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Fundamental Symmetries, Neutrons, and Neutrinos

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Pacific Northwest National Laboratory
& University of Washington

APS Division of Nuclear Physics Town Hall
January 12, 2026

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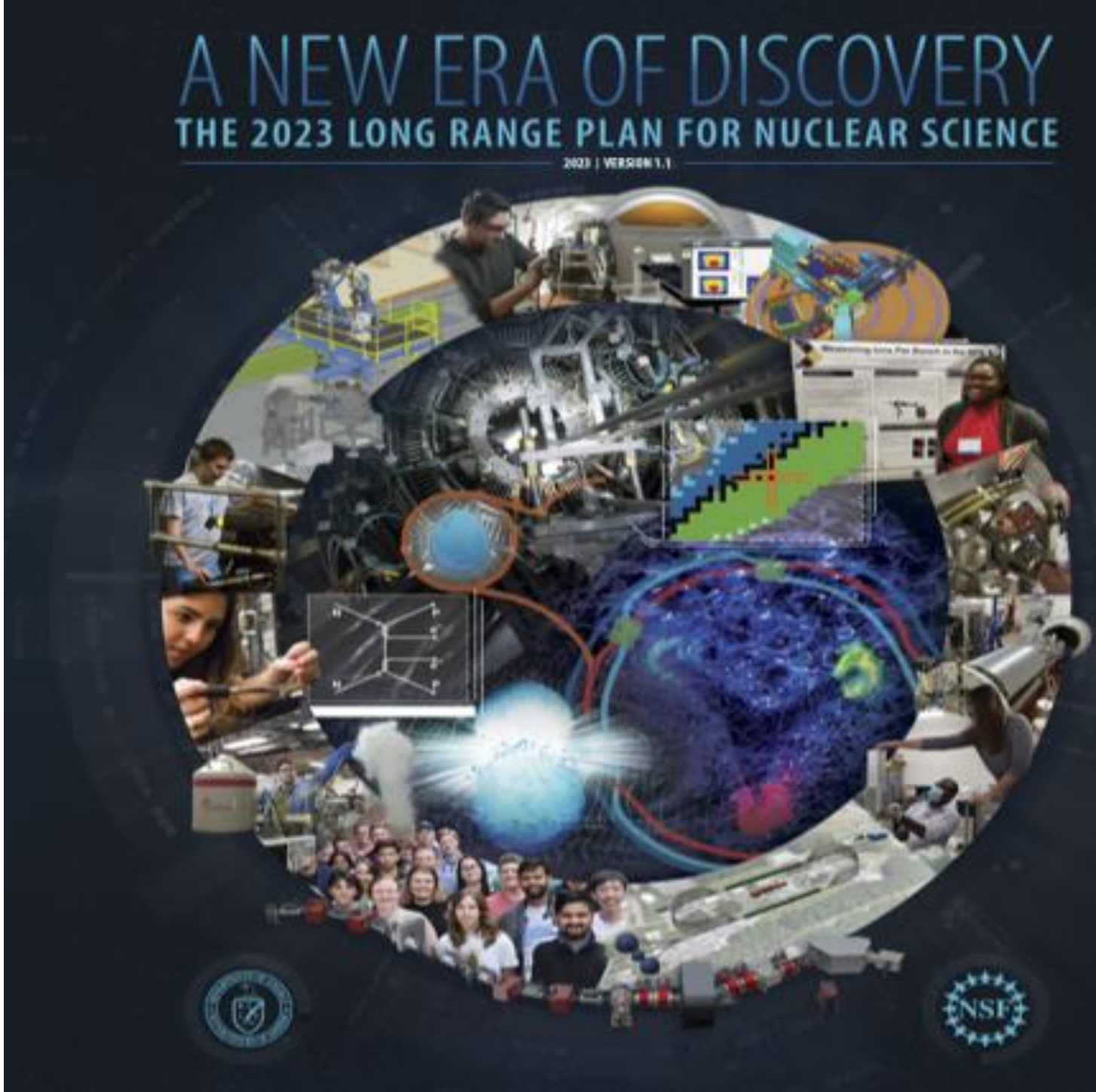
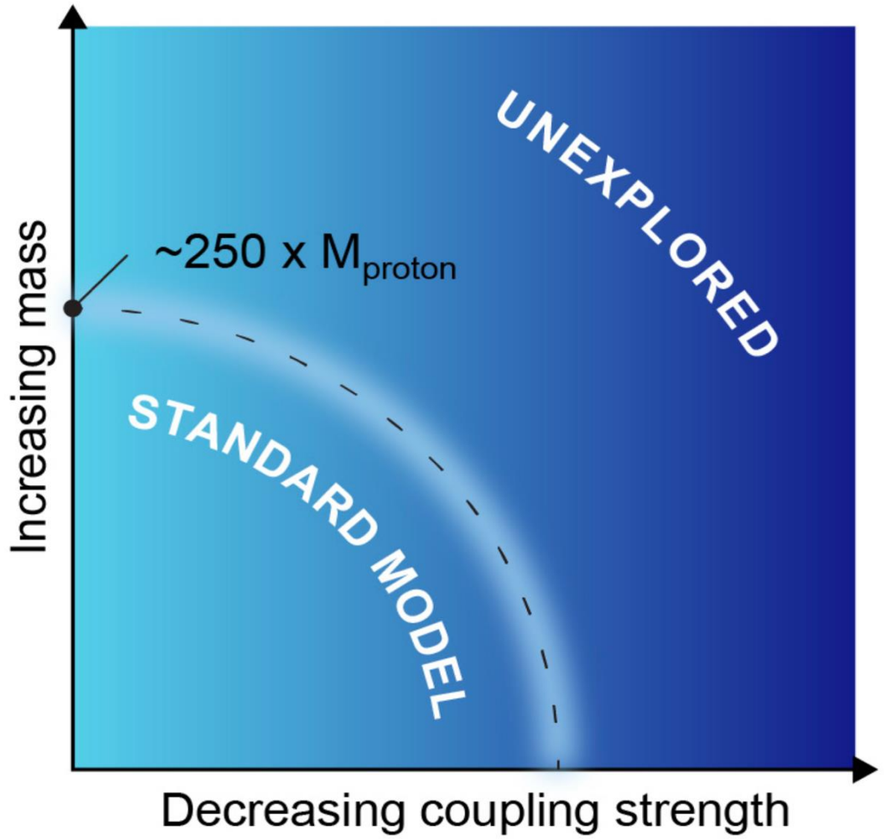


Fundamental Symmetries, Neutrons, and Neutrinos



Beyond Standard Model (BSM) physics must reside at large mass and/or weak coupling strength.

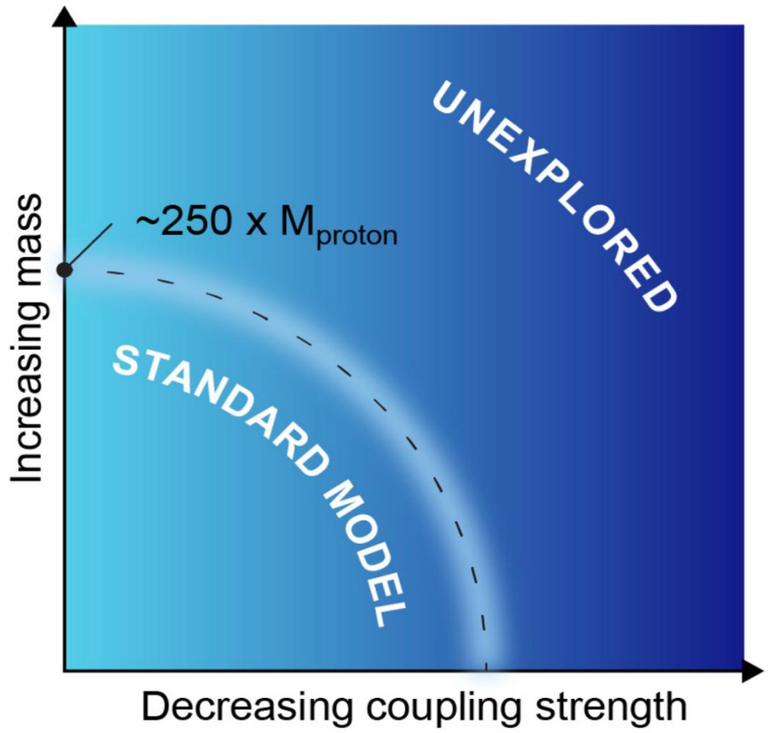
Discover BSM physics by:

1. Searches for processes that are rare or forbidden in the SM
   - Neutrinoless double-beta decay (NLDBD), permanent electric dipole moments (EDMs)…
2. High-precision measurements of processes allowed in the standard model
   - beta decays of mesons, neutrons, and nuclei…
3. Exploration of the properties of known and hypothetical light particles
   - Anomalous magnetic moments (*g-2)*
   - Neutrinos: masses, mixing, additional “sterile” species… and as messangers of other physics

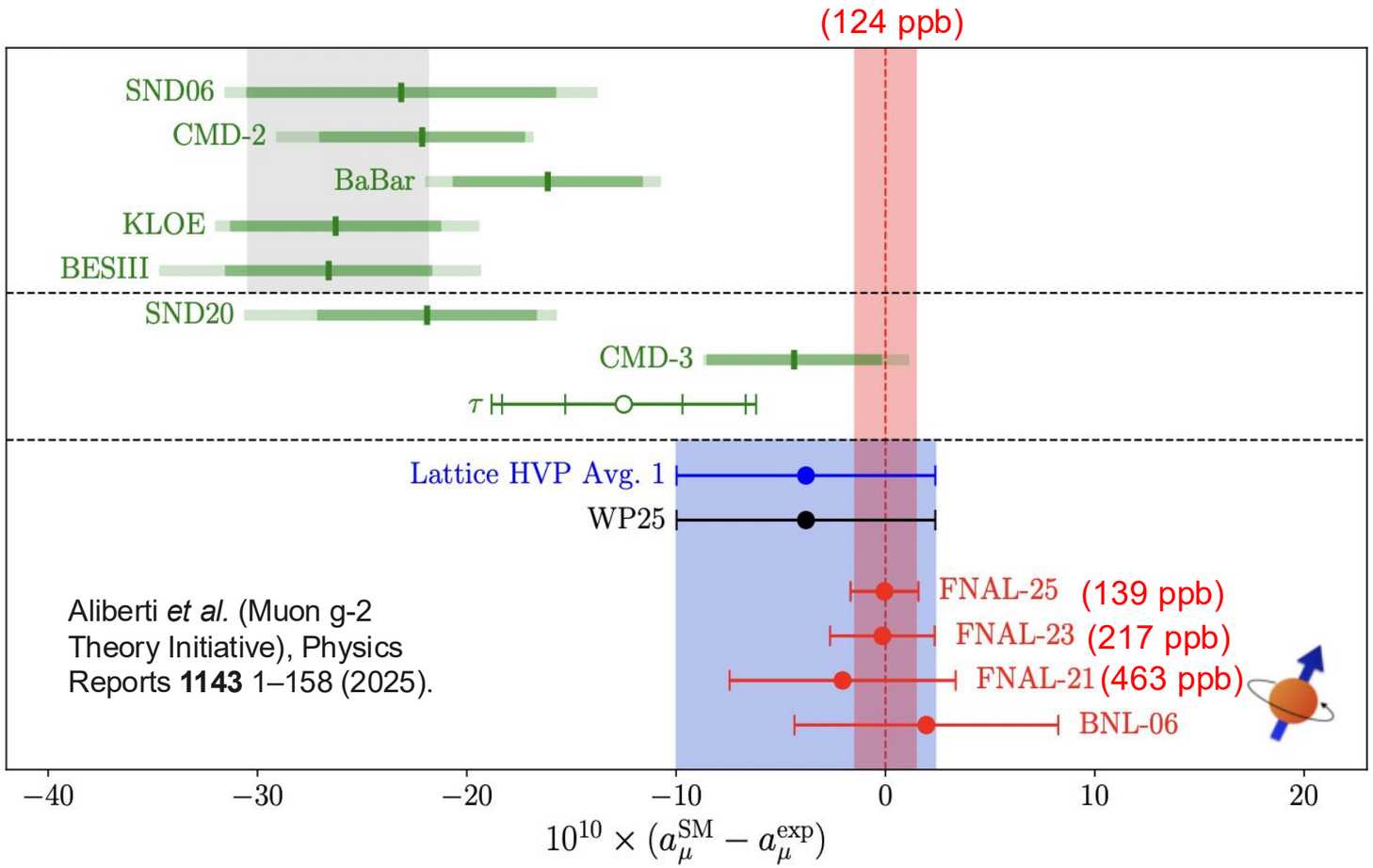
Outline

This talk is a whirlwind tour of select results in Fundamental Symmetries, Neutrons and Neutrinos:

- Major results and milestones
  - Muon *g*-2 (experiment and theory)
  - KATRIN sub-eV results, sterile limits, and end of m_ν data run, and the future of direct measurement
  - SNO+: C13 cross-section, reactor and geoneutrino results
  - Nab early results
- Progress and setbacks for electric dipole moments
  - Neutrons EDMs:
    - nEDM@SNS
    - nEDM@LANL
  - Radioactive-molecules EDMs
- Neutrinoless double beta decay
  - Recommendation II
  - nEXO
  - CUPID
  - LEGEND



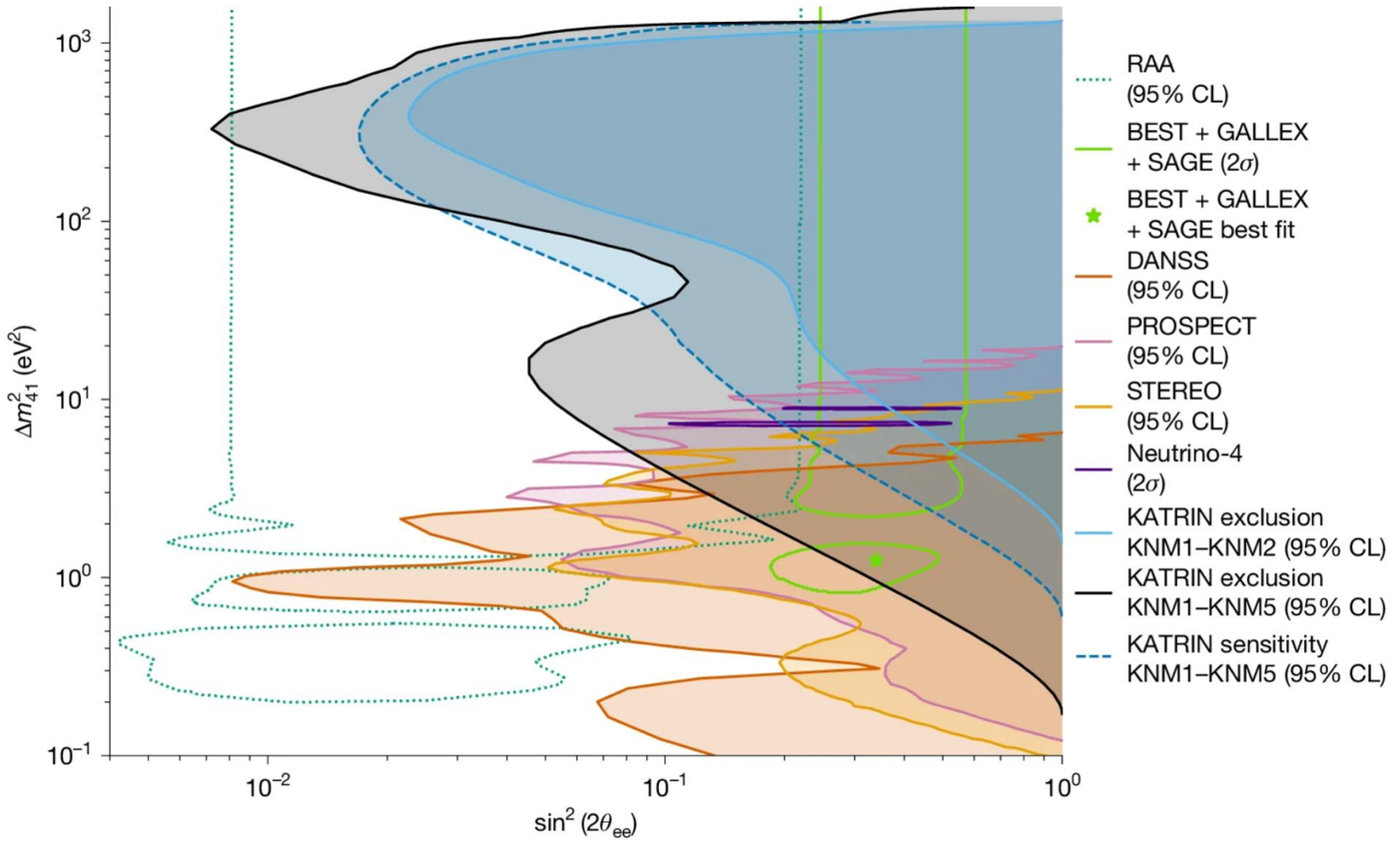
Muon Anomalous Magnetic Moment (g – 2)



- 2025 g-2 results (139 ppb) dominate world exp average (124 ppb).
- Recommended theory value (WP25) is consistent w/ exp., but *only* includes lattice HVP calcs.
- Data-driven values (green) show significant internal tesion and cannot be used for now.
- This situation is temporary and the theory value may move again.
- **Reports of the g-2 anomaly's death have been greatly exaggerated.**

KATRIN – Sub-eV Neutrino Mass and End of Run

- $m_\nu < 0.45$ eV (90% confidence) [1] and sterile exclusion [2] based on 259 days of data.
- Neutrino mass runs are concluded with >1000 days total.
- Anticipate ultimate sensitivity $m_\nu < 0.3$ eV (90% confidence).
- Transition to TRISTAN [3] phase in 2026 – detector upgrades to permit ~keV sterile neutrino searches.
- Critical US contributions to analysis, beamline components, and DAQ remain, but no further US operations support.



KATRIN sterile neutrino exclusion [2]

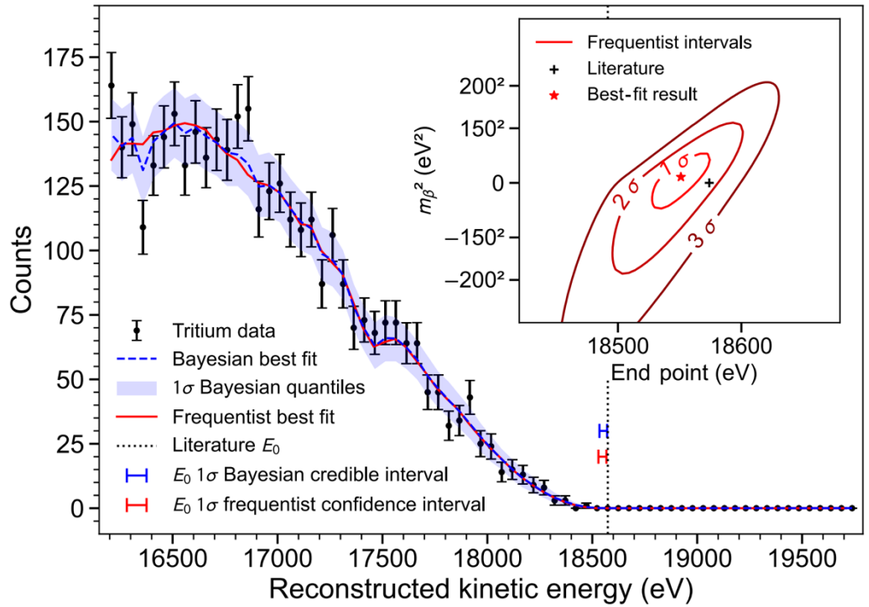
[1] Aker *et al.* (KATRIN), Science **388** 180 (2025).
[2] Achrya *et al.* (KATRIN), Nature **648** 70 (2025).
[3] Carminati *et al.*, NIM A **1049** 168049 (2023).

The Future of Neutrino Mass Measurements

Recommendation 4: We recommend capitalizing on the unique ways in which nuclear physics can advance discovery science and applications for society by investing in additional projects and new strategic opportunities.

Opportunities to advance discoveries include “emerging technologies for measurement of neutrino mass and electrical dipole moments.”

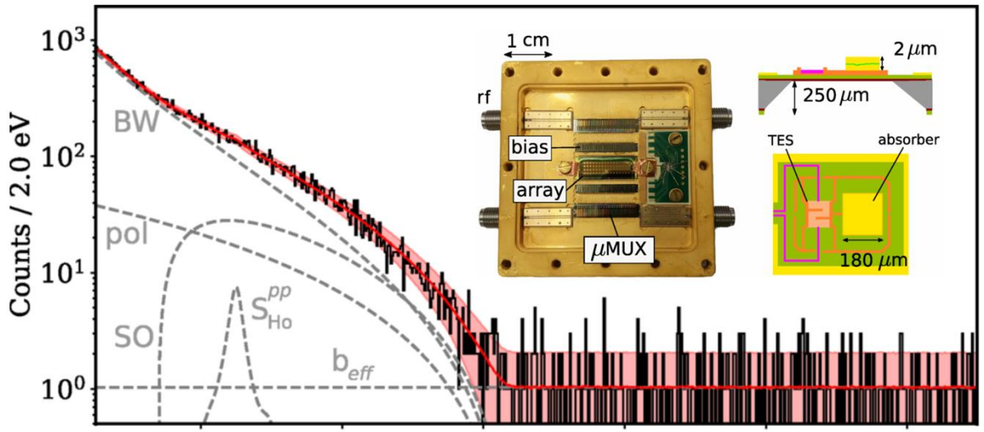
Tritium (^{3}H) Beta Decay



Project 8: $m_\beta < 155$ (152) eV [90% credible (confidence)]

Ashtari Esfahani *et al.* (Project 8), Phys. Rev. Lett. **131** 102502 (2023).

^{163}Ho Electron Capture



HOLMES TES detector array and spectrum

HOLMES (ECHo) report $m_\beta < 27$ (15) eV (90% credible)

Alpert *et al.* (HOLMES), Phys. Rev. Lett. **135** 141801 (2025).
Adam *et al.* (ECHo), arXiv:2509.03423v1 (2025).

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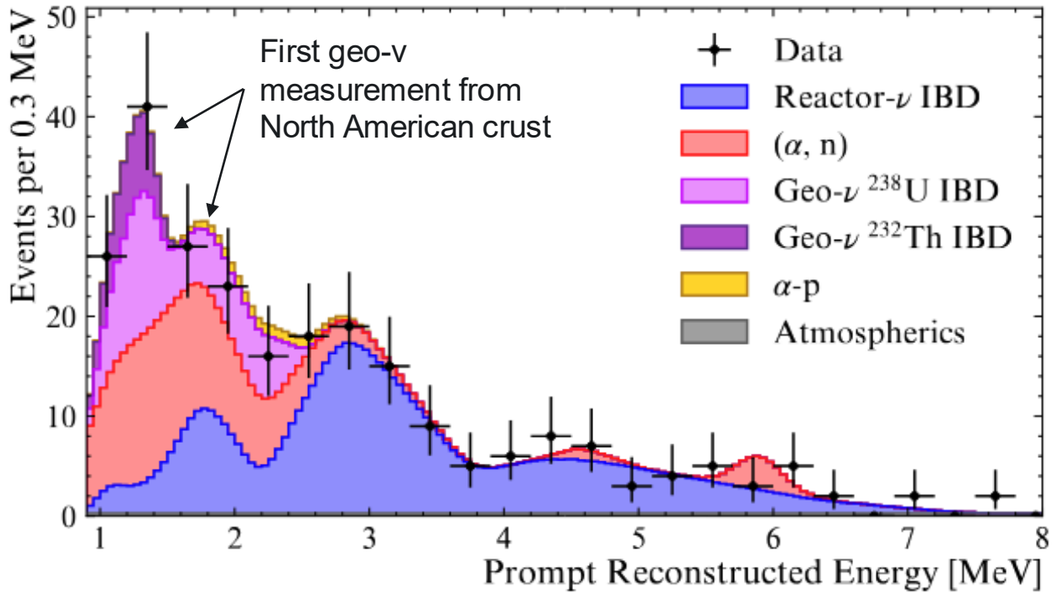
SNO+

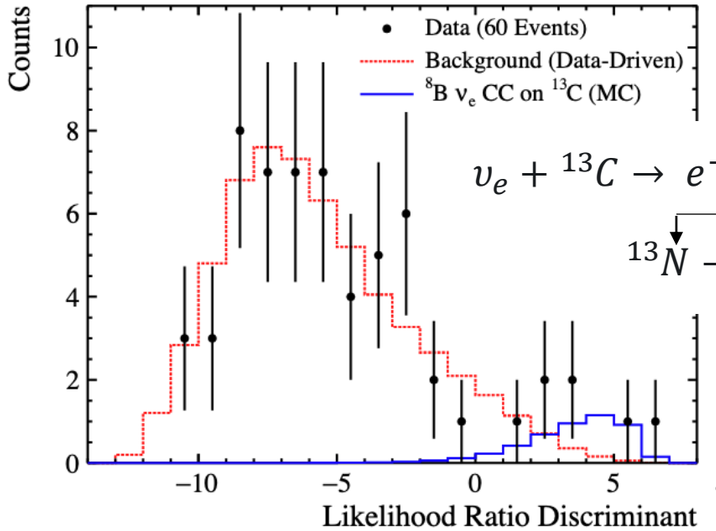
Improved Δm^2_{21} using > 240 km reactor baseline [1]



- World avg improves to $\Delta m_{21}{}^2 = 7.58^{+0.18}_{-0.17}$
- Geo-ν flux: 73^{+47}_{-43} terrestrial neutrino units (TNU), first western hemisphere measurement

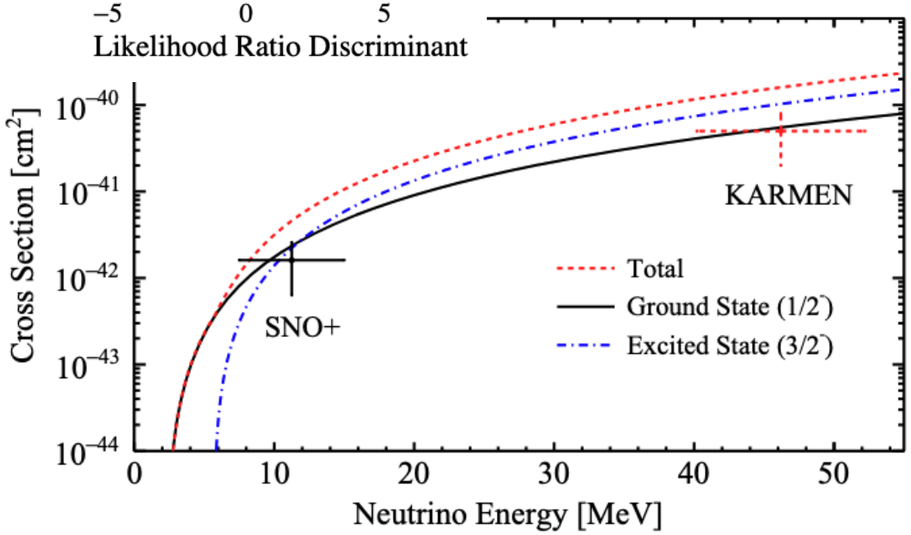
[1] Abreu *et al.* (SNO+) Phys. Rev. Lett. **135** 121801 (2025).

First observation of solar ν_e CC reaction on ^{13}C [2]



$$\nu_e + {}^{13}C \rightarrow e^- + {}^{13}N$$

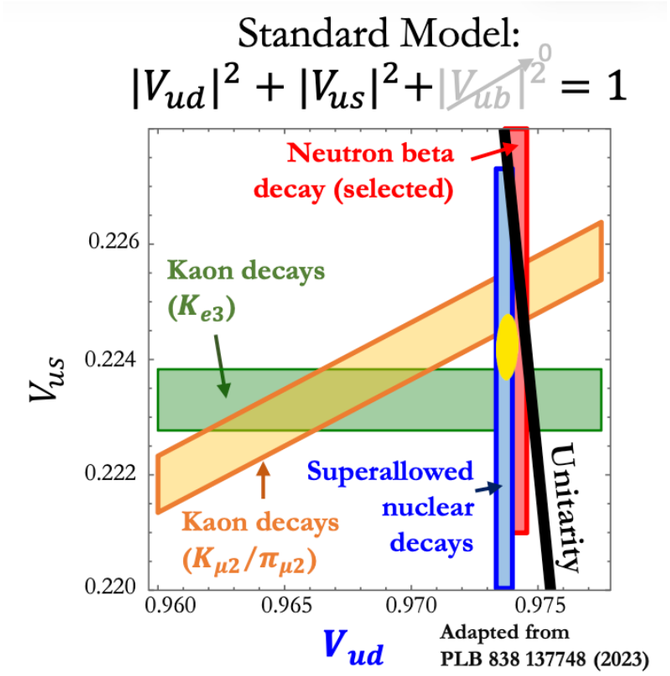
$${}^{13}N \rightarrow e^+ + \nu_e + {}^{13}C \ (T_{1/2} \approx 10\text{m})$$



- First measurement of a ν cross section using precise solar ^8B flux
- Second `realtime' CC solar ν observation (after SNO)

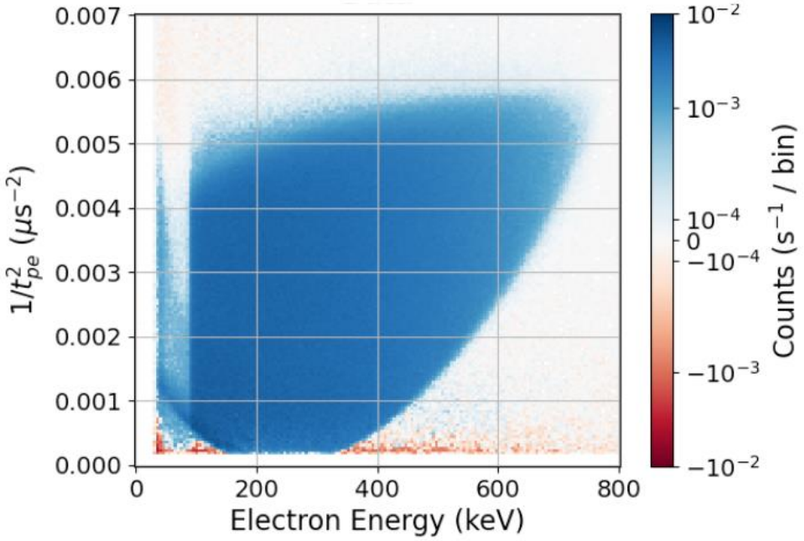
[2] Abreu *et al.* (SNO+) Phys. Rev. Lett. **135** 241803 (2025).

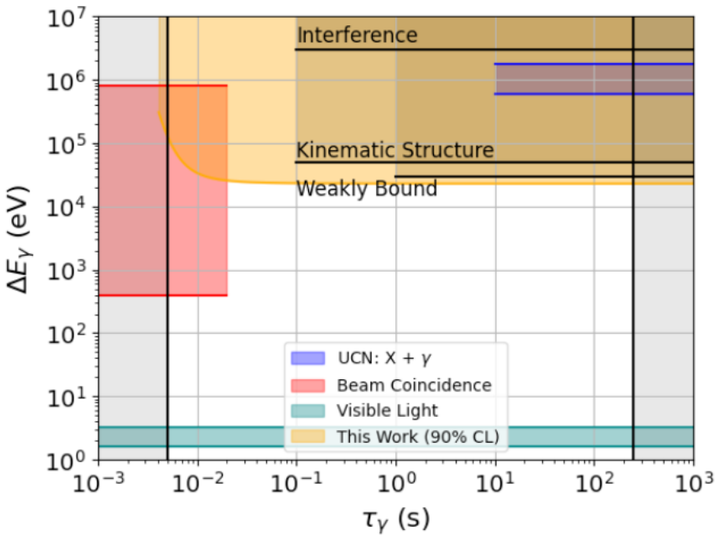
Nab – Precision Data Collection Begins



High priority to resolve few-σ CKM Unitarity disagreement. V_{ud} dominated by nuclear decays, but neutons could lead with resolution of lifetime and correlation (λ) anomalies.

- Nab precision data collection has begun:
  - First Dalitz plot and limits on hypothesized "excited neutrons" published [1]
  - Unprecedented λ_a precision expected from Nab's neutron "Dalitz" plot
  - First precision data collection completed, expect stat uncertainty better than current best ($\delta\lambda_a/\delta\lambda_a$ ~ 0.2 % by aSPECT)
  - Nab goal: $\delta\lambda_a/\delta\lambda_a$ ~ 0.04%

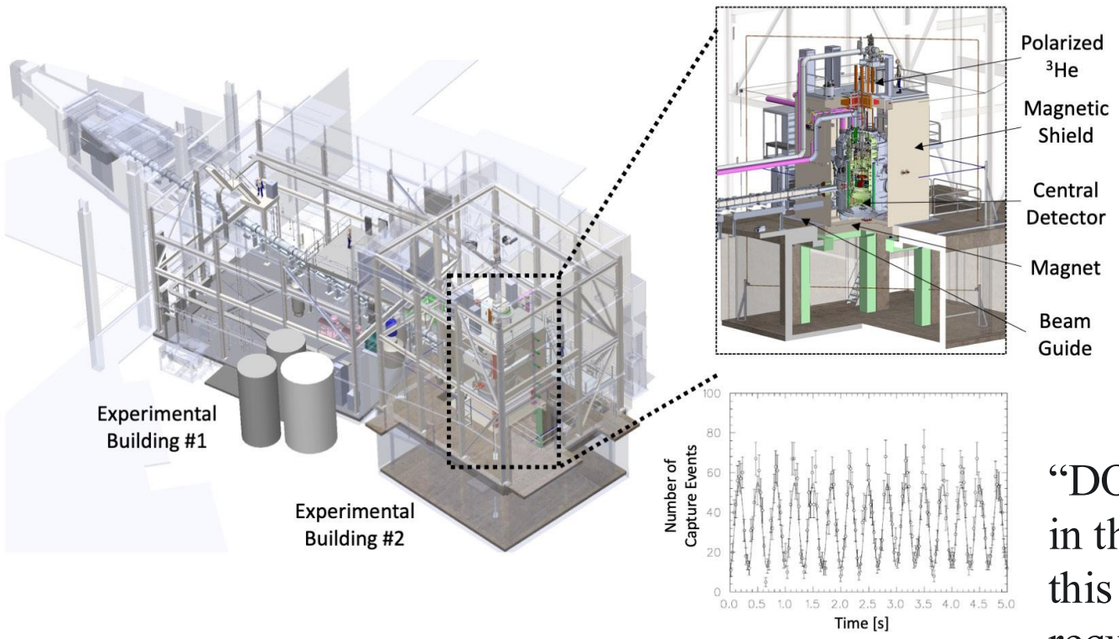




[1] Gonzalez *et al.* (Nab), accepted by Phys. Rev. C (arXiv:2508.16045)

Electric Dipole Moments – Neutrons (nEDM@SNS)

nEDM@SNS was to be the world's flagship EDM experiment, w/ sensitivity 3×10^{-28} *e*-cm



- Sensitivity 2 OOM below current limits
- Advantages over current generation:
  - Real-time precession measurement
  - Systematic checks w/ spin dressing, control of main systematic – geometric phase
- Despite significant R&D and construction progress…
- **nEDM@SNS was terminated in Nov 2023:**

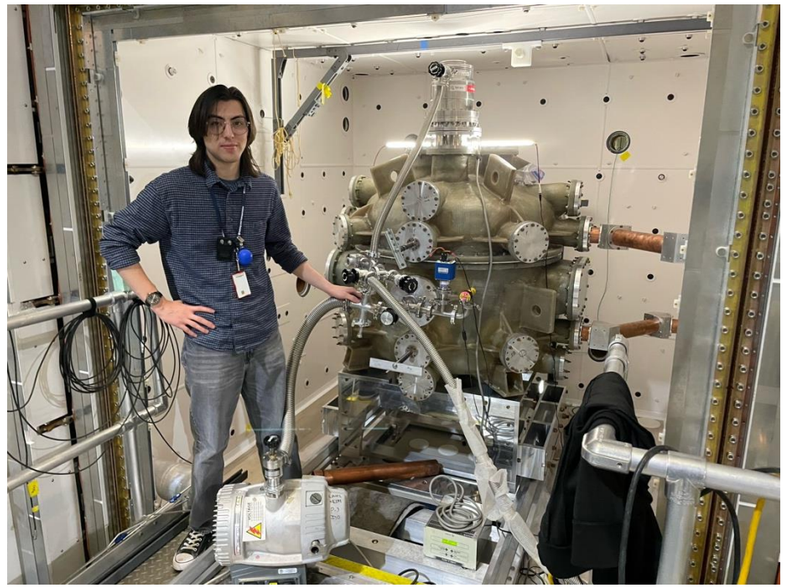
"DOE NP and NSF conclude there remains sufficiently large uncertainty in the cost, schedule, and technical risk to a successful completion of this activity that continued expenditure of cost and effort that would require sacrificing support in other areas is not justified."

(Excerpt from 2023 annual review report)

- nEDM searches remain highly motivated → 850 participants in "Rapid Response" workshop on strong-*CP* problem (December 2025)
- Ongoing discussions with the European Spallation Source for a future cryogenic nEDM experiment

Electric Dipole Moments – Neutrons (nEDM@LANL)

nEDM@LANL is a room temperature experiment, w/ projected sensitivity 2×10^{-27} *e*-cm



- Poised to be among the first to reach O(10^{-27}) *e*-cm sensitivity
- Comparable sensitivity to international competitors (n2EDM@PSI, TUCAN@TRIUMF, PanEDM@ILL)
- Demonstrated ultra-cold neutron density
- Recent highlights:
  - Development of magnetic impurity scanner (sensitivity ~1 pT)
  - UCN storage test in two precession chambers inside the vacuum chamber, demonstrating the full functionality of the UCN cell valves
  - Successful test of the double arm simultaneous spin analyzer
  - Demonstration of 10^5 shielding factor for the magnetically shielded room

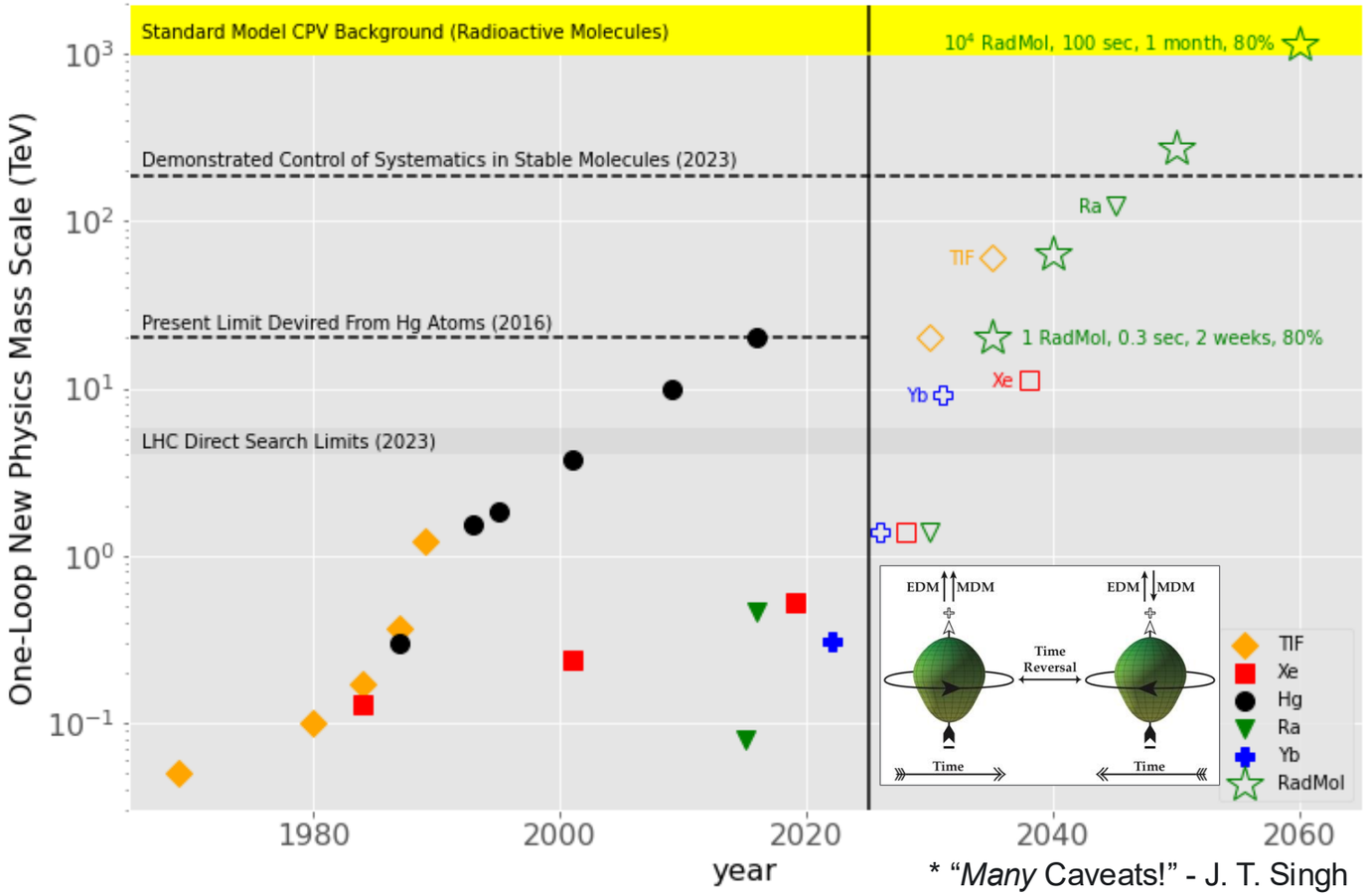
Schedule:

- **CY2026:** full engineering run to test UCN storage and spin transport/precession
- **CY2027+**: commissioning and data taking

Radioactive-Molecule EDMs

Recommendation IV: The other noted opportunity to advance discovery in FS is in emerging EDM seach techniques.

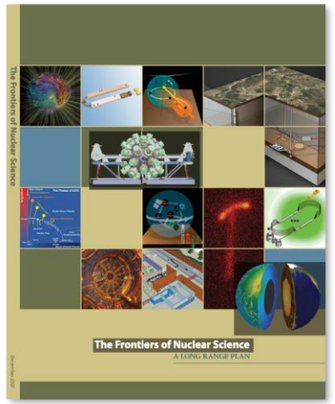
Radioactive Molecule EDMs potentially span the entire BSM physics discovery window for hadronic *CP*-violation*



* "*Many* Caveats!" - J. T. Singh

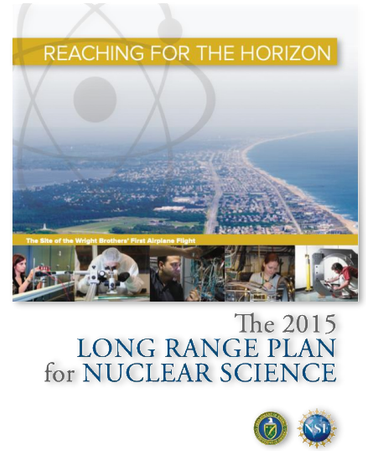
- Multiple teams are working coherently **across platforms and disciplines towards the larger goal** of launching at least one 1st-generation RadMol EDM experiment hosted at **FRIB** within the next 10 years.
- Significant and **rapid progress** is being made in the laser cooling, trapping, and assembly of **neutral radioactive molecules**.
- Significant progress has been made in the **formation, loading, and quantum state readout** of **single radioactive molecular ions.**
- **New EDM results** are expected in the next 5 years for Yb, Xe, TlF, & Ra.

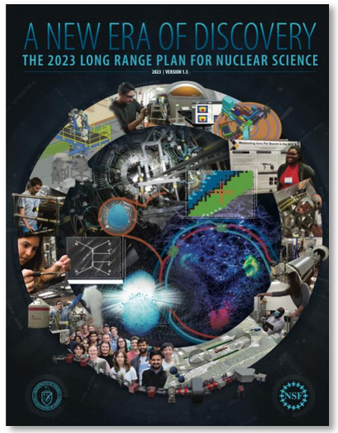
Ton-scale Neutrinoless Doube-beta Decay in the LRP



2007 Recommendation III: We recommend a targeted program of experiments to investigate neutrino properties and fundamental symmetries. These experiments aim to discover the nature of the neutrino…

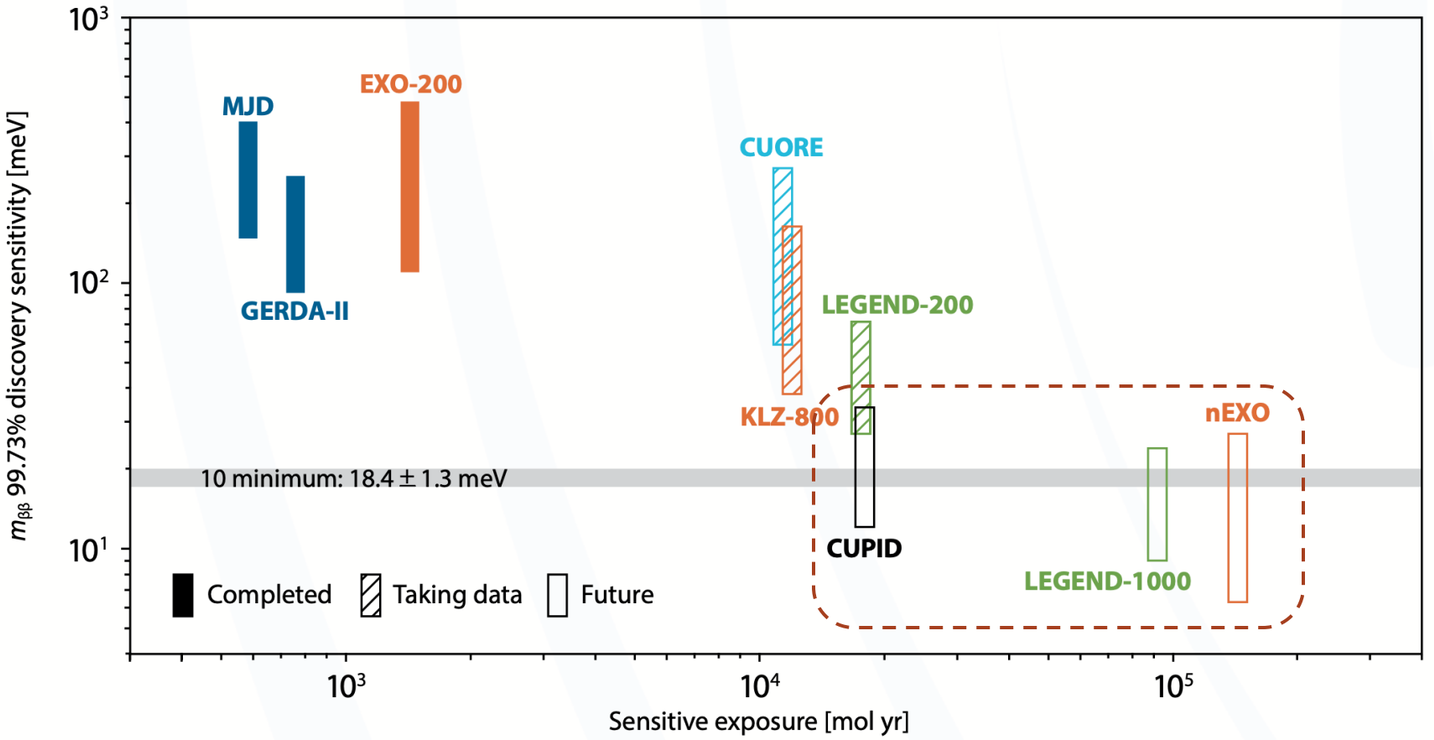
2015 Recommendation II: We recommend the ***timely development*** and deployment of a ***U.S.-led*** ton-scale neutrinoless double beta decay experiment. (emphasis added)





2023 Recommendation 2: As the highest priority for new experiment construction, we recommend that ***the United States lead*** an international consortium that will undertake a neutrinoless double beta decay campaign, featuring the ***expeditious construction*** of ton-scale experiments, using ***different isotopes and complementary techniques***. (emphasis added)

Candidate Ton-scale Experiments



nEXO, CUPID and LEGEND-1000 capable* of IO discovery

* "capable" = based on demonstrated technology, and expert peer-reviewed

- Since 2015, three concepts capable* of probing inverted-order (IO) neutrino mass scales emerged, **nEXO, CUPID and LEGEND-1000**.
- Complementary isotopes are key due to: small discovery signals, long construction and run times, and need for timely corroboration of highly consequential results.
- **To satisfy "different isotopes and complementary techniques" requires at least two of these**

DOE Ton-scale Project Decision, December 2024

"…[NP's] analysis recognizes that projections for available resources preclude building multiple experiments simultaneously…

The decision is to move forward with LEGEND-1000 in the near term…

While **CUPID and nEXO** are viewed as demonstrating high potential for scientific impact, under constrained budgets **it is unlikely that U.S. funding will allow these projects to advance significantly in the near term**. R&D activities will continue, supported through the DOE NP fundamental symmetries research program, with the level dependent upon appropriations."

(Excerpt from message received by nEXO, CUPID and LEGEND leadership from NP, December 2024. Bold emphasis is added.)

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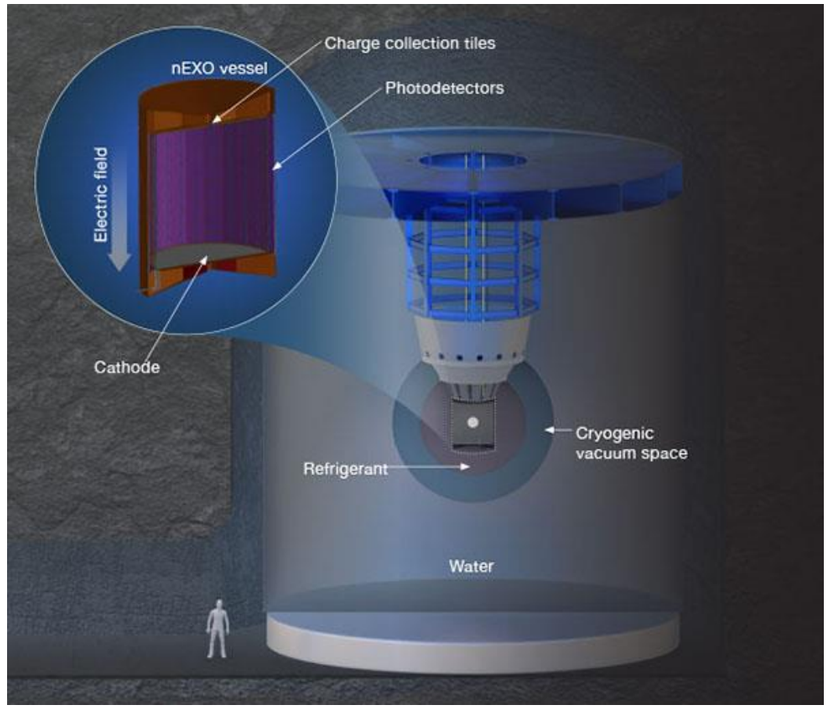
nEXO



nEXO: A 5-ton liquid-xenon TPC w/ 90% ^{136}Xe enrichment targeting 1.35×10^{28} y half-life sensitivity.

- nEXO groups have been prolific in memorializing R&D accomplishemnts:

The nEXO Radioassay Program	In collaboration review
Design of a high voltage connection for noble liquid time projection chambers	In collaboration review
Novel High-Radiopurity Doped Amorphous Silicon Resistors for Low-Background Detectors	arXiv:2601.05985
Characterization of CRYO ASIC for charge readout in the nEXO experiment	arXiv:2512.11116
Ultra-pure Nickel for Structural Components of Low-Radioactivity Instruments	arXiv:2508.08230
Enhanced sensitivity to trace U impurity of sapphire via coincidence neutron activation analysis	accepted at Phys. Rev. C
Background-free Searches for ^{136}Xe Charged-Current Interactions in nEXO: Solar Neutrinos and Fermionic Dark Matter	Phys. Rev. D 112, 103010
Ultra-sensitive radon assay using an Electrostatic Counter in a recirculating system	NIM A 1081,2026, 170876

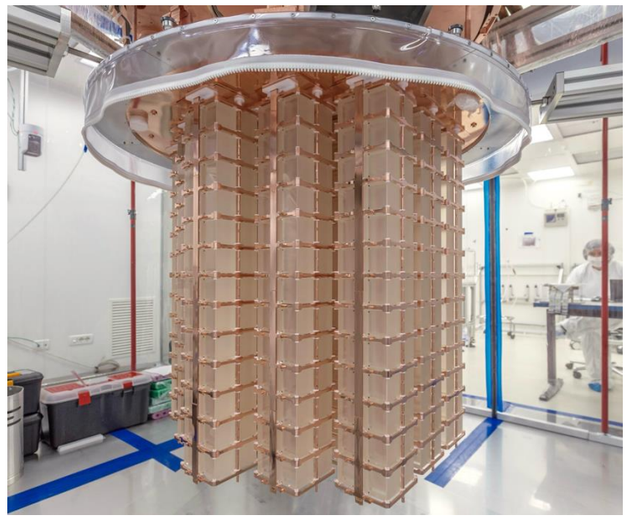
- US-based groups are moving on to other topics
- Canadian groups seeking support to execute nEXO w/ Canadian leadership
- **The opportunity for US-leadership on ^{136}Xe NLDBD is probably lost for the ton-scale**

CUPID

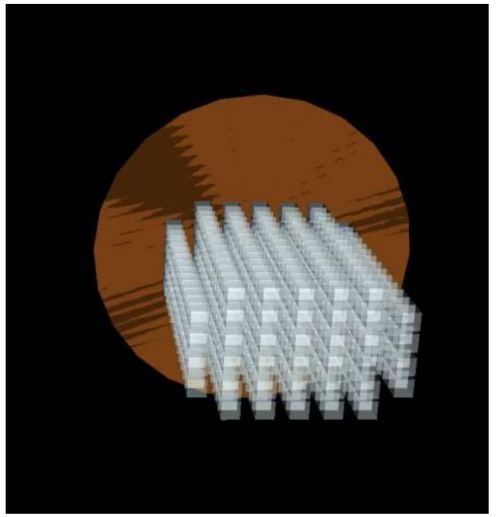
CUORE: 2+ ton-years ^{130}Te
$m_{\beta\beta}$ < 70–250 meV

Science **390** 1029 (2025)

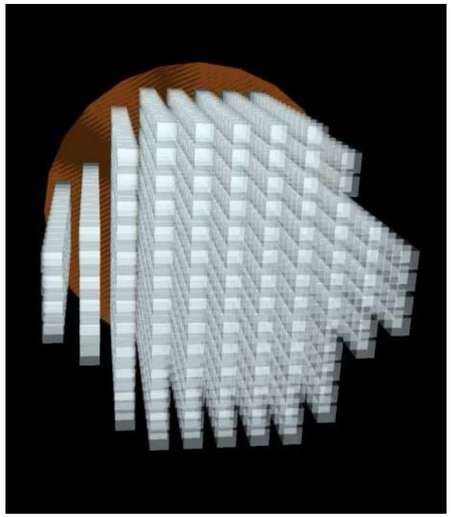
- 472 kg (**240 Kg**) of $Li_2{}^{100}MoO_4$(^{100}Mo), **10** yr runtime, staged deployment
- CUPID discovery sensitivity: $T_{1/2} > 10^{27}$ y (3σ), $m_{\beta\beta}$ ~12–36 meV
- Experiment was restructured following DOE project decision. CUPID proceeds as as INFN-led experiment with contributions from US and France.
- US will provide critical technical and scientific contributions, coordinated by LBNL.



CUORE (Through Summer 2026)



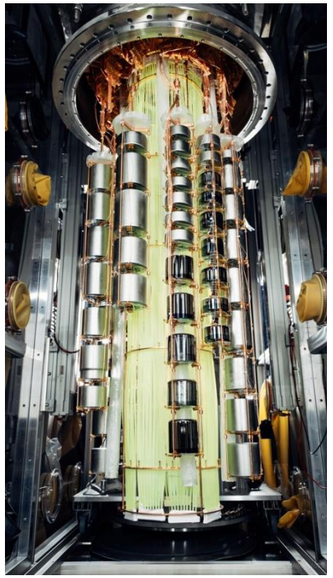
1/3 CUPID (2030–2033)



CUPID (2034+)

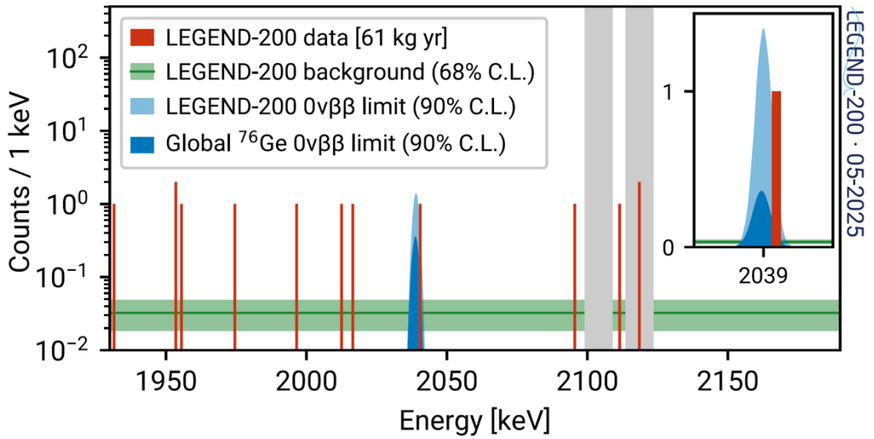
Technically-limited (resource-dependent) schedule

- NLDBD search in ^{76}Ge using an array of enriched HPGe detectors immersed in a liquid argon (LAr) scintillation detector
  - Best achieved energy resolution (0.12% FWHM at $Q_{\beta\beta}$): HPGe instrumented with low-noise electronics
  - Lowest achieved ROI background (1.4 cts/FWHM t yr): radiopure materials, strong suppression via LAr anti-coincidence and pulse-shape discrimination
  - Best achieved half-life exclusion sensitivity to date (combined with MAJORANA/GERDA): 2.8 x 10^{26} yr



L200 HPGe strings and WLS fibers

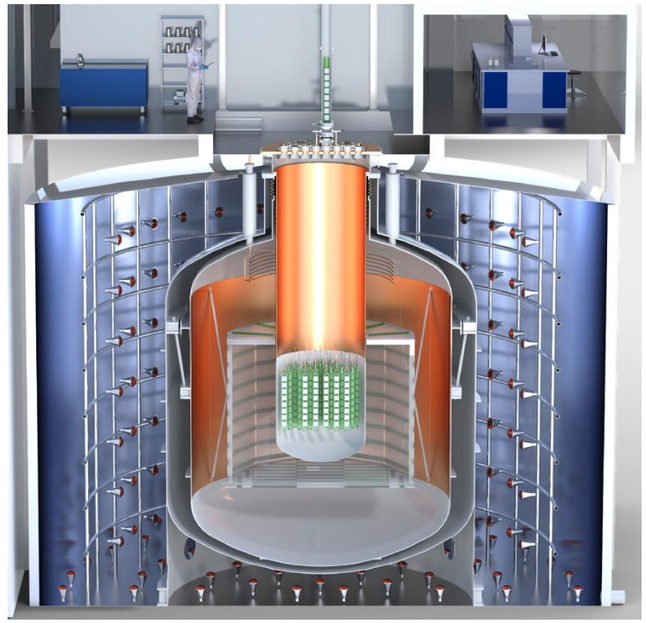
- First phase LEGEND-200 running now at LNGS
  - New, larger “inverted coax” (IC) detectors, outfitted with MAJORANA-style materials and front-end electronics, deployed in GERDA’s LAr cryostat with upgraded instrumentation
  - First results from 61 kg•yr exposure to appear in PRL [1]: 11 events after cuts → $T_{1/2}$ > 1.9 x 10^{26} yr (L200+GERDA+MAJORANA)
  - New deployment (~130 kg) with reduced U/Th and more IC detectors now taking data



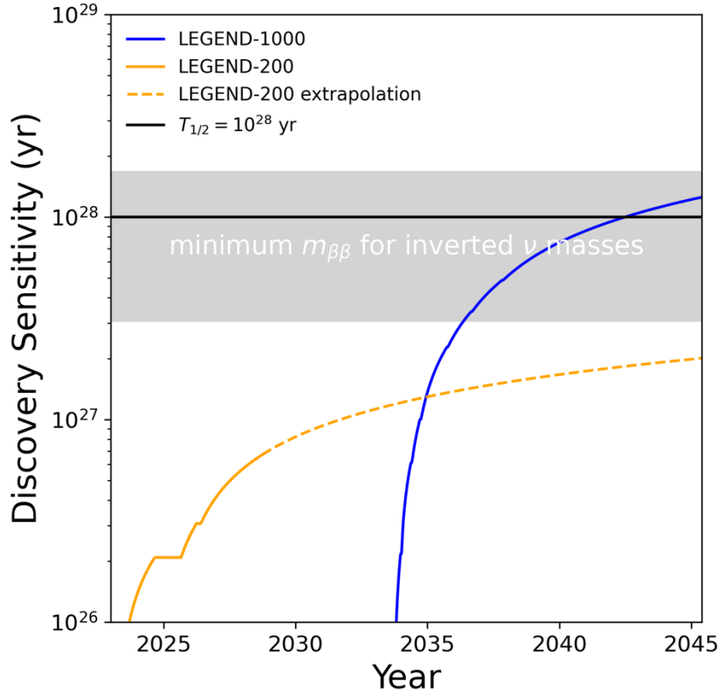
[1] H. Acharya *et al.* (LEGEND), accepted at Phys. Rev. Lett. (Sep 2025)

- Proposed future phase LEGEND-1000, building on L200 success. Key updates:
  - 1 ton of enriched inverted coax detectors
  - Inner volume of underground-sourced Ar to further reduce background
  - 42 single-string modules, individually deployable
  - ASIC-based readout, mounted very close to the detectors in the LAr

- First data scheduled for early 2030's. Project status:
  - Italy: L1000 approved to proceed at LNGS, infrastructure preparation underway
  - Germany: MPG approved funding for cryostat; LEGEND on BMFTR short list of research infrastructure facilities, site visit scheduled for April 2026
  - Poland, Switzerland: received initial funding, additional funding expected
  - UK: proposal in preparation
  - NSF: MREFC for first science – final design funds awarded Summer 2025, final design reviews scheduled through late 2026
  - DOE: successful CD1 Independent Project Review in November 2025, progress currently limited by anticipated funding



LEGEND-1000 concept



Summary and Conclusions

- **Tremendous progress** on all aspects of fundamental symmetries, more than was noted in this short talk

- But also **major setbacks**:
  - Cancellation of nEDM@SNS
  - Probable loss of US leadership on nEXO / ^{136}Xe

- **Recommendation II: The opportunity still exists** to achieve IO sensitivity to neutrinoless double-beta decay in multiple isotopes w/ CUORE and LEGEND-1000
  - maintaining leading contributions from the US will continue to be stressful for the collaborations and funding agencies
  - **Success is not assured, and will required sustained perseverence and diligence!**

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