Experimental status and prospects in neutrinoless double beta decay

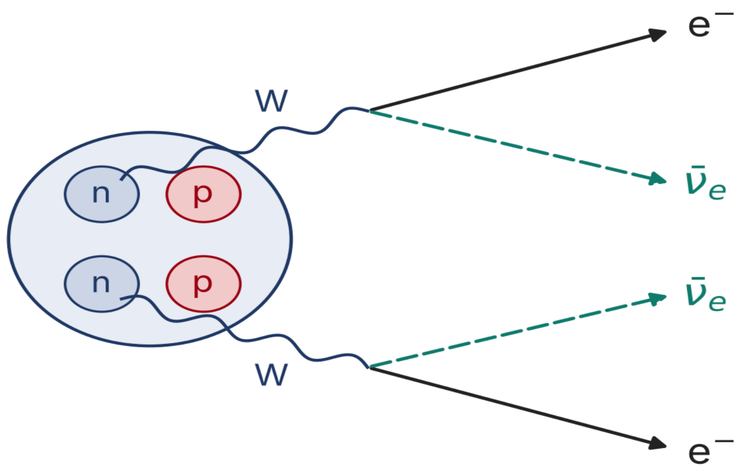
Eunju Jeon
CUP, Institute for Basic Science

NNN 2026 · Chung-Ang University · Oct 28, 2026

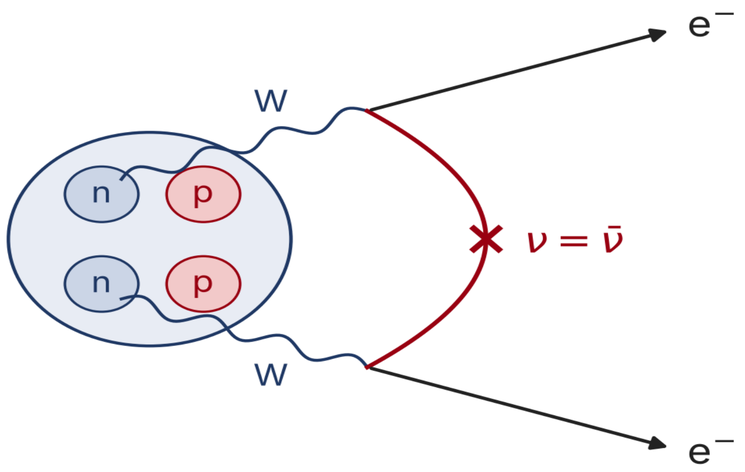
Double beta decay

In some even–even nuclei, single β decay is forbidden. Only ββ decay is possible, with energy $Q_{\beta\beta}$

$2\nu\beta\beta$ — allowed in the Standard Model



$0\nu\beta\beta$ — requires a Majorana neutrino



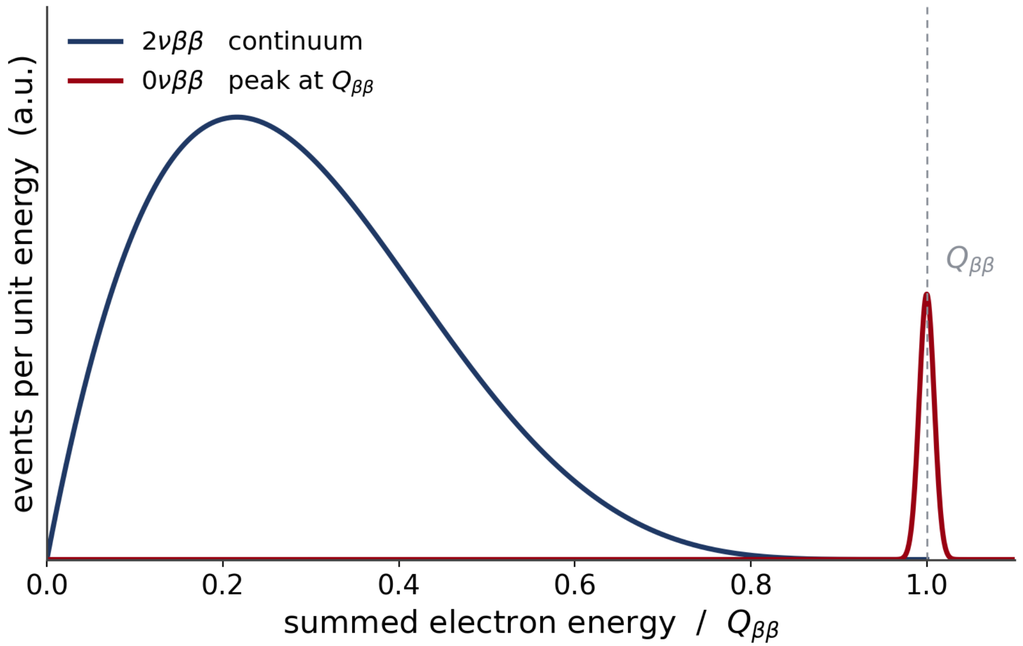
If 0νββ is observed, it means:

ΔL = 2
lepton number is not conserved

Majorana neutrino
the neutrino is its own antiparticle

Neutrino mass scale
$1/T_{1/2} \propto \langle m_{\beta\beta} \rangle^2$
(light Majorana-ν exchange)

From counts at $Q_{\beta\beta}$ to a neutrino mass



A detector measures the number of counts in a window around $Q_{\beta\beta}$

(1) counts → half-life

$$N = \ln 2 \cdot N_A \cdot (a/A) \cdot \varepsilon \cdot M{\cdot}T \;/\; T_{1/2}^{0\nu}$$

the signal you would expect

$$N_{up} = S_{up}(B), \quad B = b \cdot \Delta E \cdot M{\cdot}T$$

what the background still allows

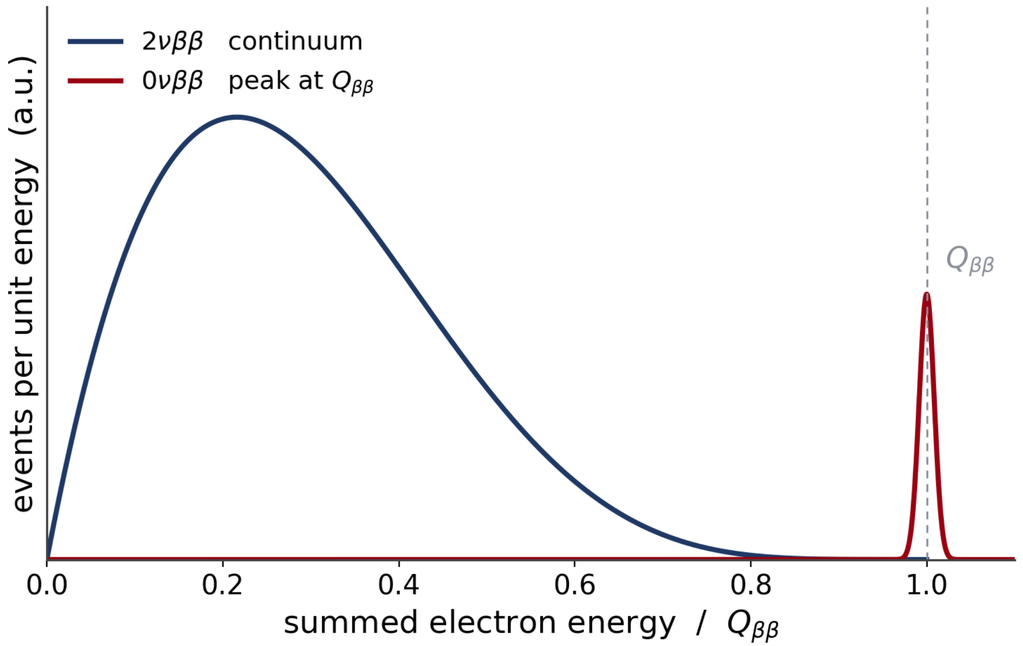
no excess ⇒ $N < N_{up}$ ⇒ *a lower limit on* $T_{1/2}^{0\nu}$

Zero background: S_{up} constant → $T_{1/2} \propto M{\cdot}T$

With background: $S_{up} \propto \sqrt{B}$ → $T_{1/2} \propto \sqrt{(M{\cdot}T)}$

More detector mass alone is not enough.

From counts at $Q_{\beta\beta}$ to a neutrino mass



A detector measures the number of counts in a window around $Q_{\beta\beta}$

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More detector mass alone is not enough.

(2) half-life → mass

$$[T_{1/2}^{0\nu}]^{-1} = G^{0\nu} \cdot |M^{0\nu}|^2 \cdot (\langle m_{\beta\beta} \rangle / m_e)^2$$

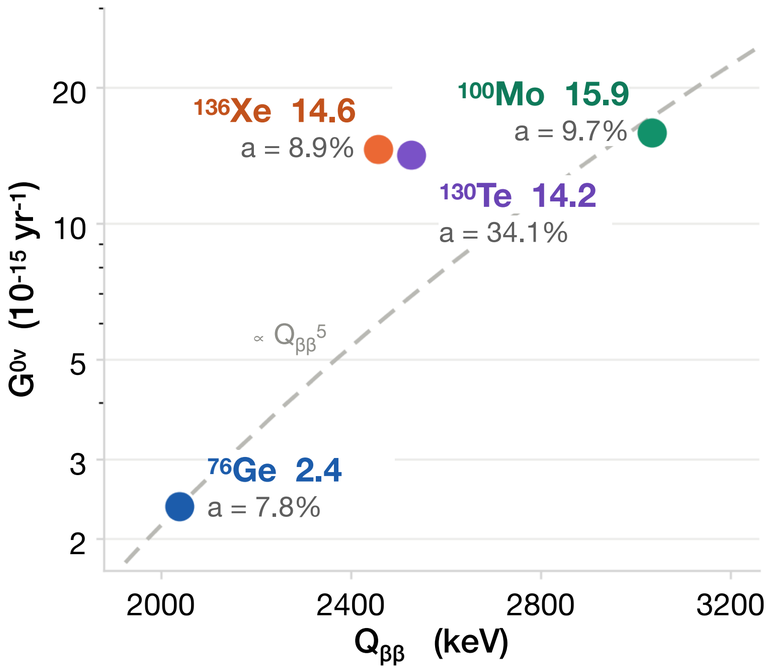
$M^{0\nu}$ is model dependent and enters squared ⇒ *one limit maps onto a range in* $\langle m_{\beta\beta} \rangle$

What the isotope sets: $Q_{\beta\beta}$, $G^{0\nu}$, $M^{0\nu}$

$$[T_{1/2}^{0\nu}]^{-1} = G^{0\nu} \cdot |M^{0\nu}|^2 \cdot (\langle m_{\beta\beta} \rangle / m_e)^2$$

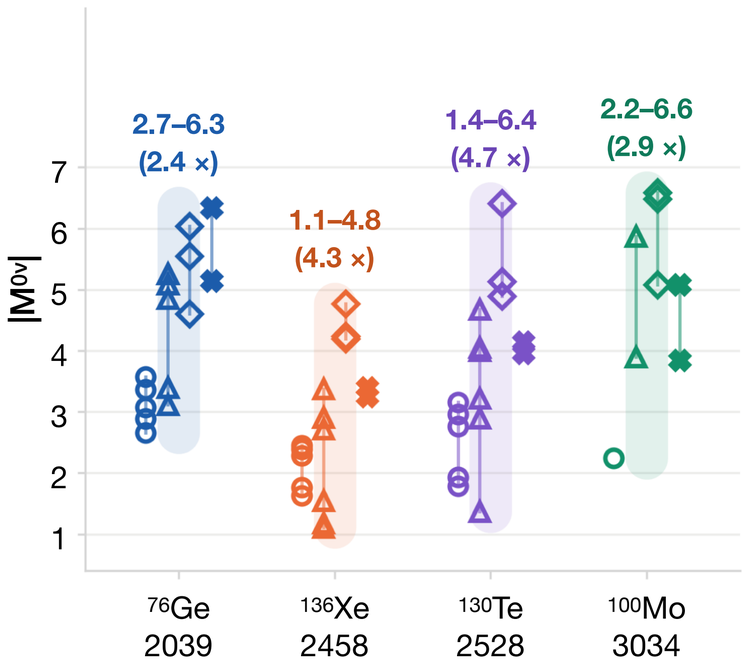
① phase space $G^{0\nu}$

well known — kinematics + Coulomb (Z)



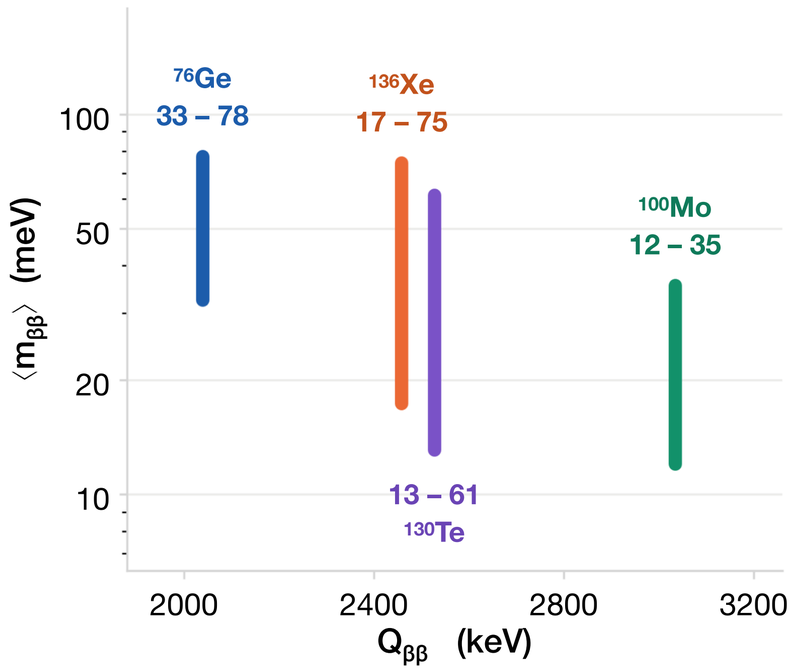
② nuclear matrix element $|M^{0\nu}|$

NSM QRPA EDF IBM



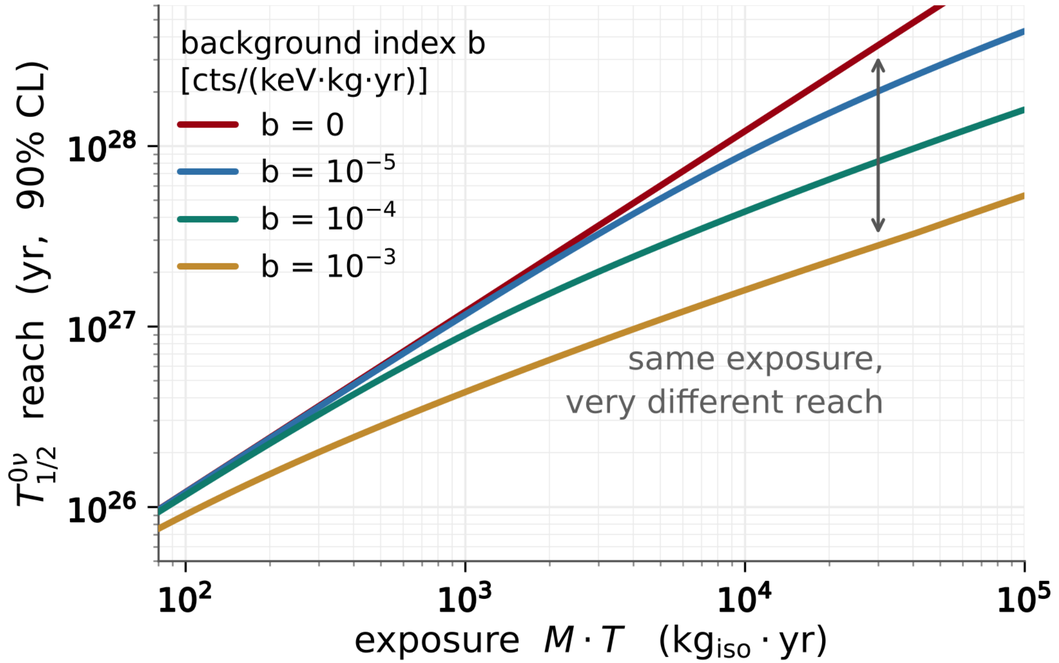
③ the two combined

$\langle m_{\beta\beta} \rangle$ at the same $T_{1/2} = 10^{27}$ yr



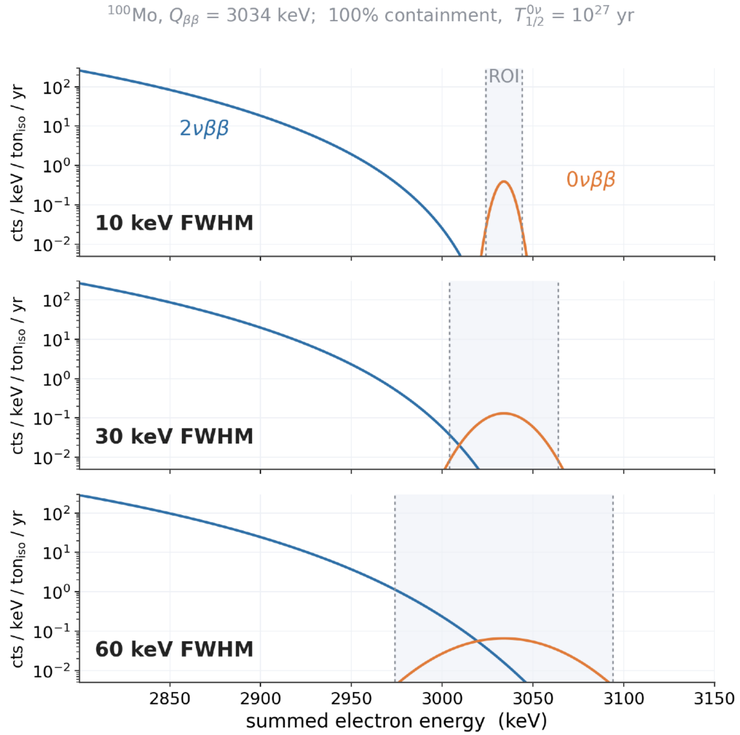
What the experiment sets: exposure and background

① exposure M · T



Exposure is not enough; the background sets the slope. With zero background, $T_{1/2}$ grows as M·T. With background, it grows only as √(M·T).

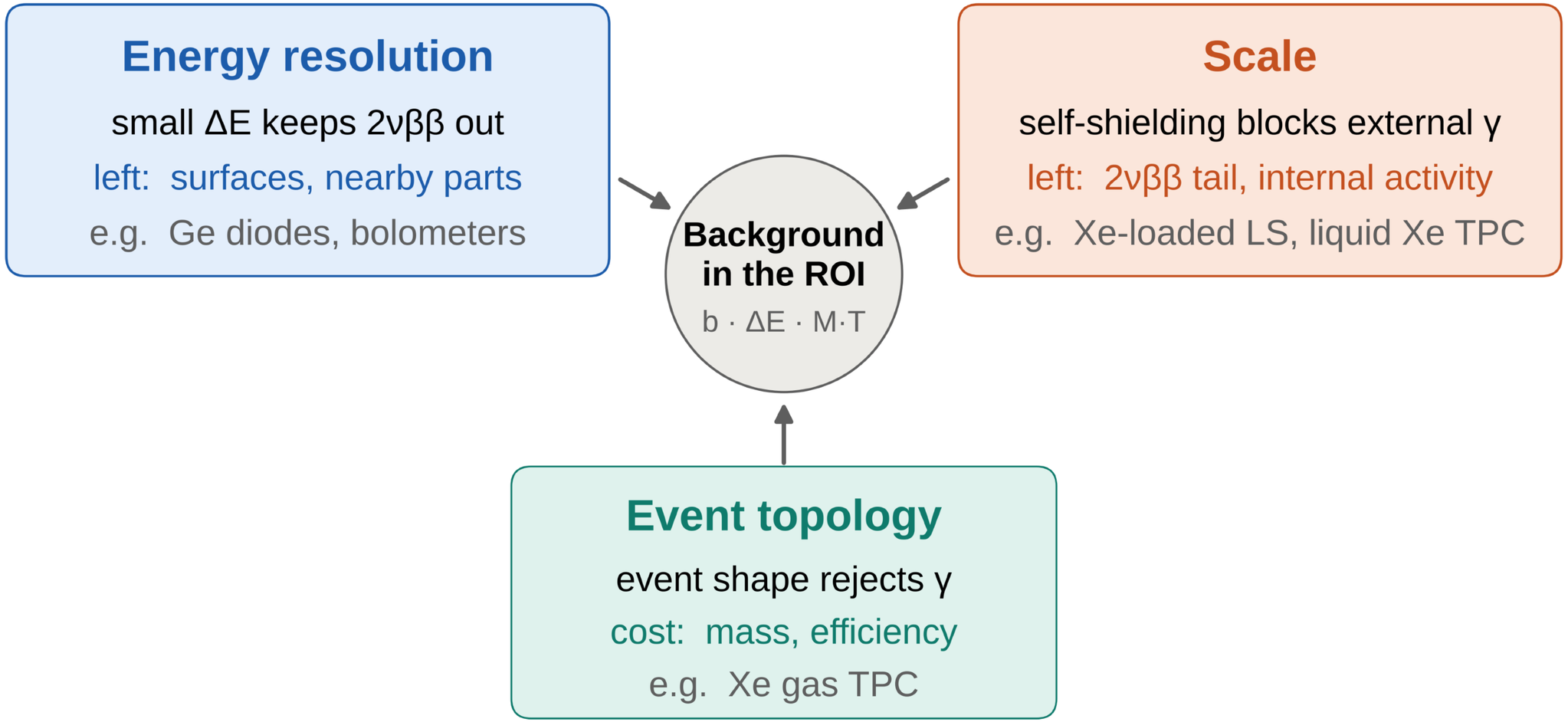
② background b · ΔE — resolution sets the 2νββ floor



Worse resolution widens both spectra. The 2νββ tail enters the ROI and the 0νββ peak becomes wider.

Shielding or clean materials cannot remove this 2νββ background. Only better resolution can.

Three ways to fight the background

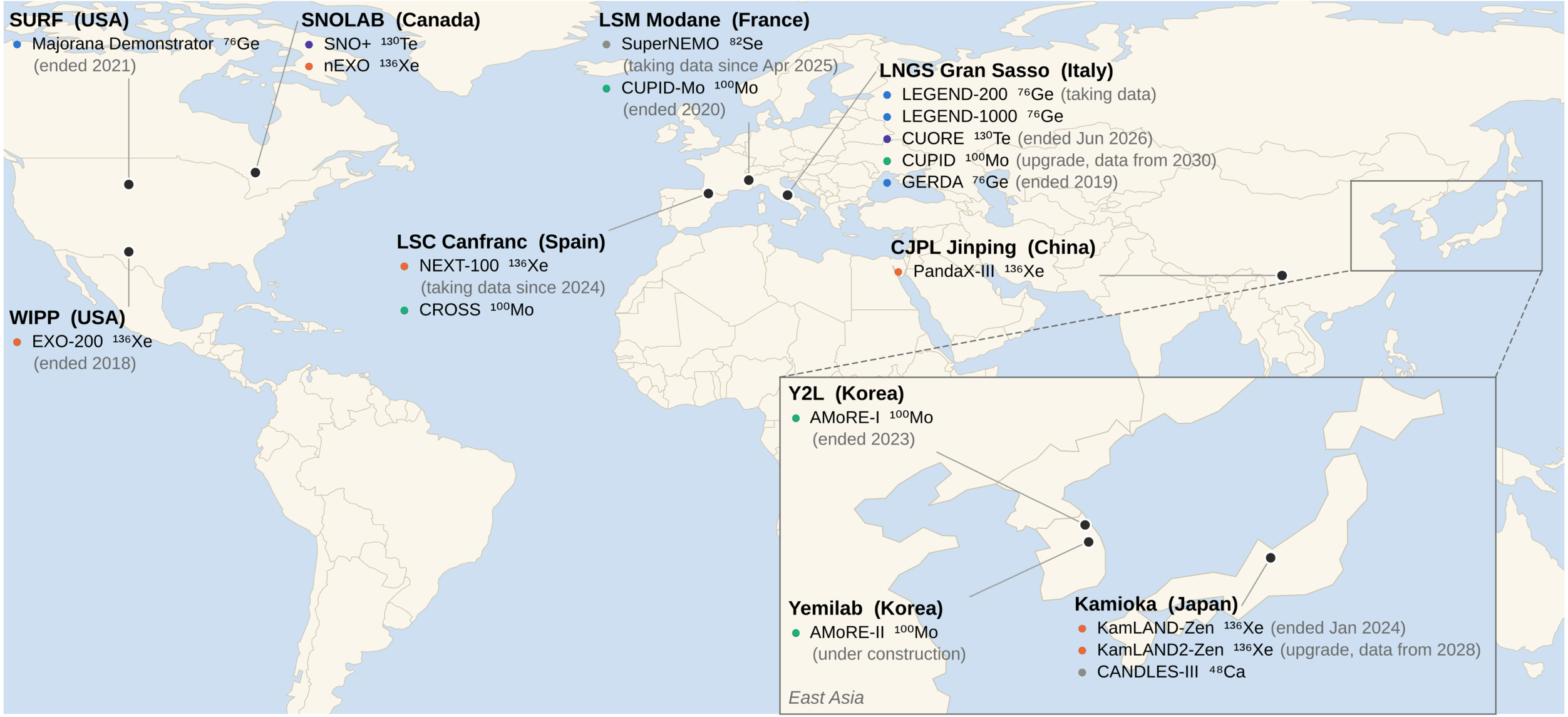


Experimental requirements lead to three design choices. Each collaboration chooses differently

Underground laboratories hosting 0νββ experiments

^{76}Ge ^{136}Xe ^{100}Mo ^{130}Te other (^{82}Se, ^{48}Ca)

colour = isotope · status in brackets, as of October 2026



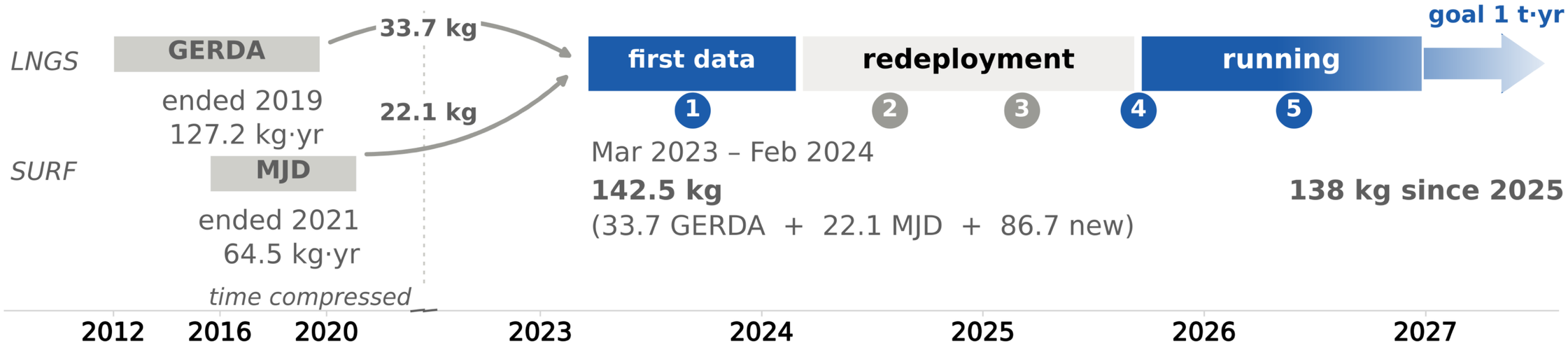
Isotopes and experiments

Covered here: energy resolution and scale

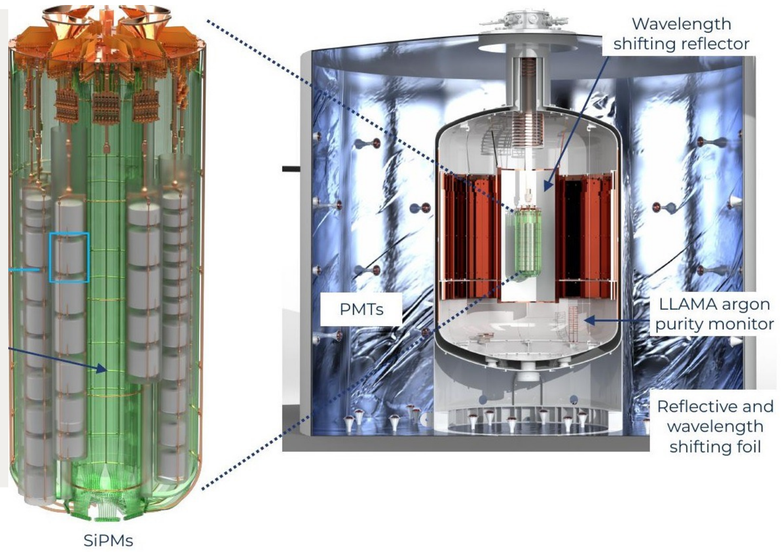
Isotope	$Q_{\beta\beta}$ (keV)	Detector technique	Experiments	$T_{1/2}$ limit (90% CL)
^{76}Ge	2039	HPGe, source = detector	**LEGEND-200 (running)** + legacy GERDA (ended 2019), MJD (ended 2021) → LEGEND-1000 (planned)	**> 1.9 × 10^{26} yr**
^{136}Xe	2458	Xe-loaded liquid scintillator	**KamLAND-Zen 400+800 (ended 2024)** → KamLAND2-Zen (in construction)	**> 3.8 × 10^{26} yr**
		Liquid Xe TPC	**EXO-200 (ended 2018)** → nEXO (R&D)	**> 3.5 × 10^{25} yr**
^{130}Te	2528	TeO_2 cryogenic bolometer	**CUORE (ended 2026)**	**> 3.5 × 10^{25} yr**
^{100}Mo	3034	Li_2MoO_4 bolometer + Ge light detector	**CUPID-Mo (demonstrator, ended 2020)** → CUPID (in construction) → CUPID-1T (R&D)	**> 1.8 × 10^{24} yr**
		$CaMoO_4$ / Li_2MoO_4 bolometer (MMC) + Ge/Si light detector (MMC)	**AMoRE-I (ended 2023)** → AMoRE-II (in construction, Yemilab)	**> 2.9 × 10^{24} yr**

Next-generation goal: $T_{1/2}$ ~ 10^{27} – 10^{28} yr

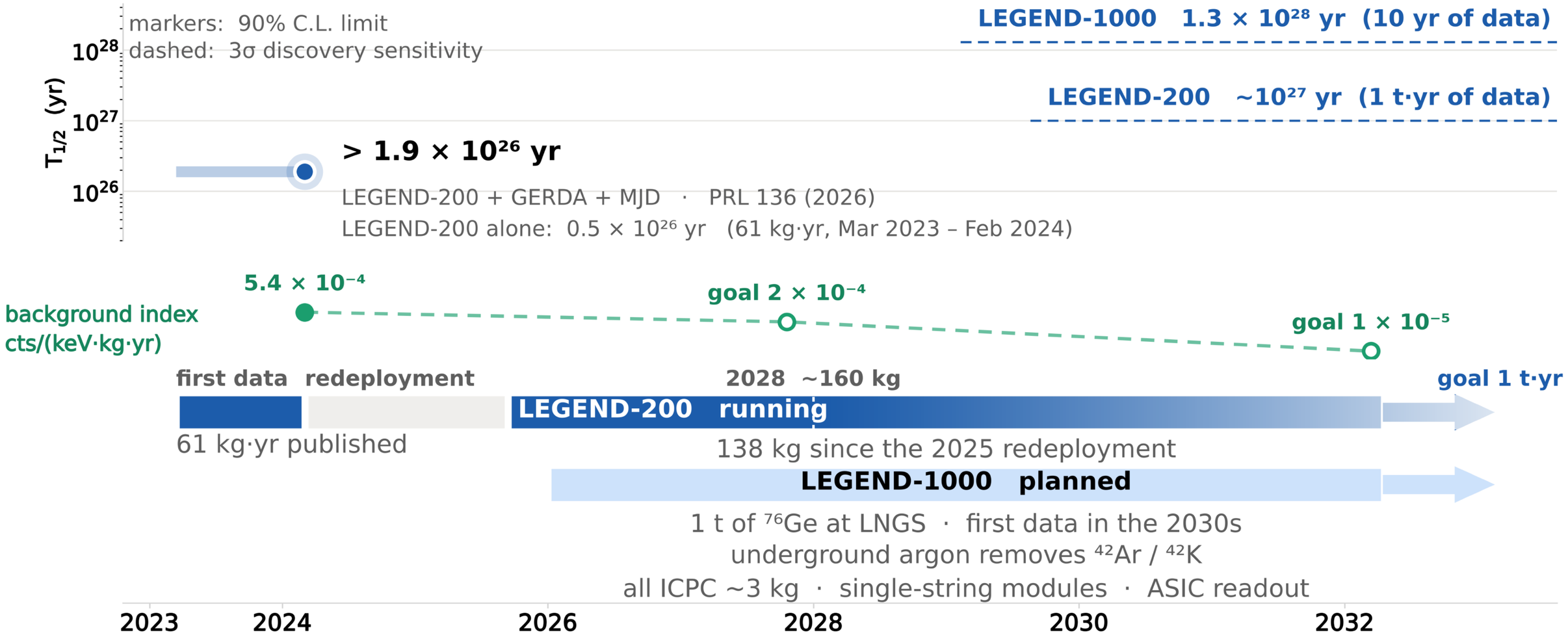
LEGEND-200



1. Background came out 2.5× above prediction
2. The array was taken out and every part was assayed
3. Surface U (^{214}Bi) and Th (^{208}Tl) found on some parts
4. July 2025: 138 kg redeployed, 94% ICPC, parts re-etched
5. ^{214}Bi and ^{208}Tl ~2× lower; running again since autumn 2025

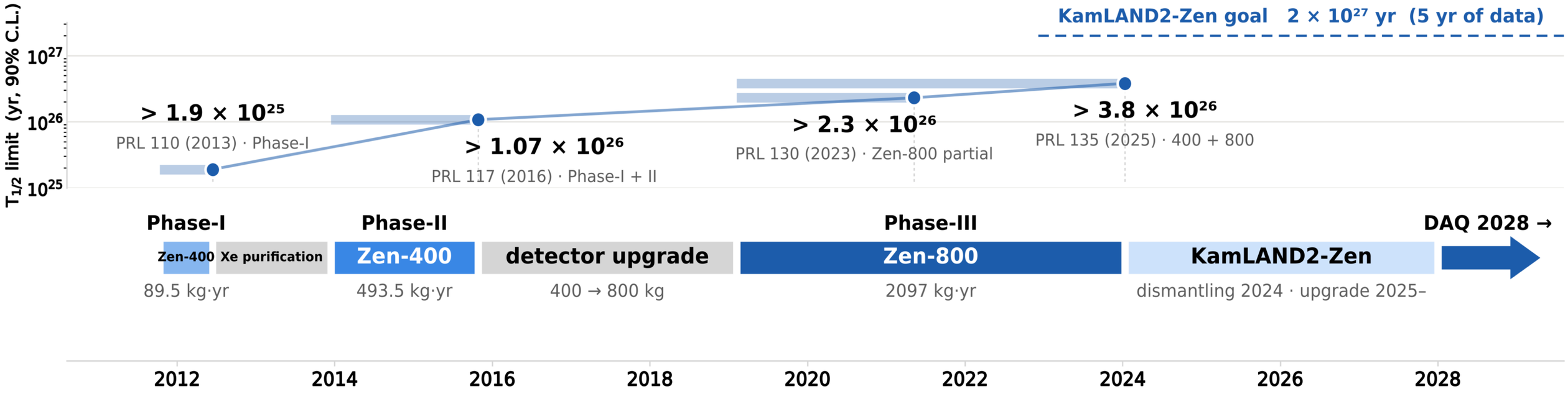


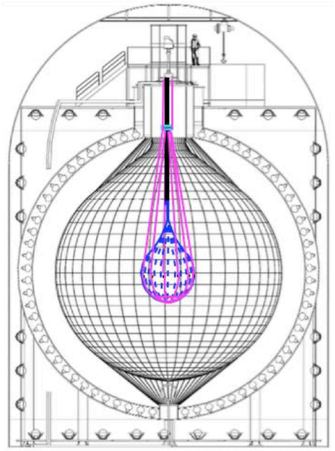
LEGEND-200 and LEGEND-1000

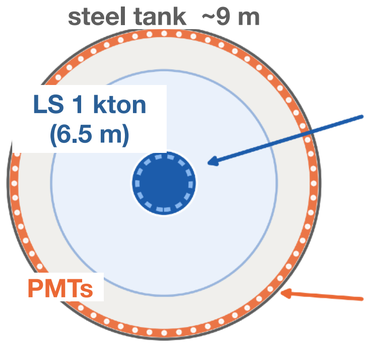


KamLAND-Zen

^{136}Xe exposure grew 23× (89.5 → 2097 kg·yr) while the limit grew 20× · "400" / "800" = kg of enriched xenon · bars = data-taking period behind each limit







KamLAND-Zen — what changes, and where

400 → 800 : only the central balloon grew

R 1.54 → 1.90 m Xe 320–380 → 745 kg (×2.0)

KamLAND2-Zen : the wall is rebuilt

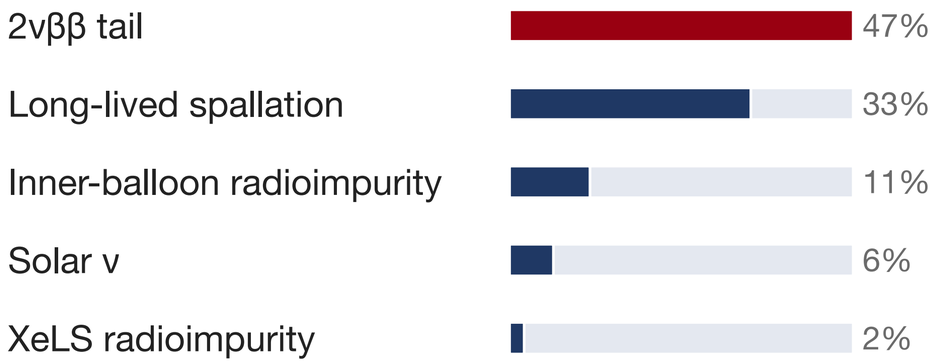
Winston cones + HQE PMTs + PEN balloon → 4% → 2%



KamLAND-Zen and KamLAND2-Zen

- 745 kg Xe (90.85% ^{136}Xe) in liquid scintillator; resolution ~4% at $Q_{\beta\beta}$
- **$T_{1/2} > 3.8 \times 10^{26}$ yr, $\langle m_{\beta\beta} \rangle < 28$–122 meV (PRL 135, 262501)**

ROI background breakdown



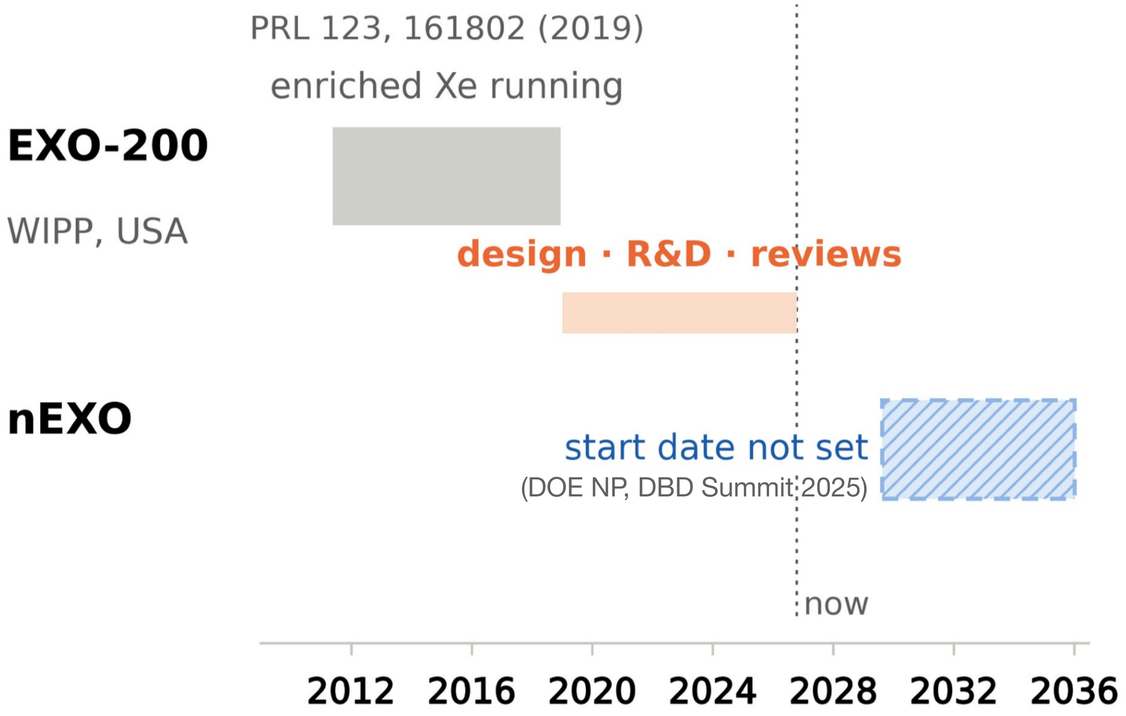
KamLAND2-Zen

same source, upgraded detector

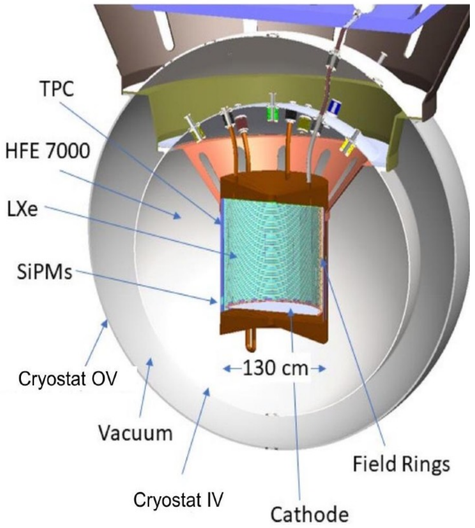
- 2vββ tail dominates (47%) → collect more light: resolution 4% → 2%
- Xe spallation (33%), balloon (11%) → better tagging, scintillating balloon
- $T_{1/2} \sim 2 \times 10^{27}$ yr, $\langle m_{\beta\beta} \rangle \sim 20$ meV in 5 yr (90% C.L.)
- Main DAQ from 2028

(Ö. Penek, Neutrino 2026 plenary)

nEXO



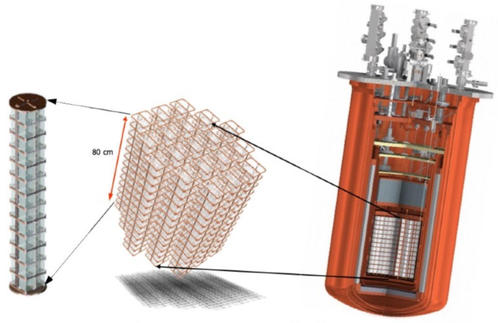
^{136}Xe mass	σ/E at $Q_{ββ}$	$T_{1/2}$ (90% C.L.)
175 kg LXe	1.2%	> 3.5 × 10^{25} yr 234.1 kg·yr BI 1.7–1.9 × 10^{-3} ckky
5000 kg (goal)	0.8% (design)	1.35 × 10^{28} yr 10-year run BI 1.5 × 10^{-6} ckky 3σ 0.74 × 10^{28} yr (J. Phys. G 49, 015104 (2022))

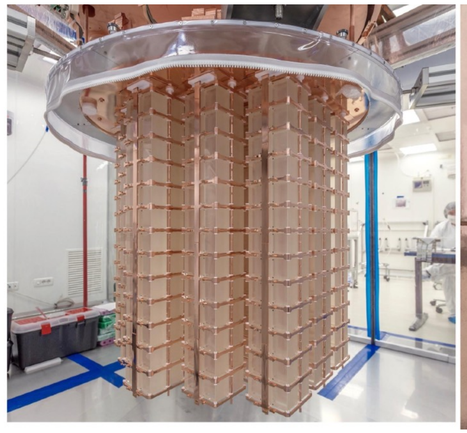


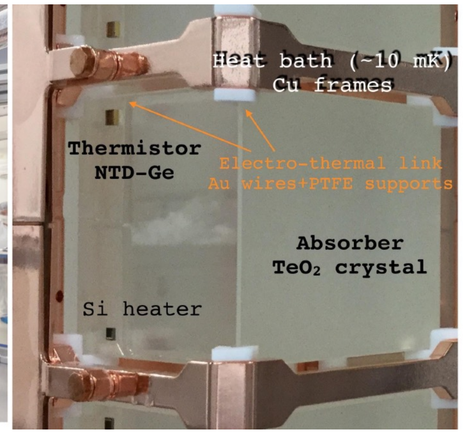
(CUP seminar 2026, G. Gratta)

CUORE

- 988 TeO_2 crystals (5×5×5 cm^3, 750 g) — 742 kg TeO_2, ~206 kg ^{130}Te, at LNGS (~3600 m.w.e.)
- ^{130}Te needs no enrichment: natural abundance 34%, $Q_{\beta\beta}$ = 2528 keV
- Operated from 2017; data taking completed 9 June 2026
  - > 99% active detectors, ~0.3% FWHM at $Q_{\beta\beta}$
- 3.37 t·yr TeO_2 accumulated; 2 t·yr analysed
- Also: the most precise ^{130}Te 2νββ half-life; spectral shape prefers SSD







(Neutrino 2026, M. Sisti)

$T_{1/2} > 3.5 \times 10^{25}$ yr

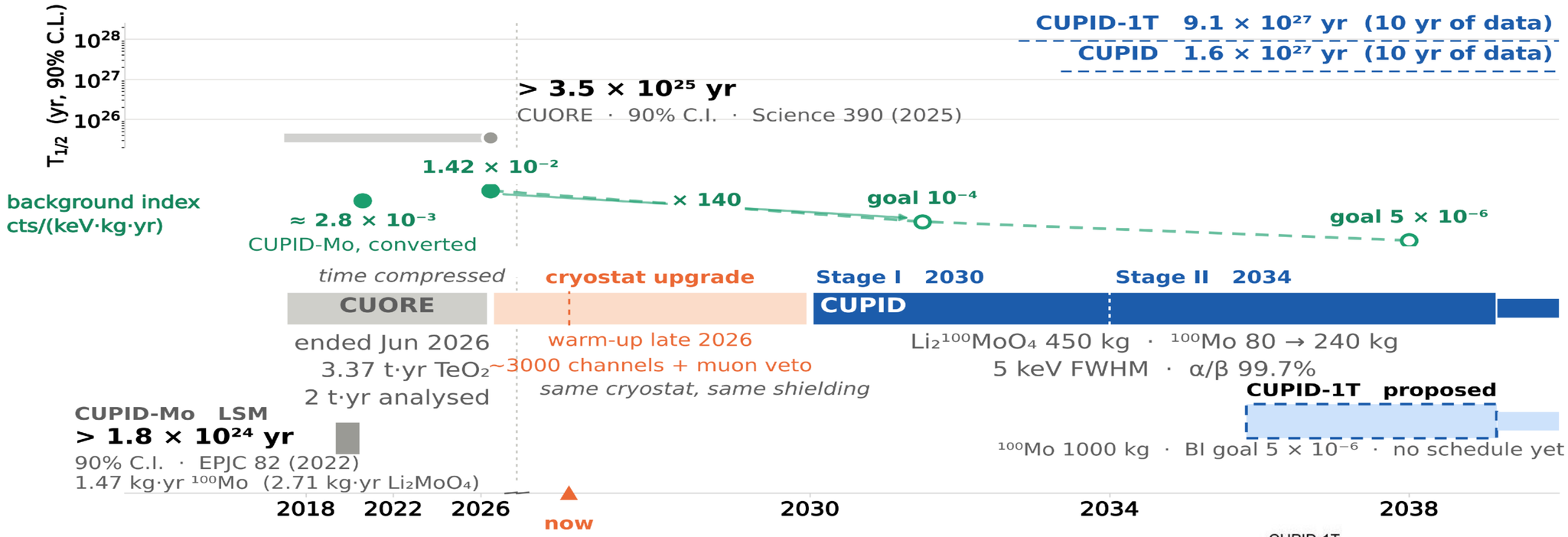
$\langle m_{\beta\beta} \rangle < 70–250$ meV

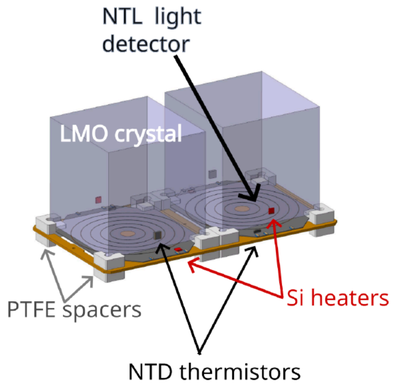
2 t·yr, 90% C.I.

CUORE operated a tonne-scale millikelvin detector stably for almost 10 years. This is the basis for the next bolometric experiments.

Limiting background: α events from nearby surfaces (~75% of ROI) → CUPID adds light readout

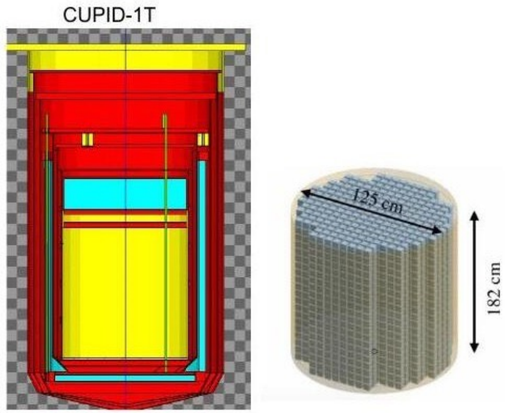
CUPID and CUPID-1T





(Neutrino 2026, M. Sisti)

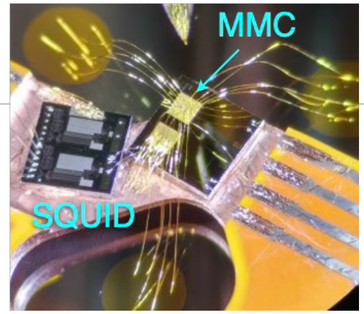
	CUPID	CUPID-1T
Detector mass	450 kg	1871 kg
^{100}Mo mass	240 kg	1000 kg
FWHM	5 keV	5 keV
BI [cts/(keV·kg·yr)]	10^{-4}	5×10^{-6}
$T_{1/2}$ discovery (3σ)	1×10^{27} yr	8×10^{27} yr
$\langle m_{\beta\beta} \rangle$ discovery (3σ)	12–35 meV	4.3–12.5 meV

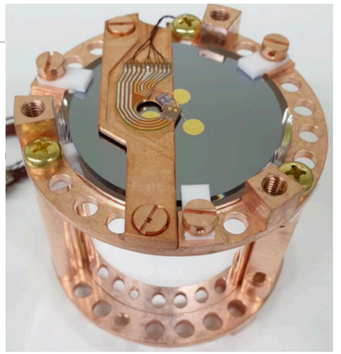


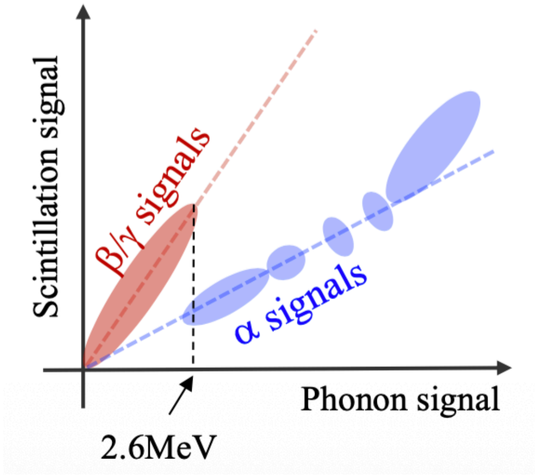
(Neutrino 2026 poster, P. Surukuchi)

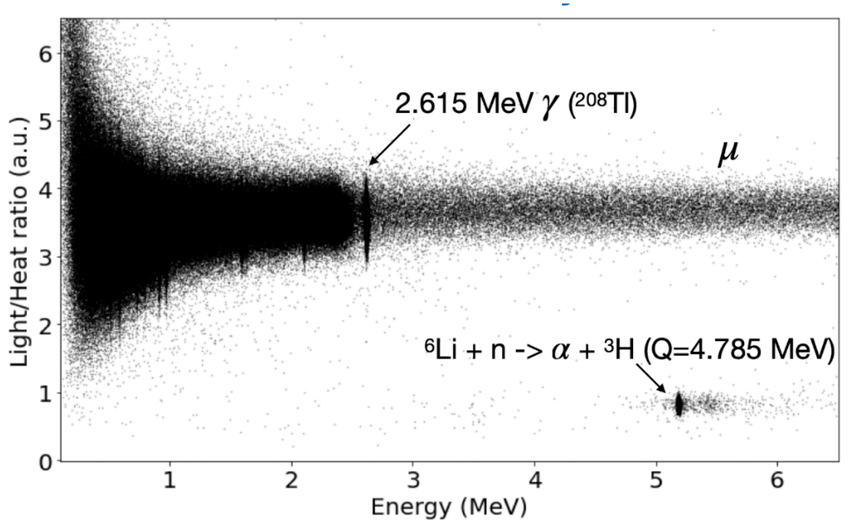
AMoRE

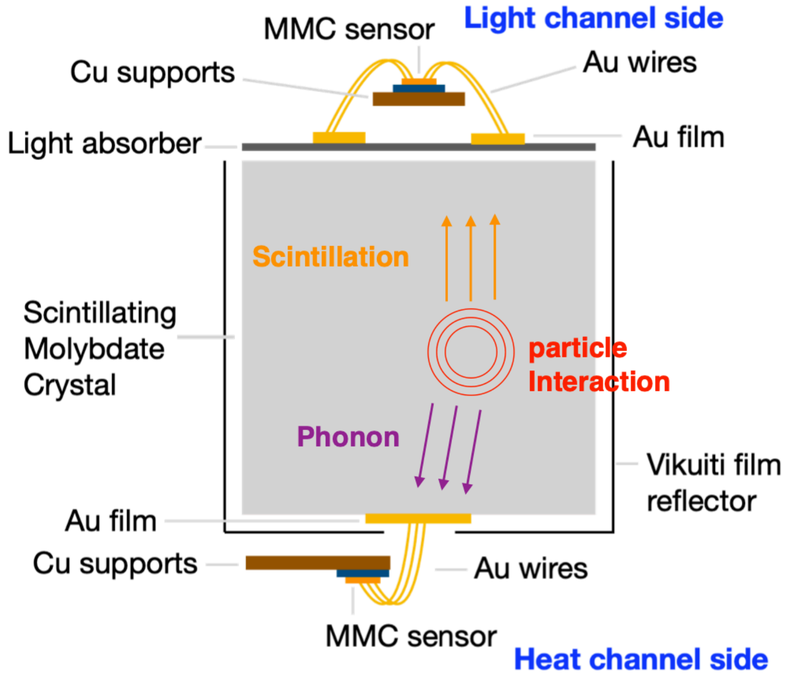
- **^{100}Mo: $Q_{\beta\beta}$ = 3034 keV — above the ^{208}Tl 2615 keV line; natural abundance 9.7%**
- **^{100}Mo based scintillating crystals**
  - $^{48depl}CaMoO_4$, Li_2MoO_4 with enrichment of ^{100}Mo ~95%
- Dual readout at millikelvin: heat + scintillation, both via MMC + SQUID sensors
  - Metallic Magnetic Calorimeter (MMC)
  - α discrimination; a different technology from CUPID (NTD + Ge light detectors)









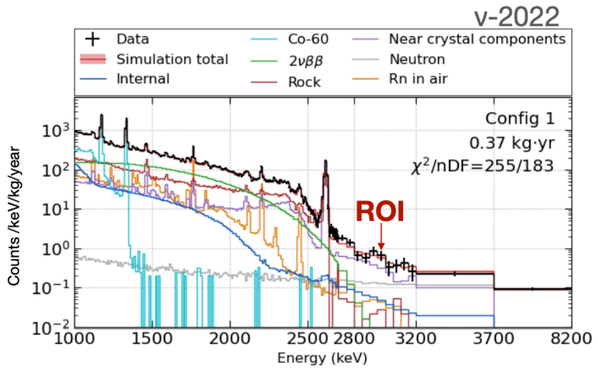


AMoRE-pilot

2015–2018



6 $^{48dep}CaMoO_4$ crystals:
1.9 (0.88) kg of CMO (^{100}Mo)
Yangyang Underground Lab
(Y2L, 700 m depth)



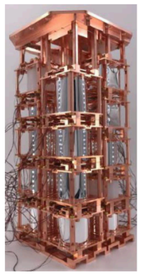
- Live exposure ~ 0.32 $kg_{Mo\text{-}100}$·yr.
- Background at ROI

  ~0.5 cnts/keV/kg/year.
- $T_{1/2}^{0\nu} > 3.2 \times 10^{23}$ yrs (90% CL)

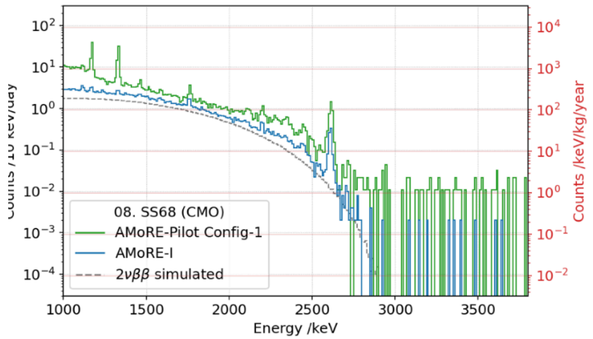
Astropart. Phys. 162 102991 (2024)
EPJC 79:791 (2019)

AMoRE-I

2020–2023



13 CMOs
+ 5 Li_2MoO_4 crystals :
6.2 (3.0) kg of XMO (^{100}Mo)
Y2L



- Live exposure ~ 4 $kg_{Mo\text{-}100}$·yr.
- Background at ROI~0.025 ckky.
- $T_{1/2}^{0\nu} > 2.9 \times 10^{24}$ yrs (90% CL)
- World best limit for 0νββ of ^{100}Mo.

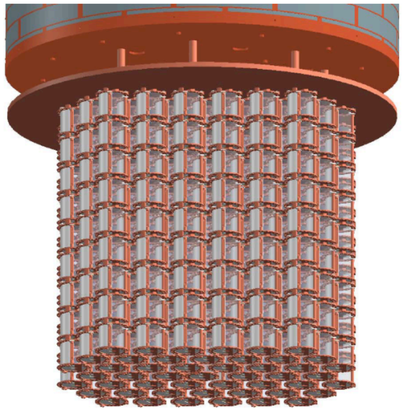
PRL 134 082501 (2025)

AMoRE-II

2025–

Stage 1:
90 LMOs
(27 kg)

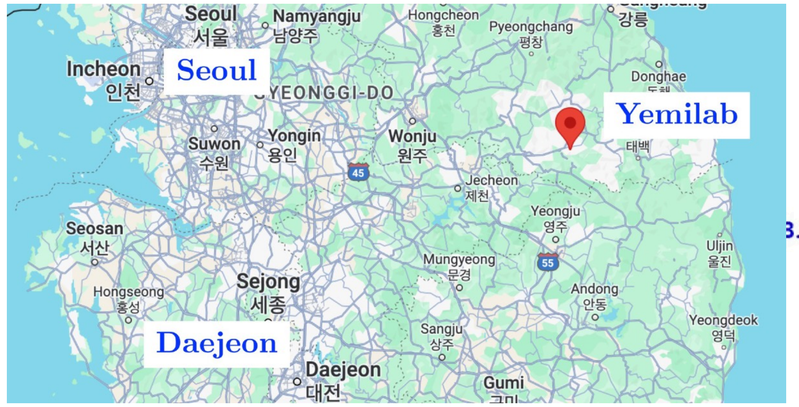


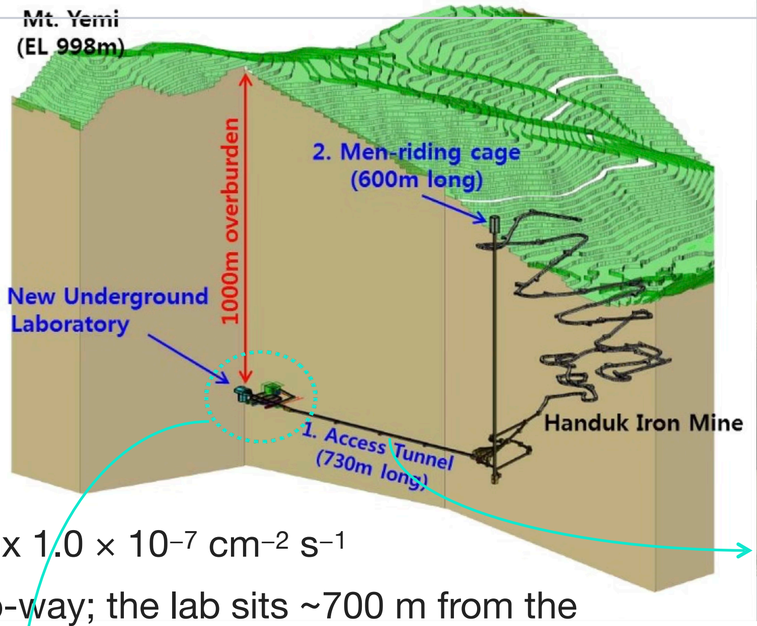


Stage 2:
360 crystals (157 kg)

- ~ 85 kg of ^{100}Mo (Stage 2)
- In Yemilab, 1000 m depth.
- Exposure > 500 $kg_{Mo\text{-}100}$·yr.
- Background at ROI~10^{-4} ckky.
- Aiming at $T_{1/2}^{0\nu} = 4.8 \times 10^{26}$ yrs

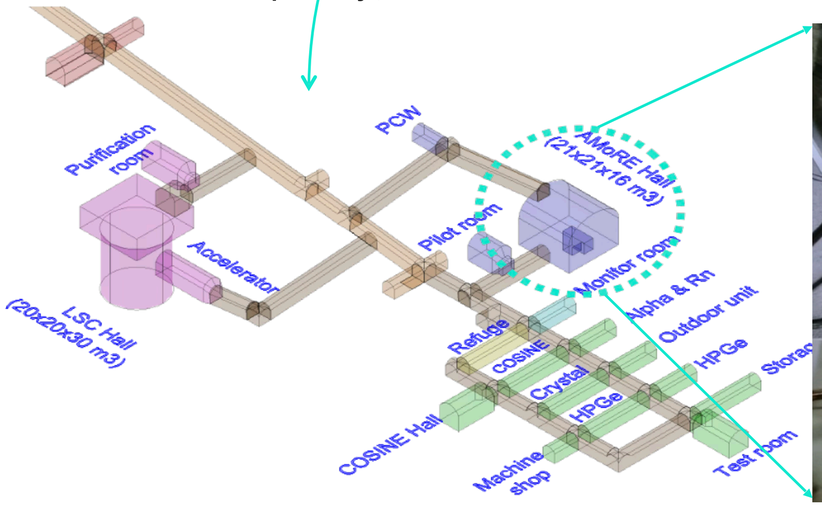
AMoRE-II at Yemilab







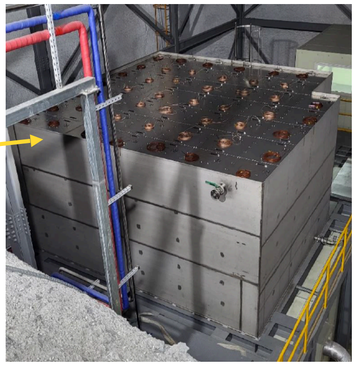
- ~1000 m underground (~2700 m.w.e.); muon flux 1.0 × 10^{-7} cm^{-2} s^{-1}
- Reached by a 600 m cage shaft or a 6 km ramp-way; the lab sits ~700 m from the active mining area
- AMoRE hall (21 × 21 × 16 m^3)





AMoRE-II: muon veto, shielding and cryostat



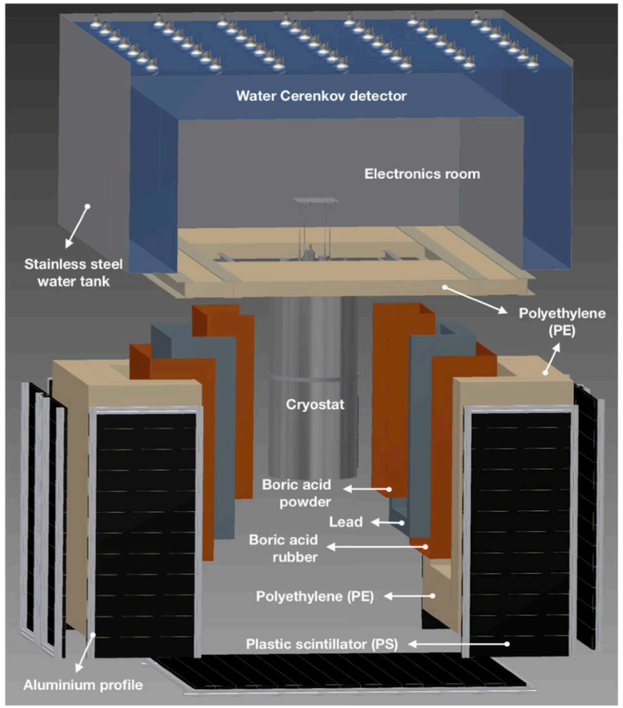


Water Cherenkov muon detector

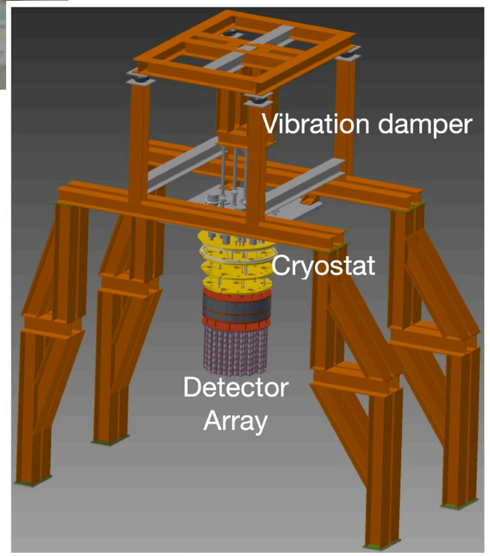


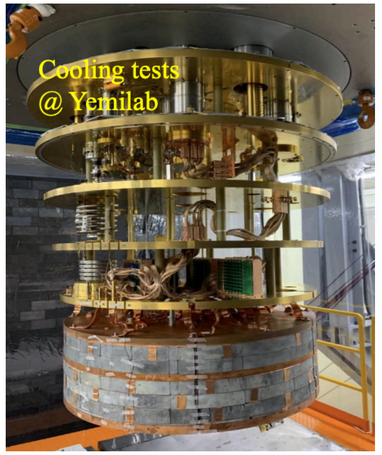
Plastic scintillator muon detector

(TAUP 2025, S.C. Kim)

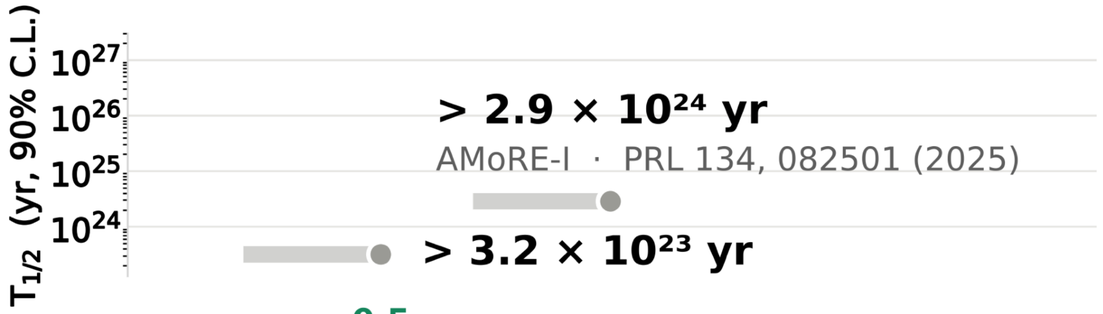


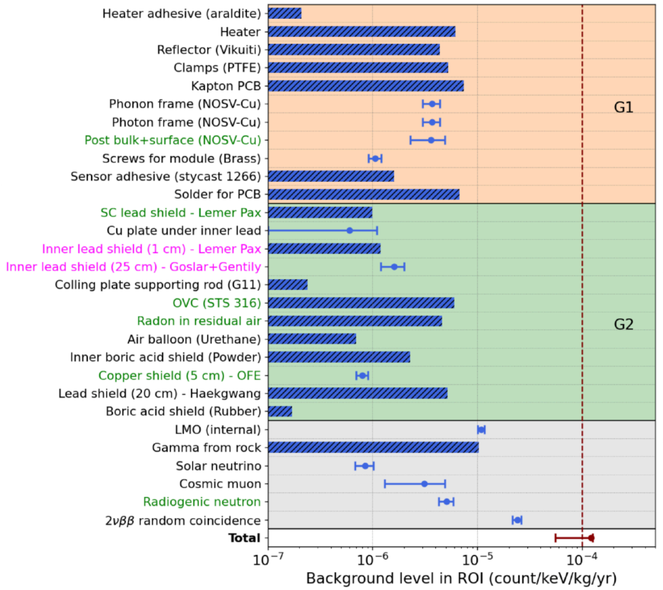






AMoRE-II: plan & background





AMoRE-III 1.0 × 10²⁷ yr

AMoRE-II 4.8 × 10²⁶ yr

(III: 5 yr · II: ~6 yr of data)

background index
cts/(keV·kg·yr)

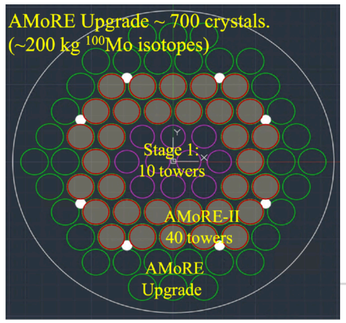
0.5 → 0.025 → × 250 → goal < 10^{-4} → goal 2 × 10^{-5}

simulation, Oct 2026 1.2 × 10^{-4}

Y2L *700 m* *Yemilab* *1000 m*

AMoRE-II stage 1 | stage 2

AMoRE-III proposed



AMoRE-pilot 2015 – 2018 · 0.88 kg ^{100}Mo · 0.32 kg·yr

AMoRE-I 2020 – 2023 · 3.0 kg ^{100}Mo · 3.89 kg·yr

stage 1 90 crystals, ^{100}Mo ~15 kg · being installed now

stage 2 360 crystals, ^{100}Mo ~85 kg · 7 keV FWHM · α/β DP > 10

AMoRE-III ~700 crystals, ~200 kg in the same cryostat

time compressed

Major Background

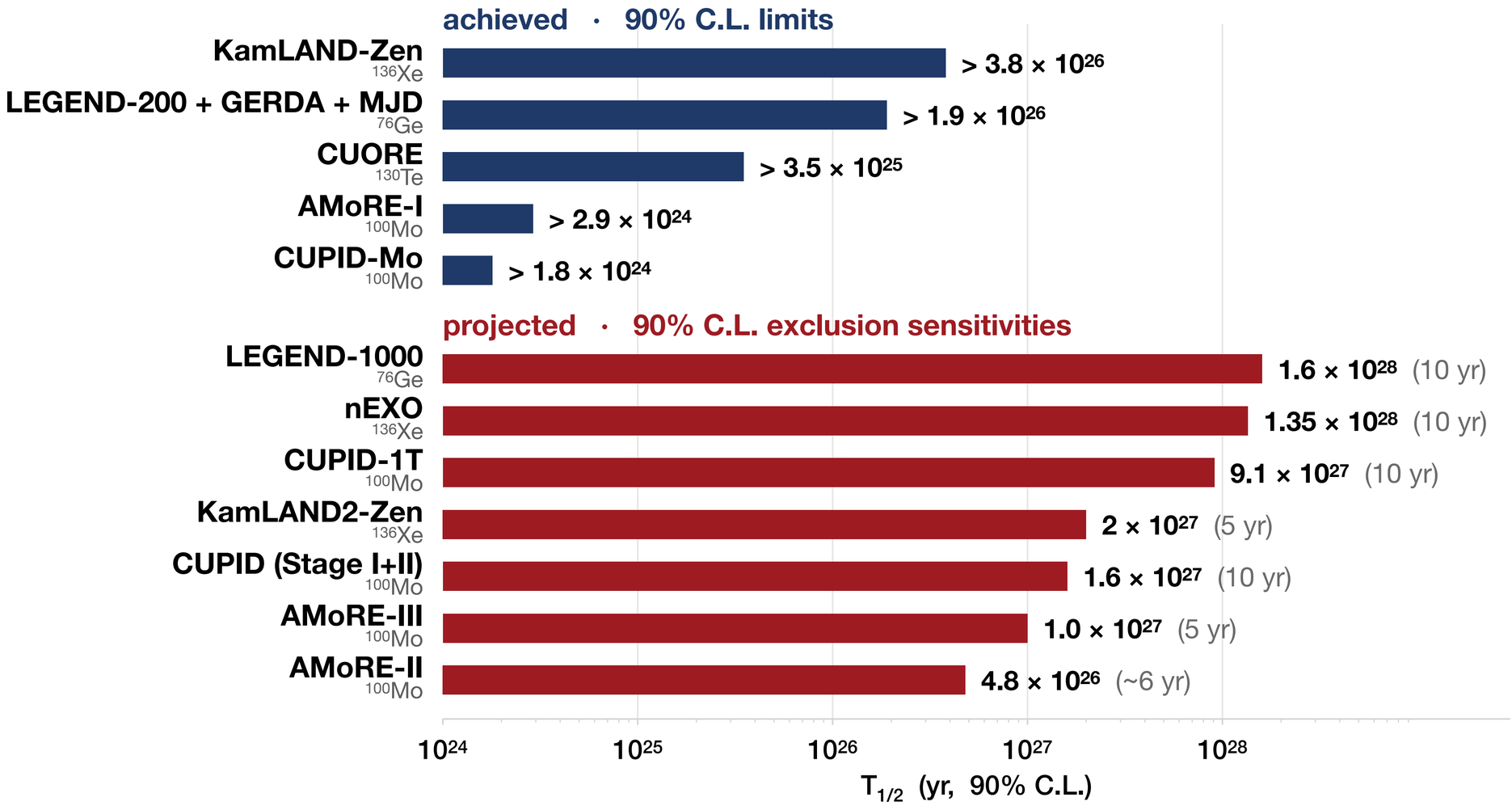
- LMO internal: ~10^{-5} ckky
- LMO surface
  - ~6 × 10^{-4} ckky from AMoRE-I alpha modeling.
  - Lower in AMoRE-II surface treatment.
- Rock gammas: ≤ 10^{-5} ckky
- Pileup events: ~3 × 10^{-5} ckky
  - Could reduce them using the light signal rise time analysis

2016 · 2020 · 2024 · 2026 (now) · 2028 · 2030 · 2032

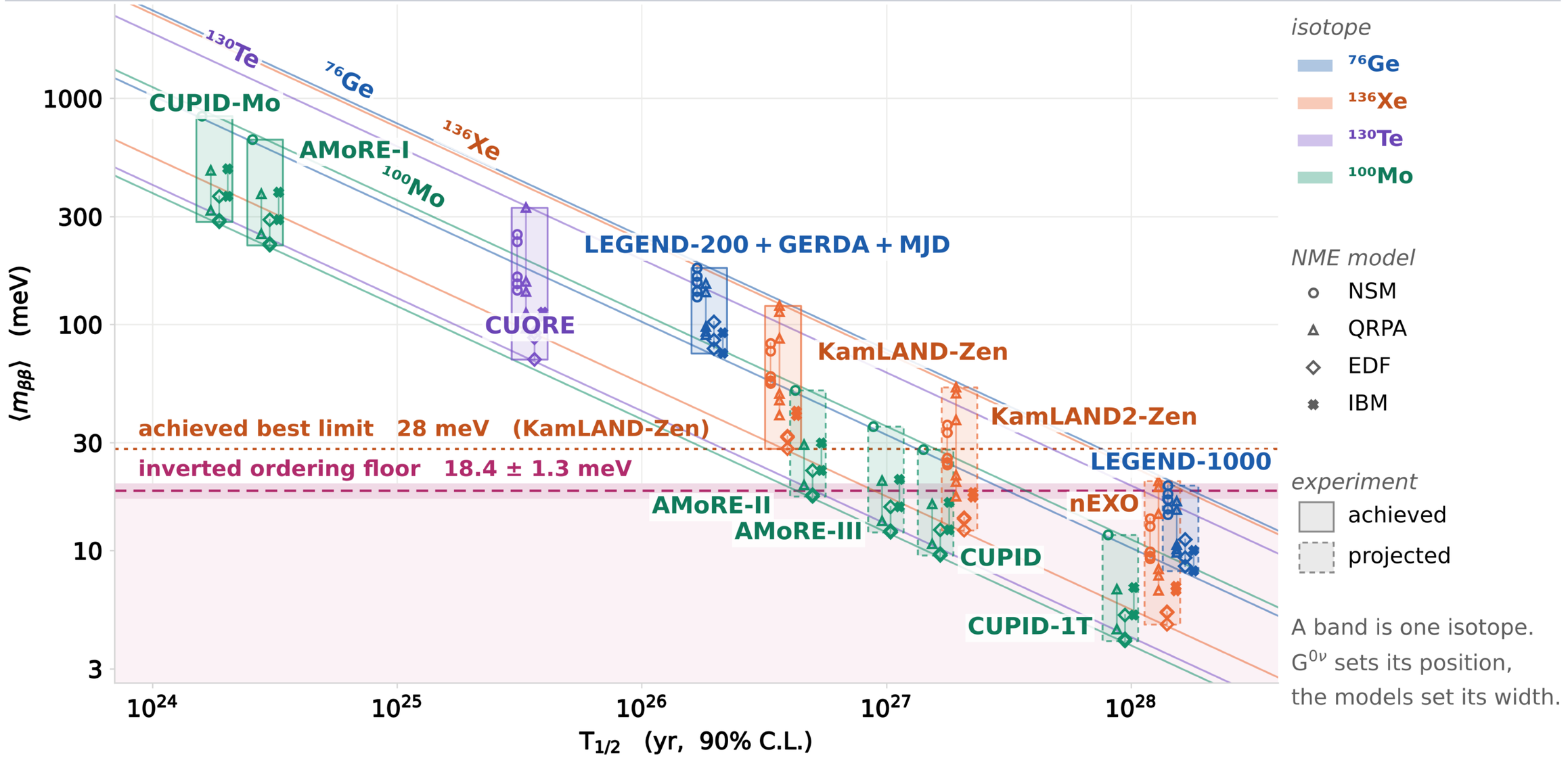
What limited each result, and what comes next

	Energy resolution Ge, bolometers	**Scale** Xe LS, liquid Xe TPC
Strength	small ΔE (0.1–0.4%)	large mass, one volume
What limited the result	LEGEND-200: surface ^{214}Bi / ^{208}Tl CUORE: α from nearby parts AMoRE-I: shield radioactivity, neutrons, radon	KamLAND-Zen: ΔE → 2νββ tail EXO-200: too small, U/Th γ
Next step	LEGEND-200 (running): cleaned up, ^{42}K from Ar remains LEGEND-1000: underground Ar, less ^{42}K CUPID: α/β by light AMoRE-II: Yemilab, redesigned clean shield	KamLAND2-Zen: ΔE 4% → 2% nEXO: 5 t, self-shielding

Achieved limits and projected sensitivities



How far does each experiment reach in $\langle m_{\beta\beta} \rangle$?



Summary

The question	0νββ tests lepton-number violation (ΔL = 2) and the Majorana nature of the neutrino
What sets the reach	The isotope fixes $Q_{\beta\beta}$, $G^{0\nu}$ and $M^{0\nu}$; the experiment sets ε, M·T and b·ΔE. Another order of magnitude needs zero background, not only more mass
Where we are	$T_{1/2} > 10^{26}$ yr in ^{76}Ge (1.9×10^{26} yr) and ^{136}Xe (3.8×10^{26} yr; $\langle m_{\beta\beta} \rangle < 28$–$122$ meV). CUORE ran a tonne-scale mK detector for almost 10 years
Next generation	Goal 10^{27}–10^{28} yr: LEGEND-1000, nEXO, CUPID, KamLAND2-Zen, AMoRE-III. AMoRE-II (Yemilab, 4.8×10^{26} yr) is being installed. Each targets its own limiting background
What is needed	Signals in more than one isotope to confirm a discovery and pin down $\langle m_{\beta\beta} \rangle$

Backup

Reaching below the inverted ordering

