THE FUTURE OF

NEUTRINOLESS DOUBLE BETA DECAY

Probing the Majorana Nature of Neutrinos and Physics Beyond the Standard Model

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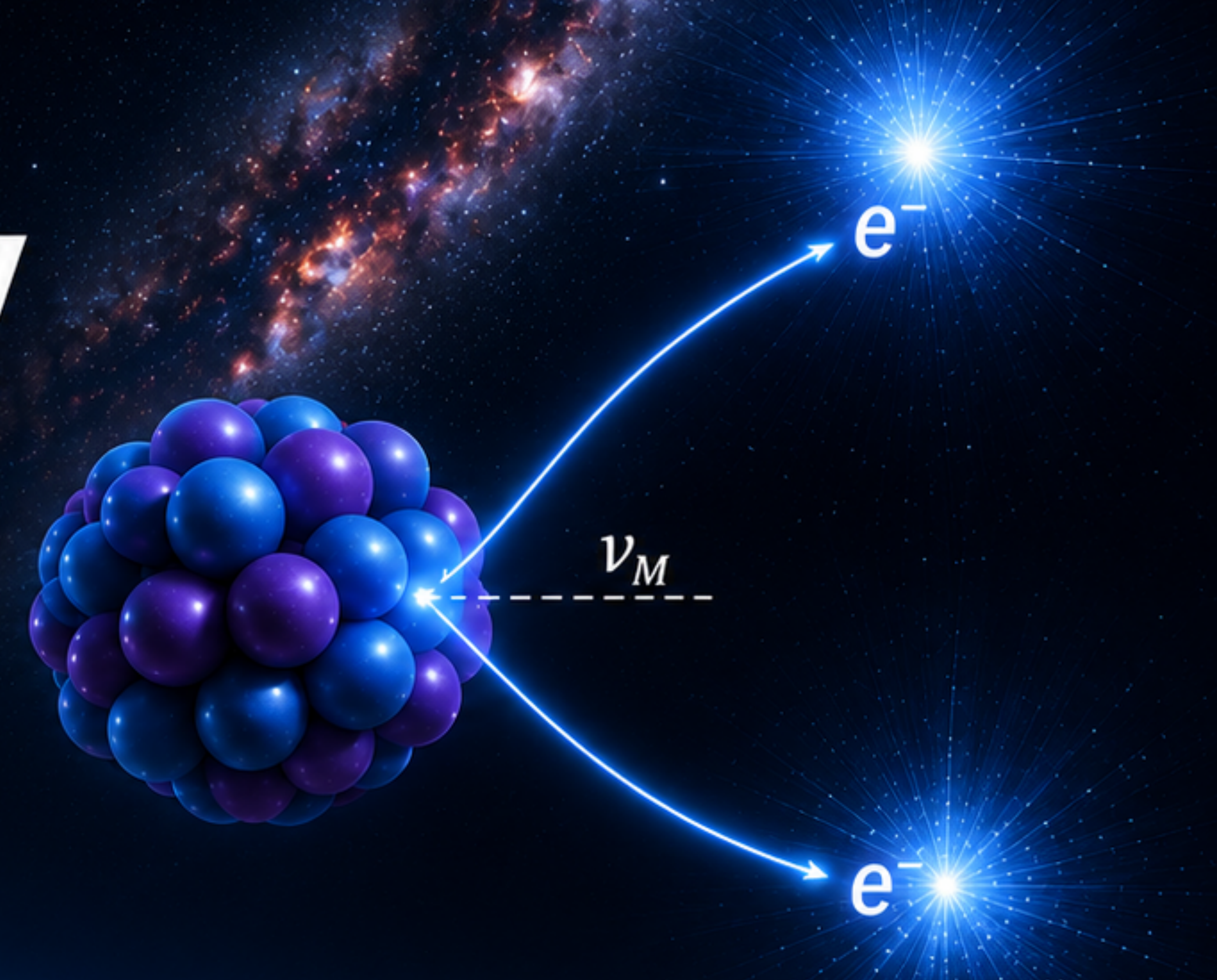

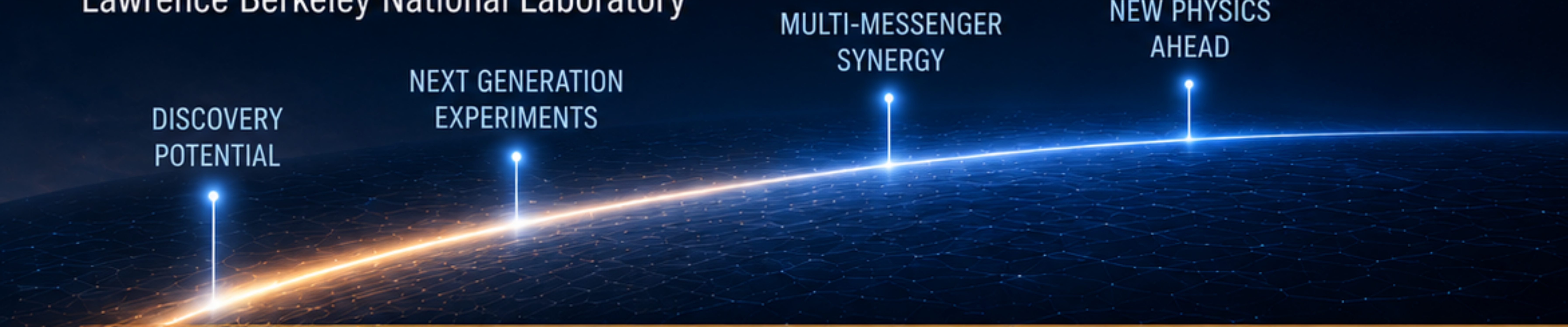

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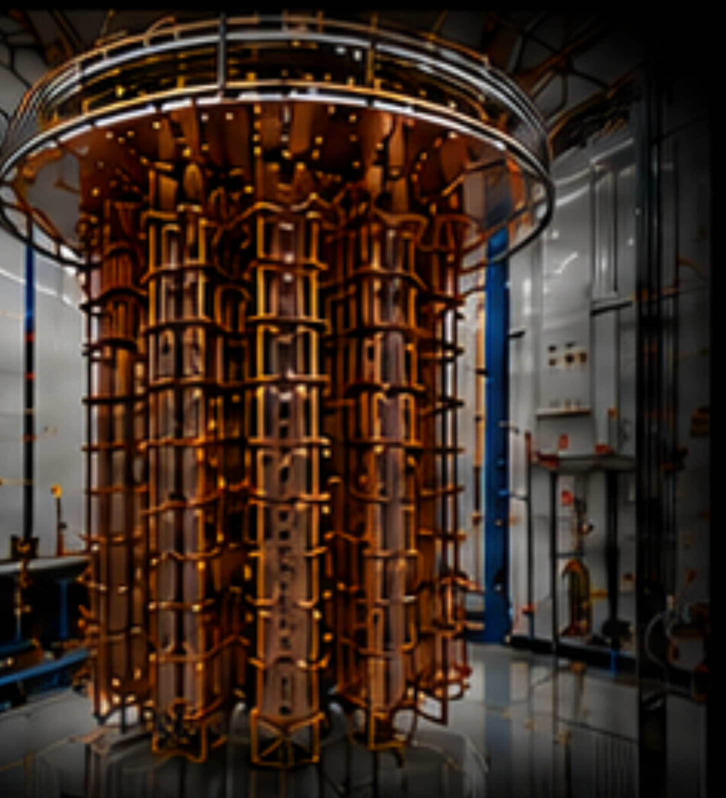
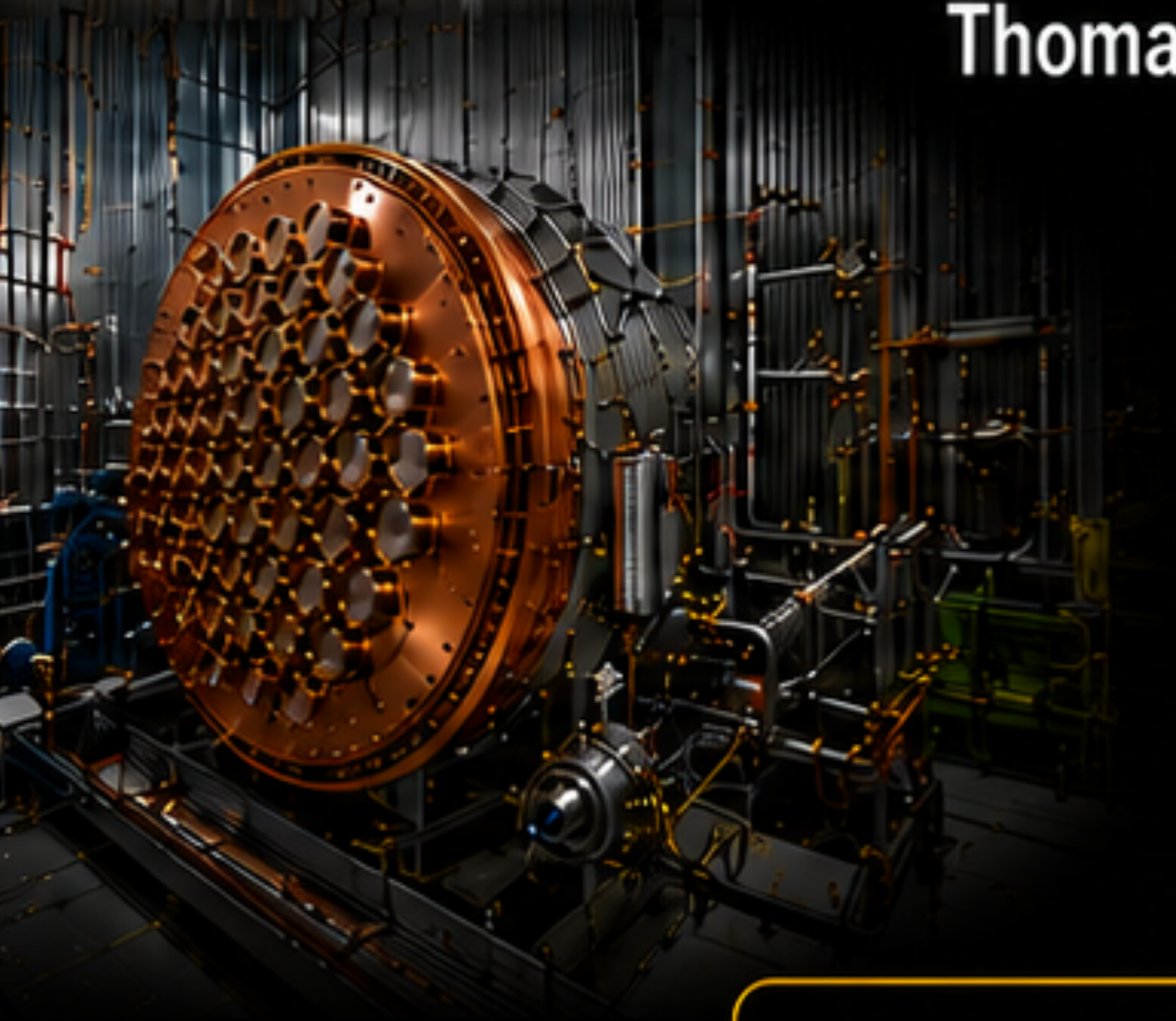
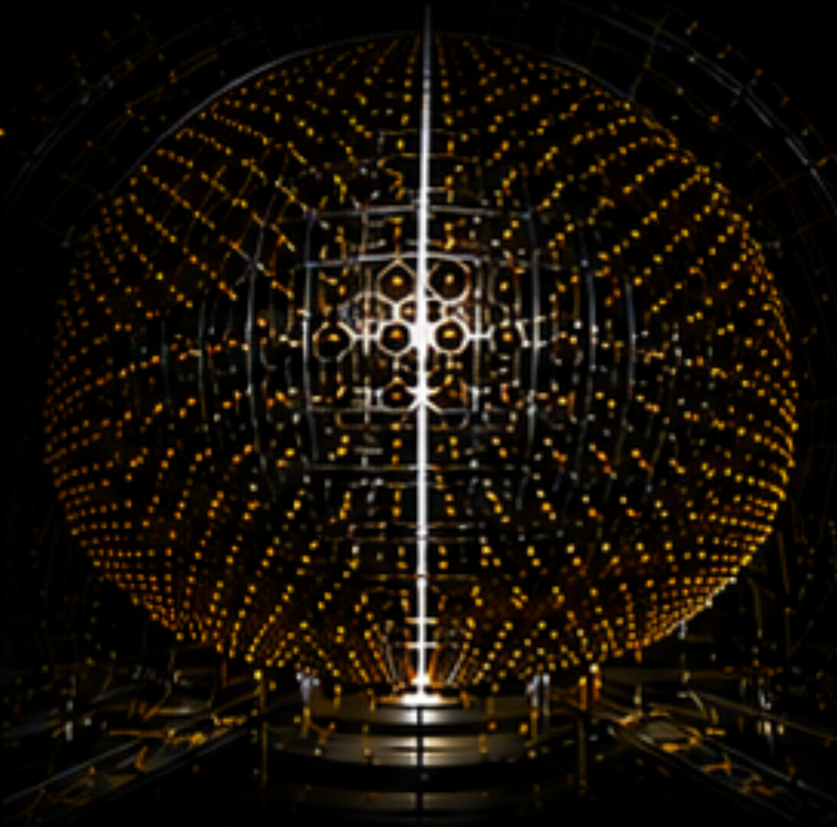
THANK YOU

With gratitude to colleagues who contributed material, advice, and discussion







Erica Caden • Álvaro Chavarría • Mark Chen • Jason Detwiler • Giorgio Gratta

Juan Gómez-Cadenas • Ke Han • Karsten Heeger • Tanner Kaptanoglu • Josh Klein

Yury Kolomensky • Cheryl Patrick • Oemer Penek • Marc Schumann • Stefan Schoppmann

Thomas Brunner • Saori Umehara • Yifang Wang • Liangjian Wen • Yeongduk Kim

EXPERIMENTS REPRESENTED

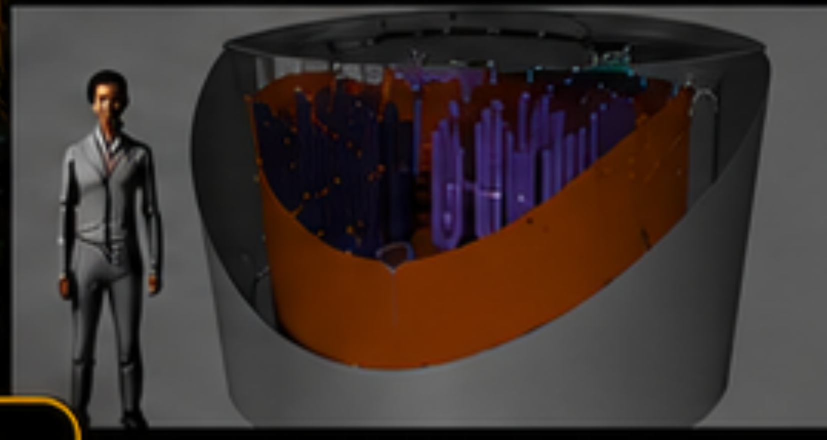
CUPID • AMoRE • LEGEND

NEXT • SuperNEMO

nEXO • XLZD • PandaX

KamLAND-Zen • SNO+ • JUNO • Theia

CANDLES • Selena • NuDoubt



No single technology has emerged as the inevitable winner.
Instead, the field is converging on a common physics goal while diverging into a rich portfolio of technical approaches.

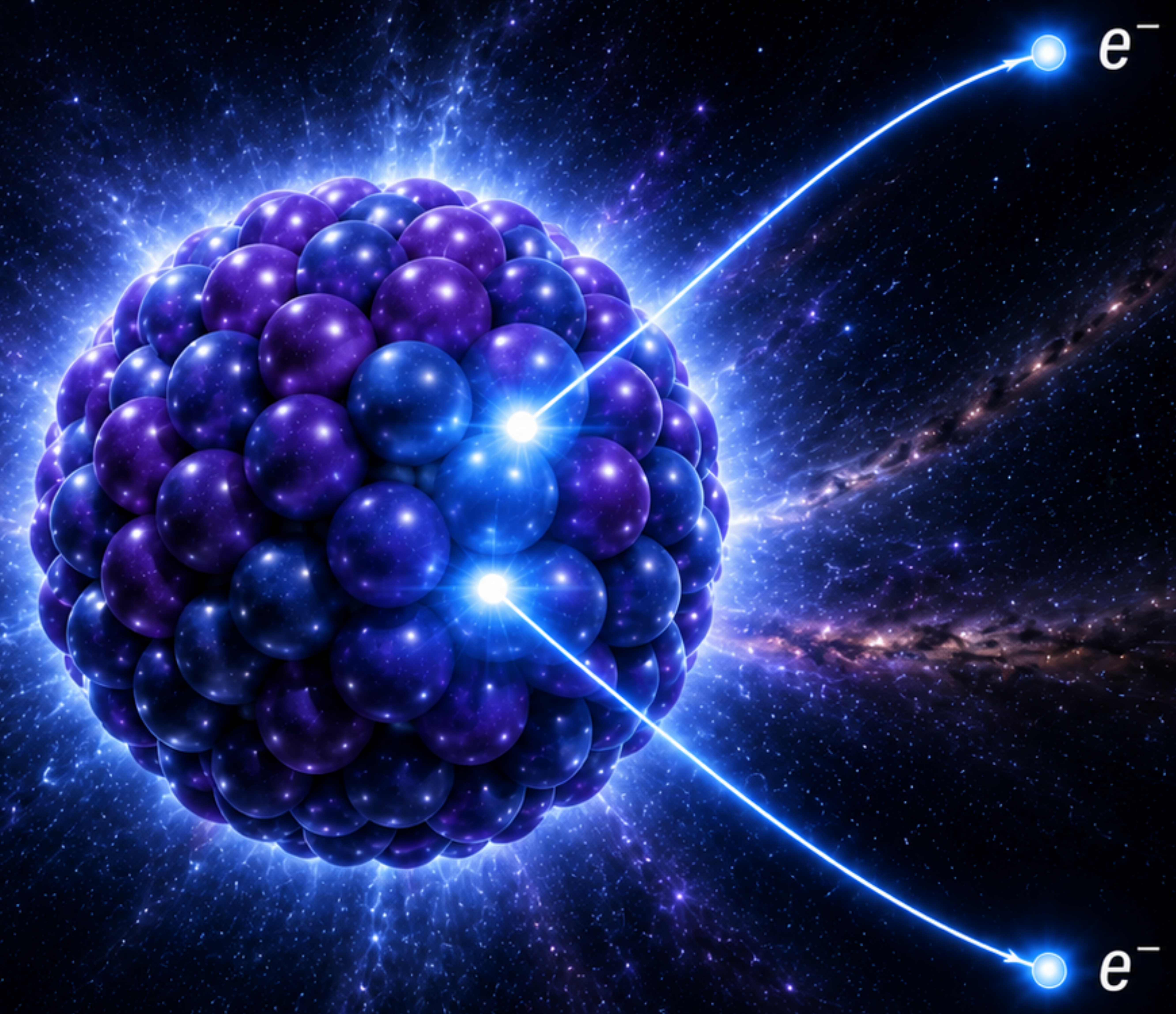
Many paths. One goal.

Selected conceptual illustrations developed with Ianus (AI assistant)

Why $0\nu\beta\beta$?

One process.
Three fundamental questions.

- Is lepton number conserved?
- Are neutrinos Majorana particles?
- Did neutrino physics help create the matter-dominated universe?



One discovery could reshape our understanding of particle physics and cosmology.

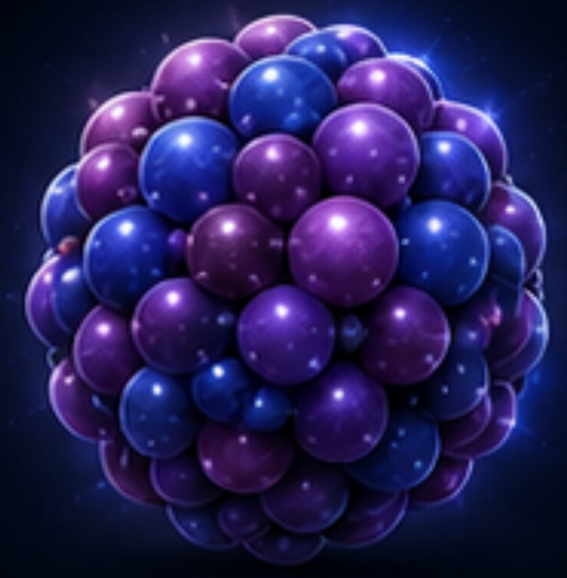
Twenty years ago, many of us expected the field would eventually **converge** on a single optimal technology.

Instead, the **opposite** has happened.

As we push toward the next order of magnitude in sensitivity, the field **remains remarkably diverse**—suggesting that key technical questions are **not yet settled**.

The Challenge

Why is this so hard?



Target Mass

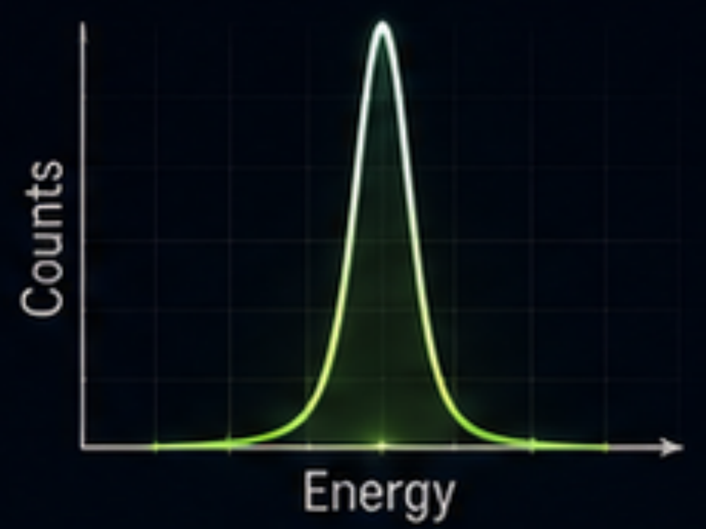
Can we get enough isotope to reach the inverted-ordering region and beyond?

Enrichment, procurement, loading fraction, total isotope mass.

Backgrounds

Can we suppress backgrounds to ultra-low levels?

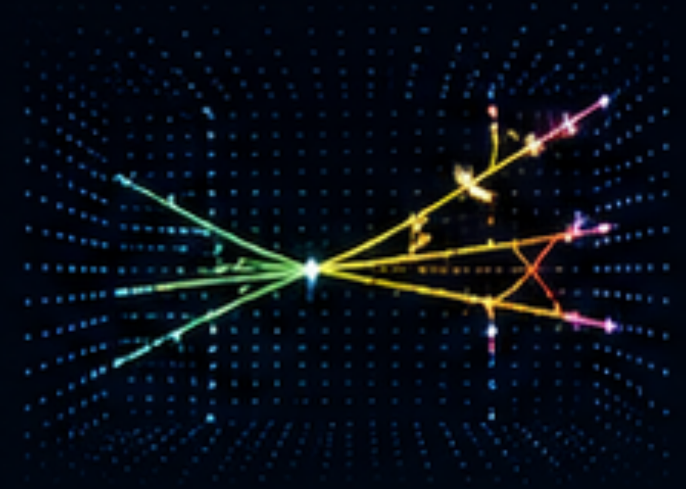
Radiopurity, shielding, material selection, active veto, environment.



Energy Resolution

Can we measure energy precisely enough to separate signal from background?

Resolution determines discovery potential.



Event Topology

Can we identify the signal by how the energy is deposited?

Topology and pattern recognition provide powerful discrimination.

Detector Scale

Can the detector maintain its performance as it grows to many tonnes?

Light collection, electronics, cryogenics, calibration, construction, operation.

Cost

Can we build and operate these detectors in a sustainable way?

Materials, complexity, infrastructure, time, long-term operation.

Nature has not yet provided us with the perfect detector.

Every experiment solves *this puzzle differently.*

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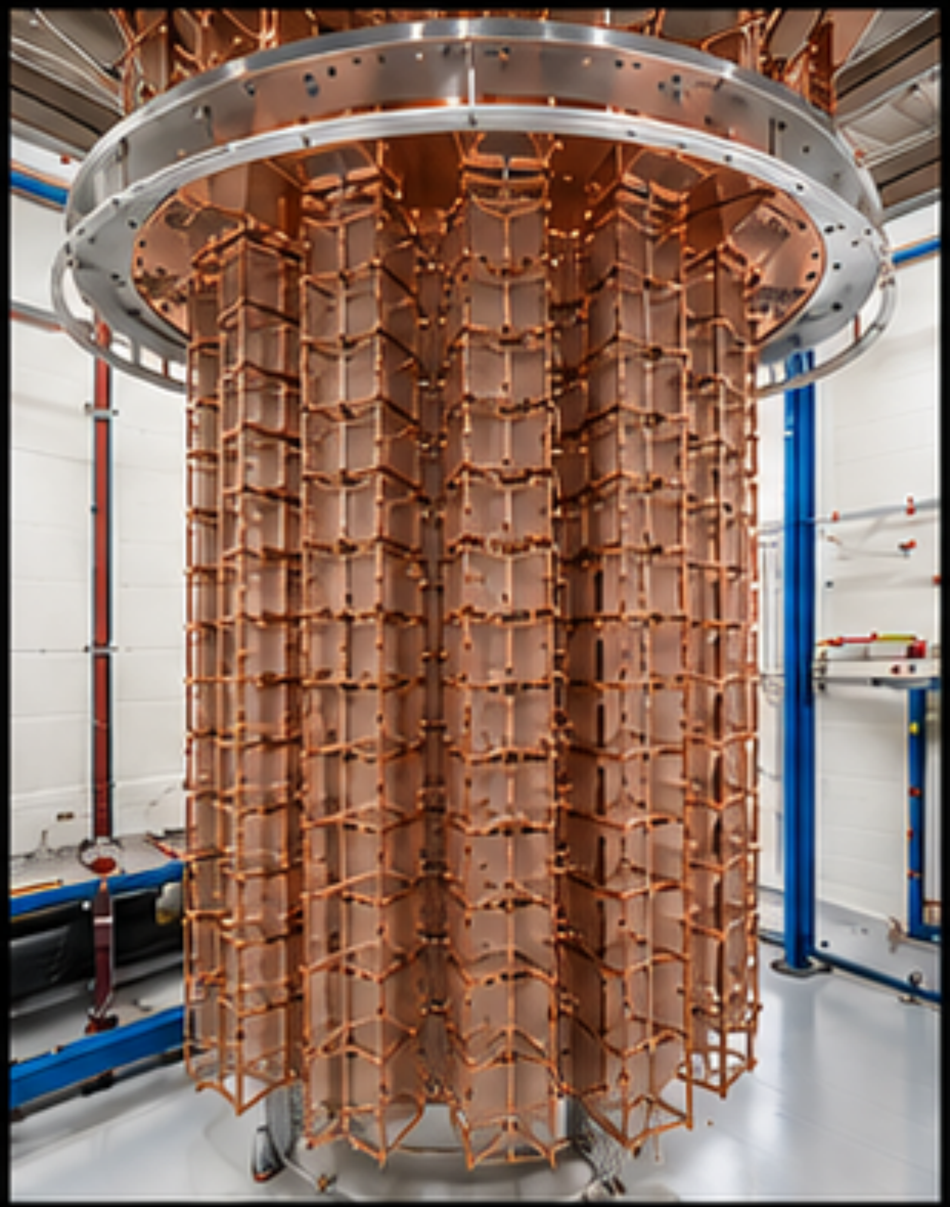
MULTIPLE PATHS TO DISCOVERY

Different strengths. Common goal.

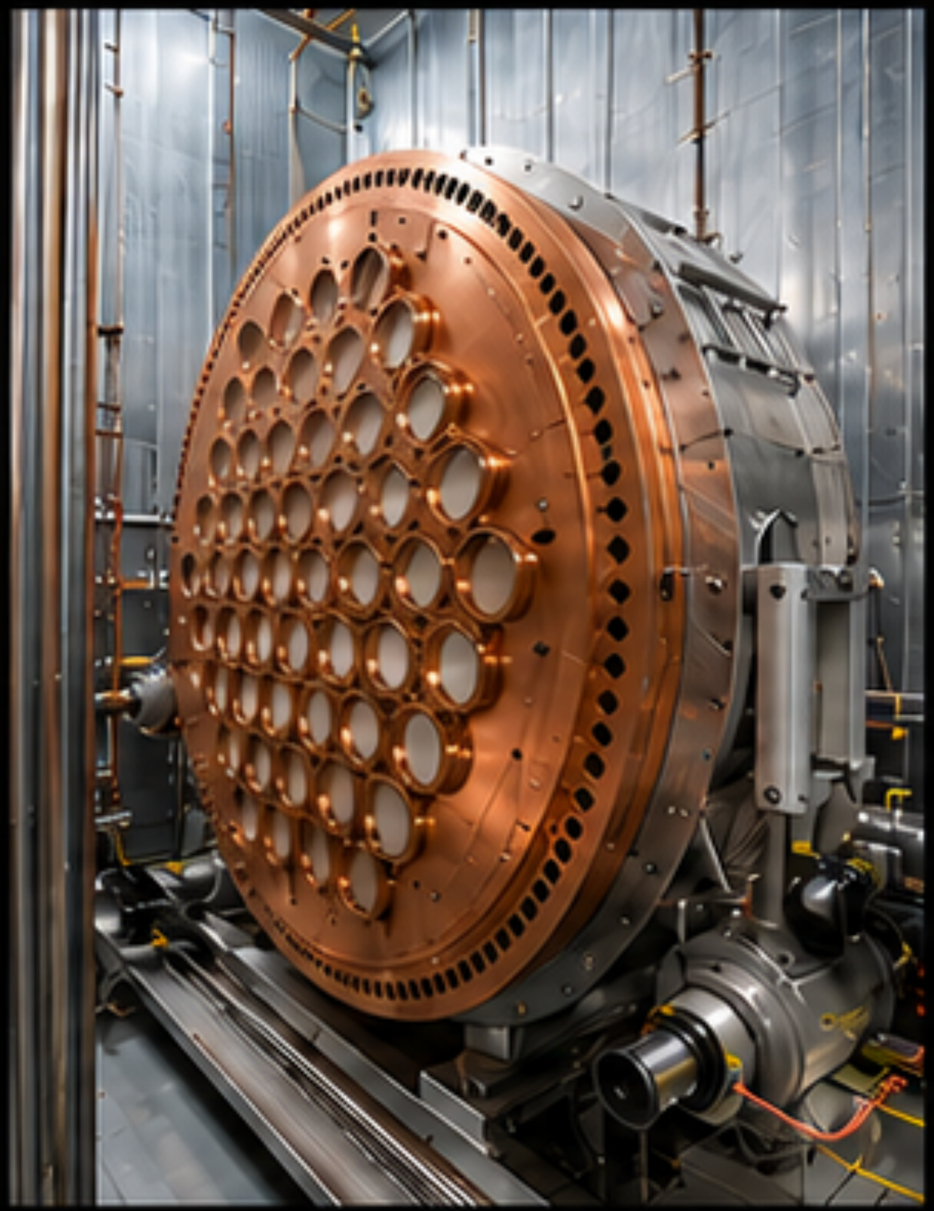
PRECISION ENERGY MEASUREMENT



- Outstanding energy resolution
- Powerful background rejection
- Proven technology

Examples:
CUPID, AMoRE, LEGEND

EVENT TOPOLOGY



- Full event topology
- Backgrounds identified and rejected
- Model-independent handle

Examples:
NEXT, SuperNEMO

LARGE HOMOGENEOUS LXe TPCS

- Enormous isotope masses
- Self-shielding and uniform response
- Powerful background rejection

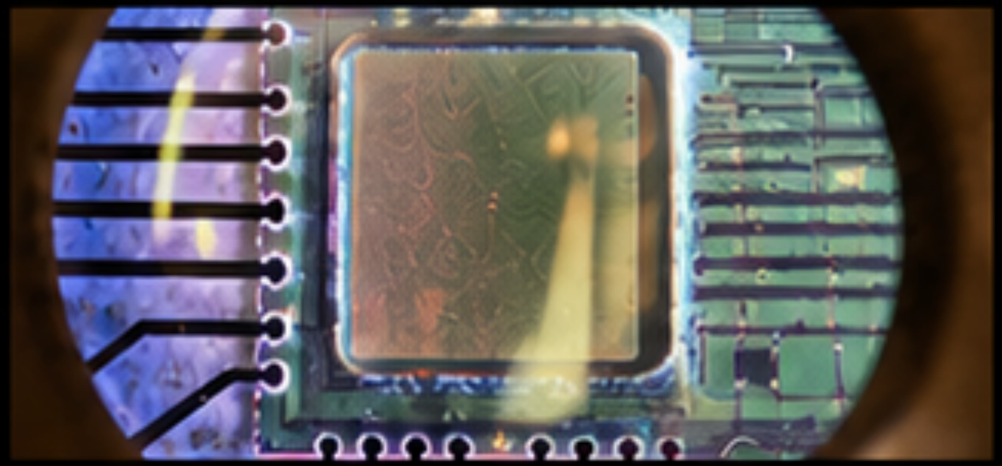
Examples:
nEXO, XLZD, PandaX

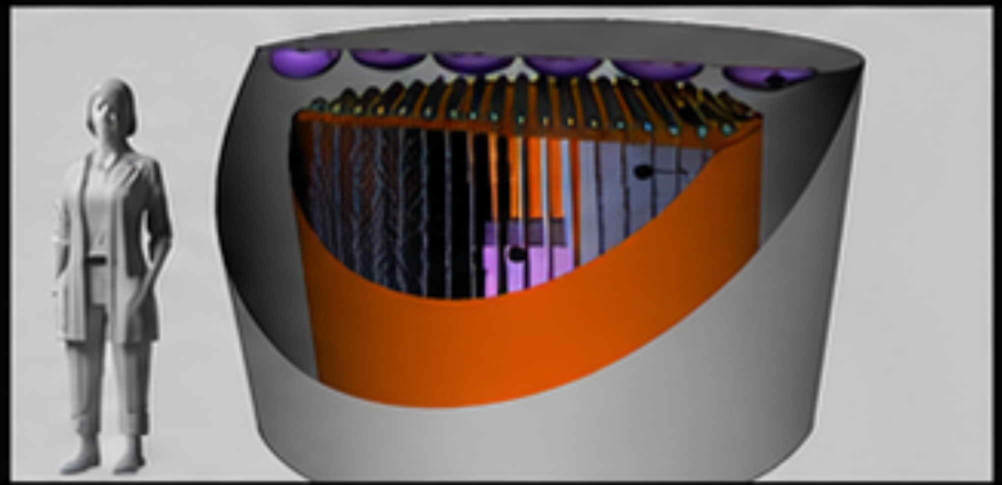
SCALE THROUGH OBSERVATORIES

- Kiloton-scale target masses
- Multiple physics programs
- Flexible isotope deployment
- Long-term discovery platforms

Examples:
KamLAND-Zen, SNO+, JUNO, Theia

ALTERNATIVE ISOTOPES & NOVEL CONCEPTS





- Access to different isotopes
- Cross-checks and confirmation
- Probe the mechanism

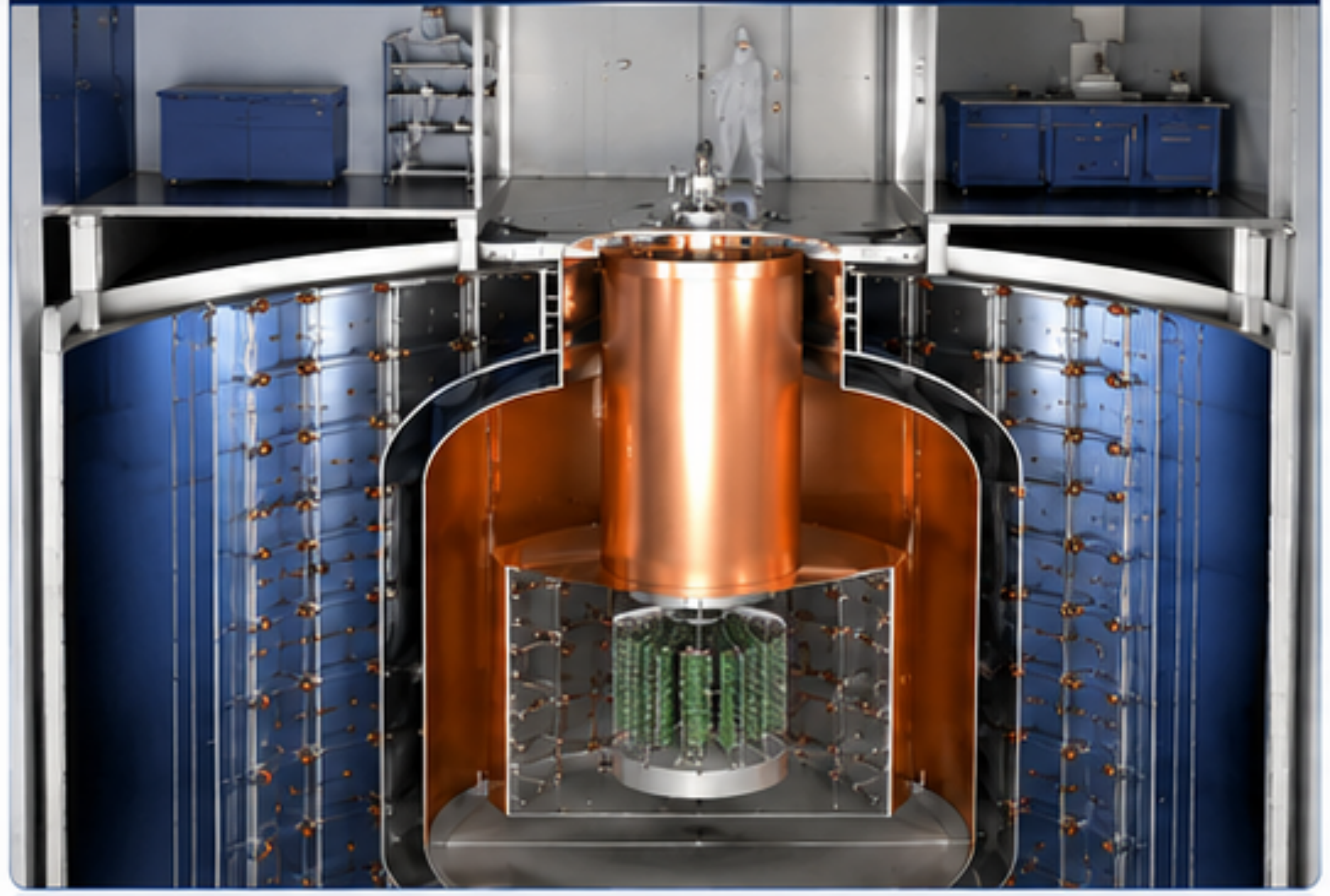
Examples:
CANDLES, Selena, NuDoubt

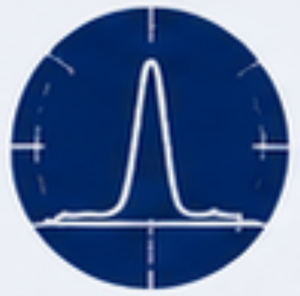
No single approach is perfect. ***Together, they maximize our chance of discovery.***

PRECISION-DRIVEN EXPERIMENTS

Different technologies, same goal: background-free operation

LEGEND LEGEND-6000 (Concept)



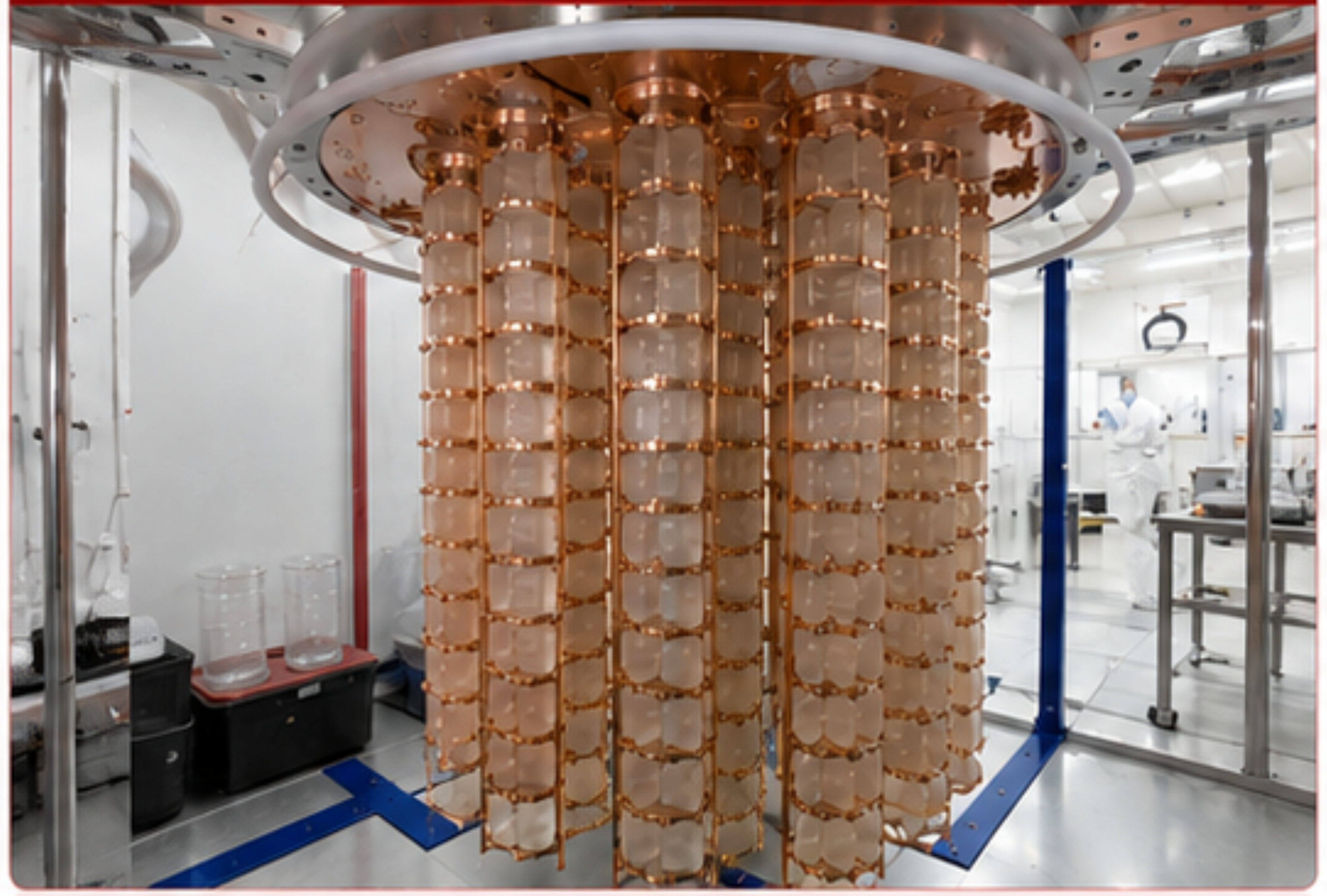


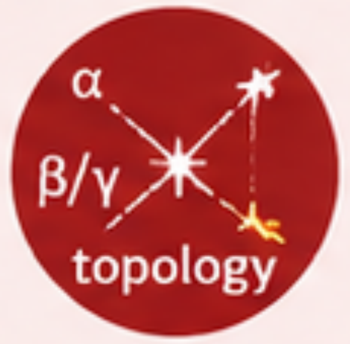
Precision Spectroscopy

Ultra-high energy resolution to isolate the signal

- 0.12% FWHM at $Q_{\beta\beta}$ (best resolution at $0\nu\beta\beta$ Q-value)
- Post-LEGEND-1000 concept: LEGEND-6000
- 133 strings of larger detectors: 6 tons Ge
- 15 years livetime / 100 t·yr exposure
- $T_{1/2}$ sensitivity ~ 10^{29} yr ⟶ $m_{\beta\beta} \approx 3\text{–}6$ meV

CUPID CUPID-1T (Concept)



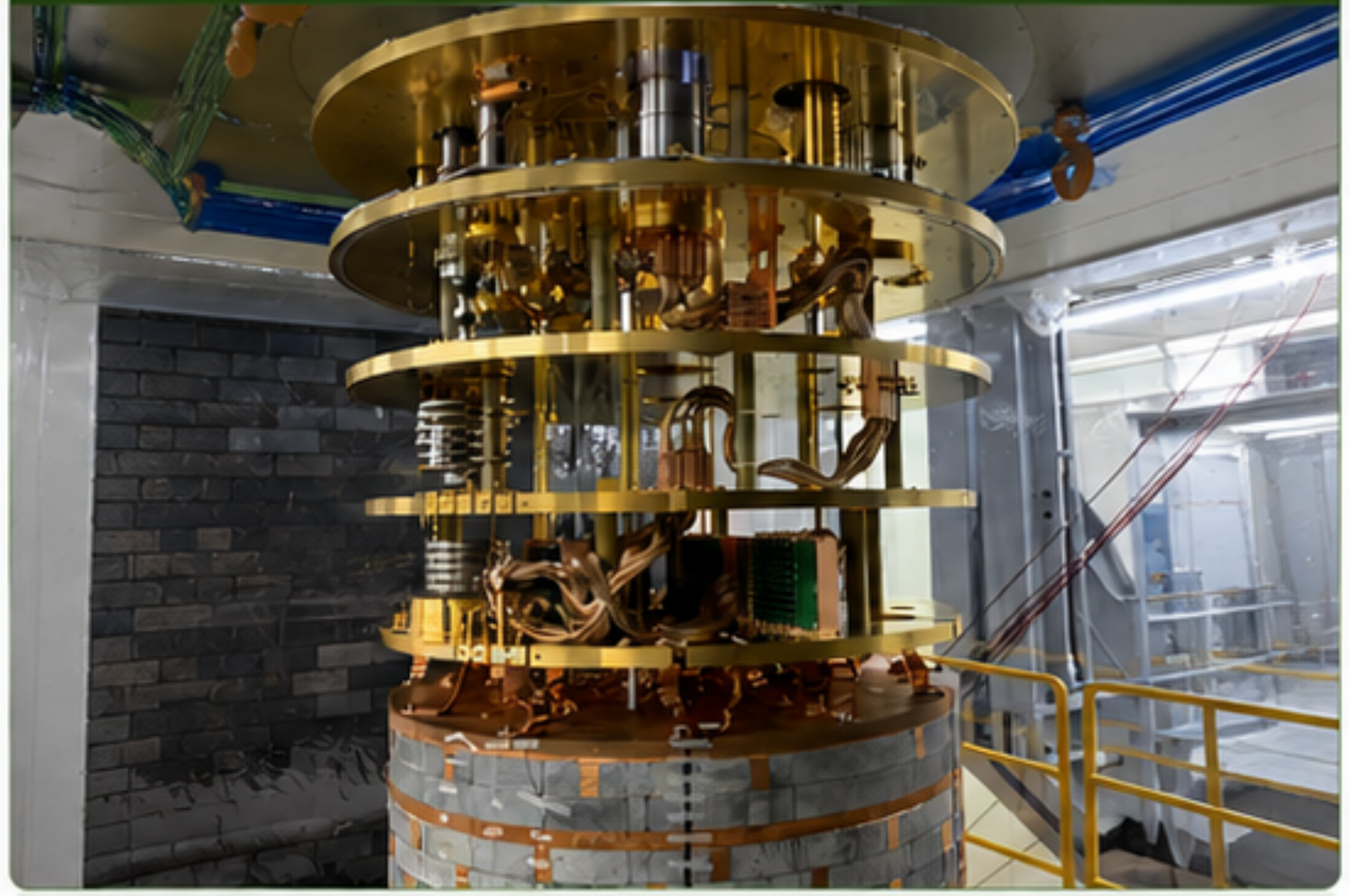


Particle Identification

Discriminate α, β/γ and event topology

- 1000 kg ^{100}Mo $Li_2{}^{100}MoO_4$ crystals
- β/γ, α and topological discrimination
- Background-free goal: 5×10^{-6} counts/(keV·kg·yr)
- Eliminate pileup and other subdominant backgrounds
- $T_{1/2} > 8 \times 10^{27}$ yr (Normal Hierarchy)

AMoRE AMoRE-III (Upgrade)



Dual Readout

Measure phonons and photons for powerful background rejection

- MMC + SQUID readout
- 185 kg ^{100}Mo (85 kg in AMoRE-II + 100 kg upgrade)
- ΔE (FWHM) ~ 7 keV @ 2614 keV
- Background < 10^{-4} ckky
- 4.5×10^{26} yr sensitivity in 5 years (AMoRE-II)

Three complementary paths to the same destination:
maximizing information per event to achieve background-free sensitivity.

EVENT RECONSTRUCTION

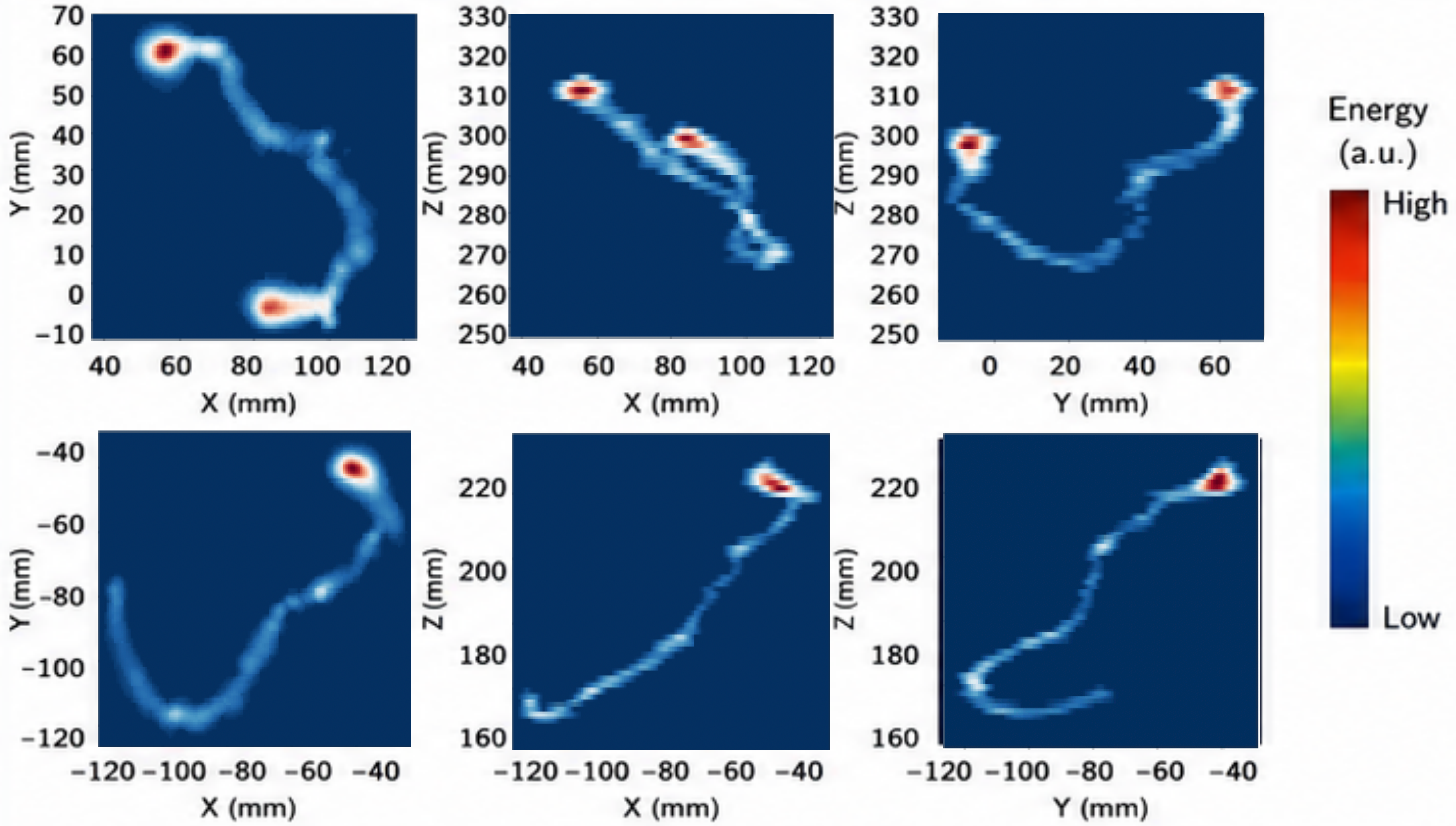
Identify the signal event itself

NEXT

High-Pressure Xenon Electroluminescent TPC

Double-electron topologies in real data

(1.6 MeV double escape peak of ^{208}Tl)



HPXe Electroluminescent TPC

- Two-blob topology
- 0.5–0.7% FWHM target
- Multi-ton roadmap to 10^{28} yr sensitivity
- Future Ba^{2+} tagging (NEXT-BOLD)

Signal =
single track with two electron blobs

NEXT ROADMAP

NEXT-100
~100 kg HPXe Demonstrator / first physics

NEXT-HD
Multi-ton HPXe programme
Target $T^{0\nu}_{1/2} \sim 10^{28}$ yr (5 ton × 10 yr)

NEXT-BOLD
Ba^{2+} tagging R&D for near-background-free operation

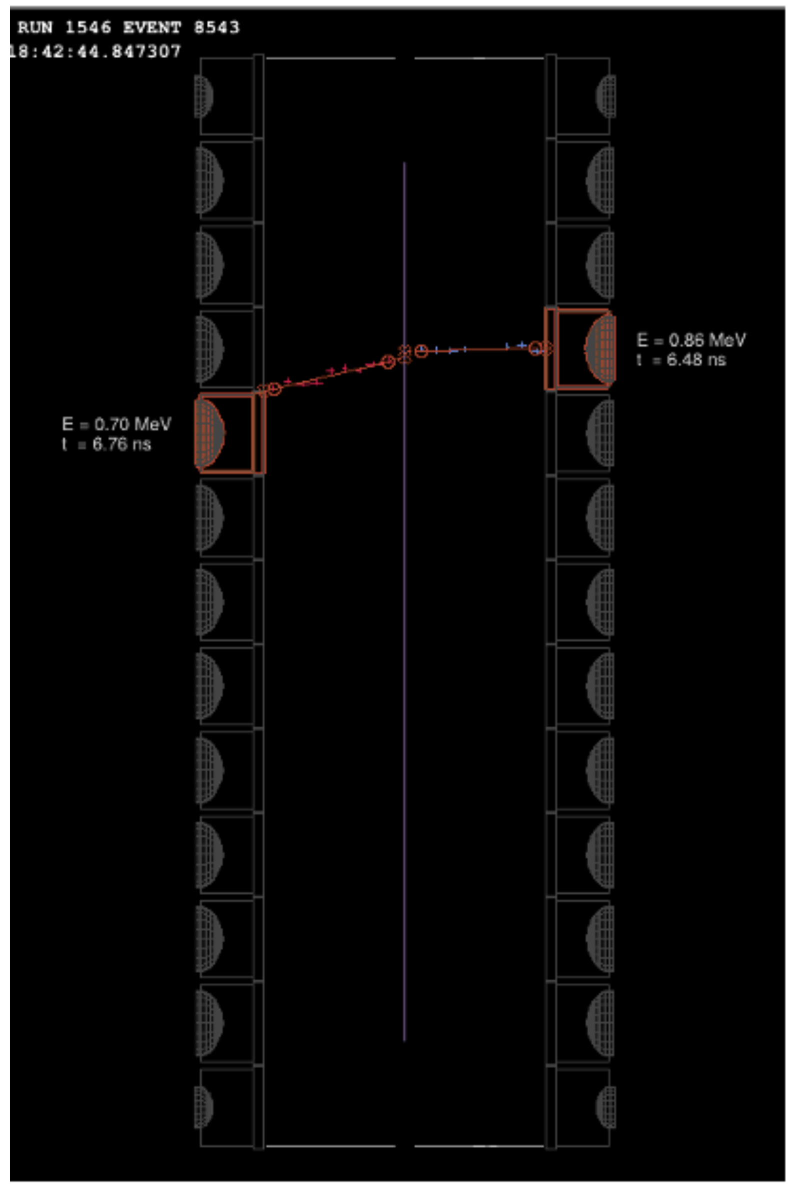
SuperNEMO

Tracker + Calorimeter at LSM, France

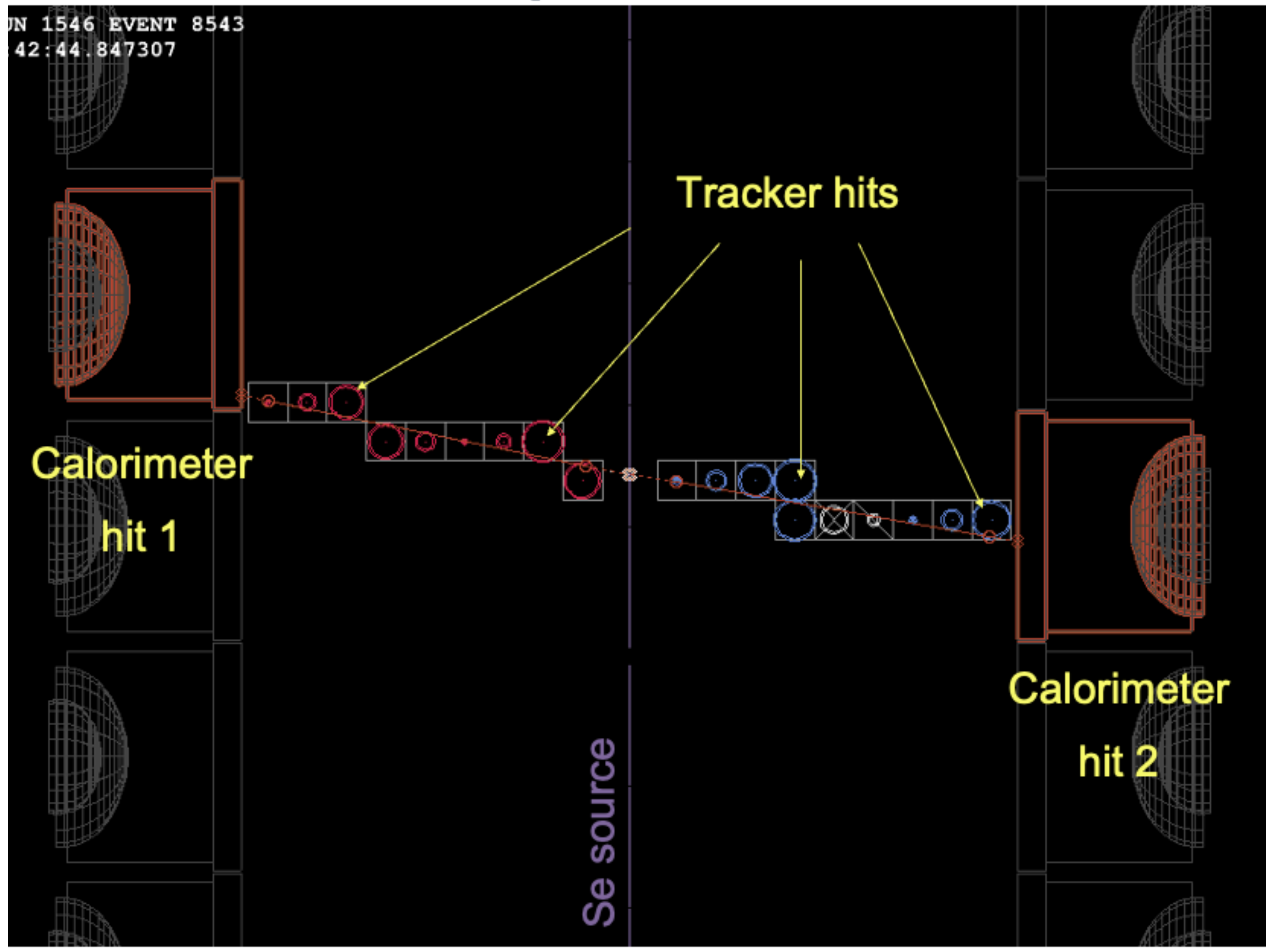
Our first $\beta\beta$-candidate event (10 April 2025)

Currently taking data at LSM, France

Side view



Top view



Tracker + Calorimeter

- Individual particle identification
- Energy + angle reconstruction
- Flexible **isotope choice**
- Measurement of **key background channels**

Signal =
fully reconstructed event

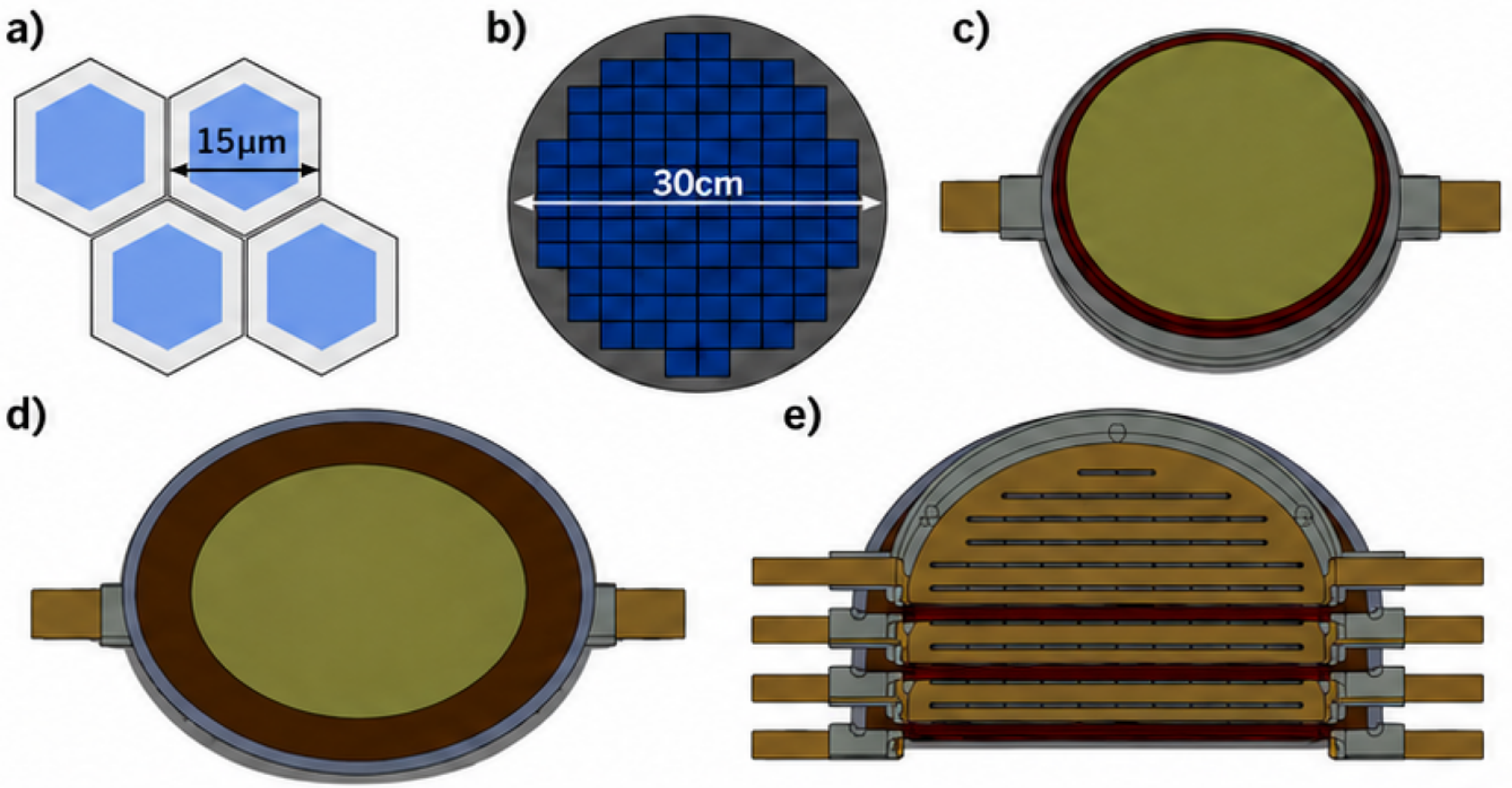
Rn-free air and nominal runtime critical to physics reach!

EMERGING RECONSTRUCTION CONCEPTS

Imaging the electrons directly

Selena

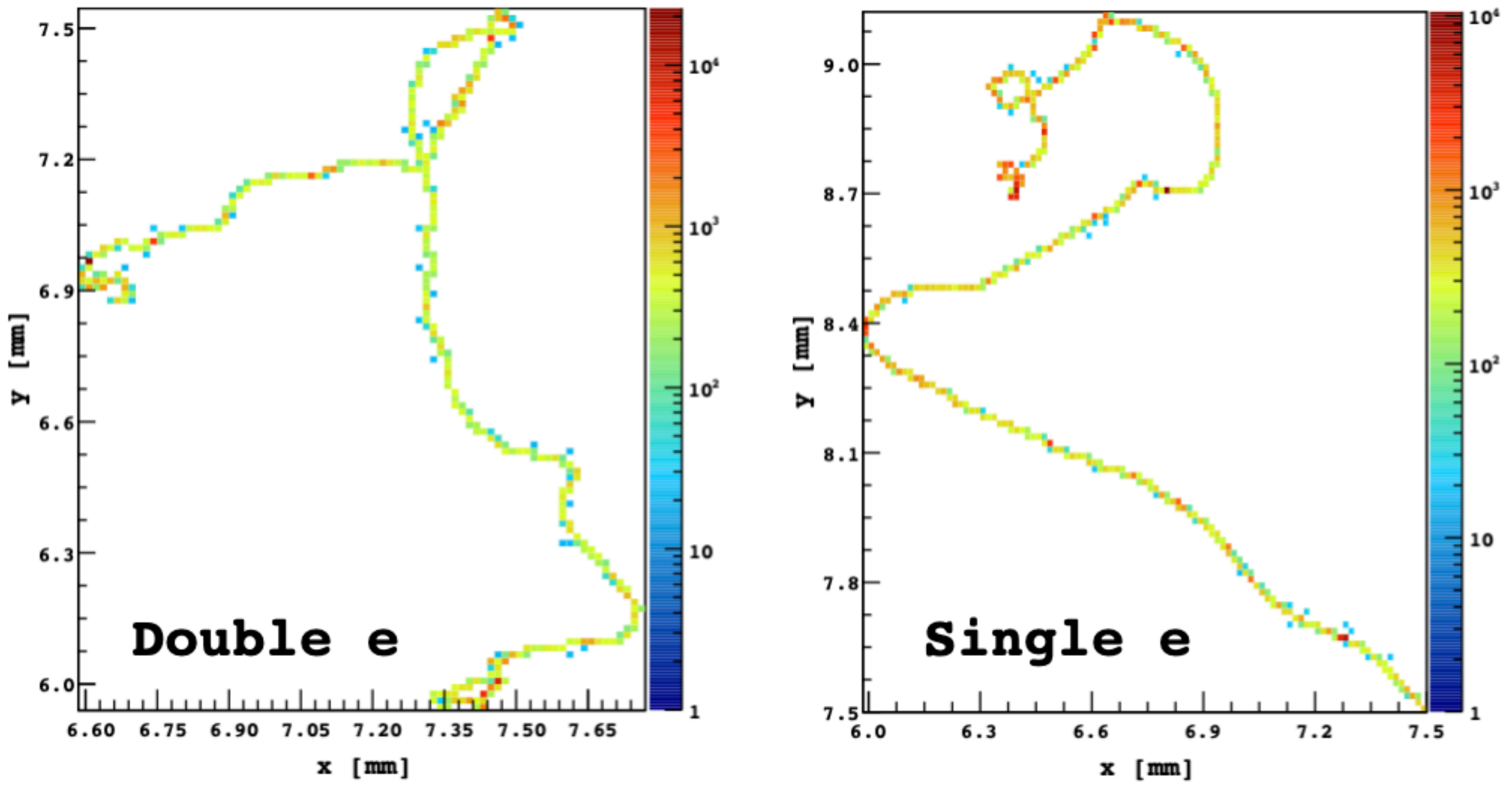
10 t ^{82}Se active target



- ^{82}Se — 10 t ^{82}Se active target
- Hybrid CMOS imagers
- Industrial-scale technology

Large-area hybrid CMOS imagers with ~5-mm thick layers of amorphous ^{82}Se

Simulation:



Bragg peak identification

- **10^{-3} single-e rejection** with ~50% signal acceptance
- **α/β particle ID** suppresses bulk backgrounds
- **Spatial correlations** further reduce background

Sensitivity target: $m_{\beta\beta} \approx$ 4–8 meV

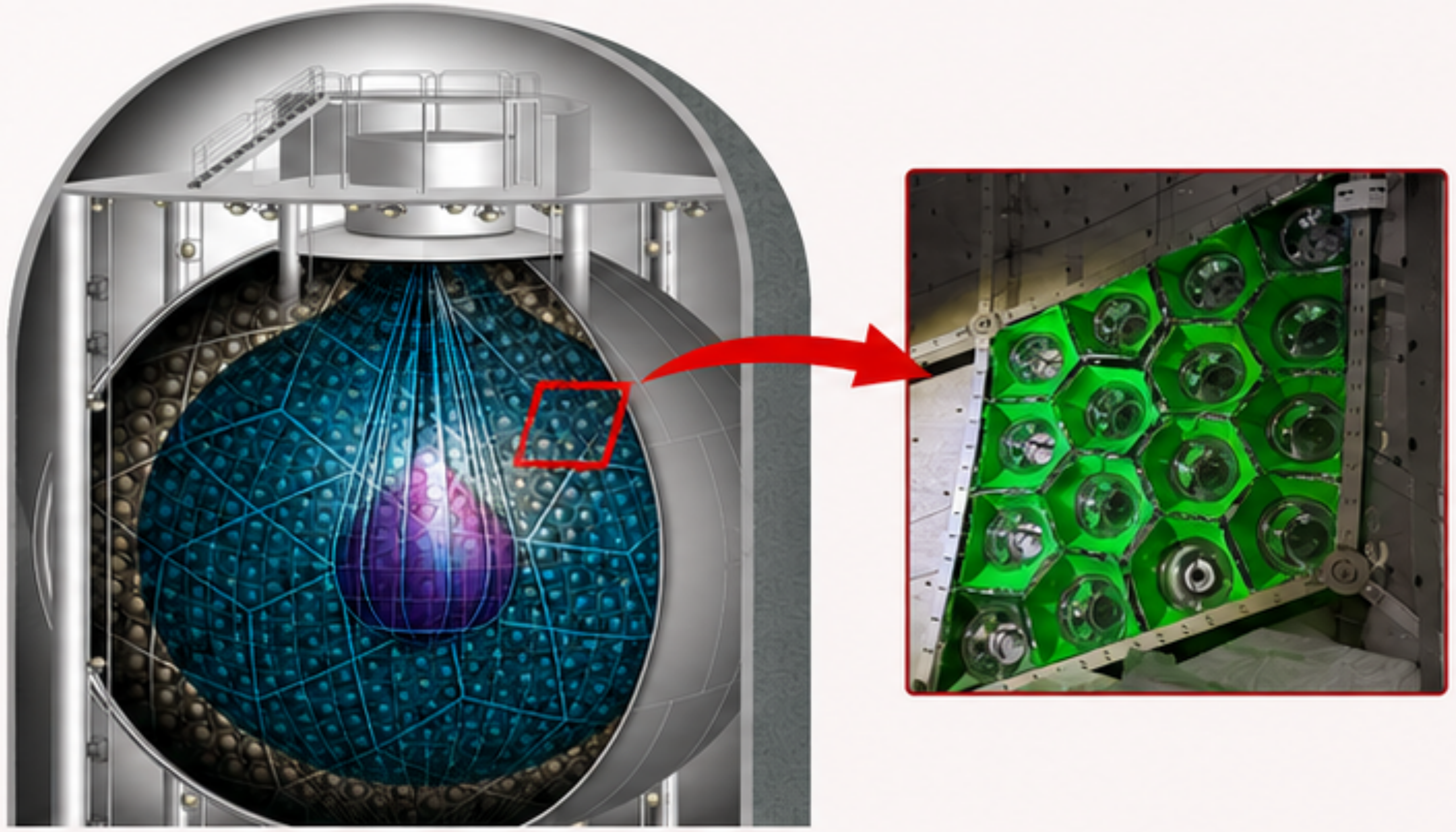
Background rate: $< 6 \times 10^{-5}$ counts/(keV · t · y)

3σ discovery: $T_{1/2} = 2 \times 10^{28}$ y in ^{82}Se

Scale Through Dedicated 0νββ Experiments

Two paths to the same goal

KamLAND2-Zen

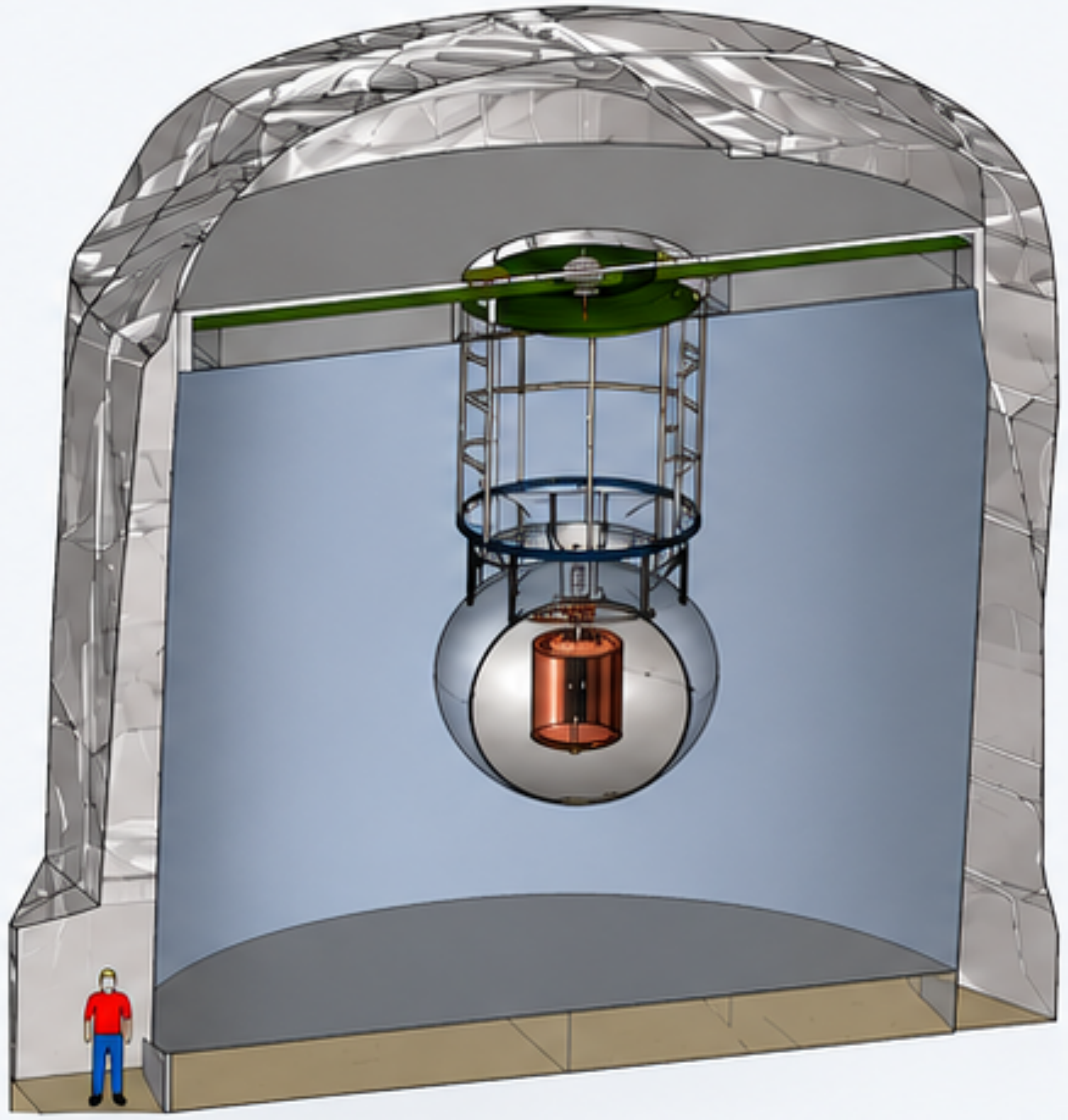


Upgrade an existing observatory

- More light: mirrors + HQE PMTs
- 5× photons / MeV
- ~2% energy resolution at $Q_{\beta\beta}$
- AI-enabled reconstruction and spallation rejection
- More isotope: Xe-loading upgrade → several tonnes of ^{136}Xe

Main DAQ start: 2028
Target sensitivity: $\langle m_{\beta\beta} \rangle \sim 20$ meV (5 years)

nEXO



Build a dedicated detector from the ground up

- Multi-ton enriched xenon (~5 tonnes ^{136}Xe)
- Monolithic LXe TPC
- Self-shielding: ultra-low background environment
- Topological discrimination: energy, topology & standoff

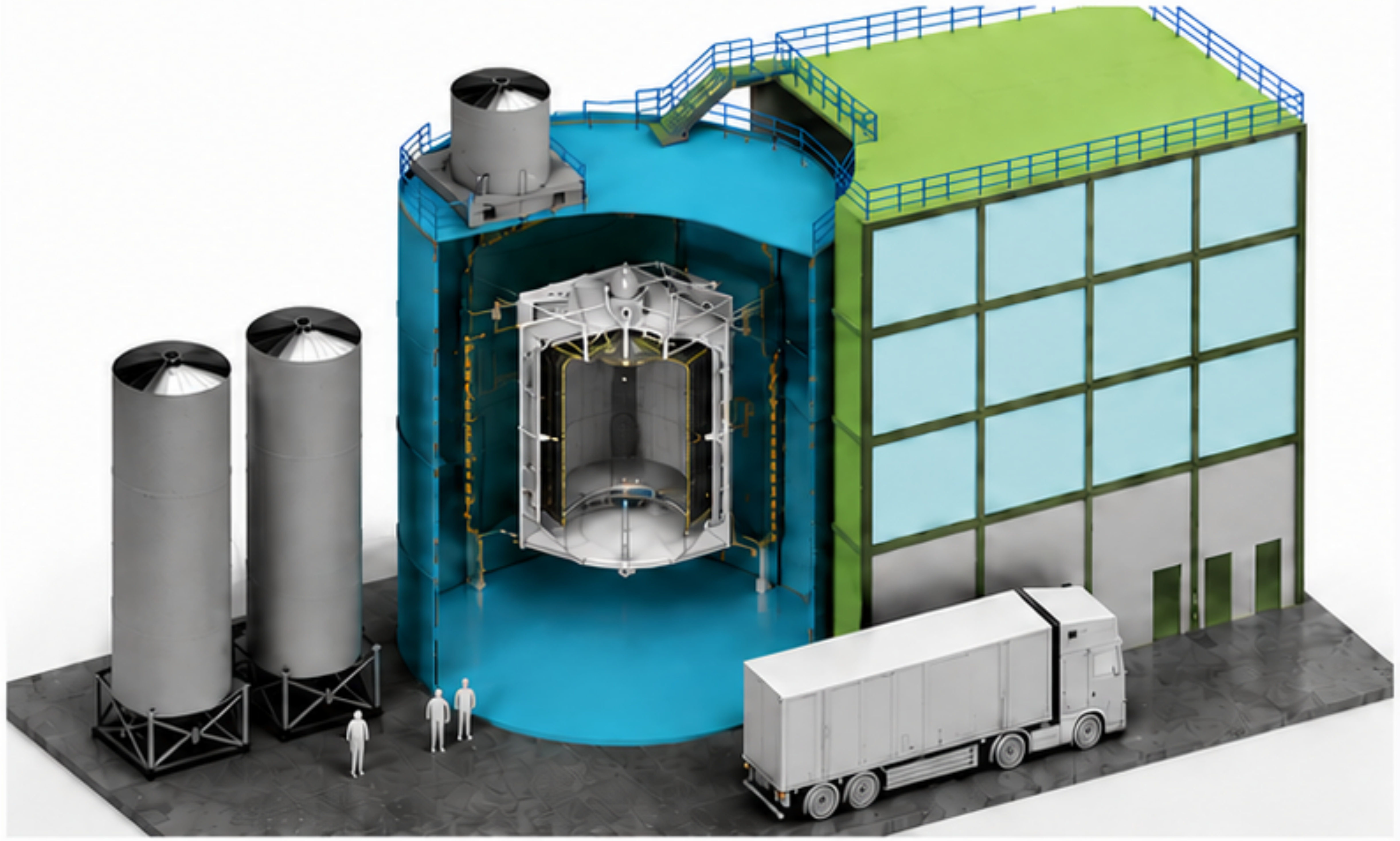
Design goal: background-free
Sensitivity approaching 10^{28} yr

Two paths to the same goal:
maximize isotope mass while maintaining background control.

Multi-Purpose Xenon Observatories

Simultaneously pursuing dark matter, 0νββ, and neutrino physics

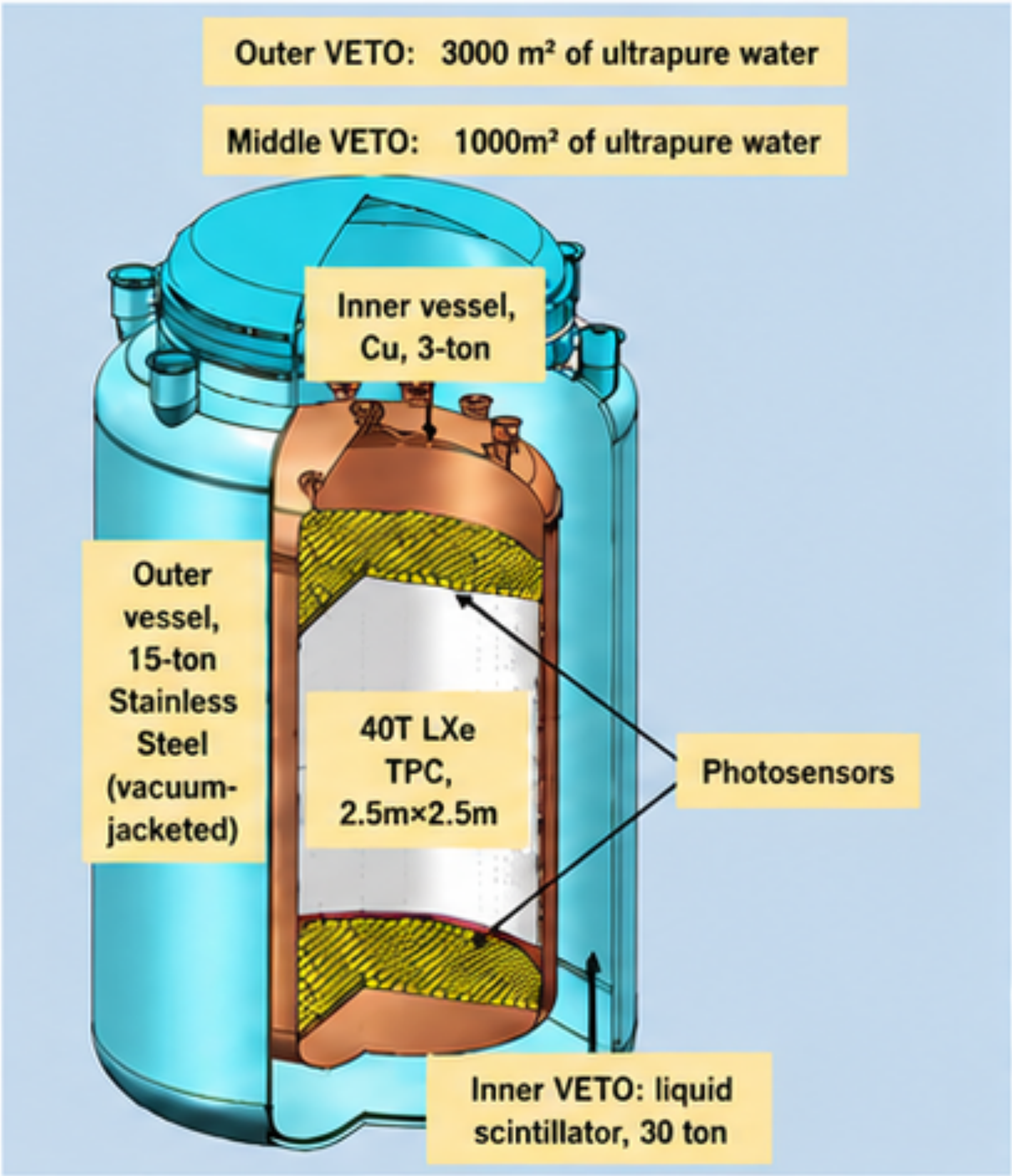
XLZD



A xenon observatory for rare events

- 60–80 t liquid xenon target
- Dark matter & 0νββ flagship
- Solar & supernova neutrinos
- Xenon + LZ + **DARWIN** expertise

PandaX-xT



Scaling a proven xenon program

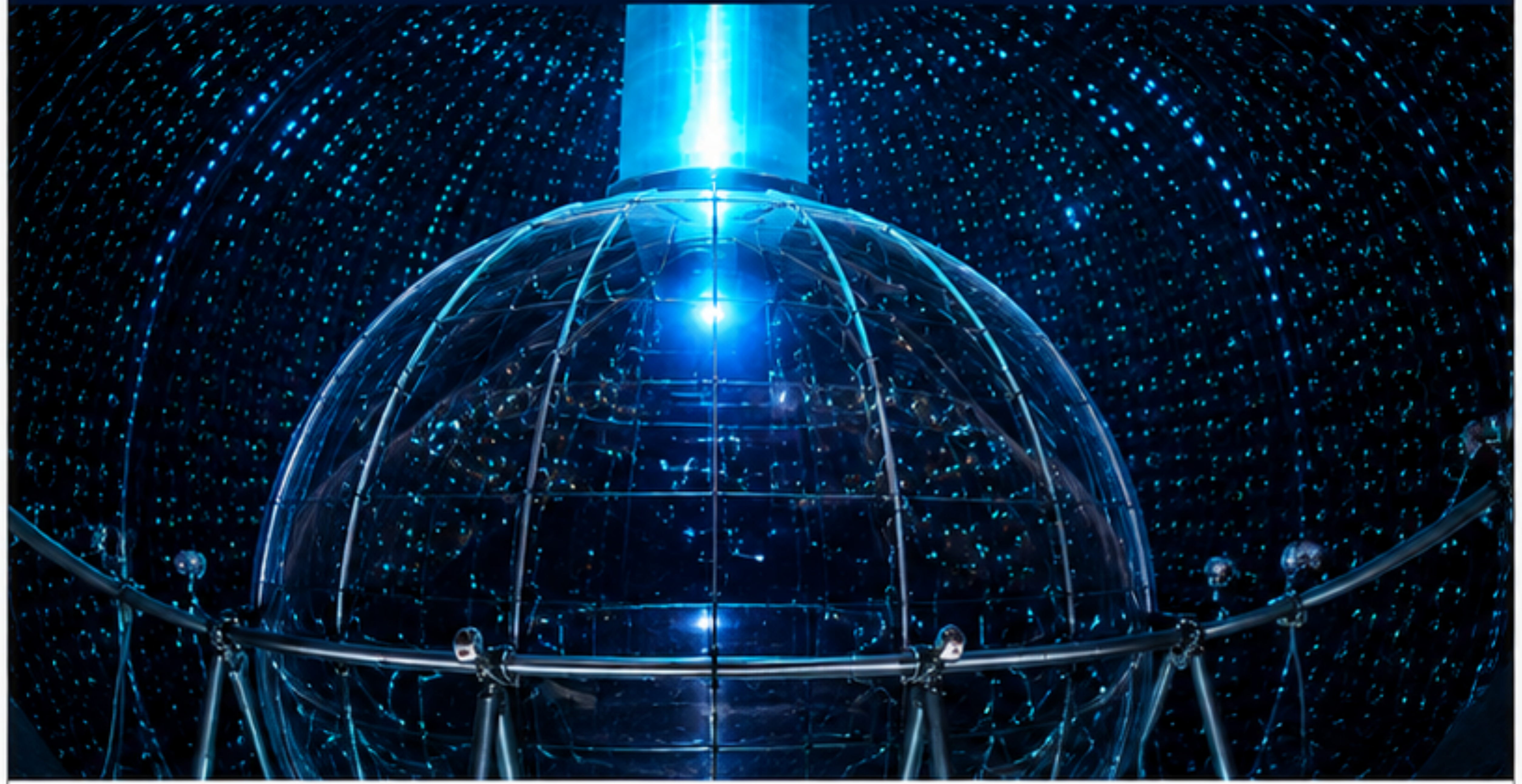
- 43 t liquid xenon target
- Dark matter & 0νββ flagship
- 20 t first stage fully funded
- Planned operation in 2028

Next-generation xenon observatories pursue dark matter and 0νββ simultaneously.

Existing Neutrino Observatories

Leveraging major neutrino facilities for future 0νββ searches

SNO+

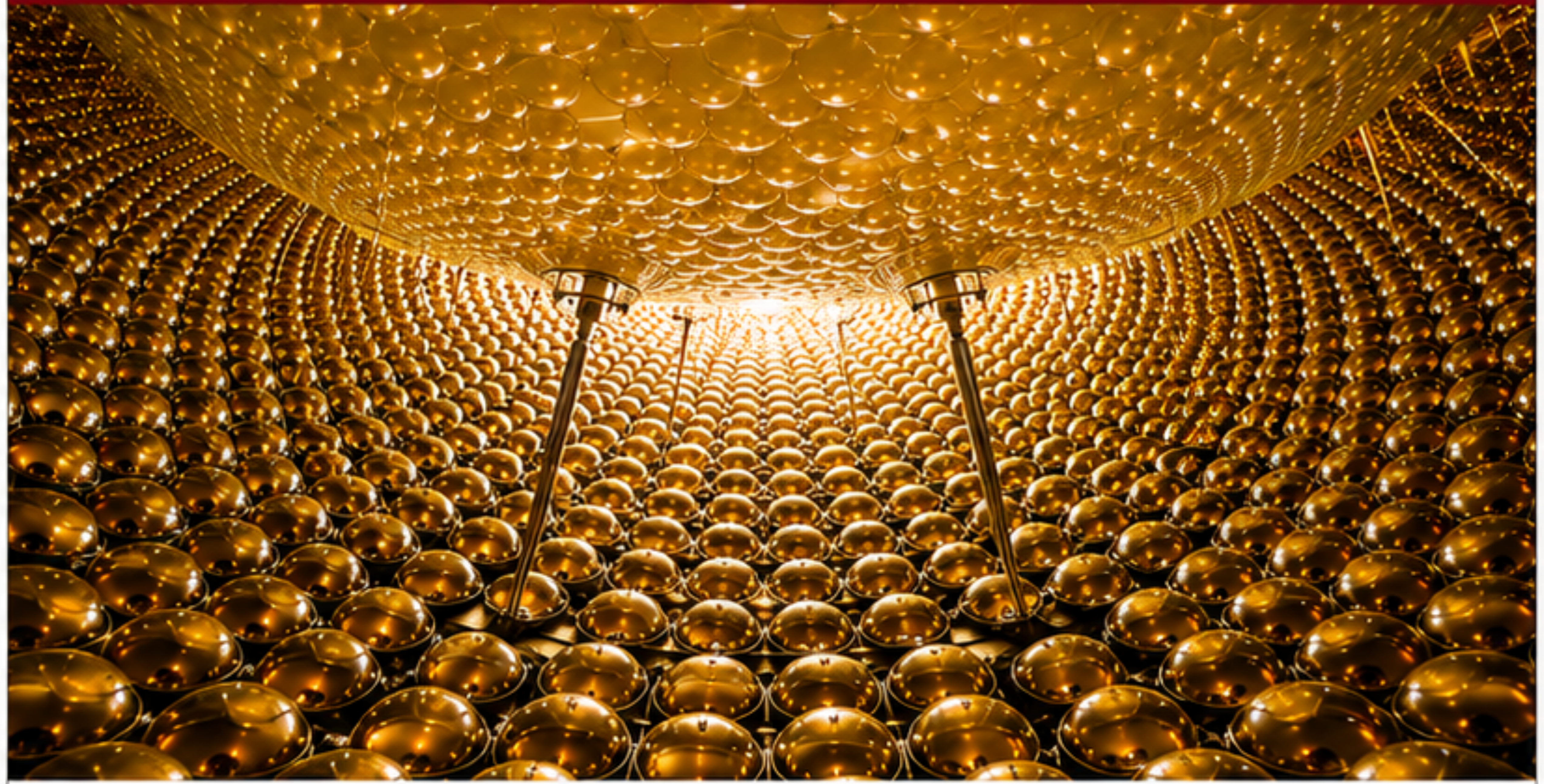


0νββ within a mature neutrino observatory

- 780 t liquid scintillator
- Deep underground (6070 m.w.e.)
- Solar, reactor & geo-neutrinos
- ^{130}Te loading planned for 2027

Existing underground infrastructure

JUNO



Infrastructure at unprecedented scale

- 20 kton liquid scintillator
- Precision oscillation physics
- Observatory-scale infrastructure
- Future isotope-loading studies

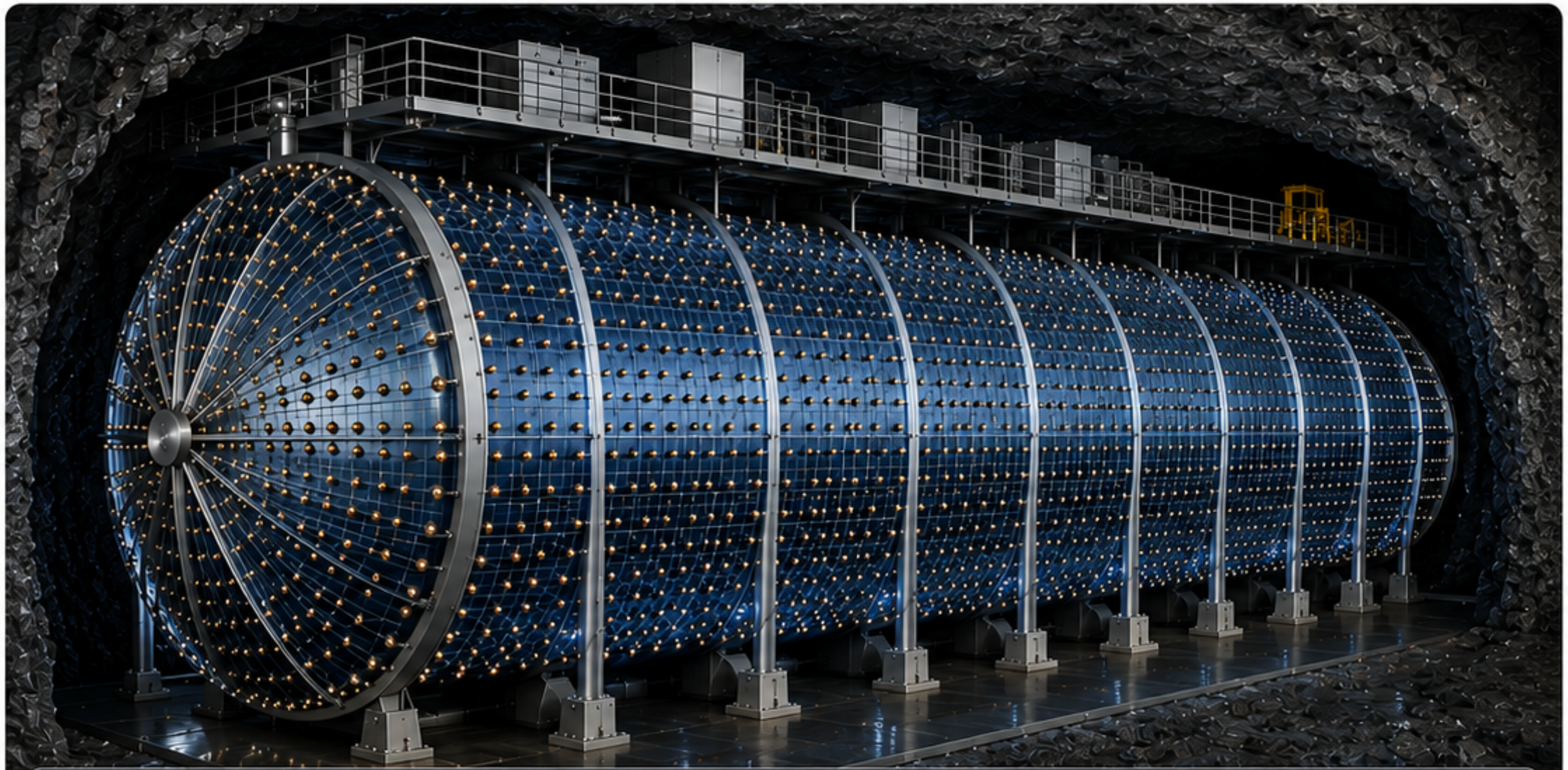
Scale beyond any previous LS experiment

Observatory-scale infrastructure may enable the next leap in isotope mass.

Future Neutrino Observatory Concept

THEIA

A next-generation, multi-purpose neutrino observatory



25 kilotonnes total volume	60% optical coverage 20” + 8” PMTs (HQE)	Deep underground at SURF or SNOLAB

SCALE

- Multi-kiloton isotope loading
- Hundreds of tonnes of ^{130}Te possible
- Sensitivity into the few-meV regime for $0\nu\beta\beta$

RECONSTRUCTION

- Cherenkov + scintillation detection
- Directionality from Cherenkov light
- Event-by-event discrimination
- Hybrid photon reconstruction

BREADTH

- $0\nu\beta\beta$
- Solar neutrinos
- Supernova neutrinos
- Long-baseline oscillations
- Nucleon decay

Can a single observatory combine scale, imaging, and broad physics reach?

CANDLES: The ^{48}Ca Path

Highest-Q ββ isotope (Qββ = 4.27 MeV)

CANDLES-III
Current ^{48}Ca detector

- CaF_2 crystals enriched in ^{48}Ca
- Proven low-background operation
- Current 0νββ search program

THE CHALLENGE

Qββ = 4.27 MeV
Highest-Q ββ isotope

↓

Natural abundance 0.187%

↓

Historically impossible
to scale

↓

Laser isotope
separation

↓

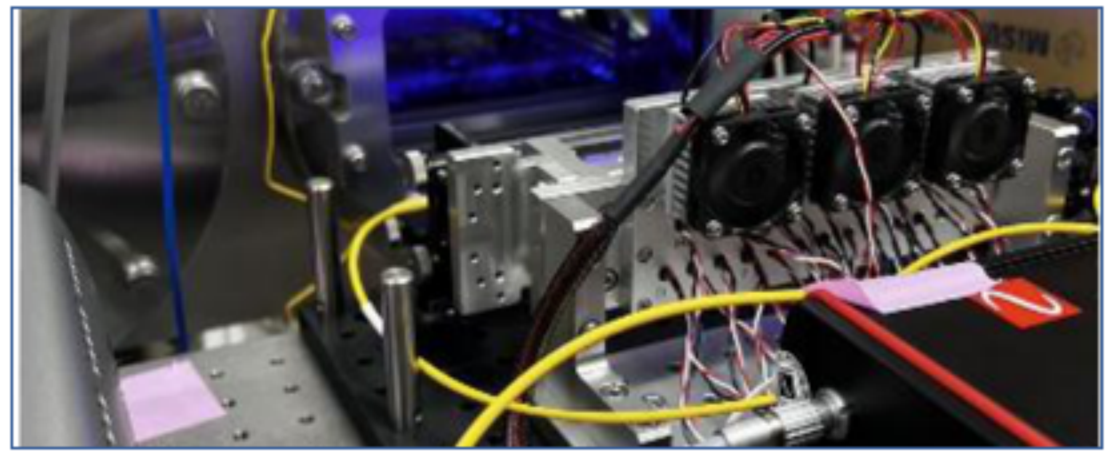
>50% enrichment goal

↓

Ton-scale ^{48}Ca target

THE OPPORTUNITY
Laser isotope separation

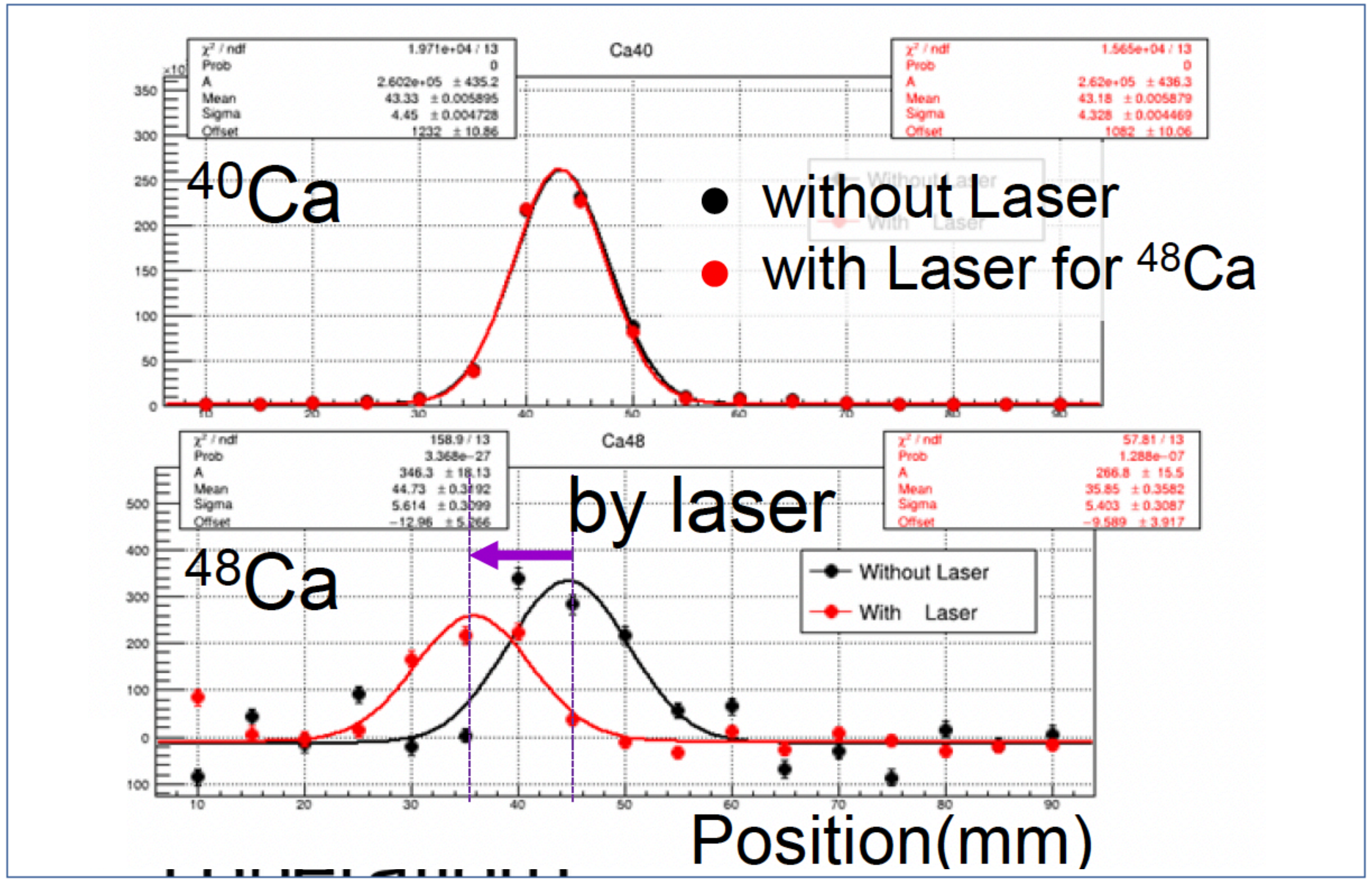
Laser system



80 mW × 24 = 2 W

Main chamber

- 6 laser ports
- 3 heater chambers, crucible

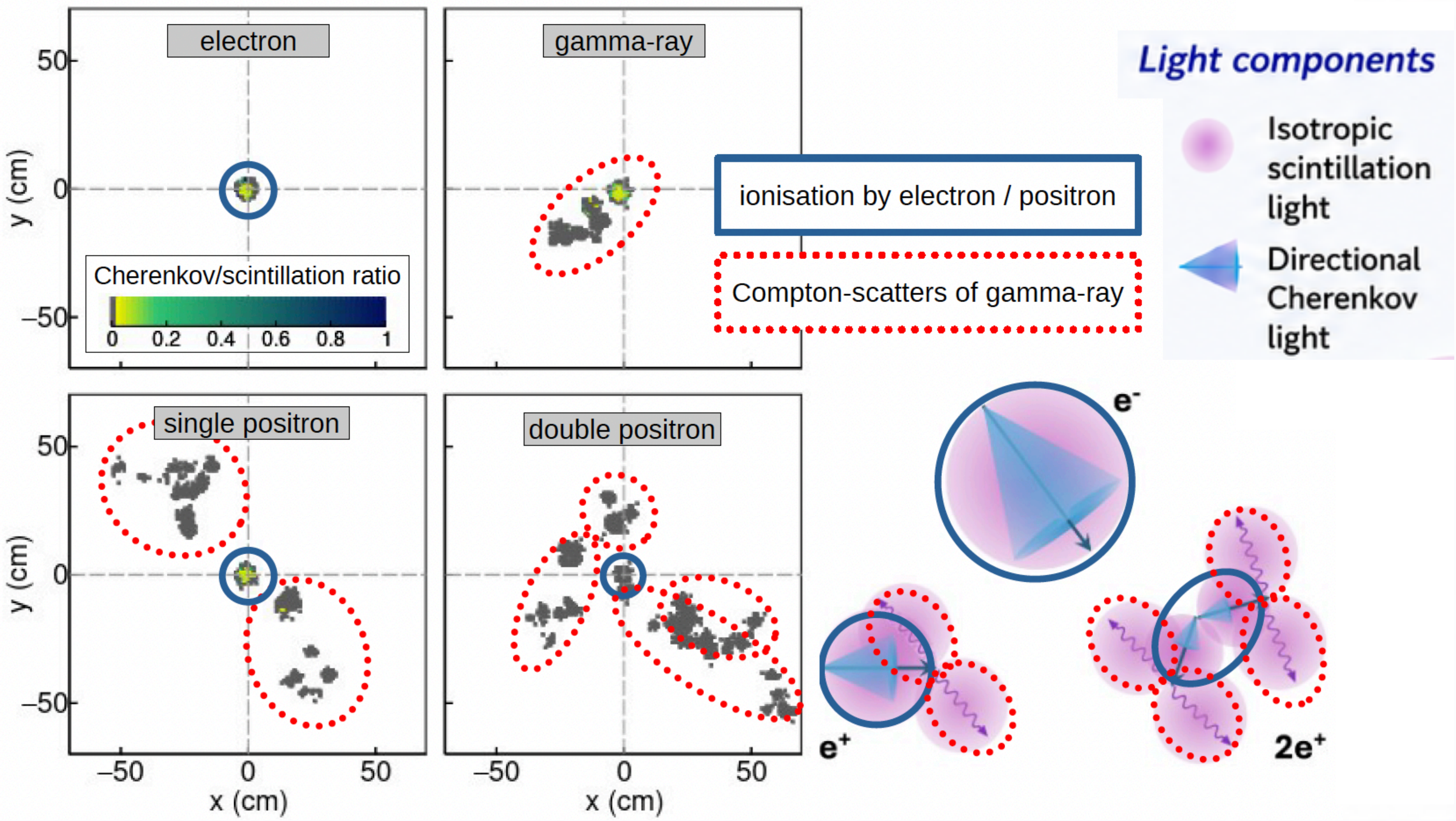


NuDoubt++

Hybrid + Opaque Scintillator for $\beta^+\beta^+$ Searches

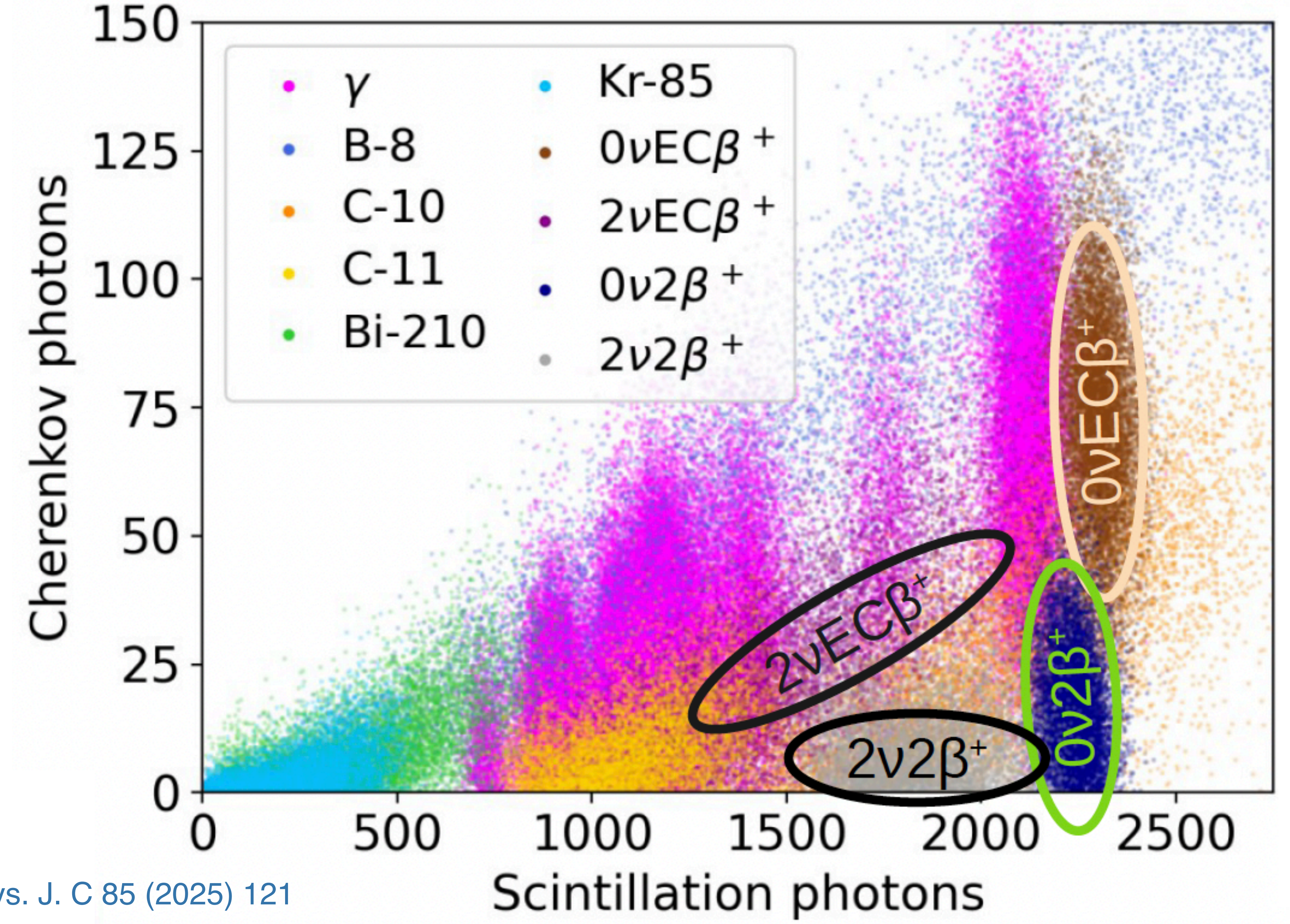
TOPOLOGY RECONSTRUCTION IN OPAQUE SCINTILLATOR

Different particle signatures → different topologies ("blobs")



CHERENKOV / SCINTILLATION SEPARATION (HYBRID SCINTILLATOR)

Distinct C/S ratios separate signal classes from backgrounds



Eur. Phys. J. C 85 (2025) 121

POSITRON TOPOLOGY

- Single positron → 1 blob + annihilation γs
- Double positron → multiple blobs
- Enables background rejection via topology

HYBRID PARTICLE IDENTIFICATION

- Cherenkov/scintillation ratio (C/S) distinguishes event classes
- Strong separation of signal from solar and radiogenic backgrounds

PHYSICS REACH (NuDoubt++)

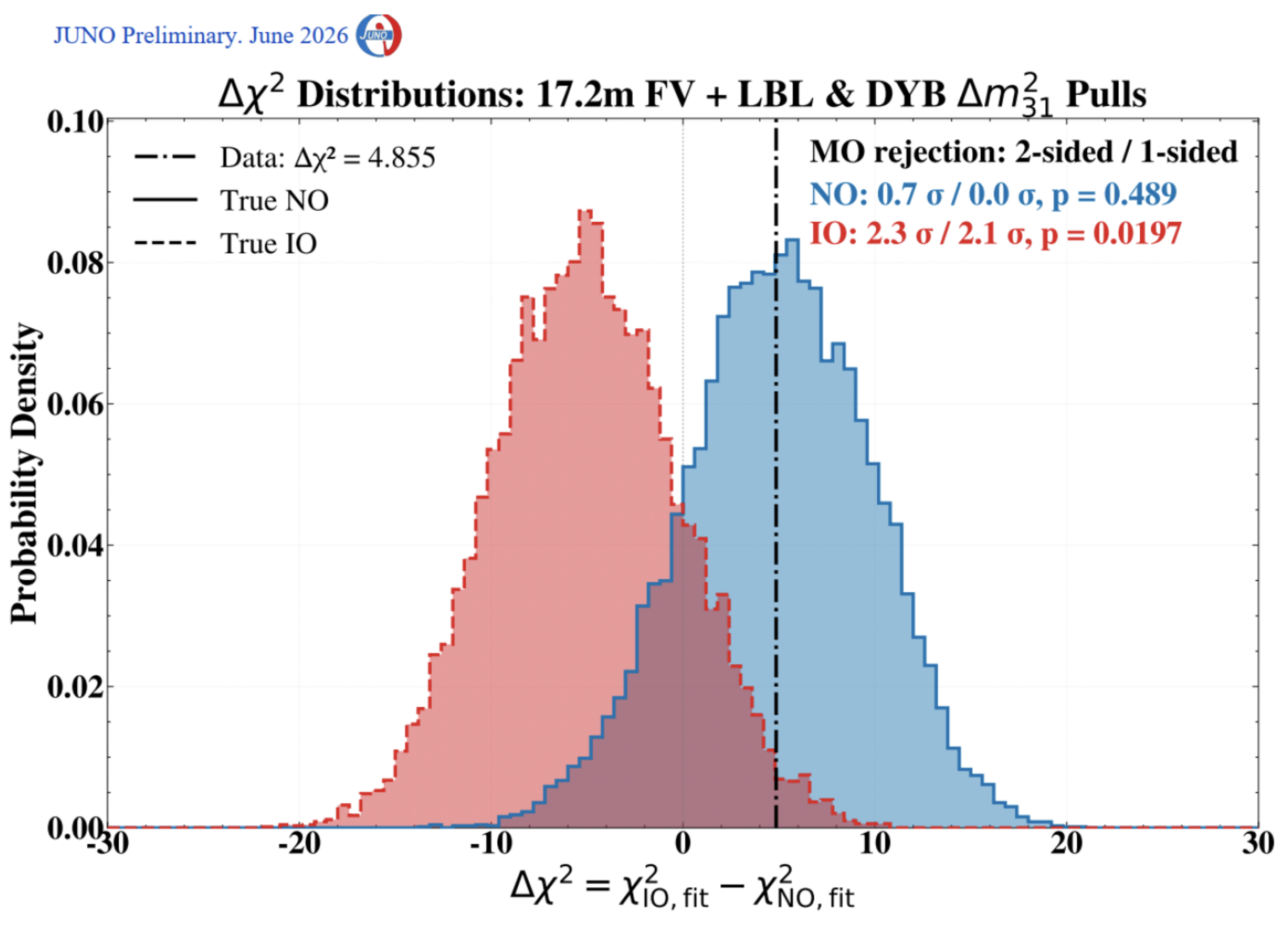
- 5σ observation of $2\nu EC\beta^+$ in ~ 2 years (10 kg target)
- Improved sensitivity to $0\nu EC\beta^+$ and $0\nu\beta^+\beta^+$
- New access to positron-emitting double-beta decay modes

Combining topology and particle ID opens a new window on positron-emitting double-beta decays.

BEYOND MASS ORDERING

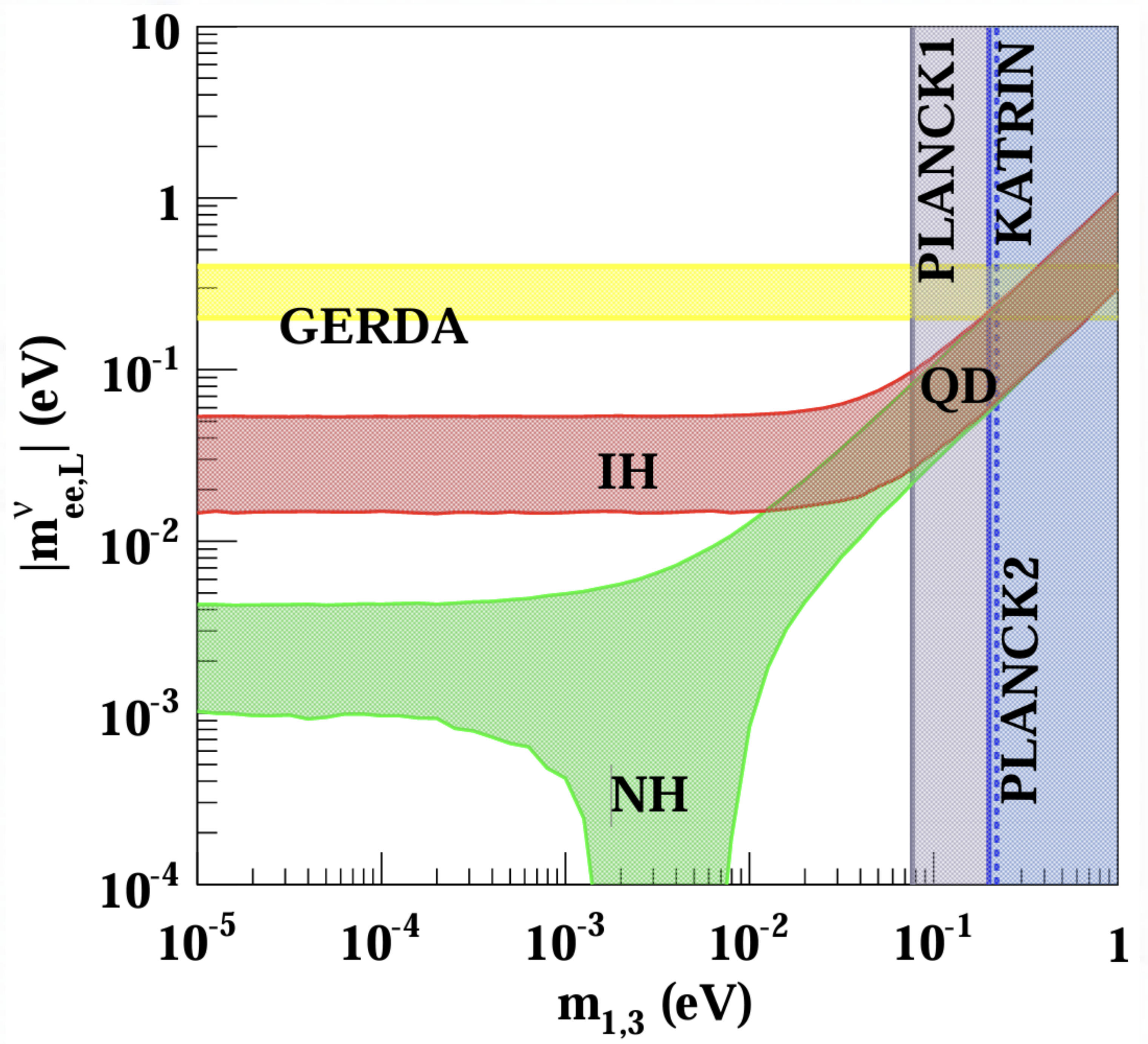
Why Normal Ordering does not end the 0νββ story

JUNO PRELIMINARY (June 2026)



Evidence increasingly favors Normal Ordering

STANDARD MASS MECHANISM (light neutrino exchange)



J. High Energ. Phys. **2016**, 147 (2016)

DEGENERATE MASSES REMAIN POSSIBLE

ALTERNATIVE LNV MECHANISMS CAN MODIFY EXPECTATIONS

DIFFERENT MECHANISMS PREDICT DIFFERENT OBSERVABLES

DISCOVERY STILL REQUIRES:
- MULTIPLE ISOTOPES
- MULTIPLE TECHNOLOGIES
- TOPOLOGY & KINEMATICS

*Determination of the mass ordering provides important **boundary conditions** for 0νββ searches.*
*A discovery will still require **interpretation:** the mechanism may matter as much as the rate.*

BEYOND MASS ORDERING

Why Normal Ordering does not end the 0νββ story

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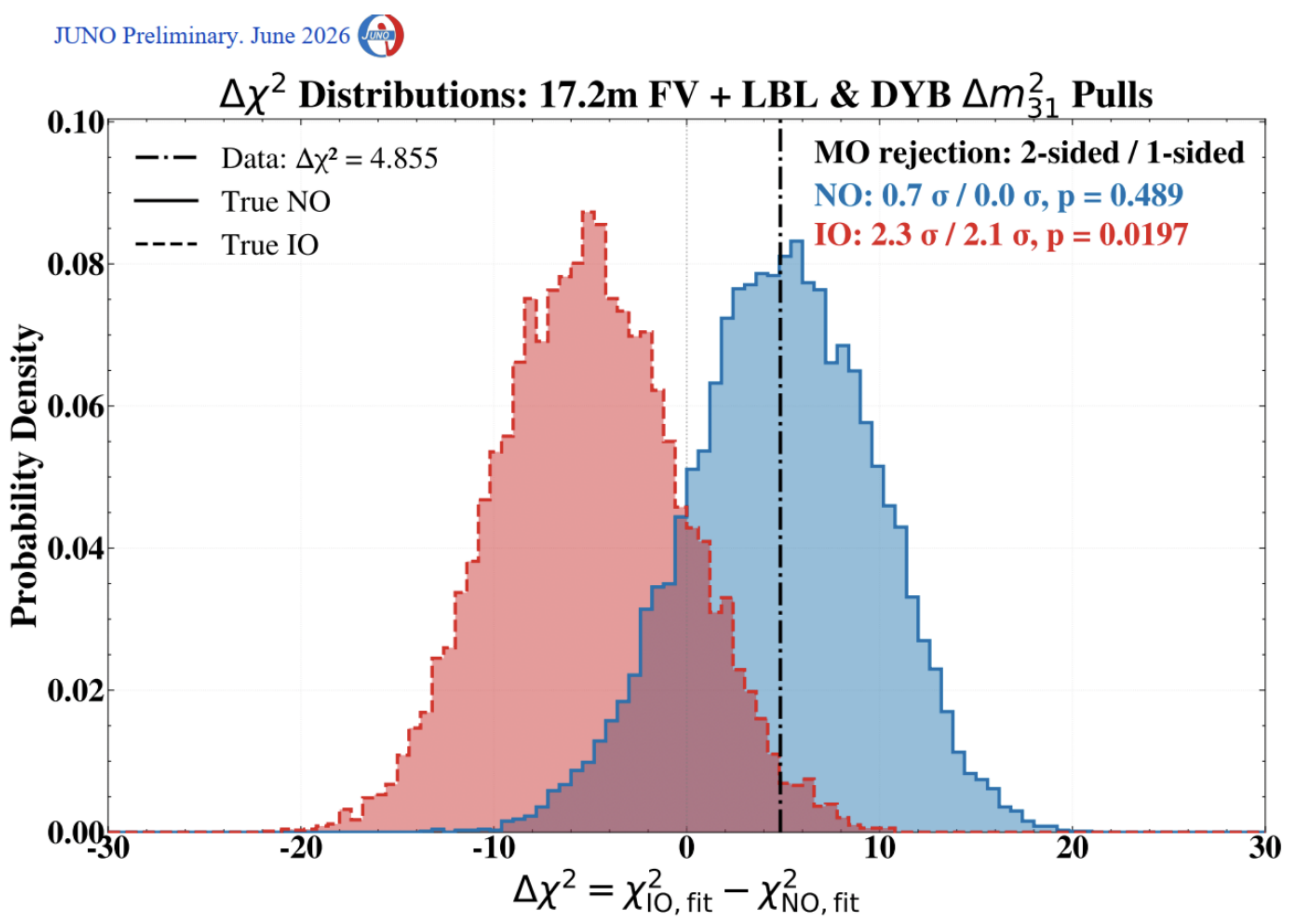
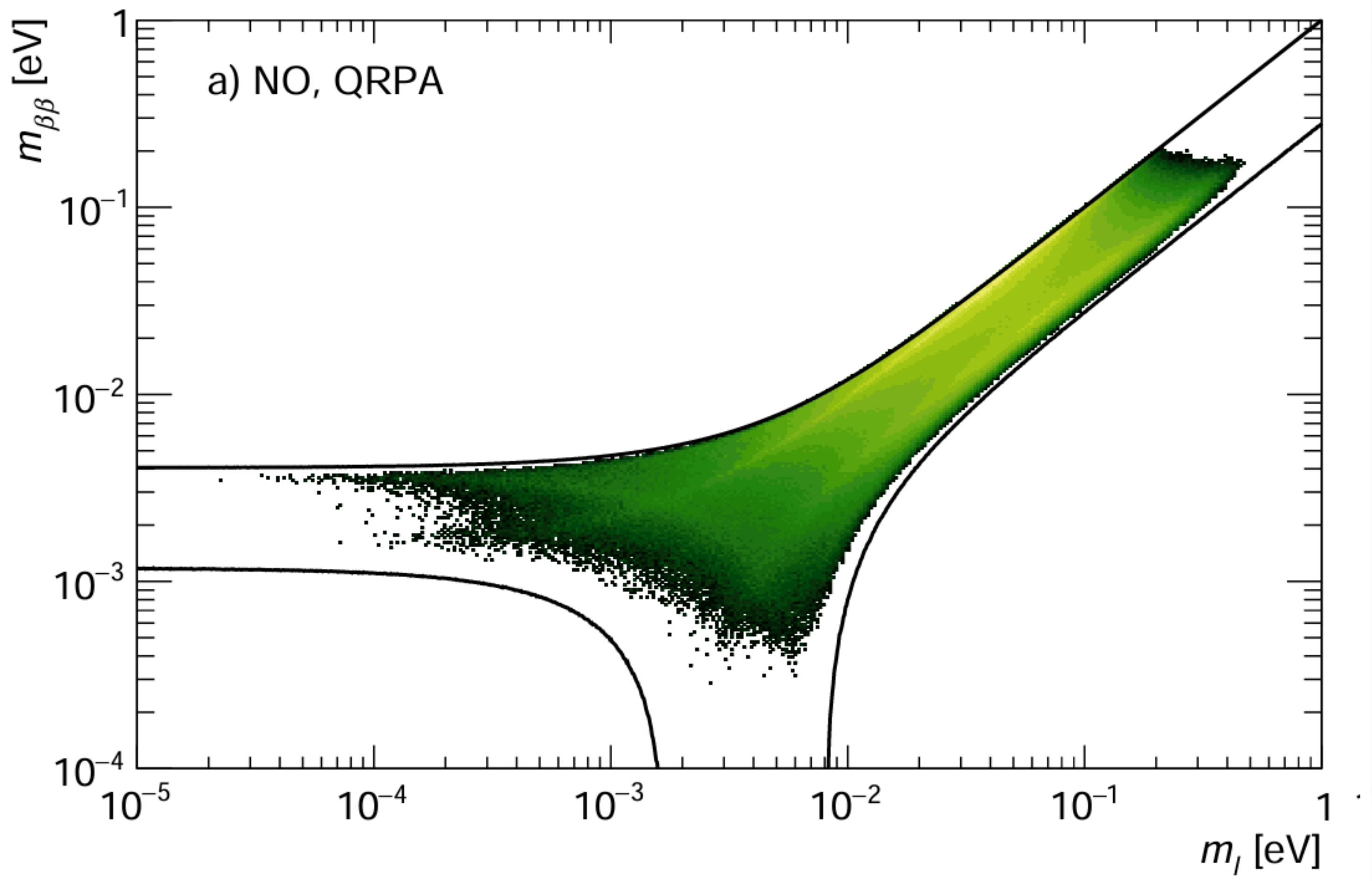


Evidence increasingly favors Normal Ordering

STANDARD MASS MECHANISM (light neutrino exchange)

The allowed phase space is not uniformly populated



Agostini, Benato & Detwiler, Phys. Rev. **D96**, 053001 (Sept **2017**)

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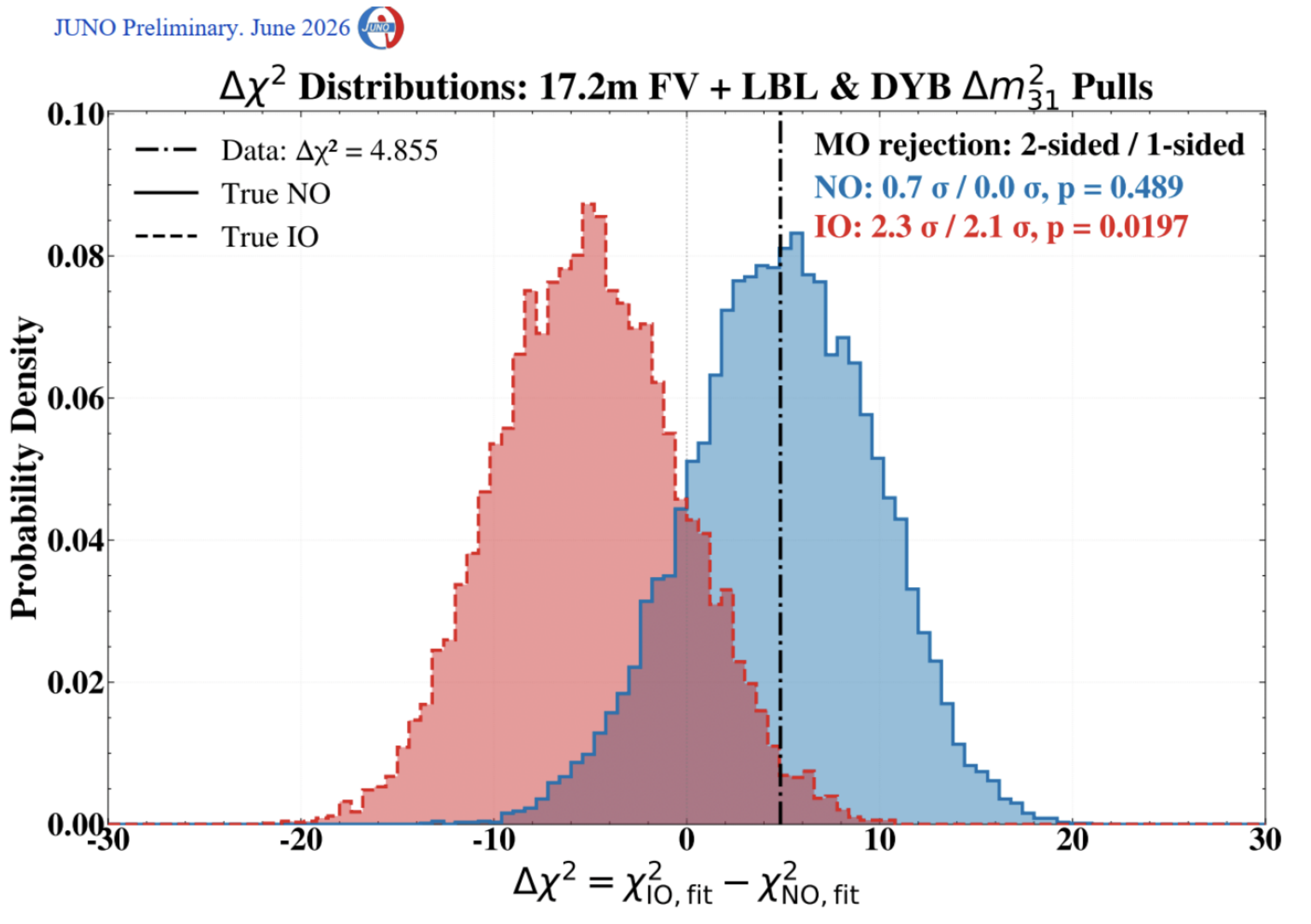

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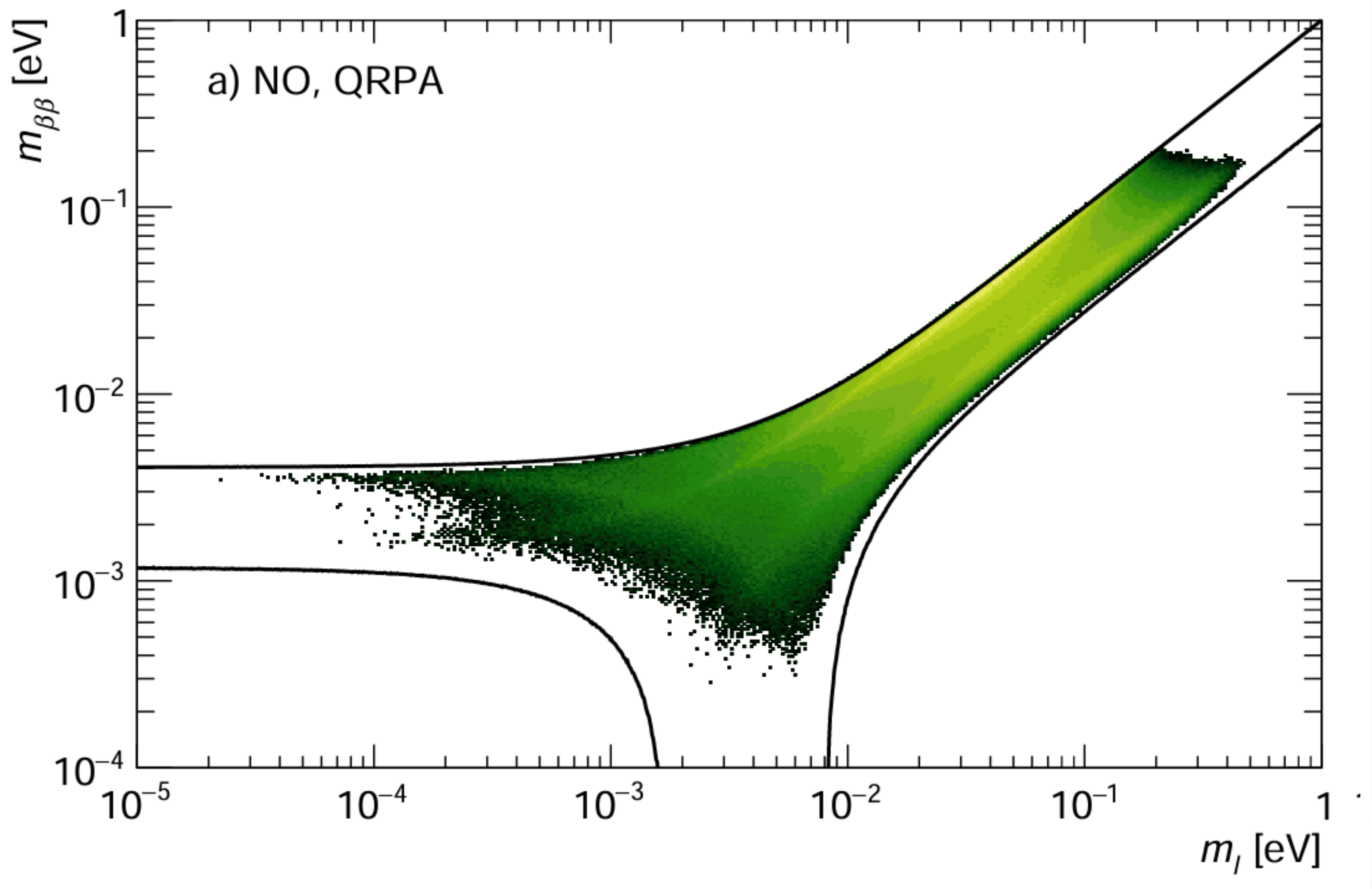
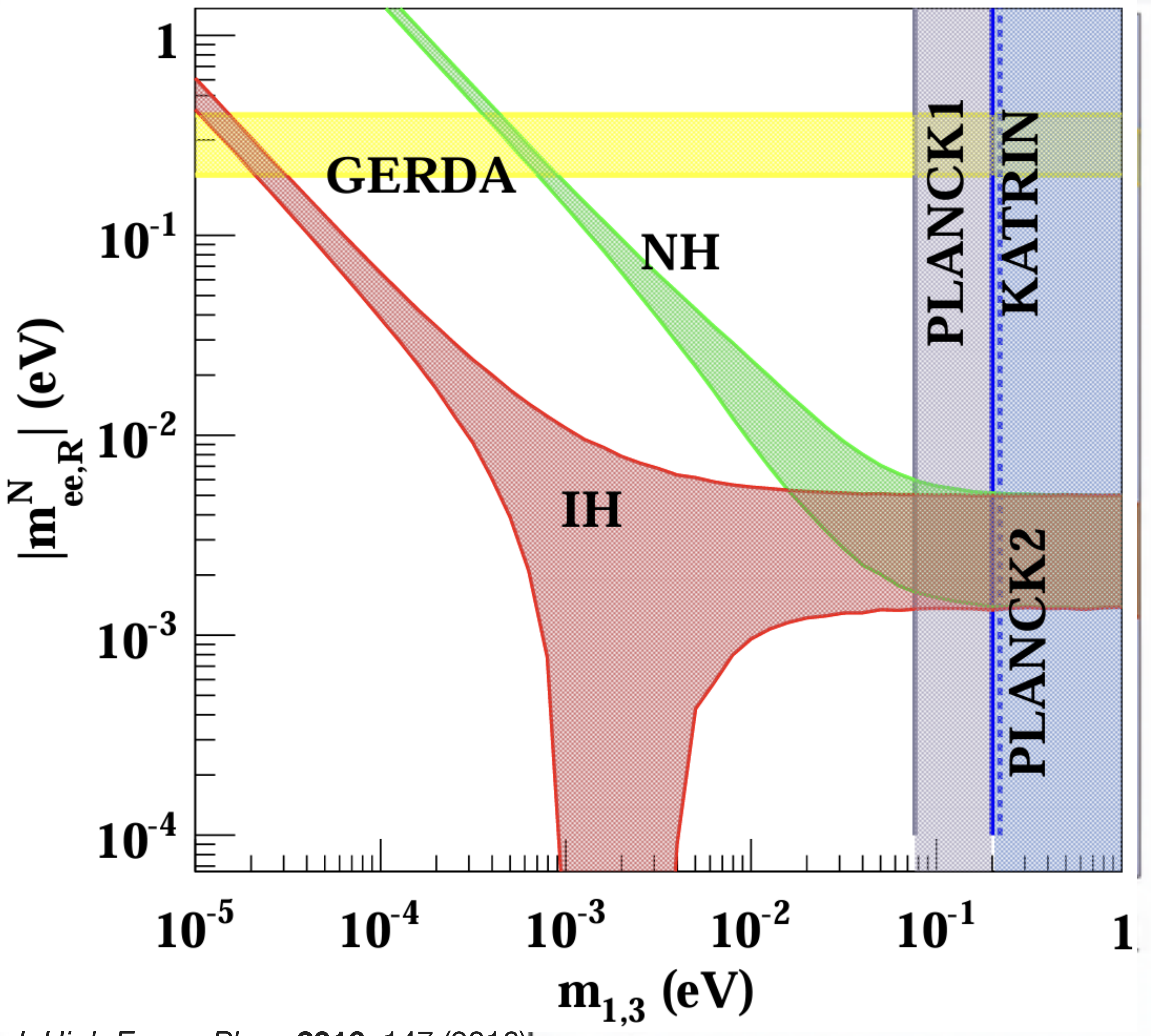


Agostini, Benato & Detwiler, Phys. Rev. **D96**, 053001 (Sept **2017**)

ALTERNATIVE LNV MECHANISM Example: right-handed currents



J. High Energ. Phys. **2016**, 147 (2016)

DEGENERATE MASSES REMAIN POSSIBLE

ALTERNATIVE LNV MECHANISMS CAN MODIFY EXPECTATIONS

DIFFERENT MECHANISMS PREDICT DIFFERENT OBSERVABLES

DISCOVERY STILL REQUIRES:
- MULTIPLE ISOTOPES
- MULTIPLE TECHNOLOGIES
- TOPOLOGY & KINEMATICS

Determination of the mass ordering provides important boundary conditions for 0νββ searches. A discovery will still require interpretation: the mechanism may matter as much as the rate.

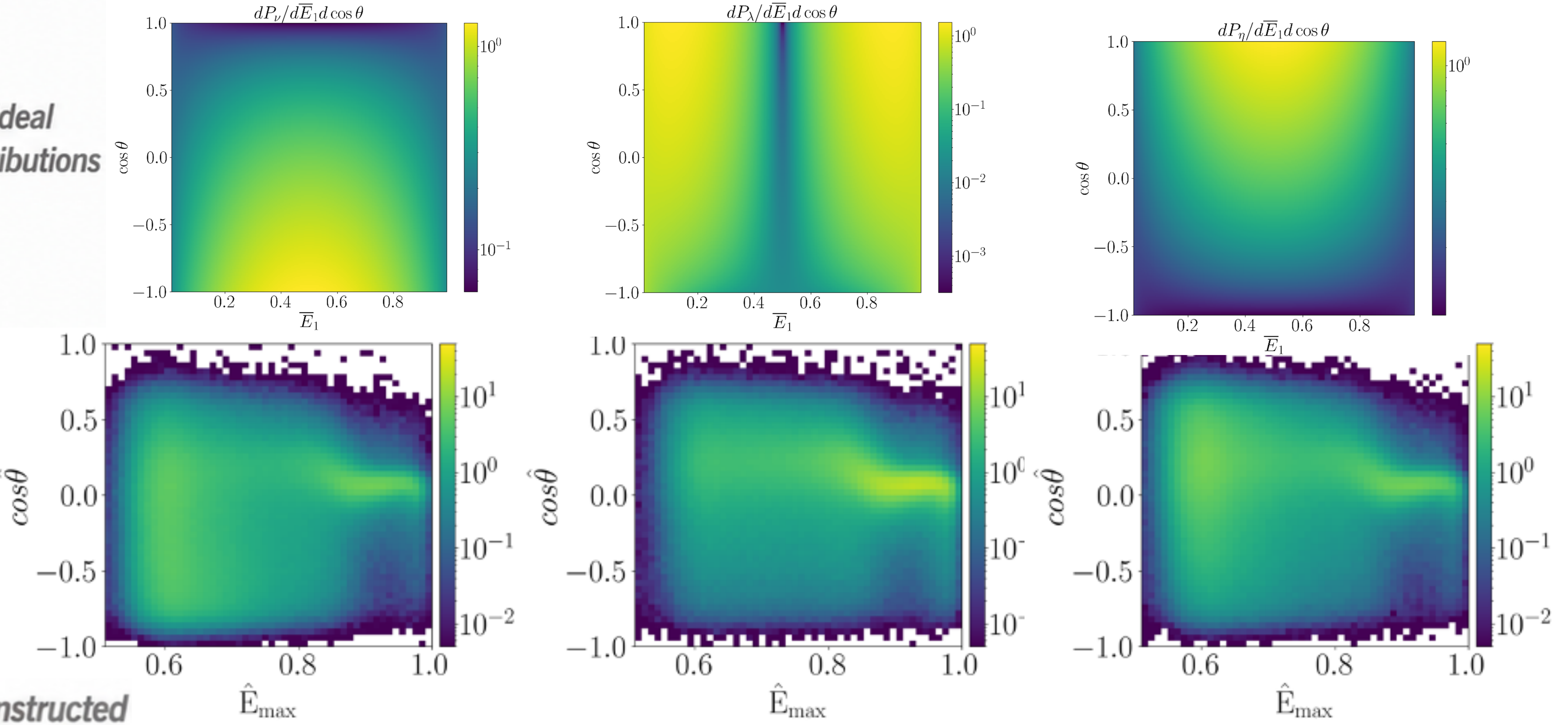
Beyond Discovery

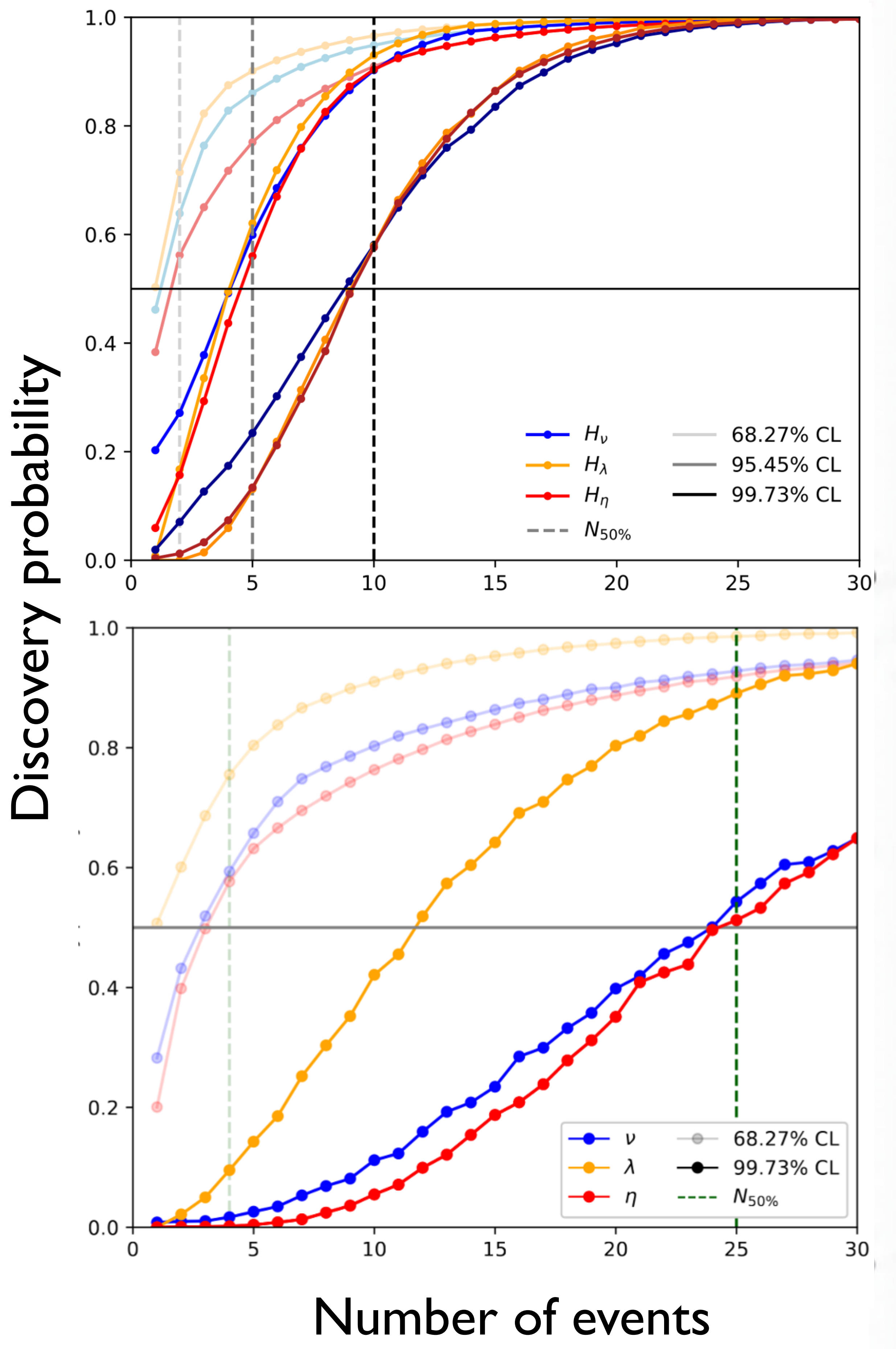
Can discovery become diagnosis?

Light ν Exchange | **Right-Handed Currents** | **Alternative Currents**

Ideal distributions

Reconstructed distributions





OBSERVATION → **MECHANISM IDENTIFICATION**

Topology can reveal the mechanism

Event kinematics may distinguish competing explanations for neutrinoless double beta decay.

Detwiler, Han & Li, arXiv:2605.21315 (2026)

How do we test leptogenesis?

Credit: Hitoshi Muruyama

How do we test leptogenesis?

Estimated energy scale:	Current collider record:
10^{10}–10^{15} GeV	10^4 GeV (LHC)

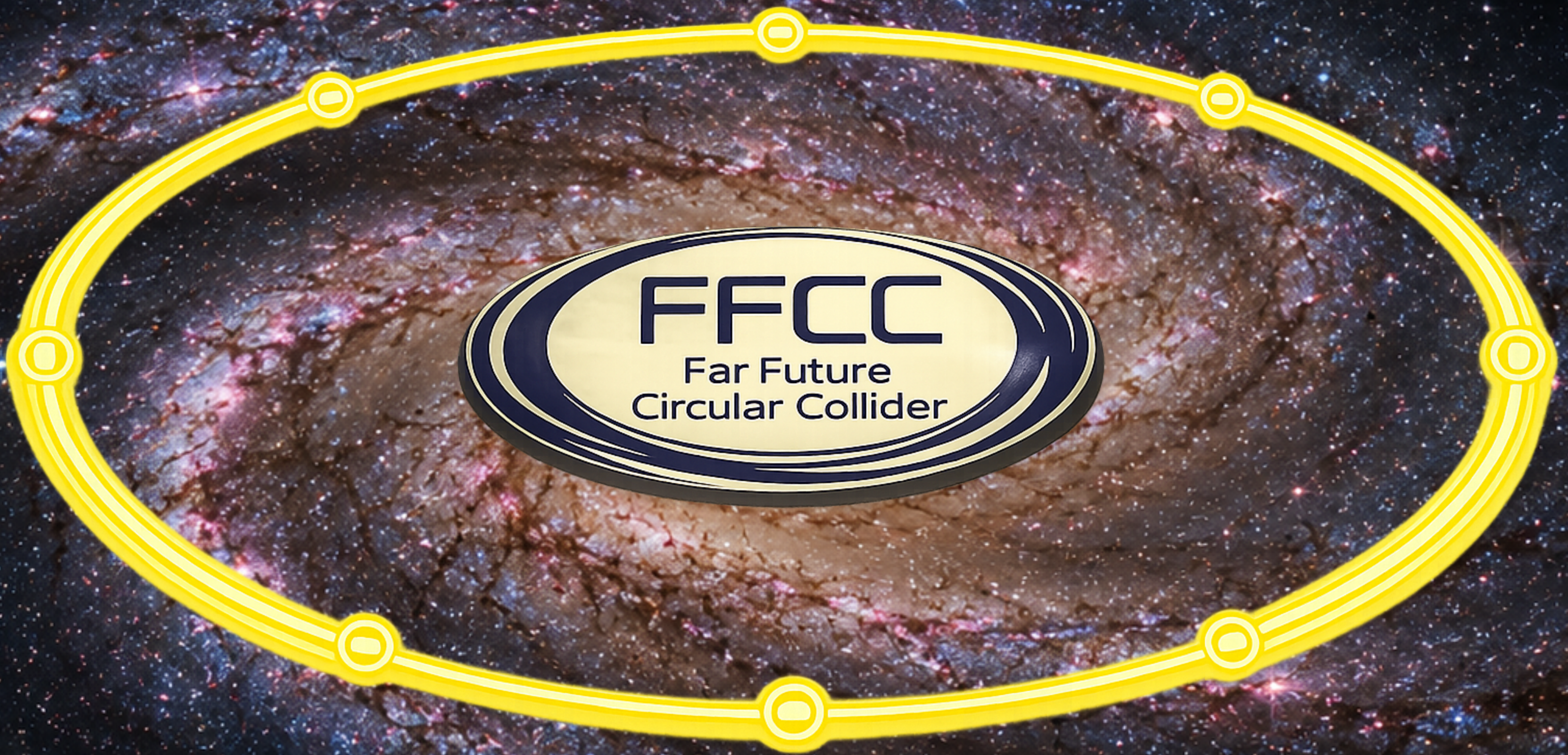
Estimated construction site:

Milky Way Galaxy

Credit: Hitoshi Muruyama

How do we test **leptogenesis?**

Funding outlook:
Not currently in the DOE Long Range Plan.



Estimated energy scale:	Current collider record:
10^{10}–10^{15} GeV	10^4 GeV (LHC)

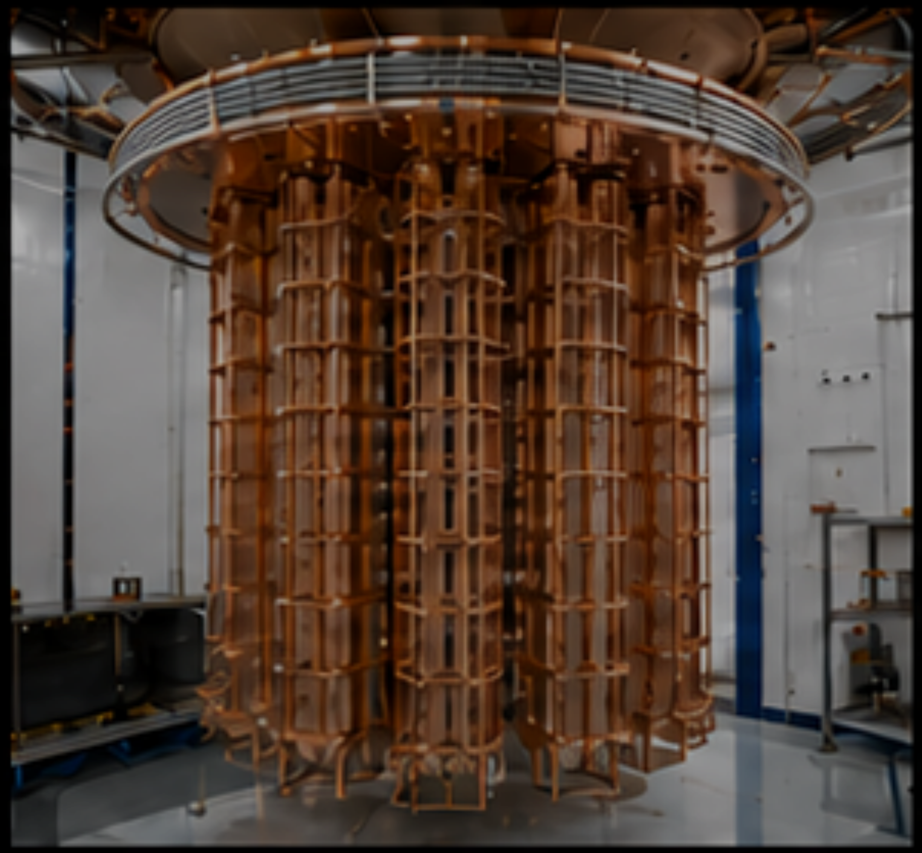
Estimated construction site:
Milky Way Galaxy

ONE GOAL. MANY PATHS.

Complementary strategies. Converging on discovery.

PRECISION ENERGY MEASUREMENT

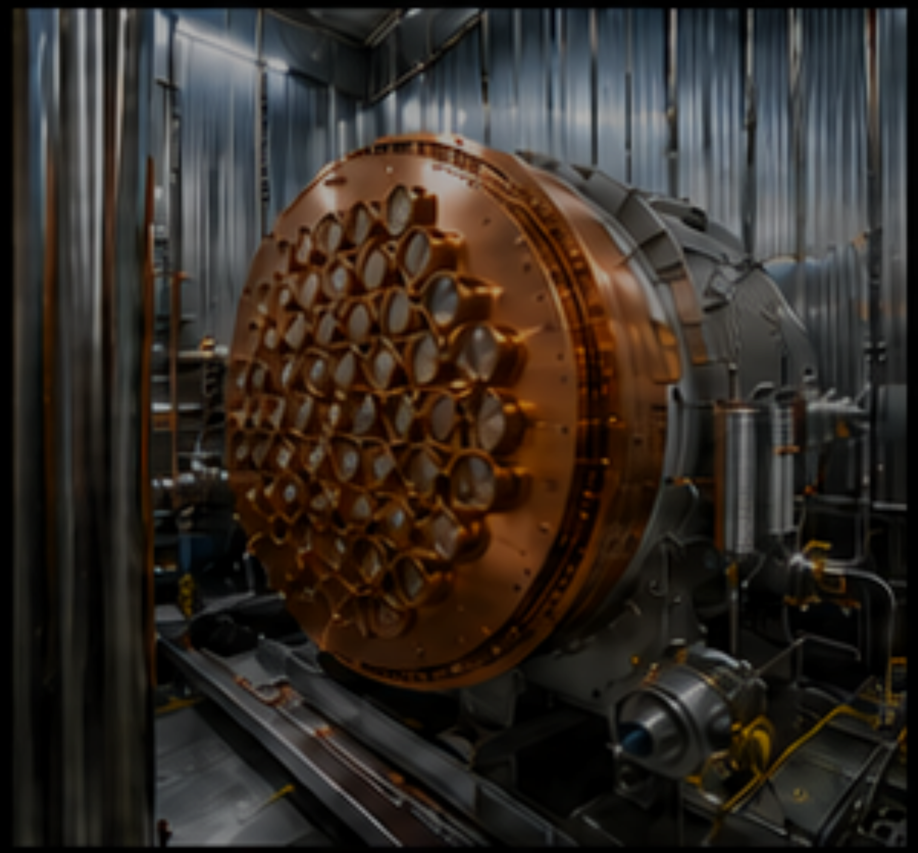
Better resolution



Examples:
CUPID, AMoRE, LEGEND

EVENT TOPOLOGY

More discrimination



Examples:
NEXT, SuperNEMO

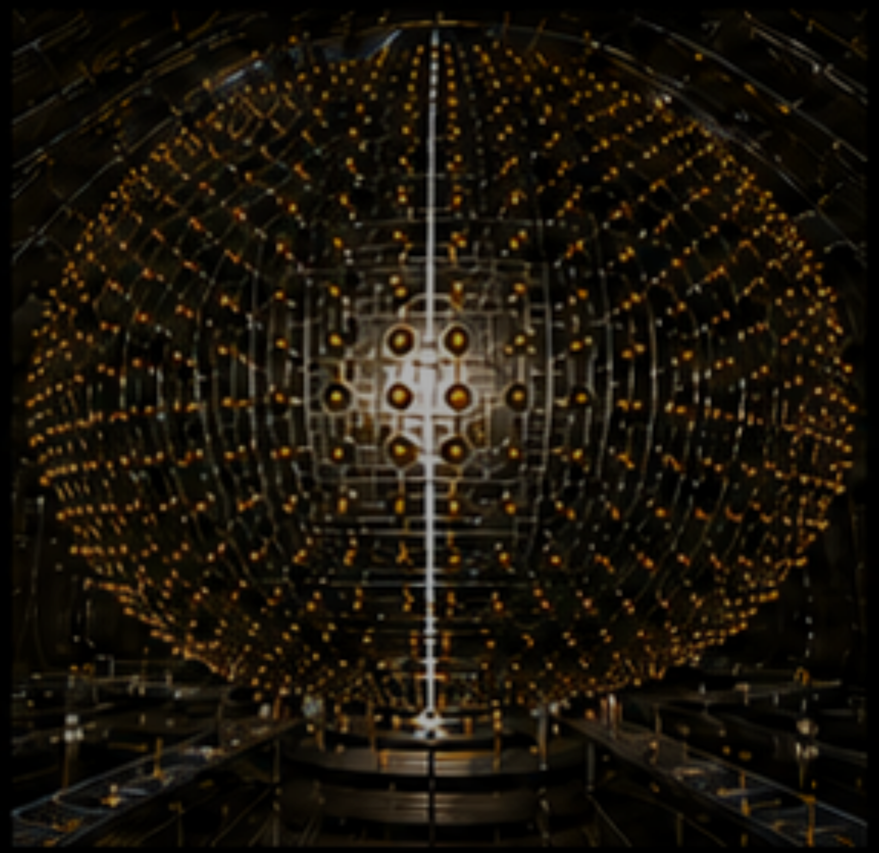
LARGE HOMOGENEOUS LXe TPCS

More isotope (self-shielded)

Examples:
nEXO, XLZD, PandaX

SCALE THROUGH OBSERVATORIES

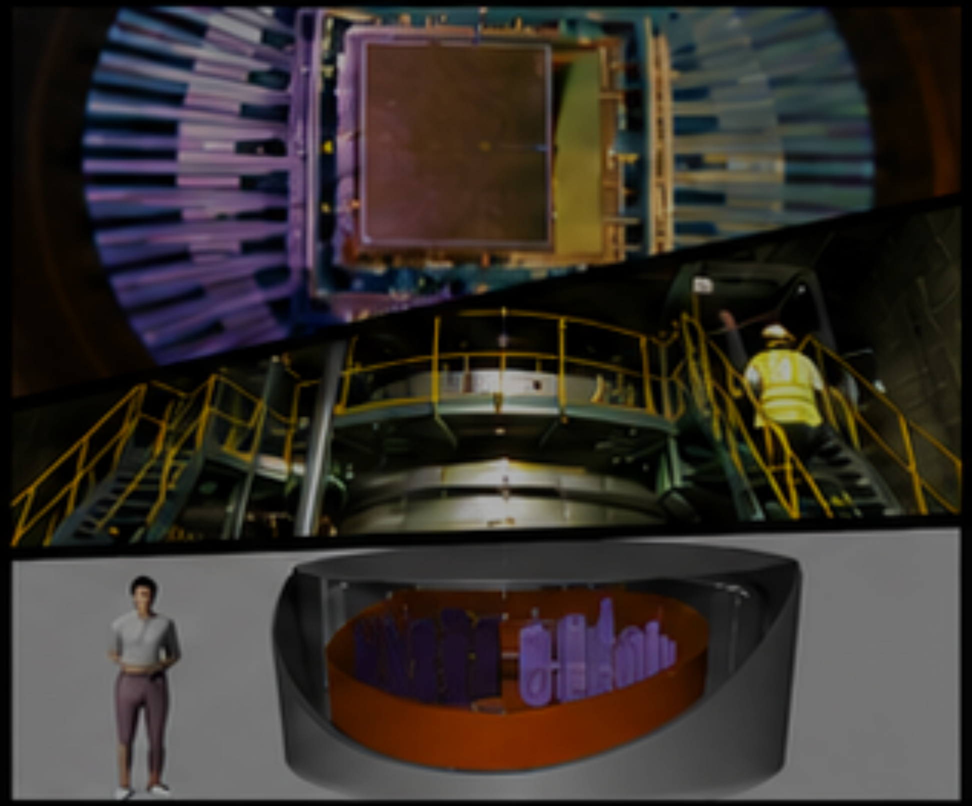
More scale & flexibility



Examples:
KamLAND-Zen, SNO+, JUNO, Theia

ALTERNATIVE ISOTOPES & NOVEL CONCEPTS

Independent confirmation
& ultimate reach



Examples:
CANDLES, Selena, NuDoubt

Discover Neutrinoless Double Beta Decay

Understand the Nature of Neutrinos | Uncover Physics Beyond the Standard Model

We are approaching sensitivity to the inverted-ordering region—an *extraordinary achievement.*

The challenge now is the *Normal-Ordering regime,* which will require the next order of magnitude in background suppression, scale, and innovation.

Multiple isotopes and complementary technologies will likely be essential—*both to discover 0νββ and to establish and elucidate the underlying physics when it is discovered.*

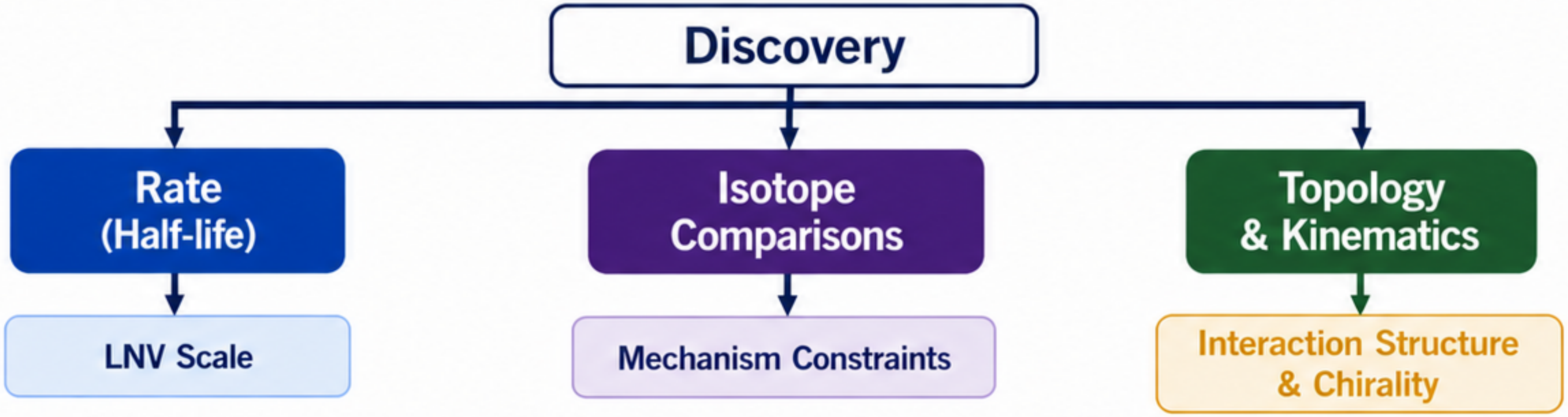
✓ Different strengths ✓ Cross-checks & confirmation ✓ Innovation & competition ✓ Resilience & adaptability ✓ Greater chance of discovery

Diverse paths. United purpose. Our best chance to discover—and to understand.

Beyond Discovery

What do we learn after we see $0\nu\beta\beta$?

Three complementary routes to *understanding* the signal



Examples of observables

Observable	Physics information
Half-life	Overall lepton-number violating scale
Multiple isotopes	Mechanism constraints
Electron energy sharing	Operator structure
Opening angle	Chirality of the interaction
Event topology	Mechanism discrimination

Emerging message

- Discovery and characterization may proceed together
- Isotope comparisons and topology provide complementary information
- Imaging and tracking detectors add unique observables
- The goal is not only to discover $0\nu\beta\beta$, but to understand its origin

The future challenge may not be discovering $0\nu\beta\beta$ — it may be understanding what we have discovered.