Walter C. Pettus

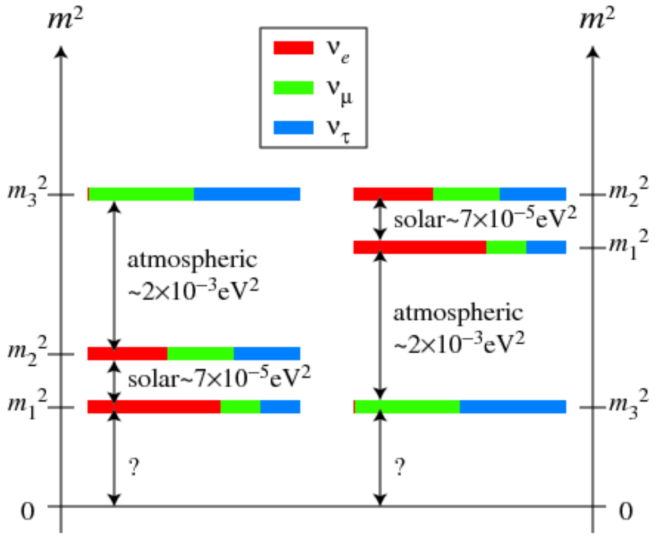
Tritium Results from Project 8 Phase II

XIX International Workshop on Neutrino Telescopes

23 February 2021

INDIANA UNIVERSITY

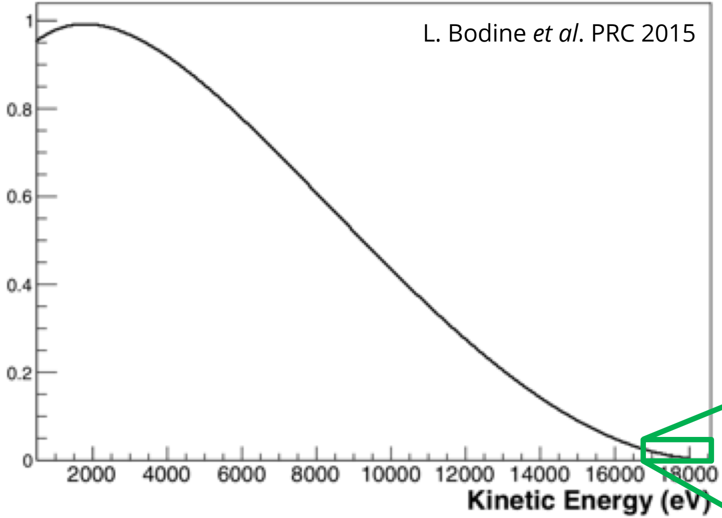
Measuring Neutrino Mass



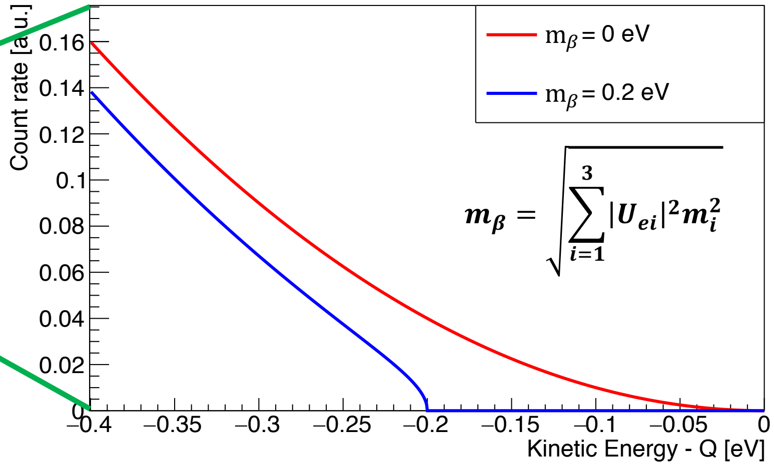
- Neutrino oscillations provide clear evidence for neutrino mass
- But oscillation measurements only reveal the mass splittings

- Measuring the neutrino absolute mass scale requires a different probe
  - Cosmology: $\sum_{i=1}^{3} m_i$
  - 0νββ: $\langle m_{\beta\beta} \rangle = \left| \sum_{i=1}^{3} U_{ei}^2 m_i \right|$
  - Endpoint measurements: $m_\beta = \sqrt{\sum_{i=1}^{3} |U_{ei}|^2 m_i^2}$

Direct Experiments – Endpoint Technique

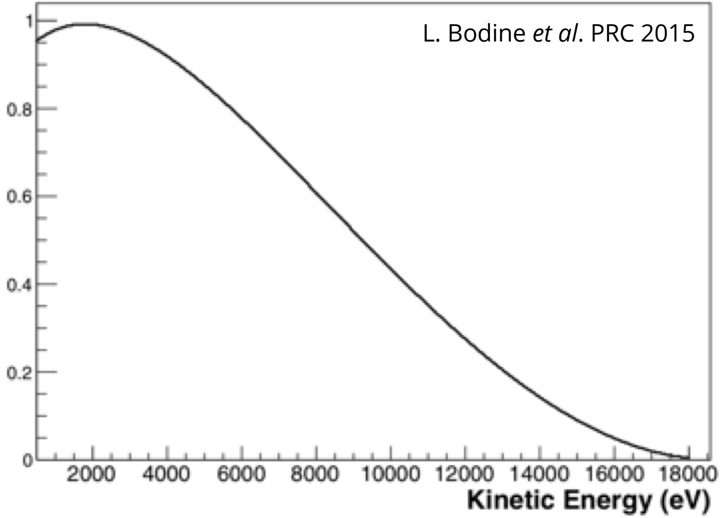


- Neutrino information imprinted on beta (or electron capture) spectrum

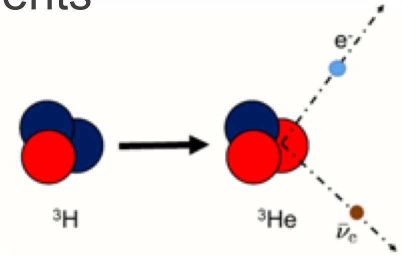


- Effect of neutrino mass alters beta spectrum near endpoint

Direct Experiments – Tritium

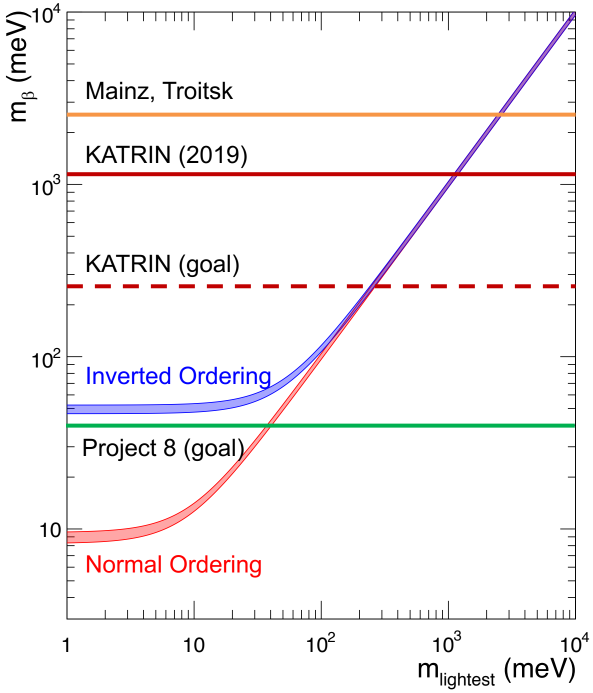


- Tritium is workhorse of direct mass experiments



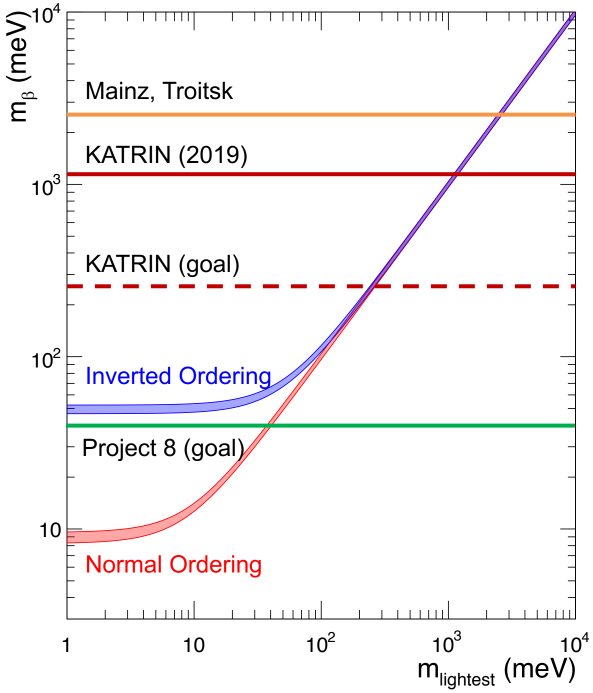
- $^{3}_{1}H \rightarrow {}^{3}_{2}He^{+} + e^{-} + \overline{\nu_e}$
  - Endpoint: 18.6 keV
  - Half-life: 12.3 yr
  - Superallowed decay

Direct Experiment Sensitivity



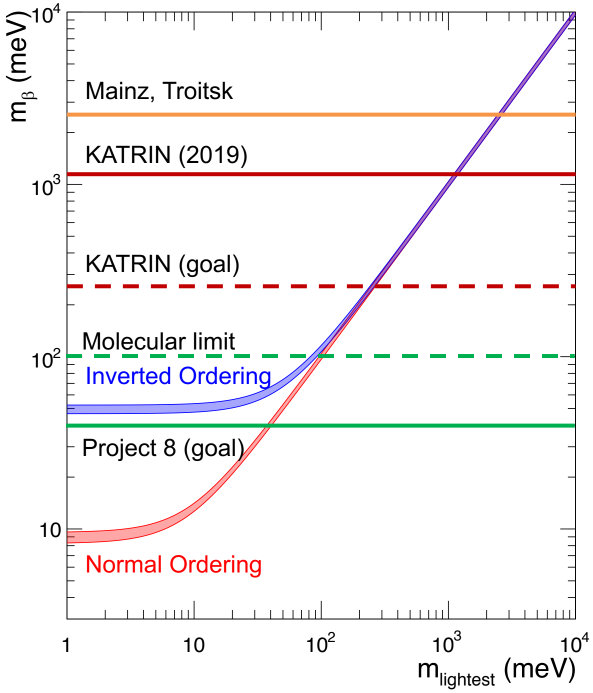
- Direct mass experiment "observable", m_β, has minimum possible value
  - $m_\beta = \sqrt{\sum_{i=1}^{3} |U_{ei}|^2 m_i^2}$
- KATRIN experiment places most stringent limit
  - Will continue delivering world-leading sensitivity through its operation
  - *See talk by T. Lasserre, tomorrow morning*
- Project 8 conceived as next-generation experiment to mass range allowed under inverted ordering

Challenges for Future Experiments

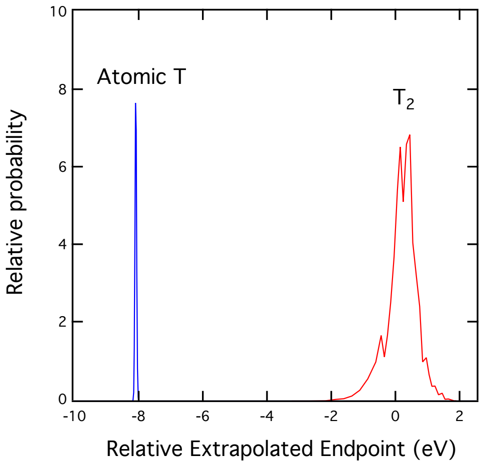


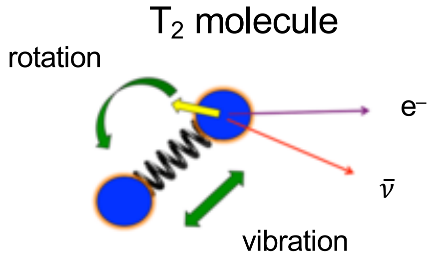
- Statistical sensitivity to m_β scales as $\sim 1/N^{1/4}$
  - Existing detector technology reached limit of scalability

Challenges for Future Experiments



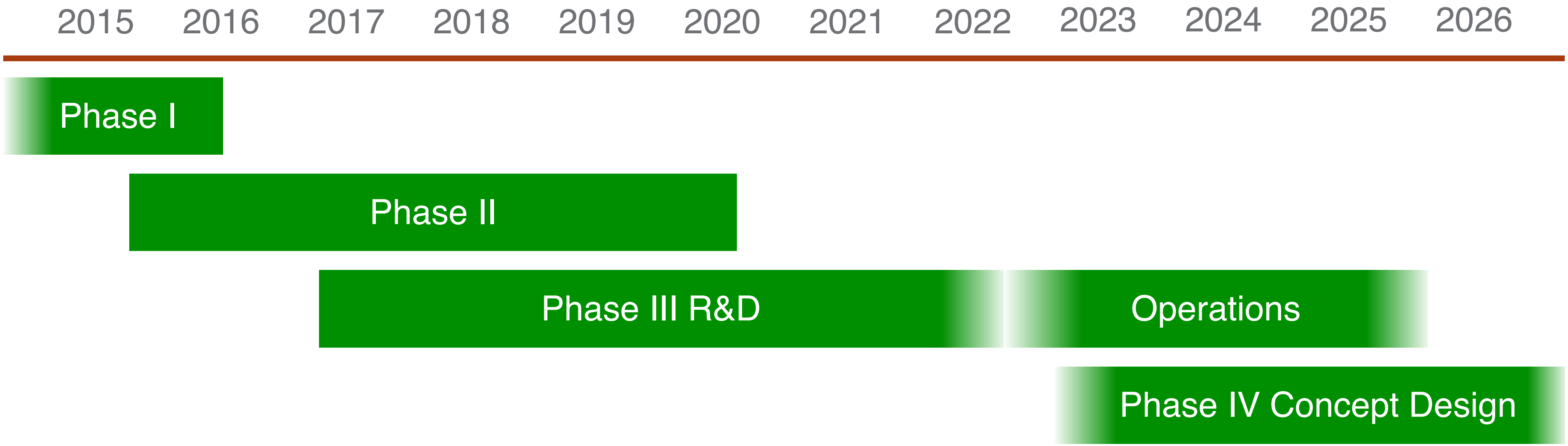
- Statistical sensitivity to m_β scales as $\sim 1/N^{1/4}$
  - Existing detector technology can't scale
- Irreducible systematics associated with molecular final states at ~100 meV





Project 8 Experiment

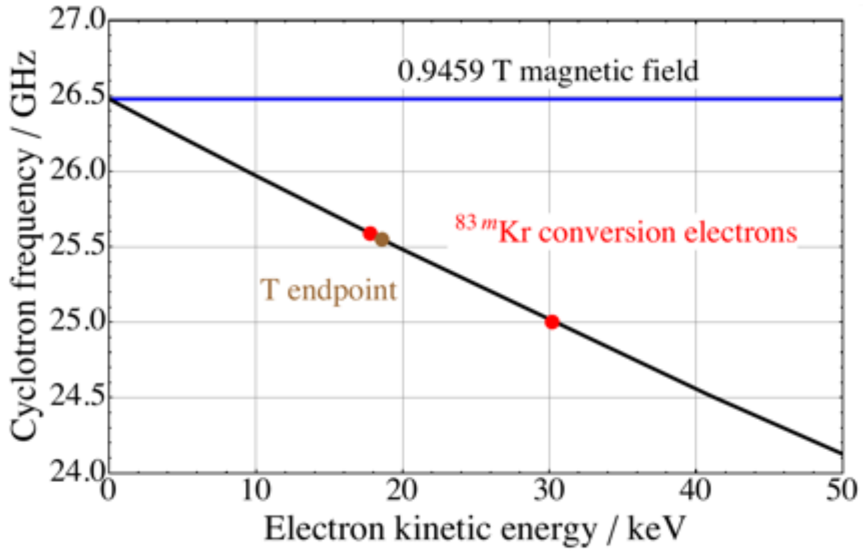
- A phased tritium beta endpoint experiment
- Employs novel Cyclotron Radiation Emission Spectroscopy (CRES) technique

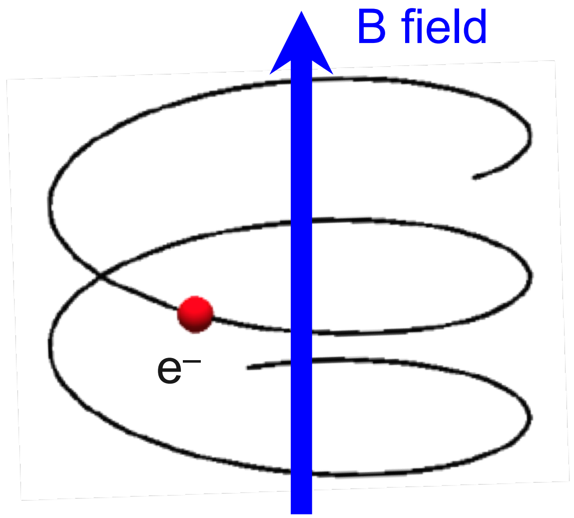


Cyclotron Radiation Emission Spectroscopy (CRES)

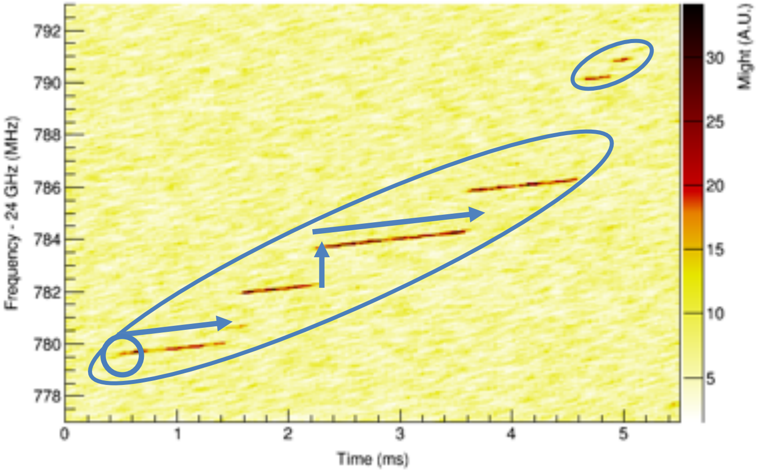
- Harness frequency-energy relation for relativistic electrons

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





CRES Fundamentals

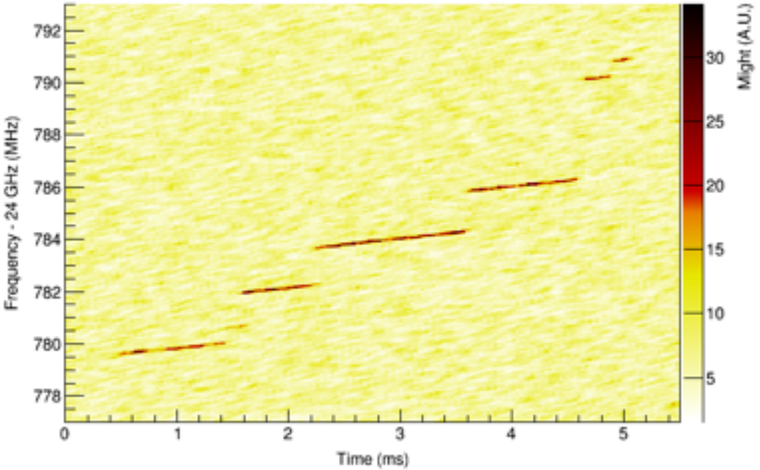


observation of single trapped electron

- High power bins are single electron signal
- Slow chirp of cyclotron radiation loss
- Abrupt collisional loss off residual gas
- Electron born in trap

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

CRES Fundamentals

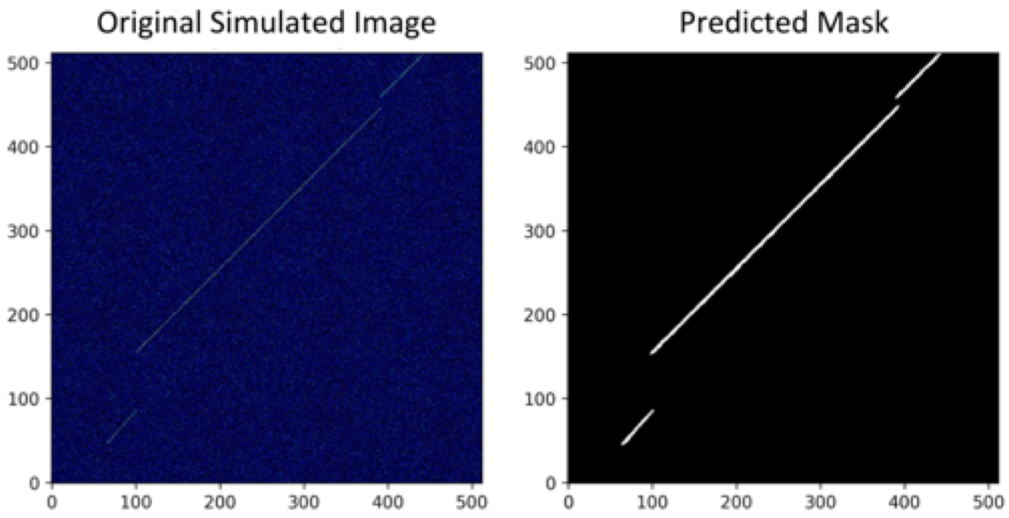


observation of single trapped electron

- Frequency-based measurement
  - Excellent energy resolution achievable
- Source is detector
  - Transparent to own microwave radiation
  - No electron transport
- Differential spectrum technique
  - Increased statistical efficiency

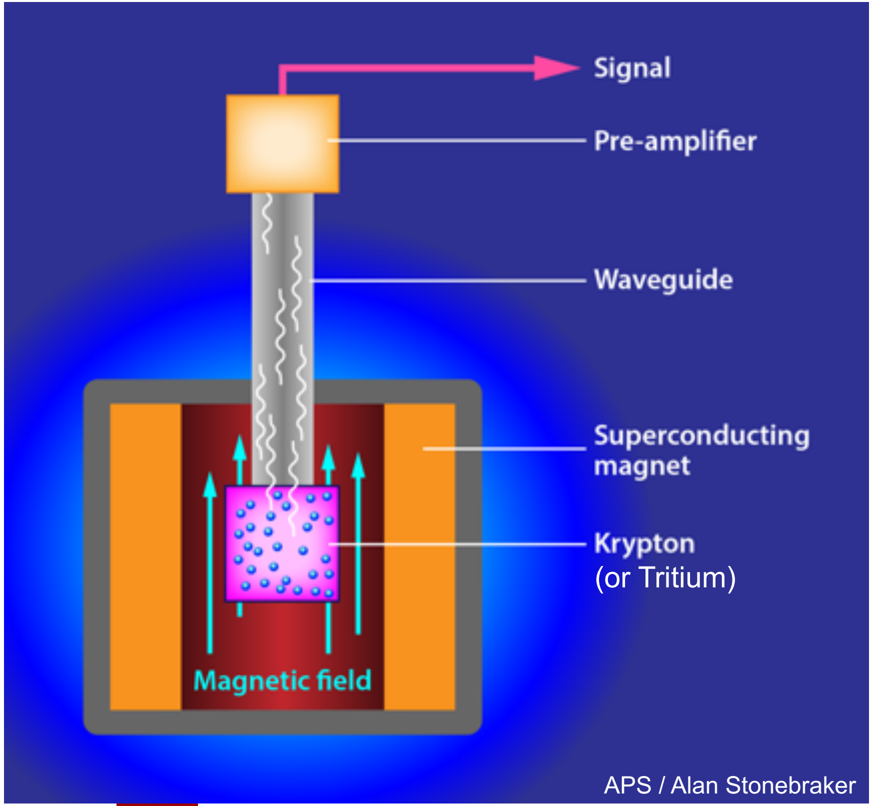
Machine Learning Applications

- Track-finding application well suited to machine learning techniques

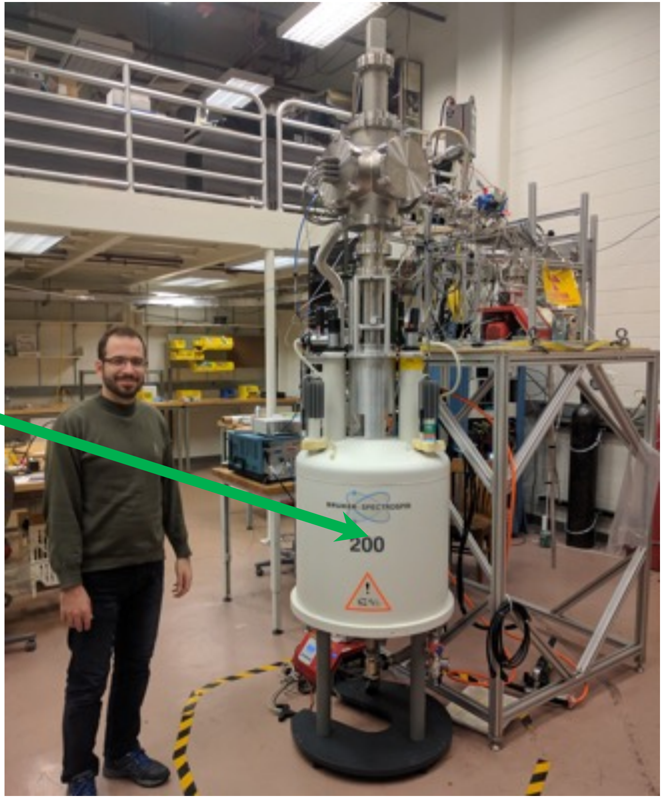


- Track classification using SVM
  - *see also arXiv:1909.08115*
  - New J. of Physics, 2020
- Track identification using CNN
  - *Work in progress*
- Locust simulation framework
  - *see also arXiv:1907.11124*
  - New J. of Physics, 2019

Waveguide Experimental Concept

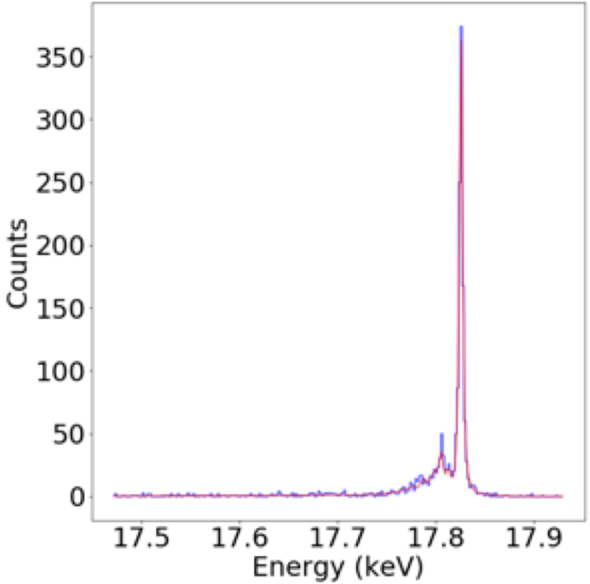


APS / Alan Stonebraker



^{83m}Kr Measurements – Resolution

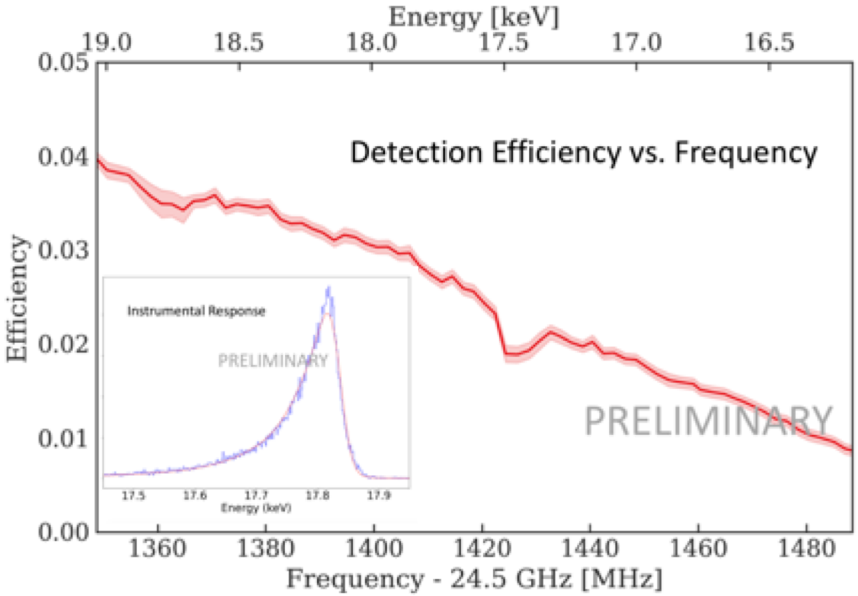
- Use ^{83m}Kr to demonstrate technique, characterize apparatus
  - Monoenergetic conversion electrons at 18, 30, 32 keV



- Achieved resolution of 2.0 ± 0.5 eV (FWHM)
  - For high-resolution “shallow-trap” data
- Instrumental resolution surpasses natural linewidth of 2.8 ± 0.1 eV (of 17.8 keV line)
- Low-energy features well-described by model
  - Accounts for scattering off residual gas, shakeup/shakeoff features

^{83m}Kr Measurements – Statistics

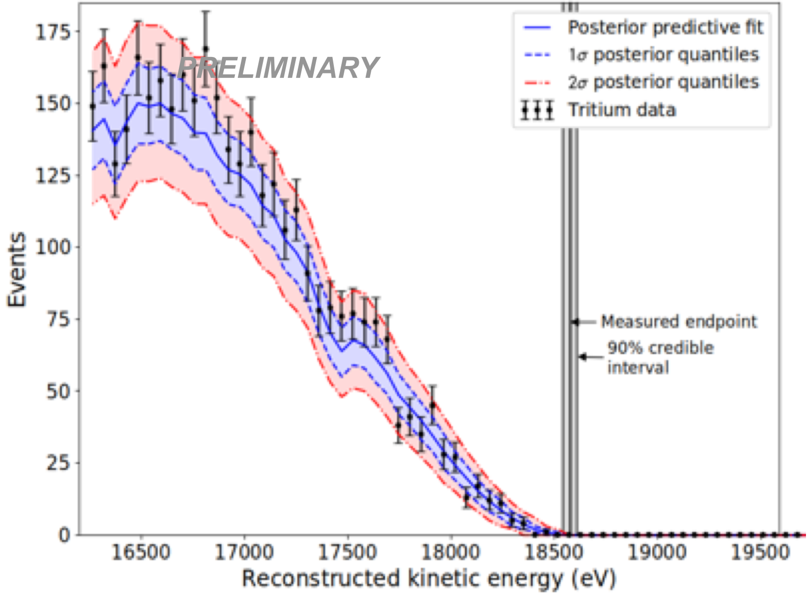
- Use ^{83m}Kr to demonstrate technique, characterize apparatus



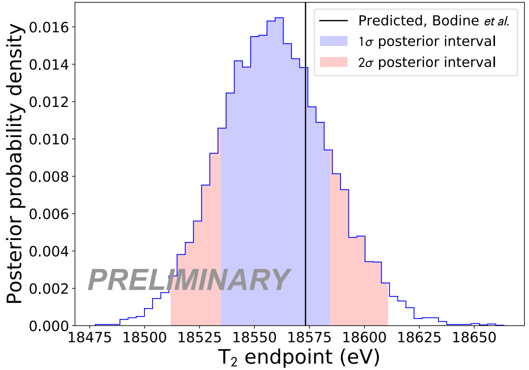
- "Deep trap" configuration employed for tritium run
  - Sacrifices resolution in favor of higher statistics
  - *See also* A. Ashtari Esfahani *et al*., Phys. Rev. C **99** (2019) 055501
- Lineshape model still represents data
- Magnetic field swept to study efficiency across region of interest

Tritium Beta Endpoint Measurement

- Extensive Kr data allows thorough characterization of systematics
- Three month tritium run taken to accumulate statistics



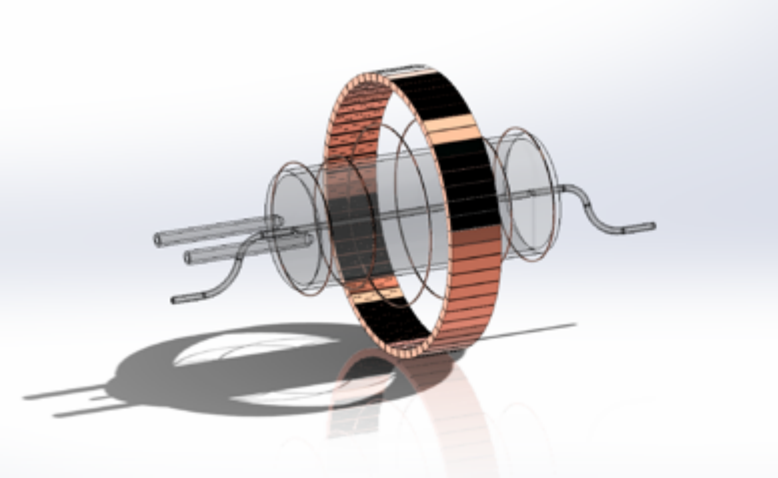
- Preliminary endpoint result:
  - $E_0 = 18559.4^{+24.9}_{-24.7}$ eV
- No background events observed
  - $B < 3\times10^{-10}\ \mathrm{eV^{-1}s^{-1}}\ (90\%\ \mathrm{C.I.})$



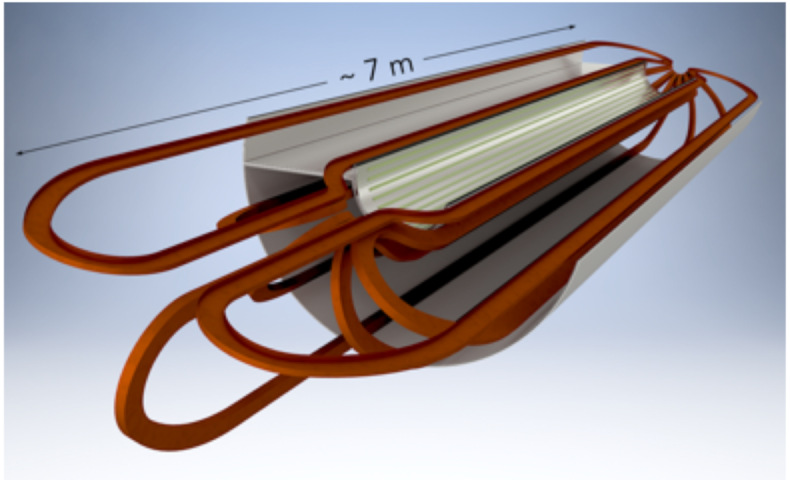
Where Next? Phase III

- ~Five year R&D program in critical technology demonstrations

Free Space CRES Demonstrator



Atomic Trap Demonstrator



See Juliana Stachurska's talk this morning

Phase IV – Putting Together the Pieces

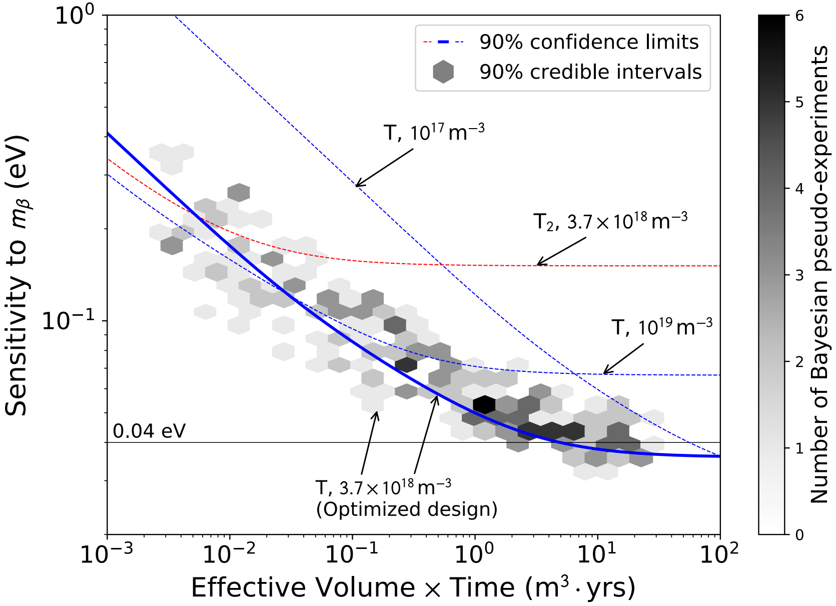
Framework developed for investigating sensitivity of ultimate experiment

- *See* arXiv:2012.14341 (A. Ashtari Esfahani *et al.* 2020)

Achieving 40 meV sensitivity requires

- Multi m^3·yr effective exposure
- High flux atomic tritium source
- ~0.1 eV resolution
- 10^{-7} field uniformity

With potential to independently measure hierarchy



Conclusions

- CRES established as promising technique for next generation neutrino mass experiment
  - Also other physics applications
- Phase II operations complete
  - Systematics investigated through ^{83m}Kr measurements
  - “High-statistics” tritium dataset collected
- Work ongoing to key technology demonstrators towards 40 meV experiment

Project 8 Collaboration

Case Western Reserve University
- Razu Mohiuddin, Ben Monreal, Yu-Hao Sun

Indiana University
- Walter Pettus

Johannes Gutenberg University, Mainz
- Sebastian Böser, Christine Claessens, Martin Fertl, Alec Lindman, Christian Matthé, Rene Reimann, Florian Thomas

Karlsruhe Institute of Technology
- Thomas Thümmler

Lawrence Livermore National Laboratory
- Kareem Kazkaz

Massachusetts Institute of Technology
- Nicholas Buzinsky, Joseph Formaggio, Mingyu Li, Junior Pena, Juliana Stachurska, Wouter Van de Pontseele

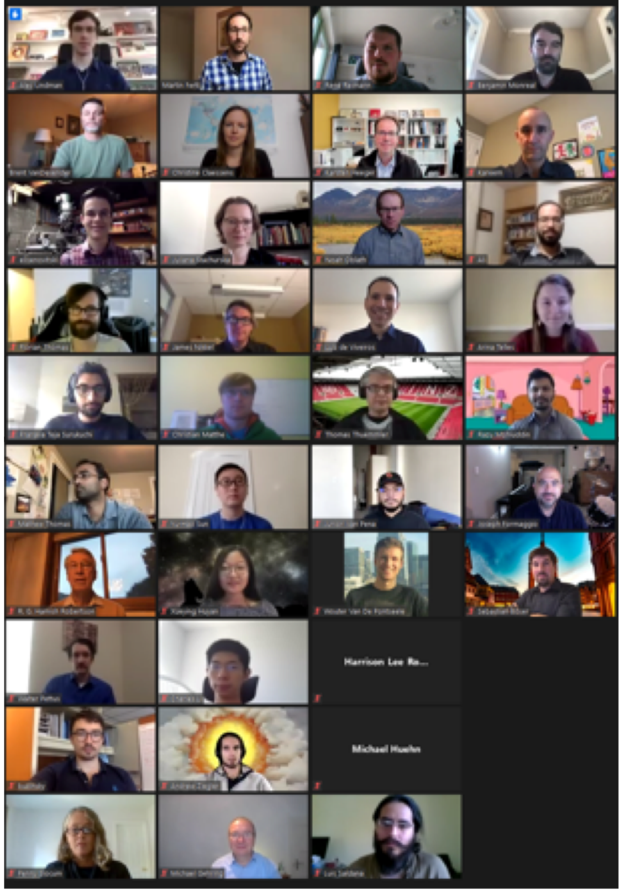
Pacific Northwest National Laboratory
- Maurio Grando, Xueying Huyan, Mark Jones, Noah Oblath, Malachi Schram, Jonathan Tedeschi, Mathew Thomas, Brent VanDevender

Pennsylvania State University
- Luiz de Viveiros, Andrew Ziegler

Smithsonian Astrophysical Observatory
- Shep Doeleman, Jonathan Weintroub

University of Washington
- Ali Ashtari Esfahani, Peter Doe, Elise Novitski, Hamish Robertson, Leslie Rosenberg, Gray Rybka, David Sweigart

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



This work is 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 institutions.