Charting the Path to Discovery:
The Status and Future of Neutrinoless Double Beta Decay

Stefan Schönert | TU München

MAYORANA (Multi-Aspect Young ORiented Advanced Neutrino Academy) Workshop

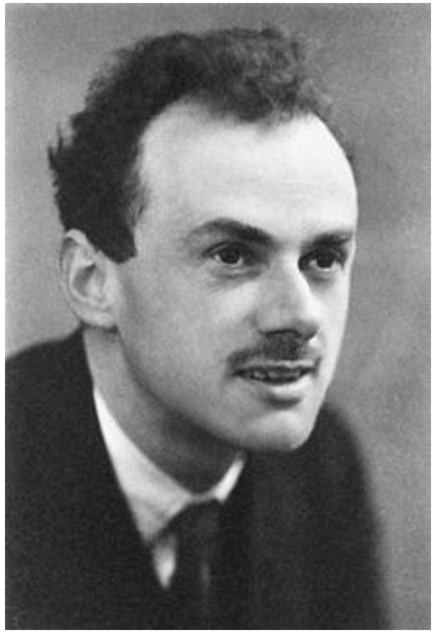
June 16, 2025

Modica

TECHNISCHE UNIVERSITÄT MÜNCHEN
SFB 1258 Neutrinos Dark Matter Messengers
erc
ORIGINS Excellence Cluster
Bundesministerium für Bildung und Forschung

The Quest: Are neutrinos their own anti-particles?

Ettore Majorana



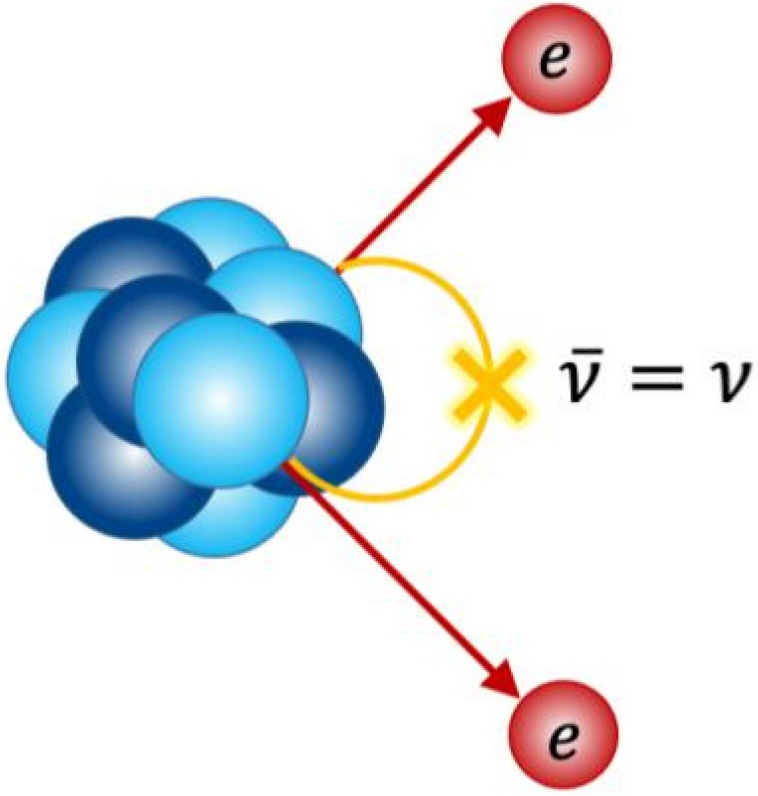
Paul Dirac

Majorana neutrinos

- Violate lepton number conservation
- Explain how neutrinos get their mass
- Explain why their masses are so much lighter than those of charged fermions
- Shed light on the origin of the matter anti-matter asymmetry in the Universe

Search for lepton number violation:

Creation of (leptonic) **matter** without balancing emission of anti-matter[#]

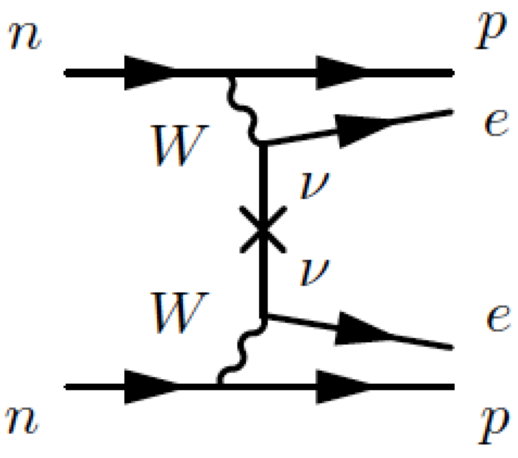


Neutrinoless double beta decay ($0\nu\beta\beta$)

[#] F. Vissani

Search for lepton number violation:

Creation of (leptonic) **matter** without balancing emission of anti-matter#



Standard paradigm:
Exchange of **light Majorana neutrinos**

Expected decay rate:

$$(T_{1/2}^{0\nu})^{-1} = G^{0\nu}(Q,Z)\,|M^{0\nu}|^2\,\langle m_{ee}\rangle^2$$

Phase space integral Nuclear matrix element

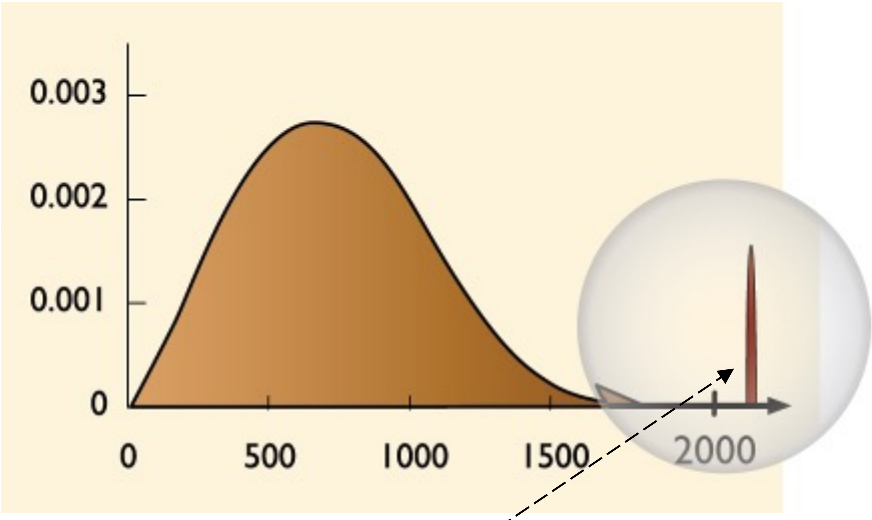
$$\langle m_{ee}\rangle = \left|\sum_i U_{ei}^2\, m_i\right|$$ Effective neutrino mass

U_{ei} Elements of (complex) PMNS mixing matrix

F. Vissani

Search for lepton number violation:

Creation of (leptonic) **matter** without balancing emission of anti-matter#



Expected decay rate:

$$(T_{1/2}^{0\nu})^{-1} = G^{0\nu}(Q,Z)\,|M^{0\nu}|^2 \left\langle m_{ee} \right\rangle^2$$

Phase space integral Nuclear matrix element

$$\left\langle m_{ee} \right\rangle = \left| \sum_i U_{ei}^2\, m_i \right|$$ Effective neutrino mass

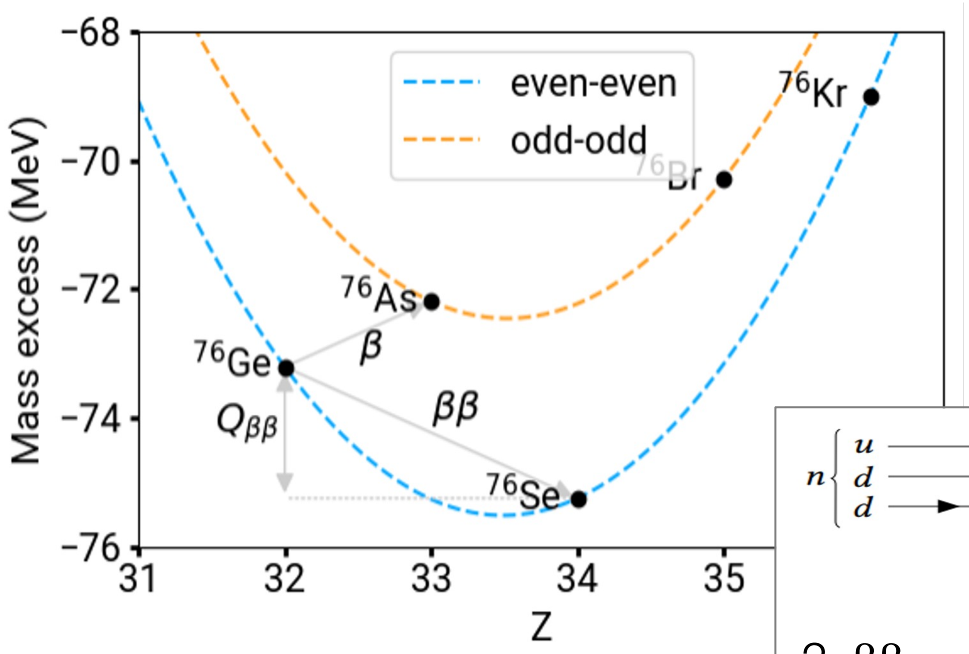
U_{ei} Elements of (complex) PMNS mixing matrix

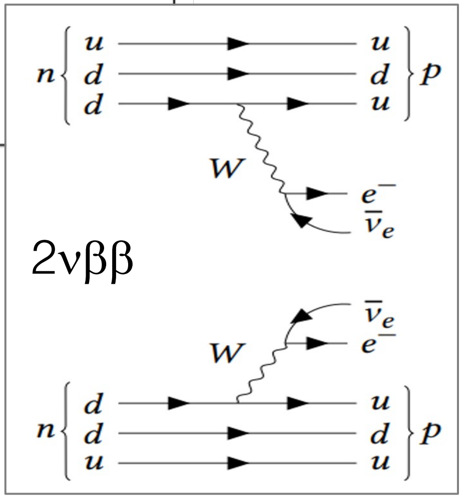
Experimental signatures:

- Peak at $Q_{\beta\beta}$
- Two electrons from vertex

F. Vissani

Double beta decay isotopes

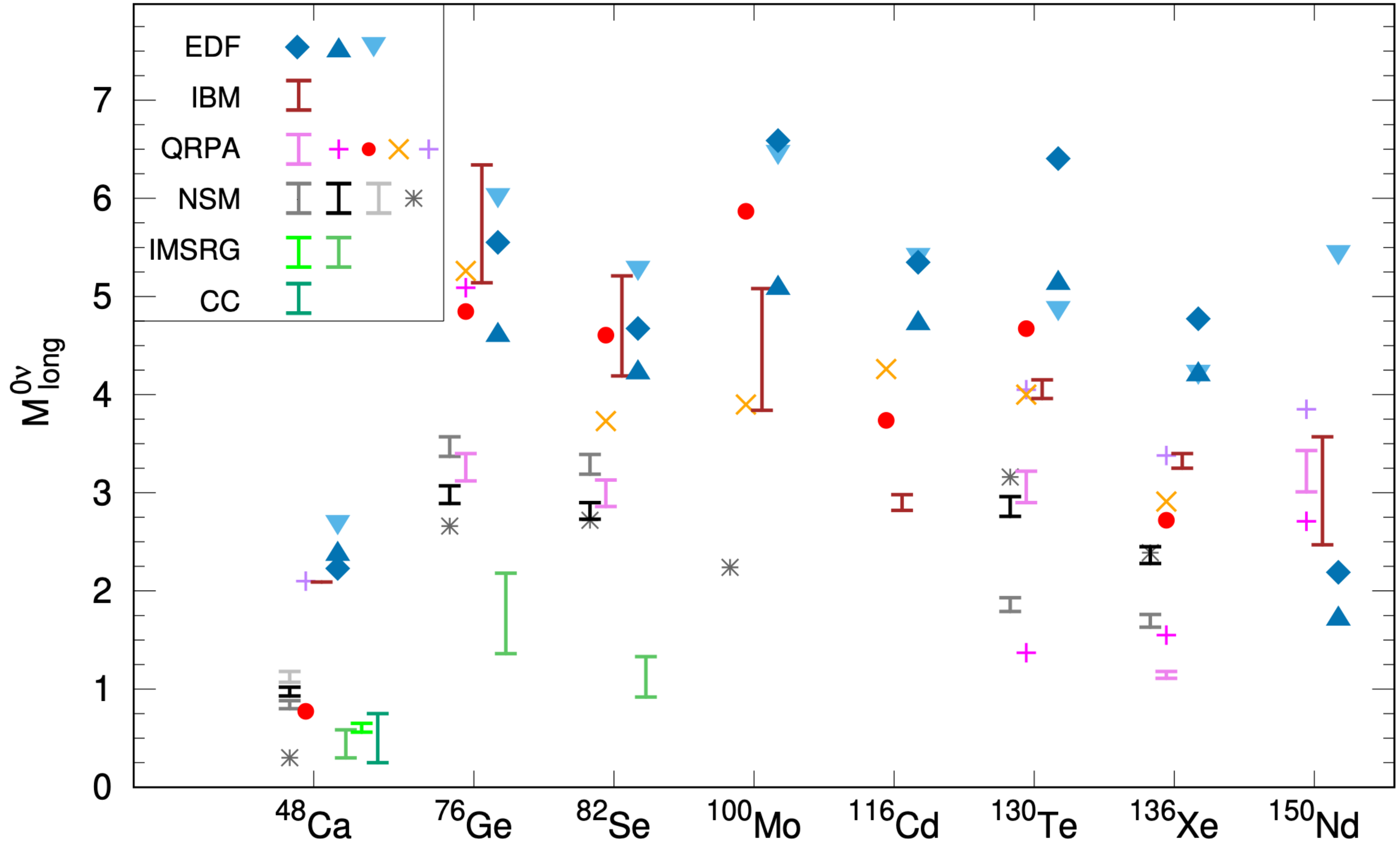




isotope	$Q_{\beta\beta}$ [keV]	$T_{1/2}^{2\nu\beta\beta}$ [yr]
^{48}Ca	4267.98 ± 0.32	6.4×10^{19}
^{76}Ge	2039.0610 ± 0.0007	2.022×10^{21}
^{82}Se	2997.9 ± 0.3	8.60×10^{19}
^{96}Zr	3356.097 ± 0.086	2.35×10^{19}
^{100}Mo	3034.40 ± 0.17	7.12×10^{18}
^{116}Cd	2813.50 ± 0.13	2.63×10^{19}
^{130}Te	2527.5180 ± 0.0013	7.71×10^{20}
^{136}Xe	2457.83 ± 0.37	2.165×10^{21}
^{150}Nd	3371.38 ± 0.20	9.34×10^{18}

Cuore, SNO+, possibly JUNO

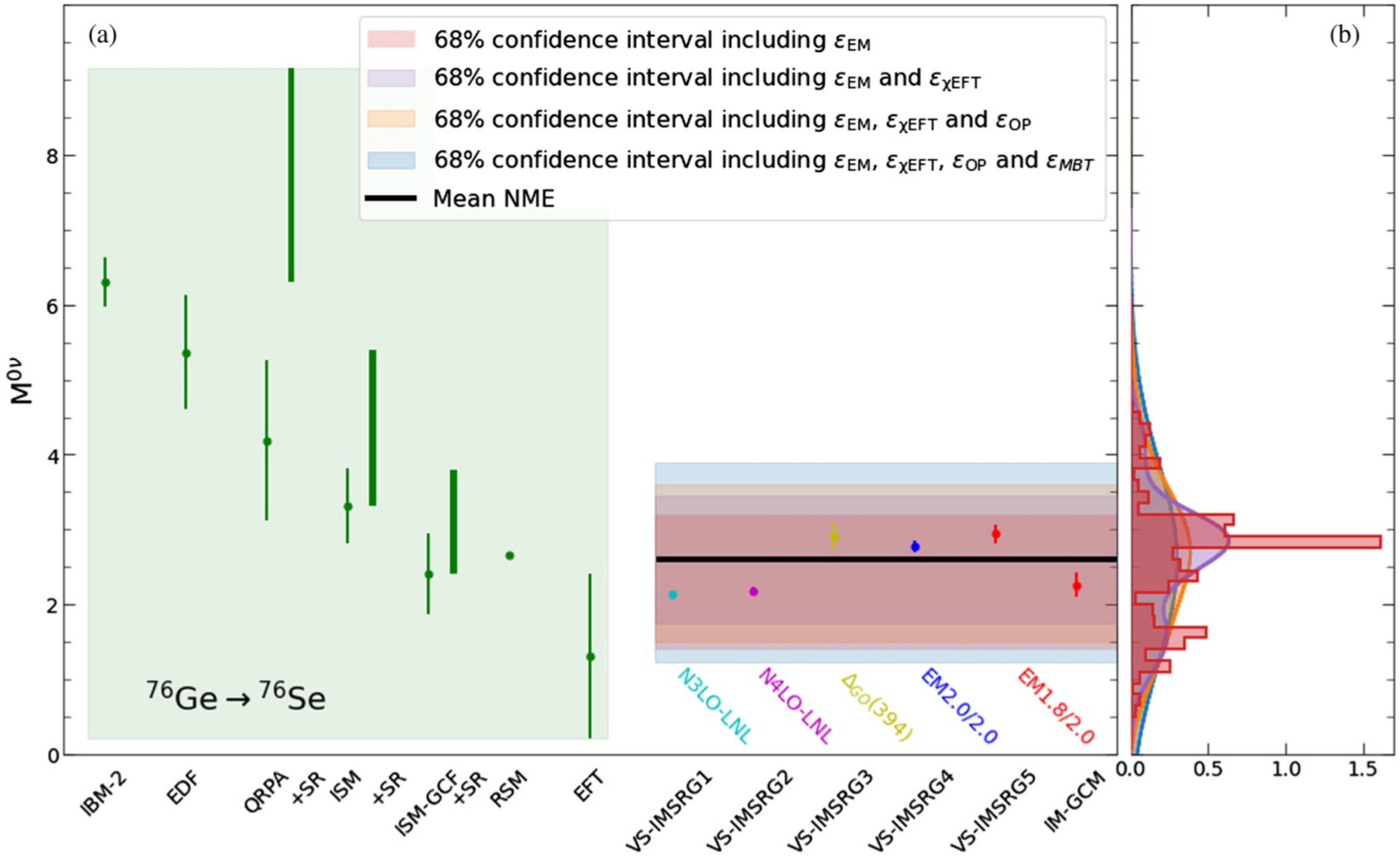
Nuclear matrix elements: phenomenological models



Nuclear matrix elements $M^{0\nu}$ for light-neutrino exchange from different many-body methods

Rev. Mod. Phys. 95, 025002 (2023)

Nuclear Matrix Elements: ab-initio calculations



Example: Ge-76

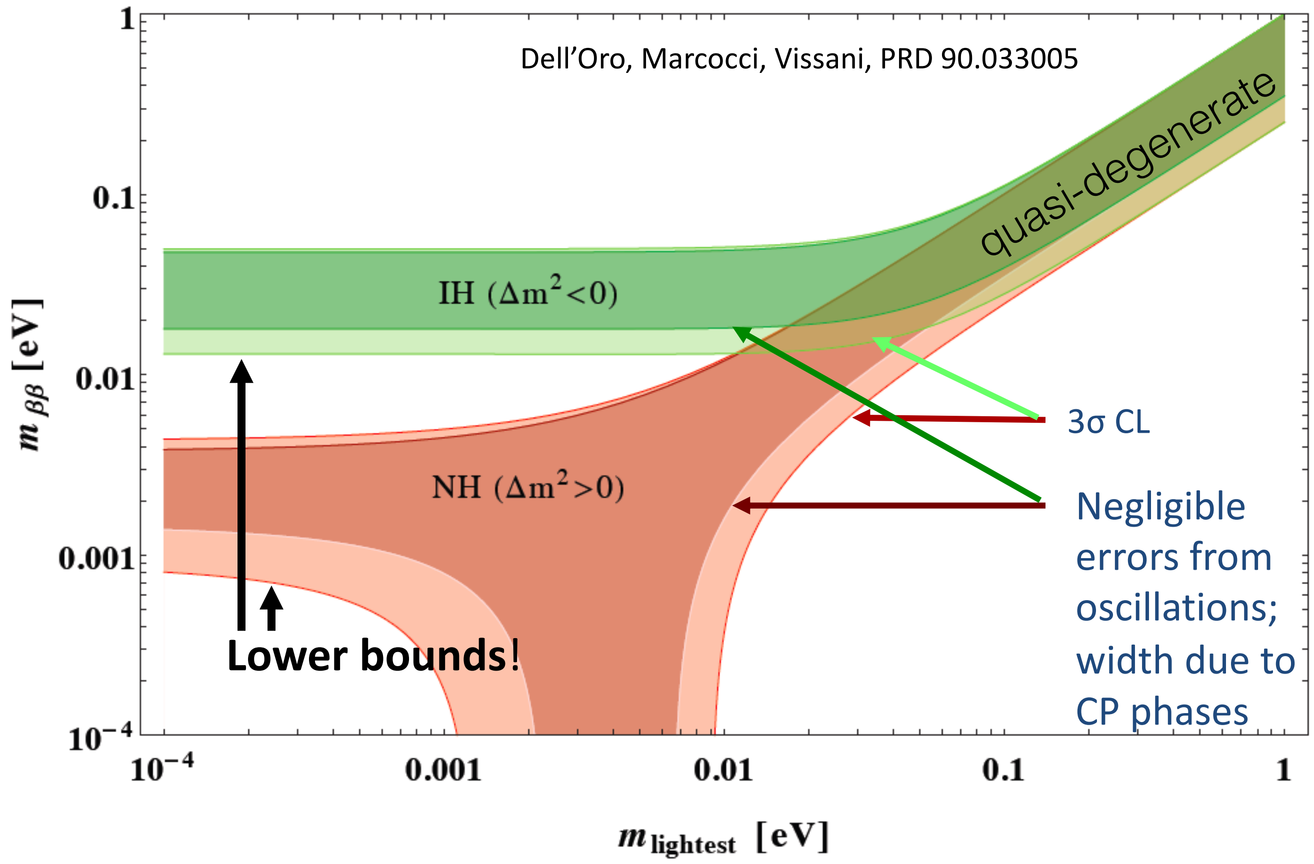
- Ab-initio calculations based on chiral effective field theory and advanced many-body methods including uncertainty quantification
- Yet, large uncertainties

A. Belley et al., PRL 2024

0νββ: Range of m_{ee} from oscillation experiments

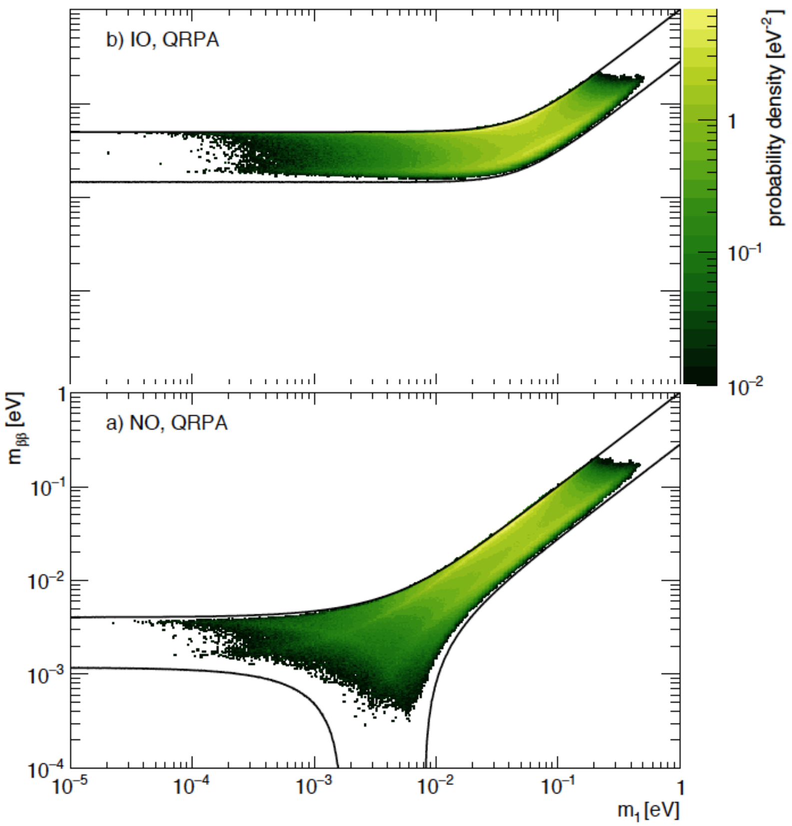
$$m_{ee} = f(m_1, \underbrace{\Delta m^2_{sol}, \Delta m^2_{atm}, \theta_{12}, \theta_{13}}_{\text{from oscillation experiments}}, \alpha\text{-}\beta)$$

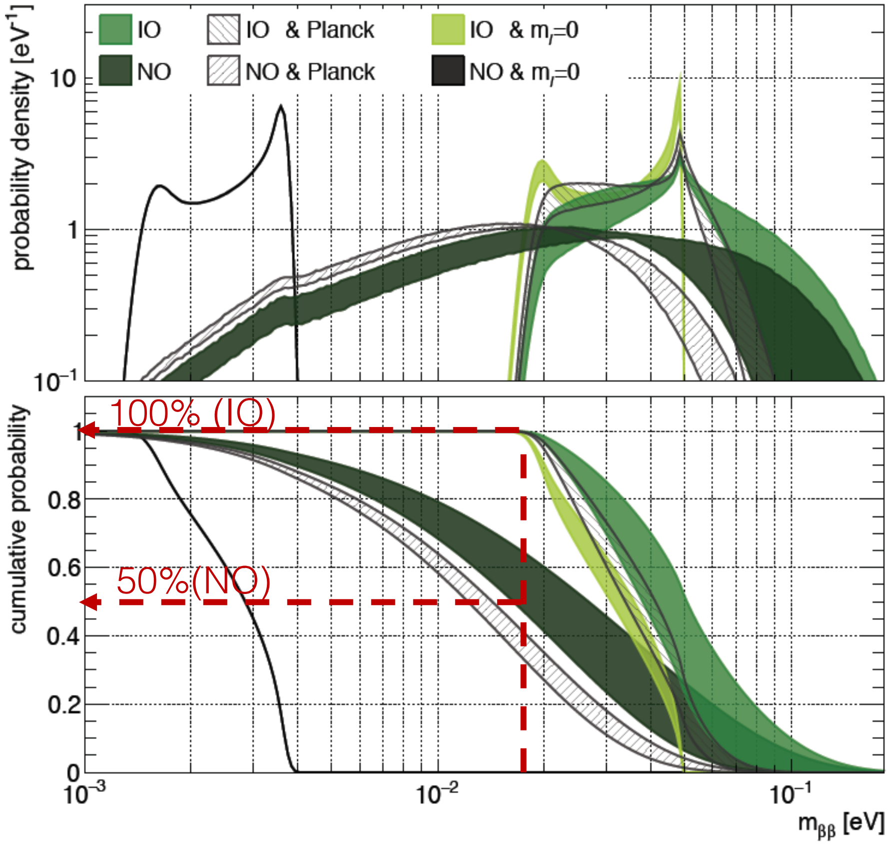
Goal of next generation experiments:



Discovery probabilities

- Global Bayesian analysis including ν-oscillation, m_β $m_{\beta\beta}$, Σ
- Priors: Majorana phases (flat); m_1 (scale invariant)

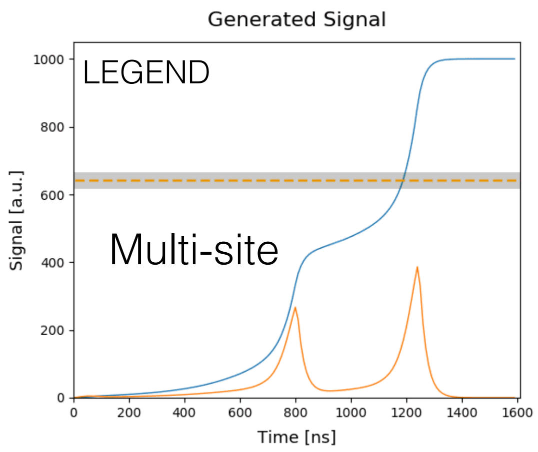


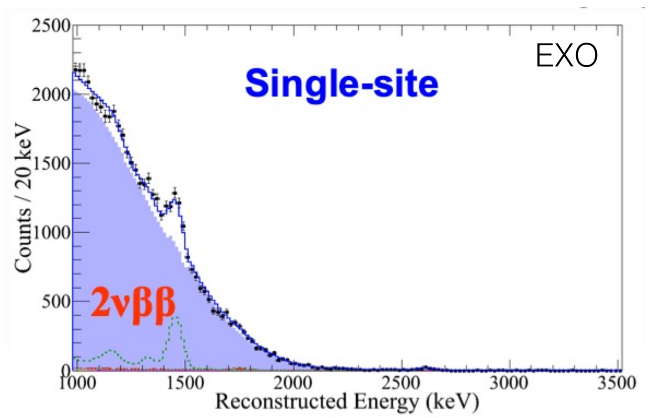


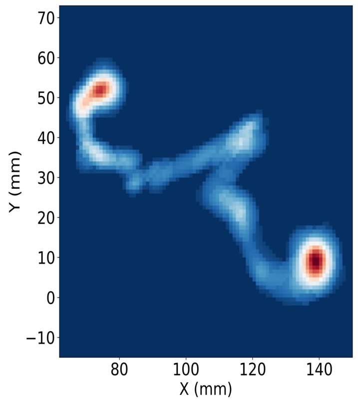
Agostini, Benato, Detwiler arXiv:1705.02996

Ton-scale experiments for discovery

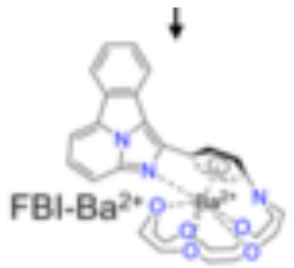
- Need to measure half-lives of up to 10^{28} years
- **One decay** per **ton-year** of material
- Need many **ton-years** of data
- Need extreme **low background rate** and best possible **energy resolution**
- Need to exploit **topology information** of signal and background
- And, if possible, identify **daughter nucleus**







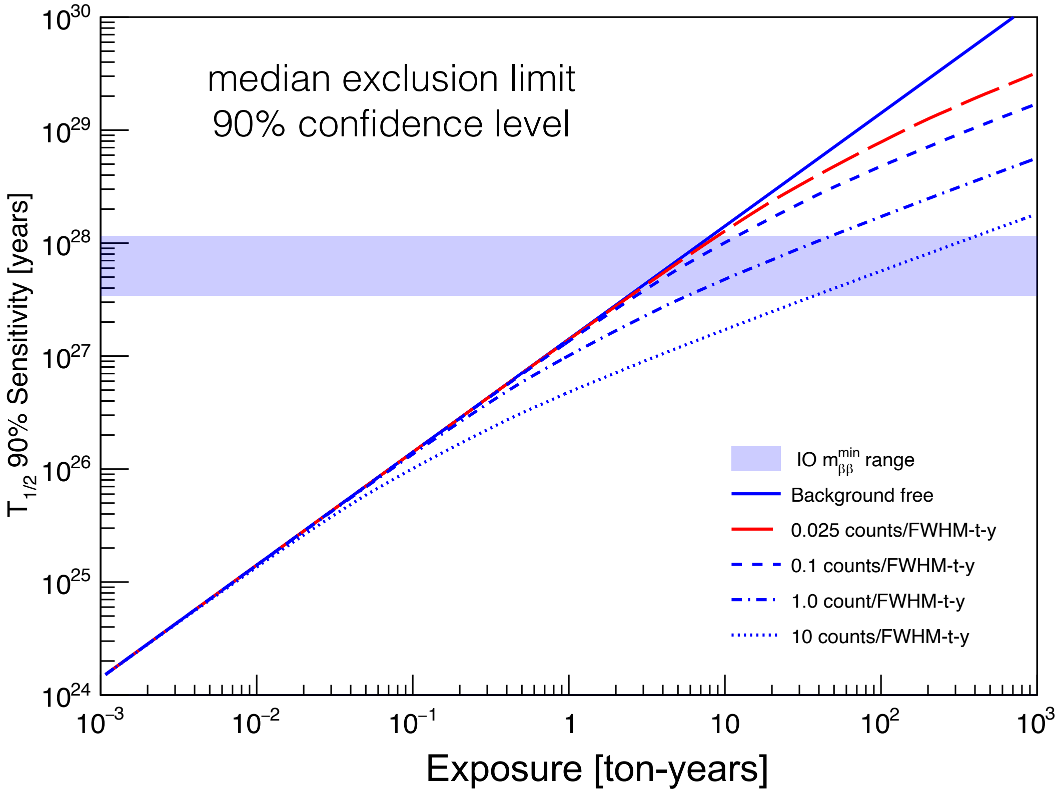
NEXT

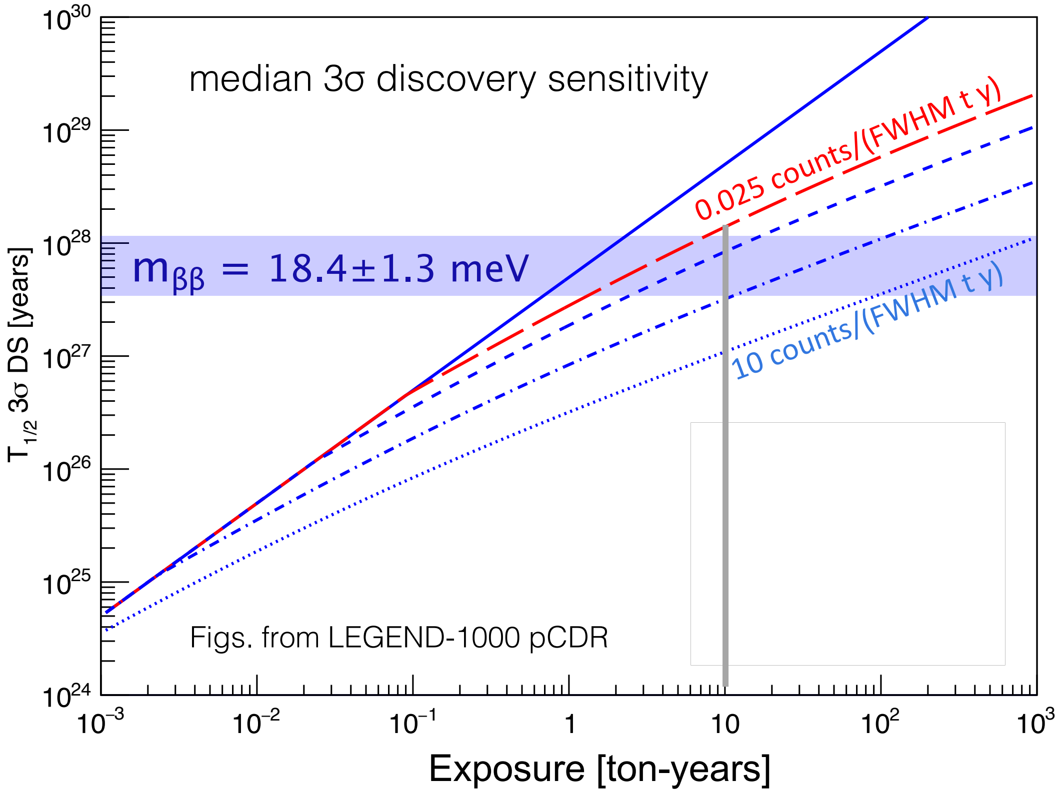


The Effect of Background: Discovery sensitivity vs. exclusion limit

- Ton-scale experiments aim for a **discovery**
- Background-free: Sensitivity rises **linearly with exposure**
- Background-limited: Sensitivity rises as the **square root of exposure**

=> **quasi-background-free**[1] operation makes most efficient use of valuable isotopes





[1] Less than one background count expected in a 4σ Region of Interest (ROI) with 10 t y exposure

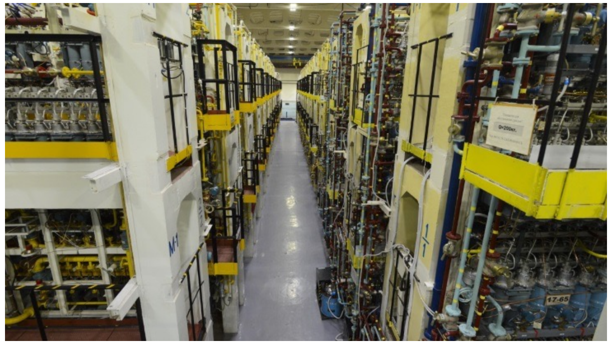
Double beta decay isotopes

Isotope enrichment:

- Past & current experiments obtained $0\nu\beta\beta$ isotopes primarily from **Russia**
- Since the **Russian invasion of Ukraine**, no procurement of $0\nu\beta\beta$ isotopes from Russia by **Western countries**
- Part of $0\nu\beta\beta$ isotopes were also procured from **European** producer (^{76}Ge, ^{82}Se, …)
- Urenco (European producer) is ready to **increase production capacities for** ^{76}Ge
- **IPCE China** began producing stable isotopes, including ^{100}Mo

Natural isotopic composition:

- Te (34% ^{130}Te): Cuore, SNO+, JUNO
- Xe (8.9 % ^{136}Xe): XLZD, nEXO 2.0 (first phase)



An isotope production facility at ECP
(Image: TVEL)

European – North American Coordination

3rd International Summit on the Future of Neutrinoless Double-beta Decay

26–27 May 2025
Max Planck Institute for Nuclear Physics
Europe/Berlin timezone

Enter your search term

https://indico.ph.tum.de/event/7802/

- Overview
- Timetable
- Contribution List
- Registration
- Participant List
- Travel Information

Support

anja.berneiser@mpi-hd....

^{136}Xe:
- nEXO 2.0
- XLZD
- NEXT

^{100}Mo:
- CUPID

^{76}Ge:
- LEGEND

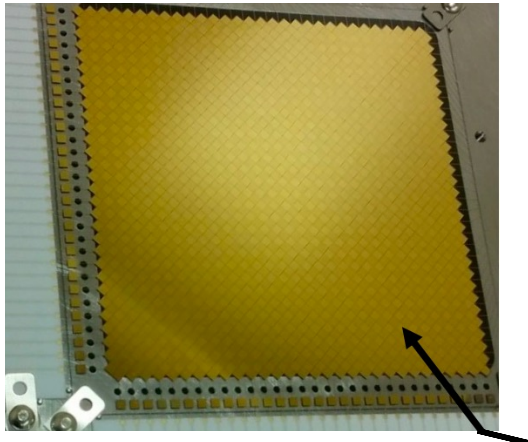
European and North American research institutions & **funding agencies** to advance discussions on the strategy and roadmap for next-generation neutrinoless double-beta decay experiments.

nEXO 2.0 @ SNOLAB: 5t single-phase liquid Xe TPC

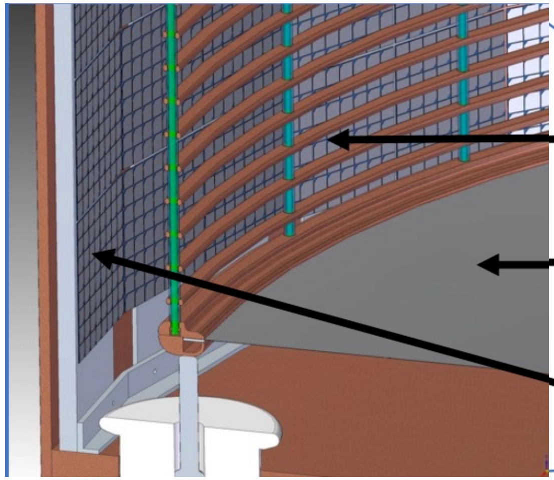
- 4.5 m^2 SiPM for 175nm scintillation light detection,
- segmented anode for charge read out in liquid Xe.

=> 3D event reconstruction.

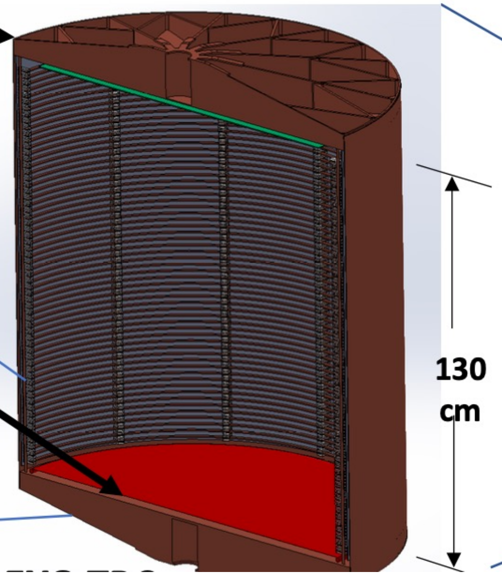
- Combine charge and light readout. Goal: $\sigma/E < 1\%$ at Qbb.
- 1.5 kt water-Cherenkov detector for muon tagging and shielding.
- Sensitivity: 10^{28} years [arXiv:2106.16243].

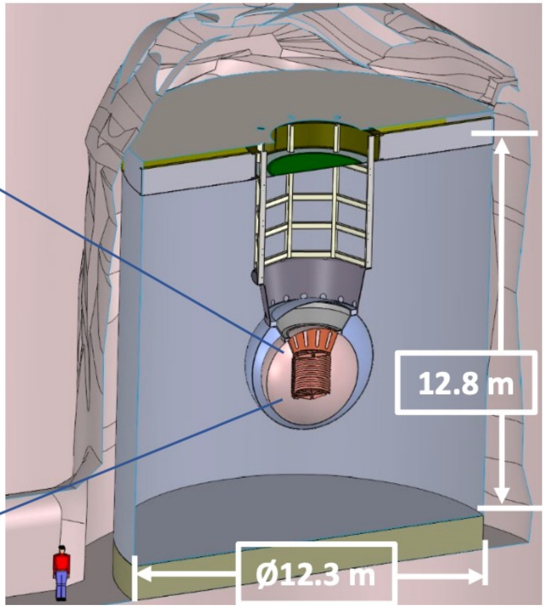


10 x 10 cm^2 tile prototype
JINST 13, P01006 (2018)



pCDR, arXiv:1805.11142

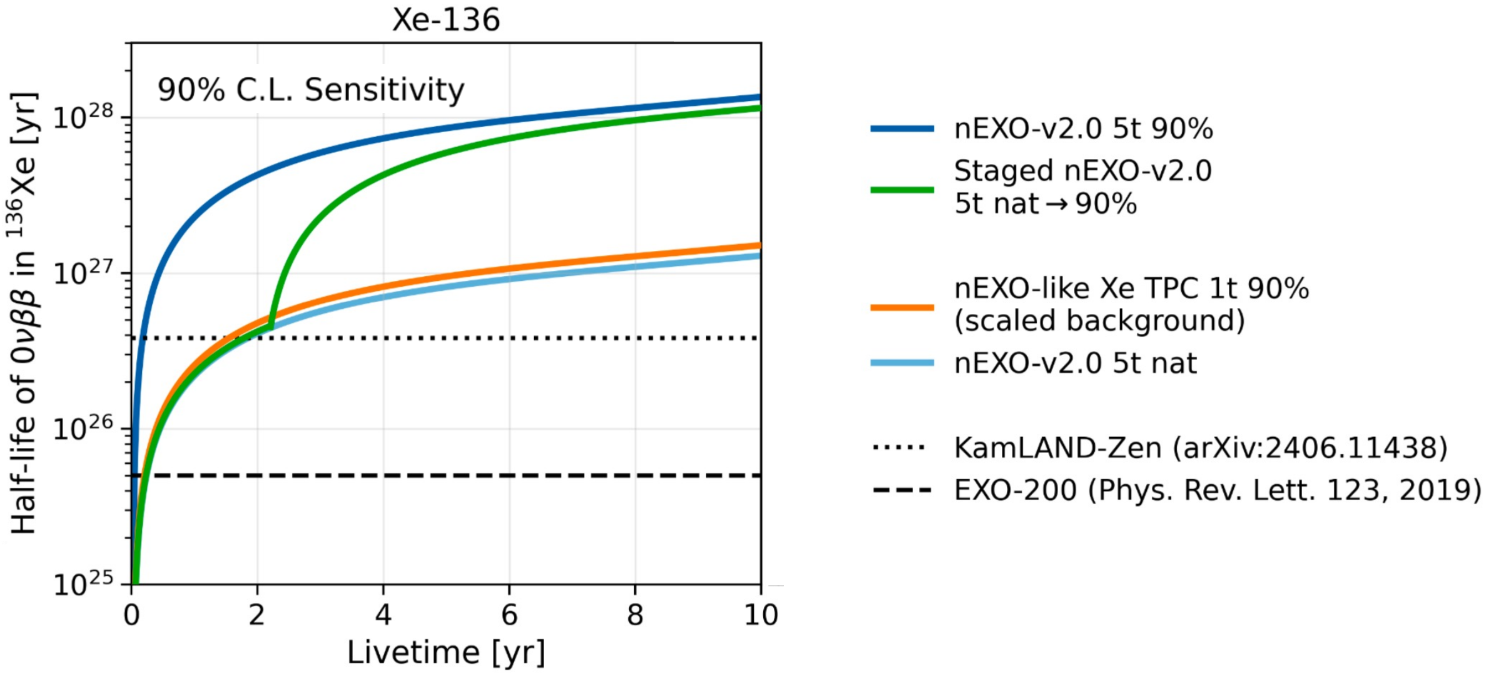




nEXO at the SNOLAB Cryopit

nEXO 2.0 @ SNOLAB: phased approach

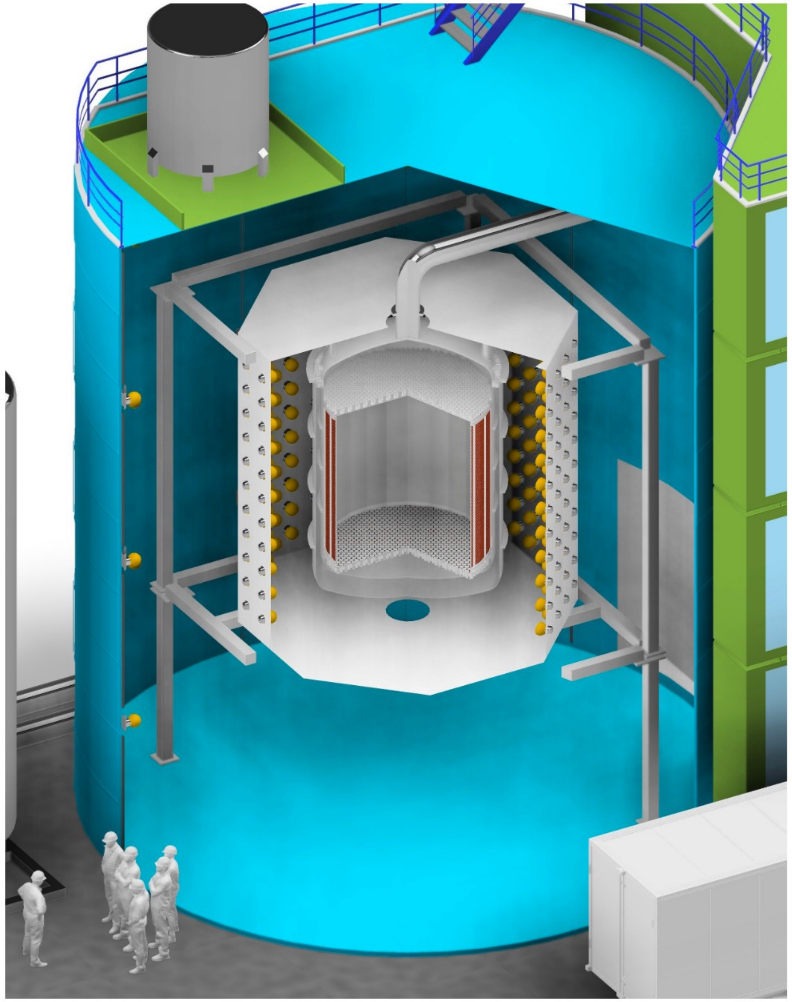
Phase 1	Phase 2
5 tonne	
Natural	Nat → 90%
1.3 x 10^{27}	~1.1 x 10^{28}



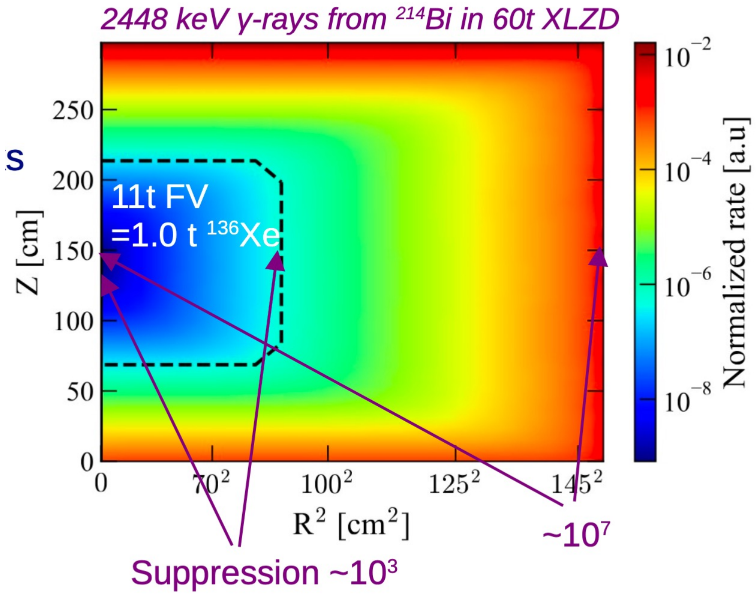
nEXO-v2.0 5t 90% enrichment, 10 yr livetime:

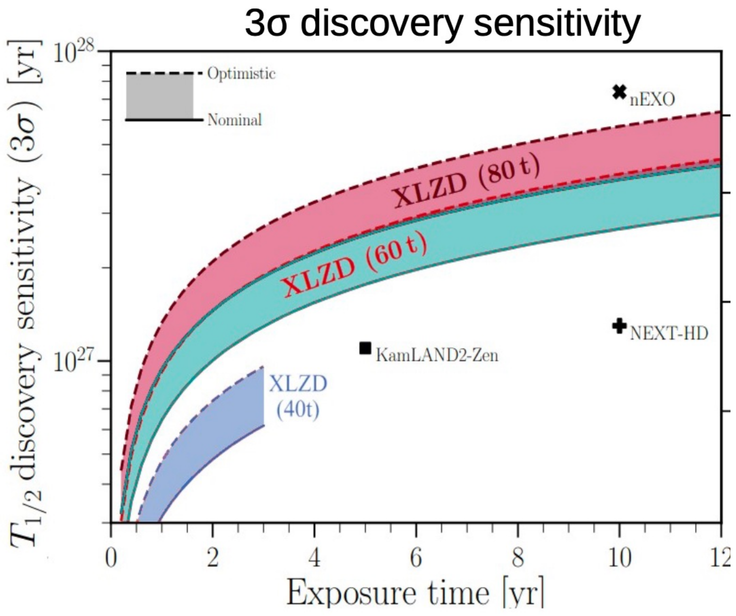
- Median Discovery Potential (3σ): 0.74 x 10^{28} yr
- Median Sensitivity (90% C.L.): 1.35 x 10^{28} yr

XLZD: liquid $^{natural}Xe$ dual-phase TPC



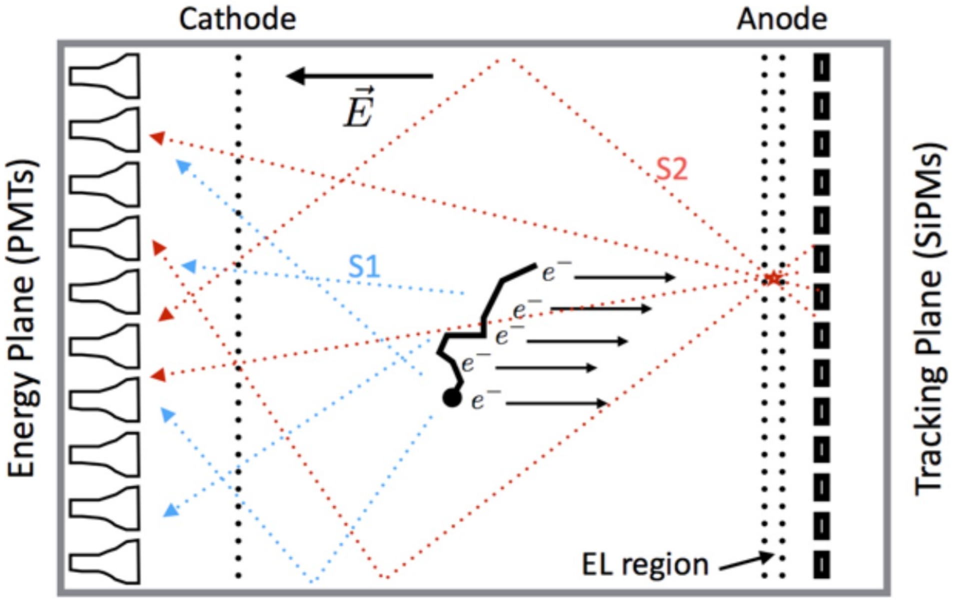
60 t active (78 t total) ^{nat}Xe target for DM search
FV contains 1t ^{136}Xe
σ/E=0.65% @ Qbb

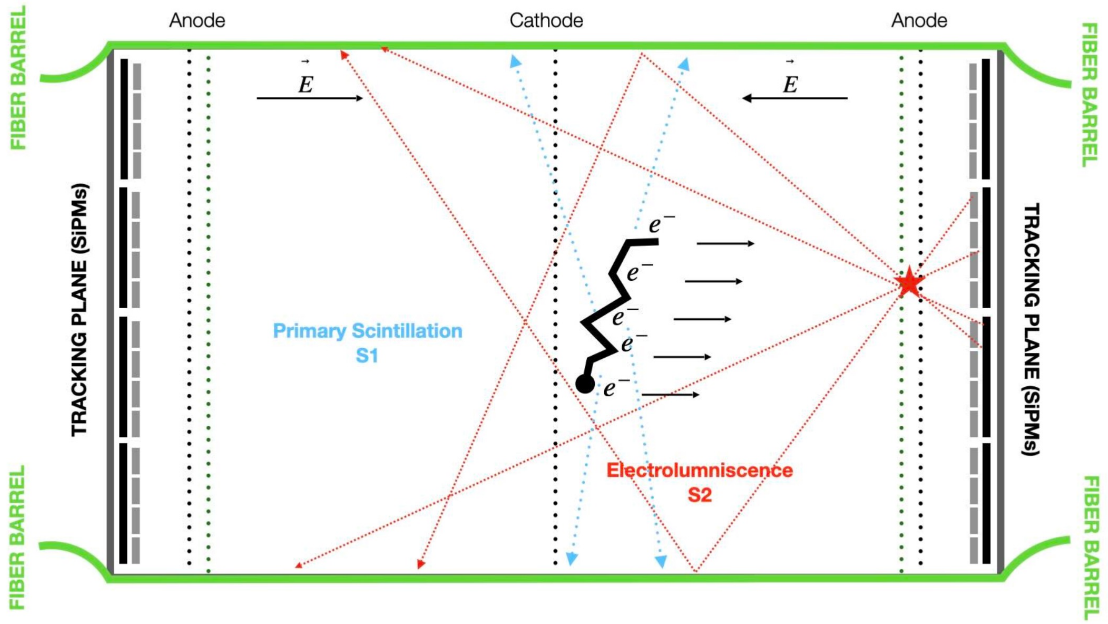




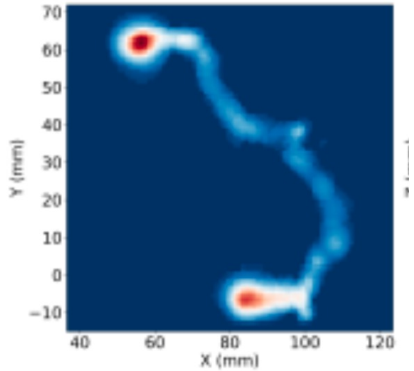
J. Phys. G 52, 045102 (2025)

^{136}Xe high-pressure gaseous TPC





NEXT-100 (100 kg)
- start 2022
- 1% FWHM at $Q_{\beta\beta}$
- Topology info: here 2-electron event



HD (High-Definition)
- Up to 1 ton enriched Xe gas @ 20 bar
- Replacement of PMTs by SiPMs
- Xe-He mixture: lower diffusion, better definition
- Sensitivity: $2{\times}10^{27}$ y (6 ton yr)

NEXT-BOLD (Barium On Light Detection)
- HD including Ba-tagging by single-molecular-fluorescence imaging => $8{\times}10^{27}$ y (10 ton yr)

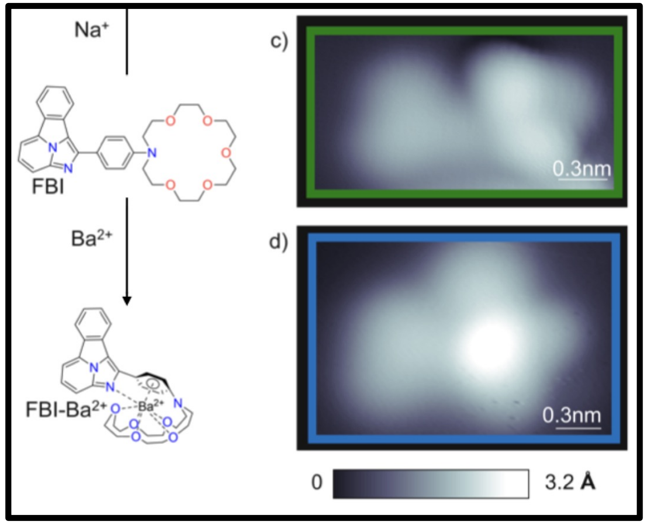
Phys. Rev. Lett. 120, 132504 (2018)

^{136}Xe: Barium tagging NEXT

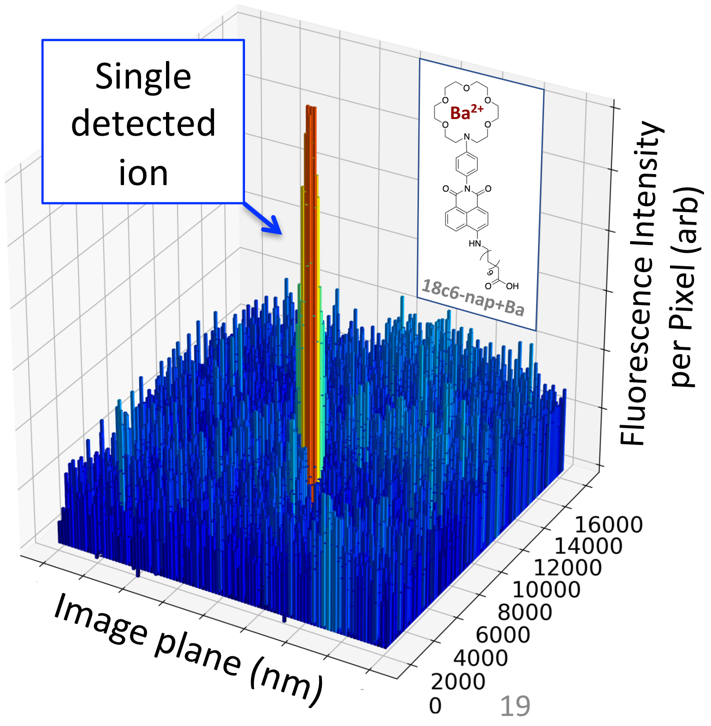
- Detection of **single barium ion** in coincidence with **<1% FWHM energy resolution** and **event topology** essential for background free $0\nu\beta\beta$ search in Xe (NEXT-BOLD)

- NEXT pursues single molecule fluorescent imaging (SMFI) based barium tagging sensors.
- R&D to date has realized molecular ion sensors that:
  - Exhibit barium chelation in vacuum &
  - Enable single ion sensing in xenon gas
  - ON/OFF and Bi-color approaches

STM shows barium location in molecule after chelation



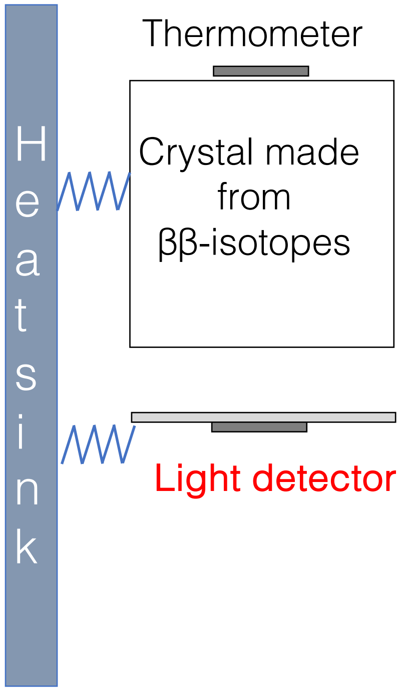
SMFI + high pressure microscopy enables Ba2+ detection in Xe gas



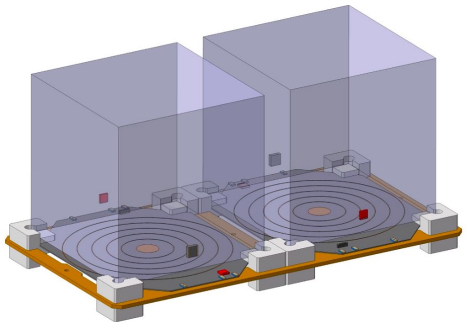
J.Phys.Conf.Ser. 650 (2015) 1, 012002; JINST 11 (2016) 12, P12011; Phys. Rev. Lett. 120 (2018) 13, 132504. Sci.Rep. 9 (2019) 1, 15097; Nature 583 (2020) 7814, 48–54; ACS Sens. (2021) 6, 1, 192–202; arXiv:2201.09099, arXiv:2109.05902, Nature Com. Vol.15, 10595 (2024)

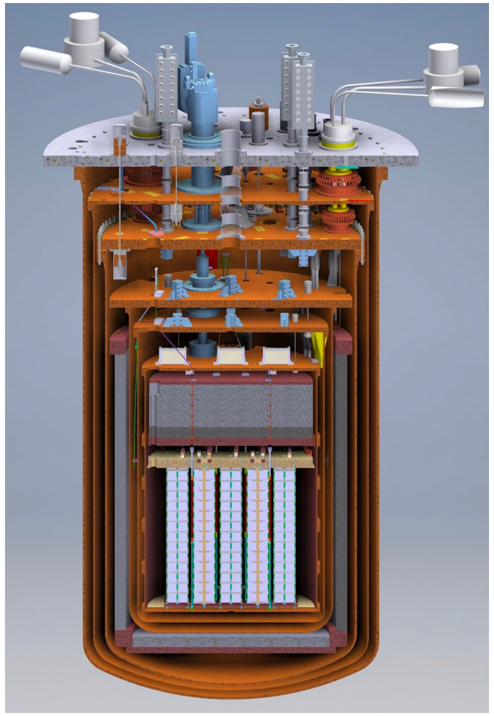
Courtesy M. Sorel, J. Gomez Cadenas

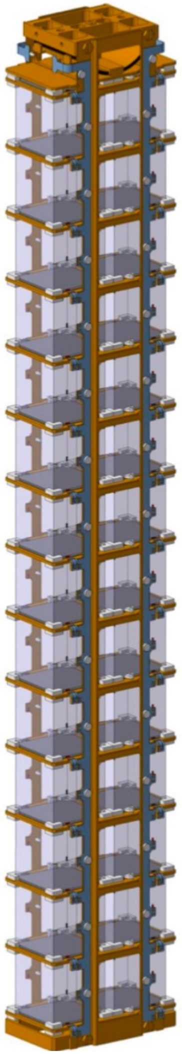
CUPID: ^{100}Mo cryogenic detectors @ LNGS



- Simultaneous readout of **heat and light**: surface alpha rejection
- Single module: **$Li_2{}^{100}MoO_4$** 45×45x45 mm –> 280 g
- 57 towers of 14 floors with 2 crystals each -> 1596 crystals
- **240 kg of ^{100}Mo** with >95% enrichment
- Bolometric Ge NTL **light detectors**
- Re-use **CUORE cryogenic infrastructure** @ LNGS
- 10 y **discovery sensitivity** 1.1×10^{27}

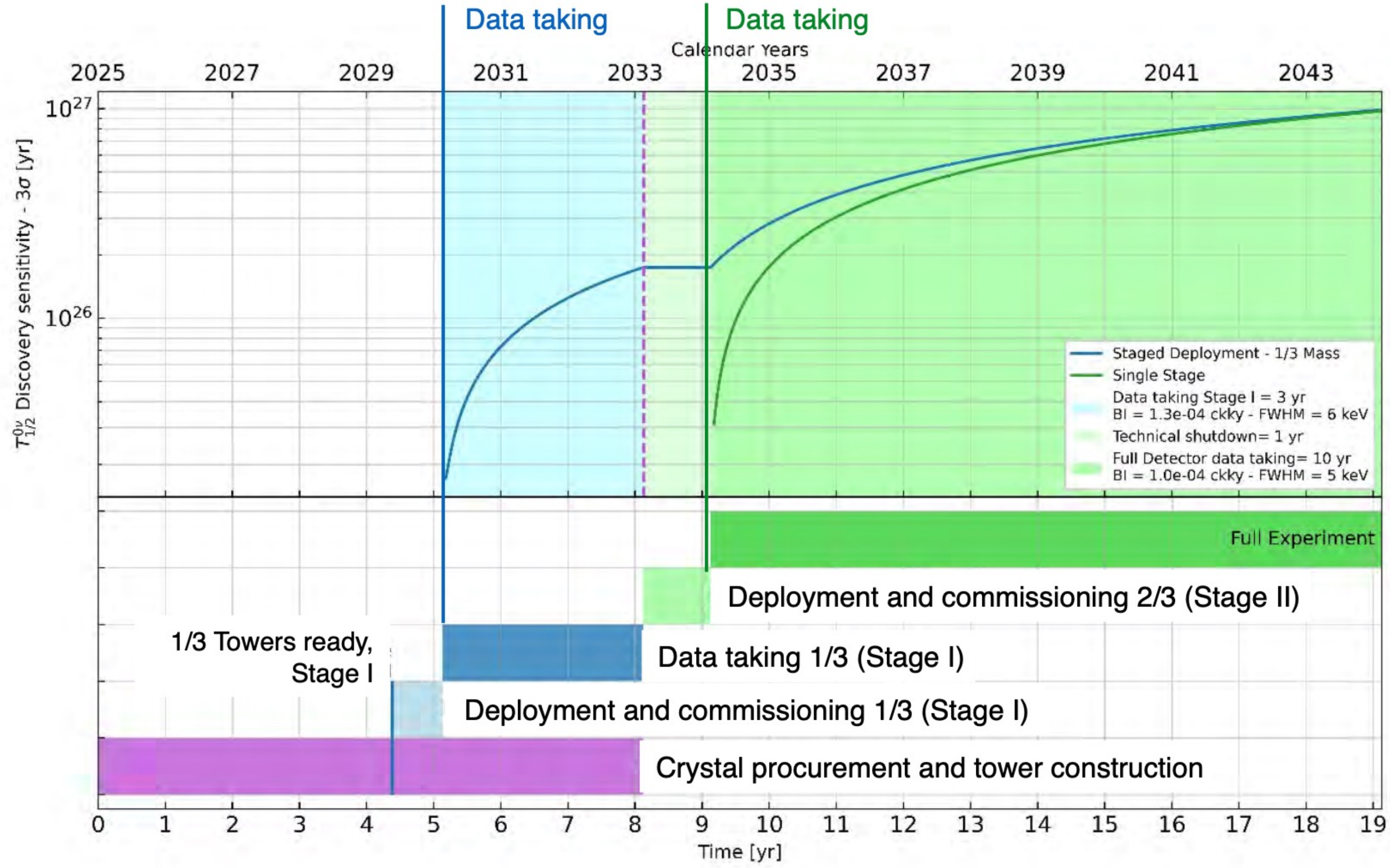


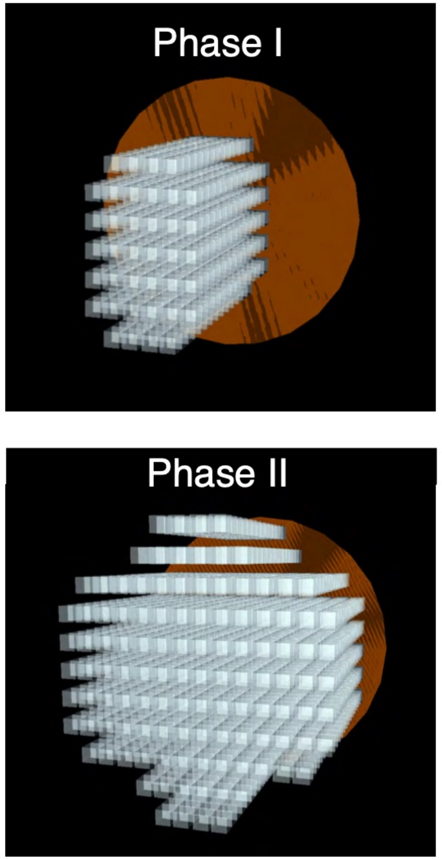




Slide adopted from M. Pavan, 3rd 0nbb summit, May 2025

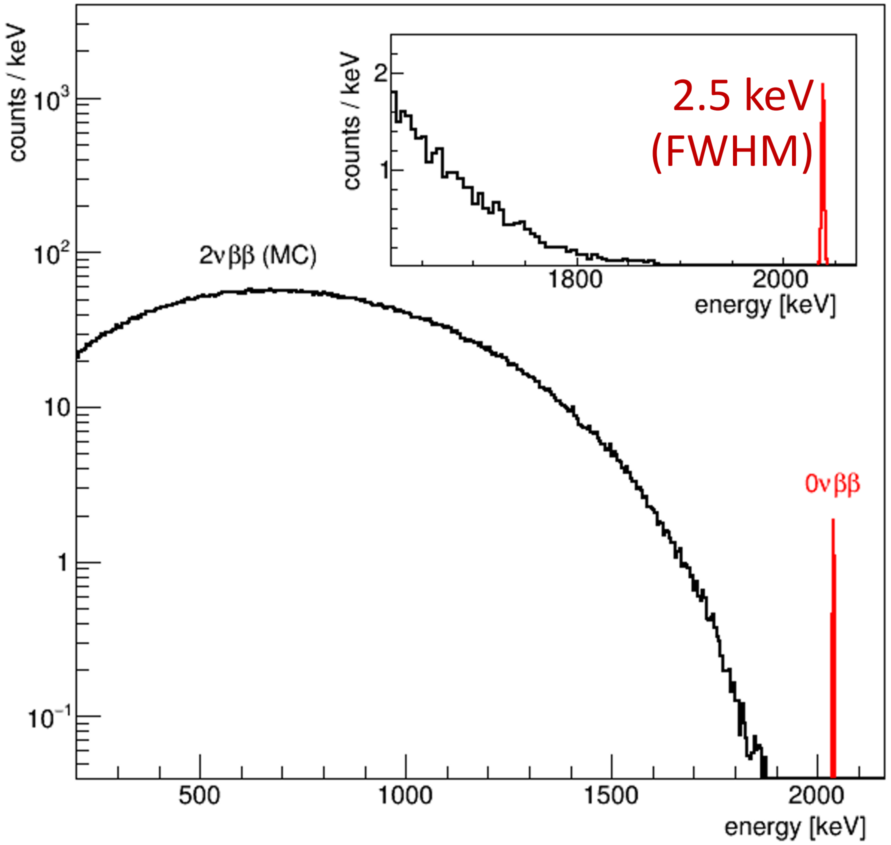
CUPID: staged deployment





Key features of ^{76}Ge $0\nu\beta\beta$ searches

- $^{76}Ge \rightarrow {}^{76}Se + 2e^-$
- Q-value of ^{76}Ge: $Q_{\beta\beta}$ = 2039 keV
- High purity Ge detectors (>90% ^{76}Ge)
    - source = detector => high detection efficiency
    - high purity => no intrinsic background
    - high density => $0\nu\beta\beta$ point like events
    - semiconductor => ΔE ~0.12% (FWHM) at $Q_{\beta\beta}$
- **$0\nu\beta\beta$ signature:**
    - Point-like energy deposition in detector bulk volume
    - Sharp energy peak at 2039 keV (FWHM ~ 2.5 keV)

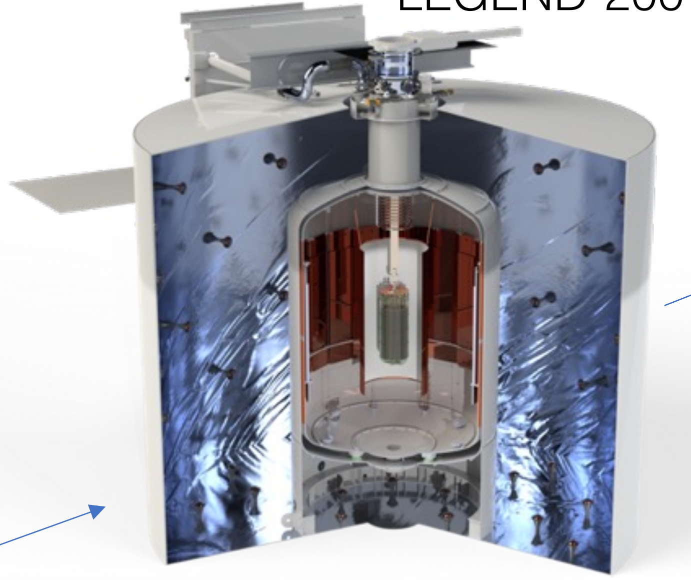


LEGEND: ^{76}Ge HPGe detectors operated in liquid argon

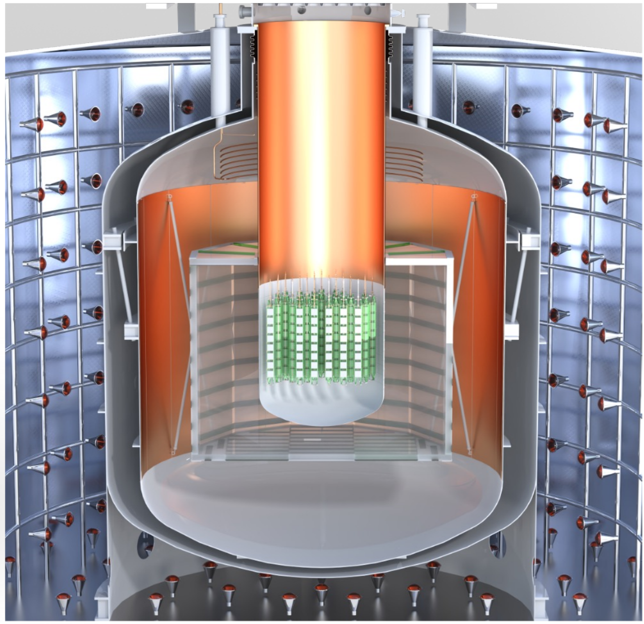
The LEGEND design builds on a track record of breakthrough developments

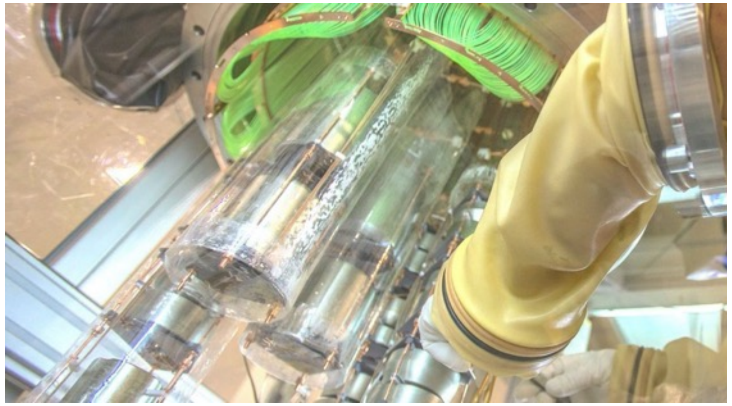
- GERDA : BEGe, LAr instrumentation, cryostat in water shield, fast detector deployment, …
- MAJORANA DEMONSTRATOR (MJD): PPC, EFCu, low-noise front-end electronics,…
- LEGEND-200: Inverted-Coaxial (IC) detectors, polyethylene naphthalate (PEN)…

LEGEND-200



LEGEND-1000





GERDA

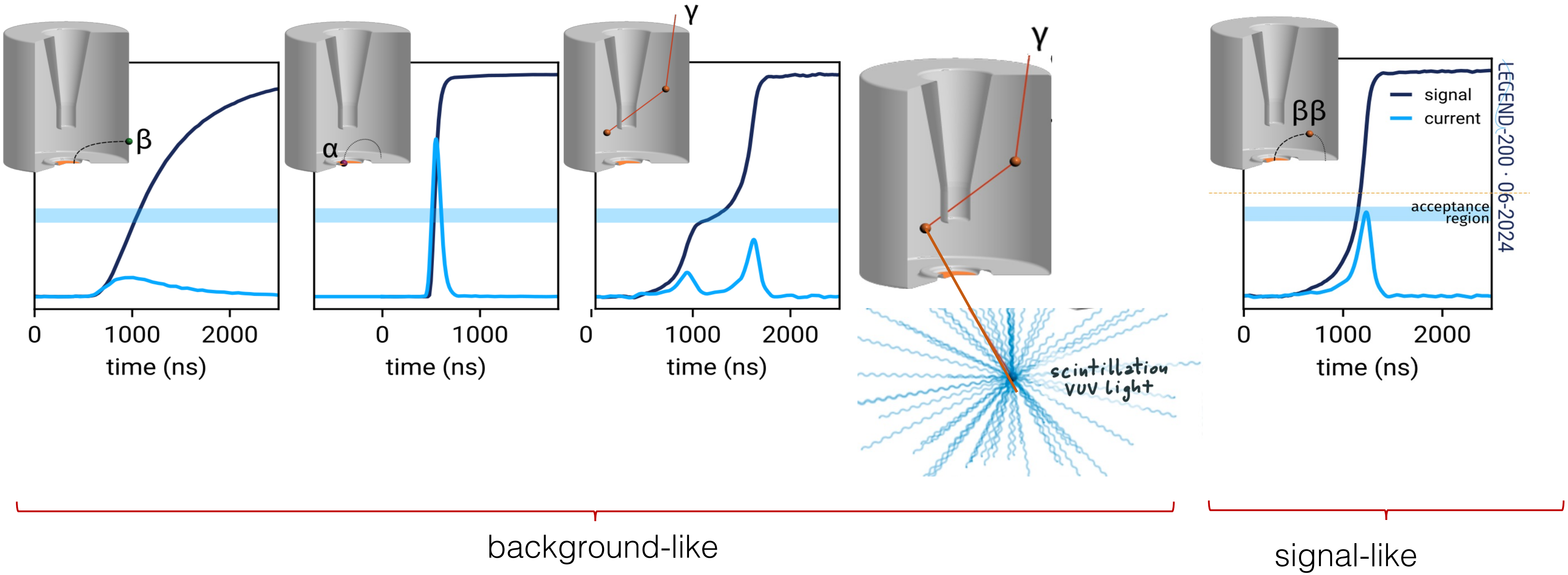
MJD

BEGe: (modified) Broad Energy Ge detectors

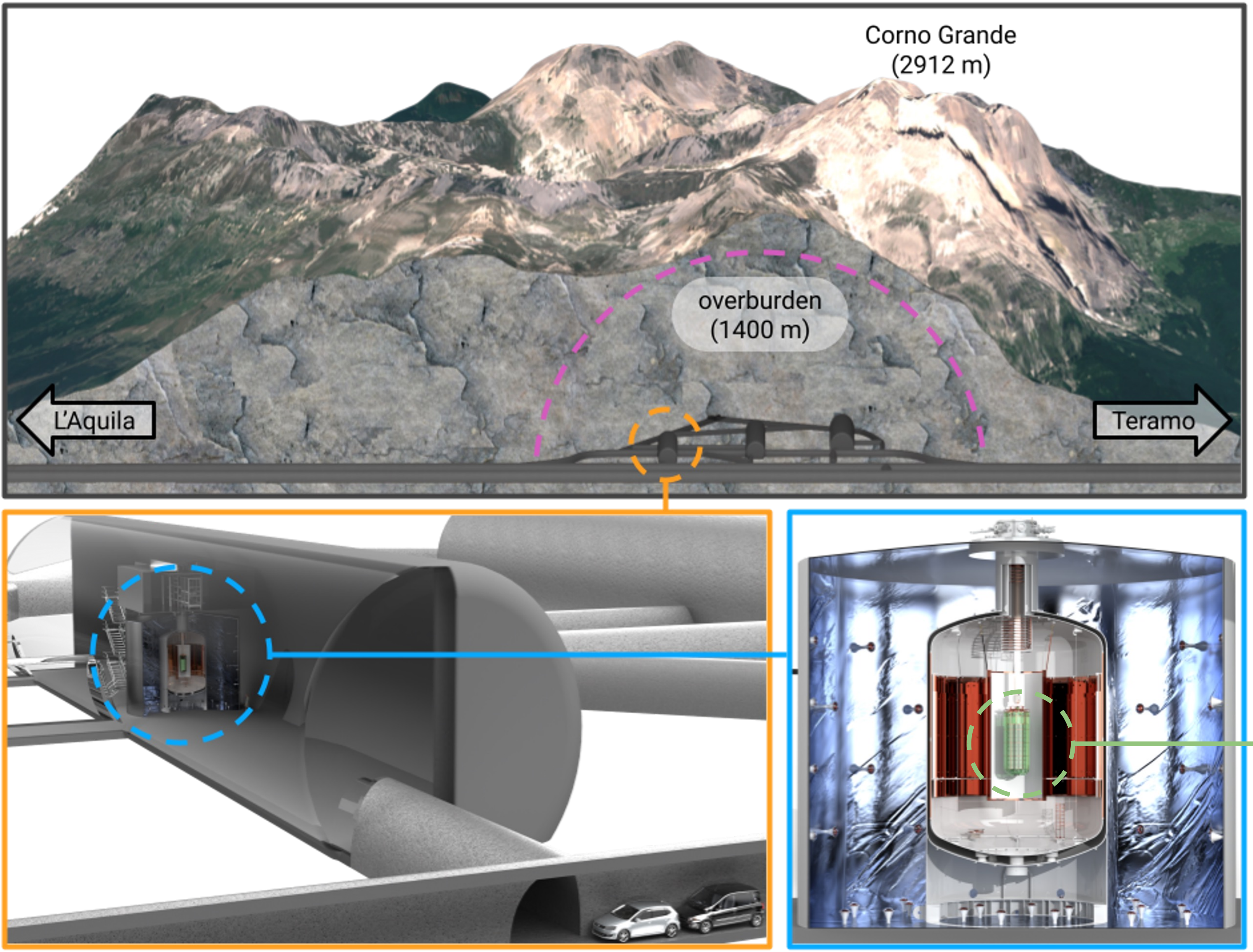
PPC: p-type Point Contact Ge detectors

EFCu: Electroformed copper

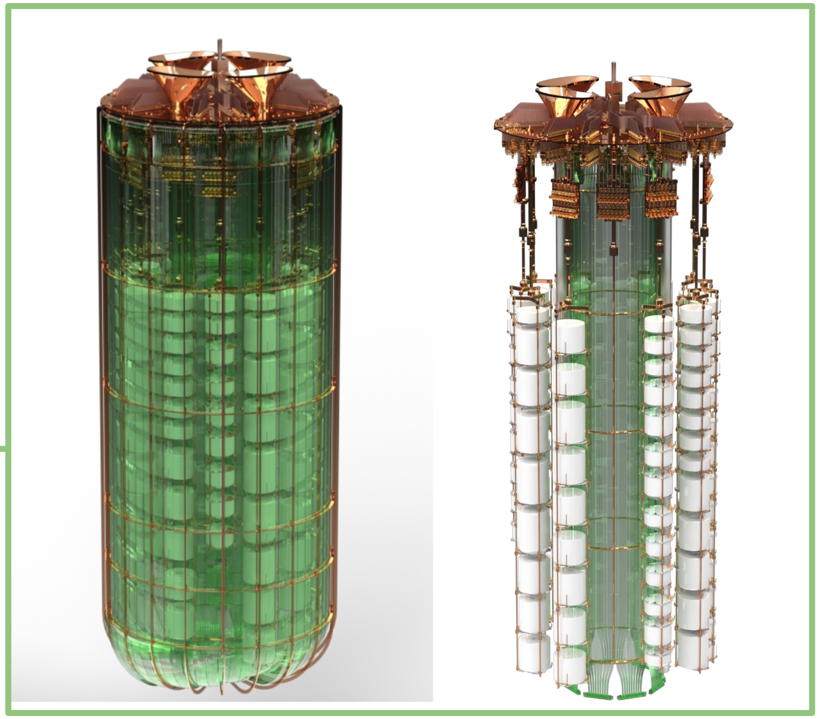
LEGEND event topologies



LEGEND-200 @ LNGS



- 200 kg HPGe Detectors
- LAr instrumentation (Two fiber shrouds)
- Infrastructure of GERDA
- Background < $2 \cdot 10^{-4}$ cts/(keV kg yr)
- $T_{DP} \sim 1 \cdot 10^{27}$ yr

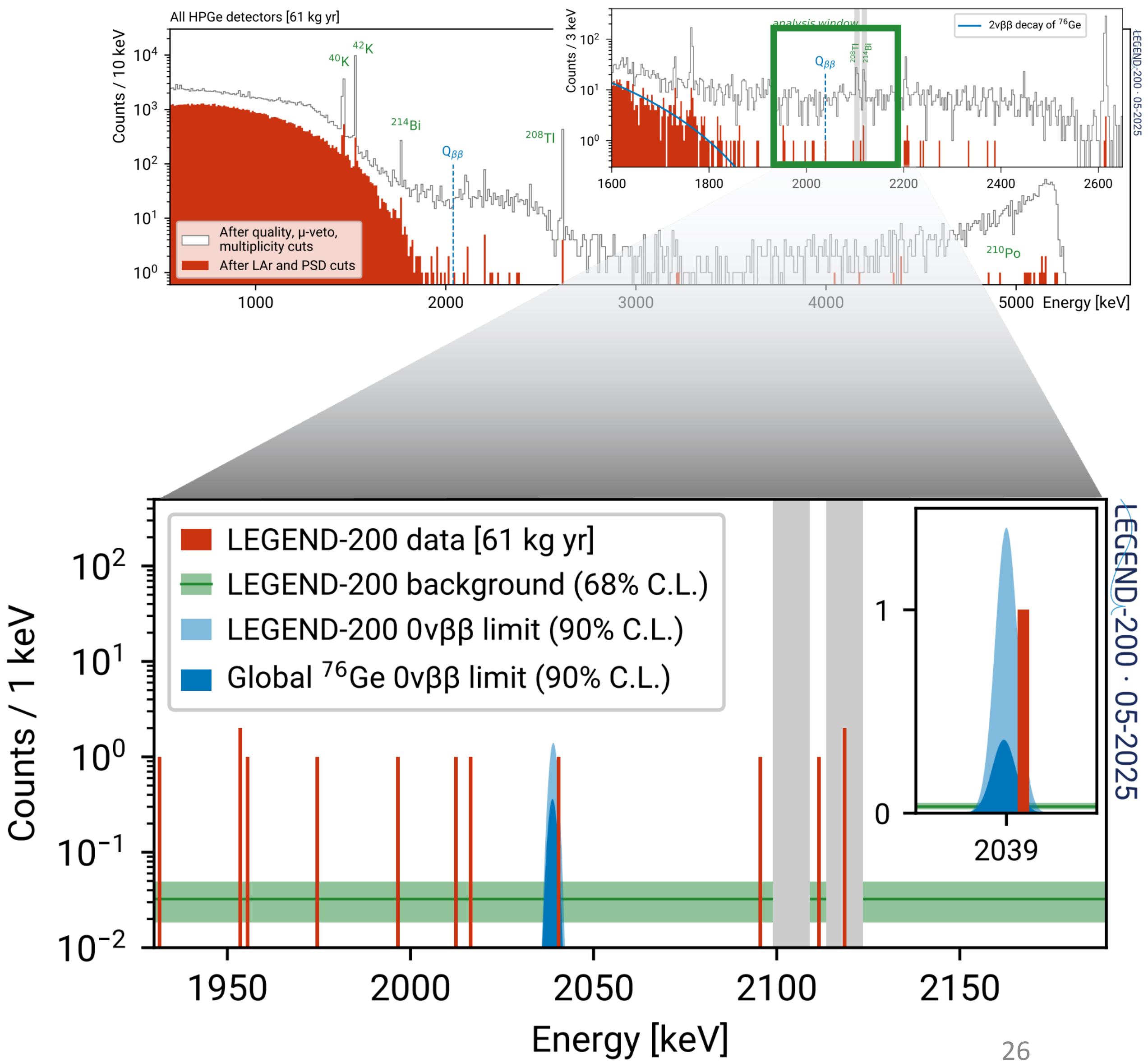


LEGEND-200: Result

- ~ 100 Ge-detectors (142 kg) installed
- ~ 61 kg years of exposure
- **Leading energy resolution:**
  ~ 0.12% FWHM at $Q_{\beta\beta}$
- **Leading background performance:**
  ~ 0.5 cts/keV/t/year
- **Leading sensitivity:** (LEGEND + GERDA + MAJORANA)
  $T_{1/2} > 2.8 \cdot 10^{26}$ years (90% CL)

✓ $T_{1/2} > 1.9 \cdot 10^{26}$ years (90% CL)

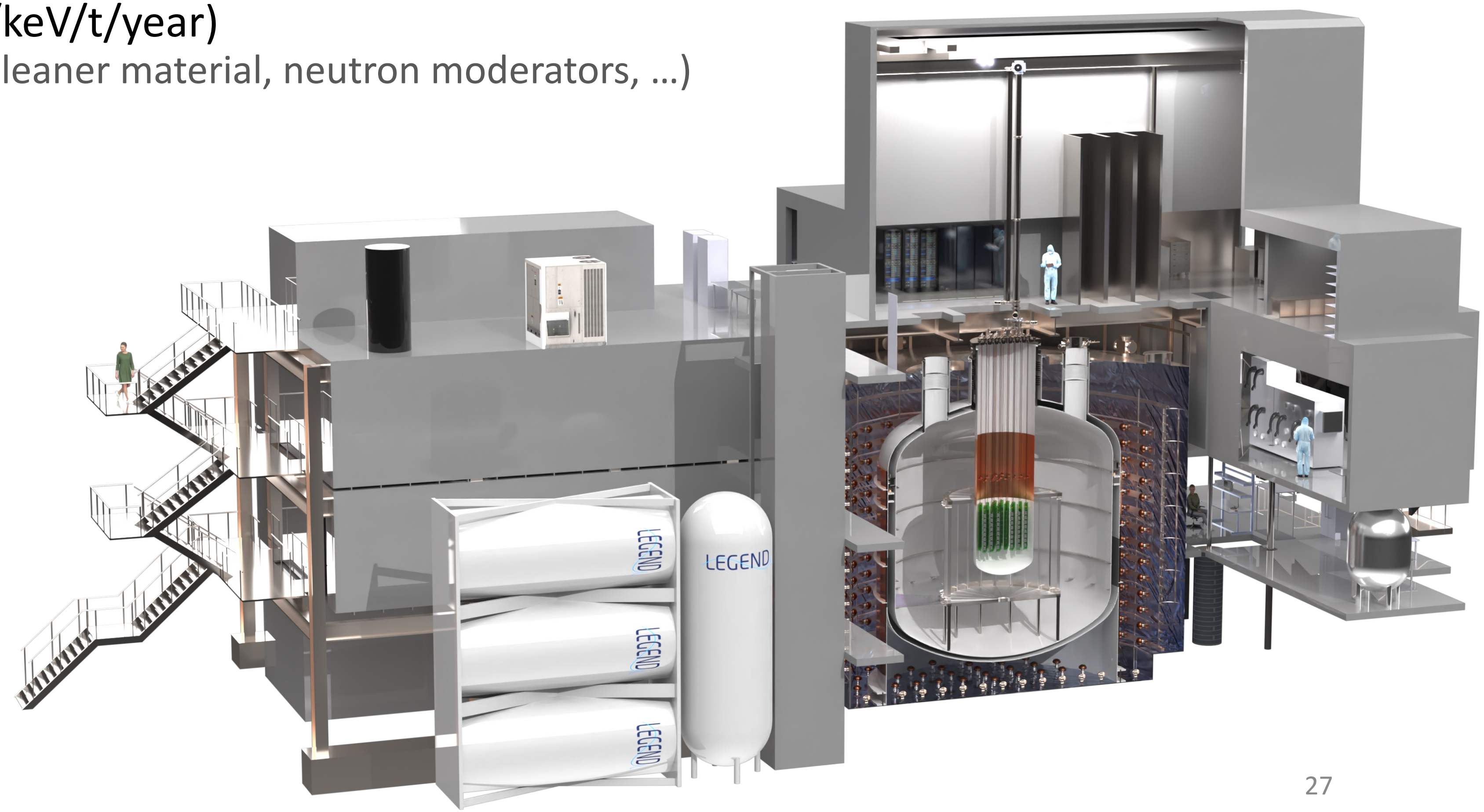
✓ $m_{\beta\beta} < 75 – 200$ meV*



PRL 125, 252502 (2020)
PRL 130, 062501 (2022)
arXiv:2505.10440 [hep-ex] (2025) *Exposure: 250 kg · y ^{76}Ge, NME = 1.6 - 4.8

LEGEND-1000 @ LNGS

- more mass (1000 kg)
- lower background (0.01 cts/keV/t/year)
  (underground-sourced argon, cleaner material, neutron moderators, …)



LEGEND-1000: Novelties

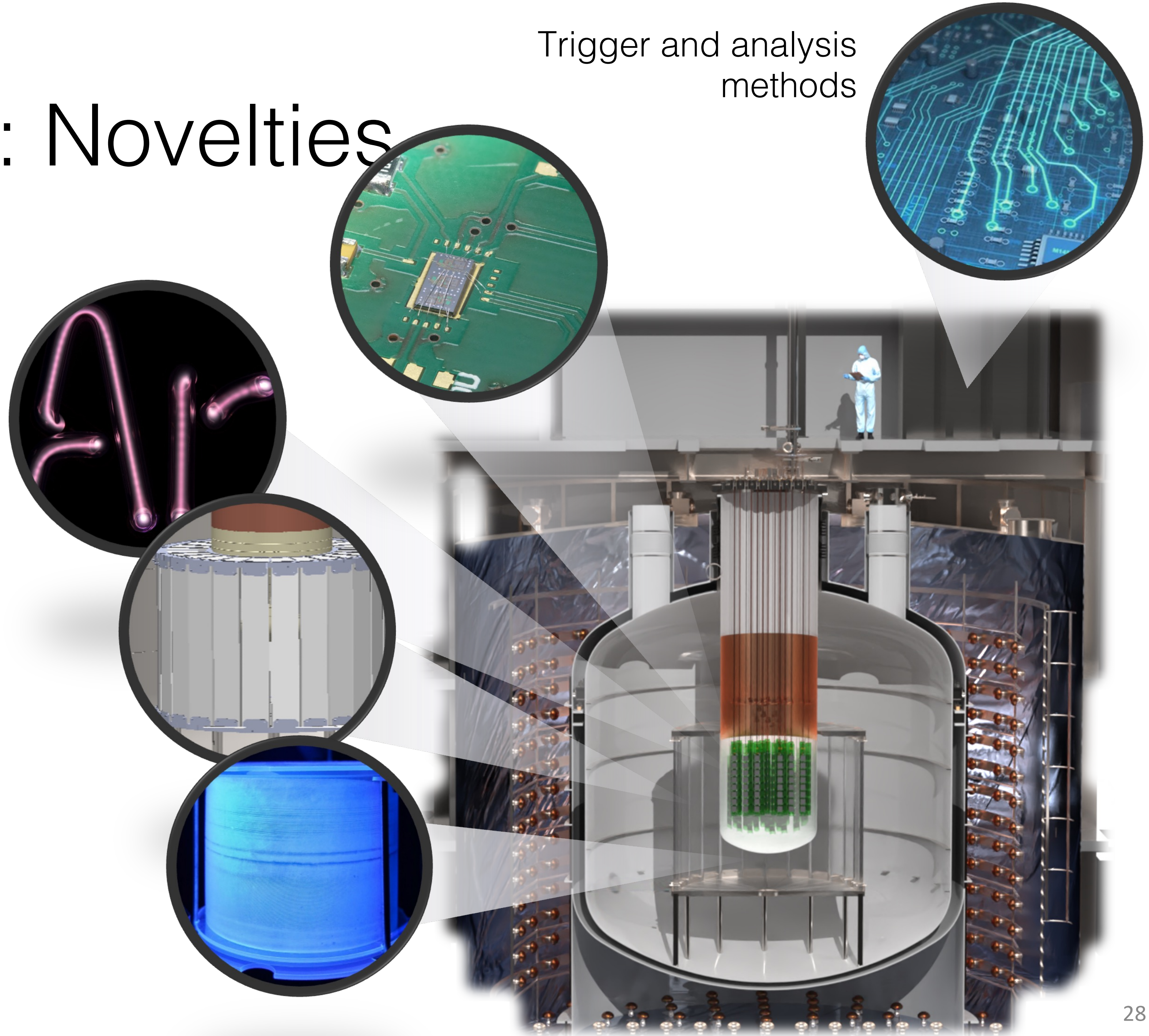
Trigger and analysis methods

ASIC-based readout
Improved signal quality

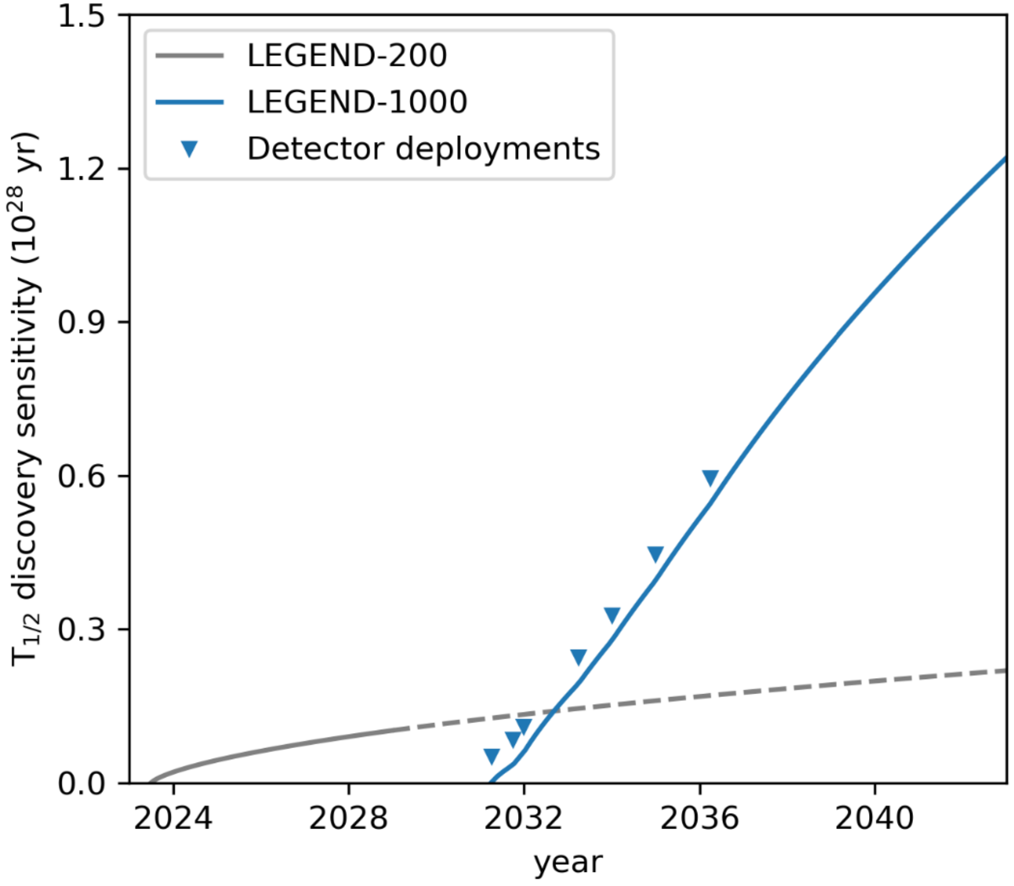
Underground argon
Reduction of argon-42

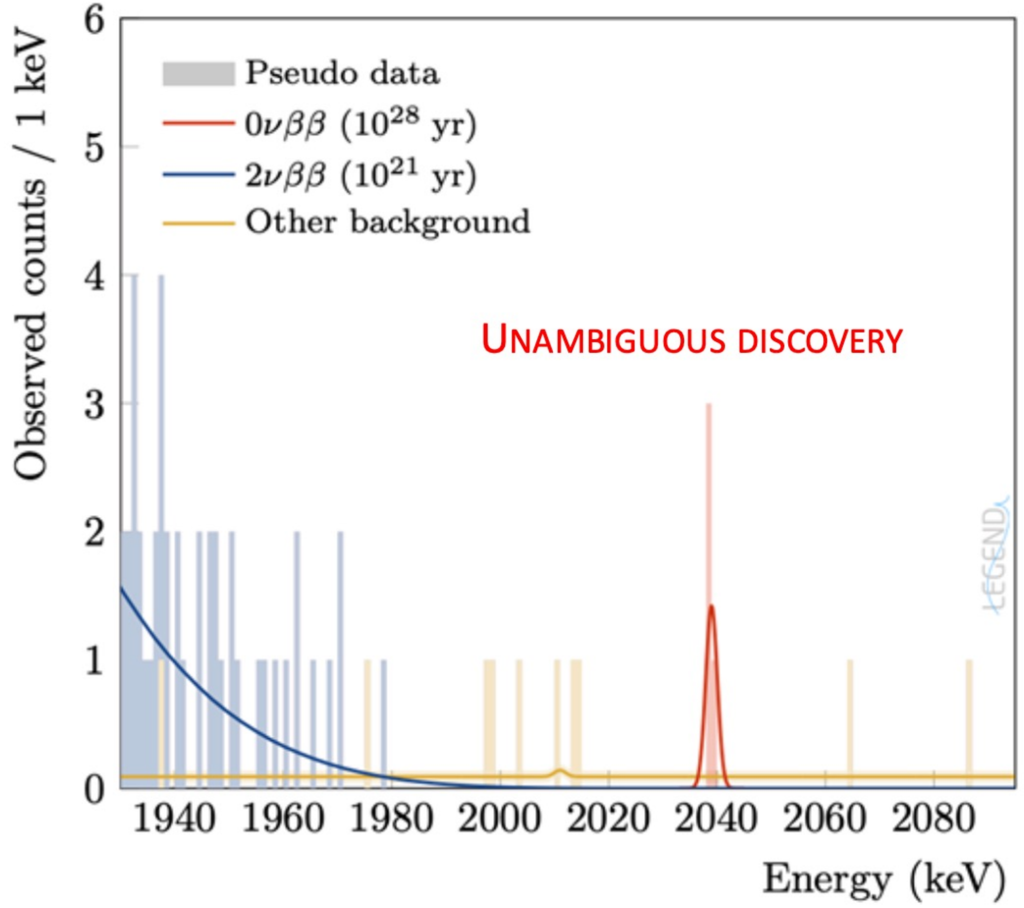
Neutron moderator + tagger
Reduction of neutron-induced bg

Clean and scintillating materials
Improved background



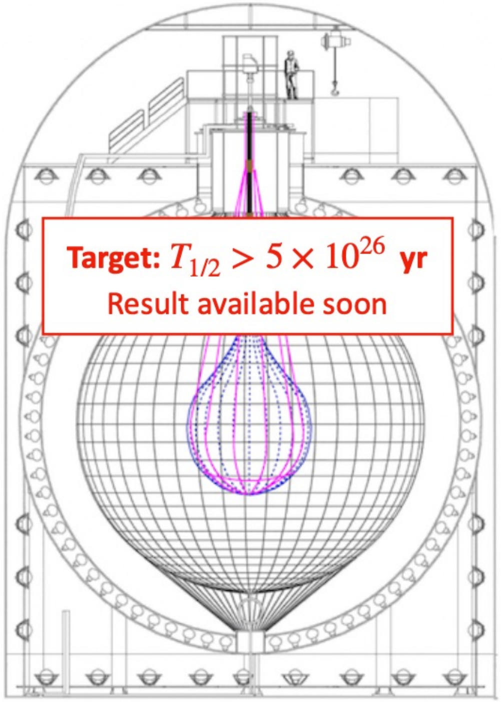
LEGEND-1000: Discovery sensitivity

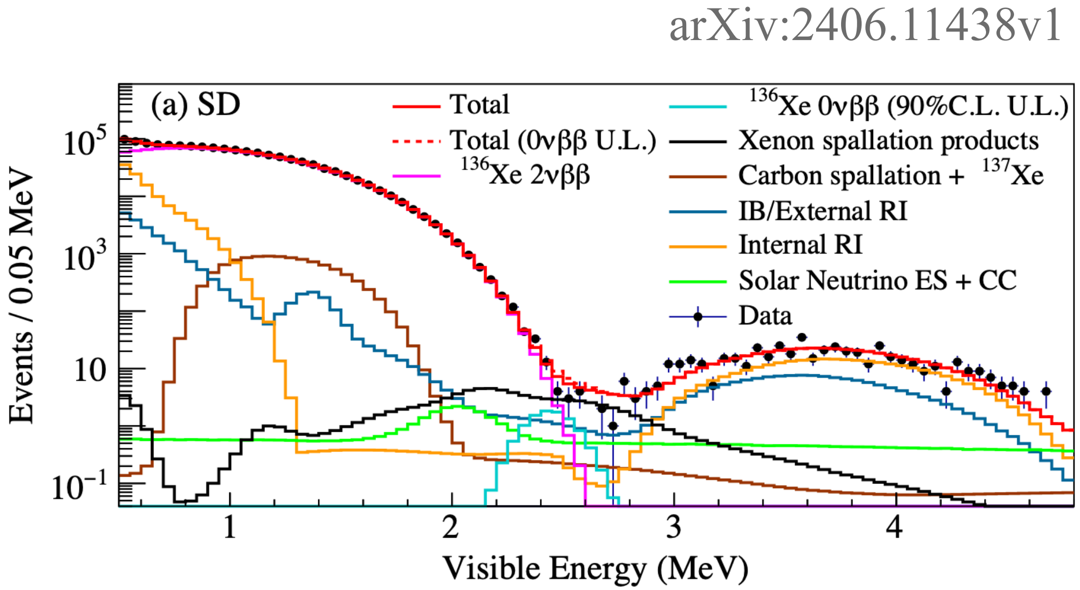


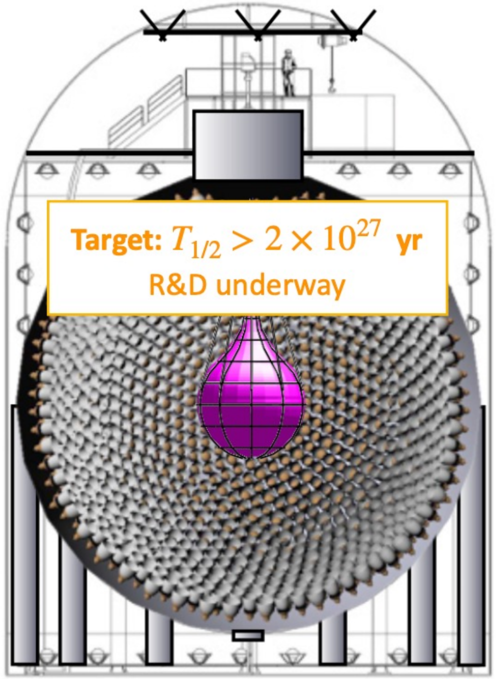


Projects in Asia

KamLAND-Zen: ^{136}Xe loaded liquid scintillator







KamLAND-Zen 800:

- Mini-balloon Radius = 1.90 m
- Xenon mass = 745 kg
- Data taking starts Jan. 2019

Completed

- Sensitivity: > 2.6 10^{26} yr (90% C.L.)
- Limit: > 3.8 10^{26} yr (90% C.L.)

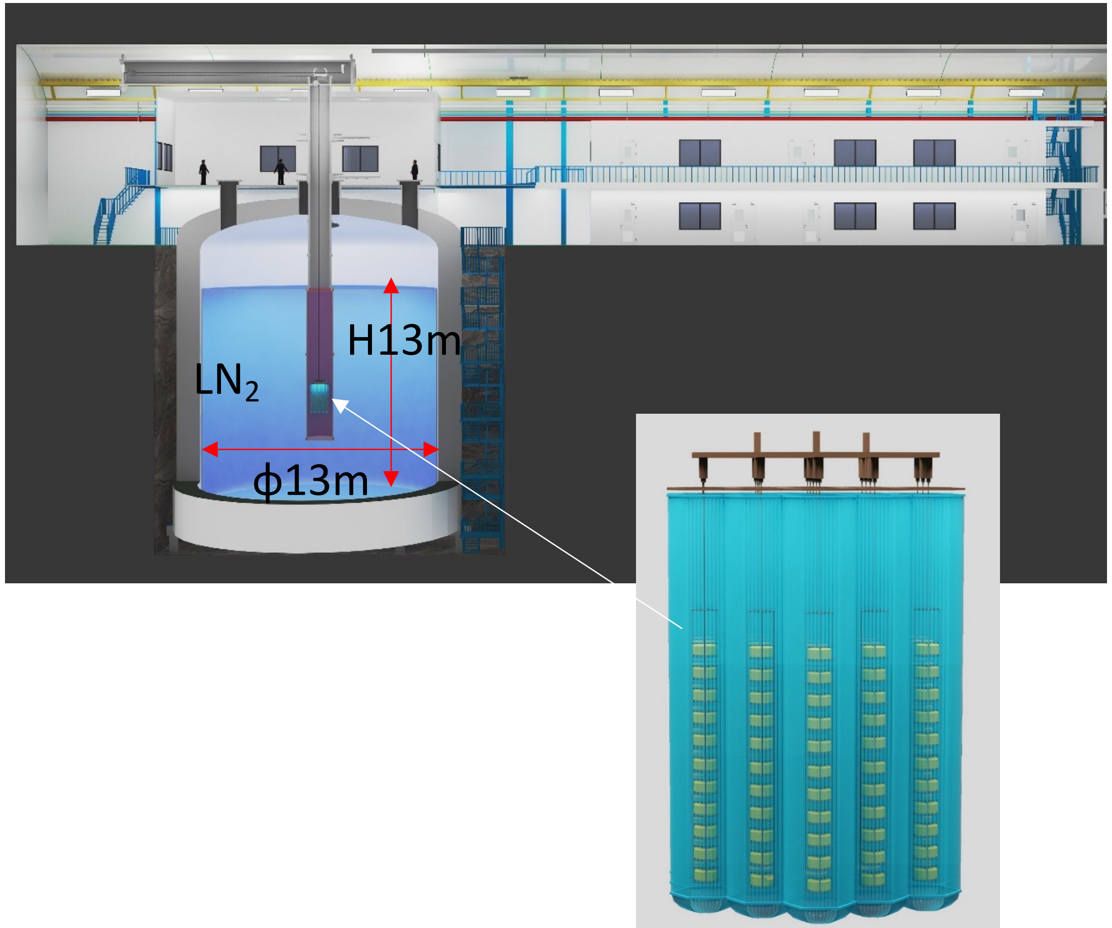
KamLAND2-Zen:

- Xenon mass ~ 1ton
- Aiming at 100% Photocoverage
- PEN scintillation balloon film

Under preparation ~2027

^{76}Ge: CDEX-300v @ CJPL

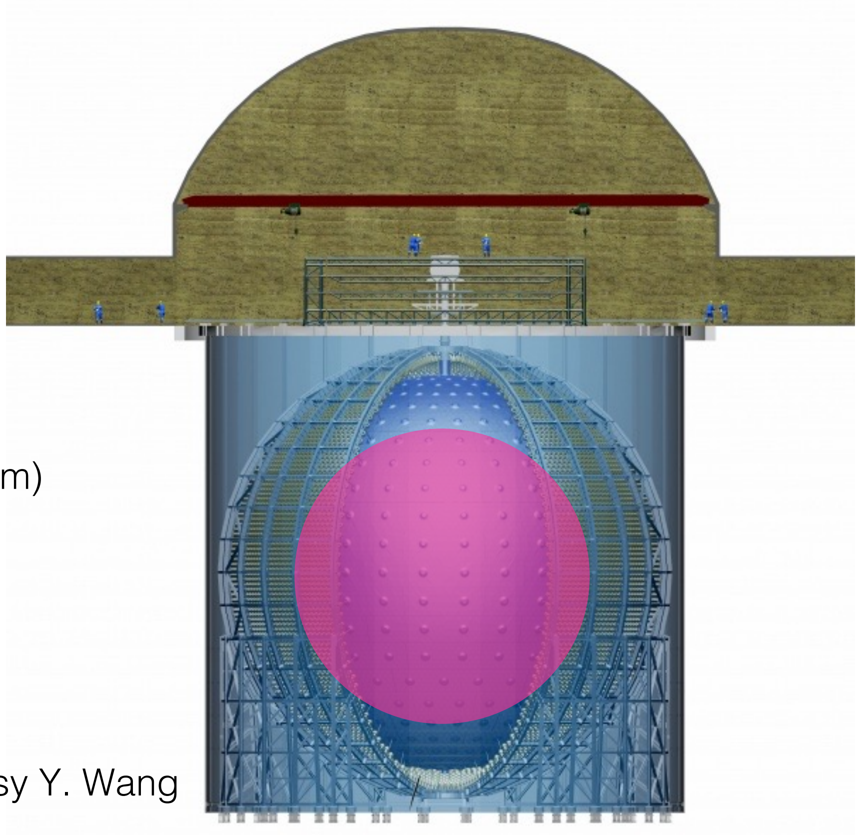
Adaptation of LEGEND concept



- 1725m^3 LN_2 for shielding and Cooling;
- Φ1.5m*8m copper tube filled with **LAr** and immersed into LN_2 for cooling;
- Enriched Ge array in LAr media for cooling and **active LAr shielding.**
- 1st 100kg >86% $^{76}GeO_2$ in CJPL, 2nd 100kg ready in the first half of 2023; 3rd 100kg: under preparation;
- Enriched **BEGe** detectors: First batch (30-40 detectors) at CJPL in 2023

^{nat}Te-loaded liquid scintillator: JUNO

- 20 kt LS (LAB, 2.5 g/L PPO, 3 mg/L Bis-MSB)
- Main goals: **neutrino mass ordering** with reactor neutrinos, geo-, solar, atm-nu's
- After completion of mass ordering **(~2030)** upgrade for 0nbb search with ^{nat}Te or ^{136}Xe
- Huge target mass (100 t scale) and aspired low background
- High PMT coverage => 1200 p.e./MeV
- Reported R&D results on Te-diol based LS:
    - Best performance so far with 0.6% Te-loading
    - NO measurable difference in attenuation length compared to purified LAB (A.L. > 20m)
    - NO degradation after 6 months
    - Relative light output: 60%~70% w.r.t un-loaded LS
- Ambition: towards exploration of normal mass ordering

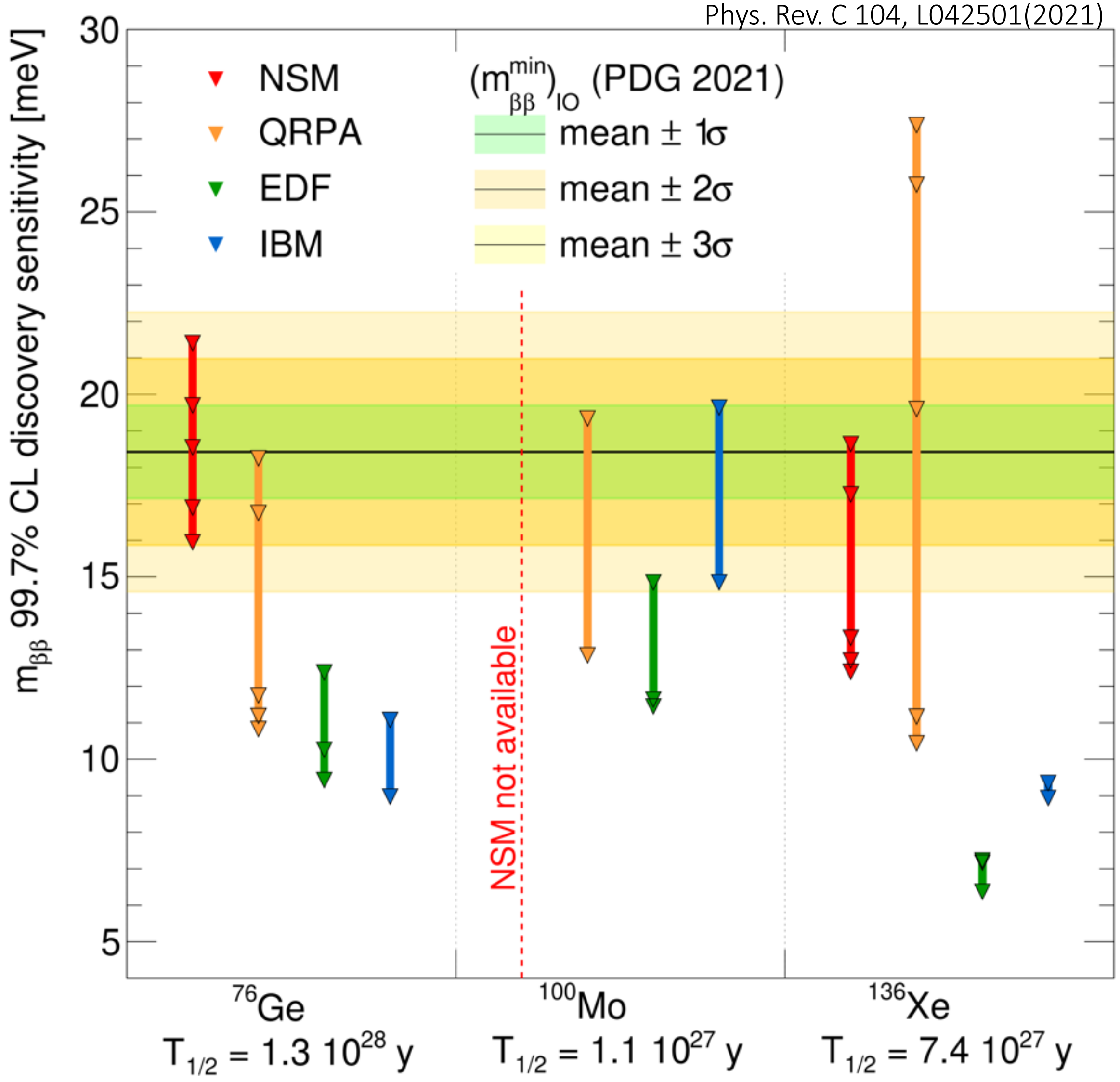


Courtesy Y. Wang

Comparison of $m_{\beta\beta}$ sensitivities

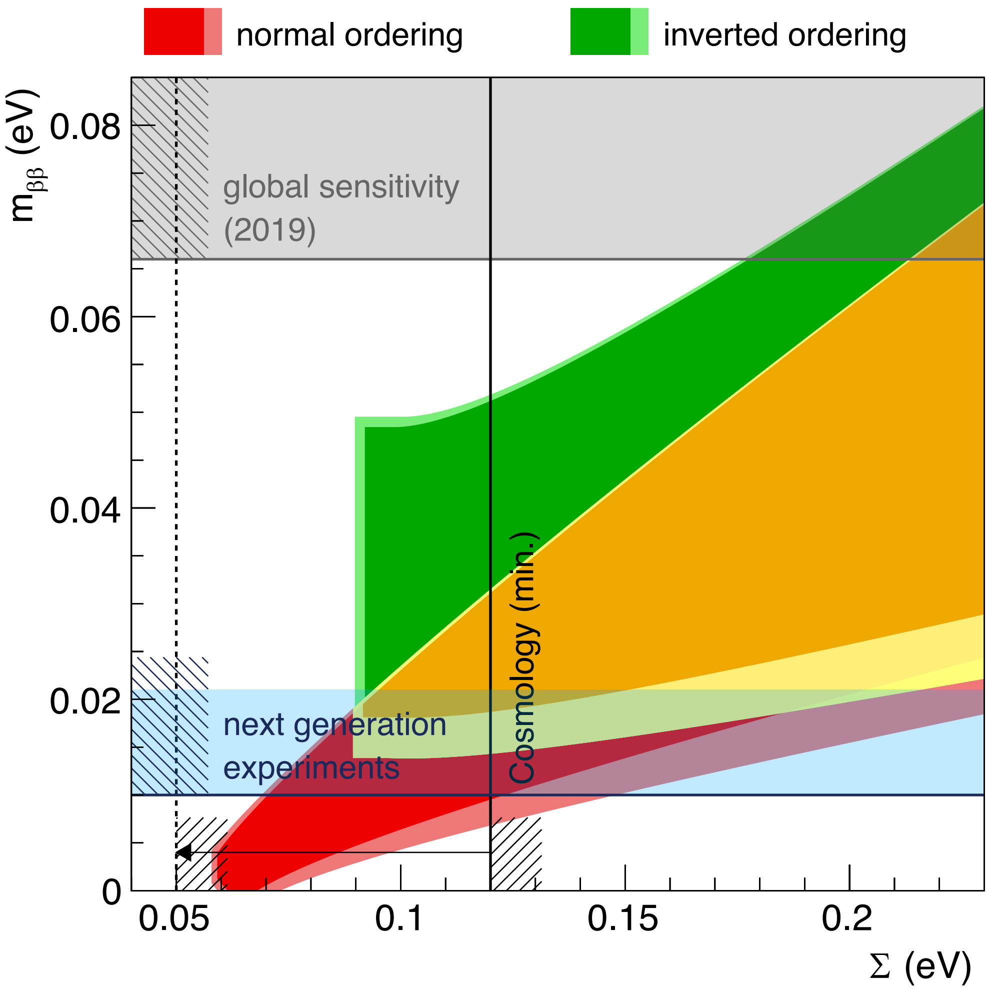
- Inverted ordering: $m_{\beta\beta} > 18.4 \pm 1.3$ meV
- M → 4 many-body methods, each with specific systematics
- Multiple, different set of calculations for each many-body method and isotope

Agostini, Detwiler, Benato, Menendez, Vissani
"Testing the Inverted Neutrino Mass Ordering with 0νββ Decay"
Phys. Rev. C 104, L042501(2021)



Summary & Outlook

- Major progress for preparation of **ton-scale** experiments over last few years
- Experiment design for **discovery** (not limit setting)
- Will fully explore **IO** and large part of **NO**
- Several DBD isotopes and techniques required, given **NME uncertainties** and **confirmation** in case of discovery
- Formidable **experimental challenges** to acquire ton yr exposure quasi **background free**
- North-American – European **convergence on portfolio** of experiments contingent on funding: current front-runners are LEGEND-1000, CUPID and nEXO; key R&D on Ba-tagging by NEXT
- Asia: KL2Z (under preparation), Amore, CDEX, JUNO
- **Availability of DBD isotopes** from Western & Chinese supplier
- How to go to **bottom of NO**? Assess **performance** of ton-scale experiments first. All upcoming experiments have the potential to further **increase exposure** and reduce **backgrounds**



Courtesy C. Wiesinger