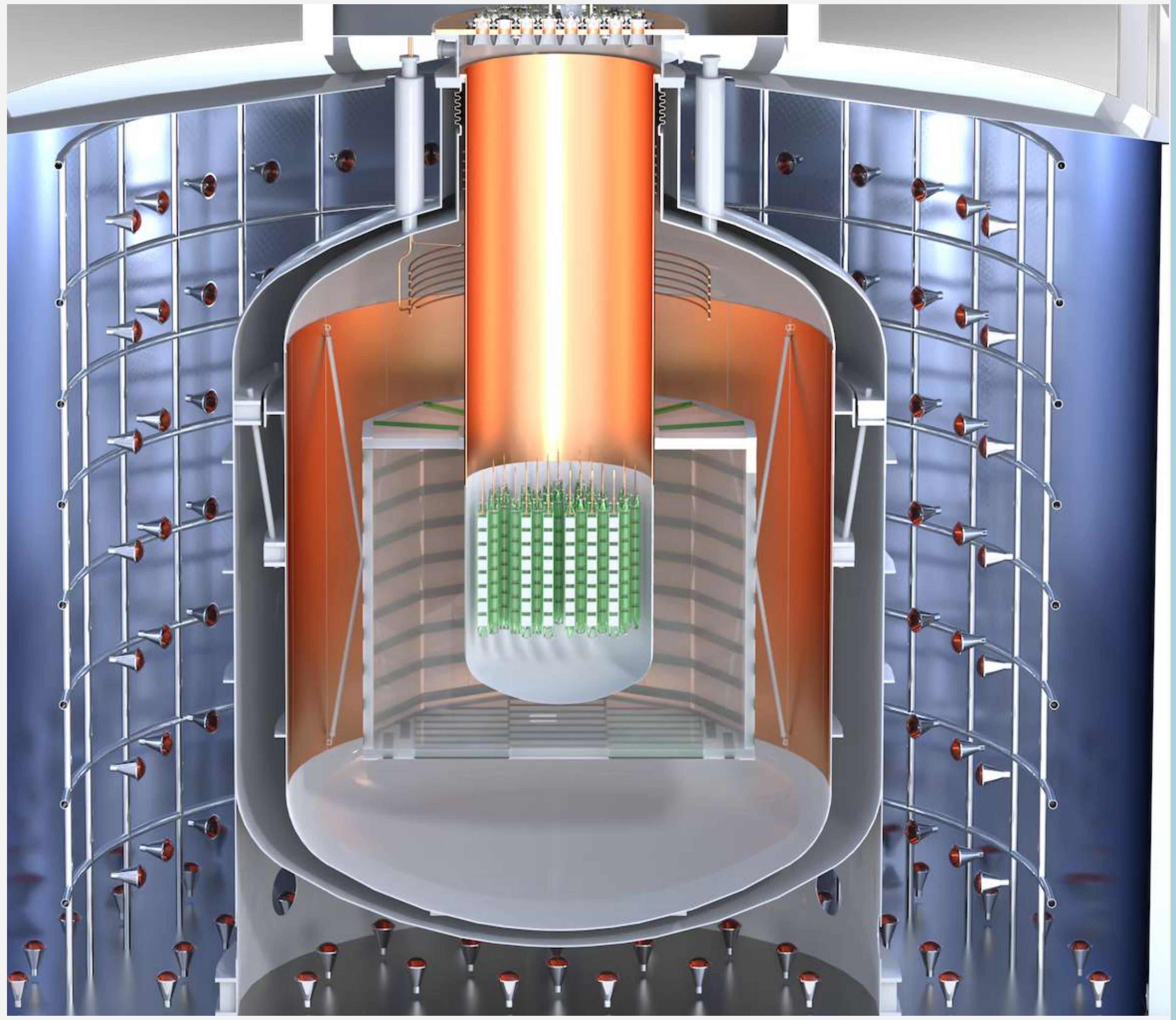
The LEGEND Search for Neutrinoless Double Beta Decay

LEGEND
Large Enriched Germanium Experiment for Neutrinoless $\beta\beta$ Decay



J.F. Wilkerson
Univ. of North Carolina/Triangle Universities Nuclear Laboratory

IUPAP WG9 Nuclear Science Symposium
April 16, 2026

The University of North Carolina at Chapel Hill

TUNL

NSF

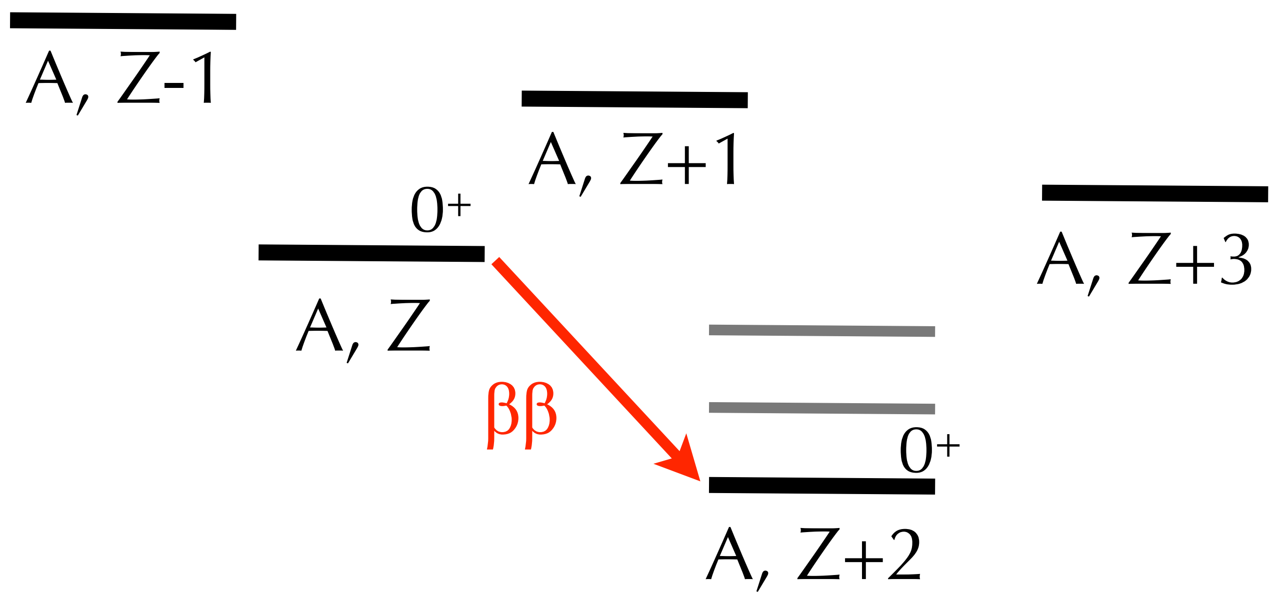
U.S. DEPARTMENT of ENERGY | Office of Science

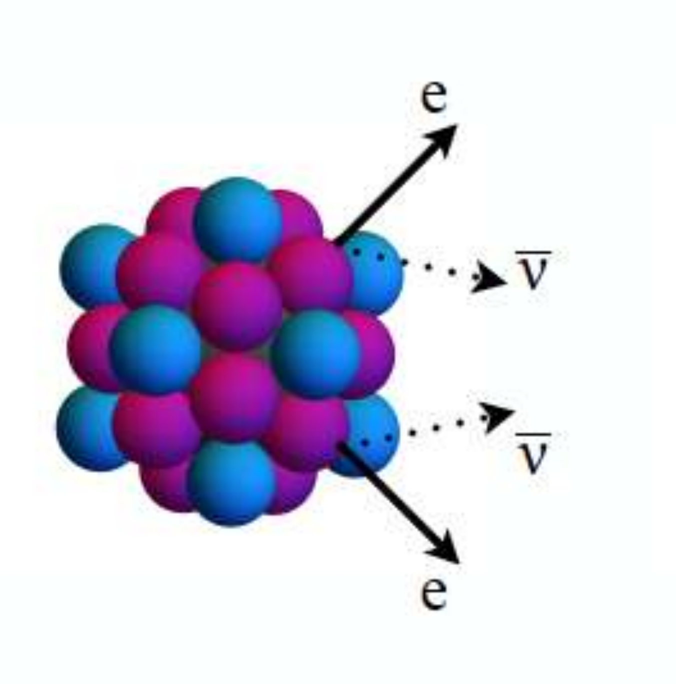
Double-Beta Decay

2ν double-beta decay (2νββ): Nucleus (A, Z) → Nucleus (A, Z+2) + e^- + $\bar{\nu}$ + e^- + $\bar{\nu}$

Allowed second-order weak process

Maria Goeppert-Mayer (1935)





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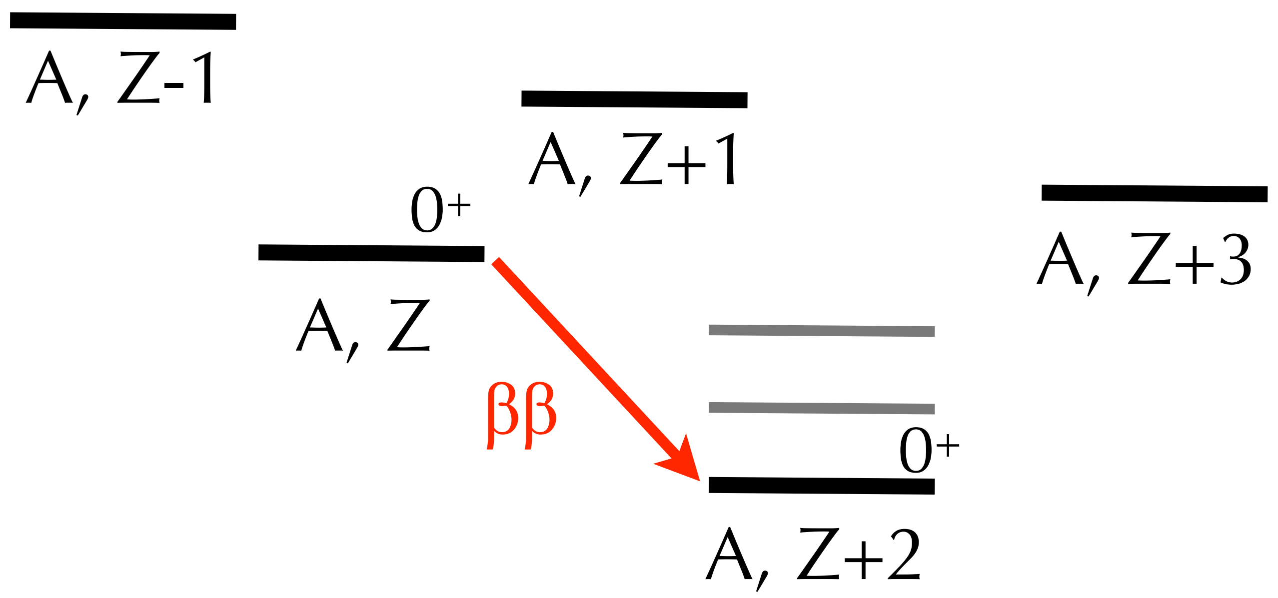
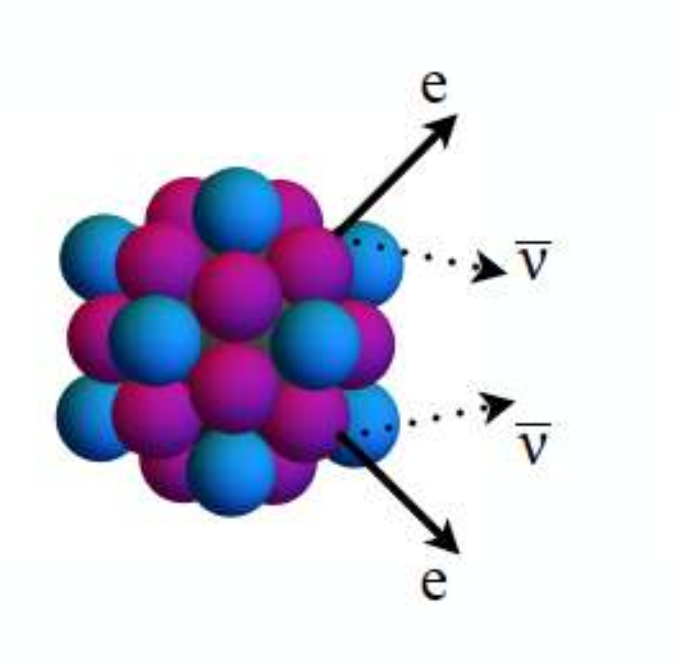
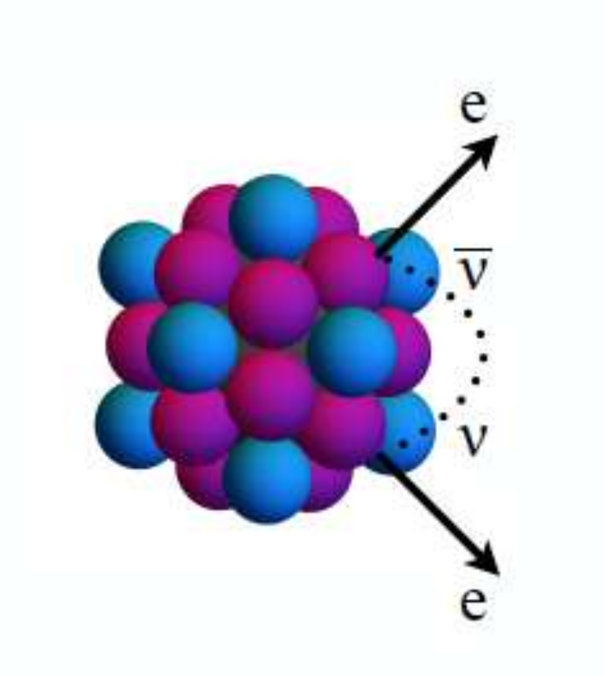




0ν double-beta decay (0νββ): Nucleus (A, Z) → Nucleus (A, Z+2) + e^- + e^-

Ettore Majorana (1937) realized symmetry properties of Dirac's theory allowed the possibility for electrically neutral spin-1/2 fermions to be their own anti-particle



Racah (1937)

$$\mathbf{n \rightarrow p + e^- + \bar{\nu}}$$

$$\nu + \mathbf{n \rightarrow p + e^-}$$

Double-Beta Decay

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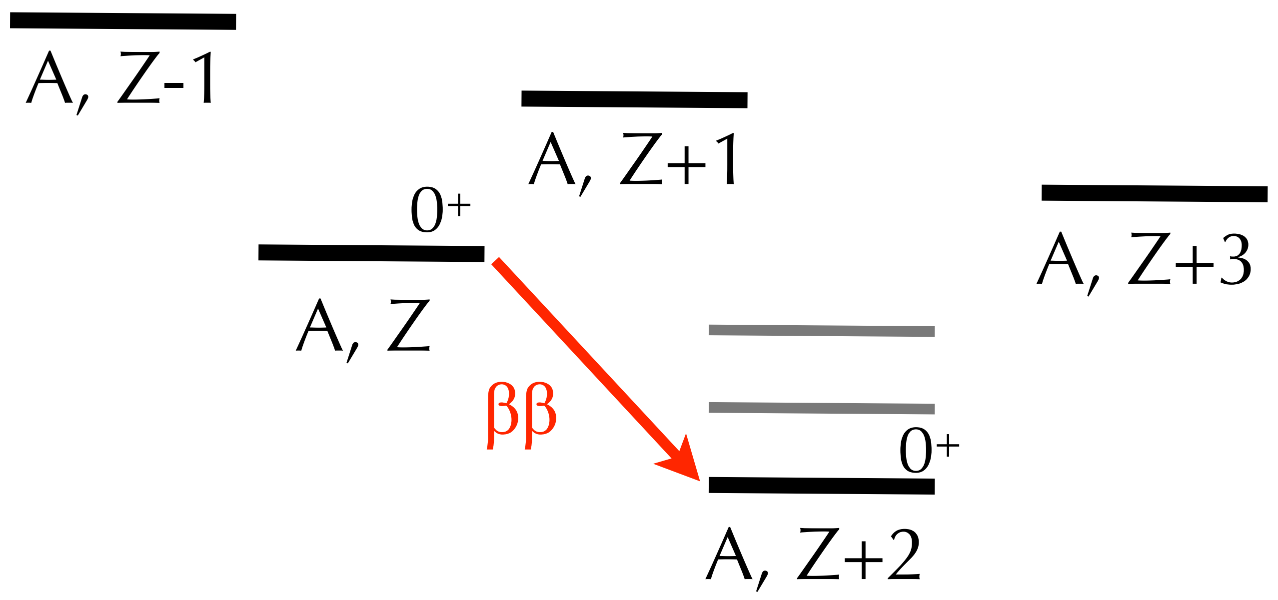

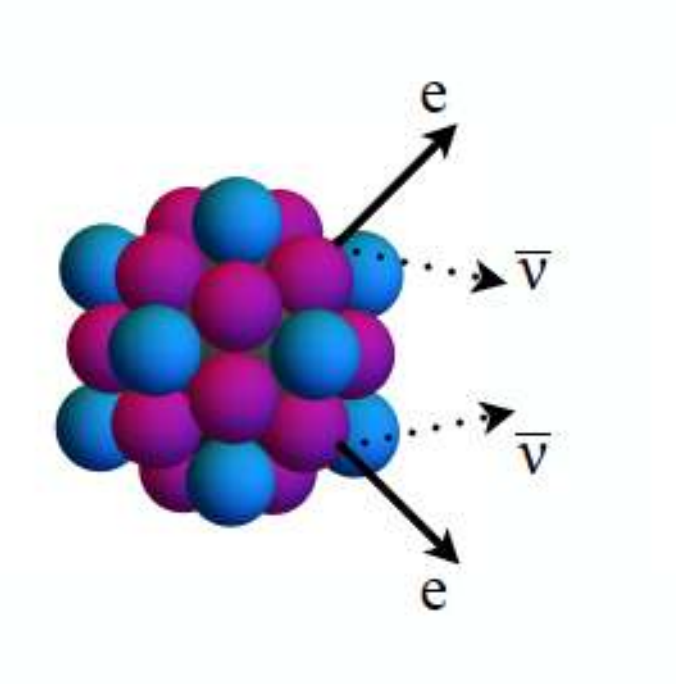

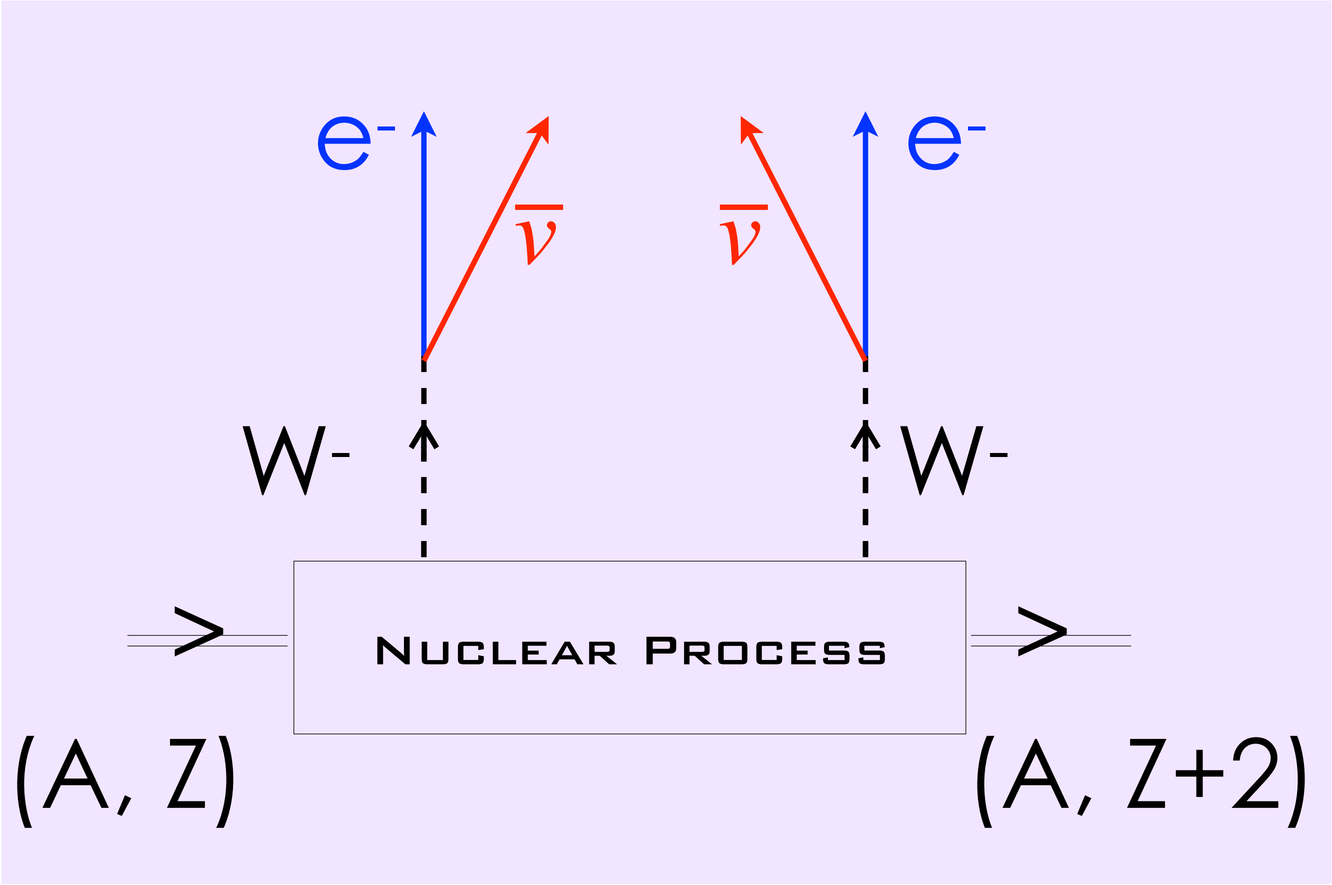

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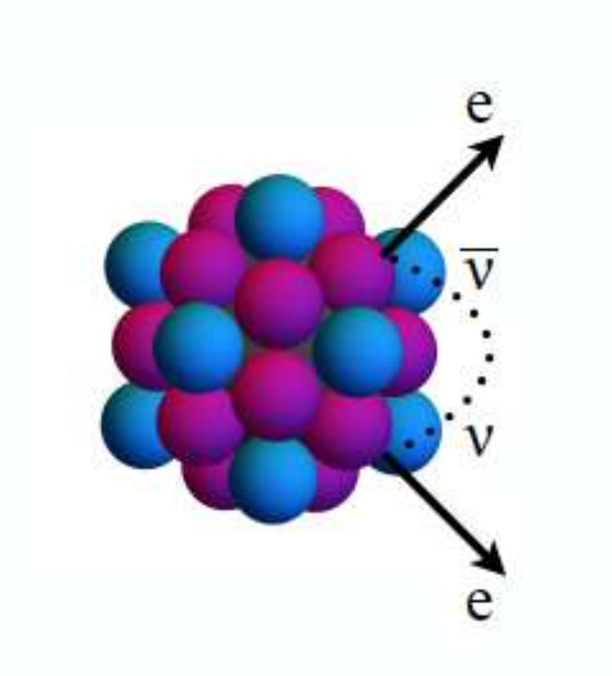
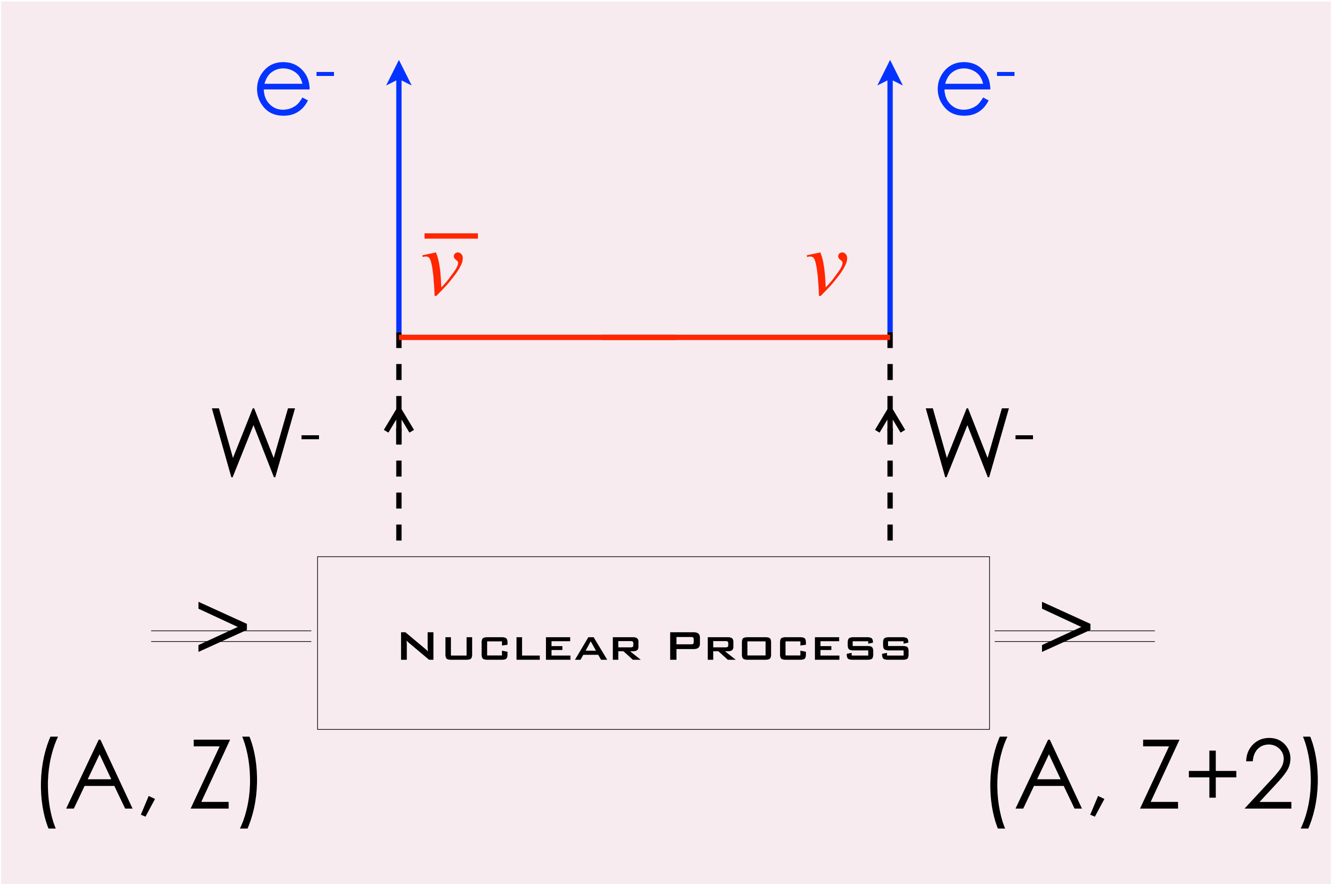


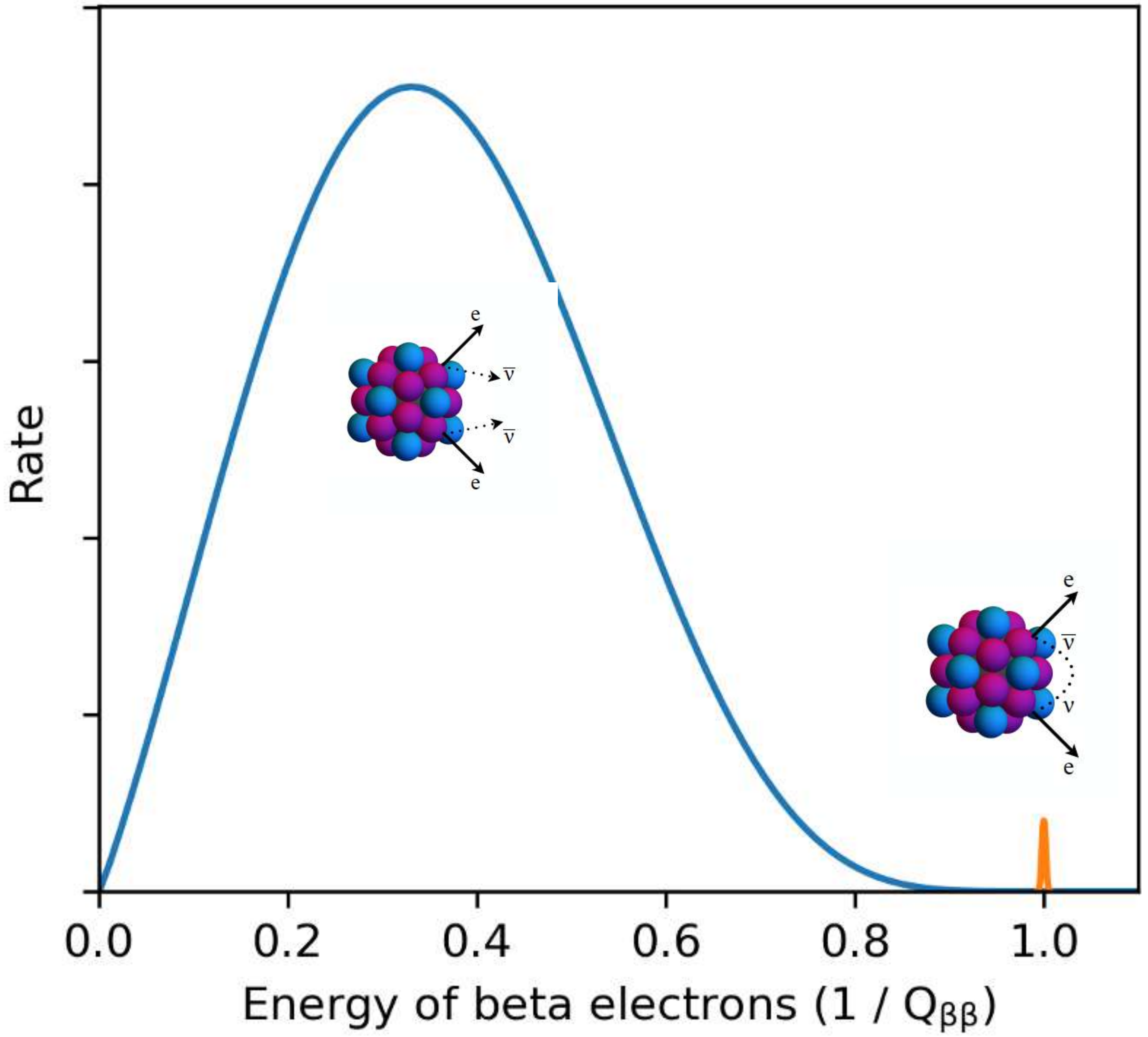
Racah (1937)

$$n \rightarrow p + e^- + \bar{\nu}$$

$$\nu + n \rightarrow p + e^-$$



Experimental signature for 0νββ-decay



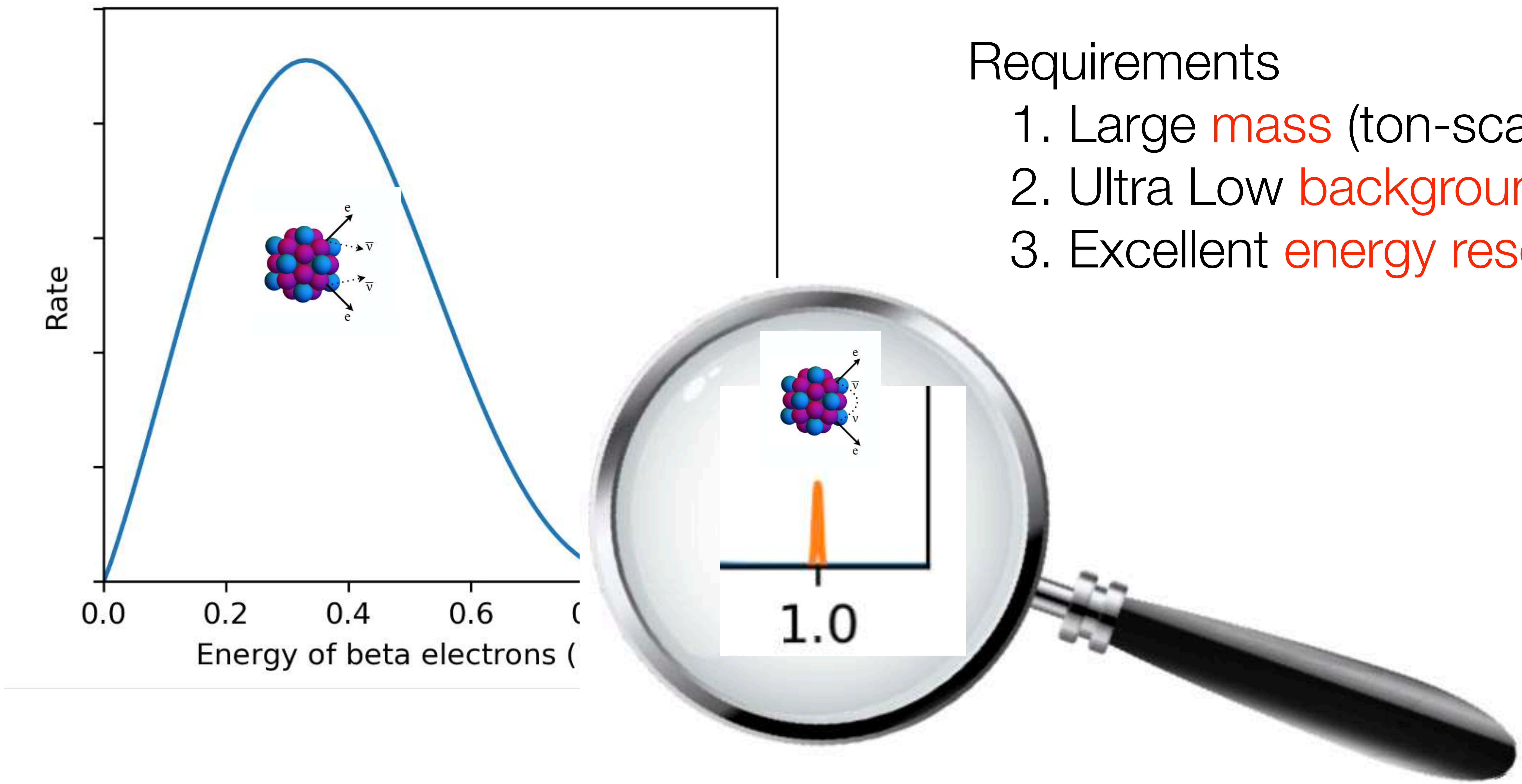
0νββ Half life (years)	~Signal (cnts/ton-year)
10^{25}	500
10^{26}	50
10^{27}	5
10^{28}	0.5
10^{29}	0.05

Current & proposed experiments' sensitivities:

0νββ $T_{1/2} \sim 10^{27} - 10^{28}$ years

(Observed 2νββ $T_{1/2} \sim 10^{19} - 10^{21}$ years)

0νββ-decay Measurement Challenges



Requirements

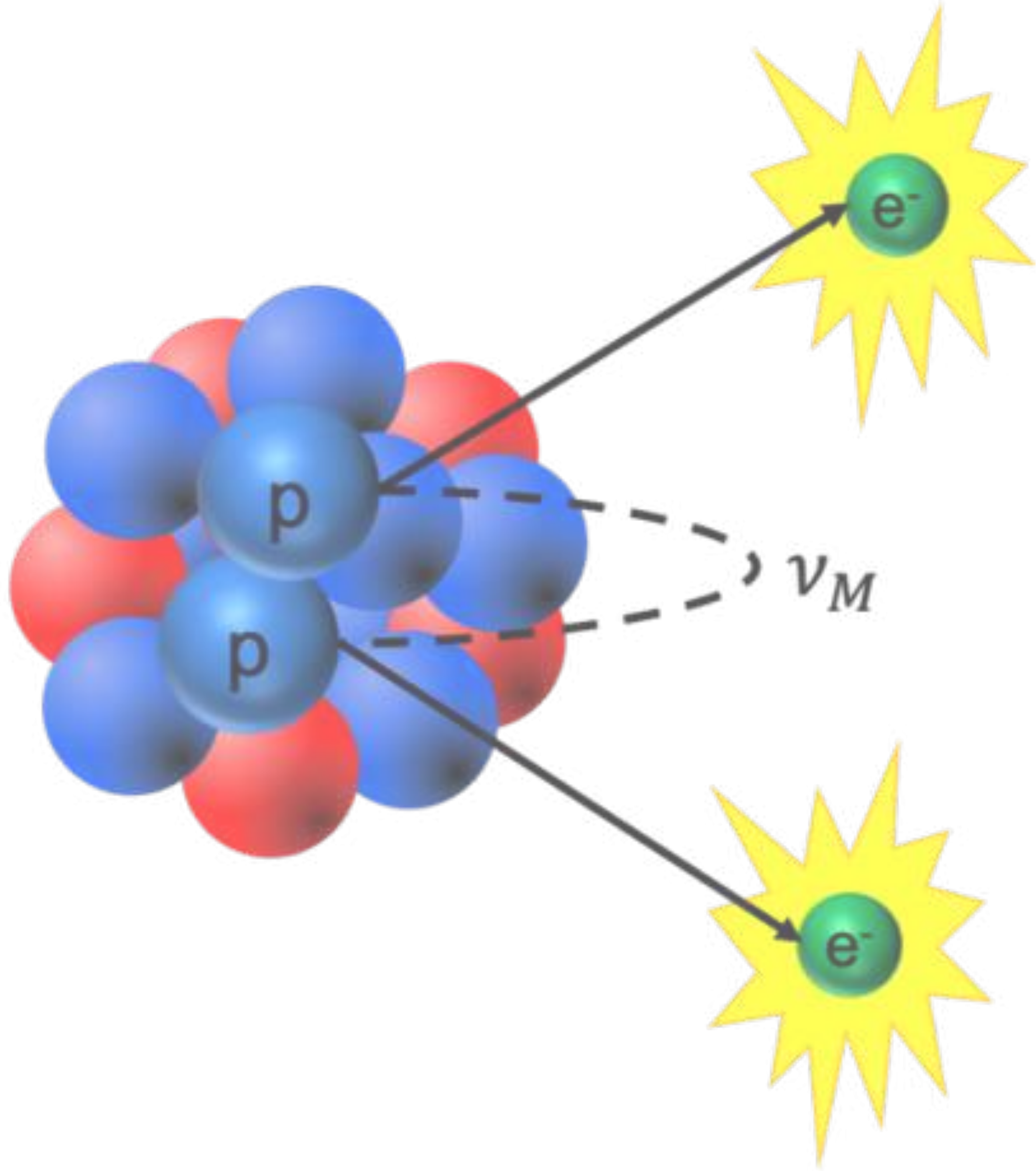
1. Large mass (ton-scale)
2. Ultra Low backgrounds (< 1 event / year)
3. Excellent energy resolution (0.1%)

Current & proposed experiments' sensitivities:

0νββ $T_{1/2}$ ~ 10^{27}- 10^{28} years

(Observed 2νββ $T_{1/2}$ ~ 10^{19} - 10^{21} years)

Neutrinoless Double Beta Decay Discovery Science



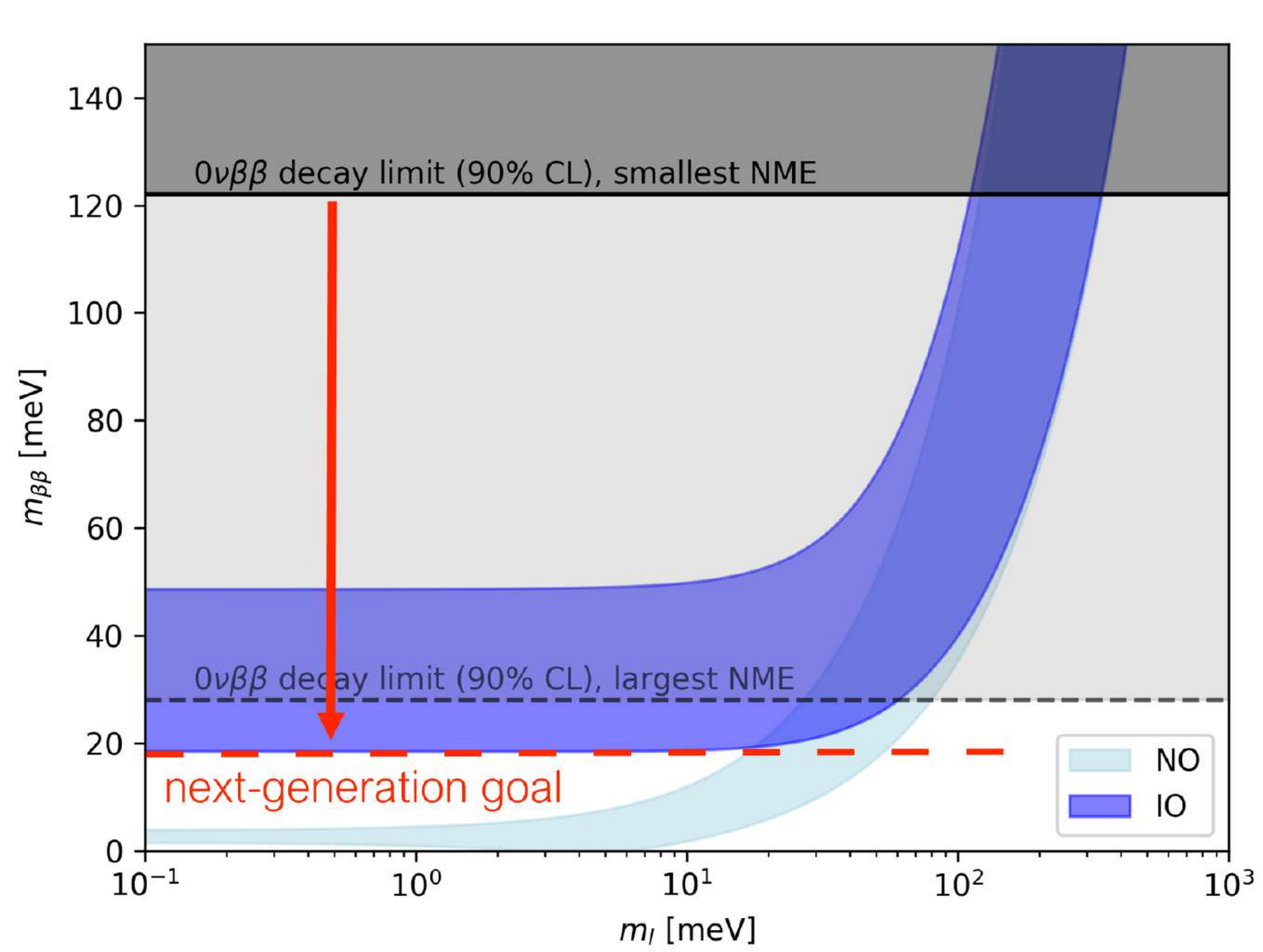
- The observation of 0νββ would reveal the quantum nature of the neutrino and dramatically revise our foundational understanding of physics and the cosmos
  – Matter creation (Lepton number is not conserved)
  – The neutrino is its own anti-particle (Majorana particle)
  – Provide a mechanism for generating the predominance of matter to antimatter in the cosmos (the matter - antimatter asymmetry).
  – Demonstrate a new means for the generation of mass

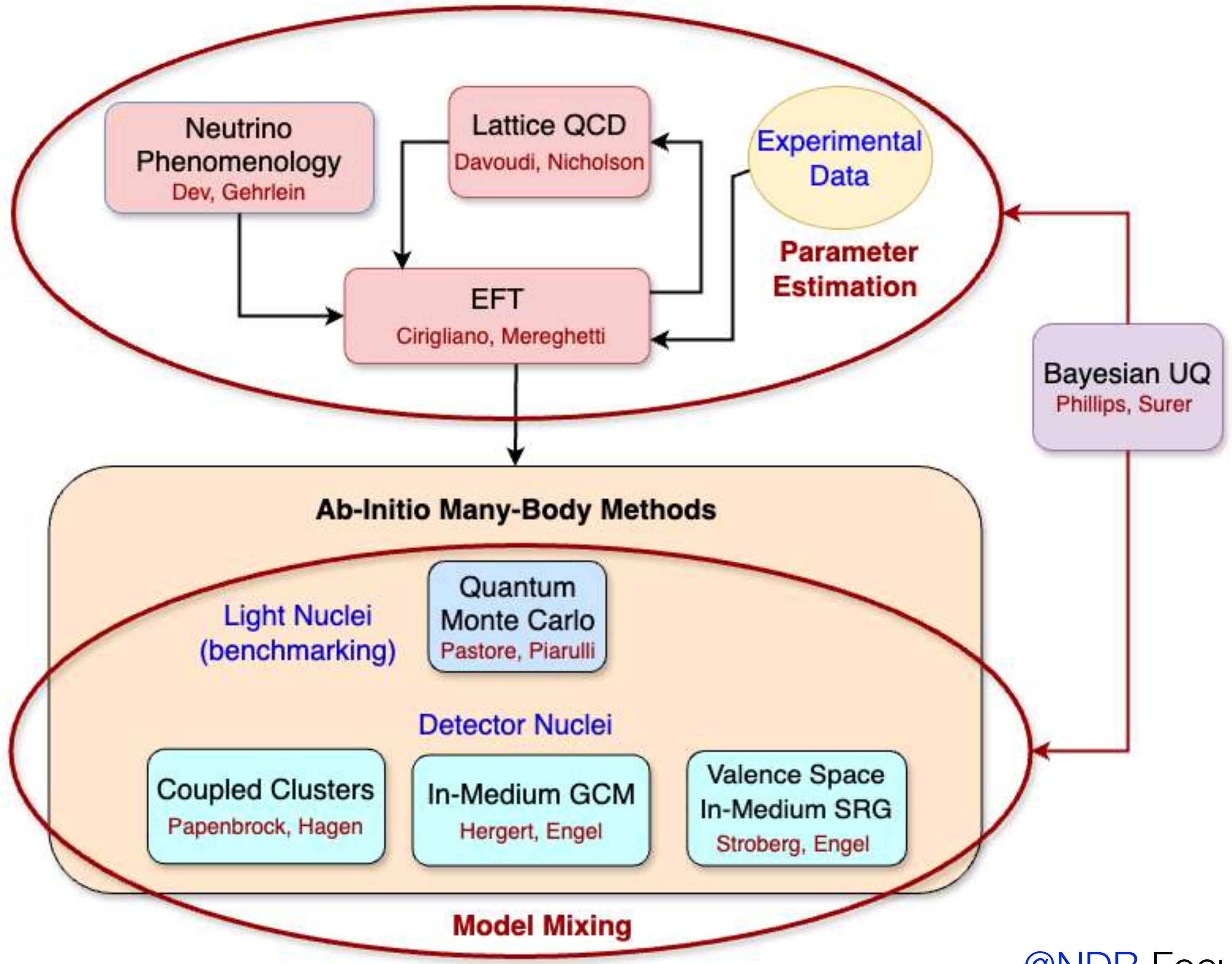
The search for 0νββ decay is one of the most compelling and exciting challenges in all of contemporary physics

$0\nu\beta\beta$ Decay & neutrino mass

Light neutrino exchange: $\left[T_{1/2}^{0\nu}\right]^{-1} = G_{0\nu}\left|M_{0\nu}\right|^2\left|\frac{\langle m_{\beta\beta}\rangle}{m_e}\right|^2$

- Current experiments are probing the upper inverted-ordering (IO) bulk for some nuclear matrix element (NME) calculations
- Next-generation experiments with sensitivity to ~10^{28} yr will probe the full IO bulk even for pessimistic NME
- NO and other exchange mechanisms will also be probed by another ~order of magnitude

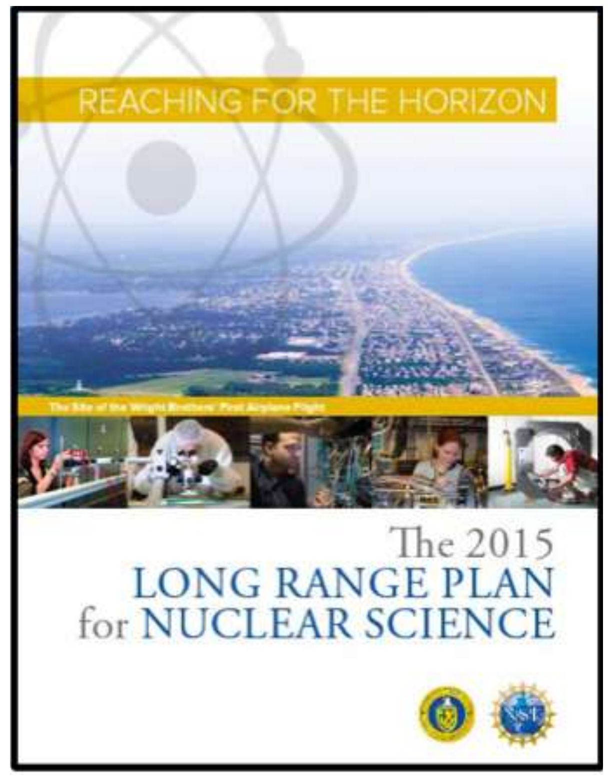




- $0\nu\beta\beta$ Nuclear Theory — goal is accurate computation, with meaningful uncertainty estimates, of the nuclear matrix elements that govern neutrinoless double-beta decay in important isotopes.

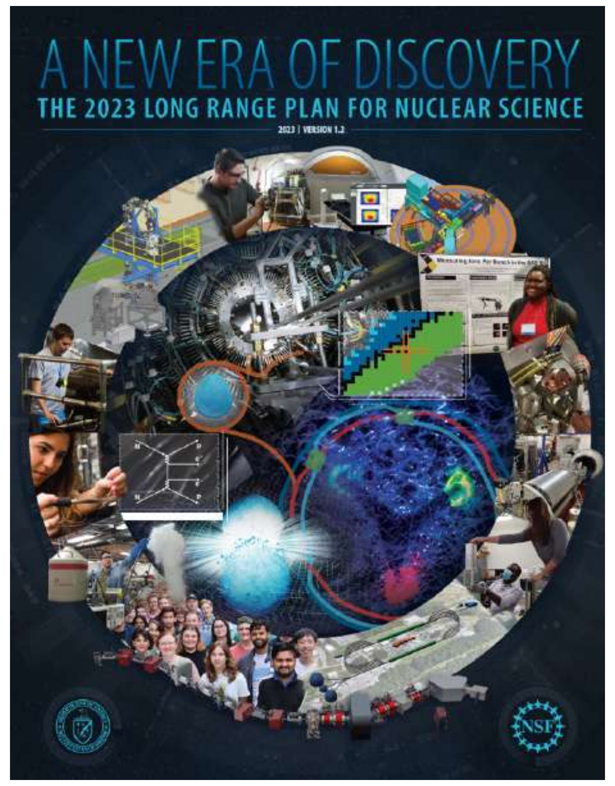
@NDB Focused Research Hub in Theoretical Physics, Jon Engel

Community Prioritization



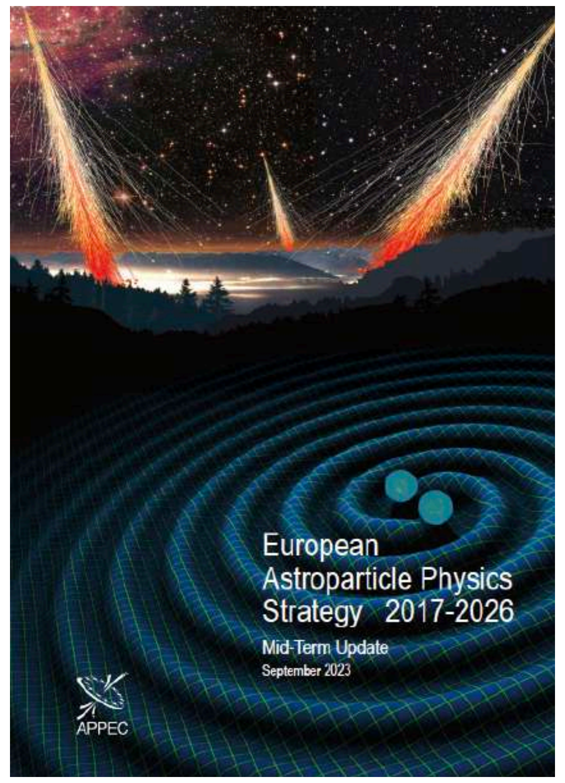
- U.S. 2015 Long Range Plan for Nuclear Science, Recommendation 2:

  We recommend the timely development and deployment of a U.S.-led ton-scale neutrinoless double beta decay experiment.



- U.S. 2023 Long Range Plan for Nuclear Science, Recommendation 2:

  As the highest priority for new experiment construction, we recommend that the United States lead an international consortium that will undertake a neutrinoless double beta decay campaign, featuring the expeditious construction of ton-scale experiments, using different isotopes and complementary techniques.



- 2023 Astroparticle Physics European Consortium (APPEC) Midterm Update, Neutrino Mass and Nature Recommendation:

  APPEC strongly supports the CUPID and LEGEND-1000 double-beta decay experiments selected in the US-European process and endorses the development of NEXT.

NSAC Subcommittee on Neutrinoless Double Beta Decay

APRIL 24, 2014

The Subcommittee recommends the following guidelines be used in the development and consideration of future proposals for the next generation experiments

1.) Discovery potential: Favor approaches that have a credible path toward reaching 3σ sensitivity to the effective Majorana neutrino mass parameter $m_{\beta\beta}$=15 meV within 10 years of counting, assuming the lower matrix element values among viable nuclear structure model calculations.

2.) Staging: Given the risks and level of resources required, support for one or more intermediate stages along the maximum discovery potential path may be the optimal approach.

3.) Standard of proof: Each next-generation experiment worldwide must be capable of providing, on its own, compelling evidence of the validity of a possible non-null signal.

4.) Continuing R&D: The demands on background reduction are so stringent that modest scope demonstration projects for promising new approaches to background suppression or sensitivity enhancement should be pursued with high priority, in parallel with or in combination with ongoing NLDBD searches.

5.) International Collaboration: Given the desirability of establishing a signal in multiple isotopes and the likely cost of these experiments, it is important to coordinate with other countries and funding agencies to develop an international approach.

6.) Timeliness: It is desirable to push for results from at least the first stage of a next-generation effort on time scales competitive with other international double beta decay efforts and with independent experiments aiming to pin down the neutrino mass hierarchy.

NSAC Subcommittee on Neutrinoless Double Beta Decay

APRIL 24, 2014

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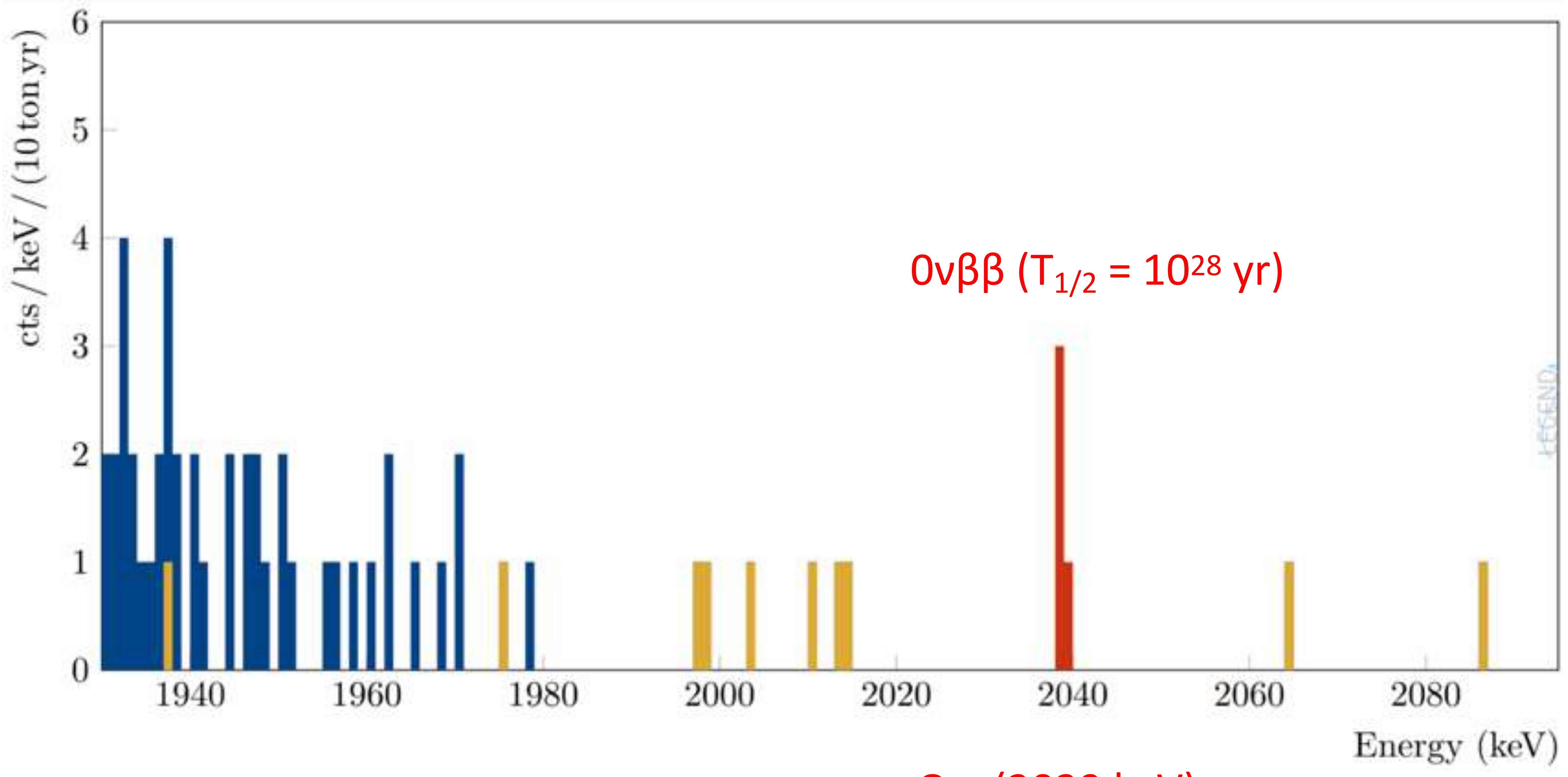
3σ 0νββ Discovery

LEGEND-1000 ^{76}Ge

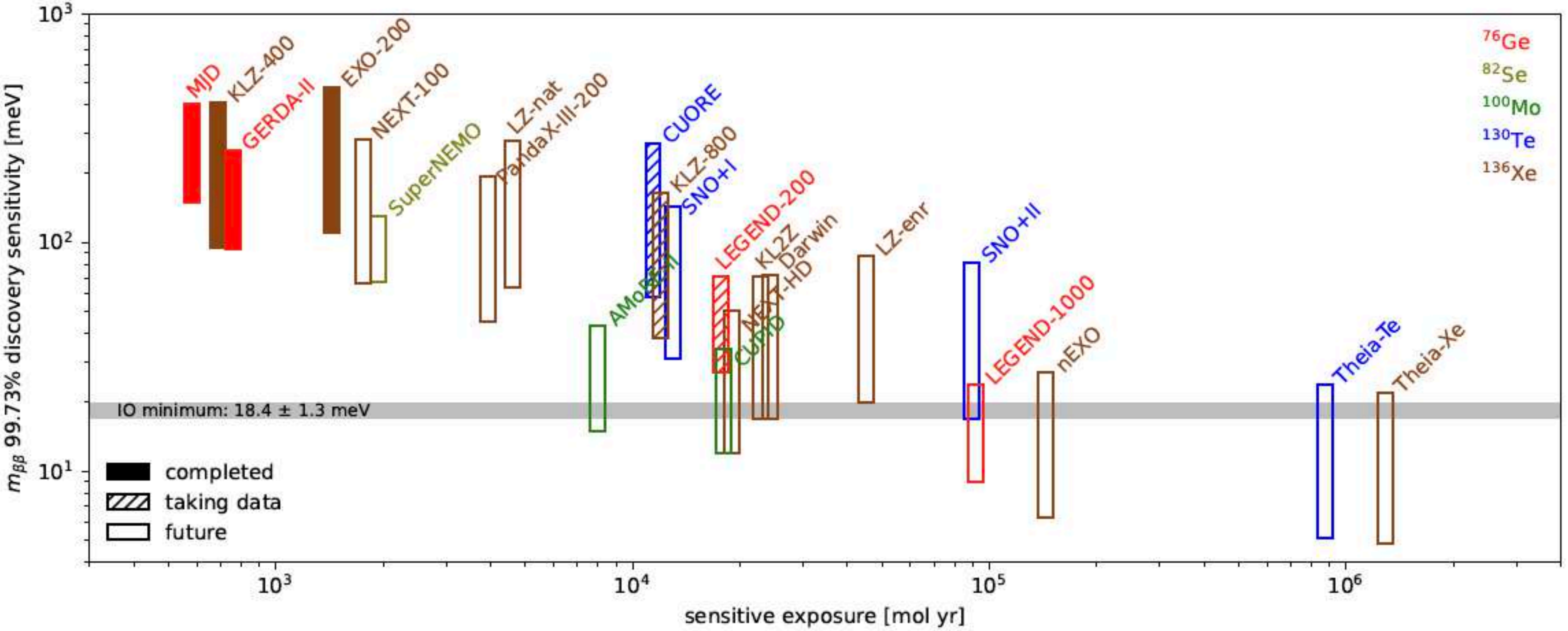
Simulated predicted spectrum, after cuts, from 10 ton years of data



0νββ ($T_{1/2}$ = 10^{28} yr)

$Q_{\beta\beta}$ (2039 keV)

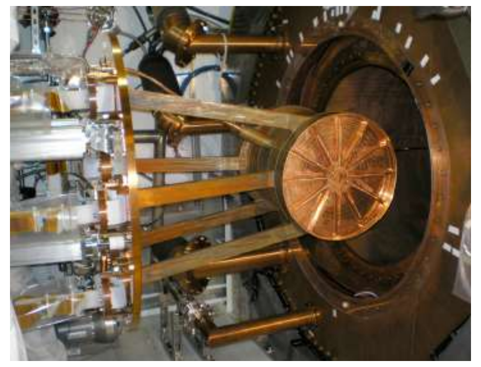
Worldwide searches for 0νββ decay



Fundamental Symmetries, Neutrons, and Neutrinos (FSNN): Whitepaper for the 2023 NSAC Long Range Plan

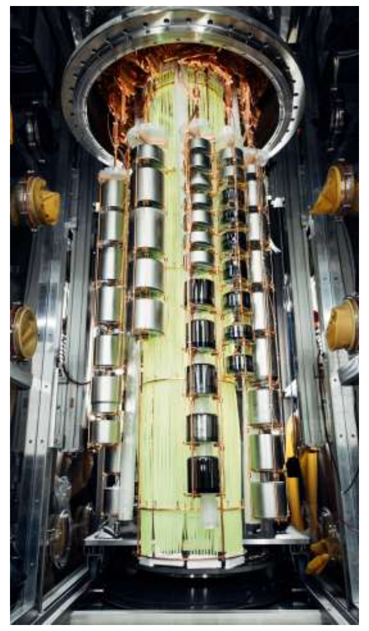
0νββ decay Experiments Summary

KamLAND Zen



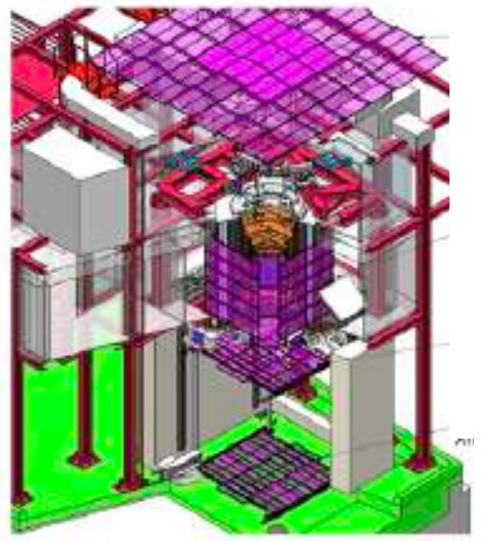
EXO-200

CUORE

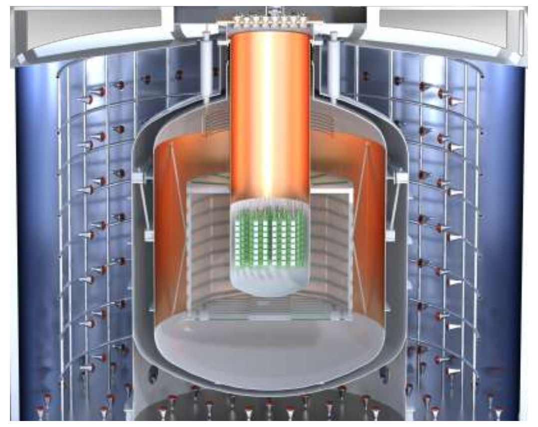


LEGEND-200

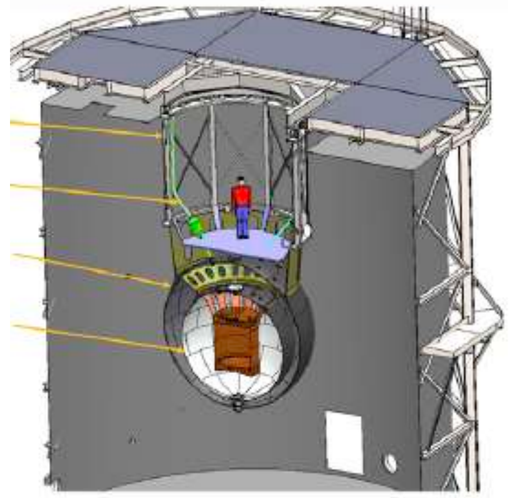
Experiment	Collaboration (2026)	Isotope	Technique	Planned Exposure (mol yr)	Status
CUORE	Italy/US	Te-130	TeO_2 Bolometer	~1 • 10^4	Op: Science 390, 6777 p 1029 (2025)
LEGEND-200	US/EU/UK	Ge-76	Point contact with active veto	1.8 • 10^4	Op: PRL **136**, 022701, (2026)
KamLAND2-Zen	Japan/US	Xe-136	Xe suspended in scint.	~2.5 • 10^4	Construction (upgrade) PRL 135, 262501 (2025)
SNO+	INT/US	Te-130	0.5% ^{nat}Te suspended in scint.	1.5 • 10^4	Commissioning
CDEX-300	China	Ge-76	Point contact with active veto	1 • 10^4	Construction
CUPID	Italy/US	Mo-100	Li_2MoO_4 Bolometer & scint.	1.8 • 10^4	Proj (CUORE)
LEGEND-1000	US/EU/UK	Ge-76	Point contact with active veto	9 • 10^4	Proj (MJD, GERDA, LEGEND-200)
nEXO	INT/US	Xe-136	Xe liquid TPC	1 • 10^5	(EXO-200)
AMoRE II	S. Korea/INT	Mo-100	Li_2MoO_4 Bolometer & scint.	8 • 10^3	Construction (AMoRE I)
NEXT-HD	INT/US	Xe-136	High pressure Xe TPC	1.8 • 10^4	Dem : NEXT-100
PandaX-xT	China/INT	Xe-nat	high pressure Liquid TPC	~1.5 • 10^4	Commissioning
SNO+ II	INT/US	Te-130	1.5% ^{nat}Te suspended in scint.	9 • 10^4	Future
XLZD 0νββ	US/INT	Xe-nat	Xe liquid TPC	~1.3 • 10^5	Future
Theia 0νββ	US/INT	Te or Xe	Te or Xe suspended in Scint/ Chernkov	~1 • 10^6	Future
JUNO 0νββ	China/INT	Te or Xe	Te or Xe suspended in scint.	~1 • 10^6	Future



CUPID



LEGEND-1000



nEXO

LEGEND

Large Enriched Germanium Experiment for Neutrinoless ββ Decay

LEGEND

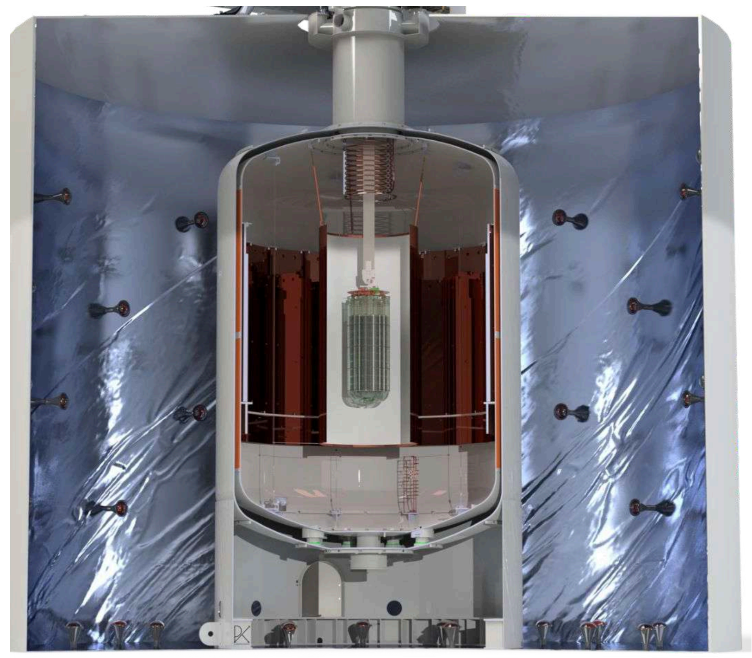
~350 researchers from about ~60 institutions from around the world

Combines the technological expertise and experience from the predecessor experiments GERDA and the MAJORANA DEMONSTRATOR

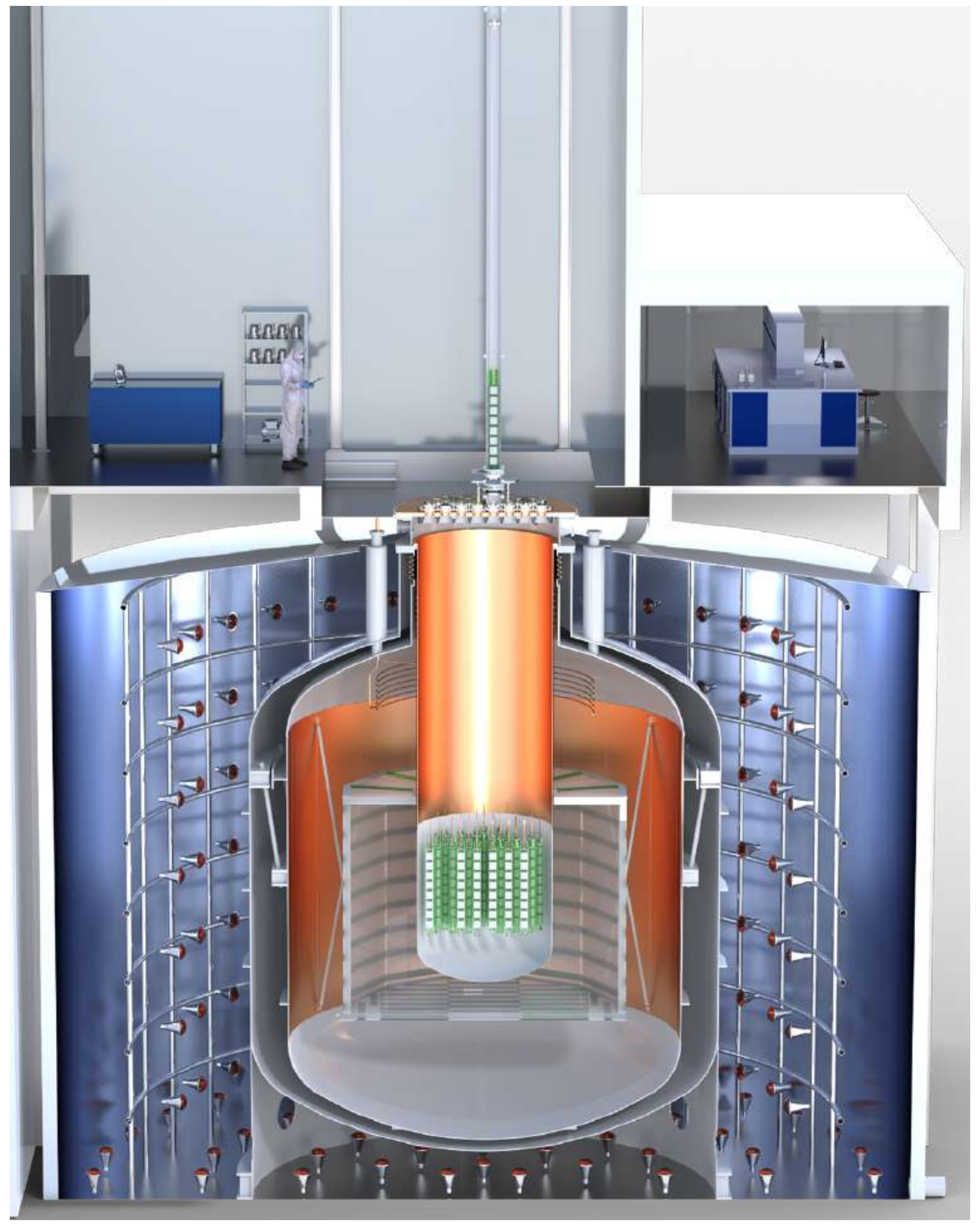
LEGEND aims to improve the half-life discovery sensitivity for ^{76}Ge 0νββ by two orders of magnitude, with discovery sensitivity of

$$T_{1/2} > 1.3 \times 10^{28} \text{ yrs } (3\sigma) \quad m_{\beta\beta} \sim 10\text{-}25 \text{ meV}$$

- **LEGEND-200:** up to 200 kg of 90%-enriched Ge detectors deployed in the GERDA liquid argon (LAr) cryostat, running now at LNGS
- **LEGEND-1000:** 1 ton of 90%-enriched Ge detectors deployed in a new experimental infrastructure at LNGS, initial data taking in the 2033-2035.



LEGEND-200



LEGEND-1000

Laboratori Nazionali del Gran Sasso (LNGS)

1400 m of rock overhead

Cosmic ray flux reduction 1.000.000

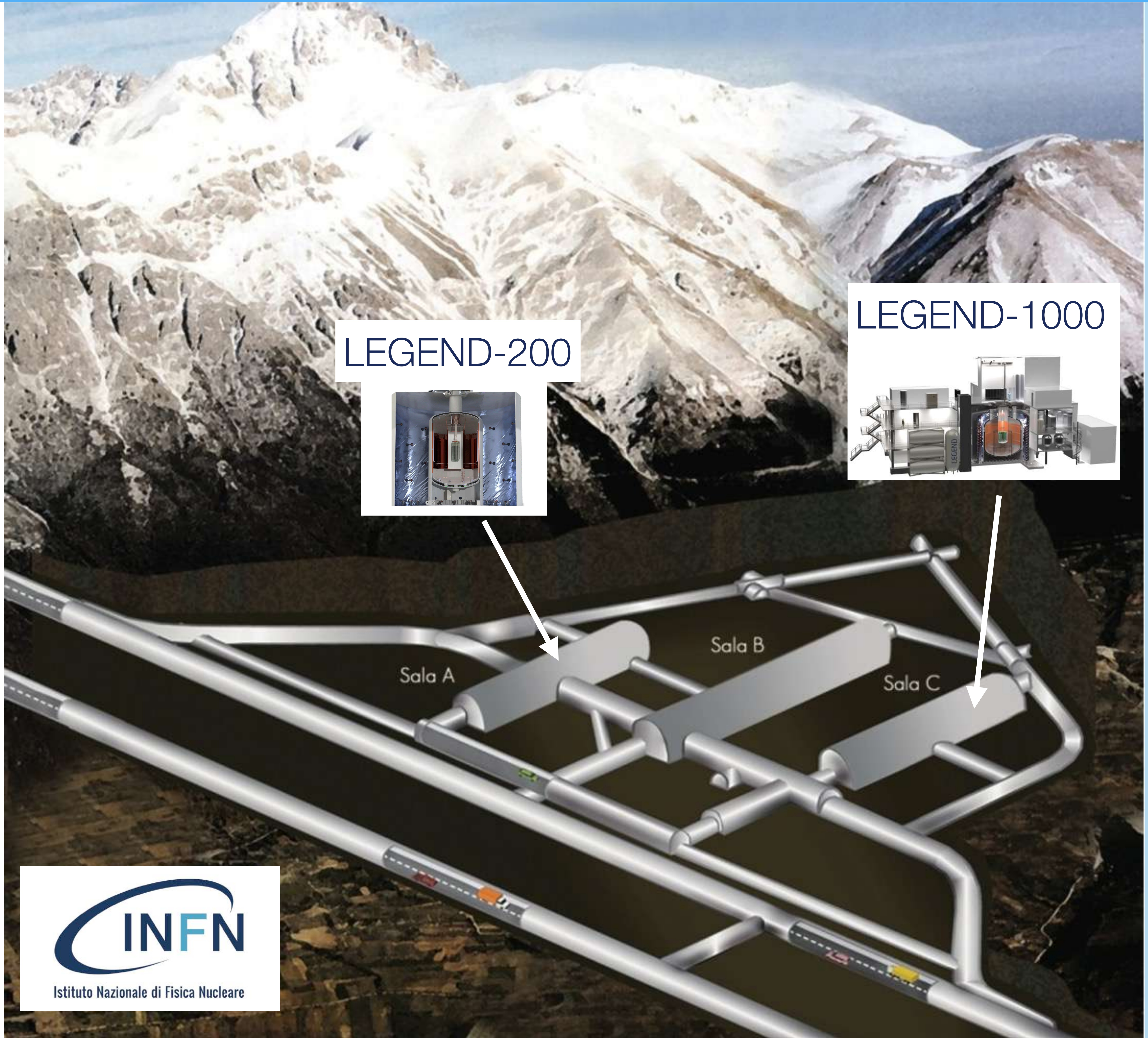
The 3 experimental halls of
100 m length, 20 m width, 18 m height

About 22 experiments in data taking or under construction

LNGS scientific users

Total: 768 (~1619*)
Italian: 380 (~528*)
Foreign: 388 (~1090*)

from Ezio Previtali, LNGS Director



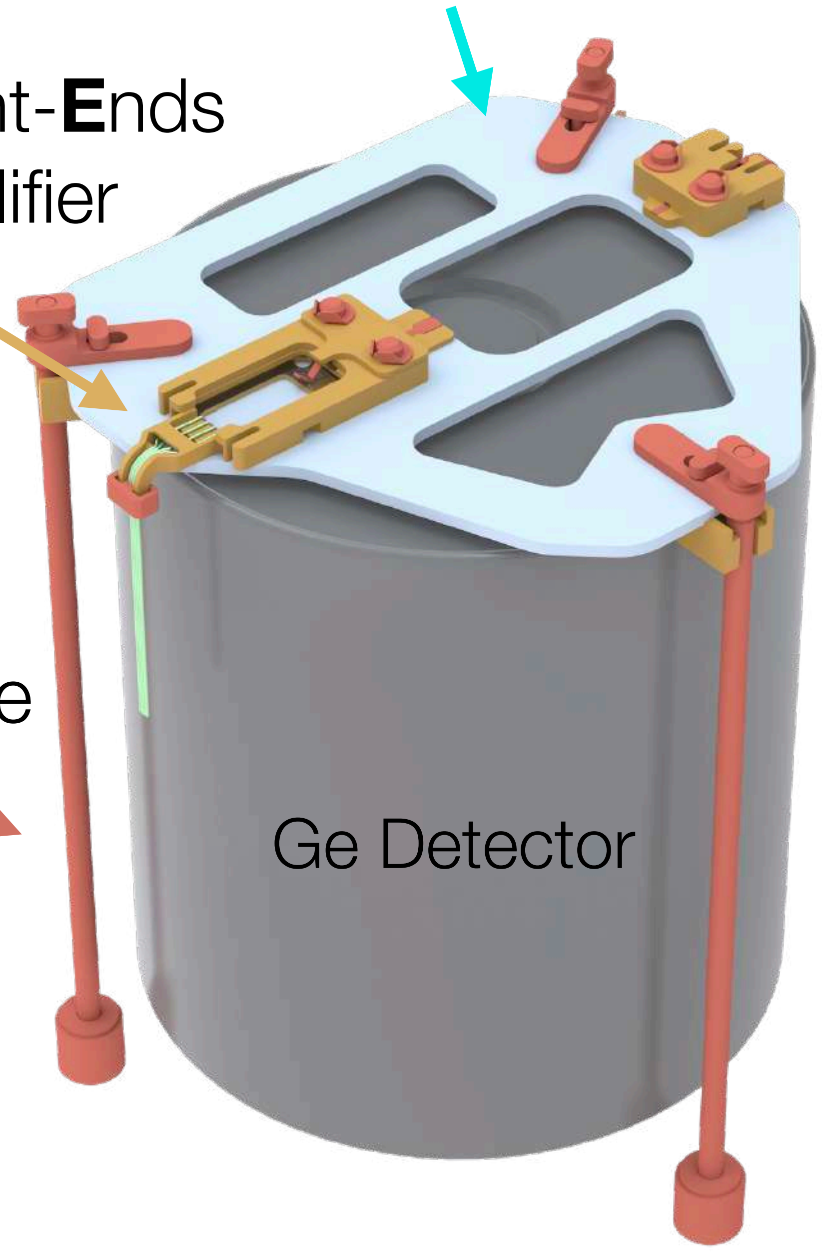
LEGEND-200 Experiment Overview

Ge Detector Unit:

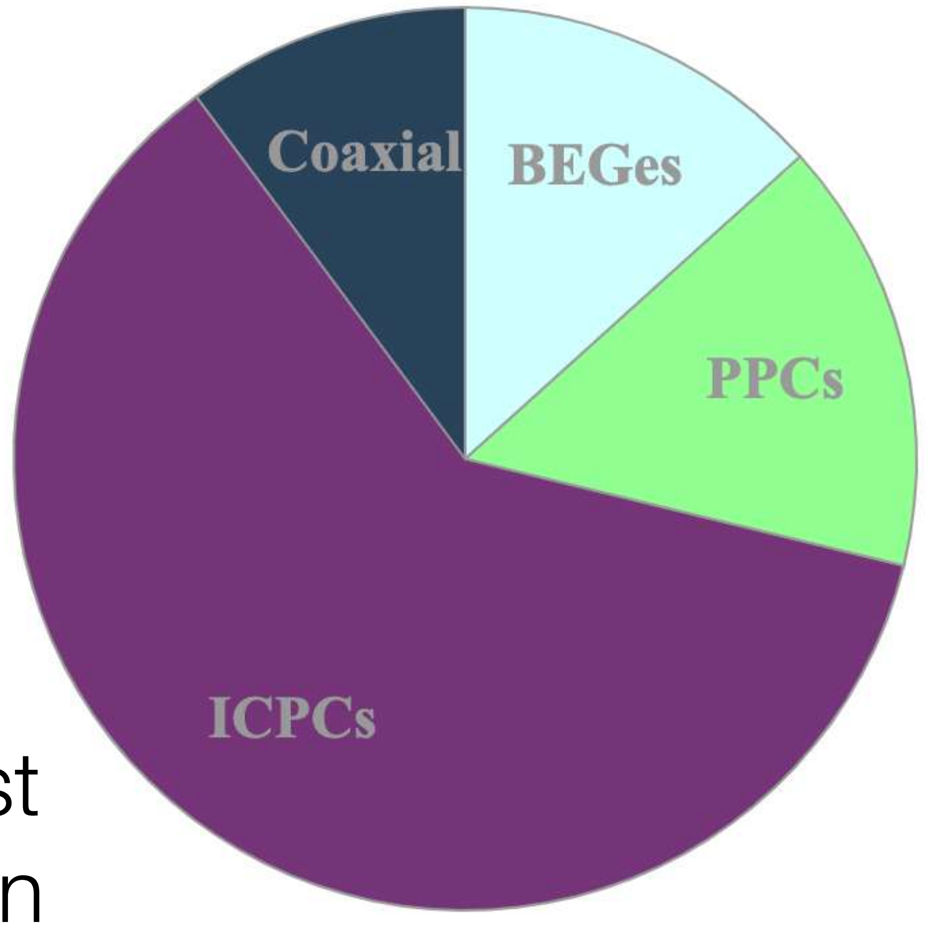
Poly**e**thylene **N**apthalate (PEN) baseplate

Low **M**ass **F**ront-**E**nds (LMFE) amplifier

Underground electro-formed copper structure



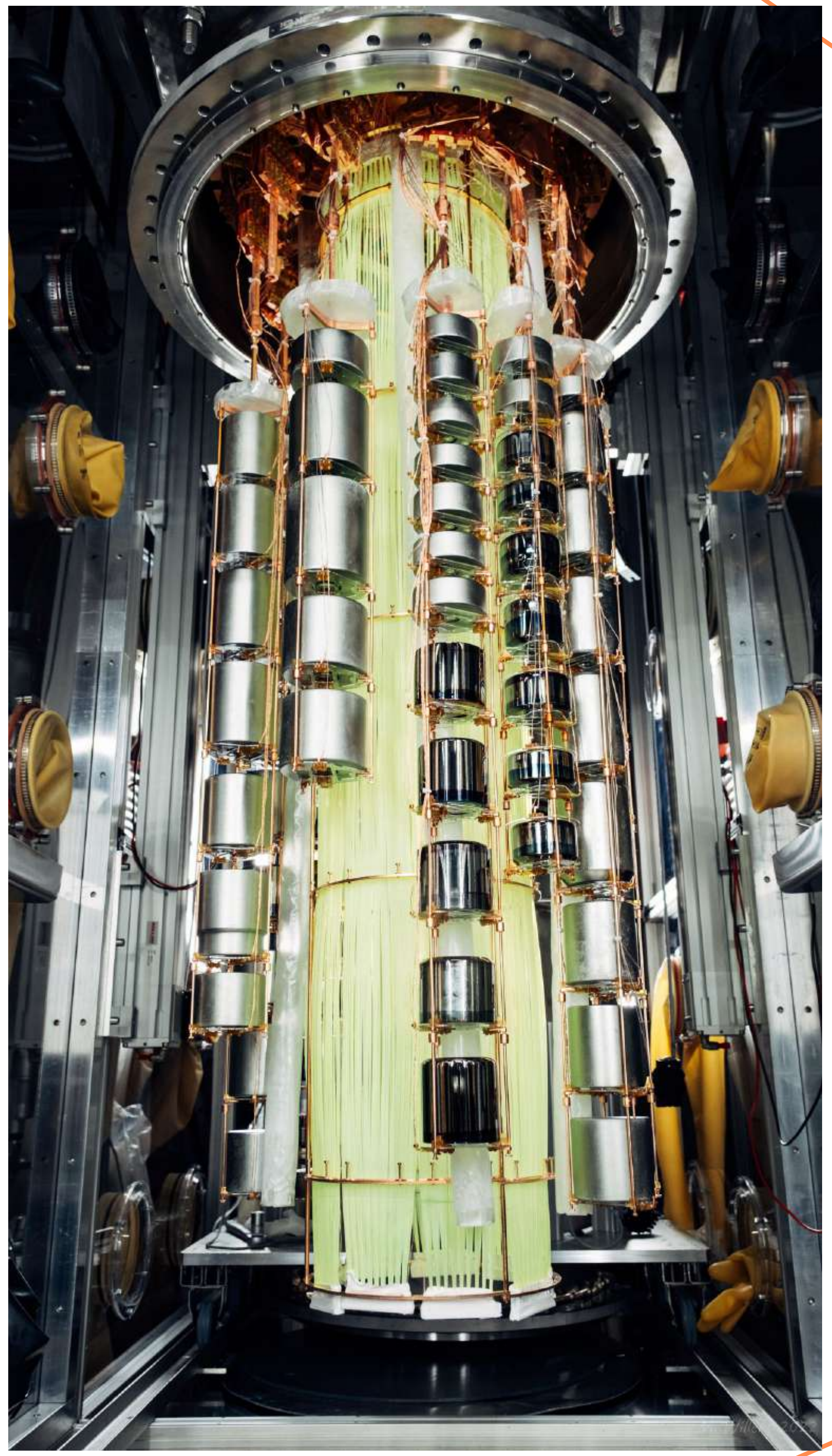
Inverted detector unit with an ICPC detector



Ge Detectors during 1st measurement campaign

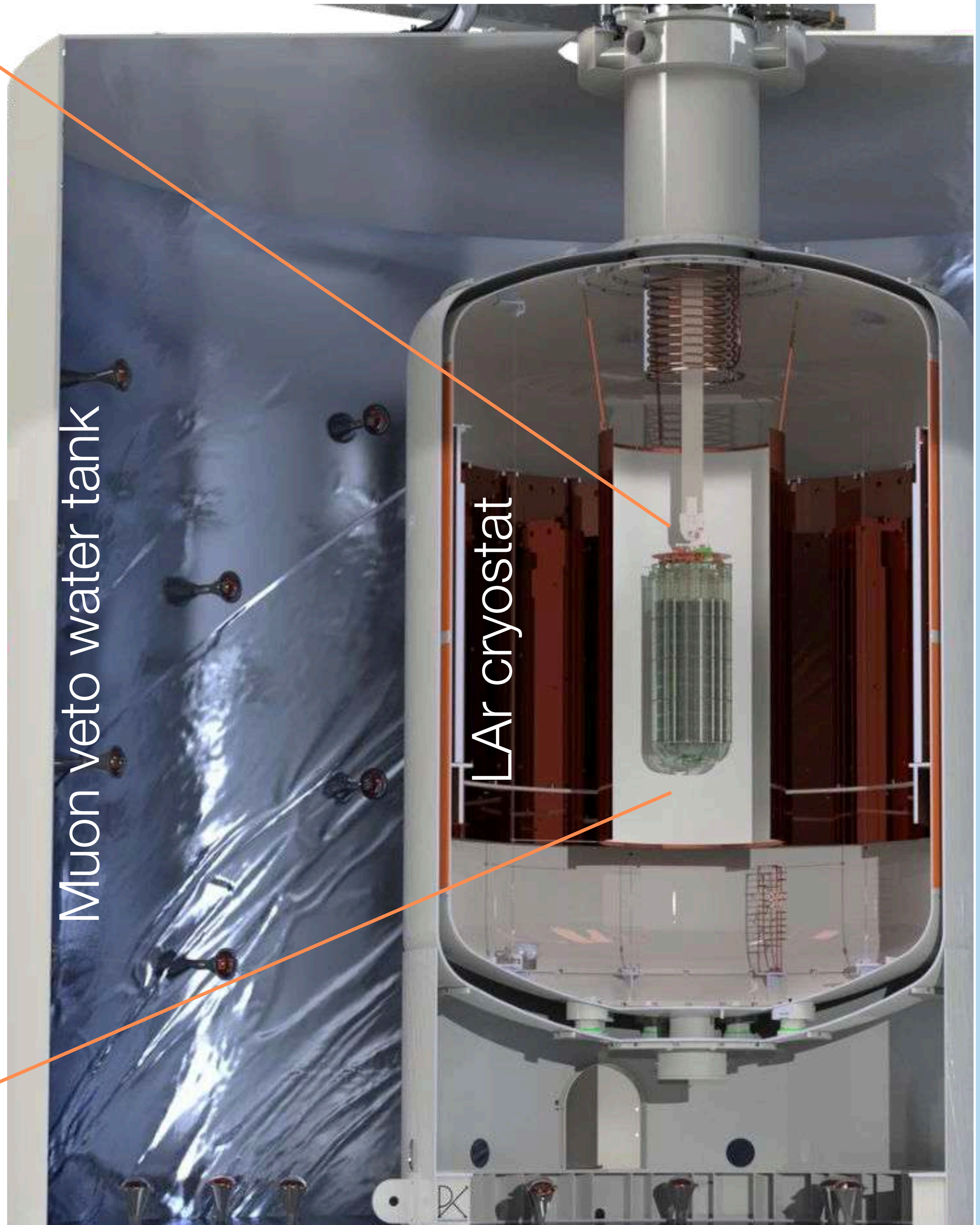
Ge Array and LAr instrumentation:

- Inner barrel of fiber shroud for LAr instrumentation
- 12 String locations
- Outer fiber shroud installed after detectors (not yet installed in photo.)



Infrastructure:

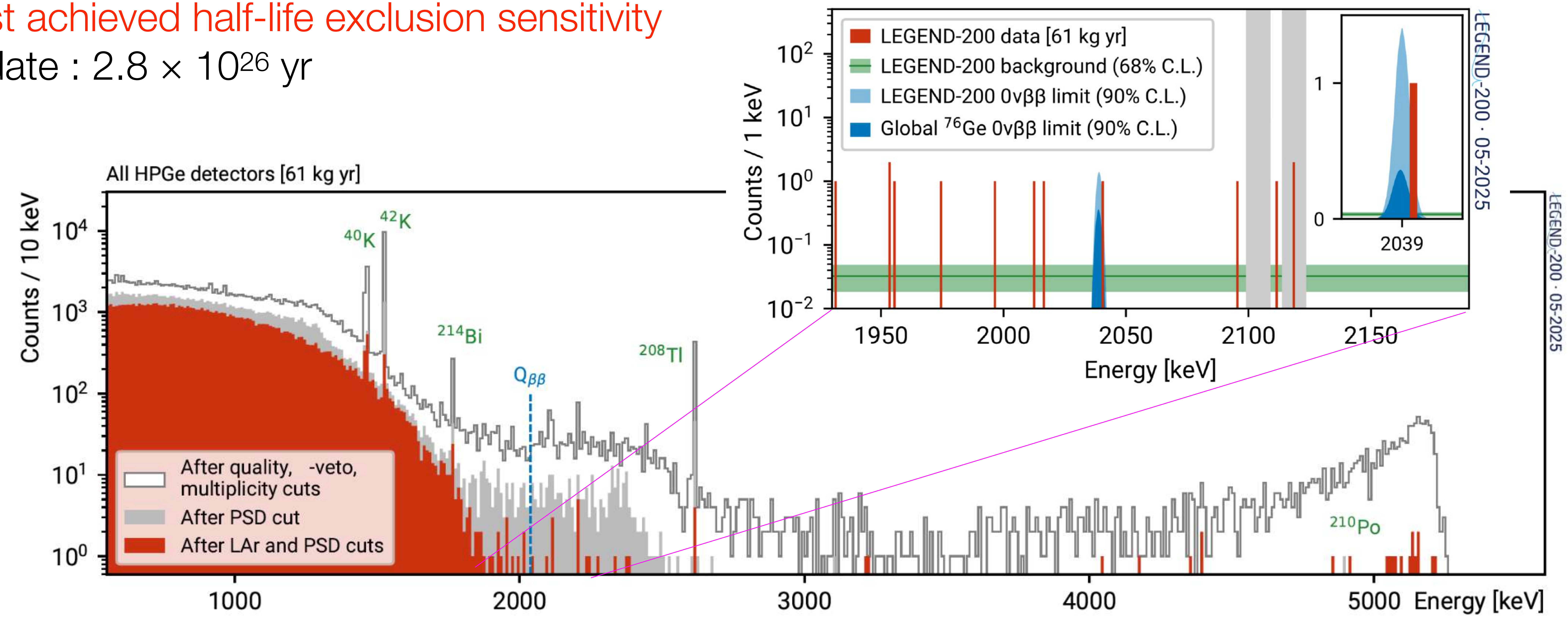
- LAr cryostat with wavelength shifting fibers
- LAr purification and quality monitoring
- Water tank equipped with PMTs for muon veto



LEGEND-200 First Results

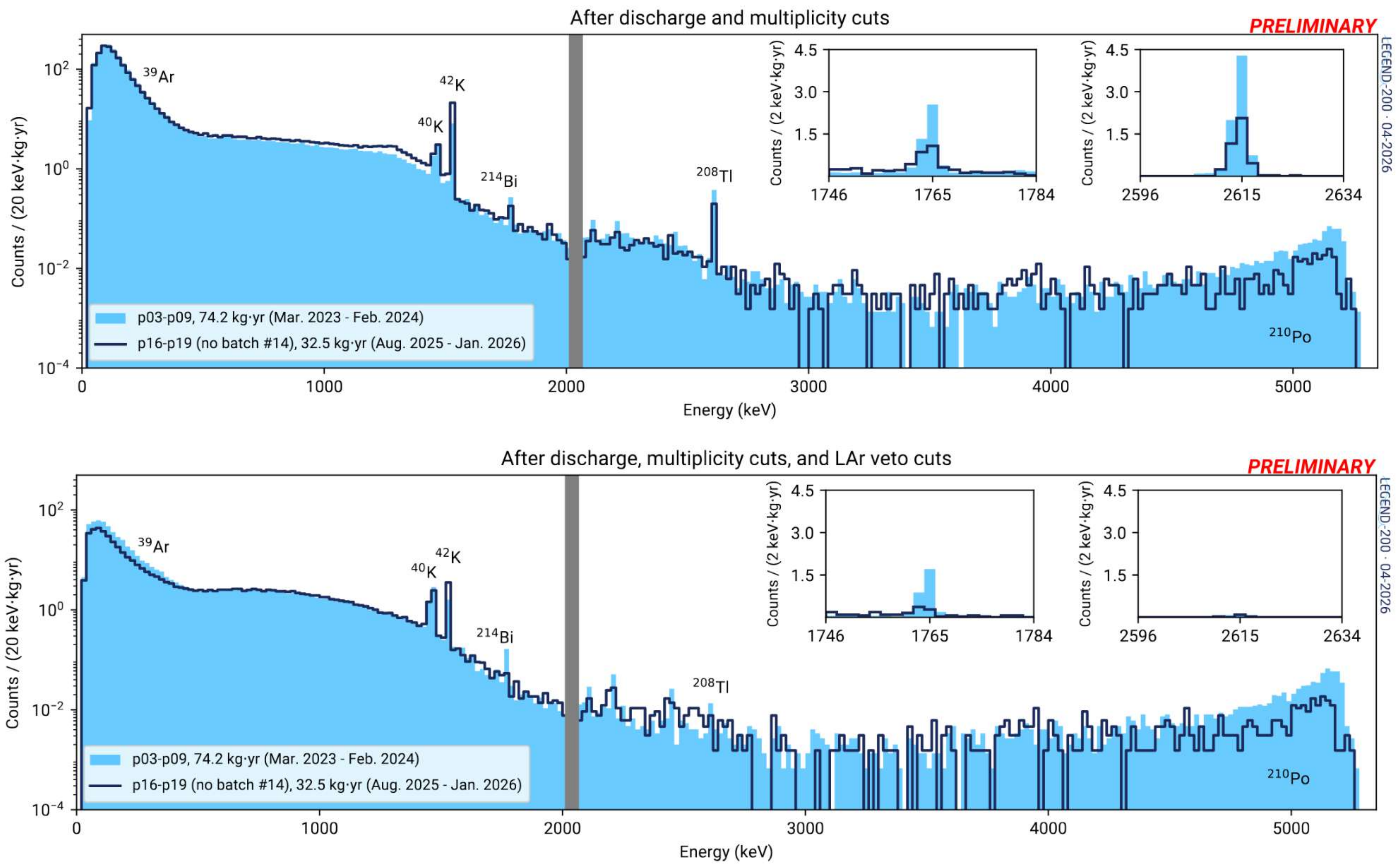
PRL **136**, 022701, (2026)

- Best achieved energy resolution (0.12% FWHM at $Q_{\beta\beta}$): HPGe instrumented with low-noise electronics
- 61 kg yr exposure; 11 events after cuts, including 1 event near Qββ (BI = $5.4^{+2.7}_{-2.0} \times 10^{-4}$ cts/(keV kg yr))
- Lowest achieved ROI background (1.4 cts/FWHM t yr): radiopure materials, strong suppression via LAr anti-coincidence and pulse-shape discrimination
- GERDA + MJD + LEGEND-200 combined: $T_{1/2} > 1.9 \times 10^{26}$ yr (90% CL)
- Best achieved half-life exclusion sensitivity to date : 2.8×10^{26} yr



LEGEND-200 Background Performance

- 2026 PRL background index (BI) a factor of ~3 higher than design goal with an elevated U/Th levels in pre-cuts spectrum
- Embarked on extensive forensic assay campaign, including in-situ (with array partially disassembled), followed by full disassembly with radioassay, ICP-MS, radon emanation component measurements.
- 2025 redeployment
  - New components produced
  - All components thoroughly cleaned with QC verification
  - Decision to remove smaller mass and coax detectors
  - With added new detectors: 140 kg

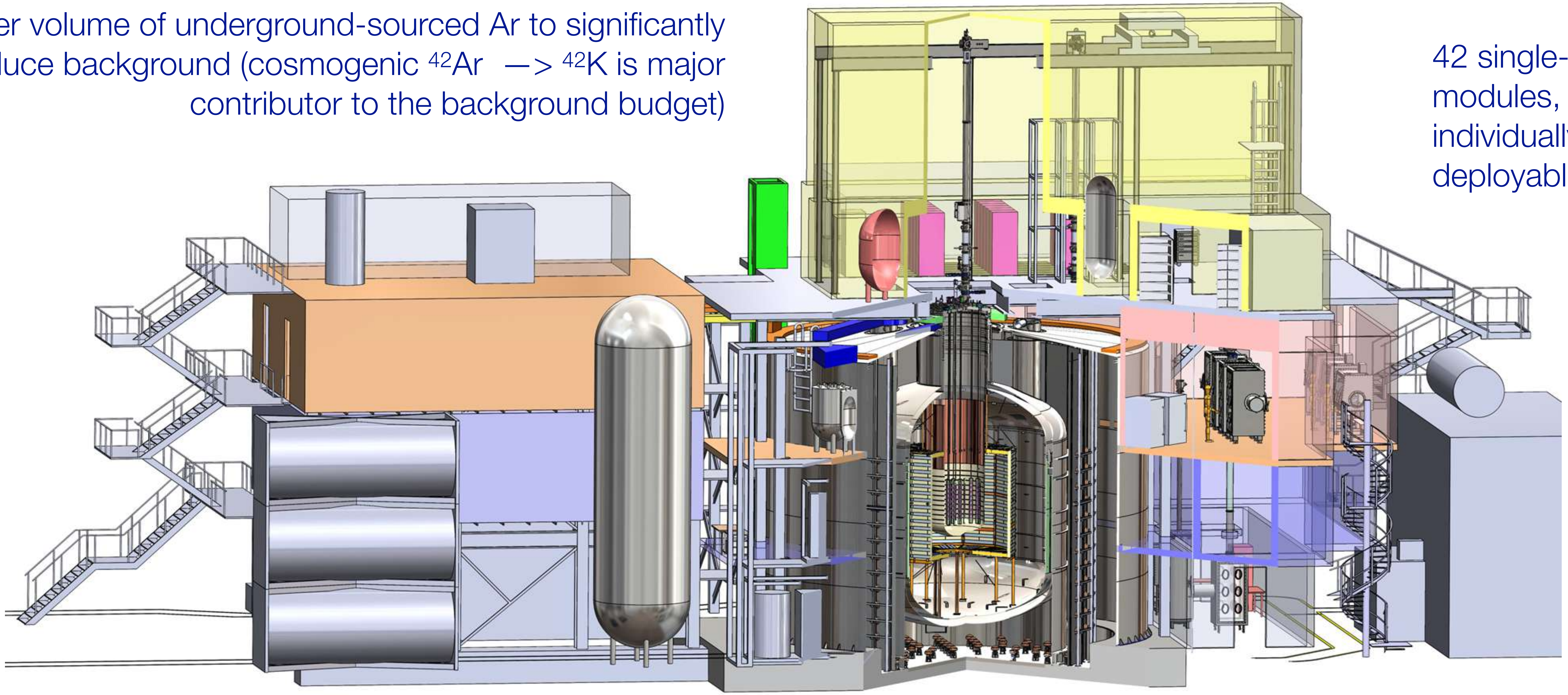


- U/Th lines suppressed by ~x2 before cuts relative to PRL dataset.
- After LAr cuts:
  - U suppressed by ~x4
  - Th ~eliminated at current stats
- Updated background index measurement in preparation

LEGEND-1000 Experiment Overview

- Mass: 1 ton of 90% enriched inverted coax detectors (~3 kg per detector)
  - Major challenge : market restrictions on obtaining ^{nat}Ge
- Background goal : 50x lower than achieved in LEGEND-200 (2026 PRL)
- Improved noise performance: ASIC-based readout, mounted very close to the detectors

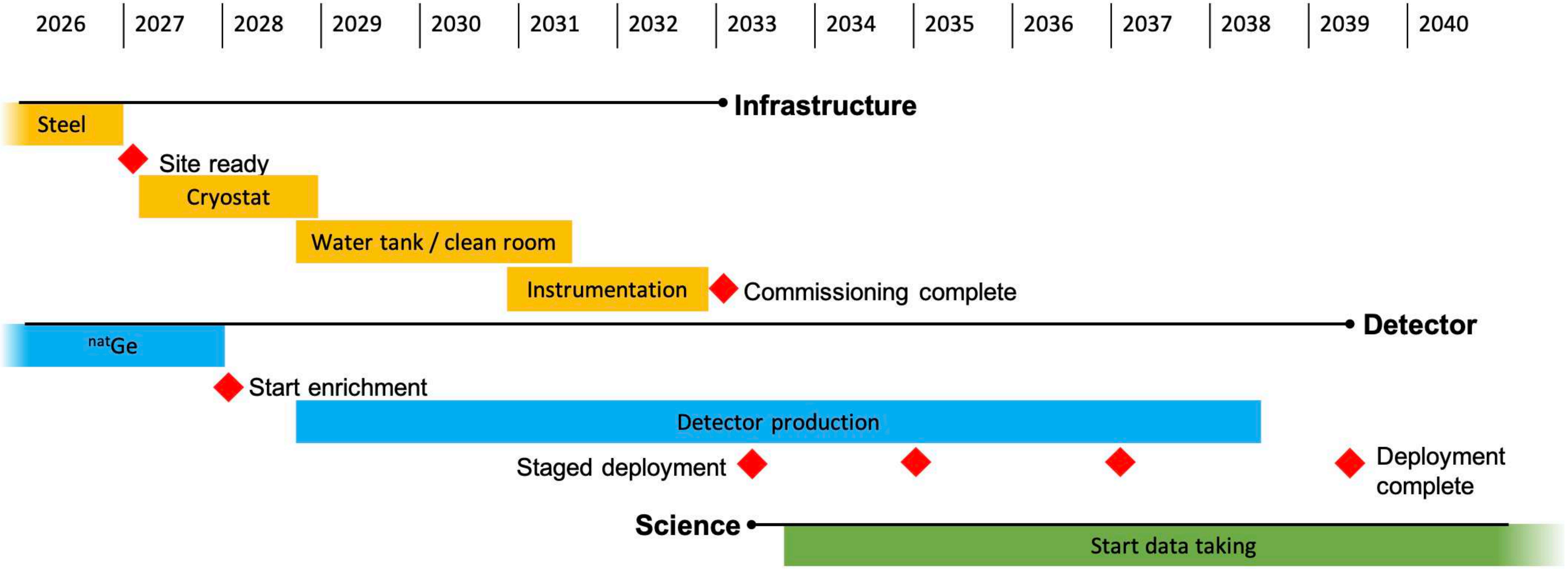
Inner volume of underground-sourced Ar to significantly reduce background (cosmogenic ^{42}Ar —> ^{42}K is major contributor to the background budget)



42 single-string modules, individually deployable

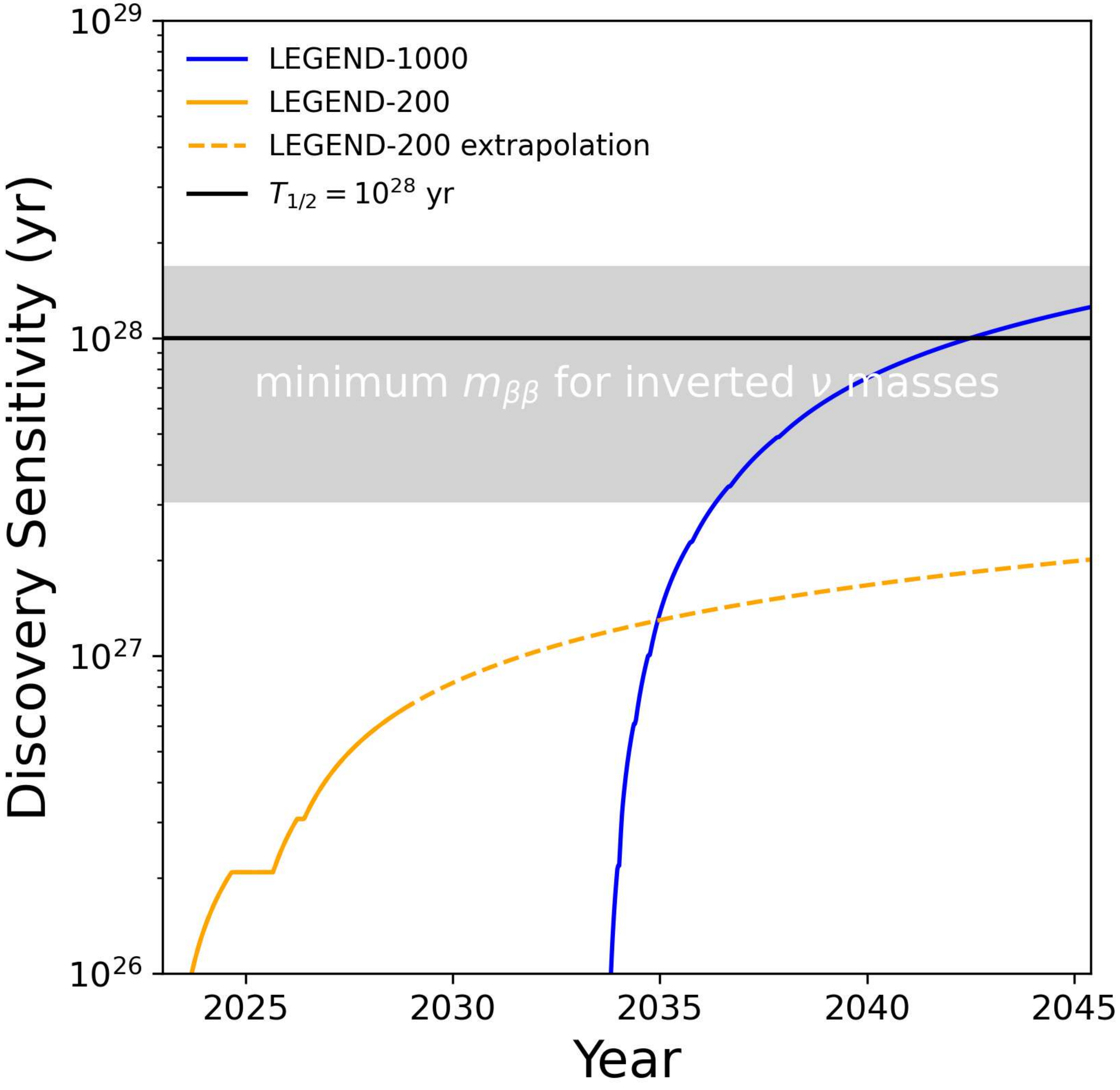
LEGEND-1000 Funding and Schedule

- Italy: LEGEND-1000 is an approved and supported experiment at LNGS, infrastructure preparation underway
- Germany: Germany: MPG approved funding for cryostat; LEGEND prioritized for BMFTR research infrastructure funding (FIS), site visit completed earlier this week (April 2026). Report expected in July.
- Poland, Switzerland: received initial funding, additional funding expected
- UK: proposal in preparation
- NSF: MREFC Final Design Funding awarded July 2025, final design review scheduled early 2027.
- DOE: successful CD1 Independent Project Review in November 2025, progress currently limited by anticipated funding



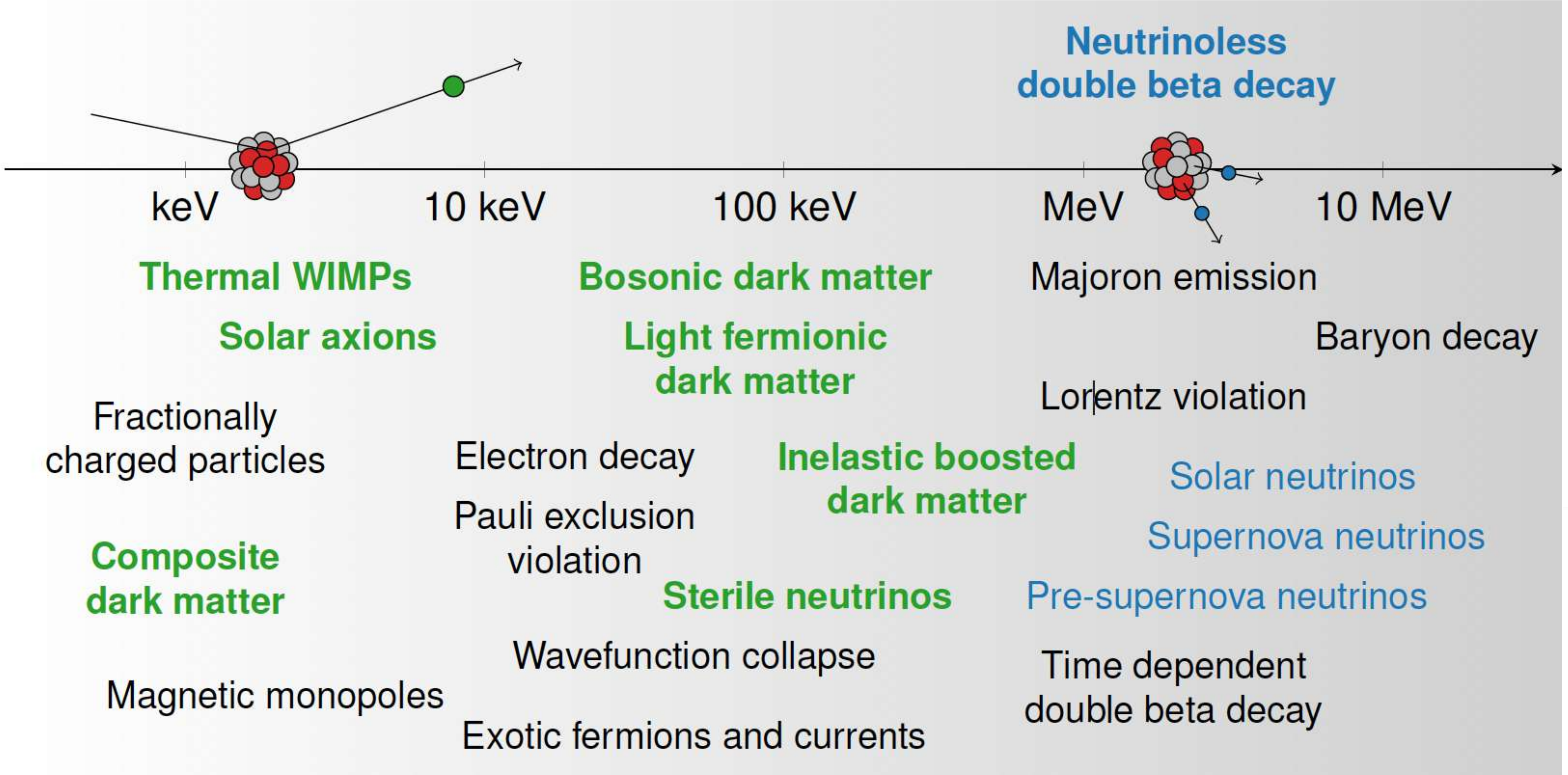
Summary and Outlook

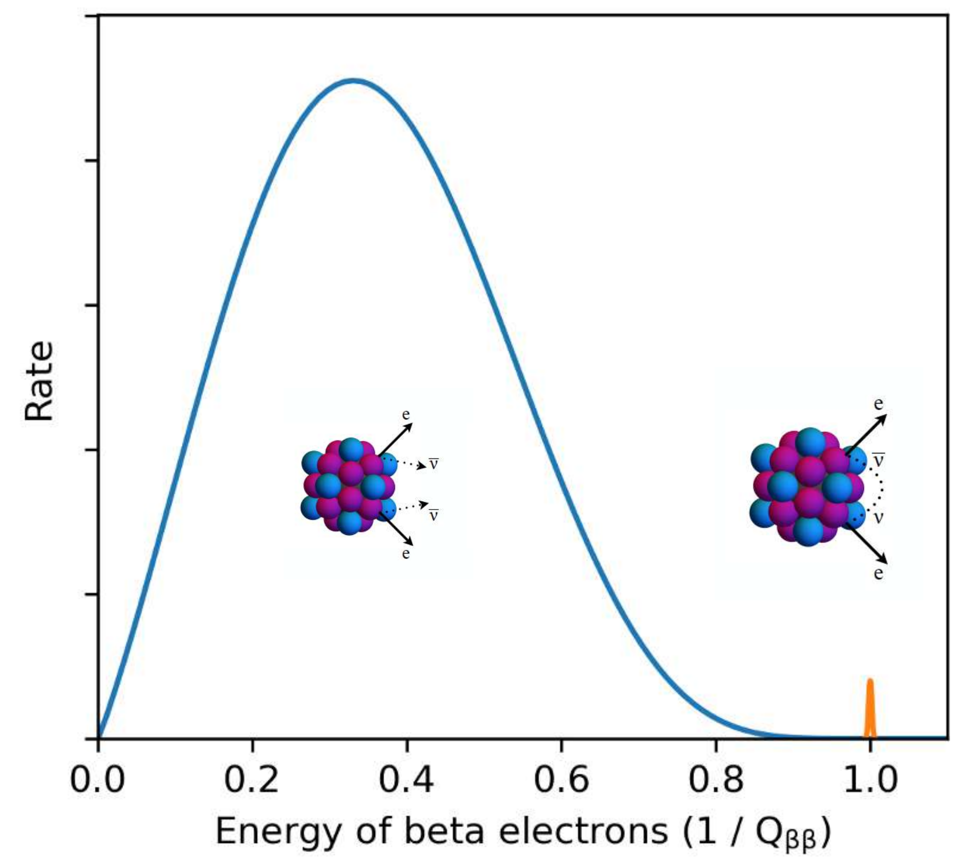
- Observing $0\nu\beta\beta$ would reveal the quantum nature of the neutrino and dramatically revise our foundational understanding of physics and the cosmos.
- Worldwide efforts are underway searching for $0\nu\beta\beta$ with $T_{1/2}$ of 10^{27} to 10^{28} years, covering the inverted ordering $m_{\beta\beta}$ region.
- Nuclear theory is progressing towards accurate NME computations with meaningful uncertainties.
- **LEGEND-200:** On track to collect 200 kg years within the next 2 yrs.
  - → New discovery sensitivity territory for $0\nu\beta\beta$!
- **LEGEND-1000:** Initial site preparation is underway. Some materials being procured and assayed. Good prospects for significant funding in 2027.



Backup

LEGEND-1000 research portfolio





In addition to searching for 0νββ, LEGEND-1000 will search for new physics via various channels including: neutrino physics (blue), searches for dark matter (green), and other beyond standard model phenomena (black). These signatures appear across a wide range of energies.