



Precision Tritium Beta Decay Measurement for Neutrino Mass with Project 8

Walter C. Pettus

Indiana University

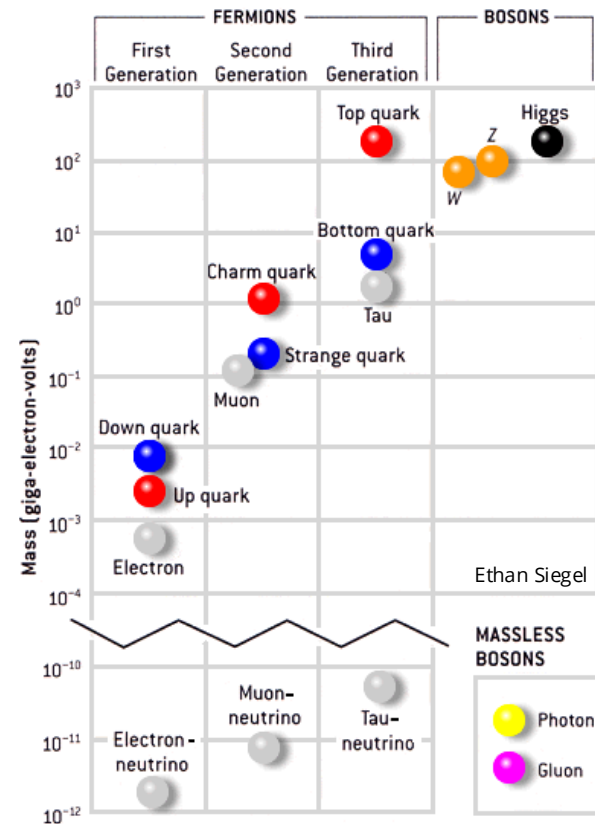
FRIB-TA: Future Directions in Nuclear Beta Decay

11 September 2025

PROJECT 8

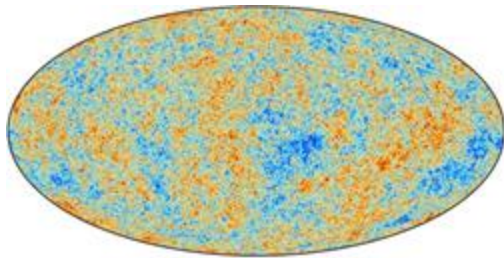
Mystery of the Neutrino Mass Scale

- Neutrinos are only Standard Model fundamental fermions with unmeasured mass
- Scale of neutrino mass sets them apart from all other particles of Standard Model
- Physics behind neutrino mass linked to many interesting questions in nuclear, particle, and astro physics
- Direct and model independent measurement of neutrino mass possible from beta decay



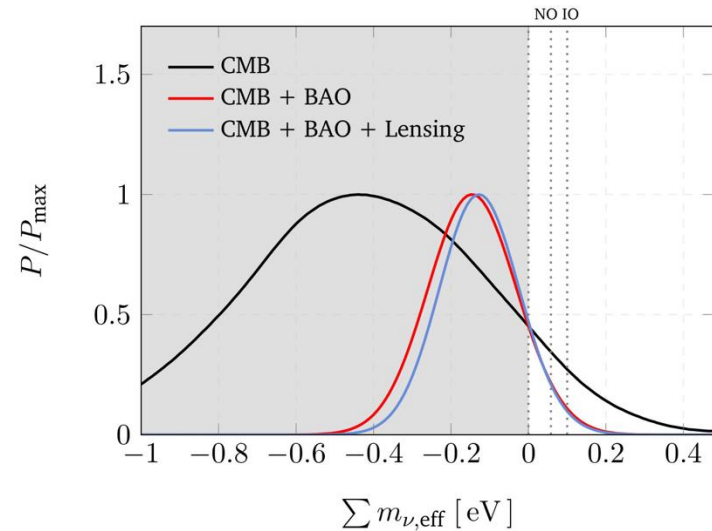
Probing the Neutrino Mass Scale

W. Elbers *Neutrino 2024*
arXiv:2503.14744

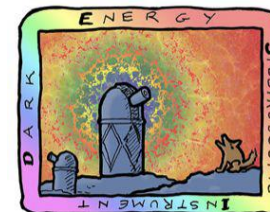


Cosmology

$$\sum m_\nu = \sum_{i=1}^3 m_i$$



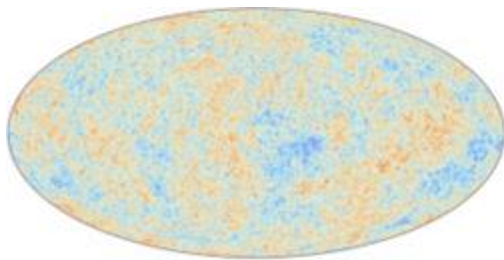
- Most stringent neutrino mass limits currently derived from cosmology
- Rely on 7+ parameter fits to extended Λ CDM model
- Fits increasingly prefer *negative* neutrino mass



**DARK ENERGY
SPECTROSCOPIC
INSTRUMENT**

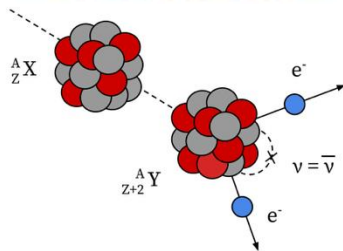
U.S. Department of Energy Office of Science

Probing the Neutrino Mass Scale



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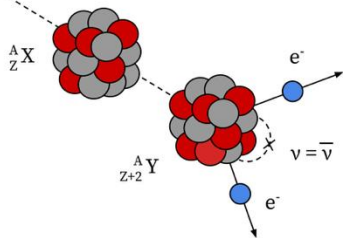
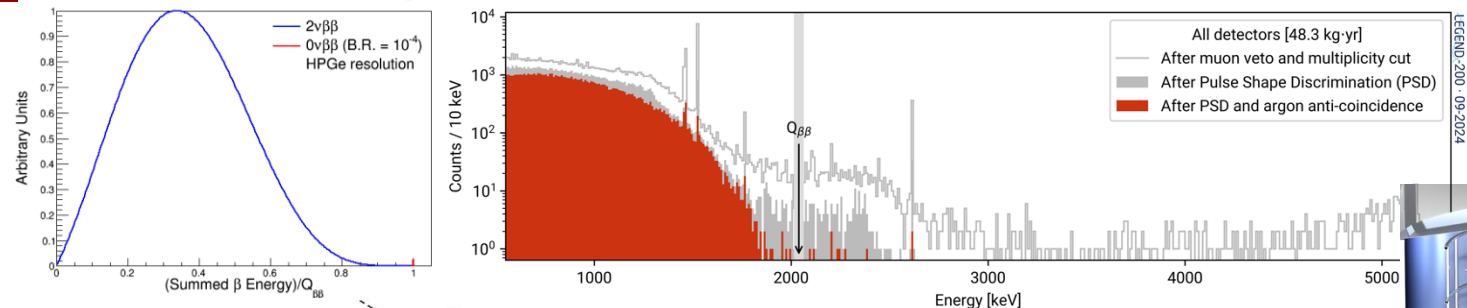


Neutrinoless Double-Beta Decay

$$\langle m_{\beta\beta} \rangle = \left| \sum_{i=1}^3 U_{ei}^2 m_i \right|$$

- Capable of probing Majorana nature of neutrino
 - Model dependent sensitivity to neutrino mass with explanation of disparate mass scale
- Tonne-scale program is top experiment recommendation of 2023 NSAC LRP

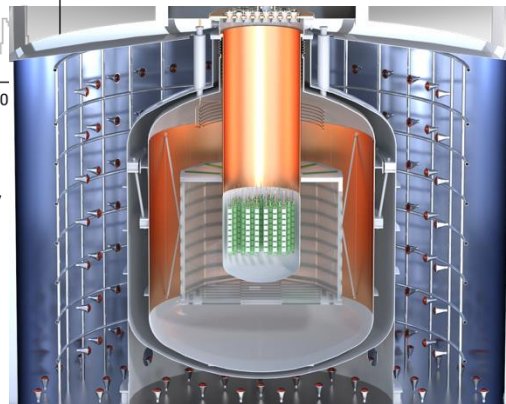
Probing the Neutrino Mass Scale



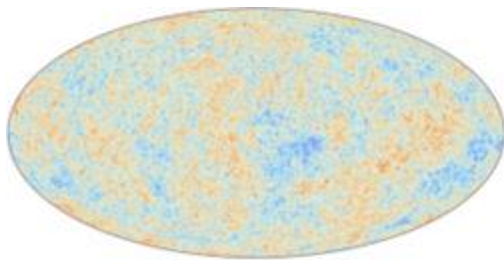
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- Tonne-scale program is top experiment recommendation of 2023 NSAC LRP
 - LEGEND-1000 to be flagship US-led experiment

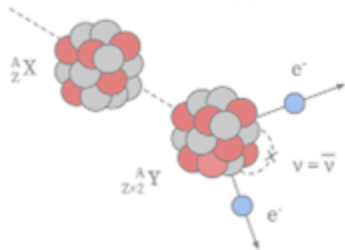


Probing the Neutrino Mass Scale



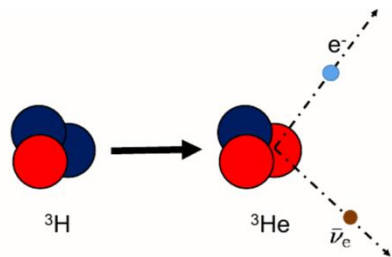
Cosmology

$$\sum m_\nu = \sum_{i=1}^3 m_i$$



Neutrinoless Double-Beta Decay

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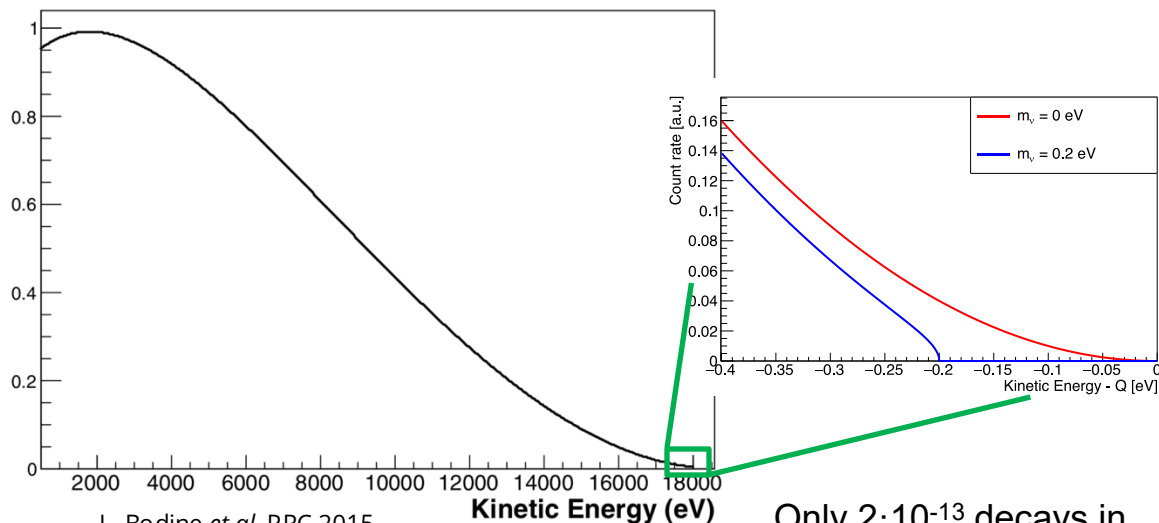
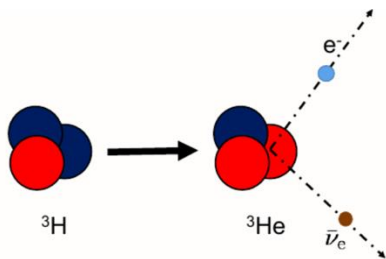
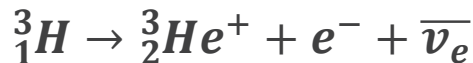
Endpoint Measurements (β -decay and EC)

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

Tritium Beta Decay

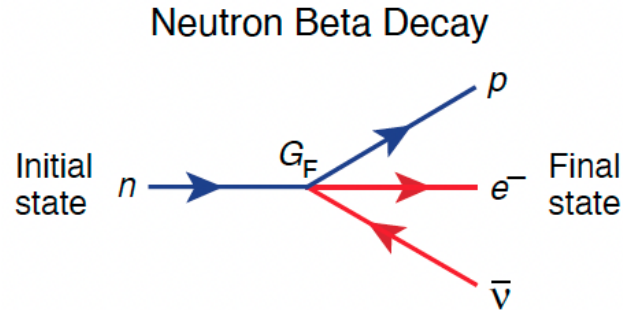
- Tritium has been the workhorse of the direct neutrino mass field
 - Best limits for 75+ years (since 1948), and counting

- Endpoint: 18.6 keV
- Half-life: 12.3 yr
- Superaligned decay

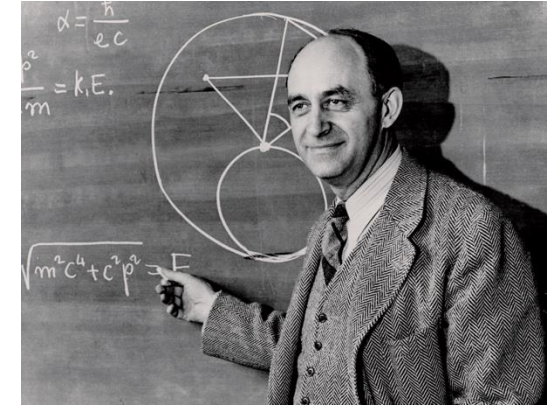


Only $2 \cdot 10^{-13}$ decays in last eV of the spectrum

Fermi (1934): Endpoint Method

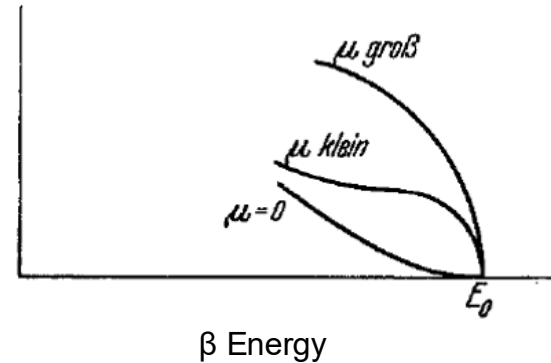


$$n \rightarrow p + e^- + \bar{\nu}$$



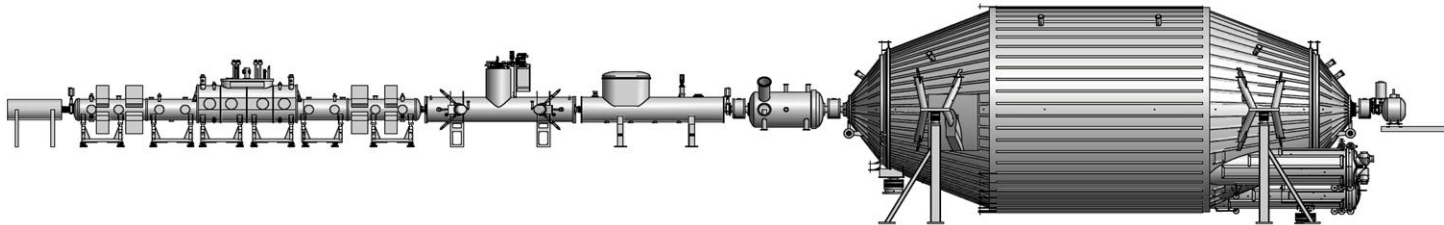
Evidence of neutrino mass imprinted on endpoint of beta spectrum

$$\frac{dN}{d\epsilon} \propto \epsilon \sqrt{\epsilon^2 - m_\beta^2}$$

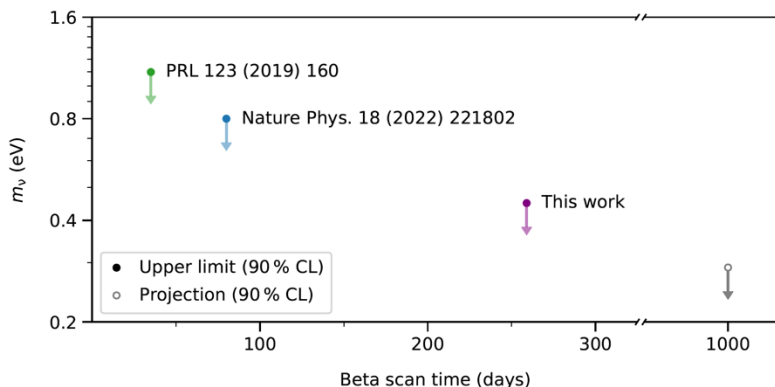


E. Fermi, Zeitschrift für Physik (1934)

KATRIN



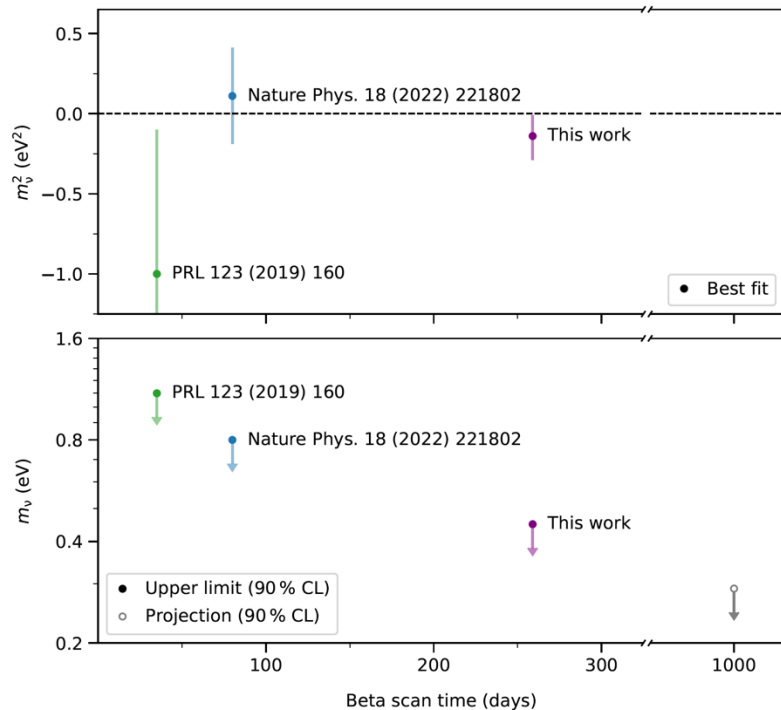
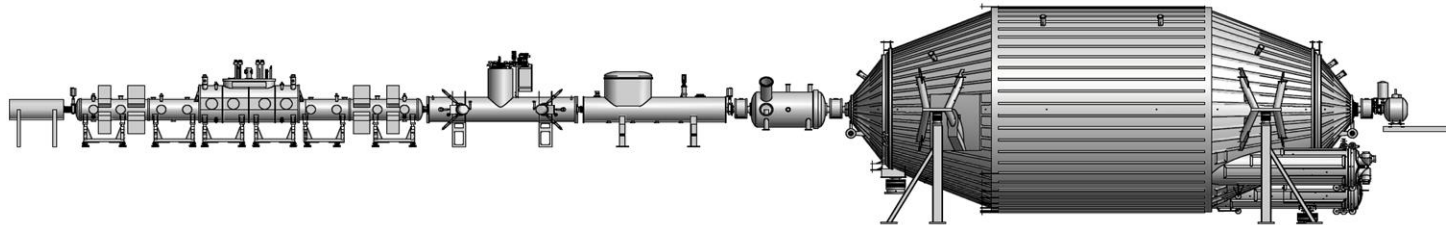
- State-of-the-art in field is KATRIN experiment
- Employs gaseous molecular tritium source and MAC-E filter



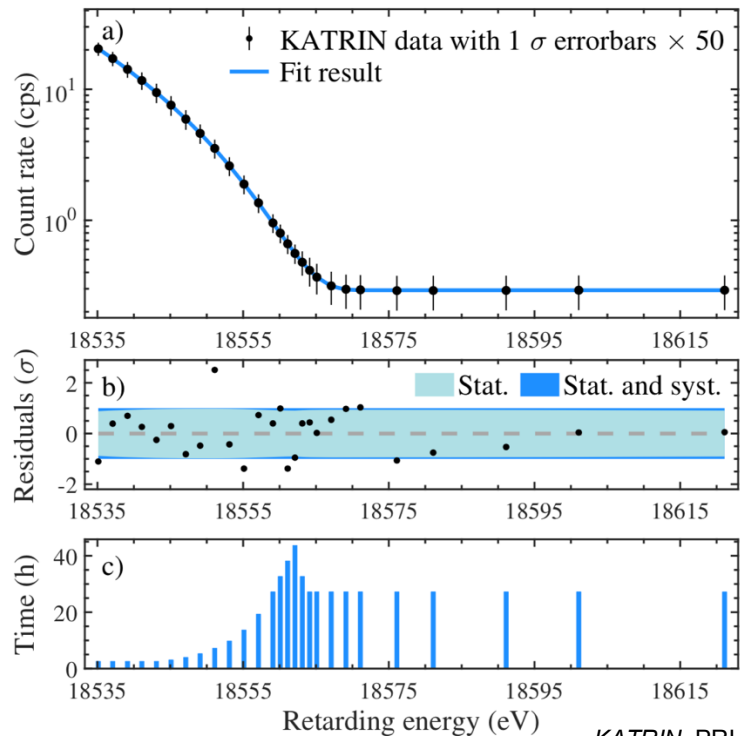
KATRIN, Science **388** (2025) 6743



KATRIN

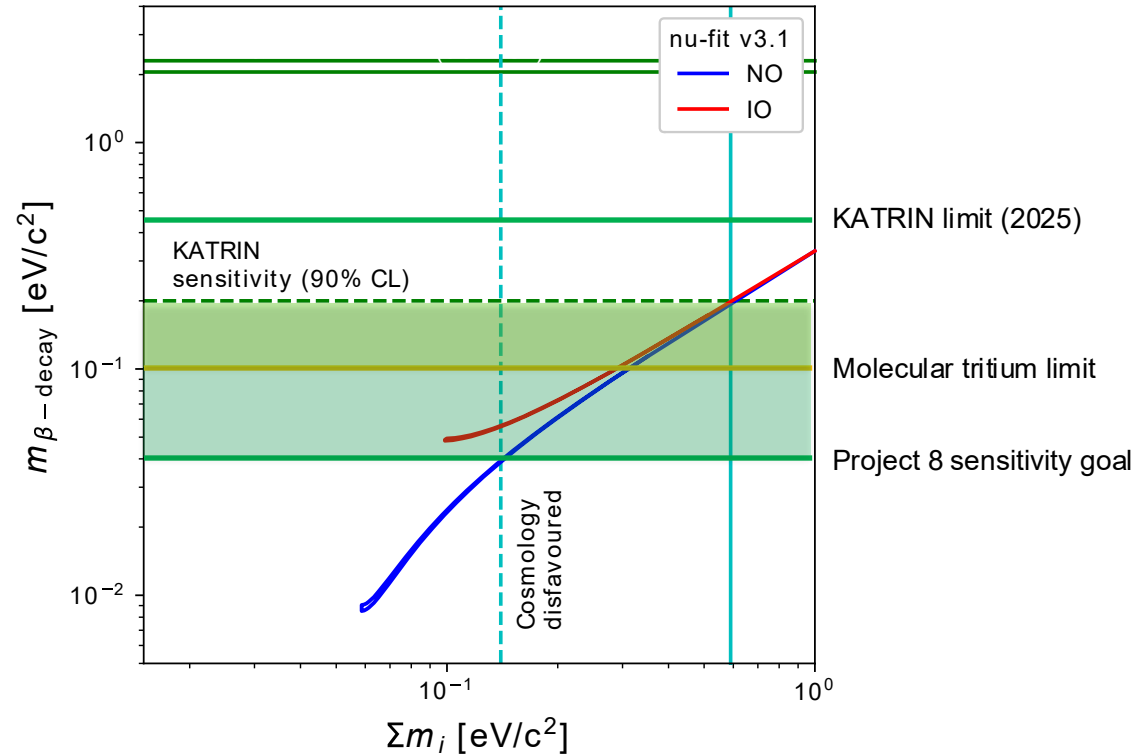


KATRIN, Science **388** (2025) 6743

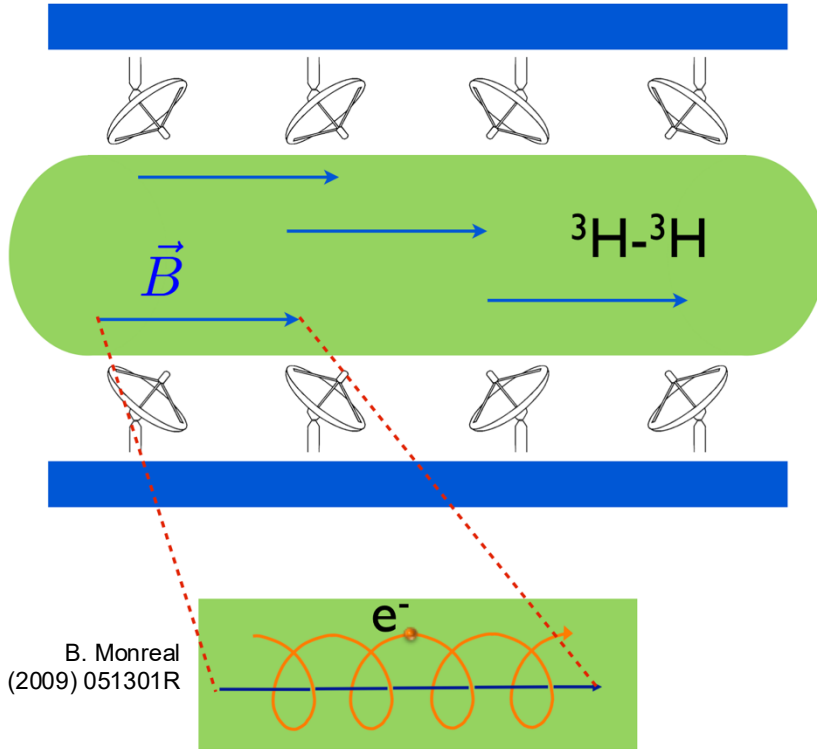


KATRIN, PRL 2019

Sensitivity after KATRIN

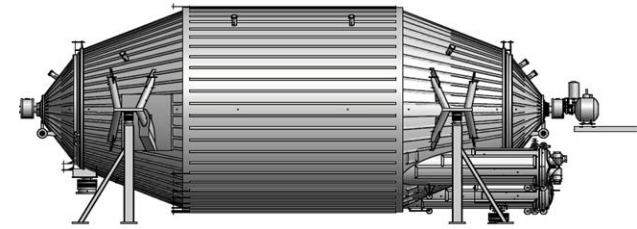


Beyond KATRIN Concept



B. Monreal

after Phys. Rev. D **80** (2009) 051301R



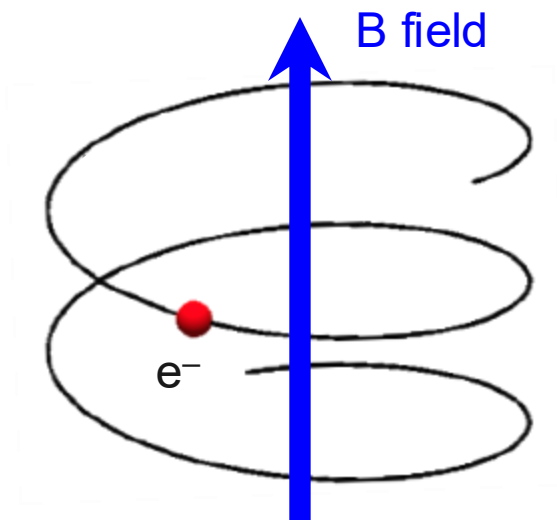
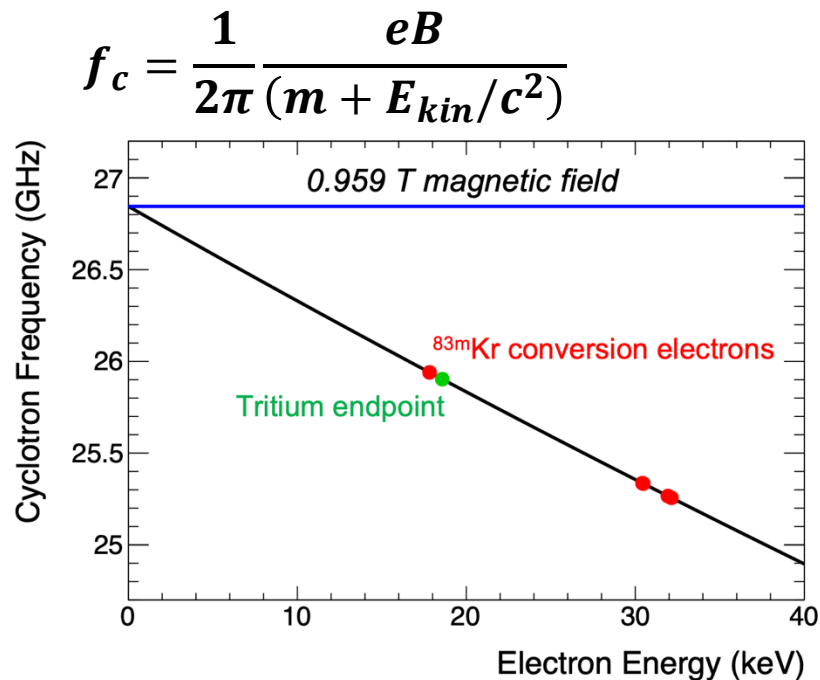
Never measure anything
but frequency.

– Arthur Schawlow



Cyclotron Radiation Emission Spectroscopy (CRES)

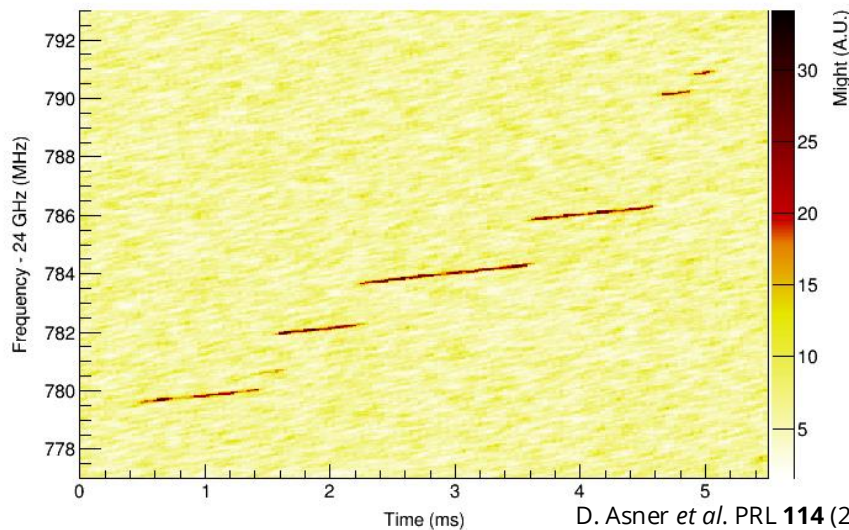
- Harness frequency-energy relation for relativistic electrons



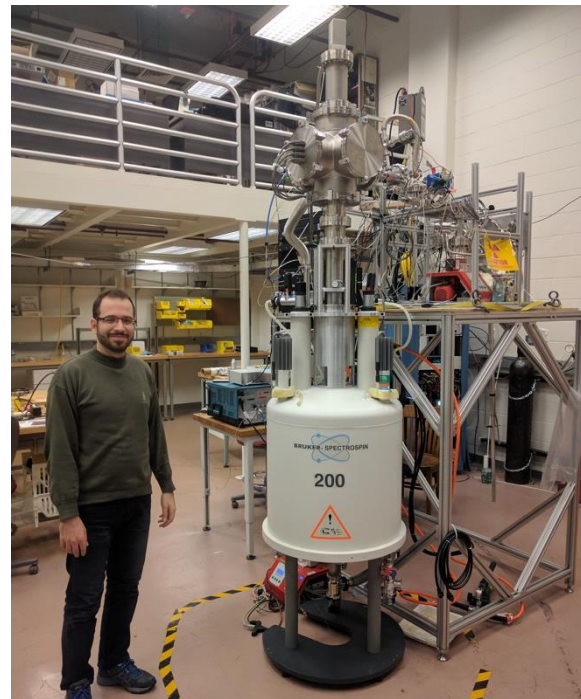
Cyclotron Radiation Emission Spectroscopy (CRES)

- Harness frequency-energy relation for relativistic electrons

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



D. Asner *et al.* PRL **114** (2015) 162501
(reprocessed)



Cheat Sheet: ^3H vs ^6He

- Endpoint: 18.6 keV
 - Physics in last $\sim\text{eV}$
- Phase II
 - $\sim 1\text{ T}$, $\sim 26\text{ GHz}$
 - 200 MHz bandwidth
 - 2 eV energy resolution
- Future phases:
 - 21 mT, 550 MHz
 - Lower power, flatter slope tracks
- Endpoint: 3.5 MeV
 - Physics across full spectrum distortion
- Existing Data
 - Variable field, $\sim\text{T}$
 - 2.3 GHz bandwidth
- Future
 - More DAQ channels, less magnet ramping

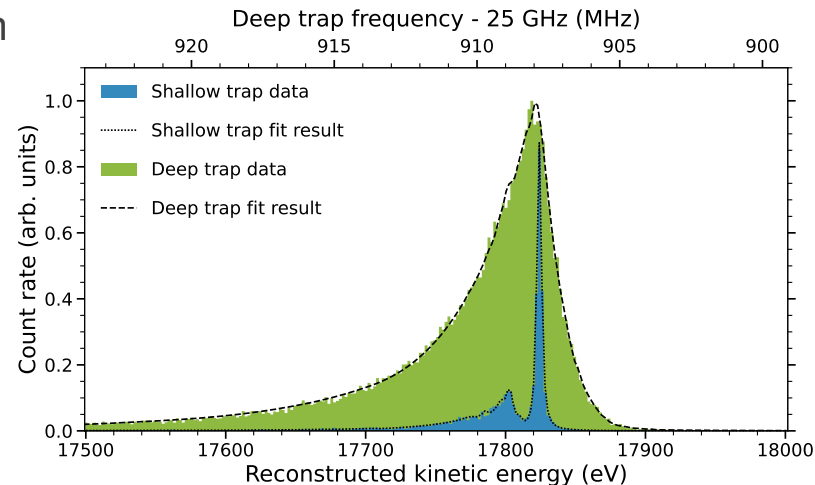
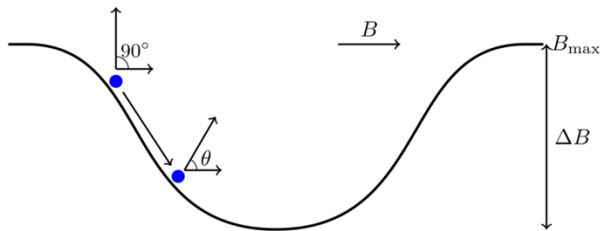
CRES Spectroscopy

- Data taken in two trap configurations
 - Shallow trap for high-resolution studies
 - Deep trap for high(er)-rate, used for tritium

Project 8, Phys. Rev. Lett.
131 (2023) 102502

- CRES frequency related to average field

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

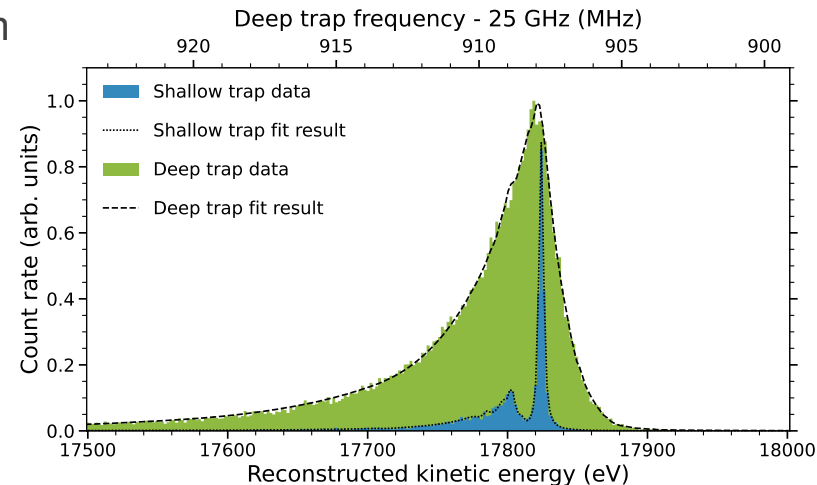


Instrumental resolution: 1.66 ± 0.19 eV
 ^{83}mKr K-line linewidth: 2.83 eV

CRES Spectroscopy

- Data taken in two trap configurations
 - Shallow trap for high-resolution studies
 - Deep trap for high(er)-rate, used for tritium
- CRES frequency related to average field
 - $$f_c = \frac{1}{2\pi} \frac{e\bar{B}}{(m+E_{kin})}$$
- Shallow trap shows low energy satellite peak
 - Both scattering and shakeup/shakeoff effects

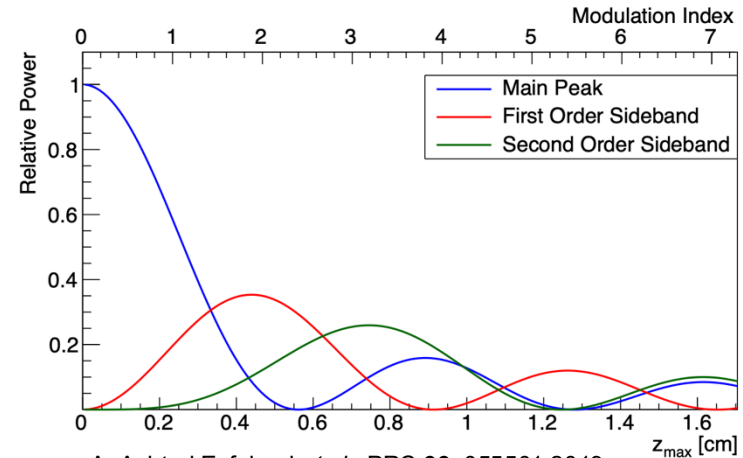
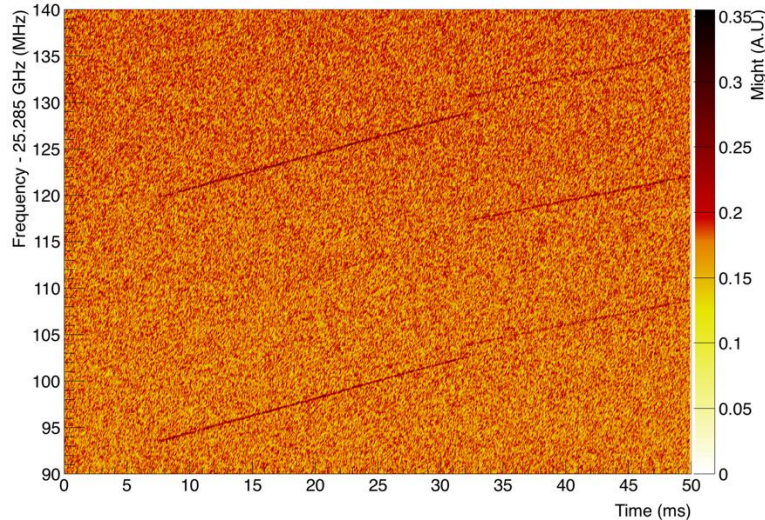
Project 8, Phys. Rev. Lett.
131 (2023) 102502



Instrumental resolution: 1.66 ± 0.19 eV
 $^{83\text{m}}\text{Kr}$ K-line linewidth: 2.83 eV

Scattering, Sidebands, & Track Visibility

- Scattering peak has contribution from short tracks and invisible (but trapped) electron pitch angles
 - Interference pattern and frequency modulation give rise to (dis)appearing tracks, variable intensity between carrier and sideband

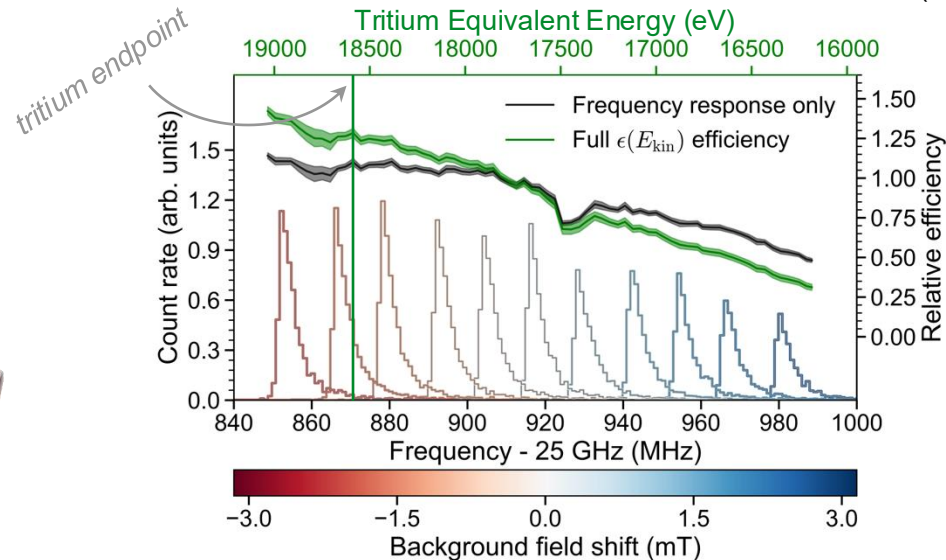


A. Ashtari Esfahani *et al.*, PRC **99**, 055501 2019

Efficiency Corrections

- Tritium analysis spanned 160 MHz (~ 3 keV) around endpoint
- Field-shifted Kr data used to study frequency-dependent efficiency
 - Analytic correction of cyclotron radiation energy dependence

Project 8, Phys. Rev. Lett.
131 (2023) 102502



Phase II: First Tritium Limits

- Improvement in spectroscopic performance
- First RF-based neutrino mass limits ($m_\beta < 155$ eV)
- Zero-background measurement ($\leq 3 \times 10^{-10}$ counts/eV/s)

Project 8, Phys. Rev. Lett.
131 (2023) 102502

Featured in Physics

Editors' Suggestion

Open Access

Tritium Beta Spectrum Measurement and Neutrino Mass Limit from Cyclotron Radiation Emission Spectroscopy

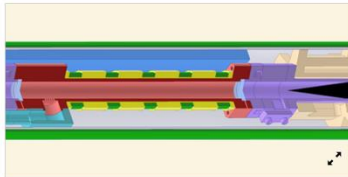
A. Ashtari Esfahani *et al.* (Project 8 Collaboration)
Phys. Rev. Lett. **131**, 102502 – Published 6 September 2023

PhysICS See synopsis:

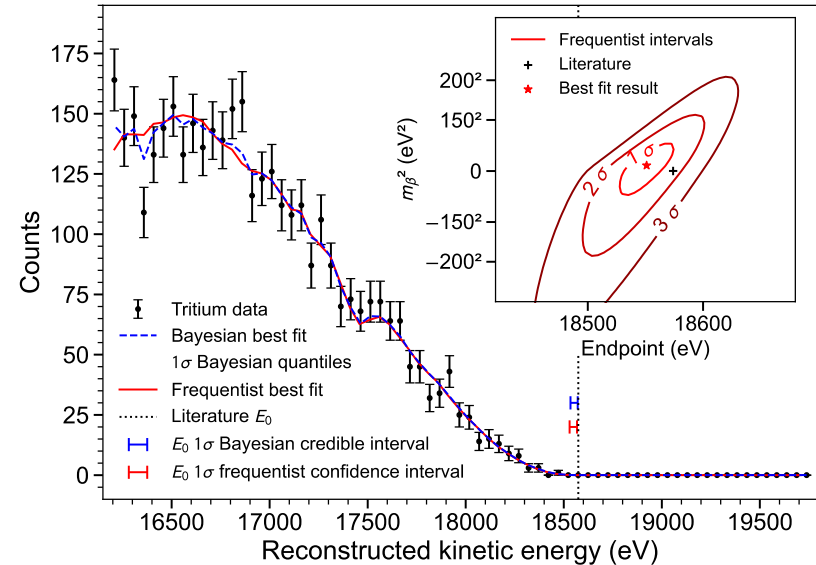
Neutrino Mass in the Crosshairs

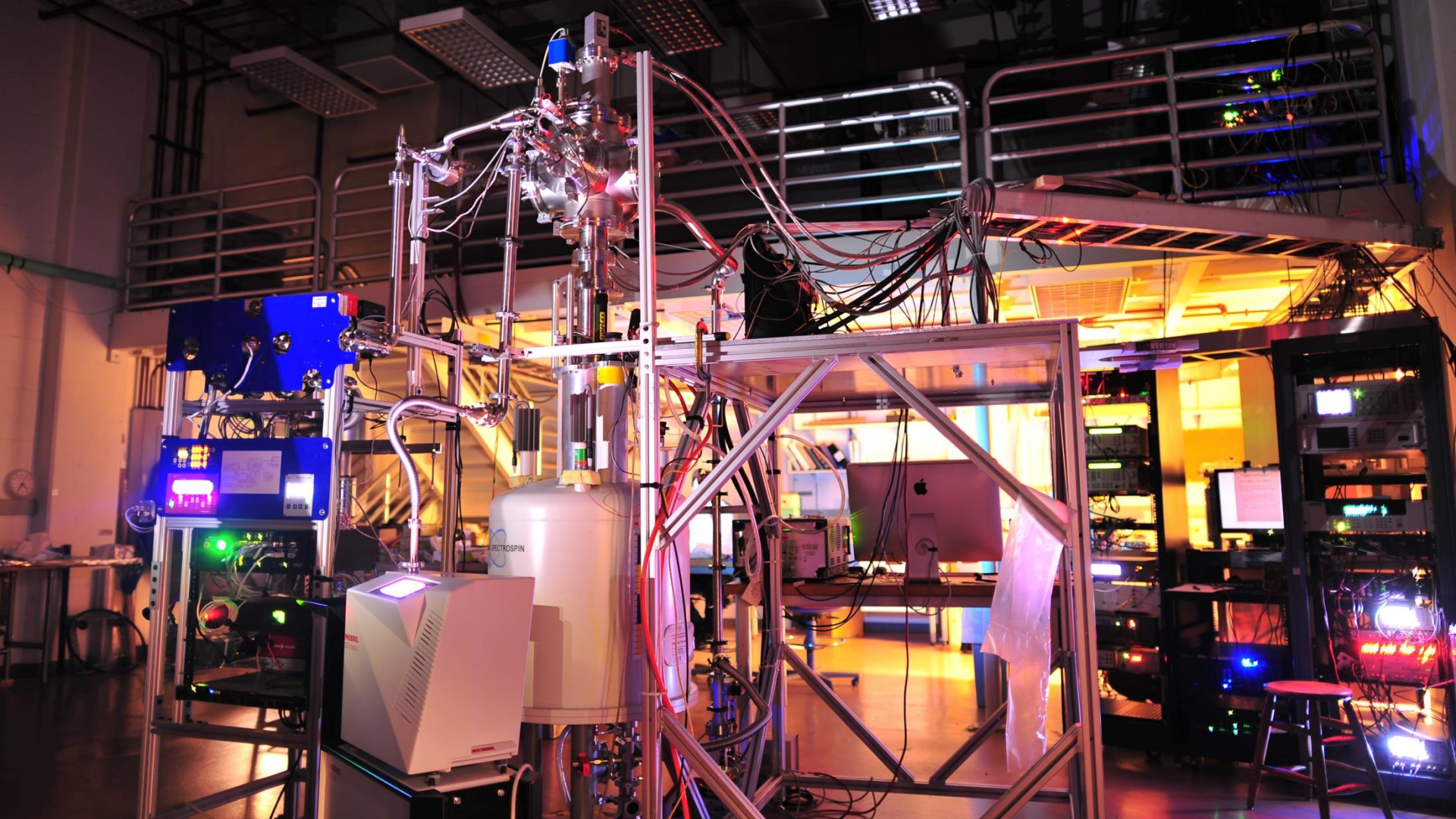
September 6, 2023 • Physics 16, s121

The first frequency-based limit on the neutrino's mass sets the stage for next-generation experiments.



A. Ashtari Esfahani *et al.* (Project 8 Collaboration) [3]



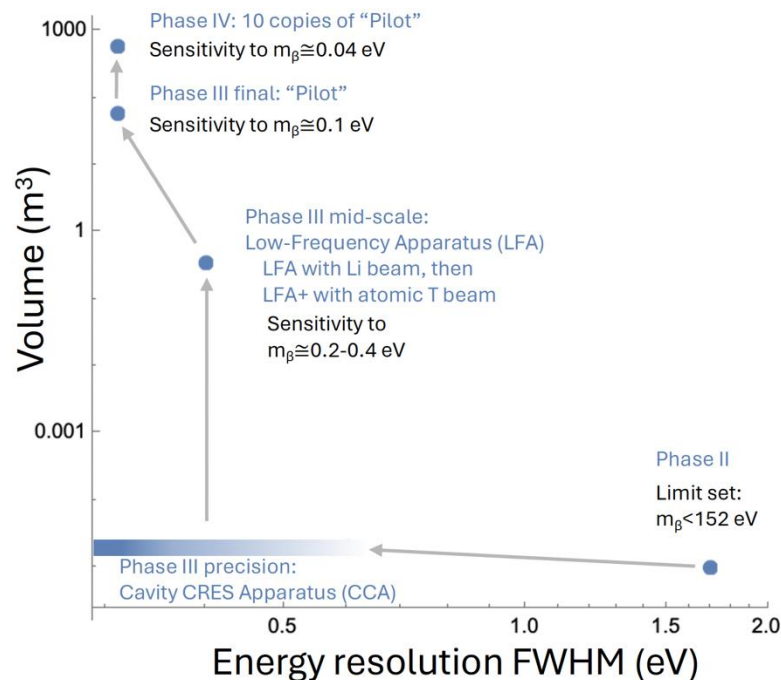


Phase III – The Path Forward

- Two major R&D thrusts to develop design of 40 meV neutrino mass experiment:
 - Cavity CRES towards large-volume, high-resolution, optimized efficiency spectroscopy
 - Atomic tritium source – production, cooling, and trapping
- Independent R&D packages come together in integrated apparatus as culmination of Phase III

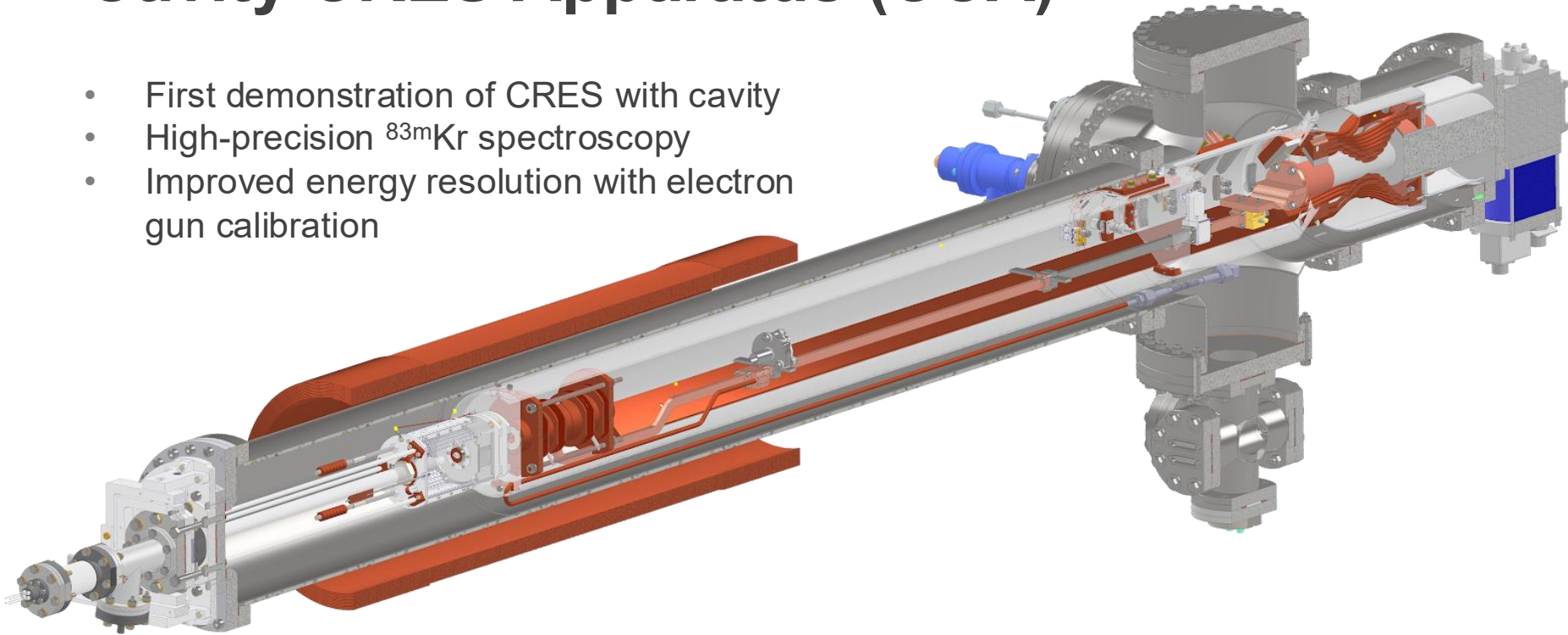
Phase III – CRES Development

- Two major R&D thrusts to develop design of 40 meV neutrino mass experiment:
 - Cavity CRES towards large-volume, high-resolution, optimized efficiency spectroscopy

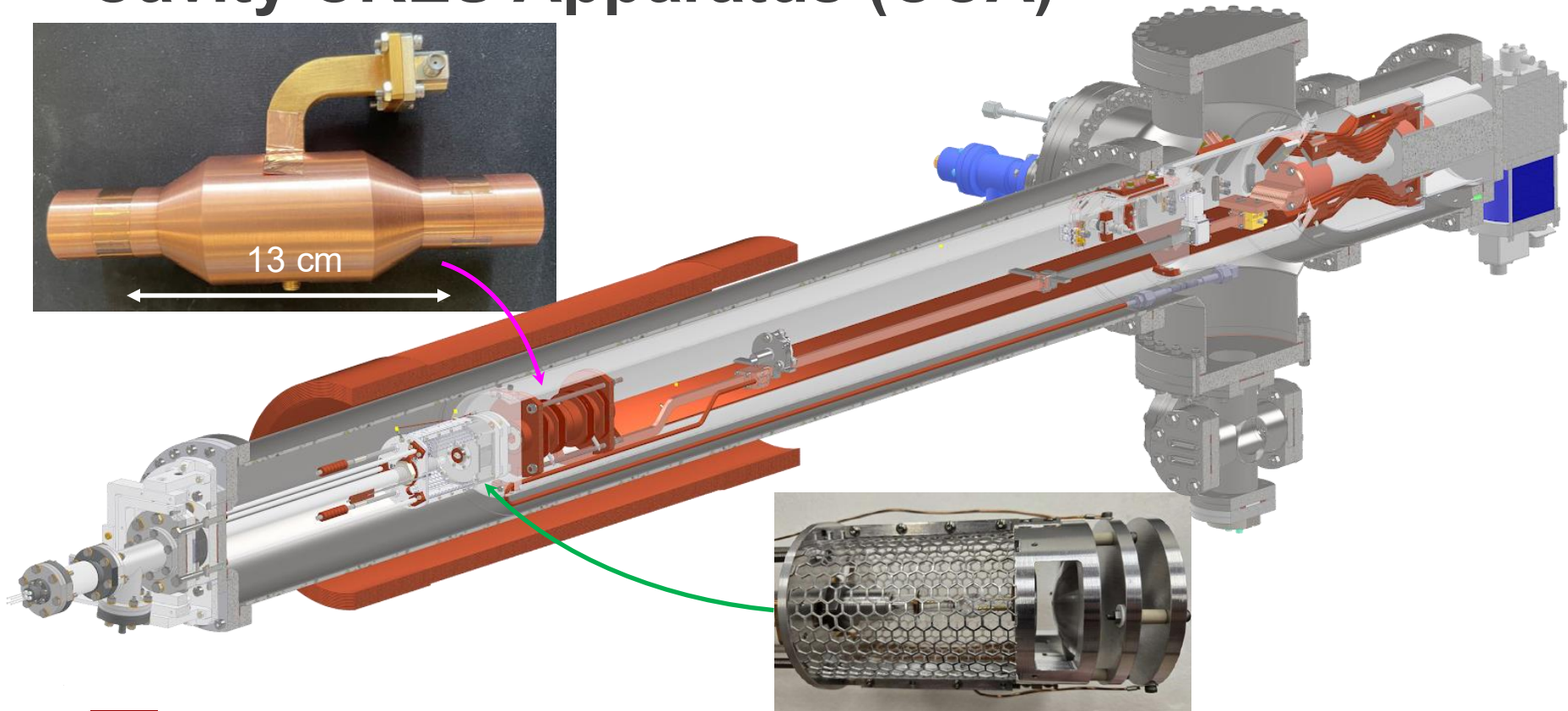
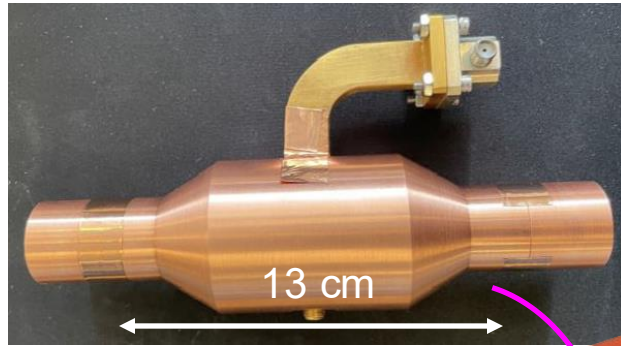


Cavity CRES Apparatus (CCA)

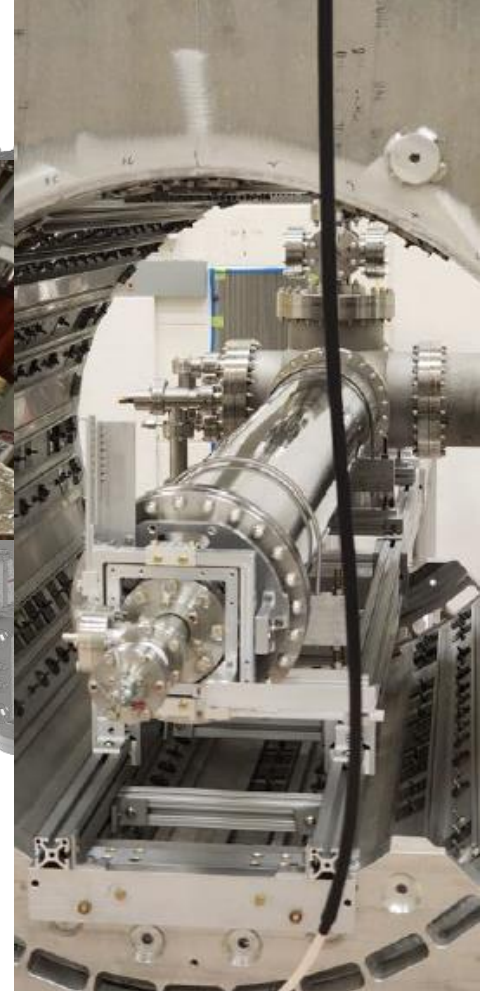
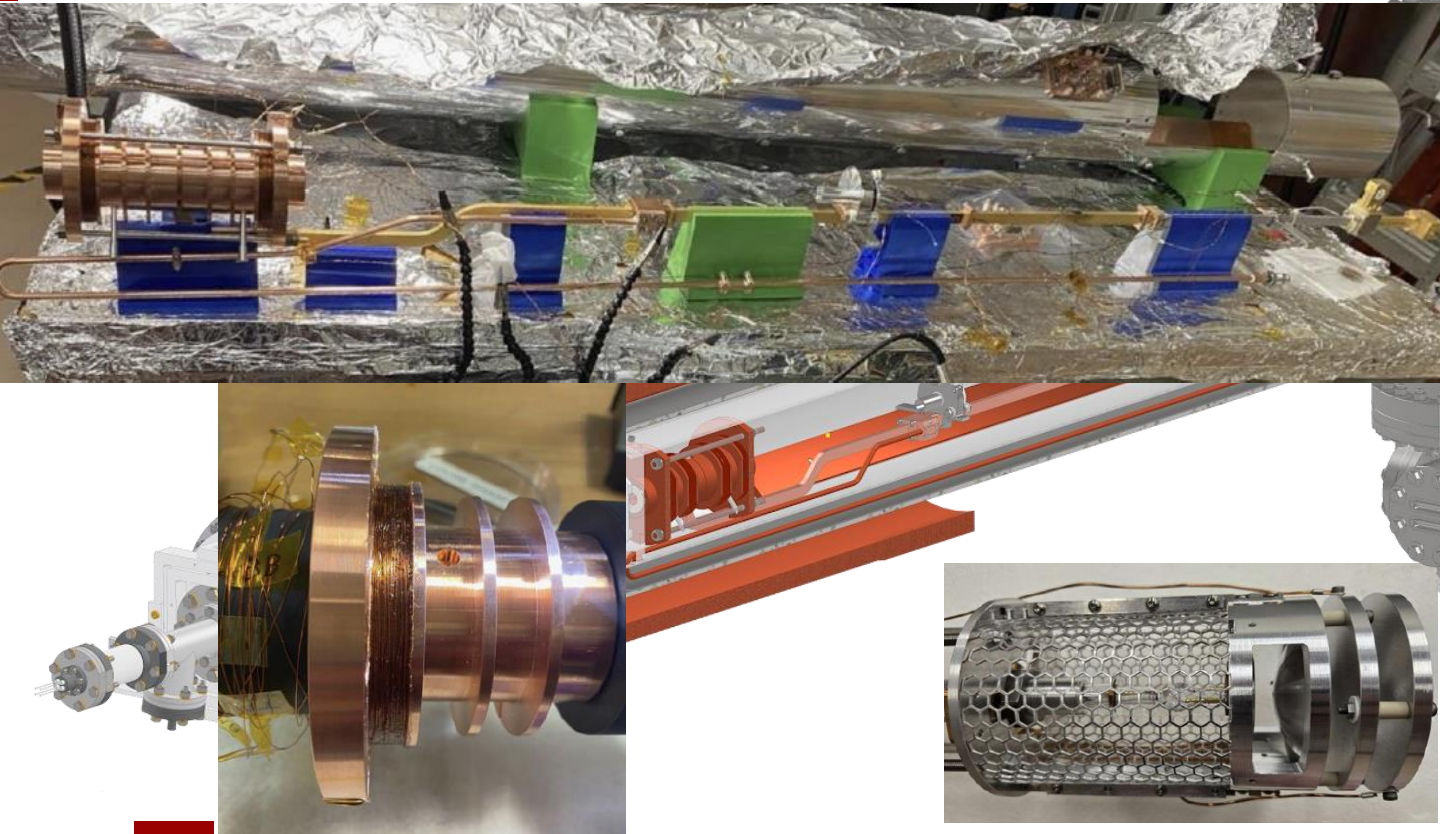
- First demonstration of CRES with cavity
- High-precision ^{83}mKr spectroscopy
- Improved energy resolution with electron gun calibration



Cavity CRES Apparatus (CCA)



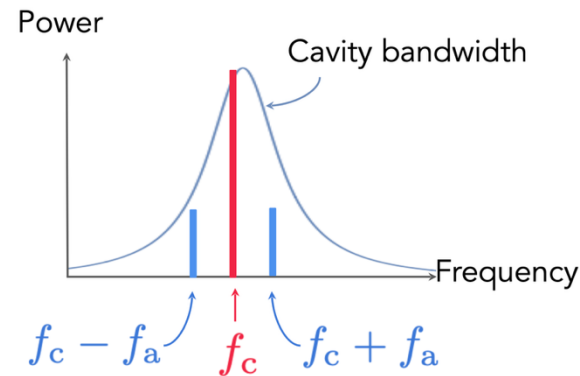
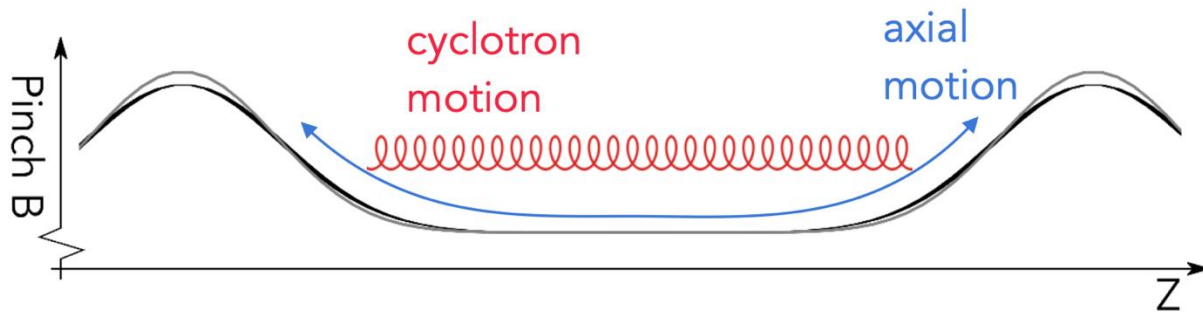
Cavity CRES Apparatus (CCA)



Sideband Reconstruction

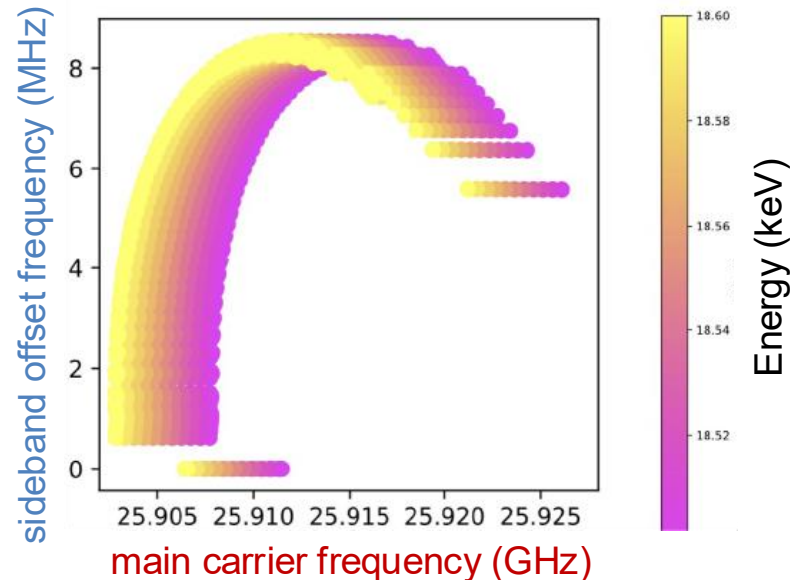
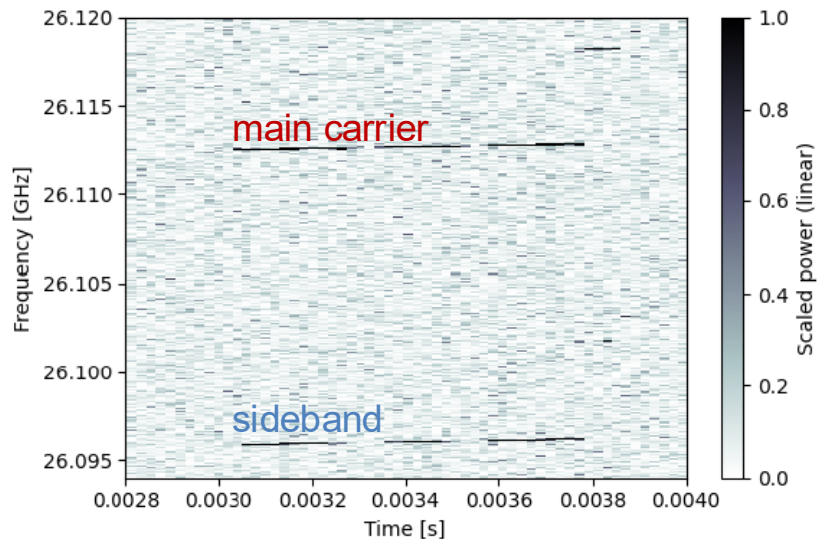
- Sideband analysis allows full electron kinematic reconstruction
 - Sideband spacing encodes axial frequency information
 - Axial frequency related to average field experienced

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



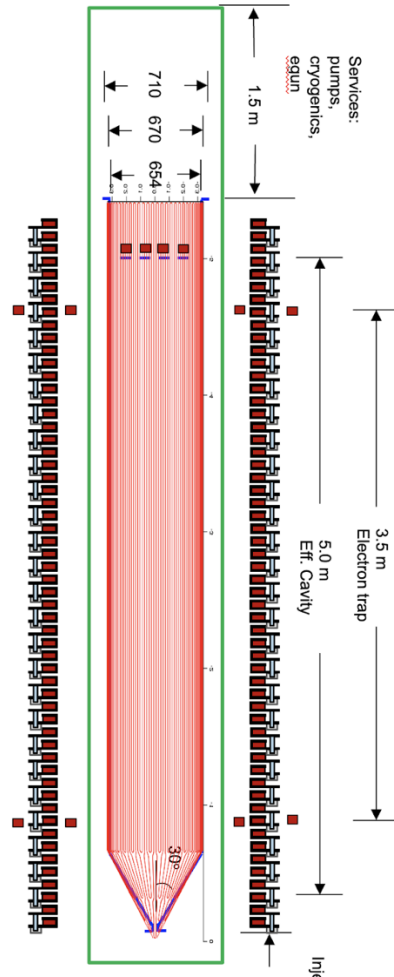
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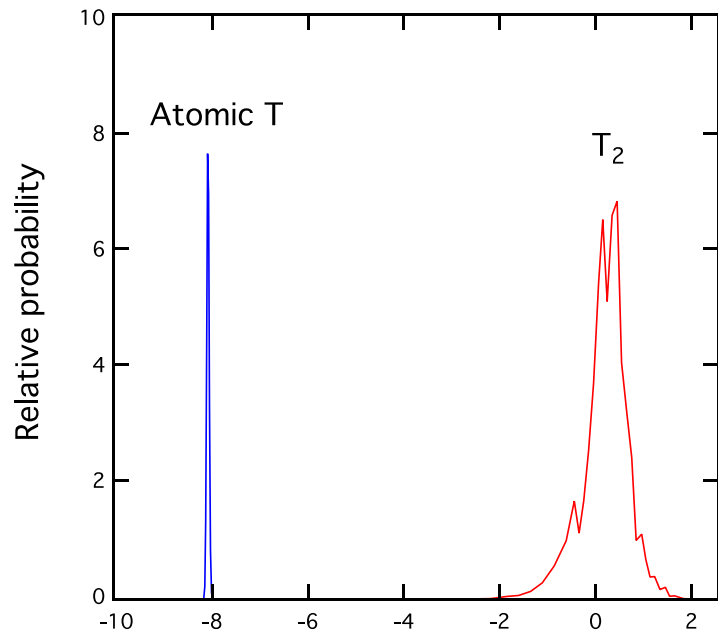
Scaling CRES: LFA

- Low Frequency Apparatus (LFA)
 - 1.5 m³ cavity at 560 MHz, 21 mT
 - Capable of ~0.3 eV neutrino mass measurement with tritium source upgrade
- Low frequency cavity naturally scales to large volume
 - Further scaling planned to Phase IV module scale
- Integrated field design to allow for tritium upgrade
 - High-multipole magnetogravitational atom trap



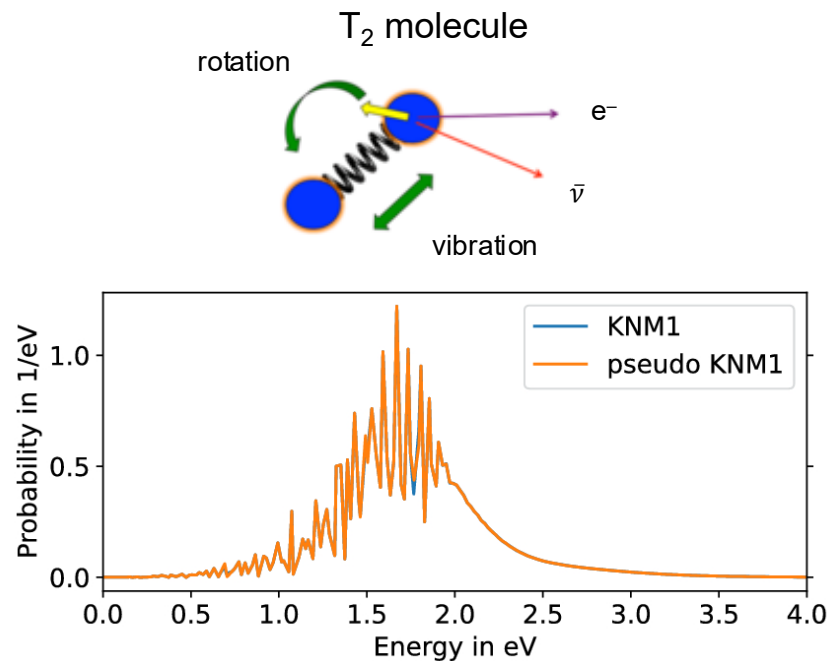
Why Atomic?

- Sensitivity beyond inverted hierarchy requires *atomic* tritium



H. Robertson

Relative Extrapolated Endpoint (eV)



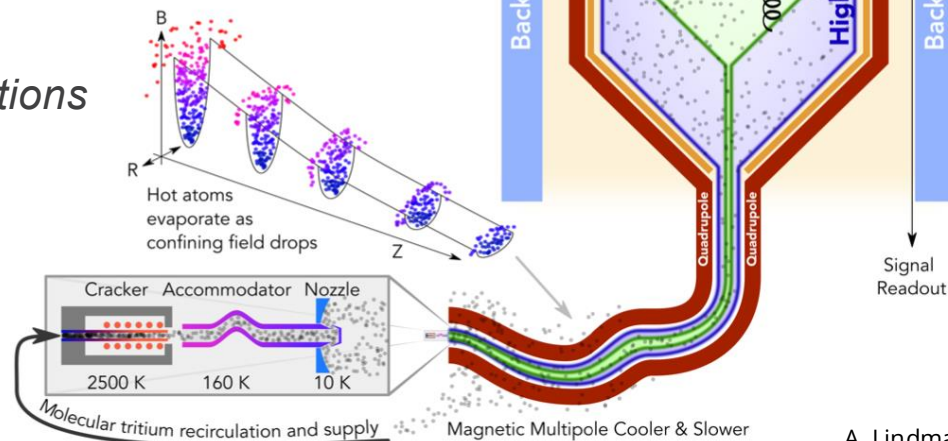
S. Schneidewind et al.
EPJ C 84 (2024) 494

Atomic Experiment Concept

Three broad sections:

- Dissociator: produce high flux of “hot” tritium atoms
- Cooling: cool with minimized losses
- Trap: hold $\sim$ mK atoms in CRES detection volume

With complicated interfaces between sections

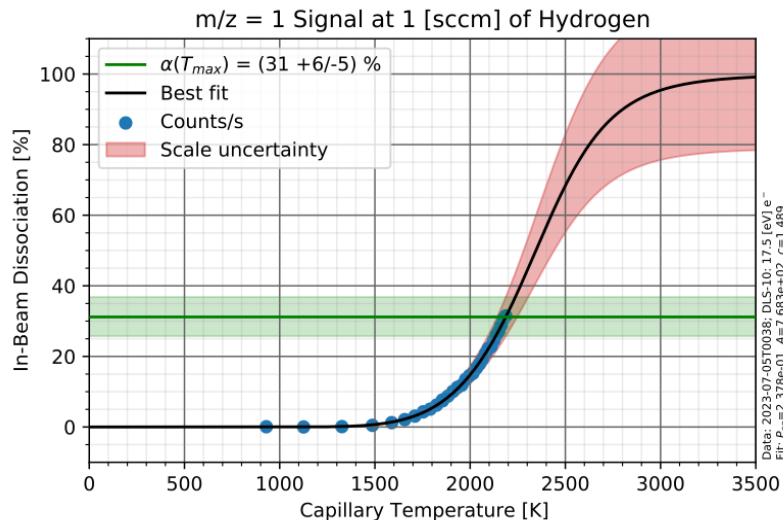
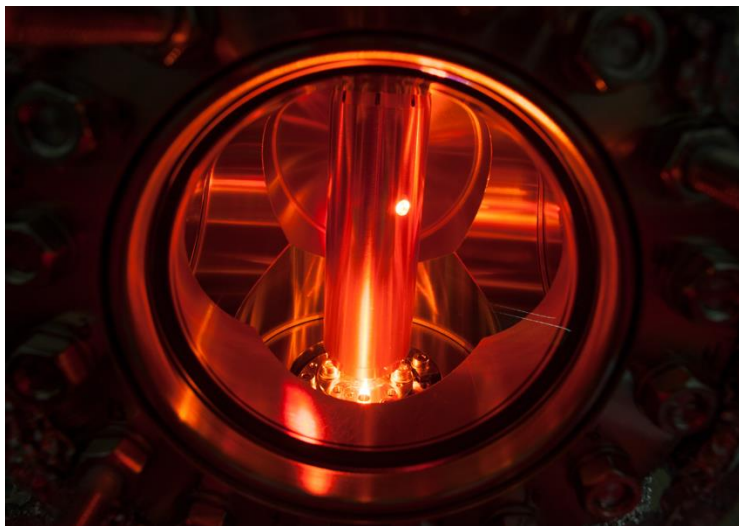


A. Lindman

Dissociation

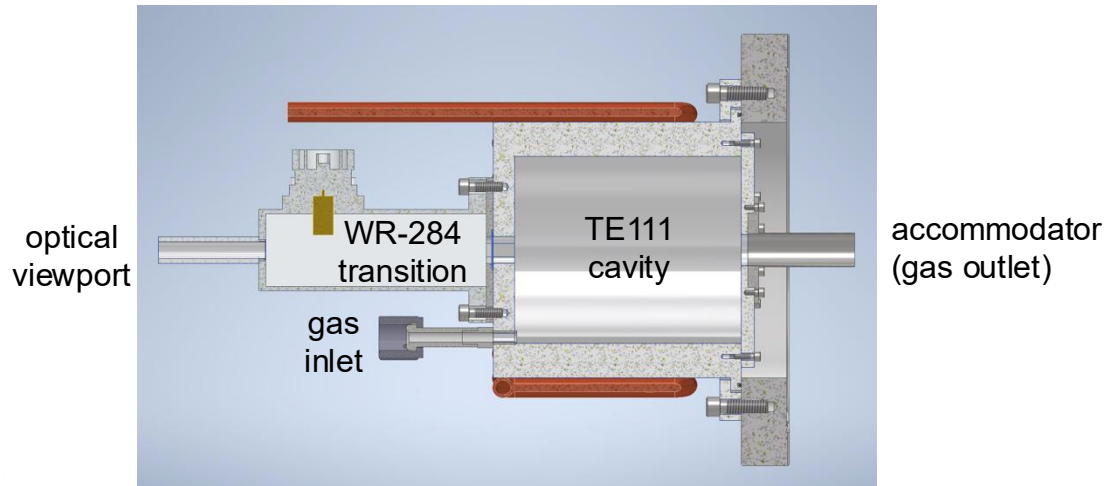
- Start with pure molecular hydrogen/tritium gas
- Dissociate high flux into atoms
 - Thermal cracking on tungsten filament

see also
Project 8, arXiv:2501.01268



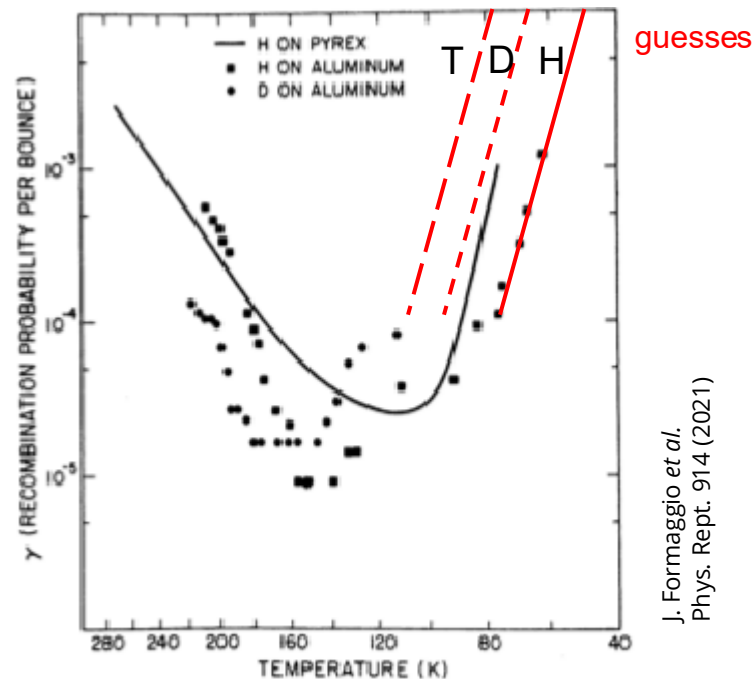
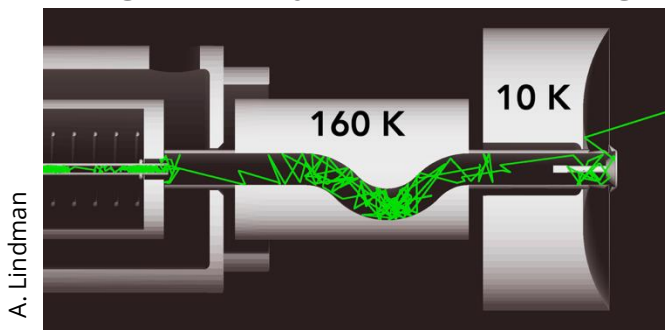
Dissociation

- Start with pure molecular hydrogen/tritium gas
- Dissociate high flux into atoms
 - Thermal cracking on tungsten filament
 - ECR plasma source



Accommodation

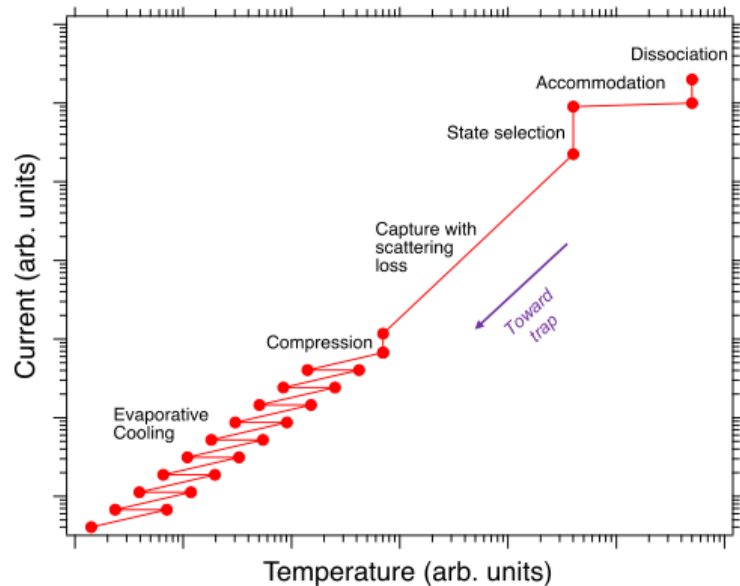
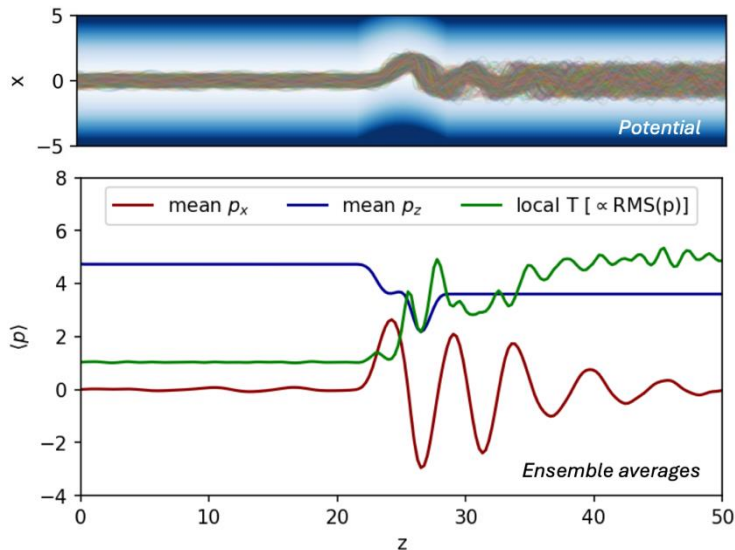
- Cooling by accommodation (collisions off cold surface) works in limited temperature range
- Somewhere around ~ 40 K optimal for T?
 - Isotopic dependence not fully explored, needs new experimental data
- Careful geometry, temperature gradient?



Evaporative Cooling

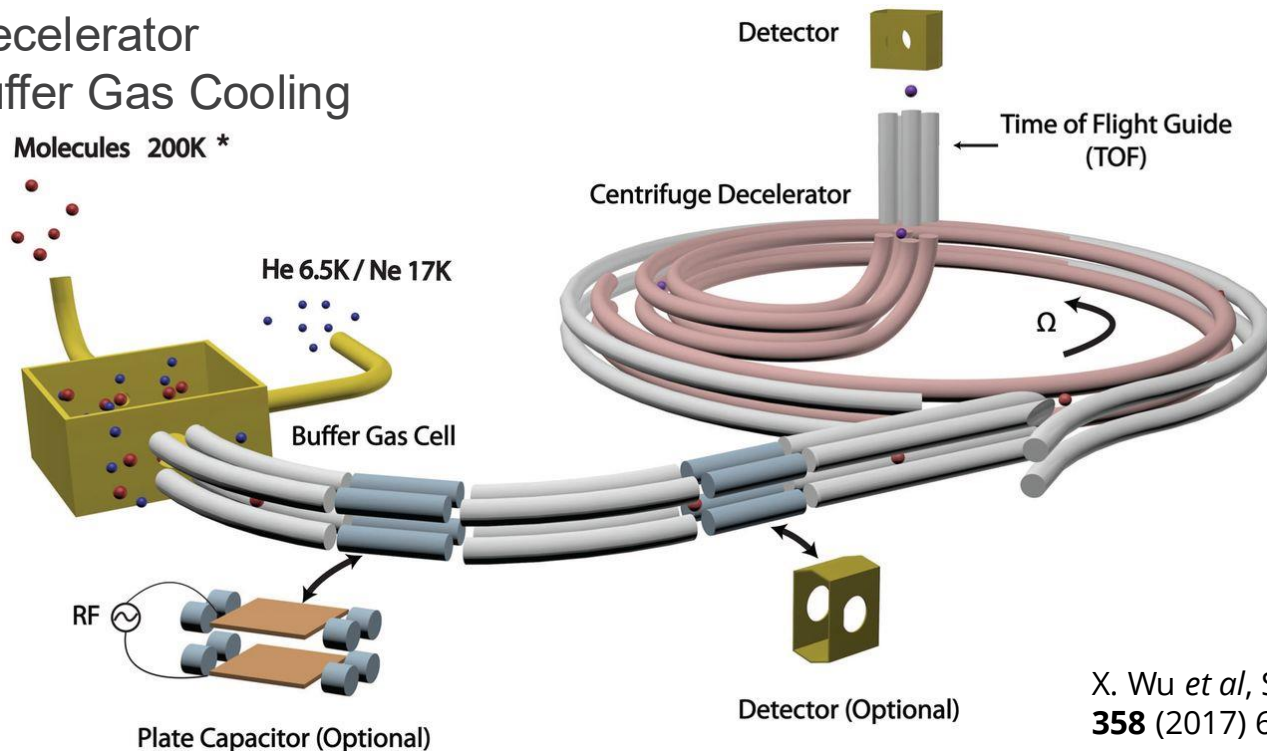
see Project 8,
arXiv:2502.00188

- Evaporative cooling will be workhorse of cooling stage
 - Efficient performance below ~ 1 K, down to 1 mK target temperature
- (Longitudinal) momentum can be redirected to transverse and cooled



Other Cooling Ideas (Xing Wu)

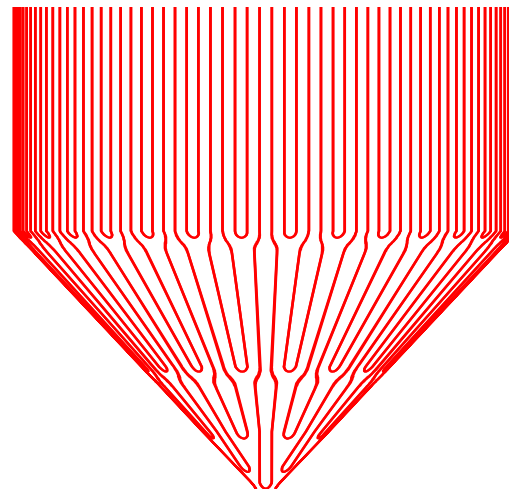
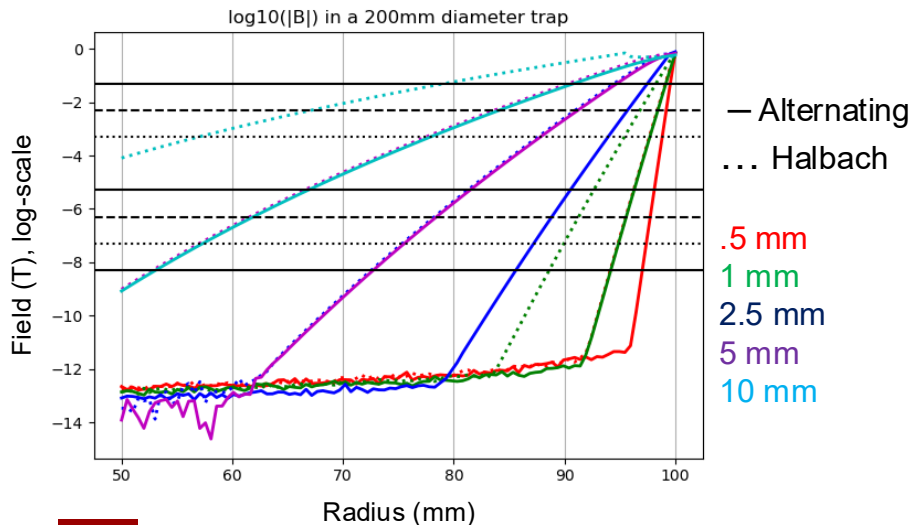
- Centrifuge Decelerator
- Cryogenic Buffer Gas Cooling



X. Wu *et al*, Science
358 (2017) 645

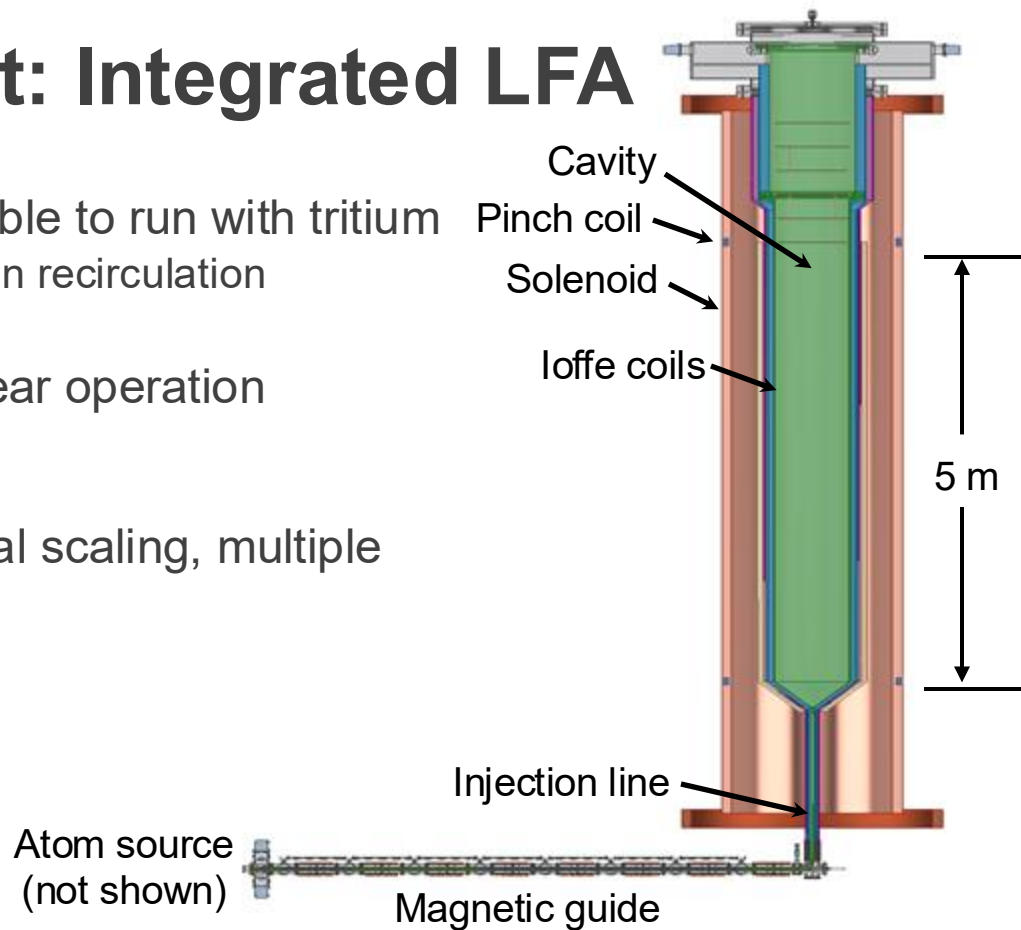
High Multipole Trap

- Need high-multipole trap to provide steep magnetic walls with large uniform field region
 - Ioffe-Pritchard (alternating current direction): EIC magnet winder at BNL
 - Halbach Array (alternating permanent magnets): UIUC group
- Will use Ioffe design for LFA trap

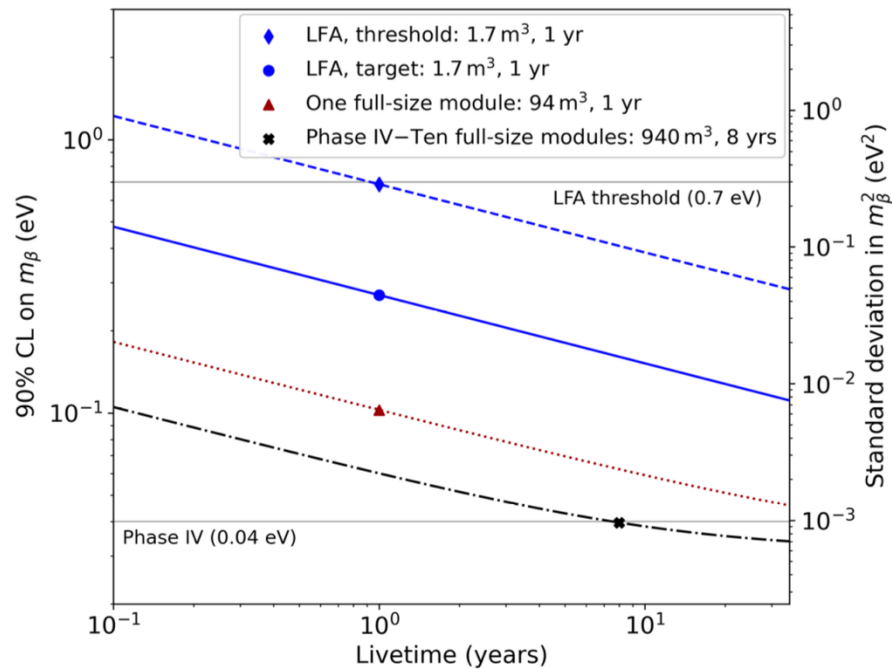


Tritium Experiment: Integrated LFA

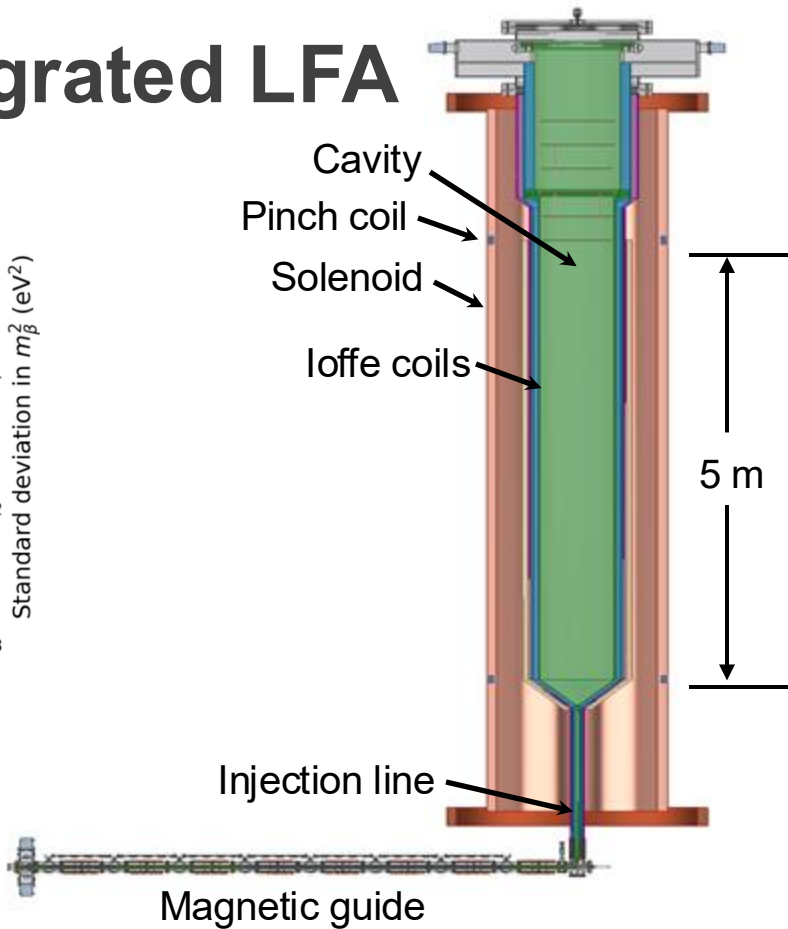
- LFA designed to be upgradeable to run with tritium
 - Inventory unclear, depends on recirculation
- 300 meV tritium limit with 1 year operation
 - Competitive with KATRIN
- Phase IV will require additional scaling, multiple modules



Tritium Experiment: Integrated LFA

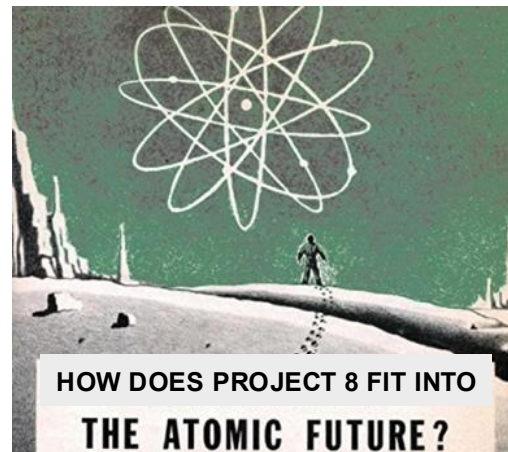


Atom source
(not shown)



Conclusions

- Understanding and measuring the neutrino mass scale remain grand open experimental challenges
 - Implications span nuclear, particle, and astro-physics
- Phase II produced first RF-based neutrino mass limits
 - Demonstrated zero-background measurement, improved spectroscopy
- Phase III will complete critical R&D
 - CRES in cavities with sub-eV resolution and scaling to large volume
 - Atomic tritium production, cooling, and storage
 - Ultimate 300 meV sensitivity with tritium upgrade
- Phase IV concept for 40 meV neutrino mass experiment under development



Project 8 Collaboration

PROJECT 8

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