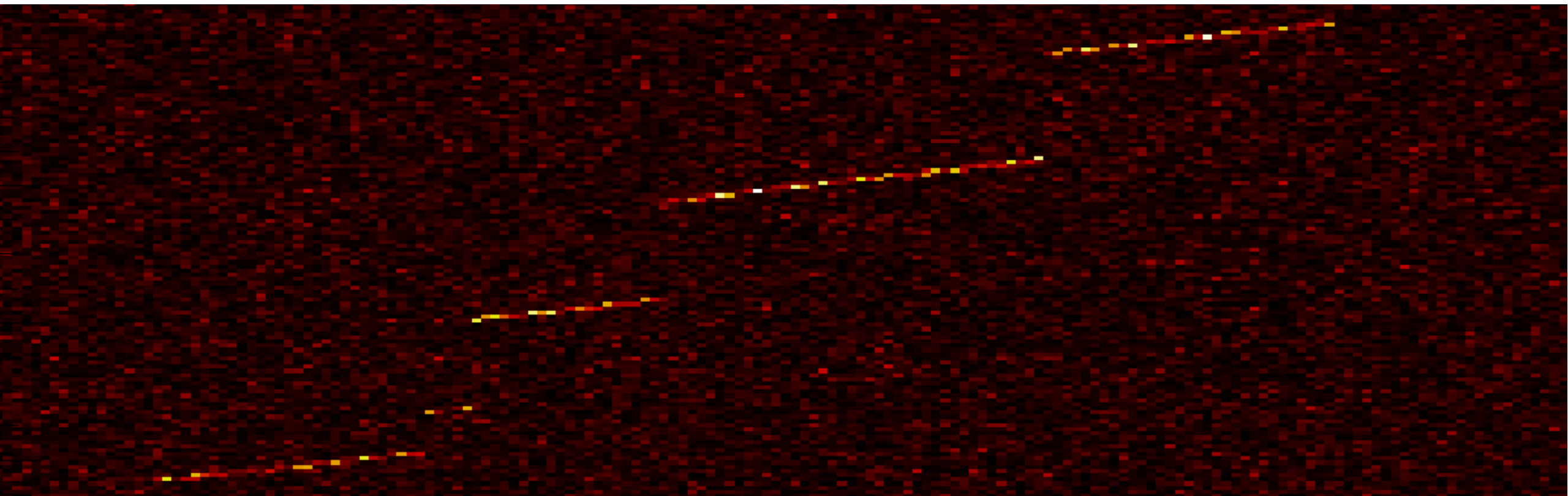


PROJECT 8



Status of the Project 8 neutrino mass experiment

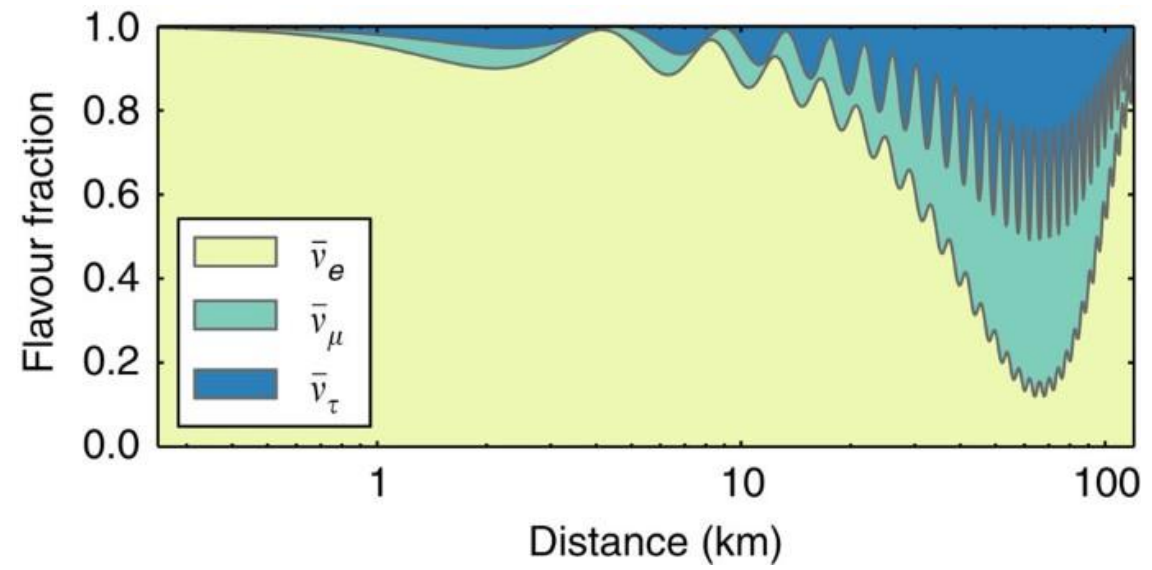
Hannah Binney, on behalf of the Project 8 experiment
Postdoctoral Researcher, MIT Laboratory for Nuclear Science
NuMass Workshop | April 13, 2026



The motivation for direct neutrino mass measurements continues to grow

Probe	Observable
Oscillation experiments	$\Delta m_{ij}^2 \equiv m_i^2 - m_j^2$
Neutrinoless double beta decay	$\langle m_{\beta\beta} \rangle = \left \sum_{i=1}^3 U_{ei}^2 m_i \right $
Cosmology	$\sum m_\nu = \sum_{i=1}^3 m_i$
Direct kinematic mass measurements	$m_\beta = \sqrt{\sum_i U_{ei} ^2 m_i^2}$

- Establishes differences between neutrino masses
- Places a lower limit on neutrino masses

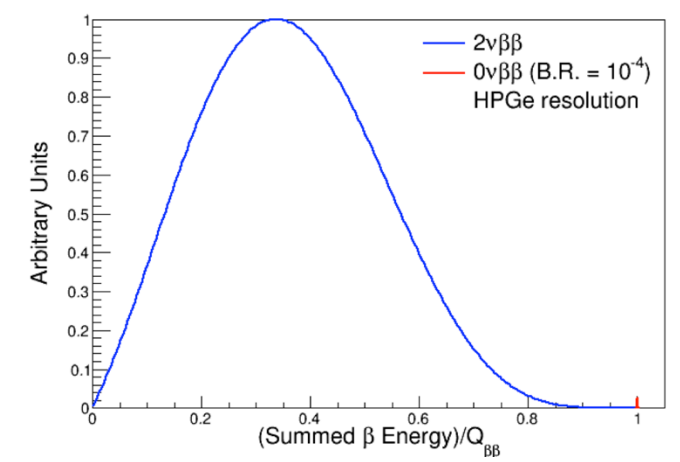
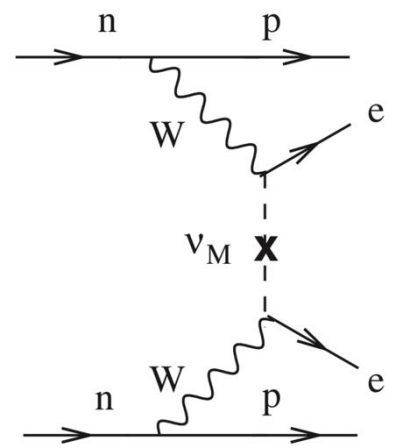


Vogel, P., Wen, L. & Zhang, C. *Nat Commun* **6**, 6935 (2015)

The motivation for direct neutrino mass measurements continues to grow

Probe	Observable
Oscillation experiments	$\Delta m_{ij}^2 \equiv m_i^2 - m_j^2$
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Cosmology	$\sum m_\nu = \sum_{i=1}^3 m_i$
Direct kinematic mass measurements	$m_\beta = \sqrt{\sum_i U_{ei} ^2 m_i^2}$

- Would measure effective Majorana mass, only if neutrinos are Majorana
- Depends on nuclear matrix elements that must be calculated

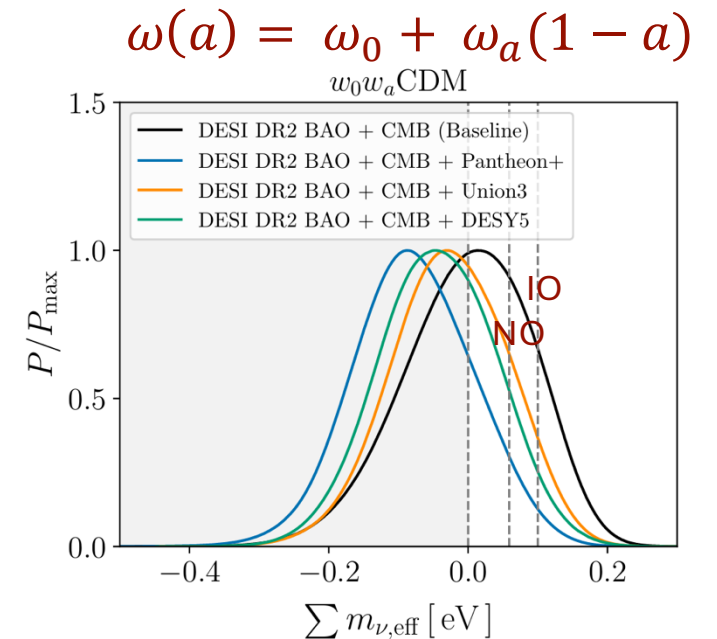
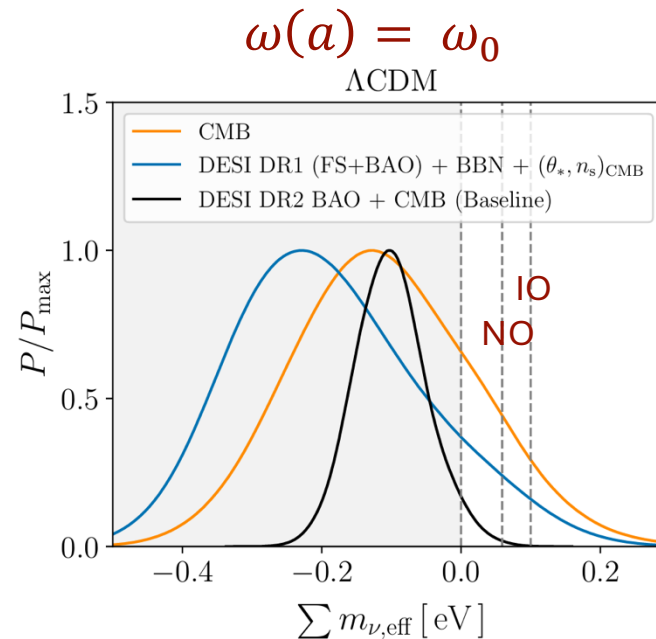


MAJORANA Demonstrator experiment

The motivation for direct neutrino mass measurements continues to grow

Probe	Observable
Oscillation experiments	$\Delta m_{ij}^2 \equiv m_i^2 - m_j^2$
Neutrinoless double beta decay	$\langle m_{\beta\beta} \rangle = \left \sum_{i=1}^3 U_{ei}^2 m_i \right $
Cosmology	$\sum m_\nu = \sum_{i=1}^3 m_i$
Direct kinematic mass measurements	$m_\beta = \sqrt{\sum_i U_{ei} ^2 m_i^2}$

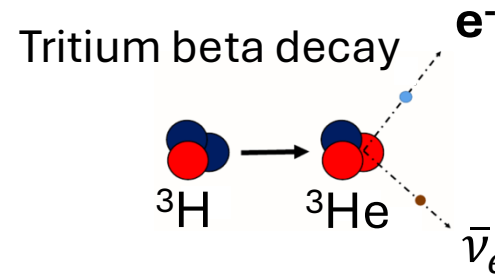
- Places strong upper limits on sum of neutrino masses
- Currently prefers negative neutrino mass
- Highly dependent on cosmological models



The motivation for direct neutrino mass measurements continues to grow

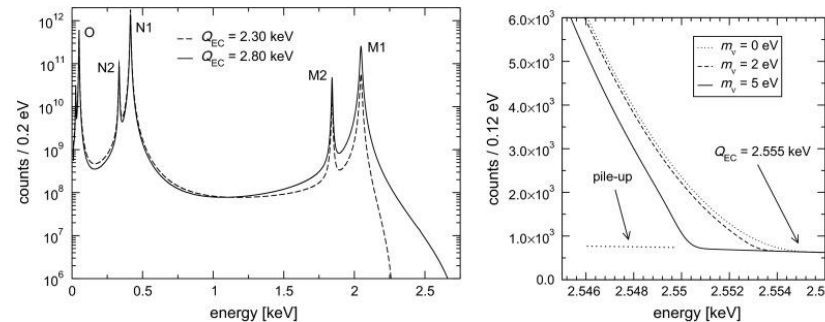
Probe	Observable
Oscillation experiments	$\Delta m_{ij}^2 \equiv m_i^2 - m_j^2$
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Cosmology	$\sum m_\nu = \sum_{i=1}^3 m_i$
Direct kinematic mass measurements	$m_\beta = \sqrt{\sum_i U_{ei} ^2 m_i^2}$

- Measurement based on distortion to endpoint of spectrum as neutrino carries energy away
- Model-independent



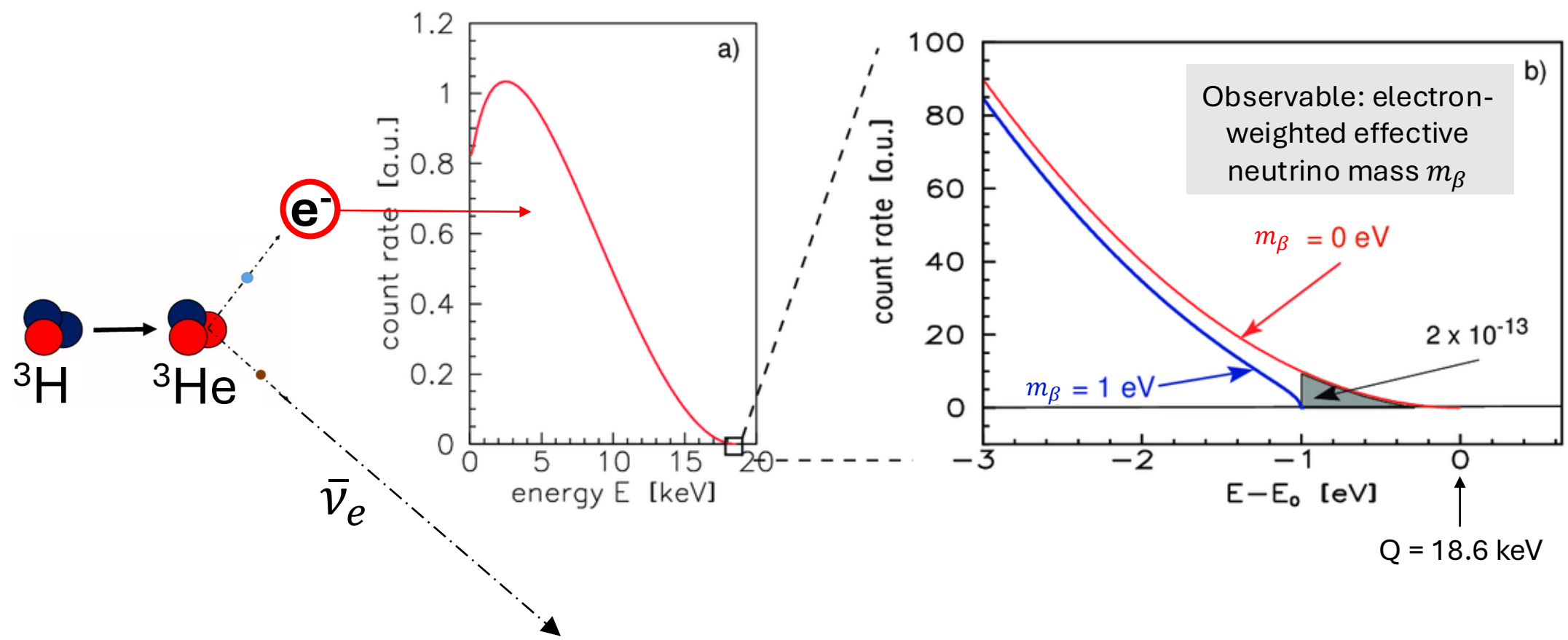
KATRIN, PTOLEMY, QTNM, **Project 8**

Electron capture decay of ^{163}Ho



ECHo, HOLMES

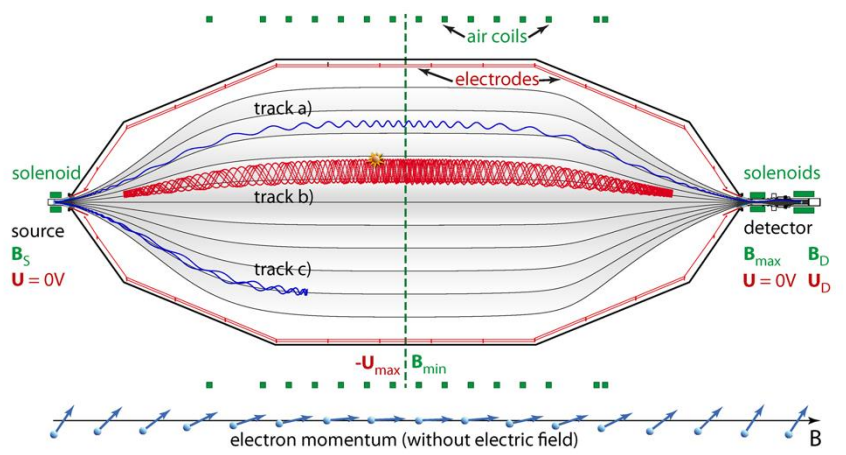
Tritium beta spectroscopy for direct neutrino mass measurement



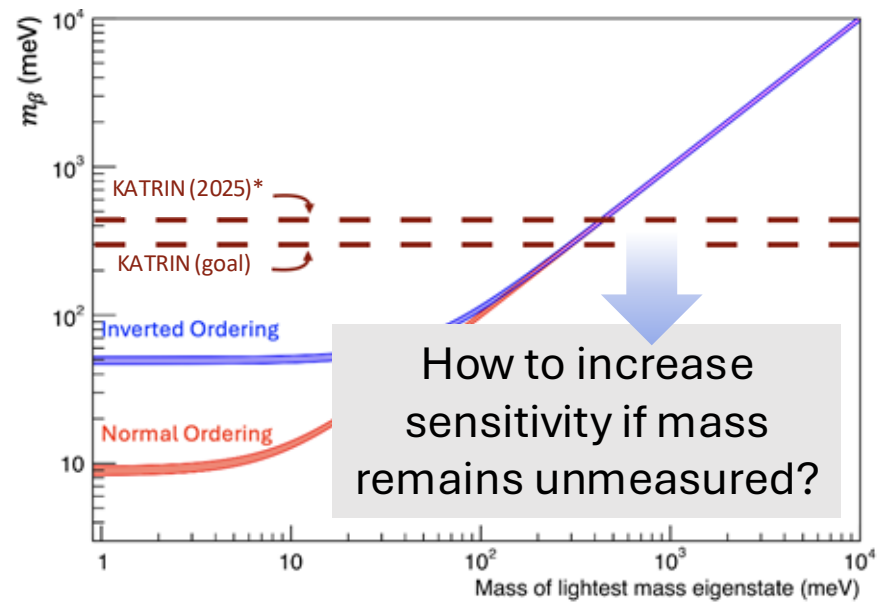
KATRIN experiment

- The KATRIN experiment has used tritium beta decay spectroscopy to great success
- **Magnetic Adiabatic Collimation** + **Electrostatic filter (MAC-E)** approach → integrating spectrometry

Electrons with enough energy to pass the analyzing plane are measured in the detector



M. Arenz et al 2016 JINST 11 P04011

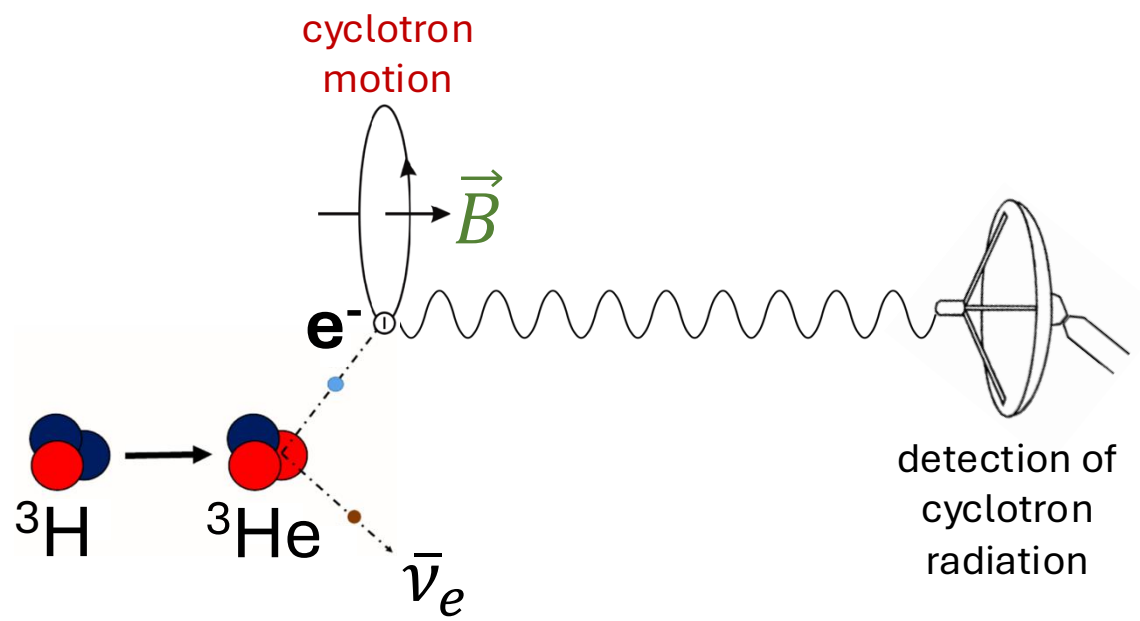


*KATRIN collaboration, Science (2025)

Reaching the limit of MAC-E scalability



Cyclotron radiation emission spectroscopy (CRES)



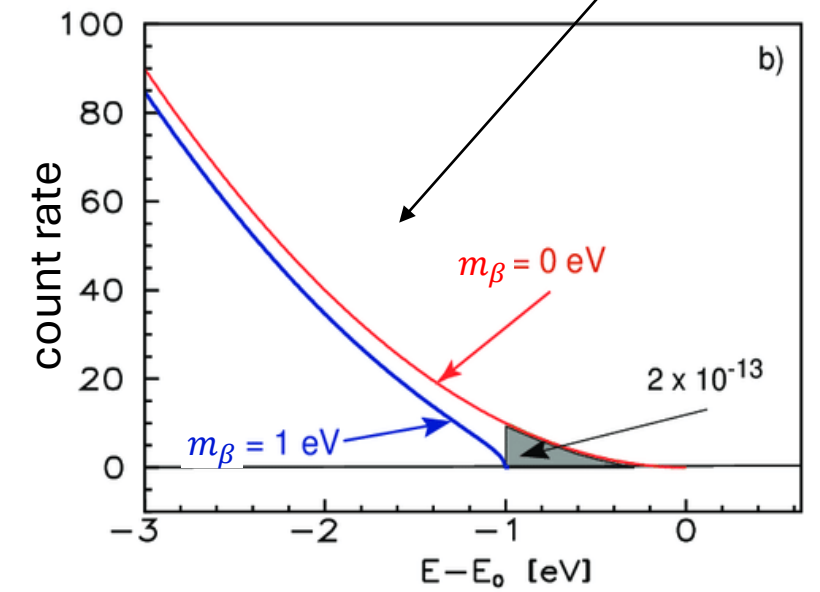
to measure

average magnetic field experienced by electron

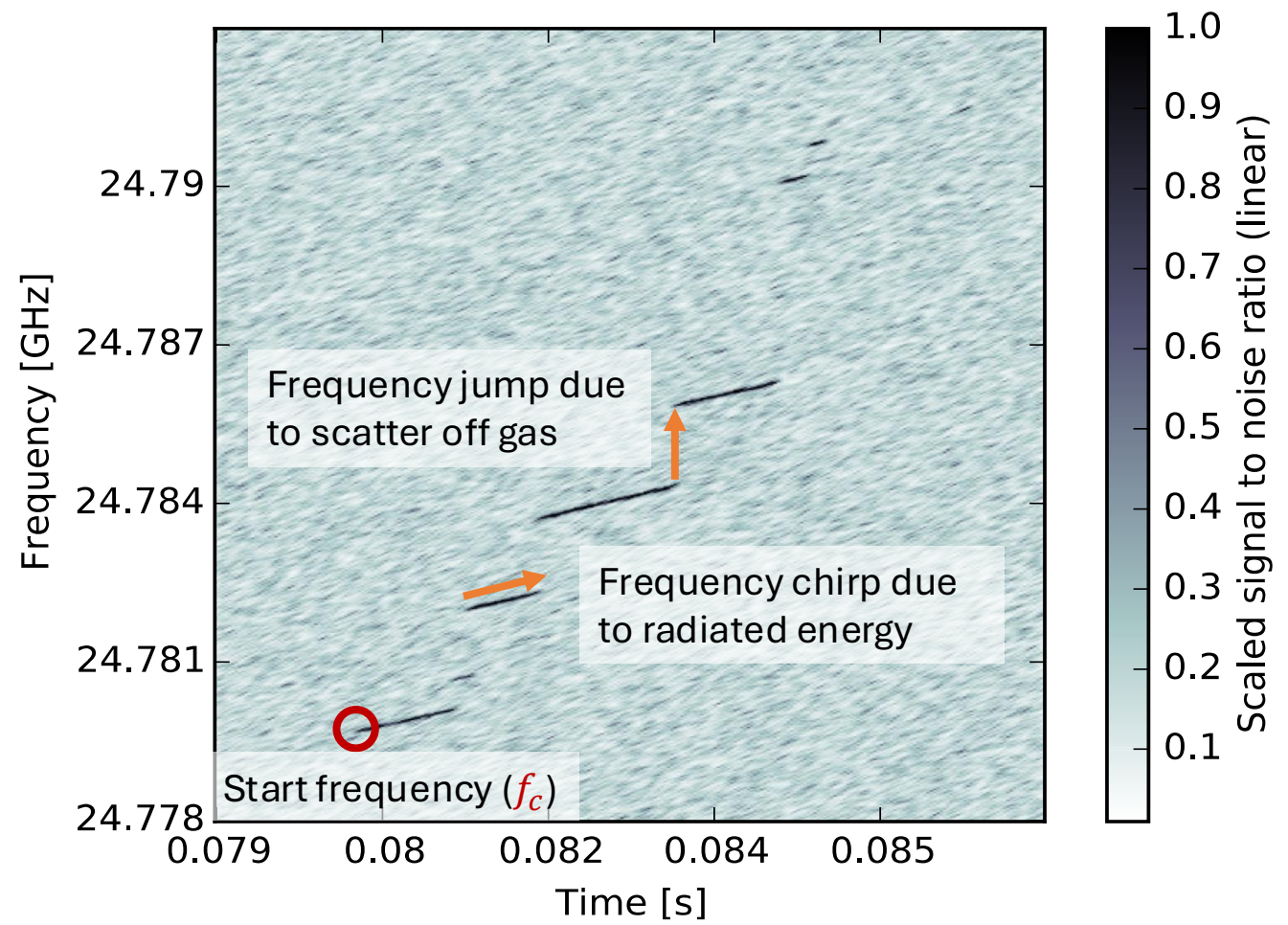
$$f_c = \frac{1}{2\pi} \frac{e \langle B \rangle}{m_e + E_{kin}/c^2}$$

cyclotron frequency

kinetic energy



Anatomy of a CRES event



$$f_c = \frac{1}{2\pi} \frac{e \langle B \rangle}{m_e + E_{kin}/c^2}$$

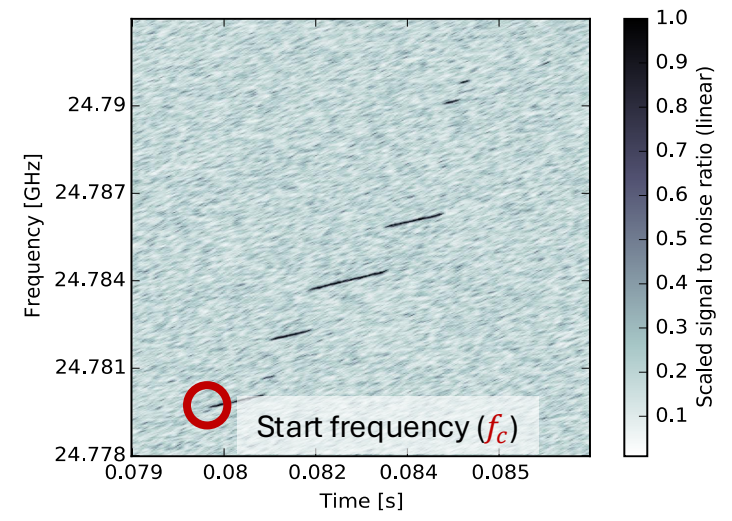
Project 8 Collaboration, *Phys. Rev. Lett.* 131, 102502 (2023)

Advantages of CRES

- It's a frequency measurement!
- Differential spectrometry
- Don't need to transport electrons from source to measure their energy
- Very low background
- Compatible with atomic tritium

Never measure anything but frequency!

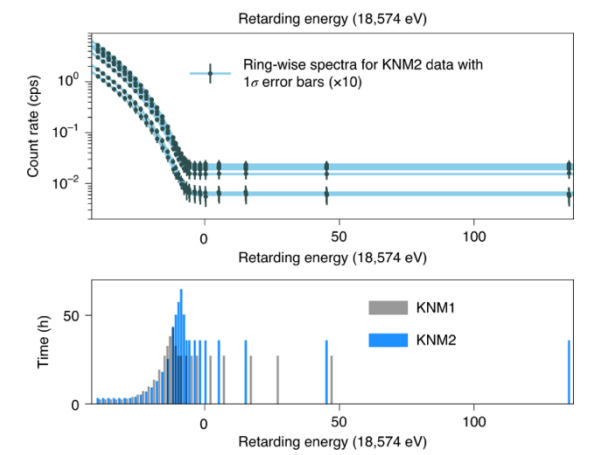
Arthur Schawlow, co-inventor of the laser and Nobel Prize winner



Advantages of CRES

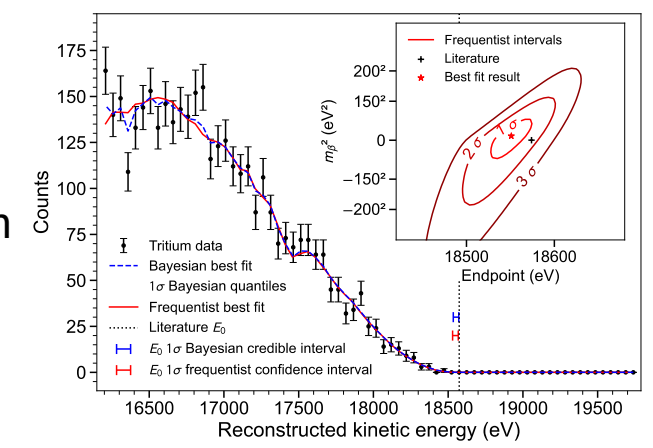
- It's a frequency measurement!
- Differential spectrometry
- Don't need to transport electrons from source to measure their energy
- Very low background
- Compatible with atomic tritium

MAC-E technique gives integral spectrum



The KATRIN Collaboration. *Nat. Phys.* **18**, 160–166 (2022).

CRES gives differential spectrum

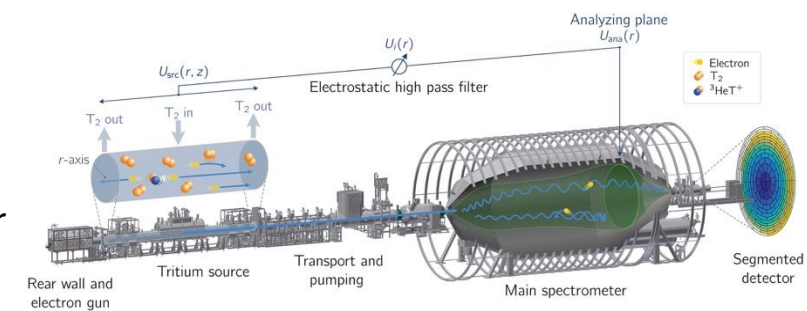


Project 8 Collaboration, *Phys. Rev. Lett.* **131**, 102502 (2023) 11
Project 8 Collaboration, *Phys. Rev. C* **109**, 035503 (2024)

Advantages of CRES

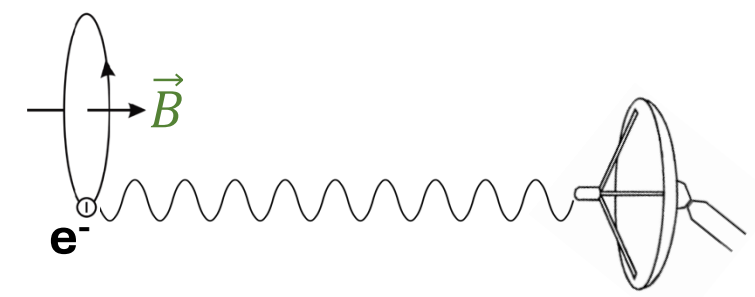
- It's a frequency measurement!
- Differential spectrometry
- Don't need to transport electrons from source to measure their energy
- Very low background
- Compatible with atomic tritium

MAC-E requires transporting electrons over long distances without perturbing their energy



KATRIN collaboration, Science (2025)

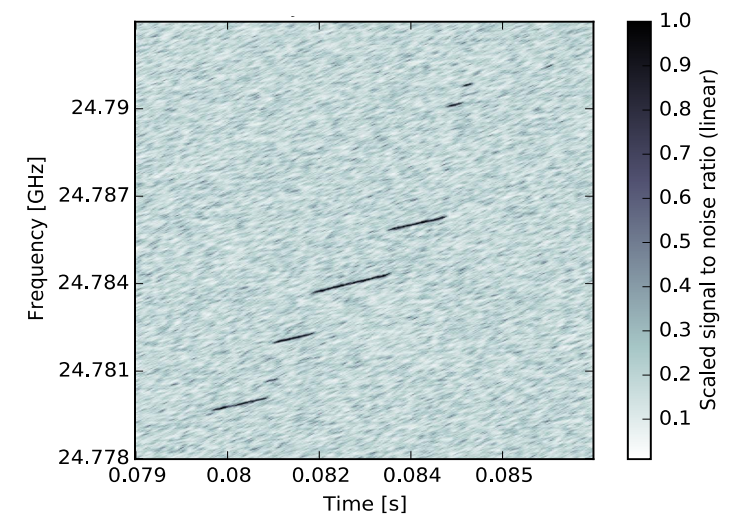
Energy can be measured without transporting electrons



Advantages of CRES

- It's a frequency measurement!
- Differential spectrometry
- Don't need to transport electrons from source to measure their energy
- Very low background
- Compatible with atomic tritium

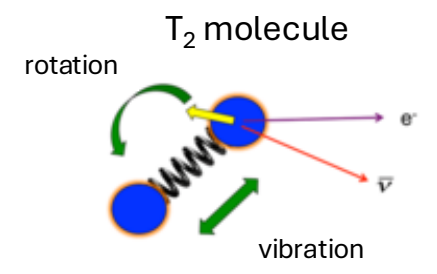
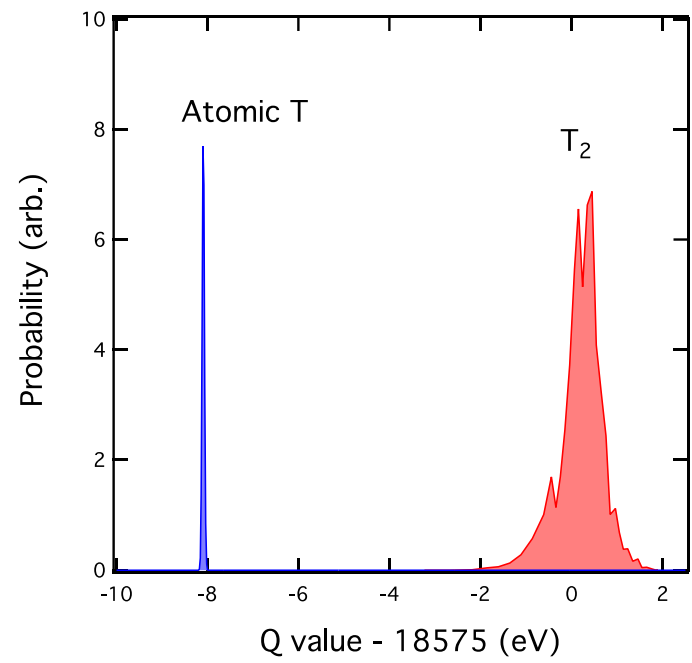
Unique signature of CRES signal makes it resistant to many types of backgrounds



Advantages of CRES

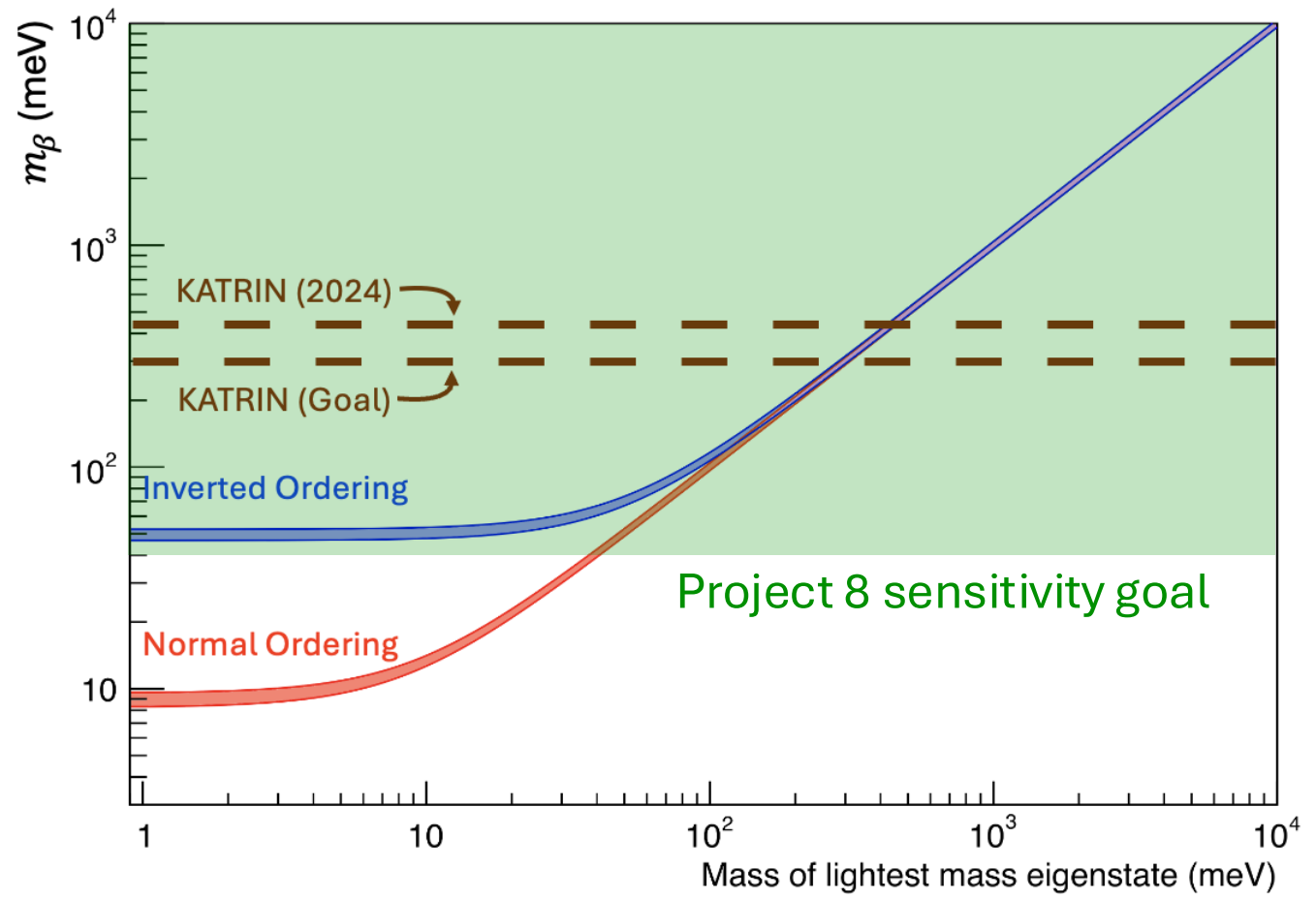
- It's a frequency measurement!
- Differential spectrometry
- Don't need to transport electrons from source to measure their energy
- Very low background
- Compatible with atomic tritium

Avoid final state broadening due to rotational and vibrational modes in the T_2 molecule



J. Formaggio et. al., Phys.Rept. 914 (2021) 1-54

Towards 0.04 eV sensitivity to m_β with the Project 8 experiment



PROJECT 8 Collaboration

University of Washington, 2026



With thanks to our funding agencies:



The path to 0.04 eV sensitivity

Phase I
First demonstration of CRES

Frequency: 24 GHz (MHz)
Time (ms)
Signal-to-noise ratio (linear)

Project 8 Collaboration, Phys. Rev. Lett. (2015)

Phase II
First CRES-based neutrino mass limit

Counts
 m_ν^2 (eV²)
Endpoint (eV)

Legend:
- Frequentist intervals
- Literature
- Best fit result
- Tritium data
- Bayesian best fit
- 1 σ Bayesian quantiles
- Frequentist best fit
- Literature ξ_2
- ξ_2 1 σ Bayesian credible interval
- ξ_2 1 σ frequentist confidence interval

Project 8 Collaboration, Phys. Rev. Lett. (2023)
Project 8 Collaboration, Phys. Rev. C (2024)

Phase III
Technology development to achieve final sensitivity
Neutrino mass sensitivity comparable to KATRIN

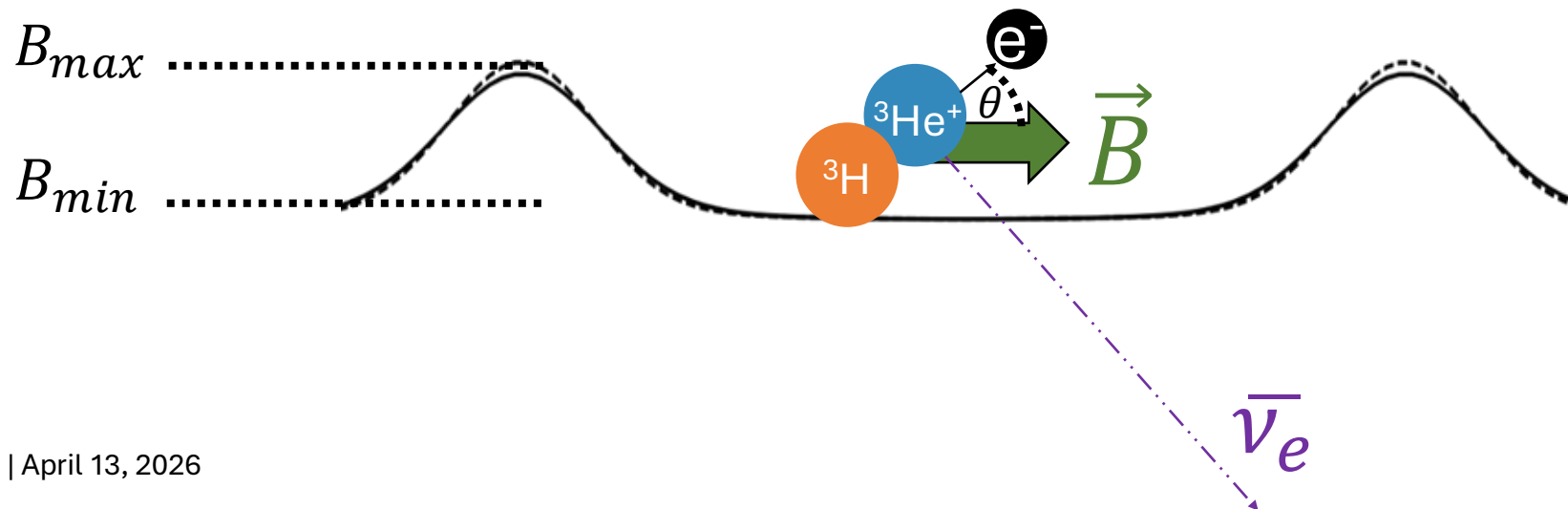
Hot atoms evaporate as confining field drops

ξ_2 (eV)
Endpoint (eV)

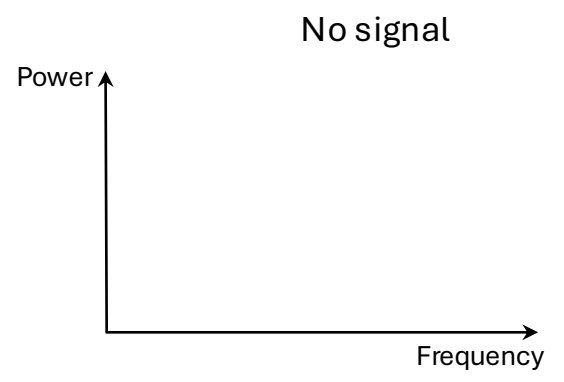
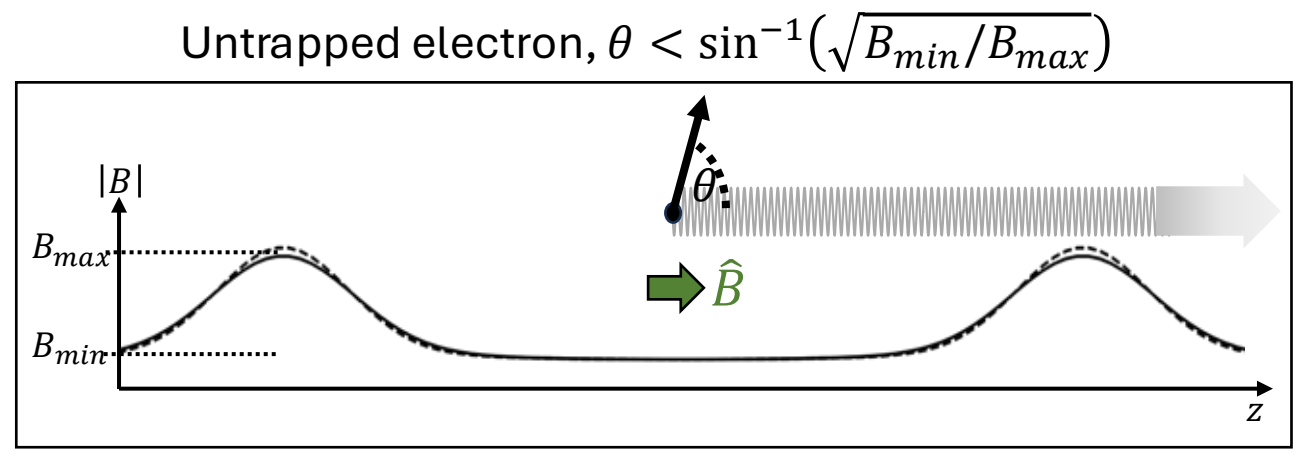
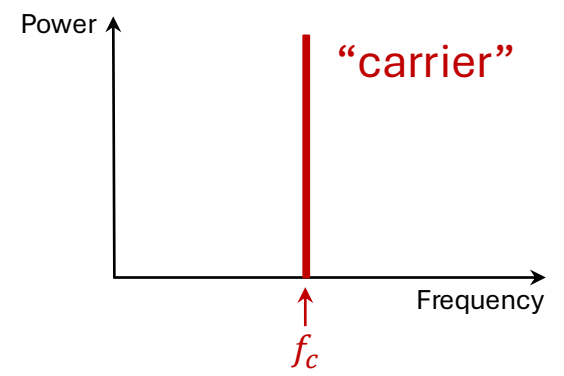
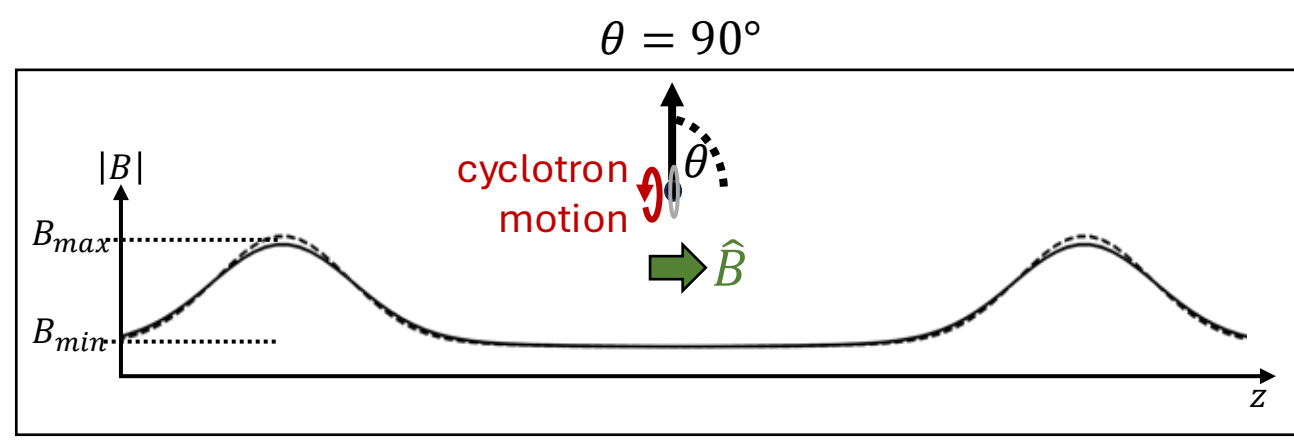
Phase IV
0.04 eV neutrino mass sensitivity

Experimental realities: dynamics of an electron in a magnetic trap

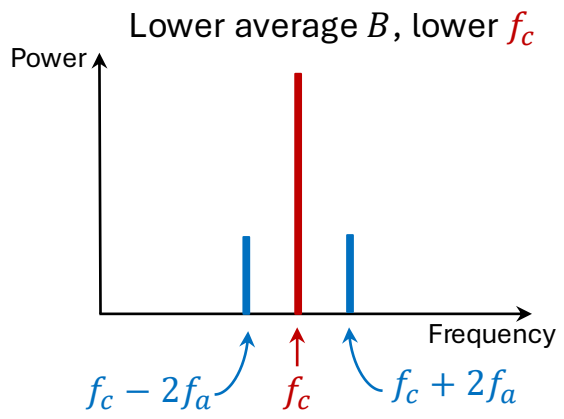
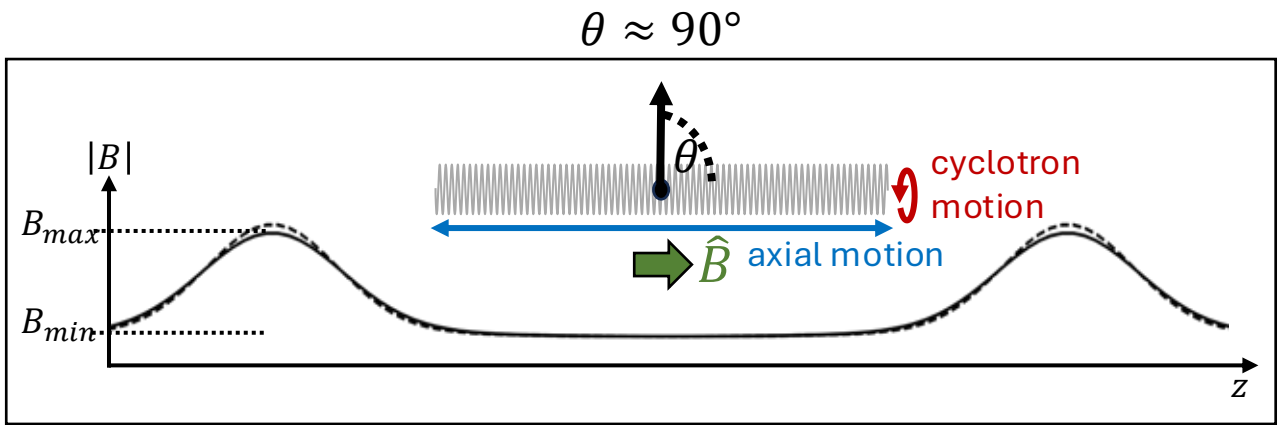
- The electron may be emitted in any direction
- Magnetic trap required to trap electrons long enough to be detected
- Pitch angle θ defined as the angle between the electron momentum and the magnetic field
- Only electrons with $\theta > \sin^{-1}\left(\sqrt{B_{min}/B_{max}}\right)$ will be stored



Dynamics of an electron in a magnetic trap



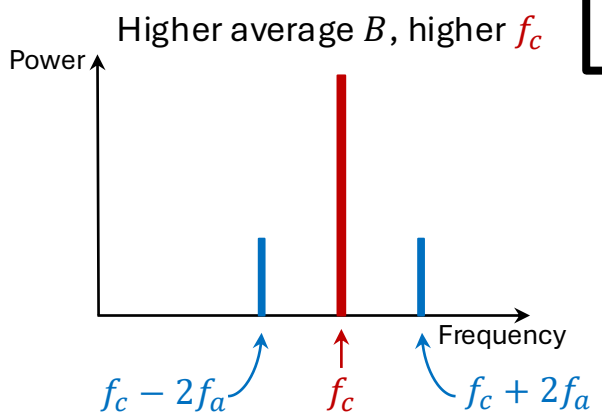
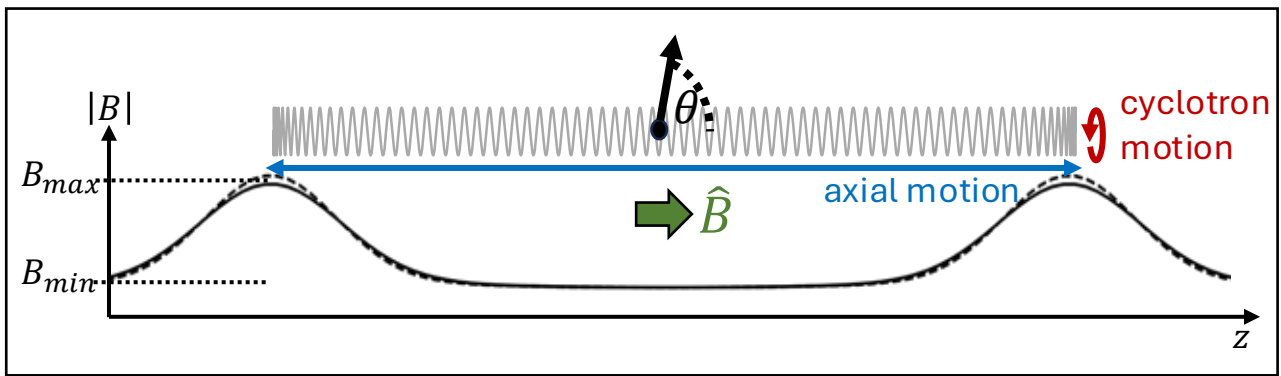
Dynamics of an electron in a magnetic trap



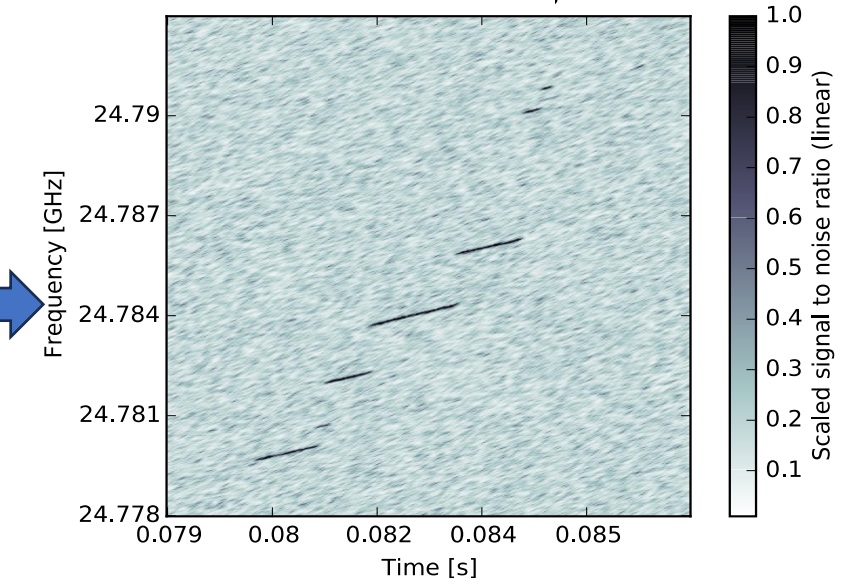
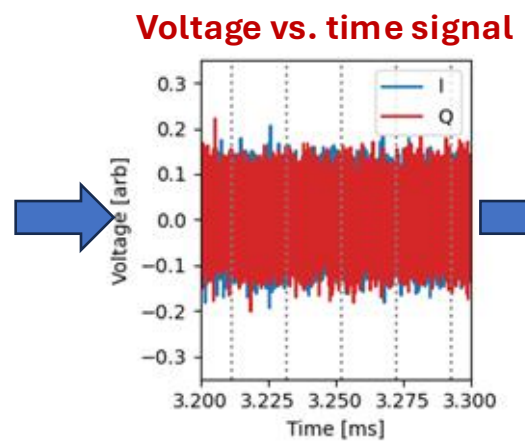
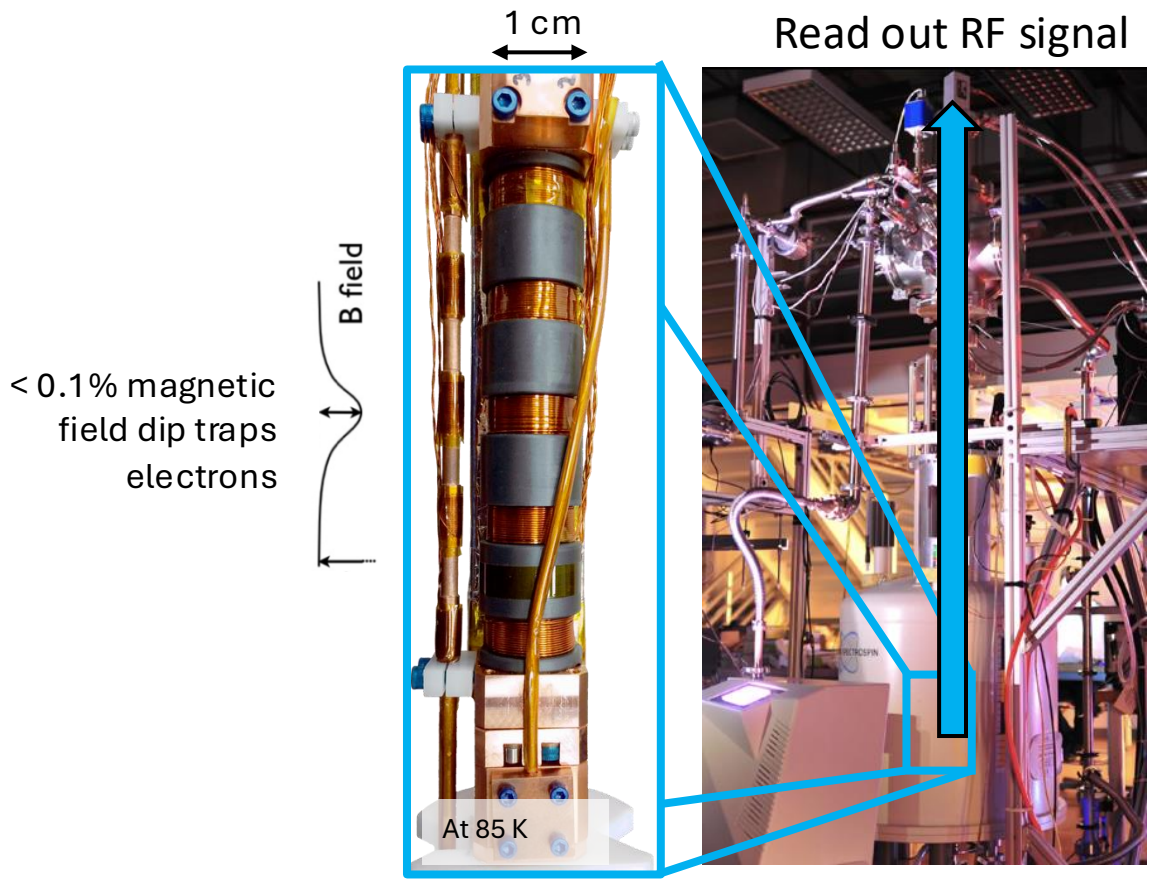
➤ Average field $\langle B \rangle$ experienced by electron depends on electron kinematics within the trap

➤ Sideband structure gives information about $\langle B \rangle$

Minimum trapped pitch angle, $\theta = \sin^{-1}(\sqrt{B_{min}/B_{max}})$



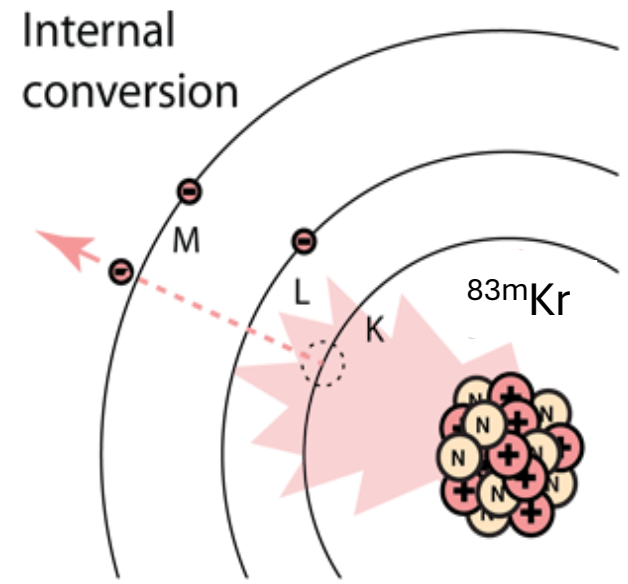
Phase II apparatus



Sidebands not visible in Phase II due to experimental design

Project 8 Collaboration, JINST (2026)

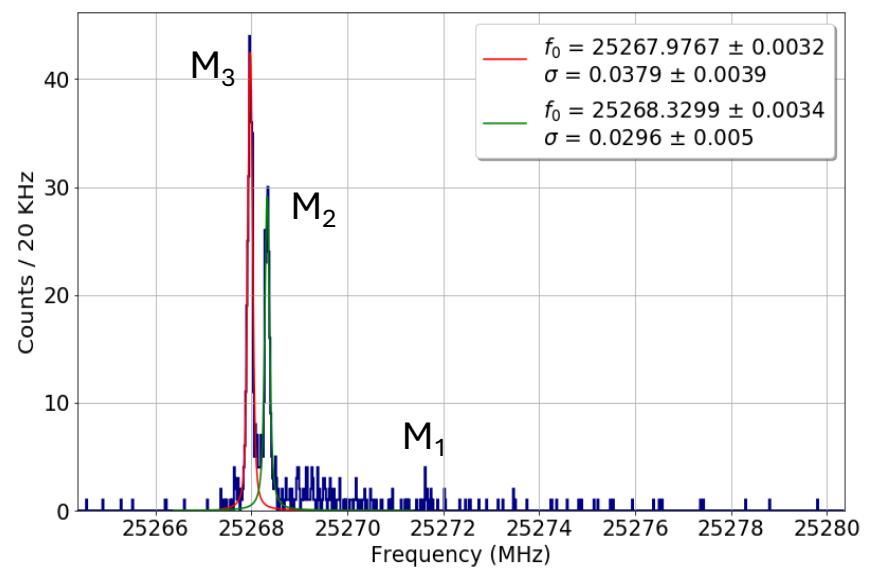
Characterizing detector response with Krypton



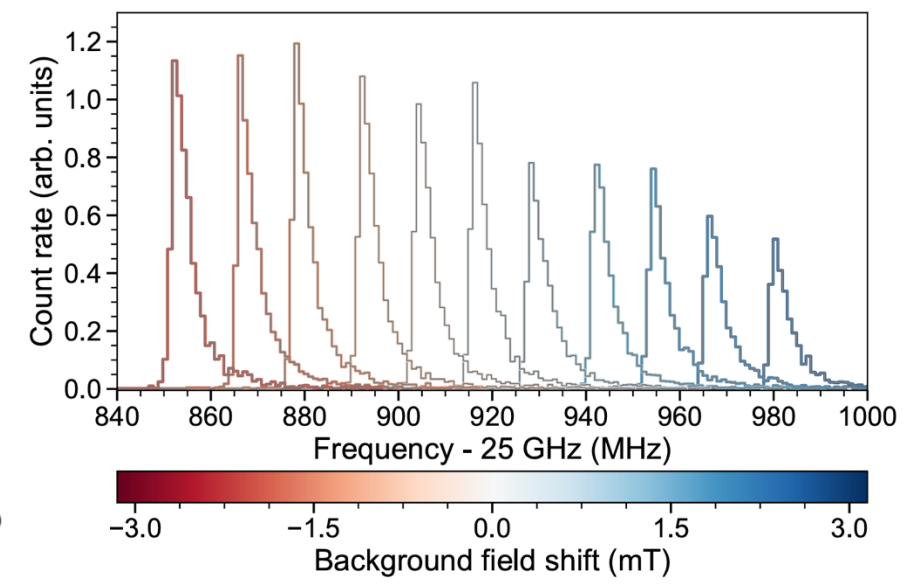
Adapted from Hyperphysics, C.R. Nave

Excited nucleus interacts with atomic electrons and one is ejected

Measurement of ^{83m}Kr conversion lines demonstrates good energy resolution



Frequency response mapping using 17.8 keV ^{83m}Kr line



Project 8 Collaboration, *Phys. Rev. Lett.* (2023)
 Project 8 Collaboration, *Phys. Rev. C* (2024)

Energy resolution dependent on trap depth

Deep trap

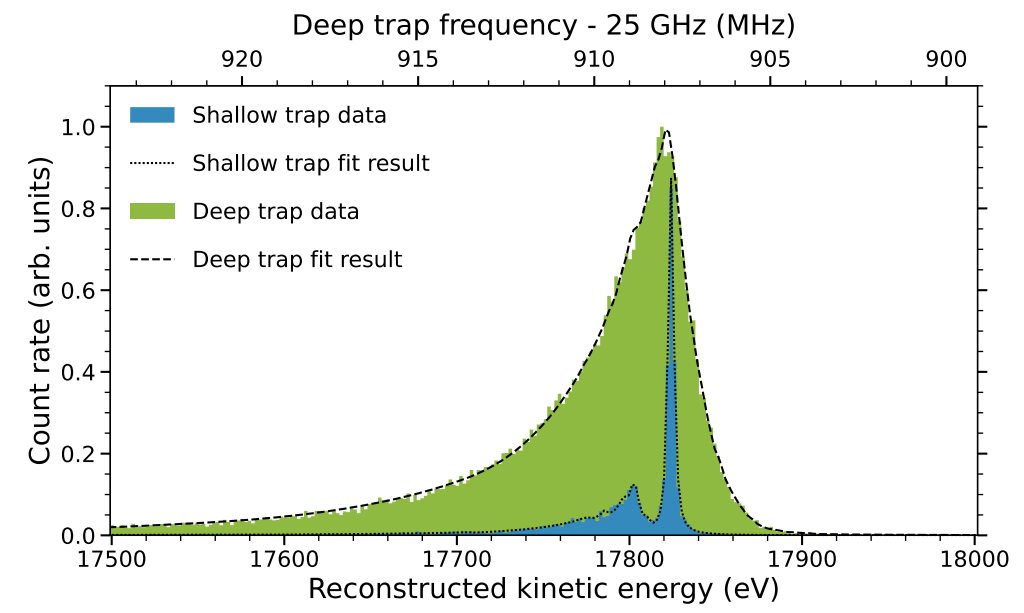


- Larger field variation experienced by electrons
- Higher statistics

Shallow trap



- Smaller field variation experienced by electrons
- Lower statistics
- Achieved energy resolution of **1.7 eV (FWHM)**



Project 8 Collaboration, Phys. Rev. Lett. (2023)
Project 8 Collaboration, Phys. Rev. C (2024)

Avoid tradeoff between statistics and resolution in future experiments by detecting sidebands

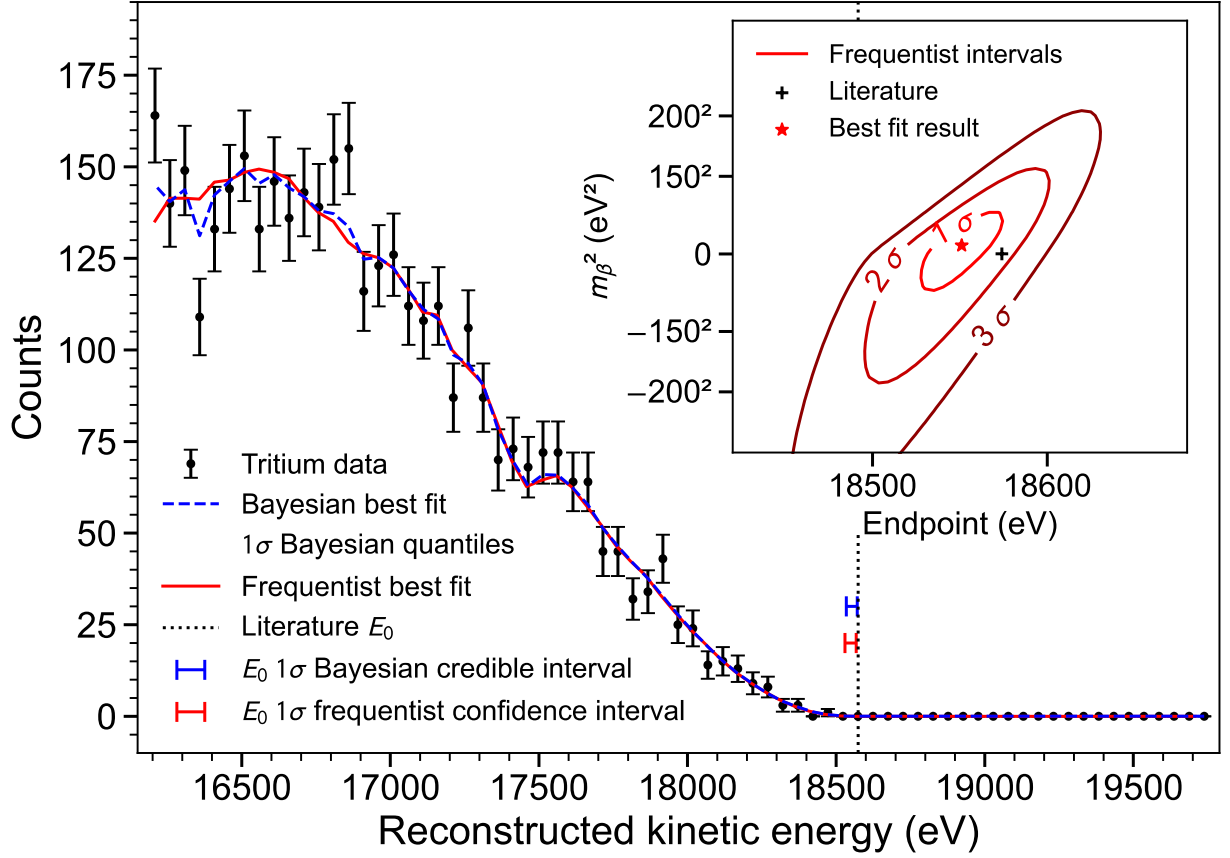
First upper limit on m_β using CRES

Background rate

- $\leq 3 \times 10^{-10} \text{ eV}^{-1}\text{s}^{-1}$ (90% C.I.)
- No events above endpoint!

Neutrino mass

- Frequentist: $\leq 152 \text{ eV}/c^2$ (90% C.L.)
- Bayesian: $\leq 155 \text{ eV}/c^2$ (90% C.L.)




Project 8 Collaboration, Phys. Rev. Lett. 131, 102502 (2023)
Project 8 Collaboration, Phys. Rev. C 109, 035503 (2024)

Spectrometer size comparisons



KATRIN

KATRIN spectrometer


Project 8 Phase II
spectrometer
(to scale)

The path to 0.04 eV sensitivity

Phase I
First demonstration of CRES

Project 8 Collaboration, Phys. Rev. Lett. (2015)

Phase II
First CRES-based neutrino mass measurement

Project 8 Collaboration, Phys. Rev. Lett. (2023)
Project 8 Collaboration, Phys. Rev. C (2024)

You are here

Phase III
Technology development to achieve final sensitivity
Neutrino mass sensitivity comparable to KATRIN

Phase IV
0.04 eV neutrino mass sensitivity

Factors contributing to sensitivity to m_β

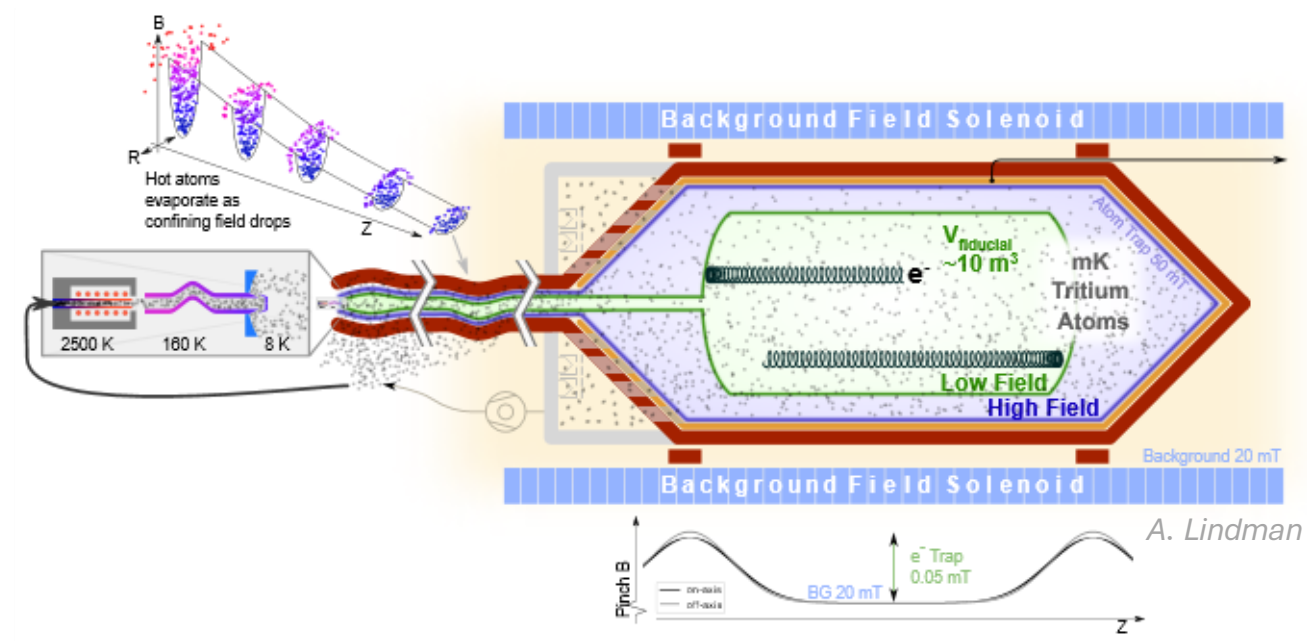
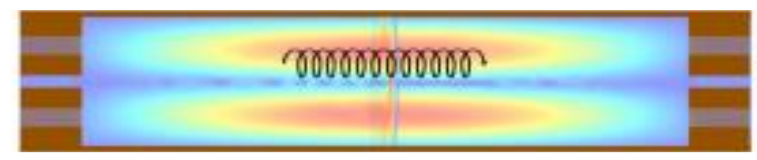
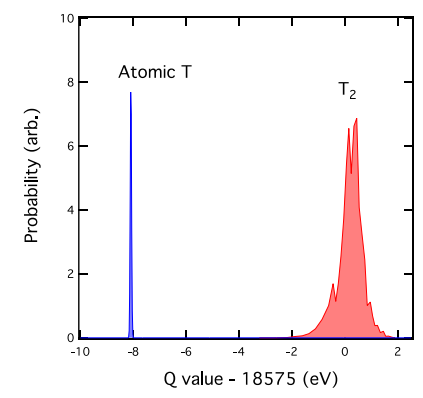
$$\sigma_{m_\beta^2} = 4 \sqrt{\frac{1}{(6 C_T V_{\text{eff}} n t)^2} \left[C_T V_{\text{eff}} n t \Delta E + \frac{b t}{\Delta E} \right] + \sum_i \sigma_i^2(n) \cdot \delta \sigma_i^2}$$

Effective volume (volume × efficiency) → V_{eff}
Runtime → t
Source gas density → n
Background → b
Response function stdevs. (resolution) → $\sigma_i^2(n)$
Uncertainties on response function → $\delta \sigma_i^2$

- Massively scale up detection volume using resonant cavities
- Achieve sufficiently high density of atomic tritium
- Maintain low background
- Improve energy resolution
- Understand response function using various calibration sources

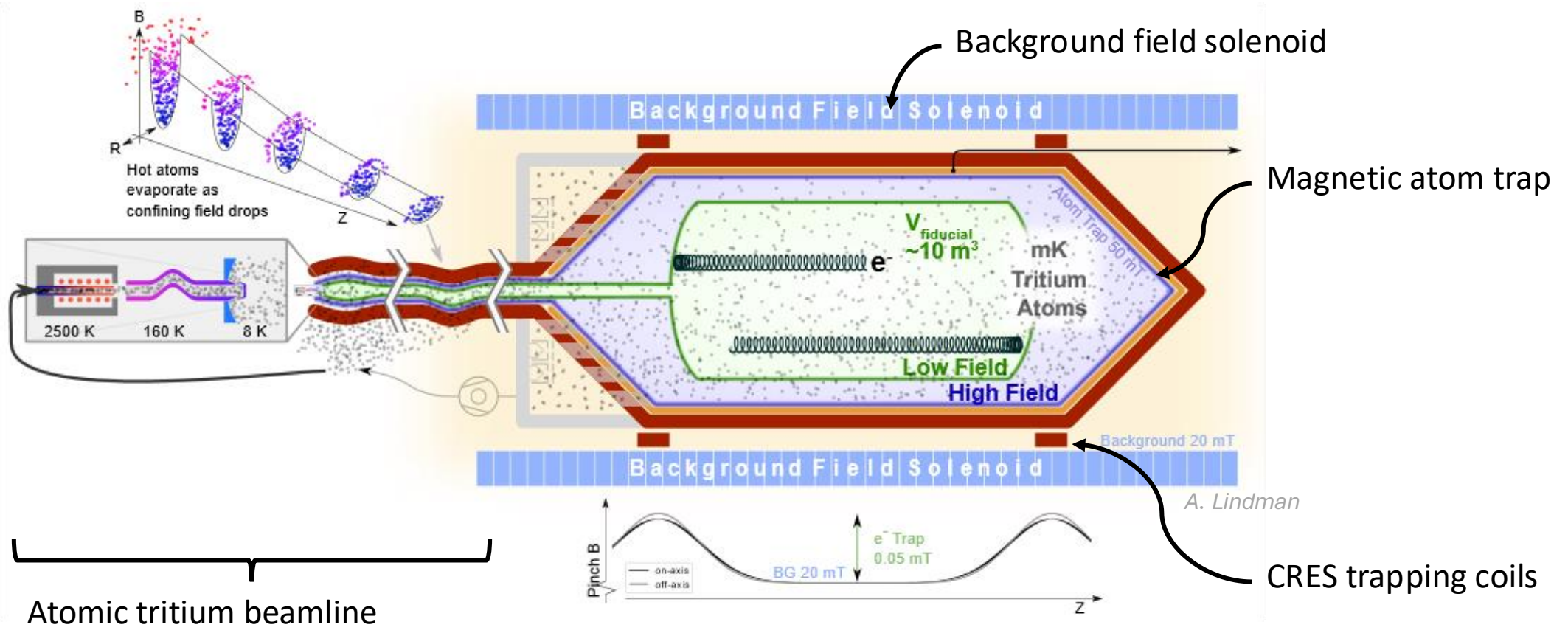
Phase III goals to achieve final sensitivity

- Magnetically trapped cold atomic tritium (n)
- Massively scaling up detection volume (V_{eff})
 - Resonant cavities allow for increased volume with resonant enhancement of SNR
- Integrated magnetic field design of atom trap and CRES trap



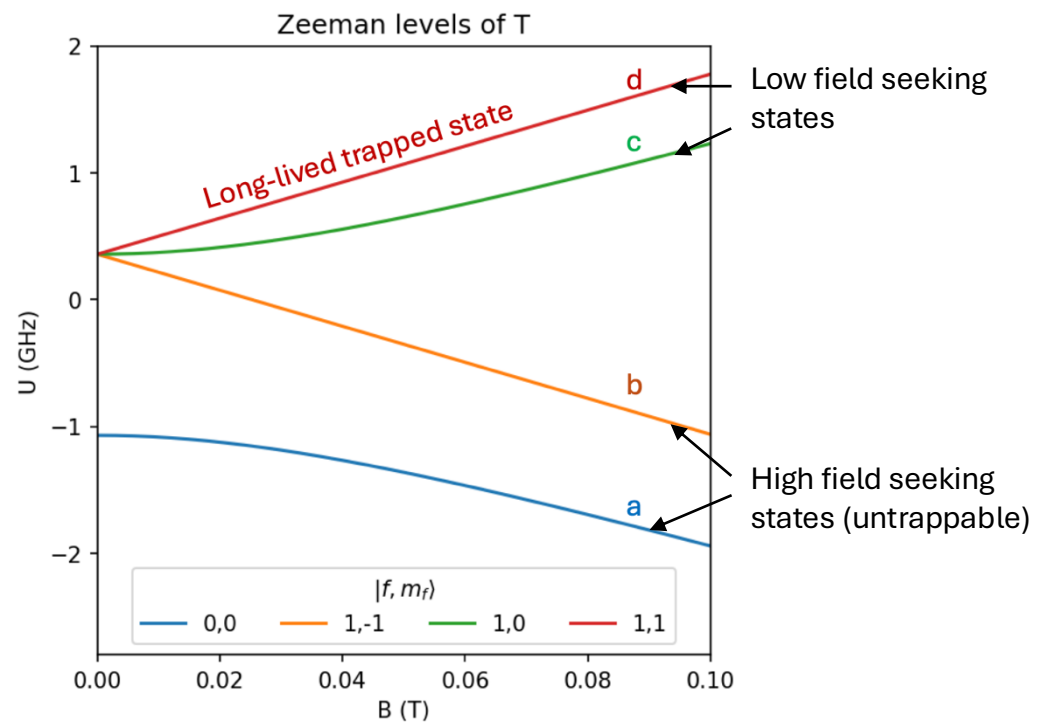
A. Lindman

Integrated design for future experiments



Progress is still being made toward understanding tritium physics...

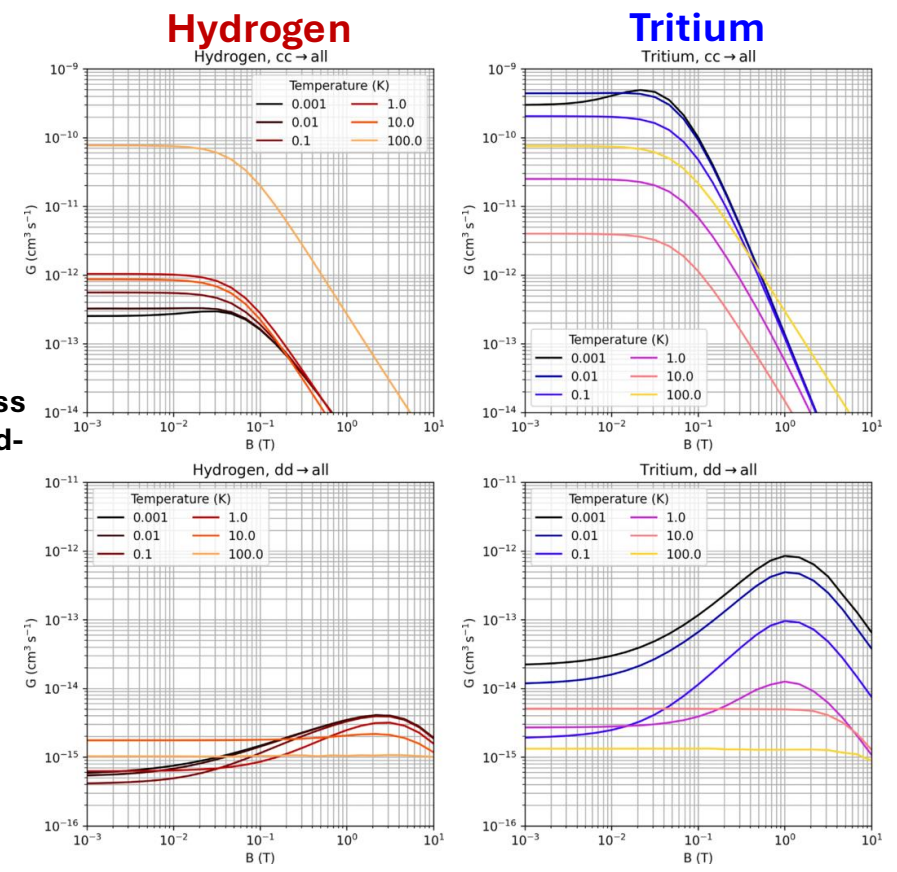
Low-field seeking states of atomic tritium can be magnetically trapped



Tritium-tritium interactions cause atoms to scatter into untrappable states at a much higher rate than hydrogen

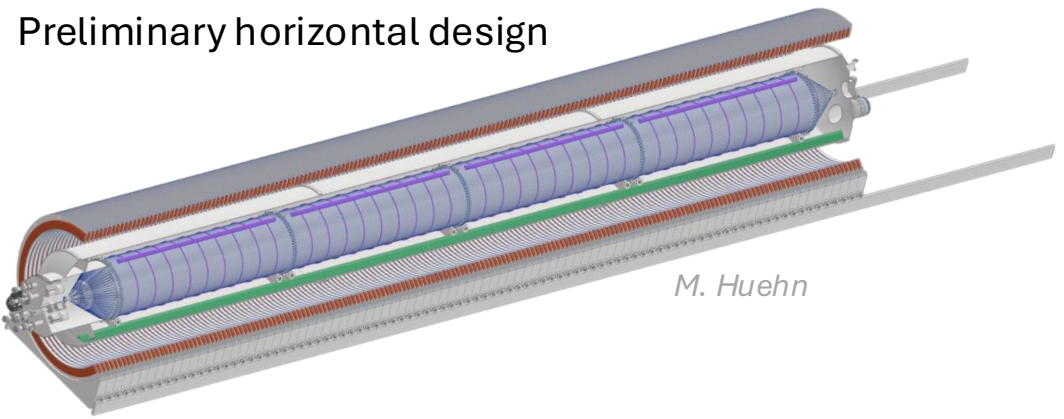
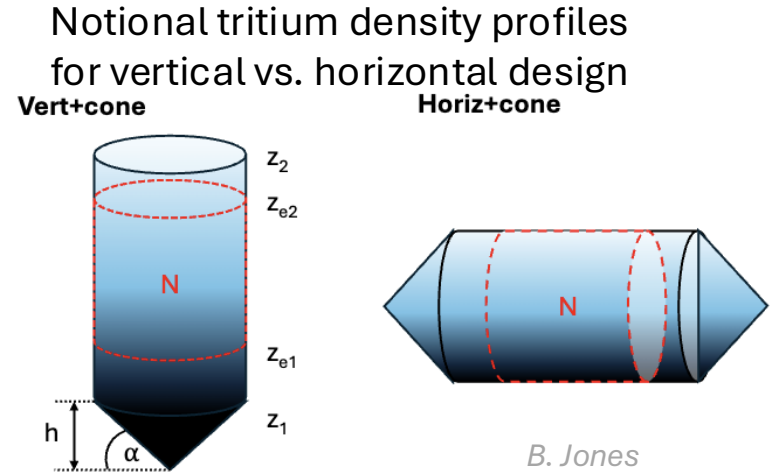
M. G. Elliott and B. J. P. Jones, *Elastic and spin-changing cross sections of spin-polarized atomic tritium*, Phys. Rev. A (2025)

Rate constants for loss of trappable high-field-seeking states

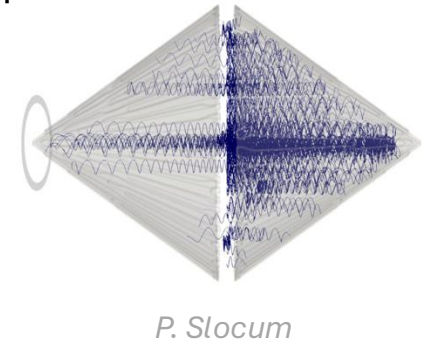


...Resulting in updates to the experimental design

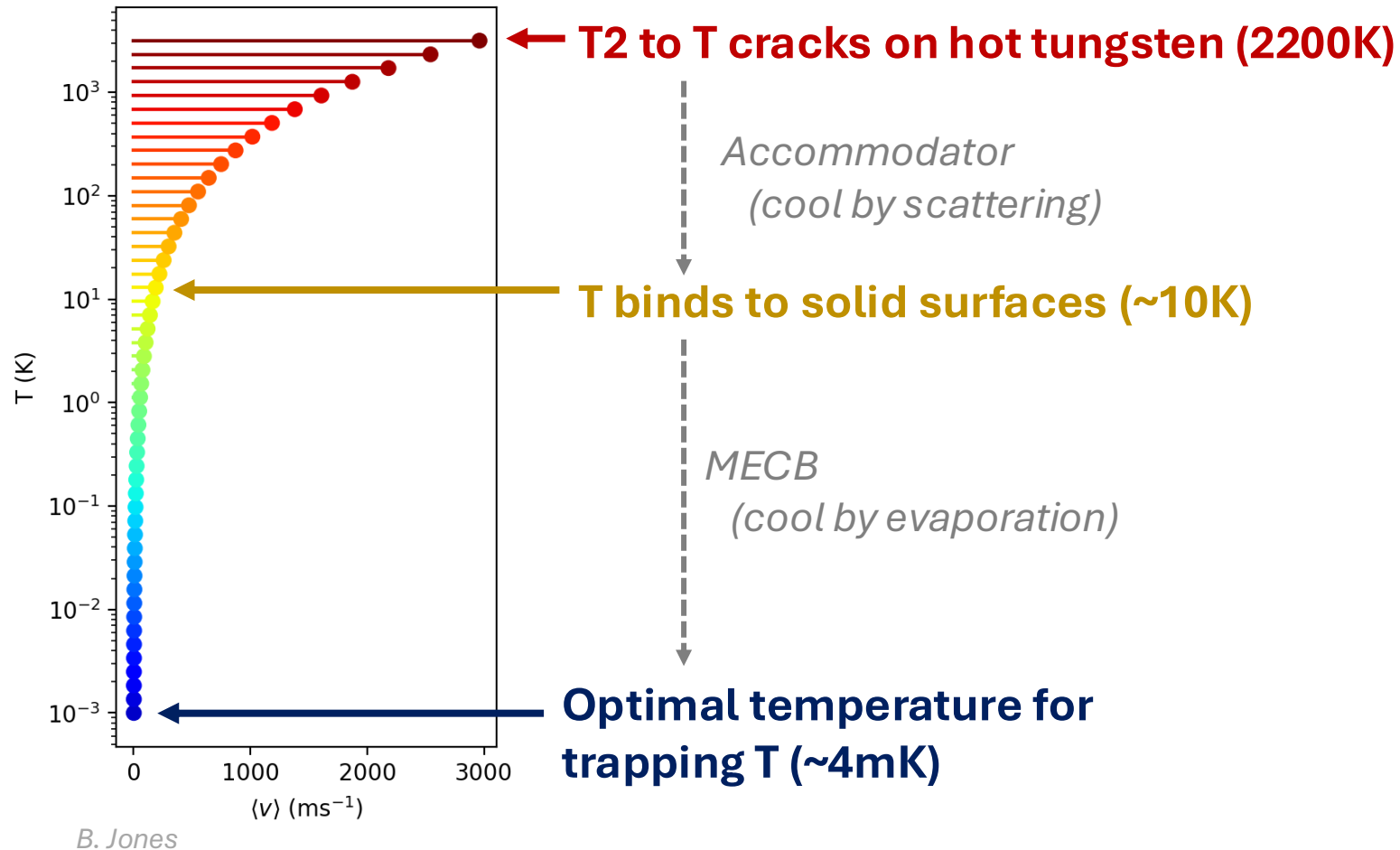
- Project 8 originally planned for magnetogravitational tritium trap
 - Tritium loss is enhanced due to pooling at the bottom
- → movement toward fully magnetic design
- Simulations suggest that overtrapping of low pitch angle electrons is mitigated by loss at cones used for tritium loading



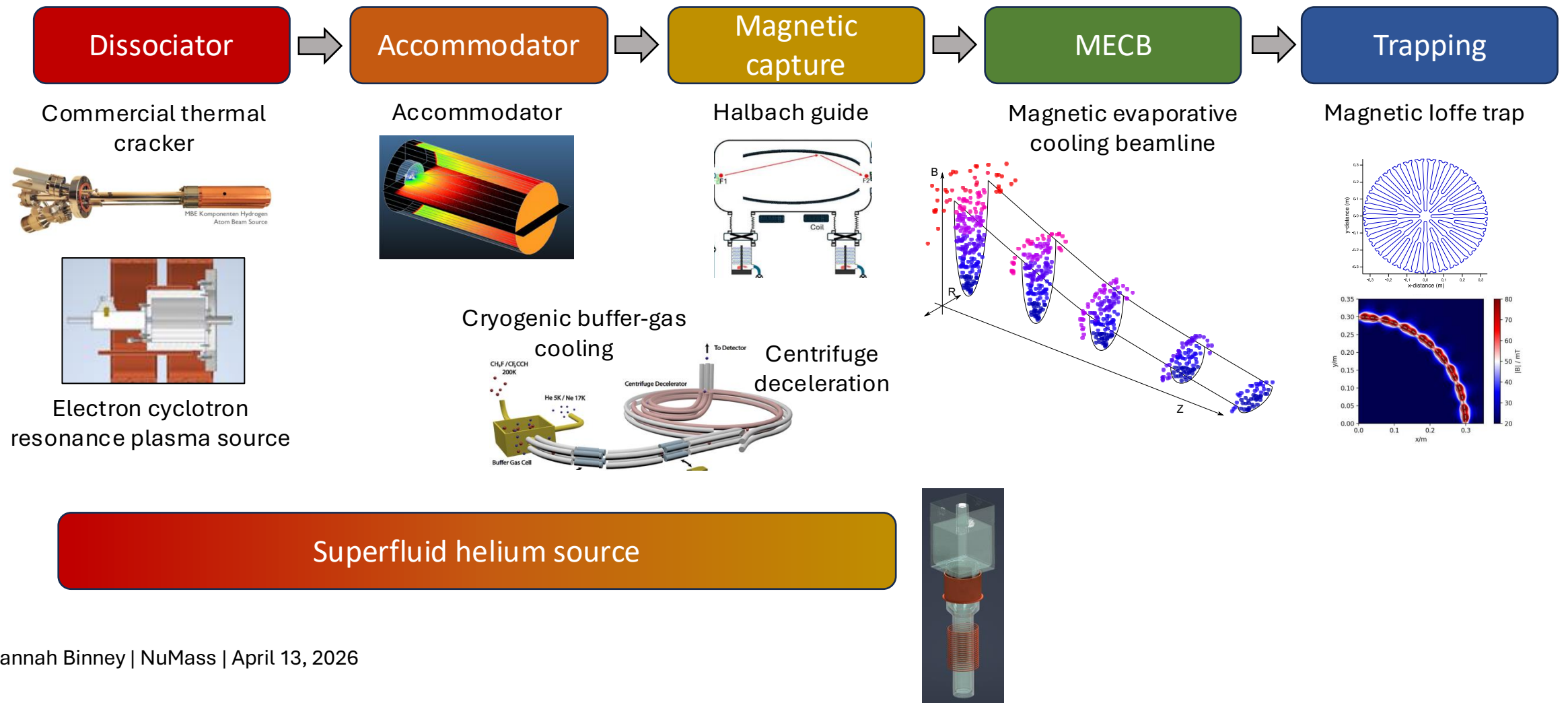
Most electrons overtrapped by atom trap hit the cones and are lost



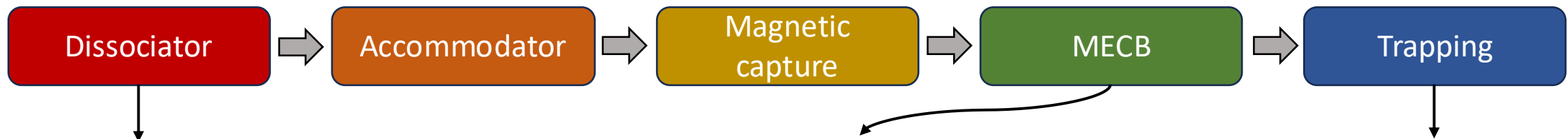
Creating and cooling atomic tritium without recombination is very challenging



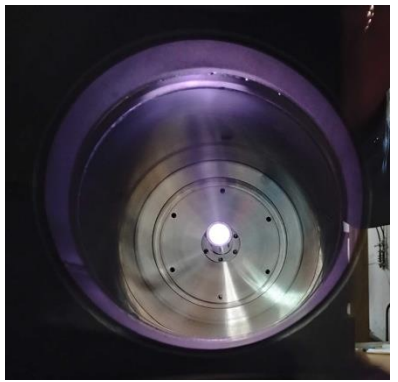
Atomic tritium source development



Atomic tritium highlights



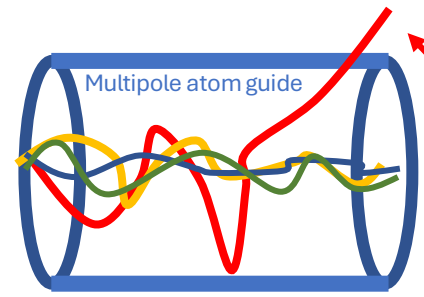
First dissociation in ECR source



M. Oueslati

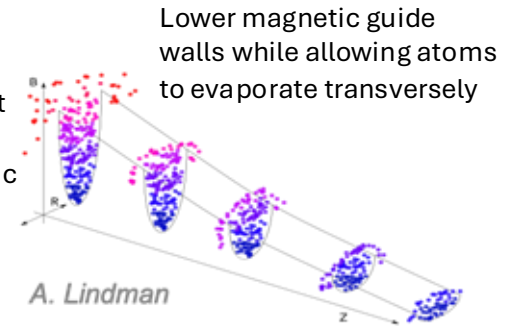
Magnetic Evaporative Cooling Beamline (MECB) design

Project 8 Collaboration, Phys. Rev. A 112, 033311 (2025)



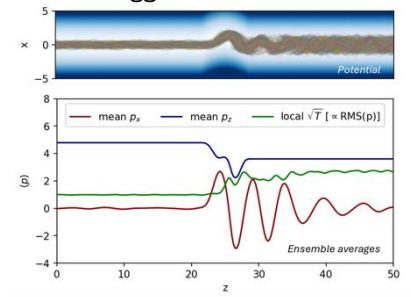
Only the highest energy atoms escape magnetic potential

B. Jones

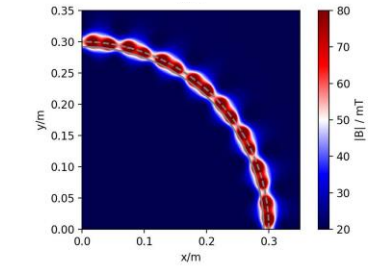
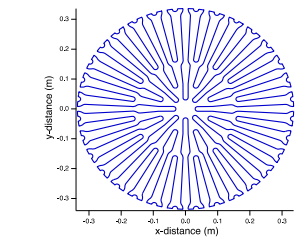


A. Lindman

Use wiggles to slow the beam

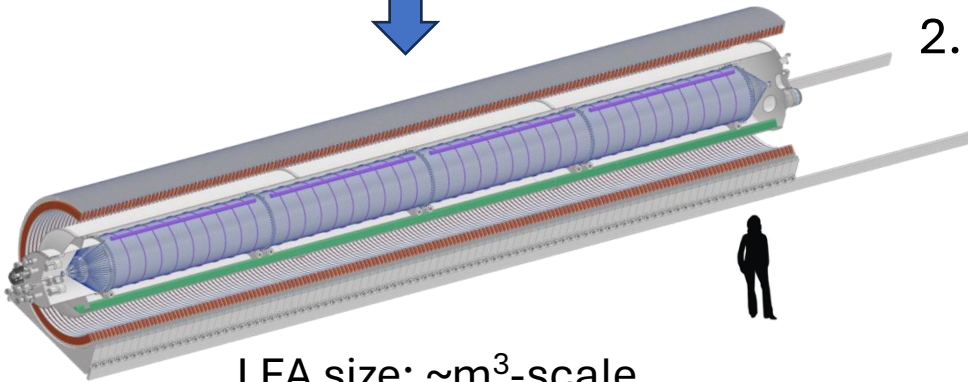
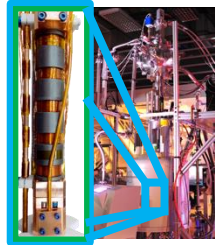


Ioffe trap design



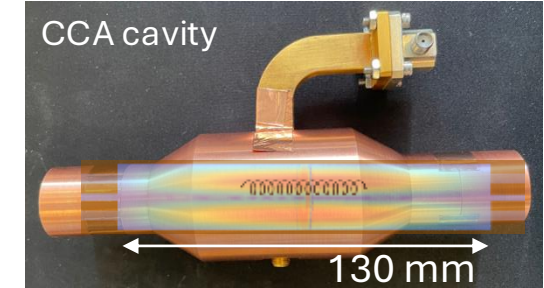
Massively scale up detection volume V_{eff} using resonant cavities

Phase II:
~mm³-scale effective volume



LFA size: ~m³-scale effective volume

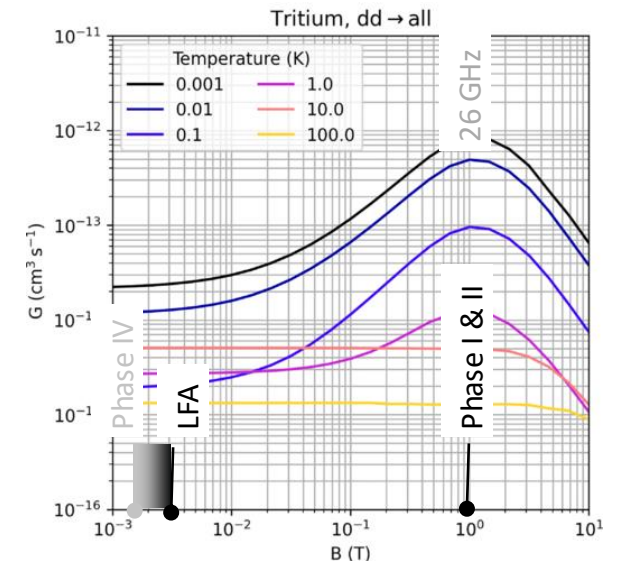
1. Test that CRES works in a resonant cavity with the Cavity CRES apparatus (CCA)
 - Same frequency as Phase II, allowing for reuse of electronics and setup
 - *Krypton and electron gun CRES only, no neutrino mass measurement



2. Test that experiment works at low frequency and large scale with the Low Frequency Apparatus (LFA), $V \approx m^3$

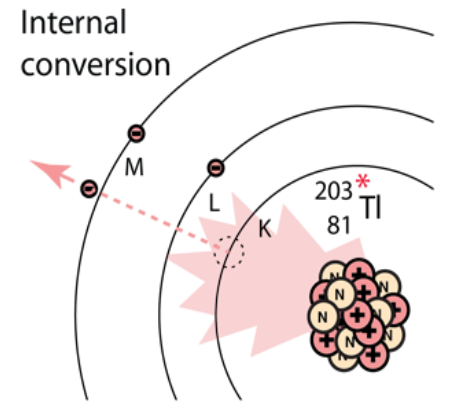
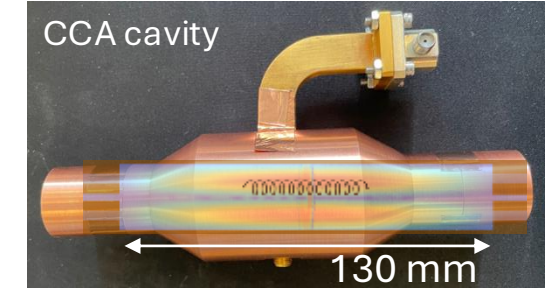
3. Scale up even more for Phase IV

Low field/low frequency required to keep atoms trapped



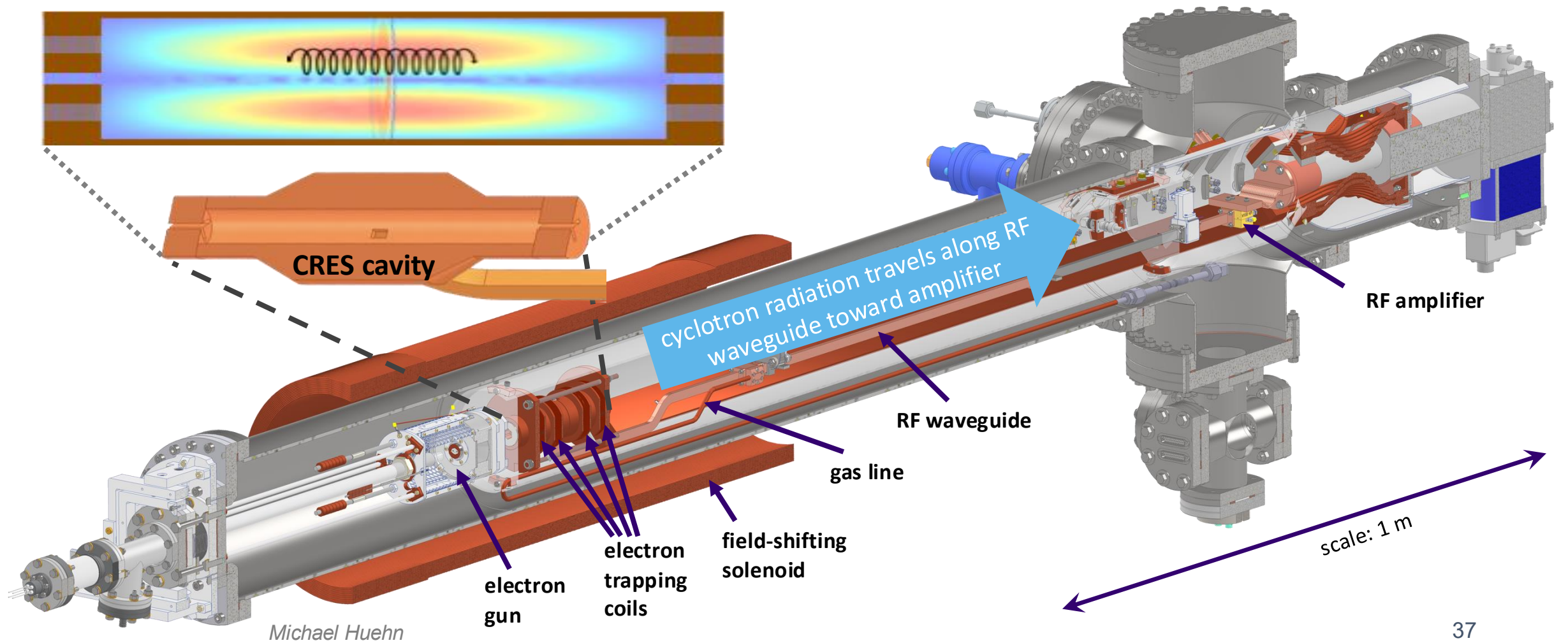
Goals of the Cavity CRES Apparatus (CCA)

- First demonstration of CRES in a resonant cavity
- Calibration info encoded in CRES signal and careful magnetic trap design → factor of ~5 narrower detector response σ_i
- New calibration techniques → detector response width $\delta\sigma_i$ characterization to ~2%
- Science goal: spectroscopy of K-, L-, M-, and N-conversion electrons from the 32 keV ^{83m}Kr transition
 - Precisely characterize shakeoff and shakeup
 - Resolve the N_2 -32 and N_3 -32 conversion electron lines



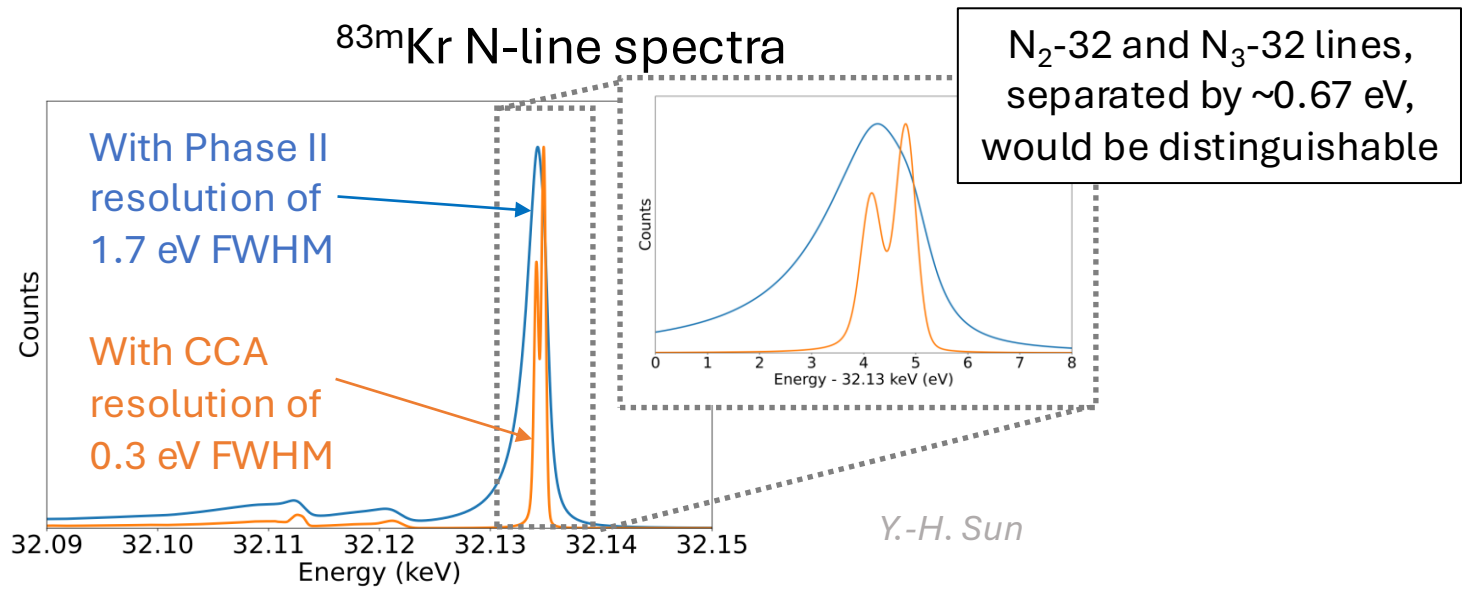
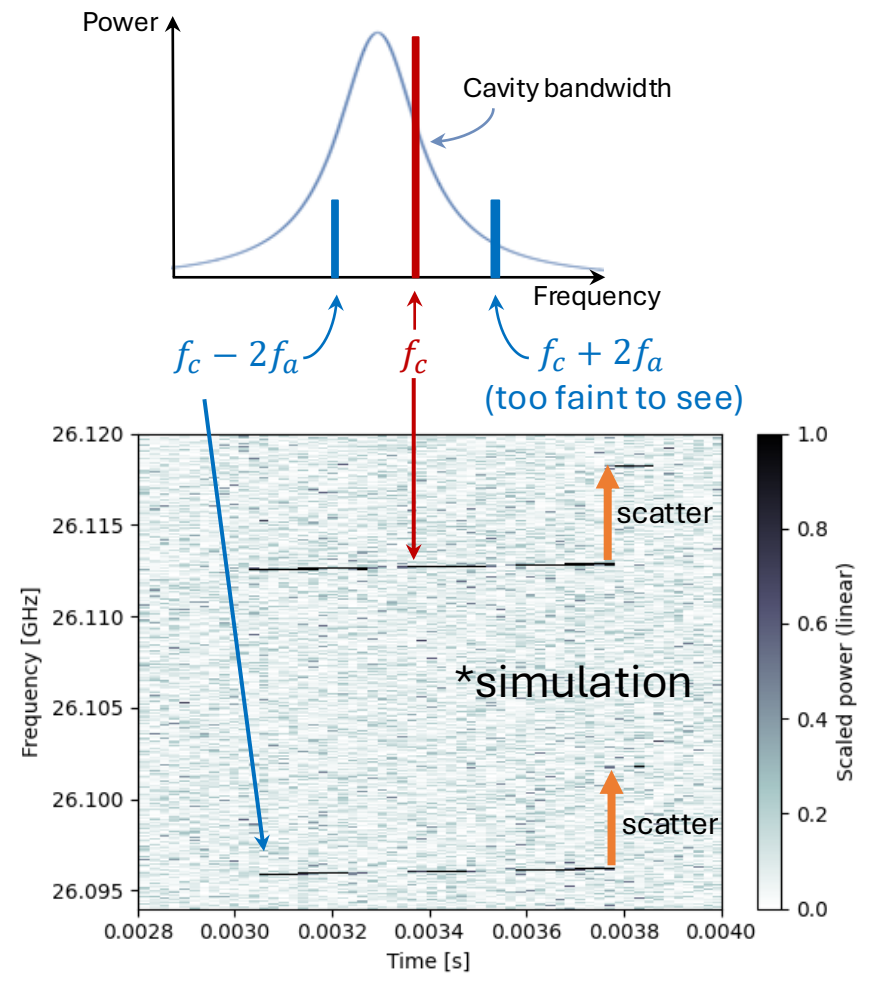
Hyperphysics

Design of the cavity CRES apparatus (CCA)

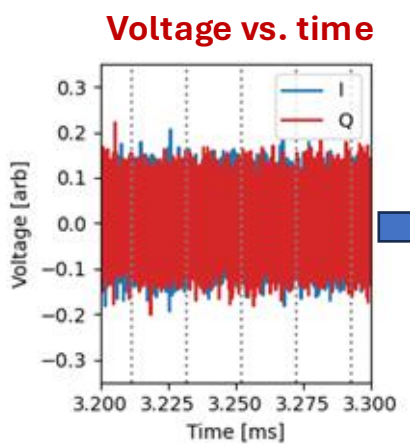


Electron-by-electron magnetic field corrections for sub-eV energy resolution

- Require cavity bandwidth wide enough to see side bands
- Extracting the axial frequency allows event-by-event magnetic field corrections

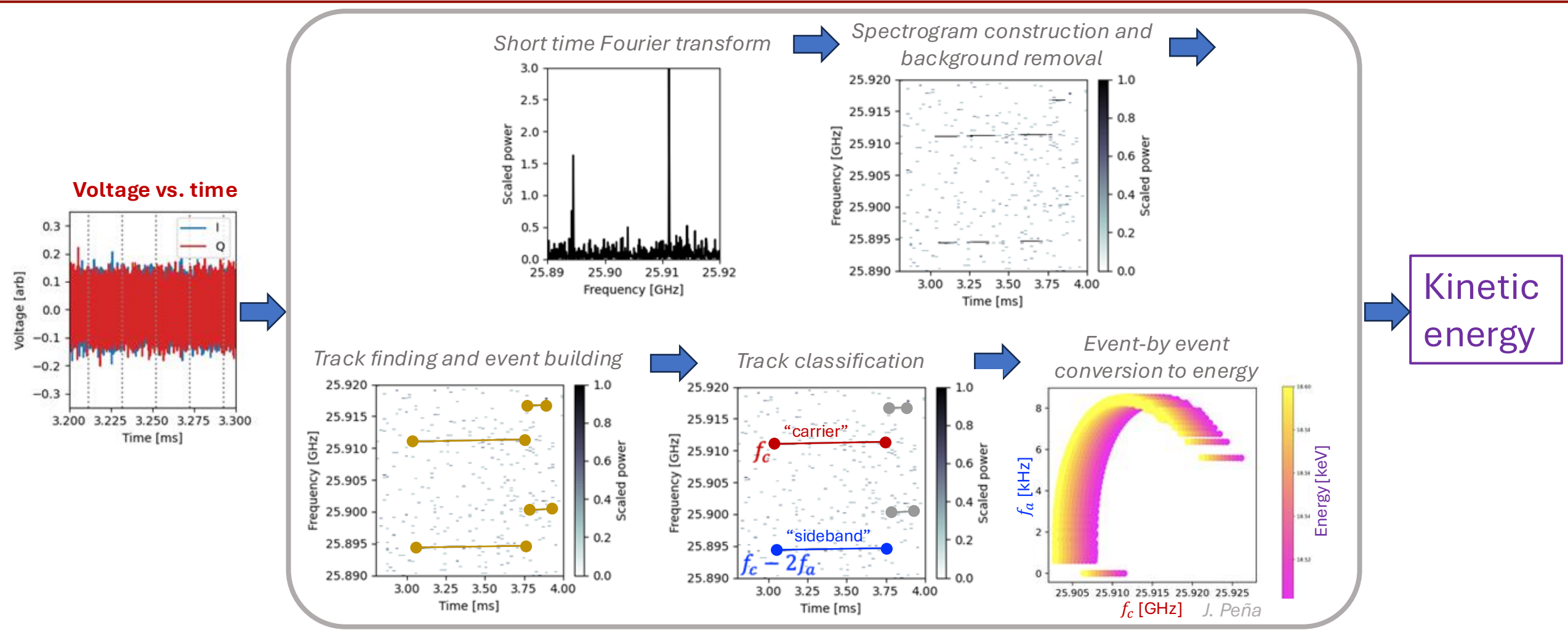


Reconstruction for the Project 8 experiment

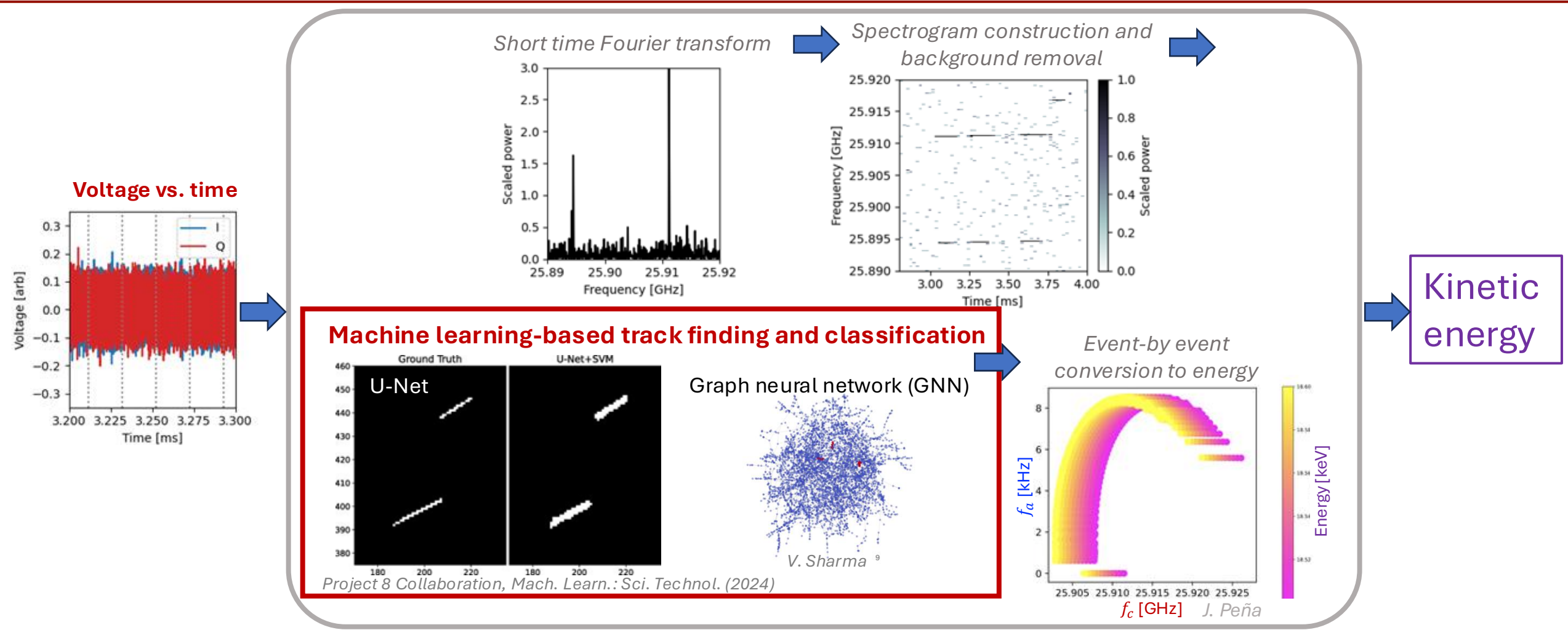


Kinetic energy

Frequency-based reconstruction algorithm for the CCA



Advanced reconstruction algorithms for the CCA and future

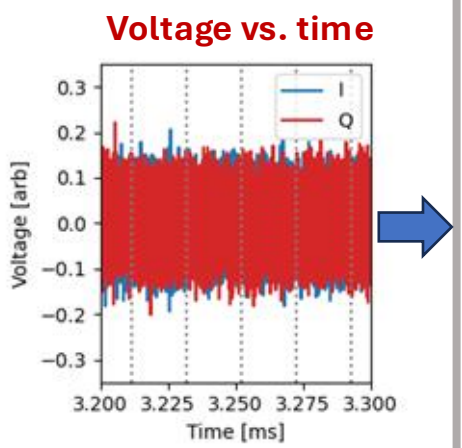


Advanced reconstruction algorithms for the CCA and future

New time series approaches

Matched filtering on time series data

State space machine learning models



Time-Domain Matched Filtering

Amplitude vs. Time (ms). The plot shows a noisy signal (black) and a red dashed line representing the Signal Template. The amplitude ranges from -2 to 2, and time ranges from 0.0 to 1.0 ms.

Correlation

Correlation vs. Delay (ms). The plot shows a blue line for Correlation and a red dot for Current Correlation. The correlation ranges from -1.0 to 1.0, and delay ranges from 0.0 to 1.0 ms.

E. Karim

Denosing results using SSM

PSD [arb/Hz] vs. Frequency [MHz]. The plot shows three traces: Noisy input (blue), Clean target (orange), and Denoised (green). The y-axis is logarithmic, ranging from 10^{-22} to 10^{-6} . The x-axis ranges from 0 to 200 MHz.

Energy reconstruction

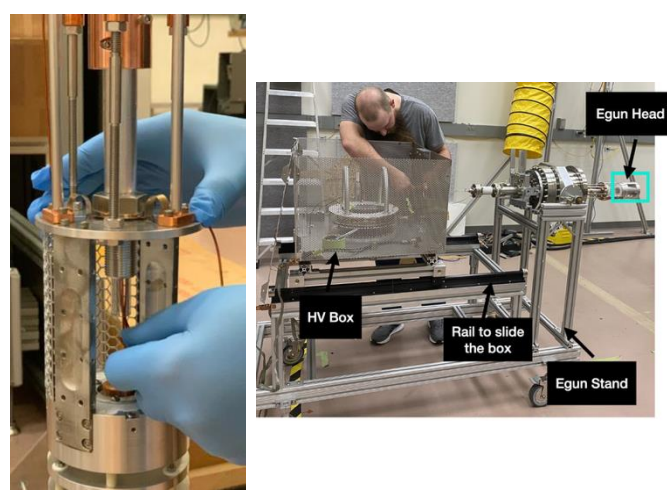
A.U. vs. Residual Energy [eV]. The plot shows a blue histogram and a red curve representing the reconstruction. The y-axis ranges from 0.00 to 0.04, and the x-axis ranges from -2 to 2 eV.

H. Binney, L. Felipe Koehler Domingues, C. Reissel

Kinetic energy

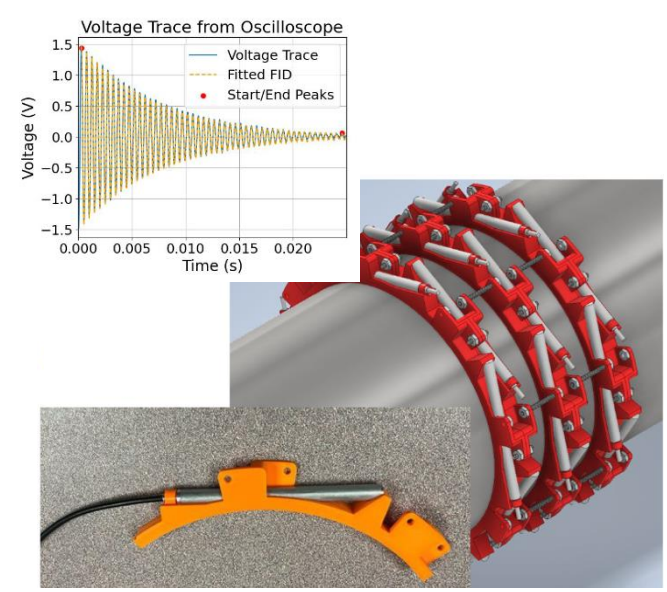
Development of improved calibration methods for the CCA and future

Electron gun calibration source with near-monoenergetic electrons provides information about detector response



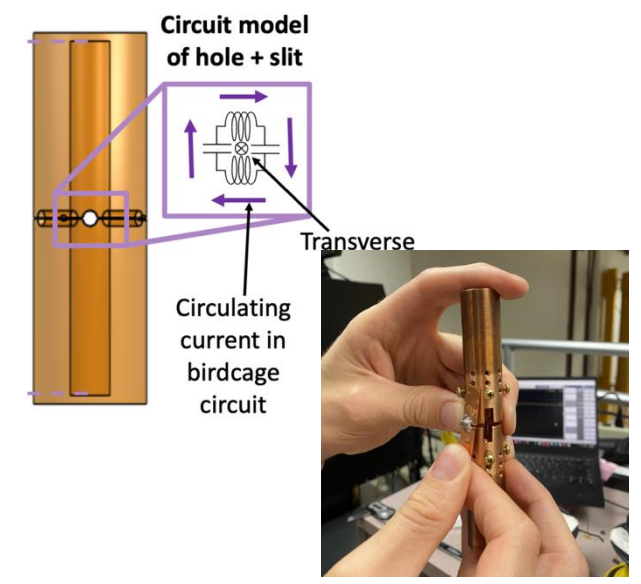
M. Kallander

Proton NMR probes outside the detector region for field monitoring



P. Kolbeck

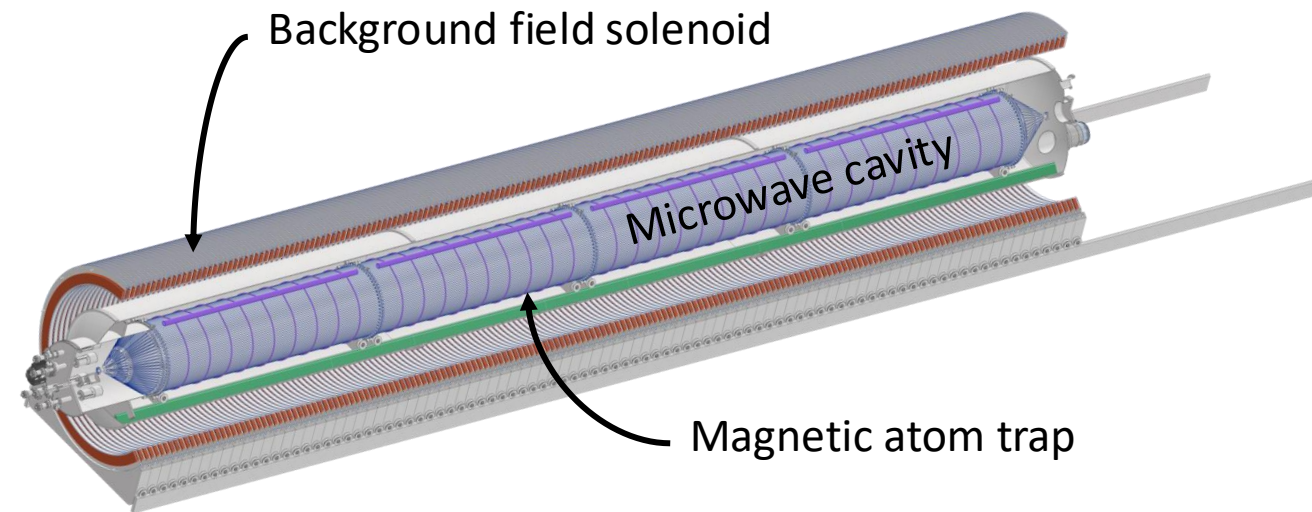
In-situ magnetometry development using polarized helium



A. Kurmus, S. Kuenstner

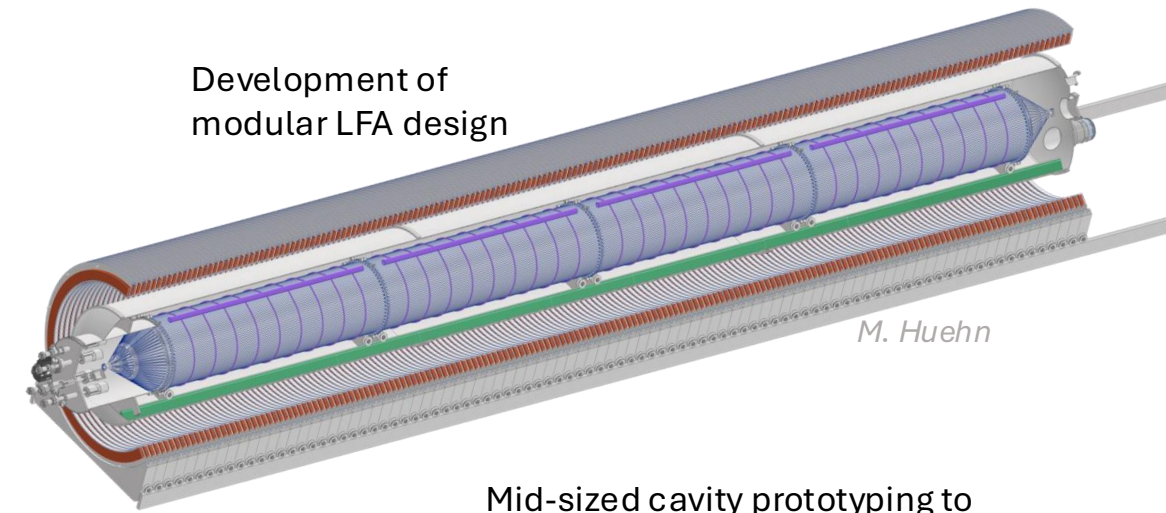
Moving towards the Low Frequency Apparatus (LFA)

- Next neutrino mass experiment in Project 8 R&D program
- TE₀₁₁ mode at **560 MHz** frequency
- **21 mT** field, larger volume
- Upgradable to use atomic tritium
 - Goal of KATRIN-like sensitivity to m_β

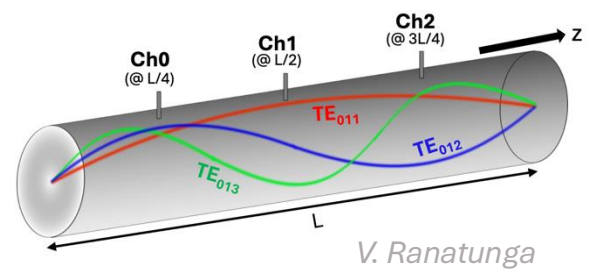


Scaling up cavities for the LFA

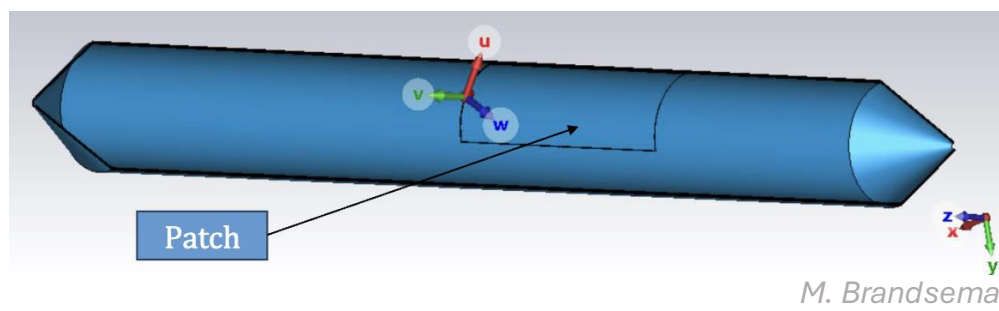
- Significant progress on scaling cavity designs to reach desired performance for the LFA
- Progress on multimode cavities, patch readouts, magnet fabrication...



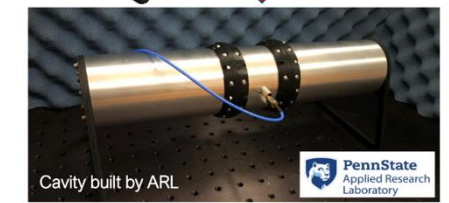
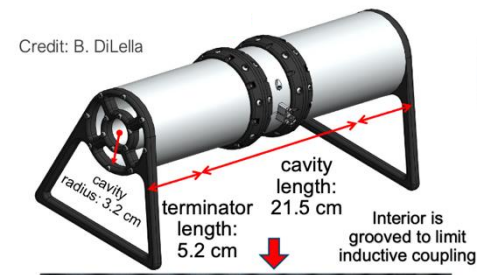
Testing of multimode designs to read out TE₀₁₁ and TE₀₁₂



New readout schemes (patch antennae)

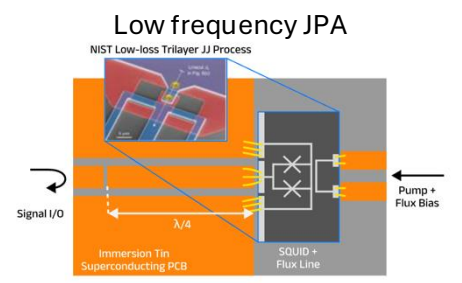


Mid-sized cavity prototyping to test readout and mode filtering

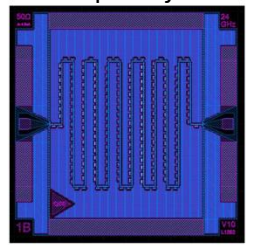


...And many other developments for Phase III

Quantum electronics for improved SNR



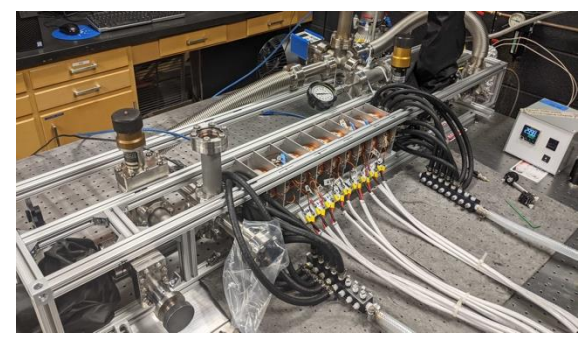
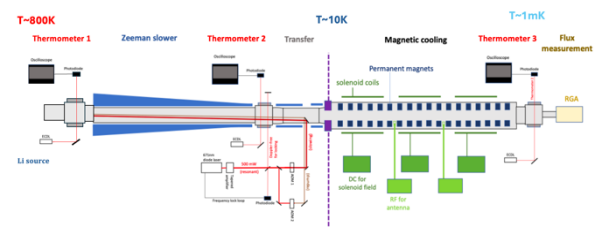
Low frequency TWPA



Parallel Plate Nb trilayer process
0.9 GHz Uniform TWPA

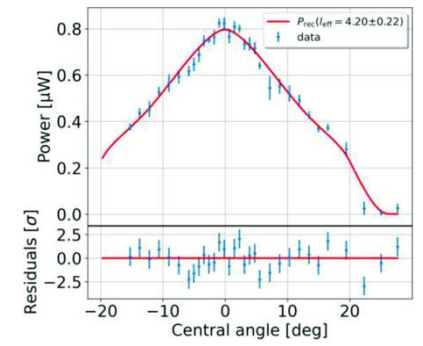
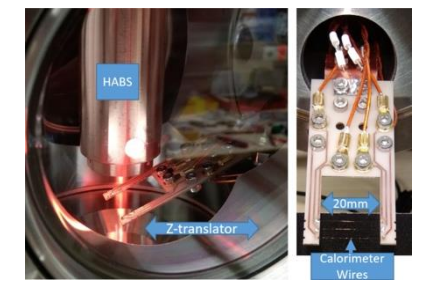
W. Van de Pontseele, J. Wang, C. Denney

Lithium MECB demonstrator



A. Negi, B. Jones

Calorimetric wire detector for atomic beam measurement



C. Matthé
Project 8 Experiment, Eur. Phys. J. (2025)

The path to 0.04 eV sensitivity

Phase I
First demonstration of CRES

Project 8 Collaboration, Phys. Rev. Lett. (2015)

Phase II
First CRES-based neutrino mass measurement

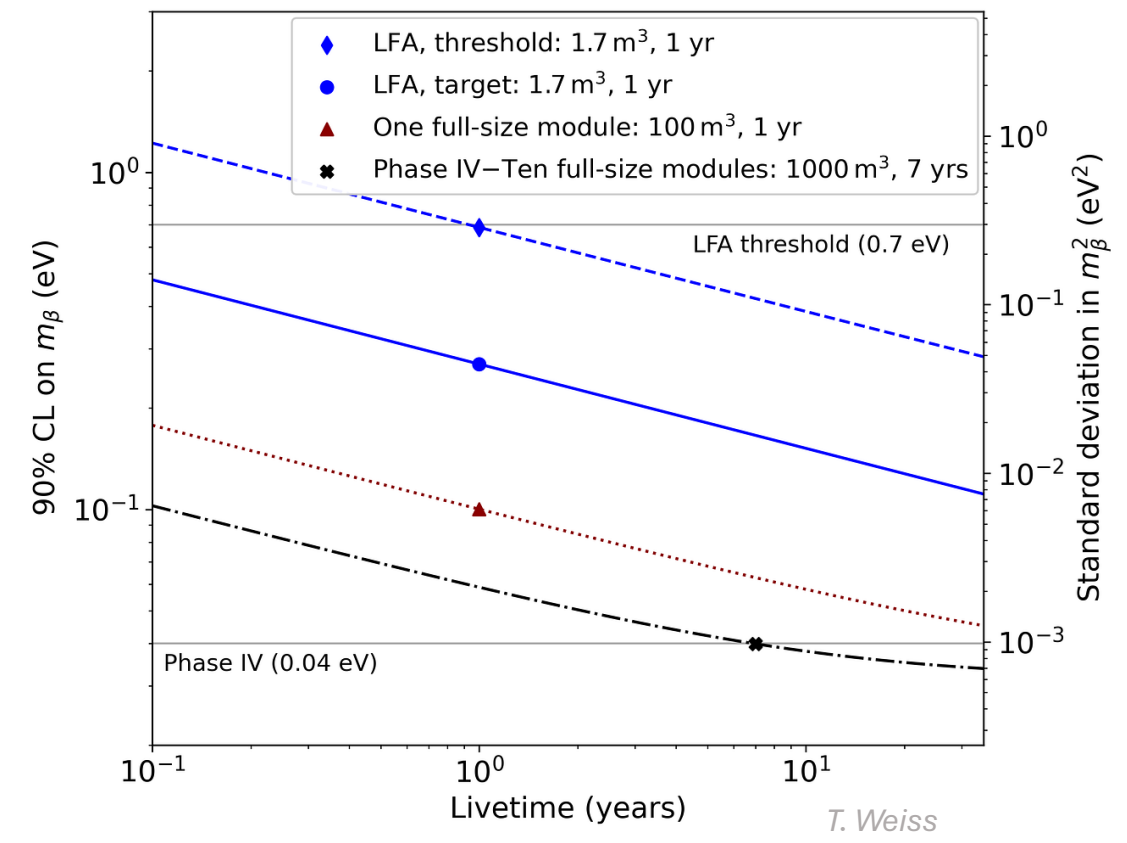
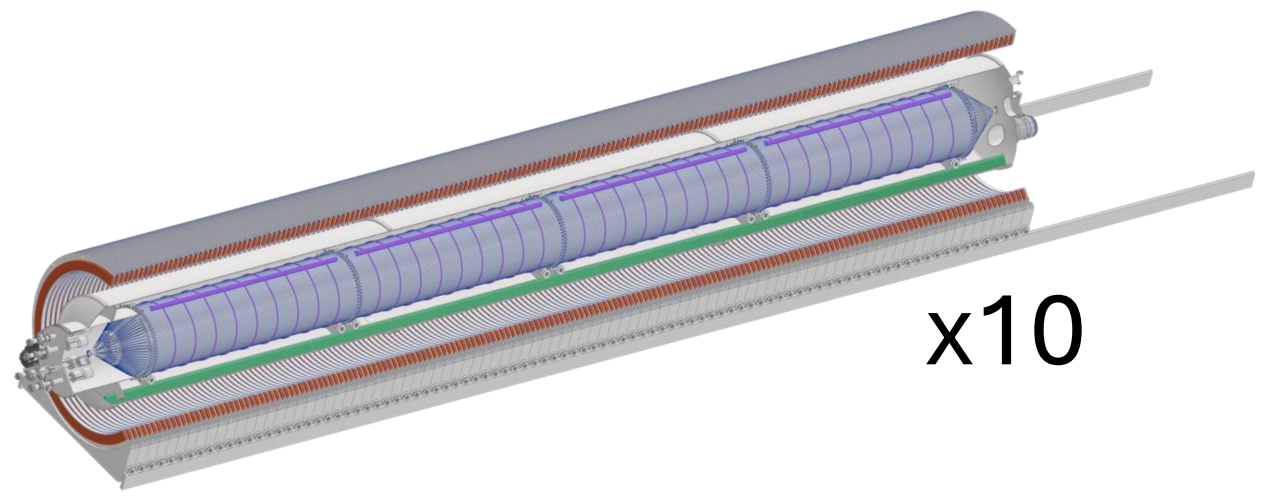
Project 8 Collaboration, Phys. Rev. Lett. (2023)
Project 8 Collaboration, Phys. Rev. C (2024)

Phase III
Technology development to achieve final sensitivity
Neutrino mass sensitivity comparable to KATRIN

Phase IV
0.04 eV neutrino mass sensitivity

Achieving 0.04 eV sensitivity

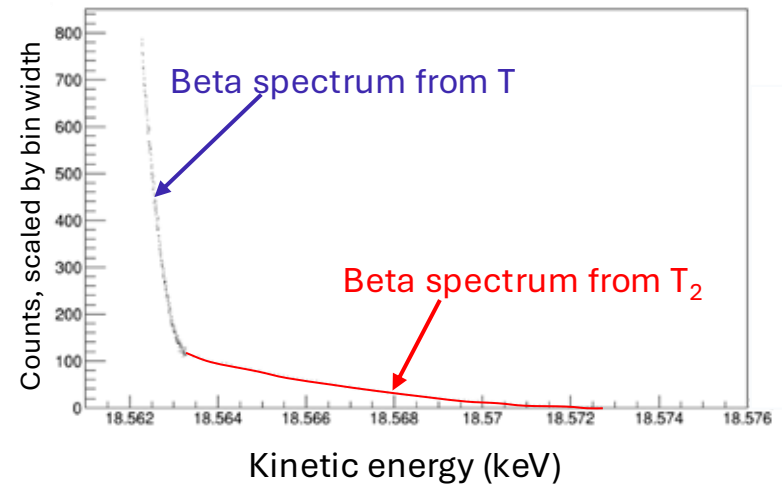
- Lower frequency and larger volume than the LFA



Backgrounds and systematics for current and future experiments

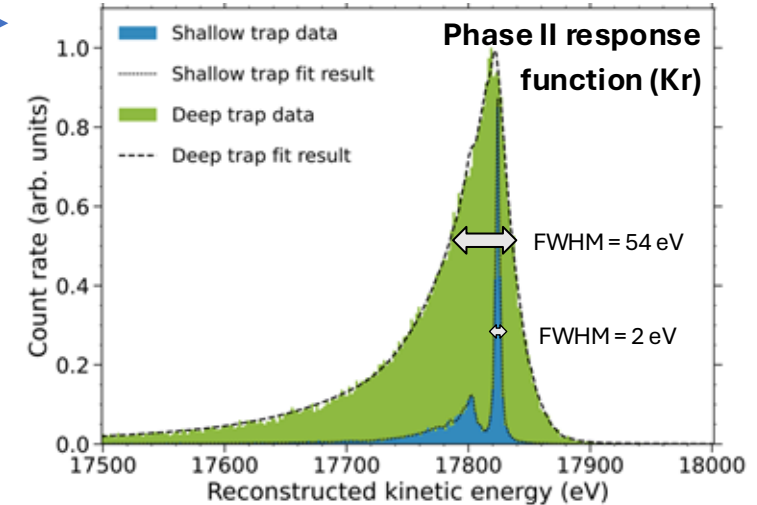
Contributions to background *b*

- False events from noise
 - Tradeoff between noise rate and detection efficiency depends on SNR
- Cosmic ray interactions with T
- Source purity
 - Must keep $N(T_2)/N(T)$ below 10^{-4}



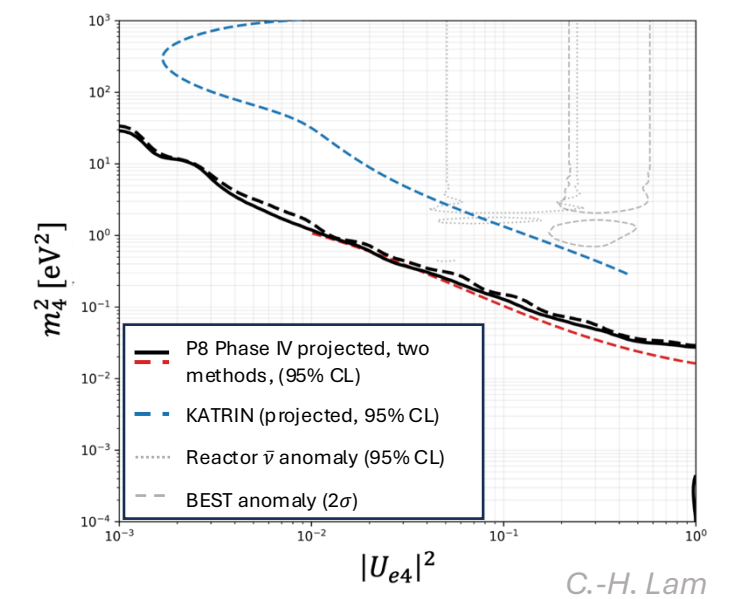
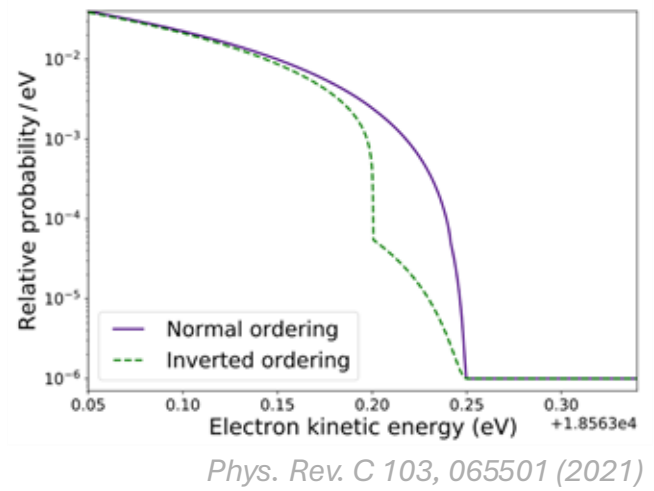
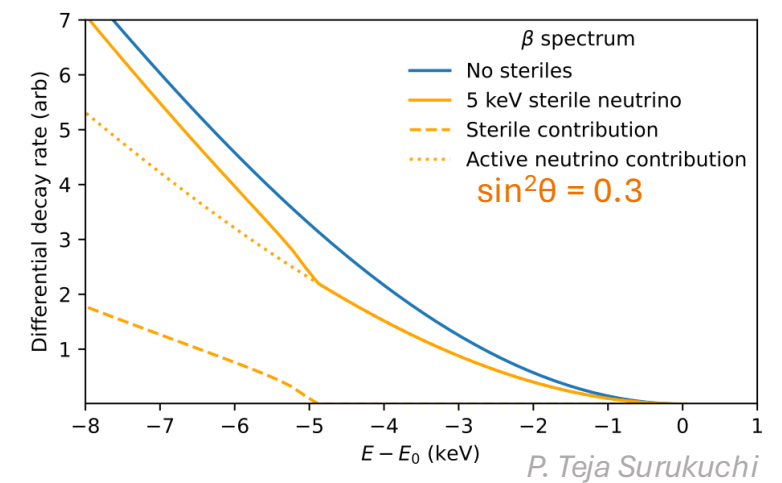
Contributions to response function (energy resolution) σ_i

- Knowledge of magnetic field
 - Requires good calibration, good reconstruction, good detector response characterization
 - B-field uncertainty dominated in Phase II, will likely dominate in future phases
- Thermal doppler broadening, scattering, plasma effects, pileup, ...



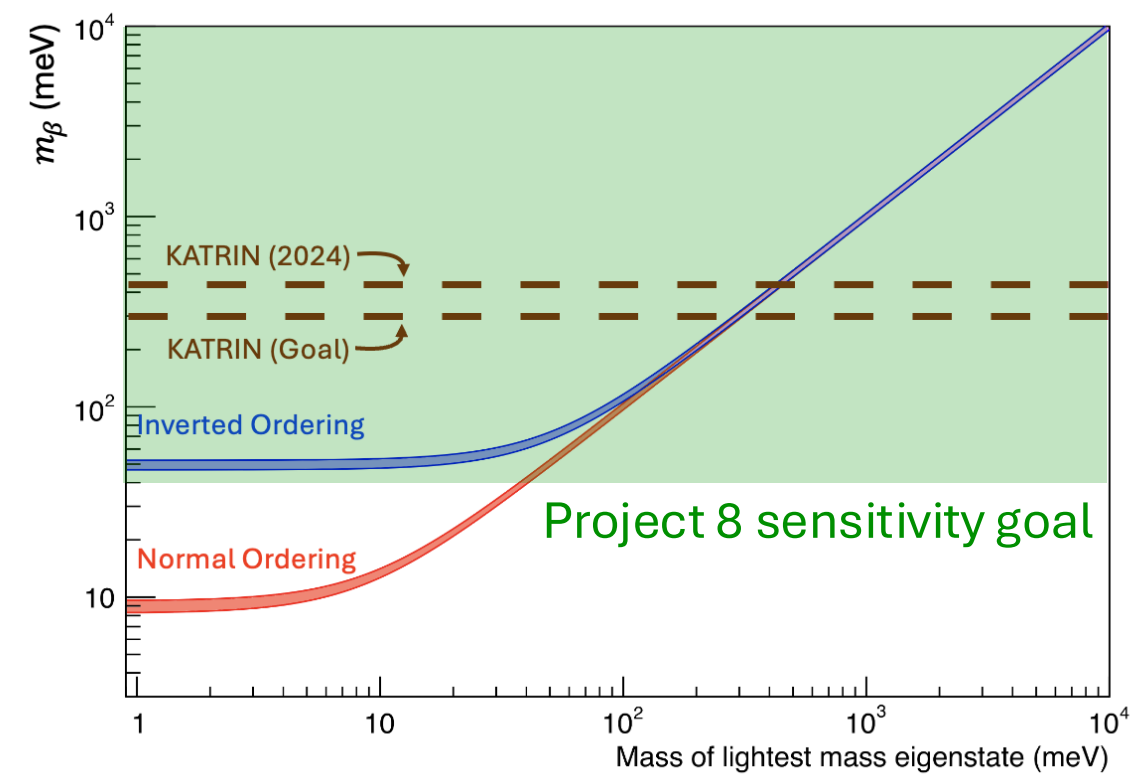
Sensitivity to secondary physics

- Simultaneous measurement of active neutrino mass and search for sterile neutrinos
- Sterile neutrino state causes a distortion (kink) in the tritium beta decay spectrum
- Plan to search for eV-scale sterile neutrinos
- Sensitivity to cosmic neutrino background; still under investigation
- Sensitivity to mass ordering



Summary

- Project 8 is developing CRES technique for next generation neutrino mass measurement
- Next prototype (CCA) will demonstrate high energy resolution and CRES in cavity geometry; commissioning underway now!
- Implementing a staged R&D approach in many areas, including cavity design, reconstruction, cold atomic tritium source, calibration, ...
- **Project 8 aims to achieve 40 meV sensitivity to the neutrino mass**

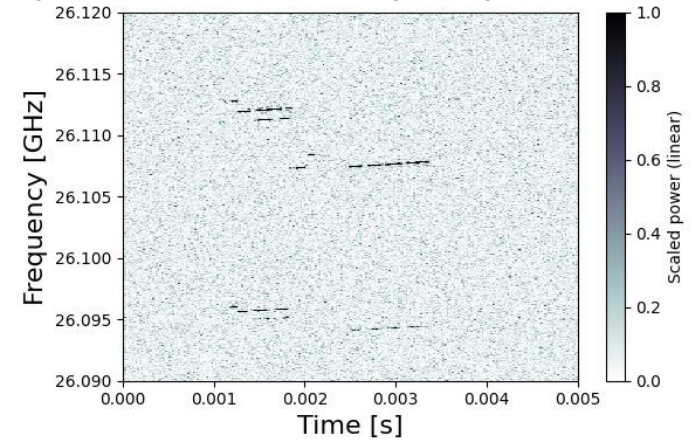


Backup

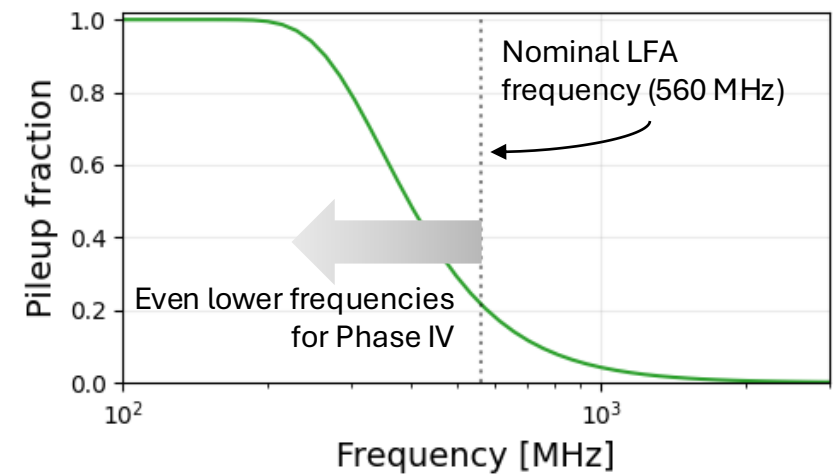
Signals in future stages will pose analysis challenges

- Pileup will increase as detection volume increases
- Signal power will decrease with large cavities
 - Expect ~aW power!
- Very high energy resolution required
- Justifies investigating creative reconstruction and analysis ideas!

Example simulation with pileup and scattering



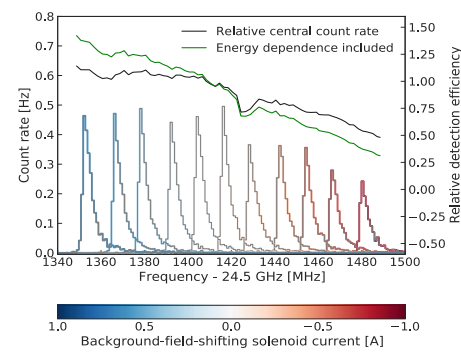
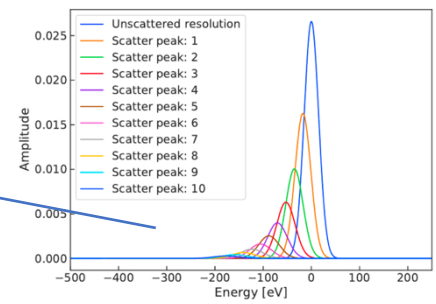
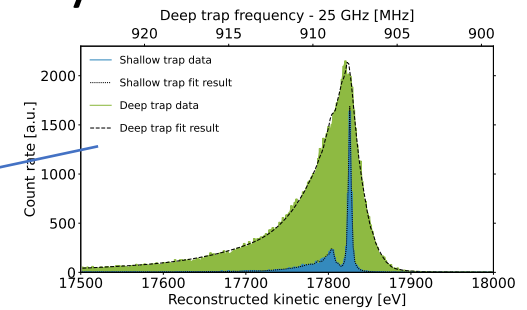
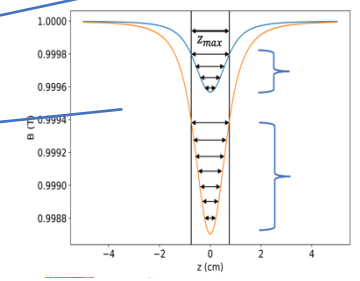
Fraction of the the time another event starts before scatter



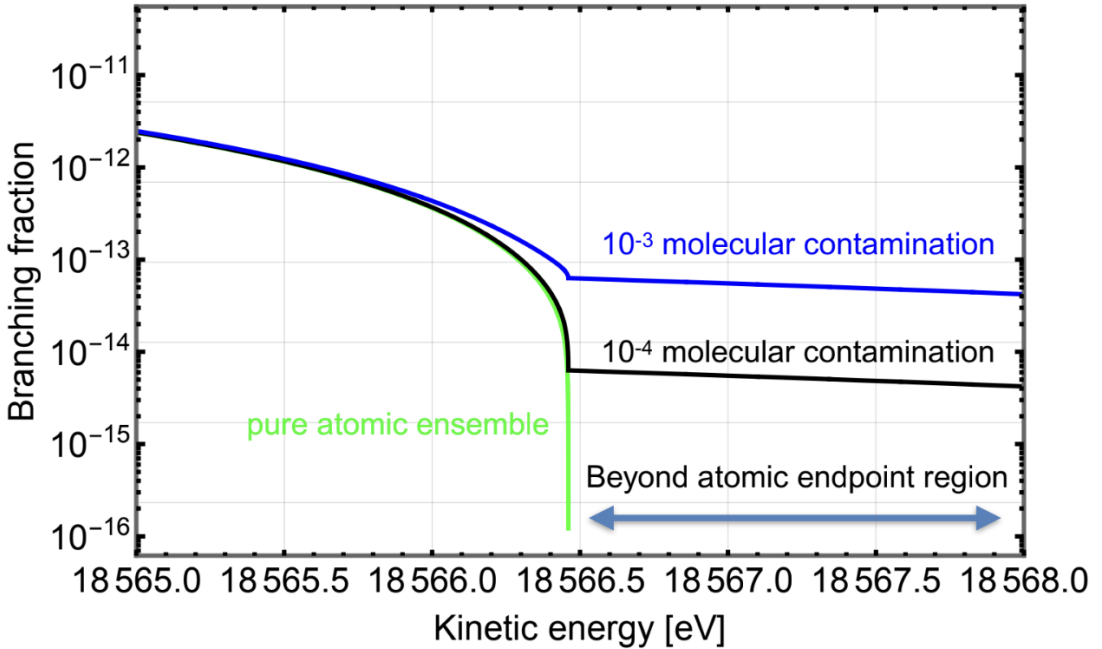
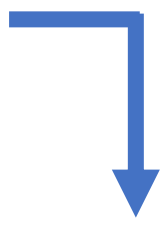
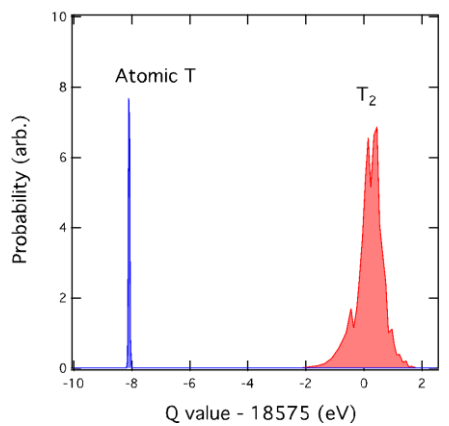
Phase II tritium results: uncertainties

- Statistics-limited; demonstrates understanding and control of systematics
- We have paths to improving all these sources of uncertainty

Uncertainty	$\sigma(E_0)$ [eV]
Magnetic field	4
Magnetic field broadening	4
Scattering	6
Efficiency variation	4
Other freq. dependence	6
Systematics total	9
Statistical	17



Requirements, Part 2

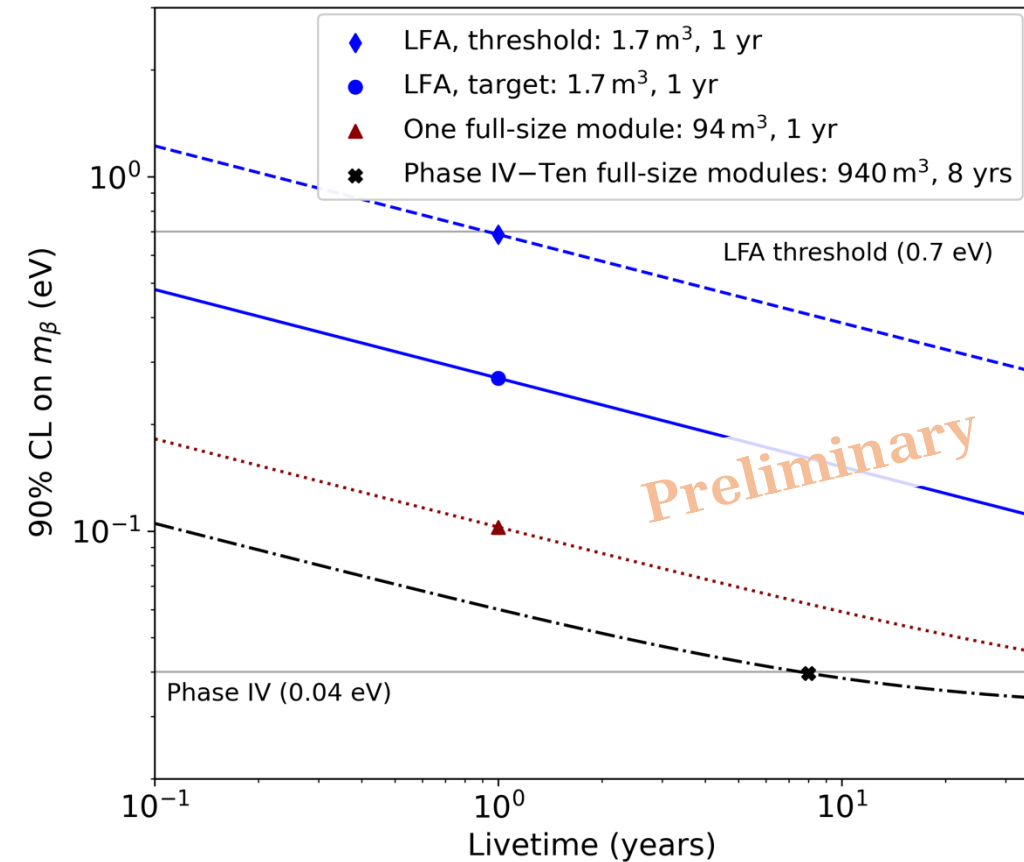


- T₂ contamination leads to events past the endpoint.
Need T₂ contamination <10⁻⁴ of T density
- Storage of large quantities of T in the beamline itself leads to a radioactivity load problem
Should pump out recombined T₂ gas from the beam to recirculate rather than freezing / storing on the walls
- Technical interventions in tritium system are very challenging
Must run without intervention for long periods with high reliability.

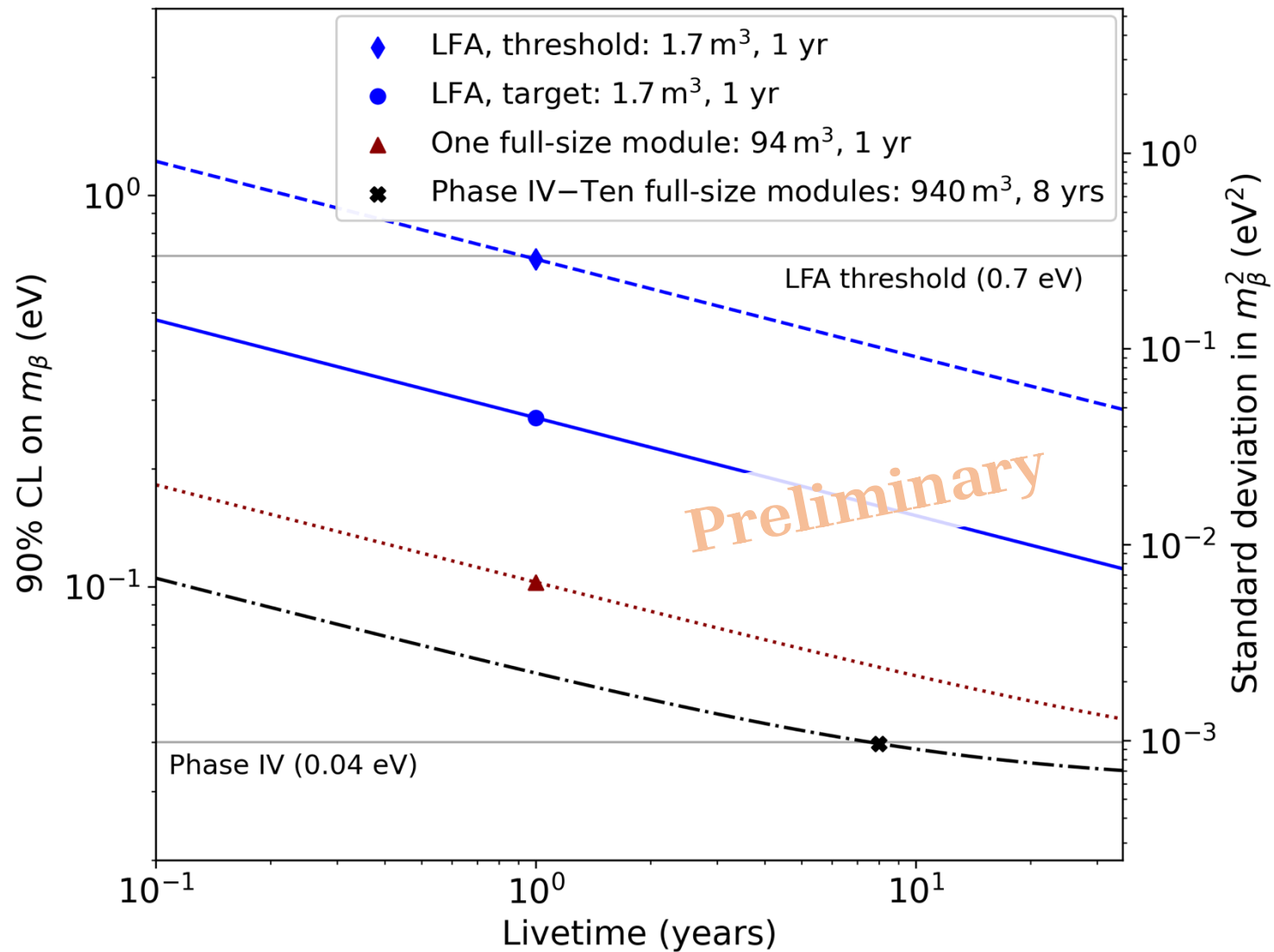


^ Glove boxes at TLK, from Magnus's talk

LFA neutrino mass sensitivity



Calculated Parameter	LFA Target	LFA Threshold
Limit on m_β, 90% CL	0.27 eV	0.69 eV
Operating tritium density in electron trap	$8.6 \times 10^{16} / \text{m}^3$	$1.0 \times 10^{16} / \text{m}^3$
Total background rate	$2.2 \times 10^{-10} / \text{eV/s}$	$3.2 \times 10^{-9} / \text{eV/s}$
SNR of 1 ms event ($\theta = 90^\circ$)	250	80
Total energy resolution, stdev.	86 meV	300 meV
From $\sigma_f^{\text{carrier}}$ and $\sigma_f^{\text{sideband}}$ due to noise	11 meV	
From field variation and reconstruction	85 meV	
From thermal Doppler effect	1.5 meV	
Total efficiency	0.029	0.011
Trapping efficiency	0.049	
Detection efficiency	0.76	
Efficiency from limits on useful radii	0.76	



Example Phase IV scenario:

- 10 cavities with TE011 mode at 150 MHz
- Livetime = 8 yrs
- Background field = 5.5 mT
- Trap length = 17.5 m
- Cavity temperature = 2 K
- Resolution contribution from magnetic field variation and reconstruction = 85 meV