Project 8: a radiofrequency approach to the neutrino mass

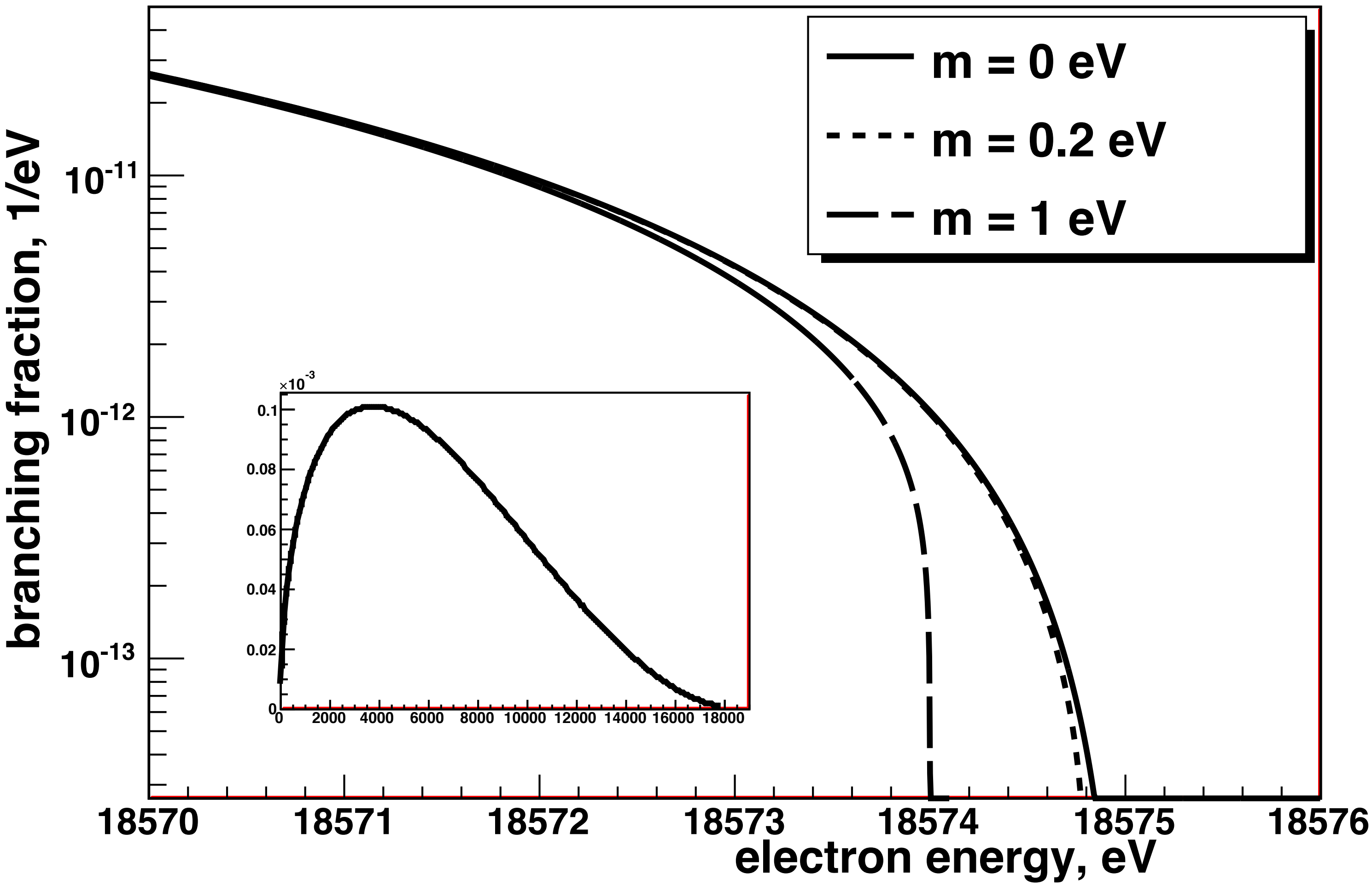
Ben Monreal, UC Santa Barbara

Project 8 collaboration

- UCSB: Ben Monreal, Michelle Leber, Matthew Bahr
- MIT: Joe Formaggio, Noah Oblath
- University of Washington: Hamish Robertson, Peter Doe, Leslie Rosenberg, Michael Miller, Gray Rybka, Brent Vandevender, Laura Bodine
- NRAO: Rich Bradley

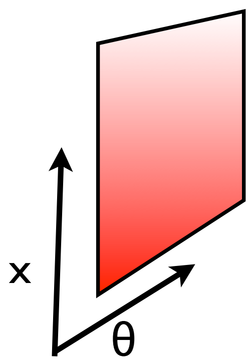
BM & JF, Phys. Rev. D 80, 051301(R) (2009)

Neutrino mass

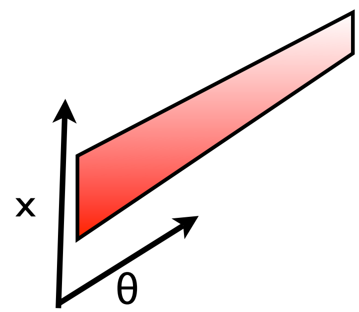


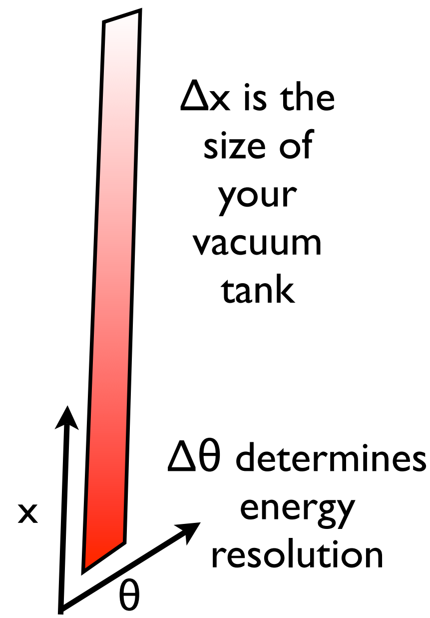
Liouville's theorem

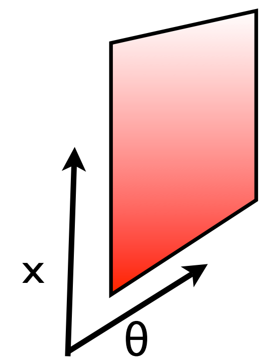
The volume of phase space is conserved
for any system obeying T symmetry

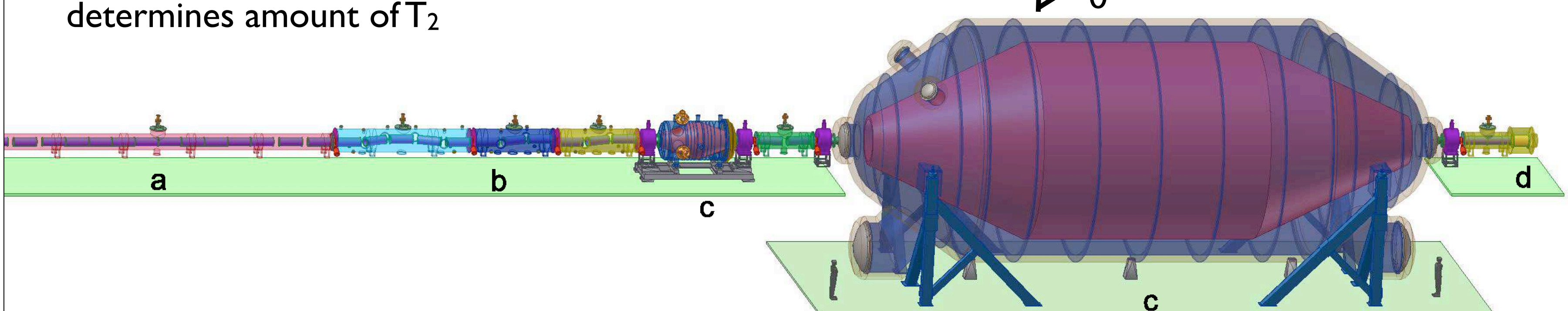


Source area ΔθΔx
determines amount of T_2









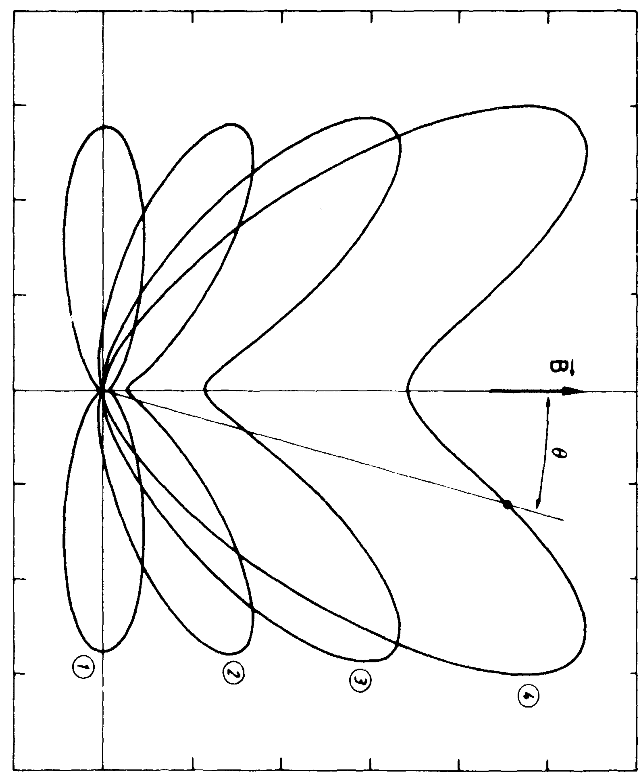
Cyclotron radiation

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

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

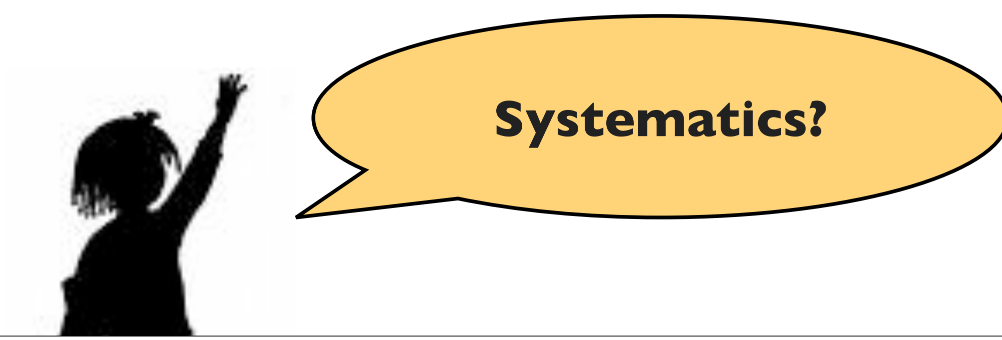
$$P_{\text{tot}} = \frac{1}{4\pi\epsilon_0}\frac{2q^2\omega_c^2}{3c}\frac{\beta_\perp^2}{1-\beta^2}$$

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



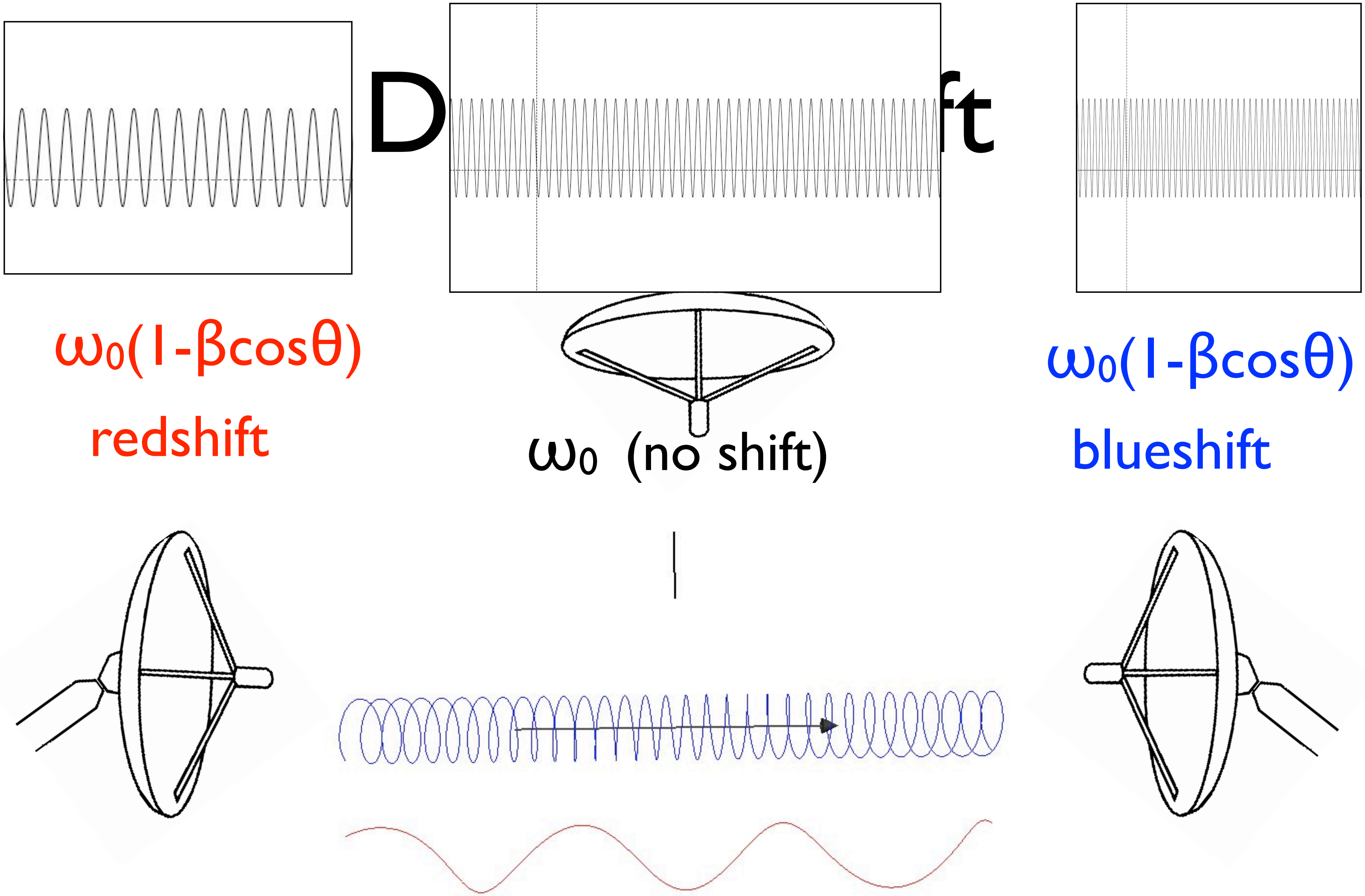
Complications

- Frequency resolution? *long mean free path*
- Doppler shift? *no conceptual problem, just bandwidth*
- Magnetic field uniformity? *OK, just analysis problem*
- Background from low-E betas? *surprisingly little effect so far*
- Available power *fine in theory, but prototype will tell*



Frequency

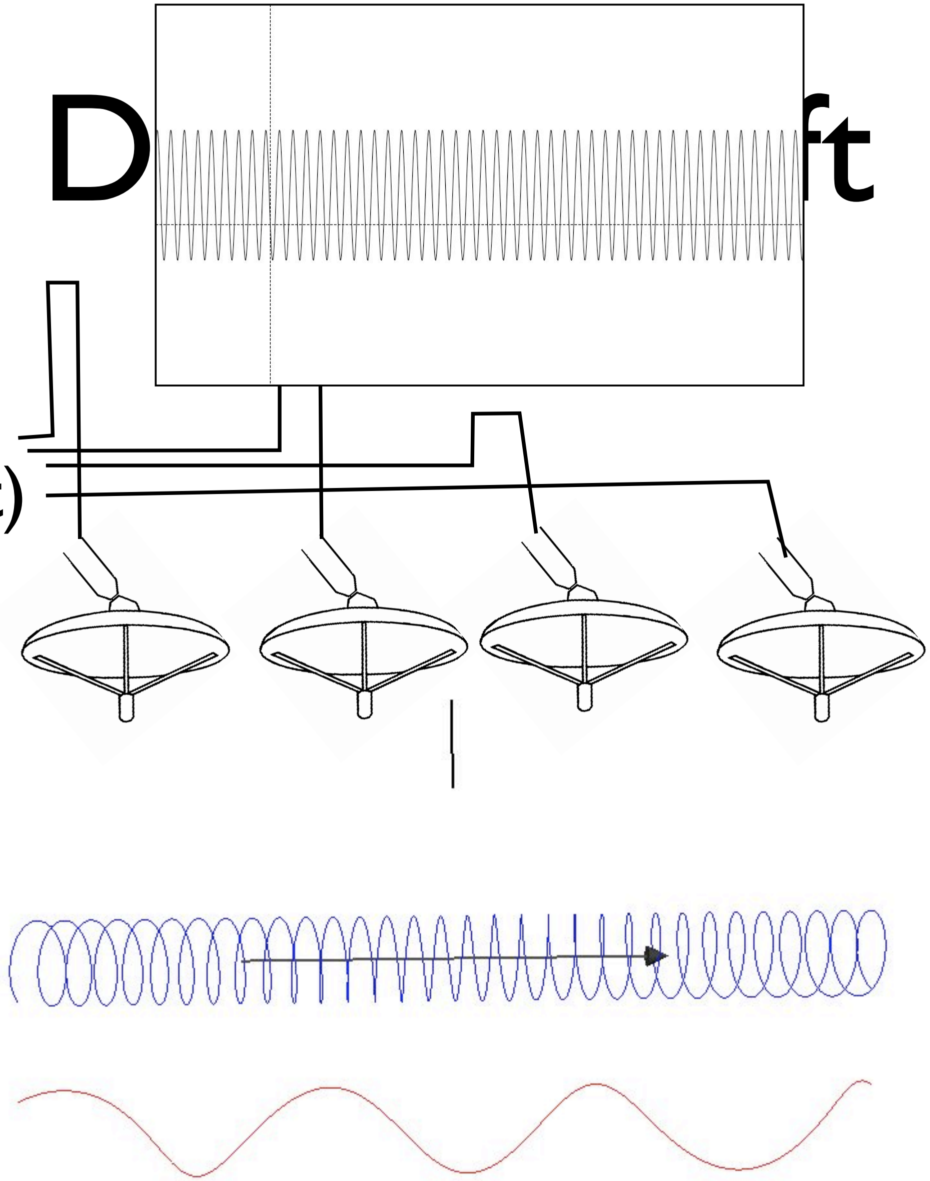
- Schawlow: “Never measure anything but frequency”
- $f \cdot \Delta E/E \sim \Delta f = 1/\Delta t$
- 1 eV energy resolution
  - $\Delta f / f = 2 \times 10^{-6}$ (easy!)
  - $\Delta t = 20 \mu s$ (hard!)
    - $\beta c \cdot \Delta t = 1400$ meters



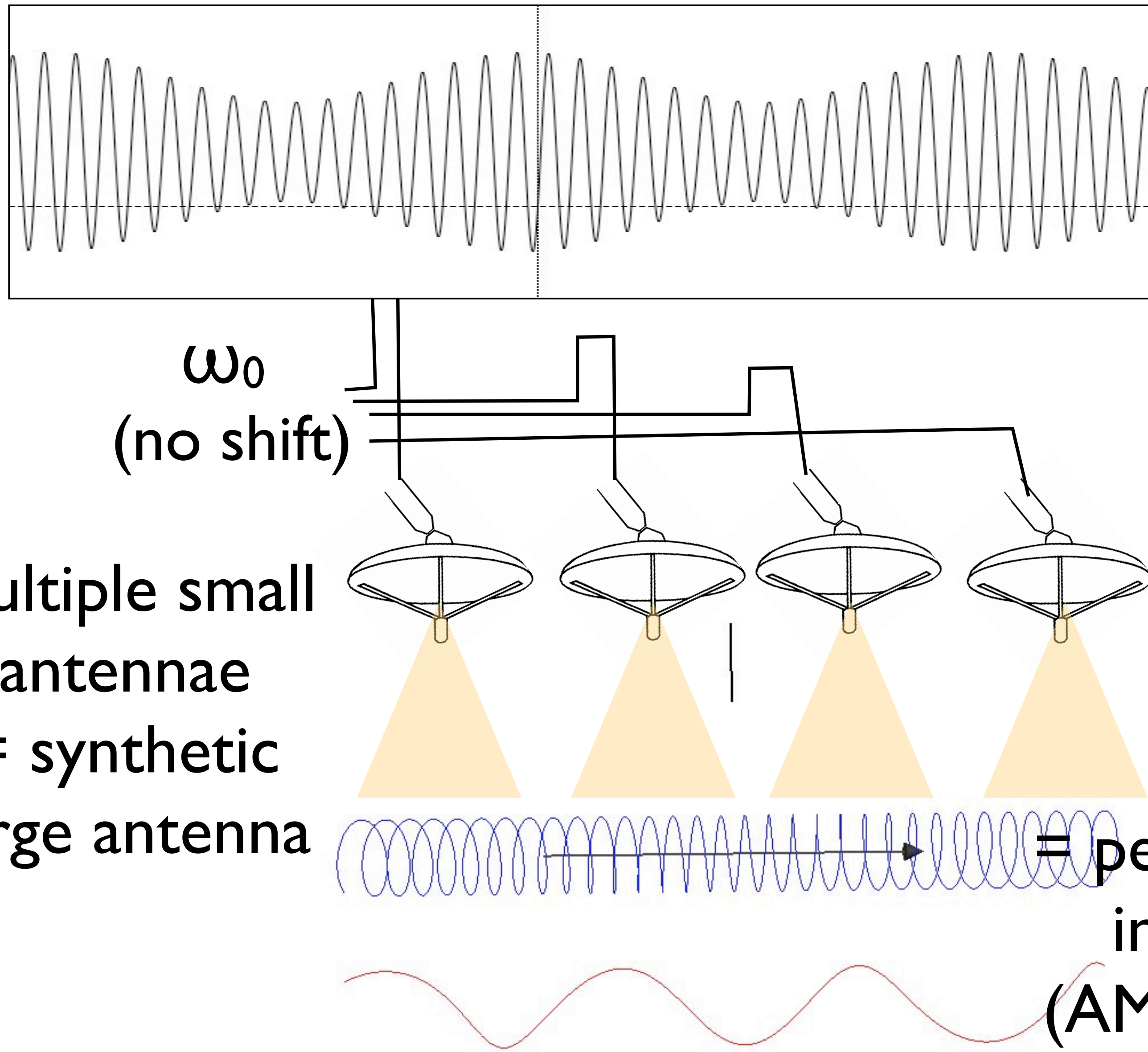
ω0(1-βcosθ)
redshift
ω0 (no shift)
ω0(1-βcosθ)
blueshift

D ft

ω_0
(no shift)



Multiple small antennae = synthetic large antenna

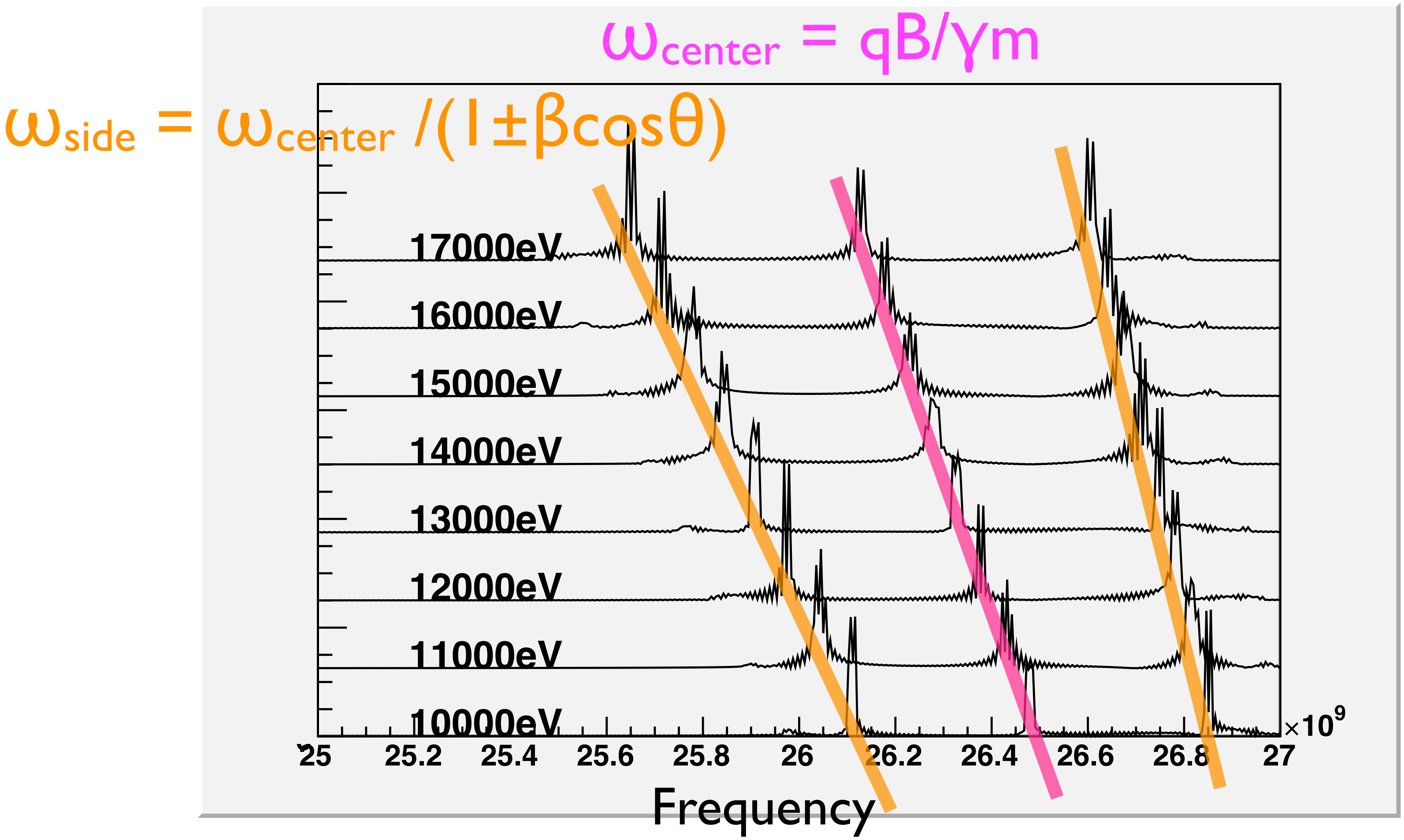


Multiple small antennae = synthetic large antenna

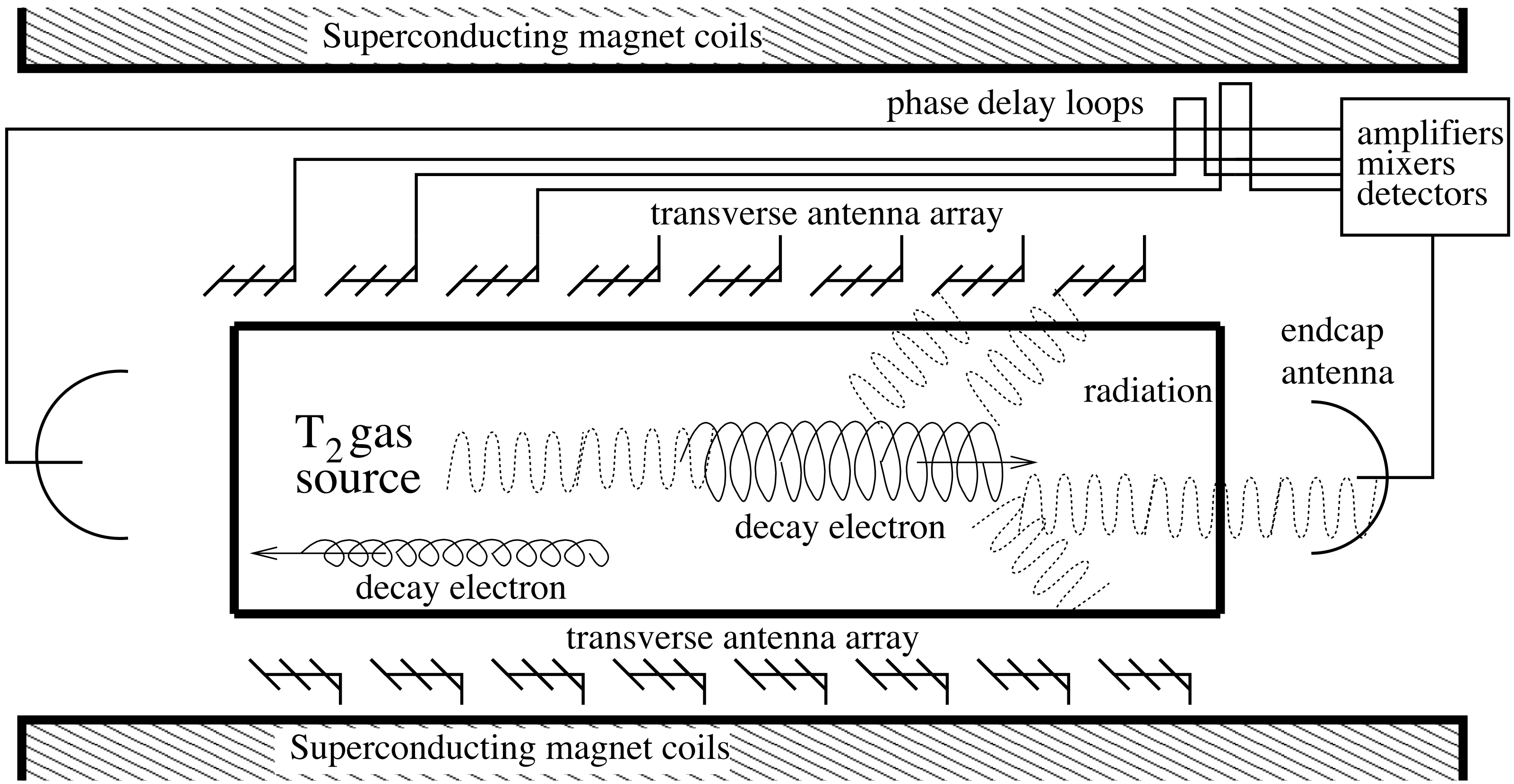
Electron moves in and out of antenna sensitivity

= periodic change in amplitude (AM modulation)

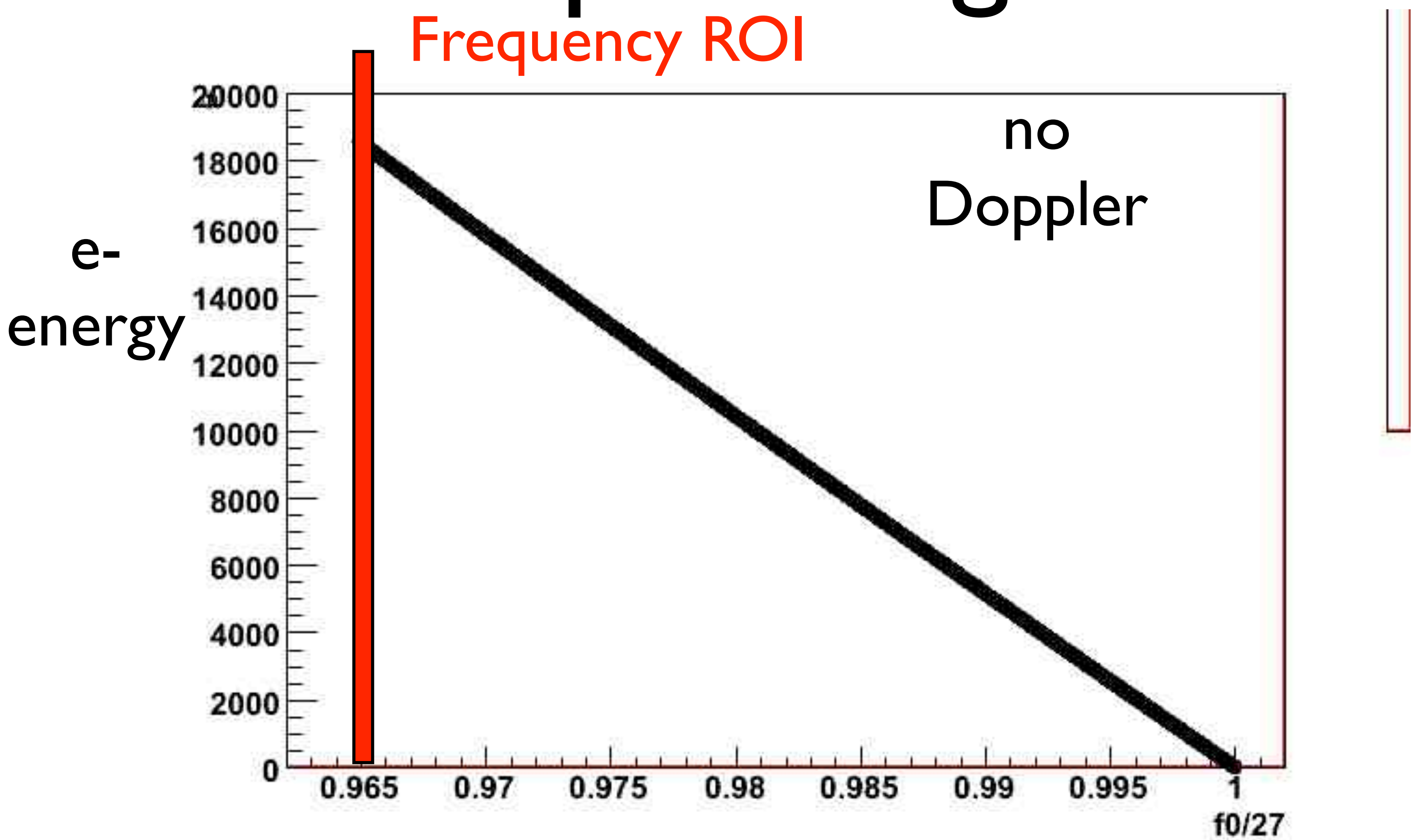
In frequency space



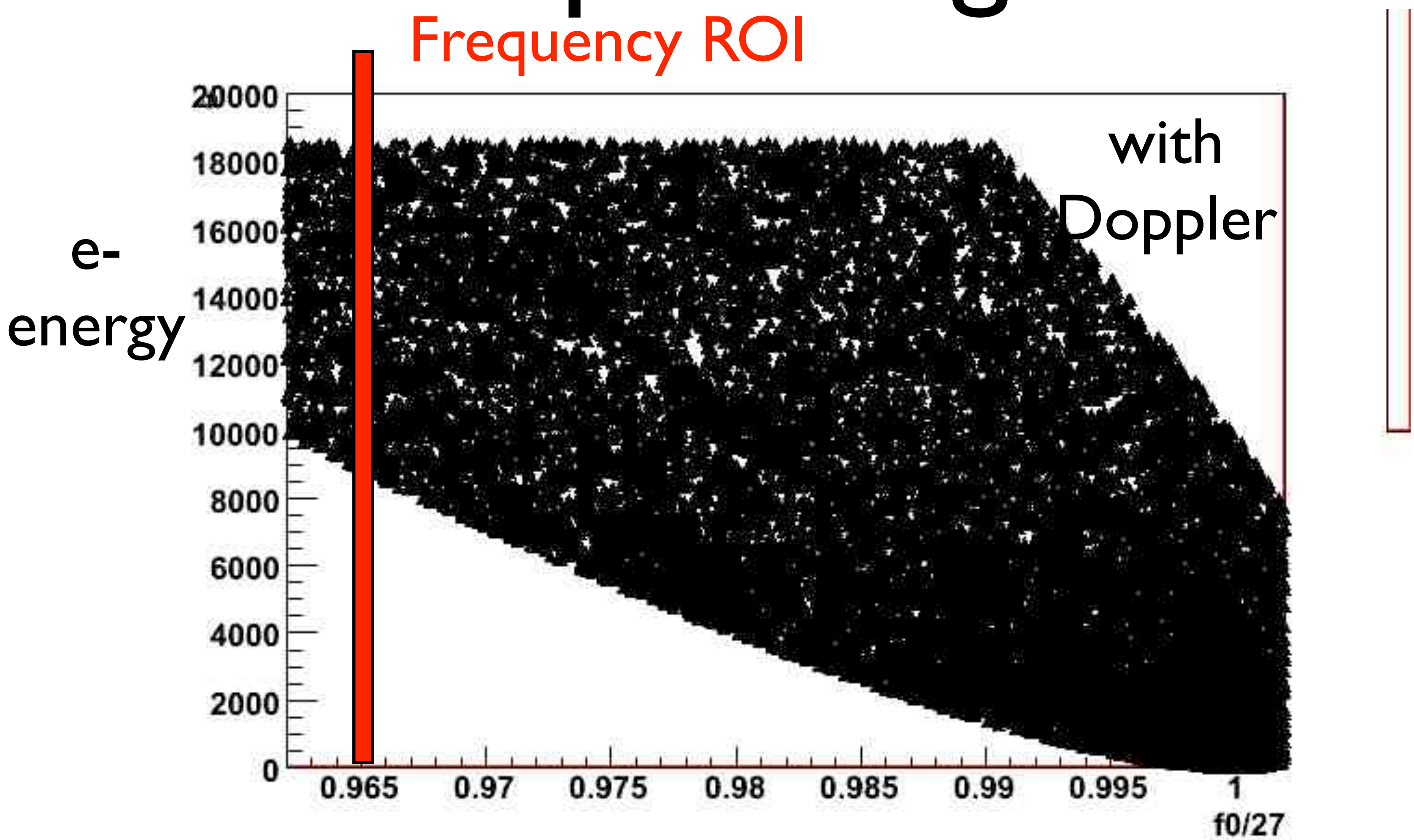
The experiment

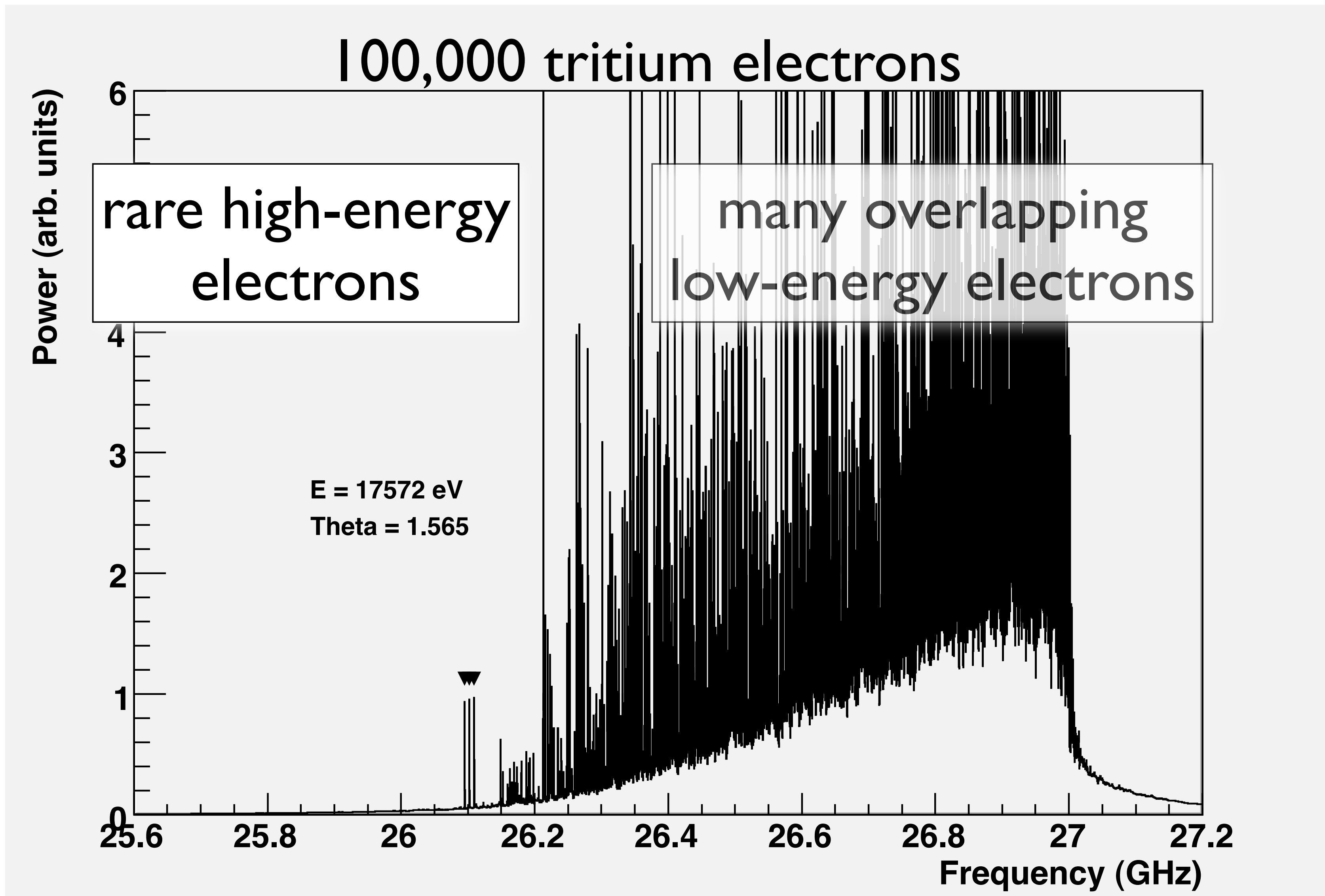


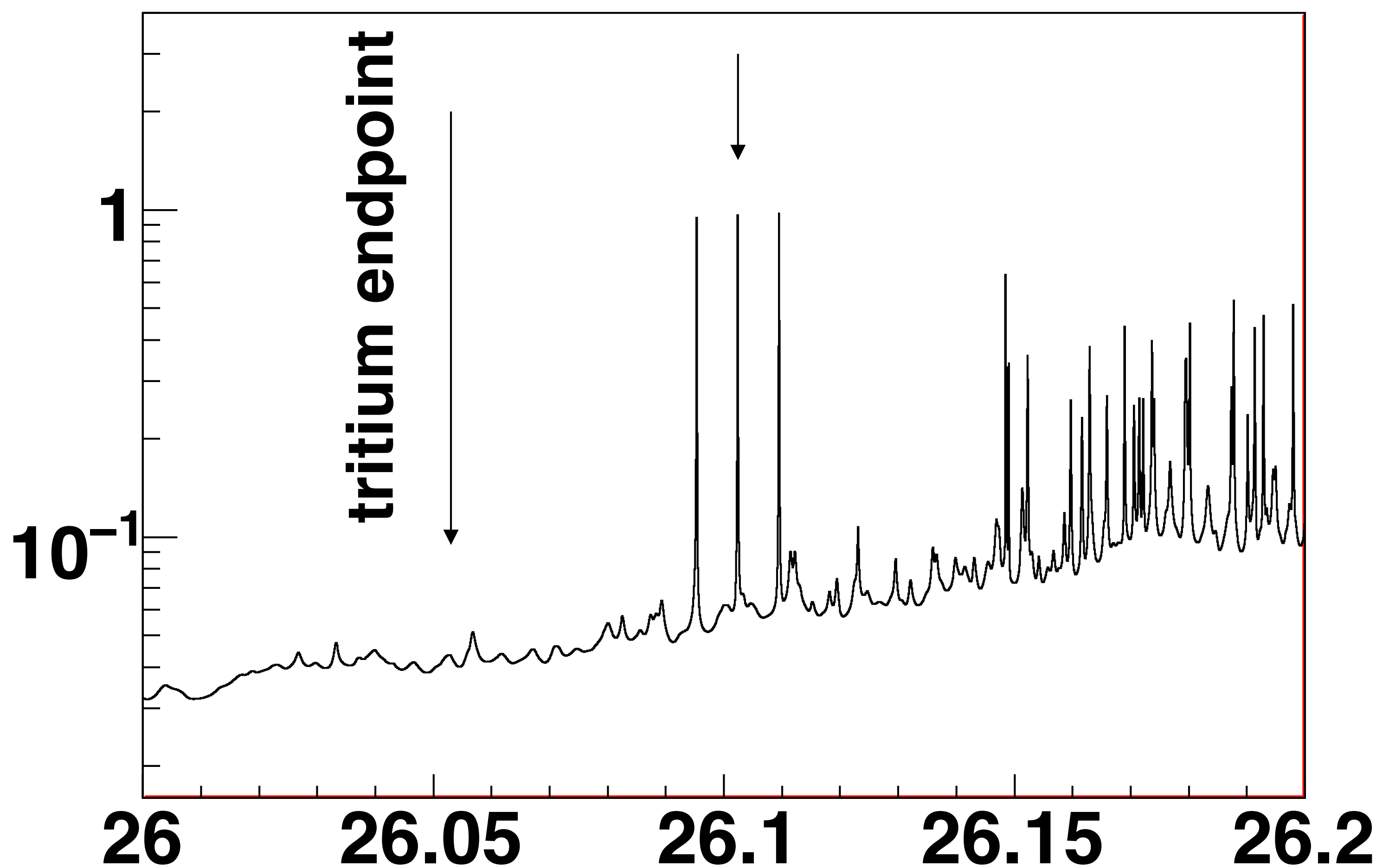
Endpoint signals



Endpoint signals

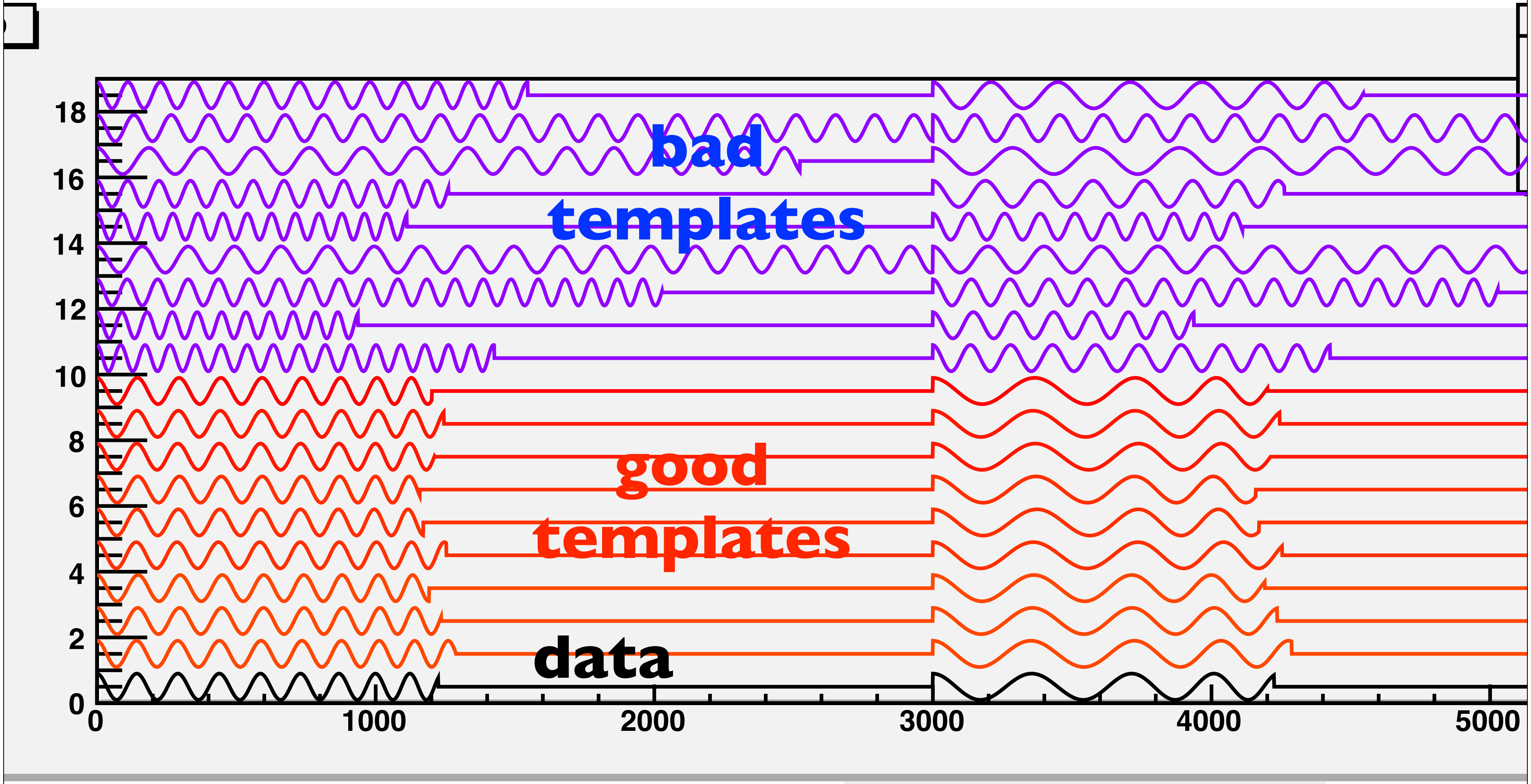



100,000 tritium electrons
rare high-energy electrons
many overlapping low-energy electrons
E = 17572 eV
Theta = 1.565
Power (arb. units)
Frequency (GHz)
0
1
2
3
4
6
25.6
25.8
26
26.2
26.4
26.6
26.8
27
27.2

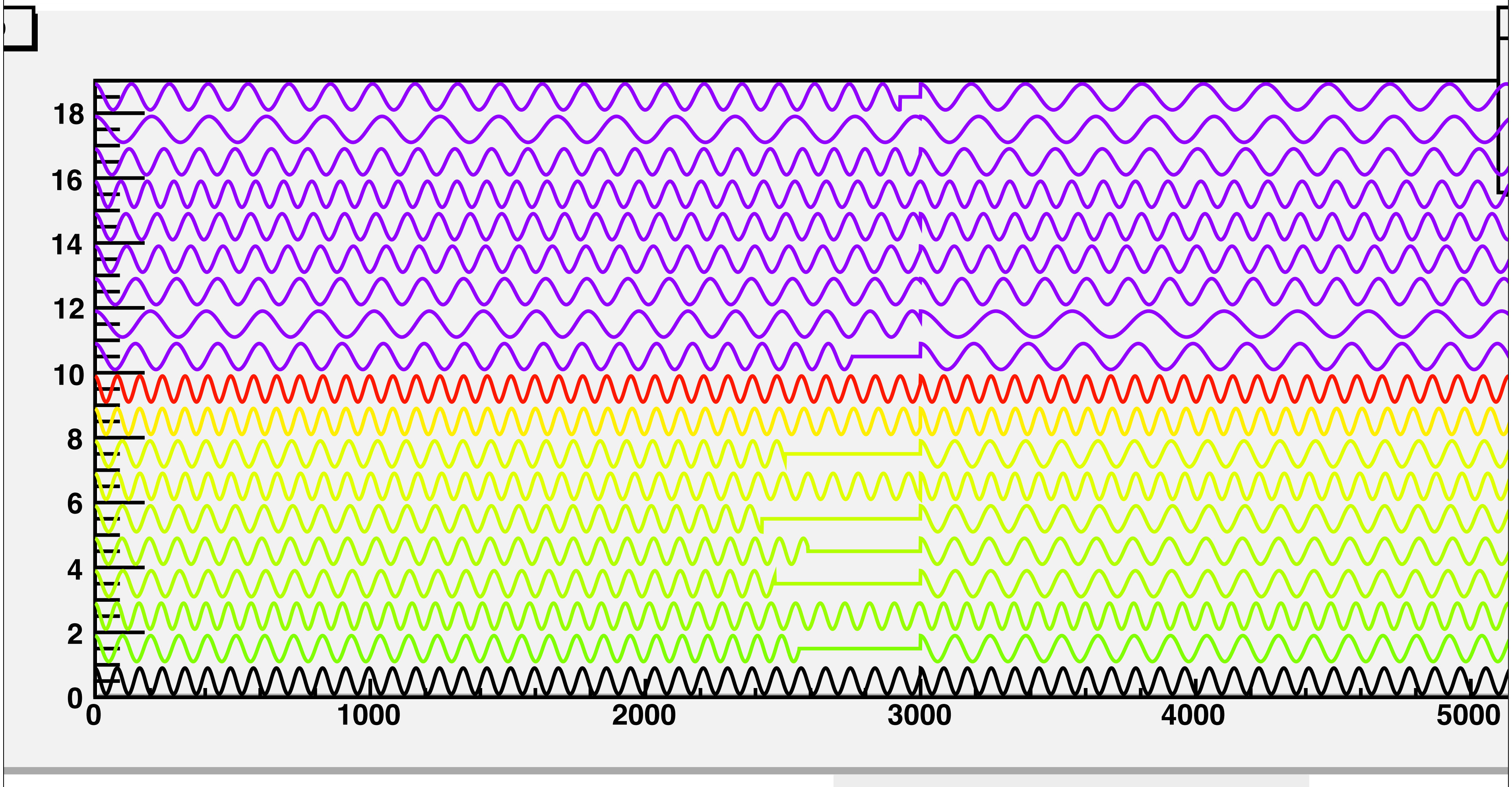

tritium endpoint
1
10^{-1}
26
26.05
26.1
26.15
26.2

B-field nonuniformity

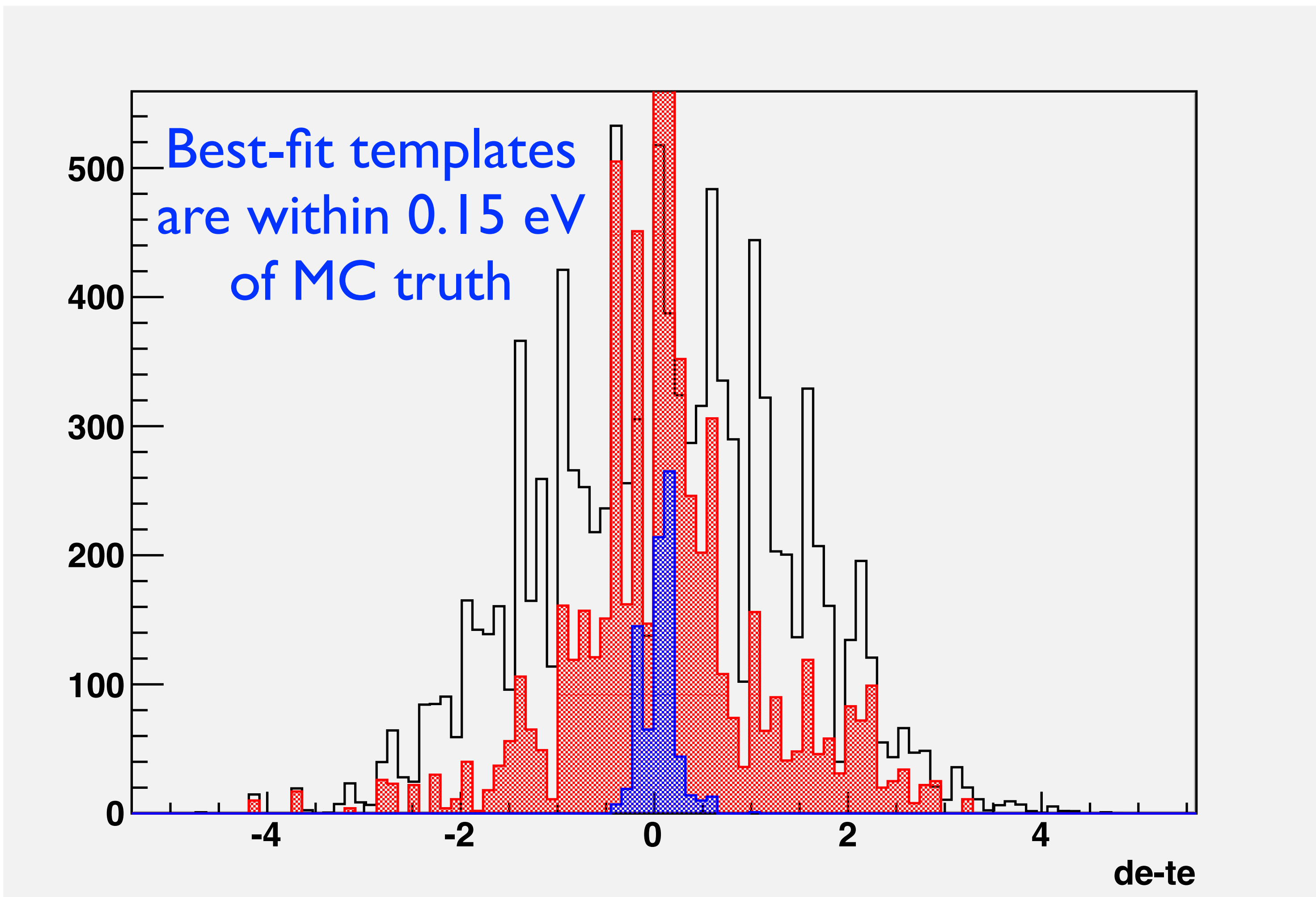
- Radiation is coherent but not monochromatic
- ~~Fourier transform~~ *template matching*
- How many templates?
    - one per ROI energy bin
    - one per pitch angle (?)
    - one per starting position in B field $N = (\Delta B/B)/(\Delta E/m)$
- Template size ~ 1-10 kb?



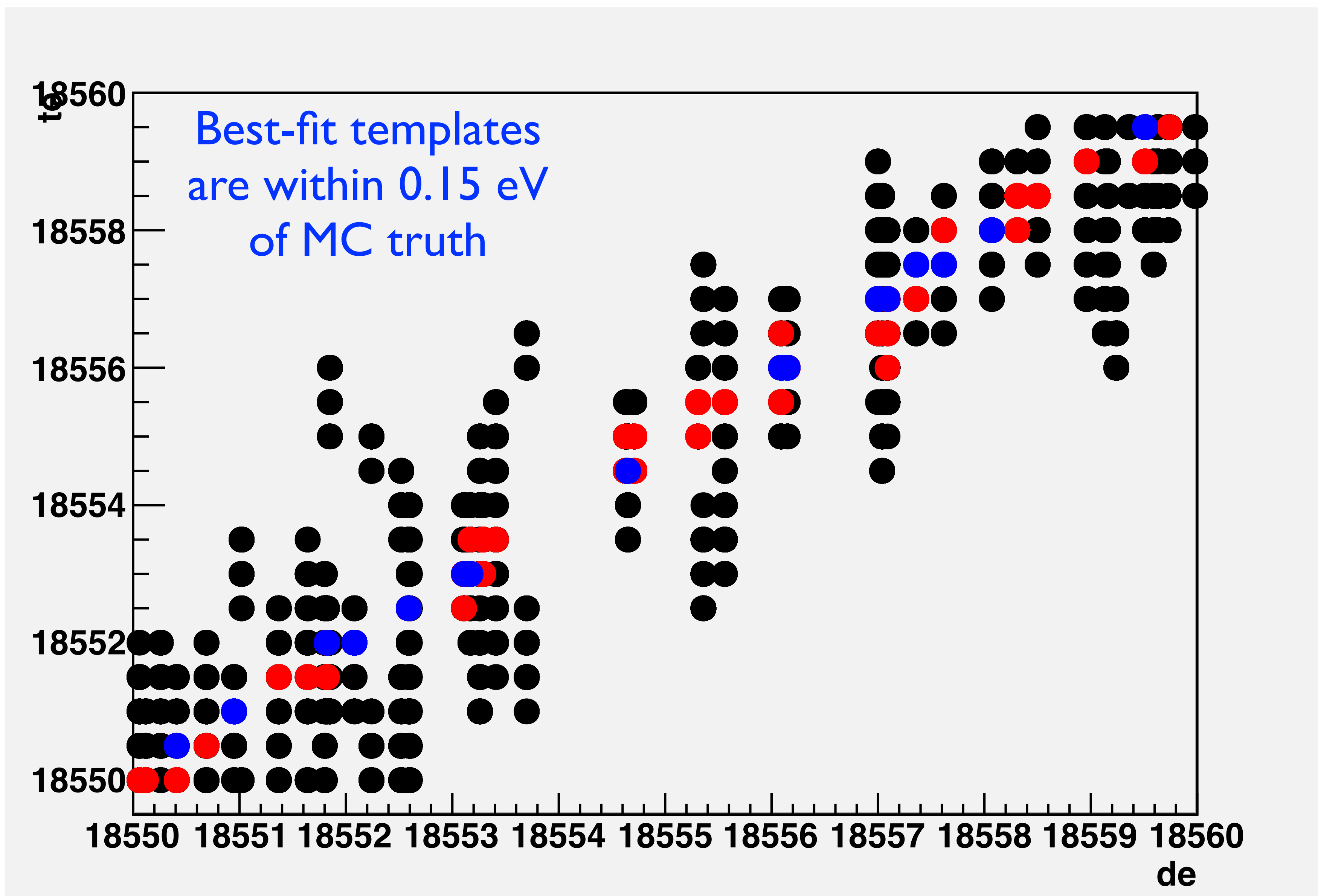
bad templates
good templates
data
0
2
4
6
8
10
12
14
16
18
0
1000
2000
3000
4000
5000



0
2
4
6
8
10
12
14
16
18
0
1000
2000
3000
4000
5000



Best-fit templates
are within 0.15 eV
of MC truth
500
400
300
200
100
0
-4
-2
0
2
4
de-te



Best-fit templates
are within 0.15 eV
of MC truth
18560
18558
18556
18554
18552
18550
to
18550 18551 18552 18553 18554 18555 18556 18557 18558 18559 18560
de

Scaling laws

$$R = 10^{10}(\frac{L}{10m})^2(\frac{r}{1m})^2(\frac{B}{1T})^2(\frac{\Delta E}{1eV})^2 \text{ decays/second}$$

$$bg = 10^{12}(\frac{Lr^2}{10m^3})(\frac{B}{1T})(\frac{\Delta E}{1eV}) \text{ decays/second}$$

1) set pressure to allow mean free path consistent with dE

2) length of tube determines what pitch angles have a long enough path to be seen

3) volume determines total rate

Still hard to translate this into an experiment sensitivity.

Resolution function shape, shape systematics, background are all very important.

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**

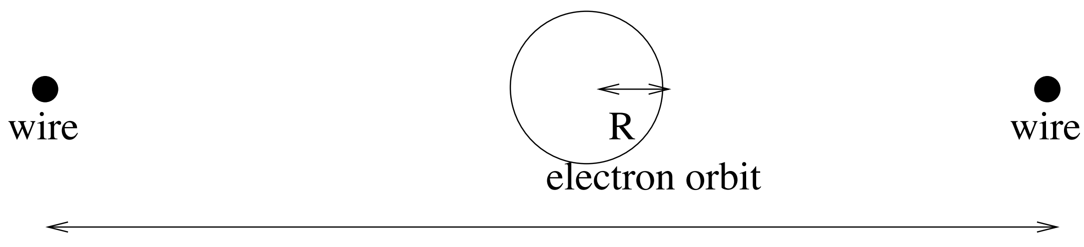
Systematics

- 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

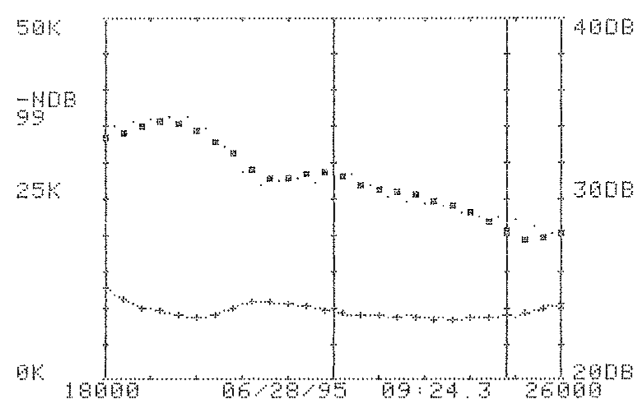
Real-world designs

- Gray Rybka, UW: two-wire antenna

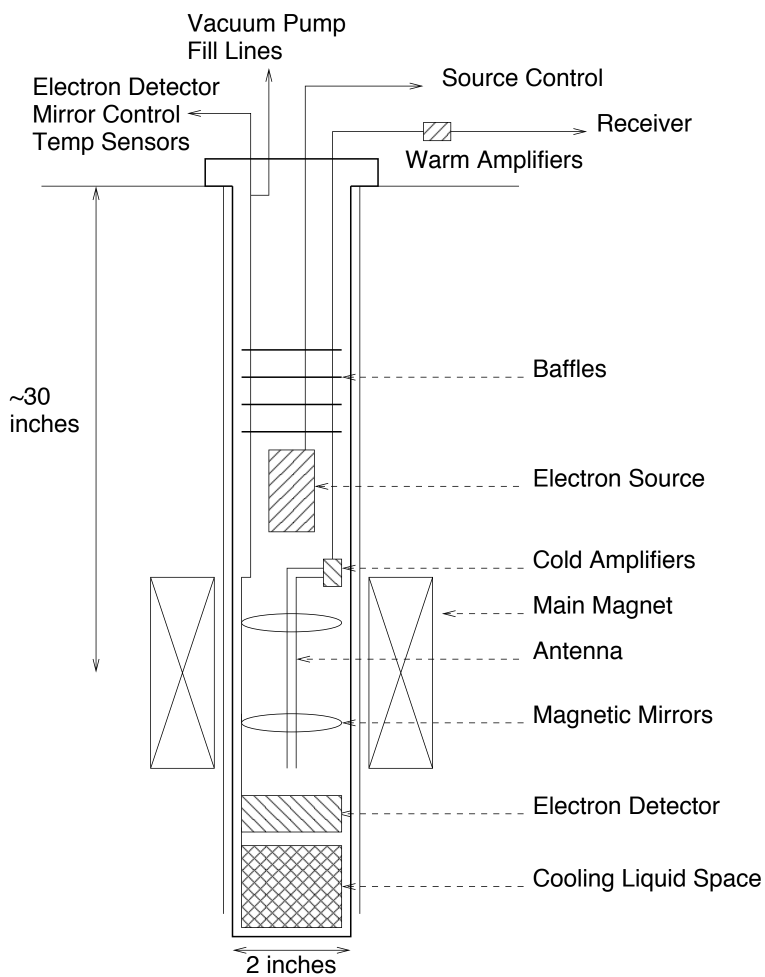
$$7.5 \times 10^{-17}\,\mathrm{Watts} \times \beta_{\perp}^{2} \left(\frac{1\,\mathrm{cm}}{d}\right)^{2}$$



- Rich Bradley, NRAO: microwave receivers from radio astronomy



UW prototype



Conclusions

- UCSB: Ben Monreal
- MIT: Joe Formaggio, Asher Kaboth
- 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