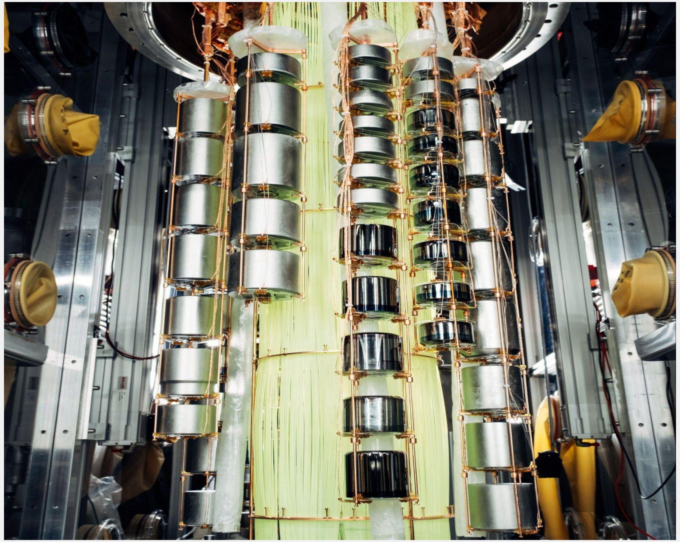
$0\nu\beta\beta$ experiments with ^{76}Ge



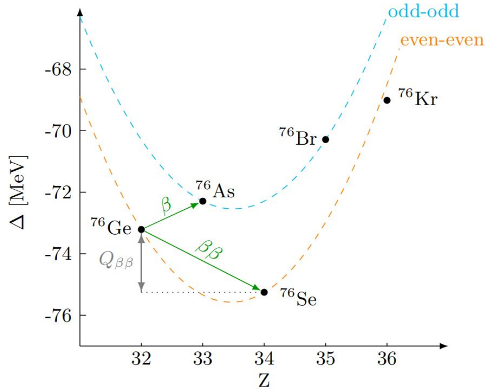
Louis Varriano

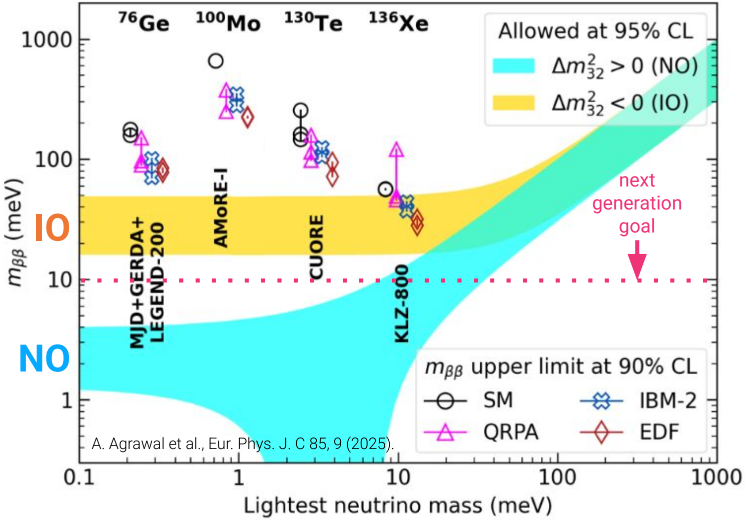
Center for Experimental Nuclear Physics and Astrophysics,
University of Washington

21 July 2026

^{76}Ge for 0νββ searches

- $Q_{\beta\beta}$ = 2039 keV
- $$T^{2\nu}_{1/2} = (2.022 \pm 0.018_{\text{stat}} \pm 0.038_{\text{syst}}) \times 10^{21} \text{ years}$$
  GERDA collaboration [M. Agostini et al., PRL **131**, 142501 (2023).]
- 7.75% natural abundance → can enrich to ~90%
- source == detector → high intrinsic purity and containment efficiency
- HPGe detectors have excellent energy resolution (~0.1% FWHM) and pulse shape discrimination
- Lowest achieved background per FWHM (~1 count per tonne-year)
- Quasi-background free spectrum gives unambiguous identification of 0νββ signal
- Knowledge of background model post-cuts has limited impact / not required for 0νββ statistical inference





A. Agrawal et al., Eur. Phys. J. C 85, 9 (2025).

0νββ signal rate

Assuming light neutrino exchange

signal efficiency

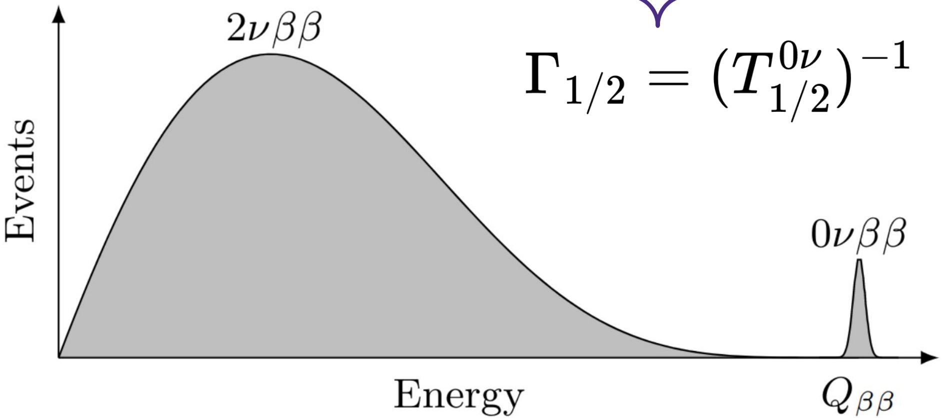
exposure = enr. mass × time

phase space factor*

nuclear matrix element (NME)*

Majorana mass

$$s \propto \epsilon \, \mathcal{E} \, \underbrace{\mathcal{G}^{0\nu} g_{\mathrm{A}}^{4} \left|\mathcal{M}^{0\nu}\right|^{2} \left(\frac{m_{\beta\beta}}{m_{\mathrm{e}}}\right)^{2}}_{\Gamma_{1/2} = (T^{0\nu}_{1/2})^{-1}}$$



**** decay specific***

What about backgrounds?

Assuming light neutrino exchange

signal efficiency

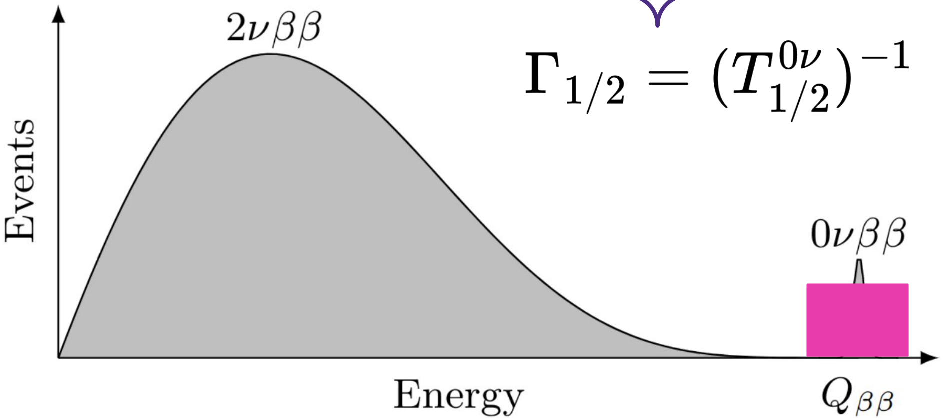
exposure = enr. mass × time

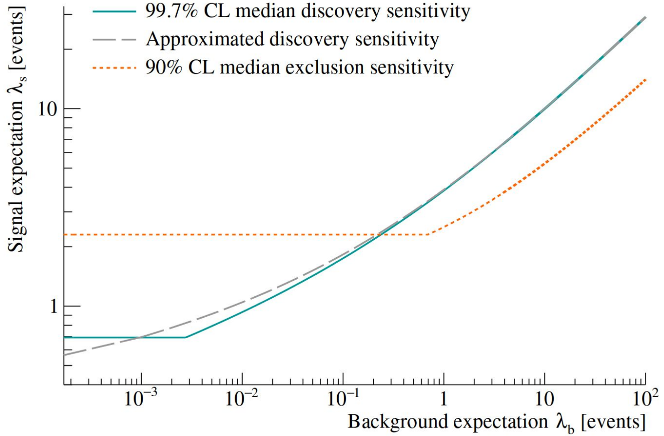
phase space factor*

nuclear matrix element (NME)*

Majorana mass

$$s \propto \epsilon\,\mathcal{E}\,\underbrace{\mathcal{G}^{0\nu} g_{\mathrm{A}}^{4} \left|\mathcal{M}^{0\nu}\right|^{2} \left(\frac{m_{\beta\beta}}{m_{\mathrm{e}}}\right)^{2}}_{\Gamma_{1/2} = (T^{0\nu}_{1/2})^{-1}}$$





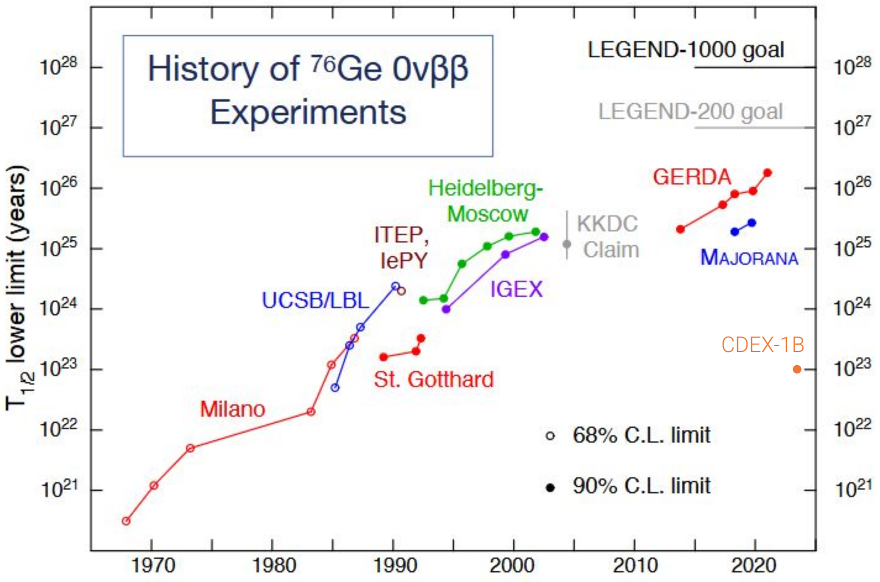
M. Agostini et al., Rev. Mod. Phys. 95, 025002 (2023).

Background limits discovery sensitivity

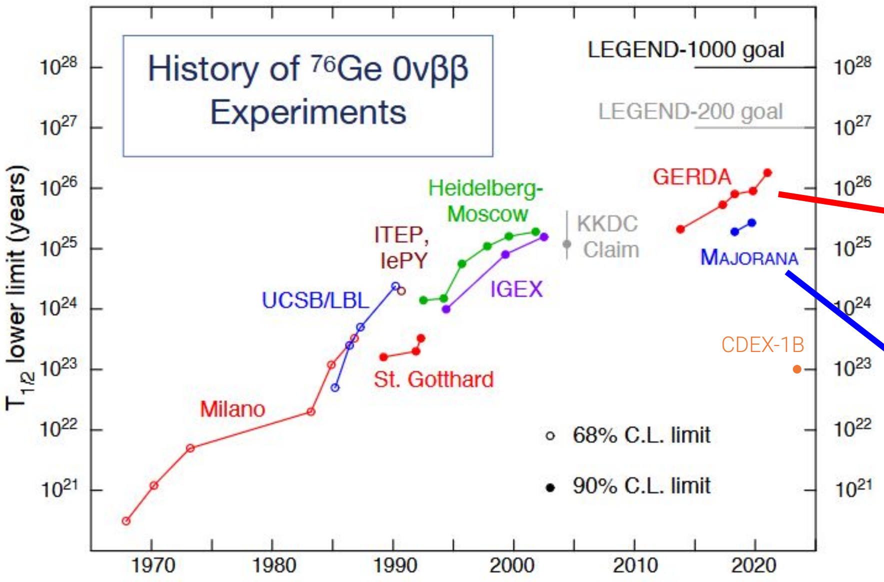
- higher $Q_{\beta\beta}$* → fewer natural bkg
- better energy resolution
- passive shielding
- active background event rejection

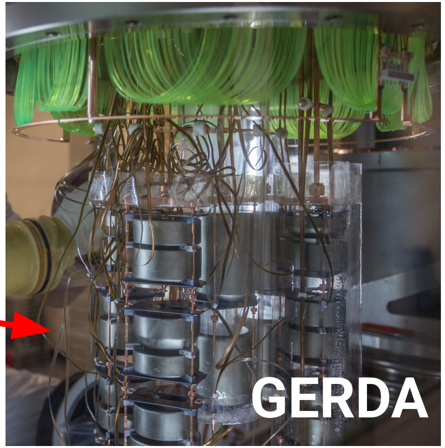
***** *decay specific***

^{76}Ge $0\nu\beta\beta$ experiments



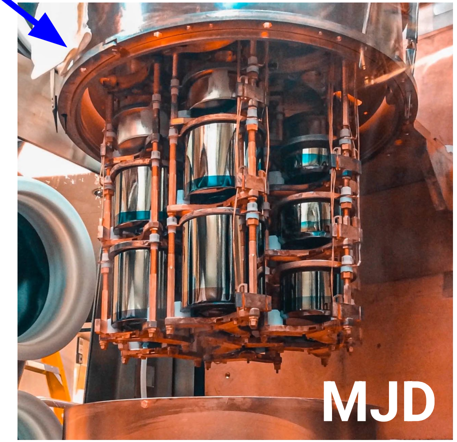
^{76}Ge 0νββ experiments - previous generation





GERDA key features

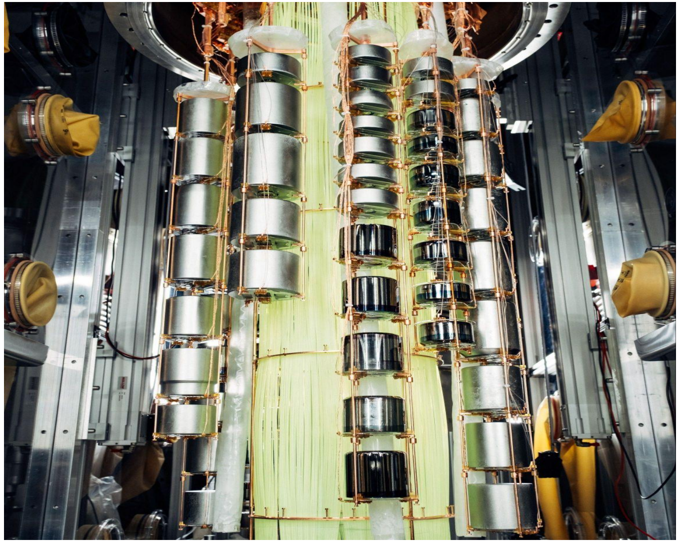
- Direct detector deployment in liquid argon
- Light readout of active shielding



MJD key features

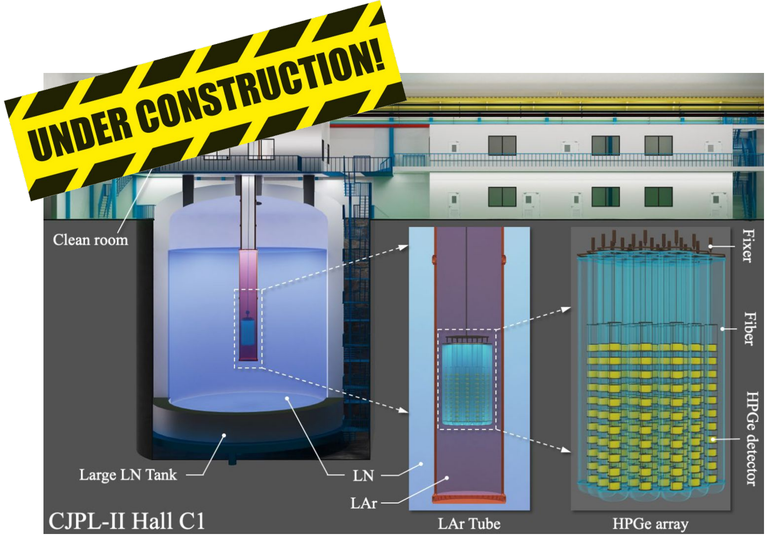
- Underground electroformed copper and high radiopurity
- Low noise electronics
- Low energy threshold

^{76}Ge 0νββ experiments - current generation



LEGEND-200

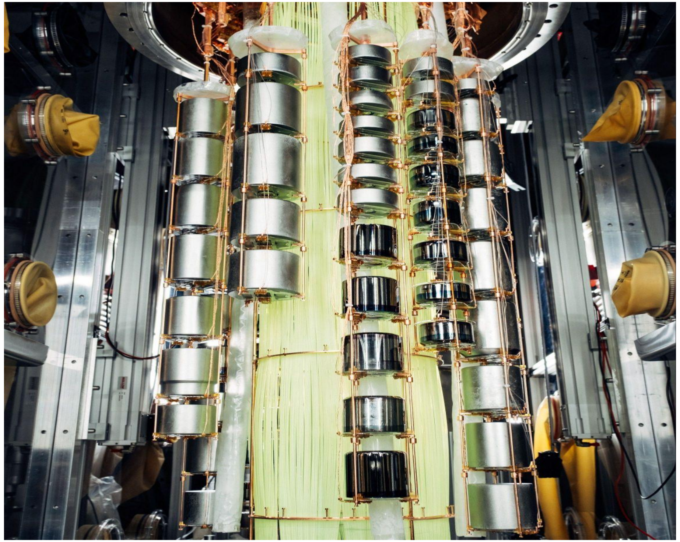
currently operating



CDEX-300ν

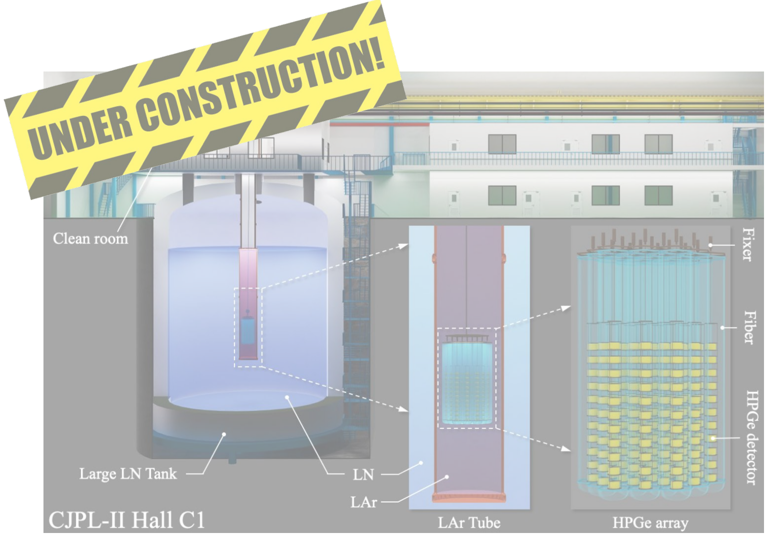
design, construction, and R&D

^{76}Ge 0νββ experiments - current generation



LEGEND-200

currently operating



CDEX-300ν

design, construction, and R&D

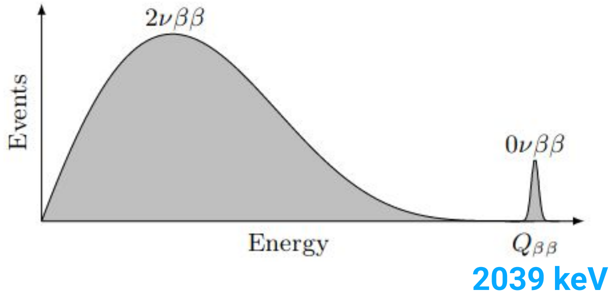
very similar technologies and experimental design - will focus on LEGEND for some general descriptions

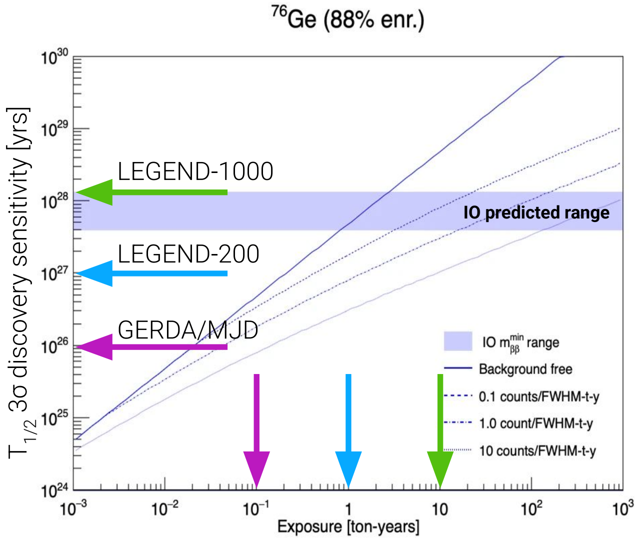
Large **E**nriched **G**ermanium **E**xperiment for **0νββ** **D**ecay

- HPGe detectors in liquid argon to reject backgrounds via scintillation
- ~0.1% FWHM resolution at $Q_{\beta\beta}$= 2039 keV
- **Nearly background-free search**
    - LEGEND-200 background goal: 2×10^{-4} cts/(keV·kg·yr)
- **First physics result recently published!**

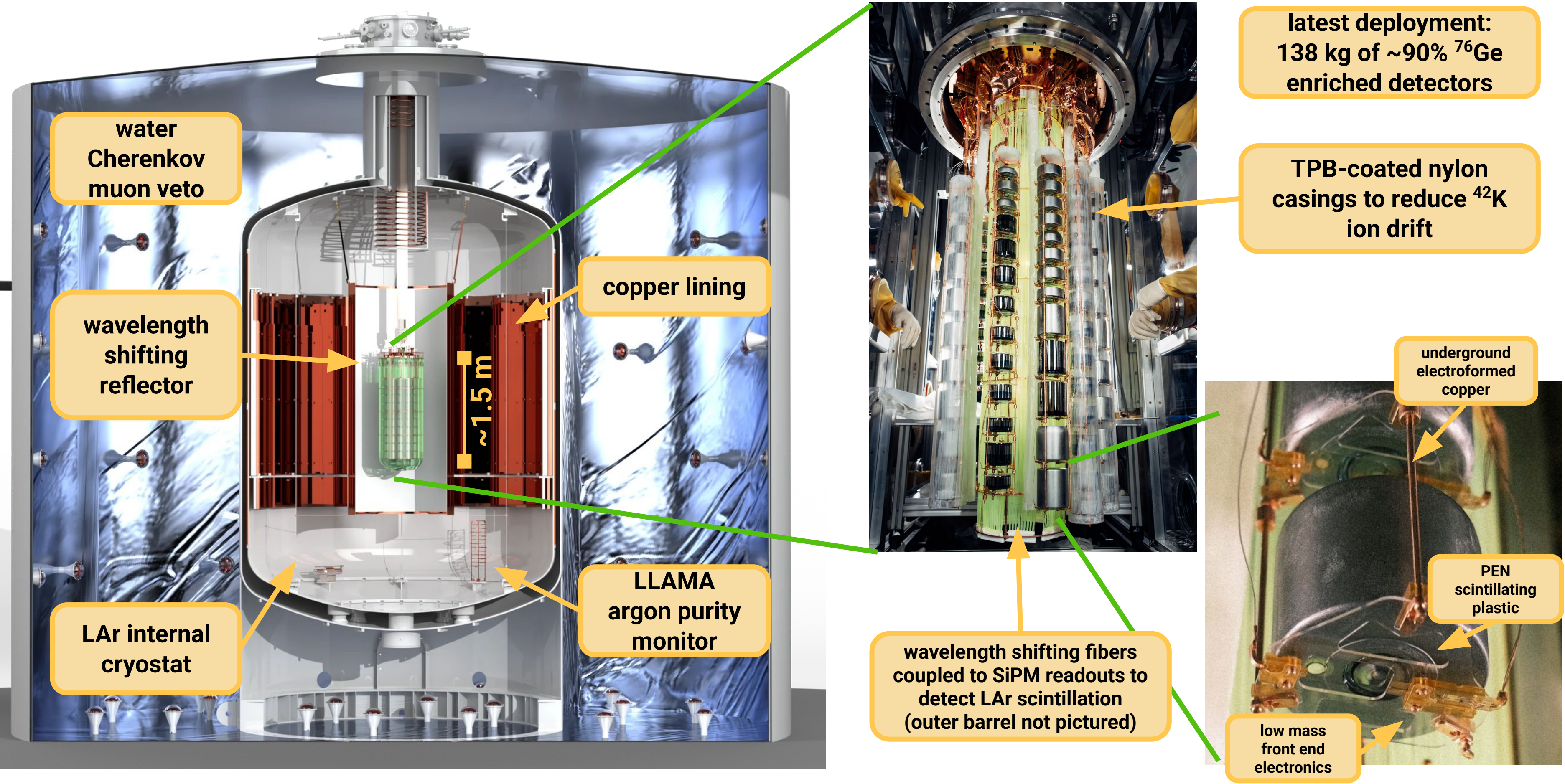
  H. Acharya et al., PRL **136**, 022701 (2026).

- No observation of 0νββ - global ^{76}Ge $T_{1/2} > 1.9 \times 10^{26}$ years
- Future LEGEND-1000 experiment aims to cover neutrino mass IO



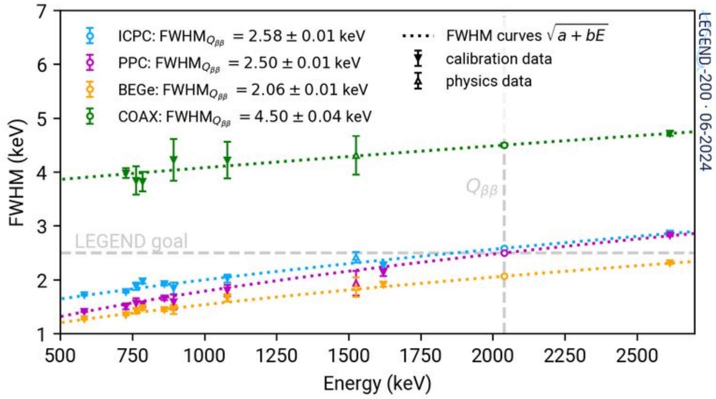


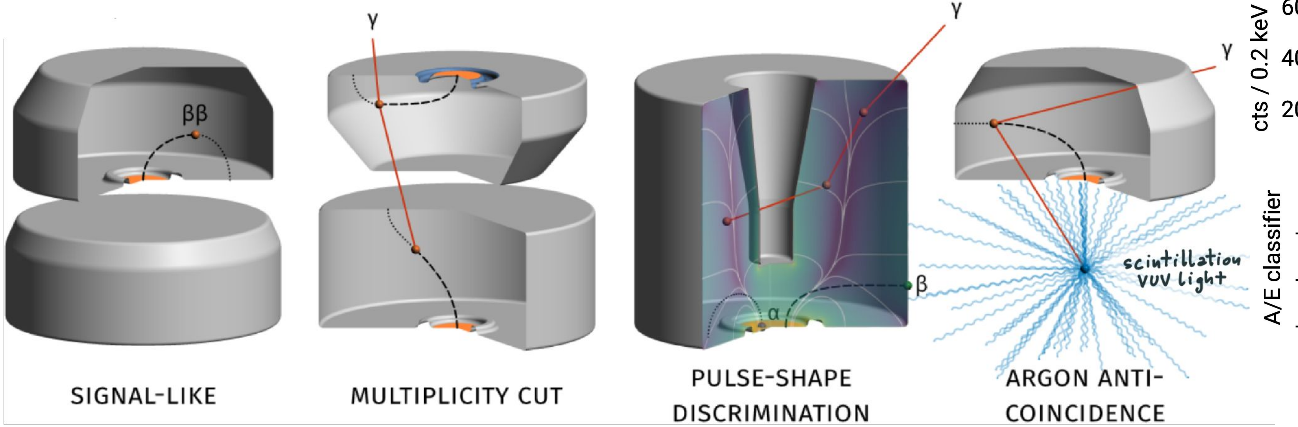
LEGEND-200 - 200 kg of ^{76}Ge enriched detectors



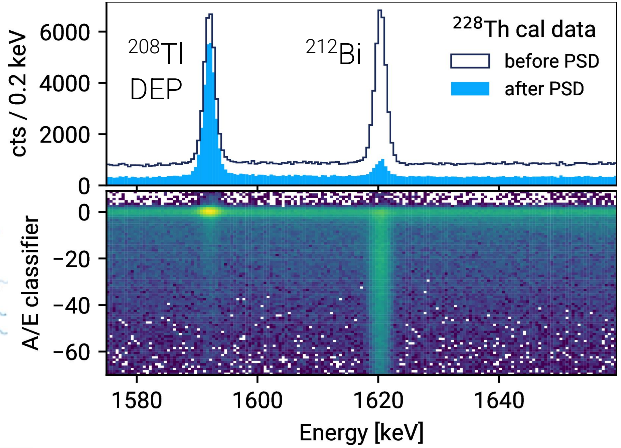
Detectors and active background suppression

- ~90% enriched in ^{76}Ge
- Pulse shape discrimination (PSD) and liquid argon (LAr) anti-coincidence to actively suppress backgrounds.
- L1000 will use exclusively ICPCs - large mass ($\gtrsim$ 3.5 kg) with energy resolution of 2.5 keV FWHM @ $Q_{\beta\beta}$



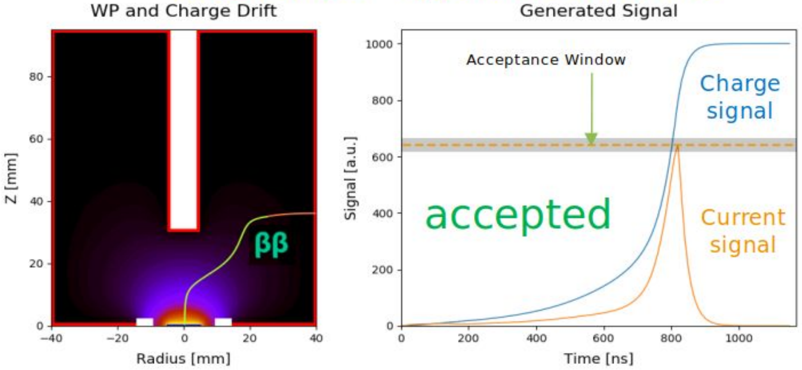


Luigi Pertoldi & David Hervas

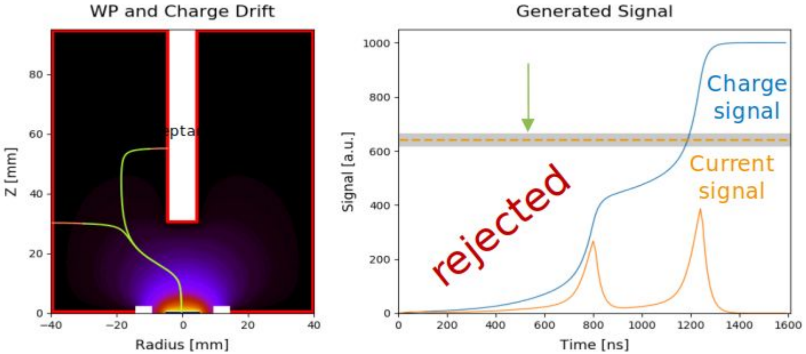


PSD to reject backgrounds

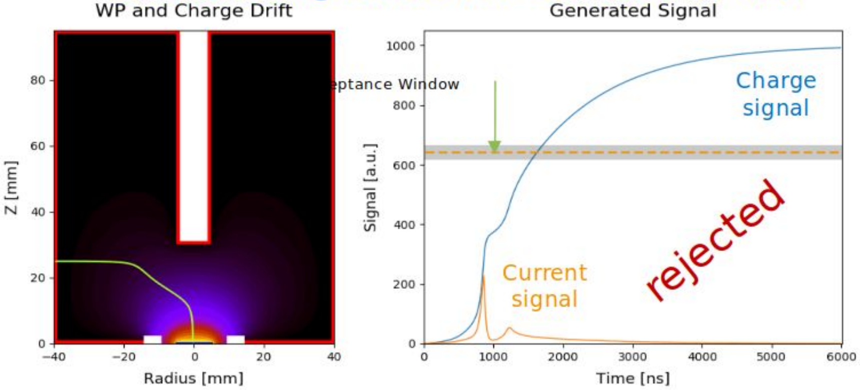
Single-sited - $0\nu\beta\beta$ event candidate



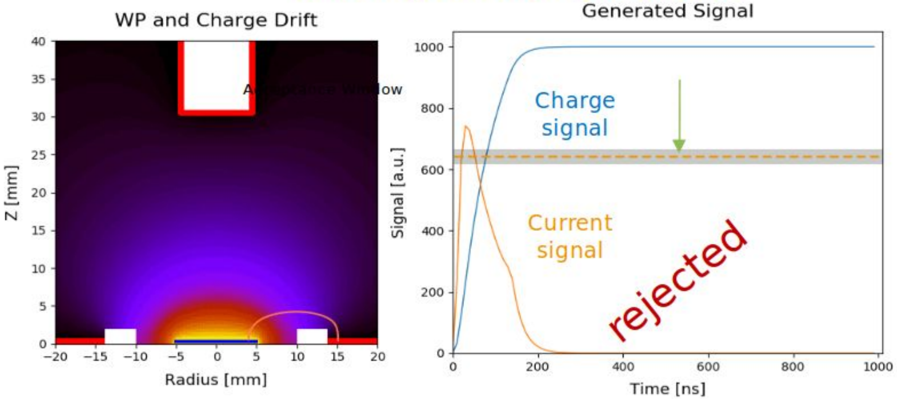
Multi-sited γ-ray background



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

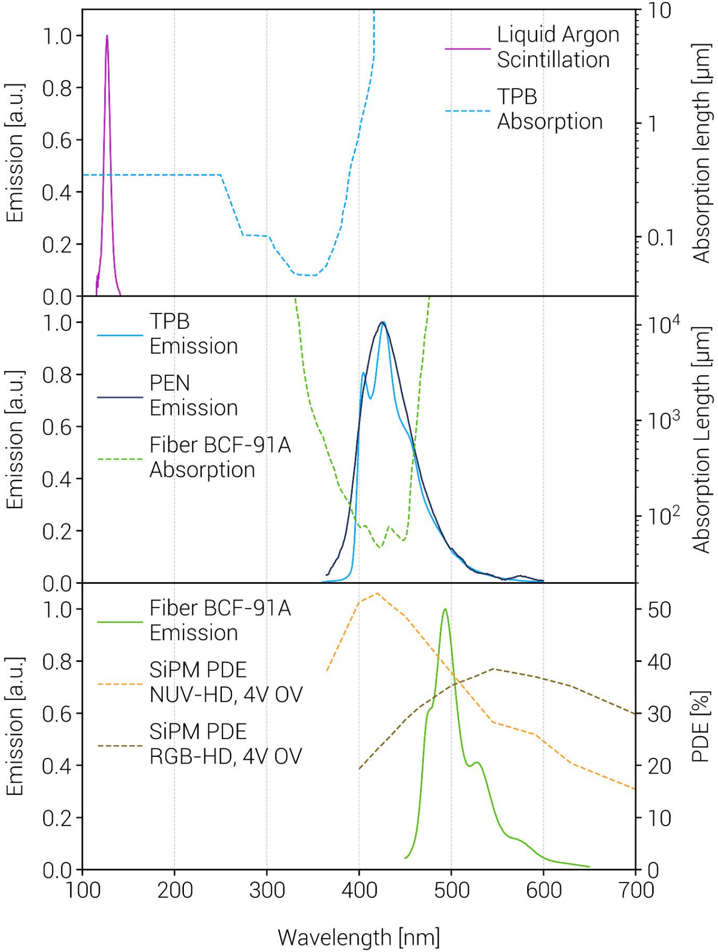


α-background on p+ contact



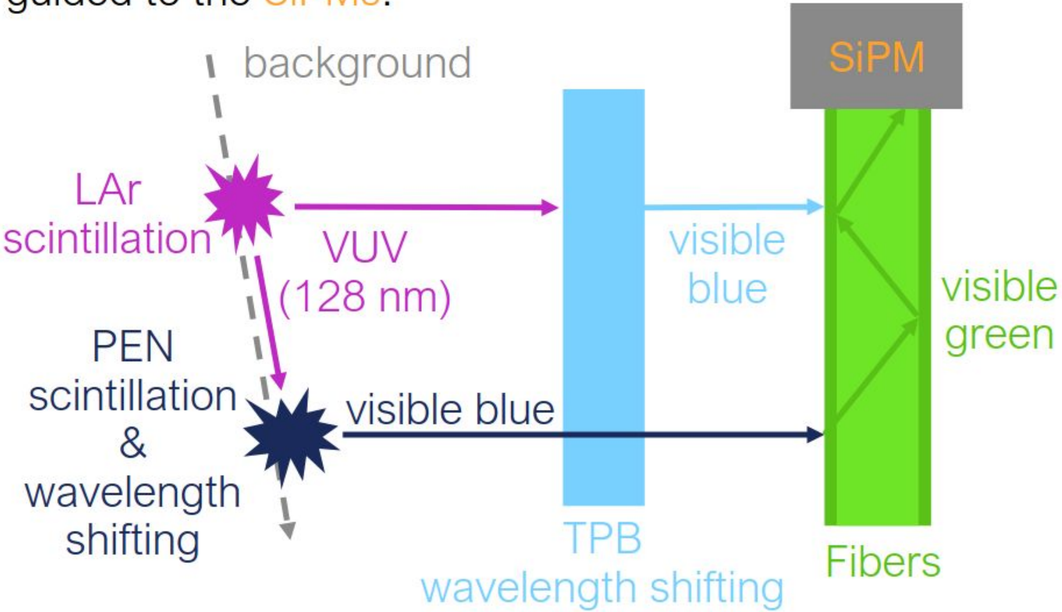
Harisree Krishnamoorthy

Liquid argon instrumentation

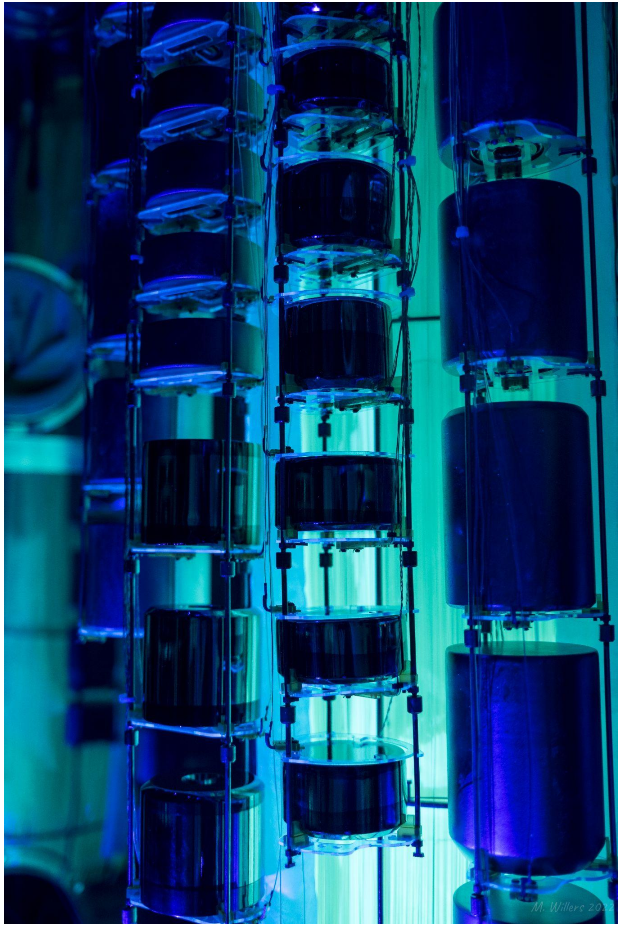


The LAr scintillation light (128 nm) is shifted to the visible blue by TPB (coating on fibers & WLSR) and PEN (detector holder plates).

The blue light is shifted to visible green by the fibers and guided to the SiPMs.



Liquid argon instrumentation



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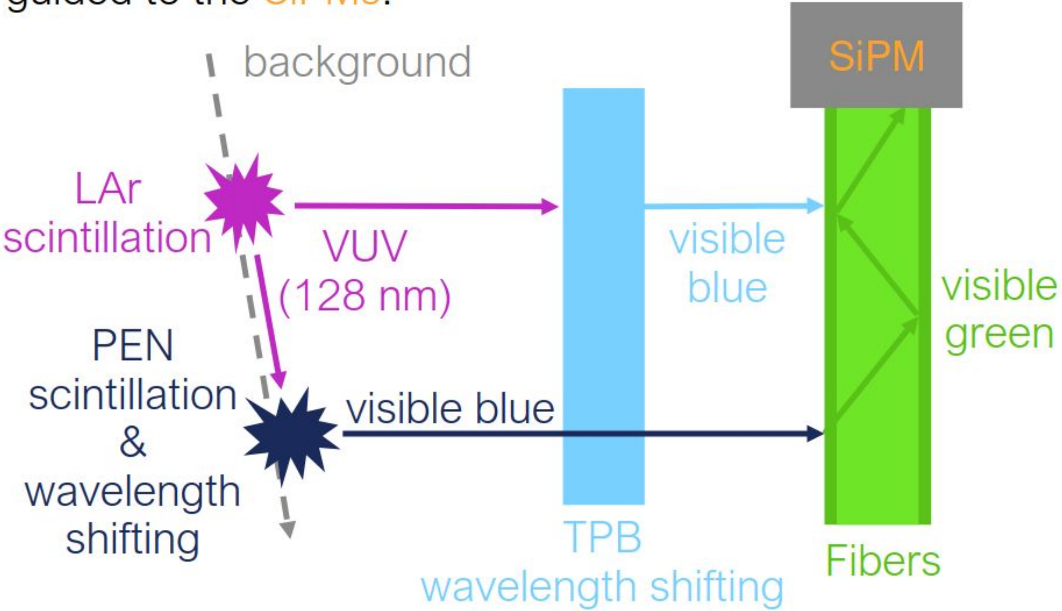
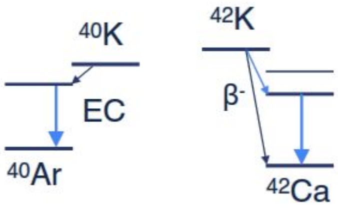
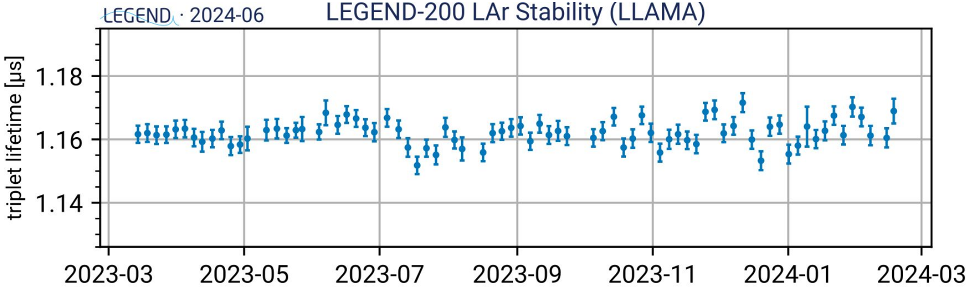
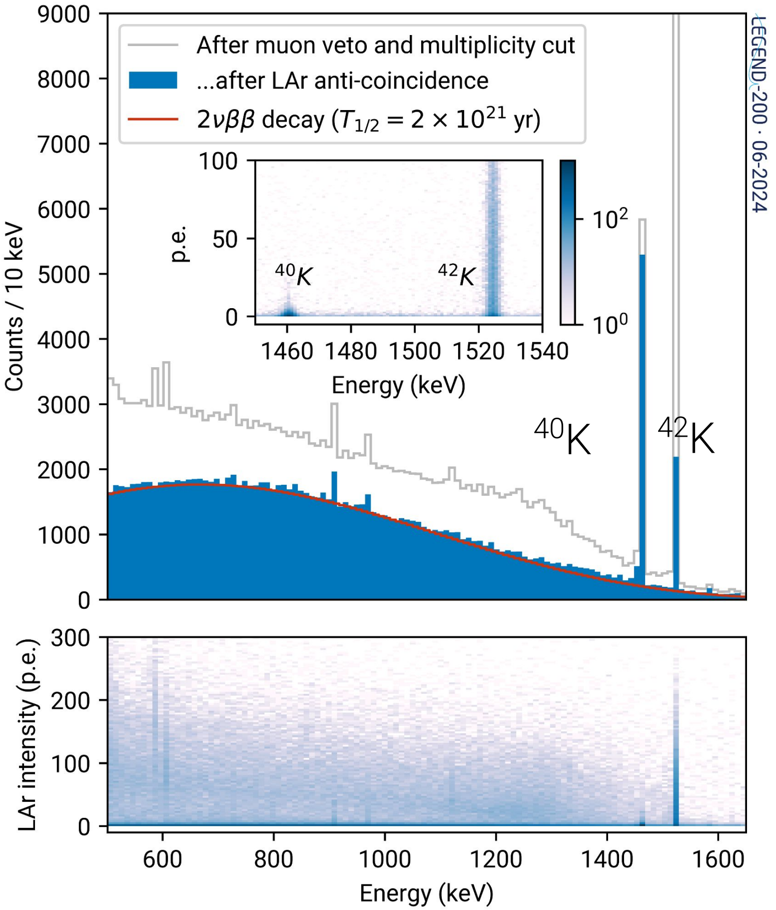


Liquid argon performance

- Event rejection depends on topology - strong rejection of ^{42}K, minimal rejection of ^{40}K
- Strong rejection of ^{40}K Compton continuum with high acceptance of full-energy peak.

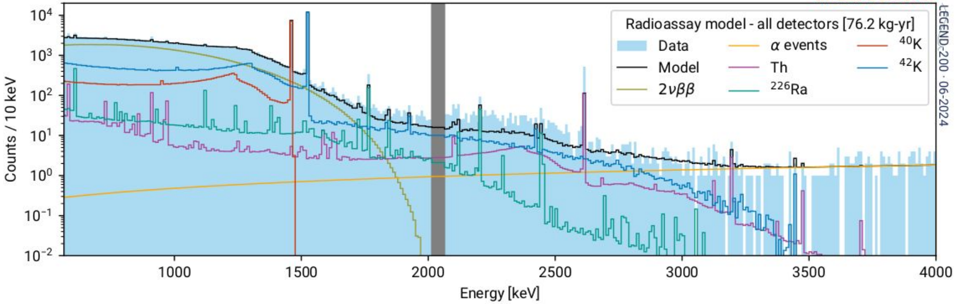


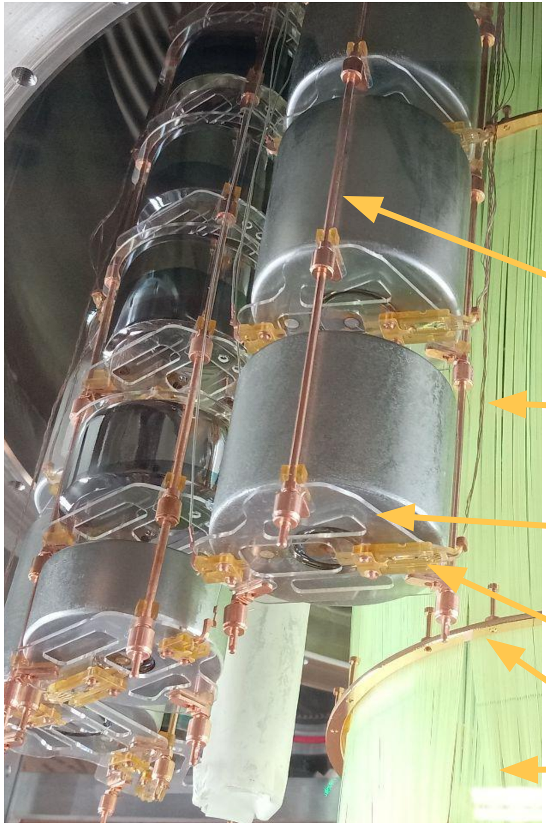




Low background materials for LEGEND

- Both ICP-MS and gamma assays for *most* materials with gamma assays preferred.
- Evidence that secular equilibrium is broken for at least some components
- Only some isotopes relevant background for LEGEND
- From nearby materials:
  - ^{238}U chain: ^{214}Pb, ^{214}Bi
  - ^{232}Th chain: ^{228}Ac, ^{212}Bi, ^{208}Tl
- Other major sources:
  - Rn chain alphas on sensitive detector surfaces
  - ^{42}K (from ^{42}Ar)

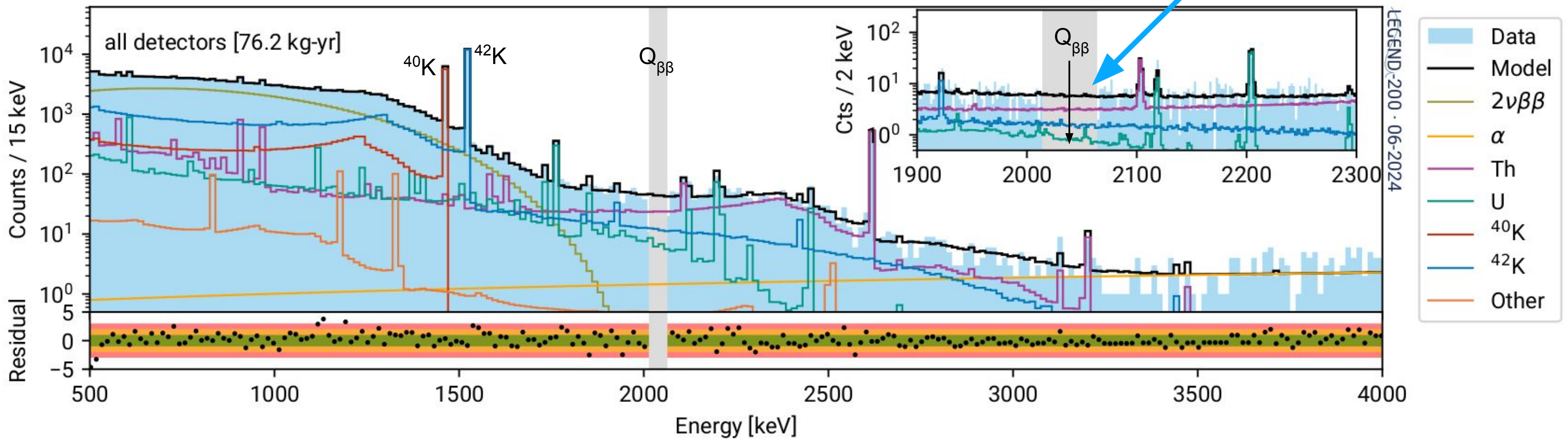




Data before analysis cuts

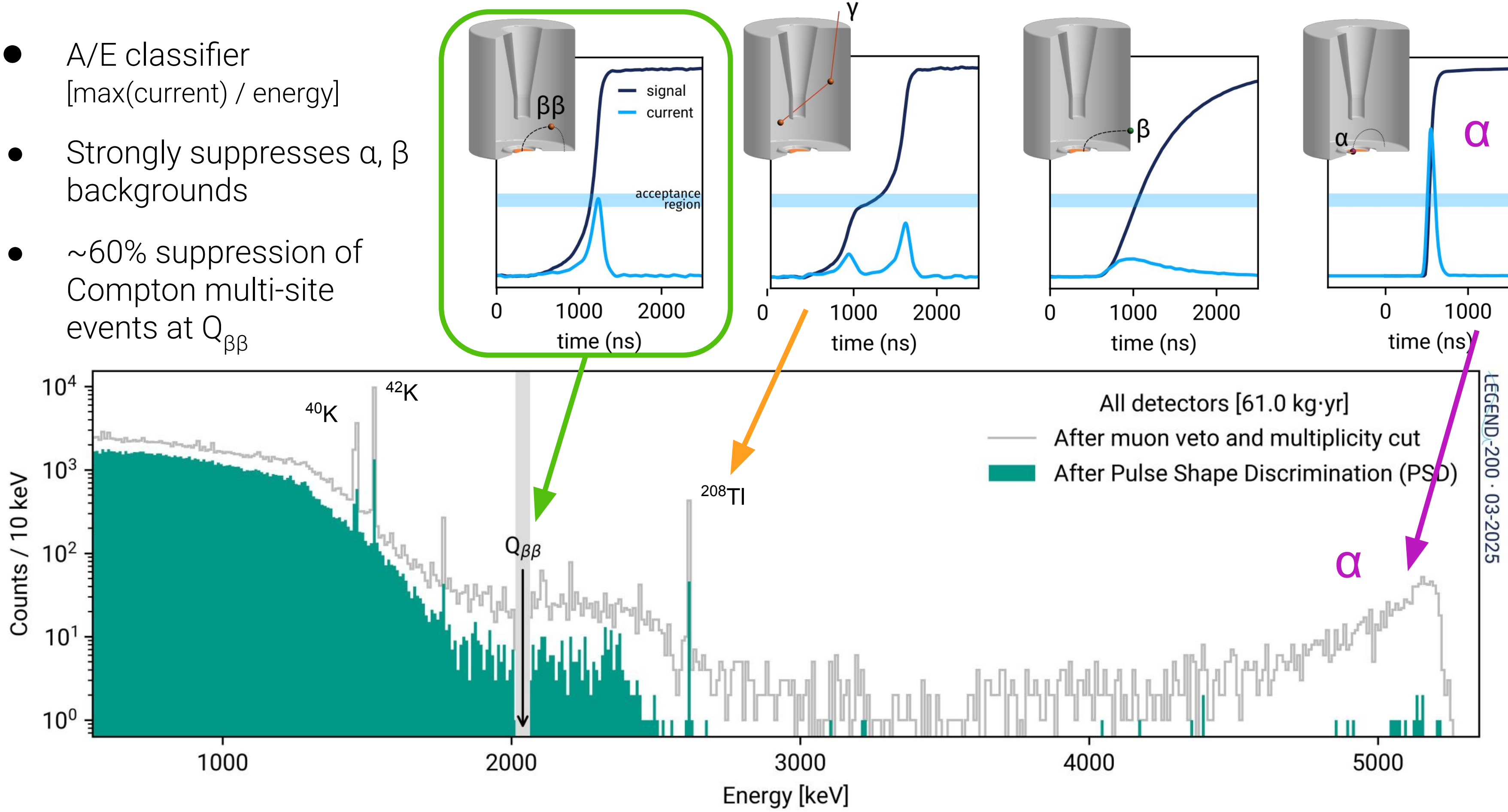
- Spectral shape matched well by fit to data.
- Backgrounds near $Q_{\beta\beta}$ highly suppressed by analysis cuts.
- Cleaning campaign to reduce background further recently finished - second physics data taking in next ~months.

flat, featureless background near $Q_{\beta\beta}$



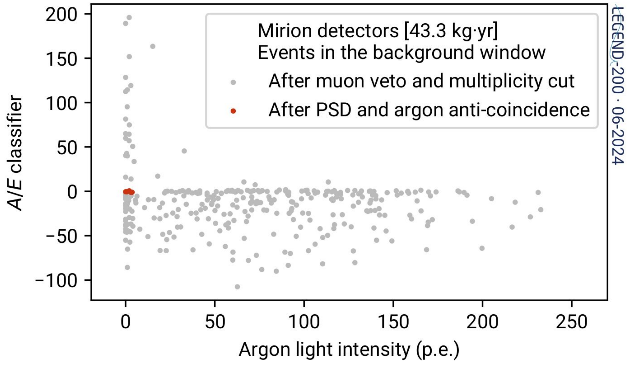
Pulse shape discrimination (PSD)

- A/E classifier [max(current) / energy]
- Strongly suppresses α, β backgrounds
- ~60% suppression of Compton multi-site events at $Q_{\beta\beta}$

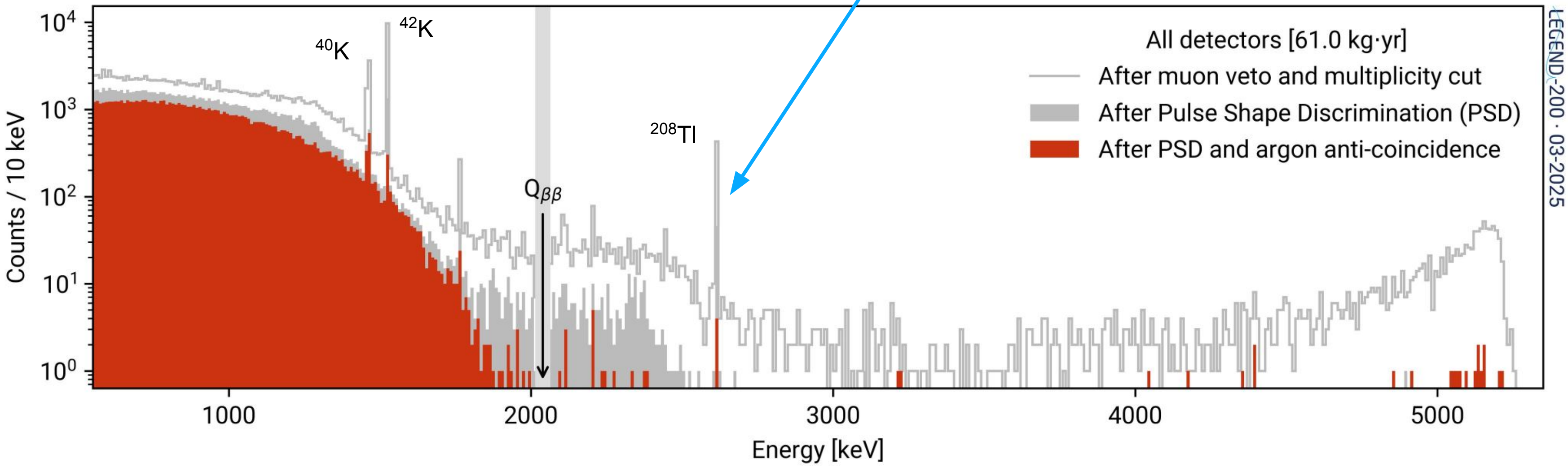


Liquid argon anti-coincidence

- Improved x3 light yield compared to GERDA.
- 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



Unblinded results [61.0 kg·yr]

H. Acharya et al., PRL **136**, 022701 (2026).

LEGEND

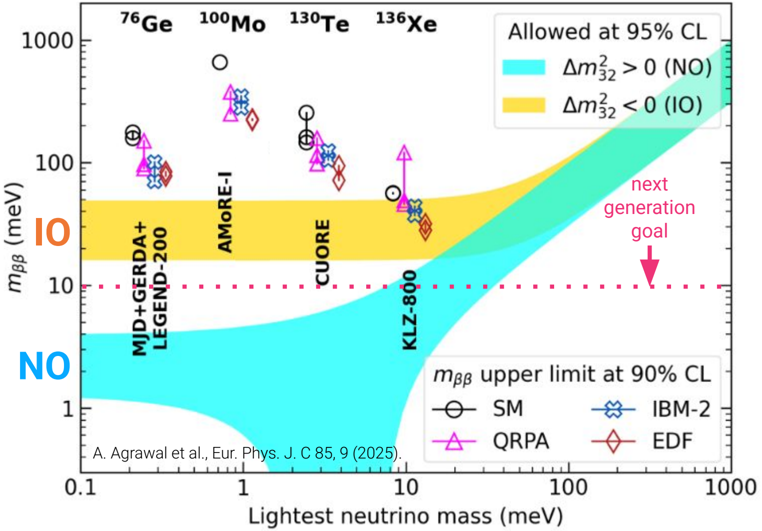
11 events after cuts

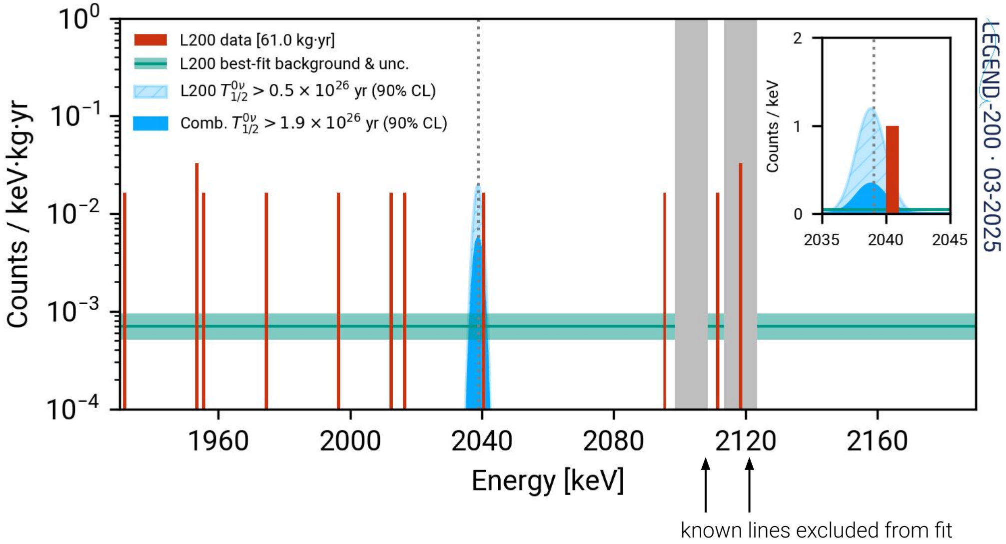
background indices (profiled) of

BI_{gold} [48 kg·yr]: $5.4^{+2.7}_{-2.0} \times 10^{-4}$ cts/(keV·kg·yr)

BI_{silver} [13 kg·yr]*: $13^{+8.0}_{-5.4} \times 10^{-4}$ cts/(keV·kg·yr)

*primarily coaxial detectors with seemingly worse bkg rejection





GERDA, MAJORANA, and LEGEND
^{76}Ge combined result

	Observed (90% CL)	Sensitivity (90% CL)	Bayesian limit (90% CI)
$T_{1/2}$	**> 1.9 × 10^{26} yr**	2.8 × 10^{26} yr	>1.9 × 10^{26} yr

phenom. NME: $2.35 - 6.34$

$m_{\beta\beta} < 75 - 200$ meV

Uncertainty quantified NMEs

H. Acharya et al., PRL **136**, 022701 (2026).

LEGEND

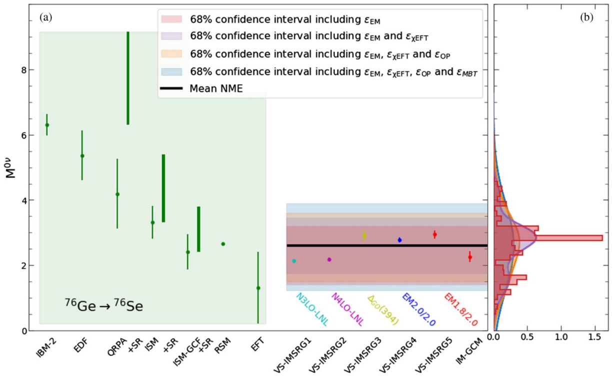
- Recent *ab initio* methods include **quenching and short-range physics, as well uncertainty quantification for ^{76}Ge NME.**

  → **Include this uncertainty directly into our limit on $m_{\beta\beta}$.**

- Most natural framework is a Bayesian approach:

uncertainty quantified NME: $2.6^{+1.28}_{-1.36}$

Bayesian (90% CI): $m_{\beta\beta} < 320\ \mathrm{meV}$



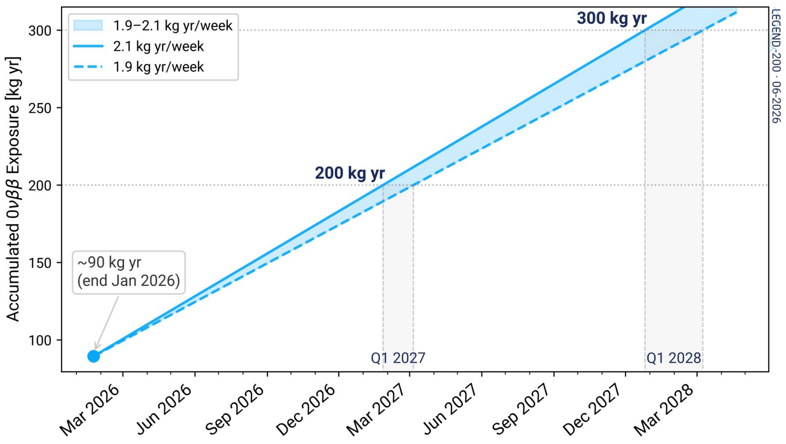
nominal with ±1σ theory uncertainties for comparison: $m_{\beta\beta} < 180^{+190}_{-60}\ \mathrm{meV}$

A. Belley et al., PRL 132, 182502 (2024).

Entering era of uncertainty-quantified NMEs, but ***the uncertainties are still quite large!***

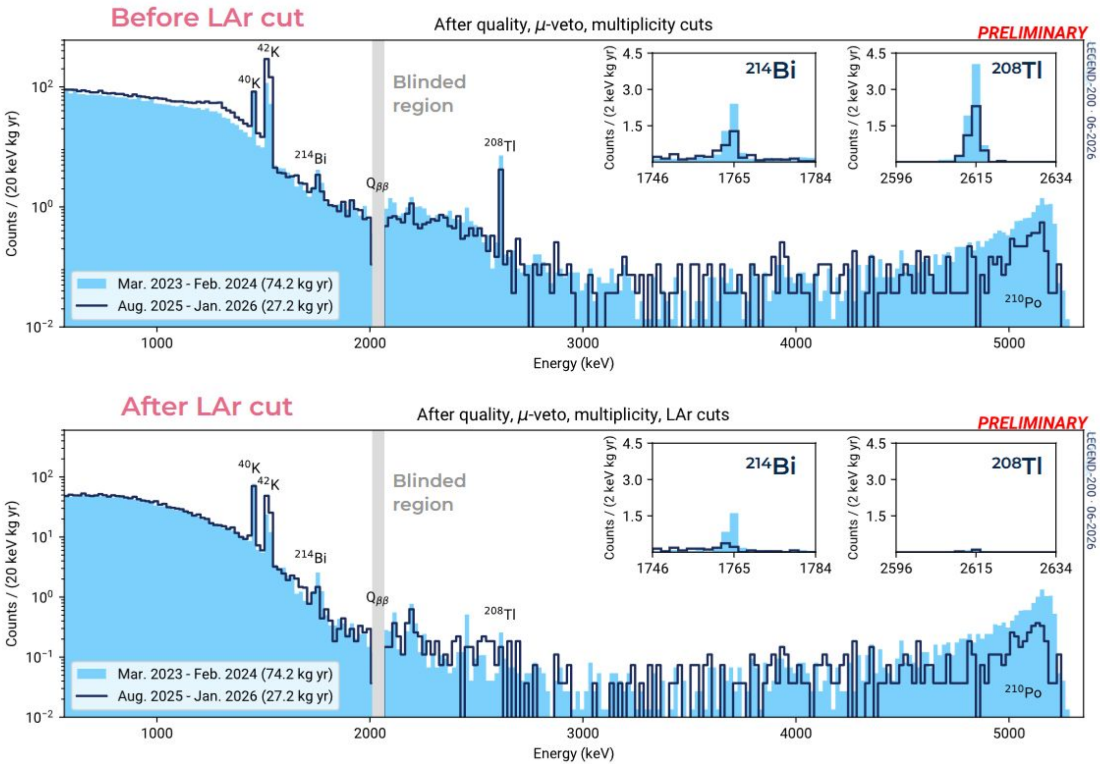
LEGEND-200 timeline

- Background higher than desired in first physics deployment
- Disassembled array → re-cleaned and assayed components
- Surface contamination likely culprit → parts re-cleaned
- Second physics deployment since fall 2025
    - Primarily using IC detectors (L1000 style)
- Third physics deployment planned ~2028 with additional detector production on-going for total of ~160 kg HPGe.



LEGEND-200 second physics deployment

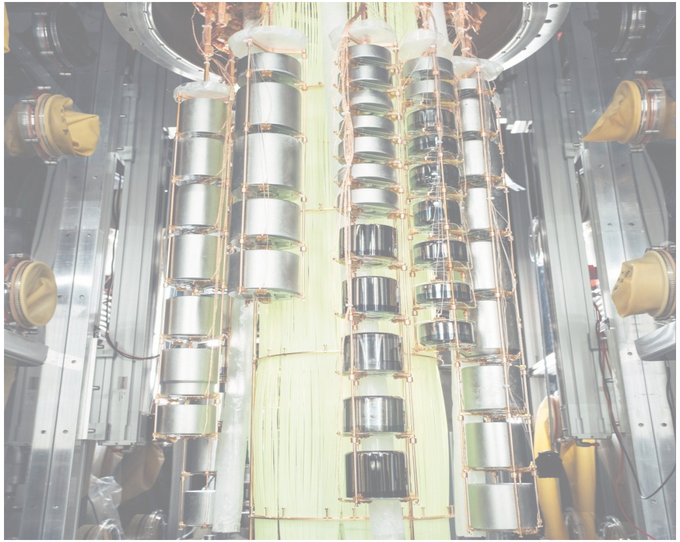
- Reduction in ^{214}Bi and ^{208}Tl by ~2× before cuts!
- After LAr cut, ~5× reduction in ^{214}Bi and no remaining ^{208}Tl at current statistics.
- Background after cuts now seems dominated by ^{42}K from surface events.
- Work in progress for additional PSD / analysis rejection



Continue to maximize 0νββ exposure while expanding physics program!

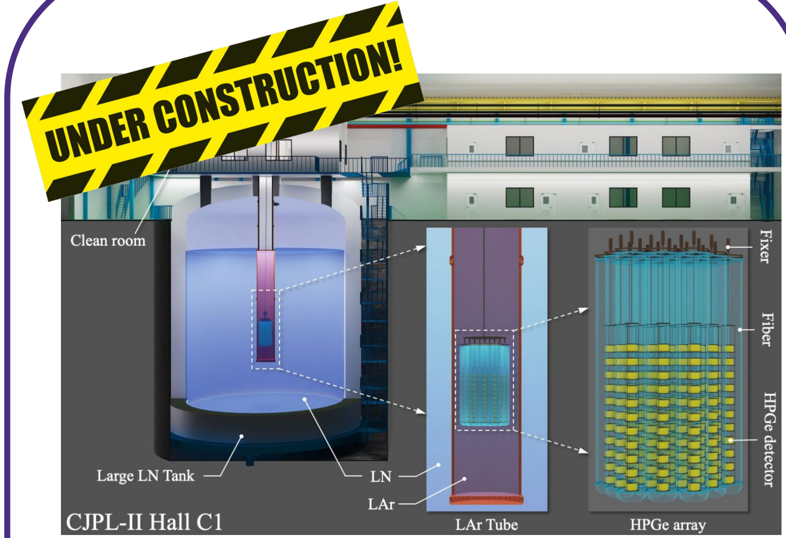
Louis Varriano | ^{76}Ge experiments | 21 July 2026

^{76}Ge 0νββ experiments - current generation



LEGEND-200

currently operating



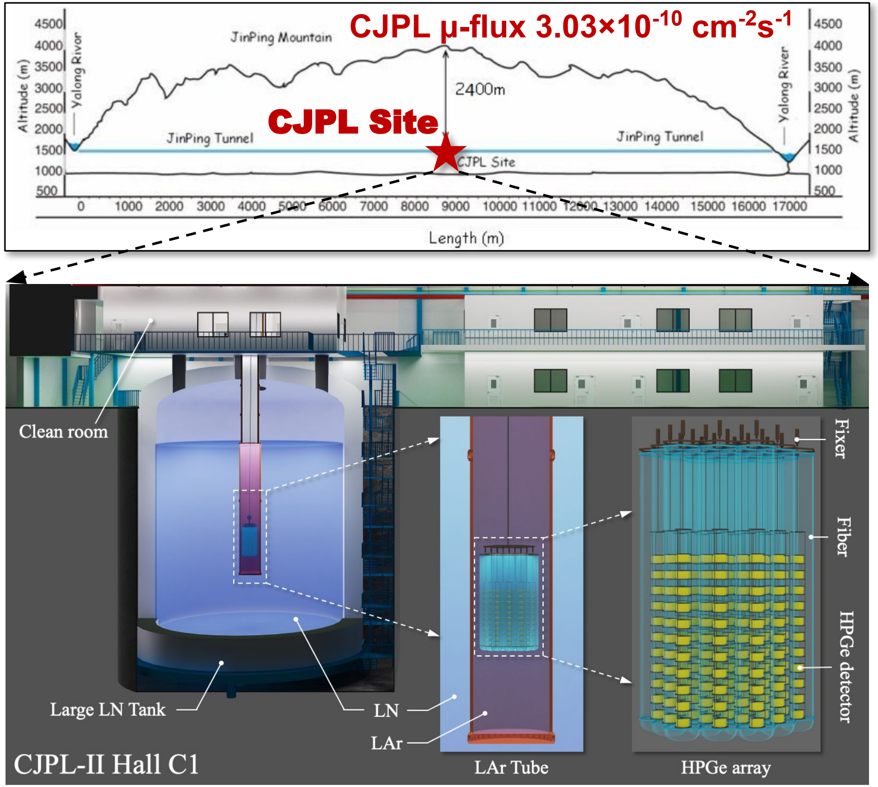
CDEX-300ν

design, construction, and R&D

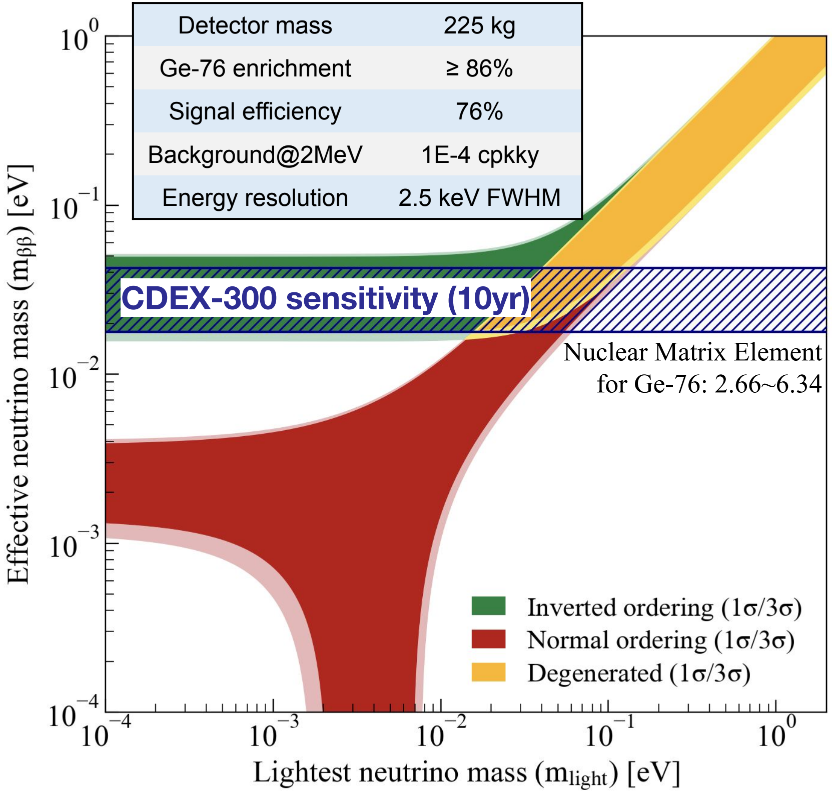
CDEX-300 0νββ experiment at CJPL

Slide from Hao MA

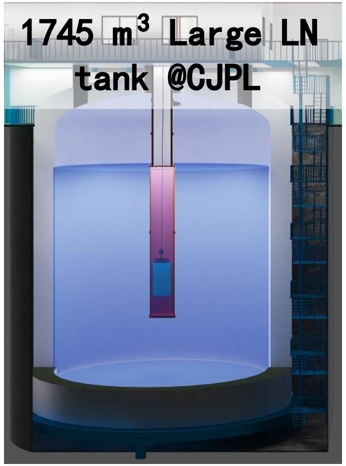
- Searching for Ge-76 0νββ decay at Inverted Ordering (IO) region
- 225 kg enriched (Ge-76>86%) BEGe detectors + LAr veto + 1725 m^3 LN shield

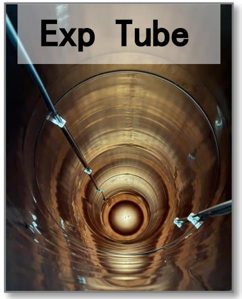


Detector mass	225 kg
Ge-76 enrichment	≥ 86%
Signal efficiency	76%
Background@2MeV	1E-4 cpkky
Energy resolution	2.5 keV FWHM



CDEX-300 Status: infrastructure





Large LN_2 tank

- LN_2 filling completed, LN_2 level ~10 m
- Three Cu experiment tubes installed
- Design of thermal isolation of LN_2&LAr, cycling and purification of LAr underway

Detector test facilities

- Facility for testing HPGe performance in LN has been operated at CJPL
- A LAr prototype in Xichang ground auxiliary lab to study purification and light transmission performance of LAr

Enriched HPGe detector

Slide from Hao MA
LIDINE 2025

Procurement of Enriched Ge detector

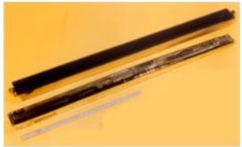
(Technical chain established: Ge-76 enrichment → Ge metal → Crystal growth → Detector fabrication)

We have 200 kg enriched GeO_2 in hand

$^{76}GeO_2$ Power (Storage)

Enrichment (GeF_4 Gas)

Ge Metal



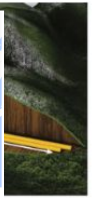
Zone Refining

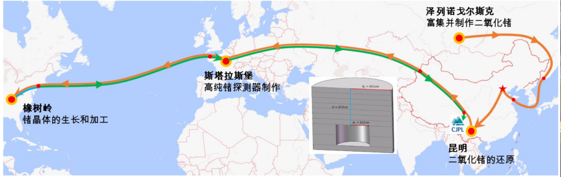
Crystal Growth

Detector Fabrication

Transport (w. steel shields)

CJPL





JINST 19:P03002, 2024

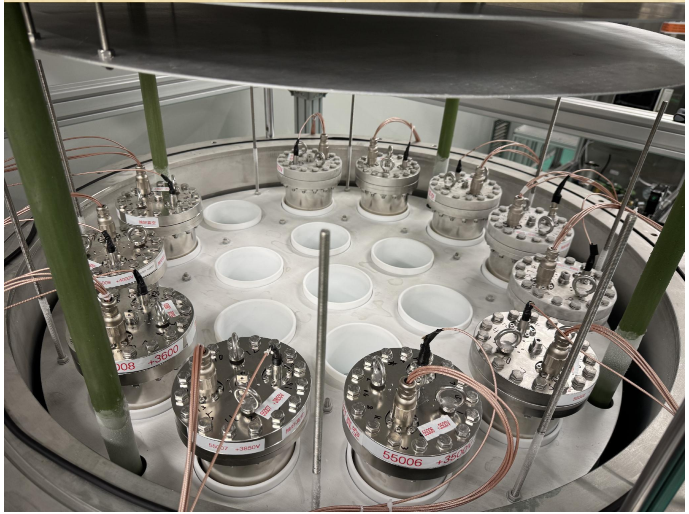
CDEX-300 Status: Enriched HPGe

Slide from Hao MA

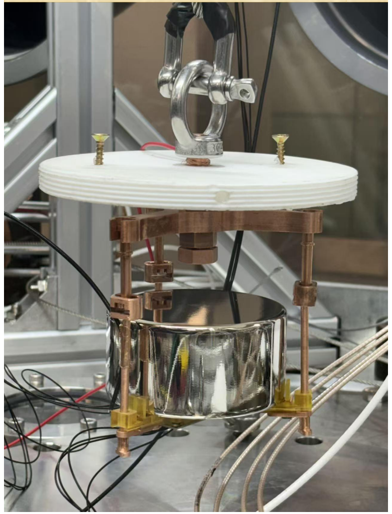
- Test & storage system for HPGe established
- Stability test of Ge-76 enriched HPGe in Cryostat & LN_2 (bare crystal) ongoing
- Array mechanical structure & front-end electronic test is underway

Bare crystal LN_2 test @CJPL

Cryostat test/storage @CJPL



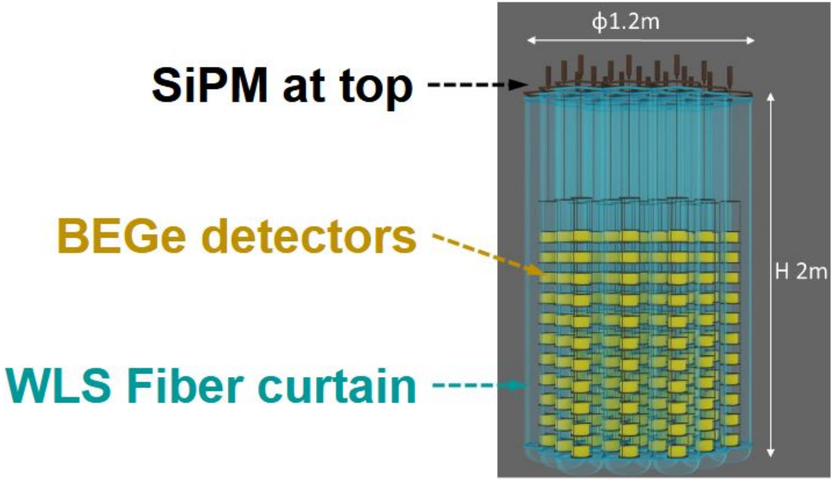
Det. assembly

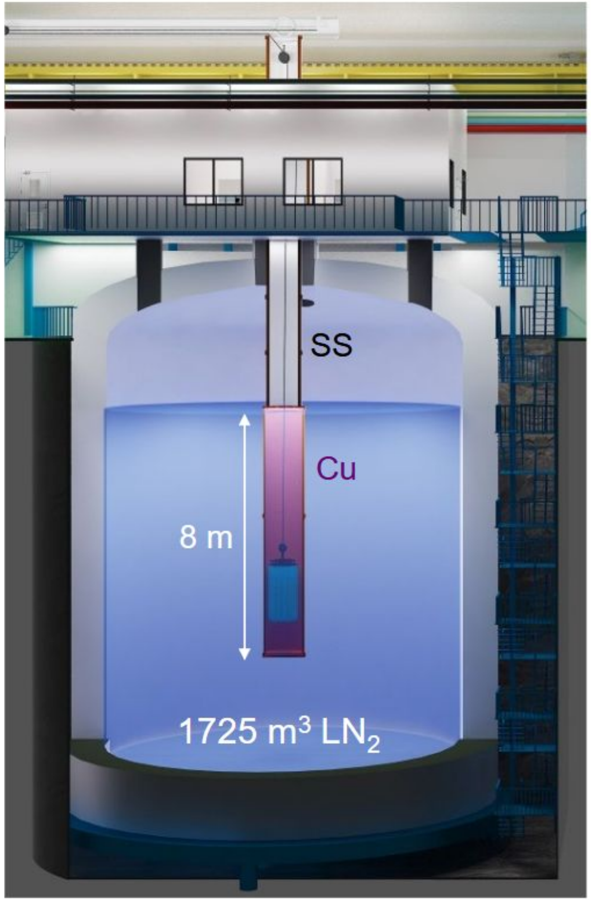


The LAr Veto System

Baseline design:

- ~20 t LAr held by Cu / SS cryostat
- Atmosphere argon
- LAr constantly purified
- LAr cryostat immersed in LN_2
- LAr light read out by WLS Fiber + SiPM





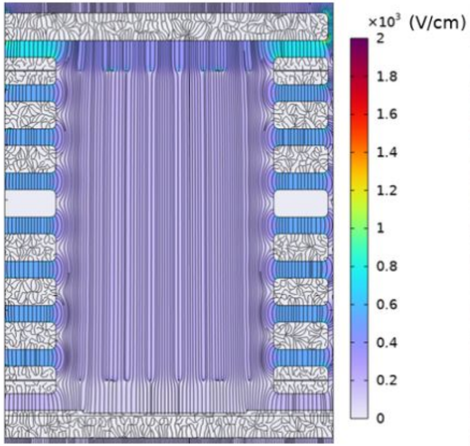
CDEX-300 Status: LAr impurity monitor

Slide from Hao MA

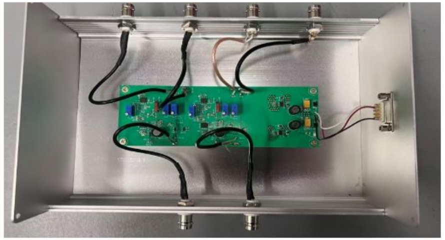
- In-situ monitoring of O_2/H_2O in LAr by measuring electron drift lifetime
- Monitoring O_2 equivalent impurity in LAr at few ppb level
- A prototype been built and further test is ongoing

Prototype Device

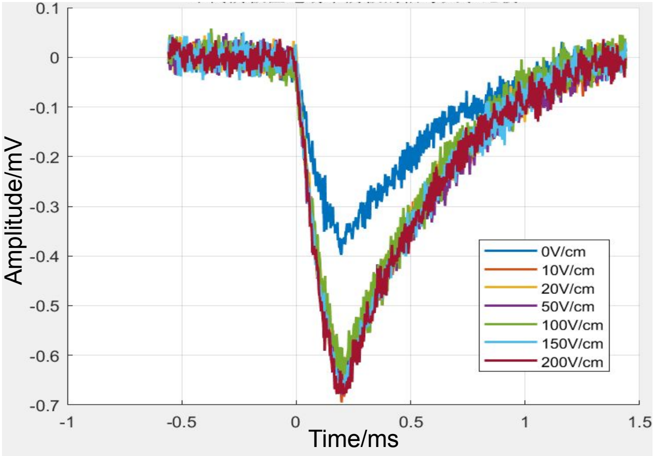
Electron drift field design



Electronics (HV & Readout)



Cathode signal in vacuum test (under different voltage)

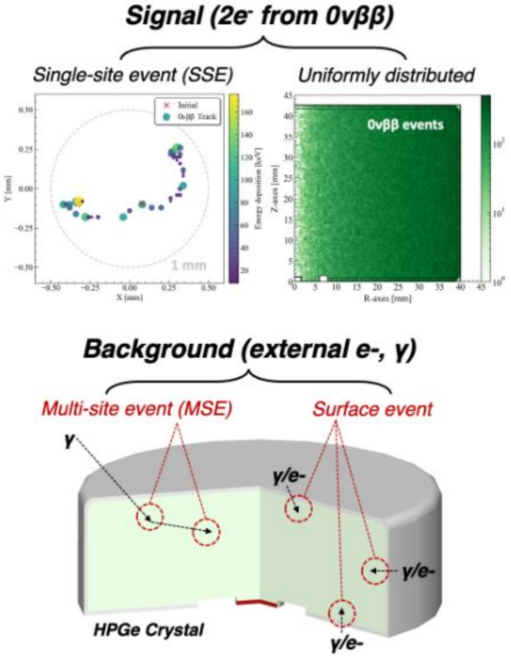


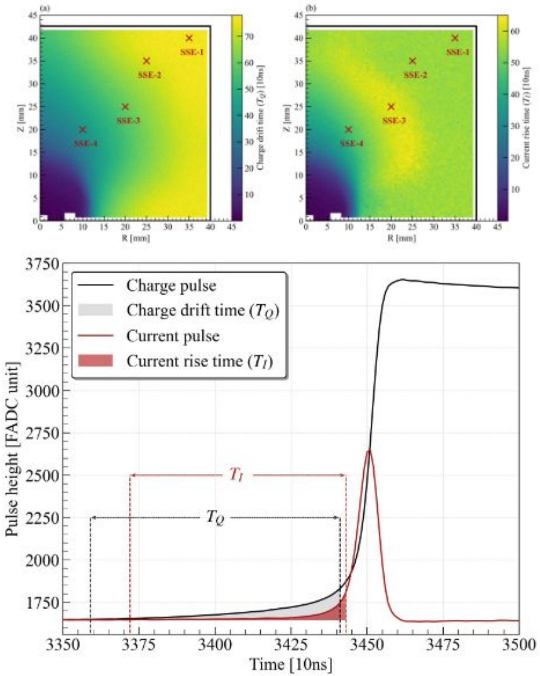
R&D on New PSD Method

Slide from Hao MA
LIDINE 2025

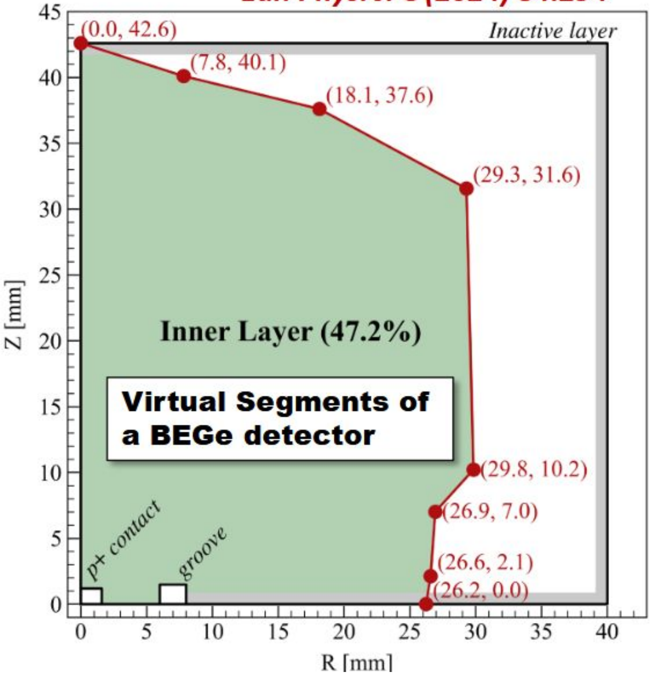
Virtual Segmentation of single-readout Point-contact HPGe

- Infer single-site events (SSEs) position by Pusle shape analysis
- Potential way to further suppress Ar-42 (K-42) surface background





Eur. Phys. J. C (2024) 84:294



Other progress

Slide from Hao MA
LIDINE 2025

☐ Material Background Control

ALL materials to be screened and selected

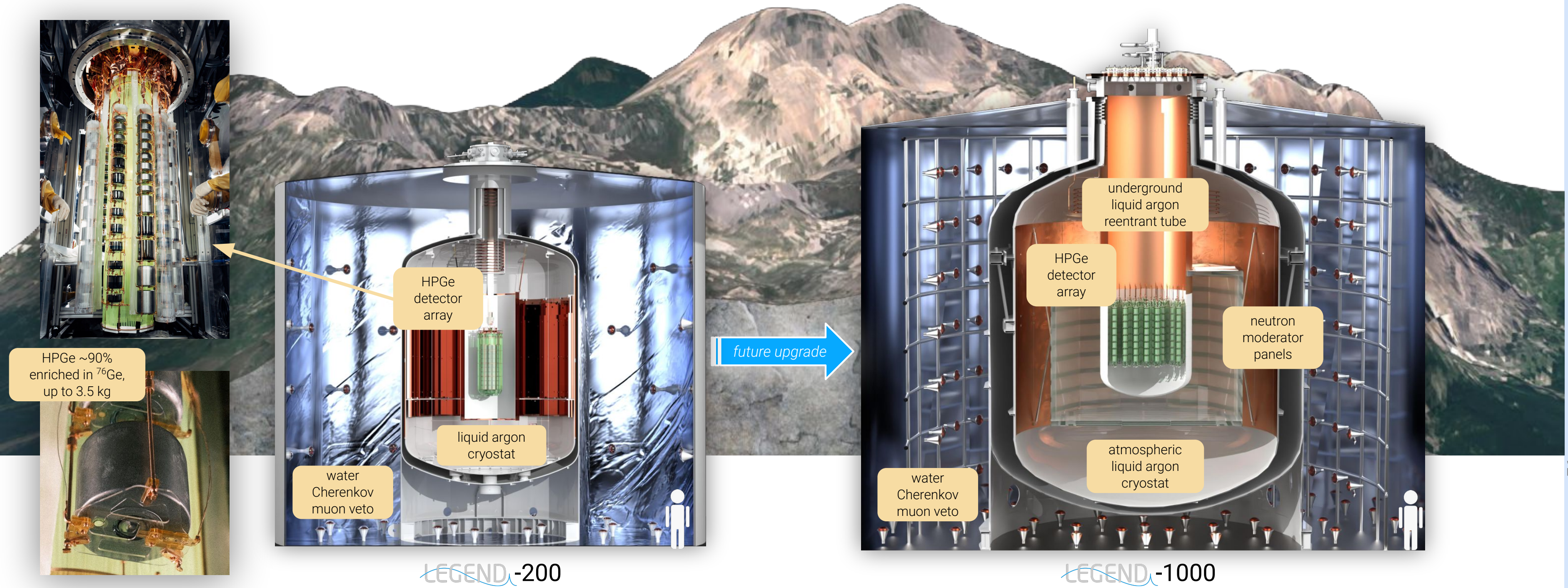
☐ Ge detector & FEE

- Mitigation of cosmic activation on the ground
- Low-mass & pure detector structures
- Low background cables or flexible PCB
- CMOS ASIC Front-end Electronics
- Underground fabrication of Ge detectors

☐ Underground Electro-forming Cu

- U/Th activity <10 μBq/kg
- Free of cosmogenic radioactivity

LEGEND experimental program - next generation



LEGEND-200
currently operating

LEGEND-1000
next generation

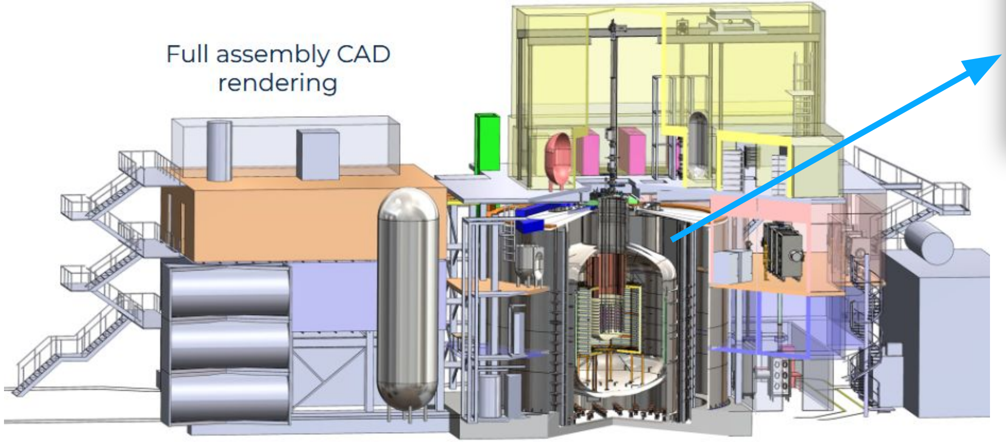
LEGEND-1000 will definitively probe inverted ordering $m_{\beta\beta}$ with $0\nu\beta\beta$ half-life discovery sensitivity $>10^{28}$ yr with background goal of 10^{-5} cts/(keV·kg·yr) and 10 tonne·yr exposure.

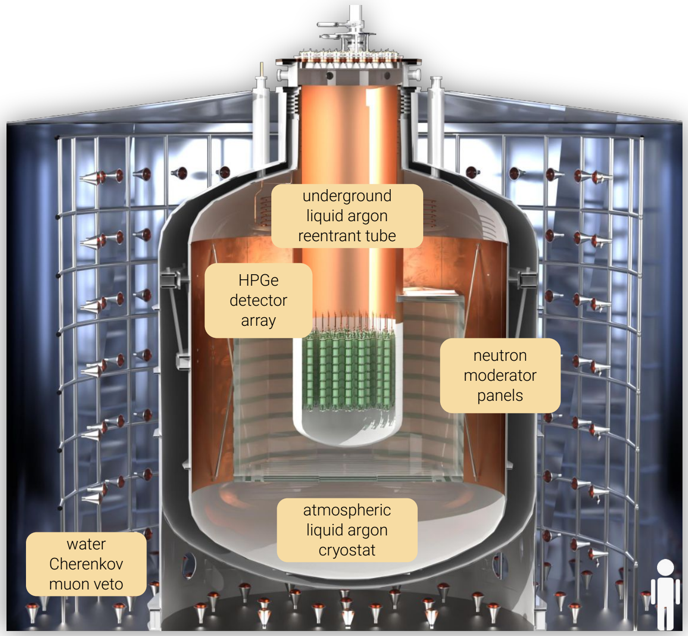
LEGEND-1000 Pre-conceptual Design Report [arXiv:2107.11462]

LEGEND-1000 key improvements

- Will be located at LNGS
- Underground-sourced argon to avoid ^{42}Ar background
- Large mass ($\gtrsim$ 3 kg) IC detectors
- Single string detector modules deployable in liquid argon as detector production continues

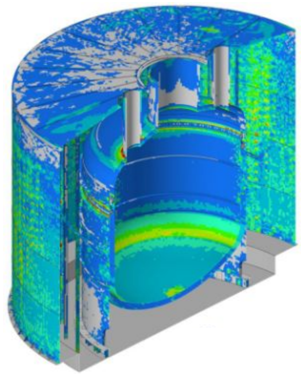
Full assembly CAD rendering

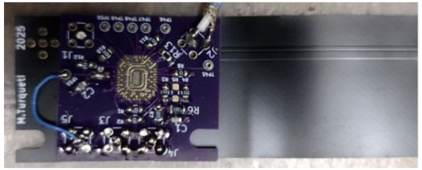


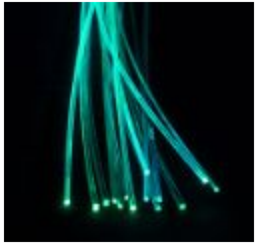


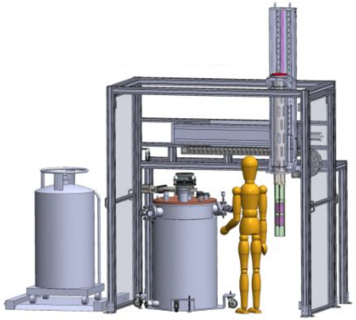
LEGEND-1000 R&D

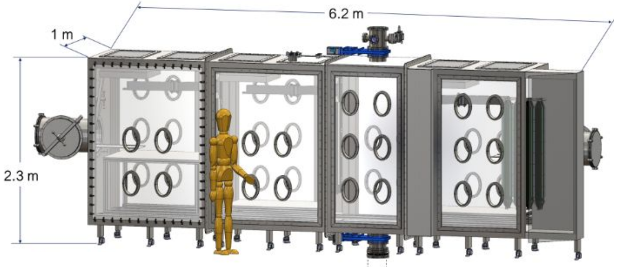
- Improved SiPMs and scintillation fibers for LAr readout
- Reentrant tube welding and burst tests underway
- Ge procurement and enrichment - in discussion with suppliers
- ASIC development underway with two parallel designs
- Underground argon extraction to follow DarkSide extraction → plant under commissioning in Colorado
- BOREXINO dismantling and site preparation about to start at LNGS
- LEGEND-1000 cryostat and water tank in advanced design
    - Cryostat steel procured and assayed



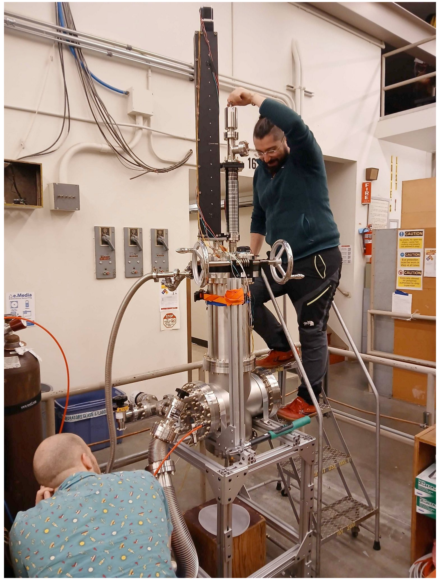


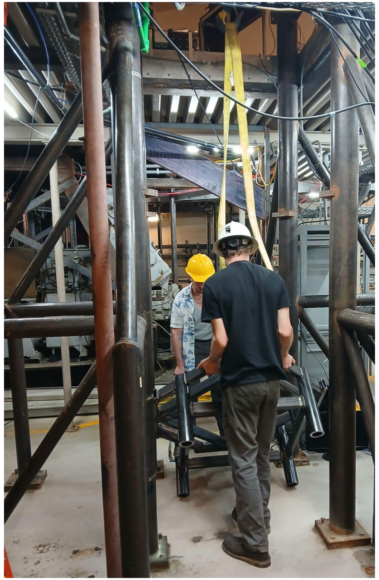


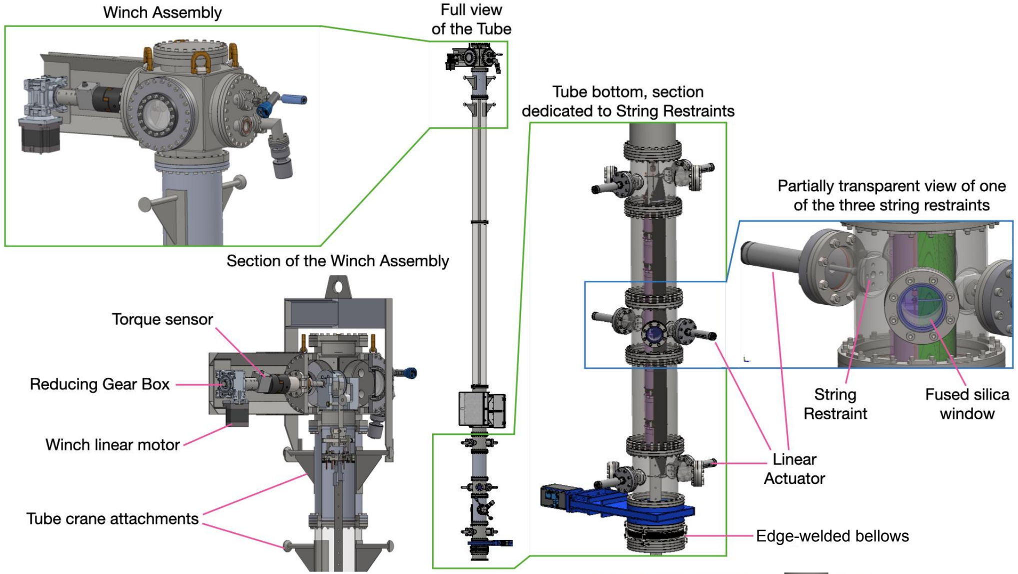


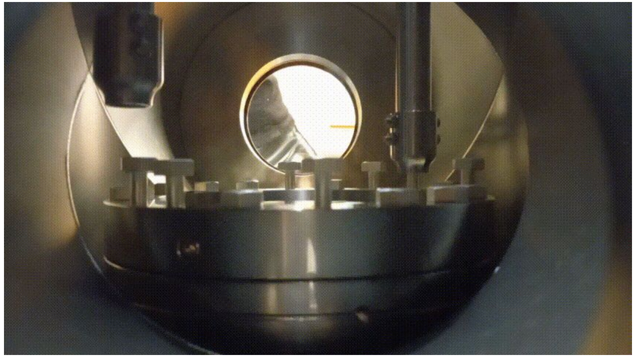


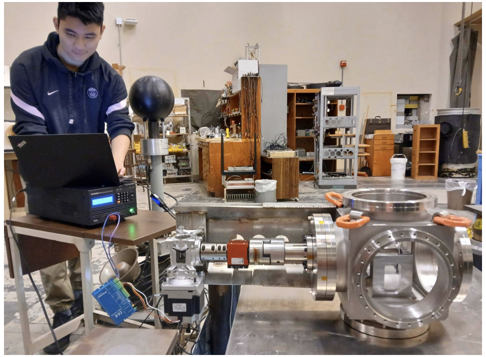
Detector deployment prototyping at UW

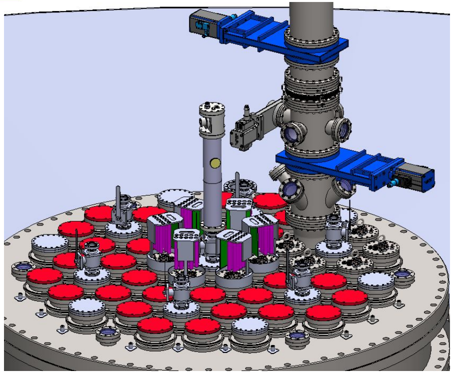






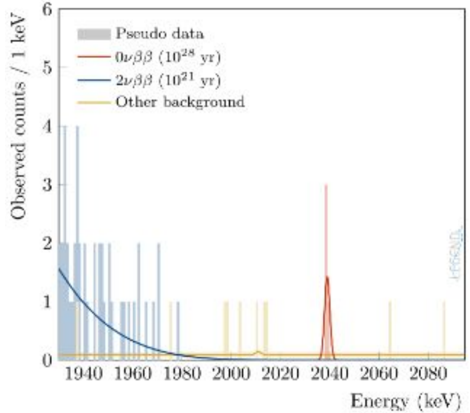


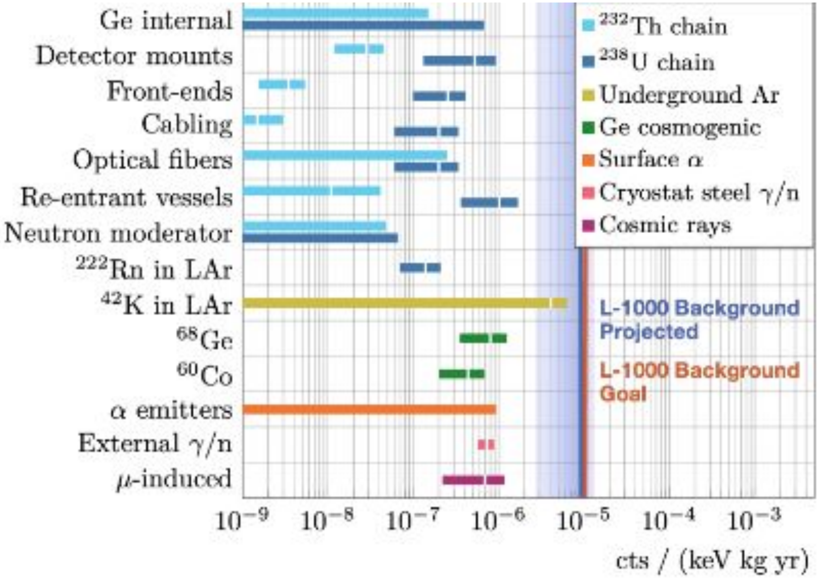


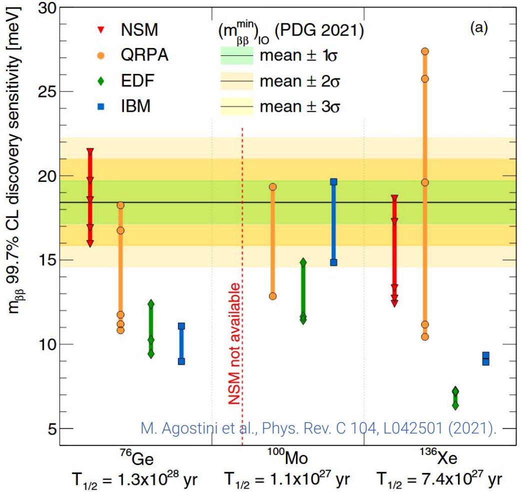


LEGEND-1000 expected background and sensitivity

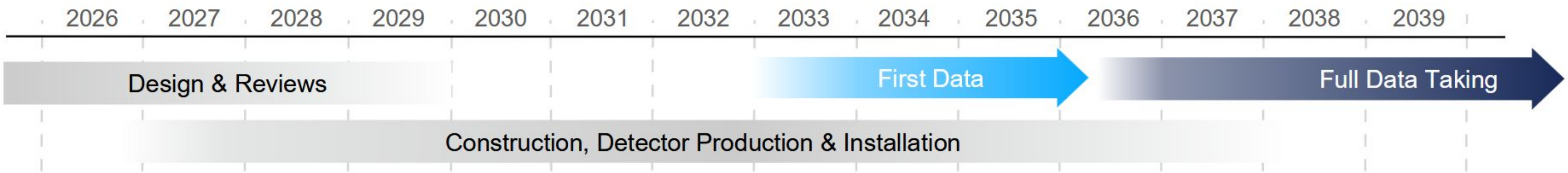
- Underground-sourced argon, plus improvements in material purity and handling, leads to required background reduction.
  - Conservative estimate of ^{42}K shown below







LEGEND-1000 schedule

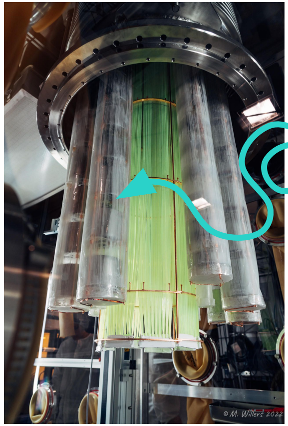


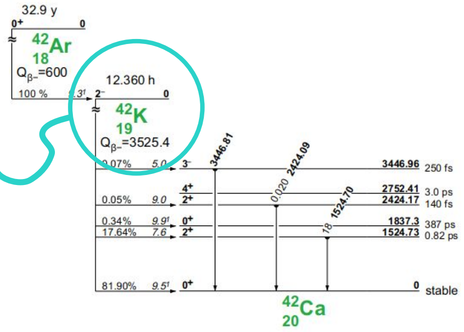
Funding status

- US: NSF (final design phase MREFC) & DOE (CD-1 review).
- Europe: MPG and DFG support; German FIS National Research Infrastructure process (recommendation July 2026); INFN flagship project; contributions from Switzerland and Poland; UK roadmap pending

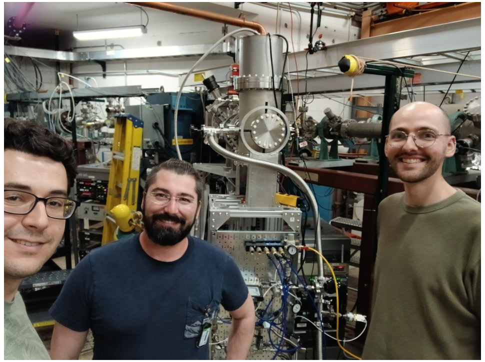
New ^{42}Ar source for background studies

- Important background from cosmogenic ^{42}Ar, 33 year half-life, 60 μBq/kg in atmospheric argon





- Some not well-understood combination of convection, field drift accumulates ^{42}K onto detector surface
- 3.5 MeV β penetrates ~1 mm n$^+$ detector dead layer, covering $Q_{\beta\beta}$
- Seems to be highest background in L200 in second physics run?
- L1000 will use underground-source argon to avoid ^{42}Ar



- **This past weekend → produced ~100s nCi 42Ar source for lab-based mitigation studies of background!**
- **First tritium beam at ATLAS (ANL) - 12 MeV tritium beam at 1 pμA with ^{40}Ar(t, p)^{42}Ar reaction**
- Tritium beam will be useful for many nuclear structure and reaction studies - possibly useful for 0νββ studies?

Conclusions

- LEGEND-200 currently taking physics data - needs improvement to ^{42}Ar background through either cuts or hardware mitigations to improve physics discovery reach!

- CDEX-300ν continuing to design and build!

- Major technical and funding milestones for LEGEND-1000 - on track to deliver a tonne-scale search for neutrinoless double-beta decay.

- New ^{42}Ar source should enable new lab-based investigations to further reduce LEGEND backgrounds!

LEGEND Collaboration