CRES — A NEW METHOD TOWARDS MEASURING THE ν-MASS

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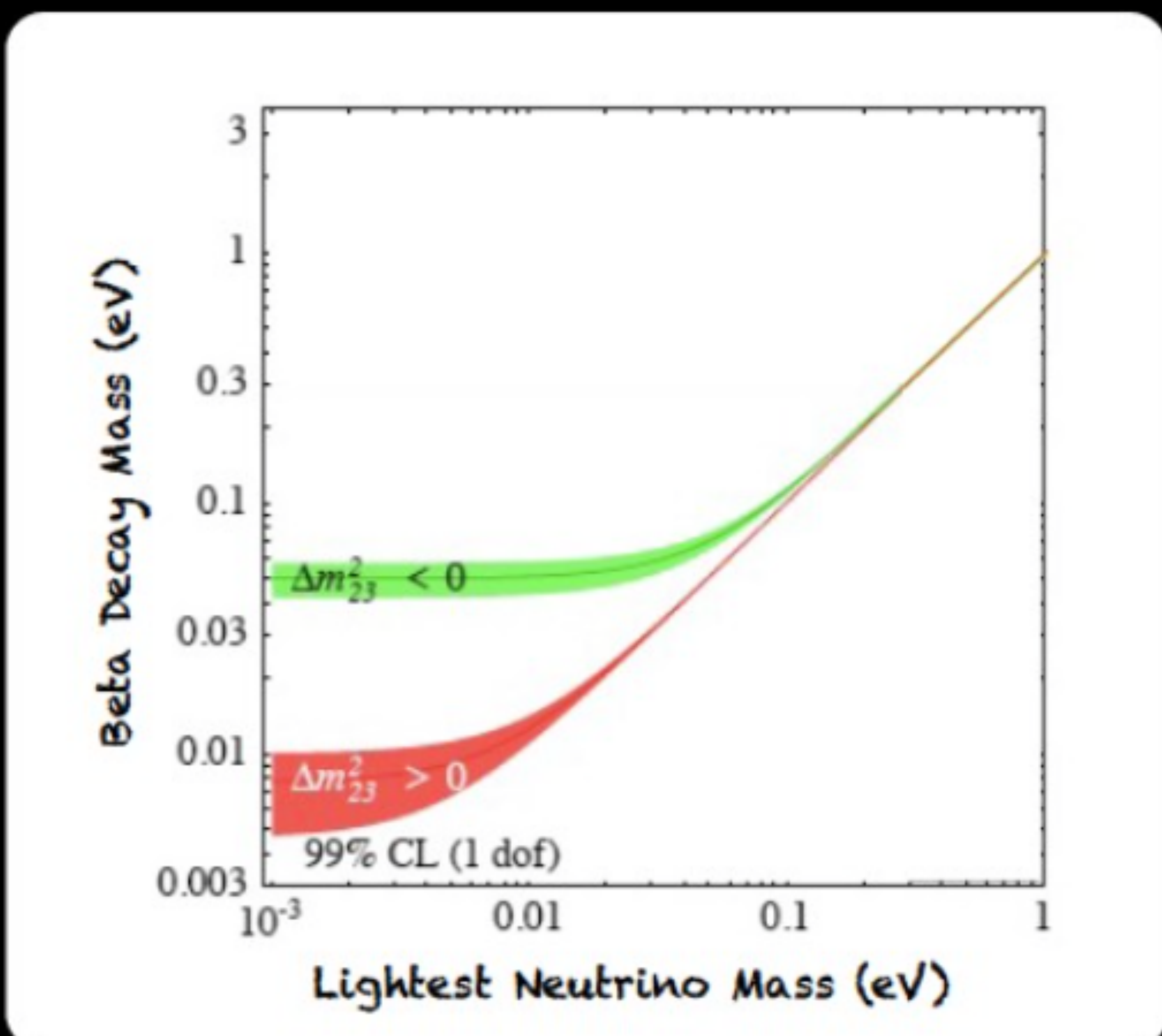
7TH JUNE 2016 | GDR NEUTRINO 2016 | GRENOBLE

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

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

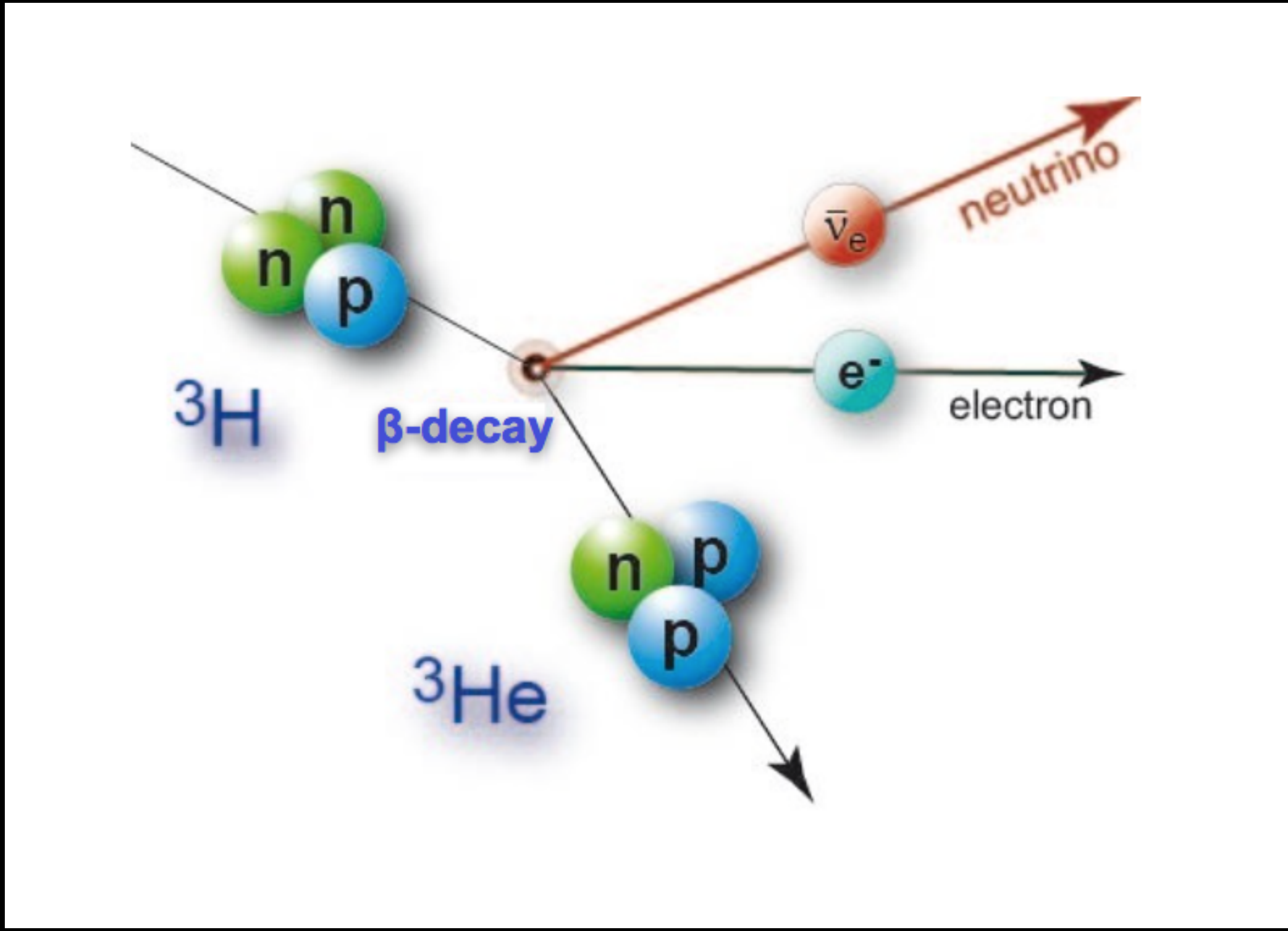
0νββ Measurements

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

Beta Decay Measurements

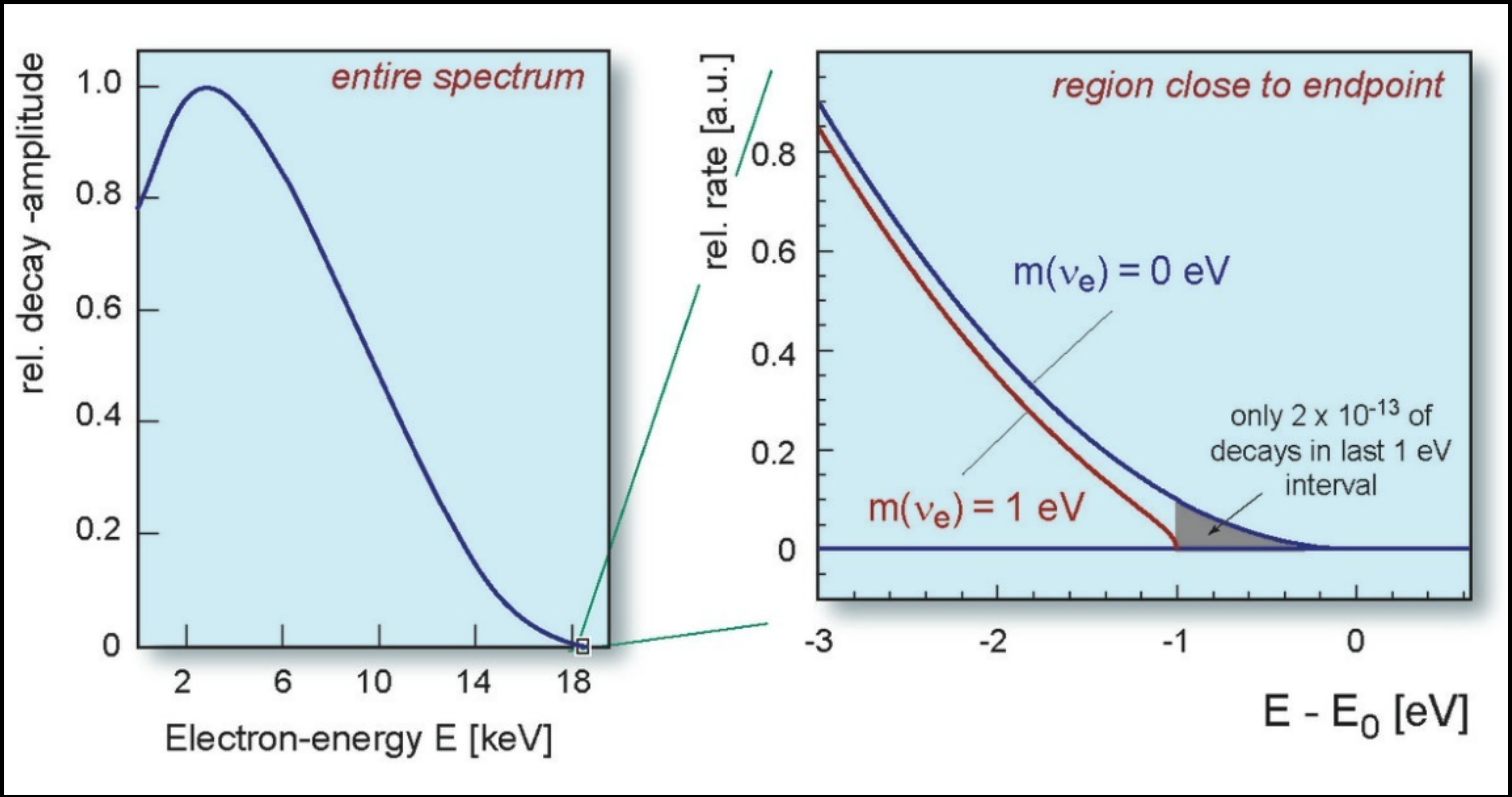
TRITIUM BETA-DECAY

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



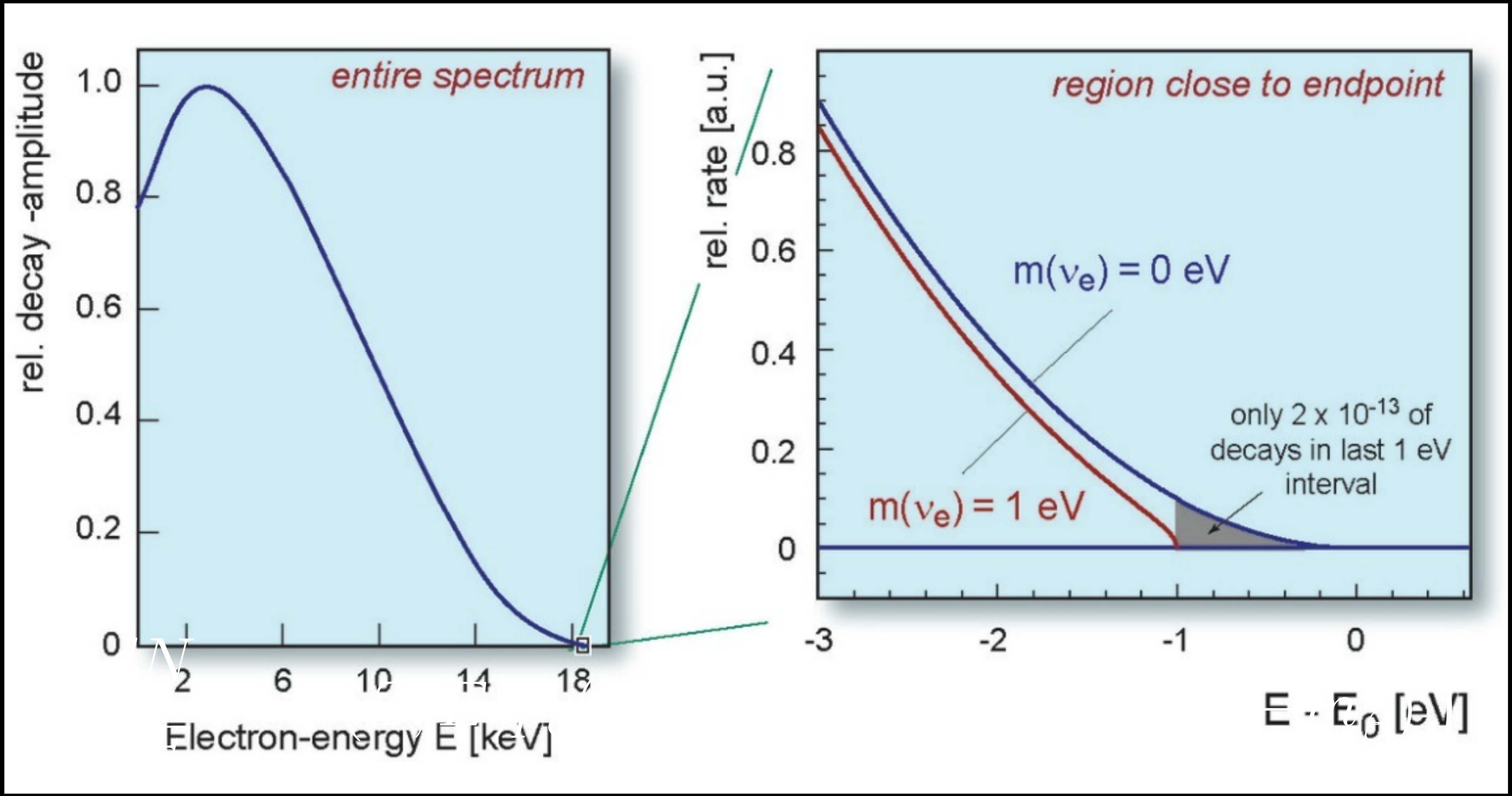
- Sum of masses and kinetic energy must add up to mass of initial nucleus

TRITIUM BETA-SPECTRUM



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

TRITIUM BETA-SPECTRUM

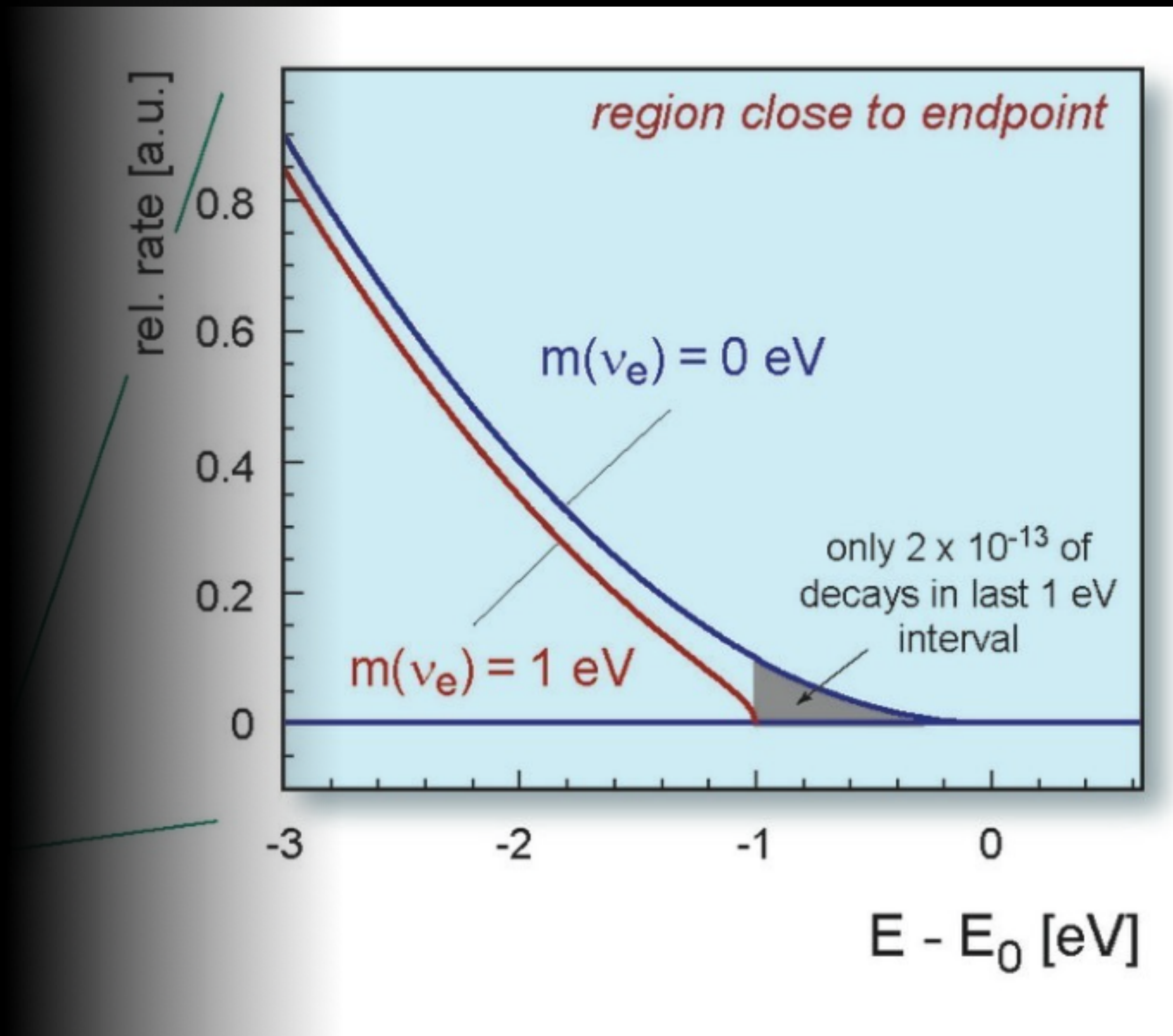


Endpoint of spectrum changes with ν-mass

→ direct measurement of mass
(independent of "nature" of mass)

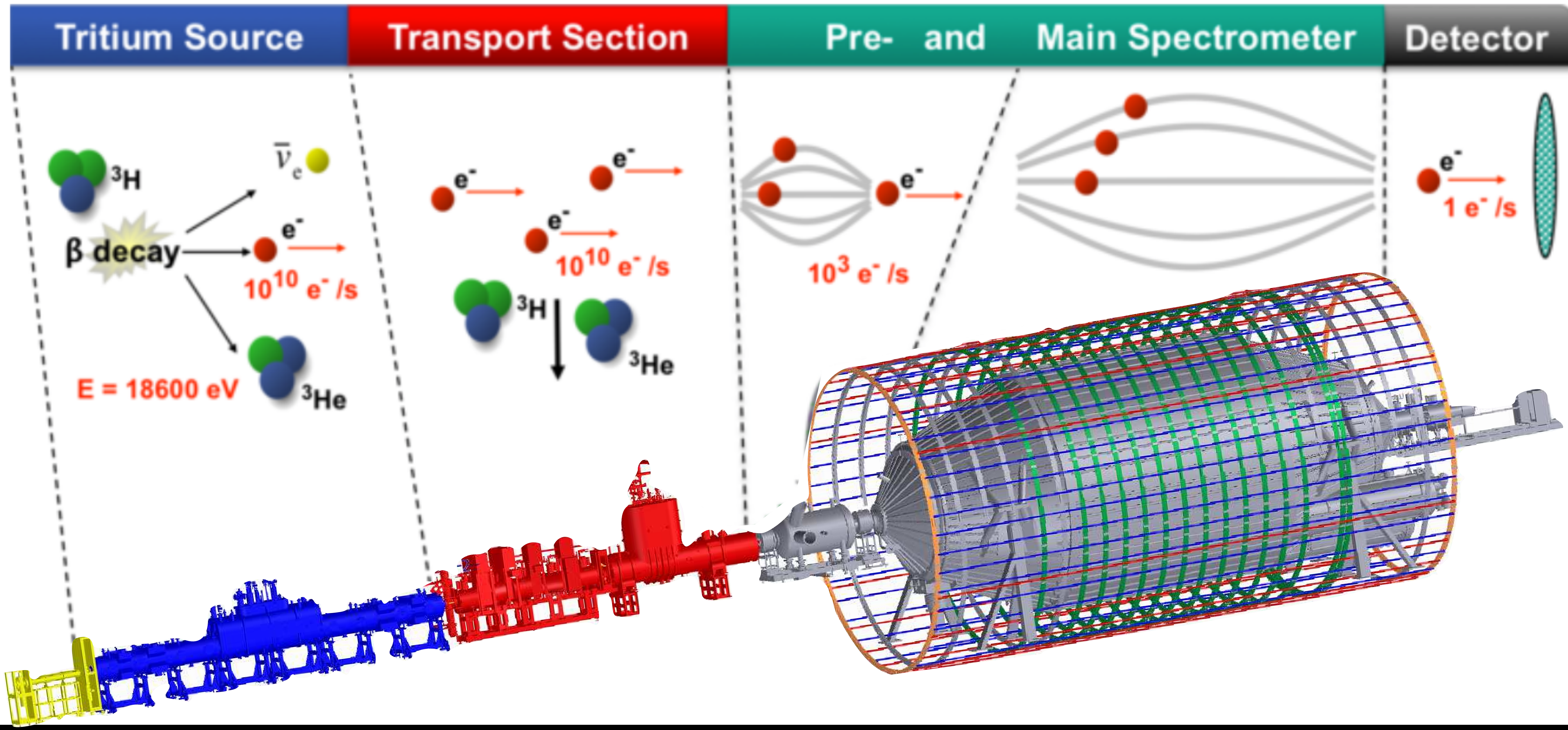
TRITIUM BETA-SPECTRUM

- 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 of nature of mass)

STATE OF THE ART — KATRIN



Key component: MAC-E filter

- align e$^-$ momentum $p_\perp \to p_\parallel$

KATRIN
Karlsruhe Trititum Neutrino Experiment

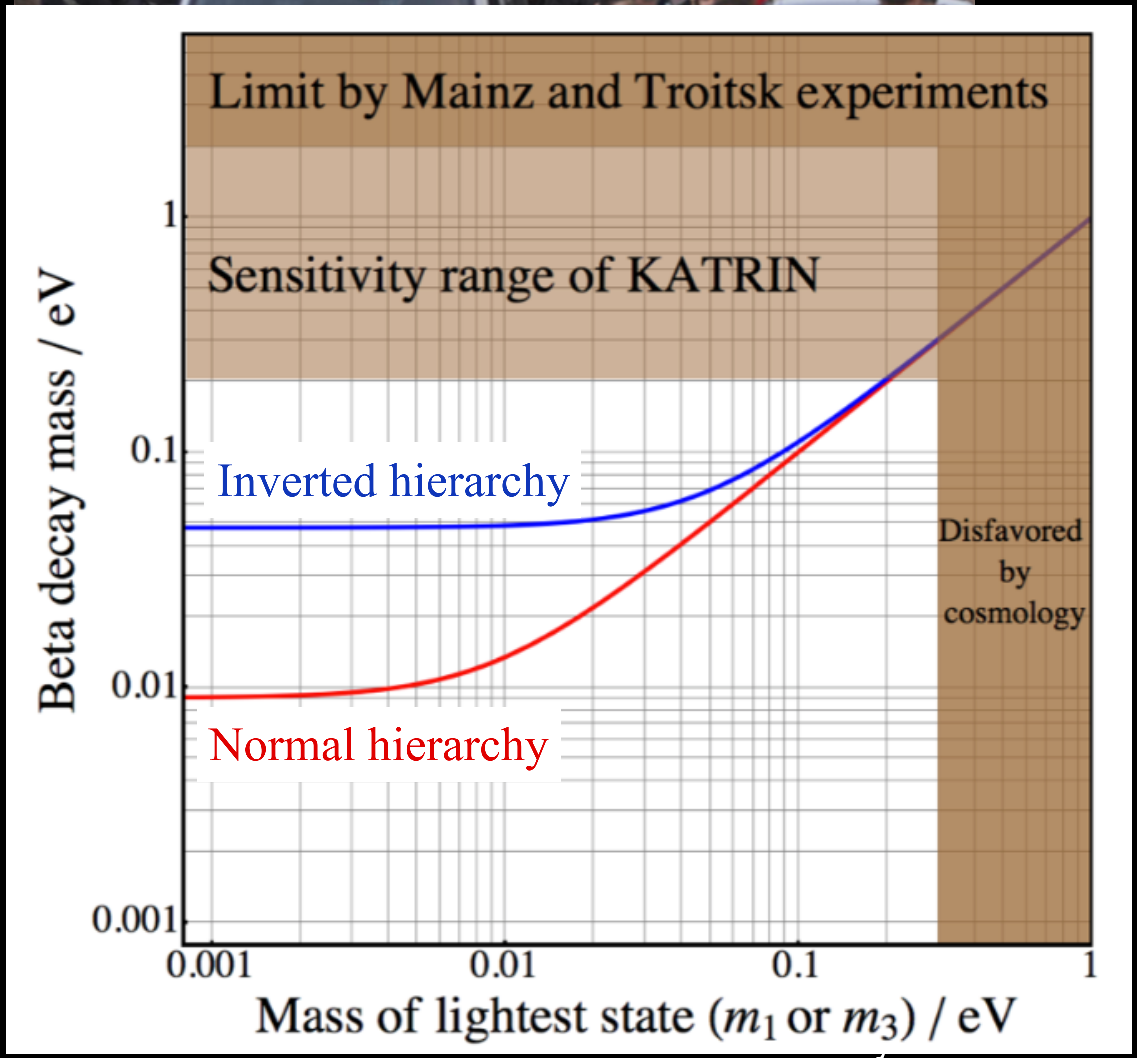
Sensitivity goal

- $m_\beta < 200\text{meV}$

Limited by

- size of spectrometer
- systematic effects

➔ need a new and complementary approach



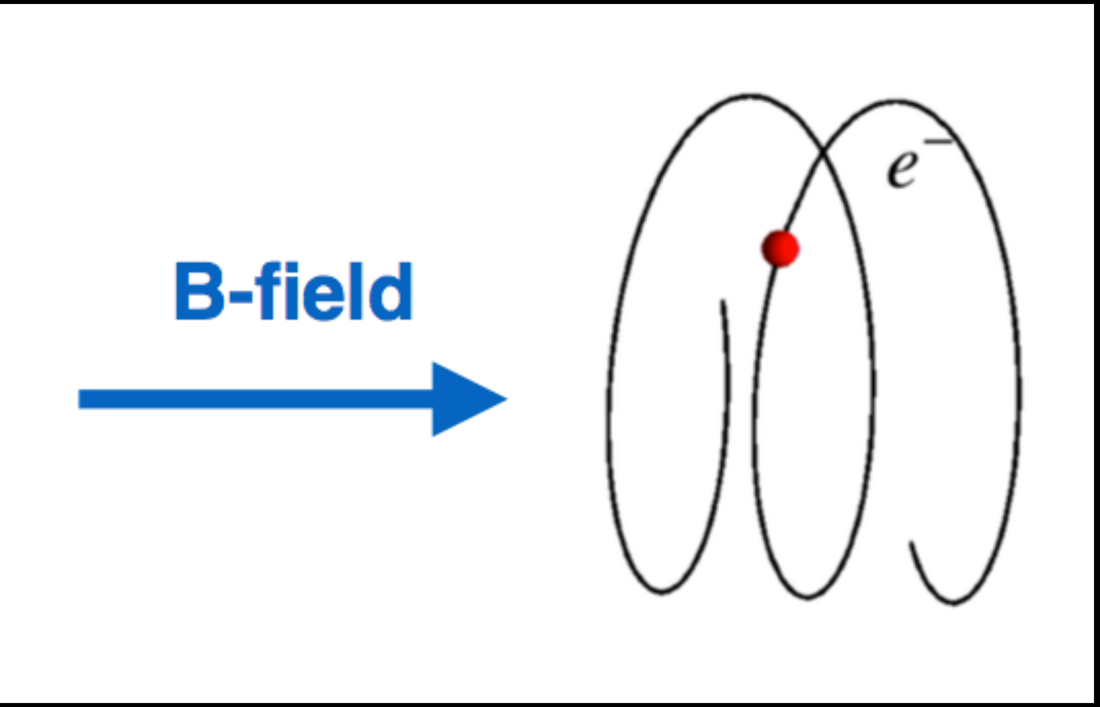
CYCLOTRON RADIATION

Cyclotron radiation

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

relativistic correction

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



"*Never measure anything but frequency*" - A. L. Schawlow

RESOLUTION

Energy resolution

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

- $\Delta E/E \sim 1\text{eV} / 511\text{ keV} = 2\text{ppm}$
  → easy!

Frequency resolution

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

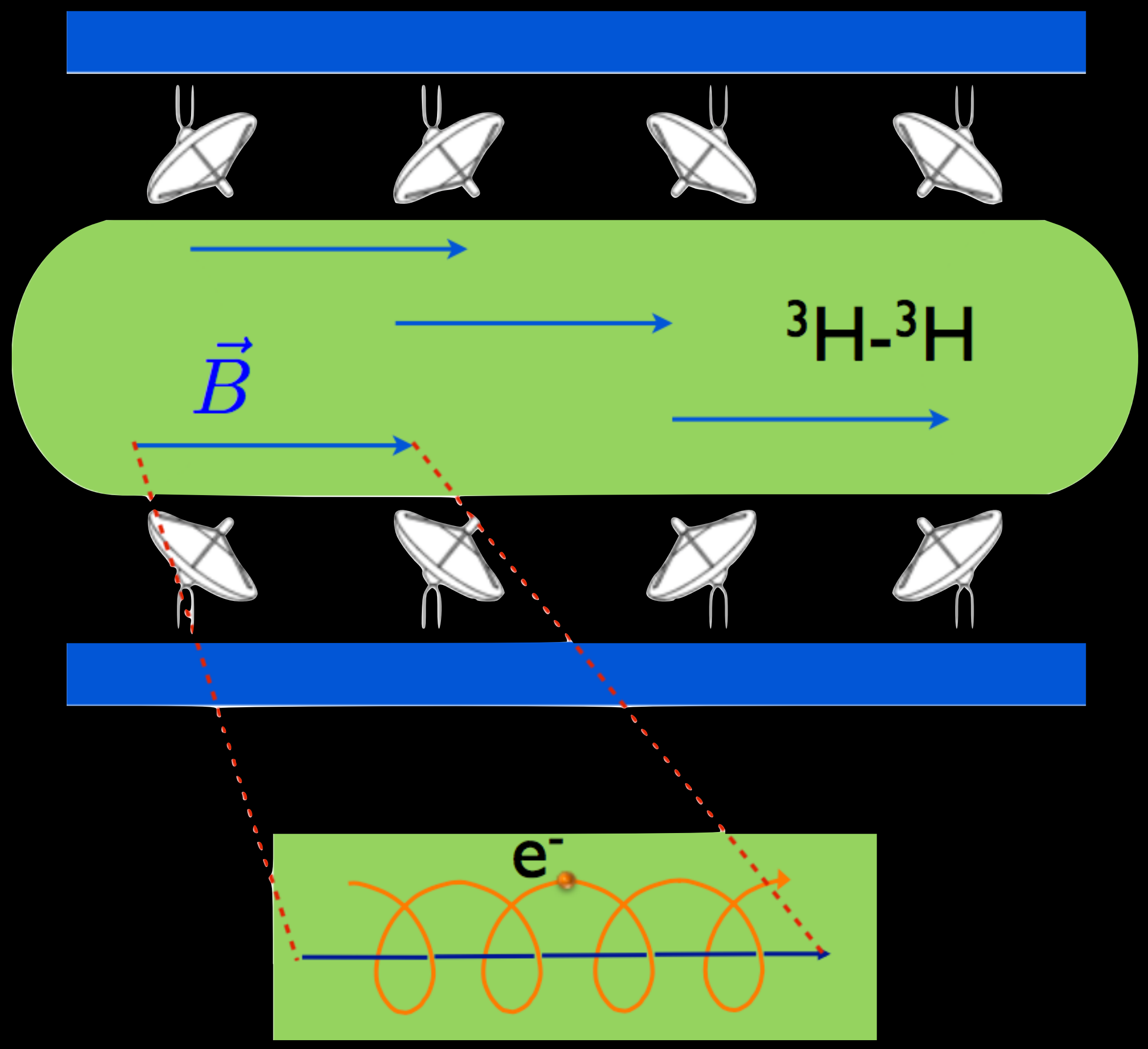
- $\Delta t = 20\mu s \sim 1400\text{m}$ @ 18keV
  → hard!

A. L. Schawlow

PROJECT 8

Idea

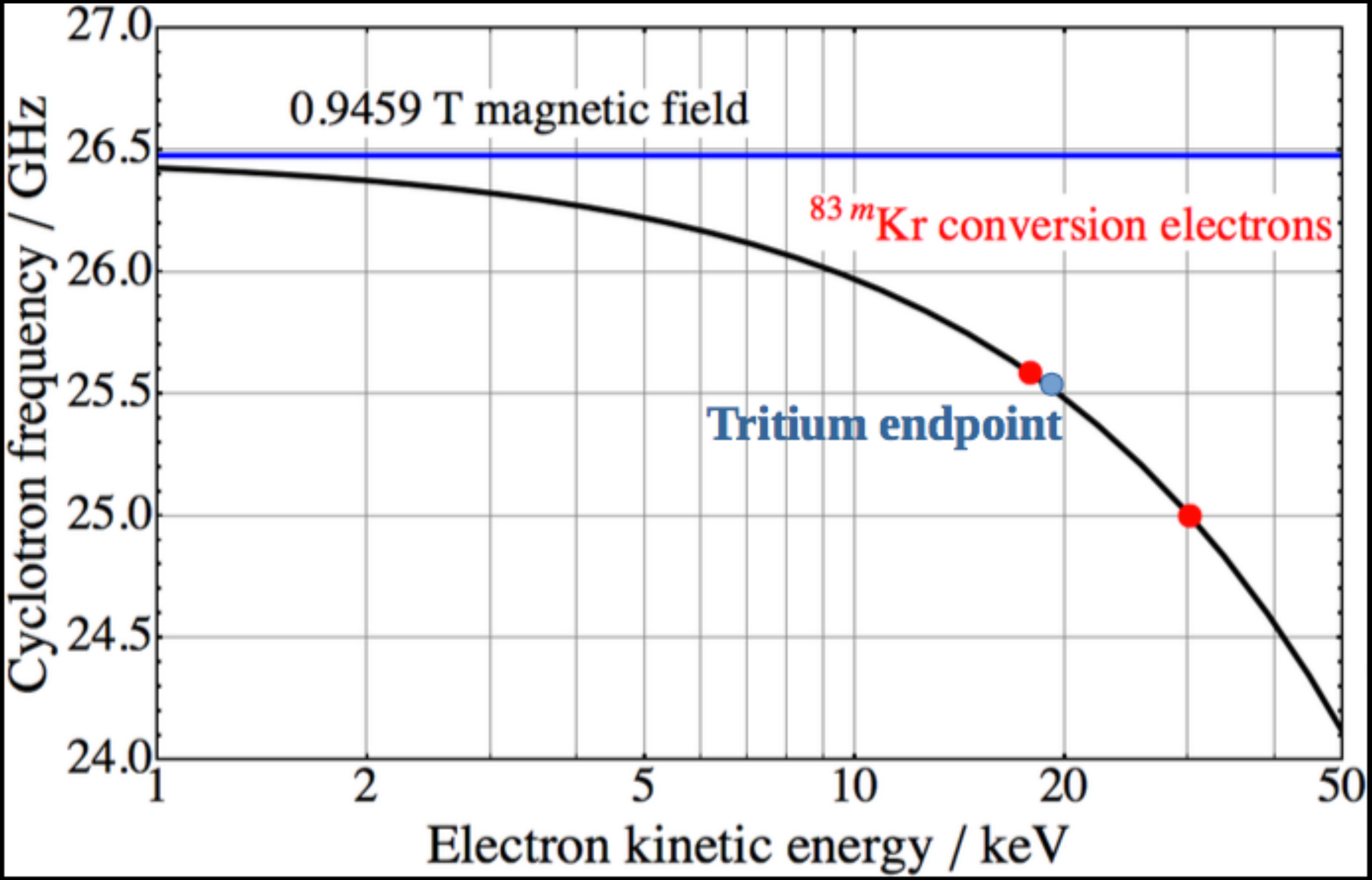
- fill volume with ^3H gas
- add magnetic field
- decay electrons spiral around field lines
- add antennas to detect cyclotron radiation



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

FREQUENCY SCALE

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

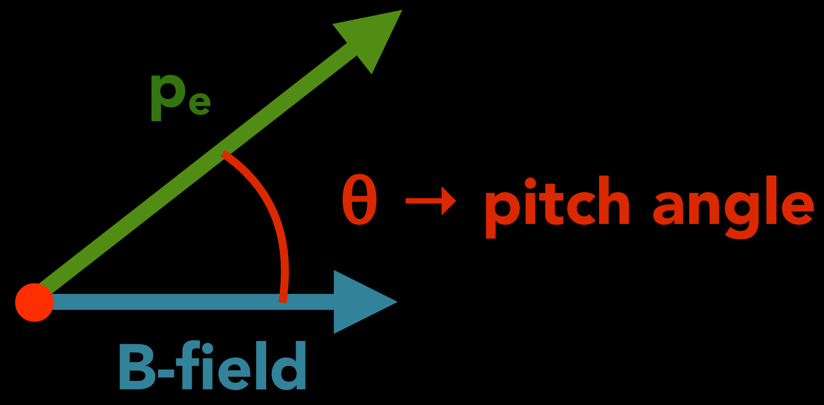


^{83m}Kr provides electrons close to tritium endpoint

RADIATED POWER

Larmor formula

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



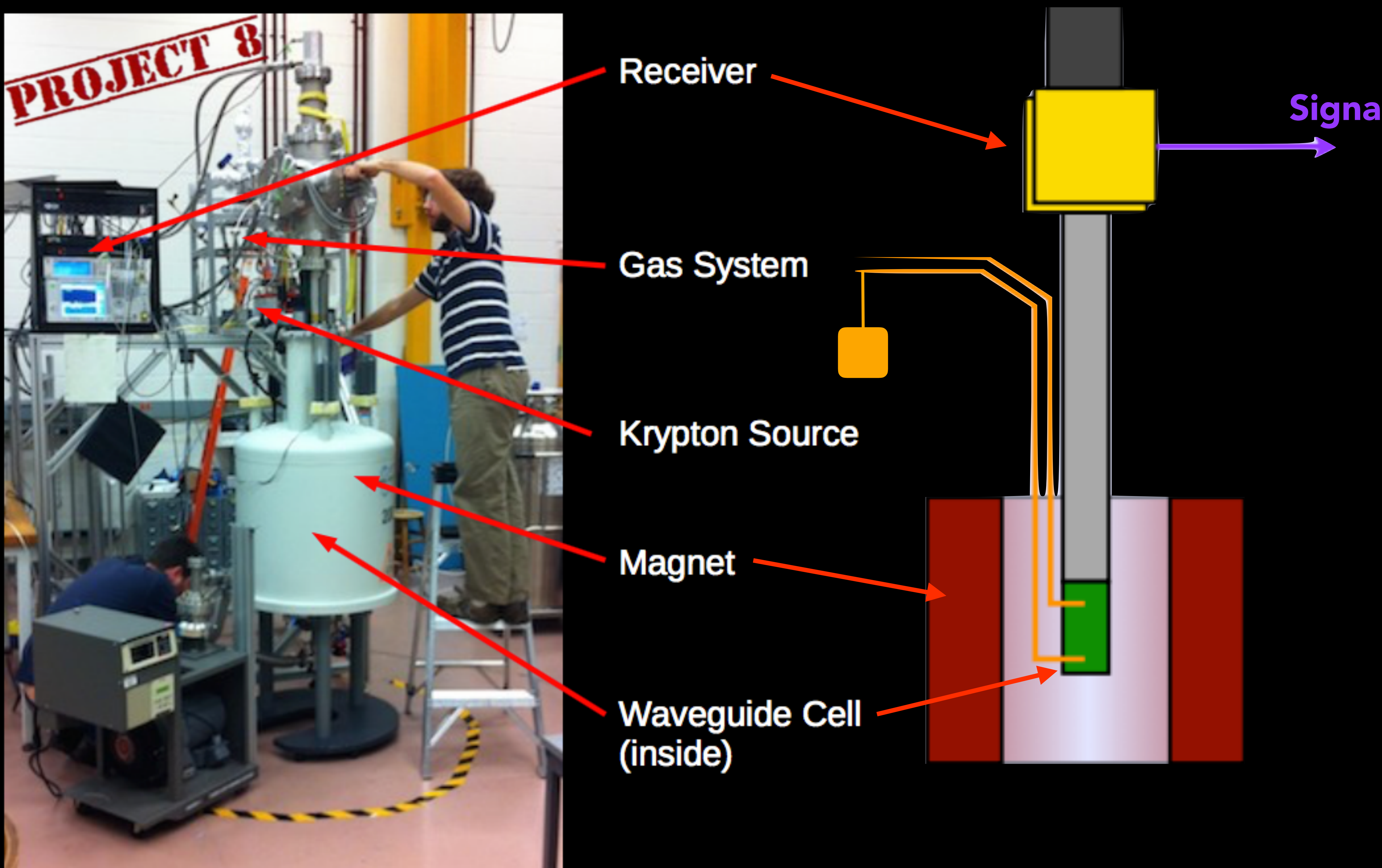
Emitted power

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

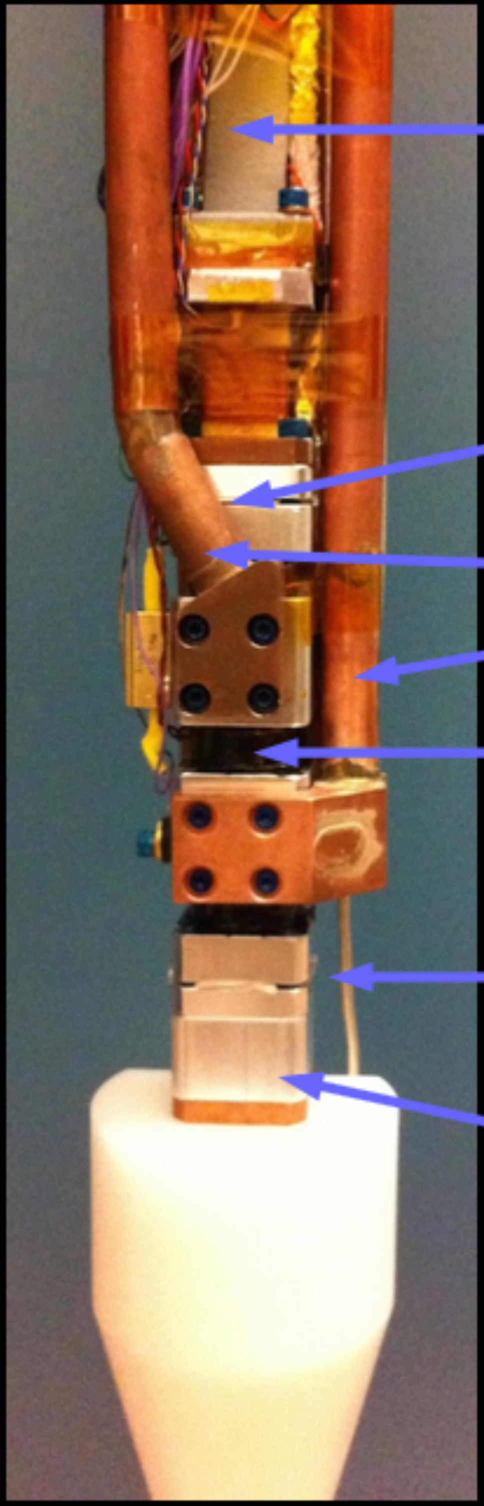
→ Low-noise cryogenic RF-system needed!

University of Washington

PROJECT8 PROTOTYPE



WAVEGUIDE CELL



Waveguide to amplifiers

Cell upper window

Gas Lines

Magnetic Bottle Coil

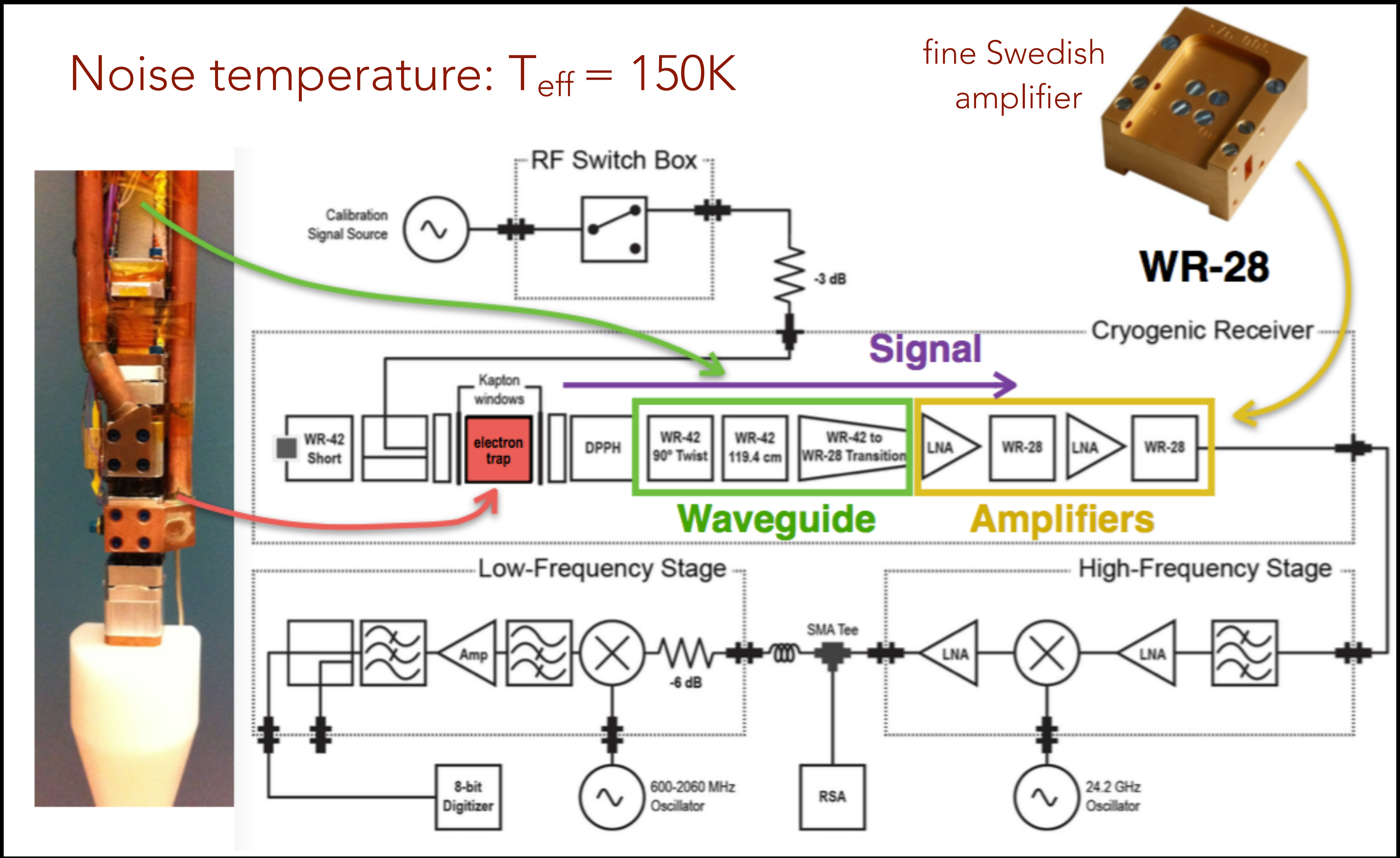
Cell lower window

Test signal injection port

SIGNAL AMPLIFCATION AND NOISE

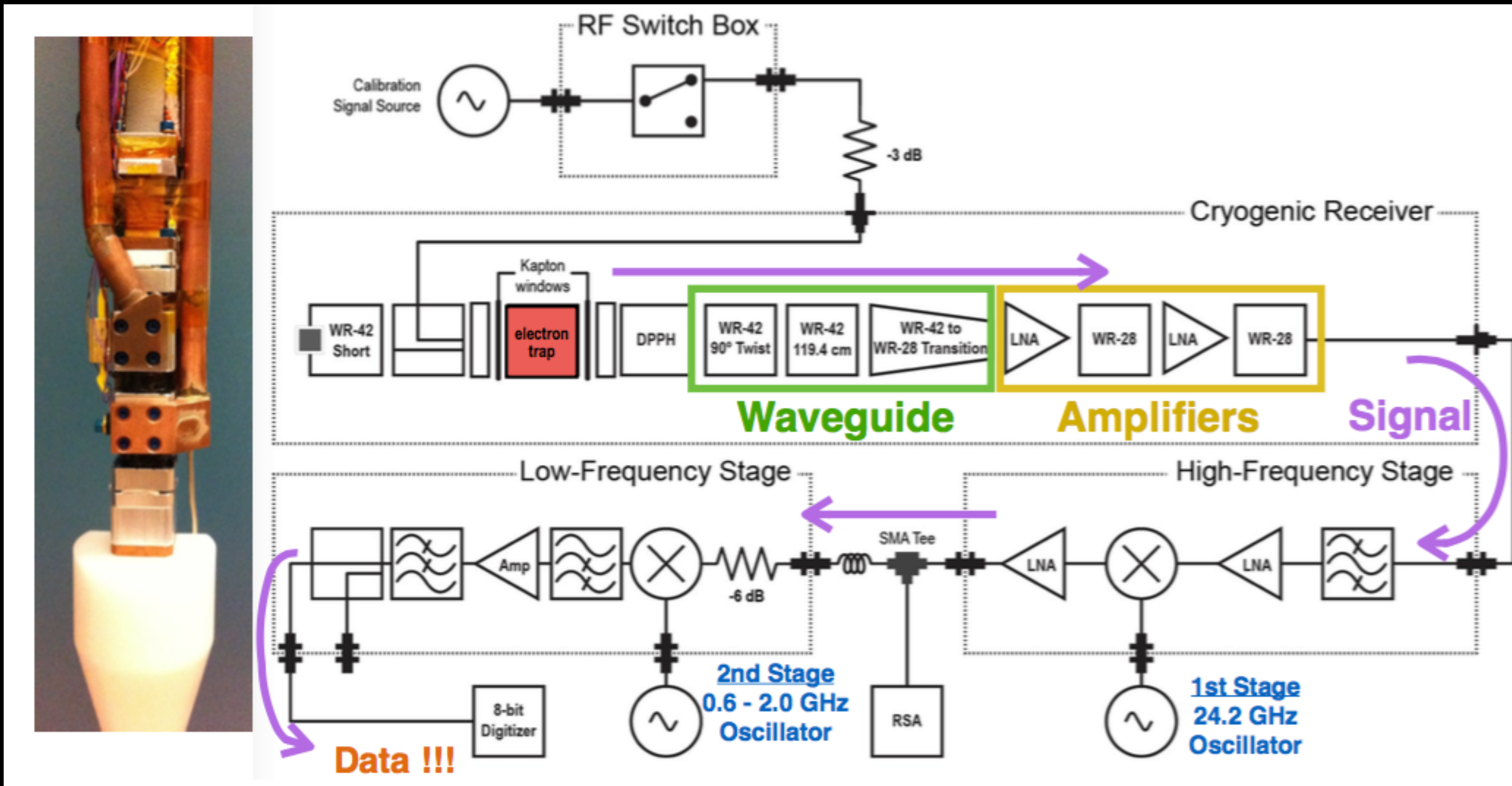
Noise temperature: T_{eff} = 150K

fine Swedish amplifier



- Primary background
  → thermal noise from waveguide and amplifiers

RECEIVER STAGE

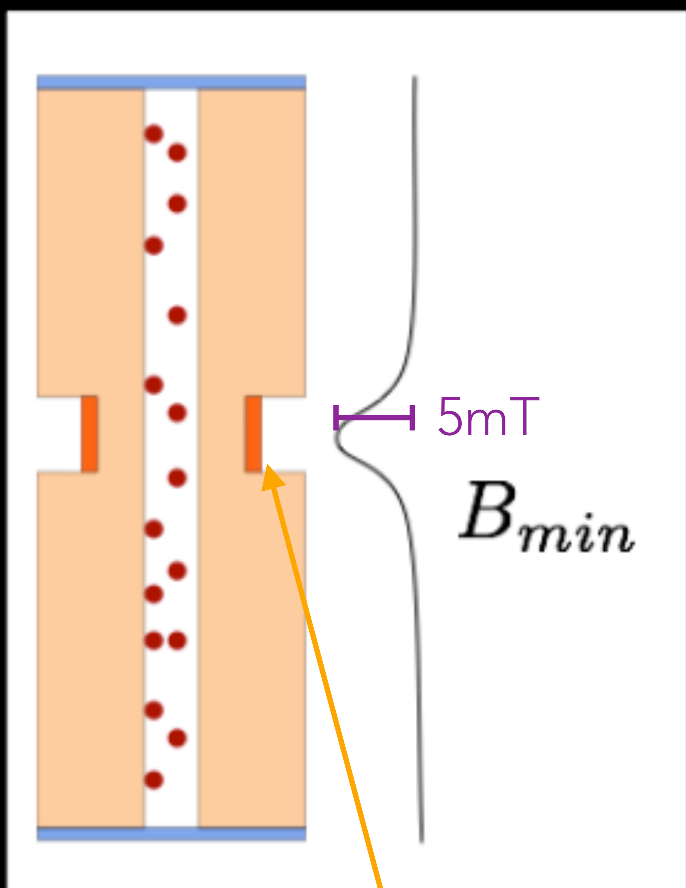


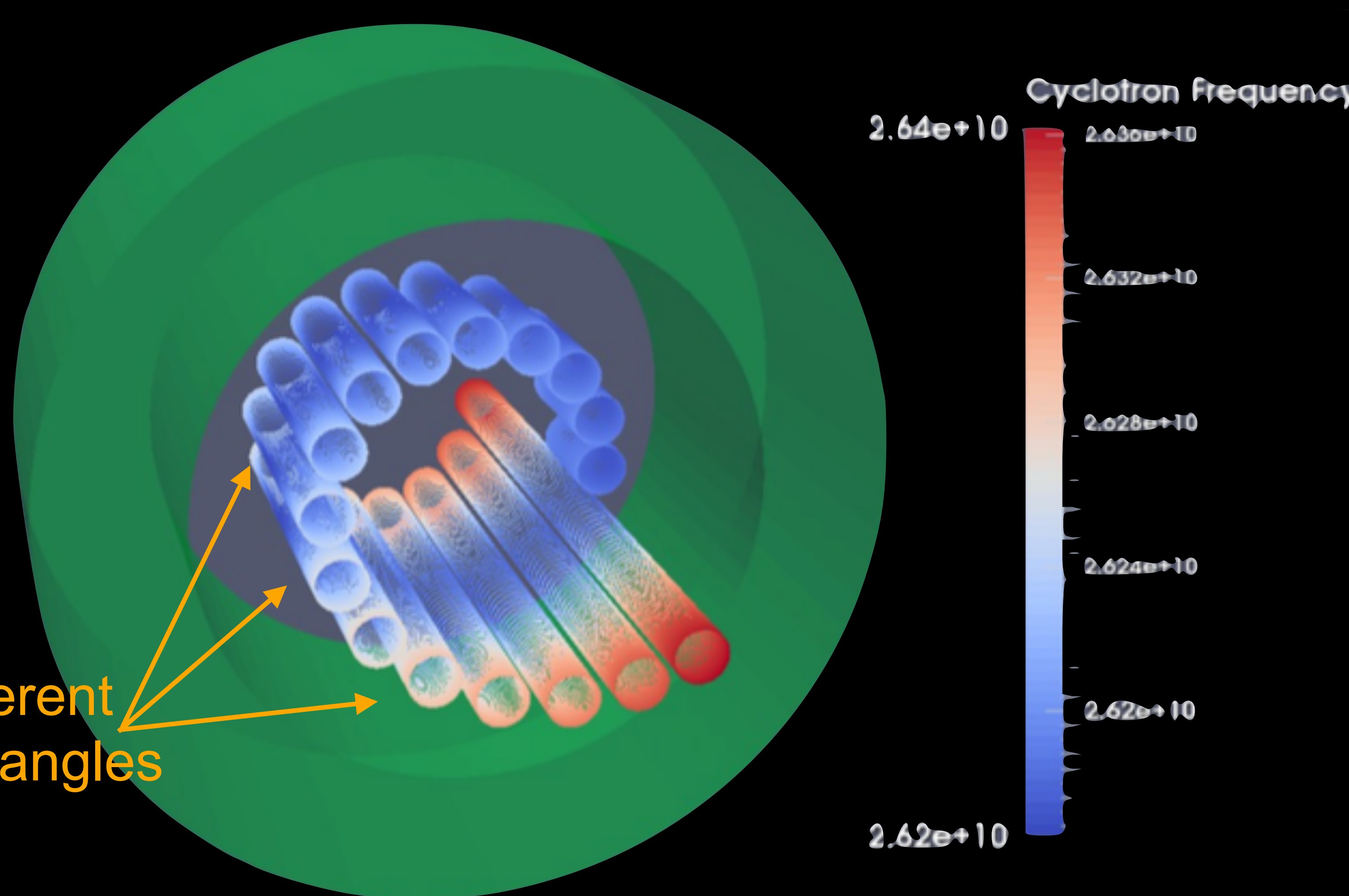
- Double-stage down-mixing
- Digitizer: 8-bit, 500Ms/s, 125MHz bandwidth
  → untriggered

MAGNETIC BOTTLE

Harmonic e⁻ trap →

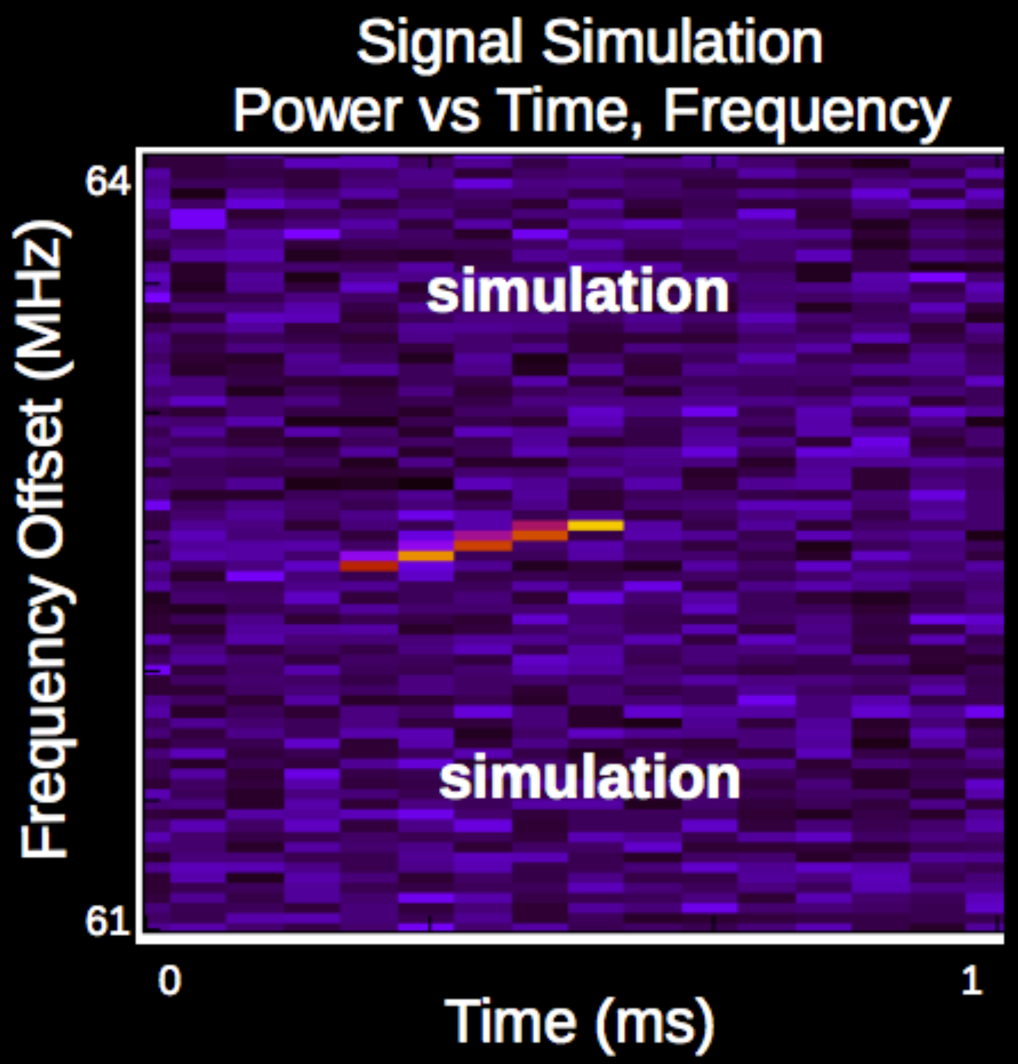
$$f_\gamma = \frac{f_c}{\gamma} = \frac{1}{2\pi}\frac{eB}{m_e + E_{\text{kin}}}\left(1 + \frac{\cot^2\theta}{2}\right)$$





Effect of trap on measured frequency easily calculable!

EXPECTED SIGNAL



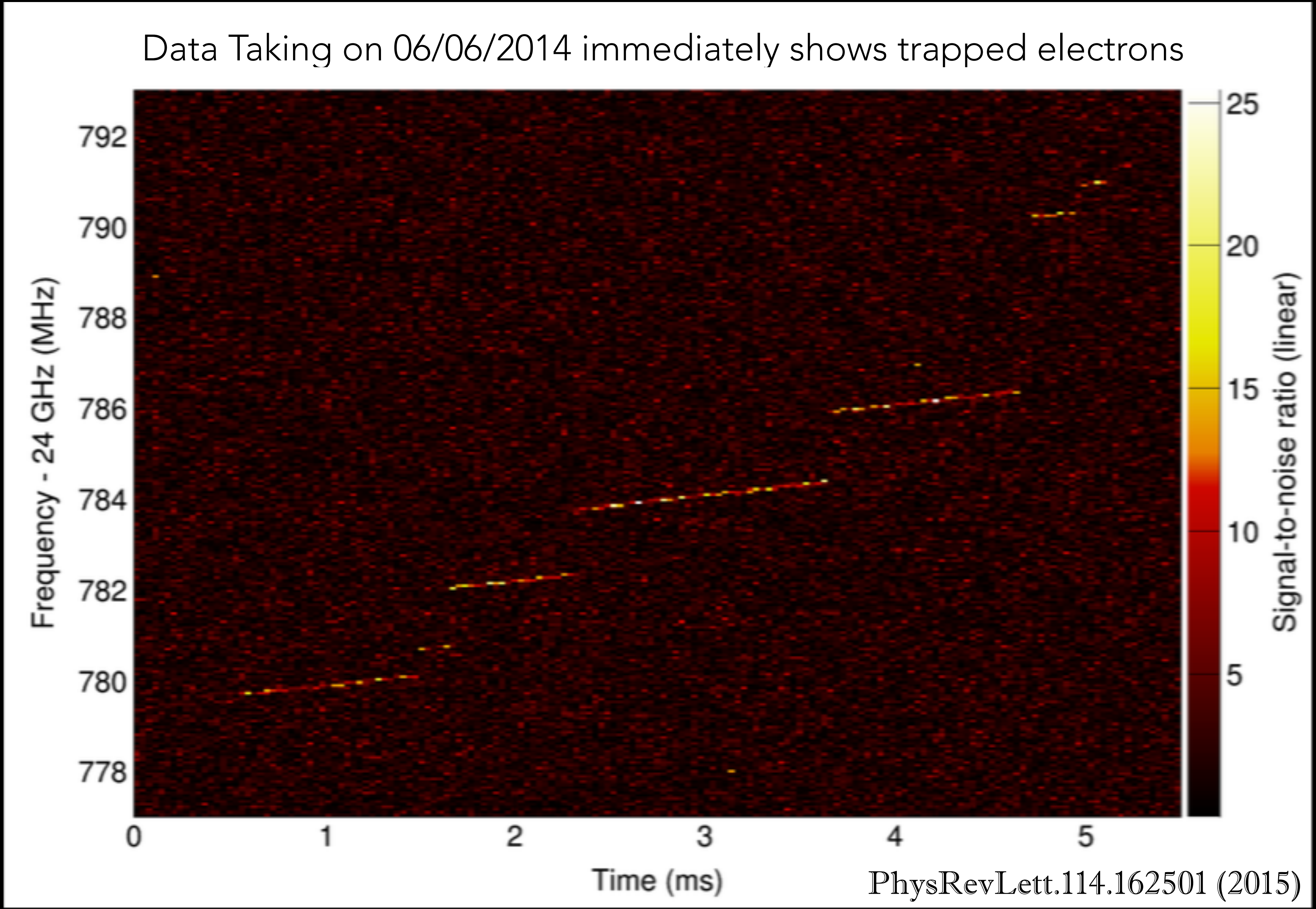
Spectrogram

- time slices
  → consecutive
  power spectrum

Signal

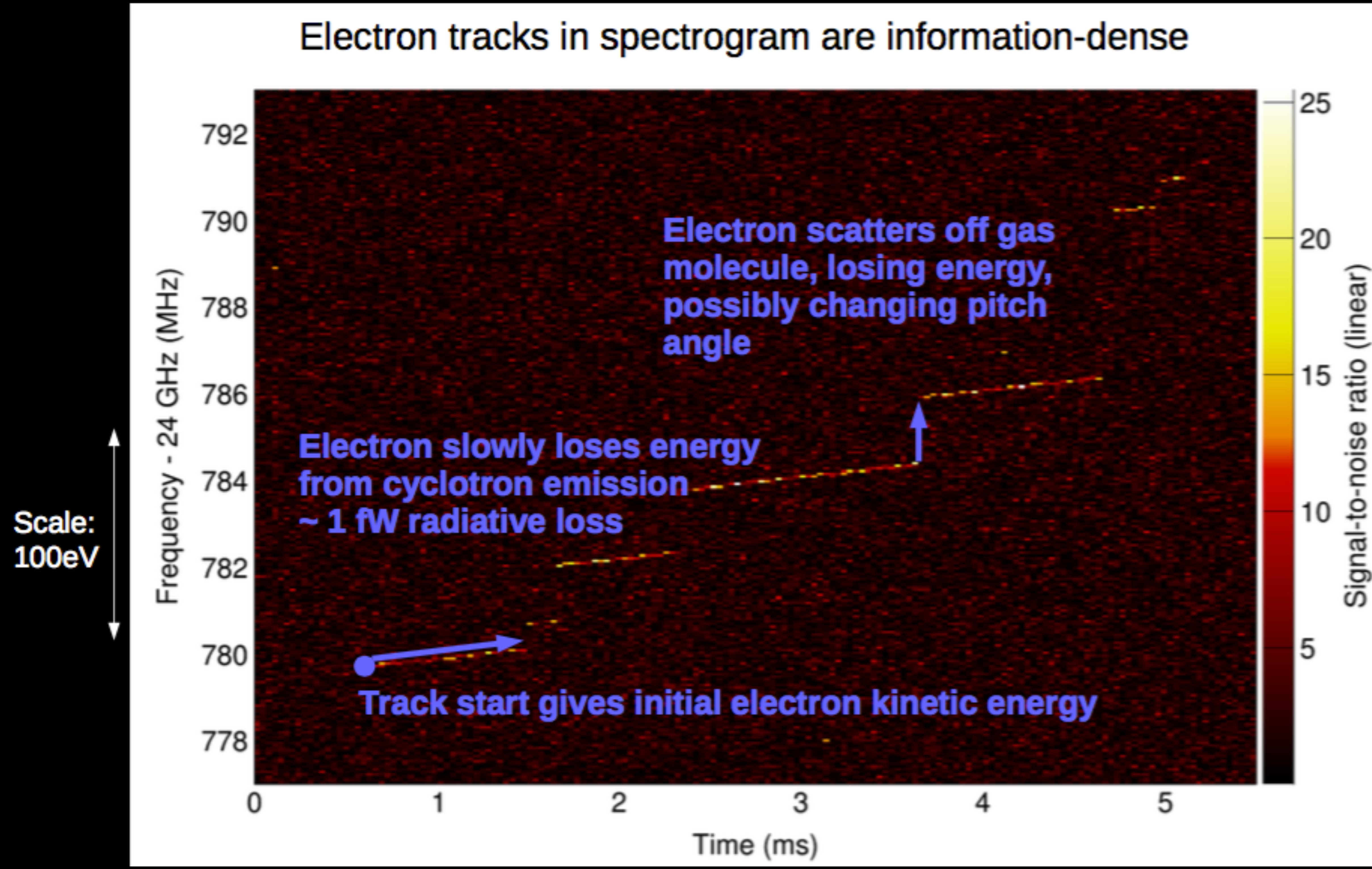
- narrow-band
  → horizontal line
- energy loss by radiation
  → line is tilted

ACTUAL SPECTROGRAM

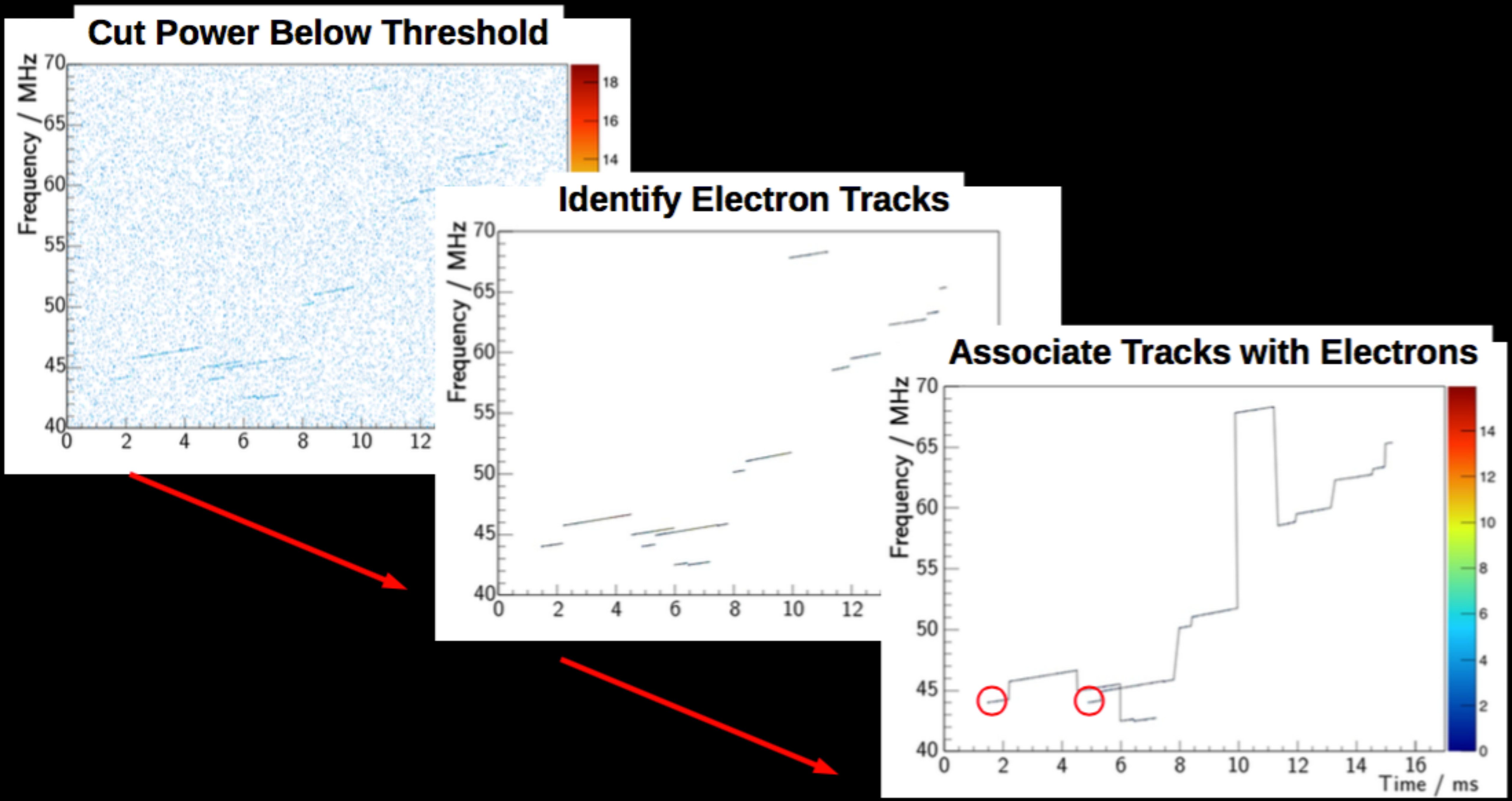


First detection of single-electron cyclotron radiation!

SPECTROGRAM INFORMATION

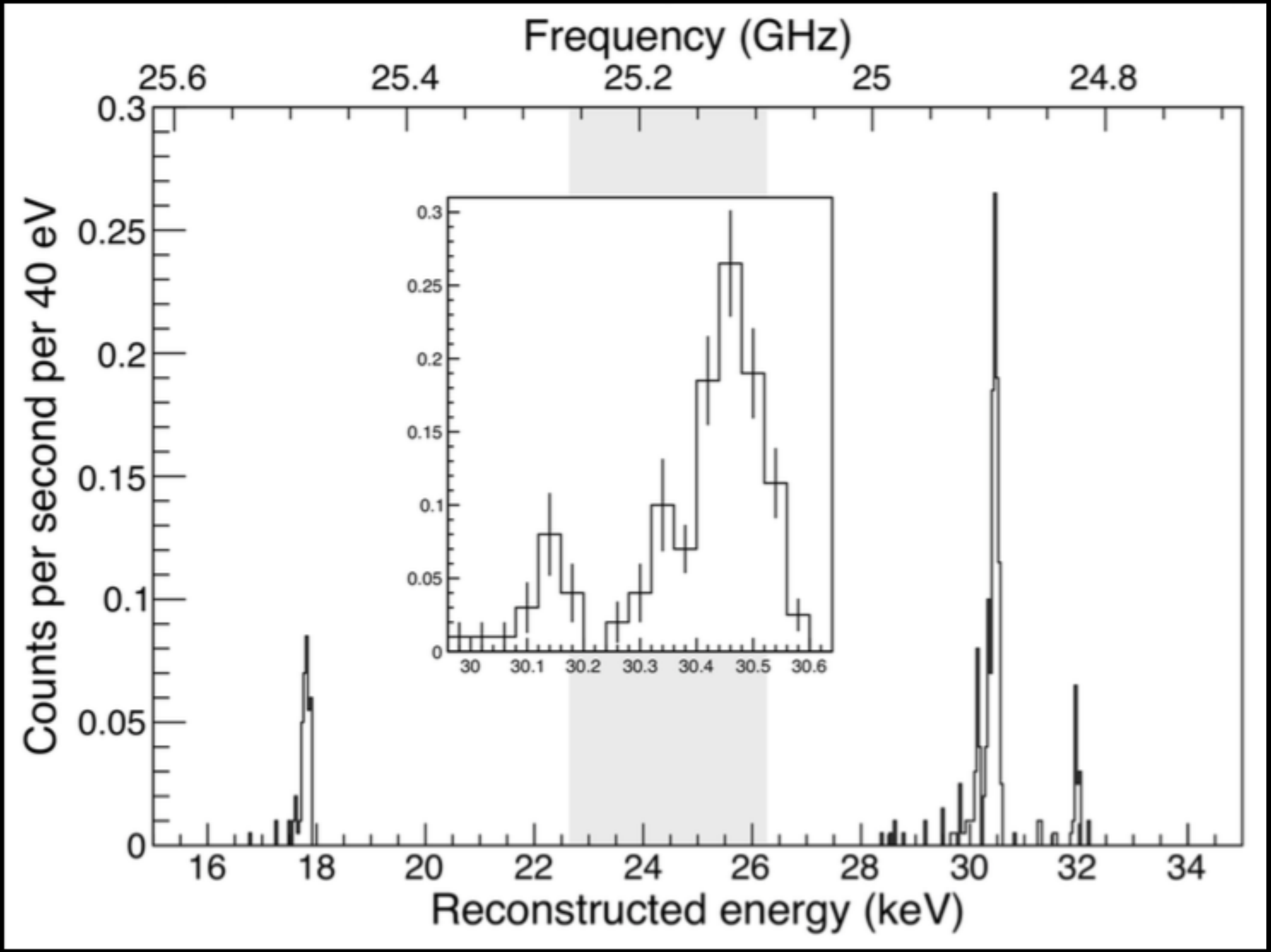


ENERGY SPECTRUM



Initial frequency determines initial energy

FIRST ENERGY SPECTRUM



Phys. Rev. Lett. 114, 162501 (2015)

Both ^{83m}Kr lines
→ clearly seen

Resolution

- FWHM: 140 eV

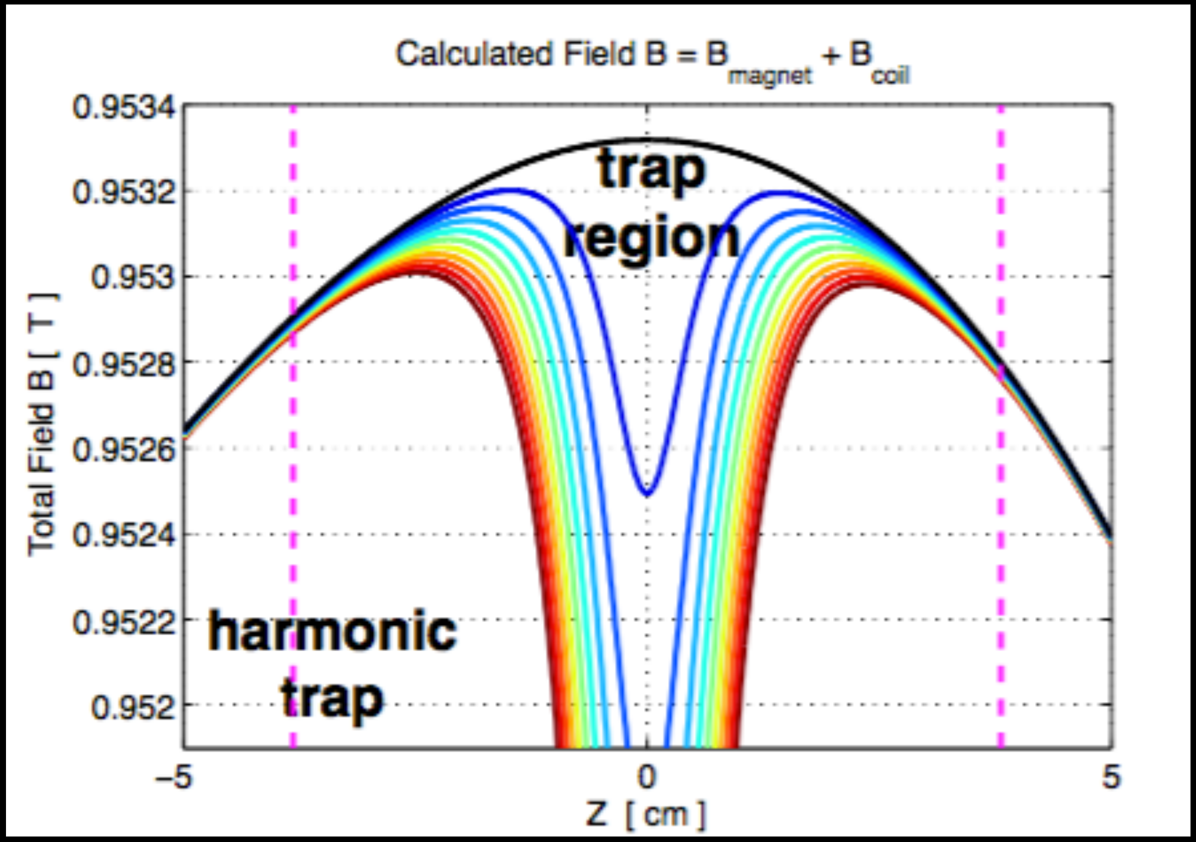
IMPROVED TRAP

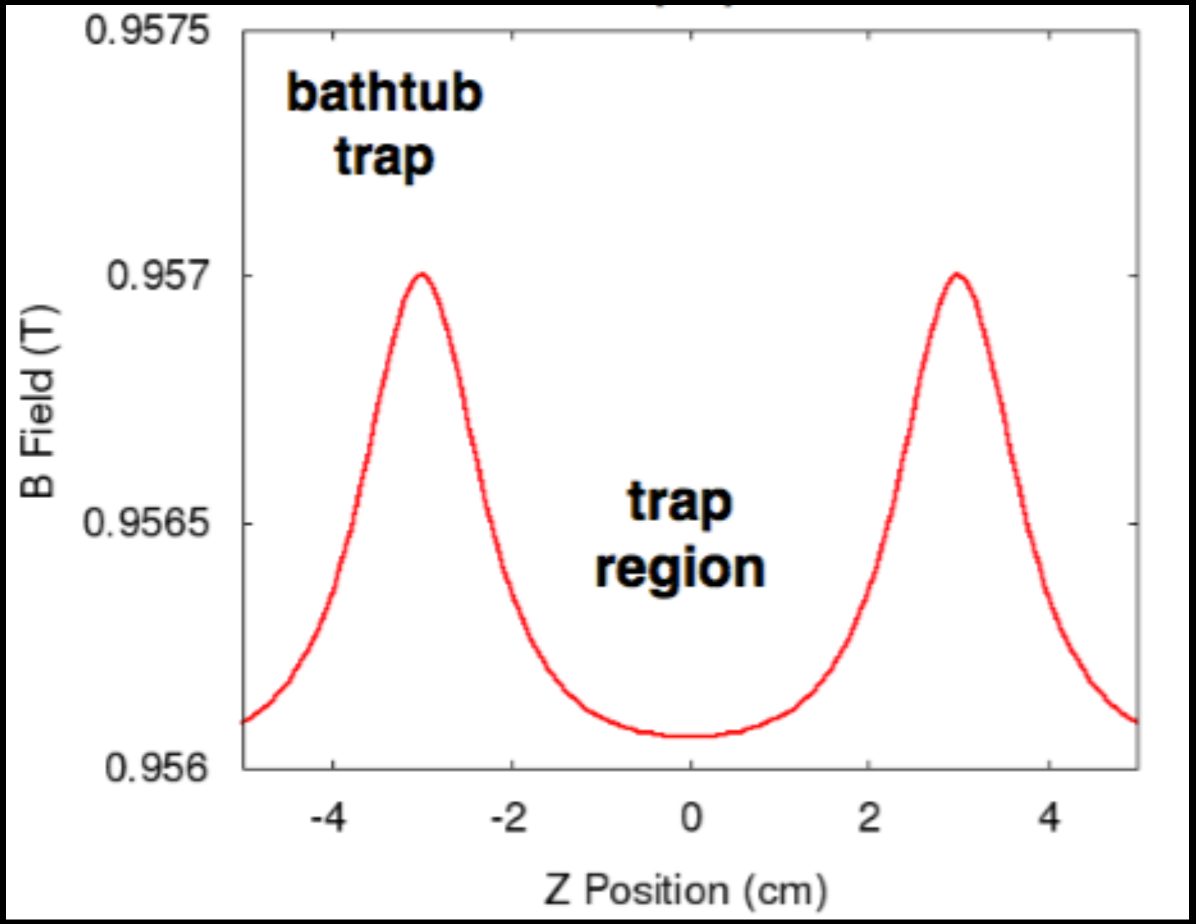
Shallower *Harmonic* trap

- 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

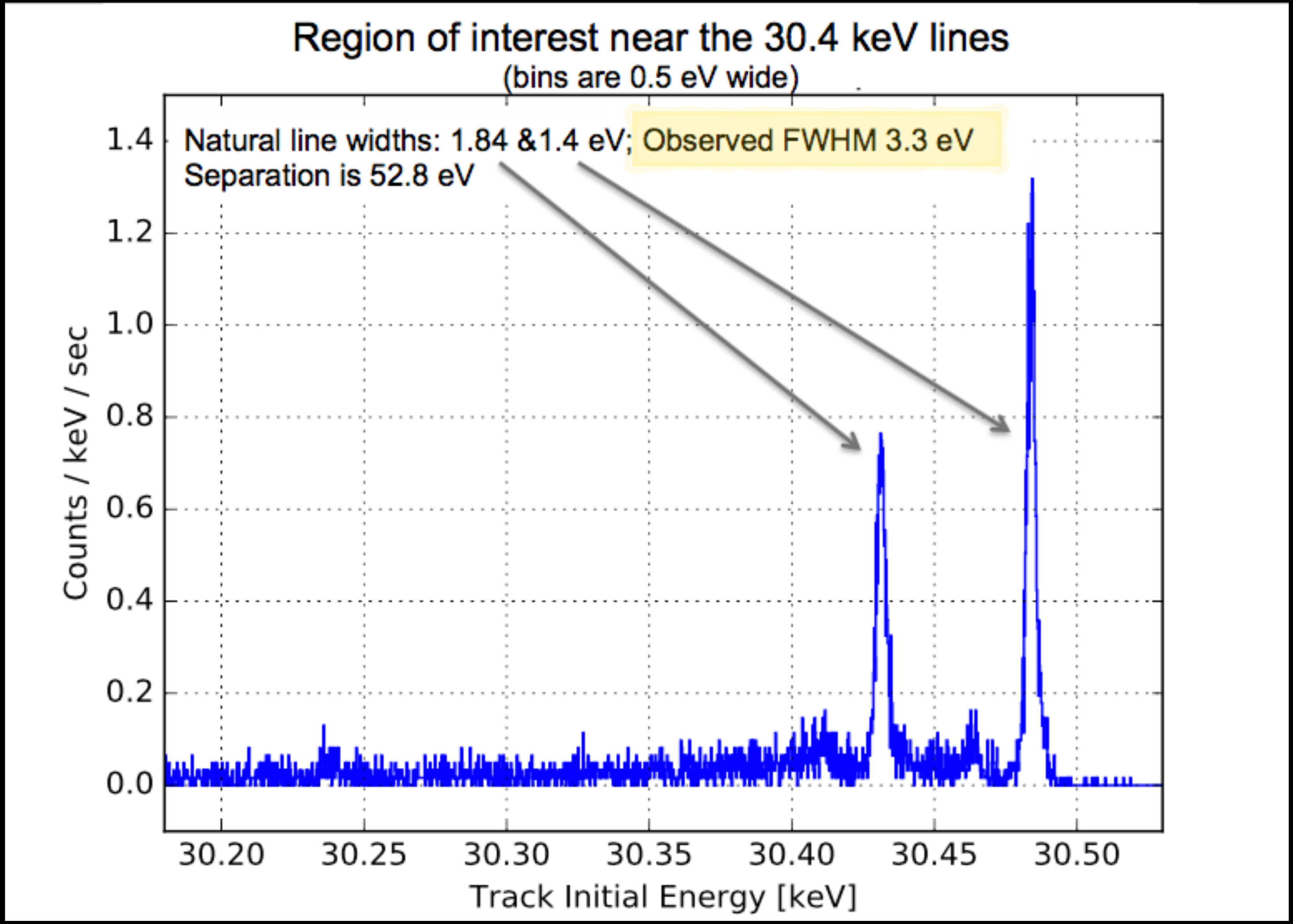




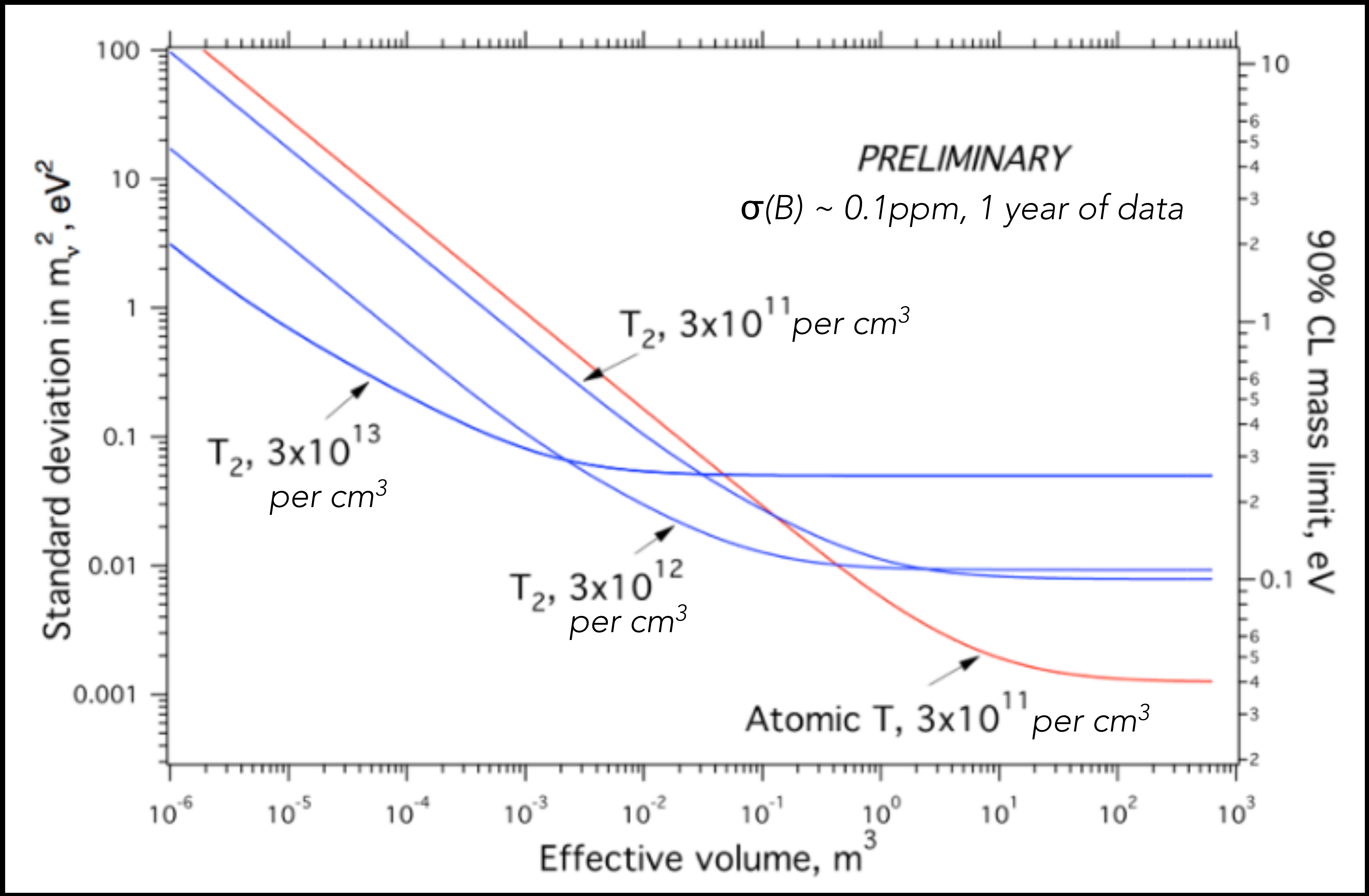
CRES — CYCLOTRON RADIATION EMISSON SPECTROSCOPY

Hardware improvements

- better field uniformity
- reduced noise level
- better temperature stability

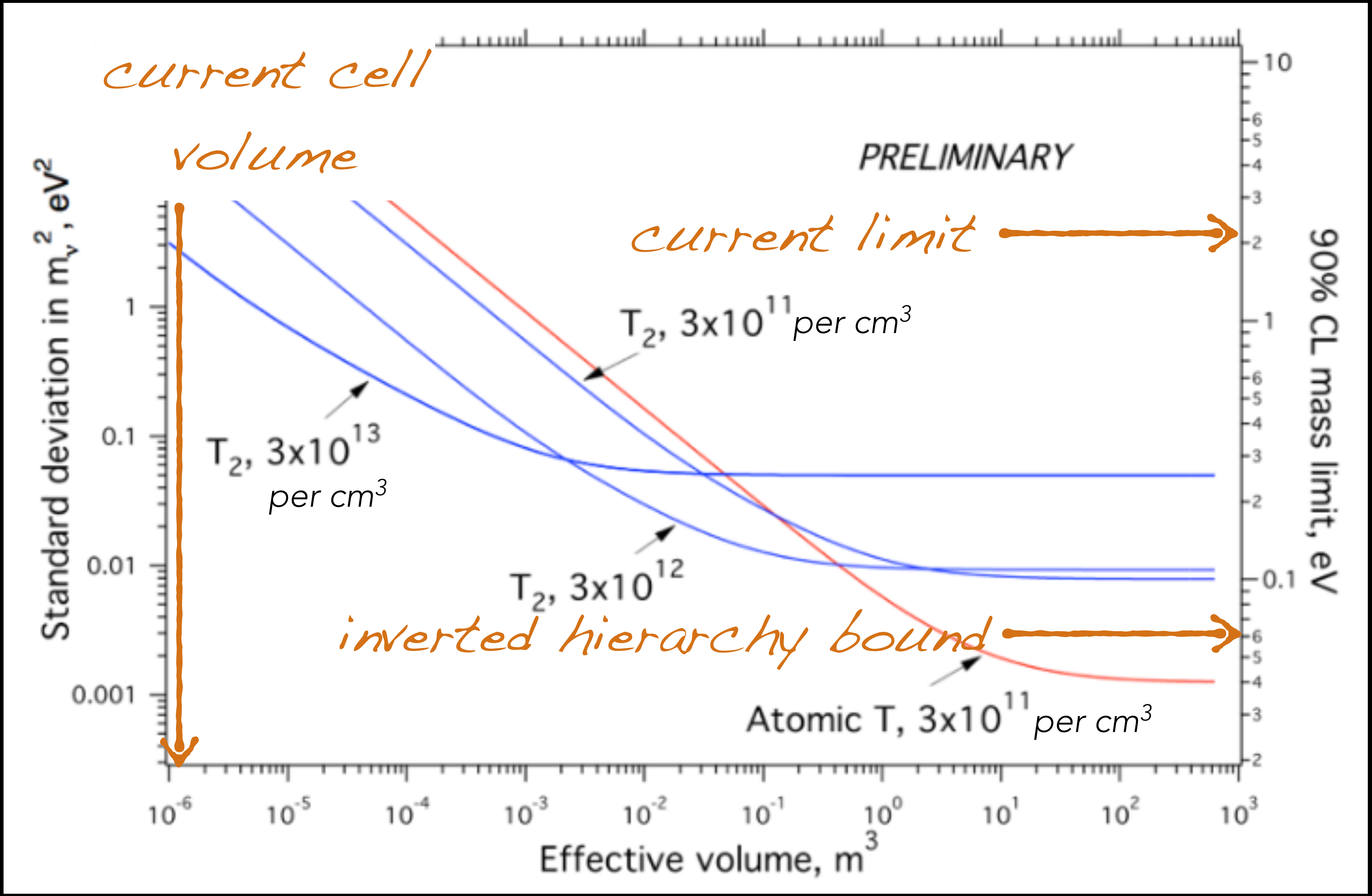


POTENTIAL ν-MASS REACH



Sensitivity limited by gas density!

POTENTIAL ν-MASS REACH



Inverted hierarchy limit in reach with atomic tritium!

PROJECT 8 COLLABORATION

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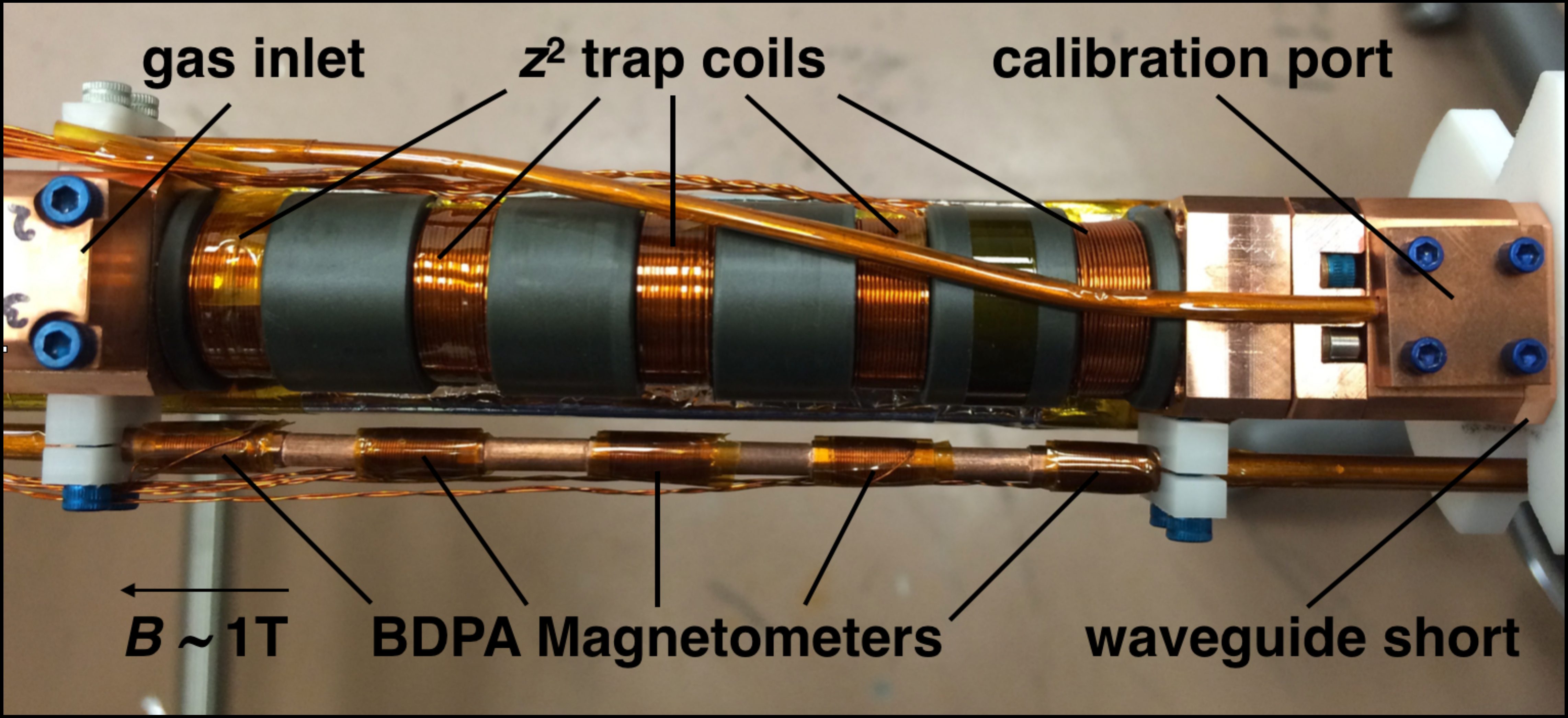
A PHASED APPROACH

Phase	Timeline	Source	R&D Milestones	Science Goals
I	2010–2016	^{83m}Kr	• single electron detection • proof of concept	• conversion electron spectrum of ^{83m}Kr COMPLETED
II	2015–2017	T_2	• Kurie plot • systematic studies	• Final-state spectrum test • $^3H-^3He$ mass difference • m_ν < 10–100 eV/c^2
III	2016–2020	T_2	• high-rate sensitivity • B-Field mapping	• m_ν < 2 eV/c^2
IV	2017...	T	• atomic tritium source	• m_ν < 40 meV/c^2 • measure m_ν or determine normal hierarchy

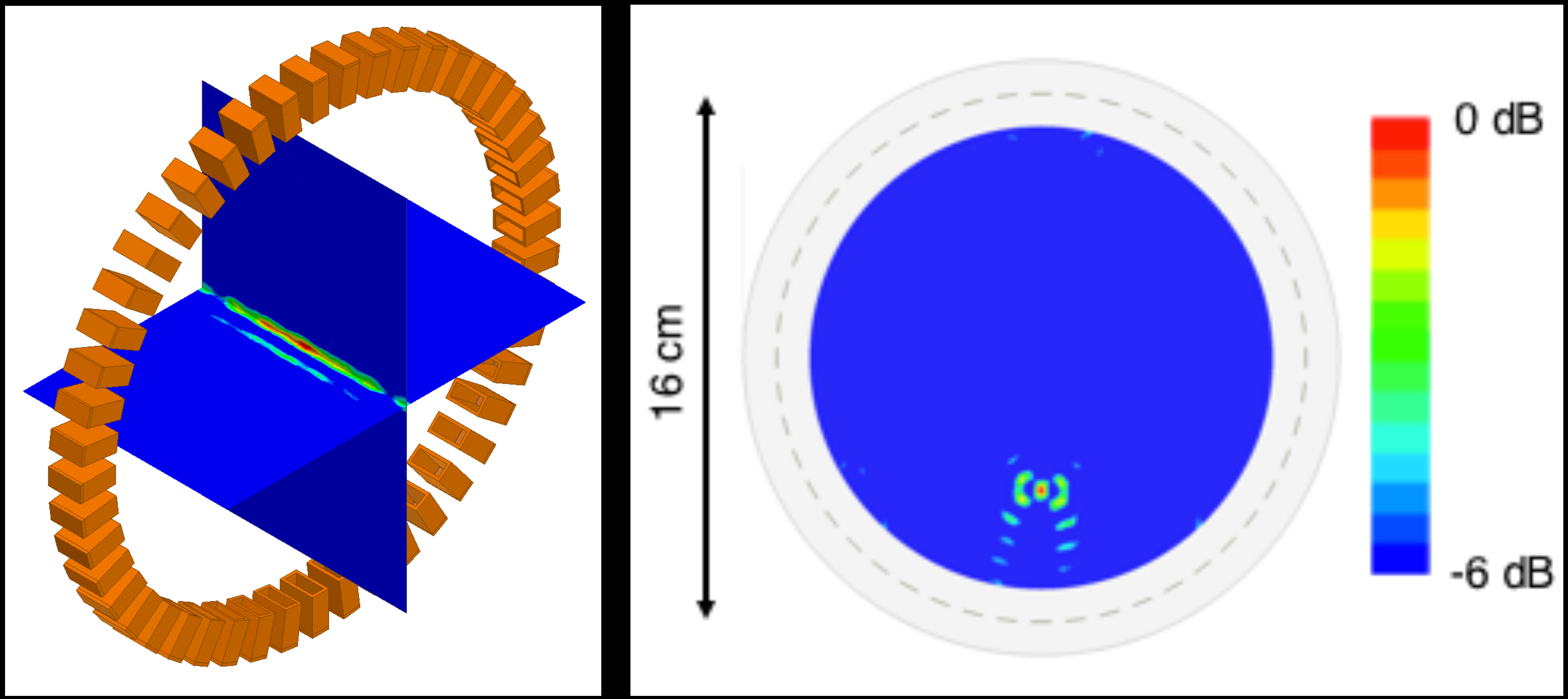
PHASE-II : TRITIUM



Improved insert installed

- first ^{83m}Kr data available → very promising
- T_2 - system ready to be installed

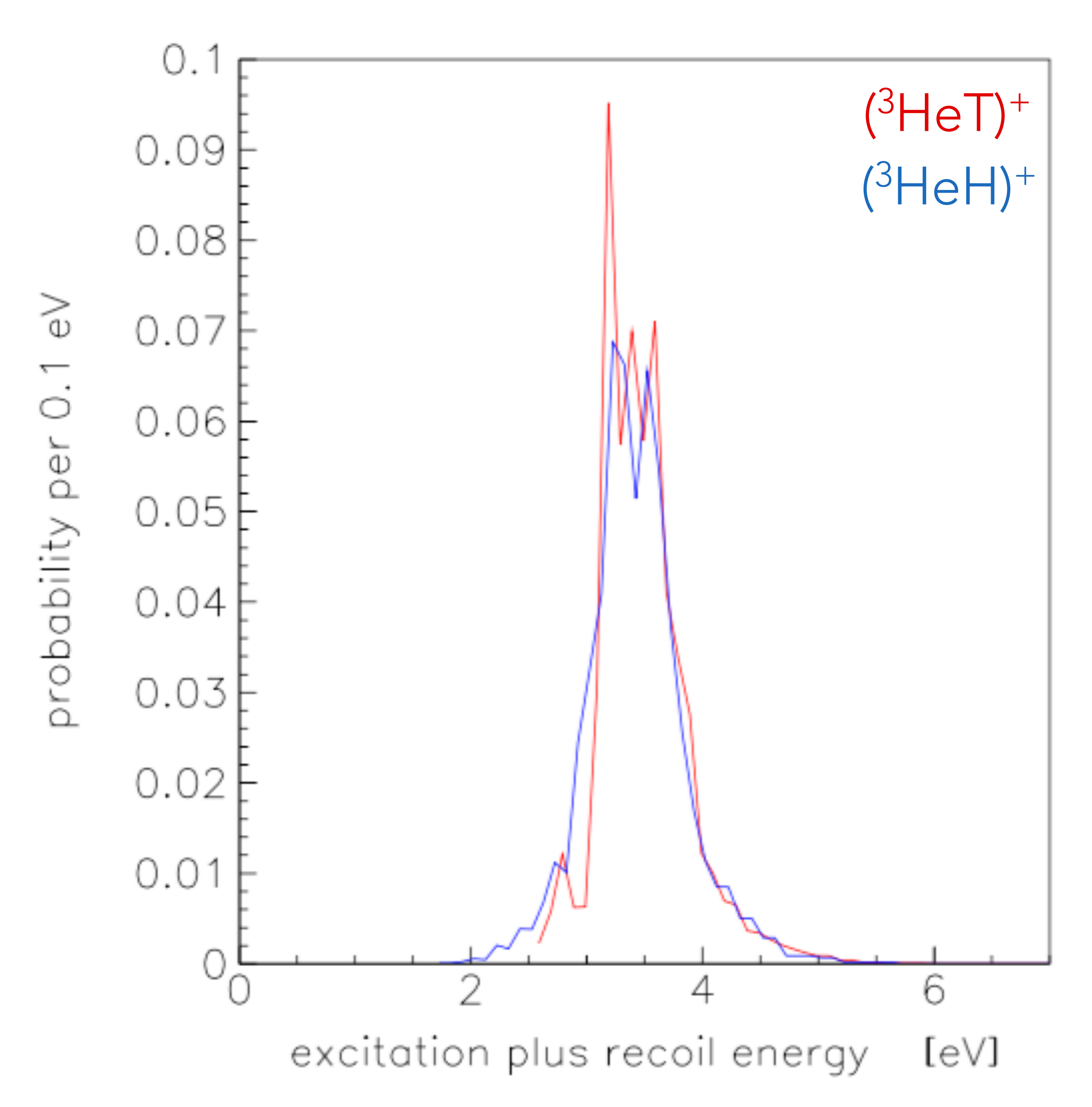
PHASE III - LARGE VOLUME



Example antenna configuration and vertex resolution being modeled

- Larger bore ~1T magnet → exists
- Phased array antenna configurations → under study

MOLECULAR TRITIUM LIMITATIONS



Advances in High Energy Physics 2013 (2013) 39

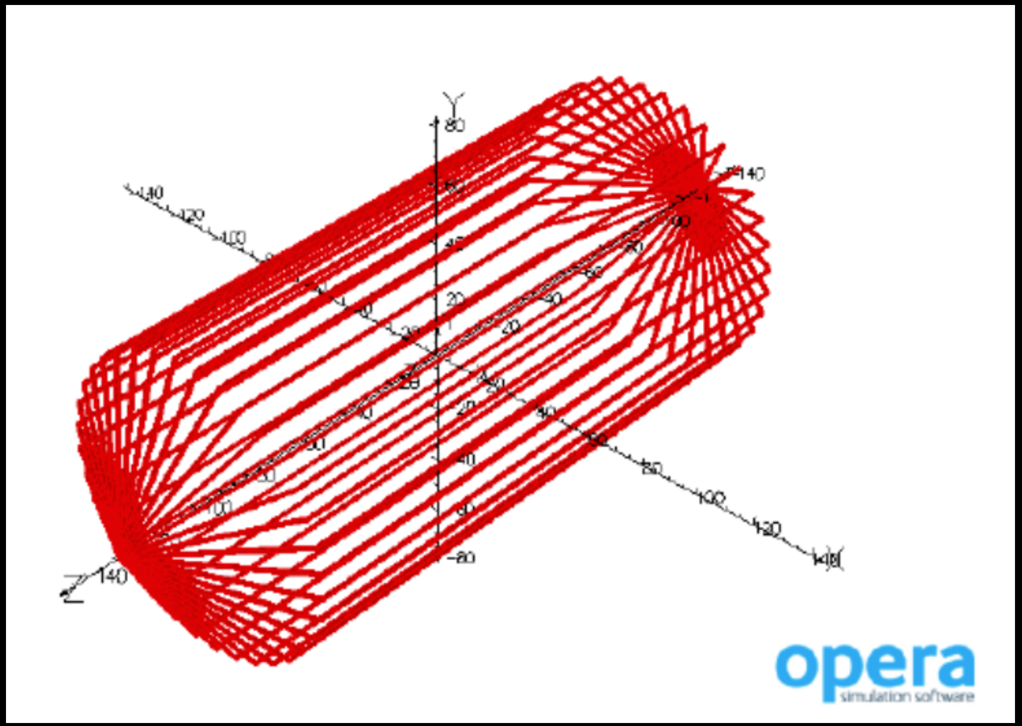
Molecular excitations in daughter molecule

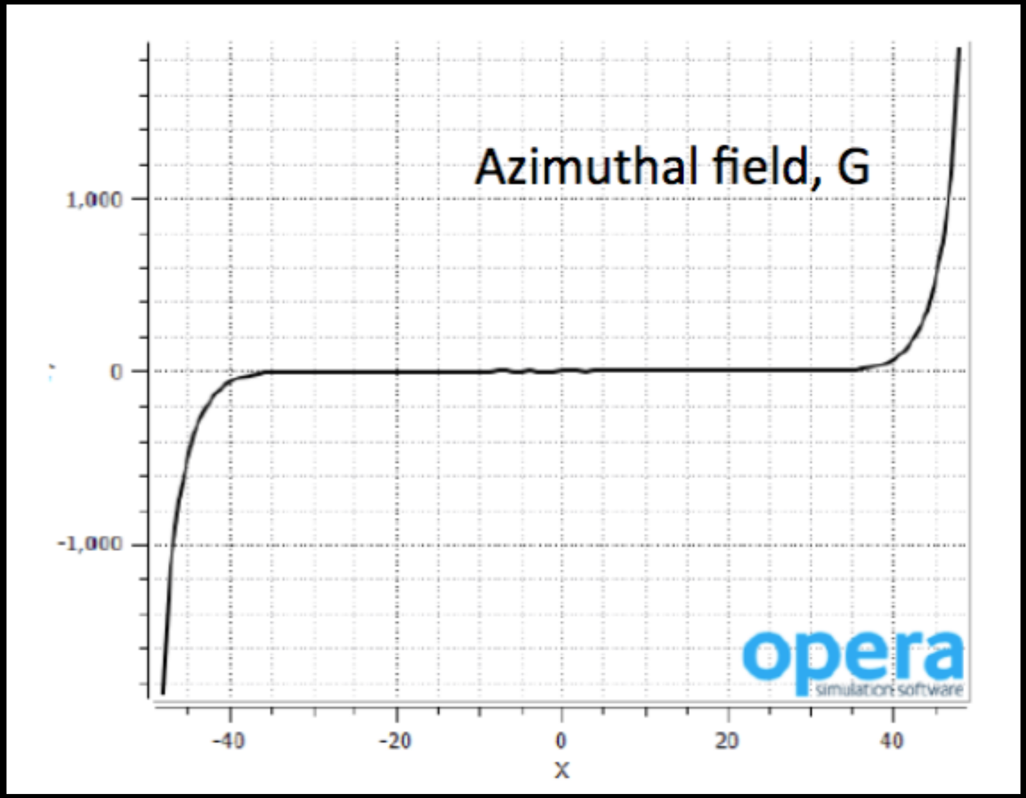
- blur tritium endpoint

→ fundamental limit to measurement of ν-mass

Need atomic tritium for ultimate experiment!

PHASE IV: ATOMIC TRITIUM





Alexi Radovinsky, MIT Magnet Lab

Studying Ioffe-Pritchard trap

- couple to nuclear magnetic moment

$$\Delta E = -\vec{\mu} \cdot \vec{B}$$

- similar to BEC and anti-hydrogen traps (ALPHA)

Challenges

- cool atomic tritium to sub-Kelvin
- need high T/T_2 purity

SUMMARY

Project 8:

- new technology: CRES - Cyclotron Radiation Emission Spectroscopy

Next step

- measure full tritium spectrum

Longer-term future

- large scale setup limited by tritium density and molecular excitations
  → phased antenna array
  → atomic tritium source

BACKUP

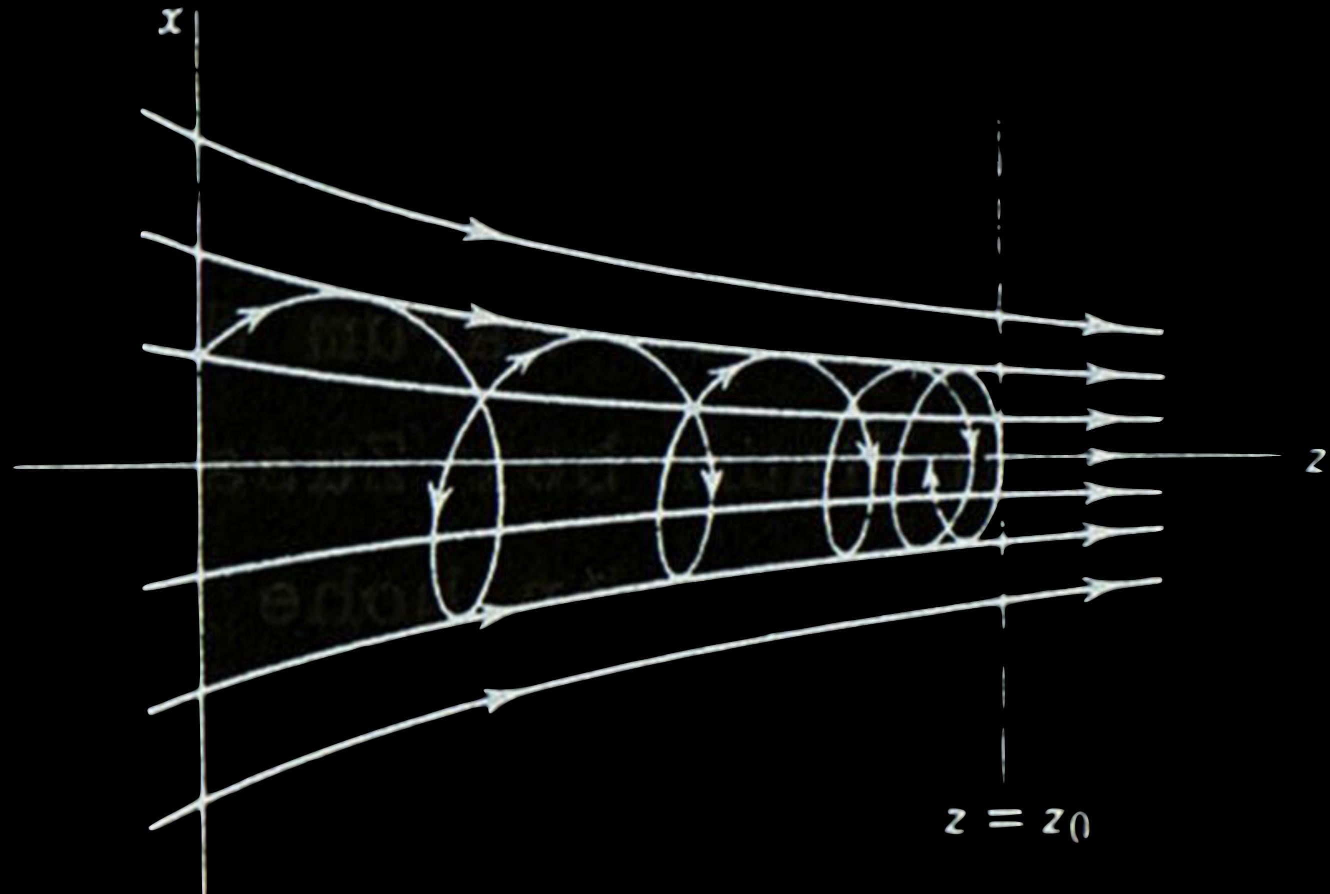
ADIABATIC INVARIANCE

Adiabatic invariance

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

Slowly changing B

- $p_\perp \rightarrow p_\parallel$



MAC-E FILTER

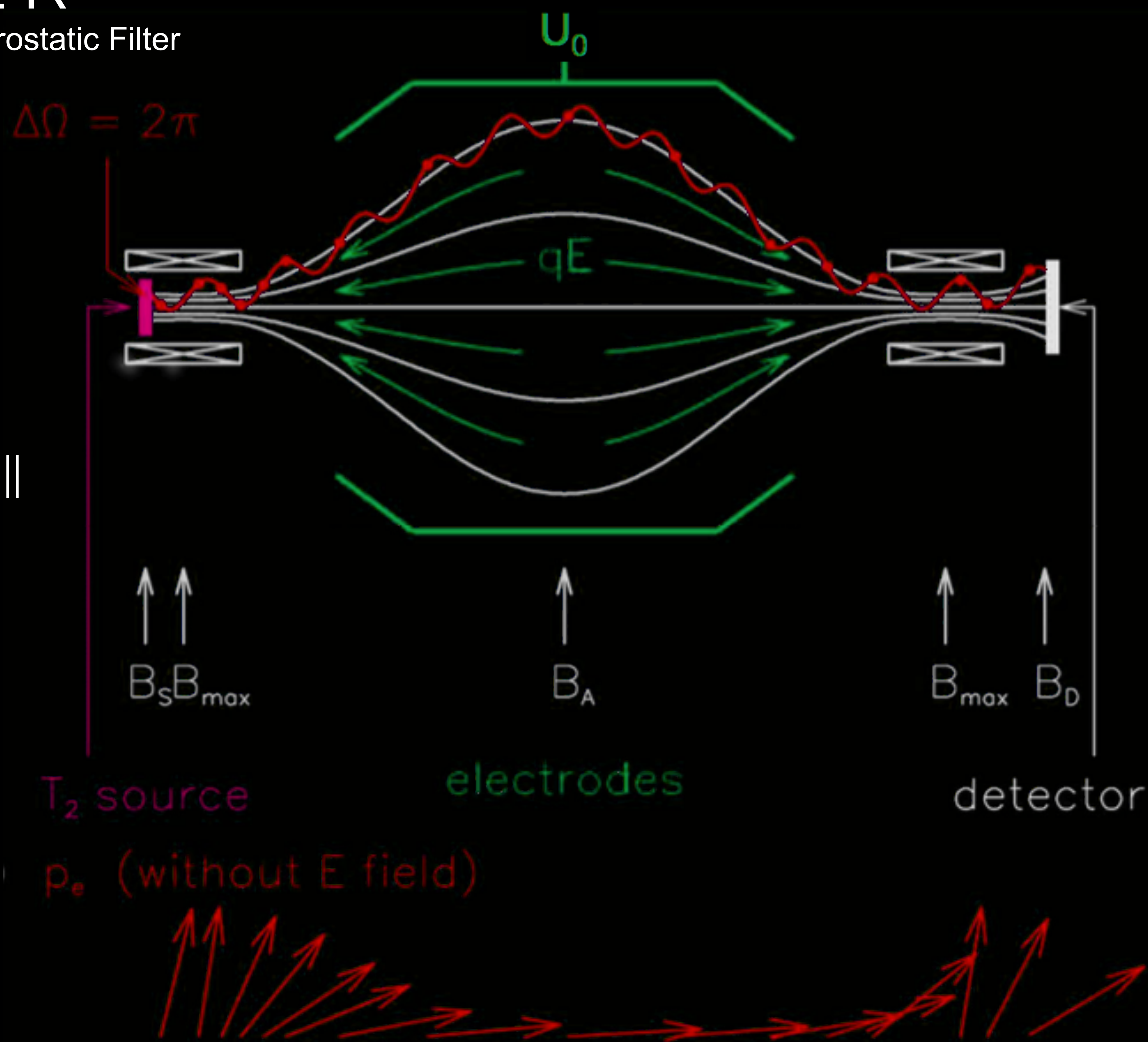
Magnetic Adiabatic Collimation with Electrostatic Filter

Combination of

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

Resolution

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



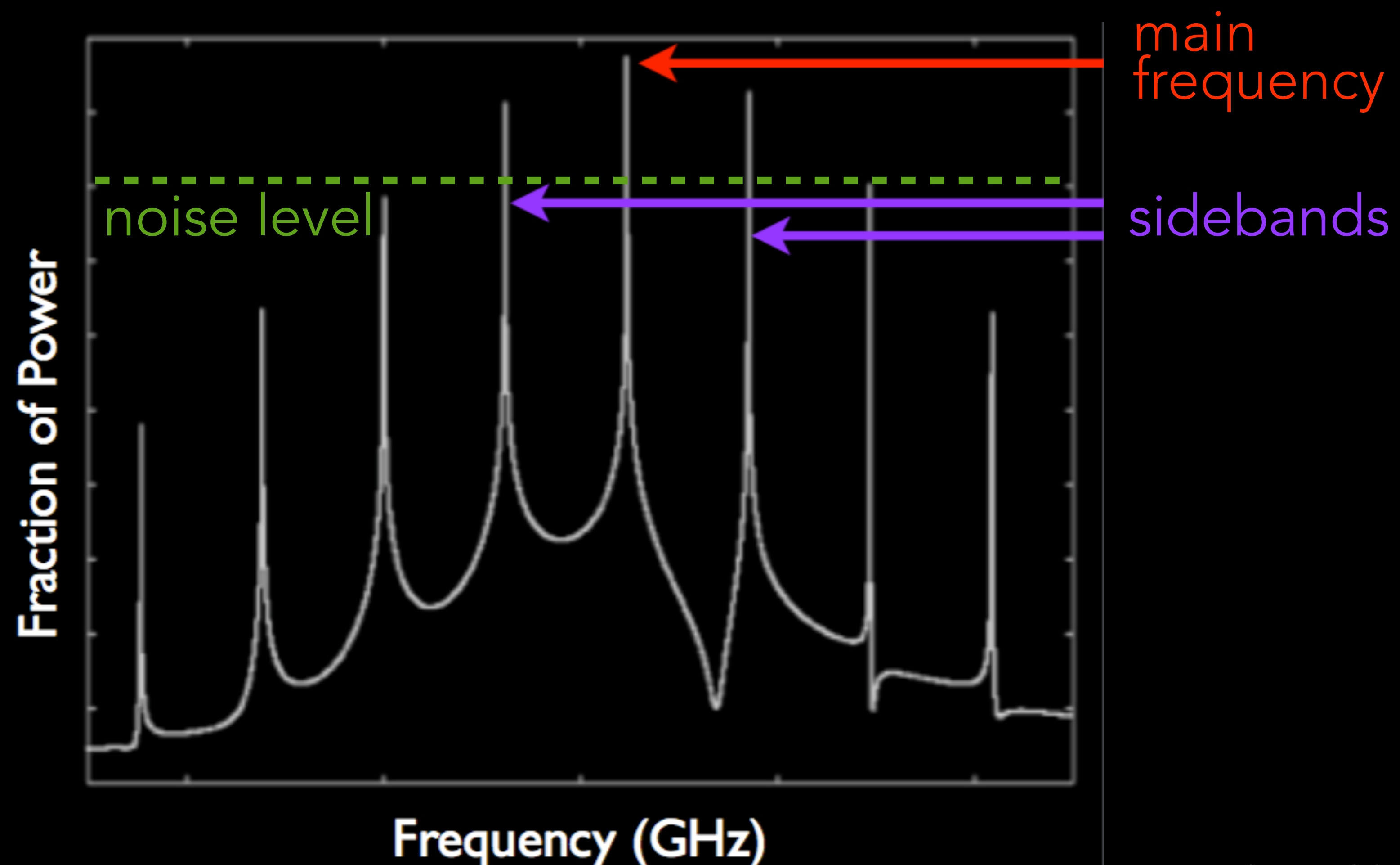
DISENTANGLING ENERGY AND ANGLE

Electron oscillates in trap

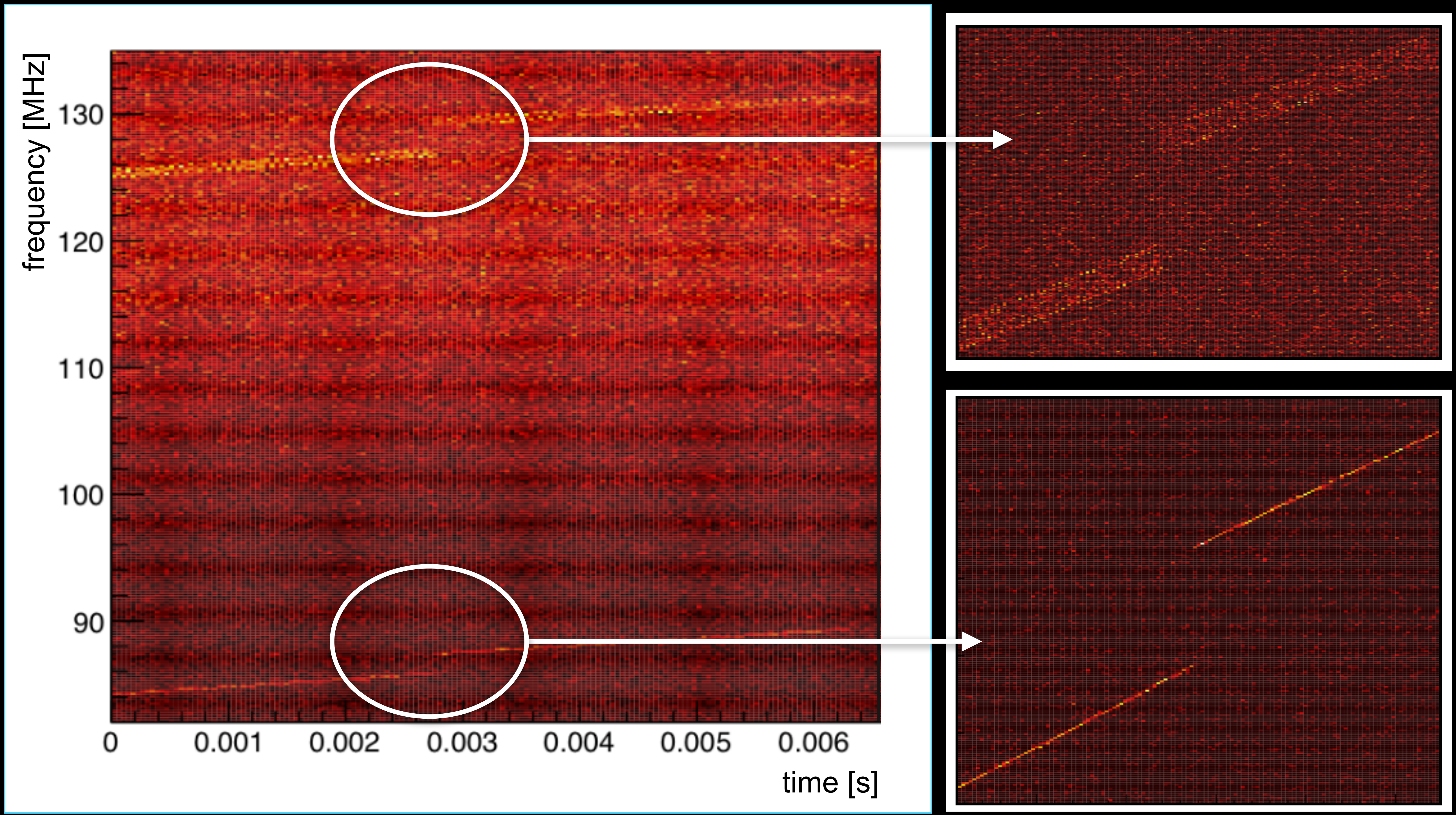
- axial mode (in harmonic trap)

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

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



SIDEBAND OBSERVATION



THREE DEGREES OF FREEDOM