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Project 8: Towards a Neutrino Mass Measurement with Tritium Beta Decays

NOAH OBLATH
for the Project 8 Collaboration

Fermilab Neutrino Seminar
February 15, 2018

U.S. DEPARTMENT OF ENERGY

Talk Outline

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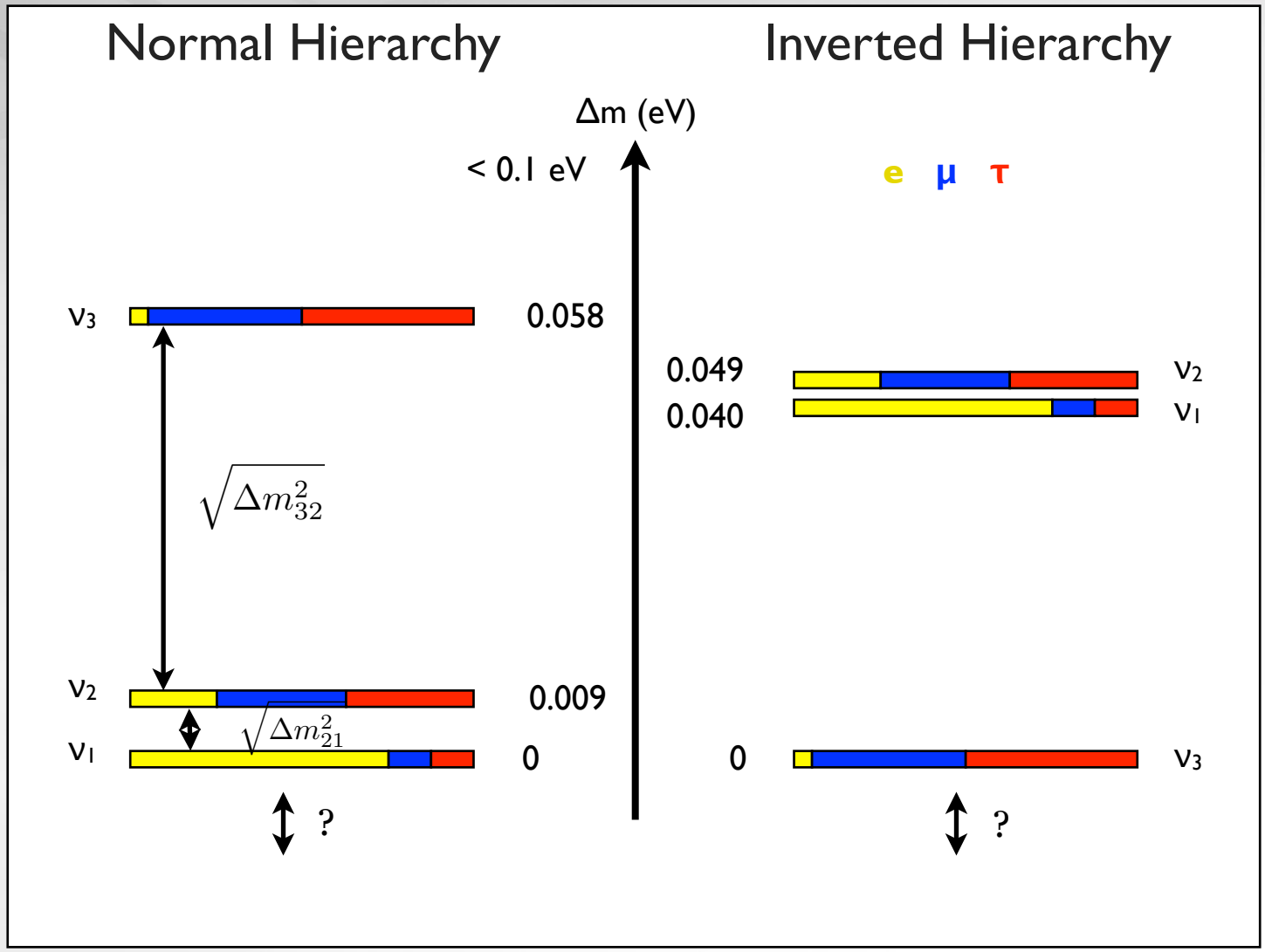
- Neutrino mass
- Cyclotron Radiation Emission Spectroscopy (CRES)
- Project 8 up to now
- Future developments

Big Questions in Neutrino Physics

- Are neutrinos their own antiparticles?
- Why are neutrinos so light?
- What is the absolute neutrino mass scale?

Neutrino Mass: What we Know



Probing Neutrino Mass

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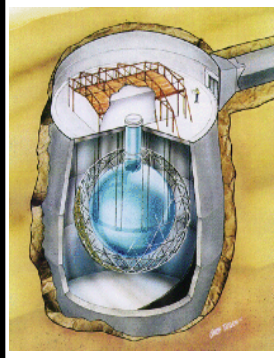
Neutrino Oscillations



Sensitive to mass differences

Quantum mechanical effects

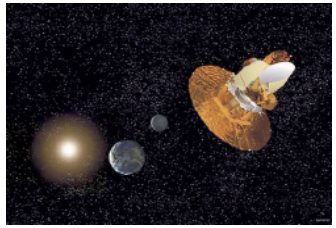
Sources: Reactor, solar, atmospheric, beams

Cosmology

Sensitive to the total neutrino mass

Depends on cosmological models

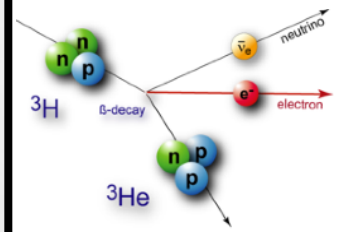
Measured by satellites & ground-based observatories



ν

Single Beta Decay

Sensitive to the absolute mass scale



Assumes conservation of energy

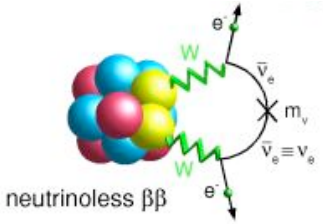
Model independent

0ν Double Beta Decay

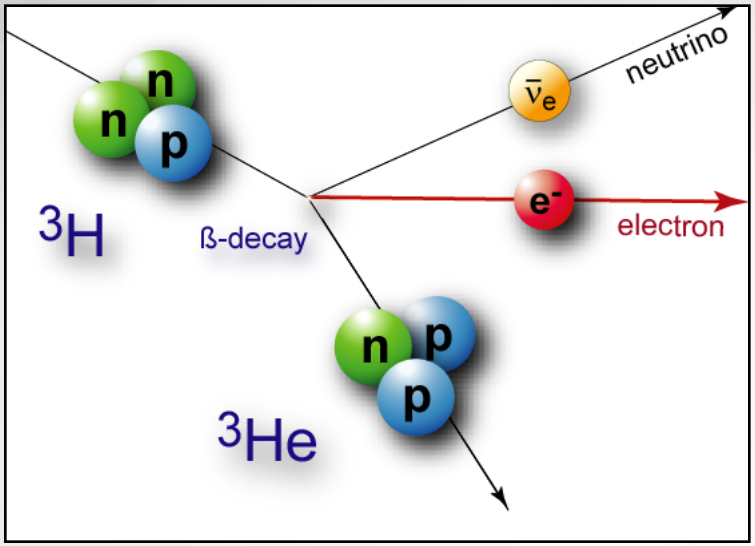
Sensitive to the Majorana masses

Rarest decays

Probes the nature of neutrinos



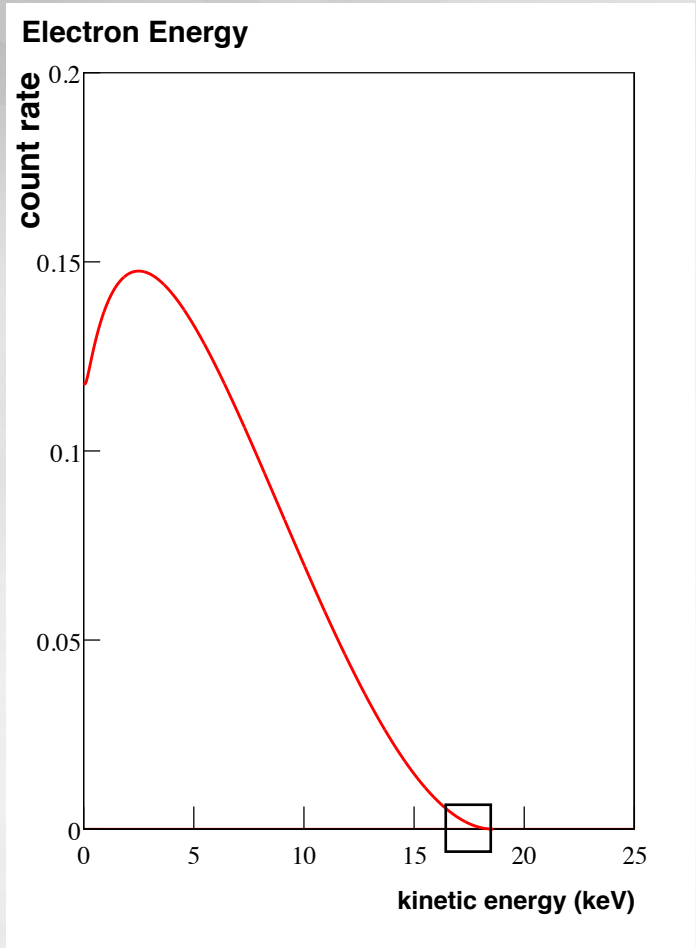
Tritium Beta Decay



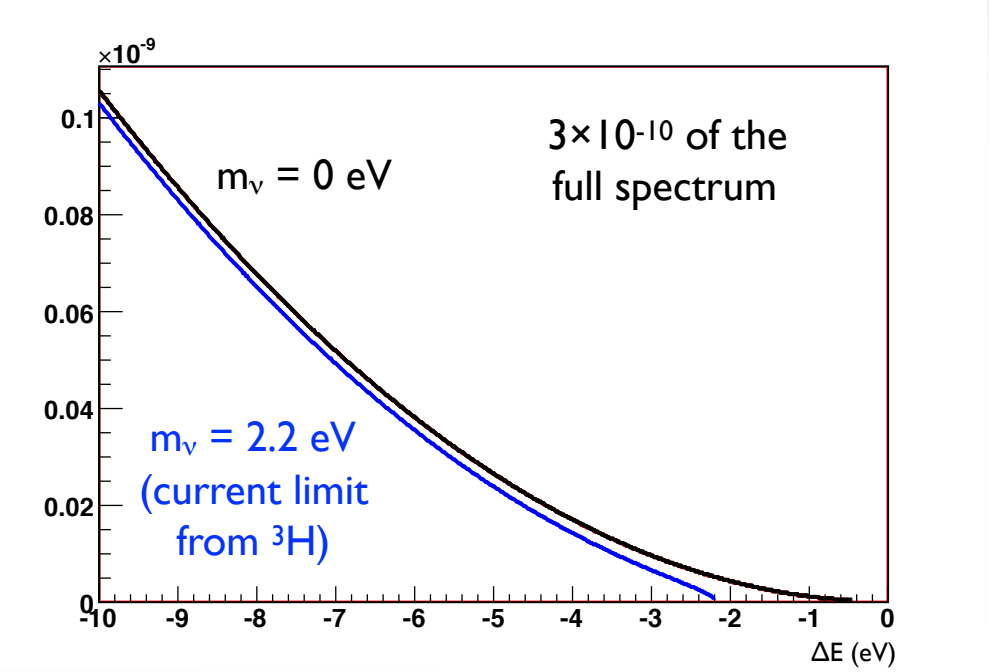
. . . from which we detect the electron

Beta decay allows precise measurement of the absolute neutrino mass scale.

Using Tritium β Decay



Zoom in on the endpoint . . .



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

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

A Sample of Tritium Experiments

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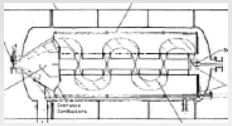
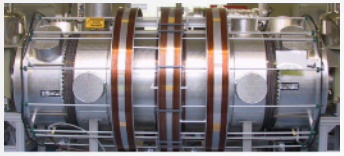
Los Alamos (1987)



$m_\beta < 9.5$ eV

Mainz (2000)

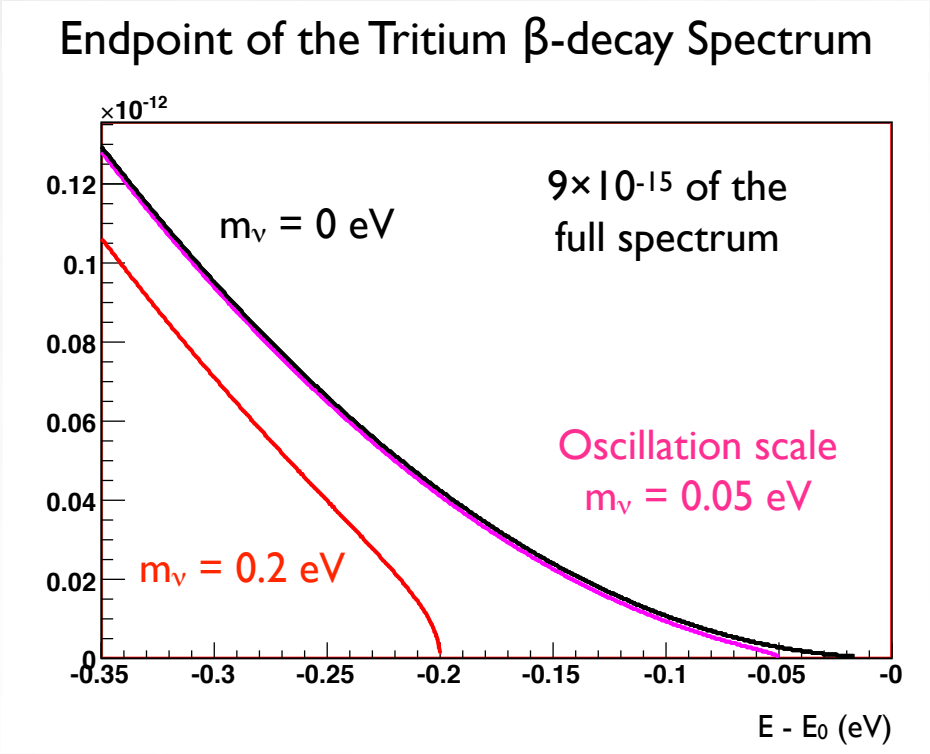


$m_\beta < 2.2$ eV

KATRIN (2018-2023)

$m_\beta < 0.2$ eV

Beyond KATRIN



Novel Technique: CRES

Cyclotron Radiation Emission Spectroscopy

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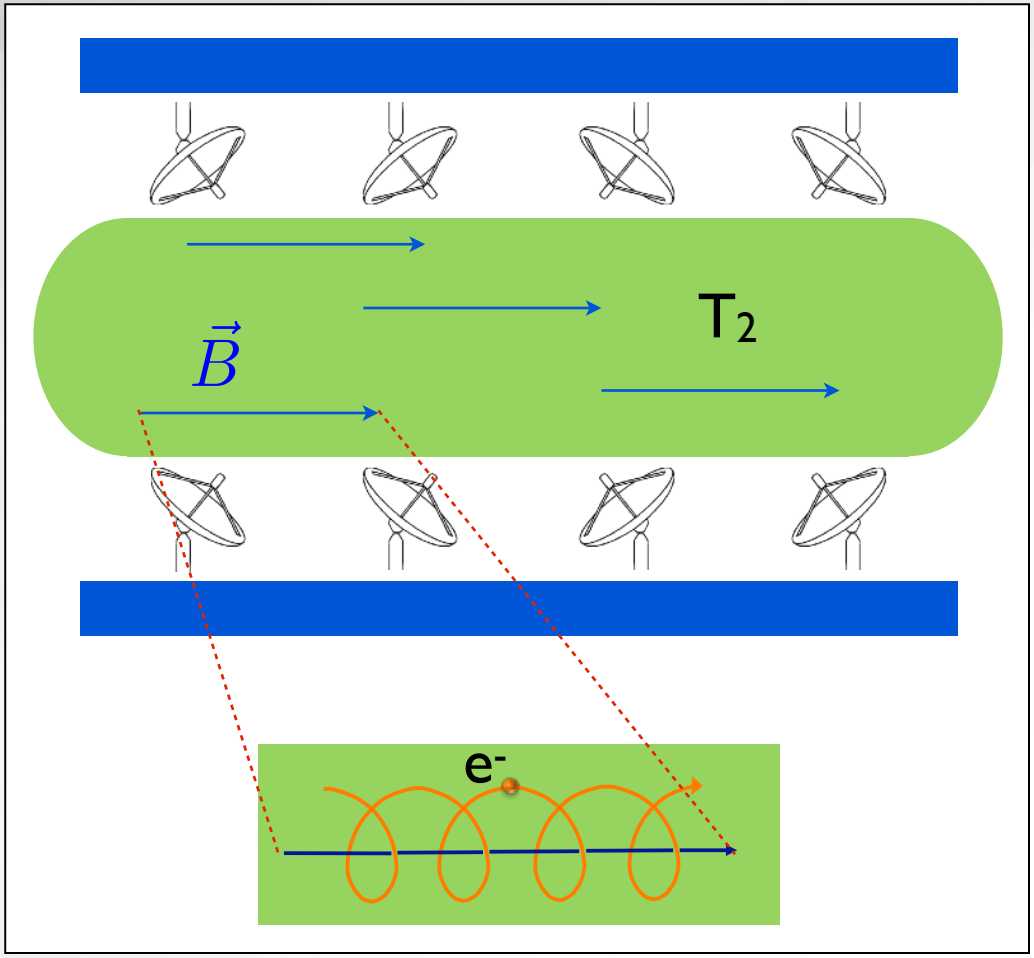
- Enclosed volume
- Fill with tritium gas
- Add a magnetic field

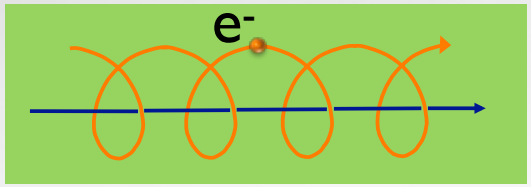


- Decay electrons spiral around field lines
- Add antennas to detect the cyclotron radiation

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

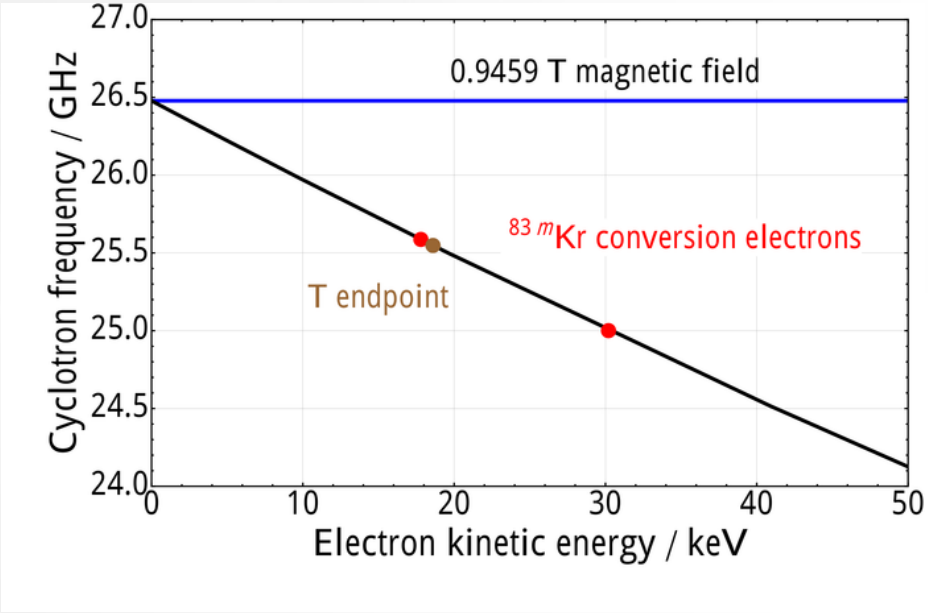
Cyclotron Radiation

- An electron traveling in a magnetic field emits cyclotron radiation



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

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



CRES Mass Sensitivity

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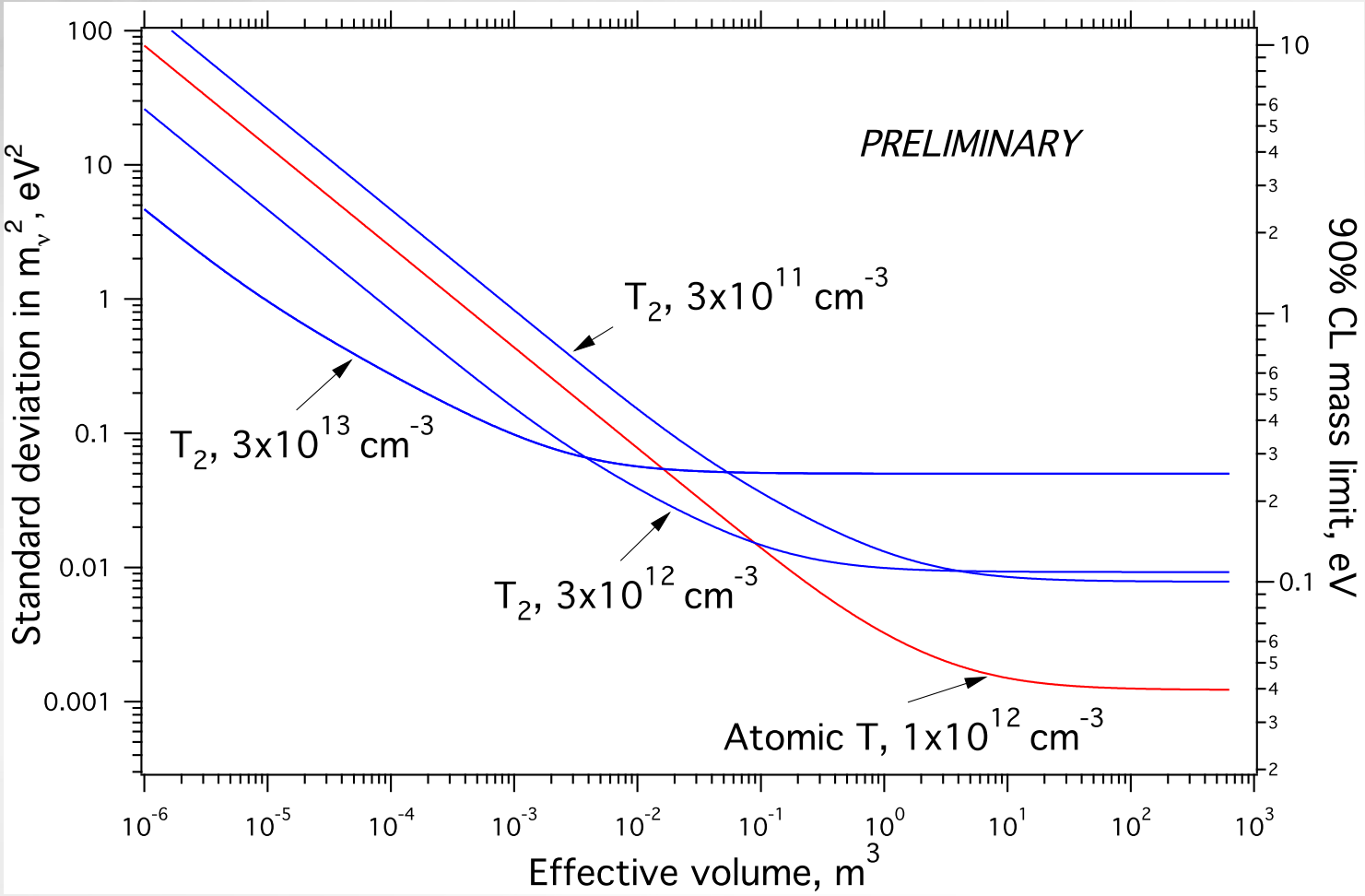
Sensitivities for different gas densities (number per cm³)



CRES Mass Sensitivity

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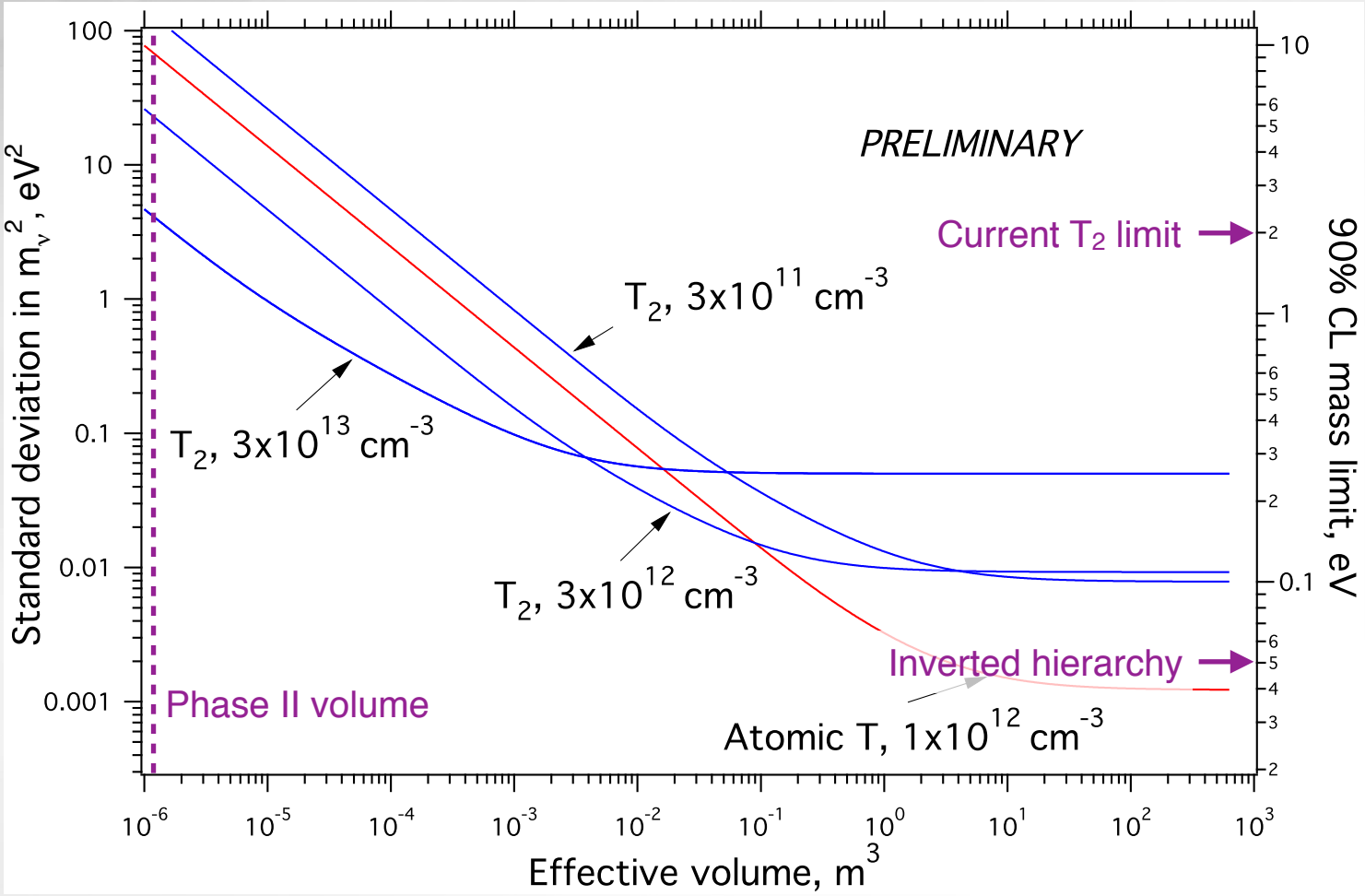
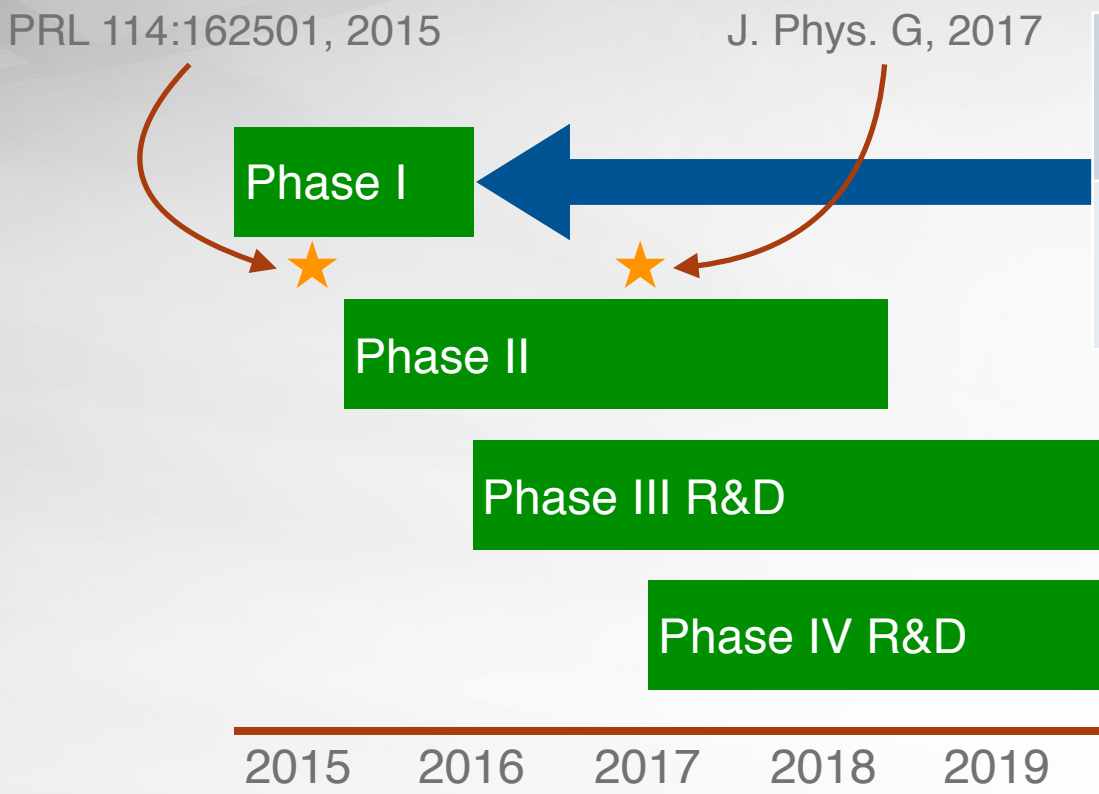


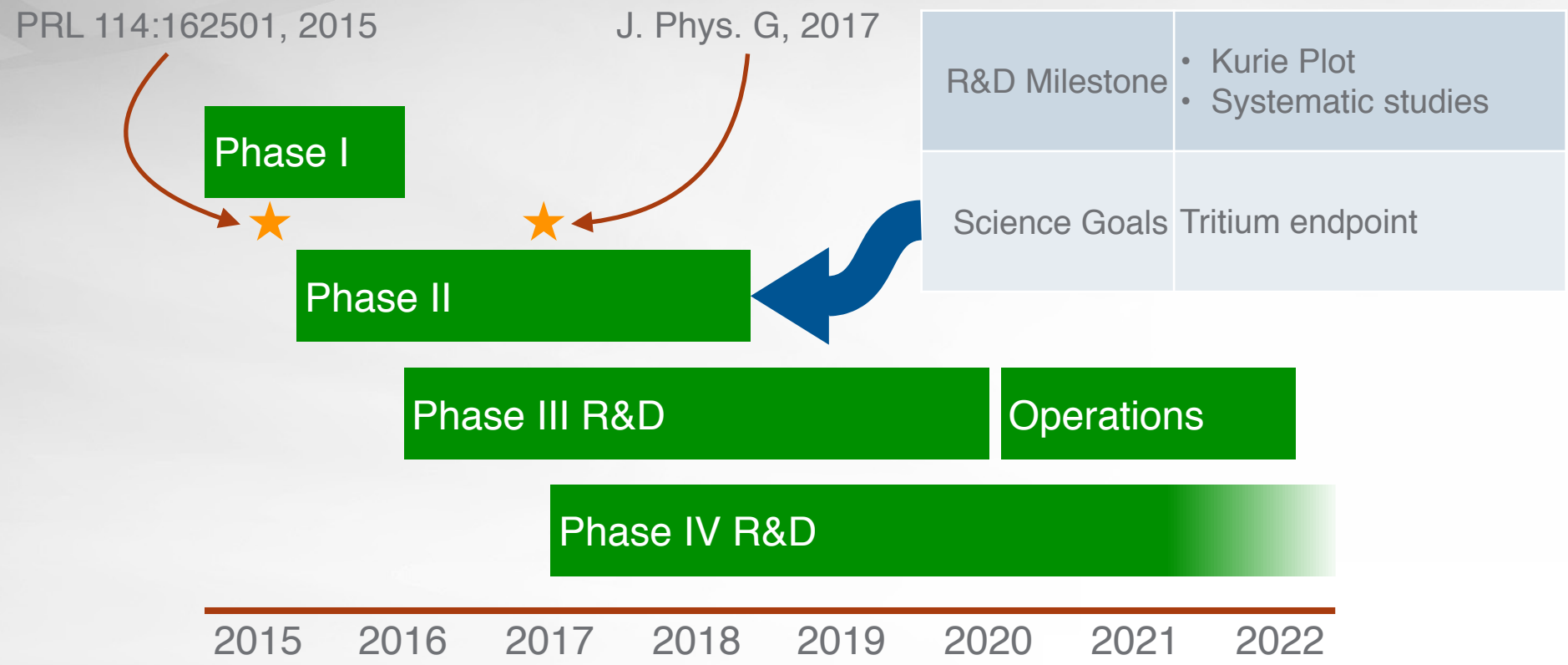
Calculations by R.G.H. Robertson

Moving Forward with a Phased Approach



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

Moving Forward with a Phased Approach



R&D Milestone	• Kurie Plot • Systematic studies
Science Goals	Tritium endpoint

Moving Forward with a Phased Approach

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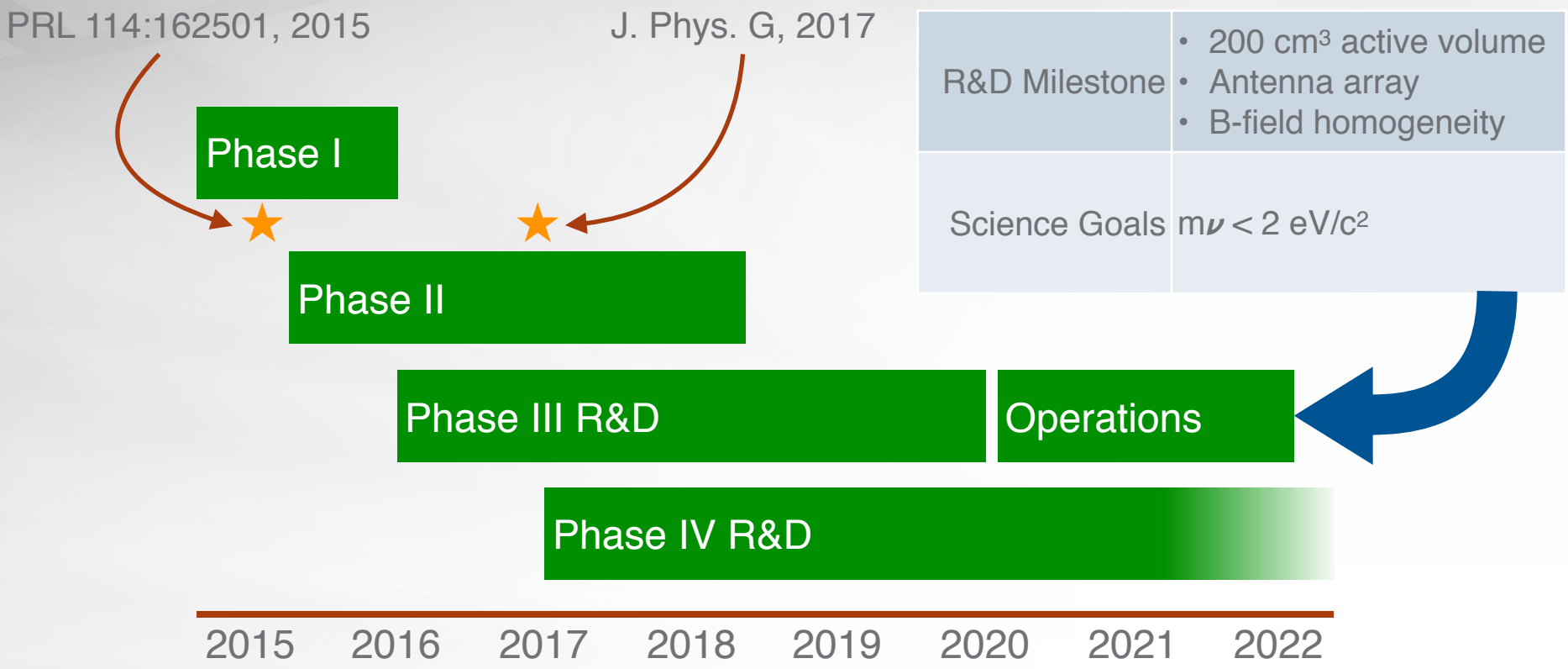

R&D Milestone	• 200 cm^3 active volume • Antenna array • B-field homogeneity
Science Goals	$m\nu < 2$ eV/c^2

Moving Forward with a Phased Approach

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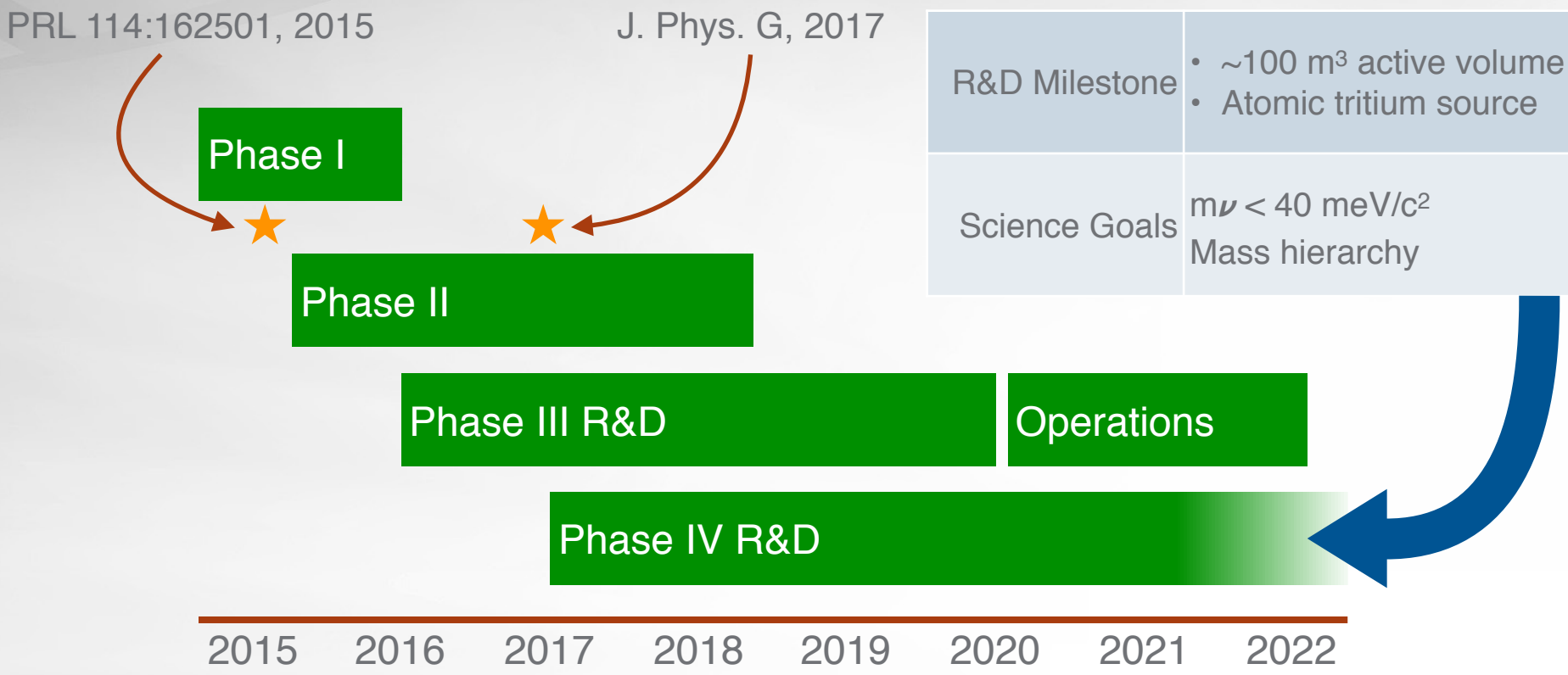
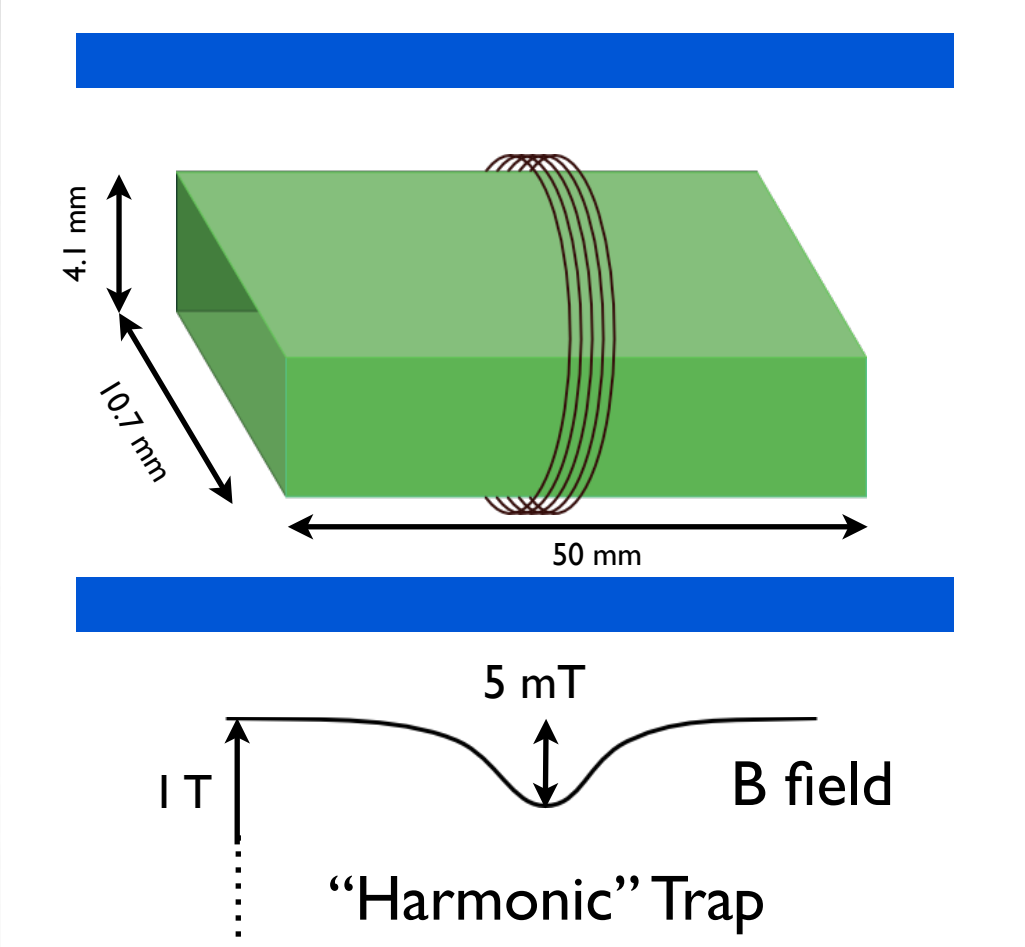


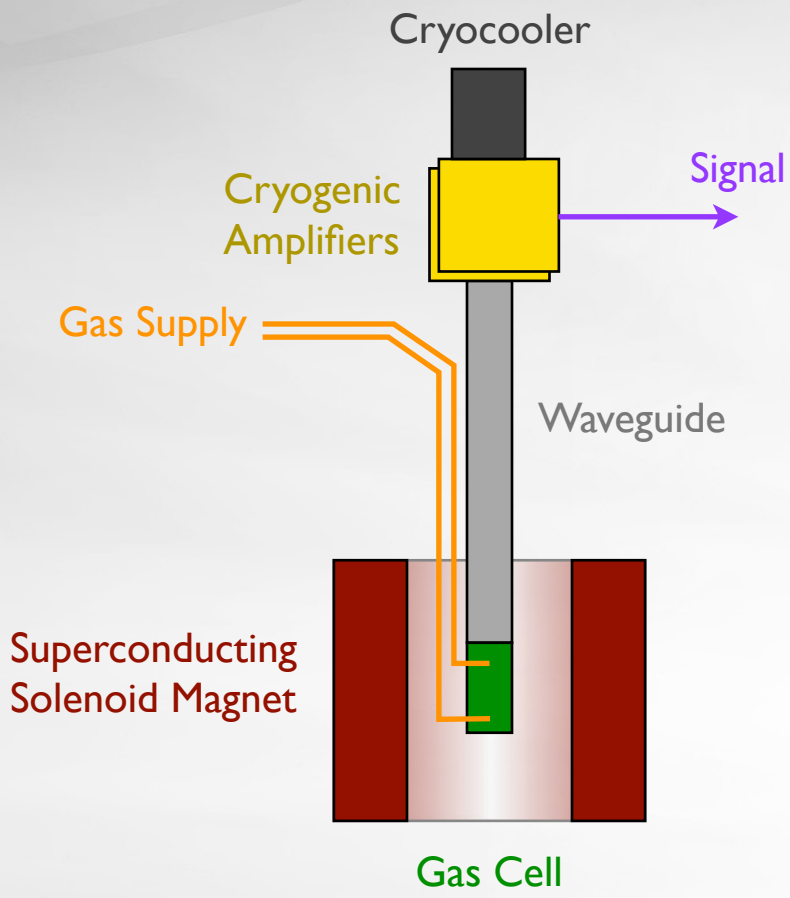
R&D Milestone	• ~100 m^3 active volume • Atomic tritium source
Science Goals	$m\nu < 40$ meV/c^2 Mass hierarchy

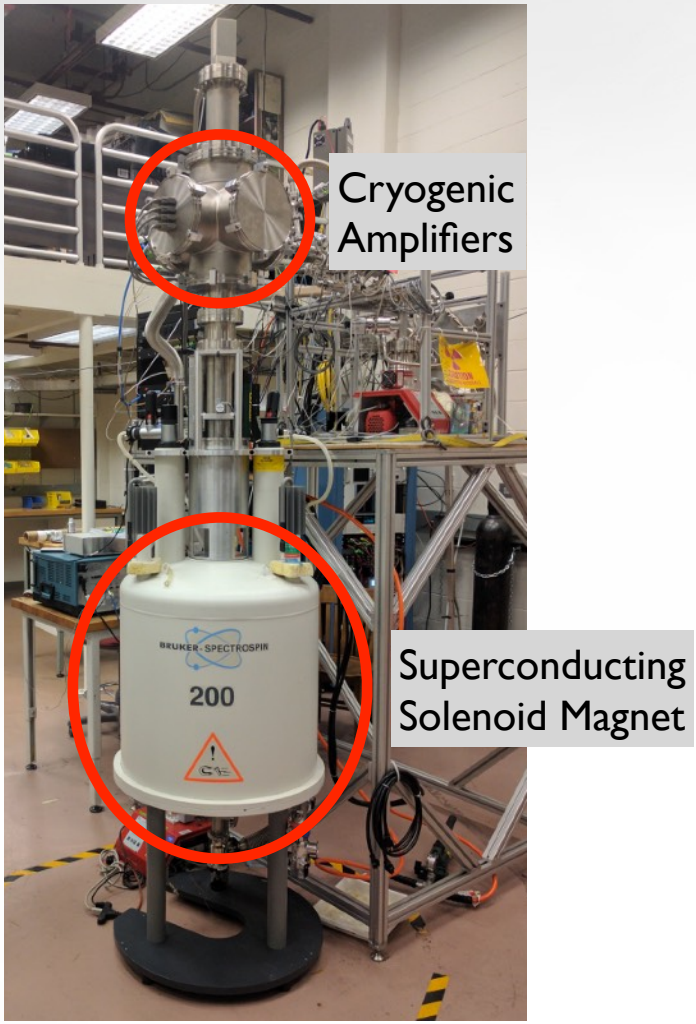
Phase I: CRES Demonstrator

- WR-42 waveguide to contain the gas and detect the cyclotron radiation
- Filled with ^{83m}Kr gas
- 1 T background magnetic field & a small 5-mT magnetic trap
- Waveguide leads to cryogenic amplifiers

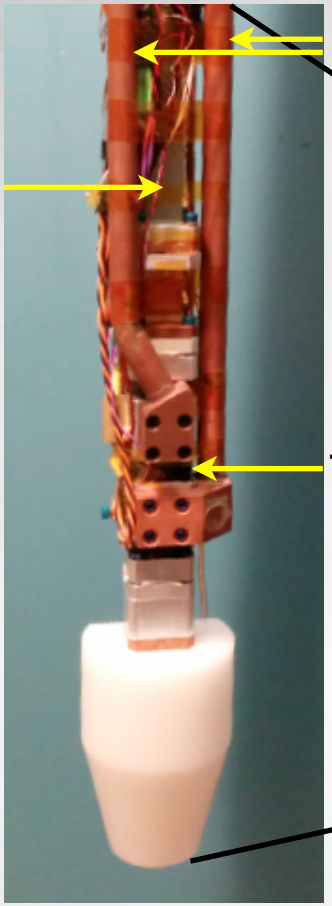


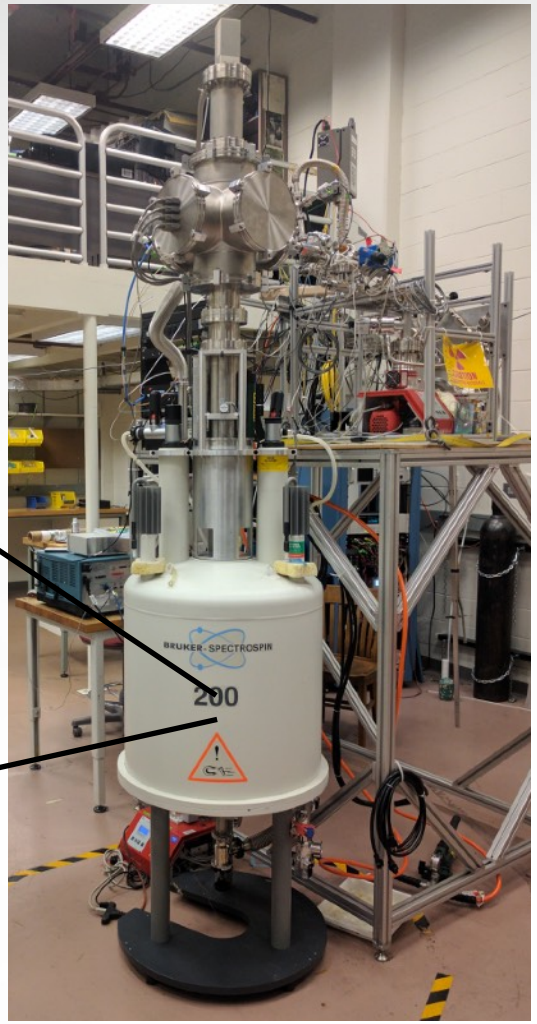
Phase I Apparatus



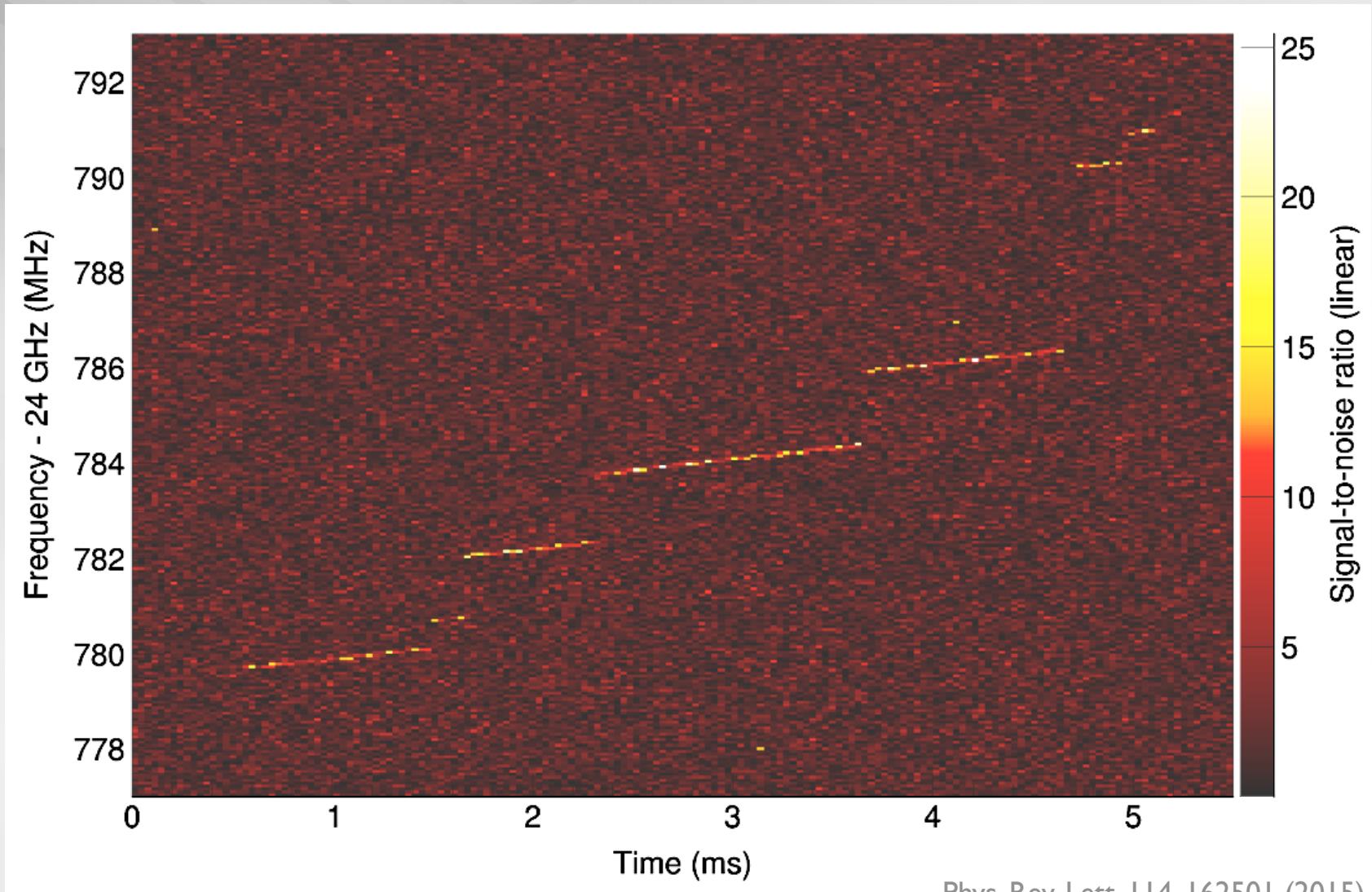


^{83m}Kr Gas Cell



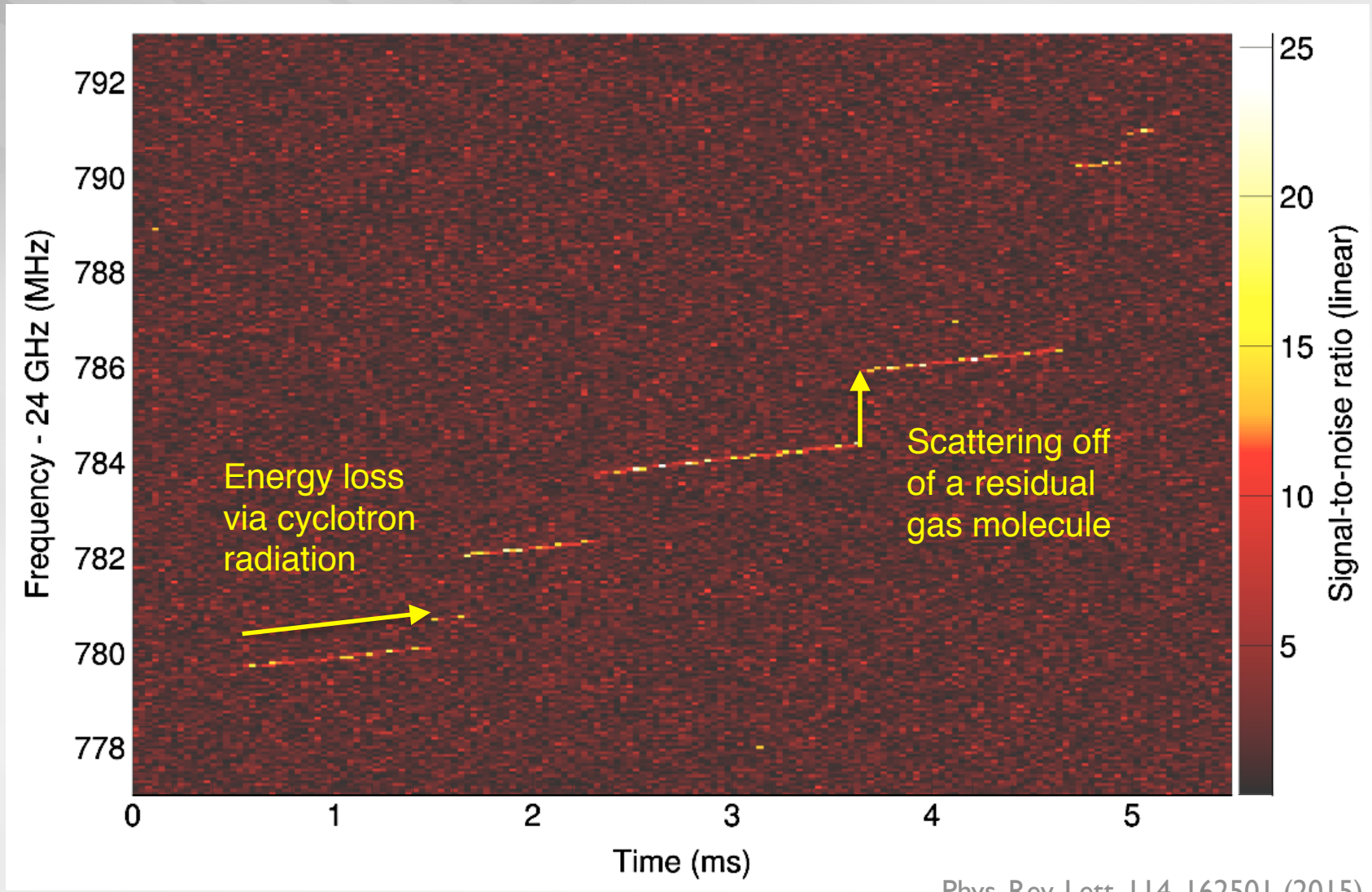


First Observation



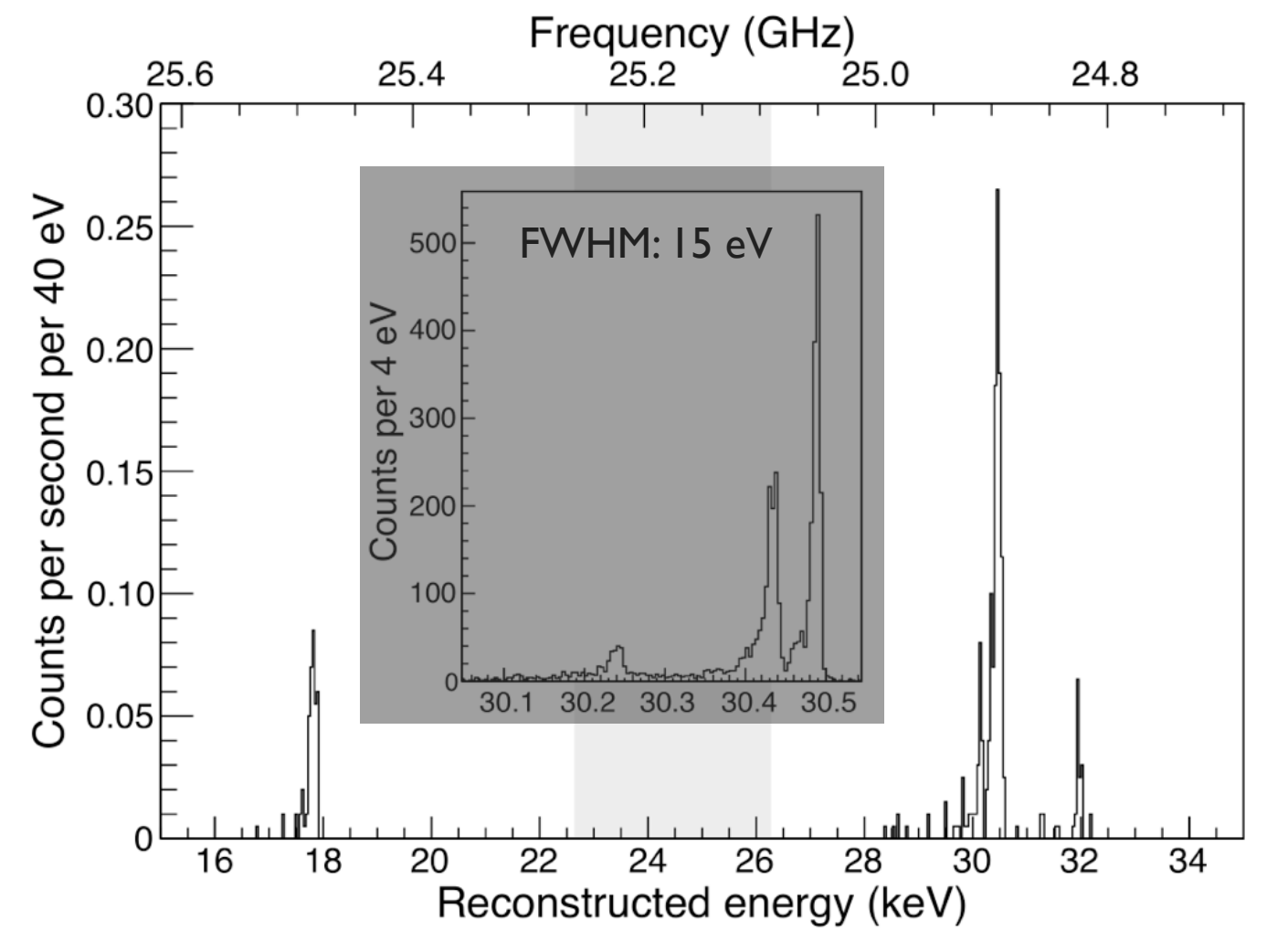
Phys. Rev. Lett. 114, 162501 (2015)

First Observation



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

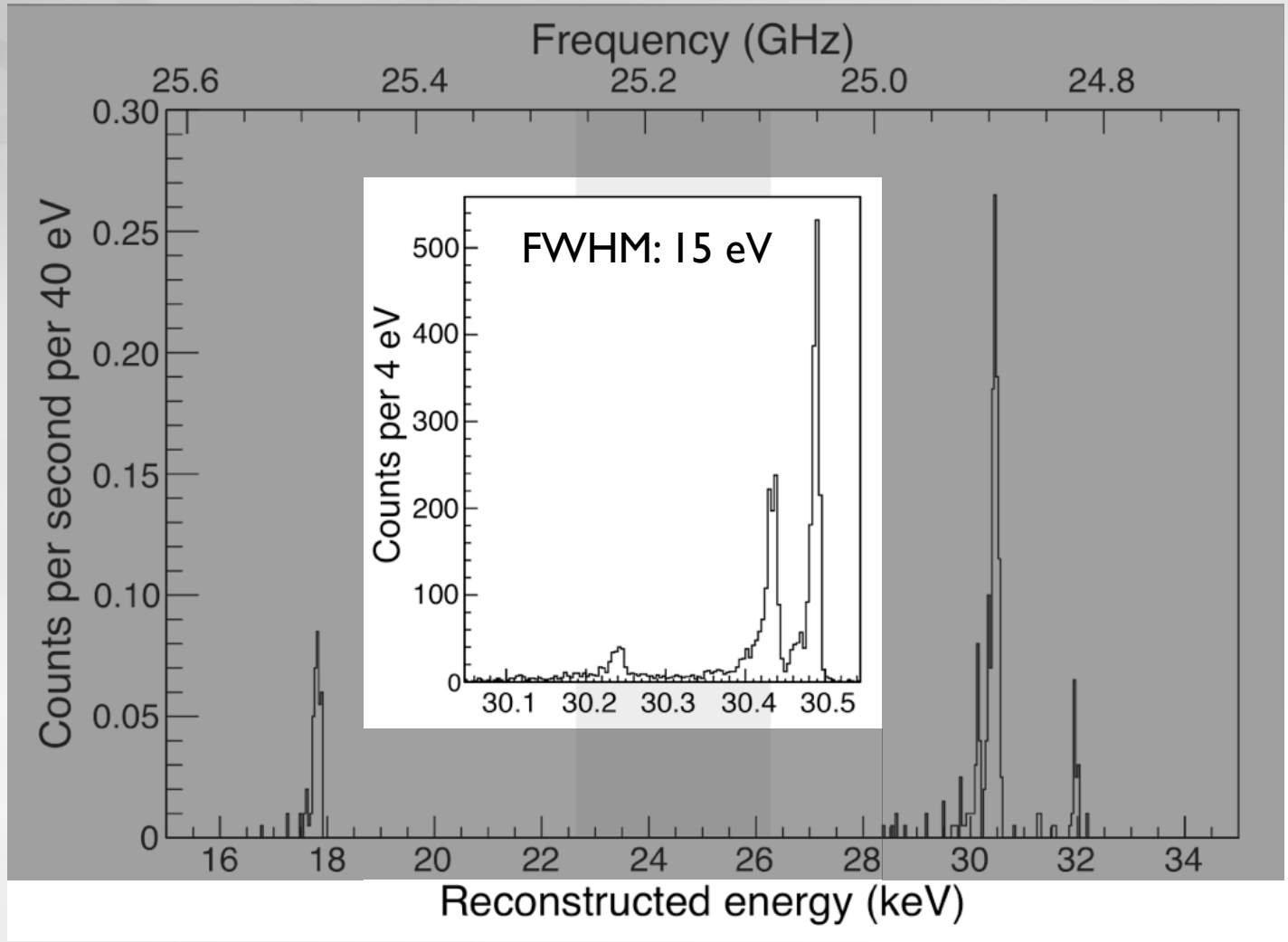
Energy Spectrum



Trap current 800 mA

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

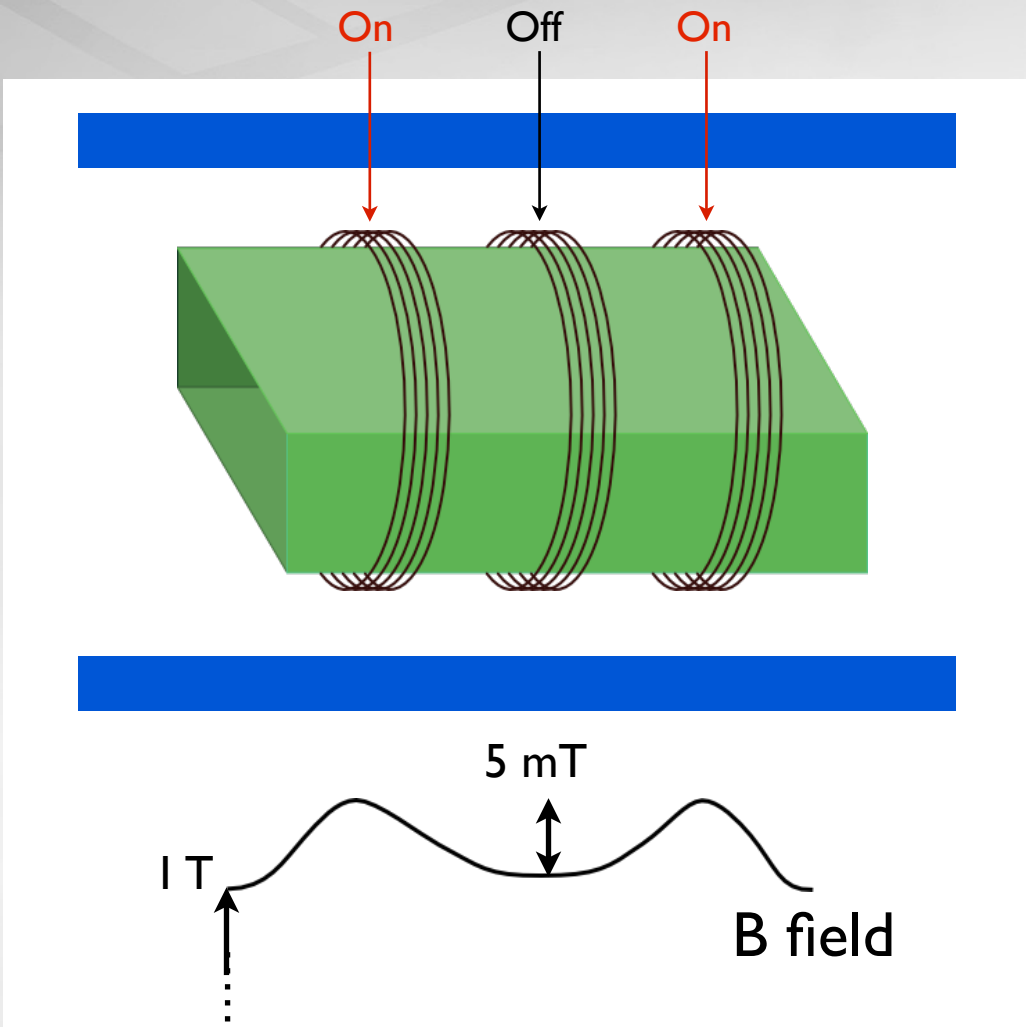
Energy Spectrum



Trap current 400 mA

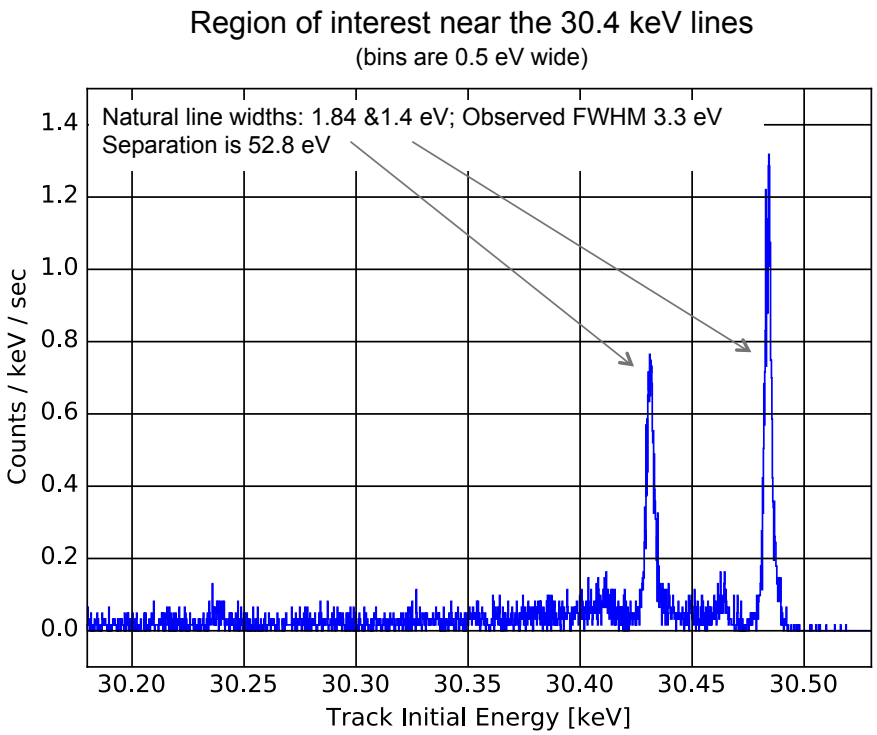
Phys. Rev. Lett. 114, 162501 (2015)

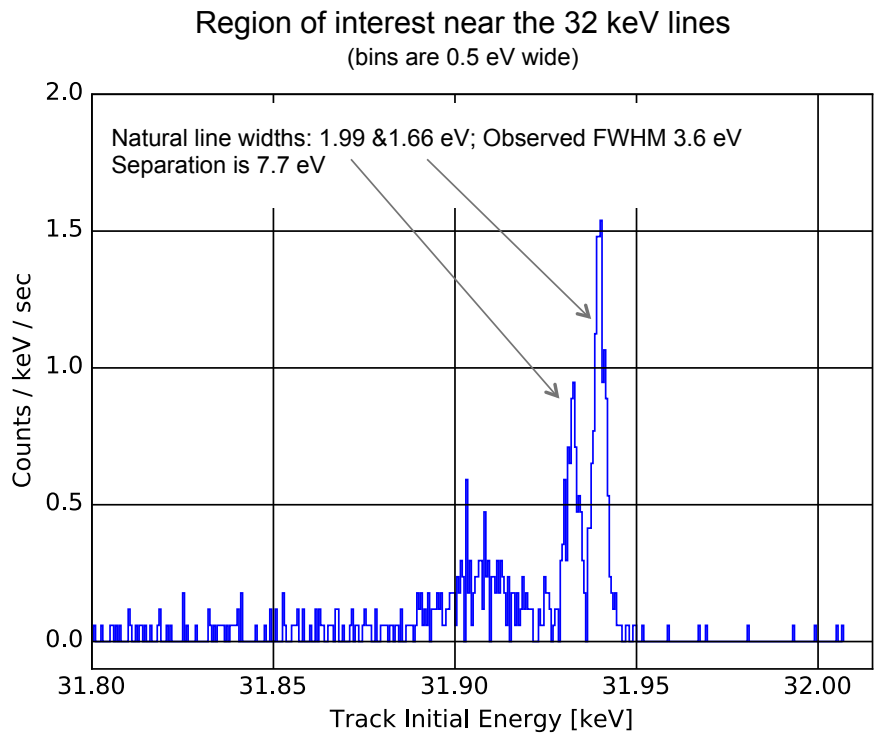
“Bathtub” Trap



- Improved field homogeneity
- Larger trapping volume

Energy Spectrum

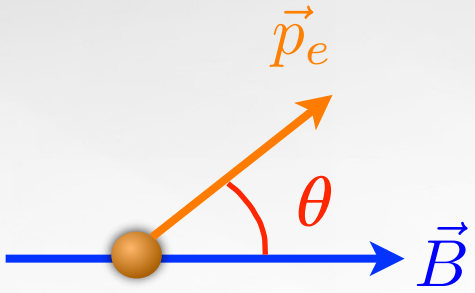




J.Phys. G 44 (2017) 5

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

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

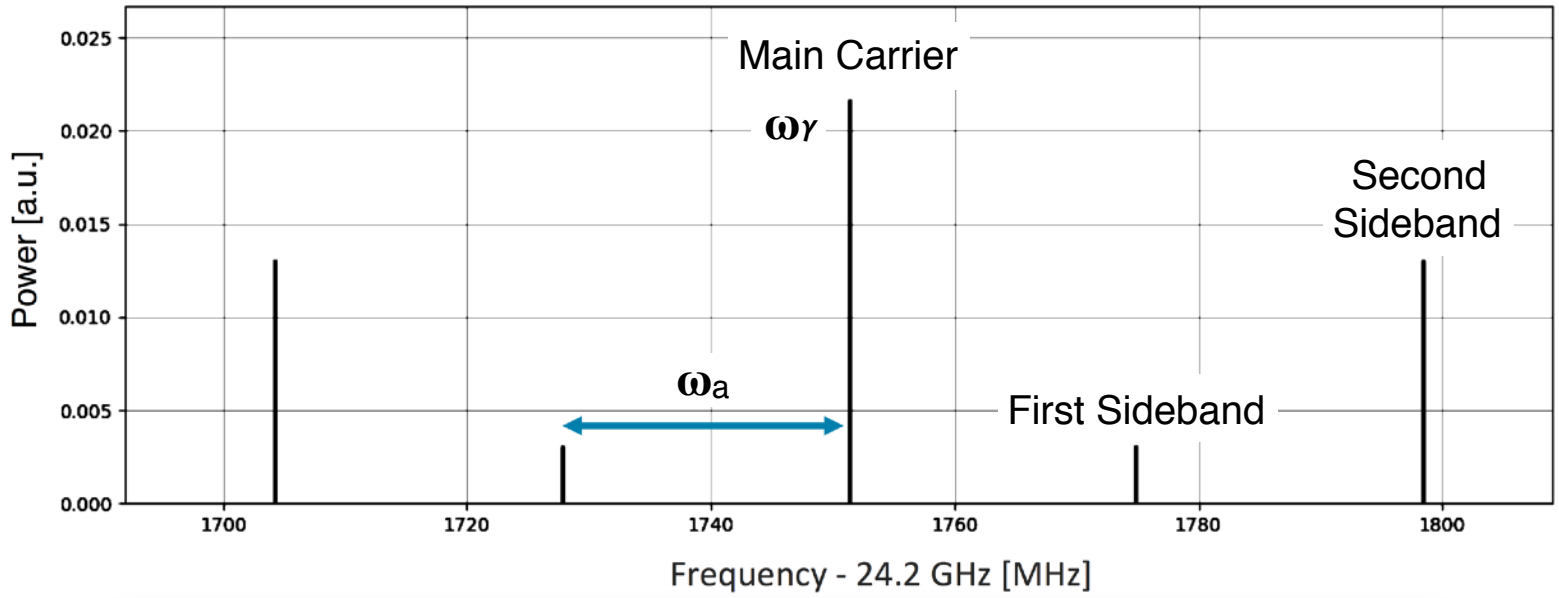
Disentangling Energy and θ

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

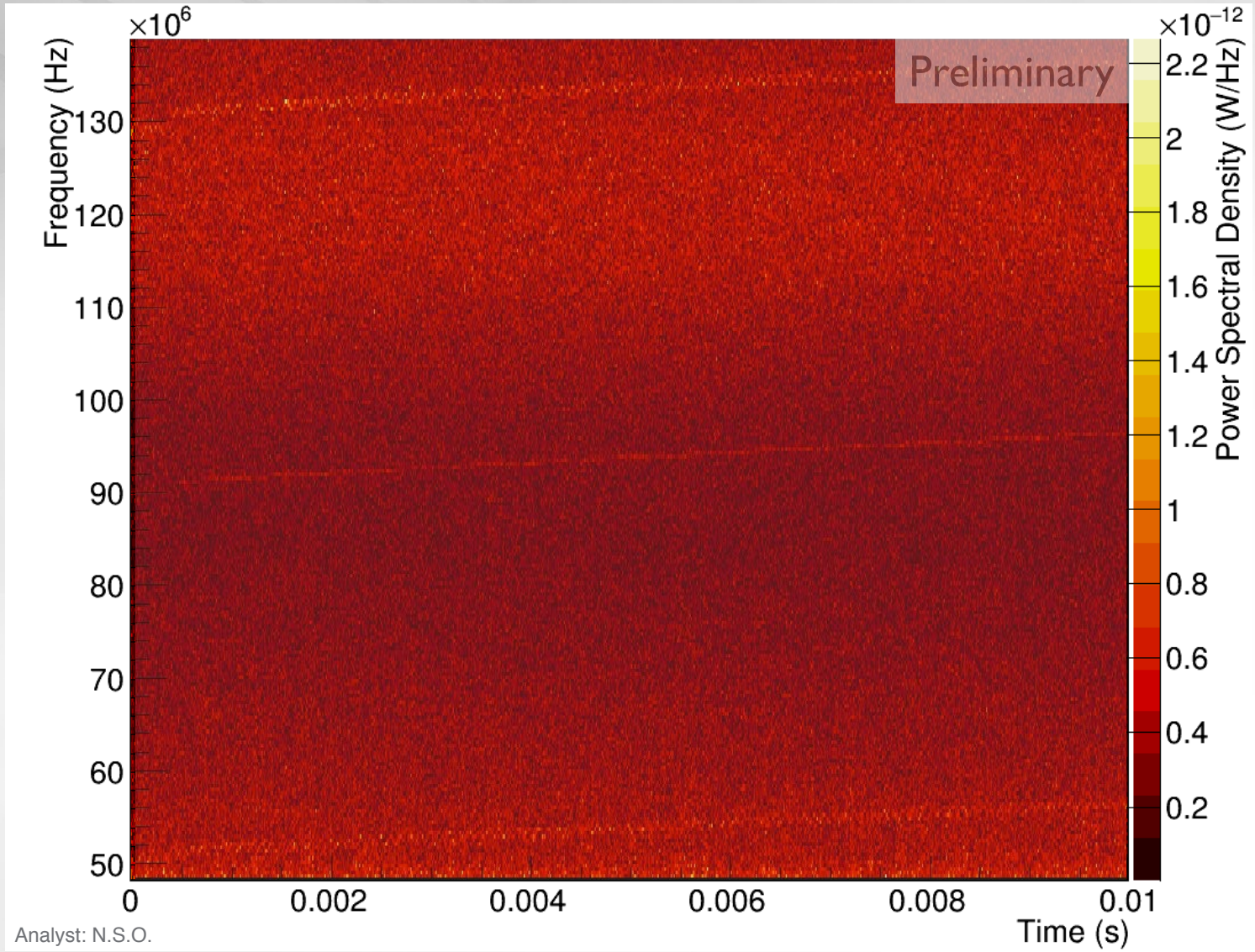
Use the axial frequency: modulation of the cyclotron radiation signal

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

For an approximation of a bathtub trap

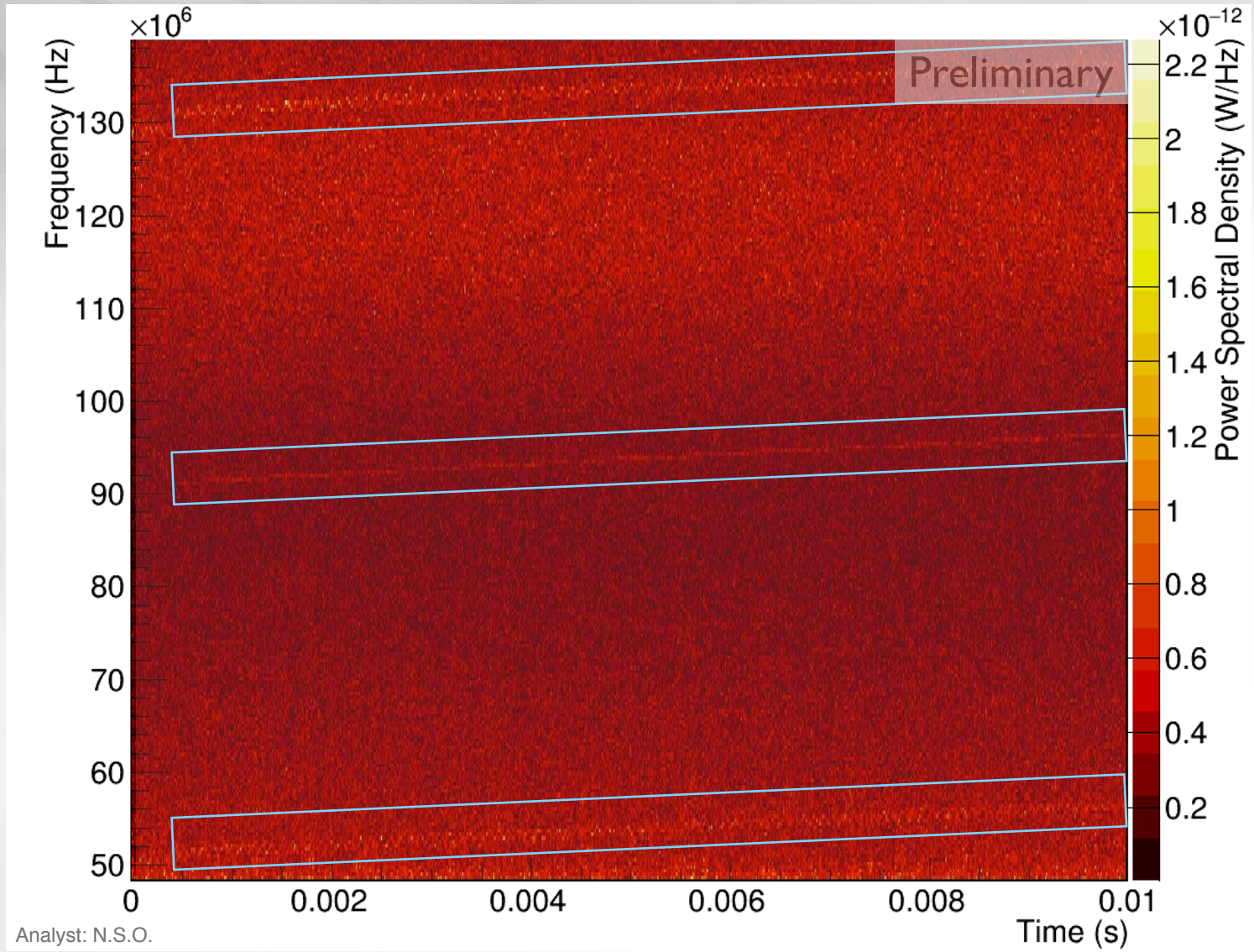


Sidebands Observed



Analyst: N.S.O.

Sidebands Observed



Analyst: N.S.O.

Sideband Oscillations

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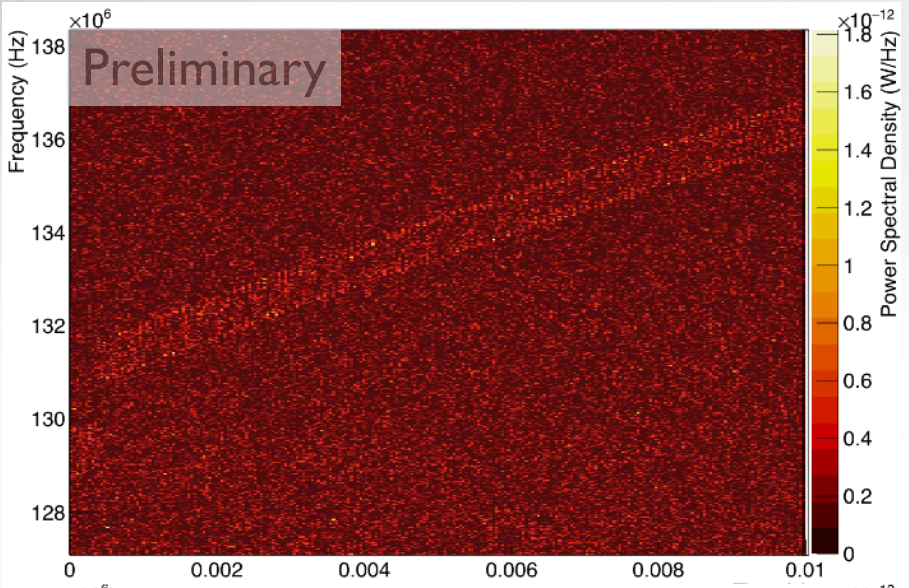
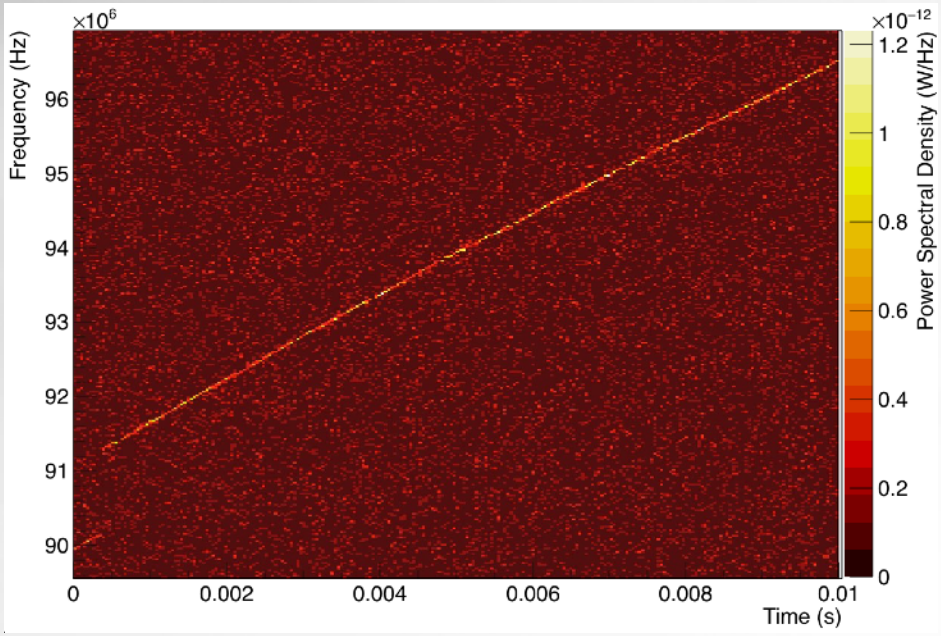
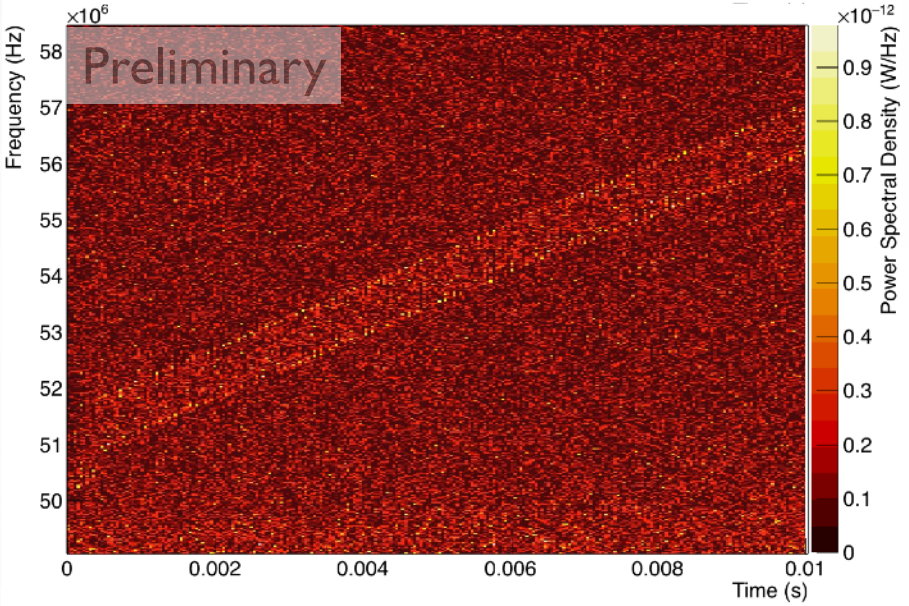
Upper Sideband



Central peak



Analyst: N.S.O.



Lower Sideband

Phenomenology

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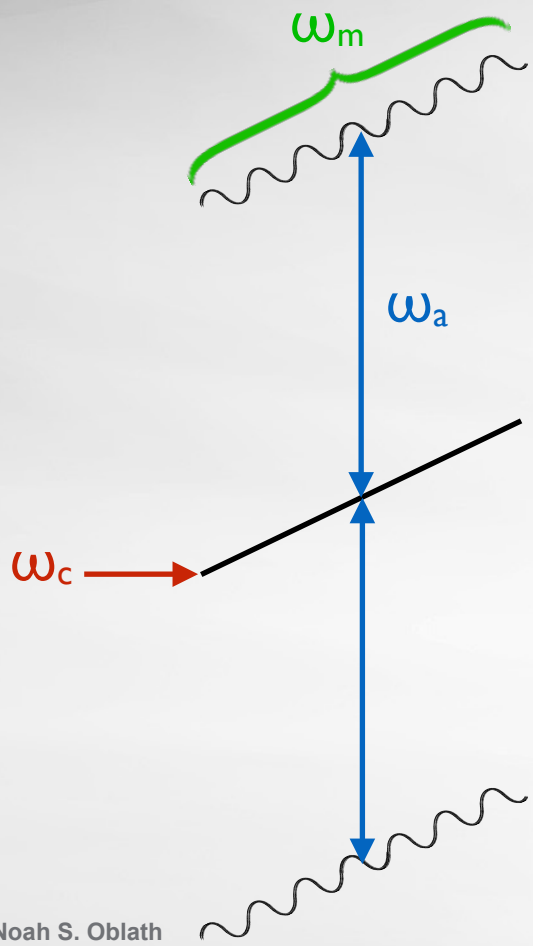
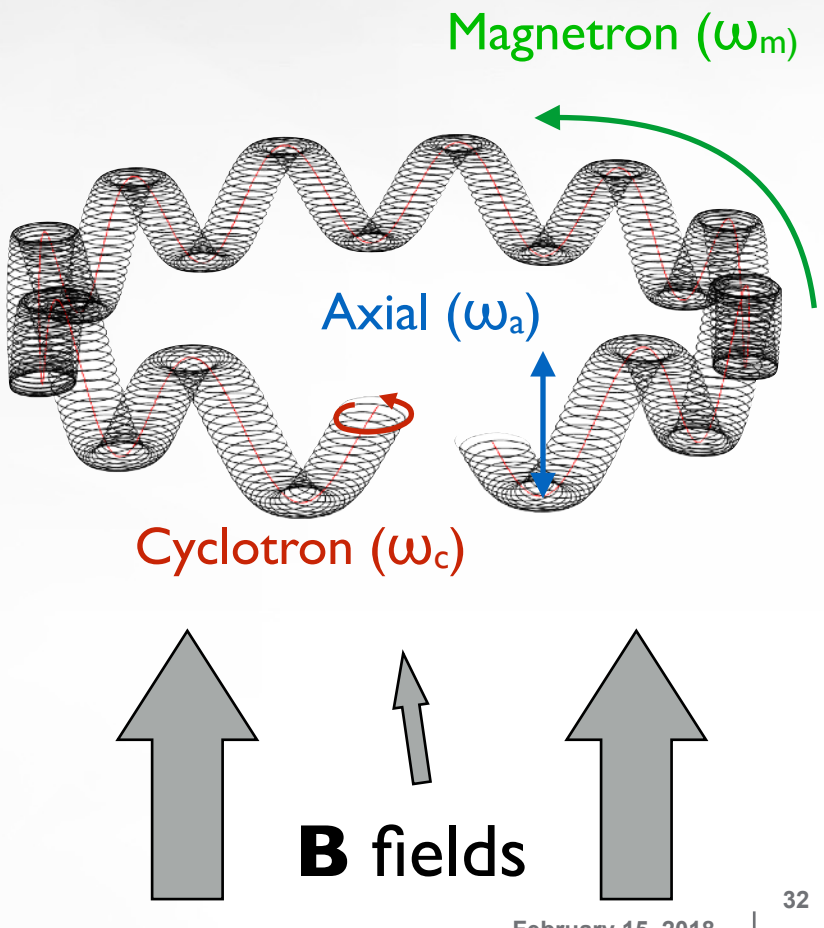
Data

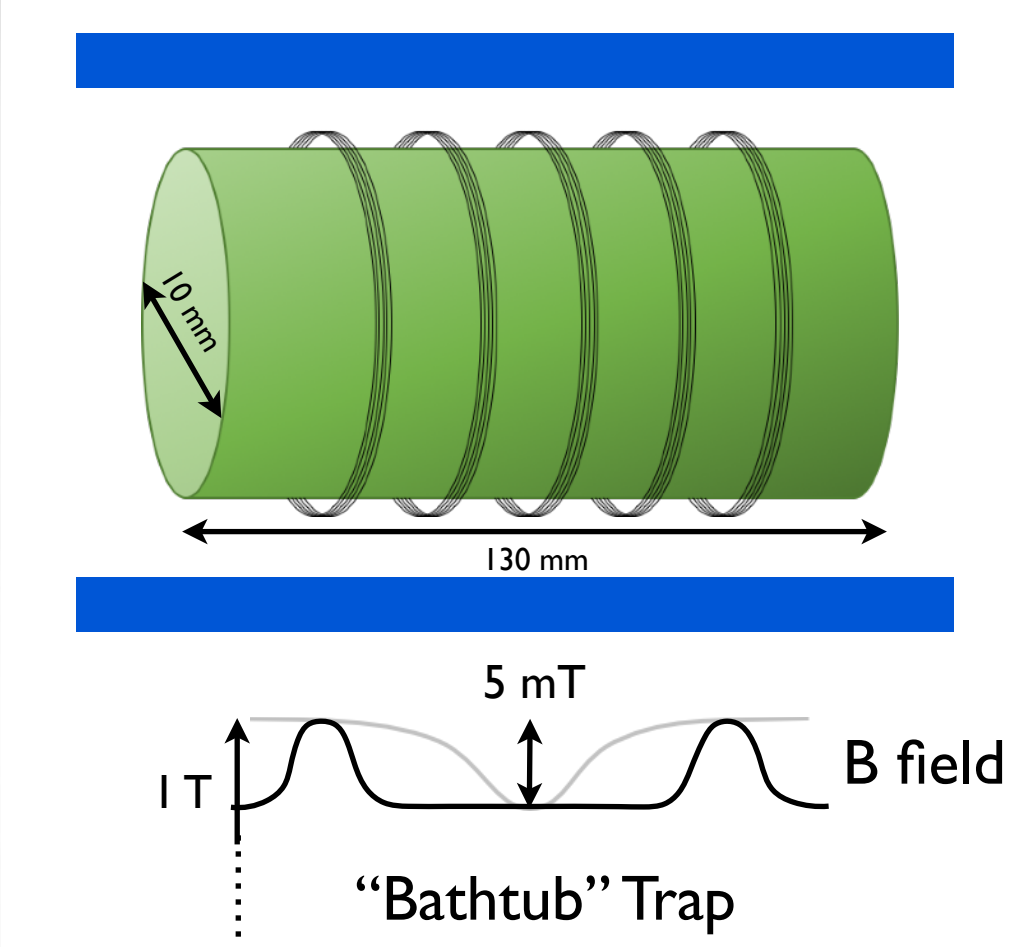


Hypothesis & Simulations

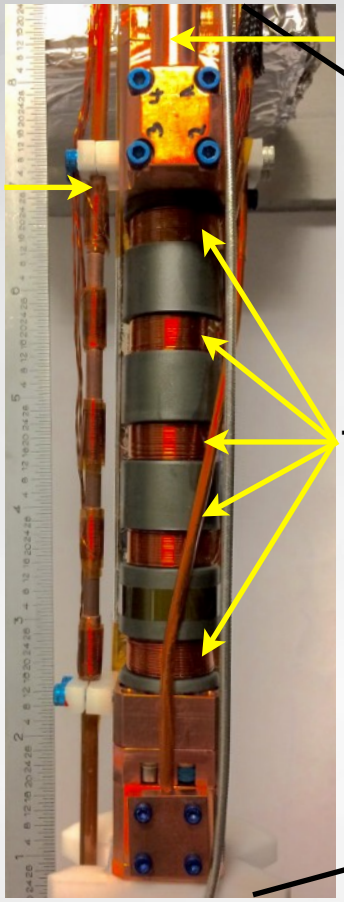


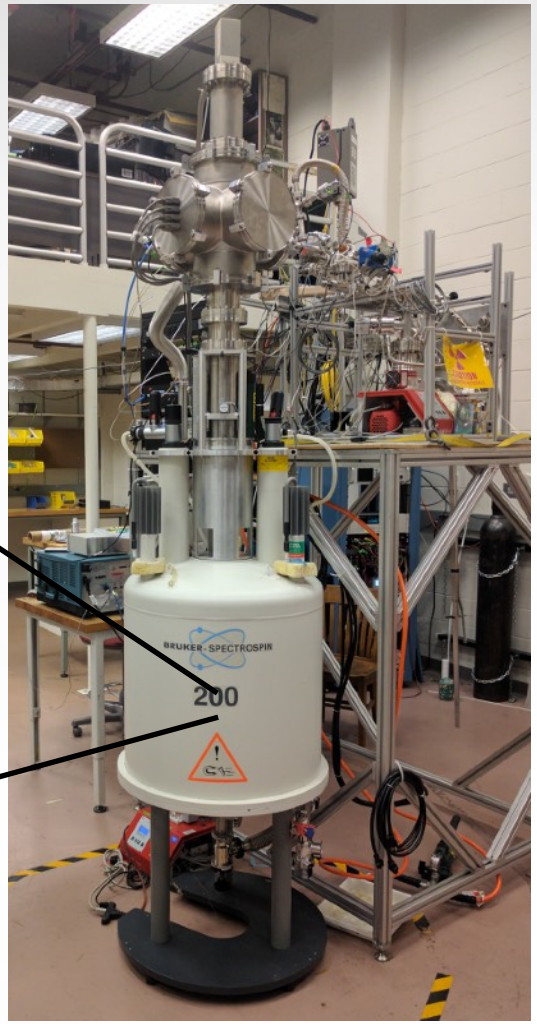
Phase 2: Tritium Demonstrator

- 1-cm circular waveguide to contain the gas and detect the cyclotron radiation
- Filled with ^{83m}Kr gas
- 1 T background magnetic field & a wider 5-mT magnetic trap
- Waveguide leads to cryogenic amplifiers



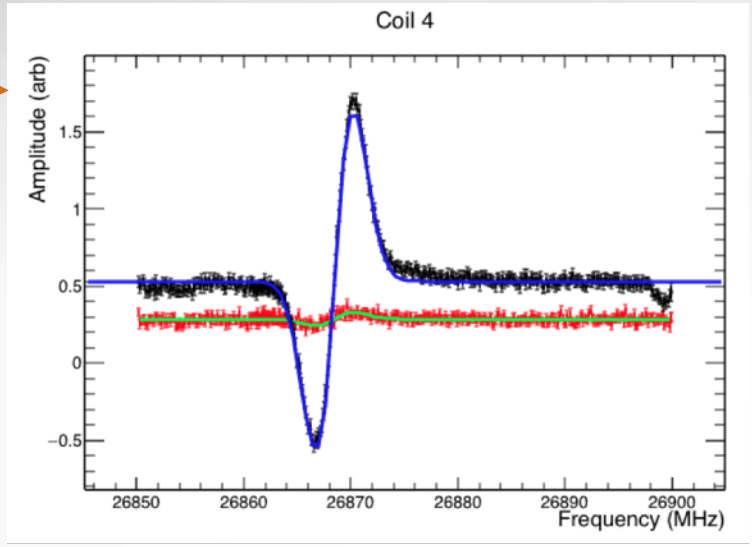
$^{83m}Kr/T_2$ Gas Cell



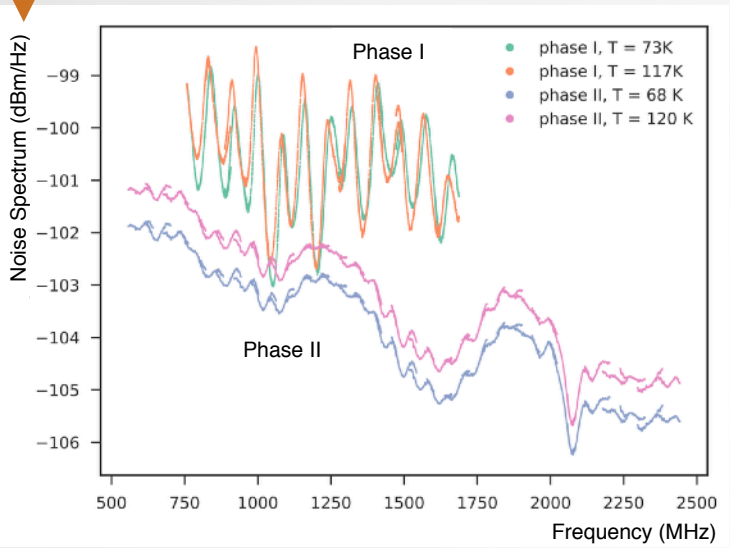


Phase II: Other Improvements

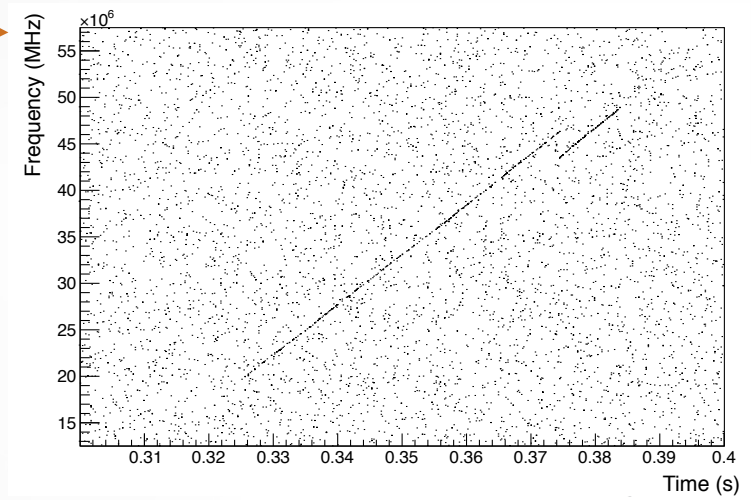
- Electron Spin Resonance (ESR) measurement at each trap coil location
- ROACH digitizer — streaming & triggered operation
- Cryogenic isolator for improved SNR



Analyst: W.C. Pettus



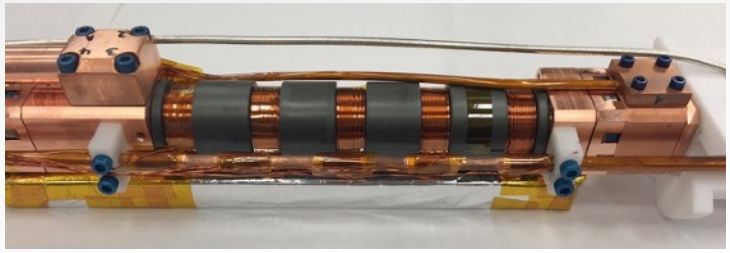
Analyst: R. Cervantes

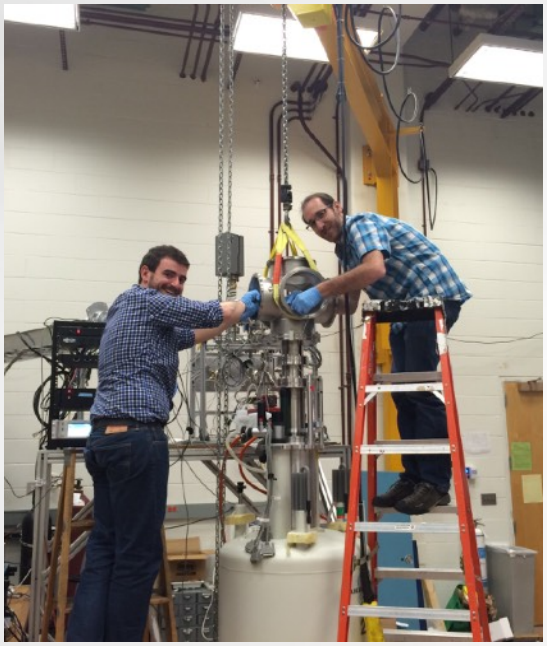


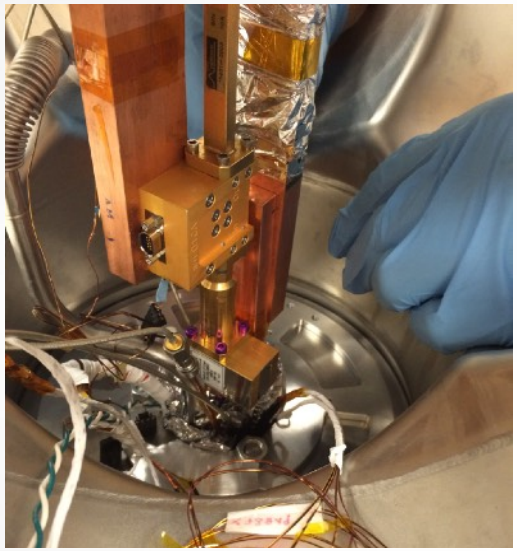
Analyst: C. Claessens

Current Status

- Commissioning activities in preparation for using T_2 gas
  - T_2/^{83m}Kr source system
  - ROACH data acquisition system

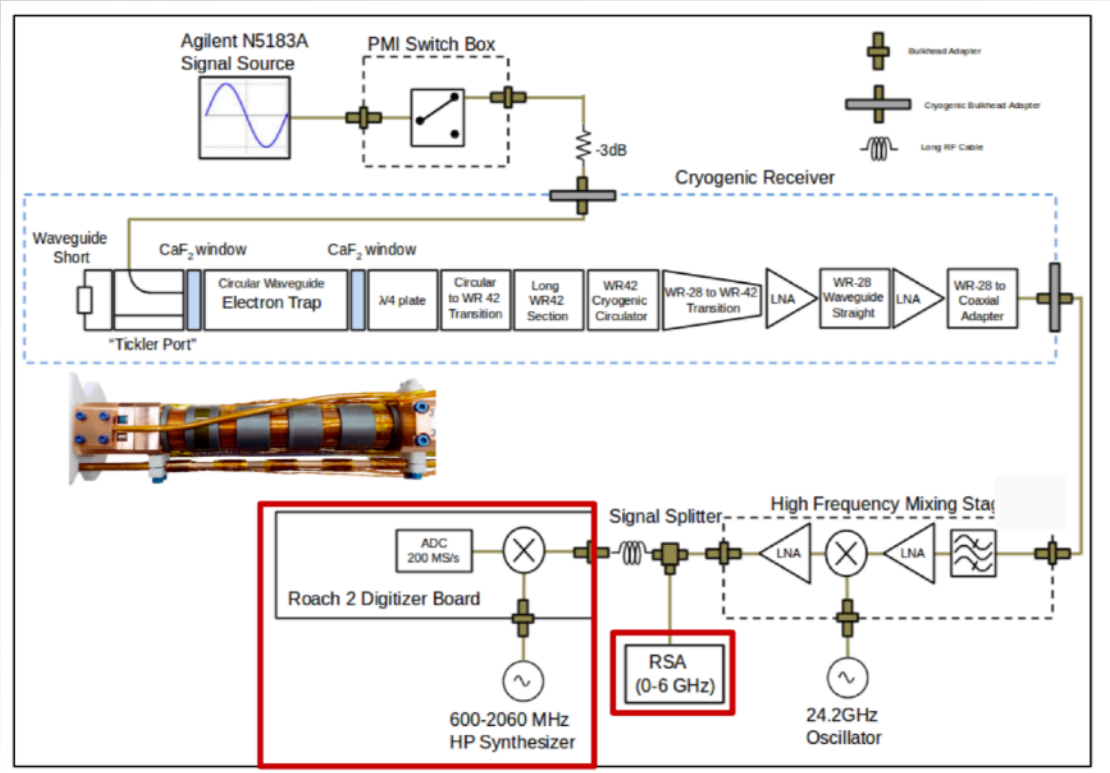




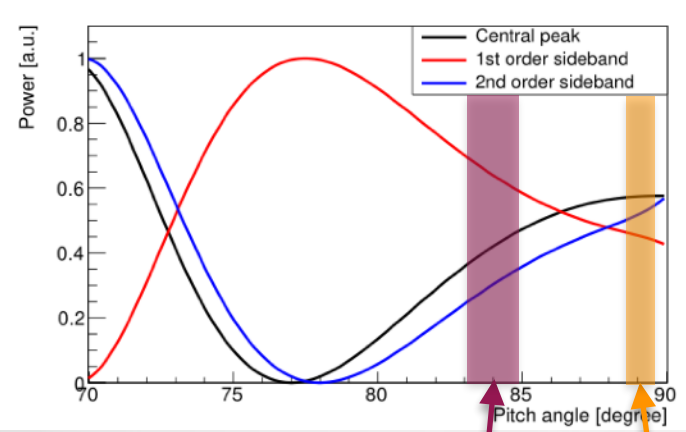


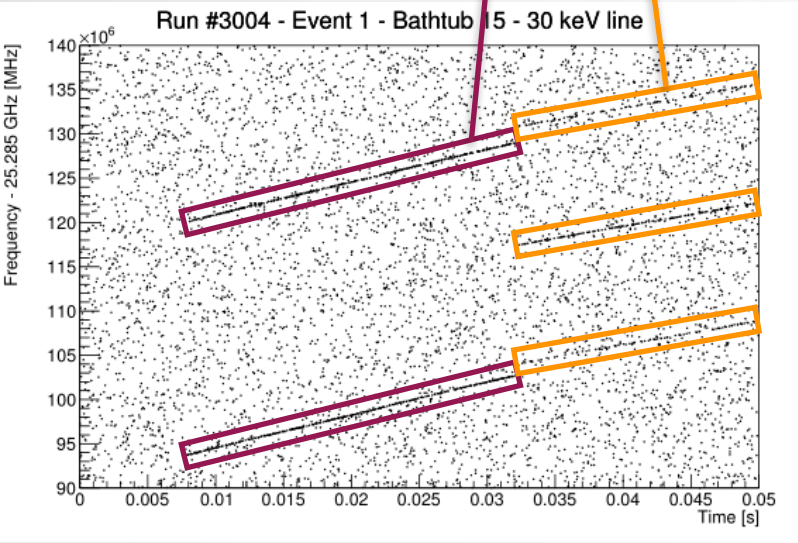
New Data Acquisition System

- Cryogenic amplifiers
- Down-mixing by 24.2 GHz
- Real-time spectrum analyzer
  - Diagnostic tool
  - Triggered acquisition
  - Significant dead time
  - Fixed acquisition length
- ROACH2
  - Reconfigurable Open-Access Hardware platform
  - Developed by the CASPER collaboration for radio astronomy
  - Deadtime-less trigger under development

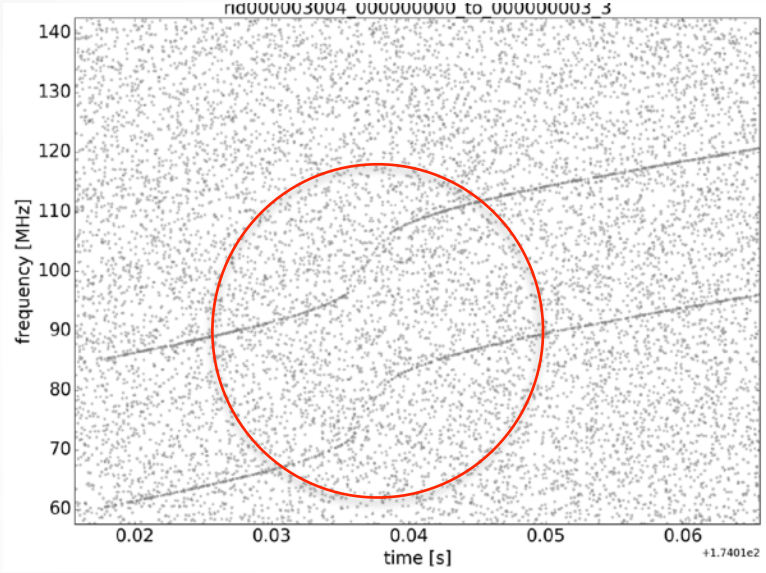


New Phenomenology





- A variety of sideband configurations are seen that depend on pitch angle
- Curved tracks are the result of coupling to the "invisible" TM_{01} mode
- Tracks are no longer always head-to-tail



Track Reconstruction

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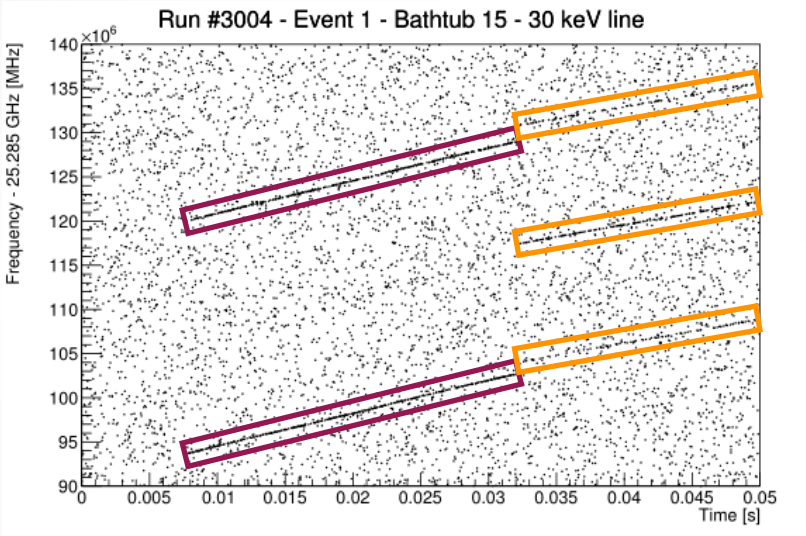
- Previous approach used spectrogram density to identify clusters

FFT & Remove low-power bins → Filter noise points → Identify clusters based on point density → Remove short and low-power tracks

- Works well for short, powerful tracks
- Has proven unreliable for long tracks with fluctuating power

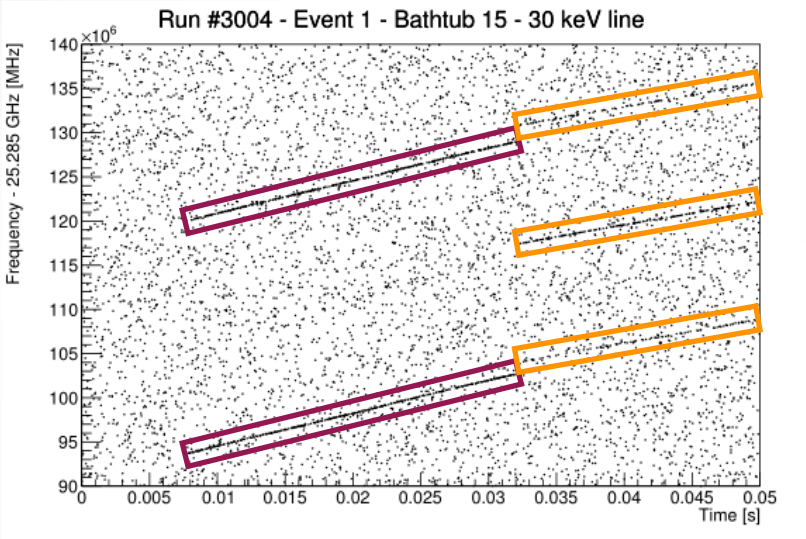


Track Reconstruction

- Linearity-based approach based on D. Furse (2015), “Techniques for Direct Neutrino Mass Measurement Utilizing Tritium β-Decay”

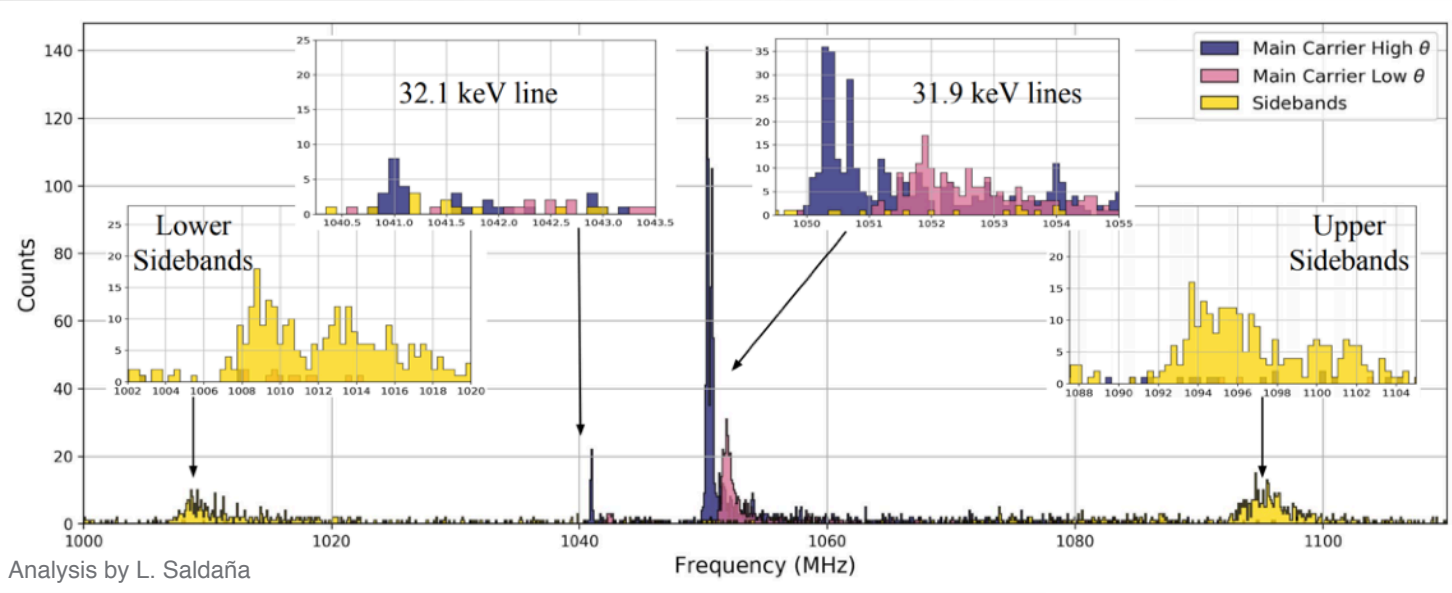
FFT & Remove low-power bins → Find neighboring points → Find linearly-aligned points with max time separation → Remove short and low-power tracks

- Works well for long, medium-power tracks
- Implemented as a sequential algorithm
- Could be used as a real-time trigger



Track Classification

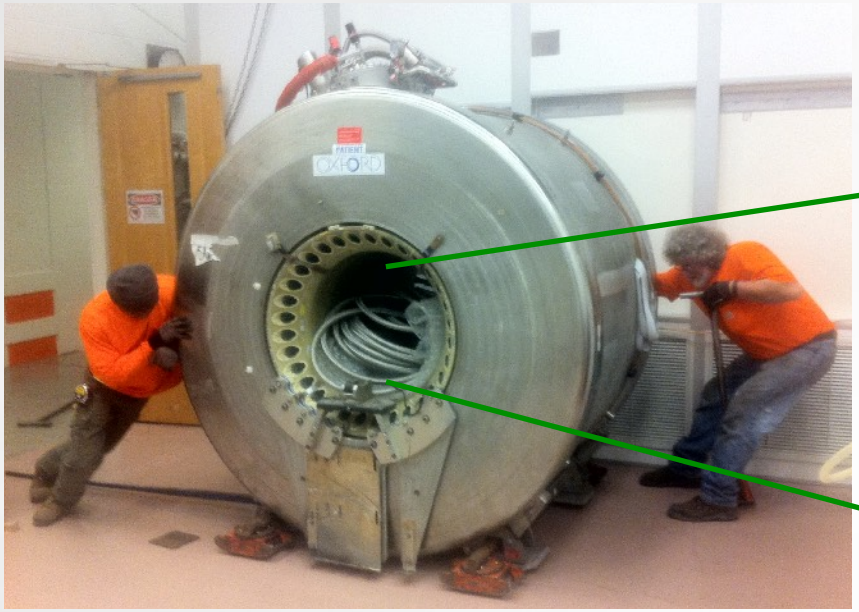
- Peak structure is complicated by parallel tracks
- Goal: classify individual tracks based on track properties
- Development of machine-learning techniques is underway
- Classifiers trained based on hand-scanned data; simulations are under development for better training
- Preliminary results are promising

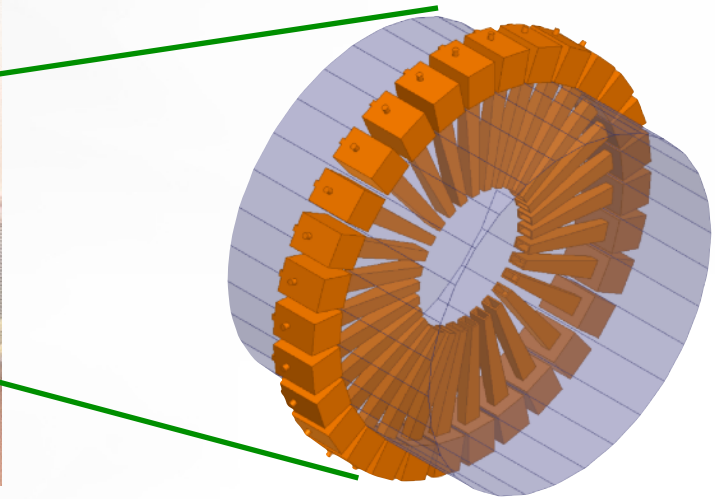


Analysis by L. Saldaña

Phase III: Scaling Up

- Scaling up the volume: 200 cm^3 volume inside an MRI magnet
- Free-space radiation detected by a ring array of antennas
- Digital beam-forming used to spatially locate electrons within the fiducial volume

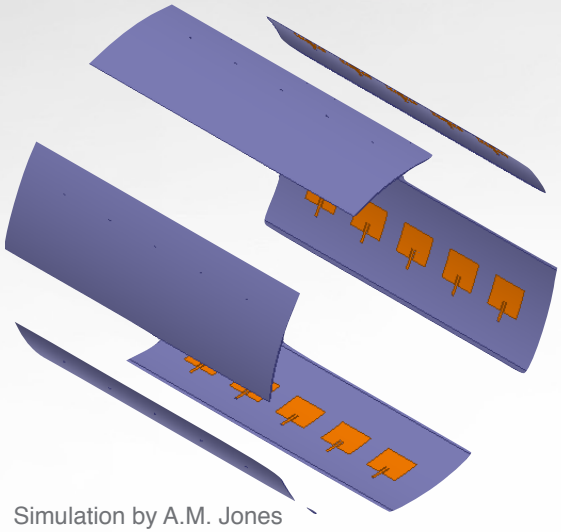




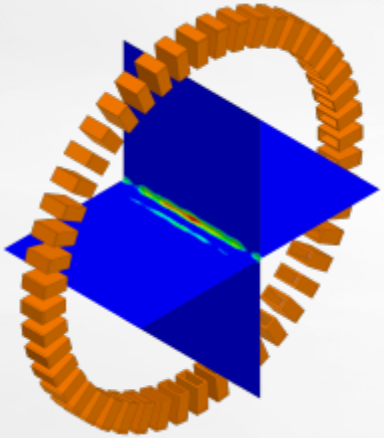
Simulation by A.M. Jones

Phase III Antenna Concepts

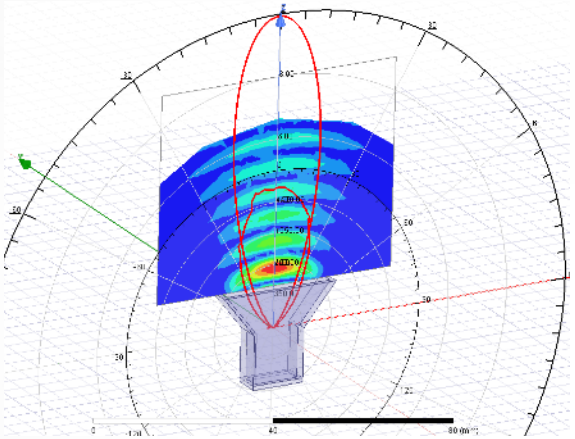
- Multiple array concepts are under investigation
  - Open-ended waveguides (bottom left)
  - Waveguides with horns (bottom right)
  - Patch antennas (right)
- Need to minimize Doppler sidebands by using a narrow axial focus



Simulation by A.M. Jones



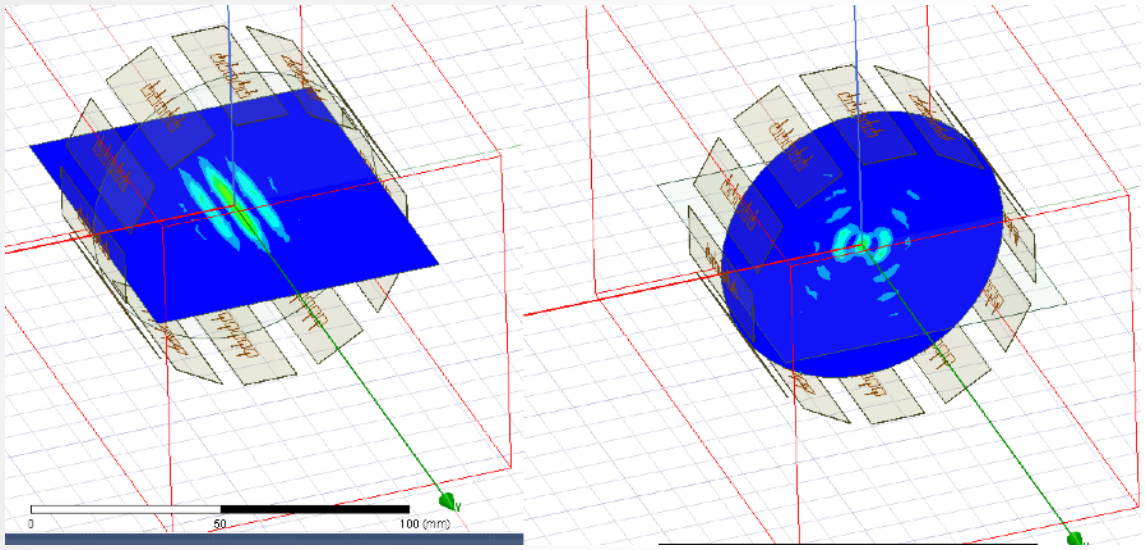
Simulation by A.M. Jones



Simulation by T. Wendler

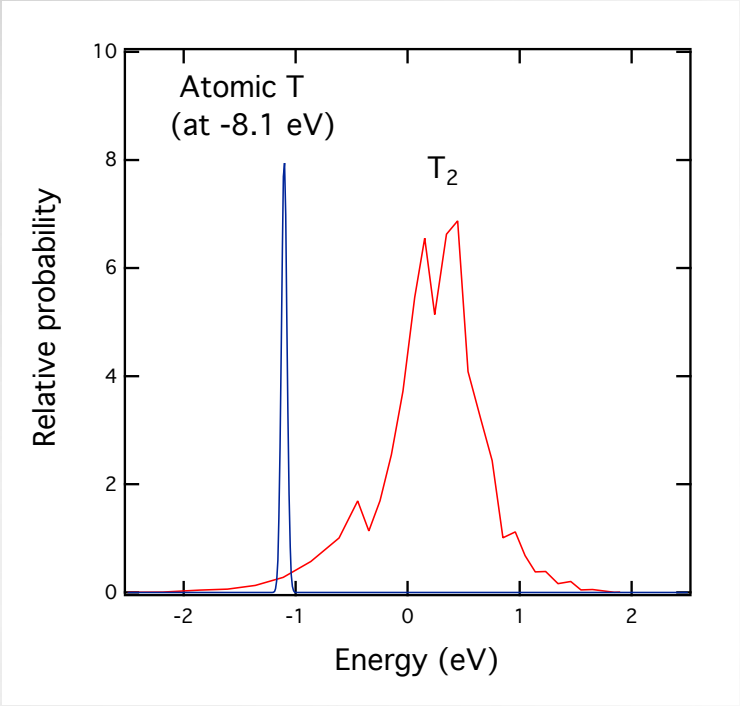
Digital Beam-Forming

- Passively combine axial strips of antennas
- Signal is present in all strips at all times; increase SNR by combining signals with the appropriate phase delays
- Sensitive region can be moved around by changing the phase delays
- Challenge: realtime beam-forming and triggering
- Reduces data volume from ≈30 channels to 1 channel per electron



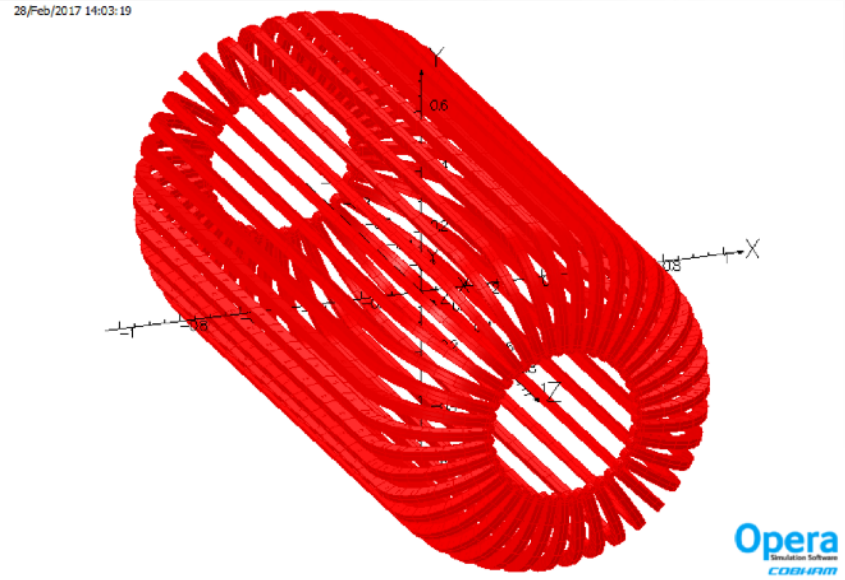
Phase IV: Atomic Tritium Experiment

- Use atomic tritium to avoid wide final-state energy distribution



T2 distribution from Saenz et al., Phys. Rev. Left. 84, 242 (2000)
T distribution calculated by R.G.H. Robertson

- Large volume: ~100 m^3
- Ioffe coils to trap atomic T



Coil design by A. Radovinsky

Atomic Tritium System

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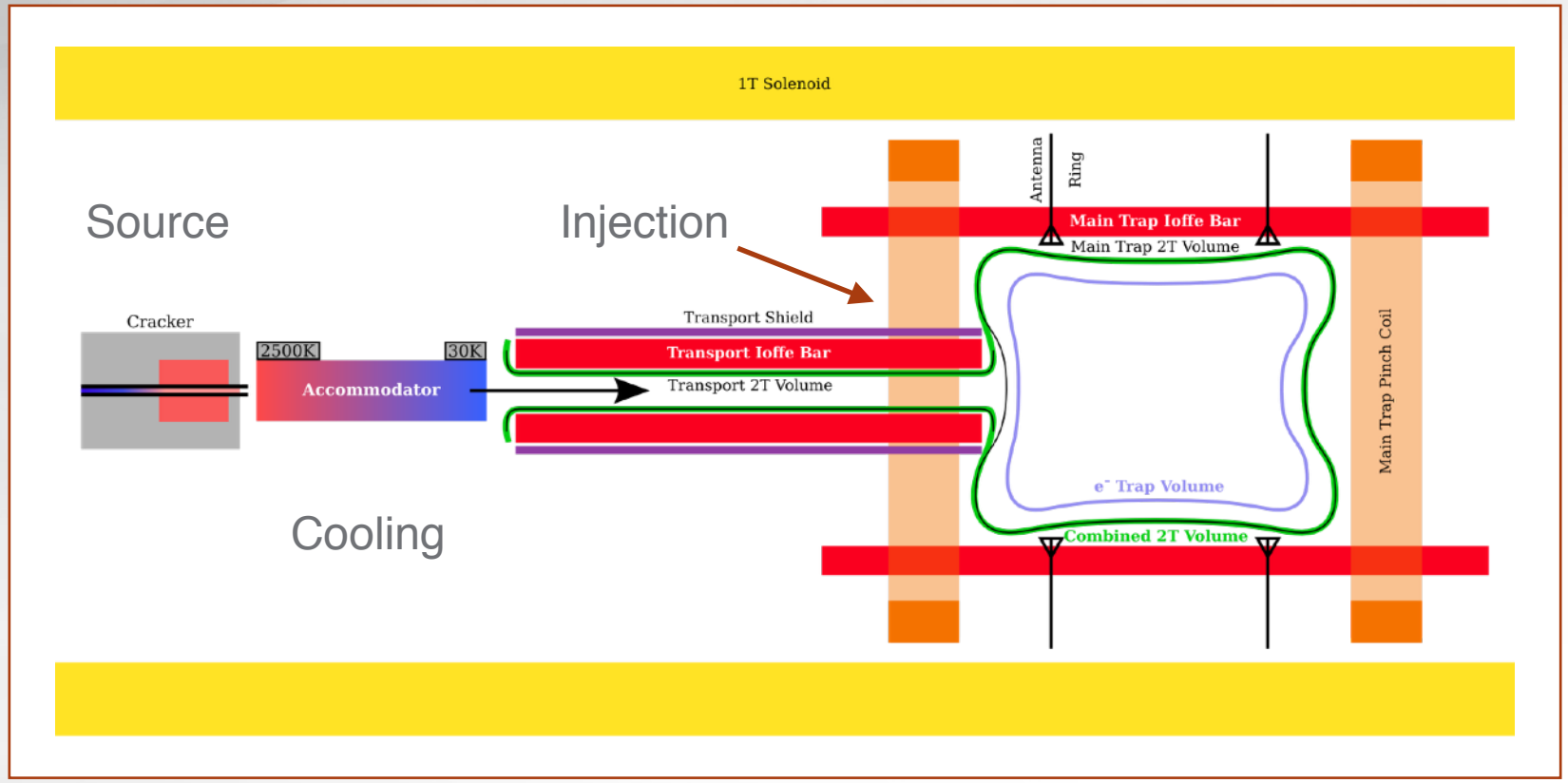
Primary Components



Summary

- Goal: use a novel technique to be more sensitive to the neutrino mass
- New technique: Cyclotron Radiation Emission Spectroscopy (CRES)
- Phase I complete: first direct measurement of single-electron cyclotron radiation made in June, 2014
- Phase II underway: currently commissioning to run with T_2 gas
- Phase III will use T_2 to measure the neutrino mass down to ~2 eV
- Phase IV will use atomic tritium to reach ~40 meV

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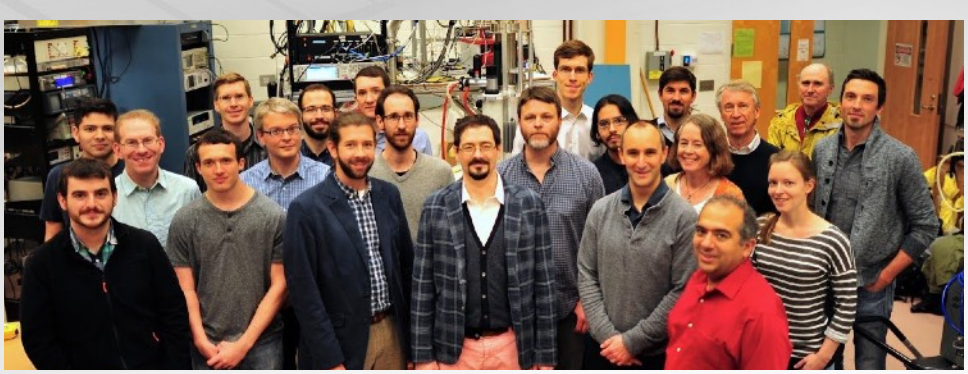
Project 8 Collaboration



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