PROJECT 8

UNIVERSITY of WASHINGTON

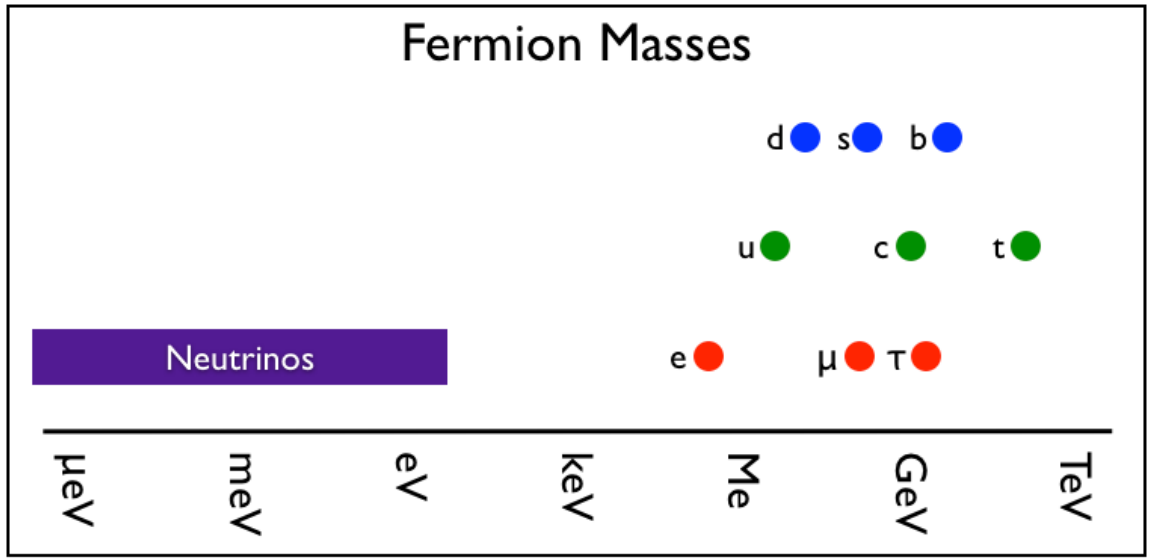
Cyclotron Radiation Emission Spectroscopy for measuring neutrino mass and searching for chirality-flipping interactions

Elise Novitski

5th International Workshop on the
Physics of Fundamental Symmetries and Interactions – PSI2019
October 24, 2019

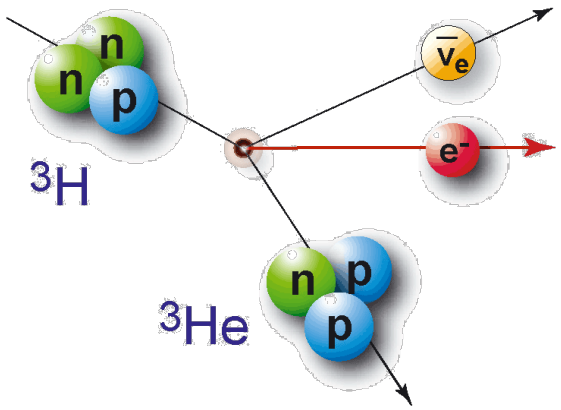
An extremely brief introduction to neutrino mass

- Neutrinos have mass
- The origins of neutrino mass are not yet understood
- The neutrinos' absolute mass scale and ordering are unknown
- Precision beta decay and electron capture experiments can make direct mass measurements

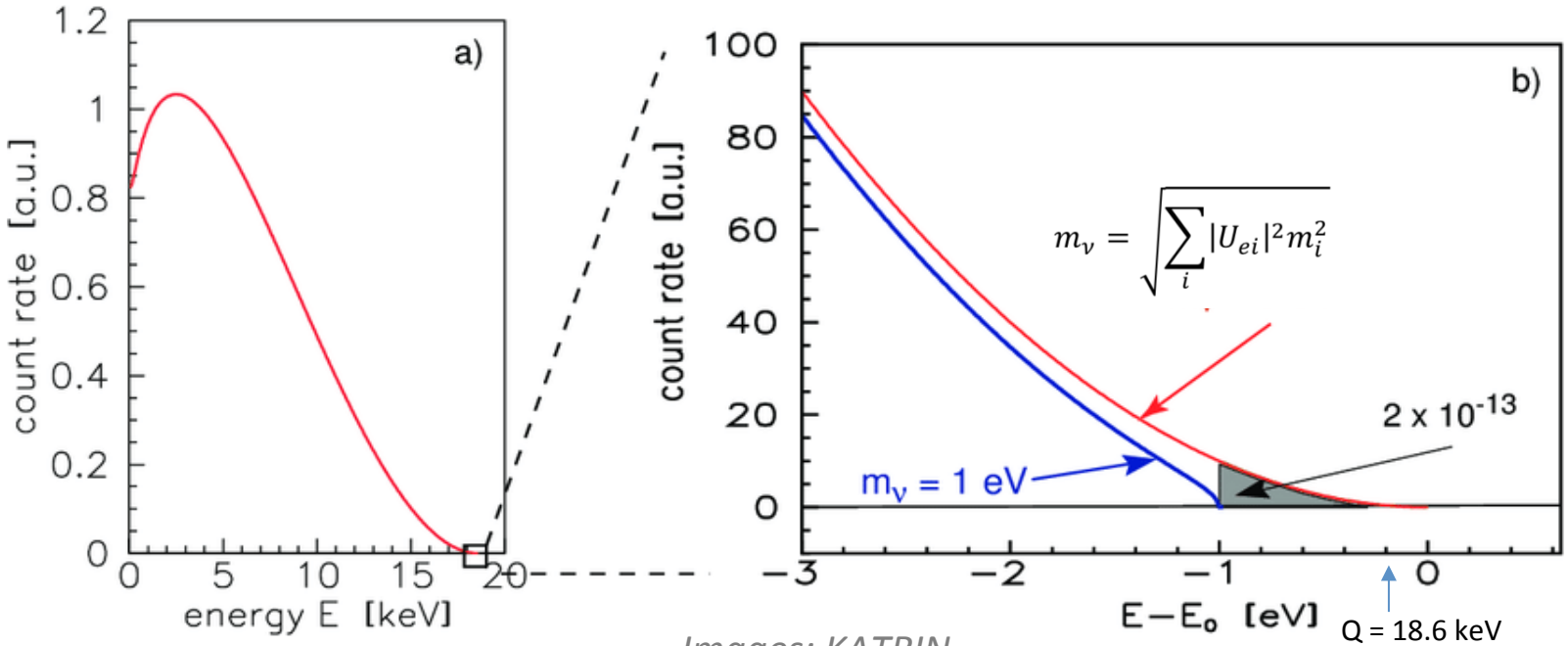


Neutrino mass from tritium β^- spectroscopy

Tritium β^- spectroscopy is the leading technique for direct neutrino mass measurements



Energy spectrum of electrons emitted from tritium β^- decay



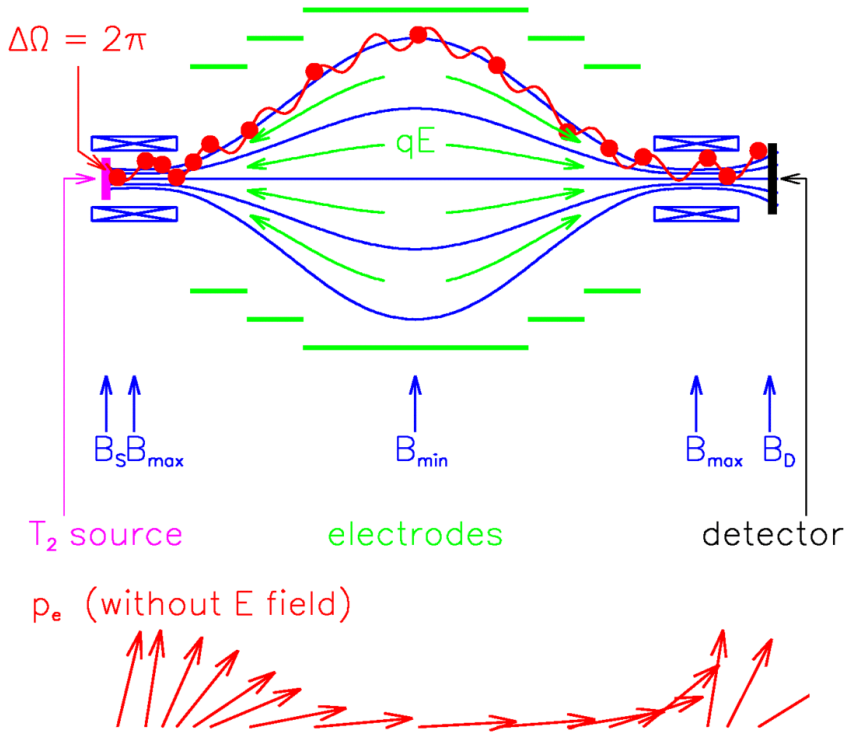
Images: KATRIN

State of the art: KATRIN

- New result! Upper limit of 1.1 eV/c^2 (90% CL) (arXiv: 1909.06048, M. Aker et. al.)
- KATRIN is designed to achieve an ultimate sensitivity of ~200 meV/c^2.
- If neutrino mass is smaller, how can we surpass 200 meV limit?

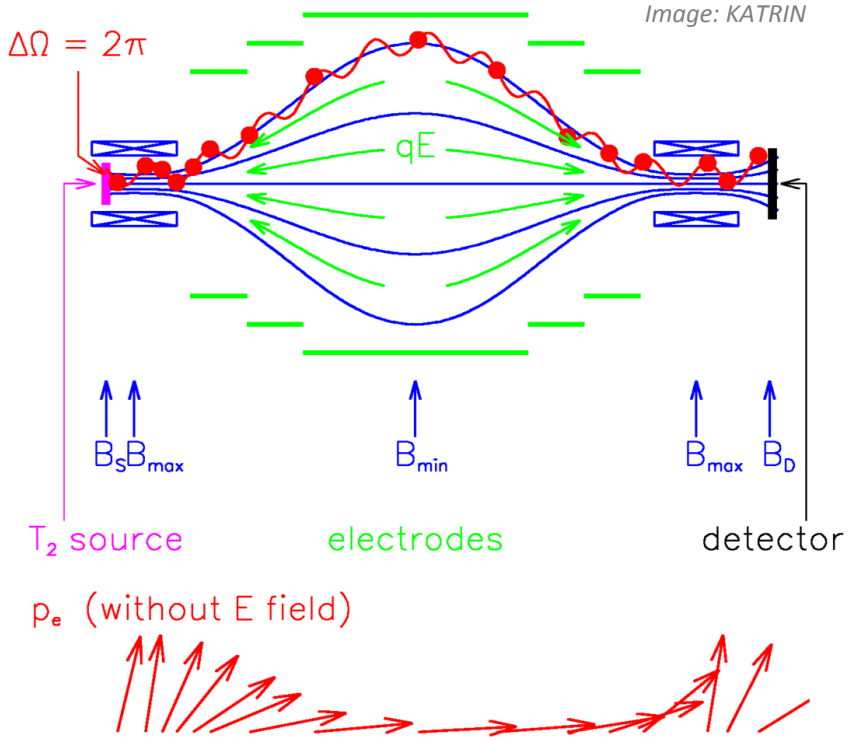
State of the art: KATRIN

- New result! Upper limit of 1.1 eV/c^2 (90% CL) (arXiv: 1909.06048, M. Aker et. al.)
- KATRIN is designed to achieve an ultimate sensitivity of ~200 meV/c^2.
- If neutrino mass is smaller, how can we surpass 200 meV limit?



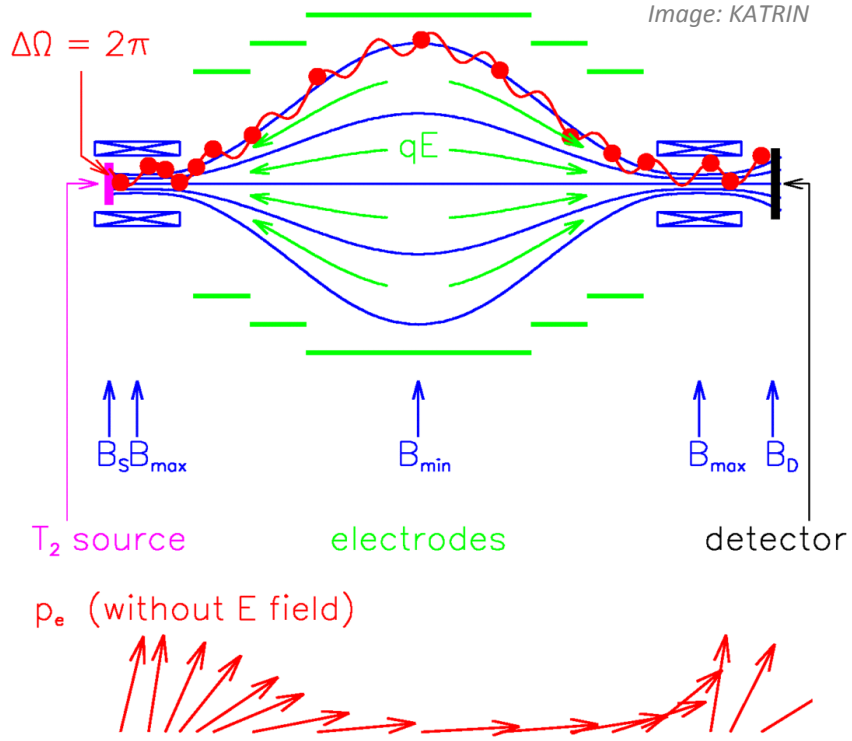
State of the art: KATRIN

- New result! Upper limit of 1.1 eV/c^2 (90% CL) (arXiv: 1909.06048, M. Aker et. al.)
- KATRIN is designed to achieve an ultimate sensitivity of ~200 meV/c^2.
- If neutrino mass is smaller, how can we surpass 200 meV limit?
- Statistical and systematic barriers to greater sensitivity with KATRIN's MAC-E filter method include:
  - Integral spectrometer



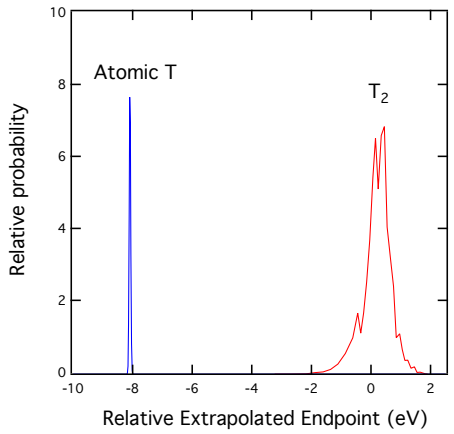
State of the art: KATRIN

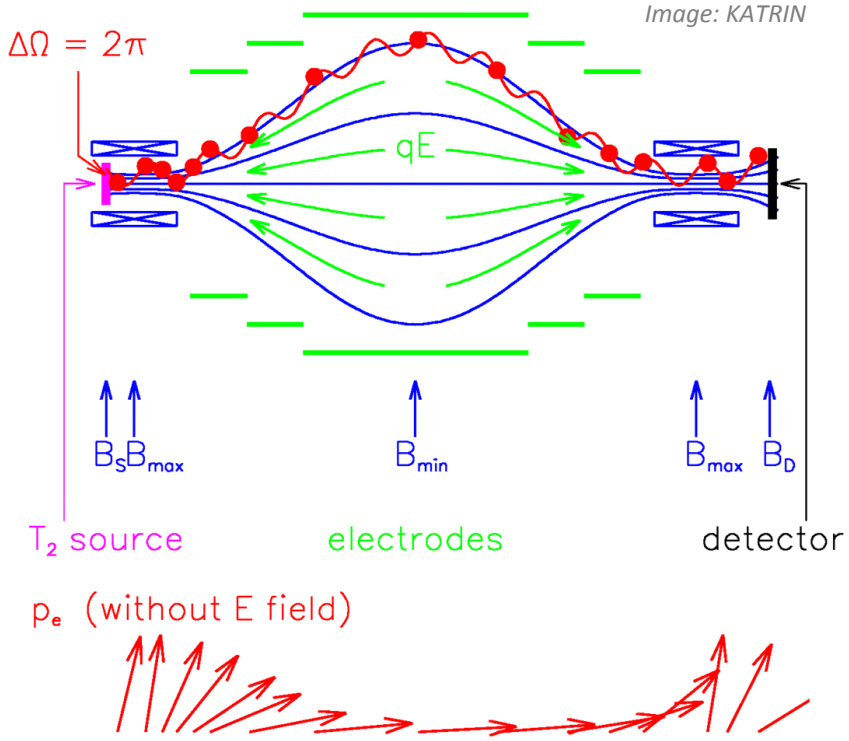
- New result! Upper limit of 1.1 eV/c^2 (90% CL) (arXiv: 1909.06048, M. Aker et. al.)
- KATRIN is designed to achieve an ultimate sensitivity of ~200 meV/c^2.
- If neutrino mass is smaller, how can we surpass 200 meV limit?
- Statistical and systematic barriers to greater sensitivity with KATRIN's MAC-E filter method include:
  - Integral spectrometer
  - Resolution~area; difficult to scale up more
  - Interactions during electron transport



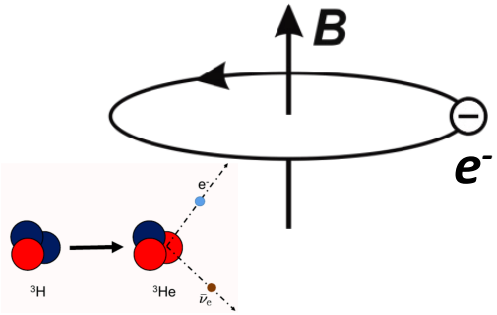
State of the art: KATRIN

- New result! Upper limit of 1.1 eV/c^2 (90% CL) (arXiv: 1909.06048, M. Aker et. al.)
- KATRIN is designed to achieve an ultimate sensitivity of ~200 meV/c^2.
- If neutrino mass is smaller, how can we surpass 200 meV limit?
- Statistical and systematic barriers to greater sensitivity with KATRIN's MAC-E filter method include:
  - Integral spectrometer
  - Resolution~area; difficult to scale up more
  - Interactions during electron transport
  - The irreducible final state distribution in $^3HeT^+$ final state after decay of molecular tritium complicates the extraction of neutrino mass from the spectrum

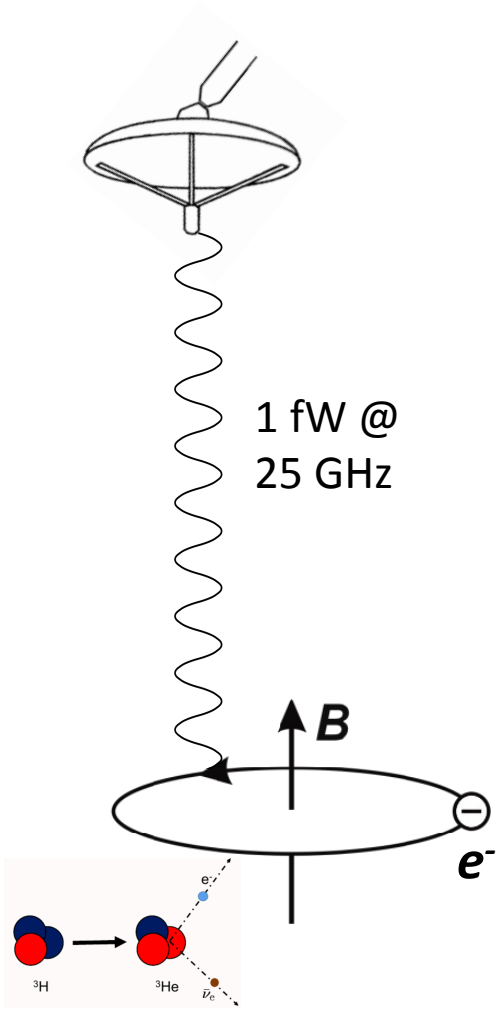




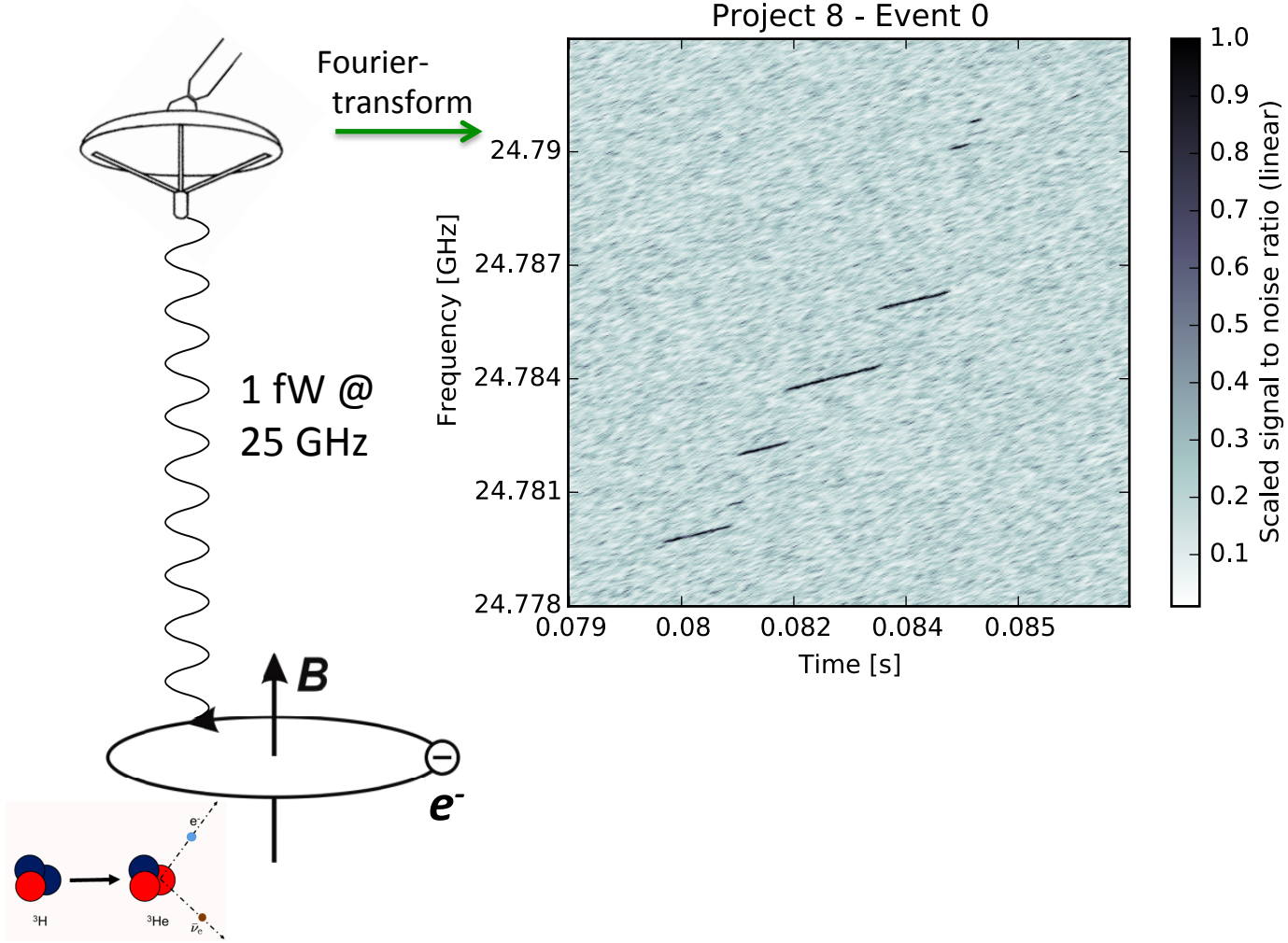
Cyclotron Radiation Emission Spectroscopy (CRES)



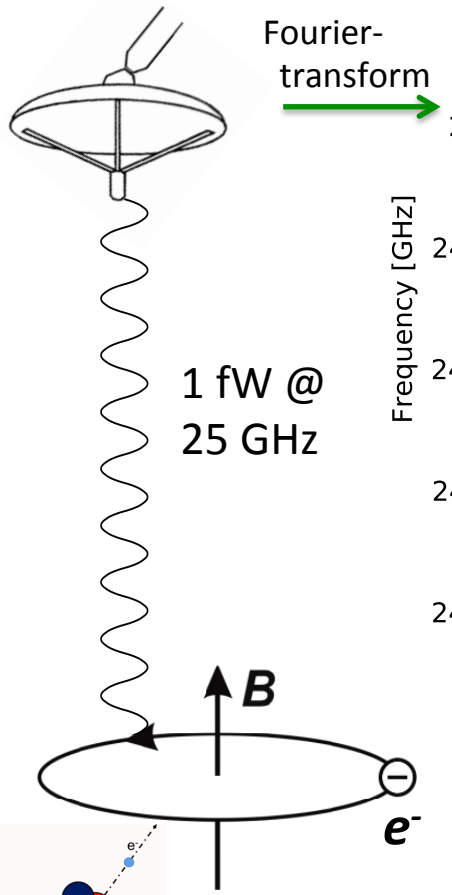
Cyclotron Radiation Emission Spectroscopy (CRES)

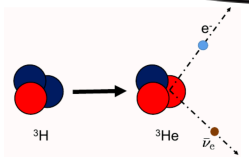


Cyclotron Radiation Emission Spectroscopy (CRES)

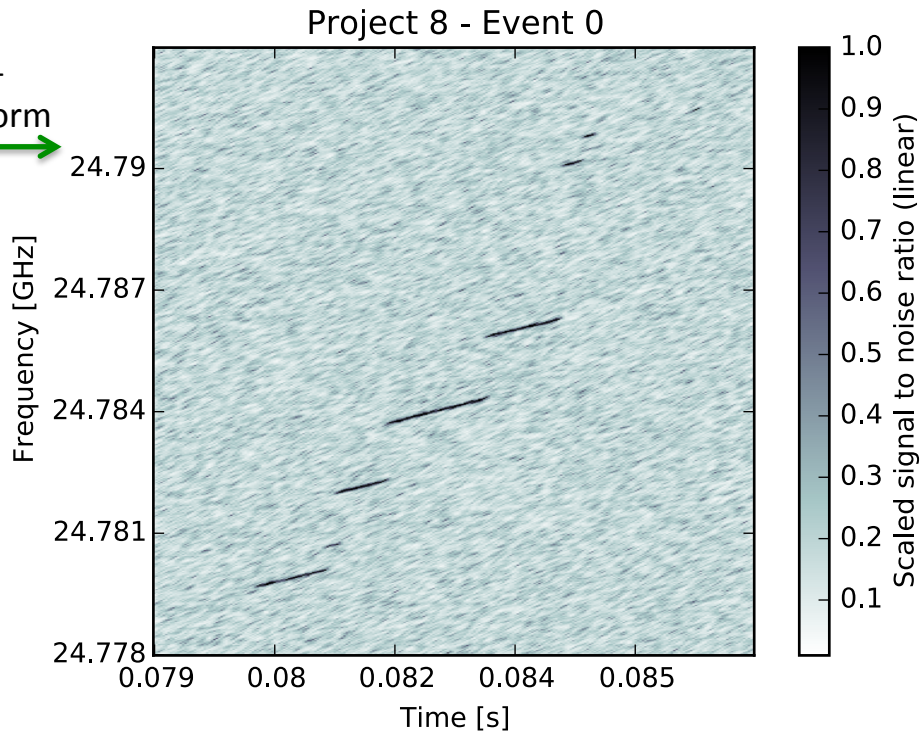


Cyclotron Radiation Emission Spectroscopy (CRES)



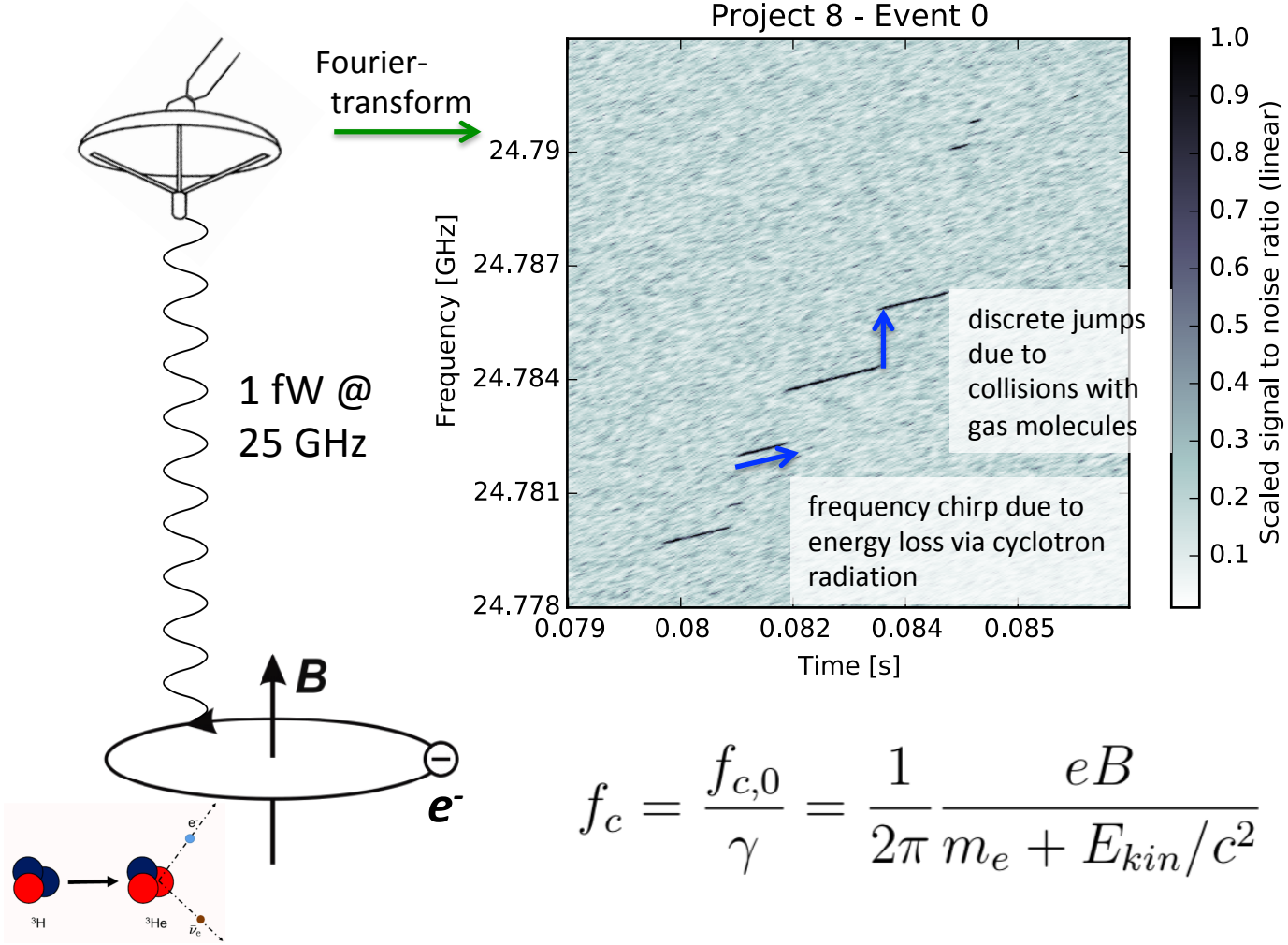


Fourier-transform



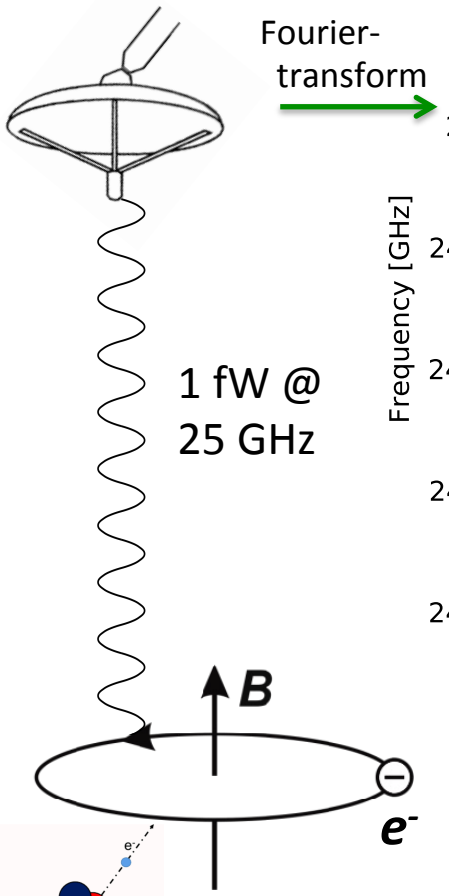
$$f_c = \frac{f_{c,0}}{\gamma} = \frac{1}{2\pi} \frac{eB}{m_e + E_{kin}/c^2}$$

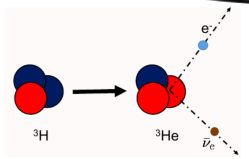
Cyclotron Radiation Emission Spectroscopy (CRES)



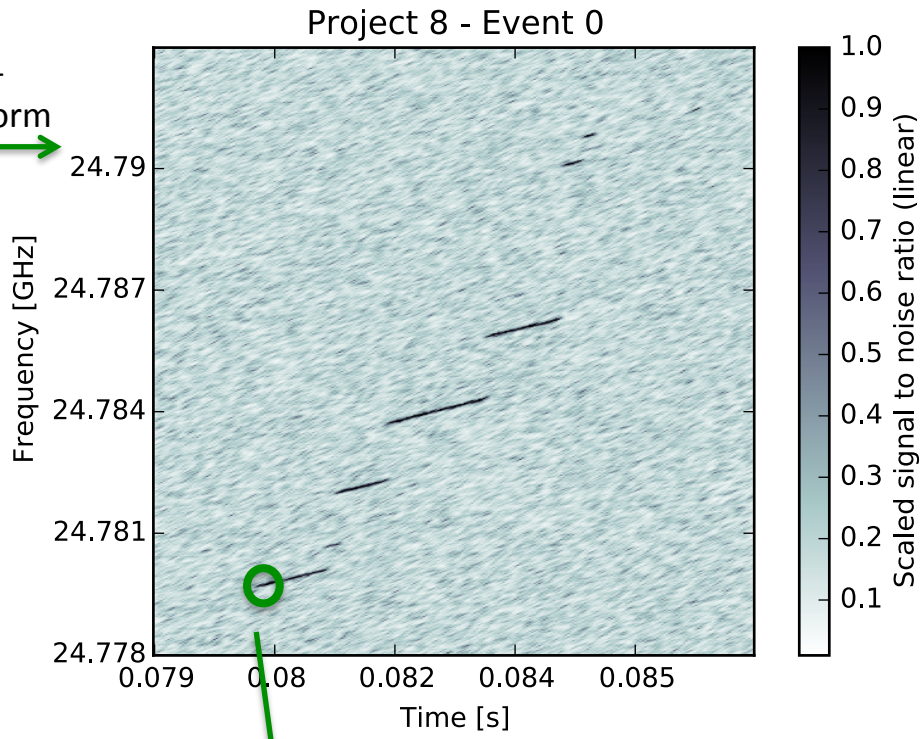
$$f_c = \frac{f_{c,0}}{\gamma} = \frac{1}{2\pi} \frac{eB}{m_e + E_{kin}/c^2}$$

Cyclotron Radiation Emission Spectroscopy (CRES)

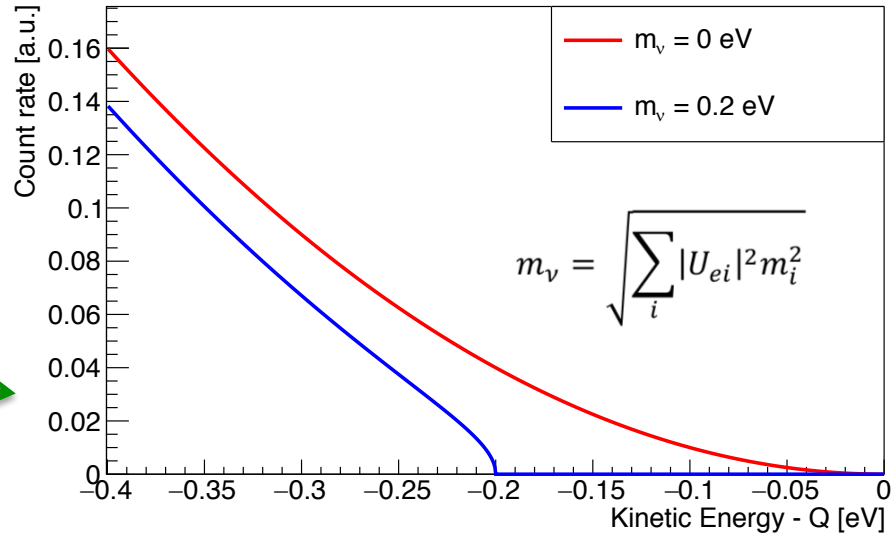




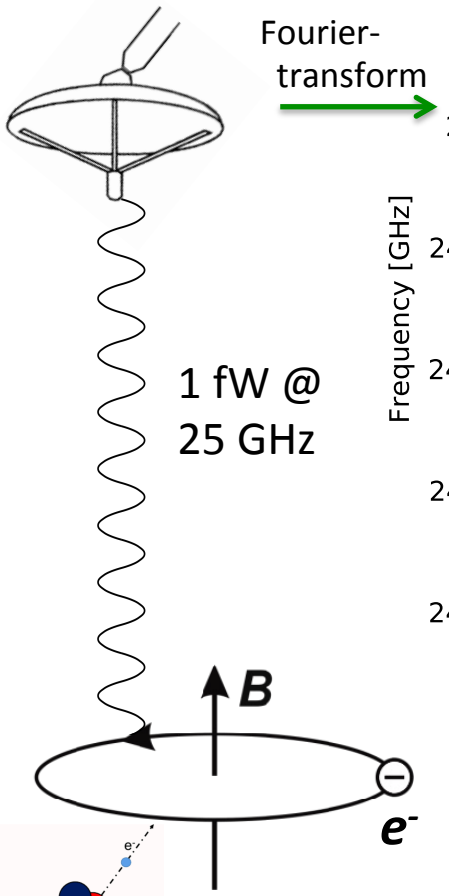
Fourier-transform

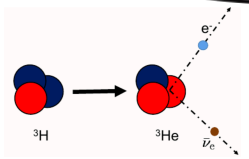


$$f_c = \frac{f_{c,0}}{\gamma} = \frac{1}{2\pi} \frac{eB}{m_e + E_{kin}/c^2}$$

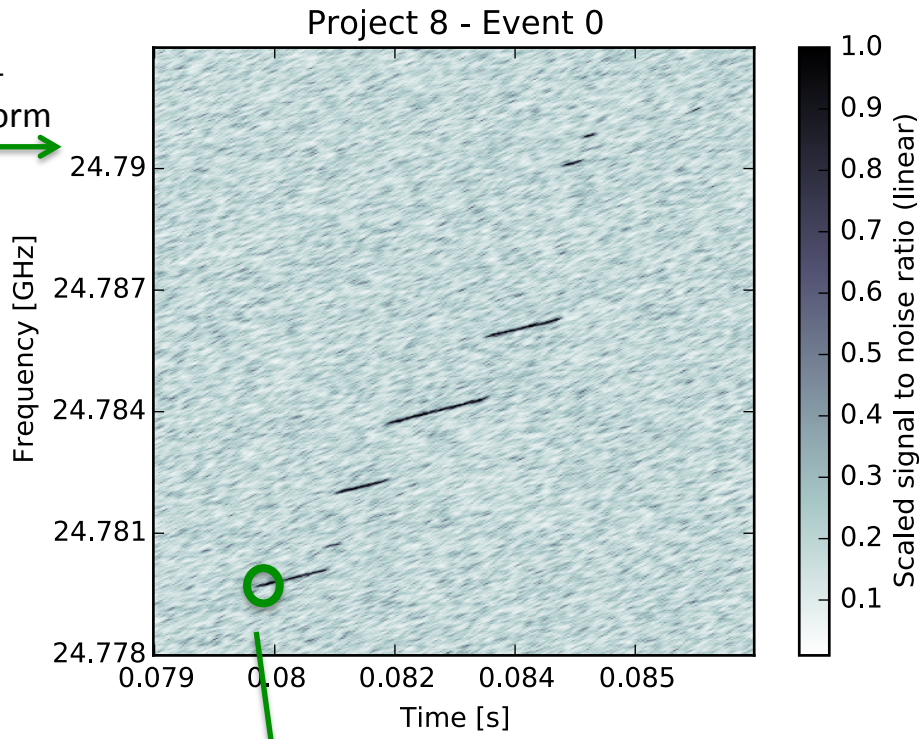


Cyclotron Radiation Emission Spectroscopy (CRES)





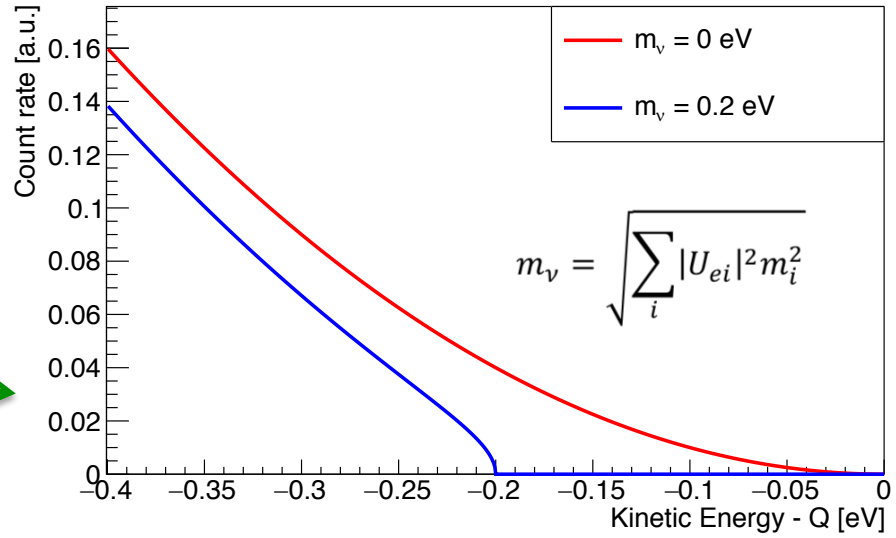
Fourier-transform



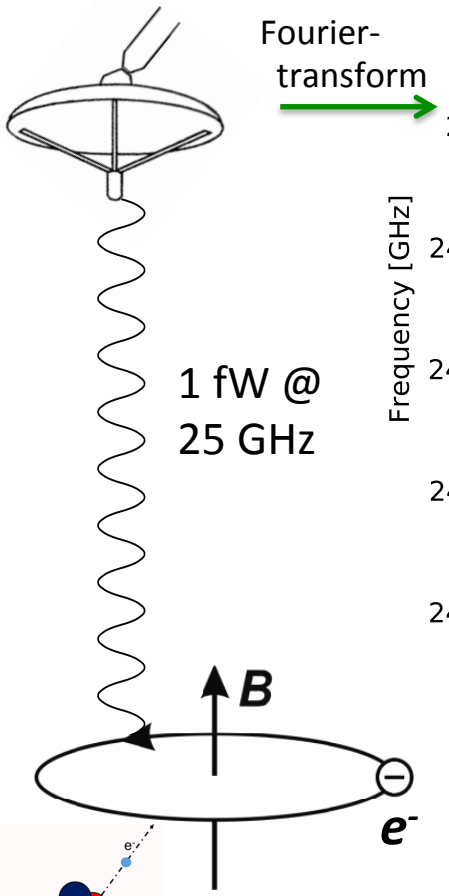
$$f_c = \frac{f_{c,0}}{\gamma} = \frac{1}{2\pi} \frac{eB}{m_e + E_{kin}/c^2}$$

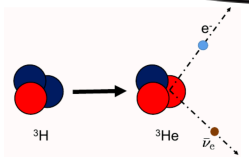
Advantages of CRES

- Frequency measurement
  ➔ high precision

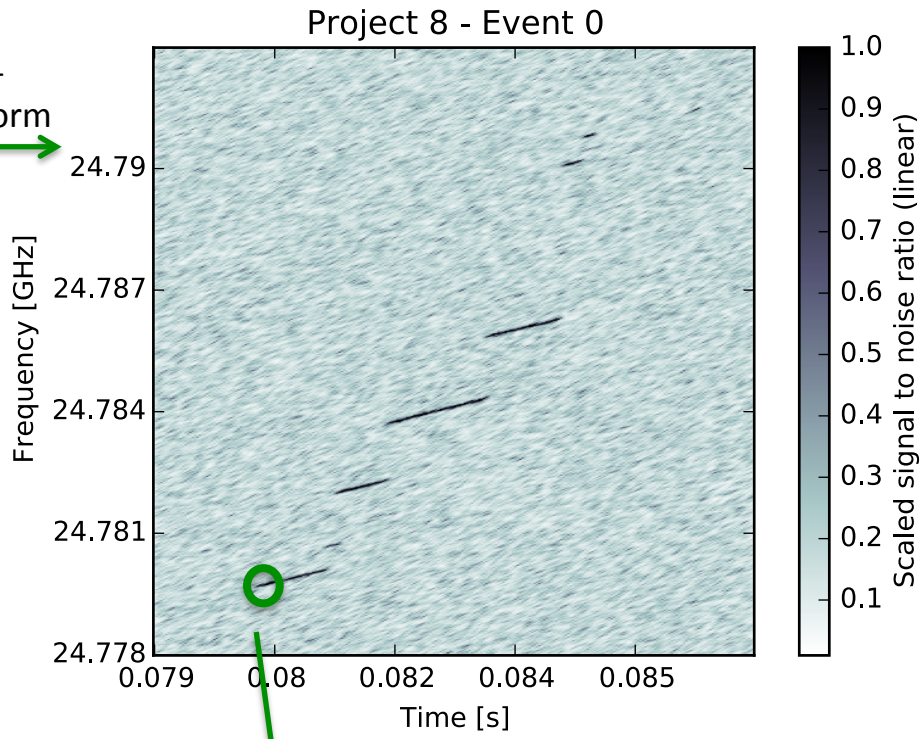


Cyclotron Radiation Emission Spectroscopy (CRES)





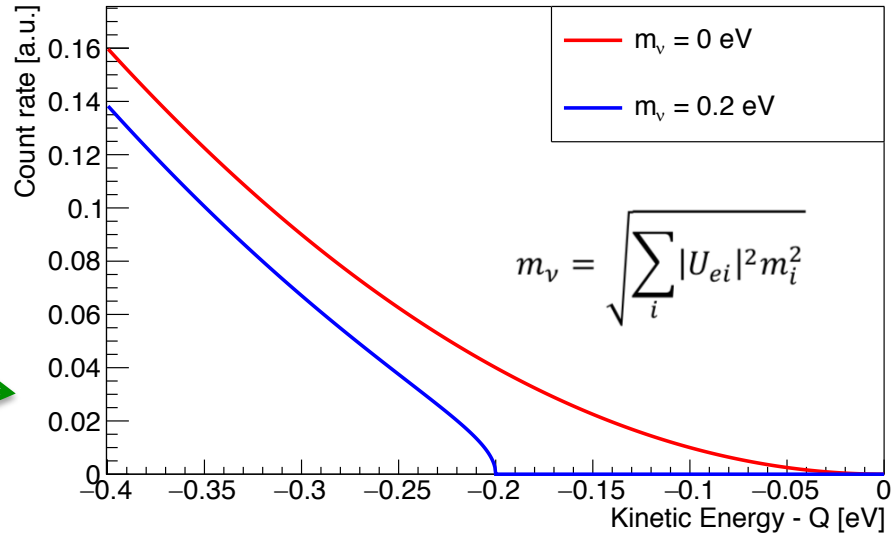
Fourier-transform



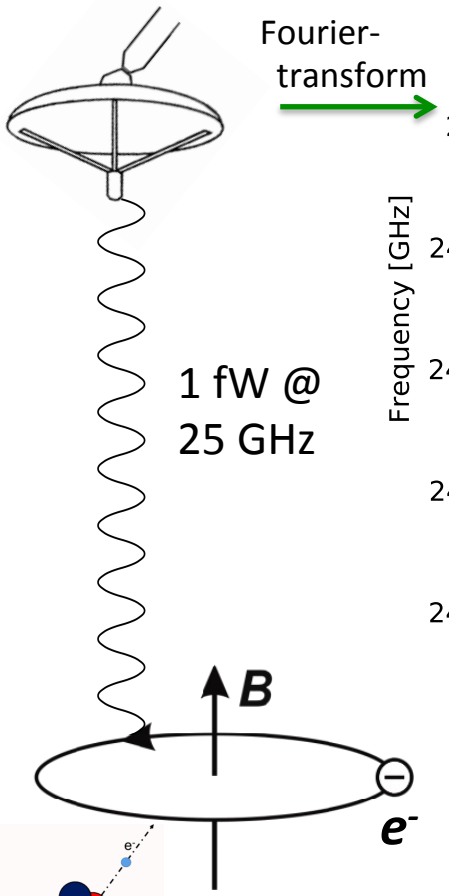
$$f_c = \frac{f_{c,0}}{\gamma} = \frac{1}{2\pi} \frac{eB}{m_e + E_{kin}/c^2}$$

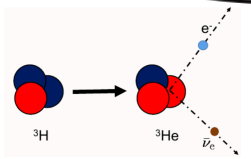
Advantages of CRES

- Frequency measurement
  ➔ high precision
- Differential spectrometer
  ➔ increased statistical efficiency

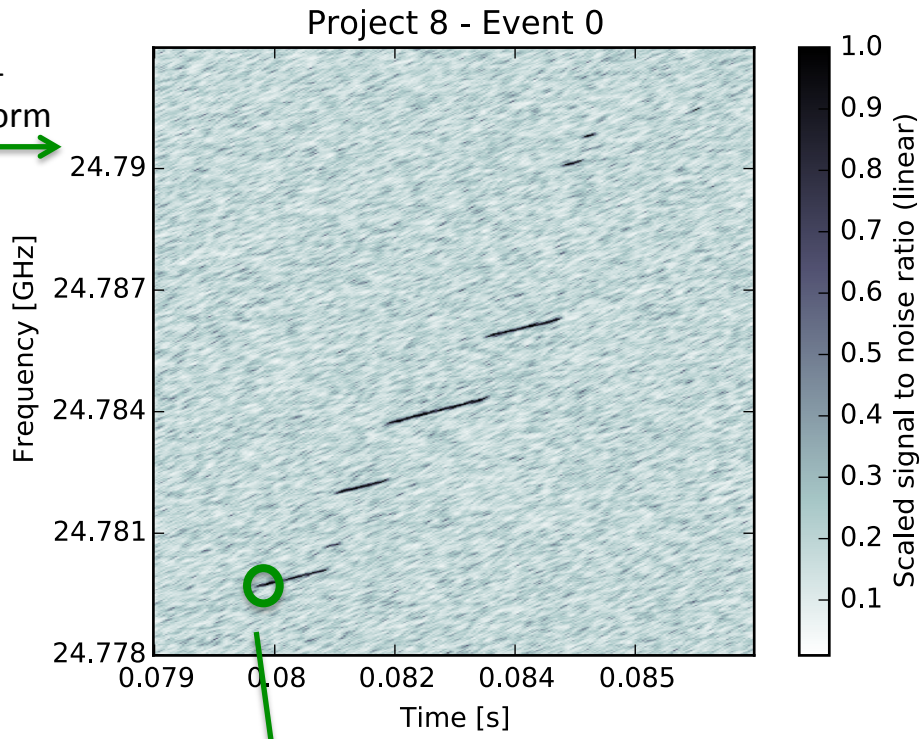


Cyclotron Radiation Emission Spectroscopy (CRES)





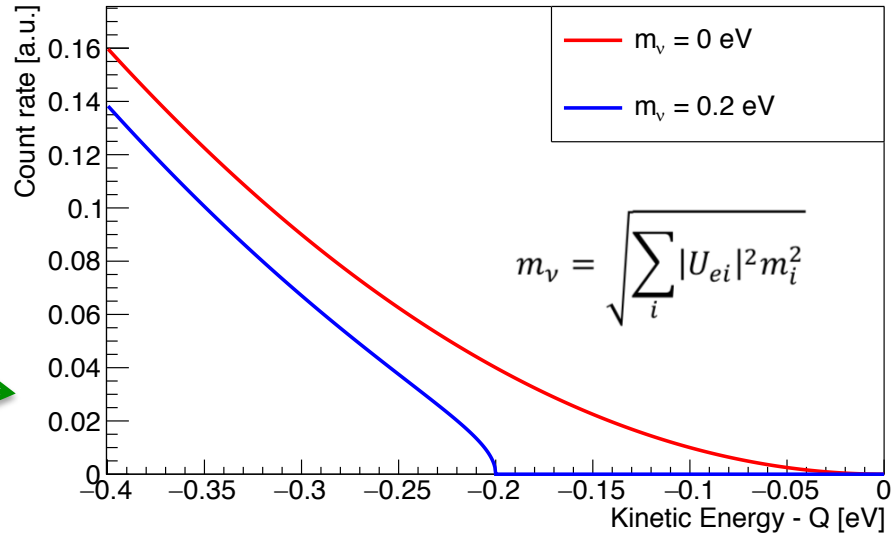
Fourier-transform



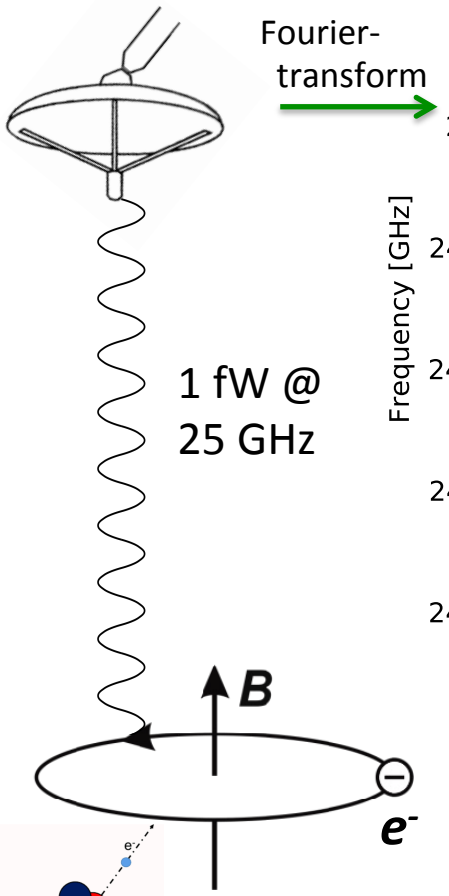
$$f_c = \frac{f_{c,0}}{\gamma} = \frac{1}{2\pi} \frac{eB}{m_e + E_{kin}/c^2}$$

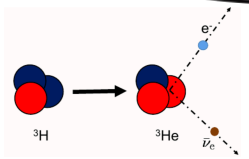
Advantages of CRES

- Frequency measurement
  ➔ high precision
- Differential spectrometer
  ➔ increased statistical efficiency
- Source is transparent to microwave radiation
  ➔ no electron transport ➔ volume scaling

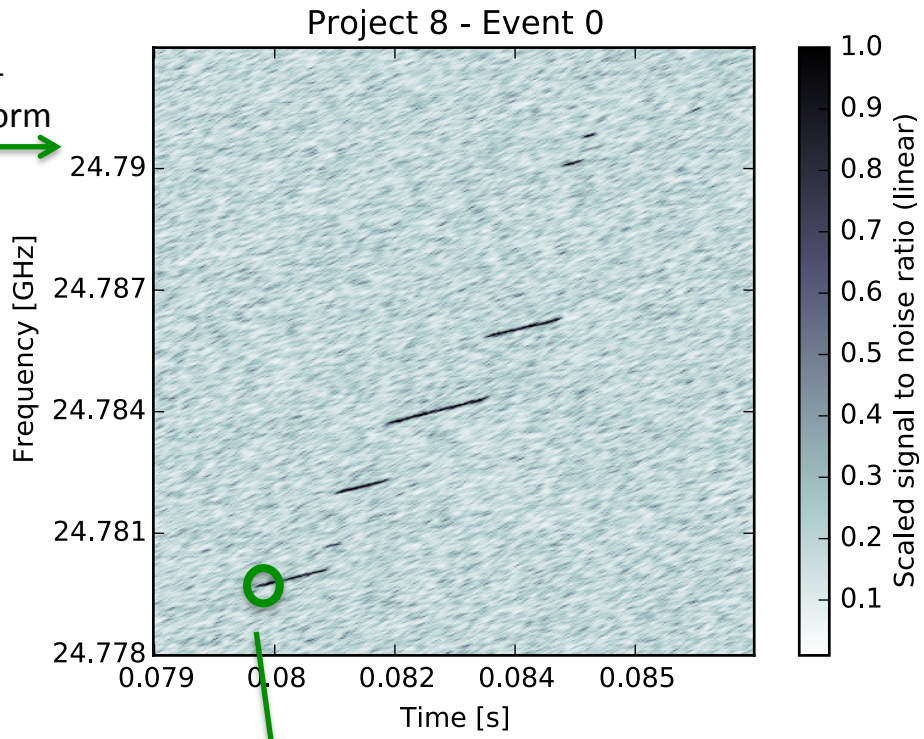


Cyclotron Radiation Emission Spectroscopy (CRES)





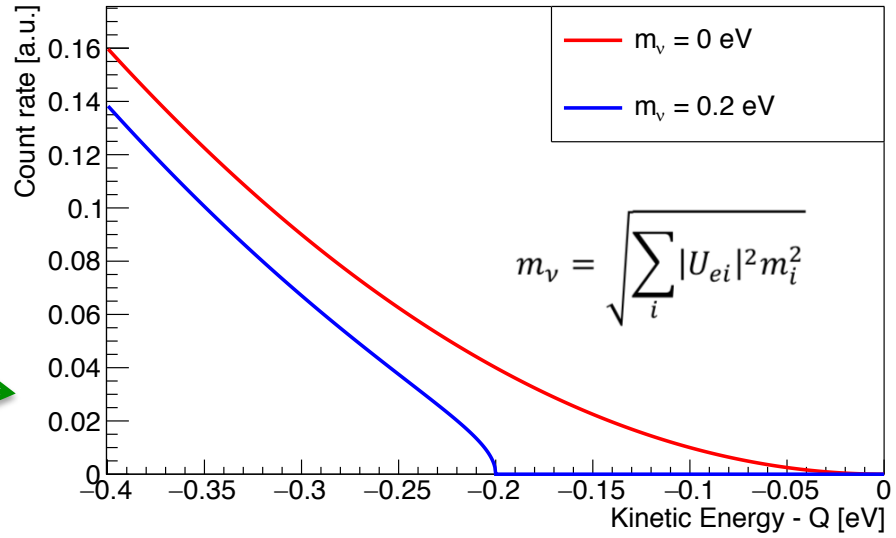
Fourier-transform



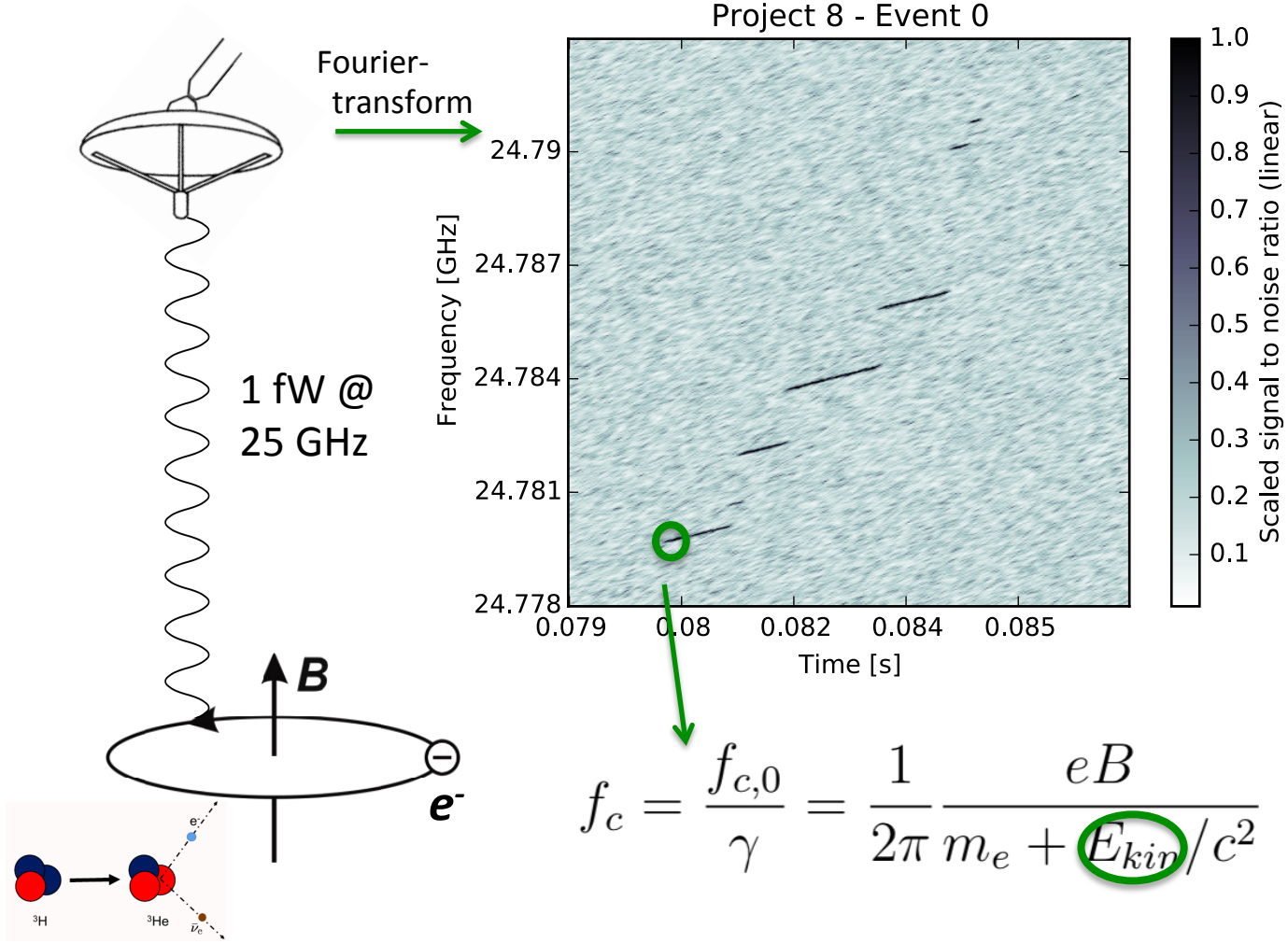
$$f_c = \frac{f_{c,0}}{\gamma} = \frac{1}{2\pi} \frac{eB}{m_e + E_{kin}/c^2}$$

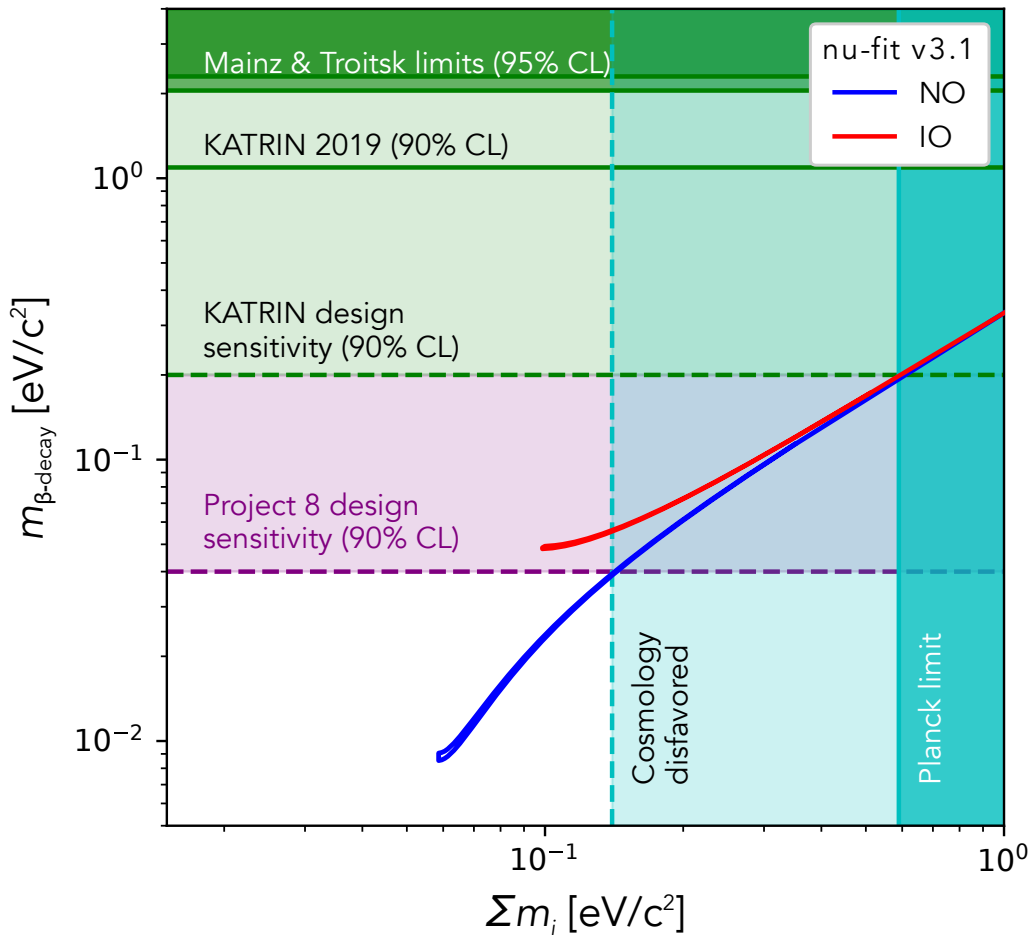
Advantages of CRES

- Frequency measurement
  ➔ high precision
- Differential spectrometer
  ➔ increased statistical efficiency
- Source is transparent to microwave radiation
  ➔ no electron transport ➔ volume scaling
- Compatible with atomic tritium
  ➔ avoids final-state spectral broadening of T_2

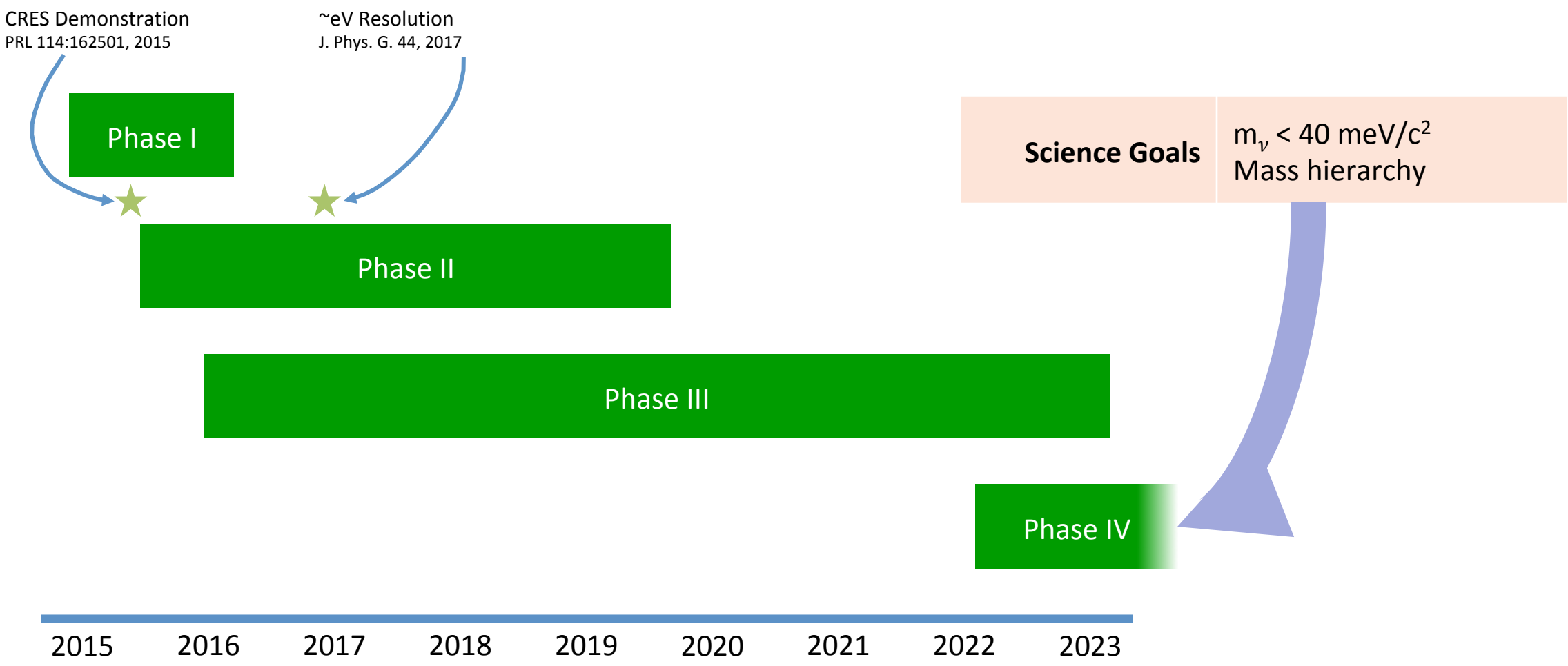


Pushing direct neutrino mass limits with Project 8

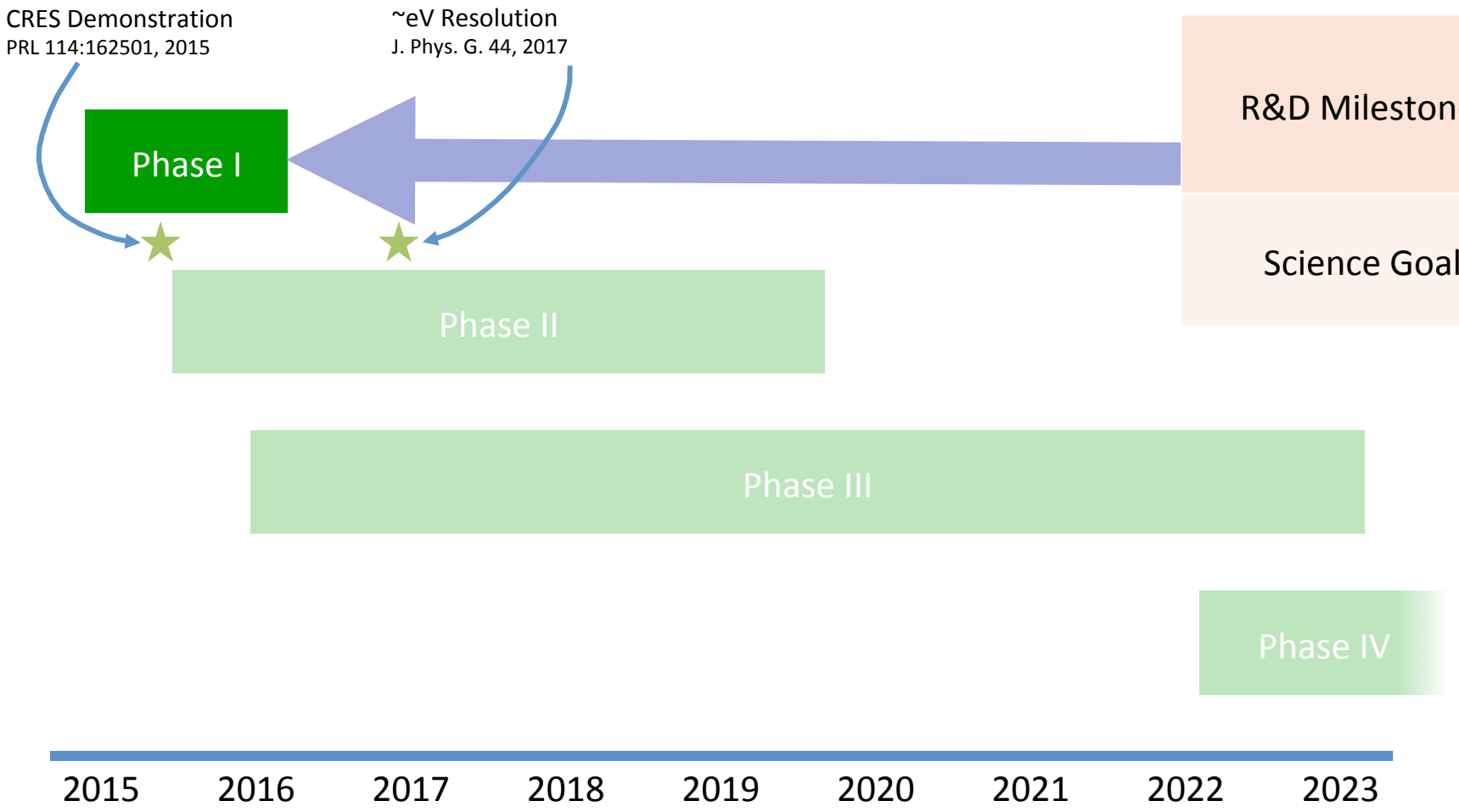




Project 8: a phased approach to neutrino mass

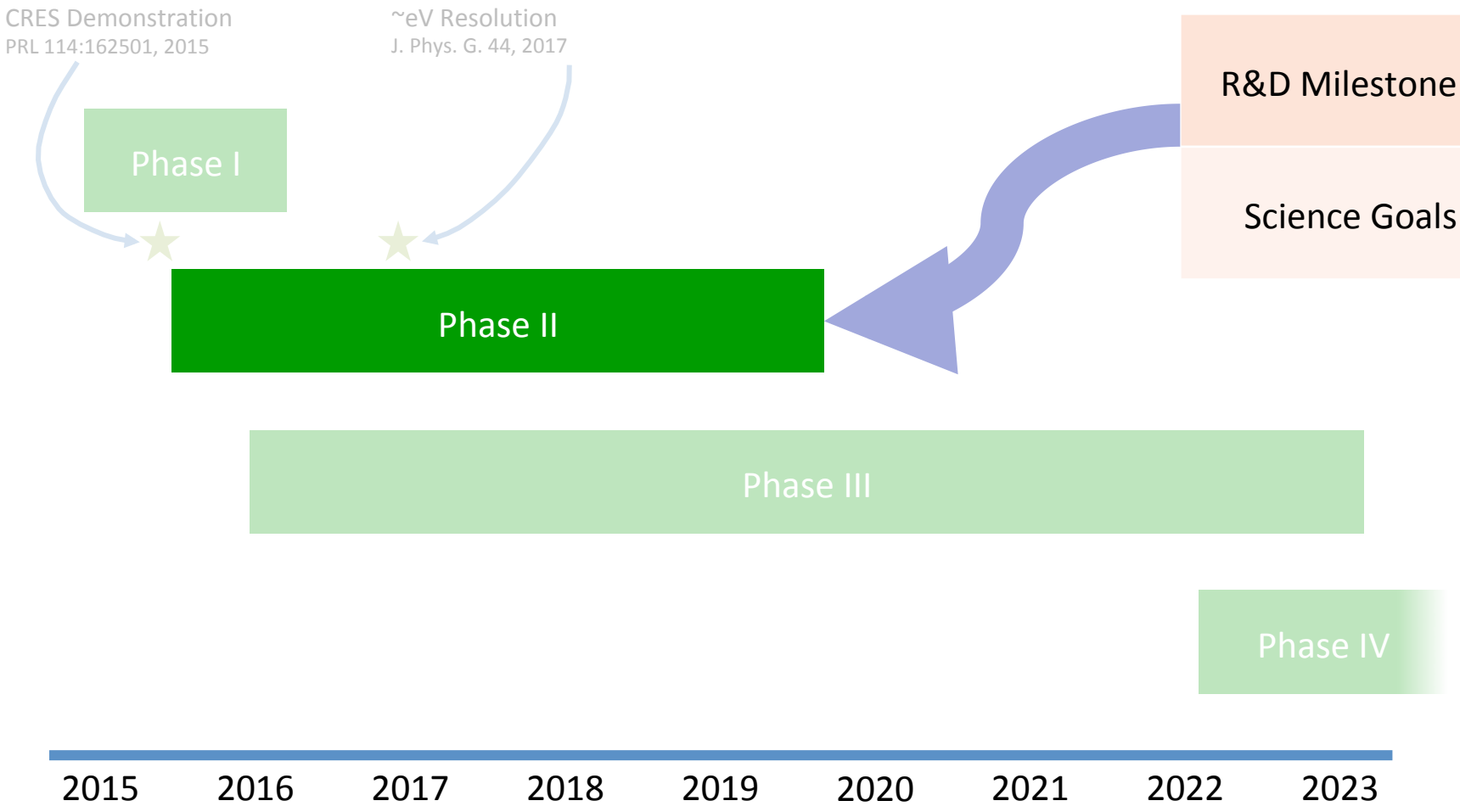


Project 8, Phase I: first demonstration of CRES



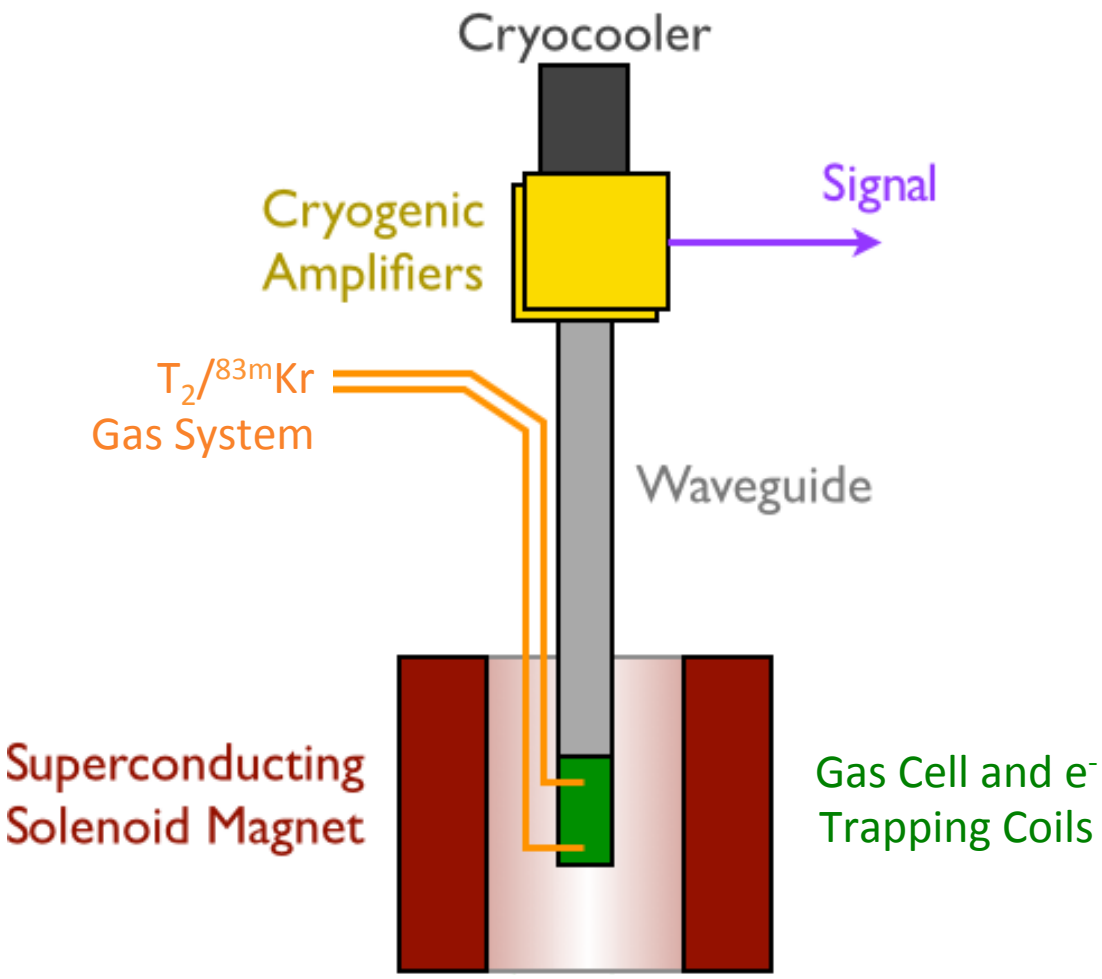
R&D Milestone	• Single-electron detection • Spectroscopy
Science Goals	^{83m}Kr conversion-electron spectrum

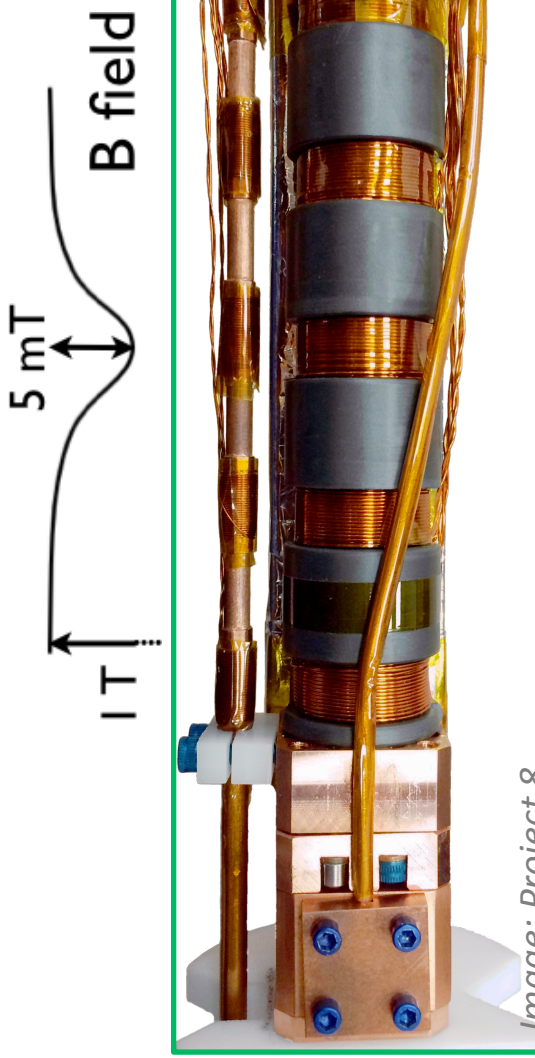
Project 8, Phase II: tritium, systematics

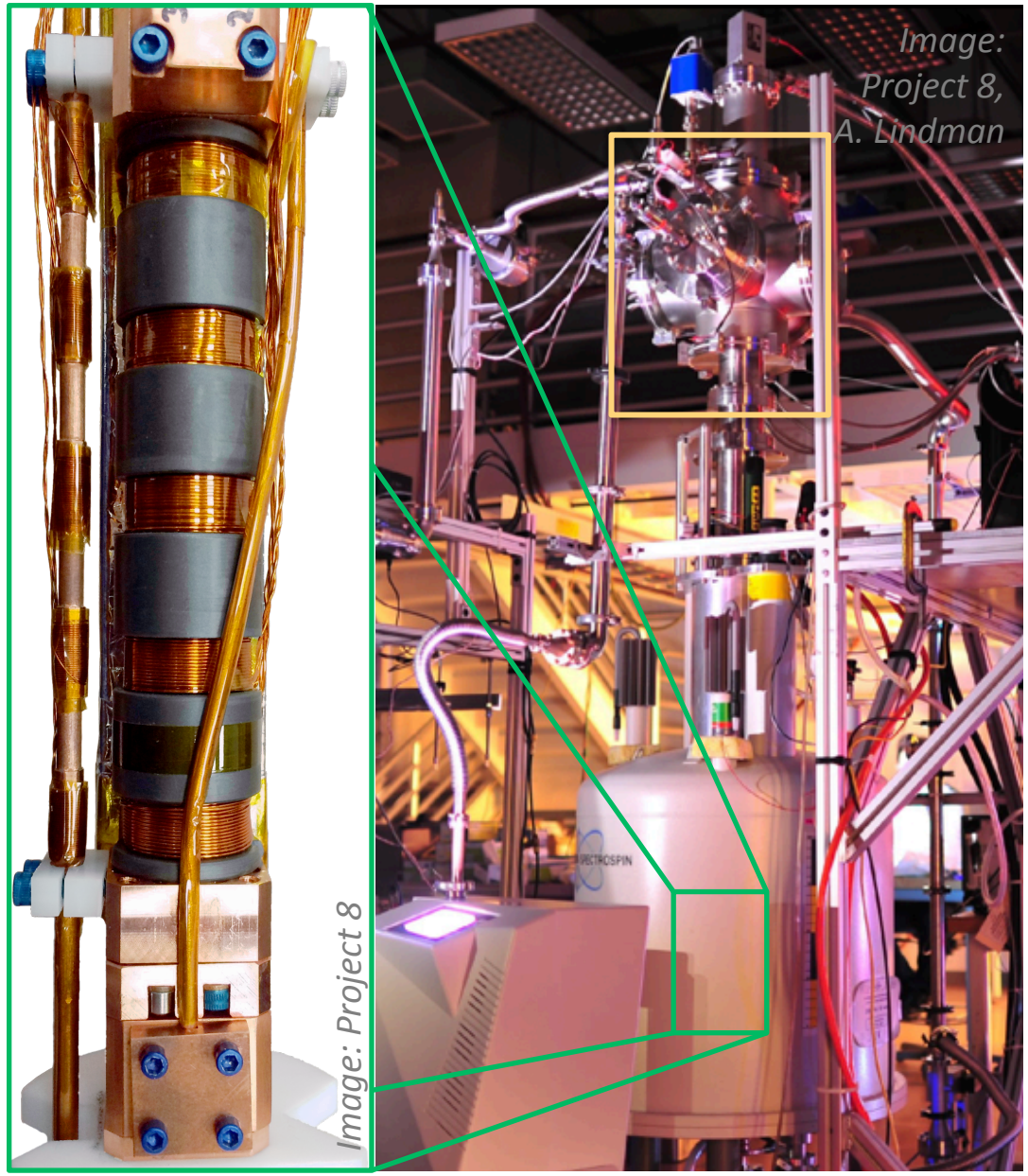


R&D Milestone	• T_2 spectrum • Systematic studies
Science Goals	Tritium endpoint Background assessment

Phase II of Project 8

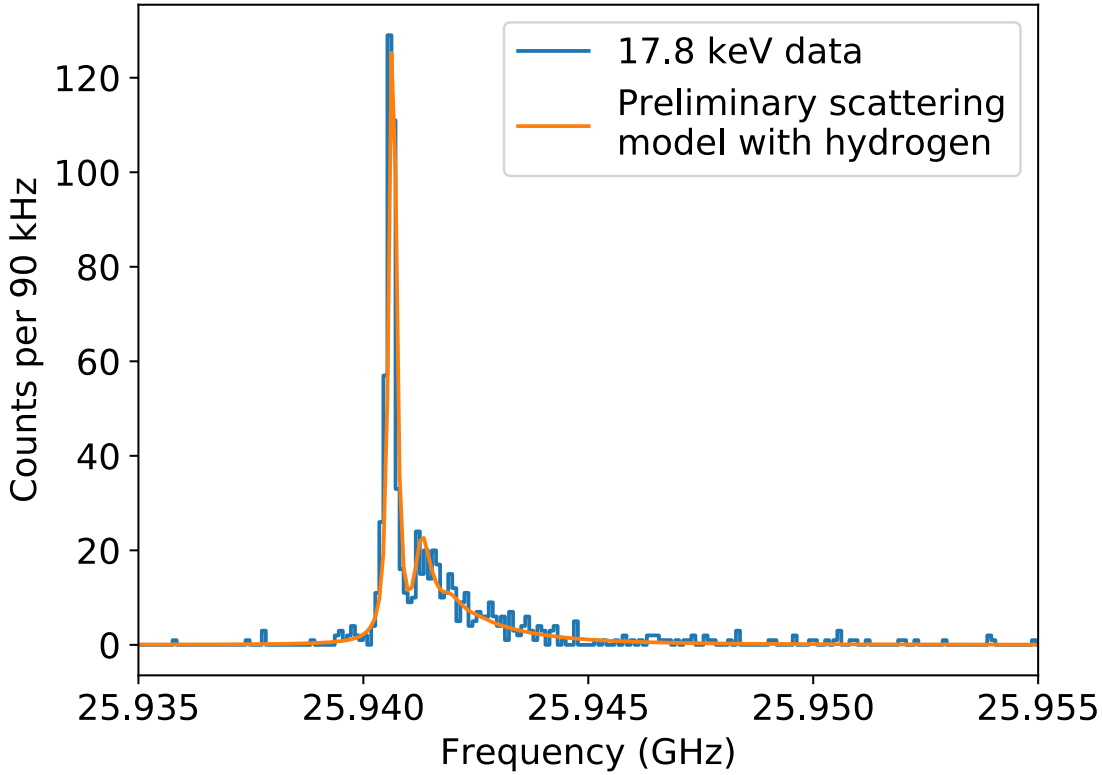




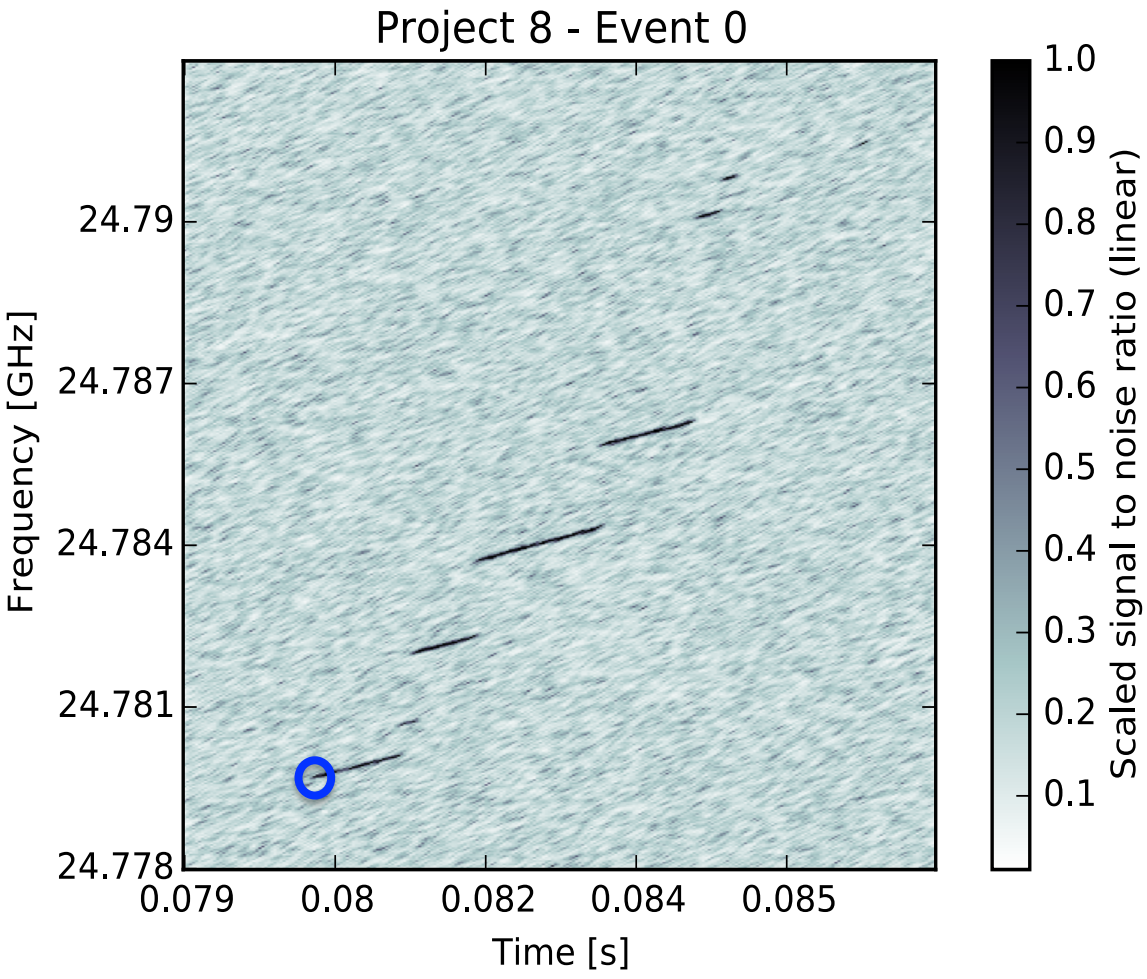


Energy resolution demonstrated with ^{83m}Kr

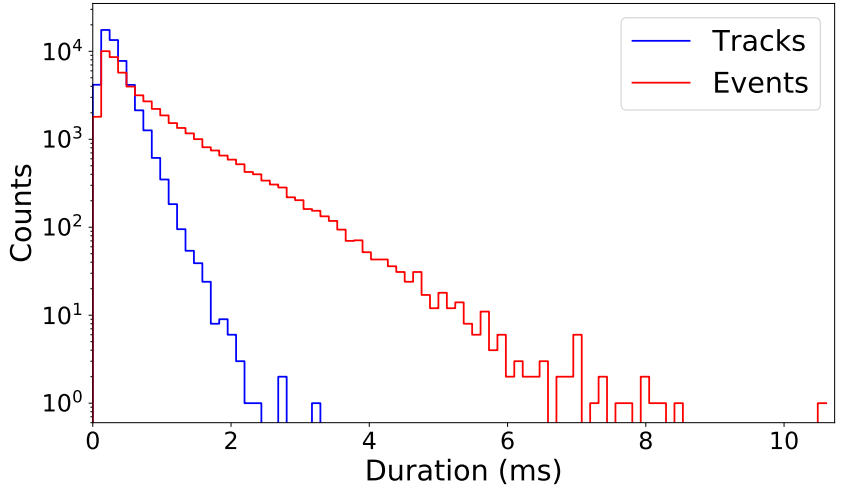
- 18, 30, and 32 keV conversion peaks observed
- Natural linewidth of 18 keV line: 2.8 ± 0.1 eV (FWHM)
- Best demonstrated instrumental width, in a shallow trap (shown at right): 2.0 ± 0.5 eV (FWHM)
- Tail is primarily due to scattering, described well by an analytical model
- Deeper trap with lower resolution used for tritium data in Phase II to increase statistics, to compensate for small 1 mm^3 effective volume



Track and event reconstruction performance

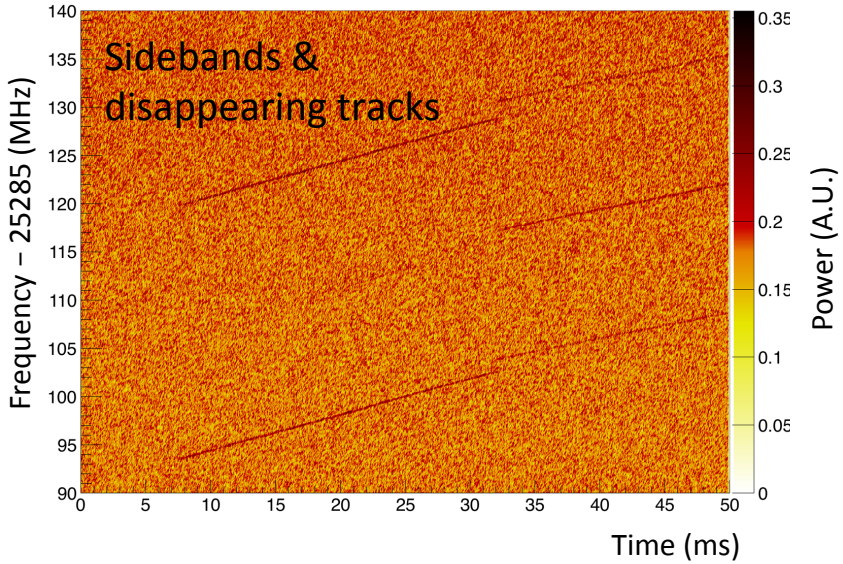


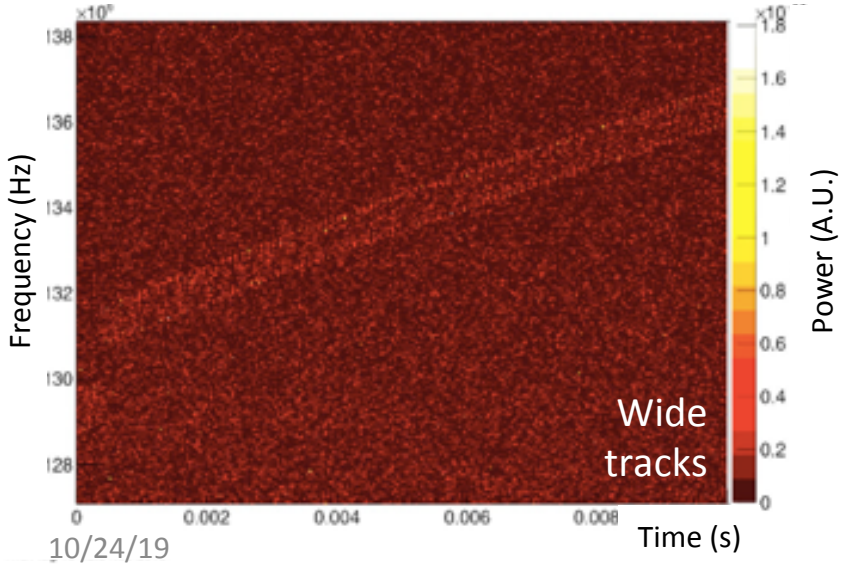
- Reconstruction must distinguish tracks from noise, group tracks into events, extract event start frequencies
- Reconstruction performance evaluated with ^{83m}Kr data and simulated data
- Efficient detection of electron tracks as short as 120 µs



- Predicted background from misreconstructed noise: <1 event in planned Phase II 100-day T_2 data campaign

Track and event reconstruction challenges

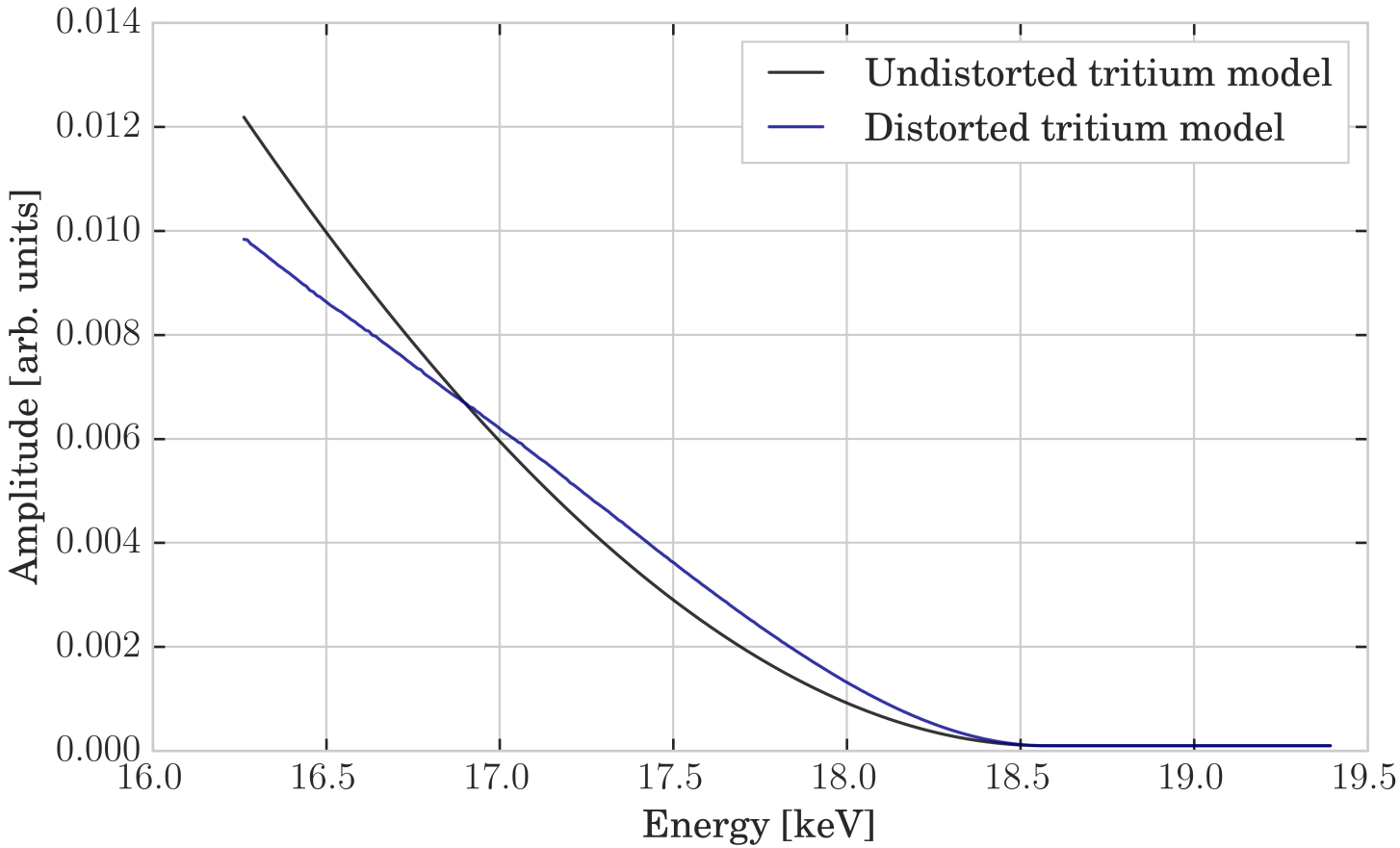




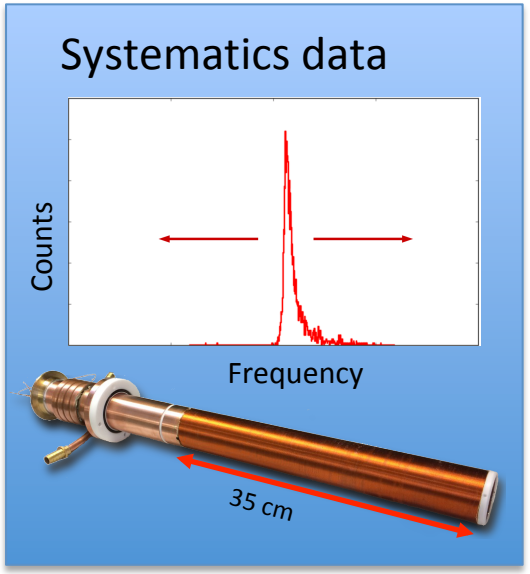
- Complex event morphologies arise due to
  - Doppler shifts
  - Interference effects
  - Electron motion through magnetic field inhomogeneities
- Understanding the phenomenology of these effects: Phys. Rev. C. 99, 2019
- RF configuration and choice of trap geometry reduce interference and give rise to simpler event structures in final Phase II data
- Machine-learning classification of main/ sidebands: arXiv:1909.08115, 2019

Understanding detection efficiency

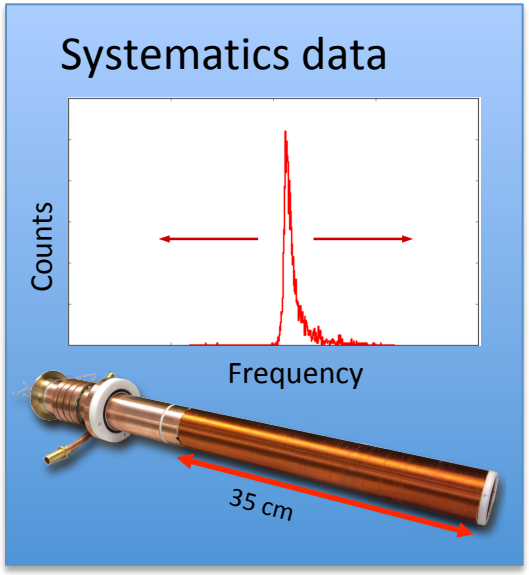
- If detection efficiency were to vary with frequency, the tritium spectrum would be distorted
- Uncorrected, this would interfere with accurate physics results (endpoint, neutrino mass)
- If variations are present, we must understand and correct for them!



Determining detection efficiency vs. frequency

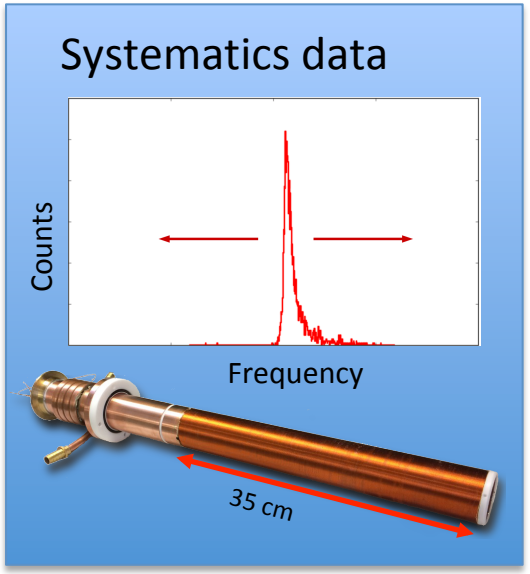


Determining detection efficiency vs. frequency



event rate vs. frequency

Determining detection efficiency vs. frequency



varies with frequency in systematics data

varies with frequency in tritium data

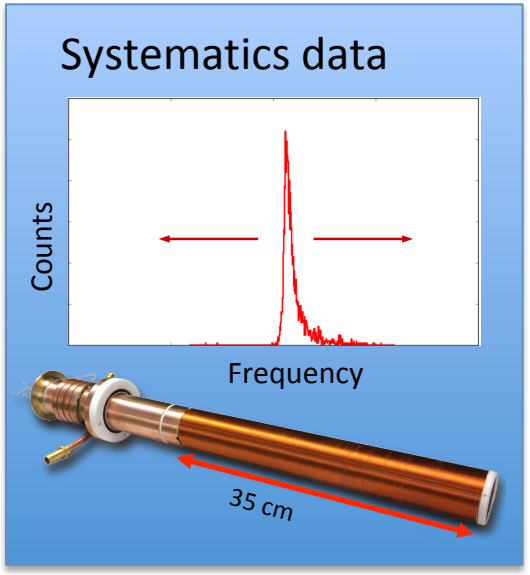
$$P = \frac{1}{6\pi\epsilon_0}\frac{e^4}{m_e^2 c}B^2(\gamma^2 - 1)\sin^2\theta$$

$$\gamma = 1 + \frac{K}{m_e c^2}$$

event rate vs. frequency

not directly applicable to tritium data

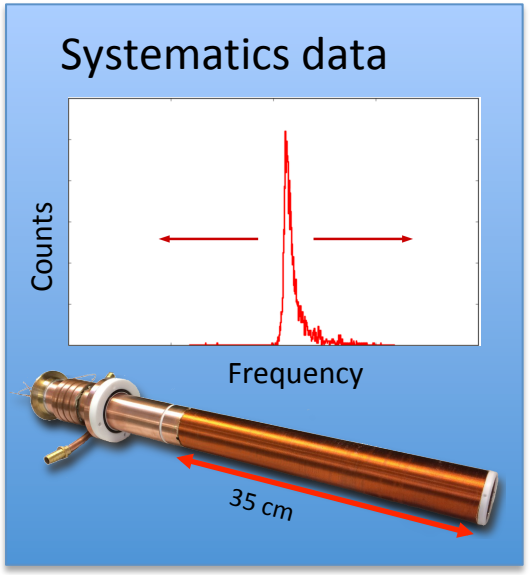
Determining detection efficiency vs. frequency

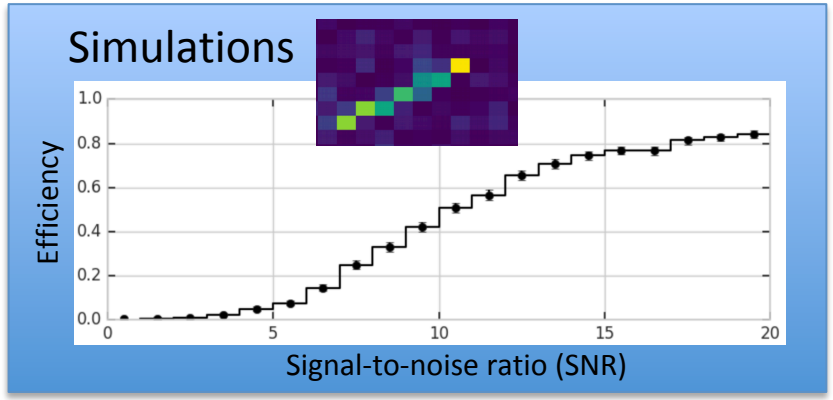


CRES event properties
(e.g., SNR)
vs. frequency

event rate vs. frequency

Determining detection efficiency vs. frequency



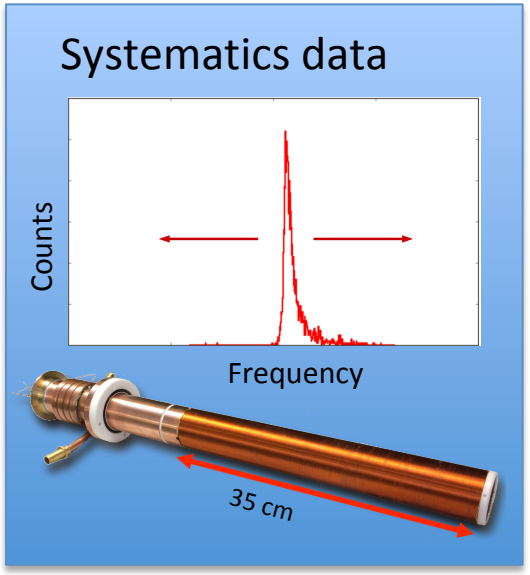


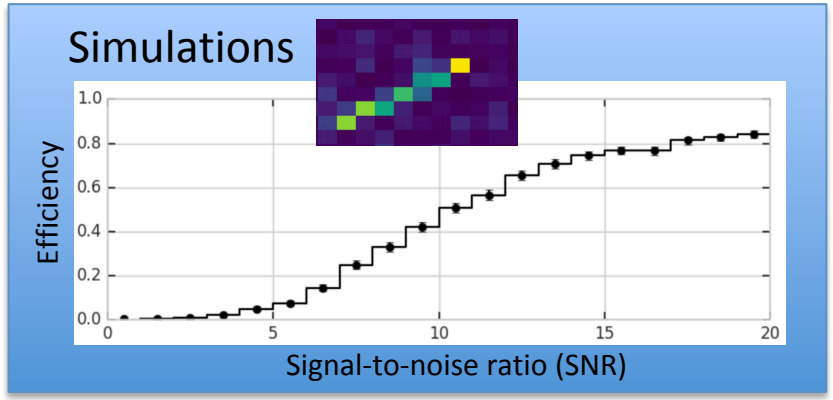
reconstruction efficiency
vs. CRES event properties (e.g., SNR)

CRES event properties
(e.g., SNR)
vs. frequency

event rate vs. frequency

Determining detection efficiency vs. frequency





reconstruction efficiency
vs. CRES event properties (e.g., SNR)

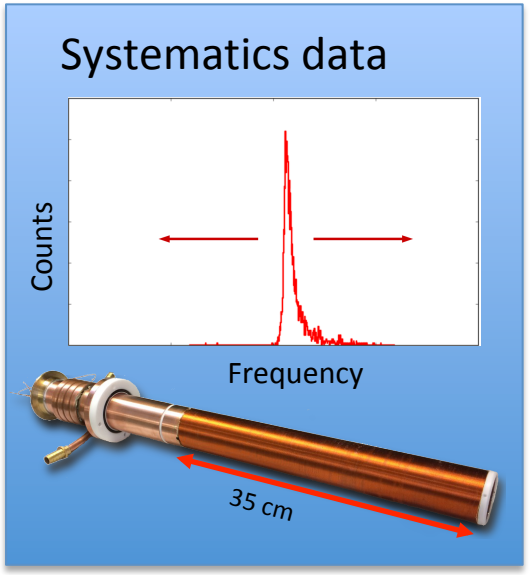
CRES event properties
(e.g., SNR)
vs. frequency

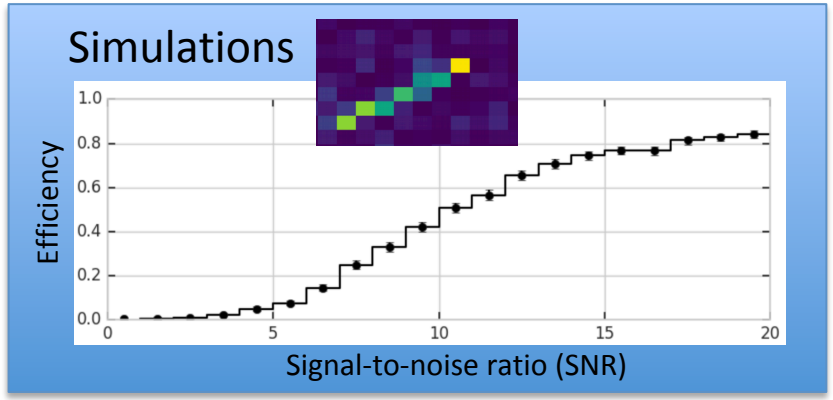
combine to get

efficiency vs. frequency

event rate vs. frequency

Determining detection efficiency vs. frequency





reconstruction efficiency
vs. CRES event properties (e.g., SNR)

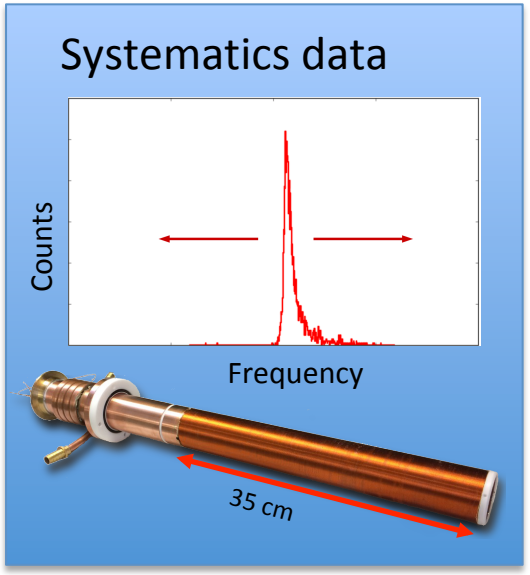
CRES event properties
(e.g., SNR)
vs. frequency

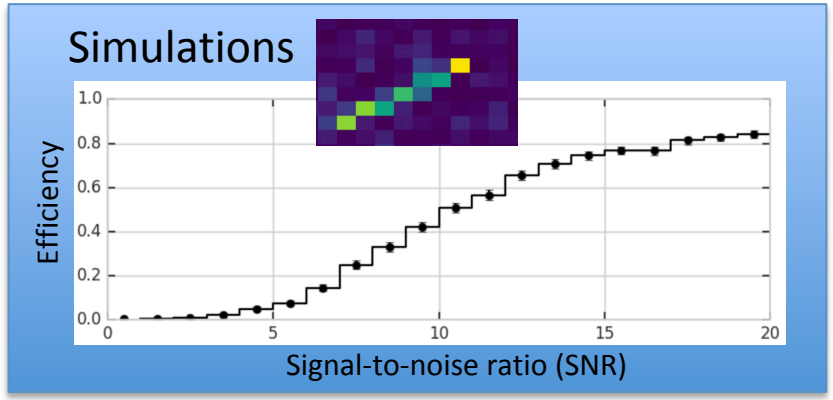
combine to get
efficiency vs. frequency

compare as
cross-check

event rate vs. frequency

Determining detection efficiency vs. frequency





reconstruction efficiency
vs. CRES event properties (e.g., SNR)

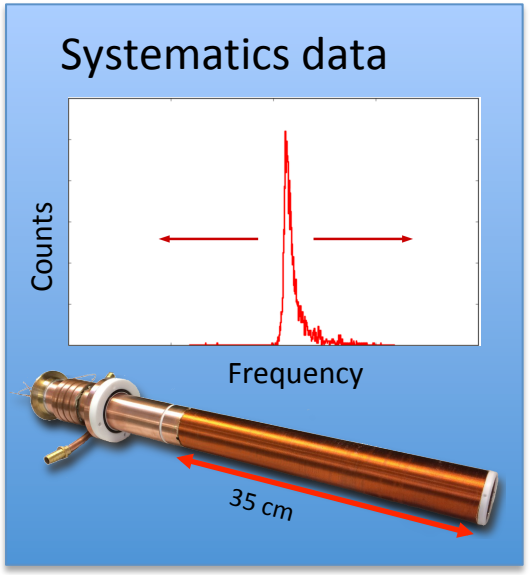
CRES event properties
(e.g., SNR)
vs. frequency

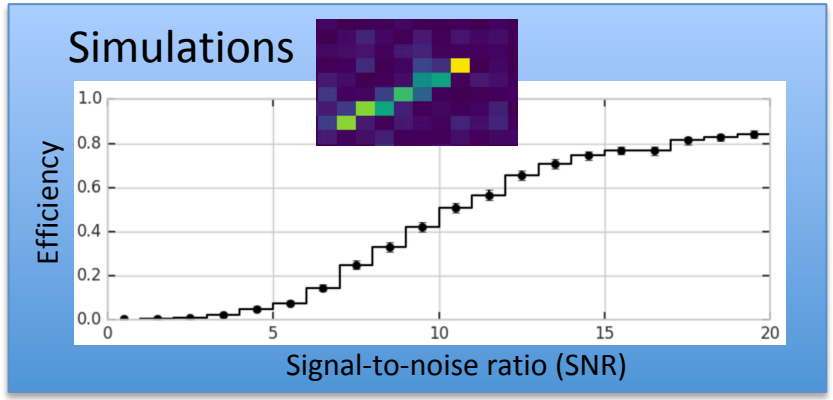
combine to get
efficiency vs. frequency

compare as
cross-check

event rate vs. frequency

Determining detection efficiency vs. frequency





reconstruction efficiency
vs. CRES event properties (e.g., SNR)

CRES event properties
(e.g., SNR)
vs. frequency

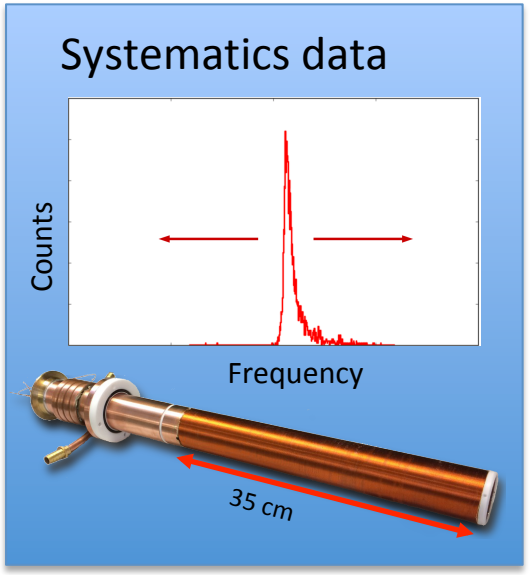
combine to get
efficiency vs. frequency

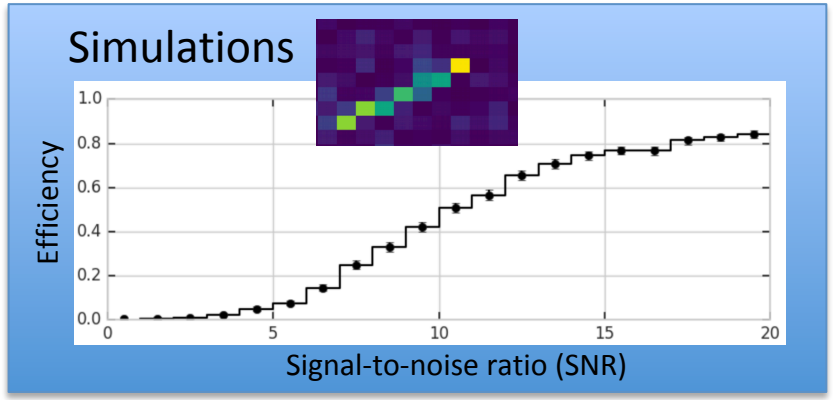
compare as
cross-check

event rate vs. frequency

Adapt efficiency vs. frequency for
tritium data
(slightly different SNR vs. frequency from Kr data...)

Determining detection efficiency vs. frequency





reconstruction efficiency
vs. CRES event properties (e.g., SNR)

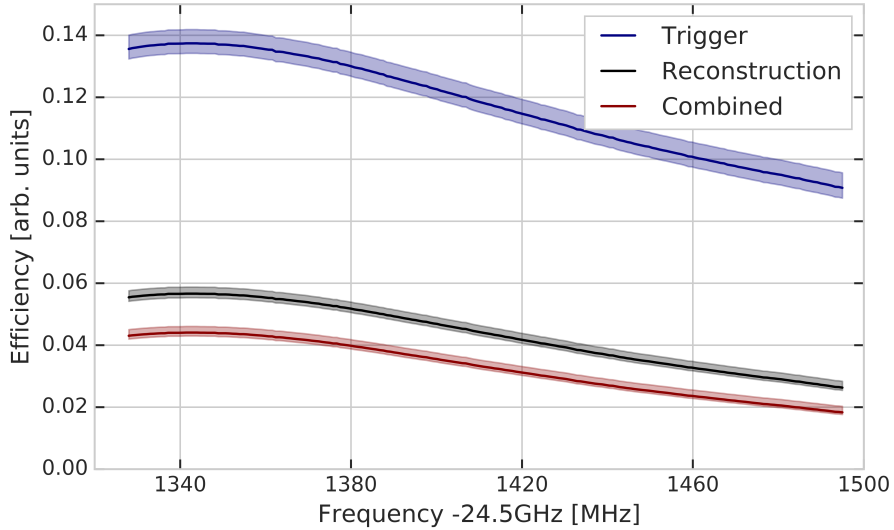
CRES event properties
(e.g., SNR)
vs. frequency

combine to get
efficiency vs. frequency

event rate vs. frequency

compare as
cross-check

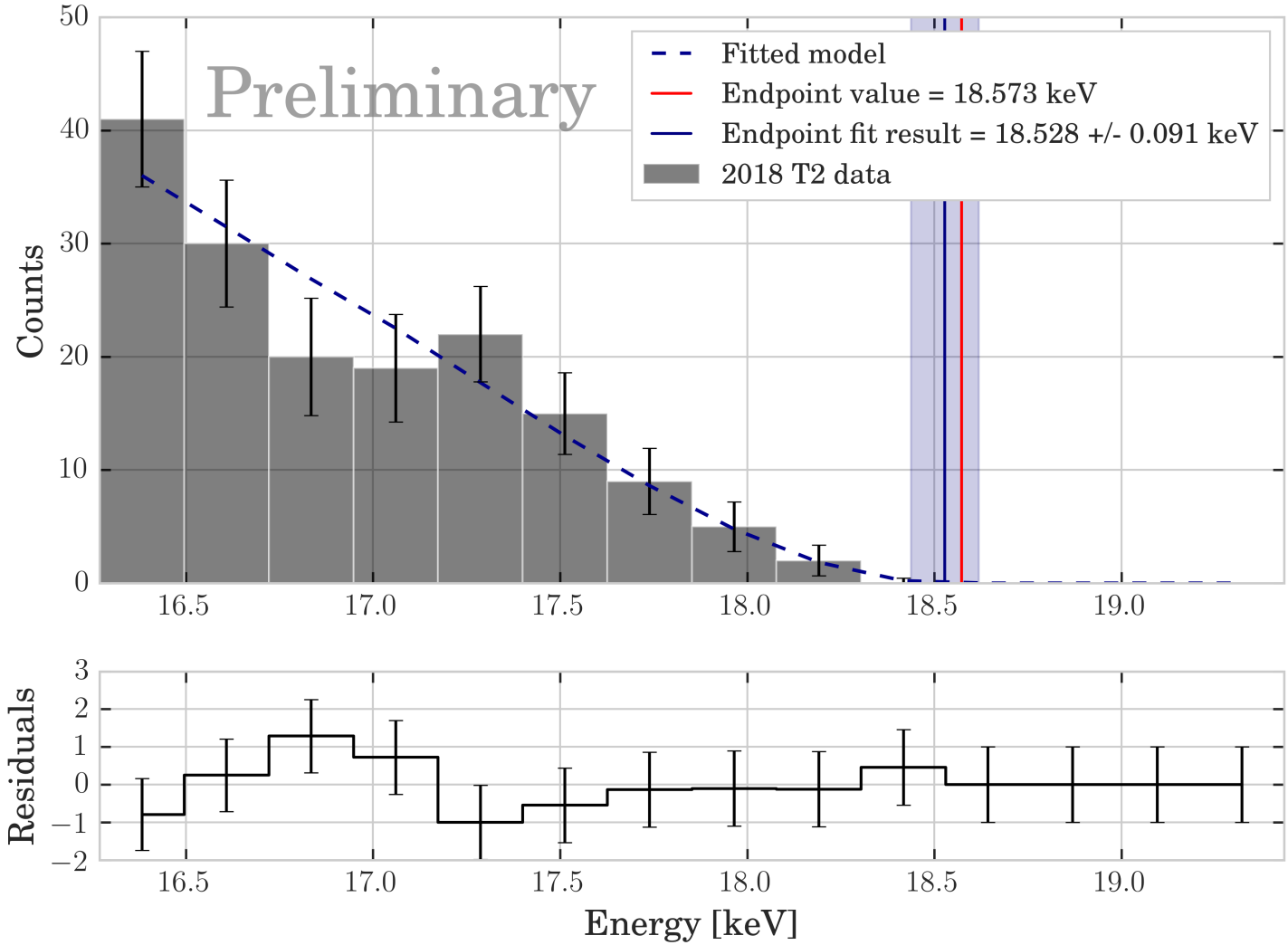
Correction to tritium spectrum!



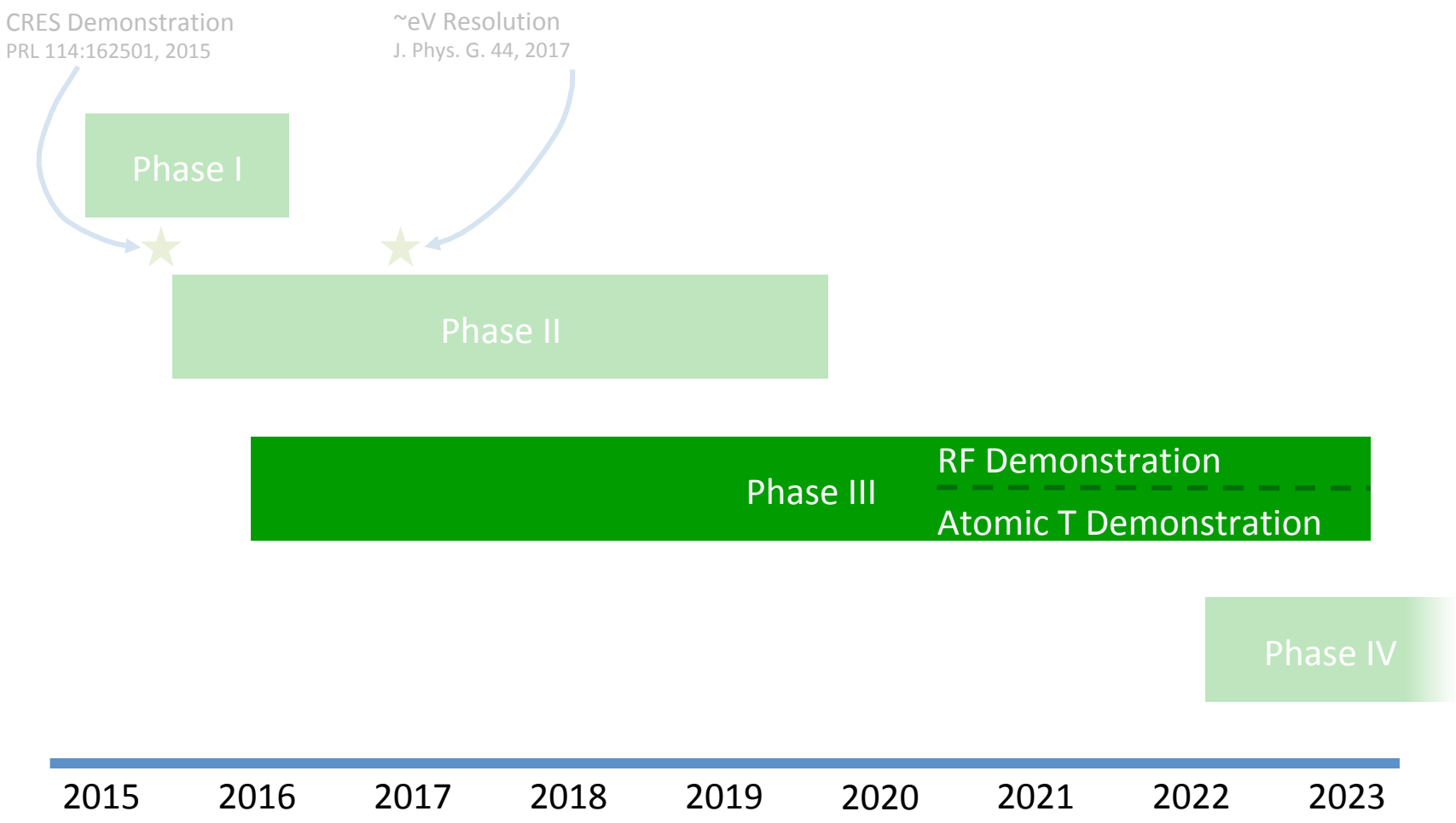
Adapt efficiency vs. frequency for
tritium data
(slightly different SNR vs. frequency from Kr data...)

First CRES tritium spectrum

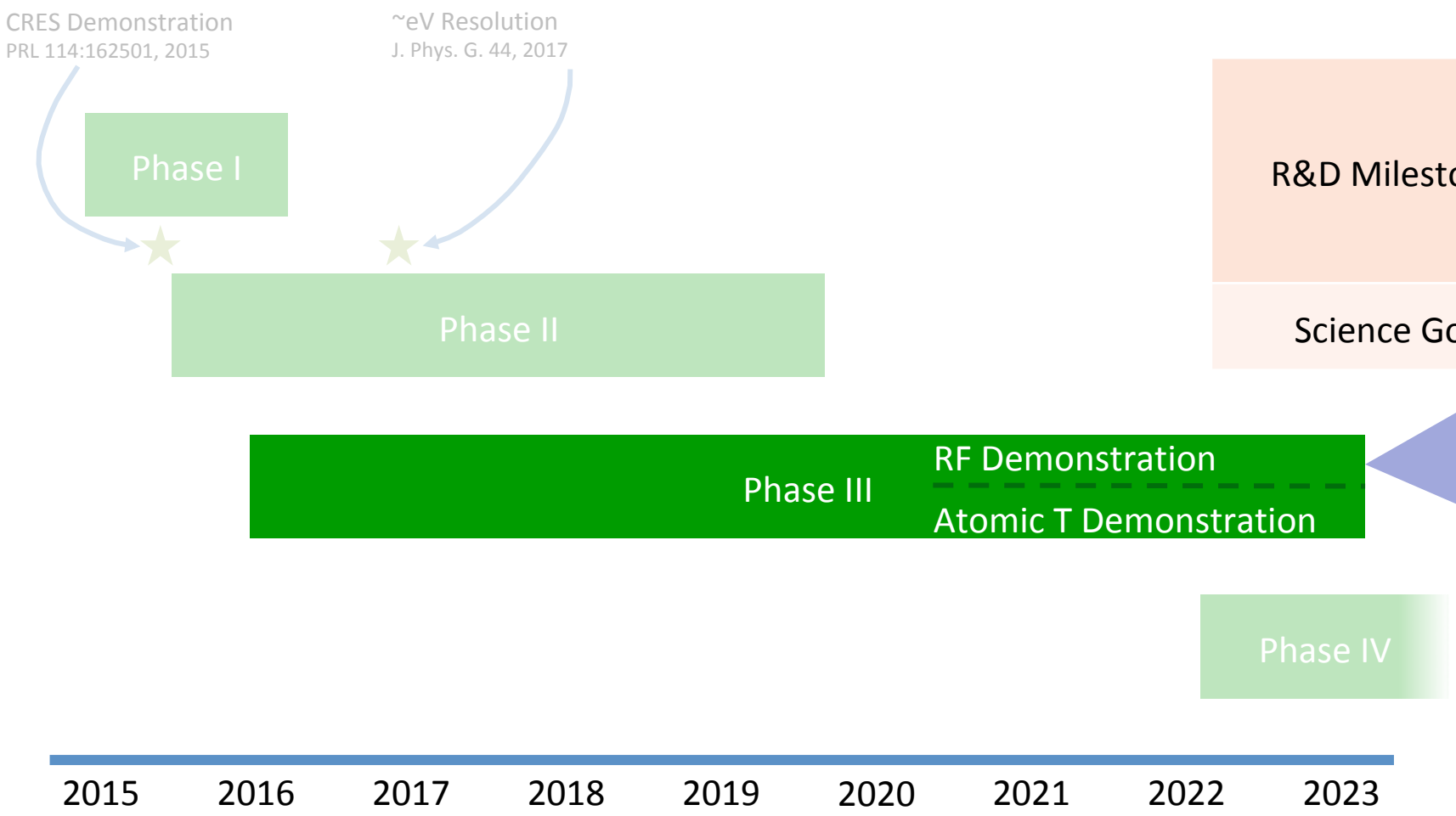
- Data from 7-day T_2 campaign
- Endpoint fit uses preliminary detection efficiency data and analysis framework
- Since then, more extensive systematics data have been taken and analysis has developed, allowing for more precise corrections in upcoming campaign
- 100-day T_2 run planned to begin later this month



Phase III: Large-volume CRES demonstration

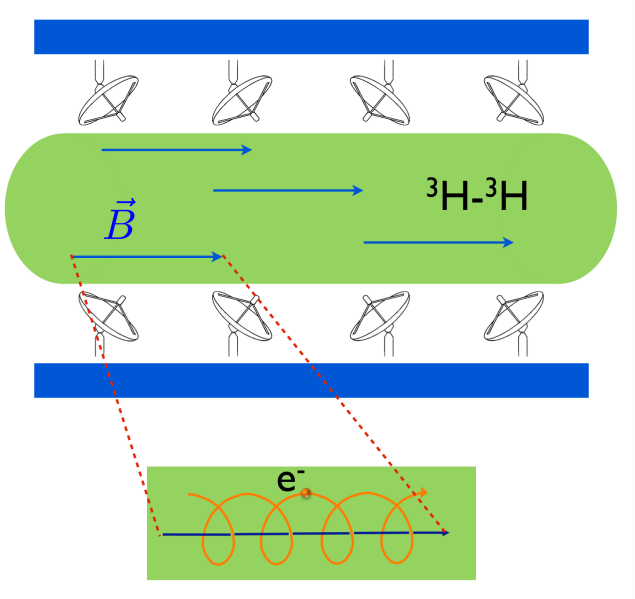


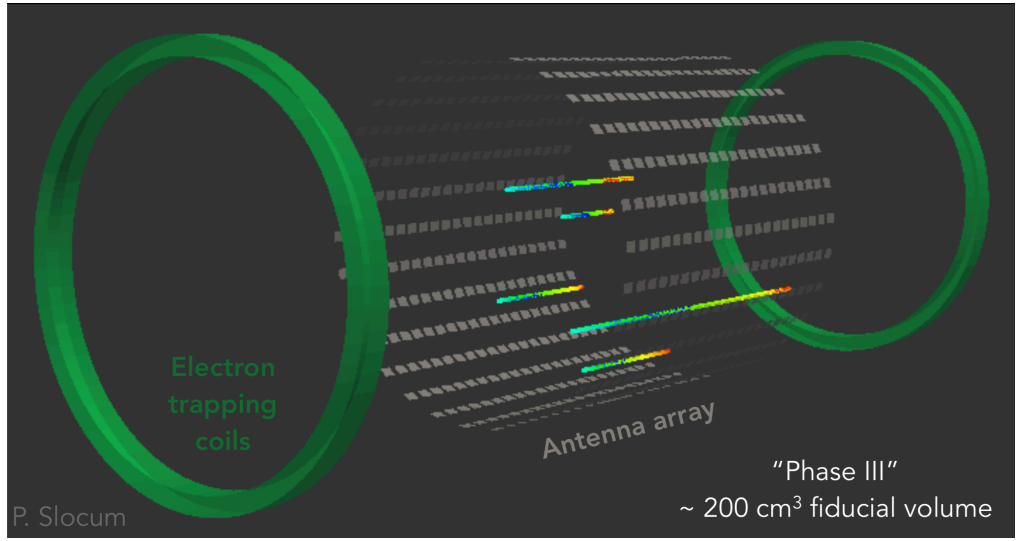
Phase III: Large-volume CRES demonstration

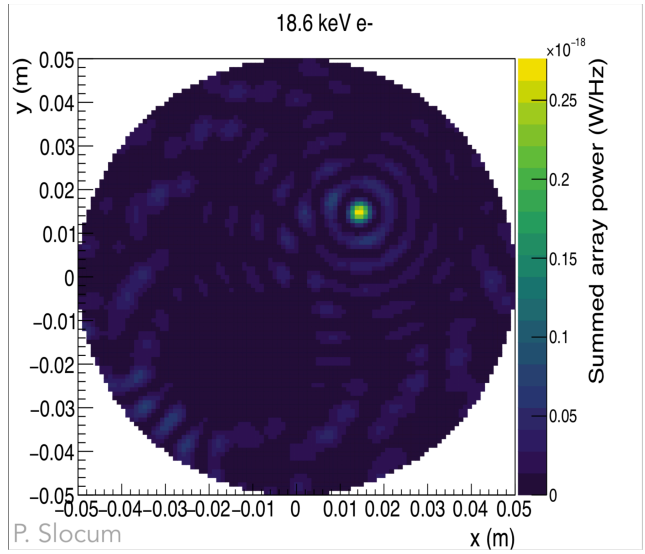


R&D Milestone	• 200 cm^3 active volume • Antenna array • B-field homogeneity
Science Goals	$m_\nu < 2\ eV/c^2$

Antenna array for large-volume CRES detector



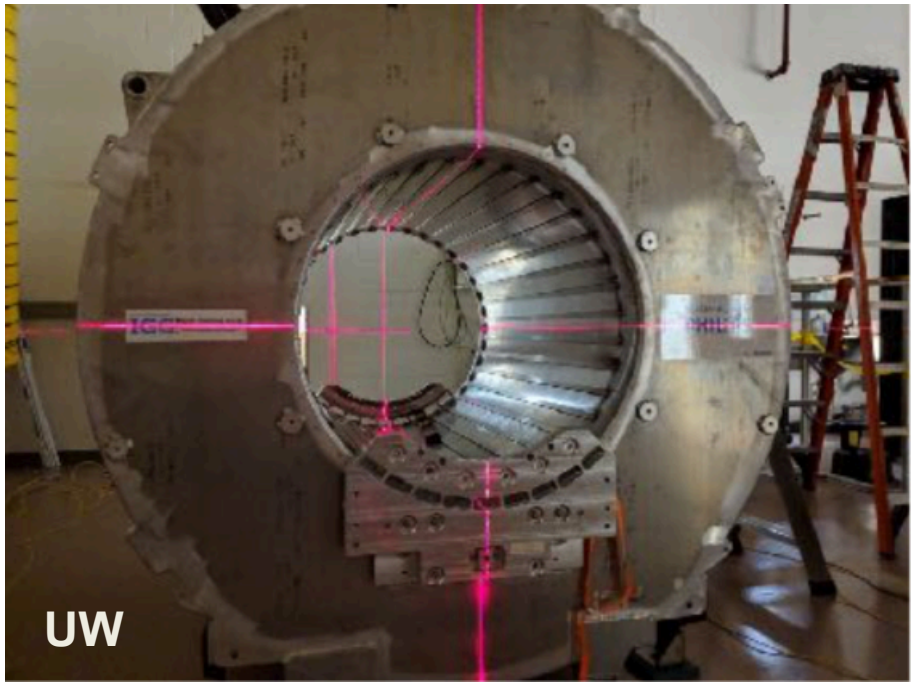


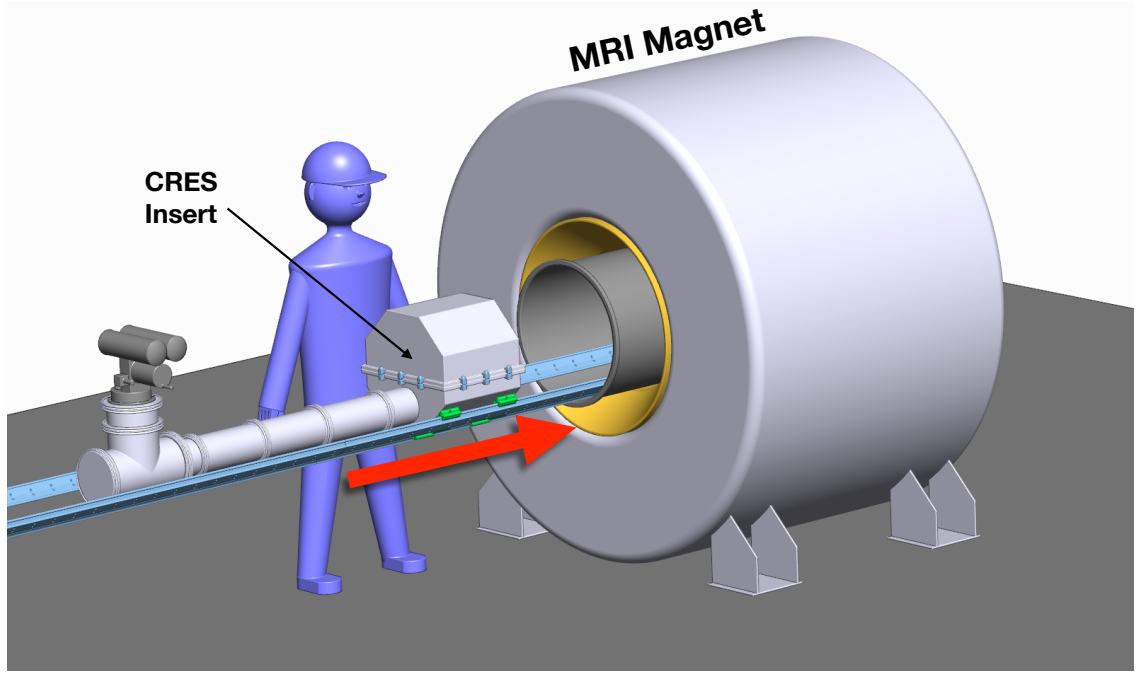


- Cyclotron radiation detected by an array of patch or slot antennas
- Multichannel, high-volume (up to a few PB) datataking will require real-time digital beamforming and track reconstruction
- Spatial tracking of electrons will enable local magnetic field corrections and counteract effects of pileup at higher gas densities
- Patch array design informed by simulations of RF detector response to time-dependent CRES fields using Project 8 Locust software (arXiv:1907.11124, 2019) and HFSS

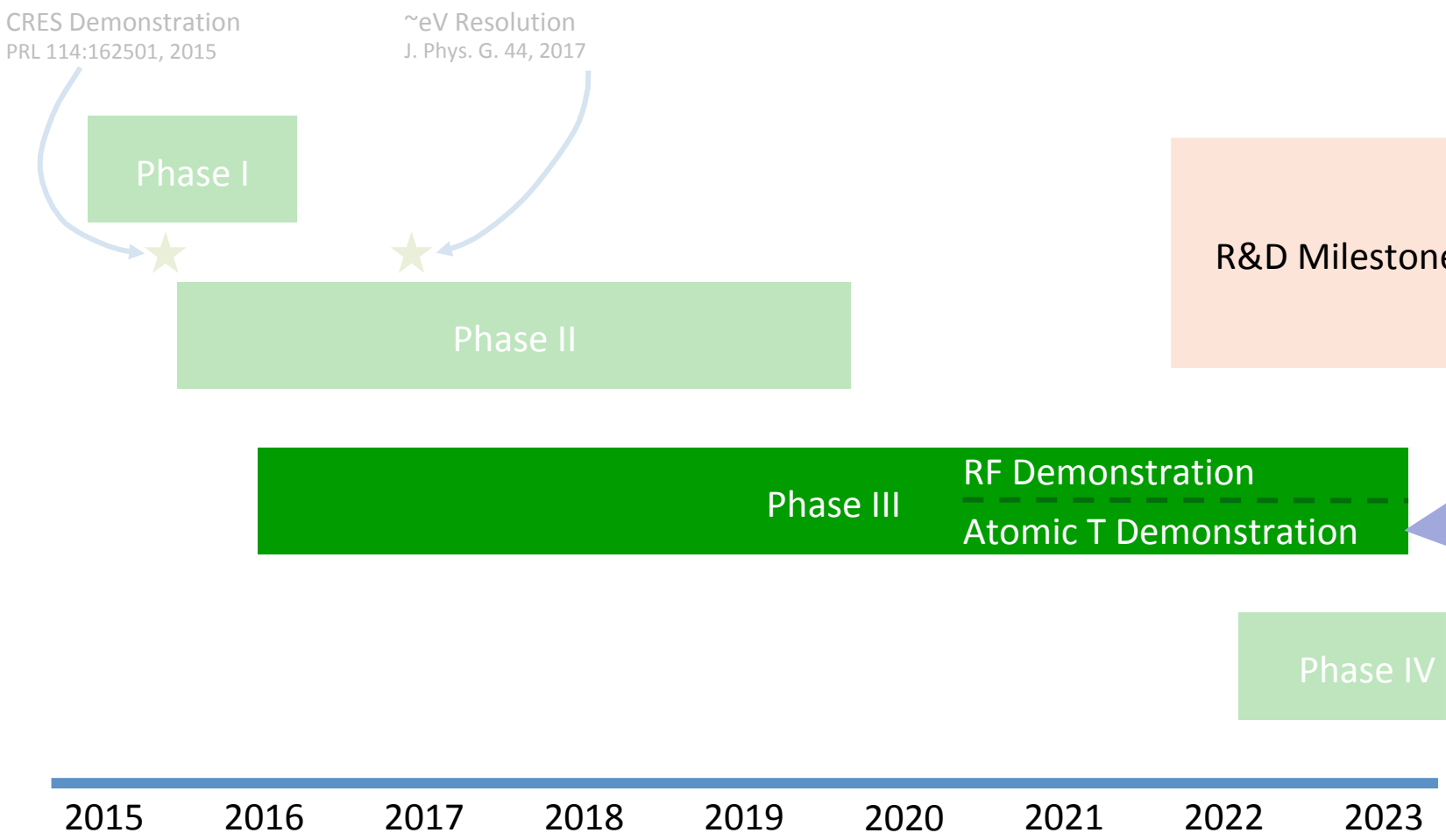
Phase III RF demonstrator

- MRI magnet at UW gives 1 ppm B homogeneity over 200 cm^3 volume
- An insert with gas cell, cryogenics, e^- trapping coils, antenna array, and field-mapping tools is under development

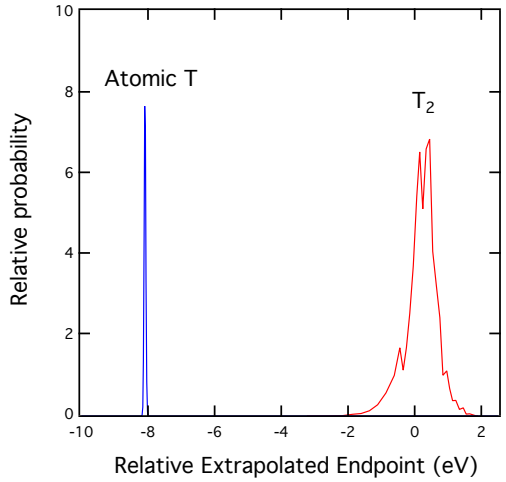




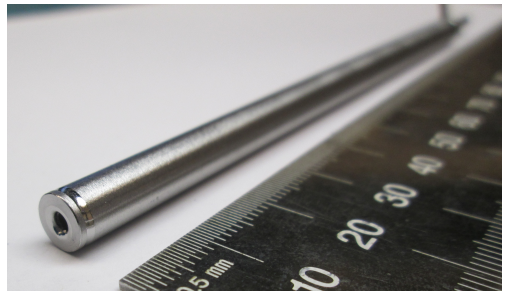
Phase III: Atomic tritium demonstration



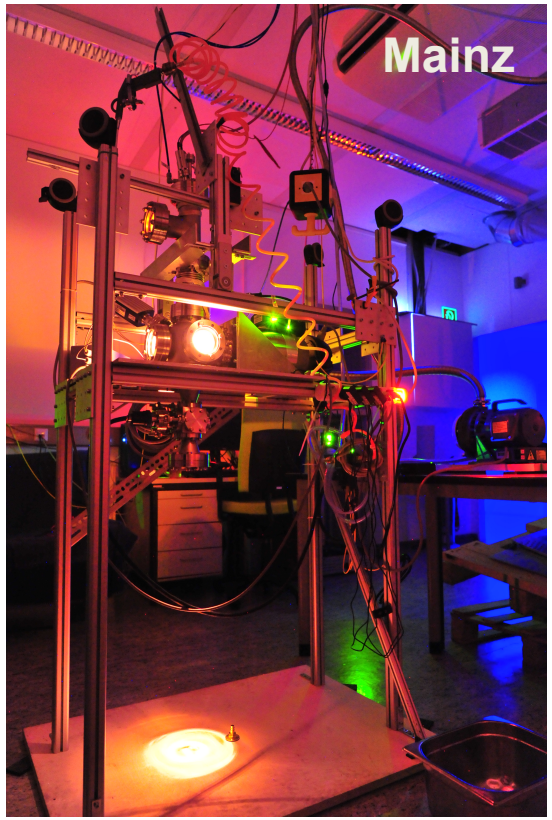
R&D Milestone	• Dissociator (cracker) • Accomodator • Velocity and state selector • Atomic Ioffe trap

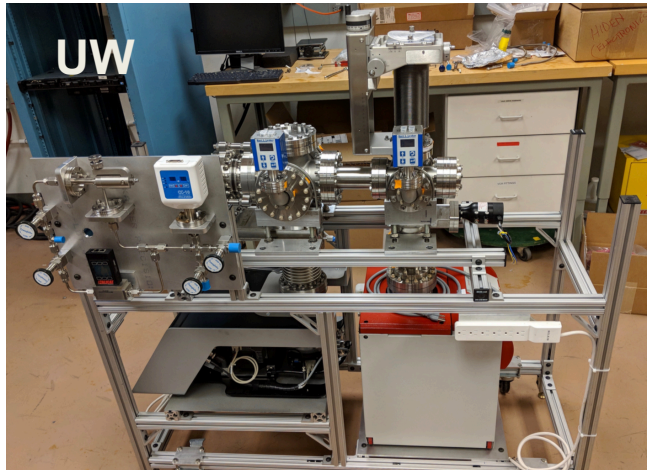


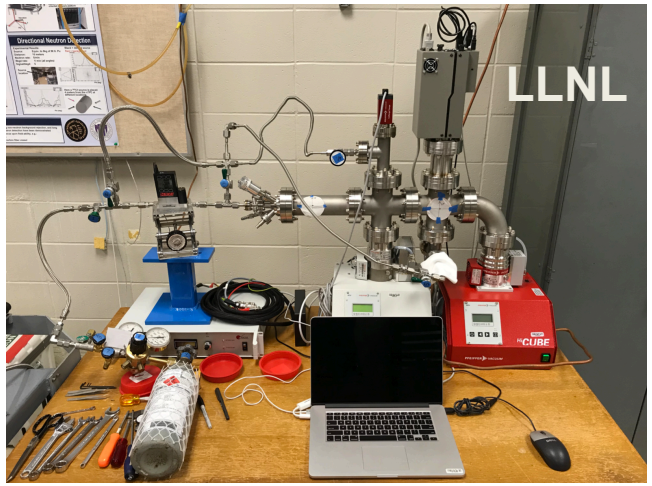
Dissociator (cracker) development



- Need cracker that
  - produces T atoms from T_2 at ~100x the flux demonstrated by commercially available crackers for H_2-> 2H
  - is compatible with tritium (cannot use RF discharge sources)
- We are exploring higher-flux ways of running commercial crackers, as well as custom crackers that increase atom flux

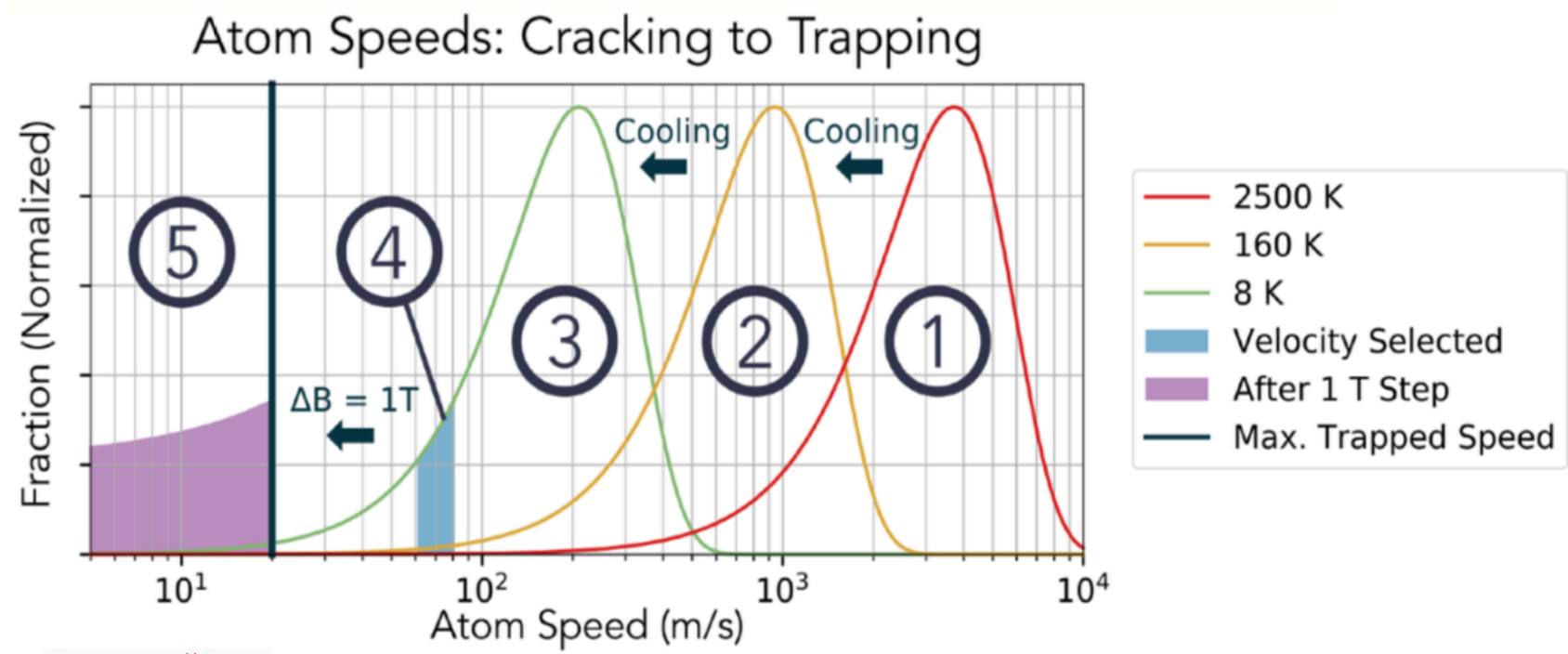




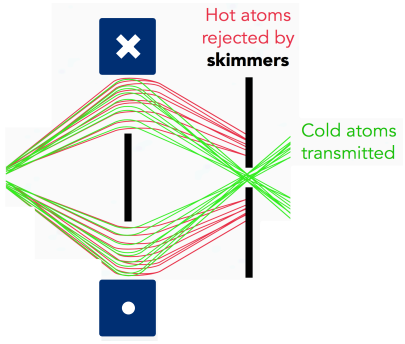


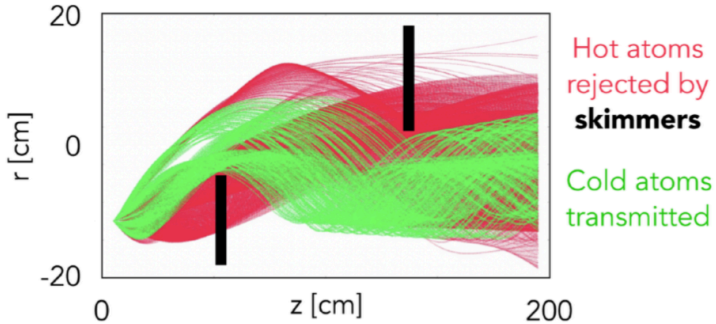
Cooling and choosing T atoms

1) Cracker
2) Accommodator
3) Nozzle
4) Velocity and state selector
5) Climb potential well into trap



Possible velocity and state selector designs under consideration:

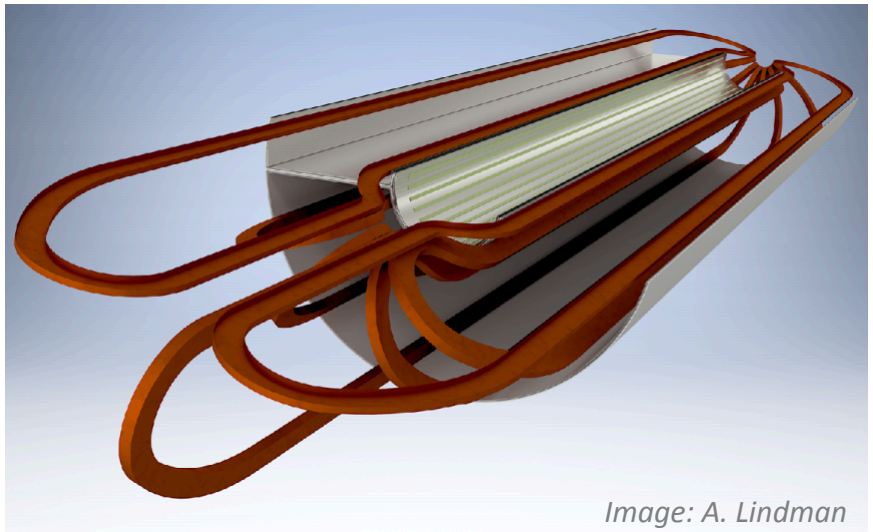


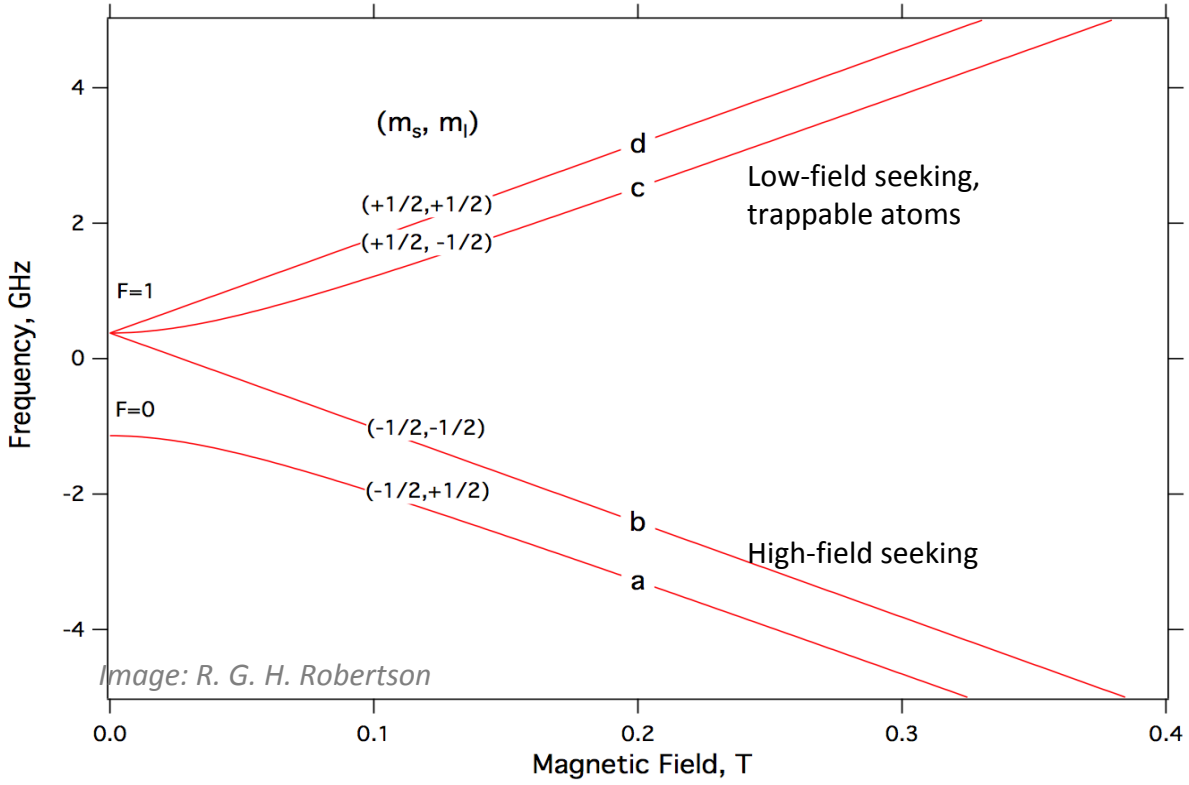


Images: A. Lindman

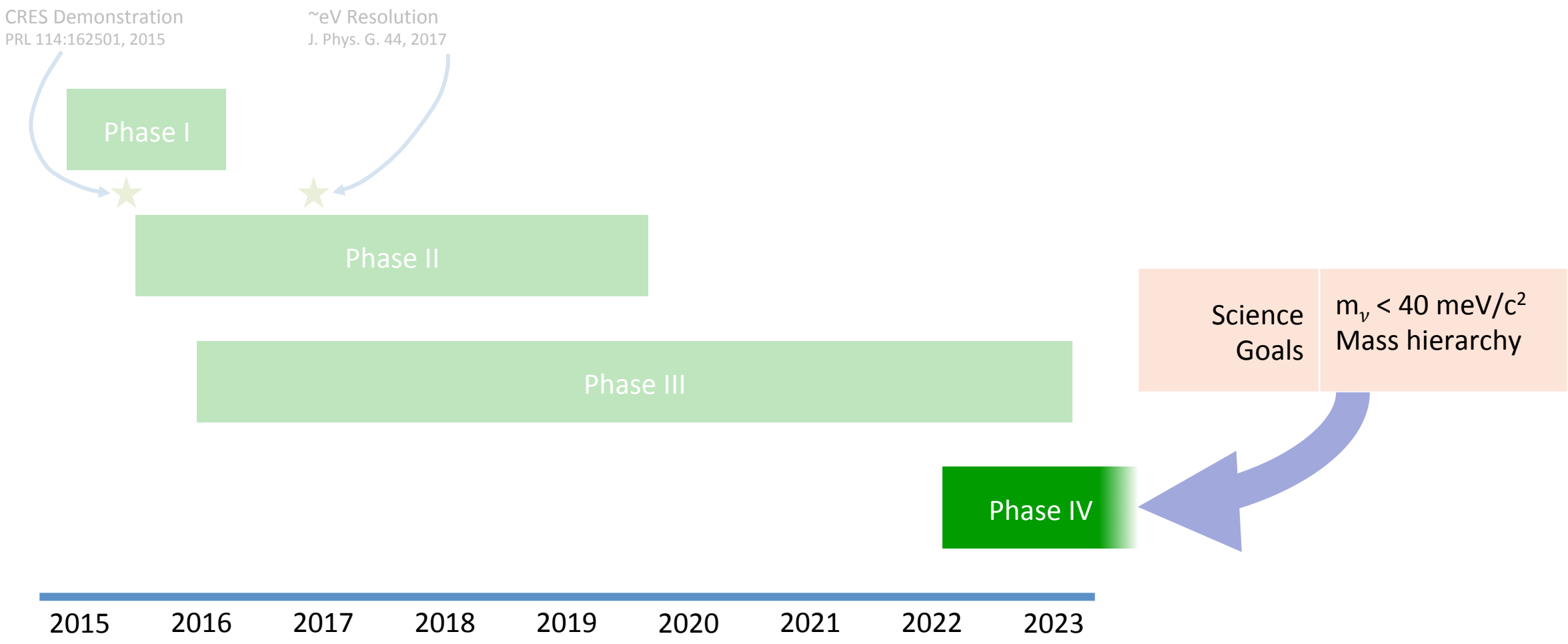
Phase III atom trapping demonstrator

- Magnetically trapping neutral tritium atoms with a Ioffe trap: need a large volume, a high B field wall, and high field homogeneity ($\Delta B/B<10^{-7}$)
- ~1 m^3 demonstrator planned to validate atom production, cooling, selection, and trapping methods



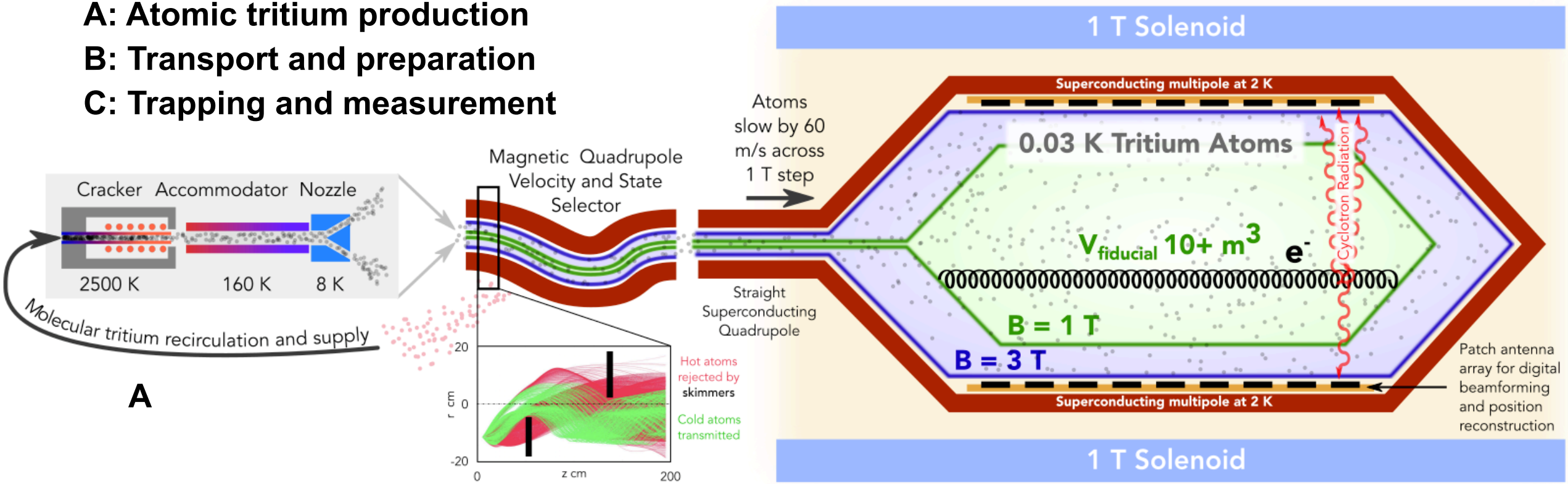


Phase IV: Putting it all together to reach target sensitivity



Conceptual design of Phase IV for 40 meV/c^2

A: Atomic tritium production
B: Transport and preparation
C: Trapping and measurement



A. Lindman

The Project 8 collaboration

See Martin Fertl (Mainz) for postdoc and graduate student opportunities!

Case Western Reserve University
- Laura Gladstone, Benjamin Monreal, Yu-Hao Sun

Harvard-Smithsonian Center for Astrophysics
- Sheperd Doeleman, Jonathan Weintroub, André Young

Johannes Gutenberg-Universität Mainz
- Sebastian Böser, Christine Claessens, Martin Fertl, Michael Gödel, Alec Lindman

Karlsruher Institut für Technologie
- Thomas Thümmler

Lawrence Livermore National Laboratory
- Kareem Kazkaz, Lucie Tvrznikova

Massachusetts Institute of Technology
- Zachary Bogorad, Nicholas Buzinsky, Joseph Formaggio, Talia Weiss, Evan Zayas

Pacific Northwest National Laboratory
- Mathieu Guigue, Mark Jones, Benjamin LaRoque, Erin Morrison, Noah Oblath, Malachi Schram, Jonathan Tedeschi, Brent VanDevender, Mathew Thomas, Maurio Grando

Pennsylvania State University
- Luiz de Viveiros, Timothy Wendler, Andrew Ziegler

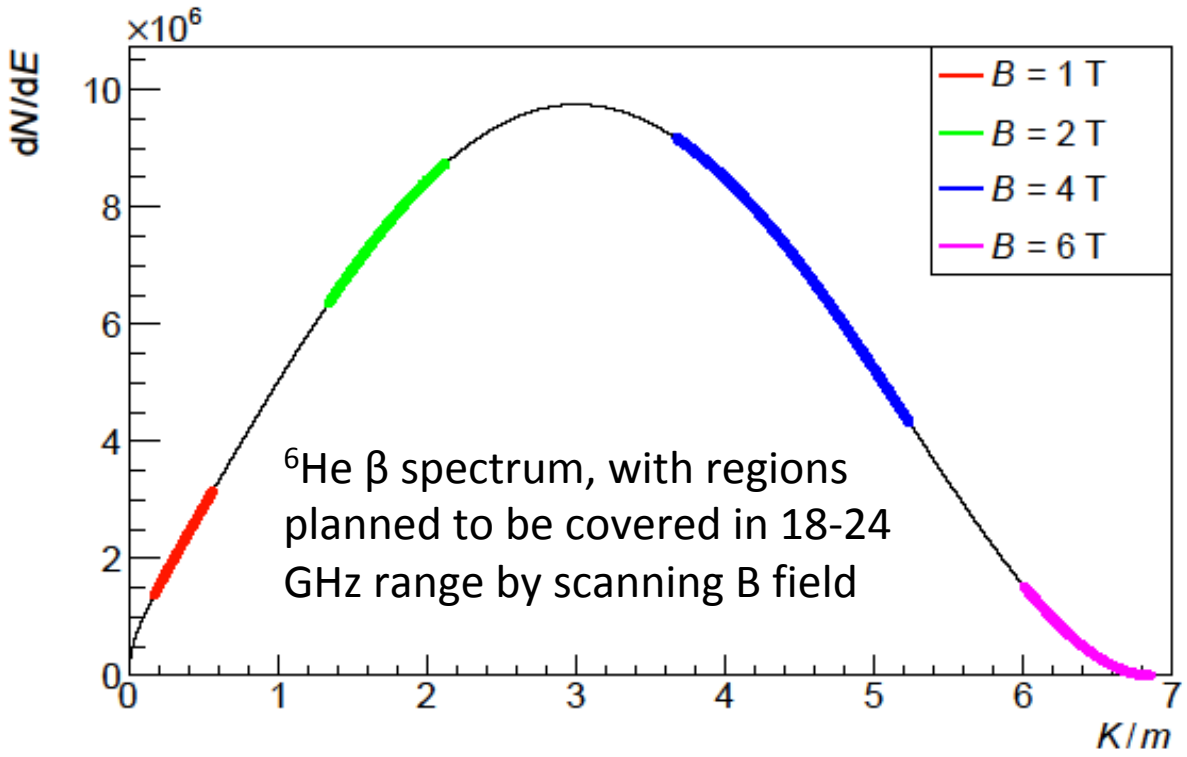
University of Washington
- Ali Ashtari Esfahani, Raphael Cervantes, Peter Doe, Eric Machado, Elise Novitski, Walter Pettus, Hamish Robertson, Leslie Rosenberg, Gray Rybka

Yale University
- Karsten Heeger, James Nikkel, Luis Saldaña, Penny Slocum, Pranava Teja Surukuchi, Arina Telles

This work was 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 collaborating institutions

Searching for chirality-flipping interactions with CRES

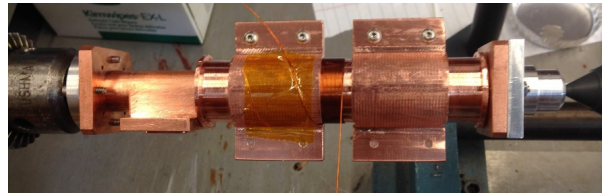
- Search for tensor couplings not present in the Standard Model, which distort β-decay spectra
- Goal: determine shape of ^{6}He β^{-} spectrum to measure "little *b*" Fierz interference term to better than 10^{-3}
- Requires extending the CRES technique to higher energy betas and to a precision determination of a continuum spectrum. Non-trivial: under development.
- Monte Carlo simulations predict 1 day of running would determine *b* one order of magnitude better than any previous experiment.
- Measurements on ^{14}O and ^{19}Ne, with different *b*s, give handle on systematic effects

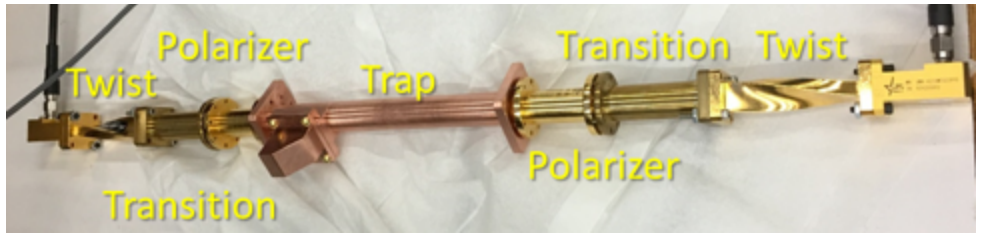


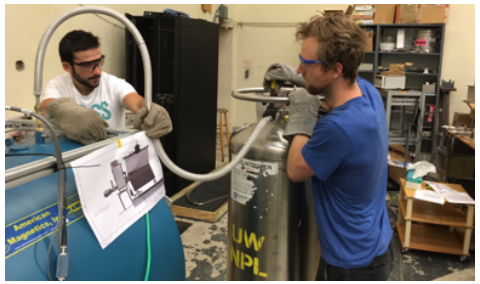
Distortion due to new physics would go like 1/E

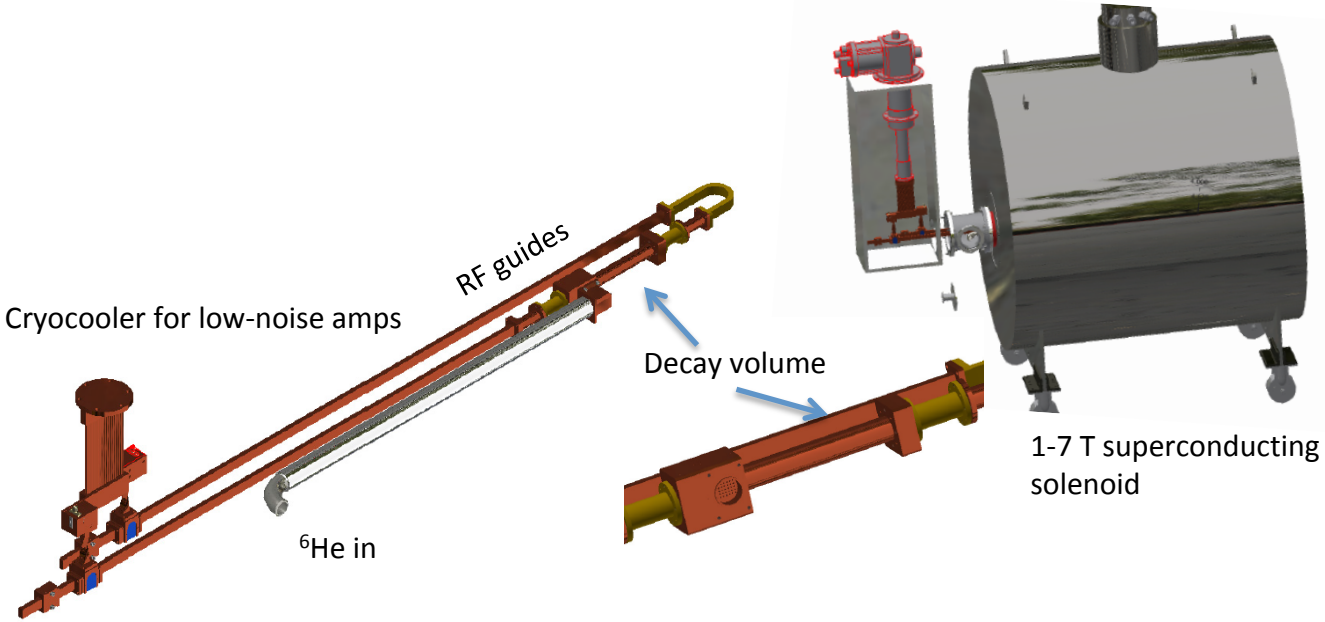
Searching for chirality-flipping interactions with CRES

- ^{6}He experiment under construction at CENPA at the University of Washington
- Collaboration: W. Byron[1], M. Fertl[1], A. Garcia[1], G. Garvey[1], B. Graner[1], M. Guigue[4], K.S. Khaw[1], A. Leredde[2], P. Mueller[2], N. Oblath[4], R.G.H. Robertson[1], G. Rybka[1], G. Savard[2], D. Stancil[3], H.E. Swanson[1], B.A. Vandevender[4], F. Wietfeldt[5], A. Young[3]
  [1]University of Washington, [2]Argonne National Lab, [3]North Carolina State University, [4]Pacific Northwest National Laboratory, [5]Tulane University
- **Phase I:** proof of principle of CRES using ^{6}He
- **Phase II:** first measurement ($b < 10^{-3}$)
- **Phase III:** ultimate measurement ($b < 10^{-4}$)



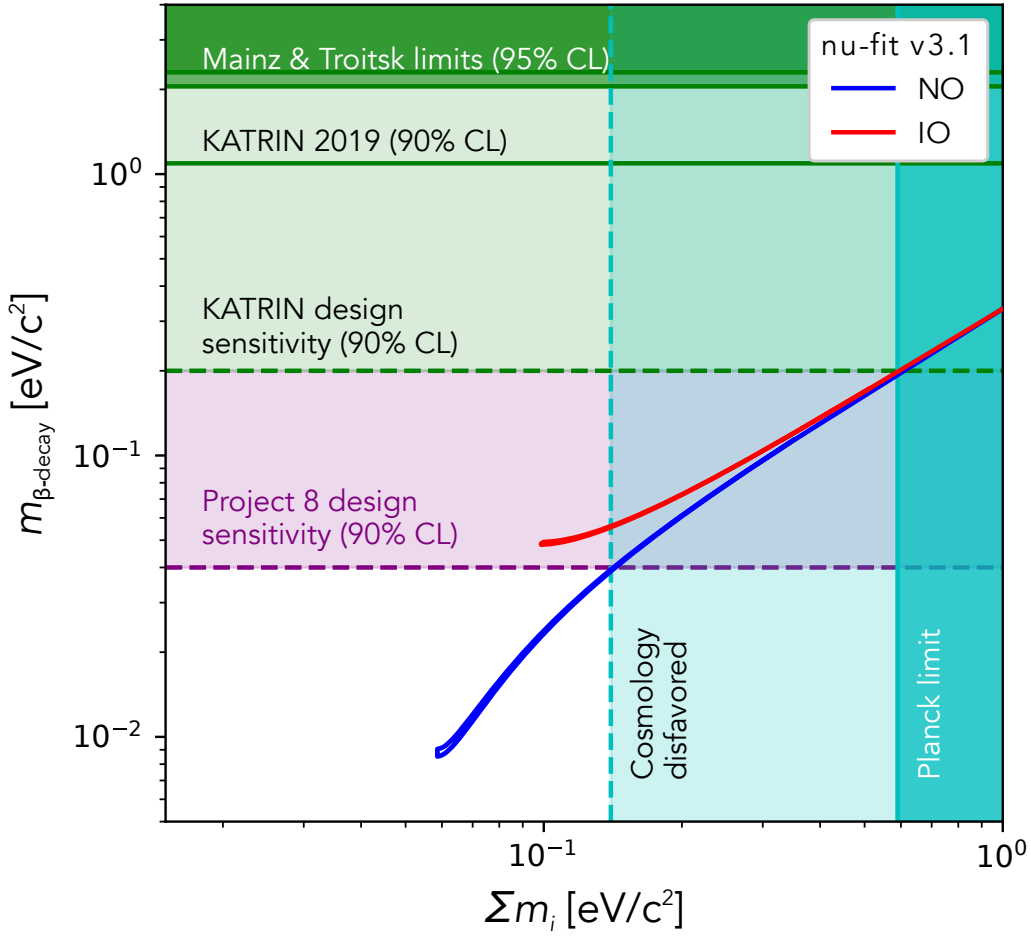






Takeaways

- Cyclotron Radiation Emission Spectroscopy (CRES) is a promising new frequency-based technique with applications in precision β^- spectroscopy
- Project 8 uses CRES for a direct neutrino mass measurement
  - Phase II: Demonstration of high resolution, low background, understanding of systematic effects, and preliminary measurement of continuous β^- spectrum from T_2 in a small-scale waveguide-based apparatus
  - Phase III: Demonstration of free-space RF detection techniques for larger volumes, as well as production, cooling, selection, and trapping methods for atomic tritium
  - Phase IV: Aiming for 40 meV/c^2 sensitivity direct neutrino mass measurement



- CRES search for chirality-flipping interactions in higher-energy ^{6}He β^- decay promises to improve measurement of Fierz interference term "little *b*" to better than 10^{-3}