Project 8: Using Radio-Frequency Techniques to Measure the Neutrino Mass

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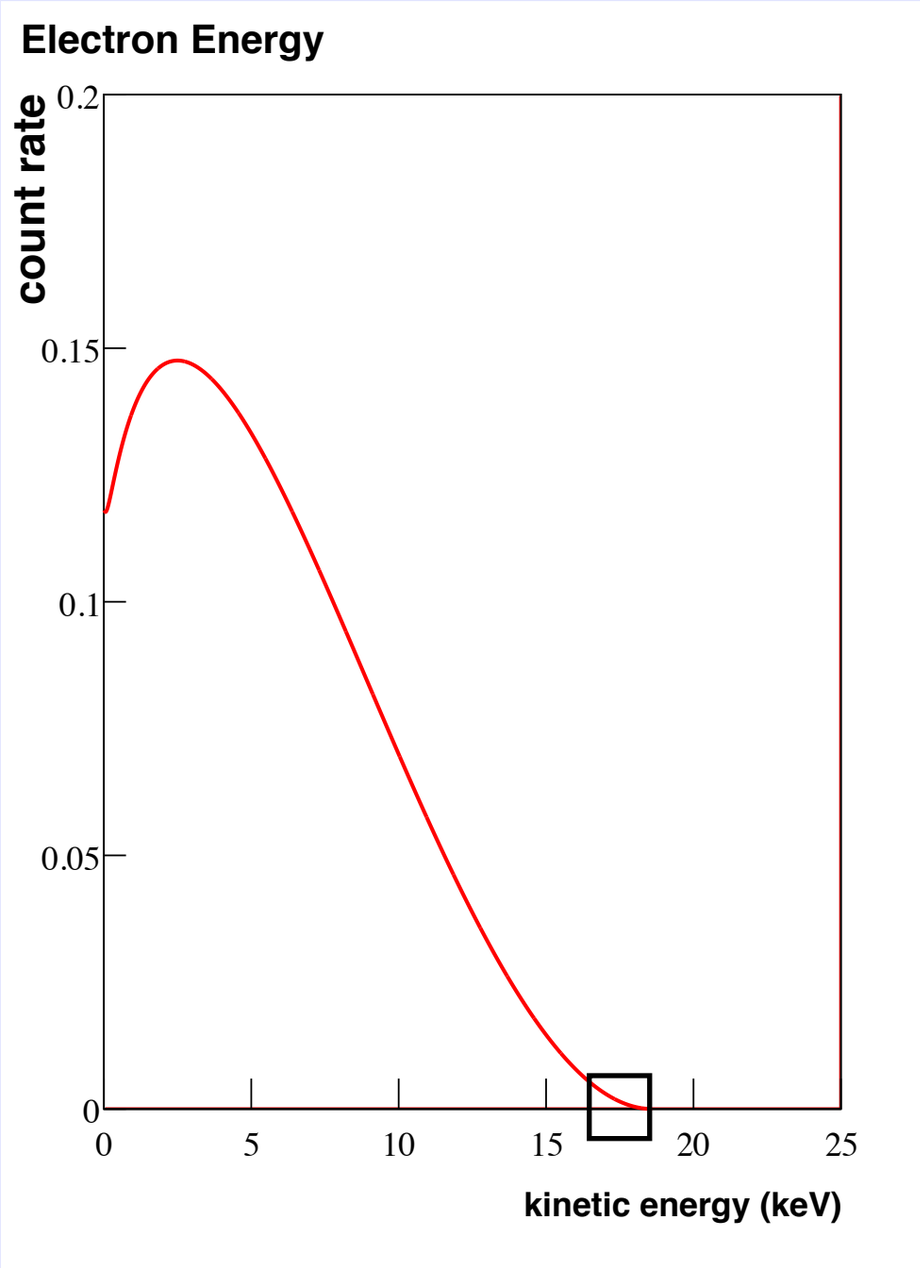
Massachusetts Institute of Technology
for the Project 8 Collaboration

Topics in Astroparticle and Underground Physics
September 9, 2015

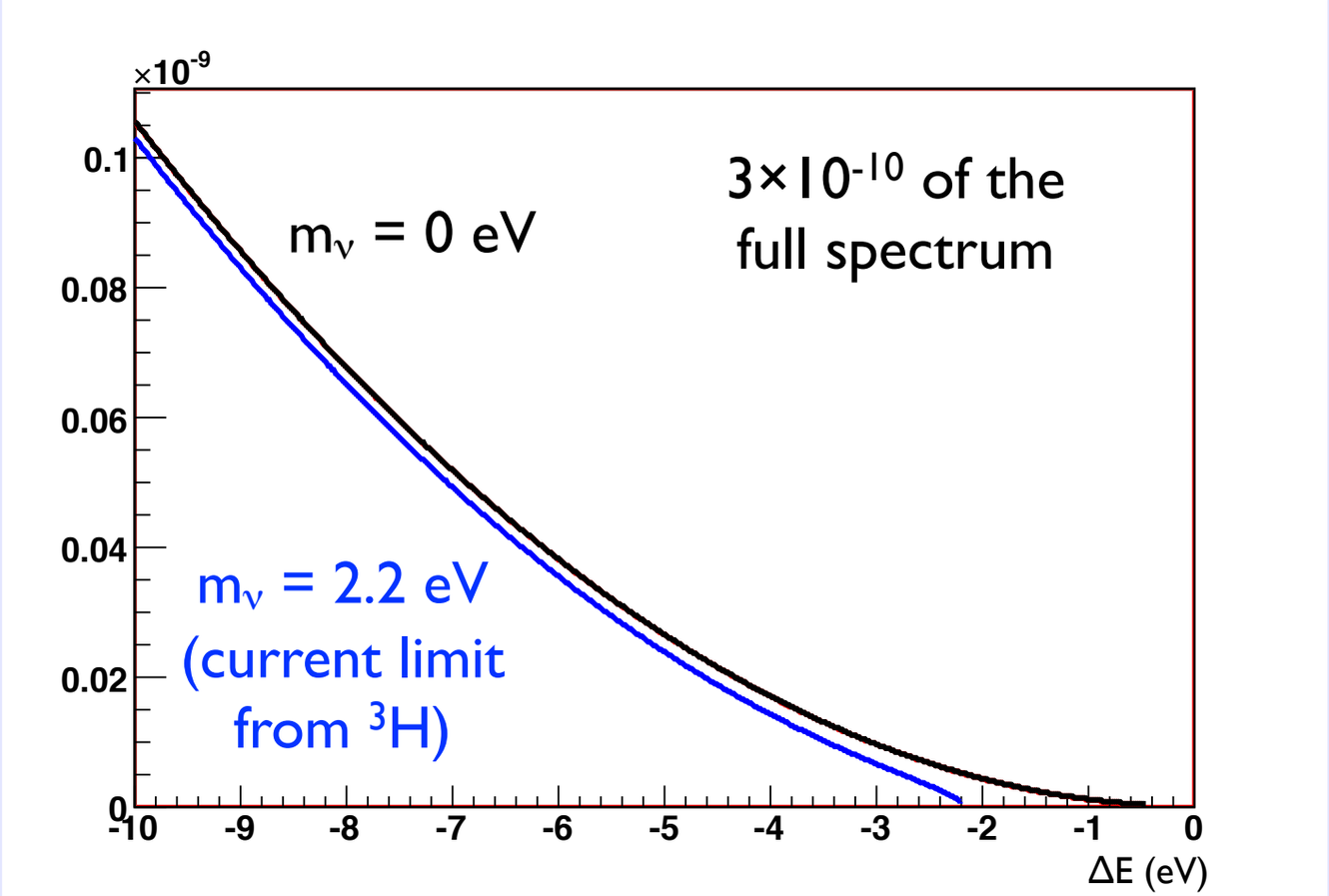
Laboratory for Nuclear Science

PROJECT 8

Using Tritium β Decay



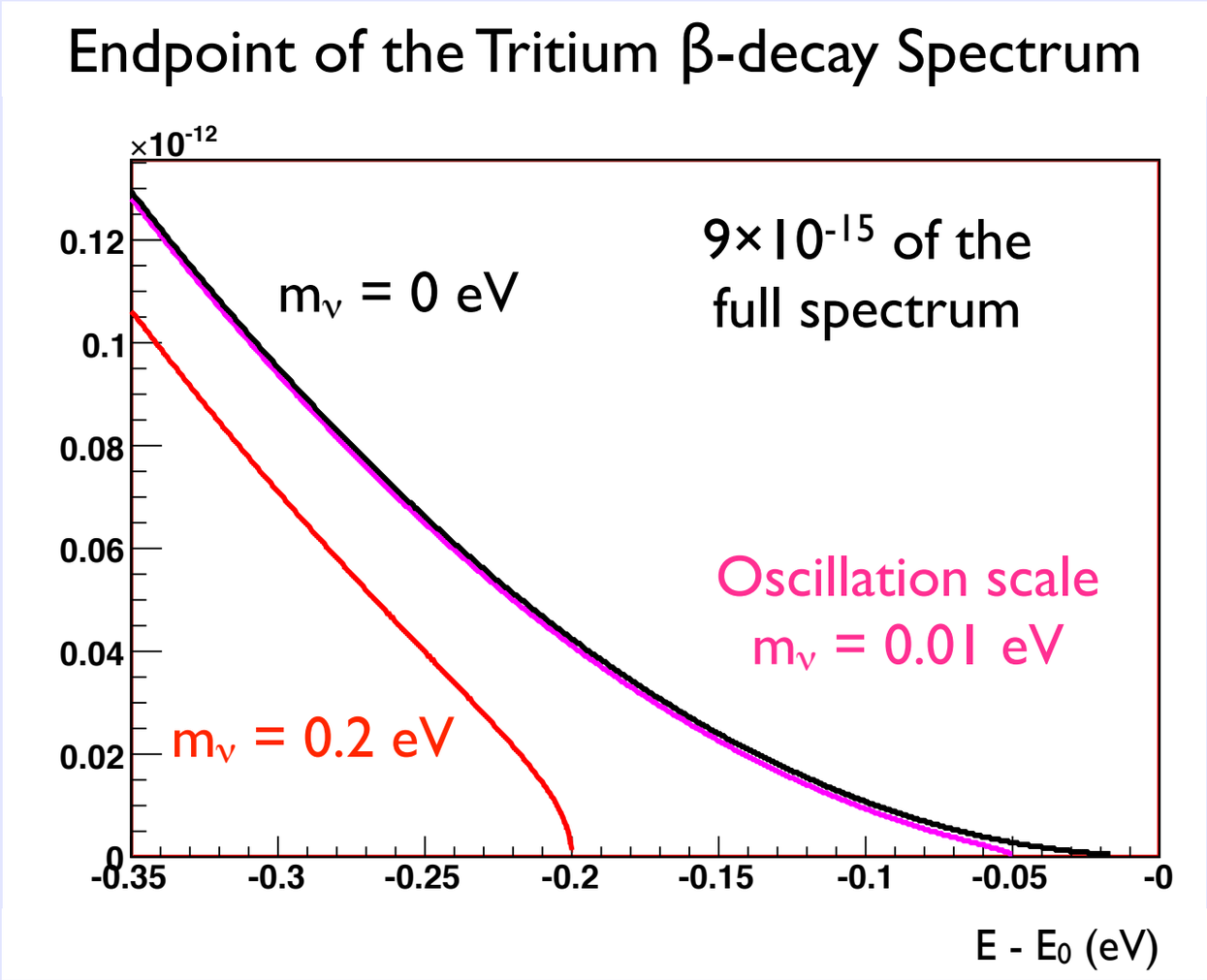
Zoom in on the endpoint . . .



$$\frac{dN}{dE} \approx KF(Z,E)p(E+m_e c^2)\left((E-E_0)^2 - \frac{1}{2}m_\beta^2\right)$$

$$m_\beta = \sqrt{\sum_i |U_{ei}^2| m_i^2}$$

Beyond KATRIN



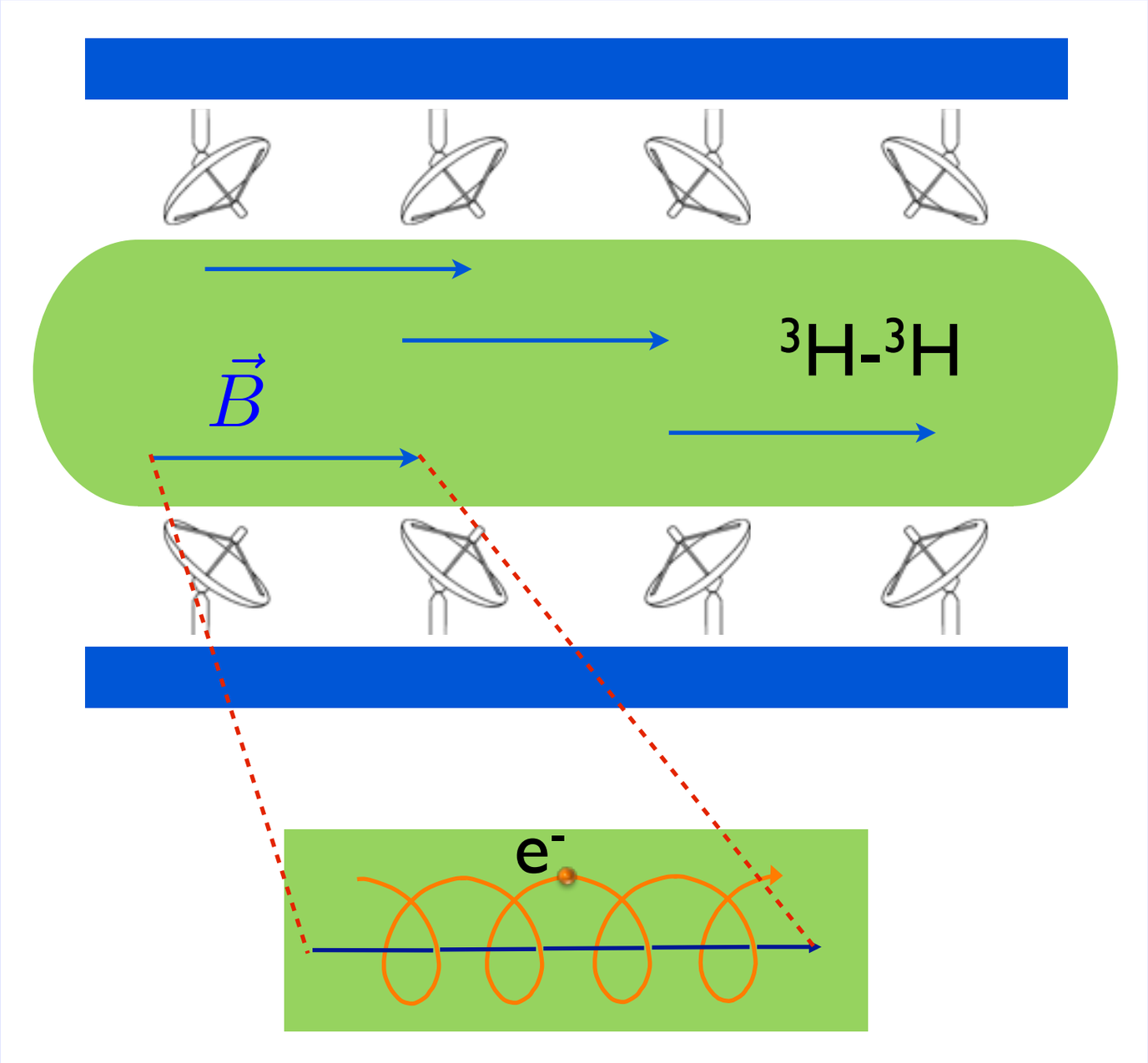
Overview

- Goal: use a novel technique to be more sensitive to the neutrino mass
- New technique: Cyclotron Radiation Emission Spectroscopy (CRES)
- First direct measurement of single-electron cyclotron radiation made in June, 2014
- Currently seeking improvements in energy resolution and statistics
- Preparing for first tritium measurement

Novel Technique: CRES

Cyclotron Radiation Emission Spectroscopy

- Enclosed volume
- Fill with tritium gas
- Add a magnetic field

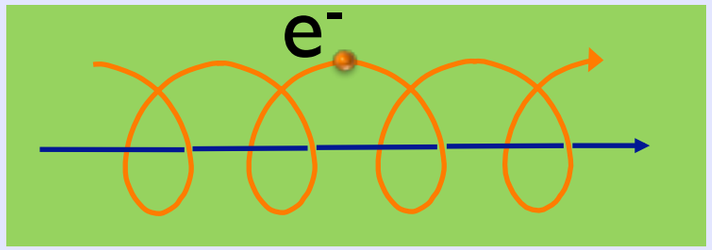


- Decay electrons spiral around field lines
- Add antennas to detect the cyclotron radiation

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

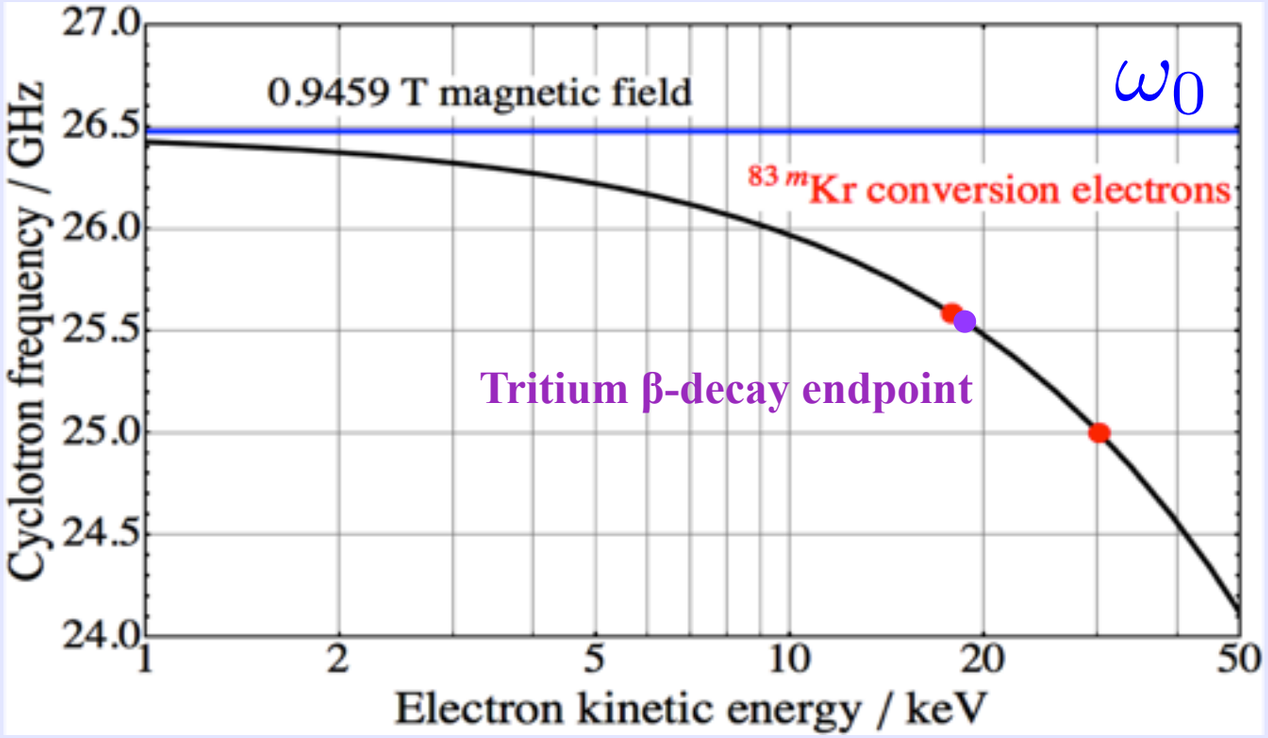
Cyclotron Radiation

- An electron traveling in a magnetic field emits cyclotron radiation



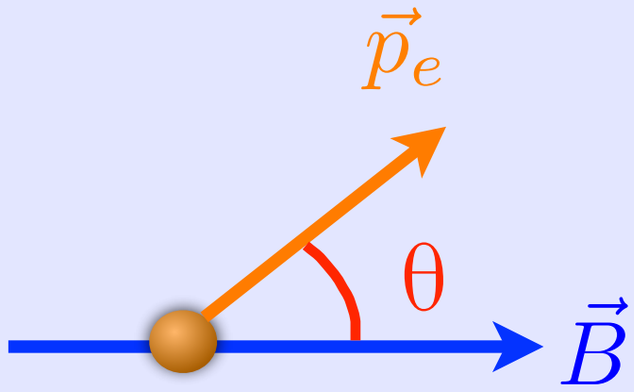
- The frequency of the emitted radiation depends on the relativistic boost

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



Pitch Angle

The angle between the electron momentum and the magnetic field



- Correction term for the cyclotron frequency

$$\omega_\gamma = \frac{\omega_0}{\gamma} = \frac{eB}{K + m_e}\left(1 + \frac{\cot^2\theta}{2}\right)$$

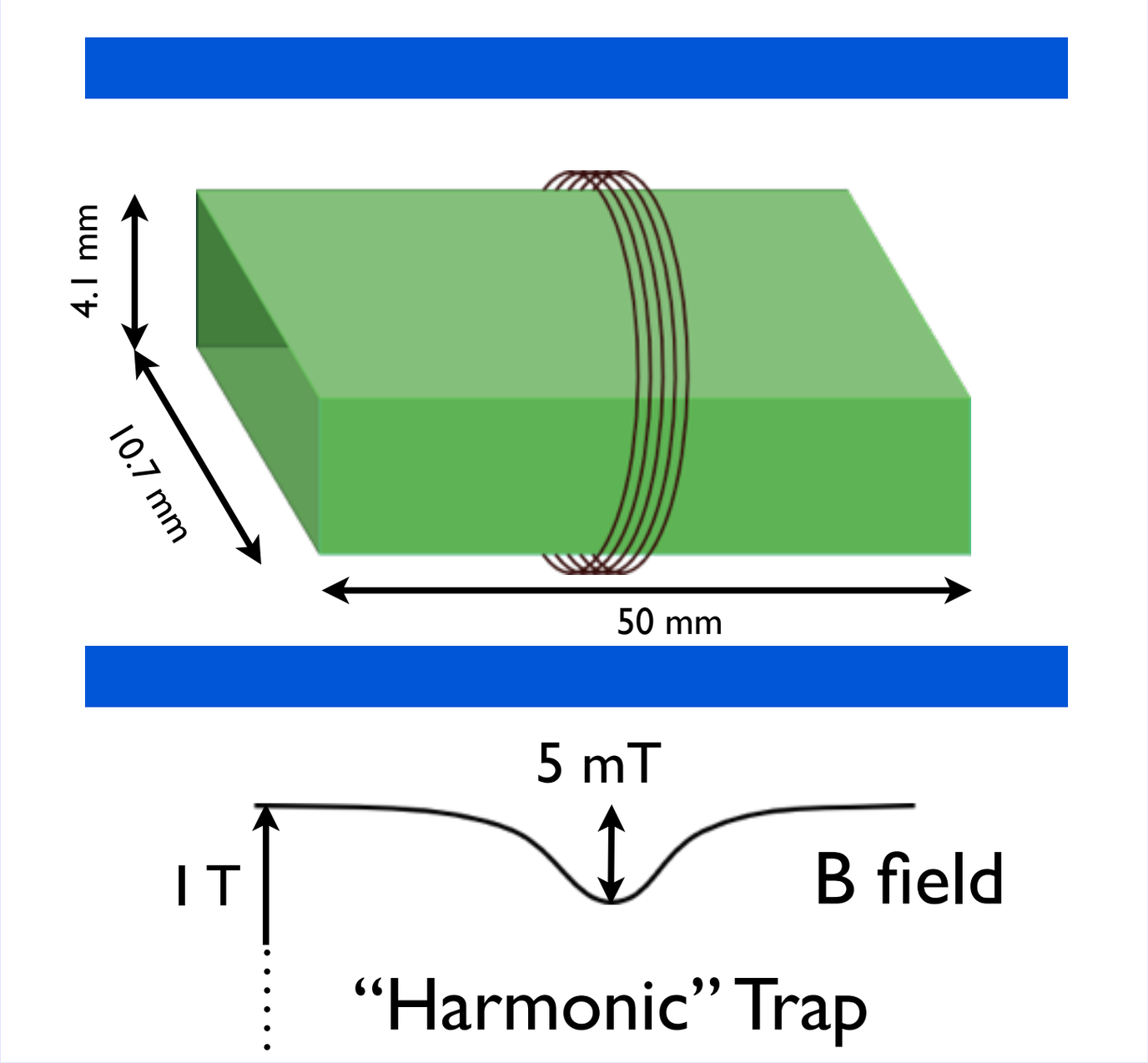
- Power emitted

$$P_{\text{tot}} = \frac{1}{4\pi\epsilon_0}\frac{2q^2\omega_c^2}{3c}\frac{\beta^2\sin^2\theta}{1-\beta^2}$$

Novel Technique: CRES

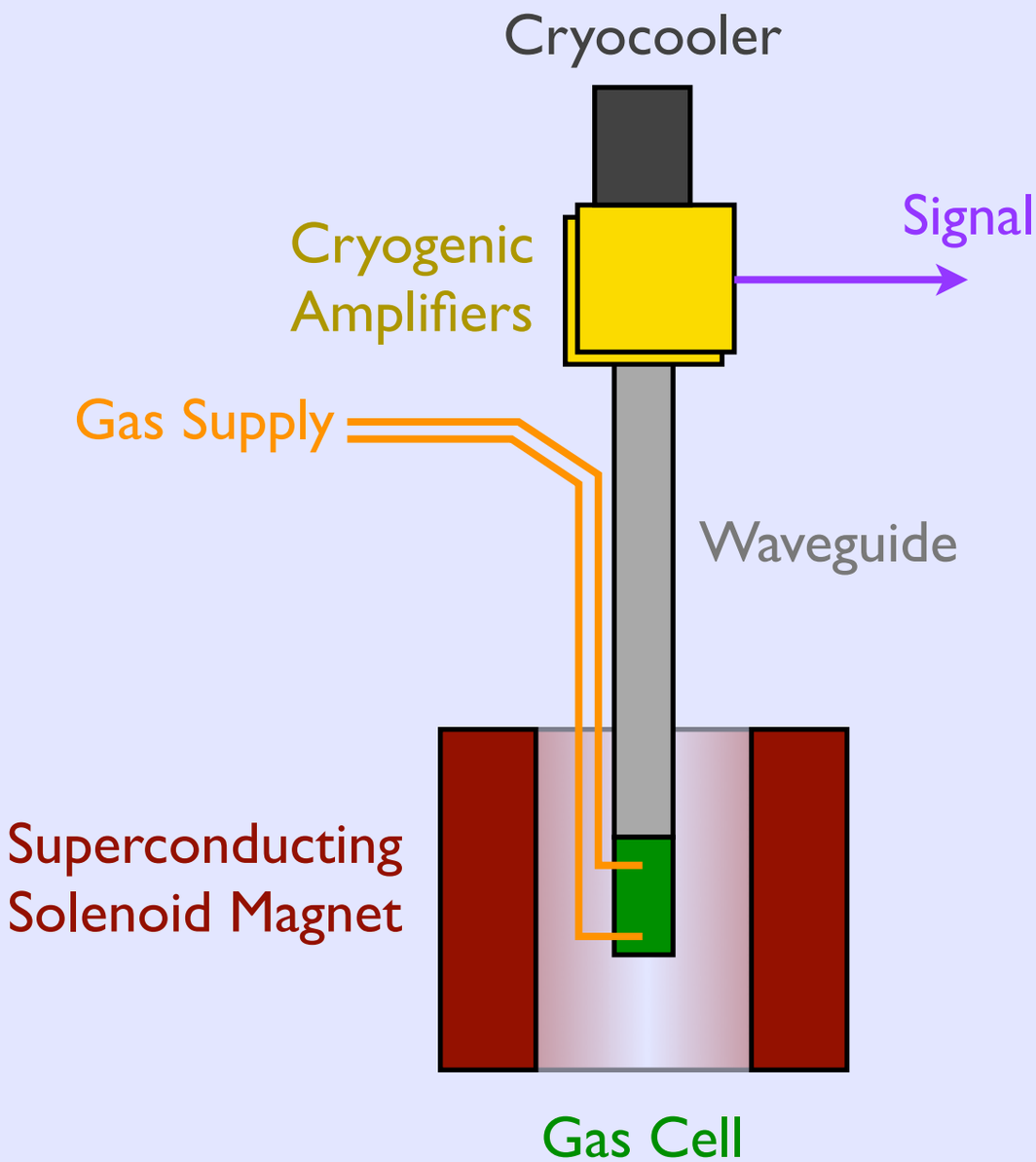
Cyclotron Radiation Emission Spectroscopy

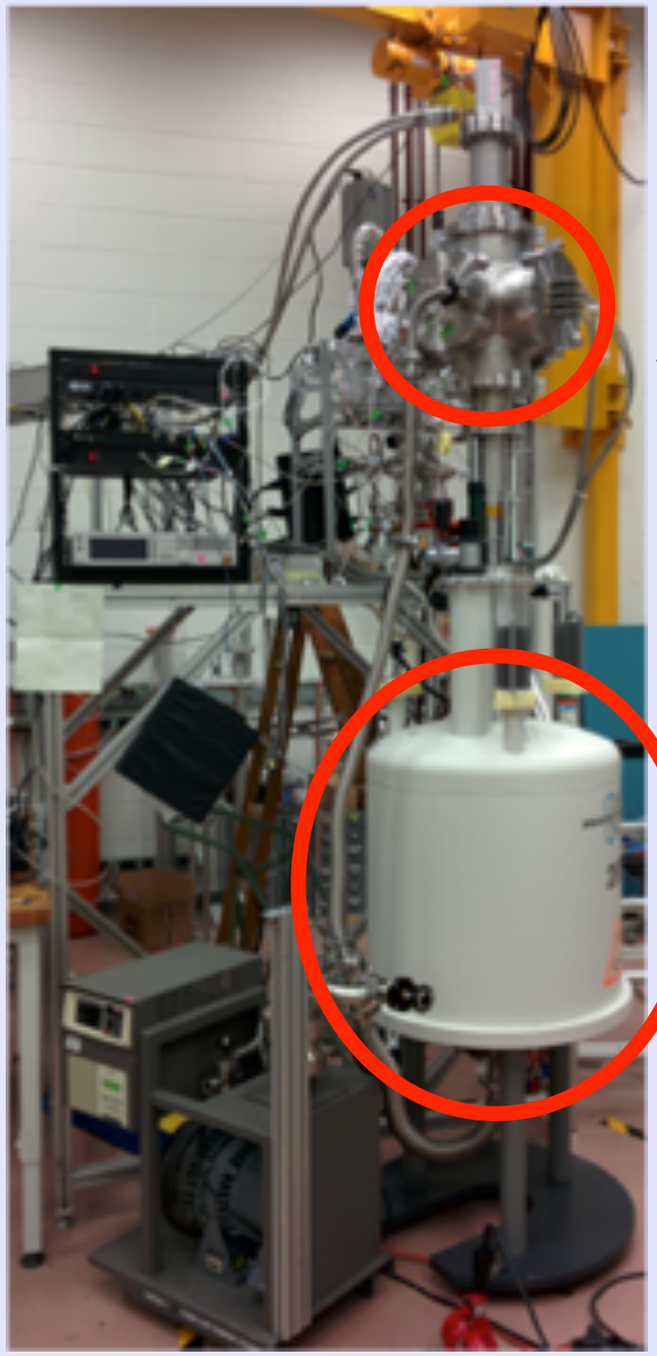
- Enclosed volume
- Fill with ^{83m}Kr gas
- Add a magnetic field



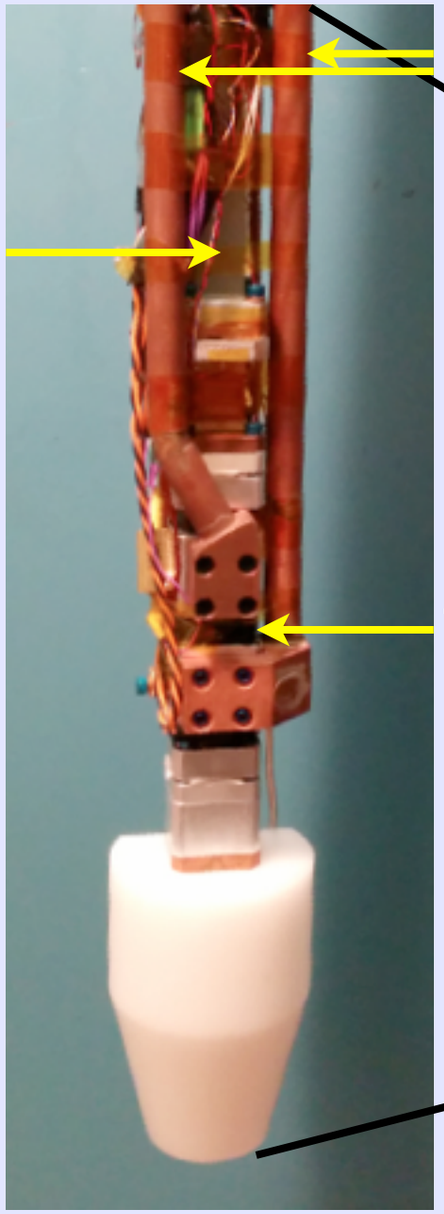
- Decay electrons spiral around field lines
- Waveguide & cryogenic amplifiers to detect the cyclotron radiation

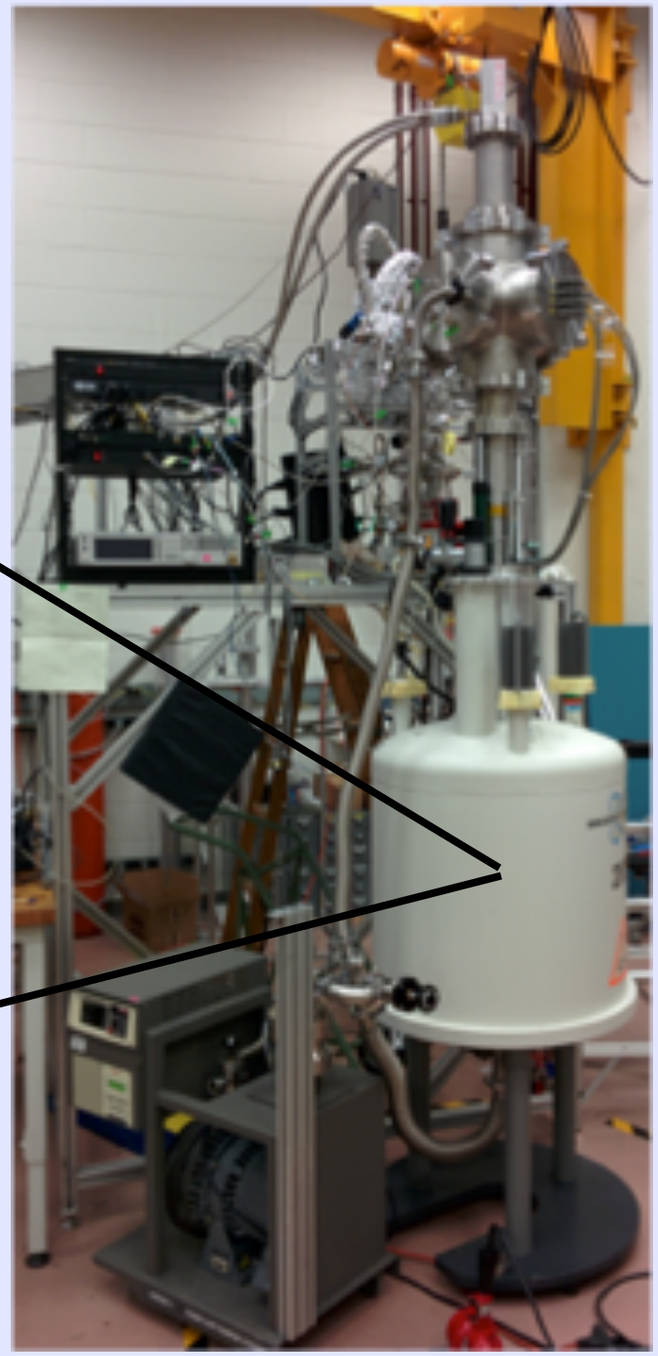
Project 8 Prototype



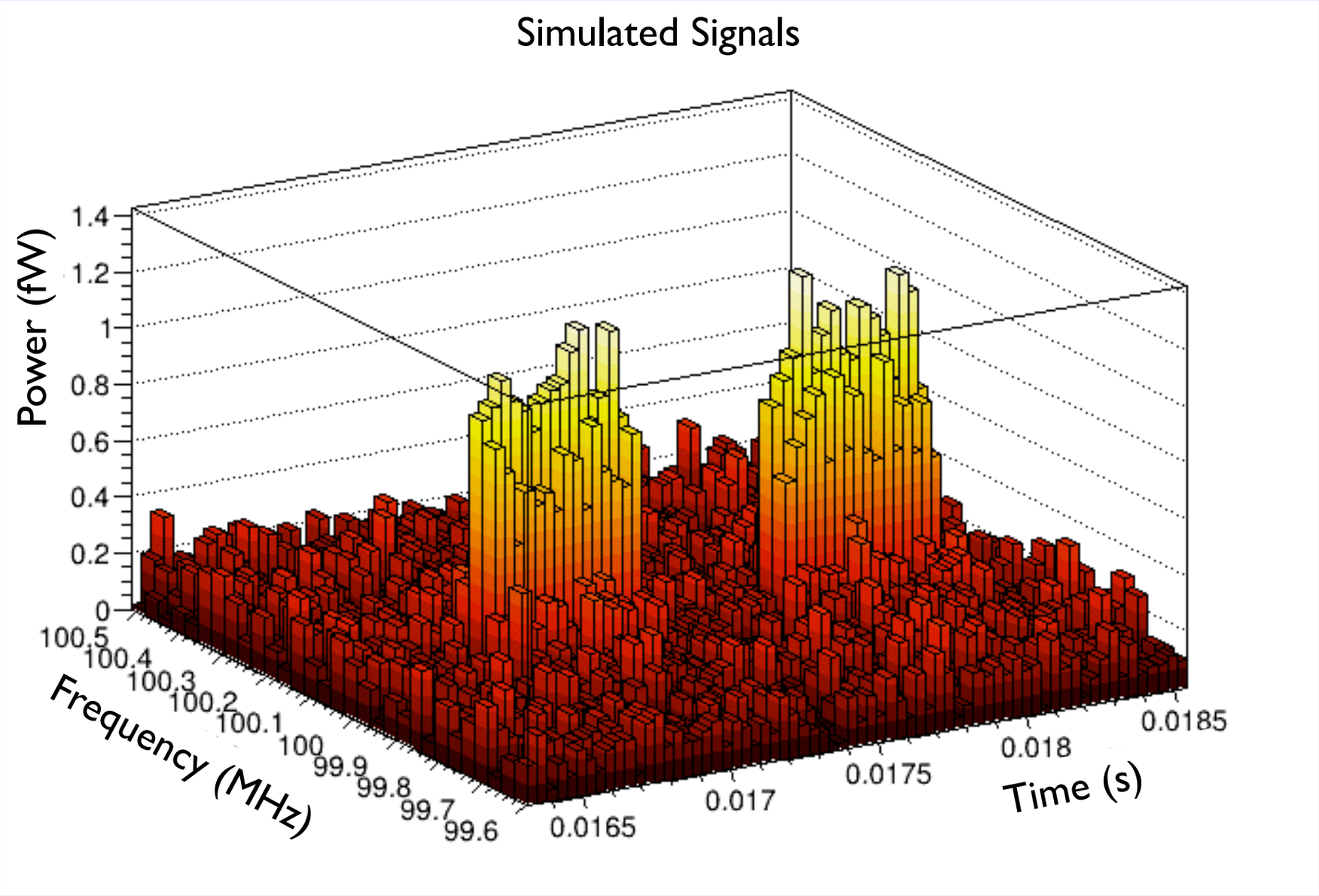


Prototype - Gas Cell

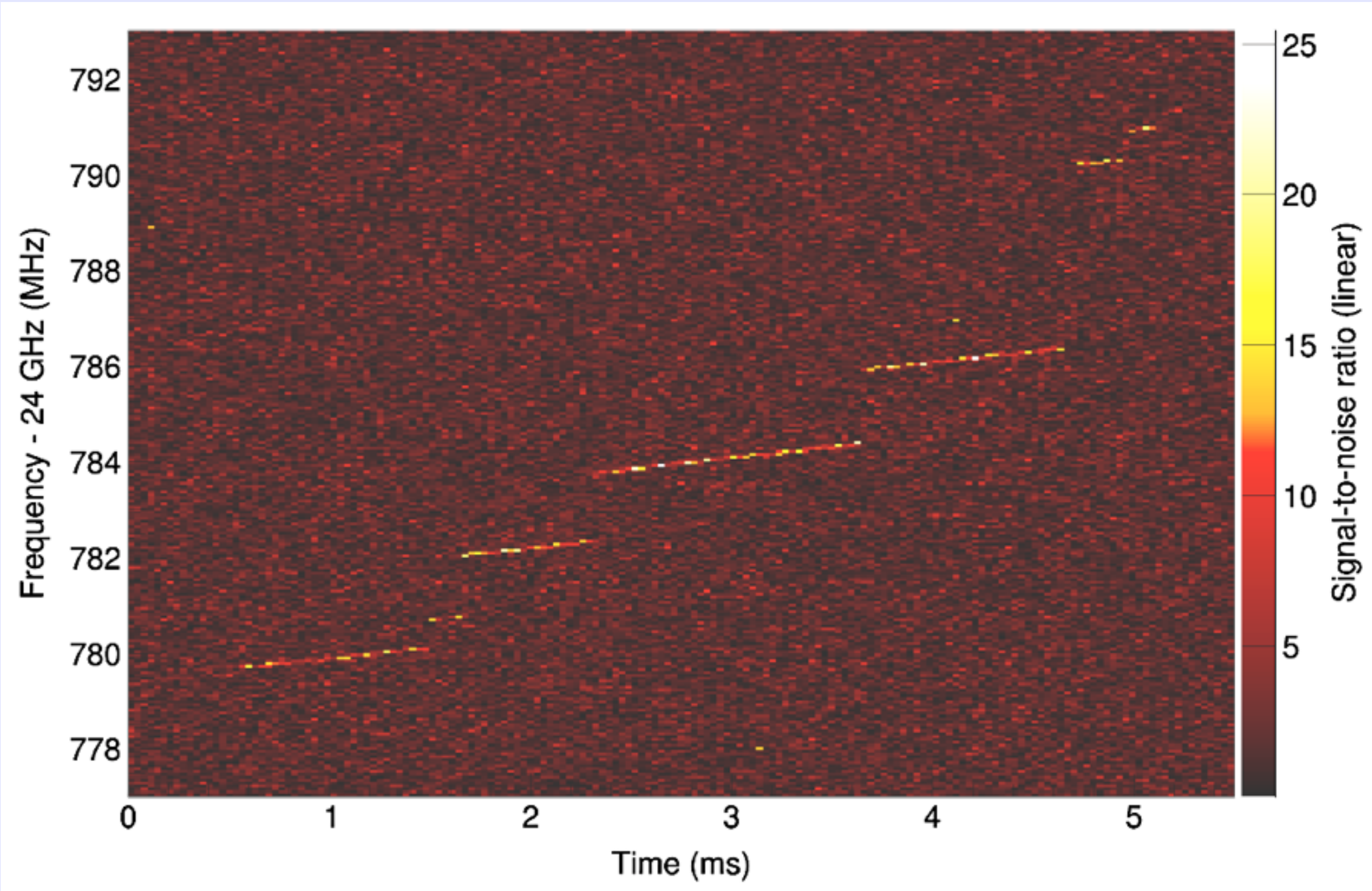




Frequency vs Time

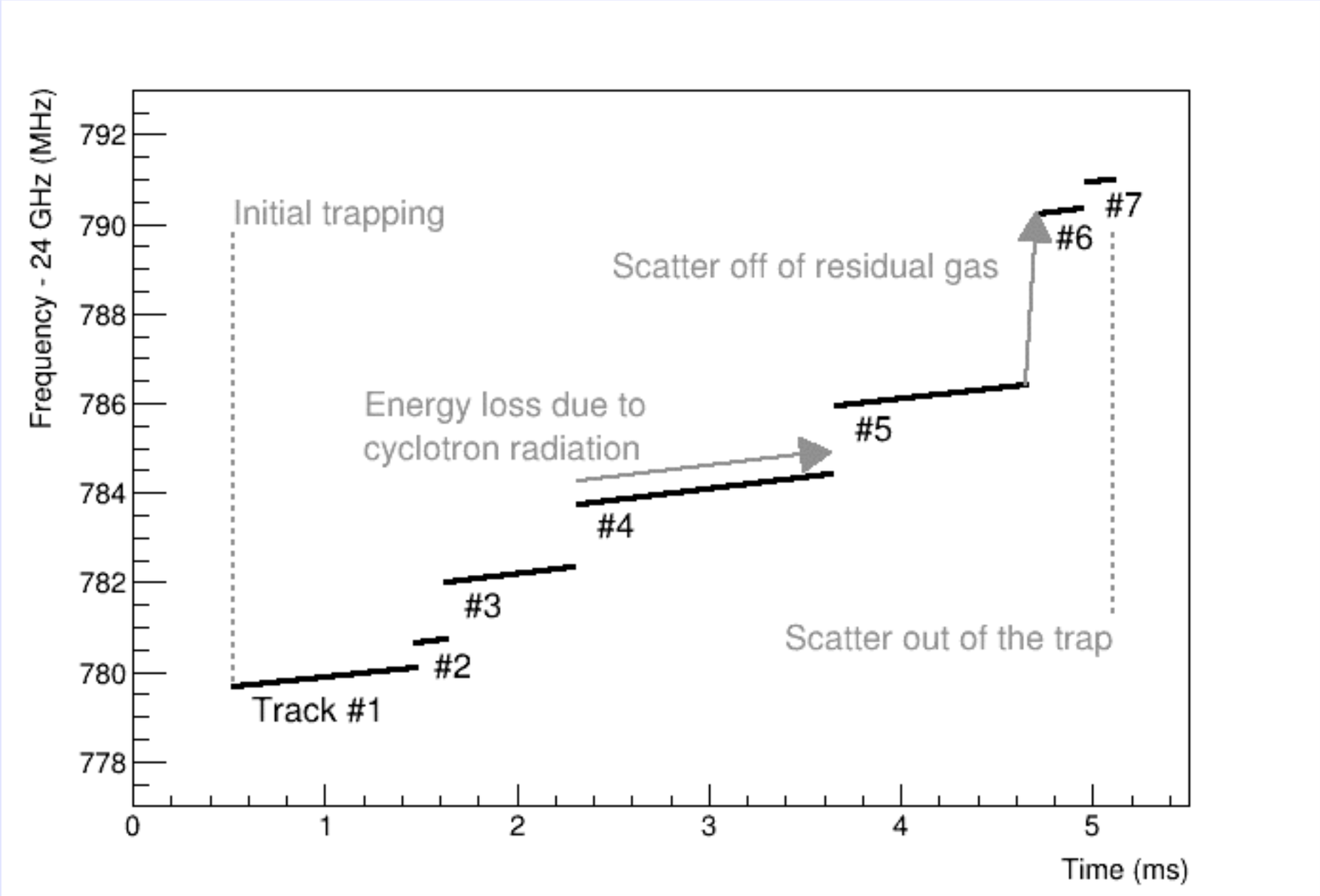


First Observation

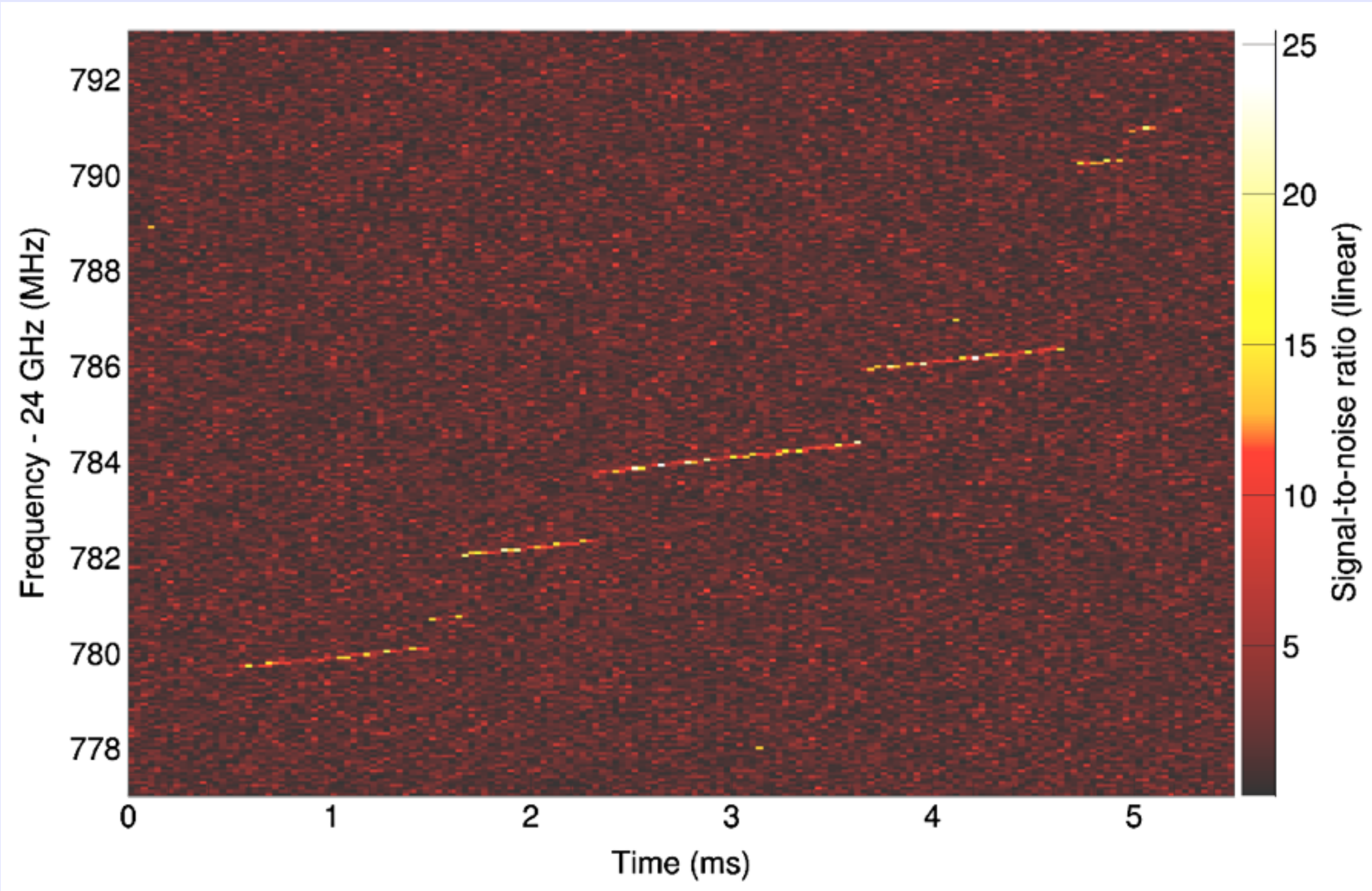


Phys. Rev. Lett. 114, 162501 (2015)

Features


Frequency - 24 GHz (MHz)
792
790
788
786
784
782
780
778
0
1
2
3
4
5
Time (ms)
Initial trapping
Scatter off of residual gas
Energy loss due to
cyclotron radiation
Scatter out of the trap
Track #1
#2
#3
#4
#5
#6
#7

First Observation



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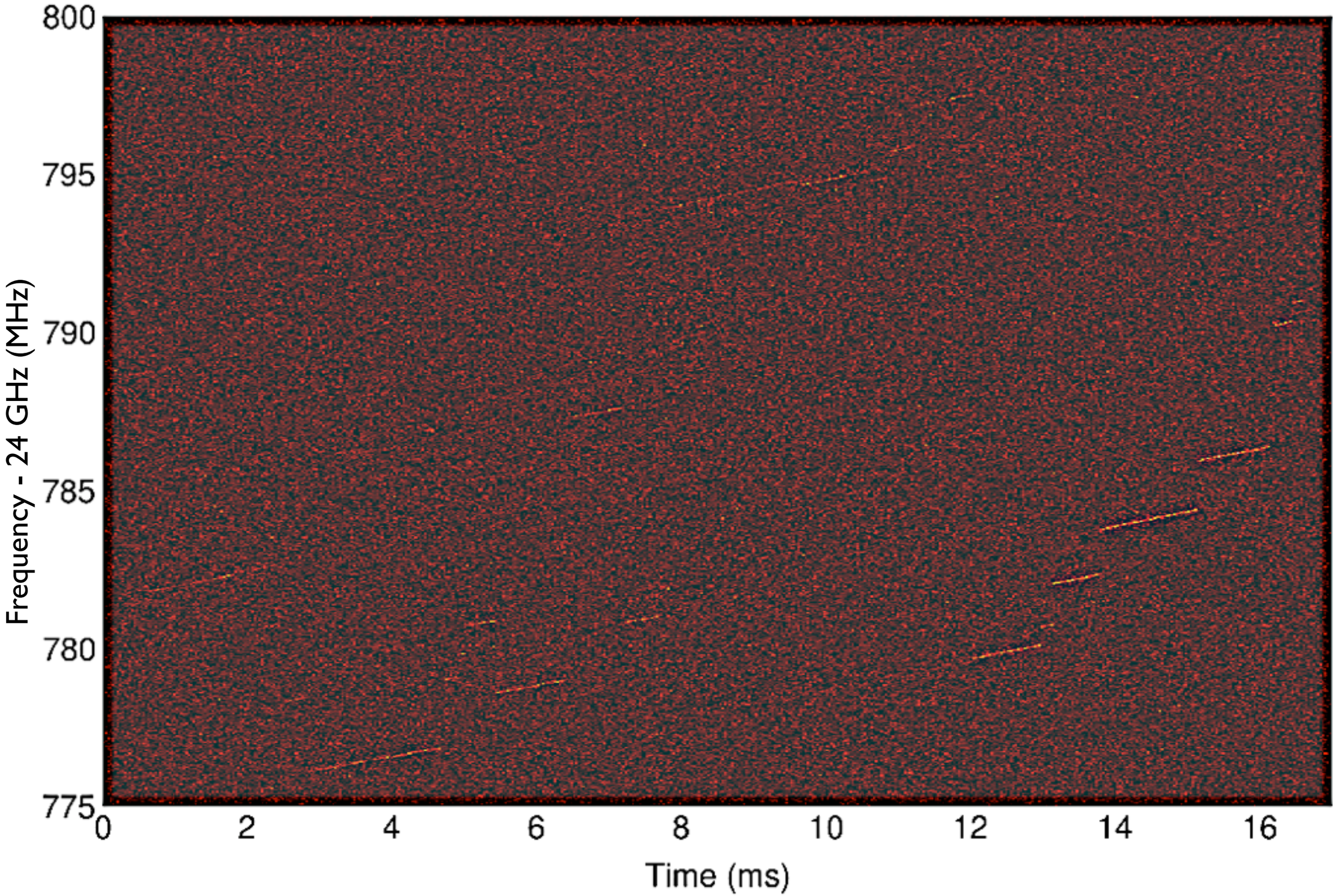
800
795
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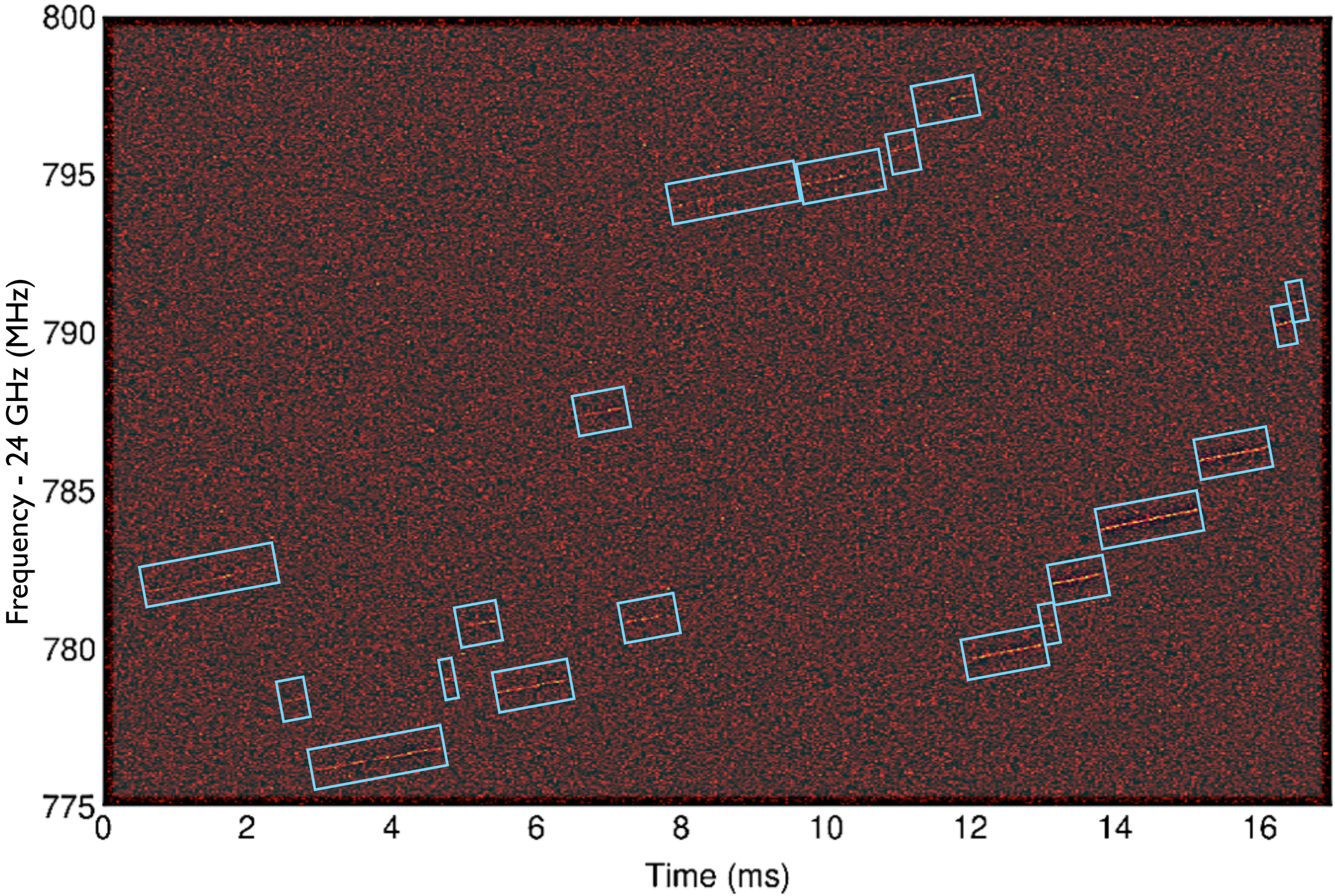
775
Frequency - 24 GHz (MHz)
0
2
4
6
8
10
12
14
16
Time (ms)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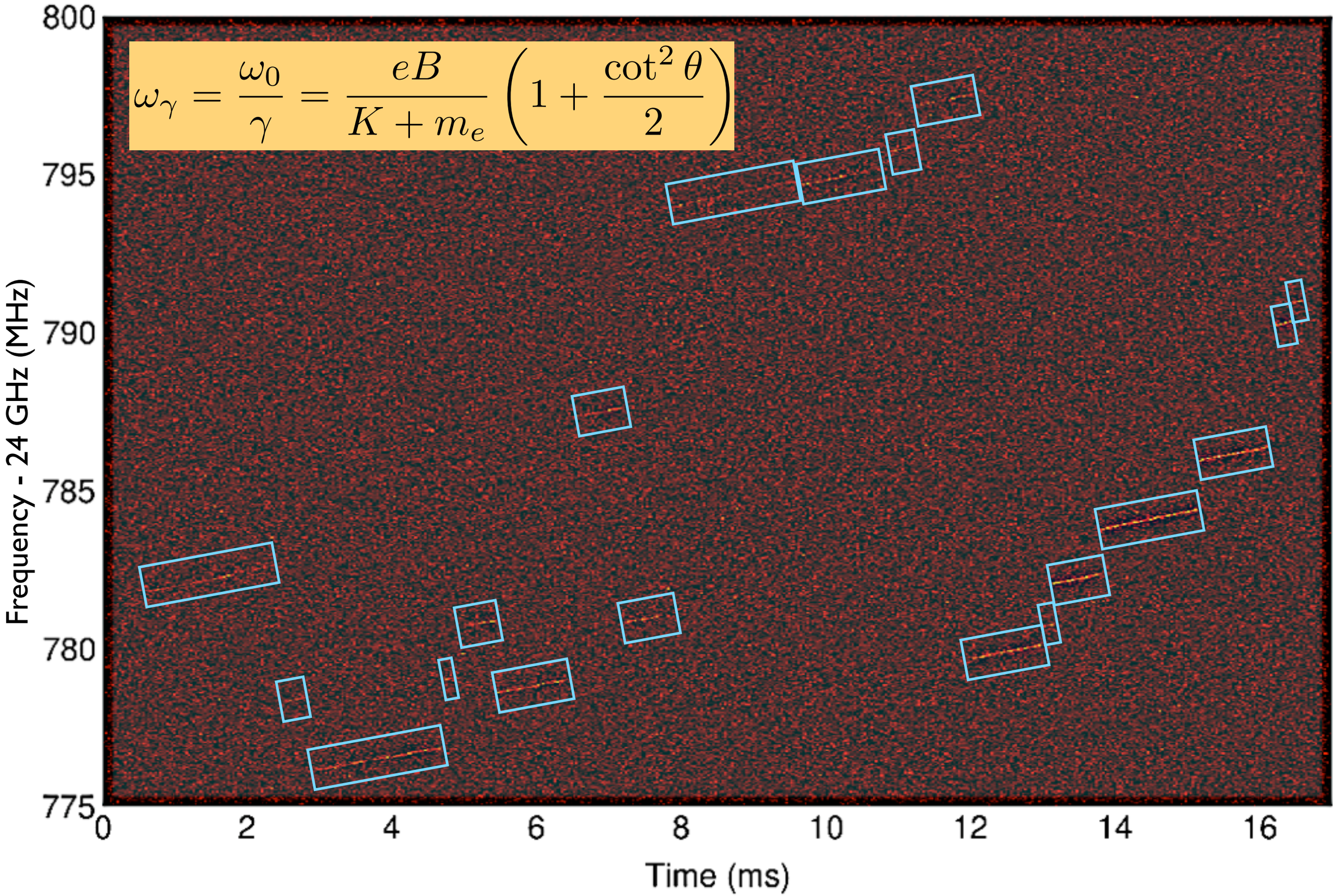
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Frequency - 24 GHz (MHz)
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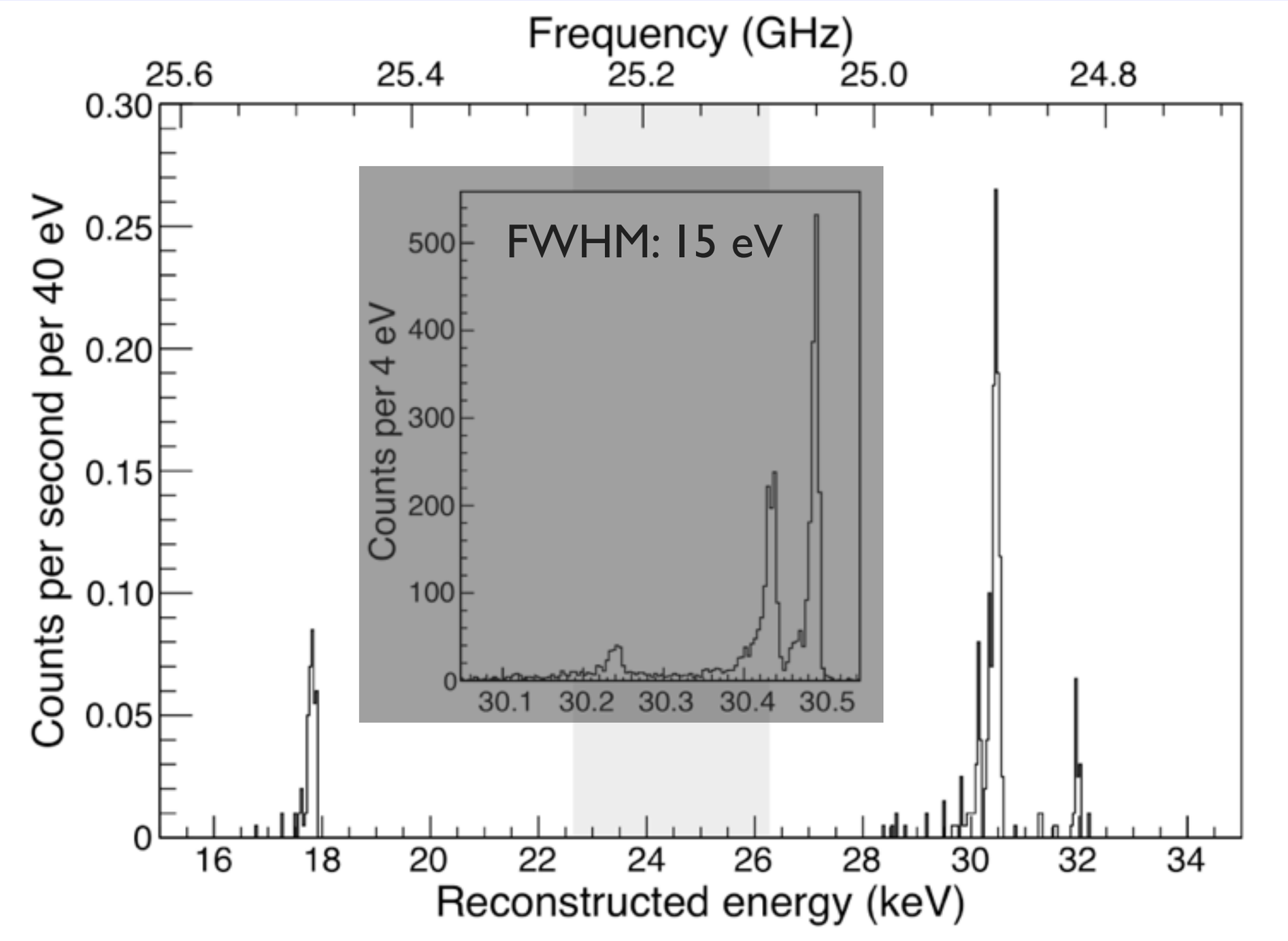
16
Time (ms)

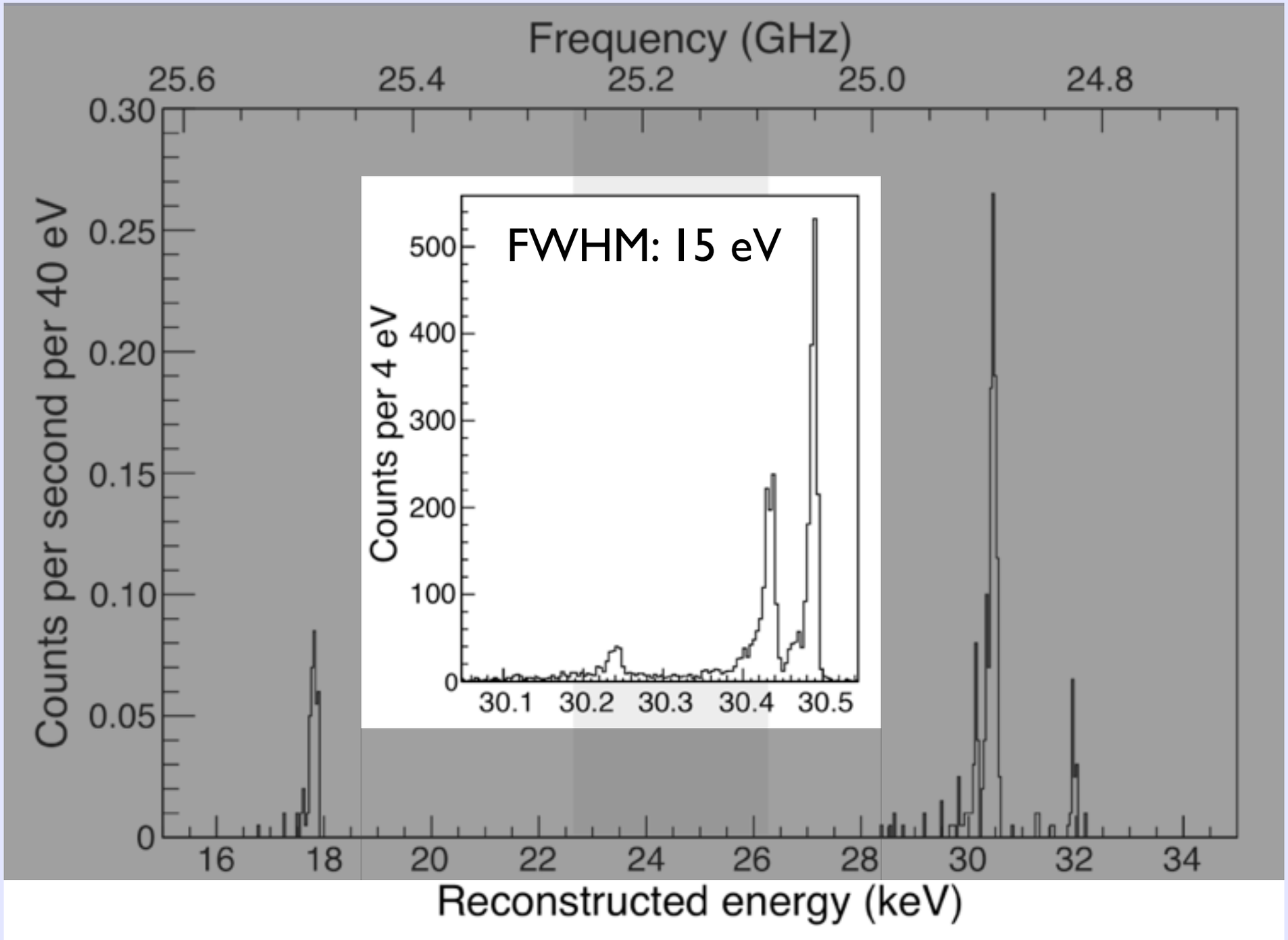
Energy Spectrum



Trap current 800 mA

Phys. Rev. Lett. 114, 162501 (2015)

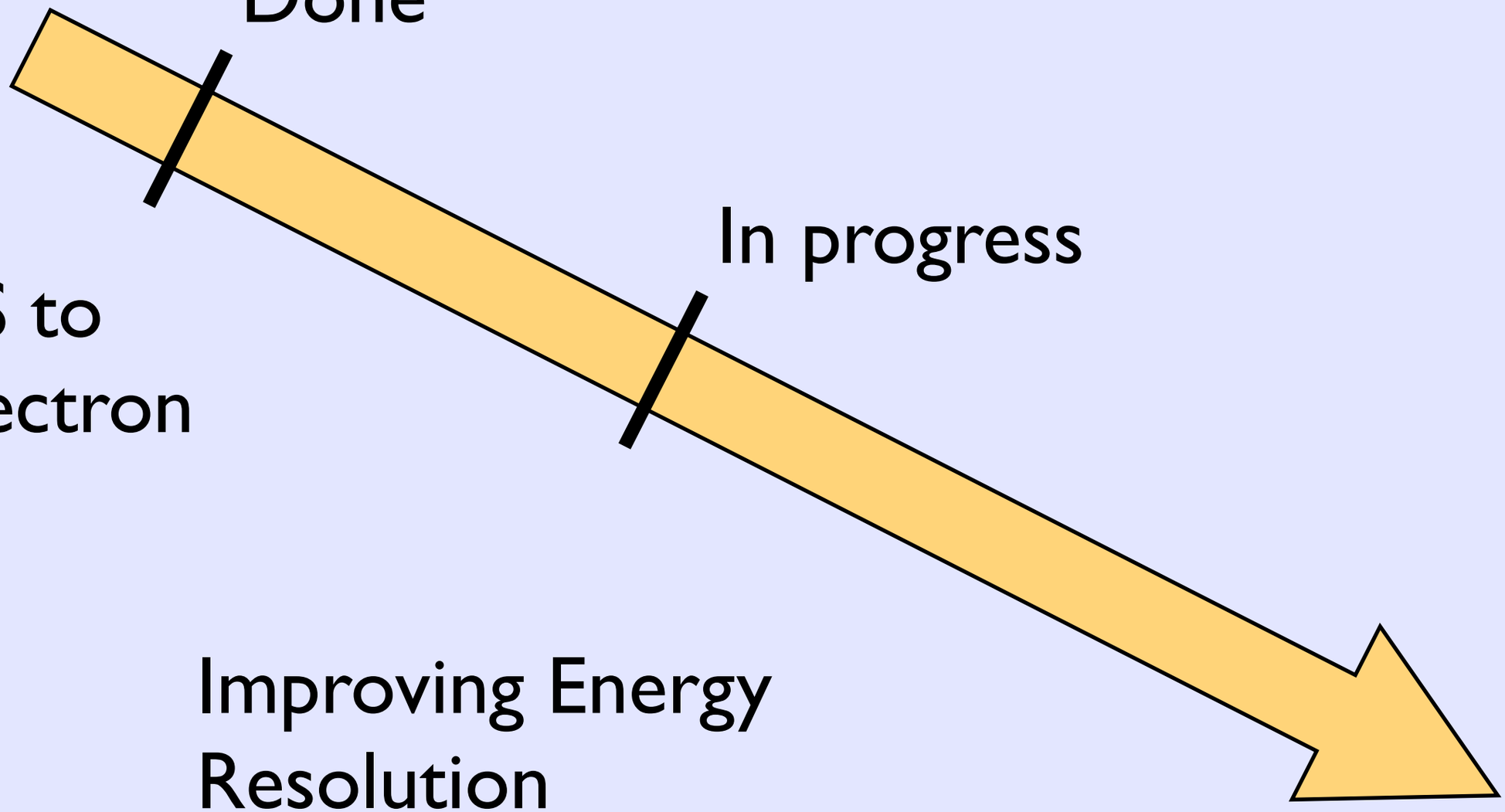
Energy Spectrum



Trap current 400 mA

Phys. Rev. Lett. 114, 162501 (2015)

Moving Forward



Using CRES to measure electron energies

Improving Energy Resolution

Measuring the tritium spectrum

Recent Improvements

- New trap geometry
- Lower noise level
  - ❖ Sidebands
  - ❖ Extended energy spectrum

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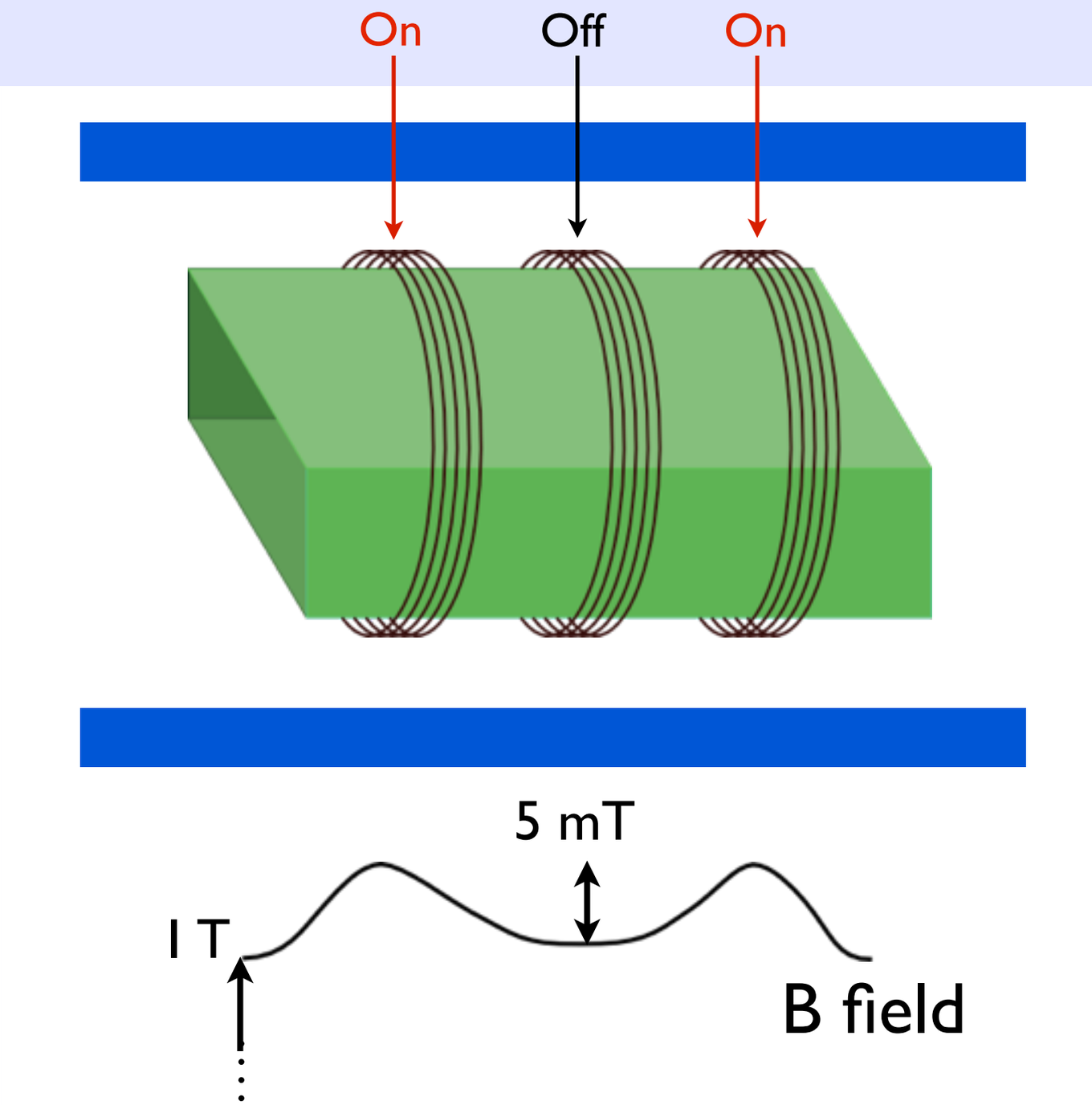
Improving energy resolution

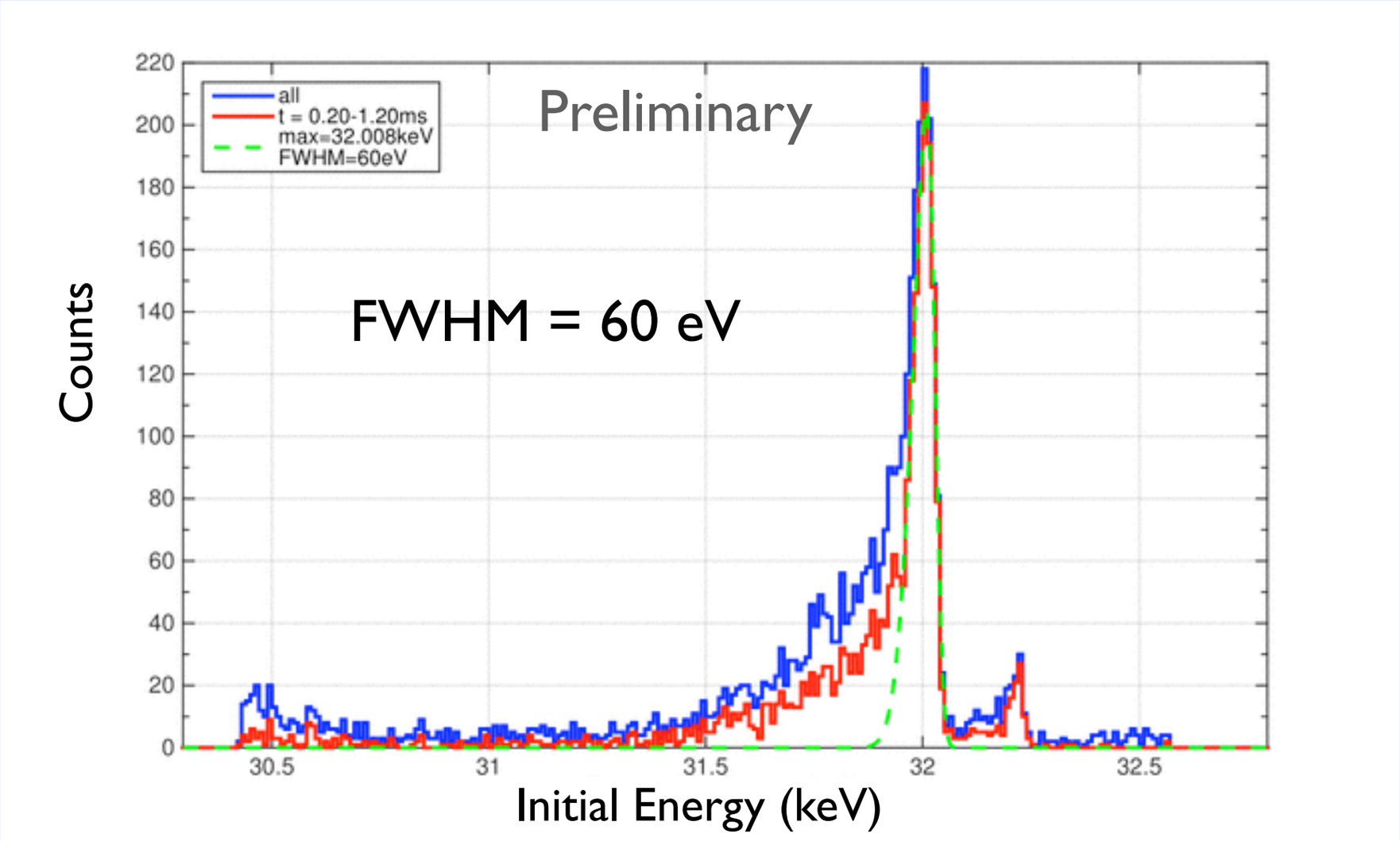
“Bathtub” Trap



- Improved field homogeneity
- Larger trapping volume

Resolution Improvement

32 keV electrons -- ½ bathtub trap @ 1A



Compare to FWHM ≈ 140 eV for a 1A harmonic trap

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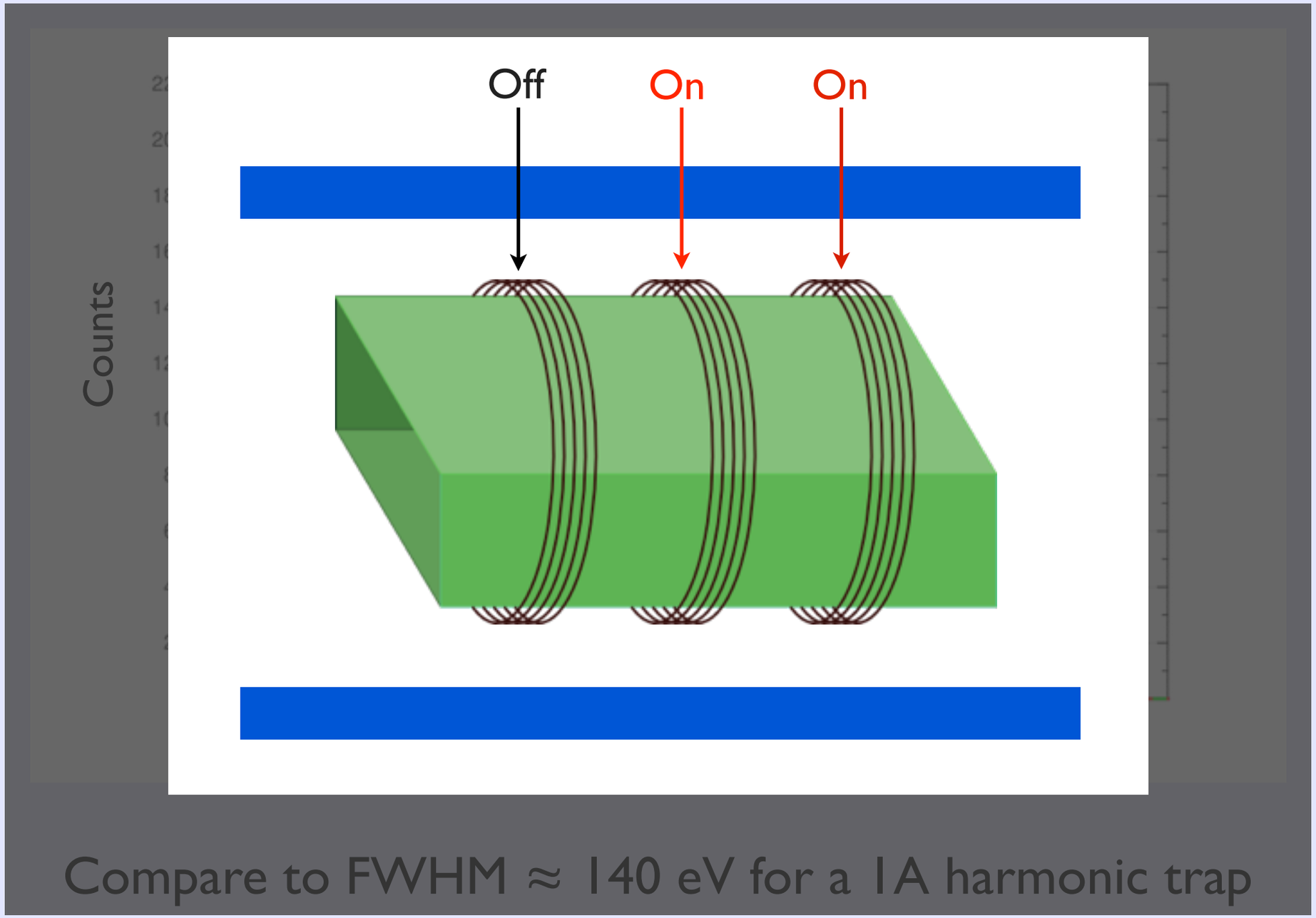

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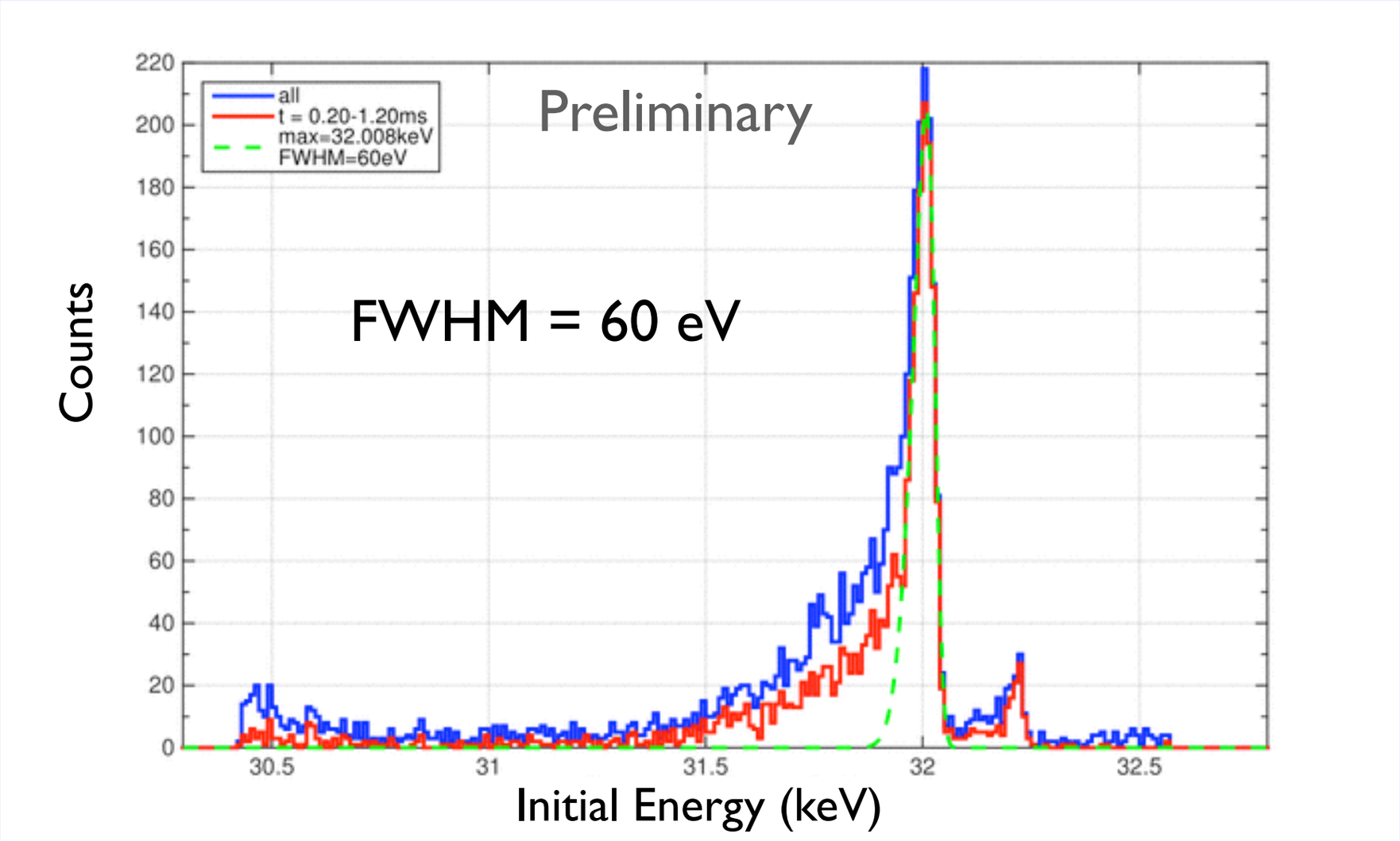

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Disentangling Energy and θ

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Use the axial frequency: modulation of the cyclotron radiation signal

$$\omega_a \propto v\left(\frac{a}{\sin\theta} + \frac{4\sin\theta}{m\cos^2\theta}\right)^{-1}$$

For an approximation of a bathtub trap

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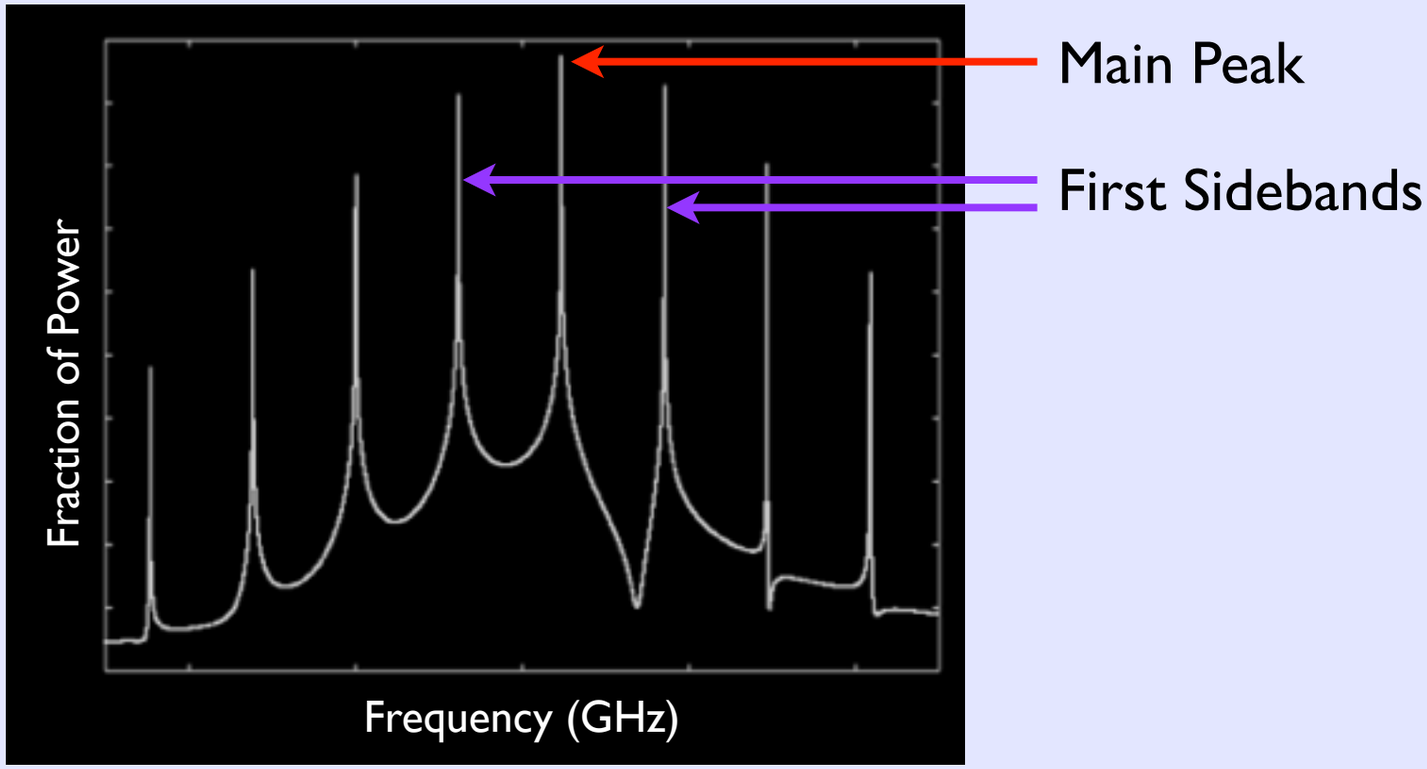
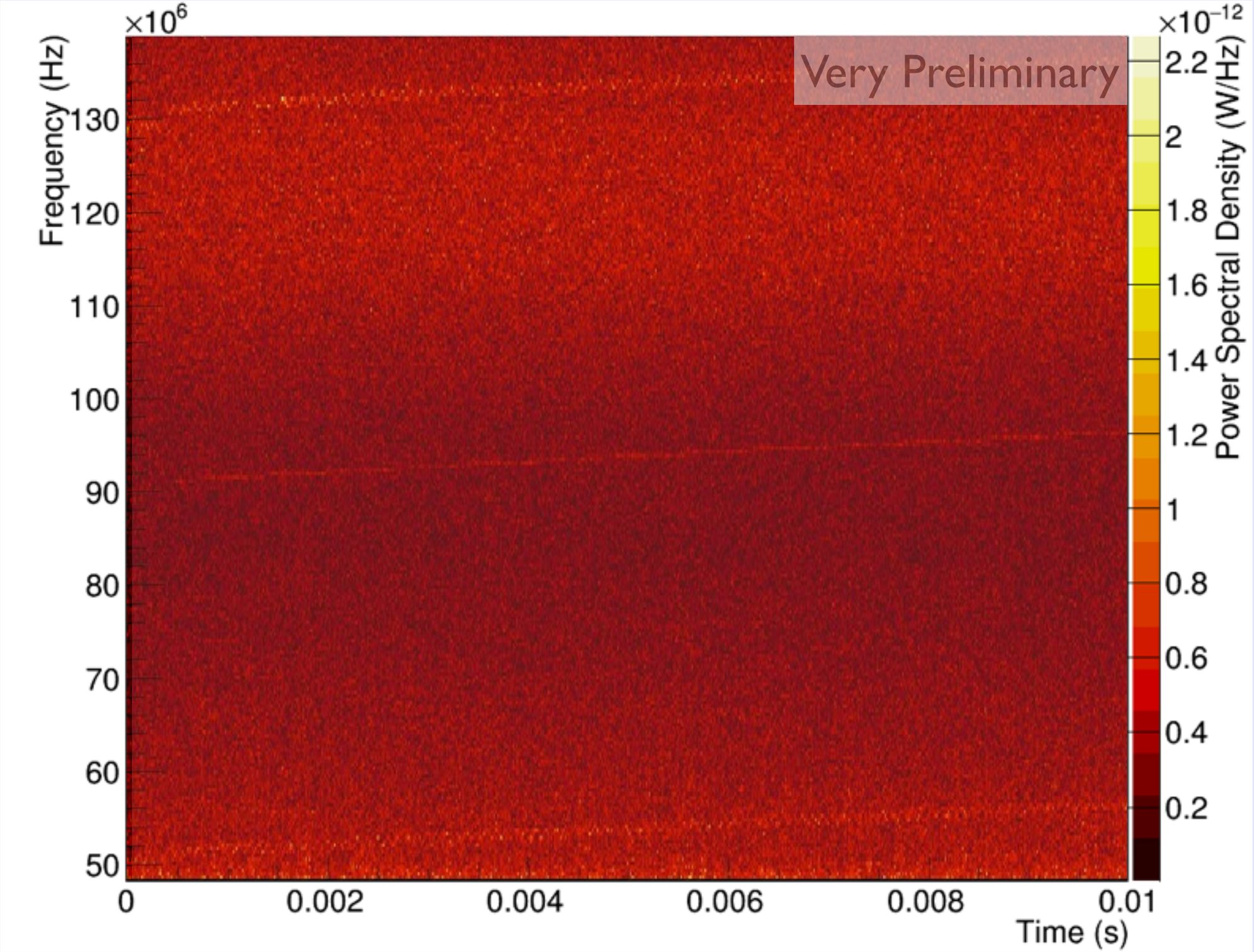
For an approximation of a bathtub trap

Expected frequencies: 50-200 MHz



Sidebands Found!



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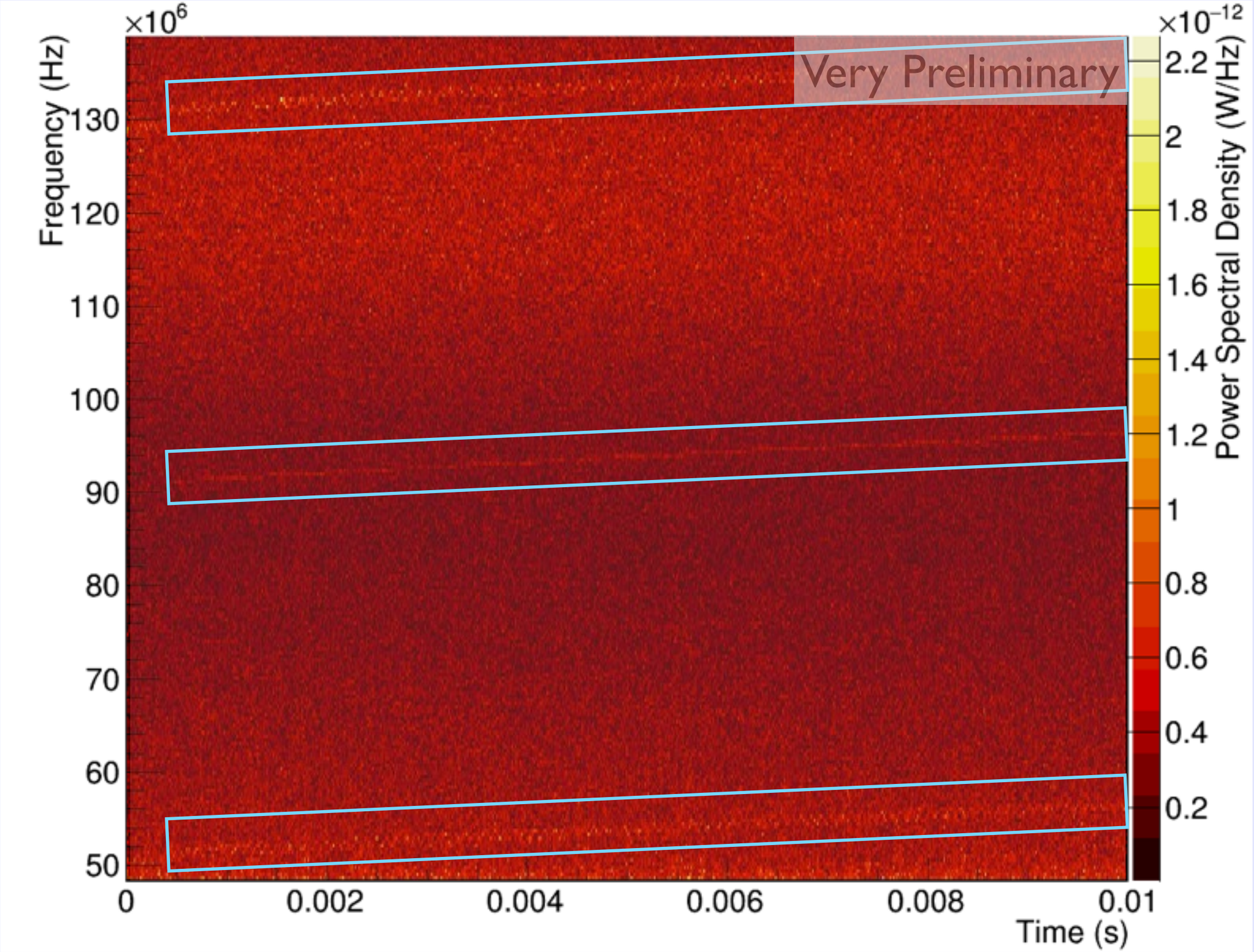
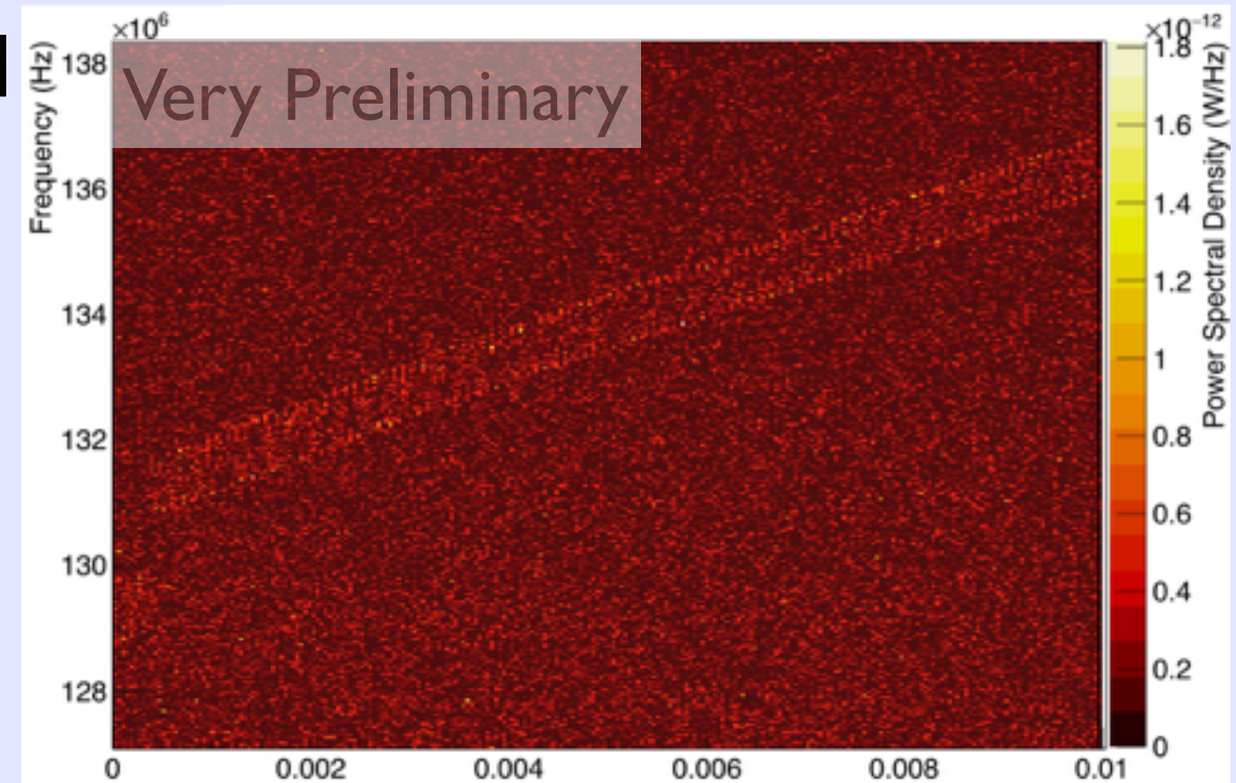
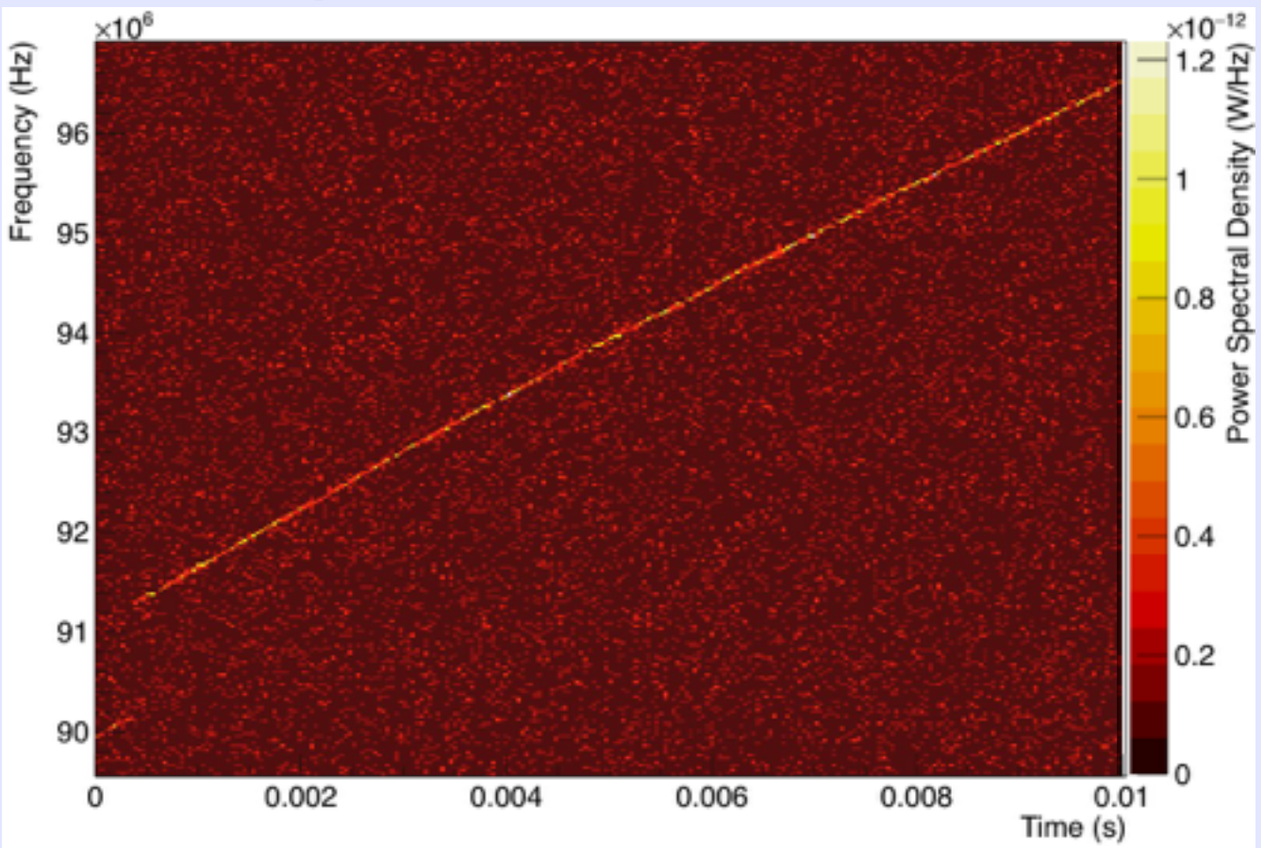


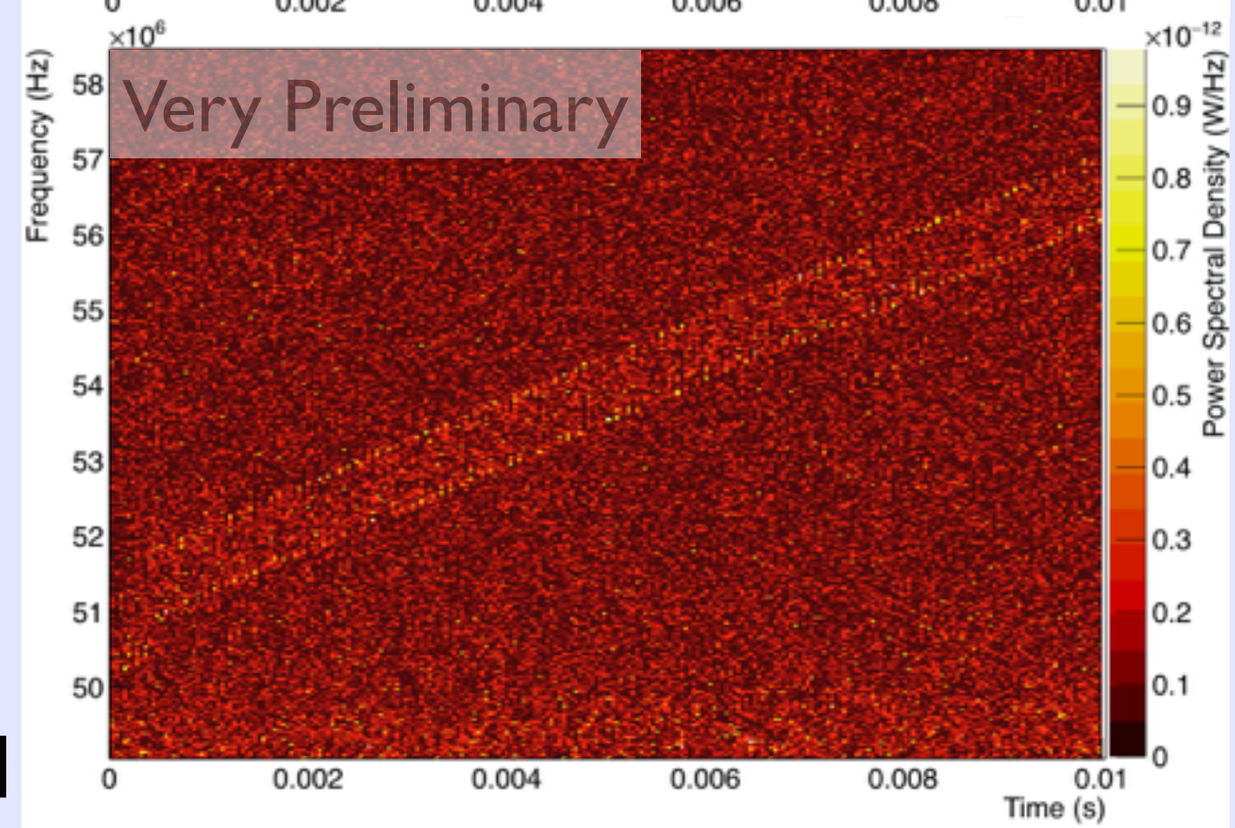
Sideband Oscillations

Upper Sideband



Central peak

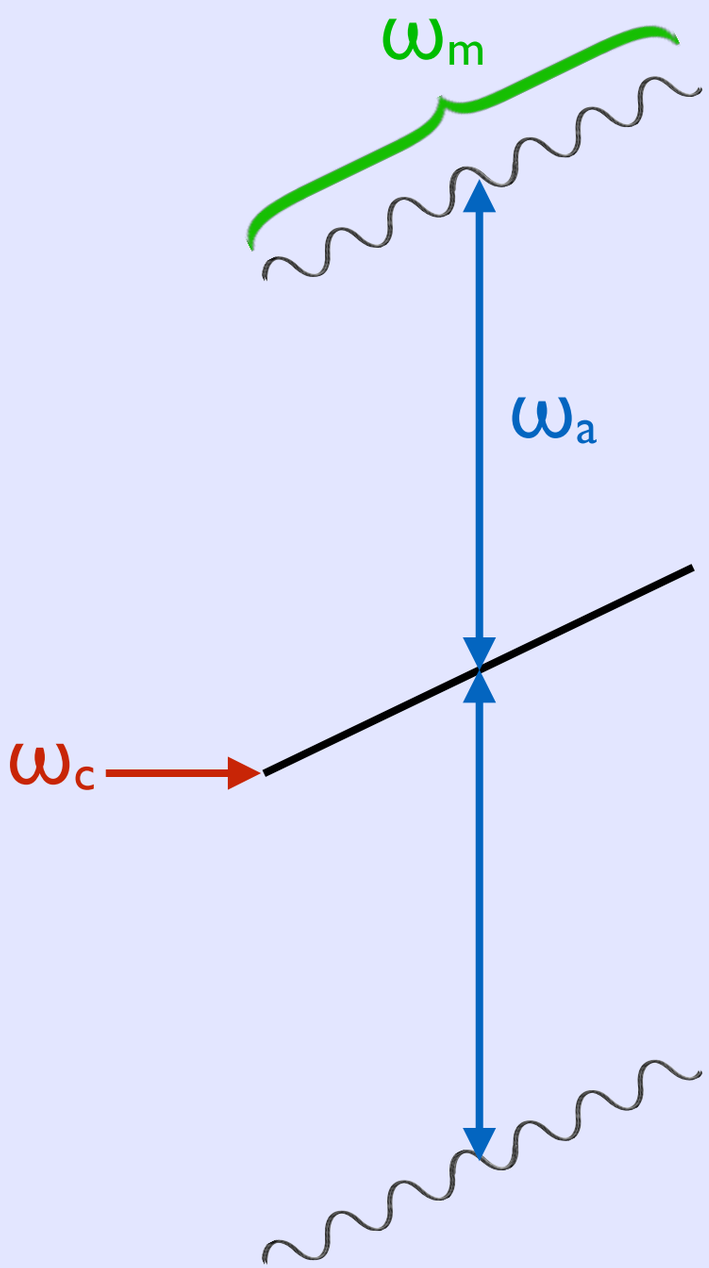




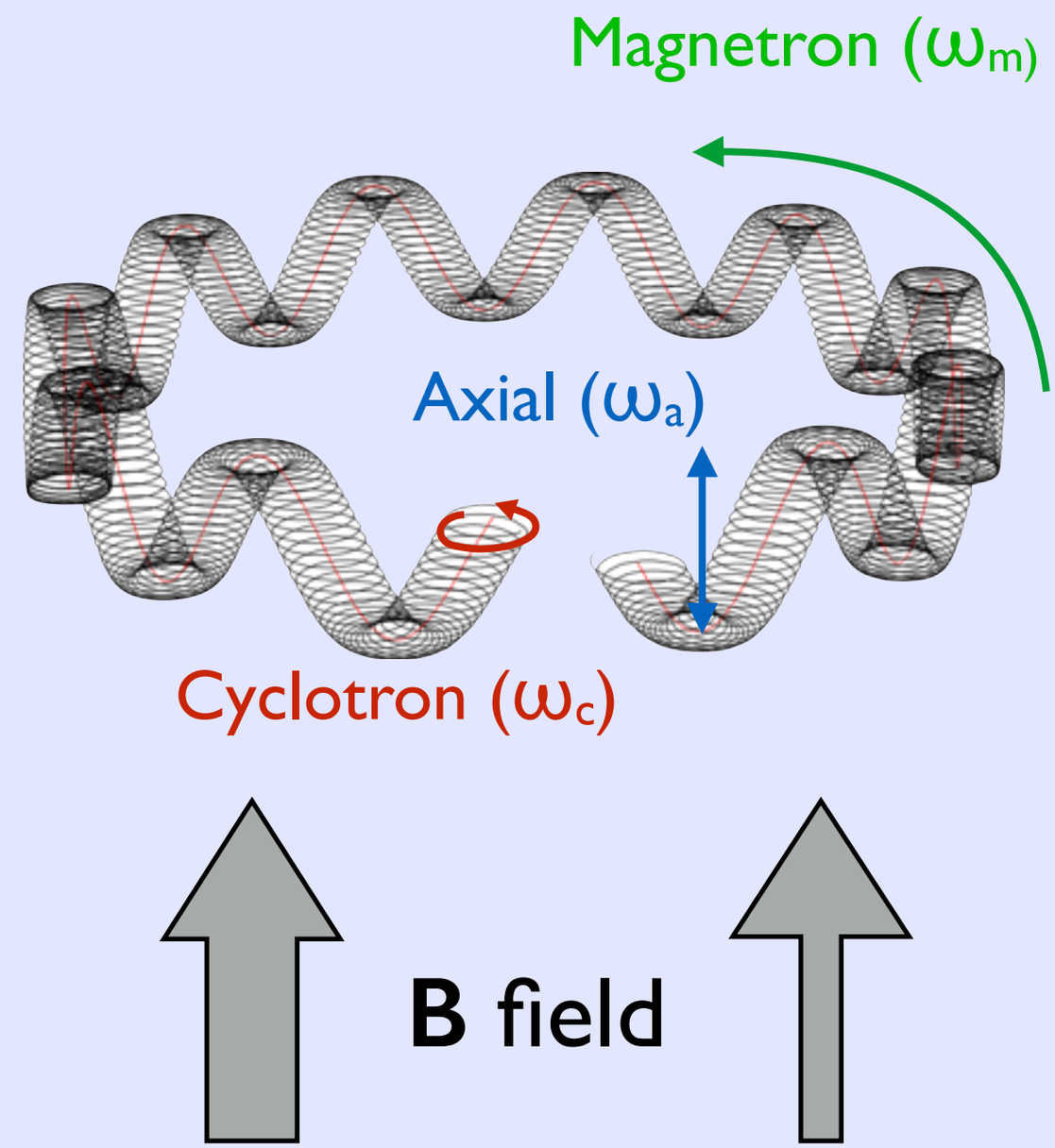
Lower Sideband

Three Degrees of Freedom

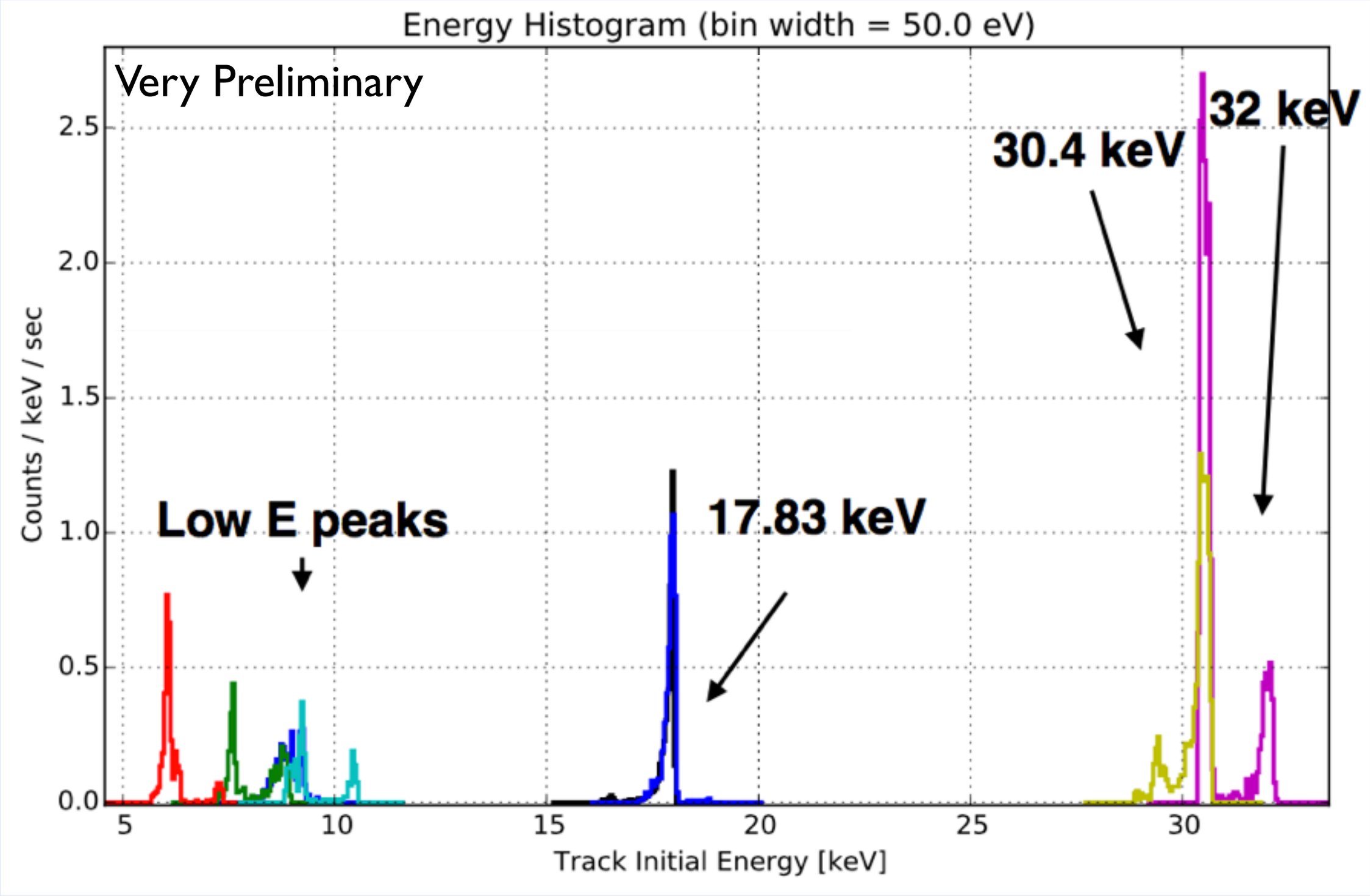
Data



Hypothesis

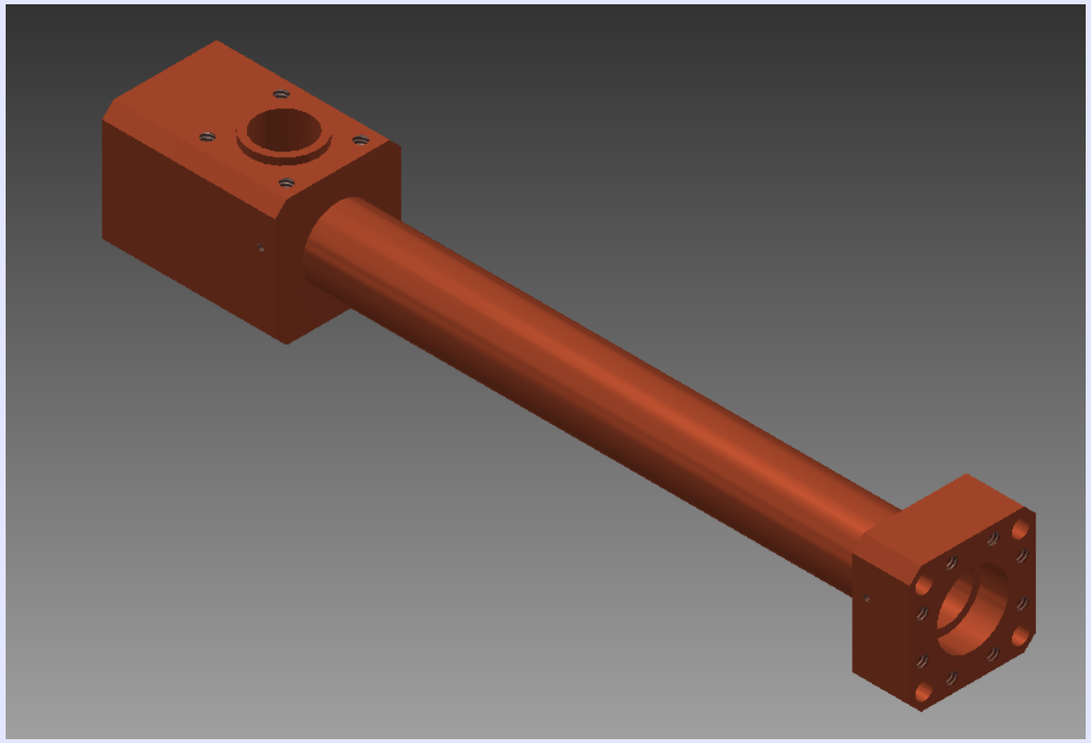


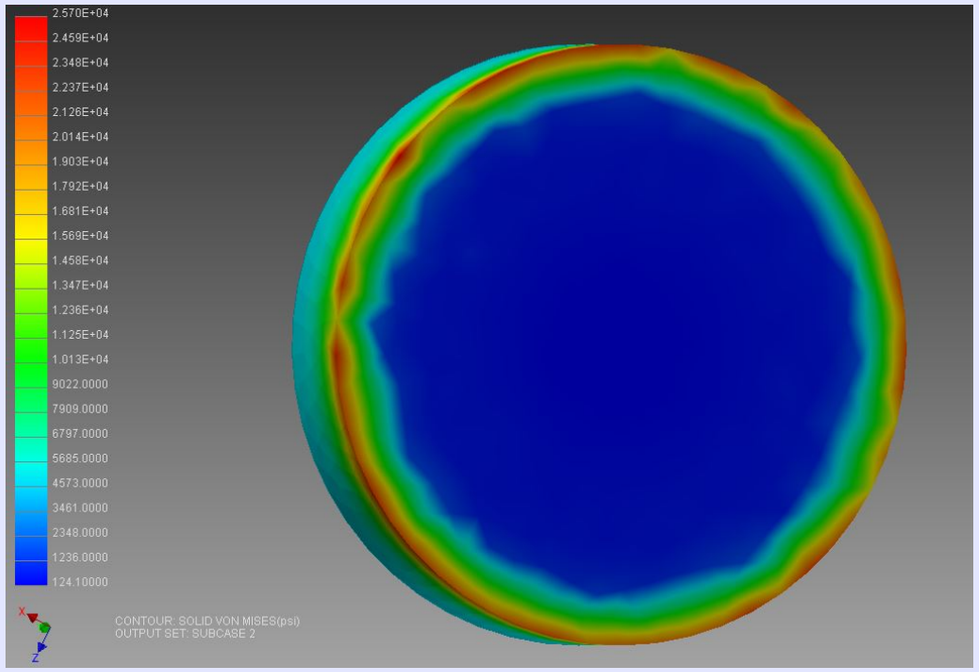
Extended Energy Spectrum



Preparing for Tritium

- New cell design
- New cell windows
- Dedicated gas source
- . . .





Summary

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- First direct measurement of single-electron cyclotron radiation made in June, 2014
- Currently seeking improvements in energy resolution and statistics
- Preparing for first tritium measurement

Project 8 Collaboration

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Yale University
K. Heeger, P. Slocum

http://www.project8.org

Projected Sensitivities

Sensitivities for different gas densities (number per cm^3)