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

Noah Oblath
MIT

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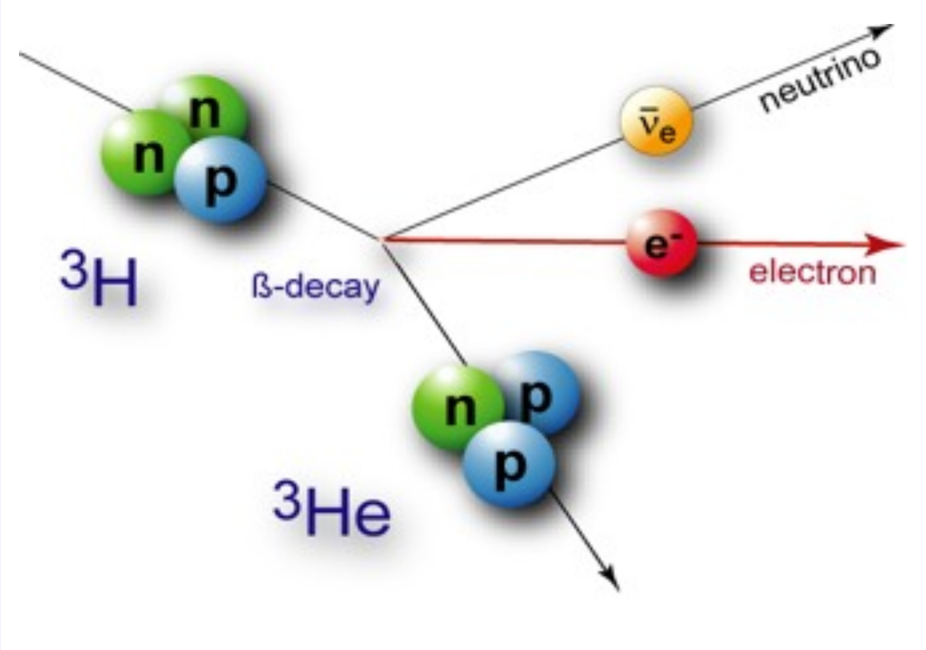
Laboratory for Nuclear Science

PROJECT 8

Tritium Beta Decay



...from which we detect the electron

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

Energy Spectrum

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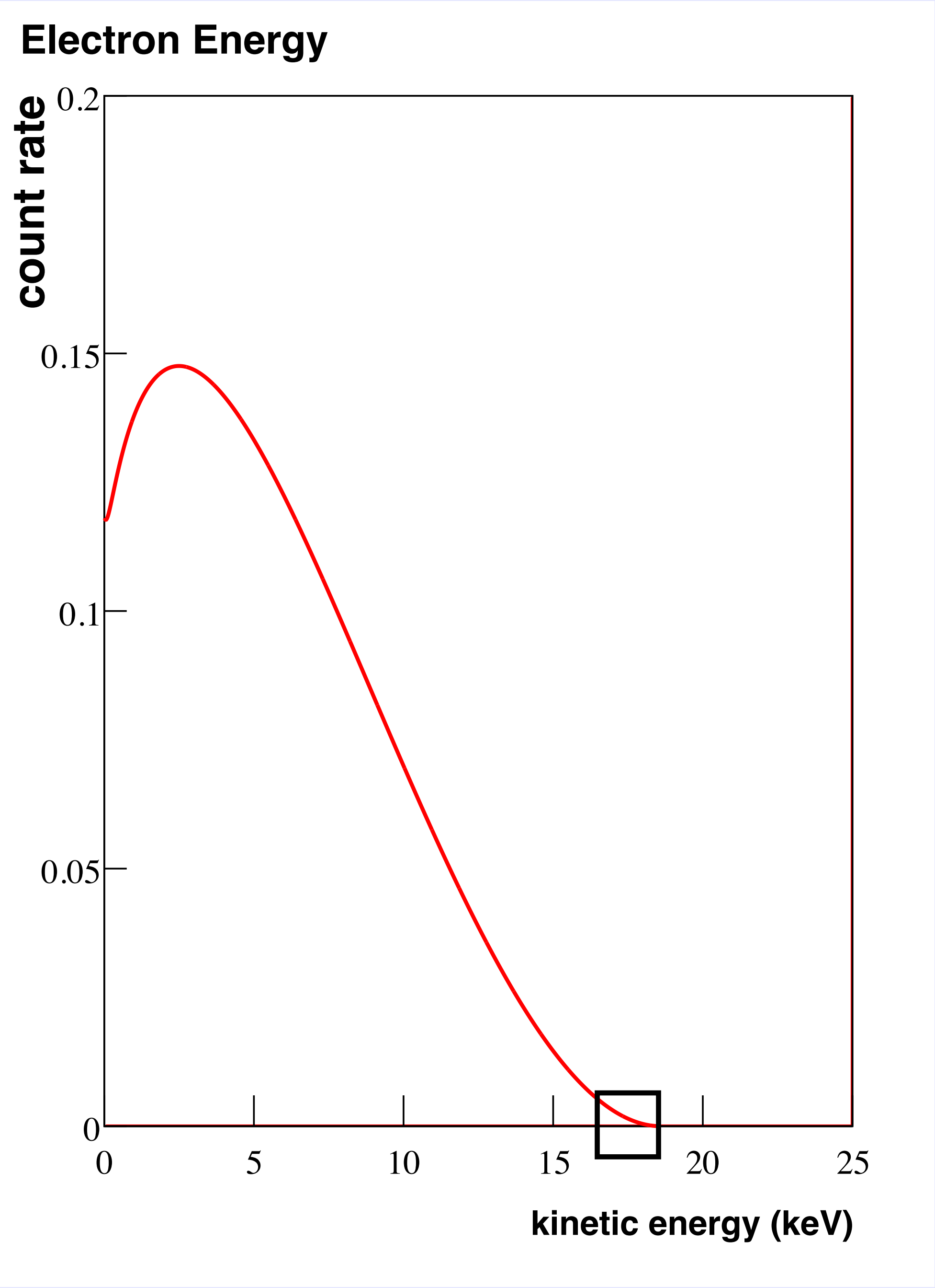
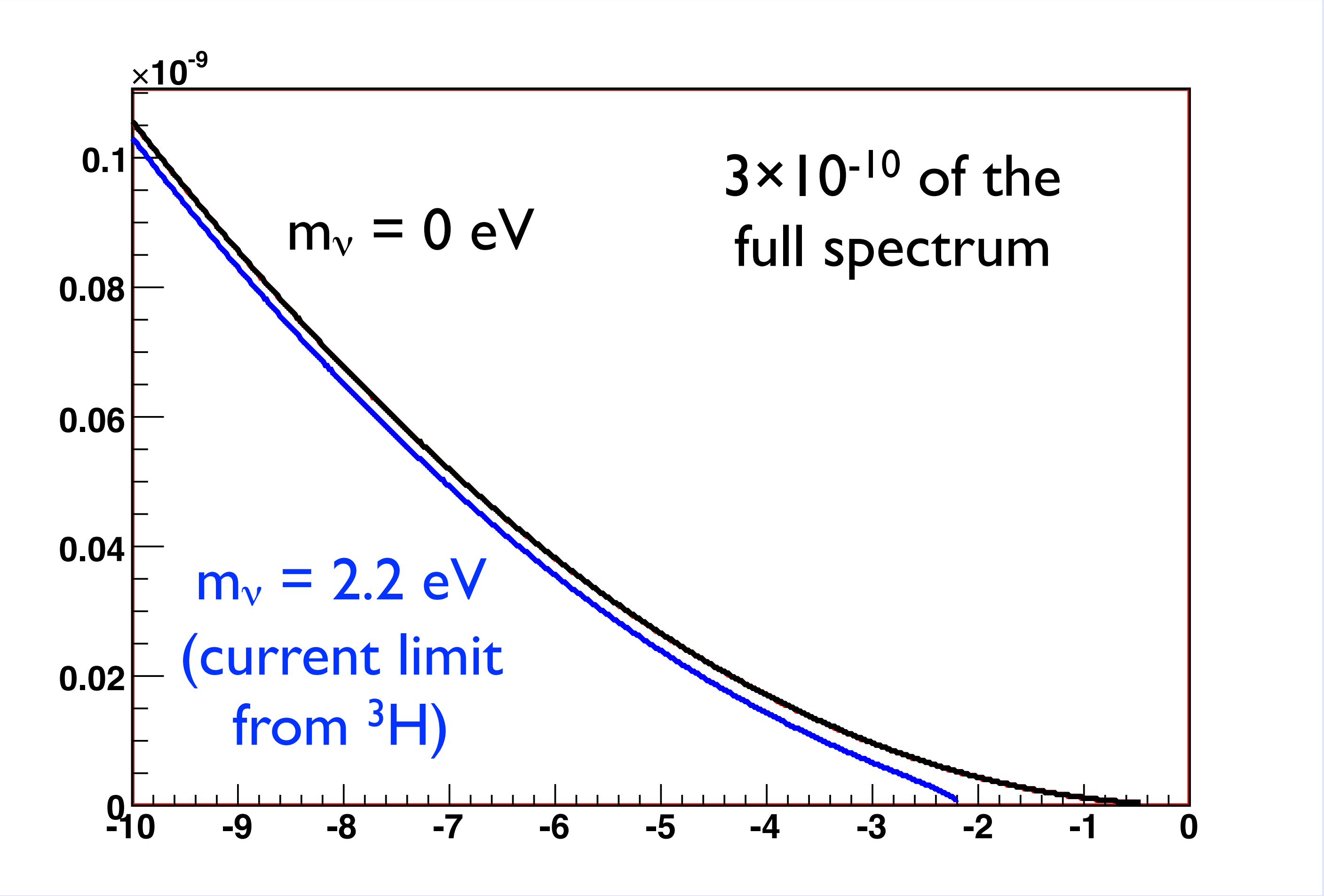
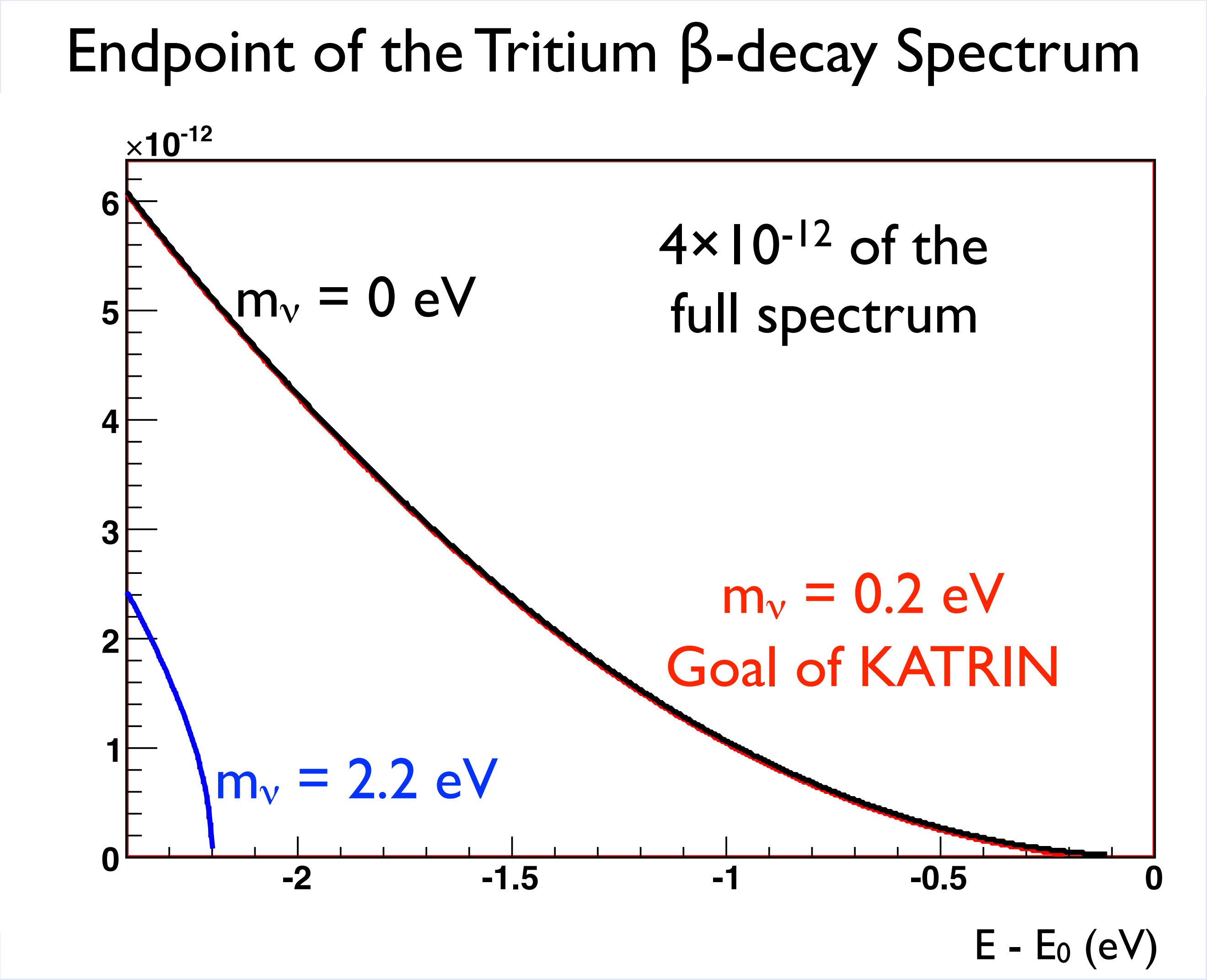
The shape is modified by the neutrino mass



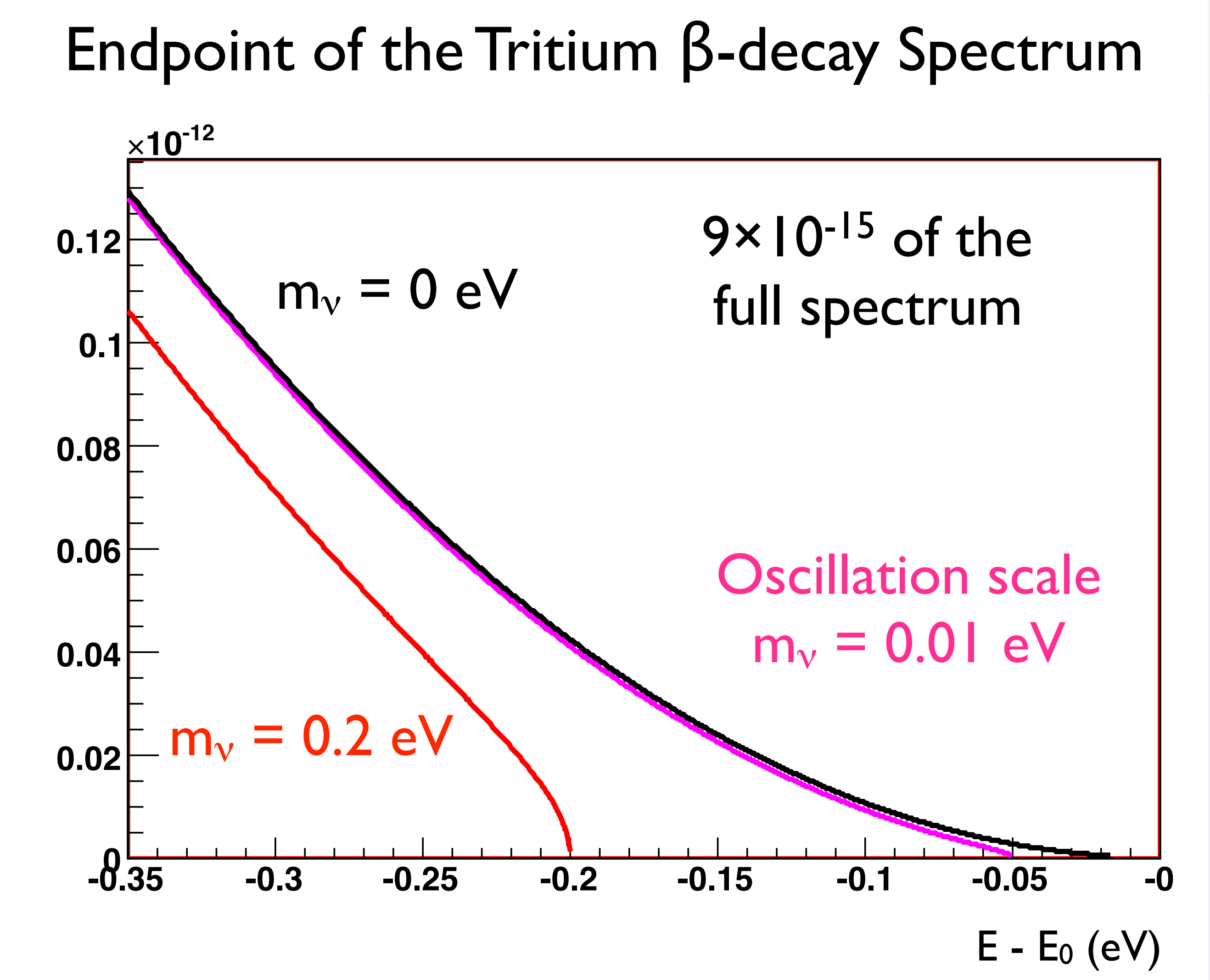
Zoom in on the endpoint . . .



KATRIN


Endpoint of the Tritium β-decay Spectrum
×10^-12
6
5
4
3
2
1
0
-2
-1.5
-1
-0.5
0
E - E0 (eV)
mν = 0 eV
4×10^-12 of the full spectrum
mν = 0.2 eV
Goal of KATRIN
mν = 2.2 eV

KATRIN



Endpoint of the Tritium β-decay Spectrum
×10^-12
0.12
0.1
0.08
0.06
0.04
0.02
0
-0.35
-0.3
-0.25
-0.2
-0.15
-0.1
-0.05
-0
m_ν = 0 eV
9×10^-15 of the full spectrum
Oscillation scale m_ν = 0.01 eV
m_ν = 0.2 eV
E - E0 (eV)

Beyond KATRIN

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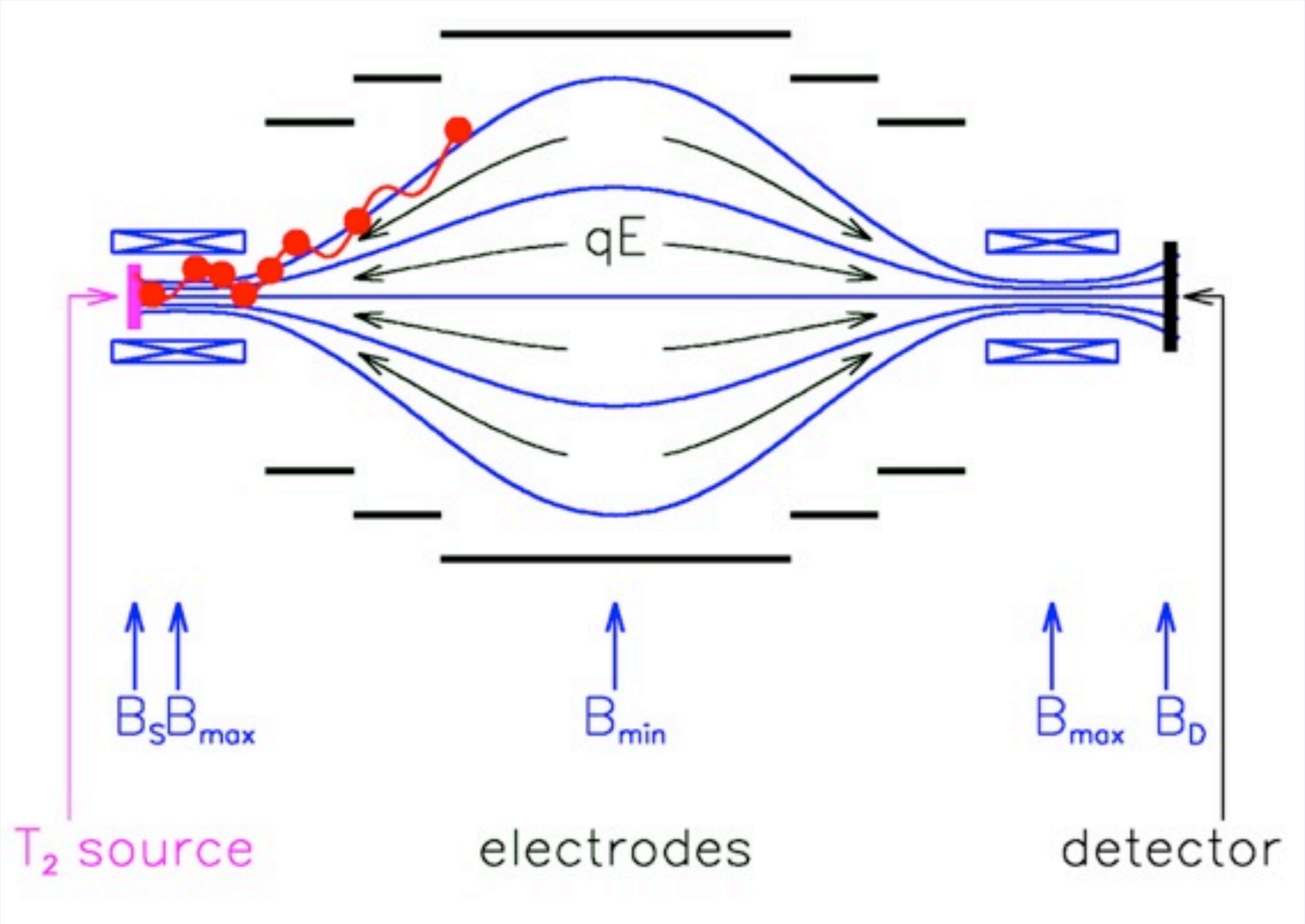
Limiting Factors

- Flux: Cannot increase source column density; can only scale up the area
- Resolution: Cannot reasonably scale up the size of the spectrometer

$$\Delta E = \frac{B_{\min} E}{B_{\max}}$$



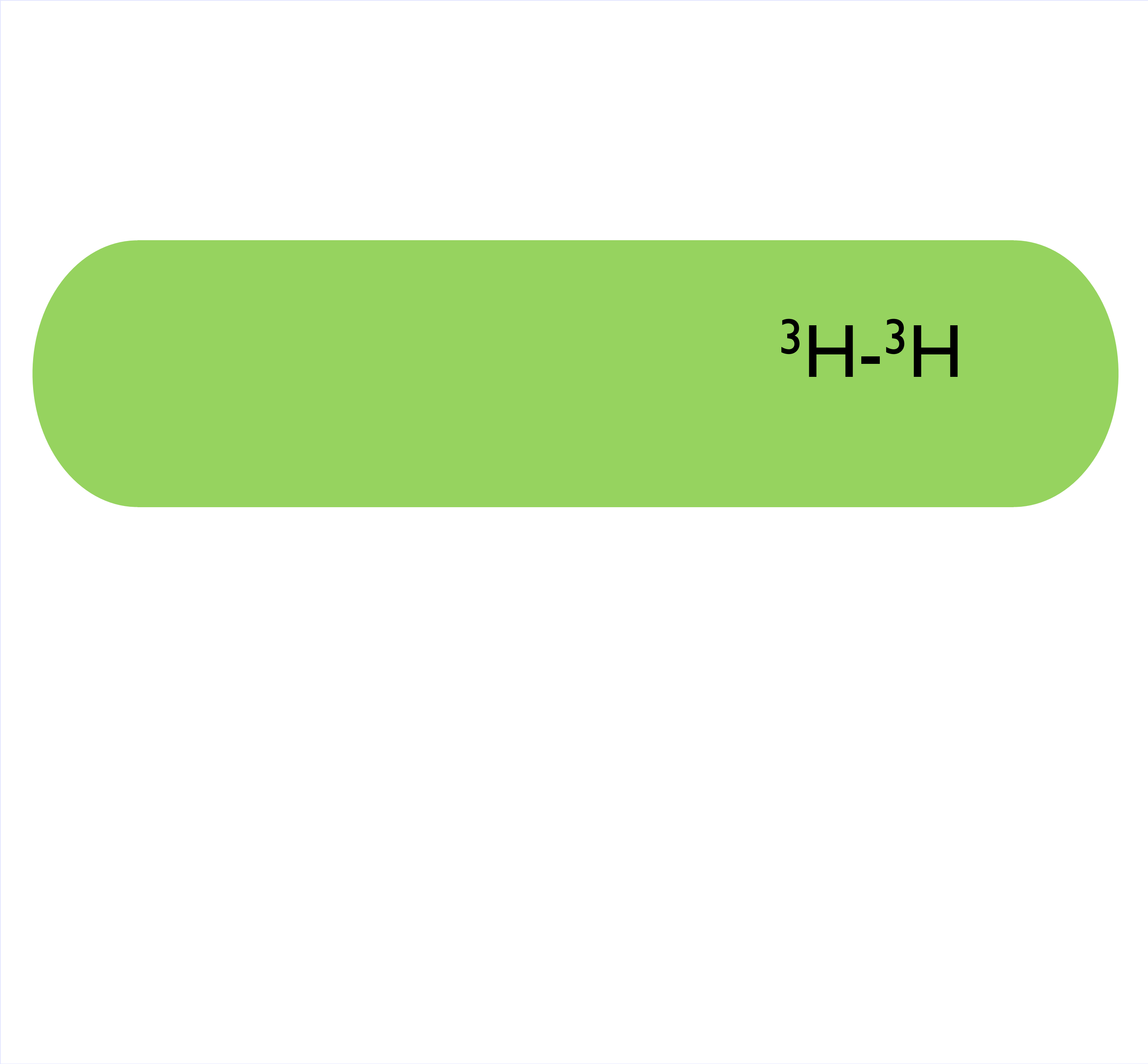
A new technique is necessary to improve on the neutrino mass sensitivity

A New Technique

- Enclosed volume

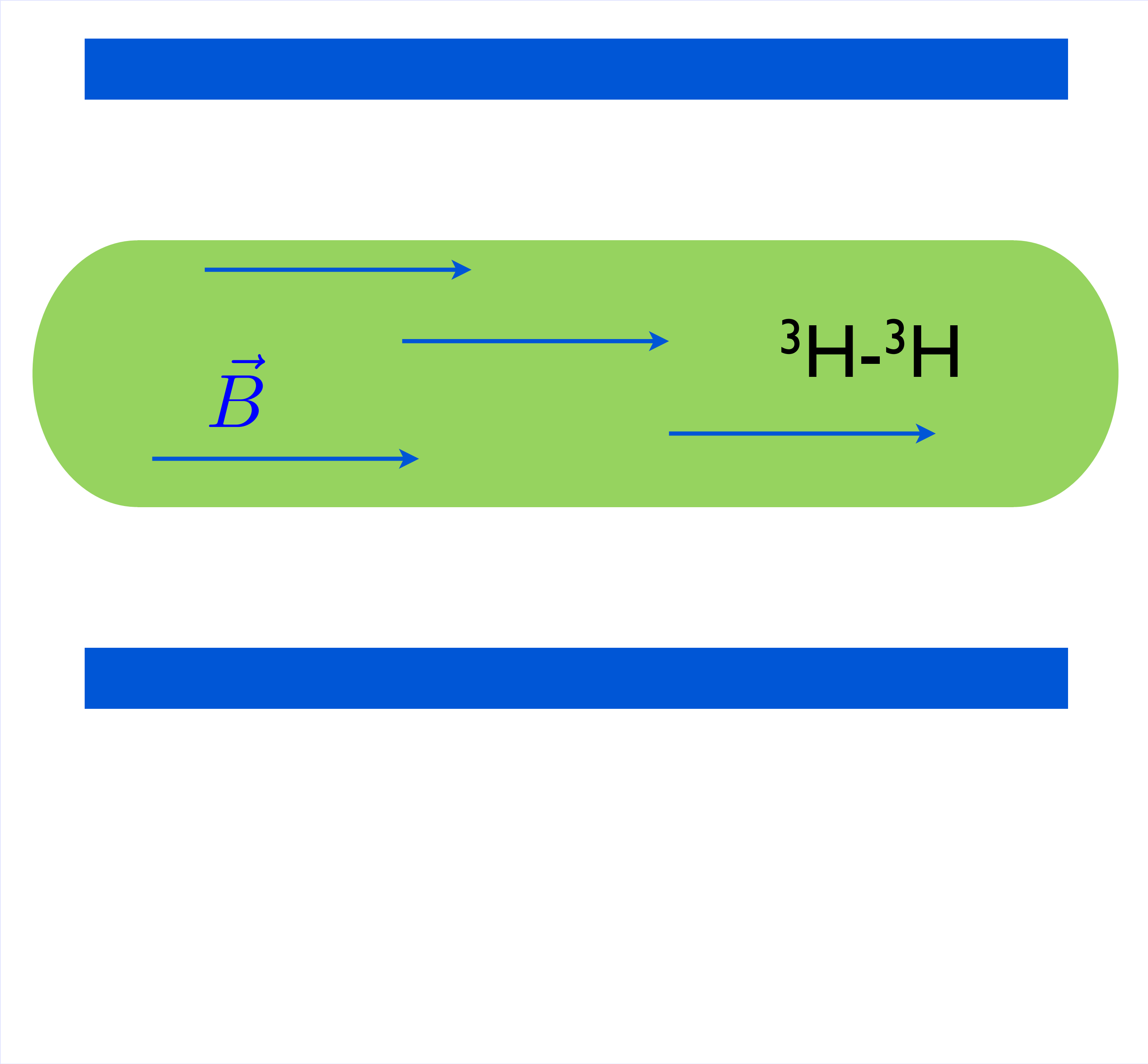
A New Technique

- Enclosed volume
- Fill with tritium gas



A New Technique

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



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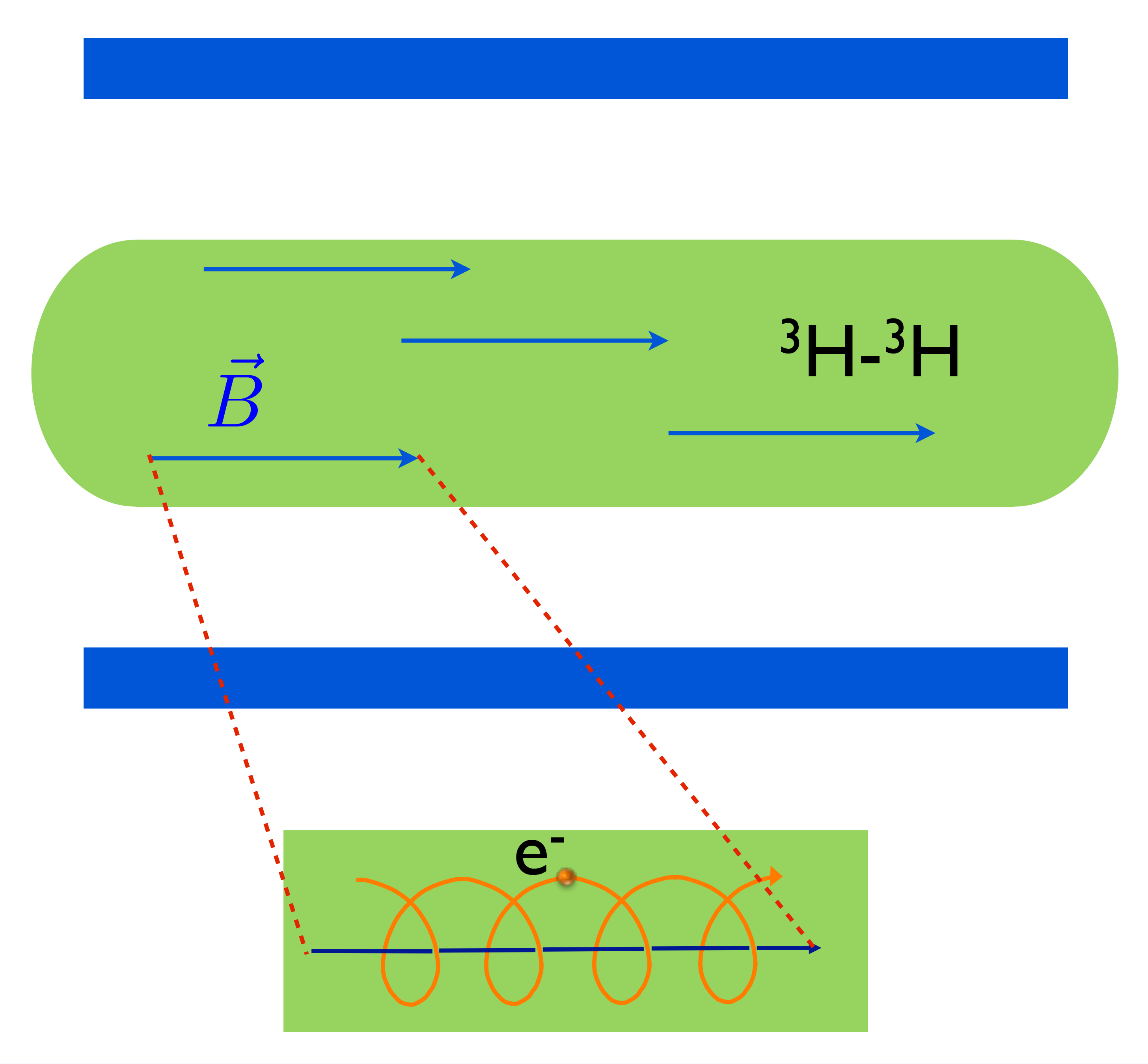
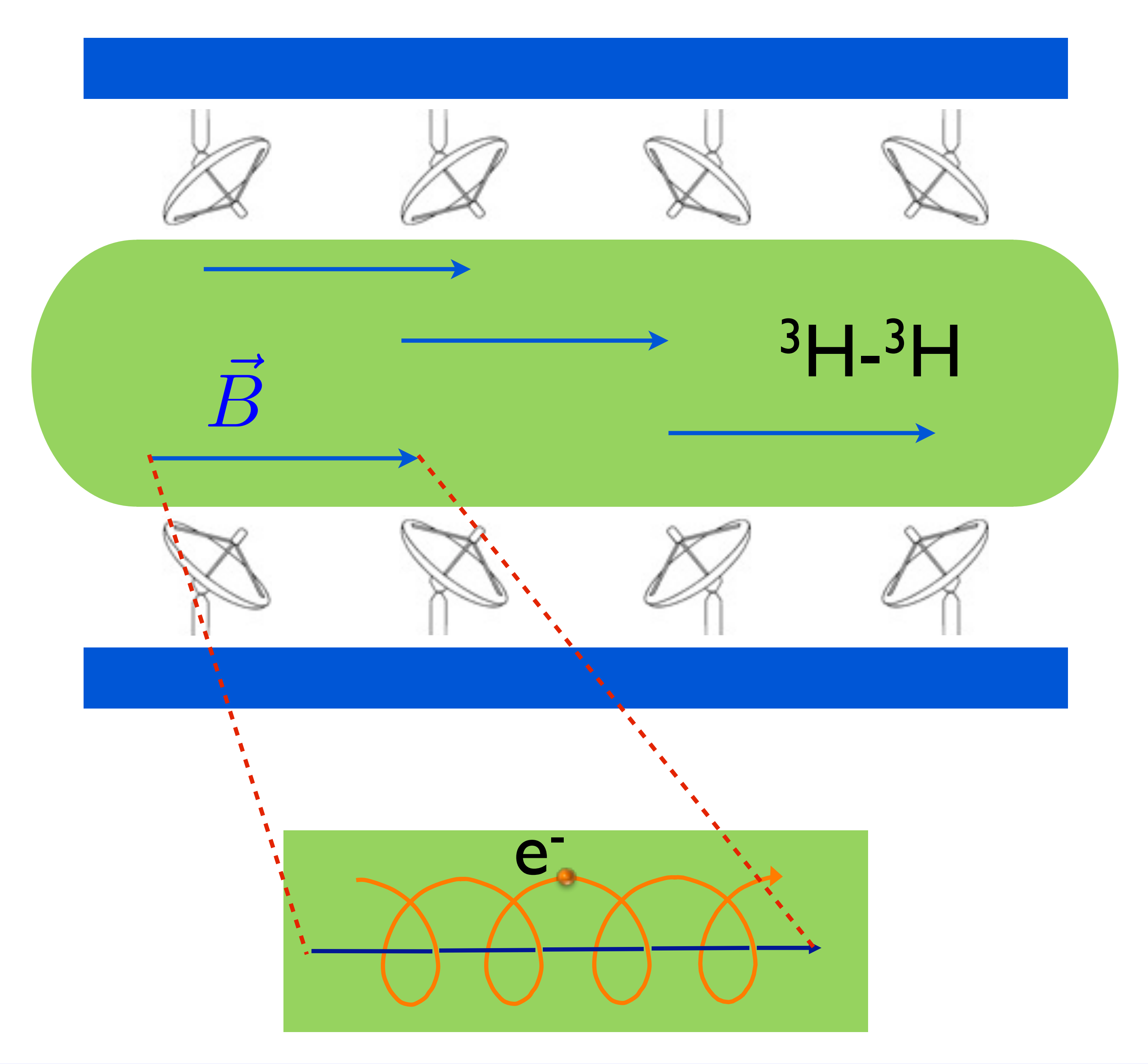


- Decay electrons spiral around field lines

A New Technique

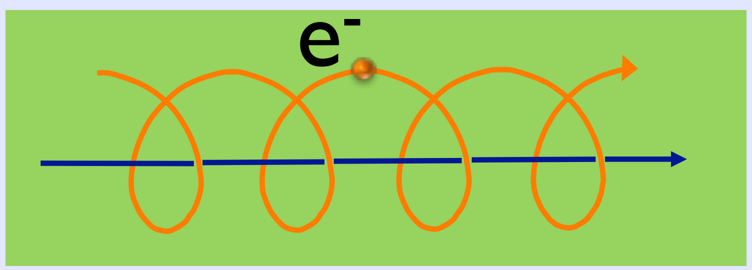
- Enclosed volume
- Fill with tritium gas
- Add a magnetic field

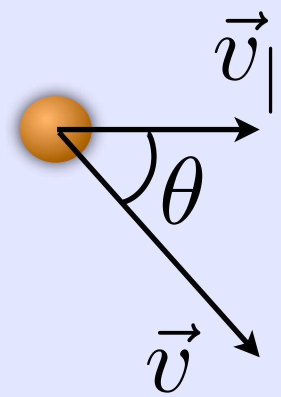


- Decay electrons spiral around field lines
- Add antennas to detect the cyclotron radiation

Cyclotron Radiation

- The frequency of the emitted radiation (ω) depends on the relativistic boost (γ and β dependence), and is independent of the pitch angle of the electron (θ)





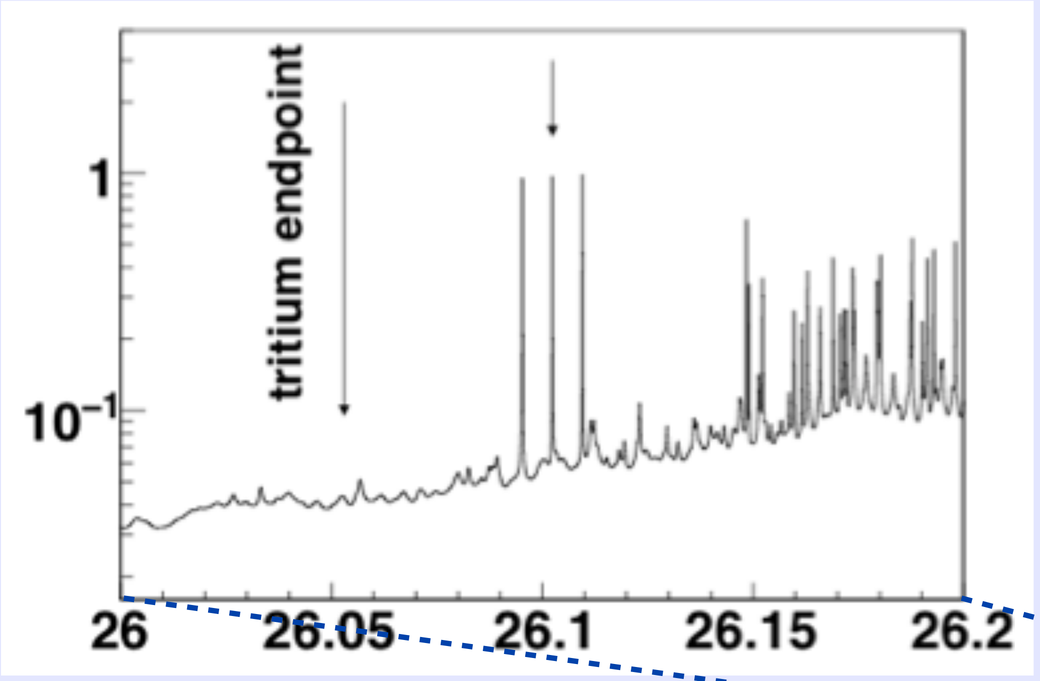
$$\omega(\gamma) = \frac{\omega_0}{\gamma} = \frac{eB}{K + m_e}$$

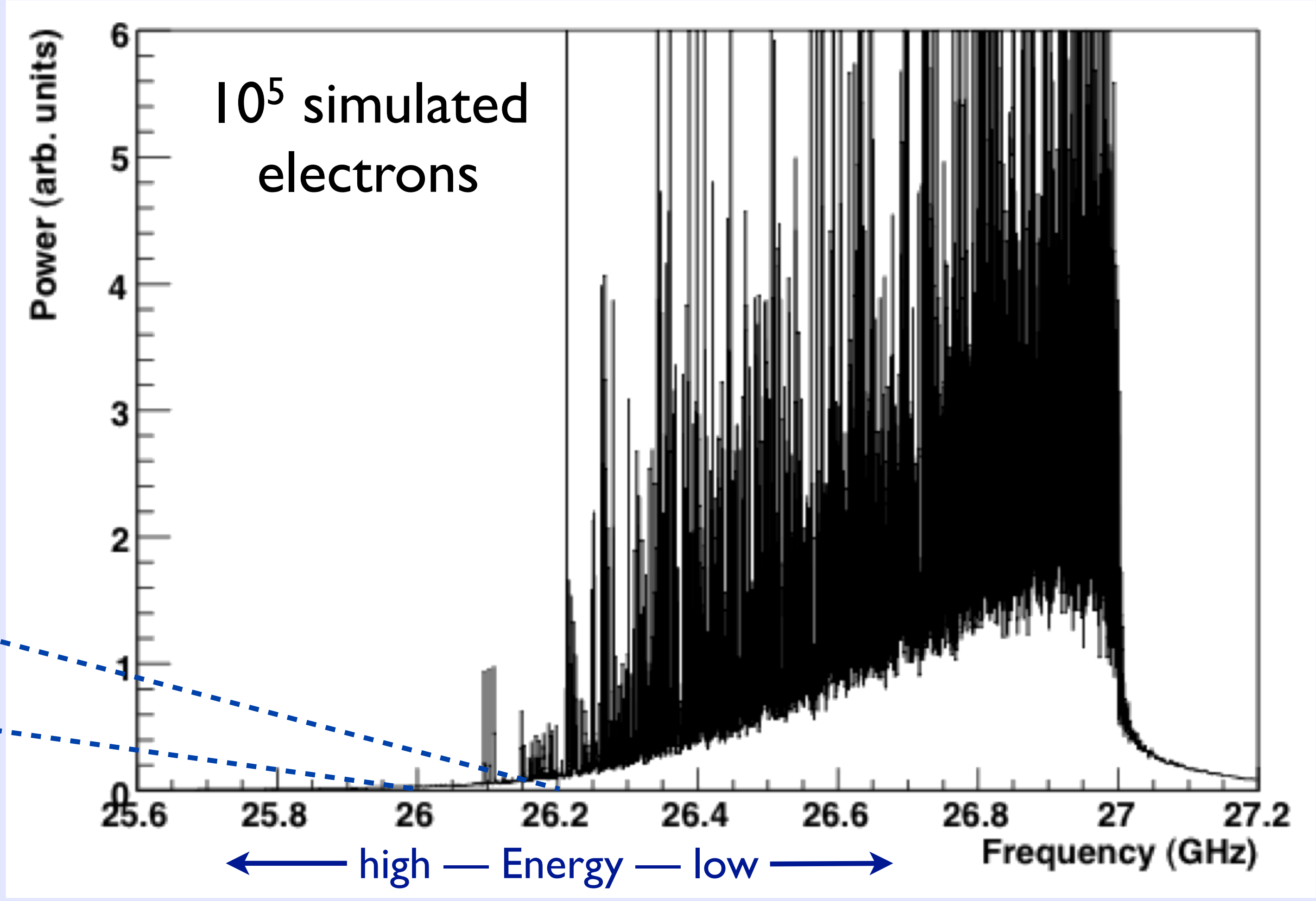
$$P_{\mathrm{tot}} = \frac{1}{4\pi\epsilon_0} \frac{2q^2\omega_c^2}{3c} \frac{\beta_\perp^2}{1 - \beta^2}$$

- The radiation emitted can be collected to measure the electron energy in a non-destructive manner

Frequency Spectrum

- Low energy electrons dominate at higher frequencies
- Rare, high energy electrons give a clean signature at the endpoint





From B. Monreal and J. Formaggio, Phys. Rev. D80 051301 (2008)

Demonstrating the Technique

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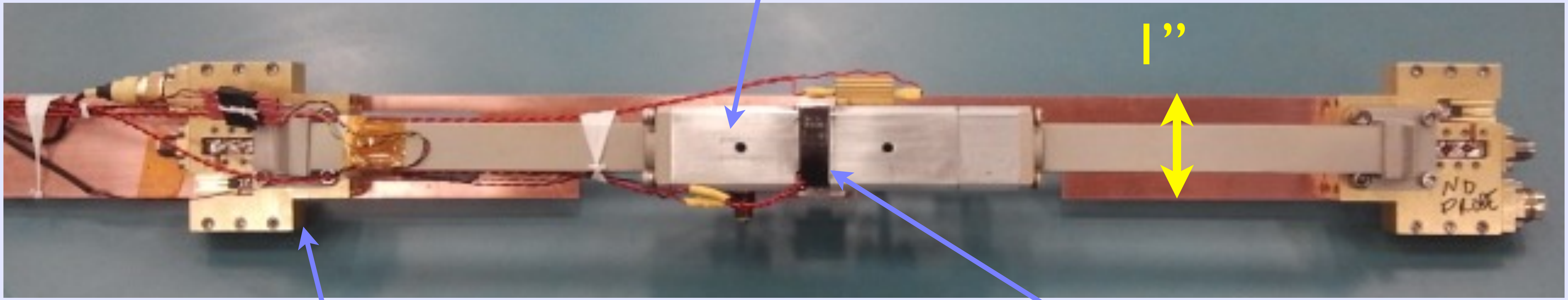
- A prototype is being built at UW
- Superconducting solenoid
- Waveguide antenna
- Questions to answer
    1. Can we detect signals from electrons?
    2. What is the resolution of the technique?
- Use a ^{83m}Kr source
    - ❖ 18 and 30 keV conversion electrons

Antenna Insert

Aluminum Rectangular Waveguide

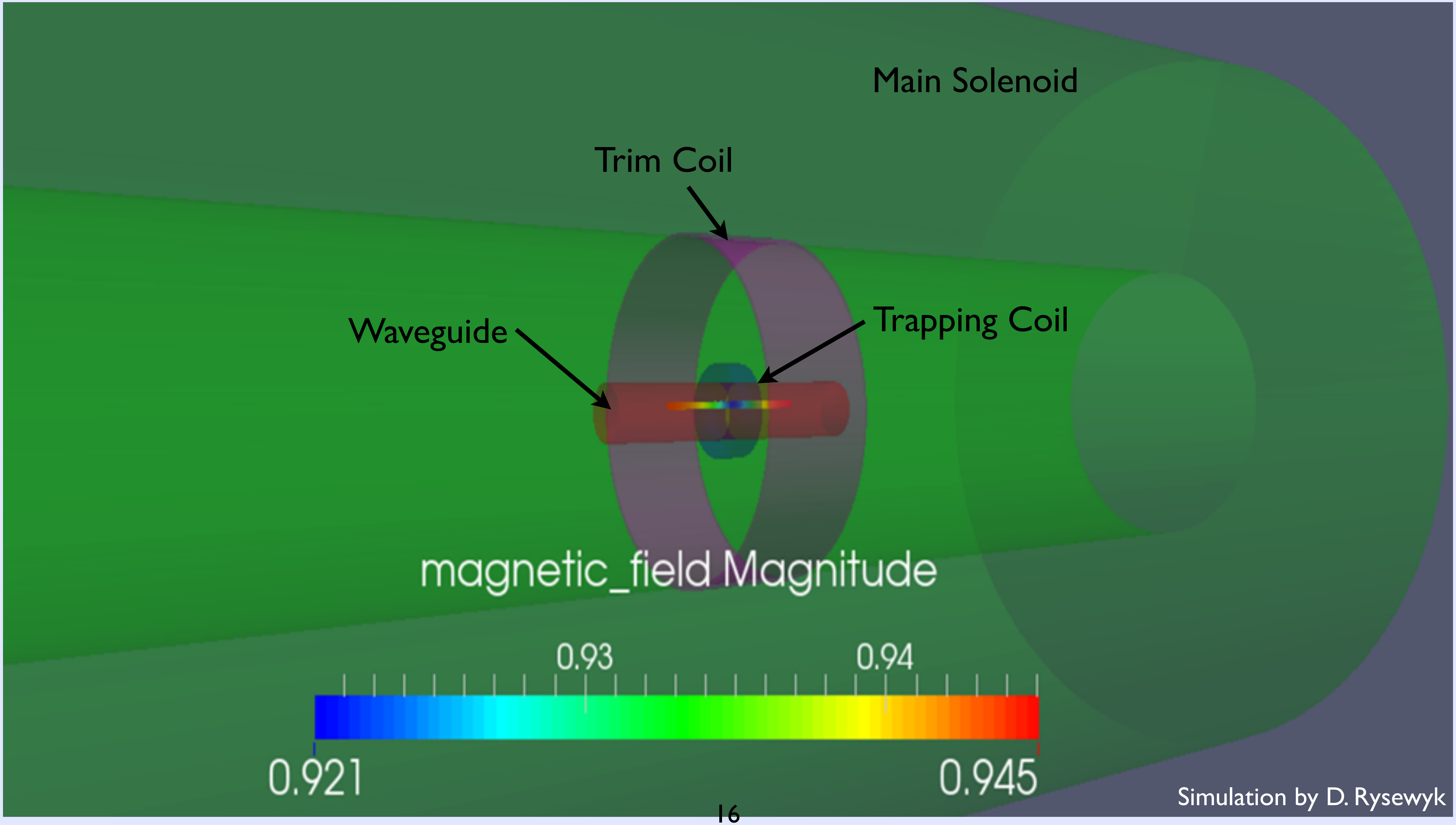


Cryogenic Amplifier

Trapping Magnet

Electron Tracking Simulations

Performed with the Kassiopeia simulation package



Electron Tracking Simulations

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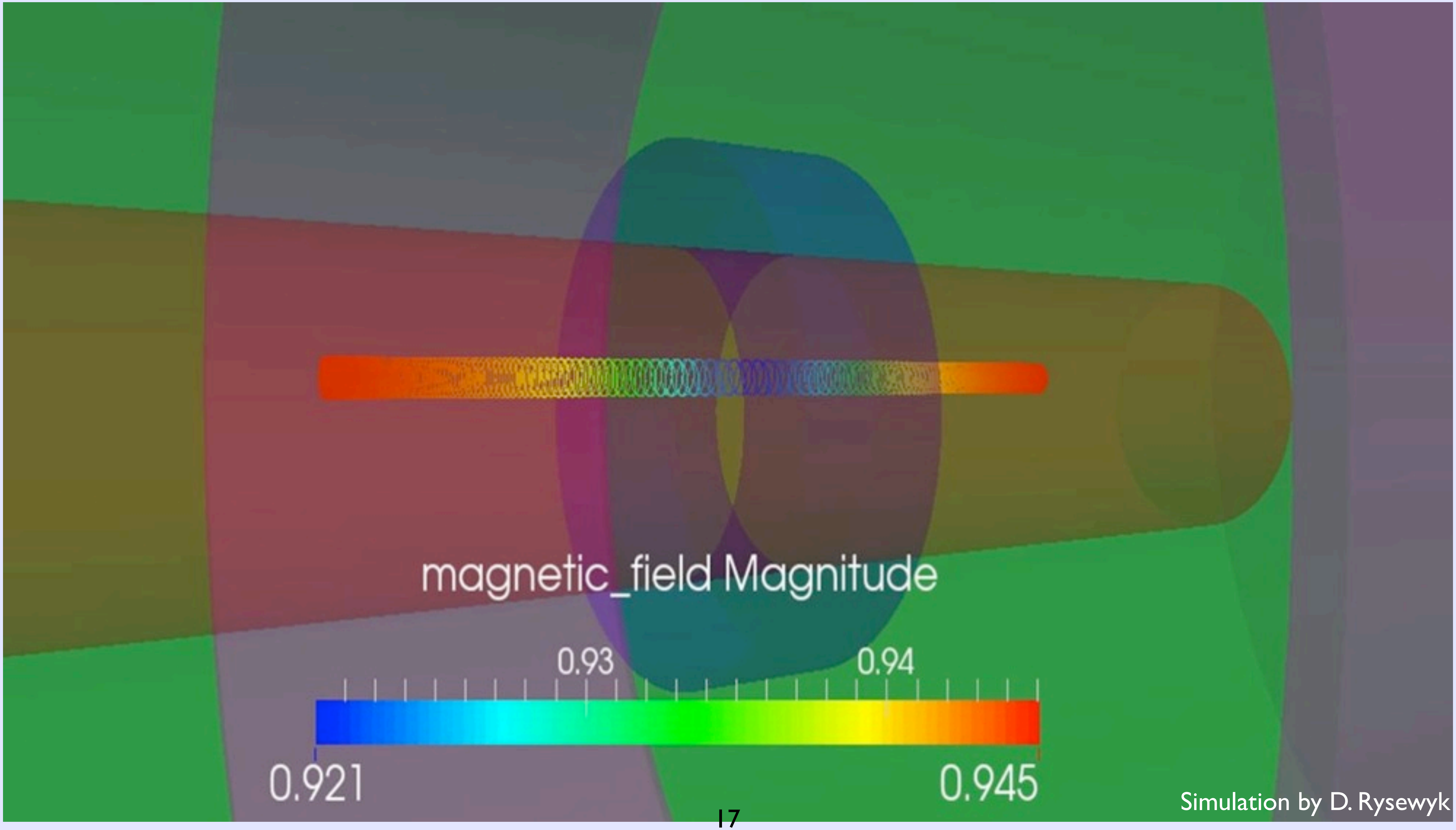
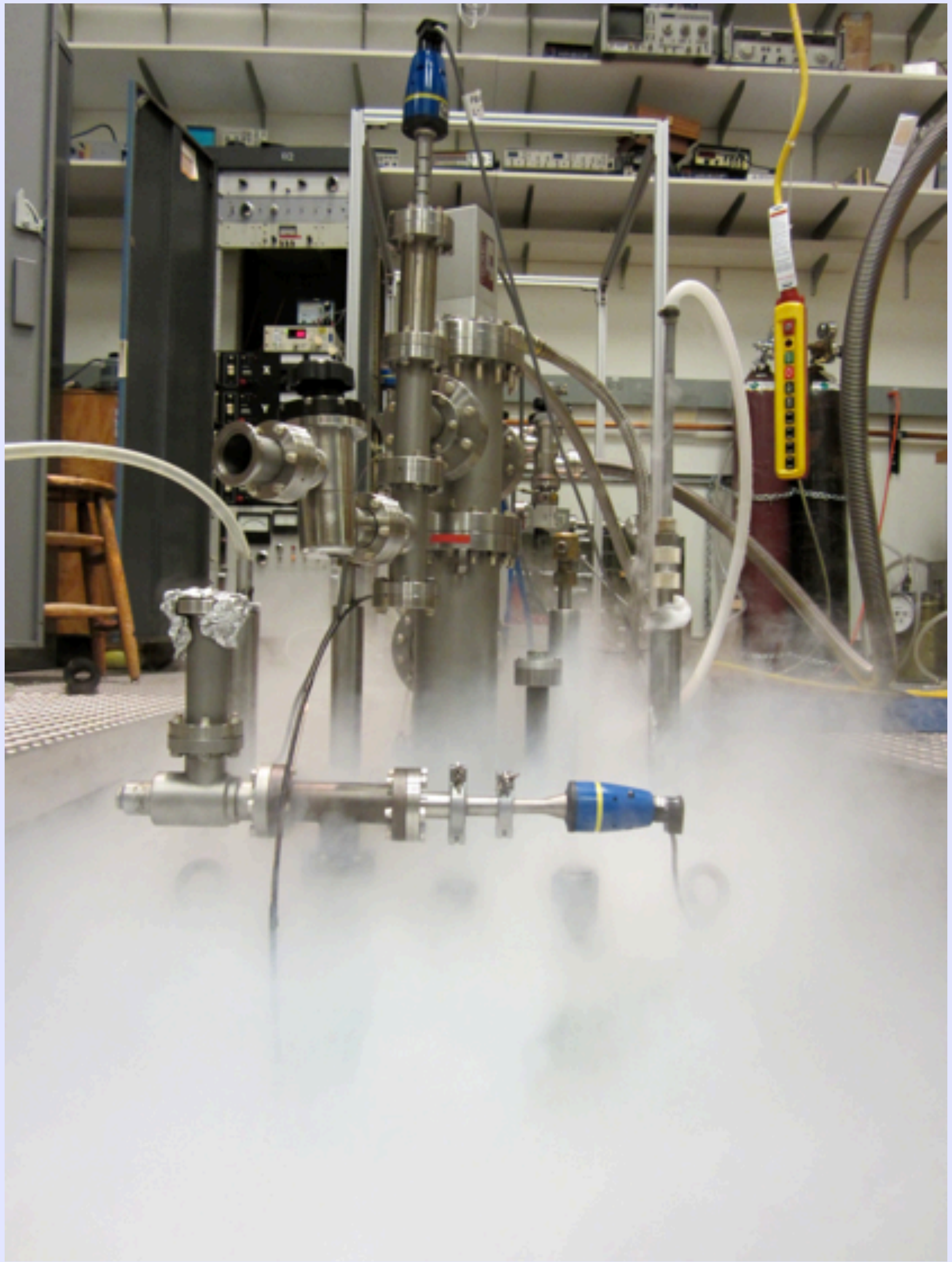


Simulation by D. Rysewyk

Other Details

- Magnetic field strength: 1 T
- Cyclotron frequency: 27 GHz
- Insert cooled to 100K
- Trapping volume: ~1 mm^3
- Bandwidth: 100 MHz



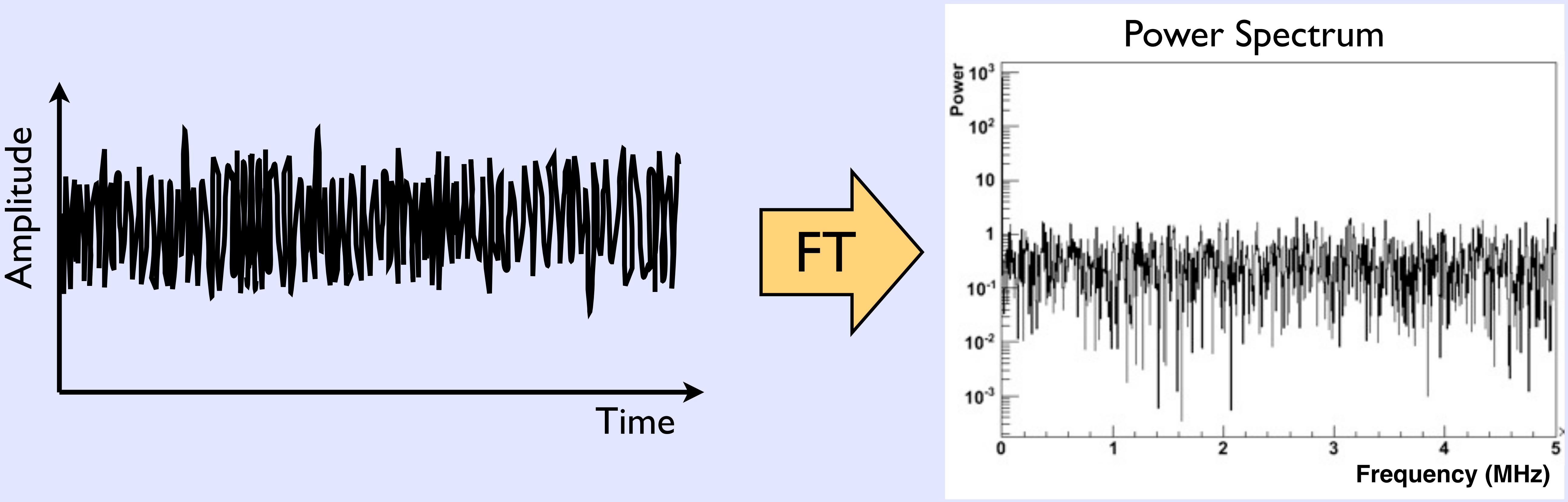
Taking Data

PROJECT 8

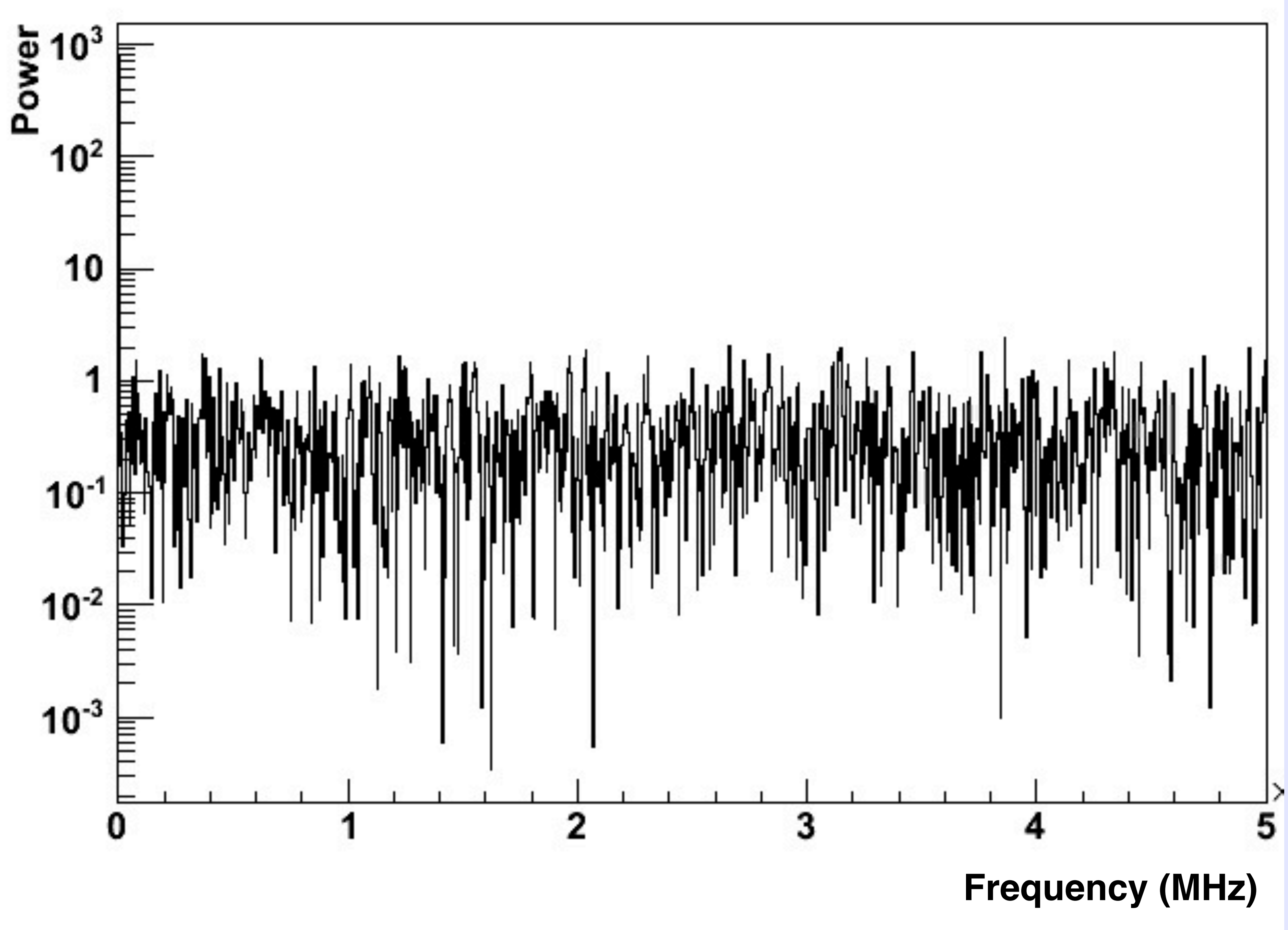
- Untriggered
- Digitize and write to disk
  - ❖ Current system: 8-bit Signatec @ 200 MHz
  - ❖ Upgrade: 8-bit digitizer attached to a ROACH FPGA processing board
- January dataset
  - ❖ 7.5 TB on disk
- New run planned for September

Data

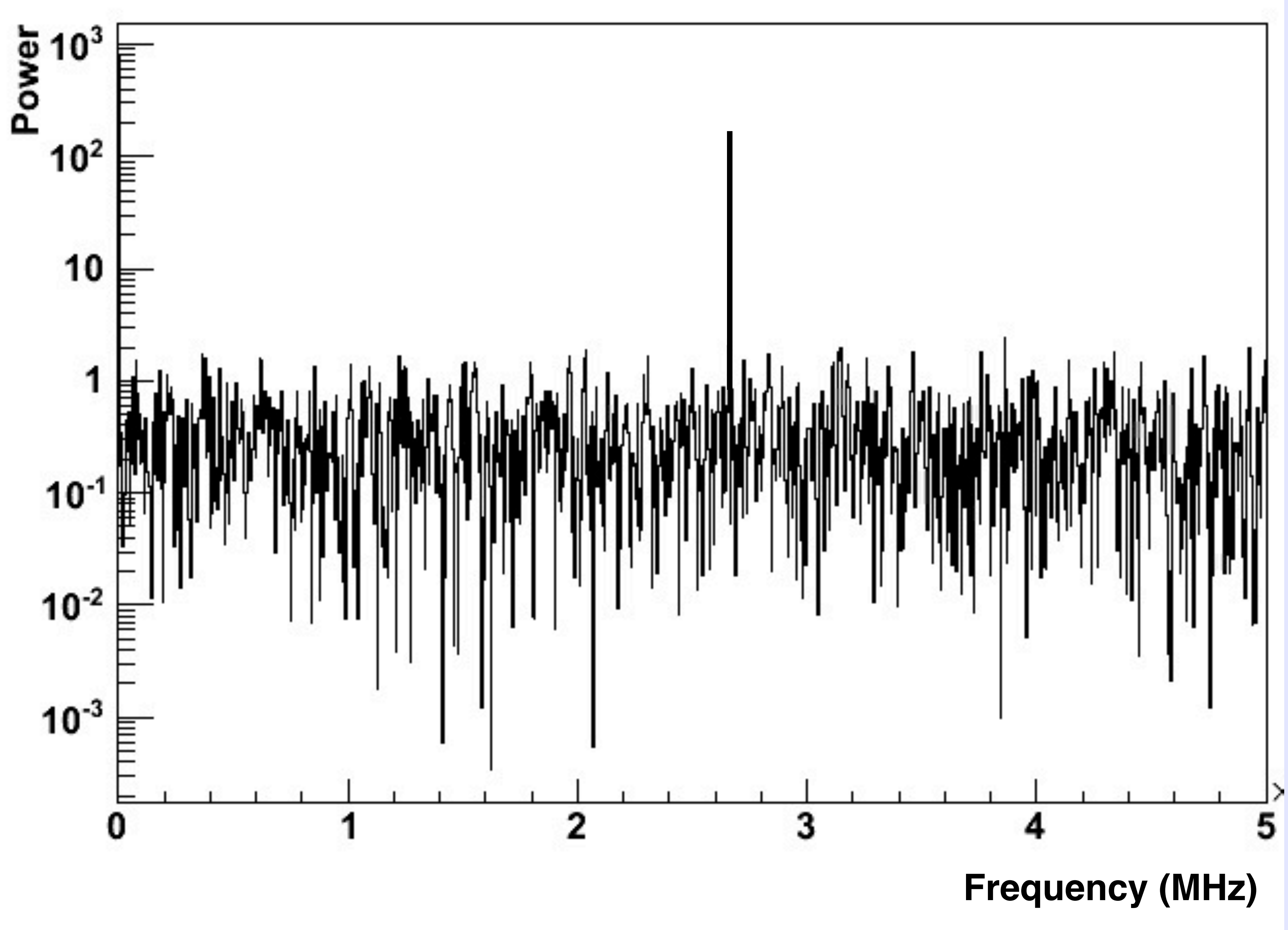
Data


Amplitude
Time
FT
Power Spectrum
Power
10^3
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
0
1
2
3
4
5
Frequency (MHz)

Power Spectrum

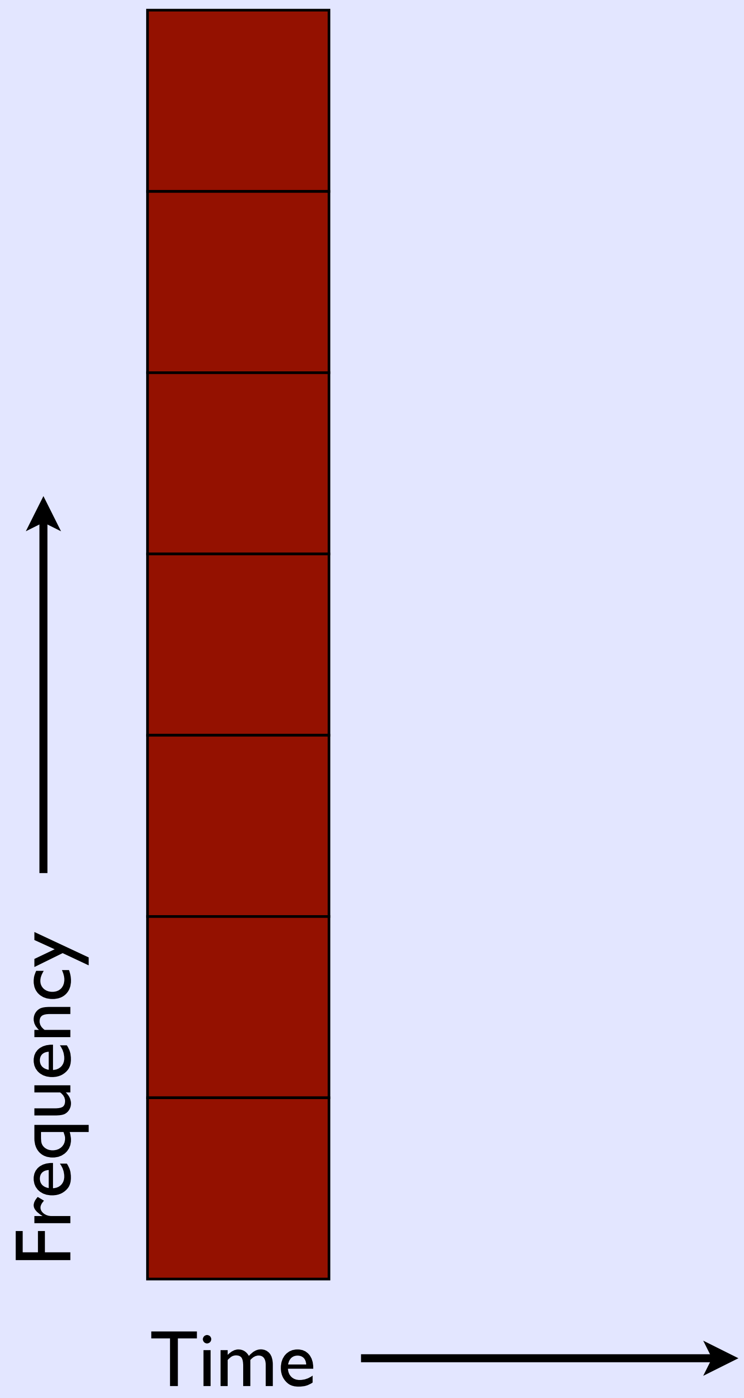


Cartoon Signal



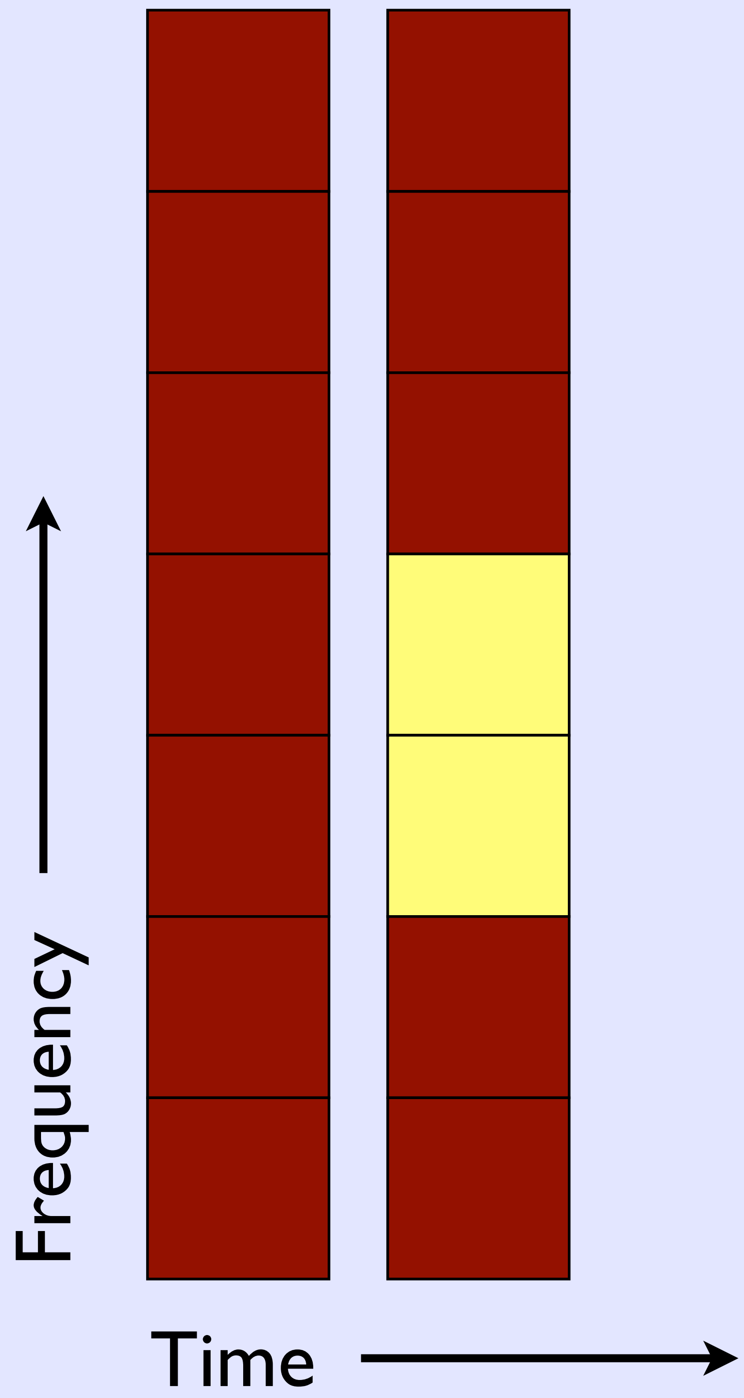
Frequency vs. Time

Color = Power Detected

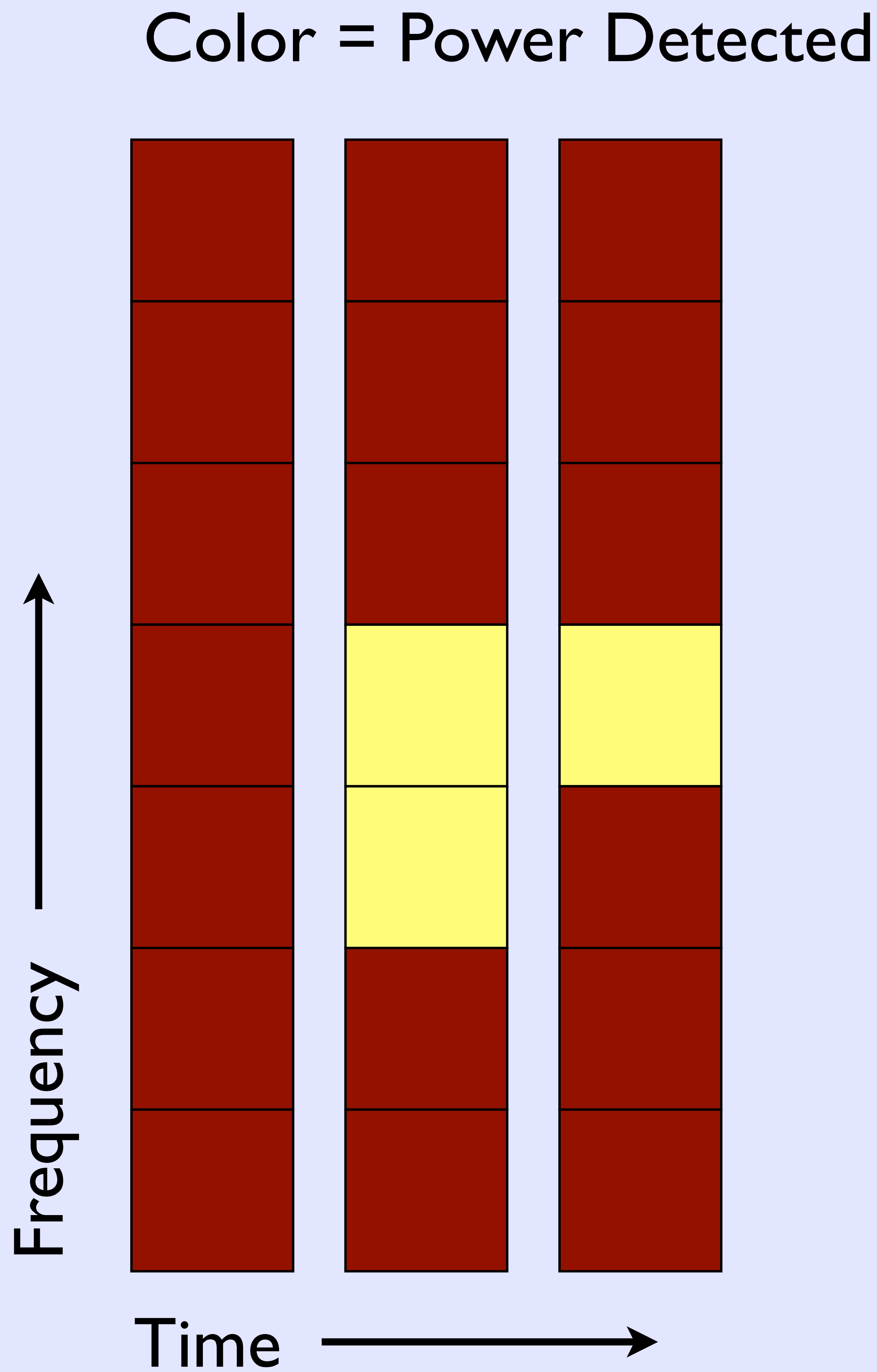


Frequency vs. Time

Color = Power Detected



Frequency vs. Time



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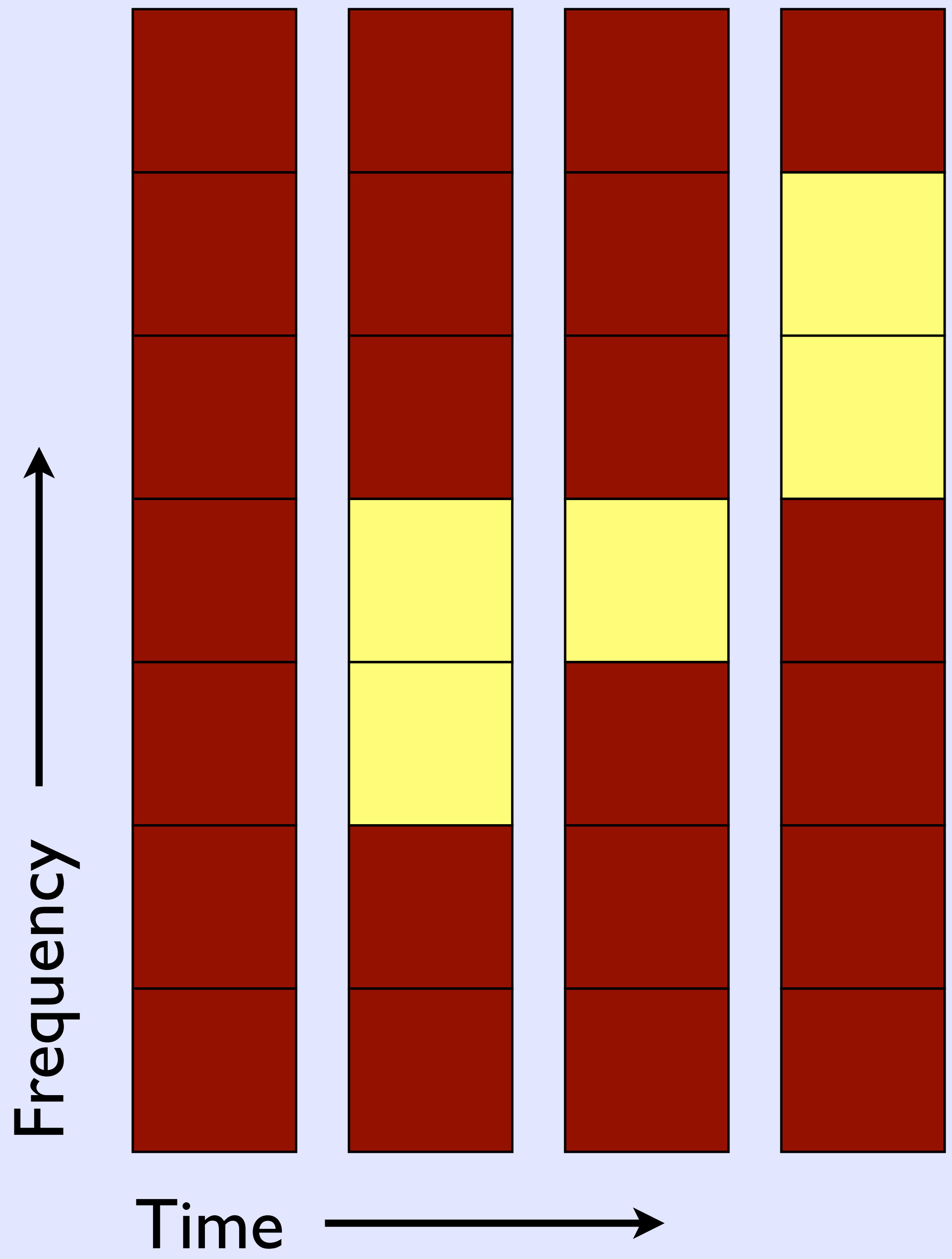

Frequency vs. Time

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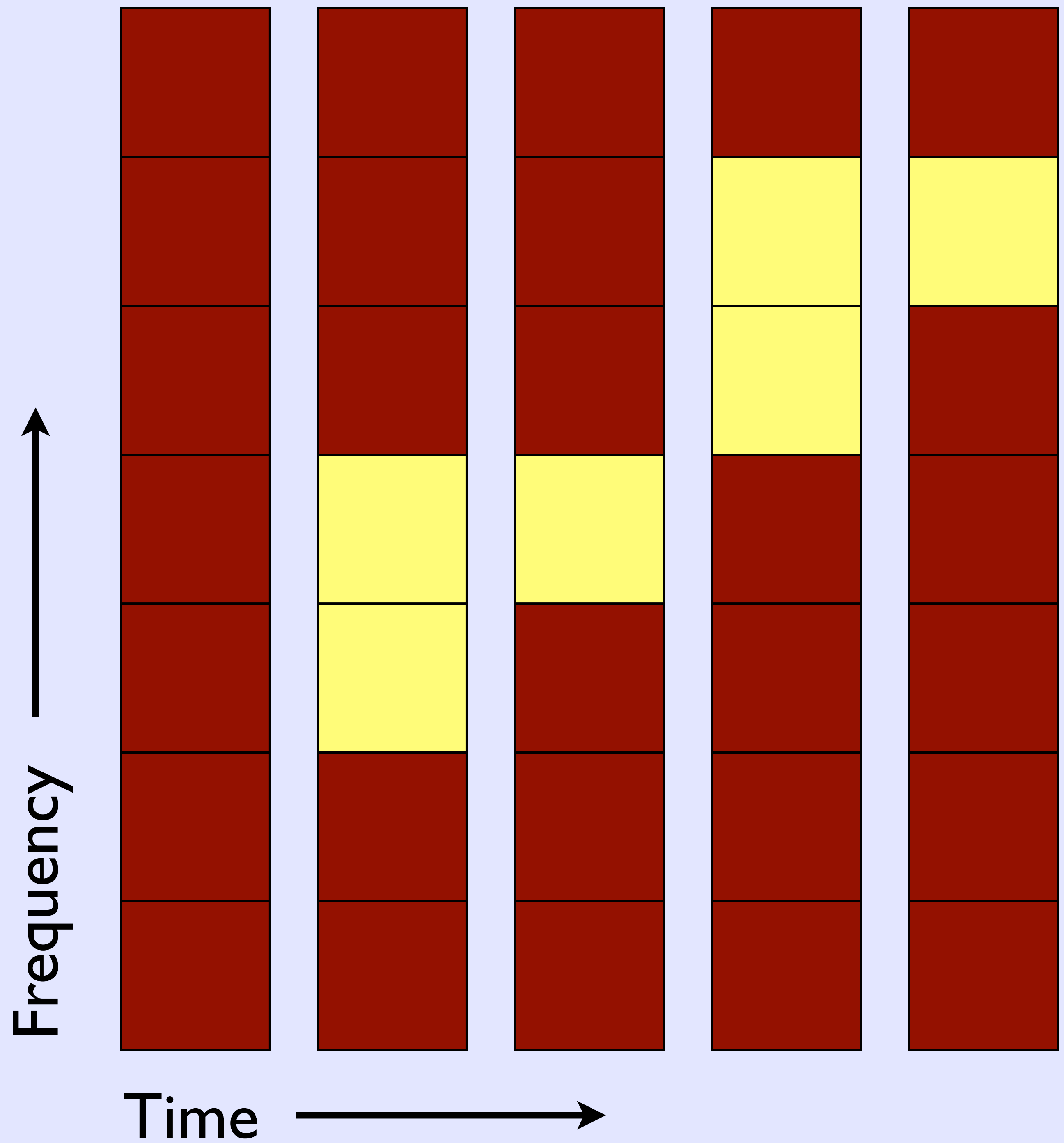
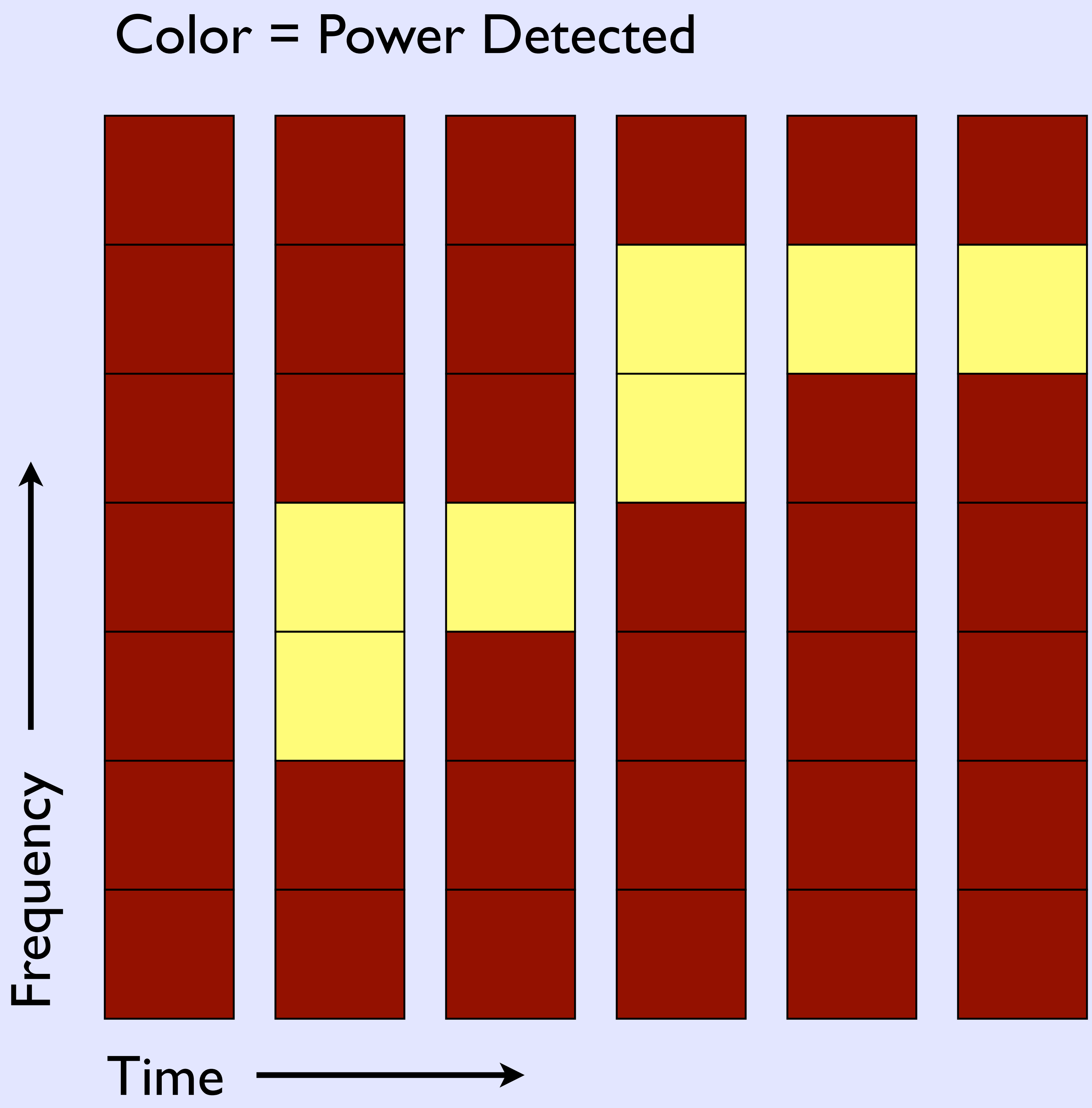
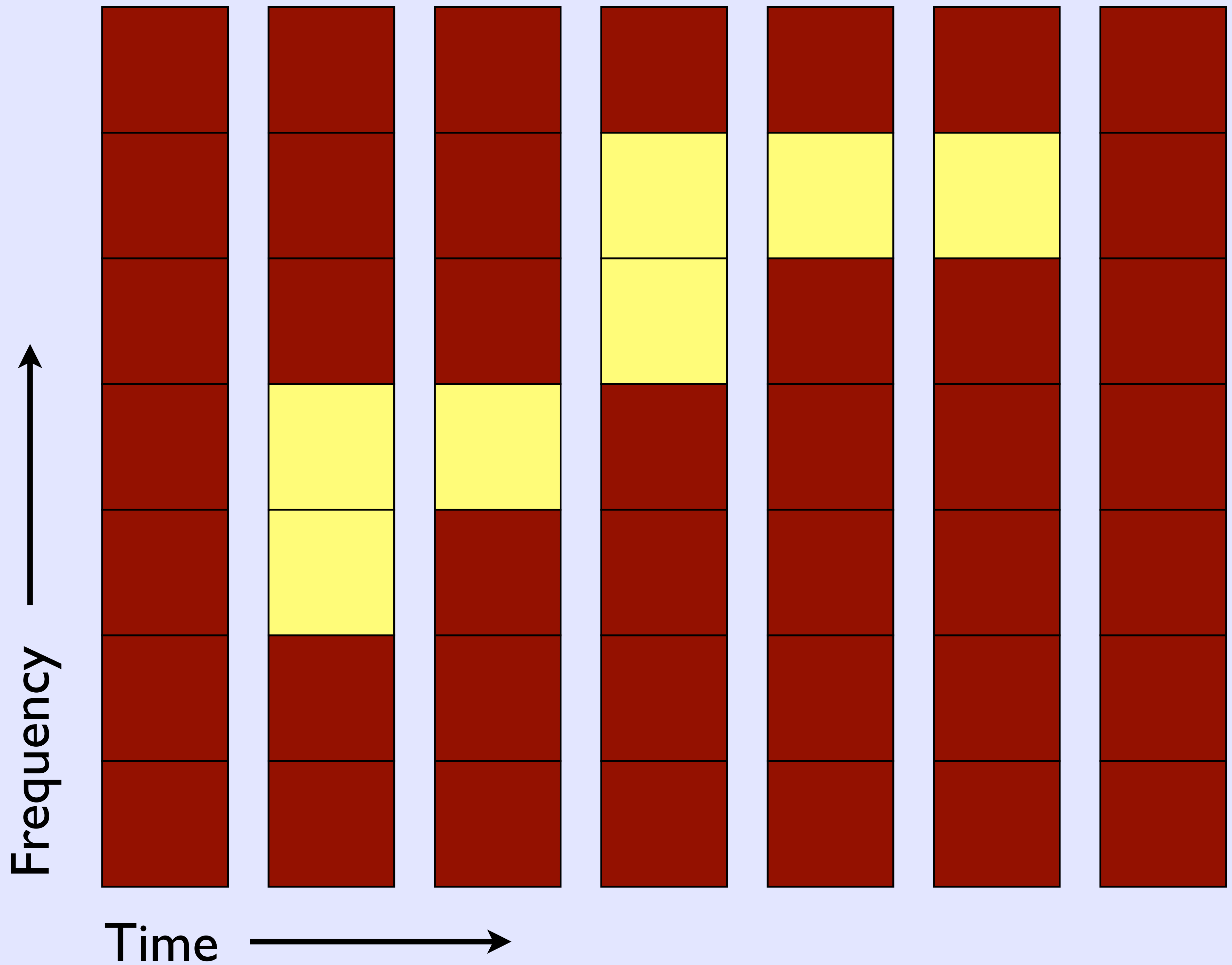


Frequency vs. Time

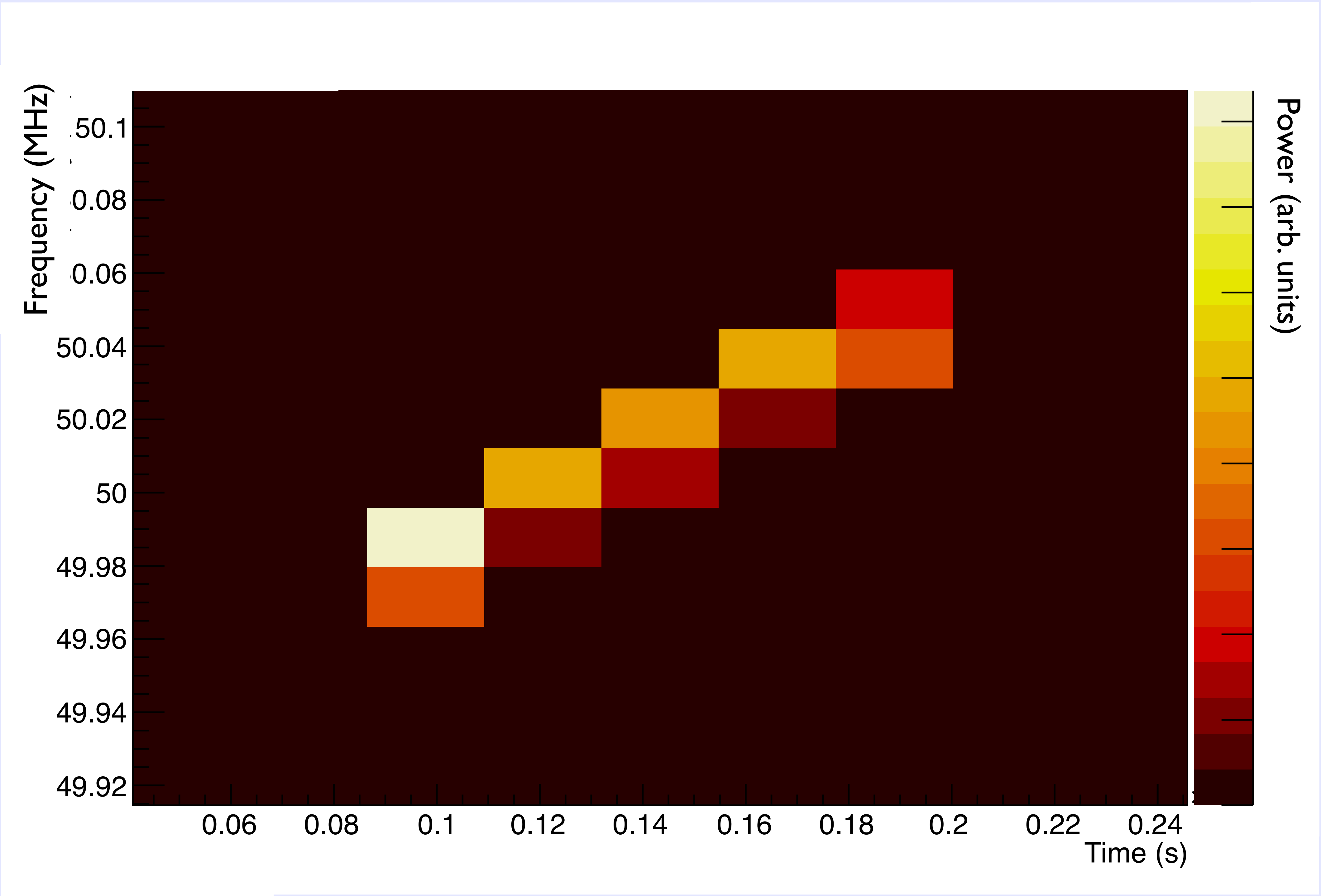


Frequency vs. Time

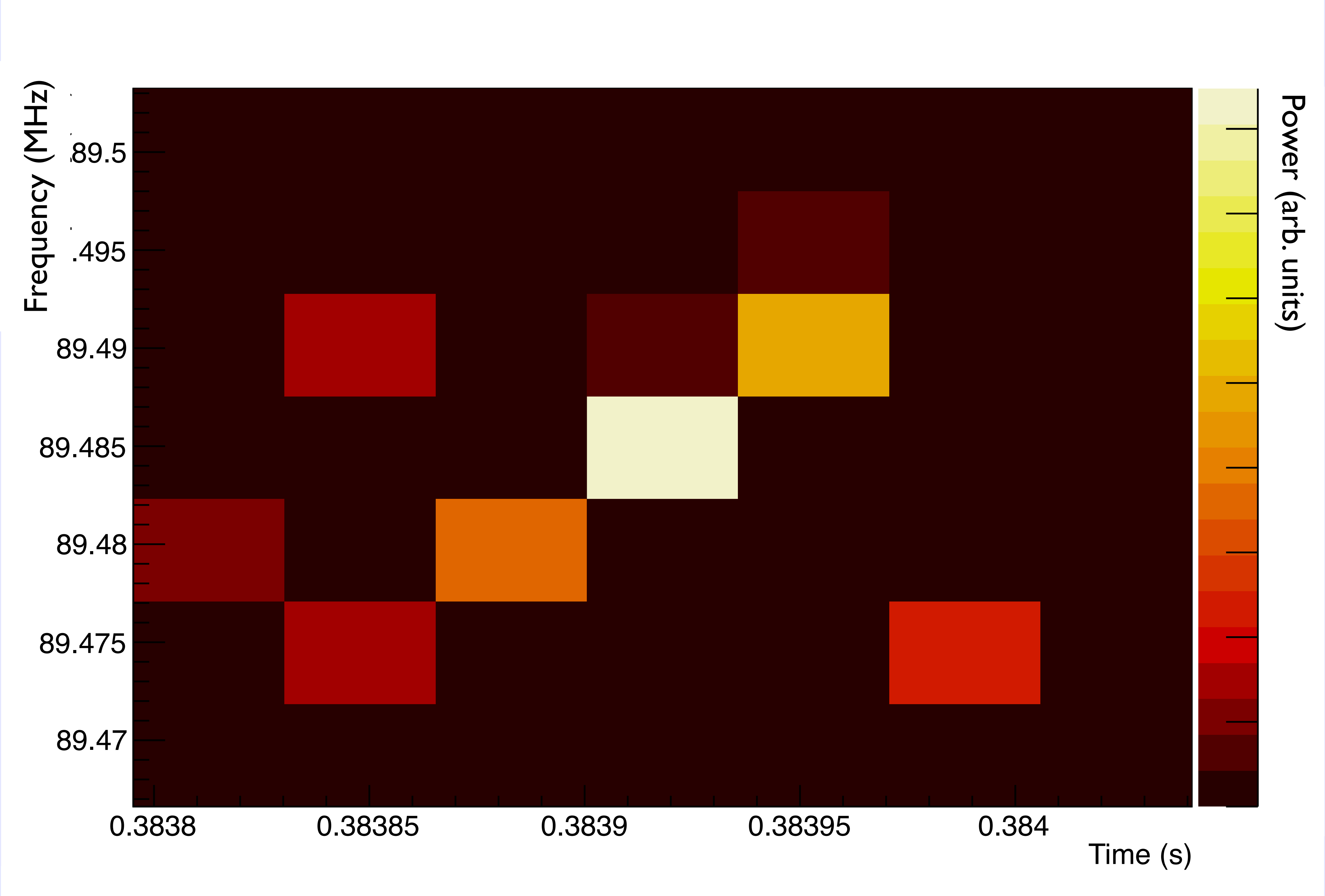
Color = Power Detected



Candidate (simulated)



Candidate



Frequency (MHz)
89.5
.495
89.49
89.485
89.48
89.475
89.47
0.3838
0.38385
0.3839
0.38395
0.384
Time (s)
Power (arb. units)

Current Status

- Analysis is underway of our existing data
- Next data run: September
  - Magnetic field measurement
  - Lower noise temperature

Moving Forward

- Assuming we are able to detect electrons . . .
- Can we improve on the sensitivity to neutrino mass?
  - ❖ Larger volume for higher statistics
  - ❖ Systematic uncertainties ultimately limited by the T_2 final state distribution
  - ❖ Atomic tritium would bypass this limit
  - ❖ R&D is beginning on a gaseous atomic tritium source

Projected Sensitivities

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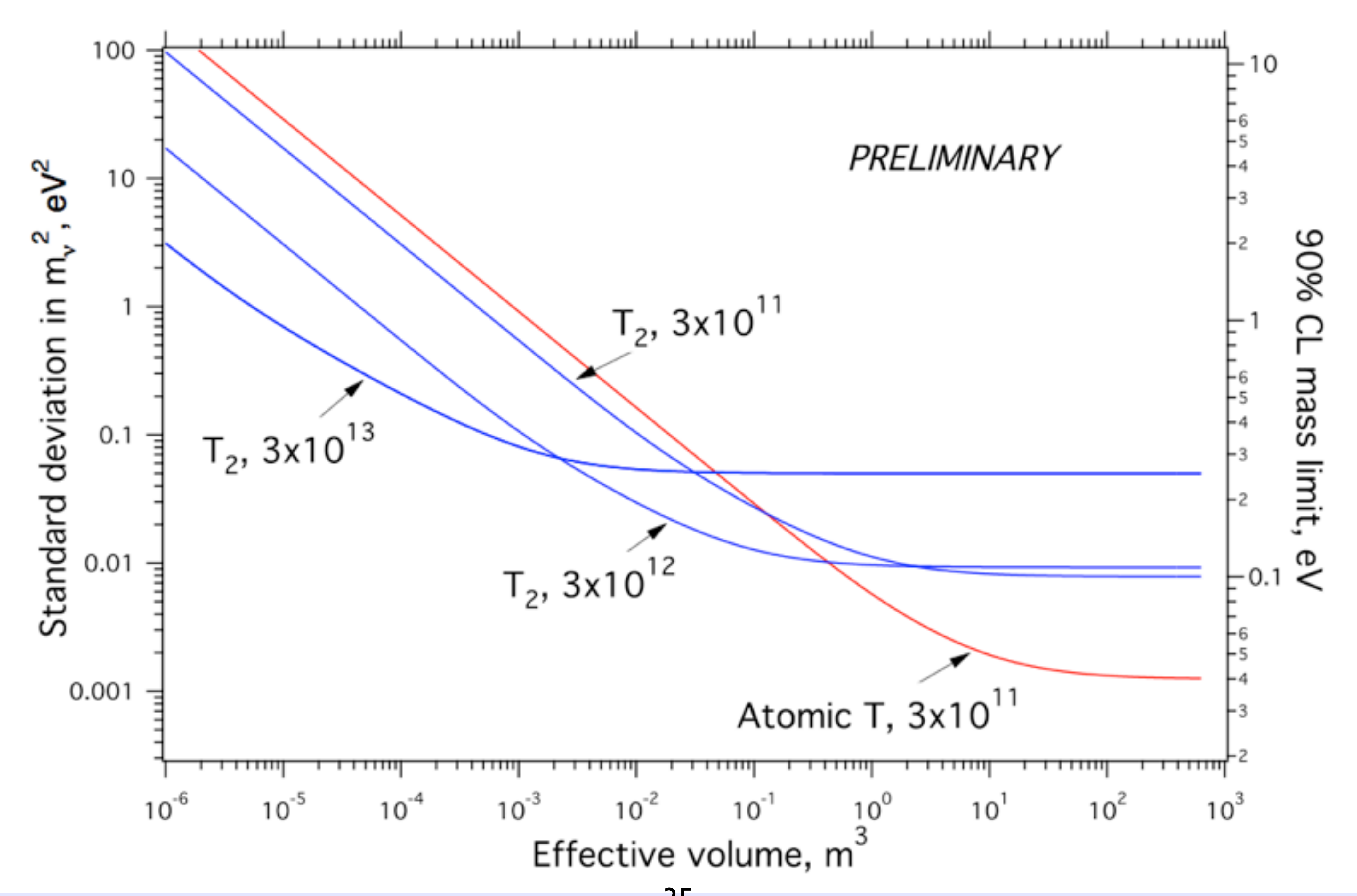
Sensitivities for different gas densities (number per cm^3)



Summary

PROJECT 8

Current effort to detect electrons

- Analyzing existing data
- Further data taking planned for September

Moving to a tritium measurement

- Scaling up volume
- Atomic tritium source

PROJECT 8

Caltech
R. Patterson

Karlsruhe Institute of Technology
T. Thuemmler

Massachusetts Institute of Technology &
MIT Haystack Observatories
J.A. Formaggio, N.S. Oblath, S. Cisneros, D. Furse, J. Barrett, P. Mohanmurthy, D. Rysewyk — A. Rogers, S. Doeleman

National Radio Astronomy Observatory
R. Bradley

Pacific Northwest National Laboratory
B. Vandevender, D. Asner, M. Jones

University of California at Santa Barbara
B. Monreal, M. Ghilea, M. Bahr, B. LaRoque

University of Washington
R.G.H. Robertson, L. Rosenberg, M. Miller, G. Rybka, J. Kofron, L. McBride