NEUTRINOLESS DOUBLE BETA DECAY

AN EXPERIMENTAL OVERVIEW

Erice 2026

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LBNL | UC Berkeley

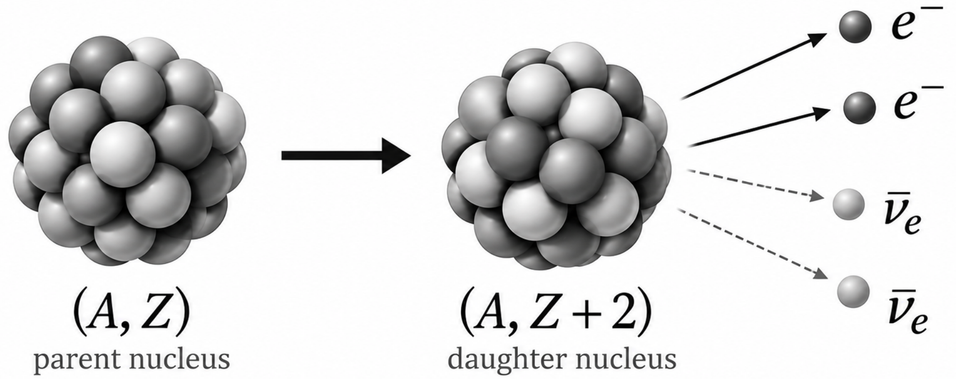
Overview

- Where did we come from?
- Why 0νββ?
- Discovery potential
- Experimental approaches
- Where do we go from here?

Where did we come from?

1935 — Goeppert Mayer

$$(A, Z) \rightarrow (A, Z+2) + 2e^- + 2\bar{\nu}_e$$



(A, Z)
parent nucleus

$(A, Z+2)$
daughter nucleus

SEPTEMBER 15, 1935 PHYSICAL REVIEW VOLUME 48

Double Beta-Disintegration

M. GOEPPERT-MAYER, *The Johns Hopkins University*

(Received May 20, 1935)

From the Fermi theory of β-disintegration the probability of simultaneous emission of two electrons (and two neutrinos) has been calculated. The result is that this process occurs sufficiently rarely to allow a half-life of over 10^{17} years for a nucleus, even if its isobar of atomic number different by 2 were more stable by 20 times the electron mass.

1. INTRODUCTION

IN a table showing the existing atomic nuclei it is observed that many groups of isobars only isobars of even difference in atomic number occur.

A metastable isobar can, however, change into a more stable one by simultaneous emission of

1937 — Majorana

Can a neutral fermion be its own antiparticle?

TEORIA SIMMETRICA DELL'ELETTRONE
E DEL POSITRONE

Nota di ETTORE MAJORANA

Sunto. - *Si dimostra la possibilità di pervenire a una piena simmetrizzazione formale della teoria quantistica dell'elettrone e del positrone facendo uso di un nuovo processo di quantizzazione. Il significato delle equazioni di* DIRAC *ne risulta alquanto modificato e non vi è più luogo a parlare di stati di energia negativa; nè a presumere per ogni altro tipo di particelle, particolarmente neutre, l'esistenza di « antiparticelle » corrispondenti ai « vuoti » di energia negativa.*

L'interpretazione dei cosidetti « stati di energia negativa » pro-

1939 — Furry

Putting the pieces together

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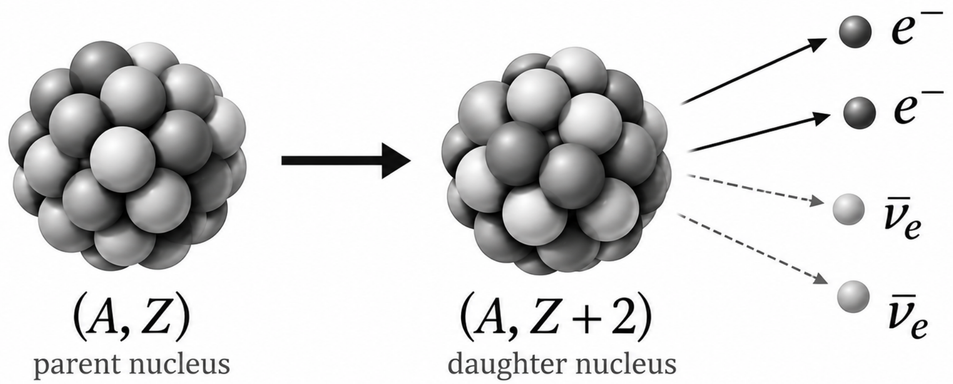

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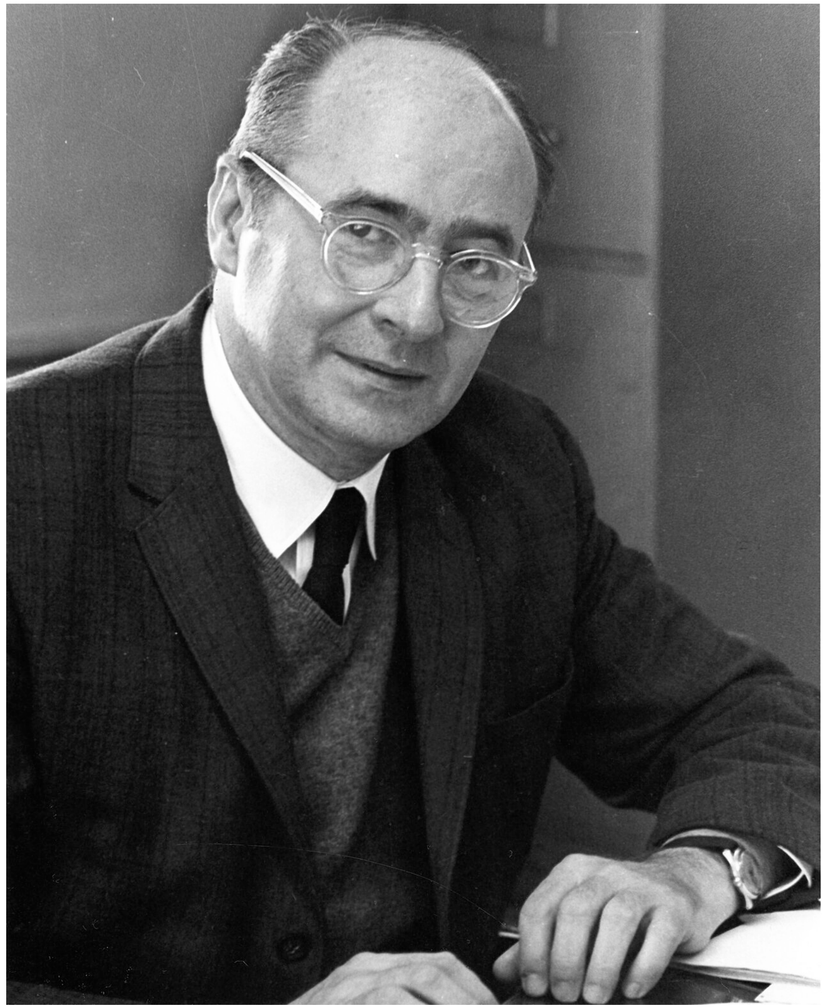

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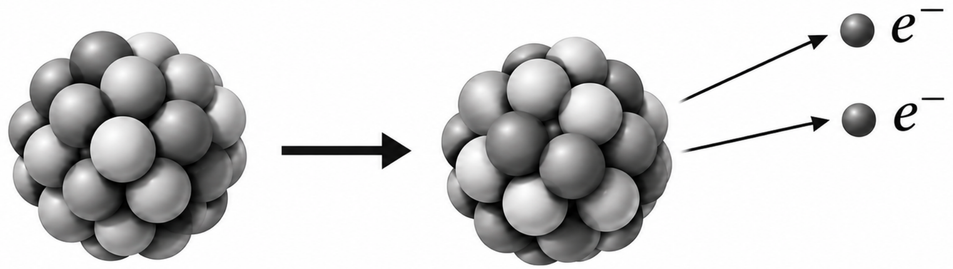

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DECEMBER 15, 1939 PHYSICAL REVIEW VOLUME 56

On Transition Probabilities in Double Beta-Disintegration

W. H. FURRY
Physics Research Laboratory, Harvard University, Cambridge, Massachusetts

(Received October 16, 1939)

The phenomenon of double β-disintegration is one for which there is a marked difference between the results of Majorana's symmetrical theory of the neutrino and those of the original Dirac-Fermi theory. In the older theory double β-disintegration involves the emission of four particles, two electrons (or positrons) and two antineutrinos (or neutrinos), and the probability of disintegration is extremely small. In the Majorana theory only two particles—the electrons or positrons—have to be emitted, and the transition probability is much larger. Approximate values of this probability are calculated on the Majorana theory for the various Fermi and Konopinski-Uhlenbeck expressions for the interaction energy. The selection rules

1950 - 1987 — From evidence to observation

25. Further Results on the Double Beta Decay of Te^{130}

By Richard J. Hayden and Mark G. Inghram [1]

One of the few instances where the difference between the Majorana and the Dirac theories of the neutrino predicts different conceivably measurable effects is the case of the simultaneous emission of two beta particles. The reactions involved in the two cases are:

$$Z \rightarrow (Z+2) + 2\beta(\text{Majorana})$$

$$Z \rightarrow (Z+2) + 2\beta + 2n_0(\text{Dirac})$$

The half-life, according to the Dirac theory, is much longer than that predicted by the Majorana theory. Fireman [2] has, by means of coincidence counting detected activity in tin which he ascribed to double beta decay of Sn^{124}. He assigned a half-life of 4 to 9×10^{15} yr, a result in rough agreement with the Majorana theory. Later counting results indicate that his activity probably came from another source. Inghram and Reynolds [3,4] measured the Te^{130} double beta half-life by extracting Xe from an old tellurium mineral and measuring the isotopic composition of the Xe with a mass spectrometer. Knowing the amount of Xe^{130} extracted, the amount of Te^{130} in the sample, and the geological age of the sample, the double beta half-life may be computed. Inghram and Reynolds (table 1) found excess Xe^{130} (after normal had been subtracted by means of Xe^{132} peak) which gave Te^{130} a half-life of 1.4×10^{21} yr. For allowed transitions with 1.6 Mev available energy, the Majorana theory predicts a half-life of 6×10^{14} yr, and the Dirac theory a half-life of 10^{24} yr. Combining the theories would allow any intermediate half-life to be predicted.

One difficulty with the Inghram-Reynolds experiment was that in addition to the excess Te^{130} large quantities of excess Xe^{129} and Xe^{131} (10 to 20 times the amount of Xe^{130}) were found. They explained these isotopes as being due to neutron absorption in tellurium (the particular ore used was taken from the neighborhood of uranium

TABLE 1. *Xenon extracted from 70-percent* Bi_2Te_3 *deep mineral*

Mass	Bi_2Te (#4)	Normal	Difference	Difference normalized
124	<0.004	0.0005	<0.0035	<0.29
126	<.005	.0005	<.0045	<.38
128	<.014	.011	<.003	<.25
129	≡1.000	.1525	.8475	71.99±0.7
130	.0652	.0236	.0416	3.48± .17
131	.4088	.1235	.2853	23.90± .3
132	.1566	≡.1566	≡.0000	≡.00
134	.0651	.0611	.0040	.33± .25
136	.0562	.0519	.0043	.36± .16

2.6×10^{-7} STP Xe

[1] Argonne National Laboratory, Chicago, Ill.
[2] E. L. Fireman, Phys. Rev. **75**, 323 (1949).
[3] M. G. Inghram & John H. Reynolds, Phys. Rev. **76**, 1265 (1949).
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Geochemical evidence — ^{130}Te

Ancient mineral as an integrating detector

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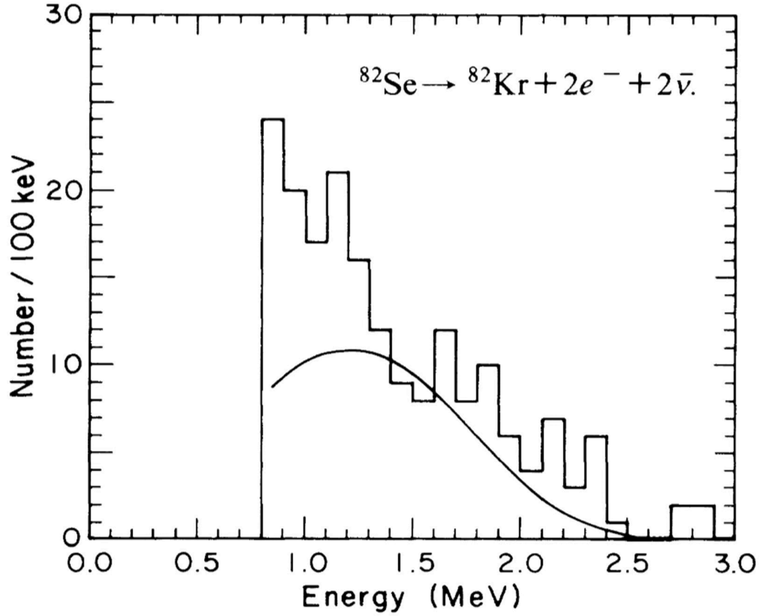


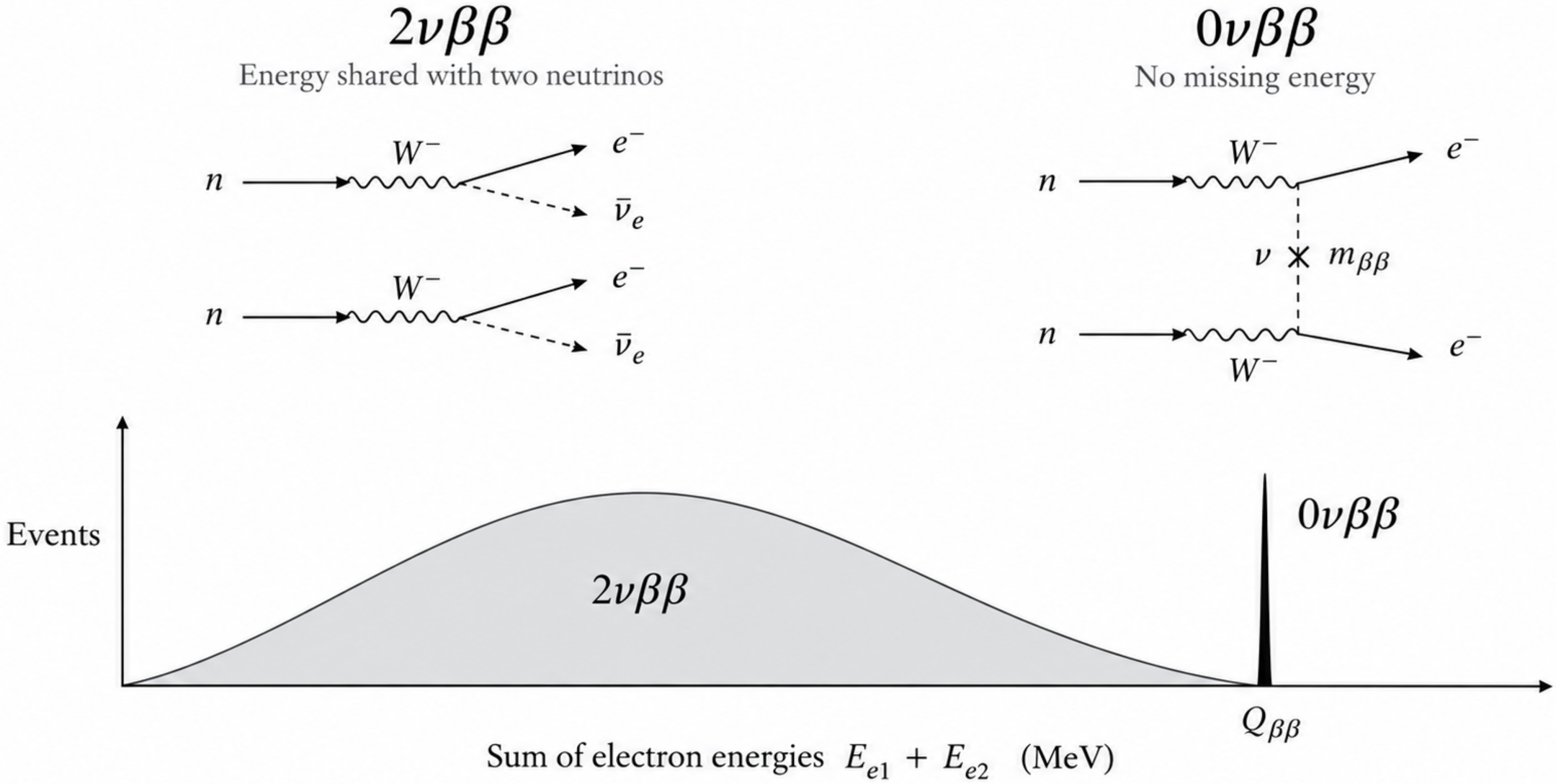
1987

First direct observation — ^{82}Se

Two-electron events observed in a TPC

$T^{2\nu}_{1/2} \sim 10^{20}$ yr

What would we observe?



Searching for $o\nu\beta\beta$

For nearly 90 years the question has remained the same

Searching for $0\nu\beta\beta$

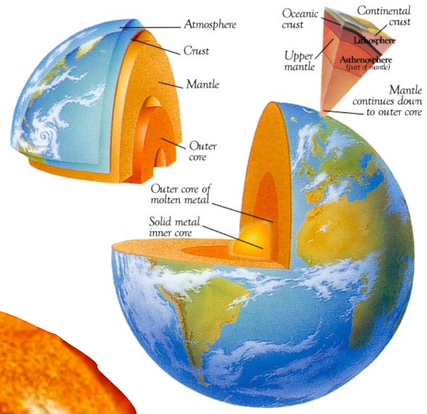
For nearly 90 years the question has remained the same

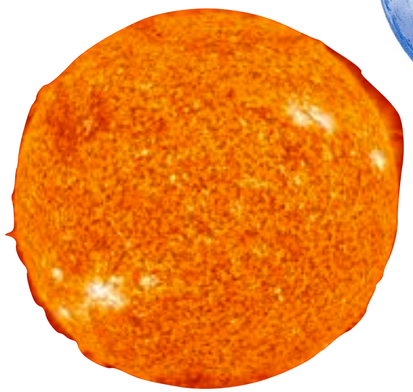
What has changed is our ability to answer it

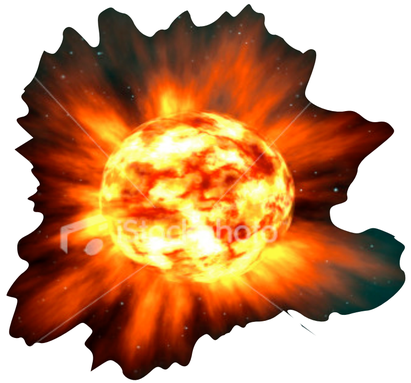
Why ονββ?

Neutrinos for fundamental science

Unique probe of otherwise unreachable regions

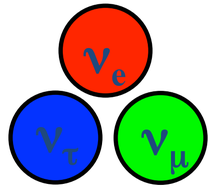


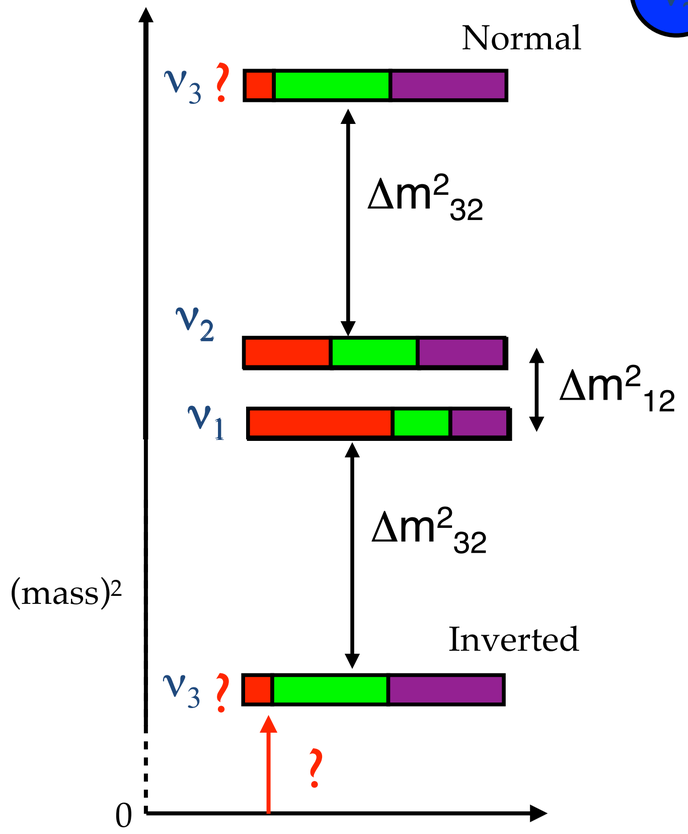




ν

Fascinating particle in its own right





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The only (known) fundamental fermion with the potential to be its own antiparticle

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Do neutrinos and anti-neutrinos behave in the same way?

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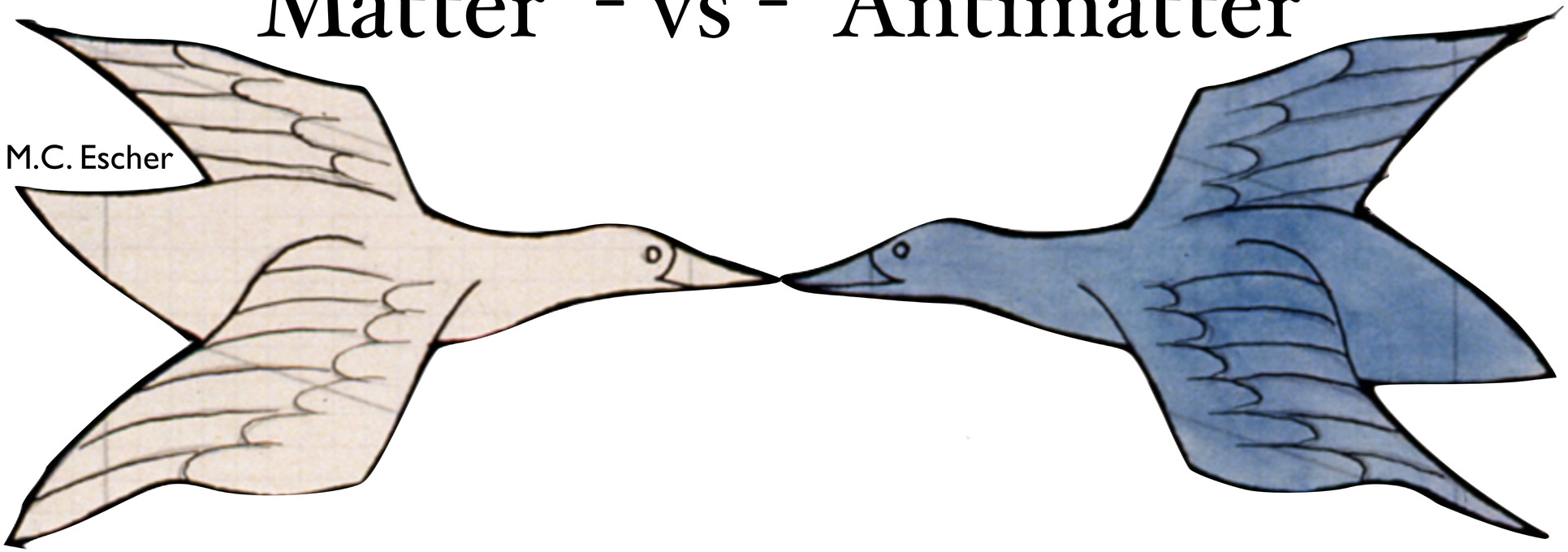
Aside

Escher travelled and sketched in Sicily in the 1930s — including Segesta, 1932

Matter - vs - Antimatter



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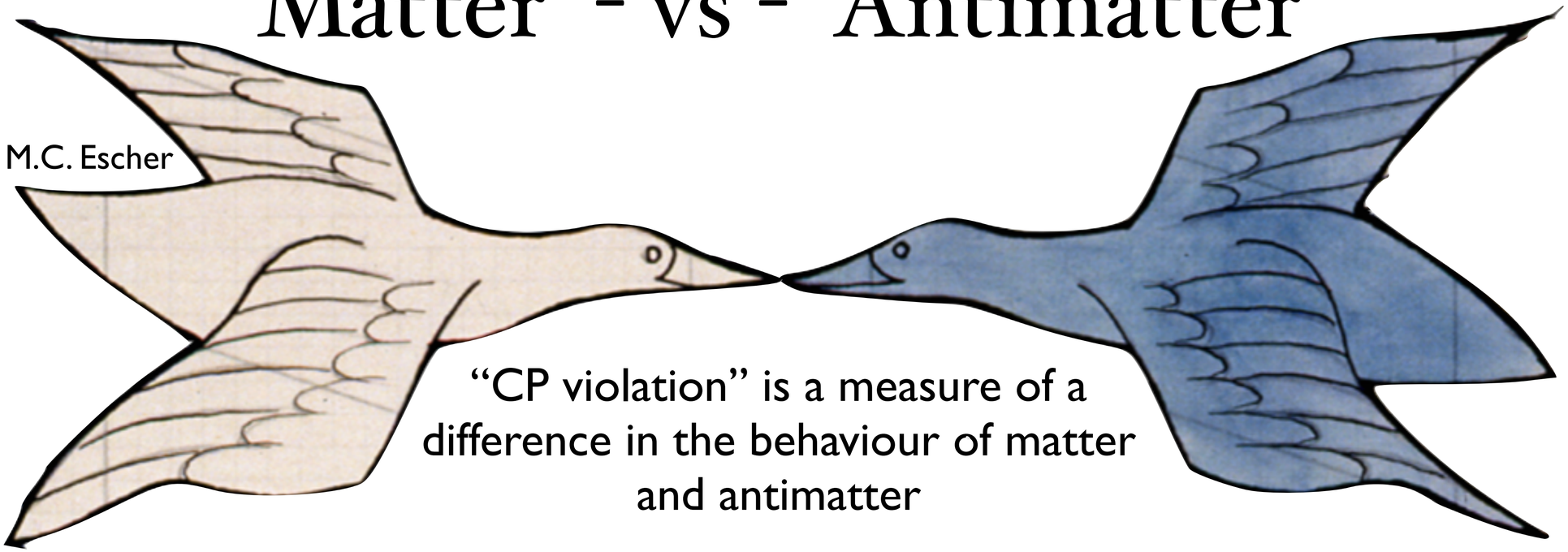

"CP violation" is a measure of a difference in the behaviour of matter and antimatter

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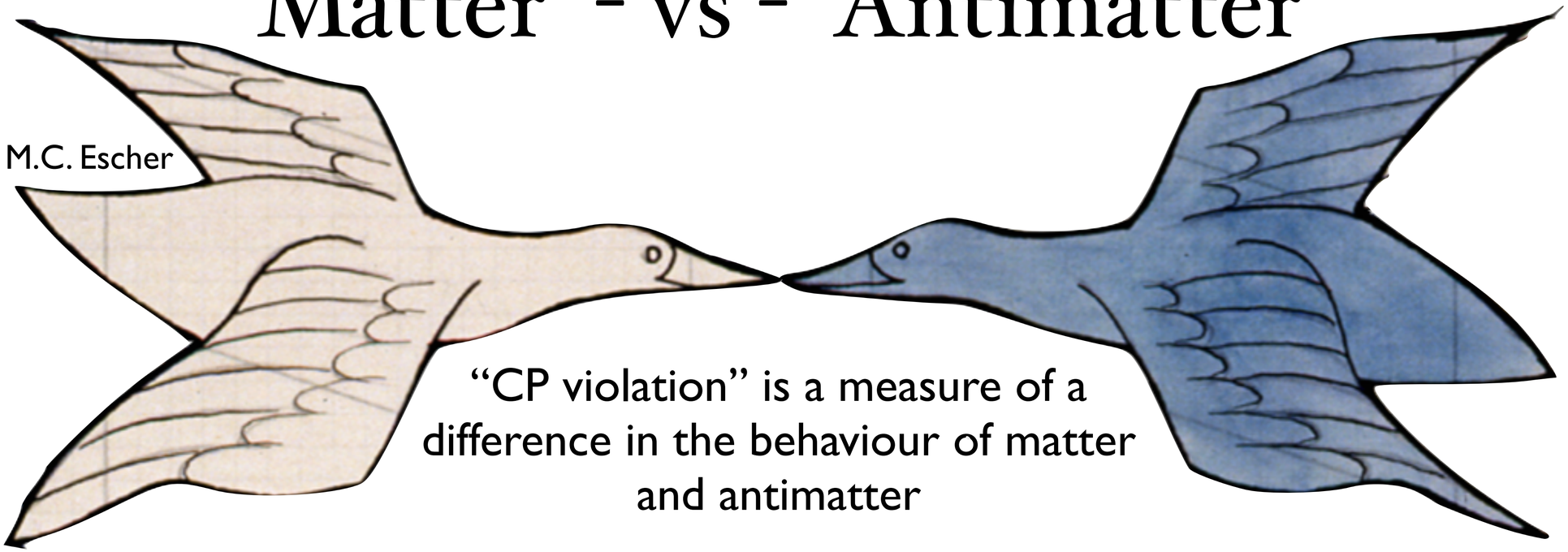

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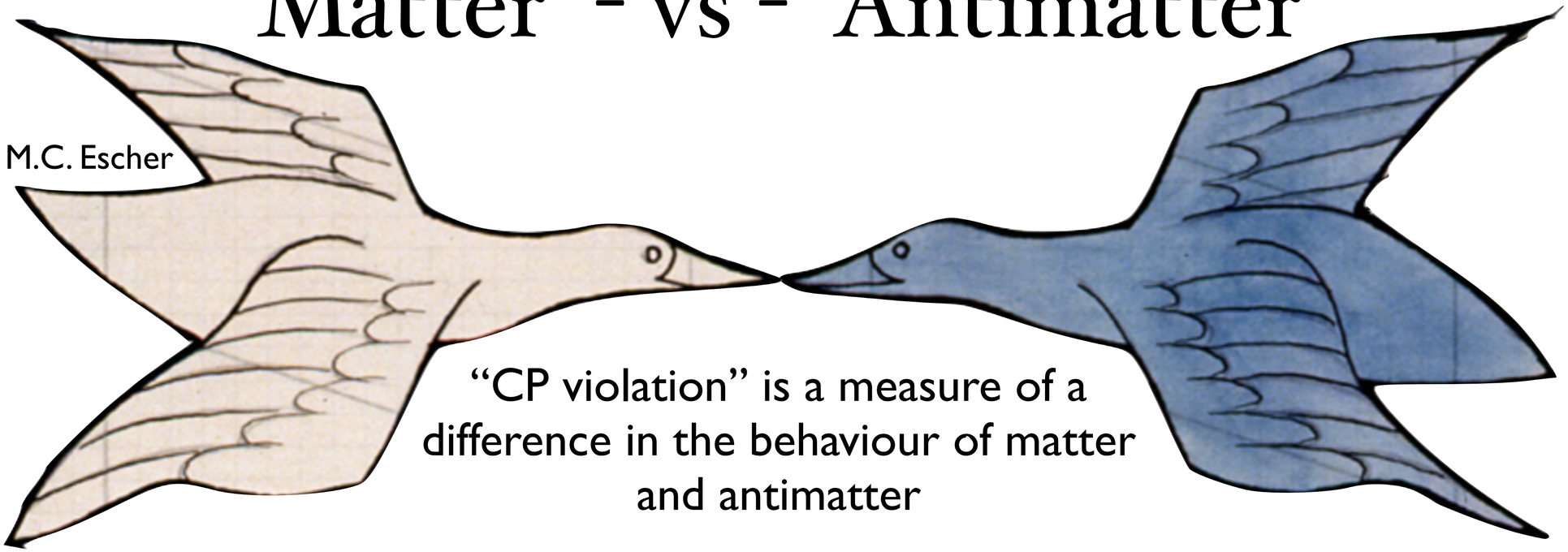

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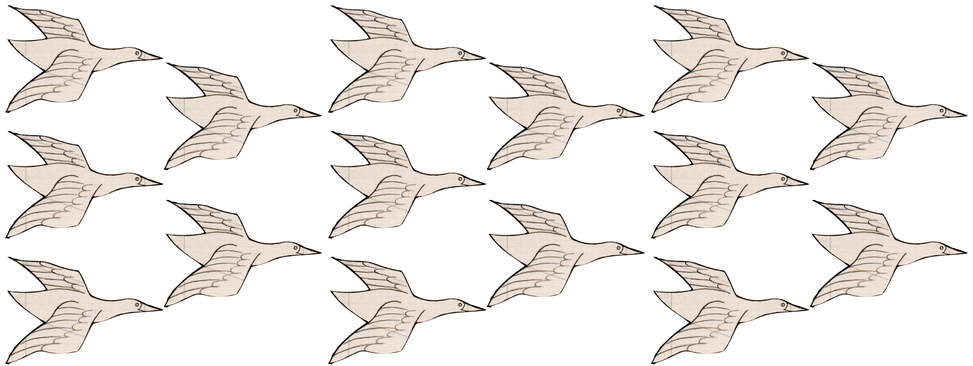

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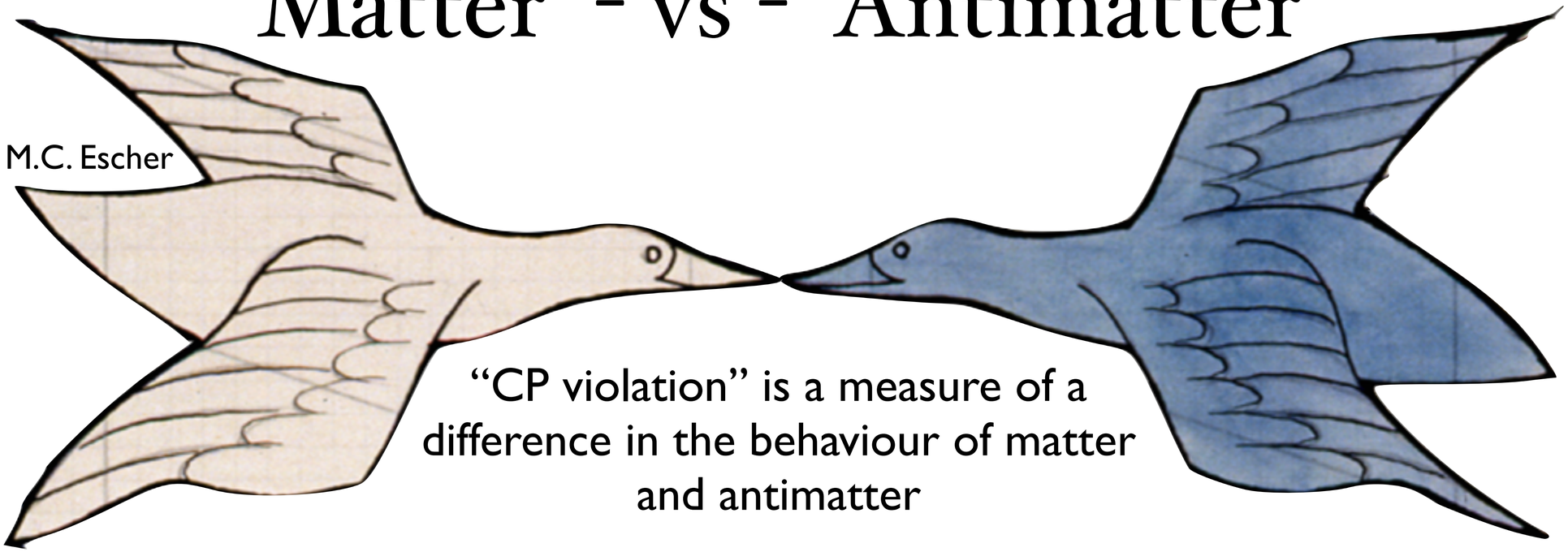

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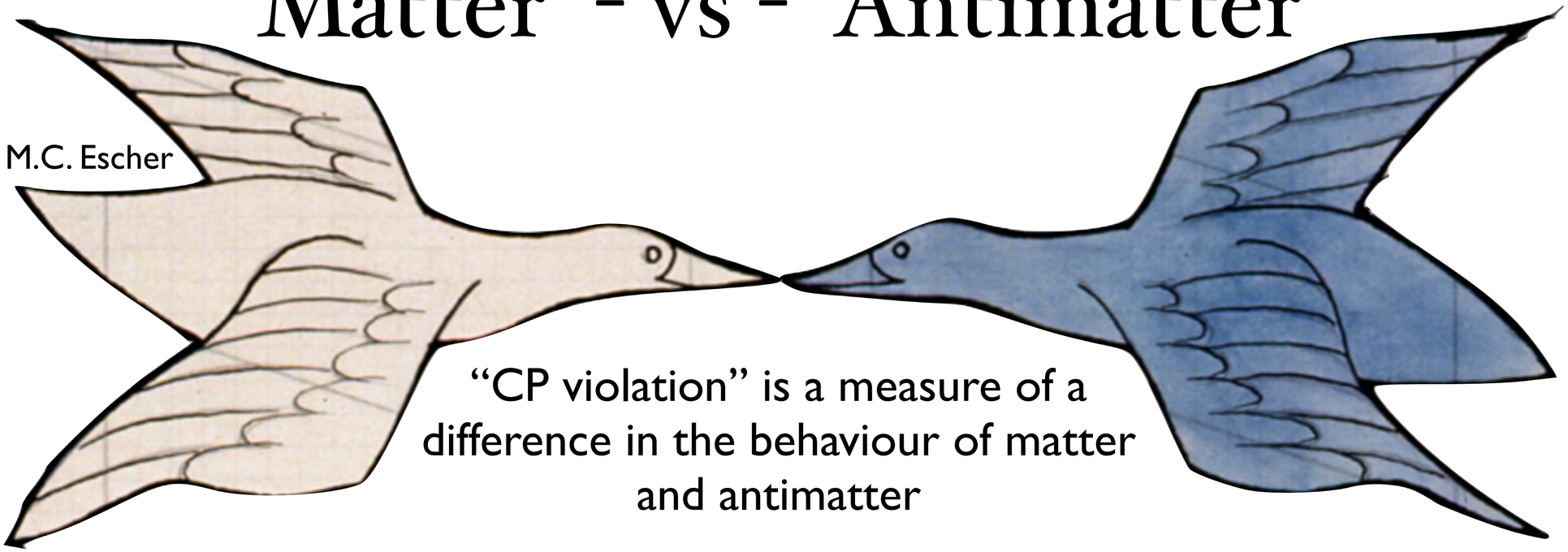

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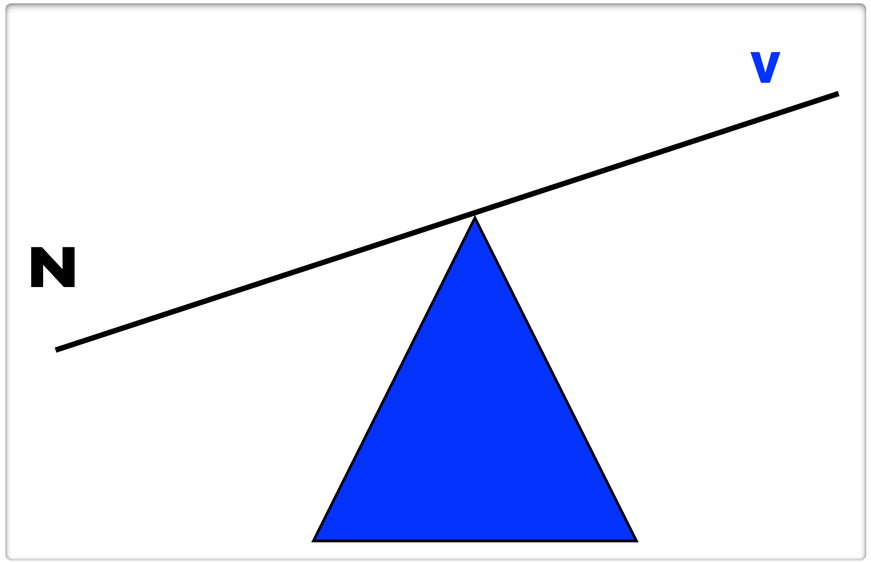
Matter & antimatter annihilate!

Majorana Neutrinos

M.C. Escher

Can have heavy partners

A big Majorana mass splits the Dirac neutrino into two neutrinos: the light neutrino **ν** and a heavy neutrino **N**



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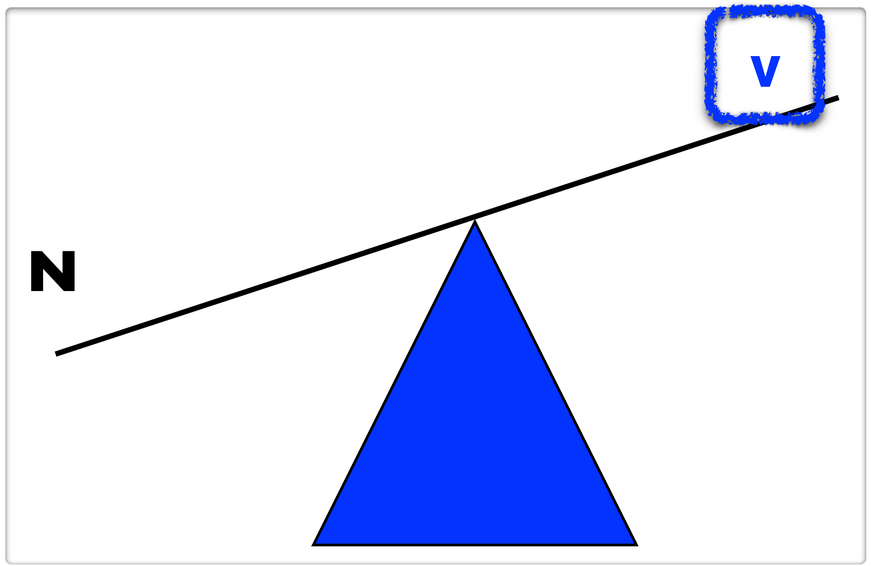

Our familiar light ν, made and detected in terrestrial experiments

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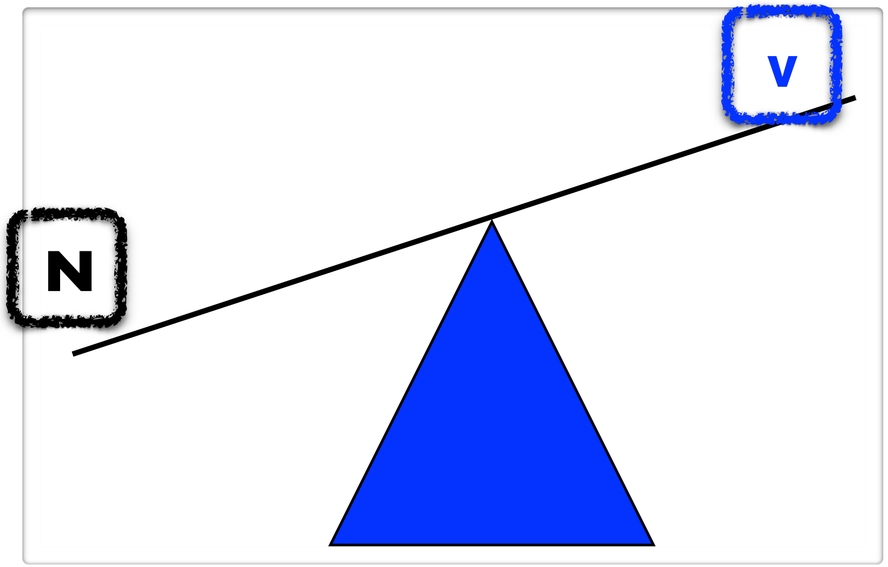

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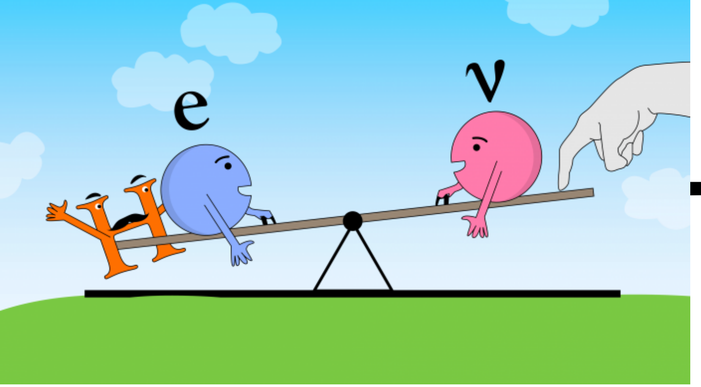
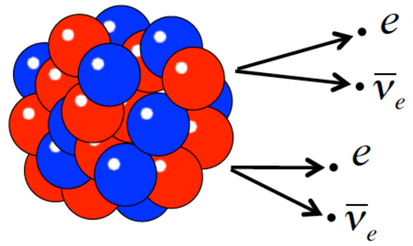
Made in the Big Bang (high energy scale) CP violation + lepton number violation in their decay could translate into current asymmetry



0ν double beta decay

$2\nu\beta\beta$



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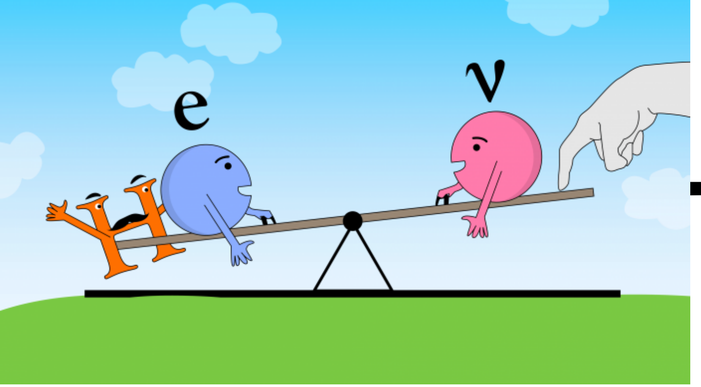

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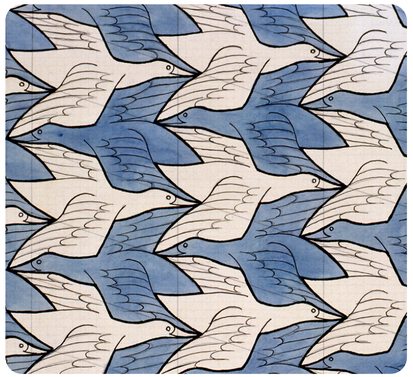

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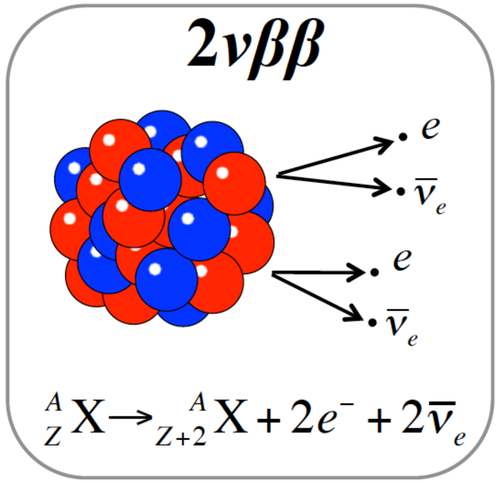

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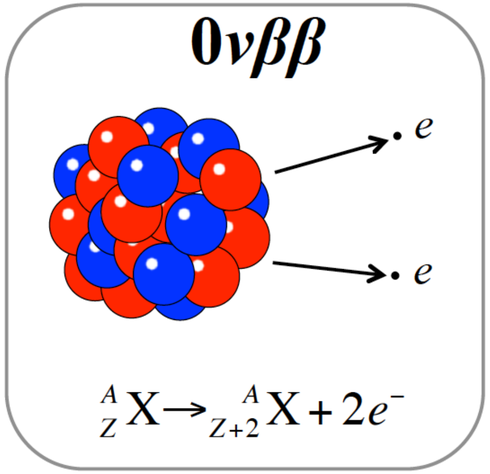
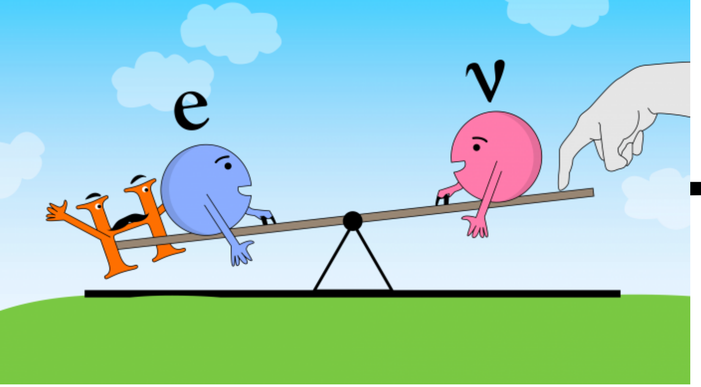


$\tau \geq 10^{26}$ y



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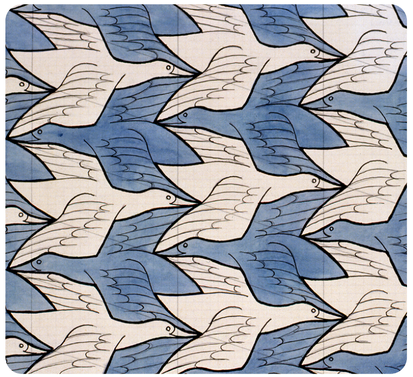

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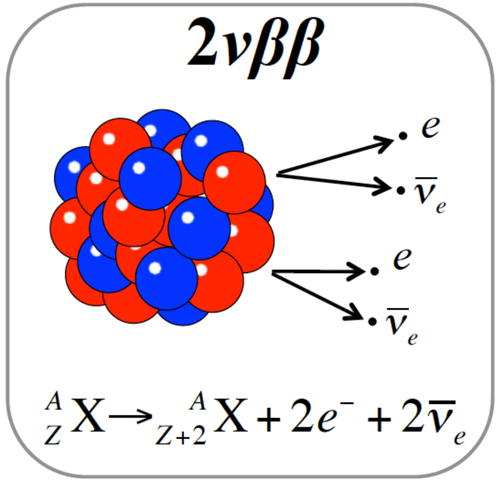

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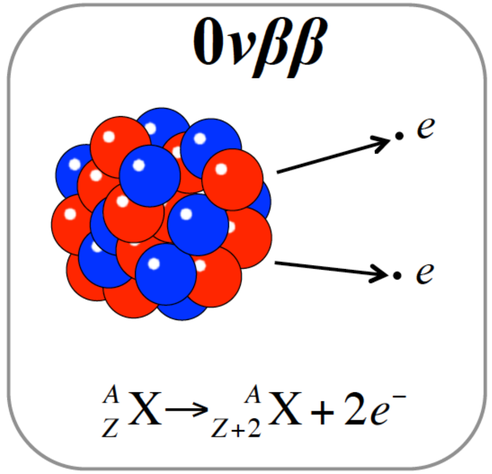

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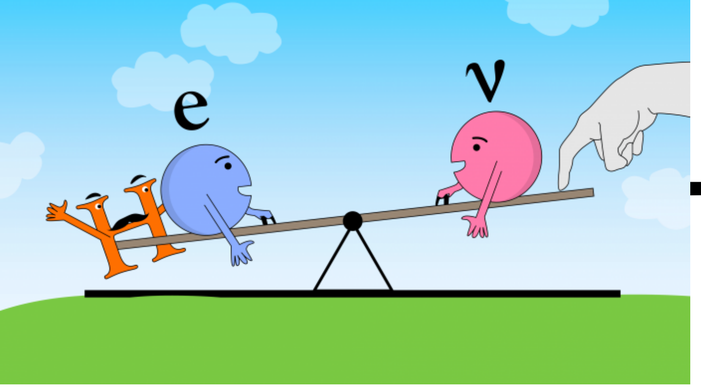
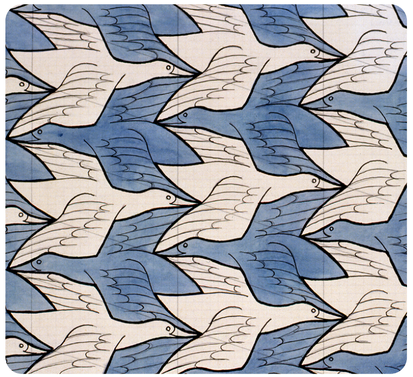
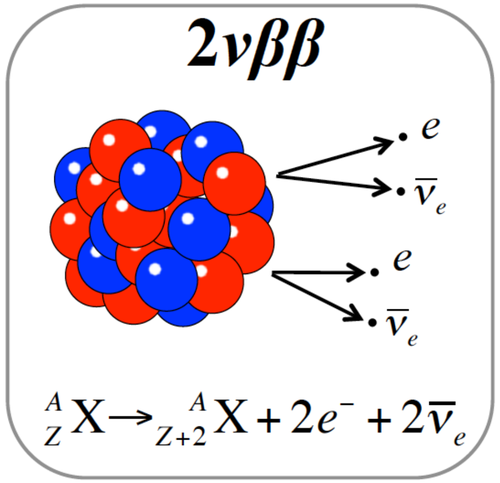
Fortunately, N_A is very large!



M.C. Escher



0ν double beta decay



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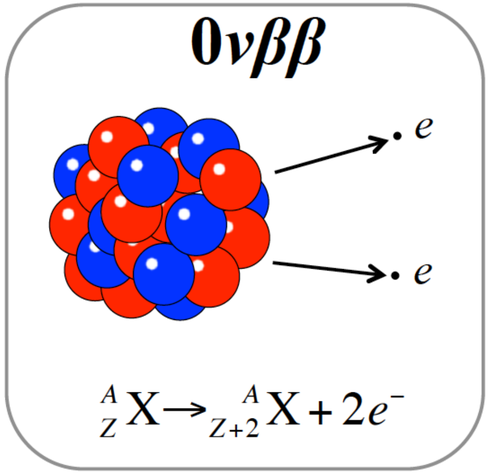

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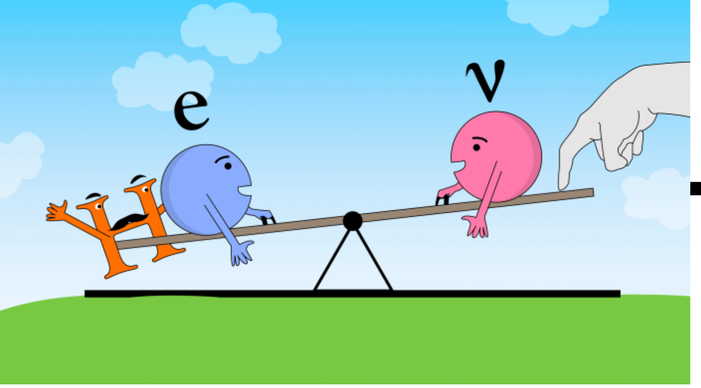

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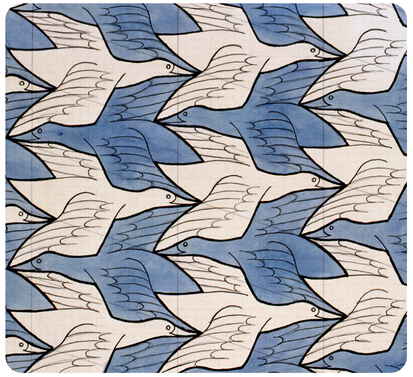

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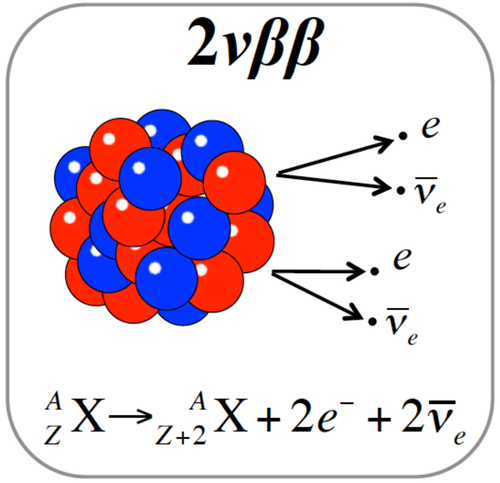

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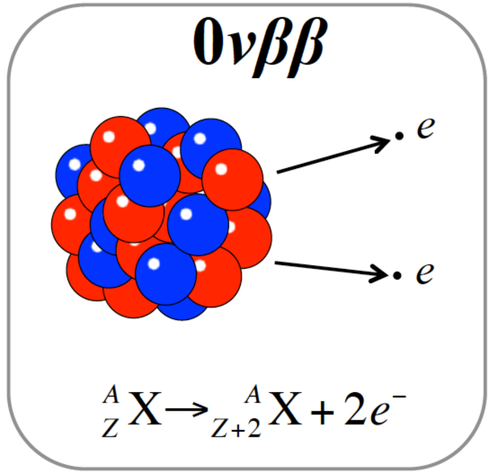

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The plan reaffirms the exceptionally high priority of two investments in new capabilities:

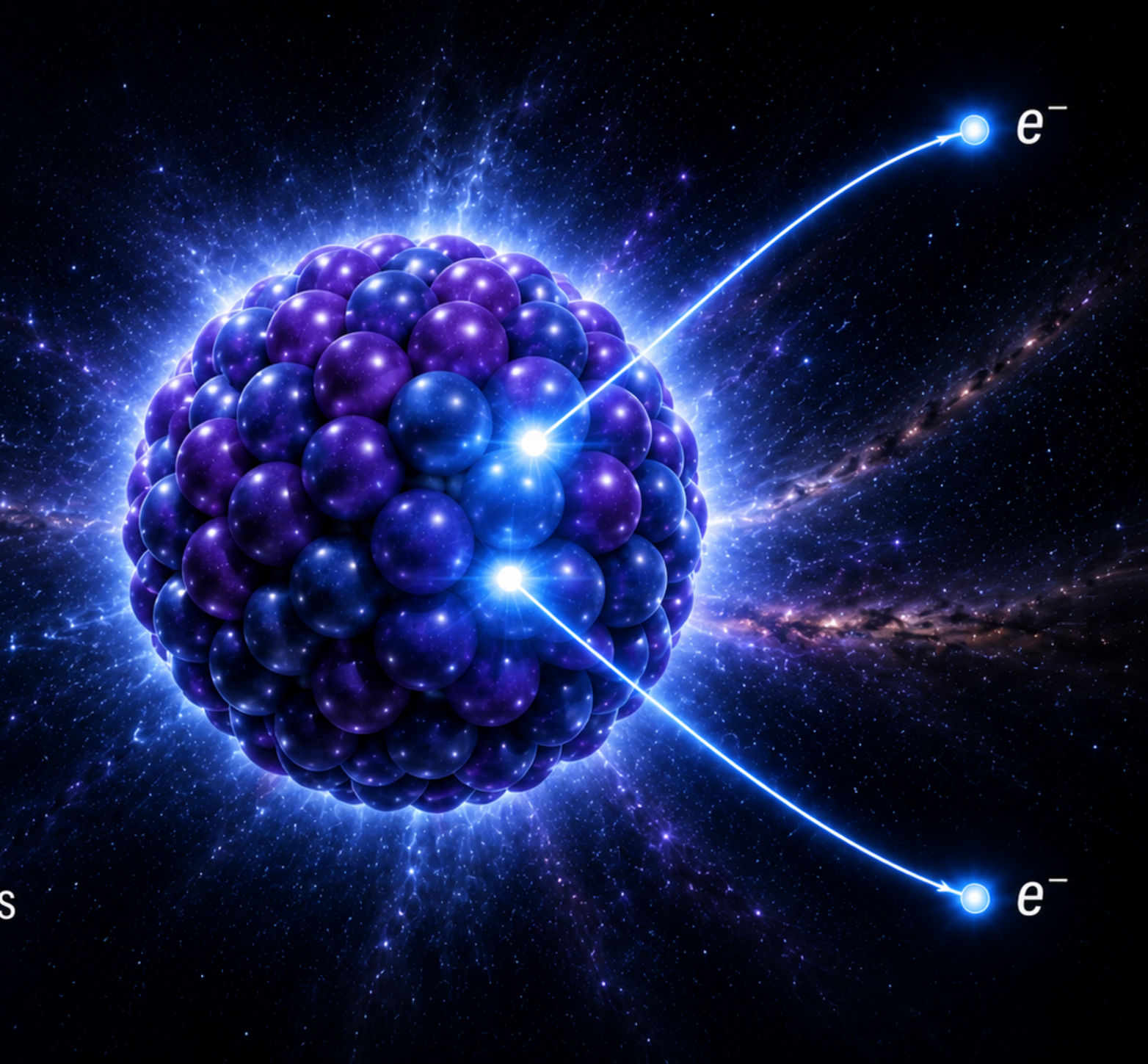
- **Support New Experiment Construction (Recommendation 2):** A campaign including expeditious construction of ton-scale neutrinoless double beta decay experiments using different isotopes and complementary techniques is the highest priority for new experiment construction. These experiments have the potential to dramatically change our understanding of the physical laws governing the universe.

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.



Discovery potential

ονββ Decay Rate

$$\Gamma = \left(T_{1/2}\right)^{-1} = G^{0\nu} \left|M'^{0\nu}\right|^2 \left|\frac{m_{\beta\beta}}{m_e}\right|^2$$

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Phase space factor
Well defined

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Nuclear Matrix Element

Nuclear theory

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$$M'^{0\nu} = \left(\frac{g_A^{eff}}{g_A}\right)^2 M^{0\nu}$$

Phenomenological correction
Accounts for use of nuclear models
to estimate NME
Taken from single-β decay
Some controversy over value

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Neutrino Mass

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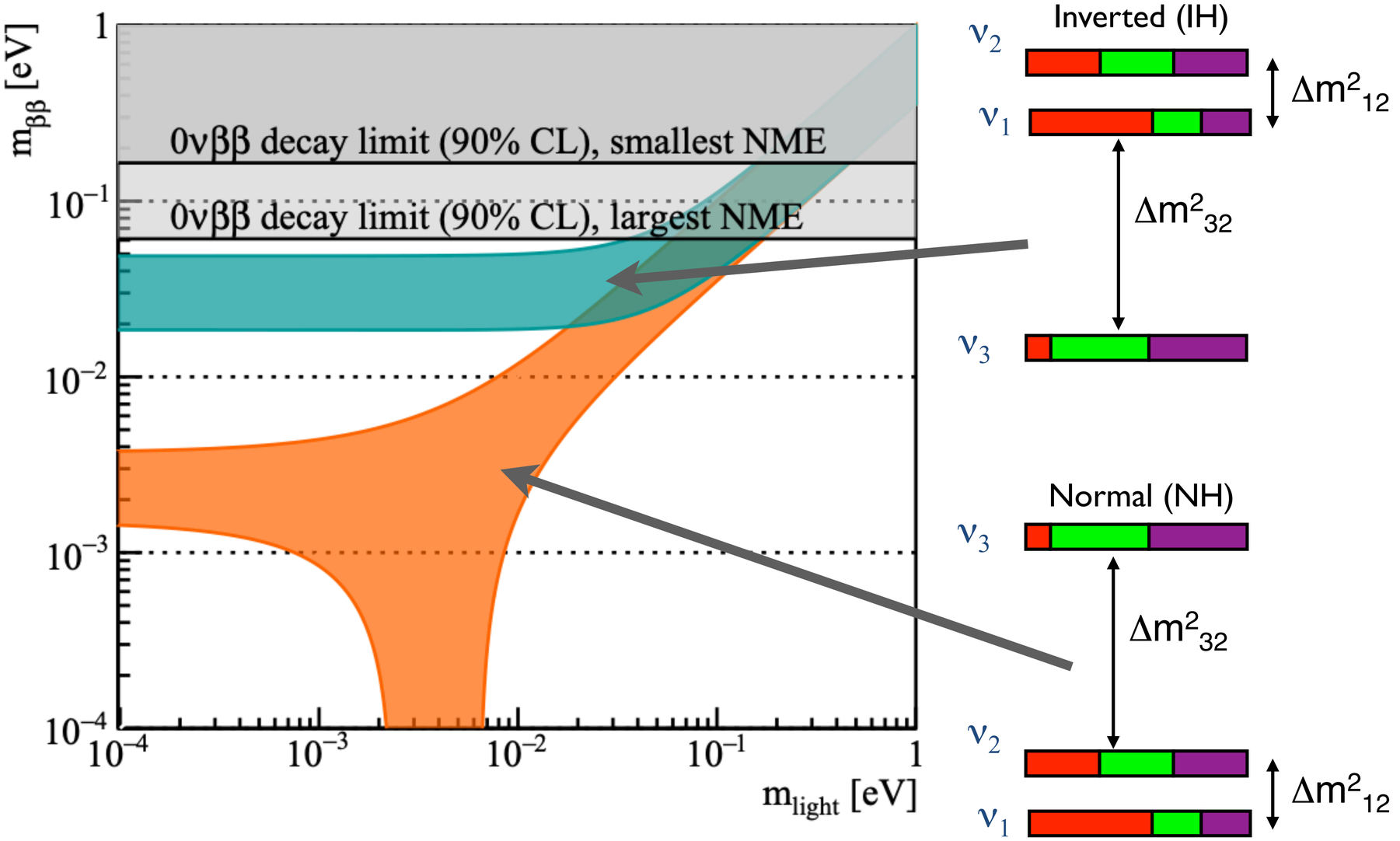
Probes absolute neutrino mass scale
Also sensitive to mass ordering

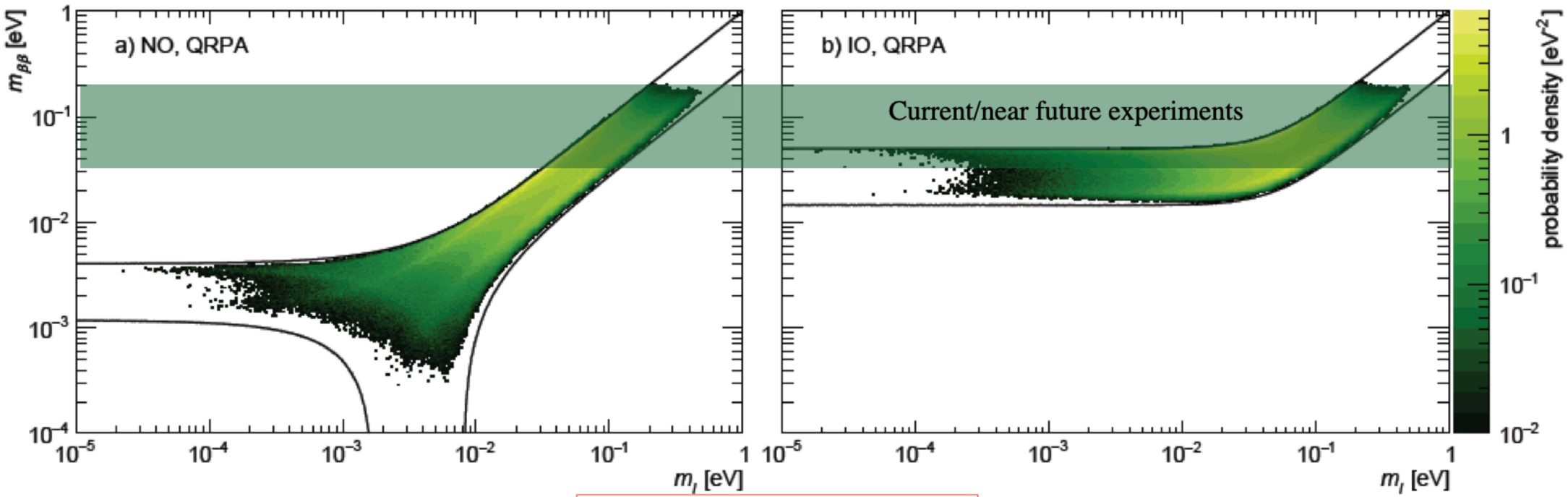
$$m_{\beta\beta} = \left|\sum_i m_i U_{ei}^2\right|$$

$$= \cos^2\theta_{12}\cos^2\theta_{13} e^{i\alpha} m_1 + \sin^2\theta_{12}\cos^2\theta_{13} e^{i\beta} m_2 + \sin^2\theta_{13} e^{-2i\delta} m_3$$

Phase space


$m_{\beta\beta}$ [eV]
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
$0\nu\beta\beta$ decay limit (90% CL), smallest NME
$0\nu\beta\beta$ decay limit (90% CL), largest NME
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
m_{light} [eV]
Inverted (IH)
ν_2
ν_1
Δm^2_{12}
Δm^2_{32}
ν_3
Normal (NH)
ν_3
Δm^2_{32}
ν_2
ν_1
Δm^2_{12}

Parameter space



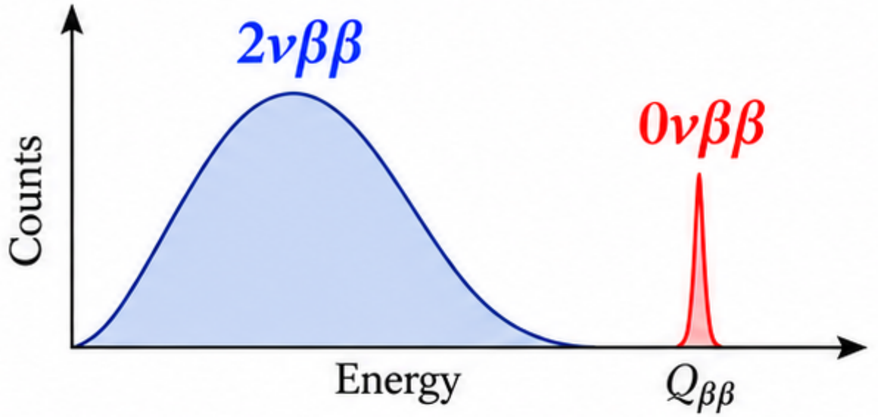
$$m_{\beta\beta} = |\sum_i m_i \cdot U_{ie}^2|$$

M. Agostini, G. Benato, J. Detwiler,
Phys. Rev. **D96**, 053001 (2017)

Note: this is under the simplest interpretation (of 3 light neutrinos).
Sterile neutrinos, or heavy new physics, could change the interpretation dramatically!

Why is this hard?

Because the process is extraordinarily rare



We are looking for a tiny peak on top of a much larger background.

Approximate $0\nu\beta\beta$ signal rate

events per tonne-year of ββ isotope

Half-life $T_{1/2}^{0\nu}$	Expected events / tonne-year
10^{26} years	~ 50
10^{27} years	~ 5
10^{28} years	~ 0.5

Order of magnitude; exact rate depends on isotope.

Probing 10^{27-28}-year half-lives demands tonne-scale exposures and ultra-low backgrounds.

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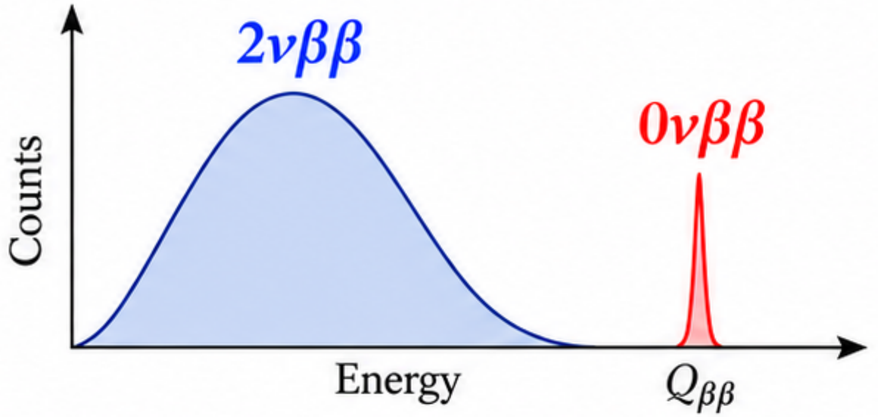

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Larger detectors
(mass × time)

More isotope
(enrichment, loading)

$$\left[T_{1/2}^{0\nu}\right] \propto \varepsilon \cdot I_{\text{abundance}} \cdot \sqrt{\frac{Mass \cdot Time}{Bkg \cdot \Delta E}}$$

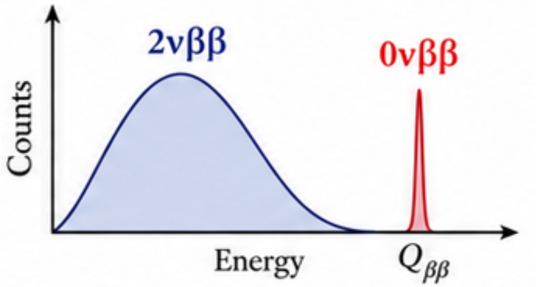
Lower backgrounds and better resolution
(smaller ΔE)

$$\left[T_{1/2}^{0\nu}\right] \propto \varepsilon \cdot I_{\text{abundance}} \cdot Mass \cdot Time$$

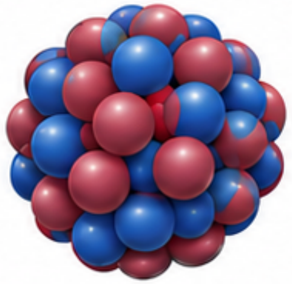
(background-free, next generation)

Probing 10^{27-28}-year half-lives demands tonne-scale exposures and ultra-low backgrounds.

Many approaches



Target Mass



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

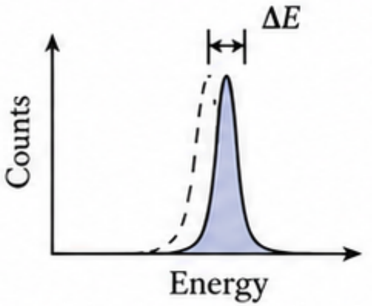
Enrichment, procurement, loading fraction, total mass.

Backgrounds

Can we suppress backgrounds to ultra-low levels?

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

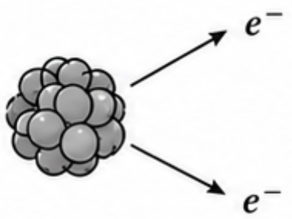
Energy Resolution



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.

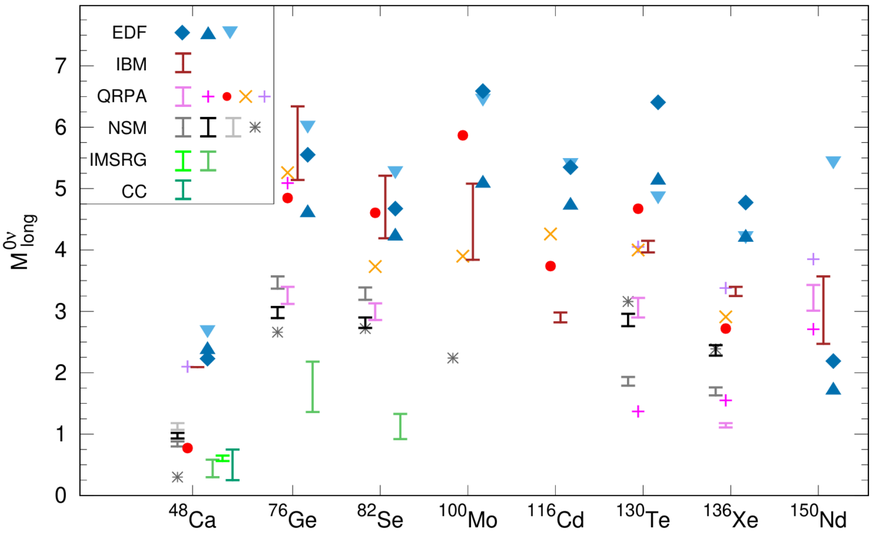
Nature has not yet provided us with the perfect detector.

Every experiment solves this puzzle differently.

Experimental approaches

The need for multiple isotopes

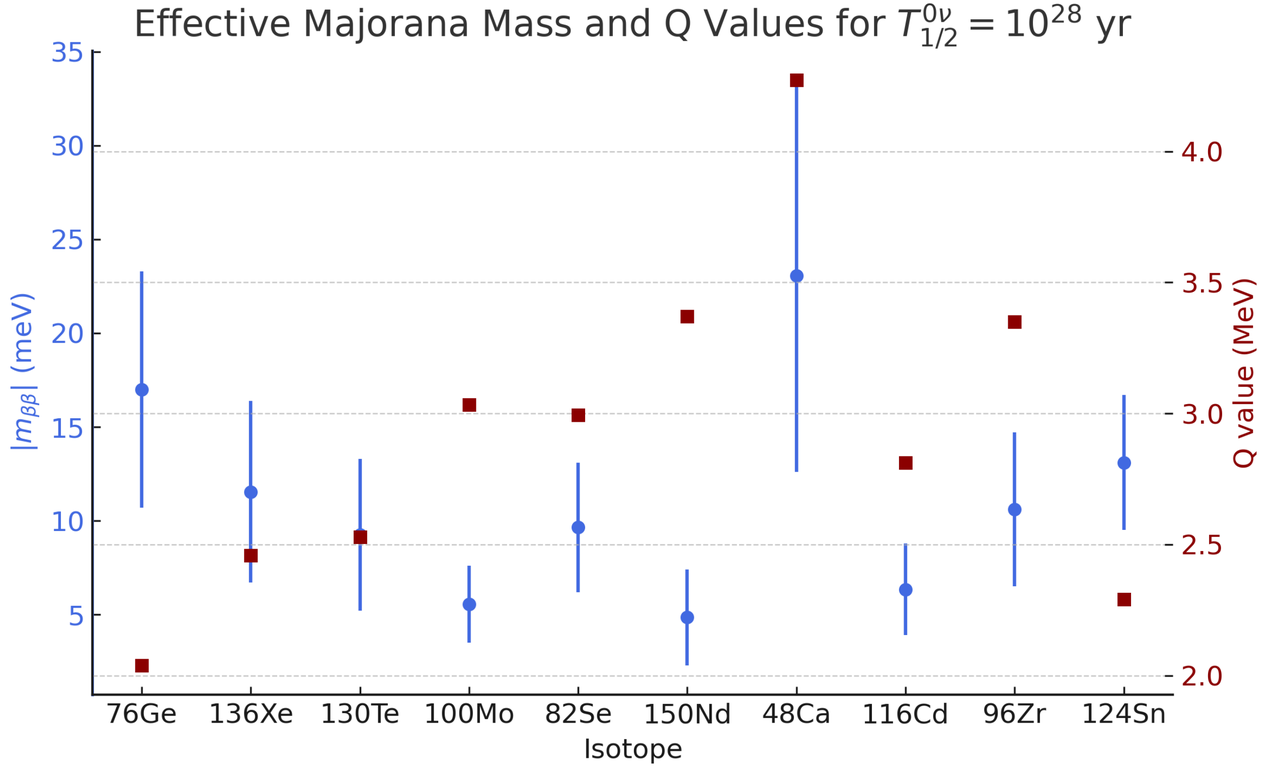
- Verification of observation given NME uncertainty



Nuclear matrix elements M0 for light-neutrino exchange from different many-body methods
M. Agostini et al, Rev. Mod. Phys. 95, 025002 (2023)

- Independent systematics
- Probe mechanism

- Different isotopes offer different mass reach for the same half life sensitivity
- Different isotopes have different backgrounds due to different Q values



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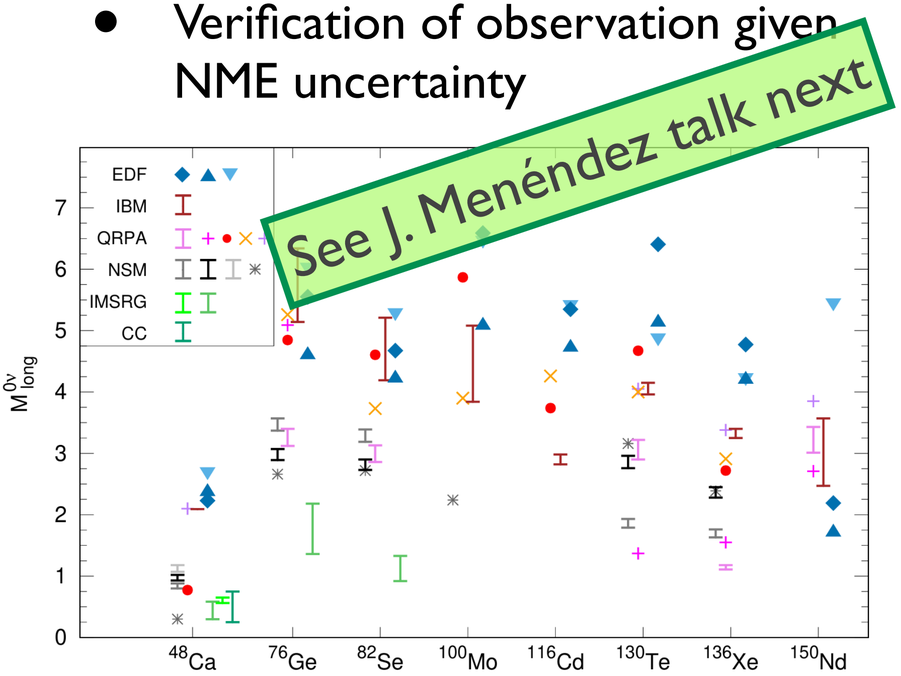

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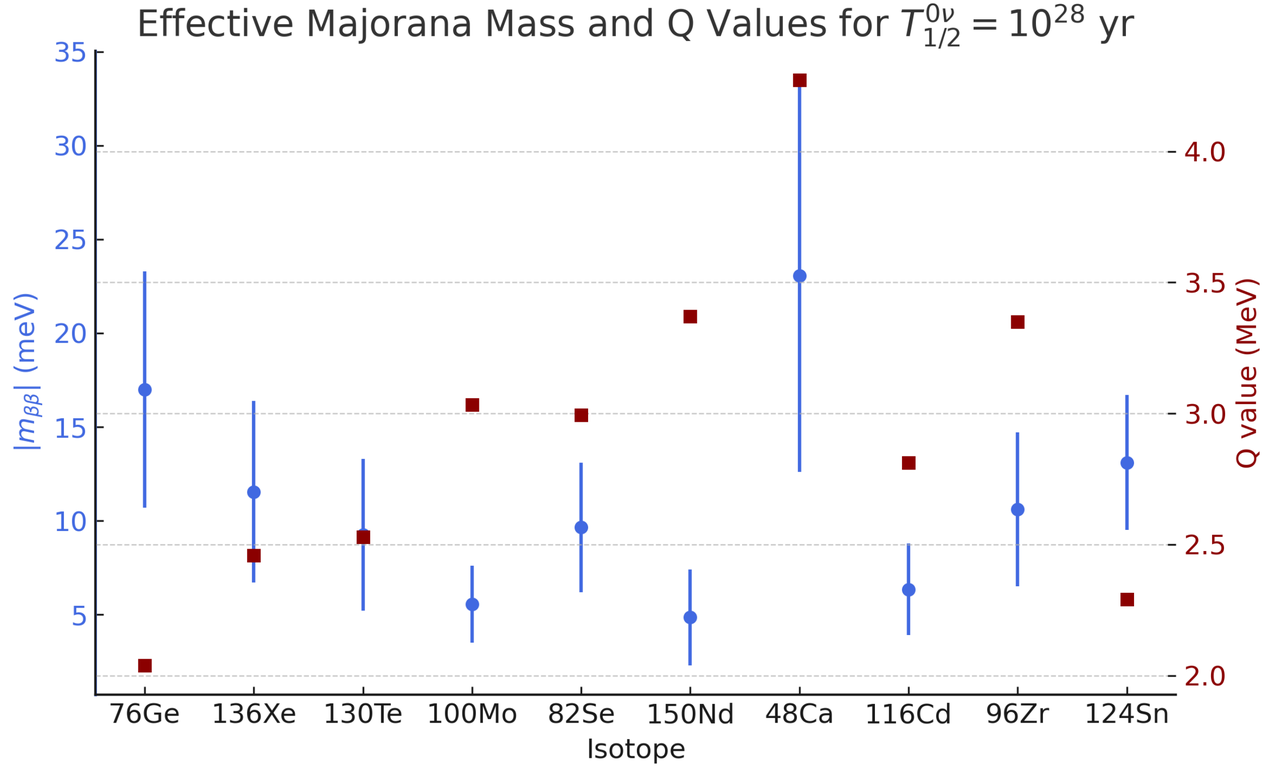
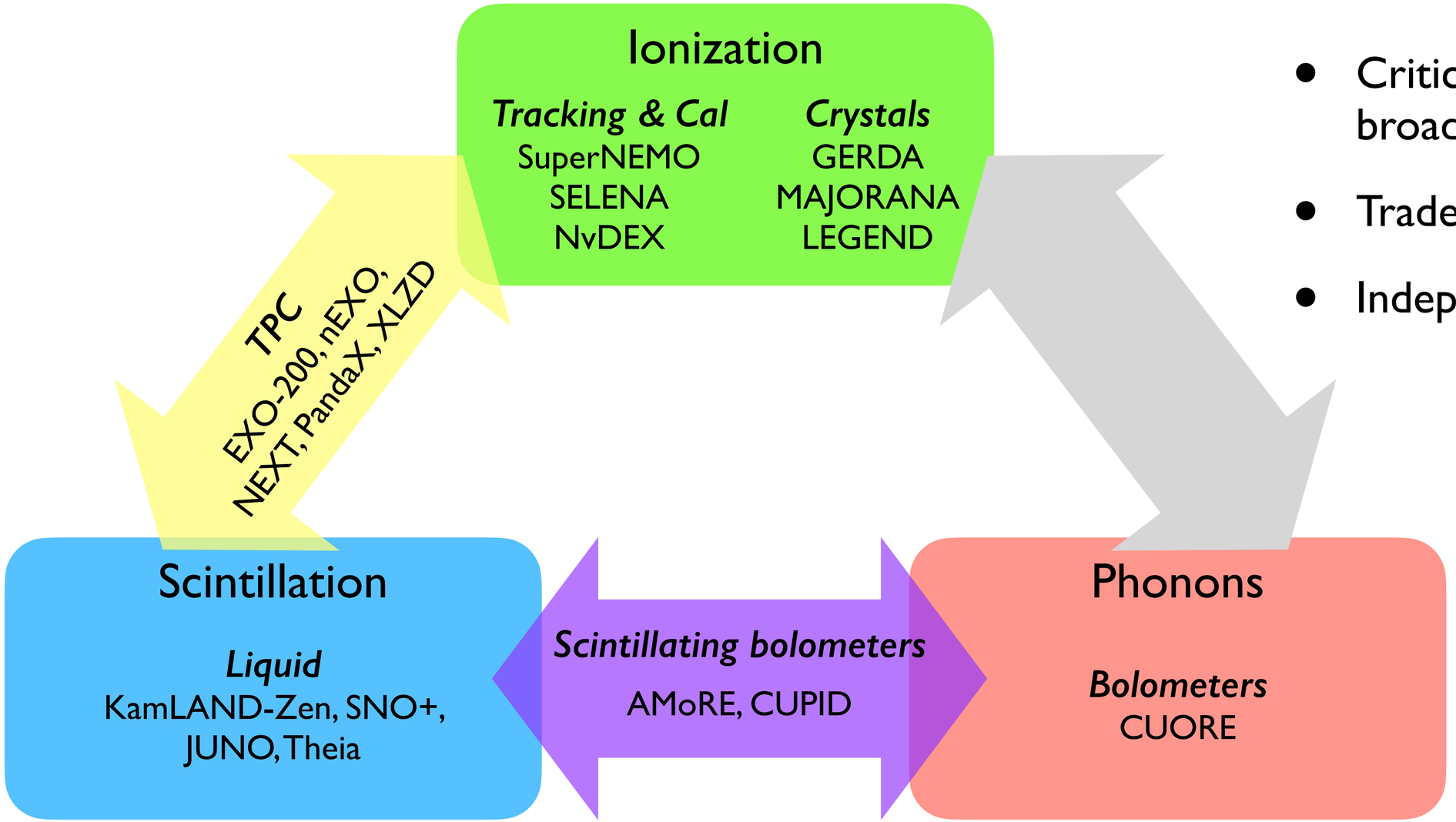


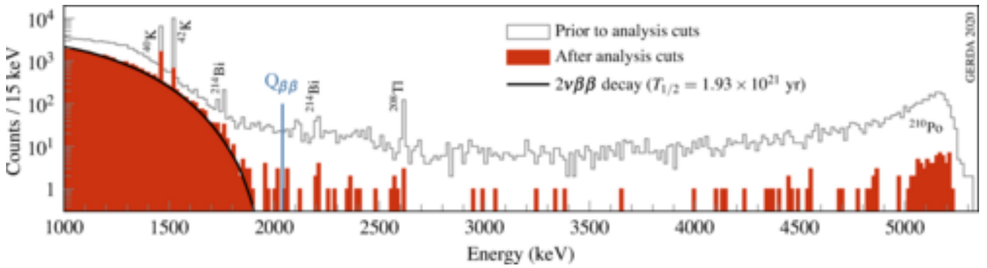
Diverse technology



- Critical to the field to have a broad range of technologies
- Trade offs in performance
- Independent systematics

Germanium: exquisite resolution

- **GERDA**
- LAr veto + radiopure construction → suppress background



Phys. Rev. Lett. **125**, 252502 (2020)

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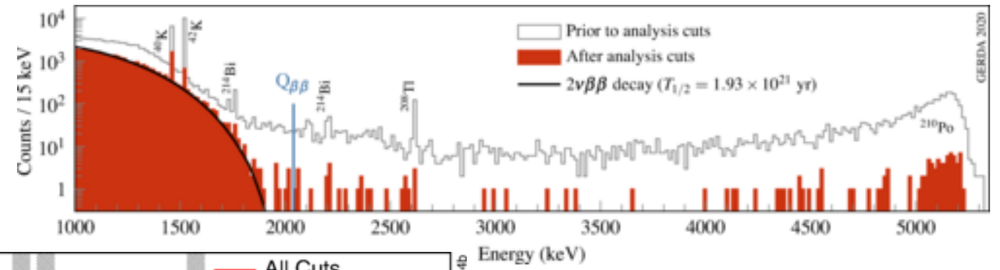
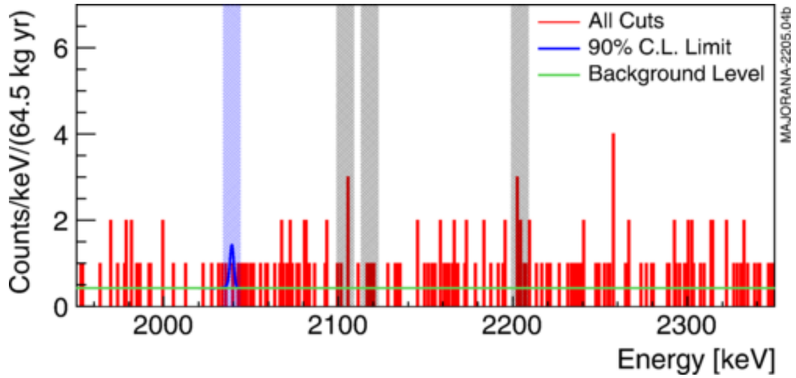


- **MAJORANA**
- Exceptional energy resolution → very narrow ROI

Phys. Rev. Lett. **130**, 062501 (2023)



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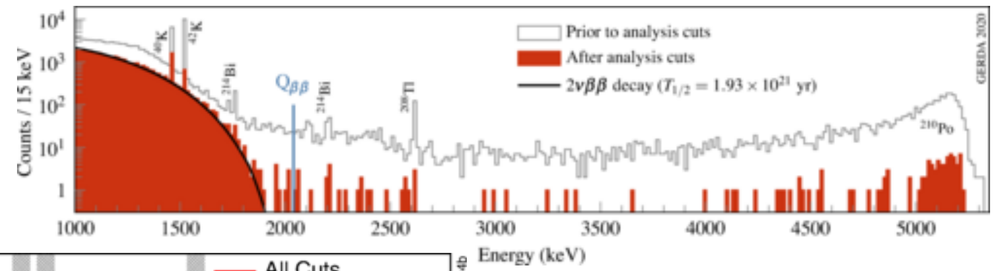

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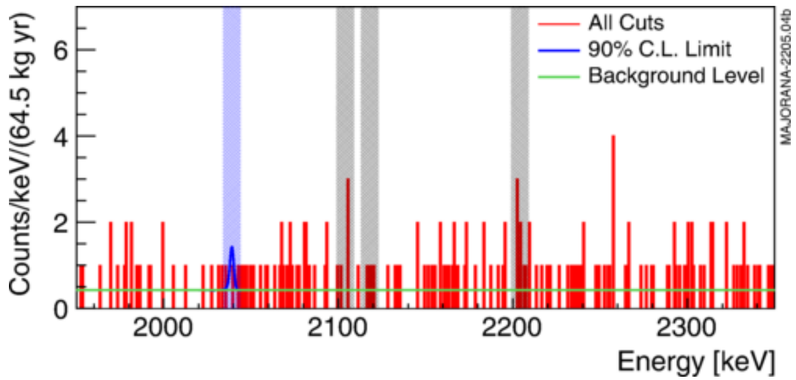
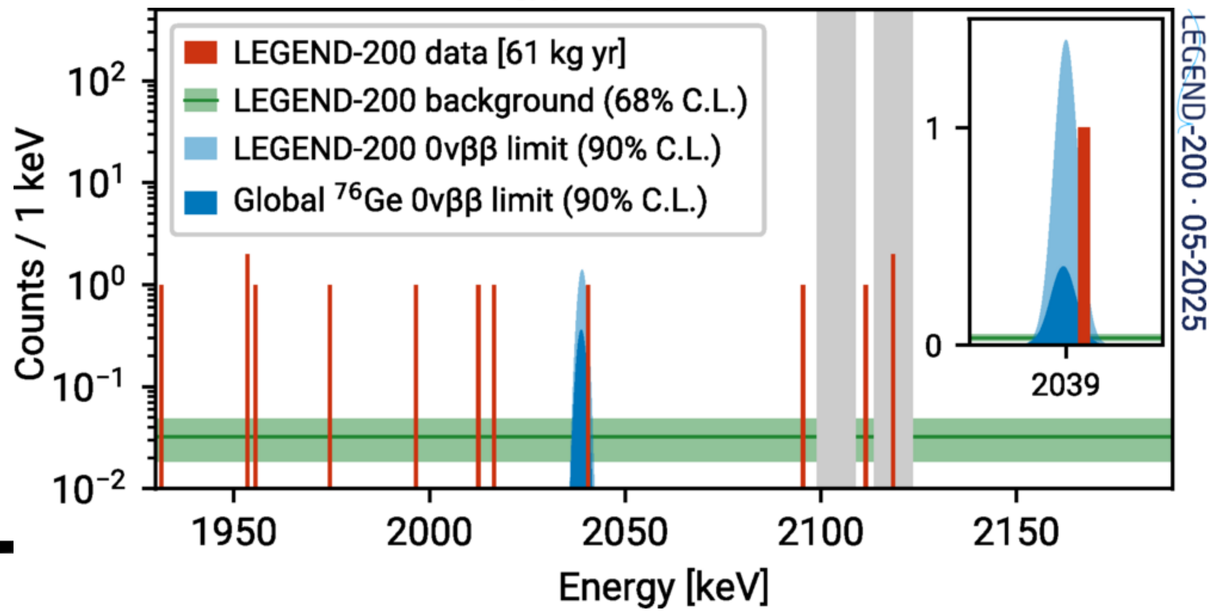


- **LEGEND-200**
- Combine both strategies
- Resolution + background rejection + increased isotope mass

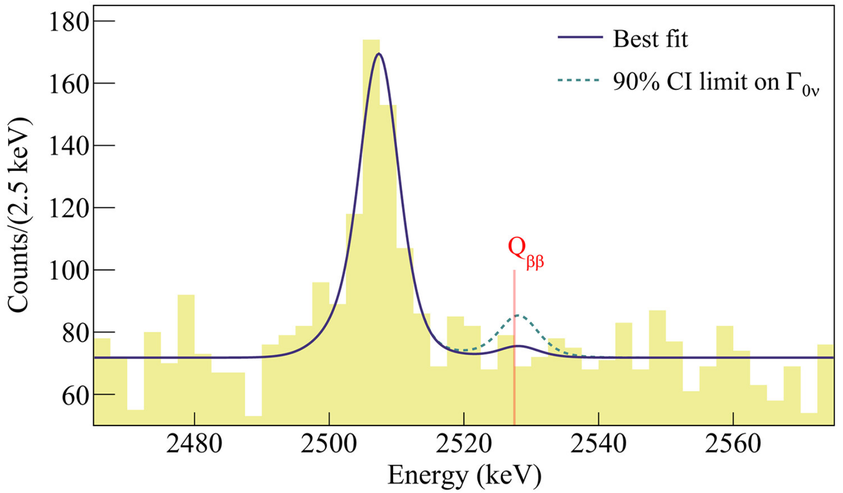
Phys. Rev. Lett. **136**, 022701 (2026)

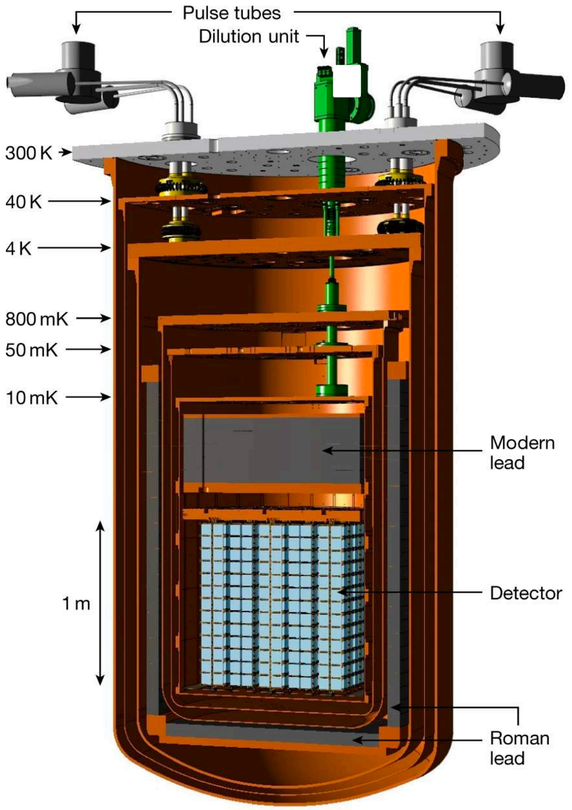


Bolometers: high resolution · low background

- **CUORE**
- Turn the isotope into the calorimeter
- Large ^{130}Te mass | excellent resolution
- Challenge: residual bkg in the ROI

SCIENCE Vol 390, Issue 6777 pp. 1029-1032 (2025)





Dell'Oro S. et al., Cryogenics 102, 9, (2019)
https://doi.org/10.1016/j.cryogenics.2019.06.011

Adams D. et al. (CUORE collaboration), Prog.Part.Nucl.Phys. 122 (2022) 103902,
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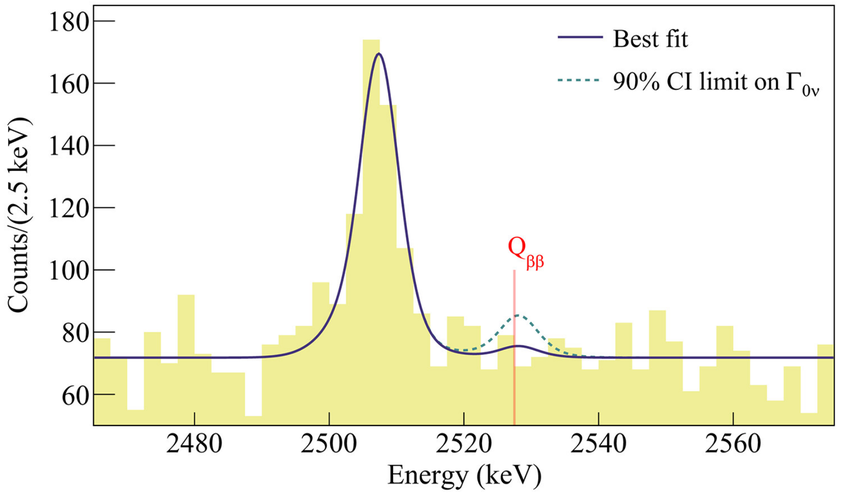

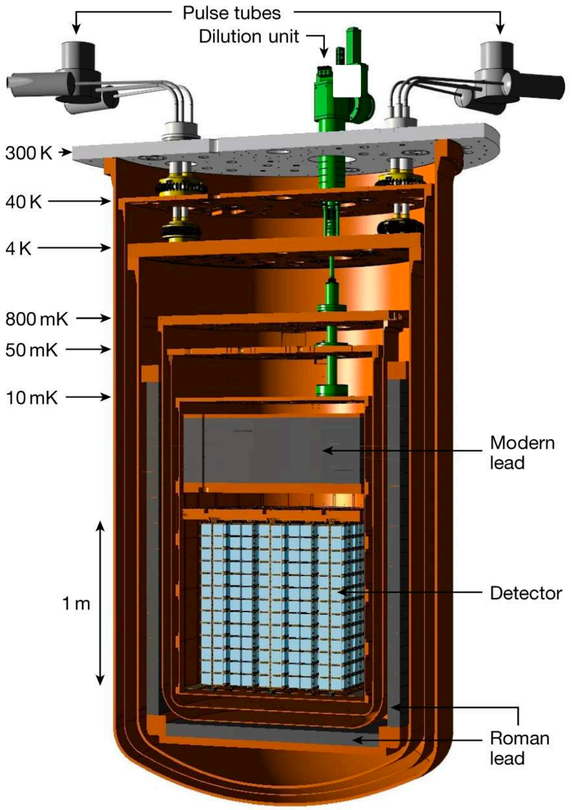

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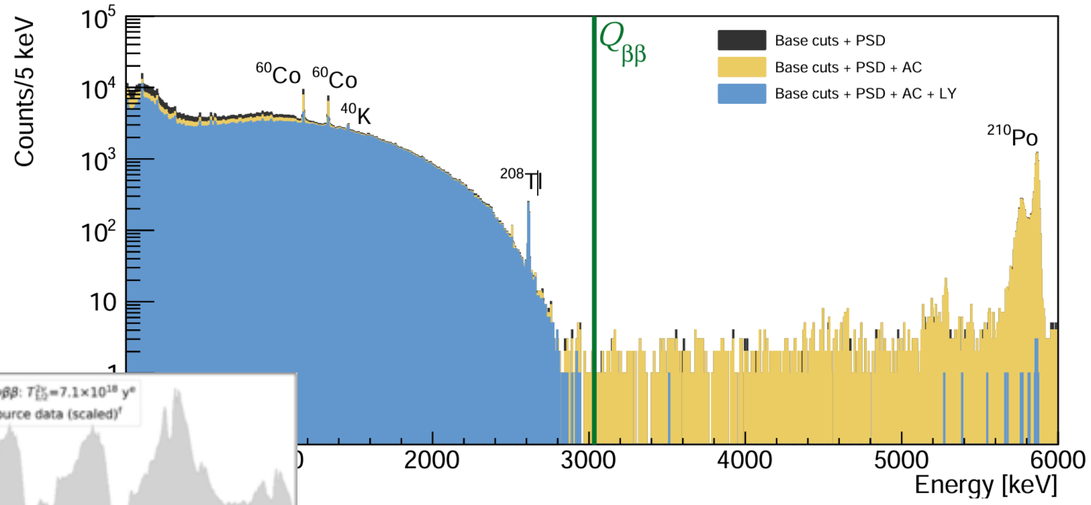
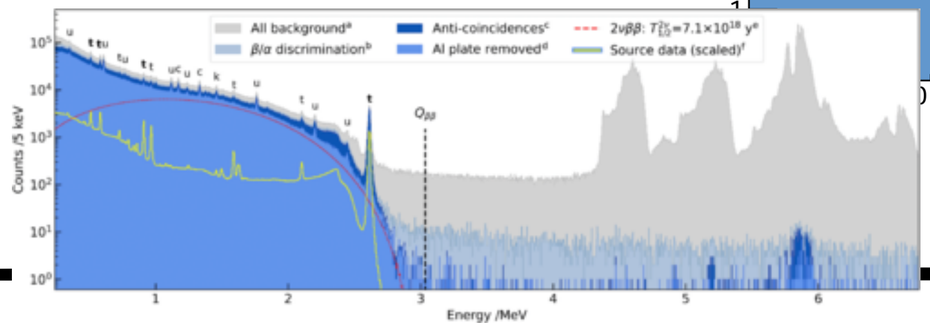
- **CUPID-0, CUPID-Mo, AMoRE**
- Add particle ID
- Heat + light → α/βγ discrimination
- Improve background rejection

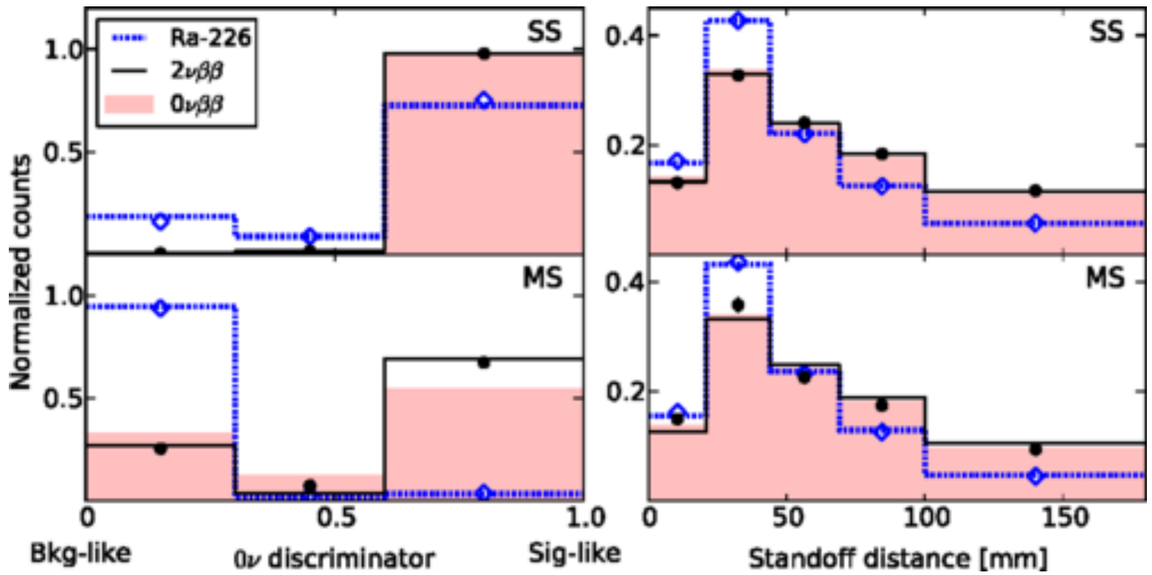




Eur. Phys. J. C 82, 1033 (2022) | Phys. Rev. Lett. **134**, 082501 (2025)

^{136}Xe: two paths to sensitivity

- **EXO-200**
- Ionization + scintillation
- Single-site / multi-site discrimination
- Position → fiducialization and background rejection



Phys. Rev. Lett. **123**, 161802 (2019)

^{136}Xe: two paths to sensitivity

- **EXO-200**
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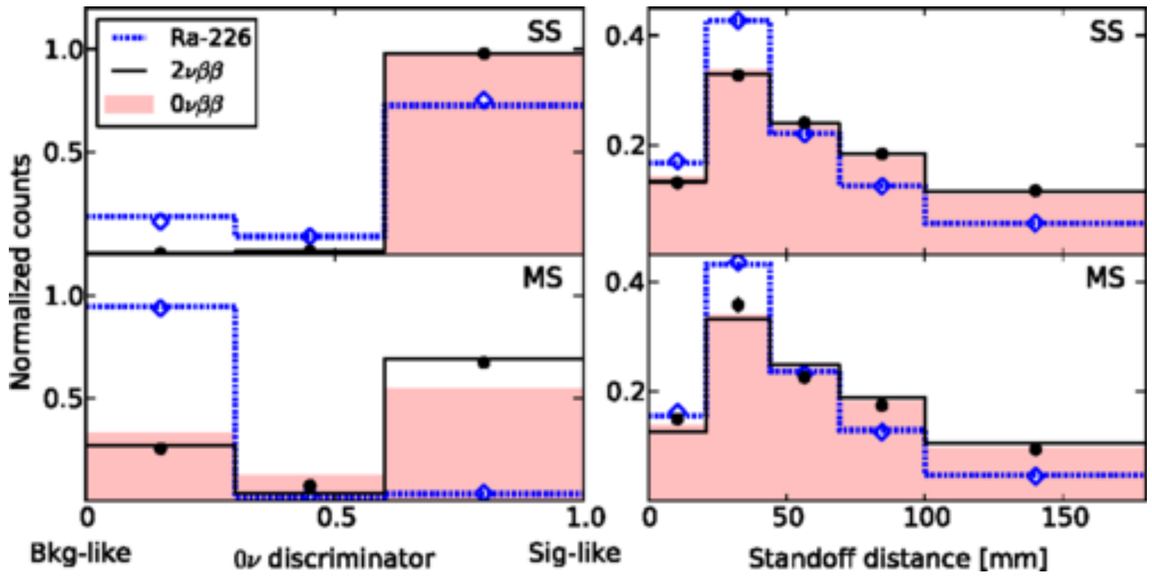
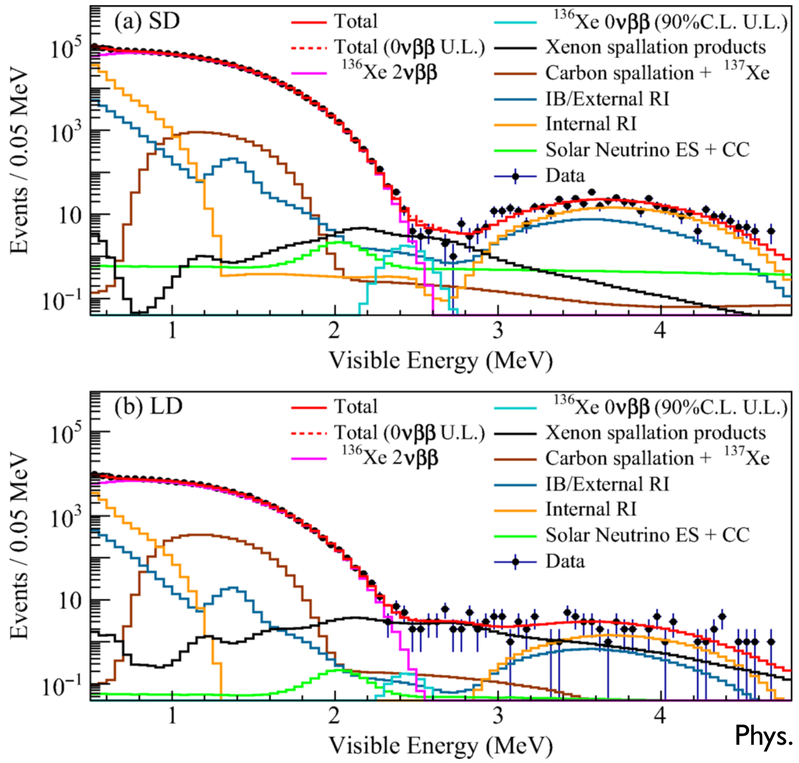


Phys. Rev. Lett. **123**, 161802 (2019)

- **KamLAND-Zen**
- Dissolve enriched Xe in a large scintillator target
- High efficiency + very large exposure
- Trade resolution/topology for scale



Phys. Rev. Lett. **135**, 262501 (2025)

Tracking: event topology

- **NEMO-3**
- Reconstruct the decay: vertex + track topology
- Measure E_1 and E_2
- And the opening angle

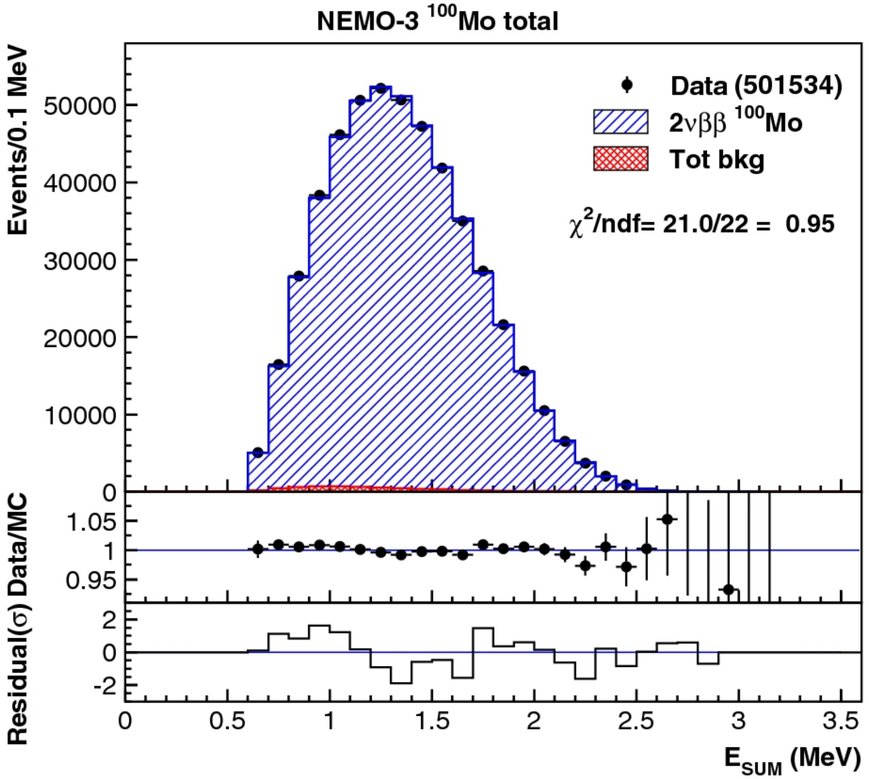
Powerful background rejection

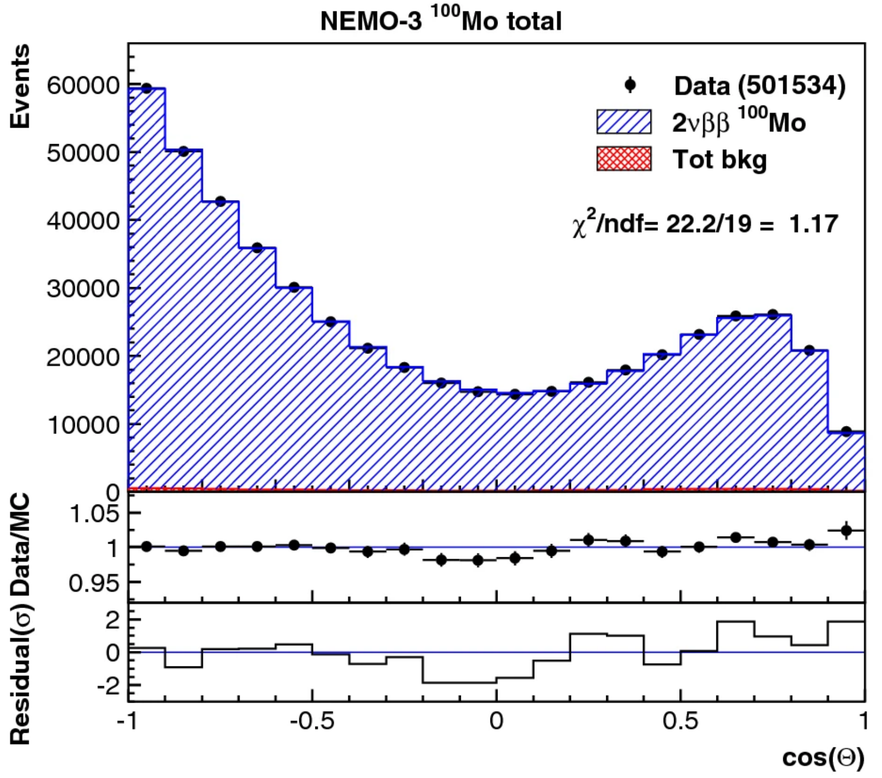
Access to the decay mechanism if a signal is found

Lower efficiency

Poorer energy resolution

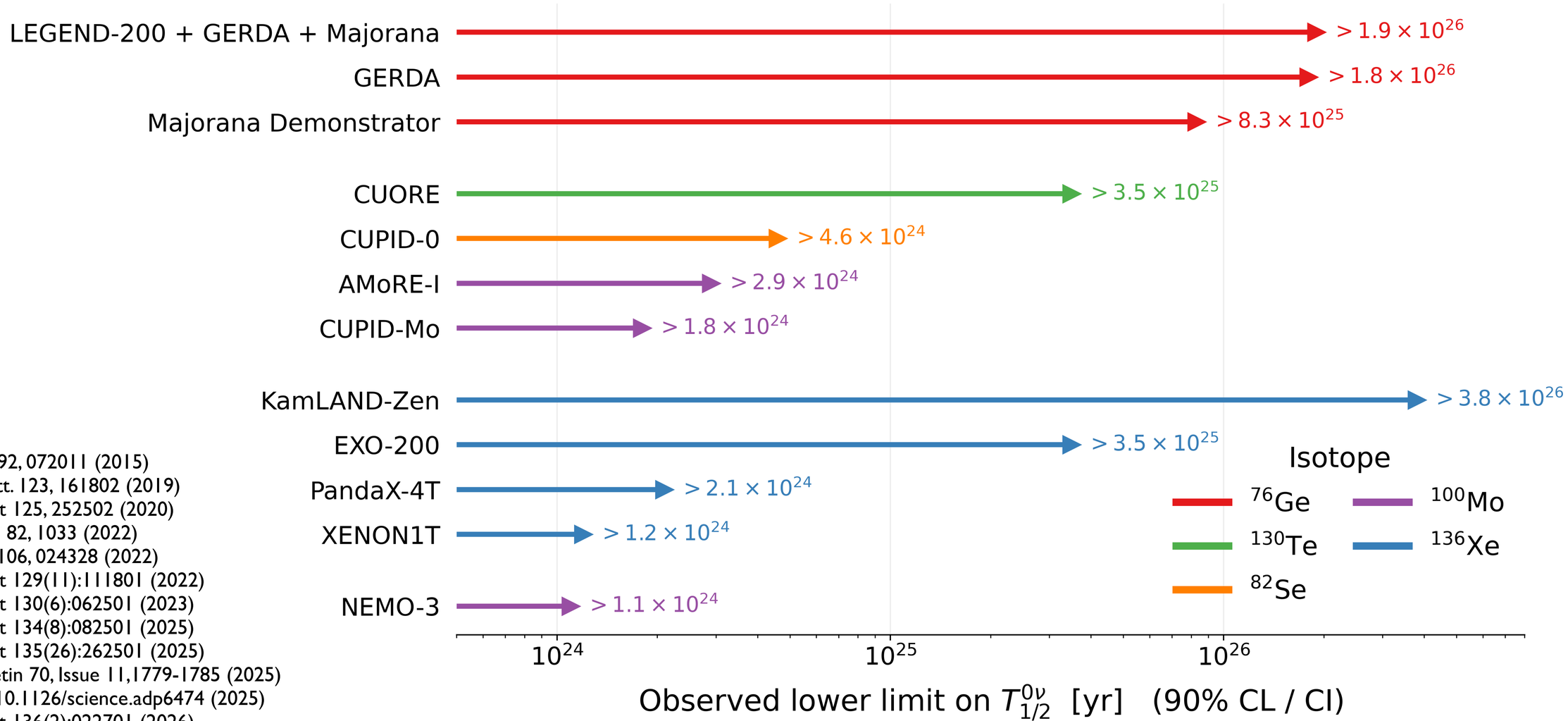
Difficult to scale





Eur. Phys. J. C 79, 440 (2019)

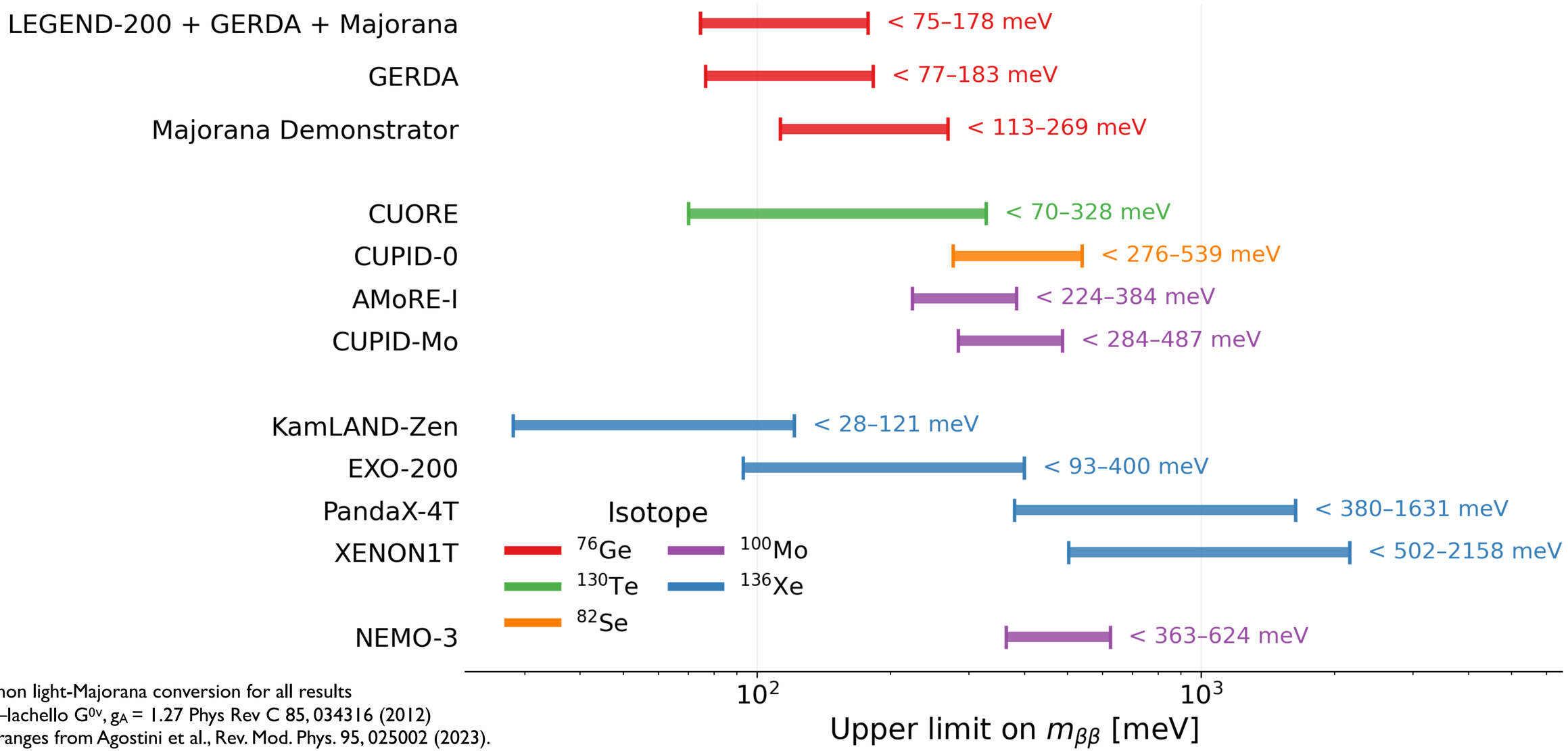
Where we are now ($T_{1/2}$)



Phys. Rev. D 92, 072011 (2015)
Phys. Rev. Lett. 123, 161802 (2019)
Phys Rev Lett 125, 252502 (2020)
Eur. Phys. J. C 82, 1033 (2022)
Phys. Rev. C 106, 024328 (2022)
Phys Rev Lett 129(11):111801 (2022)
Phys Rev Lett 130(6):062501 (2023)
Phys Rev Lett 134(8):082501 (2025)
Phys Rev Lett 135(26):262501 (2025)
Science Bulletin 70, Issue 11,1779-1785 (2025)
Science, doi:10.1126/science.adp6474 (2025)
Phys Rev Lett 136(2):022701 (2026)

Published observed limits; current through September 2026. LEGEND entry is the published combined LEGEND-200 + GERDA + Majorana result.

Where we are now ($m_{\beta\beta}$)



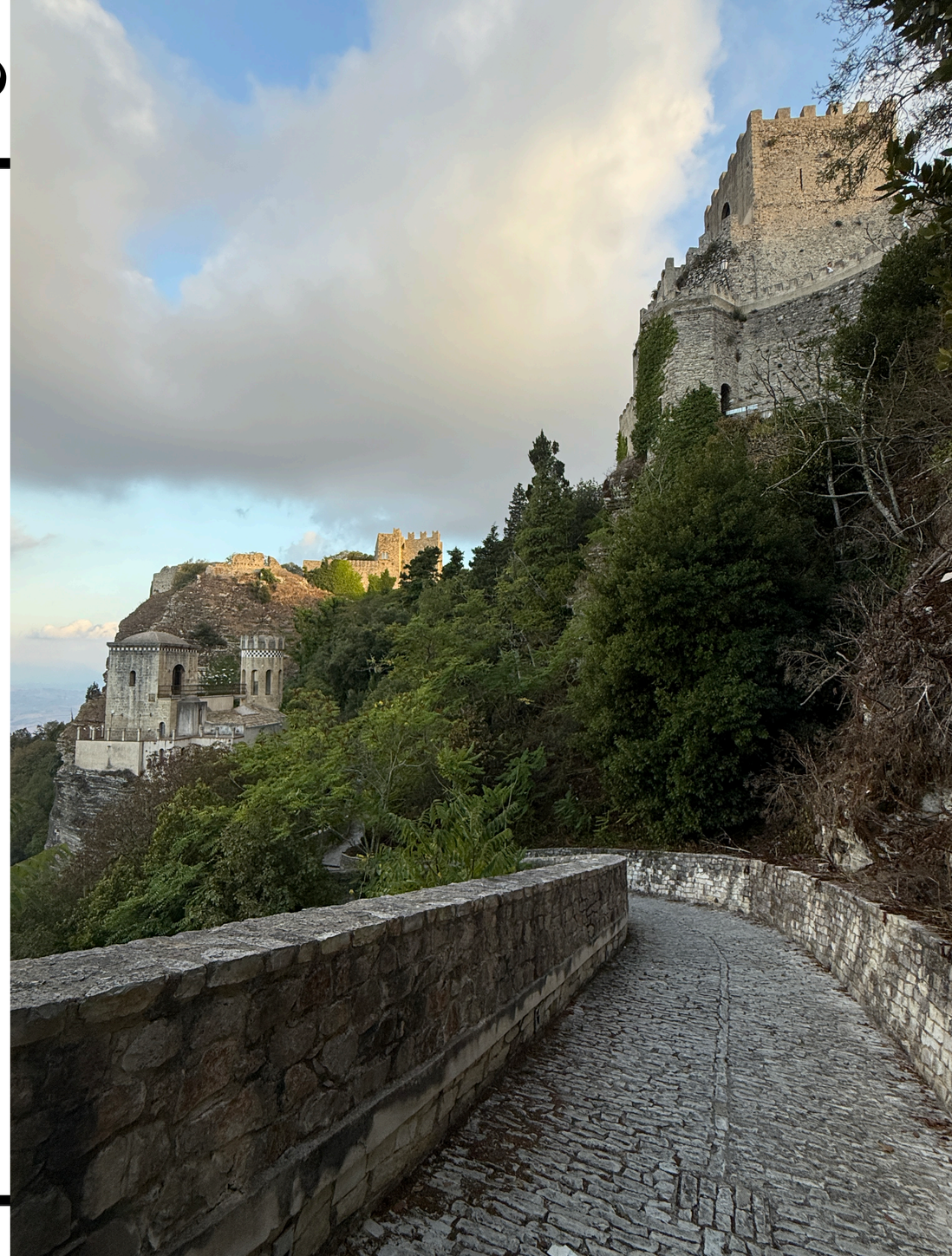
Common light-Majorana conversion for all results
Kotila–Iachello $G^{0\nu}$, g_A = 1.27 Phys Rev C 85, 034316 (2012)
NME ranges from Agostini et al., Rev. Mod. Phys. 95, 025002 (2023).
Bands show NME spread, not experimental uncertainty.

Where do we go from here?

How do we climb this hill?

- **Scale**
  More isotope → reach 10^{27-28} yr
- **Reject**
  Drive backgrounds toward zero in the signal region
- **Understand**
  Retain enough information to identify the mechanism if nature gives us a signal

The technologies diverge because no detector maximizes all three.



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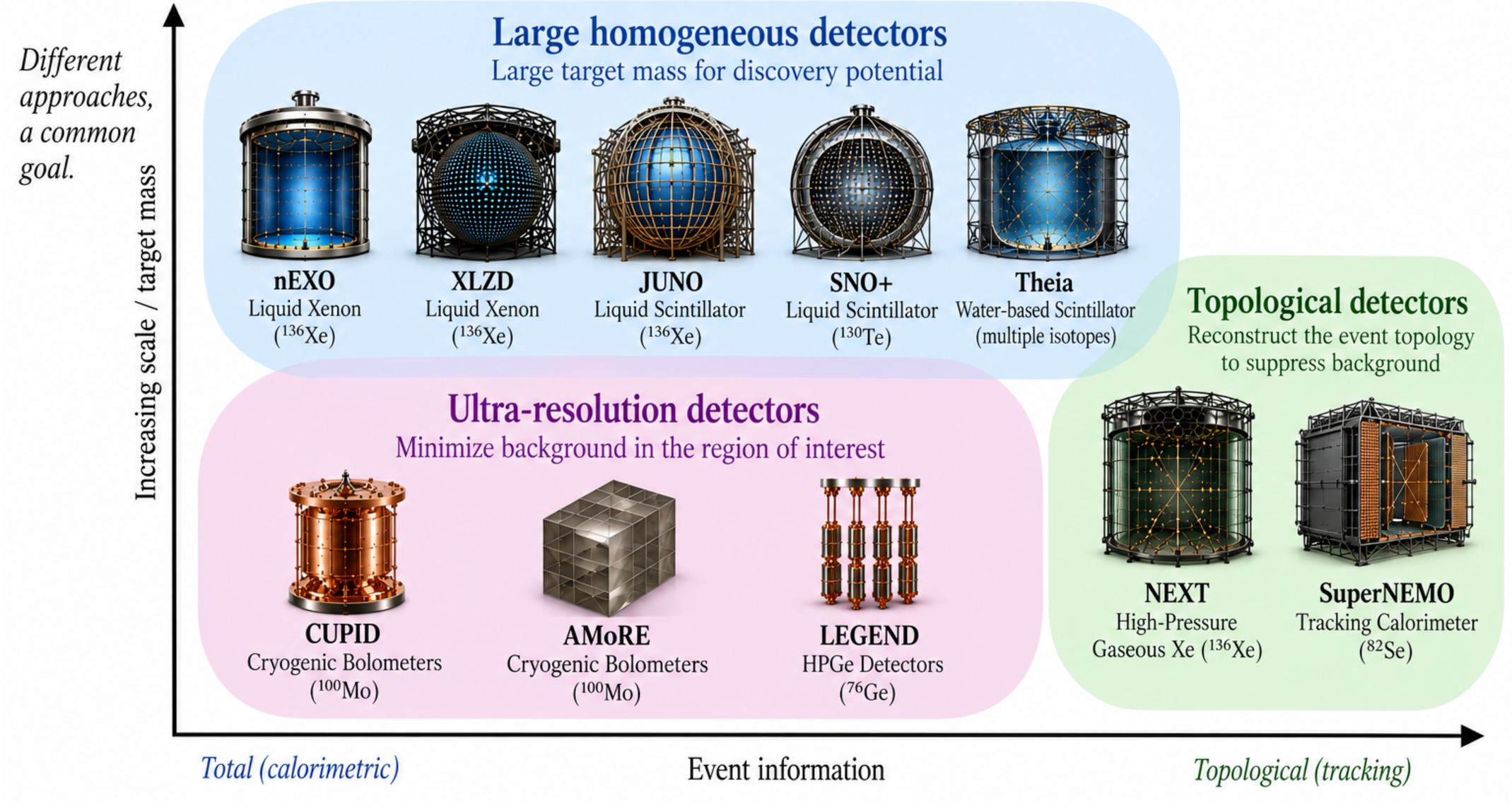
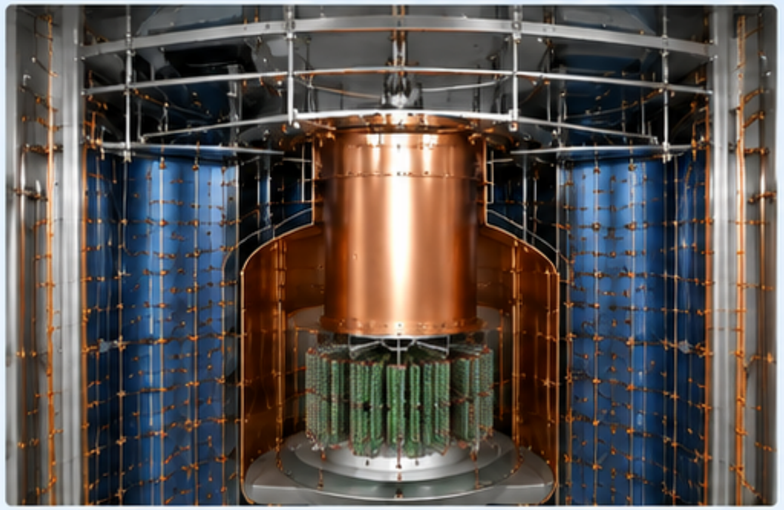
The future of neutrinoless double beta decay



Precision-driven experiments

LEGEND

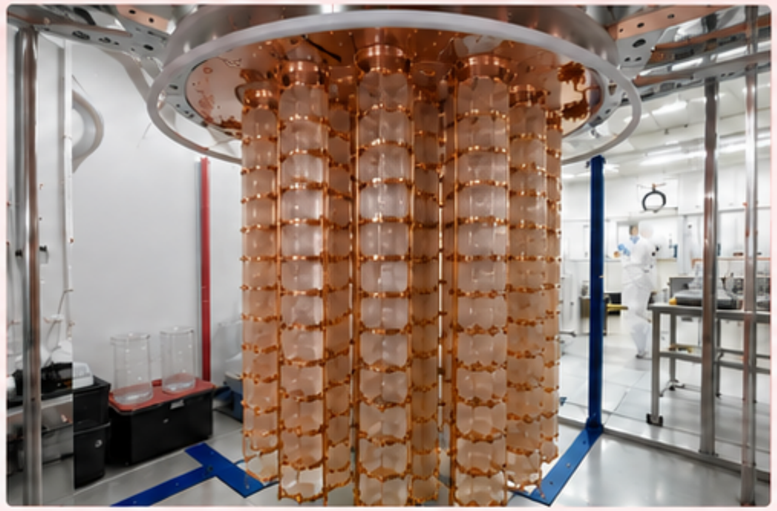
HPGe detectors (^{76}Ge)



- Precision spectroscopy
- 0.12% FWHM at 2039 keV
- Next generation: LEGEND-1000
- Target sensitivity ~ 10^{28} yr

CUPID

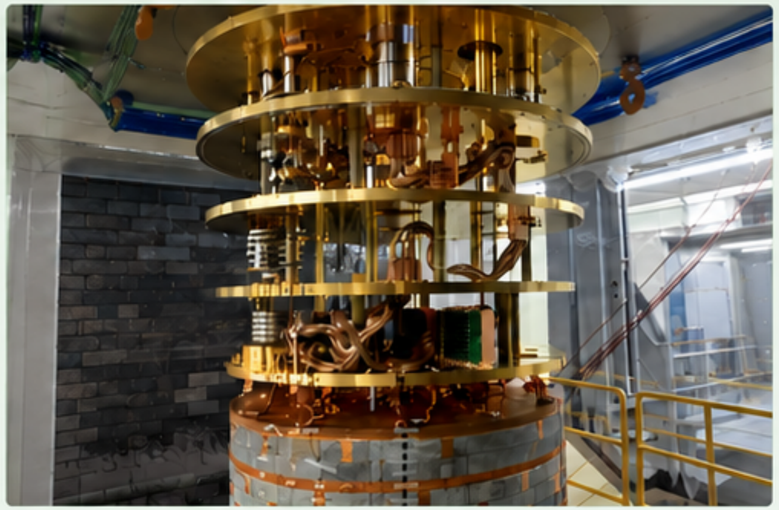
Cryogenic bolometers (^{100}Mo)



- Particle identification
- Scintillating ^{100}Mo crystals
- $\alpha/\beta(\gamma)$ discrimination
- Target sensitivity ~ 10^{27} yr

AMoRE

Cryogenic bolometers (^{100}Mo)



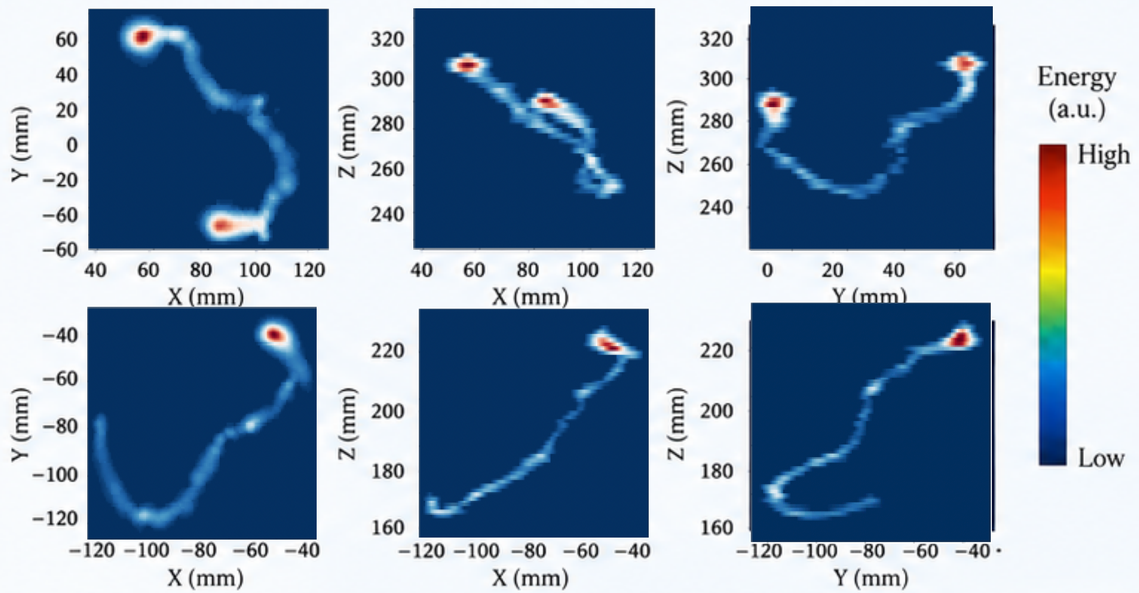
- Scalability
- ^{100}Mo crystals
- Growing detector mass (AMoRE-II)
- Target sensitivity ~ 10^{27} yr

Three complementary approaches, same destination:
maximize information per event to achieve background-free sensitivity.

Event reconstruction

NEXT

High-Pressure Xenon Electroluminescent TPC

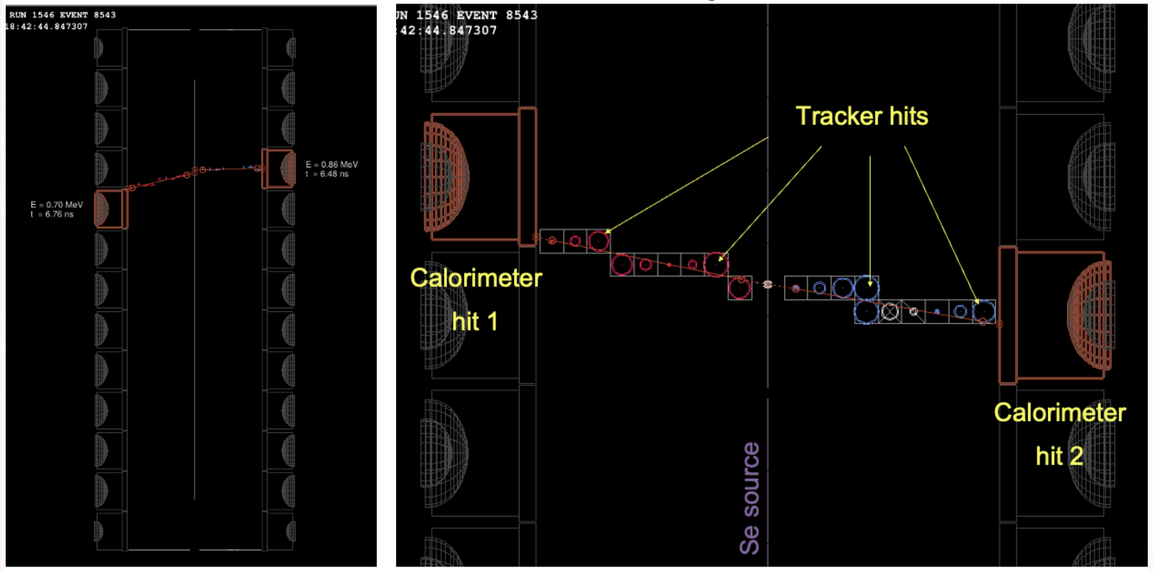


- Two-electron topologies in real data
- 0.5–0.7% FWHM target at $Q_{\beta\beta}$
- Multi-ton roadmap to 10^{28} yr sensitivity
- Future Ba^{2+} tagging (NEXT-BOLD)

Signal = single track with two electron blobs

SuperNEMO

Tracker + Calorimeter at LSM, France



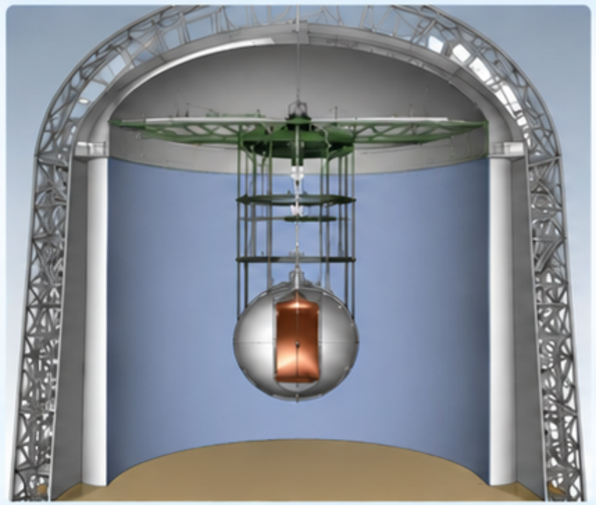
- Individual particle identification
- Energy + angle reconstruction
- Flexible isotope choice
- Measurement of **key background channels**

Signal = fully reconstructed event

Complementary approaches, same destination:
maximize information per event to achieve background-free sensitivity.

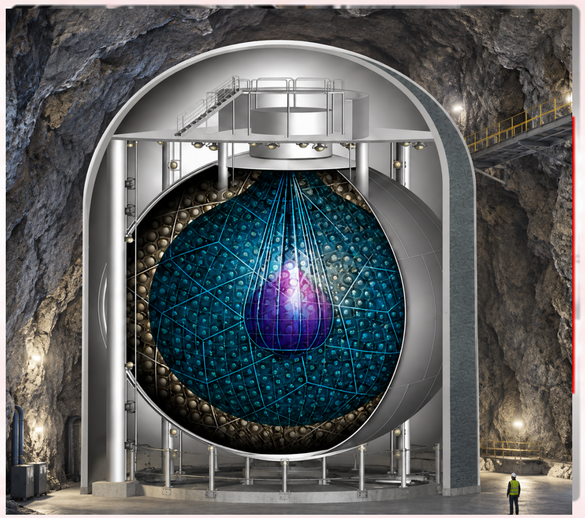
Routes to scale

Dedicated detector
nEXO



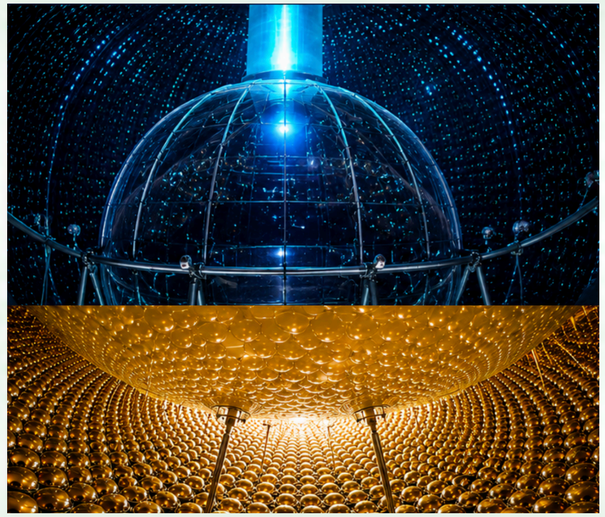
Purpose-built 0νββ detector with large isotope mass

Upgrade existing detector
KamLAND2-Zen



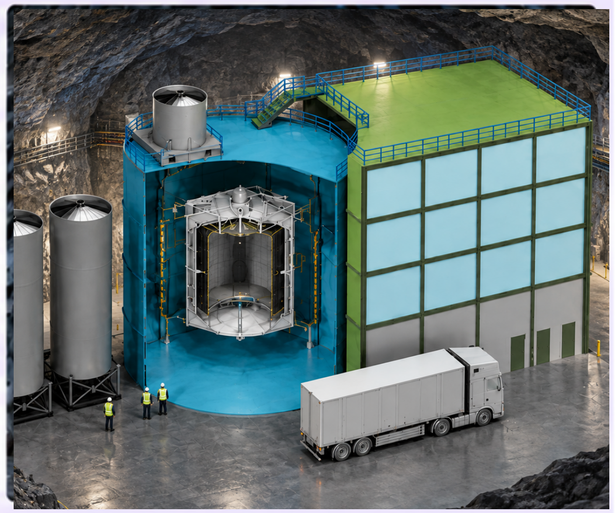
Build on existing infrastructure to enable larger isotope mass

Piggyback on existing observatory
JUNO / SNO+



Leverage major neutrino facilities to search for 0νββ

Multipurpose next-generation observatory
XLZD / Theia



Next-generation facilities with broad physics programs

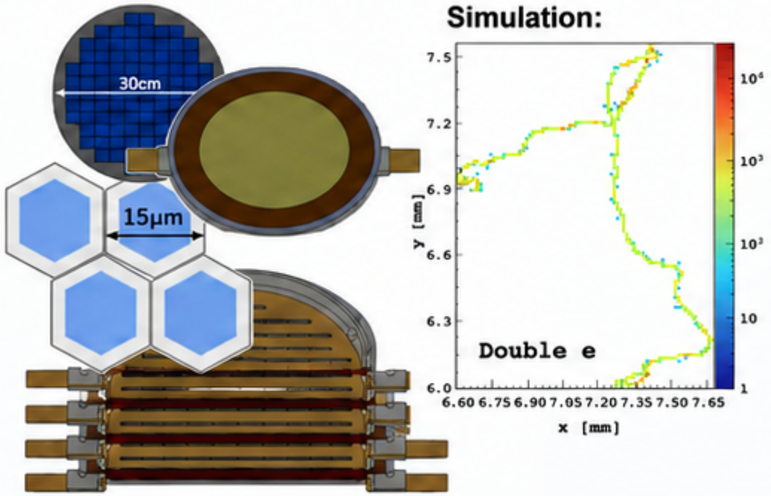
Same destination: enormous isotope exposures for 0νββ.

A diverse set of paths strengthens the global program.

Emerging concepts

Selena

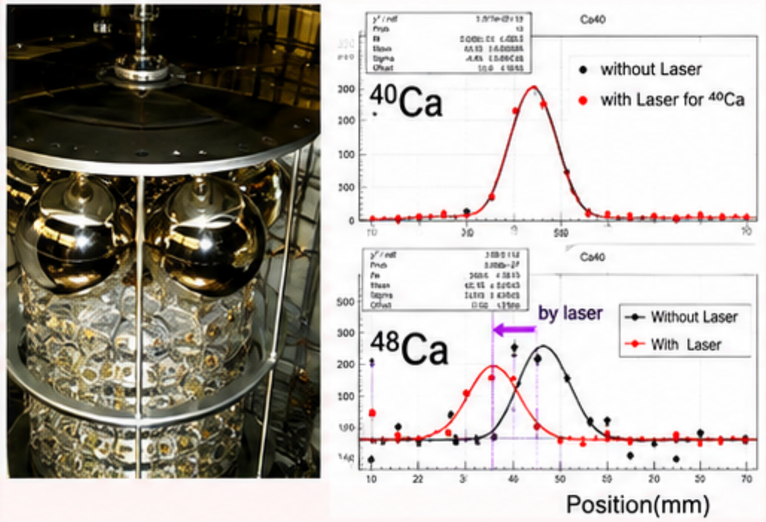
Image the electrons in ^{82}Se



- Large-area hybrid CMOS imaging detector with thin enriched ^{82}Se layers
- Directly image the two-electron topology
- Powerful background rejection through topological/event-level information

CANDLES

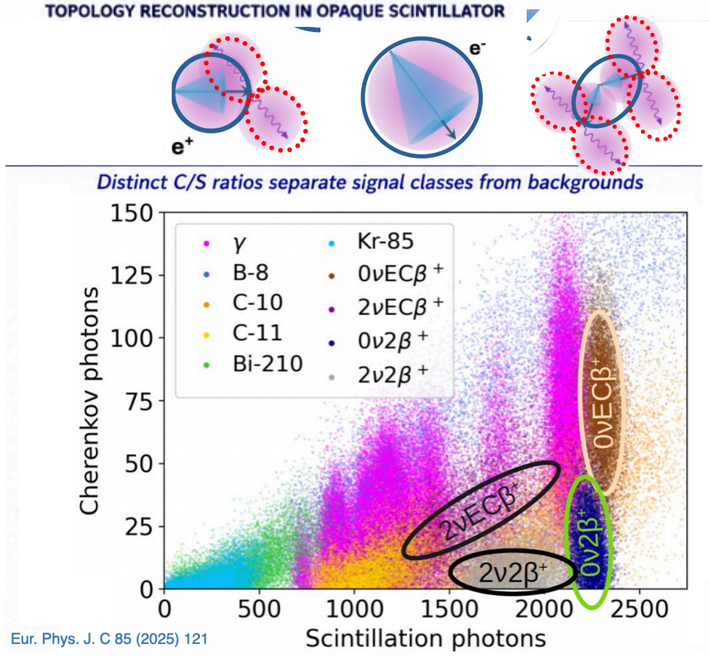
Use ^{48}Ca in CaF_2 scintillation crystals



- CaF_2 scintillation crystals containing ^{48}Ca (source = detector)
- Low-background environment ($Q_{\beta\beta}$ = 4.27 MeV)
- Laser isotope separation could address the very low natural abundance of ^{48}Ca (0.187%)

NuDoubt++

Search for positron-emitting modes



- Hybrid Cherenkov + scintillation detector
- Search for positron-emitting double-beta modes
- Annihilation topology and particle ID provide qualitatively different backgrounds

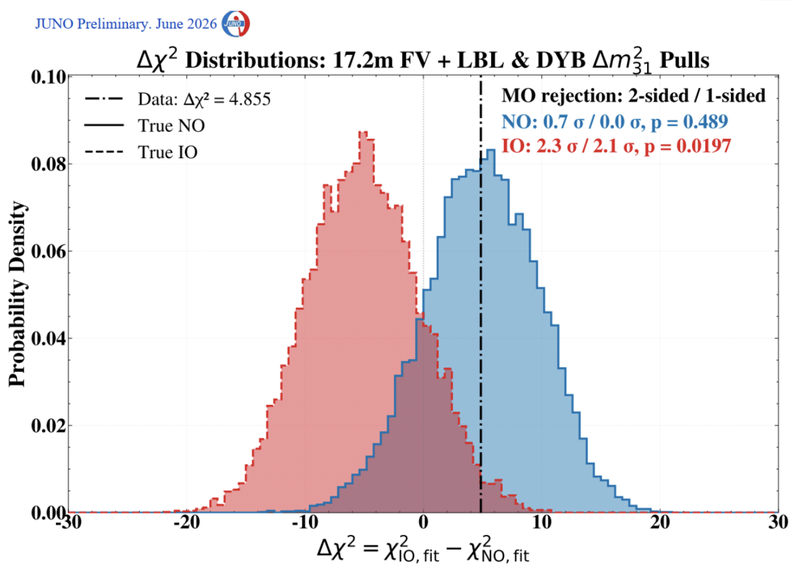
Changing the isotope or the observable may open entirely different background handles.

A diverse set of ideas strengthens the overall 0νββ program.

Beyond mass ordering

1. What oscillations tell us

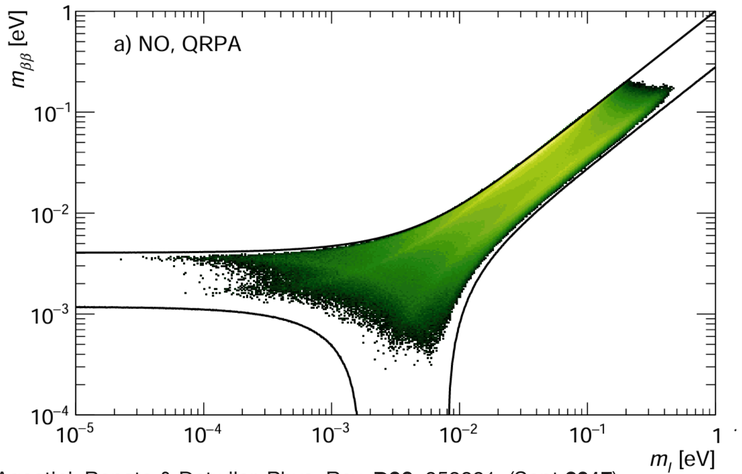
JUNO preliminary (June 2026)



Normal ordering increasingly favored

2. Even the standard mechanism has no single target

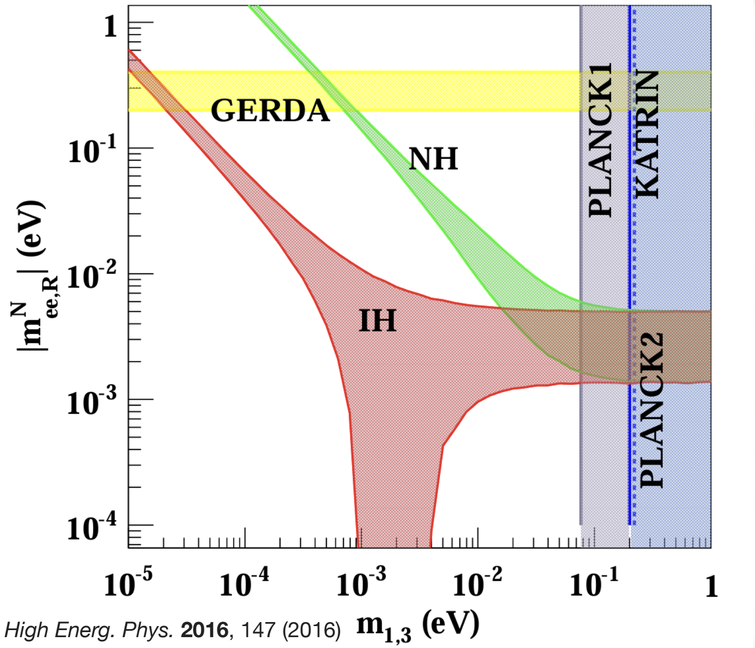
Standard 0νββ mechanism
(light neutrino exchange)



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

The allowed phase space is not uniformly populated

3. The mechanism may be different



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

Alternative LNV mechanisms change the landscape

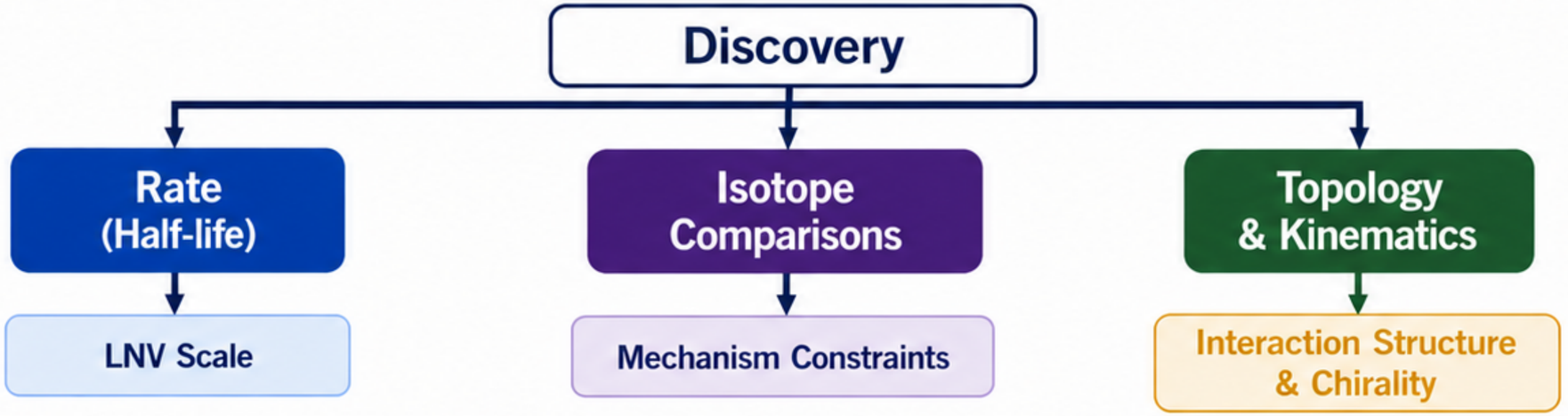
Mass ordering sets boundary conditions for the search —
it does not determine either the discovery reach or how a signal should be interpreted.

Multiple isotopes, technologies and observables remain essential.

Beyond Discovery

What do we learn after we see 0νββ?

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 *0νββ*, but to understand its origin

The future challenge may not be discovering 0νββ — it may be understanding what we have discovered.

How do we test leptogenesis?

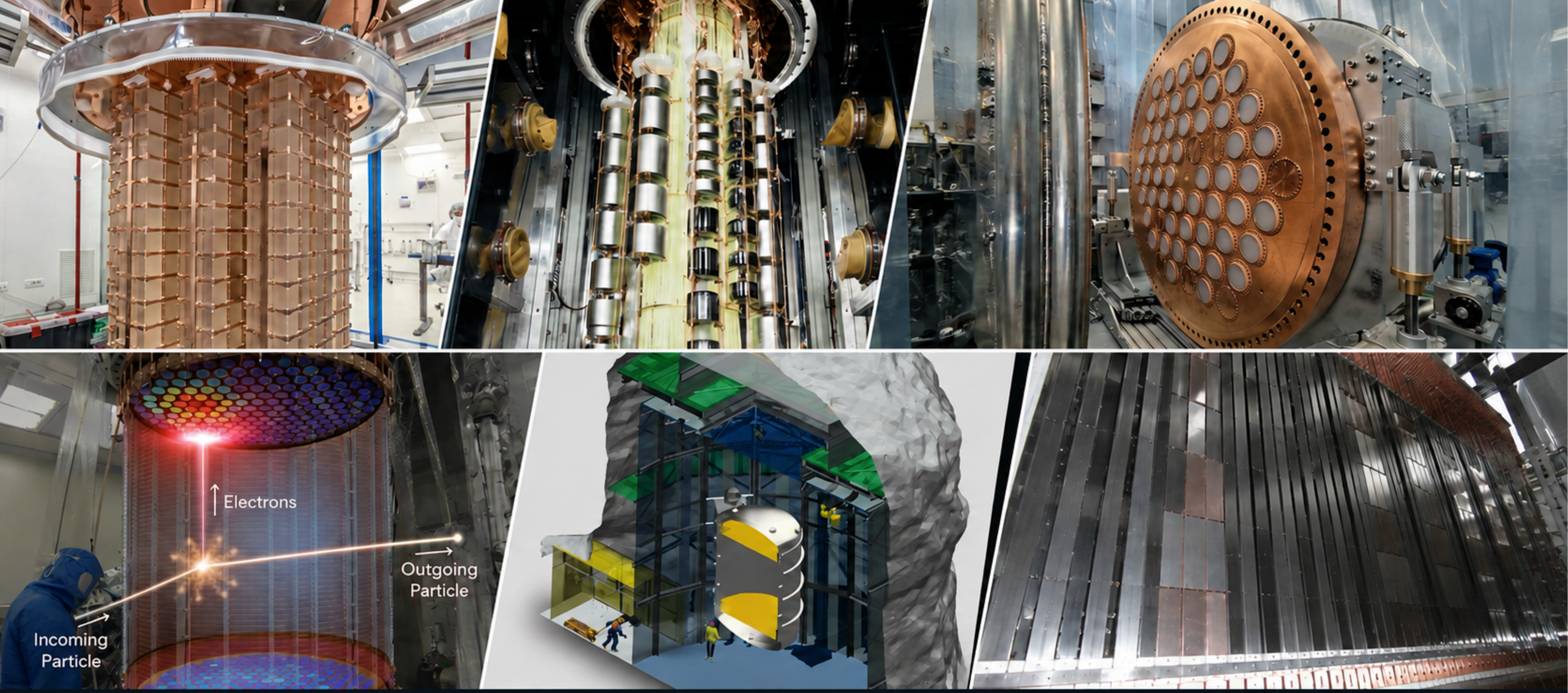
Credit: Hitoshi Muruyama

How do we test leptogenesis?

Estimated energy scale:
10^{10}–10^{15} GeV

Current collider record:
10^{4} GeV (LHC)

Estimated construction site:
Milky Way Galaxy



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**.

- $0\nu\beta\beta$ would establish lepton-number violation — and open a unique window on the origin of neutrino mass and matter
- Experiments are now probing 10^{26}-yr $T_{1/2}$; next-gen experiments target $10^{27\text{-}28}$ yrs
- There is no perfect detector: resolution, background rejection, topology and scale offer complementary routes to discovery
- Multiple isotopes are essential — both to establish a signal and to understand its origin
- Discovery would be the beginning of the story, not the end

Conclusions

THANK YOU

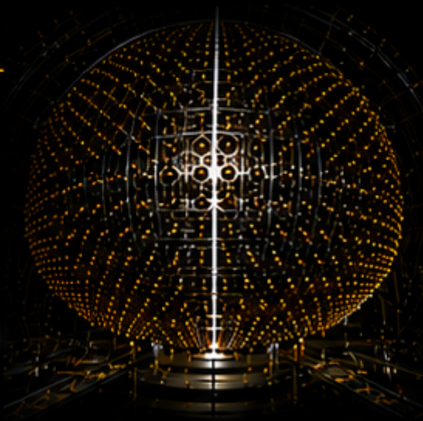
With gratitude to colleagues who contributed material, advice, and discussion

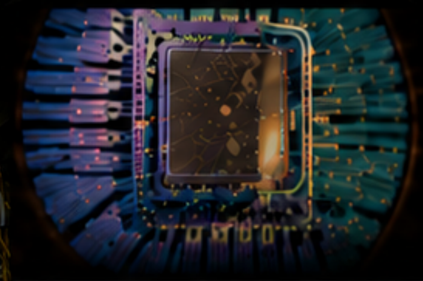
Erica Caden • Álvaro Chavarría • Mark Chen • Jason Detwiler • Giorgio Gratta

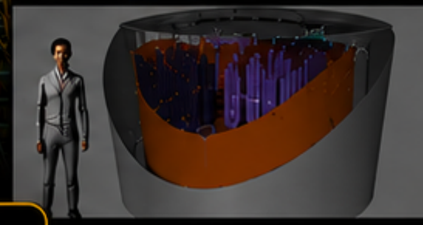
Juan Gómez-Cadenas • Ke Han • Karsten Heeger • Tanner Kaptanoglu • Josh Klein

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)

SPARE SLIDES

Dirac vs Majorana

- ***Dirac***
- Requires new fundamental global symmetry U(1)lepton number
- New physics ?
- Matter and antimatter are fundamentally different

- ***Majorana***
- Cannot be explained by "standard" Higgs Yukawa coupling
- Lepton number violated: New Physics !
- Potentially sensitive to very high mass scales (see-saw mechanism)
- Can generate matter⇔antimatter transitions

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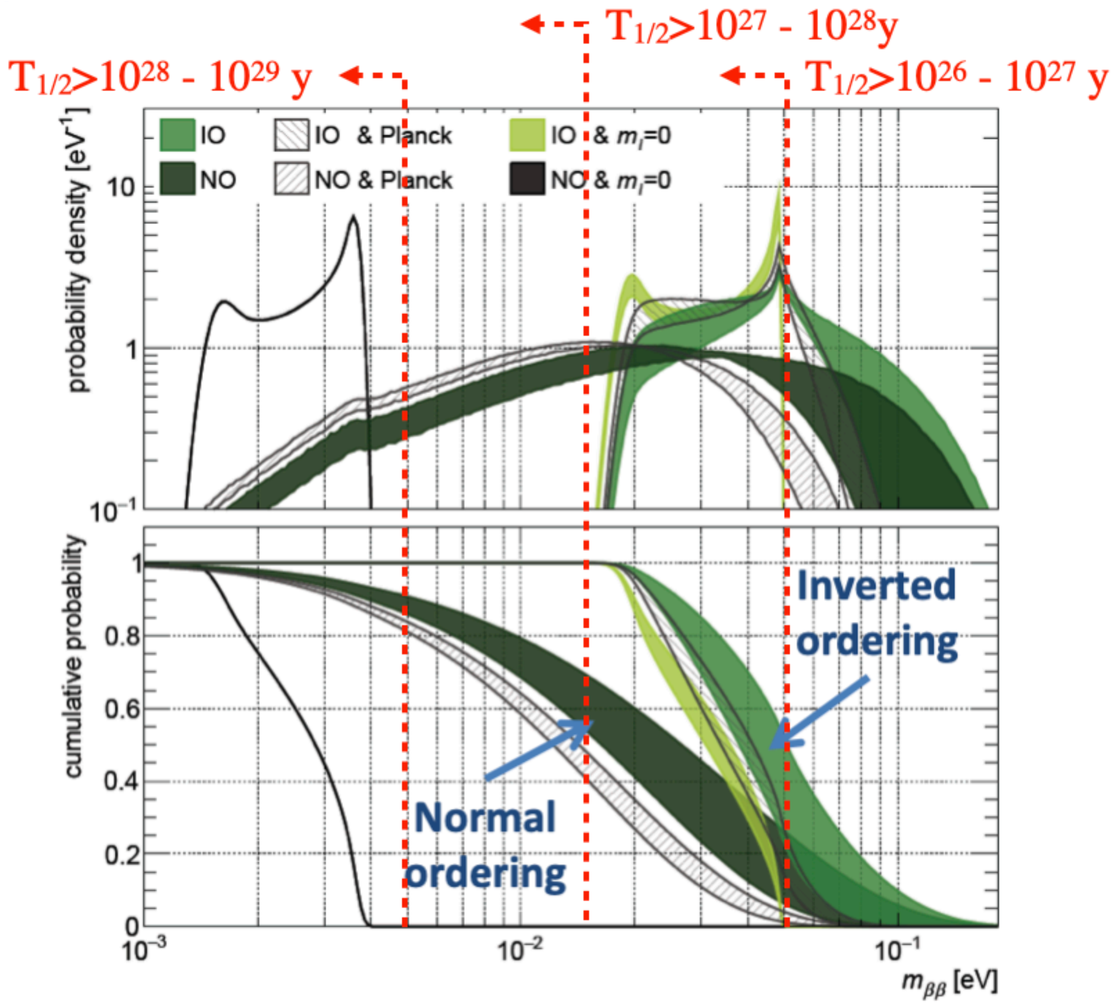
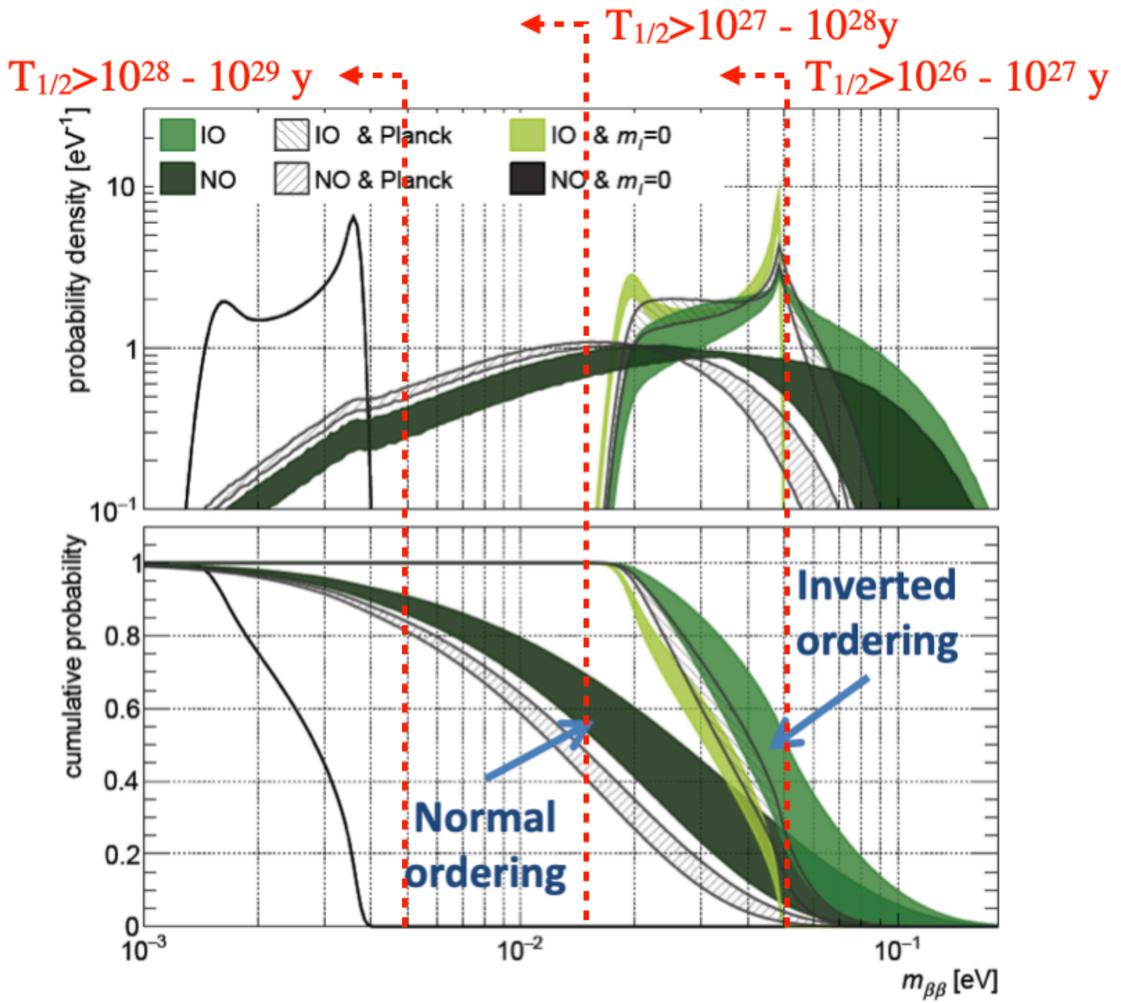
?

Opportunity for discovery



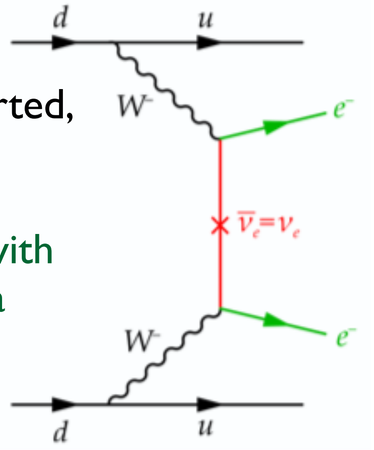
M. Agostini, G. Benato, J. Detwiler,
Phys. Rev. **D96**, 053001 (2017)

Opportunity for discovery



M. Agostini, G. Benato, J. Detwiler,
Phys. Rev. **D96**, 053001 (2017)

If the neutrino hierarchy is inverted, light neutrino exchange is dominant.
Next-generation experiments with sensitivity $T_{1/2}$>10^{27} years have a definite target



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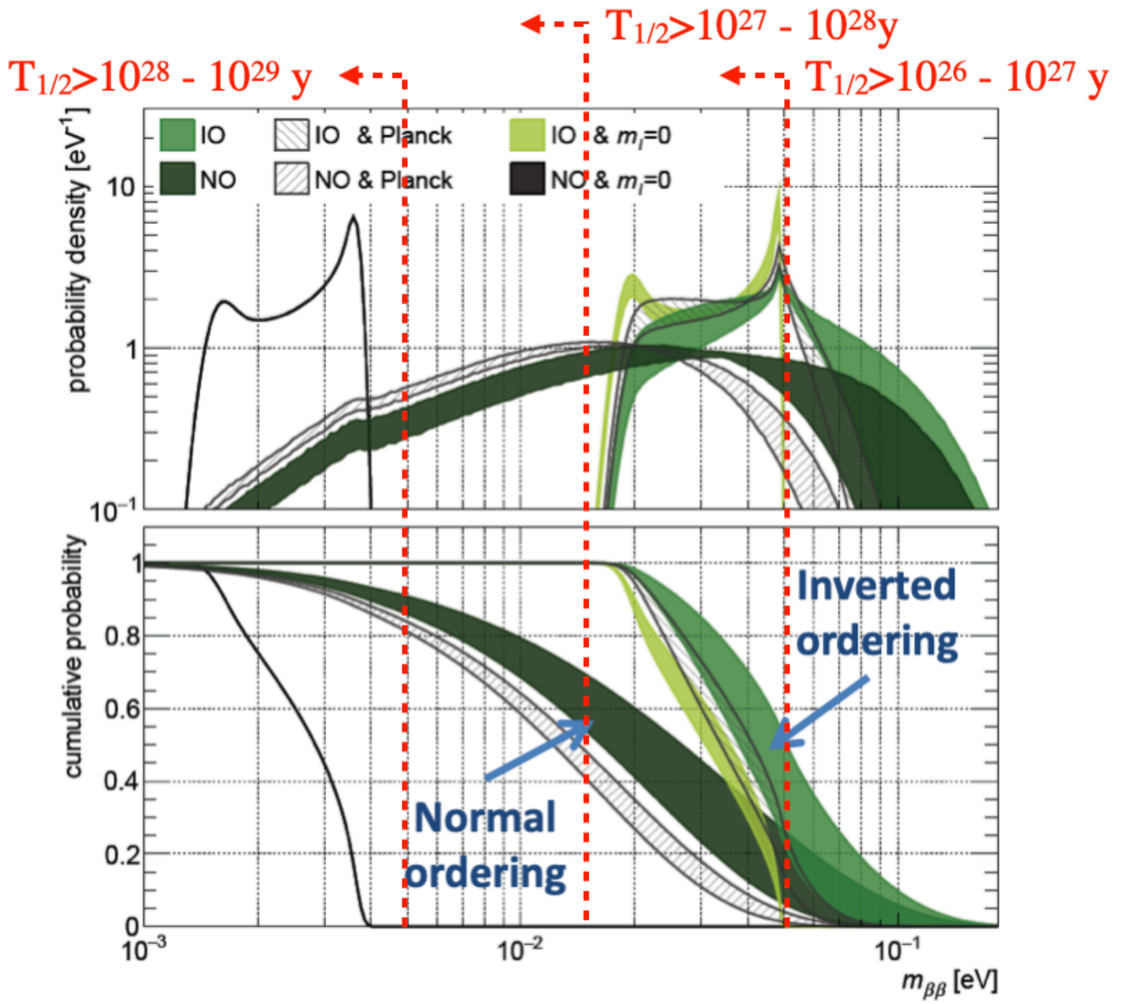

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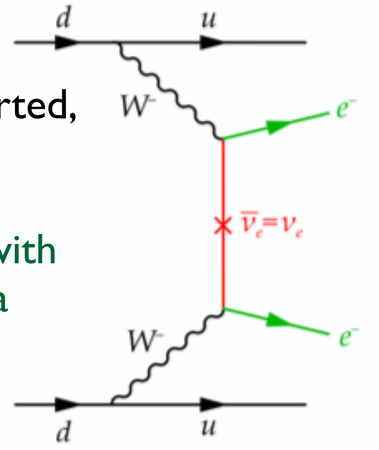
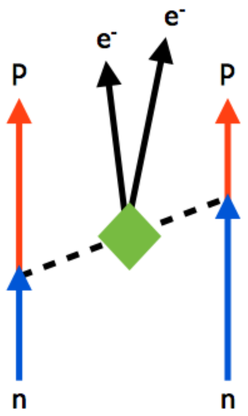
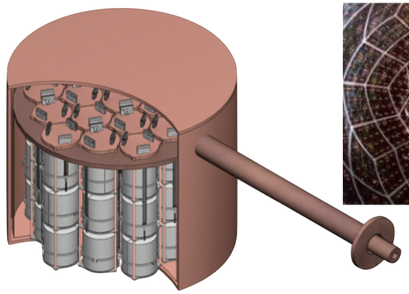
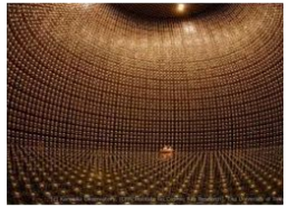


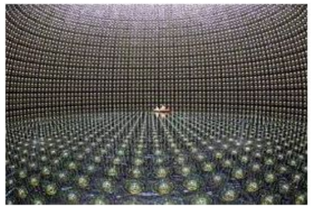
In NO case the leading contribution could come from short-range new physics effects.
Factor of 10-100 improvement in sensitivity next decade.

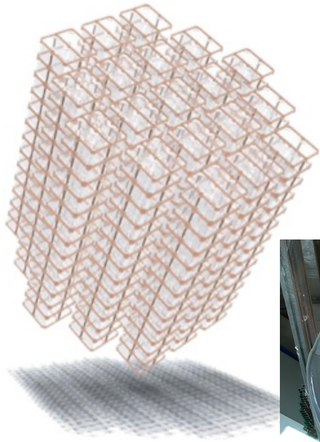


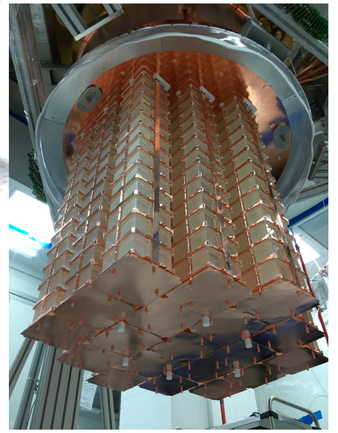
Neutrino detection technology





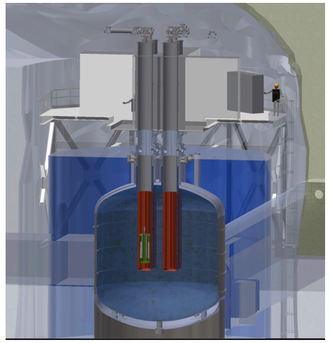


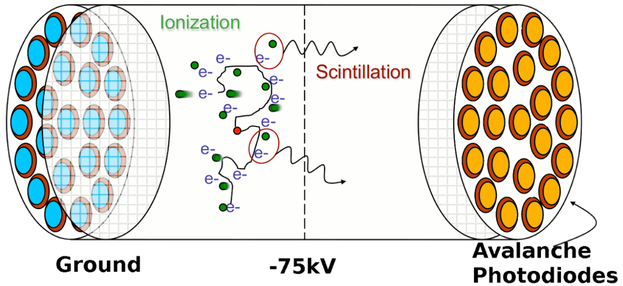


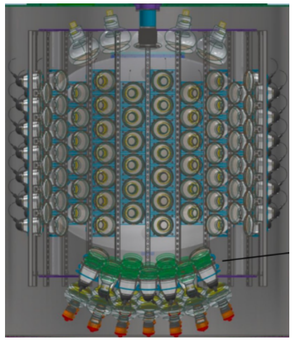


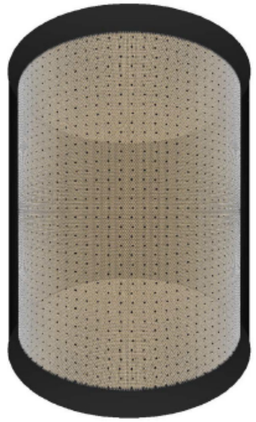
- Ultra-pure Ge
- High resolution bolometry
- Noble liquid / gas TPCs: LAr, LXr, GXe (S+I)
- Water Cherenkov
- Organic liquid scintillator / "Hybrid" detection (S+Ch)

✴ *Sample of approaches relevant for this topic*







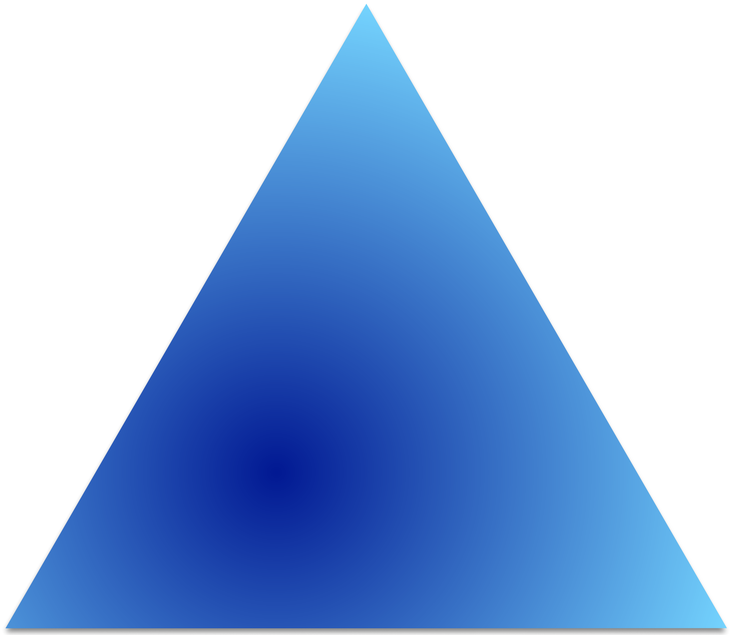


Experimental Techniques

Approach	Pros	Cons
Large self-shielding calorimetry	• Self-shielding: low ext bkg • Easily scalable to large M • Source in / source out caln • High detection efficiency	• Relatively poor E resn
Xe TPC	• Relatively easy to enrich • No long-lived r/a isotopes • Scint + ionisation signals	• $Q_{\beta\beta}$ (2.46MeV) close to ^{208}Tl • %-level E resn
High-resolution calorimetry	• Excellent E resn • Simple, compact	• No tracking • Ltd bkg suppression (exc E) • Reduced self-shielding
Tracko-calo expt	• Good bkg rejection	• Low detection efficiency • Low E resn • Very hard to scale

Detector technology

Radiopurity

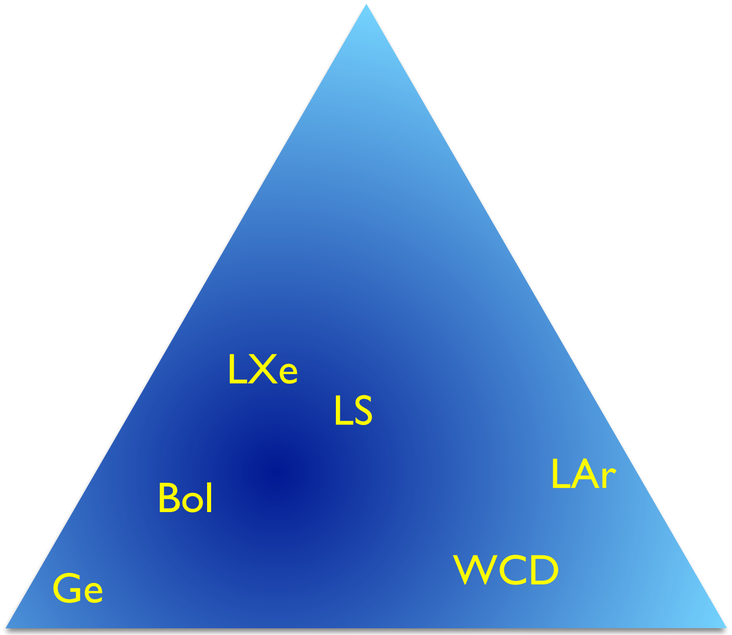


Threshold & resolution

Exposure

Detector technology

Radiopurity



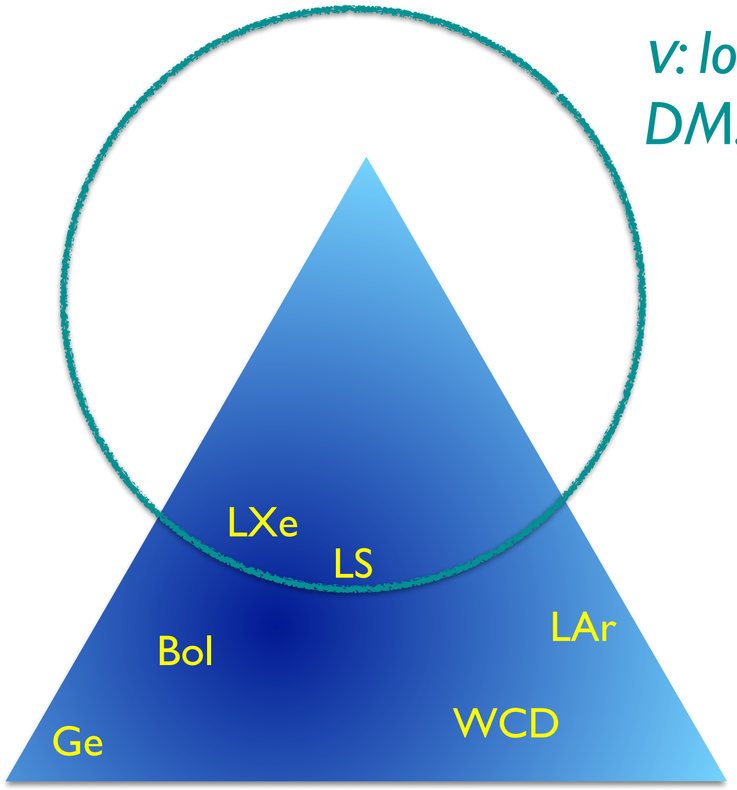
Threshold & resolution

Exposure

Detector technology

Radiopurity

ν: low-energy neutrinos,
DM: "Standard" WIMPs



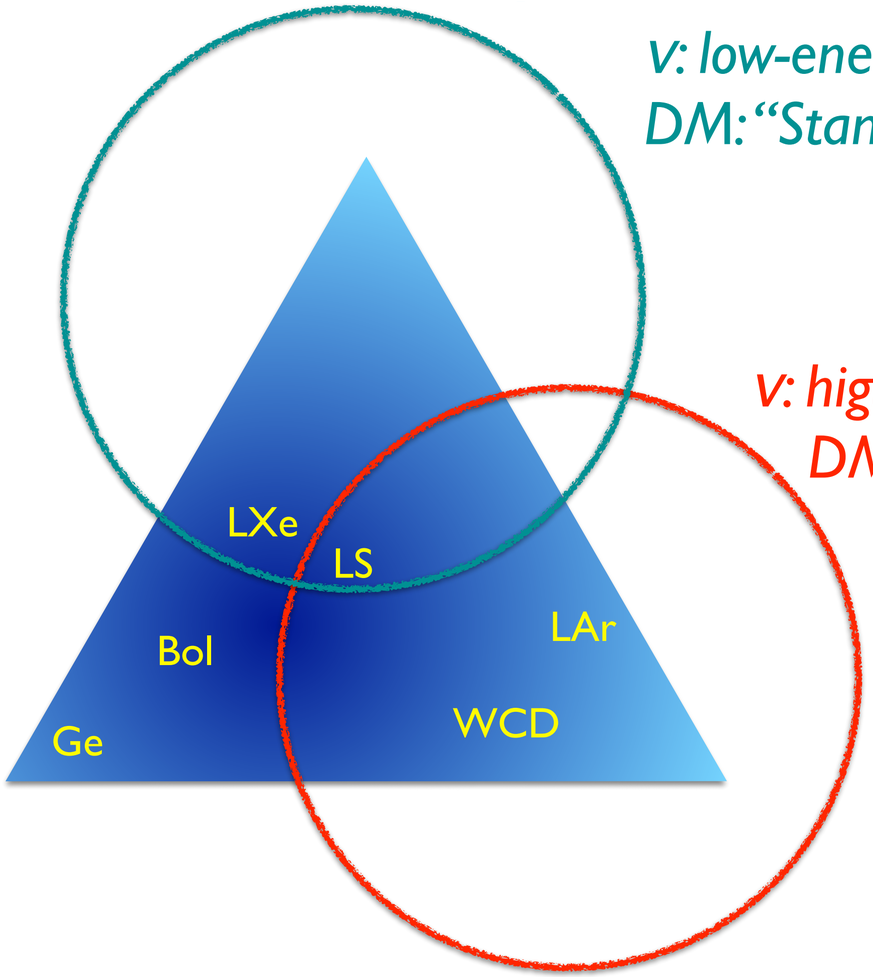
Threshold & resolution

Exposure

Detector technology

Radiopurity

ν: low-energy neutrinos,
DM: "Standard" WIMPs

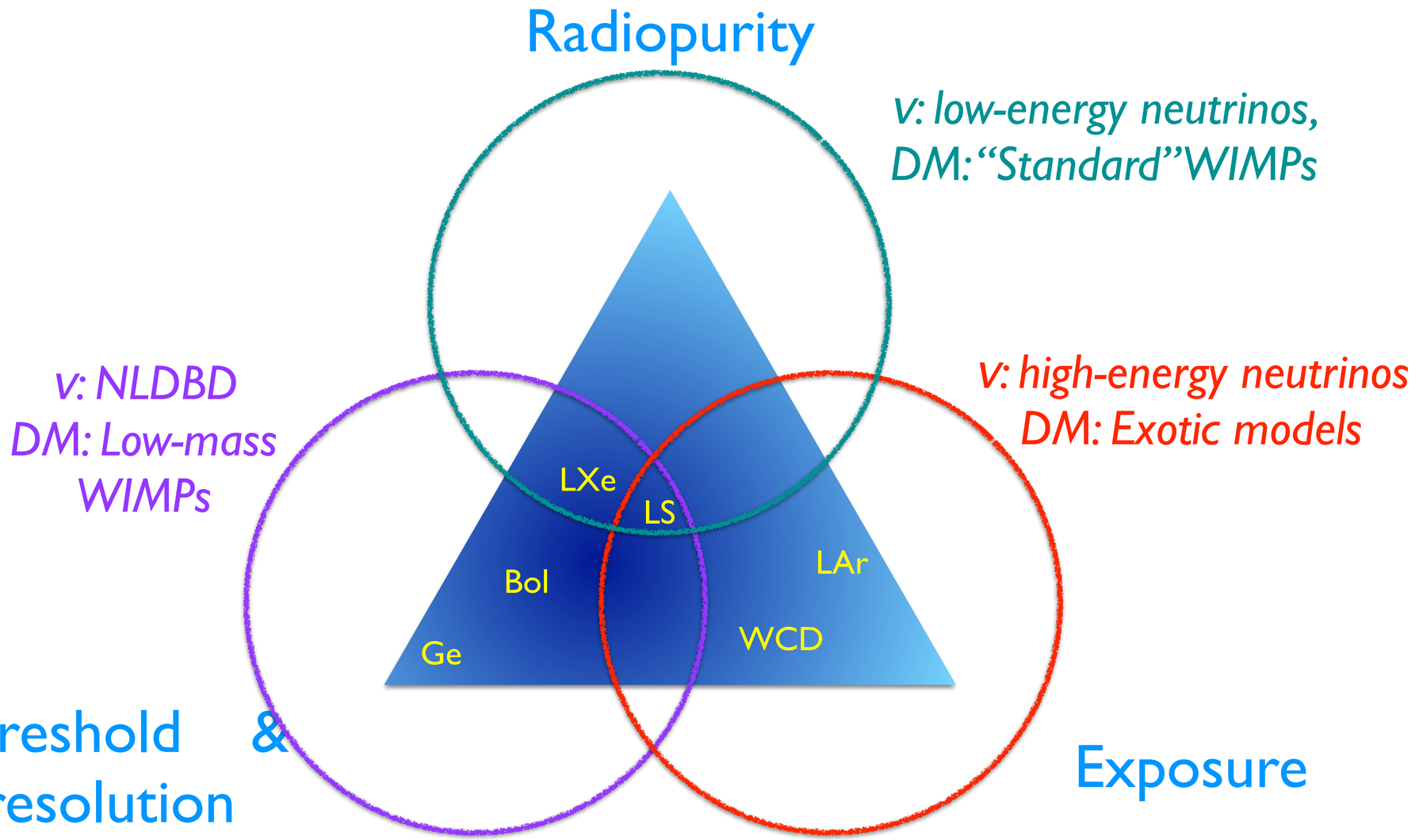


ν: high-energy neutrinos
DM: Exotic models

Threshold & resolution

Exposure

Detector technology



GERDA

, PRL 125, 252502 (2020)

I would use **Fig. 1**: the energy spectra before/after the successive analysis selections. This is the visual demonstration of the GERDA achievement. They reached a background index of 5.2×10^{-4} counts/(keV kg yr), collected 127.2 kg yr total exposure, and achieved the design goal of operating the 100 kg yr Phase-II exposure in the background-free regime. APS Journals +1

Slide message: *Background-free is not a slogan. This is what it looks like.*

I wouldn't spend slide space on their limit plot. The spectrum is much more educational.

2. Majorana Demonstrator — final ROI spectrum, PRL 130, 062501 (2023)

Majorana final-results paper and figures ↗

Here the point is completely different. The final dataset was 64.5 kg yr, but the remarkable number is **2.52 keV FWHM at 2039 keV = 0.12%**. APS Journals

Use the figure showing the narrow $Q_{\beta\beta}$ analysis region/data, ideally beside the GERDA result.

I now think these belong on **one slide**, not two:

> **Two routes to an almost empty ROI**
> Majorana — make the window tiny
> GERDA — make the background tiny

Then at the bottom:

GERDA + Majorana → LEGEND

That's a very clean story.

3. LEGEND-200 — definitely use the new 2026 data

LEGEND-200 first-results paper and figures ↗

This deserves its own slide because it is genuinely current. The first search uses 61.0 kg yr; the best detector subset reaches $0.5^{+0.3}_{-0.2}$ counts/(keV tonne yr), and the combined GERDA + Majorana + L200 result gives

$$T^{0\nu}_{1/2} > 1.9 \times 10^{26}\ \mathrm{yr}.$$

APS Journals

I'd use the **post-selection spectrum around the ROI** from the paper, with a small inset/photo of LEGEND-200. We can explicitly point out how few events remain.

Message: *The two successful Ge programmes weren't competing endpoints; their technologies became one experiment.*

This then replaces quite a bit of the descriptive material currently devoted to LEGEND on your Nu26 precision slide. That slide can subsequently become a **future comparison** rather than having to explain LEGEND from scratch. 20260624 Nu26

CUORE

4. CUORE → CUPID: use two plots to make one argument

For CUORE, use the **current 2 tonne·yr ROI data**, not the older result. The latest analysis gives

$$T_{1/2}^{0\nu} > 3.5 \times 10^{25}\ \text{yr}$$

with >2 tonne yr of TeO_2, after five years of stable operation of nearly 1000 detectors. PubMed

CUORE current results page ↗

But the pedagogical question after showing CUORE should be:

> **We have excellent calorimetry and enormous scale. What is left to improve?**

Then CUPID-0 answers it.

CUPID-0 particle-ID result and figures ↗

The CUPID-0 figure showing spectra **before and after particle-ID selections** is the one I want. Heat + scintillation light suppresses α backgrounds and achieved $3.6^{+1.9}_{-1.4} \times 10^{-3}$ counts/(keV kg yr) in the ROI even in the first result. APS Journals

So the slide sequence becomes:

CUORE: scale + calorimetry
↓
but backgrounds…
↓
CUPID demonstrators: identify the particle
↓
your existing **CUPID / AMoRE / LEGEND future precision** slide. 20260624 Nu26

That is much more compelling than introducing CUPID cold.

CUORE: the **2 tonne·yr result is real and is the one we should use**, but it is **not** the Nature 2022 Fig. 4 I previously pointed you to. The current result is the 2025 *Science* paper, *"Constraints on lepton number violation with the 2 tonne·year CUORE dataset,"* $T_{1/2}^{0\nu} > 3.5 \times 10^{25}$ yr. Beneath the Dark +1 The plot I want is its **ROI fit**: data in the $Q_{\beta\beta}$ region with the best-fit/background and 90%-limit curves. LBNL actually reproduces/describes exactly that plot on its result page. Nuclear Science …

2025 CUORE result ↗

So: **use the 2025 Science ROI figure**, not the old Nature Fig. 4. The latter is still useful if we wanted the full spectrum showing where the backgrounds come from—the Nature paper says ~90% of the continuum near the ROI was degraded α background—but it is old data. Nature

CUPID: yes, 2018 is unnecessarily old. The cleaner choice is actually **CUPID-Mo final results (2022)** rather than the first CUPID-0 paper. CUPID-Mo used $Li_2^{100}MoO_4$, i.e. essentially the technology chosen for CUPID, and its final 1.47 kg·yr ^{100}Mo exposure had **zero events in the ROI**, giving $T_{1/2}^{0\nu} > 1.8 \times 10^{24}$ yr. arXiv More importantly for our story, it demonstrated the heat+light approach with complete α/βγ discrimination and ~7 keV FWHM resolution around the relevant energy scale. Indico

CUPID-Mo final paper ↗

There is also a **2022 final CUPID-0 result**, so even if we prefer the visually striking ZnSe α-rejection plot we don't have to cite the 2018 first result: the final exposure was 8.82 kg·yr ^{82}Se and $T_{1/2}^{0\nu} > 4.6 \times 10^{24}$ yr. arXiv But pedagogically I now prefer:

> **CUORE 2025:** this is the residual-background problem.
> **CUPID-Mo 2022:** this is the demonstrated solution.
> **CUPID 2025 design:** now scale that solution in the CUORE infrastructure.

That is also very current: the full CUPID design paper appeared in EPJC in July 2025. Springer Link

5. EXO-200 — use the SS/MS data

EXO-200 complete-dataset paper and figures ↗

This is where I want the audience to understand what a TPC gives you.

The complete dataset has **234.1 kg yr of ^{136}Xe exposure**, and the final analysis uses event information to discriminate signal and backgrounds. APS Journals

I'd use the figure showing the **single-site and multi-site spectral components/data** rather than simply its ROI. That's the educational distinction:

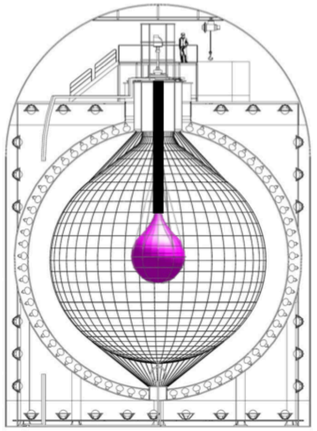
- ββ → predominantly single-site;
- many γ backgrounds → multi-site;
- position provides another handle;
- Xe itself provides shielding.

Message: *A homogeneous calorimeter can know more about an event than its energy.*

Then nEXO later feels like the scaling of a demonstrated technique rather than a concept drawing.

KamLAND-Zen

KamLAND-Zen 400

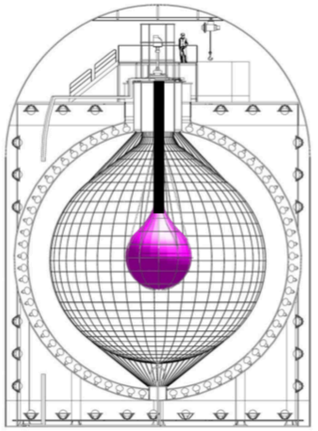


380kg deployed

$T^{0\nu}_{1/2} > 1.07 \times 10^{26}\,\mathrm{yr}$

PRL117, 082503 (2016)

KamLAND-Zen 800



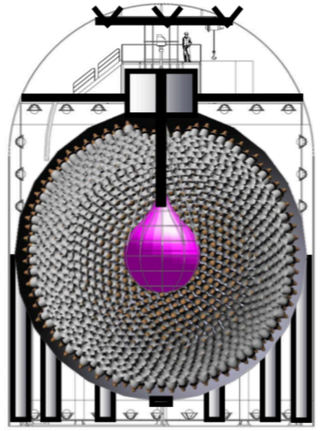
Now, 745kg deployed

$> 2.3 \times 10^{26}\,\mathrm{yr}$

PRL130, 051801 (2023)

Further improvements going on;
better neutron tagging
machine learning (ML) for long-lived tagging
ML for beta/gamma discrimination
muon-bundle tracking, and so on

KamLAND2-Zen



Mirror
HQE-PMT
new LS
full volume effective
w/ scintillation film
} x5 p.e.

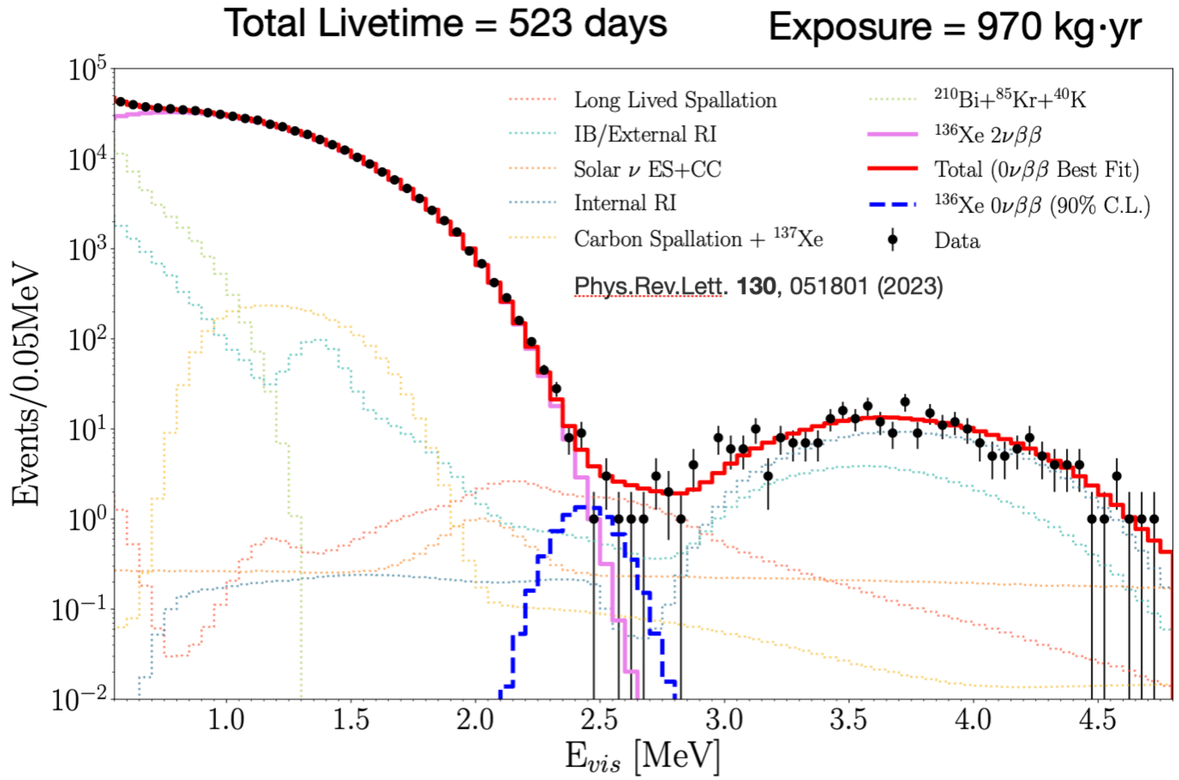
1 ton planned (scalable)

$> 2 \times 10^{27}\,\mathrm{yr}$ (target sensitivity)

$< 12 \sim 53\,\mathrm{meV}$ (corresponding mass limit)

Further technologies being developed
imaging sensor (1/10 reduction of long-lived BG)
high-p xenon deployment (2 times more xenon)

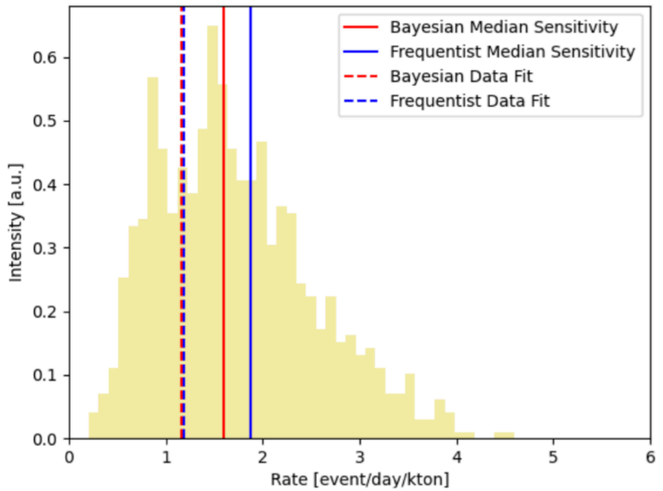
KLZ results



$$T_{1/2}^{0\nu\beta\beta} > 2.0 \times 10^{26}\text{yr}\ 90\,\%\,\text{C.L.}$$

N. Kawada: Neutrino 2022

C. Grant



Median Sensitivity:

$$T_{1/2}^{0\nu\beta\beta} > 1.5 \times 10^{26}\text{yr}\ (90\,\%\,\text{C.I.})$$

Combination of KLZ-400 and KLZ-800

$$T_{1/2}^{0\nu\beta\beta} > 2.3 \times 10^{26}\text{yr}$$

$$\langle m_{\beta\beta} \rangle < 36 - 156\,\text{meV}$$

6. KamLAND-Zen — the counterexample to almost everything above

Complete KamLAND-Zen dataset and figures ↗

Use the final **KLZ-800 spectral fit around the 0ν region**, ideally with its background components visible.

The complete dataset contains **745 kg enriched Xe and 2.1 tonne yr ^{136}Xe exposure**. The combined result corresponds to $m_{\beta\beta} < 28$–122 meV. APS Journals

The reason this is such an important teaching plot is precisely that it isn't clean in the GERDA sense.

Put EXO and KLZ next to one another conceptually:

> **Same nucleus: ^{136}Xe. Two very different answers.**

EXO: extract information about each event.
KamLAND-Zen: exploit enormous isotope exposure.

And both work.

That reinforces the entire thesis of your Nu26 deck: **nature hasn't supplied one optimal detector**.

20260624 Nu26

7. NEMO-3 — I found exactly the plot I wanted

NEMO-3 detailed \(^{100}\)Mo data and figures ↗

Fig. 3 is excellent.

It contains both the **two-electron summed kinetic-energy distribution and the opening-angle distribution** for ^{100}Mo. This isn't some handful of exotic candidates: NEMO-3 collected about 5×10^5 $2\nu\beta\beta$ **events**, S:B ~ 80, from 34.3 kg yr. Springer Nature ...

That means we can say:

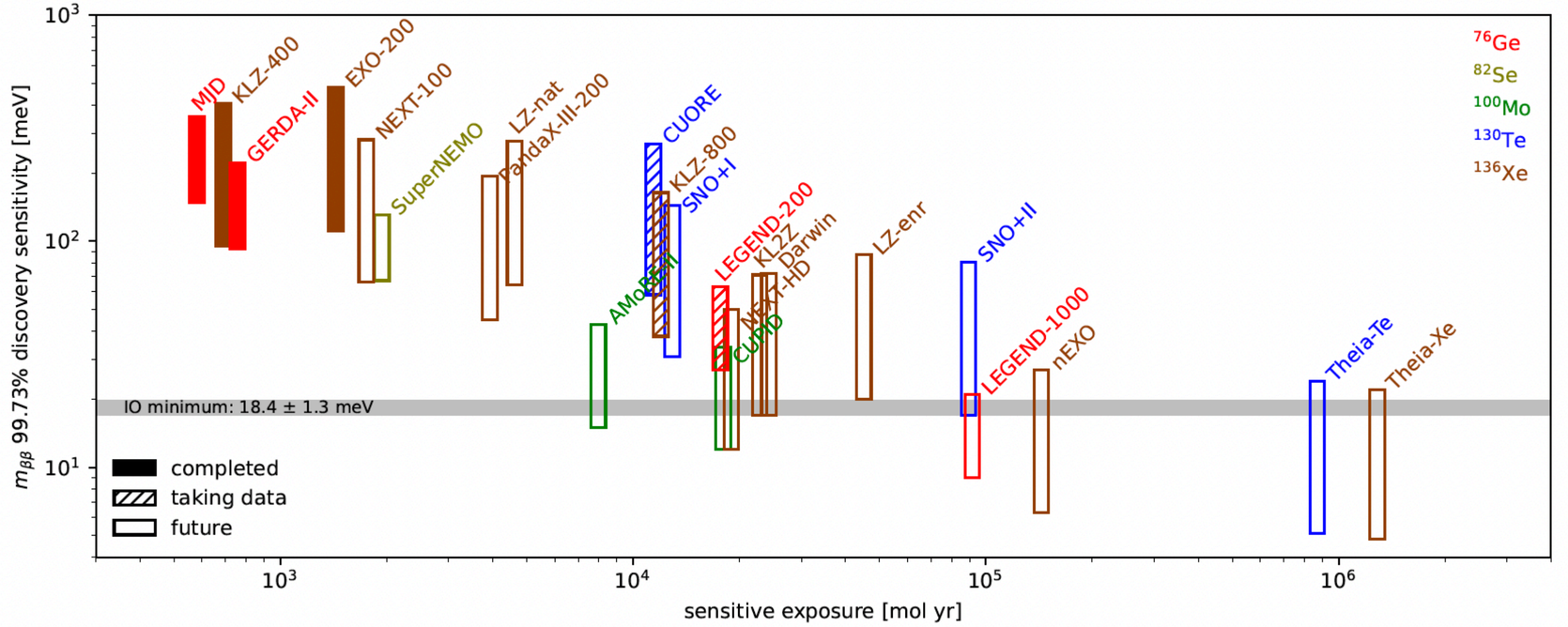
> Until now I've mostly shown you experiments that ask
> **"How much energy was deposited?"**
>
> NEMO asks
> **"What actually happened?"**

And show $E_1, E_2, E_{\text{sum}}, \cos\theta$.

Then your existing NEXT/SuperNEMO slide follows immediately and suddenly has much more intellectual weight: this is the extension of an experimentally demonstrated capability. 20260624 Nu26

Context

- An observation of 0νββ (demonstrating the Majorana nature of neutrinos) would reshape our understanding of the origins of mass and matter
- A definitive demonstration that neutrinos are *not* Majorana implies the existence of a new fundamental global symmetry associated with lepton number
- Discovery at the ton-scale would motivate advanced techniques to probe the mechanism
- Else, new detectors with greater sensitivity are needed to reach sensitivity beyond inverted mass ordering

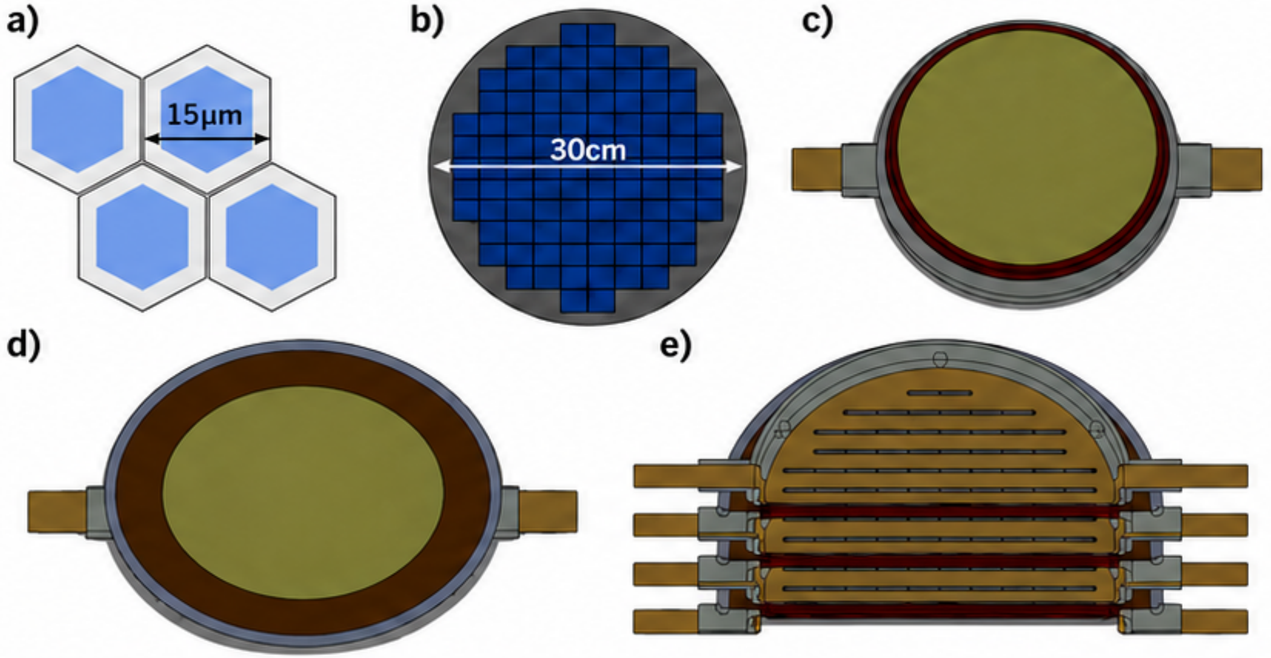


EMERGING RECONSTRUCTION CONCEPTS

Imaging the electrons directly

Selena

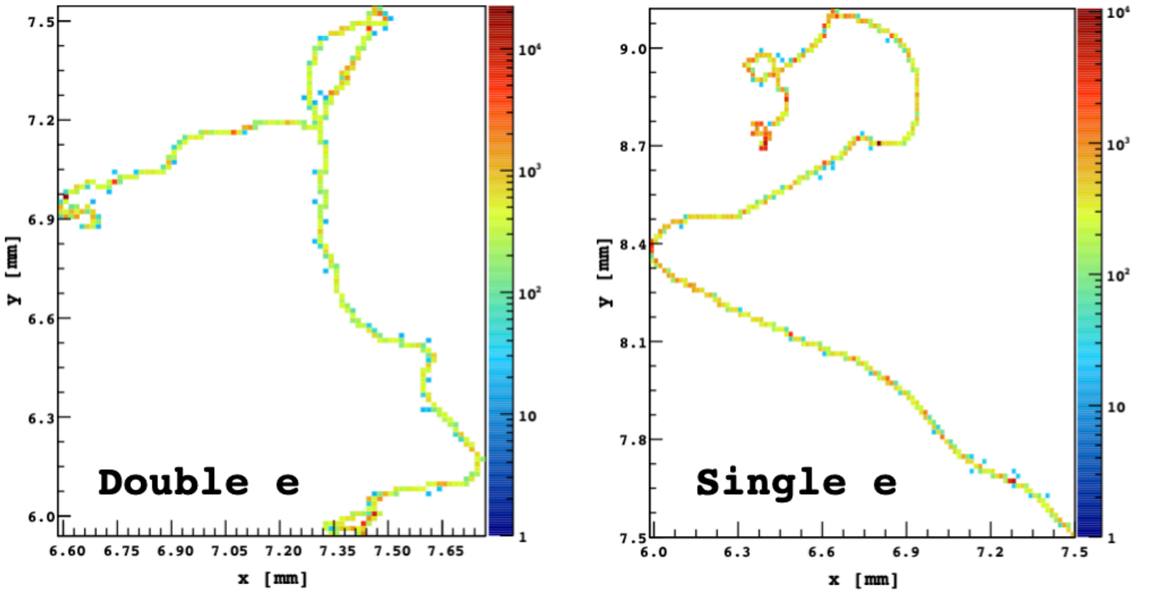
10 t ^{82}Se active target



- **^{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: $m_{\beta\beta} \approx 4\text{–}8$ meV

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

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

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

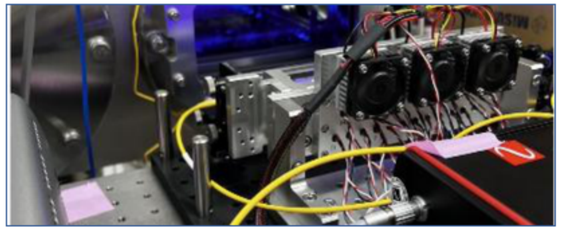
↓

Ton-scale ^{48}Ca target

THE OPPORTUNITY

Laser isotope separation

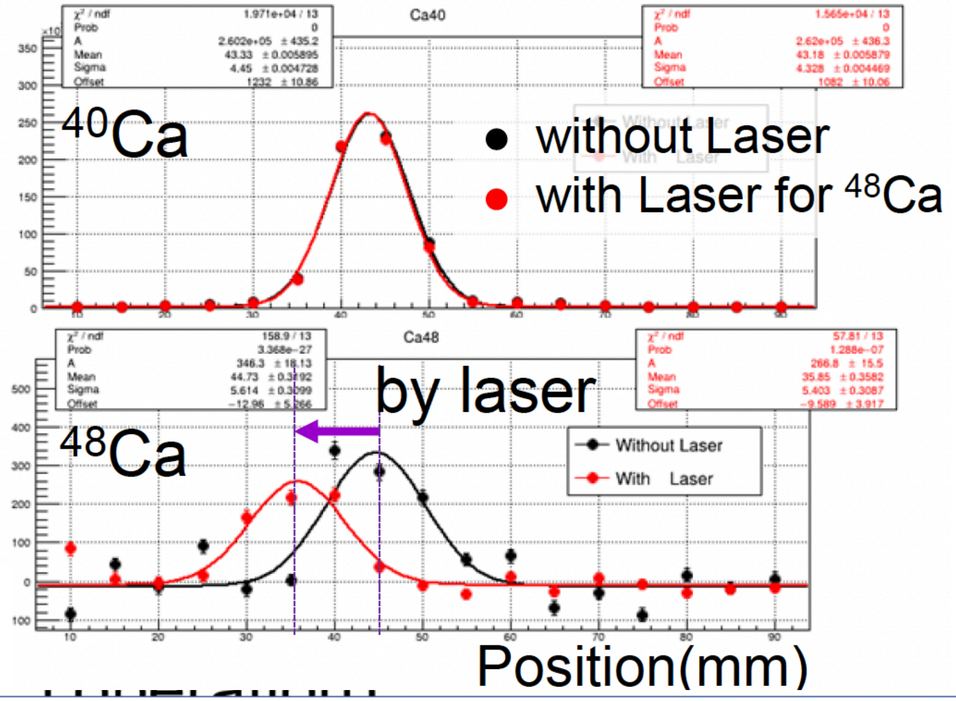
Laser system



80 mW × 24 = 2 W

Main chamber

- 6 laser ports
- 3 heater chambers, crucible

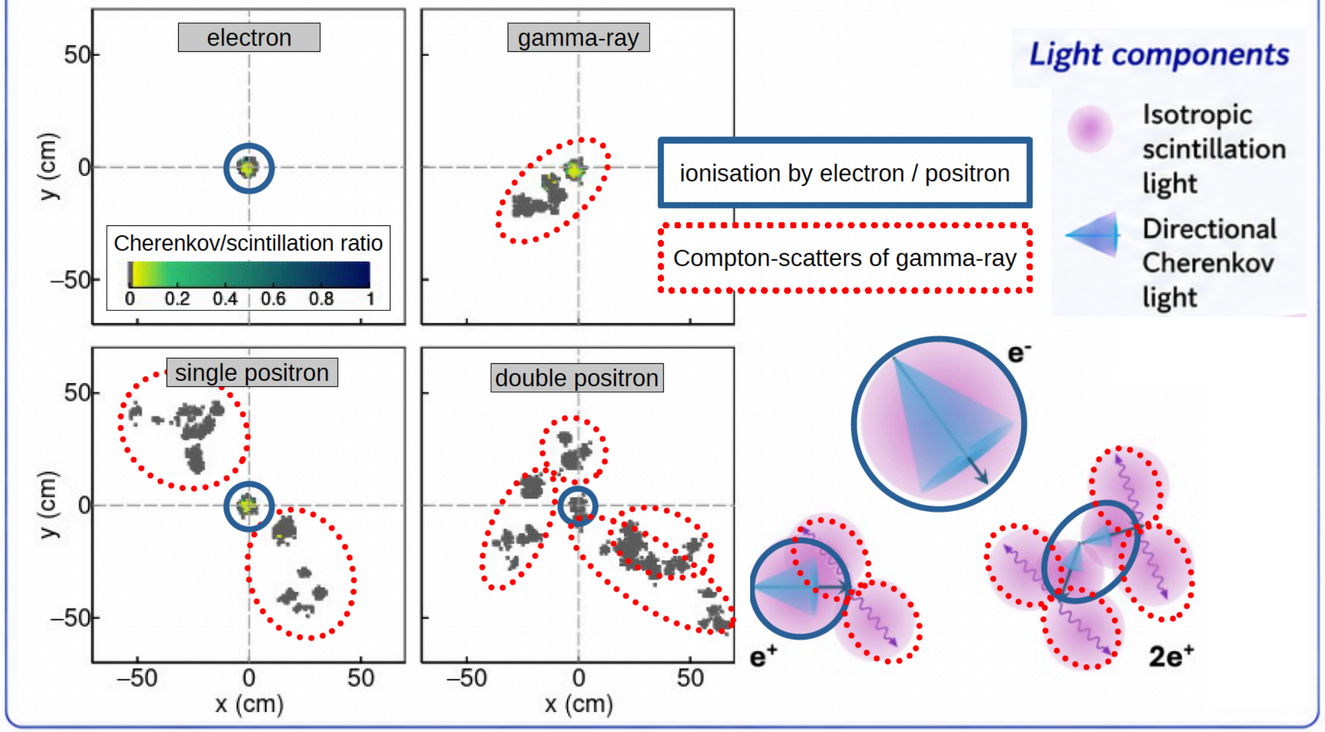


NuDoubt++

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

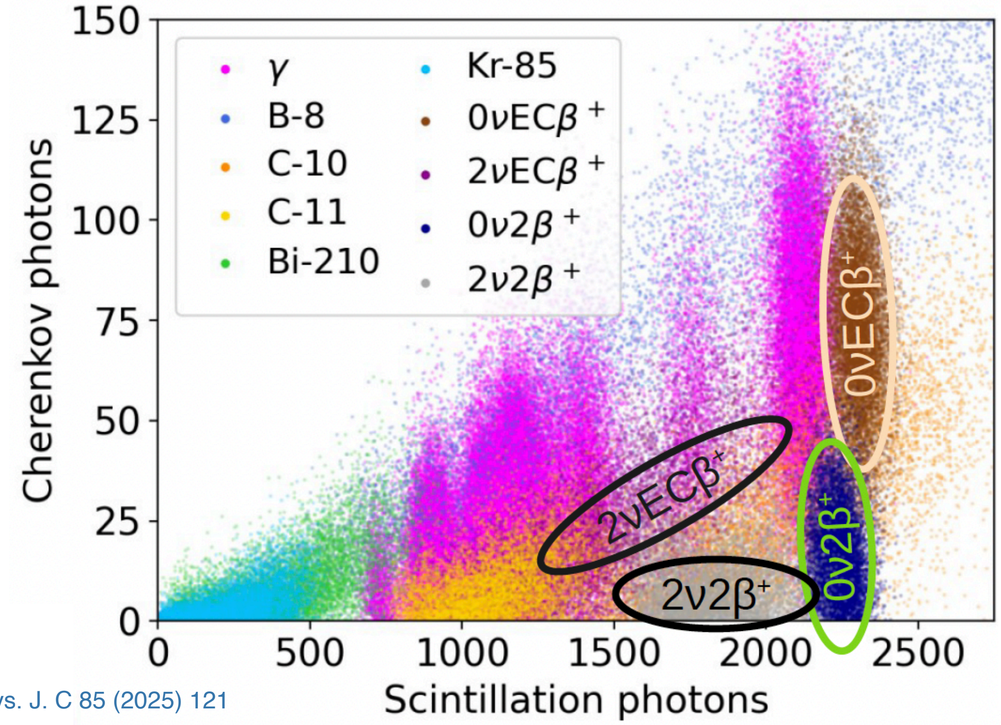
TOPOLOGY RECONSTRUCTION IN OPAQUE SCINTILLATOR

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

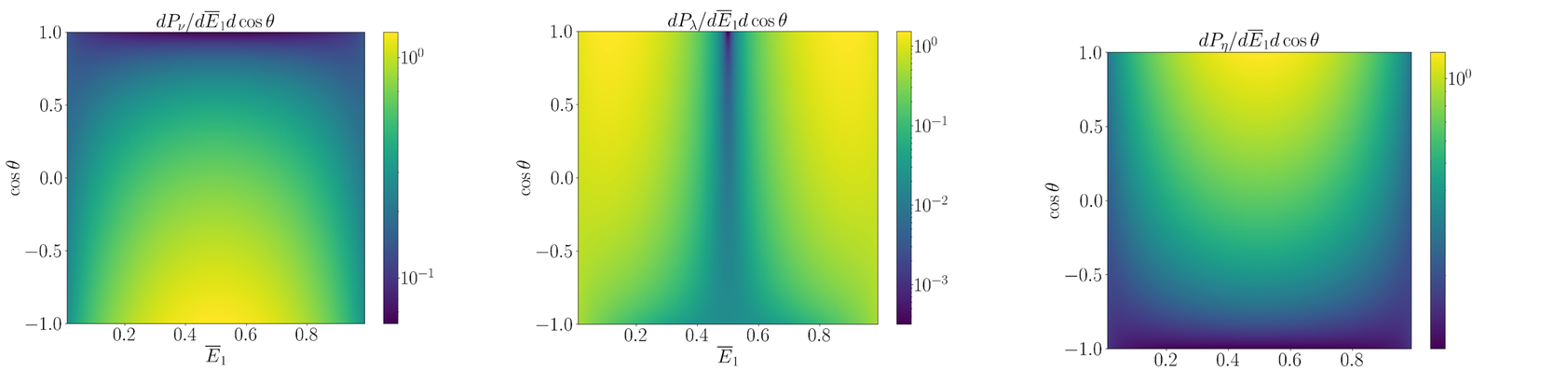
Combining topology and particle ID opens a new window on positron-emitting double-beta decays.

Beyond Discovery

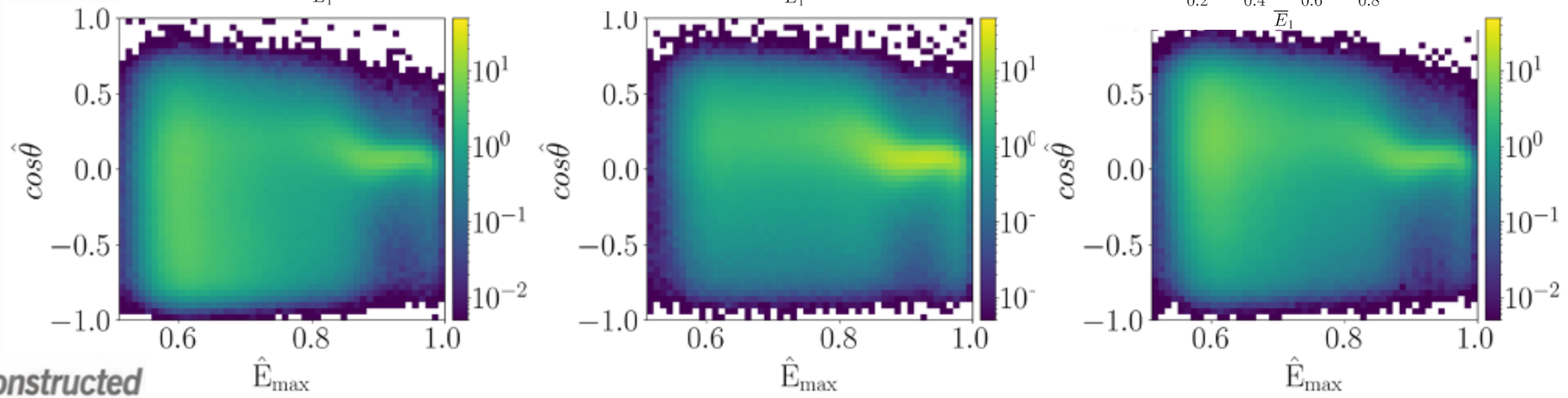
Can discovery become diagnosis?

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

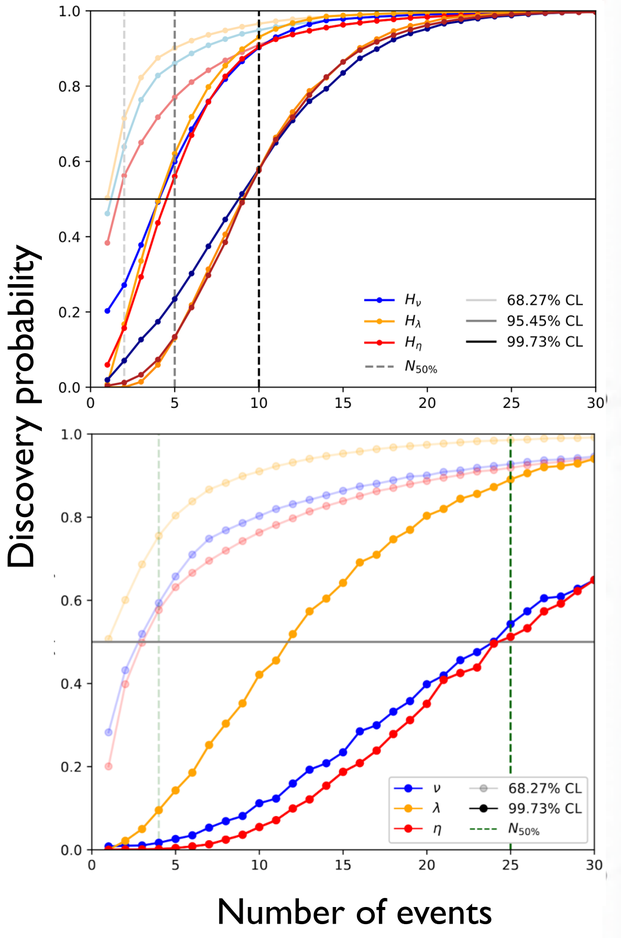
Ideal distributions



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)