Project 8: a radiofrequency approach to the neutrino mass

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Project 8 collaboration

- UCSB: Ben Monreal
- MIT: Joe Formaggio, Asher Kaboth, Daniel Furse
- University of Washington: Hamish Robertson, Peter Doe, Leslie Rosenberg, Michael Miller, Gray Rybka, Brent Vandevender, Adam Cox, Michelle Leber, Laura Bodine
- NRAO: Rich Bradley

BM & JF, arxiv:0904.2860, shortly in PRD

Neutrino mass

Kurie, Richardson, & Paxton 1936

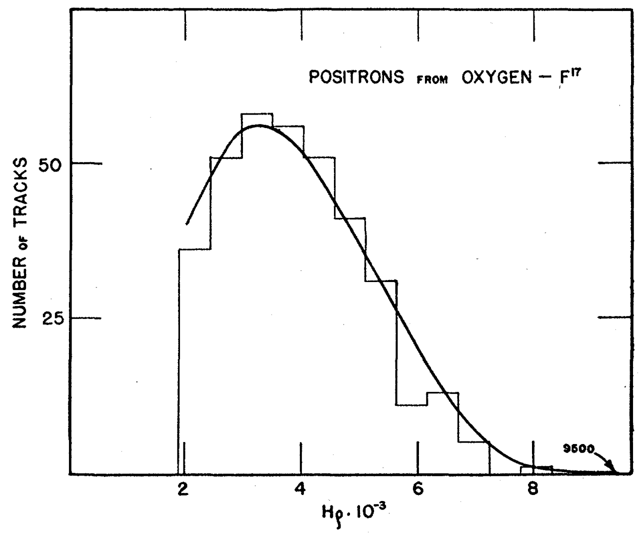


FIG. 3. Distribution histogram for the positrons emitted from activated oxygen (F^{17}) together with the theoretical K–U curve. The endpoint of the theoretical curve is at $9500H\rho$.

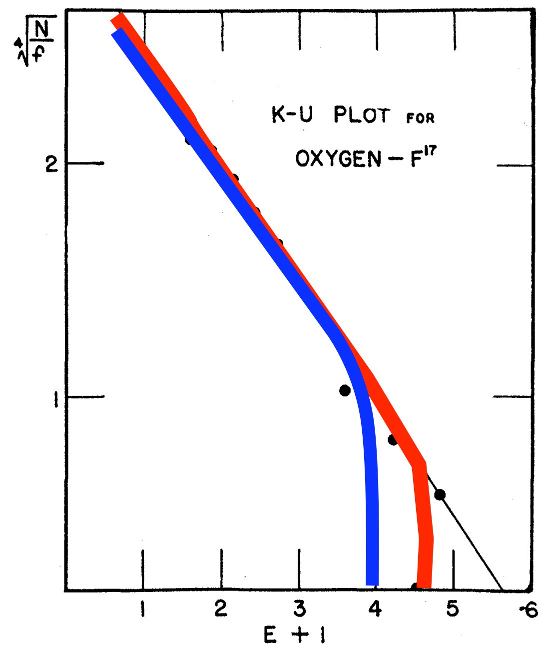


FIG. 4. K–U plot for activated oxygen. This plot is again linear and extrapolates to an upper limit at $E+1=5.7$.

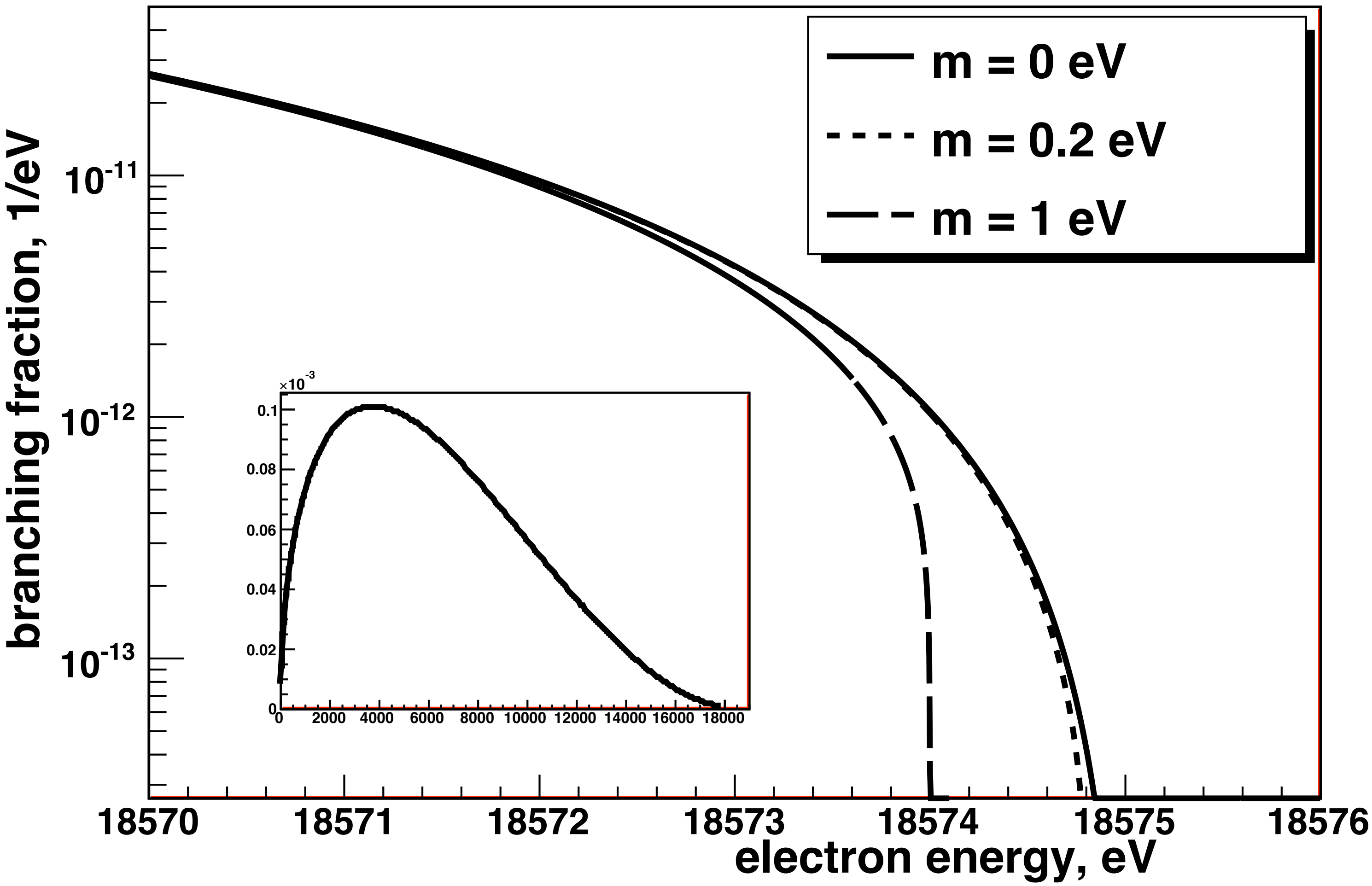
when the target chamber was full of oxygen. A strong sample of F^{17} is driven by recoil onto the foil.

Fig. 3 shows the distribution histogram together with a K–U curve which has been fitted to it by means of the linear plot in Fig. 4. The

Sodium Na^{24} (electron emitter)

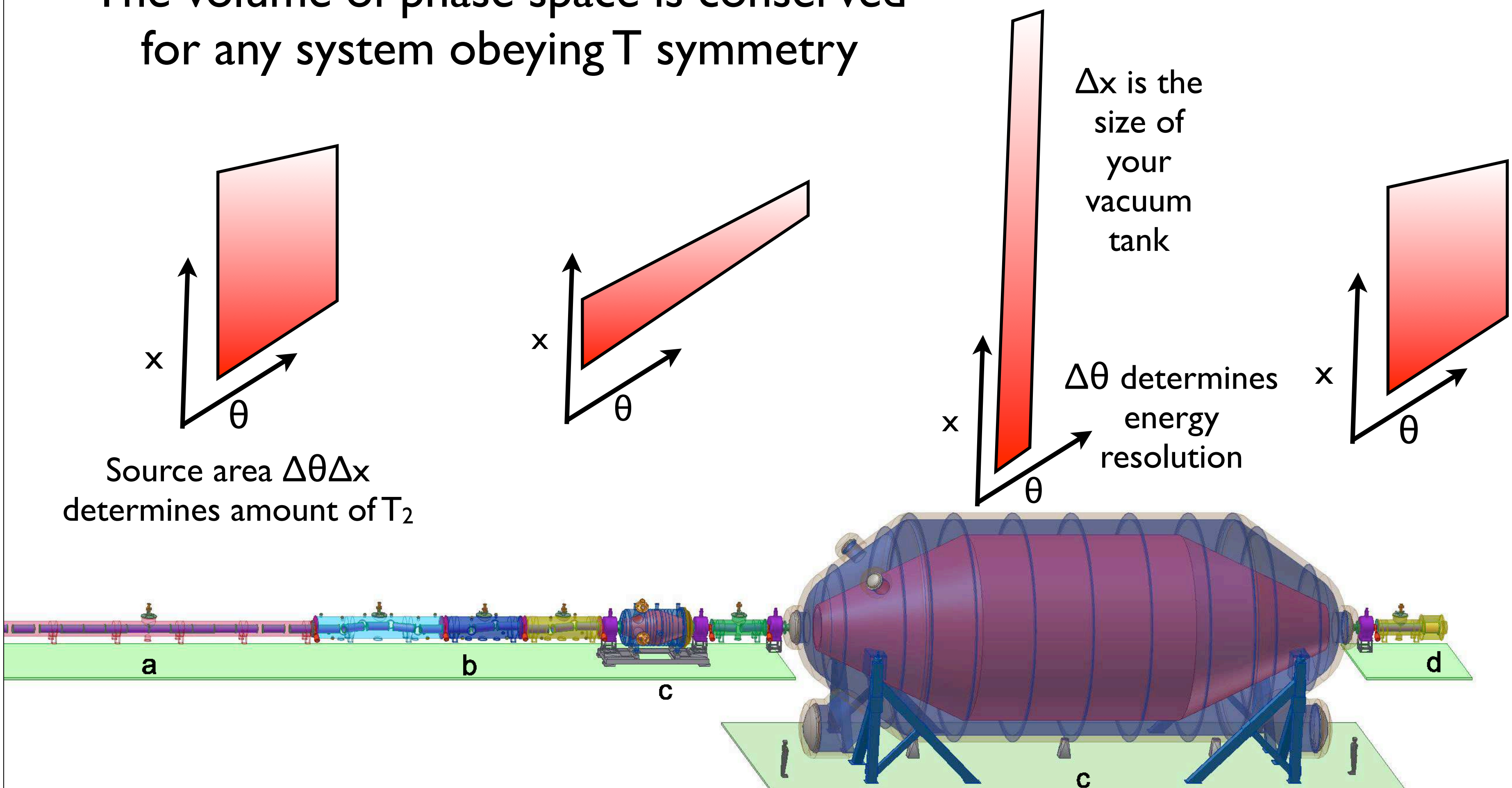
Radio-sodium has been extensively studied by E. O. Lawrence.[18] Substances of the same decay period have been prepared by Fermi and his

Neutrino mass



Liouville's theorem

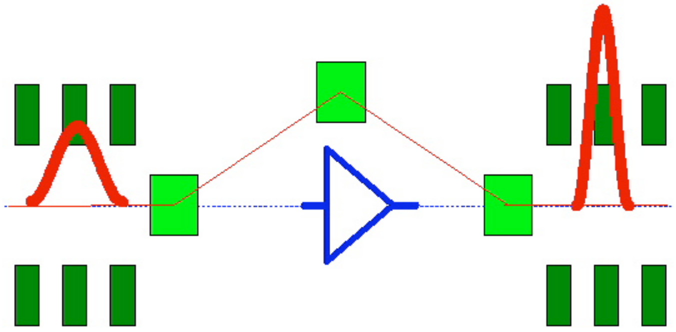
The volume of phase space is conserved for any system obeying T symmetry



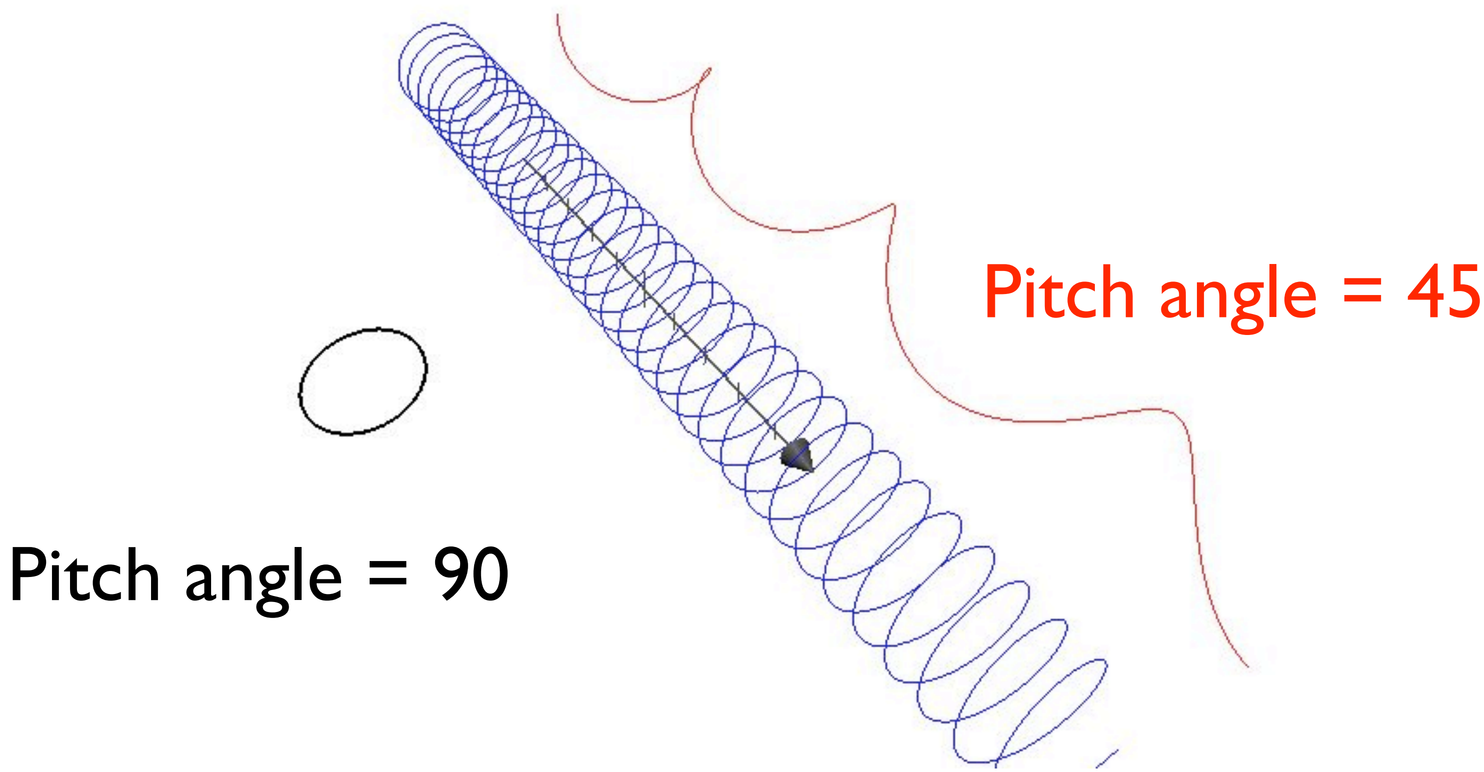
Nondestructive measurement

- Maxwell's Demon

- Stochastic cooling



Cyclotron motion



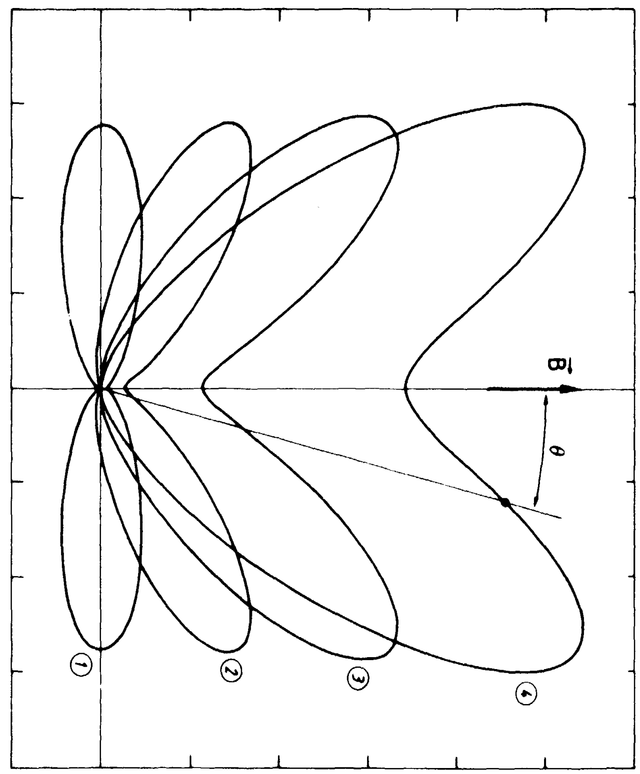
Cyclotron radiation

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

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

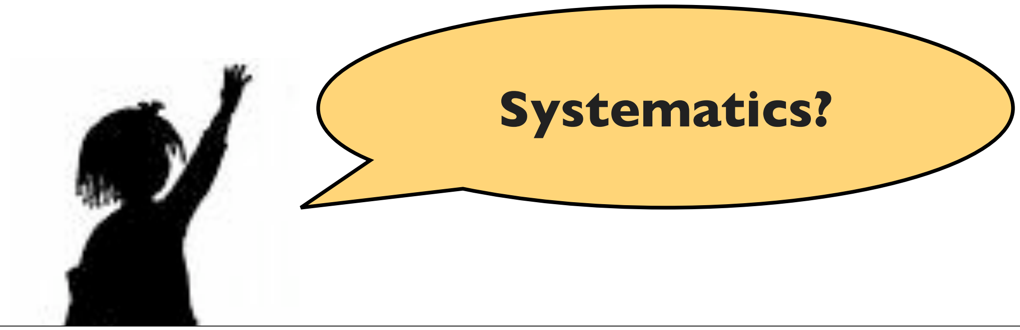
$$P_{\mathrm{tot}} = \frac{1}{4\pi\epsilon_0}\frac{2q^2\omega_c^2}{3c}\frac{\beta_\perp^2}{1-\beta^2}$$

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



Complications

- Frequency resolution?
- Doppler shift?
- Huge fluxes!
- Available power

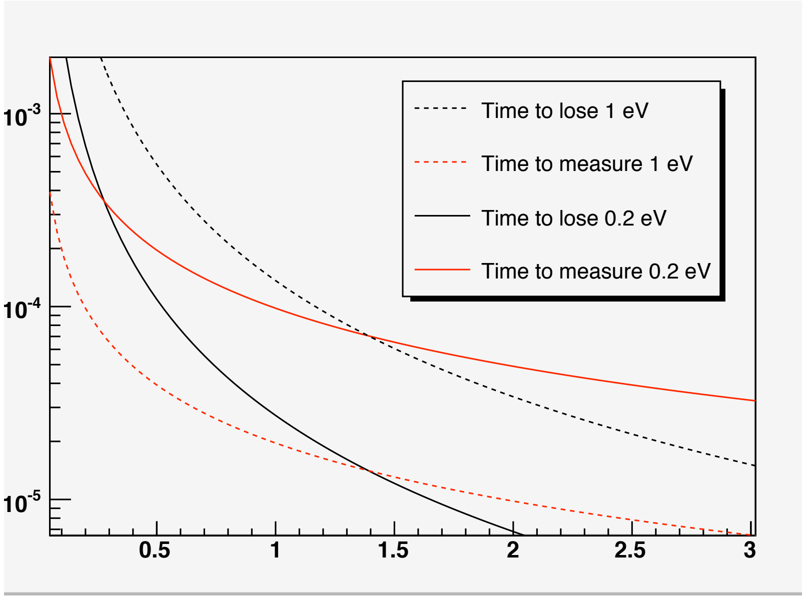


Frequency

- 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

Radiative losses

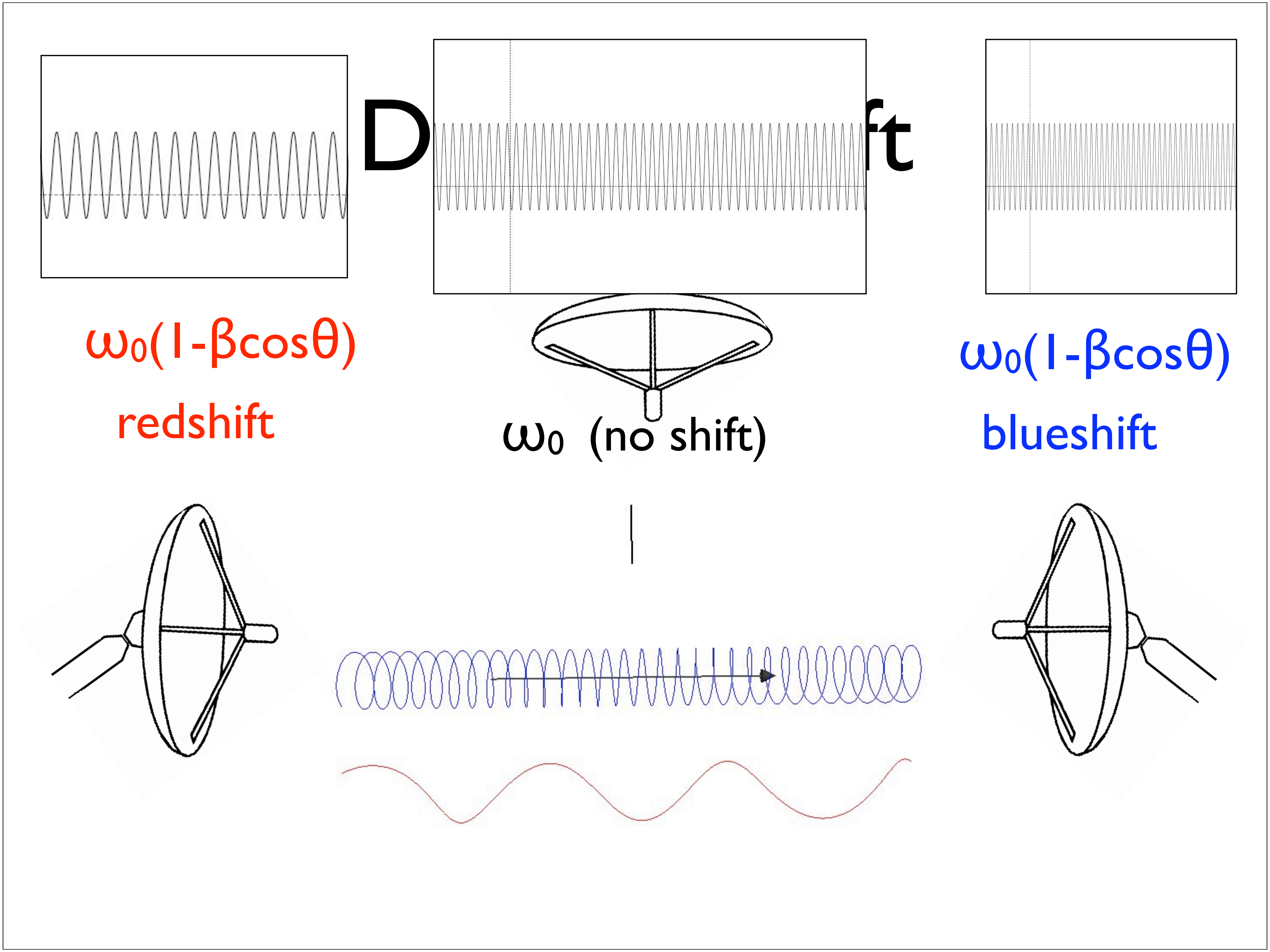
- E changes during measurement (cyclotron radiation)
- Decay rate $\Delta E/\Delta t \propto B^2$
- Fourier limit $\Delta E\, \Delta t \propto B^{-1}$
    - <u>Prevents high-res experiment at high B</u>
    - ~1 Tesla works for 0.5 eV



Complications

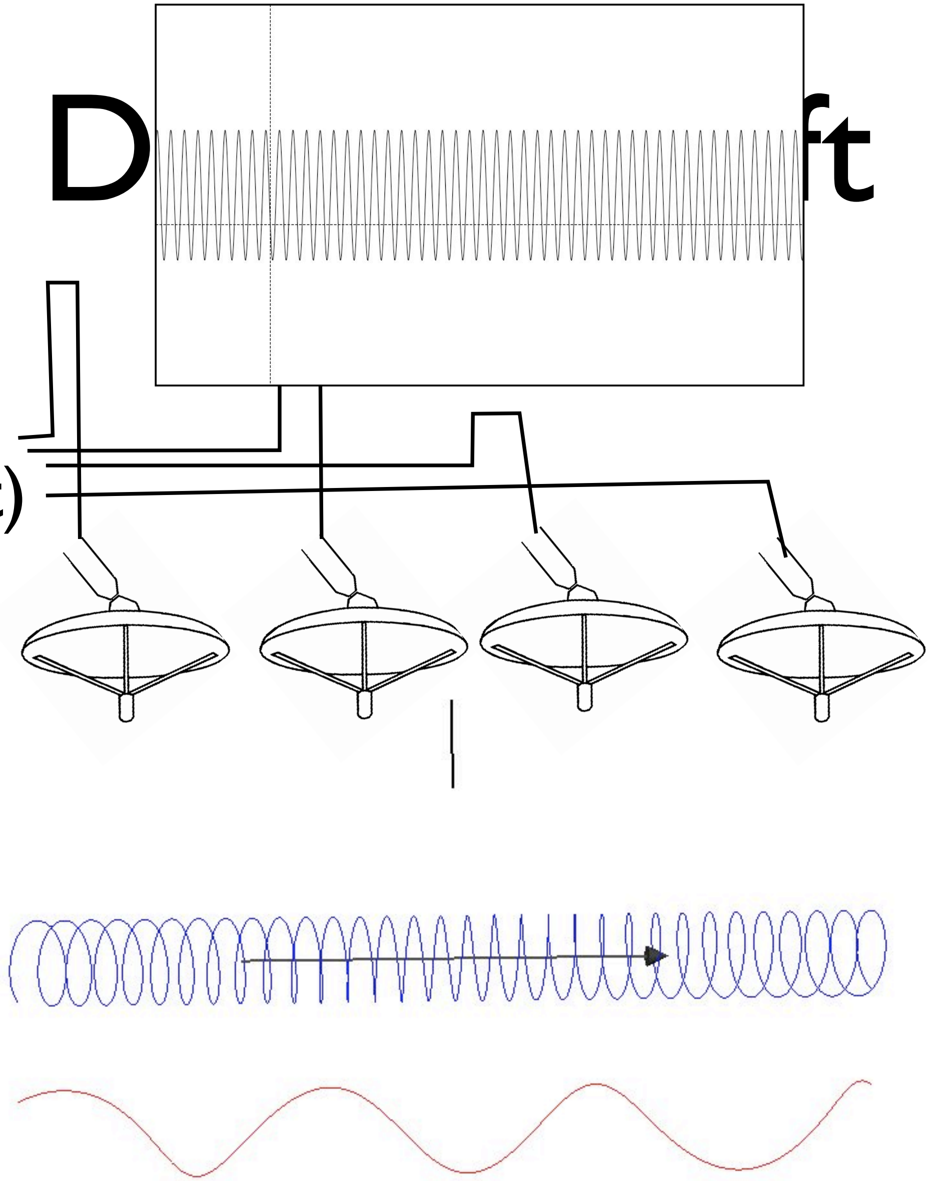
- Frequency resolution?
- Doppler shift?
- Huge fluxes!
- Available power

store > 10^6 cycles

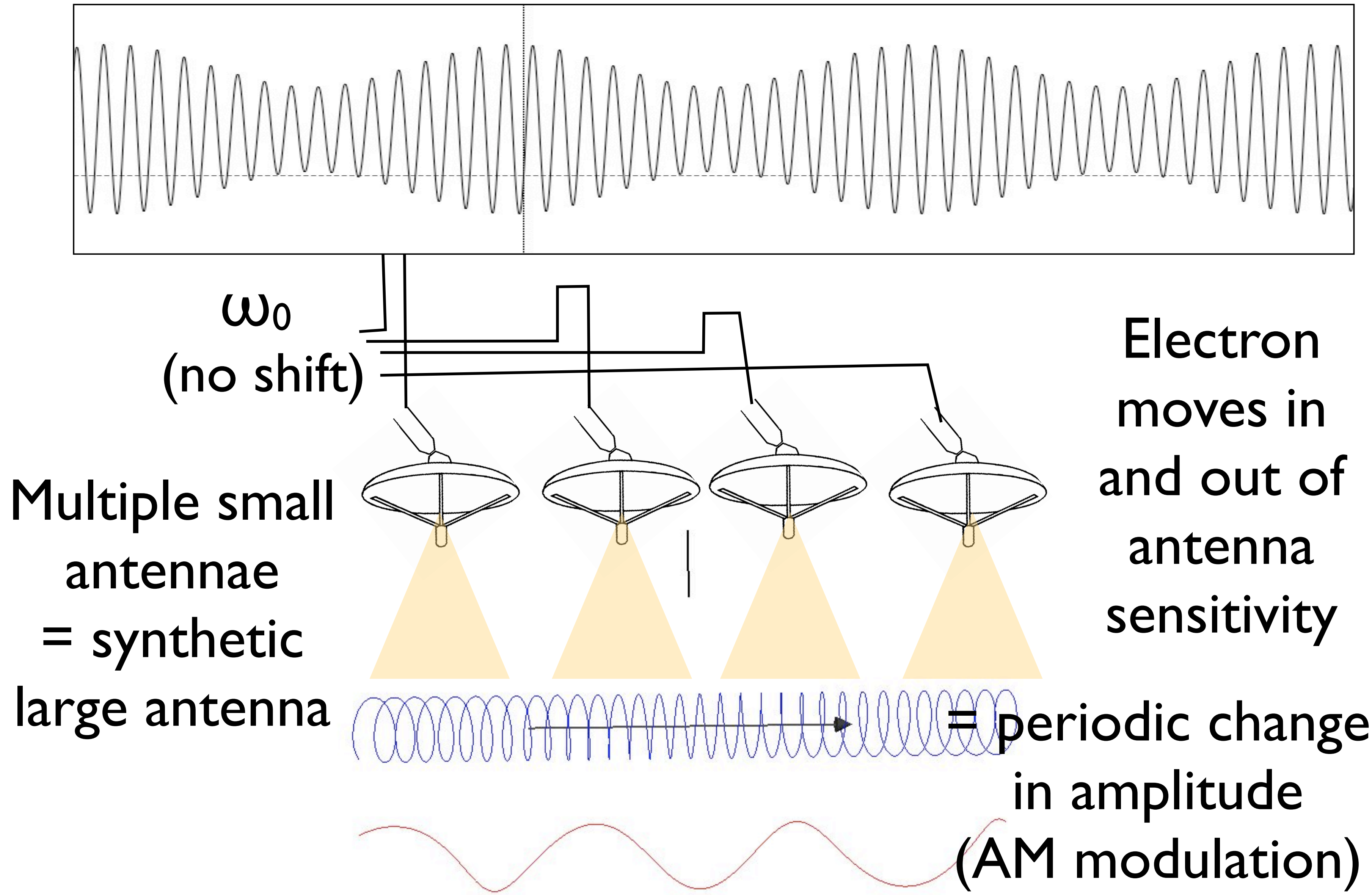

D
ft
$\omega_0(1-\beta\cos\theta)$
redshift
ω_0 (no shift)
$\omega_0(1-\beta\cos\theta)$
blueshift

D ft

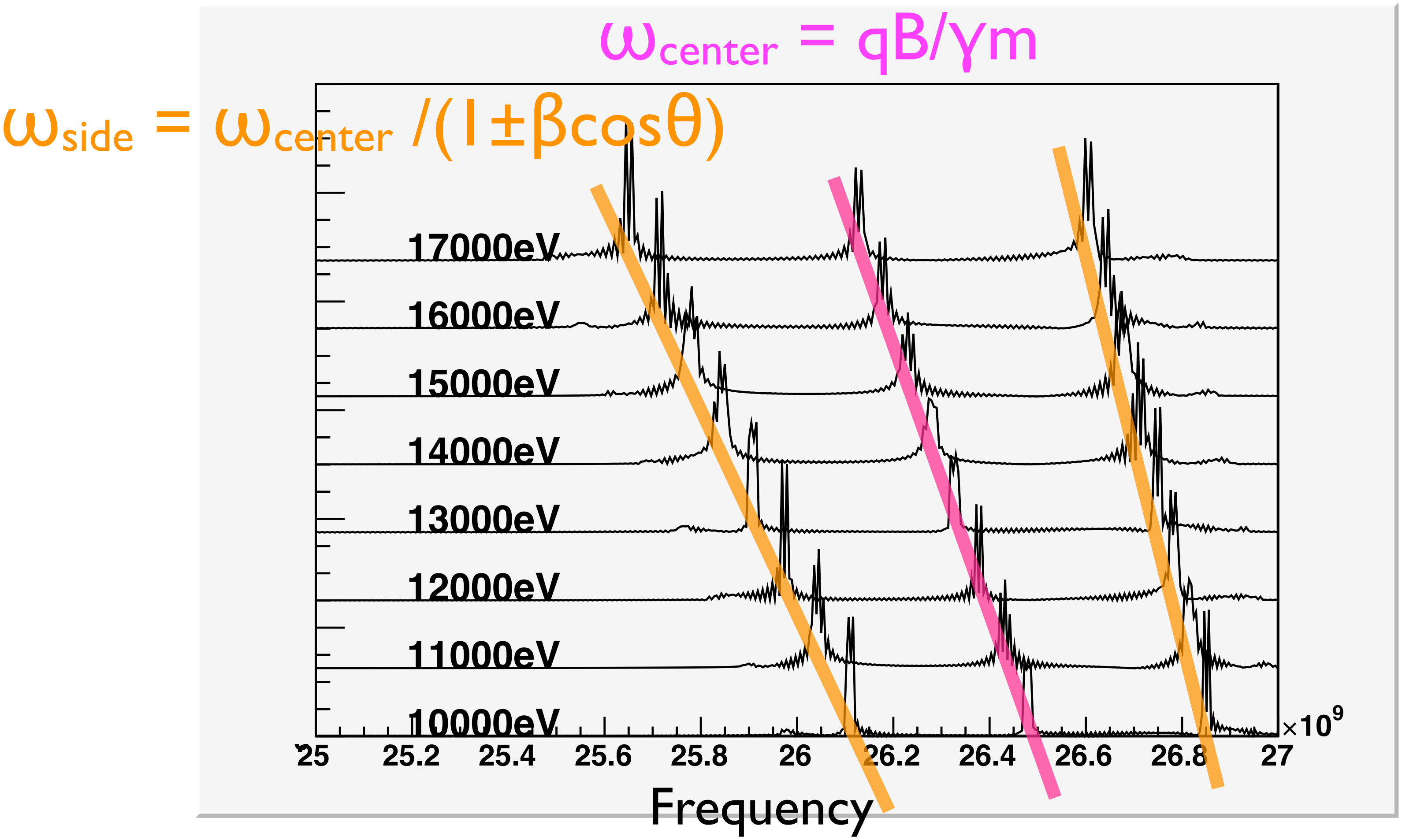
ω_0
(no shift)



Multiple small antennae = synthetic large antenna


ω_0
(no shift)
Multiple small antennae
= synthetic large antenna
Electron moves in and out of antenna sensitivity
= periodic change in amplitude
(AM modulation)

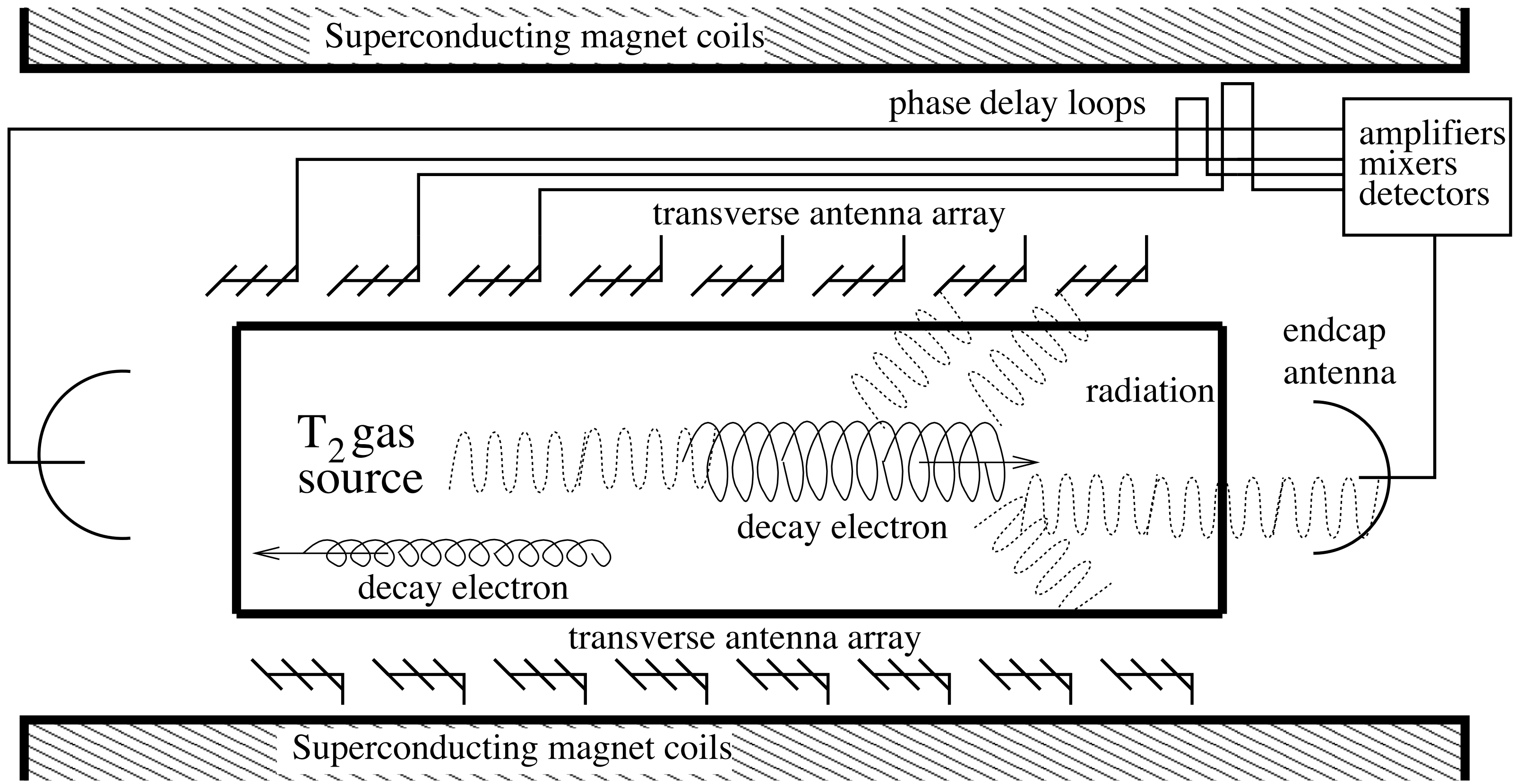
In frequency space



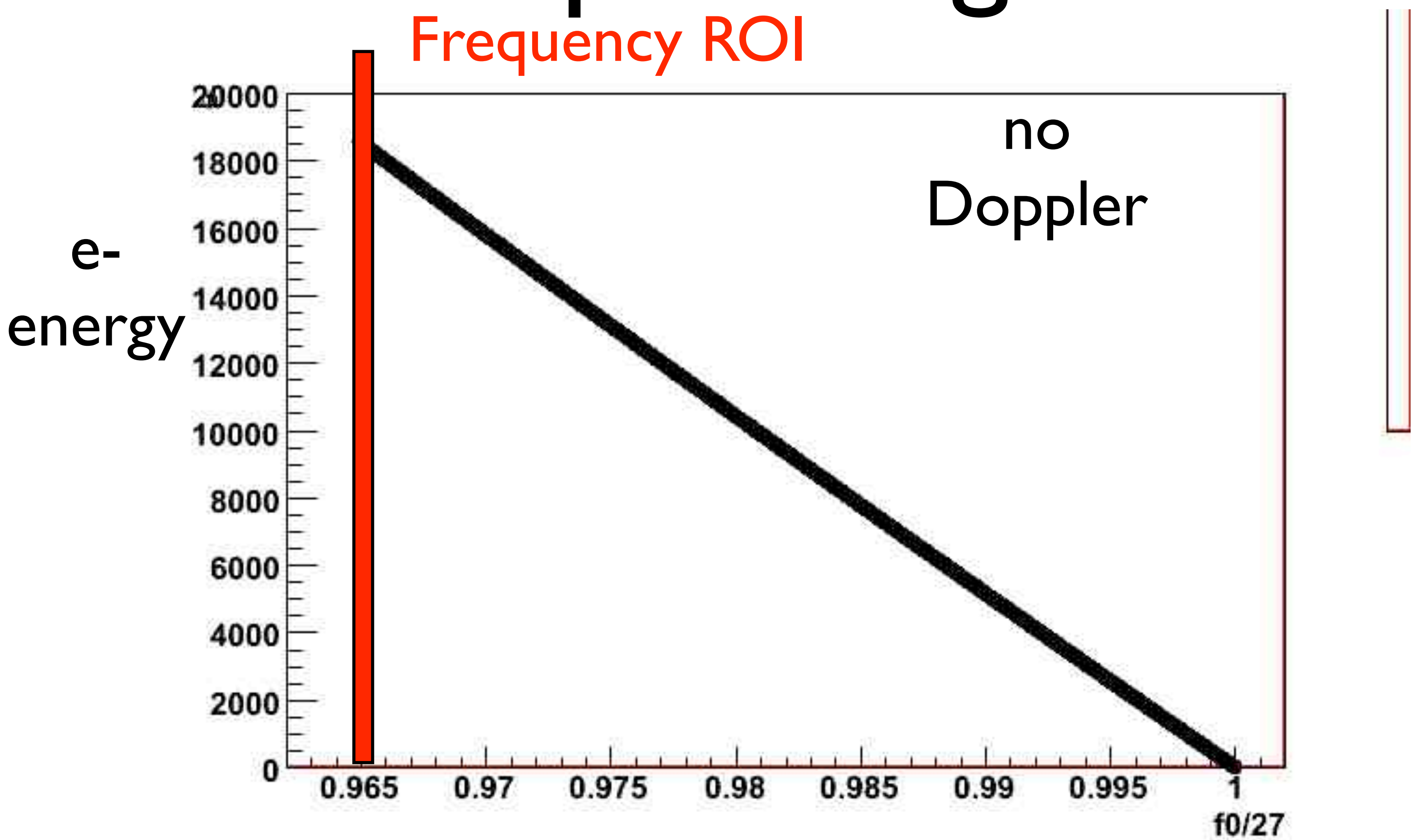
Complications

- Frequency resolution? **store > 10^6 cycles**
- Doppler shift? **ω_0 still obtainable**
- Huge fluxes!
- Available power

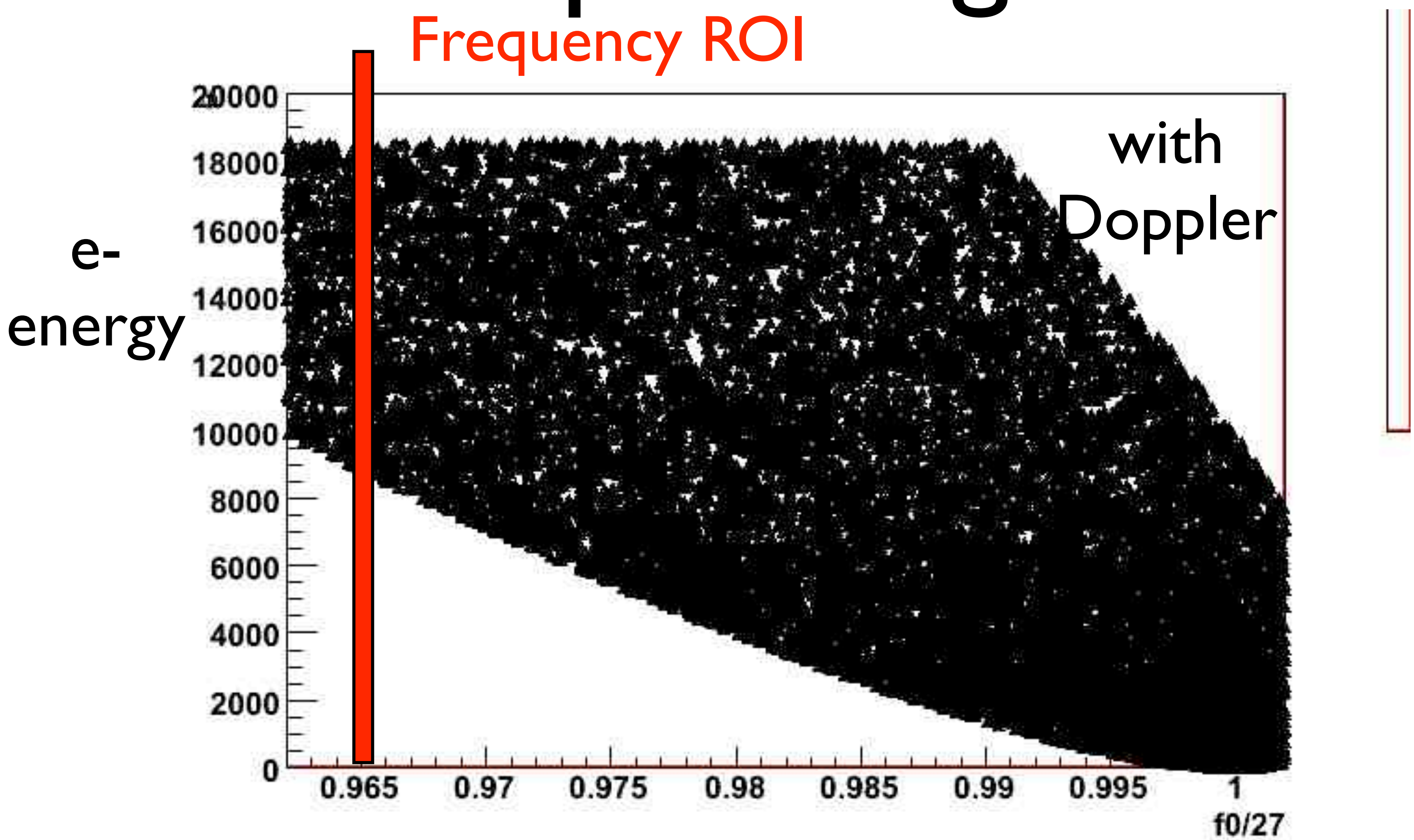
The experiment



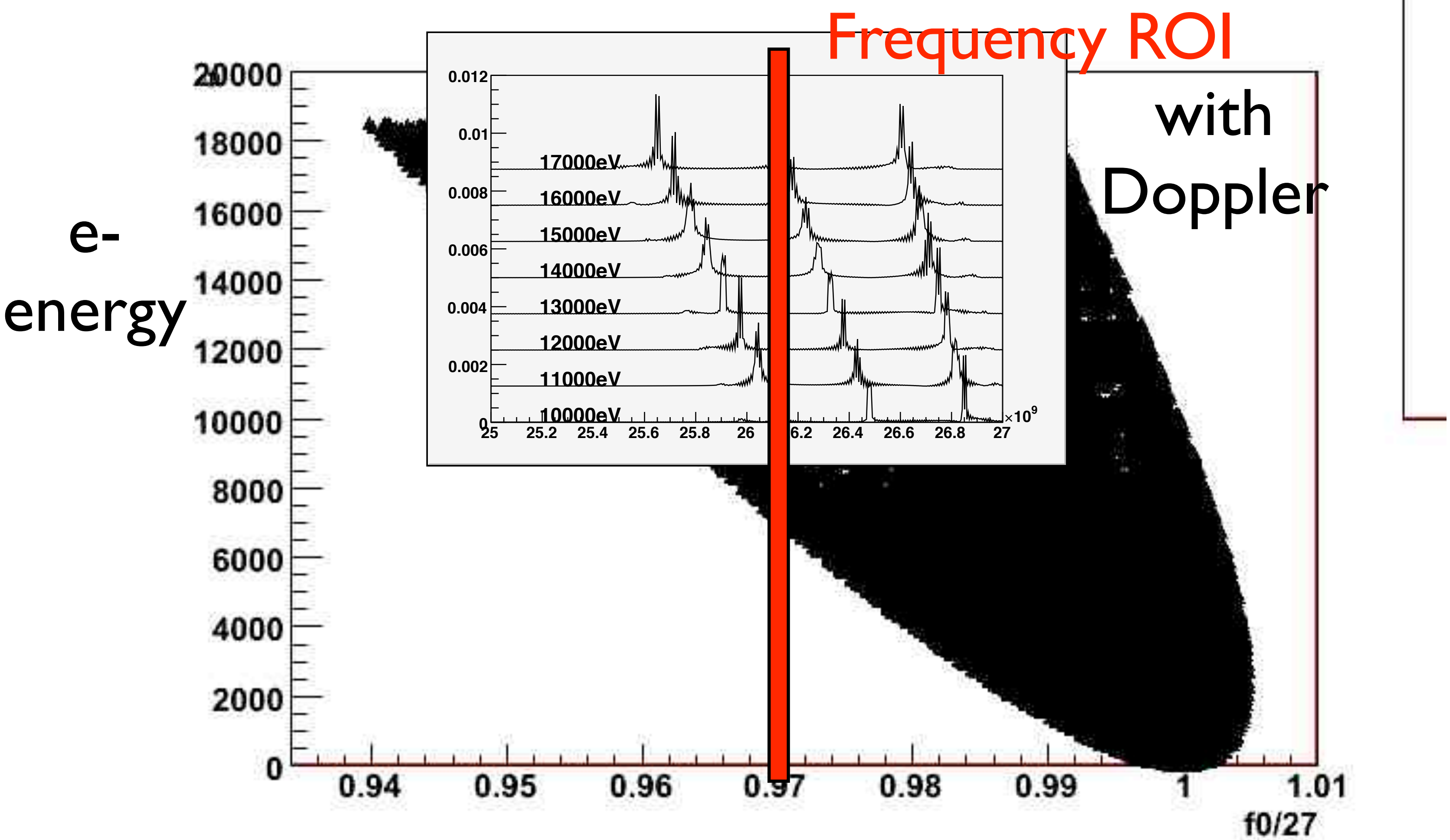
Endpoint signals

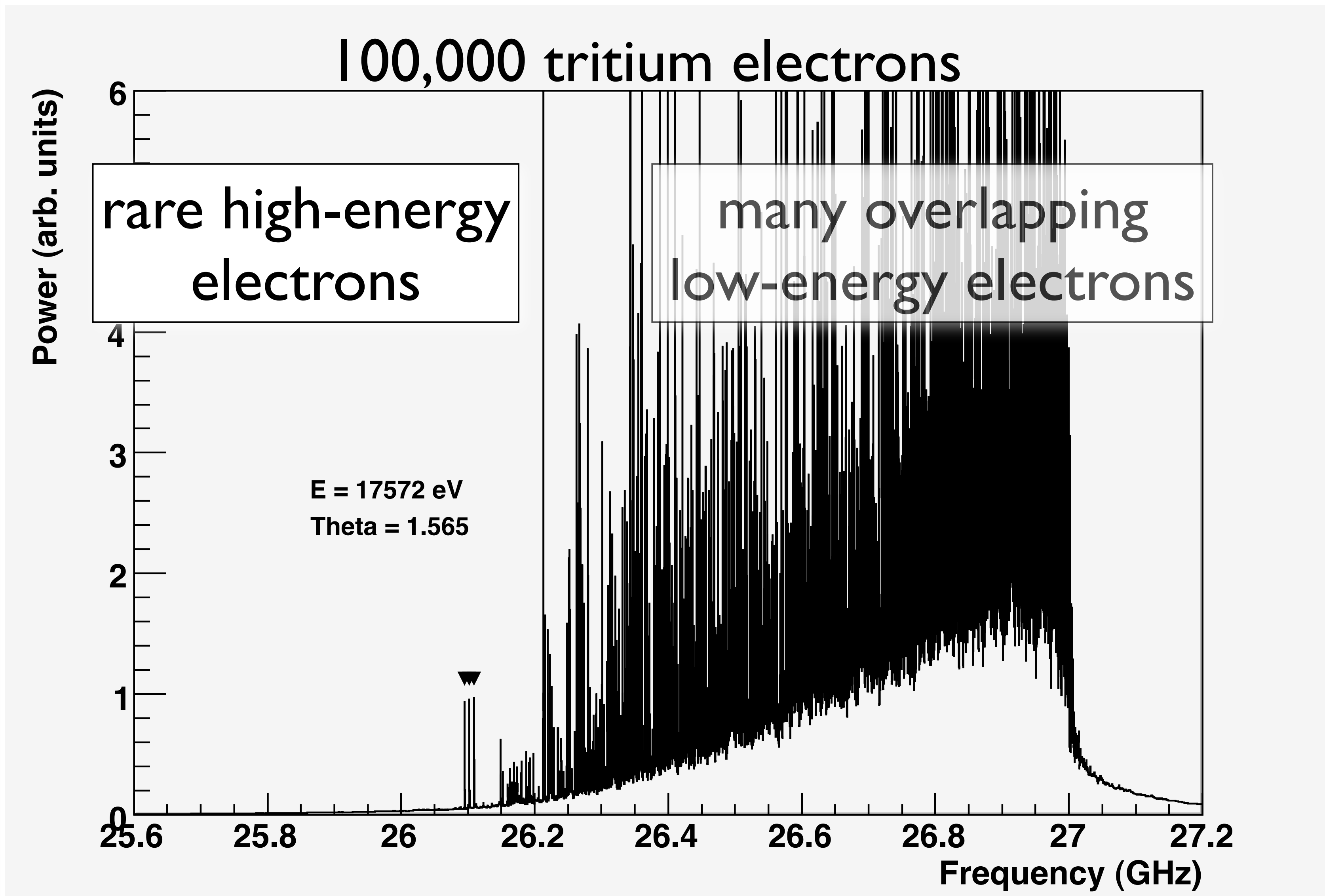


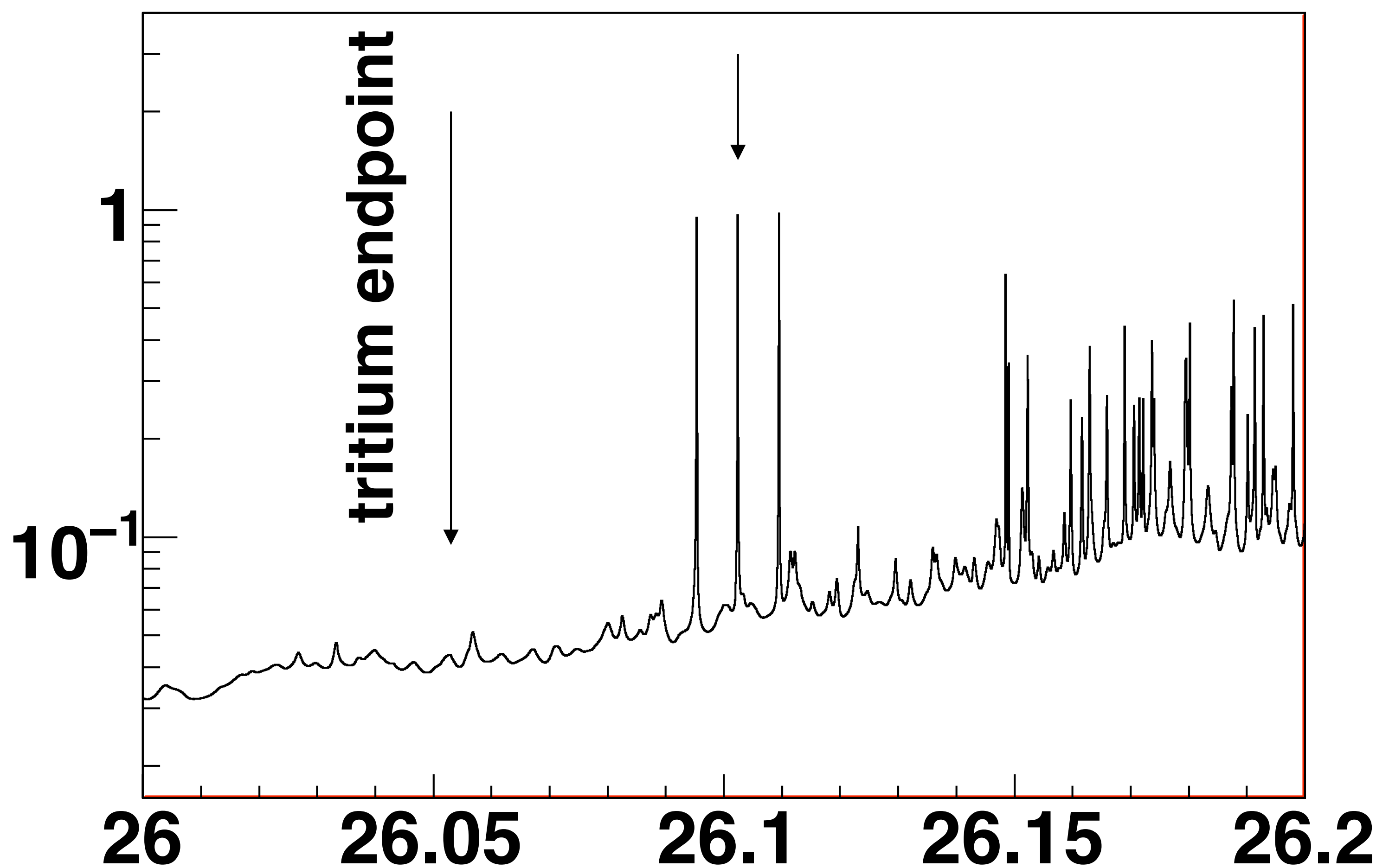
Endpoint signals



Endpoint signal




100,000 tritium electrons
Power (arb. units)
6
4
3
2
1
0
rare high-energy electrons
many overlapping low-energy electrons
E = 17572 eV
Theta = 1.565
25.6
25.8
26
26.2
26.4
26.6
26.8
27
27.2
Frequency (GHz)


tritium endpoint
1
10^-1
26
26.05
26.1
26.15
26.2

Complications

- Frequency resolution? **store > 10^6 cycles**
- Doppler shift? **ω_0 still obtainable**
- Huge fluxes! **do not fake signal in ROI**
- Available power

Power

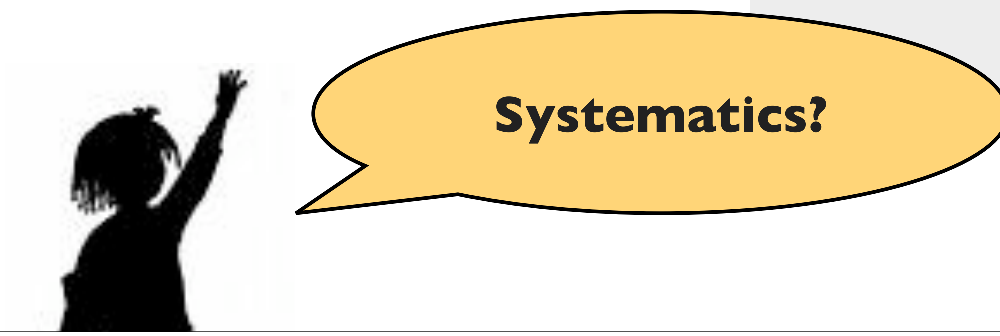
how much detected?
divided among
how many channels?

- At 1T, 18 keV electron emits 10^{-15} W
- A 1-eV-resolution experiment will see this power in a 50kHz band
- noise power = 6×10^{-19} W/K
- noise RMS = 6×10^{-21} W/K
- **4K experiment seems possible**

Keep an eye on signal
width: many broadening
sources may appear

Complications

- Frequency resolution? **store > 10^6 cycles**
- Doppler shift? **ω_0 still obtainable**
- Huge fluxes! **do not fake signal in ROI**
- Available power **needs detailed RF design**



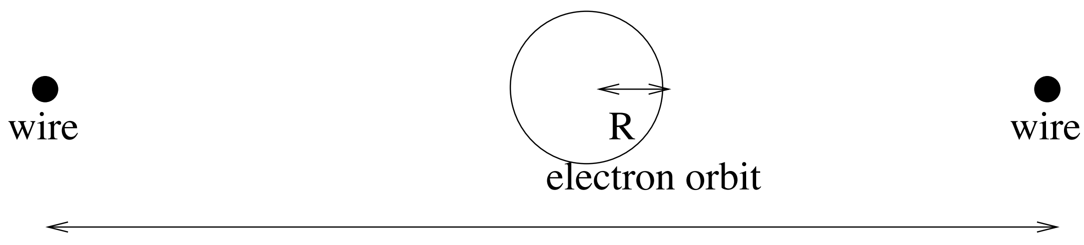
Systematics

- Magnet inhomogeneity and drift: should respond well to source calibrations
- e-T and <u>e-wall</u> scattering
  a) Run at low density
  b) Each scattering event shifts/broadens the cyclotron frequency
  c) fiducialize?
- Full differential spectrum; no first-order correction for source strength
- No electrostatics; source is grounded
- <u>T_2 molecular final state</u> = irreducible 0.3 eV (+/- 0.01 eV?) blurring of endpoint

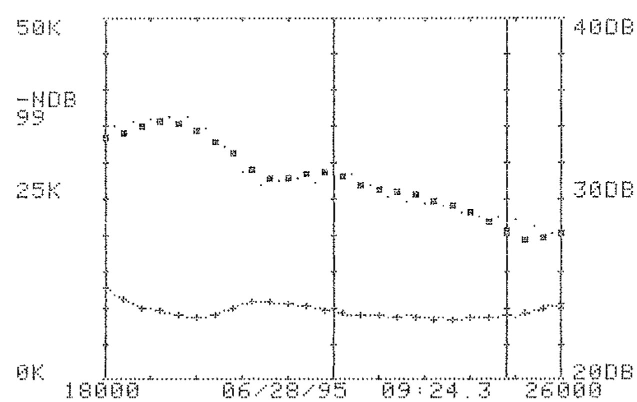
Real-world designs

- Gray Rybka, UW: two-wire antenna

$$7.5 \times 10^{-17}\,\mathrm{Watts} \times \beta_\perp^2 \left(\frac{1\,\mathrm{cm}}{d}\right)^2$$

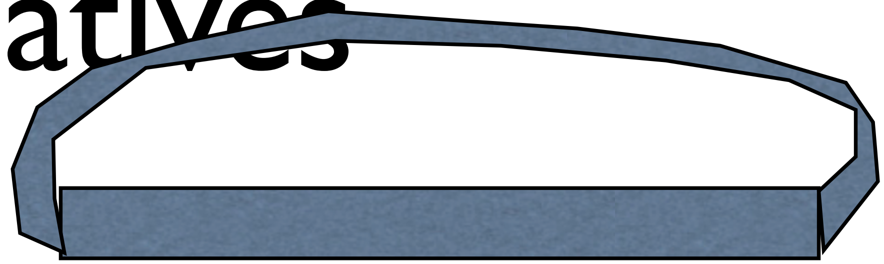


- Rich Bradley, NRAO: microwave receivers from radio astronomy



Alternatives

- Toroidal magnetic field?



- Magnetic bottle?

Measuring frequency in one pass: $\Delta f = \Delta t^{-1}$

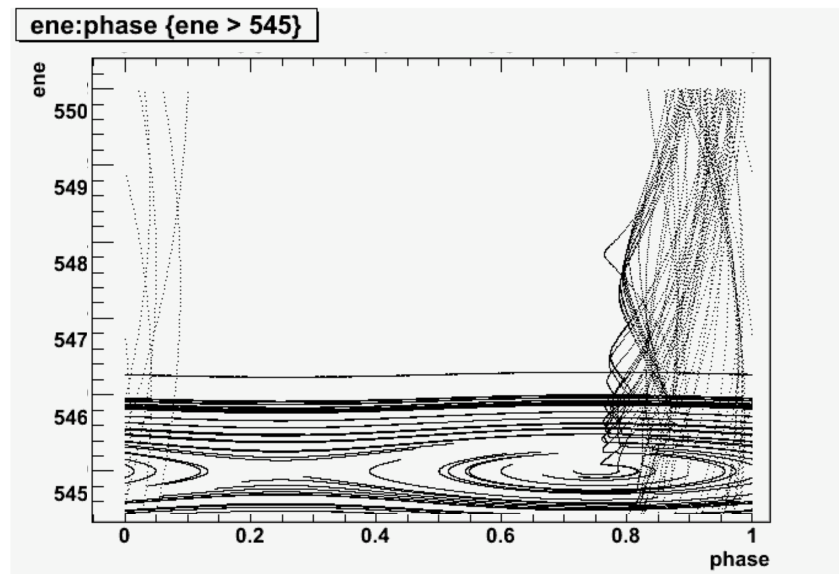
N passes of Δt *each:* $\Delta f = (\Delta t \sqrt{N})^{-1}$

- Ramsey spectroscopy?

- Bucket spectroscopy?

Bucket spectroscopy

- Shoot microwave beam (at ROI frequency) into magnet.
- Electron cyclotron in microwave field = electron bunch in synchrotron RF bucket
- Use "bucket" to grab and store ROI electrons, later accelerate to make detectable



- Decouples time constraints from detection constraints

Conclusions

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