Direct Neutrino Mass Searches Covering the Inverted Mass Ordering

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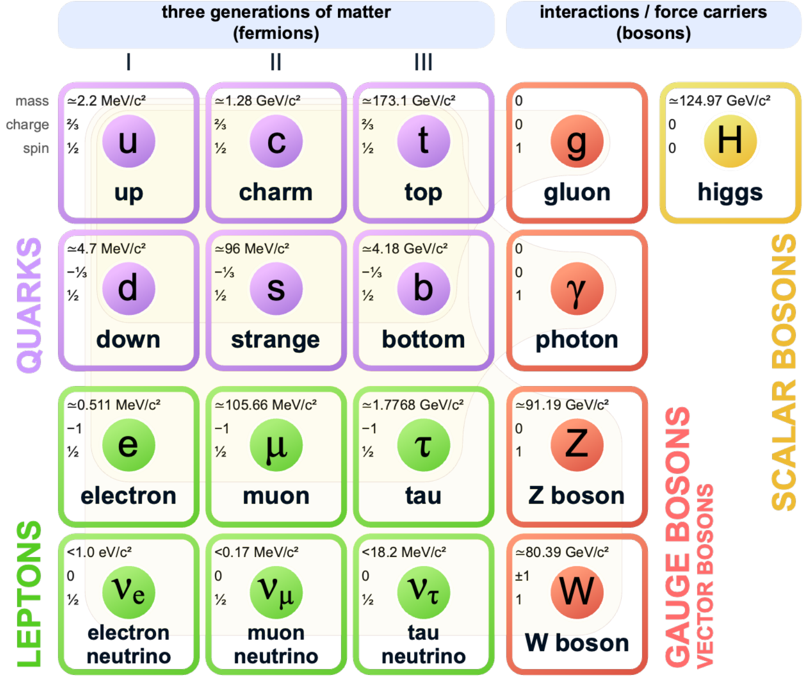
APS GPMFC Workshop

14 April 2023

PROJECT 8

Questions of Neutrino Mass

- Neutrinos are only fundamental fermions with unmeasured mass
- Non-zero neutrino mass is in conflict with original formulation of Standard Model
- Neutrino mass scale is vastly disparate from all other fundamental fermions
- Neutrino mass connected via 0νββ to fundamental symmetries

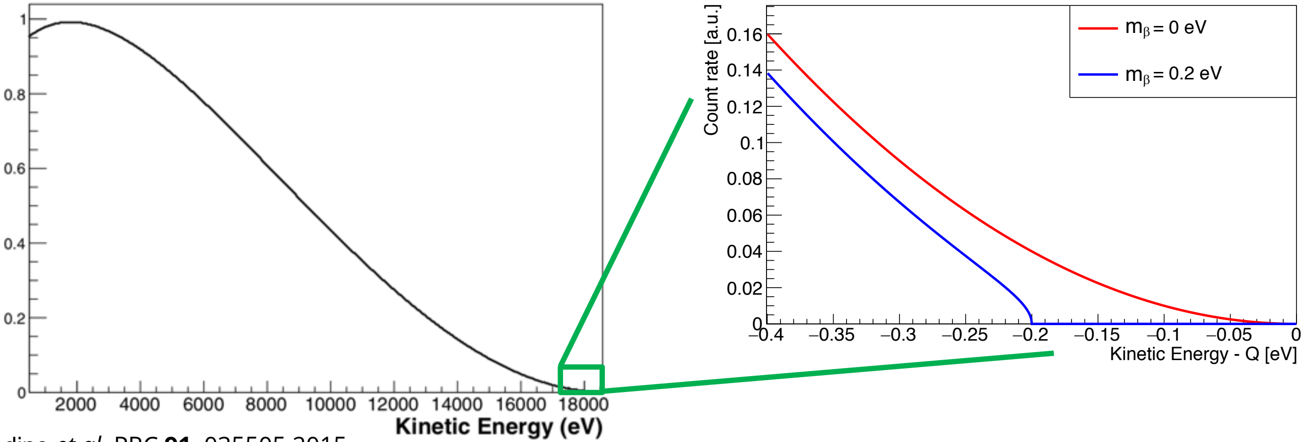


Wikimedia Commons

Direct Neutrino Mass Measurement

- Endpoint technique is only direct and model independent method to measure neutrino mass
    - Non-zero mass results in shift in maximum electron energy and shape distortion at endpoint

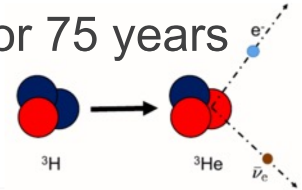
$$m_\beta = \sqrt{\sum_{i=1}^{3} |U_{ei}|^2 m_i^2}$$



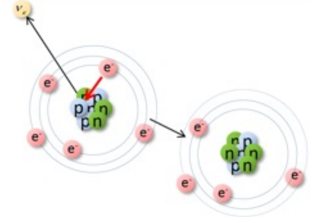
L. I. Bodine *et al*. PRC **91**, 035505 2015

Endpoint Search Candidates

- Tritium beta decay has yielded leading direct limits for 75 years
  - ${}^{3}_{1}H \rightarrow {}^{3}_{2}He^{+} + e^{-} + \overline{\nu_e}$
  - Endpoint: 18.6 keV; half-life: 12.3 yr



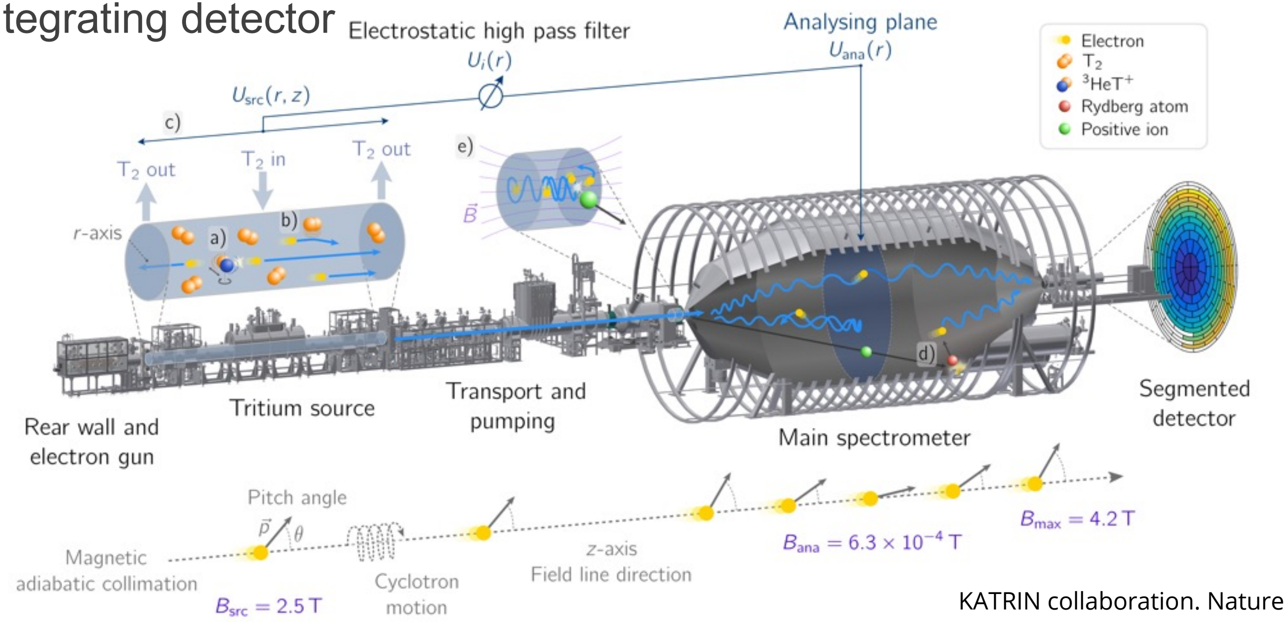
- Holmium electron capture decay
  - ${}^{163}_{67}Ho \rightarrow {}^{163}_{66}Dy^{*} + \nu_e$
  - Endpoint: 2.8 keV; half-life: 4570 yr



- Other isotopes have received interest attention: ^{187}Re, ^{115}In
  - No currently viable experimental program
  - Orders of magnitude worse figure-of-merit for quantity of isotope per decay in last eV

KATRIN: State-of-the-Art

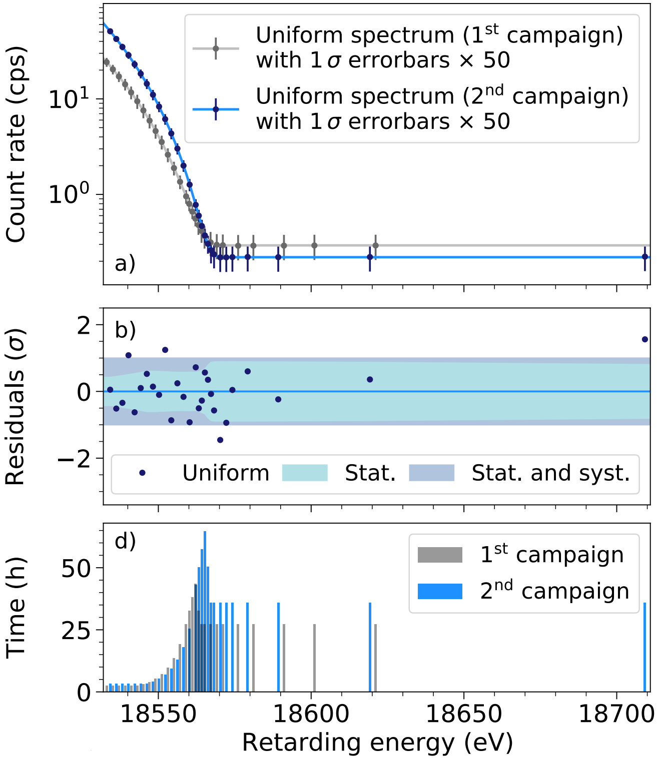
- Culmination of decades of experience in magnetic + electrostatic spectrometers
  - Electrons guided from tritium source, through filtering spectrometer, to integrating detector



KATRIN collaboration. Nature Physics **18**, 160 (2022)

see Andrew Gavin, K15.001

KATRIN: State-of-the-Art



KATRIN collaboration. Nature Physics **18**, 160 (2022)

- 2022 result yielded sub-eV sensitivity
  - Experimental limit of $m_\beta < 0.8$ eV (90% C.L.)
  - Only data from 2019
- Further results expected this year with ~0.5 eV sensitivity
- Neutrino mass operations continue through 2025 to reach 0.2 eV sensitivity
- Science program beyond turns to keV sterile neutrino search with TRISTAN detector

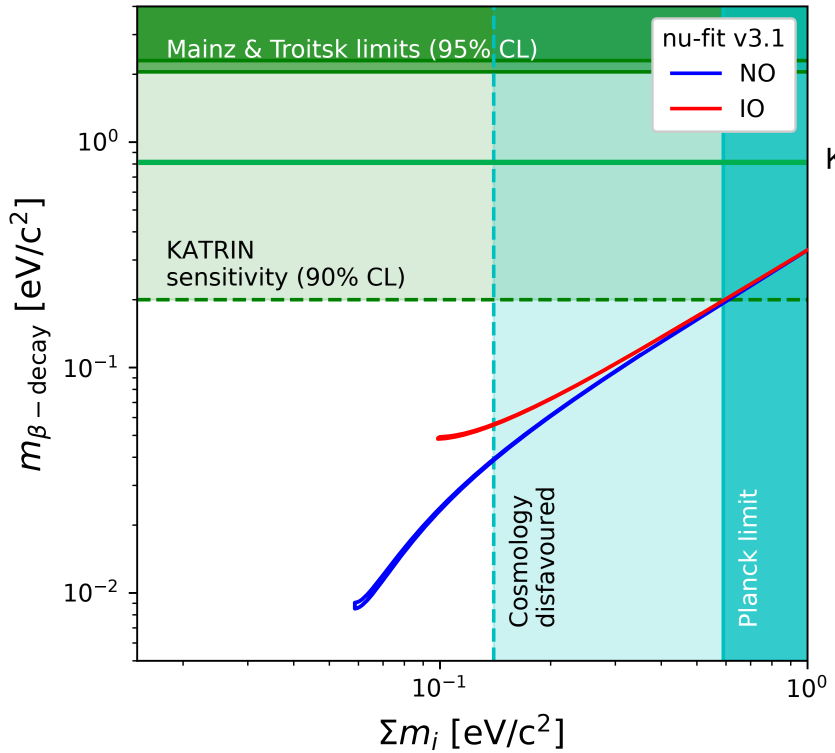
see Andrew Gavin, K15.001

Beyond KATRIN

- MAC-E technology reaching technical scaling limit with KATRIN
    - Larger spectrometer required for improved resolution
    - Integrating spectroscopy reduces statistical power
    - New spectrometer-related backgrounds discovered at KATRIN scale

- Molecular tritium source introduces systematic uncertainty due to molecular effects

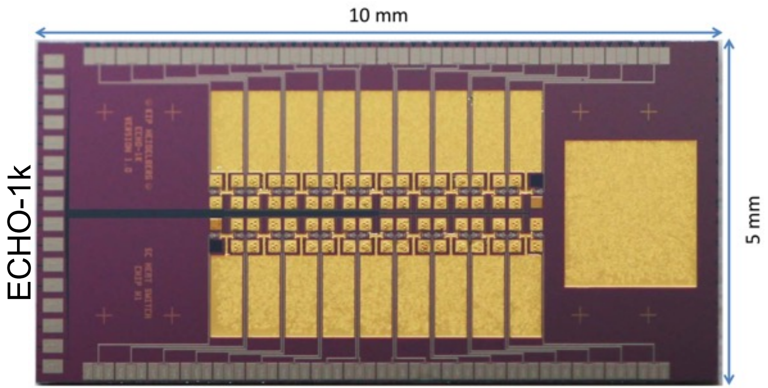
Beyond KATRIN: Sensitivity



KATRIN limit (2021)

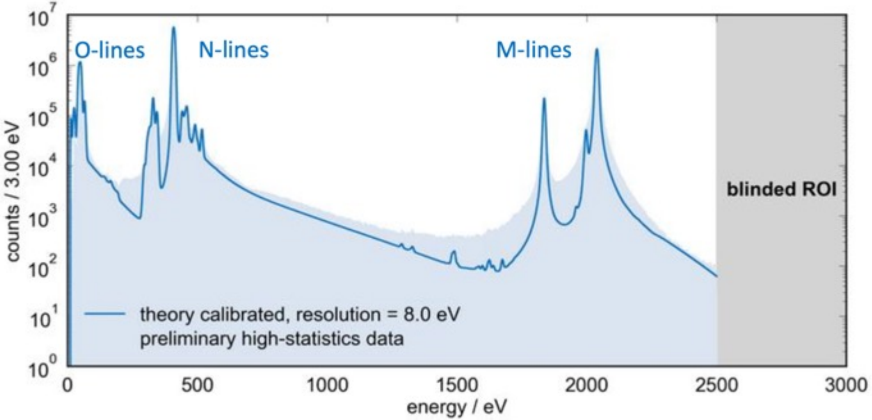
Holmium Electron Capture

- Microcalorimeters implanted with ^{163}Ho isotope



F. Mantegazzini *et al.* NIM A **1030**, 166406 (2022)

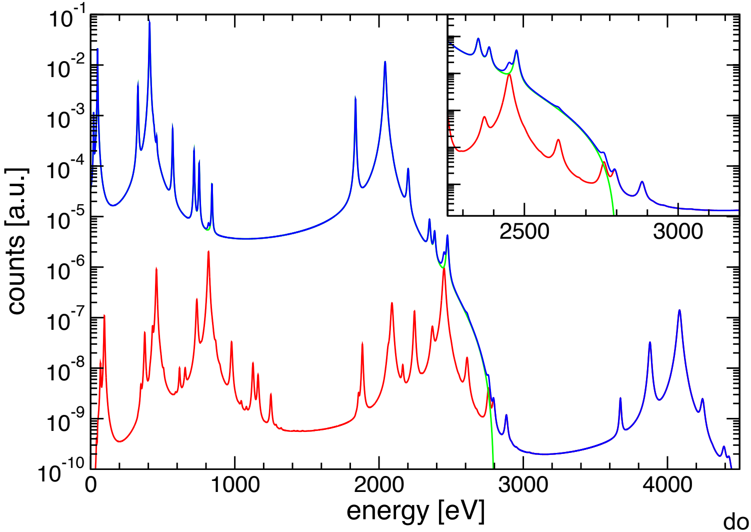
L. Gastaldo. Neutrino 2022



- Endpoint determination precision exceeds current Penning trap measurement
  - Calorimeter: $Q_{EC} = 2860 \pm 2_{stat} \pm 5_{syst}$ eV (preliminary)
  - Penning: $Q_{EC} = 2833 \pm 30_{stat} \pm 15_{syst}$ eV

Micro-Calorimeter Challenges

- Complicated spectral corrections due to electronic shell effects
- Slow readout creates pileup in spectrum
- Large number of channels (~10^9) required
  - Multiplexing many channels together possible (required)

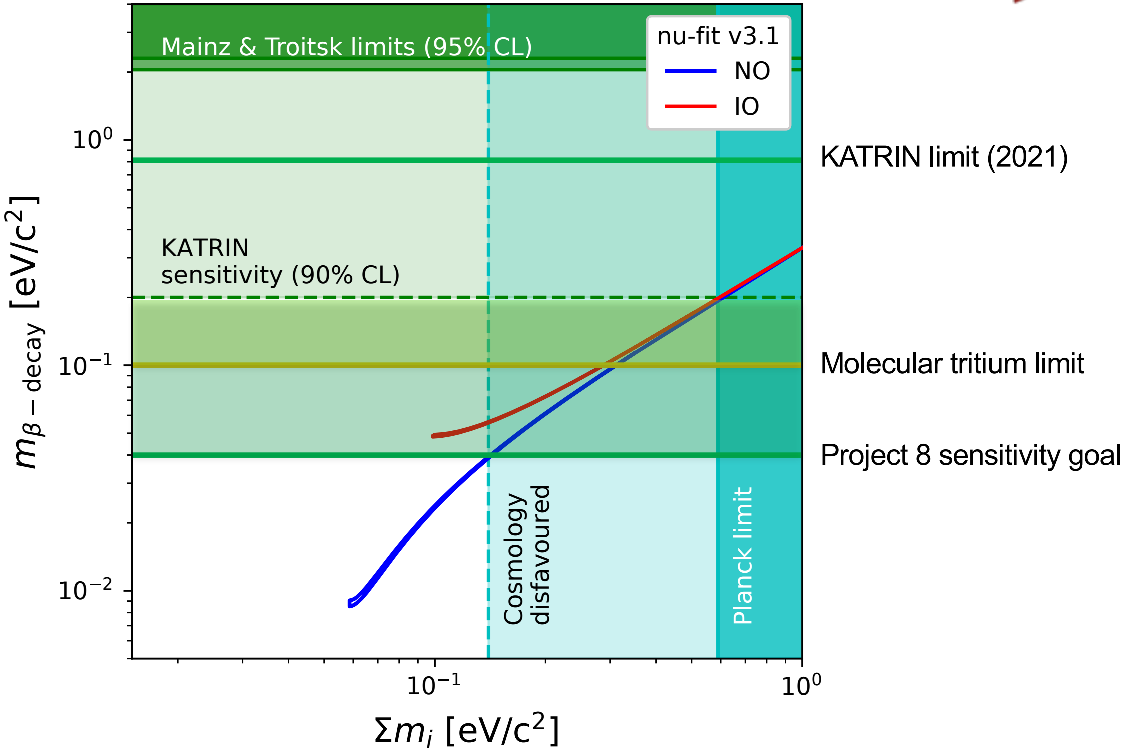


see also Snowmass LoI
arXiv:2203.07572

A. Nucciotti. AHEP (2016)
doi:10.1155/2016/9153024

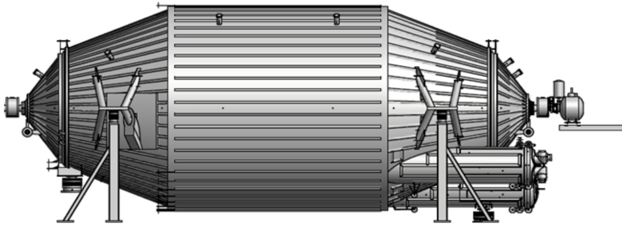
Beyond KATRIN: Project 8 Sensitivity

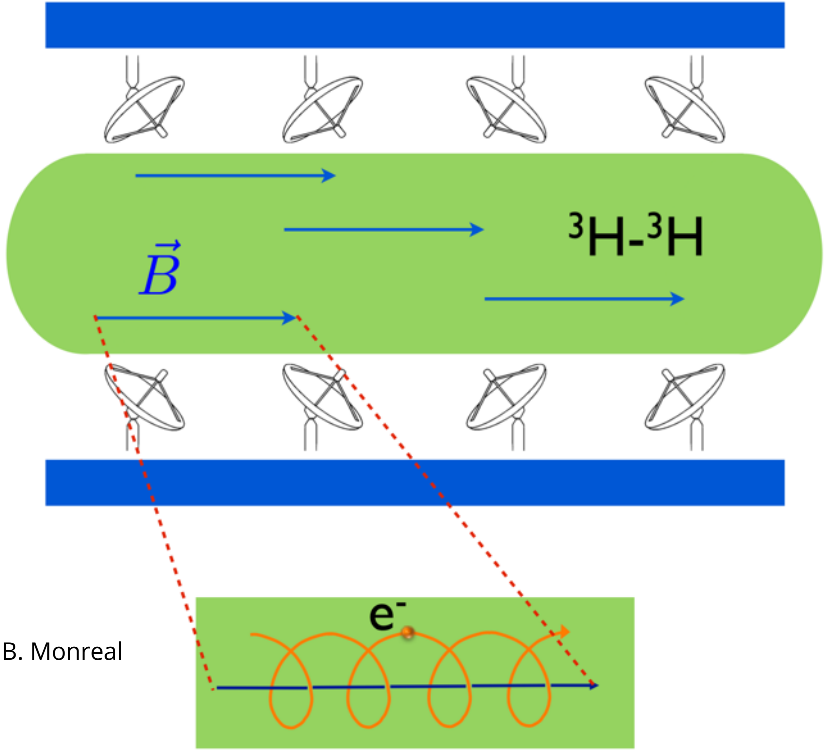
PROJECT 8



see Luiz de Viveiros, K15.004

Beyond KATRIN Concept





B. Monreal

Never measure anything but frequency.

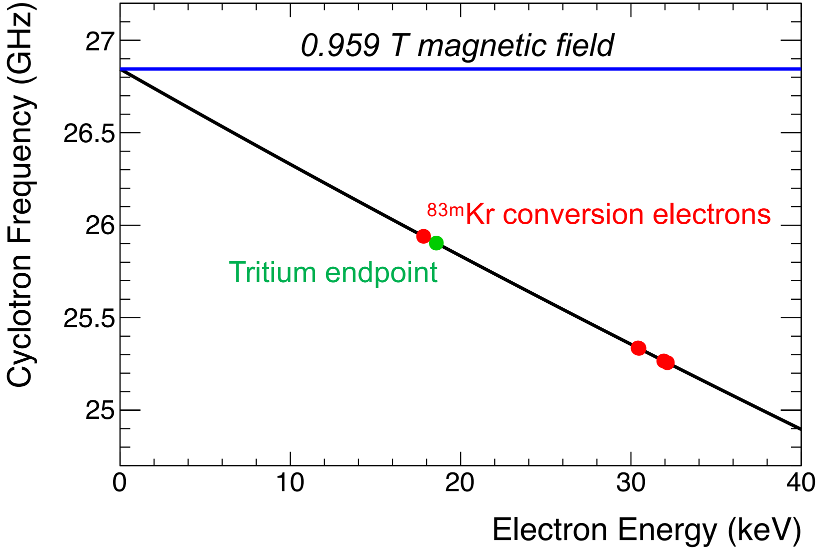
– Arthur Schawlow

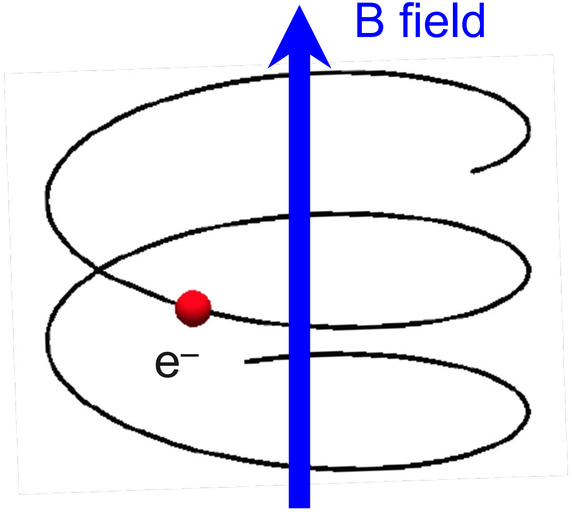
see Luiz de Viveiros, K15.004

Cyclotron Radiation Emission Spectroscopy (CRES)

- Harness frequency-energy relation for relativistic electrons

$$f_c = \frac{1}{2\pi}\frac{eB}{(m + E_{kin})}$$





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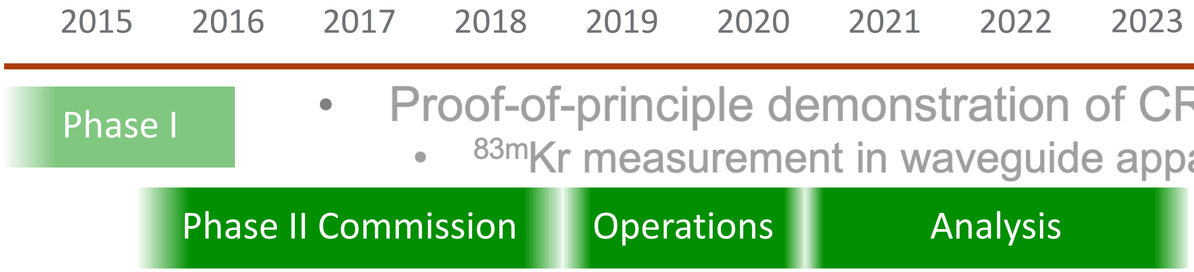
Project 8 Experiment

- A phased tritium beta endpoint experiment to measure the electron neutrino mass



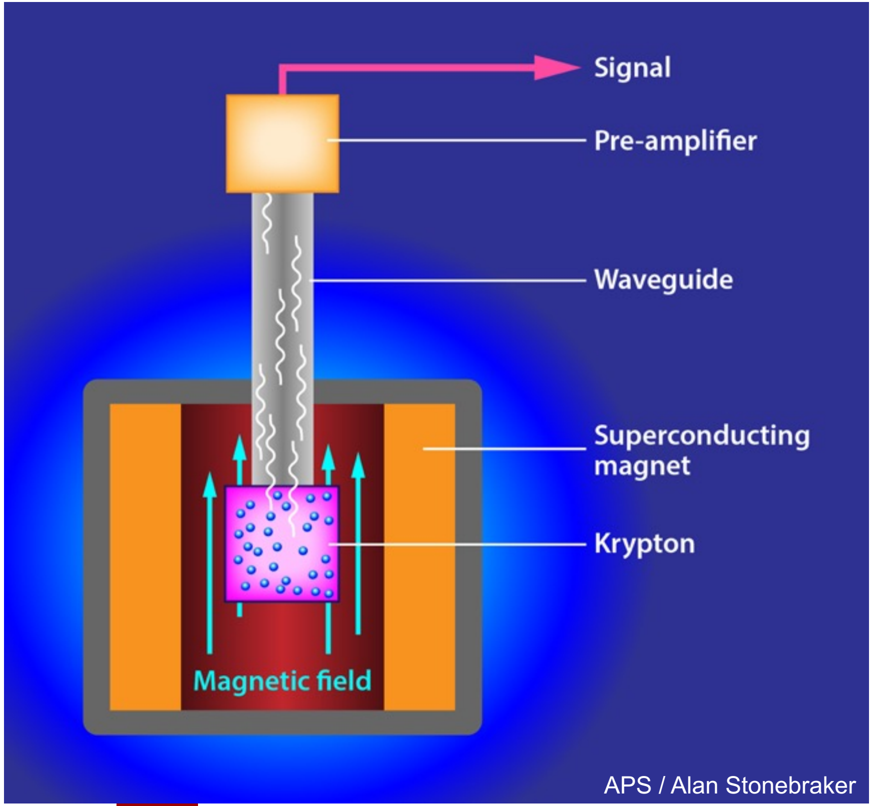
- Proof-of-principle demonstration of CRES technique
  - ^{83m}Kr measurement in waveguide apparatus

Final results, see:

- arXiv:2212.05048 (submitted to PRL)
- arXiv:2303.12055 (submitted to PRC)

- High-resolution Kr measurements
- First tritium measurement and first neutrino mass limit with CRES
  - Zero-background beyond endpoint
  - Control of systematics effects

Waveguide Experimental Concept



Signal

Pre-amplifier

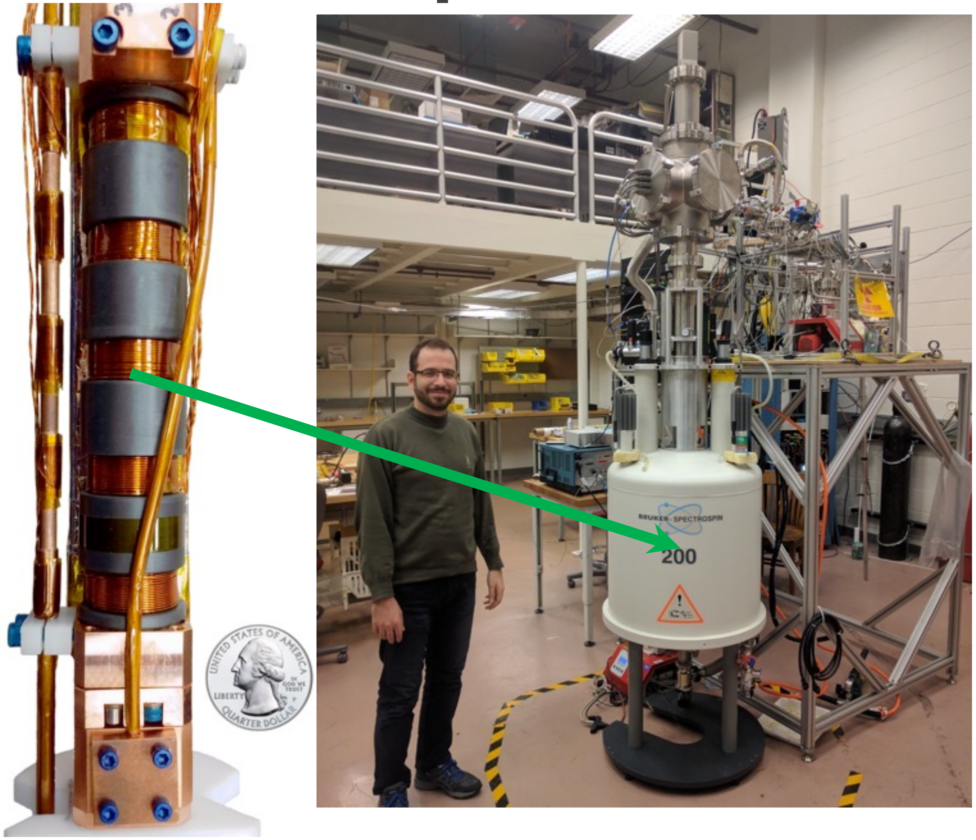
Waveguide

Superconducting magnet

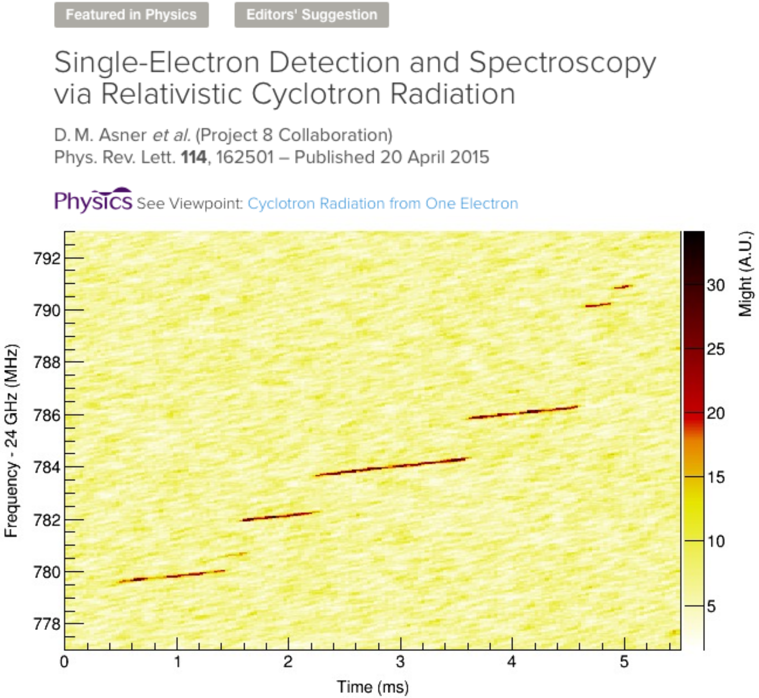
Krypton

Magnetic field

APS / Alan Stonebraker



Waveguide CRES Results



Featured in Physics

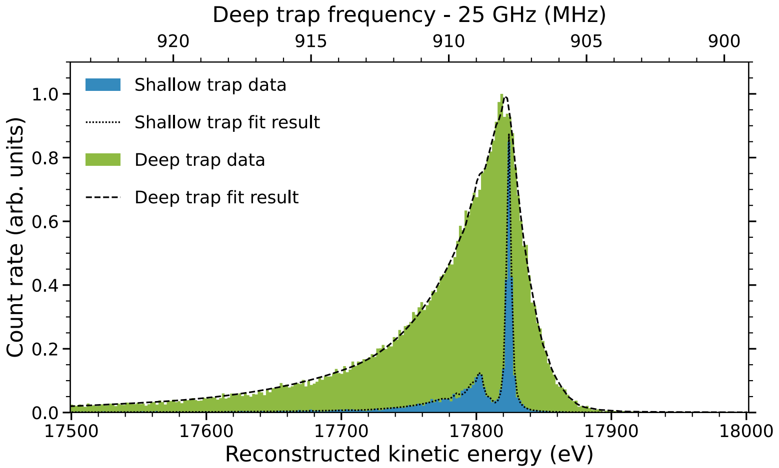
Editors' Suggestion

Single-Electron Detection and Spectroscopy
via Relativistic Cyclotron Radiation

D. M. Asner *et al.* (Project 8 Collaboration)
Phys. Rev. Lett. **114**, 162501 – Published 20 April 2015

Physics See Viewpoint: Cyclotron Radiation from One Electron

D. Asner *et al*. Phys. Rev. Lett. 114, 162501 (2015)
(reprocessed)

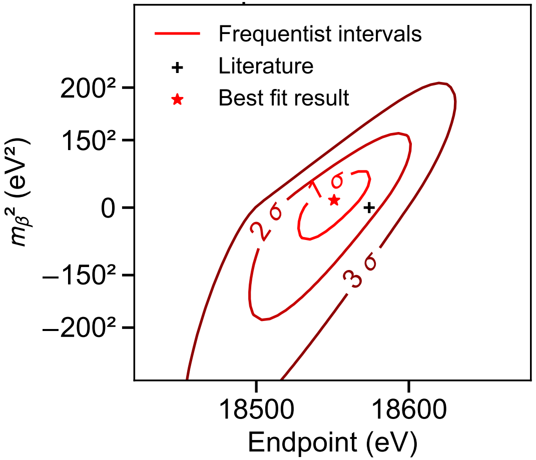


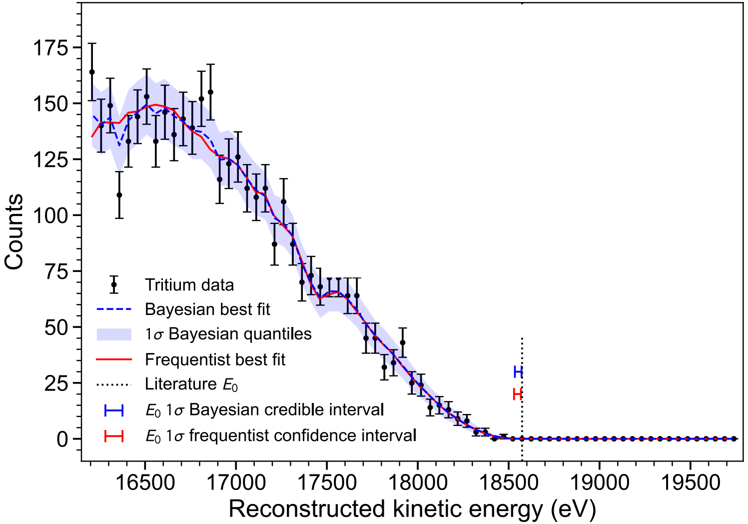
arXiv:2212.05048

Instrumental resolution (1.7±0.2 eV) now better than natural CE linewidth (2.8 eV)

First Tritium Spectrum

- Collected 3 months stable run of tritium
  - ~4000 events across all signal channels
  - Zero background beyond endpoint





T_2 endpoint:

$$E_0 = \left(18553^{+18}_{-19}\right)\ \text{eV (90\% C.I.)}$$

Neutrino mass:

$\leq$ **155** eV/c² (90% C.I.) *Bayesian*

$\leq$ **152** eV/c² (90% C.L.) *Frequentist*

Background rate:

$\leq \mathbf{3\times10^{-10}}\ \text{eV}^{-1}\text{s}^{-1}$ (90% C.I.)

Final results, see:

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Project 8 Experiment

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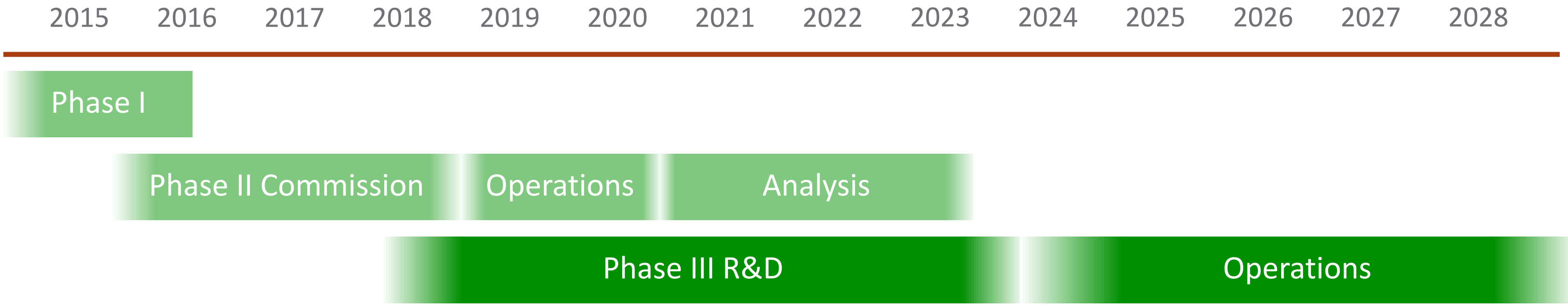
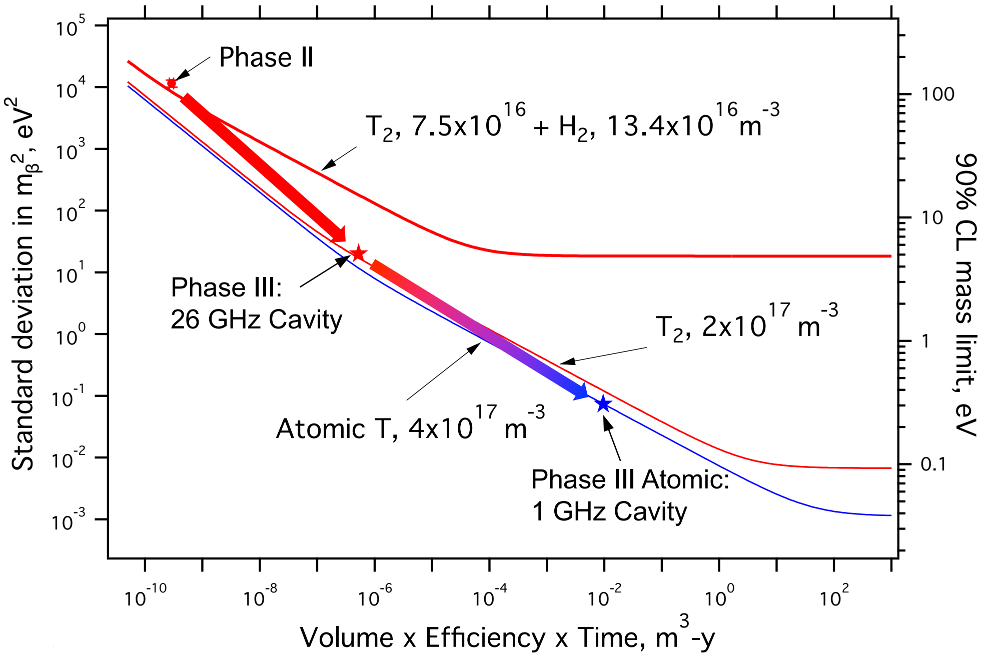


- Critical R&D demonstrations of technologies
  - Large-volume CRES measurement, first with single-mode cavity
  - Atomic tritium production, transport, and trapping
  - Culminates with first atomic tritium endpoint measurement

CRES – The Path Forward

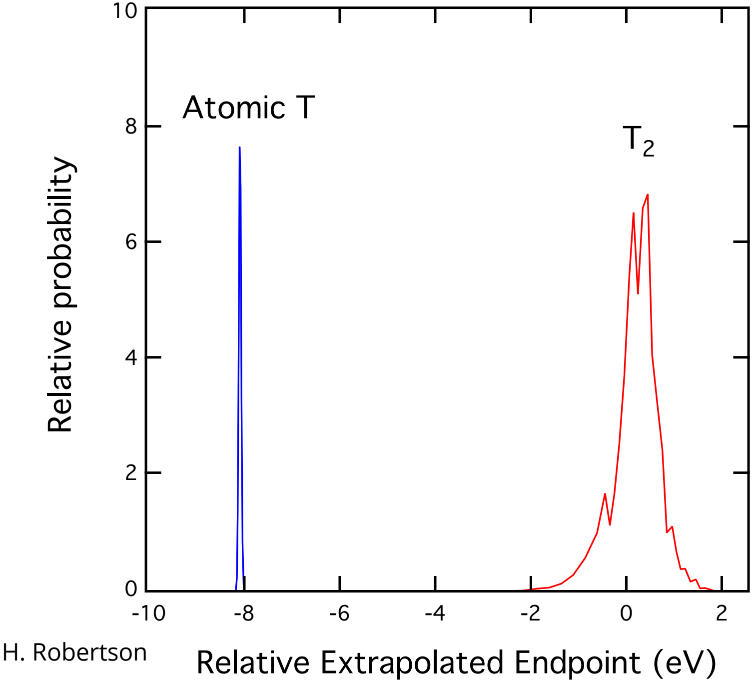
Phase II was heavily statistics-limited



- Develop atomic source
  - Overcome systematic of molecular final states
- Increase volume
- Improve SNR
  - Higher density with shorter tracks
- Improve control of systematics, field homogeneity, scattering effects

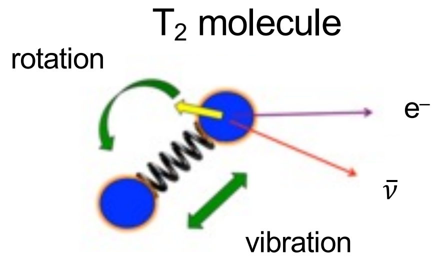
Phase III ATD – Molecular Limitation

- Sensitivity beyond inverted hierarchy requires atomic tritium



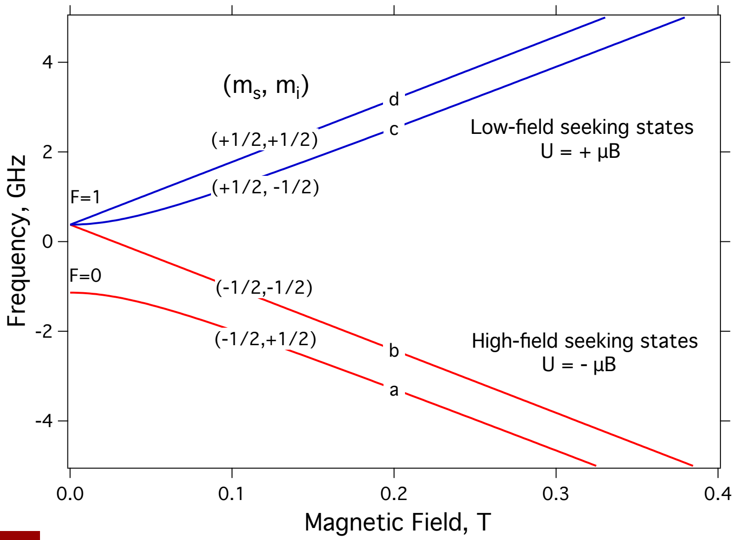
H. Robertson

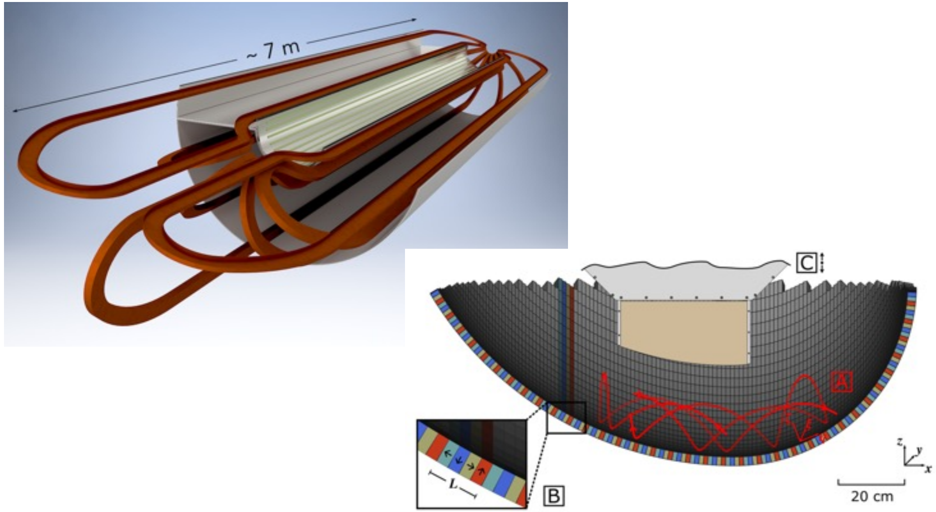
…and pure atomic tritium, as molecular endpoint is higher



Phase III ATD – Trapping Atoms

- Magnetic moment of atomic species allows for guiding and trapping
  - Unpaired electron of atomic T (or H, D) gives it magnetic moment
  - “Low-field-seeking” states trapped by magnetic bottle
  - Requires high-multipole trap to achieve uniform CRES field region

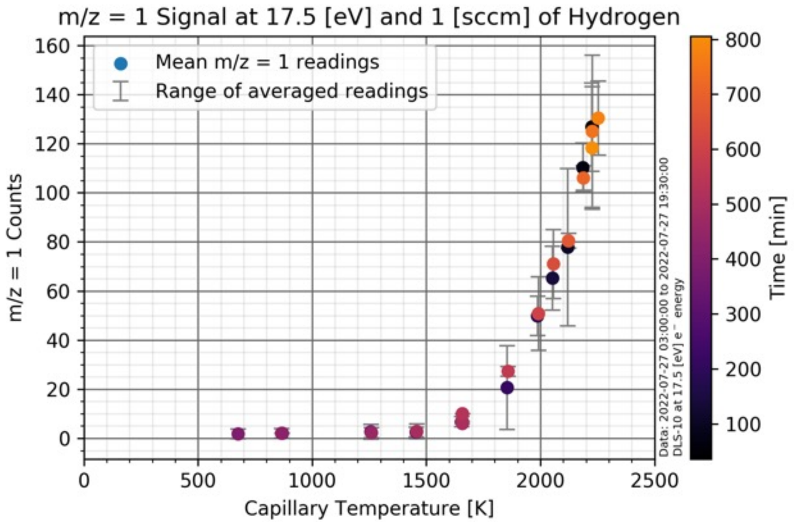




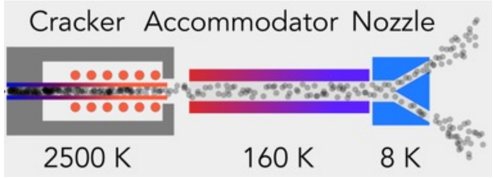
UCNτ, PRC **100**, 015501 (2019)

Phase III ATD – Supplying Atomic Tritium

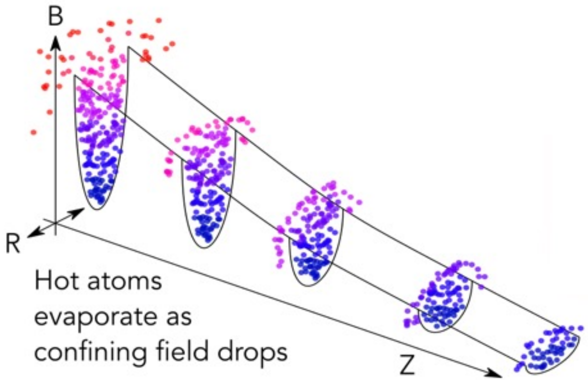
- Molecular tritium thermally cracked at ~2500 K



- Then cooled by accommodator to ~10 K



- Then cooled evaporatively down to mK



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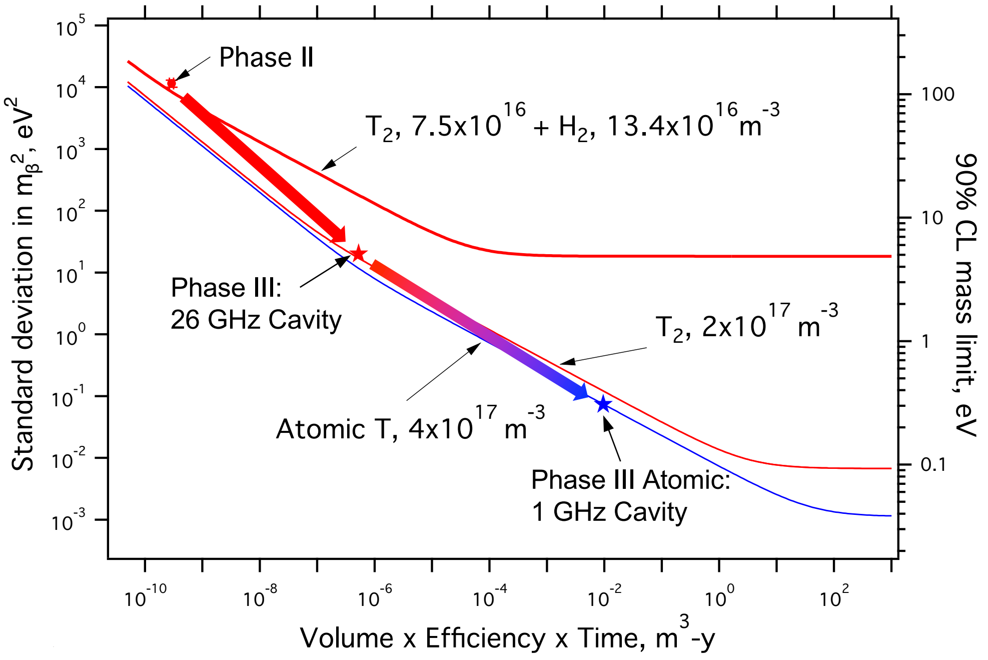
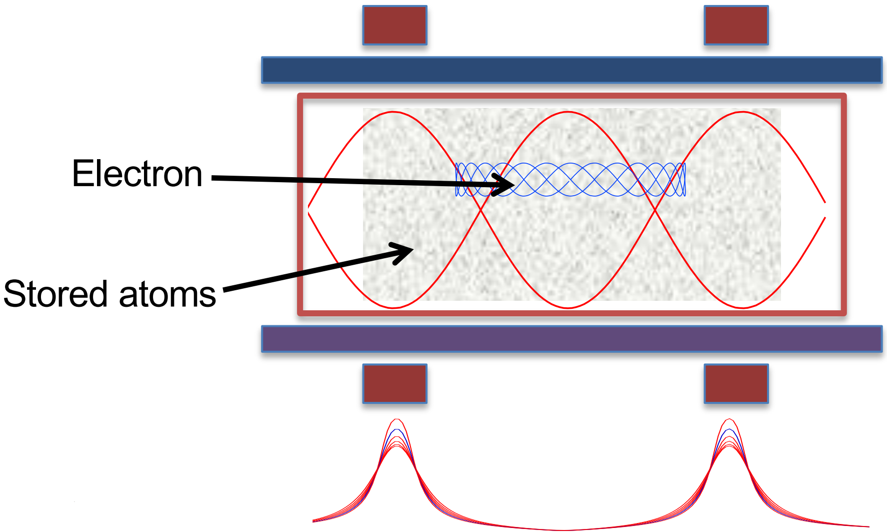


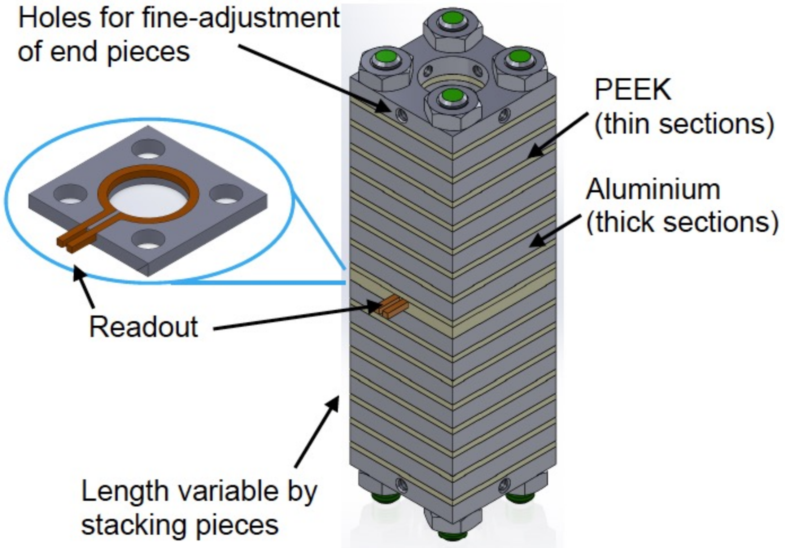
- Develop atomic source
  - Overcome systematic of molecular final states
- Increase volume
- Improve SNR
  - Higher density with shorter tracks
- Improve control of systematics, field homogeneity, scattering effects

Phase III – Beyond Waveguide

- Demonstrate scalability of CRES technique
- Cavity efficiently couples electron power to readout antenna
  - Mode-filtering reduces complexity of mode structure
  - Open-ended terminated cavity still allows gas injection



26 GHz Cavity Model



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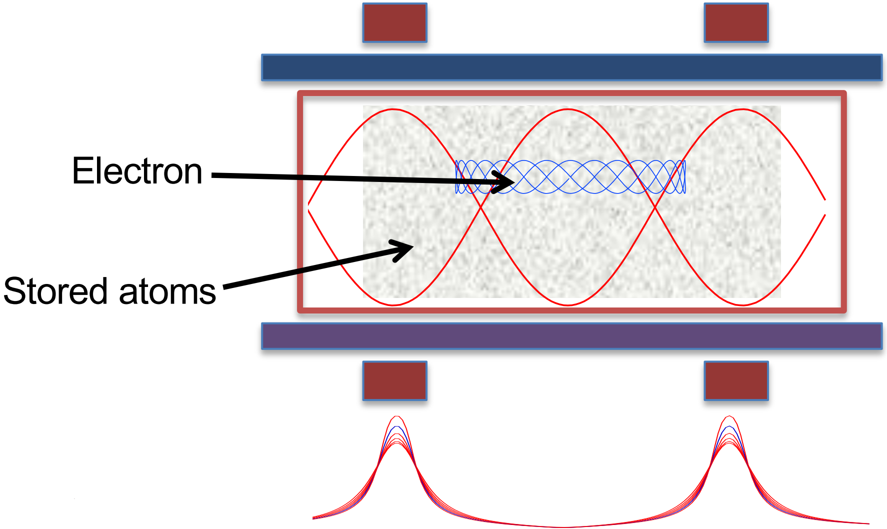
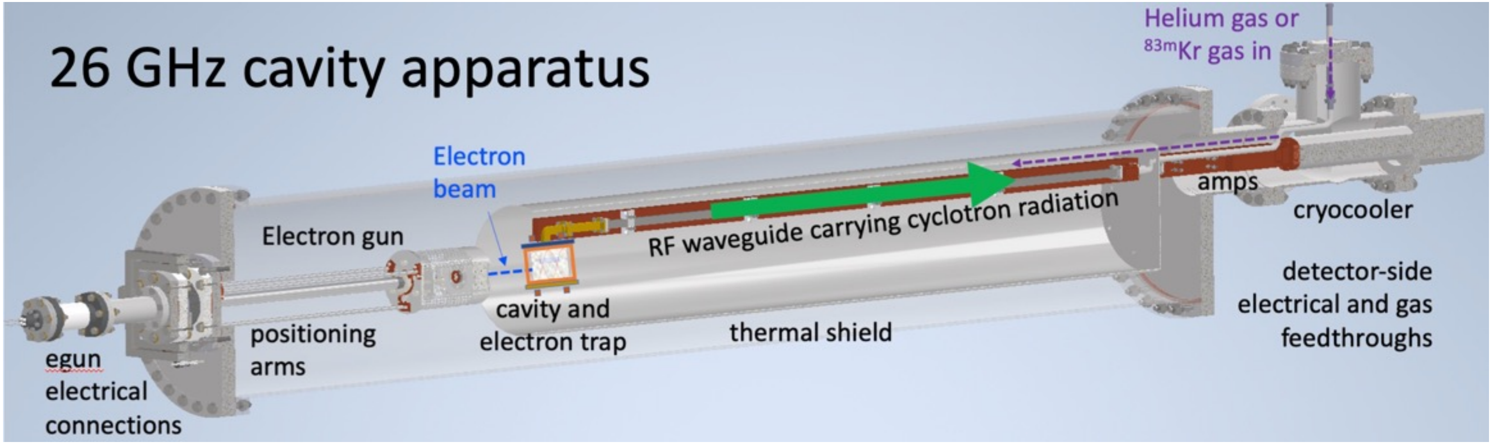


26 GHz Cavity CRES Demonstrator (CCD)

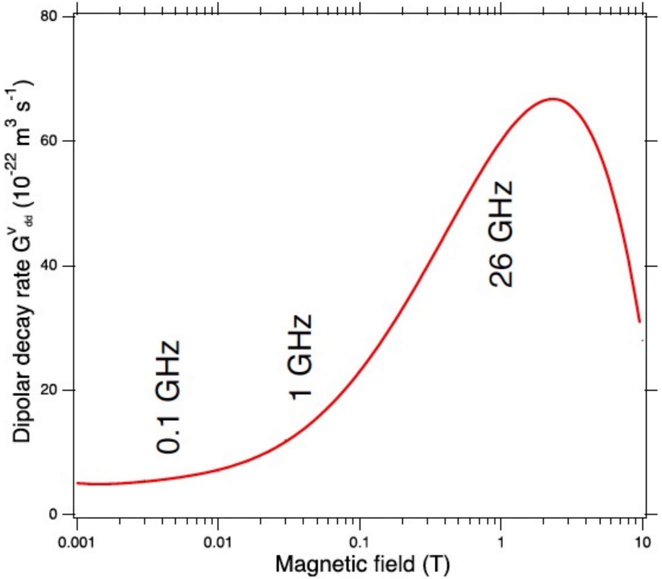
- First cavity demonstrator will operate at 26 GHz / 1 T
  - Installation this summer at University of Washington



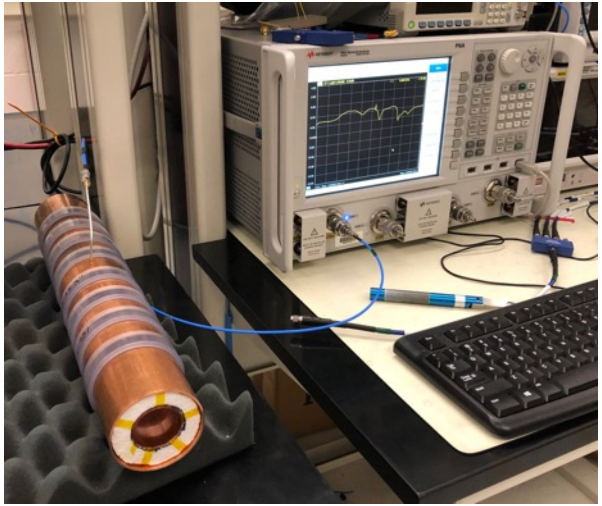
- Demonstration of high-precision calibration with electron gun source
- Science from ^{83m}Kr spectroscopy measurements

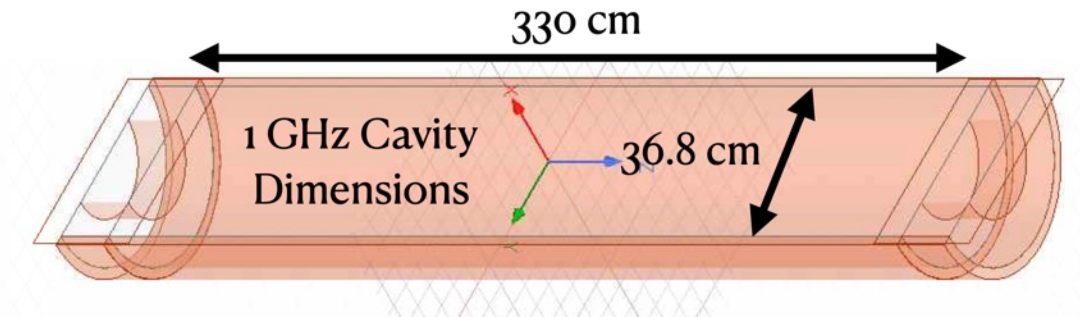
Future Cavities & Lower Frequency

- Cavity R&D must press to lower frequency
  - 26 GHz has unacceptably high dipolar spin flip losses
  - Targeting 1 GHz or lower



6 GHz Prototype
@ Penn State





Project 8 Experiment

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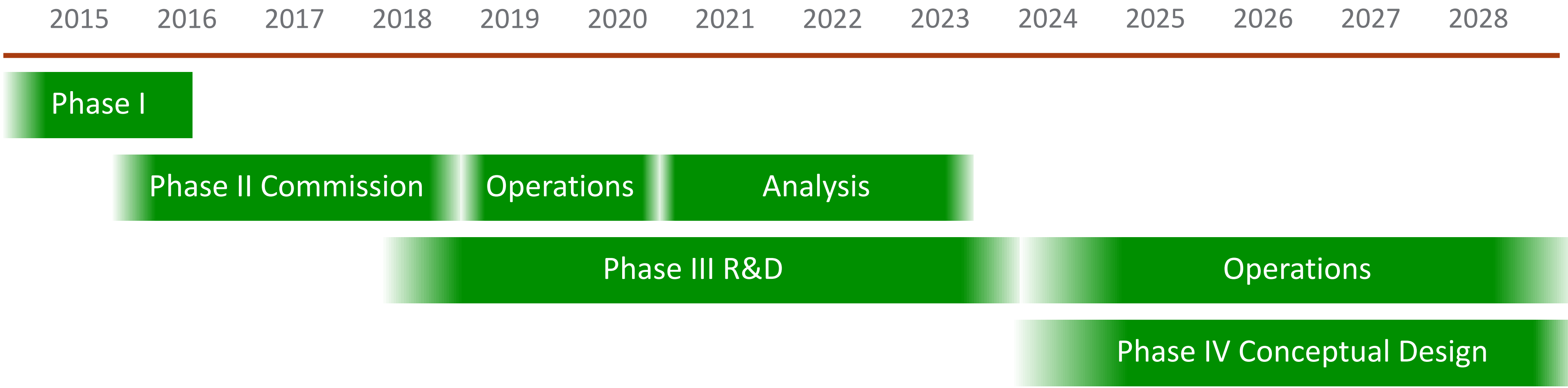


2015 2016 2017 2018 2019 2020 2021 2022 2023 2024 2025 2026 2027 2028

Phase I

Phase II Commission

Operations

Analysis

Phase III R&D

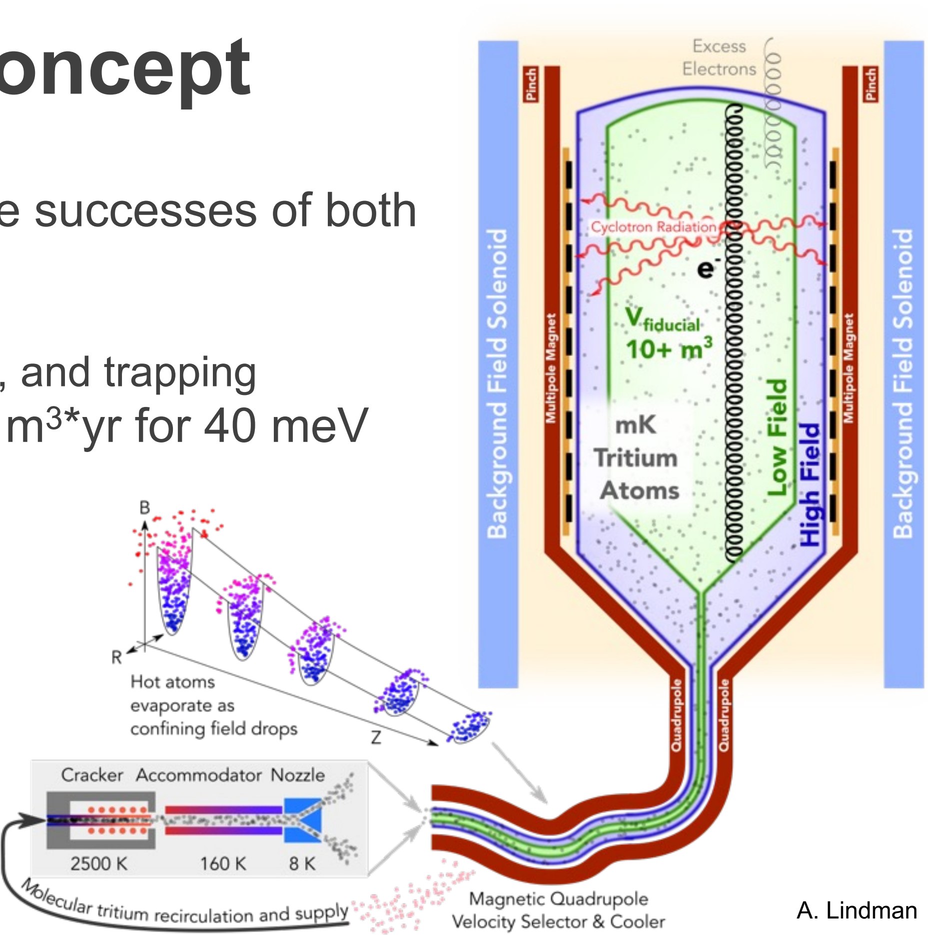
Operations

Phase IV Conceptual Design

- Atomic tritium endpoint measurement covering inverted ordering allowed region

Atomic Experiment Concept

- Experiment must ultimately combine successes of both R&D pathways:
  - Large-volume CRES detection
  - Atomic tritium production, transport, and trapping
- Requires effective exposure of ~10 m^3*yr for 40 meV (inverted ordering) sensitivity



A. Lindman

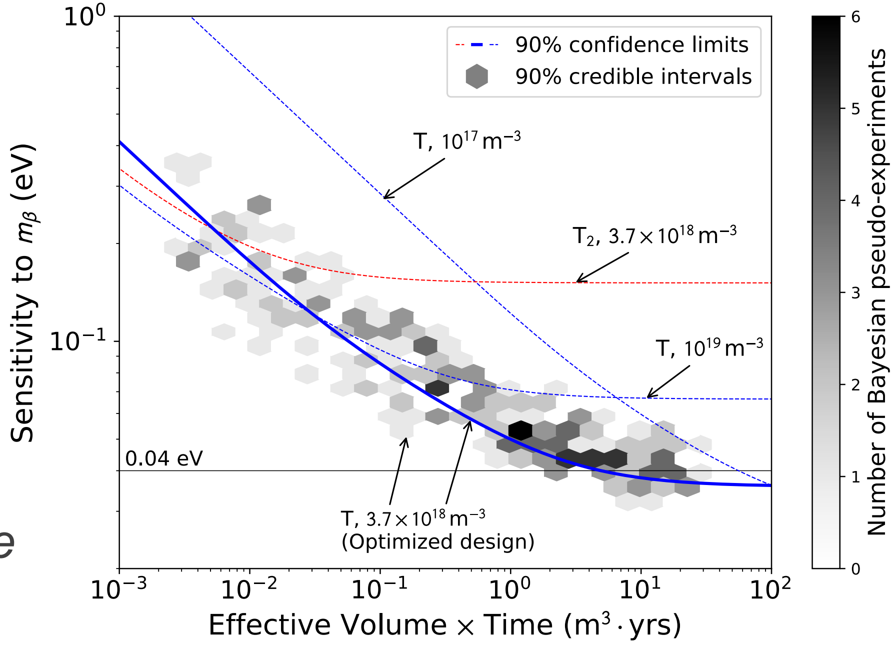
Phase IV Sensitivity

Framework developed for investigating sensitivity of ultimate experiment

Achieving 40 meV sensitivity requires

- Multi m^3·yr effective exposure
- High flux atomic tritium source
- ~0.1 eV resolution
- 10^{-7} field uniformity

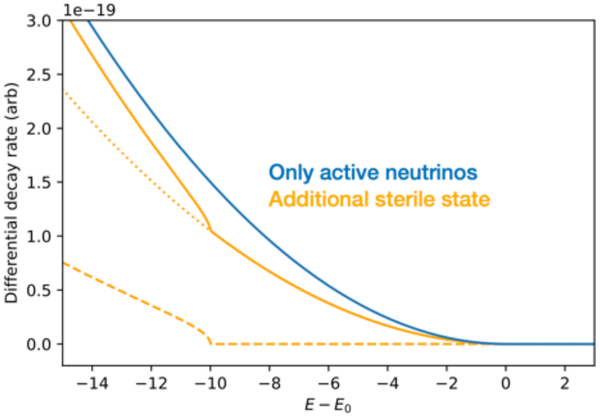
With potential to independently measure hierarchy

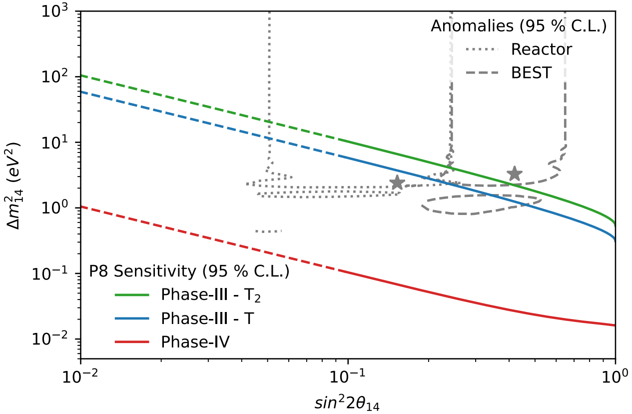


Phys. Rev. C **103**, 065501 (2021)

Other Science Reach

- Precision spectroscopy of tritium beta decay also yields sensitivity to new physics, with same neutrino mass dataset
  - eV-scale sterile neutrinos via kink search





  - Relic neutrino overabundance via peak beyond the endpoint

Conclusions

- Understanding and measuring the absolute neutrino mass scale remain grand open experimental challenges
- KATRIN continues to deliver world-leading mass limits
  - Full exposure in 2025, target sensitivity of 200 meV
- Project 8 developing Cyclotron Radiation Emission Spectroscopy (CRES) as promising technique for a next-generation neutrino mass experiment
  - Phase II results finalized last month
    - Kr resolution below natural linewidth with full modeling of lineshape
    - First neutrino mass limit from RF technique
    - Zero background experiment
    - Control of systematics over broad energy range on continuous T_2 beta spectrum
  - R&D program underway tackling critical technology demonstrations for future inverted-hierarchy-covering (40 meV) experiment
    - Atomic tritium production, cooling, guiding, and trapping
    - Large volume CRES detection

Project 8 Collaboration

PROJECT 8

- Case Western Reserve University
  - Razu Mohiuddin, Ben Monreal, Yu-Hao Sun
- Heidelberg University
  - Felix Spanier
- University of Illinois
  - Chen-Yu Liu
- Indiana University
  - Manjinder Oueslati, Walter Pettus
- Johannes Gutenberg University, Mainz
  - Sebastian Böser, Martin Fertl, Alec Lindman, Christian Matthé, Brunilda Muçogllava, René Reimann, Florian Thomas, Larisa Thorne
- Karlsruhe Institute of Technology
  - Thomas Thümmler
- Lawrence Livermore National Laboratory
  - Kareem Kazkaz
- Massachusetts Institute of Technology
  - Joseph Formaggio, Mingyu Li, Junior Peña, Juliana Stachurska, Wouter Van de Pontseele
- Pacific Northwest National Laboratory
  - Jeremy Gaison, Noah Oblath, Dan Rosa de Jesús, Jonathan Tedeschi, Brent VanDevender
- Pennsylvania State University
  - Carmen Carmona-Benitez, Richard Mueller, Luiz de Viveiros, Andrew Ziegler
- University of Washington
  - Ali Ashtari Esfahani, Christine Claessens, Peter Doe, Sanshiro Enomoto, Alexander Marsteller, Elise Novitski, Hamish Robertson, Gray Rybka
- Yale University
  - Karsten Heeger, James Nikkel, Penny Slocum, Pranava Teja Surukuchi, Arina Telles, Talia Weiss

This work is supported by the US DOE Office of Nuclear Physics, the US NSF, the PRISMA+ Cluster of Excellence at the University of Mainz, and internal investments at all institutions.