GRAN SASSO SCIENCE INSTITUTE
SCHOOL OF ADVANCED STUDIES
Scuola Universitaria Superiore

INFN LNGS

First results from LEGEND

Valentina Biancacci

on behalf of the LEGEND collaboration

NOW 2024

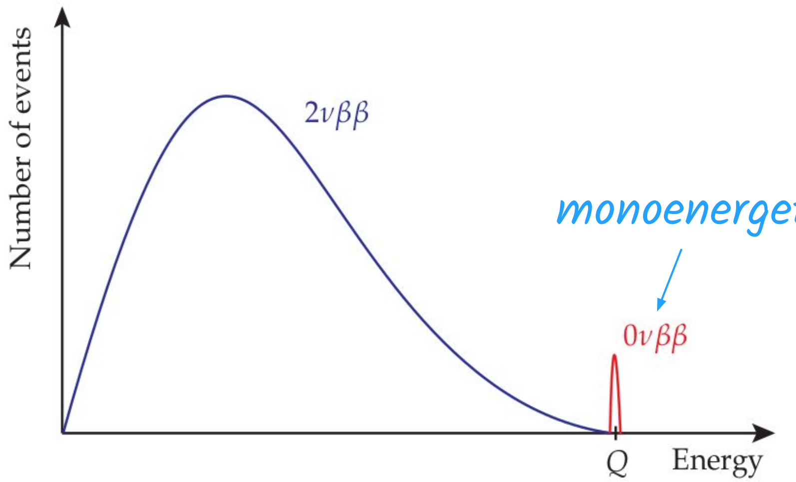
06.09.2024

Searching for 0νββ

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

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

"creation of matter without antimatter"



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

- 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
} *exposure*
BI: background index
ΔE: energy resolution at $Q_{\beta\beta}$

Desirable design for an experiment searching for 0νββ signal:

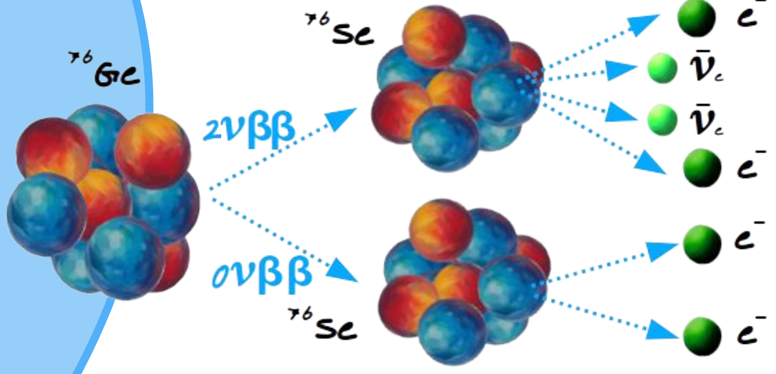
- Low background level
- Good energy resolution of the detector
- Large exposure
- Large $Q_{\beta\beta}$

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

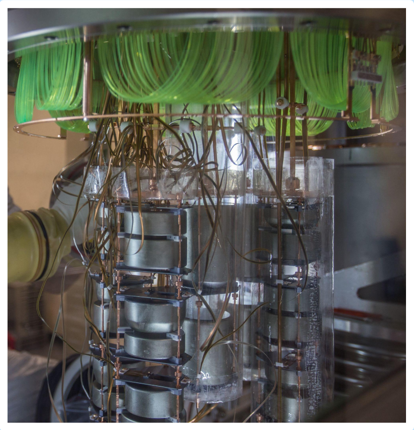
LEGEND collaboration

look at the links!

Majorana Demonstrator

GERDA

+

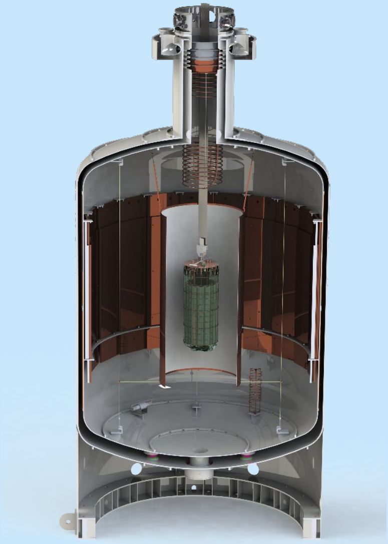


Best energy resolution

Lowest background index

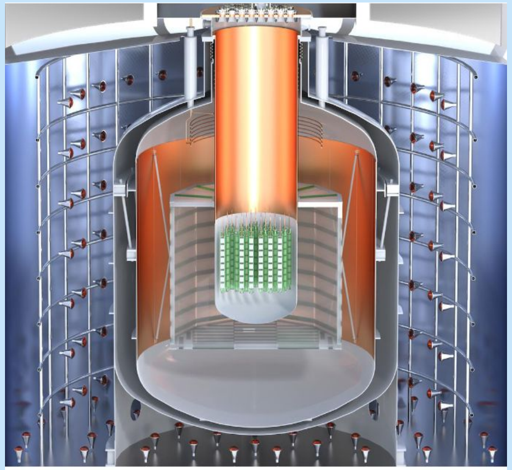
=

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**

...

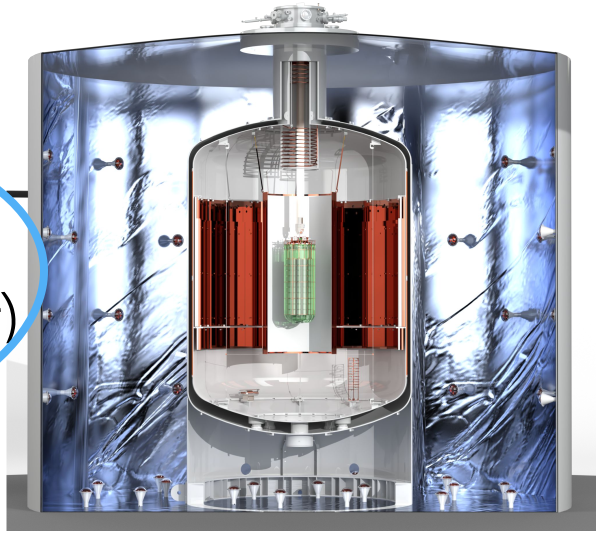
commissioning will start in **2026**

The LEGEND project

First Stage: LEGEND-200

- ~**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

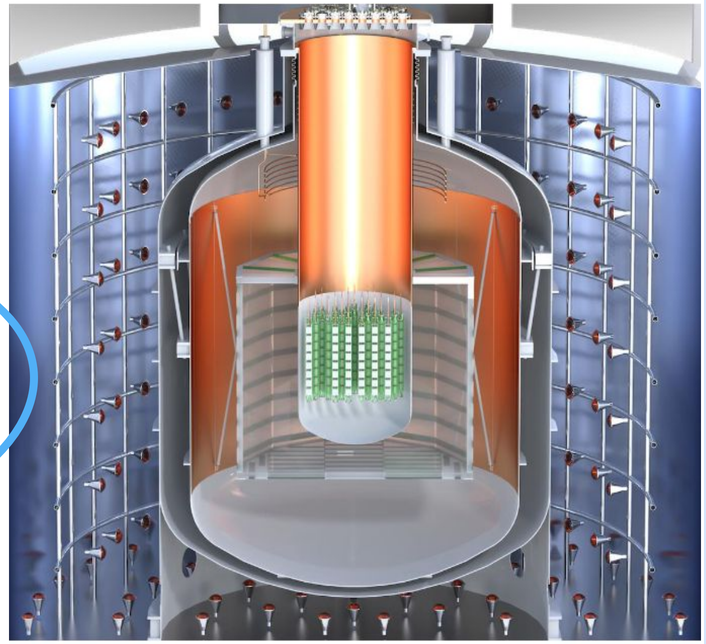
$T^{0\nu}_{1/2}$ 10^{27} yrs
m 30-70 meV
B $2 \cdot 10^{-4}$ cts/(keV $\cdot$ kg $\cdot$ yr)



Further Stage: LEGEND-1000

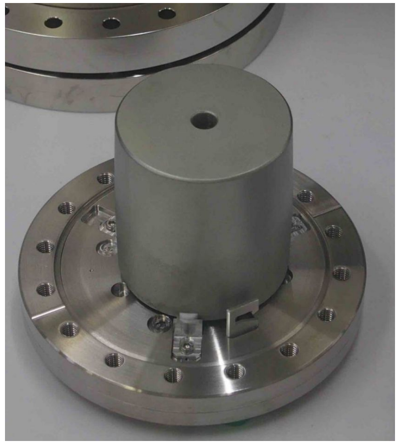
- Staged installation of **1000 kg** detector mass (ICPC)
- Detector strings immersed in radiopure underground LAr (UGLAr)
- Pending funding approval

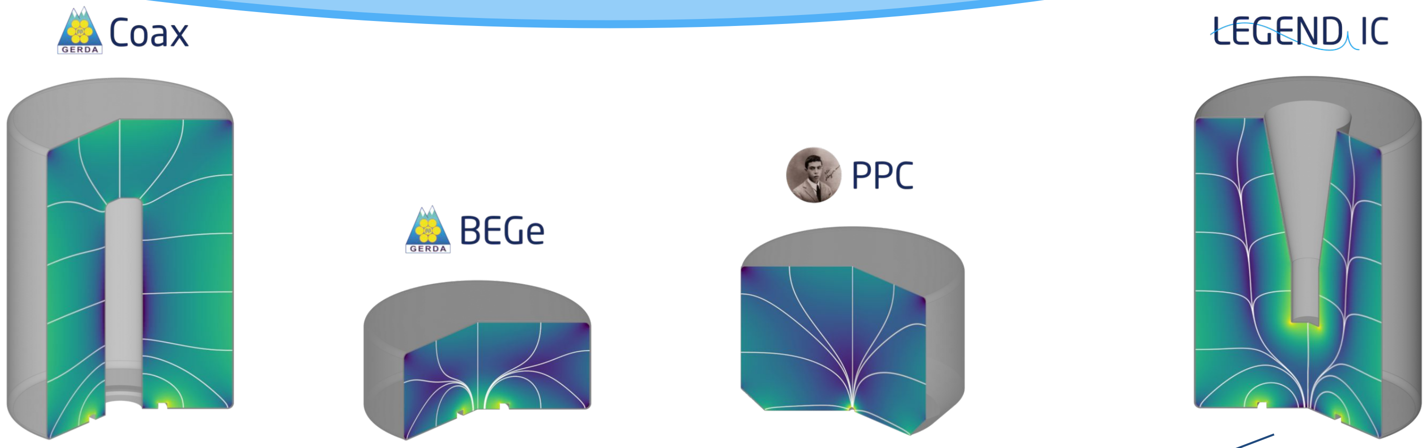
$T^{0\nu}_{1/2}$ 10^{28} yrs
m 10-20 meV
B 10^{-5} cts/(keV $\cdot$ kg $\cdot$ yr)



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

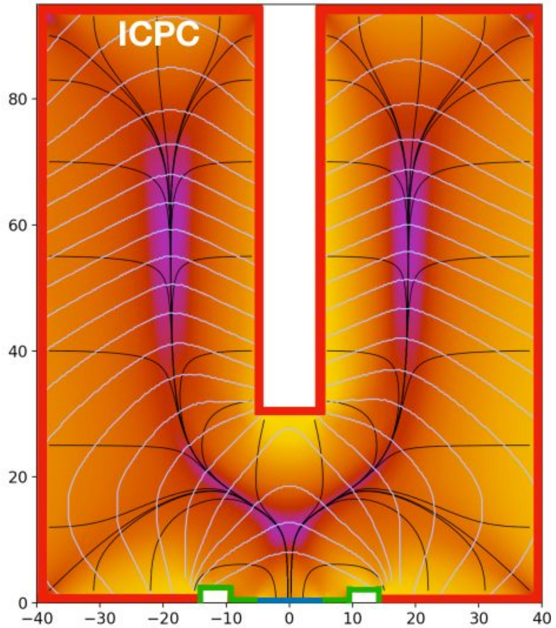




Inverted Coaxial Point Contact (ICPC) detectors:

- 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%)

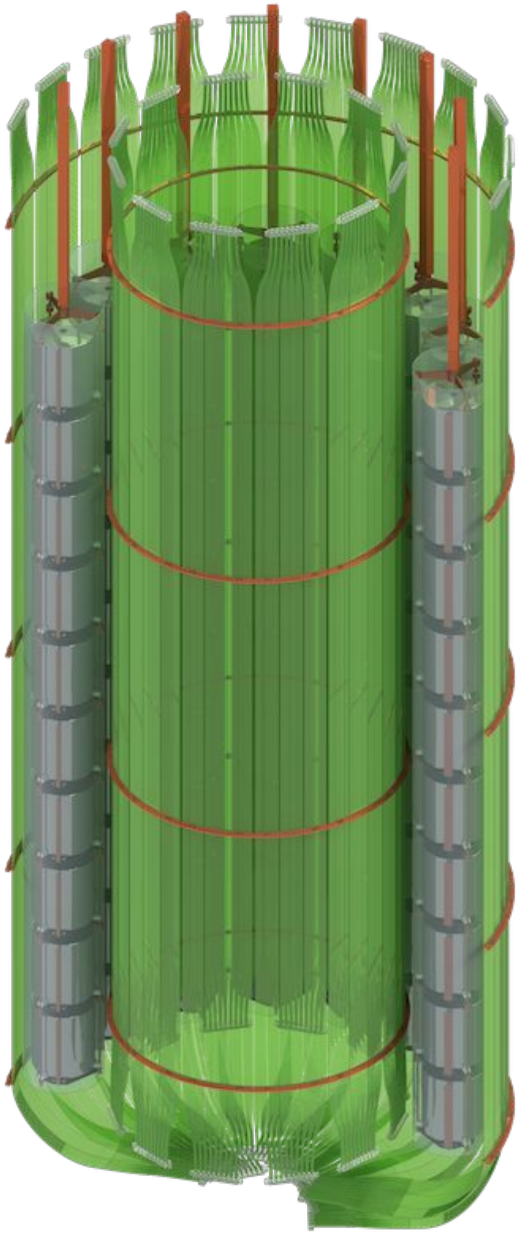
n+ electrode
p+ electrode
passivation

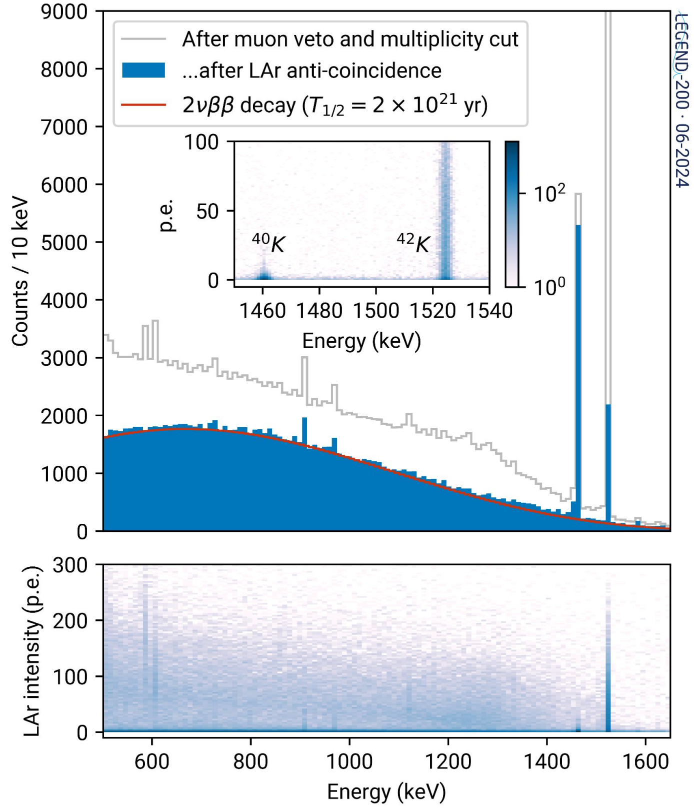


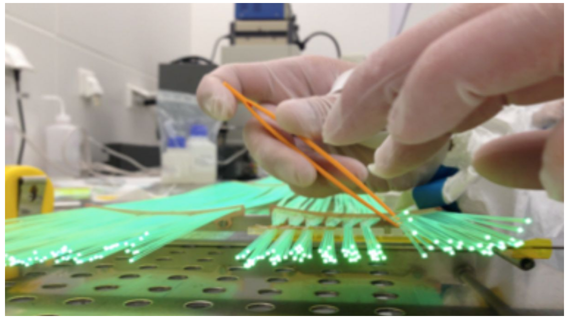
Liquid Argon Veto

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
- Improved light yield compared to GERDA

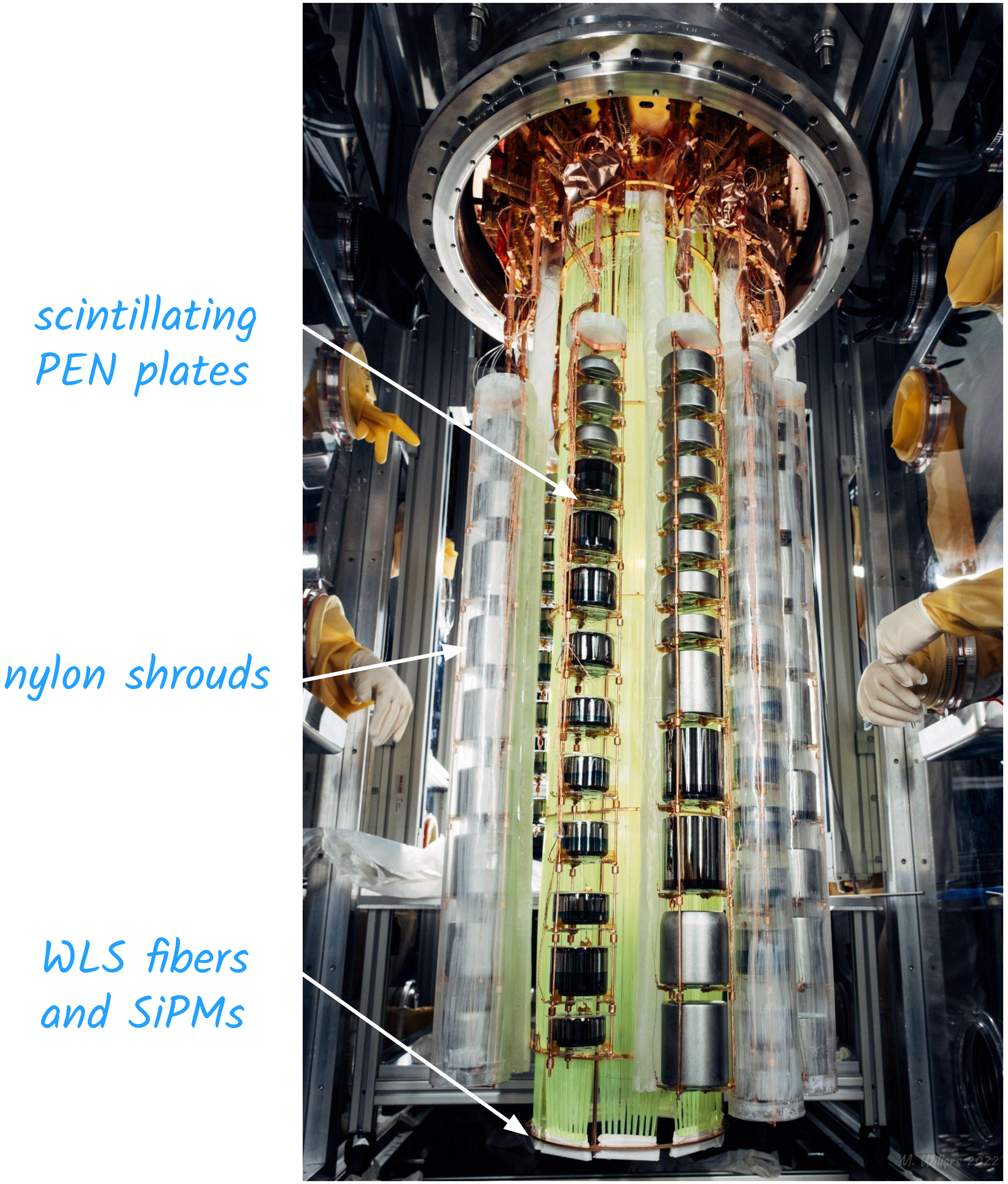




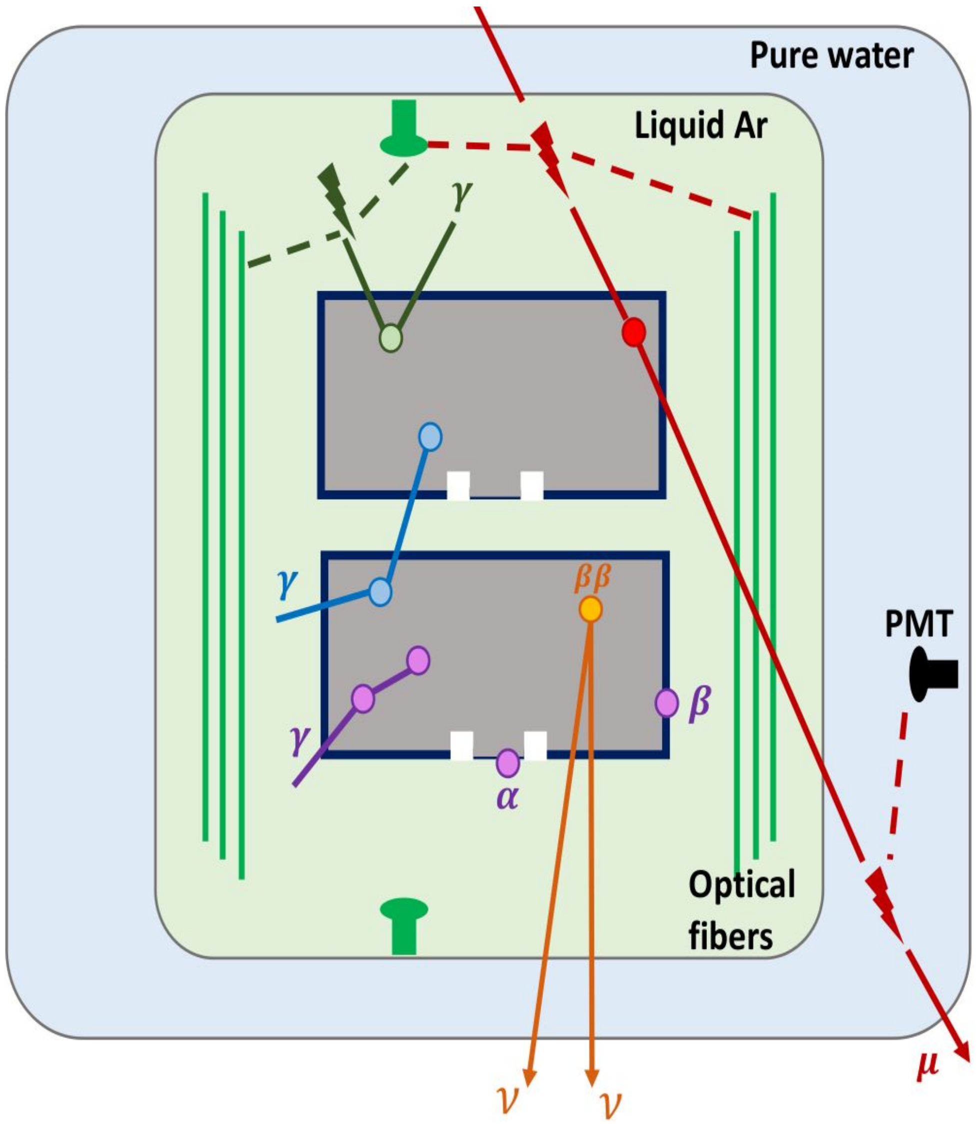


LEGEND-200: current status

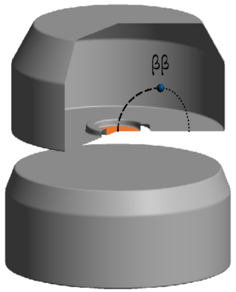
- Location at hall A, LNGS: muon flux is reduced by 6 orders of magnitude respect to the surface
- HPGe detectors:
  - 10 string arrays
- Low Mass Front End
- LAr:
  - 64 m^3 LAr Volume in a stainless steel cryostat
  - 58 read-out modules of SiPMs coupled to WLS fibers
- Electroformed copper plates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



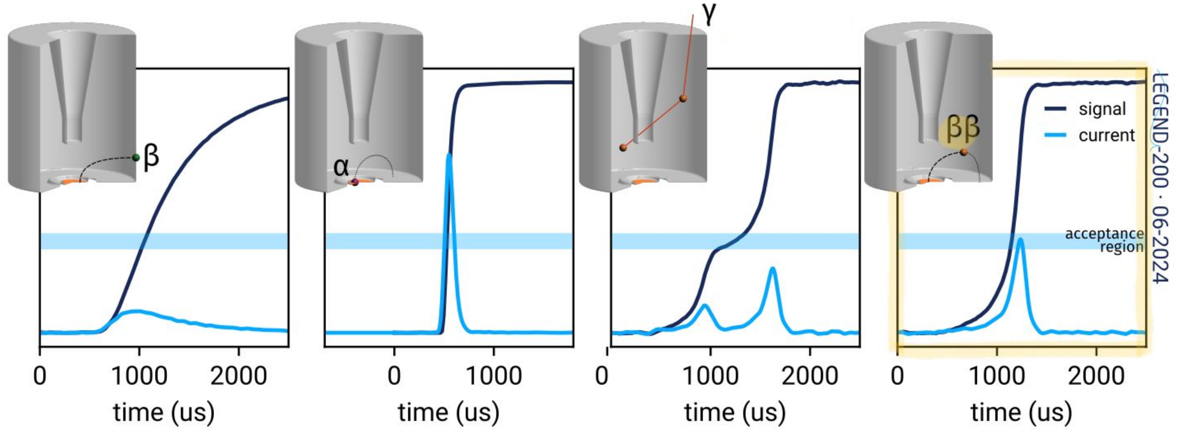
Active background reduction tools



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



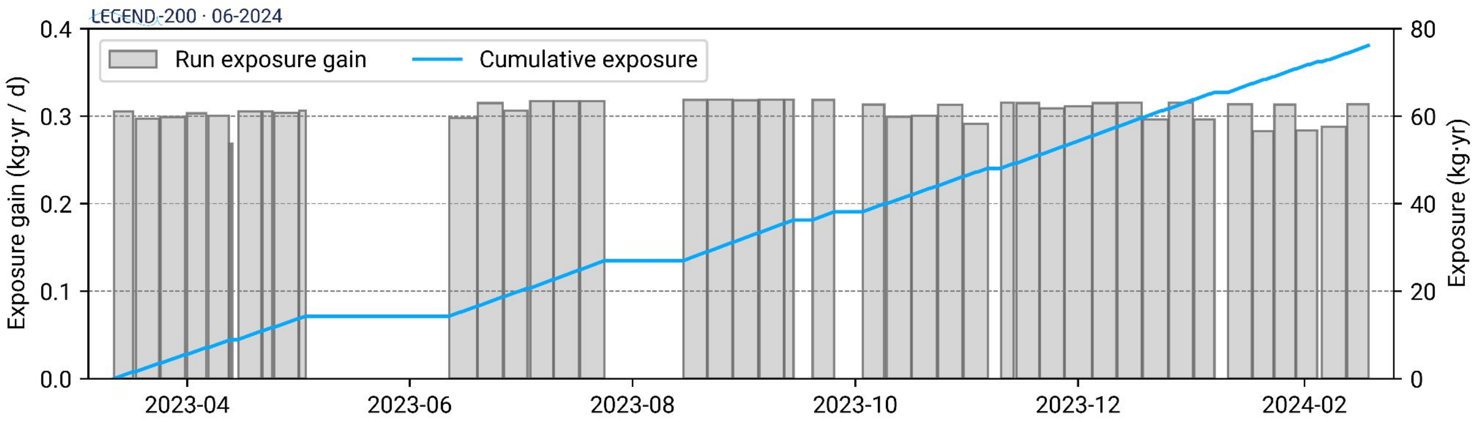
- Anti-coincidence with the muon veto
- Anti-coincidence between detectors (multisite cuts)
- Active veto using LAr scintillation (LAr Veto)
- Pulse shape discrimination (PSD)



Exposure and energy resolution

Exposure:

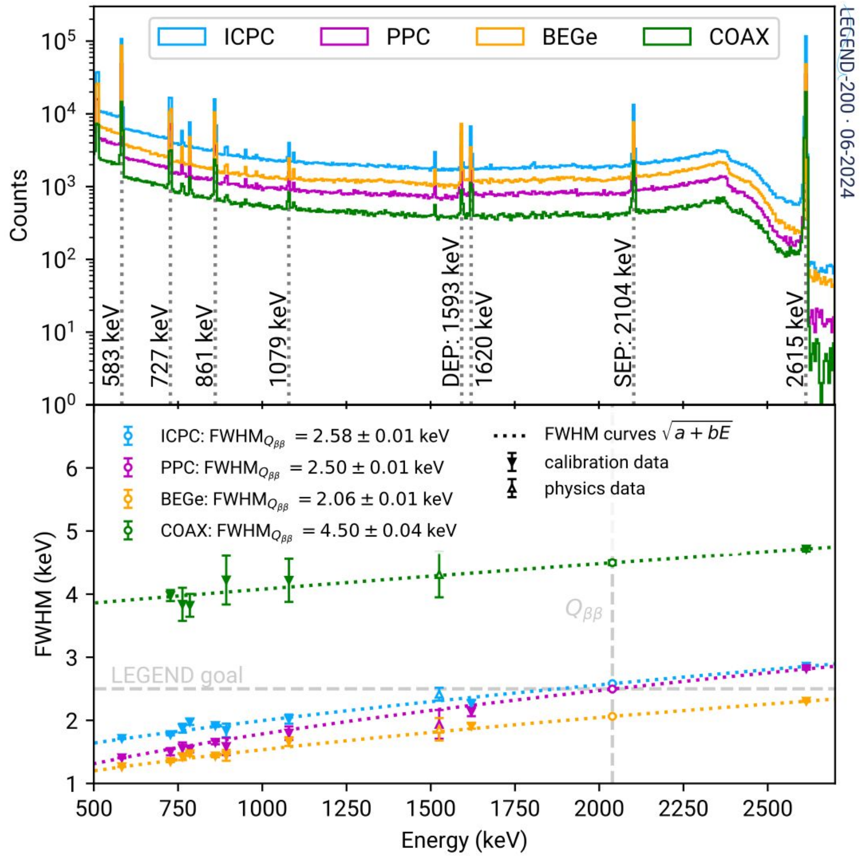
- SILVER DATASET → Background and performance (76.2 kg yr)
- GOLDEN DATASET → $0\nu\beta\beta$ data (48.3 kg yr)



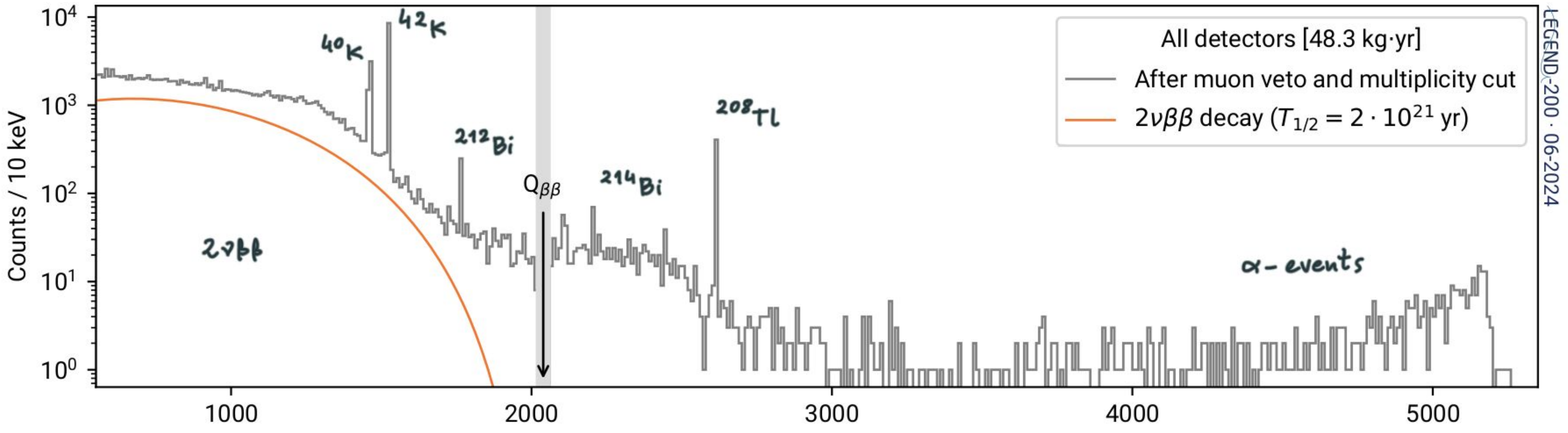
Energy resolution:

Full report on performance @ TAUP2023

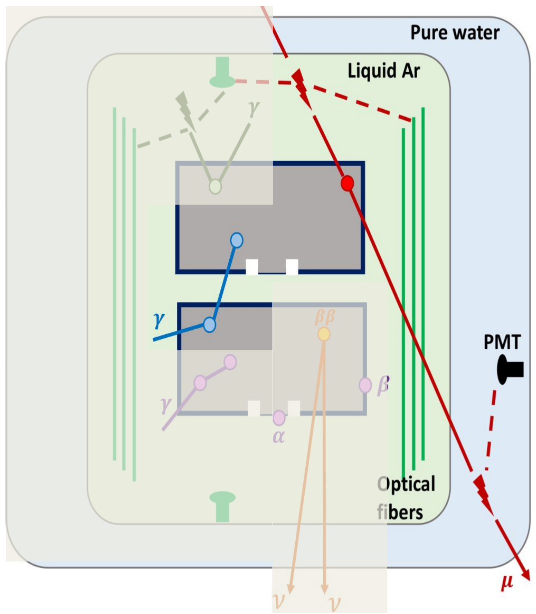
- FWHM ~ 0.1% keV at $Q_{\beta\beta}$
- Shifts monitored with weekly ^{228}Th calibrations
- Second-order variations tracked in time



Muon veto and multiplicity cut

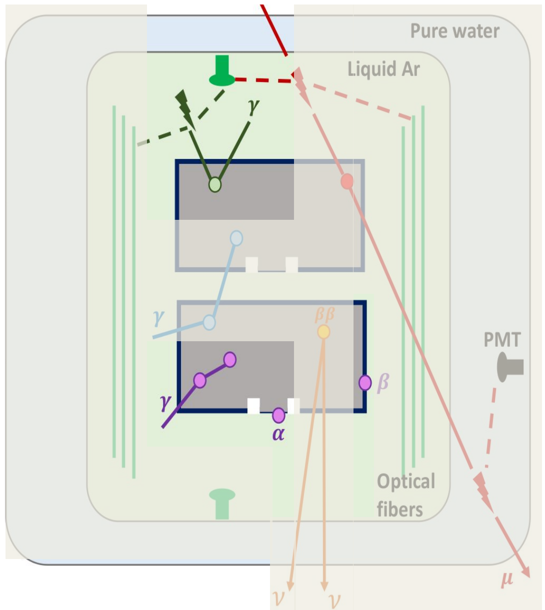


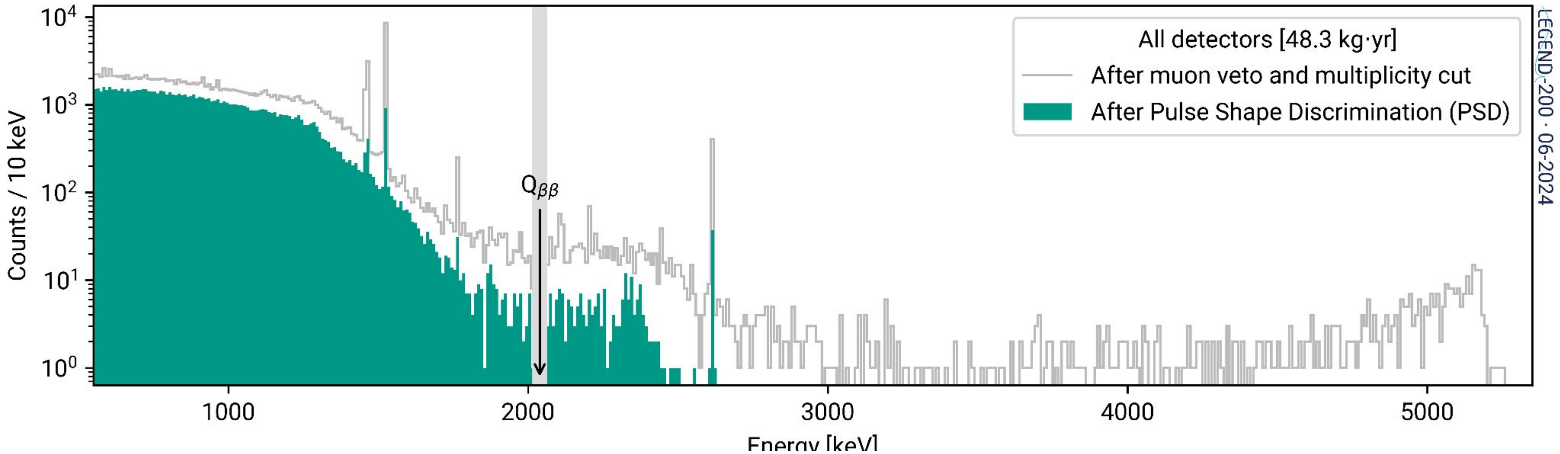
- Blinding applied at $Q_{\beta\beta}$ = 2039 keV (50 keV window)
- > 95% survival of physical events after data cleaning
- 26% of events rejected by Multiplicity cut at $Q_{\beta\beta}$
- 2 events removed by Muon Veto at $Q_{\beta\beta}$

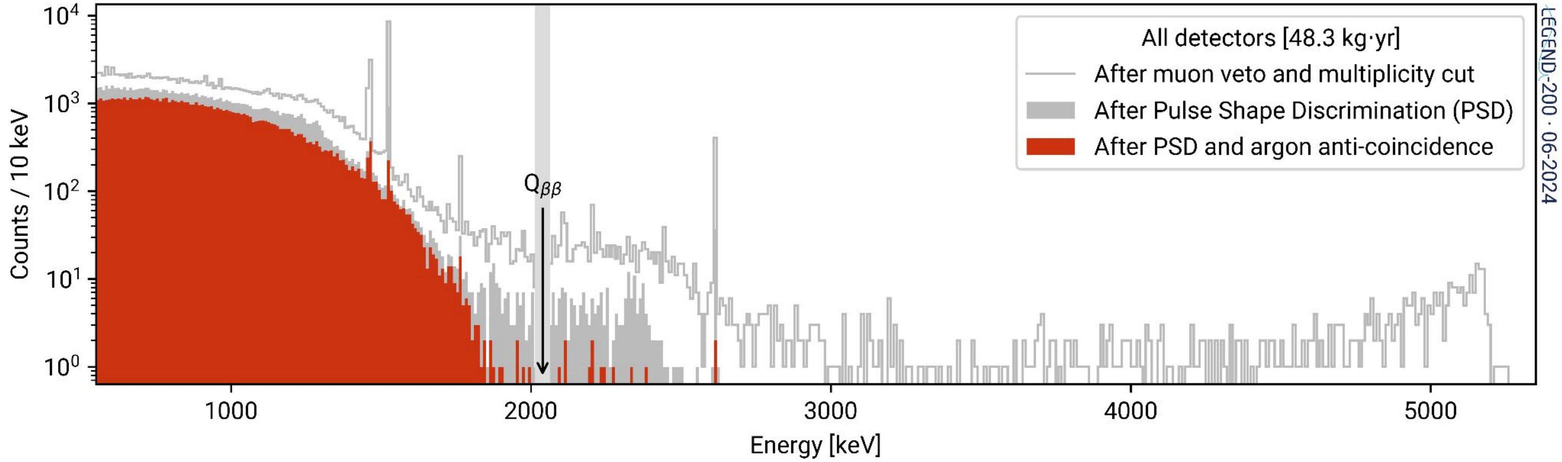


PSD and Argon anticoincidence cut

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







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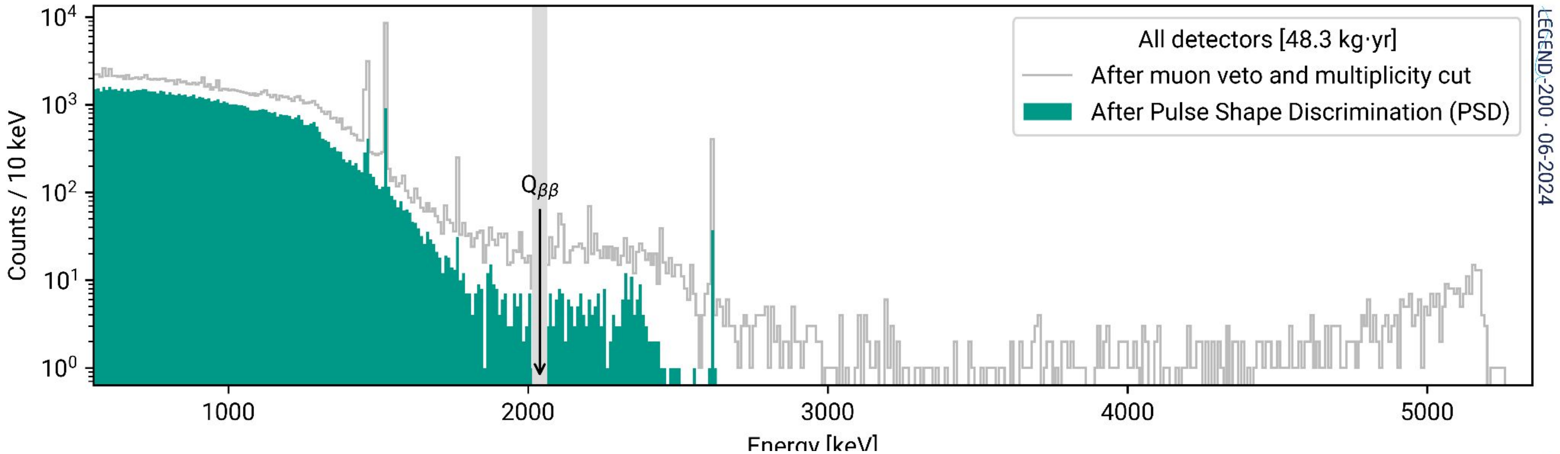
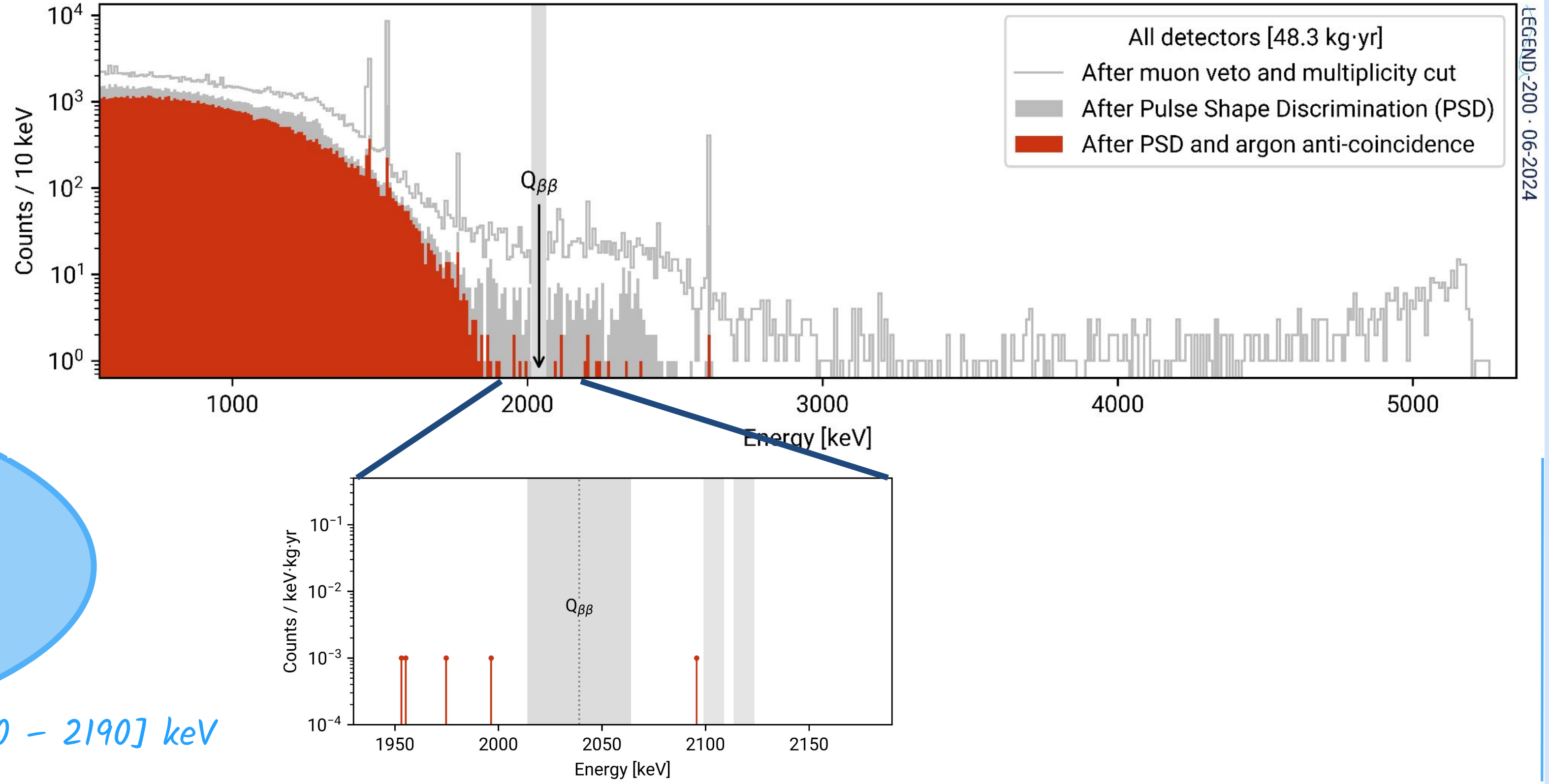




Only 5 events surviving in the background estimation window

[1930 – 2190] keV

First year results

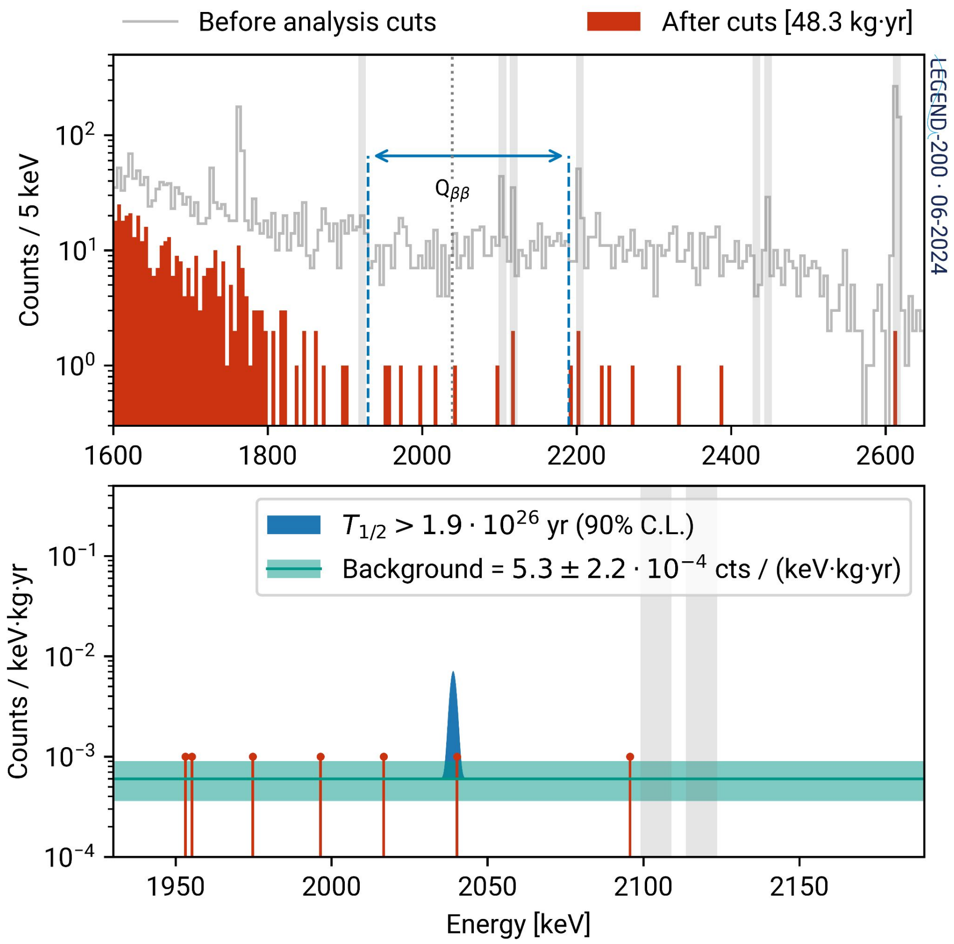
- + 2 events in blinding window after unblinding (Qbb ± 25 keV)
- Background index: *comparable to GERDA**

  BI = 5.3 ± 2.2 · 10^{-4} cts / (keV kg yr)

- Half life limit: *preliminary!*

  $T^{0\nu}_{1/2}$ > 1.9 · 10^{26} yr (GERDA, MAJORANA and LEGEND combined fit)

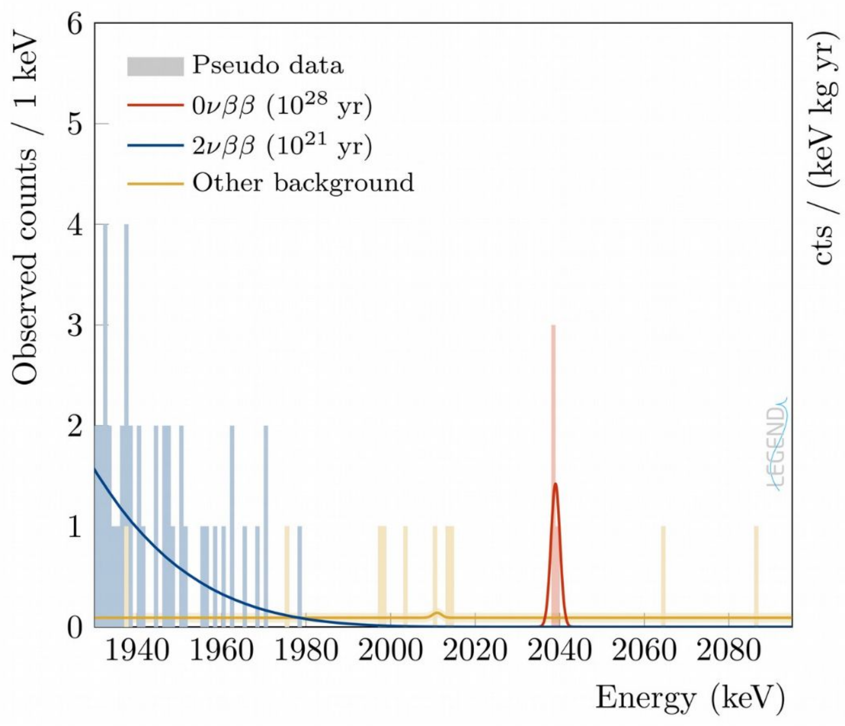
**developed a background model to understand how to mitigate it*



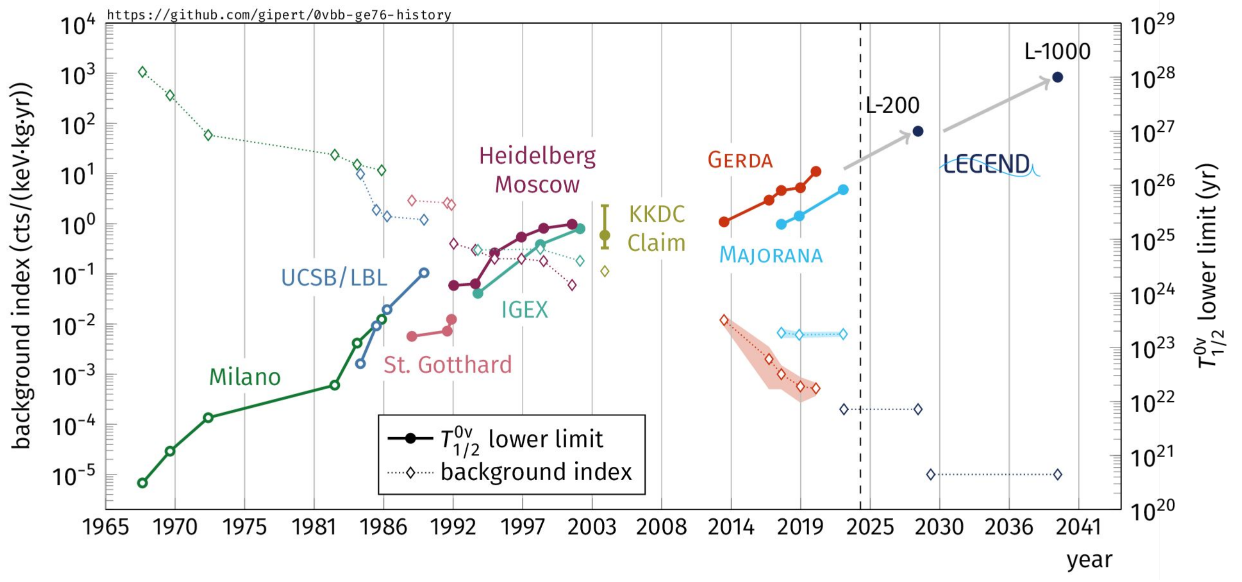
Full report @ Neutrino2024

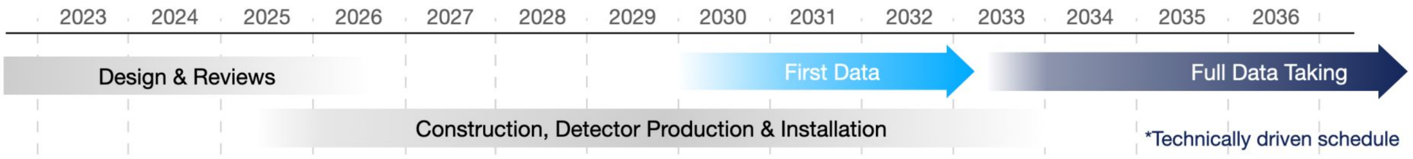
LEGEND-1000: prospects

- 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





Conclusion

- LEGEND will search for 0νββ decay in ^{76}Ge via 2 stages.
- **LEGEND-200** has collected data over the last year and completed its first 0νββ unblinding.
- Currently in "background characterization" phase; restarting data taking later in 2024.
- Installing additional ~35 kg of HPGe detectors.
- Publication of first results is in progress.
- Pursuing funding for **LEGEND-1000** in the US and Europe; preparations are underway at LNGS.
- More about LEGEND in **https://legend-exp.org**

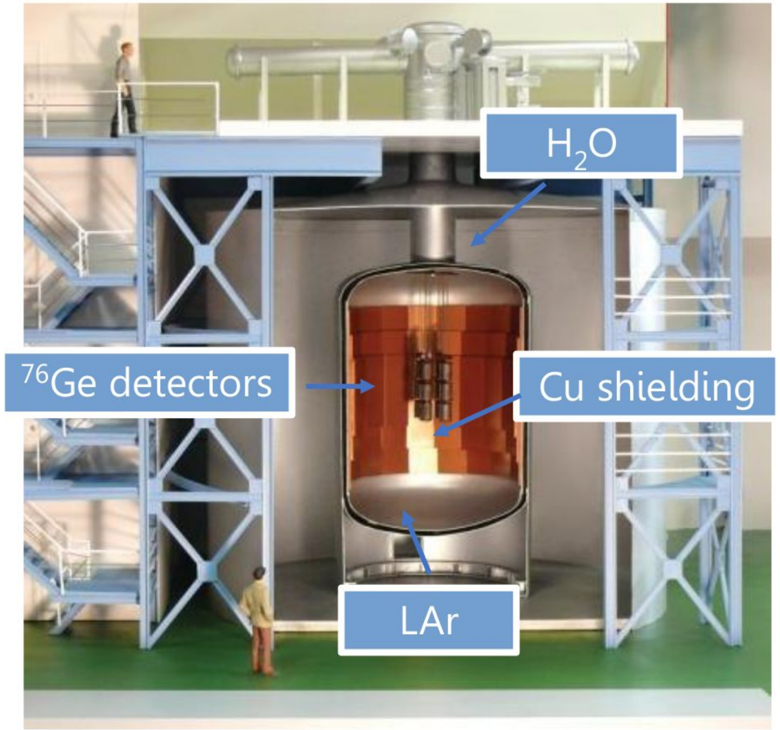
...stay tuned!

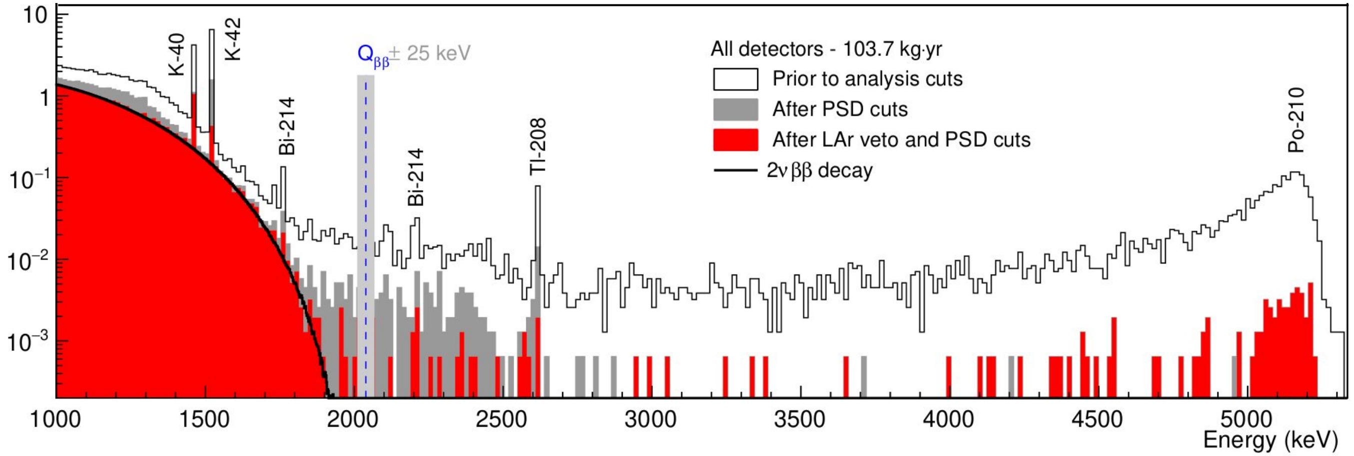
Backup

GERDA experiment

- The GERDA experiment was proposed in 2004 as a new ^{76}Ge double-beta decay experiment at LNGS (Italy).
- Up to **41 enriched ^{76}Ge** detectors deployed from Dec 2015 to Dec 2019.

- The array of germanium detectors was placed in a liquid argon (**LAr**) cryostat.
- A tank filled with 590 m^3 pure water surrounded the cryostat.
- The water tank was equipped with PMTs detecting Cherenkov light.





	Goals	*Achievements*
Background	10^{-3} cts/(keV kg yr)	$5.2^{+1.6}_{-1.3} \cdot 10^{-4}$ cts/(keV kg yr)
Exposure	≥ 100 kg yr	103.7 kg yr *phase II*
Sensitivity	$T^{0\nu\beta\beta}_{1/2} \geq 10^{26}$ yr	$T^{0\nu\beta\beta}_{1/2} \geq 1.8 \cdot 10^{26}$ yr

[GERDA , PRL 125 (2020) 252502]

MAJORANA DEMONSTRATOR experiment

- MAJORANA DEMONSTRATOR experiment is still operating at Sanford Underground Research Facility (SURF) but it finished its ^{76}Ge program in 2021.
- Array of 40.4 kg P-type Point Contact (PPC) and ICPC detectors
- 27.2 kg detectors are up to 88% ^{76}Ge enrichment
- High-purity electroformed copper cryostat
- Ultra-clean detector near-parts

Achievements

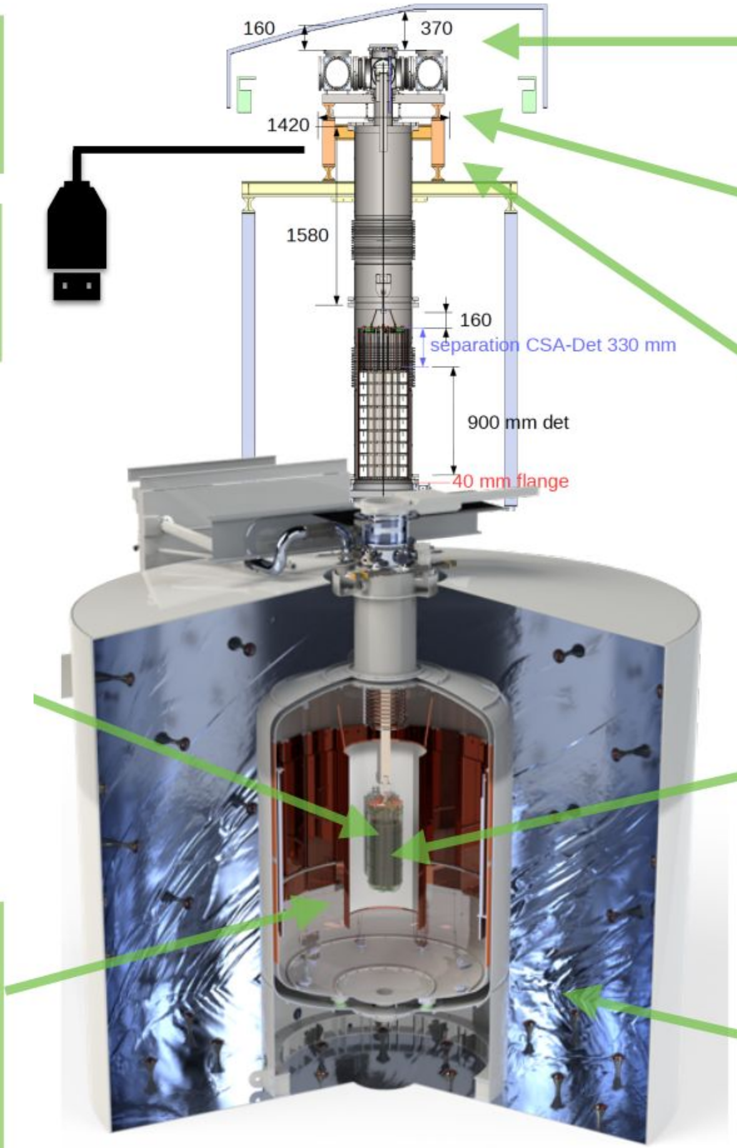
- ΔE = 2.52 keV FWHM at $Q_{\beta\beta}$ (0.13%)
- $T_{1/2} > 8.3 \times 10^{25}$ yr (90%C.L.)
- $|m_{\beta\beta}| < 113 - 269$ meV

[MAJORANA, PRL 130, 062501 (2022)]

Last Upgrades

Electronics:
- New low-mass front-end
- Custom-made readout

Software:
- Two new analysis pipelines based on Python and Julia



Clean room:
- Height extended

Lock system:
- Built and installed
- Currently commissioned

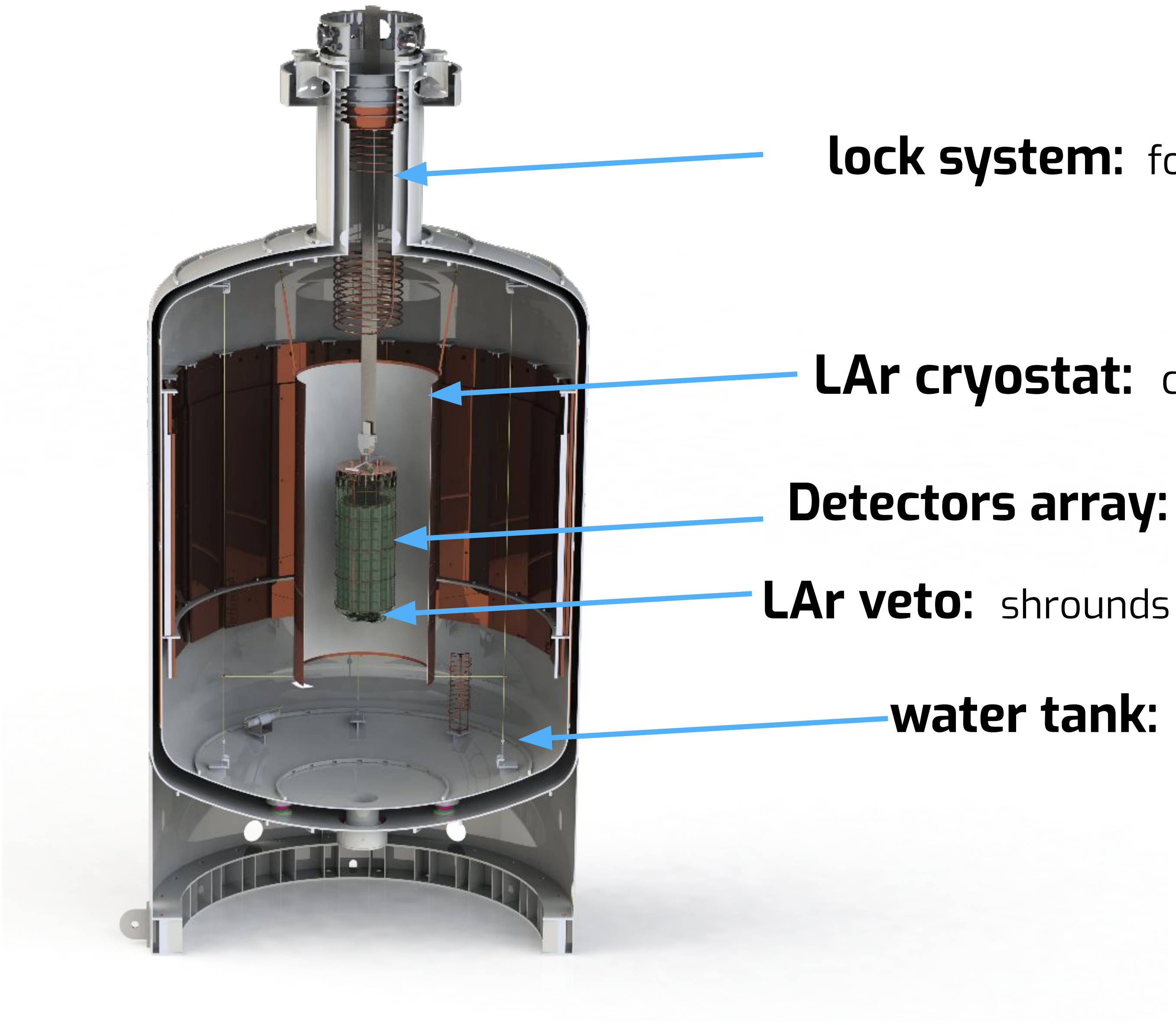
Calibration sources:
- Custom build ^{228}Th sources
- New deployment system

Detectors modules:
- Electroformed copper
- PEN holders produced
- New cables

Liquid argon:
- Emptied and refilled
- New LAr instrumentation for larger detector array
- LLAMA installed
- Continuous purification

Water tank:
- Internal maintenance
- Damaged PMT exchanged

General layout of LEGEND-200



lock system: for the deployment of the Ge detectors

LAr cryostat: coolant shielding

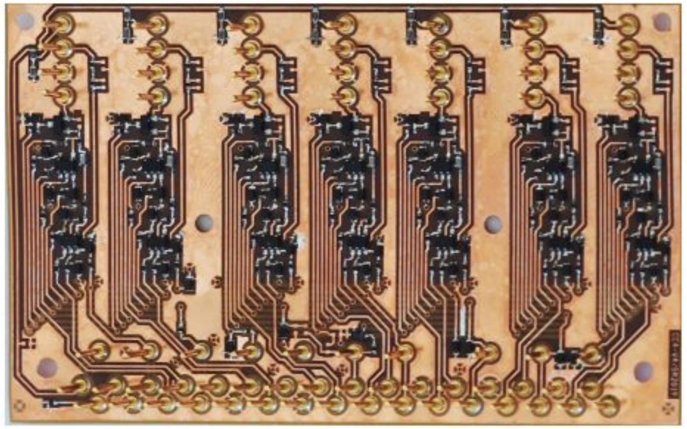
Detectors array: string of naked enriched germanium detectors

LAr veto: shrounds with scintillating fibers for the detection of the light

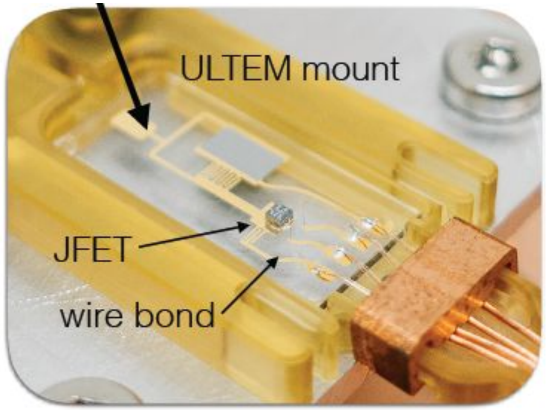
water tank: neutron moderator/absorber muon Cherenkov veto

Low-mass front-end electronics

- A combination of the Liquid Argon (LAr) operated preamplifier of GERDA with the ultra-clean Low-Mass Front-End Electronics (LMFE) of the Majorana Demonstrator has been developed. The LMFE couples an amorphous germanium (aGe) feedback resistor (1 – 5 GΩ) to a bare die junction gate field-effect transistor (JFET).

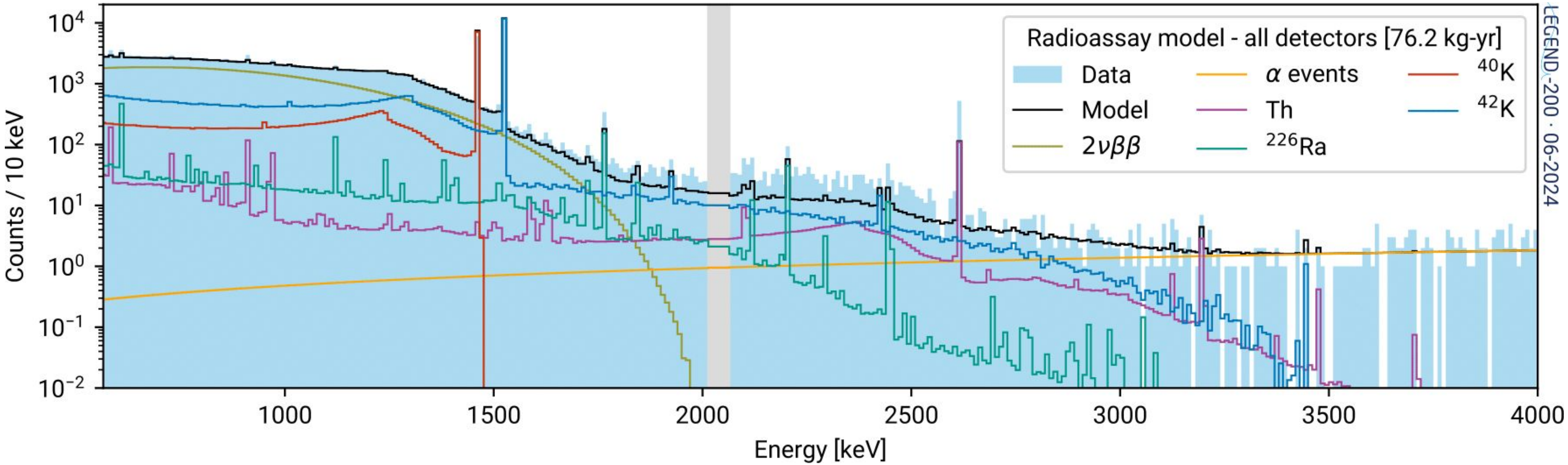


preamplifier operated in LAr



aGe + bare fie JFET LMFE

Background model



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

Some numbers

LEGEND DATA TAKING

Mar 2023 - Feb 2024 (~242 days) with 142.5 kg detector mass
130 kg operational (12 kg OFF due to hardware issues)

COMBINED ANALYSIS

Total exposure: **48.3 kg yr** (L200 Golden dataset) + **127.2 kg yr** (GERDA) + **64.5 kg yr** (MJD) = **240 kg yr**

BACKGROUND INDEX (BI)

L200: $(5.3 \pm 2.2) \times 10^{-4}$ cts / (keV kg yr) → **0.15 counts**
GERDA: $(5.2^{+1.6}_{-1.3}) \times 10^{-4}$ cts / (keV × kg × yr) → **0.34 counts**

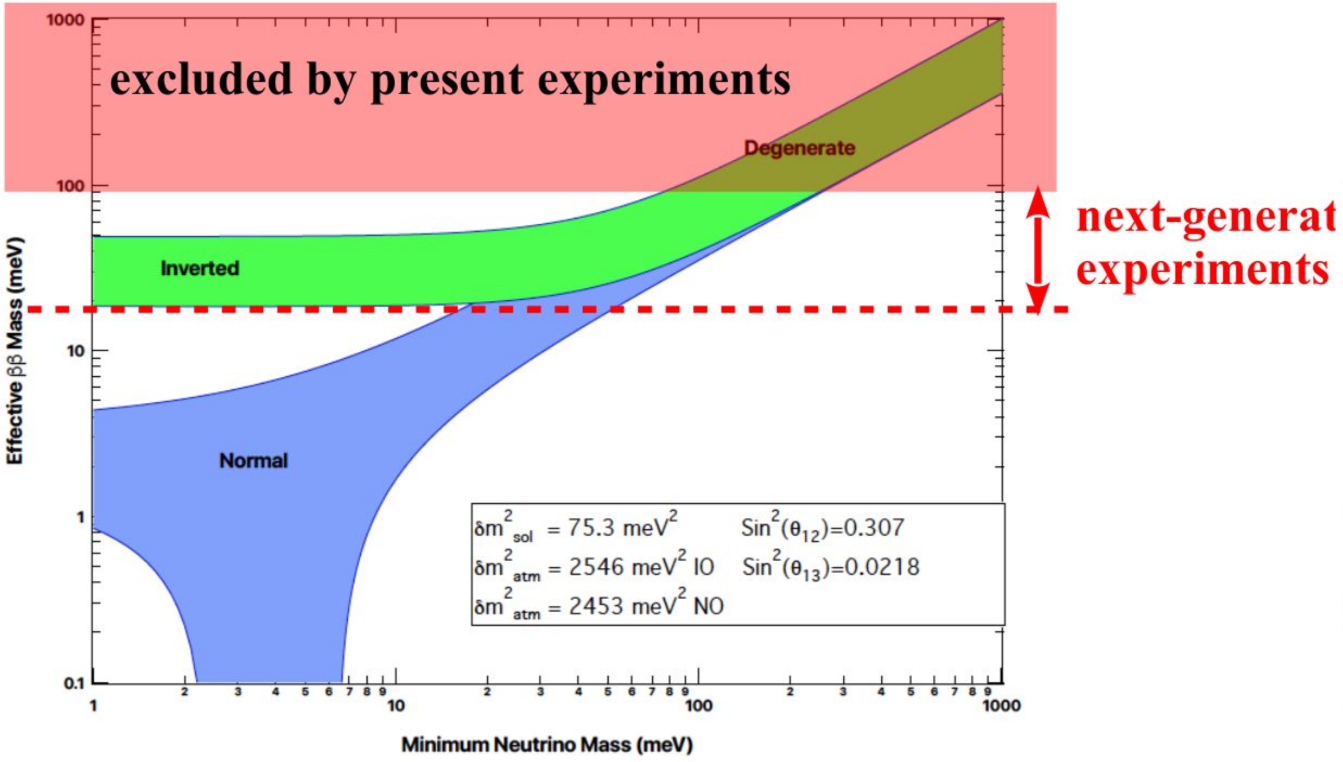
L200 goal: 2×10^{-4} cts / (keV kg yr) → 1 count
L1000 goal: 1×10^{-5} cts / (keV kg yr) → 0.5 counts

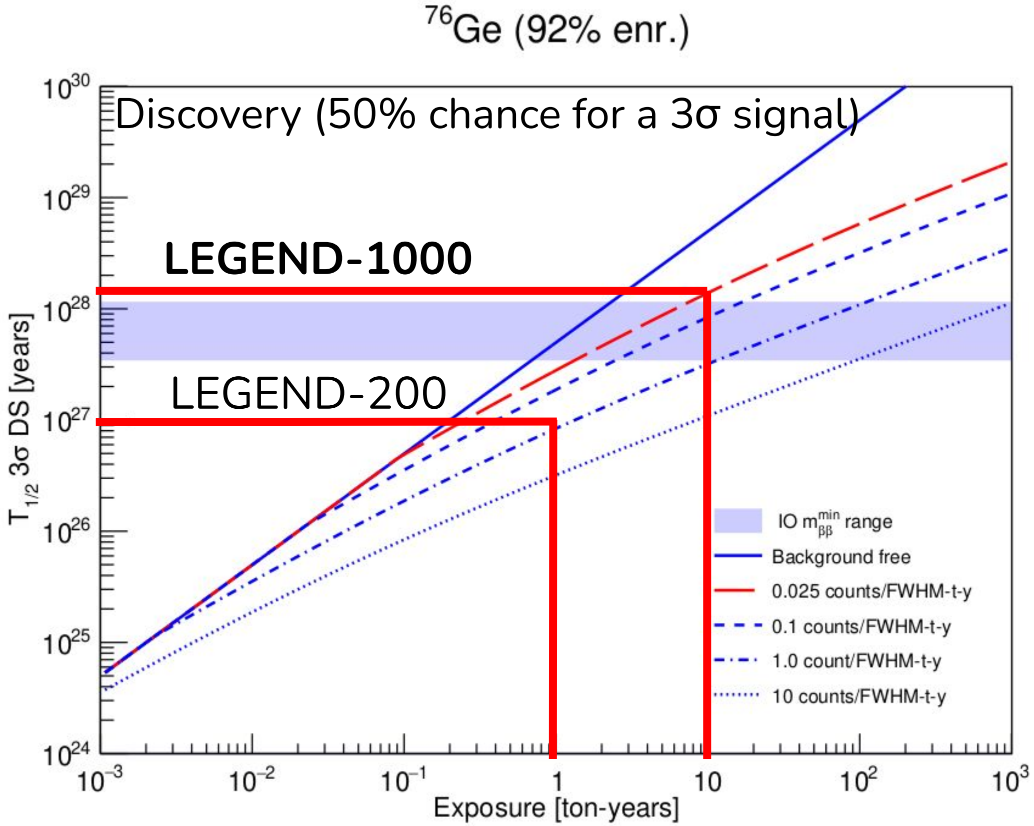
HALF LIFE LIMIT $T_{1/2}$(0nbb)

COMBINED	**> 1.9×10^{26} yr** at 90% C.L. (Sensitivity 2.8×10^{26} yr)
L200	**> 2.1×10^{26} yr** at 90% C.L.
GERDA	**> 1.8×10^{26} yr** at 90% C.L.
MJD	**> 8.3×10^{25} yr** at 90% C.L.

Goals

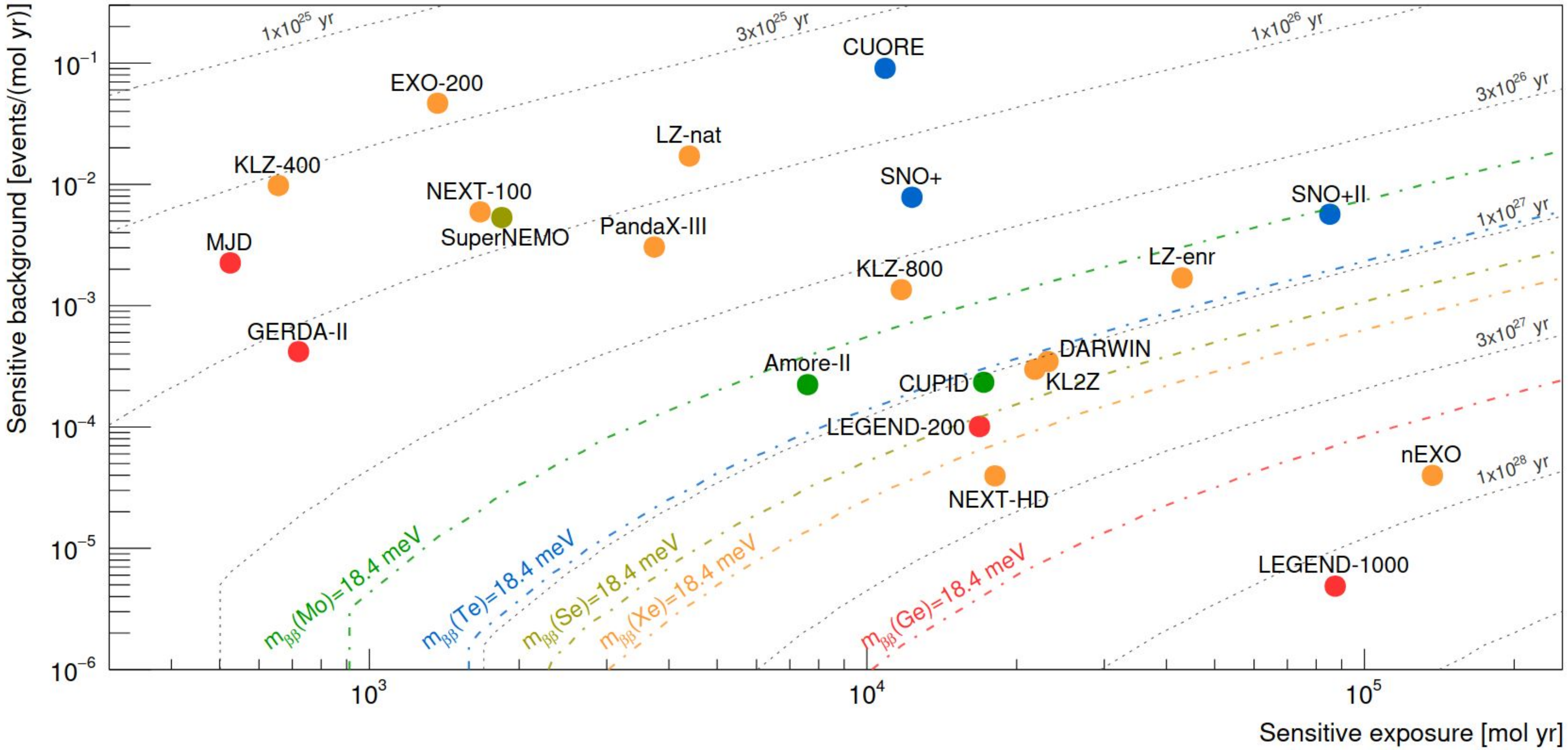
Bkg Index cts/(FWHM·ton·yr)		
	LEGEND-200	0.6
	LEGEND-1000	**0.025**





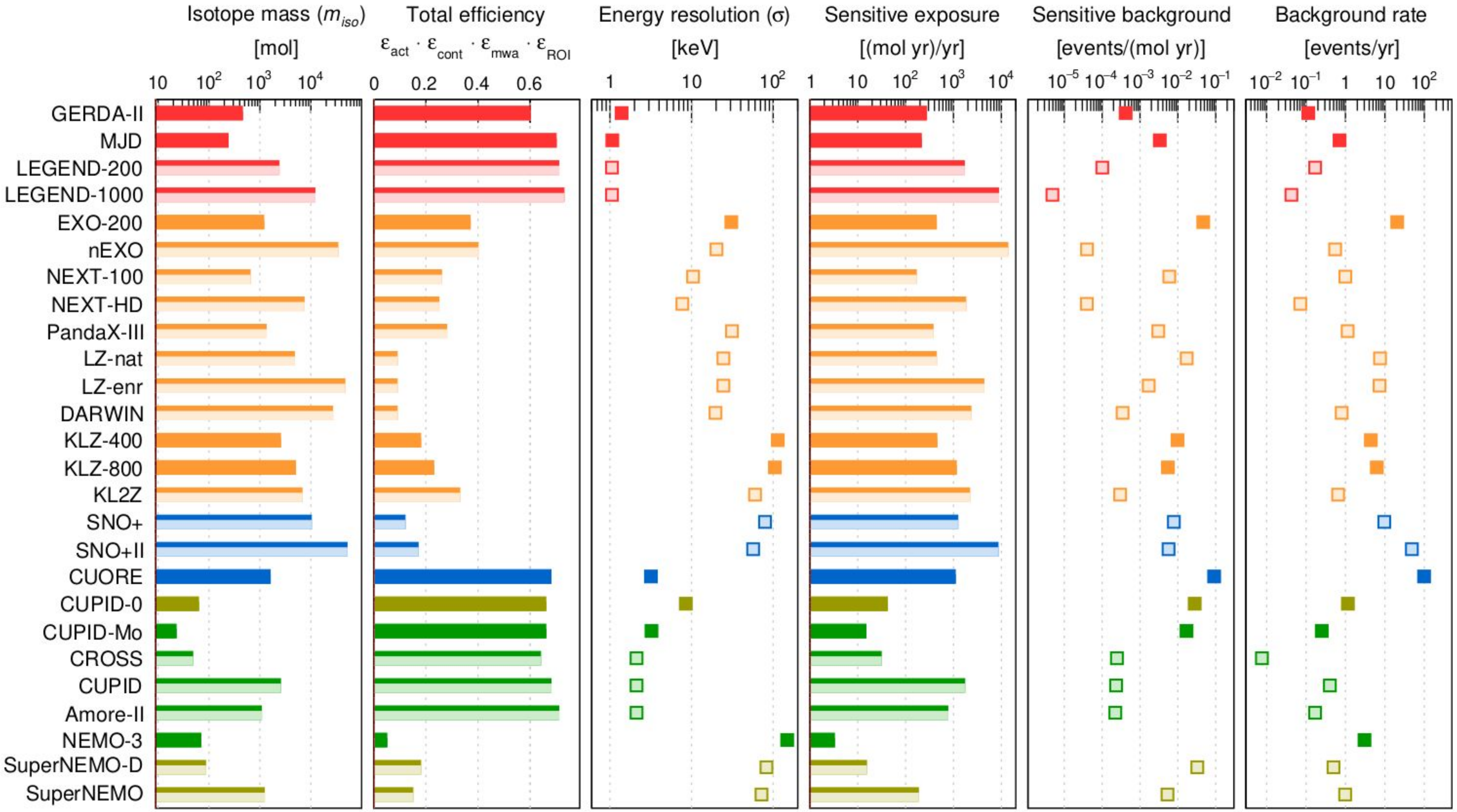
Discovery sensitivity

Comparison of rough sensitivity between ongoing & planned experiments



[ArXiv:2202.01787]

Discovery sensitivity



[ArXiv:2202.01787]