Berkeley
UNIVERSITY OF CALIFORNIA

Neutrinoless Double Beta Decay

Current Status and Future Prospects

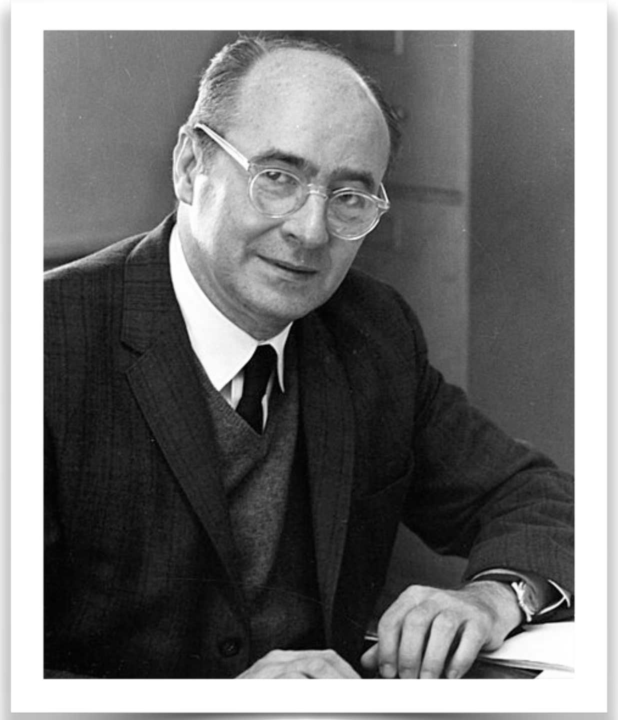
Historical Introduction

- **1930:** Wolfgang Pauli proposes the neutrino to explain energy conservation in beta decay.
- **1935:** Maria Goeppert-Mayer predicts double beta decay (2νββ), where two neutrons decay simultaneously, emitting two electrons and two neutrinos.
- **1937:** Ettore Majorana theorizes that neutrinos could be their own antiparticles (Majorana fermions).
- **1939:** Wendell H. Furry proposes neutrinoless double beta decay (0νββ), which would violate lepton number conservation and prove the Majorana nature of neutrinos.
- **Ongoing (85 years on!):** Experimental searches for 0νββ continue, aiming to determine the nature of the neutrino and its mass.


Pauli


Goeppert-Mayer

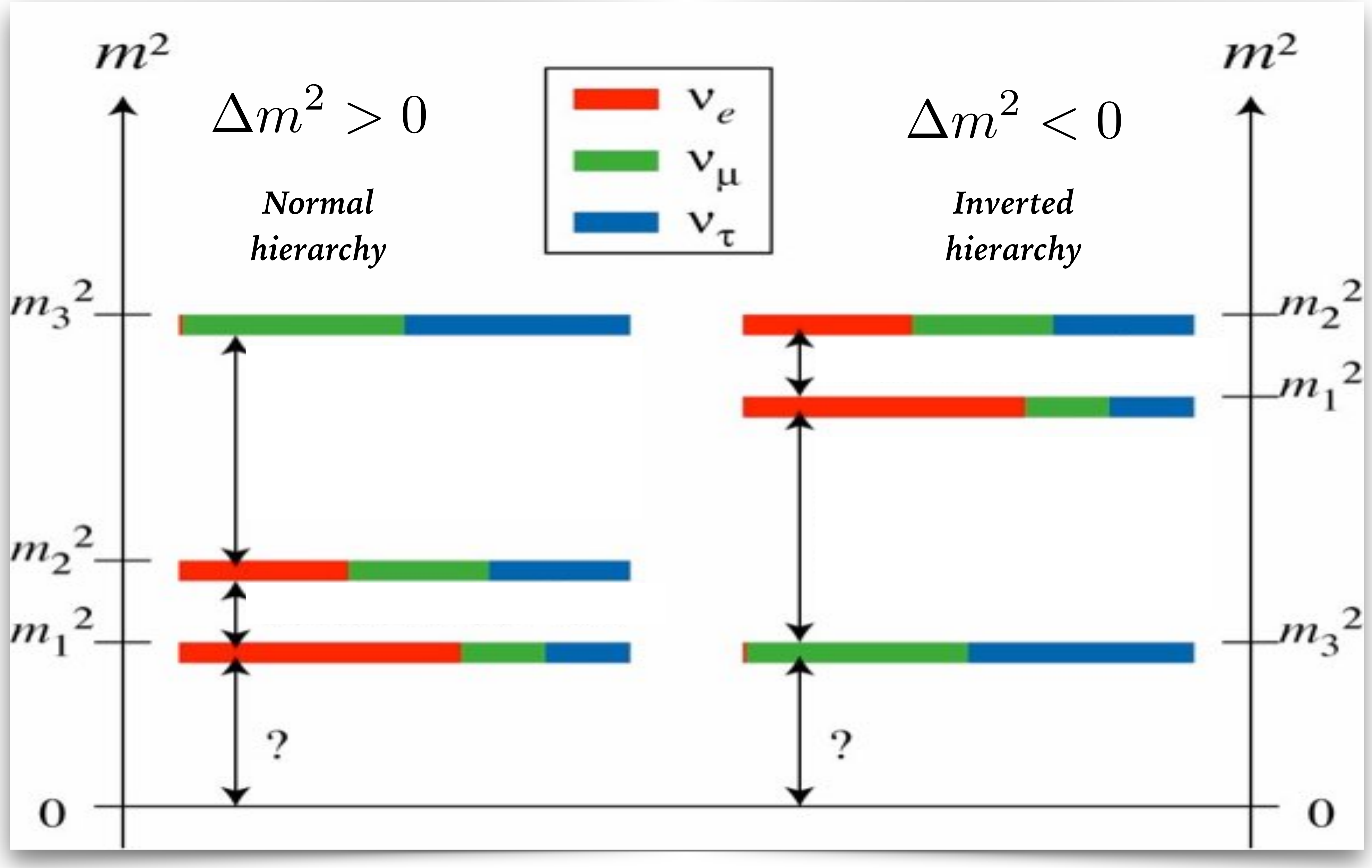

Majorana


Furry

Neutrinos

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta} & 0 & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}1 & 0 & 0\\ 0 & e^{i\frac{\alpha_2}{2}} & 0\\ 0 & 0 & e^{i\frac{\alpha_3}{2}}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

Experiments:	Atmospheric /Accelerator	Reactor/ Accelerator	Solar/ Reactor	$0\nu\beta^-\beta^-$



$$\Delta m^2_{21} = m_2^2 - m_1^2$$

$$\Delta m^2 = m_3^2 - (m_2^2 + m_1^2)/2$$

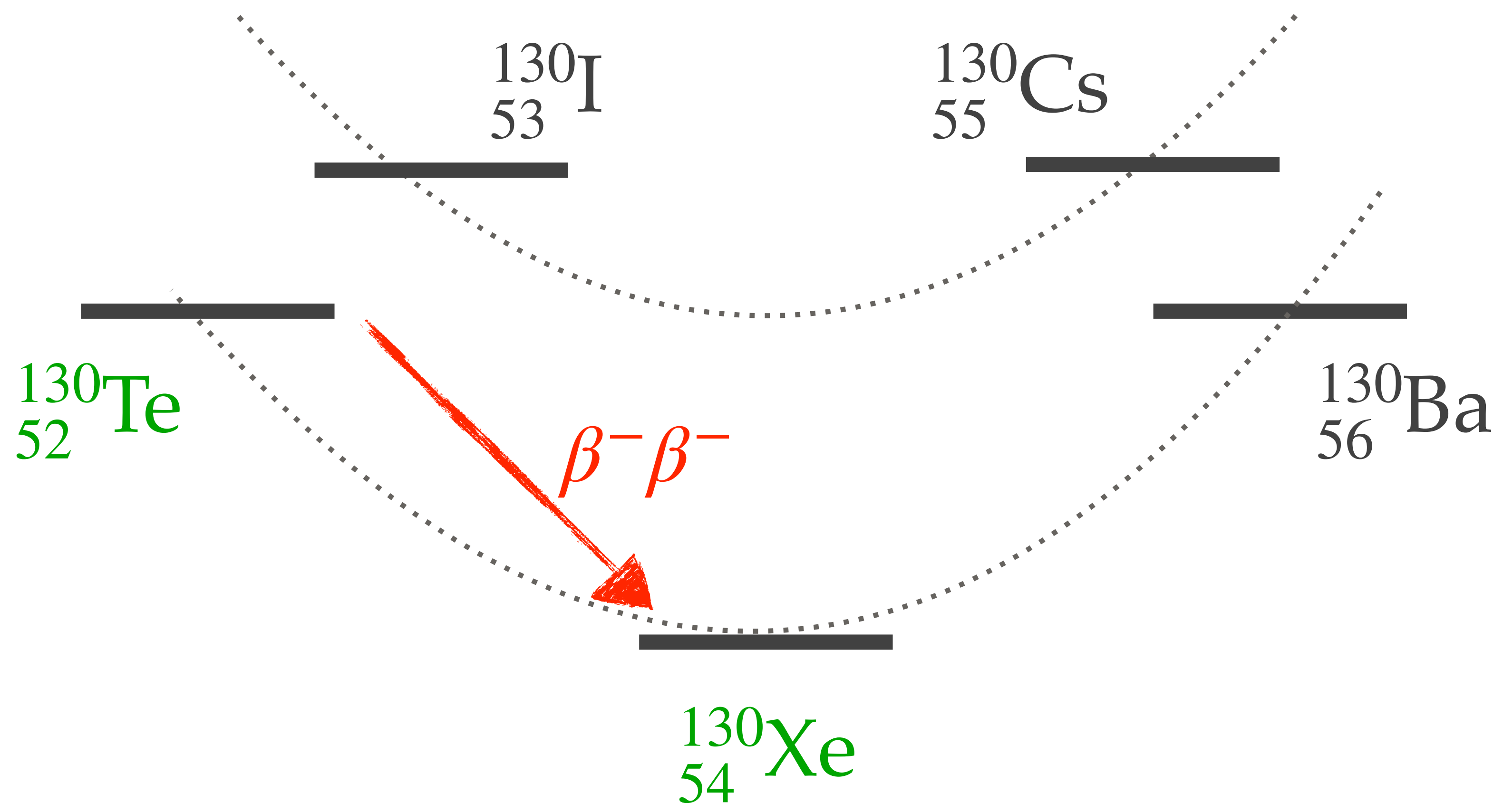
Open questions:

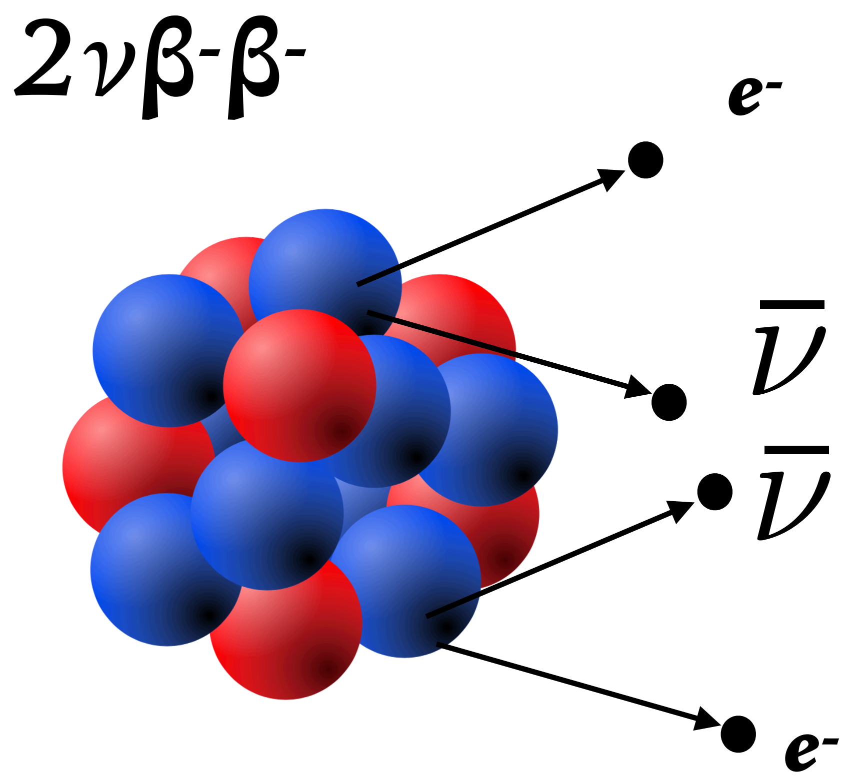
- Are there only three neutrinos?
- What is the mass scale?

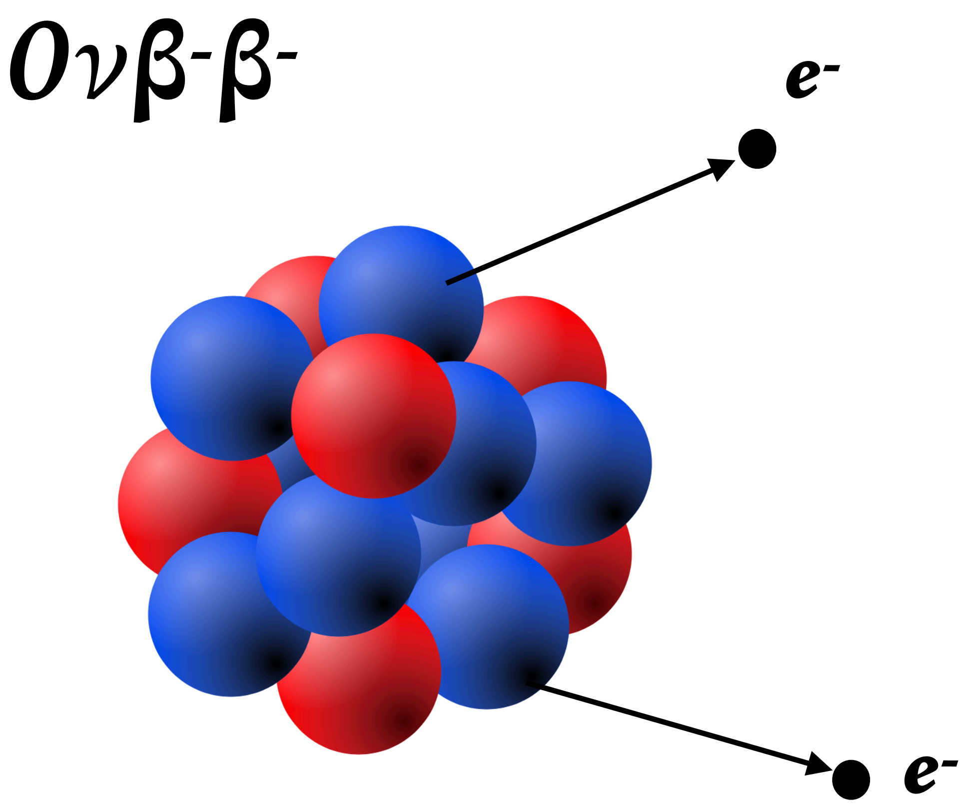
Other properties that cannot be probed using oscillation data:

- Are neutrinos their own antiparticles? (Majorana or Dirac?)
- Can neutrinos shed light on lepton number conservation?
- Are neutrinos responsible for matter anti-matter asymmetry in the universe?

Neutrinoless Double Beta Decay (0νββ)





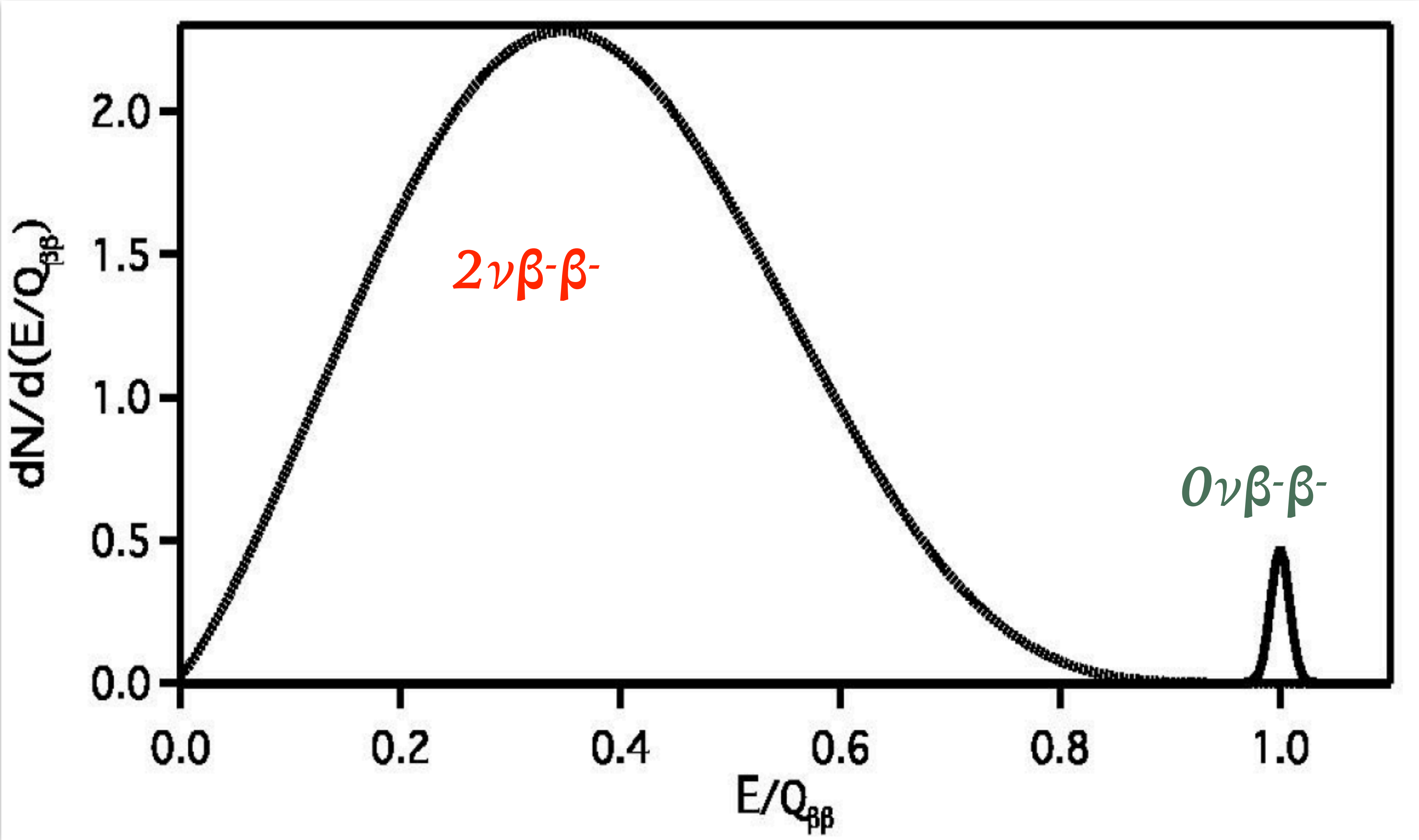


- **Single beta decay forbidden.**

- **~35 nuclei candidates**

- **Can happen only if neutrinos are Majorana particles.**
- **Lepton number violation ($\Delta L = 2$)**
- **Requires physics beyond standard model.**
- **Only 11 have $Q_{\beta\beta}$ > 2MeV**

Experimental Signature & the Decay Rate



- Sum energy of emitted electrons: Peak at Q value of the decay.
- $G^{2\nu}(Z,Q)$ for (2νβ-β-) ∝ Q^{11}
- $G^{0\nu}(Z,Q)$ for (0νβ-β-) ∝ Q^5

$$[T_{\frac{1}{2}}^{0\nu}]^{-1} = \sum_i G_i^{0\nu}(Z,Q) \cdot \left| M_i^{0\nu} \right|^2 \cdot \zeta_i^2$$

- $G^{0\nu}(Z,Q)$is the phase-space factor that depends on the proton number (Z) of the decaying nucleus and the Q-value of the decay,
- $M_i^{0\nu}$is the nuclear matrix element (NME), and
- ζ_i depends on the mechanism and mode of the lepton-number-violating process.

In the scenario light-neutrino exchange

$$[T_{\frac{1}{2}}^{0\nu}]^{-1} = G^{0\nu}(Z,Q) \cdot (g_A)^4 \cdot \left| M^{0\nu} \right|^2 \cdot \frac{m_{\beta\beta}^2}{m_e^2}$$

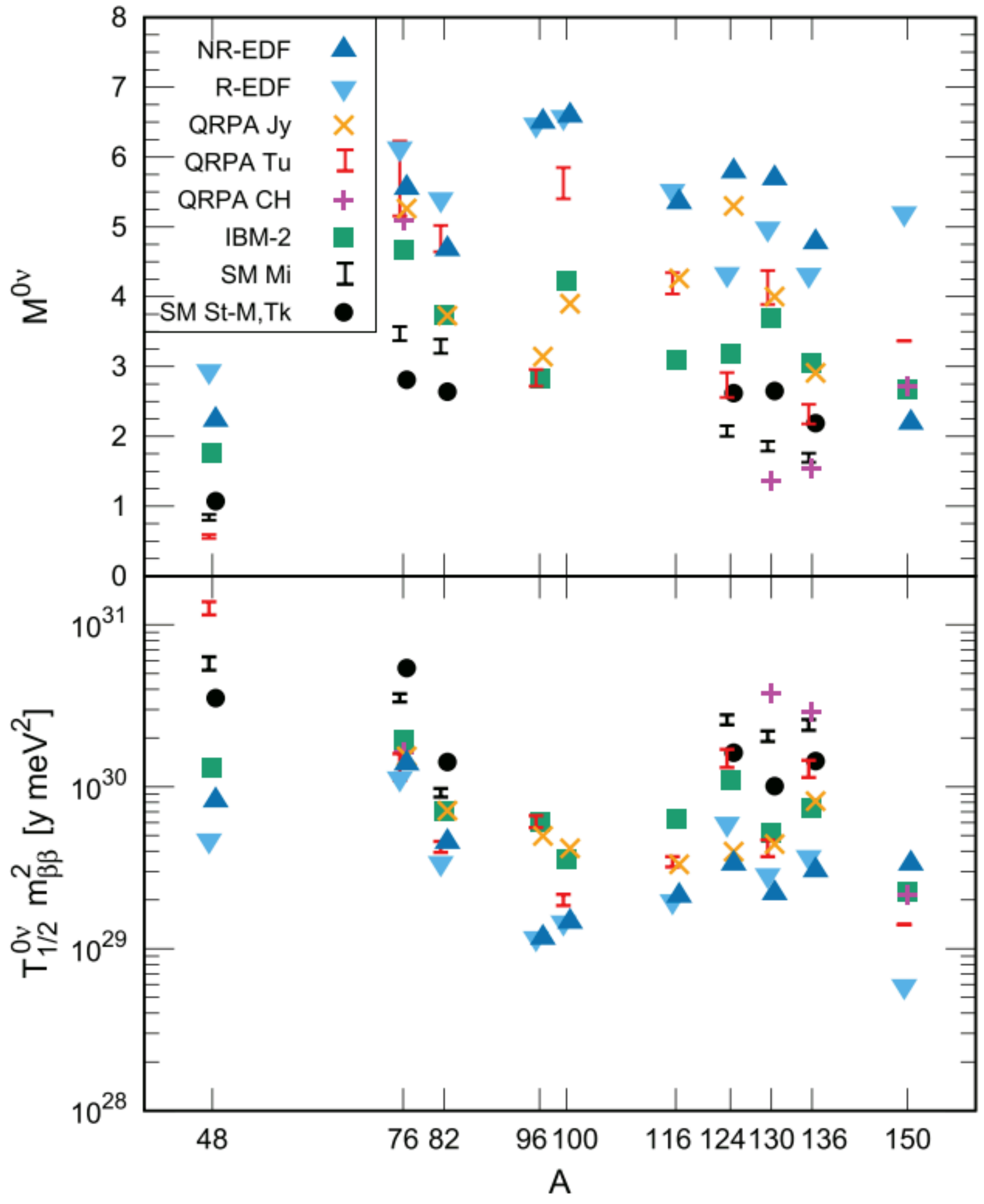
Axial vector coupling (factored out of NME)

Effective Majorana mass

$$|m_{\beta\beta}| = |\sum_{i=1}^{3} U_{ei}^2 m_i|$$

Nuclear Matrix Elements Calculations

- Extremely hard problem to solve
- Both microscopic and macroscopic nuclear models are used to calculate NMEs, each with its own strengths and limitations
- Different successful approaches (e.g., IBM, QRPA, EDF) disagree by a factor of 2-3
- Difficult to quantify errors in a reliable way
- Ab-initio methods but not yet applicable to heavy nuclei
- Various experimental probes, including charge exchange reactions, nucleon exchange, muon capture, double gamma decay, etc are used to test and constrain NME calculations



: Jonathan Engel and Javier Menéndez 2017 Rep. Prog. Phys. 80 046301

Experimental Sensitivity

$$T^{0\nu}_{1/2} \propto \epsilon \cdot \sqrt{\frac{M \cdot t}{B \cdot \Delta E}}$$ (Background Limited)

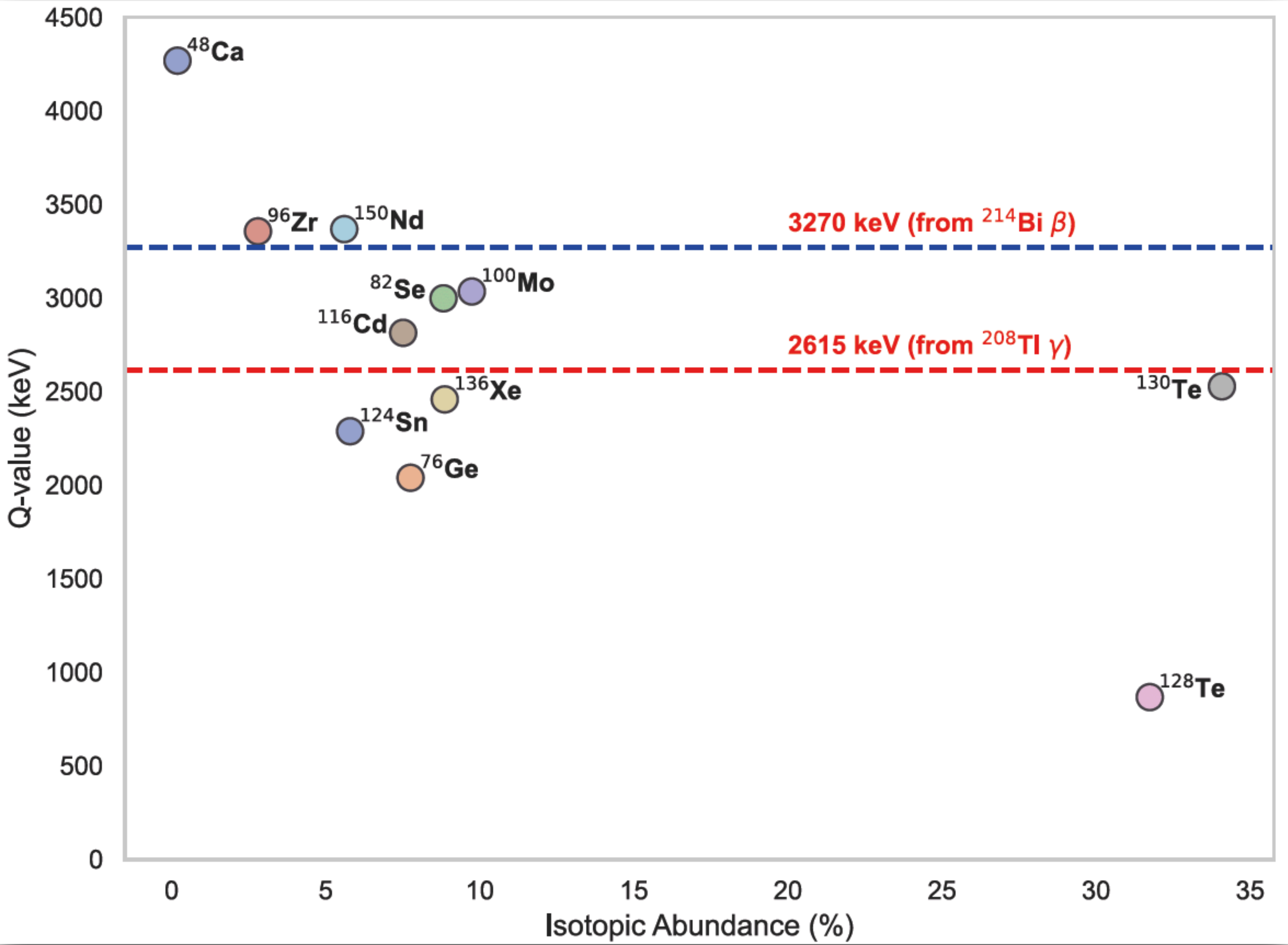
$$T^{0\nu}_{1/2} \propto \epsilon \cdot M \cdot t$$ (Background “free”)

M = mass of the isotope used in an experiemnt

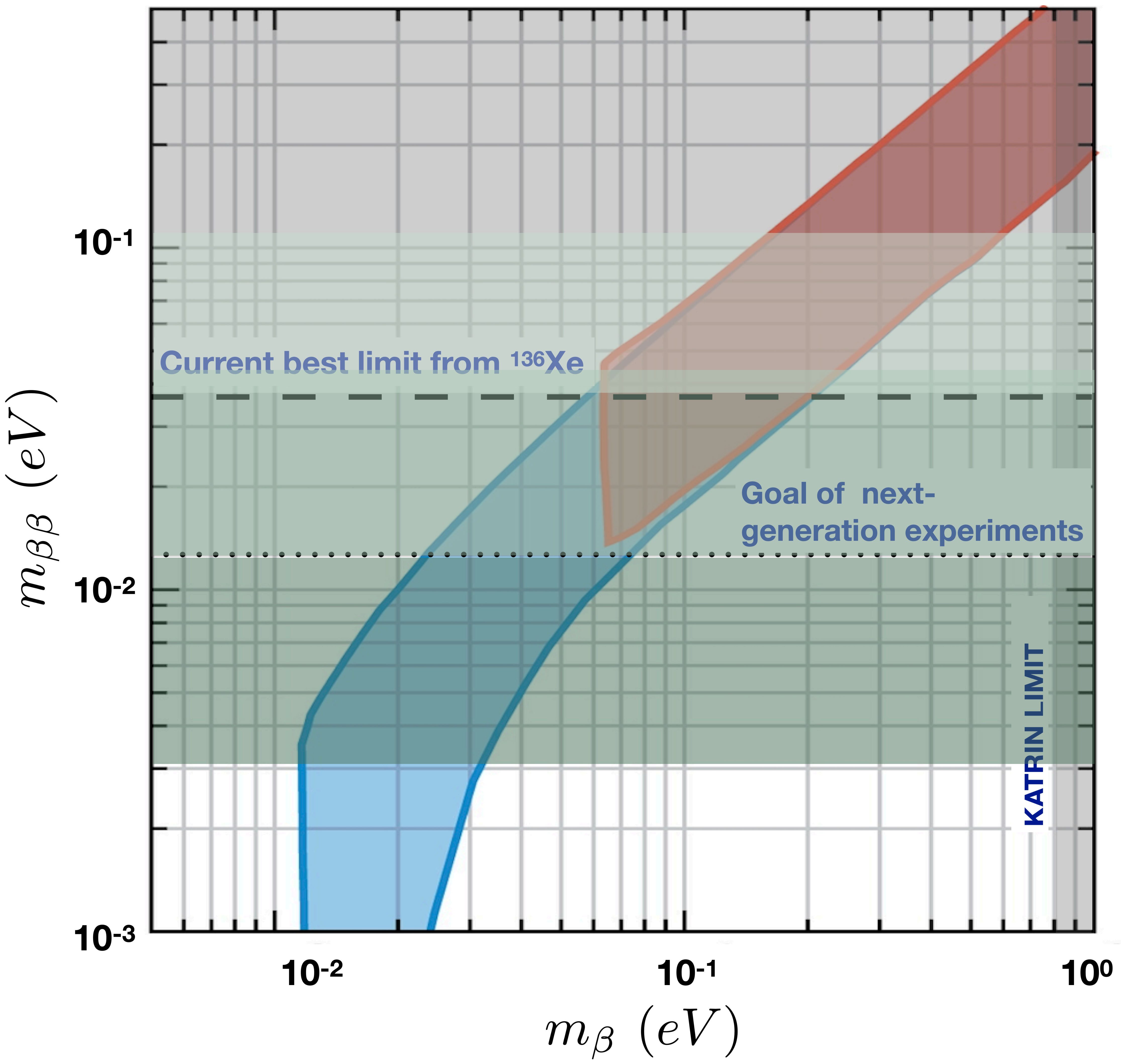
ϵ = Efficiency of detector

ΔE = energy resolution in region-of-interest

B = background in counts per detector mass, energy, and time e.g, counts/(keV·kg·year)



Implications



Past and Present (~10 kg)

Past and Near Future (~100 kg)

Future (~1000 kg)

Dreams (~10000 kg ?)

- Neutrinos are Majorana fermions.
  - Physics beyond the Standard Model.
- Constraints on absolute mass scale.
  - Probes the mass hierarchy of the neutrinos.
- Constraints on CP violating phases?

Where do we stand right now?

Adapted from Parno, D.S., Poon, A.W.P, Singh, V. , Philosophical Transactions A 382.2275 (2024): 20230122.

- **Diverse Research:** Experiments use a variety of isotopes to search for neutrinoless double beta decay.
- **Active Field:** Several experiments have already been completed, providing valuable data.
- **Future Focused:** New, more sensitive experiments are under construction and planned, promising increased sensitivity and potential for discovery.

Experiment	Status	Isotope	$T^{0\nu}_{1/2}$ [yr]	$m_{\beta\beta}$ [meV]
GERDA	Completed	^{76}Ge	$\mathbf{1.8 \times 10^{26}}$	**79—180**
MAJORANA	Completed	^{76}Ge	$\mathbf{8.5 \times 10^{25}}$	**113—269**
LEGEND-200	Taking Data	^{76}Ge	1.5×10^{27}	34—78
LEGEND-1000	Proposed	^{76}Ge	8.5×10^{28}	9—21
CDEX-300ν	Proposed	^{76}Ge	3.3×10^{27}	18—43
KamLAND-Zen	Taking Data	^{136}Xe	$\mathbf{2.3 \times 10^{26}}$	**36—156**
EXO-200	Completed	^{136}Xe	$\mathbf{3.5 \times 10^{25}}$	**93—286**
nEXO	Proposed	^{136}Xe	1.3×10^{28}	6.1—27
NEXT-100	Construction	^{136}Xe	7.0×10^{25}	66—281
CUORE	Taking Data	^{130}Te	$\mathbf{3.8 \times 10^{25}}$	**70—240**
SNO+	Construction	^{130}Te	2.1×10^{26}	37—89
AMoRE-I	Completed	^{100}Mo	3.0×10^{24}	**210—350**
AMoRE-II	Proposed	^{100}Mo	5.0×10^{26}	17—29
CUPID-Mo	Completed	^{100}Mo	$\mathbf{1.8 \times 10^{24}}$	**280—490**
CUPID	Proposed	^{100}Mo	1.5×10^{27}	10—17
CUPID-0	Completed	^{82}Se	$\mathbf{4.6 \times 10^{24}}$	**263—545**
SuperNEMO-D	Construction	^{82}Se	4.0×10^{24}	260—500
CANDLES-III	Taking data	^{48}Ca	$\mathbf{5.6 \times 10^{22}}$	**2900—1600**

Not an exhaustive list. See the following for an excellent and comprehensive review

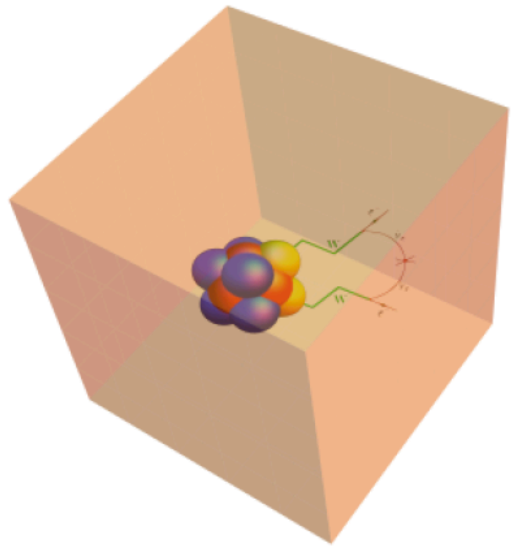
Agostini, Matteo, et al. "Toward the discovery of matter creation with neutrinoless ββ decay." Reviews of Modern Physics 95.2 (2023): 025002.

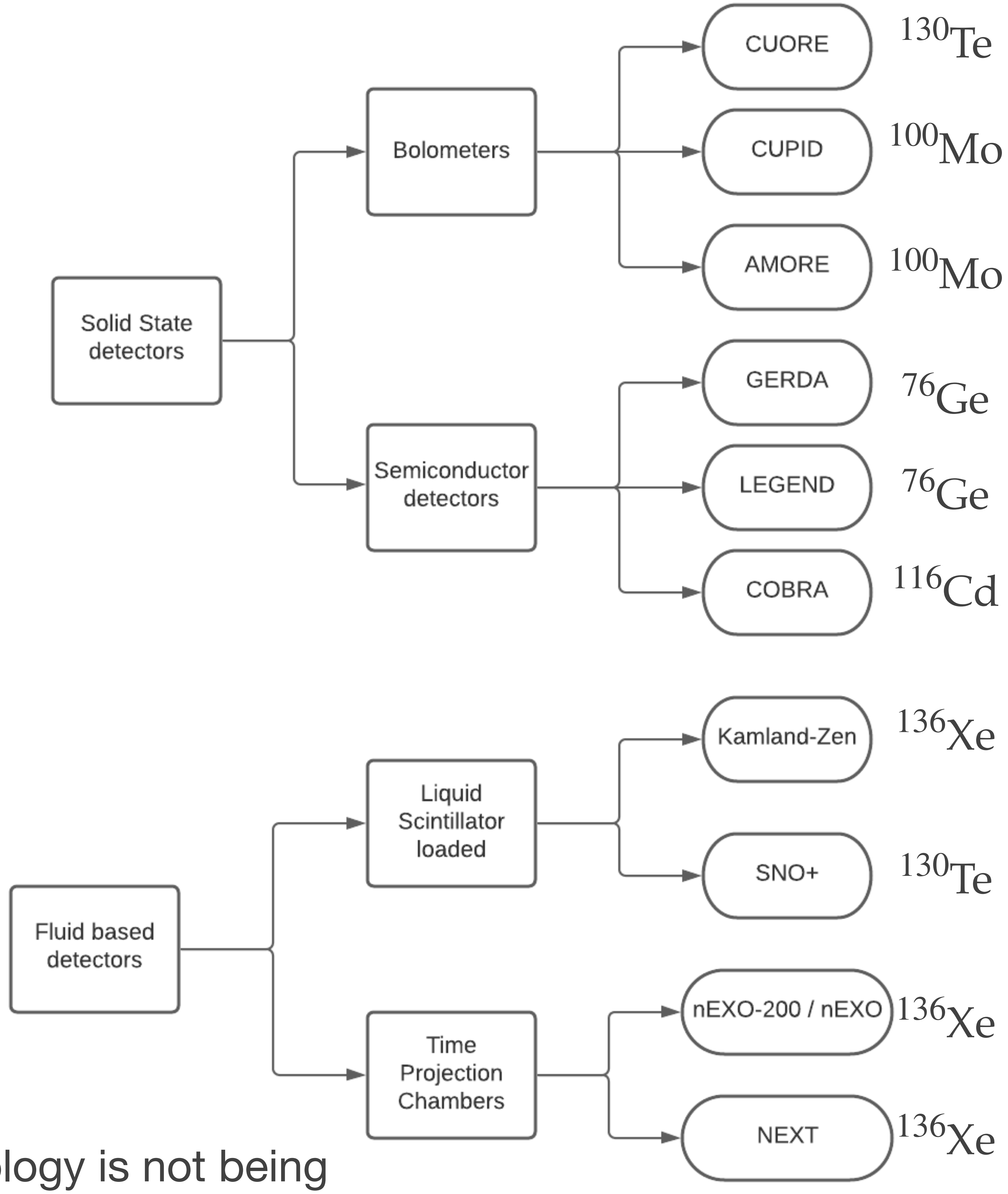
Holy Trinity - Mass, Background, Resolution

Adapted from Parno, D.S., Poon, A.W.P, Singh, V. , Philosophical Transactions A 382.2275 (2024): 20230122.

Detector Strategies

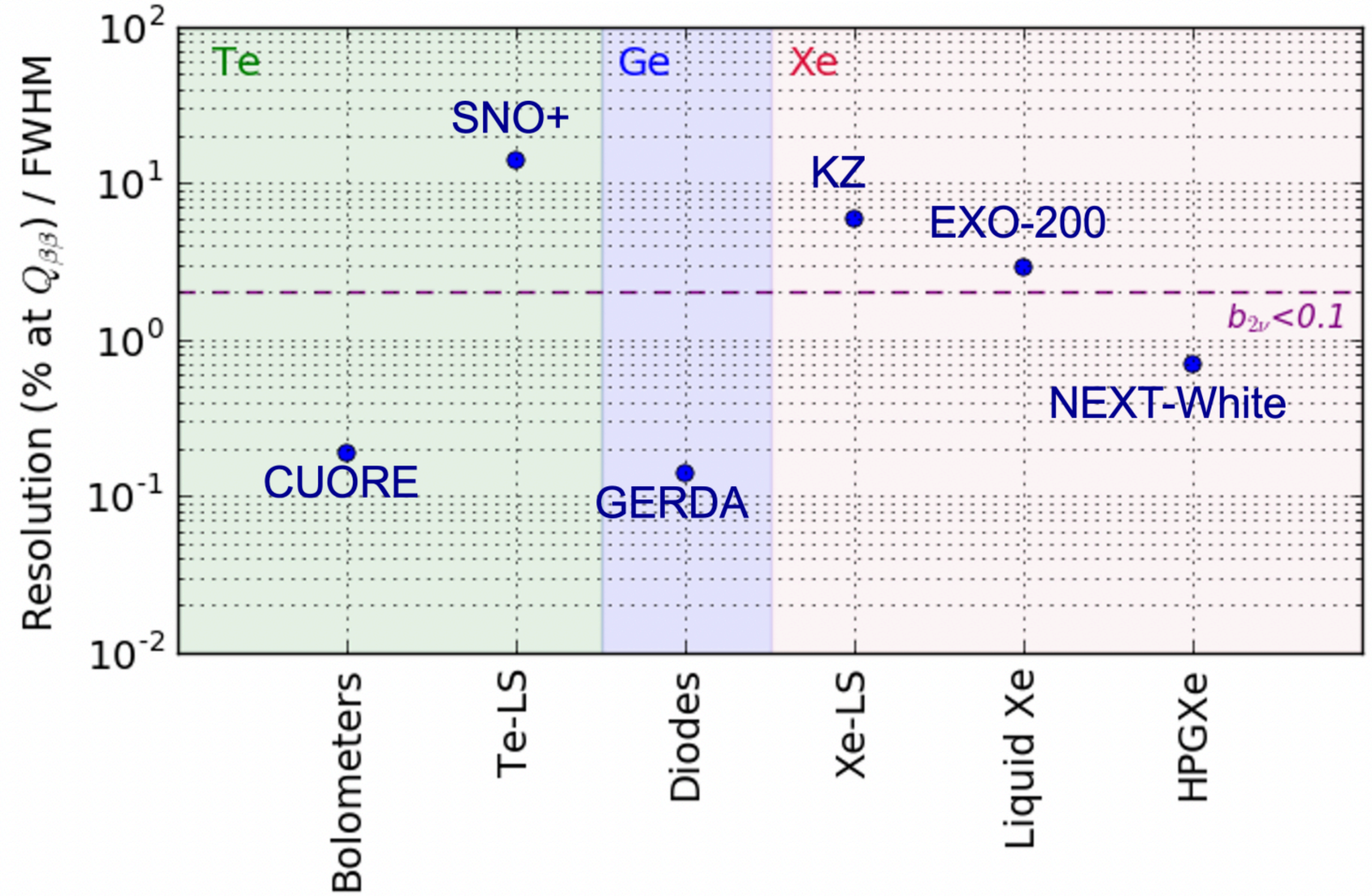
Source = detector





Source ≠ detector technology is not being pursued as a ton scale experiment.

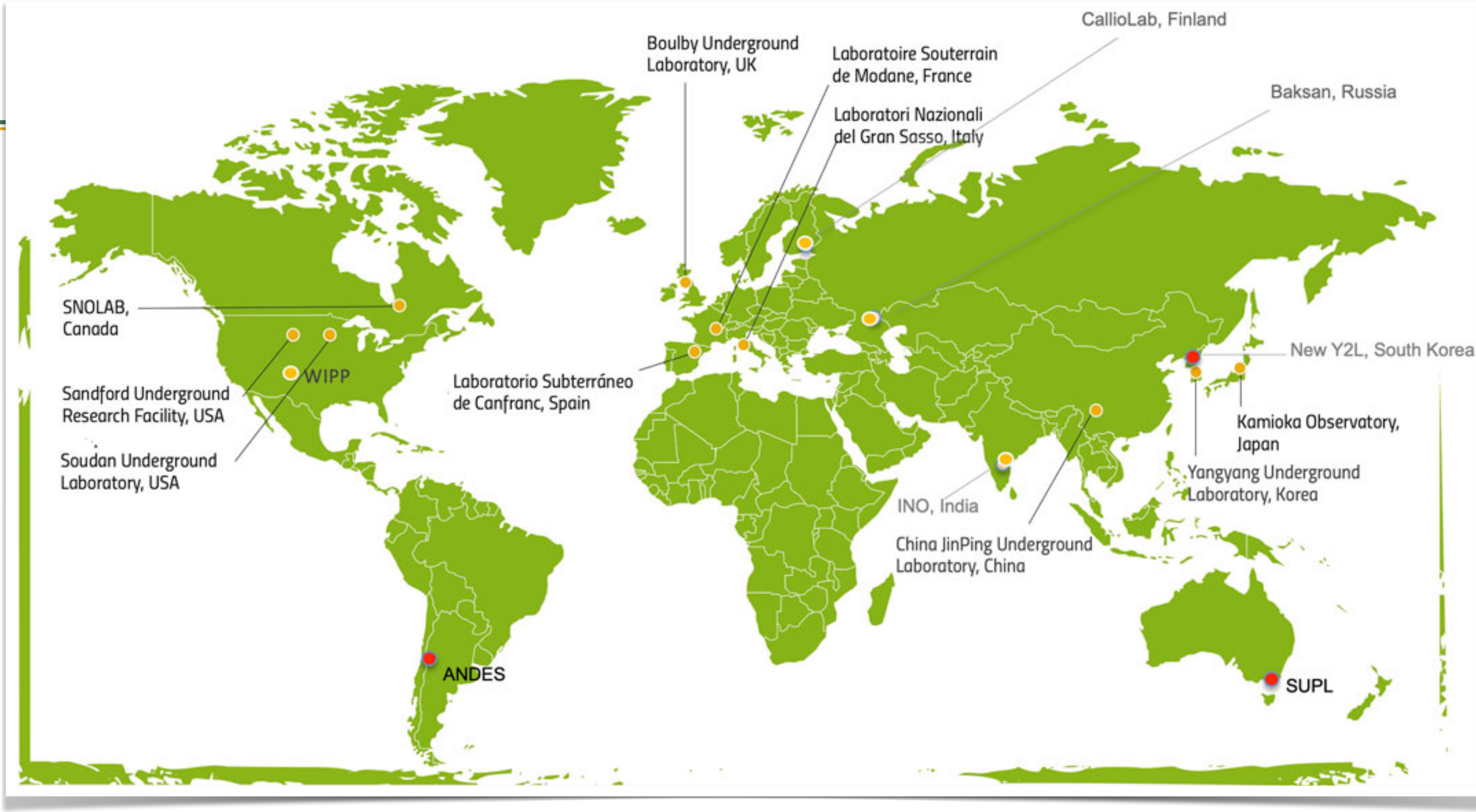
From : B.J.P. Jones arXiv:2108.09364



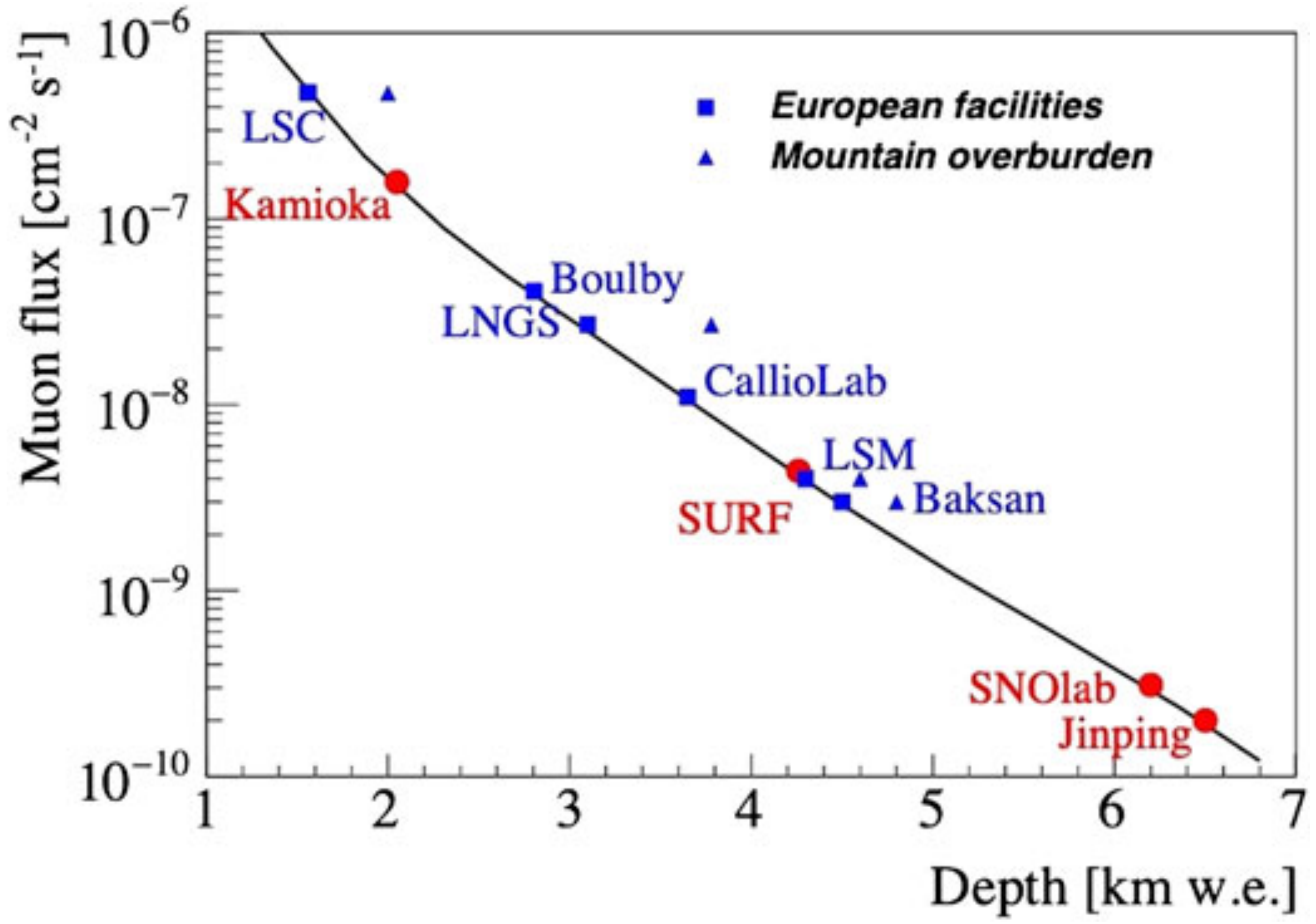
- Solid-state detectors offer the best resolutions.
- Fluid-based detectors offer easier scalability to larger isotopic masses.

Background Mitigation

- **Location, Location, Location:** Experiments are conducted deep underground to shield from cosmic rays.
- **Material Matters:** Detectors are built from radioactively pure materials to minimize internal background.
- **Shielding Strategy:** Multiple layers of passive shielding (e.g., water, lead) are used to block external radiation.
- **Active Veto:** Some shielding materials double as active detectors to identify and reject background events (e.g., cosmic muons).
- **Event Discrimination:** Sophisticated analysis techniques (timing, topology, particle ID) differentiate between signal events (0νββ) and background.



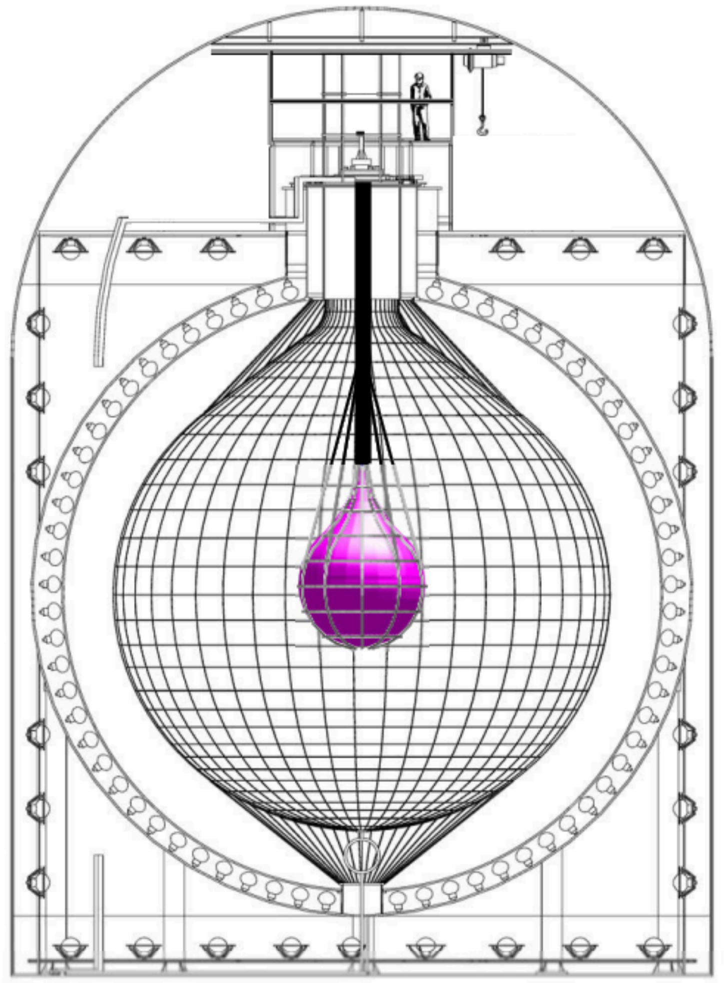
Ianni, Aldo. *Frontiers in Physics* 9 (2021): 612417.

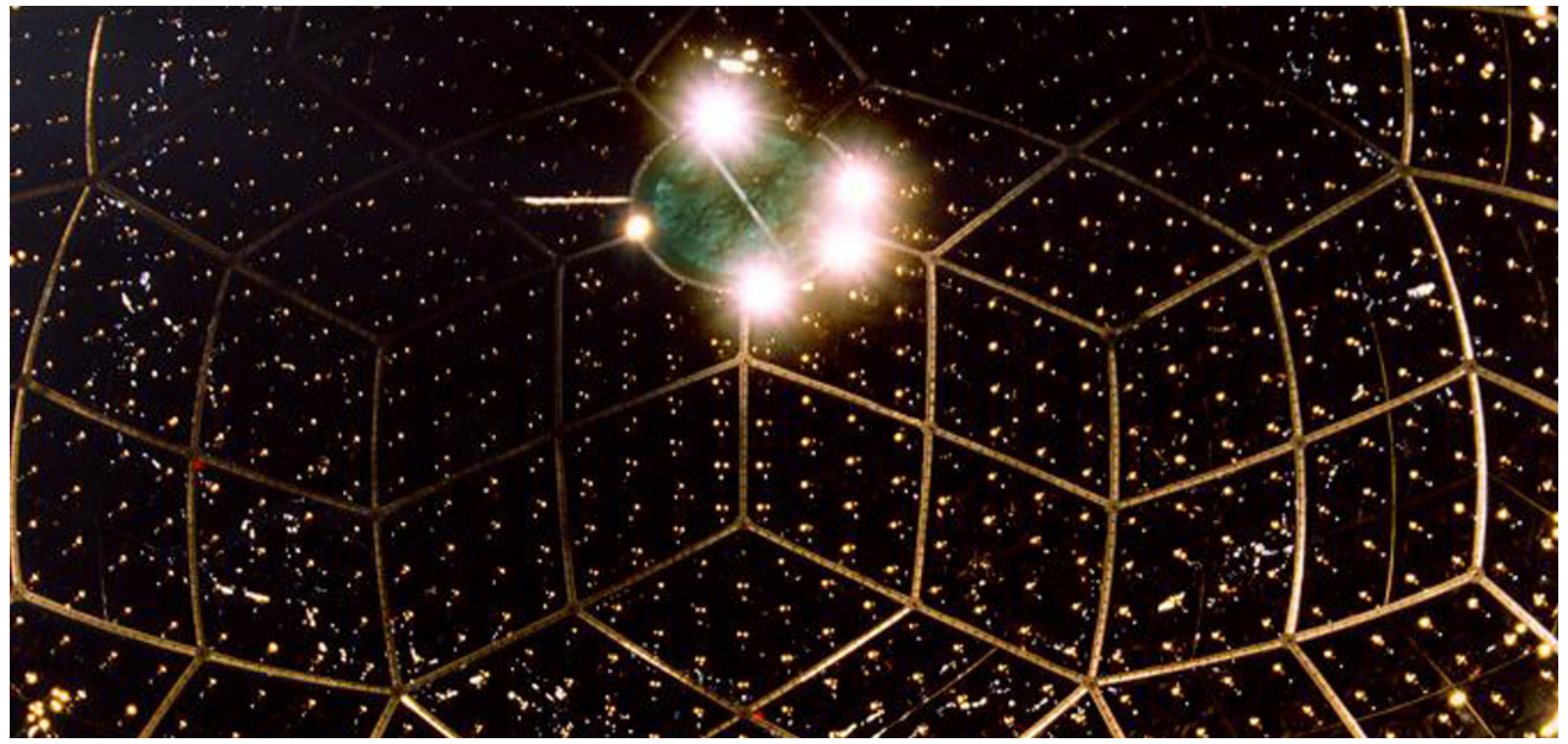


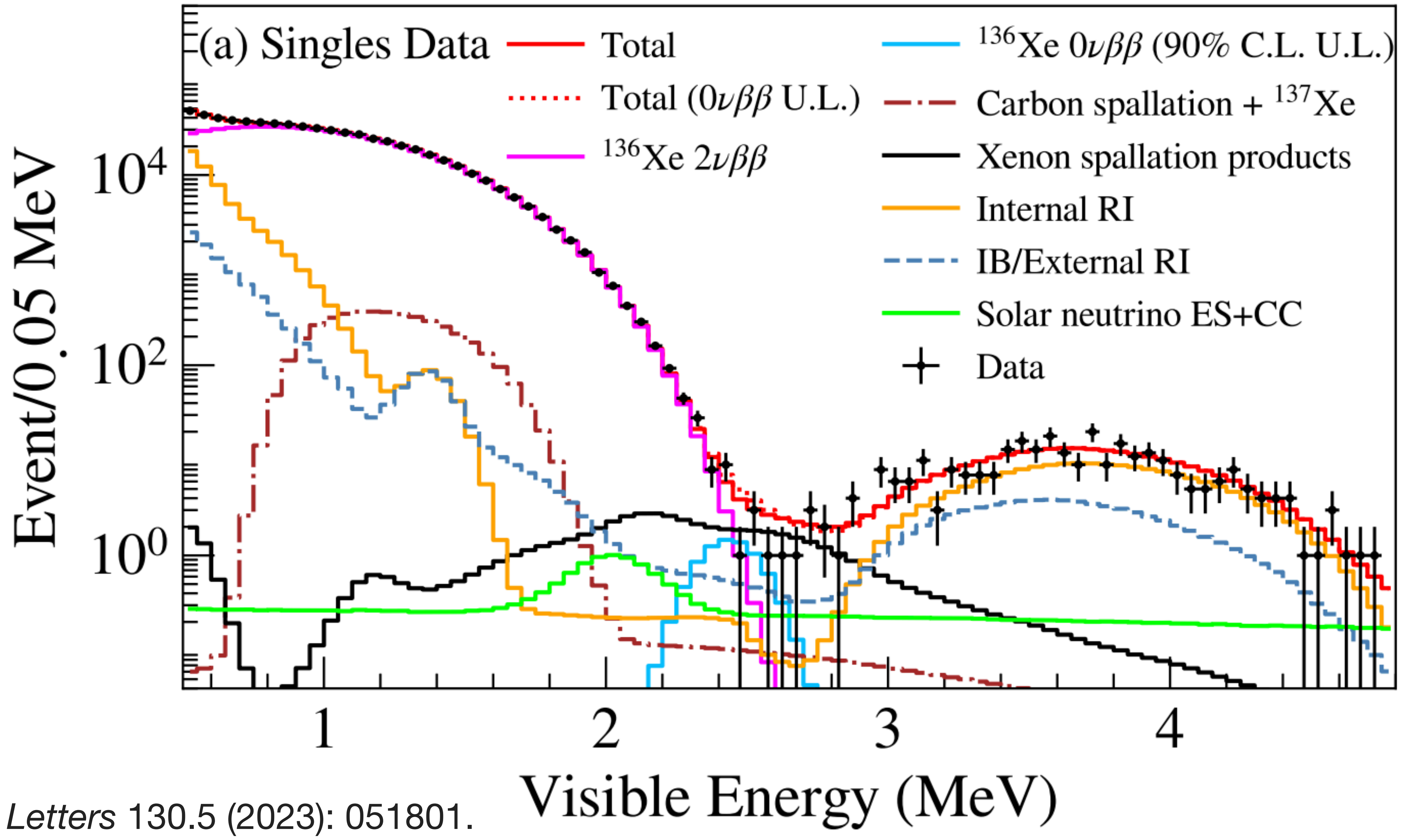
The Hunt for 0νββ: A Tour of Experiments

KamLAND-Zen 800

- Kamioka Observatory in Japan data taking started in 2019.
- KamLAND-Zen utilizes a 745 kg Xenon gas (enriched to 90-91%) dissolved into 1 kiloton of liquid scintillator.
- Dual-phase design allows the liquid scintillator to act as both target and active shield.
- Major background sources include ^{214}Bi from the decay chain of ^{238}U, cosmogenic ^{10}C, and the 2νββ decay itself.
- Despite excellent background reduction, the energy resolution is limited by the light collection efficiency in the large detector volume.
- **Current world leader for most sensitive search.**

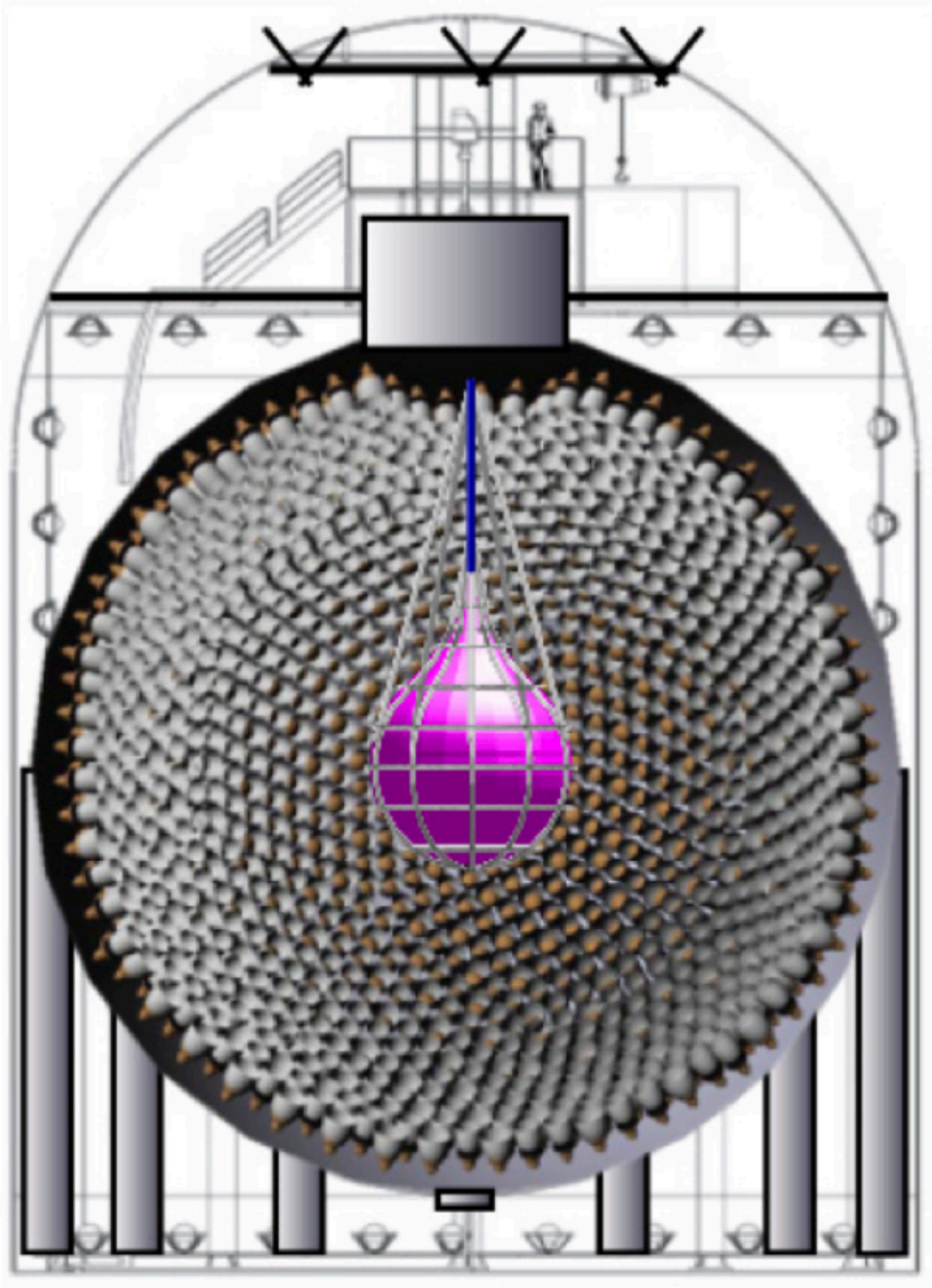






Abe, S., et al. *Physical Review Letters* 130.5 (2023): 051801.

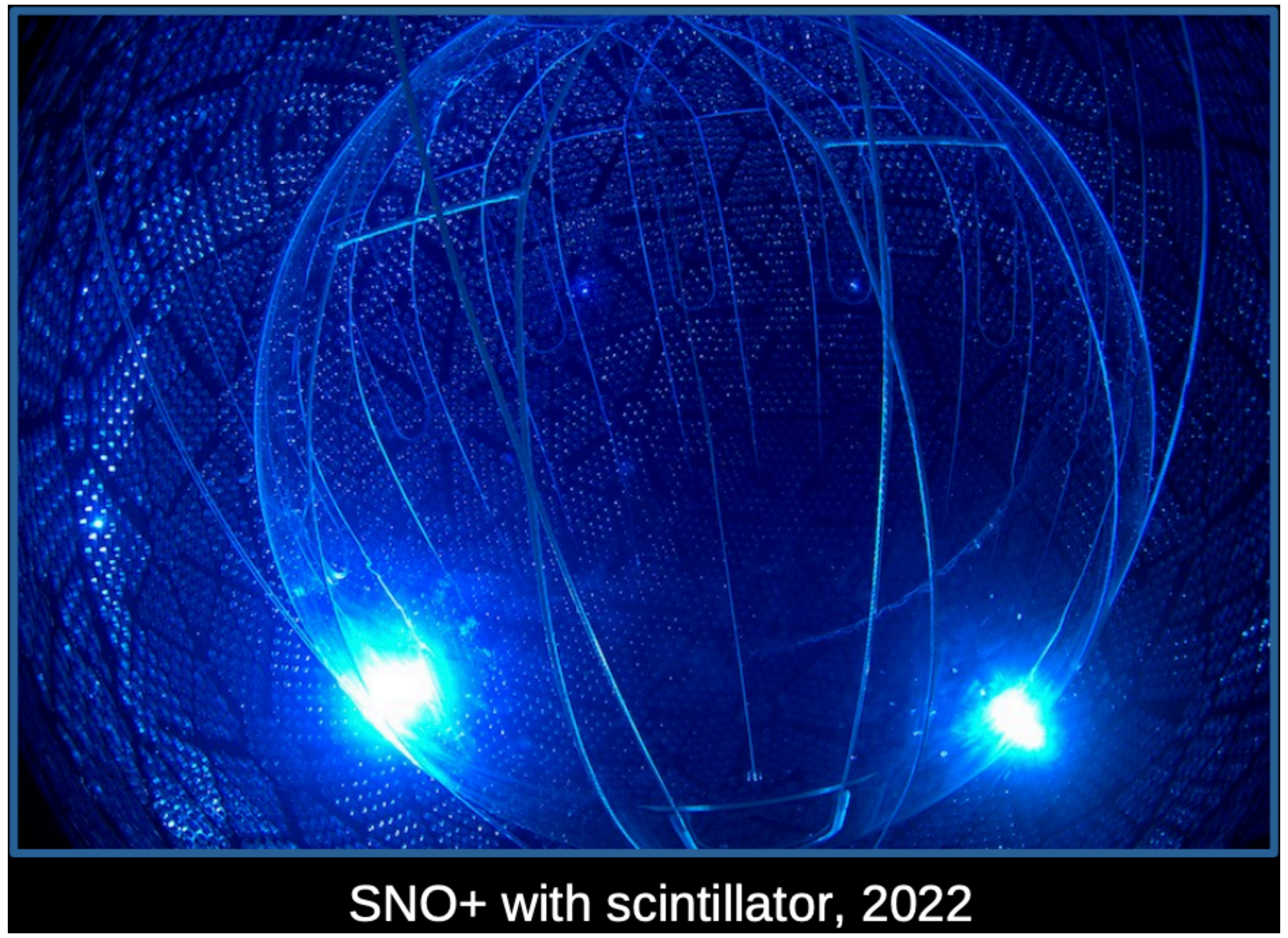
KamLAND2-Zen



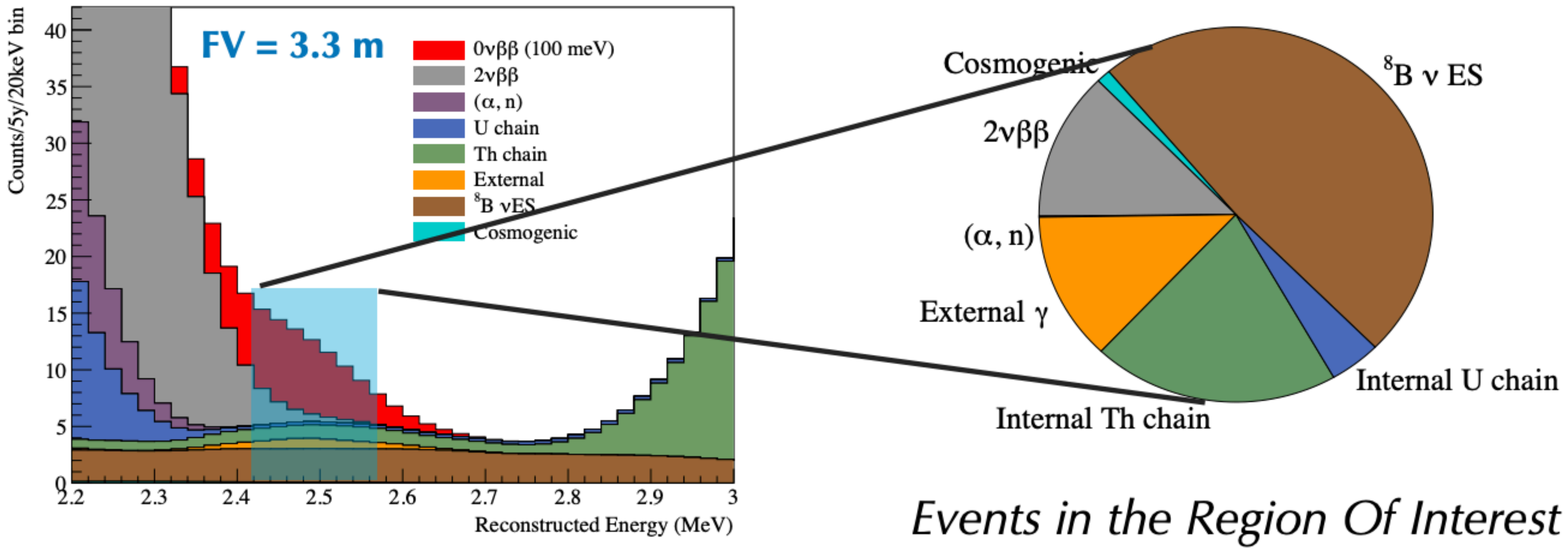
- Increase the Xenon mass to 1 ton.
- Improve energy resolution by using a brighter liquid scintillator and more efficient photomultiplier tubes.
- This upgrade aims for a half-life sensitivity of >1.1 x 10^{27} years.

SNO+

- SNO+ employs a novel technique to load Tellurium-130 into liquid scintillator, enhancing light yield and stability for improved detection.
- Situated in SNOLAB, Canada, providing significant depth for cosmic ray shielding.
- **Phased Approach:** SNO+ has undergone meticulous background characterization with water and pure scintillator phases, paving the way for Tellurium loading in 2025.
- With an initial 0.5% loading of natural Tellurium, SNO+ aims for a half-life sensitivity exceeding 2.1 x 10^{26} years after 3 years of data taking.
- **Future Upgrades:** R&D efforts demonstrate the potential to increase the Tellurium-130 loading to 3%, promising a substantial boost in sensitivity for future searches.



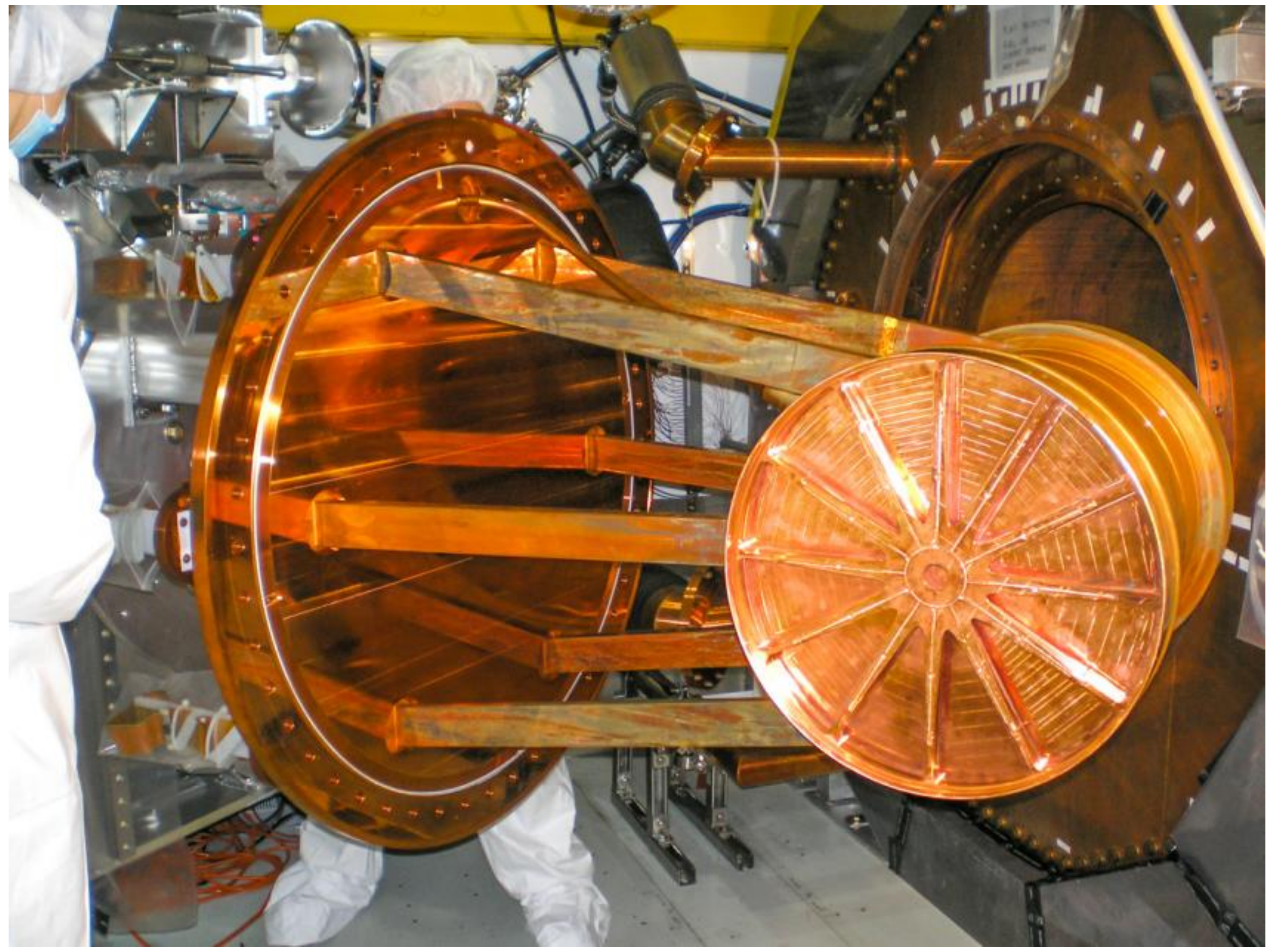
From: T. Kaptanoglu TAUP2023

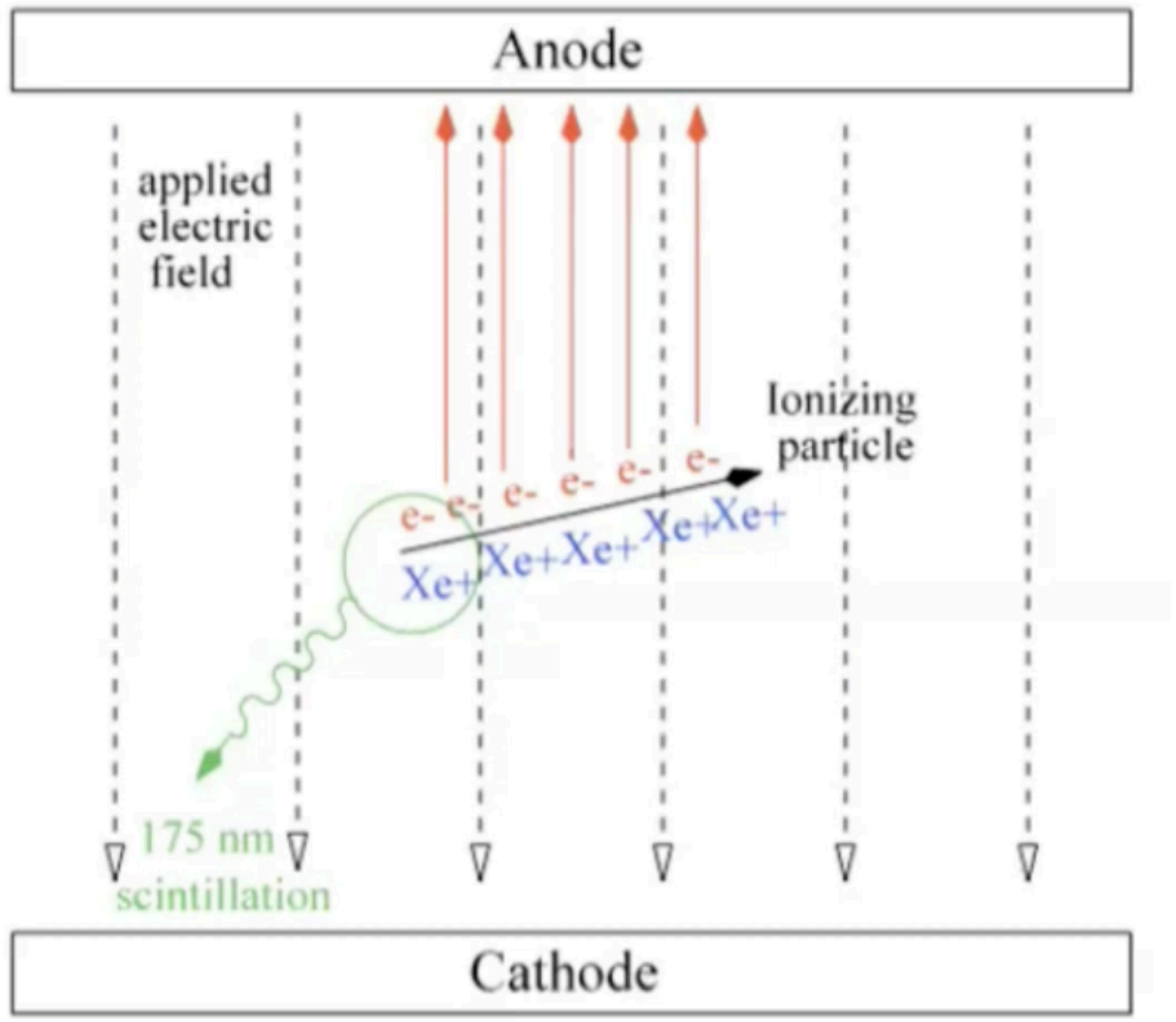


From: V. Lozza TAUP23

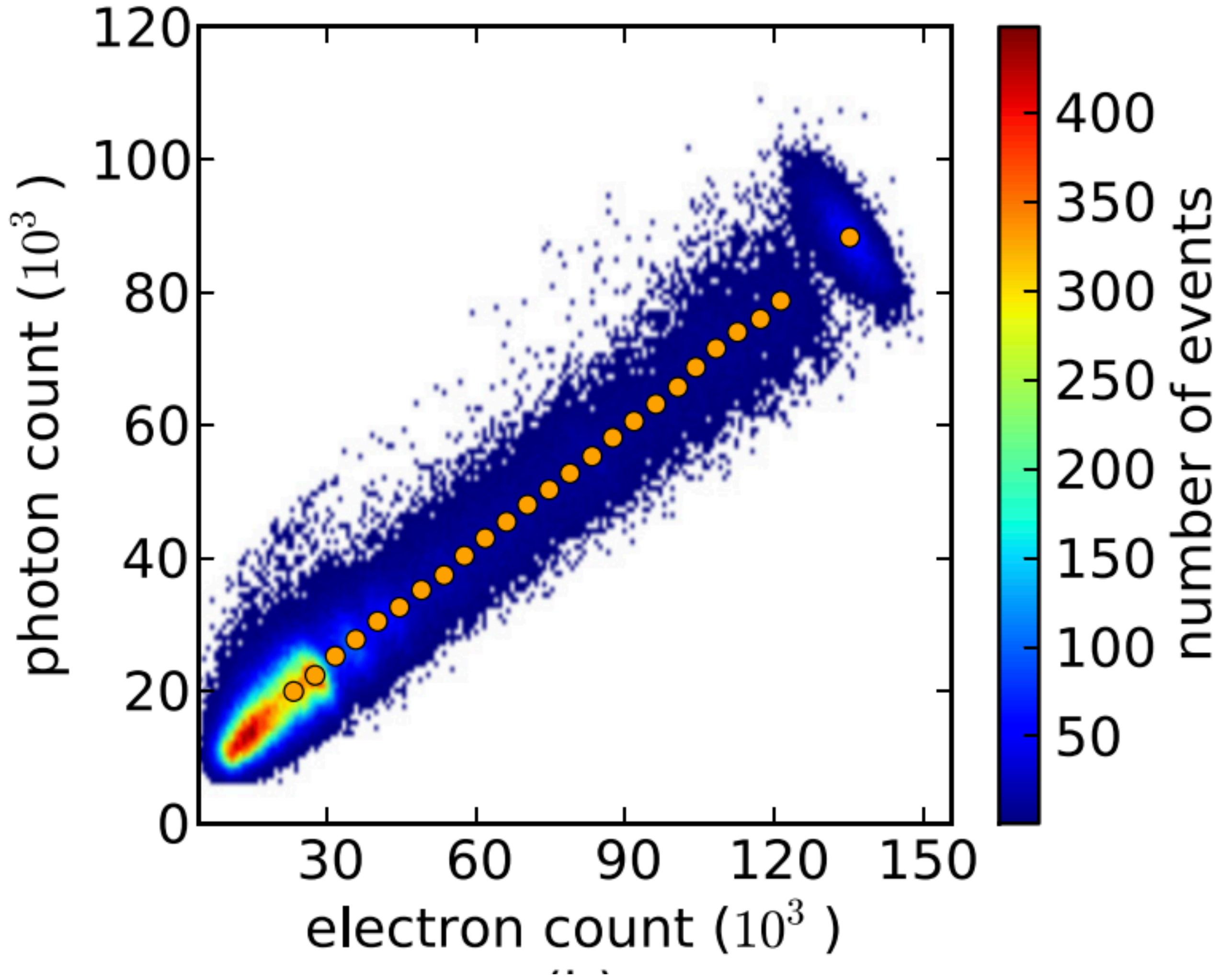
EXO

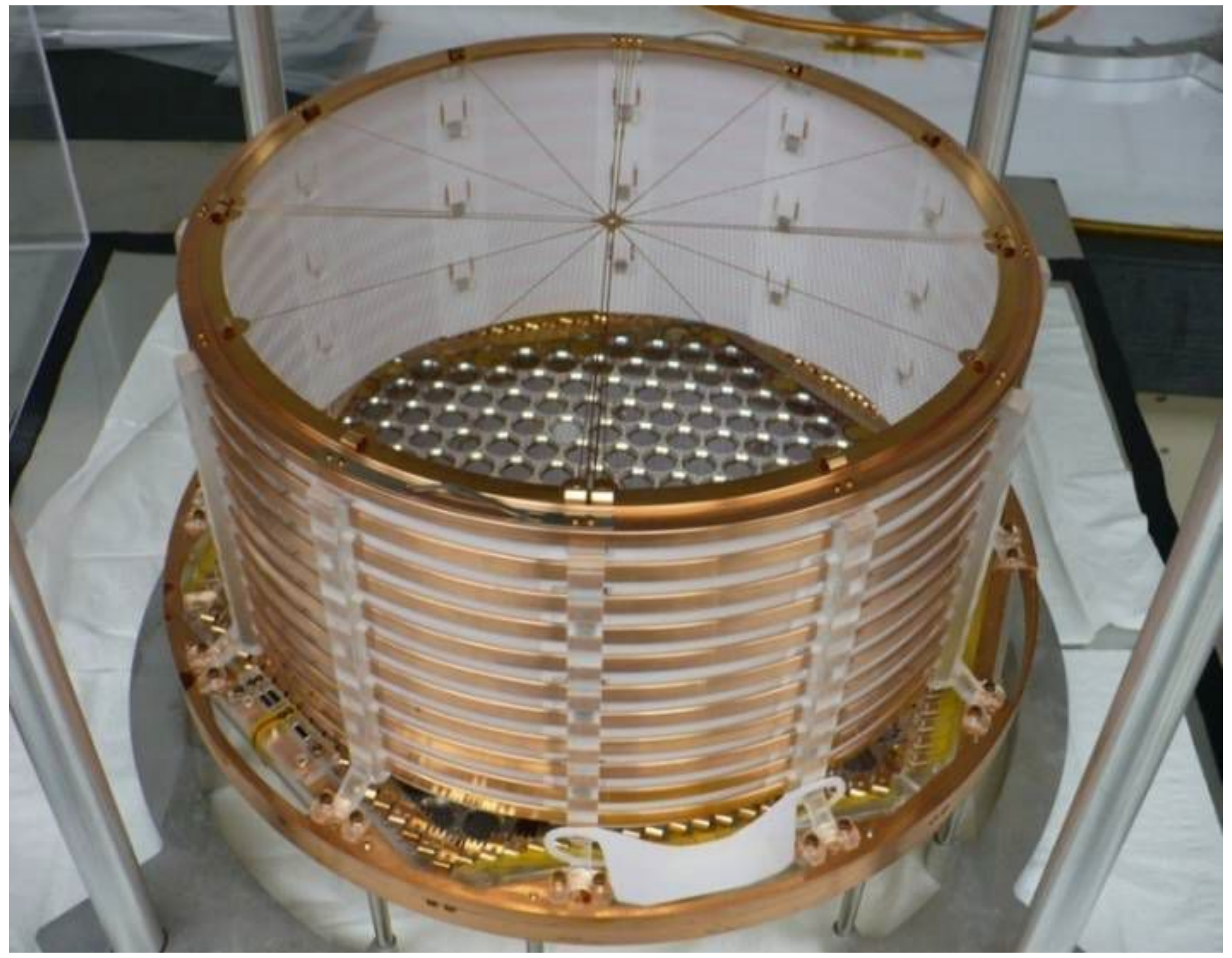
- Operated with enriched Xe at Waste Isolation Pilot Plant in two phases between 2011 and 2018.
- Liquid Xenon TPC. Readout plane made of LAAPDs + crossed wire grip.
- ~100 kg fiducial mass with 80% enriched 136-Xe.
- The TPC technology enabled detailed reconstruction of event topology, aiding in background rejection by differentiating signal events from background interactions.
- Achieved energy resolution of 1.15% (σ/E) at the Q-value in Phase-II.





Charge and light response generated by γ rays from the 228Th source.

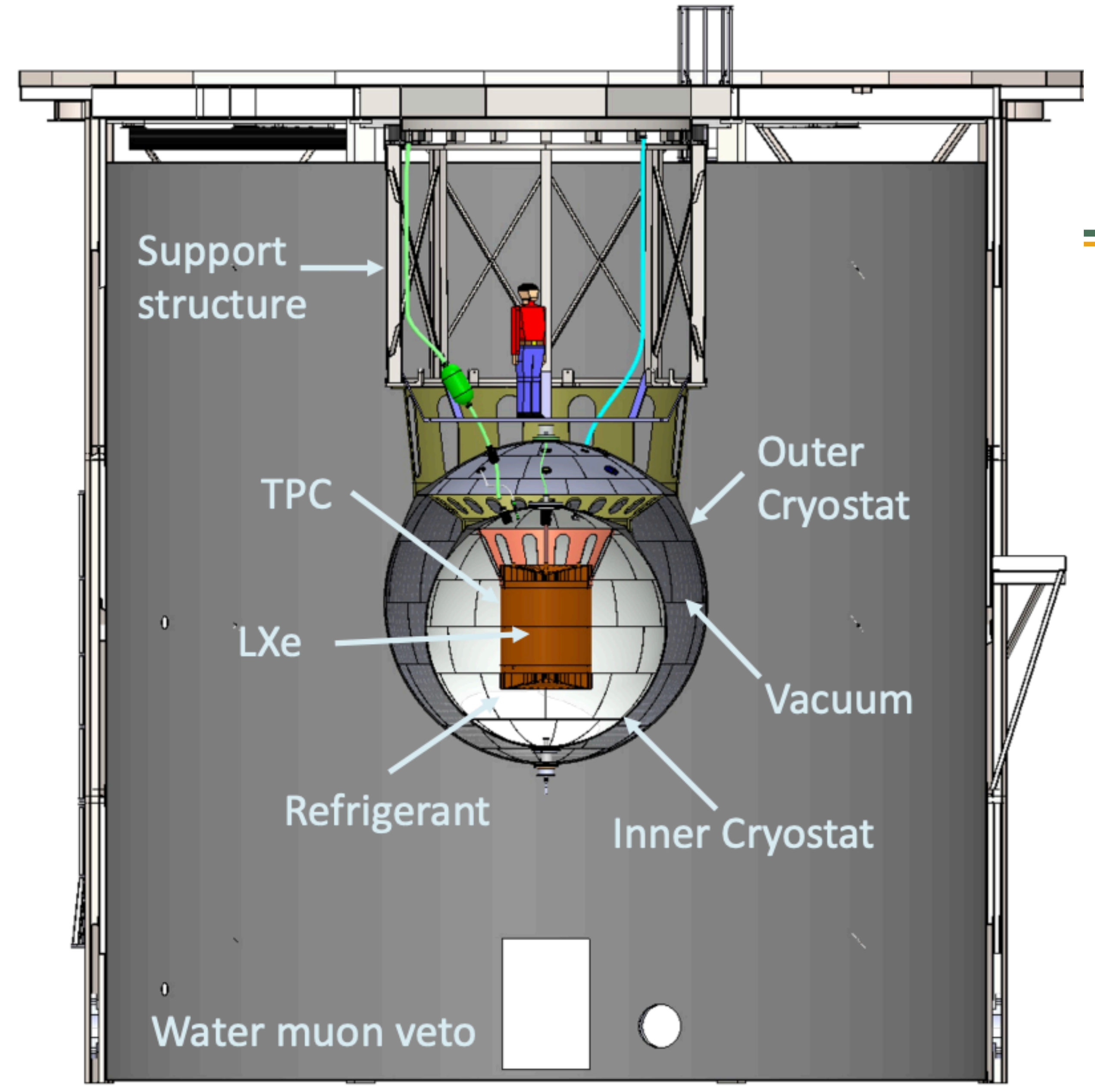


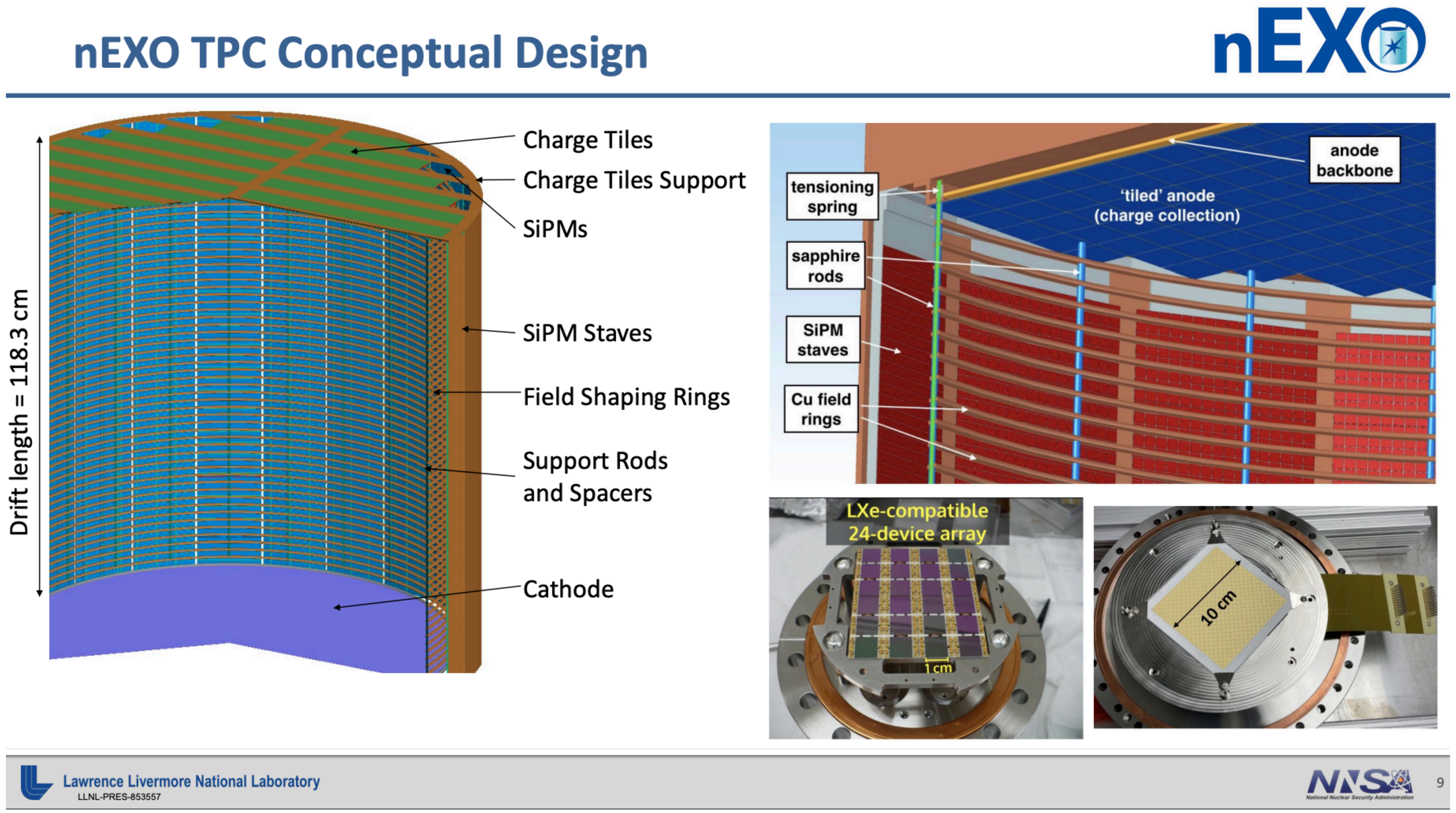


G. ANTON et al. PHYSICAL REVIEW C 101, 065501 (2020

nEXO

- A planned upgrade to EXO-200, featuring a larger liquid xenon TPC with 5 tons of enriched xenon.
- Aims for a half-life sensitivity exceeding 1.35 x 10^{28} years
- Projected to reduce background by a factor of ~1000 compared to its predecessor, EXO-200.
- Targets an energy resolution of <1% to precisely identify potential $0\nu\beta\beta$ decay events.
- Exploring a revolutionary technique to tag the barium daughter atom, potentially eliminating almost all background in a future phase.

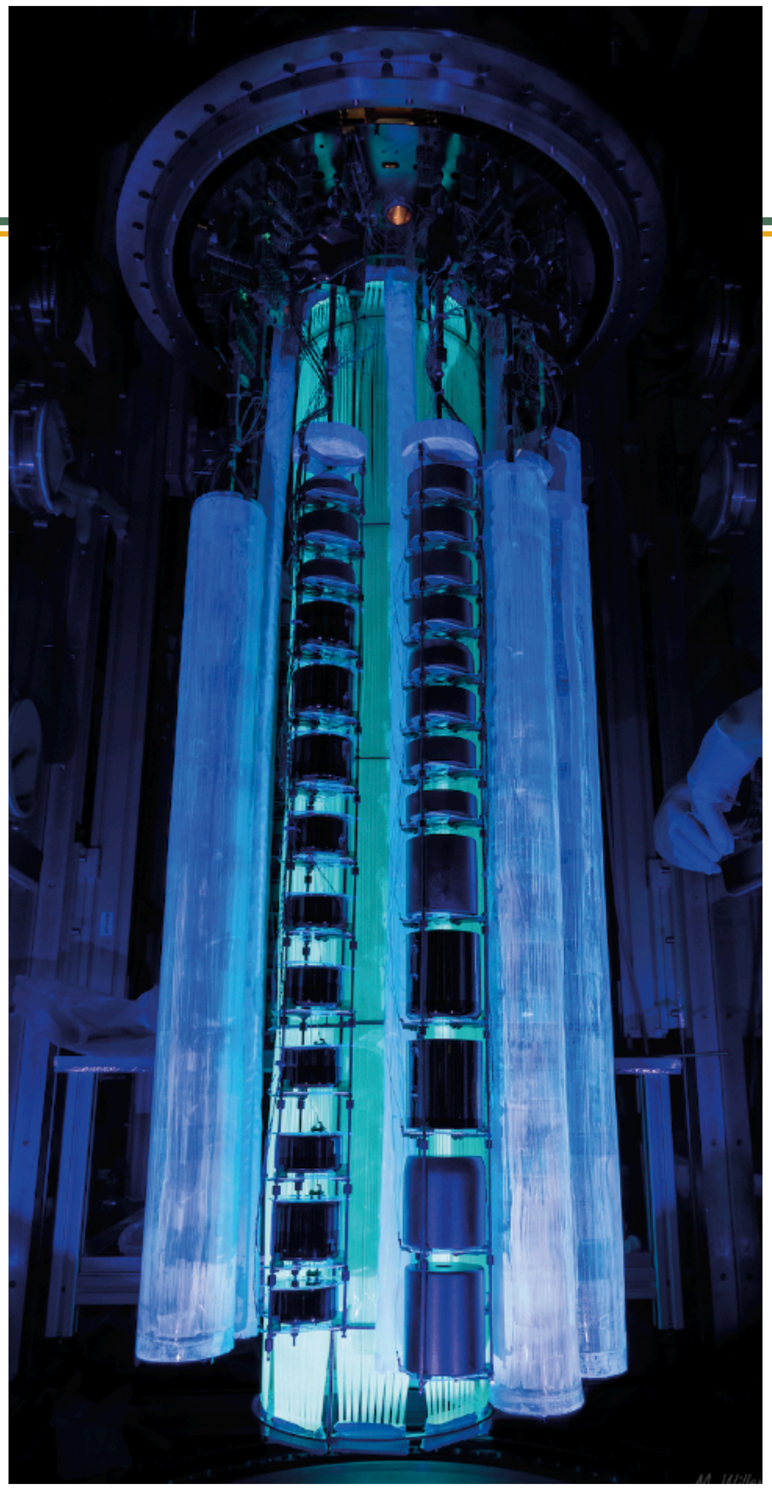




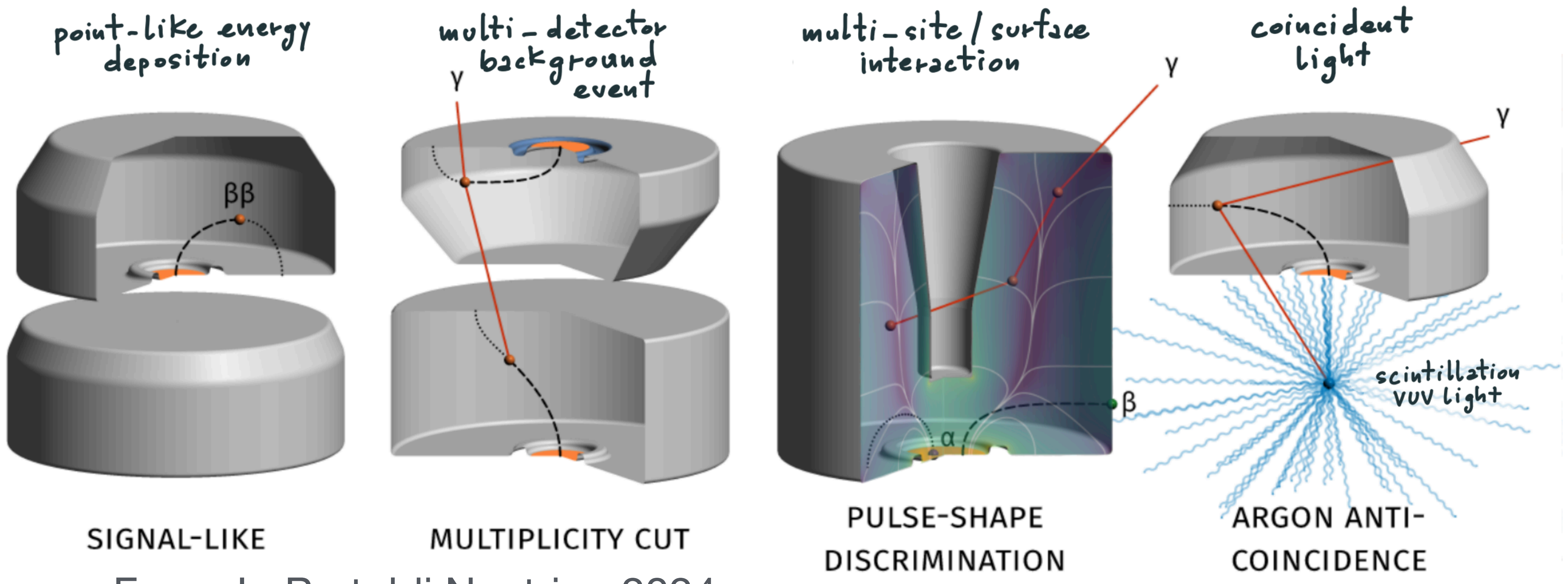
Images From: Samuele Sangiorgio TAUP 2023

LEGEND-200

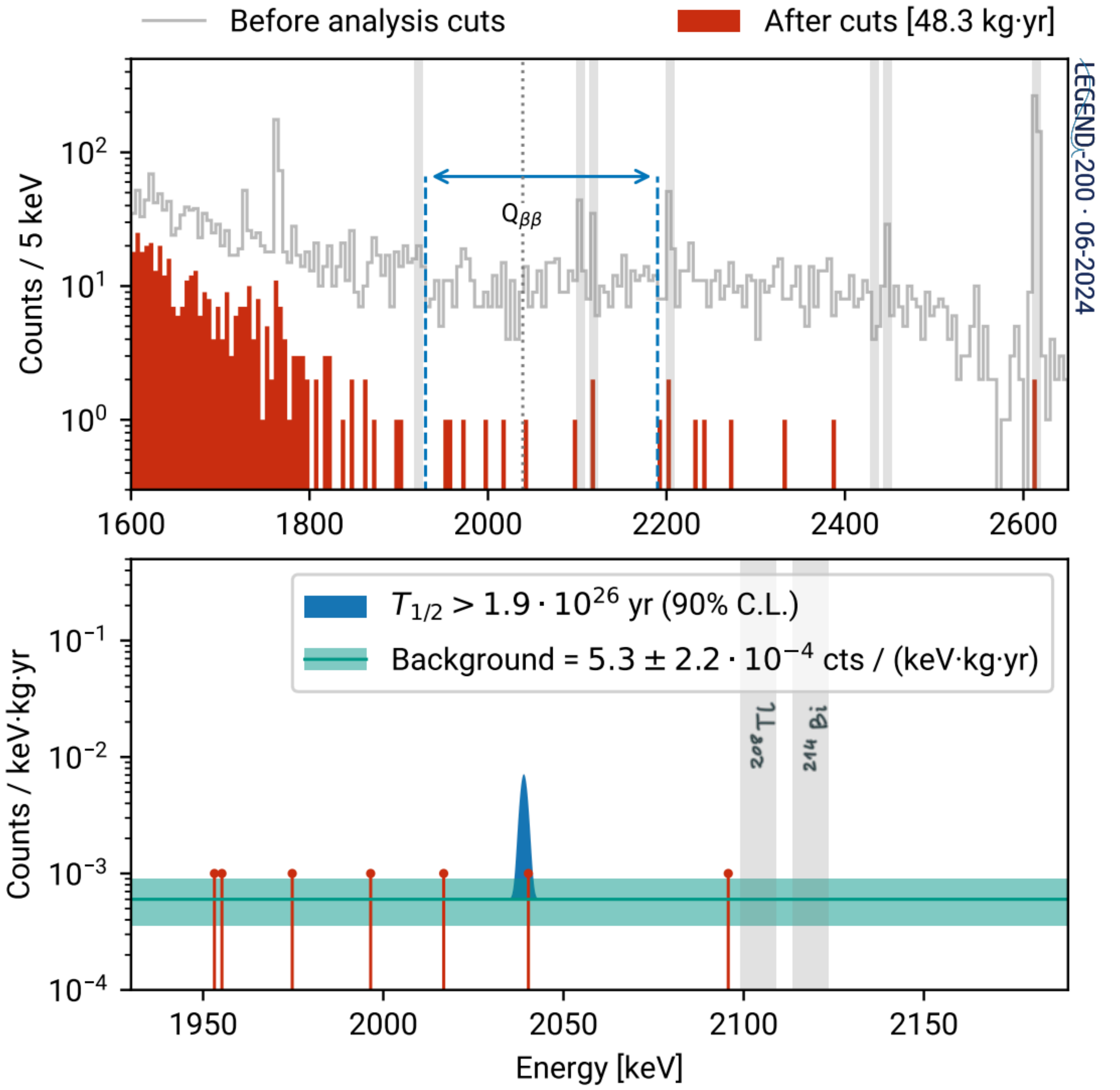
- 142 kg of HPGe detectors
- Submerged in liquid Ar
- Mesh shroud to protect from 42K
- LEGEND-200 sees a low background
- 48.3 kg-yr of data
- Preliminary BI: (5.3 ± 2.2) x 10^{-4} cts/keV/kg/yr



M. Willers TAUP 2023



From: L. Pertoldi Neutrino 2024

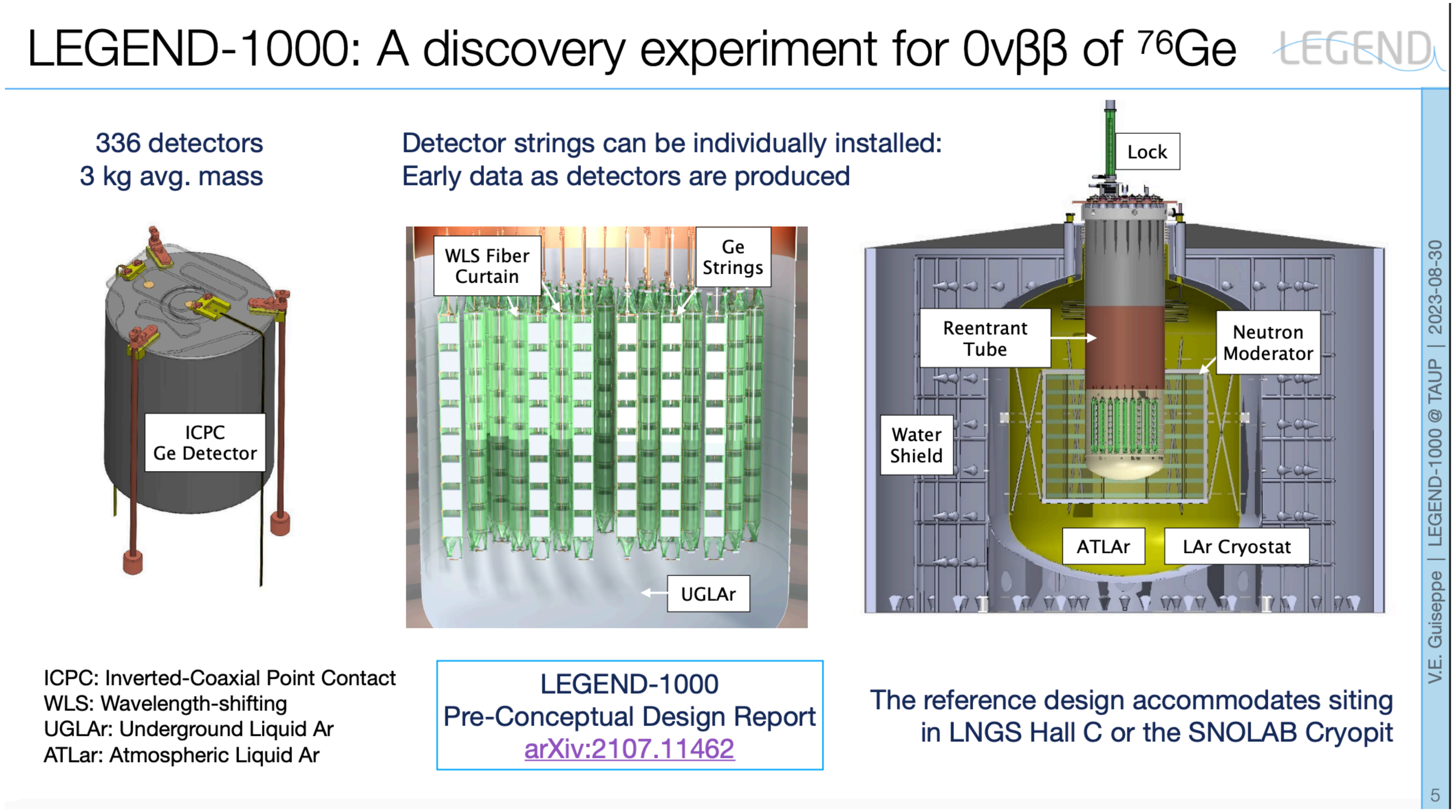


GERDA, MAJORANA and LEGEND combined fit

From: L. Pertoldi Neutrino 2024

LEGEND-1000

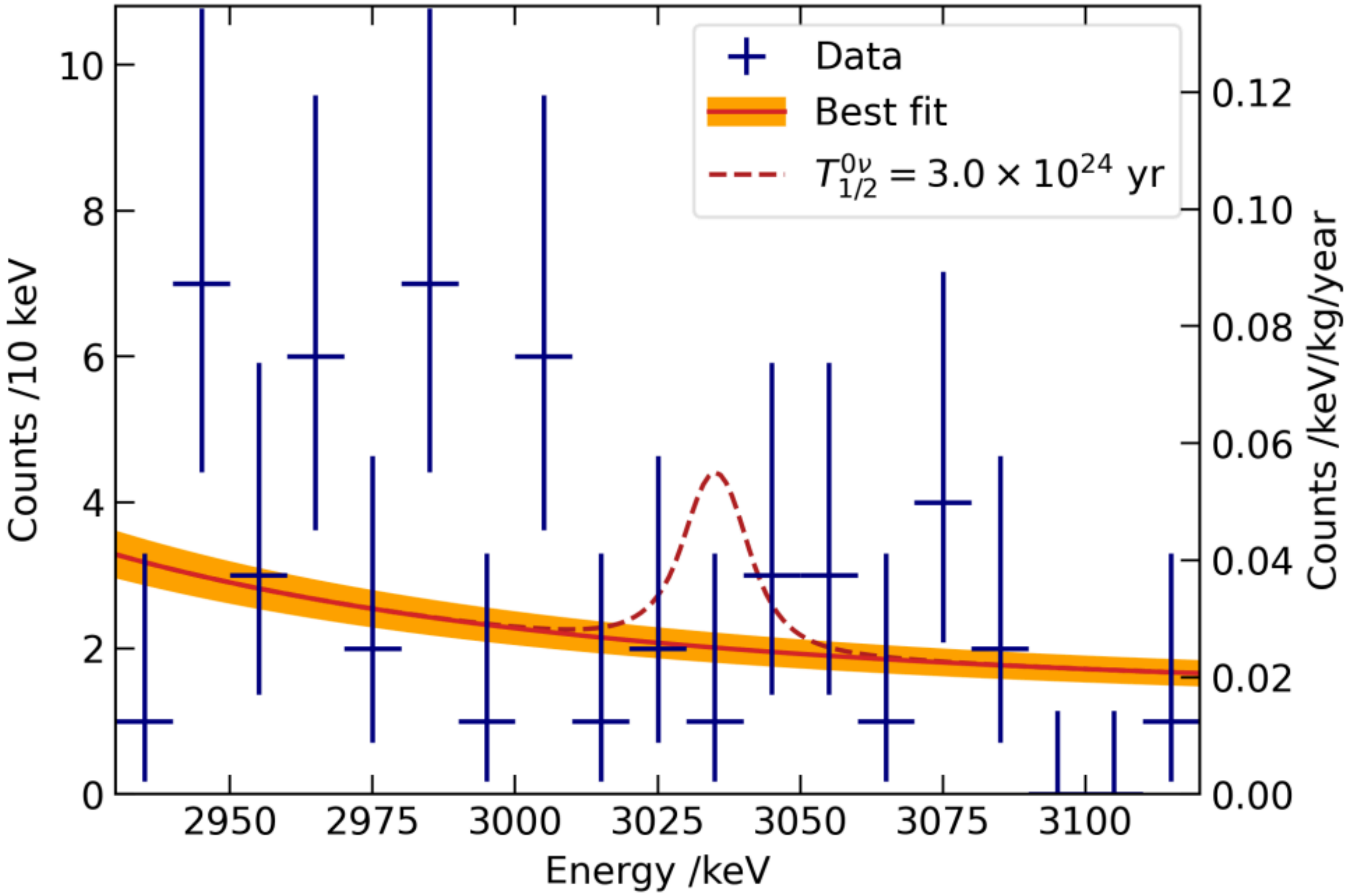
- Builds on breakthrough developments by GERDA, MAJORANA, and LEGEND-200.
- Excellent energy resolution.
- Aims to be a quasi-background-free experiment
  - Larger volume/surface ratio of the detectors to reduce background.
  - Low-mass ASIC electronics
  - Reduction in 42Ar by procuring underground liquid Argon.
  - Deeper underground site (baseline design at SNOLAB)
- Aims for a half-life sensitivity exceeding 1.3 x 10^{28} years



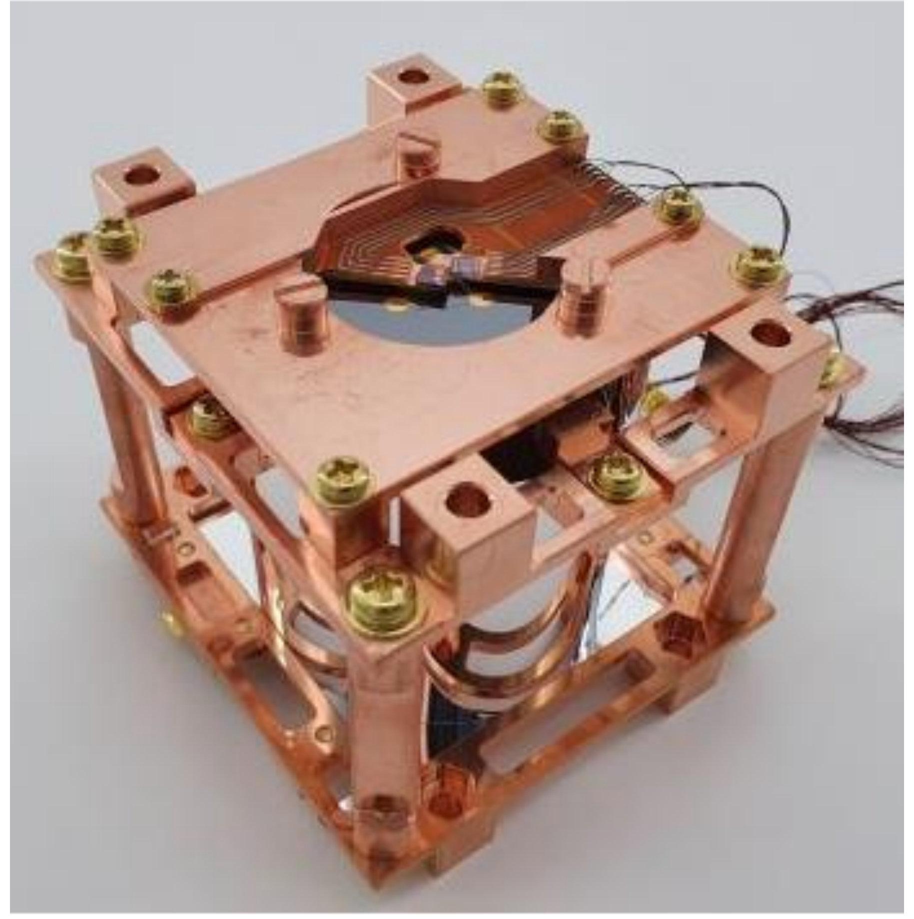
From: V. Guisippe TAUP 2023

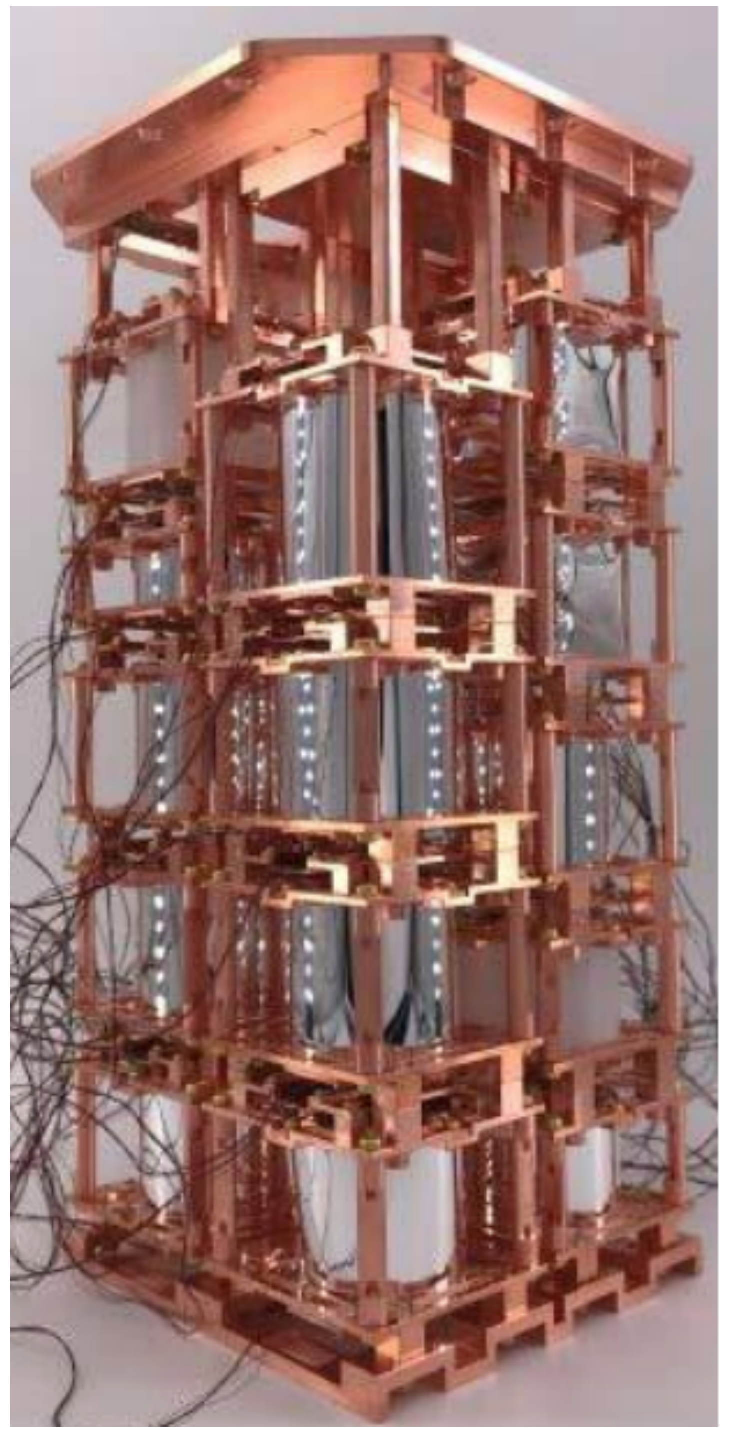
AMoRE-I

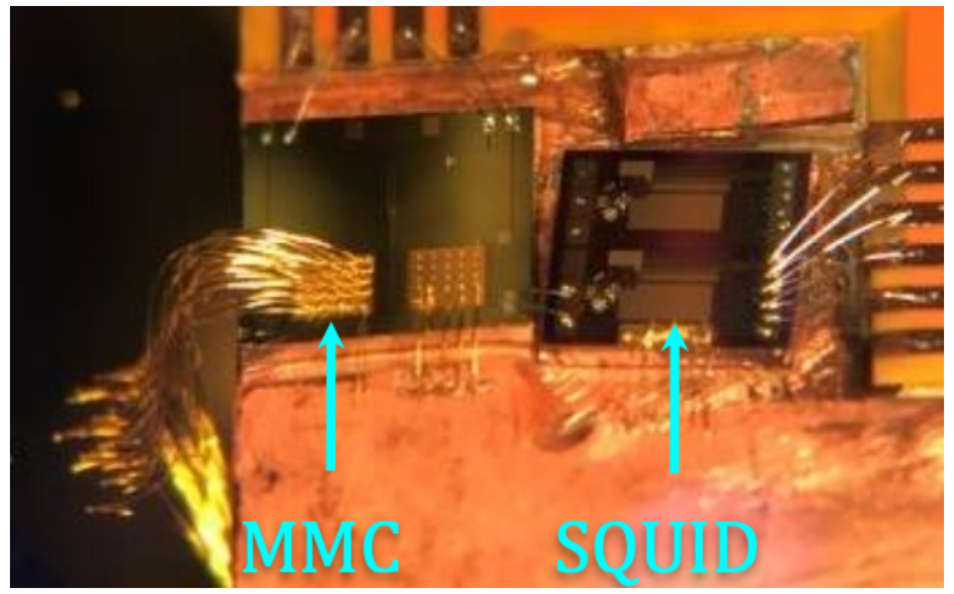
- At Y2L lab South Korea
- 13x $CaMoO_4$ and 5x Li_2MoO_4 crystals
- Readout with metallic magnetic calorimeter (MMC) + SQUID sensors



Agrawal, A., et al. *arXiv preprint arXiv:2407.05618* (2024)

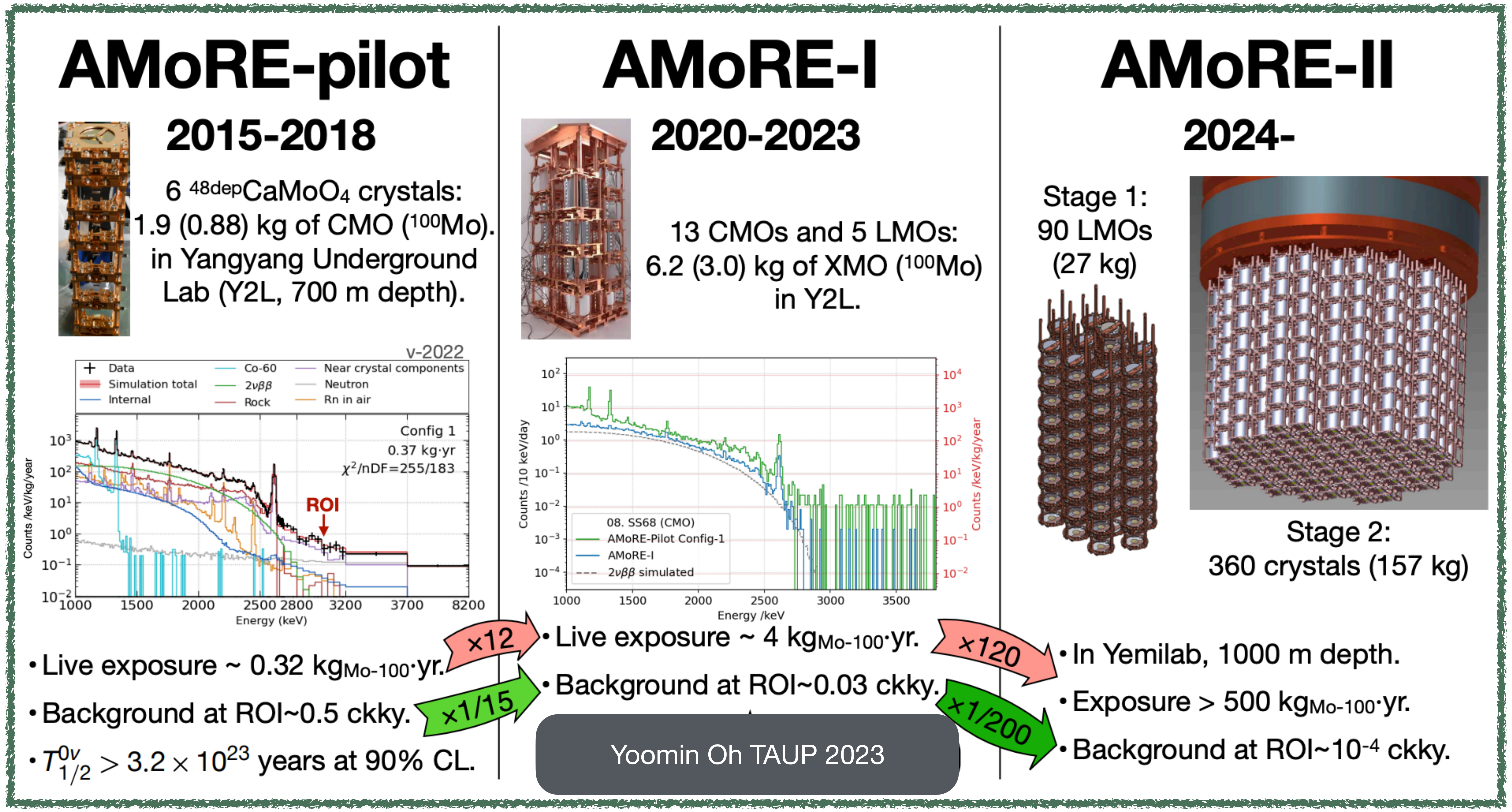






AMoRE-II

- Another next-generation ^{100}Mo experiement
- At a deeper Yemilab (1000 m rock overburden)
- Aim BI $< 1 \times 10^{-4}$ cnts/ (keV. kg. y).
- Started crystal production.
- Aims for a half-life sensitivity exceeding 4.6×10^{26} years

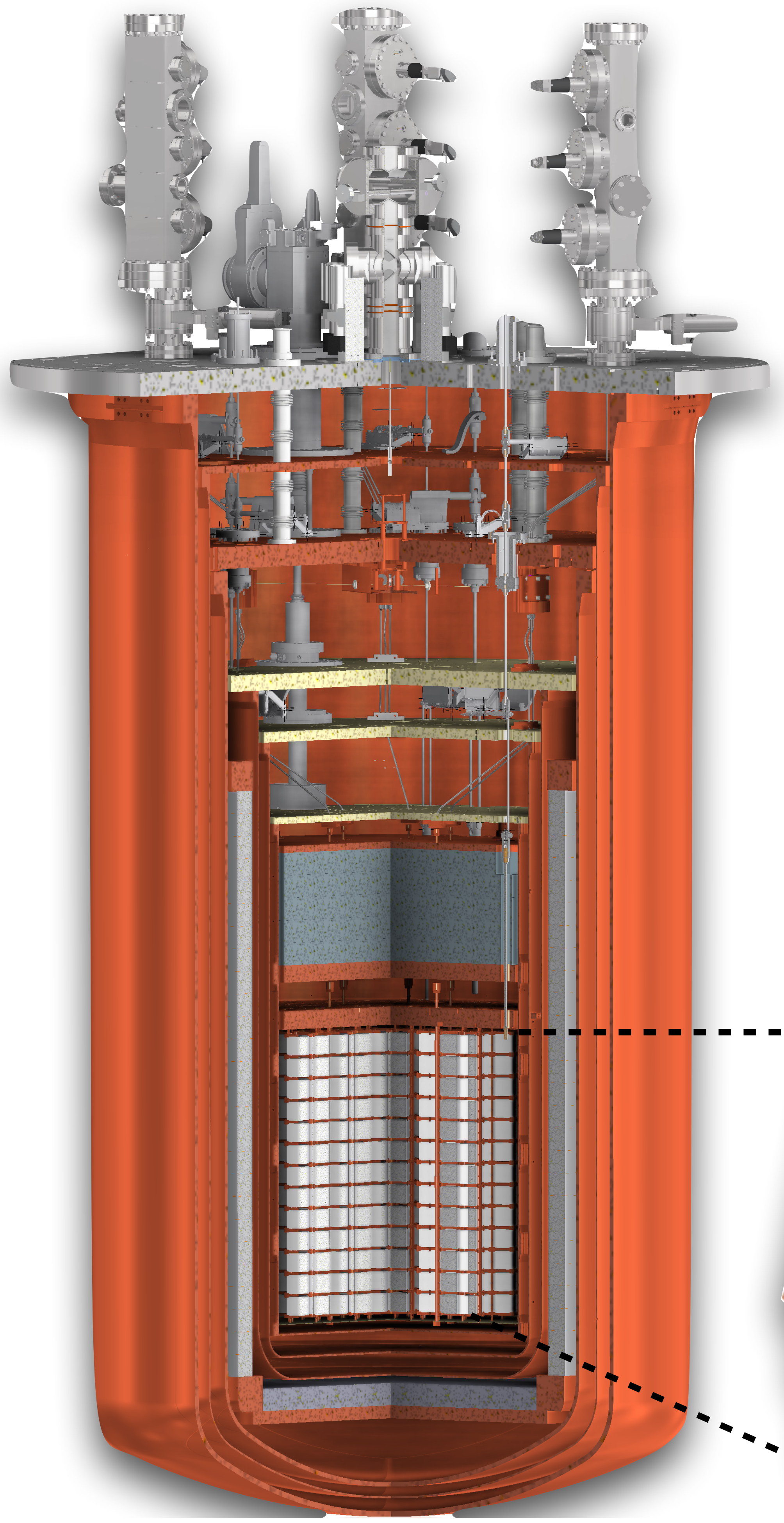
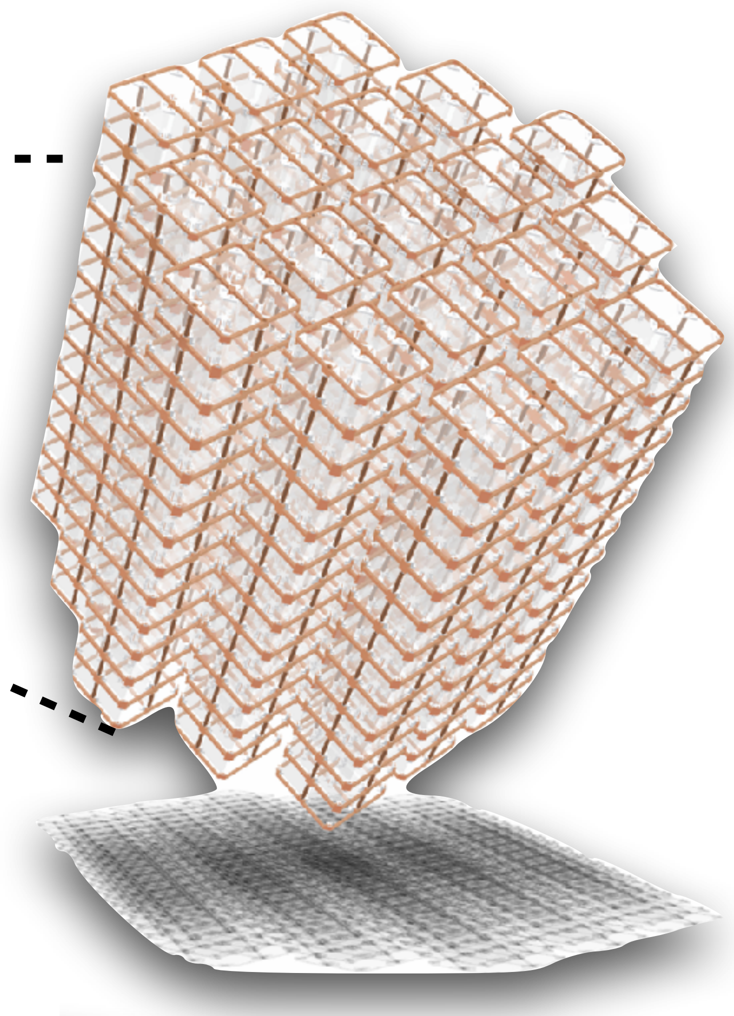


Discovery sensitivity for 500 kg. yr of exposure

$m_{\beta\beta} < 20–35$ meV

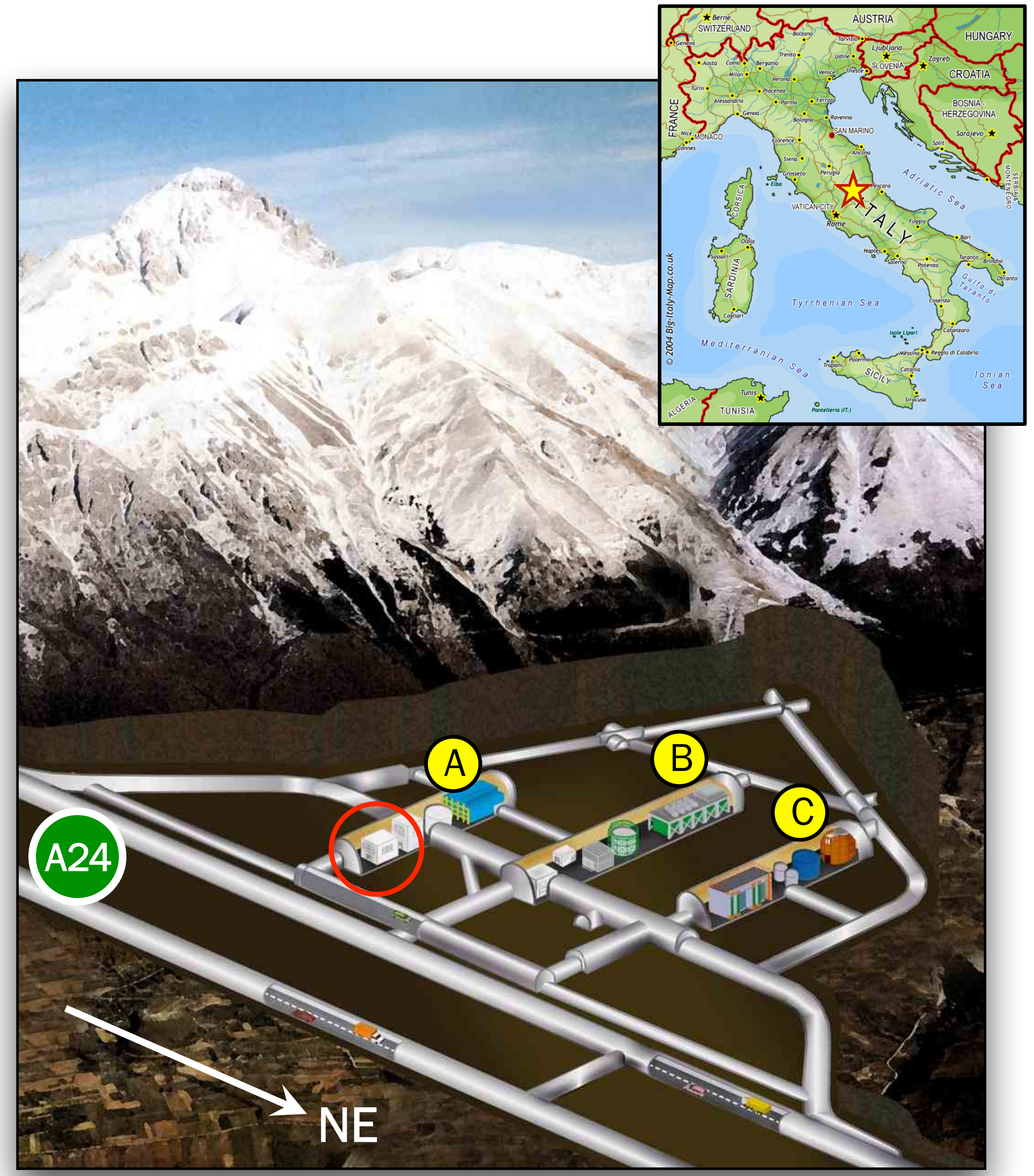
Agrawal, A., et al. *arXiv preprint arXiv:2407.05618* (2024)

CUORE

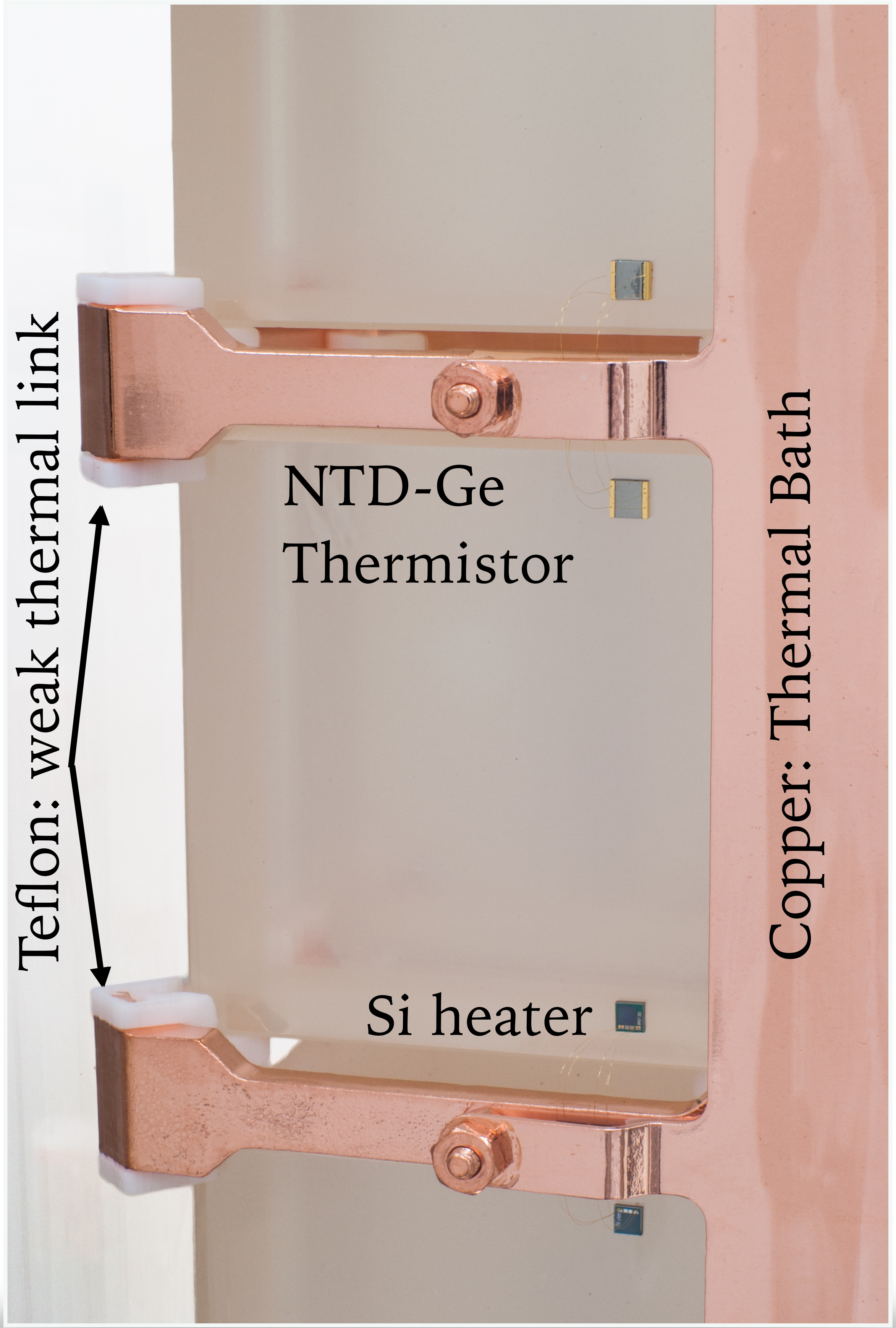
*The **C**ryogenic **U**nderground **O**bservatory for **R**are **E**vents*

- Search for $0\nu\beta\beta$ in ^{130}Te at LNGS, Italy (depth ~ 3600 m.w.e)

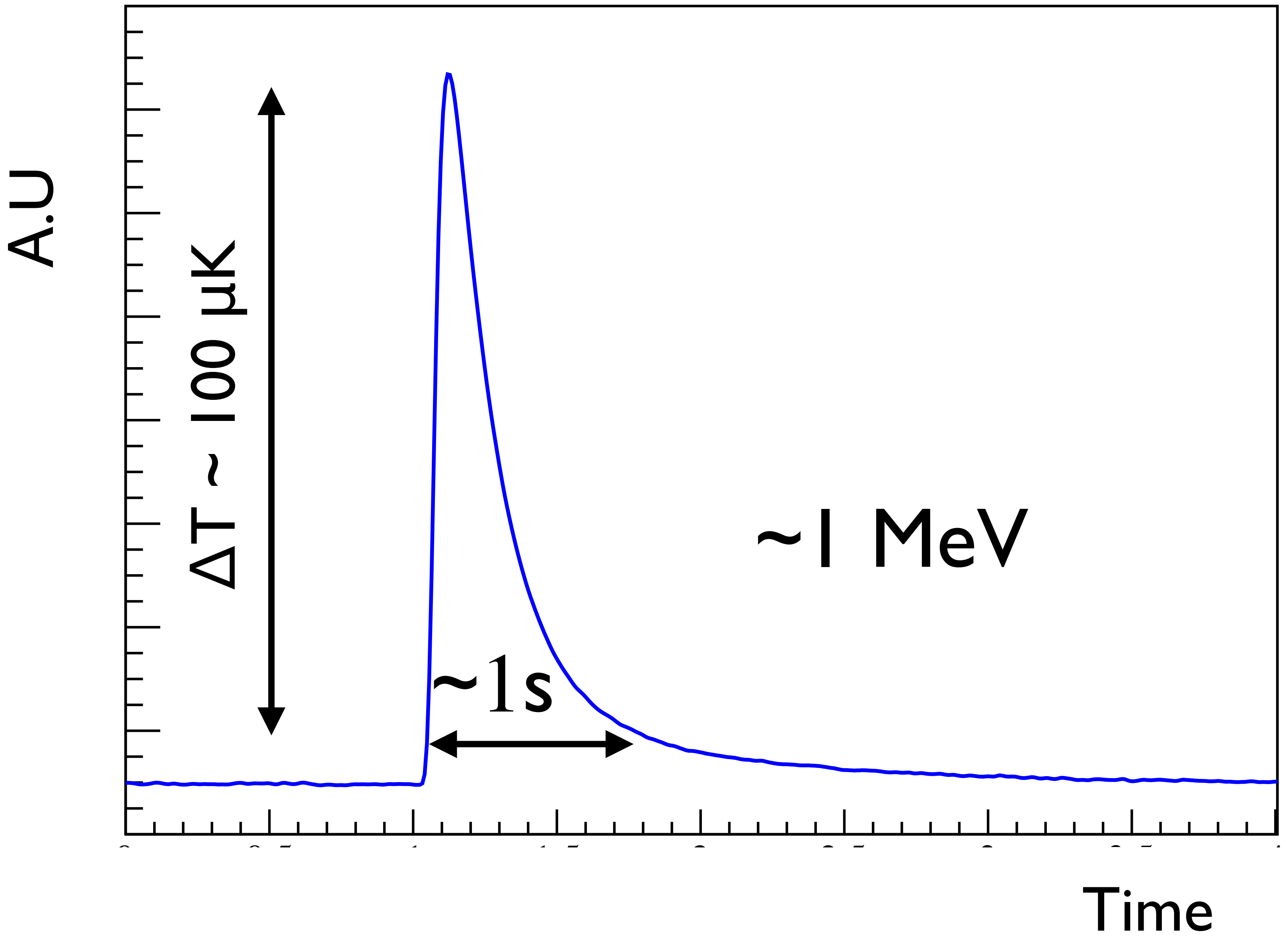


- $Q_{\beta\beta} = 2528$ keV
- Isotopic mass of ^{130}Te : 206 kg
- 988 TeO_2 crystals (arranged in 19 towers with 13 floors each)
- Massive thermal calorimeters operated at ~10 mK
- CUORE started data-taking in 2017.
- Interruptions for cryogenic optimization until 2019 but have been steadily taking data ever since.

CUORE - DETECTOR PRINCIPLE



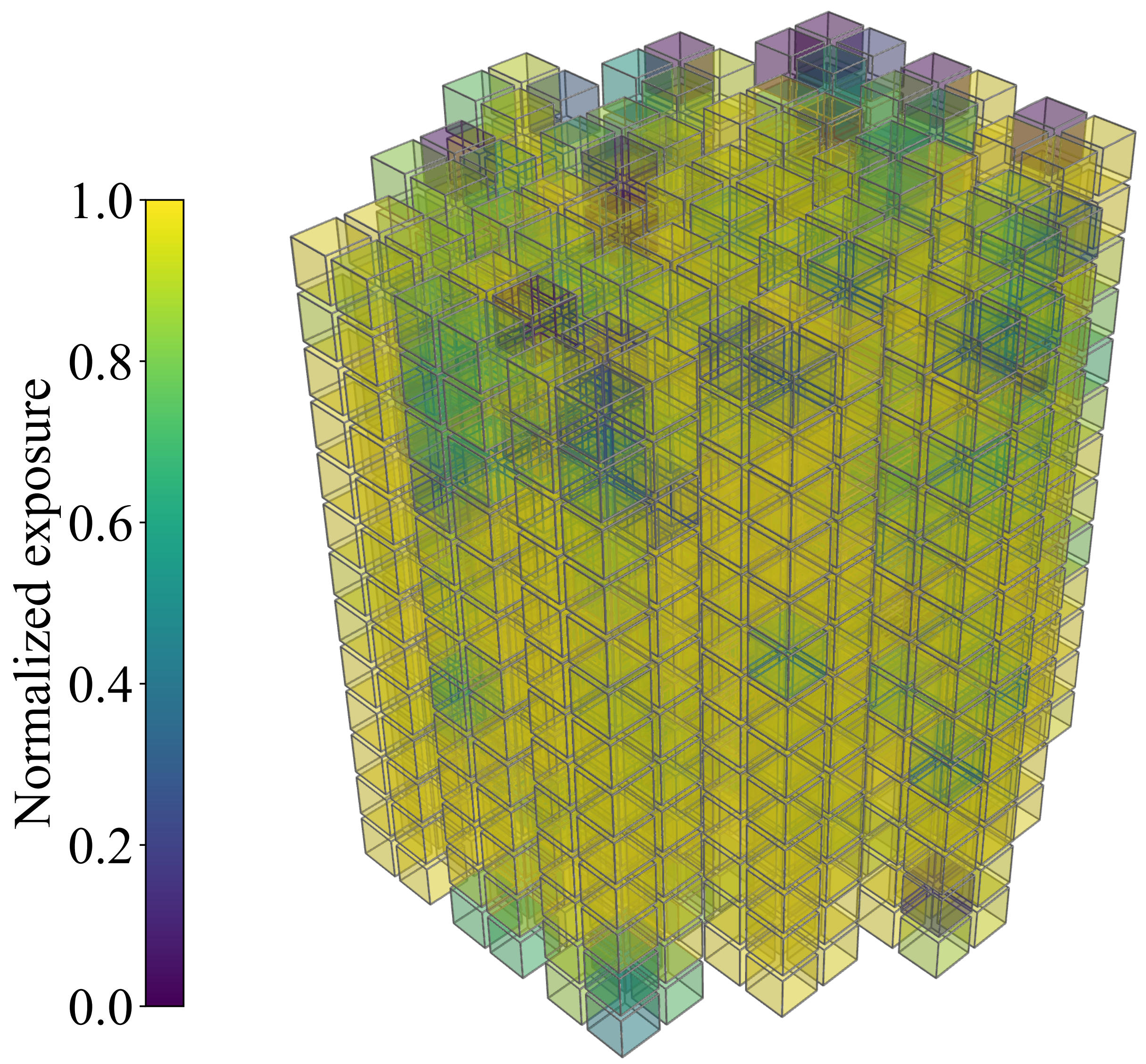
- 750 g (5x5x5 cm^3) crystal
- 988 crystals installed in CUORE
- $\triangle$T ~ 100 μK for 1 MeV energy deposit
- NTD-Ge thermistor read out
  - R(T) ~ R_0 exp [$(T_0/T)^{1/2}$]
    (large sensitivity at low T)
- Energy response calibrated using known gamma sources
- Note:
  - Signal ➛ thermal channel only
  - No active background rejection

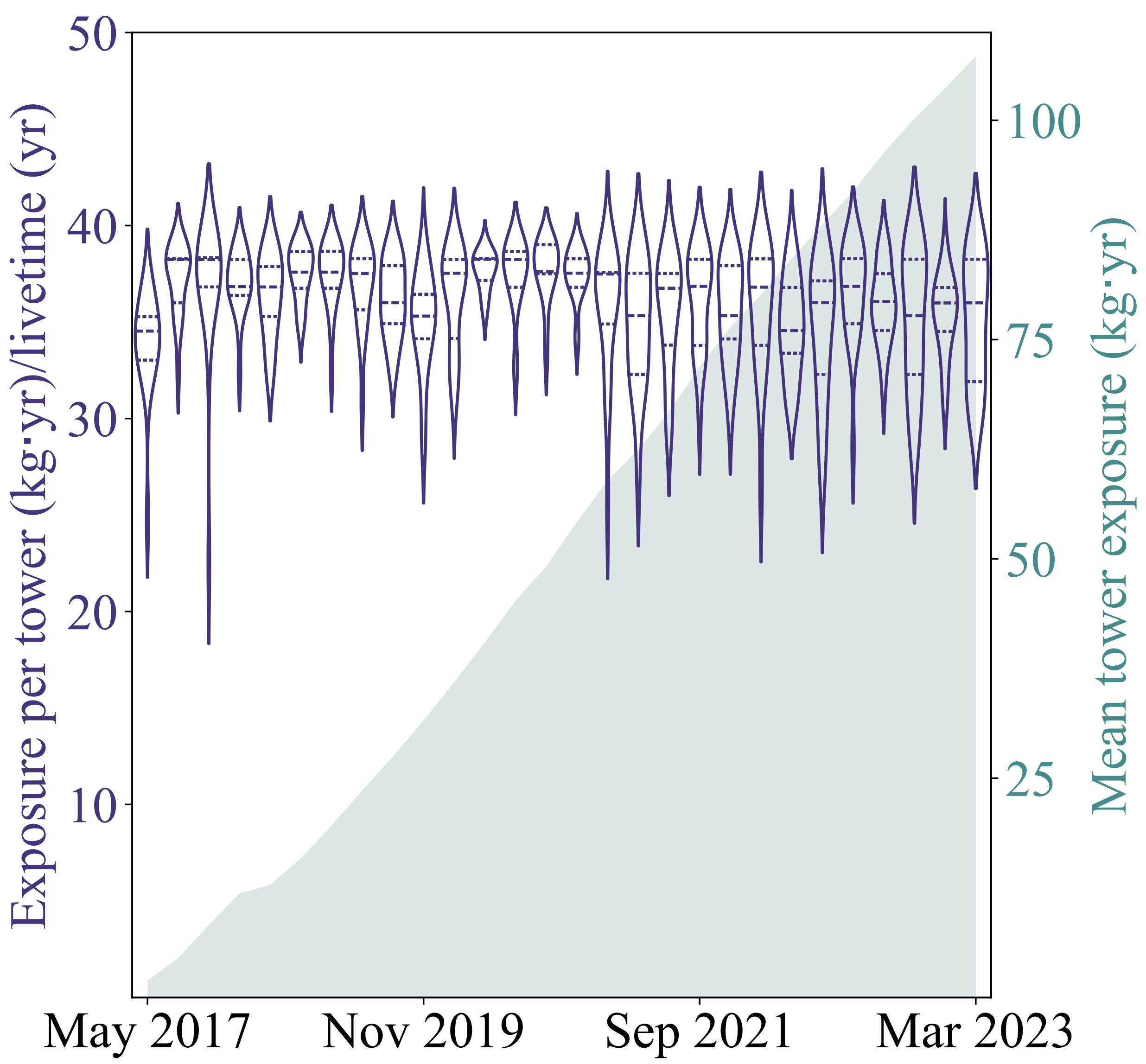


CUORE - DATA TAKING

- 34 datasets collected so far, each dataset ~1 month long (~50 kg.yr TeO2/ month)
- Published $0\nu\beta\beta$ search results in 2022 for the data collected up to 2020
- Updated search with data collected up to April 2023 (~2 tonne.yrs of TeO_2 exposure)

CUORE Preliminary 2039.0 kg.yr





arXiv: 2404.04453

365 days highlights from news & views 2022

March

Neuroimaging

Brain changes after COVID revealed by imaging

In 2020, the UK Biobank (a large-scale biomedical database and research resource) launched a COVID-19 repeat-imaging study, in which participants who had completed a medical-imaging session before the pandemic returned for an identical, second scan session. Douaud *et al.* explored these data, comparing scans pre- and post-pandemic. Participants who had tested positive for SARS-CoV-2 between the two scans exhibited changes in the brain cortex that are often associated with worsening brain health. This group also displayed increases in markers of tissue damage in brain regions connected to smell and taste. There is much more work to be done to extract all the useful information from this valuable data set. The UK Biobank's data sharing and Douaud and colleagues' release of their analysis code serve as an open invitation to join the effort.

Randy L. Gollub writing in *Nature* **604**, 633–634 (2022).
Original research: *Nature* **604**, 697–707 (2022).

April

Nuclear physics

Cryogenic mastery aids bid to spot matter creation

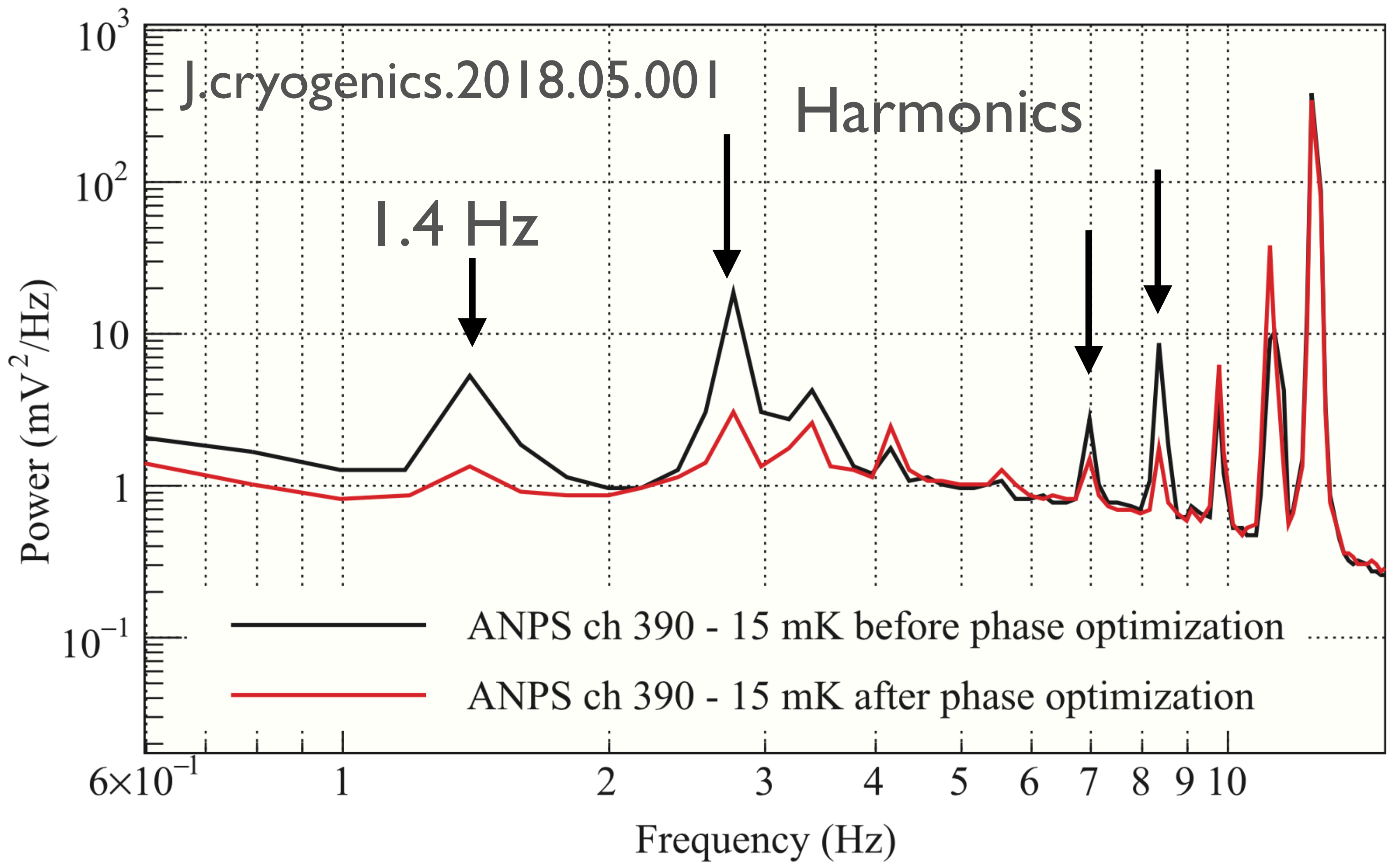
Astrophysical observations reveal that the Universe is made almost entirely of matter, with nearly no antimatter in sight. However, laboratory and particle-collider experiments have so far observed the creation of matter and antimatter in equal parts. Big Bang theories that aim to explain the cosmic-matter imbalance predict that matter could be generated without antimatter in a 'little bang', during an ultra-rare nuclear process called neutrinoless double-β decay. The CUORE Collaboration reports the most sensitive search yet for this type of decay using isotopes of tellurium. The decay was not observed, but the engineering feat was remarkable – requiring the stable operation of more than one tonne of experimental apparatus, at cryogenic temperatures close to 10 millikelvin, over several years.

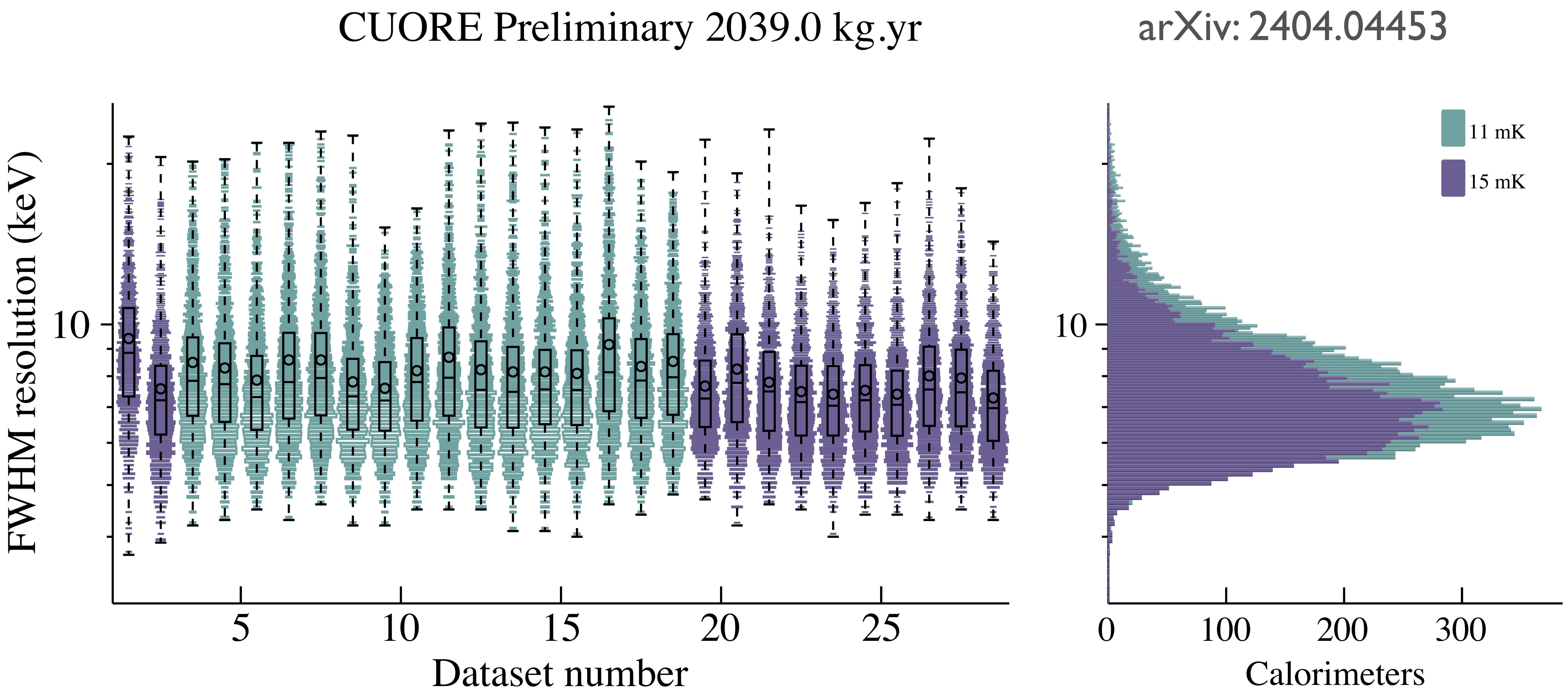
2022 Nature Highlight!

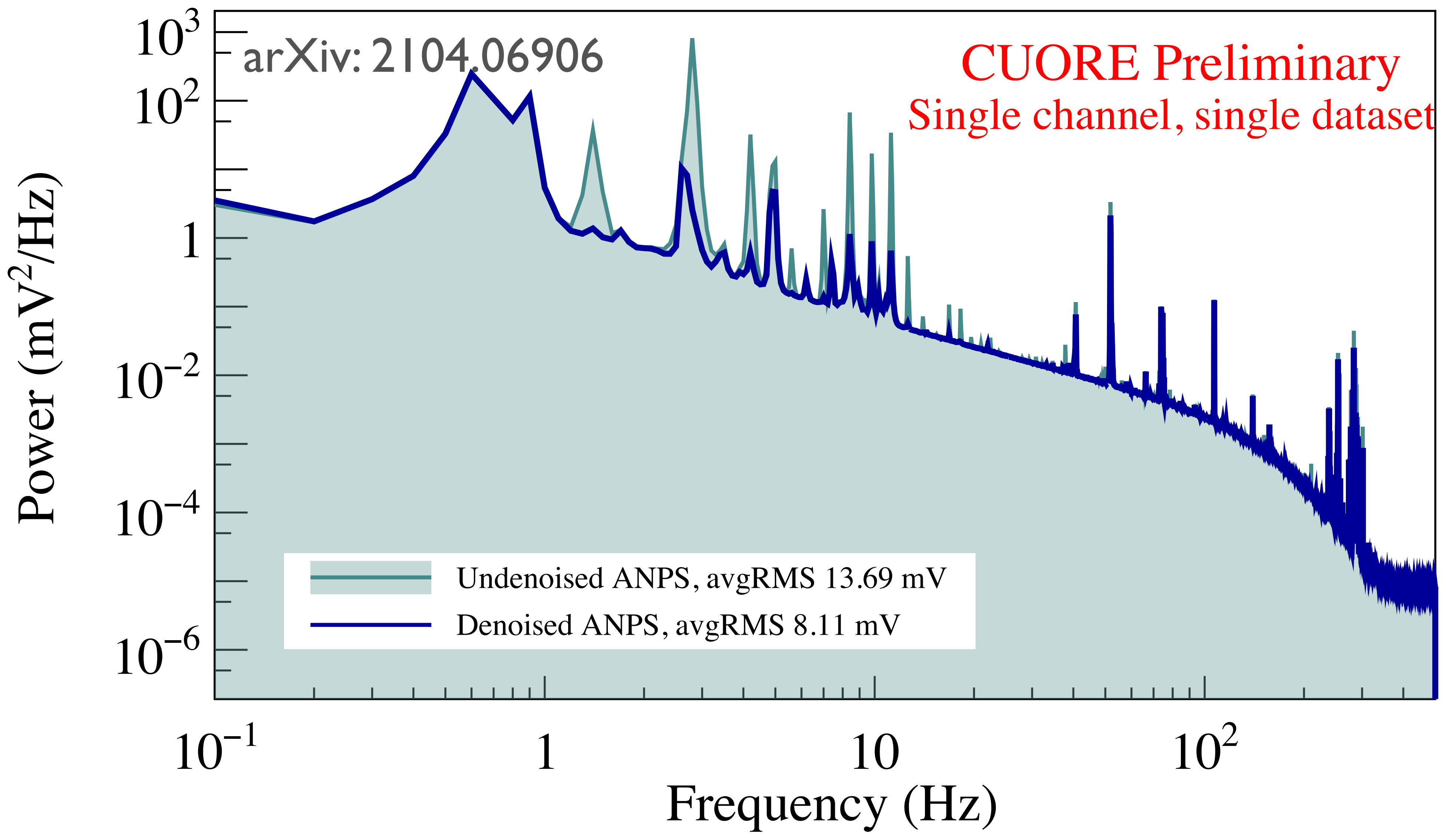
644 | Nature | Vol 612 | 22/29 December 2022

CUORE - Detector Performance

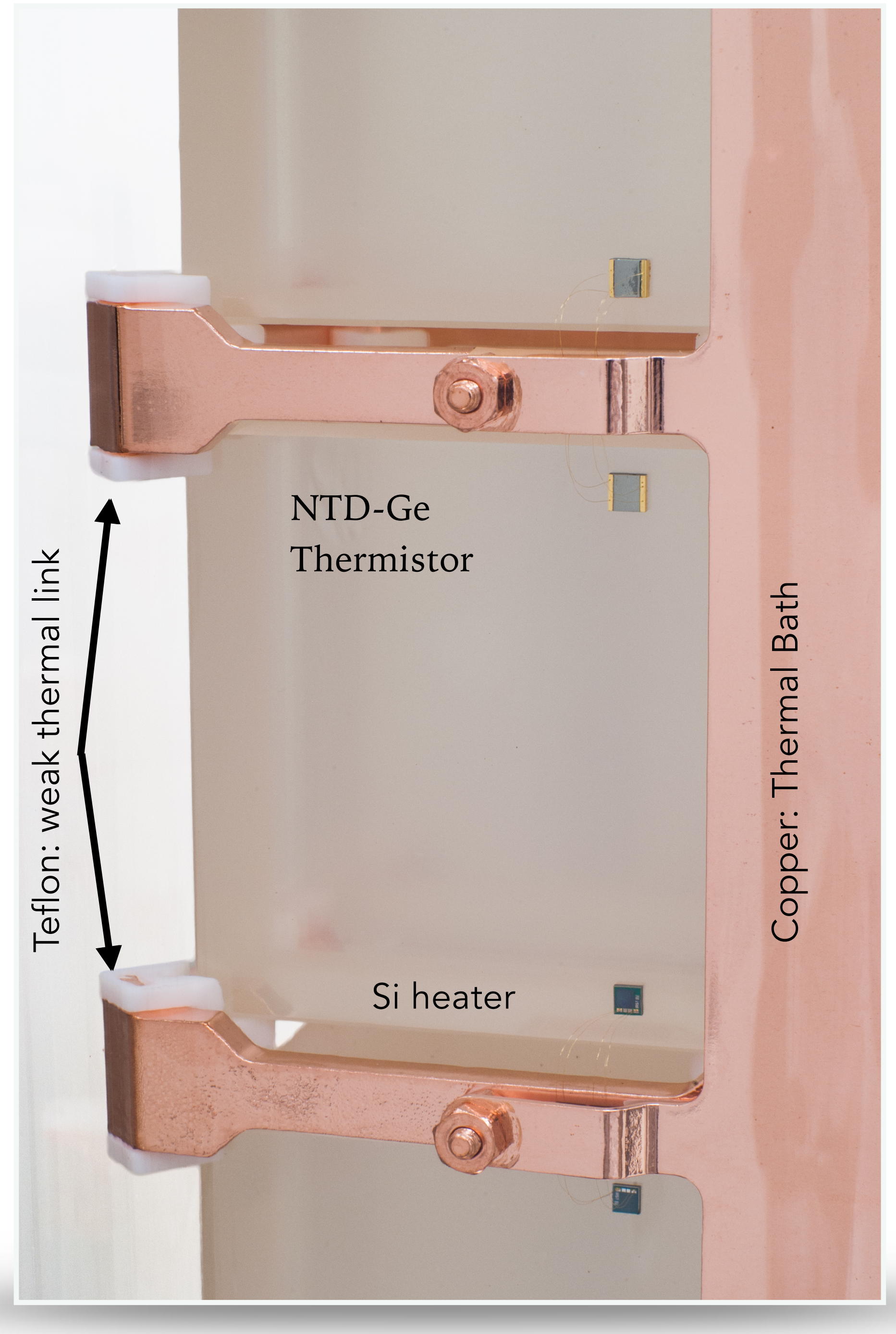
- 984 out of 988 channels active
- Vibrations one of the major sources of noise affecting resolution -> active noise reduction developed for mitigation.
- Total analysis cut efficiency 93.4 %
- Robust analysis infrastructure that can handle ~1000 channels under varying conditions

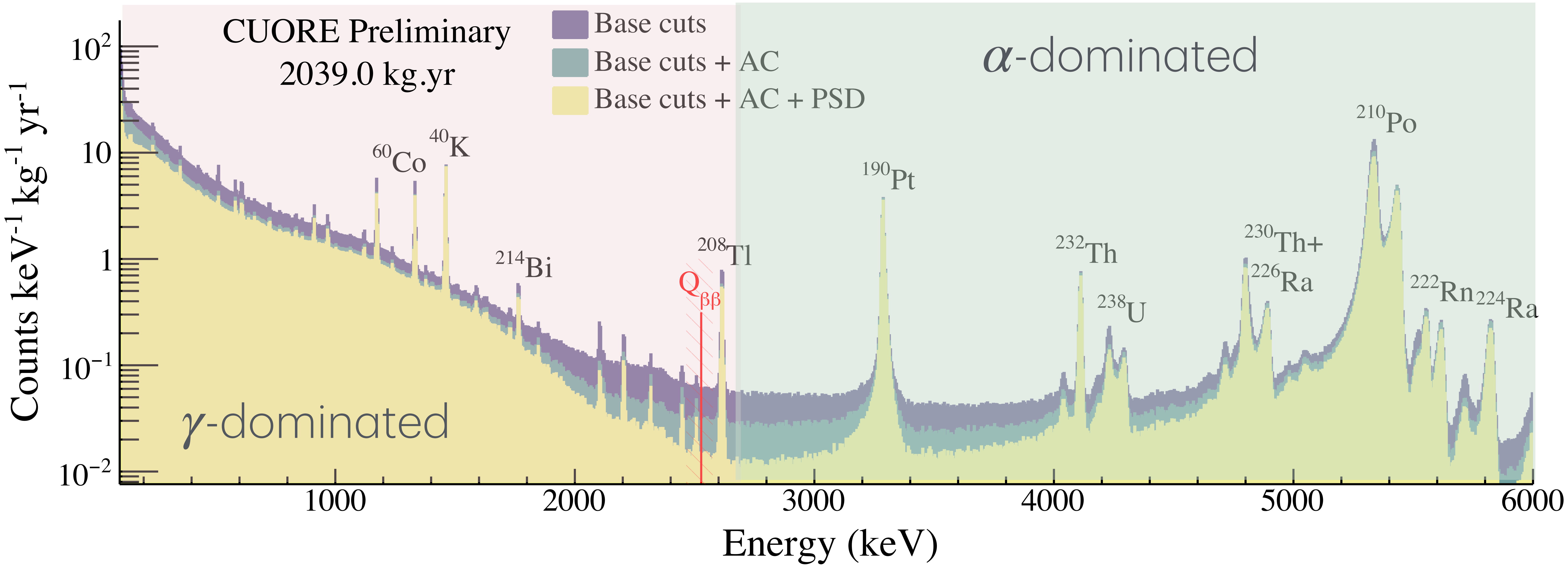






CUORE - Spectrum



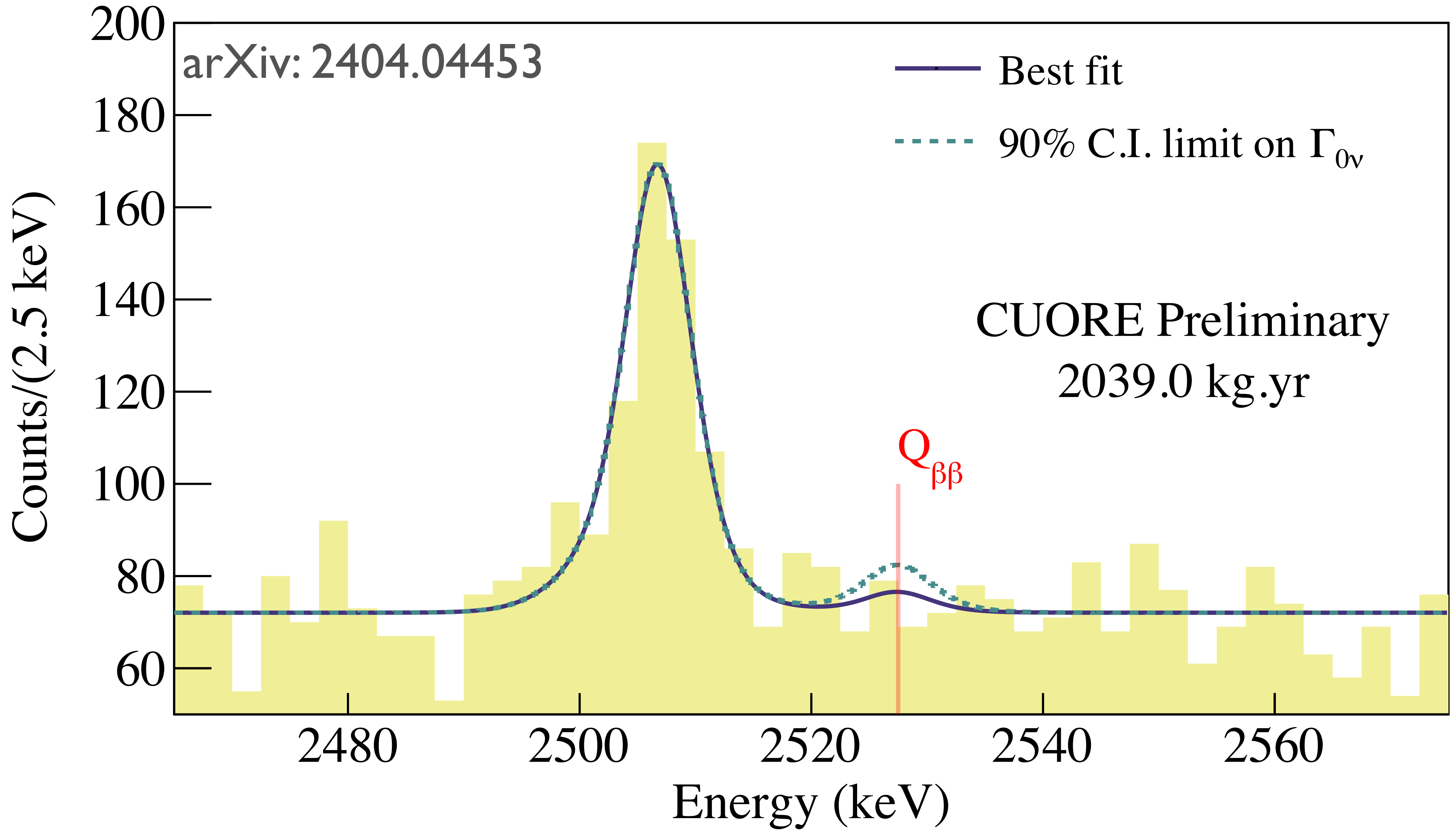


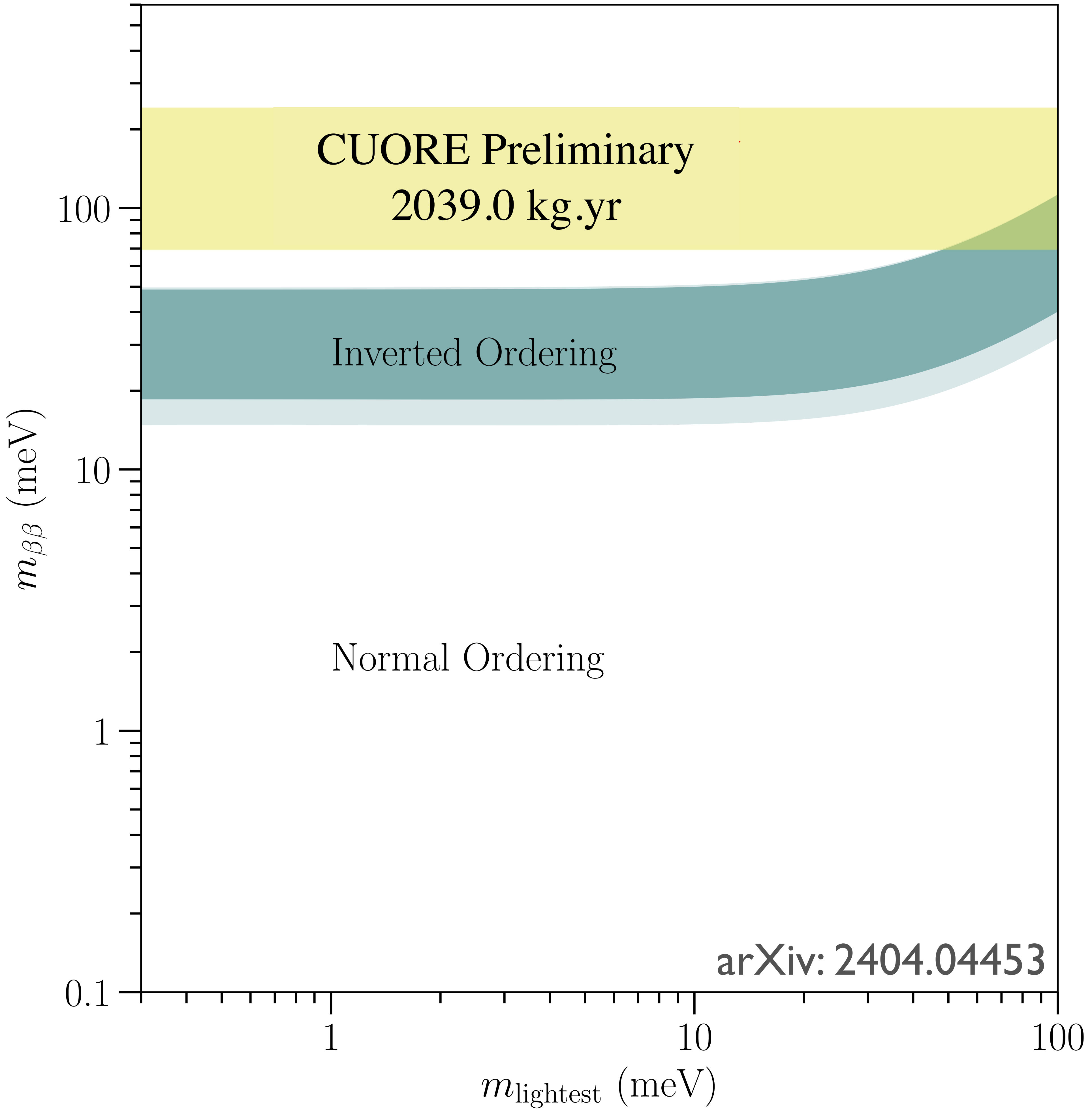
- Detector element detects only heat
- No particle ID

- ~ 90% of background in the ROI is from degraded alphas
- Muons are the next dominant background.

CUORE - Spectrum

- Fit performed over [2465, 2575] keV with fit parameters:
  - $0\nu\beta\beta$ decay rate @ $Q_{\beta\beta}$
  - ^{60}Co sum peak amplitude
  - Background (flat)
- No evidence of $0\nu\beta\beta$
- $T_{1/2}^{0\nu}$ > **3.8 x10^{25}** yr (90% C.I.)

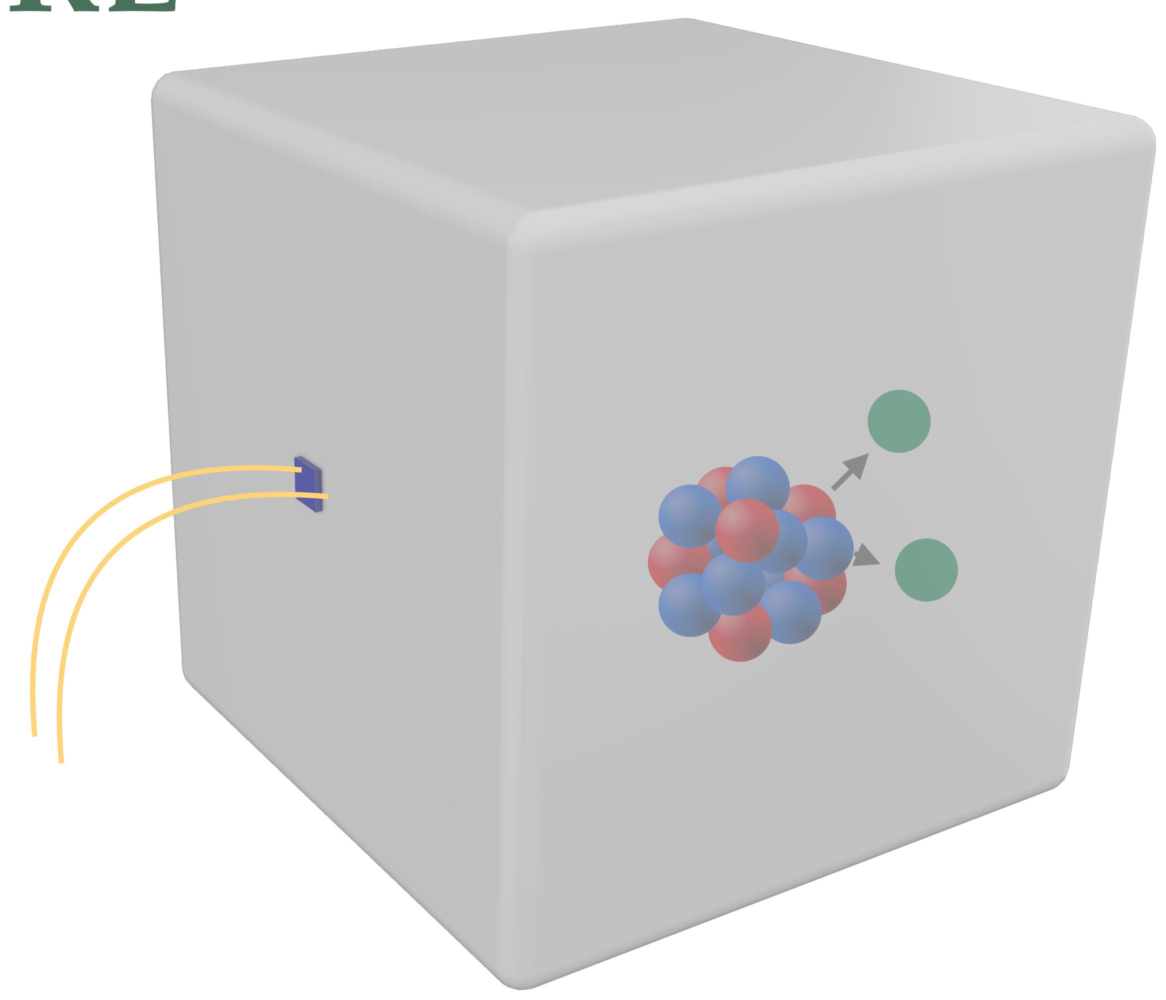




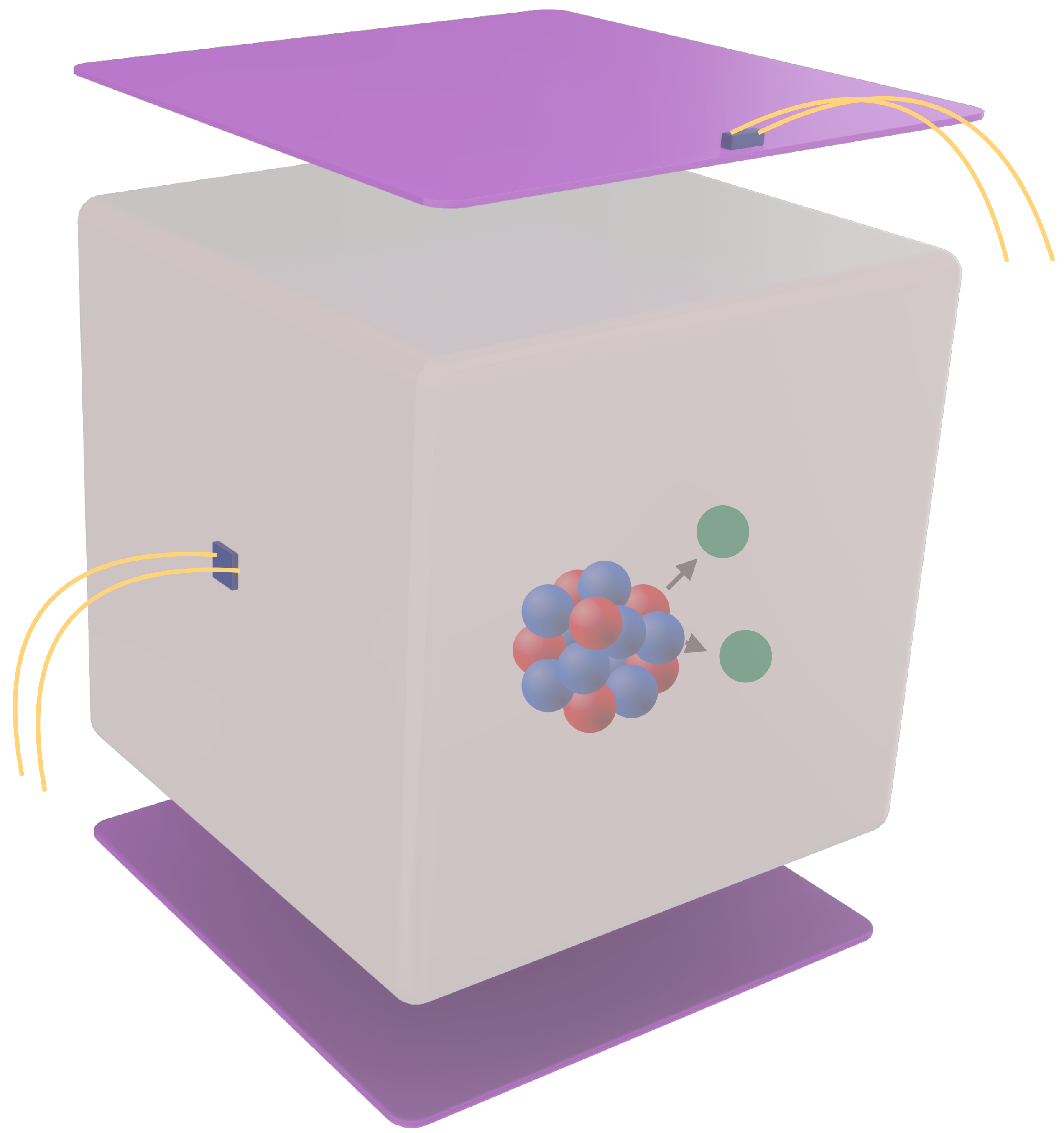
Assuming light neutrino exchange:
$m_{\beta\beta}$ < **70–240 meV**

CUPID - CUORE Upgrade with Particle ID

CUORE



CUPID



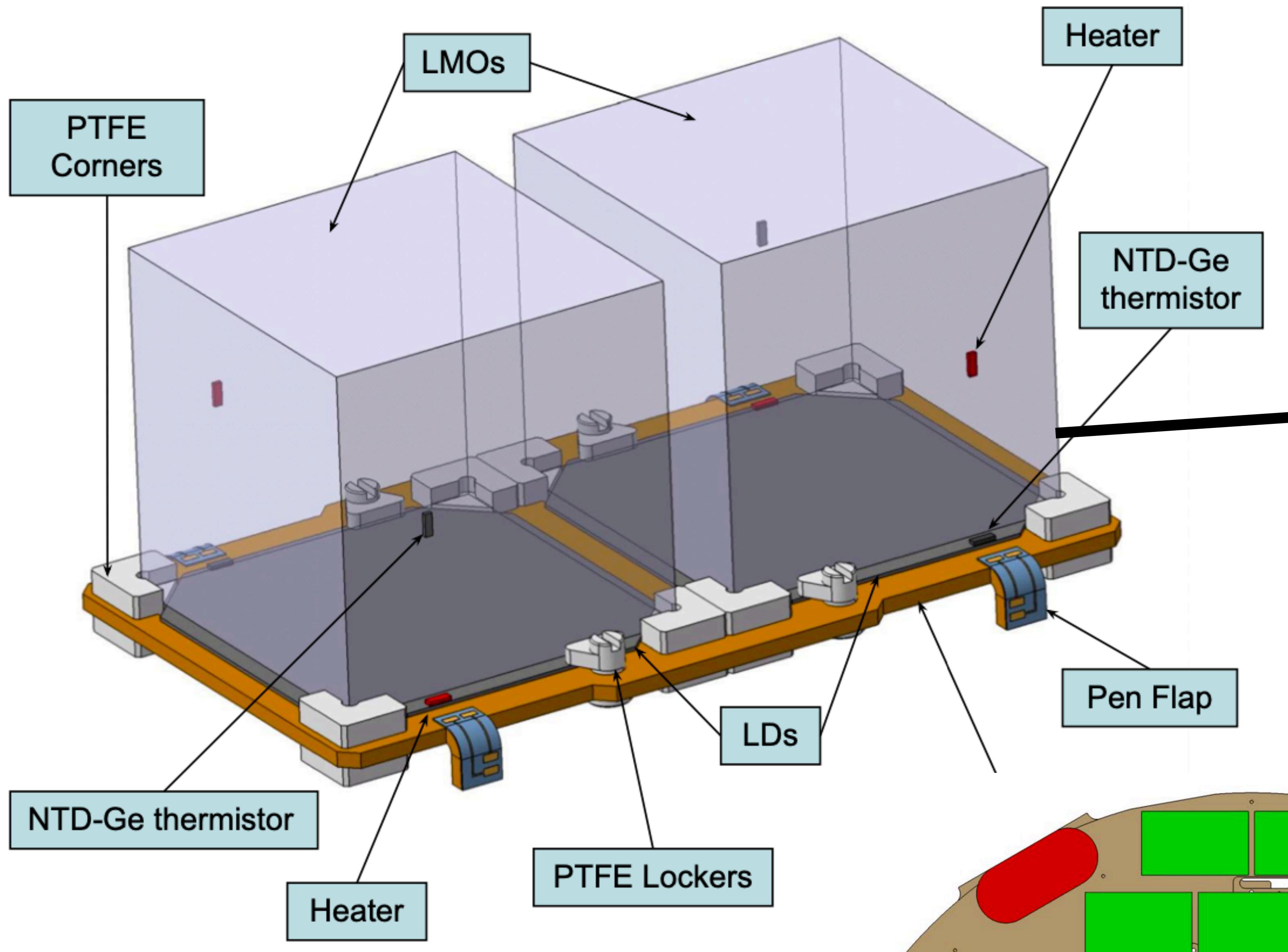
Operated at ~ 10 mK

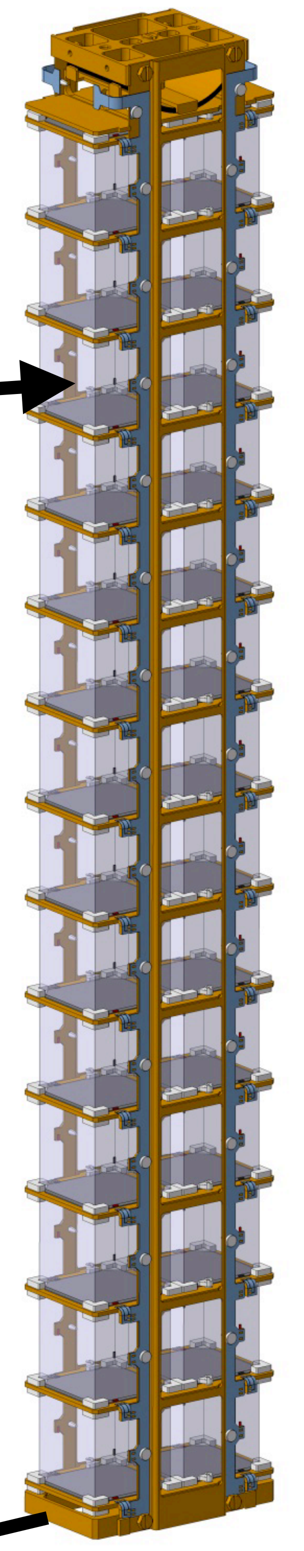
- TeO_2 crystals (^{130}Te isotope of interest)
- $Q_{\beta\beta} \sim 2528$ keV
- Measures only heat (phonons) signals.
- Background Index : 1.42×10^{-2} cnts/ (keV. kg. y)

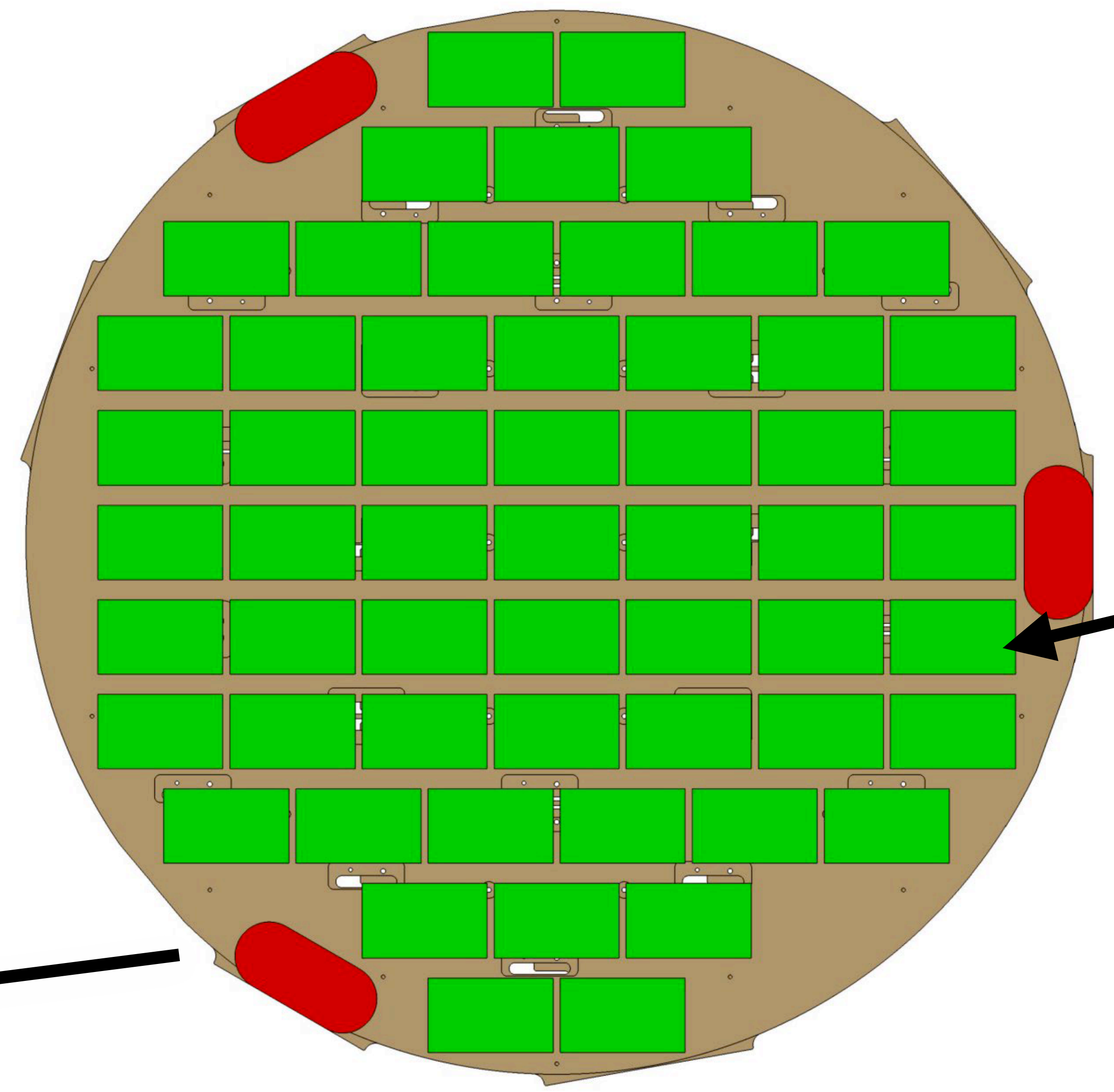
- Scintillating $Li_2{}^{100}MoO_4$ crystals (^{100}Mo isotope)
- $Q_{\beta\beta} \sim 3034$ keV
- Simultaneous measurement of absorbed heat and emitted light.
- Background Index $< 1 \times 10^{-4}$ cnts/ (keV. kg. y)

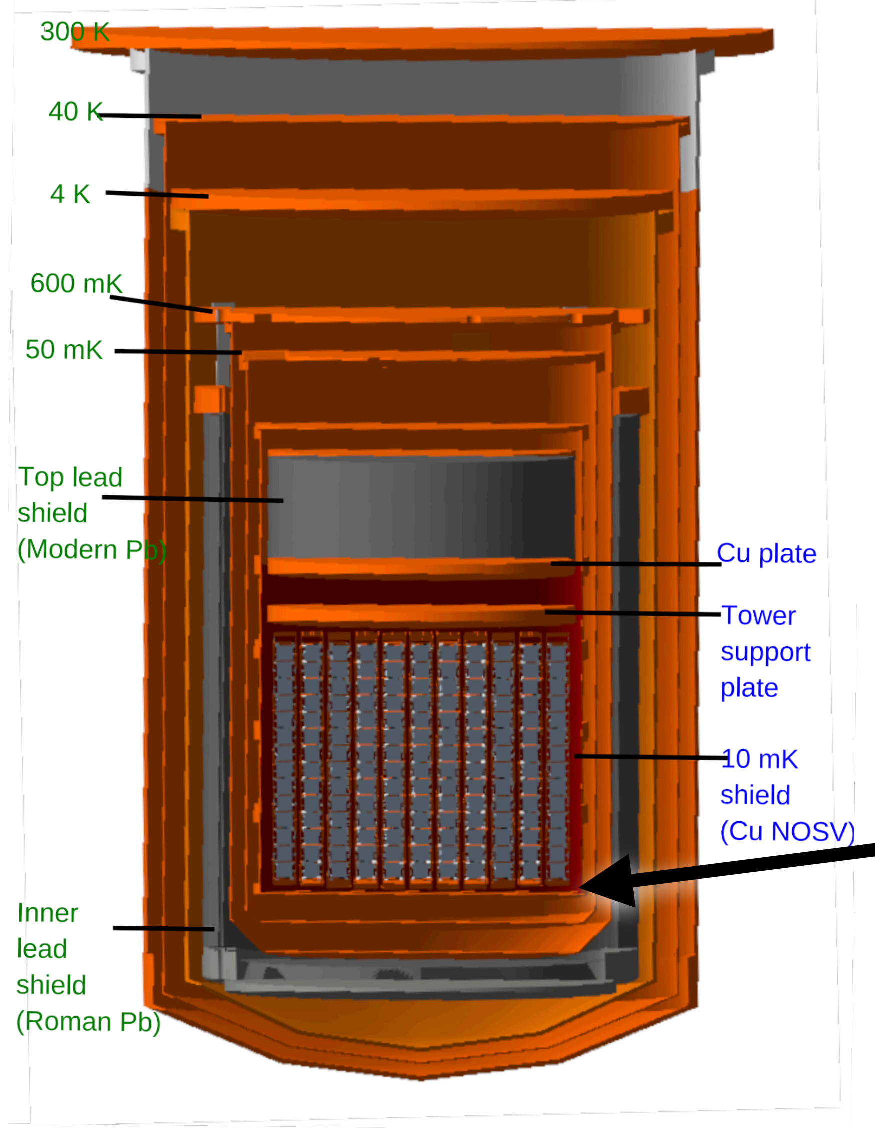
CUPID - Design

- Single detector:
  - **Absorber:** 4.5x4.5x4.5 cm^3 Li$_2$^{100}MoO$_4$ crystals (> 95% enrichment)
  - **Builds on the experience of CUORE and utilizes its cryogenic infrastructure.**
  - **Light detector:** Ge light detector with Neganov-Trofimov-Luke amplification
- Detector array:
  - Modified detector array structure
  - 57 towers (total of 1596 crystals)
  - 240 kg of ^{100}Mo
- Addition of muon and neutron shields.



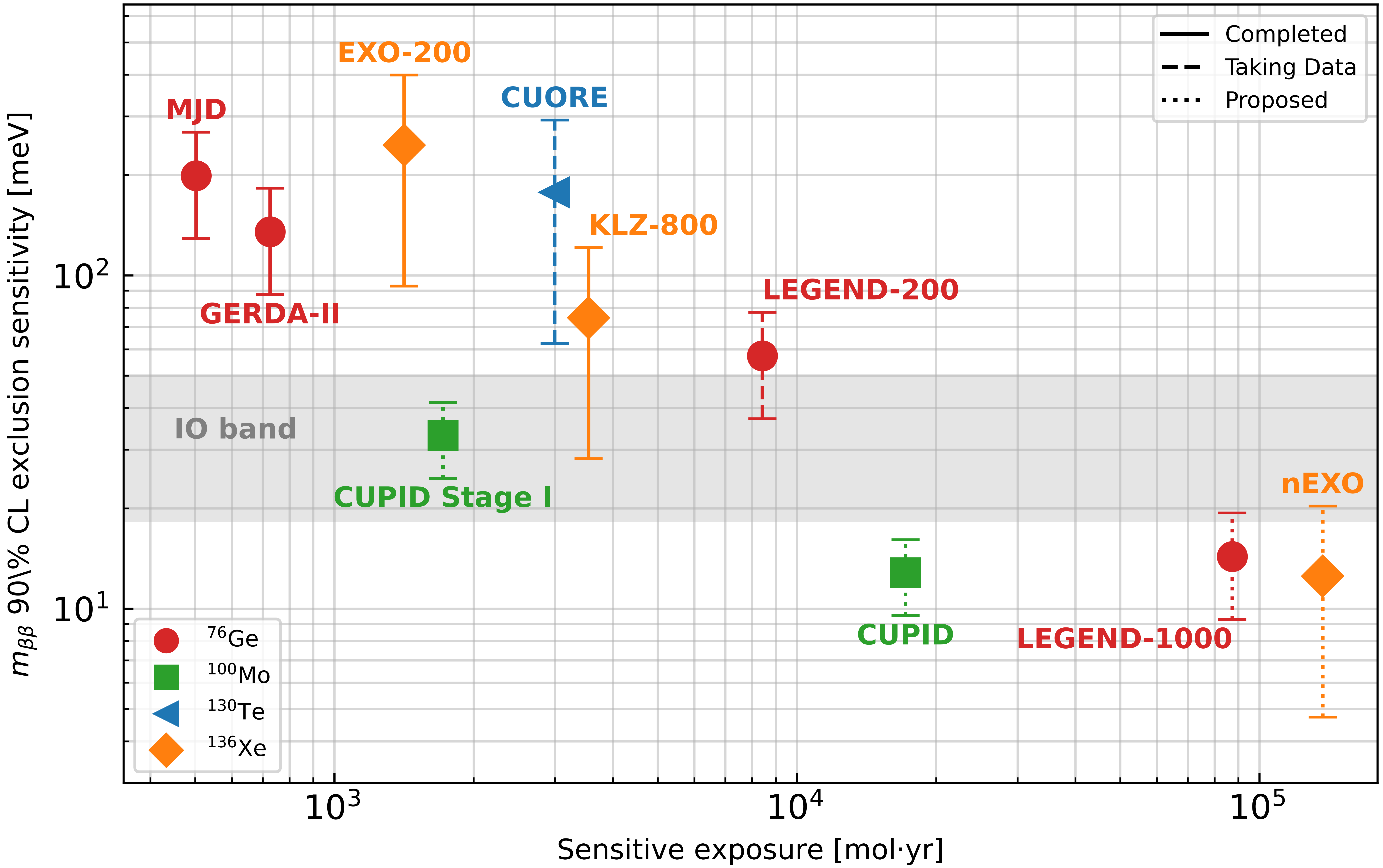


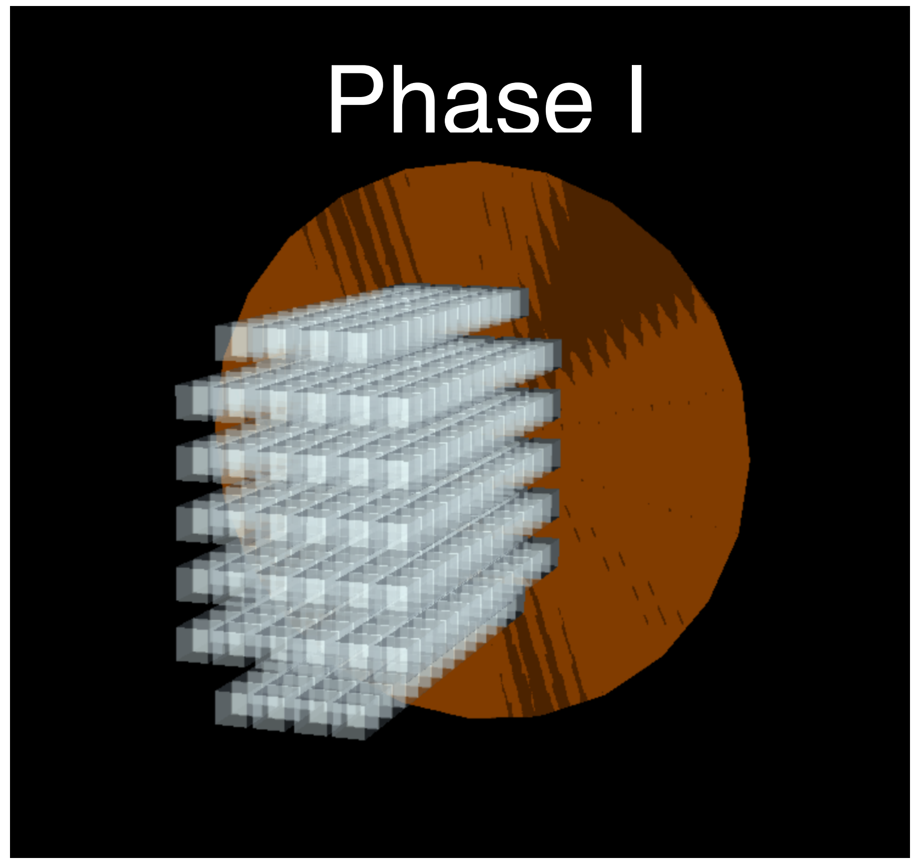




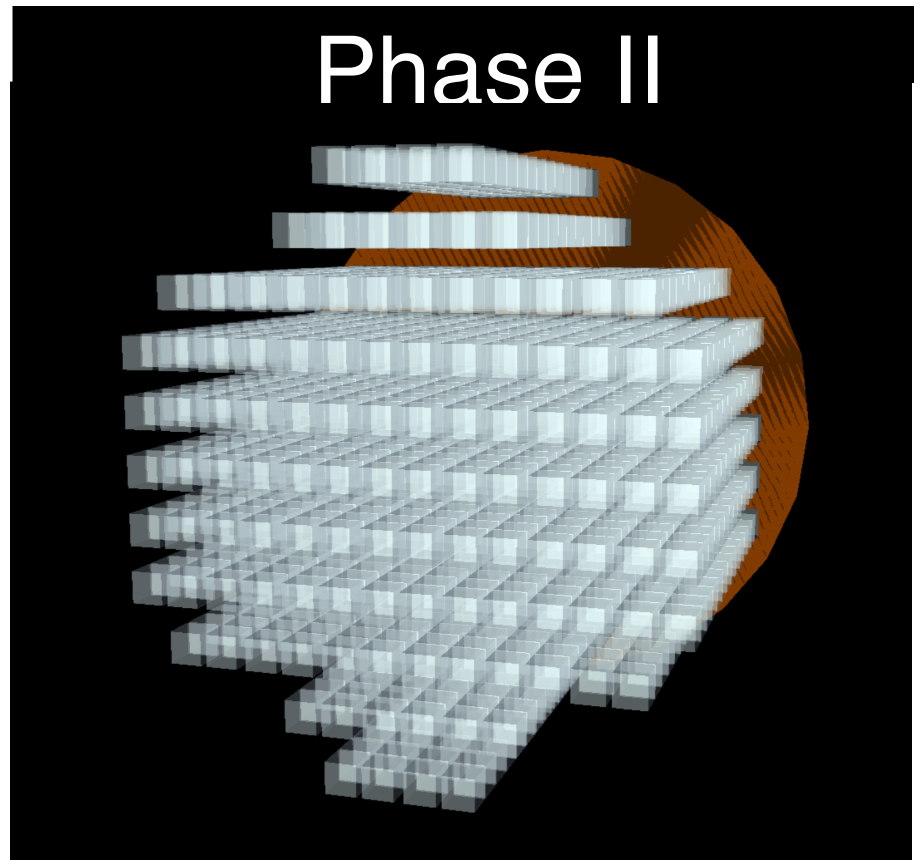
From: PT Surukuchi DNP 2024

CUPID - Sensitivity





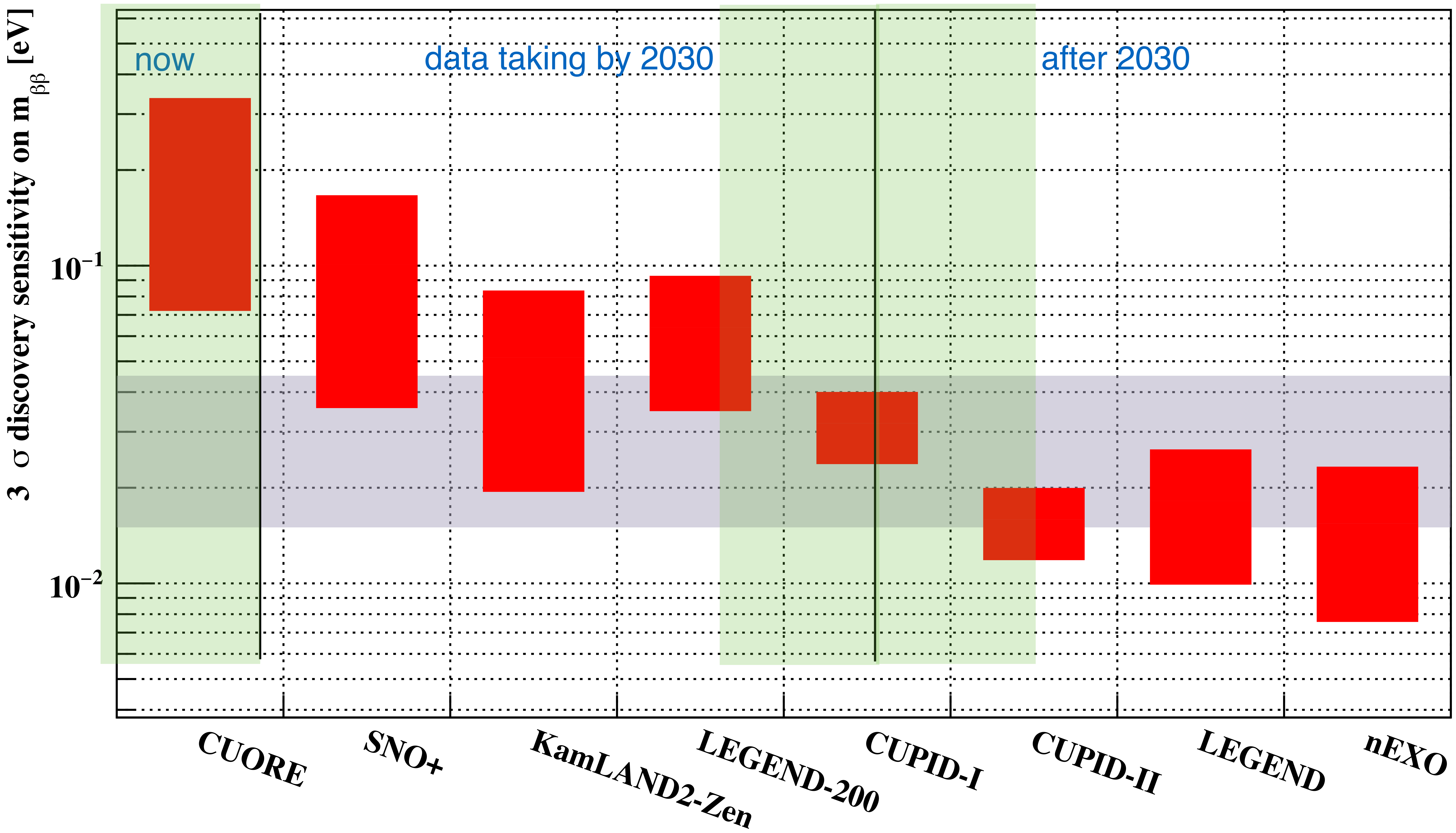
CUPID Stage I has world-leading science reach



CUPID is ton-scale experiment with competitive sensitivity

CUPID - Discovery Sensitivity

Sensitivity



Staged deployment enables first science data by 2030 with CUPID-I

Ton-scale experiment with competitive sensitivity

What if there is a discovery?

Searches in Multiple Isotopes Necesary

- **Confirmation and Understanding:** Studying 0νββ in multiple isotopes is crucial not only to confirm a discovery but also to pinpoint the specific mechanism driving the decay.
- **Diverse Sensitivities:** Different isotopes offer varying levels of sensitivity to 0νββ and background rejection capabilities, providing a more comprehensive search.
- **Independent Uncertainties:** Each isotope-based experiment has unique systematic uncertainties, allowing for cross-checks and improved reliability of results.
- **Model Validation:** Measurements across different isotopes help validate theoretical nuclear models and refine our understanding of the underlying physics.
- **Complementary Approaches:** Even experiments with limited scalability can provide valuable information, such as precise measurements of two-neutrino double beta decay and studies of specific isotopes like ^{48}Ca for benchmarking nuclear models.

Angular Correlation, single electron spectra …

SuperNEMO

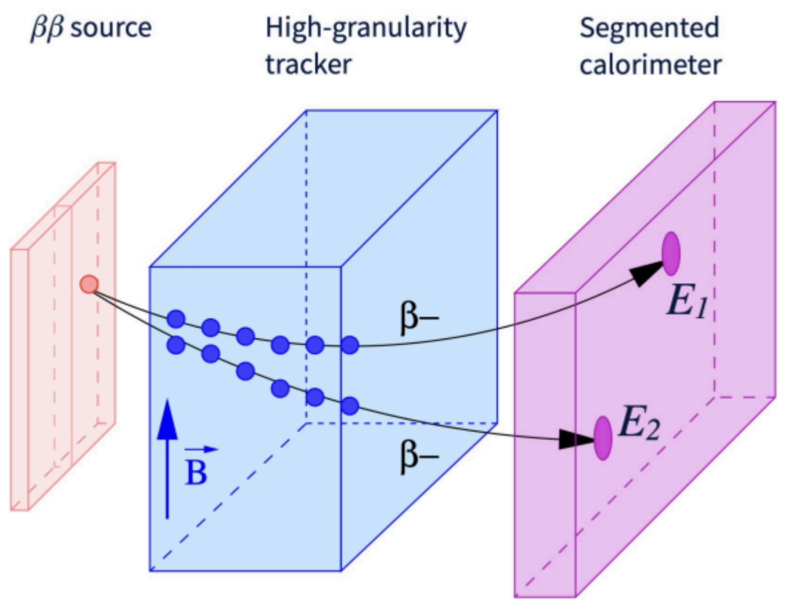
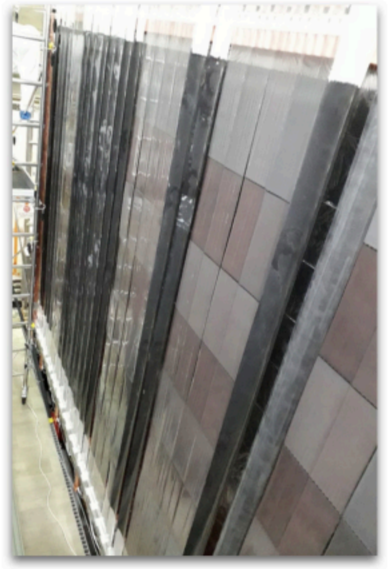


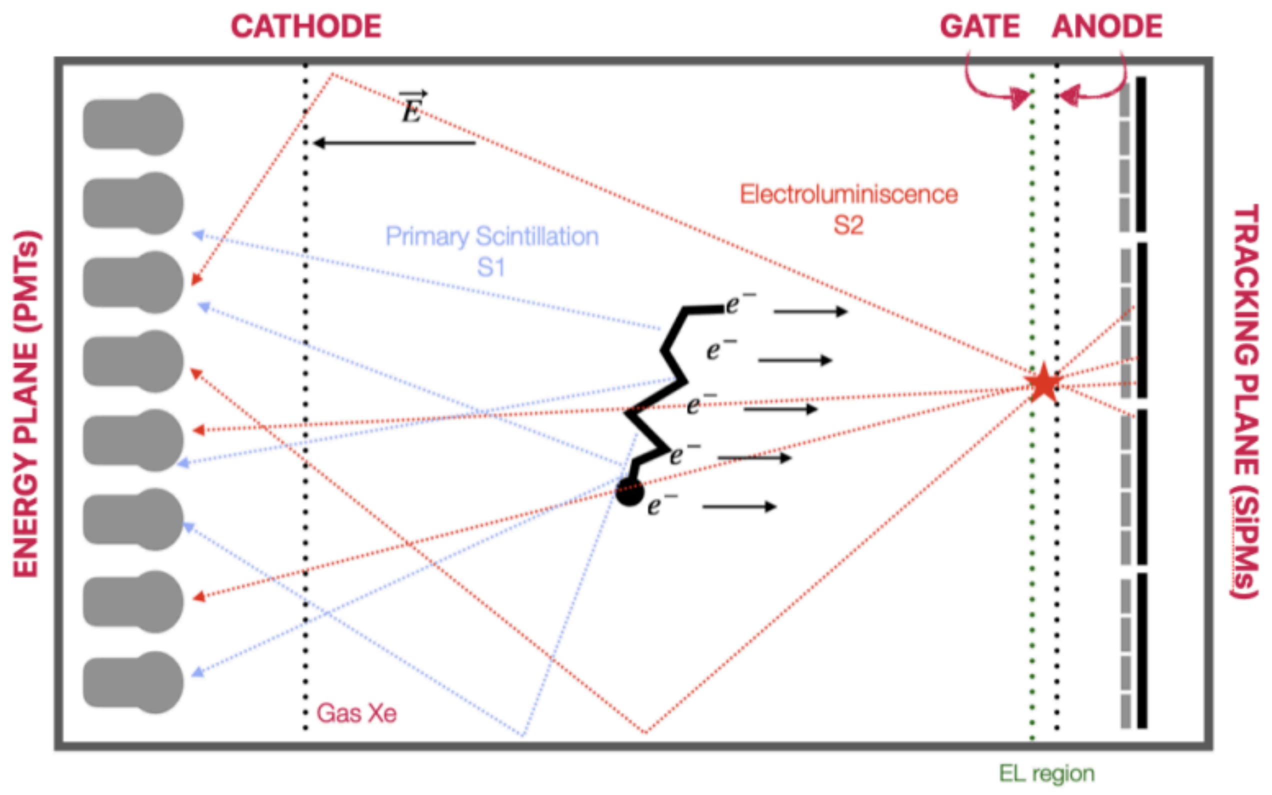
Figure 1: The NEMO technique

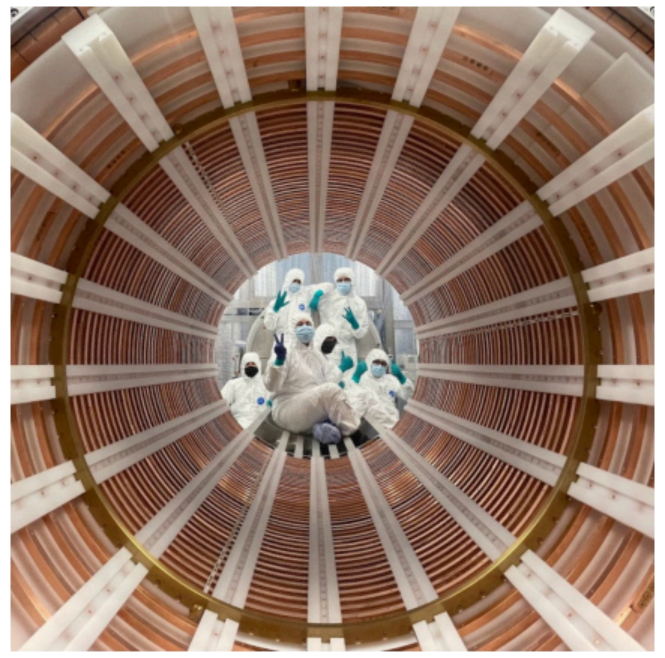
Patrick, C., and SuperNemo Collaboration. TAUP Proceedings 2024.

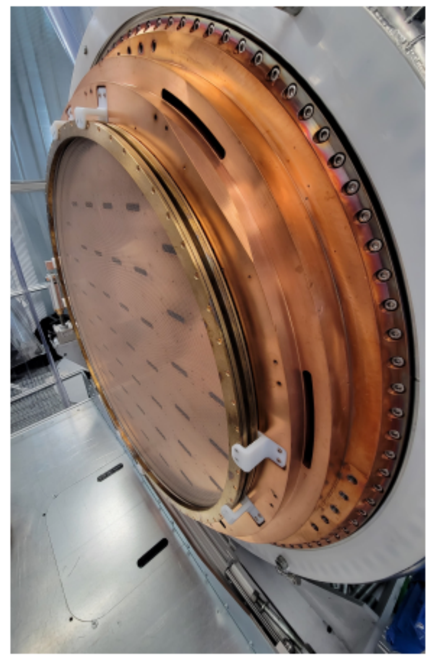


- SuperNEMO Demonstrator at LSM, France taking data with the full tracker and calorimeter from a 6.3kg Se-82 double-beta source.

NEXT







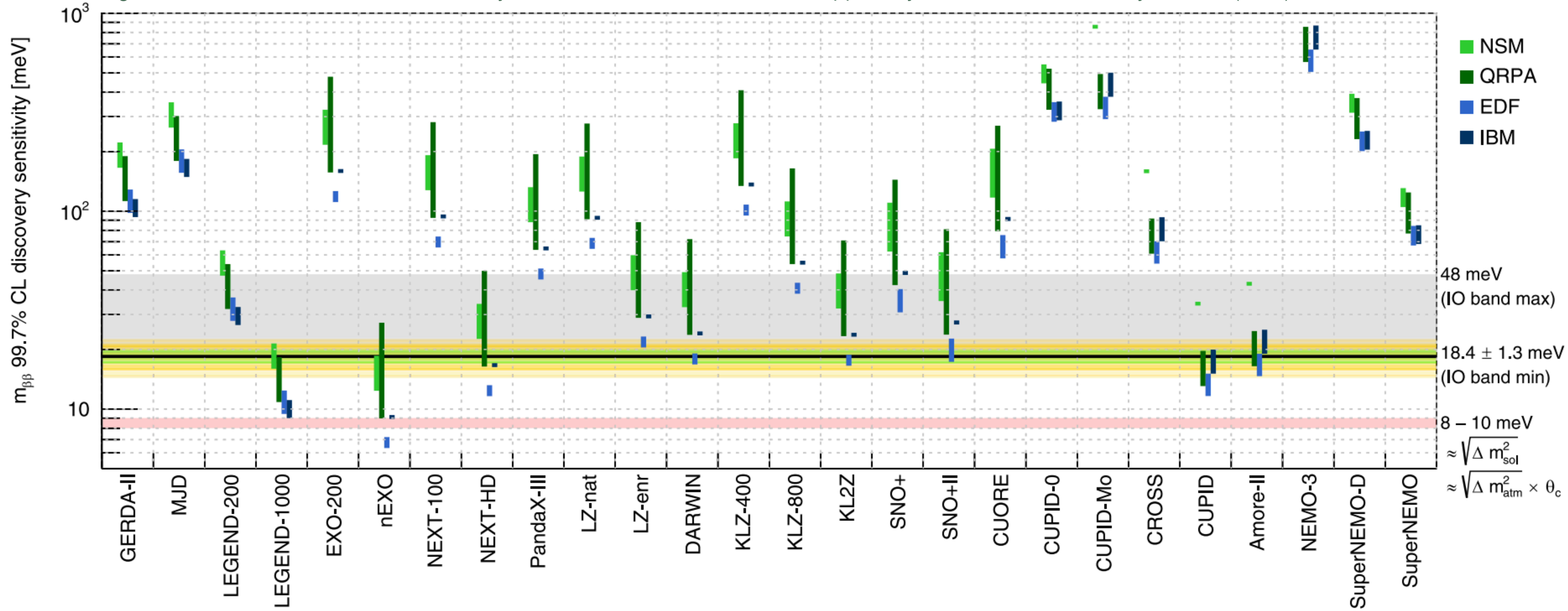
PoS EPS-HEP2023 (2024) 169

- NEXT is a high pressure gas TPC using enriched Xe
- Event topology through tracking
- NEXT-100 installation at Canfranc
- Plans to scale from 100 kg to 1 ton of Xenon
- R&D towards Ba tagging

Can shed light on the mechanism of the decay.

Outlook

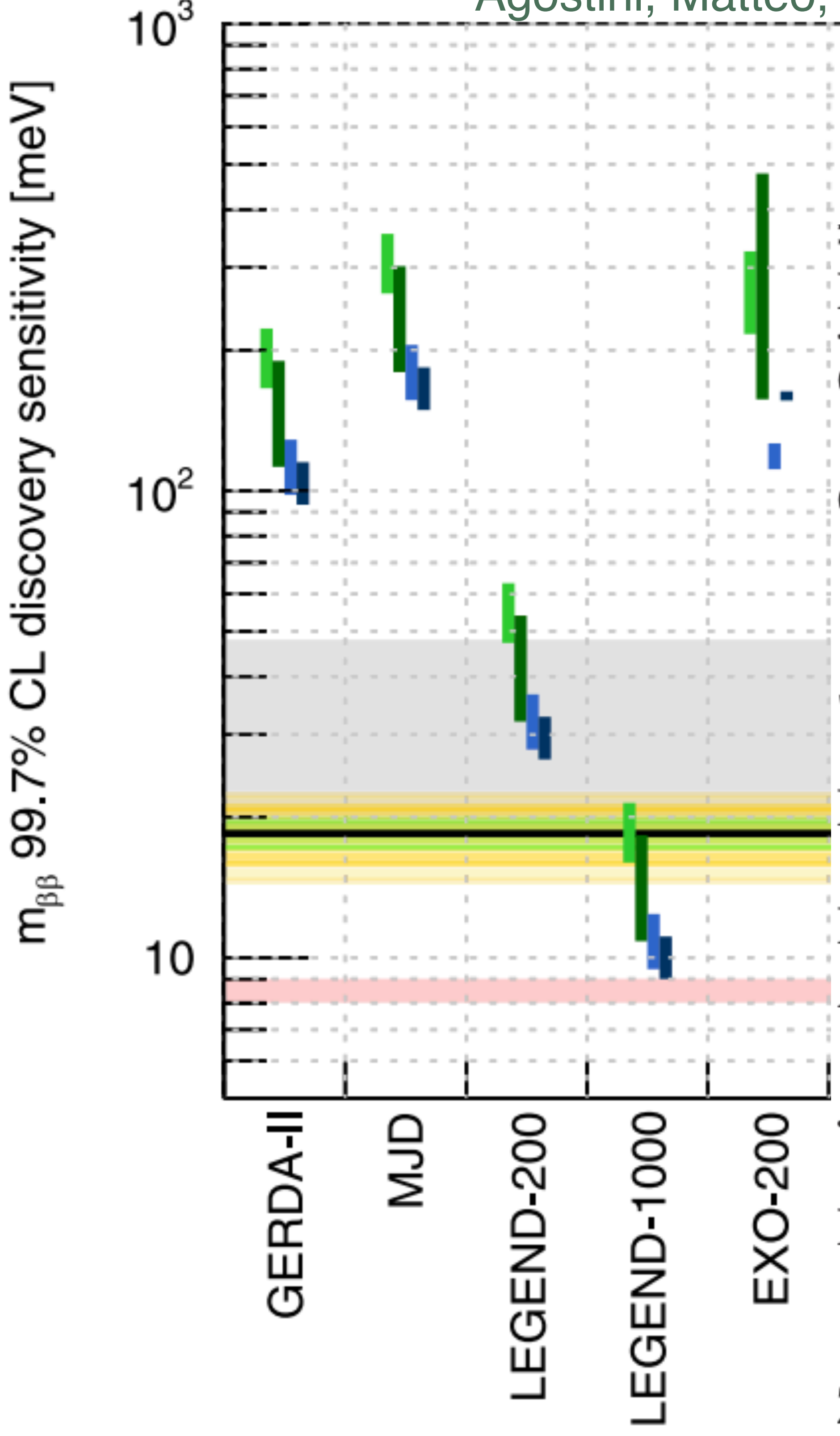
Agostini, Matteo, et al. "Toward the discovery of matter creation with neutrinoless ββ decay." Reviews of Modern Physics 95.2 (2023): 025002.



The next generation ~ton scale experiments aim for discovery (if IH) or push slightly beyond

Outlook

Agostini, Matteo, et al. "Toward the discovery of matter creation with neutrinoless ββ decay." Reviews of Modern Physics 95.2 (2023): 025002.



Project	Isotope(s)	Detector technology, main features, and reference(s)
CANDLES[a]	^{48}Ca	Array of scintillator crystals suspended in a volume of liquid scintillator. Possible operation as cryogenic calorimeters (Yoshida *et al.*, 2009; Ajimura *et al.*, 2021).
COBRA[a]	^{70}Zn, ^{114,116}Cd, ^{128,130}Te	CdZnTe semiconductor detector array. Room temperature, multi-isotope, high granularity (Zuber, 2001; Ebert *et al.*, 2016a, 2016b; Arling *et al.*, 2021).
Selena	^{82}Se	Amorphous ^{enr}Se high-resolution, high-granularity CMOS detector array. 3D track reconstruction [O(10 μm) resolution], room temperature, minimal shielding (Chavarria *et al.*, 2017).
NνDEx	^{82}Se	High-pressure gaseous $^{82}SeF_6$ ion-imaging TPC. $\lesssim$1% energy resolution, precise signal topology, possible multi-isotope (Nygren *et al.*, 2018; Mei, Sun, and Xu, 2020).
R2D2	^{136}Xe	Spherical TPC. Single readout channel, inexpensive infrastructure (Bouet *et al.*, 2021).
AXEL	^{136}Xe	High-pressure TPC operated in proportional scintillation mode. High energy resolution, possible positive ion detection (Obara *et al.*, 2020).
JUNO	···	Isotope-loaded liquid scintillator. 20 ktons of scintillator, multi-isotope, multipurpose (Zhao *et al.*, 2017; Abusleme *et al.*, 2021).
NuDot	···	Liquid scintillator with quantum dots or perovskites as wavelength shifter for Cherenkov light. Discriminate directional backgrounds, multi-isotope (Winslow and Simpson, 2012; Aberle *et al.*, 2013; Gooding *et al.*, 2018; Graham *et al.*, 2019).
ZICOS	^{96}Zr	Zr-loaded liquid scintillator. Topology and particle discrimination via Cherenkov light readout (Fukuda, 2016, 2020).
THEIA	···	Water-based loaded liquid scintillator with Cherenkov light readout. Topology and particle discrimination, multi-isotope, multipurpose, 25 ktons of water (Askins *et al.*, 2020).
LiquidO	···	Opaque isotope-loaded liquid scintillator with wavelength-shifting fibers for event topology. Room temperature, multi-isotope, multipurpose (Buck, Gramlich, and Schoppmann, 2019; Cabrera *et al.*, 2021).

Plenty more experiment driving the development of cutting-edge detector technologies.

Summary

- $0\nu\beta\beta$ would prove that neutrinos are their own antiparticles, a unique property with profound implications for particle physics.
- A $0\nu\beta\beta$ observation would allow us to finally measure the absolute mass of neutrinos, crucial for cosmology and astrophysics.
- $0\nu\beta\beta$ is a lepton-number violating process, signaling new physics beyond our current understanding.
- This field requires expertise from both nuclear and particle physics
    - Vibrant experimental program worldwide.
    - Accurate theoretical calculations of nuclear matrix elements are essential for interpreting experimental results.
    - Various experimental probes, like charge exchange reactions, muon capture, double gamma decay can help refine these calculations.