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

Noah Oblath
for the Project 8 Collaboration

XVII International Workshop on Neutrino Telescopes
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U.S. DEPARTMENT OF ENERGY

Using Tritium β Decay

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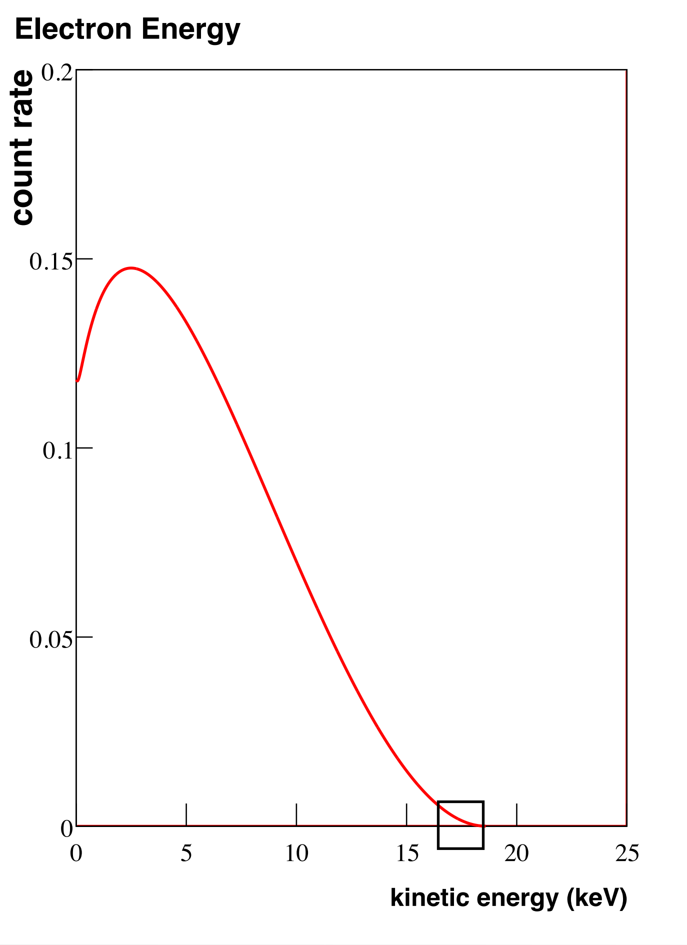
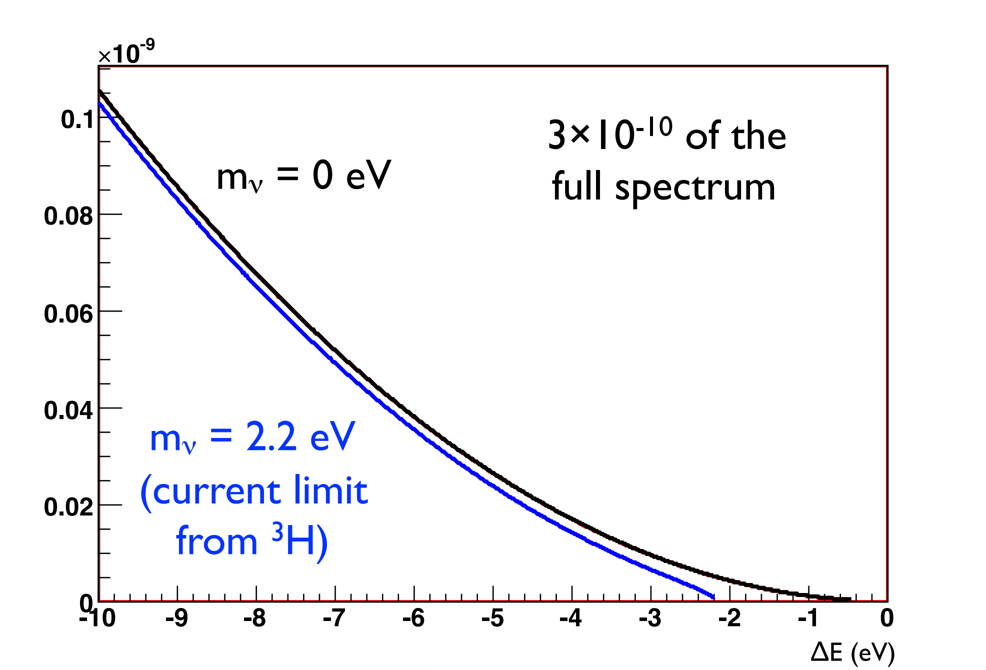


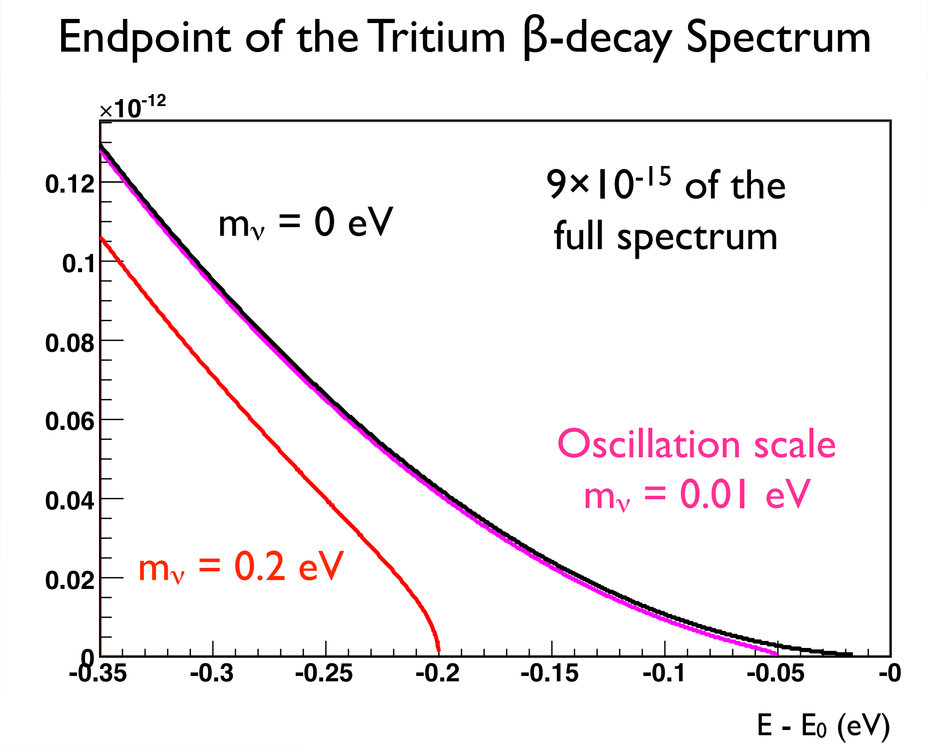
Zoom in on the endpoint . . .



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

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

Beyond KATRIN



Novel Technique: CRES

Cyclotron Radiation Emission Spectroscopy

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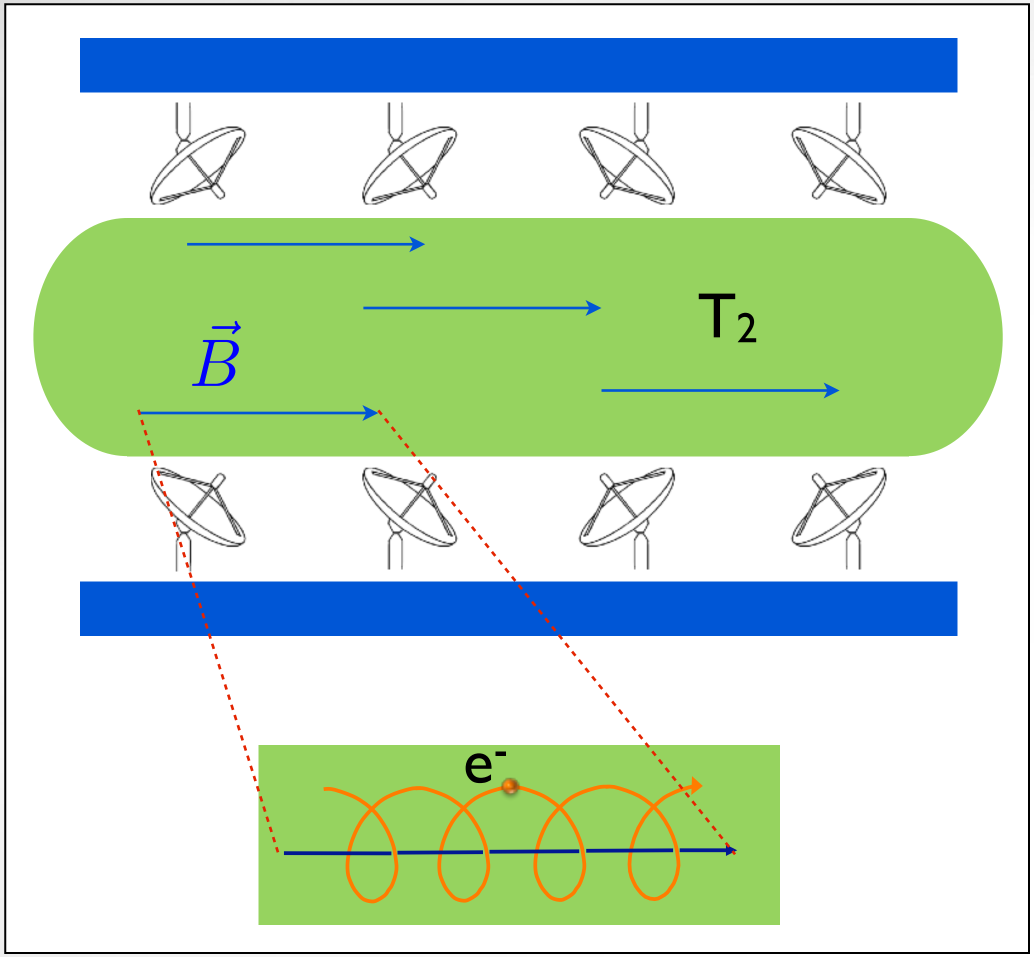
- Enclosed volume
- Fill with tritium gas
- Add a magnetic field

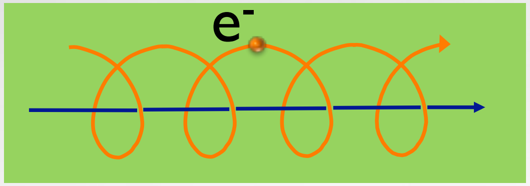


- Decay electrons spiral around field lines
- Add antennas to detect the cyclotron radiation

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

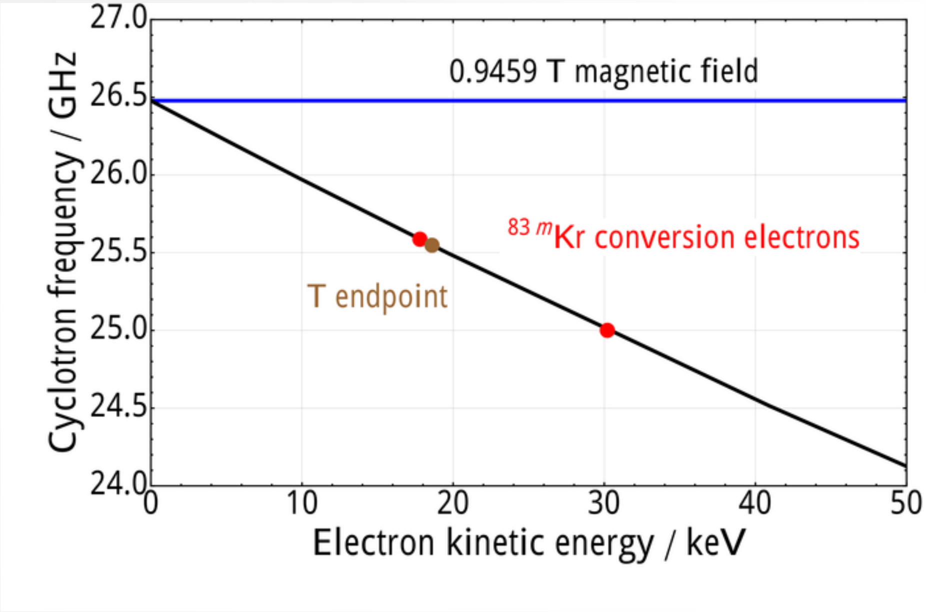
Cyclotron Radiation

- An electron traveling in a magnetic field emits cyclotron radiation



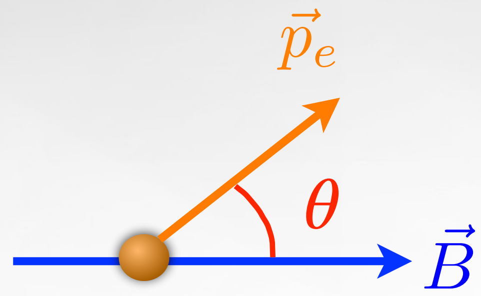
- The frequency of the emitted radiation depends on the relativistic boost

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



Pitch Angle

The angle between
the electron momentum
and the magnetic field



- Correction term for the cyclotron frequency

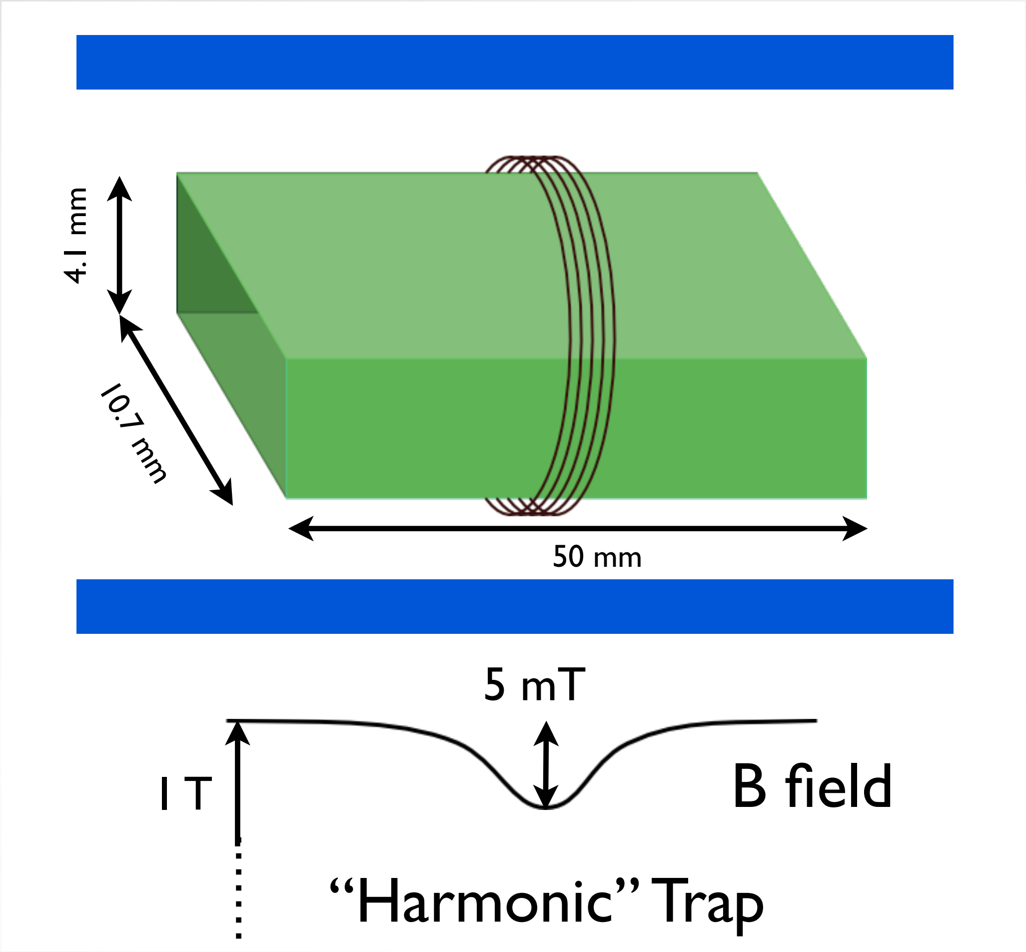
$$\omega_\gamma = \frac{\omega_0}{\gamma} = \frac{eB}{K + m_e}\left(1 + \frac{\cot^2\theta}{2}\right)$$

- Power emitted

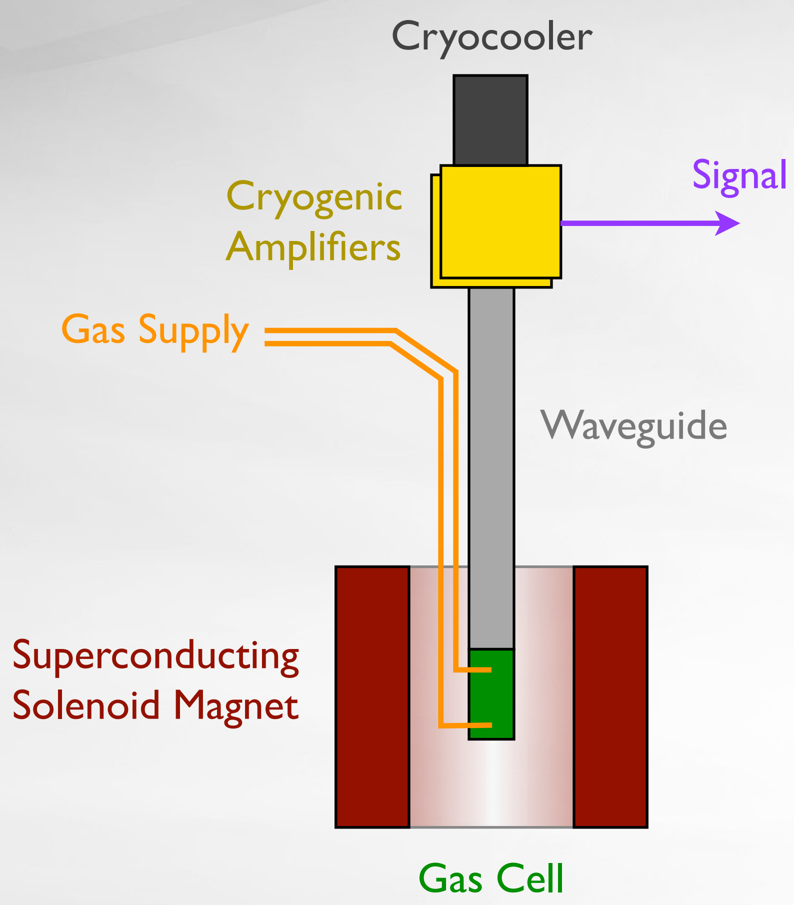
$$P_{\text{tot}} = \frac{1}{4\pi\epsilon_0}\frac{2q^2\omega_c^2}{3c}\frac{\beta^2\sin^2\theta}{1-\beta^2}$$

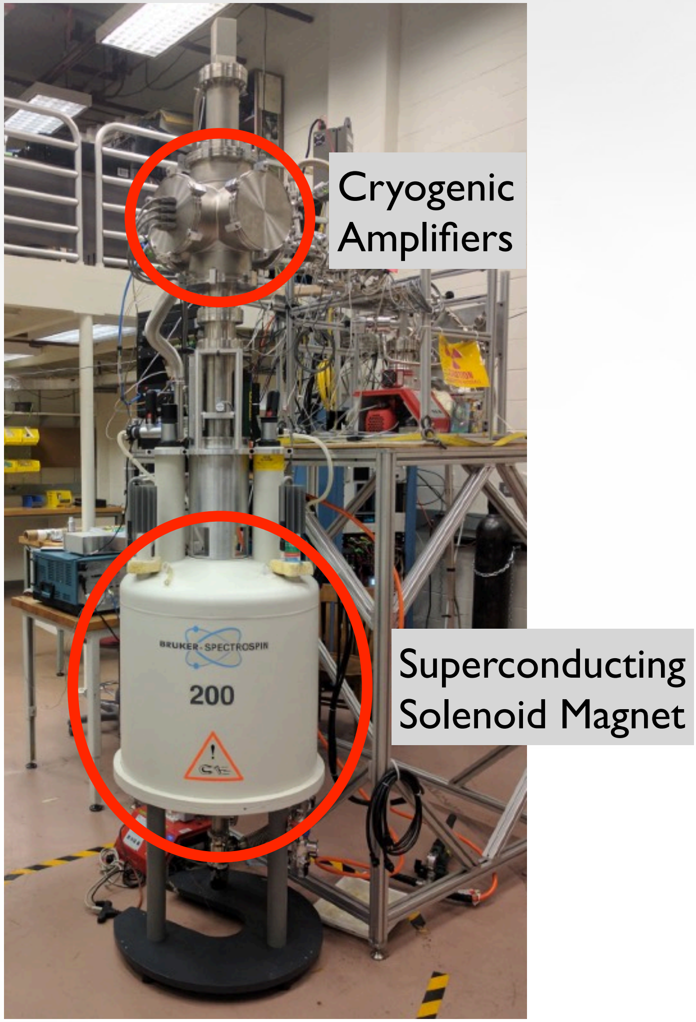
Phase I: Proof of Principle

- 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

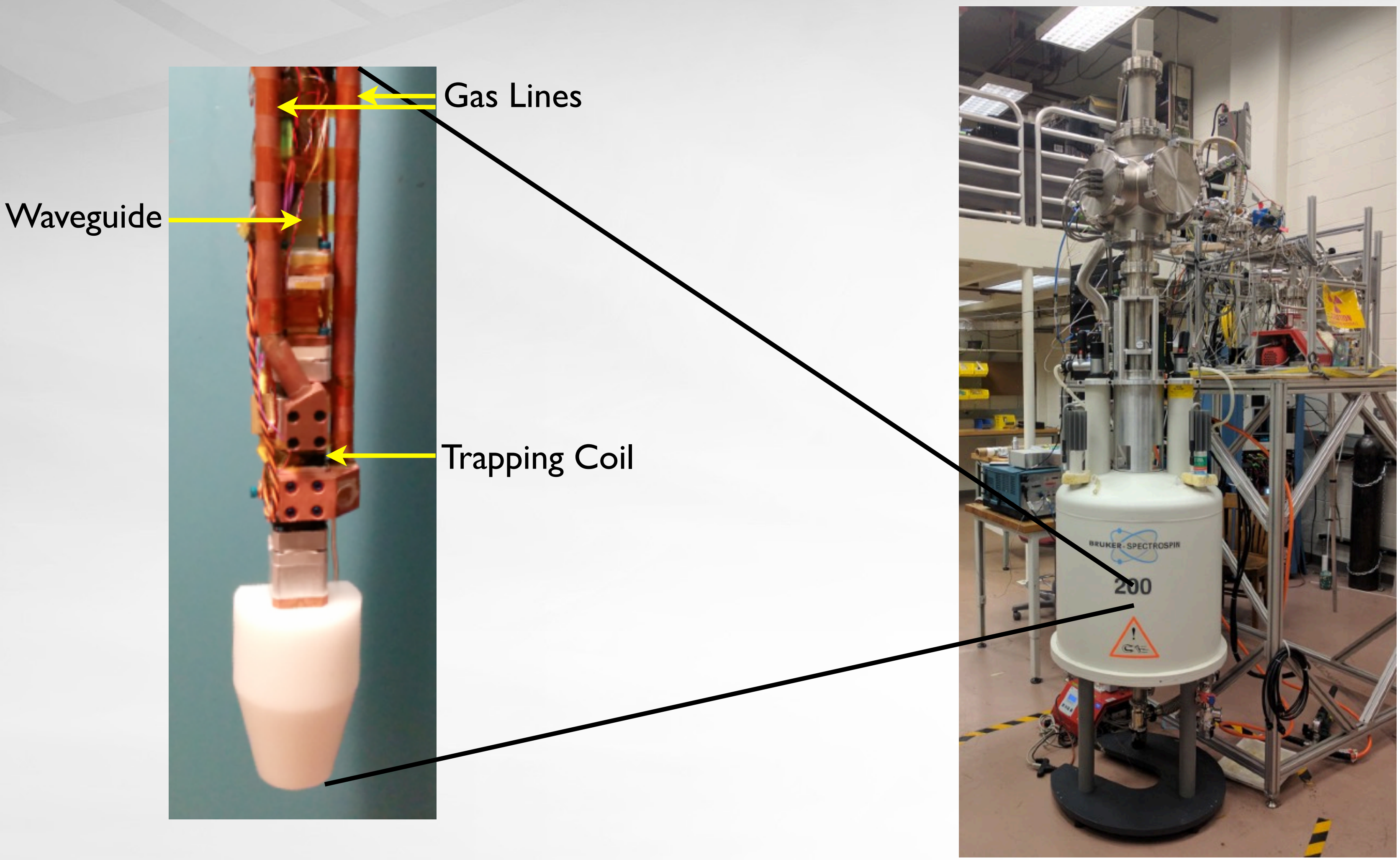


Phase I Apparatus

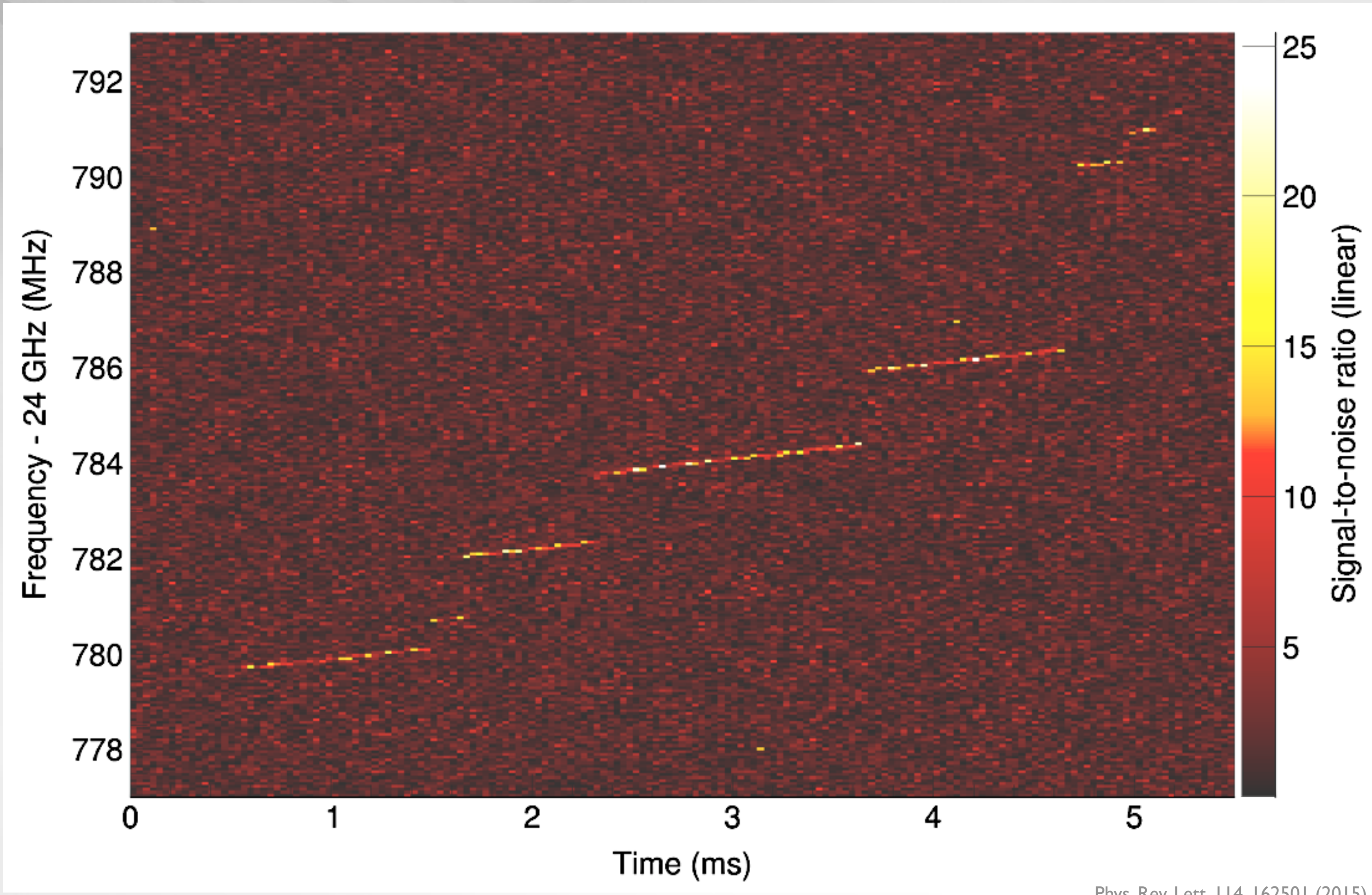




^{83m}Kr Gas Cell

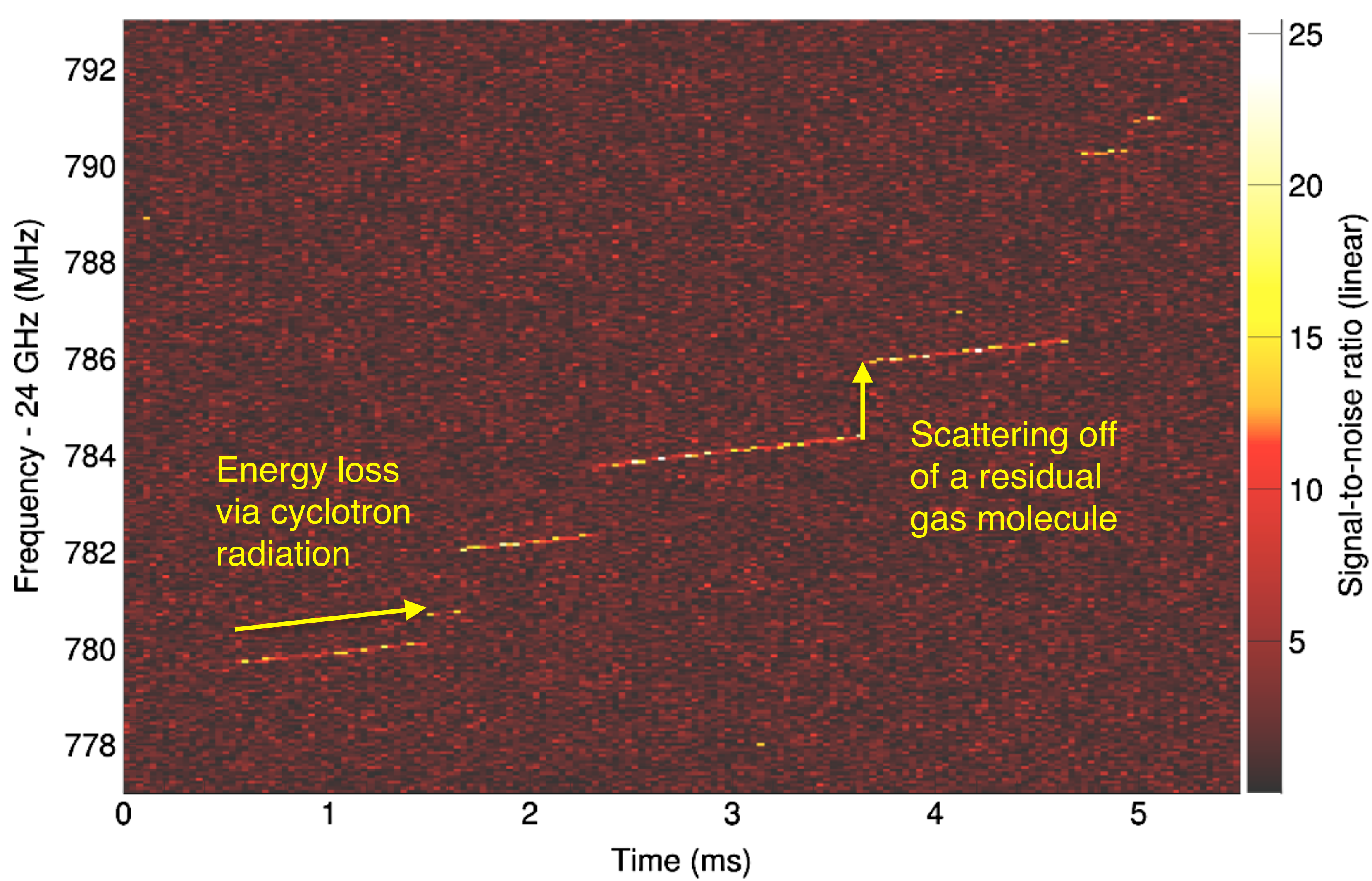


First Observation



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

First Observation



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

Energy Spectrum

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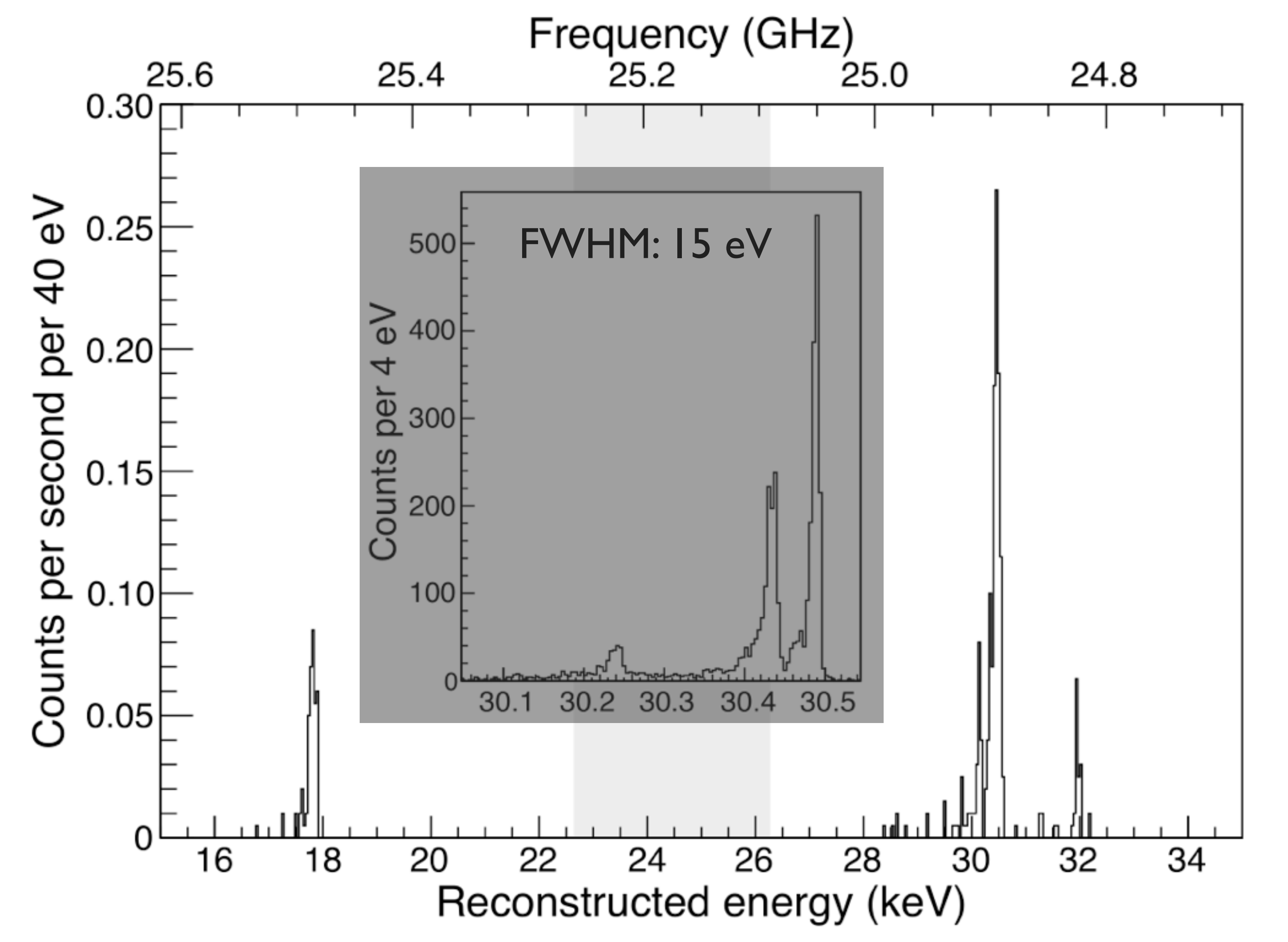
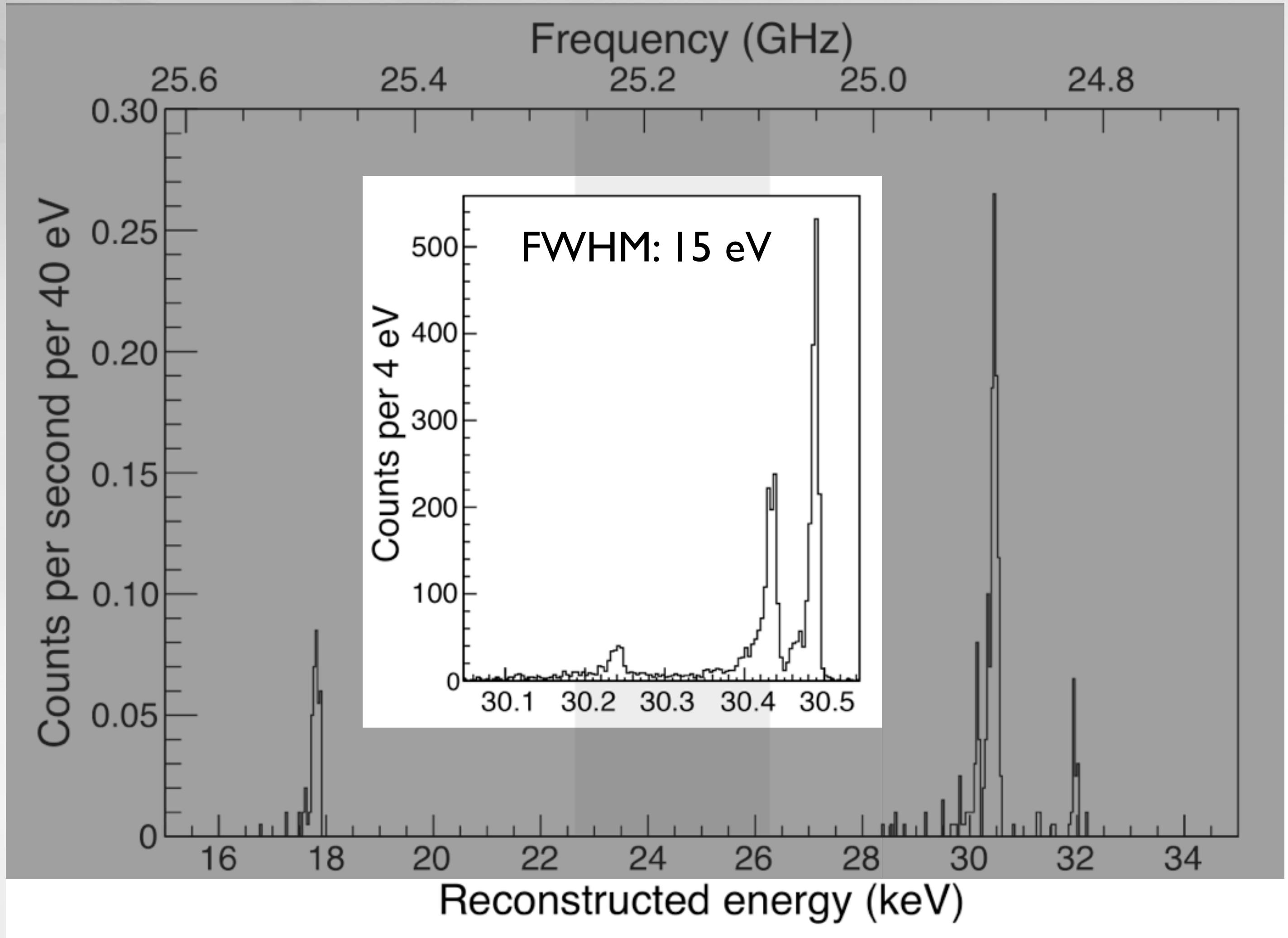


Trap current 800 mA

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

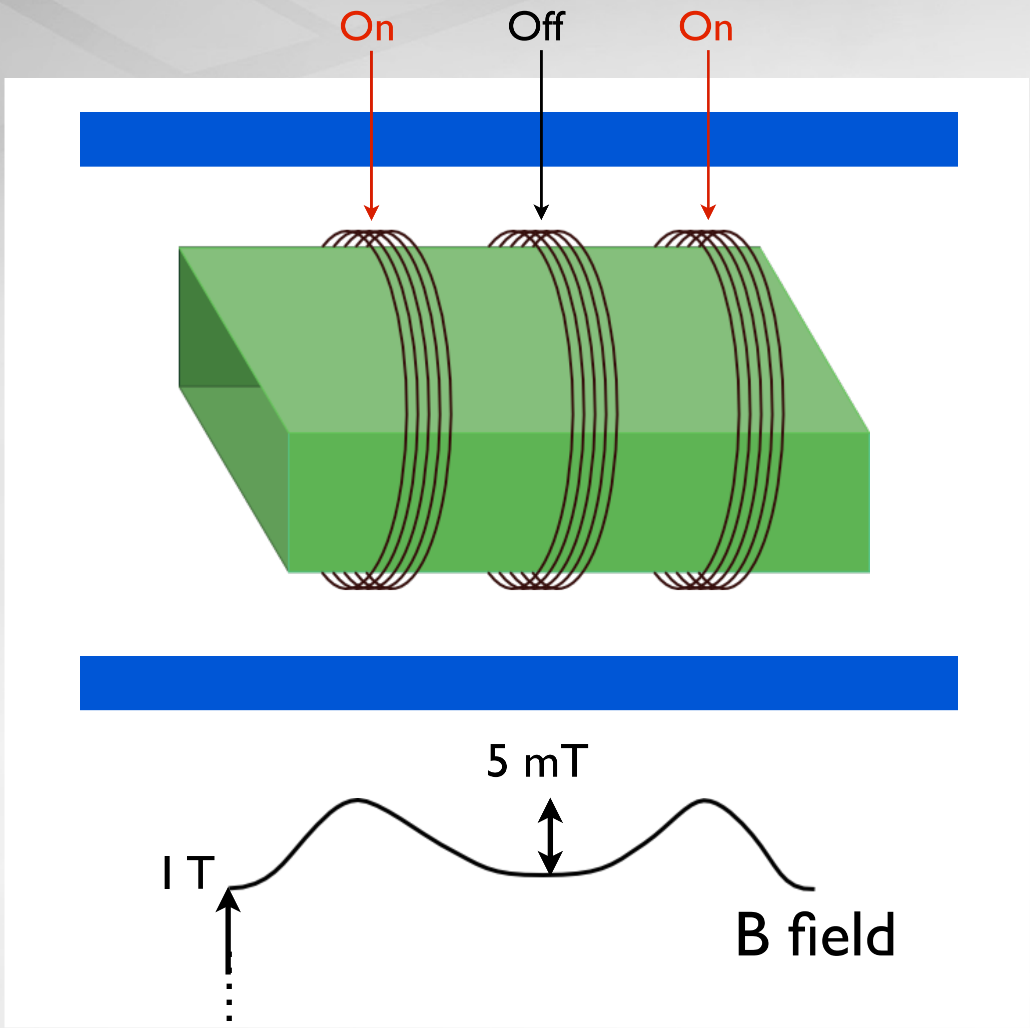
Energy Spectrum



Trap current 400 mA

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

"Bathtub" Trap



- Improved field homogeneity
- Larger trapping volume

Energy Spectrum

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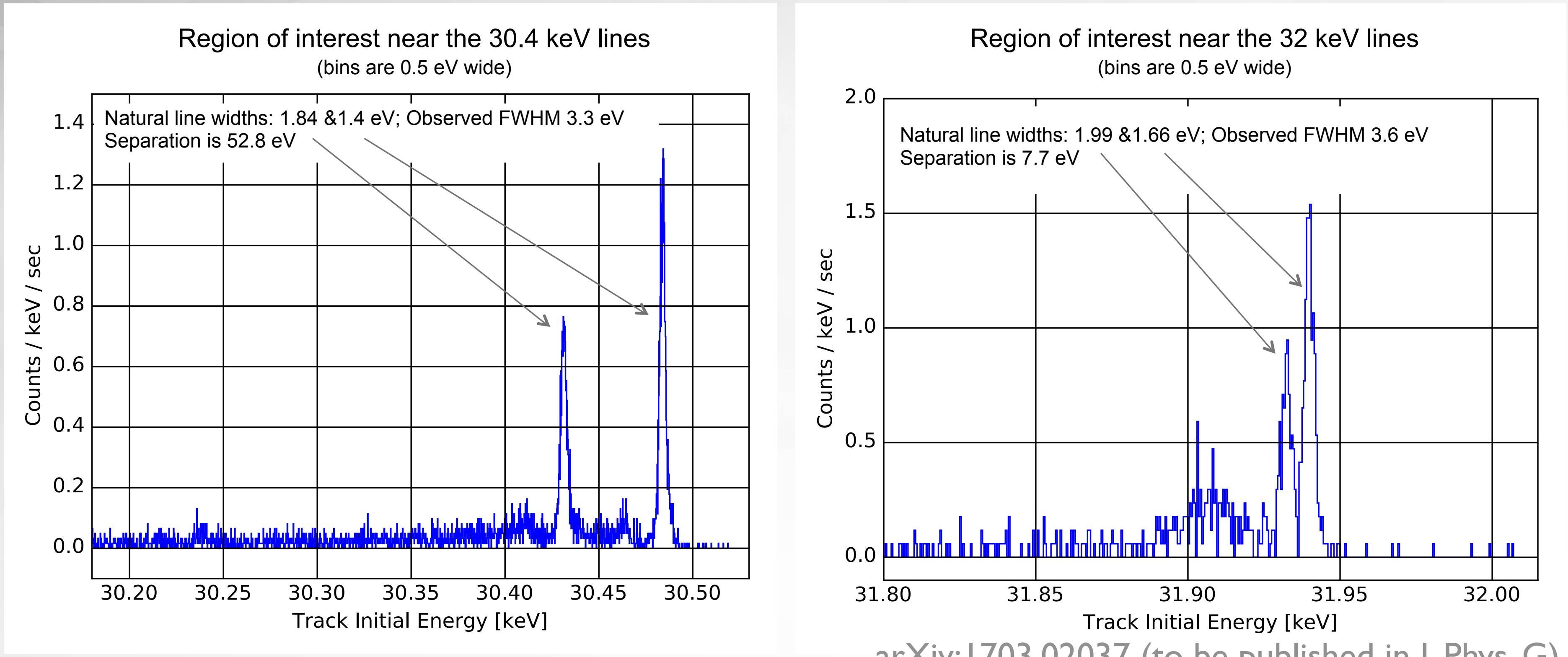


arXiv:1703.02037 (to be published in J. Phys. G)

Disentangling Energy and θ

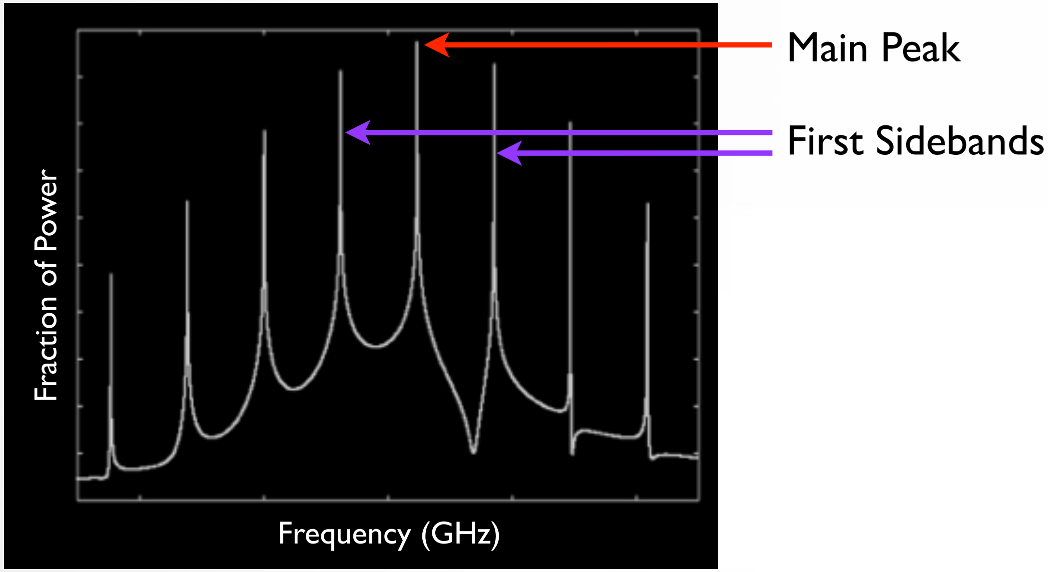
$$\omega_\gamma = \frac{\omega_0}{\gamma} = \frac{eB}{K + m_e}\left(1 + \frac{\cot^2\theta}{2}\right)$$

Use the axial frequency: modulation of the cyclotron radiation signal

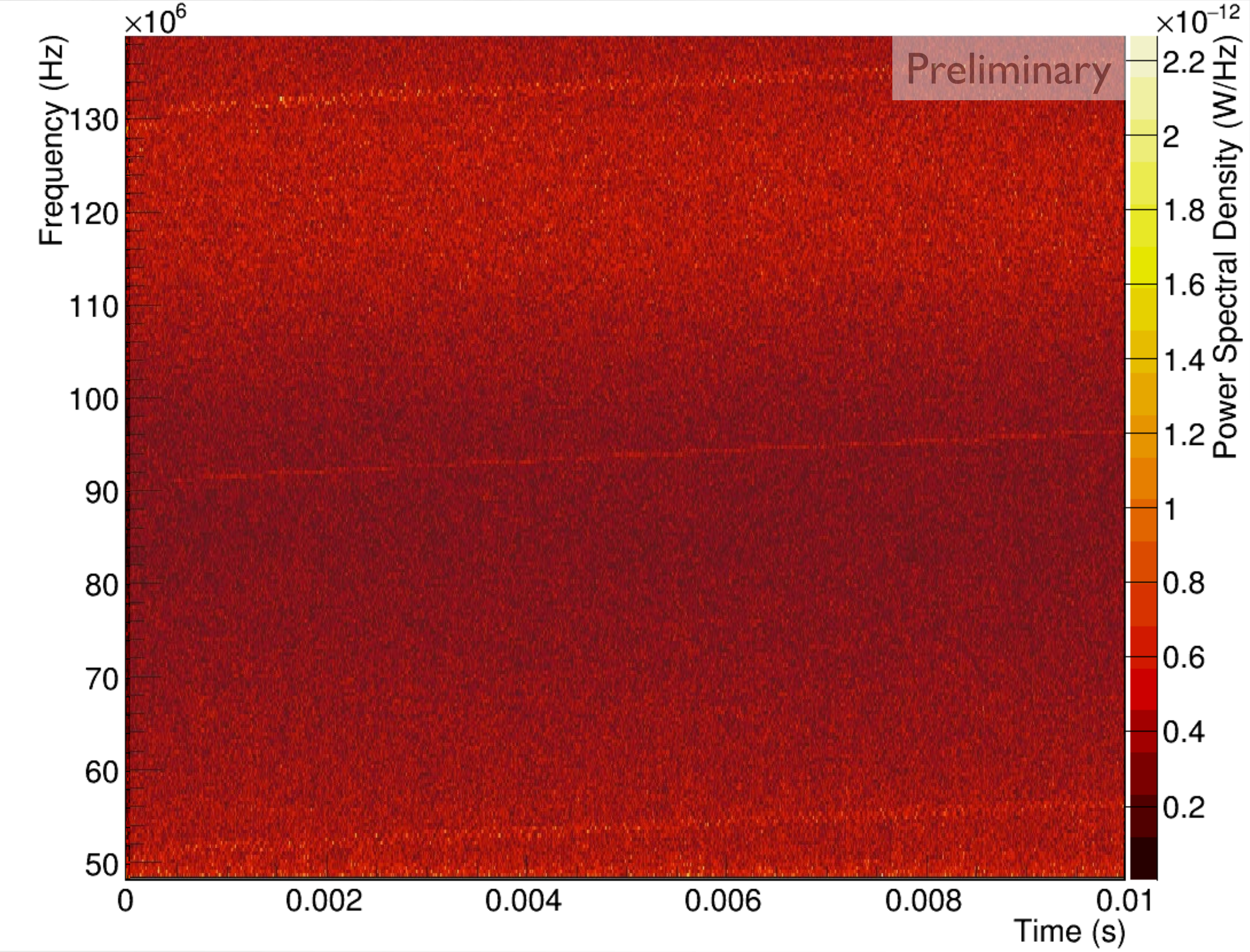
$$\omega_a \propto v\left(\frac{a}{\sin\theta} + \frac{4\sin\theta}{m\cos^2\theta}\right)^{-1}$$

For an approximation of a bathtub trap

Expected frequencies: 50-200 MHz



Sidebands Observed



Analyst: N.S.O.

Sidebands Observed

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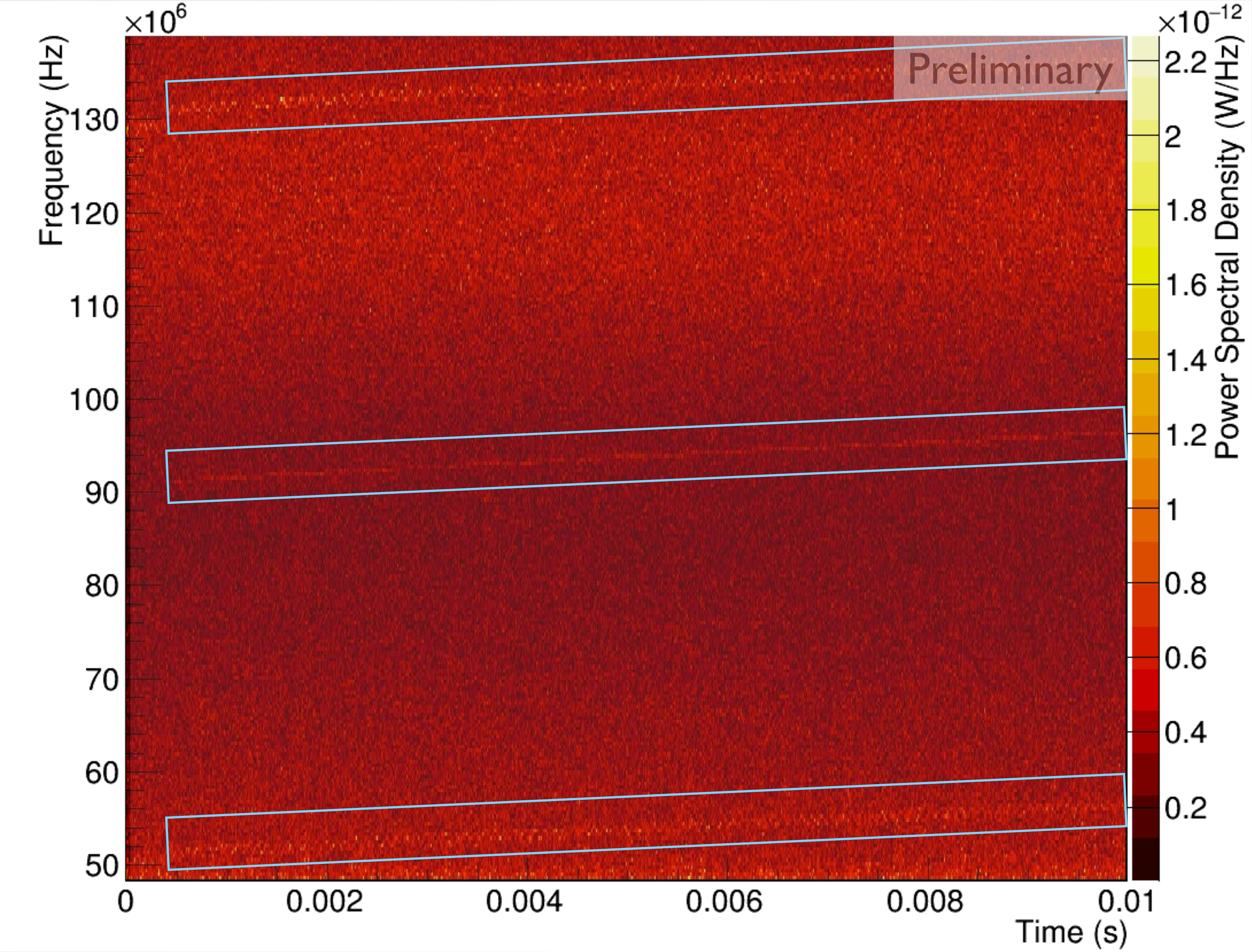

Analyst: N.S.O.

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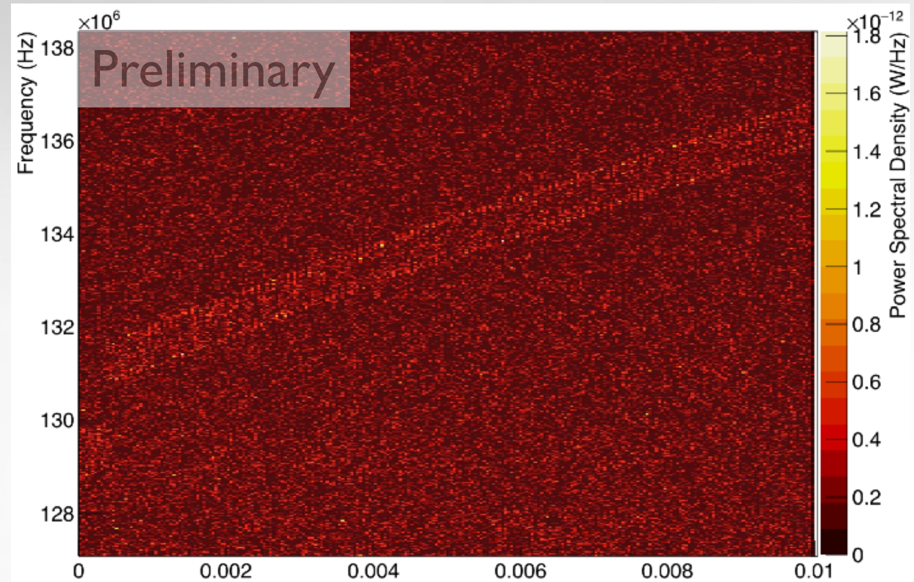
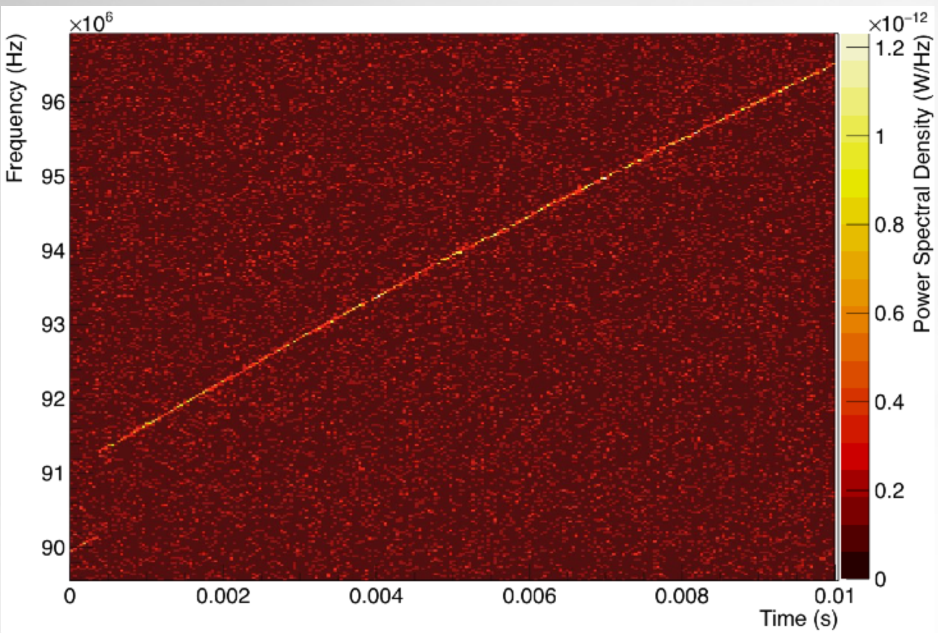
Sideband Oscillations

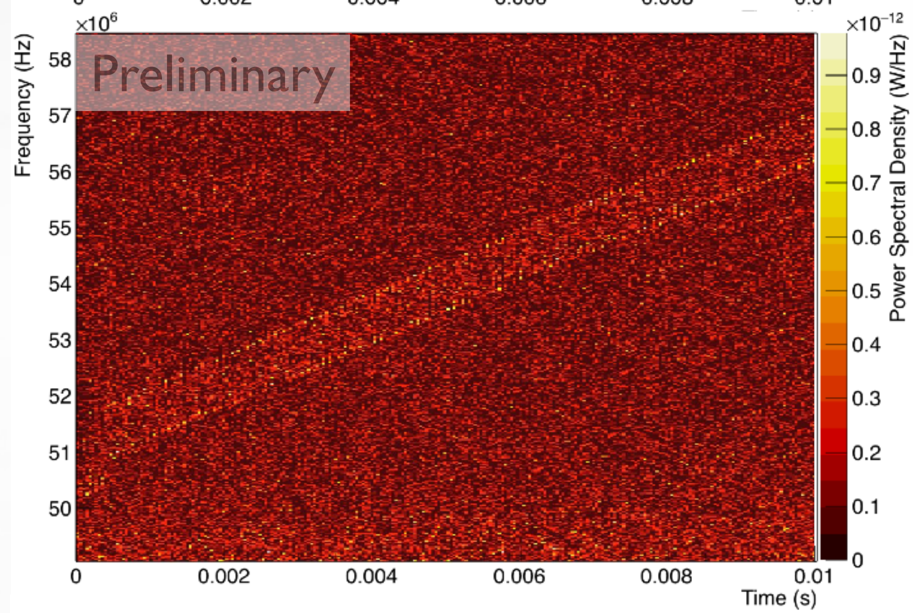
Upper Sideband



Central peak



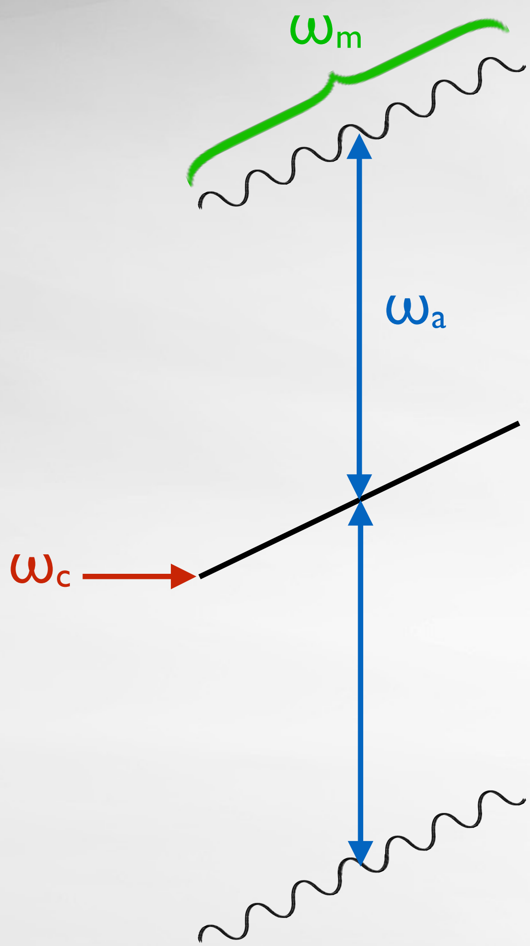
Analyst: N.S.O.



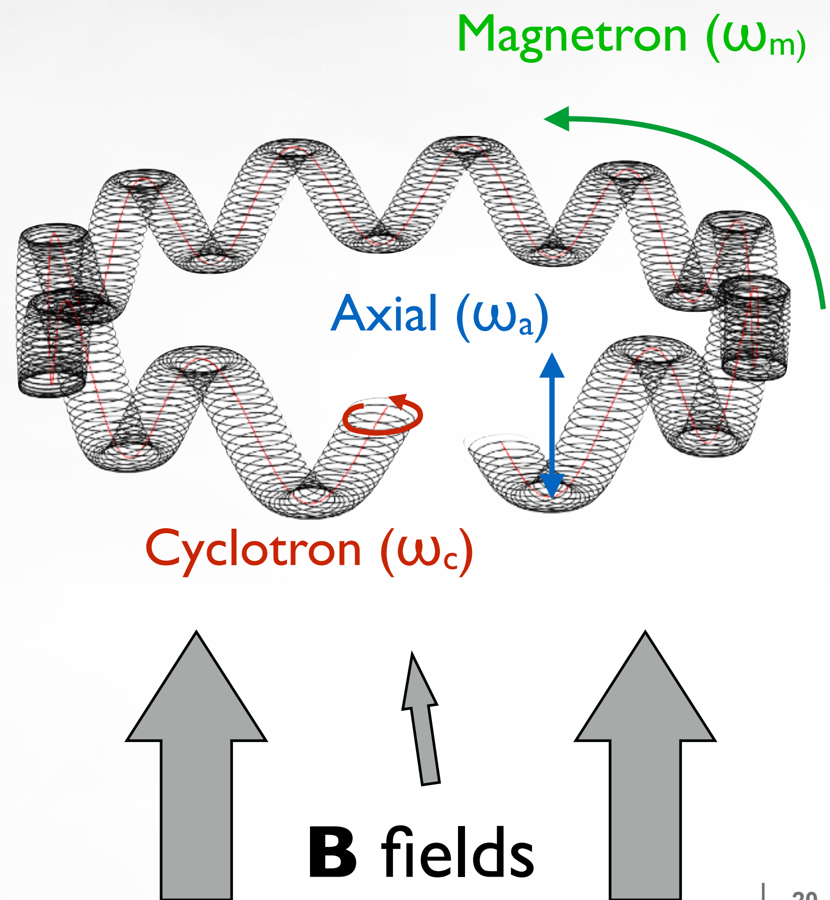
Lower Sideband

Phenomenology

Data



Hypothesis & Simulations



Moving Forward with a Phased Approach

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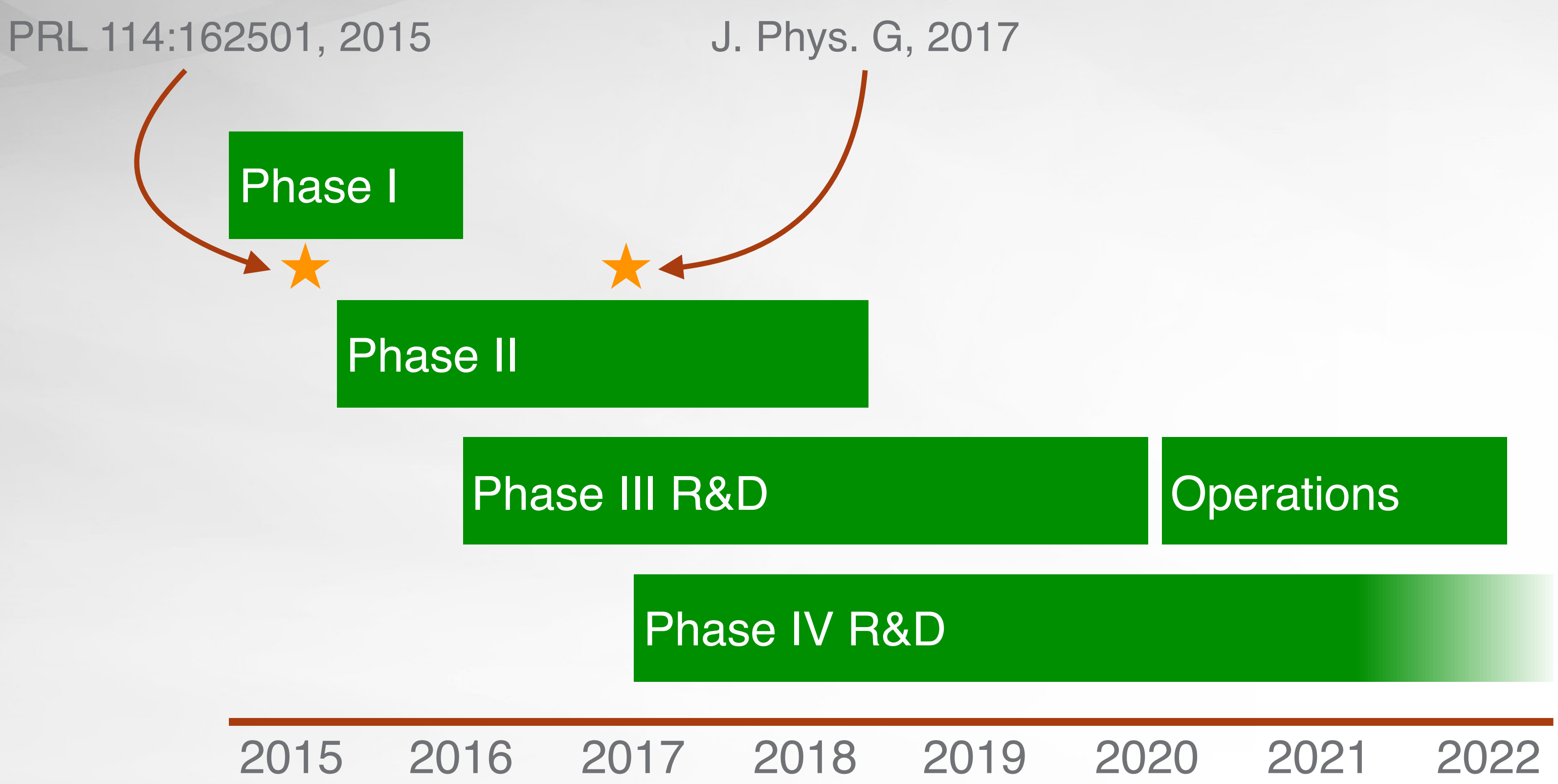

Phase 2: Tritium Demonstrator

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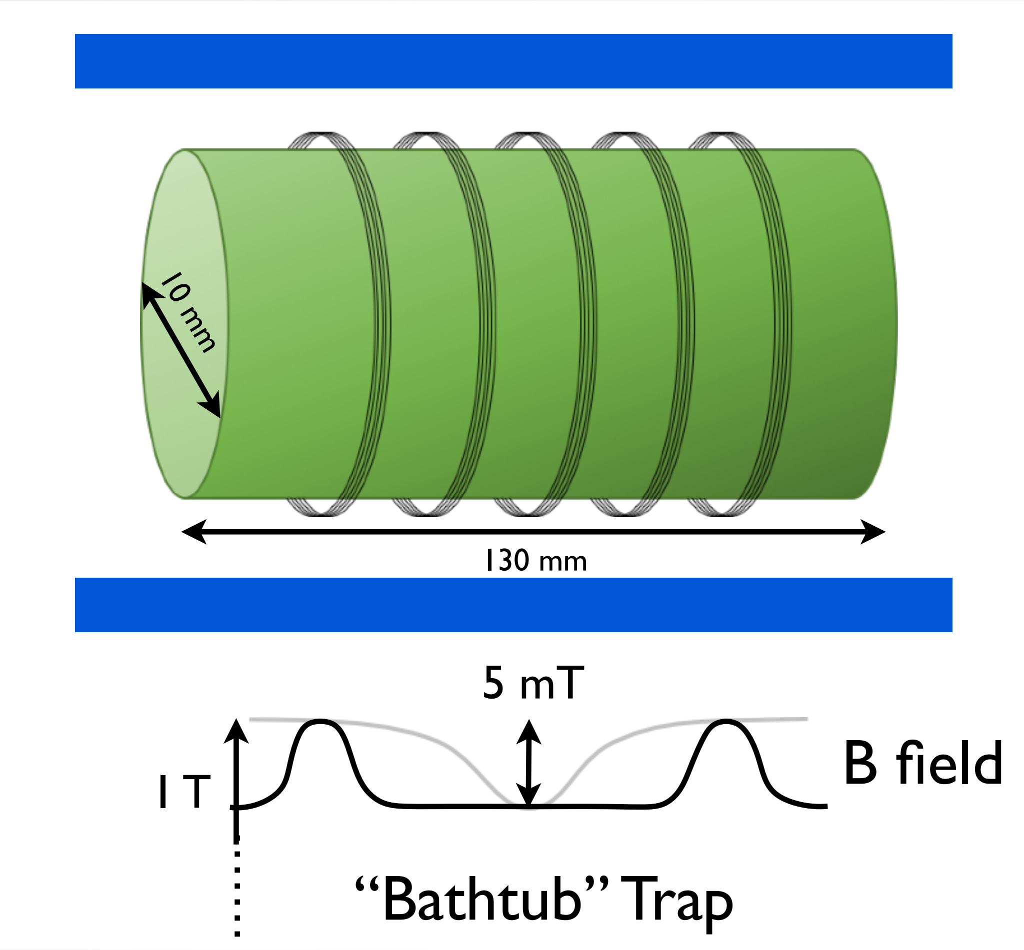
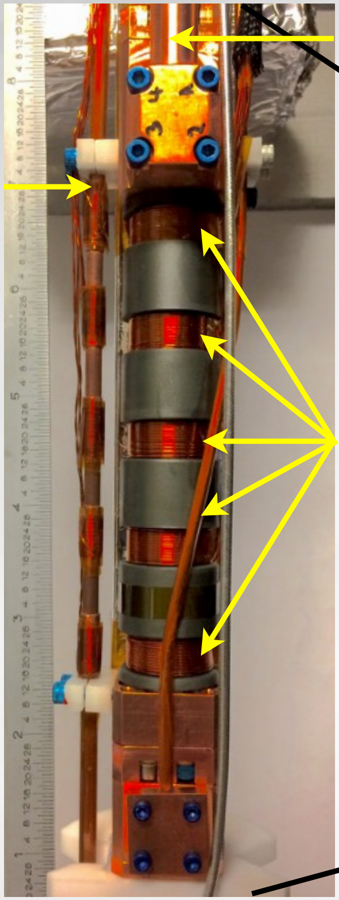
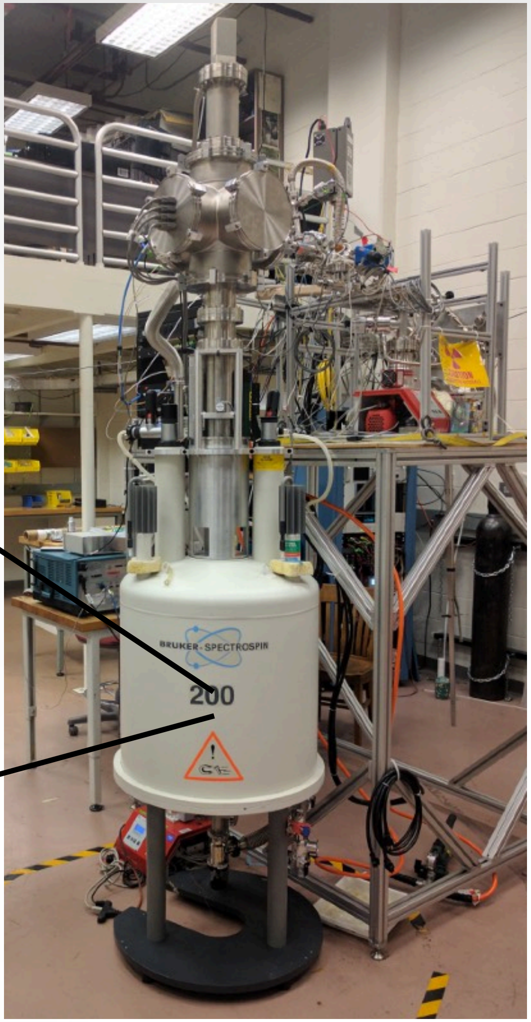
- 1-cm circular waveguide to contain the gas and detect the cyclotron radiation
- Filled with ^{83m}Kr gas
- 1 T background magnetic field & a wider 5-mT magnetic trap
- Waveguide leads to cryogenic amplifiers



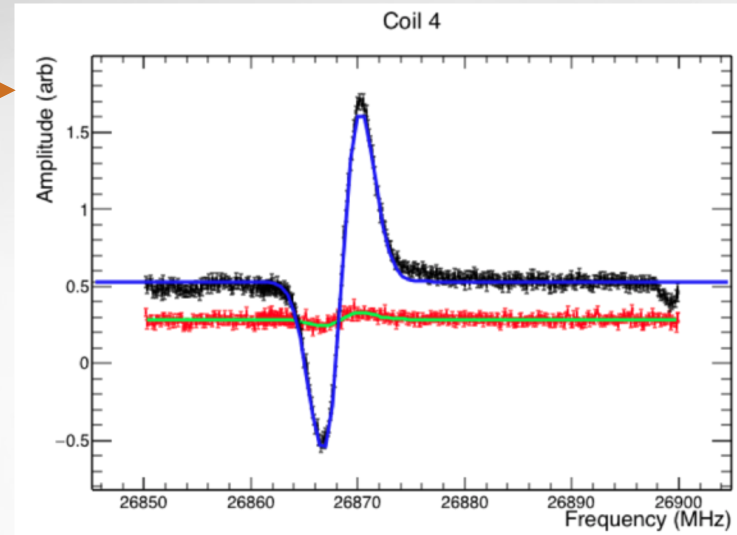
$^{83m}Kr/T_2$ Gas Cell



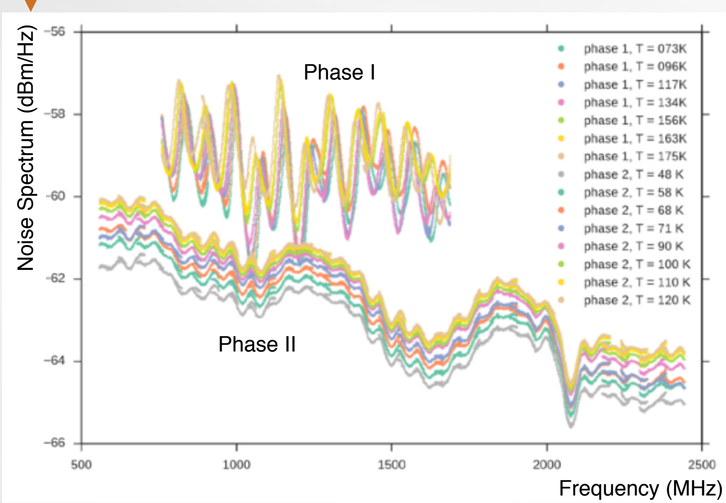


Phase II: Other Improvements

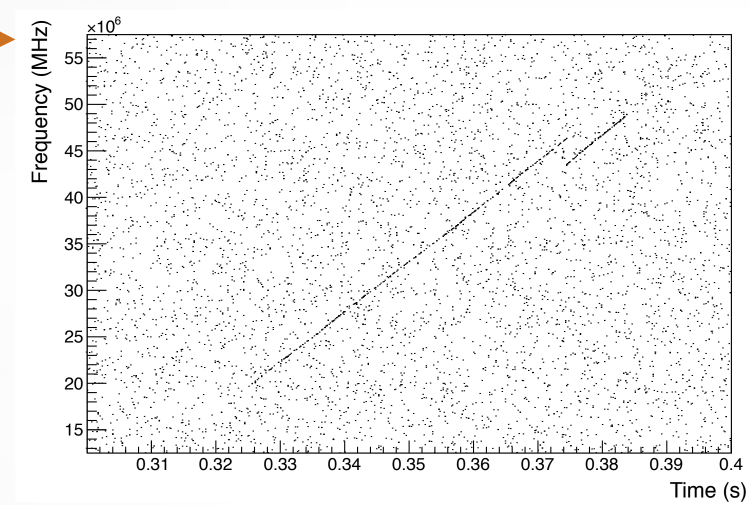
- Electron Spin Resonance (ESR) measurement at each trap coil location
- ROACH digitizer — streaming & triggered operation
- Cryogenic isolator for improved SNR



Analyst: W.C. Pettus



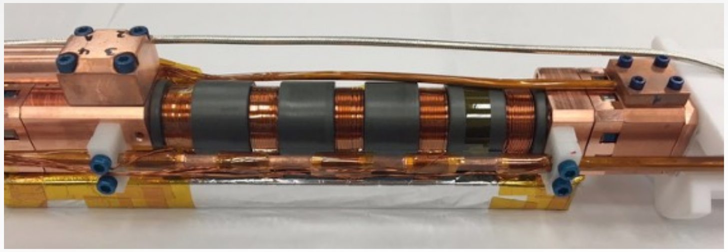
Analyst: R. Cervantes

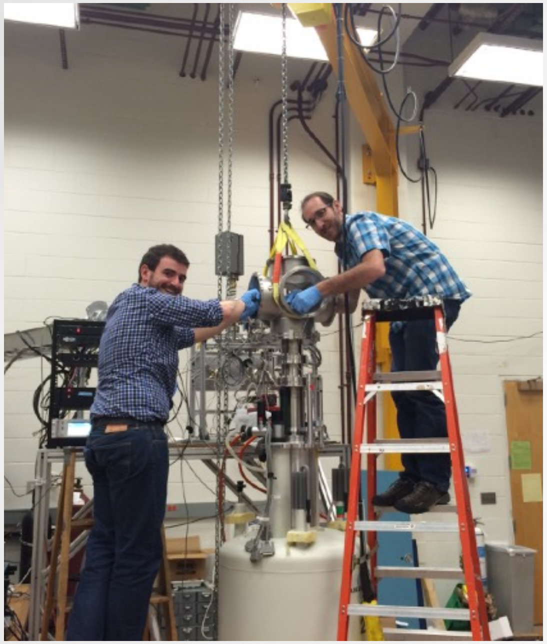


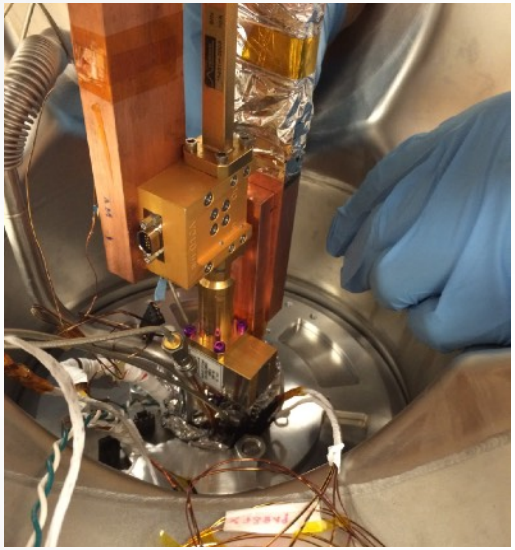
Analyst: C. Claessens

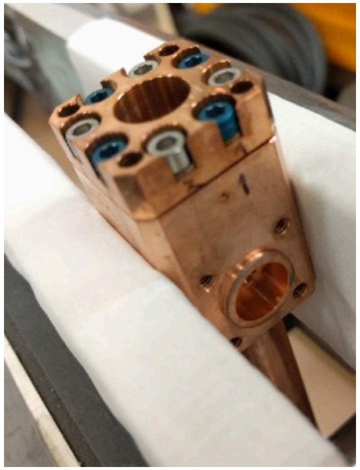
Current Status

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









Phase III: Mainz/Troitsk-Scale Limit

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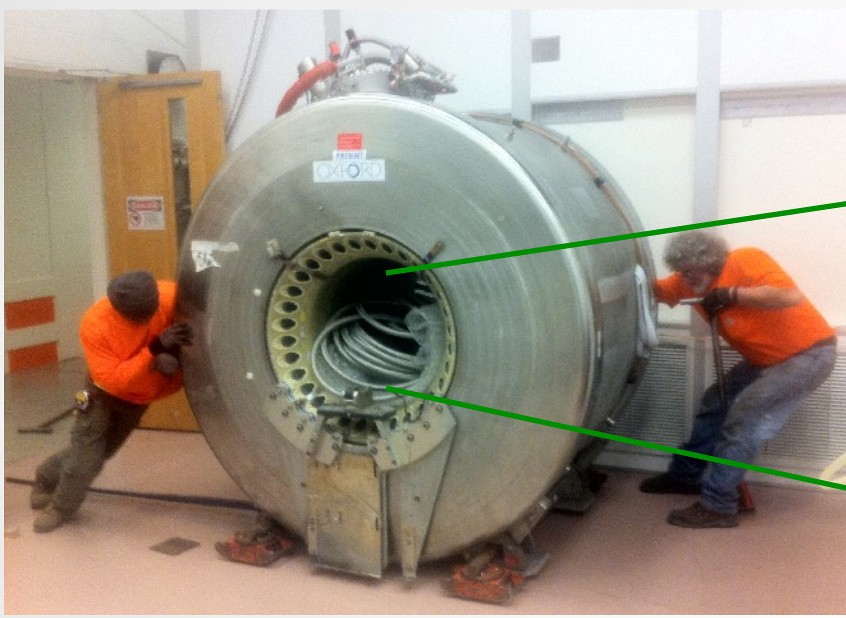
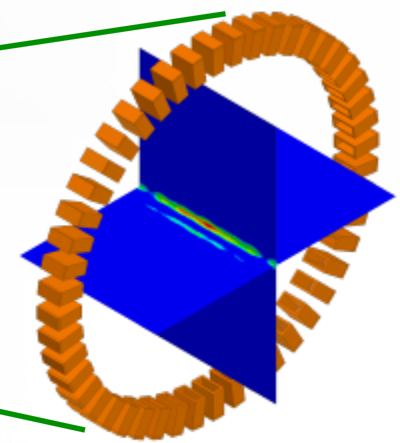
- Scaling up the volume: 200 cm^3 volume inside an MRI magnet
- Free-space radiation detected by a ring array of antennas
- Digital beam-forming used to spatially locate electrons within the fiducial volume

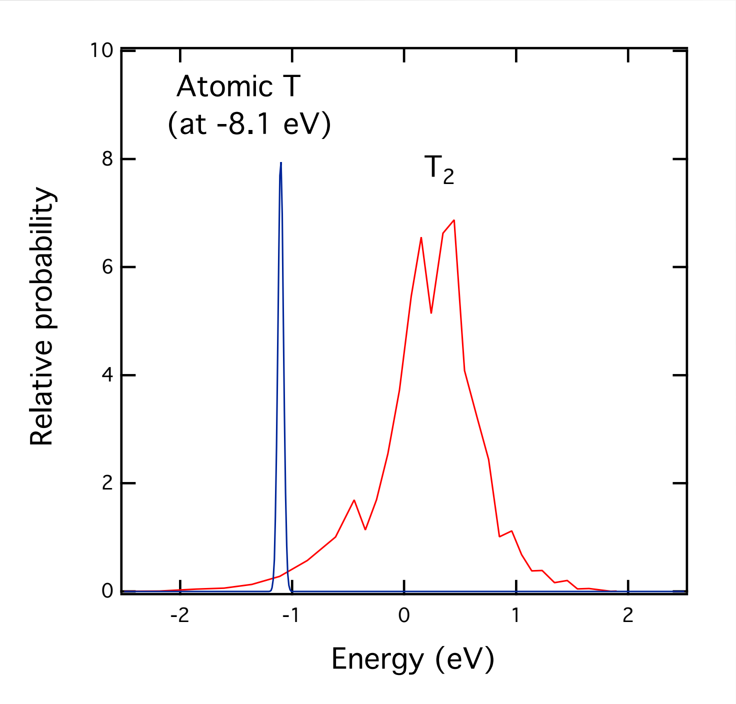




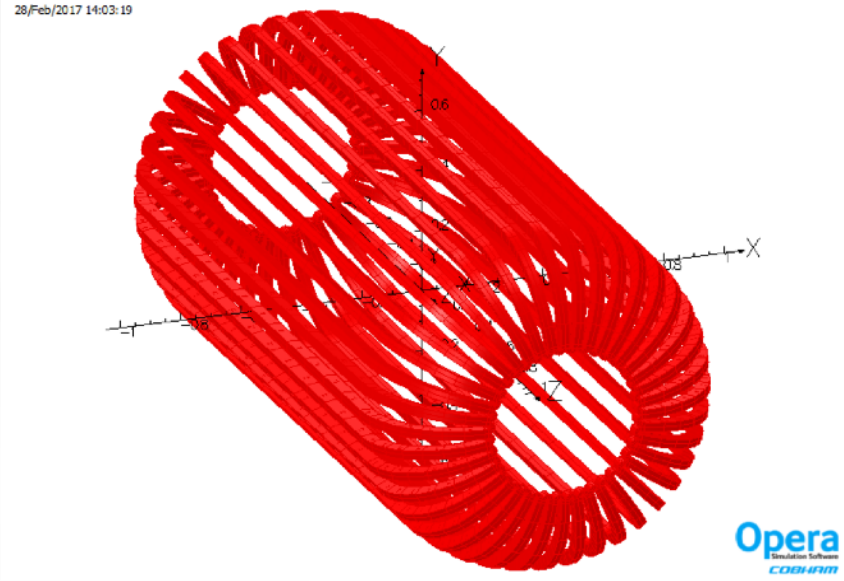
Simulation by A.M. Jones

Phase IV: Atomic Tritium Experiment

- Use atomic tritium to avoid wide final-state energy distribution
- Large volume: ~100 m^3
- Ioffe coils to trap atomic T



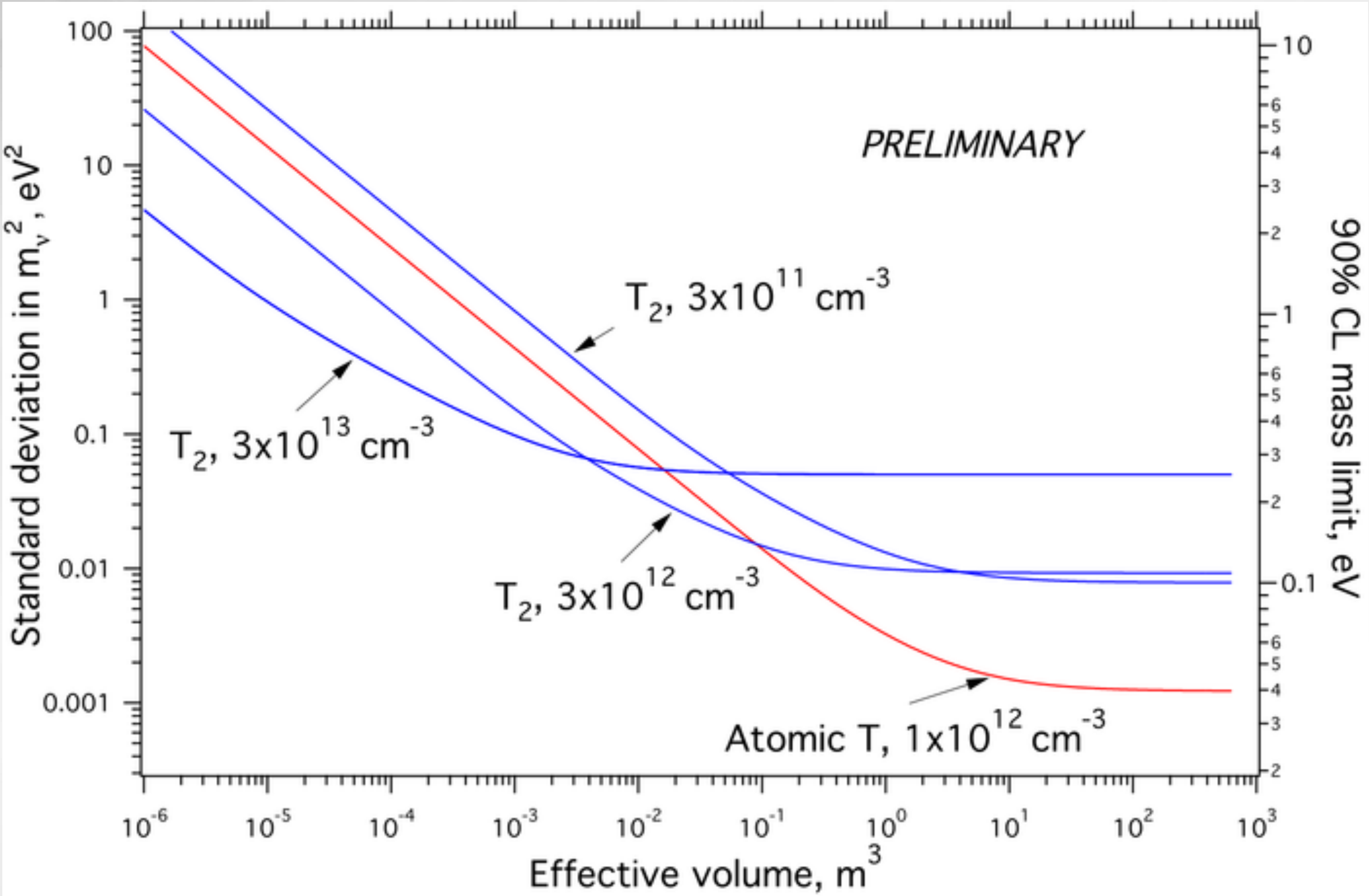
T2 distribution from Saenz et al., Phys. Rev. Left. 84, 242 (2000)
T distribution calculated by R.G.H. Robertson



Coil design by A. Radovinsky

Projected Sensitivities

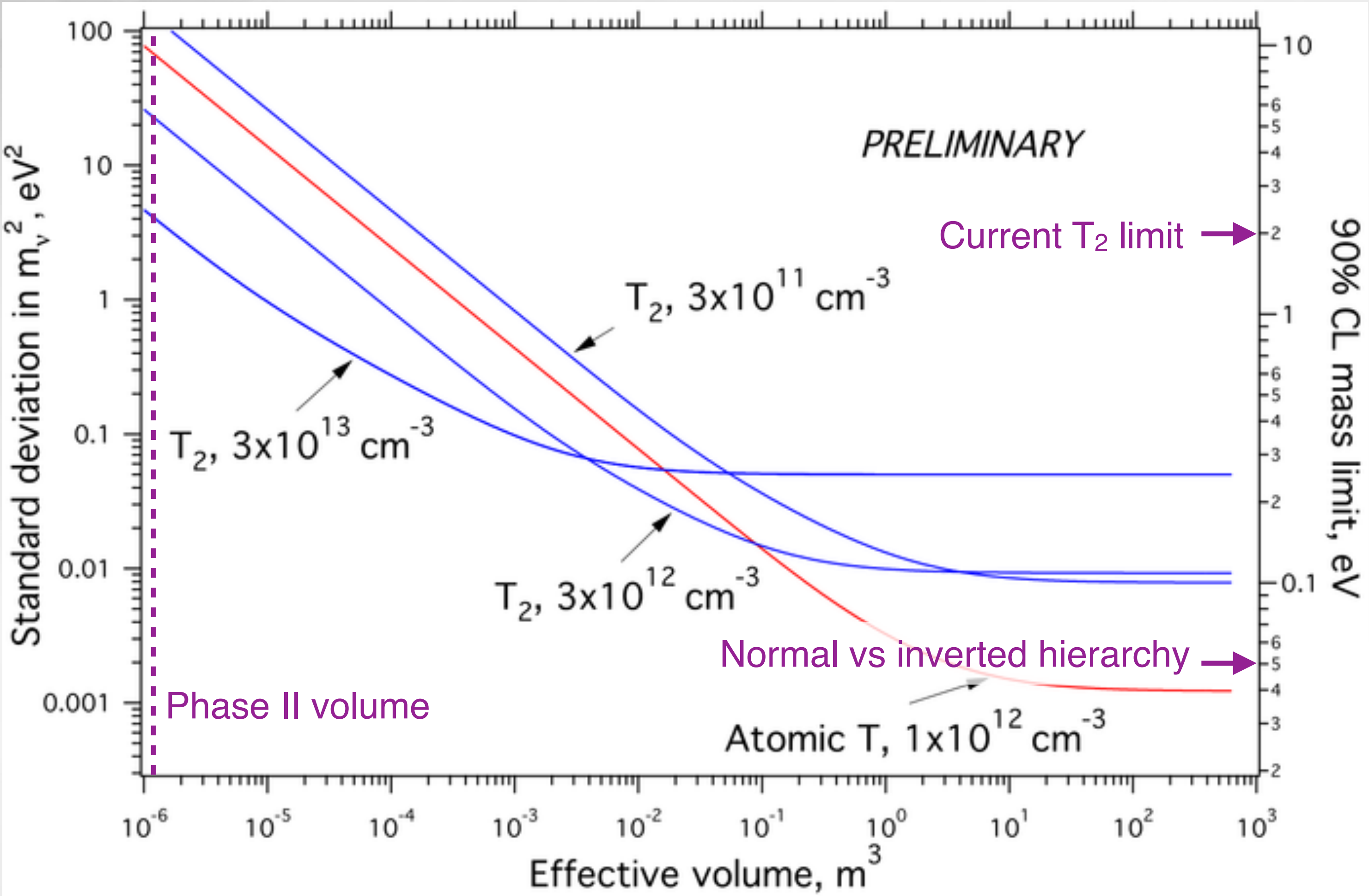
Sensitivities for different gas densities (number per cm^3)



Calculations by R.G.H. Robertson

Projected Sensitivities

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



Calculations by R.G.H. Robertson

Summary

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- 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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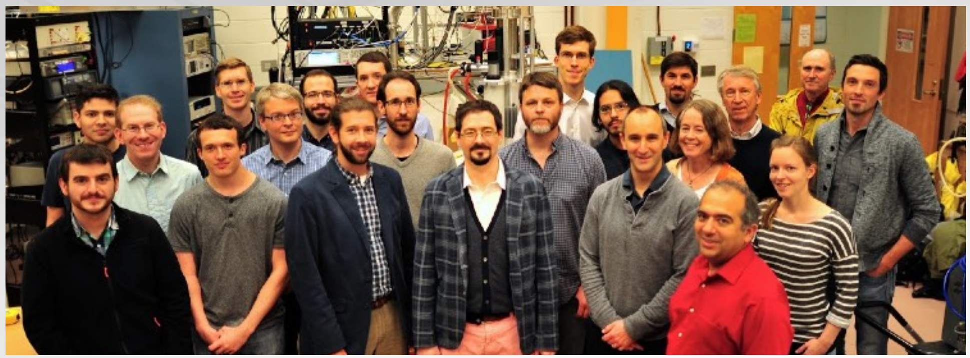
Project 8 Collaboration



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