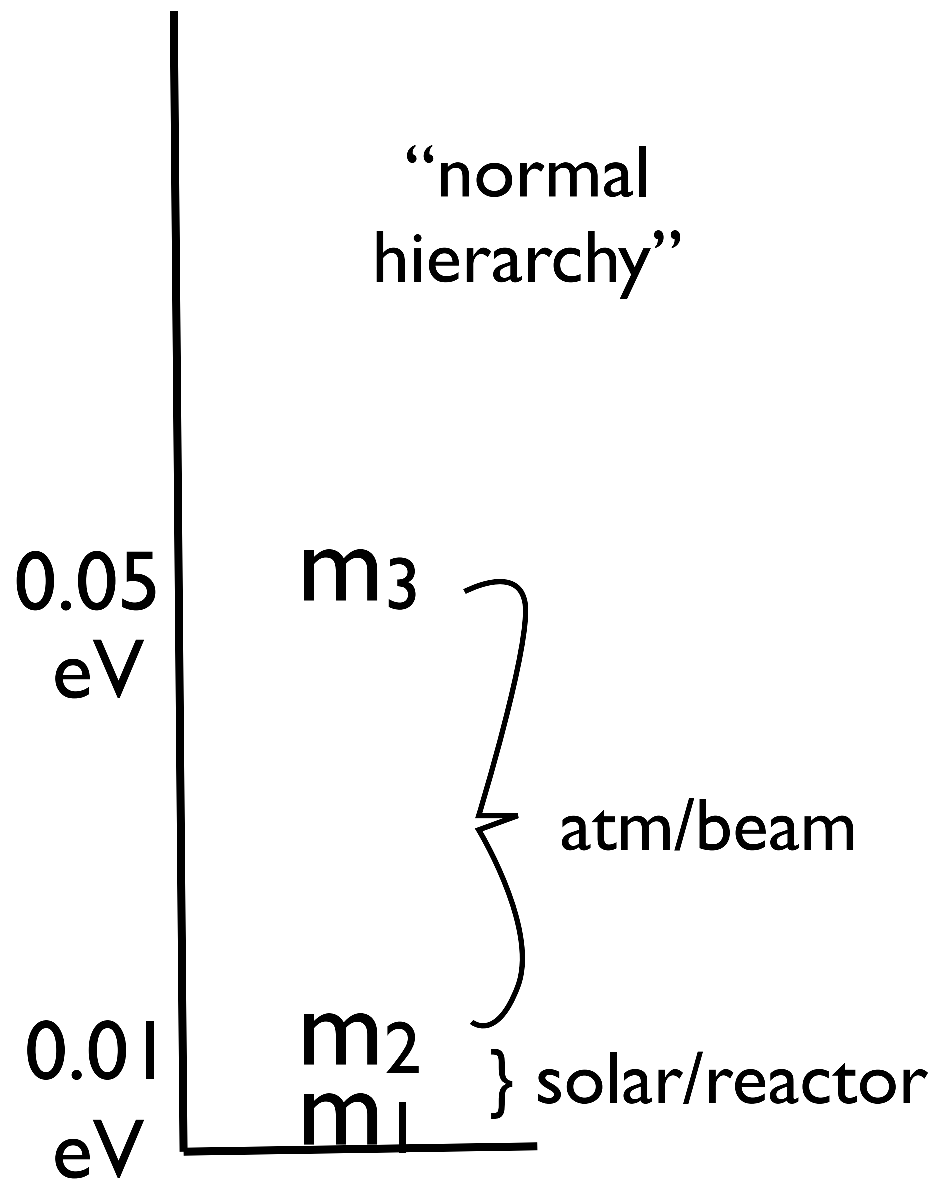
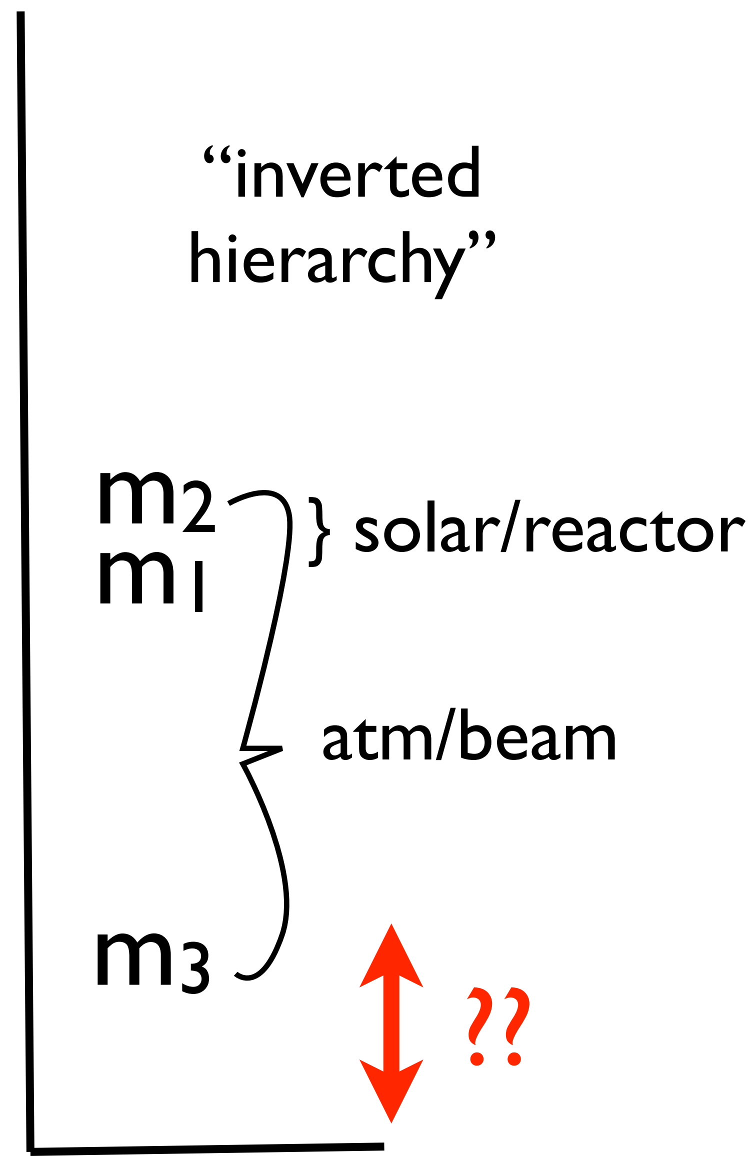
Project 8: a radiofrequency approach to the neutrino mass

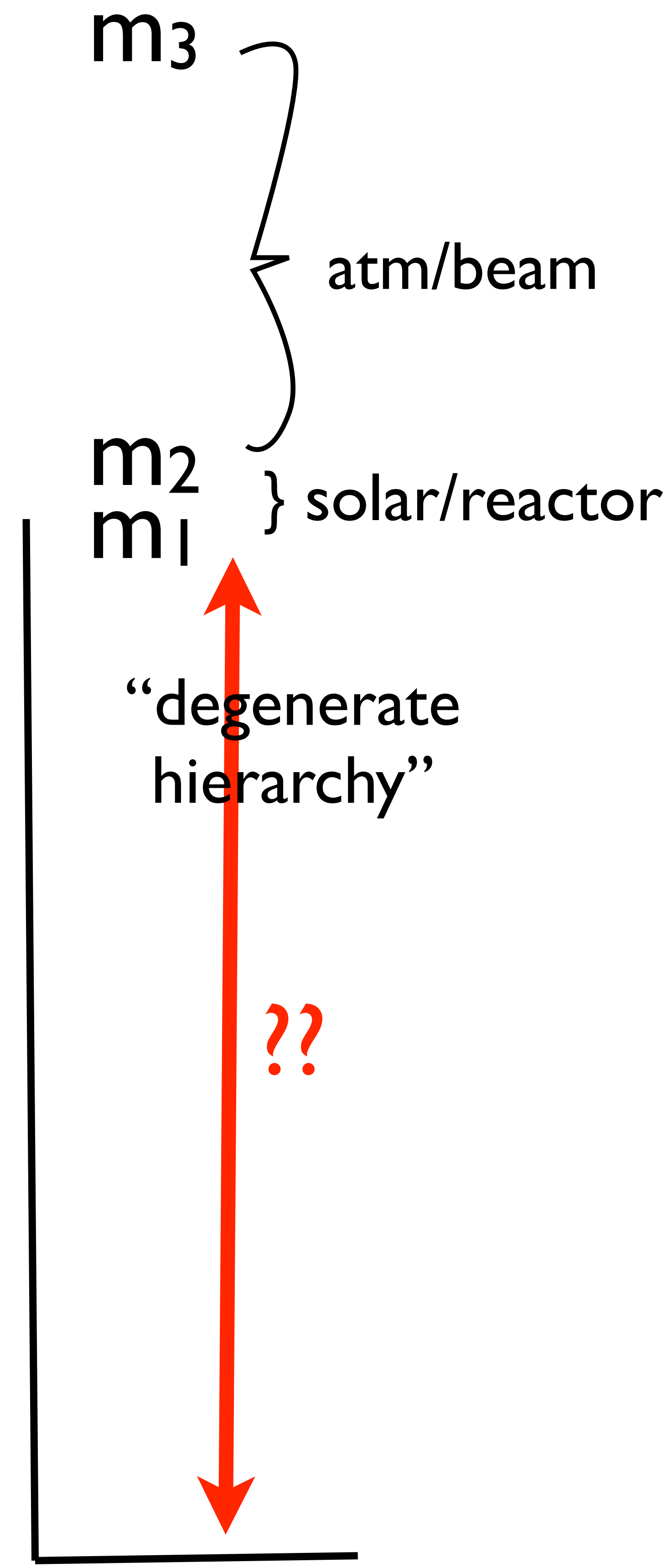
Ben Monreal, UC Santa Barbara

Neutrino mass

Oscillation experiments measure $\Delta(m^2)$

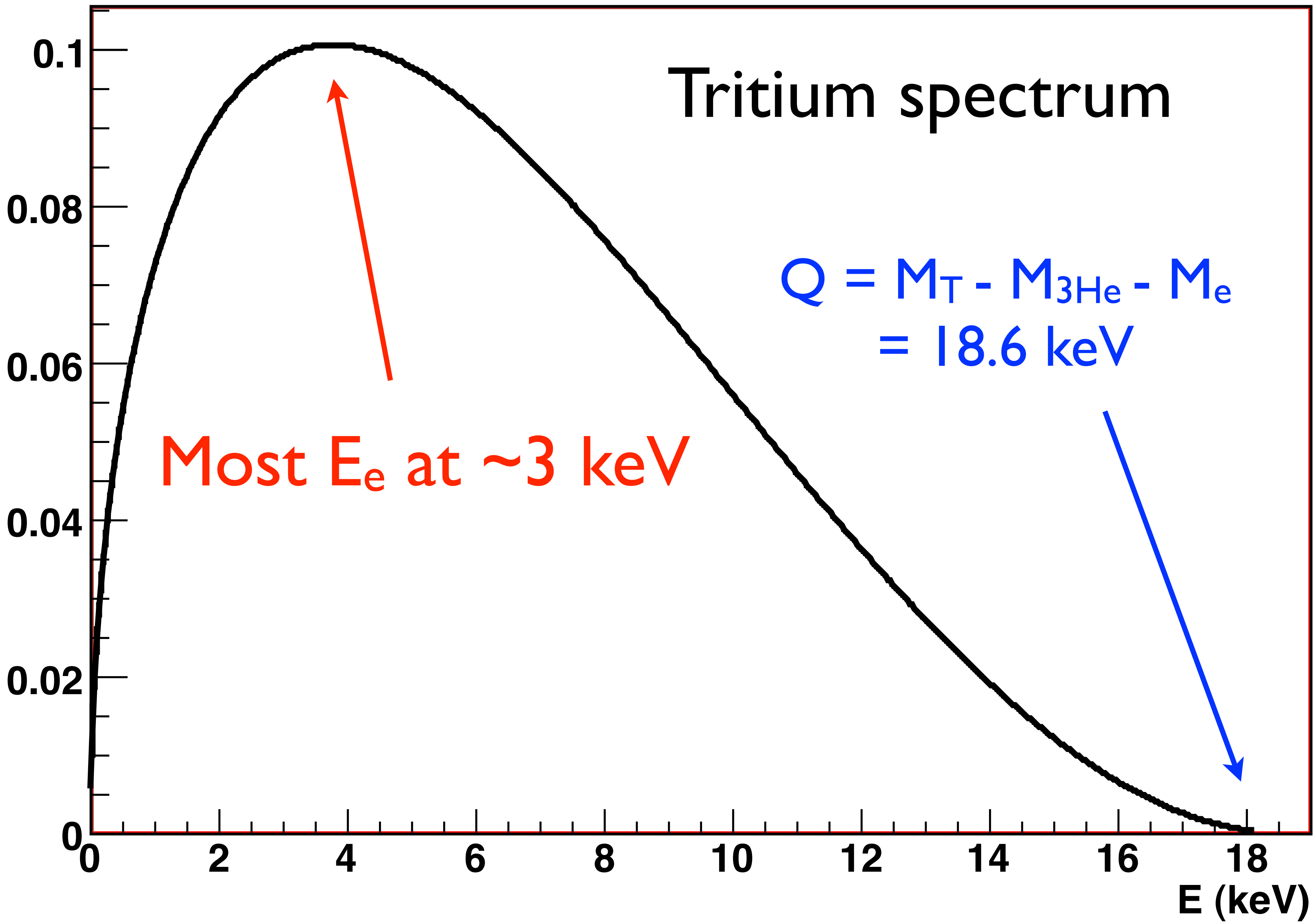




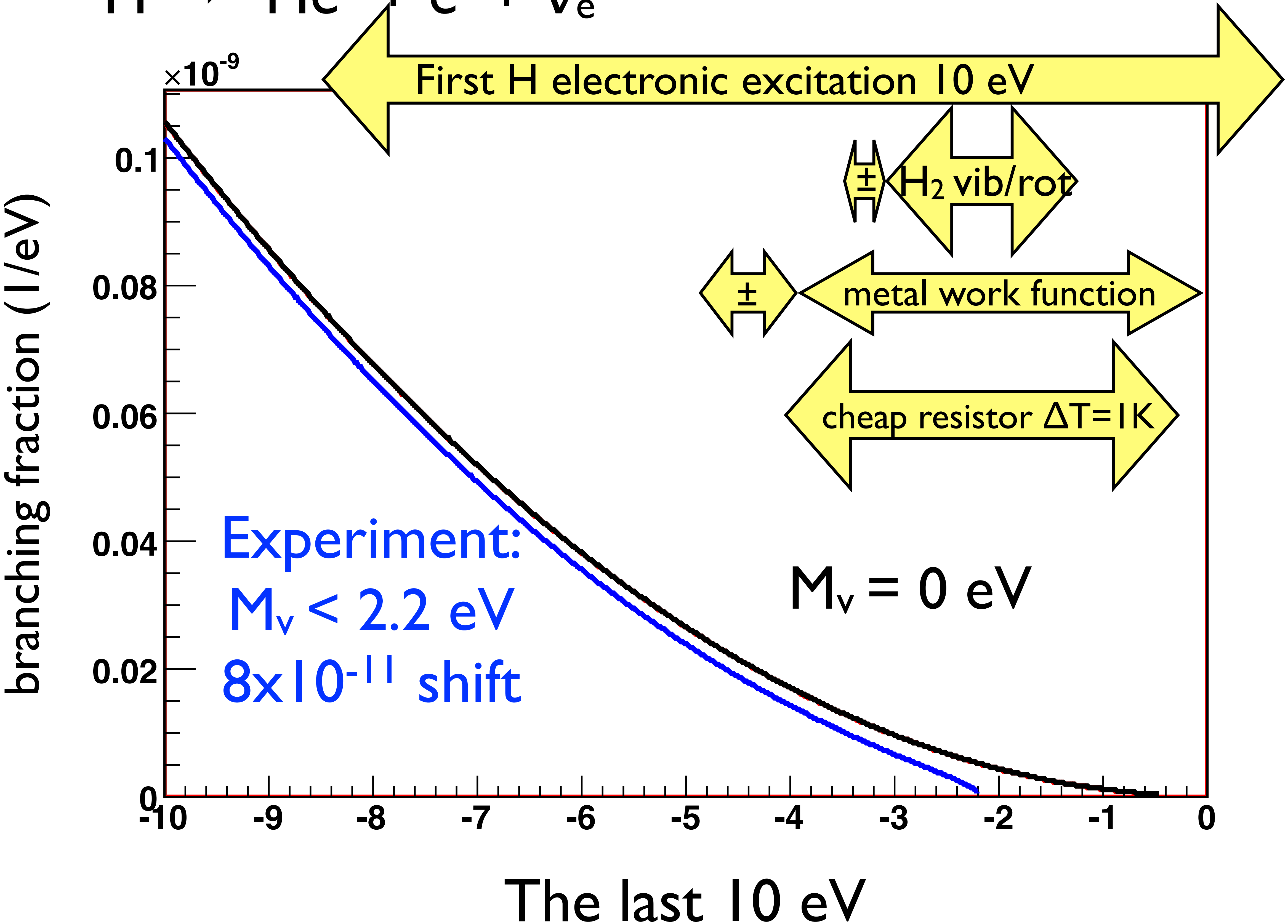


Kinematics say < 2 eV
Cosmology says (?) < 0.3 eV

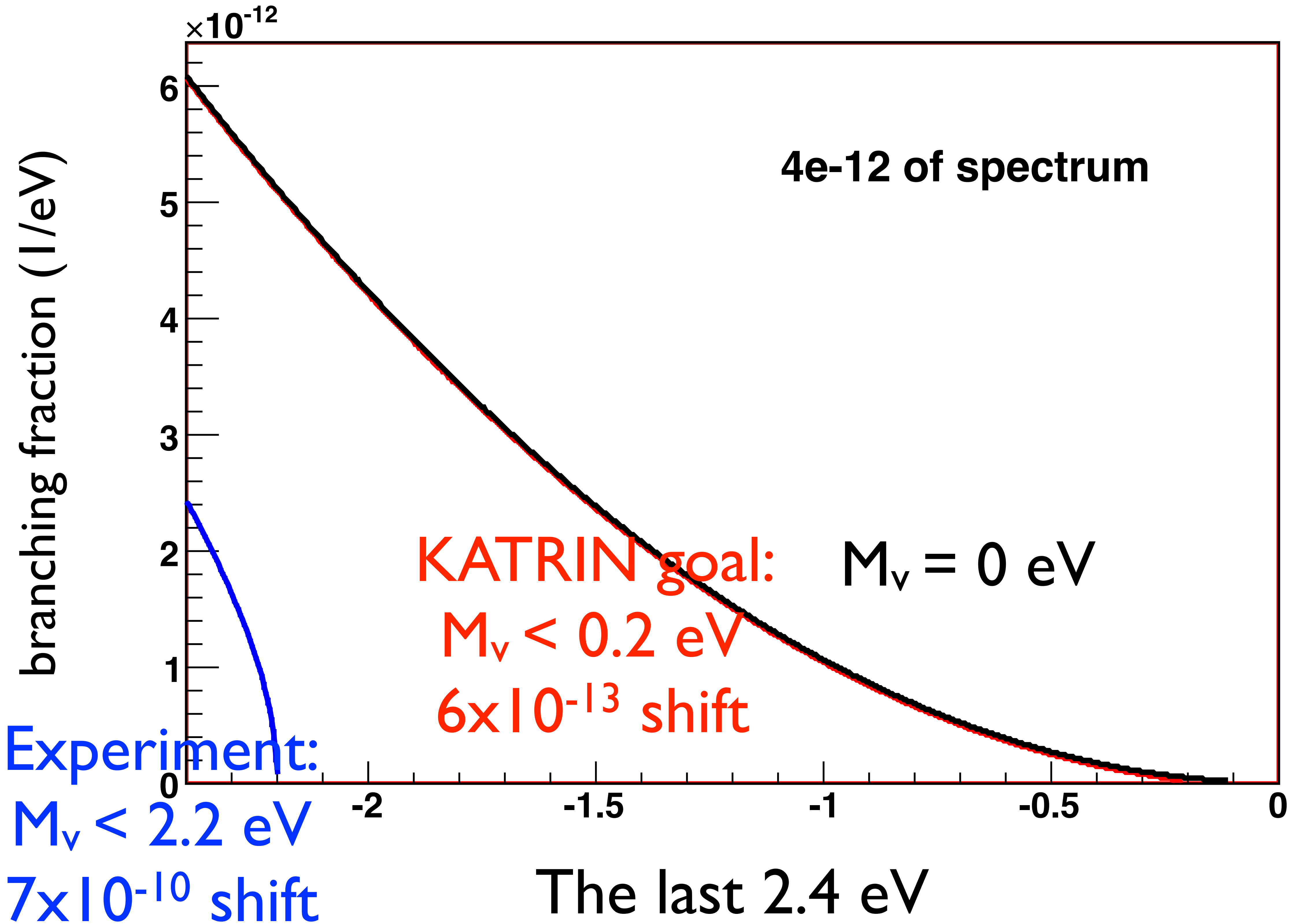
$^3H \rightarrow {}^3He^+ + e^- + \bar{\nu}_e$



$^3H \rightarrow {}^3He^+ + e^- + \bar{\nu}_e$

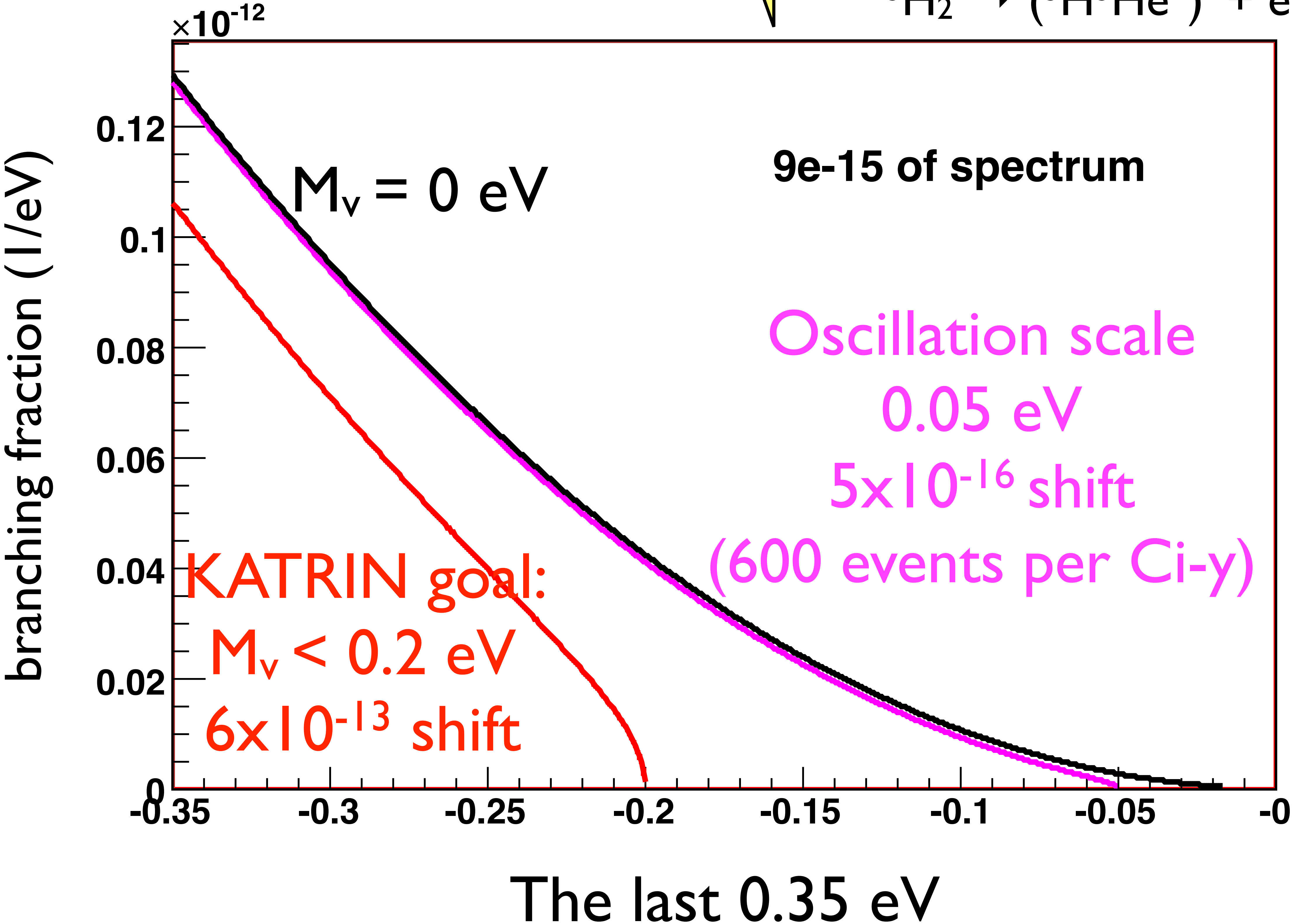


$^3H \rightarrow {}^3He^+ + e^- + \bar{\nu}_e$

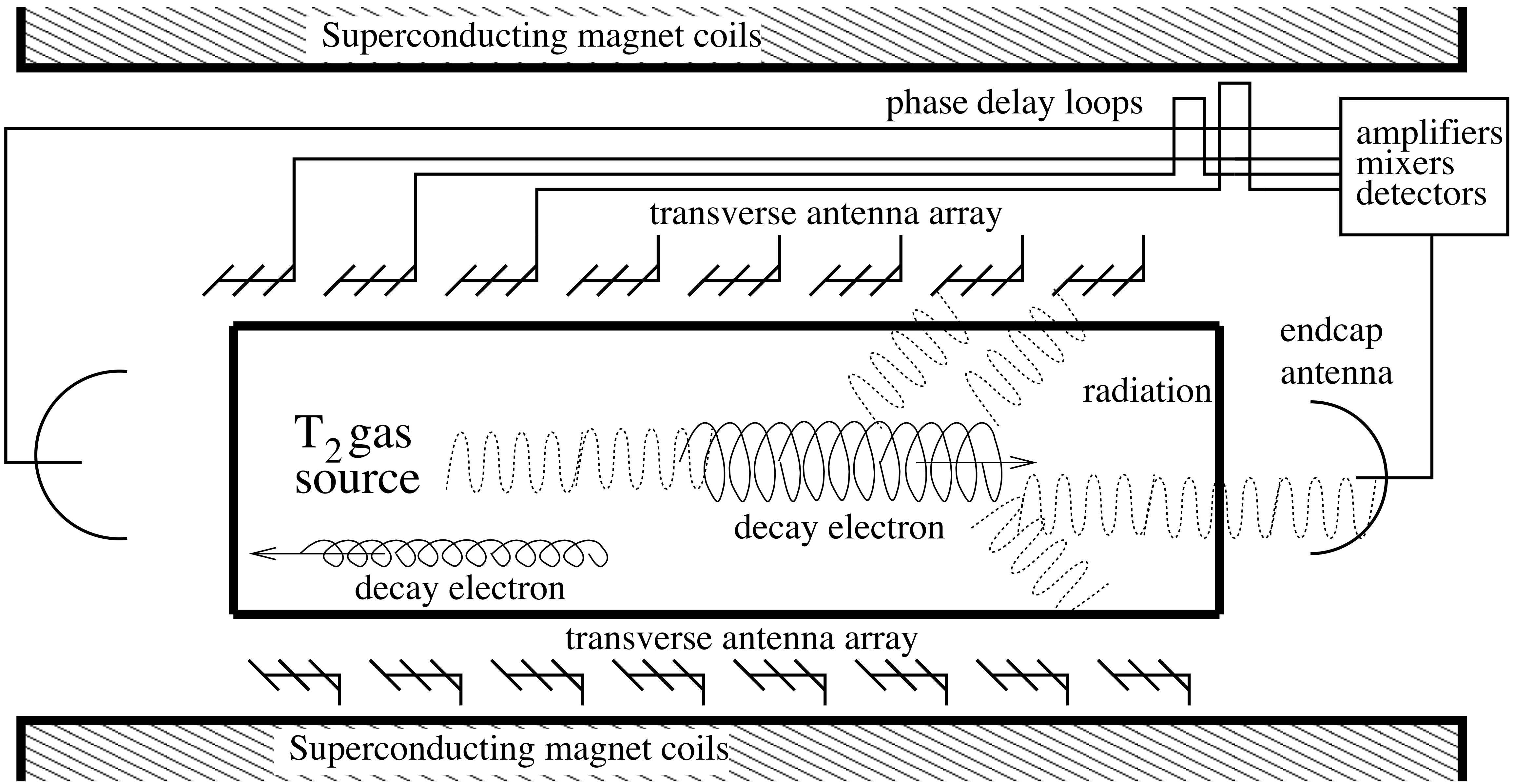


$^3H \rightarrow {}^3He^+ + e^- + \bar{\nu}_e$

$^3H_2 \rightarrow ({}^3H{}^3He^+)^* + e^- + \bar{\nu}_e$



The experiment

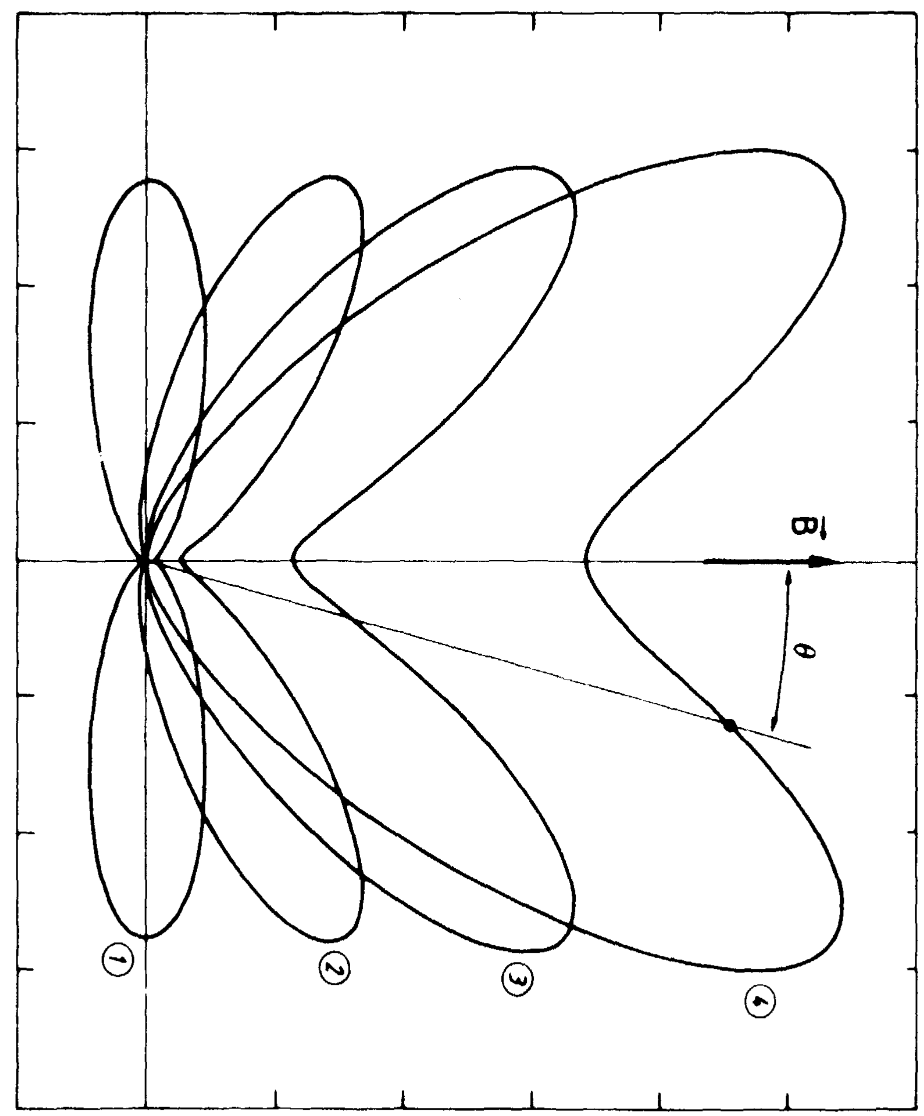


Cyclotron radiation

- accelerating charge = EM radiation
- Coherent, narrowband
- High power per electron

$$\omega = \frac{qB}{\gamma m c^2}$$

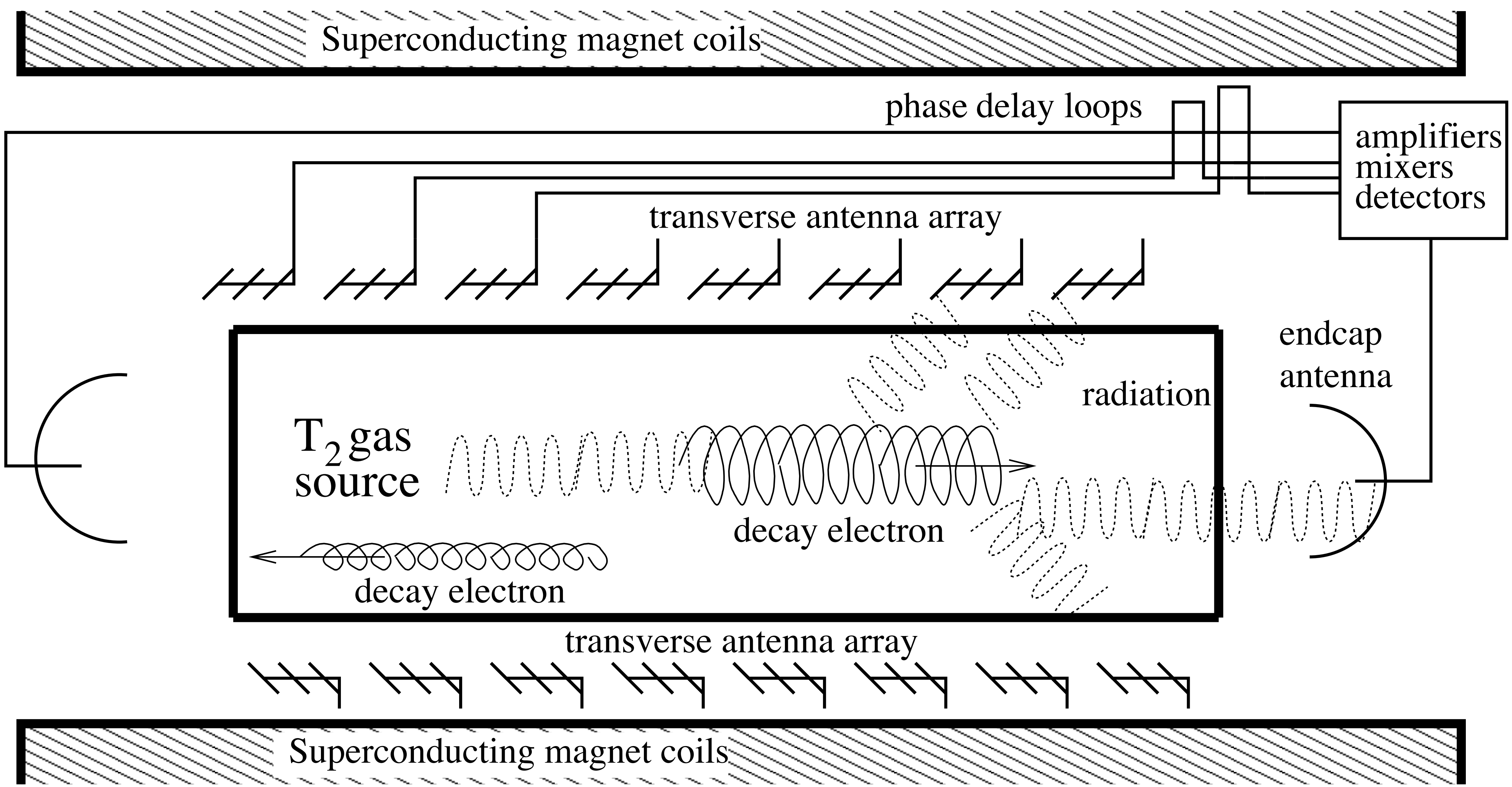
$$P_{\mathrm{tot}} = \frac{1}{4\pi\epsilon_0}\frac{2q^2\omega_c^2}{3c}\frac{\beta_\perp^2}{1-\beta^2}$$



- Electron energy contributes to velocity v, power P, frequency ω
  - *Can we detect this radiation, measure v, P, ω, and determine* E ± 1 eV?

Ben Monreal, UCSB, ANT '10

The experiment

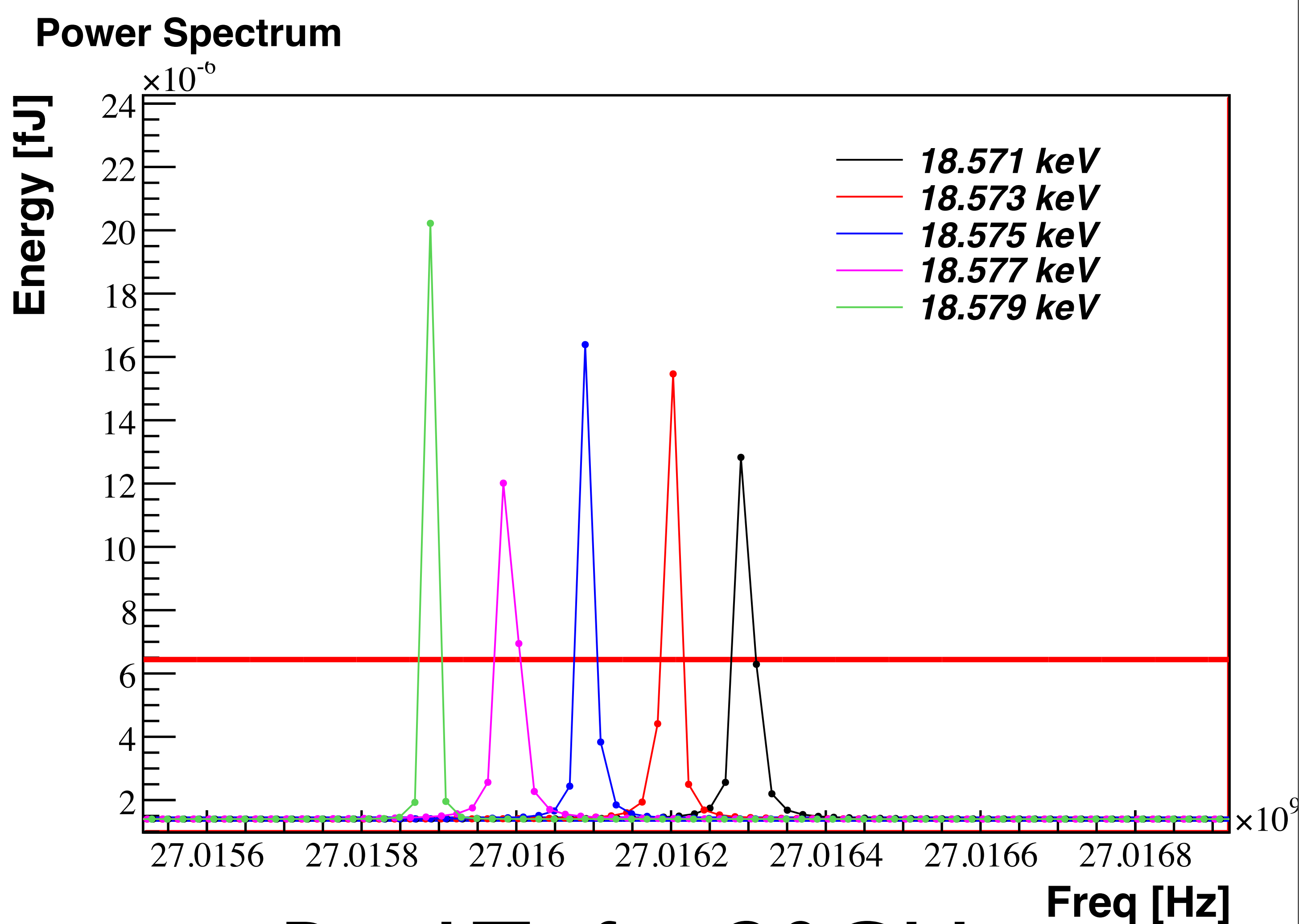


Frequency precision

- Schawlow: "Never measure anything but frequency"
- $f \cdot \Delta E/E \sim \Delta f = 1/\Delta t$
- 1 eV energy resolution
  - $\Delta f / f = 2 \times 10^{-6}$ (easy!)
  - $\Delta t = 20 \mu s$ (hard!)
    - $\beta c \cdot \Delta t = 1400$ meters
- Thermal noise:
  - $P_K(T) = k_B T \Delta f$

Frequency precision

- Schawlow: "Never measure anything but frequency"
- $f \cdot \Delta E/E \sim \Delta f = 1/\Delta t$
- 1 eV energy resolution
  - $\Delta f / f = 2\times10^{-6}$ (easy!)
  - $\Delta t = 20\mu s$ (hard!)
    - $\beta c \cdot \Delta t = 1400$ meters
- Thermal noise:
  - $P_K(T) = k_B T \, \Delta f$



$B = 1T, \; f = 30GHz$

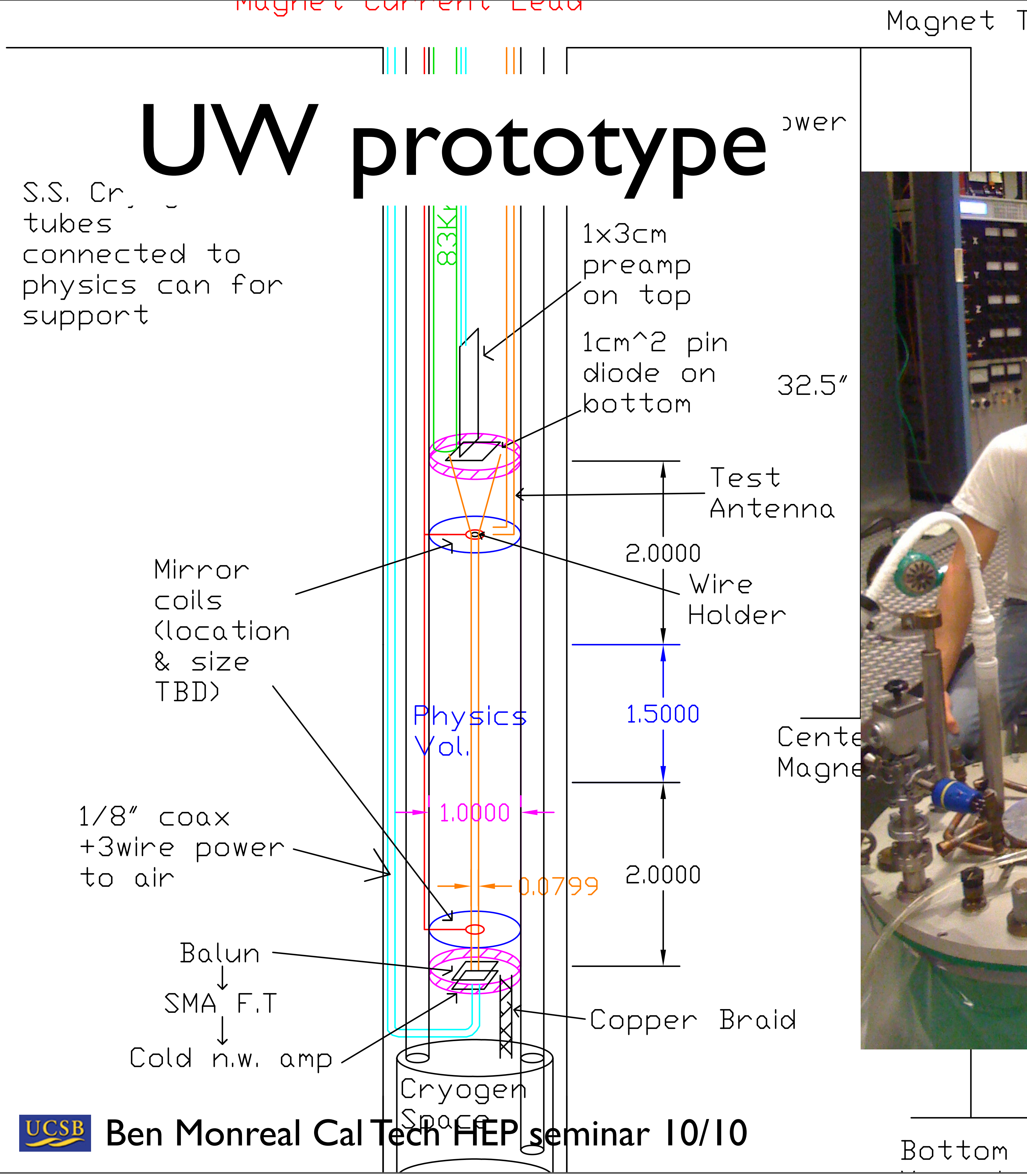
$\Delta f = 60kHz$

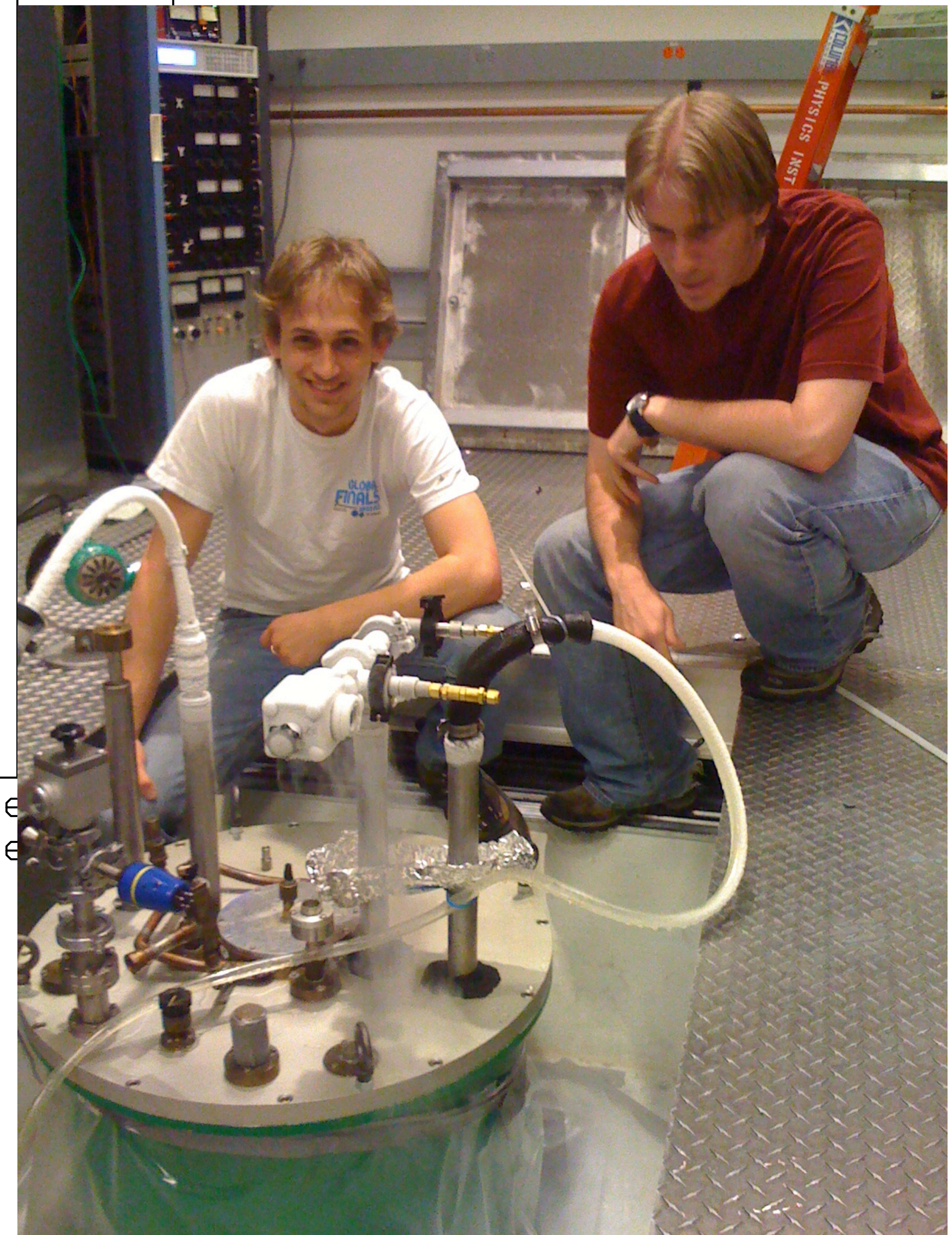
$P_{signal} = 10^{-15}$ W

$P_K(10K) = 10^{-17}$ W

Ben Monreal, UCSB, ANT '10

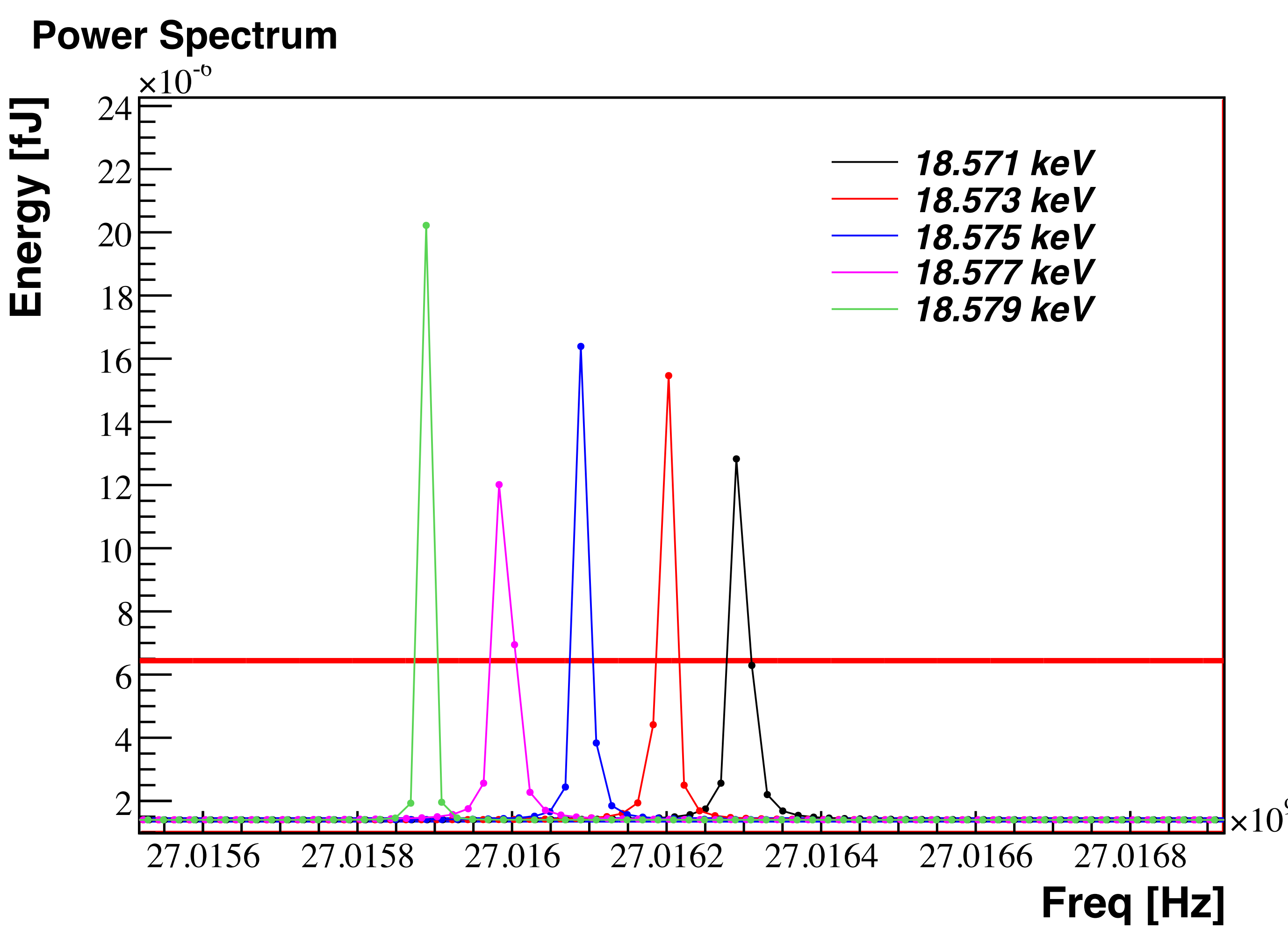
UW prototype

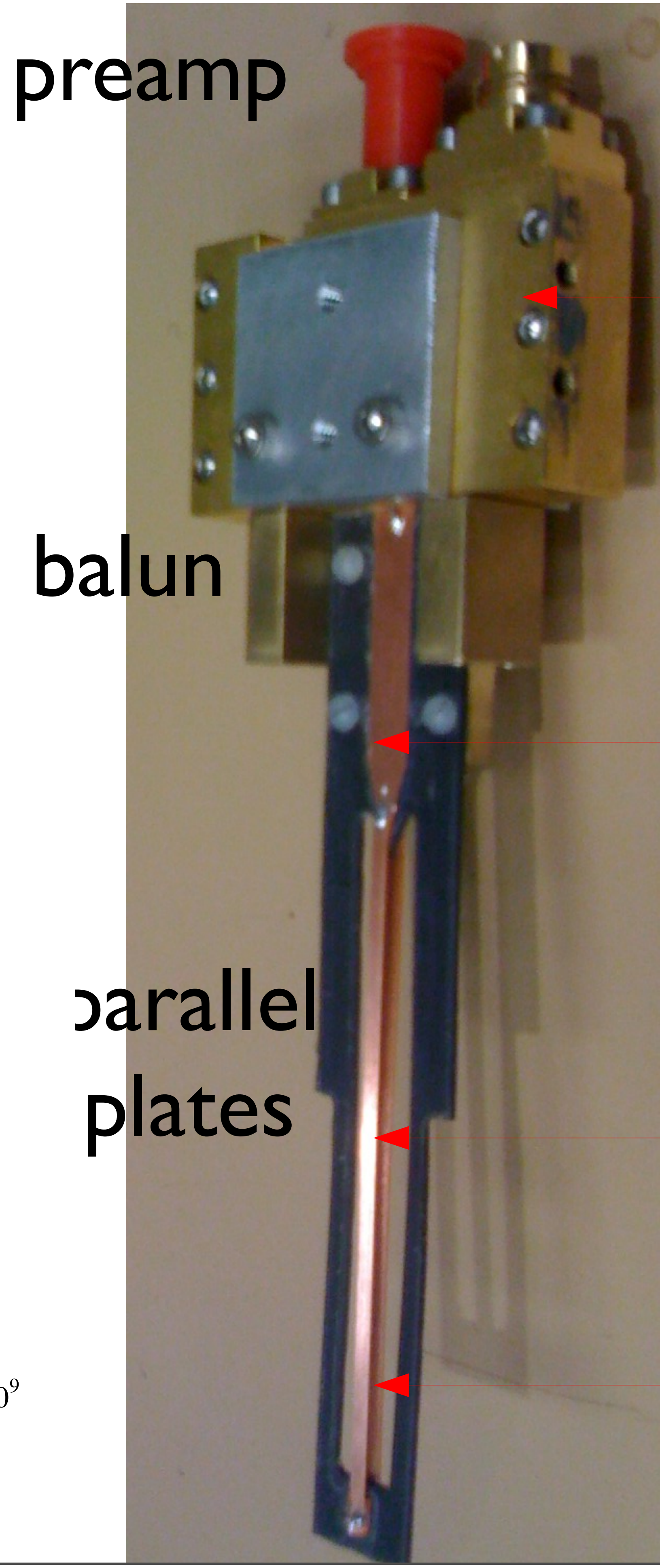


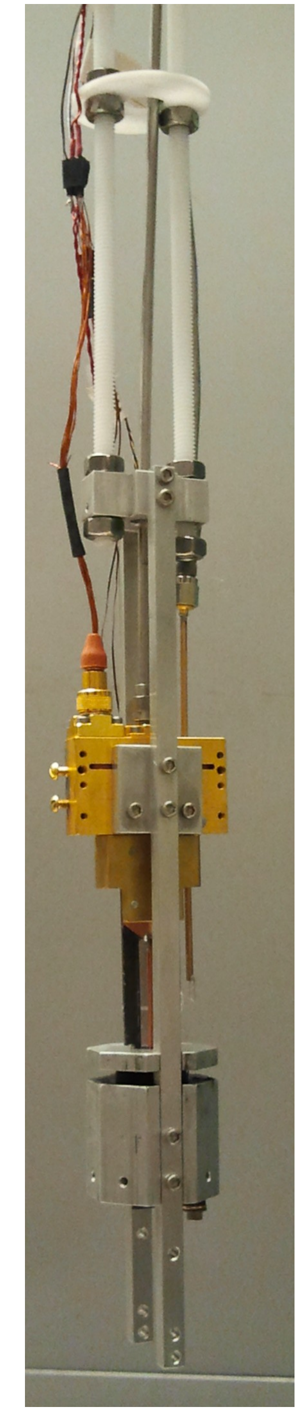


$^{83}Rb \rightarrow {}^{83m}Kr$
($t_{1/2}$=86d, BR=100%)

$^{83m}Kr \rightarrow {}^{83}Kr$ +
17.8 keV e^- + 14.3 keV γ
($t_{1/2}$=1.8h, BR=25%)



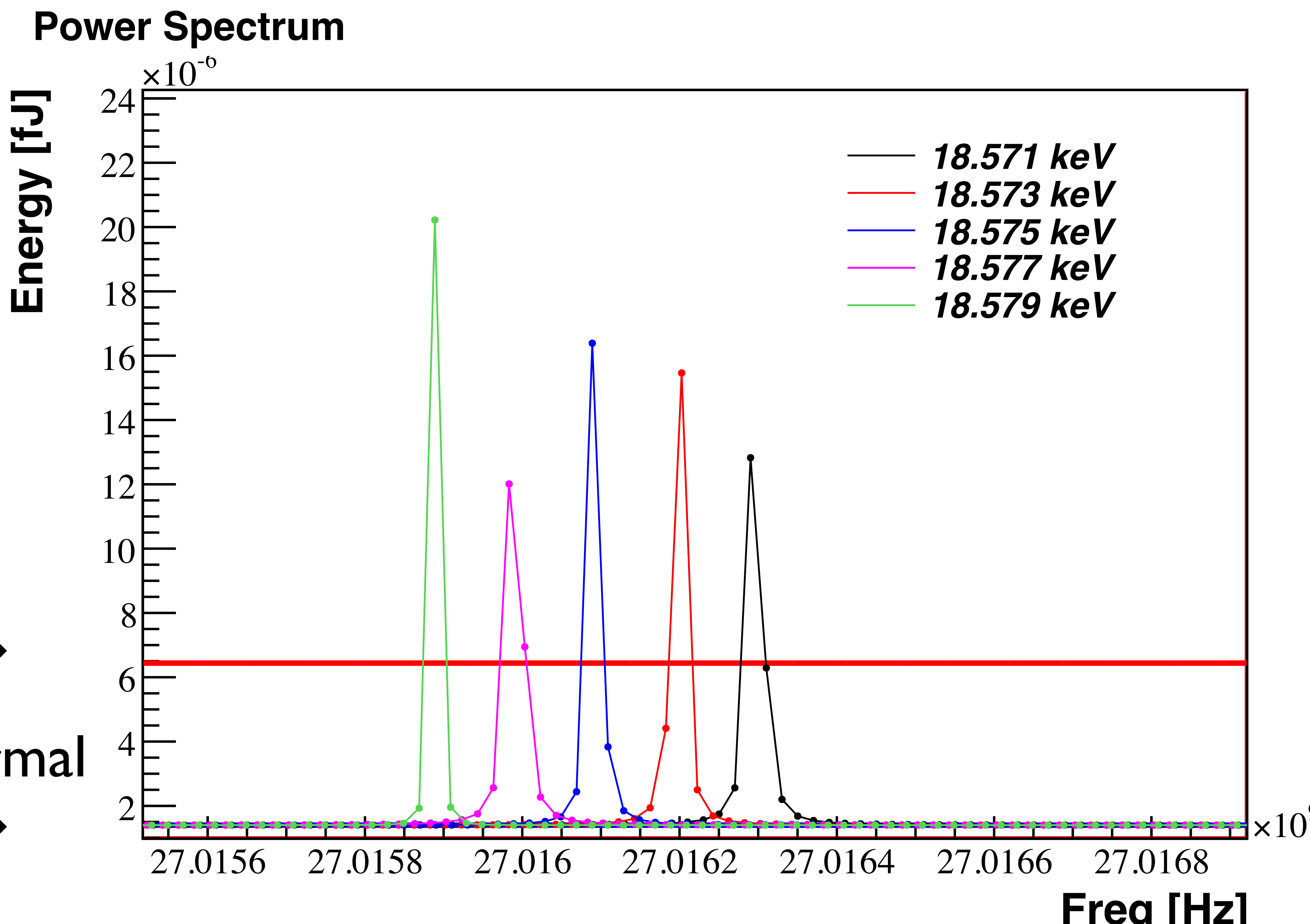




UW prototype expected to detect single e^- from $^{83m}Kr \rightarrow {}^{83}Kr^+ + e^-$(IC)

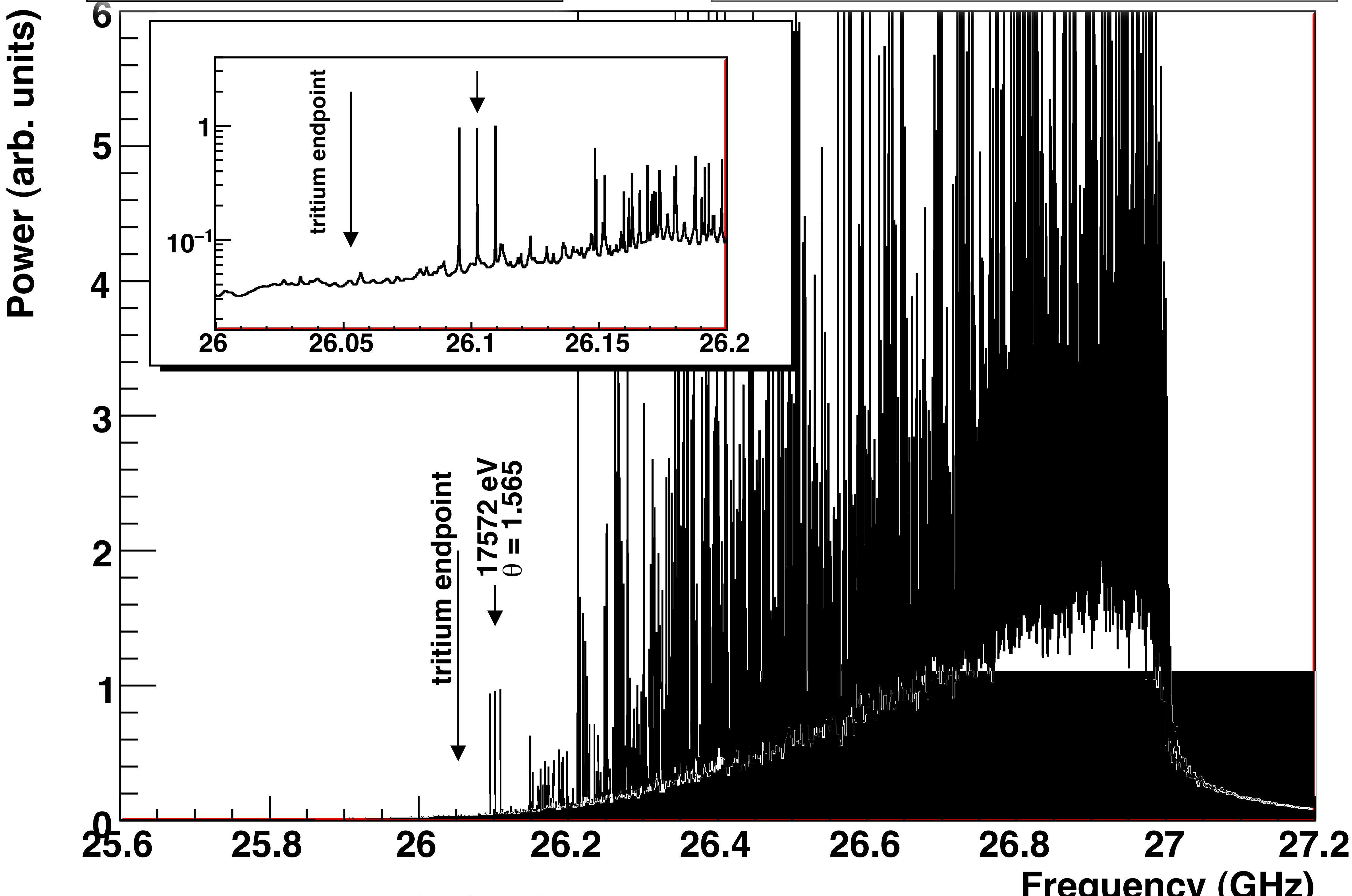
1% thermal fluctuation →

mean thermal noise→



rare high-energy electrons

many overlapping low-energy electrons



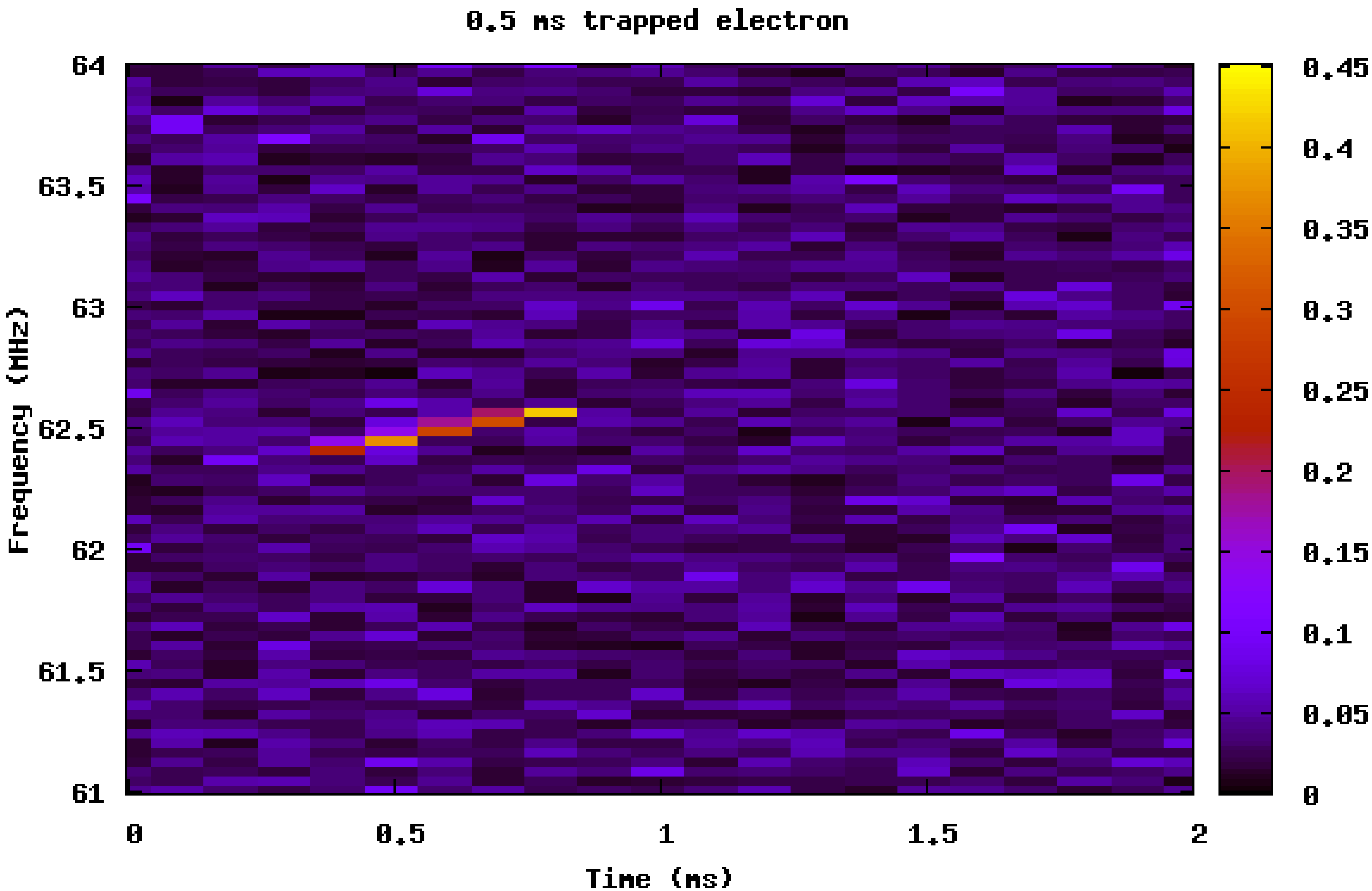
100,000 tritium electrons

Complexities

1. Electron energy not constant

Current detector simulation

(Frequency after mixing)

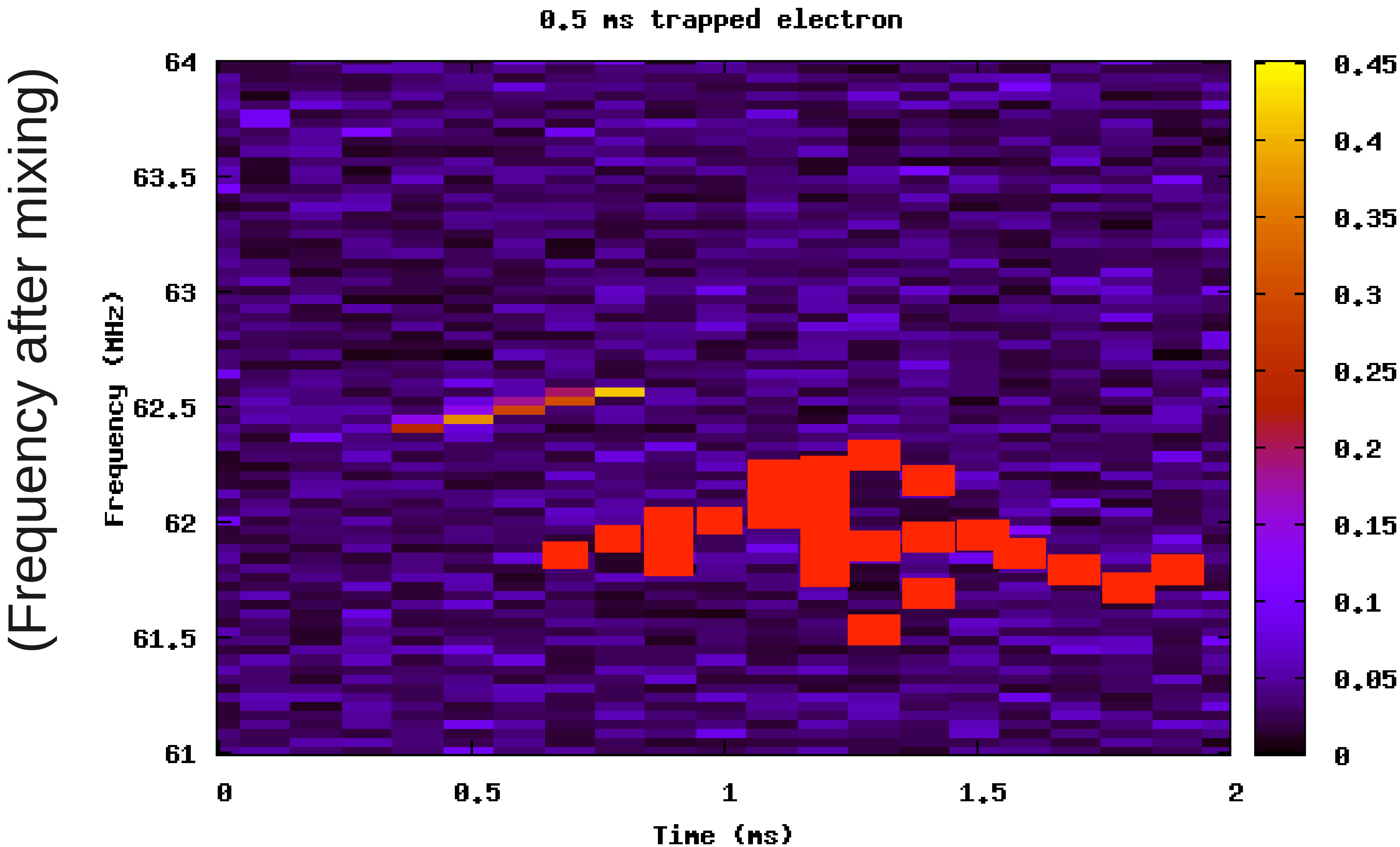


simulation M. Leber

Complexities

1. Electron energy not constant
2. B-field may not be uniform

Current detector simulation

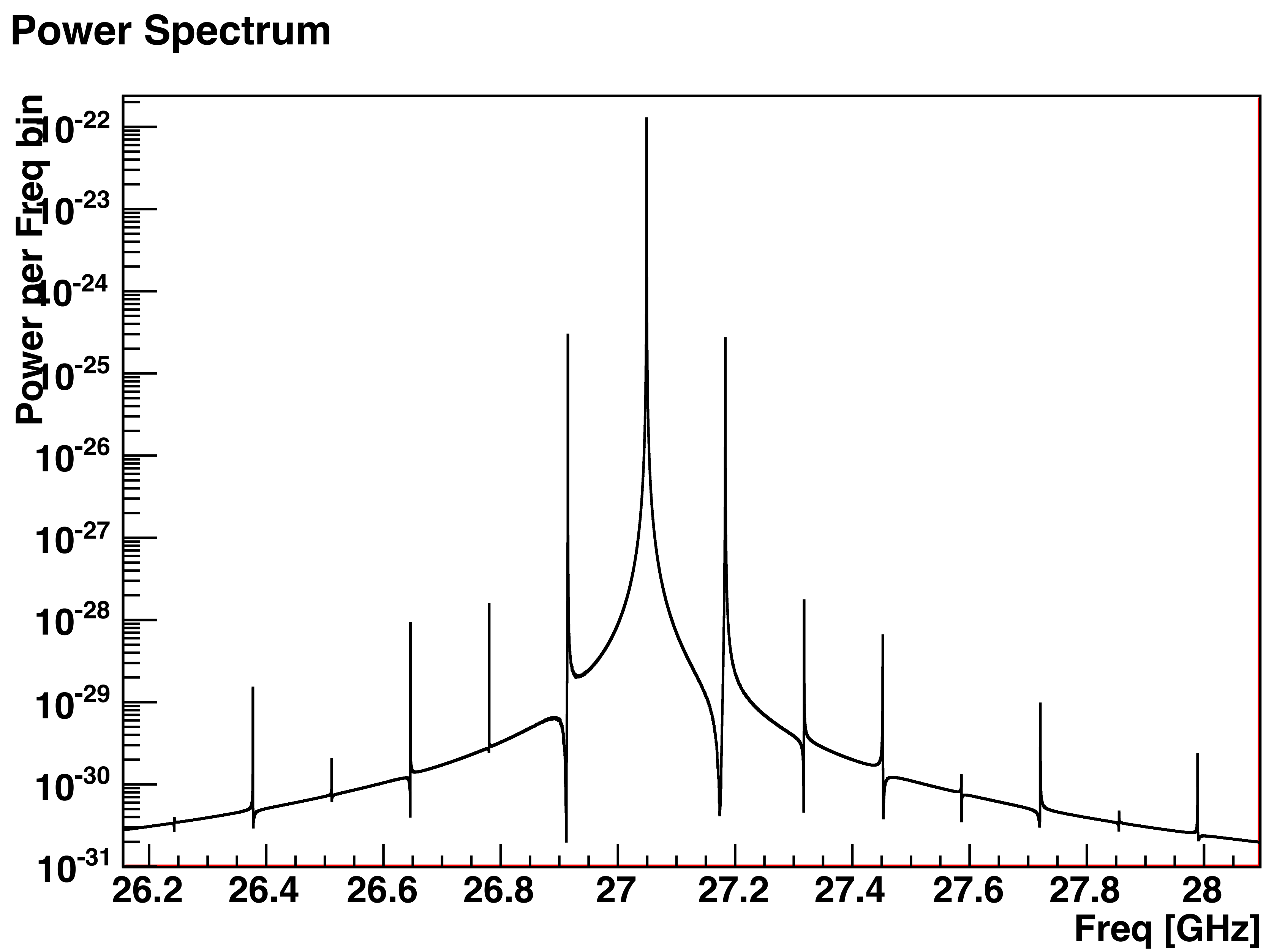


simulation M. Leber

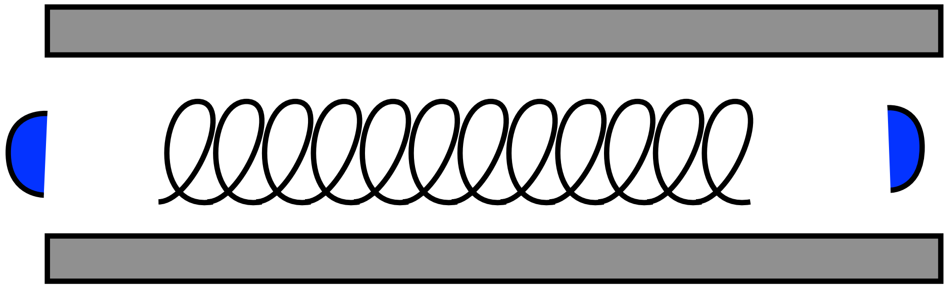
Complexities

1. Electron energy not constant
2. B-field may not be uniform
3. Oscillations, Doppler shifts = frequency sidebands

Magnet construction, DAQ, bandwidth, and SNR are all entangled

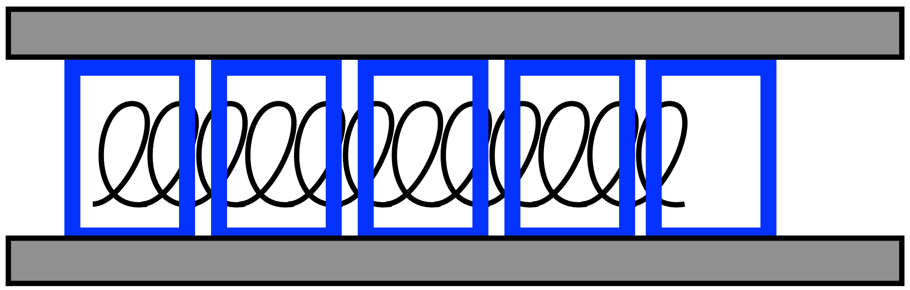


Long solenoid/waveguide



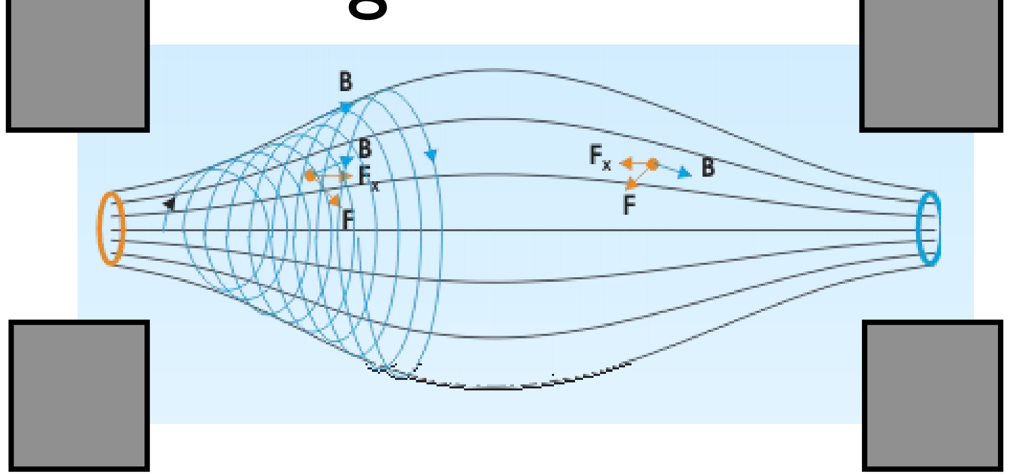
- Bad: most e^- escape in < 1 μs (long)
- Bad: no power at $f = f_0$; just red/blueshift
  - (redshift at waveguide group velocity)
  - need high-bandwidth data analysis
- Good: data analysis is JUST fourier trans

Long solenoid/cavities

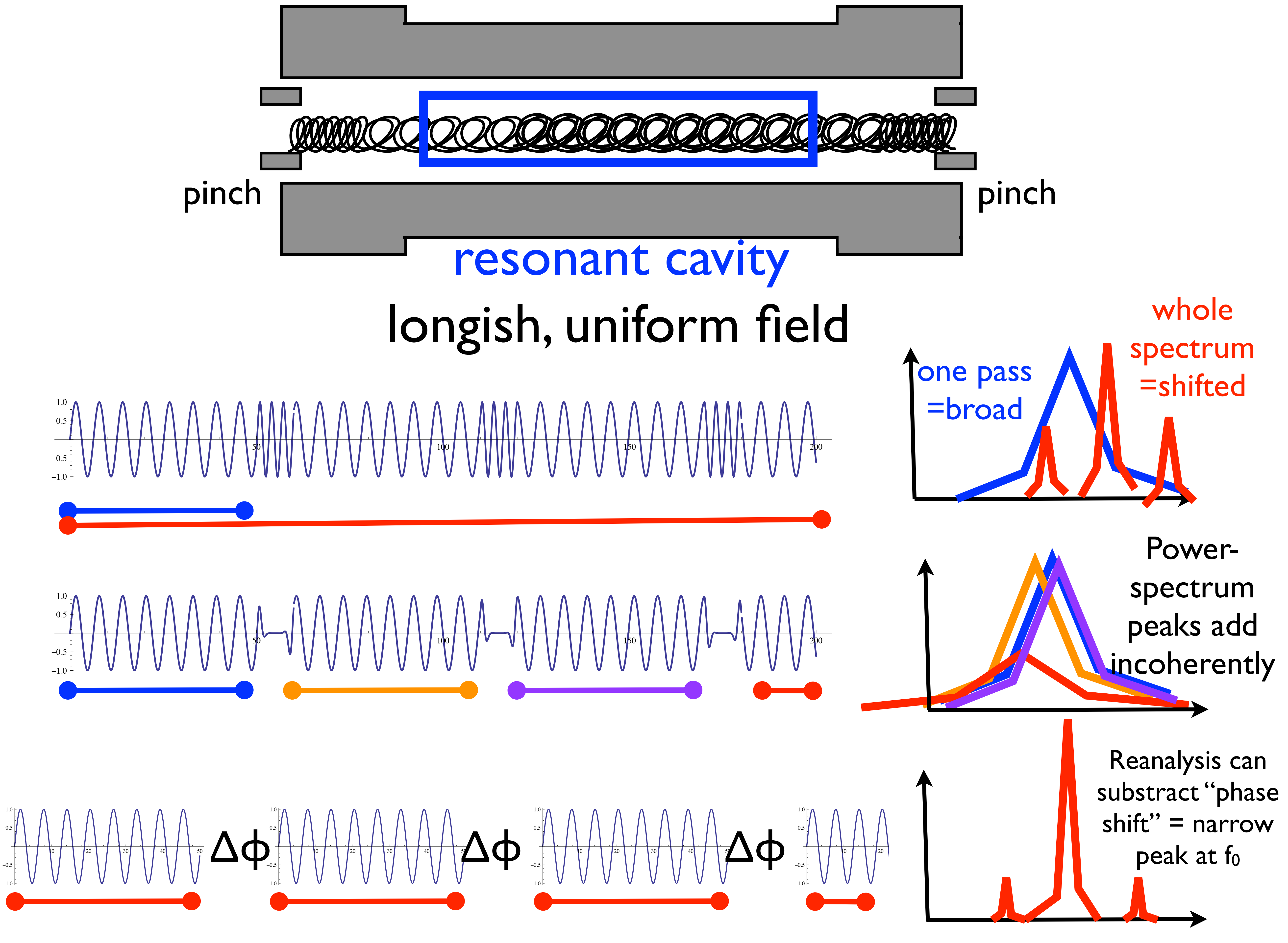


- Bad: most e^- escape in < 1 μs (long)
- Good: simplest possible spectrum (peak at f_0)
- Good: only need ~1MHz DAQ
- Bad: 30GHz is tough cavity size

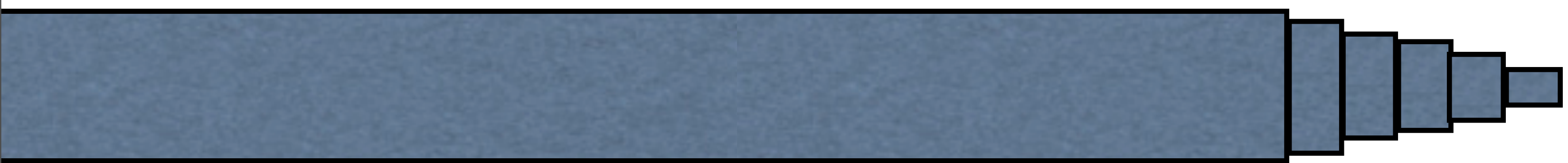
Magnetic bottle

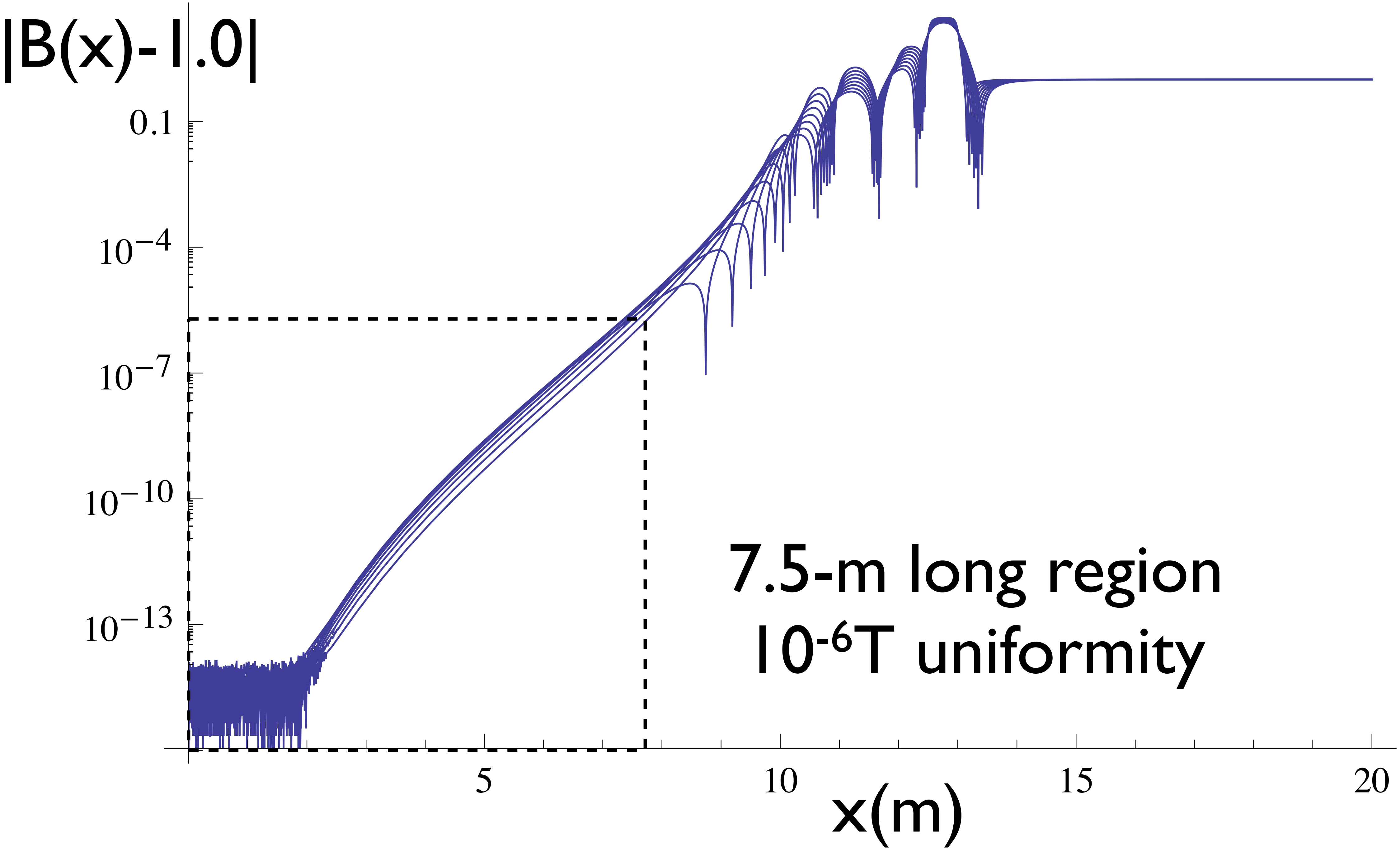


- Good: keeps e- in view of simple antenna for a long time
- Bad: center frequency depends on pitch angle, radial position
- Maybe: all of the unknowns are encoded in the rich sideband structure (??)

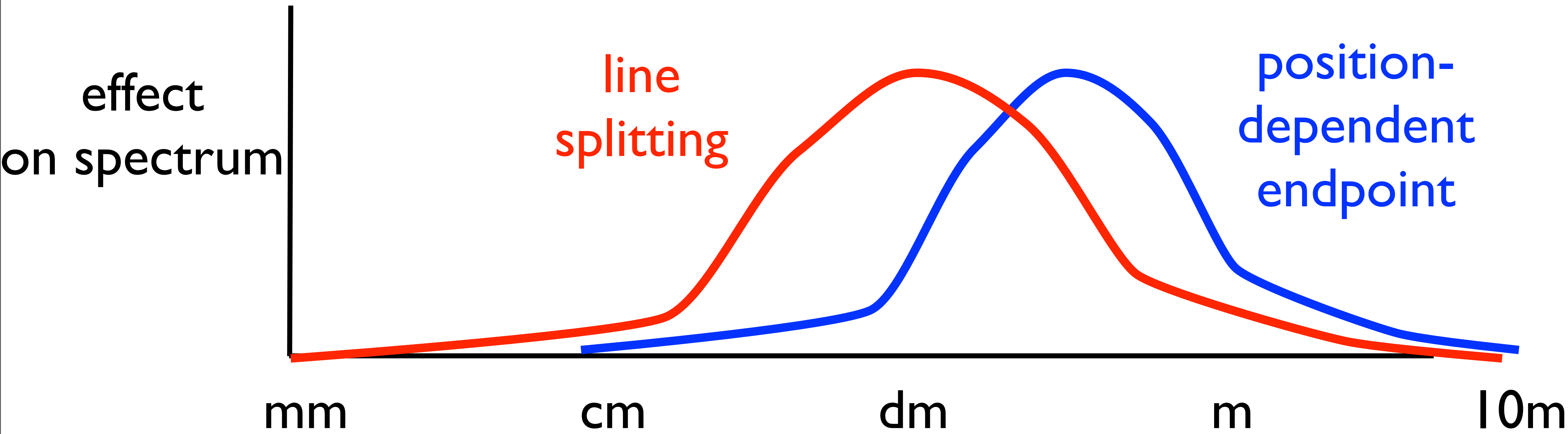

pinch
pinch
resonant cavity
longish, uniform field
one pass
=broad
whole
spectrum
=shifted
Power-
spectrum
peaks add
incoherently
Δϕ
Δϕ
Δϕ
Reanalysis can
substract "phase
shift" = narrow
peak at f0

Magnet design





What sort of uniformity?



B field averages over many wires **= OK**

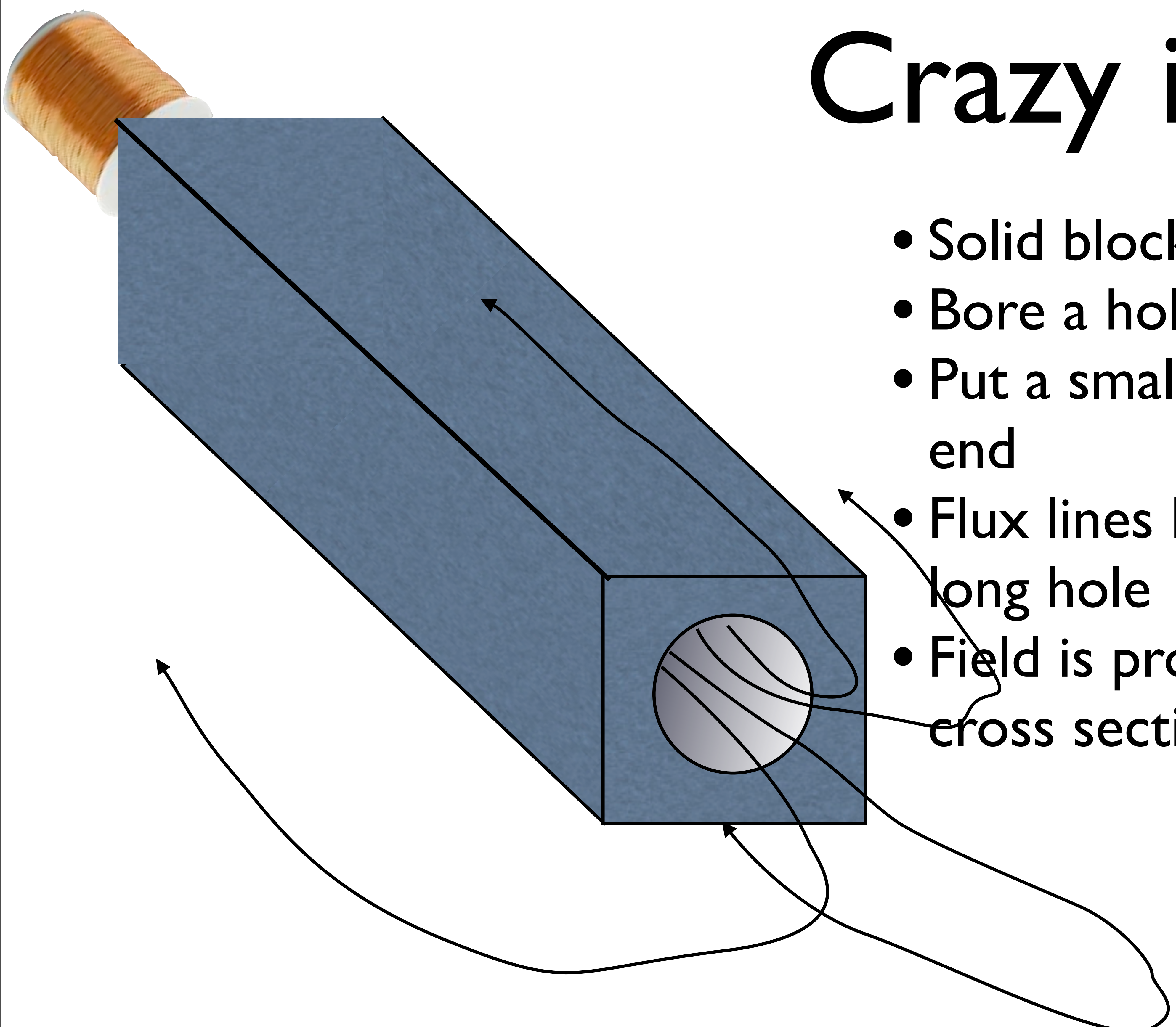
typical electron explores range of Bs. **High-bandwidth DAQ, LIGO-like templates?**

Different electrons experience different Bs. **multiple antennas, offline templates?**

Corrected out by low-order polynomial coils **=OK**

Magnet design, antenna config, and data analysis are badly entangled

Crazy ideas



- Solid block of Type-1 SC
- Bore a hole up the middle
- Put a small magnet at one end
- Flux lines have to thread long hole
- Field is proportional to cross section of hole

Conclusions

- Project 8 is the first realistic prospect for a post-KATRIN neutrino mass experiment
- Coming soon: 1st single-electron detection with ^{83m}Kr source
  - Quick low-res T_2 experiment?
- Come up with “scalable design” and build tabletop version (~few-eV m_ν sensitivity)
  - We welcome magnet and RF engineering advice
- Proposal for large experiment