



**PROJECT 8**

# The Project 8 Neutrino-Mass Experiment

Neutrino 2020 — June 22

**Noah S. Oblath**  
For the Project 8 Collaboration



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

# Outline

**PROJECT 8**

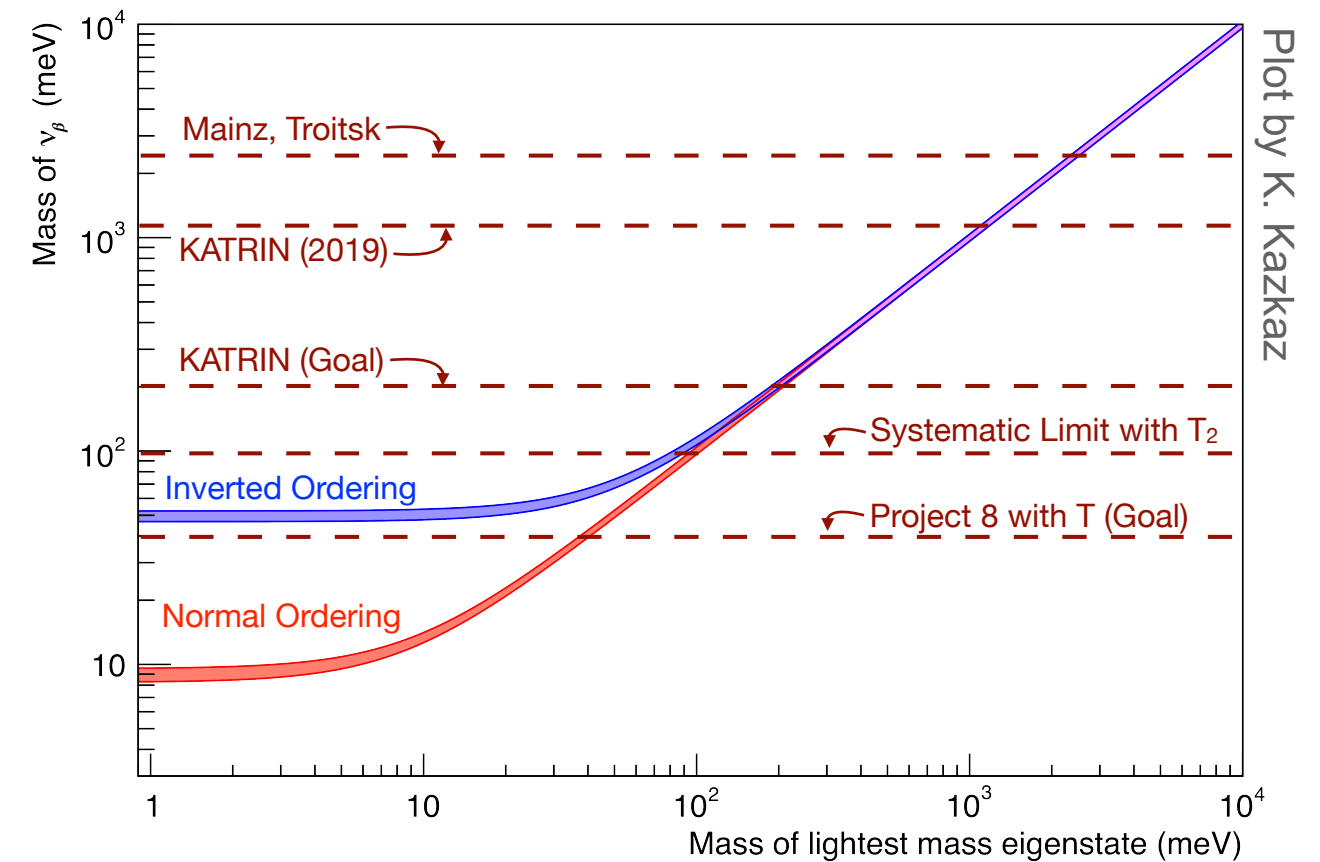
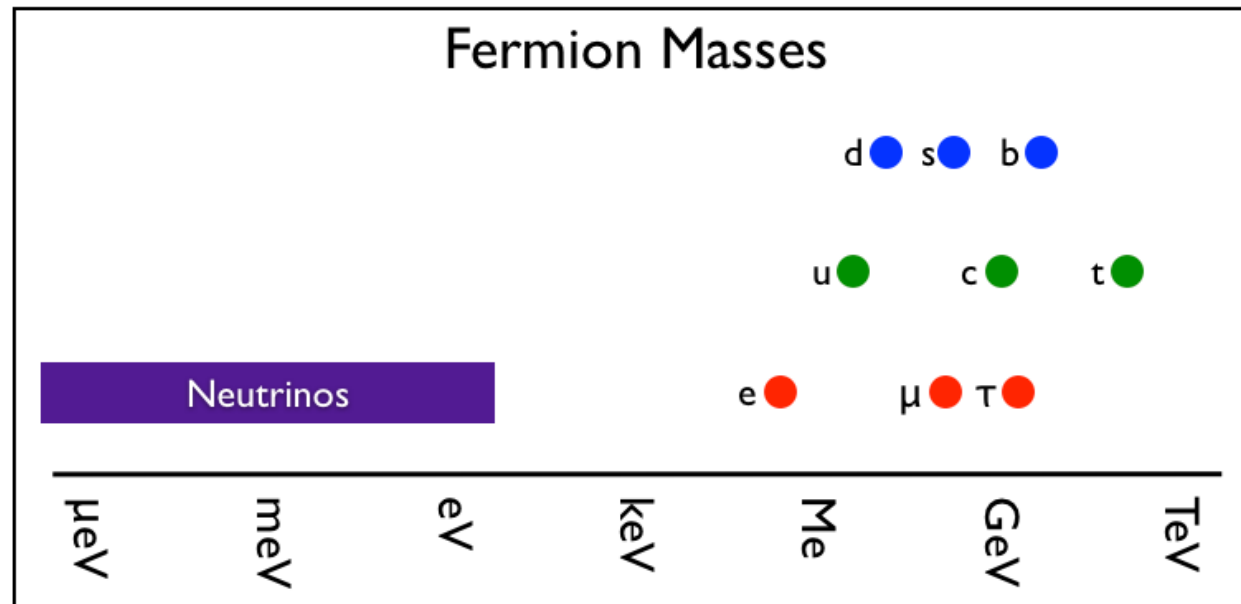
- Motivation
- CRES – Cyclotron Radiation Emission Spectroscopy
- Phase I – CRES Demonstration
- Phase II – Tritium Measurement
- Phase III – Critical R&D
- Phase IV – Final Sensitivity



# Ultra-Brief Introduction to Neutrino Mass

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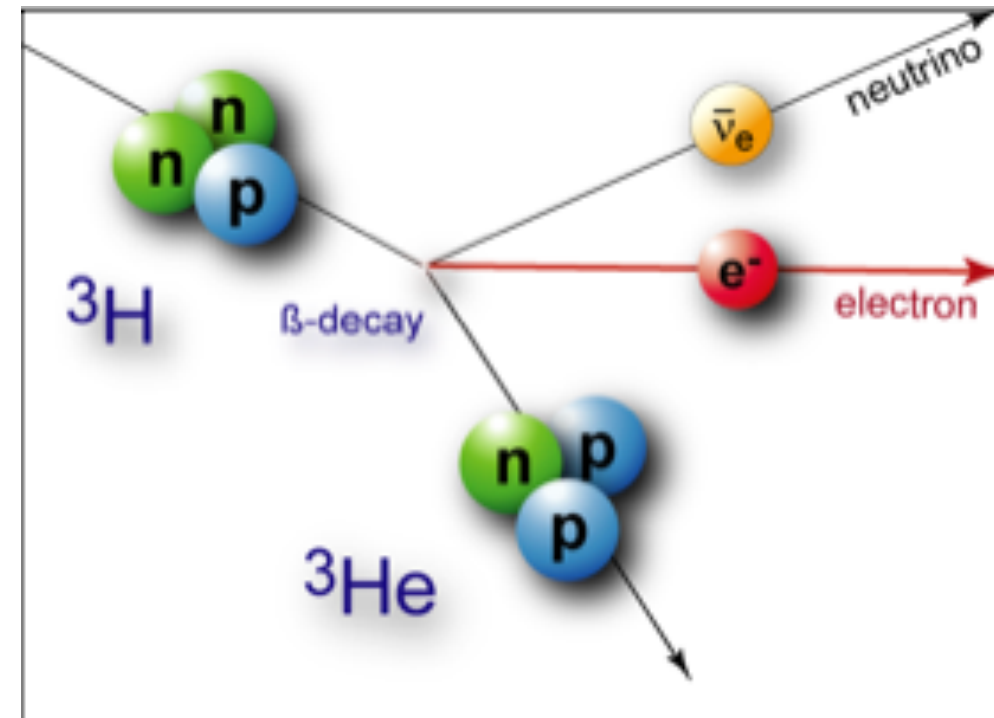
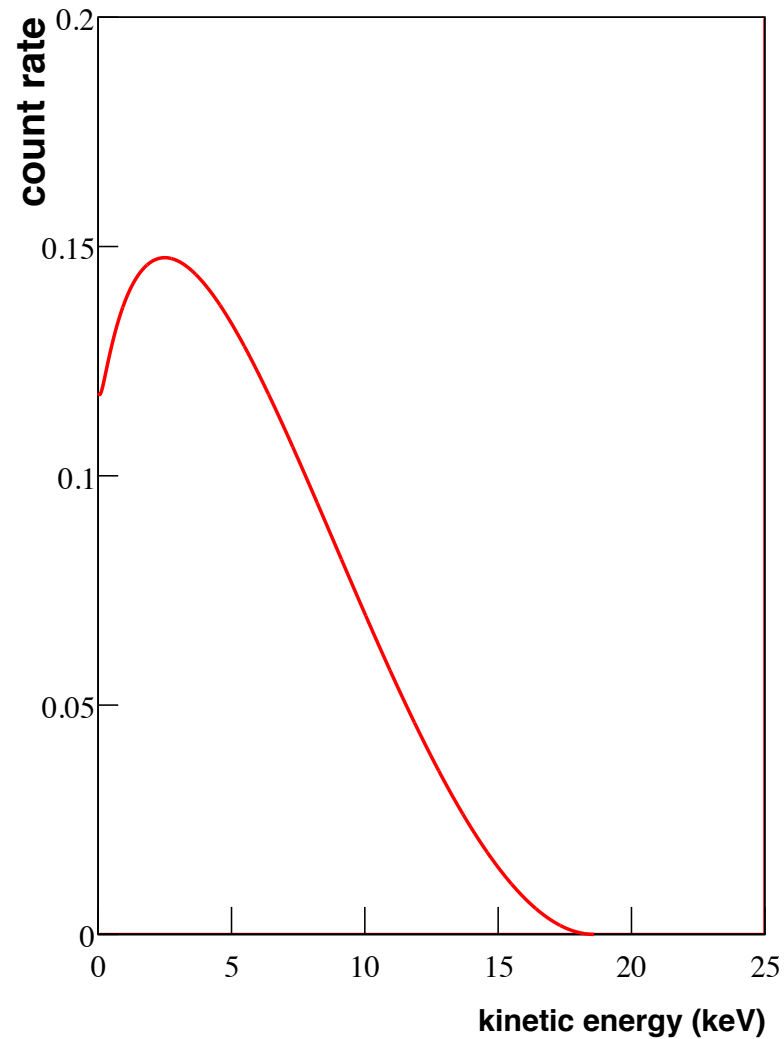
- Neutrinos have non-zero mass  
→ 2015 Nobel Prize
- Measuring the neutrino mass is one of the major open questions in particle physics
- Current direct measurements place the upper limit at  $1.1 \text{ eV}/c^2$   
KATRIN Collaboration, Phys. Rev. Lett. 123 (2019) 221803



# Using Tritium Beta Decay

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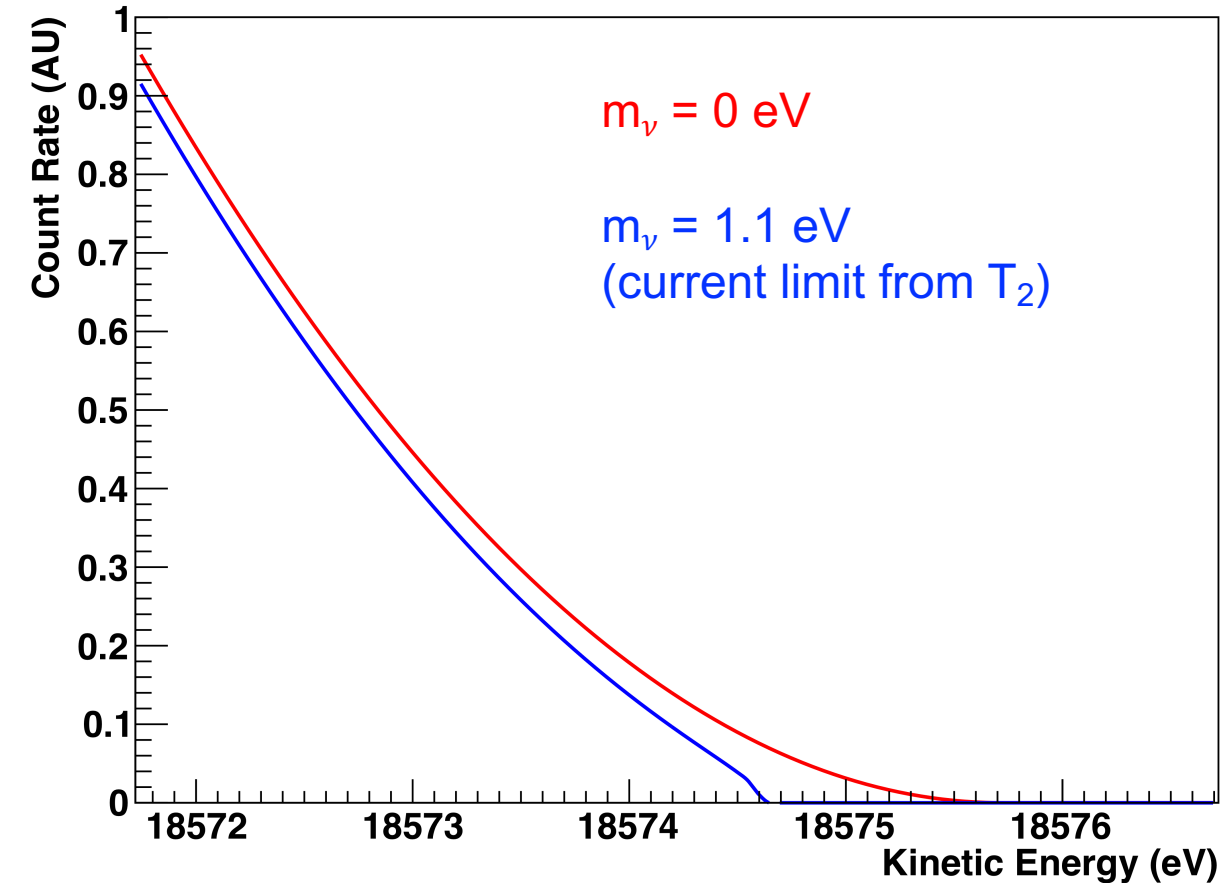
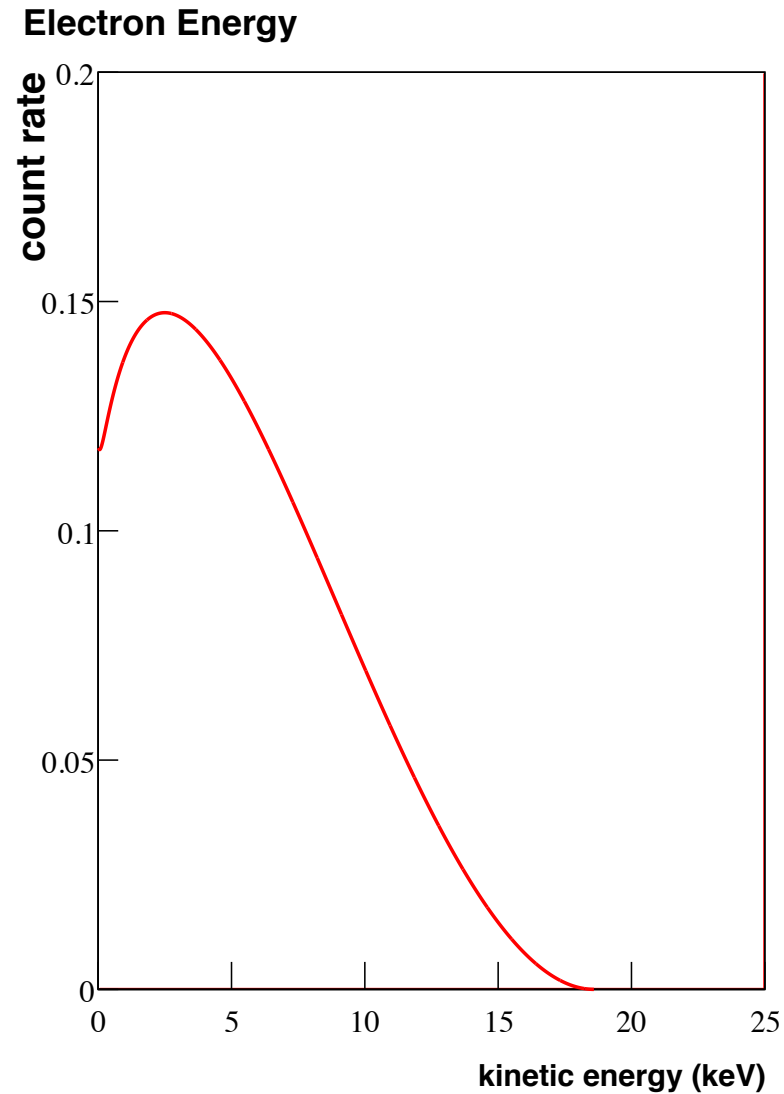
Electron Energy



$$\frac{dN}{dE} = CF(Z, E)p(E + m_e c^2)(E_0 - E) \sum_i |U_{ei}|^2 \sqrt{(E_0 - E)^2 - m_i^2}$$

# Using Tritium Beta Decay

Zoom in on the endpoint...



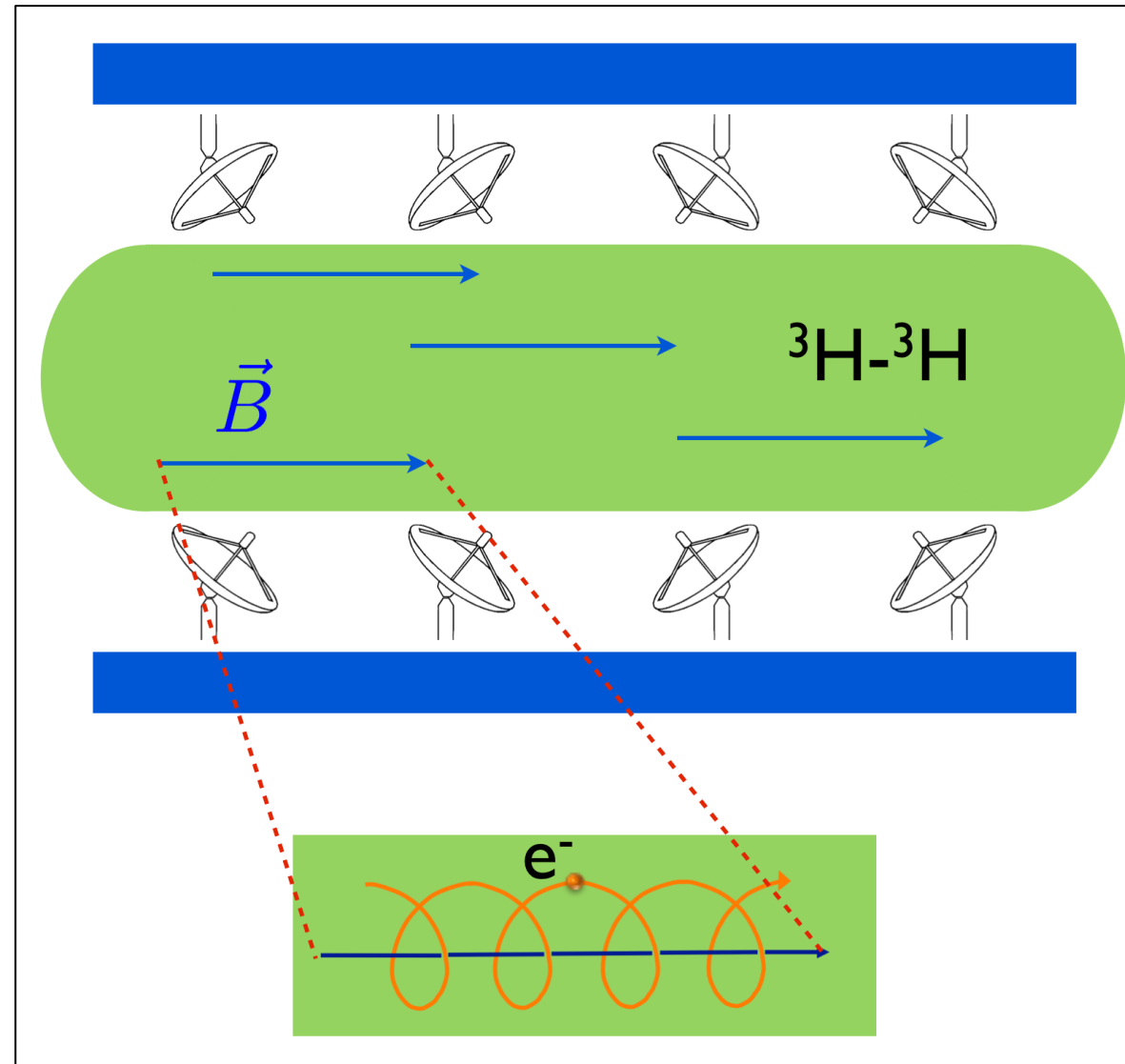
$$\frac{dN}{dE} = CF(Z, E)p(E + m_e c^2)(E_0 - E) \sum_i |U_{ei}|^2 \sqrt{(E_0 - E)^2 - m_i^2}$$

Current limit: KATRIN Collaboration, Phys. Rev. Lett. 123 (2019) 221803

# Cyclotron Radiation Emission Spectroscopy

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1. Start with an enclosed volume
2. Fill with tritium gas
3. Add a magnetic field



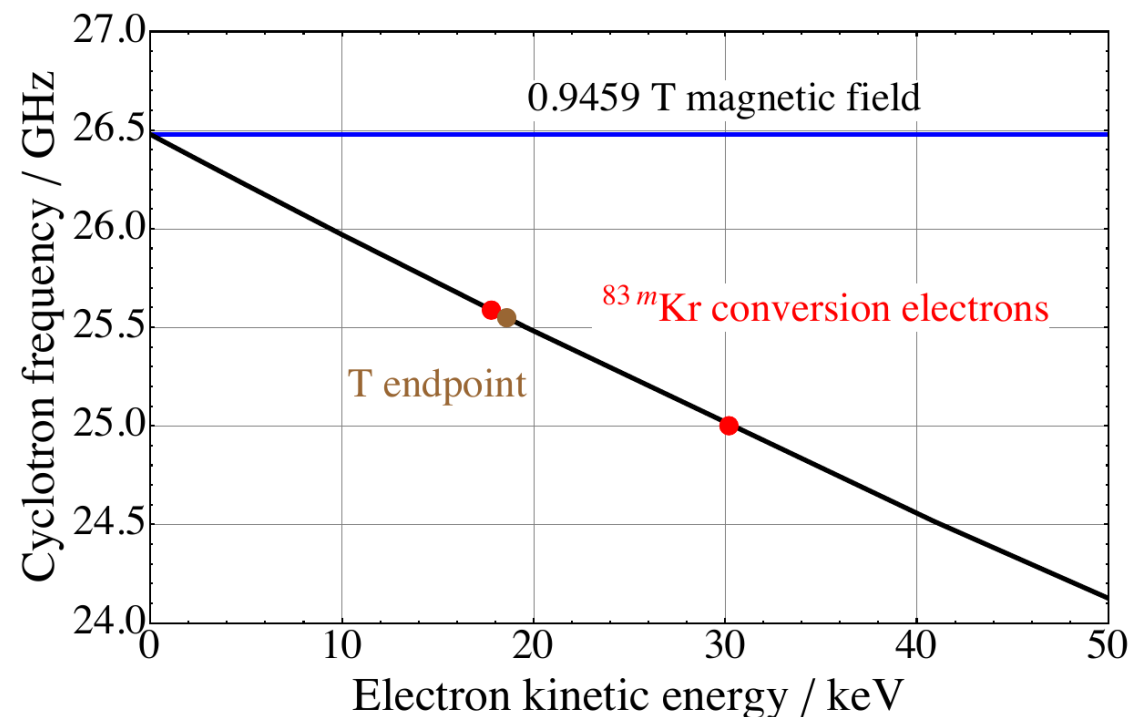
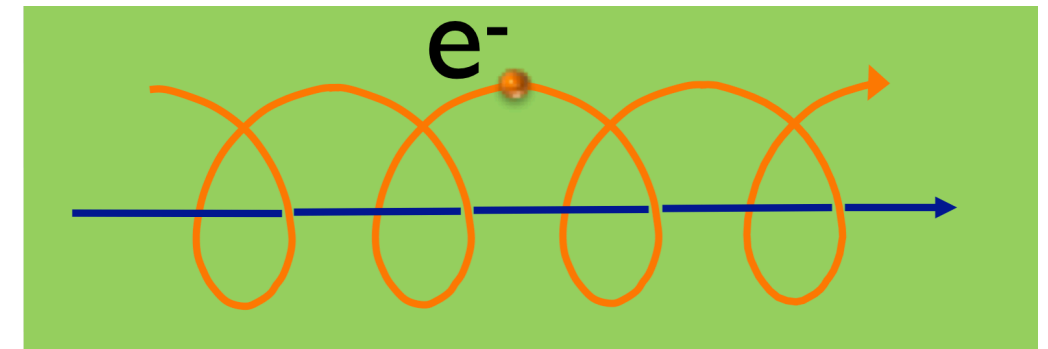
4. Decay electrons spiral around field lines
5. Add antennas to detect the cyclotron radiation

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

# Cyclotron Radiation

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- An electron traveling in a magnetic field emits cyclotron radiation
- The frequency of the emitted radiation depends on the relativistic boost



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

# The Project 8 Experiment

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CRES Demonstration  
PRL 114:162501, 2015

$\sim$ eV Resolution  
J. Phys. G. 44, 2017

Phase I

Phase II

Phase III

Phase IV

Science Goals

$m_\nu < 40 \text{ meV}/c^2$   
Mass hierarchy

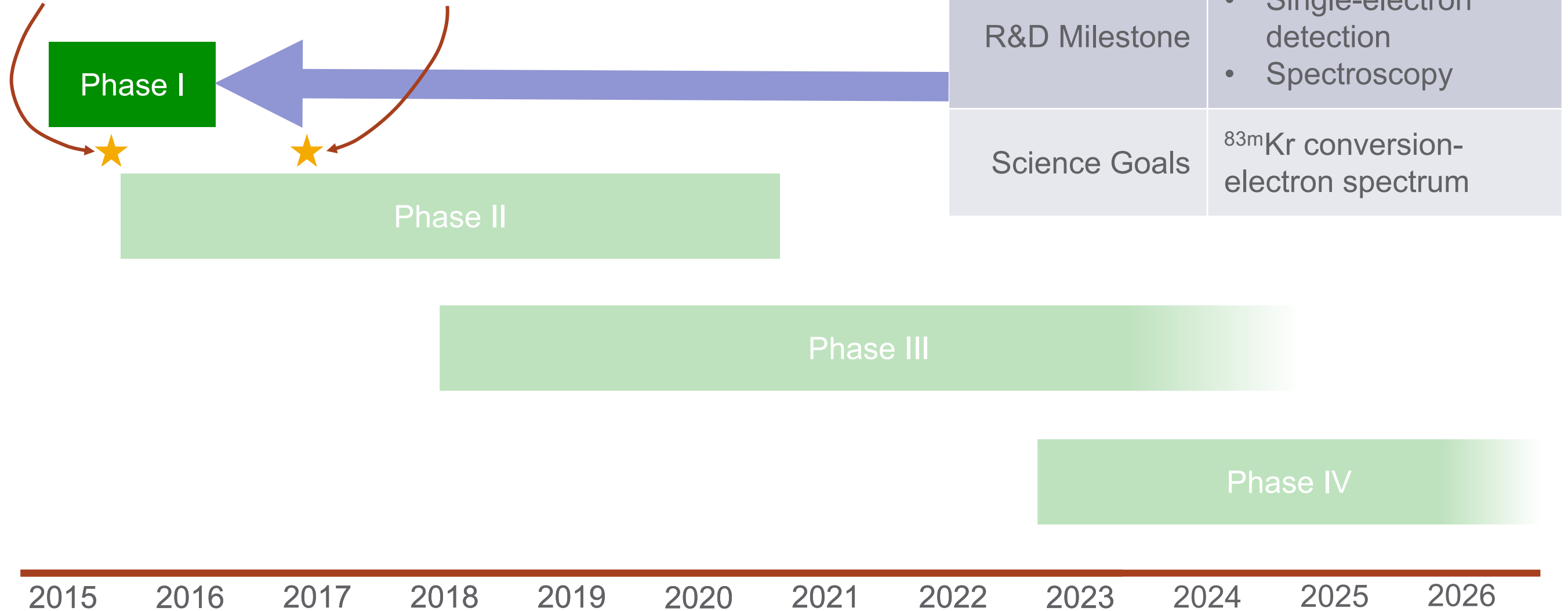
2015 2016 2017 2018 2019 2020 2021 2022 2023 2024 2025 2026

# The Project 8 Experiment

**PROJECT 8**

CRES Demonstration  
PRL 114:162501, 2015

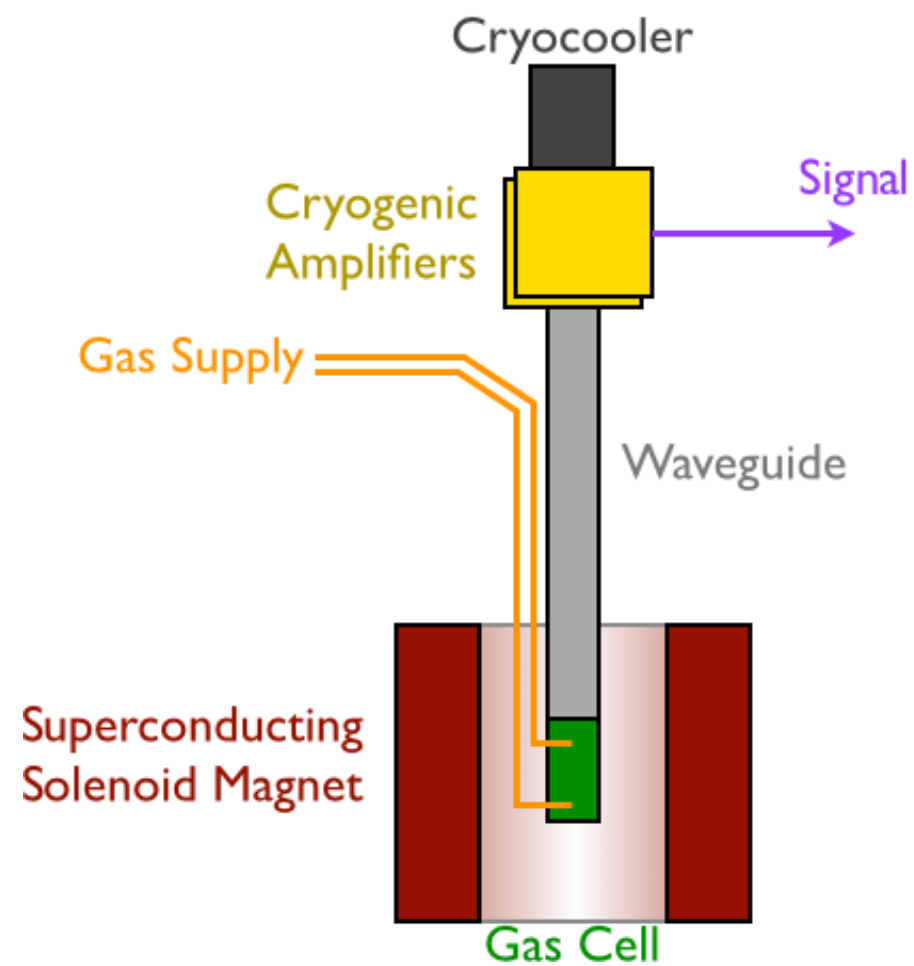
~eV Resolution  
J. Phys. G. 44, 2017



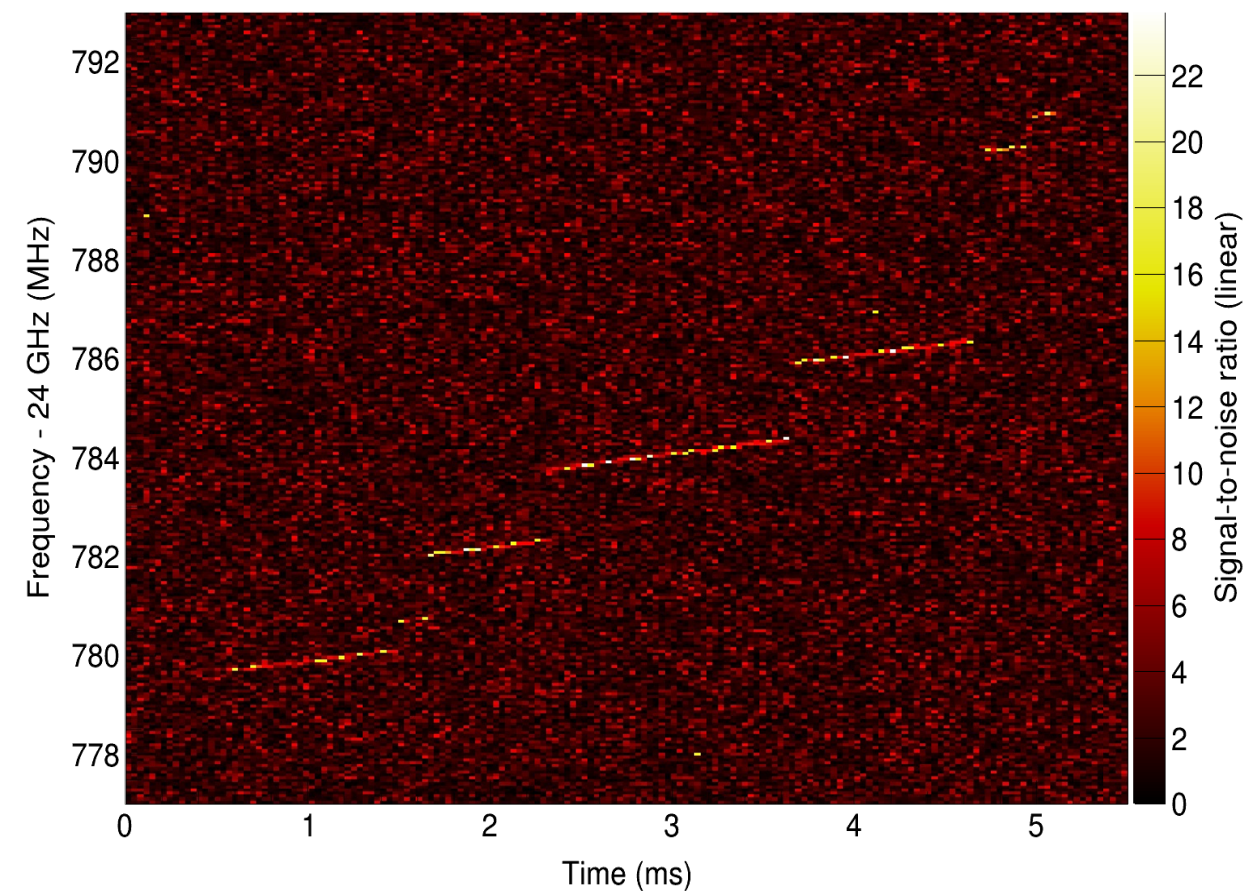


# Phase I: CRES Demonstrator

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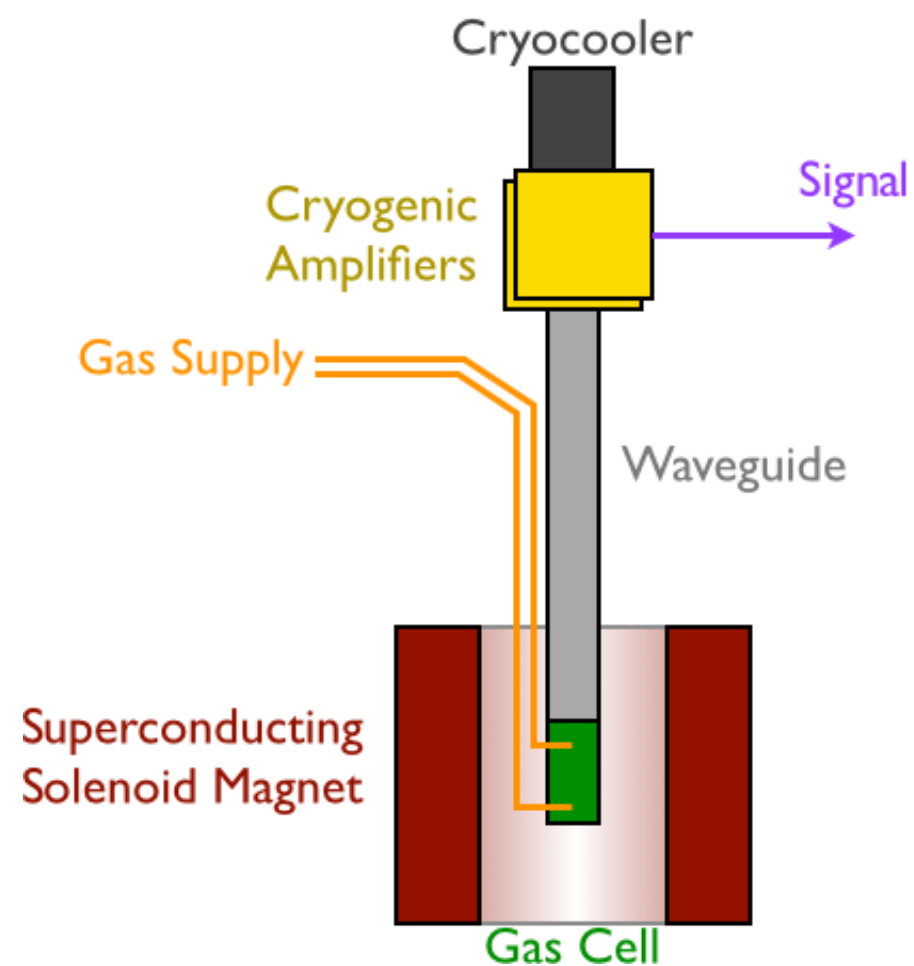
First CRES Event



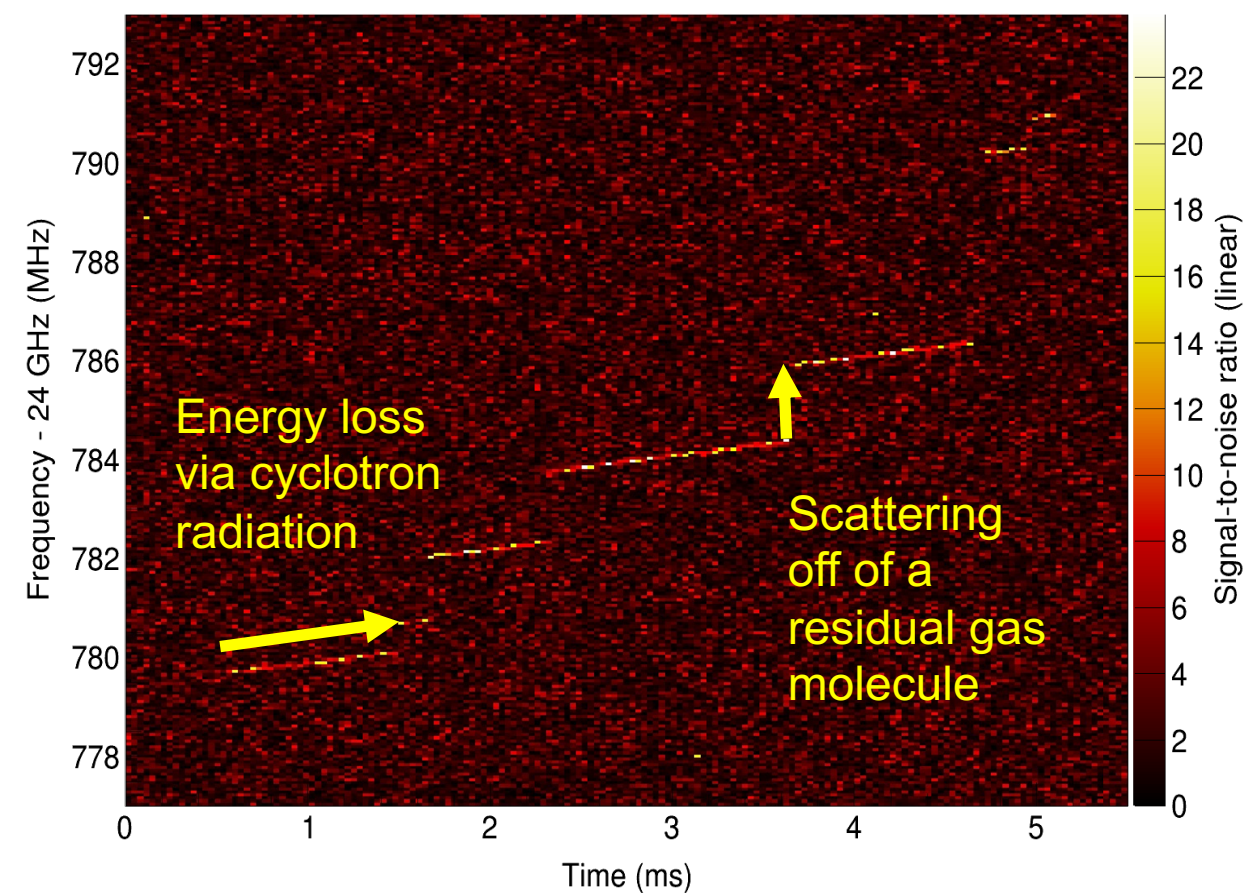


# Phase I: CRES Demonstrator

**PROJECT 8**



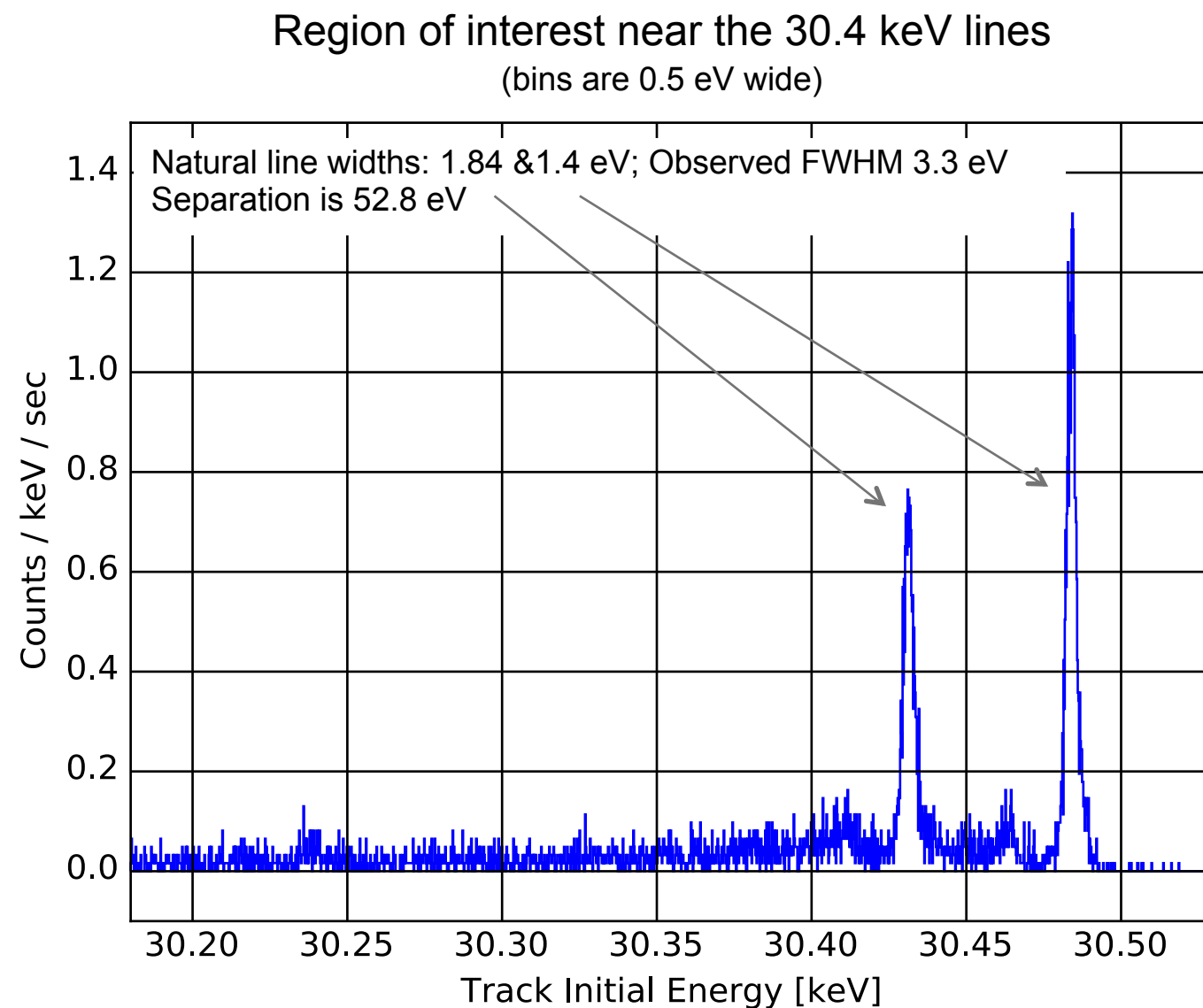
First CRES Event



# Phase I $^{83\text{m}}\text{Kr}$ Spectroscopy

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- $^{83\text{m}}\text{Kr}$  conversion-electron peaks measured
- 18-, 30-, and 32-keV electrons
- Best resolution: 3.3 eV FWHM (including 1.4 eV natural line width)



Project 8 Collaboration, J. Phys. G 44 (2017)

# Project 8 – Phase II

**PROJECT 8**

CRES Demonstration  
PRL 114:162501, 2015

~eV Resolution  
J. Phys. G. 44, 2017

Phase I

Phase II

Phase III

Phase IV

R&D Milestone

- $T_2$  spectrum
- Systematic studies

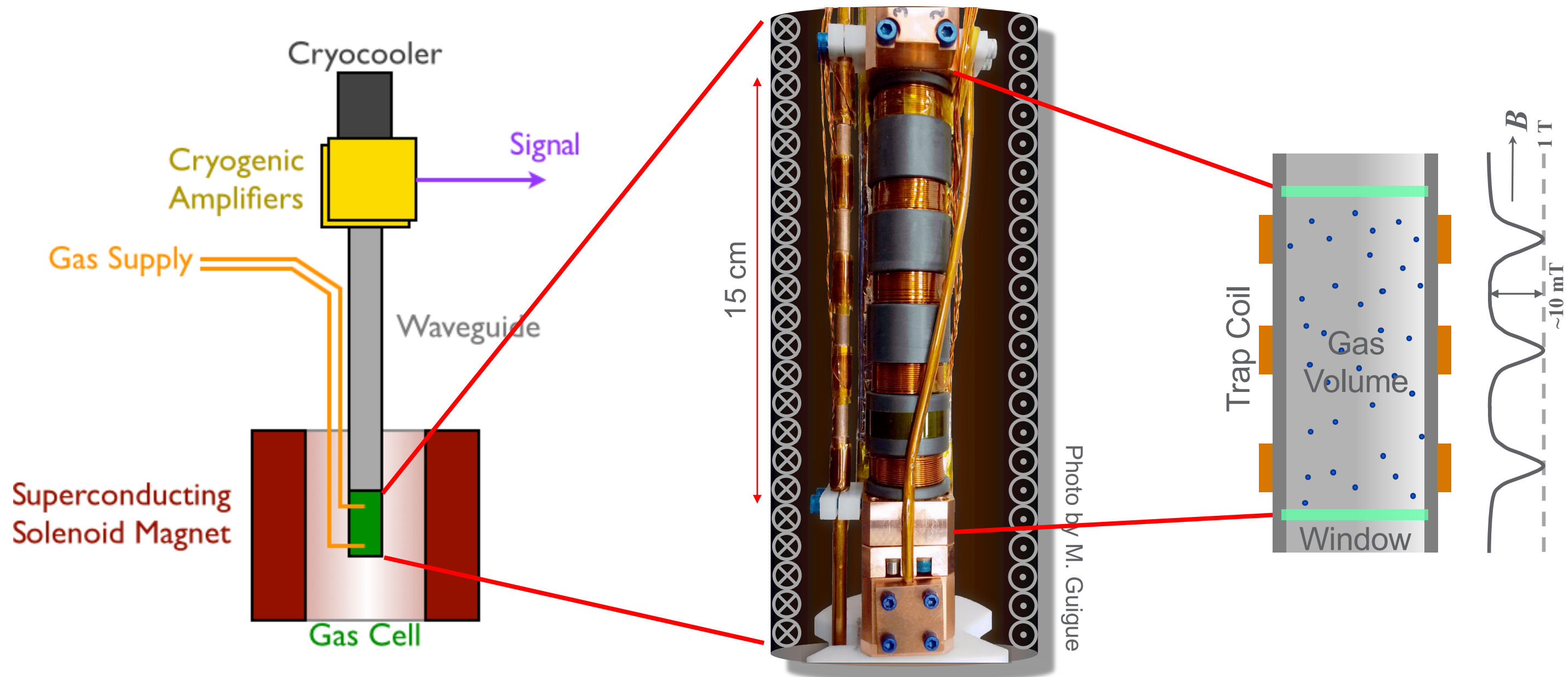
Science Goals

Tritium endpoint  
Background assessment

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

# Phase II Apparatus

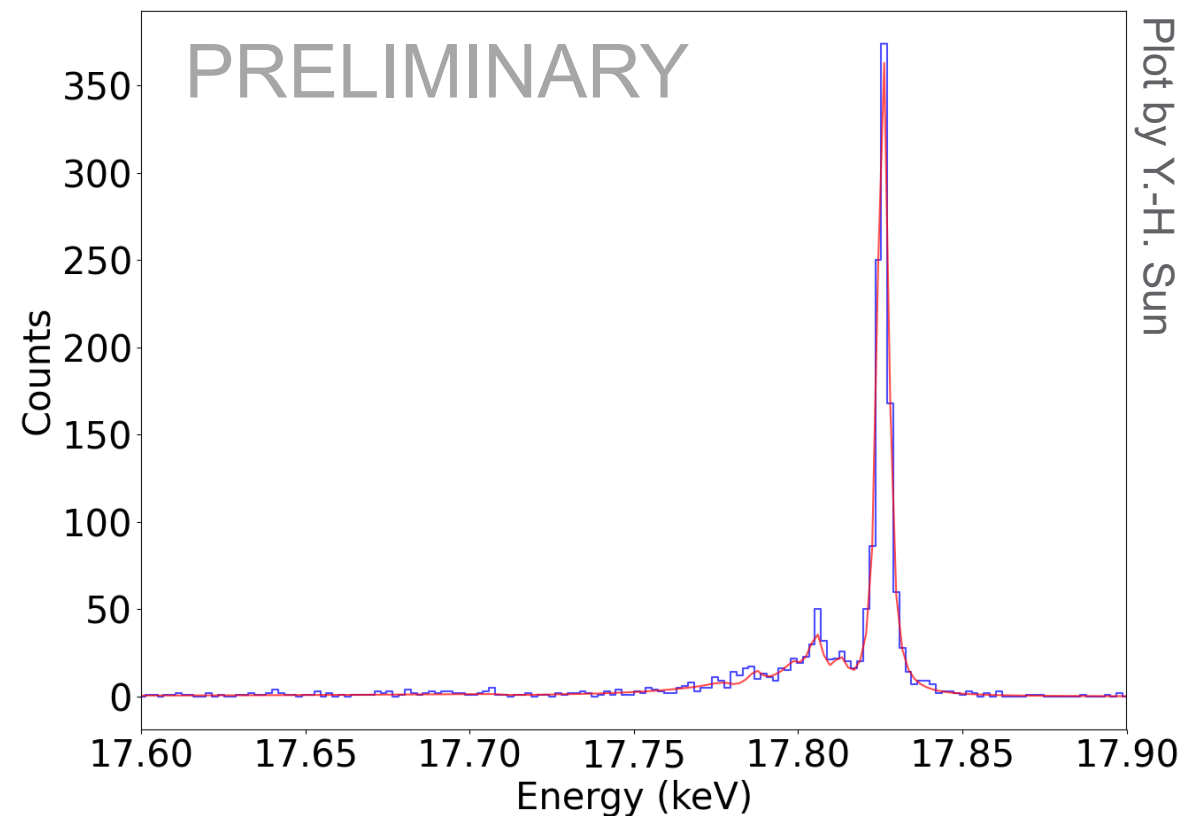
**PROJECT 8**



# High Precision with $^{83\text{m}}\text{Kr}$ Spectroscopy

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17.8-keV  $^{83\text{m}}\text{Kr}$  peak



- “Shallow trap” configuration
- Model includes Kr decay physics,  $e^-$  scattering
- Line width:  $2.8 \pm 0.1$  eV (FWHM)
- Instrumental width:  **$2.0 \pm 0.1$  eV (FWHM)**

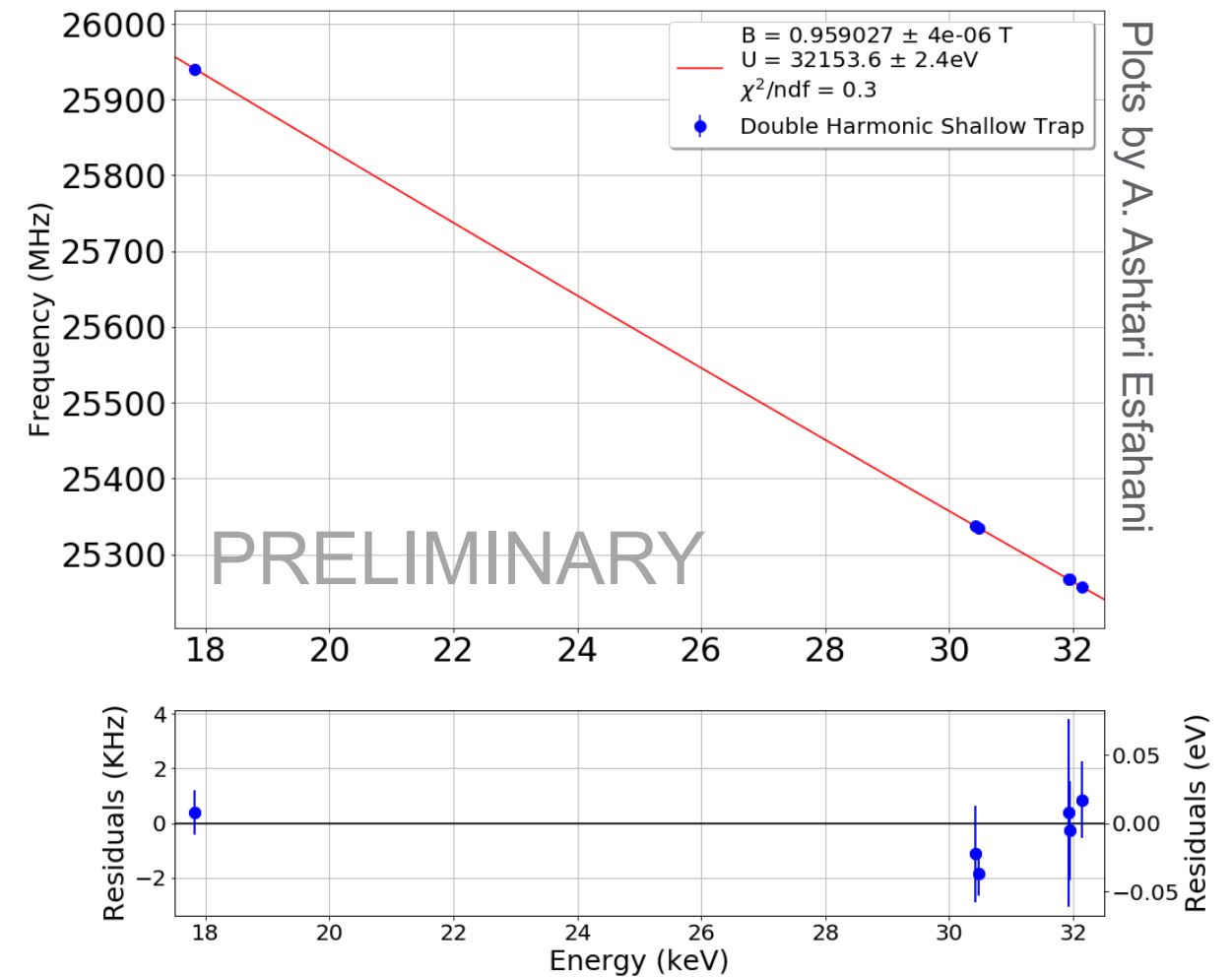


# Linearity with $^{83\text{m}}\text{Kr}$ Spectroscopy

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- “Shallow trap” configuration
- System is extremely linear:  
 $\chi^2/\text{ndf} = 0.3$
- 32-keV  $\gamma$  energy:  $(32153.6 \pm 2.4) \text{ eV}$ 
  - Vénos, et al:  $(32151.7 \pm 0.5) \text{ eV}$   
Appl. Radiat. Isot. **63** 323-7 (2005)

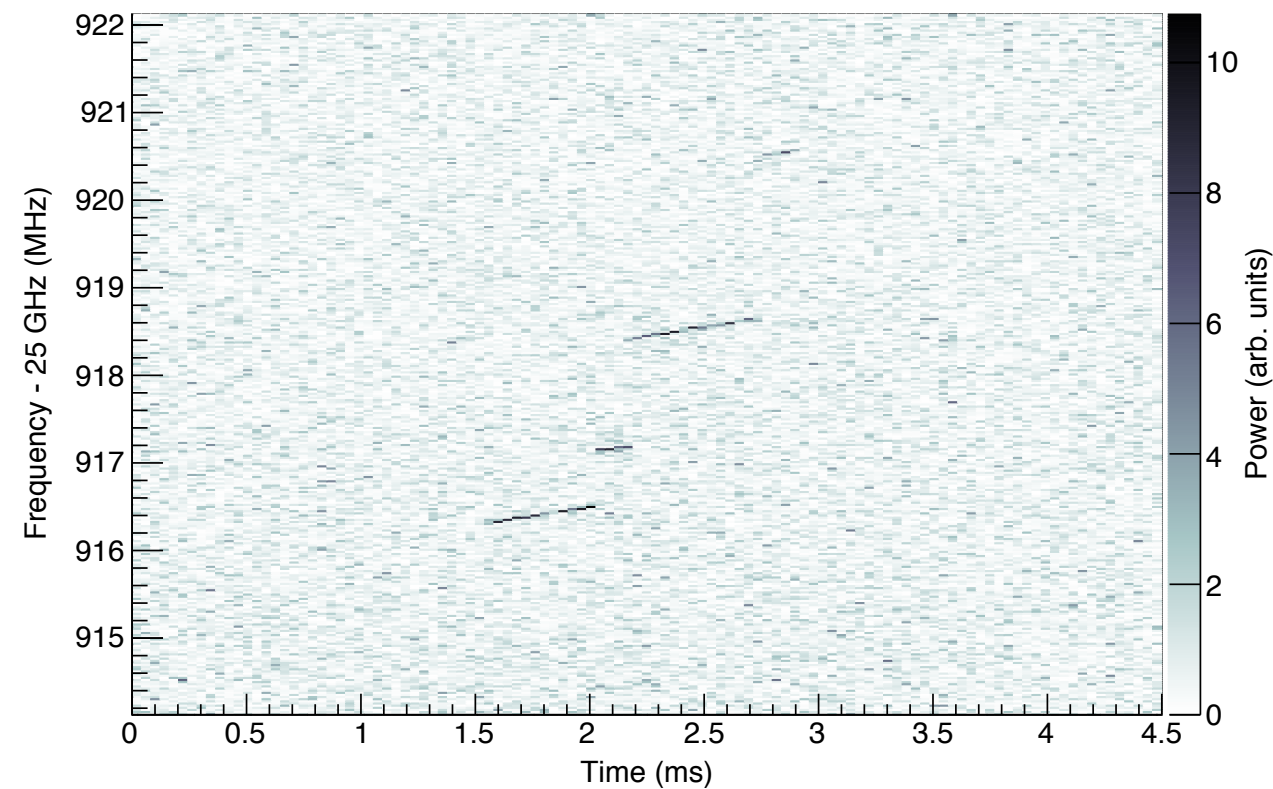
See poster by C. Claessens and Y.-H. Sun  
(session 4, #400)



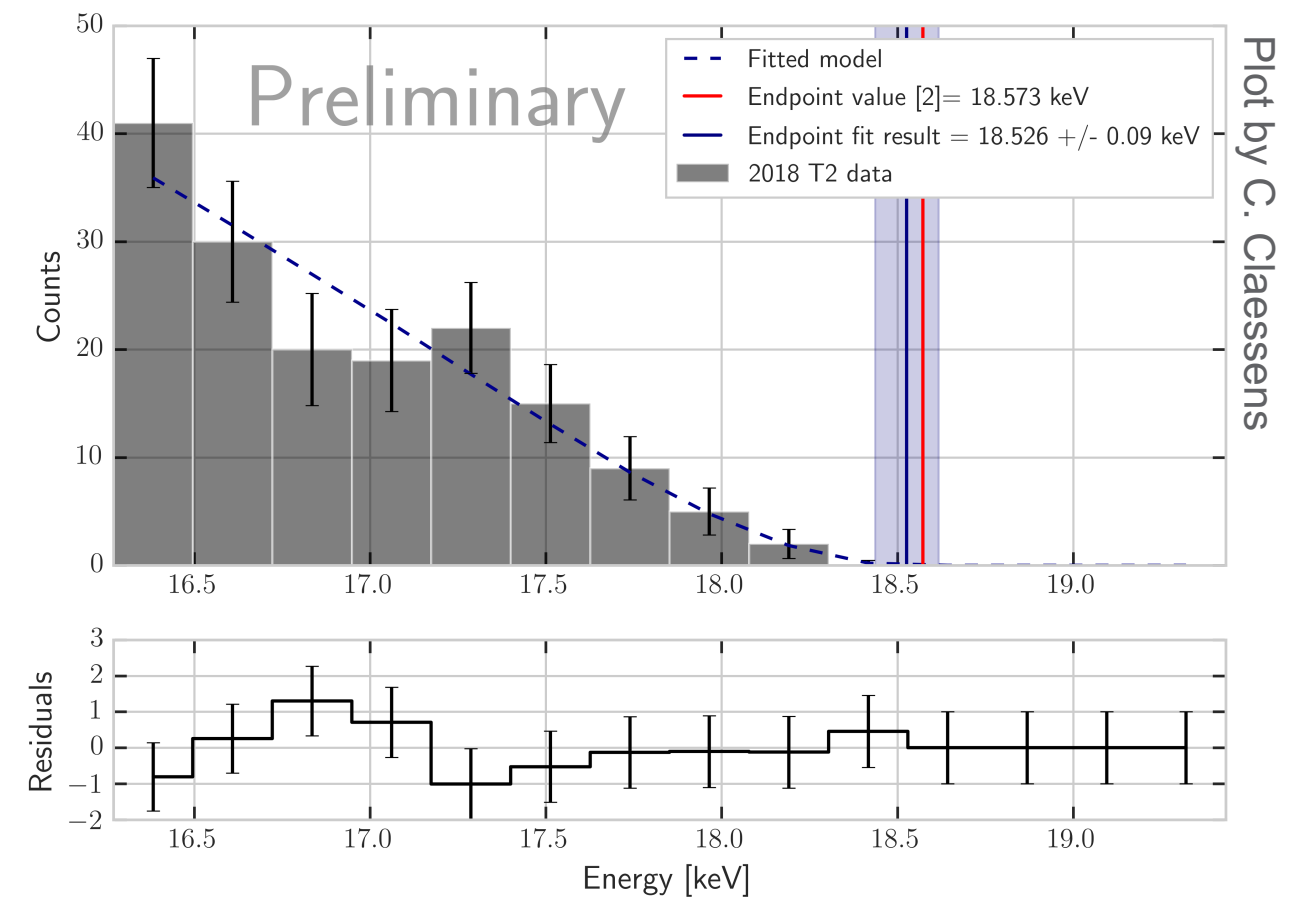
# First Observation from Tritium

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First T<sub>2</sub> Electron Event



2018 T<sub>2</sub> energy spectrum

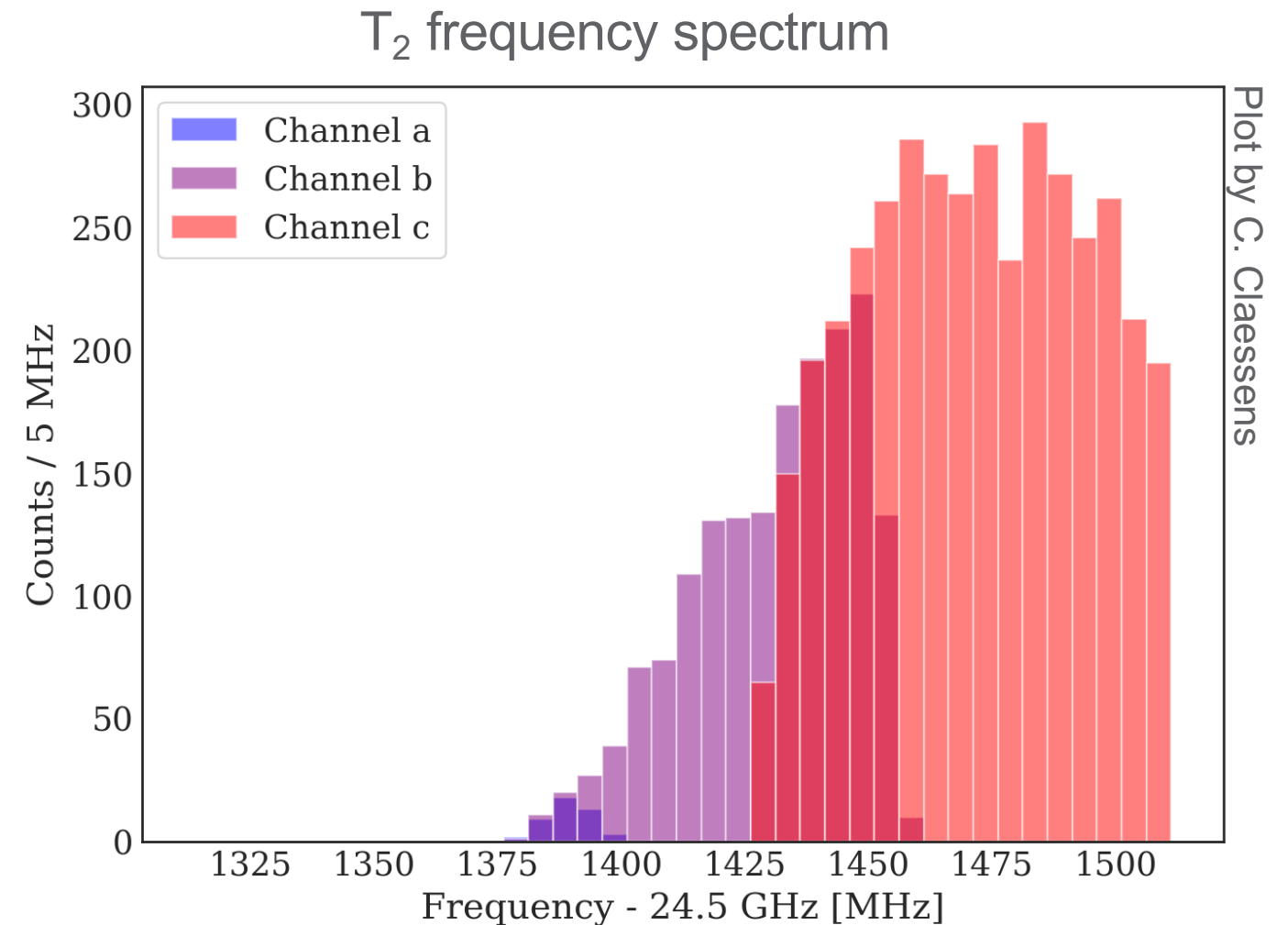


# Full Tritium Dataset

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- Winter 2019-2020
- 82 days of livetime
- Four-coil “deep trap” configuration
- Effective volume: 1 mm<sup>3</sup>
- Three overlapping frequency bands cover 16.2-18.6 keV
- 3770 unique counts

See poster by C. Claessens (session 4, #395)

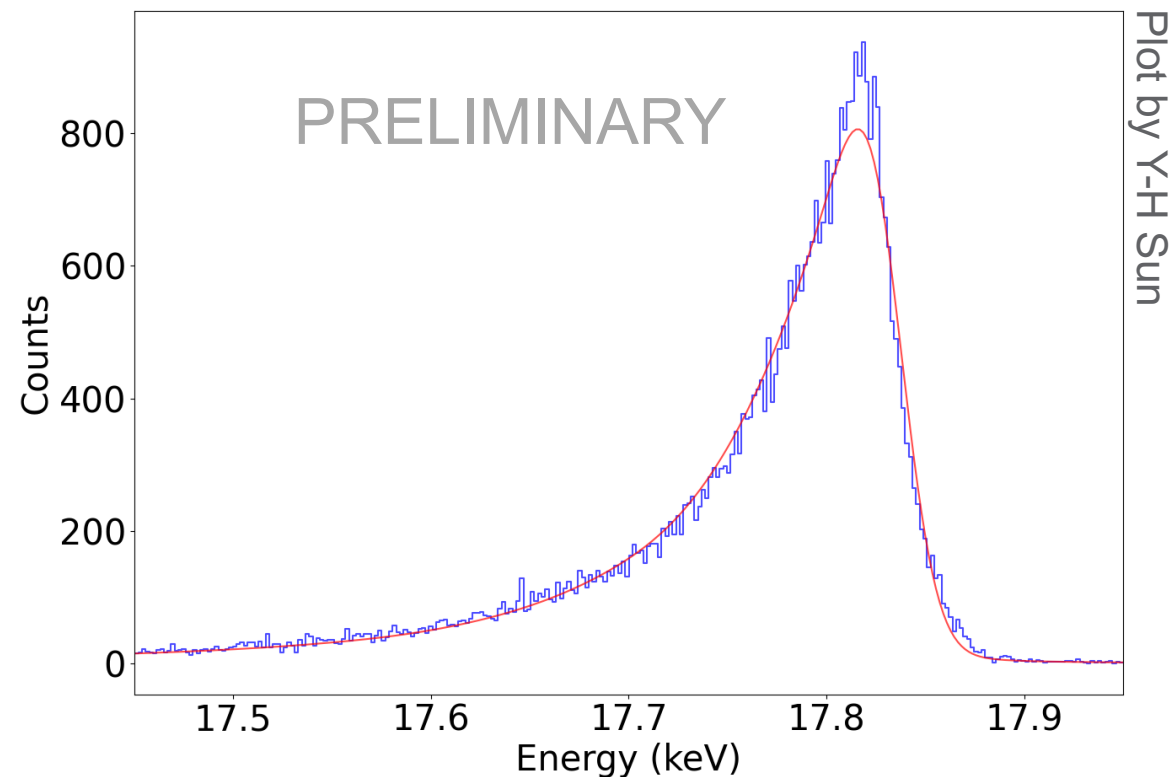




# Understanding the Systematic Uncertainties

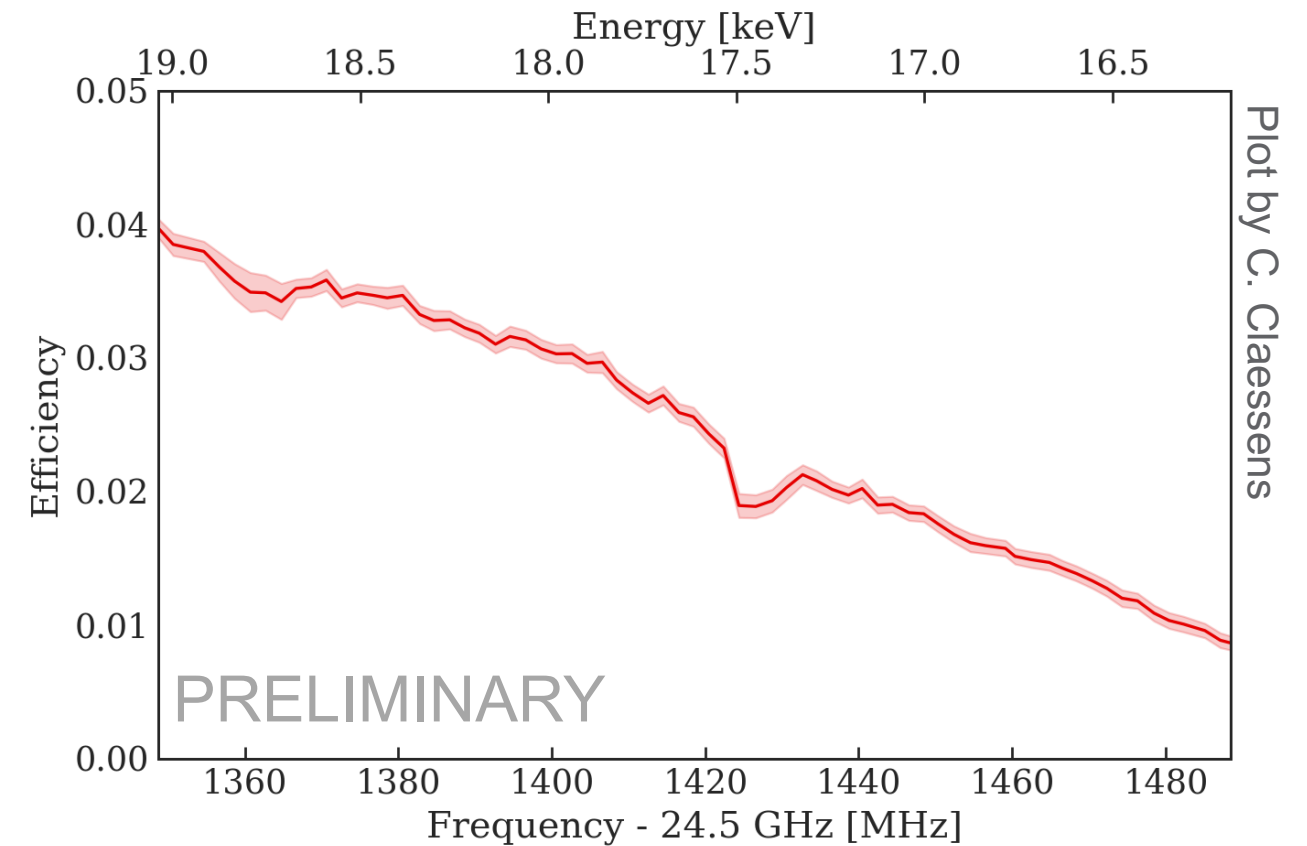
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Instrumental Lineshape



- Lineshape extracted from  $^{83\text{m}}\text{Kr}$  spectroscopy
- Very sensitive to gas composition and other experimental parameters

Detection Efficiency

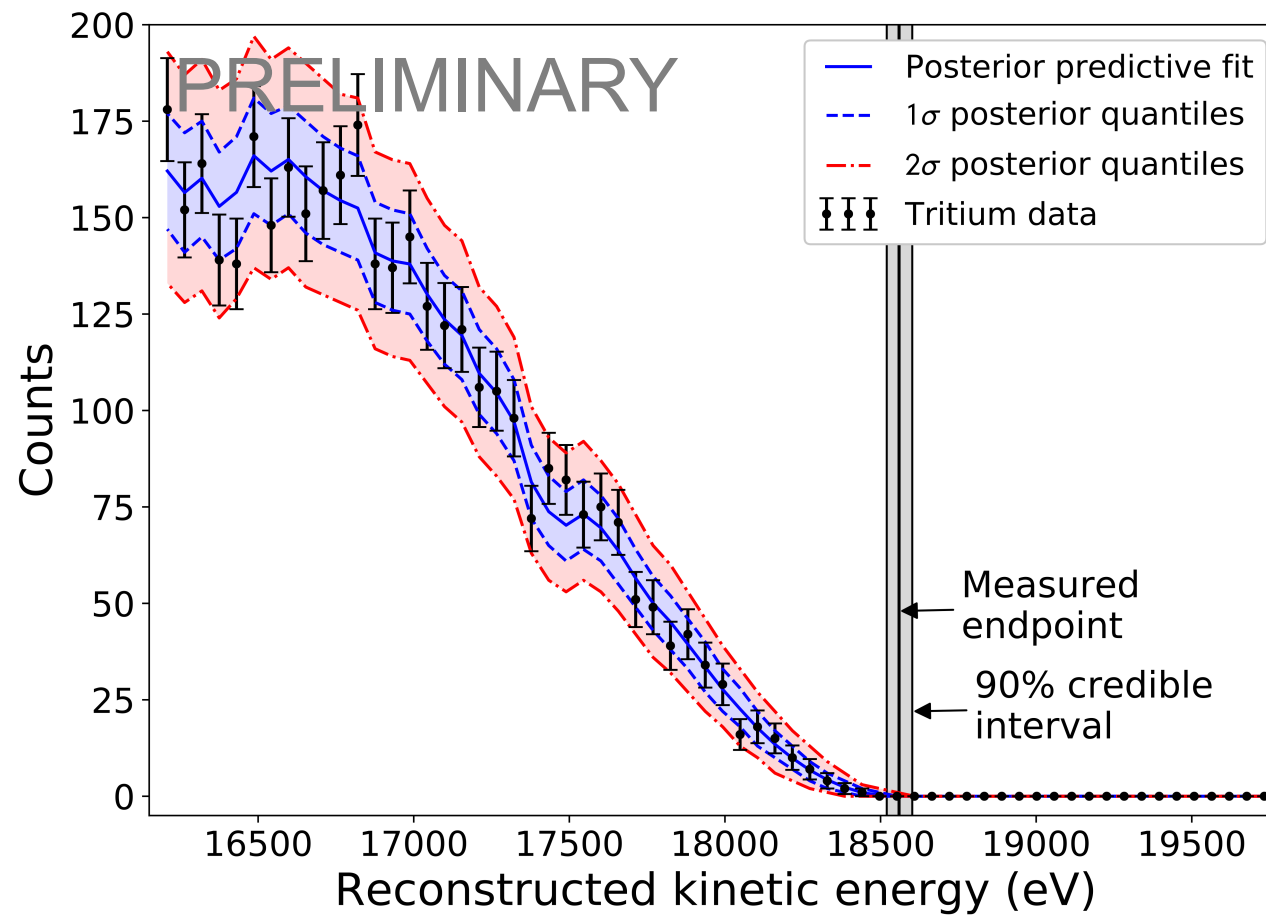


- Detection efficiency varies with frequency
- Measured by sweeping the frequency of the  $^{83\text{m}}\text{Kr}$  17.8-keV peak

# Preliminary Measurement of the $T_2$ Endpoint

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Energy spectrum and posterior fit



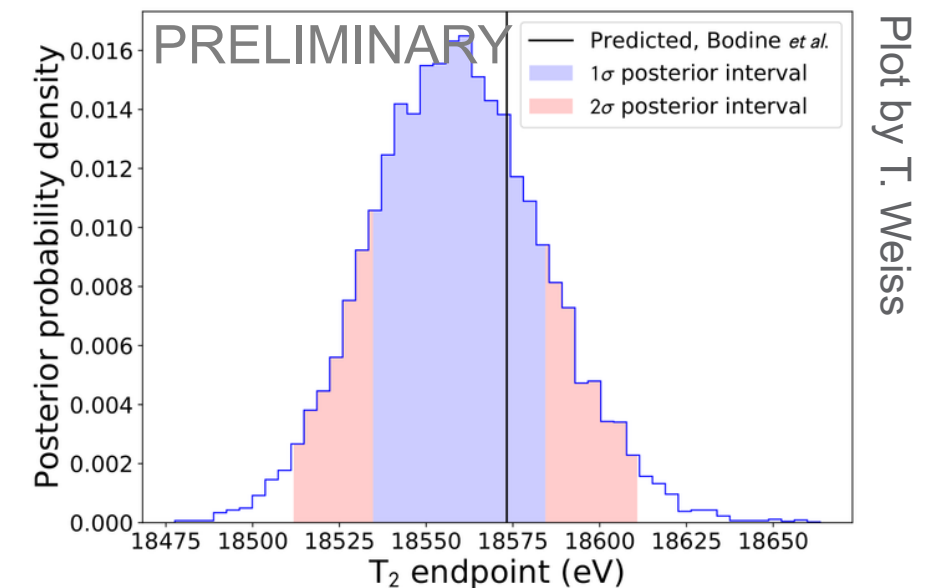
$T_2$  endpoint result:

$$E_0 = (18559.4^{+24.9}_{-24.7}) \text{ eV}$$

Background rate:

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

Posterior distribution



Final analysis will be completed this summer

Bodine, et al.: Phys. Rev. C 91 (2015)

# Project 8 – Phase III RF Demonstration

**PROJECT 8**

CRES Demonstration  
PRL 114:162501, 2015

~eV Resolution  
J. Phys. G. 44, 2017

Phase I

Phase II

Phase III

RF Demonstration  
Atomic T Demonstration

Phase IV

R&D Milestone

- 200 cm<sup>3</sup> active volume
- Antenna array
- B-field homogeneity

Science Goals

$$m_\nu < 2 \text{ eV}/c^2$$

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

# Large-Volume CRES

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- Scaling up the volume: 200 cm<sup>3</sup> inside an MRI magnet
- Free-space radiation detected by a ring array of antennas
- Digital beamforming used to spatially locate electrons within the fiducial volume

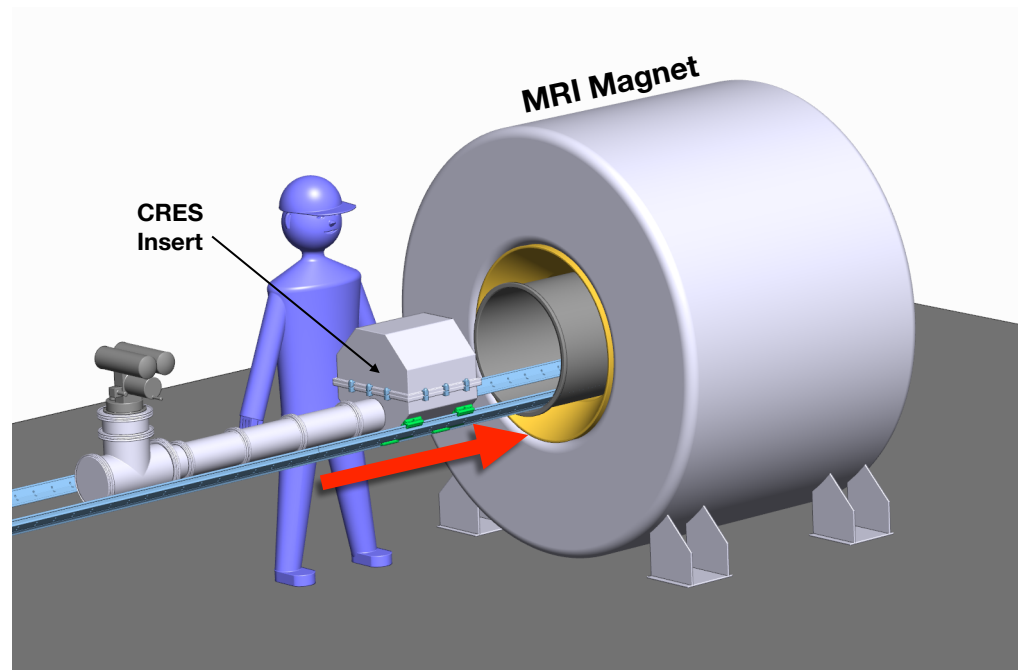


Figure by J. Nikkel

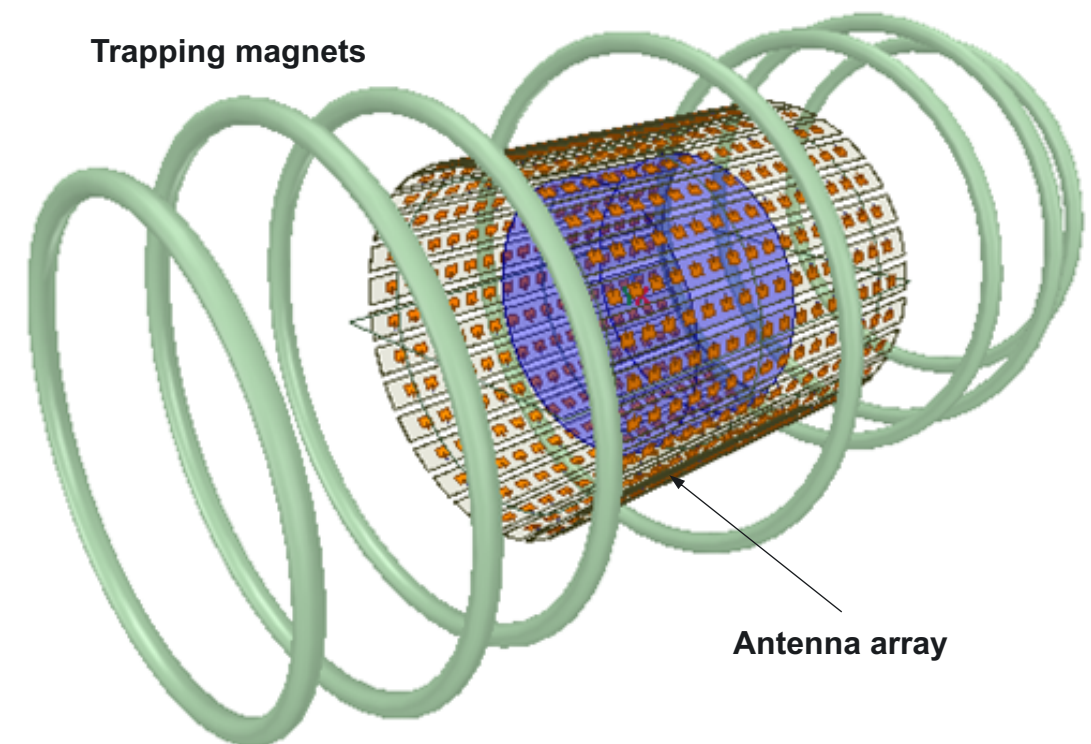


Figure by T. Wendler

See posters by A. Telles (session 1, #322) and P.T. Surukuchi (session 3, #471)

# Project 8 – Phase III Atomic T Demonstration

**PROJECT 8**

CRES Demonstration  
PRL 114:162501, 2015

$\sim$ eV Resolution  
J. Phys. G. 44, 2017

Phase I

Phase II

Phase III

RF Demonstration  
Atomic T Demonstration

Phase IV

R&D Milestone

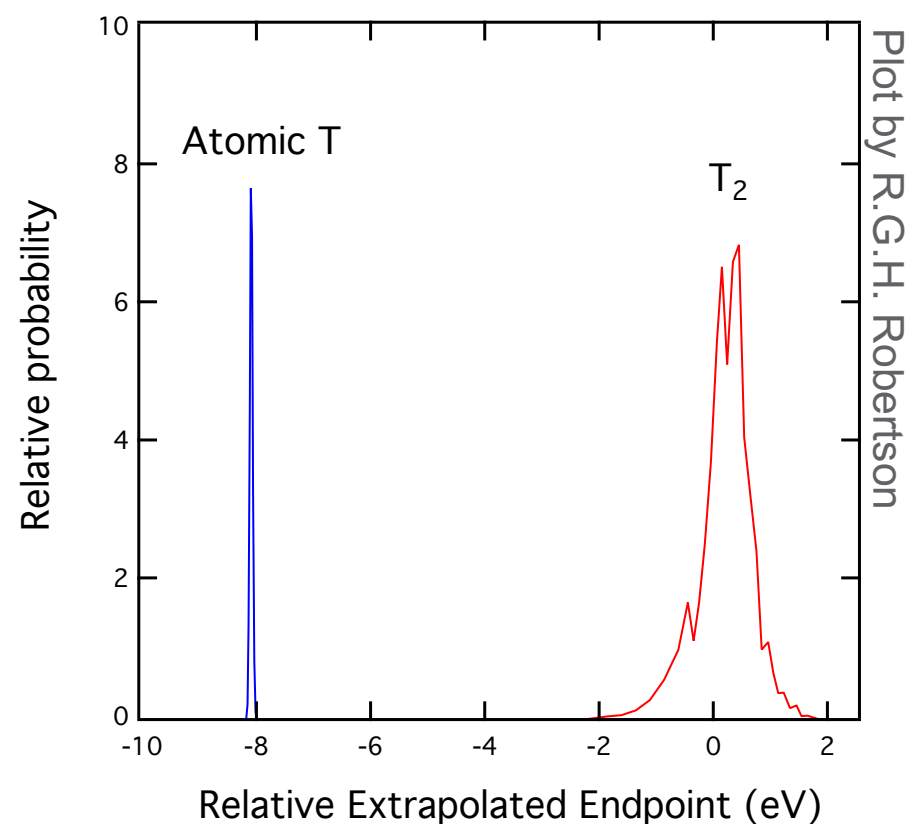
- Accommodator
- Velocity/State Selector
- Atomic trap

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



# Using Atomic Tritium

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Atomic tritium avoids the wide final-state energy distribution of molecular tritium

The main components of the atomic tritium system require R&D efforts during Phase III

- Cracker: split T<sub>2</sub> into T
- Accommodator: cool the hot T
- Transport & Trapping

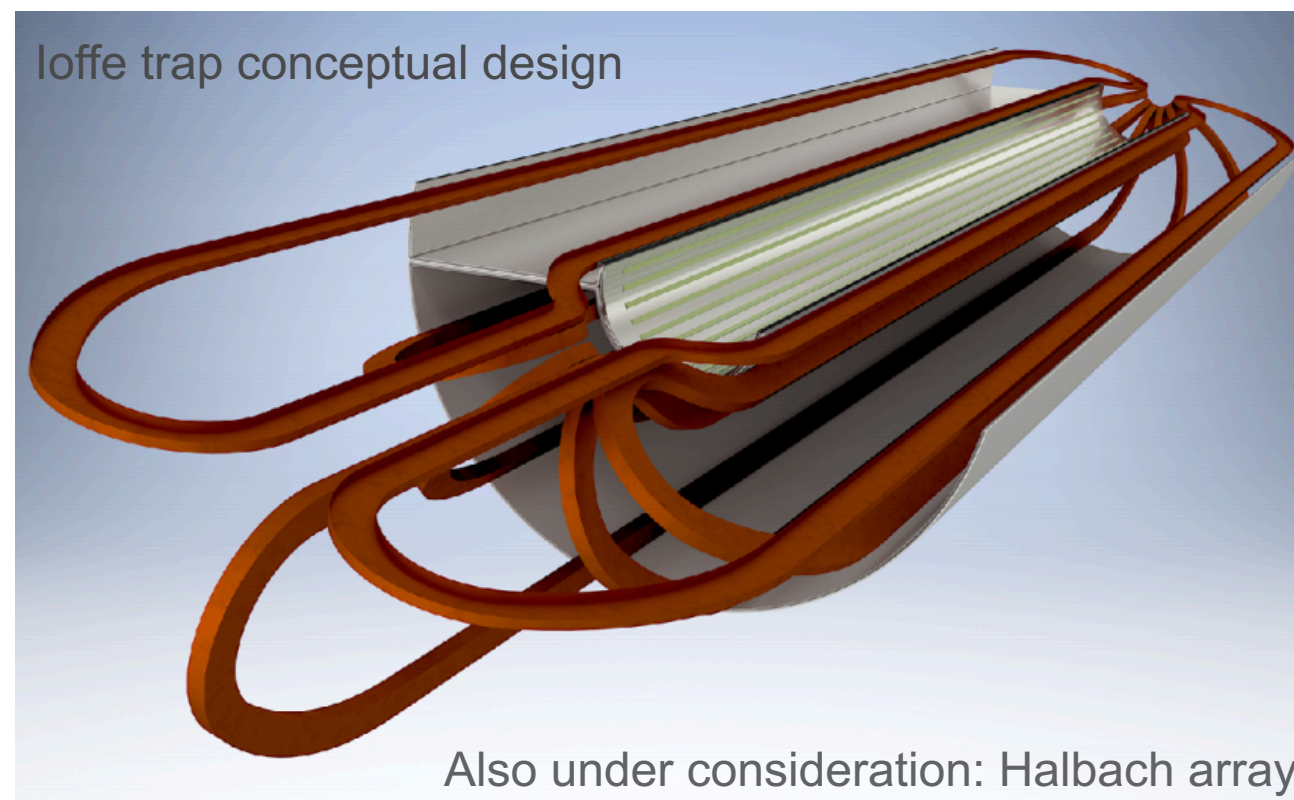


Figure by A. Lindman

See poster by A. Lindman, session 2, #92

# Project 8 – Phase IV

**PROJECT 8**

CRES Demonstration  
PRL 114:162501, 2015

~eV Resolution  
J. Phys. G. 44, 2017

Phase I

Phase II

Phase III

Phase IV

Science Goals

$m_\nu < 40 \text{ meV}/c^2$   
Mass hierarchy

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

# Phase IV Components

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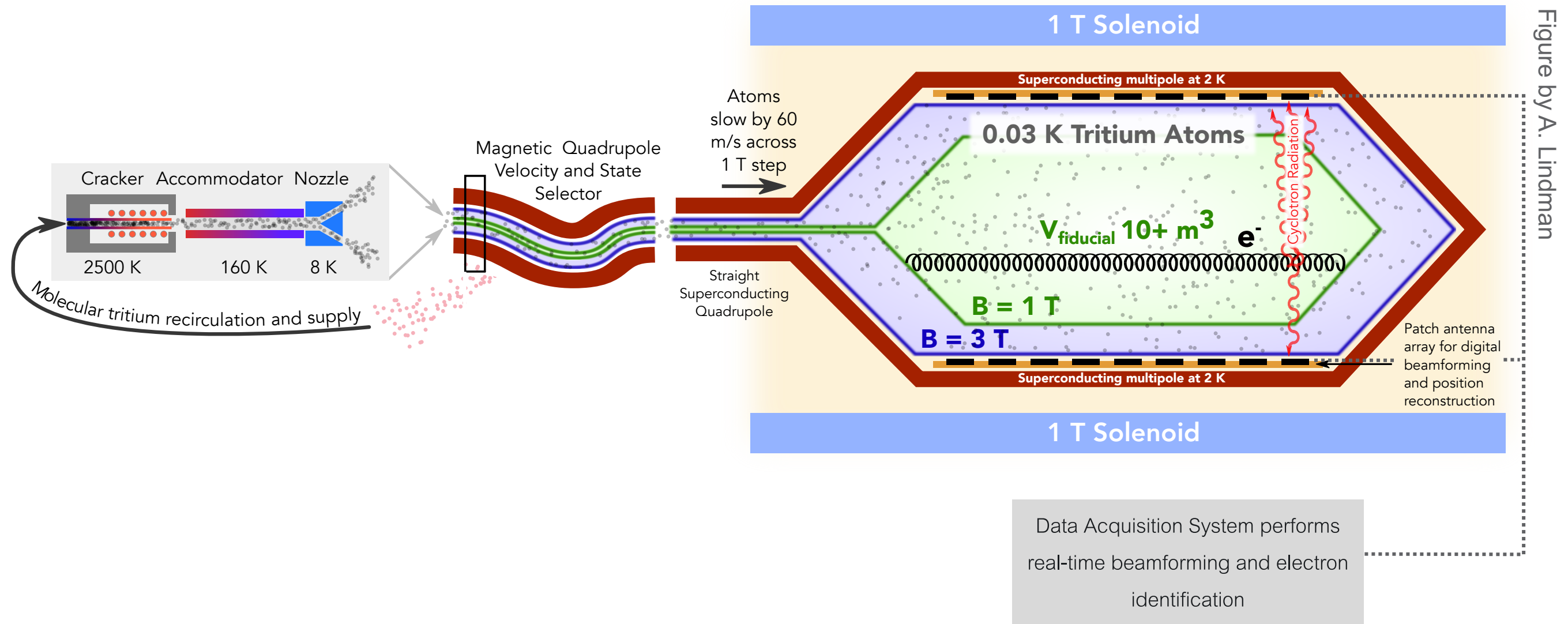
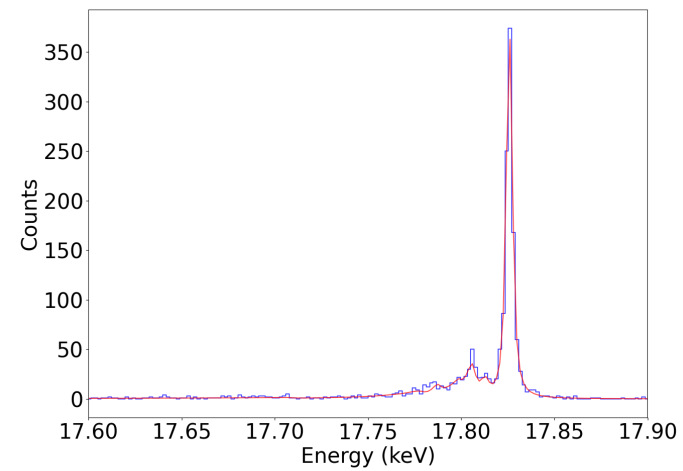
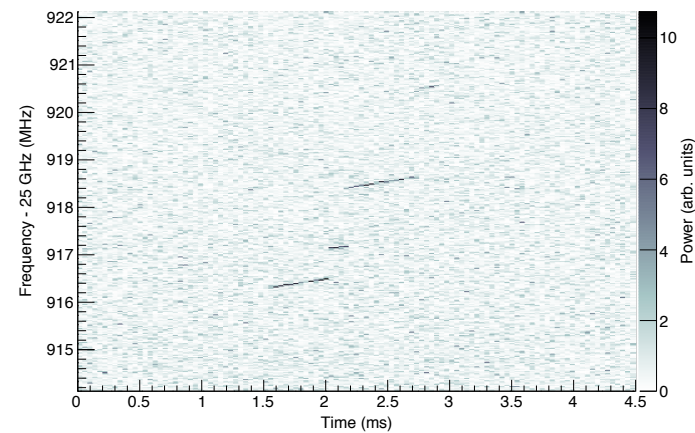


Figure by A. Lindman



# Phase IV: Bringing It All Together

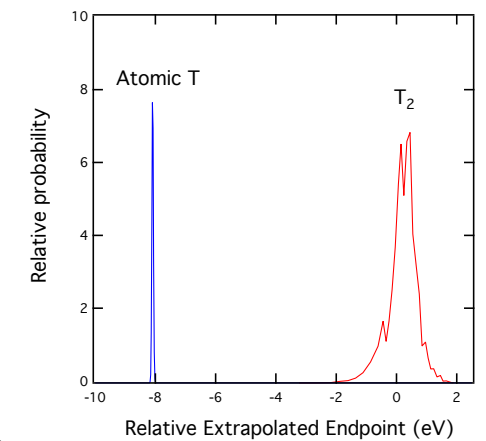
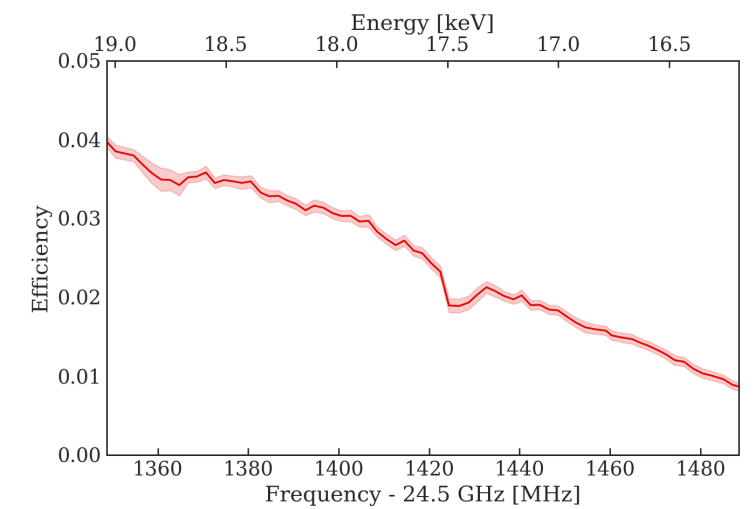
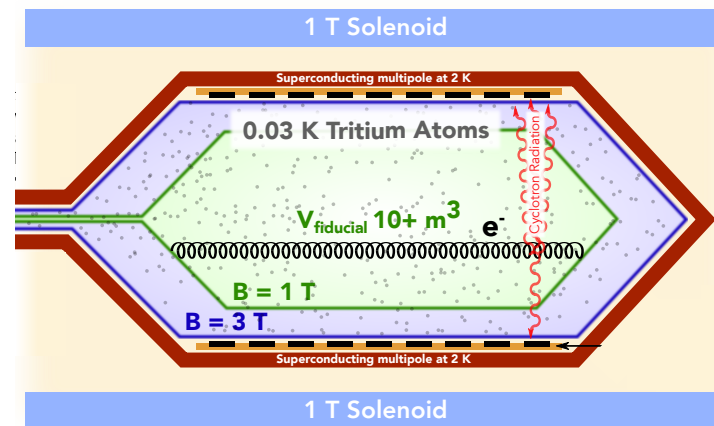
**PROJECT 8**



Control of Systematics

High Precision

Large Volume

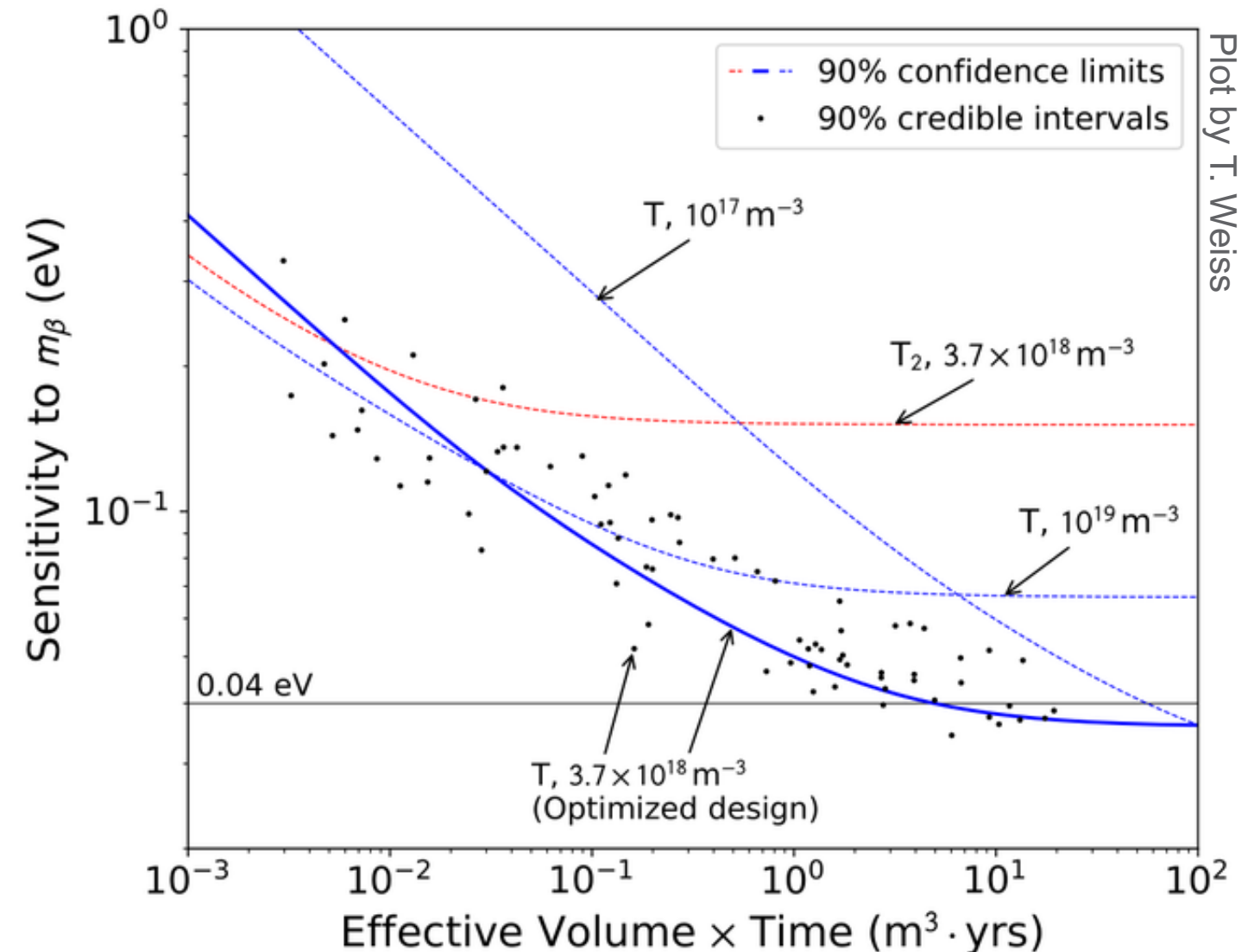


# Projected Sensitivity for Phase IV

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- Bayesian analysis used to study the potential sensitivity of Project 8
- Atomic tritium is required
- Careful control of systematics is required
- Density is optimized based on a target sensitivity of 40 meV

See poster by T. Weiss (session 2, #518)



# Summary

- Project 8 established the CRES technique that we intend to use for a neutrino-mass measurement
- We have performed the first measurement of the tritium spectrum using the CRES technique, completing Phase II
- We are entering a phase of critical R&D demonstrations, including:
  - Large-volume CRES detection
  - Atomic tritium trapping
- Phase IV will combine a large volume, high precision, and well-controlled systematic uncertainties to reach the final sensitivity

# The Project 8 Collaboration

**PROJECT 8**



## Case Western Reserve University

– Laura Gladstone, Benjamin Monreal, Yu-Hao Sun



## Harvard-Smithsonian Center for Astrophysics

– Sheperd Doeleman, Jonathan Weintraub, André Young



## Johannes Gutenberg-Universität Mainz

– Sebastian Böser, Christine Claessens, Martin Fertl, Michael Gödel, Alec Lindman, René Reimann, Florian Thomas



## Karlsruher Institut für Technologie

– Thomas Thümmel



## Lawrence Livermore National Laboratory

– Kareem Kazkaz, Lucie Tvrznikova



## Massachusetts Institute of Technology

– Zachary Bogorad, Nicholas Buzinsky, Joseph Formaggio, Joe Johnston, Valerian Sibille, Juliana Stachurska, Wouter Van de Pontseele, Talia Weiss, Evan Zayas



## Pacific Northwest National Laboratory

– Vikas Bansal, Mathieu Guigue, Mauro Grando, Xueying Huan, Mark Jones, Benjamin LaRoque, Erin Morrison, Noah Oblath, Malachi Schram, Jonathan Tedeschi, Mathew Thomas, Brent VanDevender



## Pennsylvania State University

– Luiz de Viveiros, Timothy Wendler, Andrew Ziegler



## University of Washington

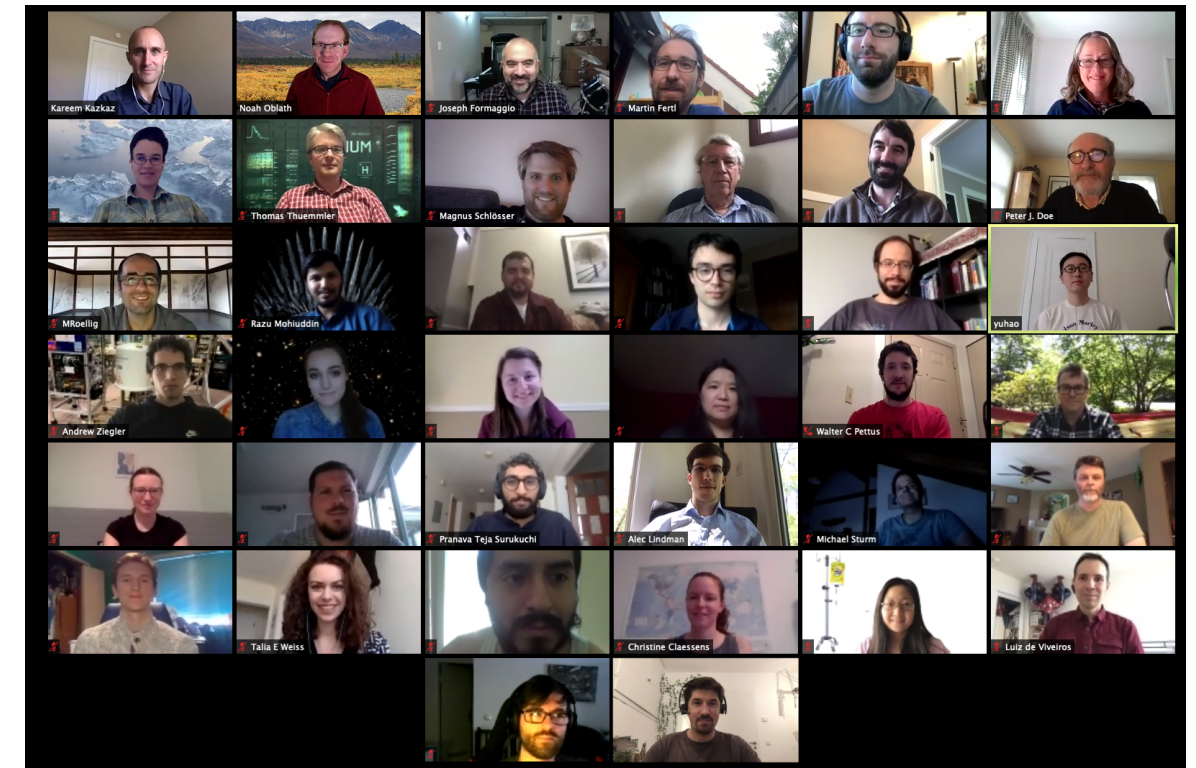
– Ali Ashtari Esfahani, Alessandro Banducci, Raphael Cervantes, Peter Doe, Jeremy Hartse, Eris Machado, Elise Novitski, Maurice Ottiger, Walter Pettus, Hamish Robertson, Leslie Rosenberg, Gray Rybka



## Yale University

– Karsten Heeger, James Nikkel, Luis Saldaña, Penny Slocum, Pranava Teja Surukuchi, Arina Telles

[www.project8.org](http://www.project8.org)



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