Large Enriched Germanium Experiment for Neutrinoless ββ Decay

THE UNIVERSITY OF NEW MEXICO

Probing Physics Beyond the Standard Model via Neutrinoless Double Beta Decay

Research Talk - Neutrino Group

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Modified by M. Gold, May 6 2026

Physics Motivation for Neutrinoless Double-Beta Decay ($0\nu\beta\beta$)

The Standard Model is Incomplete

- Gravity
- Cosmological constant
- Dark matter
- Matter–antimatter asymmetry(baryon excess)
- Neutrino masses

Tension

- No right-handed neutrino ν_R (no Higgs Field (vev) , no mass via coupling $\psi_L \leftrightarrow \psi_R$) →lepton number conserved

Experiments

- Kamiokande & SNO (1990s–2000s): Neutrino oscillations → $\Delta m_{ij}^2 \neq 0$ and $\Delta m_{21}^2 > 0$ → neutrinos are massive
- KATRIN (2024): $m_\nu < 0.45$ eV (direct limit)

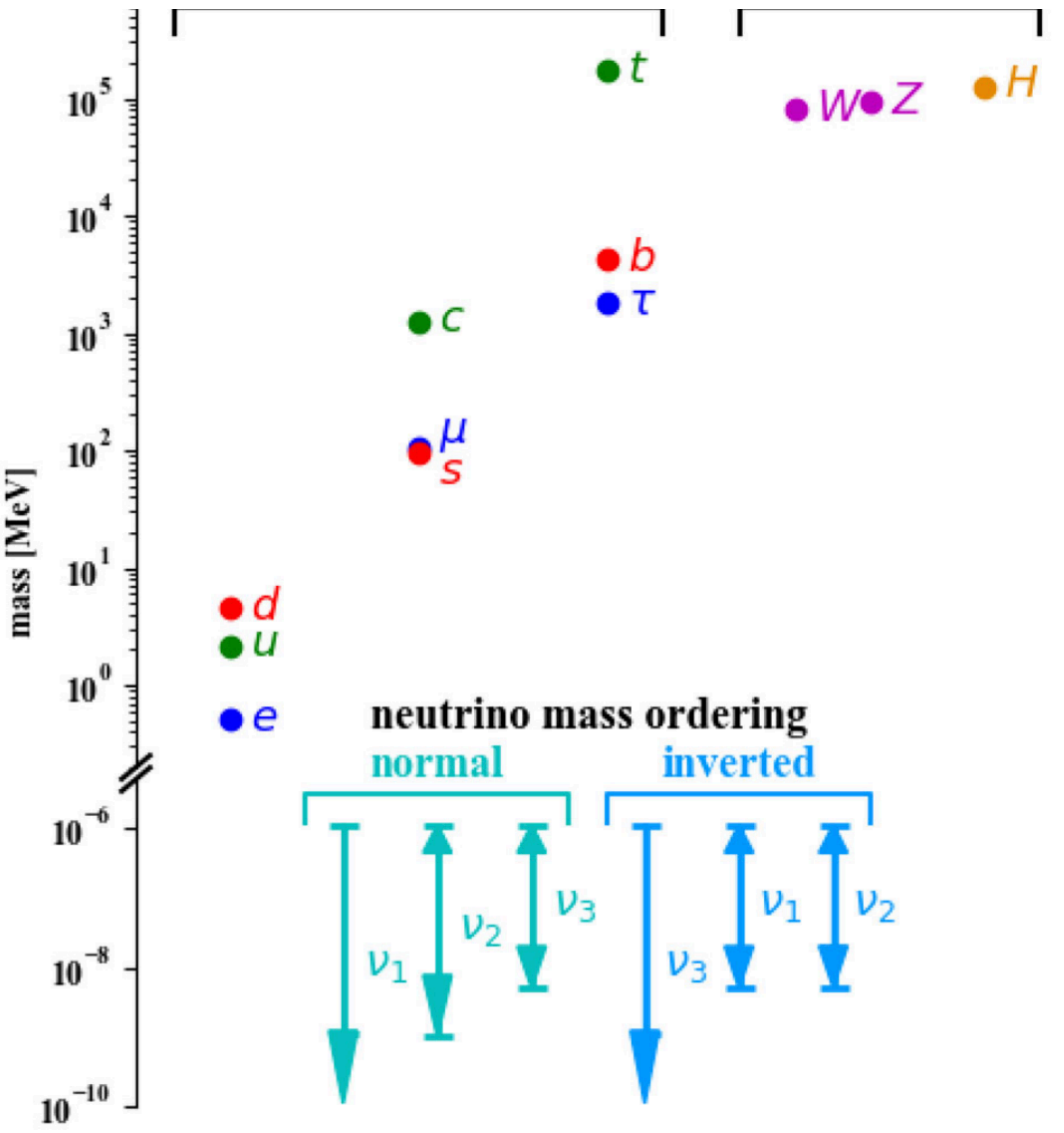


Fig. 4 Hierarchical structure of elementary particle masses. Only upper bounds for neutrino masses exi
Both normal and inverted neutrino mass ordering scenarios are shown. Mass values are taken from [17]

Proposed by Pauli to explain missing energy in β-decay —> neutral, light, weakly interacting

Now that we know they have mass:

1: Dirac Mass

- by adding ν_R and tiny coupling —> a Higgs Yukawa term is allowed: $\mathscr{L}_D = -y_\nu \bar{L}\tilde{H}\nu_R + \mathrm{h.c.}$
- Mass is via Higgs mechanism with tiny Yukawa coupling ~10^{-12}—> not explained (fine tuning?)

2: Majorana Mass (mechanisms)

- Using only ν_L, No new light fields required: $\mathscr{L}_M = \frac{1}{2} m_L \bar{\nu}_L^c \nu_L + \mathrm{h.c.}$ [1]
- $\nu = \bar{\nu}$ / $\Delta L = 2$ / Allowed only for neutral particles

Add to SM

(1) Weinberg Operator (low-energy effective description of multiple UV theories)

$\mathcal{L}_5 = \frac{c_{\alpha\beta}}{\Lambda}(L_\alpha H)(L_\beta H) + \mathrm{h.c.} \rightarrow \frac{c_{\alpha\beta} v^2}{\Lambda} \nu_{L\alpha}\nu_{L\beta}$ directly generates Majorana mass by coupling a neutrino to itself

(2) Heavy N_R (Type-I Seesaw)

$M : \begin{pmatrix} 0 & m_D \\ m_D & M_R \end{pmatrix}$ when Diagonalized: $m_\nu \approx -m_D M_R^{-1} m_D^T \simeq \frac{m_D^2}{M_R}$ explaining light neutrinos are the predicted Majorana neutrinos.

(3) Higgs Triplet (Type-II Seesaw)

Introduce a new scalar field Δ that predicts a new doubly charged scalar Δ^{++}
H2

$v_\Delta \sim \frac{\mu v^2}{M_\Delta^2}$ → direct (triplet seesaw mass) Majorana mass

All mechanisms violate "L" and hence predict "ovββ"[3]

But.. anomalies

etc..

Experimental Anomalies

Los Alamos Experiment with UNM collaboration

Excess anomaly (LSND / MiniBooNE):

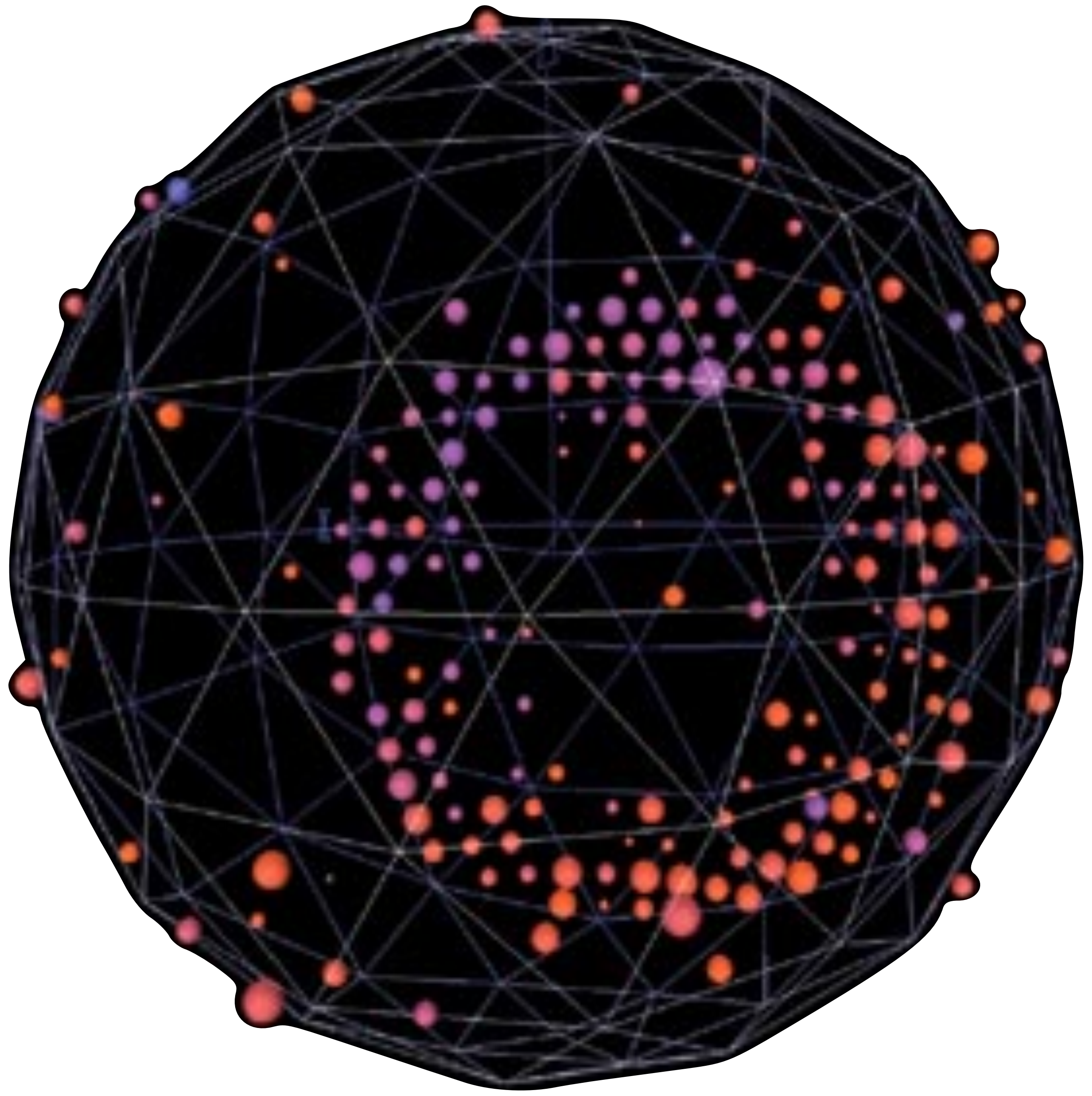
- Started with ν_μ but detected more ν_e than expected.→ extra oscillation?

Reactor anomaly (Daya Bay, RENO):

- Measured fewer $\bar{\nu}_e$ than predicted in nuclear reactors → extra oscillation?

Gallium anomaly (GALLEX, SAGE):

- Detected fewer ν_e than expected in artificial radioactive sources → short-distance oscillation to undetectable sterile neutrinos?



LSND event

Source: https://www.hep.upenn.edu/HEP_website_09/Talks/Seminars/talks/2009

Interpretation

- Some interpret as evidence ?? for a sterile neutrino

Tension

- do not fit the standard 3-neutrino oscillation framework.
- These results are inconsistent with each other under a simple sterile neutrino model

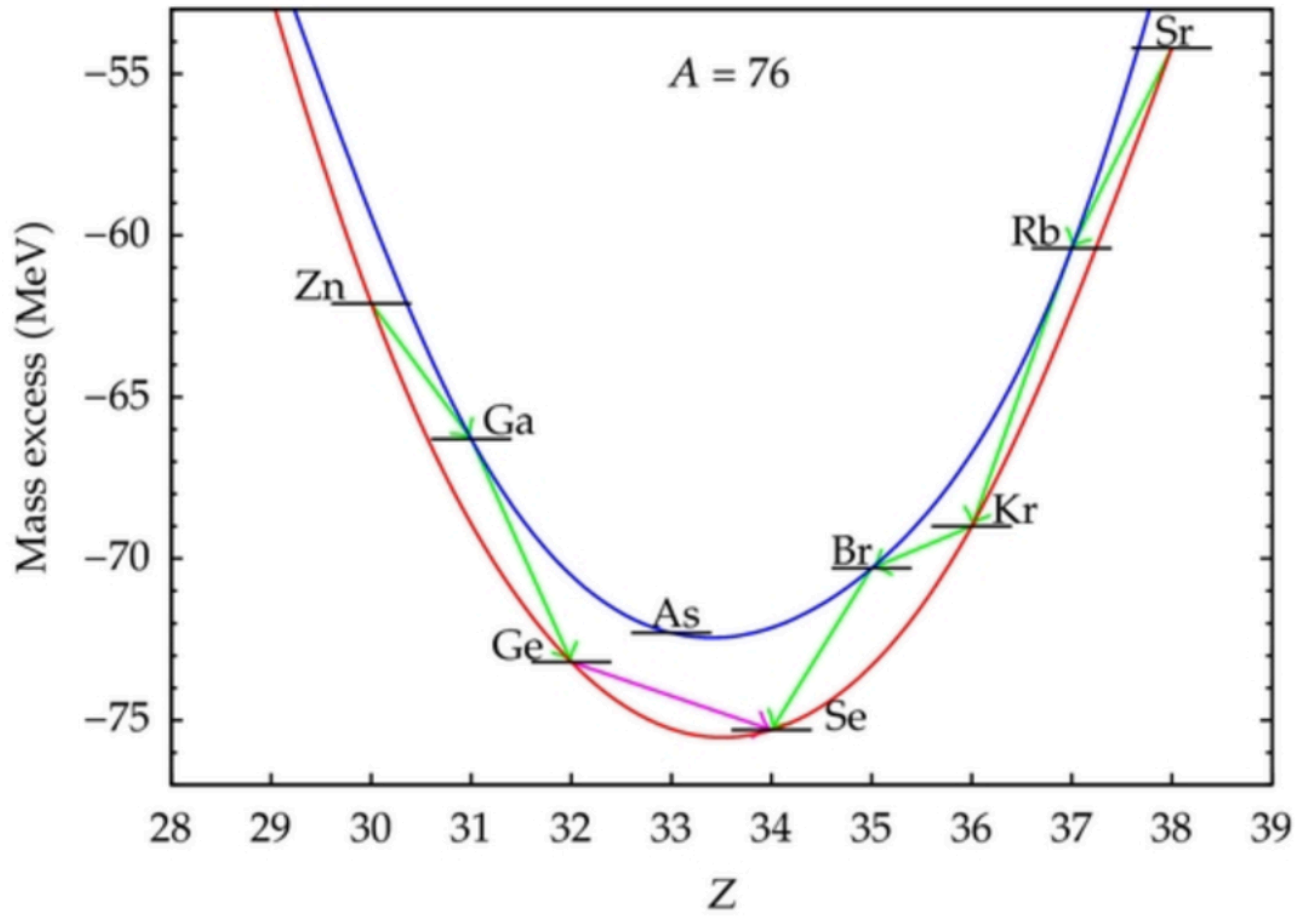
Anyways.. what was I saying about ββ

Why "Double" Beta Decay

β^- decay

2νββ Process

$(Z, A) \rightarrow (Z+2, A) + 2e^- + 2\bar{\nu}_e$ Occurs when single β decay is forbidden and happens in ~35 isotopes.

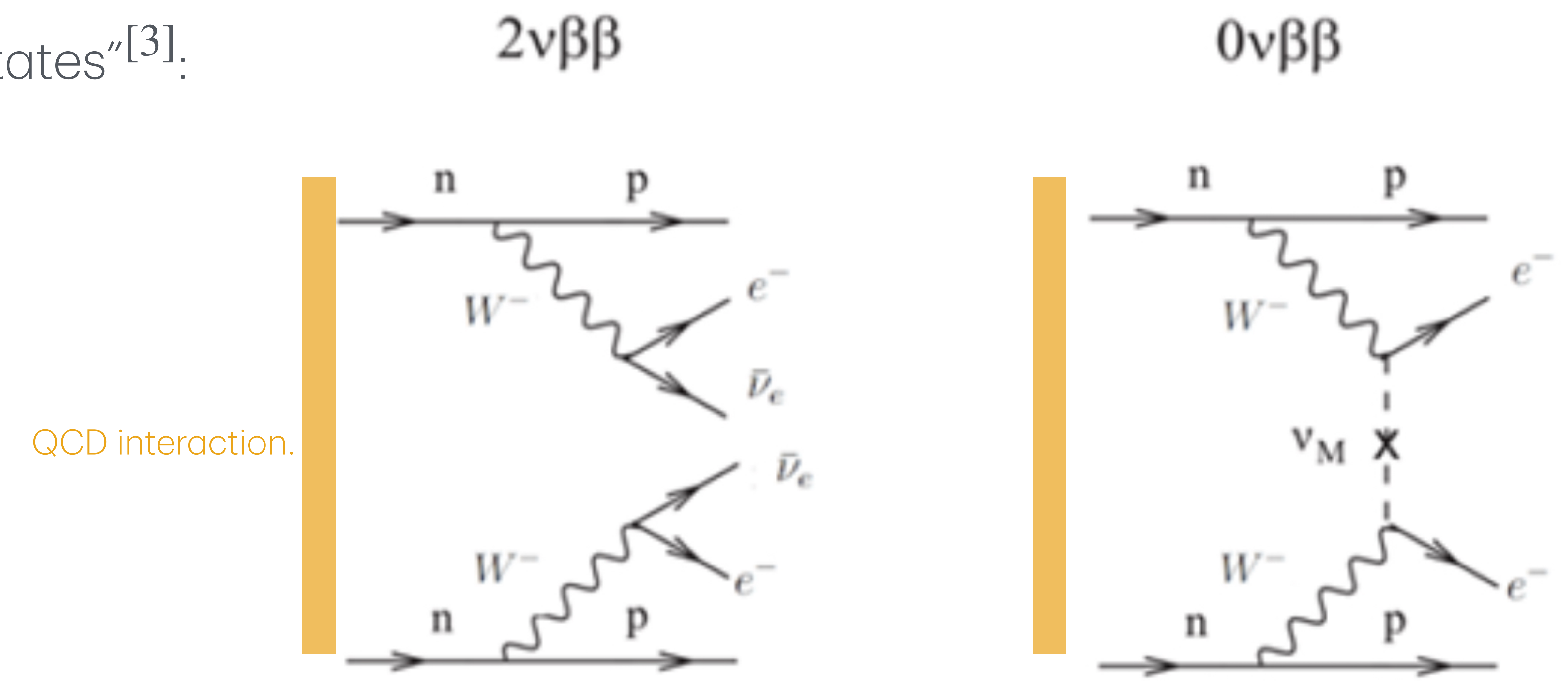


0νββ Process

$(Z, A) \rightarrow (Z+2, A) + 2e^-$ by exchanging of a virtual Majorana neutrino between two SM current vertices.

effective Majorana mass is proportional to "three mass eigenstates"[3]:

$$m_{\beta\beta} = \sum_i U_{ei}^2 m_i = c_{12}^2 c_{13}^2 e^{2i\lambda_a} m_1 + c_{13}^2 s_{12}^2 e^{2i\lambda_b} m_2 + s_{13}^2 m_3$$



the 0vββ rate depends on: $\frac{1}{T_{1/2}^{0\nu}} \propto |m_{\beta\beta}|^2 |M_{0\nu}|^2$ with Expected half-lives: $T_{1/2}^{0\nu} \sim 10^{26} - 10^{28}$ yr

Sensitive to:

- Absolute mass scale —> effective Majorana mass $m_{\beta\beta}$
- Majorana phases (not measurable in oscillations) —> nuclear matrix mass element $M_{0\nu}$
- Mass ordering —> (normal vs inverted)

Yet 0vββ is the only realistic probe of "L" violation in the neutrino sector.

Hierarchy

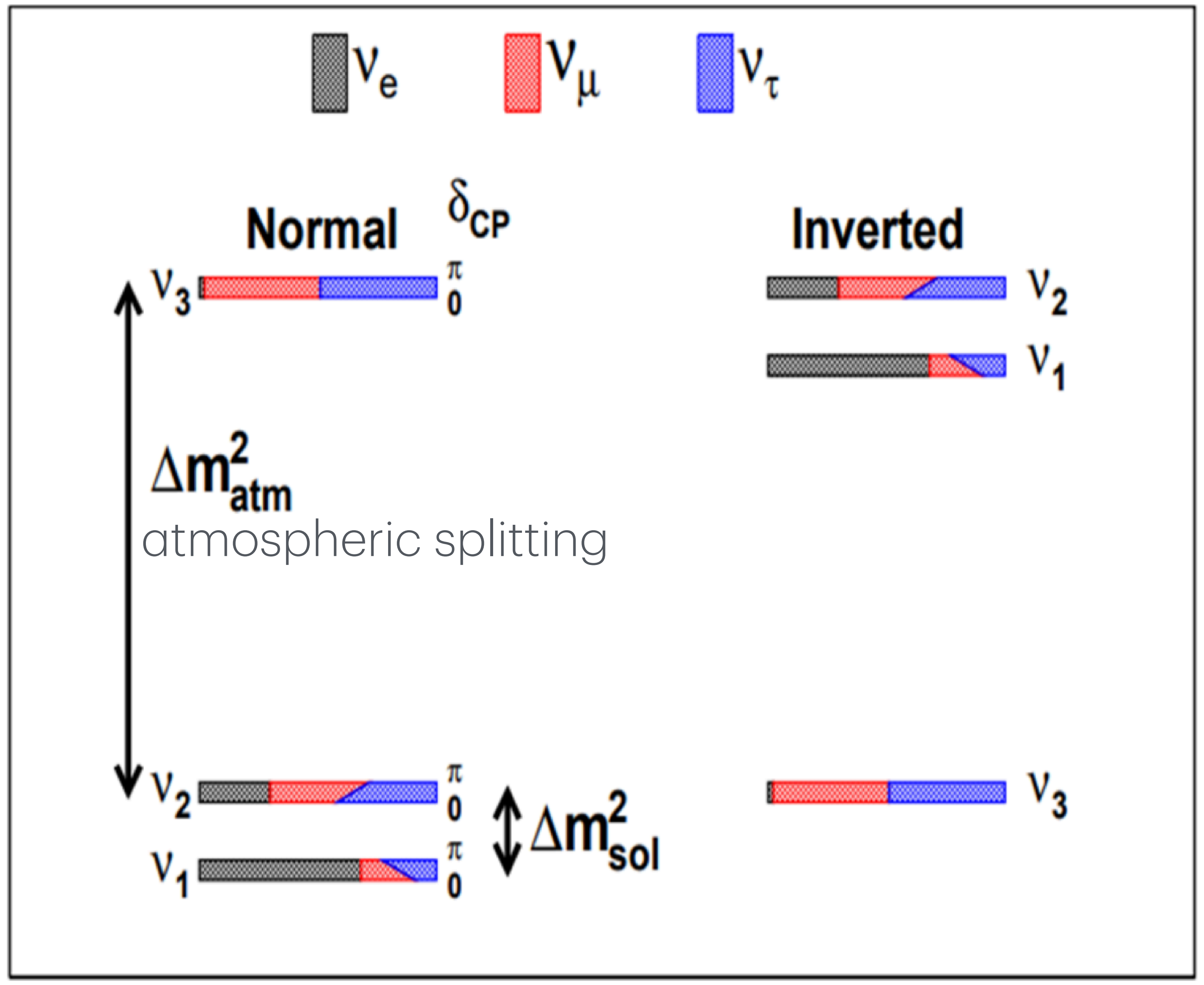
1. Mass eigenstates ν_1, ν_2, ν_3 and their flavor composition. $\nu_3$has a smaller electron-flavor component, affecting its contribution to$0\nu\beta\beta$.

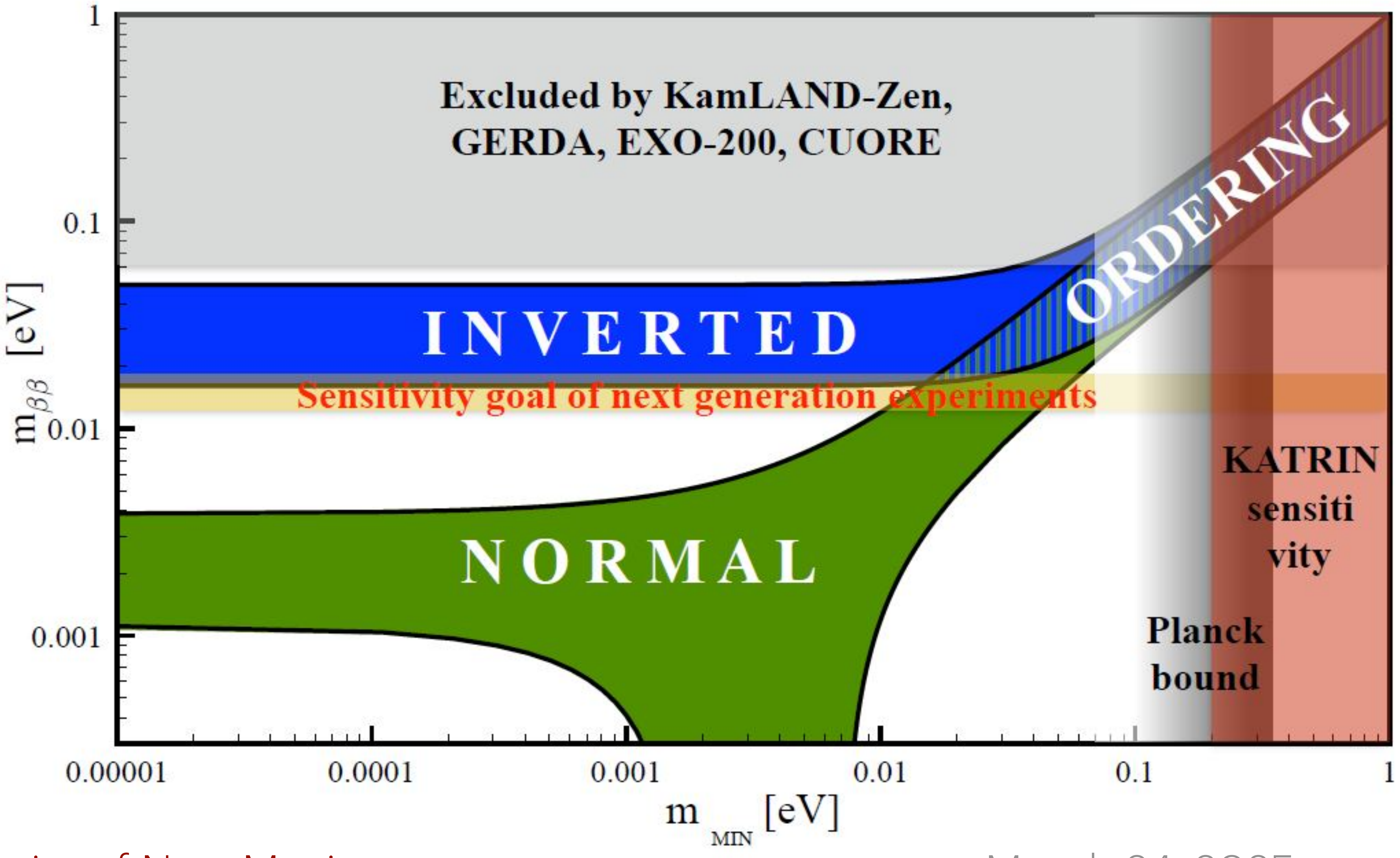
2. States contribute coherently to $m_{\beta\beta} = \left| \sum_i U_{ei}^2 m_i \right|$. so has a lower bound at $10^{-2} eV$ —> half-lives of order $T_{1/2}^{0\nu} \sim 10^{25}$ yr, so reaching this sensitivity allows experiments to fully probe the inverted hierarchy.

Experiment: **NOvA (2026)** Normal ordering favored (~2.4× over inverted) [5]

All we know are $M_i^2 - M_j^2$ and $M_2^2 > M_1^2$

Neutrino Mass Hierarchy





Cosmological Significance

CP-violating decays of heavy Majoranas

—> Generate leptogenesis

(Lepton number violation)

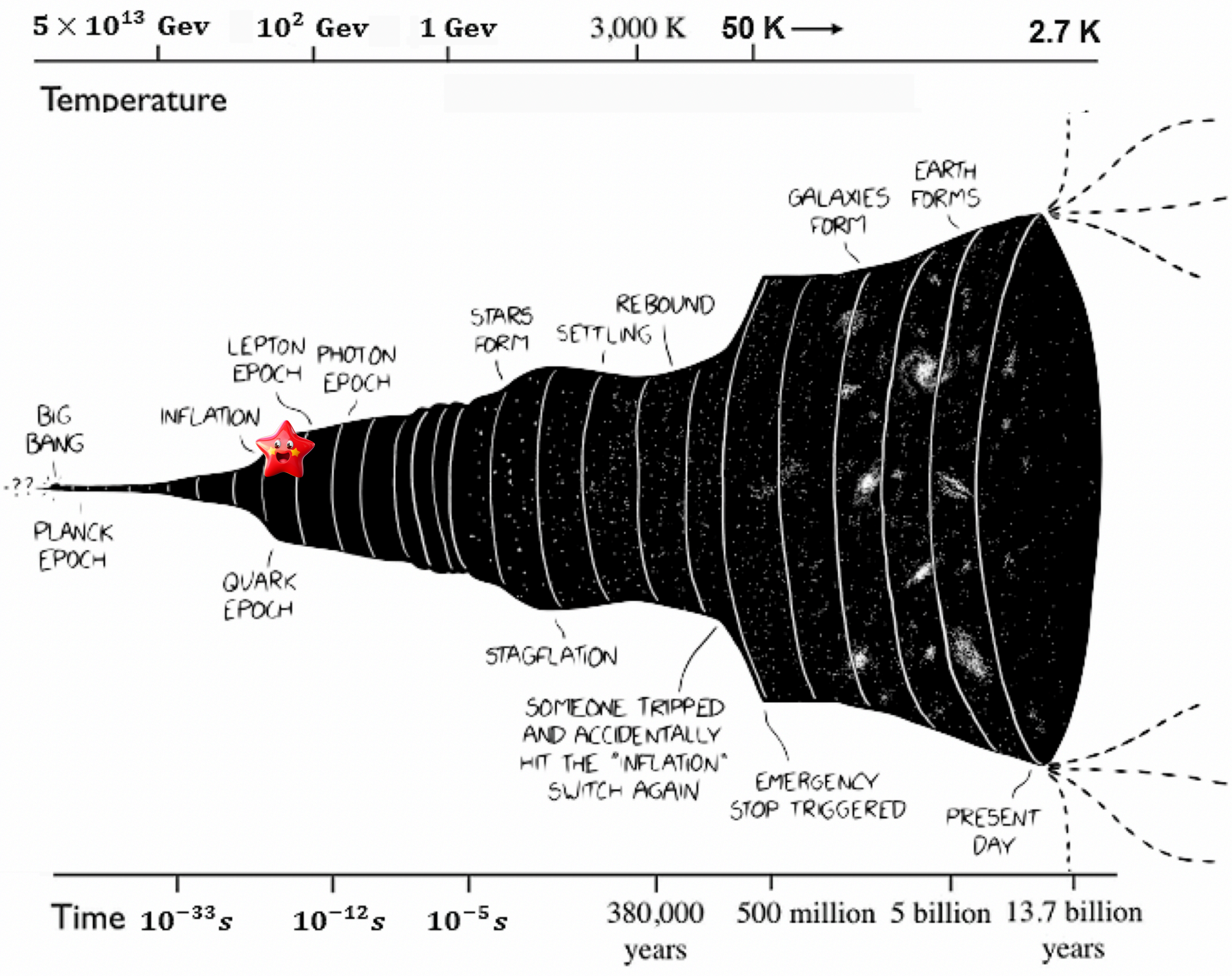
—> Converted to baryogenesis

If neutrinos are Majorana, Explains:

- Why neutrinos are light (seesaw)
- Why the universe has matter–antimatter asymmetry
- Direct window into BSM physics

0νββ is not just a rare decay:

it probes the fundamental structure of the Standard Model



Source: https://www.explainxkcd.com/wiki/index.php/2240:_Timeline_of_the_Universe

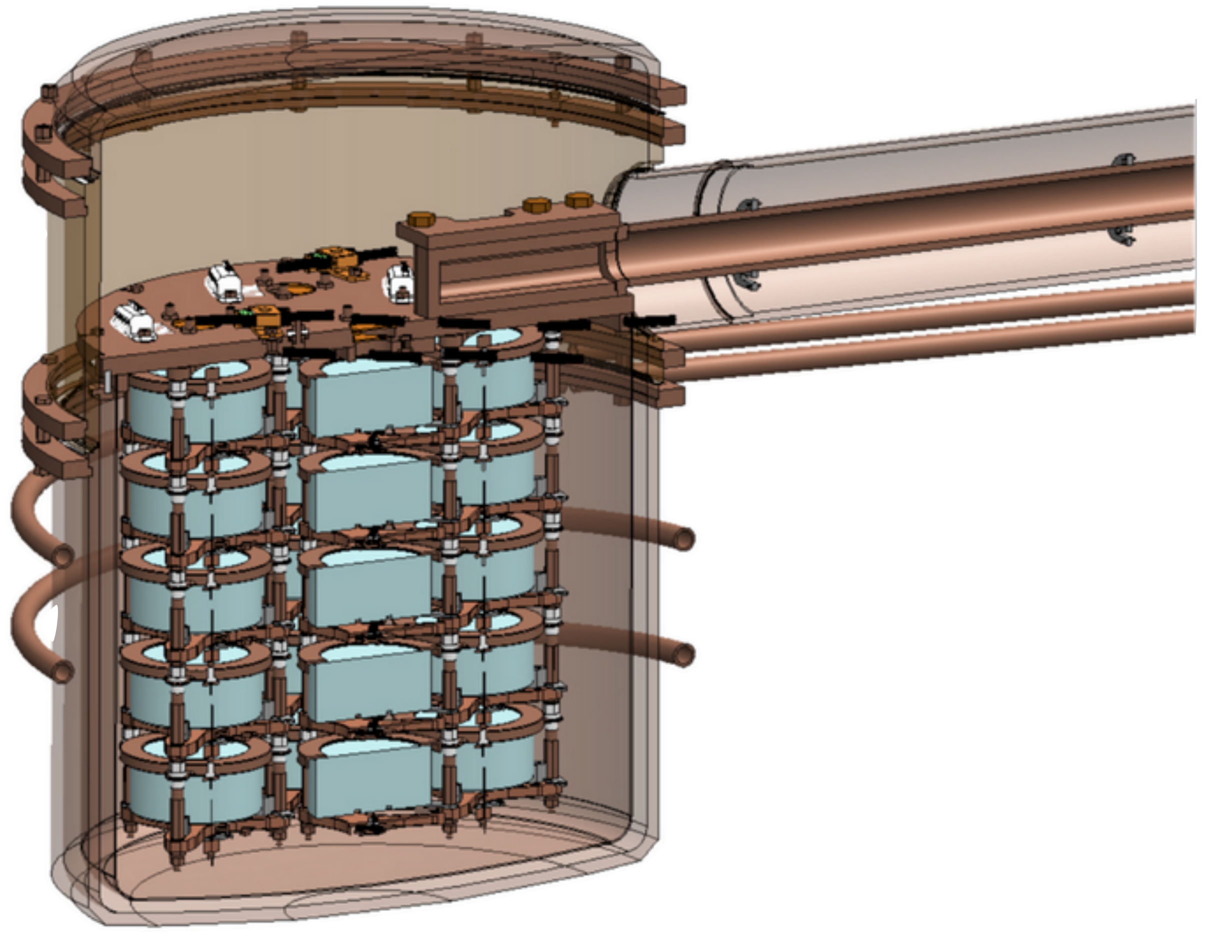
The LEGEND Experiment

From **GERDA**: LAr active veto and optimized cryostat and optical readout for background rejection, with first background free regime.

From **MAJORANA DEMONSTRATOR**: ultra-low backgrounds via radiopure materials, compact design, and PSD, demonstrating ton-scale Ge feasibility.

LEGEND-200: Early physics results and validation of low-background technologies at scale

LEGEND-1000: Discovery-level sensitivity and background-free exposure at tonne scale



Source: https://en.wikipedia.org/wiki/MAJORANA

Source: https://www.jinr.ru/posts/gerda-experiment

So backgrounds are a problem!!

Scaling of limit with background

- Background-free case

  If no background expected at $Q_{\beta\beta}$, Sensitivity scales linearly with exposure $T_{1/2}^{sens} \propto \epsilon N t$ (N = number of nuclei / ϵ= efficiency)

  So doubling exposure doubles the half-life sensitivity… ideal regime and what LEGEND aims for.

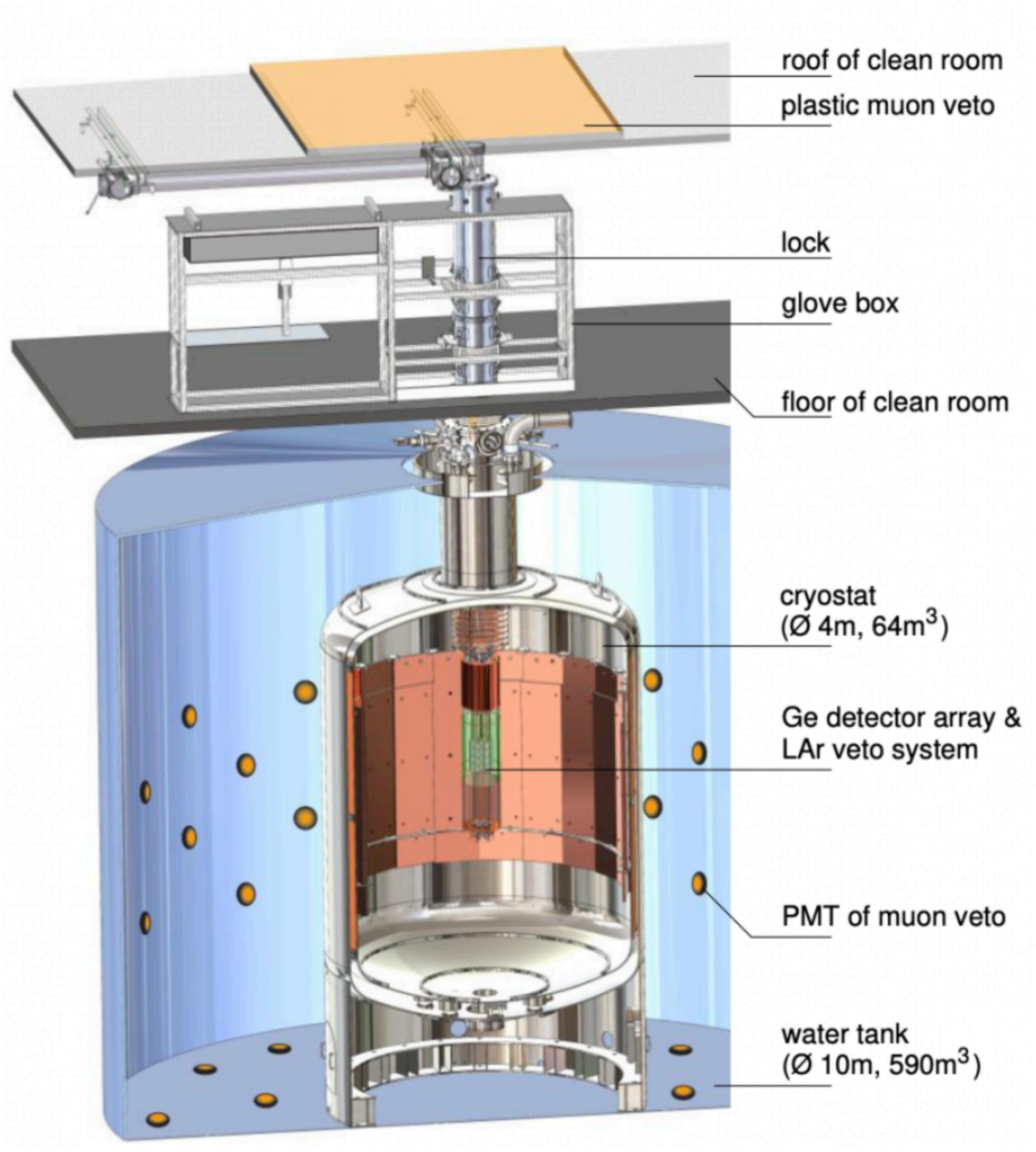
- Background-limited case

  If background events are present, Sensitivity scales only as $T_{1/2}^{sens} \propto \sqrt{\frac{Mt}{B\Delta E}}$ (detector mass / background index / energy window)

  Now improvements become much slower (square-root scaling).

Reducing background allows reaching $10^{28} - 10^{29}$ yr sensitivity[6].

LEGEND



Hardware

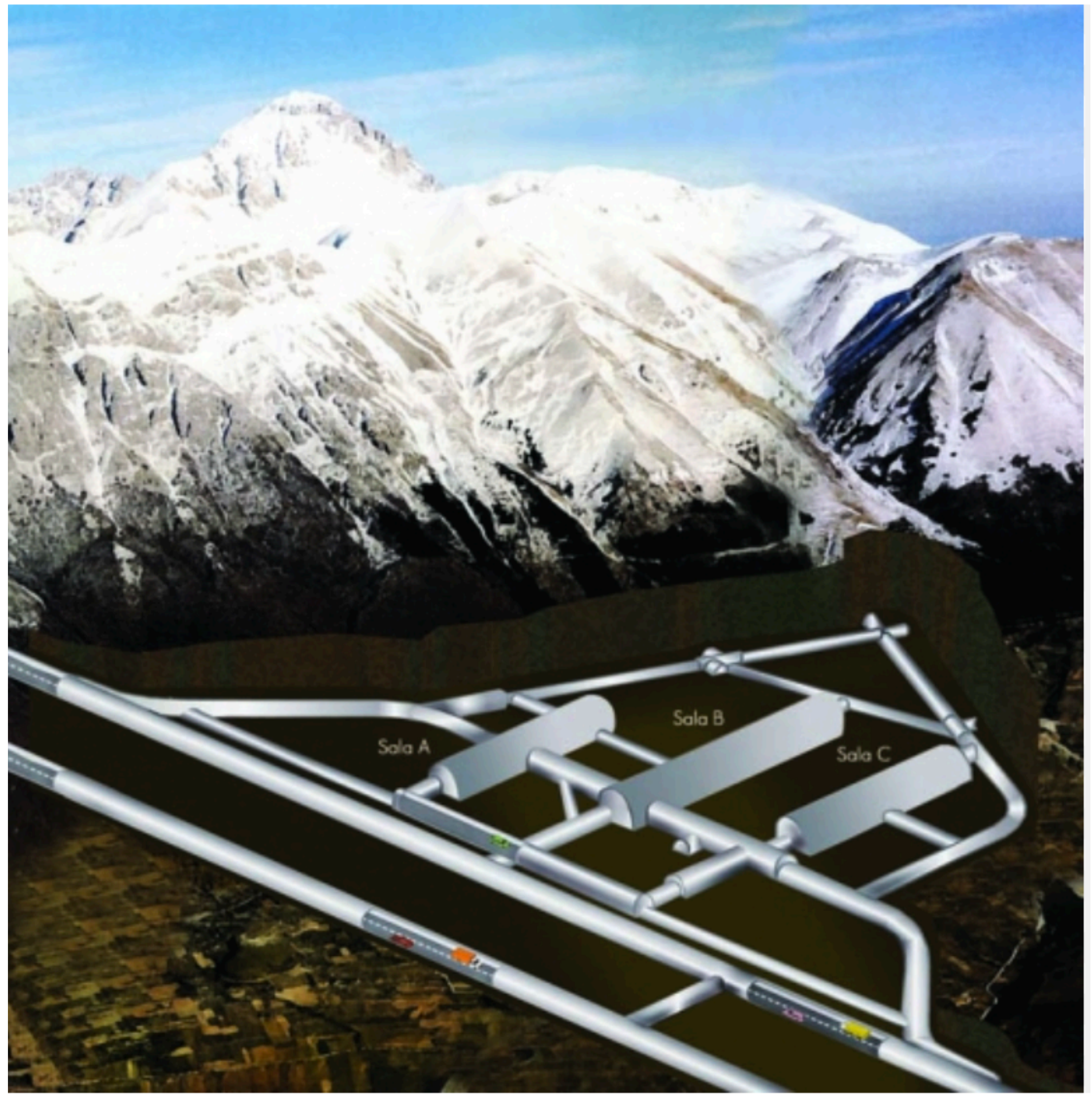
- HPGe detectors immersed in Instrumented LAr: (WLS fiber shrouds + SiPMs) provides cooling, and scintillation light background rejection

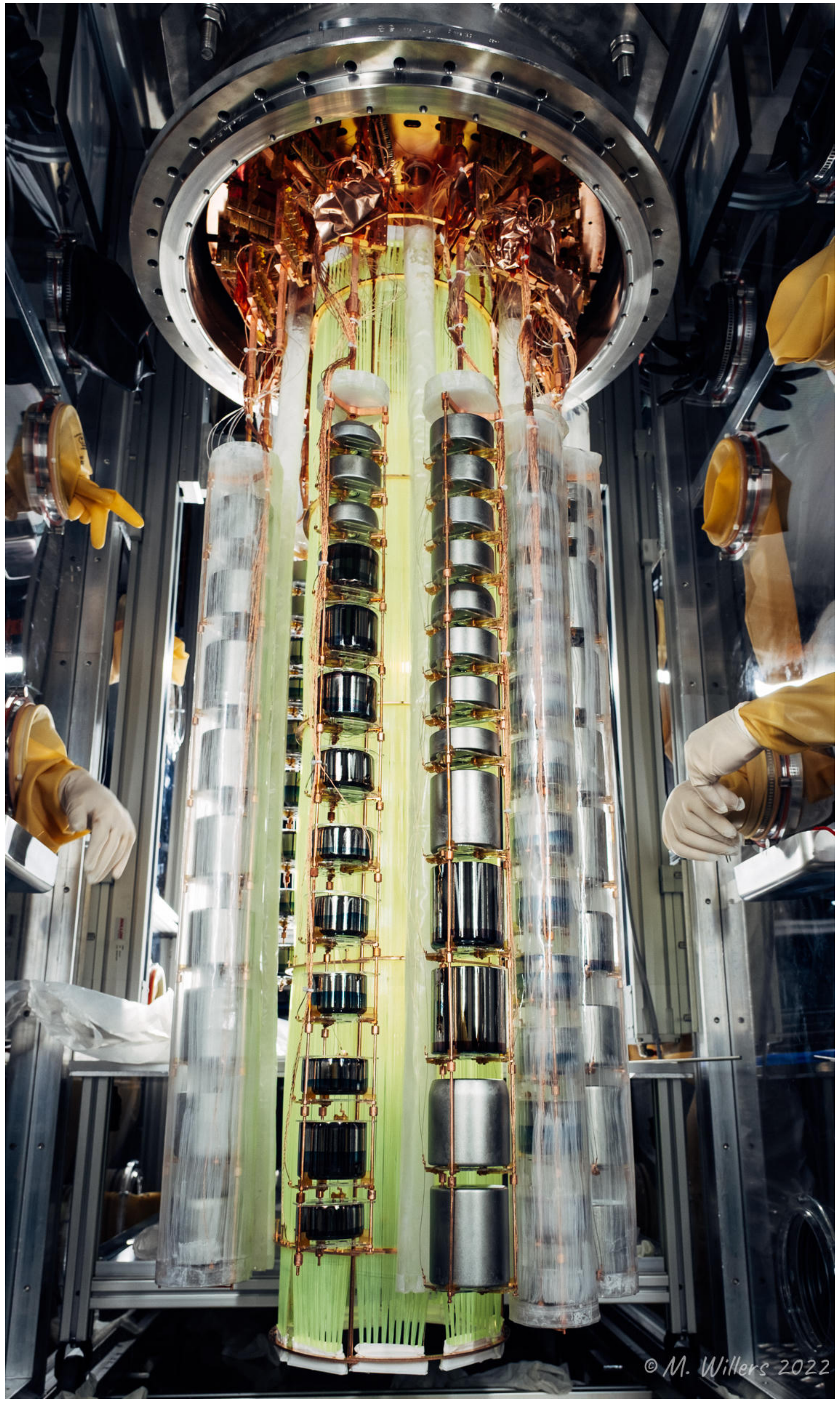
Background cuts

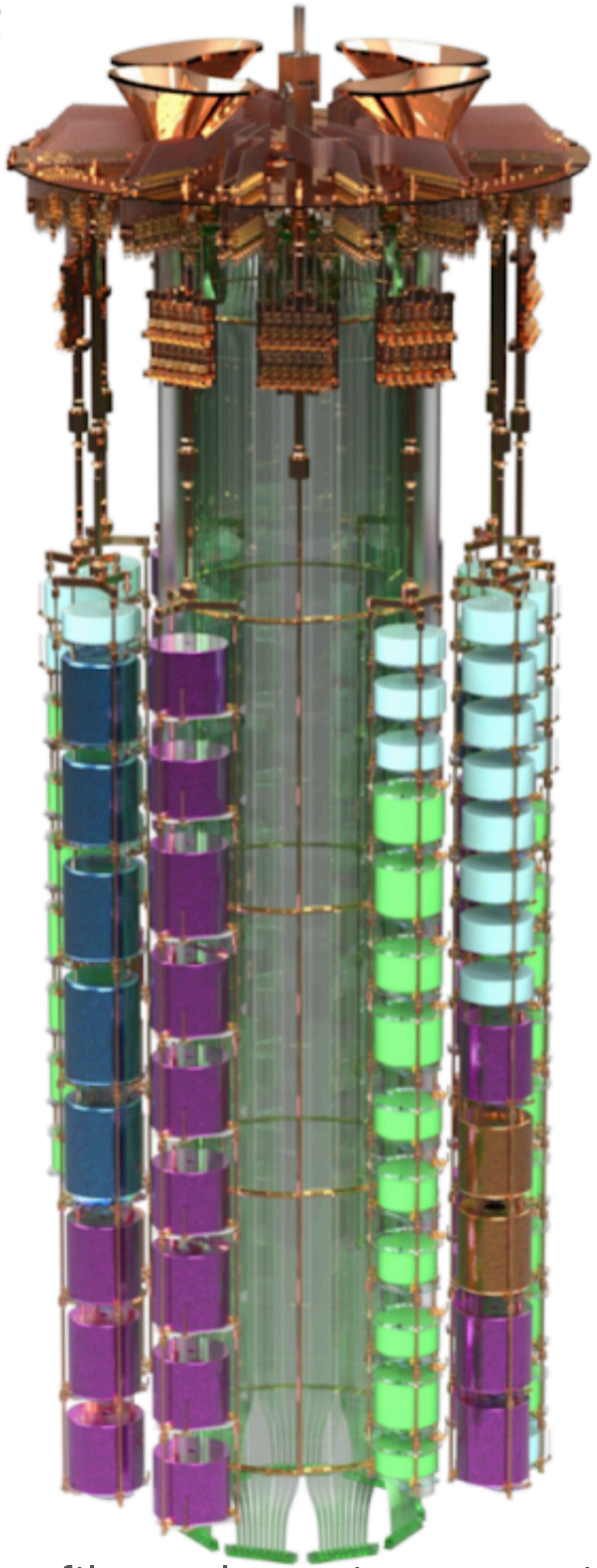
- Event rejection/cuts via: LAr energy veto / Detector anti-coincidence (multiplicity) / Pulse-shape discrimination (PSD)
- Detectors operated in a low-radioactivity cryostat and water shield deep underground at LNGS to suppress external γ, neutron, and cosmogenics.

<u>Underneath</u> Gran Sasso d'Italia

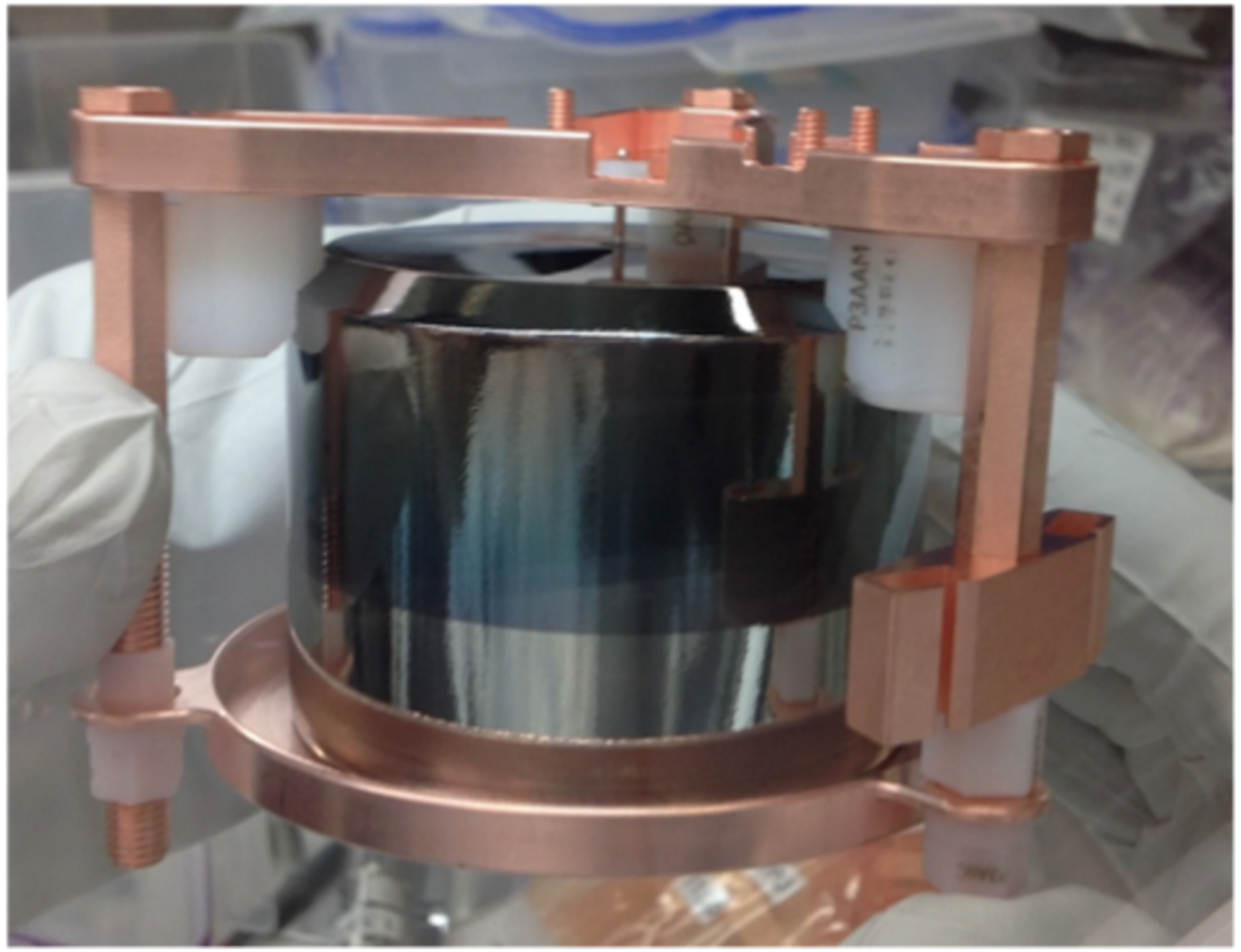
~10,000 feet high







Detectors are arranged in strings



~3kg single crystal Ge detector

fibers detecting LAr scintillation light are green

Source: legend-exp.org

Narrative

Experiment	HPGe Mass	Total Exposure	Expected 0νββ Events
MAJORANA (complete)	40.4 kg	65 kg·yr	~ 2.7
GERDA (complete)	44.2 kg	127.3 kg·yr	~ 5.3
LEGEND-200	142.5 kg (growing)	61 kg·yr	~ 2.5
LEGEND-1000 (projected)	1 ton	~ 10 ton·yr	~ 20-30

But how do we approach backgroundless $0\nu\beta\beta$?

Seeing a Rare Event

1— Precise Energy Measurement

Ultra-high energy resolution HPGe detectors

A true $0\nu\beta\beta$ event appears as a sharp mono-energetic peak (Backgrounds typically produce continuous spectra)

2— Event Topology Identification

- A true event is single-site, single-detector. Distinguishing event from background using **analysis cuts**
- Multiplicity cut (M1), Pulse Shape Discrimination (PSD)

3— Liquid Argon (LAr) Veto

Background interactions deposit energy in LAr → produce scintillation light

4— Simulation & Data Infrastructure

Geant4-based framework (REMAGE) generating idealized detector truth information

So how do **analysis cuts** work????

A true $0\nu\beta\beta$ decay deposits energy locally inside a single HPGe detector, producing a compact single-site signal.

M1

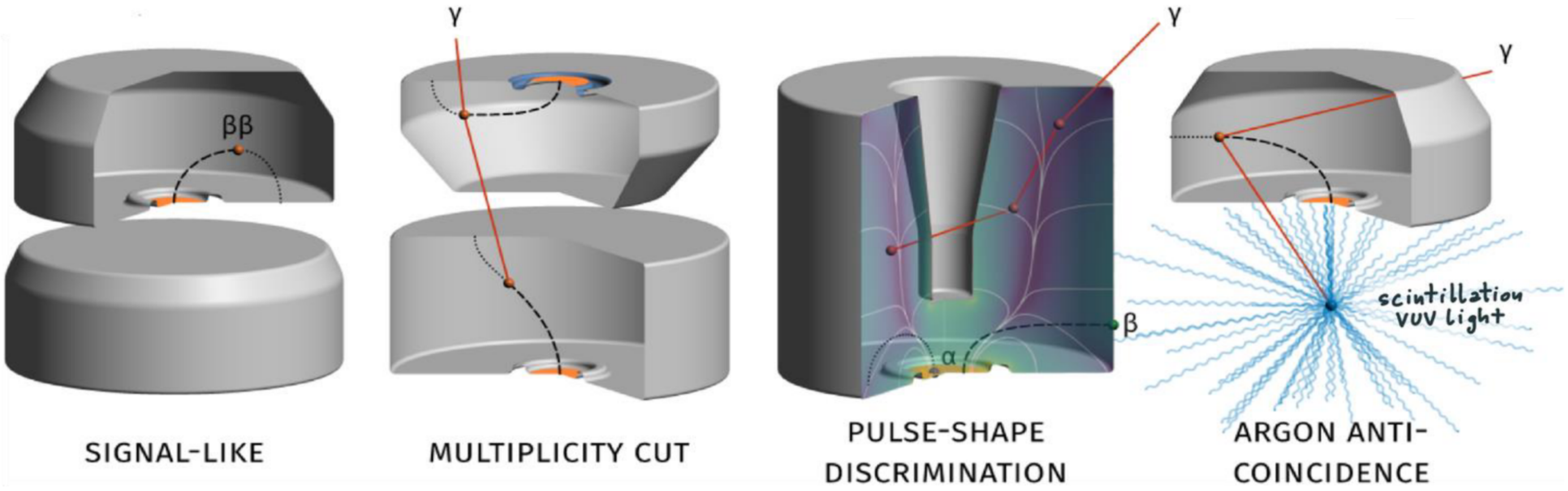
Background γ-rays often scatter between multiple detectors, so events triggering more than one crystal are rejected.

PSD

Even within one detector, γ backgrounds produce multi-site energy deposits, giving different waveforms than the single-site signal.

LAr veto

If a particle deposits energy in the LAr, it produces scintillation light; events coincident with this light are vetoed as background.

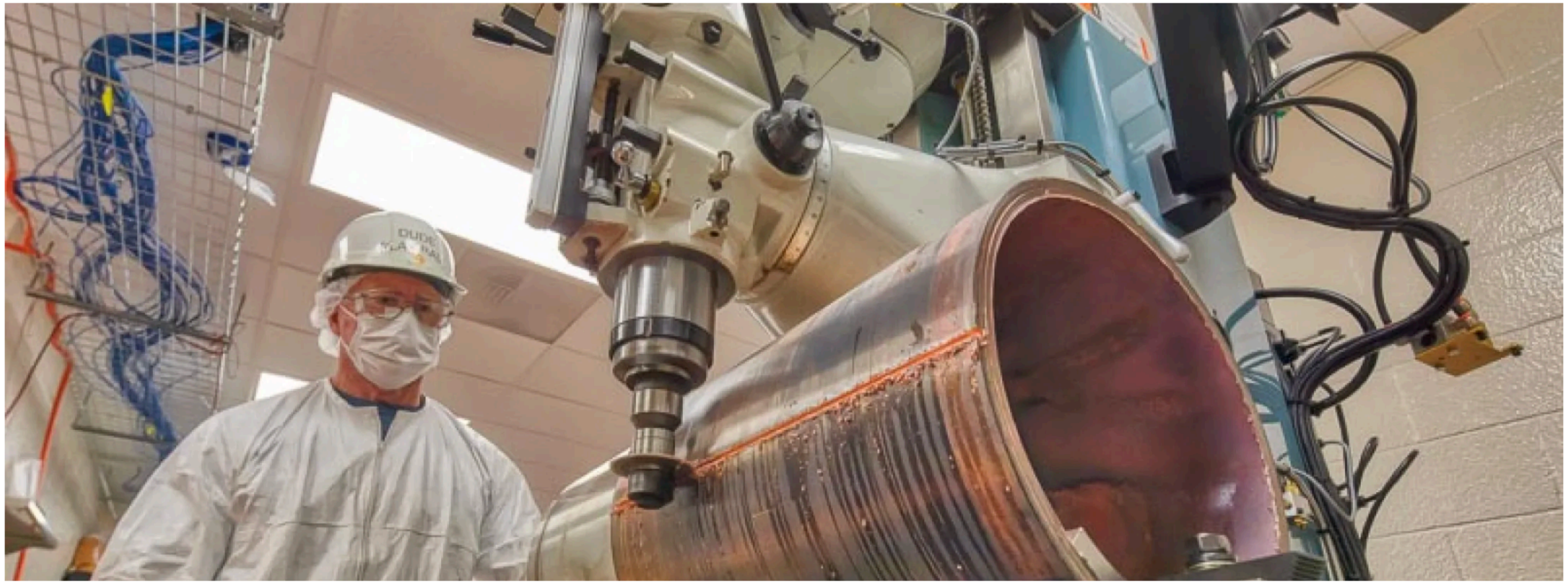


Electroforming copper underground @ Sanford Lab Lead, South Dakota

Copper nuggets before being placed in the electroforming baths. These have already been triple-etched in nitric acid.

Copper nuggets before being placed in electroforming baths.This copper requires a long soak in a dilute sulfuric acid bath. Although the copper nuggets are already very pure—99.999 percent, to be exact—there may be traces of uranium, thorium and radioisotopes like Cobalt-60, all of which could cause background noise in sensitive physics experiments.

A cut is made across a cylinder of copper by machinist



Example background study (using simulation)[*]

Copper Holder 50Million simulated $^{214}\mathrm{Bi}$ decays in $\mathbf{Cu}$ holders

Background Index (BI)

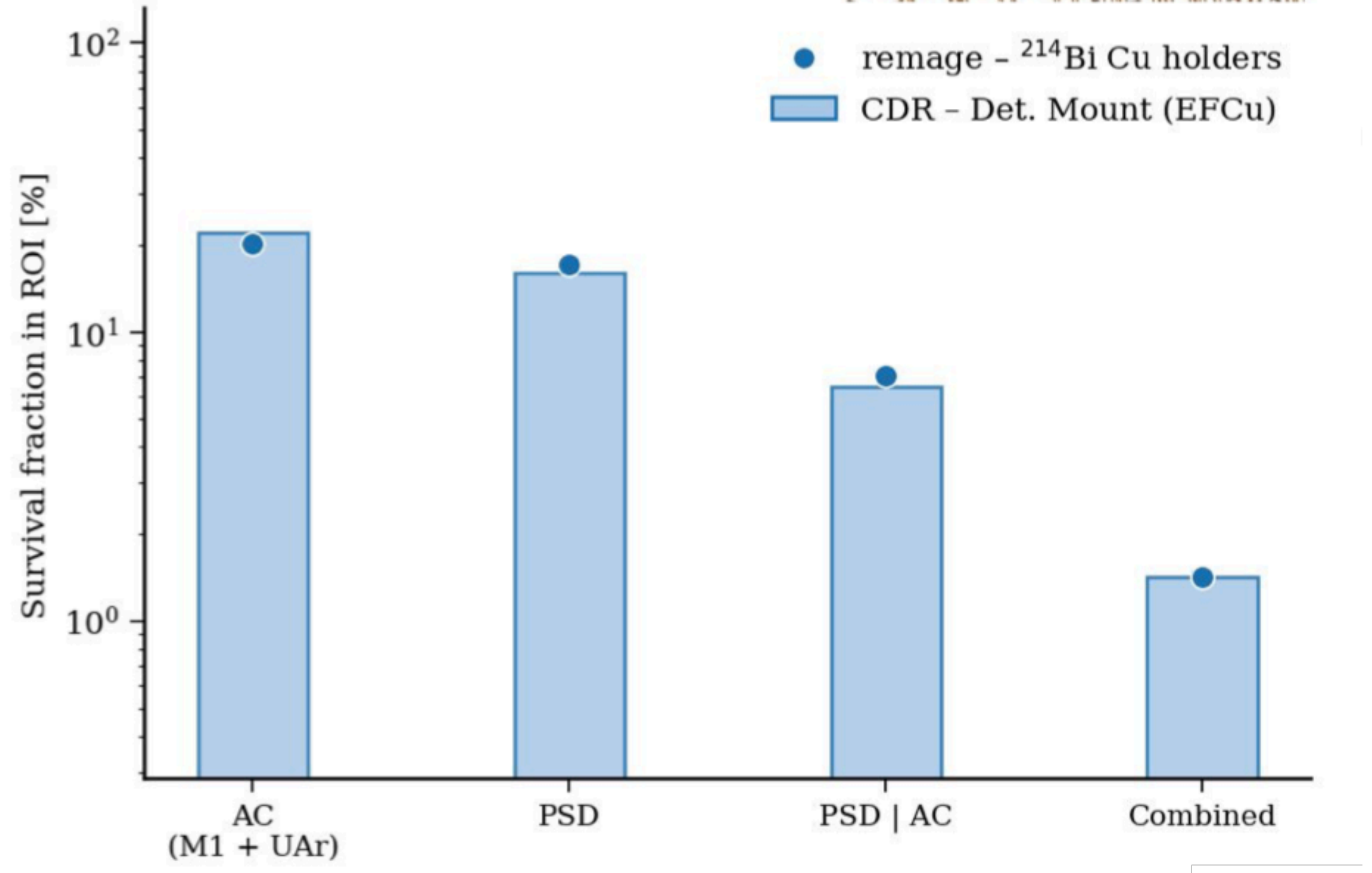
- Before cuts: $(1.06 \pm 0.56) \times 10^{-6}$ cts/(keV kg yr)
- After cuts: $(1.51 \pm 0.79) \times 10^{-8}$ cts/(keV kg yr)

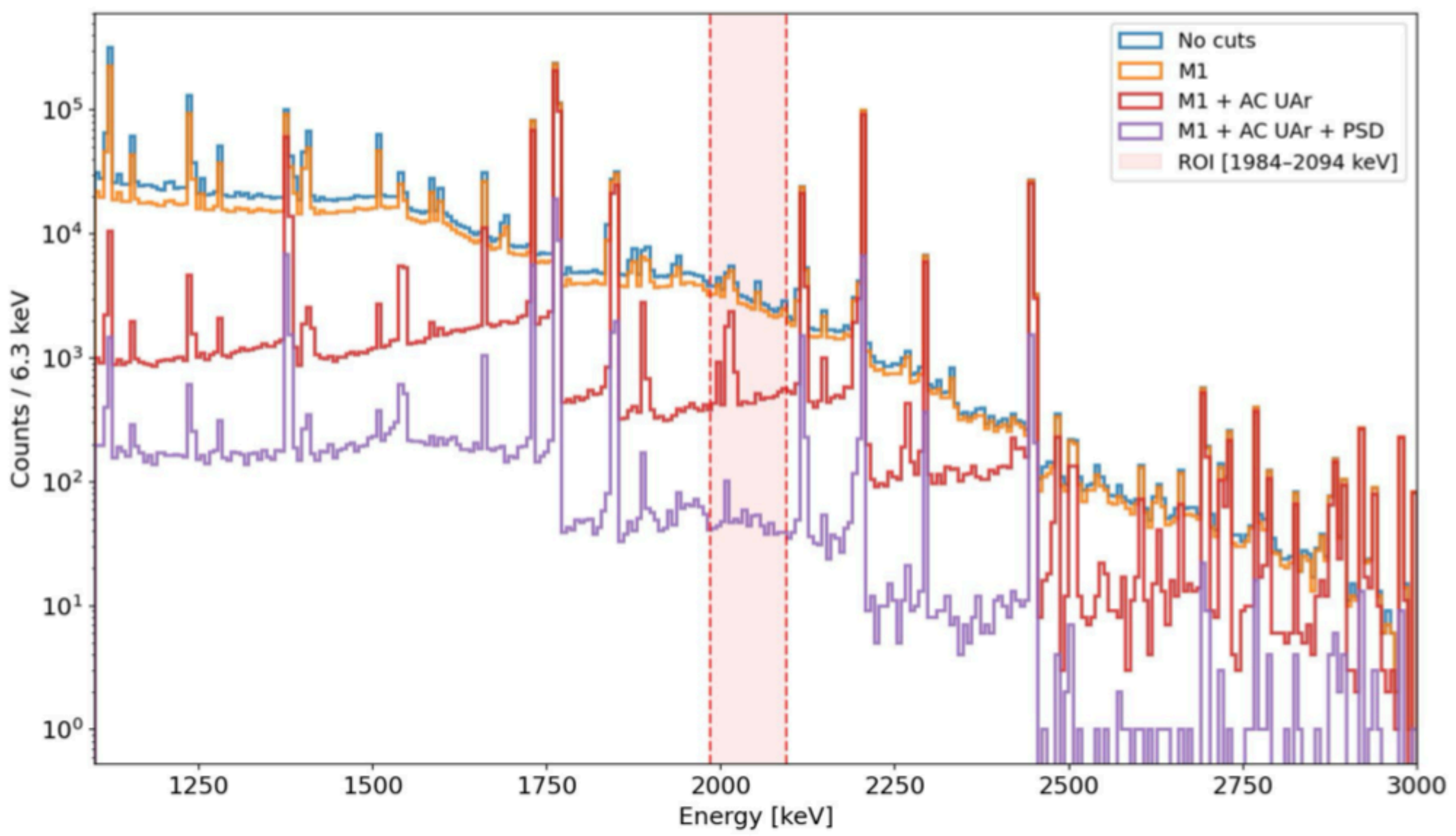
Cut Performance (ROI survival)

- Combined cuts: $\sim 10^{-2}$ level survival

Cu-holder background is well suppressed below CDR expectations

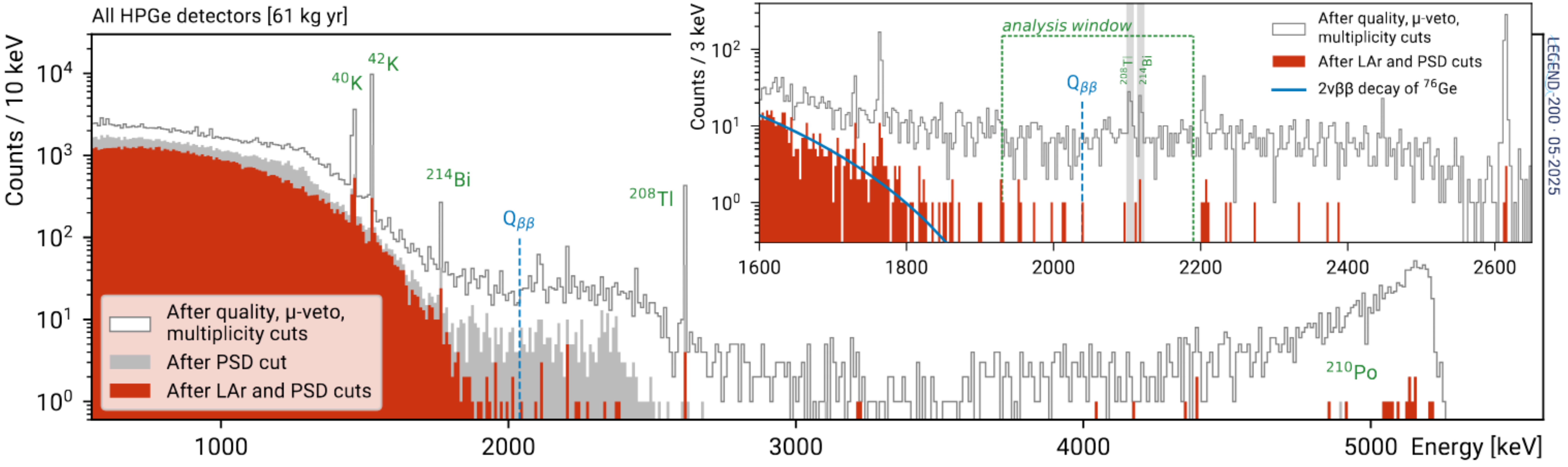
[*] Source: Status of Background Simulations in LEGEND-1000 using REMAGE, LEGEND collaboration meeting, Naples 06.03.2026





Sources of background

background control matters because Sensitivity to $0\nu\beta\beta$ depends on: Ultra-low background index (BI) and Background-free exposure near $Q_{\beta\beta} = 2039\ \text{keV}$[7] [8]



Performance data Impact near $Q_{\beta\beta}$ [*]

Intrinsic / close sources:

- Dominant background from Th-chain decays, strongly reduced by LAr veto [isotopes: ^{214}Bi (U chain), ^{208}Tl (Th chain)]

Far / very far sources:

- contributors: fiber shroud, WLS fibers, cosmogenics

Detector component resulting in this background, not completely understood

[*] L_Note_24_007.pdf internal document(Background analysis for LEGEND-200 data release at Neutrino 202)

BACoN UNM LAr experiment

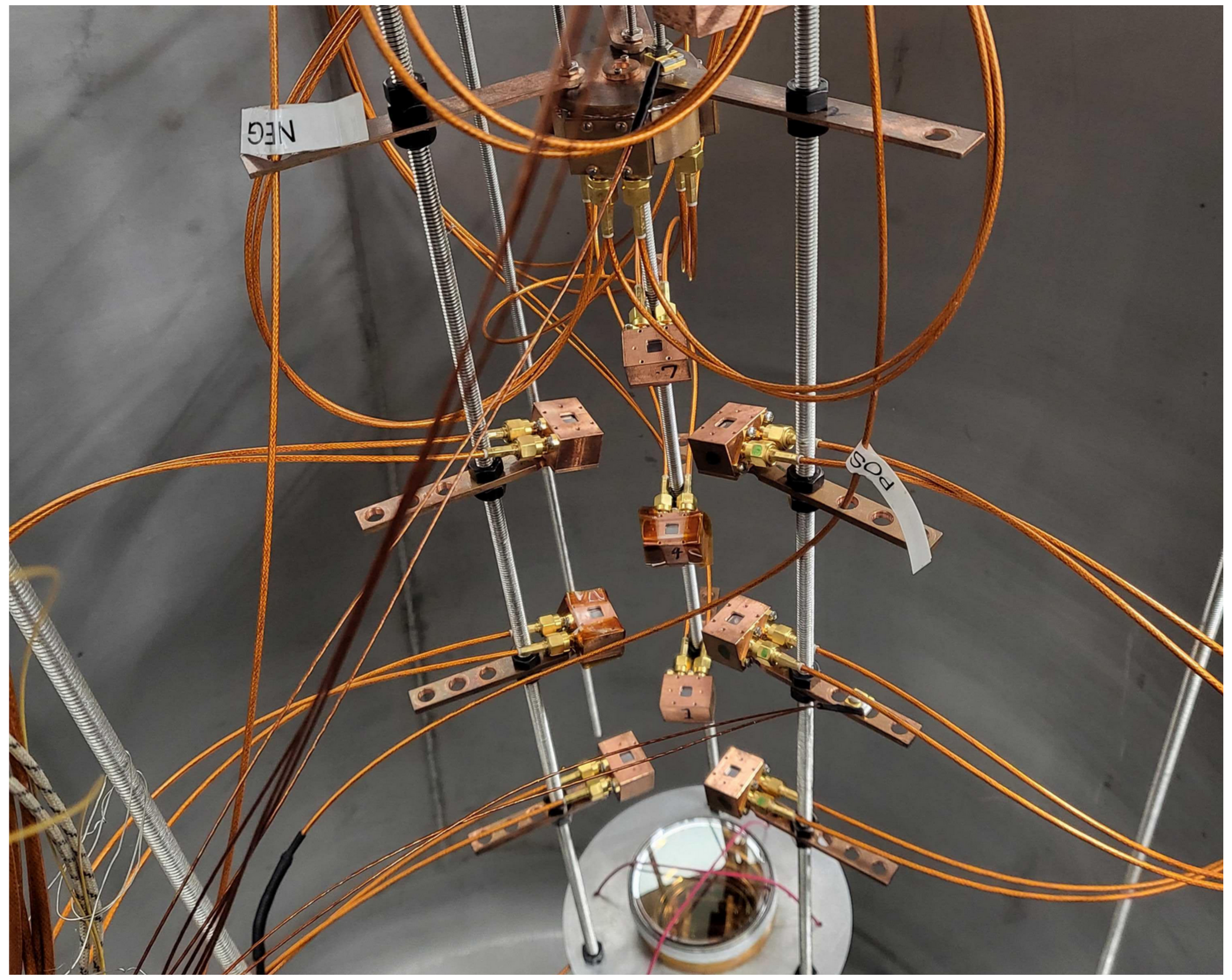
Operated in PAIS as R&D for the LAr veto design for LEGEND-1000

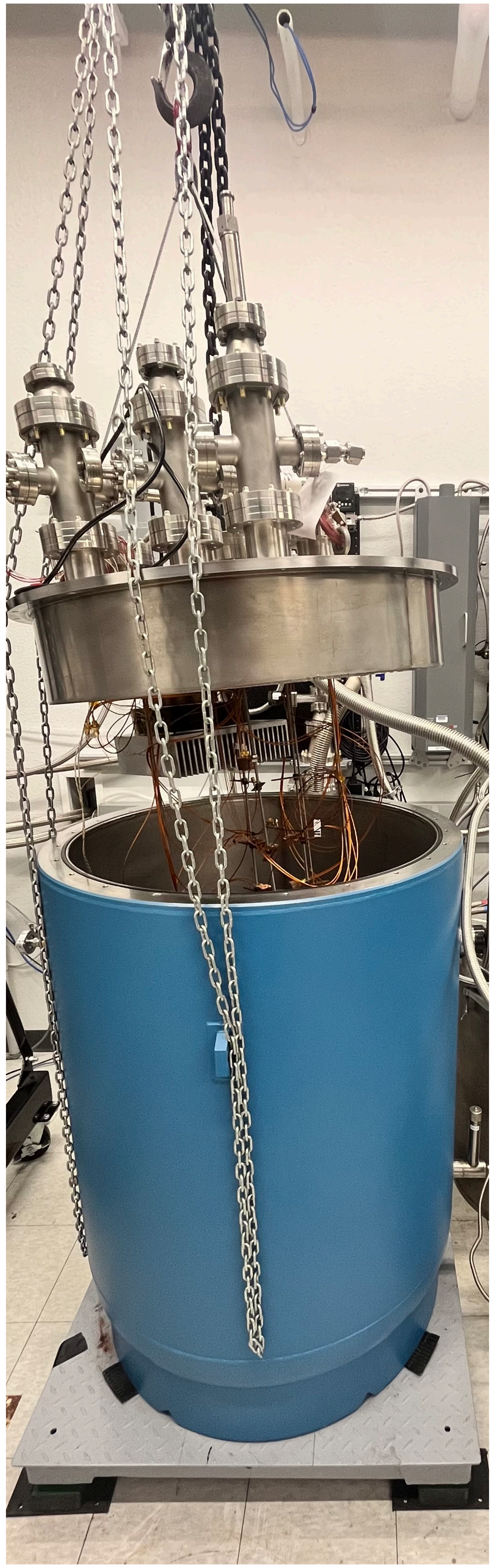
We have shown that adding 10PPM xenon ("**doping**") **increase light yield by factor of 2**. [9]

To increases total light yield (ly) [Control Xe concentration in LAr]

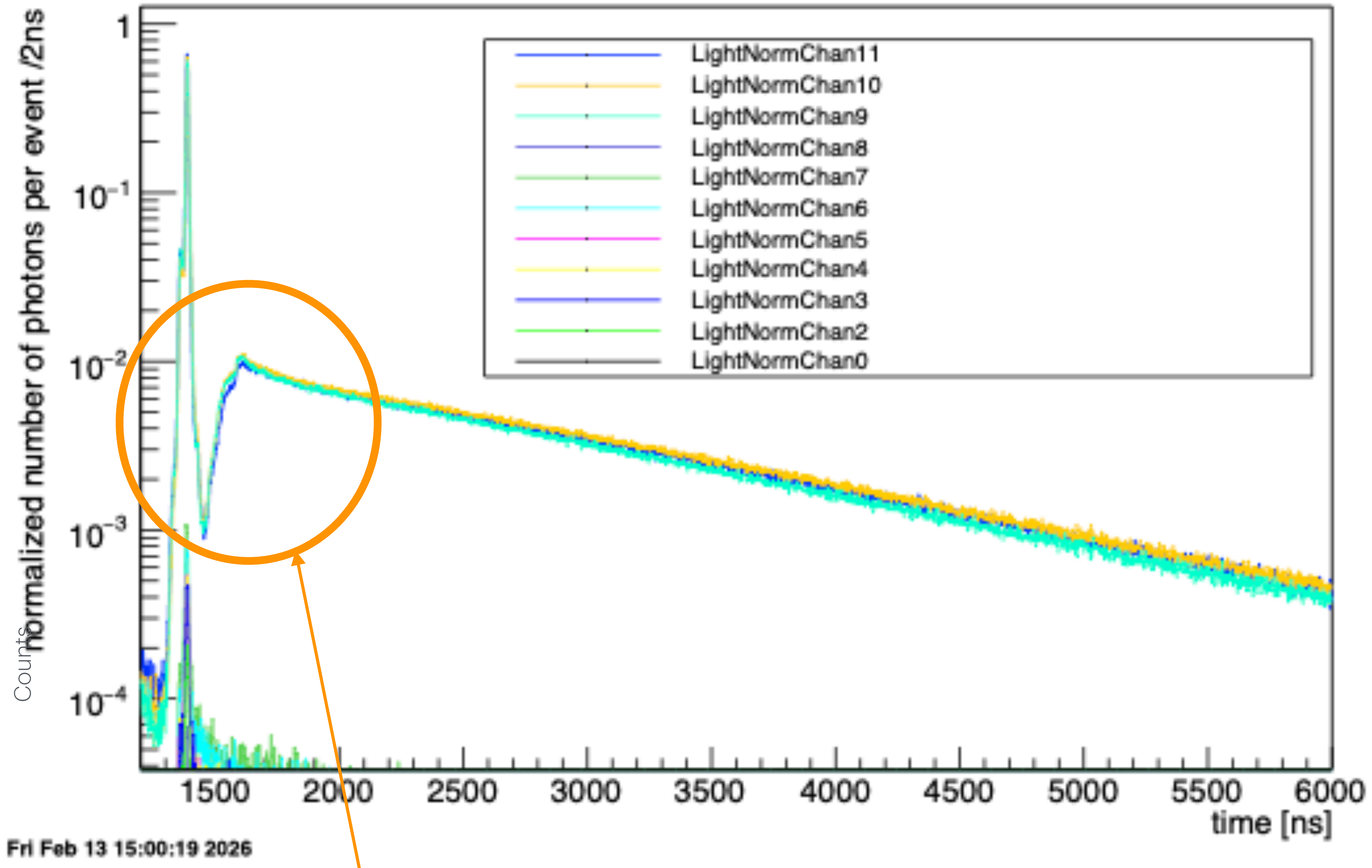
The **Better Than BACoN (BTB)** upgrade allows us to sample directly from liquid instead of Ullage

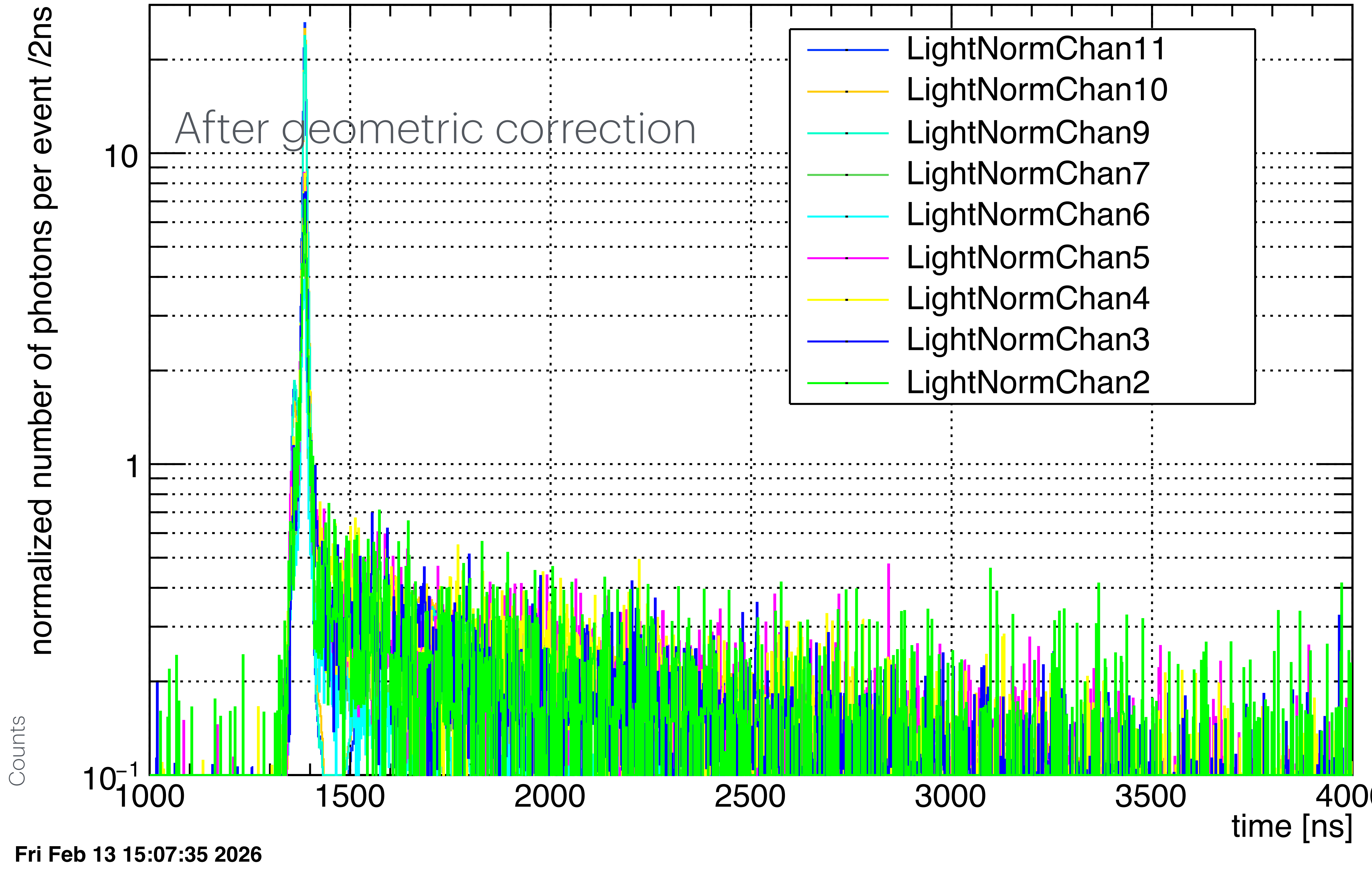
This will help reduce the backgrounds even more. And I will discuss it in depth in my candidacy talk





SiPM light curves at different distances (data)



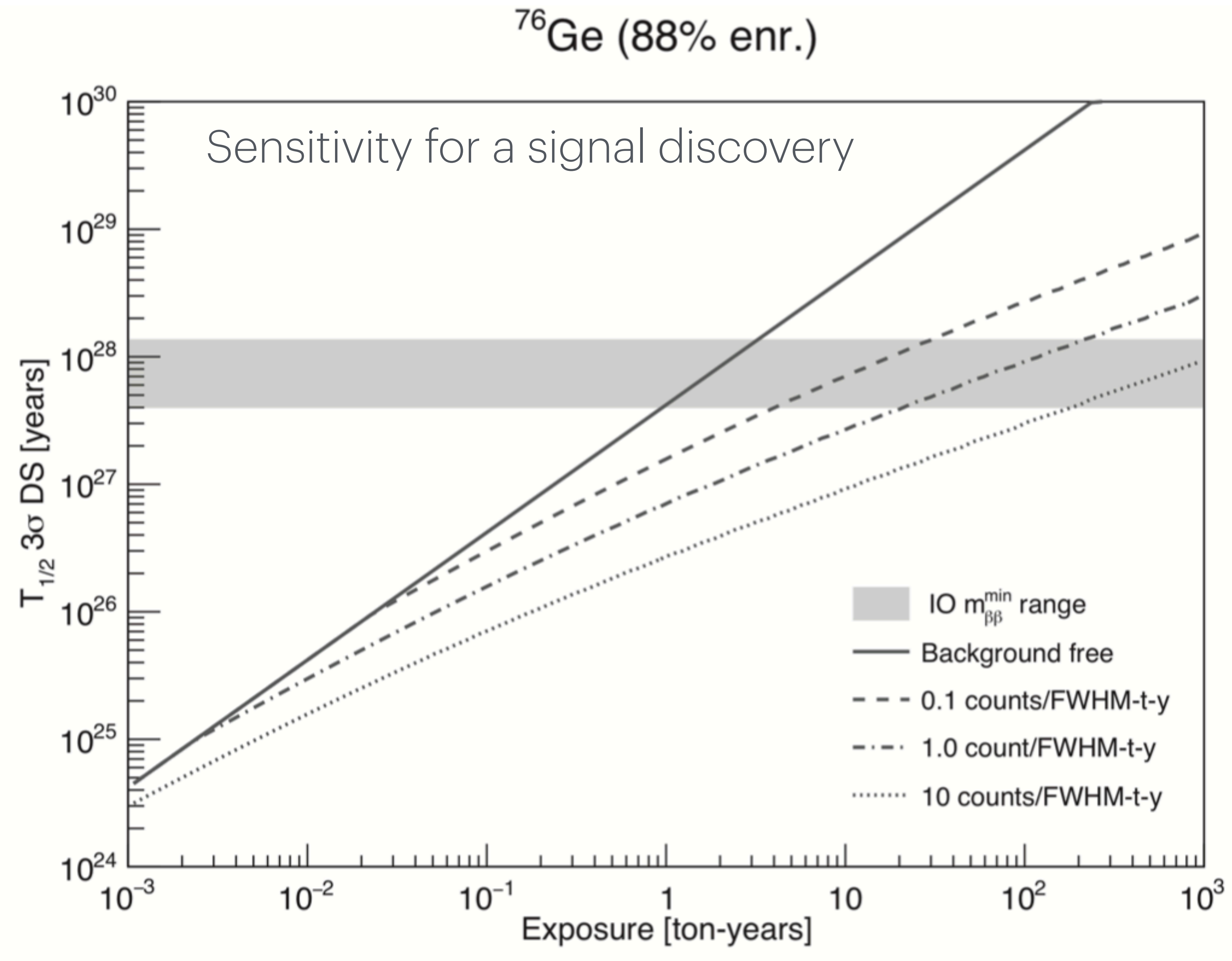


Artifact if inefficient pulse finding

I will be working on making a sim of this in C++ that extends it to Xe-doped conditions for full model validation

https://www.symmetrymagazine.org/article/majorana-demonstrator-finds-tantalizing-new-purpose

Towards 0νββ LEGEND 1000



Physics-driven modeling:

- Build a remage-based LAr scintillation model
- Eliminate run-by-run tuning
- Develop a universal Ar–Xe doping model (Predicting light yield (Ly) vs Xe concentration)
- Integrate into LEGEND simulation framework

GOAL:

- Improved LAr veto efficiency and Enhanced background suppression at ton scale
- Maintain high efficiency for signal-like (0νββ) events and Quantify gains from increased light collection

how the half-life sensitivity scales with exposure for different background levels [10]

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