Towards Measuring Neutrino masses with Cyclotron Radiation Emission Spectroscopy:

First results from Project 8

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On behalf of the Project 8 Collaboration

Fermilab Joint Experimental-Theoretical Seminar
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Brief History of Neutrinos

1930's and 40's – Neutrinos explain beta decay spectrum, could have small mass

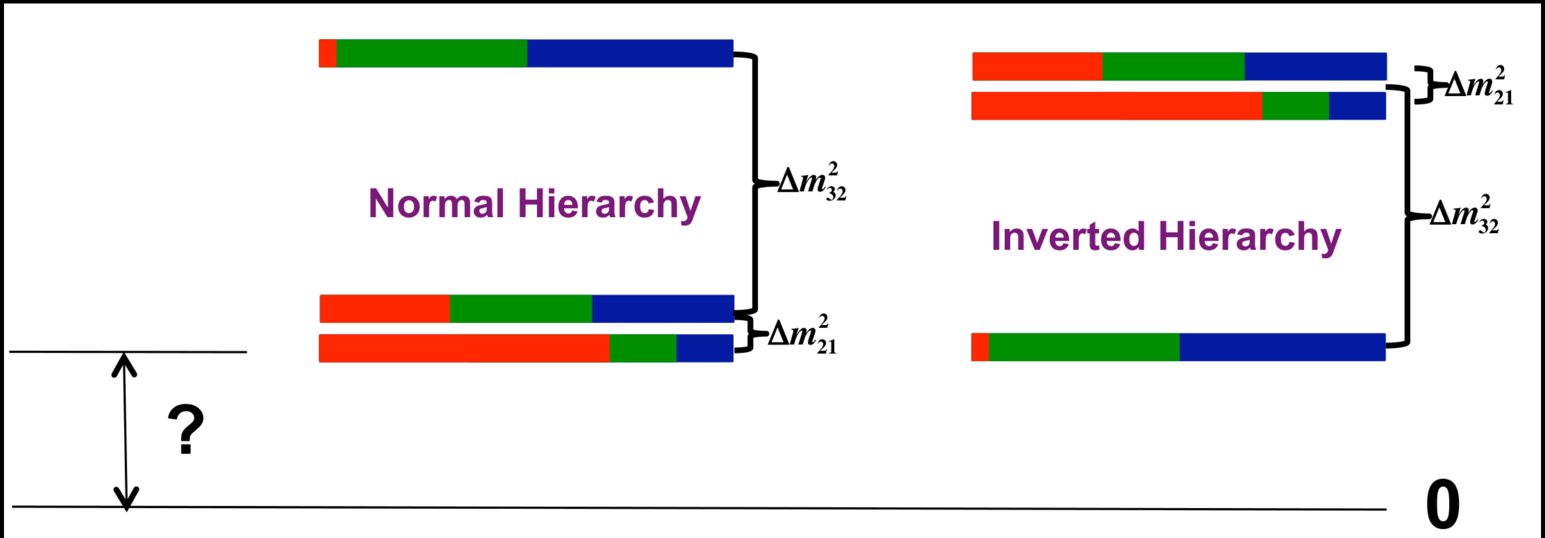
1950's and 60's – Parity violation, neutrino helicity only make sense if neutrinos have no mass

1960's through Present – Neutrino flavors oscillate, only make sense if neutrinos are massive

What is the neutrino mass scale? Where does it come from?

The Neutrino Mass Scale

Neutrino mixing measurements do not give the overall neutrino mass scale...



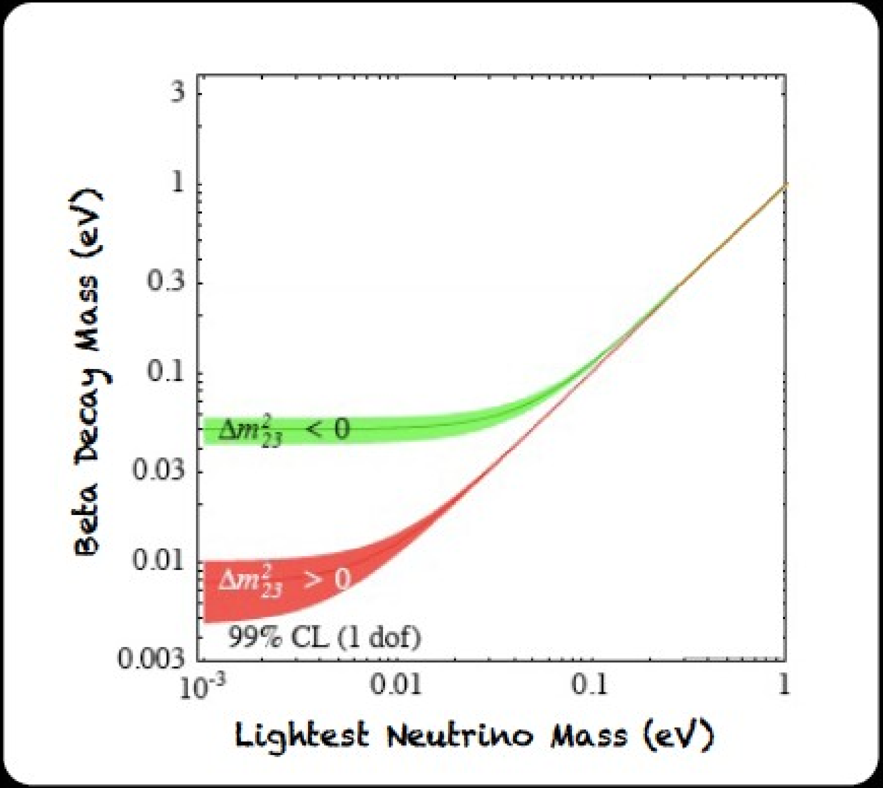
...but do suggest that it is no smaller than a few meV

Measuring the Neutrino Mass Scale

Several types of experiment give us a handle on the neutrino mass scale

$$M = \sum_{i}^{n_\nu} m_{\nu,i}$$

Cosmological Measurements



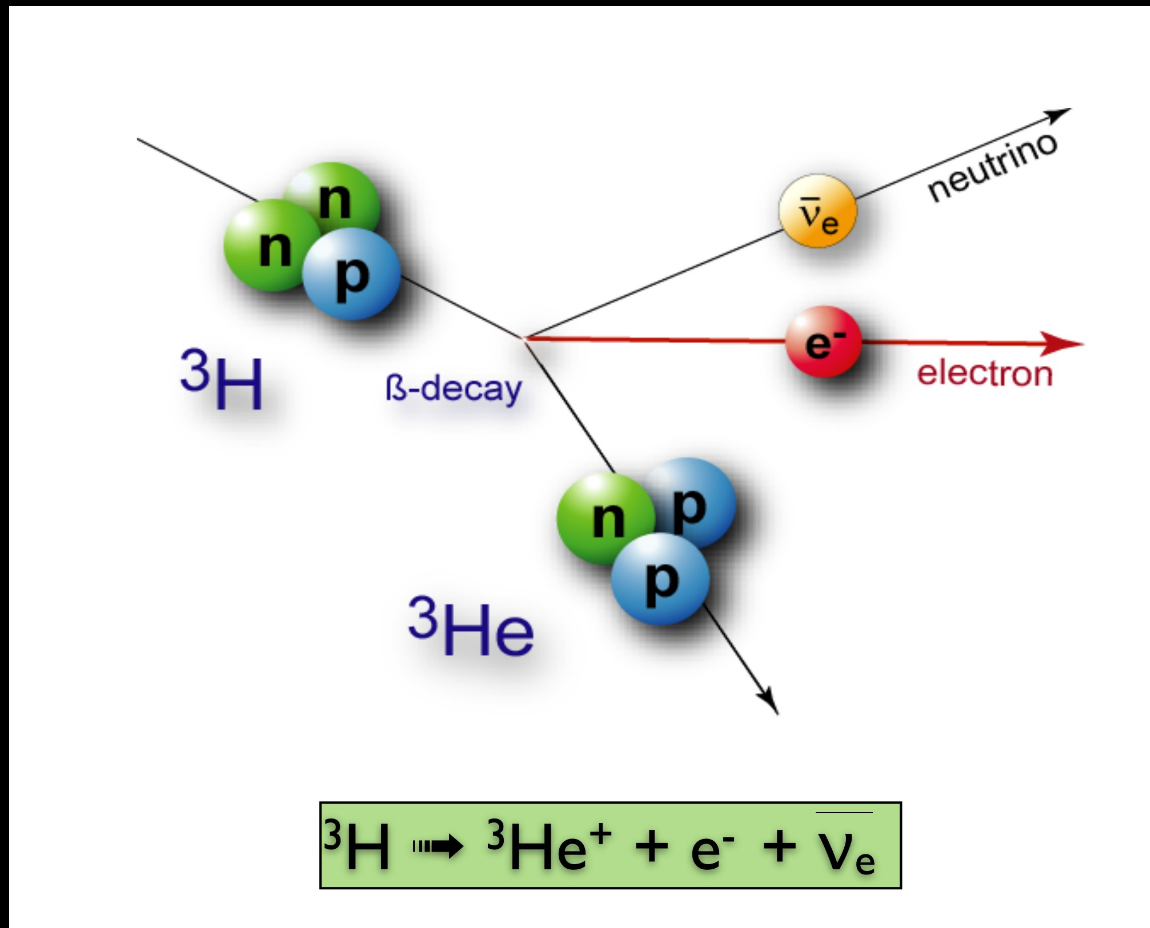
$$\langle m^2_{\beta\beta}\rangle = \left| \sum_{i}^{n_\nu} U^2_{ei} m_{\nu,i} \right|^2$$

0νββ Measurements

$$\langle m_\beta \rangle^2 = \sum_{i}^{n_\nu} | U_{ei} |^2 \, m^2_{\nu,i}$$

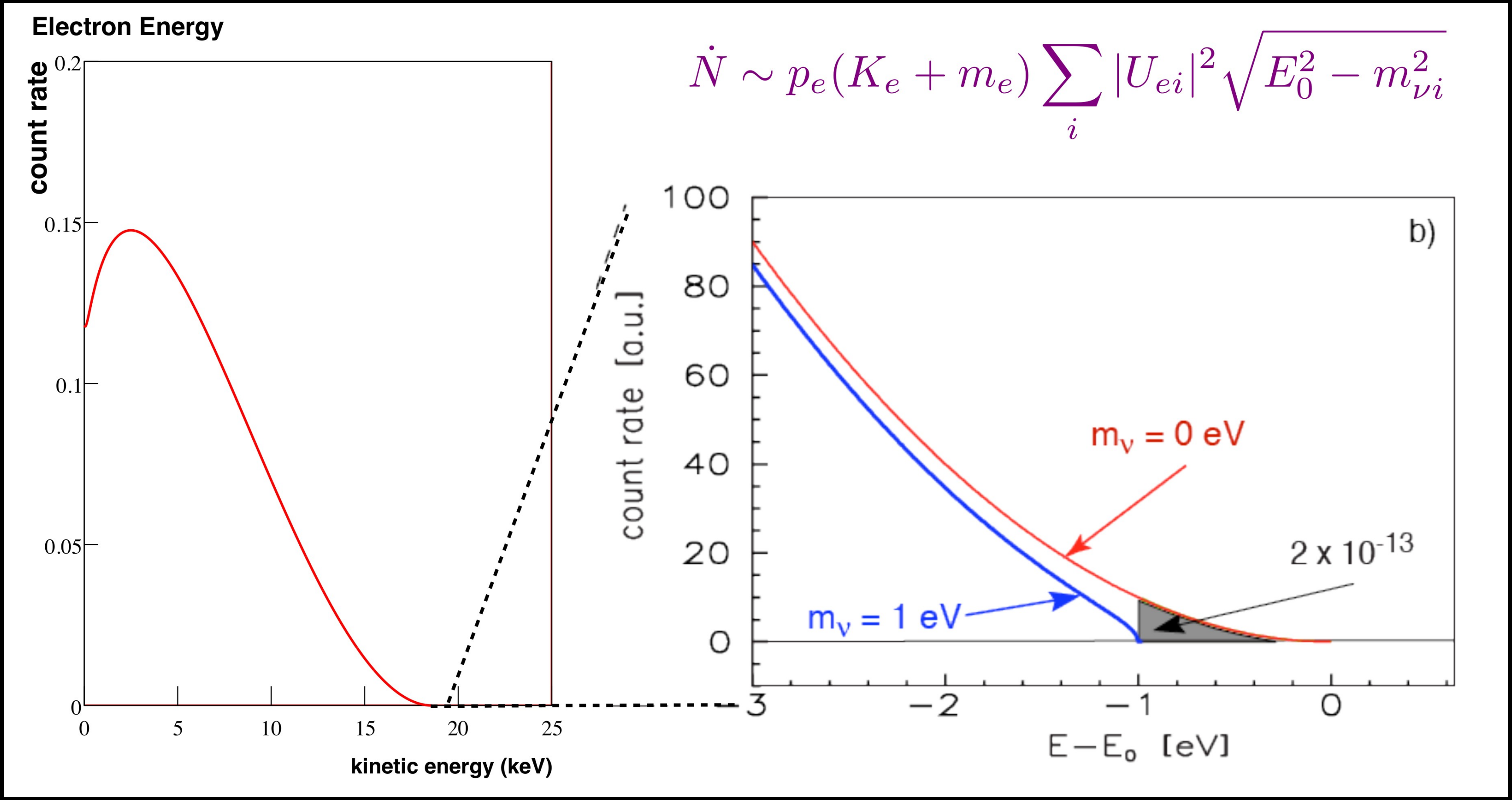
Beta Decay Measurements

Direct Neutrino Mass Measurement with Beta Decay



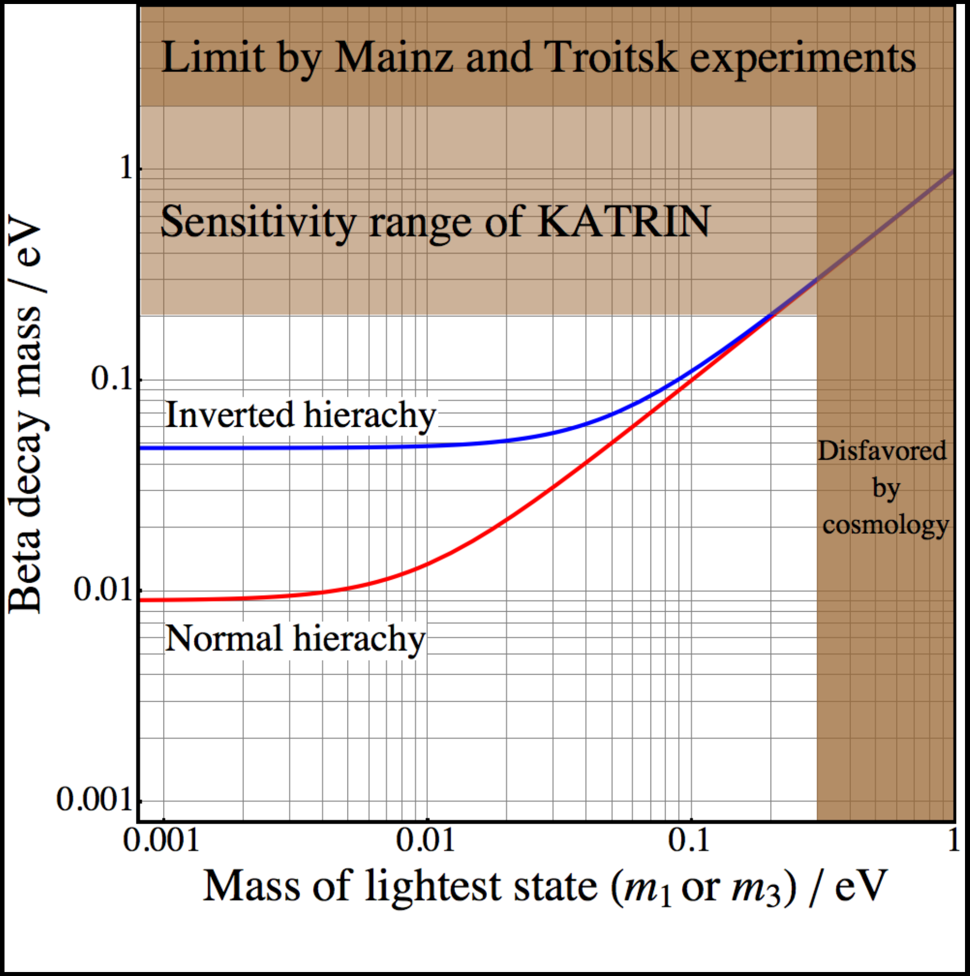
The masses and kinetic energies of the products must add up to the mass of original nucleus

Direct Neutrino Mass Measurement with Beta Decay



The endpoint of the electron spectrum is subtly changed by a neutrino mass

State-of-the-art Beta Spectrometry



source: KATRIN website

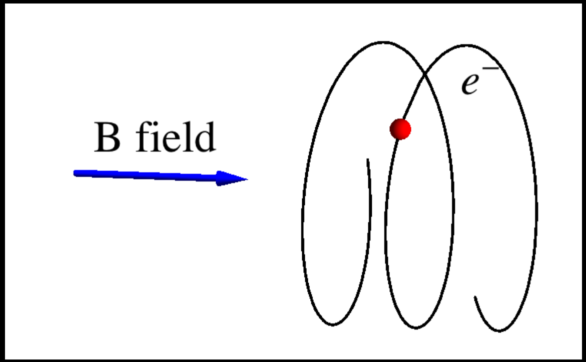
The KATRIN experiment may measure the neutrino mass scale.

How will we confirm it with different systematics?

The KATRIN experiment may set a new upper limit on the neutrino mass scale.

How will we look at lower masses?

Cyclotron Radiation



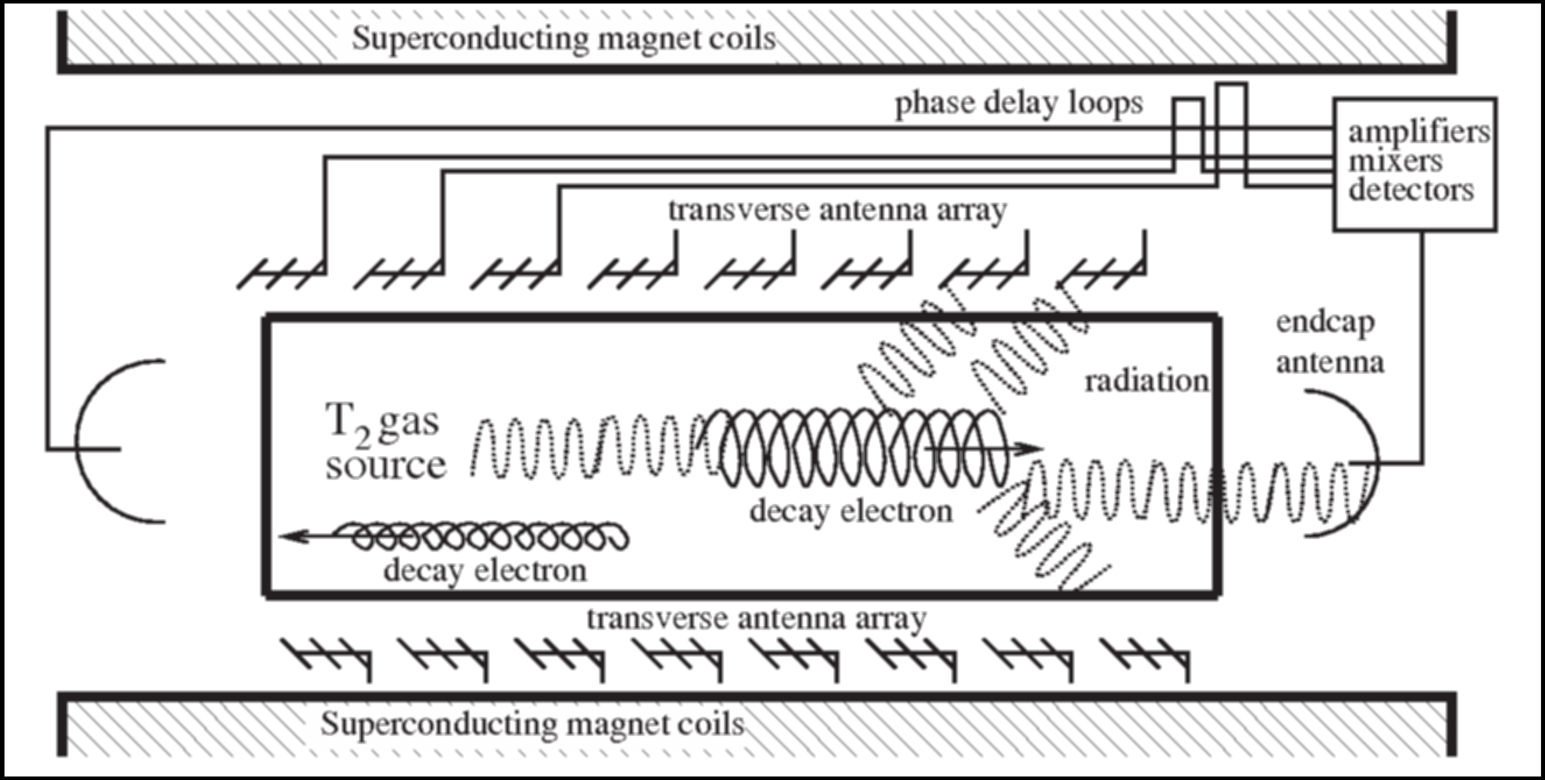
Cyclotron Frequency

$$f = \frac{1}{2\pi} \frac{eB}{m_e + E_{kin}}$$

“Never measure anything but frequency” - *A. Schawlow*

Project 8

Why not use cyclotron frequency to measure electron energy?



B. Monreal and J. Formaggio, Phys. Rev D80:051301

Project 8 Collaboration

PROJECT 8

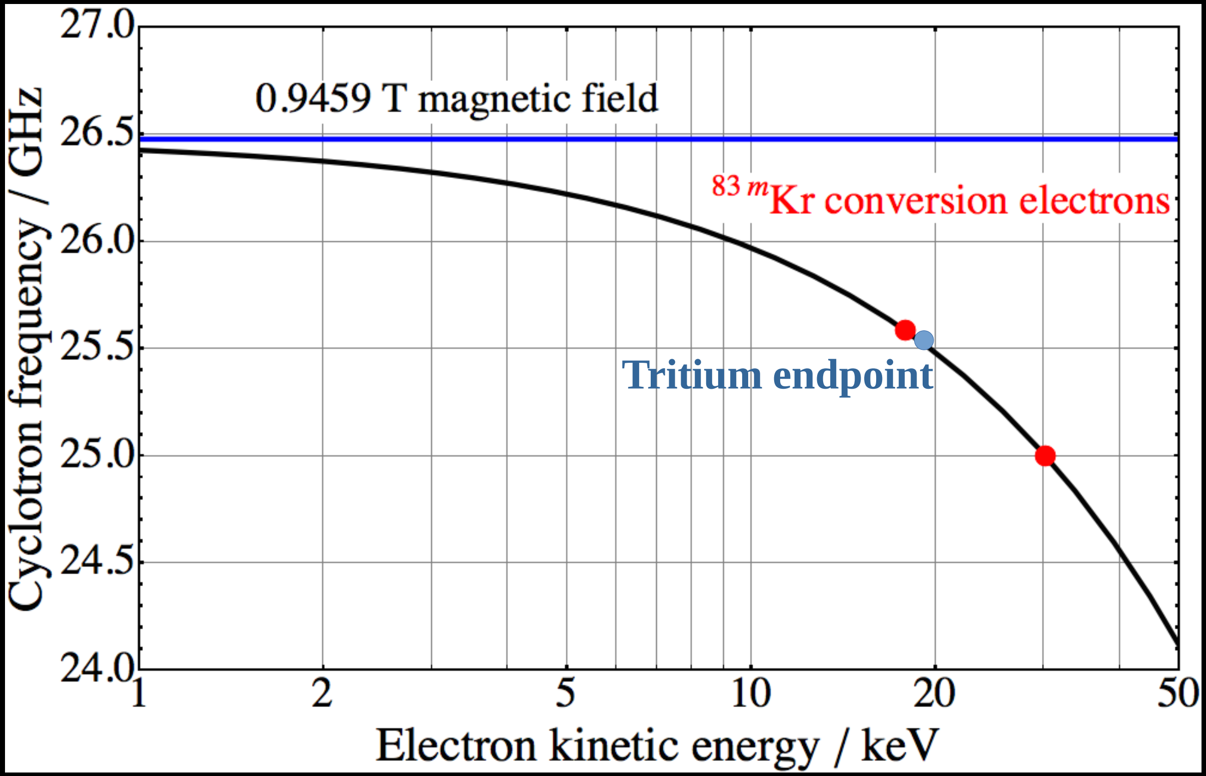
University of Washington
UC Santa Barbara
MIT
Pacific Northwest National Laboratory
Karlsruher Institute of Technology
National Radio Astronomy Observatory

Goals

- Demonstrate cyclotron frequency measurement of single electrons from radioactive decay
- Demonstrate energy resolution of technique
- Scale up to a neutrino mass measurement experiment

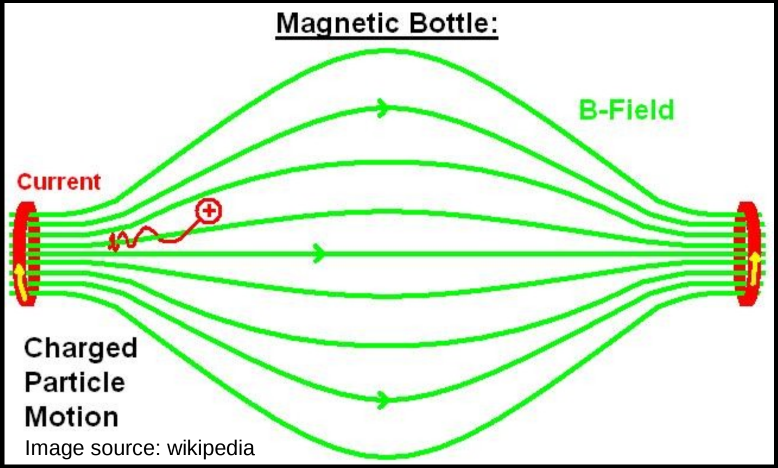
Frequency Scale

A 1 tesla field puts the cyclotron frequency in the K band



^{83m}Krypton conversion electrons are a good calibration source

Complications and Solutions

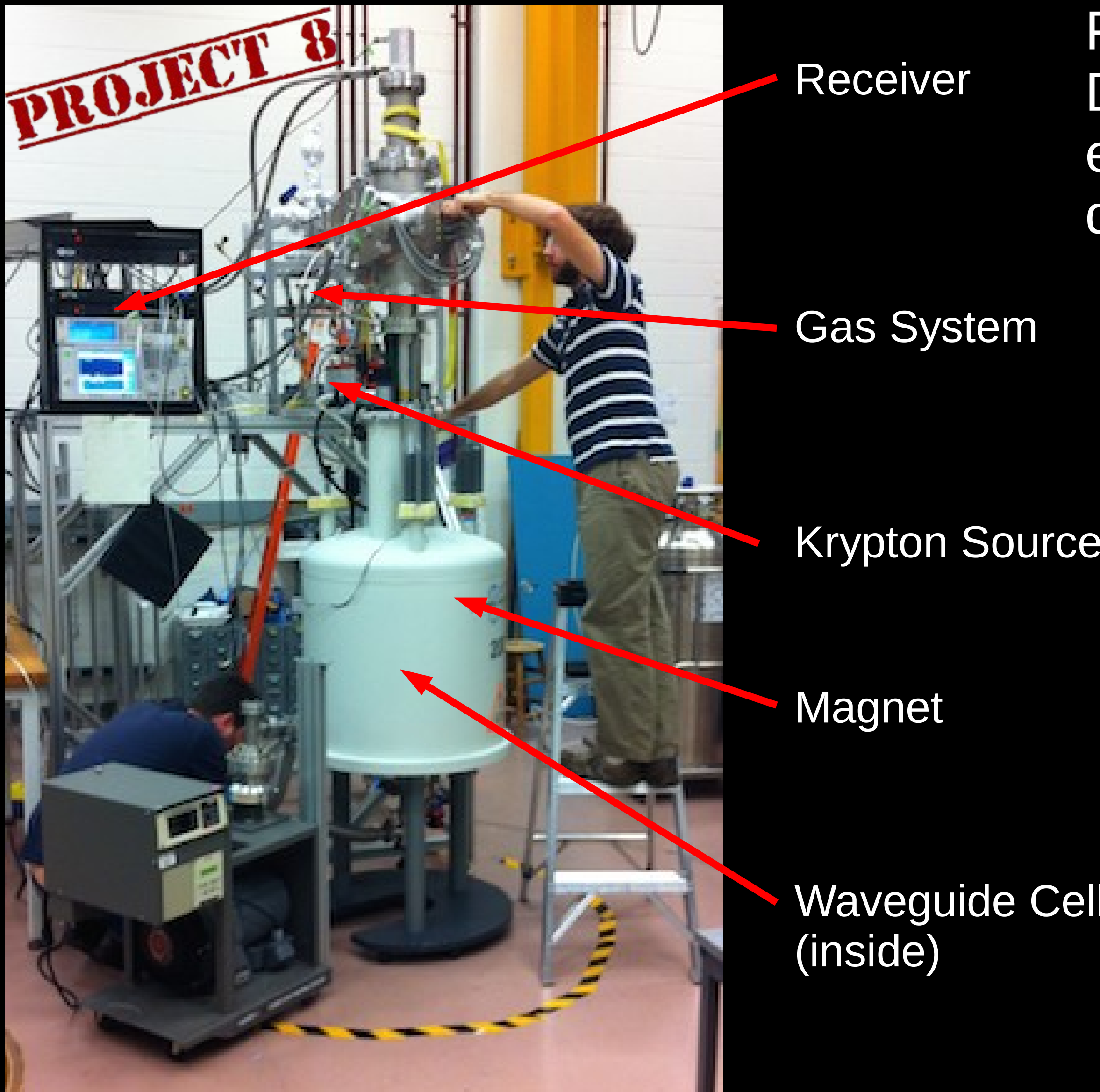


To measure the cyclotron frequency, electrons must be trapped in a magnetic bottle. This causes frequency shifts that must be accounted for.

20-40 GHz Cryogenic Amplifier

Radiated power is ~1 femtowatt, trapping times are milliseconds. Low noise cryogenic RF systems are needed to detect these small powers

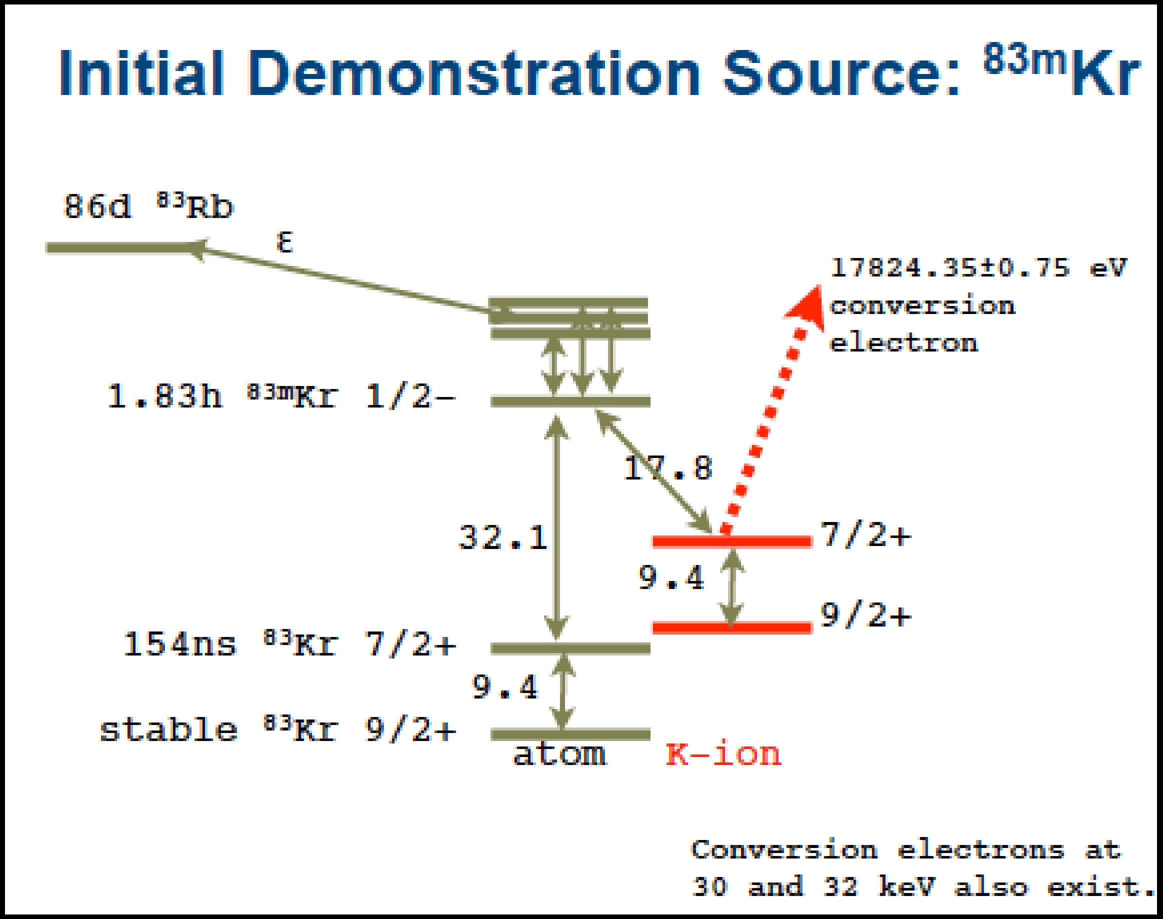
Project 8 Prototype

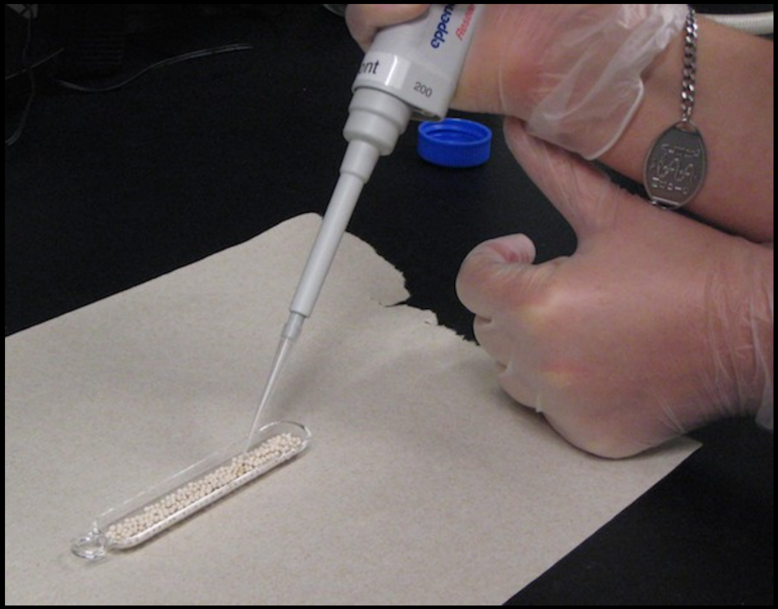


Primary Goal:
Demonstrate detection of single electrons through the passive detection of cyclotron radiation

Prototype Location:
University of Washington

Krypton Source

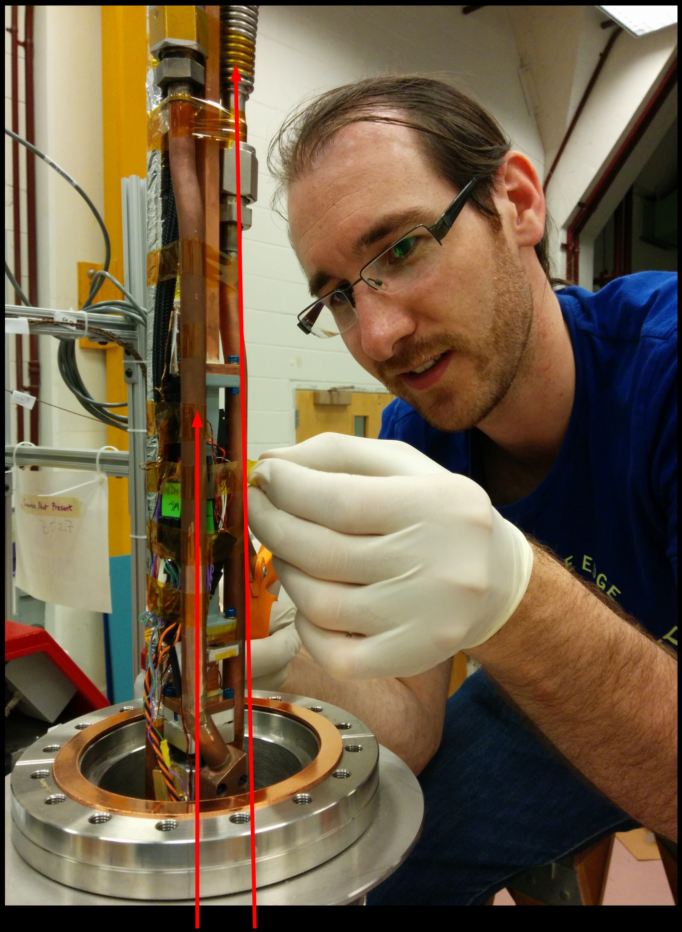




^{83}Rb is deposited on zeolite beads and placed in our gas system.

^{83m}Kr evolves from the beads and provides calibration lines at 9 keV, 18 keV, and 30 keV

Gas System



Gas lines carrying krypton to detector

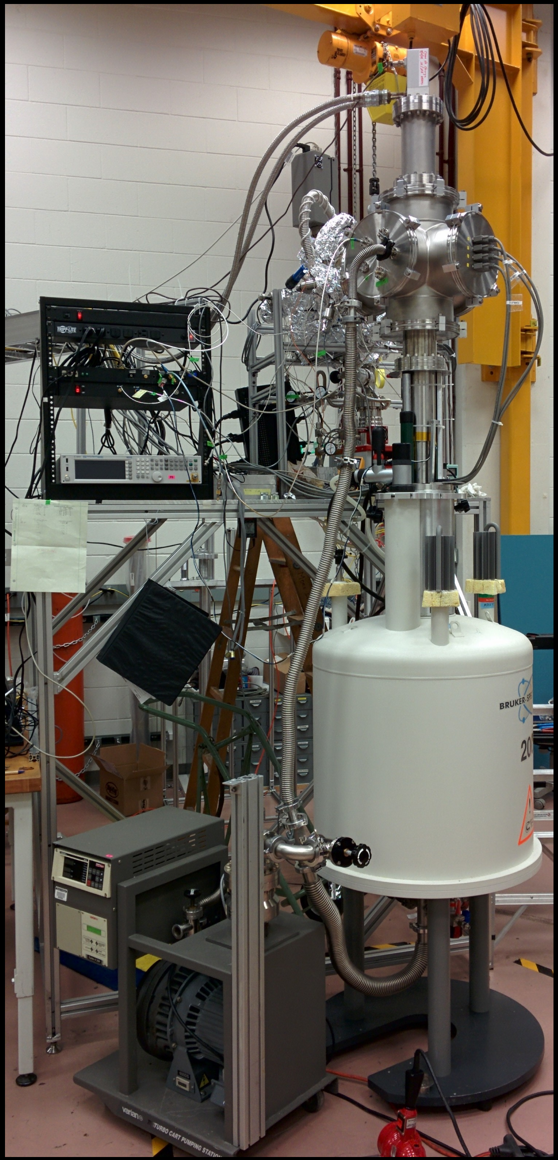
-Delivers Krypton to detector

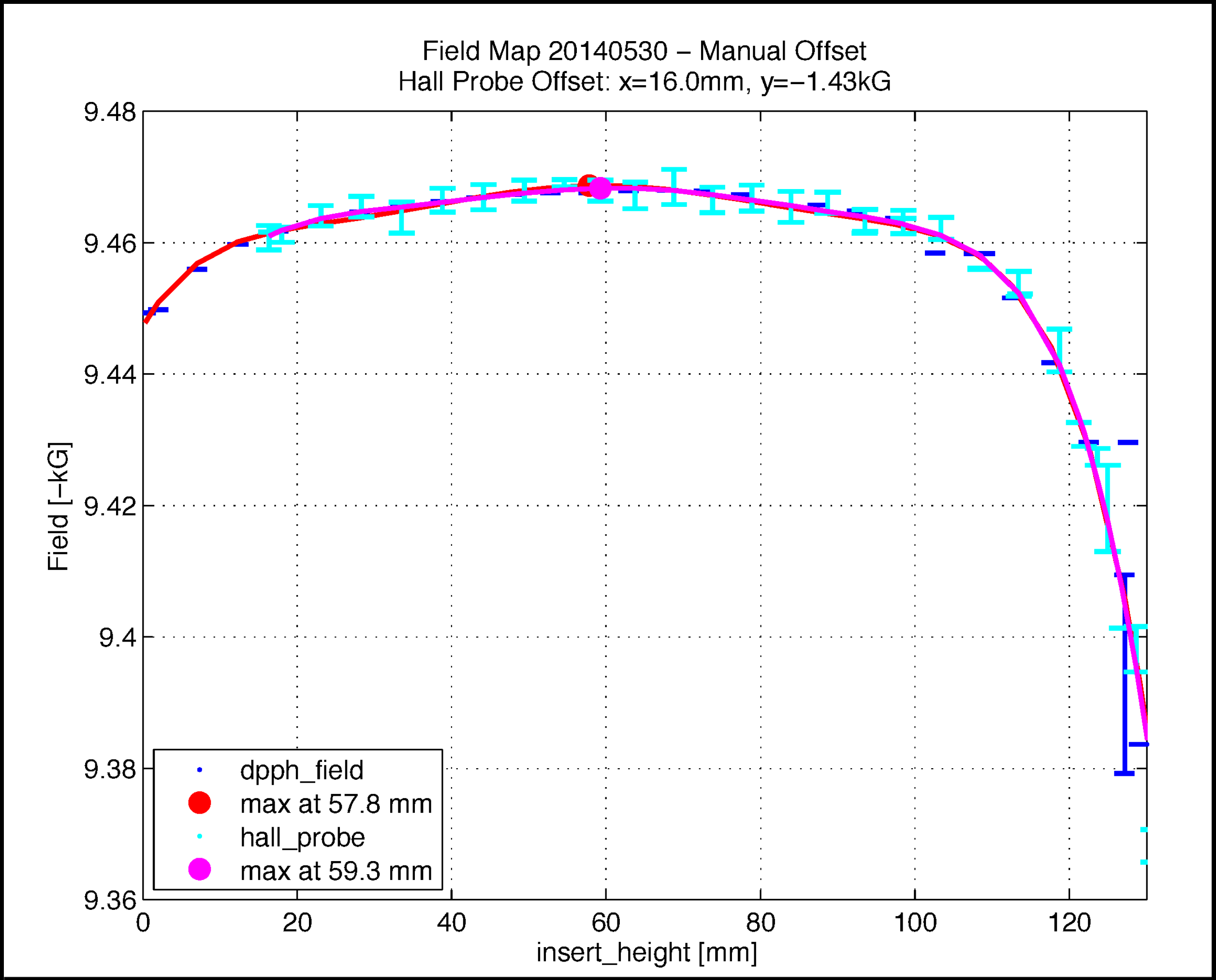
-Keeps pressure of residual gas below 10^{-6} torr so that electrons scatter infrequency

-Does not pump away Krypton

-Keeps temperature above Krypton freezing point

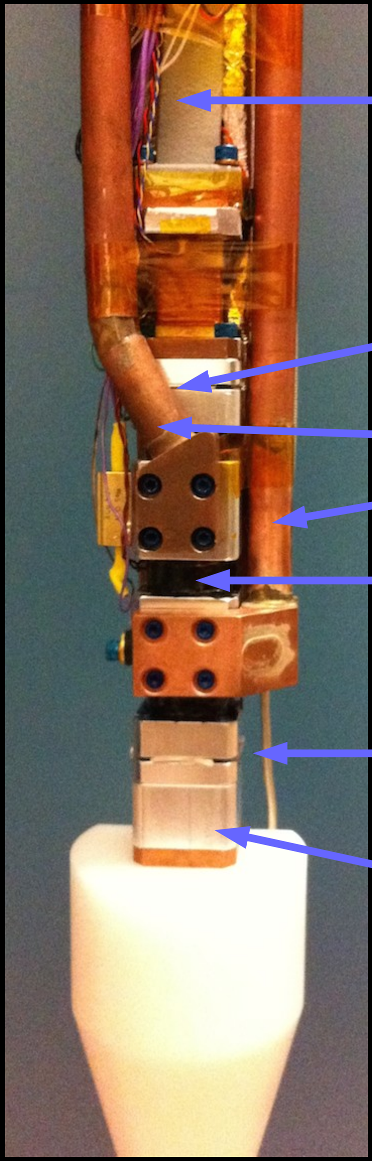
Magnet





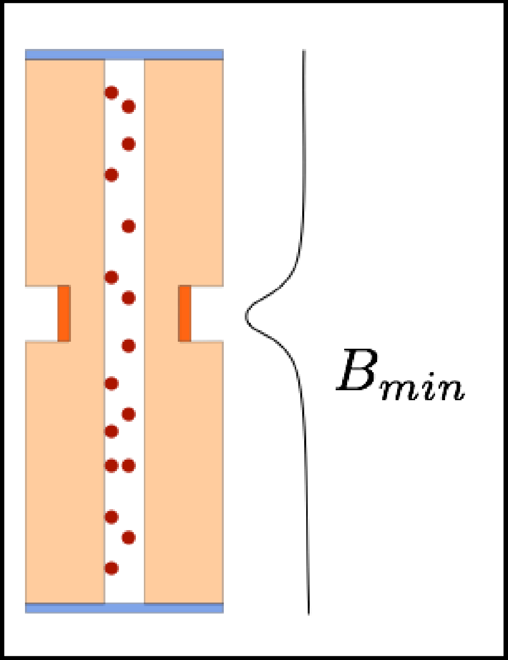
The primary field is provided by a repurposed NMR magnet

Waveguide Cell

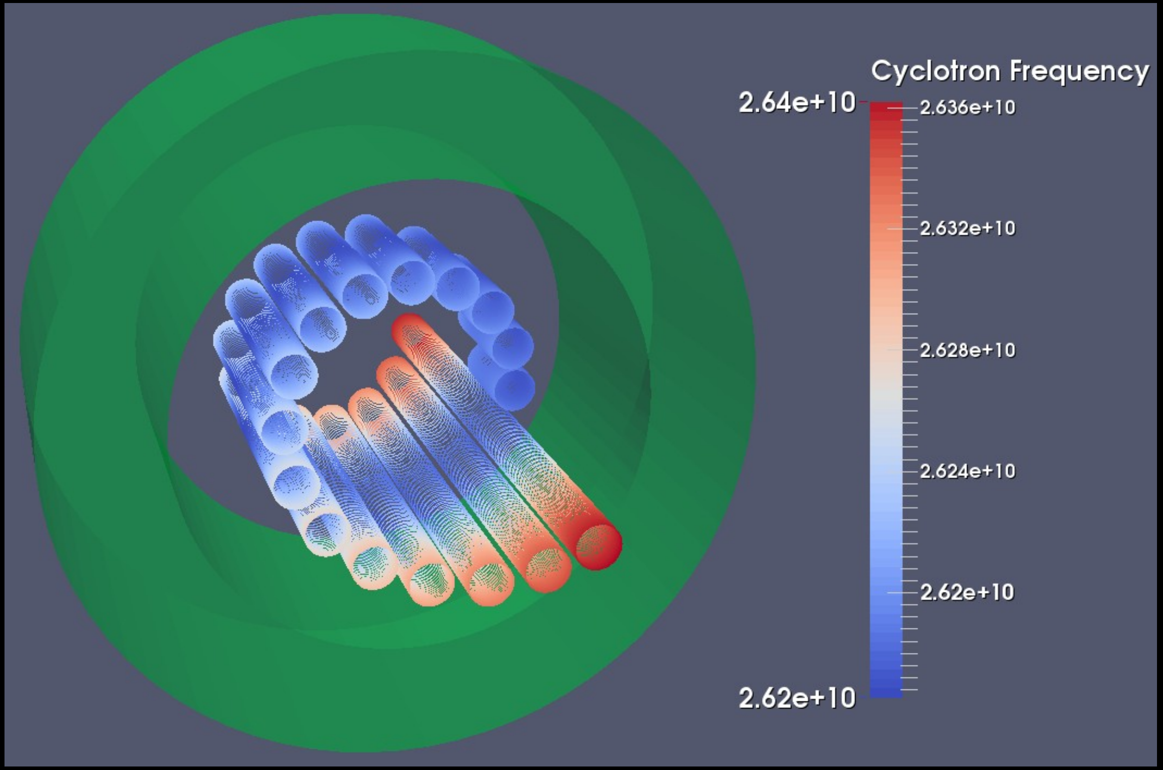


Magnetic Bottle

Waveguide Cell
Cut-Away View

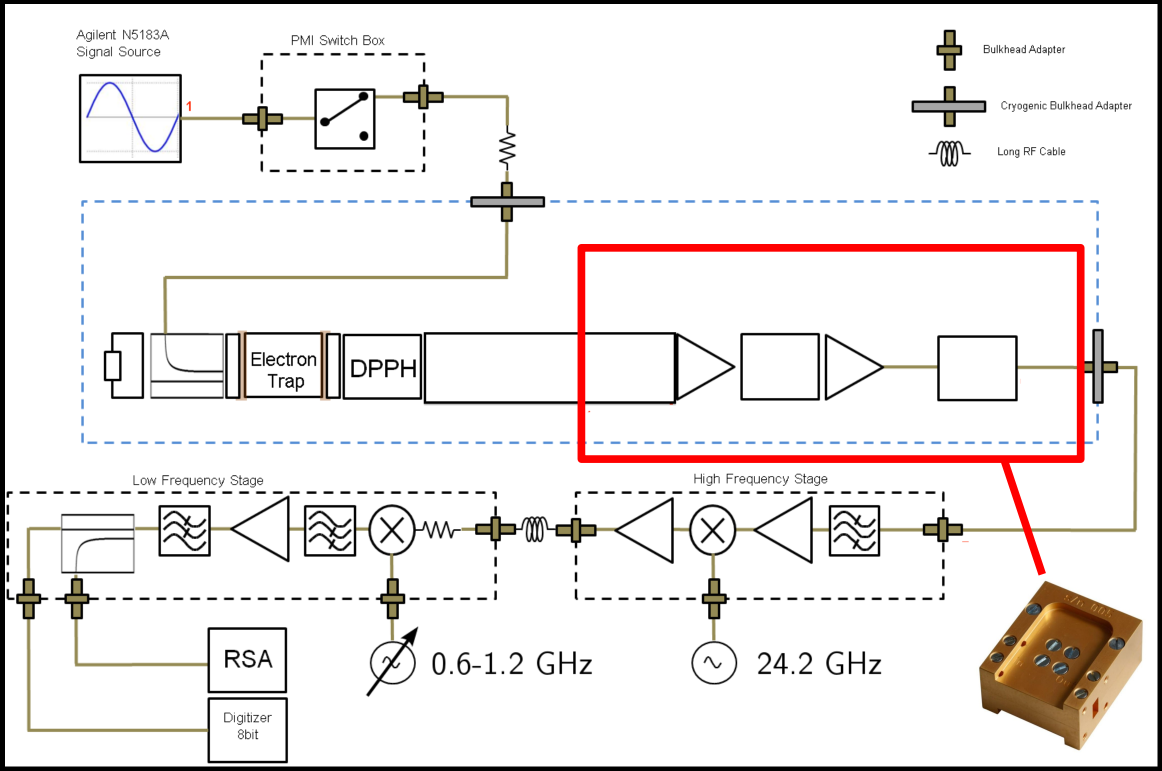


Simulation of Trapped Electron Trajectories



Effects of trap on measured frequency easily calculable

Signal Amplification and Noise

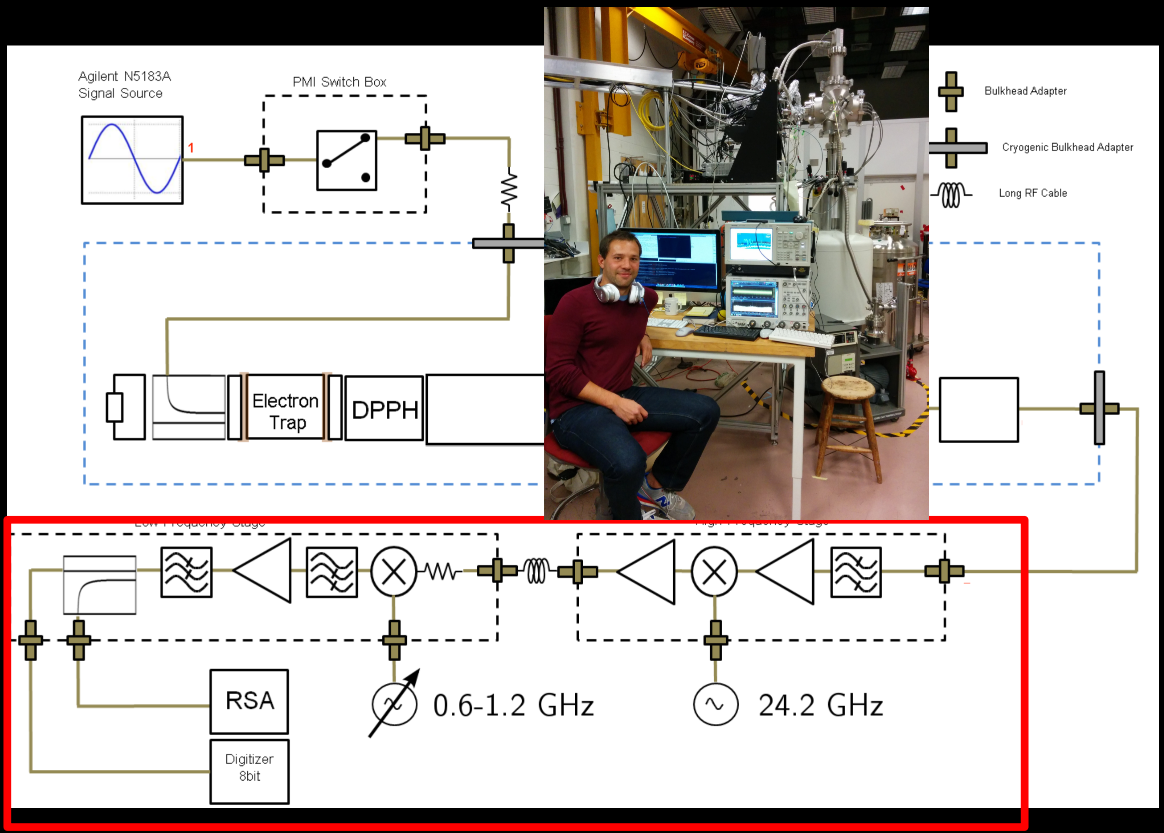


The primary background for detecting signals is thermal noise

Total noise background is the combination of the waveguide physical temperature and amplifier noise.

Noise temperature ~ 150 K

Receiver

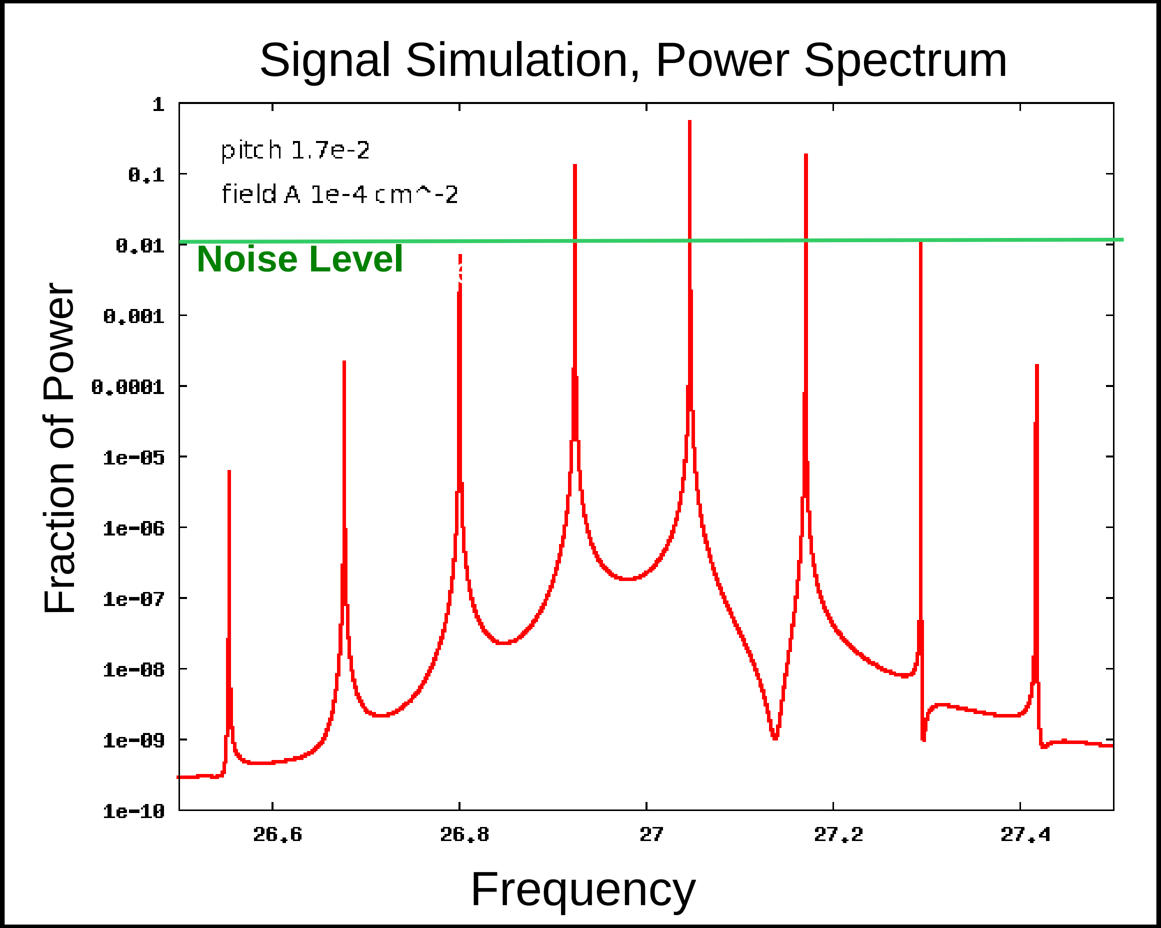


Signal is mixed down and digitized with bandwidth of 100 MHz

Receiver can be tuned to between 24.8 and 26.8 GHz

Signal is not visible in voltage-time series; spectral analysis must be used

Expected Signal – Instantaneous Power

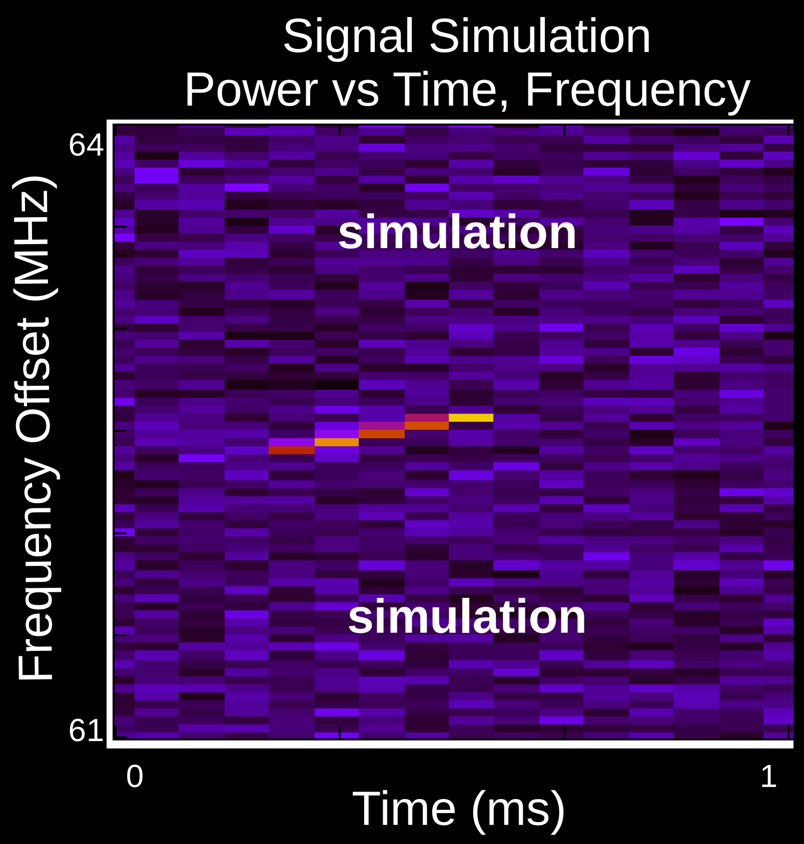


Most power will be concentrated near the cyclotron frequency

Additional structure will be introduced by motion in the trap

Cyclotron frequency will increase as energy is radiated

Expected Signal – Spectrogram



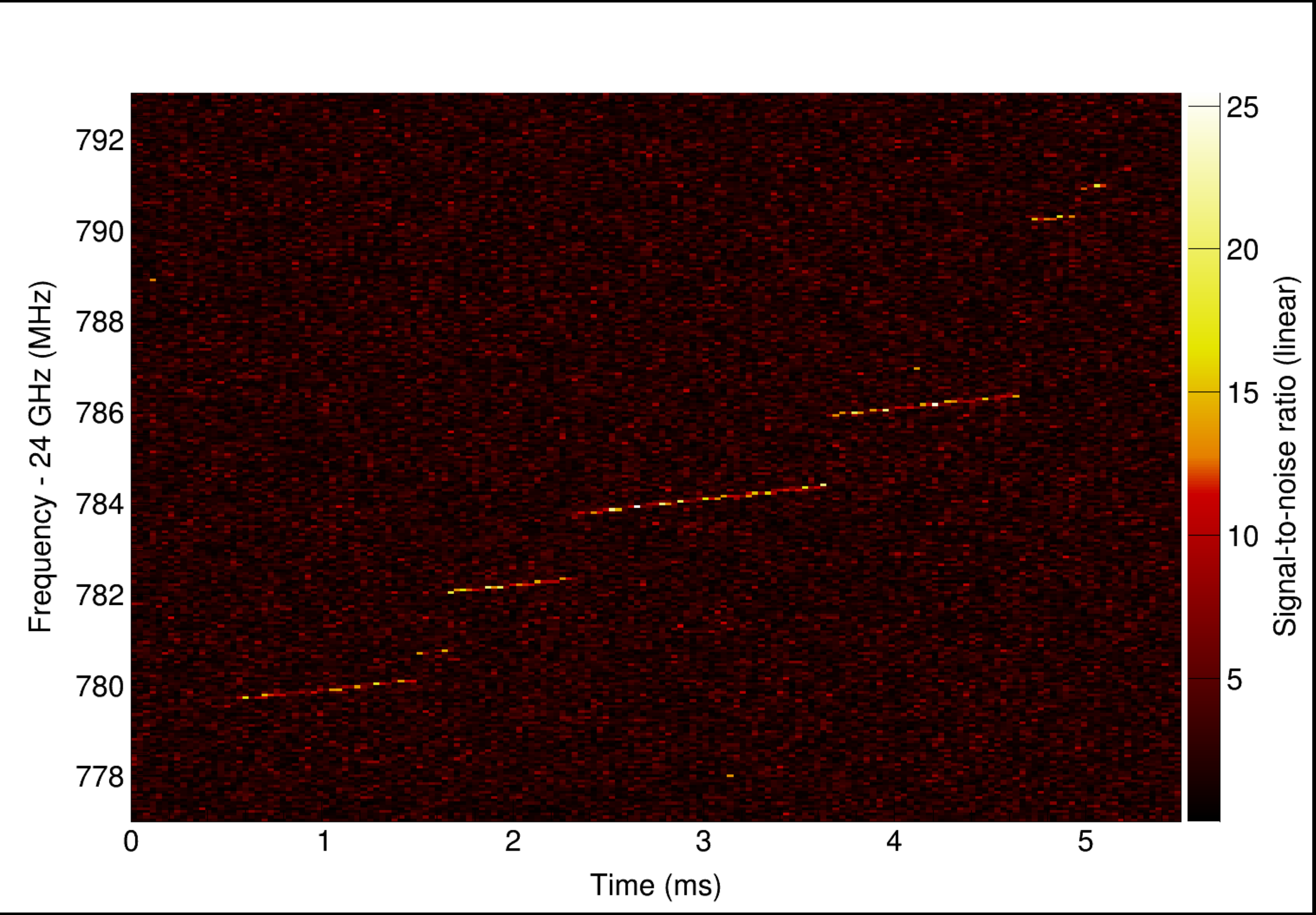
Consecutive power spectra are combined into a spectrogram

Color indicates power, so electrons radiating power are seen as upward moving streaks

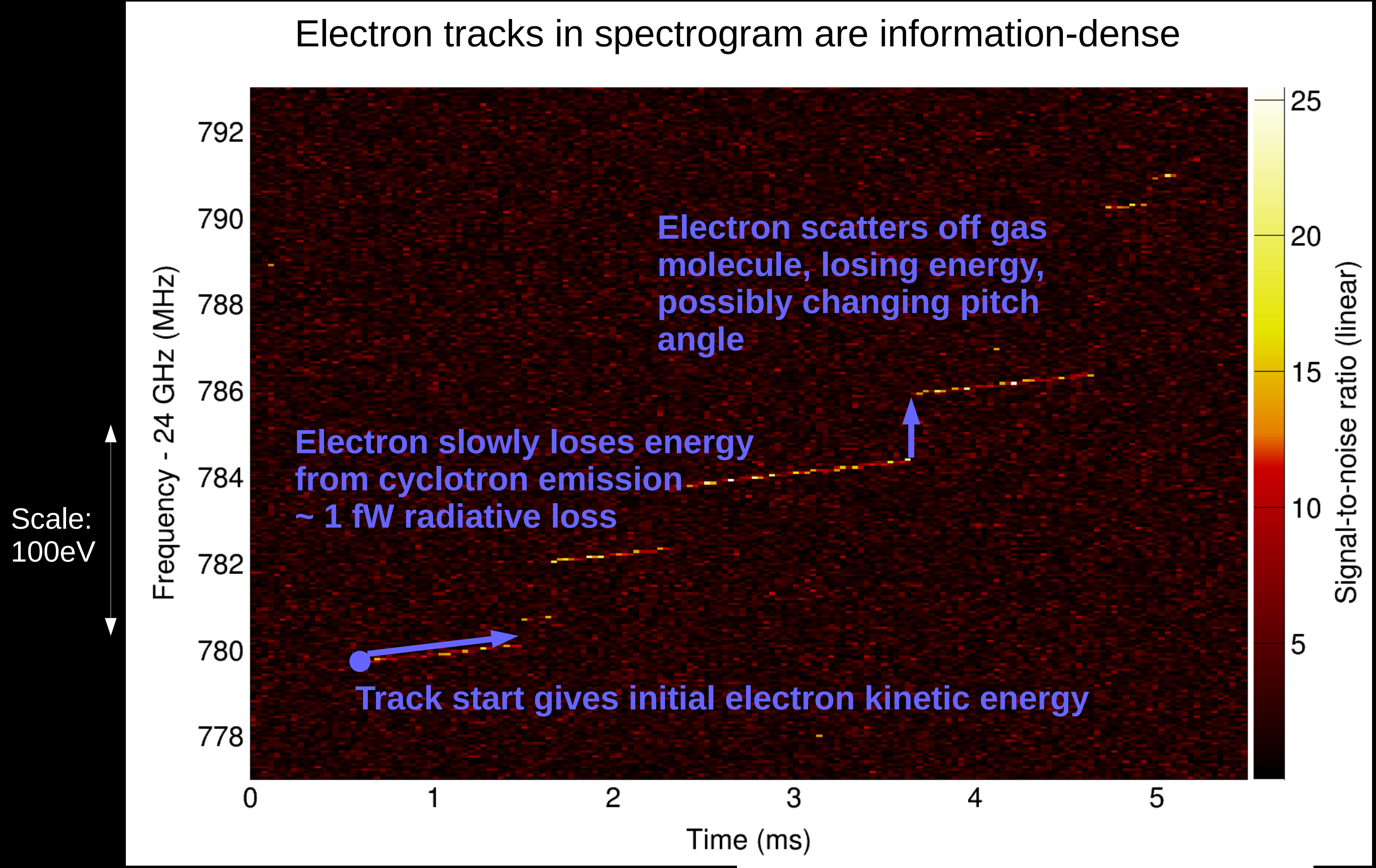
Actual Signal – Spectrogram

First detection of single-electron cyclotron radiation

Data Taking on 6/6/2014 immediately showed trapped electrons



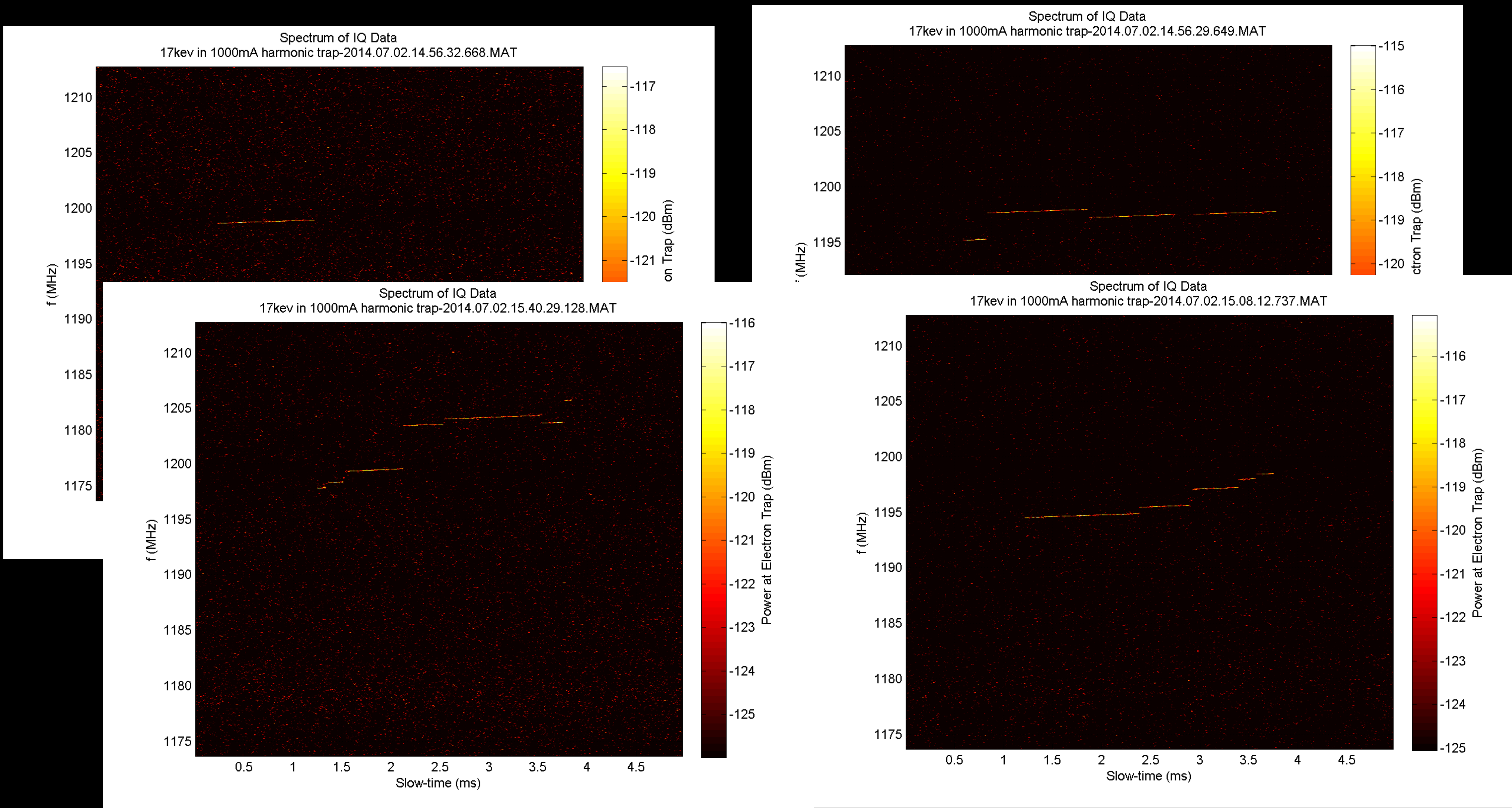
Spectrogram Information



Frequency depends on both energy and pitch angle

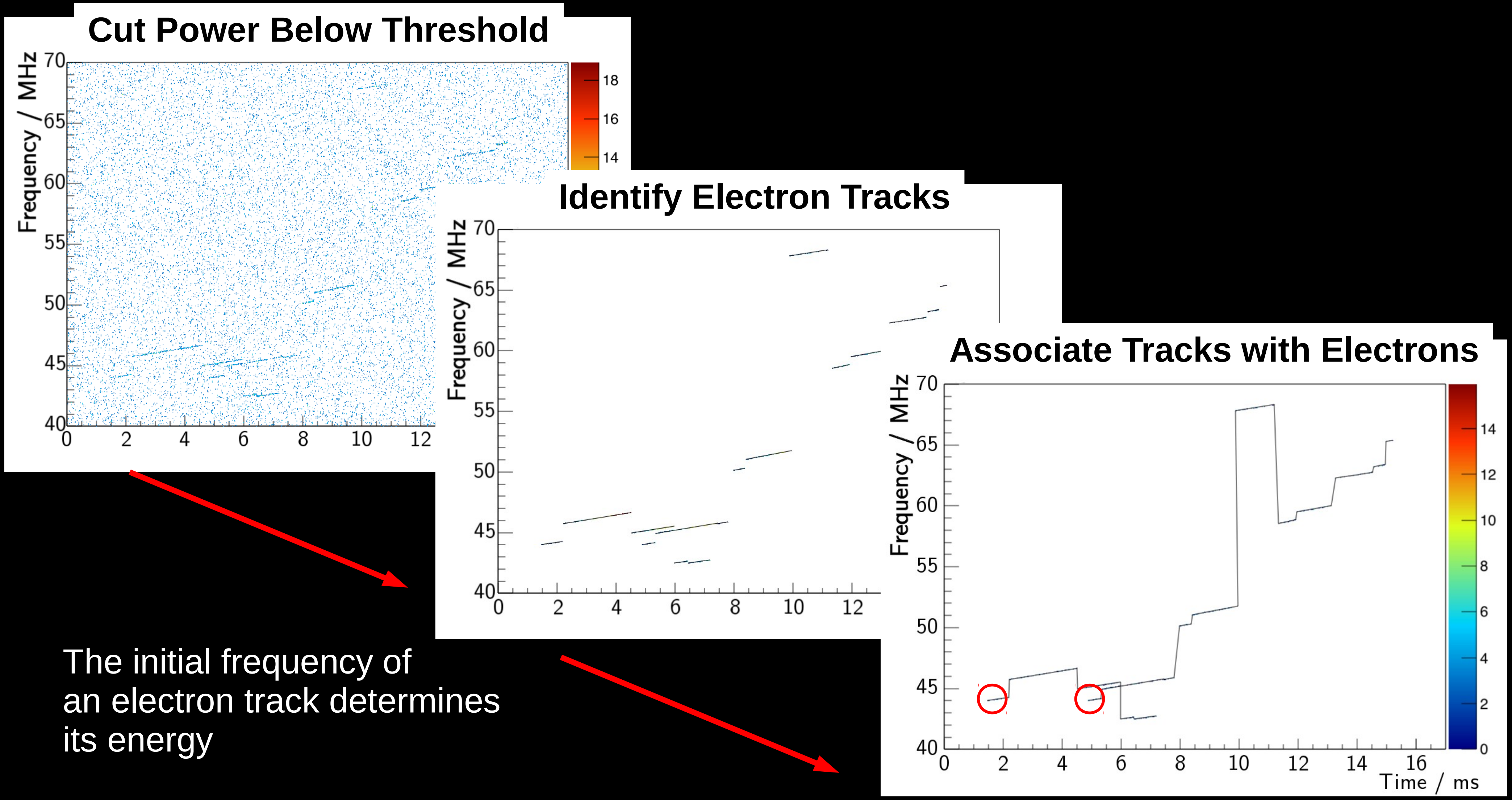
$$f \approx \frac{1}{2\pi} \frac{eB}{m_e + E_{kin}} \left(1 + \frac{1}{2} \cot^2 \theta\right)$$

Many Events



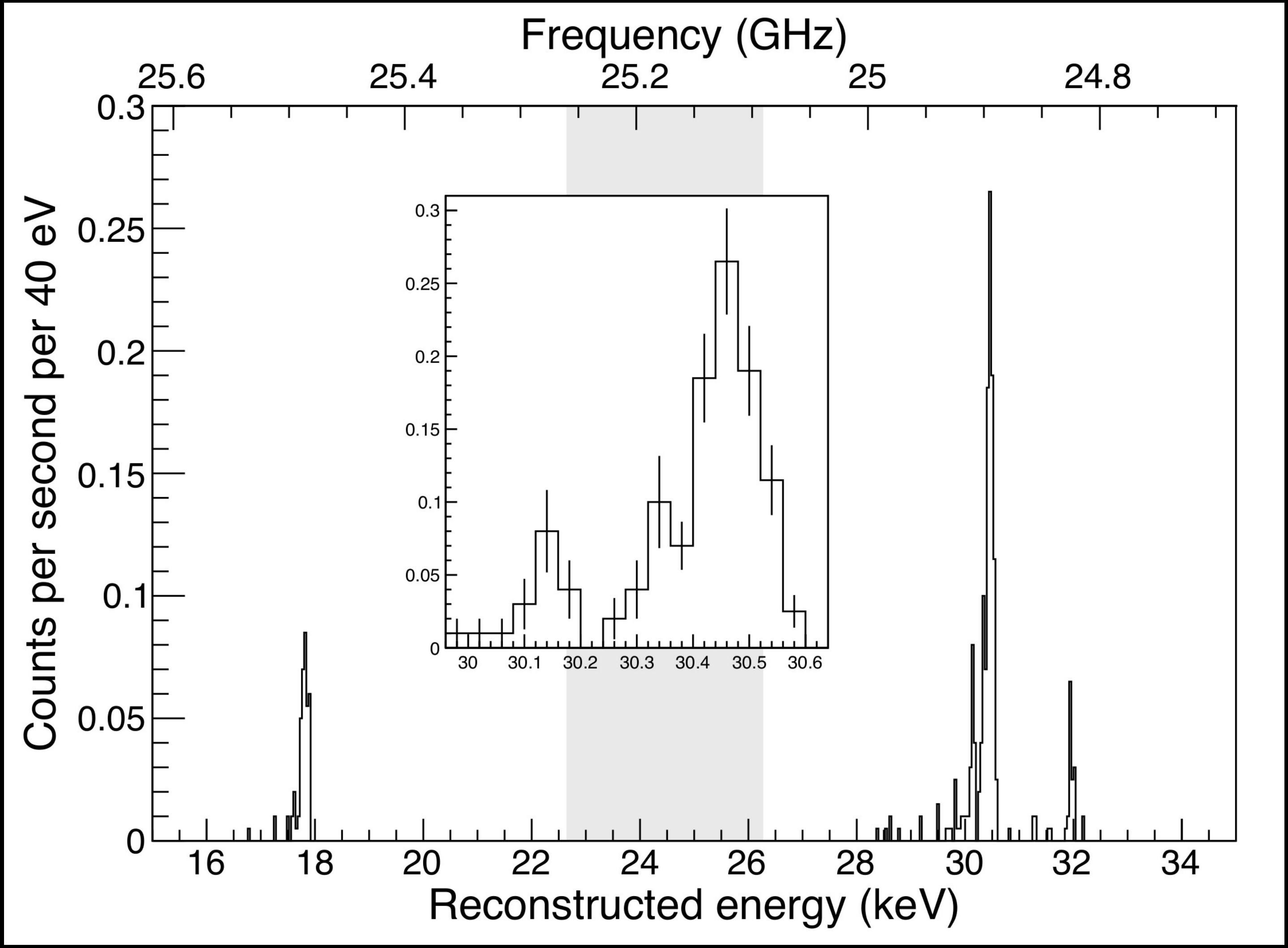
We have many events to study

Creating an Energy Spectrum



The initial frequency of an electron track determines its energy

Energy Spectrum

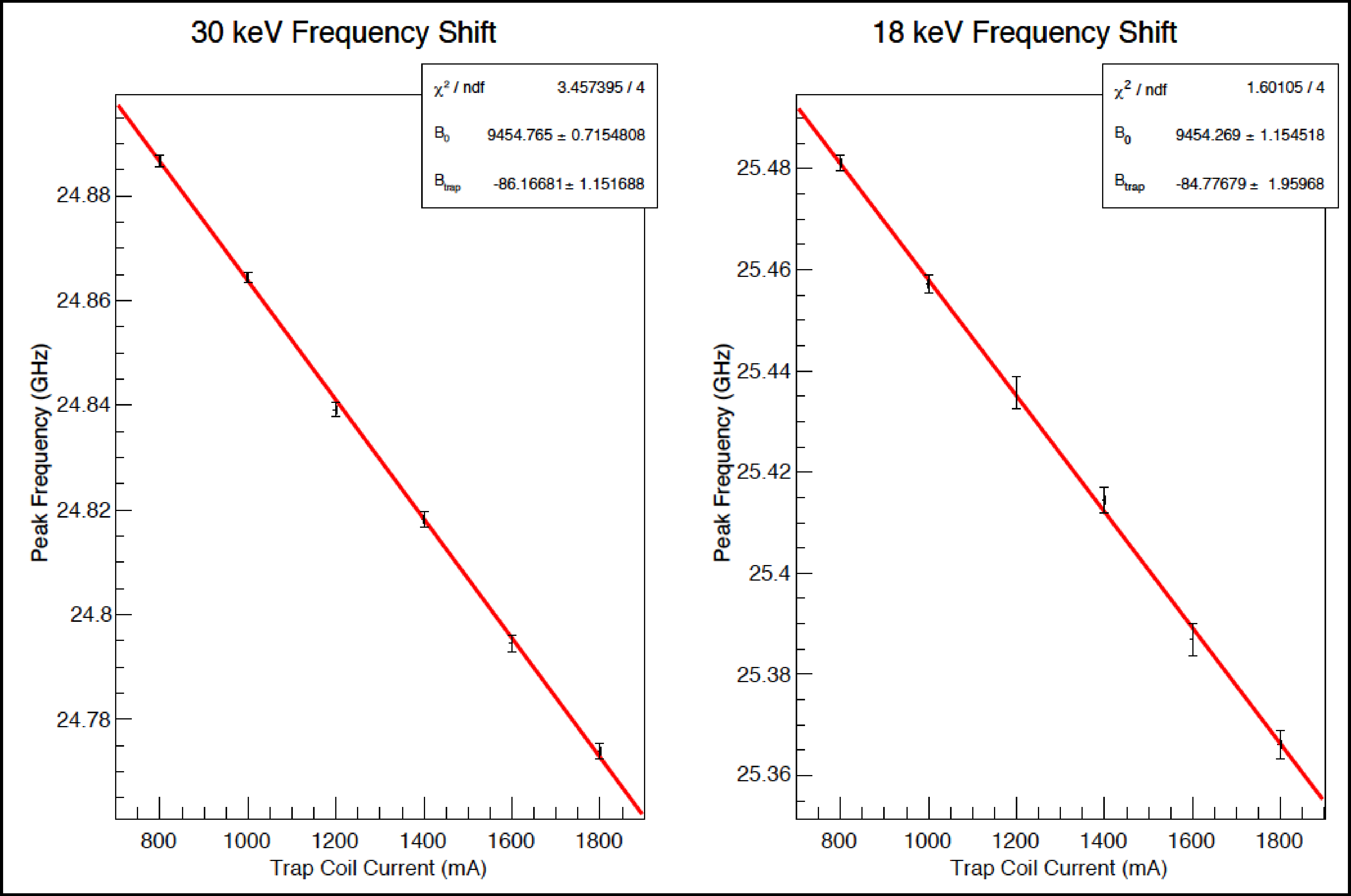


Krypton 83m
lines clearly seen

FWHM: 140 eV

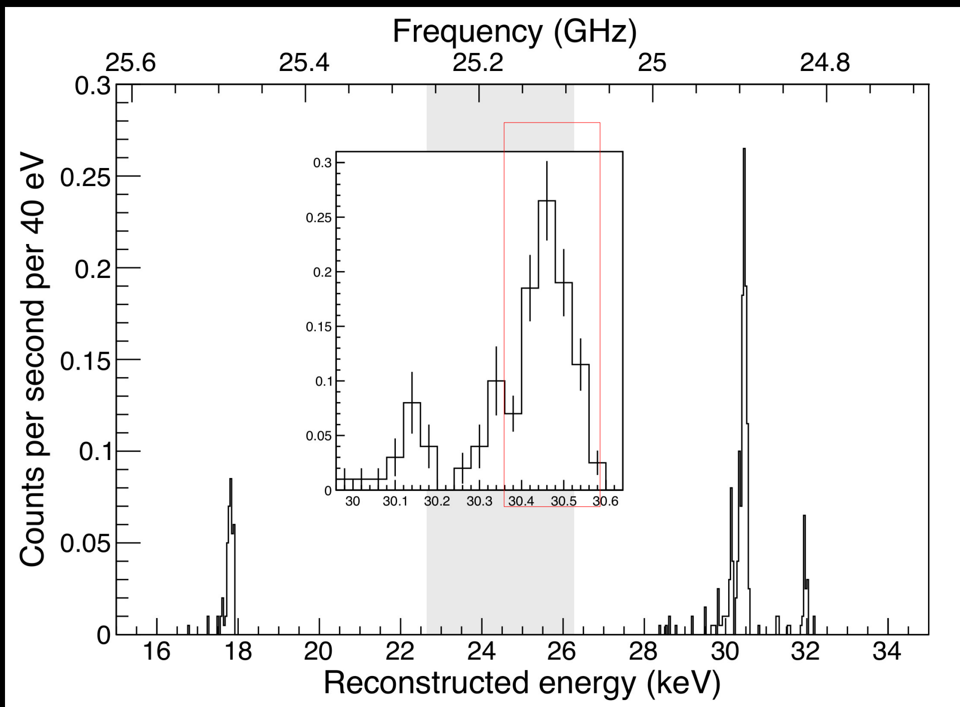
arXiv:1408.5362

Trap Effects on Frequency

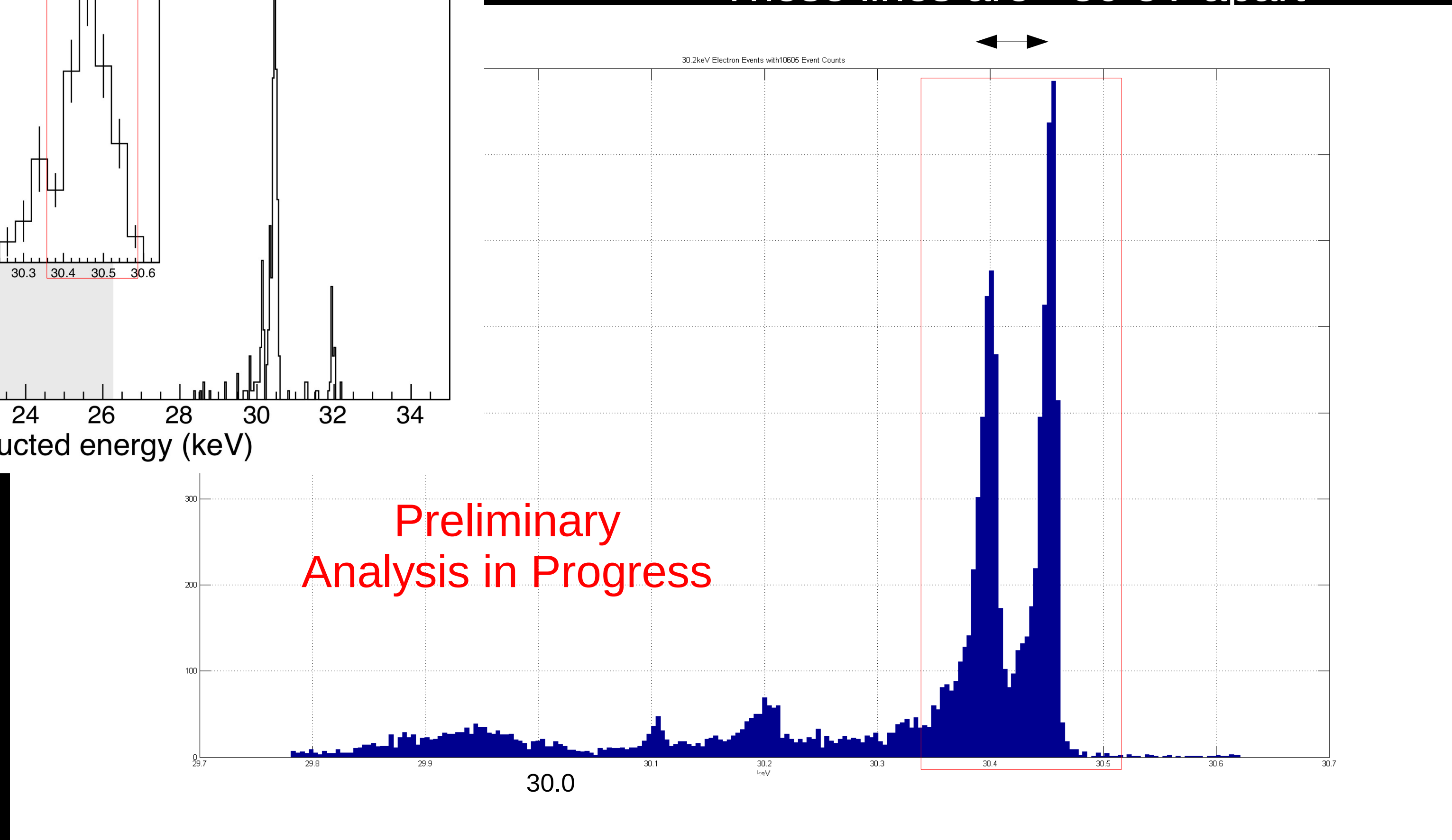


We understand and account for the frequency shift caused by the magnetic bottle

Improving Energy Resolution

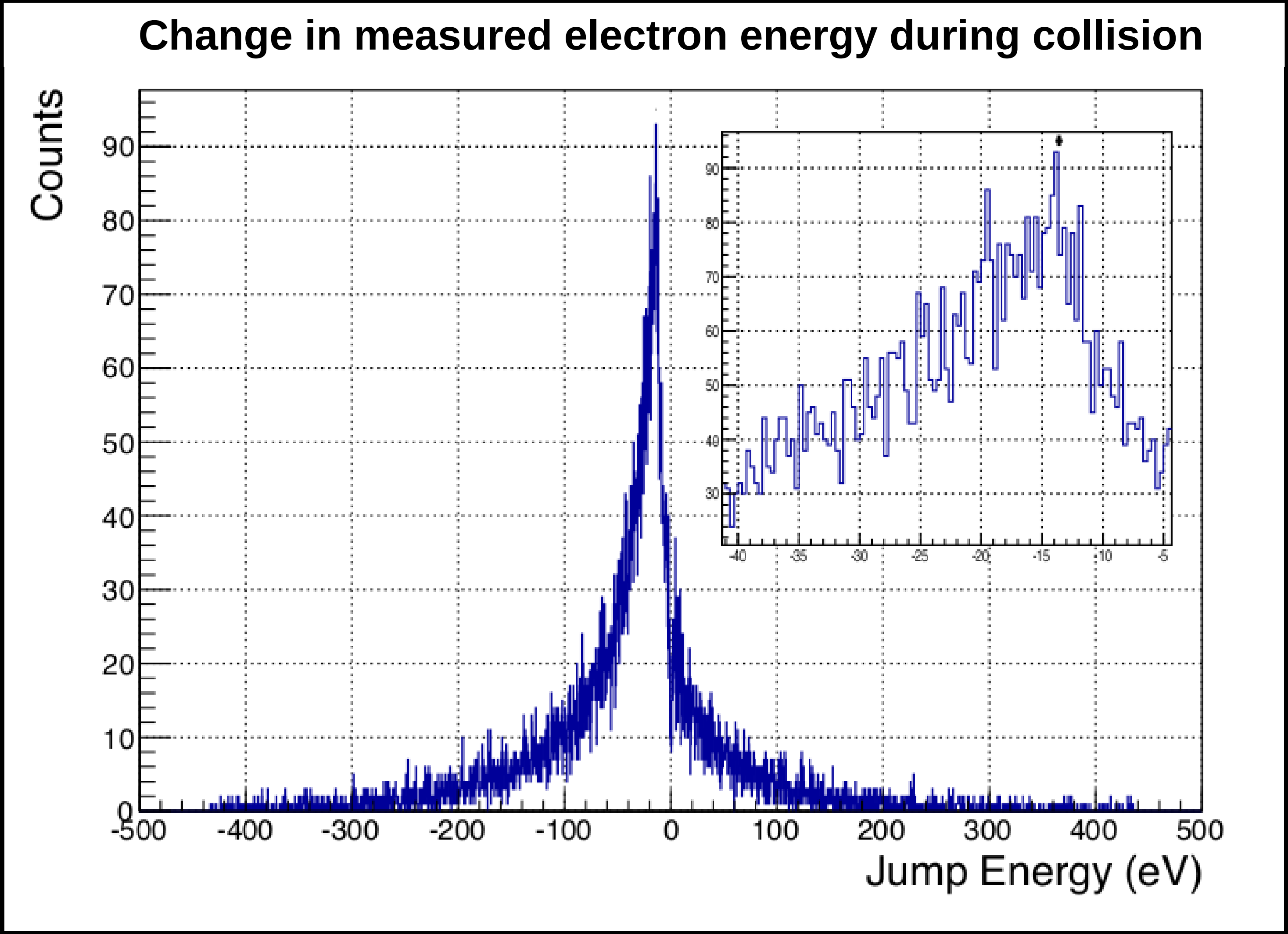


These lines are ~50 eV apart



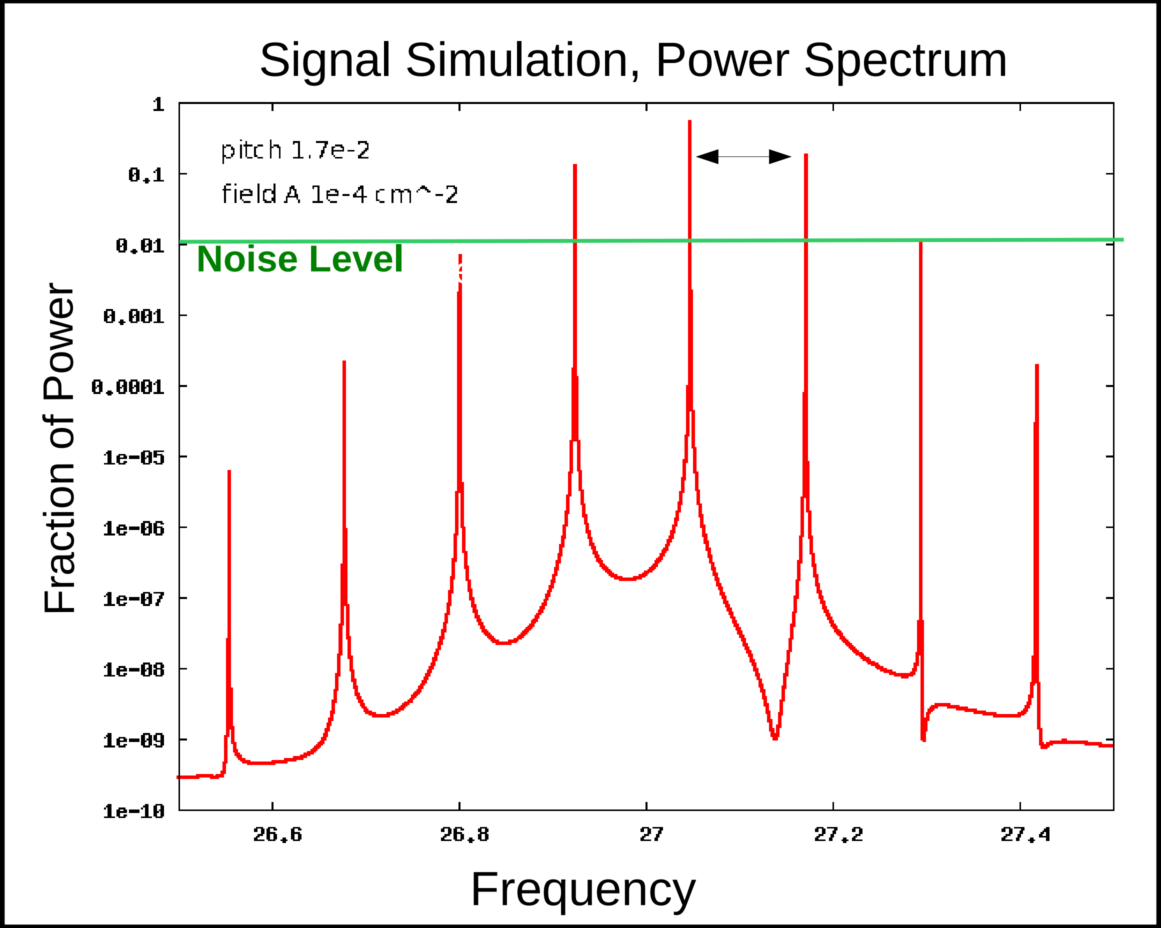
Our resolution is rapidly improving

Collision Energy Loss Spectrum

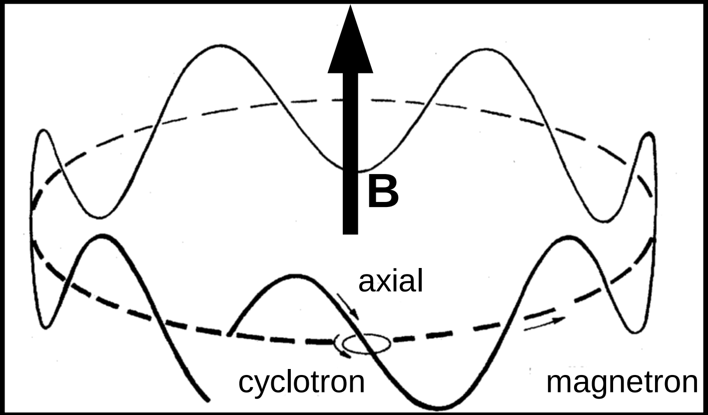


Our current estimate of the fundamental resolution of the technique is sub-eV

Near Future Analysis: Sidebands

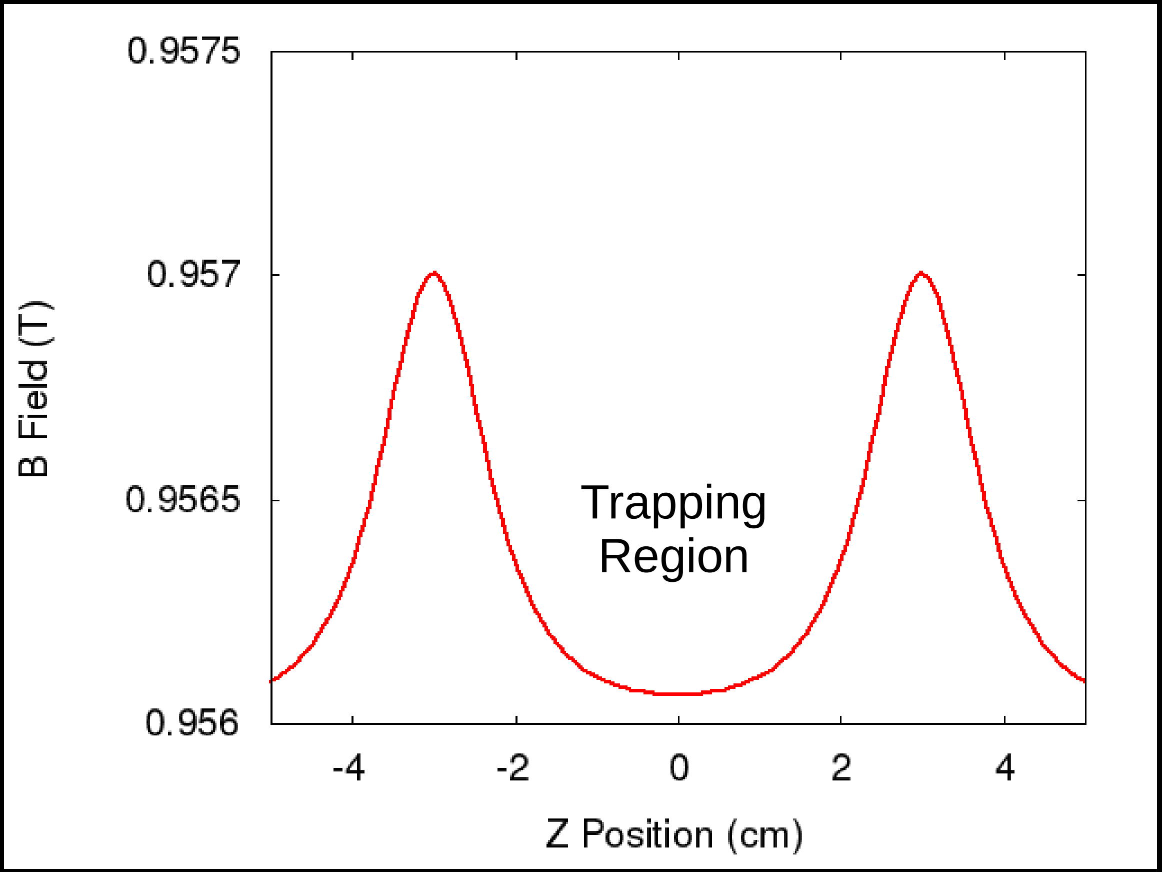


Additional spectral shape gives information about axial motion



This will allow event-by-event correction for field inhomogeneity

Near Future Hardware: “Bathtub” Trap

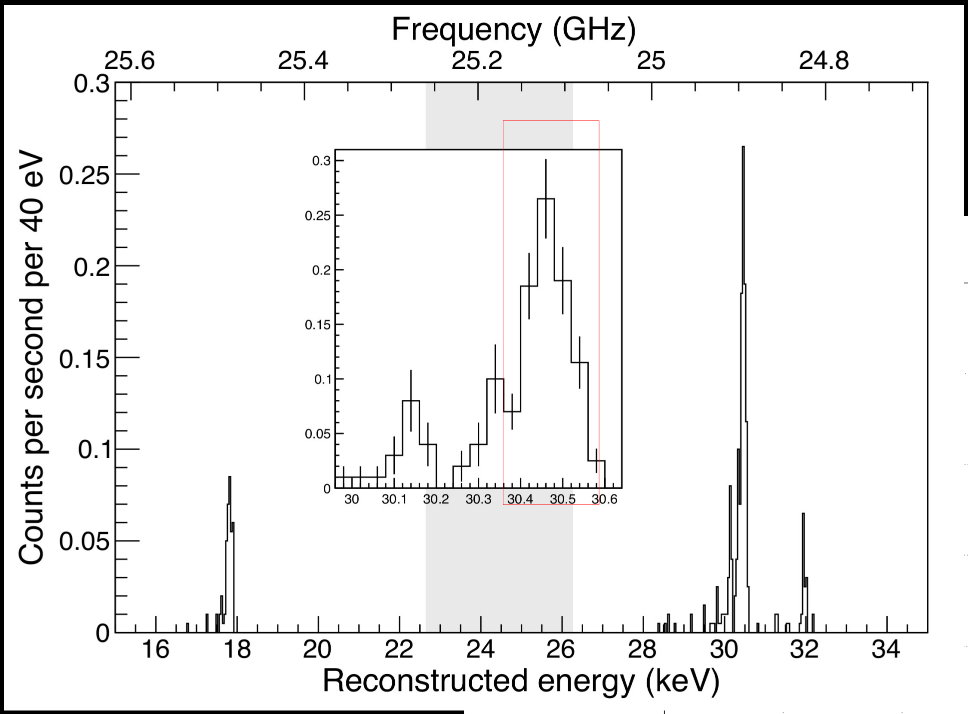


Changing magnetic bottle from one coil to two separated coils.

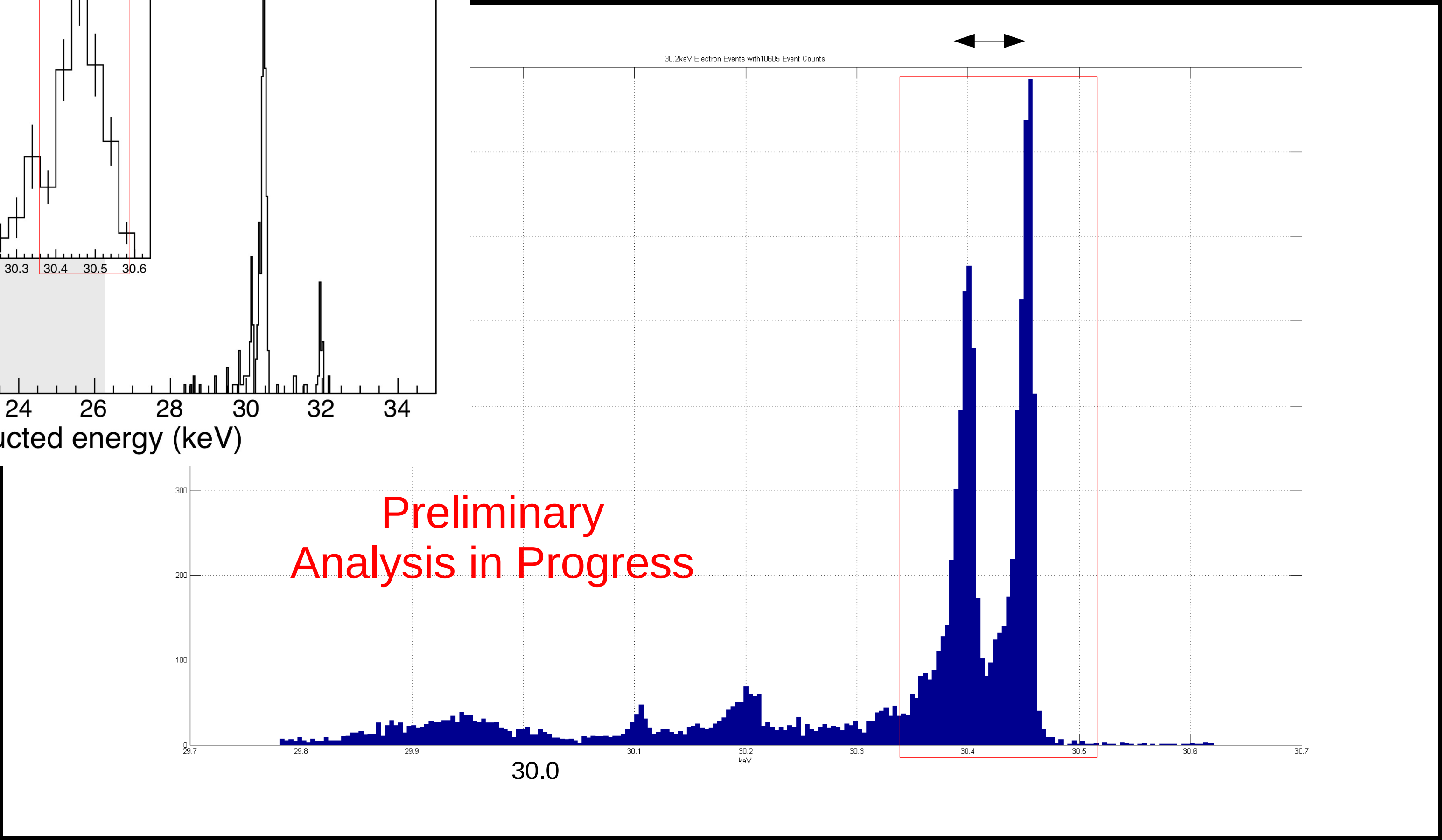
Will increase field homogeneity near center, increasing resolution

Active volume will also be increased

Applications: Nuclear Spectroscopy



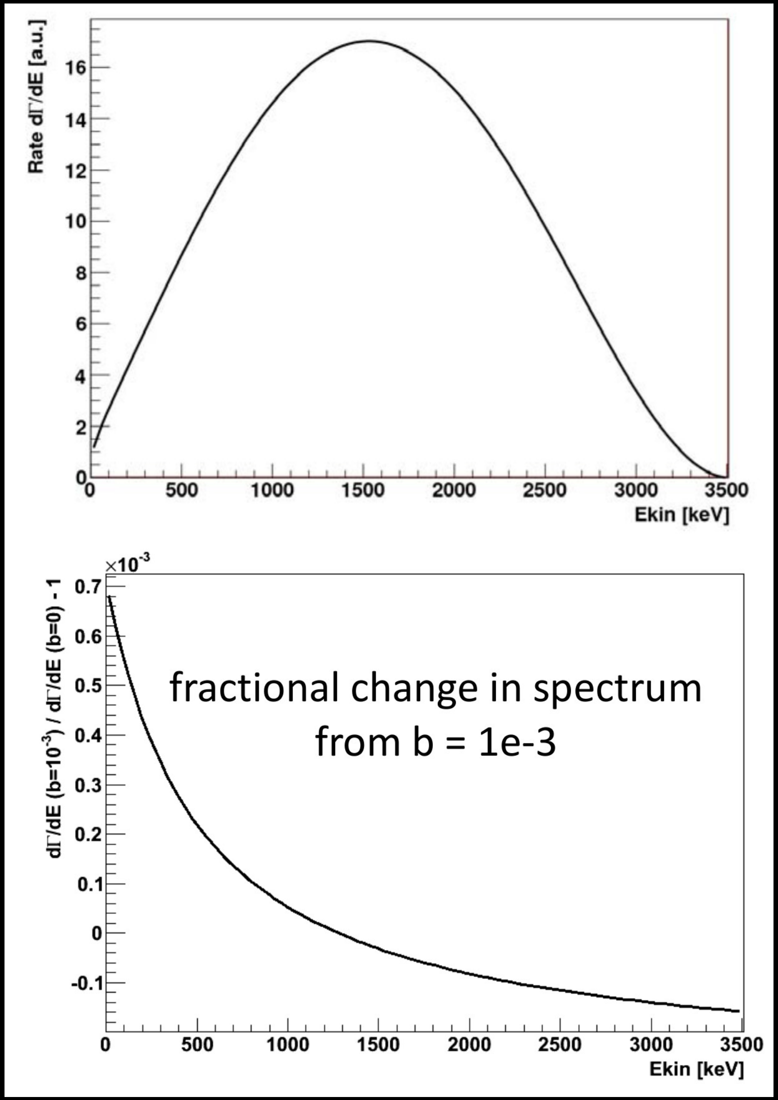
We are within an order of magnitude of making the most precise measurements of conversion electron lines



A variety of isotopes are under consideration. These are useful for both calibration and basic physics.

Applications: New Physics with ^{6}He

Helium 6 decay spectrum



The ^{6}He decay spectrum is sensitive to new physics (e.g. SUSY) that would modify the V-A nature of the weak force

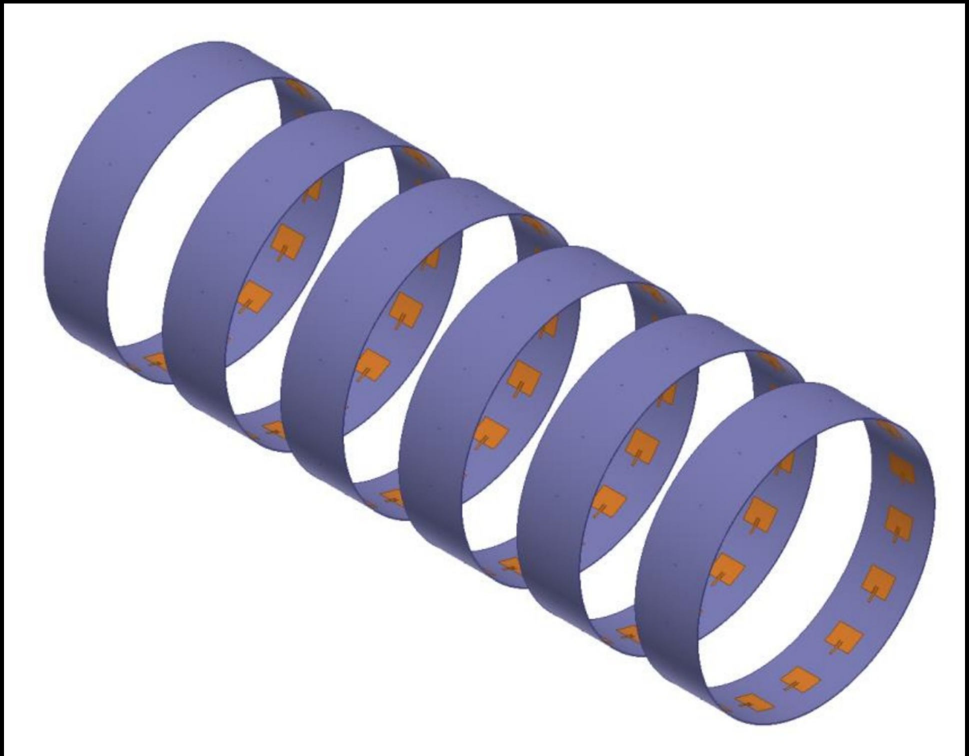
Higher energy precision spectroscopy could improve current measurements by an order of magnitude and explore interesting SUSY parameter space

This requires higher fields, larger volumes; R&D pathway under investigation.

Next Steps for Project 8: Towards a Neutrino Mass Experiment

- Improve Resolution by 1 Order of Magnitude
- Demonstrate Measurement of Tritium Energy spectrum
- Demonstrate Scalability of technique to ~ m^3
- Identify any new systematics
- Build neutrino mass experiment

Design of possible neutrino mass experiment



Example patch antenna configuration being modeled

Large bore, ~ 1 T uniform magnet

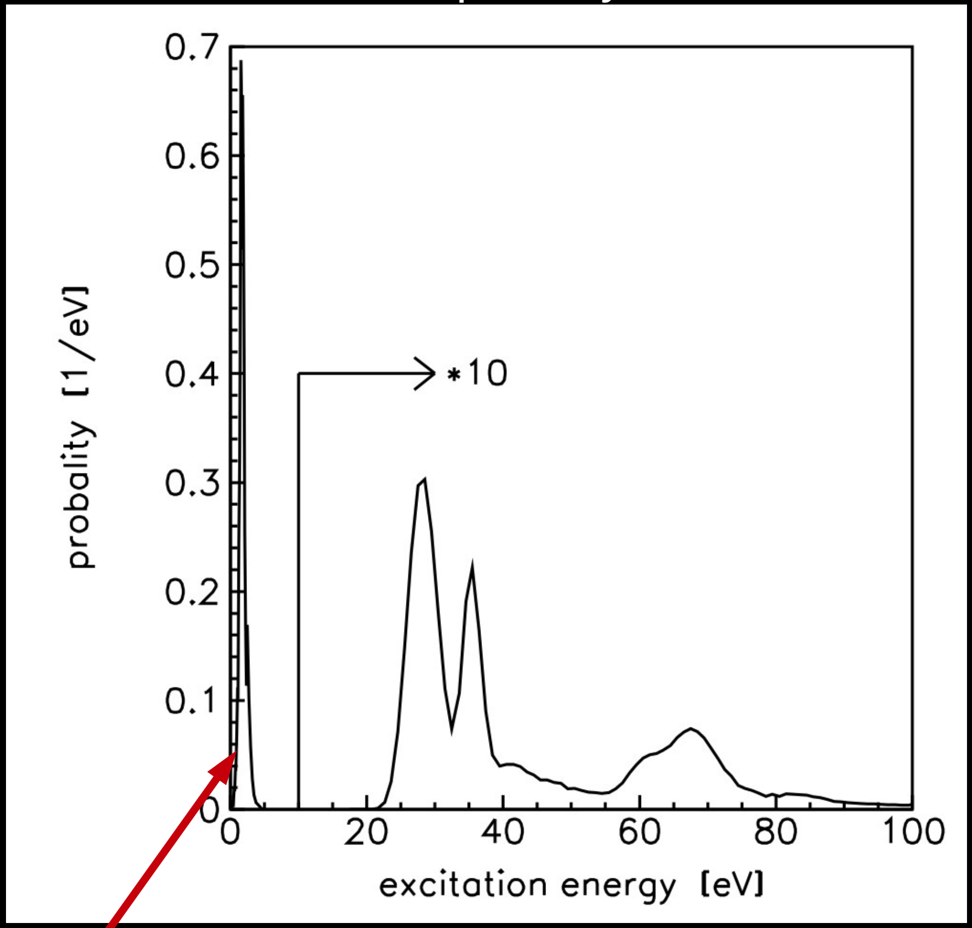
Pinch coils at either end

RF picked up by phased array of patch antennas

Phase information allows fiducialization of tracks

Molecular Tritium Limitations

Excitation Spectrum from Molecular Tritium β decay



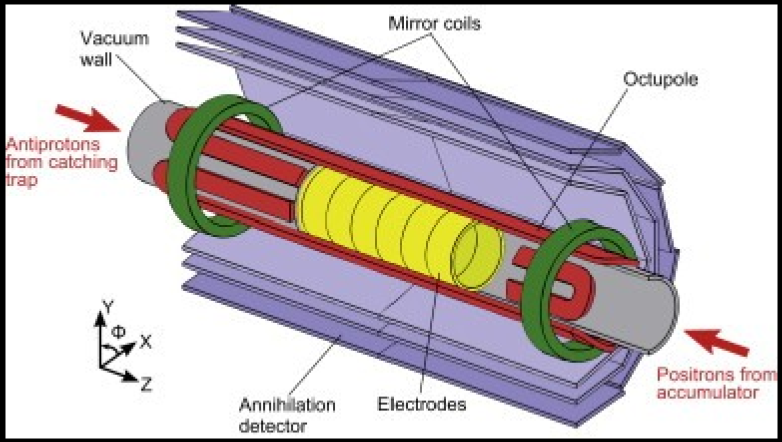
Source: Eur.Phys.J C40:447-478, 2005

This is the width that matters

Molecular excitations blur the tritium endpoint, fundamentally limiting the measurement of the neutrino mass scale

Beyond Molecular Tritium

Example: ALPHA antihydrogen trapping apparatus



Source: Amole et al. NIM A 736, 319 (2014)

Atomic tritium does not suffer from molecular excited states

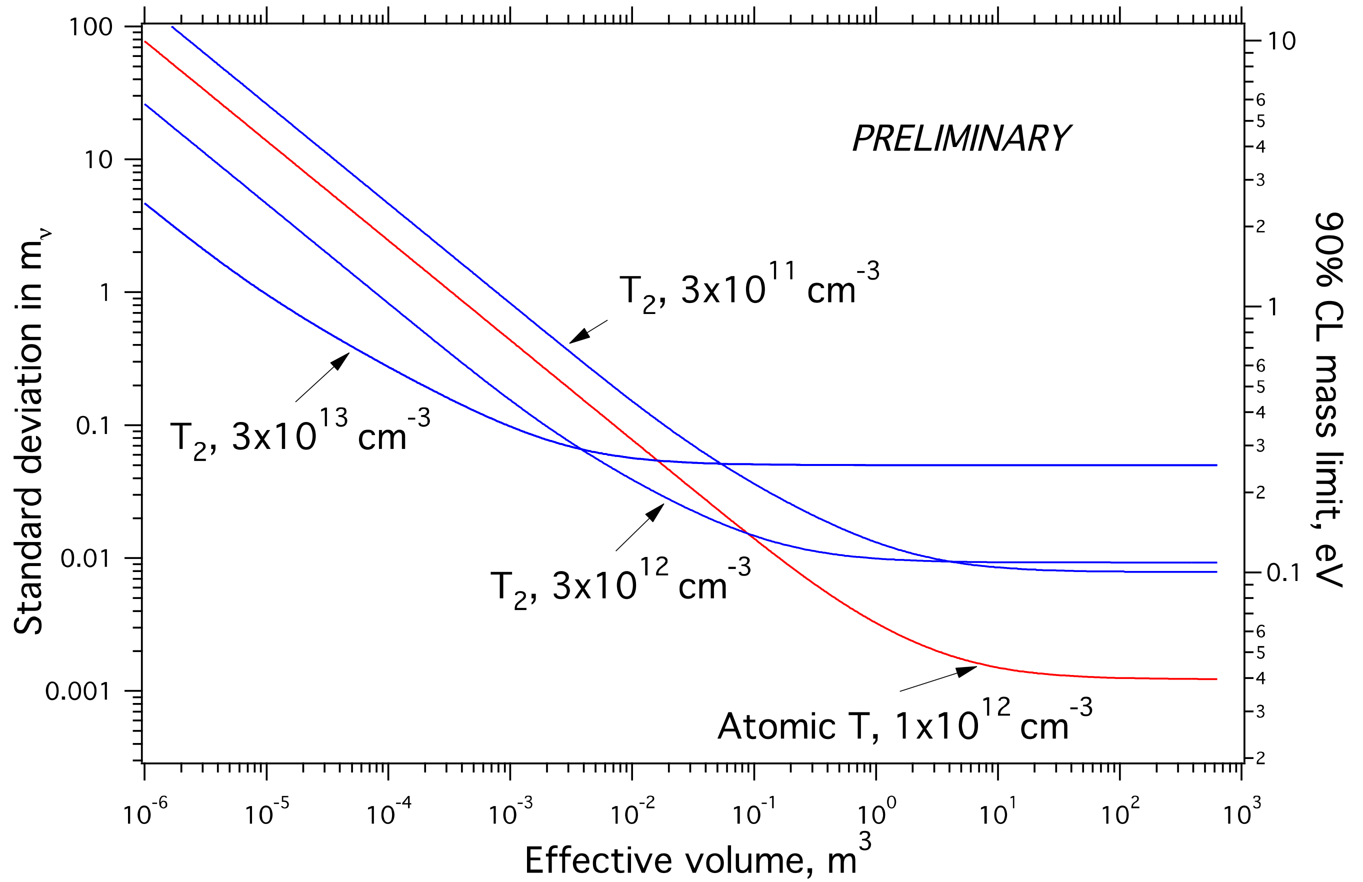
Atomic tritium sources must be prevented from recombining into molecular tritium

This likely requires an atomic trap superimposed on the electron trap

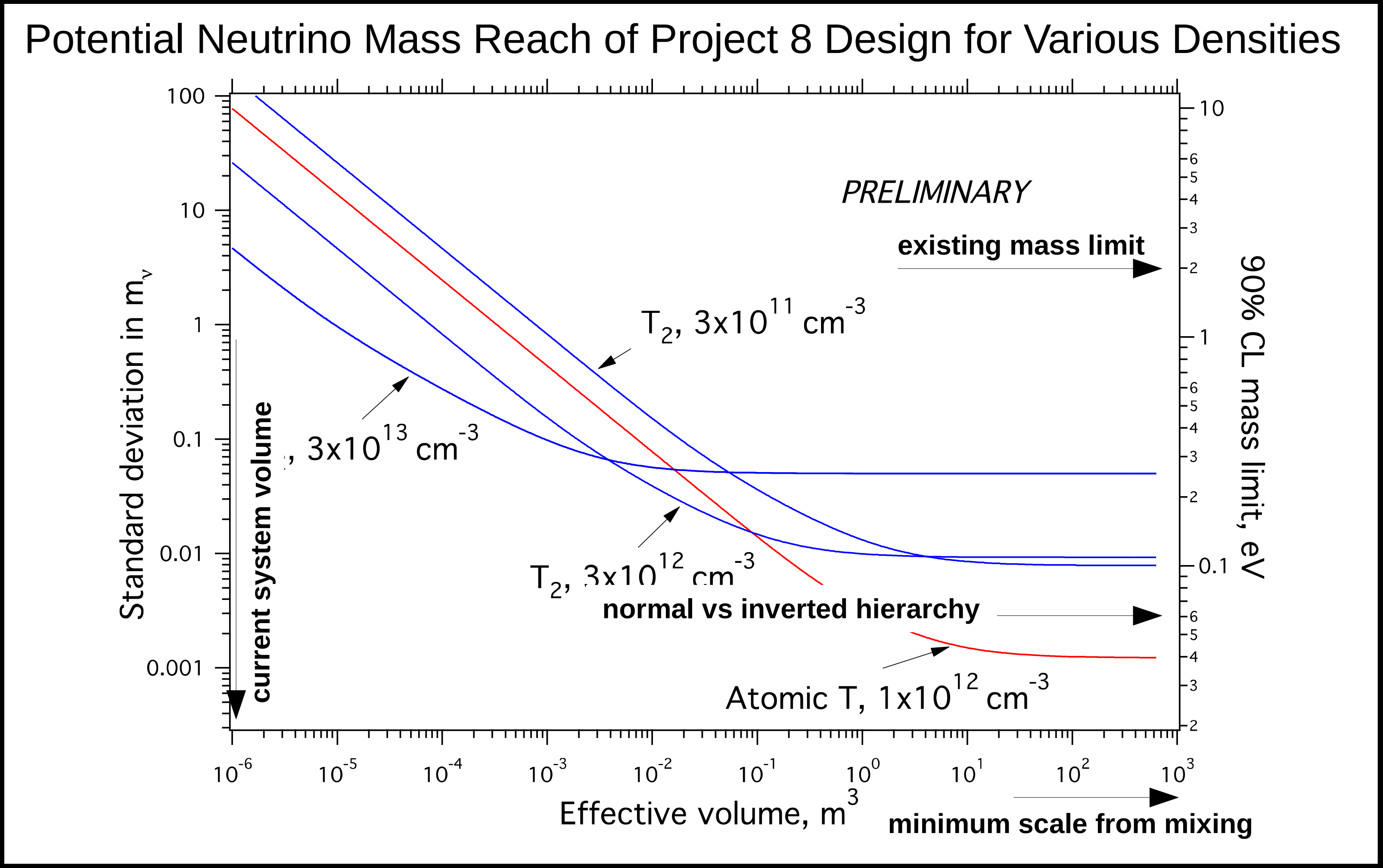
Devices to do similar tasks have been built, feasibility studies underway

Potential Neutrino Mass Reach

Potential Neutrino Mass Reach of Project 8 Design for Various Densities



Potential Neutrino Mass Reach



Conclusions

- Project 8 has demonstrated the detection of single electrons from their cyclotron radiation

- The energy resolution obtained using this technique is exquisite

- We have a clear path to developing this technology into an experiment that measures the neutrino mass scale