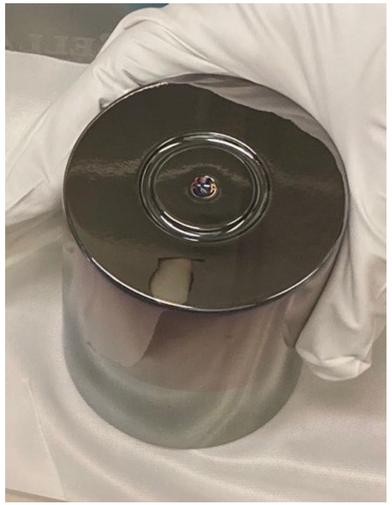






Crystal Growth



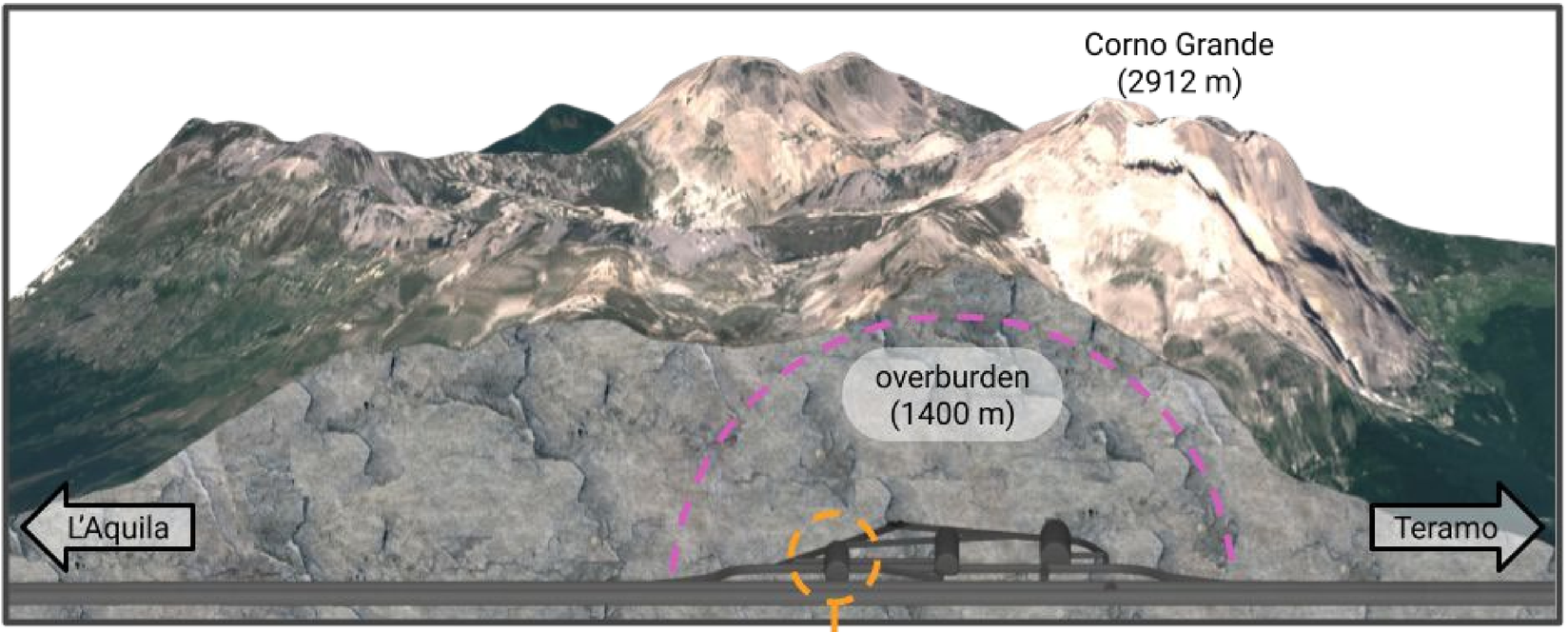


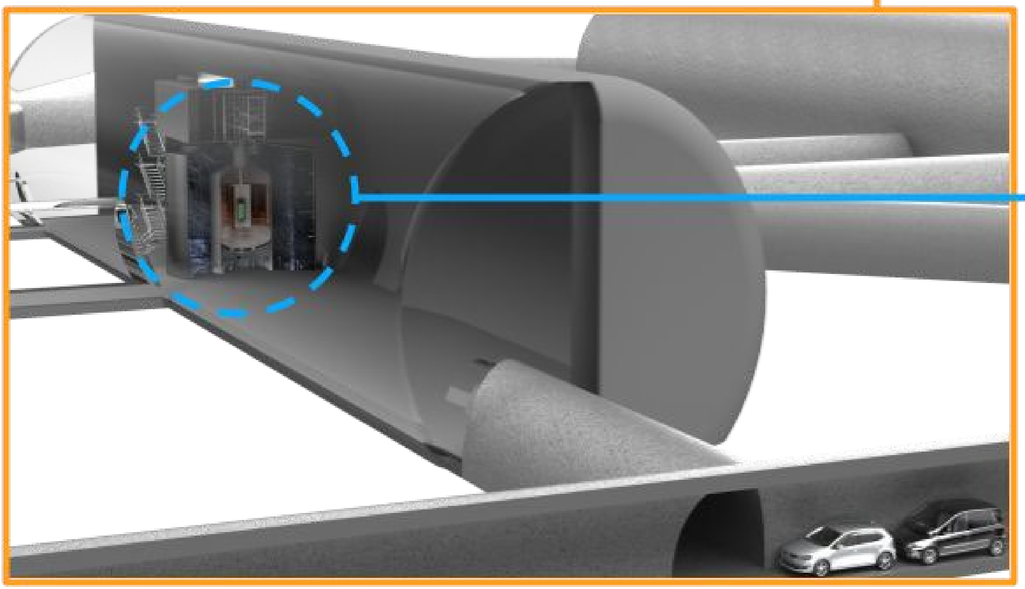
Detector Fabrication

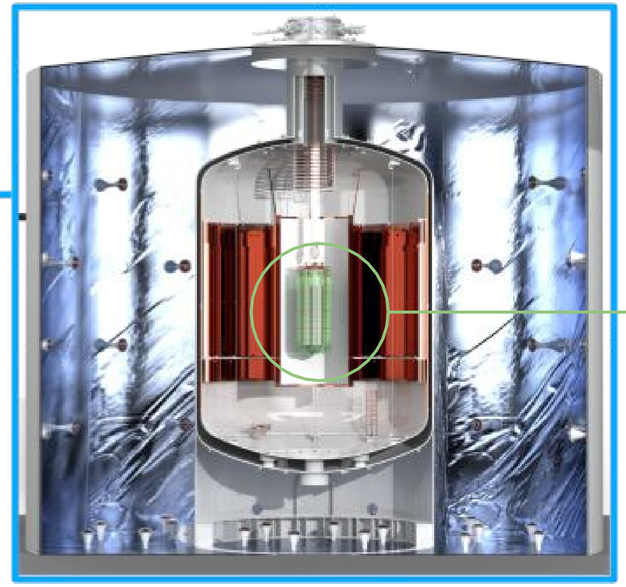


Acceptance Testing

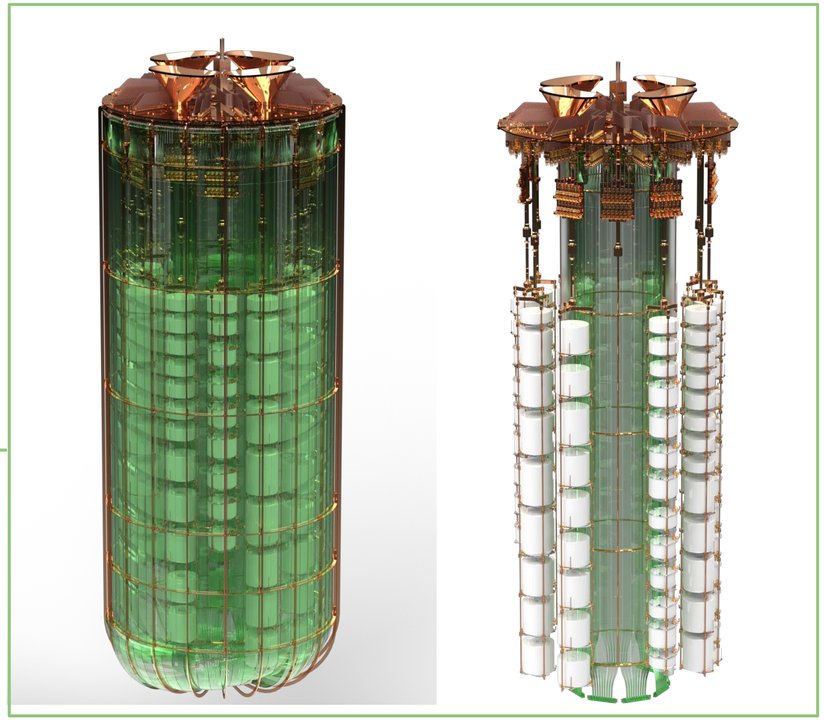
LEGEND-200: Location (LNGS Hall A) and design



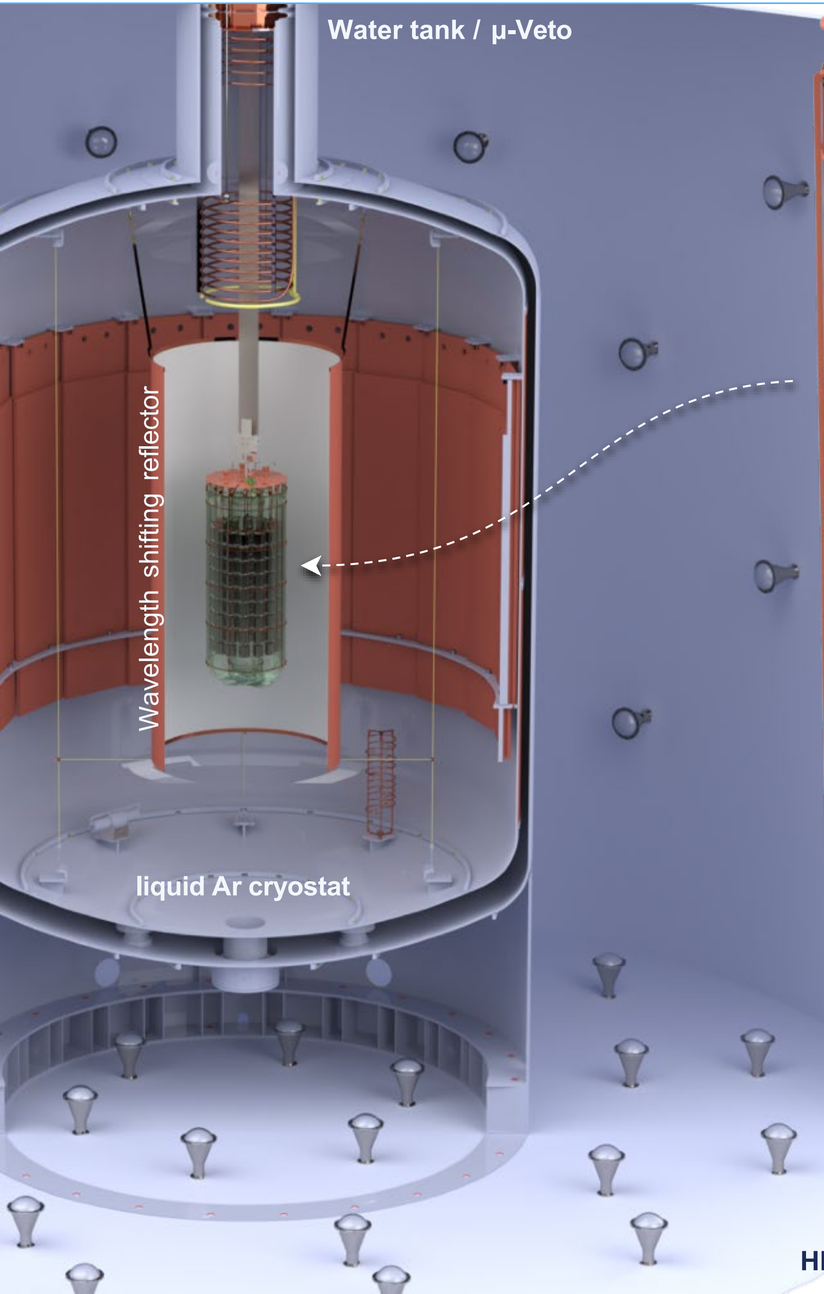


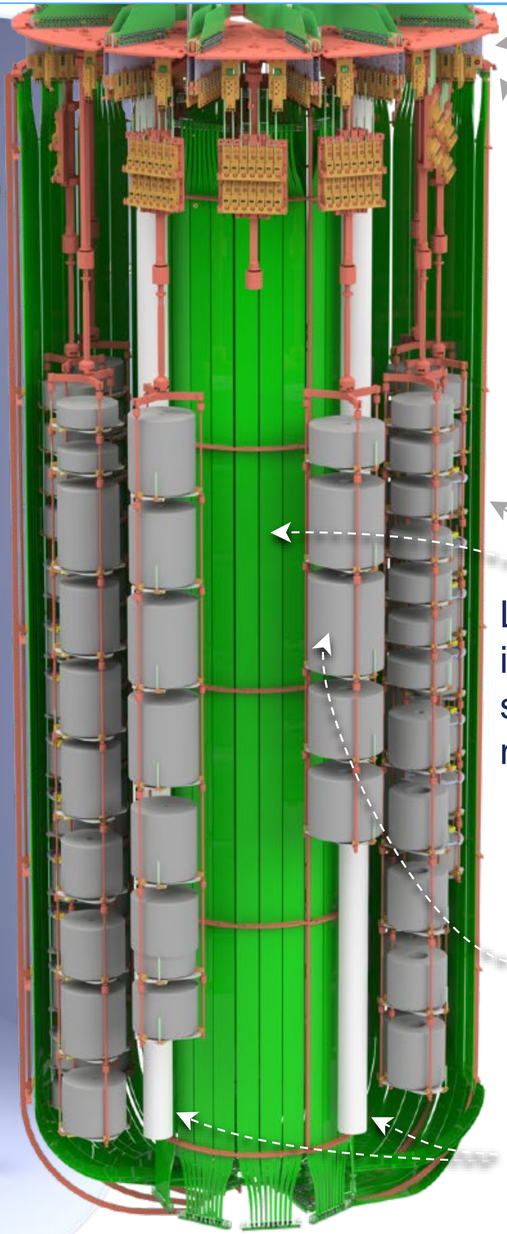


- Up to 200 kg HPGe Detectors
- LAr instrumentation (two fiber shrouds)
- Infrastructure of GERDA
- $T > 10^{27}$ yr
- $< 2 \cdot 10^{-4}$ cts/(keV kg yr)



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

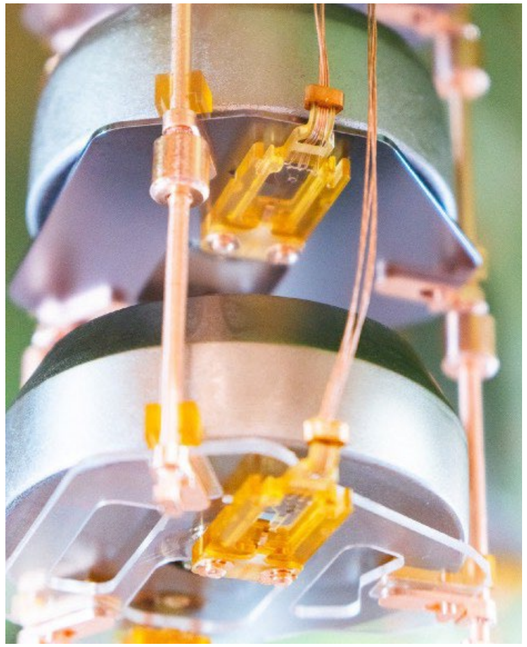


Larger mass (inverted coaxial)
HPGe detectors up to 4 kg

Source funnels for
^{228}Th calibration sources

LEGEND-200: Integration and commissioning

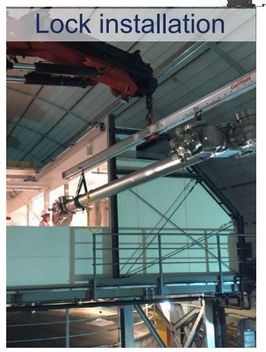
- ✓ water tank & cryostat from GERDA re-used

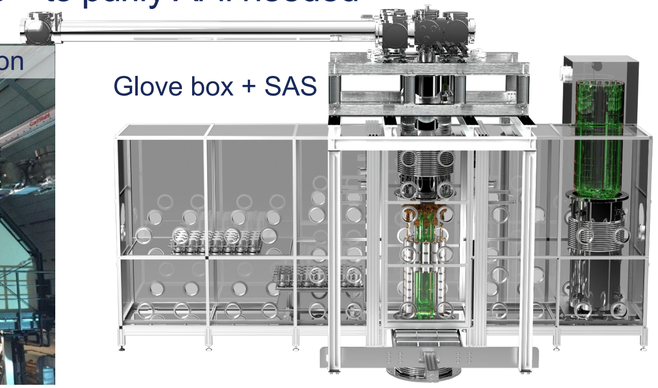


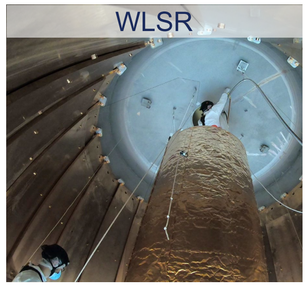
Post-GERDA Test:
First test of new technologies (HPGe electronics, PEN plates) & detectors in GERDA infrastructure

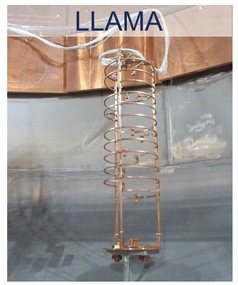
Cryostat infrastructure – completely new:

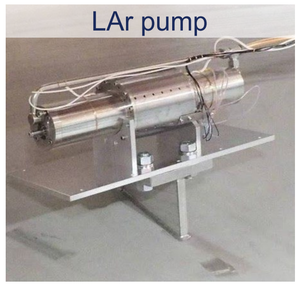
- Lock
- Mechanics
- Wiring
- Glovebox + string assembly system
- WLSR – to improve LAr veto efficiency
- LLAMA – to constantly check LAr quality
- LAr pump – to purify Ar if needed

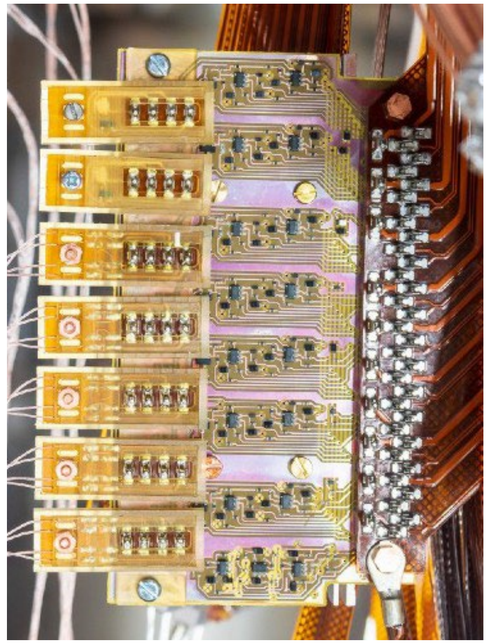






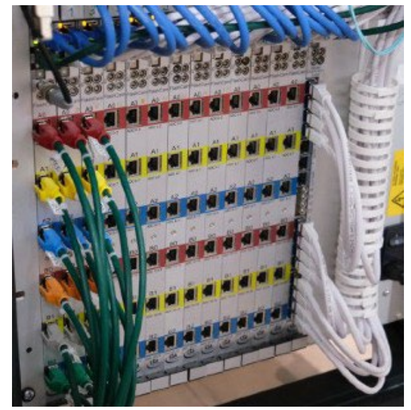








Electronics & DAQ tests:



Electronics & DAQ tests
Mechanics & glovebox installation

Post-GERDA Test

Upgrade of cryostat infrastructure

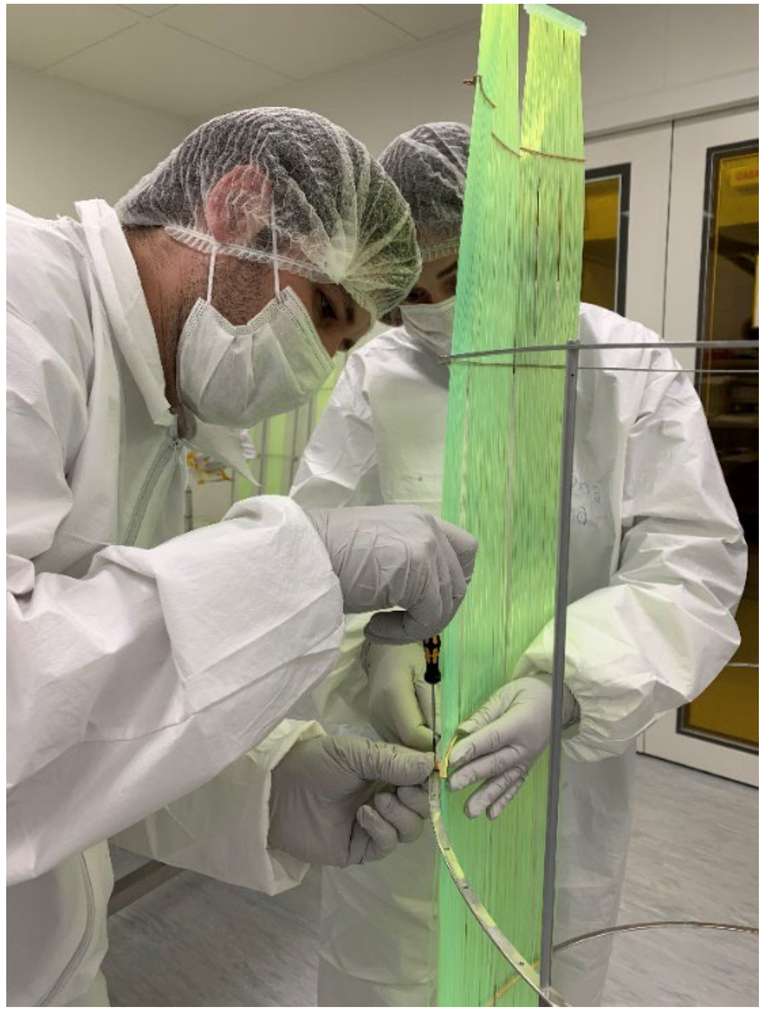
2020

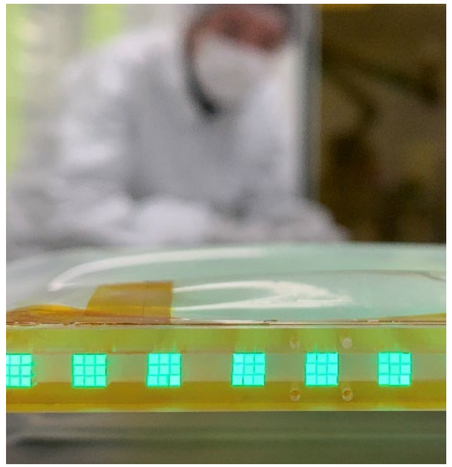
2021

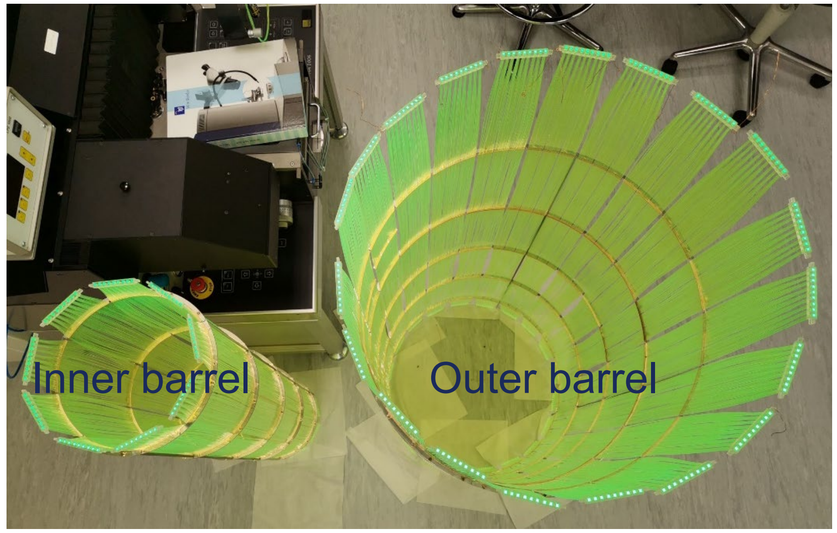
LEGEND-200: Integration and commissioning

LAr instrumentation production

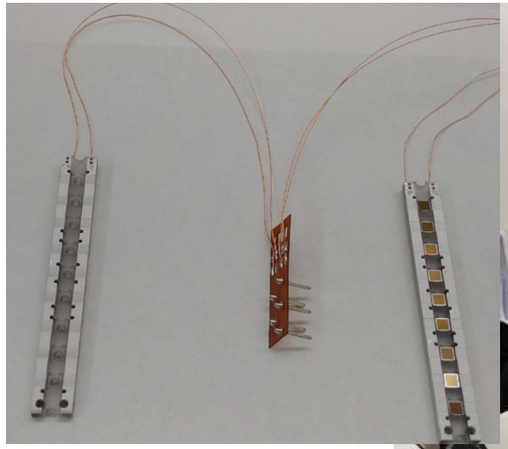
Production of LAr instrumentation modules







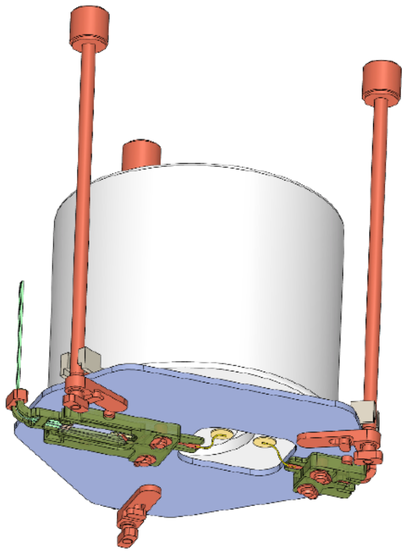
Bonding of SiPM arrays



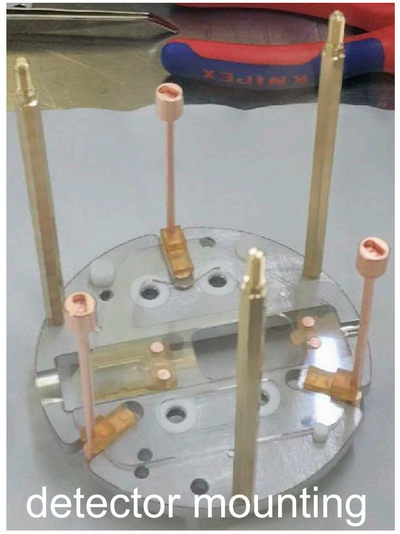


LEGEND-200: Integration and commissioning

HPGe detectors mounting and bonding and string assembly



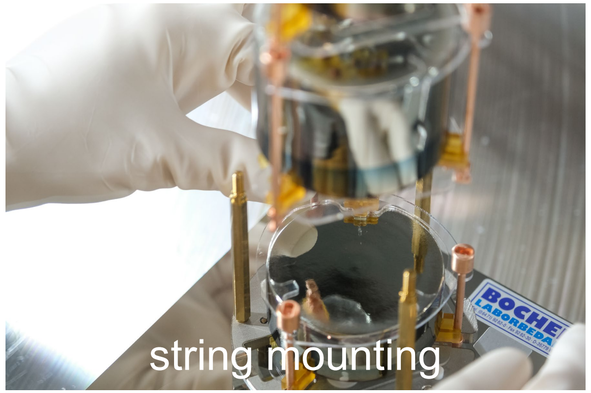
layout of bonded HV and signal contacts



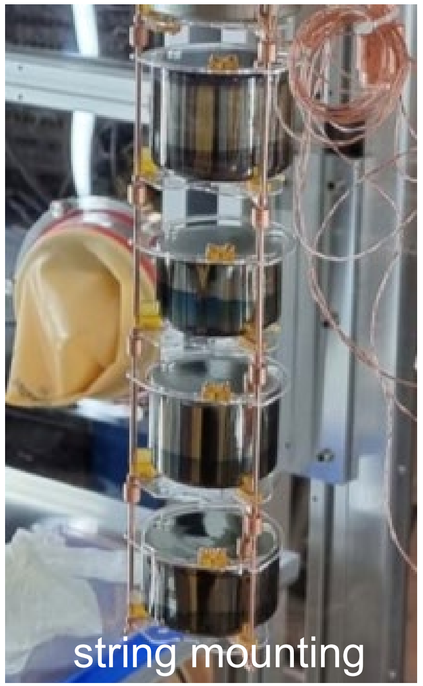
detector mounting



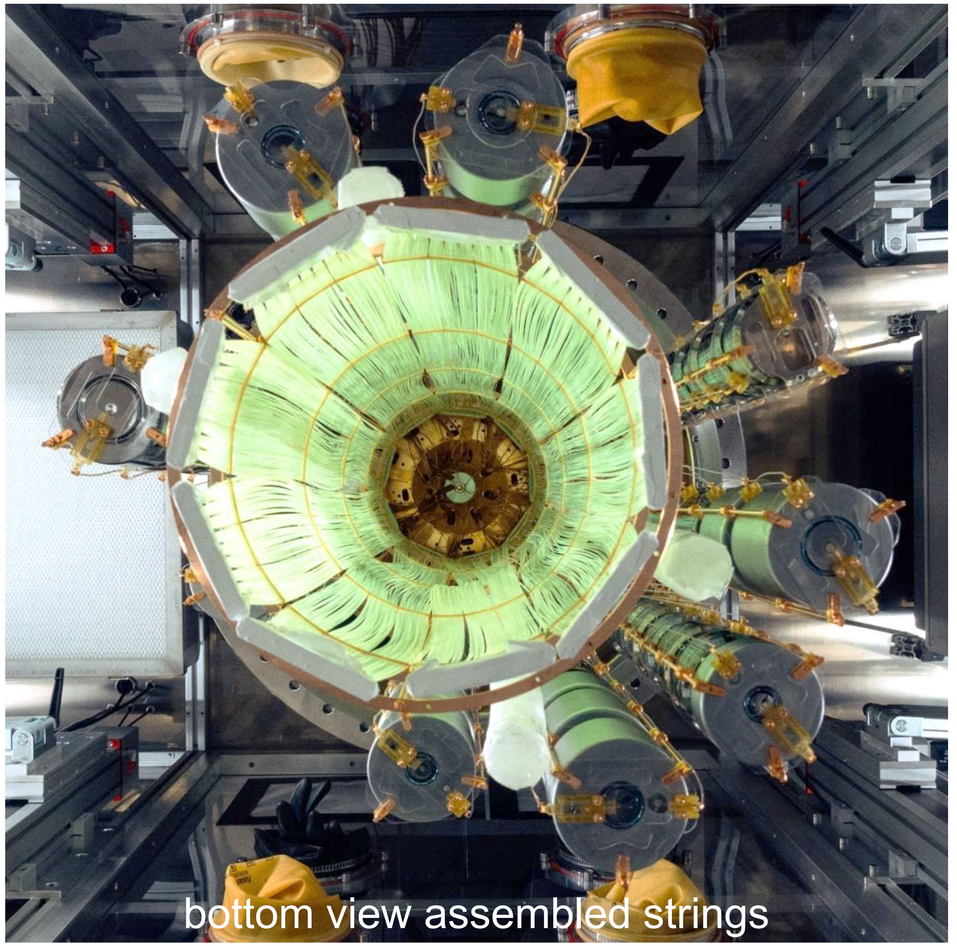
detector mounting



string mounting



string mounting



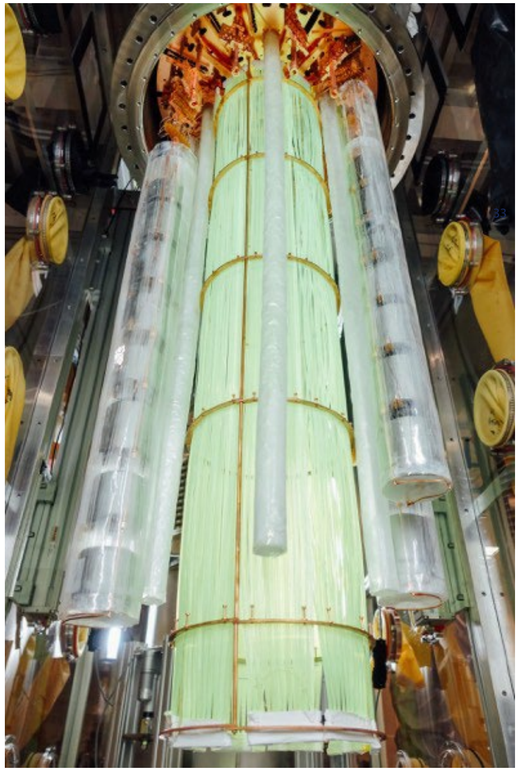
bottom view assembled strings

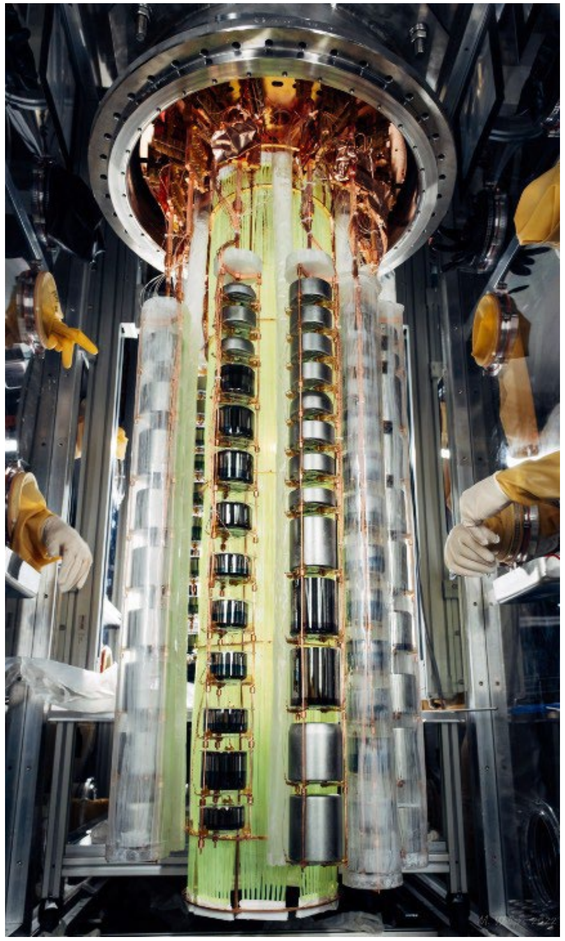
LEGEND-200: Integration and commissioning

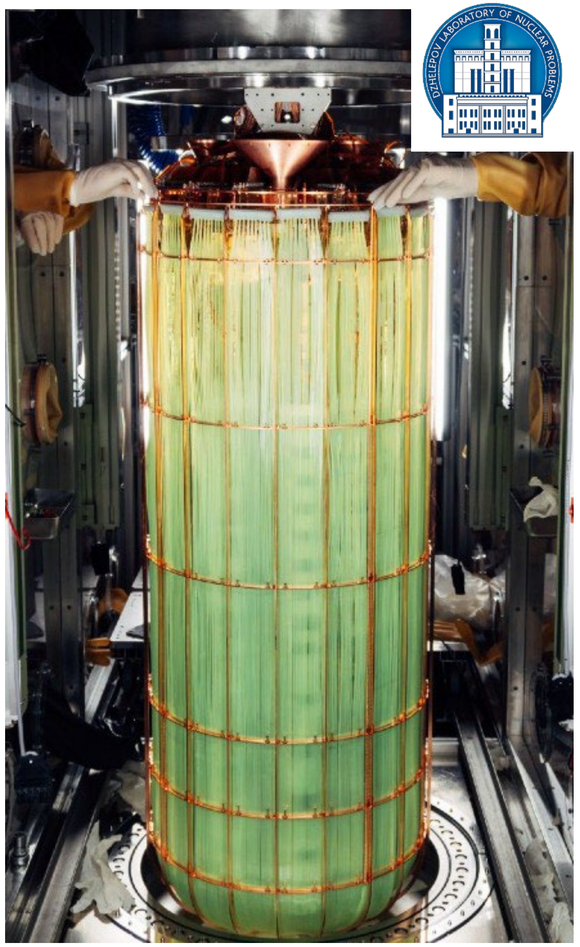


LAr instrumentation:
Commissioning of LAr instr. hardware & readout electronics.

60 kg campaign:
First operation of 60 kg of HPGe detectors and full LAr instr.
Final hardware optimisations
Special calibration runs







142 kg installation:
Installation of all available HPGe detectors as well as full LAr installation, DAQ, readout electronics

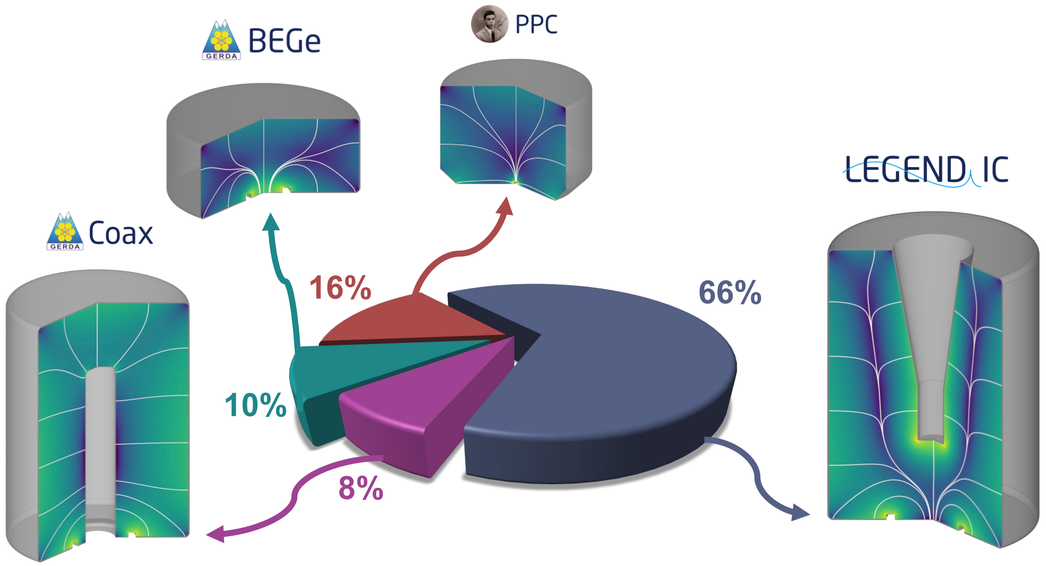
Electronics & LAr instrumentation commissioning — 2022

60 kg campaign + special calibration

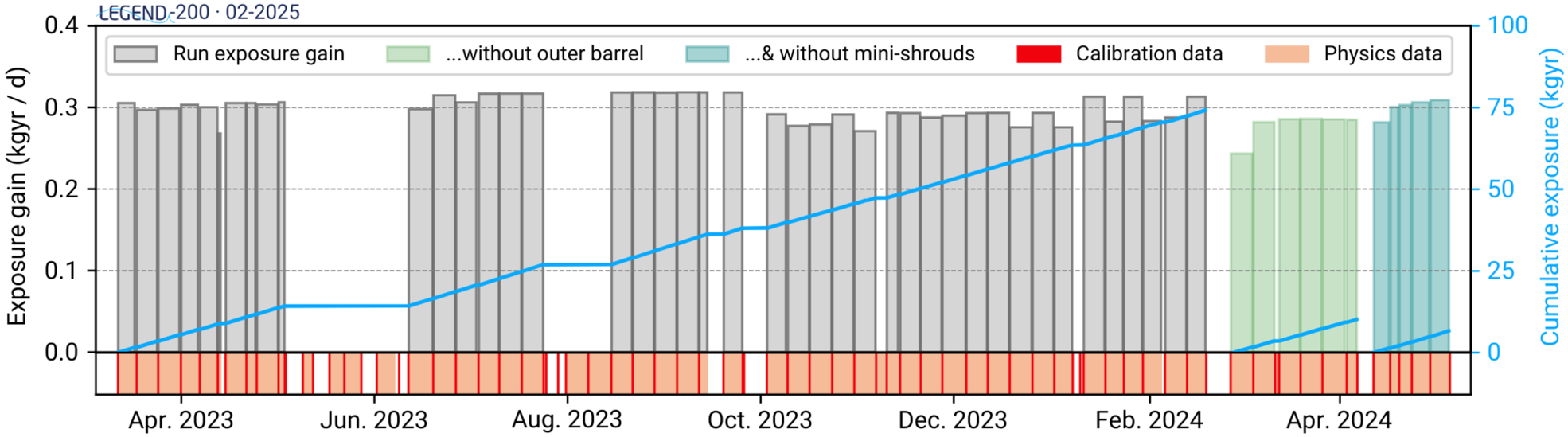
142 kg installation & commissioning — 2023

Physics data taking

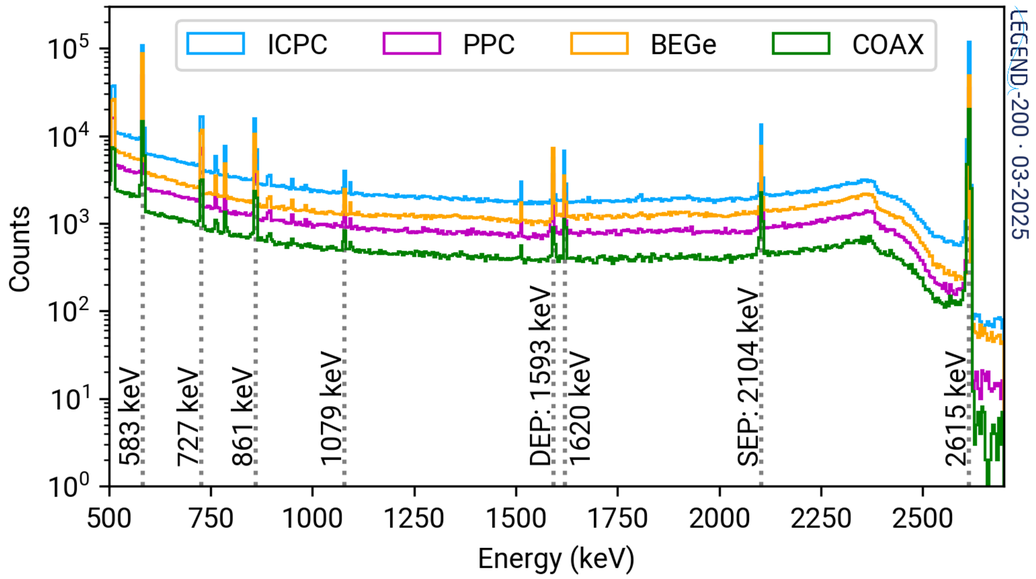
LEGEND-200: Taking first data



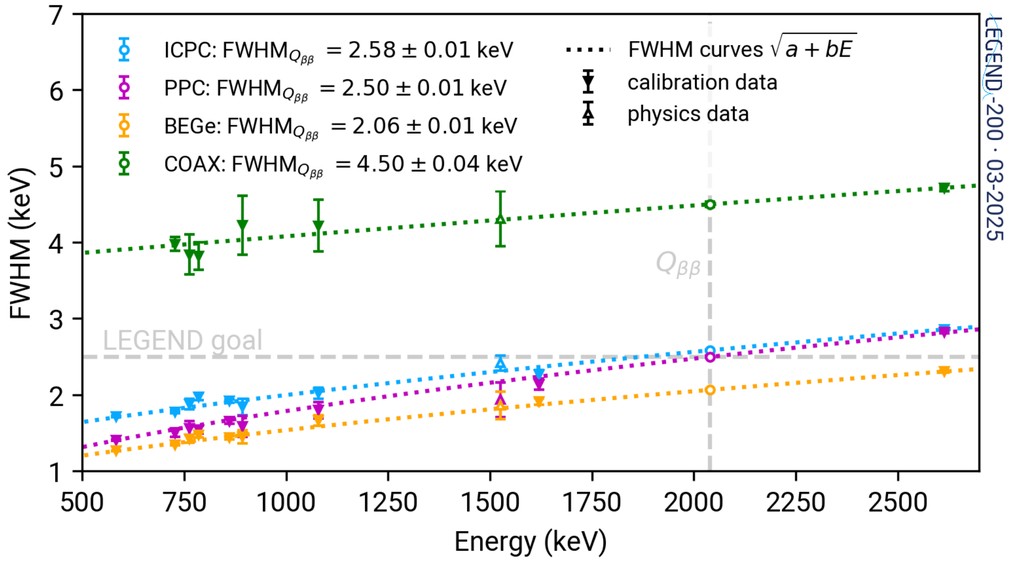
- About 1 year of data taking
- First results with 48 kg·yr exposure, updated with 61 kg·yr

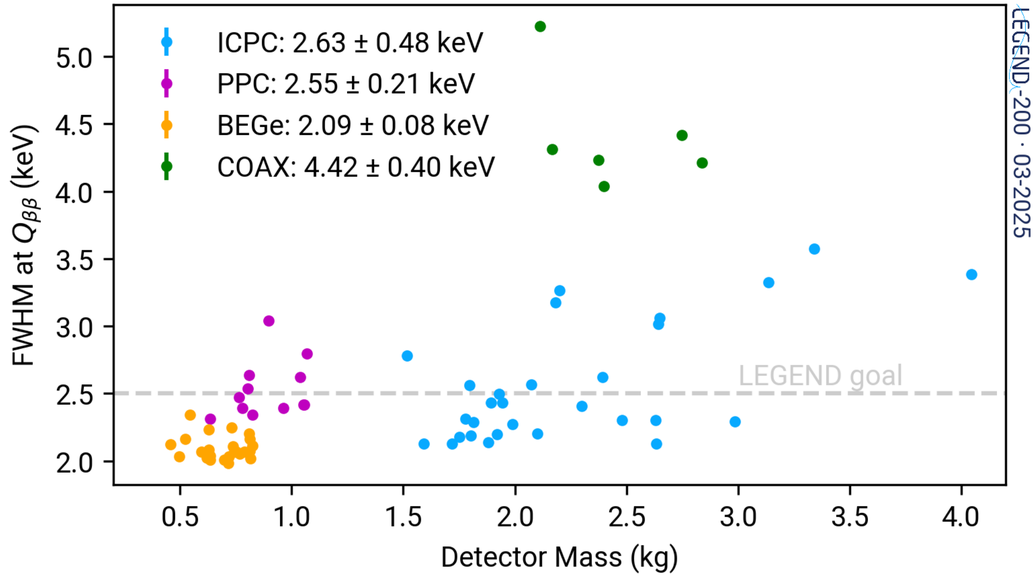


LEGEND-200: Energy Scale and Resolution

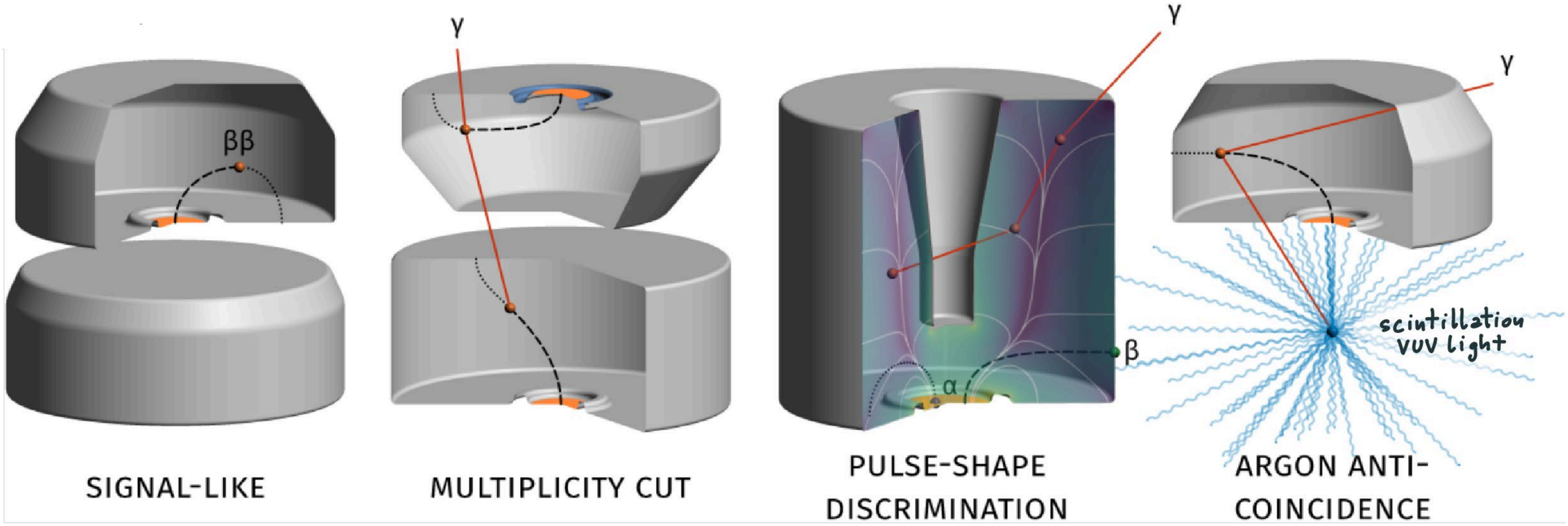


- Energy scale evaluated by weekly ^{228}Th calibration between physics runs
- Most detectors fulfill LEGEND energy resolution goal (0.12% at $Q_{\beta\beta}$)
- Stable energy scale among calibrations
- Data partitioned according to stability of energy observables

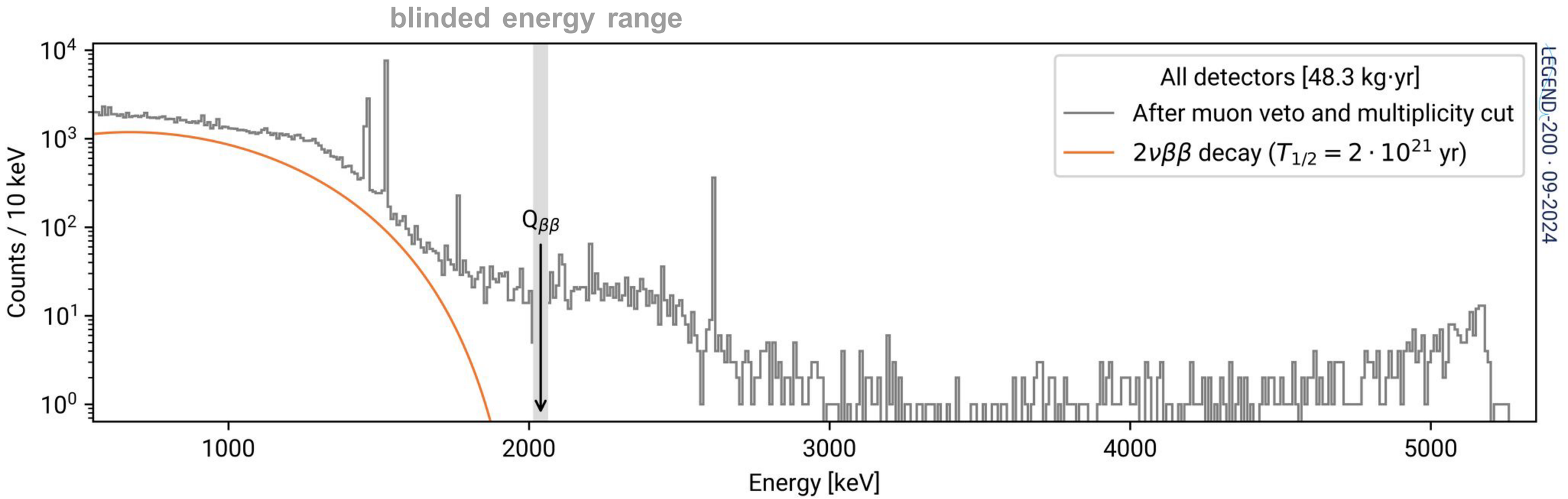




LEGEND-200: Signal and background discrimination



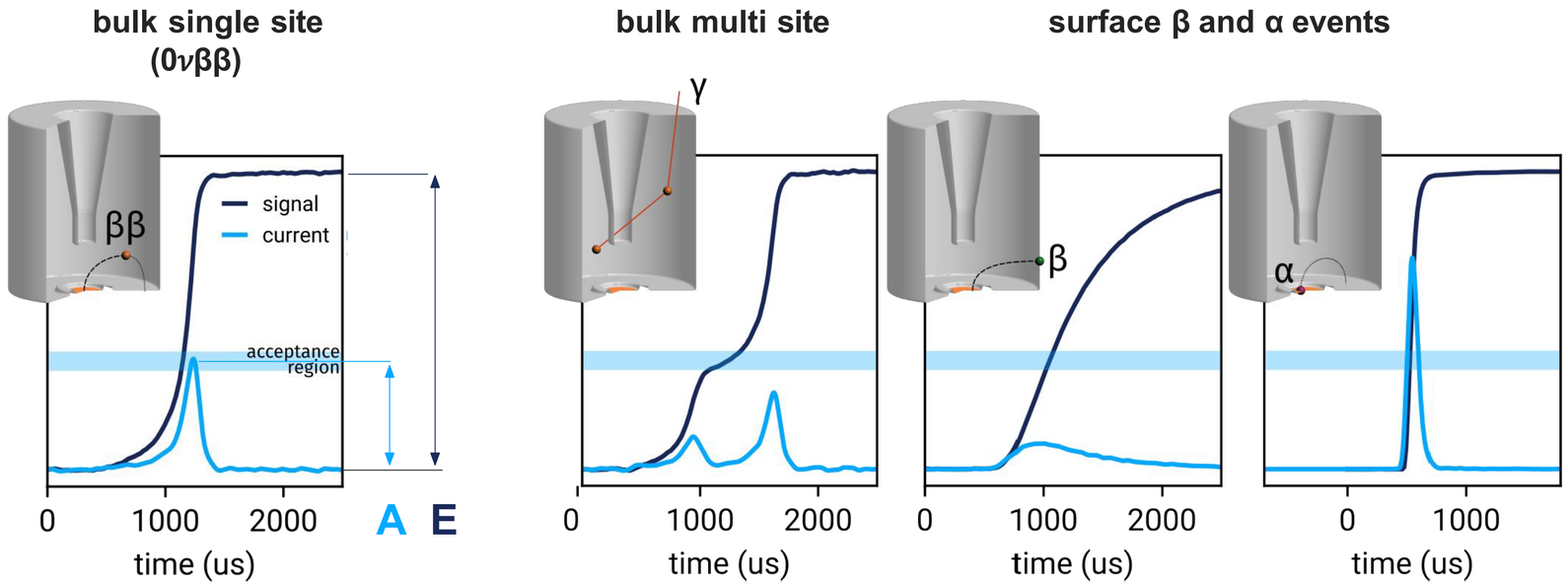
LEGEND-200: Quality, Muon Veto and Multiplicity

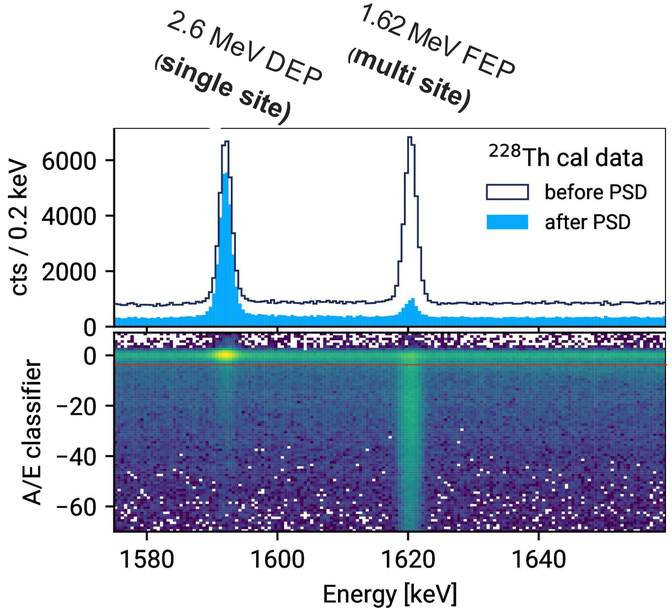


- **Blinding** applied at $Q_{\beta\beta}$ = 2039 keV (50 keV window)
- 26% of events rejected by multiplicity cut near $Q_{\beta\beta}$

LEGEND-200: HPGe Pulse Shape Discrimination

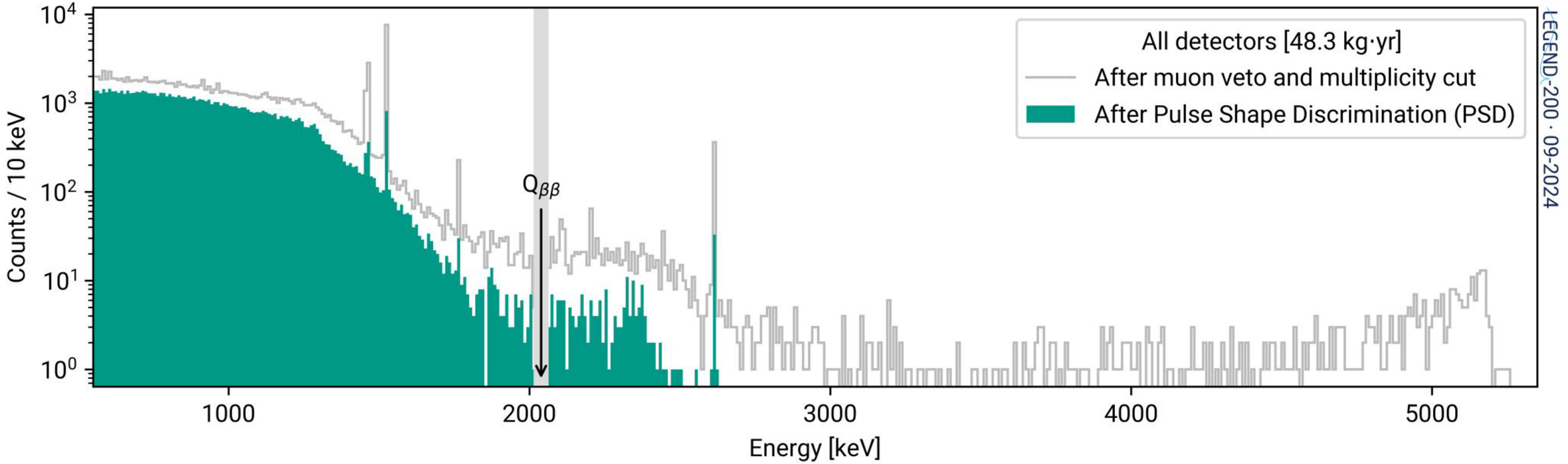
- **Pulse shape classifier: A/E = max(current) / energy**





- 0νββ survival fraction of ~(85±4)%

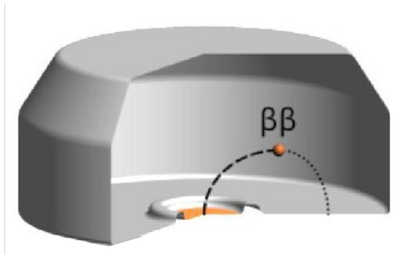
LEGEND-200: After PSD



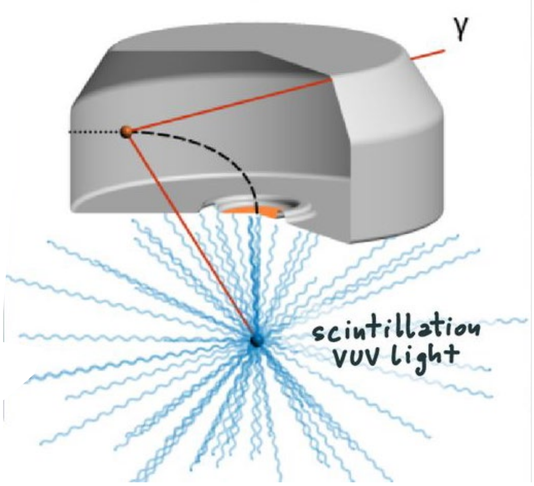
- Strong suppression of surface α and β (^{42}K) events
- ~40% of Compton are single-site events at $Q_{\beta\beta}$

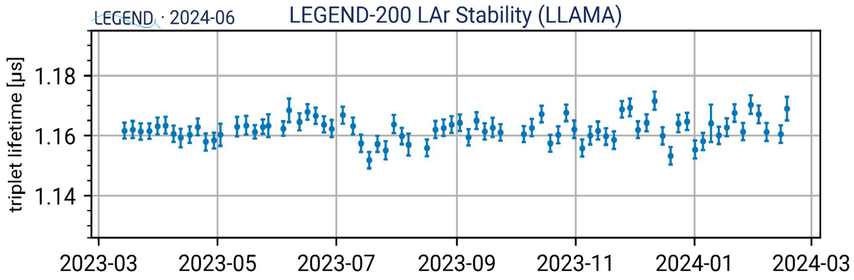
LEGEND-200: Argon anti-coincidence

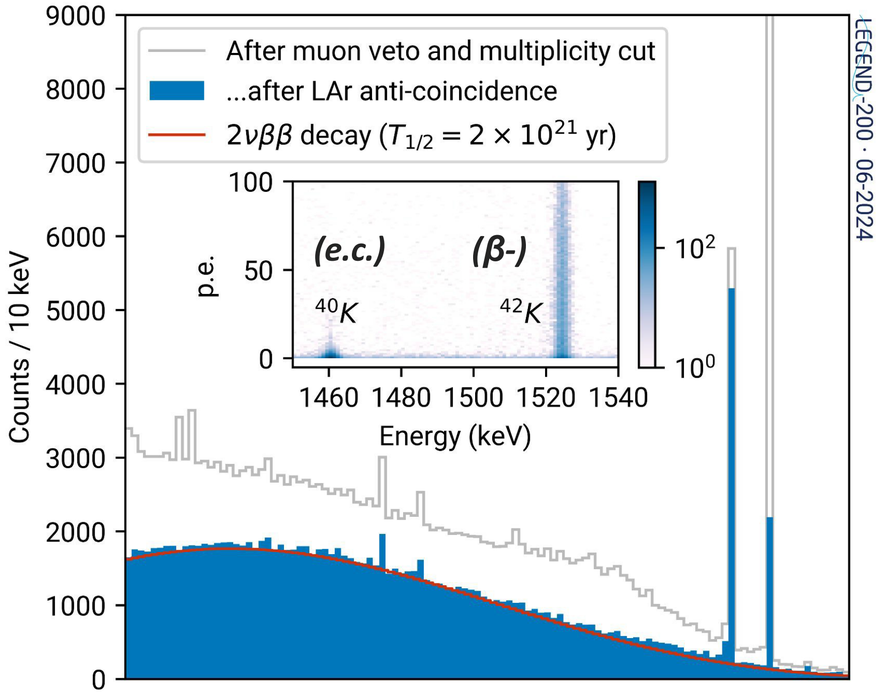
Signal
w/o scintillation light



Background
w/ scintillation light

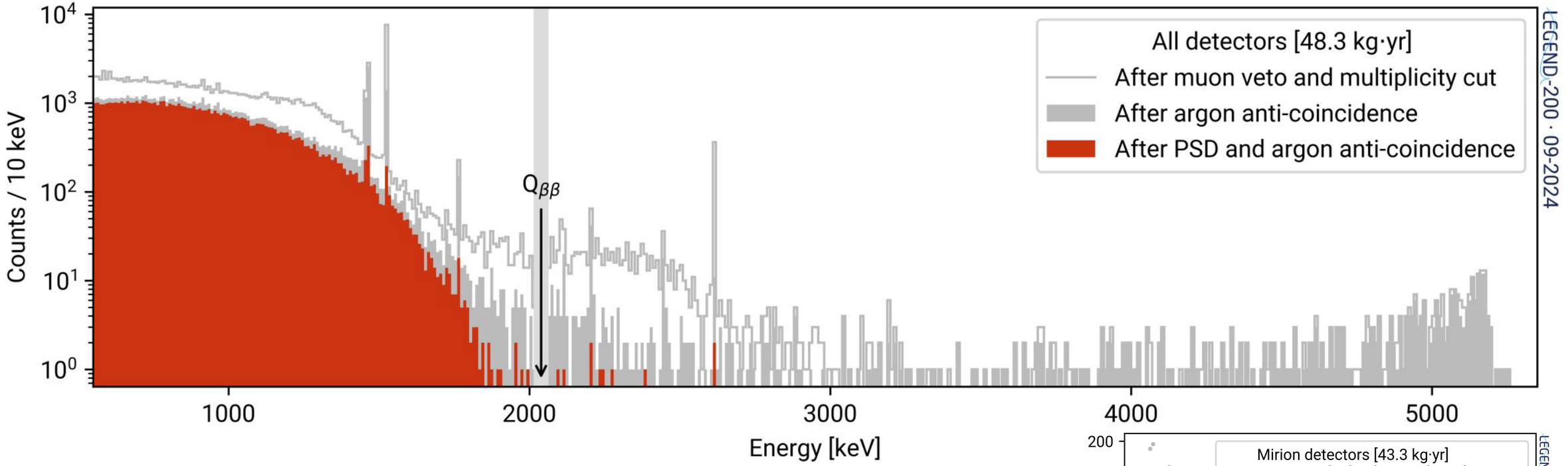




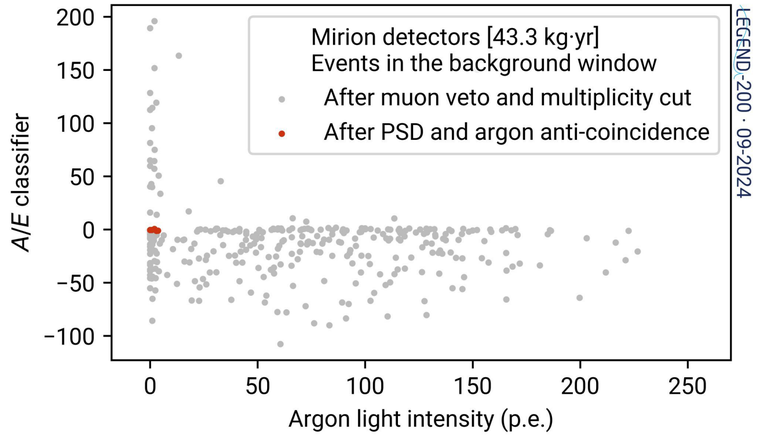


- Strong suppression of background above 2νββ
- ββ decay signal acceptance of ~93%

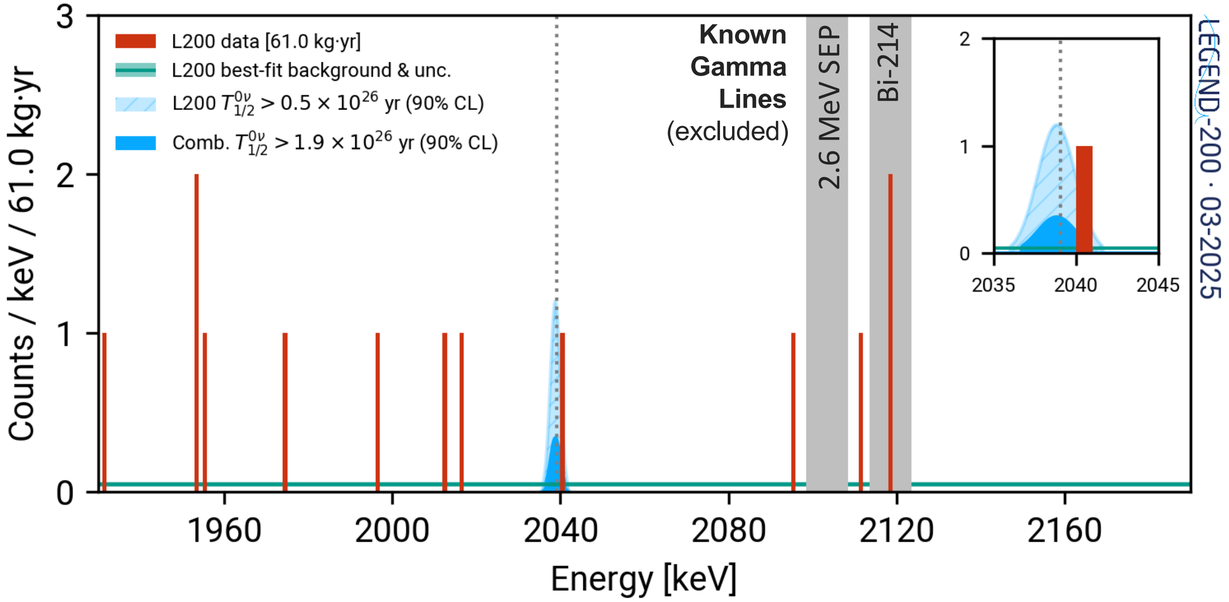
LEGEND-200: After PSD and LAr anti-coincidence



- Strong anti-correlation of argon and PSD cuts
- Overall 0νββ survival fraction of ~60%



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.)

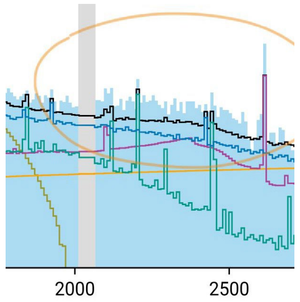
Sensitivity	Observed
2.8×10^{26} yr	$> 1.9 \times 10^{26}$ yr

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

PRL136, 022701 (2026)

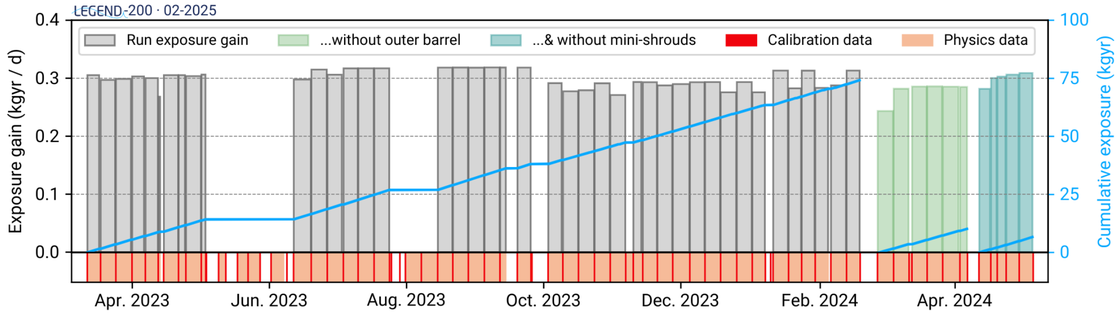
LEGEND. Episode 200: The Phantom Menace

- Background in 1st physics run ~2-3 times higher than predicted
  - Higher ^{208}Tl / ^{214}Bi levels before cuts



radio assay expectation

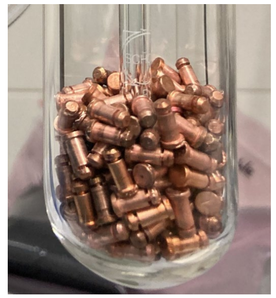
- Forensic campaign:
  - Special runs: w/o outer fiber barrel and then w/o nylon mini-shrouds



  - Array fully disassembled in 2024, and all components sent for assays



γ assay

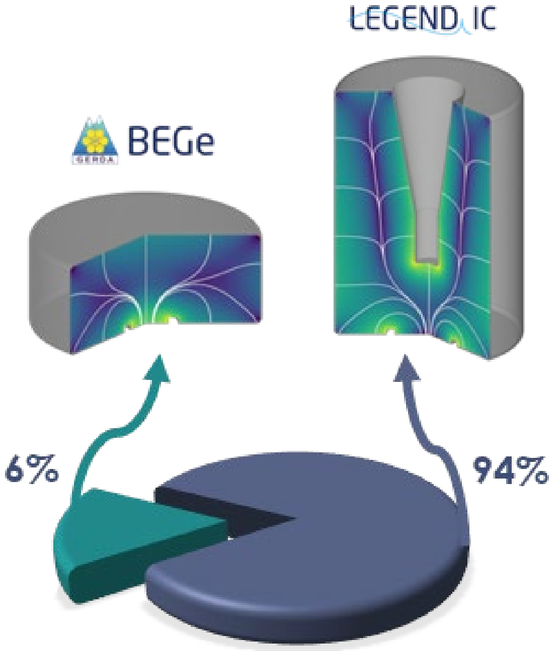


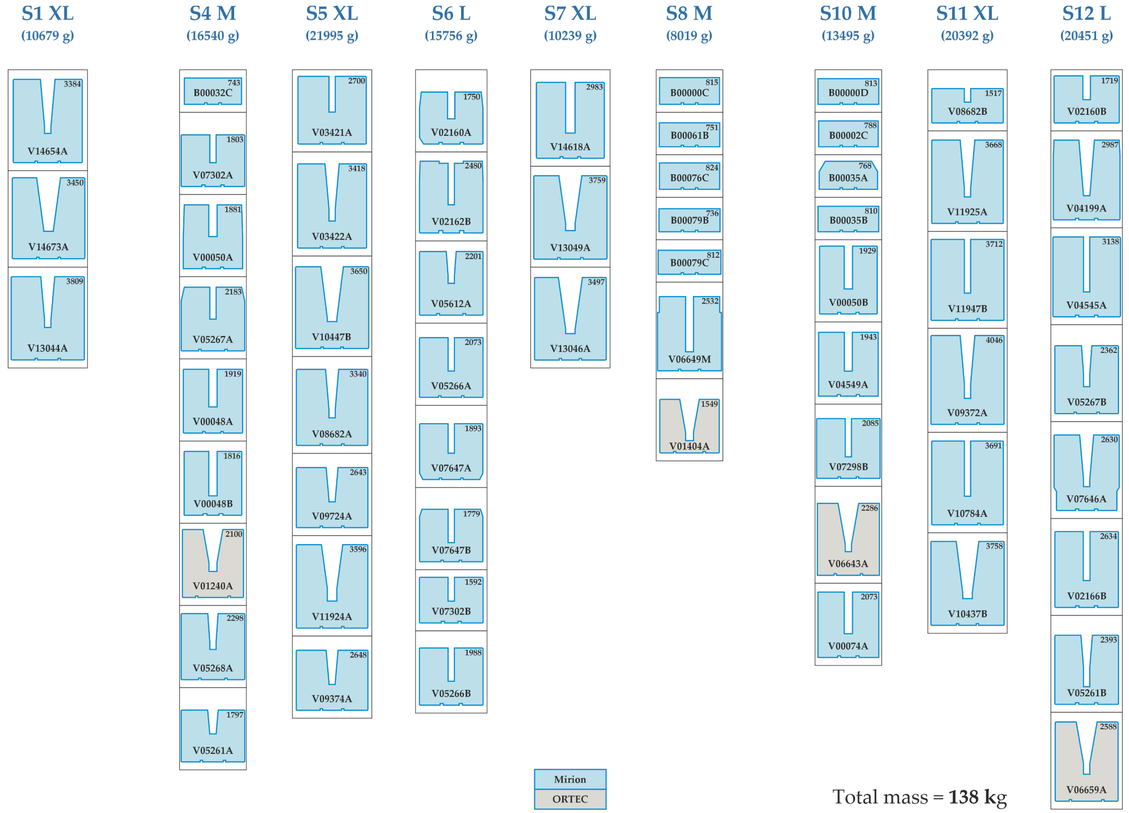
Rn emanation assay

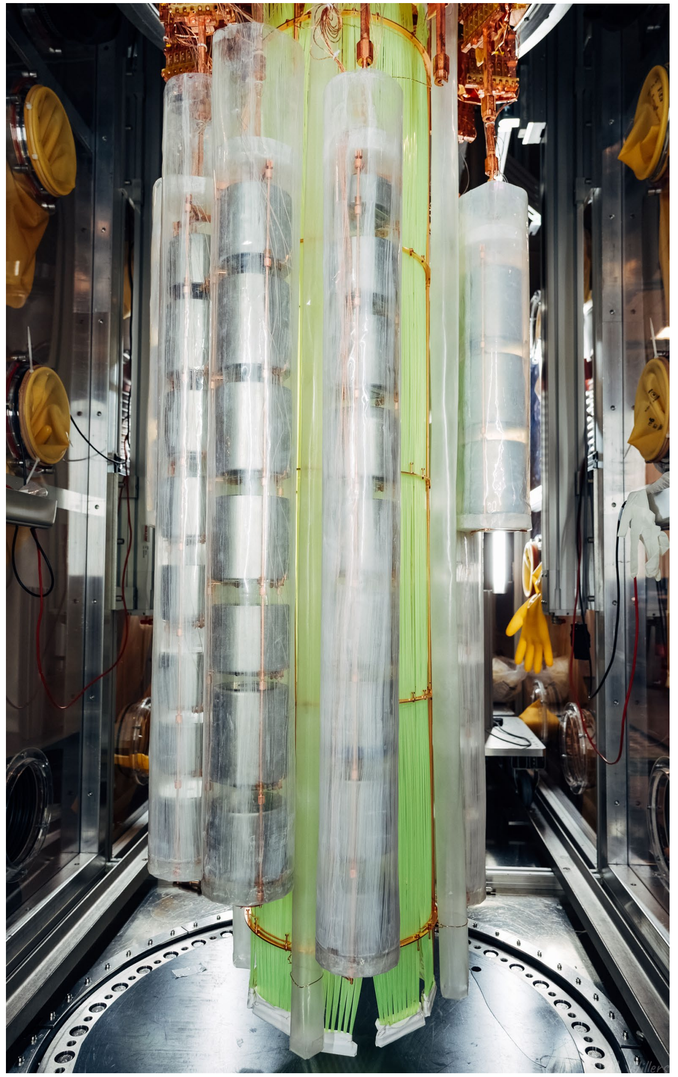
Results from assays: elevated ^{208}Tl / ^{214}Bi in some components – possible surface contamination

LEGEND-200: Redeployment

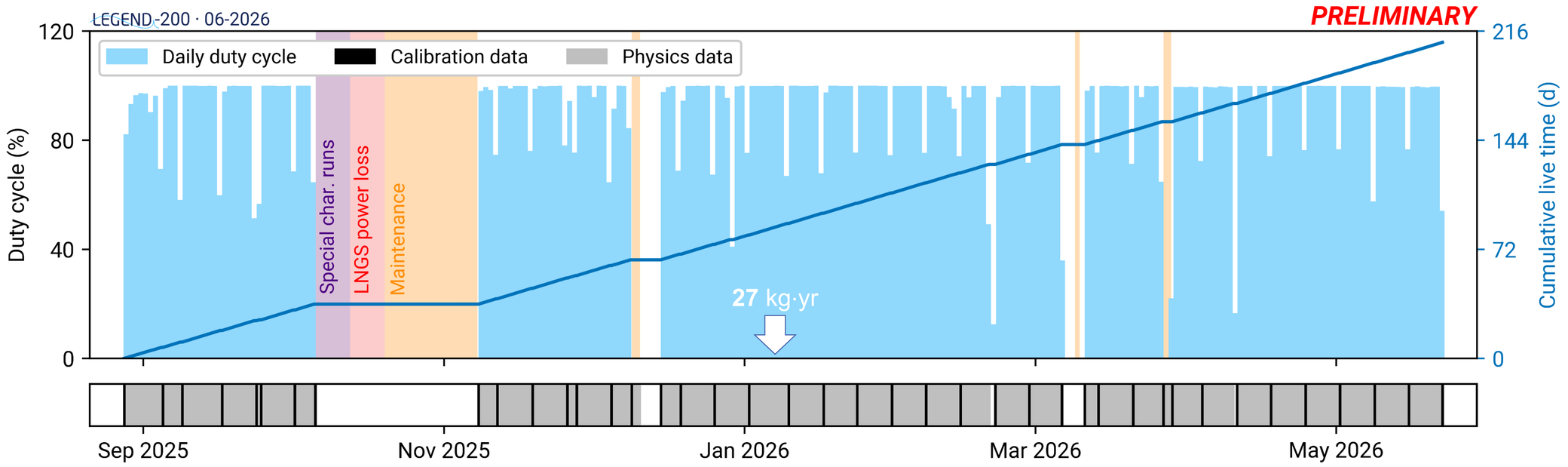
- In July 2025 after **re-etching/leaching** of all close-by **components ~138 kg** of enriched HPGe detectors were redeployed (60 detectors in 9 strings) then data taking was restarted
- The operational strategy of LEGEND-200 has been modified to primarily utilize IC detectors, aligning more closely 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-200: Status



- **Stable** data taking after redeployment for ~1 year
- **Duty cycle**: 95% w/o downtimes (70% w/)

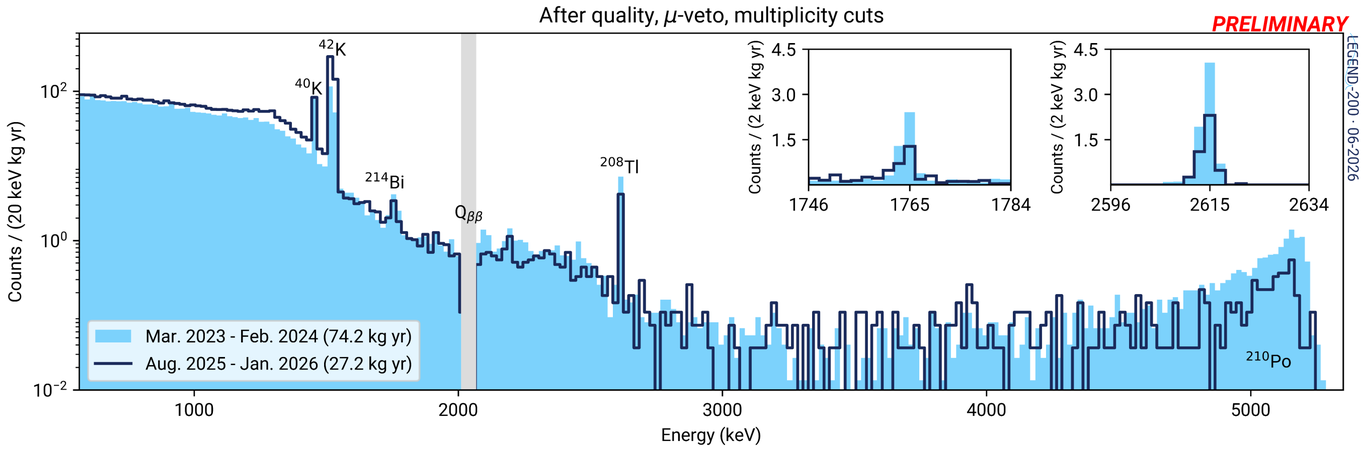
What about ^{208}Tl / ^{214}Bi?

- Data validated and shown: ~27 kg·yr exposure (Aug 2025 – Jan 2026)

LEGEND. Episode 200: A New Hope

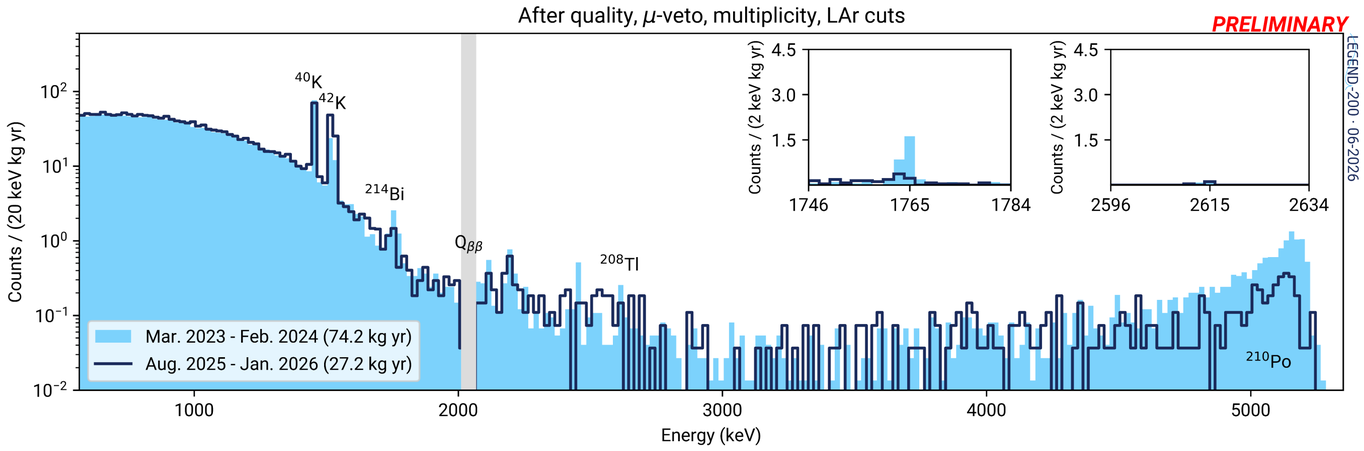
Before cuts

- ^{208}Tl / ^{214}Bi reduced by x2 compared with 1st year run



After LAr cut

- ^{214}Bi (1763 keV) – reduced by x5
- ^{208}Tl (2614 keV) – not visible @ current exposure

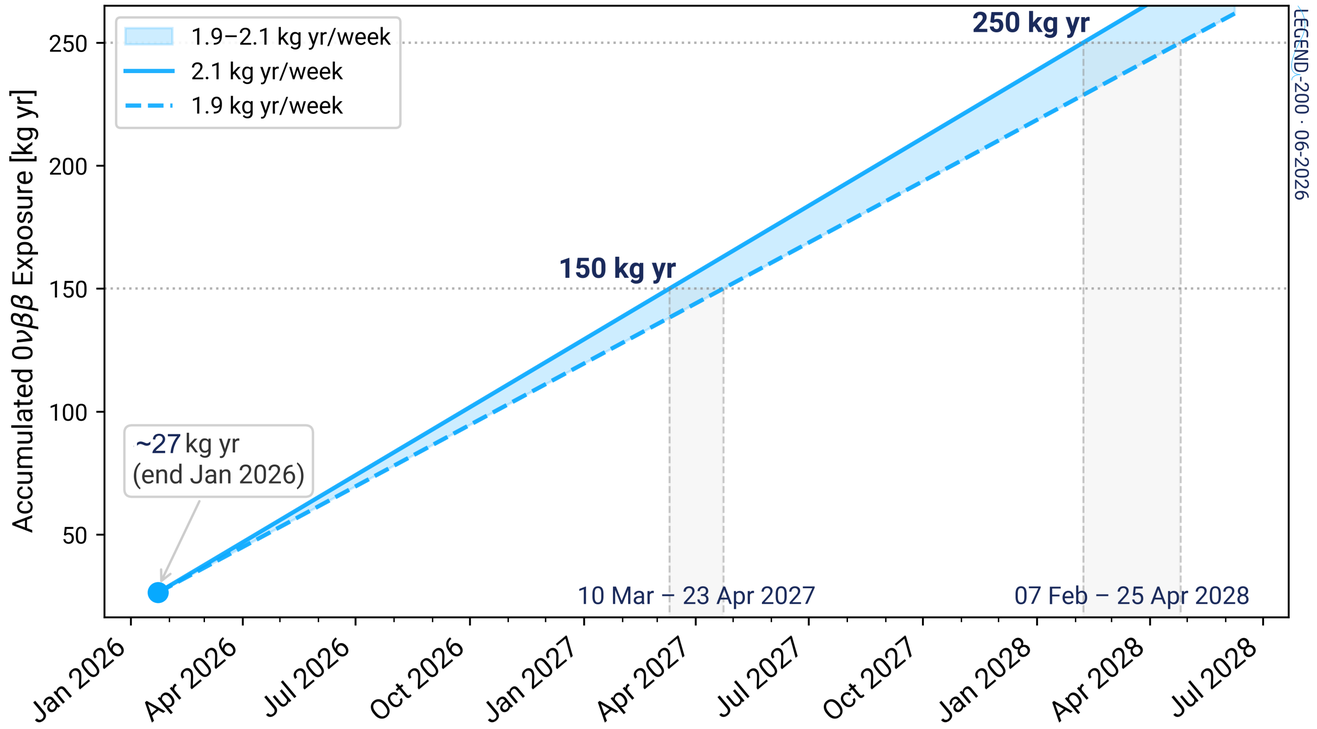


Effectiveness of re-etching and leaching shown!

LEGEND-200: Next steps

Ongoing data taking

- Take data to maximize exposure
- Residual background (after LAr & PSD) seems to be dominated by ^{42}K surface events (not a problem for L1000)

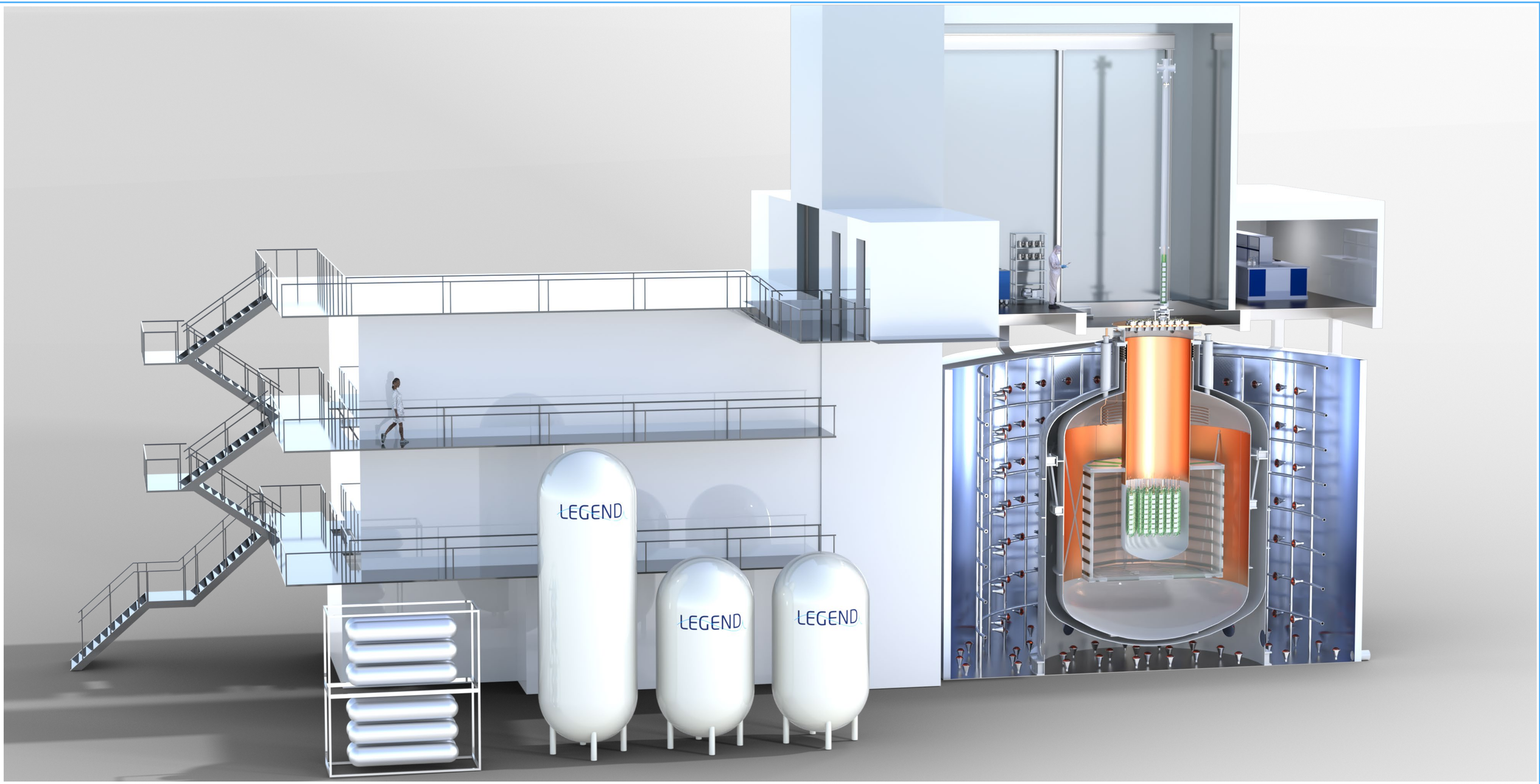


Next deployment (s?)

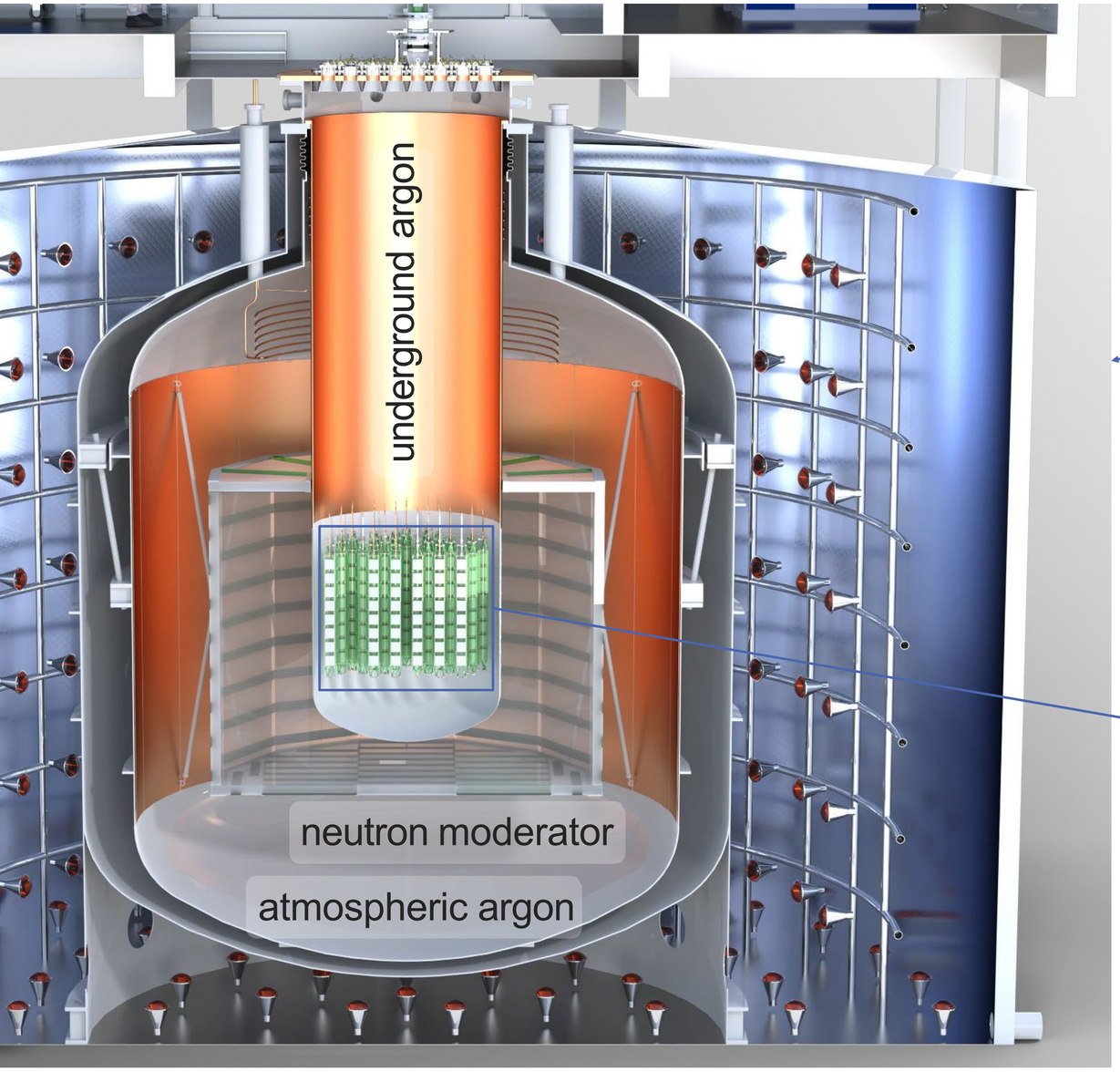
- + about 20 kg of new detectors (being produced)
- Serious R&D effort ongoing to be ready to improve the L200 setup then

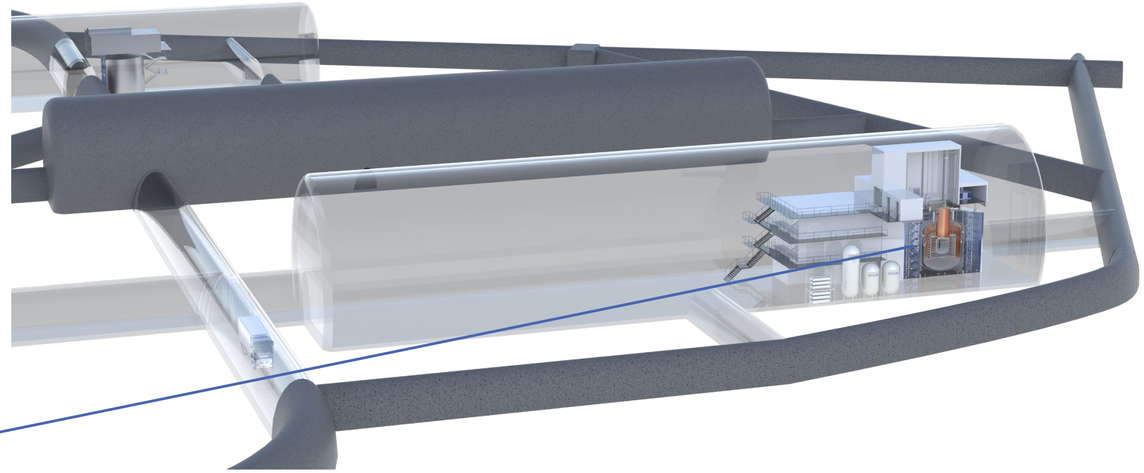
L200 is going to continue data taking until better BI in **L1000** will be shown

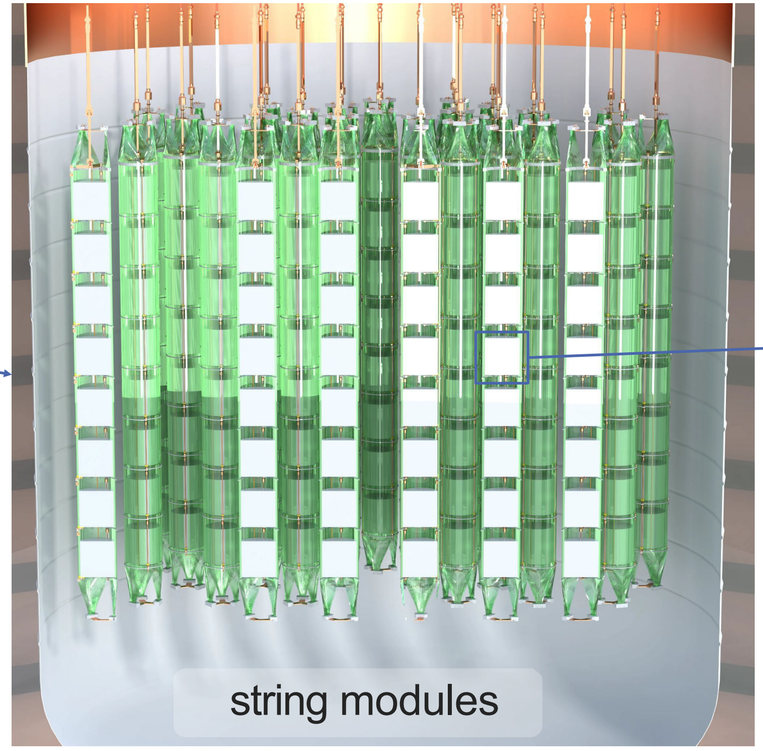
LEGEND. Episode 1000: The Force Awakens



LEGEND-1000 @ LNGS Hall C



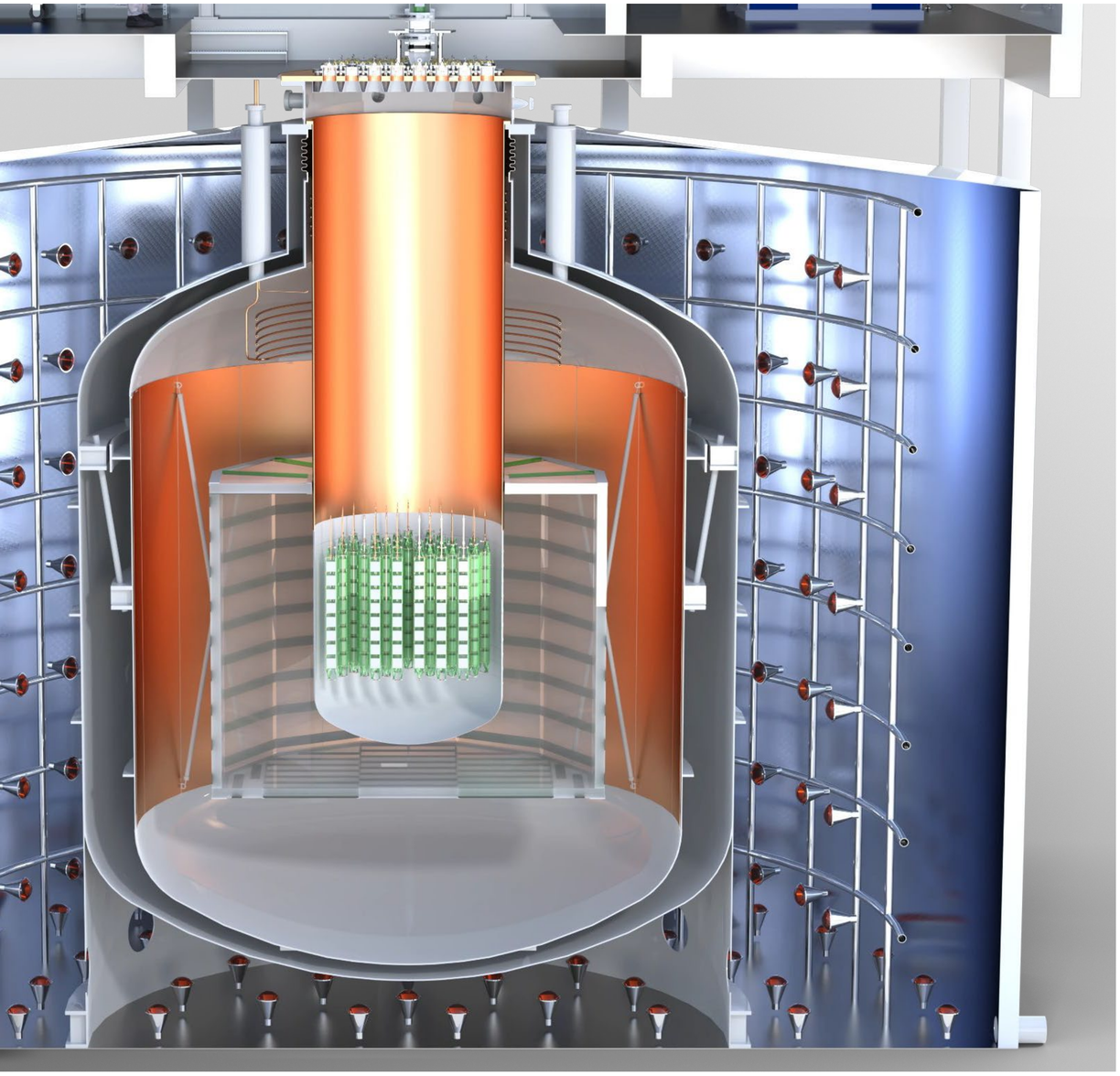






336 IC detectors
3 kg avg. mass

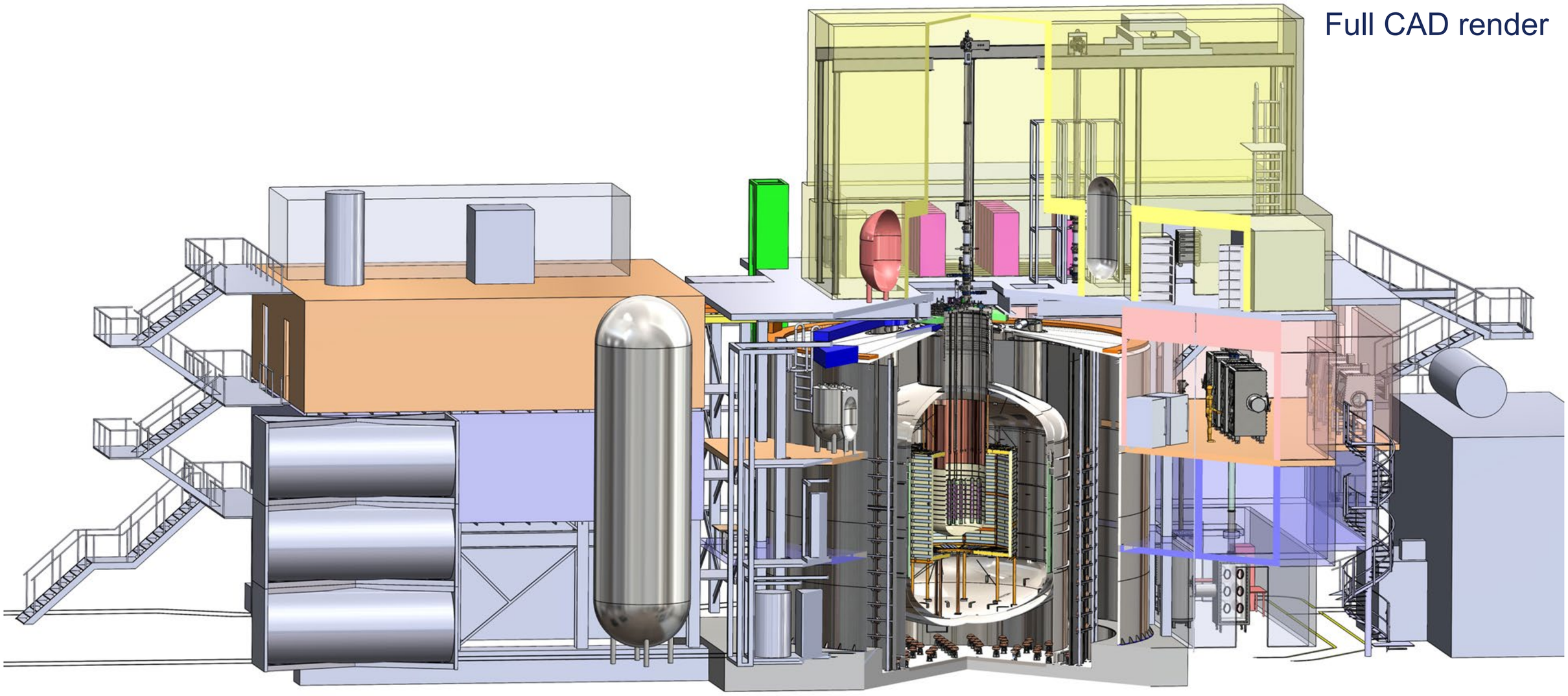
LEGEND-1000: Designed for an Unambiguous Discovery



- 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: $<1 \times 10^{-5}$ cts/(keV kg yr)

LEGEND-1000
Pre-Conceptual Design Report
arXiv:2107.11462

LEGEND-1000: Infrastructure

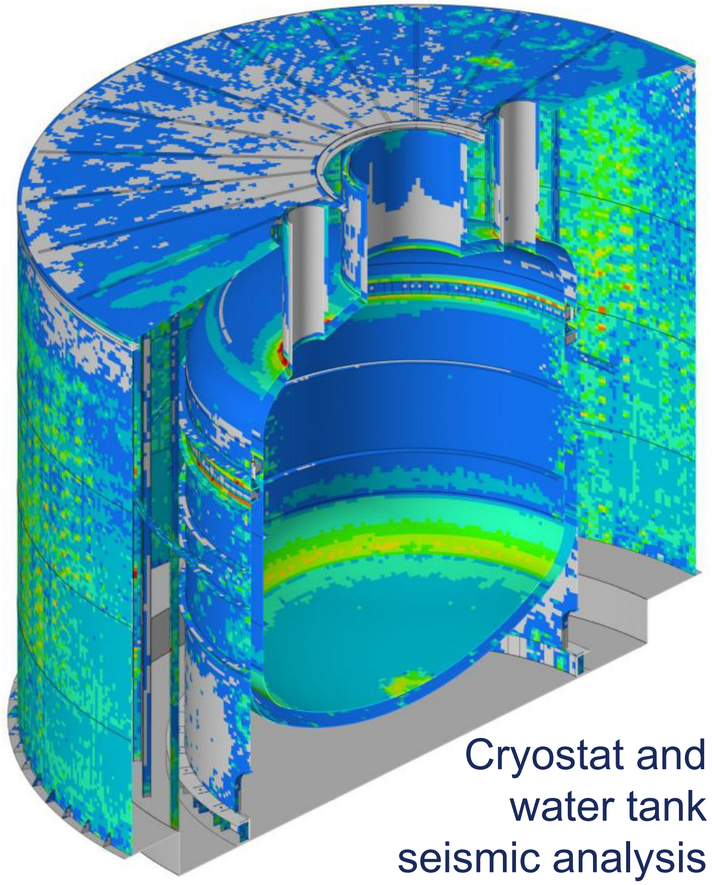


- Disassembly of BOREXINO experiment and site preparation are being started @ LNGS
- L1000 installation plan in hands

LEGEND-1000: Systems

Design of **cryostat** and water tank advanced

- Cryostat steel procured and assayed



Cryostat and
water tank
seismic analysis

UAr plant (DarkSide) being commissioned in Colorado

- Transport tank design ready for internal review



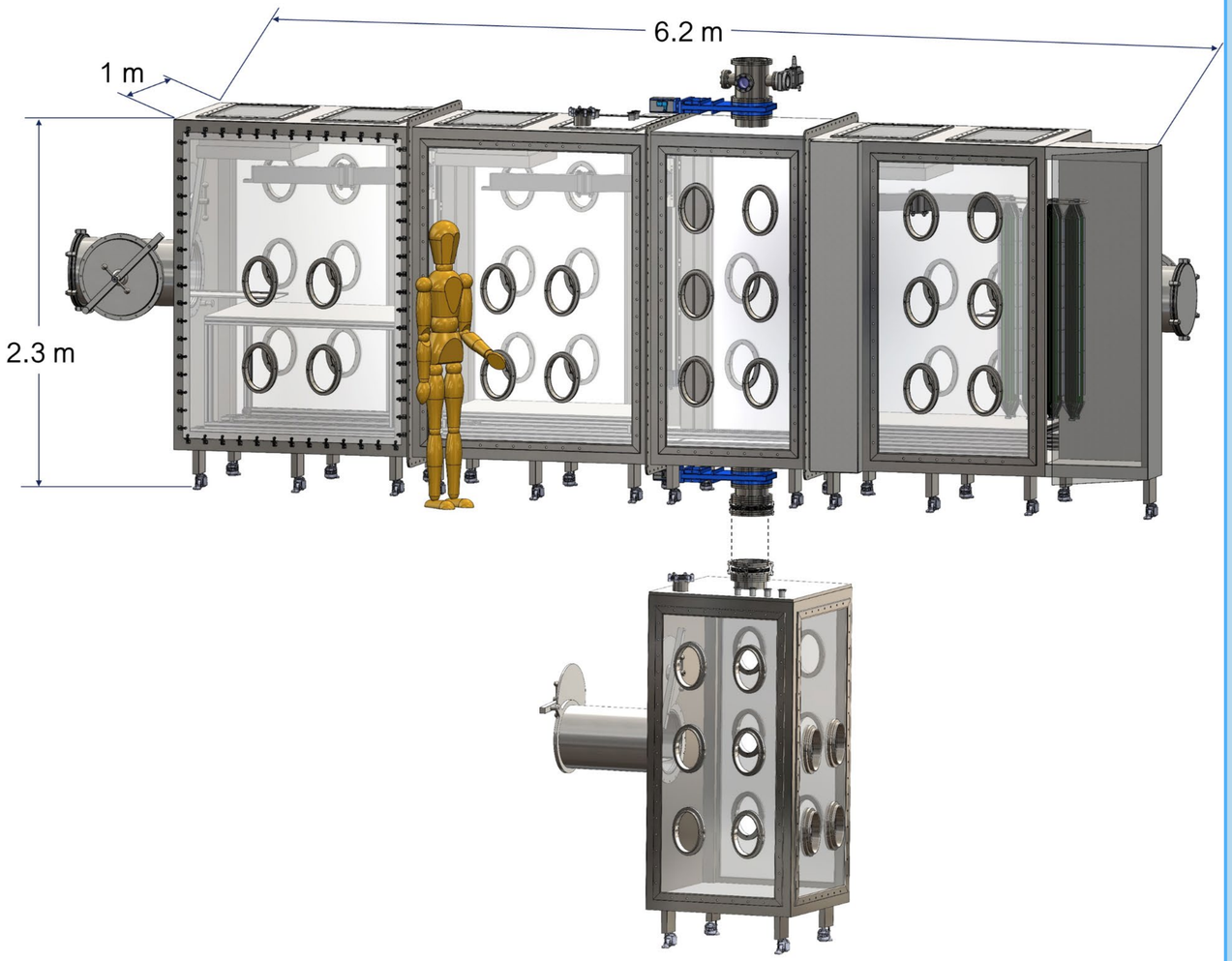
LEGEND-1000: Systems

Reentrant tube: welding tests ongoing

Deployment systems (L2 Leader: K. Gusev)

- **Glove box**(es) design well advanced (based on L200 glove box ideas developed by JINR team)
- **Single String Lock**: FDR this Summer
- **LEGENDArY** cryostat(s) design advanced (will be used for outer LAr instrumentation modules testing then for full L1000 string acceptance)
- **Calibration** systems design maturing

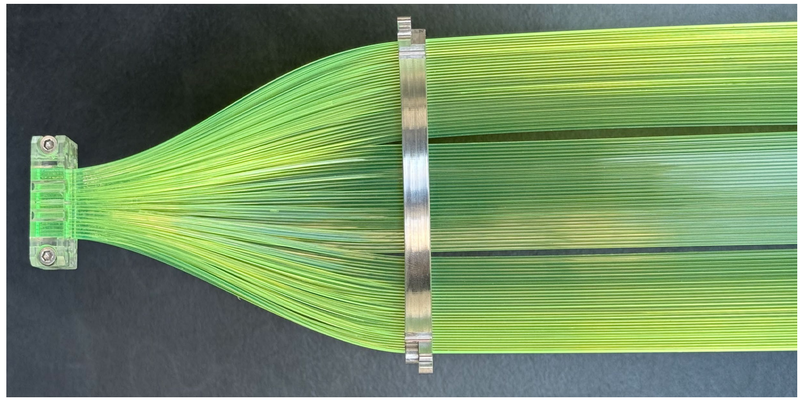
Glove boxes for string assembly and check



LEGEND-1000: Systems

Outer (atmospheric) **LAr** instrumentation

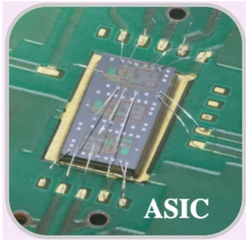
- Design optimization and simulation
- SiPM characterization and assay
- Prototype testing at LEGENDArYno ongoing



Inner (underground) **LAr** instrumentation

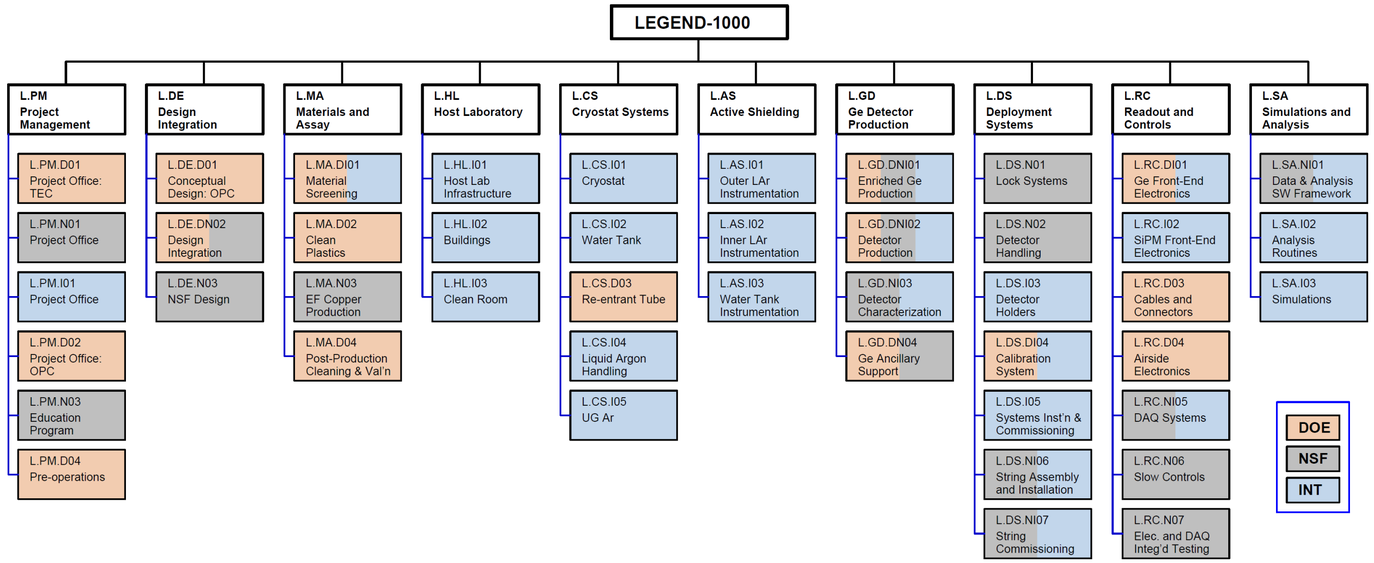
- Prototyping of modules and thermal/mechanical tests
- SiPM evaluation
- scintillation fibers R&D

Being performed @TUM by JINR/TUM team



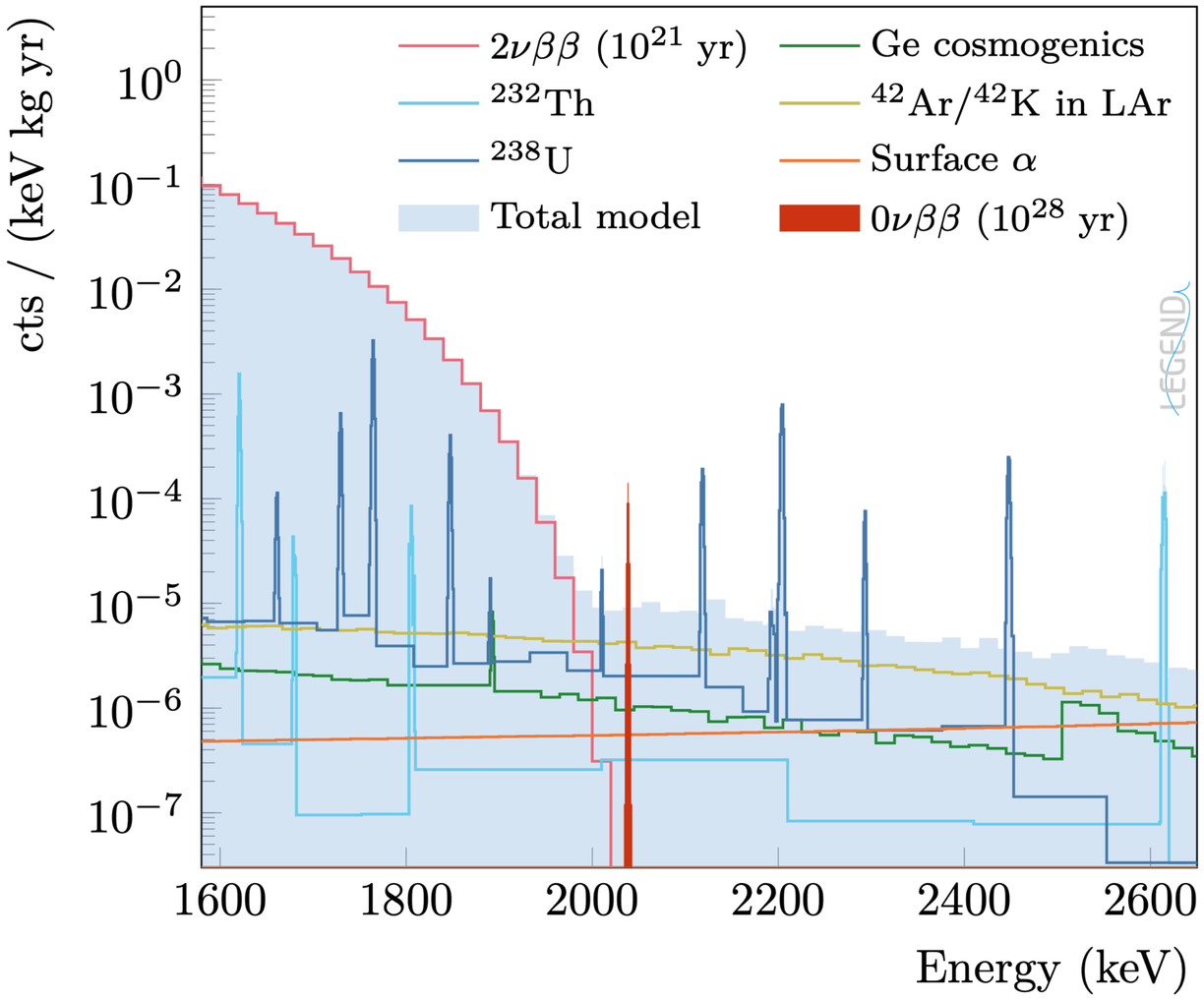
ASIC development

- Two parallel designs
- Extensive prototyping and testing

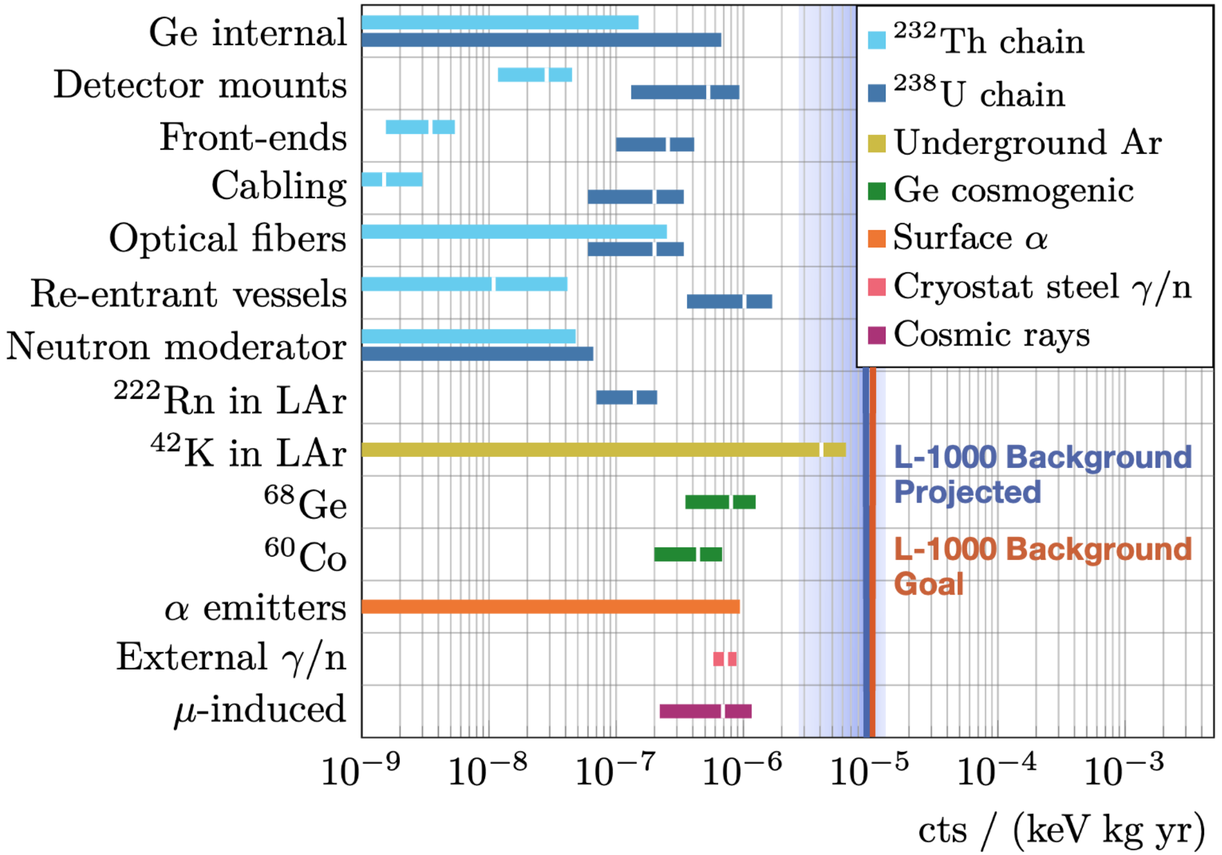


LEGEND-1000: Background Model

Simulated total background spectrum after cuts

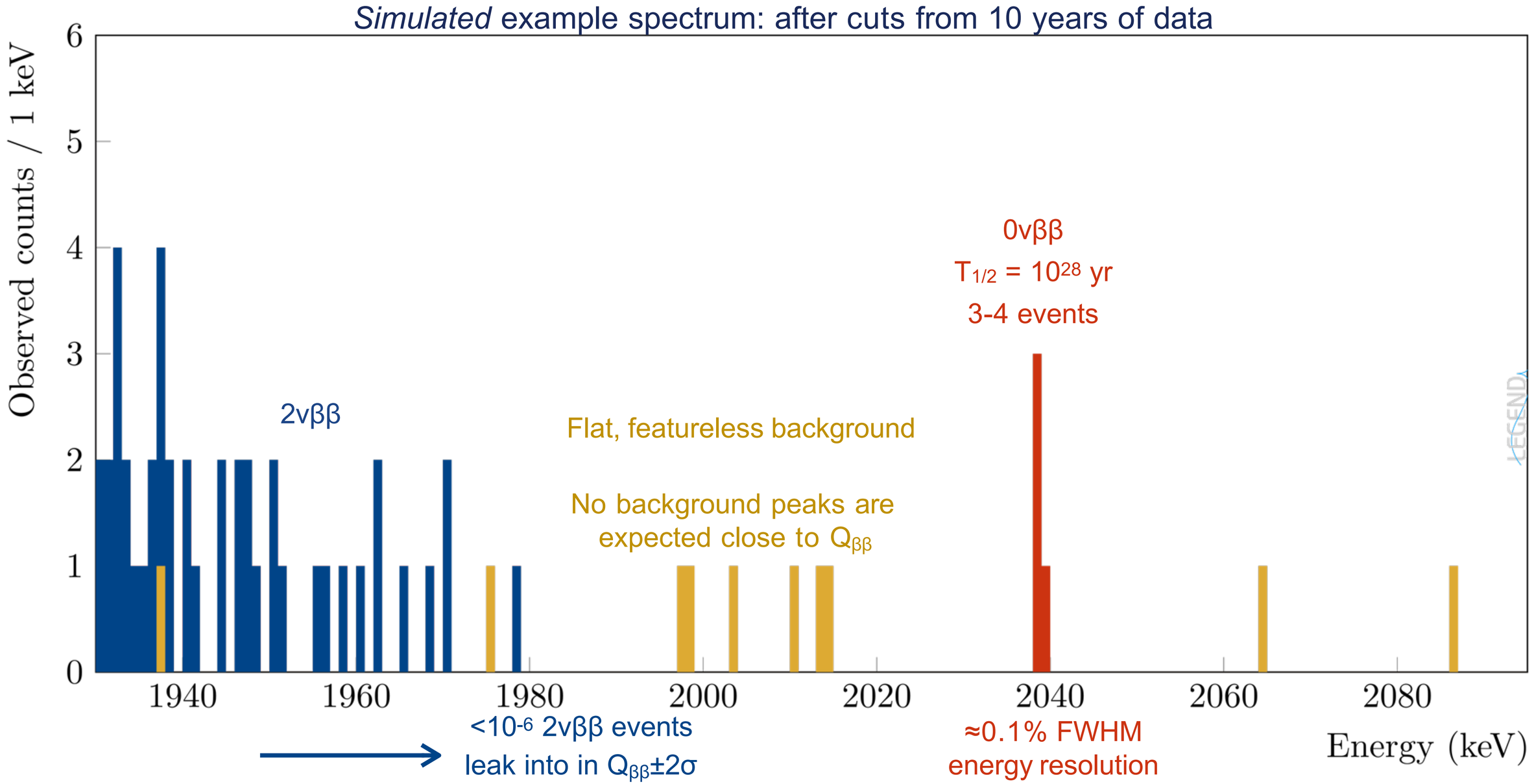


Expected background contributions (preliminary)

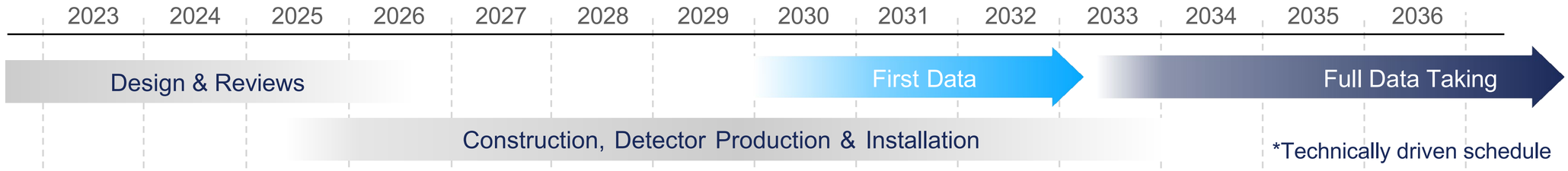


Projected background index ~ 10^{-5} cts/(keV kg yr)

LEGEND-1000: Designed for an Unambiguous Discovery



LEGEND-1000: Timeline & Funding



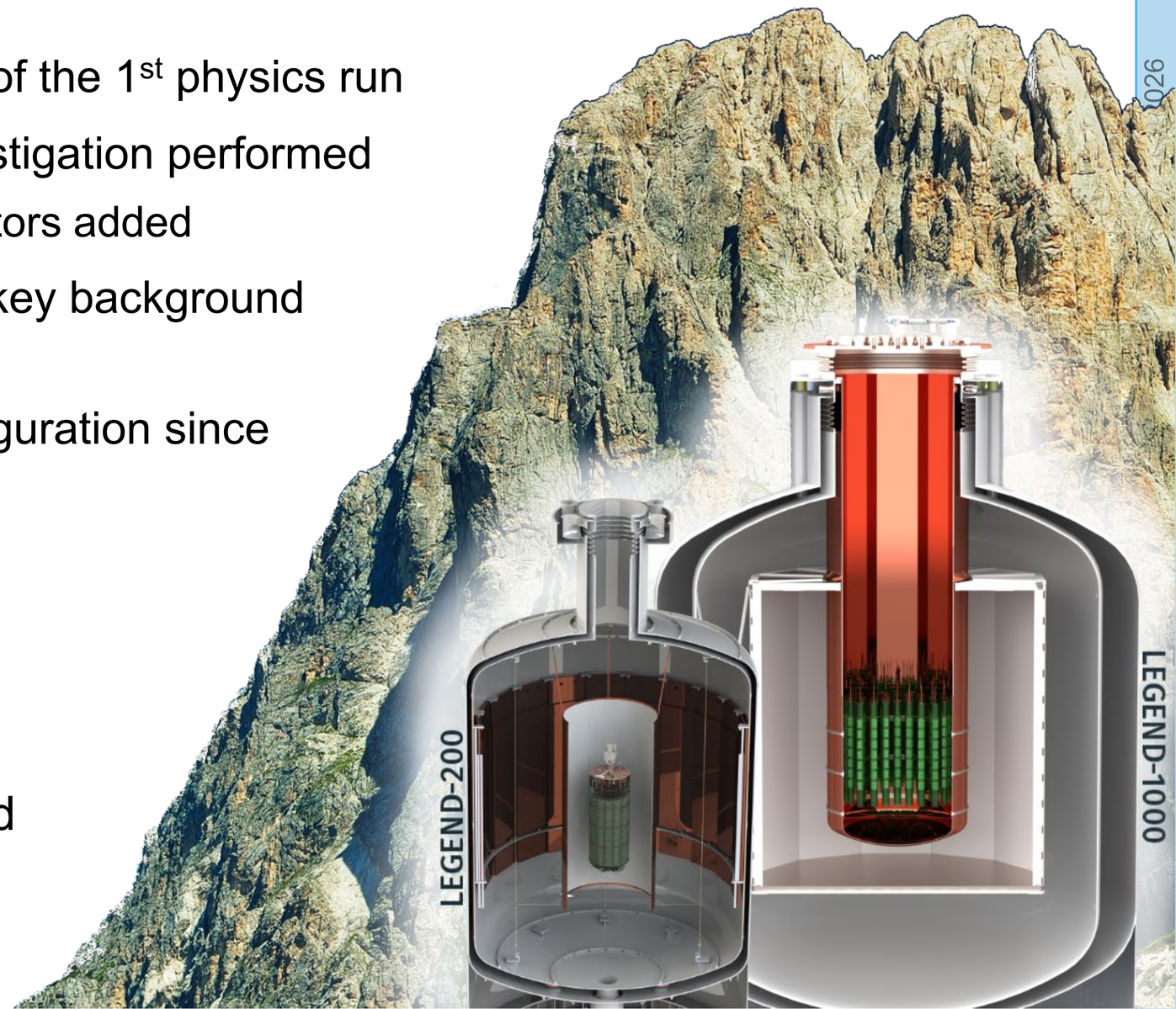
- LEGEND-1000 is optimized for a quasi-background-free 0νββ search
  - Builds on the experience (and success) of GERDA, MAJORANA, and LEGEND-200
  - Low-risk path to meet its background goal of 10^{-5} counts/(keV kg yr)
  - Ultra-low background, excellent energy resolution, and event topology discrimination allow for an unambiguous discovery of 0νββ decay at $T_{1/2} = 10^{28}$ years
- LEGEND-1000 funding
  - **US:** NSF (final design phase MREFC) & DOE (CD-1 review)
  - **Europe:** MPG and DFG support; German FIS National Research Infrastructure process (decision July 2026); INFN flagship project; contributions from Switzerland and Poland; UK roadmap pending

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

Summary of

- **LEGEND-200**
  - Published PRL paper based on the results of the 1st physics run
  - Serious maintenance and background investigation performed
    - Reassembled, parts re-cleaned, new detectors added
  - Significant reduction and understanding of key background contributions
  - Taking stable physics data in the new configuration since Summer 2025

- **LEGEND-1000**
  - Preparation at LNGS ongoing
  - Design of different systems well advanced



Backup slides

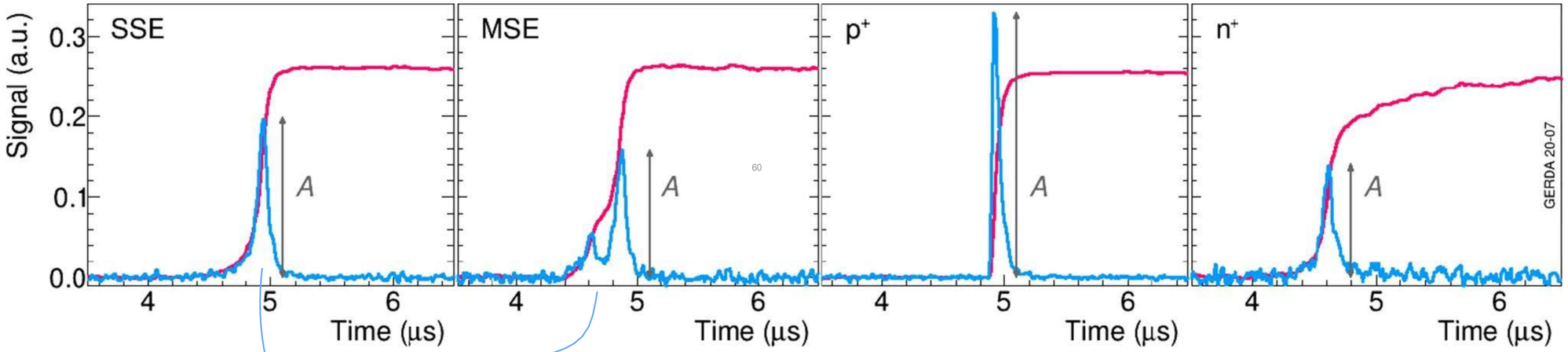
PSD in details

Single site event (e.g. ^{208}Tl DEP, ββ)

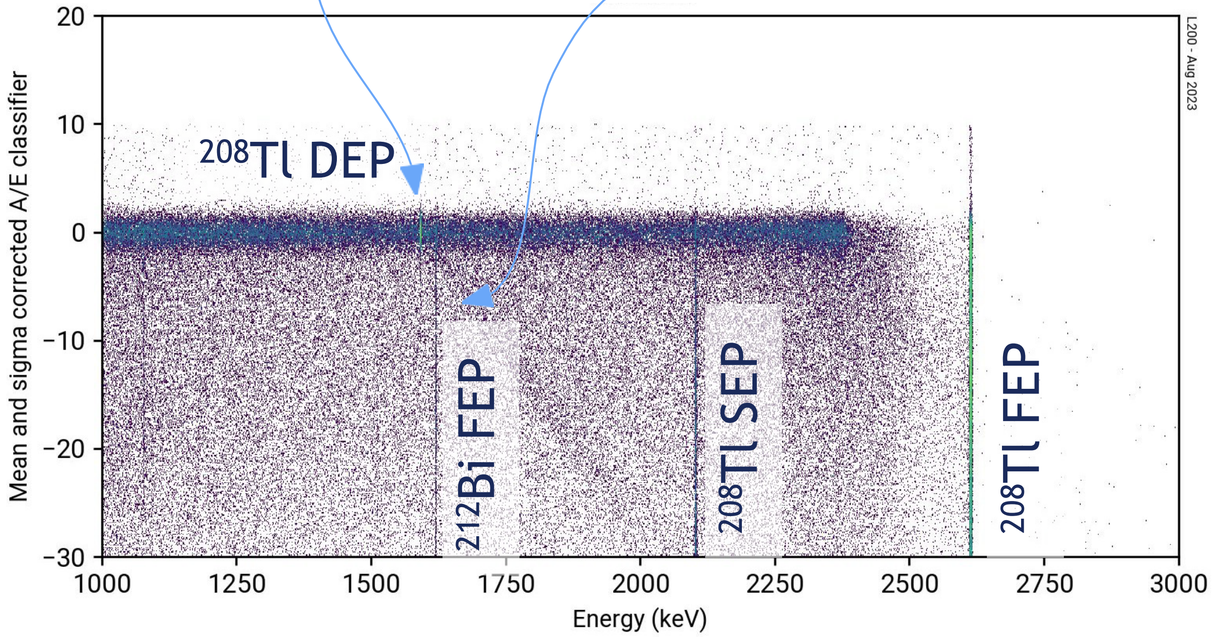
Multi site event (e.g. ^{212}Bi FEP)

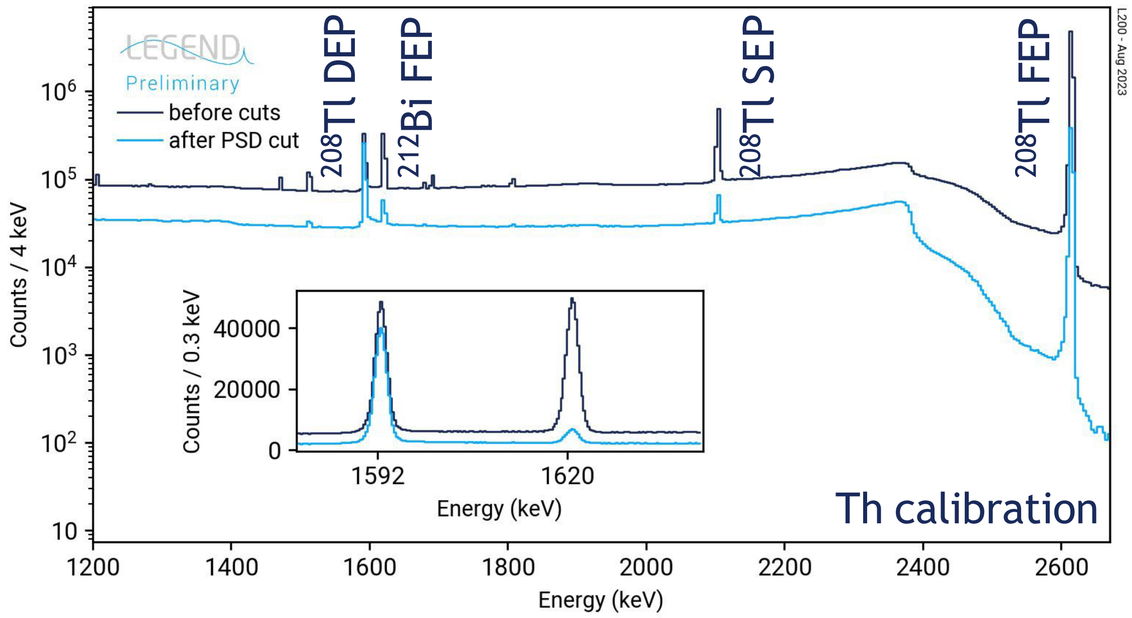
p⁺ surface event

n⁺ surface event (e.g. incomplete charge collection)

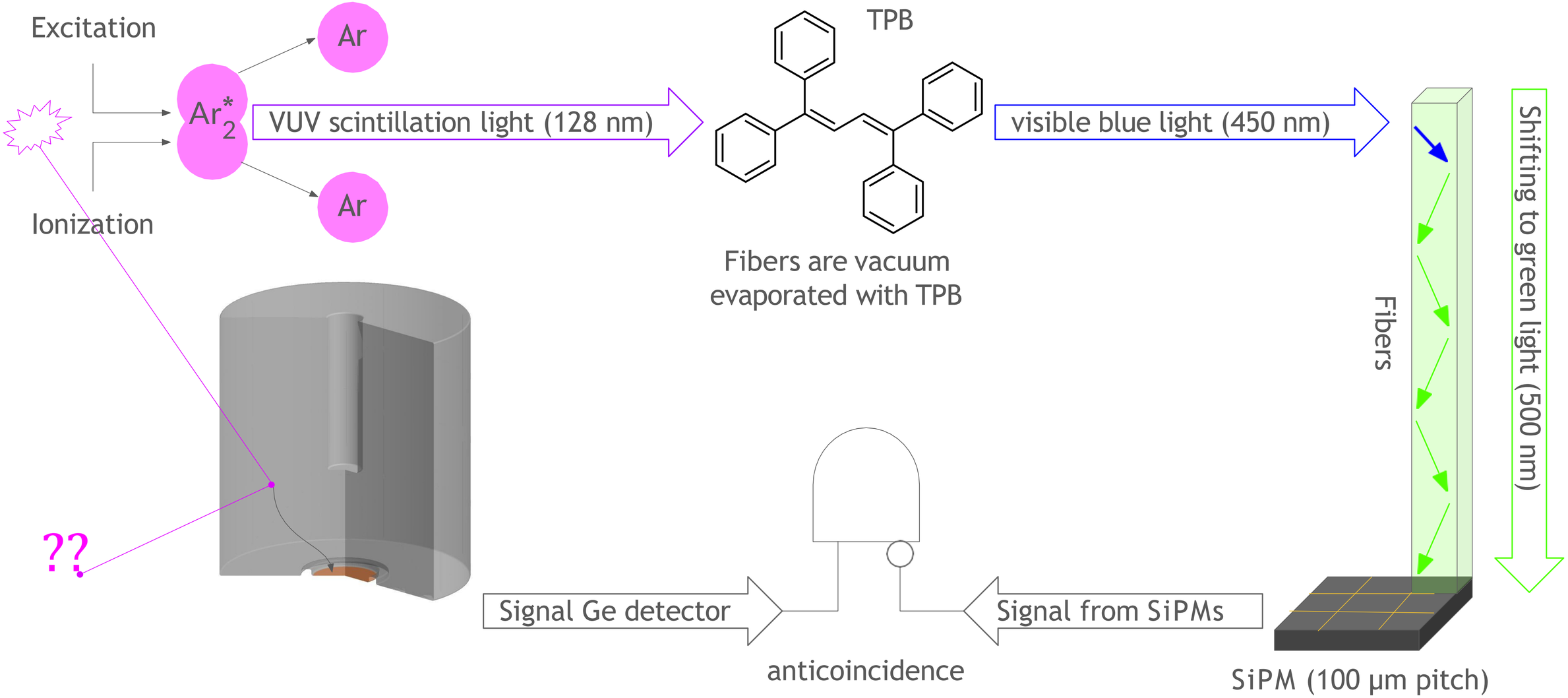


- Need to accept SSE (e.g. ββ)
- Reject the rest
- Optimize with calibration



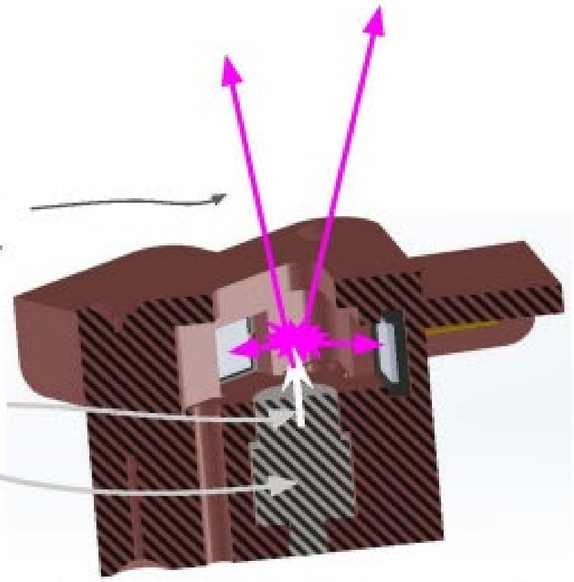


LAr scintillation principle



LEGEND LAr monitoring Apparatus

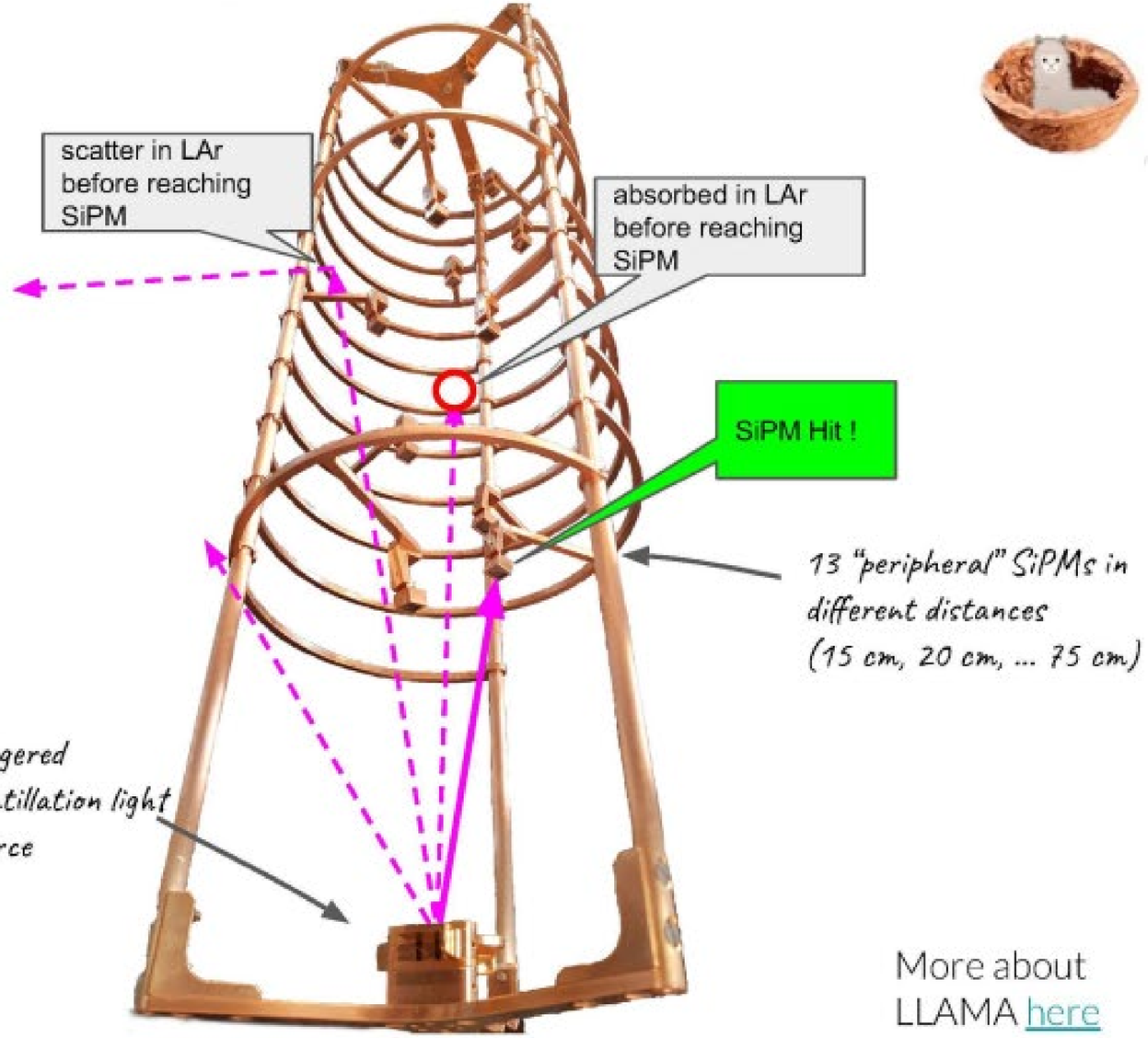
LLAMA in a nutshell





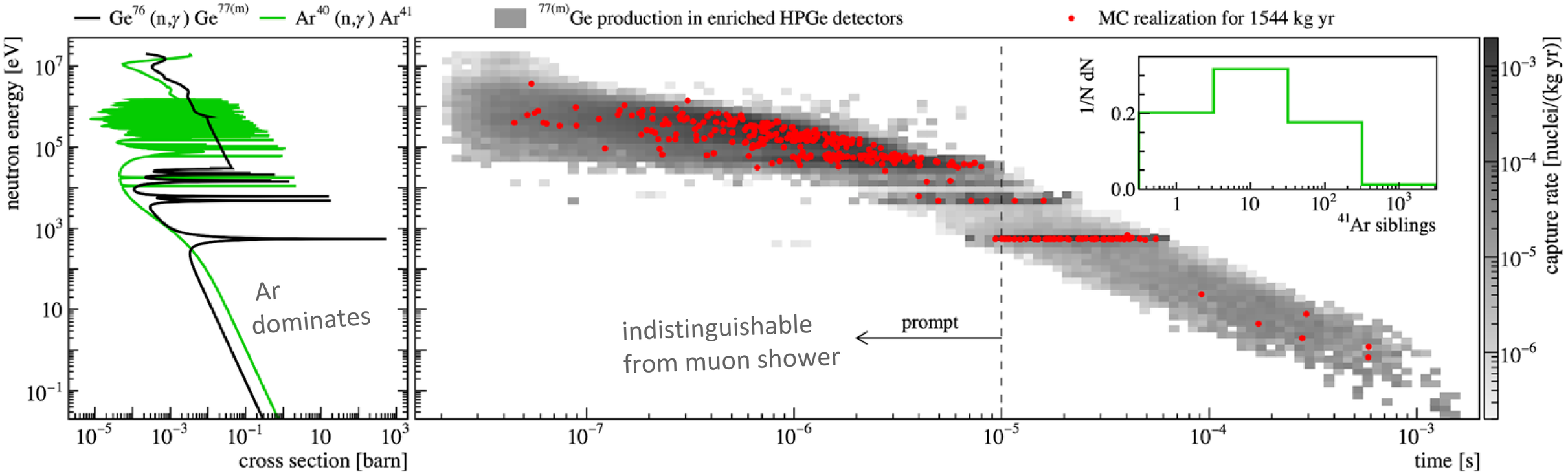
green LED -> calibration

triggered scintillation light source



More about LLAMA here

Virtual depth by active background rejection



Eur.Phys.J.C 78 (2018) 7, 597

- **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**



Other BSM Physics with LEGEND-1000

^{39}Ar reduction due to the use of underground-sourced argon enables a suite of BSM physics searches

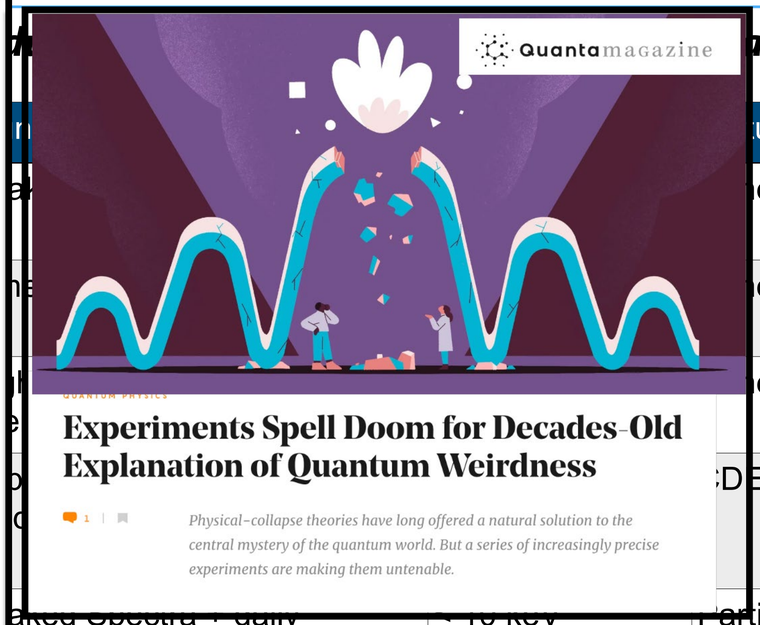
Mechanism	Signature	Energy range	Status	*Recent* Germanium References
Bosonic Dark Matter	Peak at m_b	5 — 100keV	Done in MJD, GERDA	PRL 118 (2017) 161801, PRL 125 (2020) 011801, PRL 132 (2024) 041001, EPJ C84 (2024) 940
Baryon Decay	Time Correlation, High Energy	0-10 MeV	Done in MJD	PRD 99 (2019) 072004 EPJ C83 (2023) 778
Fractionally Charged Cosmic rays	High Multiplicity-coincidence events	Few keV	Done in MJD	PRL 120 (2018) 211804
WIMP searches	Exponential Excess + Annual Modulation. Migdal Effect	< 10 keV	CDEX/MALBEK/CoGeNT	PRL 120 (2018) 241301, Phys. Procedia 61 (2015) 77
Solar axions	Peaked Spectra + daily modulation	< 10 keV	Partially Done in MJD	PRL 118 (2017) 161801; Astropart.Phys. 89 (2017) 39, Wiseman PhD Thesis
Majoron Emission	2νββ spectral distortion	$Q_{\beta\beta}$	Done in GERDA	EPJ. C75 (2015) 416
Lorentz Violation	2νββ spectral distortion	$Q_{\beta\beta}$		PRD 88 (2013) 071902
Electron Decay	Peak at 11.8 keV	~10 keV	Done in MJD	PRL 118 (2017) 161801, Nat. Phys. 20 (2024) 1078, EPJ C84 (2024) 940
Pauli Exclusion Principle Violation	Peak at 10.6 keV	~ 10 keV	Done in MJD	PRL 118 (2017) 161801, Nat. Phys. 20 (2024) 1078
BSM physics in Ar	Features in Ar Veto spectrum		ECEC in Ar36 (GERDA)	EPJ C75 (2015) 416

+ Prompt Supernova Neutrinos, SuperWIMPS, Solar Neutrinos, QM Wavefunction Collapse…

Other BSM Physics with LEGEND-1000



https://journals.aps.org/prl/issues/129/8



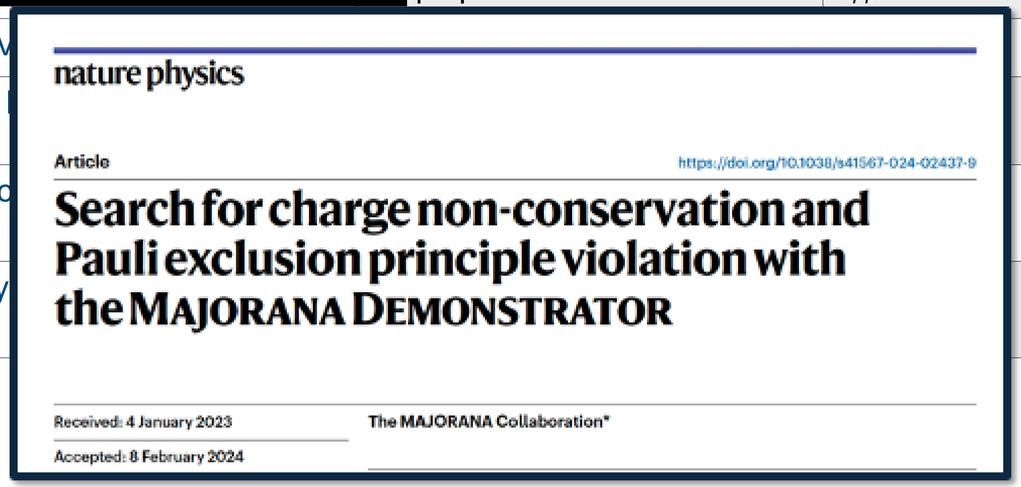


	dulation		
	ββ spectral distortion	$Q_{\beta\beta}$	
Lorentz V			
Electron			
Pauli Exc Violation			
BSM phy			

Partially Done in MJD

PRL 118 (2017) 161801; Astropart.Phys. 89 (2017)







+ Prompt Supernova Neutrinos, SuperWIMP