Cyclotron Radiation Emission Spectroscopy for Neutron Decay

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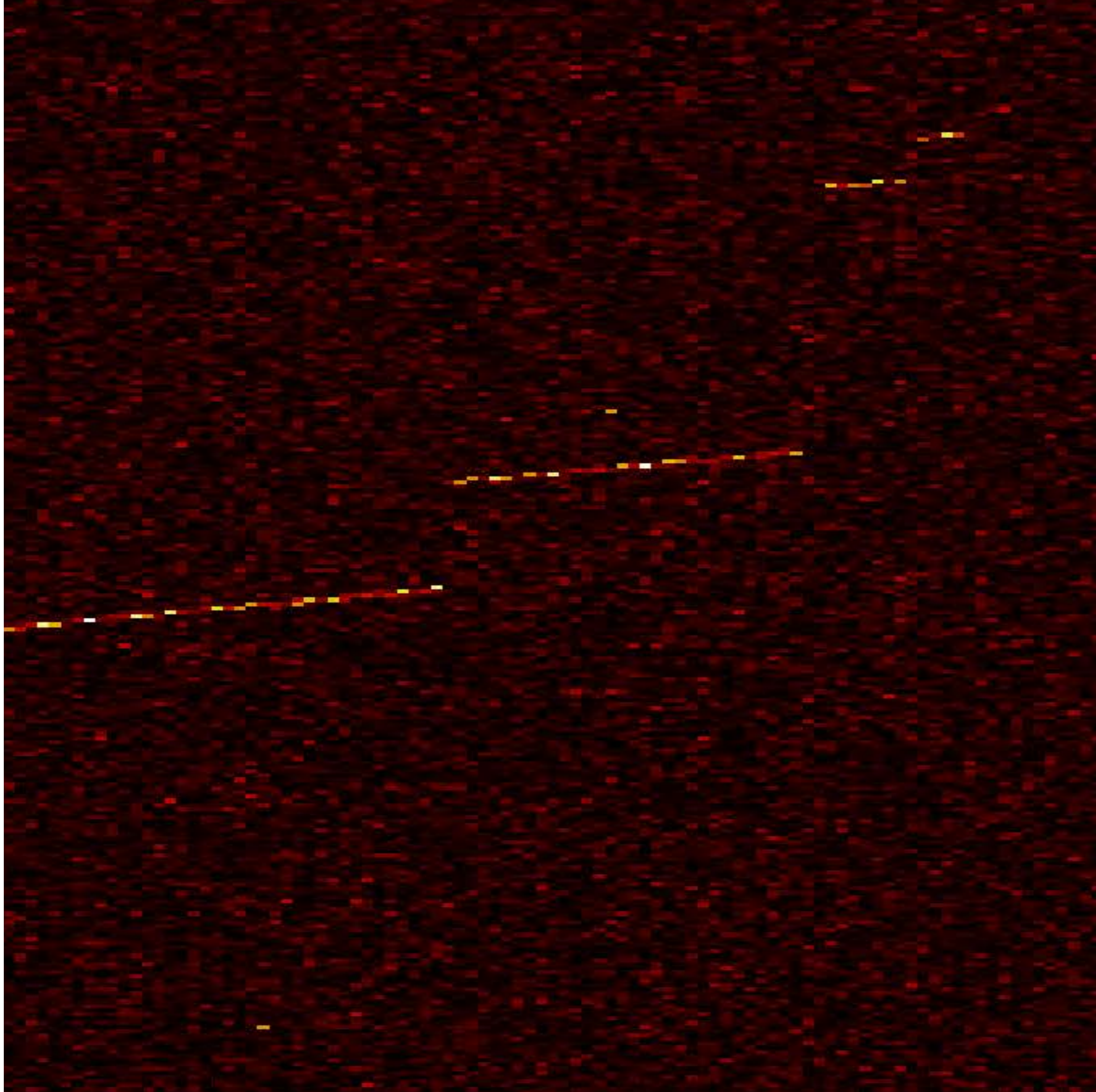
Particle Physics With Neutrons at the ESS

Nordic Institute for Theoretical Physics

Stockholm, Sweden

December 13, 2018



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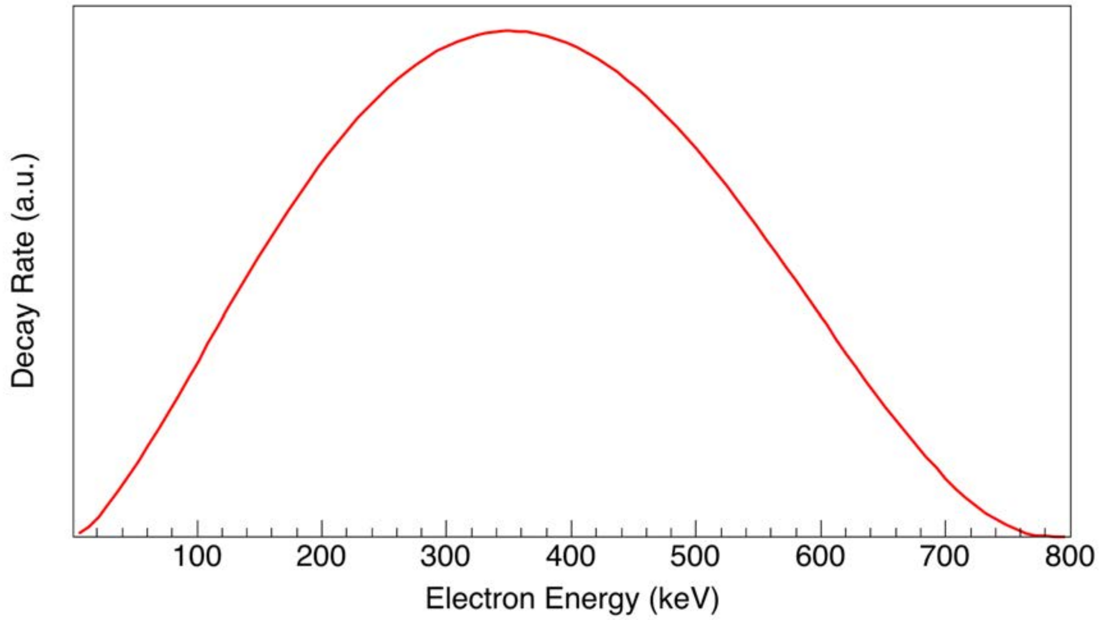
Outline

- Motivation: evade the dominant systematics in measurements of Fierz interference ("little b") in neutron decay: constrain non-SM tensor (T) interactions
- A brief background on absolute neutrino mass measurements and the tritium endpoint method
- Cyclotron Radiation Emission Spectroscopy (CRES)
- CRES progress from the Project 8 neutrino mass experiment
- CRES challenges unique to the neutron decay experiment

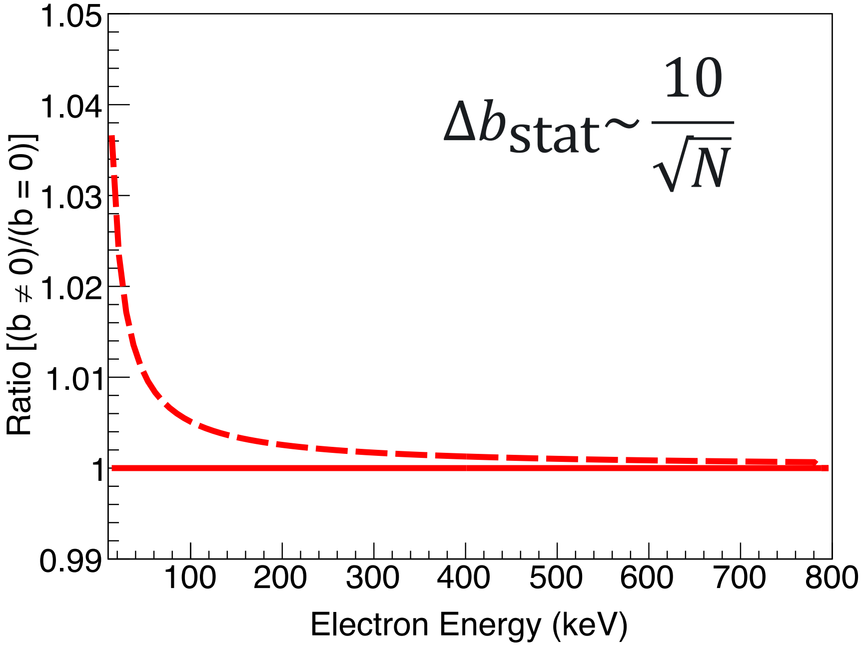
Fierz Interference in Neutron Decay

- Fierz interference term appears for non-SM *S* and *T* couplings (b_{SM}=0).
  - *S* coupling is highly constrained by superallowed beta decay studies
  - neutron decay then primarily constrains *T* couplings
  - $\Delta b \lesssim 10^{-3}$ begins to compete with pion decay constraints on *T*
- *b* determined experimentally by a fit to the measured shape of the electron spectrum in free neutron decay: $n \rightarrow p + e^- + \bar{\nu}_e$

$$\frac{d\Gamma}{dE} = \left(1 + b\frac{m}{E}\right)W(E), \;\; W(E) \propto pE(E_0 - E)^2$$



$$\left(\left.\frac{d\Gamma}{dE}\right|_{b=10^{-3}}\right) \Big/ \left(\left.\frac{d\Gamma}{dE}\right|_{b=0}\right)$$



Experimental Status of "little *b*"

- One directly determined limit by the **UCNA experiment**:

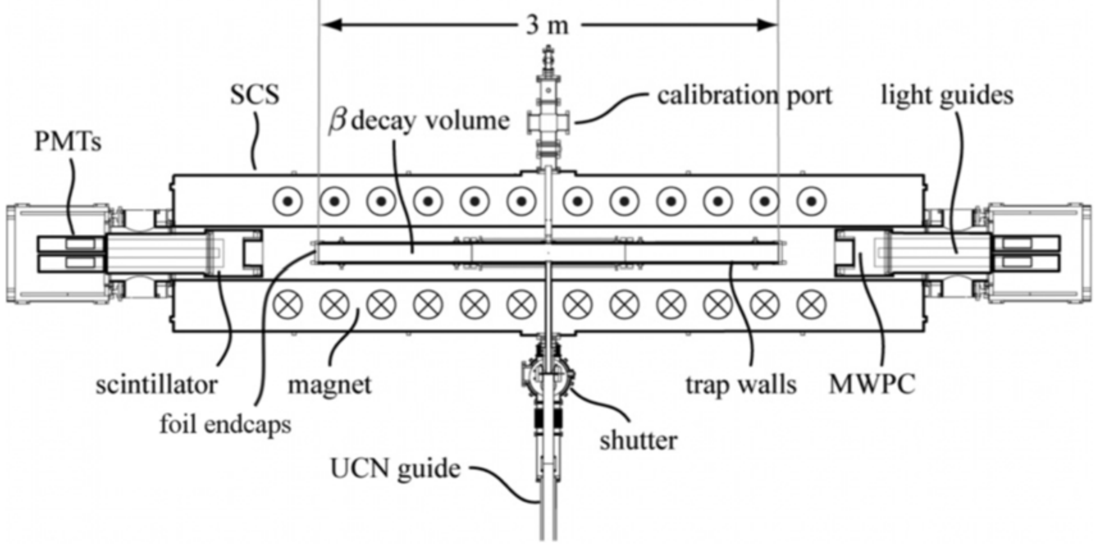
$$b = 0.067 \pm 0.005_{\text{stat}} {}^{+0.090}_{-0.061}{}_{\text{syst}}$$

Hickerson *et al.* (UCNA Collaboration), *Phys. Rev. C* **96** (2017).

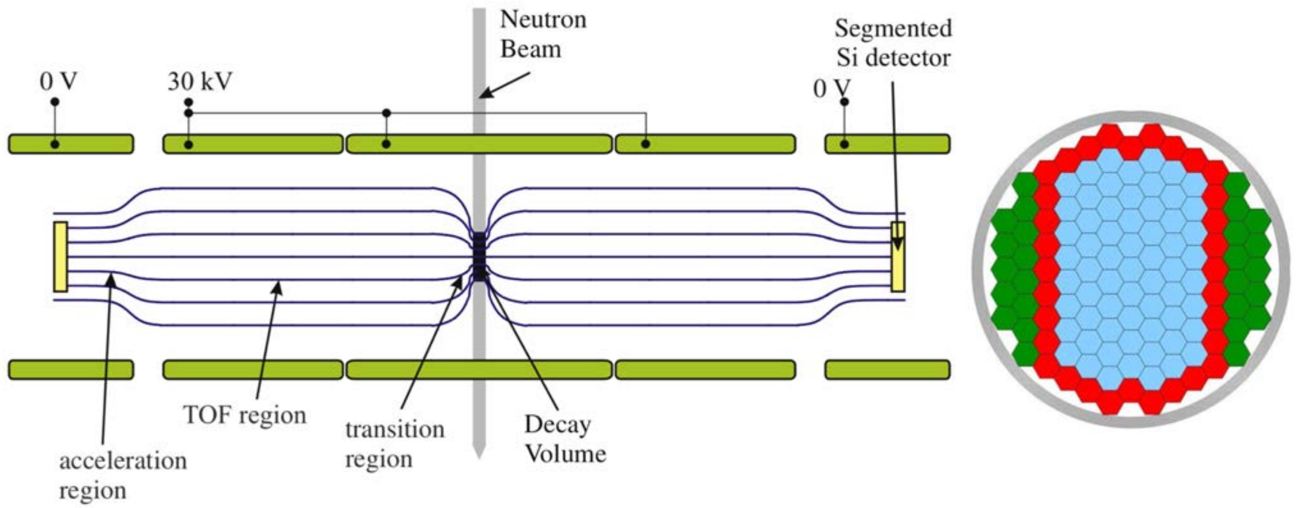
- Precision dominated by detector-related systematics, primarily
  - **Nonlinearity**
  - **Absolute energy calibration**
- **Nab** plans $\Delta b \lesssim 3\times10^{-3}$ with cold neutrons at ORNL's SNS
- Nab precision also dominated by systematics
  - **Energy calibration**
  - **Electron backgrounds**

Počanić *et al.*, *NIM* **A611** (2009).

UCNA Spectrometer



Nab Spectrometer and Detector



Hope, and a Suggestion for the $\Delta b < 10^{-3}$ Future Beyond Nab

- Measurement precision of *b* in neutron decays is and will continue to be **dominated by systematics associated with electron detector response**.

- The suggestion is therefore **not to use a traditional solid or gas detector detector at all**.

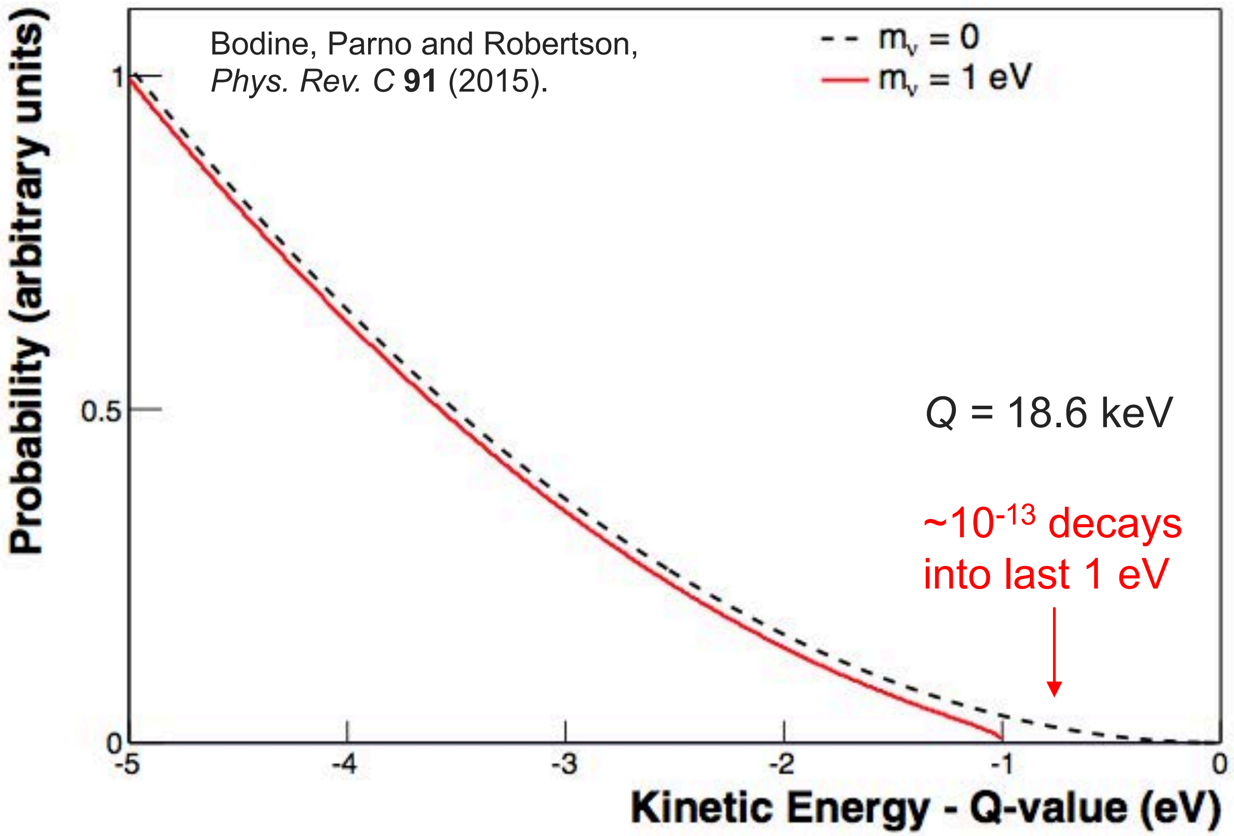
- Rather, **detect the radiation from magnetically trapped electrons**.
  - Convert the problem from the energy domain to frequency domain → **extreme precision and absolute reference calibrations**.
  - The laws of E&M are **absolutely linear**.
  - It is expected that the **background of accidentally trapped electrons is extremely small**.

- This is the approach taken by Project 8, an experiment to determine the absolute neutrino mass scale…

The Tritium Endpoint Method to Determine the Absolute Neutrino Mass Scale

- Tritium Beta Decay: ${}^{3}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + e^{-} + \overline{\nu}_e$
- High-precision spectroscopy on the e^-
- Neutrino mass manifests as a deviation at the energy endpoint
- Fit the spectral shape with $m_{\nu e}^2$ as a free parameter:

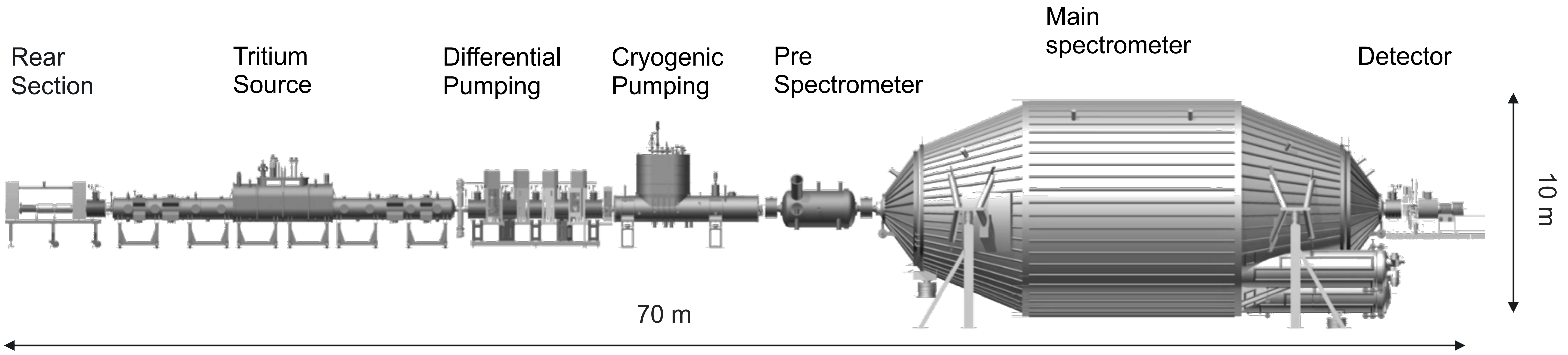
$$m_{\nu_e}^2 \equiv \sum_{i=1}^{3} |U_{ei}|^2 \, m_i^2$$



- Only extremely rare decays very near the endpoint are sensitive to m_ν
- Statistical sensitivity of $m_{\nu e}^2$ is roughly $\sim 1/N^{1/2}$, that of $m_{\nu e}$ is $\sim 1/N^{1/4}$
- Each generation of tritium endpoint experiment must accommodate *much* more intense tritium source than the last

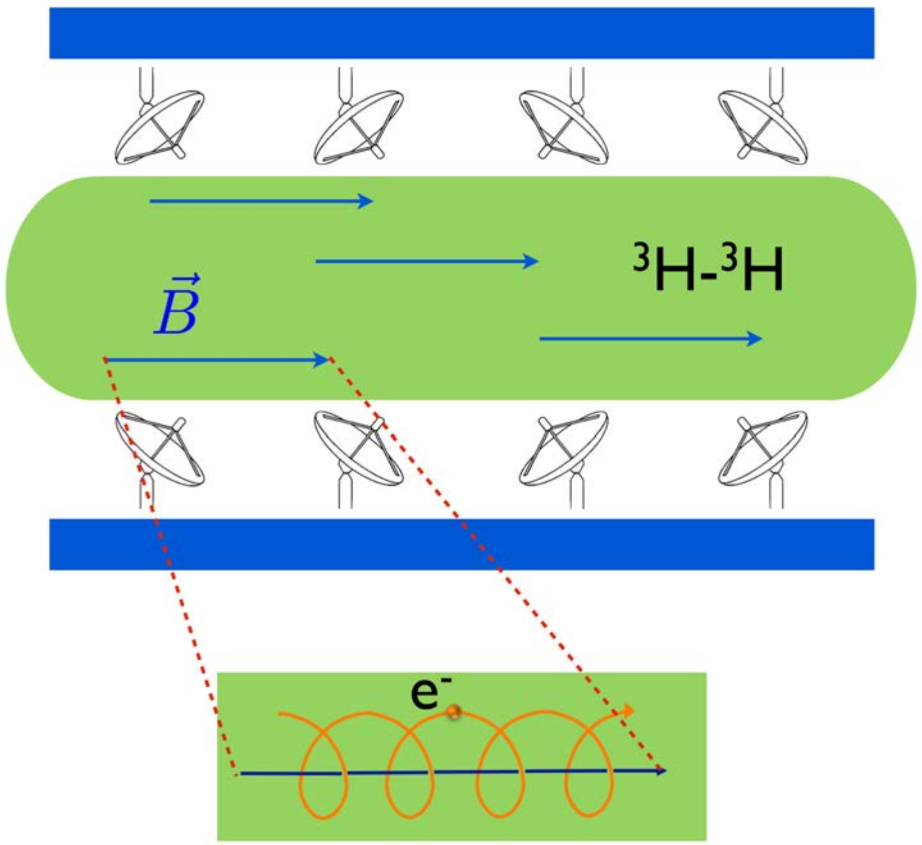
The Quest for Statistical Sensitivity to Neutrino Mass

Karlsruhe Tritium Neutrino (KATRIN) Experiment



- KATRIN uses the maximum possible source column density – statistical sensitivity can only improve by expanding the source radially.
  - The spectrometer(s) must expand proportionally.
  - Sensitivity to inverted hierarchy $m_{\nu e}$ required ~100s of meters diameter!
  - KATRIN is already the best possible experiment of its kind! It will determine $m_{\nu e}$ < 0.200 eV/c^2 (90% c.l.).
- Improvement in neutrino mass statistical sensitivity will require a spectrometer with a better source scaling relation.

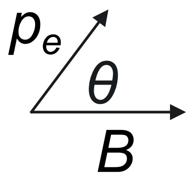
Cyclotron Radiation Emission Spectroscopy (CRES)



- Project 8 will use CRES [Monreal and Formaggio, *Phys. Rev. D* **80** (2009)]:
  - Detect microwave cyclotron radiation from magnetically trapped electrons.
  - Tritium source is transparent to μwaves. Directly instrument the source region → improved scaling ~volume.
  - Nondestructive frequency domain technique – extreme precision w/ absolute standards.

- Kinetic energy and cyclotron frequency are related by relativistic kinematics:
  - Frequency depends only on kinetic energy (*E*) and magnetic field (*B*)
  - Frequency does *not* depend on pitch angle (θ)

$$f = \frac{f_0}{\gamma} = \frac{1}{2\pi}\frac{eB}{m_e + E/c^2} \qquad P = \frac{2\pi e^2 f_0^2}{3\varepsilon_0 c}\frac{\beta^2 \sin^2\theta}{1-\beta^2}$$

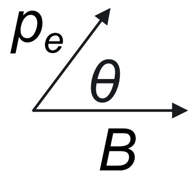


- Tritium endpoint electrons (*E*=18.6 keV) emit *P*~1 fW at *f*≈26 GHz in a 1 T *B*-field.
- *ΔE* = 1 eV → *Δf* ≈ 50 kHz and requires ~10 μs observation time.

Cyclotron Radiation Emission Spectroscopy (CRES)

- Real experiments must confine electrons in a magnetic trap for sufficient observation time:
  - *B* is the average field sampled by the electron in an observation time window.
  - Introduces pitch angle (θ) dependence.
  - Harmonic traps ($B \sim z^2$) have an analytical solution for instantaneous frequency:

$$\omega(t) \approx \Omega_c \left(\left(1 + \frac{\cos^2\theta}{2\sin^2\theta} \right) + \frac{Pt}{\gamma_0 m_e c^2} + \frac{z_{max}\Omega_a}{v_p} \cos(\Omega_a t) \right)$$

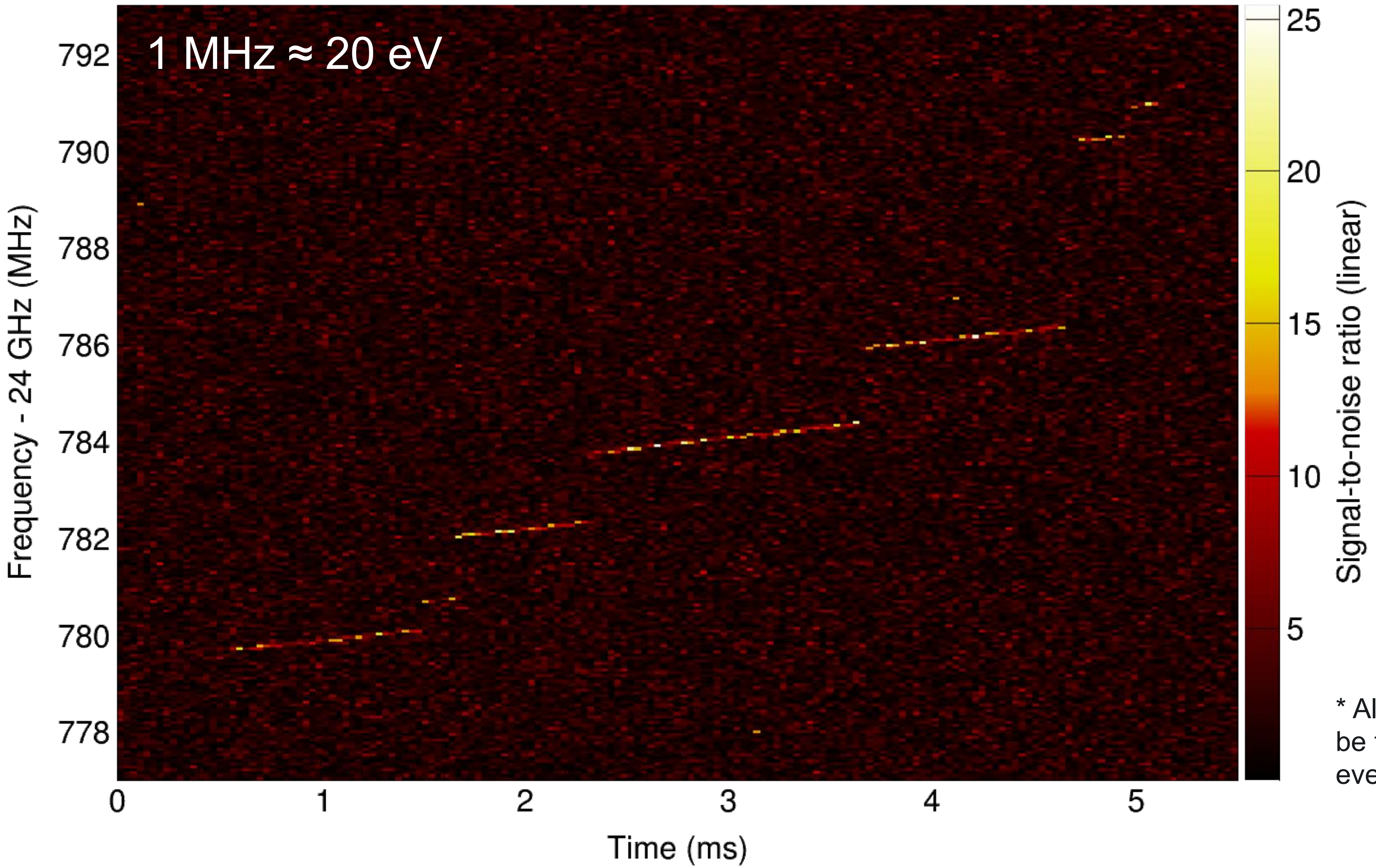


- 1st term is "naïve" cyclotron frequency plus a correction due to slightly different field variations sampled by electrons w/ different starting angles θ. Correction can be significant. (~10^{-4}, or <10 MHz ~ 200 eV).
- 2^{nd} term is a *chirp* due to energy lost to cyclotron radiation power *P* (~kHz/μs).
- 3^{rd} term is a *warble* due to reflections at the end of the trap – leads to doppler sidebands in frequency spectra.

- Range of trapped pitch angles $\delta\theta$ only depends on the ratio of magnetic fields.
- Fraction of trapped isotropically emitted electrons ε_T also depends only on the fields.

$$\epsilon_{\mathrm{T}} = \sqrt{1 - \frac{B}{B_{\mathrm{max}}}}. \qquad \delta\theta_{\mathrm{max}} = \cos^{-1}\sqrt{\frac{B}{B_{\mathrm{max}}}}.$$

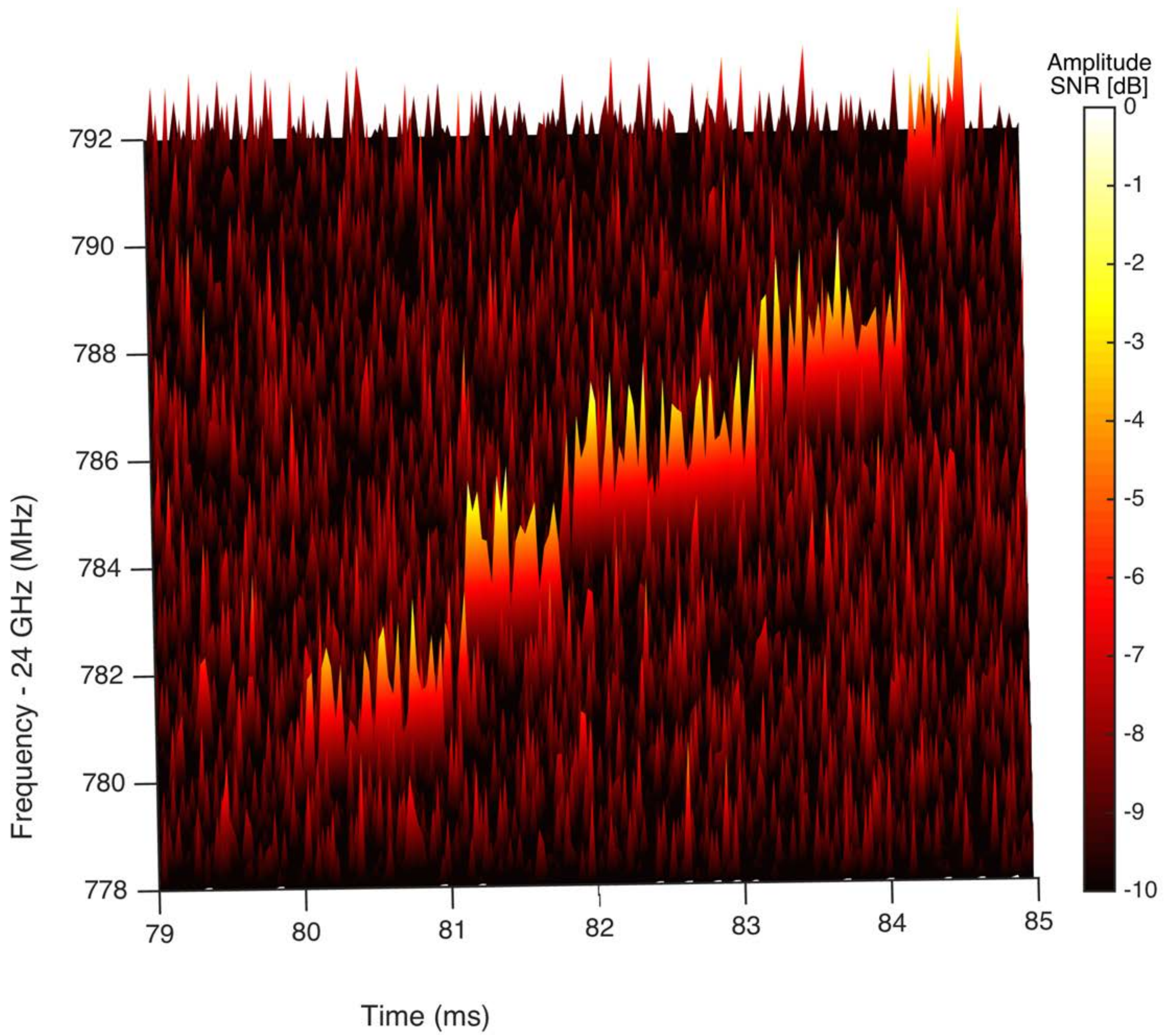
A Typical CRES Event*



* Also happens to be the first one ever observed

A Typical CRES Event*

Just in case the projector fails to render the previous view



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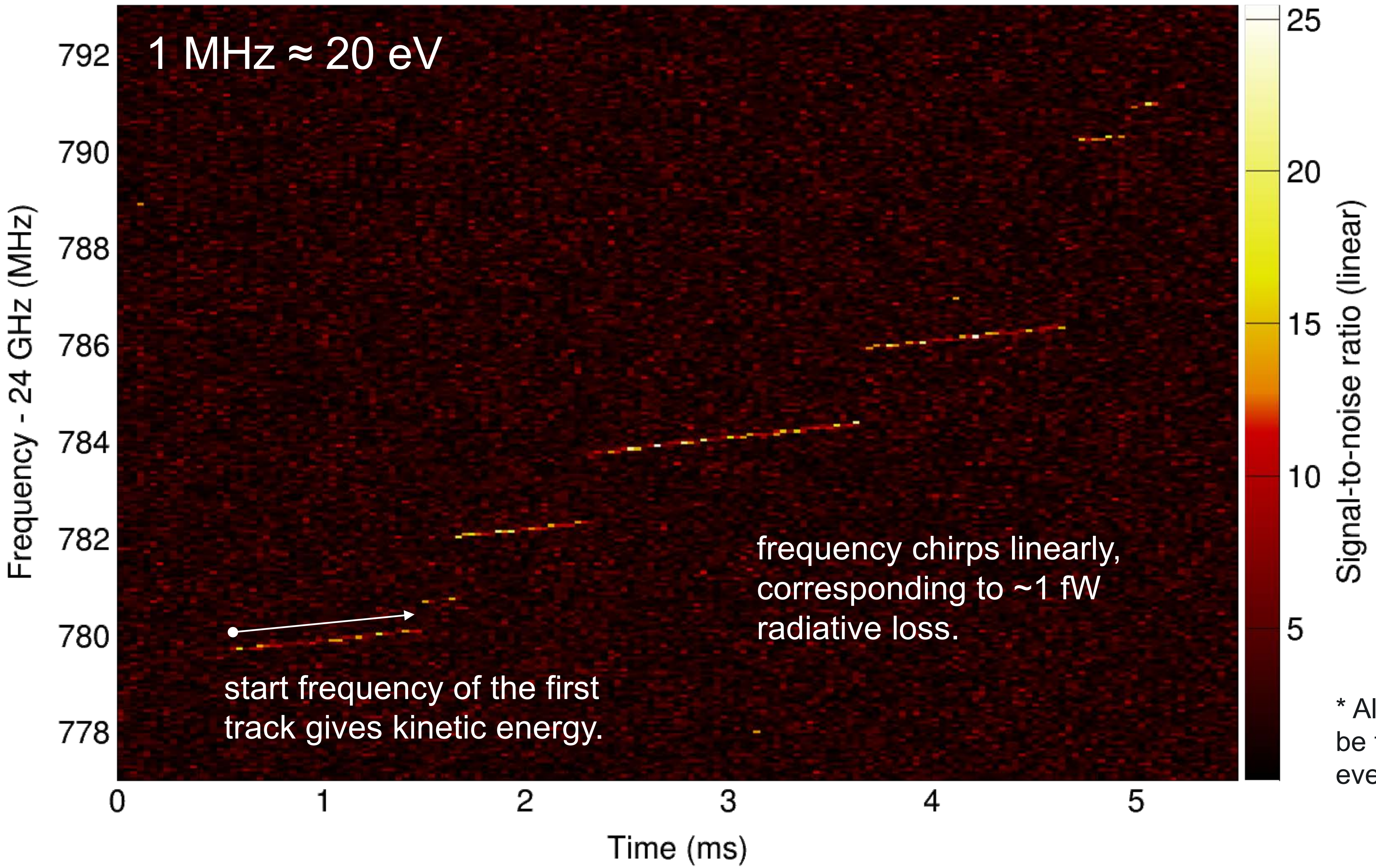

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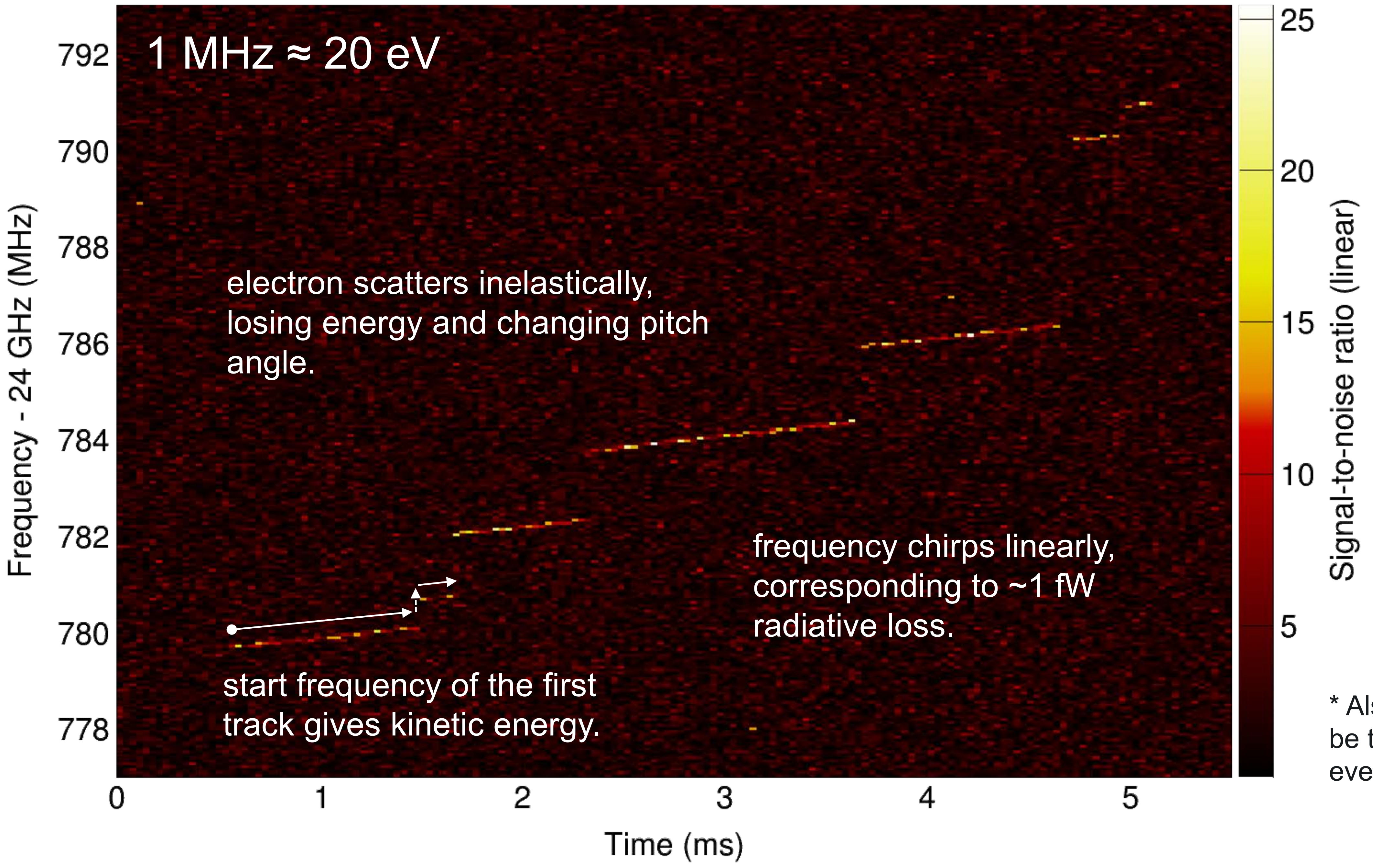
A Typical CRES Event*



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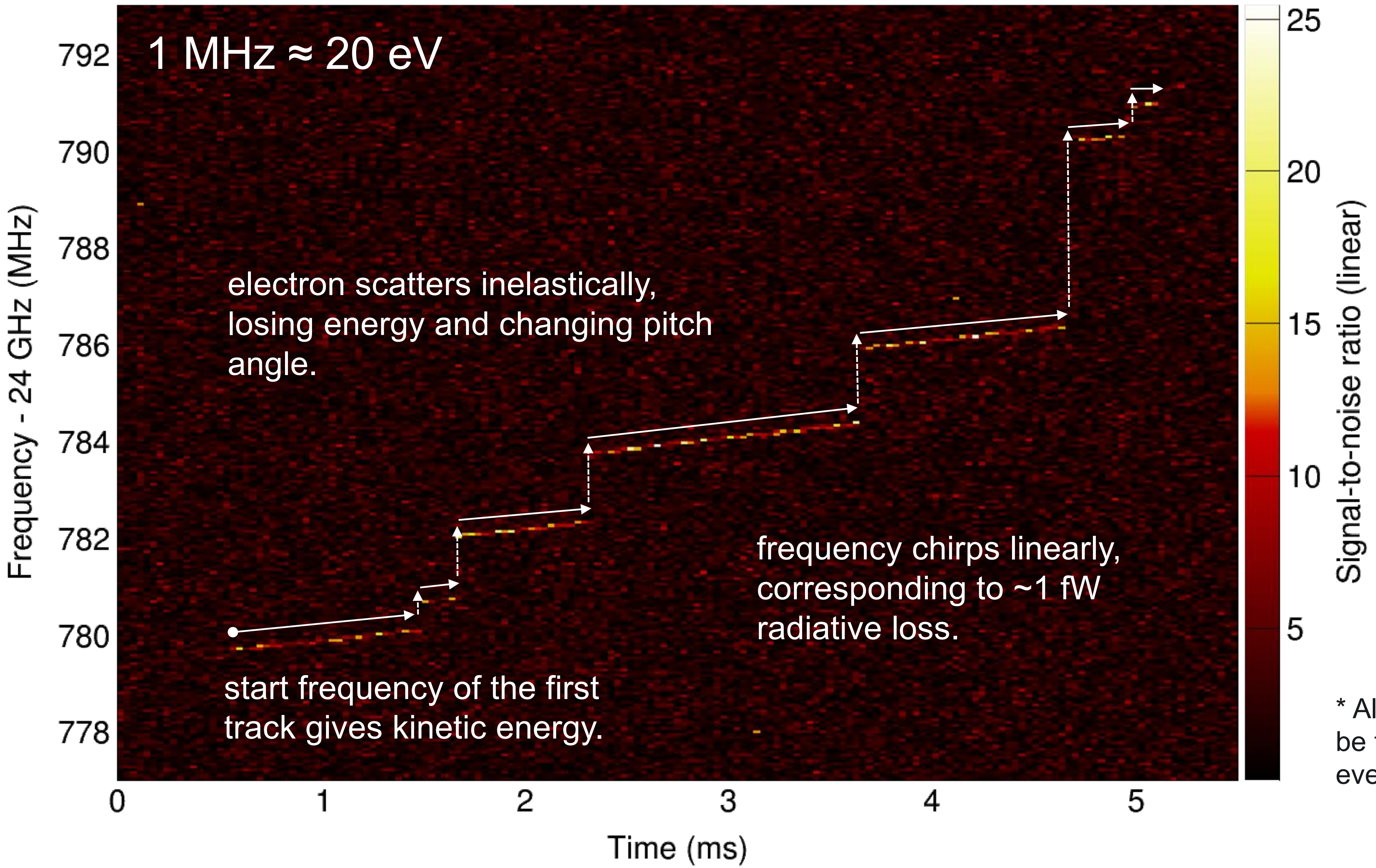
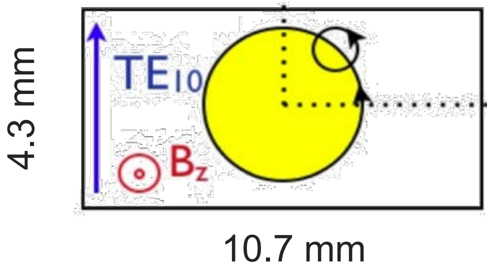
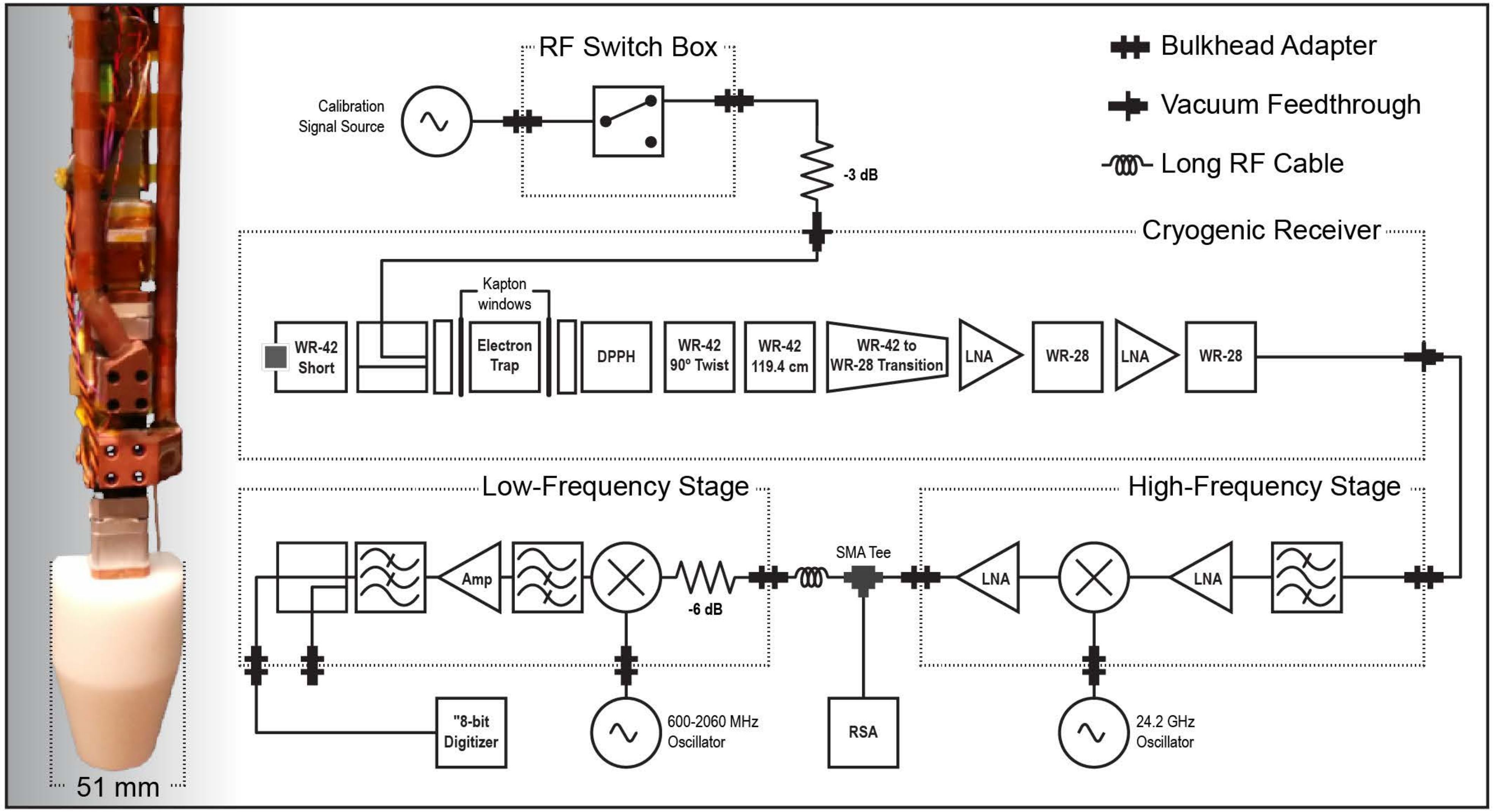
A Typical CRES Event*



* Also happens to be the first one ever observed

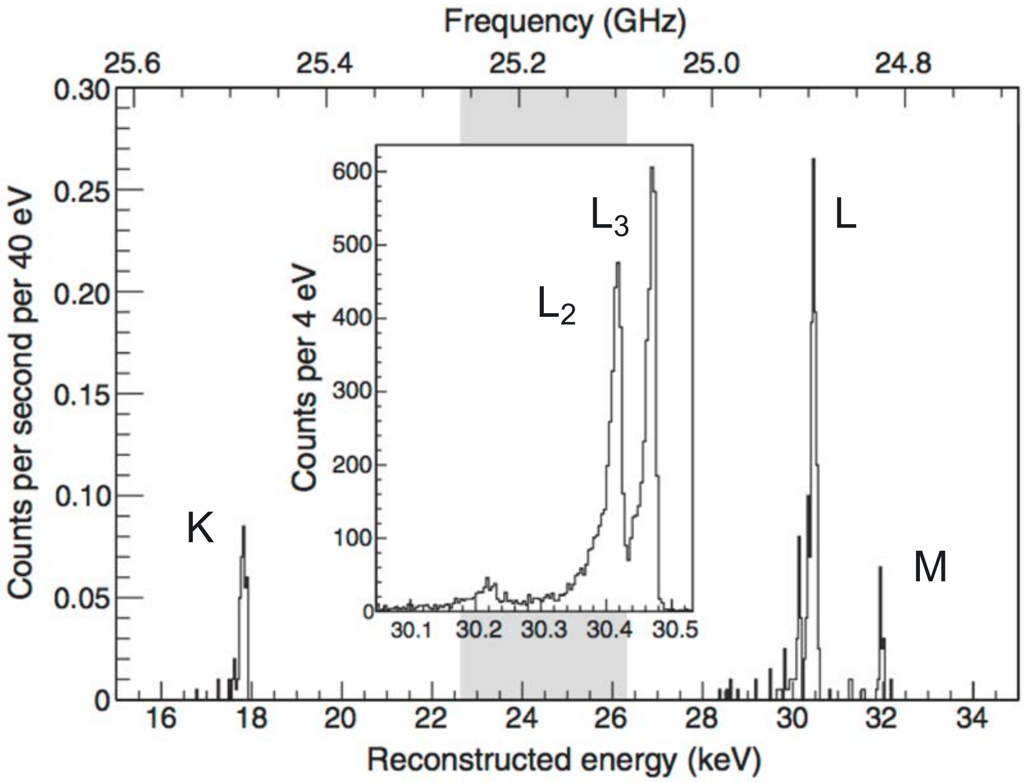
CRES Demonstration With ^{83m}Kr (Phase I)



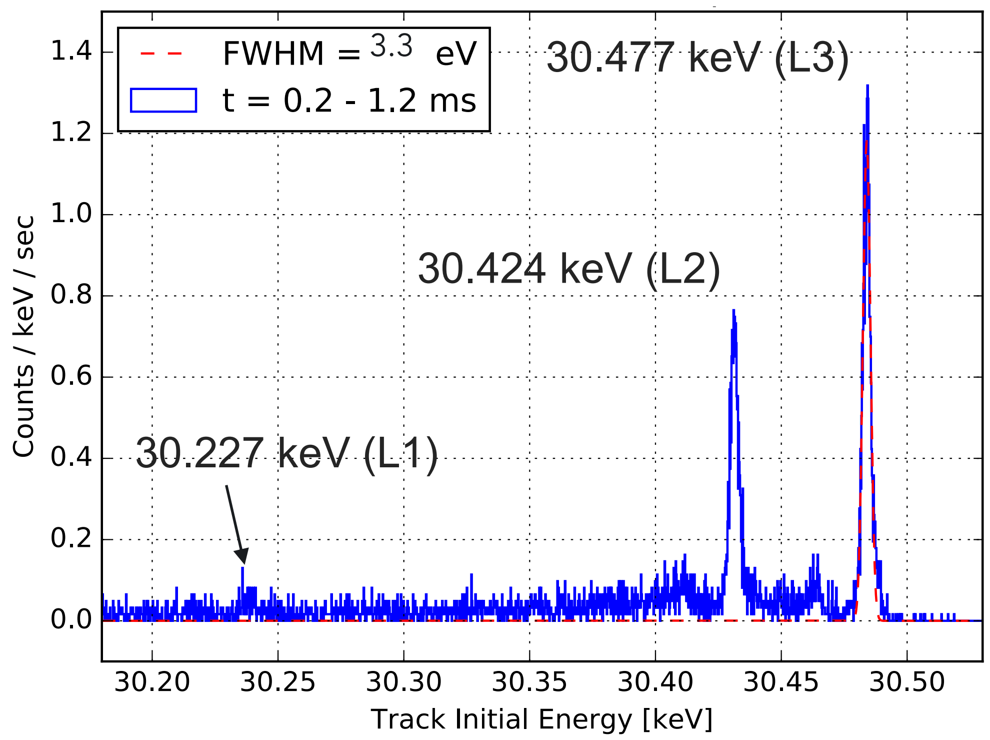


CRES Demonstration With ^{83m}Kr (Phase I)

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



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



- Very good energy resolution, with low-*E* (high-*f*) tails expected for a harmonic trap:

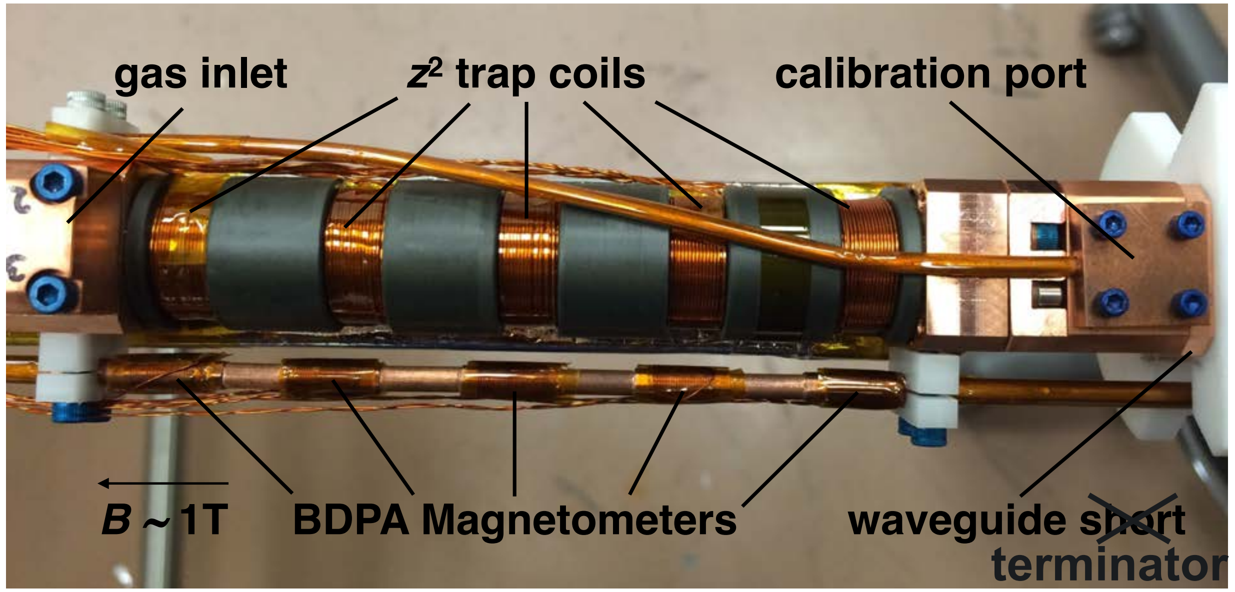
$$\Delta E_{\mathrm{L3}} = 15\ \mathrm{eV\ (FWHM)}$$

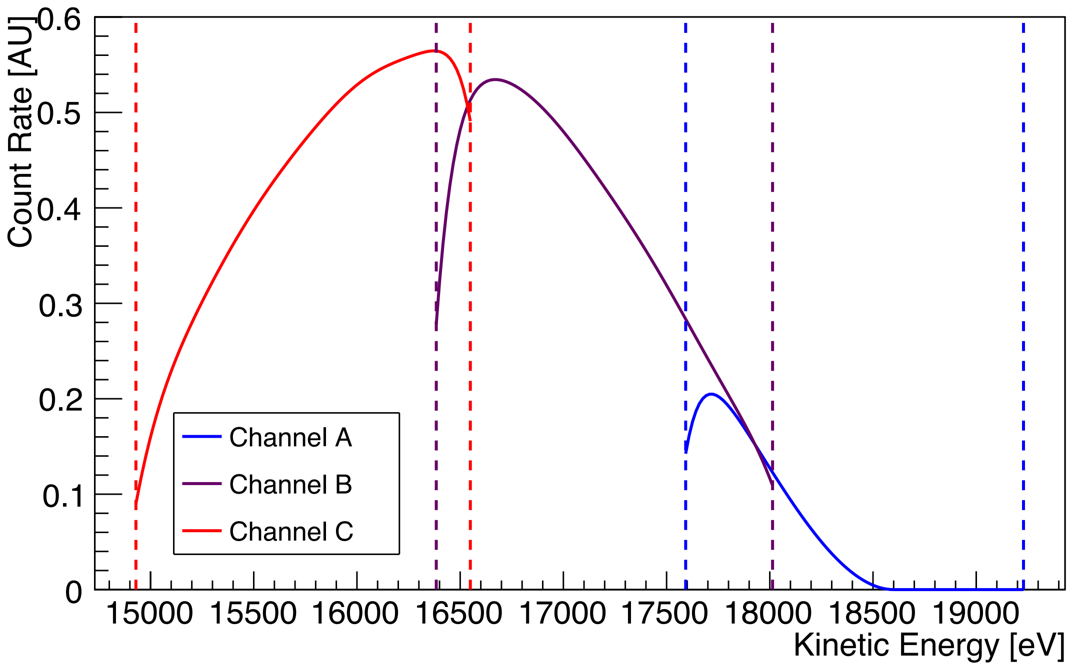
- "Linearity" of frequency-to-energy conversion at constant *B* indicated by ratio of conversion electron frequencies:

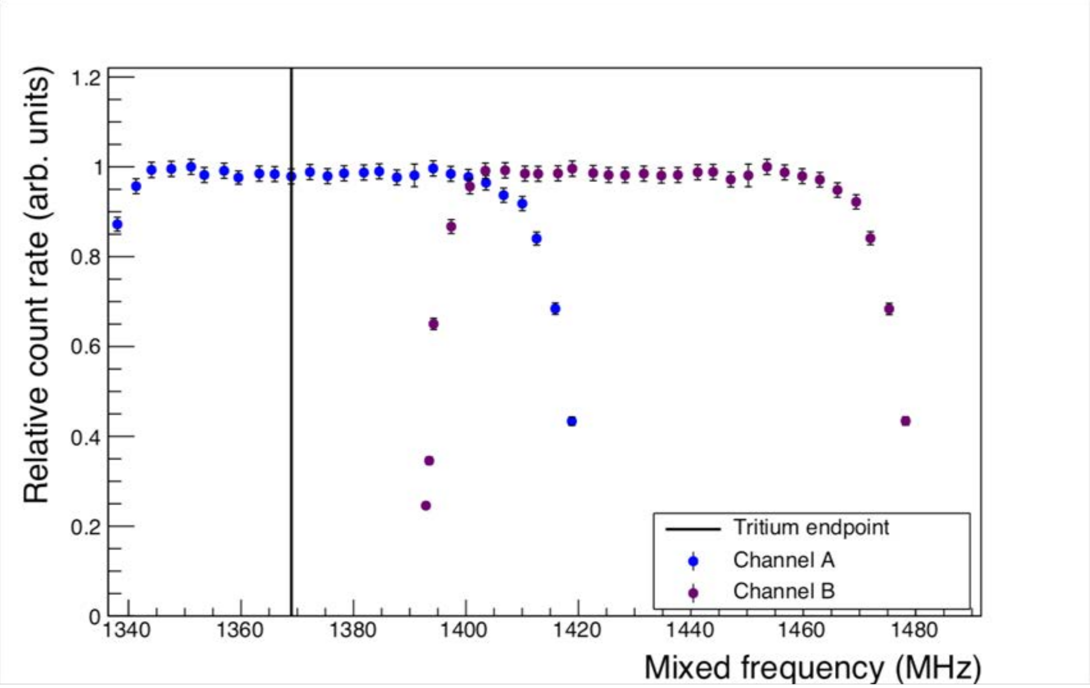
$$\frac{f_{\mathrm{L}}}{f_{\mathrm{K}}} = \begin{cases} 1.023870(60) & \text{measured} \\ 1.023875(2) & \text{predicted} \end{cases}$$

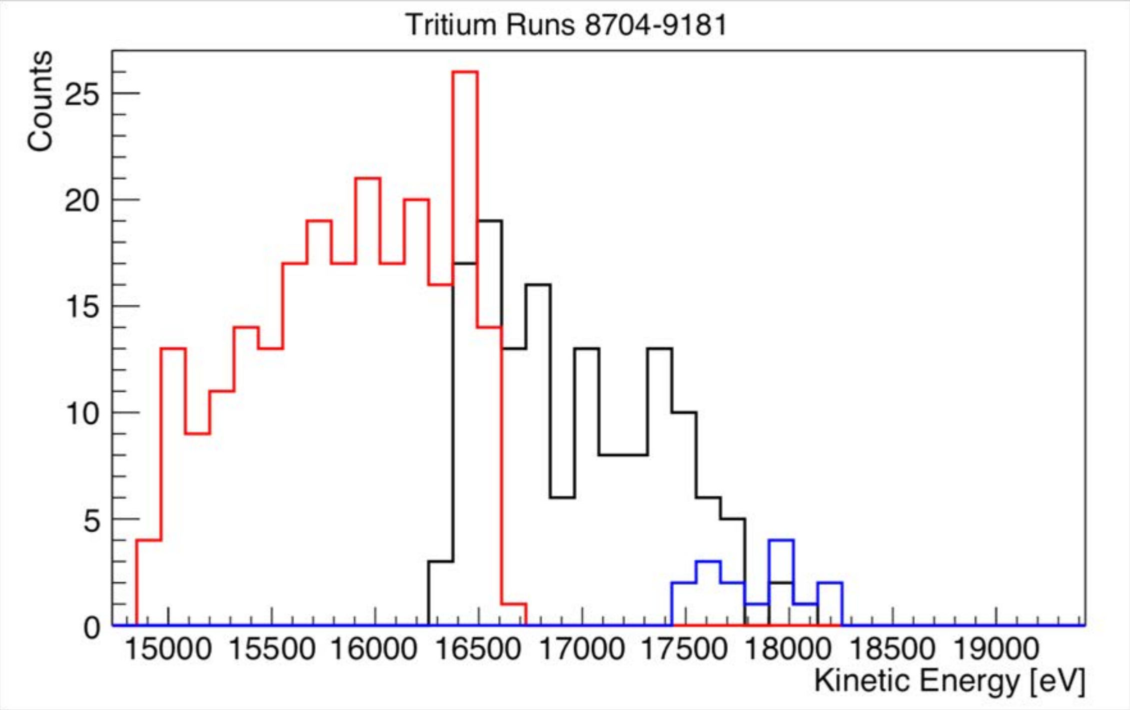
- More Recently: 3.3 eV FWHM w/ more uniform "bathtub."
- 3.3 eV resolution includes 1.4 eV of natural line width.
- Resolution is understood to follow from *B*-field variations.

First CRES Continuous (Tritium) Spectrum Measurement (Phase II)

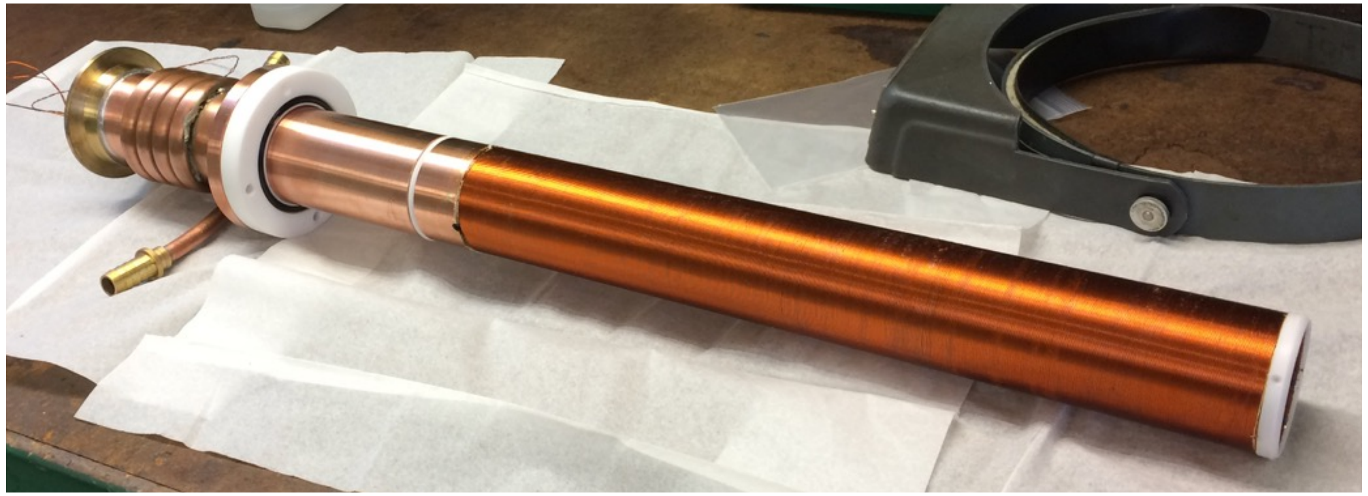


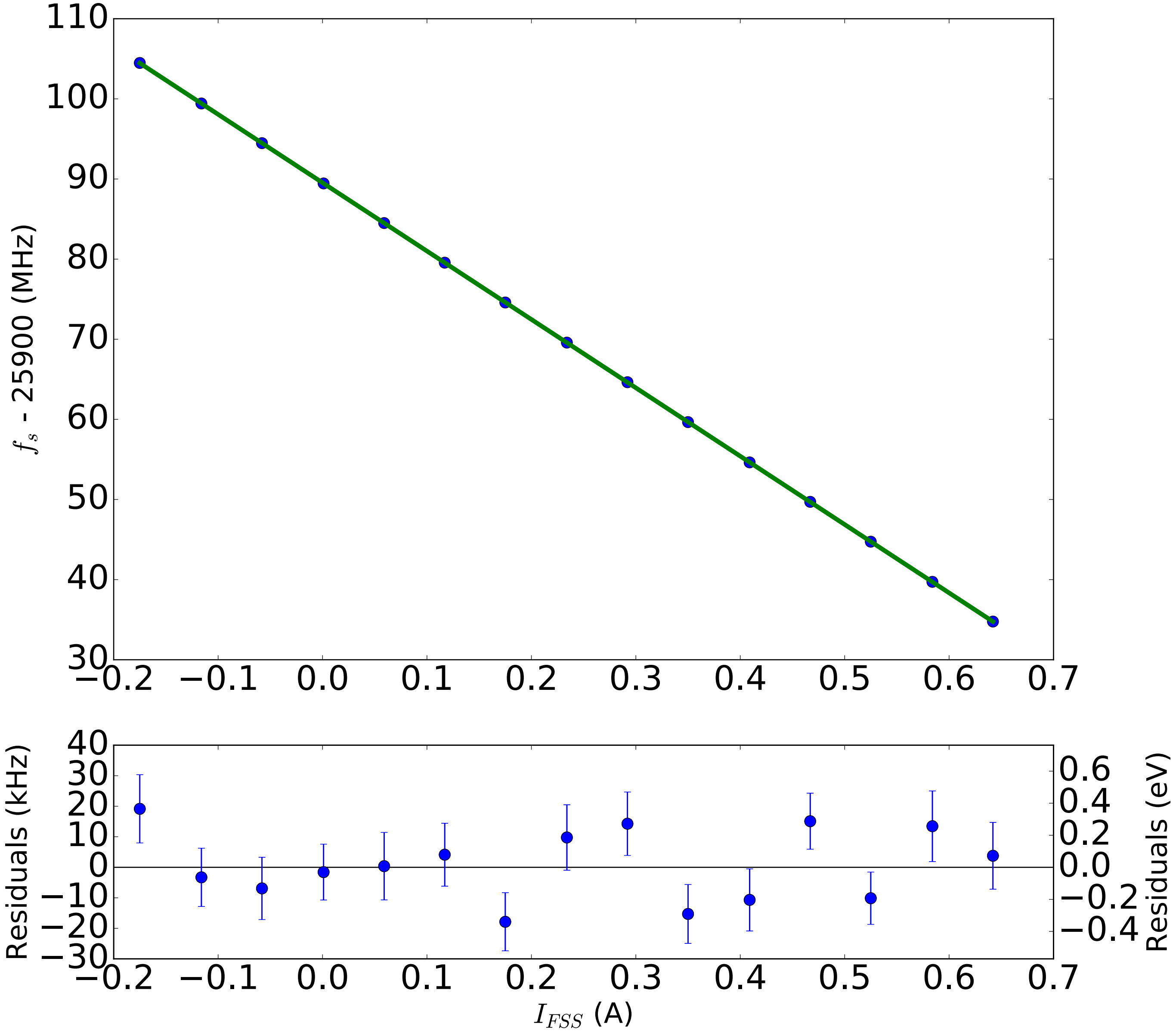






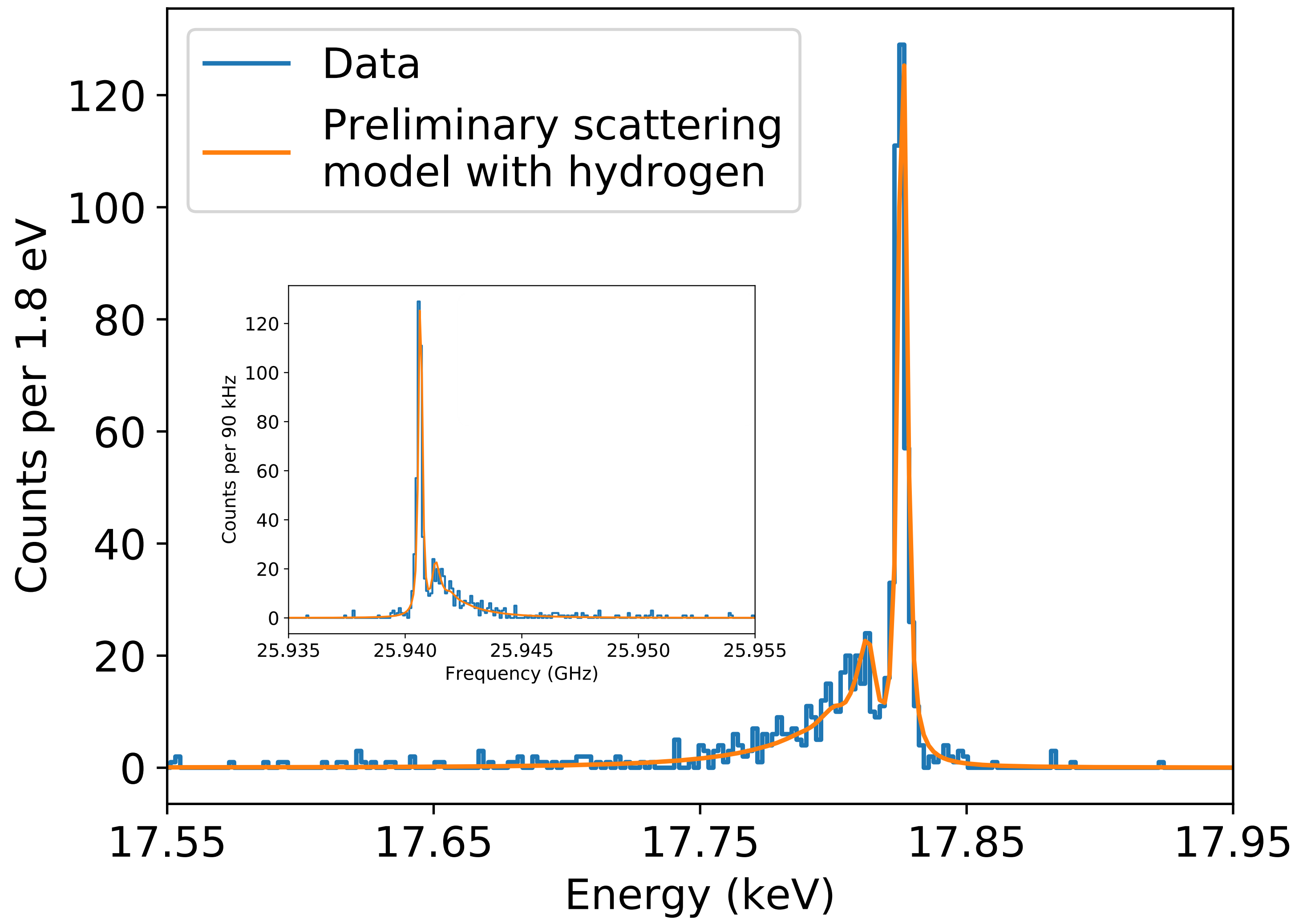
Linearity in *B*



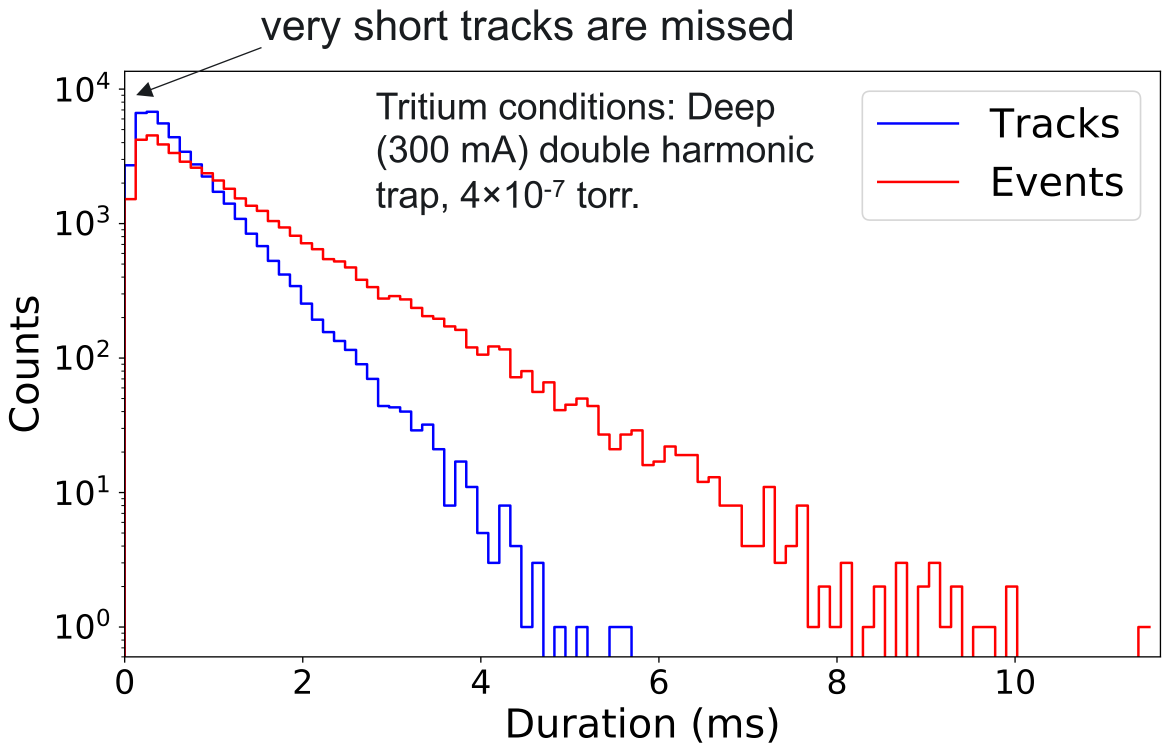


- Field-Shifting Solenoid (FSS) surrounds the CRES insert shown on the previous slide.
- Used to scan *B*, while observing the cyclotron frequency and intensity of the 17.8 keV ^{83m}Kr conversion electron (constant *E*).
- Demonstrates expected linearity of relation $f \propto B$
  - 70 MHz range (≈1.5 keV energy equivalent)
  - Residuals ~10 kHz (~0.1 eV energy equivalent)

Lineshape and Intrinsic Resolution

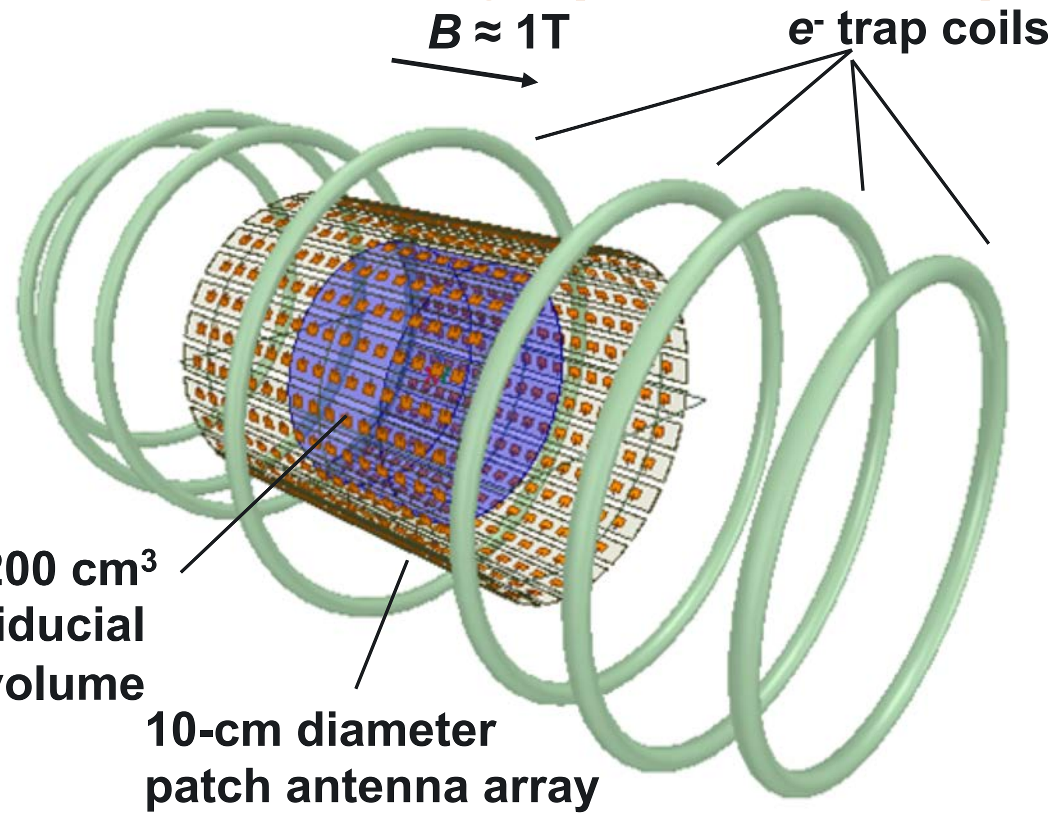


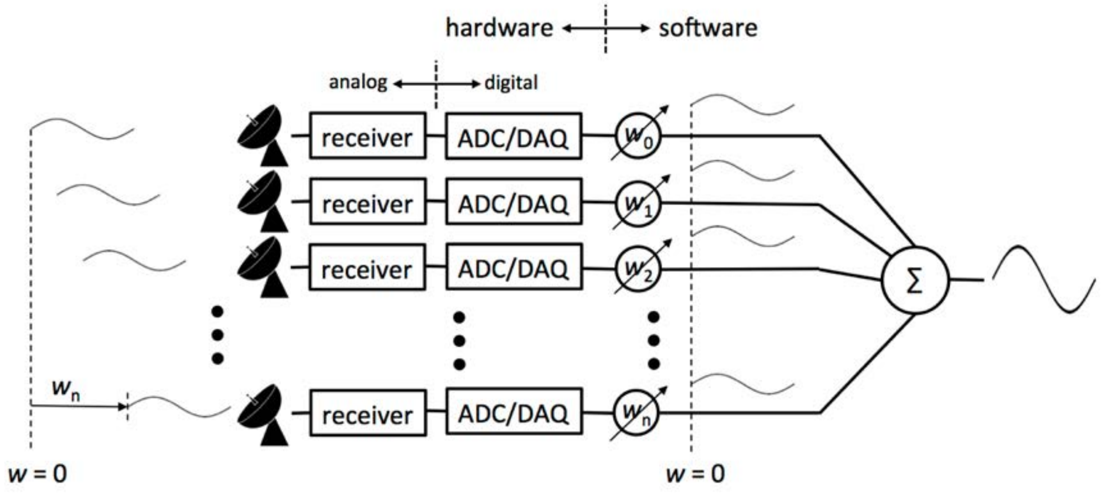
- In addition to asymmetric tail from non-flat traps, scattering before detection leads to high-*f* (low-*E*) tail.
- Simple scattering model consistent with a Voigt profile
- Data in a shallow trap demonstrates 4 eV FWHM, including 2.83 eV natural width of ^{83m}Kr 17.8 keV K conversion electron.



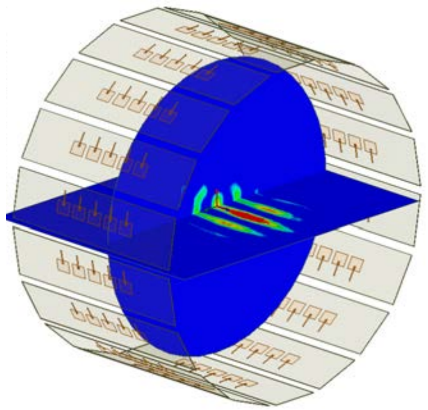
More Tritium for Statistical Sensitivity (Phase III)

- Must accommodate more tritium for statistical sensitivity
- Larger source too big for waveguide → free space environment sensed by antennas:
  - 10-cm-diameter cylindrical array
  - Resonant patch antenna elements (copper)
  - Passively fed along $B \propto z$
  - Actively instrumented around θ
- Electron trap provided by coils completely outside the array (green)





Actively combine around θ, dynamically focus by tuning relative phases w_i



Example: focus in the center (w_i=0, i=1…n)

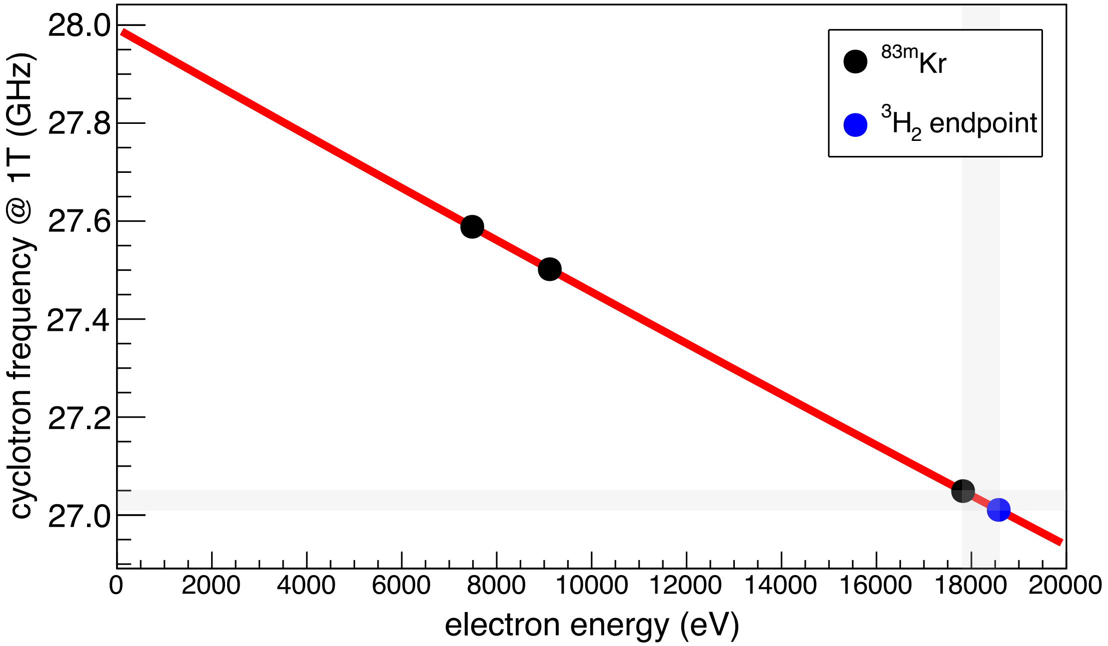
Challenges for Neutrinos and Neutrons

- Common Challenges:
  - Calibration – provided by gaseous conversion electron sources
  - Linearity – built in to Maxwell's equations
  - *B*-field Uniformity – Well known techniques borrowed from NMR/MRI experience
  - Line shape – follows from field non-uniformity and scattering effects
  - Increased volume – leave waveguide to accommodate source exposure required for stat. sensitivity
  - Data volume, triggering, and reduction

- Challenges Unique to the Neutrino Mass Measurement:
  - Extreme field uniformity $\delta B/B \sim 10^{-7}$
  - Atomic tritium to avoid molecular final states
  - Very large volumes ~10—100 m^3 required
  - Required to reach minimum neutrino masses $m_\nu \approx 50$ meV allowed by the inverted ordering

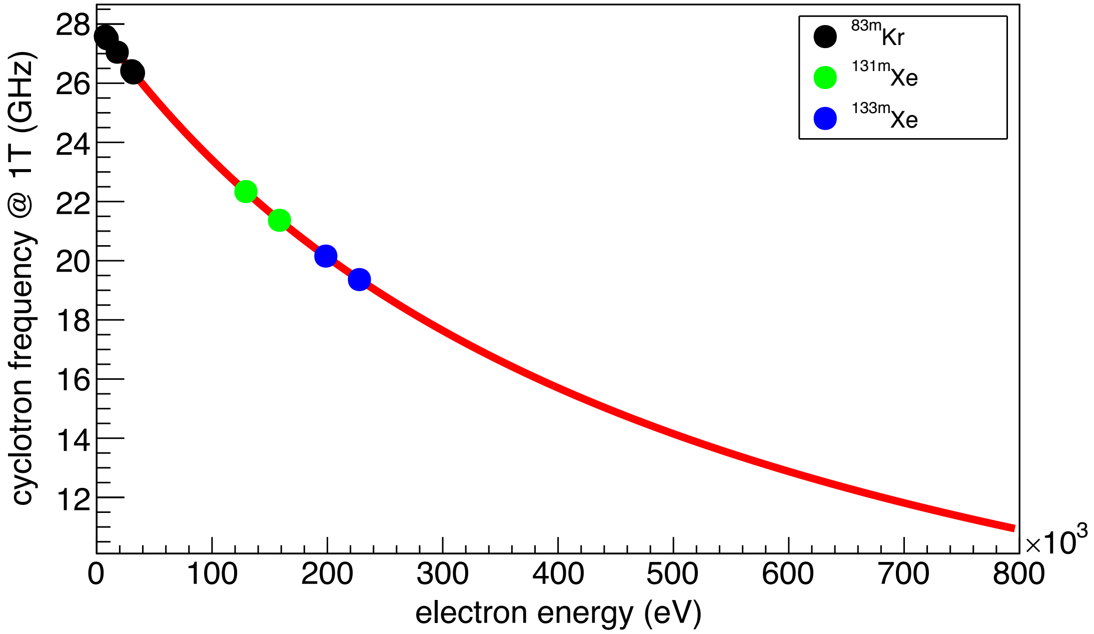
- Challenges Unique to the Neutron Measurement:
  - Extremely wide microwave bandwith.
  - Low-density source of neutrons with short trap transit time

CRES Bandwidth for Neutrinos and Neutrons

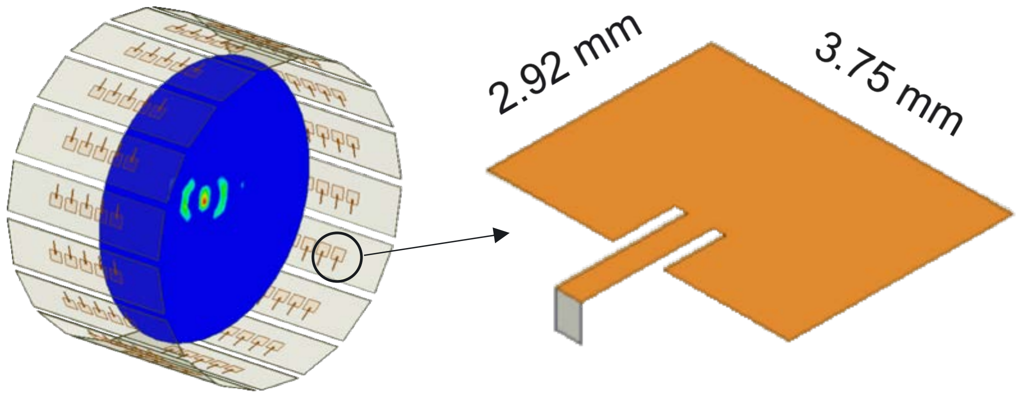


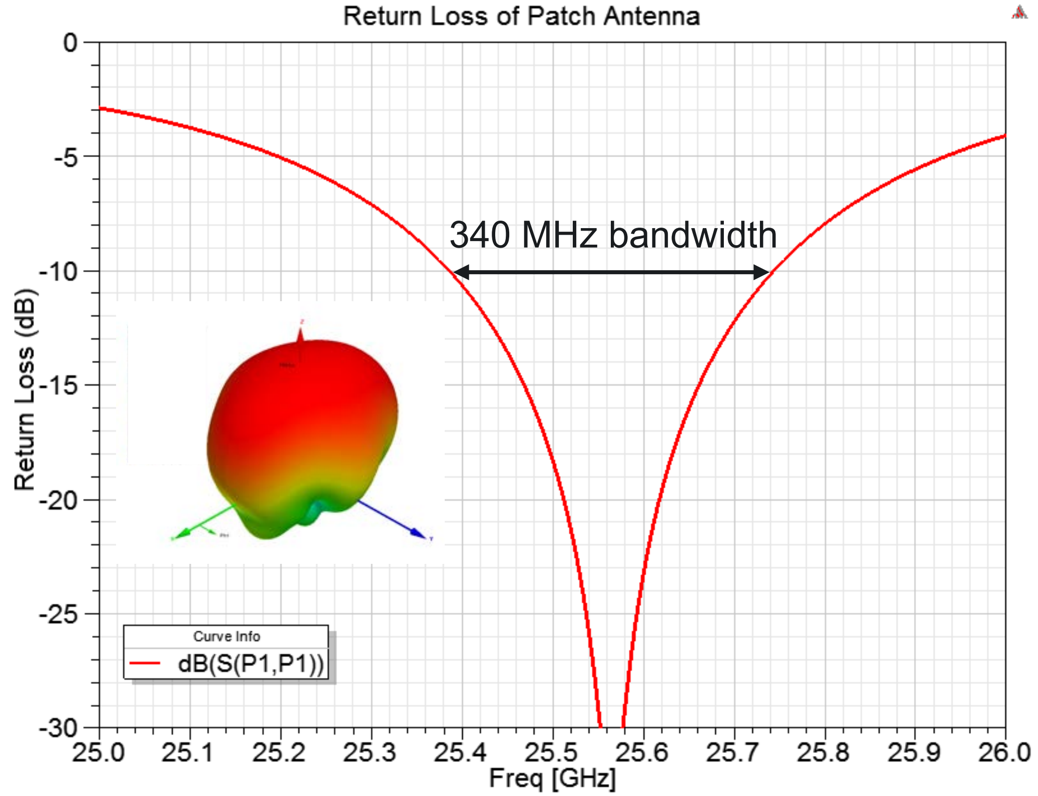
- The entire tritium spectrum (0—18.6 keV) is only δf ≈ 1GHz wide
- Only the last ≲100 eV (include δf magnitude) or less is useful to determine m_ν
- Including the last ~keV to include ^{83m}Kr K-c.e. at 17.8 keV (gray bands) is still δf ≲ 100MHz
- **Implications:**
  - **Narrow bandwidth antennas with simple feeds are sufficient**
  - **Digitizer and signal processing hardware and software is readily available from radioastronomy community (CASPAR)**
  - **K-band analog electronics commercially available**

- A neutron spectrum spans δf > 10 GHz for B = 1T
- Even if the field is reduced to B = 0.5T and only the lowest 300 keV is measured, δf ≈ 5 GHz (about 9—14 GHz)
- And consider, if you reduce the field:
  - The radiated cyclotron power is reduced ~B^2
  - The cyclotron radius increases ~B^{-1}
- **Implications:**
  - **No single set of antenna, analog and digital electronics is likely to simultaneously observe the necessary range of the neutron spectrum**



Bandwidth and Antenna Design

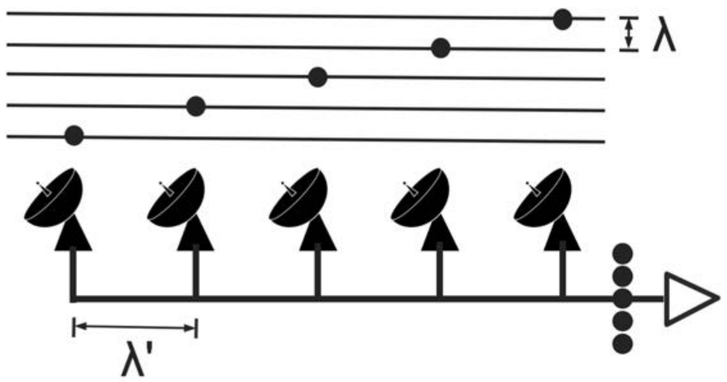




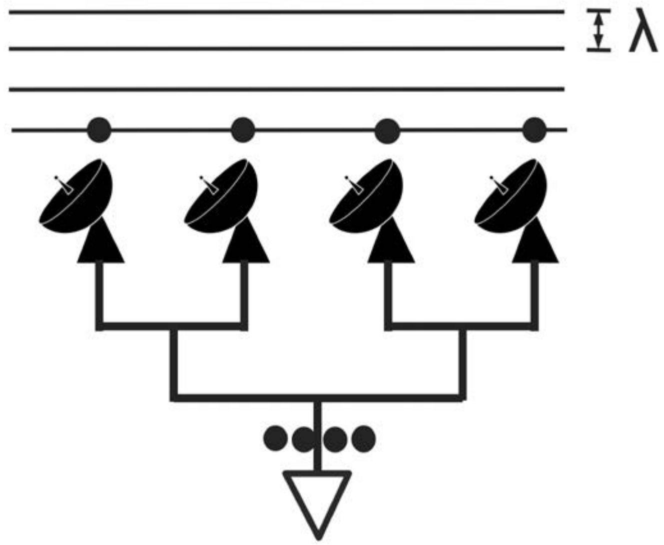
- A tritium endpoint experiment is monochromatic to good approximation for antenna design:
  - Simple resonant patches
  - Simple series feeds for passive combining
  - Currently validating with monte carlo simulation campaign

- Wider bandwidth experiments will require:
  - Different antennas for broad frequency response
  - A corporate feed to passively combine different λs coherently
  - To deal with transmission losses and physical space constraints of the corporate feed

Series feed, focus at ∞

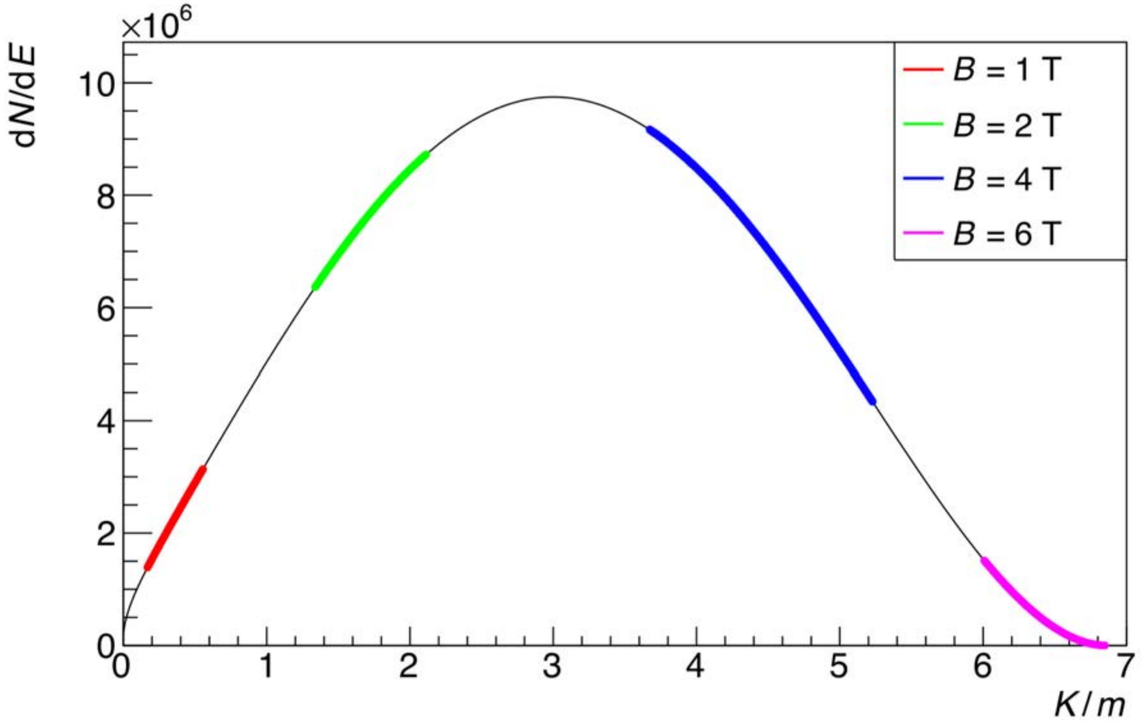


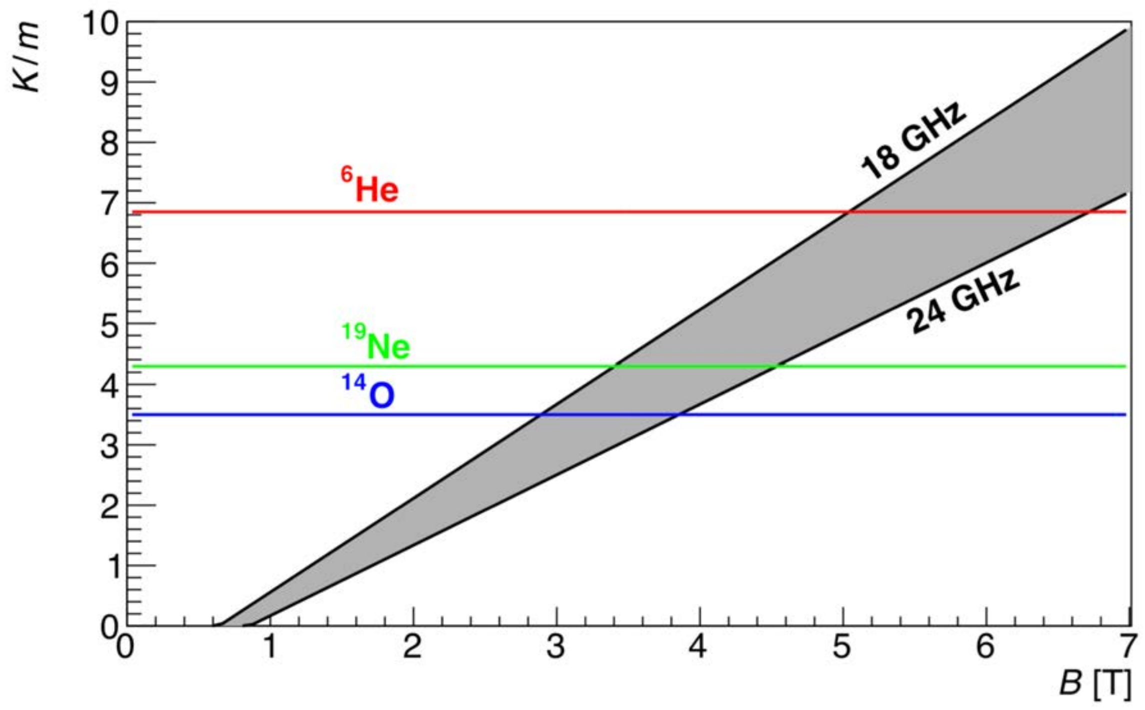
Corporate feed, focus at ∞



Non-simultaneous Spectral Measurement

- ^{6}He-CRES exploring CRES up to several MeV energies [E_0(^{6}He) = 3.5 MeV] in waveguide
- Goal to probe $\delta b \lesssim 10^{-3}$
- Prototype under construction now at the University of Washington





- 6-GHz-wide windows → 3 2-GHz analog channels → 4 500-MHz digitizer channels

Pacific Northwest
NATIONAL LABORATORY

Summary

- The path to ultimate sensitivity to Fierz interference in neutron decay must eschew physical detectors; CRES is suggested as the alternative.
- CRES enjoys the linearity of Maxwell's equations, absolute calibration standards and the extreme precision of the frequency precision, and low false-event backgrounds.
- CRES must be (is being) developed for the Project 8 tritium endpoint experiment.
- However, application to neutron decays will have the additional challenge of very large bandwidths not required for the neutrino mass measurement.

The Project 8 Collaboration

PROJECT 8

Pacific Northwest National Laboratory
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Karlsruhe Institute of Technology
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Smithsonian Astrophysical Observatory
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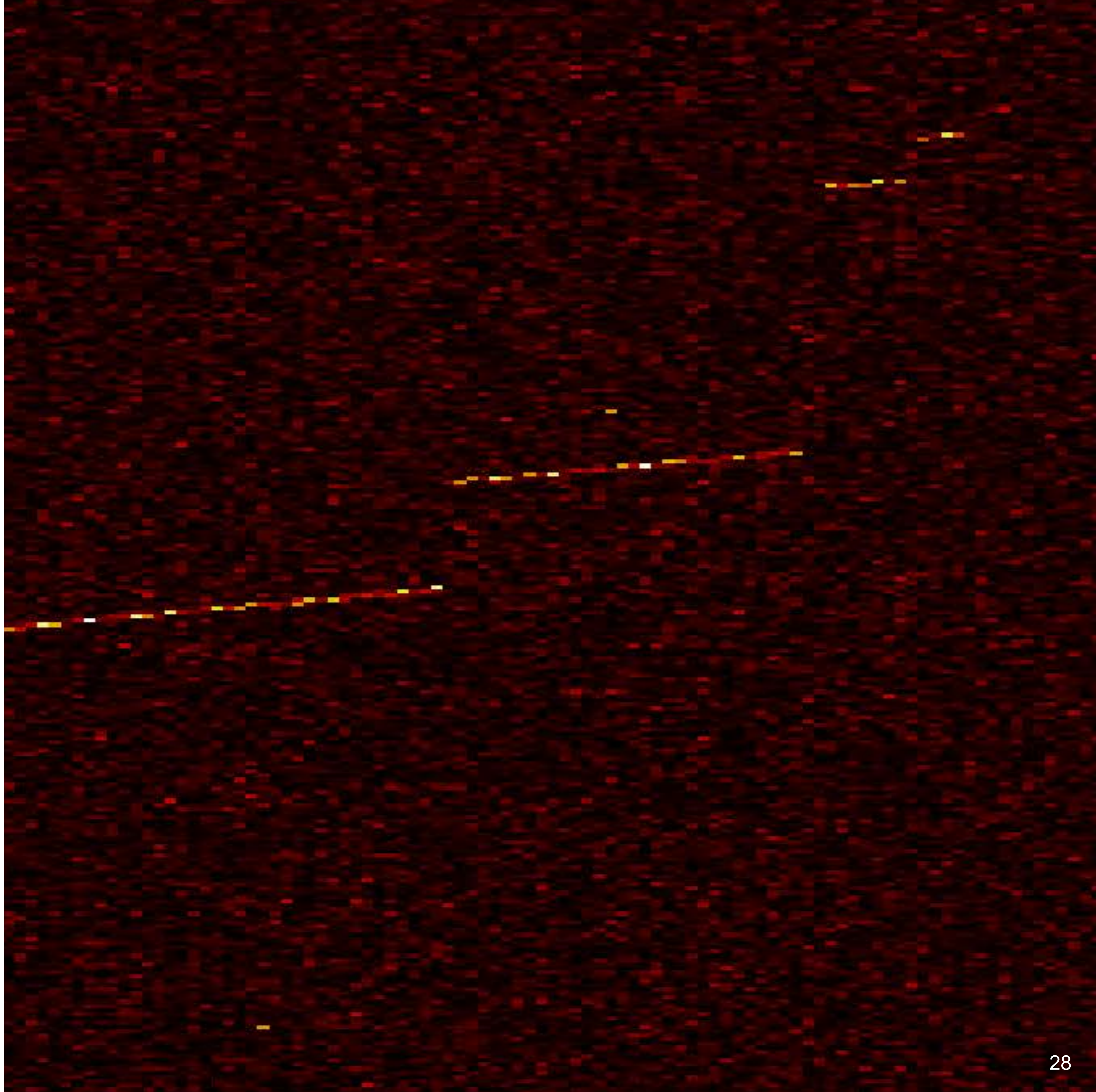
Acknowledgements

This material is based upon work supported by the following sources: the **U.S. Department of Energy Office of Science, Office of Nuclear Physics**, under Award No. DE-SC0011091 to MIT, under the Early Career Research Program to Pacific Northwest National Laboratory (PNNL), a multiprogram national laboratory operated by Battelle for the U.S. Department of Energy under Contract No. DE-AC05-76RL01830, under Award No. DE-FG02-97ER41020 to the University of Washington, and under Award No. DE-SC0012654 to Yale University; the **National Science Foundation** under Award Nos. 1205100 and 1505678 to MIT; and internal investments by all collaborating institutions. A portion of the research was performed using Research Computing at PNNL. The isotope(s) used in this research were supplied by the United States Department of Energy Office of Science by **the Isotope Program in the Office of Nuclear Physics**. We further acknowledge support from **the PRISMA Cluster of Excellence** at the University of Mainz.

Thank you



Supplemental Slides

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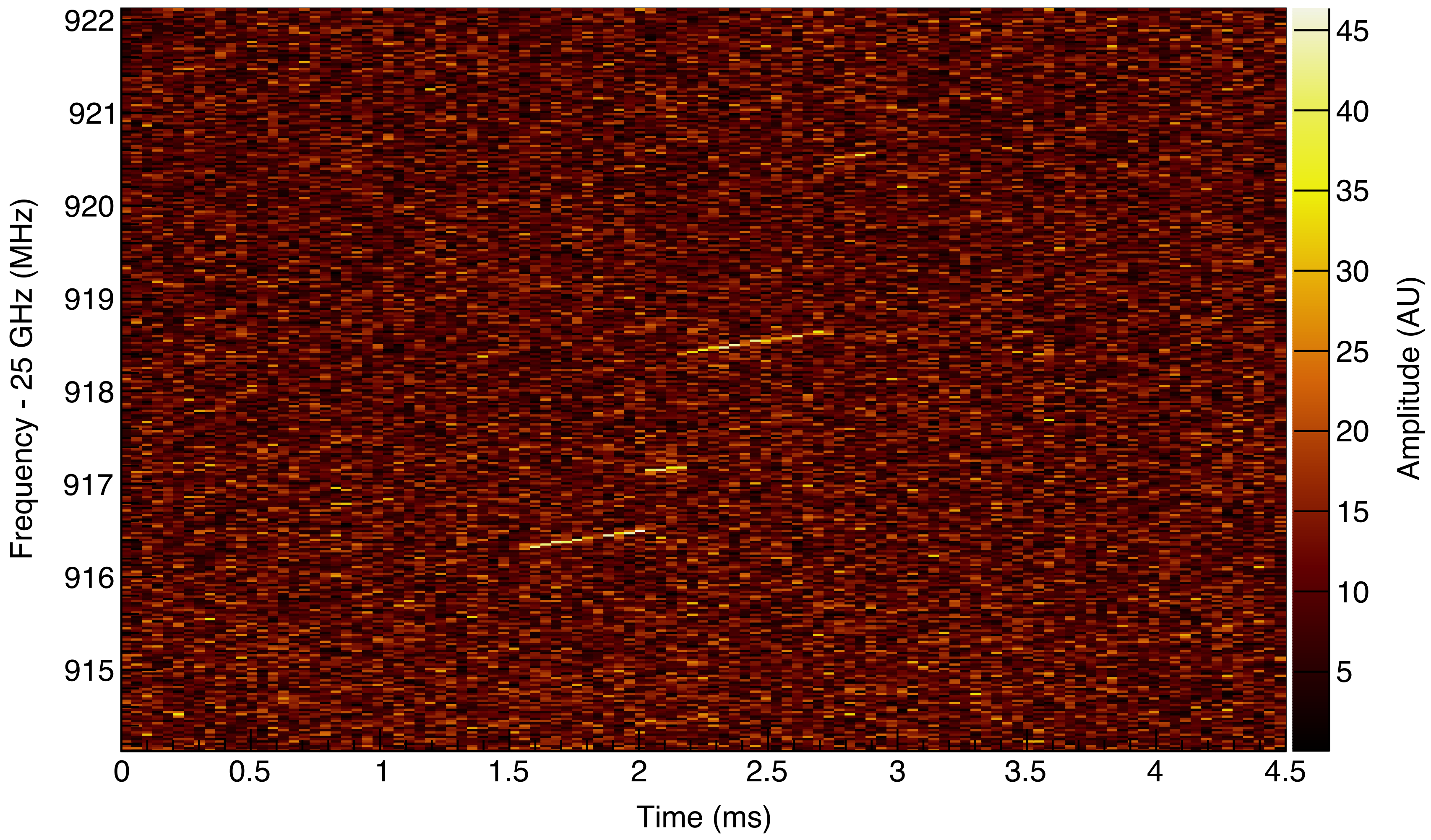
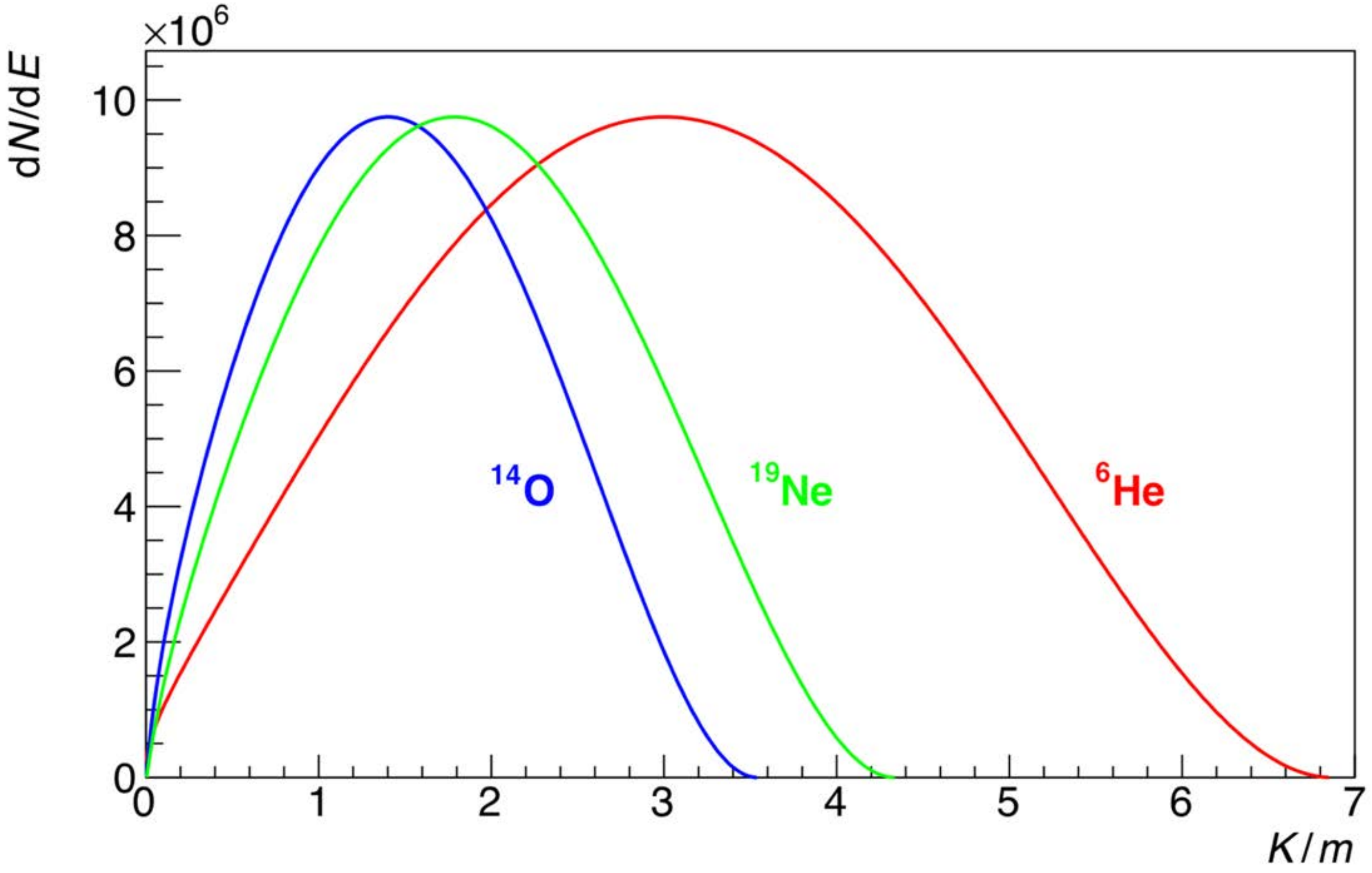
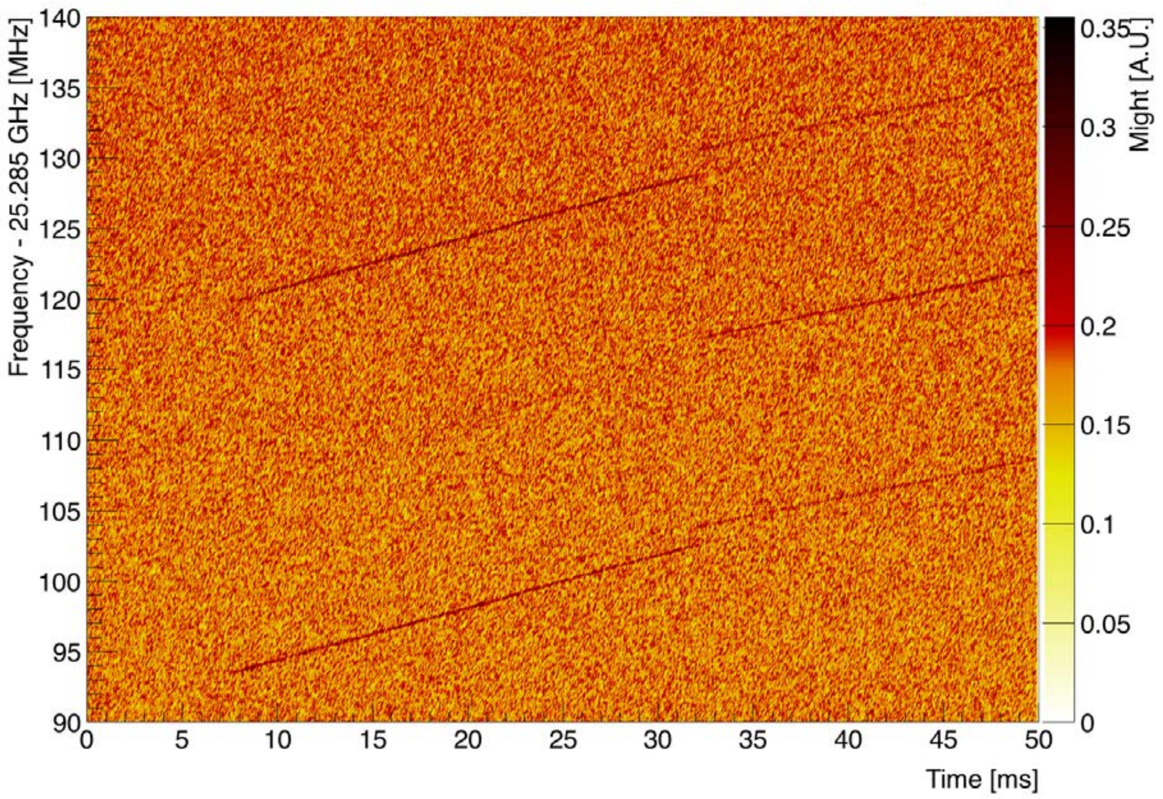
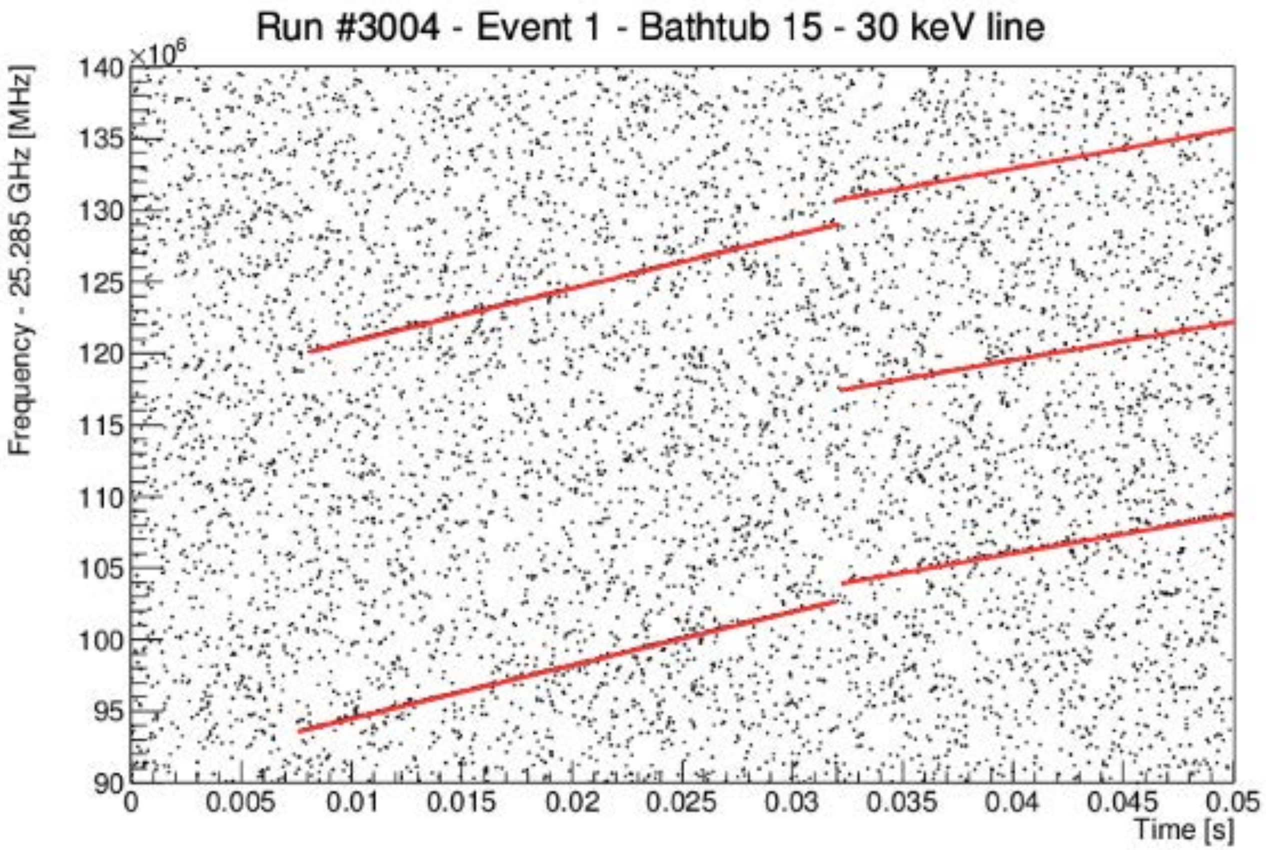


First tritium beta decay CRES event



Suerallowed decay spectra considered for CRES measurements





Doppler sidebands, frequency modulation, and disappearing carriers