GRAN SASSO SCIENCE INSTITUTE
SCHOOL OF ADVANCED STUDIES
Scuola Universitaria Superiore

INFN LNGS

Exploring Rare Event Searches with LEGEND

From $0\nu\beta\beta$ to Dark Matter

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on behalf of the LEGEND collaboration

IDM 2026 01.06.2026

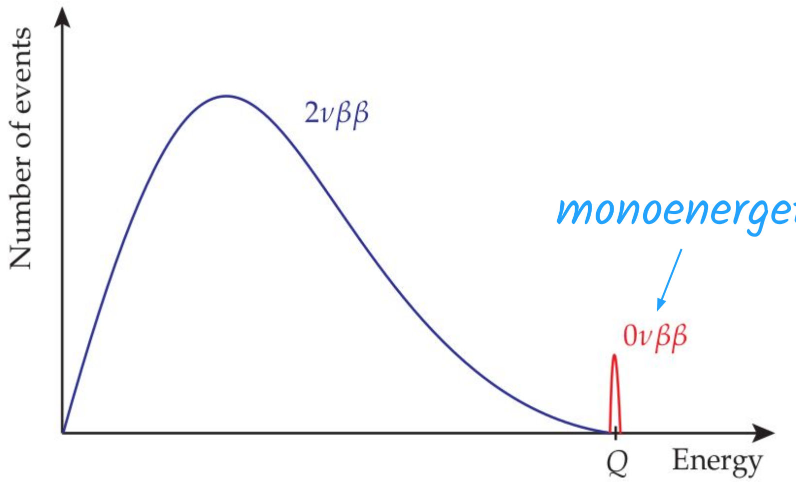
Searching for 0νββ

- The neutrinoless double beta (0νββ) decay is a hypothesized nuclear transition.

$$\boxed{(A,Z) \rightarrow (A,Z+2) + 2e^-}$$

"creation of matter without antimatter"

- 0νββ can be mediated by the exchange of two massive Majorana neutrinos.



monoenergetic peak

- In background-free regime: $BI \cdot \Delta E \cdot M \cdot t$ < 1 count

$$T^{0\nu}_{1/2} \propto M \cdot t$$

M: total detector mass
t: run time
BI: background index
ΔE: energy resolution at $Q_{\beta\beta}$

exposure

Desirable design for an experiment searching for 0νββ signal:

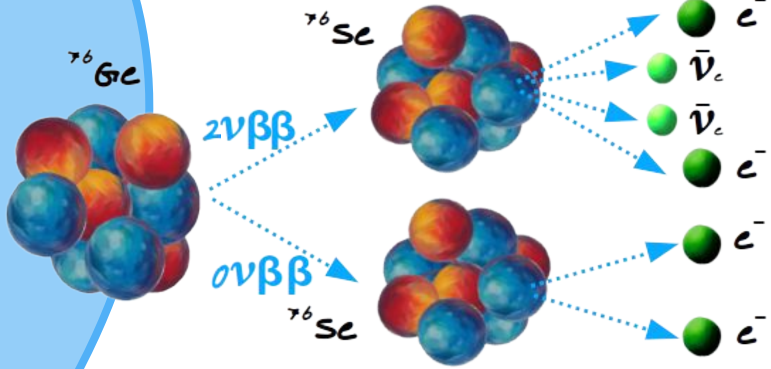
- Low background level
- Good energy resolution of the detector
- Large exposure
- Large $Q_{\beta\beta}$

LEGEND = **L**arge **E**nriched **G**ermanium **E**xperiment for **N**eutrinoless Double-Beta **D**ecay

270+ members, 50+ institutions, 11 countries Collaboration formed in October 2016

LEGEND mission:

"The collaboration aims to develop a phased ^{76}Ge based double beta decay experimental program with discovery potential at a half-life significantly longer than 10^{28} years, using existing resources as appropriate to expedite physics results."



$Q_{\beta\beta}$= 2039 keV

LEGEND collaboration

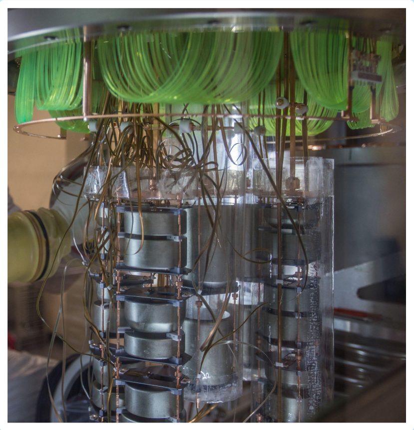
look at the links!

Majorana Demonstrator

Best energy resolution

+

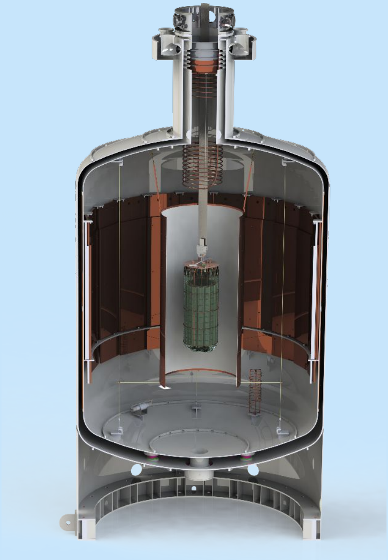
GERDA



Lowest background index

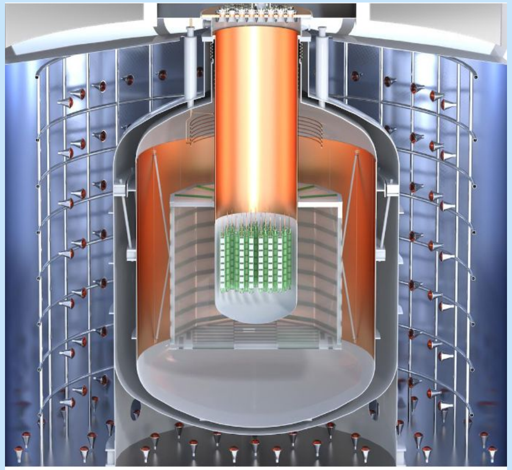
=

LEGEND-200



Situated in the existing GERDA infrastructure at LNGS

LEGEND-1000



Emerged as the **portfolio review winner**!

completed in ~ **2020**

data taking started in **2023**

...

commissioning will start in **2030**

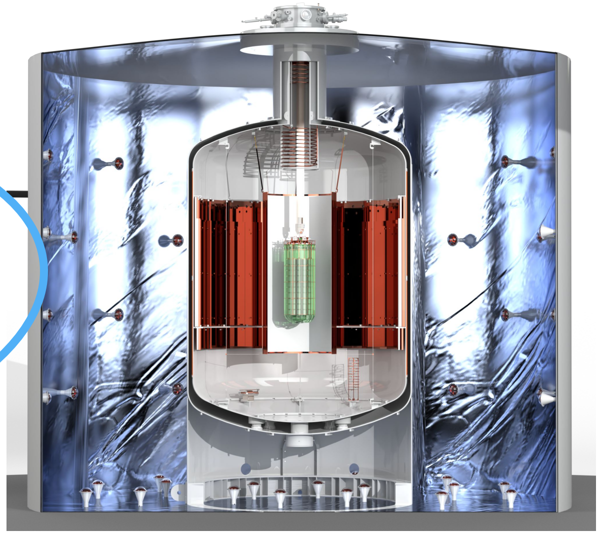
The LEGEND project

First Stage: LEGEND-200

- up to **200 kg** of detector mass: 35 kg from GERDA + 30 kg from MJD + 140 kg which are new, distributed to 14 strings
- Current data taking since March 2023 with ~142 kg of detectors deployed in LAr
- Total planned exposure 10 times larger than GERDA, up to 1 ton yr

Goals

$T^{0\nu}_{1/2}$ > 10^{27} yrs
m < 30-70 meV
B < $2 \cdot 10^{-4}$ cts/(keV · kg · yr)

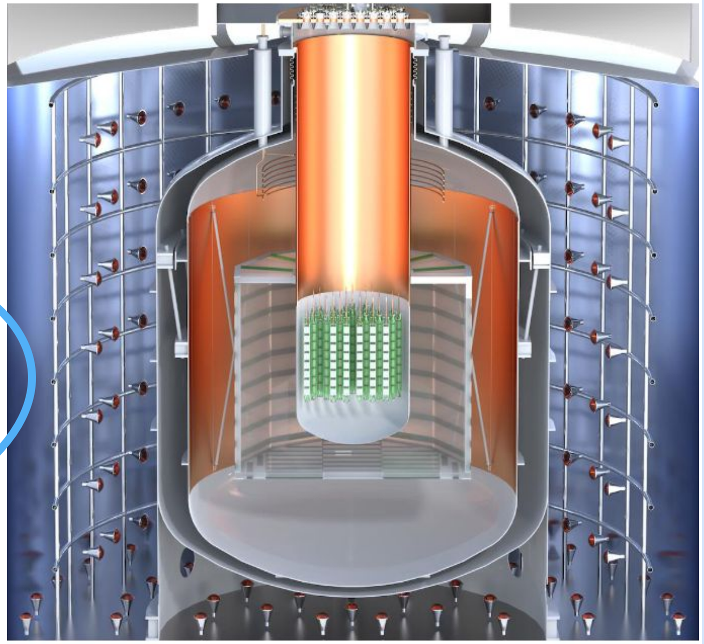


Further Stage: LEGEND-1000

- Staged installation up to **1000 kg** detector mass (ICPC)
- Detector strings immersed in radiopure underground LAr (UGLAr)
- Pending funding approval

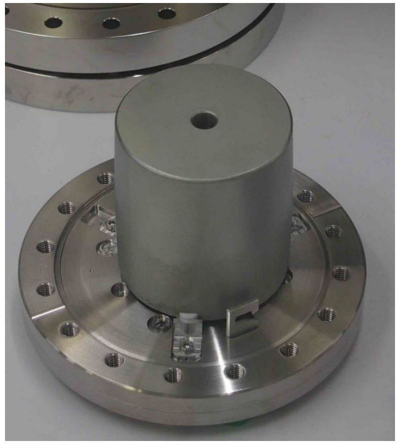
Goals

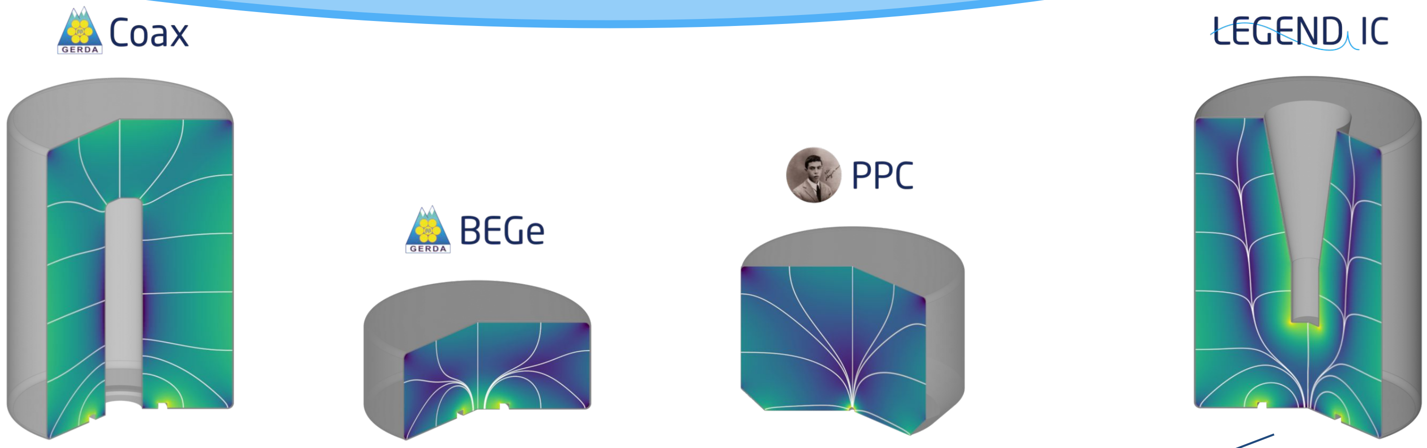
$T^{0\nu}_{1/2}$ > 10^{28} yrs
m < 10-20 meV
B < 10^{-5} cts/(keV · kg · yr)



Why germanium detectors?

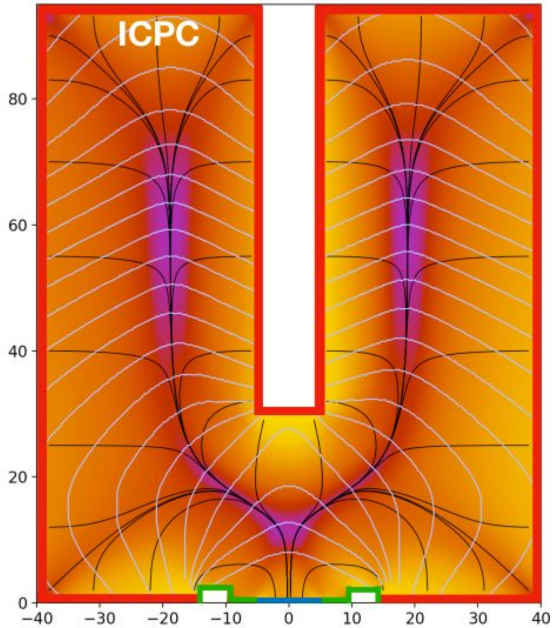
- High detection efficiency (detector = ββ source)
- Best proved energy resolution at the Q-value
- High pulse shape analysis capabilities
- Lowest background per FWHM energy resolution in the field
- Well-established technology



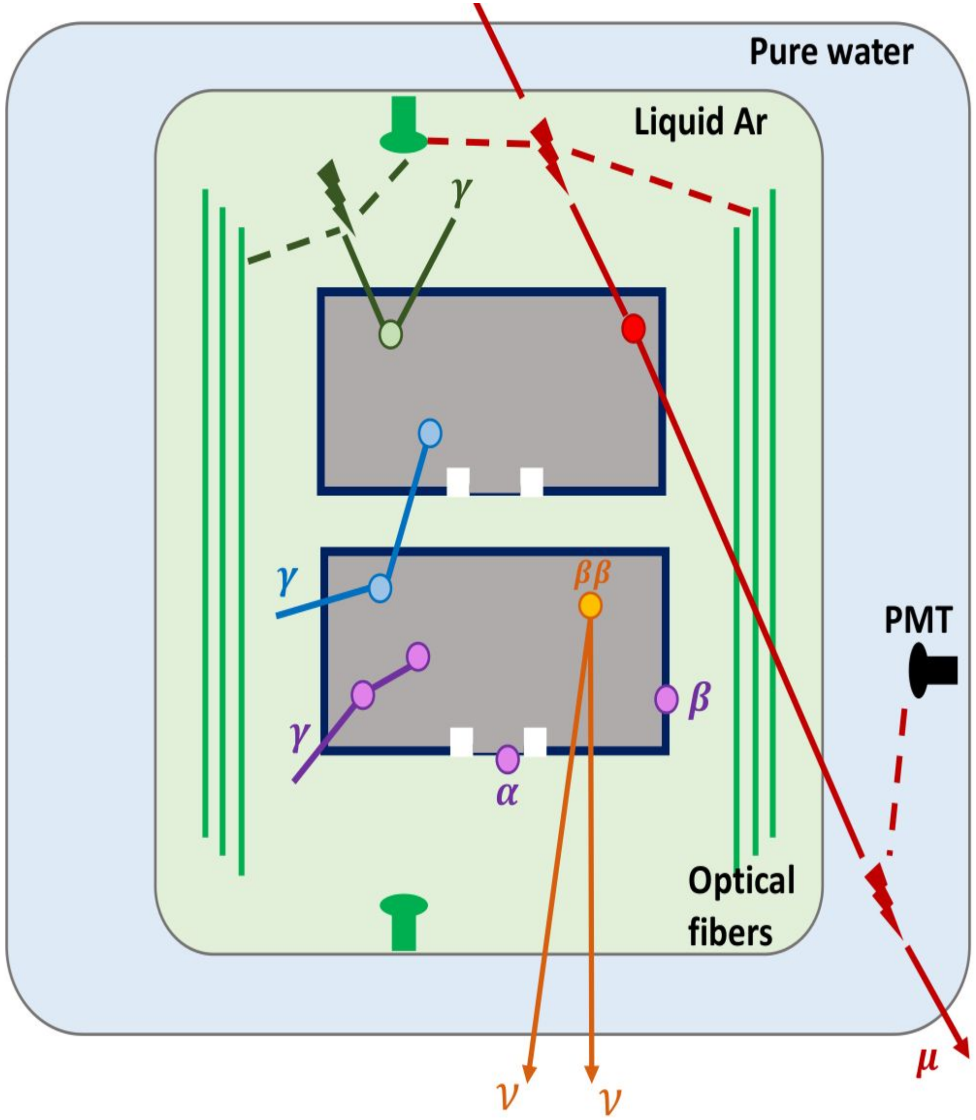


Inverted Coaxial Point Contact (ICPC) detectors:

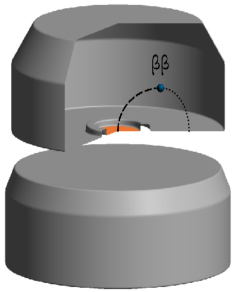
- Enriched detectors, 92% of detector material is ^{76}Ge
- Excellent energy resolution and pulse shape discrimination
- Significantly larger w.r.t. BEGe or PPC (up to 3 kg)
- Less channels, less background
- Better surface to volume-ratio (30-40%)



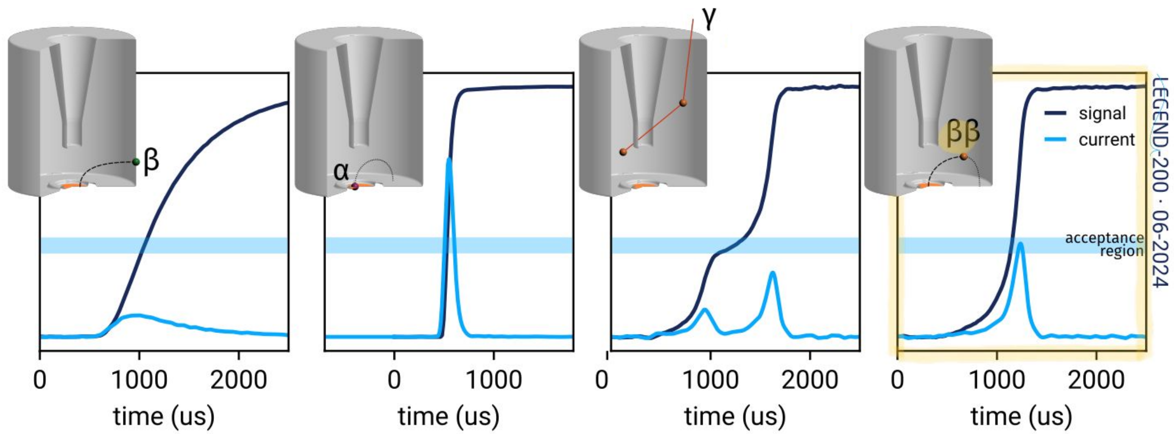
Active background reduction tools



ββ decay signal: single-site event → energy deposition in a 1 mm^3 volume



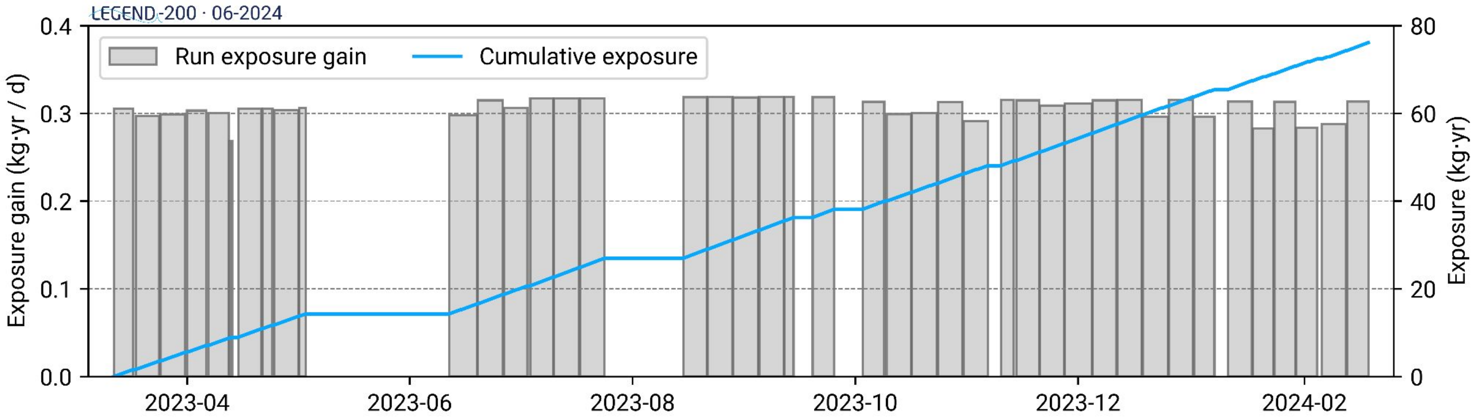
- Anti-coincidence with the muon veto
- Anti-coincidence between detectors (multisite cuts)
- Active veto using LAr scintillation (LAr Veto)
- Pulse shape discrimination (PSD)



Exposure and energy resolution

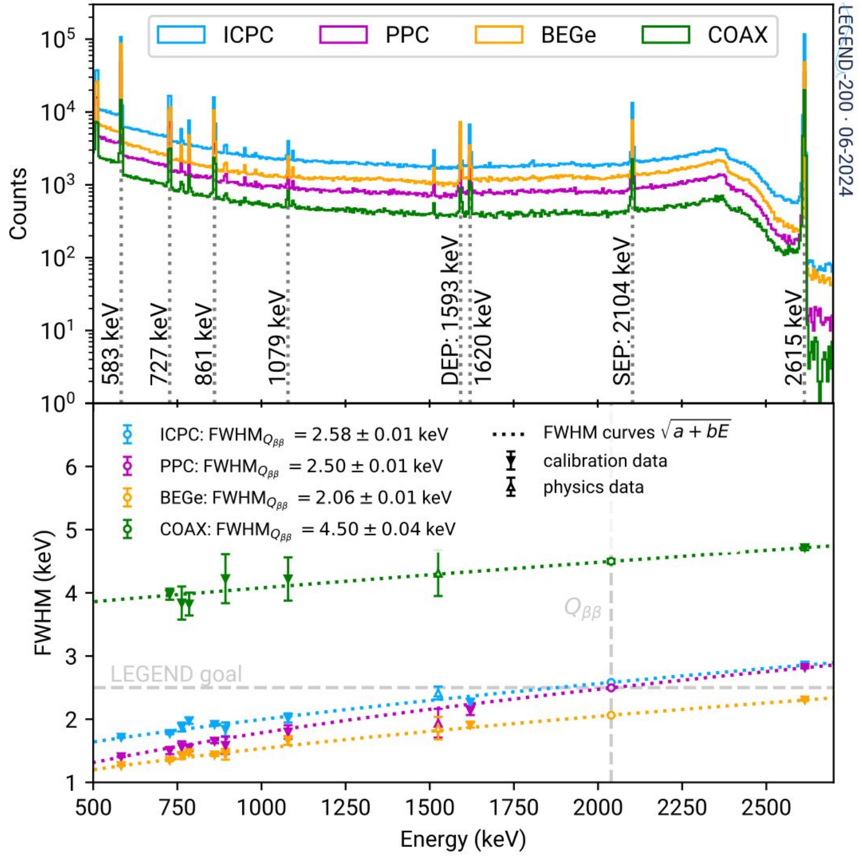
Exposure accumulated over 1 year:

- SILVER DATASET → Background and performance (76.2 kg yr)
- GOLDEN DATASET → 0νββ data (48.3 kg yr)

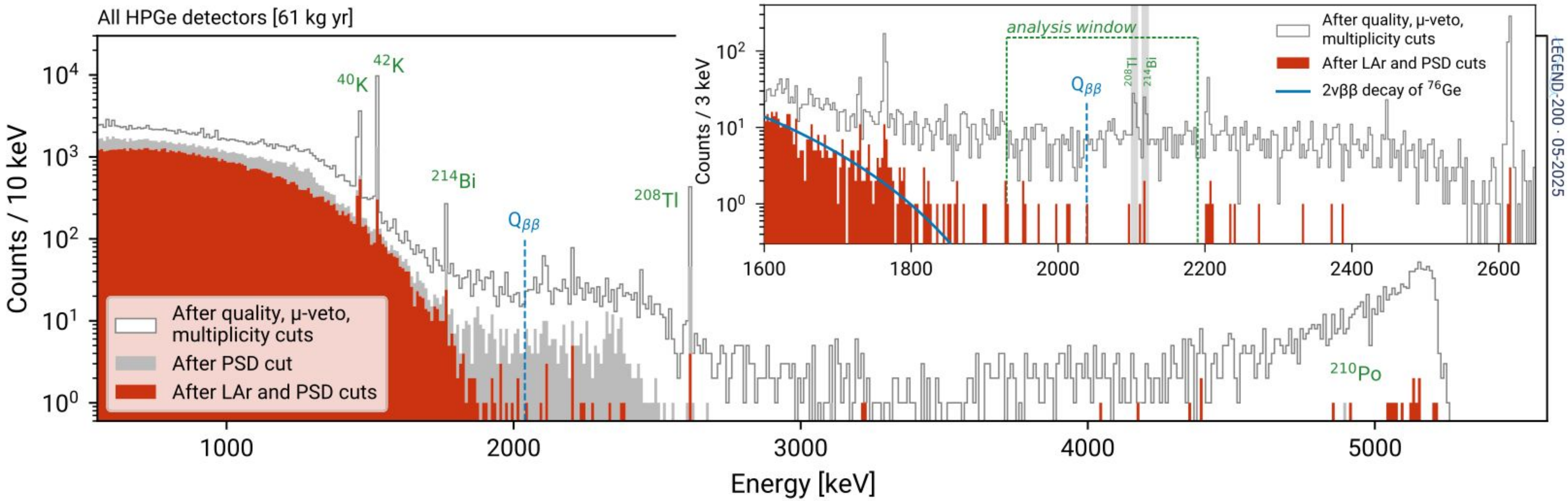


Energy resolution:

- FWHM ~ 0.1% keV at $Q_{\beta\beta}$
- Shifts monitored with weekly ^{228}Th calibrations
- Second-order variations tracked in time



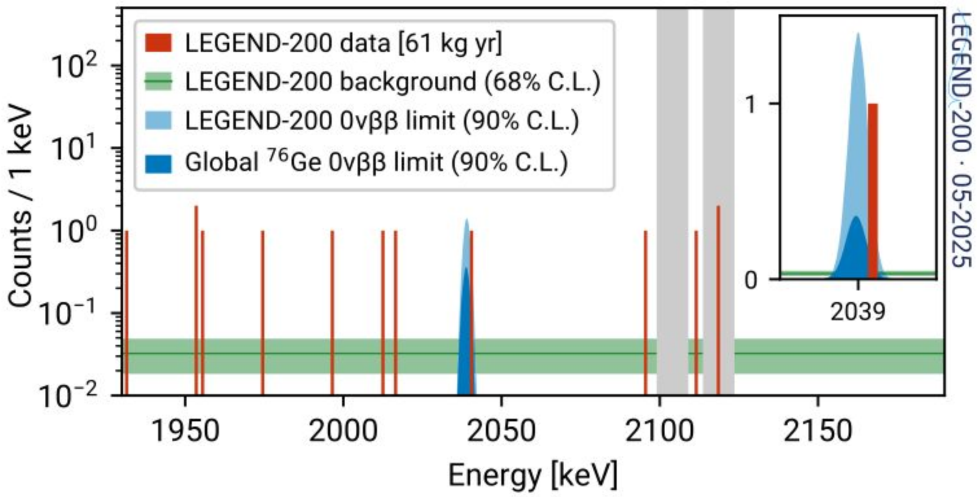
Data set after cuts



- Strong anti-correlation of argon and PSD cuts
- Strong suppression of surface α and β (^{42}K) events by PSD cut
- ~60% suppression of Compton multi-site events at $Q_{\beta\beta}$ by PSD cut
- Strong suppression of background on top of 2νββ by LAr cut
- Overall 0νββ survival fraction of ~60%
- "Pure" 2νββ distribution; few overall events surviving at $Q_{\beta\beta}$

Final results

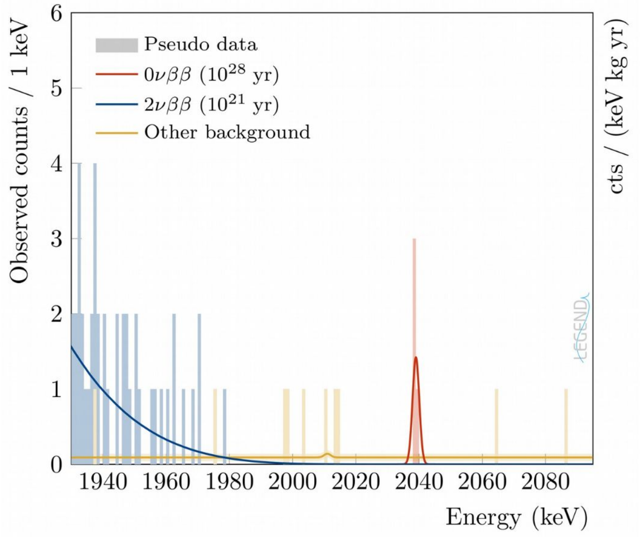
- Improved x3 light yield compared to GERDA
- Combination of cuts (QC, multiplicity, muon veto, PSD, LAr veto) suppresses nearly all background
- 11 events after cuts after unblindings
- Background indices:
  - BI_{gold} (48 kg·yr): $5.4^{+2.7}_{-2.0} \times 10^{-4}$ cts/(keV·kg·yr)
  - BI_{silver} (13 kg·yr): $13^{+8.0}_{-5.4} \times 10^{-4}$ cts/(keV·kg·yr)
- $m_{\beta\beta}$ <75-200 meV

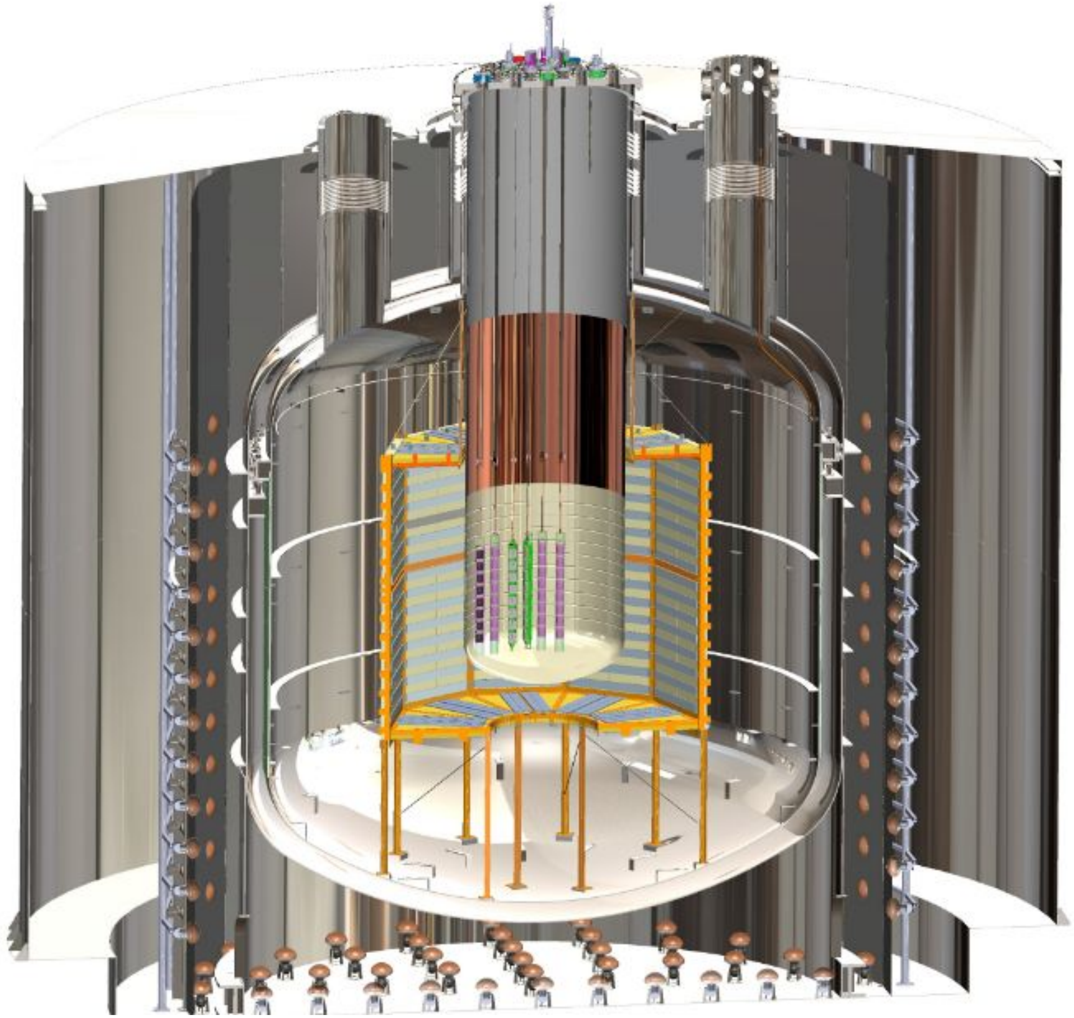


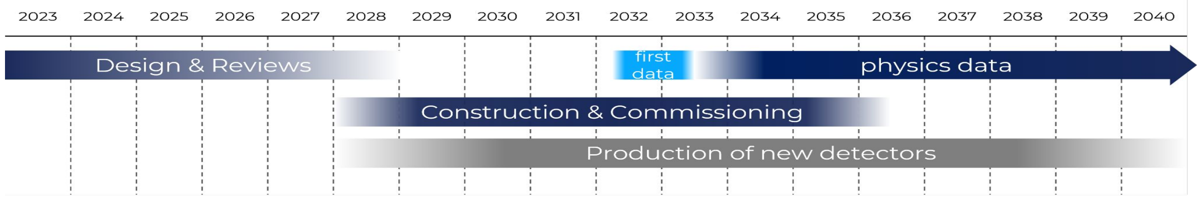
$T_{1/2}$	Observed (90% C.L.)	Sensitivity (90% C.L.)
LEGEND	**> 0.5 × 10^{26} yr**	**1.0 × 10^{26} yr**
LEGEND+GERDA +MAJORANA	**> 1.9 × 10^{26} yr**	**2.8 × 10^{26} yr**

LEGEND-1000

- Quasi-background-free for 10 ton yr exposure
- Flat background - no γ peaks close to $Q_{\beta\beta}$
- Unambiguous discovery of 0νββ - signal will be visible to the eye
- In case of no discovery, push lower limit 2 orders of magnitude above current best





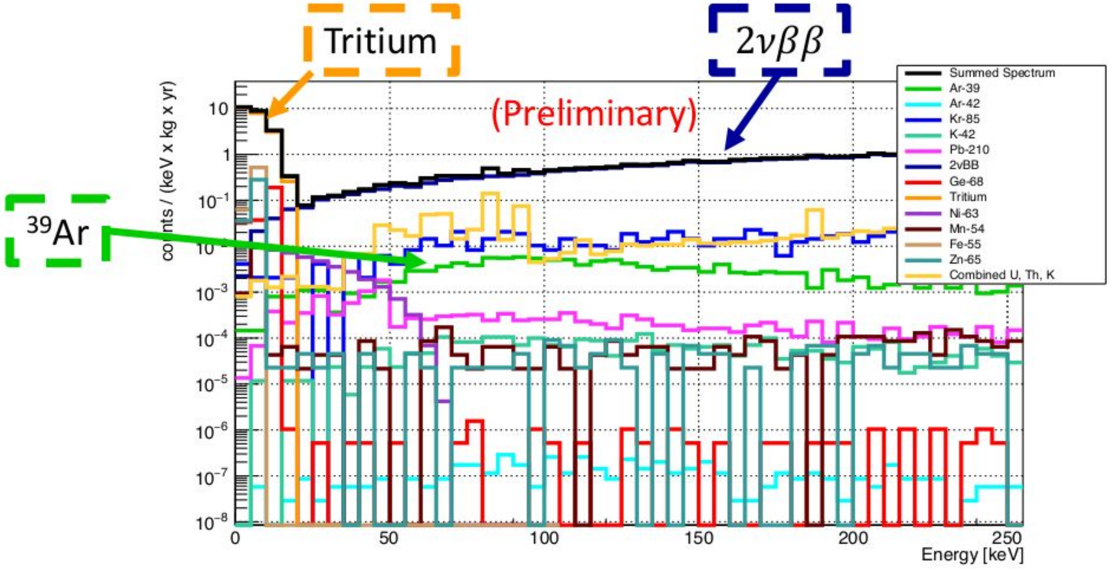


Physics opportunities beyond 0nbb

Beyond the main scope of the experiment:

- Dark Matter Candidates
  - WIMP, ALPs, composite DM, axions
- $2\nu\beta\beta$ Spectral Effects
  - Majorons, Lorentz violation, ...
- Track-like Signatures
  - LIP, magnetic monopole, ...
- Tests of Fundamental Physics
  - baryon decay, pauli exclusion principle violation, ...
- Astrophysical Neutrinos
  - solar, SN, pre-SN, ...

In LEGEND-200, domination of ^{39}Ar from AtmLAr below ~565keV



J. Waters

In LEGEND-1000 with UGLAr, the most interesting researches:

- Peak search signature
- Ultraheavy dark matter
- $2\nu\beta\beta$ spectral distortions

Extrapolation of background model at lowest energy with application of several cuts

- Multiplicity, LAr cut, detector surface events

Peak search signature

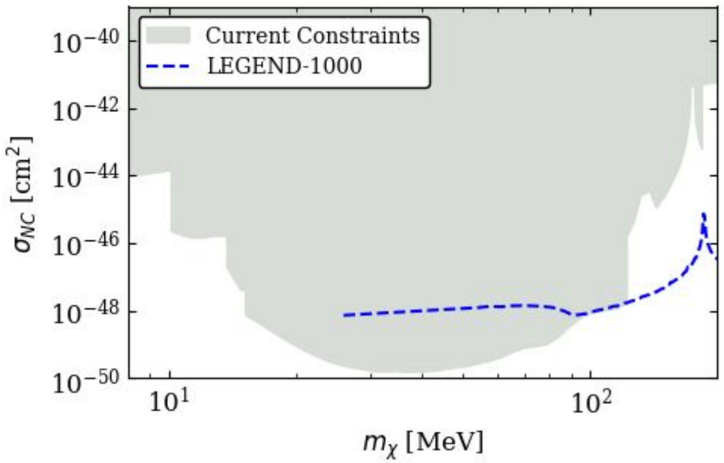
PhysRevLett.129.161805
https://arxiv.org/abs/2504.13089

LEGEND

Limits (90% C.L.) based on the statistical fluctuation above the background model within E ± 2σ

- Absorption of Fermionic Dark Matter
- keV-scale bosonic dark matter (ALP, DP)
- Sub-GeV DM-nucleus 3 → 2 scattering
- Sterile neutrino transition magnetic moment

$$R_{NC} = \frac{\rho_\chi}{m_\chi}\sigma_{NC} N_T A^2 F_N^2\,(q = m_\chi)$$

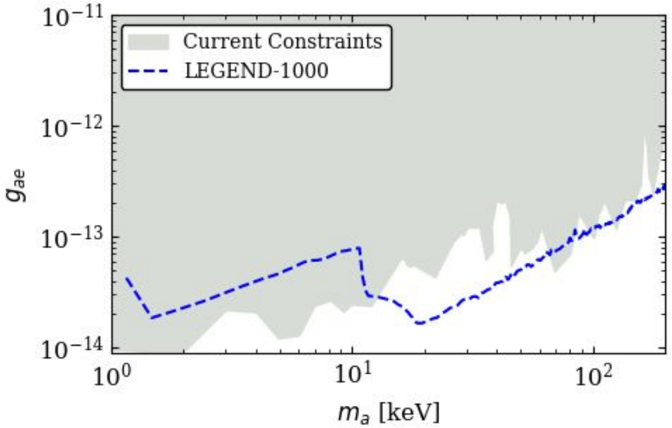


low energy threshold coupled with small atomic mass

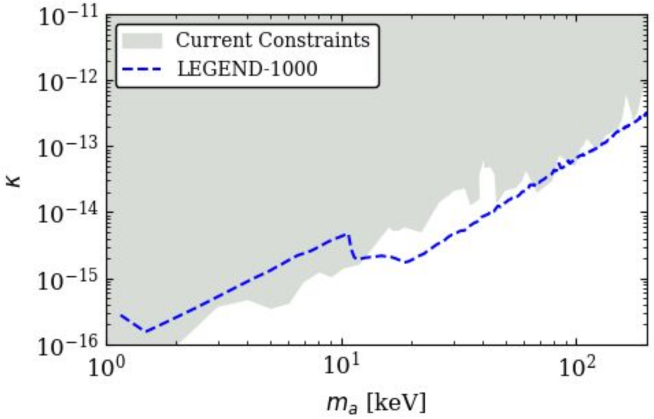
LEGEND-1000:

- exposure = 10 ton-y
- threshold = 1 keV
- energy resolution = 160 keV

$$R_a = \rho_\chi \frac{3 g_{ae}^2 c}{16\pi\alpha}\frac{m_a}{m_e^2}\sigma_{\mathrm{pe}}(m_a)$$



$$R_V = \frac{\rho_\chi}{m_V}\kappa^2 c\sigma_{\mathrm{pe}}(m_V)$$



DM masses from 1.16 keV to 200 keV in step sizes of $2\sigma_E$ = 320 eV

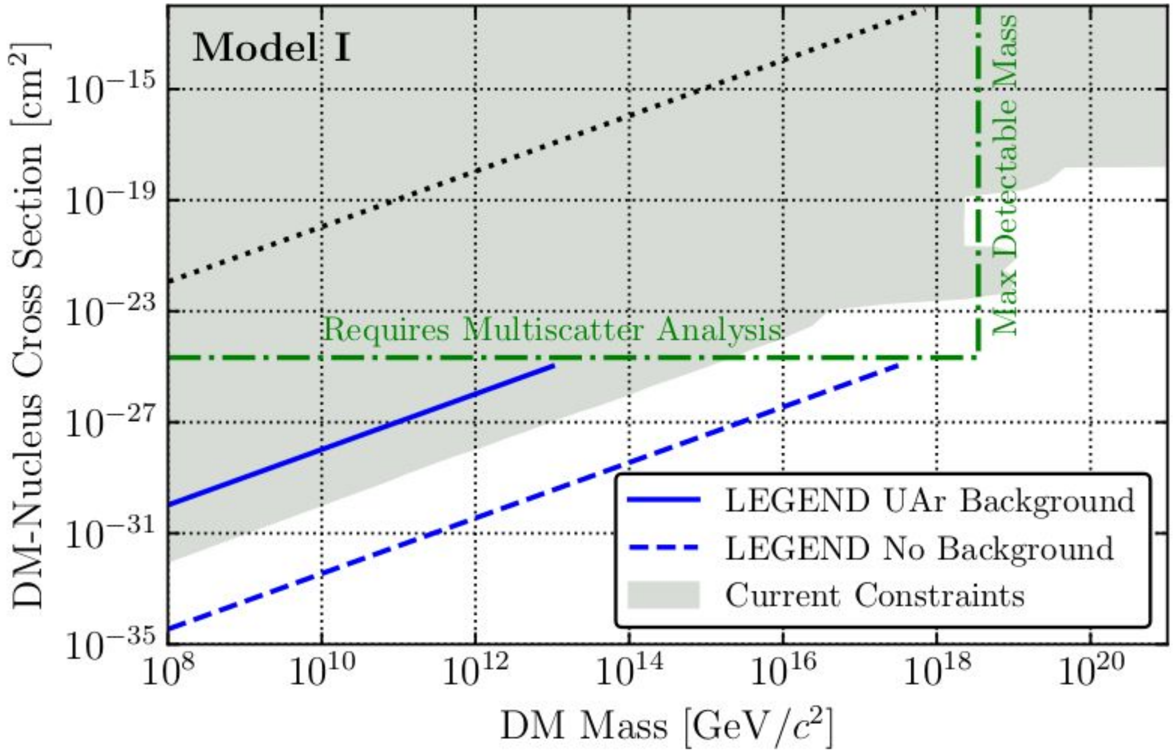
Ultraheavy DM

- Composite DM with large cross sections
  - Interact multiple times in a single event
  - interact in a line (track)

- Thanks to large exposure, potential to probe very high masses

- Great improvement if we include also signals from LAr scintillation light

- Multiscatter limits on:
  - cross section
  - maximum DM mass



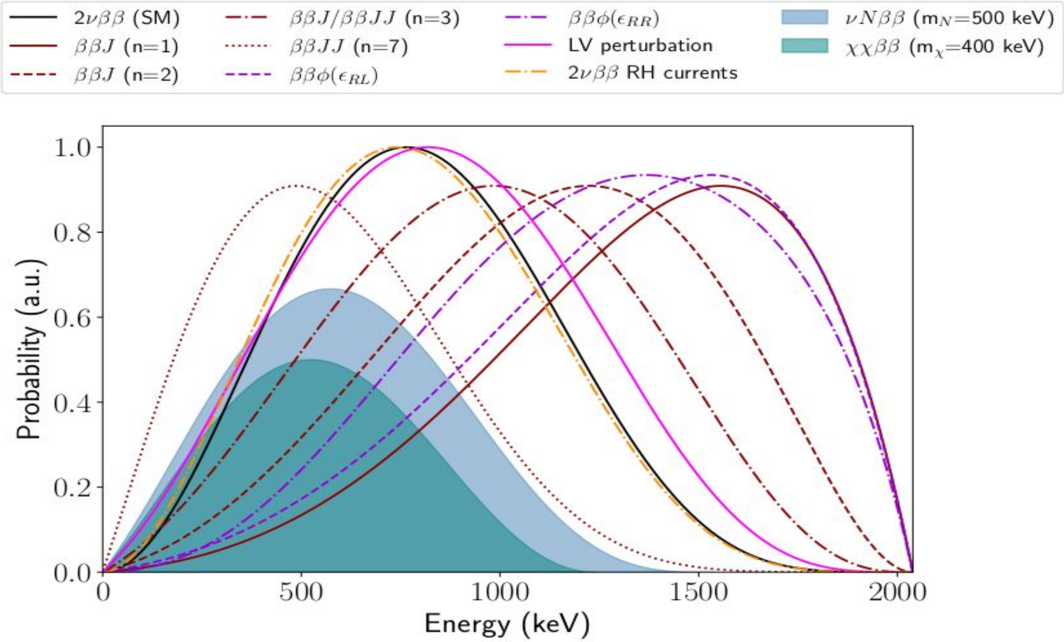
https://arxiv.org/abs/2402.08865

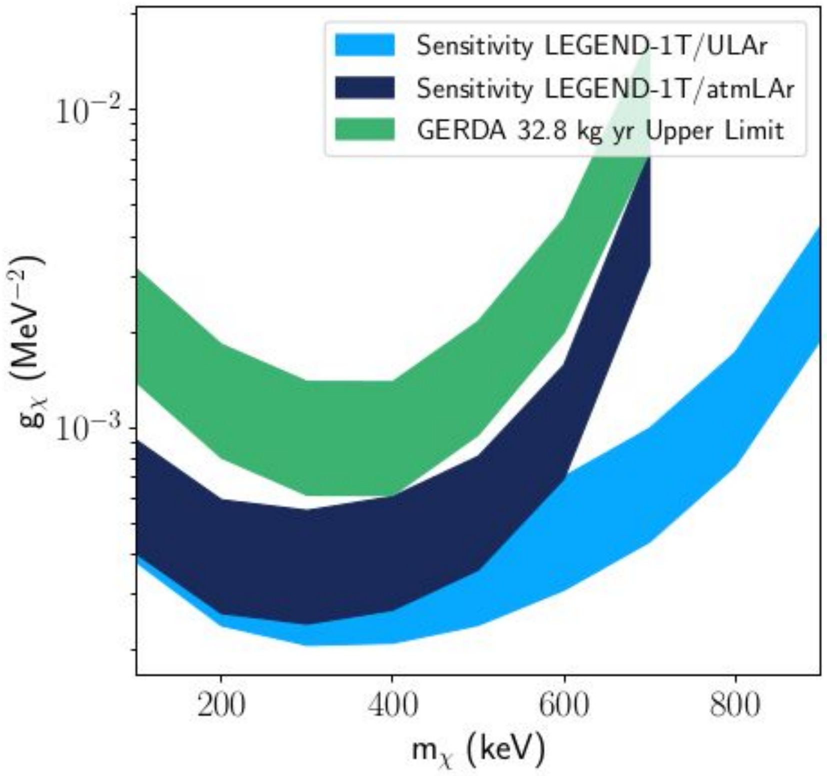
$$\sigma_{\mathrm{MIMP}} = \frac{1}{L_{\mathrm{det}} n_{\mathrm{det}}}$$

$$m_\chi^{\mathrm{max}} \approx \frac{1}{2.3} \rho_\chi A_{\mathrm{det}} v_\chi t_{\mathrm{exp}}$$

Exotic fermions

- Emission of two exotic fermions under Z_2 symmetry
- Peak of e- energy distribution depends on m_χ mass
- Limits on half-life are converted to limits on coupling constant g_χ via nuclear matrix element





from GERDA

$$(A, Z) \rightarrow (A, Z+2) + 2e + 2\chi$$

$$[T_{1/2}]^{-1} = g_\chi^2 C |\mathcal{M}_{0\nu}|^2 \cdot G^{\chi\chi}$$

Conclusion

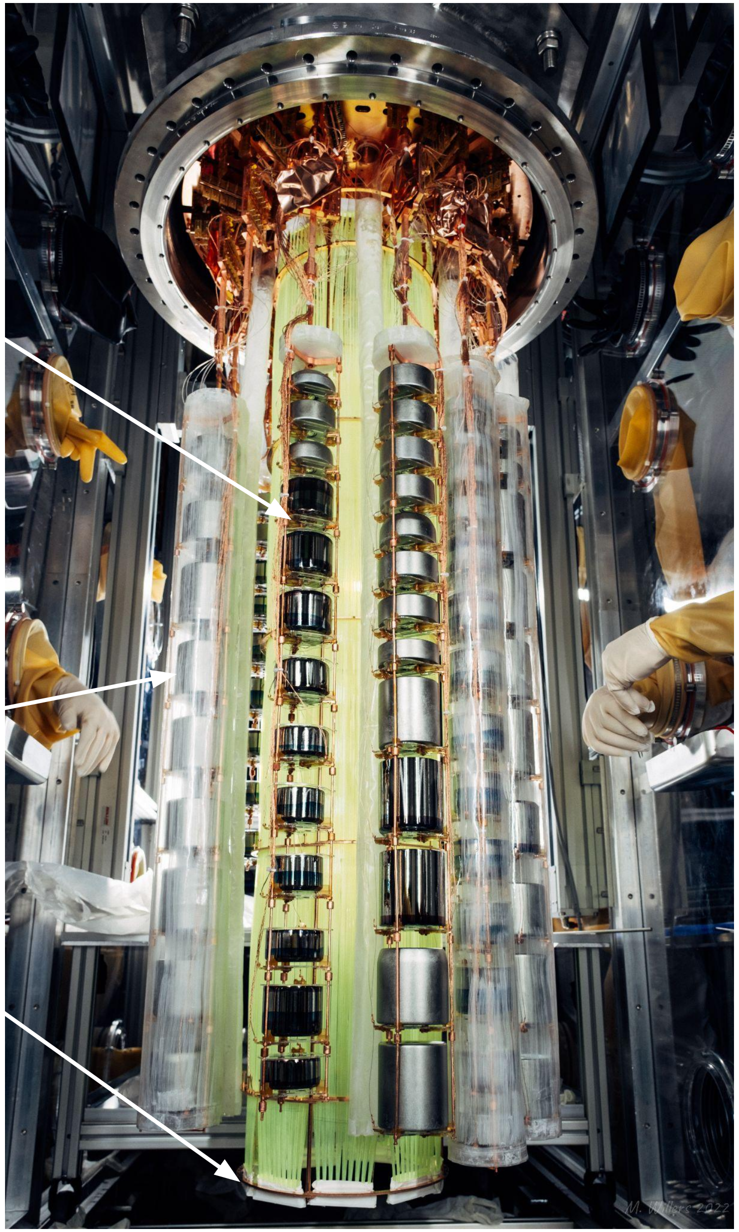
- LEGEND will search for 0νββ decay in ^{76}Ge via 2 stages.
- **LEGEND-200** has completed its first 0νββ unblinding and restarted data taking.
- Pursuing funding for **LEGEND-1000** in the US and Europe; preparations are underway at LNGS.
- LEGEND has a wide BSM physics program, including DM
- Many searches are complementary to DM experiments
- Beyond 0νββ sensitivities for LEGEND-1000 are being compiled in an upcoming white paper

...stay tuned!

Backup

LEGEND-200: current status

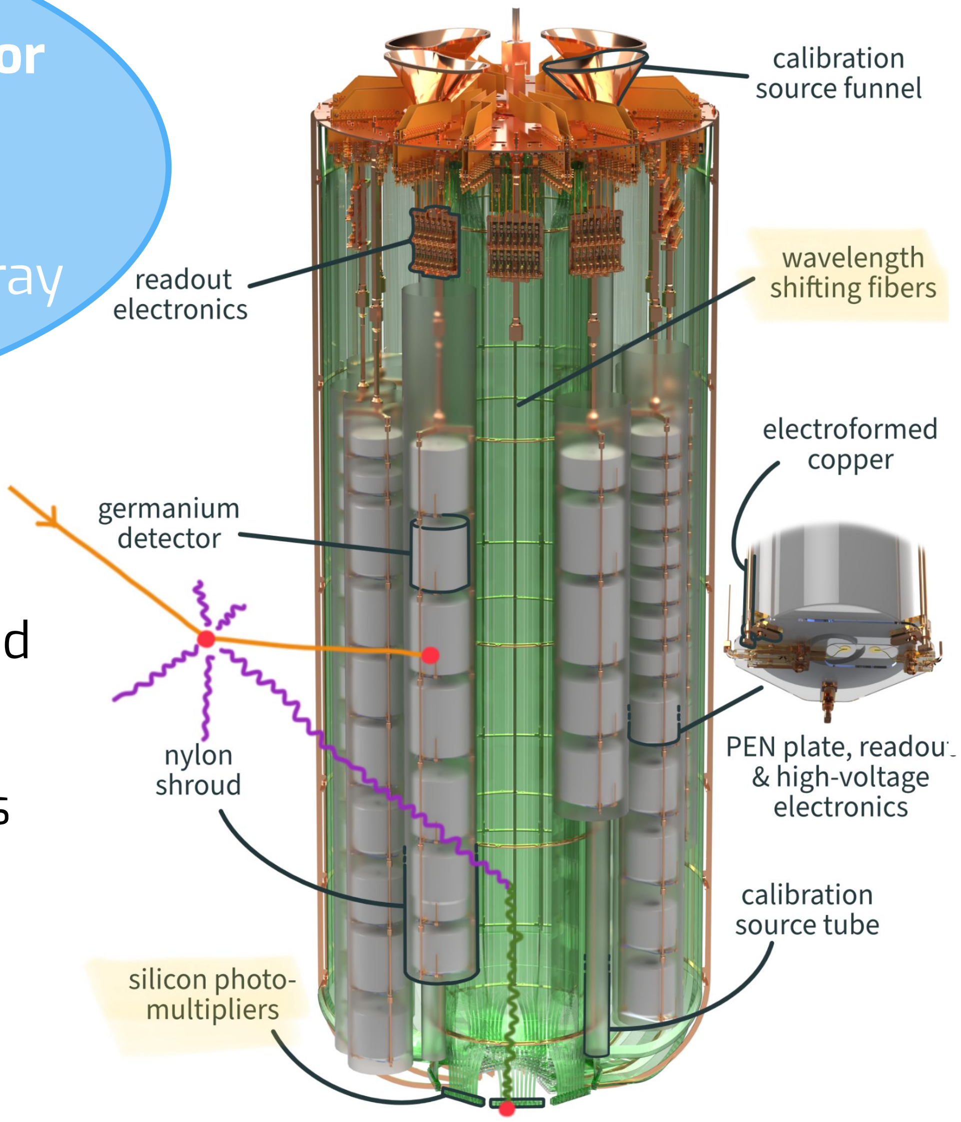
- Location at hall A, LNGS: muon flux is reduced by 6 orders of magnitude compared to the surface
- HPGe detectors:
  - 9 string arrays
- Low Mass Front End
- LAr:
  - 64 m^3 LAr Volume in a stainless steel cryostat
  - 58 read-out modules of SiPMs coupled to WLS fibers
- Electroformed copper plates
  - produced underground at SURF
- Ultrapure water tank:
  - shields n, γ
  - 66 PMTs (Cherenkov)

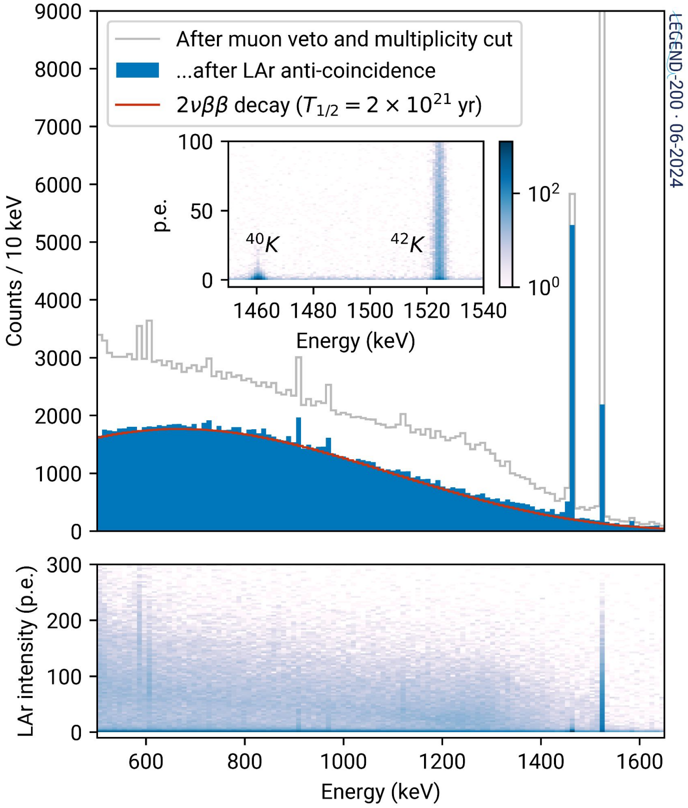


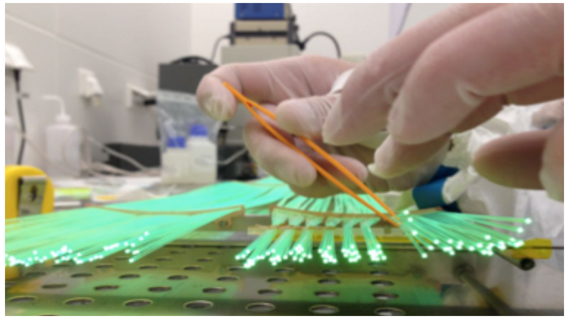
Liquid Argon Veto

LAr scintillation-light detector
active shield from any background sources in the materials surrounding the array

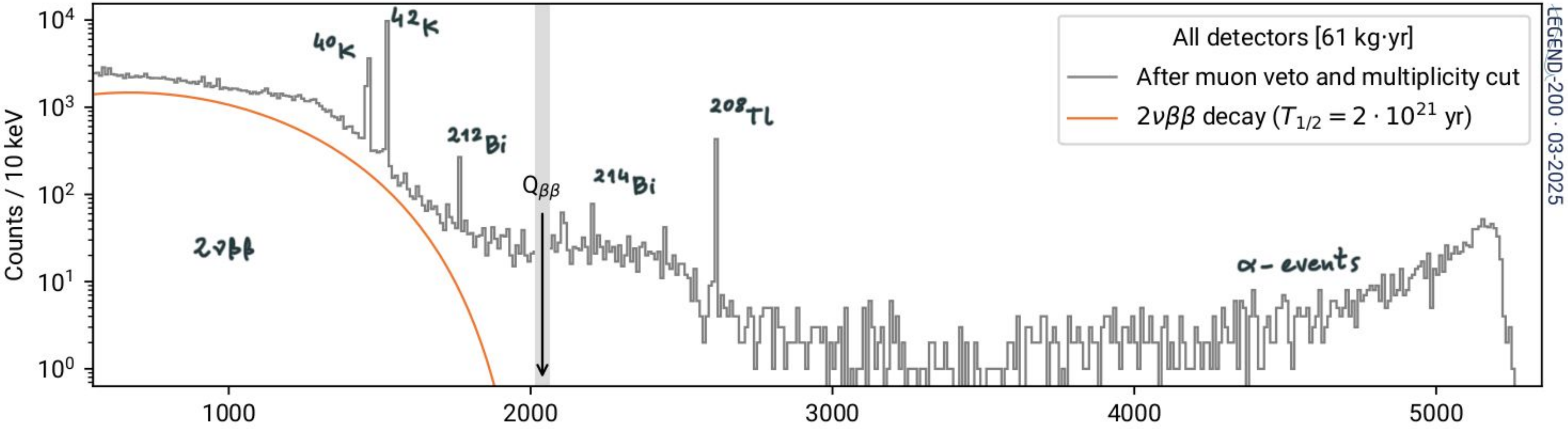
- Implemented as two-barrel geometry
- Read out via WLS fibers coupled to SiPMs
- Argon cryostat: cools detectors to approximately 87 K
- LAr Veto: suppression of background events depositing energy in the Ar



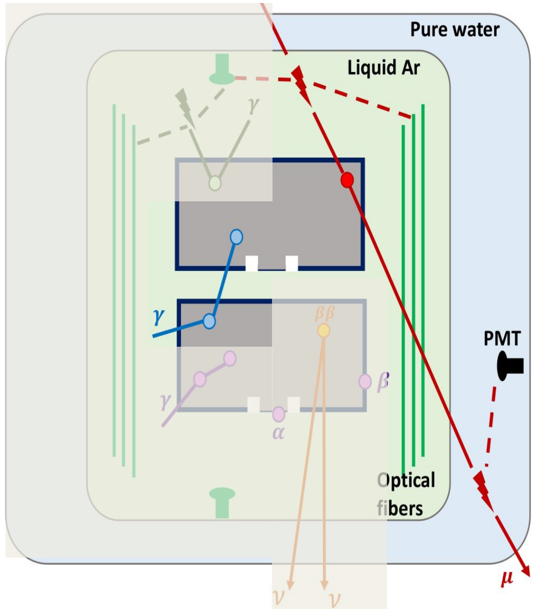




Muon veto and multiplicity cut

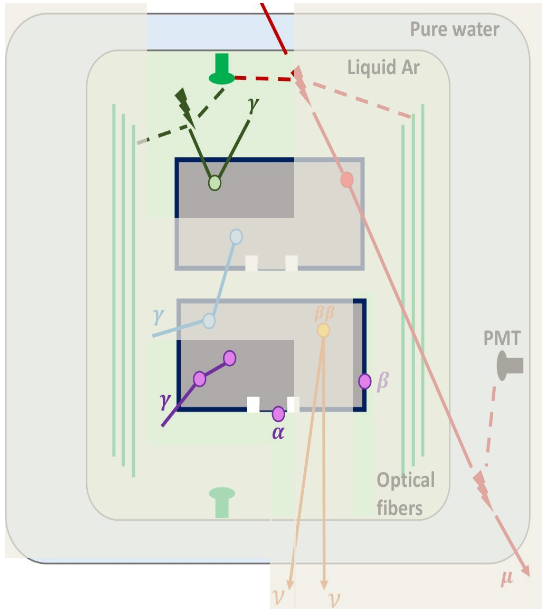


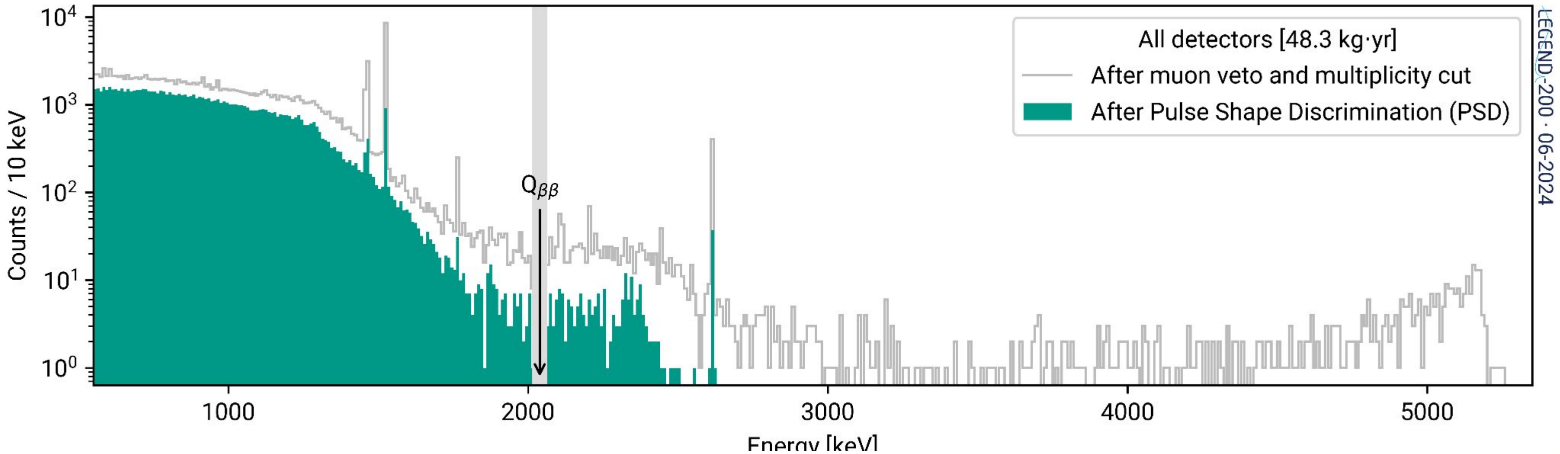
- Blinding applied at $Q_{\beta\beta}$ = 2039 keV (50 keV window)
- > 95% survival of physical events after data cleaning
- 26% of events rejected by Multiplicity cut at $Q_{\beta\beta}$
- 2 events removed by Muon Veto

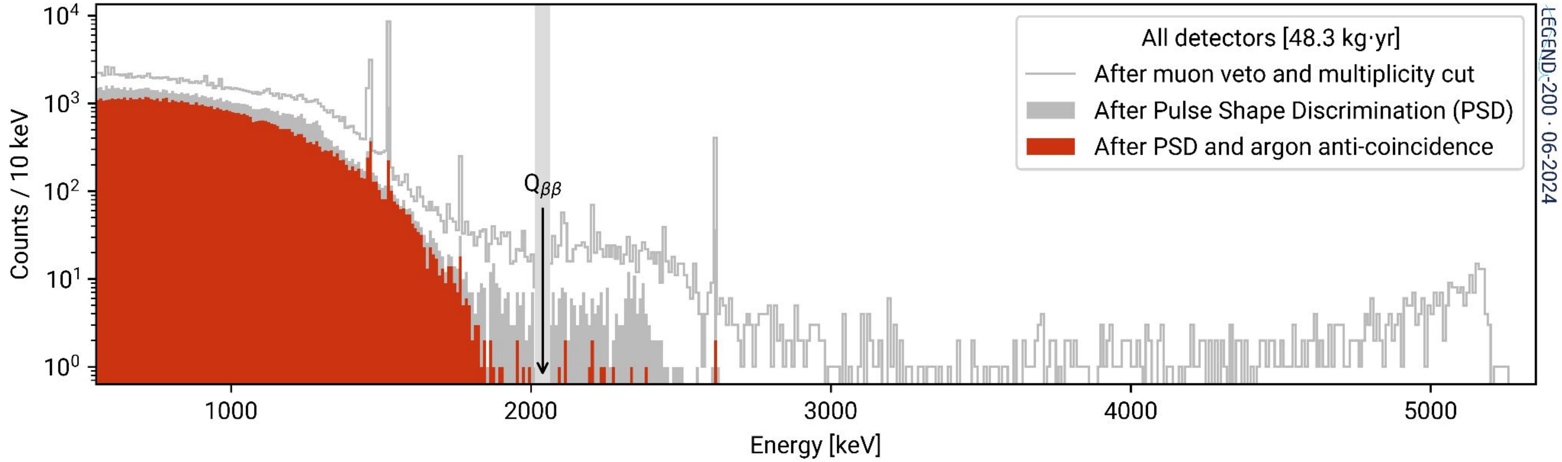


PSD and Argon anticoincidence cut

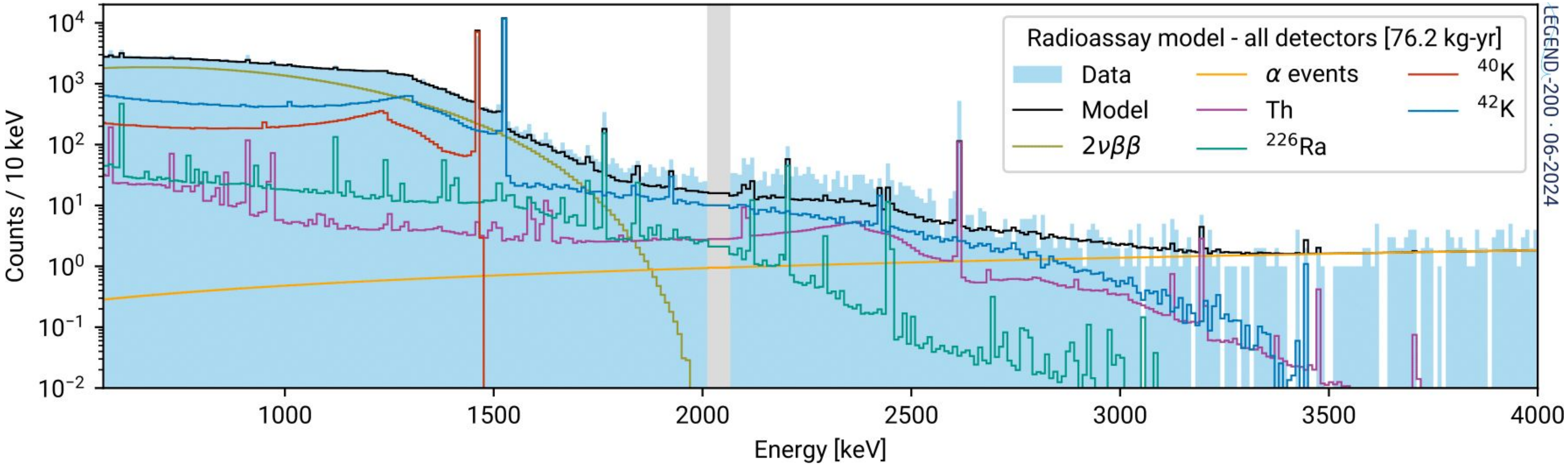
- Strong suppression of surface α and β (^{42}K) events
- Excellent suppression of Compton multi-site events
- ^{228}Th strongly suppressed
- ˜ pure" 2νββ distribution







Background model



- Data well reproduced, model is flat at $Q_{\beta\beta}$

Background model

- Data well reproduced, model is flat at $Q_{\beta\beta}$

L-1000 Background

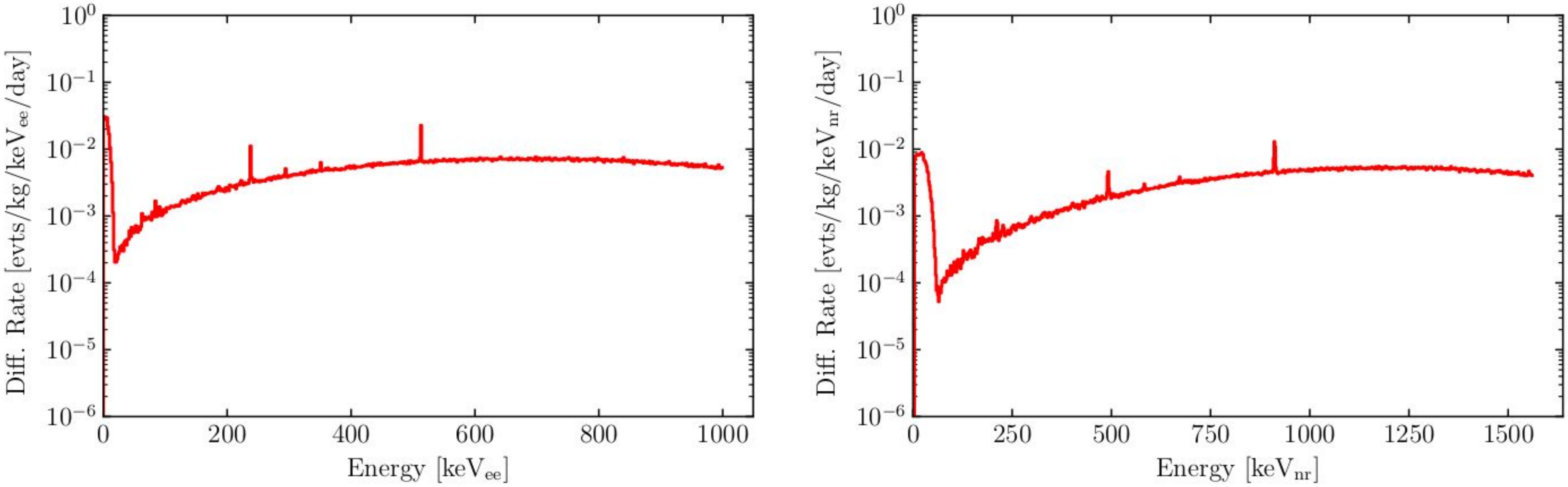
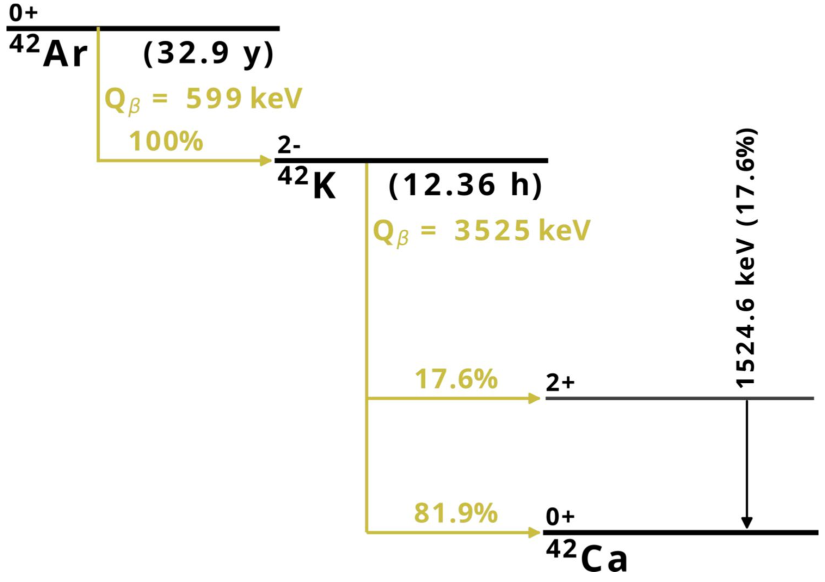
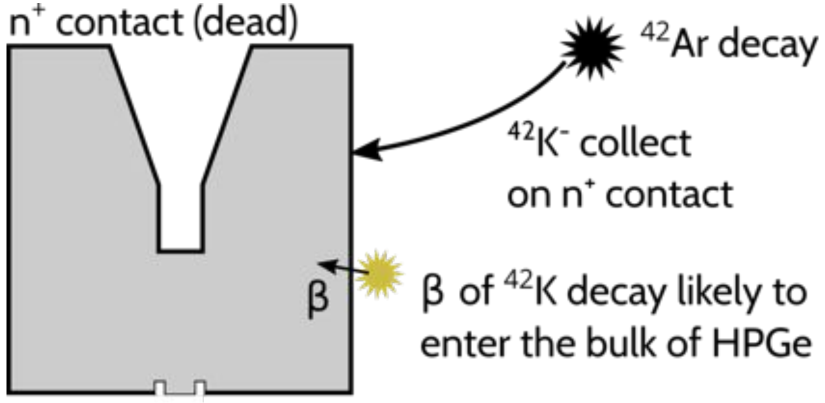


FIG. 16. (Left) The total background model at low energies in electron-equivalent units. (Right) The total background model at low energies after using the Lindhard model to convert to a nuclear recoil energy scale, where we have assumed that all events could have been nuclear recoil events.

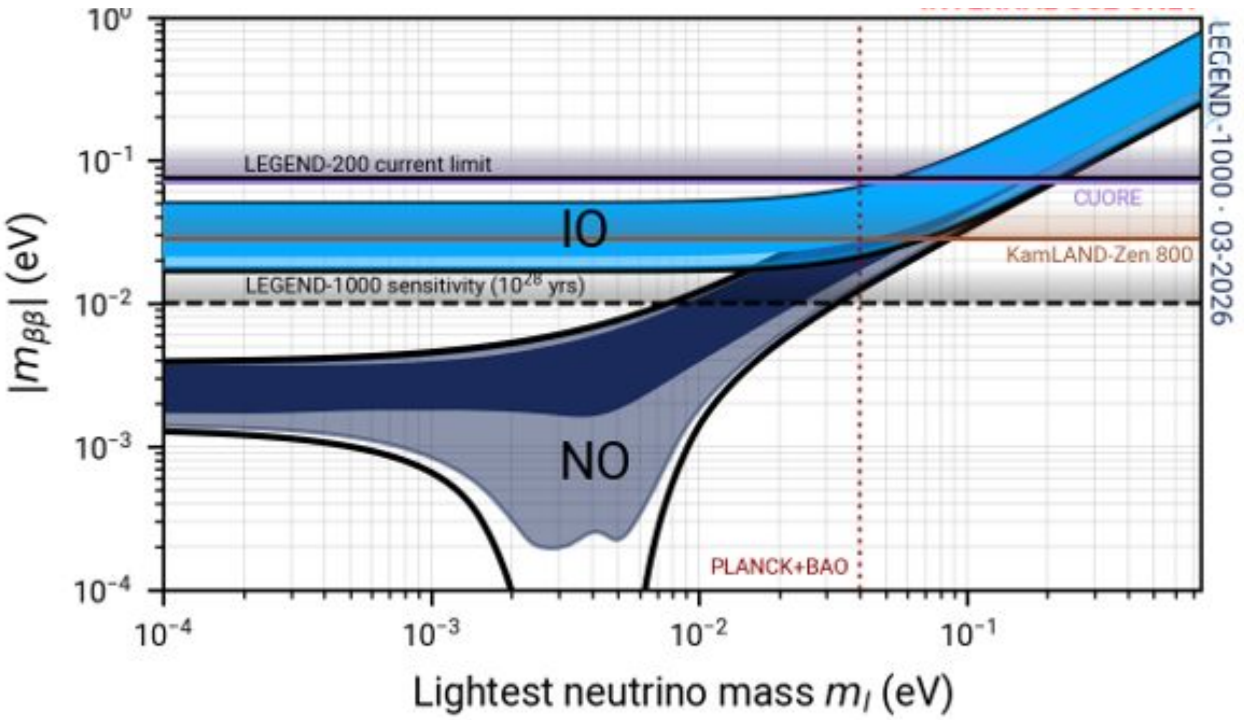
Effect of Underground LAr

- ×1400 reduction of ^{39}Ar background seen by [DarkSide]
- Expect same reduction of ^{42}Ar
  - Also cosmogenically produced
  - Its beta-decaying progeny ^{42}K is a major background in the $0\nu\beta\beta$ ROI
  - This is a key part of obtaining the low backgrounds needed!
- Use of UGLAr means we are dominated by $2\nu\beta\beta$ at low energies, not ^{39}Ar!
  - Allows lots of interesting physics searches through spectral distortions





Goals



Bkg Index cts/(FWHM·ton·yr)

LEGEND-200	0.6
LEGEND-1000	**0.025**