CRES — A NEW METHOD TOWARDS MEASURING THE ν-MASS

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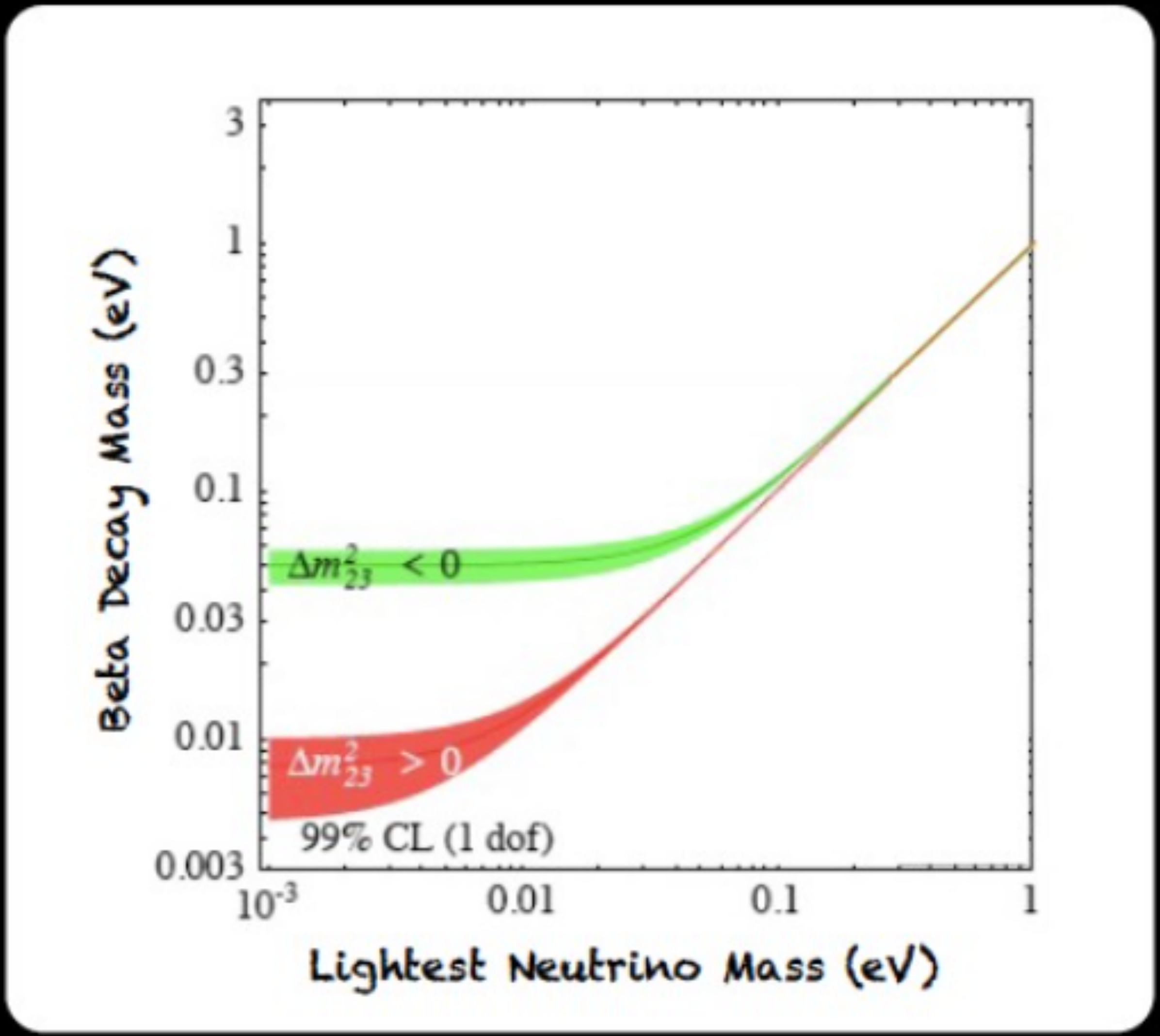
22ND JAN 2016 | TRENDS IN ASTROPARTICLE PHYSICS | ZEUTHEN

MEASURING ν-MASS

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



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

Cosmological Measurements

$$\langle m^2_{\beta\beta} \rangle = \mid \sum_i^{n_\nu} U^2_{ei} m_{\nu,i} \mid^2$$

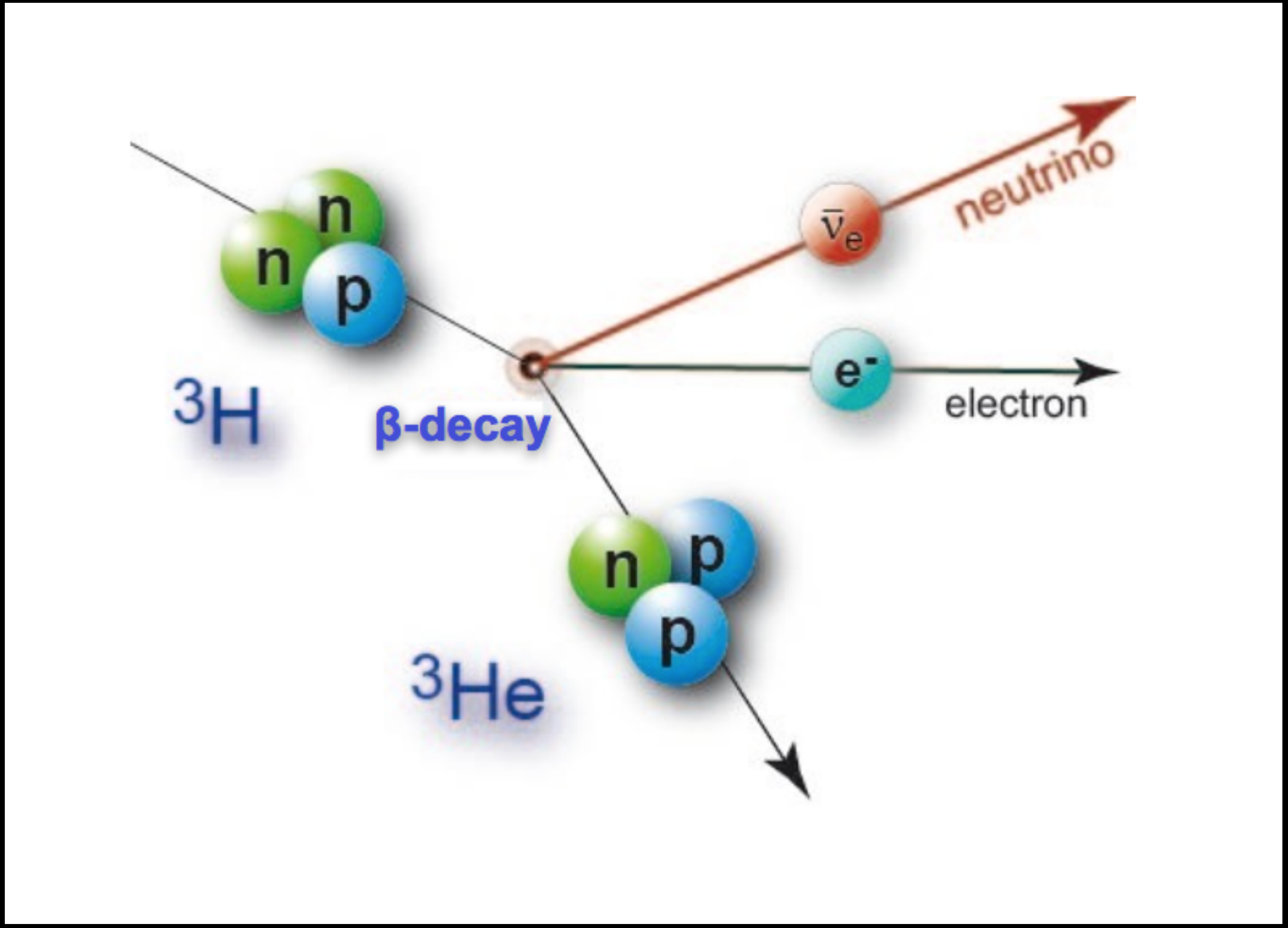
0vββ Measurements

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

Beta Decay Measurements

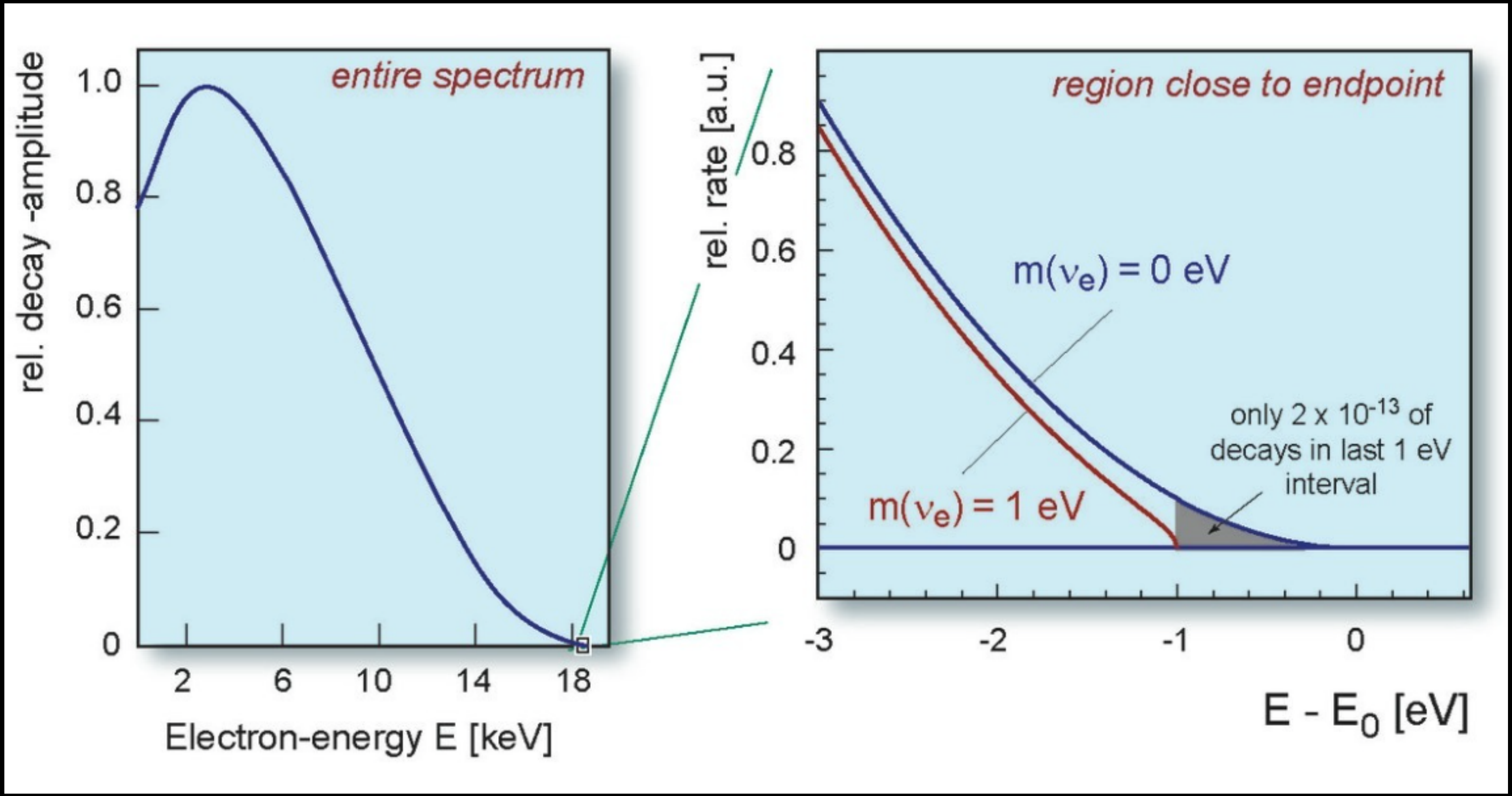
TRITIUM BETA-DECAY

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



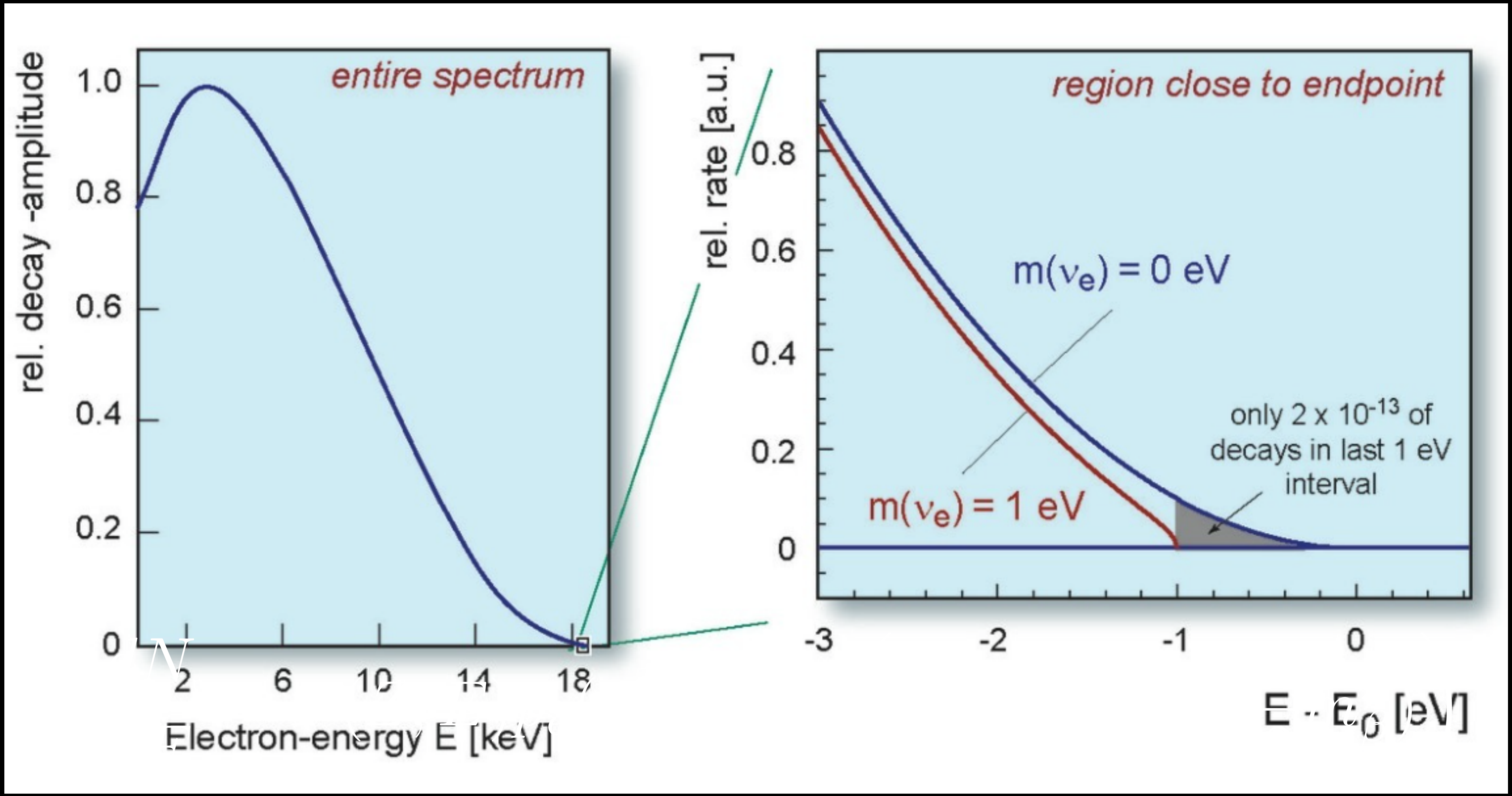
- Sum of masses and kinetic energy must add up to mass o initial nucleus

TRITIUM BETA-SPECTRUM



$$\frac{dN}{dE} \sim F(Z,E) p_e (E + m_e) \left((E - E_0)^2 - \frac{1}{2} m_\beta^2) \right)$$

TRITIUM BETA-SPECTRUM



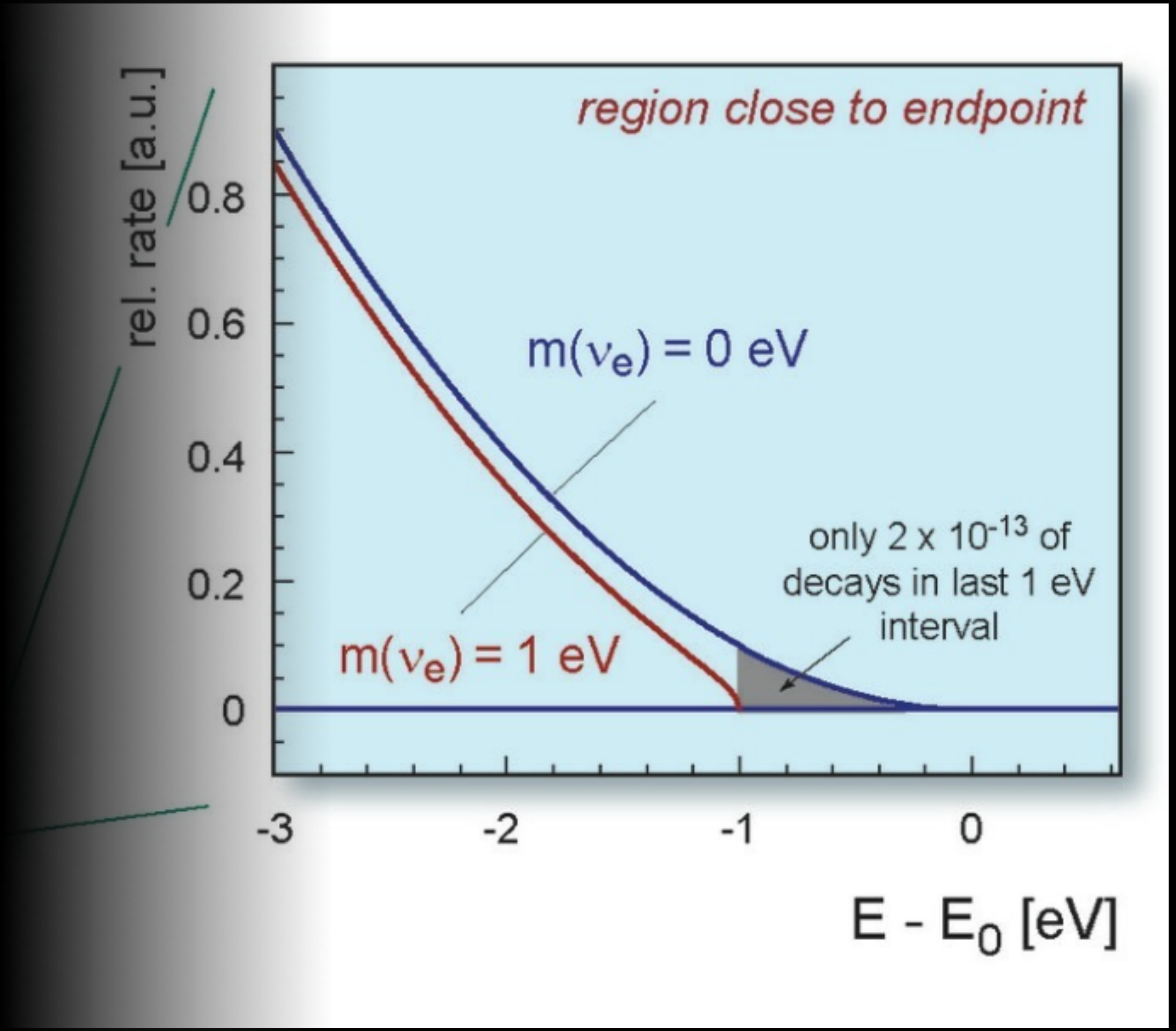
Endpoint of spectrum changes with ν-Mass

→ direct measurement of mass

(independent of "nature" of mass)

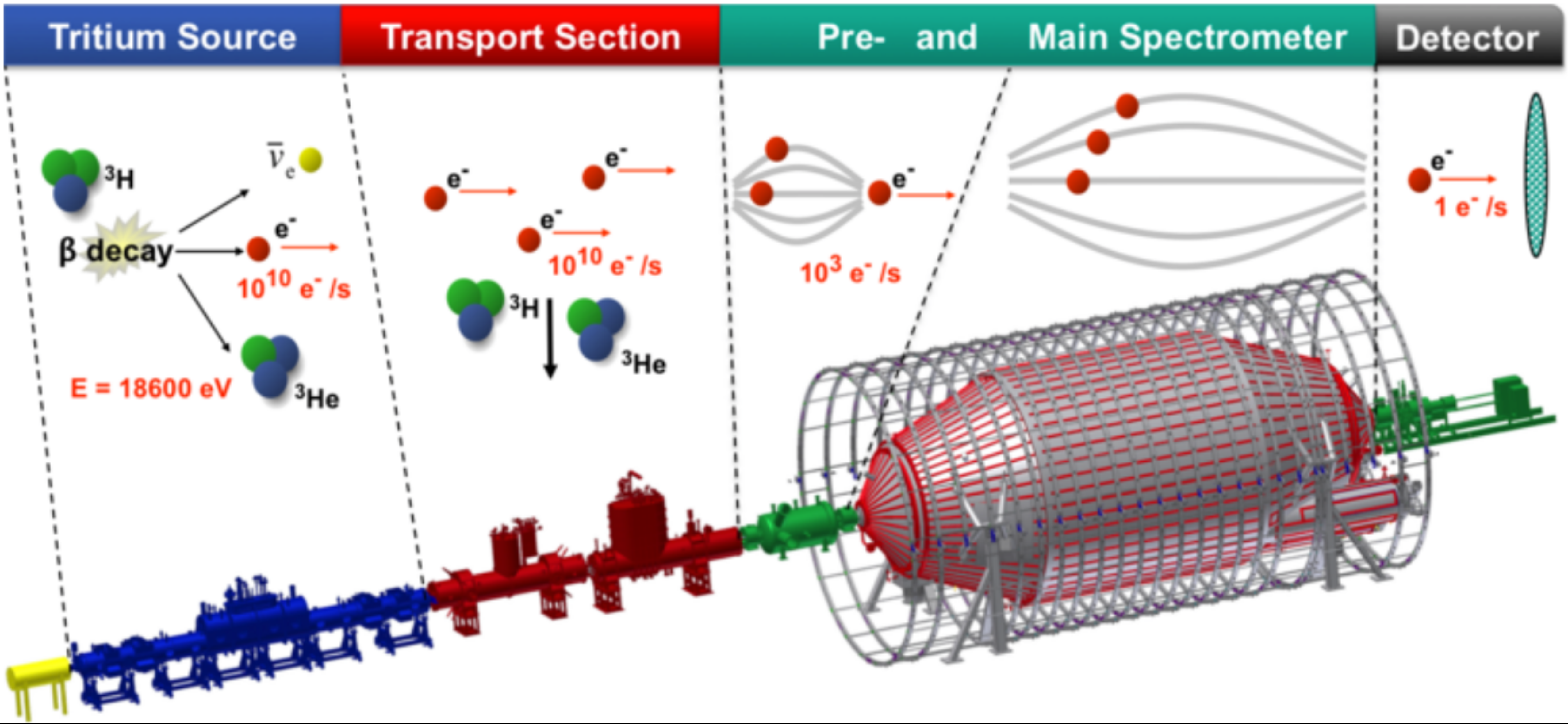
TRITIUM BETA-SPECTRUM

- Fraction of e^- in ROI
  - 10 eV: 2×10^{-10}
  - 1 eV: 2×10^{-13}
- Requirements
  - high count rate
  - high resolution



Endpoint of spectrum changes with ν-Mass
→ direct measurement of mass
(independent nature of mass)

STATE OF THE ART — KATRIN



Key component: MAC-E filter

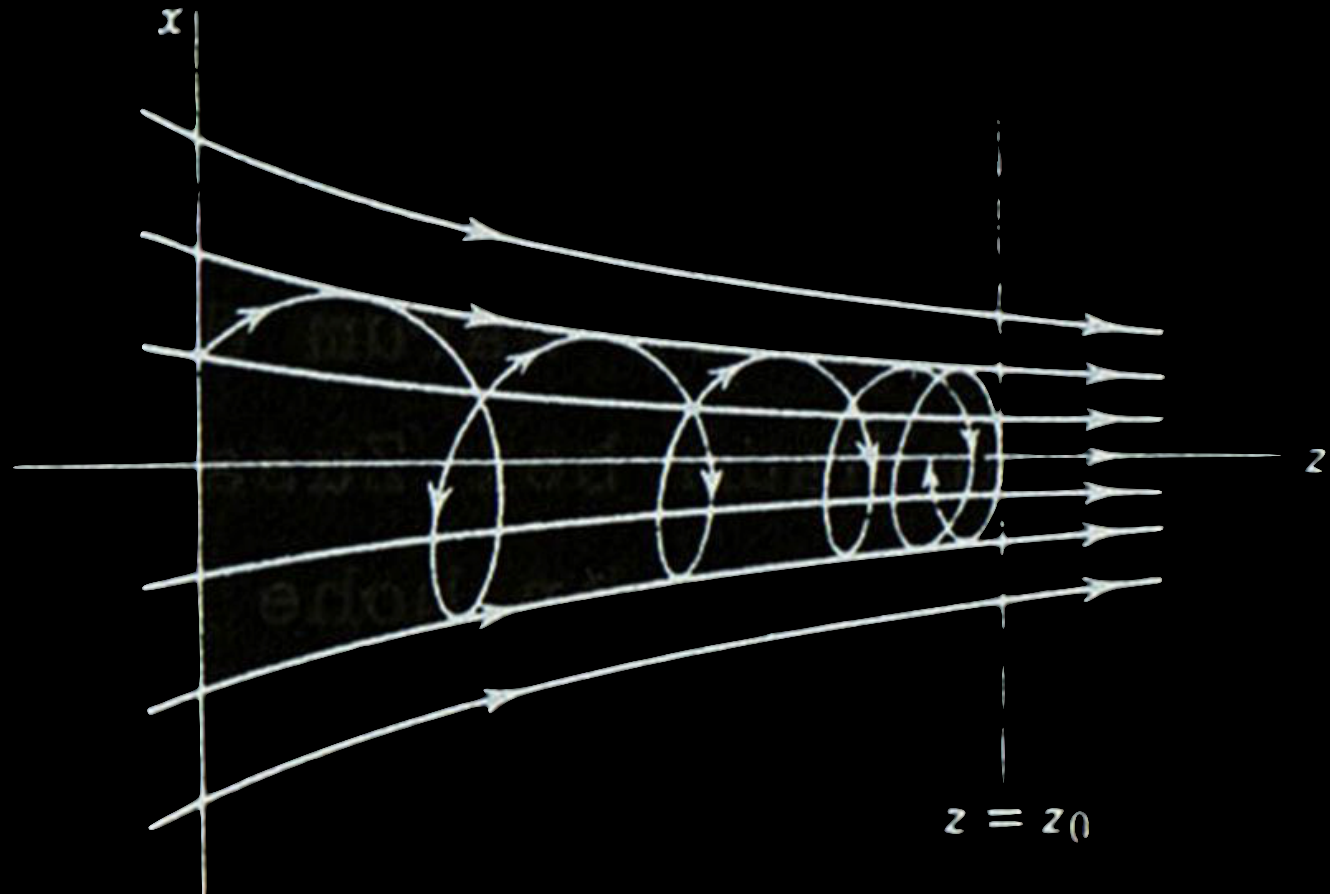
ADIABATIC INVARIANCE

Adiabatic invariance

- $\Phi = B \cdot A = B \pi r_{cycl}^2$
  $\simeq p_\perp^2 / (q \cdot B) = const$

Slowly changing B

- $p_\perp \rightarrow p_\parallel$



MAC-E FILTER

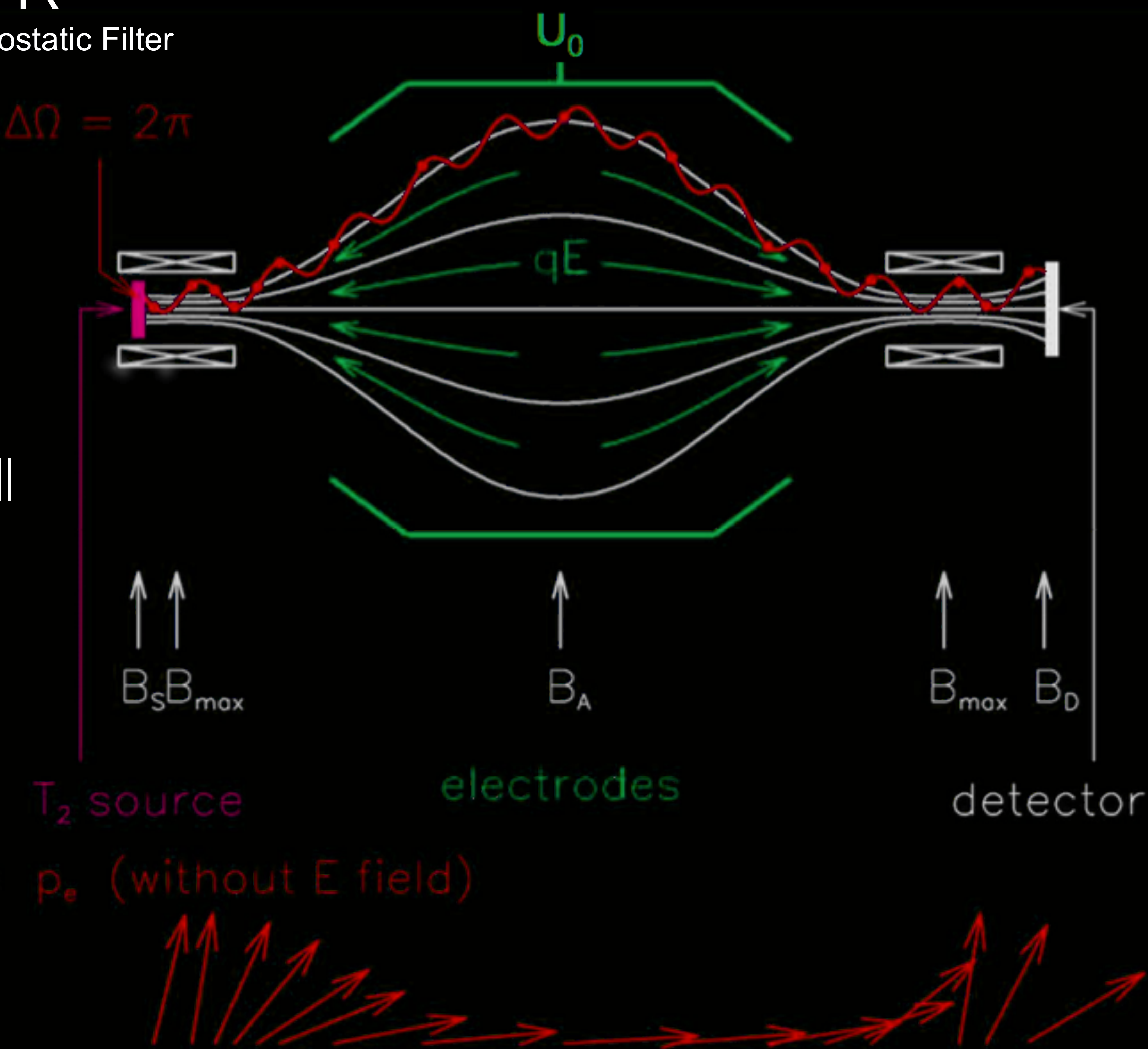
Magnetic Adiabatic Collimation with Electrostatic Filter

Combination of

- Adiabatically changing B-field
  → convert $E_\perp$ to $E_\parallel$
- E-field to filter by energy

Resolution

- ratio of B_s / B_A
  → limited by **size**



KATRIN

Karlsruhe Trititum Neutrino Experiment

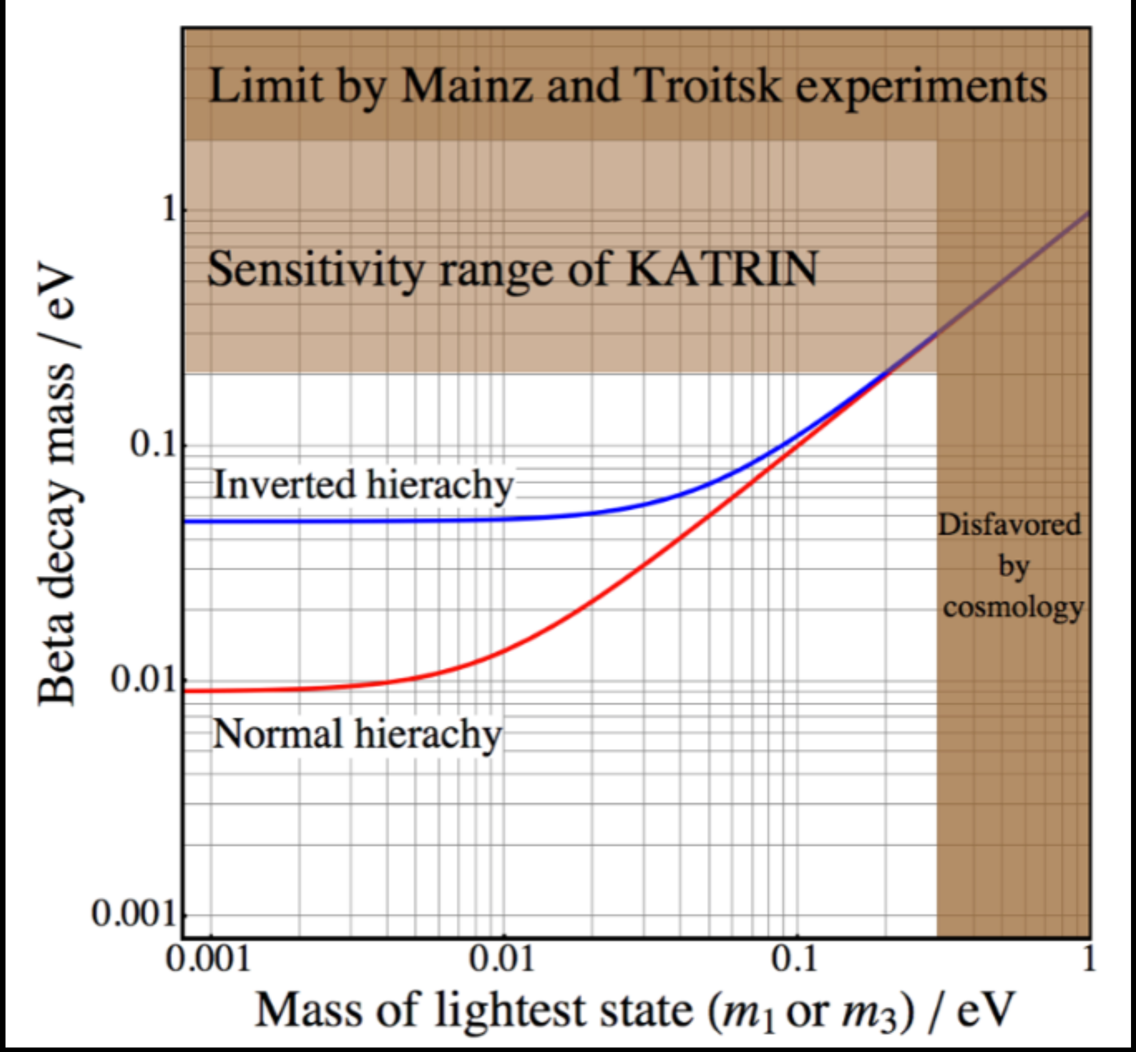
Sensitivity goal

- $m_\beta < 200$meV

Limited by

- size of spectrometer
- systematic effects

➔ need a new and complimentary approach



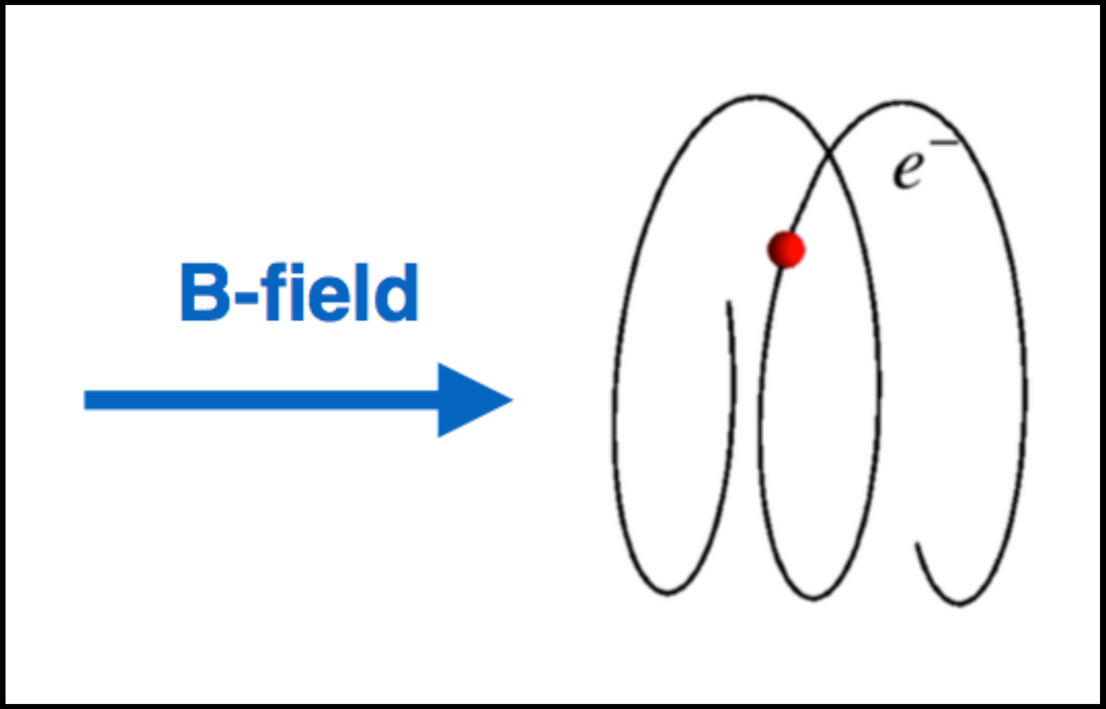
CYCLOTRON RADIATION

Cyclotron radiation

$$f_c = \frac{1}{2\pi}\frac{eB_\perp}{m_e}$$

relativistic correction

$$f_\gamma = \frac{f_c}{\gamma} = \frac{1}{2\pi}\frac{eB_\perp}{m_e + E_{\rm kin}}$$



“Never measure anything but frequency” - wise person

RESOLUTION

Energy resolution

$f \cdot \Delta E/E \sim \Delta f$

- $\Delta E/E \sim 1eV / 511\ keV = 2e^{-6}$

  → easy!

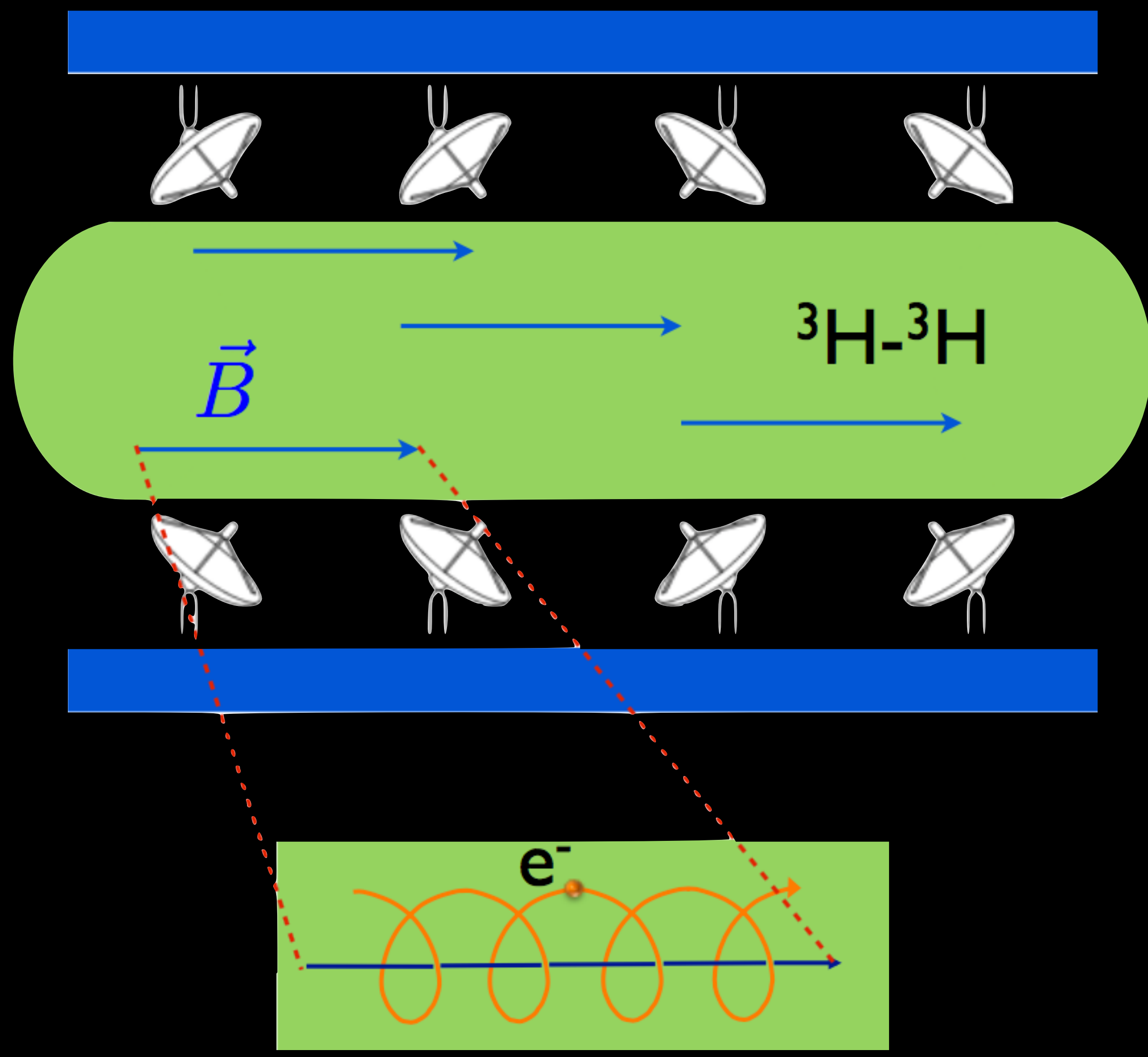
Frequency resolution

$\Delta f \sim 1/\Delta t$

- $\Delta t = 20\mu s \sim 1400m$ @ 18keV

  → hard!

PROJECT8



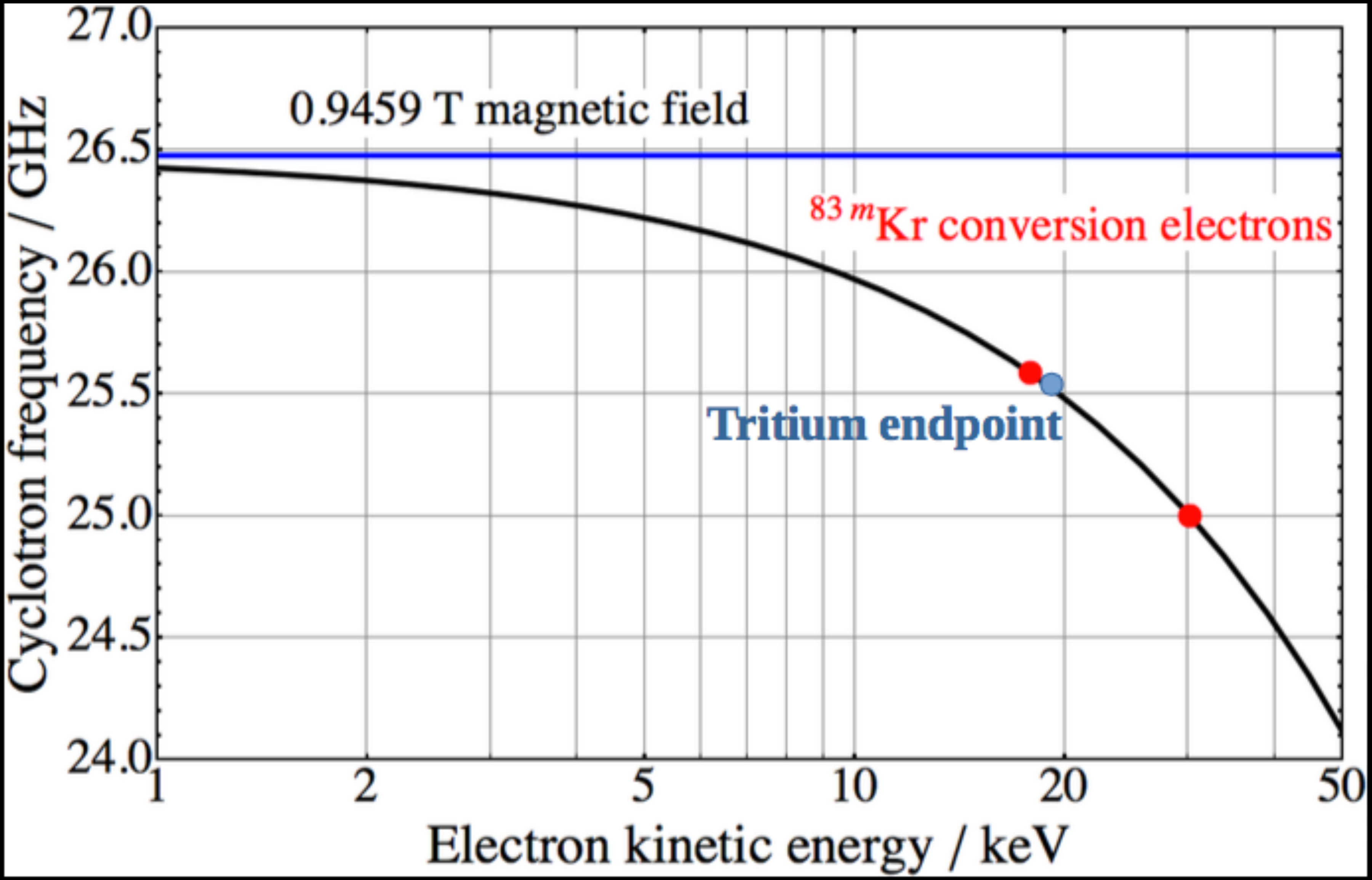
B. Monreal and J. Formaggio, Phys. Rev D80:051301

Idea

- fill volume with ^3H gas
- add magnetic field
- decay electrons spiral around field lines
- add antennas to detect cyclotron radiation

FREQUENCY SCALE

magnetic field of 1T → cyclotron frequency in K-Band

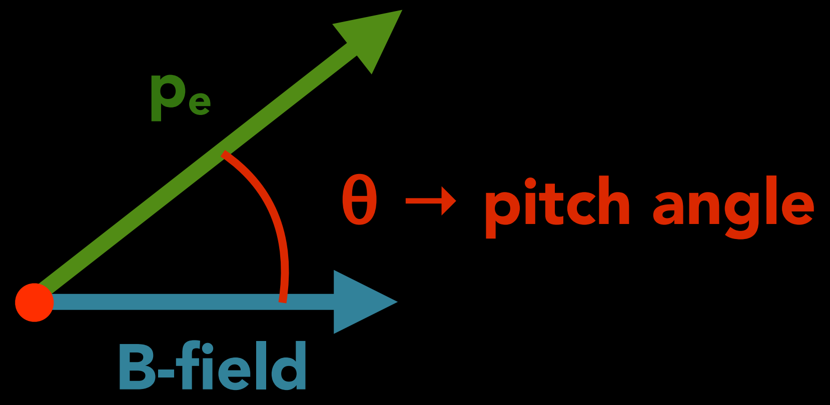


^{83}Kr provides electrons close to tritium endpoint

RADIATED POWER

Lamour formula

$$P(\gamma, \theta) = \frac{1}{4\pi\varepsilon_0} \frac{2}{3} \frac{q^4 B^2}{m_e^2} (\gamma^2 - 1) \sin^2\theta$$



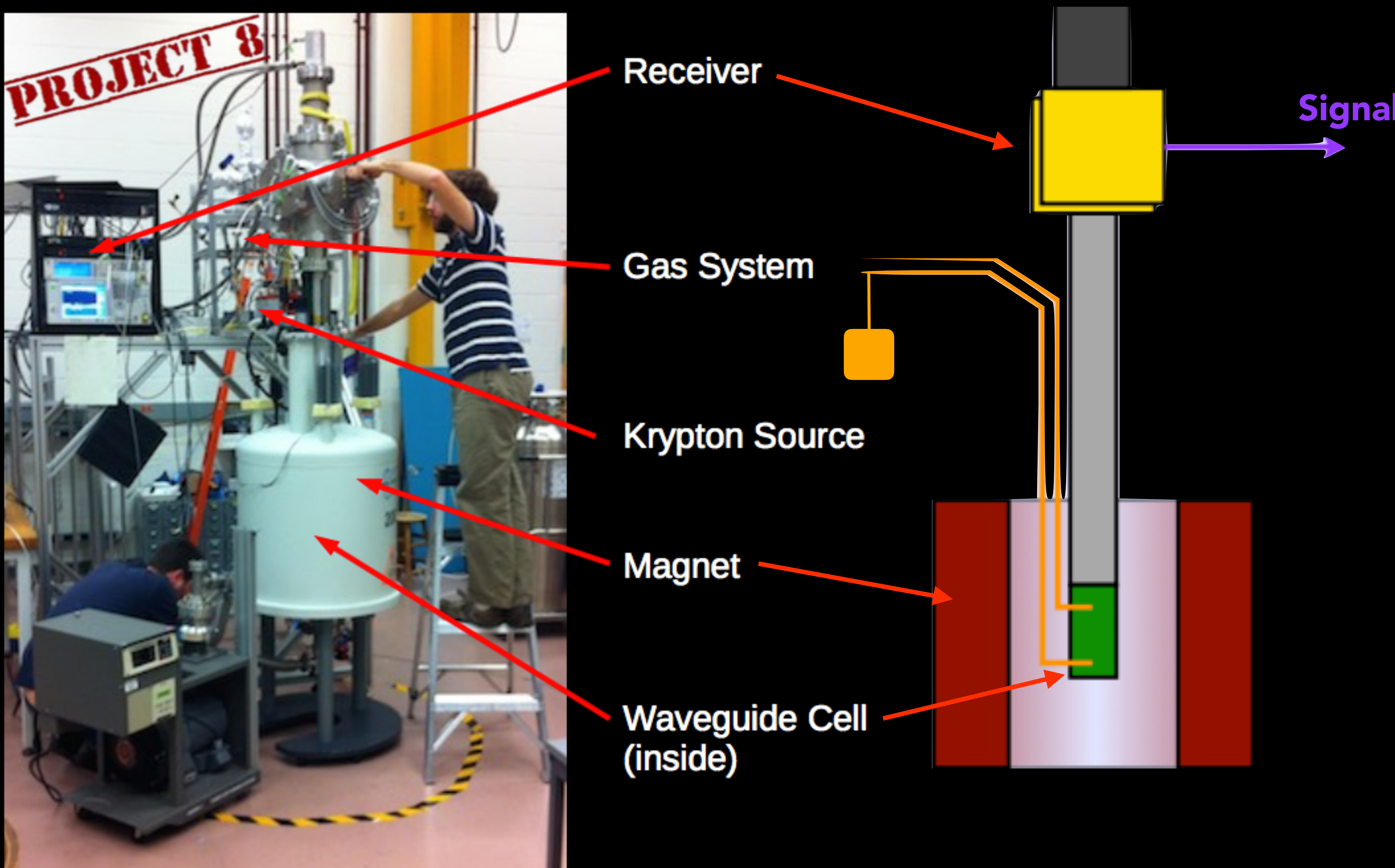
Emitted power

- 1.1 fW for 18 keV e^- at 90°
- 1.7 fW for 30.4 keV e^- at 90°

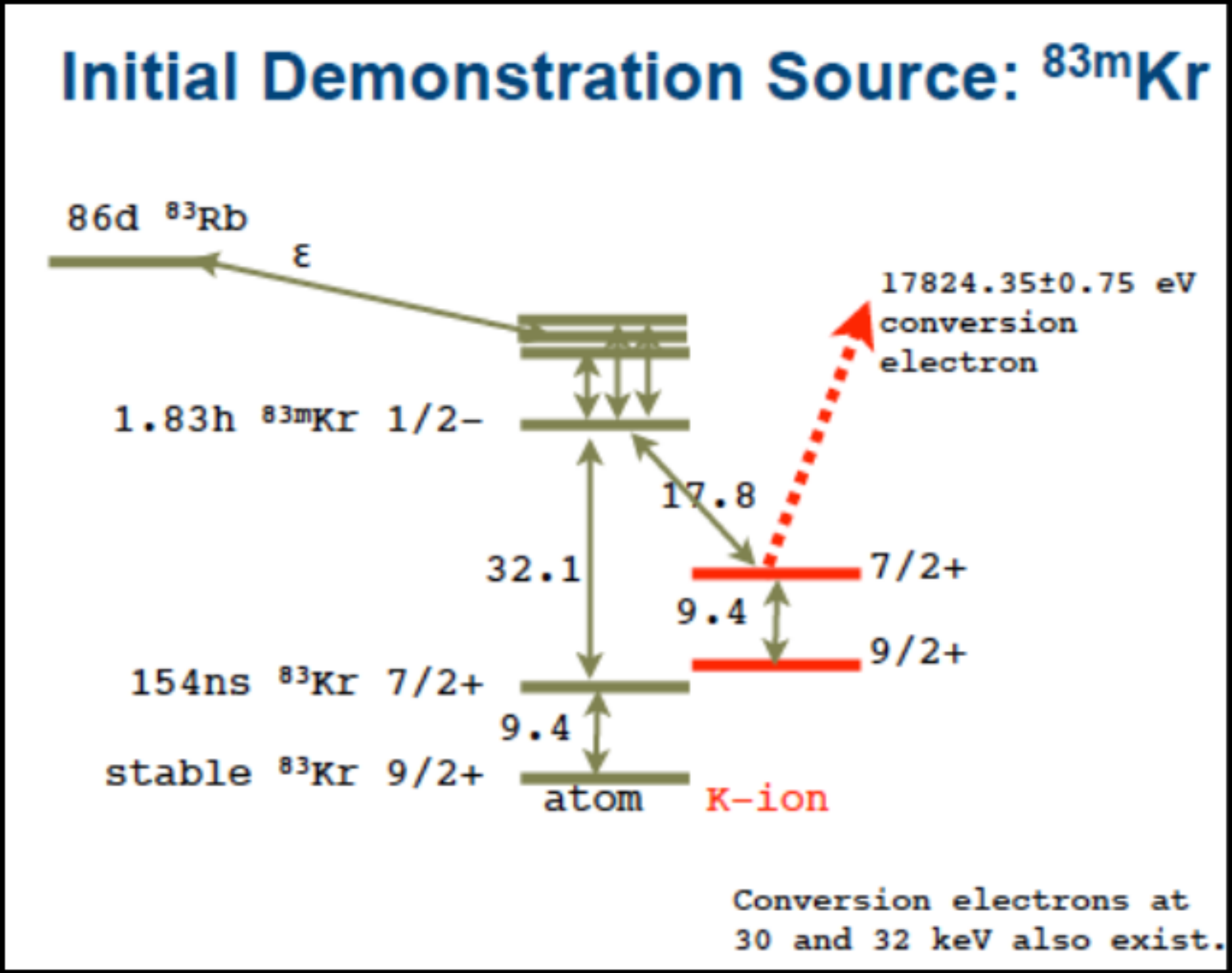
→ Low-noise cryogenic RF-system needed!

University of Washington

PROJECT8 PROTOTYPE



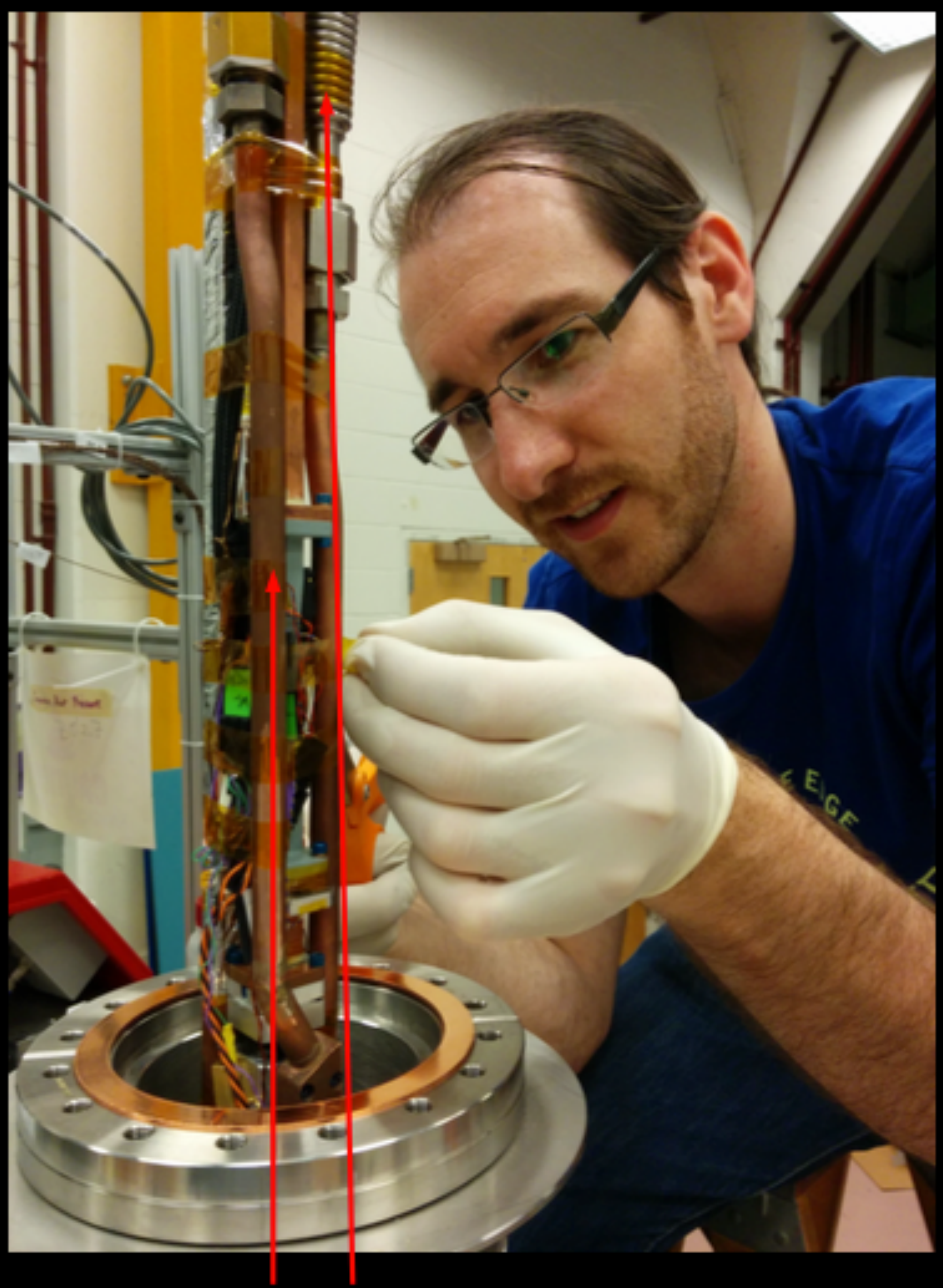
KRYPTON SOURCE



^{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

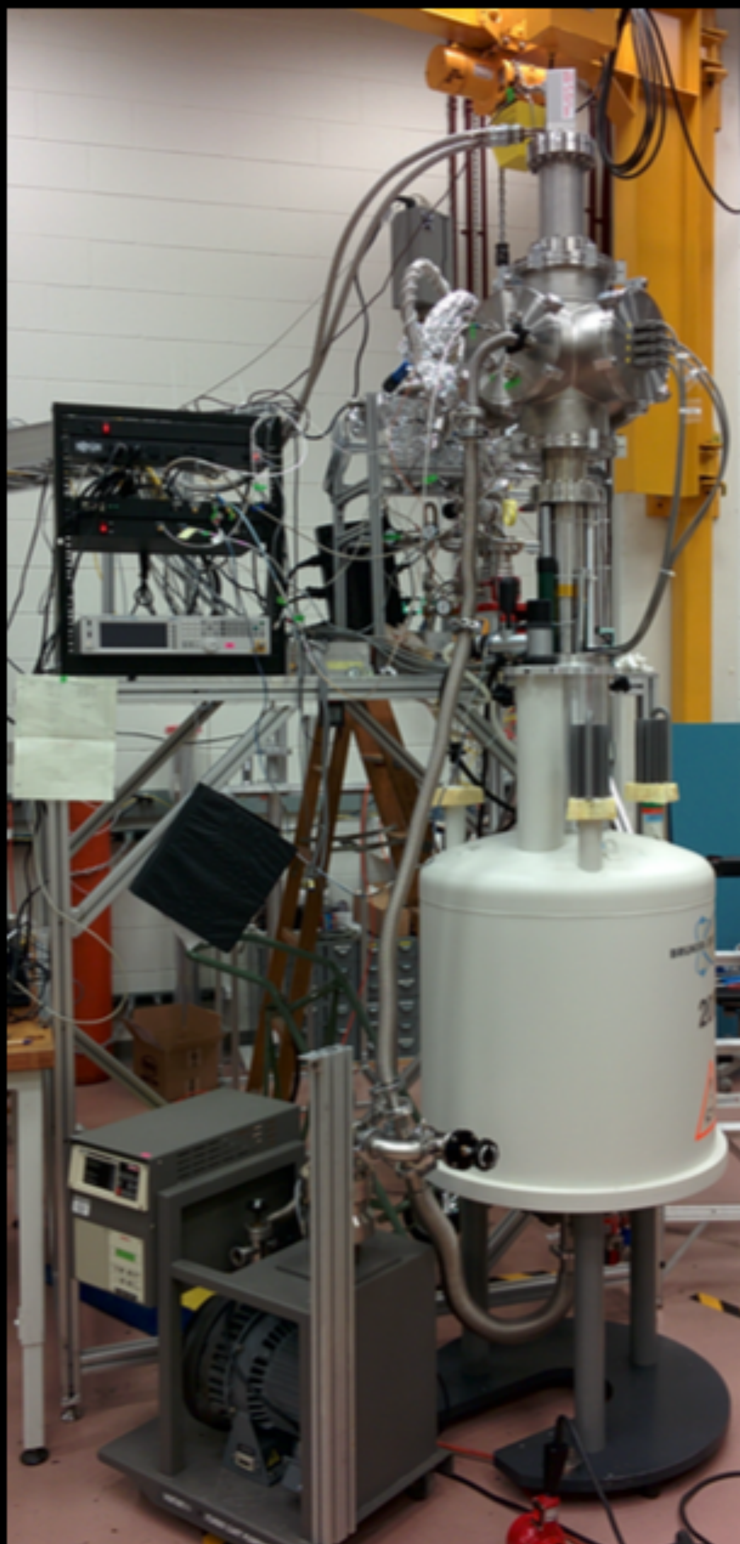
GAS SYSTEM

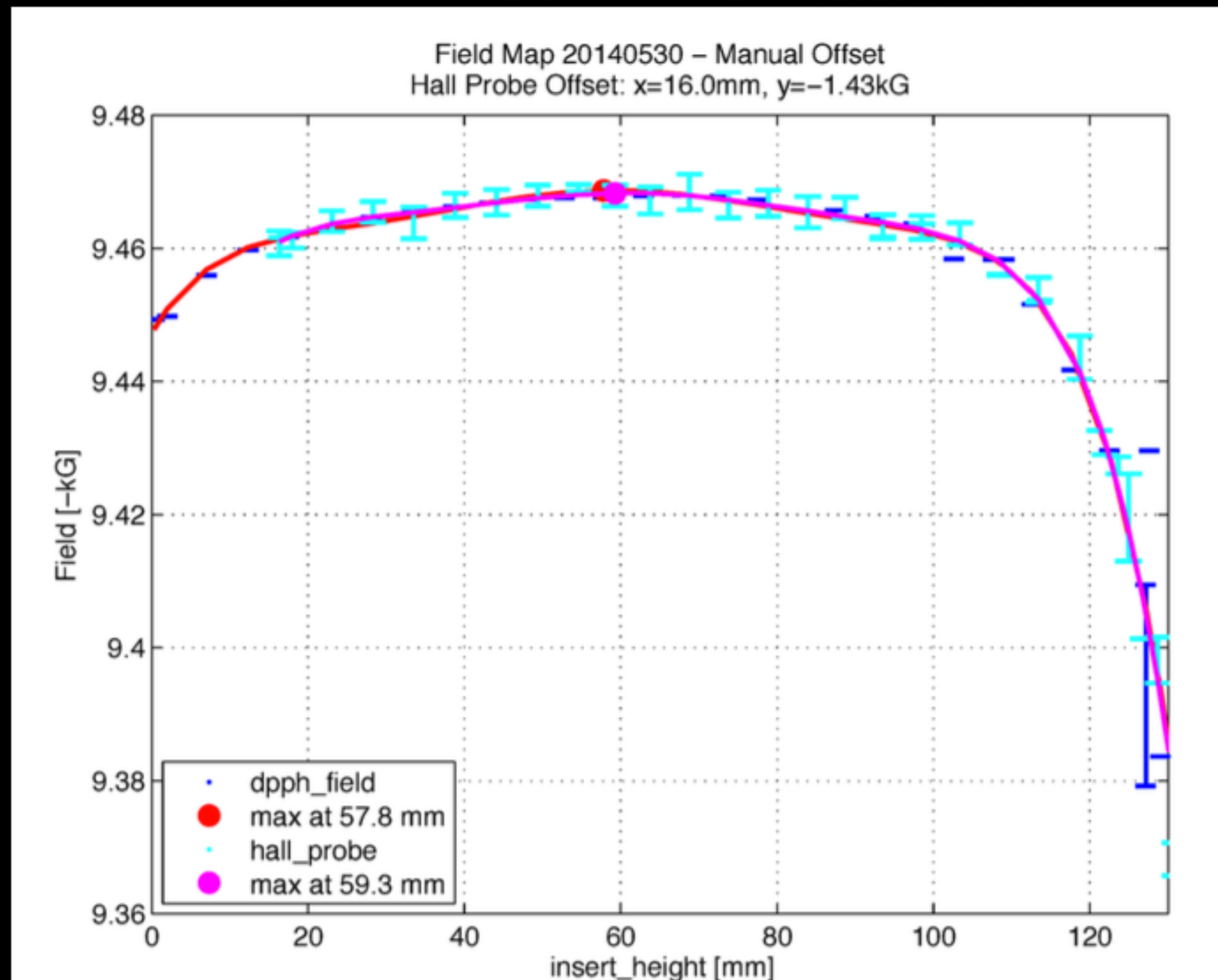


Gas lines carrying krypton to detector

- Delivers Krypton to detector
- Keeps pressure of residual gas below 10^{-6} torr
    - electrons scatter infrequently
- Does not pump away Krypton
- Keeps temperature above Krypton freezing point

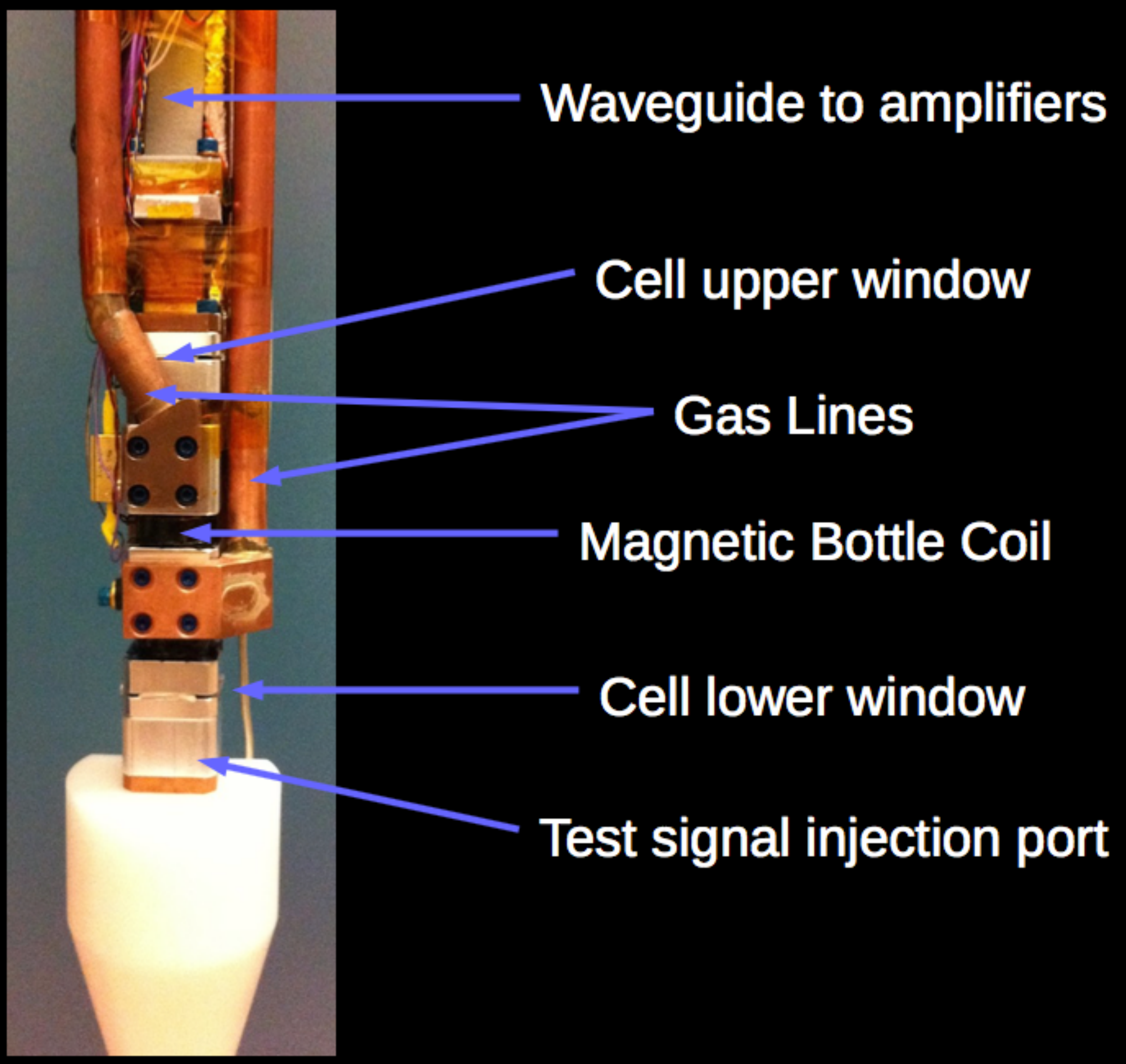
MAGNET





The primary field is provided by a repurposed NMR magnet

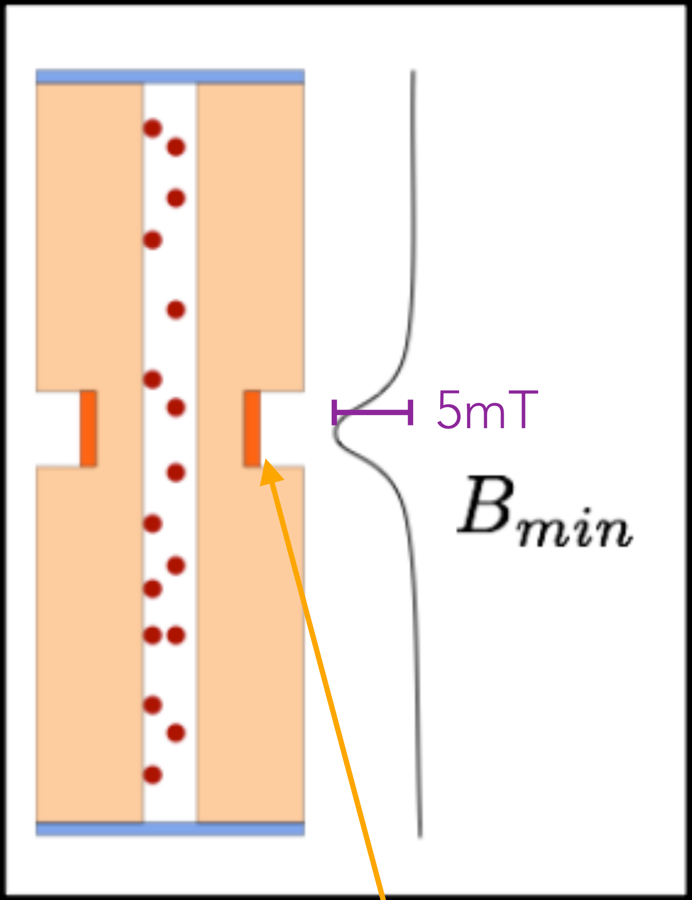
WAVEGUIDE CELL



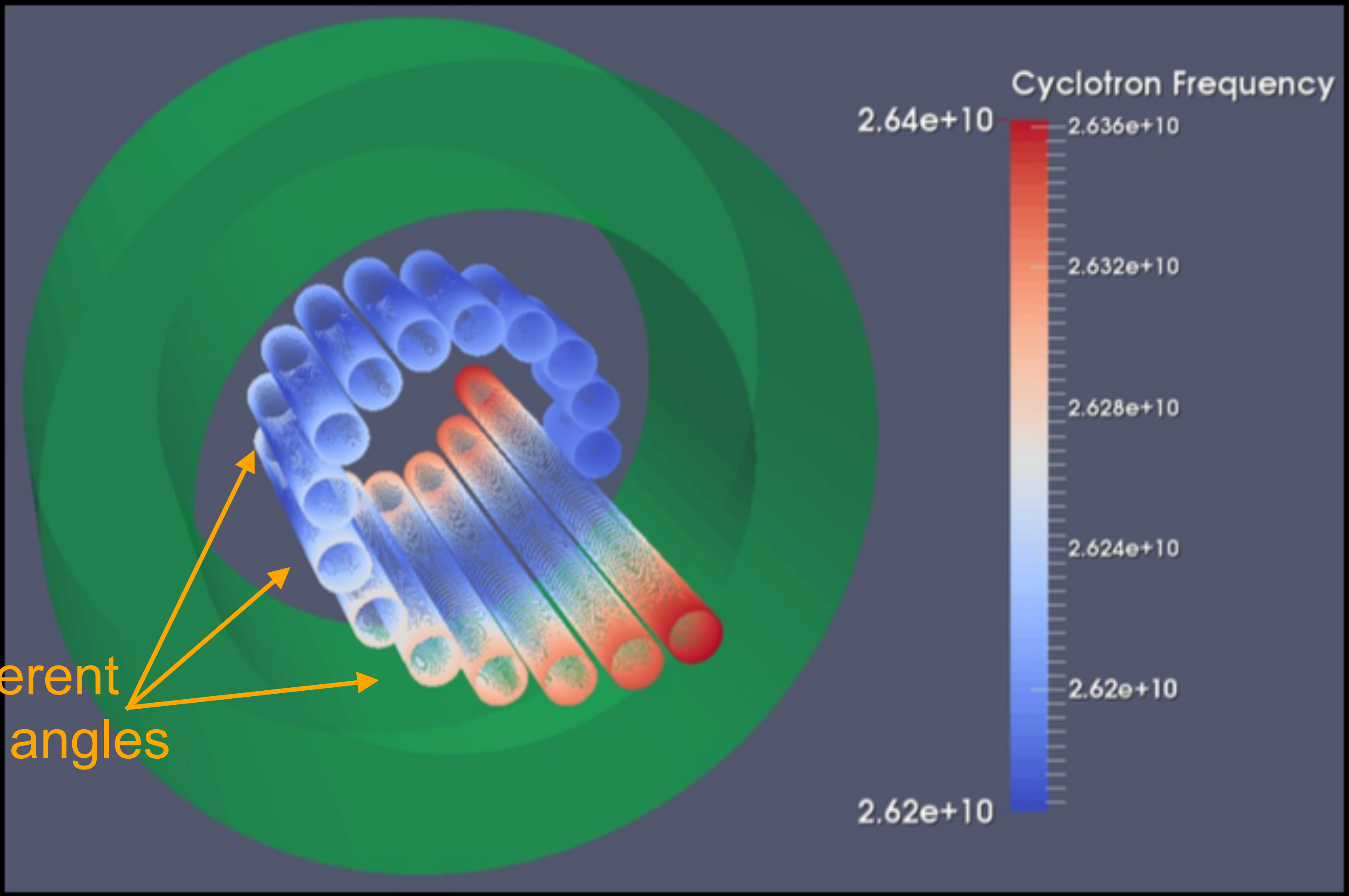
MAGNETIC BOTTLE

$$f_\gamma = \frac{f_c}{\gamma} = \frac{1}{2\pi}\frac{eB}{m_e + E_{\text{kin}}}\left(1 + \frac{\cot^2\theta}{2}\right)$$

Waveguide Cell Cut-Away View



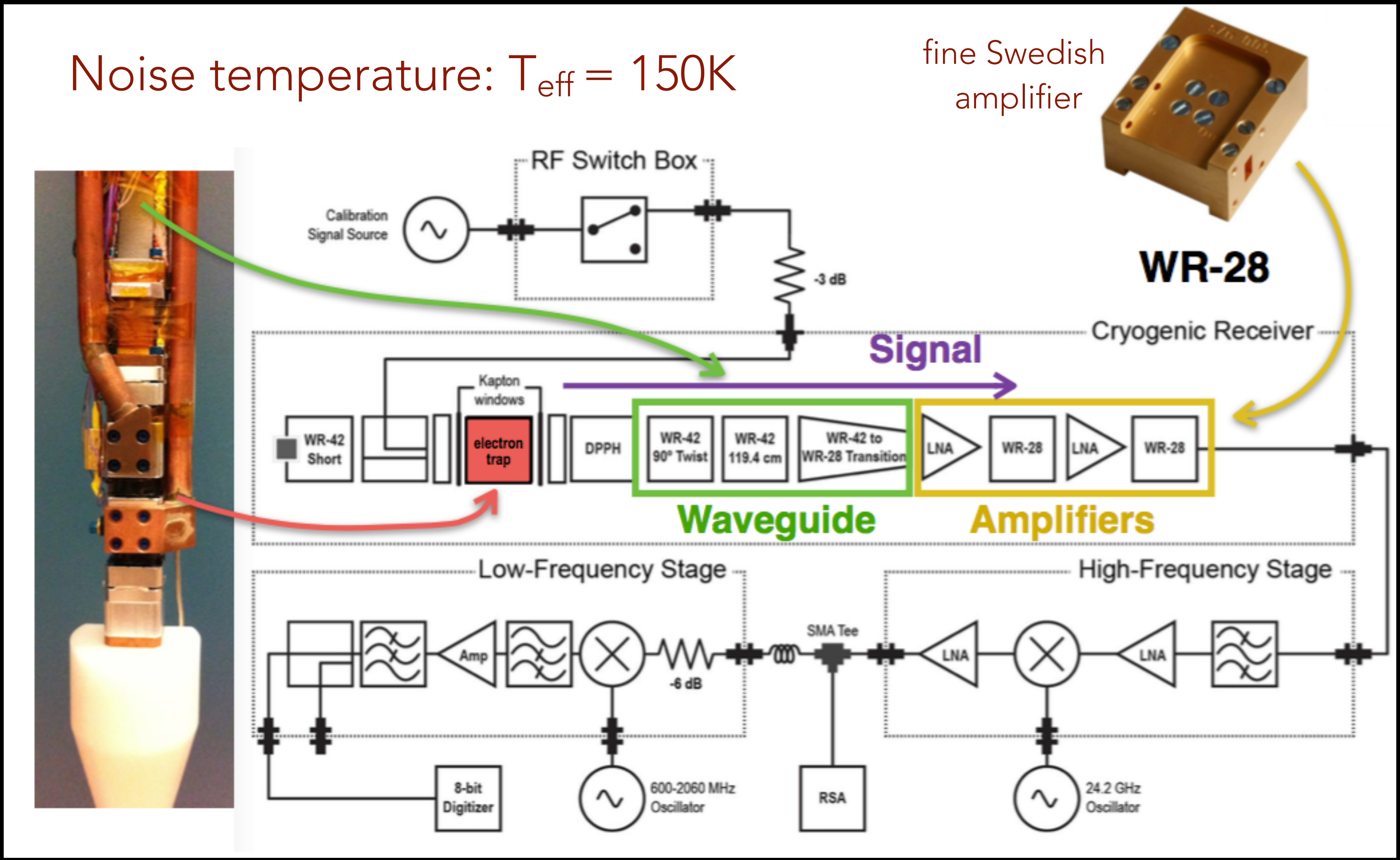
Simulation of Trapped Electron Trajectories



Effects of trap on measured frequency easily calculable

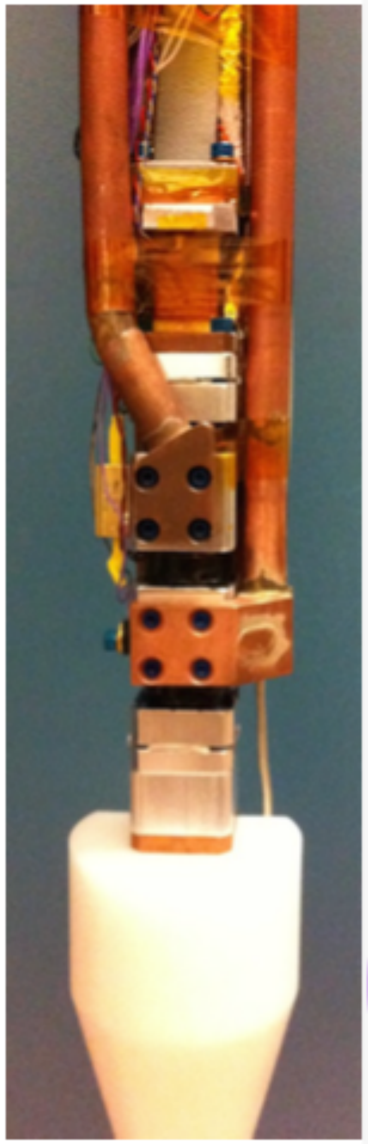
SIGNAL AMPLIFCATION AND NOISE

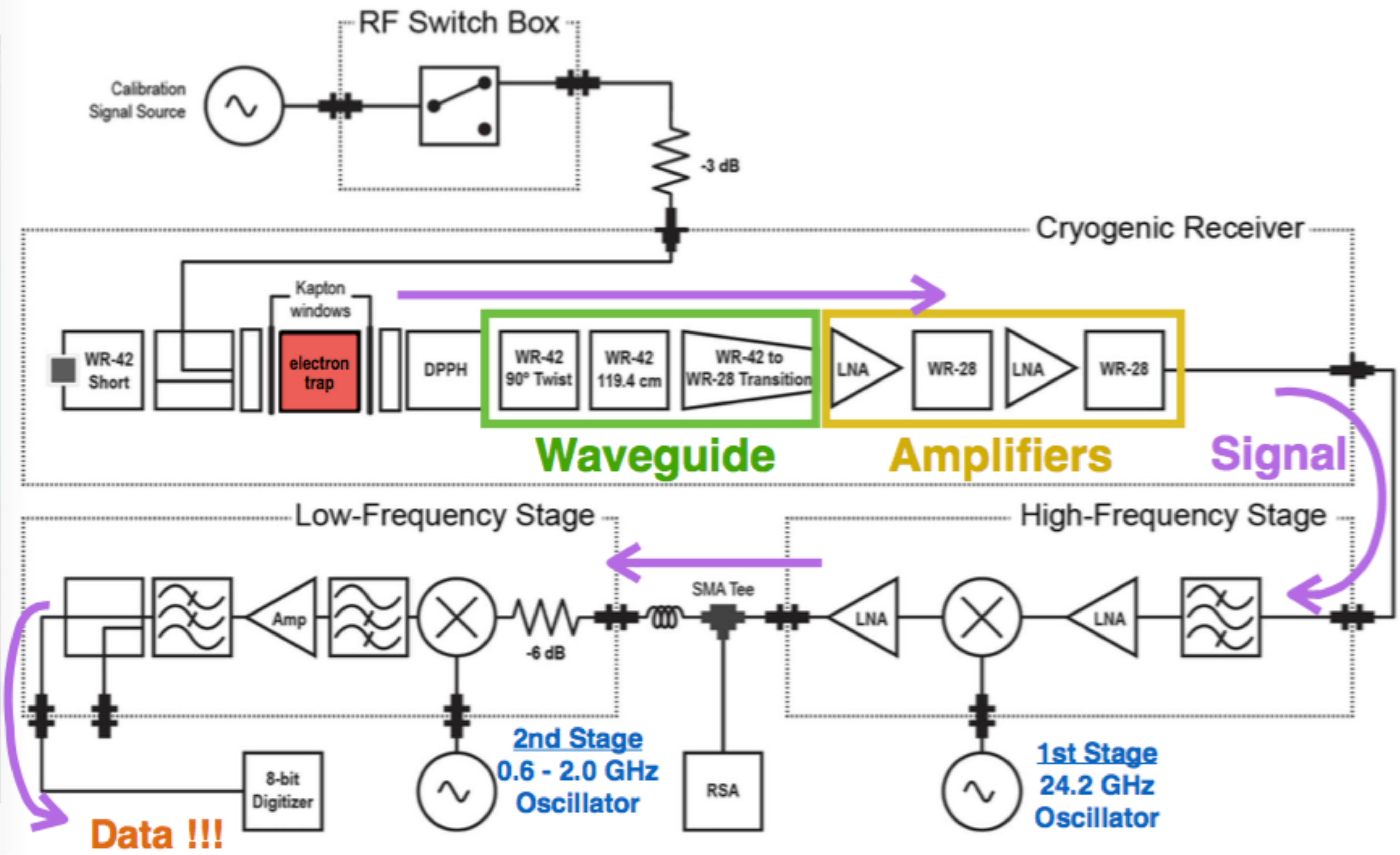
Noise temperature: $T_{eff} = 150K$



- Primary background
  → thermal noise from waveguide and amplifiers

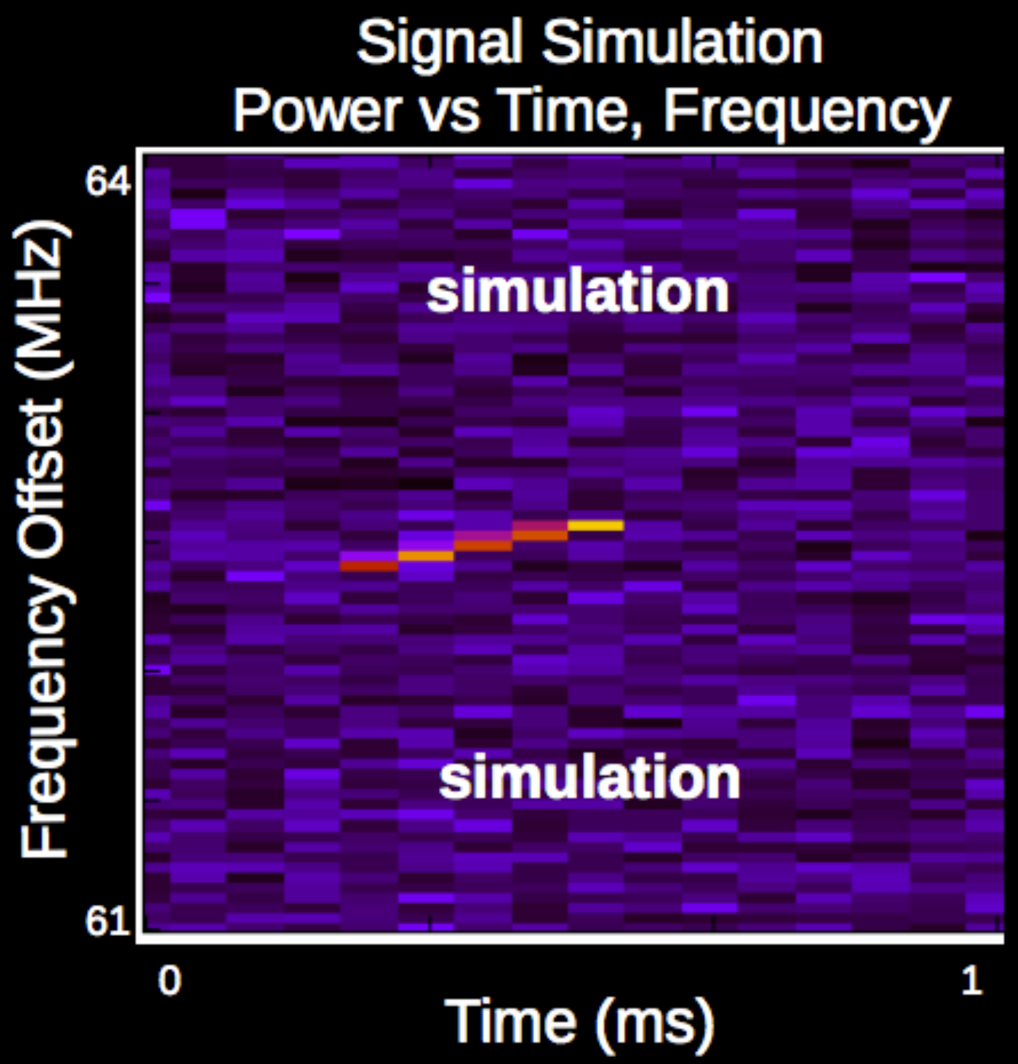
RECEIVER STAGE





- Double-stage down-mixing
- Digitizer: 8-bit, 500Ms/s, 125MHz bandwidth
  → untriggered

EXPECTED SIGNAL



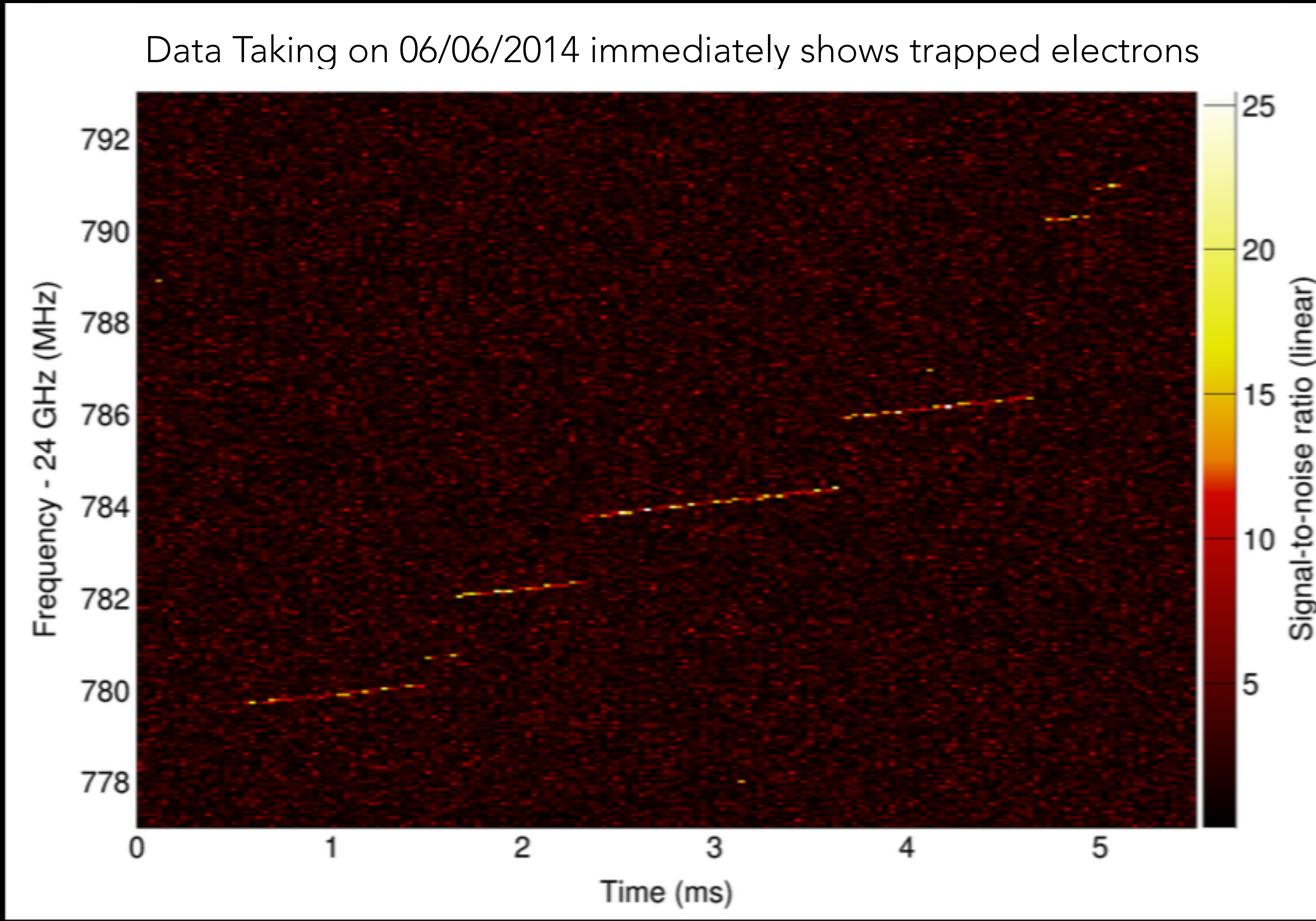
Spectrogram

- time slices
  → consecutive power spectrum

Signal

- narrow-band
  → horizontal line
- energy loss by radiation
  → tilted line

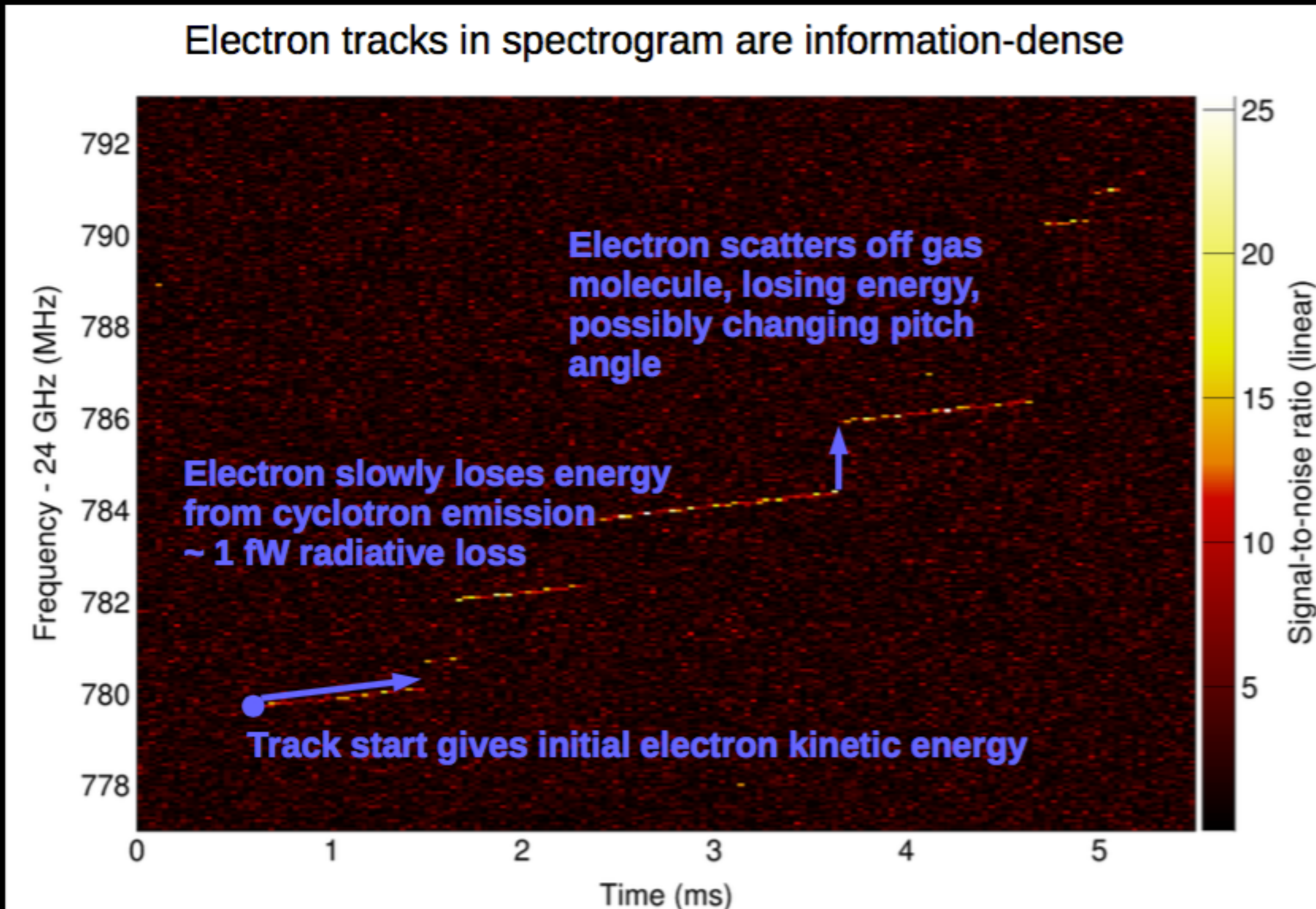
ACTUAL SPECTROGRAM



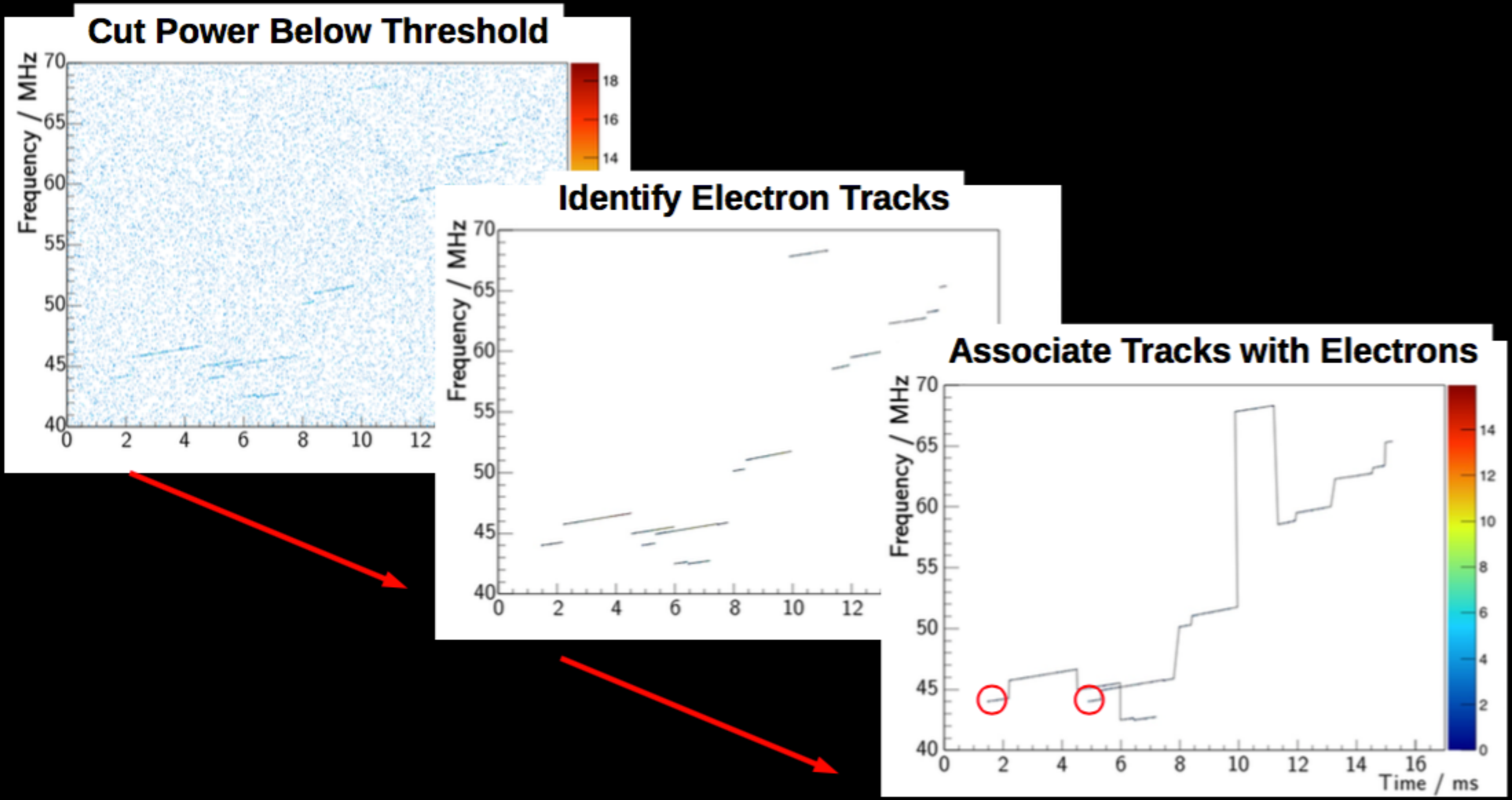
First detection of single-electron cyclotron radiation!

SPECTROGRAM INFORMATION

Scale: 100eV

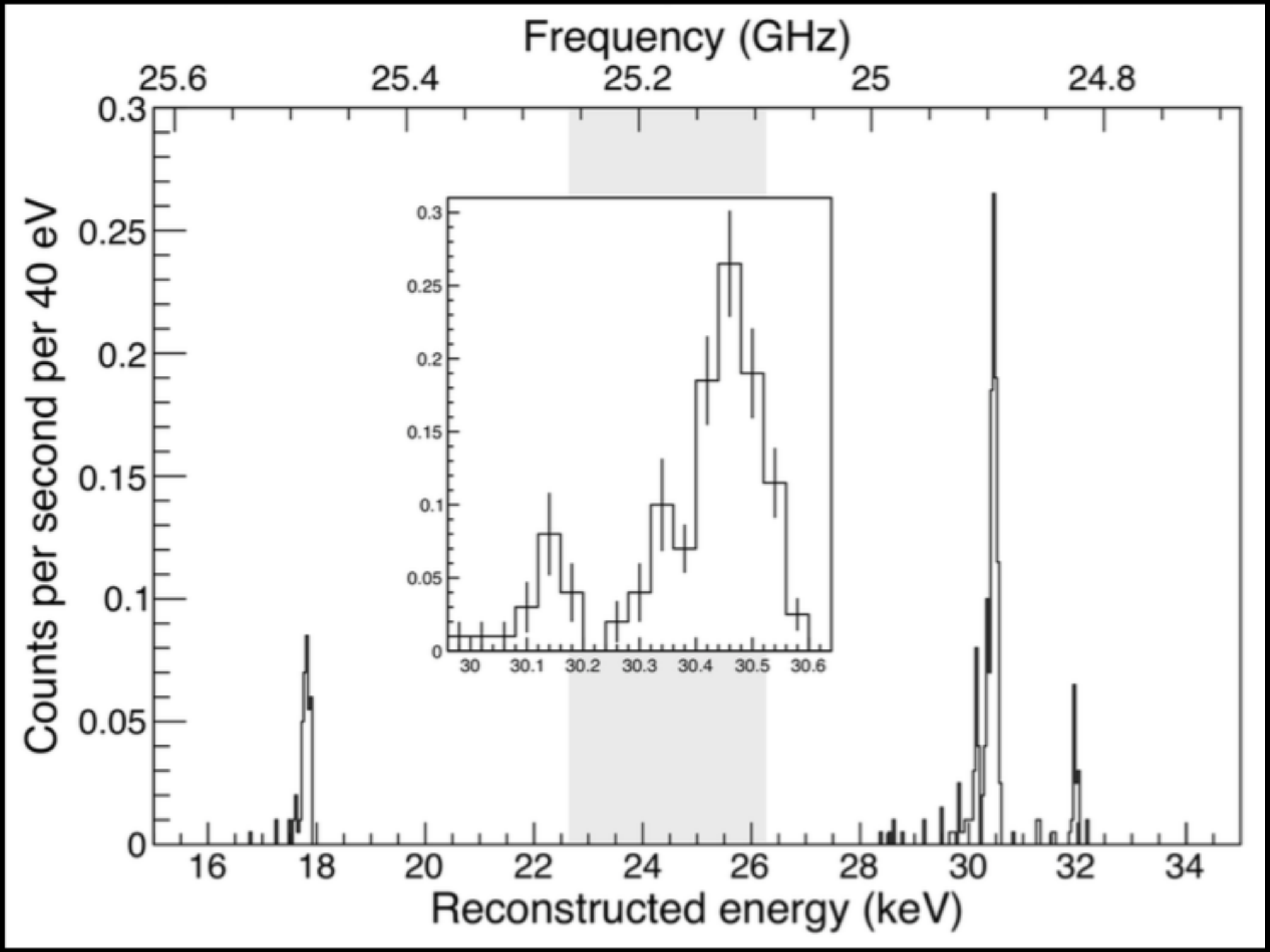


ENERGY SPECTRUM



Initial frequency determines initial energy

FIRST ENERGY SPECTRUM



[arxiv:1408:5362]

Both 83m Kr lines
→ clearly seen

Resolution

- FWHM: 140 eV

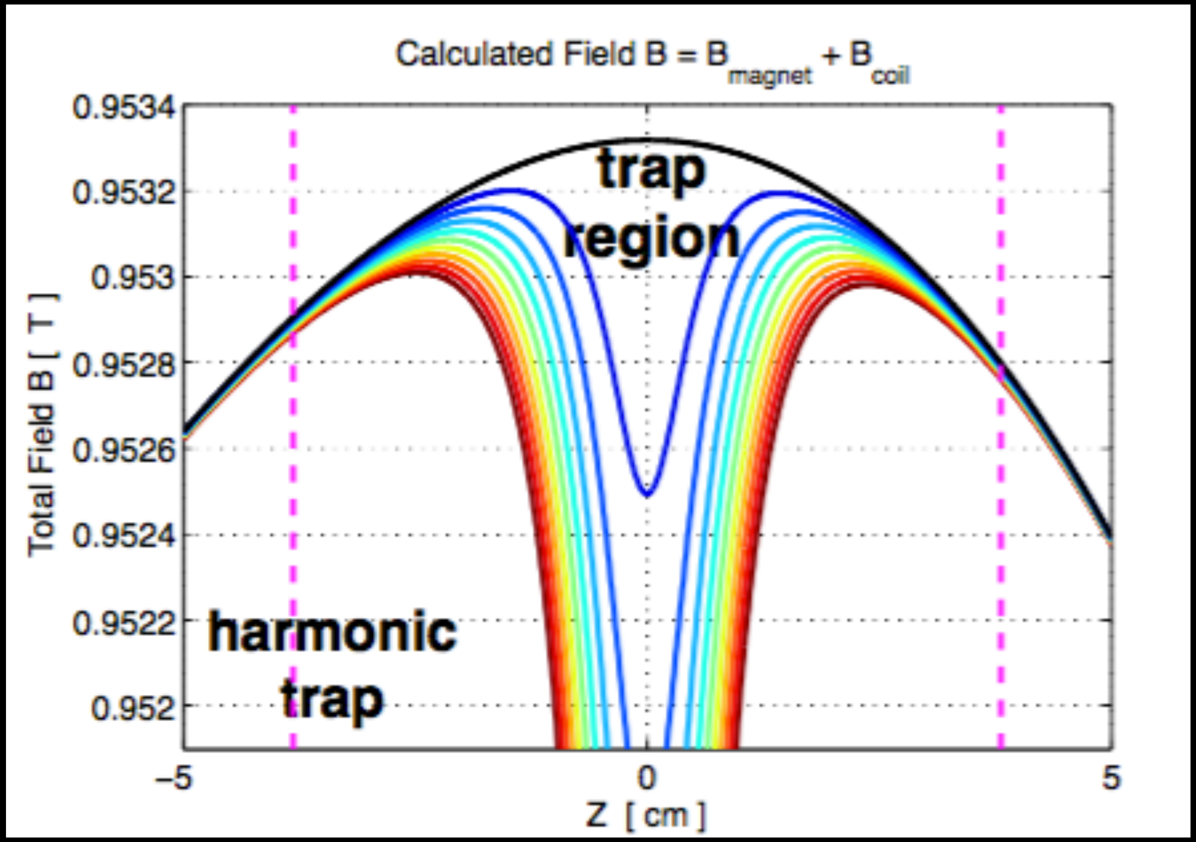
IMPROVED TRAP

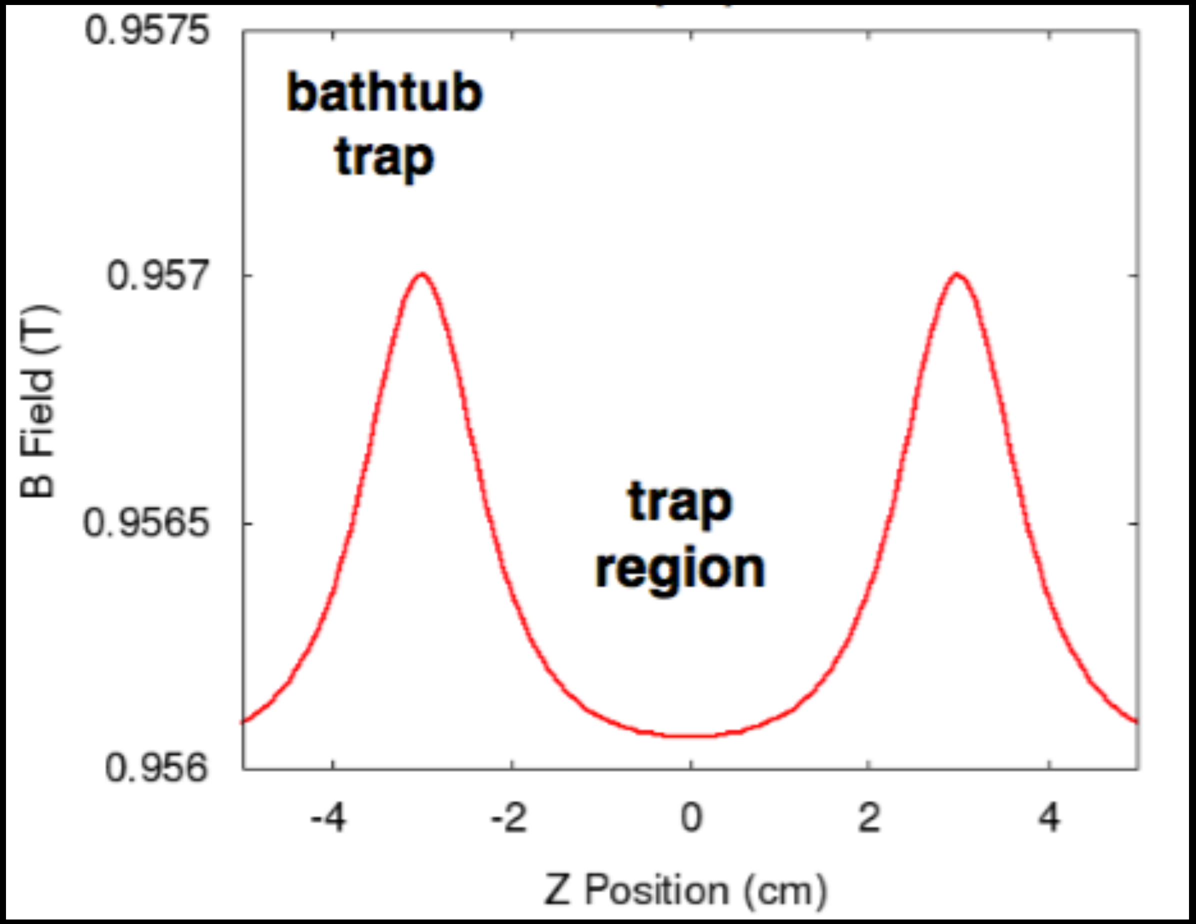
Shallower *Harmonic* trap

- better field uniformity
- smaller acceptance
  → lower rate & better resolution

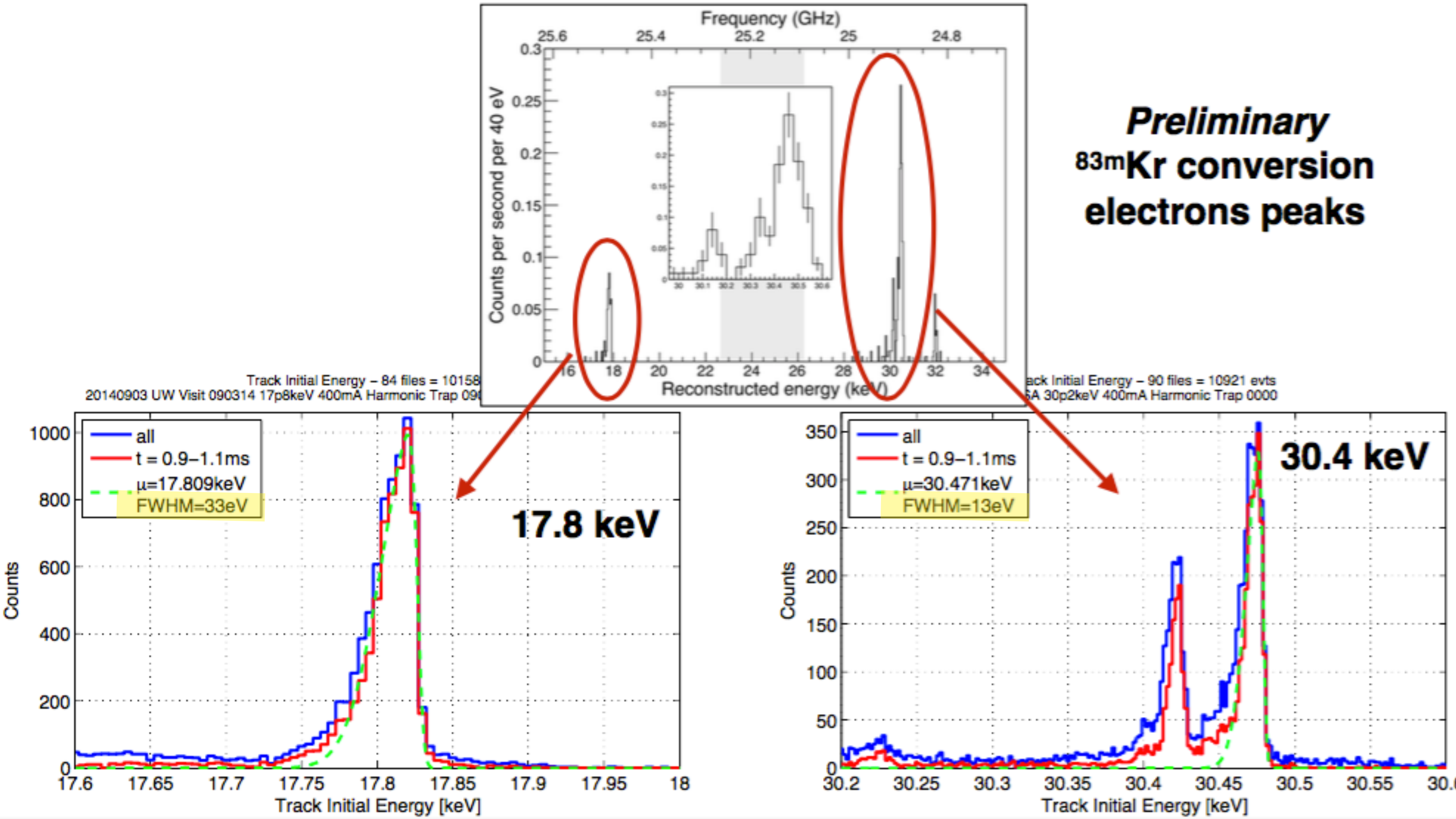
Bathtub trap

- two coils at end of cell
- better uniformity
- larger trap size
  → larger rate & better resolution





CRES — CYCLOTRON RADIATION EMISSON SPECTROSCOPY



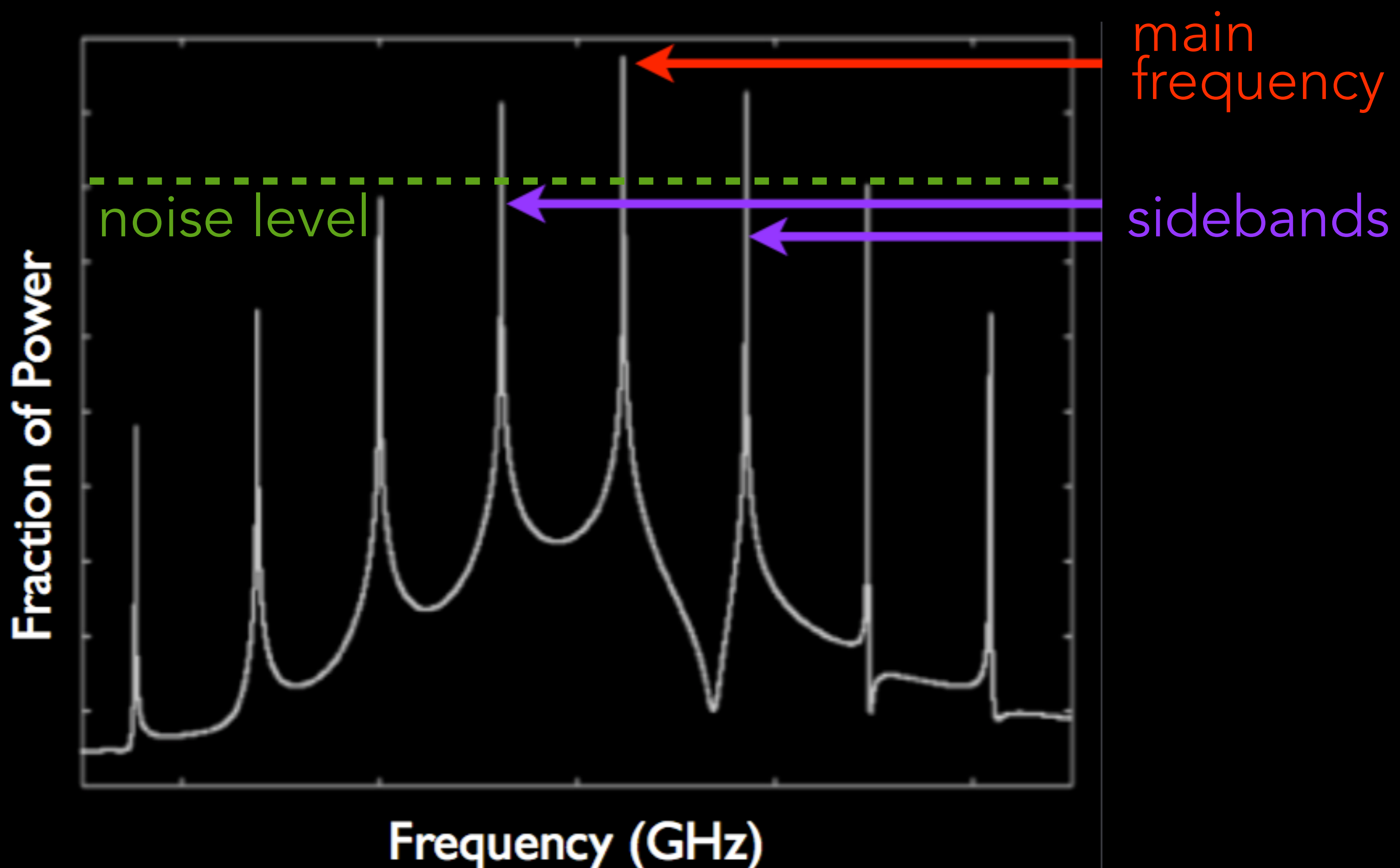
DISENTANGLING ENERGY AND ANGLE

Electron oscillates in trap

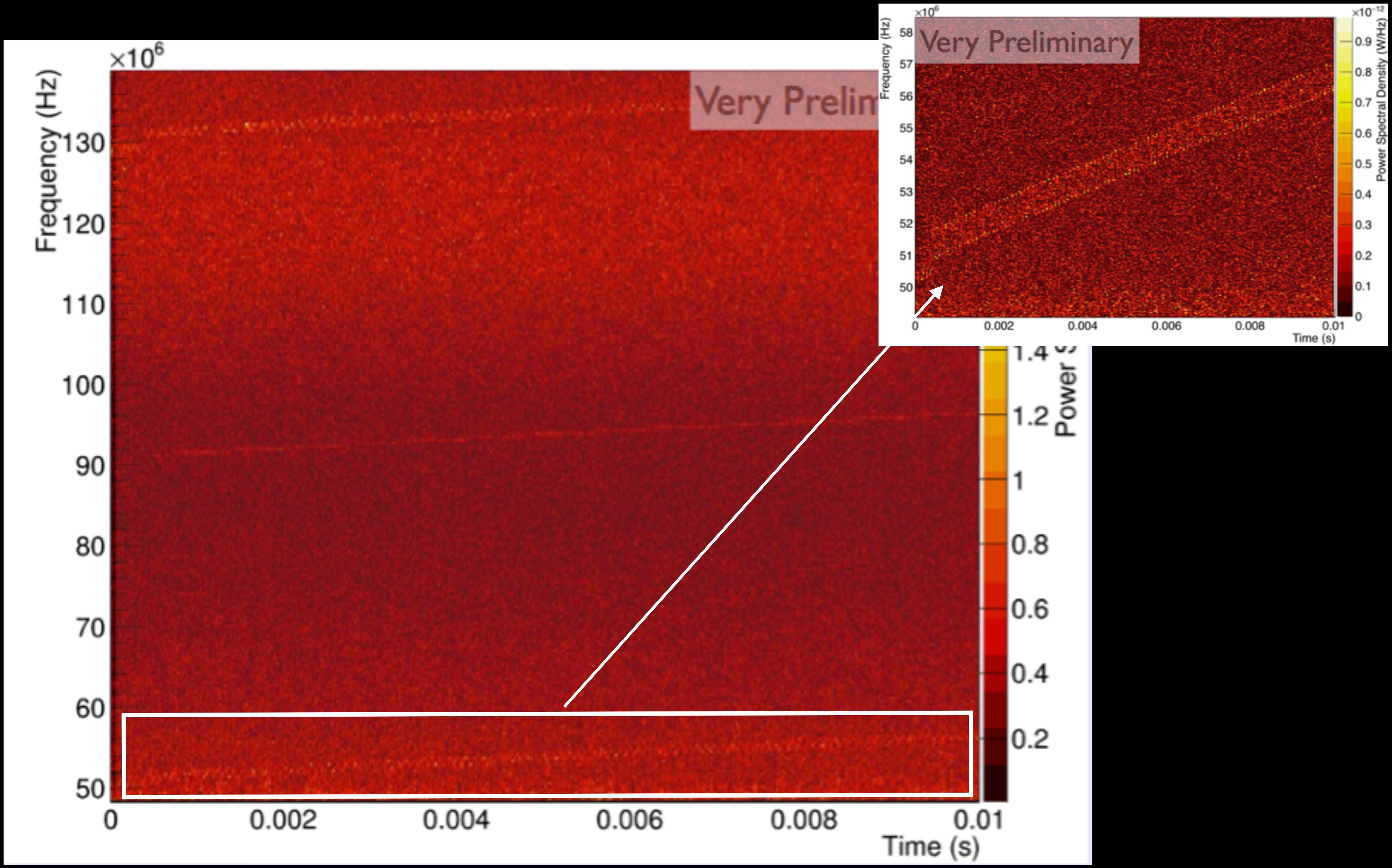
- axial mode (in harmonic trap)

$$\omega_a \propto v \left(\frac{a}{\sin\theta} + \frac{4\sin\theta}{m_e \cos^2\theta} \right)^{-1}$$

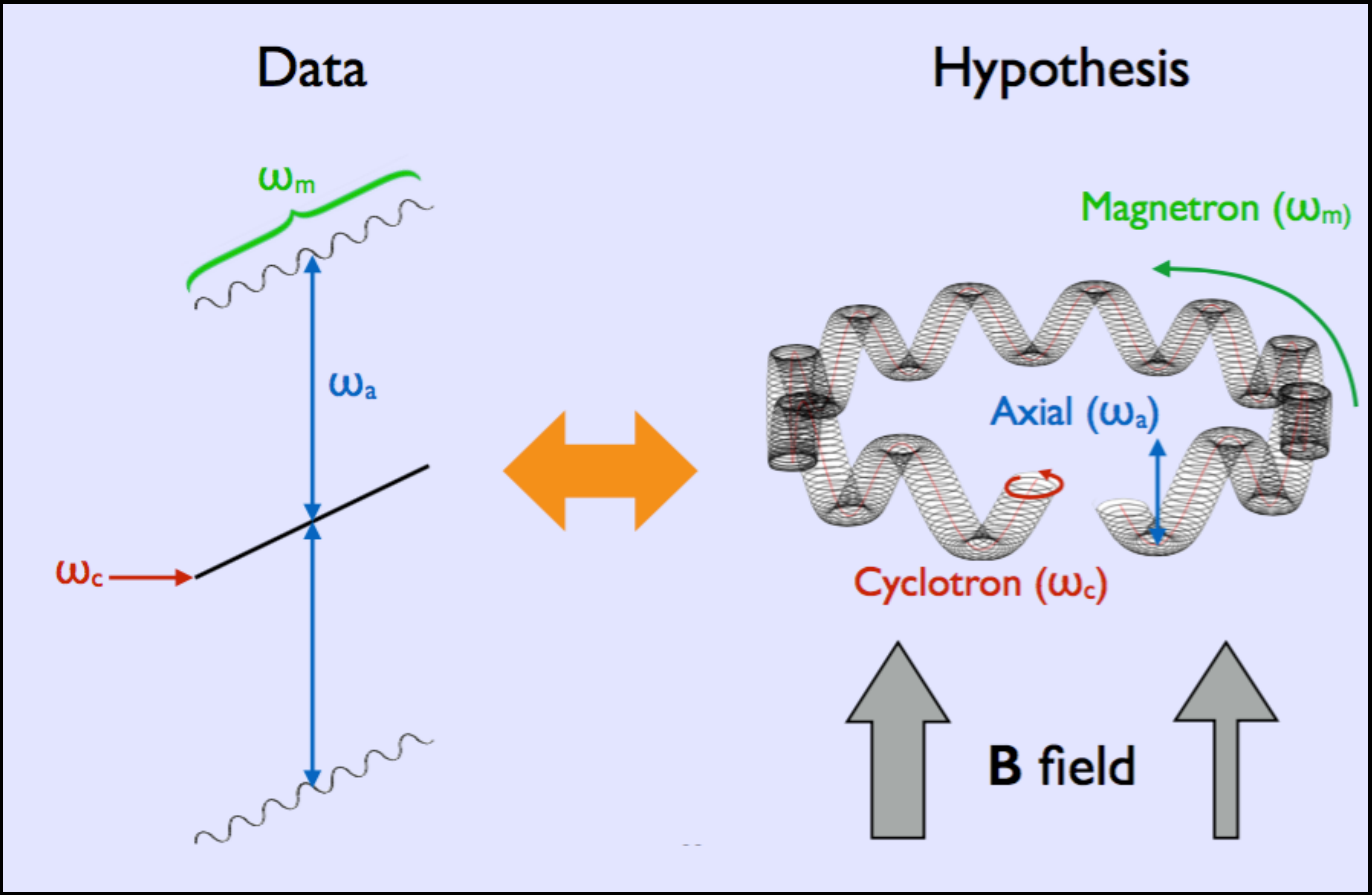
- sidebands to cyclotron peak
- distance depends on pitch angle θ



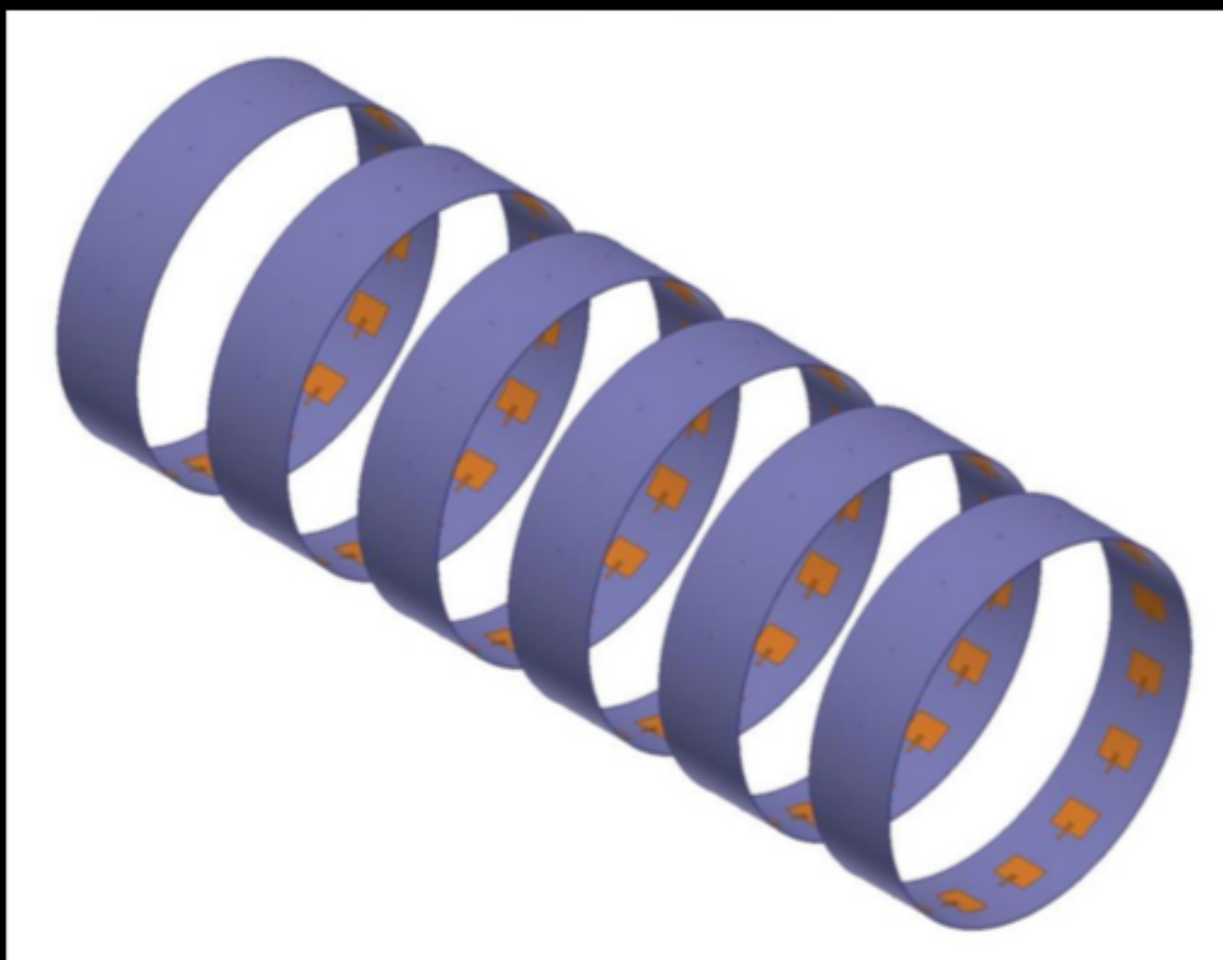
SIDEBAND OBSERVATION



THREE DEGREES OF FREEDOM



DESIGN OF ν-MASS EXPERIMENT

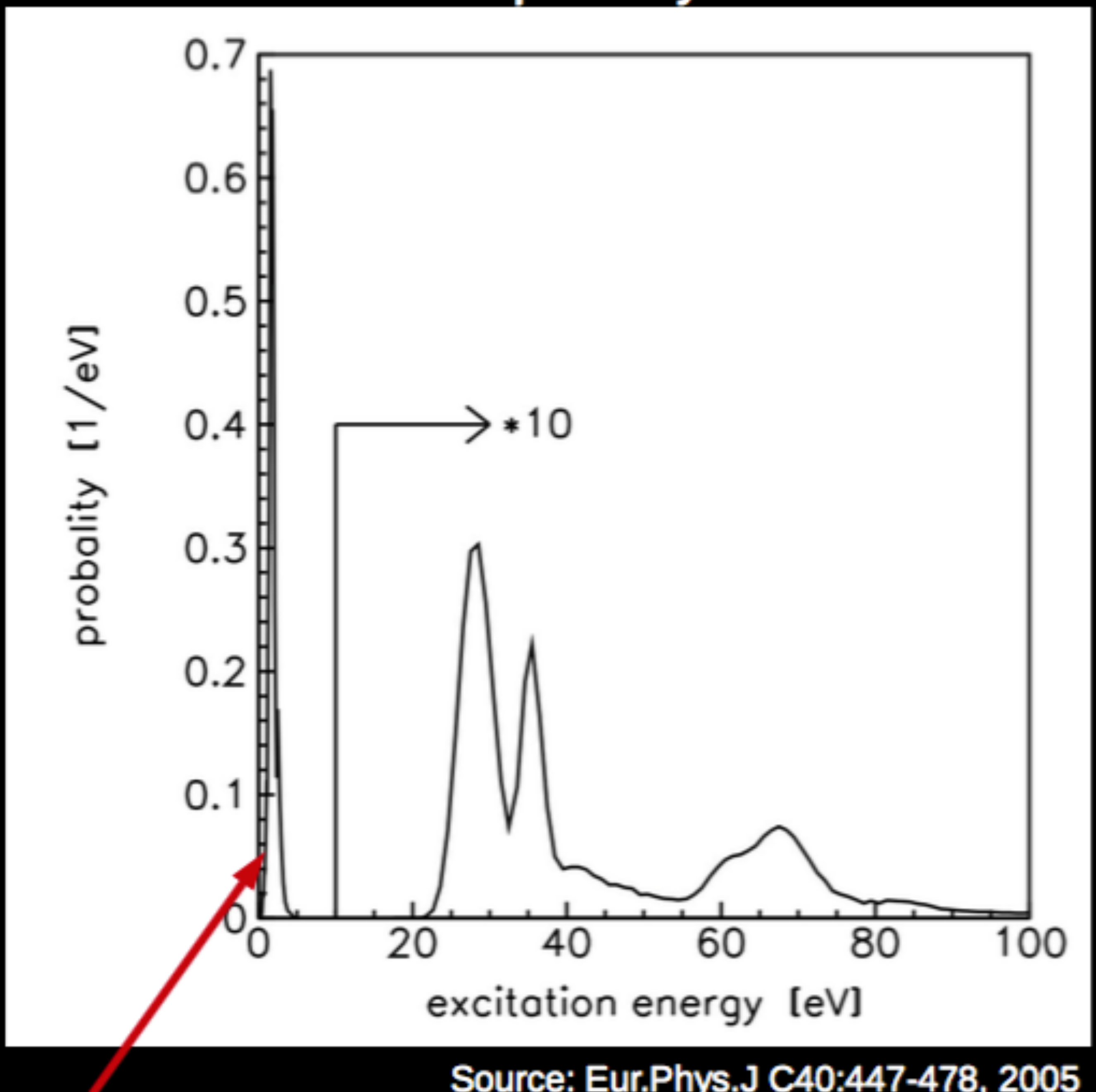


Example patch antenna configuration being modeled

- Larger bore ~1T magnet
- Pinch coils at either end
- Receiver
  - many waveguides → "rattling gun" design
  - phased array of patch antennas

MOLECULAR TRITIUM LIMITATIOINS

Excitation Spectrum from Molecular Tritium β decay



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

This is the width that matters

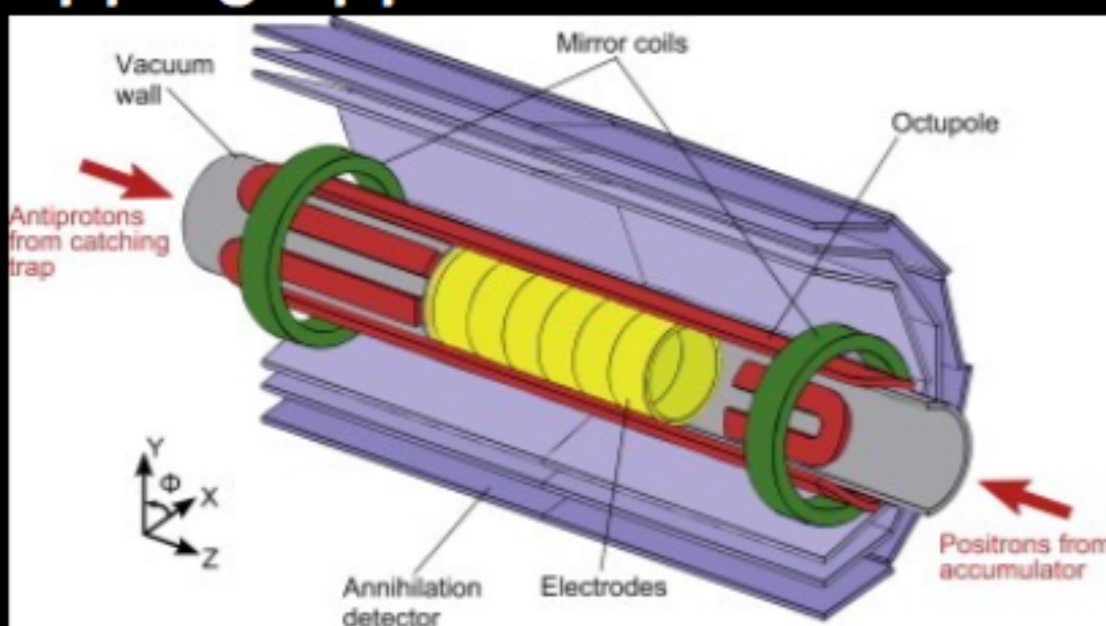
Molecular excitations

- blur tritium endpoint

→ fundamental limit to measurement of ν-mass

ATOMIC TRITIUM

Example: ALPHA antihydrogen trapping apparatus



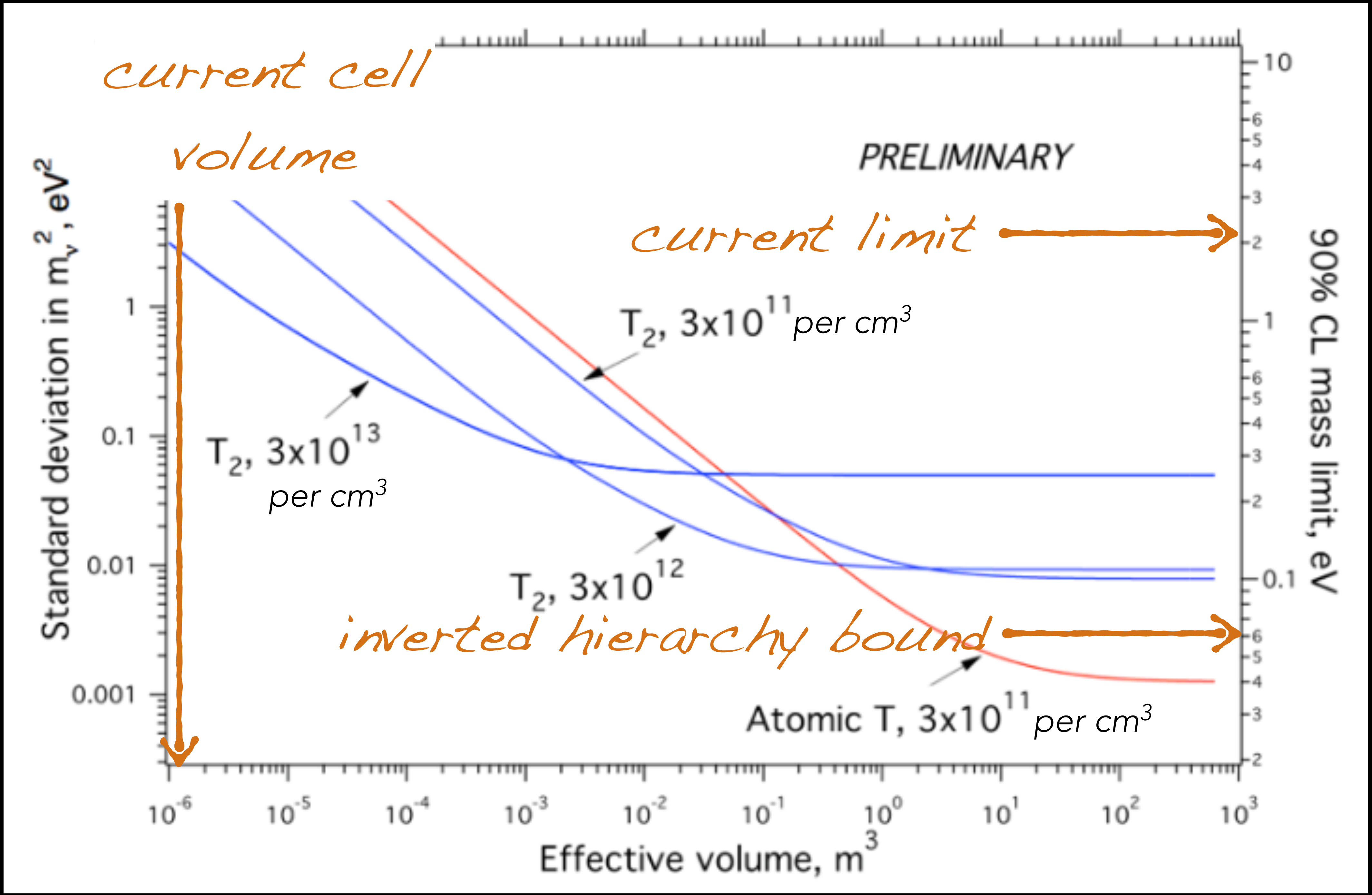
Source: Amole et al. NIM A 736, 319 (2014)

- no excited molecular states
- must be prevented from recombining

→ atomic trap superimposed on electron trap?

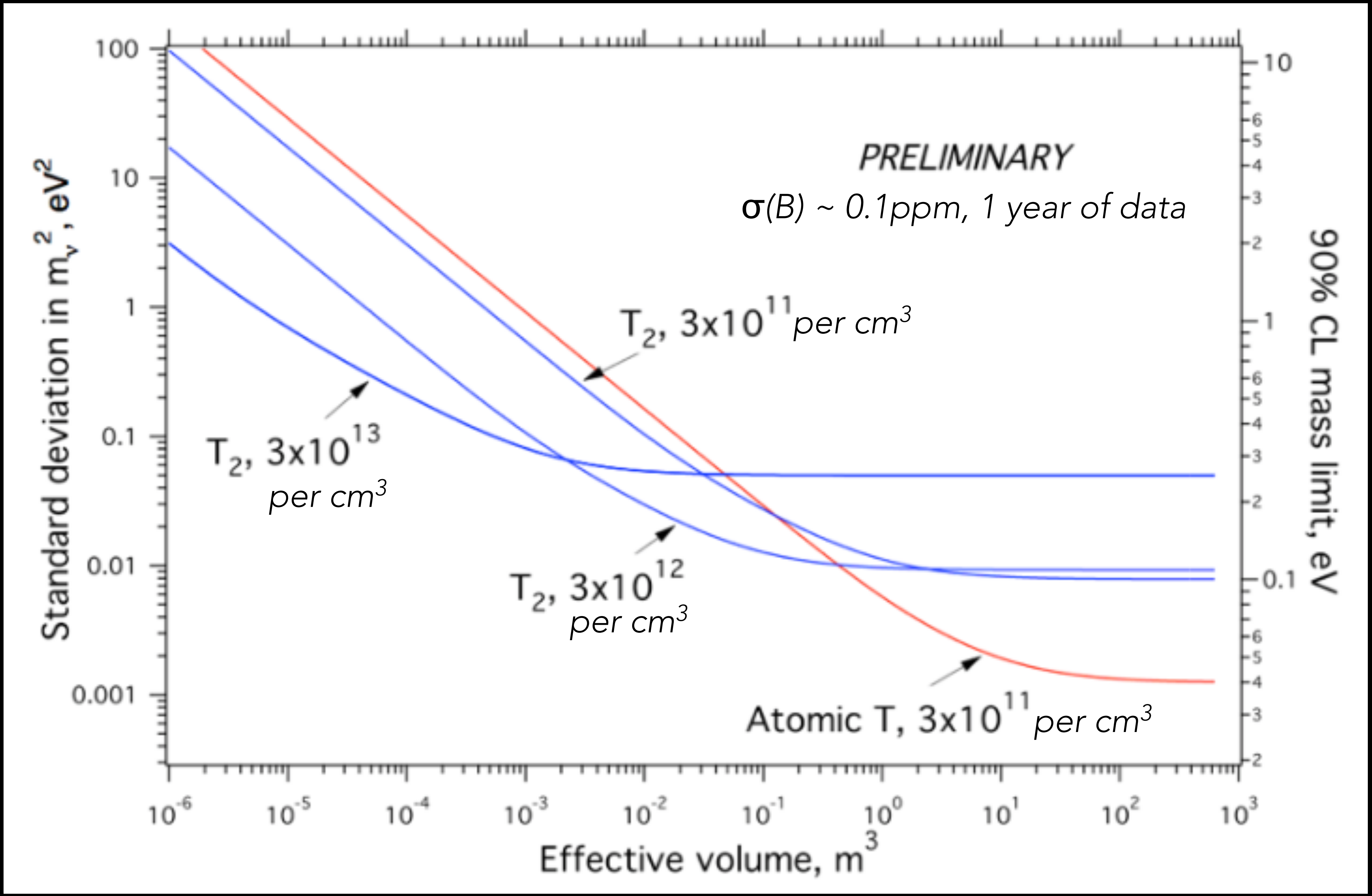
- Similar devise being build for other purposes

POTENTIAL ν-MASS REACH



Inverted hierarchy limit in reach with atomic tritium!

POTENTIAL ν-MASS REACH



Sensitivity limited by gas density!

SUMMARY

Project8:

- new technology: CRES - Cyclotron Radiation Emission Spectroscopy

Next step

- measure full tritium spectrum
  → completely new gas system

Longer-term future

- large scale limited by density and molecular excitations → atomic tritium source

PROJECT 8 COLLABORATION

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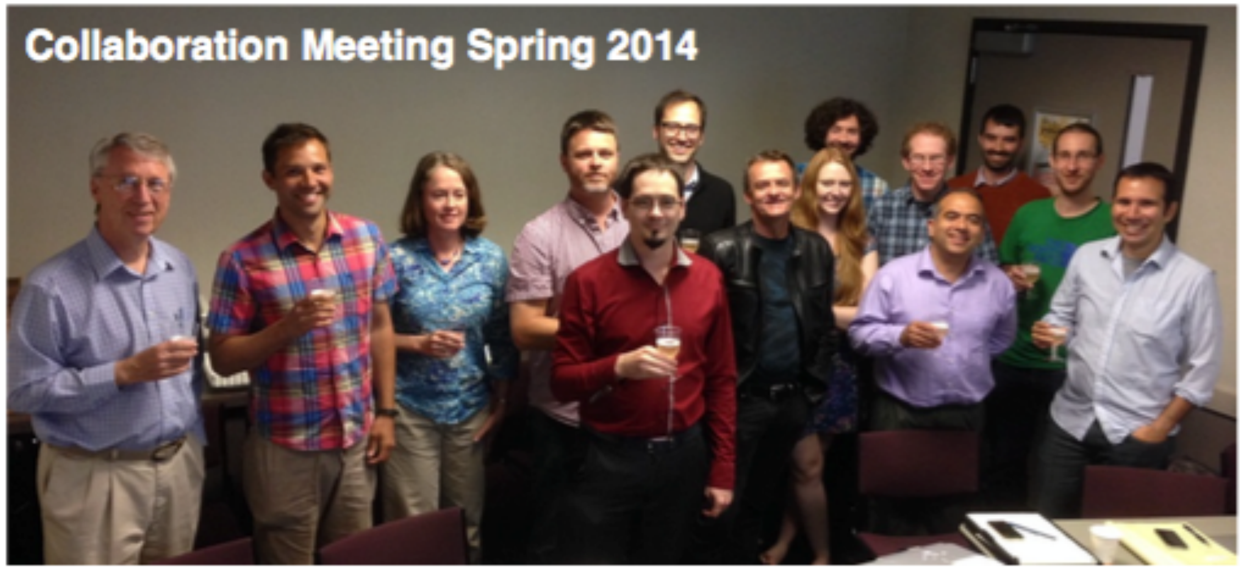

http://www.project8.org/