Pacific Northwest NATIONAL LABORATORY

PROJECT 8

First Neutrino Mass Limit from the Project 8 Experiment

August 30, 2023
XVIII TAUP
Vienna, Austria

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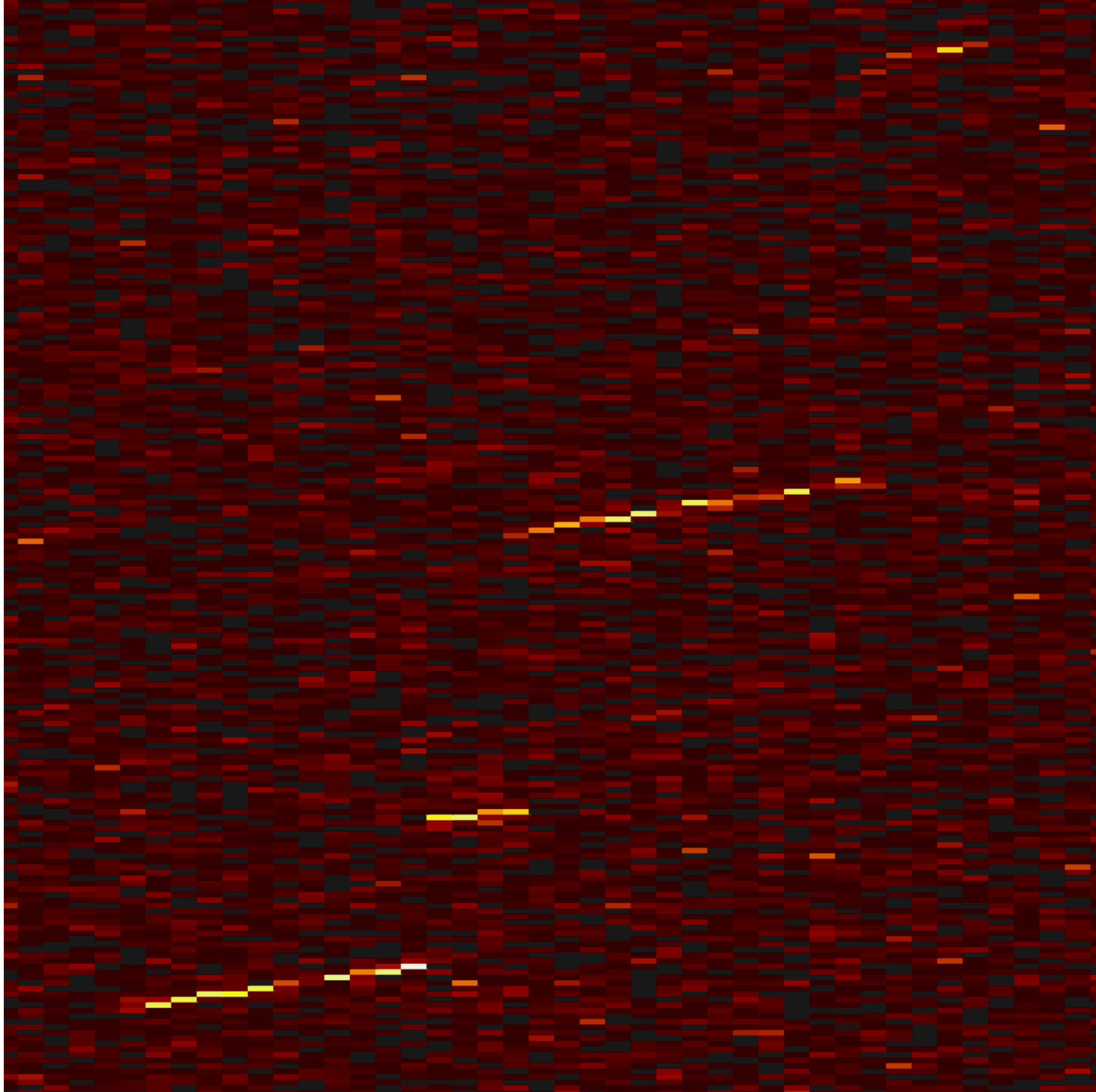
For the Project 8 Collaboration

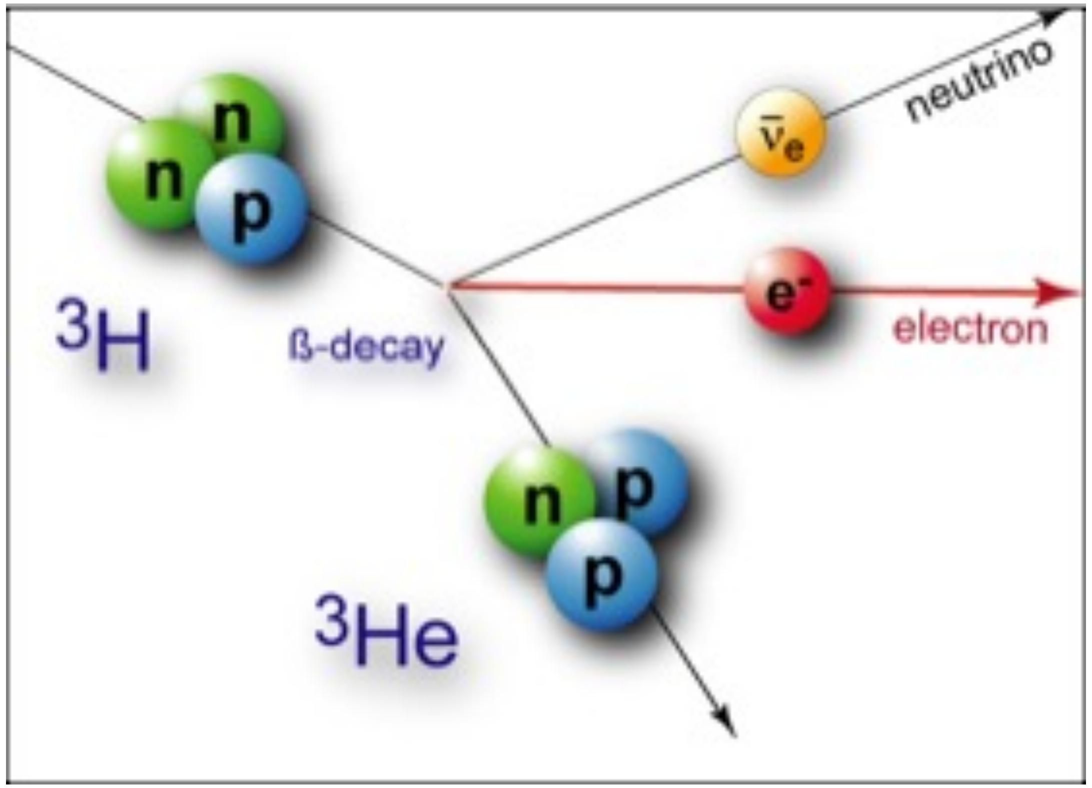
U.S. DEPARTMENT OF ENERGY BATTELLE

PNNL is operated by Battelle for the U.S. Department of Energy



Measuring Neutrino Mass with Tritium Beta Decay

- We care about neutrino mass because we do not yet know the absolute neutrino mass scale
- Neutrino mass can be probed in a straightforward way with tritium beta decay
- We measure the kinetic energy of the beta decay electrons and extract m_β
- m_β is the electron-weighted incoherent sum of the neutrino mass states
- We measure the endpoint and the shape of the spectrum at the endpoint



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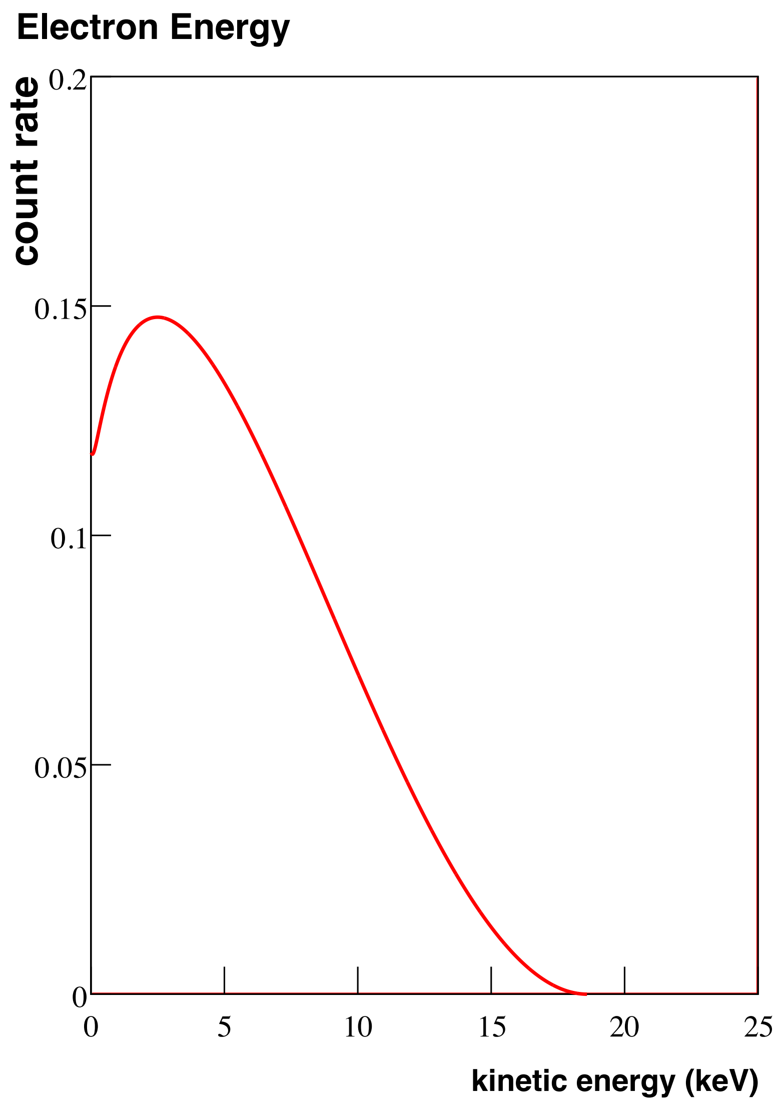

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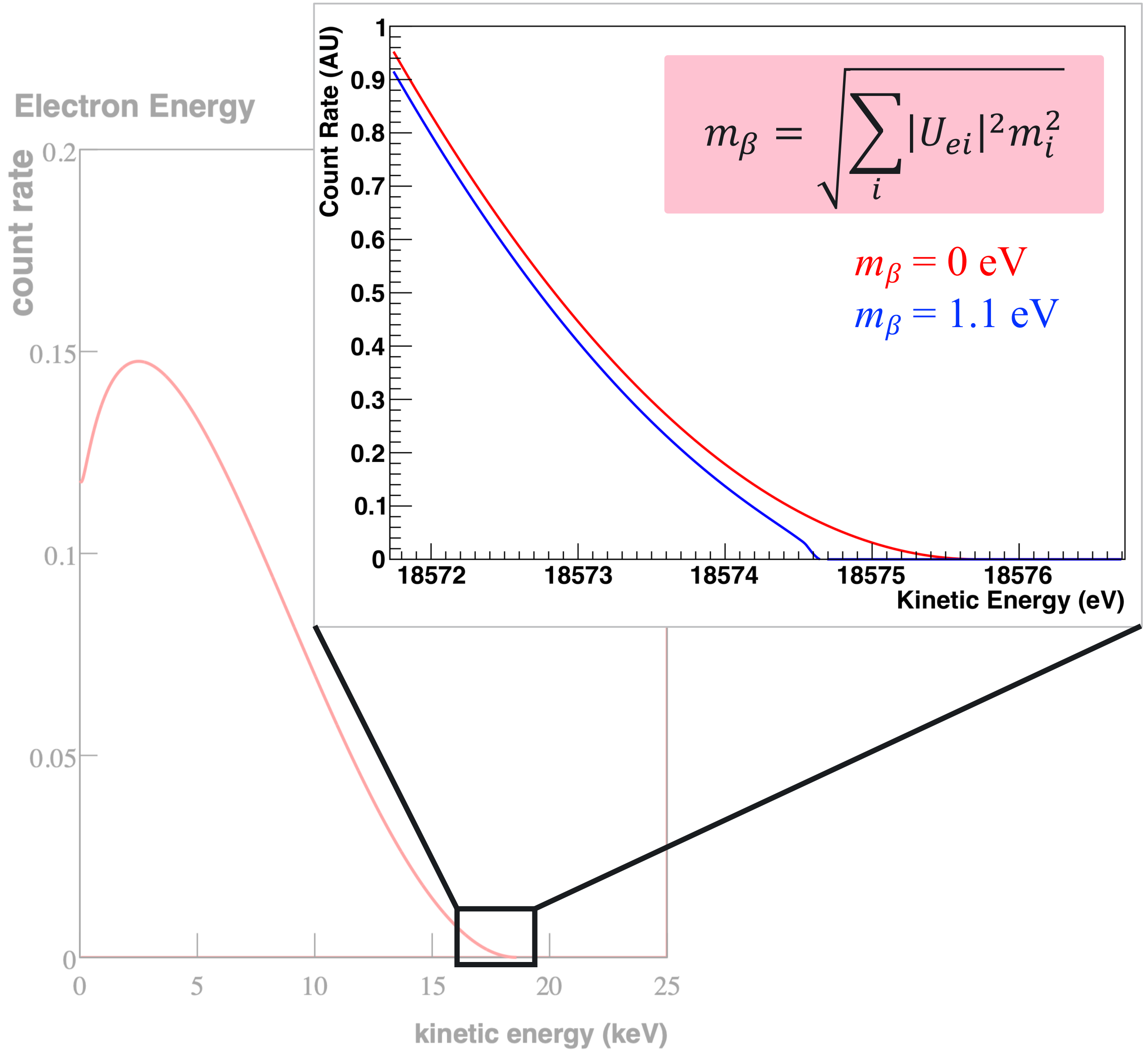
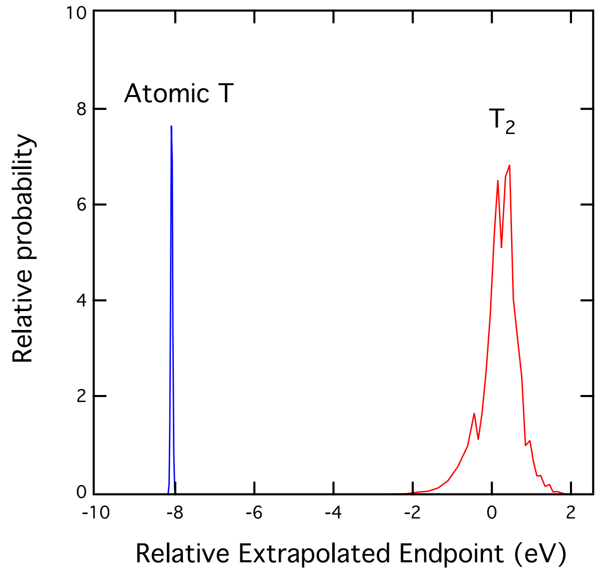


Challenges for Future Experiments

- The KATRIN experiment has the leading tritium beta decay measurement
  - Current limit is $m_\beta < 0.8$ eV
  - Projected sensitivity is $m_\beta < 0.2$ eV
- We can definitively rule out the inverted hierarchy with a sensitivity of 0.04 eV
  - Practical challenges make the needed scaling of the MAC-E filter technique impractical
- We need a new technique that:
  - Scales with volume
  - Has high precision
  - Is compatible with atomic tritium

KATRIN Main Spectrometer

Atomic T vs T_2 Energy Spread



A New Technique: Cyclotron Radiation Emission Spectroscopy

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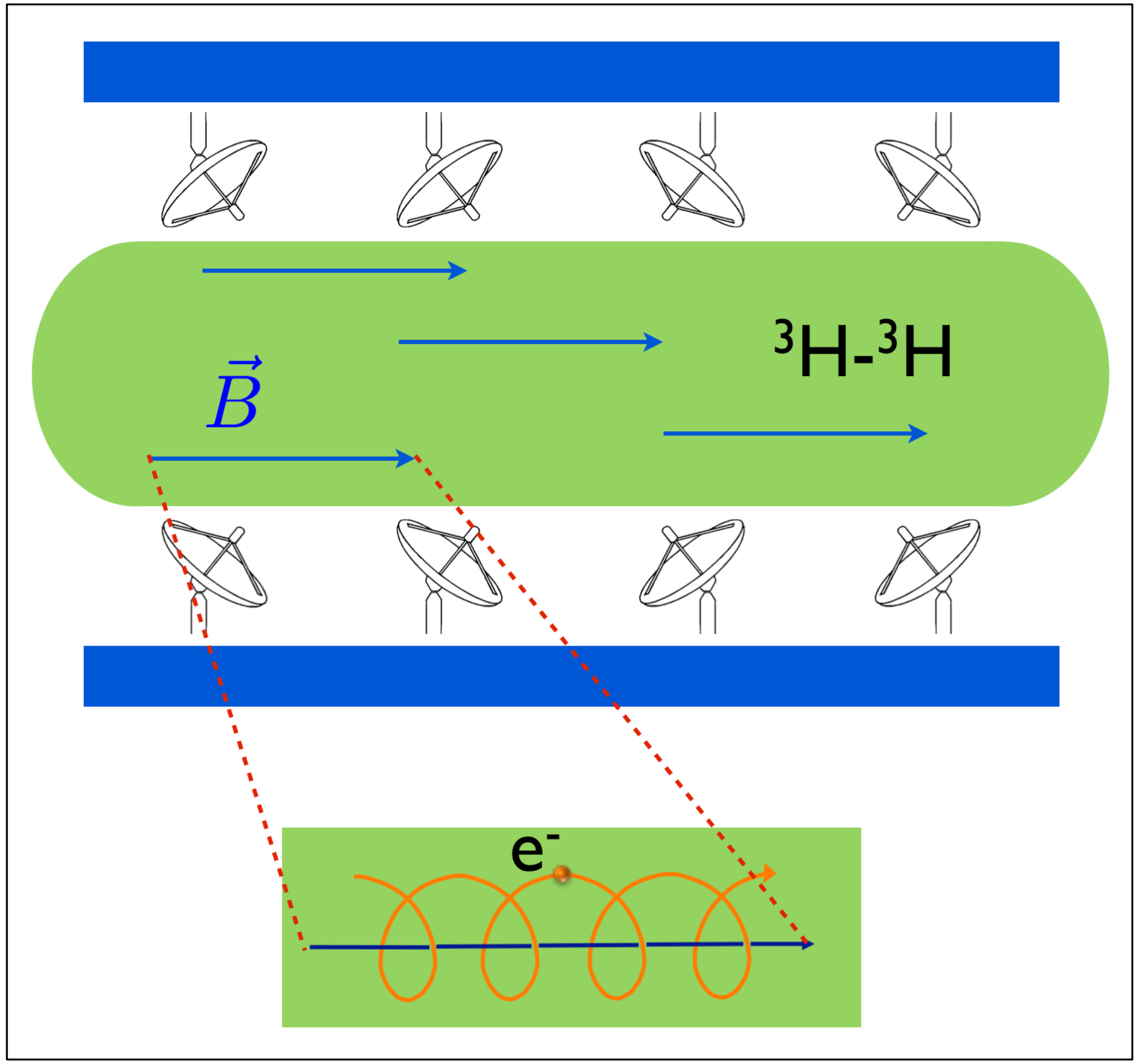
How to make a CRES measurement:

1. Place tritium in a magnetic field
2. Decay electrons emit cyclotron radiation
3. Precisely measure the frequency of the radiation to determine kinetic energy for each electron

$$\omega_\gamma = \frac{\omega_0}{\gamma} = \frac{eB}{K + m_e}$$



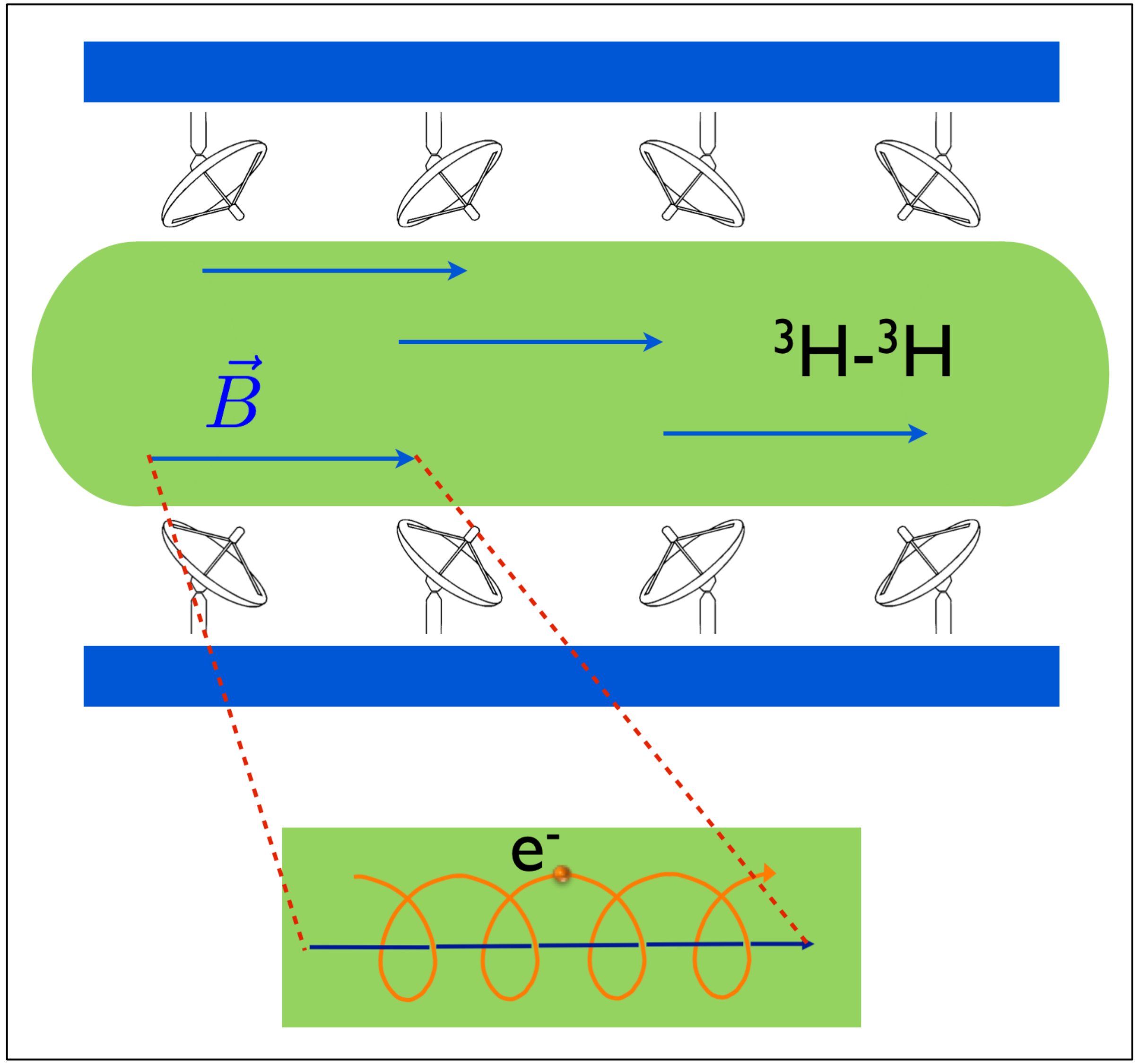
Concept: B. Monreal and J. Formaggio, Phys. Rev. D80 051301 (2009)

A New Technique: Cyclotron Radiation Emission Spectroscopy

CRES has several advantages:

- Scales with volume
- High precision from frequency measurement
- Works with a gaseous atomic tritium source
- Differential measurement for better statistics
- Potential for very low background

$$\omega_\gamma = \frac{\omega_0}{\gamma} = \frac{eB}{K + m_e}$$



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Demonstrating a New Spectroscopic Technique

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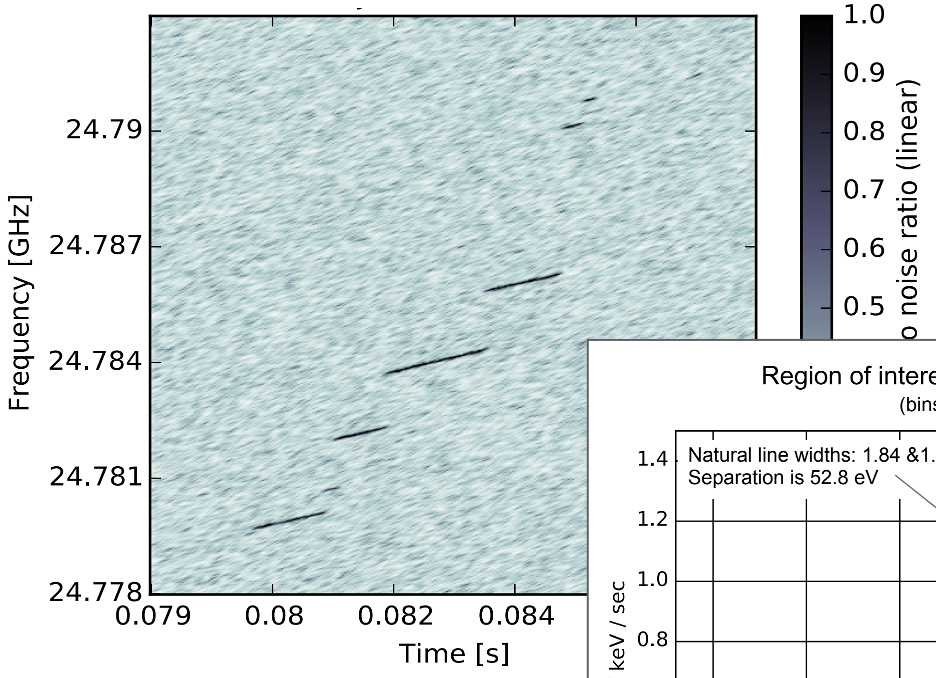
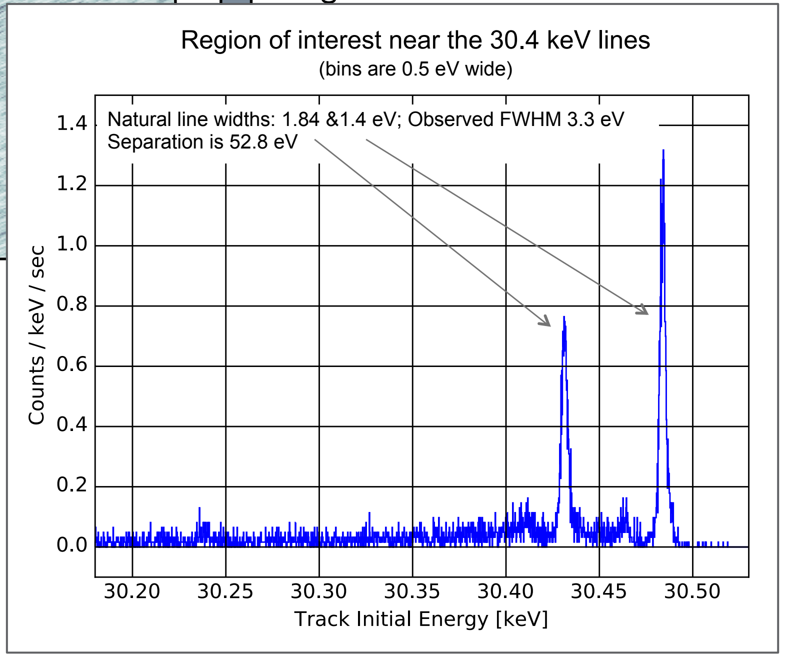
Phase I: First use of CRES for electron spectroscopy

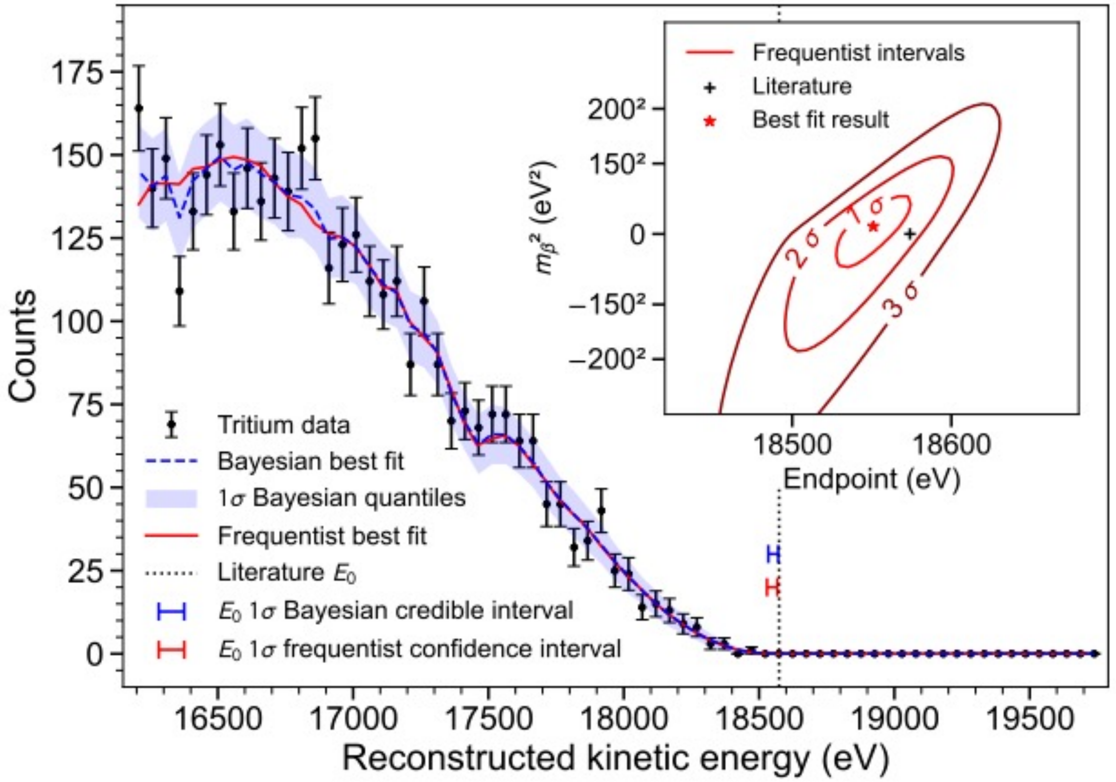


D. M. Asner, *et al.*, Phys. Rev. Lett. 114, 162501 (2015)



A. Ashtari Esfahani, *et al.*, J. Phys. G. 44, 5 (2017)

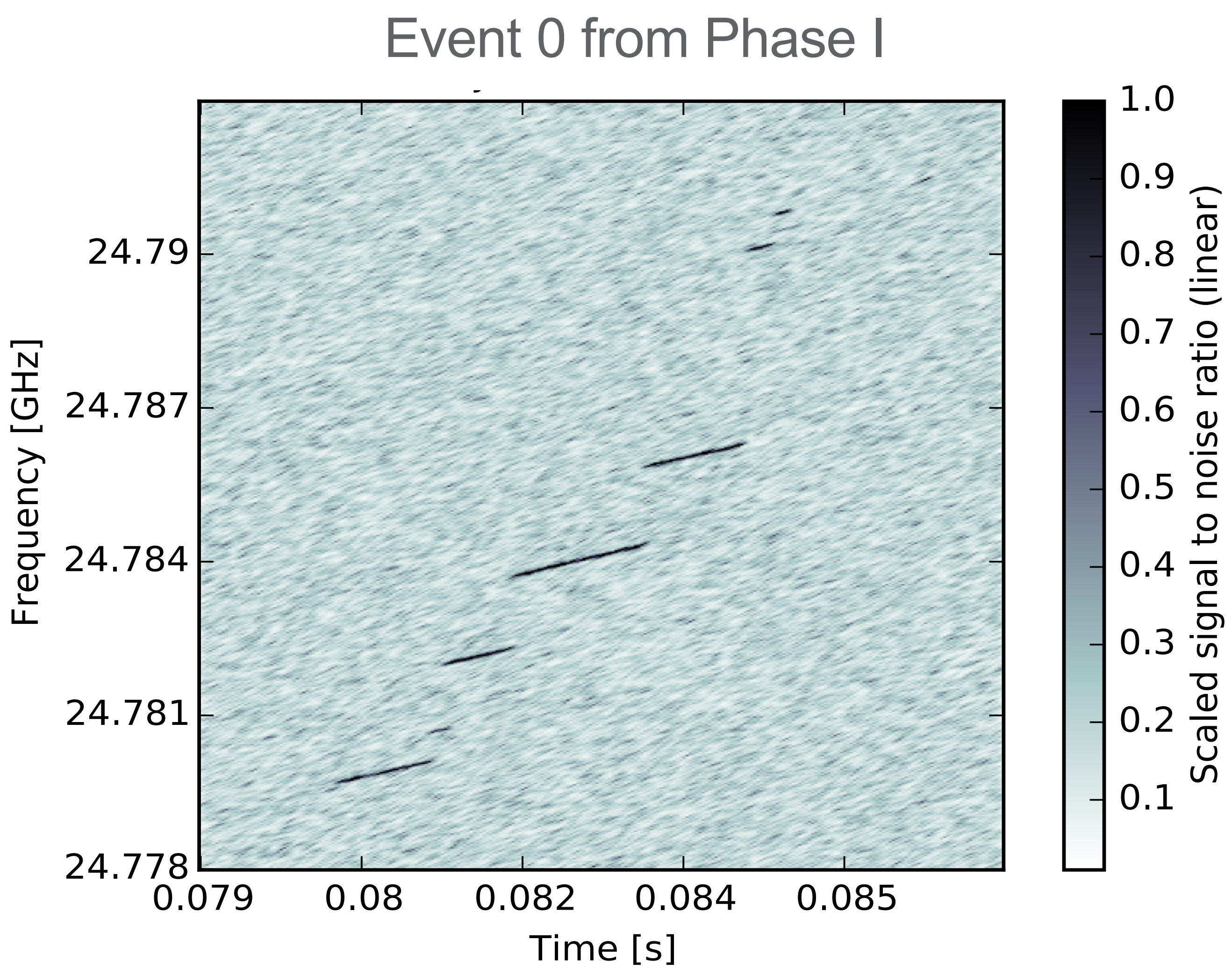
Phase II: First use of CRES for tritium spectroscopy and a neutrino-mass limit



A. Ashtari Esfahani, et al., Phys. Rev. Lett. (to be published)
arXiv 2212.05048

Electron Detection with CRES

- First electrons were detected in June 2014
- Energy lost to cyclotron radiation increases the frequency
- Jumps between "tracks" are consistent with electron scattering on residual gas molecules
- Initial frequency determines the energy of the electron at the decay



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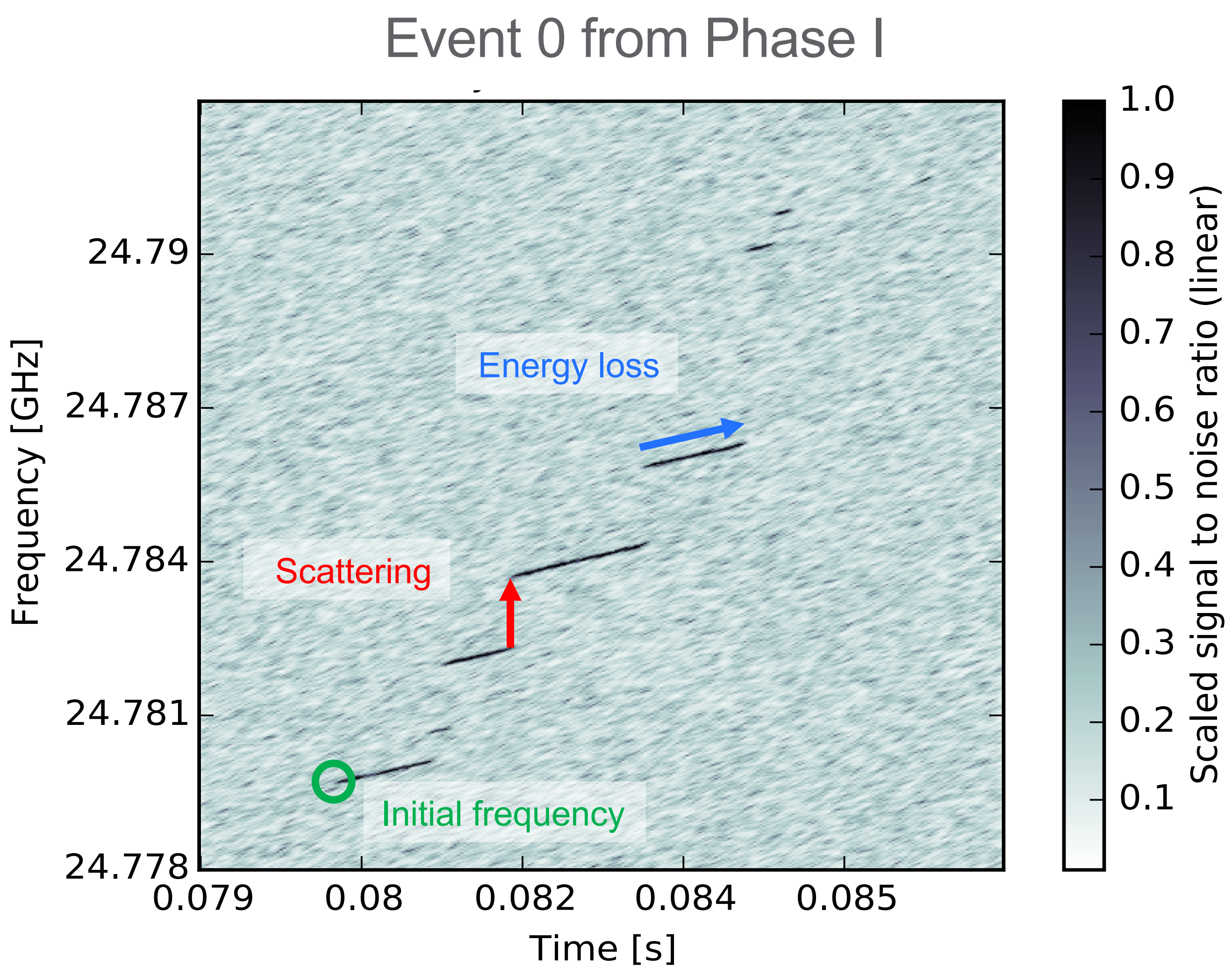
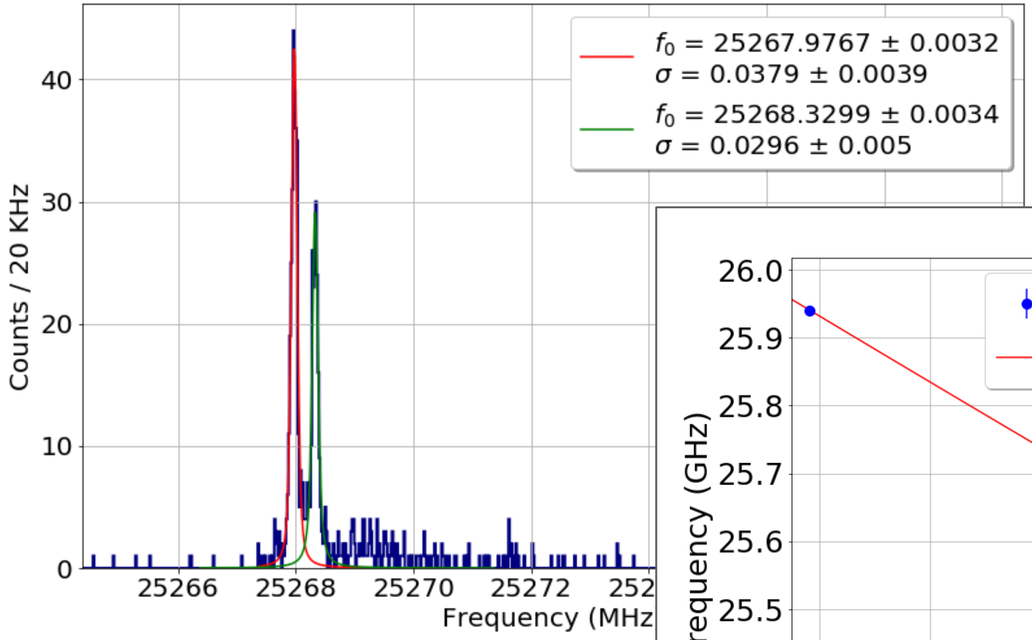
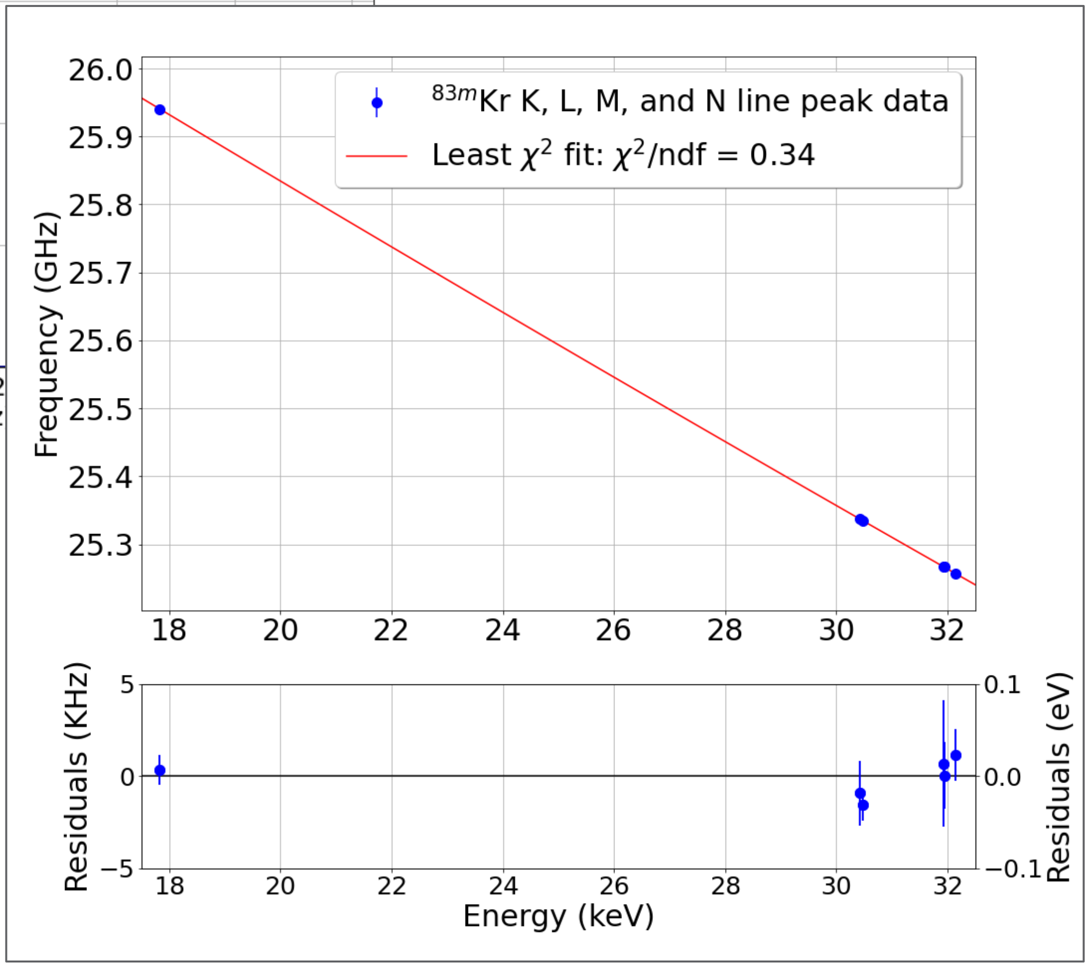


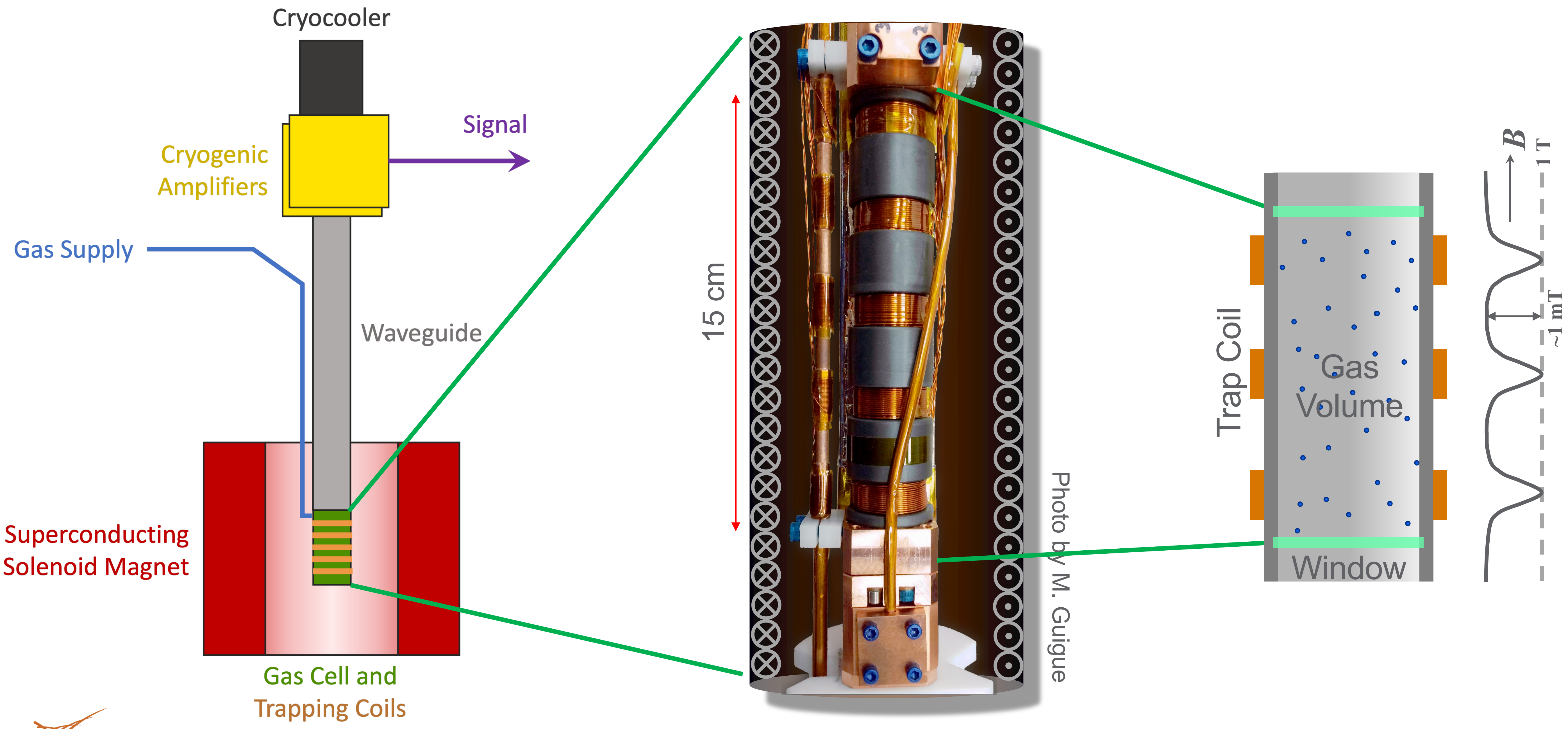
eV-Resolution Spectroscopy

- Demonstrated with ^{83m}Kr conversion-electrons
- 18-, 30-, and 32-keV electrons
- Narrow natural line widths highlight CRES resolution
- Remarkable linearity over the energy range of interest



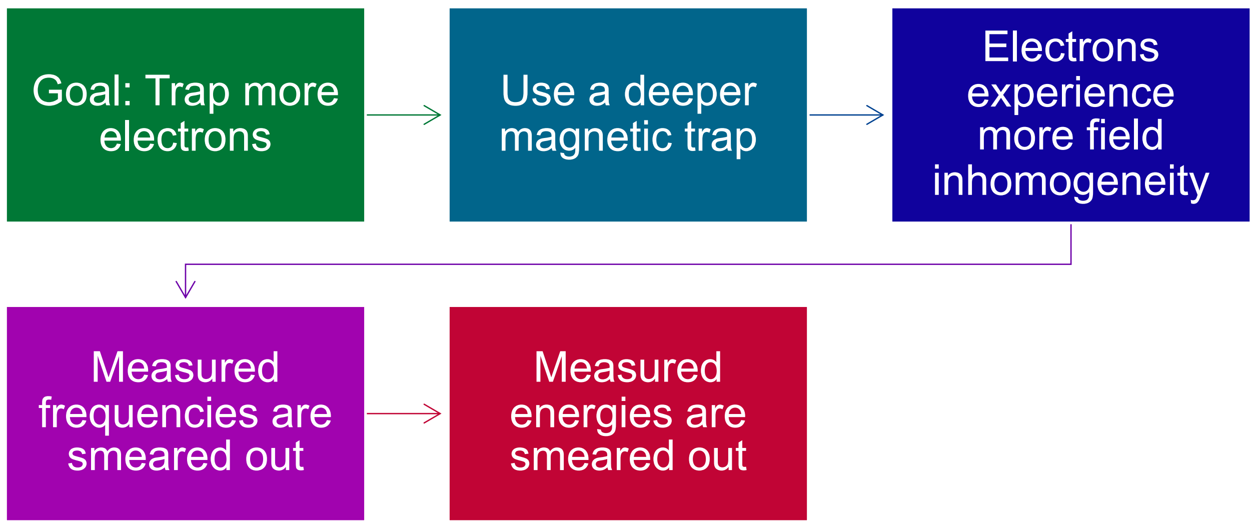


The Phase II Apparatus

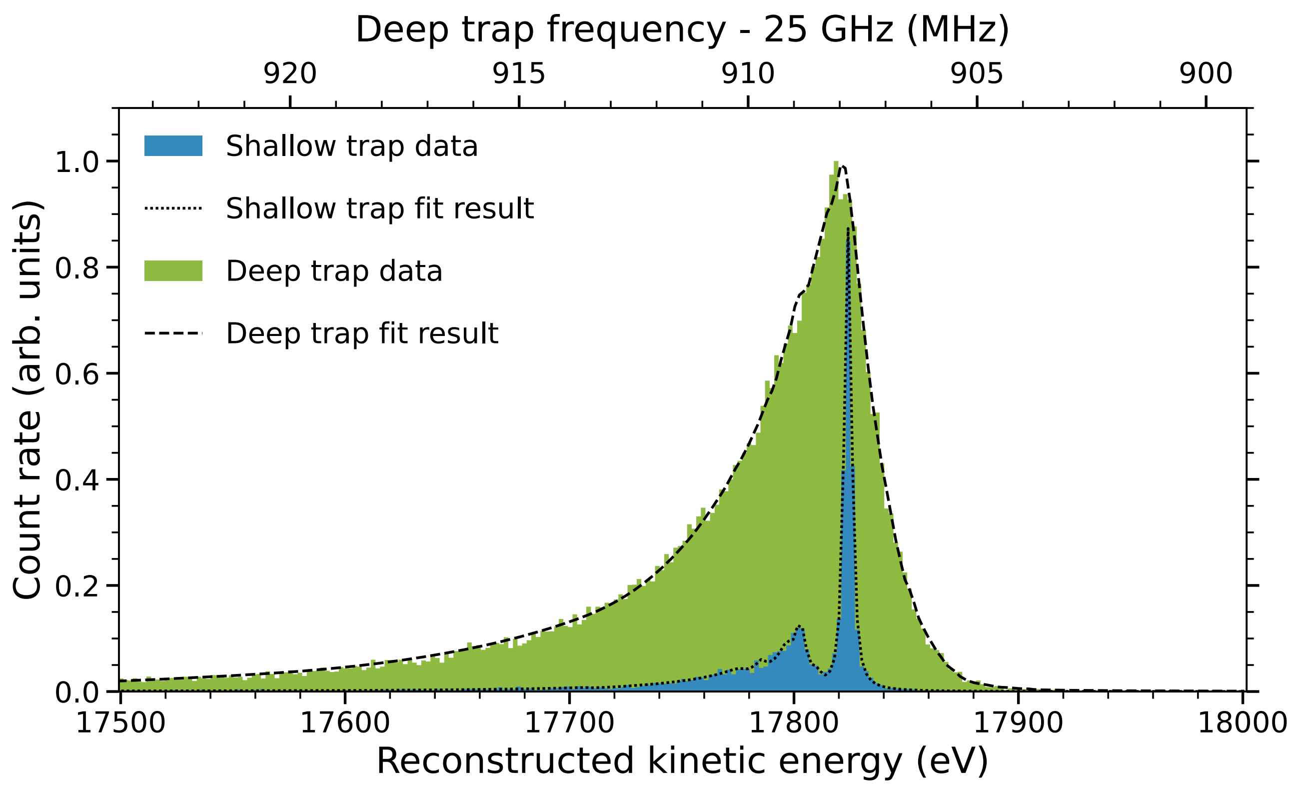


Trap Depth: Resolution vs Statistics

- In Phase II statistics and resolution are controlled by trap depth



- Tritium measurement: prioritize statistics
- ^{83m}Kr line measurements: prioritize resolution



Determining Detection Efficiency

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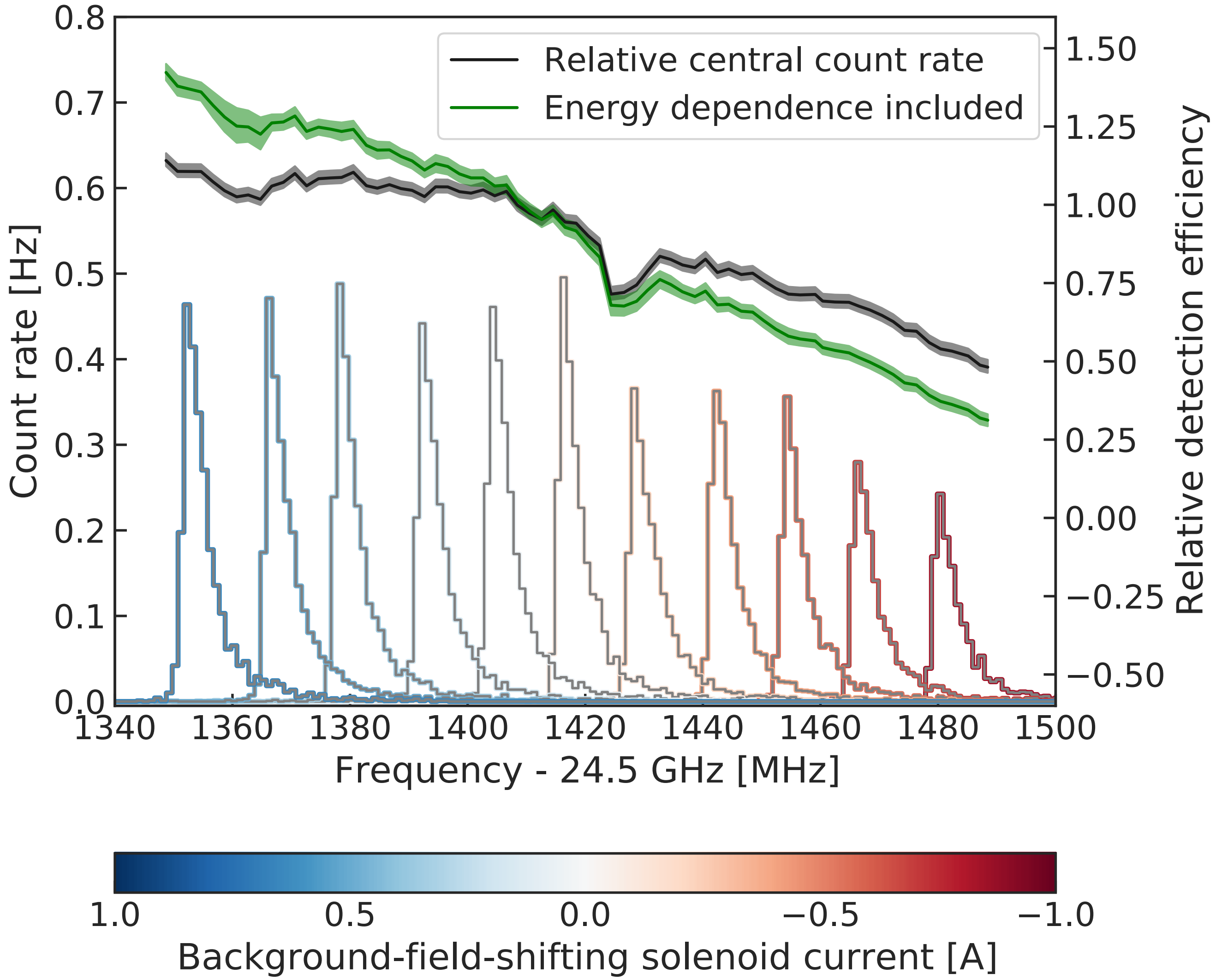
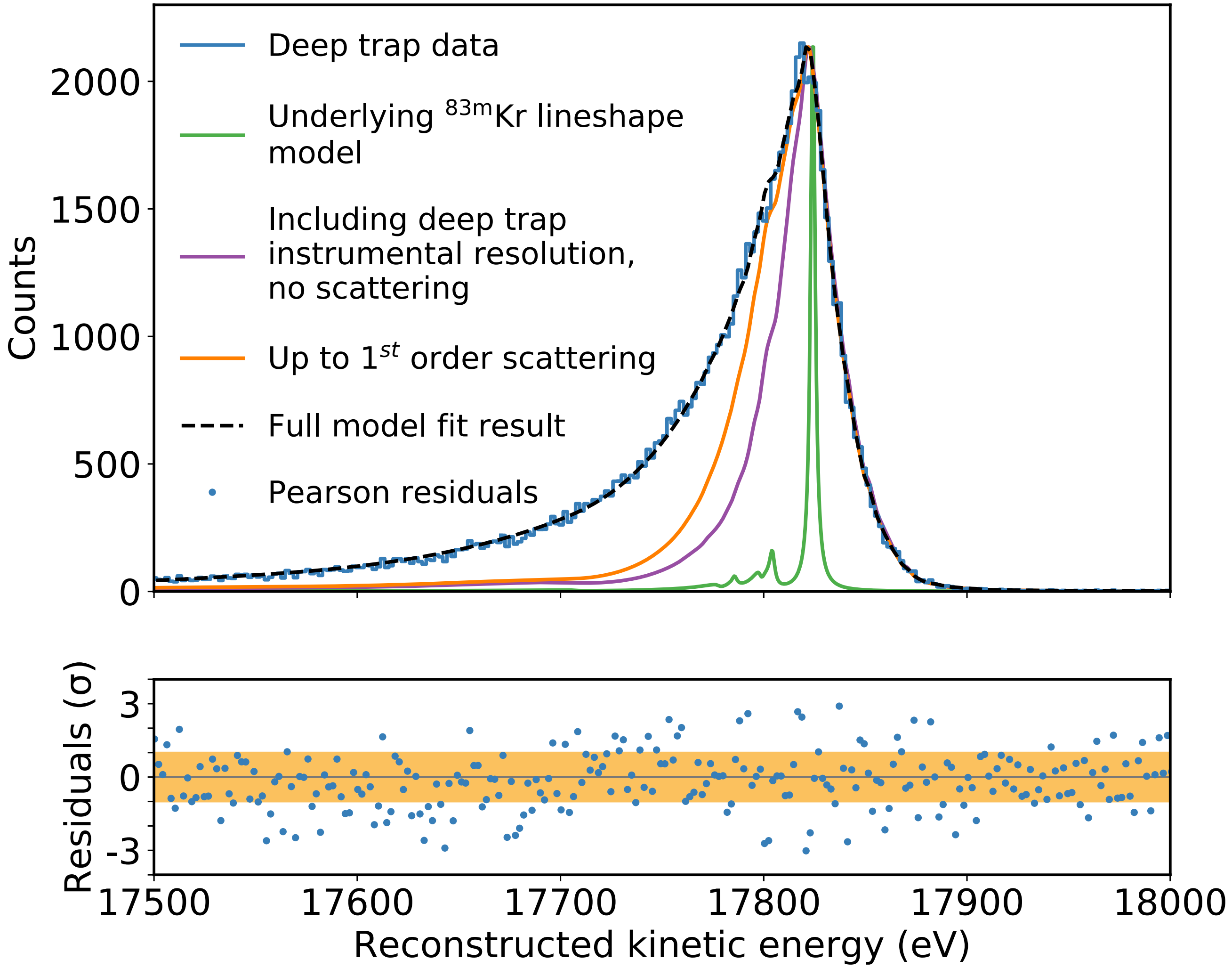
- Spectral shape depends on variation in detection efficiency with energy
- Mode structures in the cavity caused strong variations in the efficiency
- Variation with frequency was measured by detecting ^{83m}Kr K-line electrons while shifting the magnetic field
- Efficiency vs *frequency* must be corrected for SNR variations with *energy*
- SNR vs energy is determined with simulations and matching to calibration data



Measuring Detector Response

- Start with model for the underlying ^{83m}Kr lineshape
- Add instrumental resolution
  - Magnetic field inhomogeneity
- Add 1st-order scattering
  - Scattering + missed tracks
- Compare with calibration data
- Detector response is well understood



Final Phase II Tritium Spectrum Results

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- First tritium spectrum measurement with CRES
- Endpoint agrees with literature
- No background events above the endpoint

T_2 Endpoint

Bayesian: $E_0 = (18\,553^{+18}_{-19})$ eV

Frequentist: $E_0 = (18\,548^{+19}_{-19})$ eV

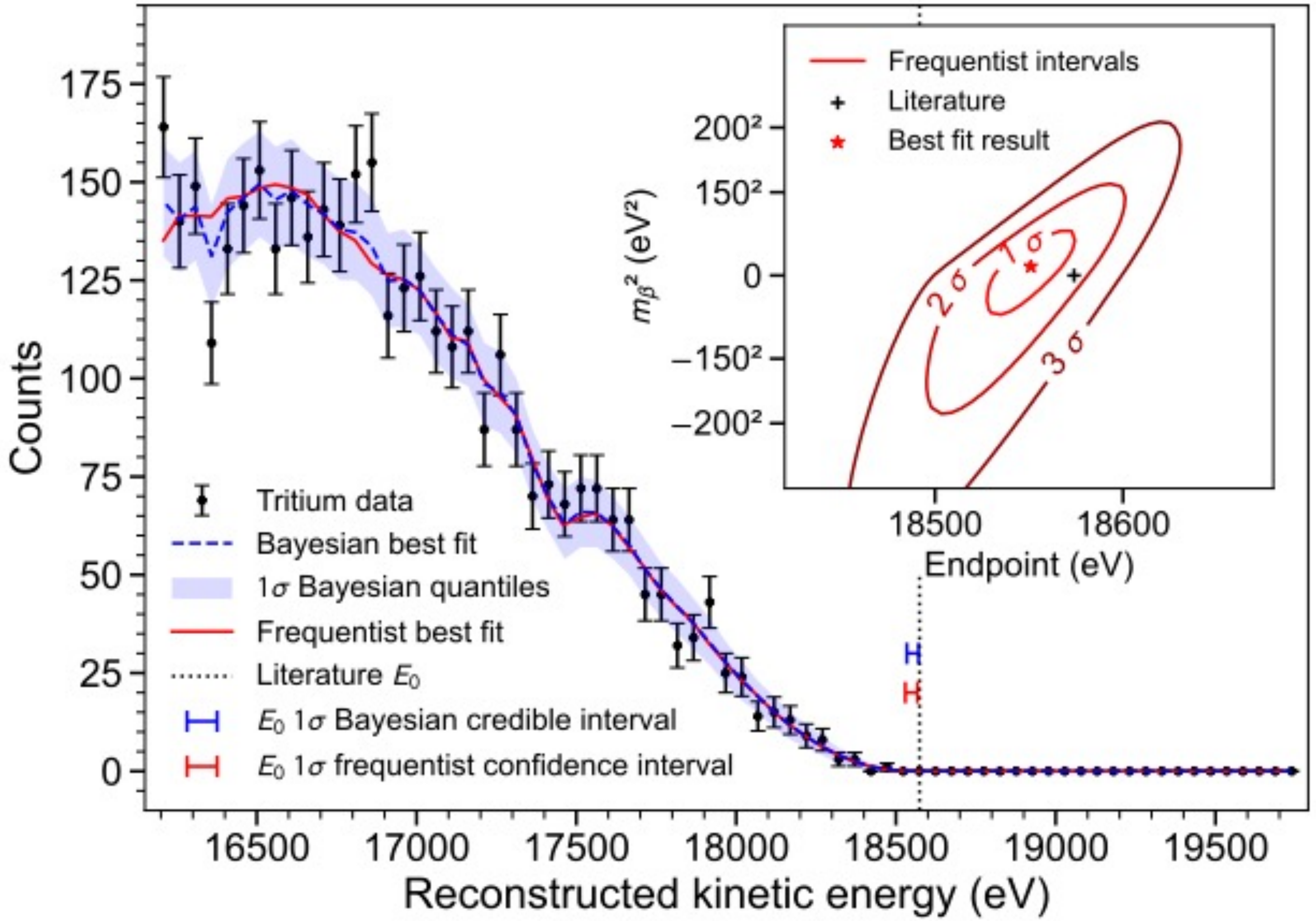
Neutrino Mass

Bayesian: $m_\beta < 155$ eV

Frequentist: $m_\beta < 152$ eV

Background rate

$< 3\times10^{-10}$ eV^{-1}s^{-1}



A. Ashtari Esfahani, *et al.*, Phys. Rev. Lett. (to be published)
arXiv 2212.05048

Evaluation of Uncertainties

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- We determined the effects of all uncertainties on the measurement of the tritium endpoint
- Systematics includes correlations
- Phase II was statistics limited

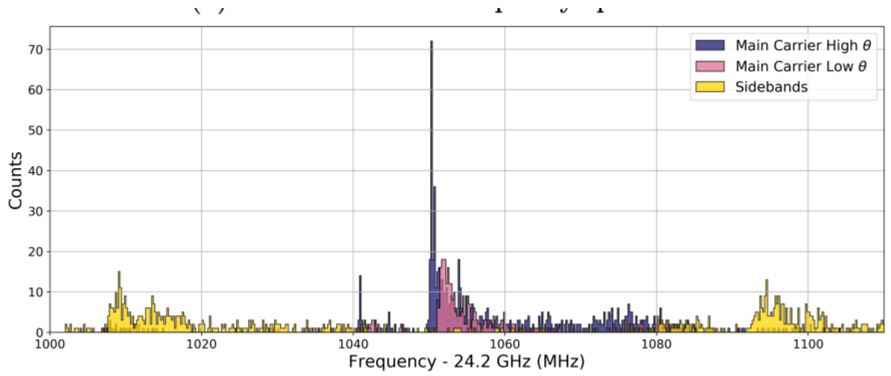
Source of Uncertainty	Contribution to Endpoint Uncertainty (eV)
Statistics	**±17**
Systematics	**±9**
Scattering	±6
Magnetic field broadening	±4
Instrumental resolution	±4
Frequency-dependence of the detector response	±6
Bin signal efficiencies	±4

Phase II References

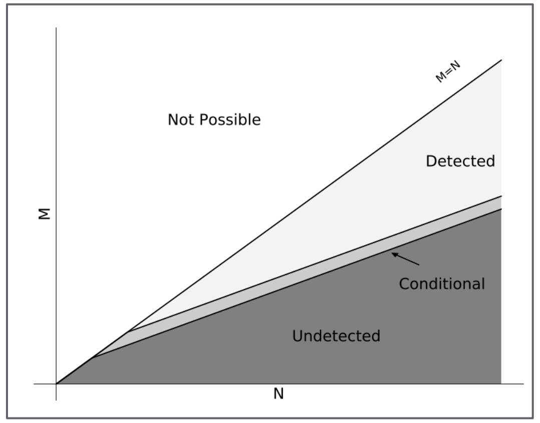
A. Ashtari Esfahani, *et al.*, Phys. Rev. Lett. (to be published) arXiv 2212.05048

A. Ashtari Esfahani, *et al.*, Phys. Rev. C (submitted) arXiv 2303.12055

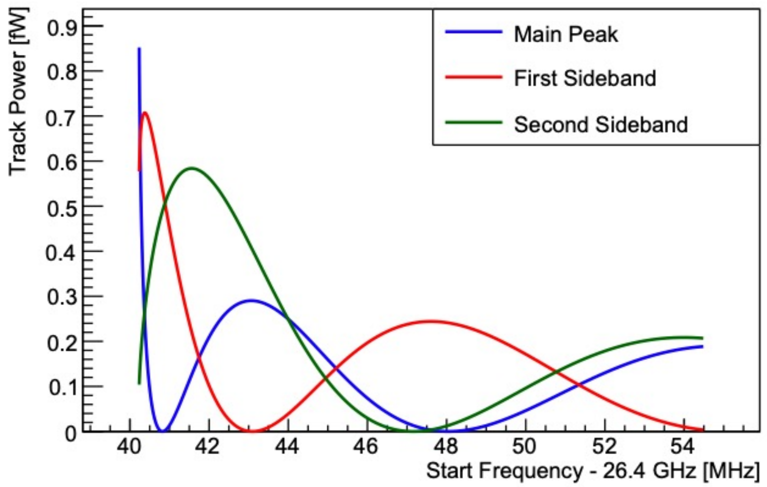
Other Phase II Accomplishments



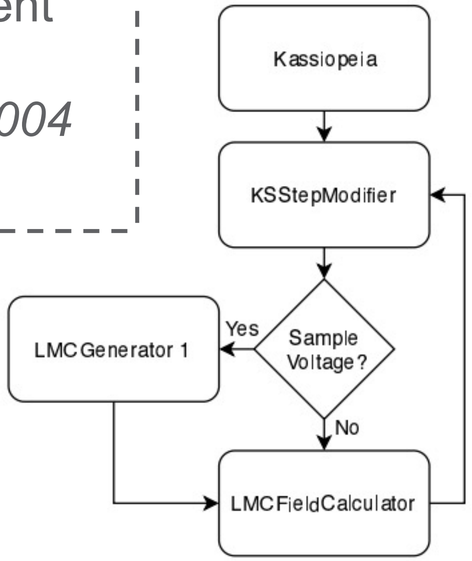
Classification of CRES signals with machine learning for improved event reconstruction
New J. of Phys., 22, 033004 (2020)



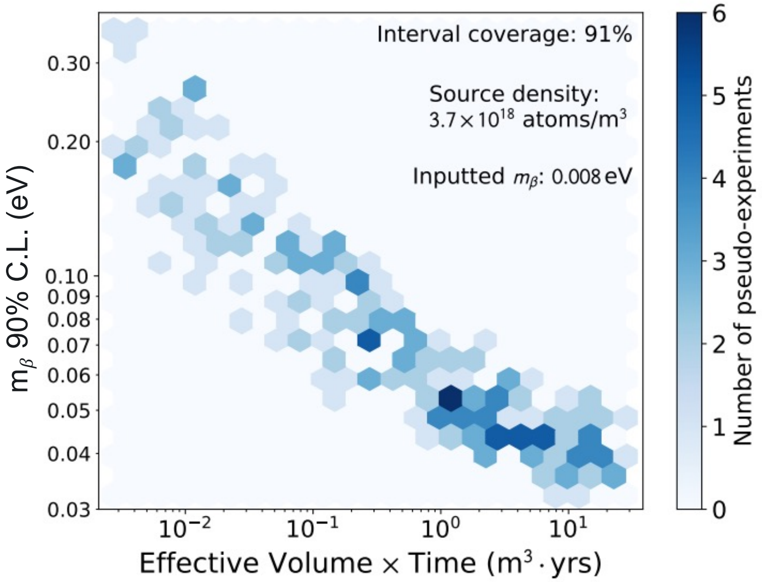
Use of information theory and the Viterbi algorithm to study the optimal detection of CRES signals
New J. Phys. 24, 053013 (2022)



Deep dive into the phenomenology of CRES events
Phys. Rev. C 99, 055501 (2019)



Custom software to accurately simulate CRES data
New J. Phys. 21, 113051 (2019)

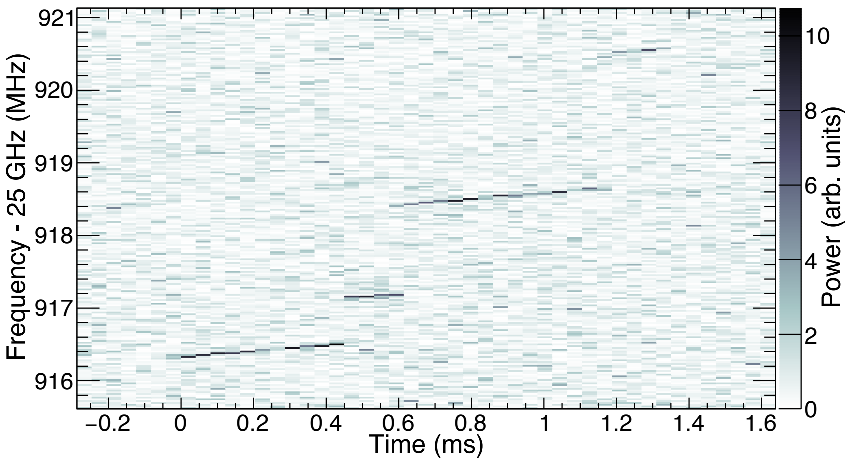


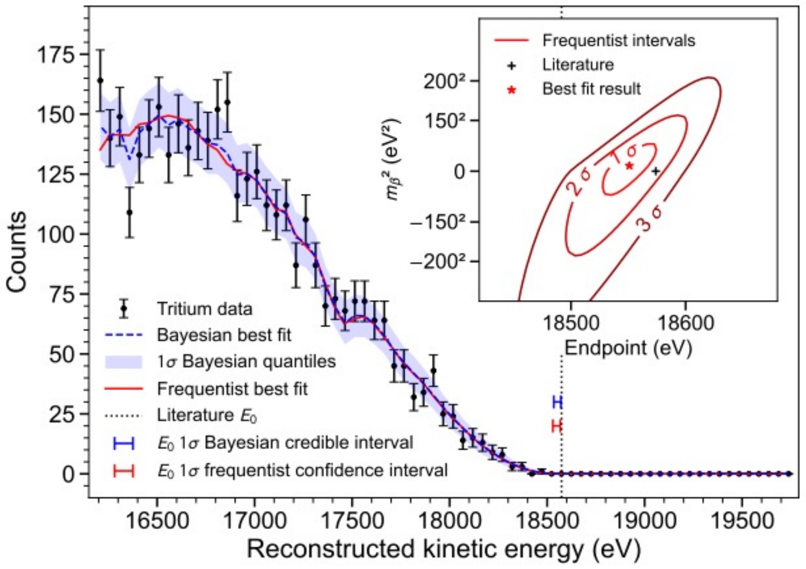
Using Bayesian inference to study the potential sensitivity of future CRES experiments to the neutrino mass
Phys. Rev. C 103, 065501 (2021)

Successful Demonstration of Tritium Spectroscopy with CRES

PROJECT 8

- Project 8 has demonstrated the use of CRES to place a limit on the neutrino mass
- Phase II showed the ability to control backgrounds, and quantitatively evaluate systematic uncertainties
- Project 8 is using the Phase II success to motivate and plan the path to the 40 meV experiment





More Project 8 at TAUP

Juliana Stachurska, CRES with Cavities in Phase III, August 29 at 5:30 pm

Larisa Thorne, Atomic Tritium for Phase III, August 30 at 3:15 pm

Project 8 Collaboration

Case Western Reserve University
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