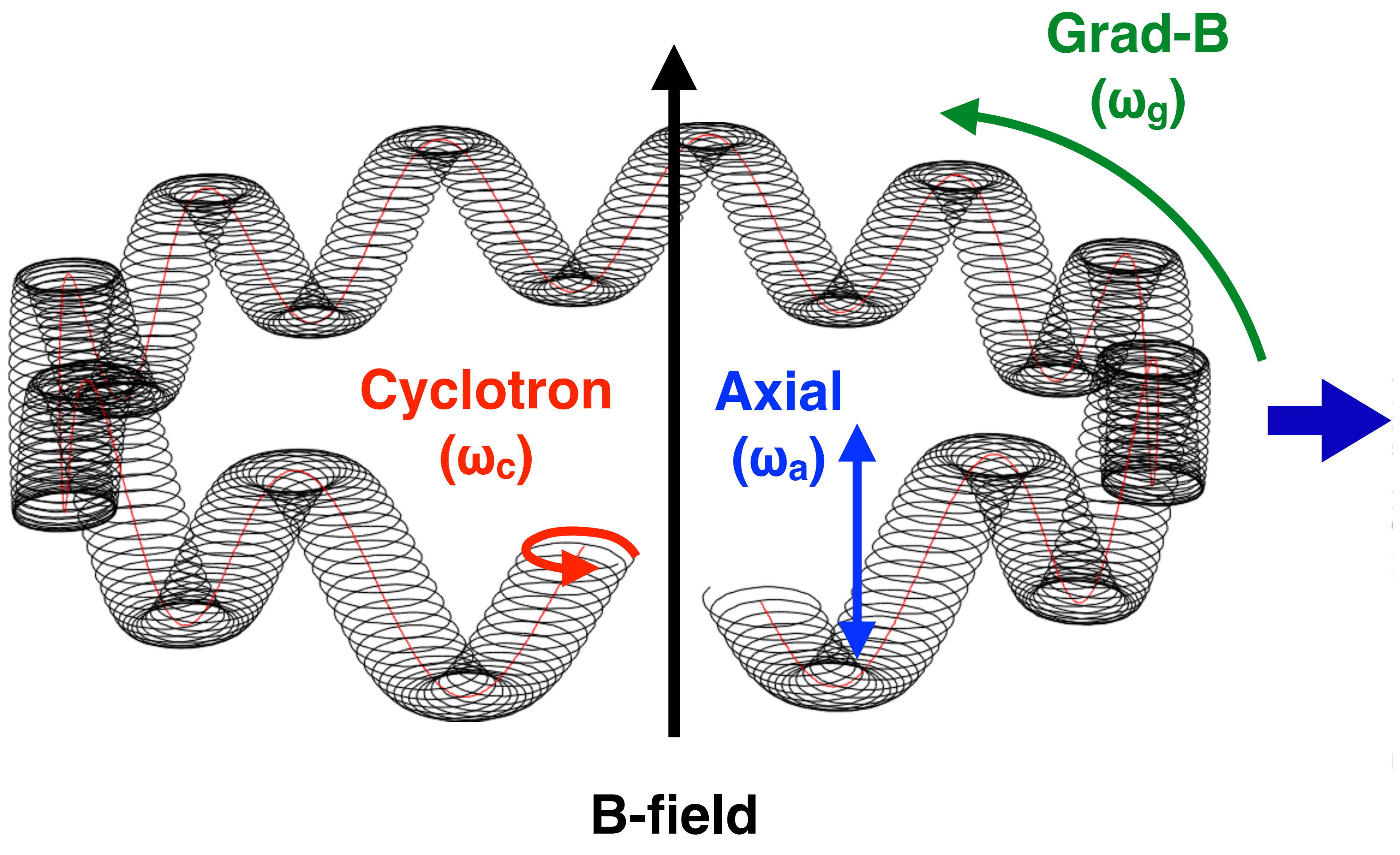
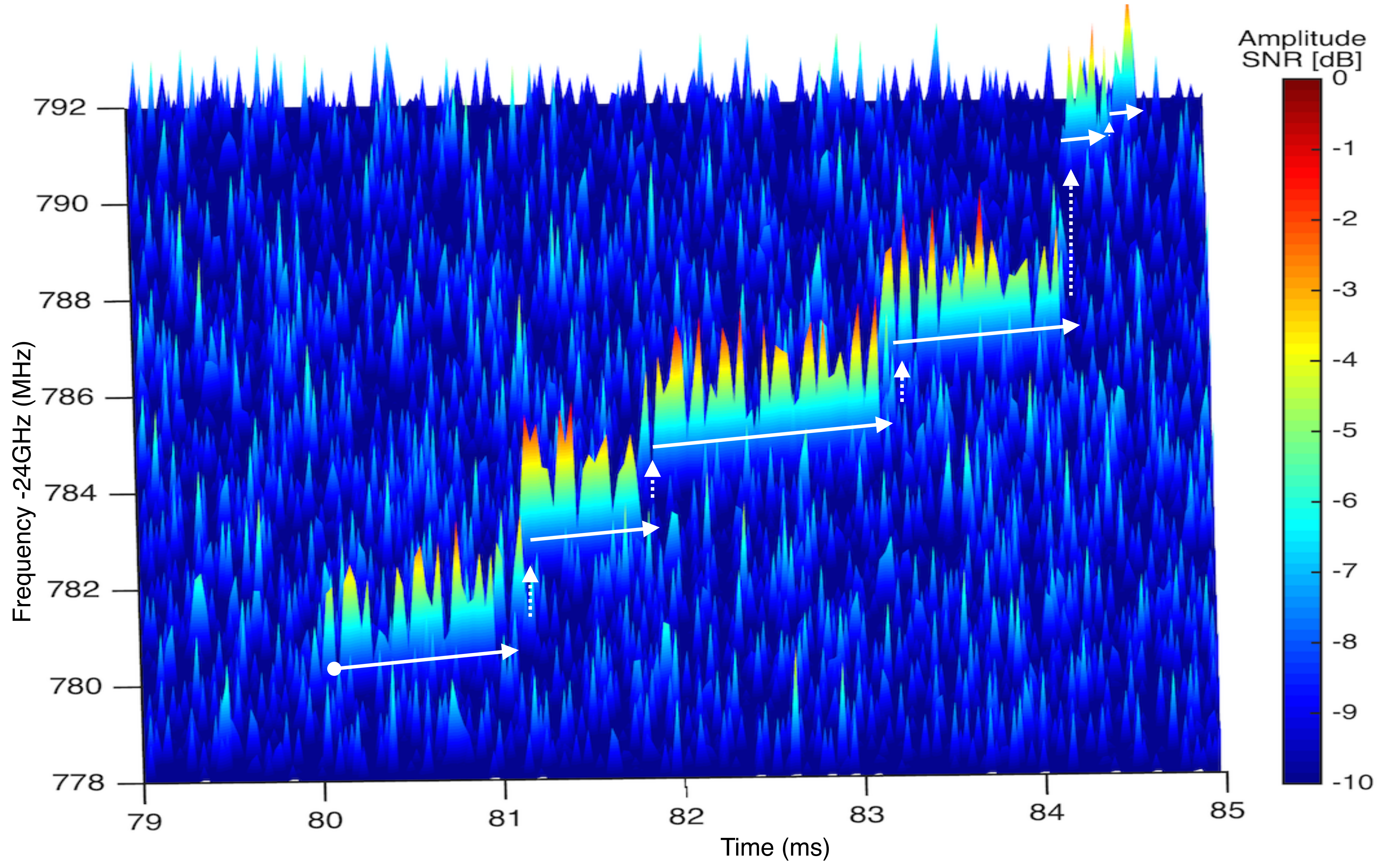
The Status of the Project 8 Neutrino Mass Experiment

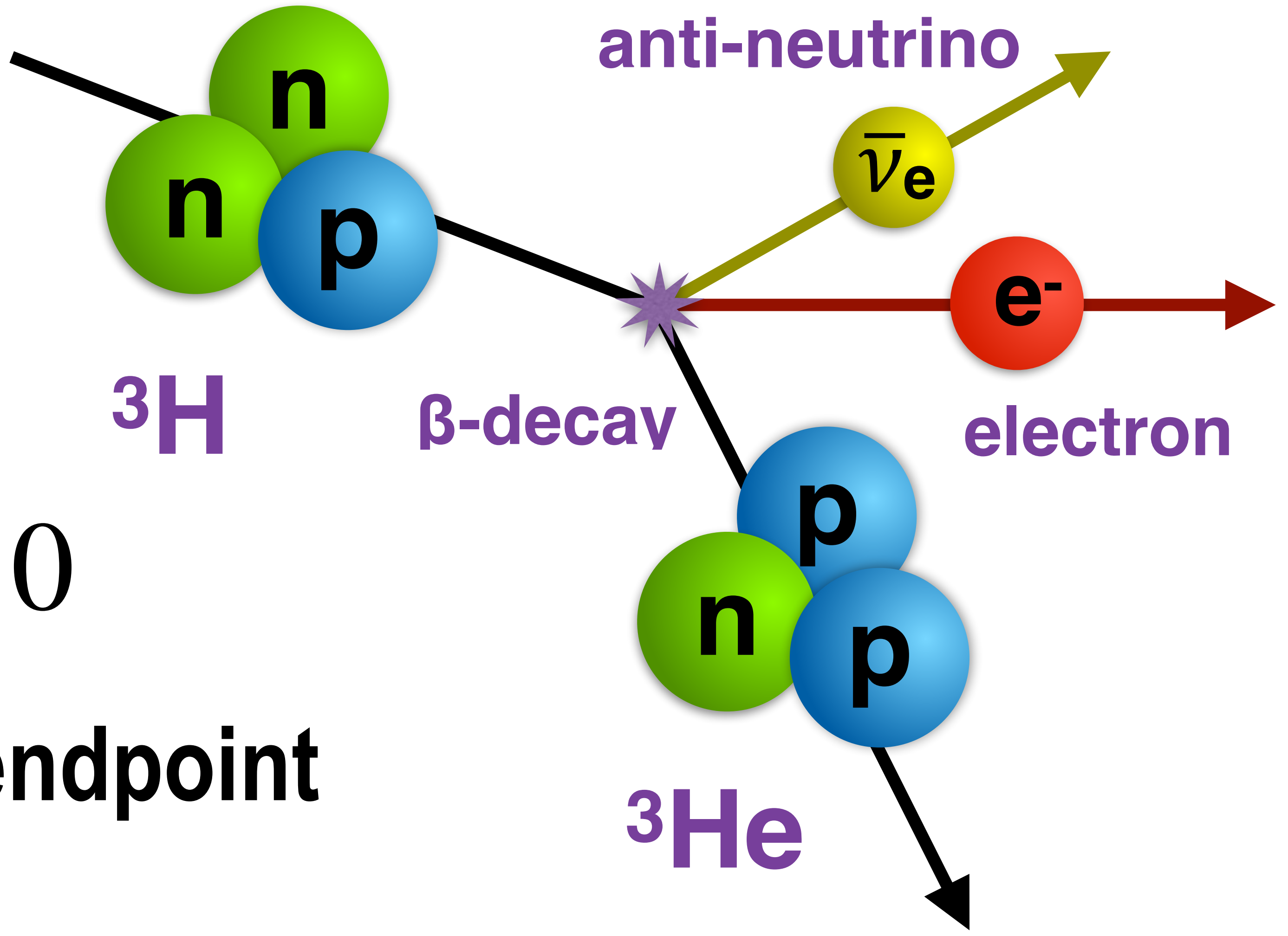


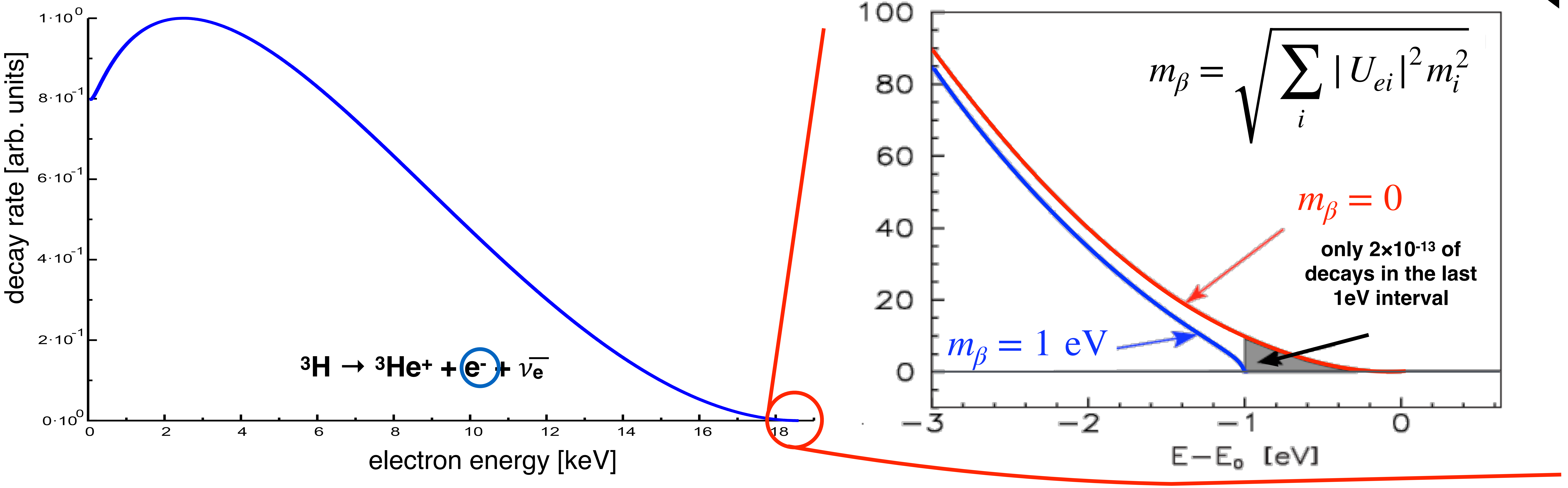


Luiz de Viveiros - Penn State
Project 8 Collaboration

Beta Decays and the Neutrino Mass

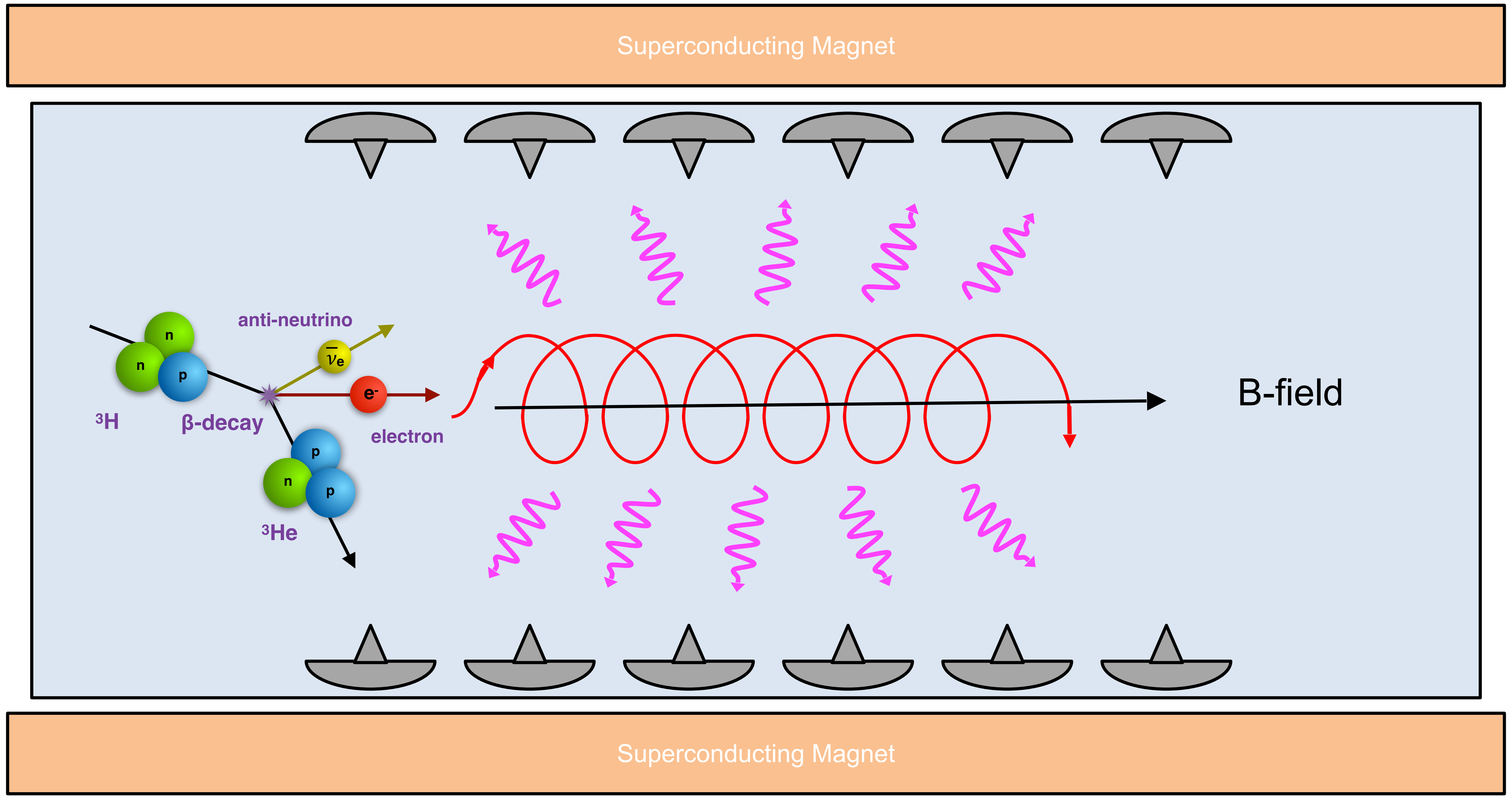
- Absolute mass scale and ordering are still unknown
- Tritium β- spectroscopy is the leading technique for direct neutrino mass measurements
- Beta decay endpoint should match the mass difference (~18.6 keV) for $m_{\nu_e} = 0$
- Determine the neutrino mass from the shape of the tritium β-decay spectrum endpoint





The Idea: Cyclotron Radiation Emission Spectroscopy

- New spectroscopy technique: Cyclotron Radiation Emission Spectroscopy (CRES)
  - Formaggio and Monreal, Phys. Rev. D 80, 051301(R), 2009
- Electron on a magnetic field: cyclotron motion; emitted cyclotron radiation depends on electron kinetic energy
- Frequency falls in the microwave K-band for ~ 1 T fields
  - Tritium endpoint at 18.6 keV
    $\Longrightarrow$ For B ~ 0.95 T, f ~ 25.6 GHz
  - ^{83m}Kr conversion electrons (e.g. 17.8 keV) can be used for calibration → f ~ 25.0 - 26.5 GHz
- Radiated Power P = ~ 1 fW for 18.6 keV electrons
- Surprisingly, this had never been observed for a single electron!



$$f_\gamma = \frac{eB}{2\pi\,(m_e + K/c^2)}$$

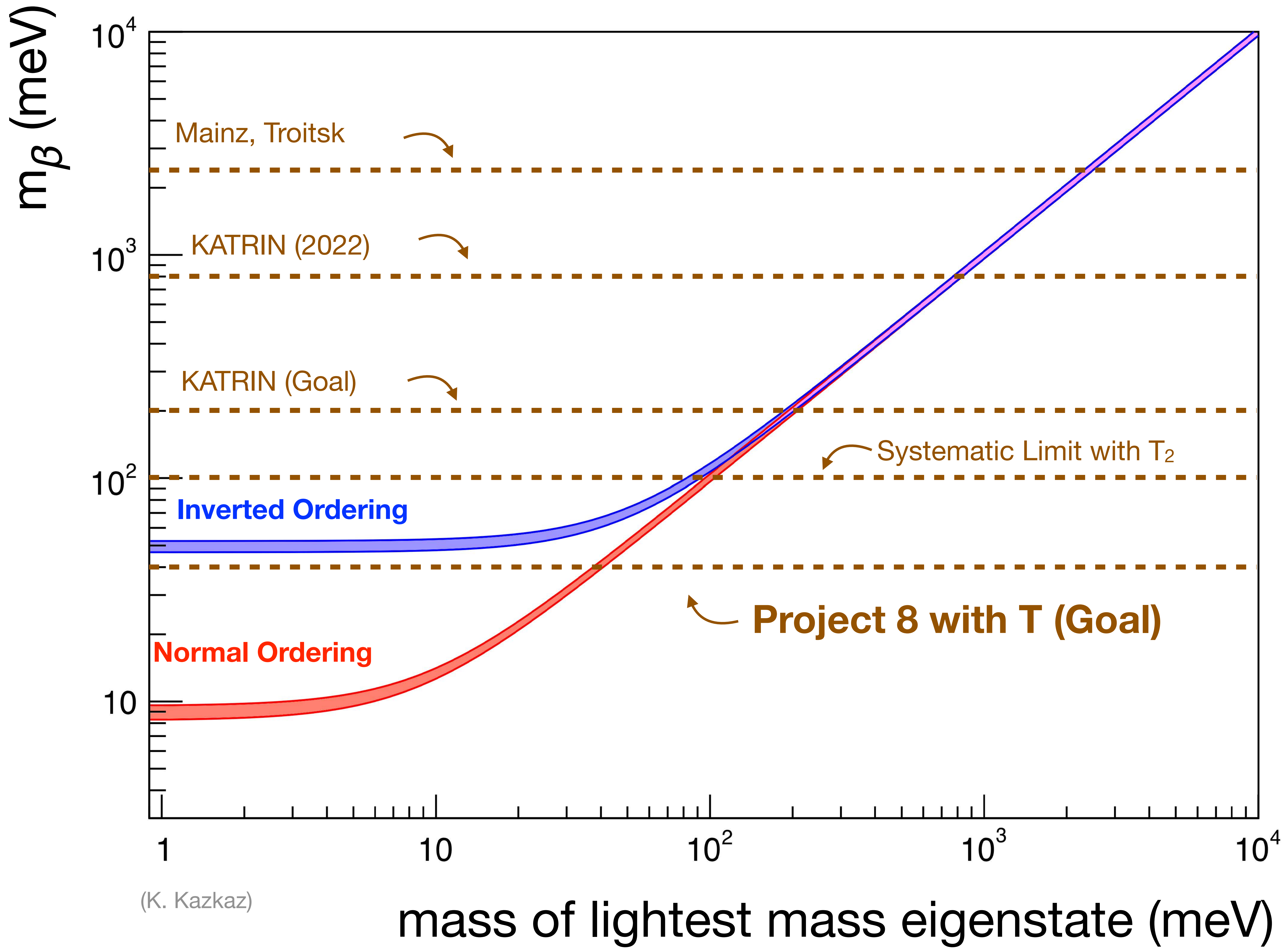
kinetic energy factor

GOALS

- **Sensitivity to 40 meV/c² neutrino mass**

$$m_\beta = \sqrt{\sum_i |U_{ei}|^2 m_i^2}$$

- **Measure neutrino mass or exclude inverted hierarchy**



PROJECT 8

Case Western Reserve University

Indiana University

Johannes Gutenberg Universitat, Mainz

Karlsruhe Institute of Technology

Lawrence Livermore National Laboratory

Massachusetts Institute of Technology

Pacific Northwest National Laboratory

Pennsylvania State University

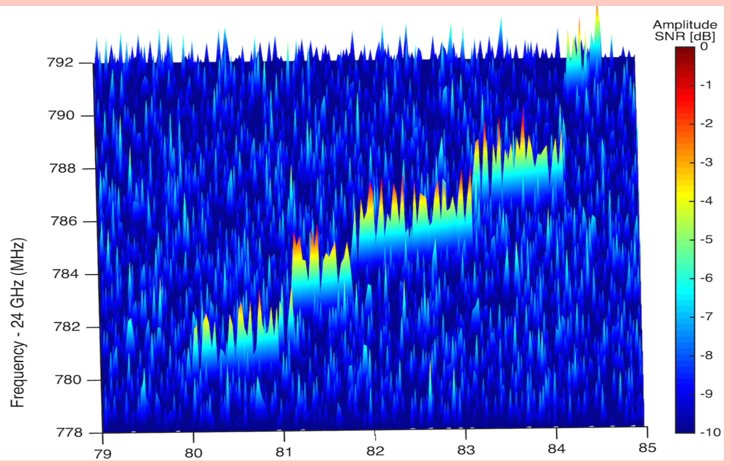
University of Illinois

University of Washington

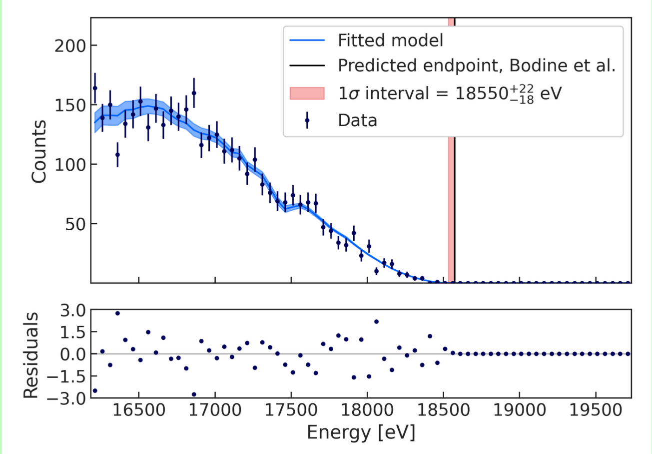
Yale University

THE PROJECT 8 SCIENTIFIC PROGRAMME: A PHASED APPROACH

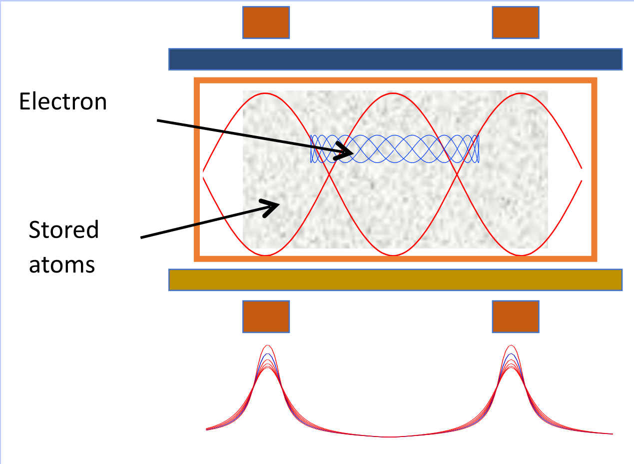
Phase I:
Demonstrate CRES technique on 83mKr mono-energetic electrons.
Status: Complete! Technique demonstrated.



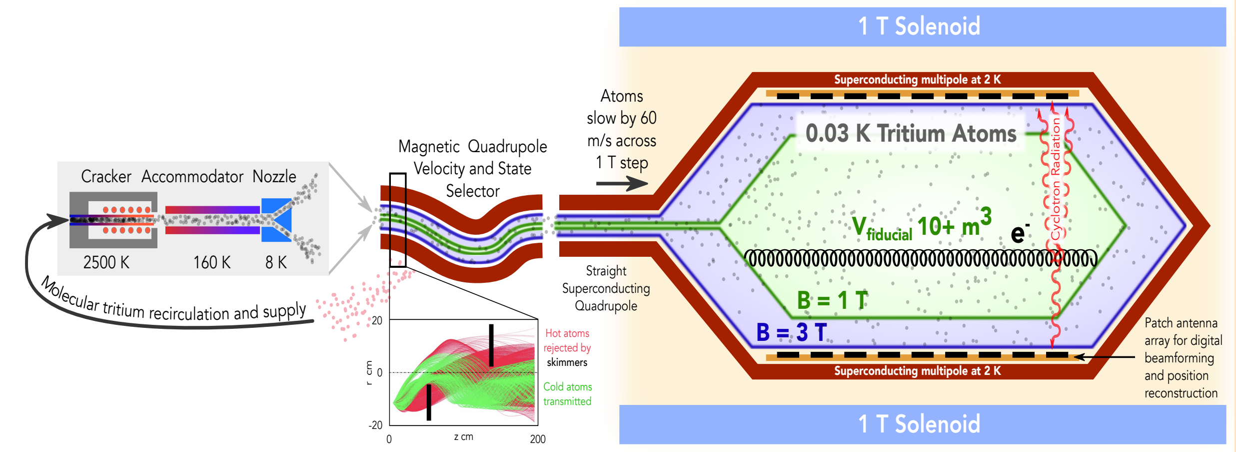
Phase II:
First T2 spectrum. Extract endpoint. Study systematics and backgrounds.
Status: Nearing completion



Phase III:
(a) “Large Volume” CRES
(b) Atomic tritium production and trapping at high densities



Phase IV:
Large atomic tritium experiment. Inverted mass ordering reach (40 meV)

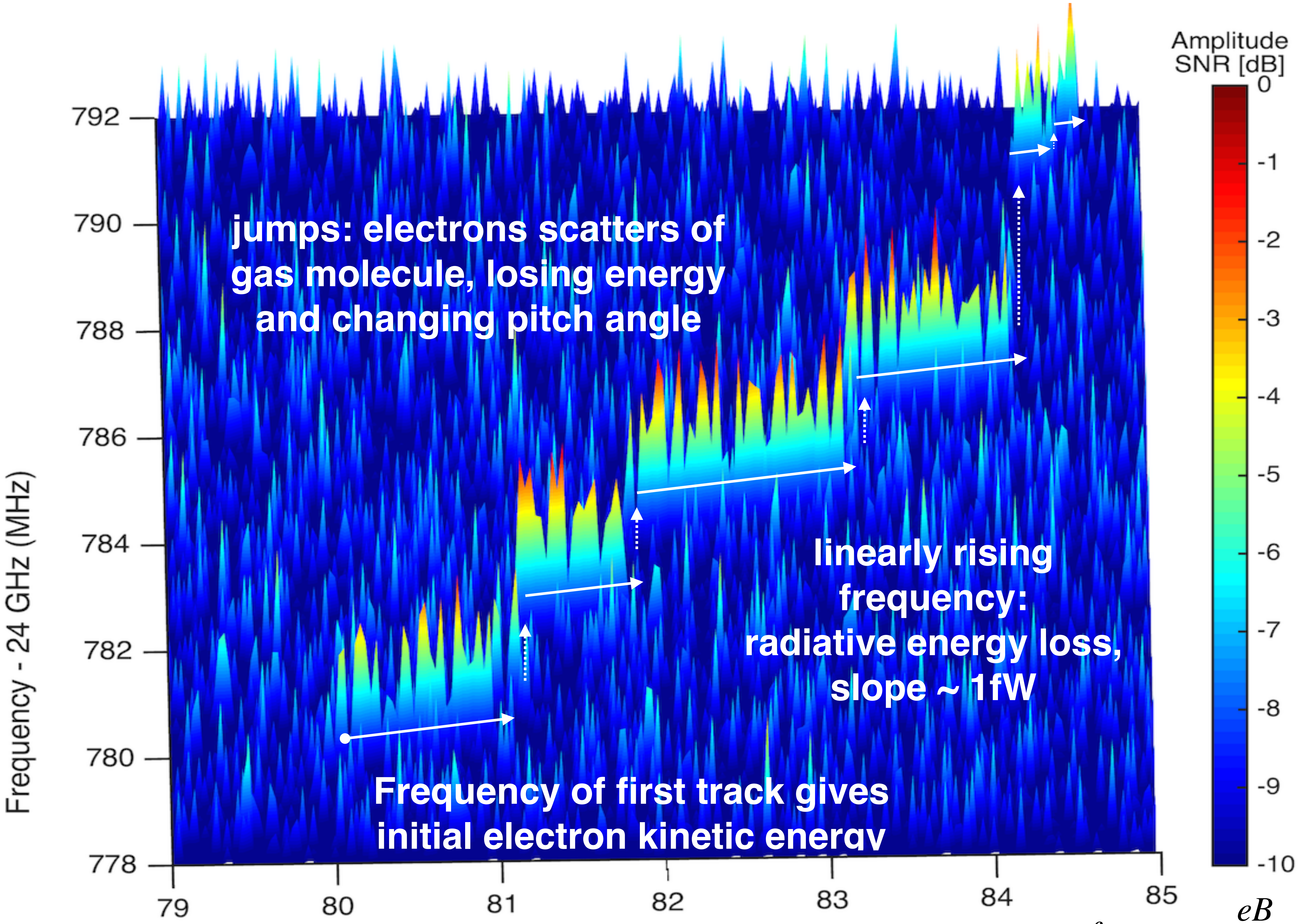


Phases I and II - The Detector

- Assembled at the University of Washington in Seattle, WA
- Phase I: ^{83m}Kr only (2016);   Phase II: ^{83m}Kr and T_2 (being completed now)

First Data

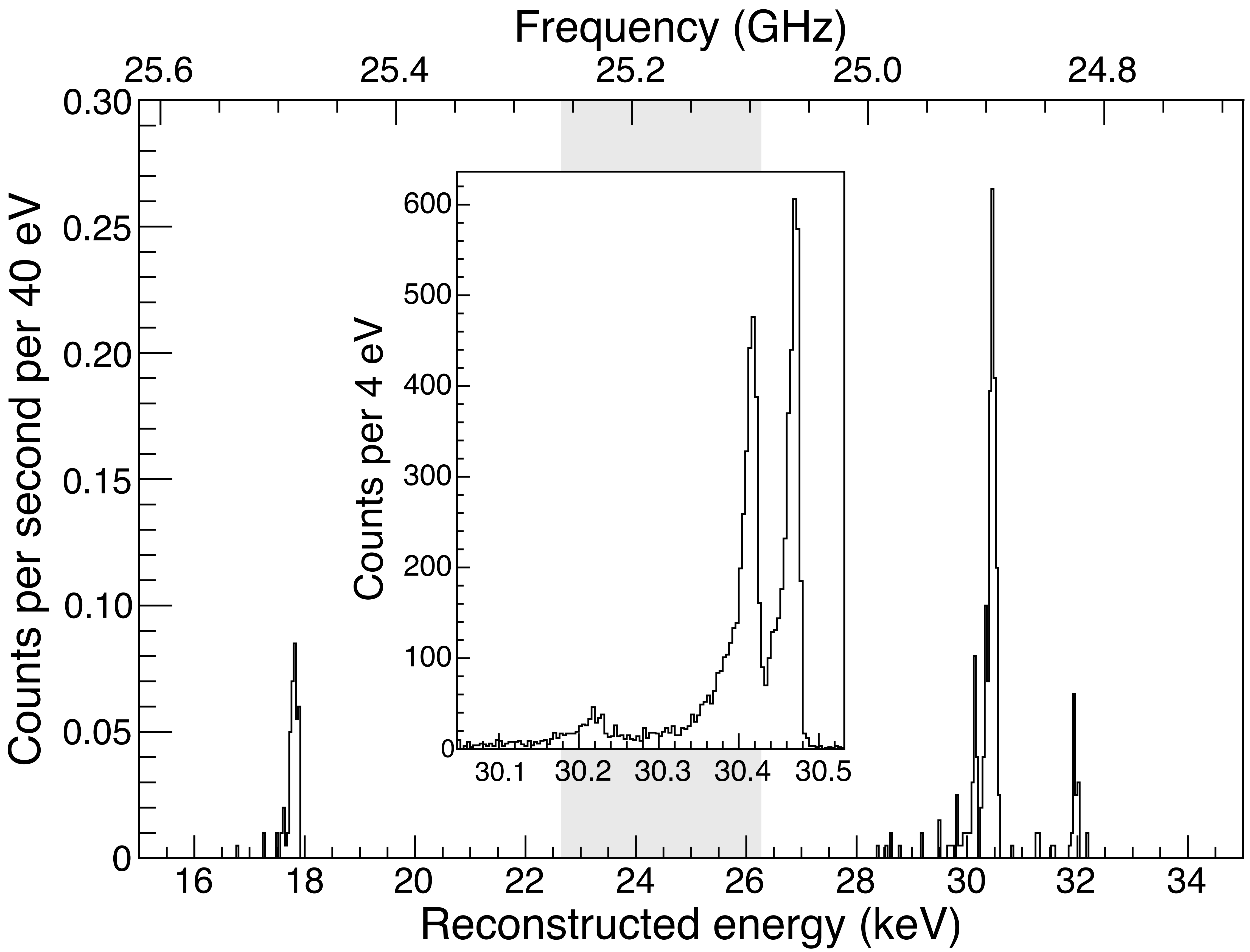
- First detection of single-electron cyclotron radiation - Phys. Rev. Lett. 114, 162501 (2015)
  - Data taking started on 6/6/2014
  - Energy reconstructed from the event initial frequency: ^{83m}Kr lines: 17.8 keV, 30.4 keV, 32 keV, and more



scale: 1 MHz ~ 20 eV

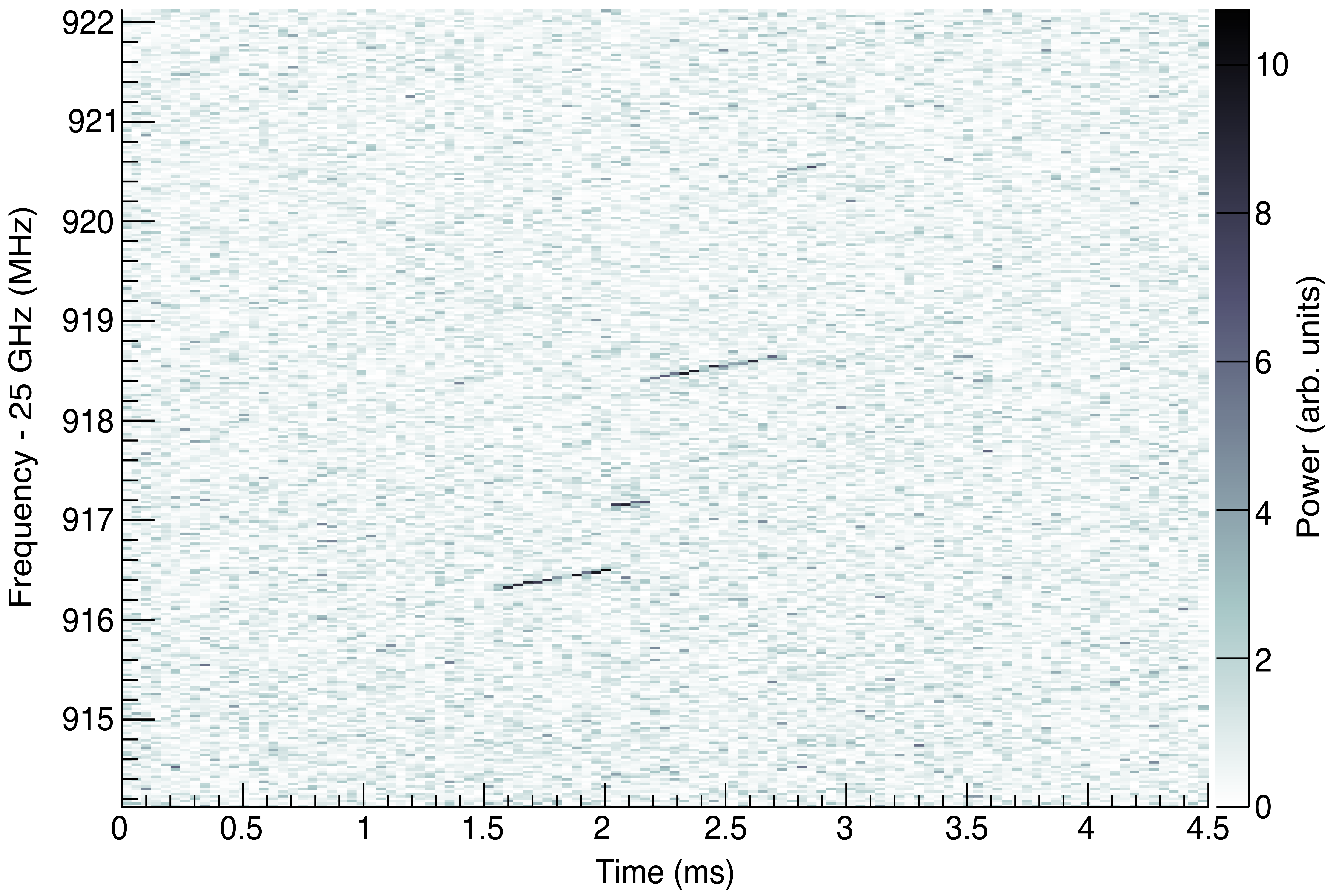
time (ms)

$$f_\gamma = \frac{eB}{2\pi\,(m_e + K/c^2)}$$



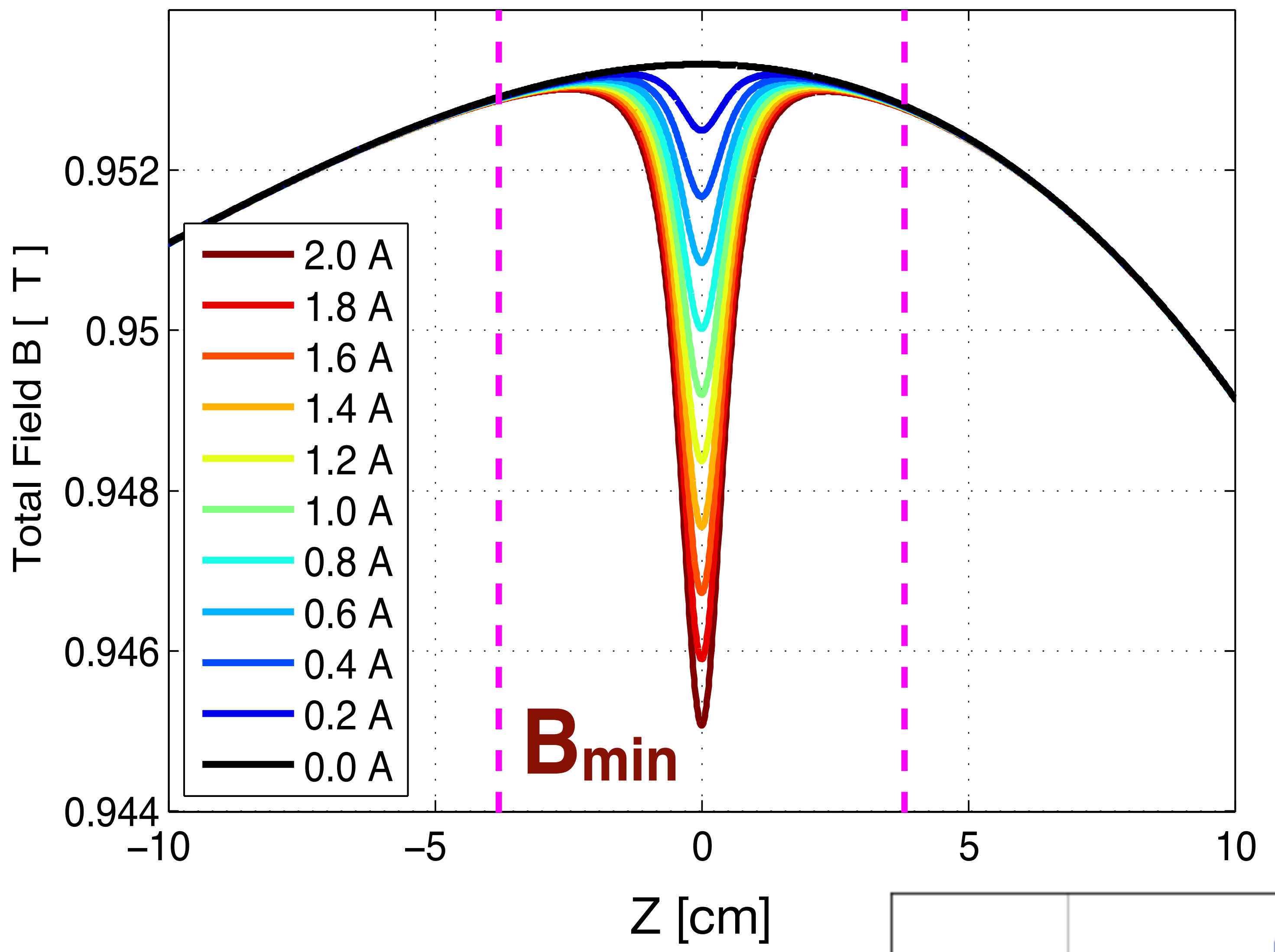
First Tritium Data

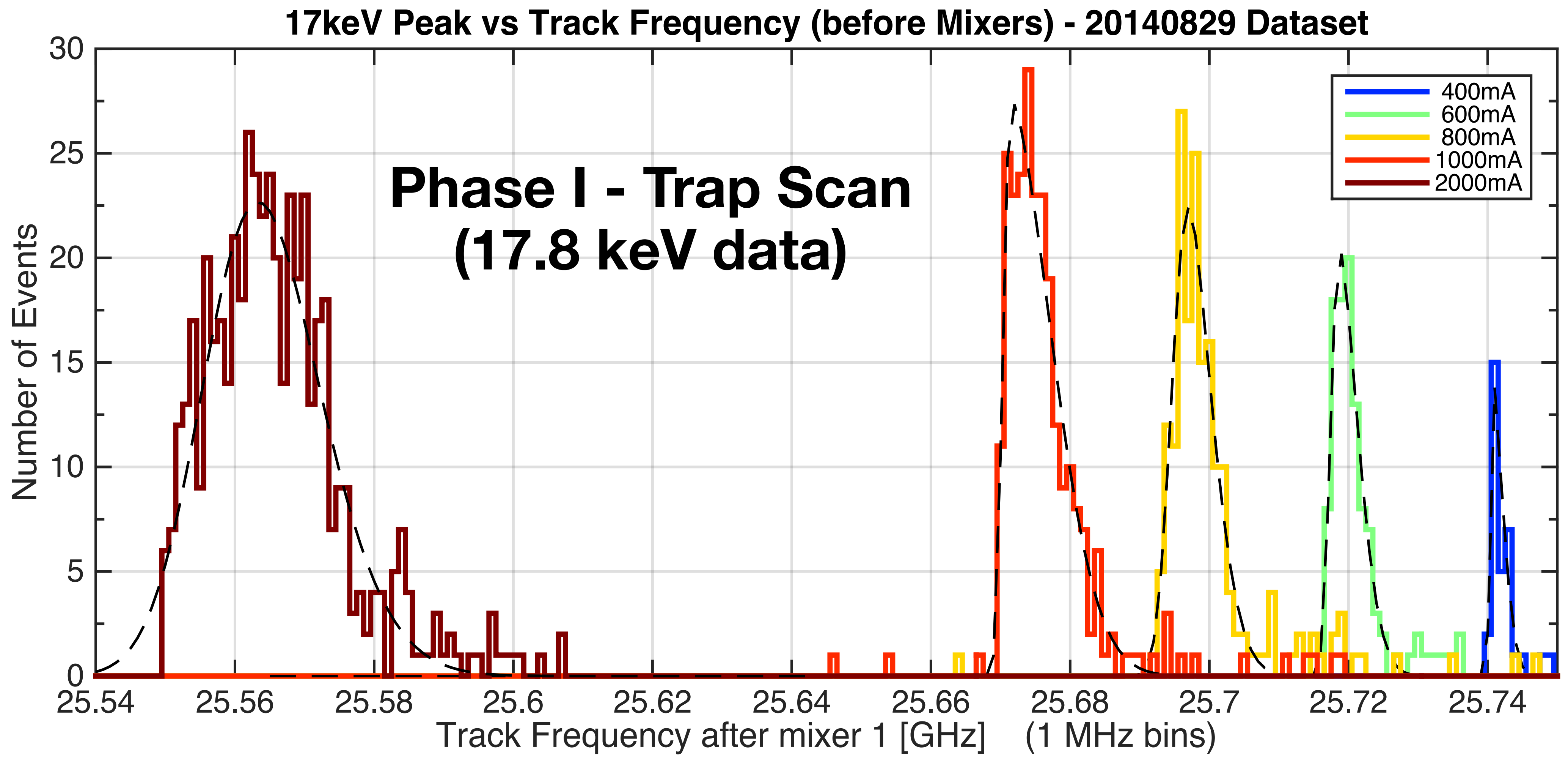
- First Tritium Event - Same general features as seen in Kr data
- Short initial run followed by a systematics campaign → Study of spectral distortions due to efficiency and lineshape are critical



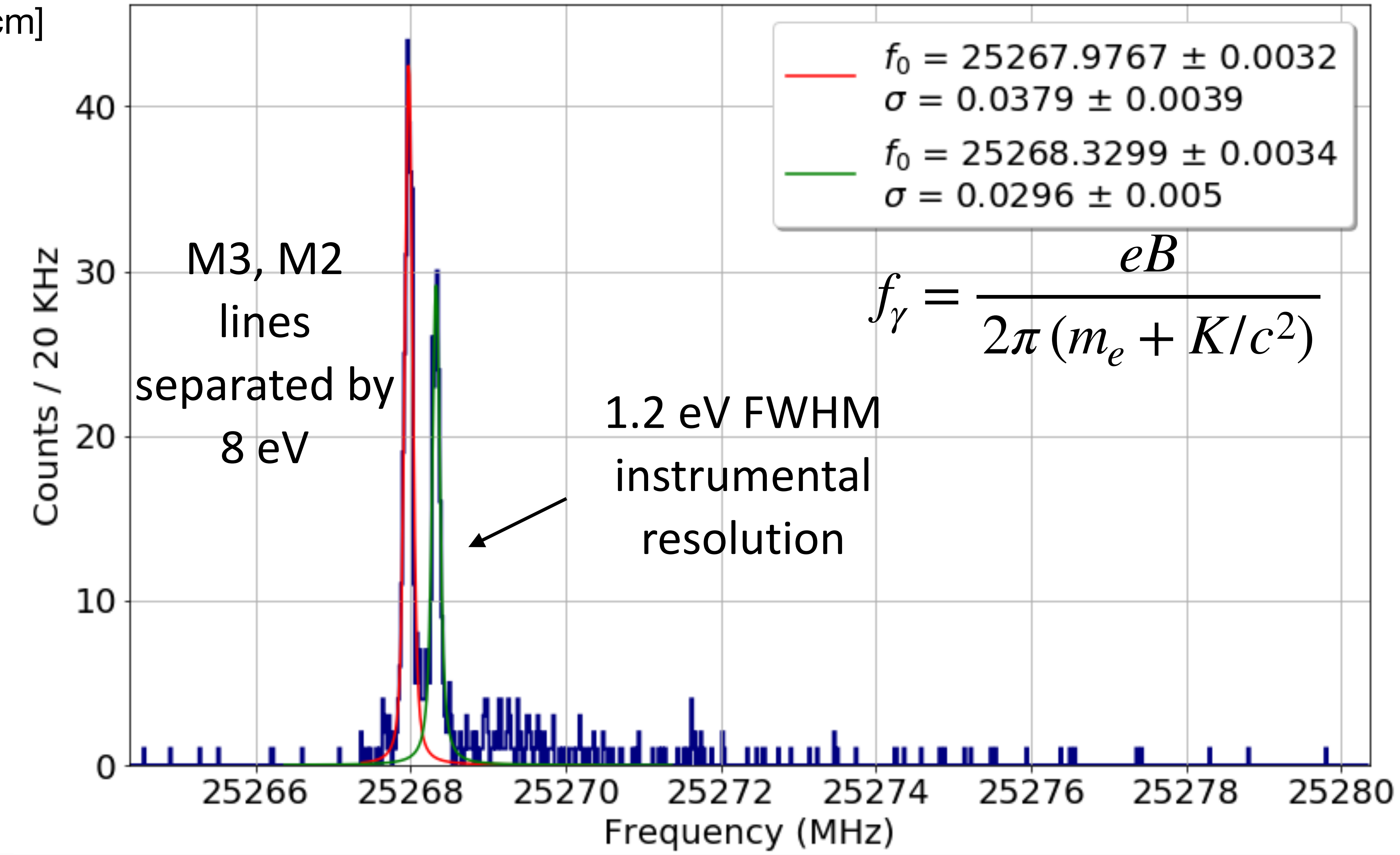
ACHIEVING eV-SCALE RESOLUTION

- Decreasing trap depth reduces event acceptance, increases field uniformity
  - ➡ Reduces event rate
  - ➡ Improves resolution





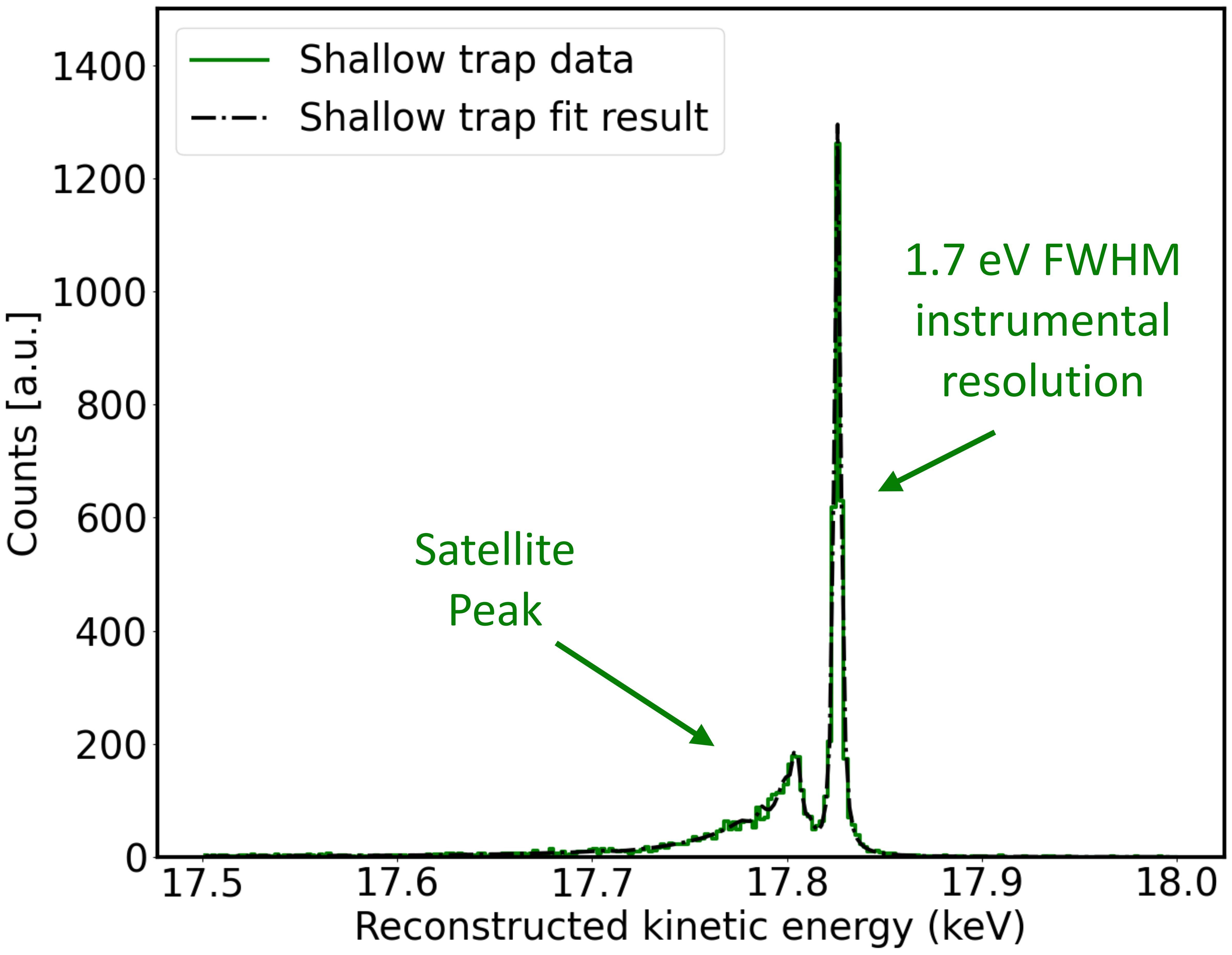
- Resolution measured by fitting ^{83m}Kr calibration data: 17.8, 30, 32 keV
- Best demonstrated instrumental resolution: FWHM = 1.2 eV
  - For the 32 keV line from ^{83m}Kr



$$f_\gamma = \frac{eB}{2\pi\,(m_e + K/c^2)}$$

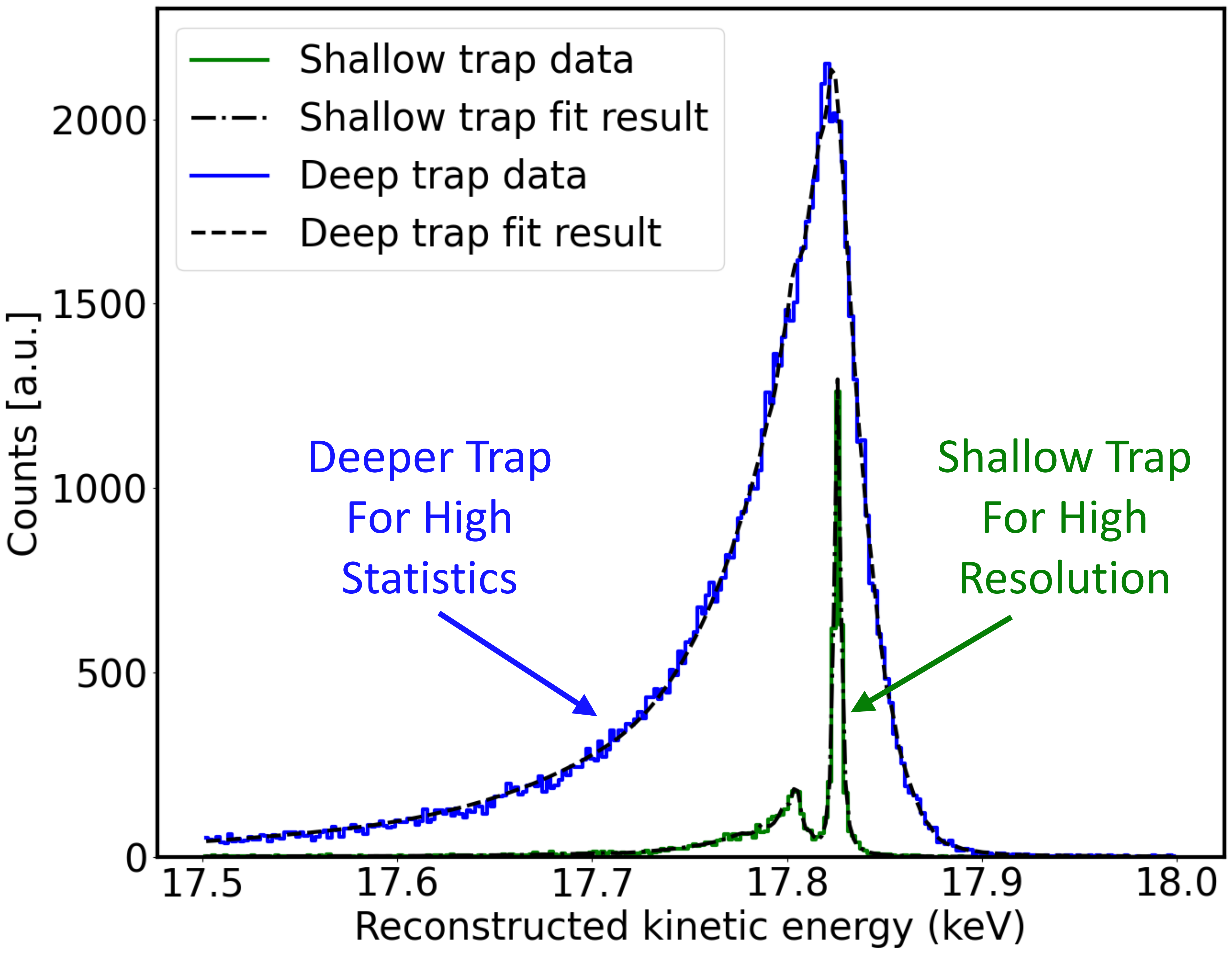
ENERGY RESOLUTION AND TRAP CONFIGURATION

- In Phase II, we usually operate in one of two possible configurations:
  - *Shallow harmonic trap* for high precision scans
  - *Deep harmonic trap* for high statistics
- Resolution measured by fitting ^{83m}Kr calibration data
  - 17.8 keV K-line from ^{83m}Kr, with FWHM = 2.8 ± 0.1 eV natural line width
- Best demonstrated instrumental width:
  FWHM = 1.7 ± 0.2 eV
  - Satellite peak from shake-up/shake-off and scattering from residual gas
  - Detected line shape well-described by model



Energy Resolution and Trap Configuration

- In Phase II, we usually operate in one of two possible configurations:
  - *Shallow harmonic trap* for high precision scans
  - *Deep harmonic trap* for high statistics
- Resolution measured by fitting ^{83m}Kr calibration data
  - 17.8 keV K-line from ^{83m}Kr, with FWHM = 2.8 ± 0.1 eV natural line width
- Tritium dataset uses deeper trap: FWHM = 54.3 eV
  - Higher statistics at cost of energy resolution → Better predicted sensitivity to endpoint for ~100 day run
  - Compensate for small 1 mm³ effective volume
  - Detector response model still works well
    - Effects from magnetic field inhomogeneity, scattering, and missed tracks are understood

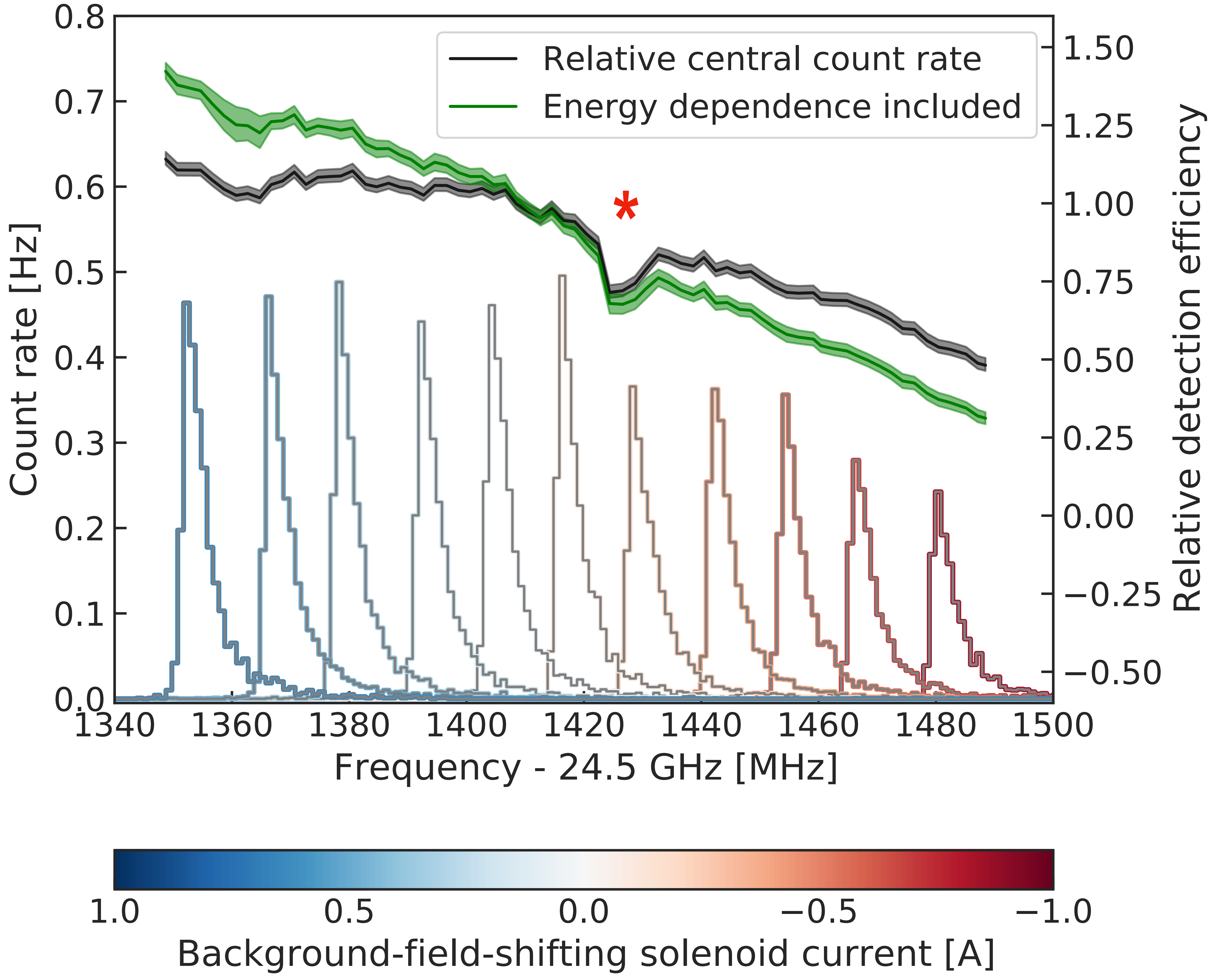


^{83m}Kr MEASUREMENTS: FREQUENCY DEPENDENCE

- Magnetic field swept to study efficiency and scattering effects across frequency ROI
- Using 17.8 keV Kr line

$$f_\gamma = \frac{eB}{2\pi(m_e + K/c^2)}$$

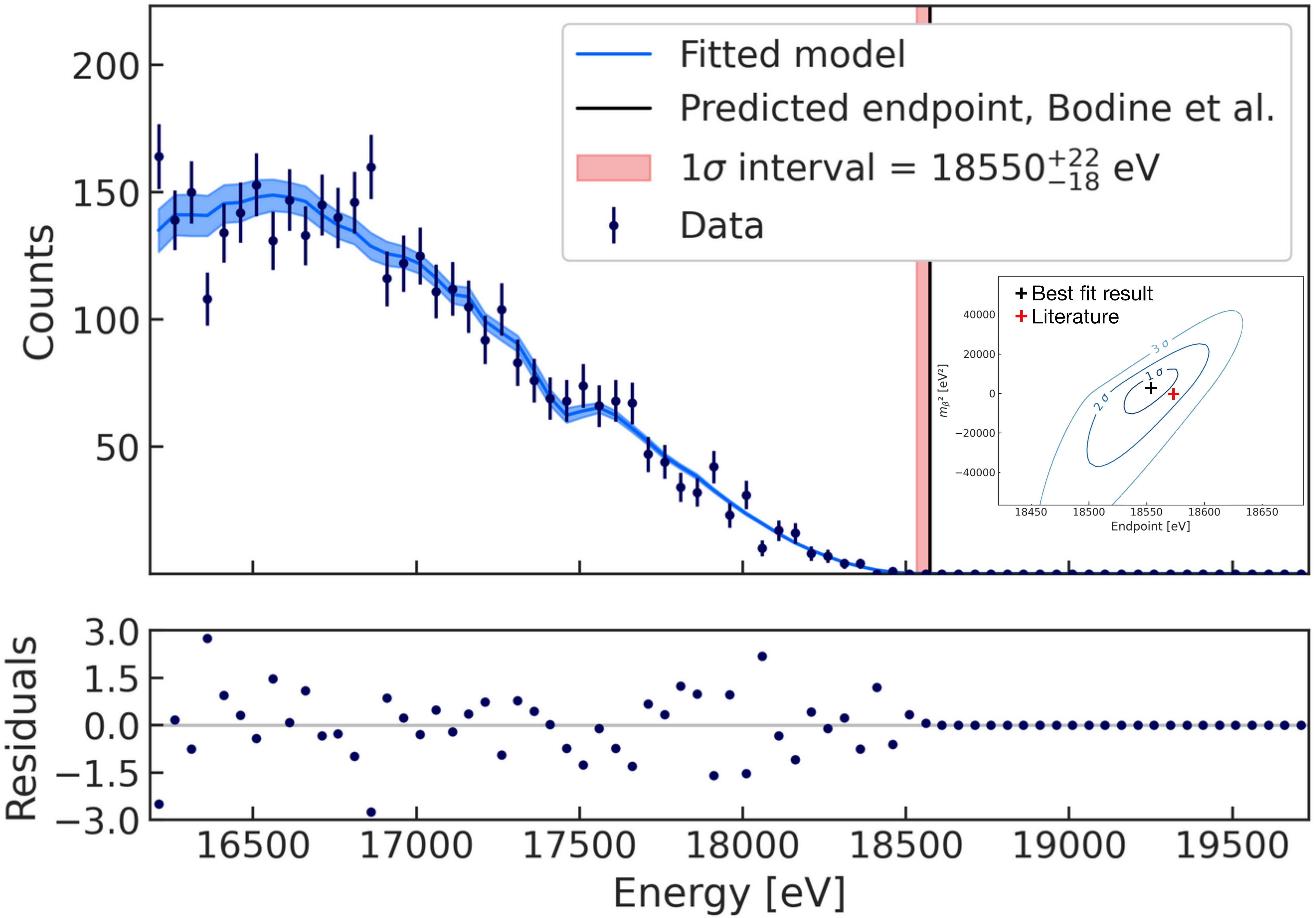
- Direct characterization of significant RF response variation of the waveguide
- Notch in efficiency is understood (*)
  - Caused by the interaction with TM_{01} mode of detection cavity
  - Quantitatively characterized and is accounted for in analysis



Phase II Tritium Results

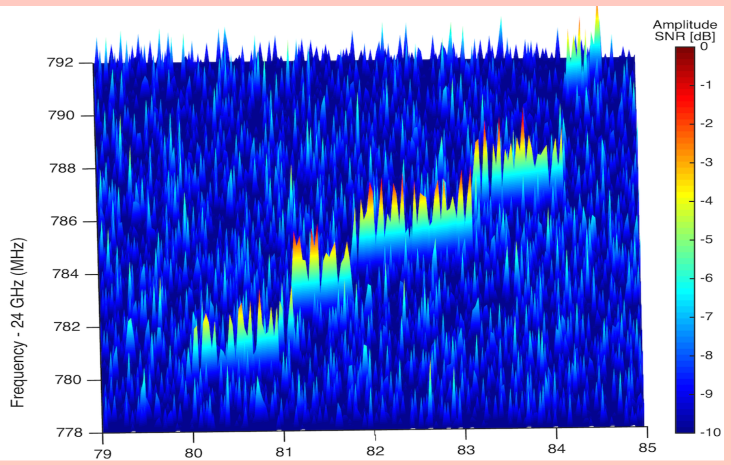
- Long science run completed in 2020
  - 82 net days of data taking, 3770 events
  - 4 trapping coils, 1 mm³ effective volume
- T_2 endpoint measurement in agreement with literature
  - Frequentist: $E_0 = \left(18550^{+22}_{-18}\right)$ eV (1σ)
  - Bayesian: $E_0 = \left(18553^{+17}_{-17}\right)$ eV (1σ)
- First neutrino mass measurement using CRES !
  - Frequentist: ≤ 178 eV/c^2 (90 % C.L)
  - Bayesian: ≤ 169 eV/c^2 (90 % C.L)
- No events past endpoint
  ⇒ sets limit on background rate:

$\leq 3 \times 10^{-10}$ eV^{-1}s^{-1} (90 % C.L.)

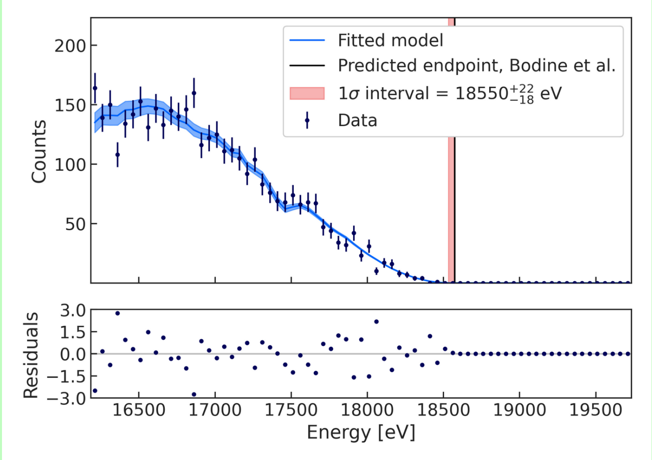


The Project 8 Scientific Programme: A Phased Approach

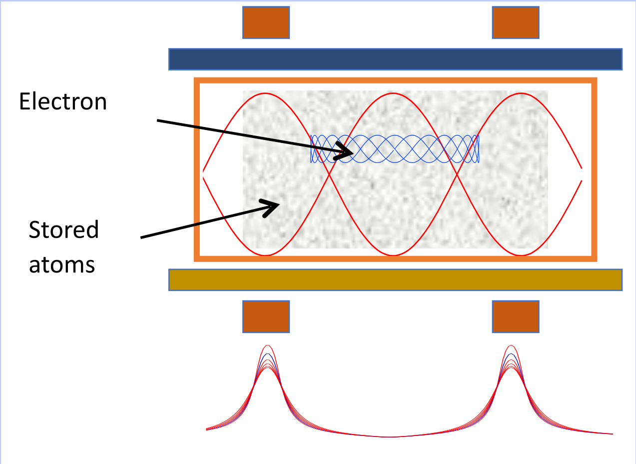
Phase I:
Demonstrate CRES technique on 83mKr mono-energetic electrons.
Status: Complete! Technique demonstrated.



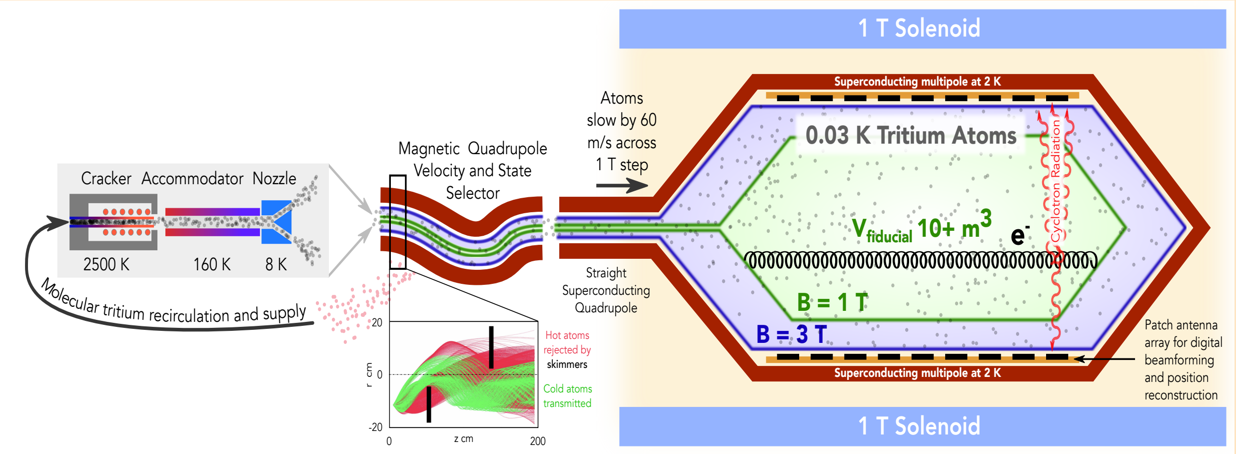
Phase II:
First T2 spectrum. Extract endpoint. Study systematics and backgrounds.
Status: Nearing completion



Phase III:
(a) "Large Volume" CRES
(b) Atomic tritium production and trapping at high densities



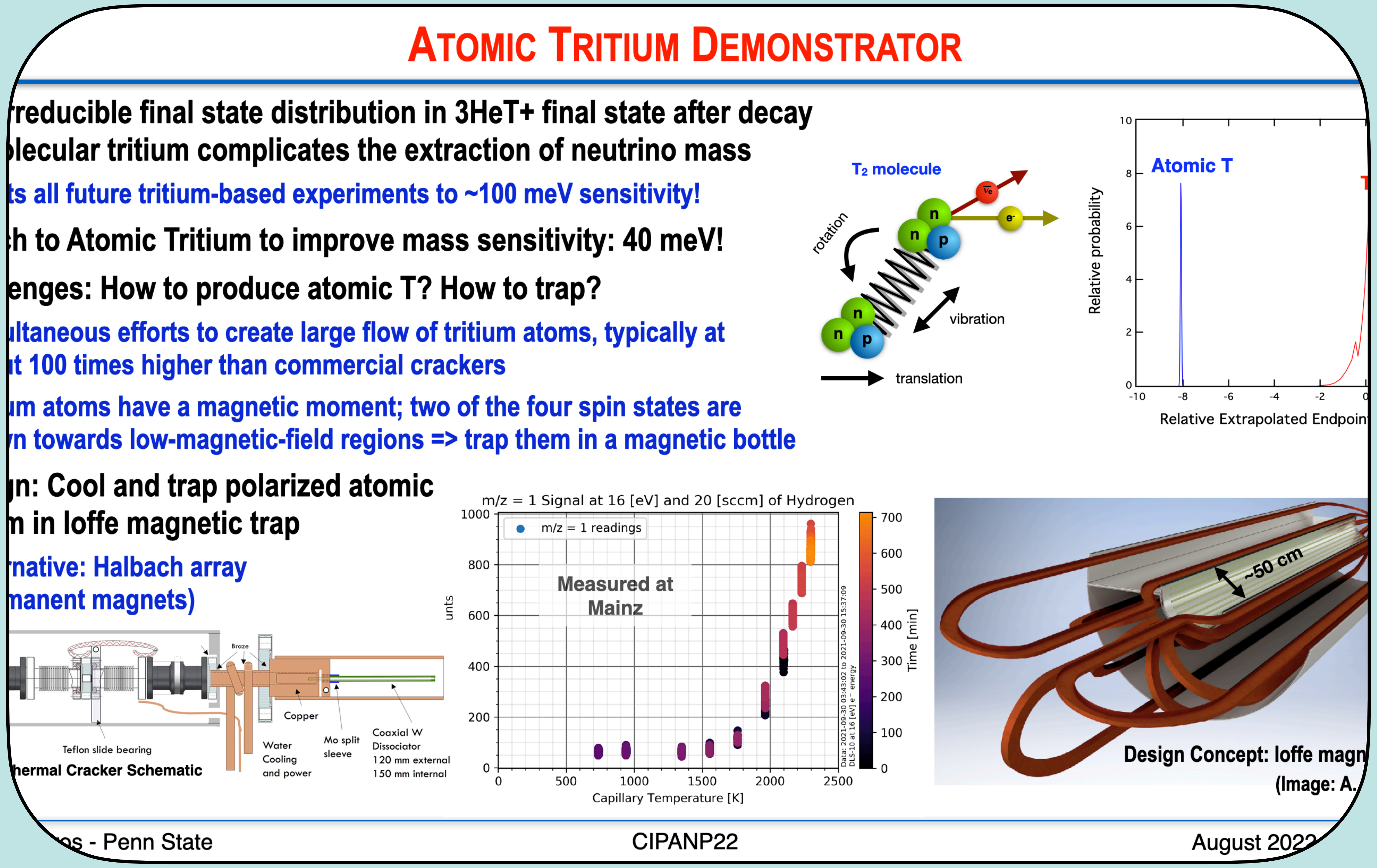
Phase IV:
Large atomic tritium experiment. Inverted mass ordering reach (40 meV)



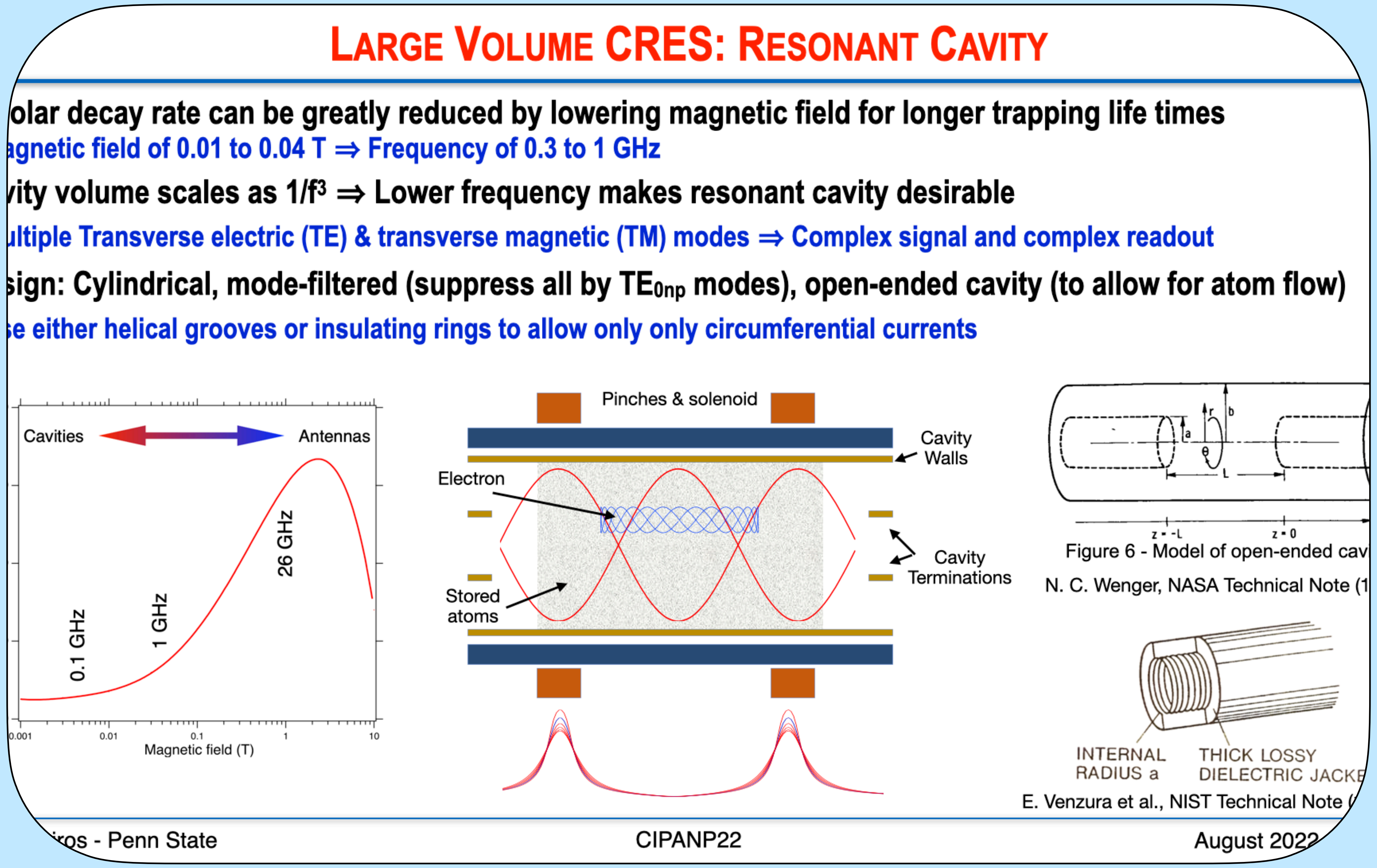
PHASE-III

- Phase-III: Develop the new techniques needed to achieve the Project 8 goal sensitivity

Atomic Tritium
⇒ Decrease Final State Uncertainty

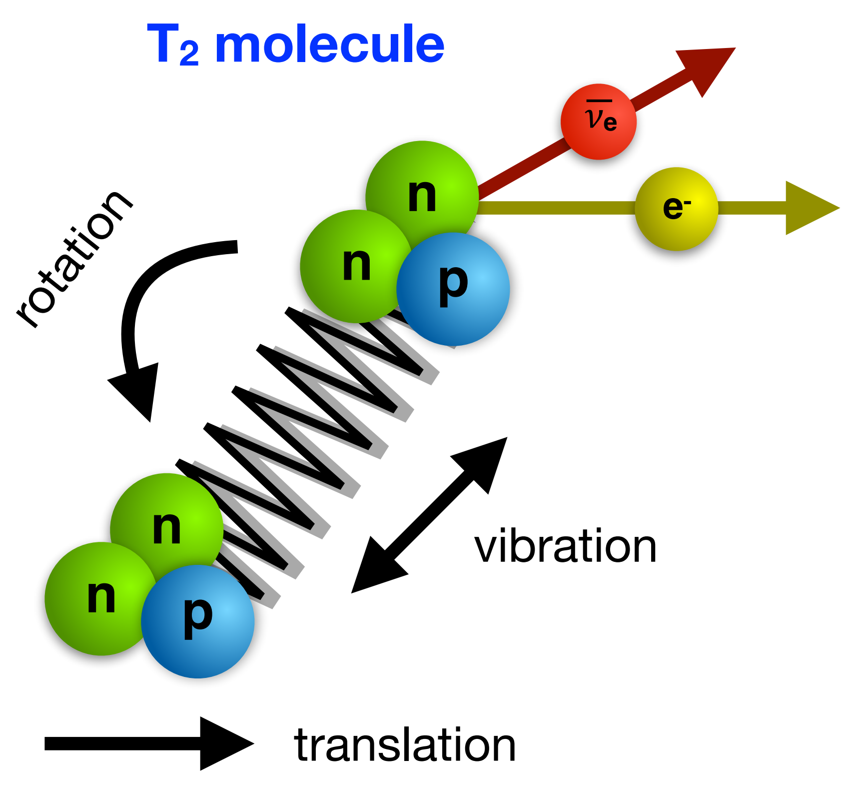


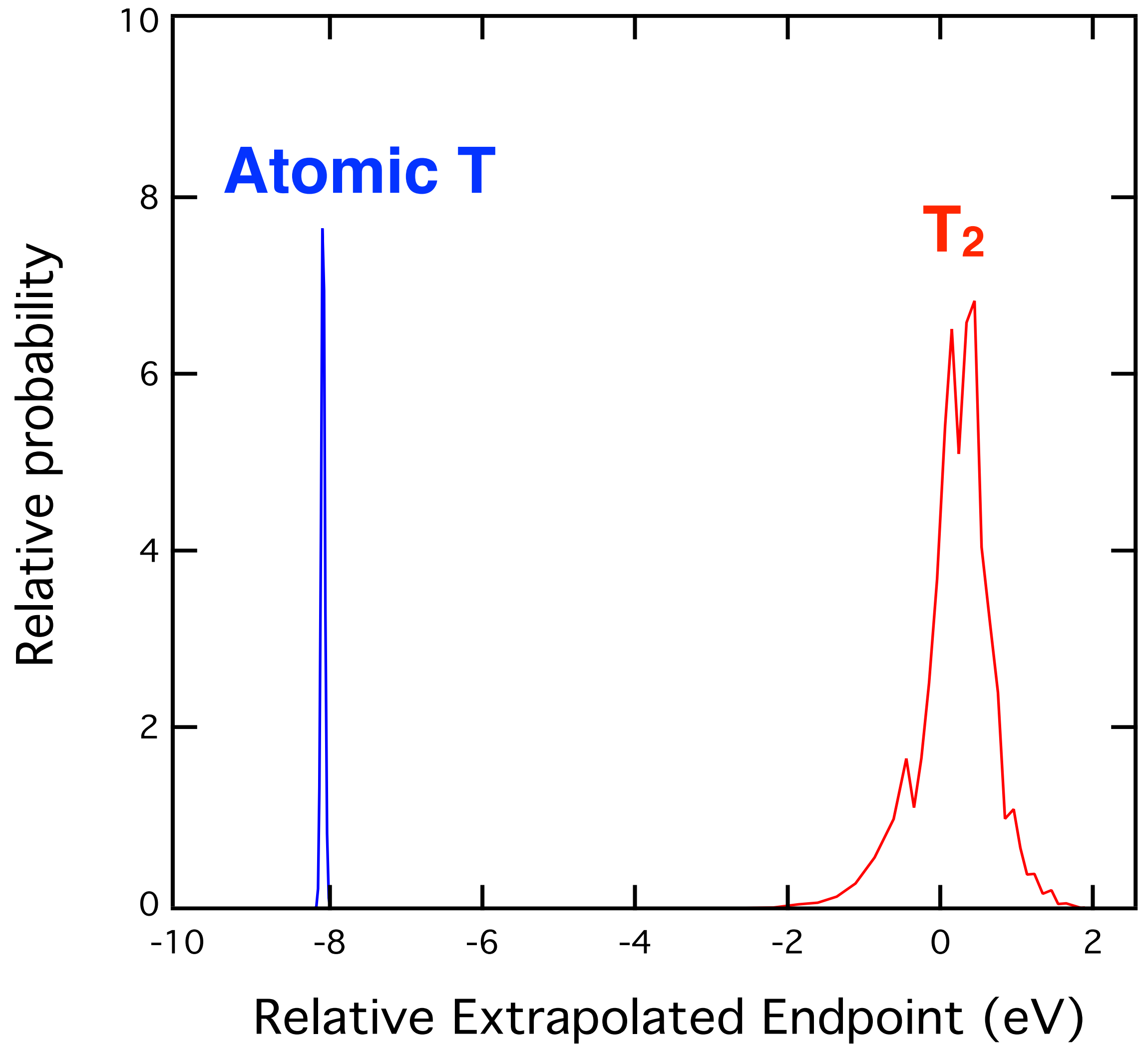
CRES in Large Volumes



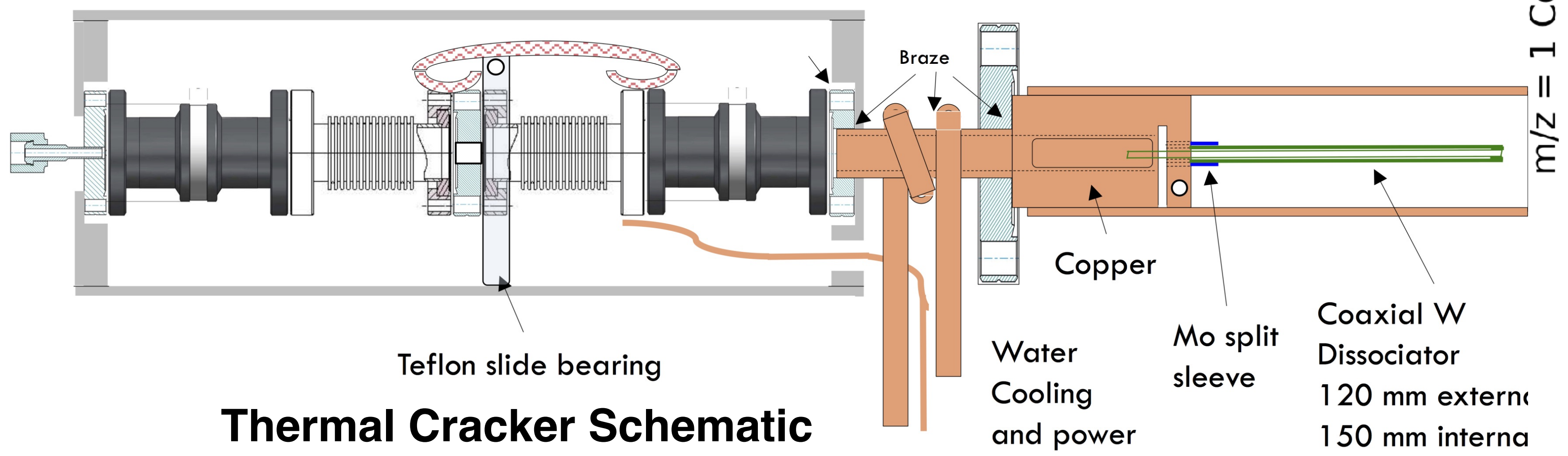
ATOMIC TRITIUM

- The irreducible final state distribution in 3HeT+ final state after decay of molecular tritium complicates the extraction of neutrino mass
  - Limits all future tritium-based experiments to ~100 meV sensitivity!
- Switch to Atomic Tritium to improve mass sensitivity: 40 meV!
- Challenges: How to produce atomic T? How to trap?
  - Simultaneous efforts to create large flow of tritium atoms, typically at about 100 times higher than commercial crackers
  - Tritium atoms have a magnetic moment; two of the four spin states are drawn towards low-magnetic-field regions => trap them in a magnetic bottle

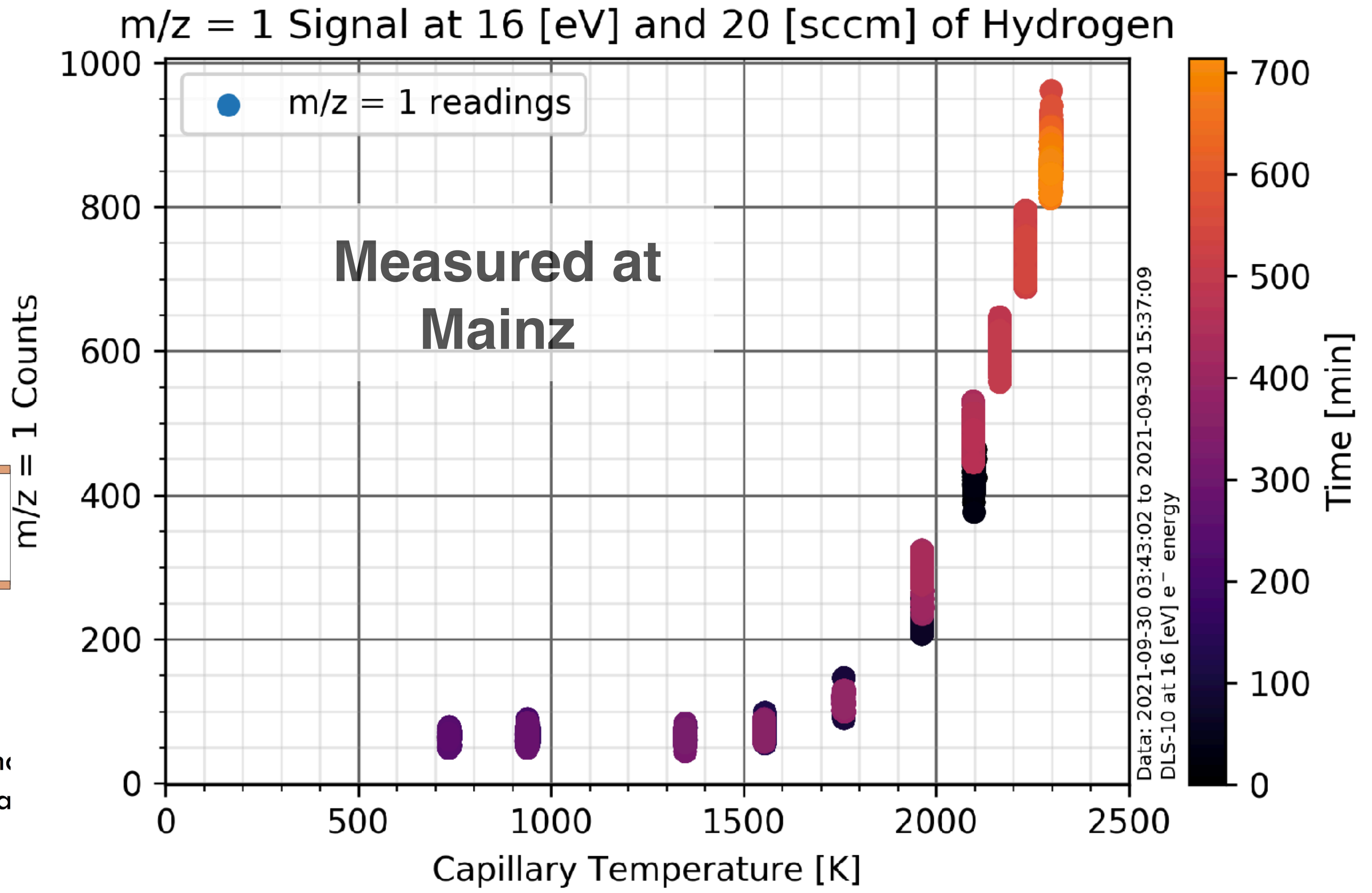


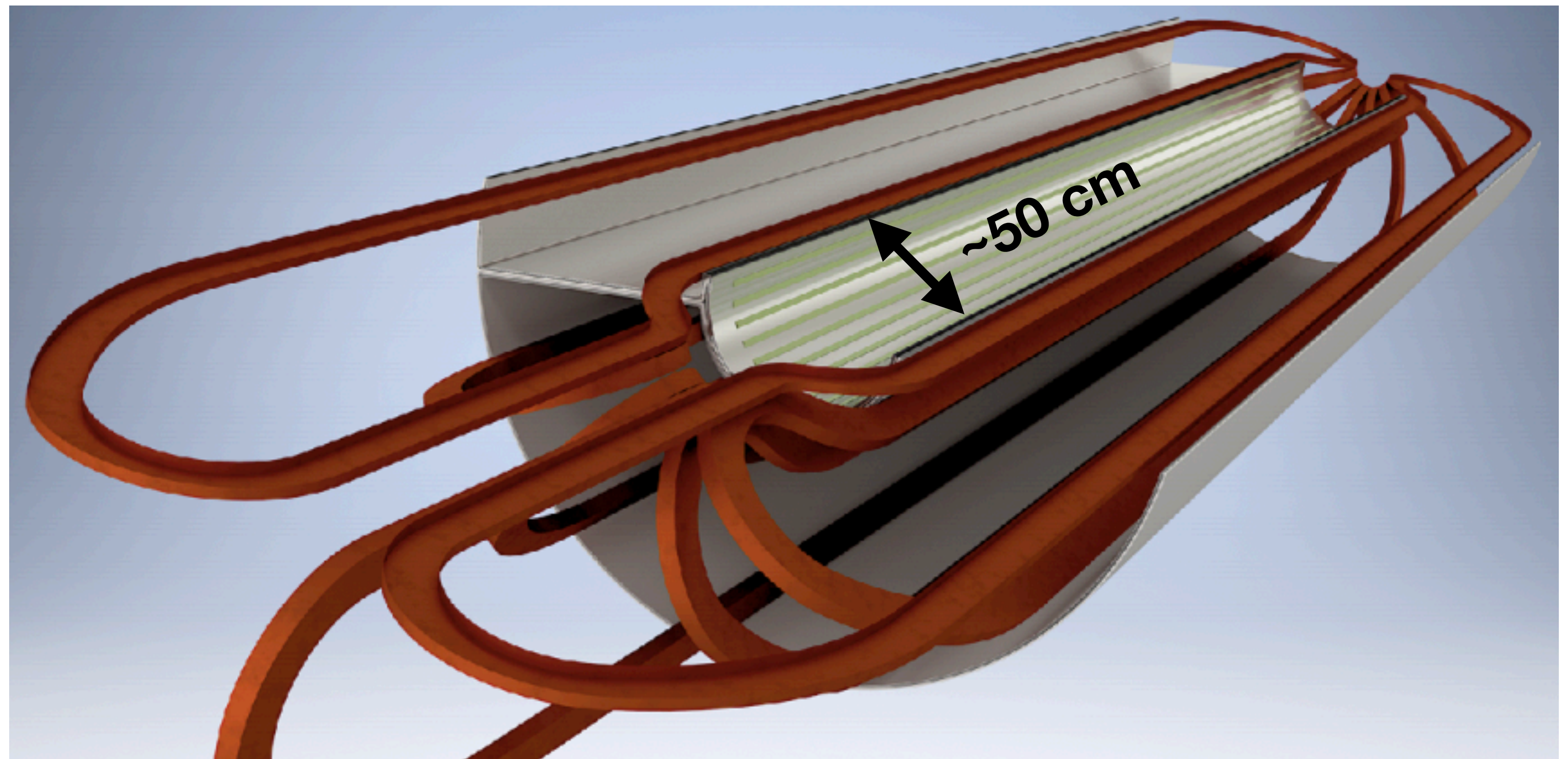


- Design: Cool and trap polarized atomic tritium in Ioffe magnetic trap
  - Alternative: Halbach array (permanent magnets)



Thermal Cracker Schematic

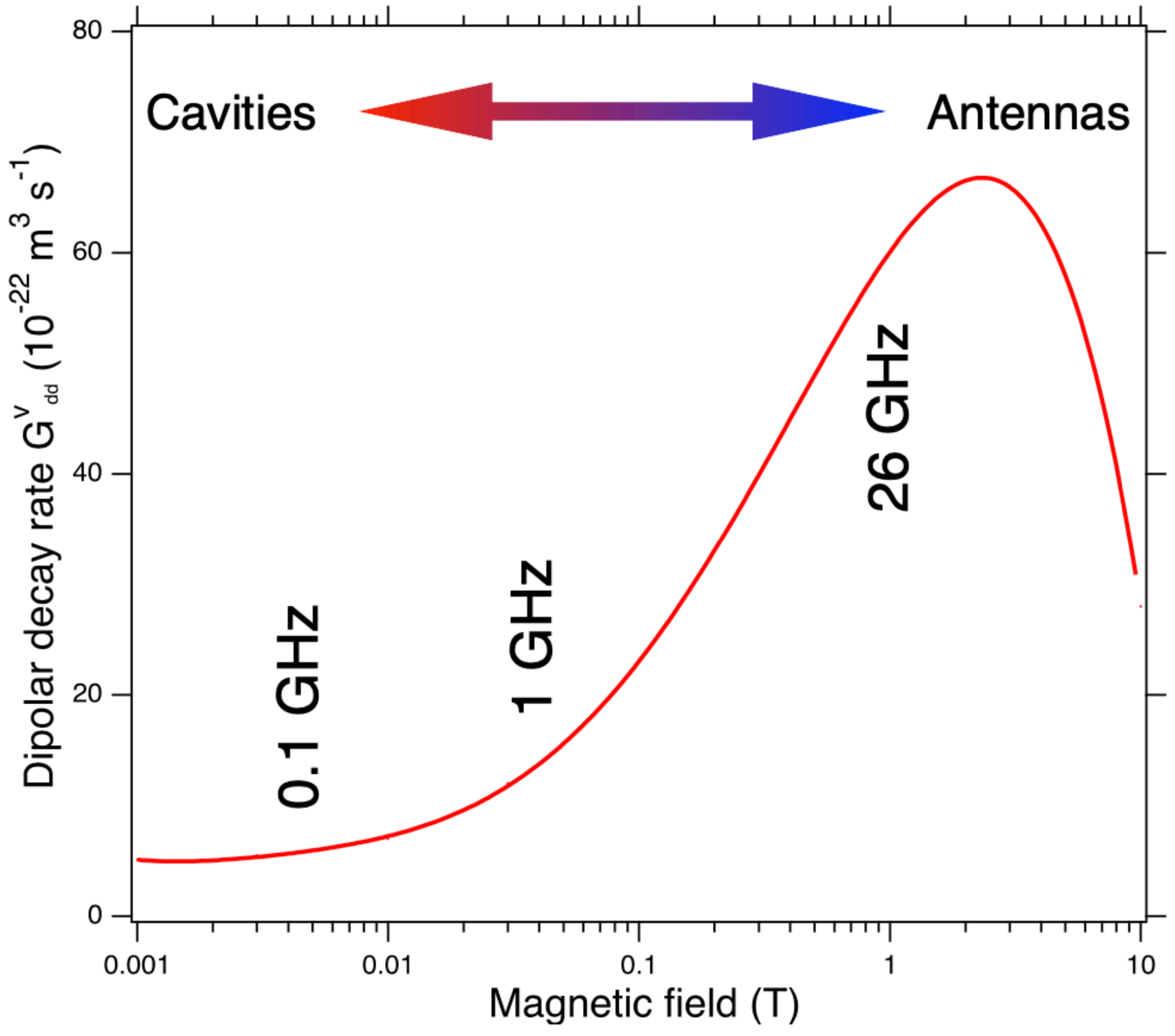


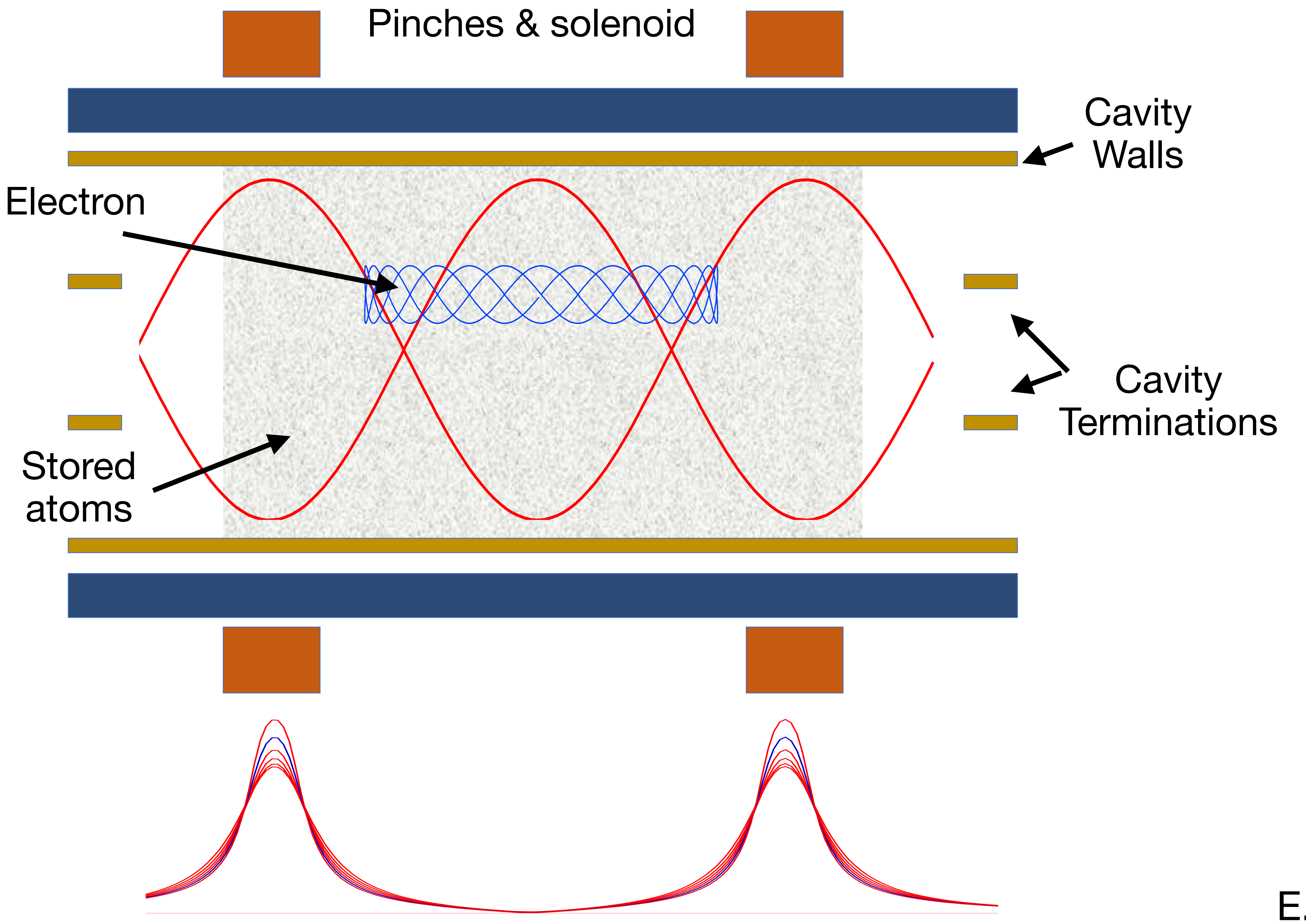


Design Concept: Ioffe magnetic trap (Image: A. Lindman)

Large Volume CRES: Resonant Cavity

- Dipolar decay rate can be greatly reduced by lowering magnetic field for longer trapping life times
  - Magnetic field of 0.01 to 0.04 T ⇒ Frequency of 0.3 to 1 GHz
- Cavity volume scales as $1/f^3$ ⇒ Lower frequency makes resonant cavity desirable
  - Multiple Transverse electric (TE) & transverse magnetic (TM) modes ⇒ Complex signal and complex readout
- Design: Cylindrical, open-ended (to allow for atom flow), mode-filtered (suppress all by TE_{01p} modes) cavity
  - Use either helical grooves or insulating rings to allow only only circumferential currents





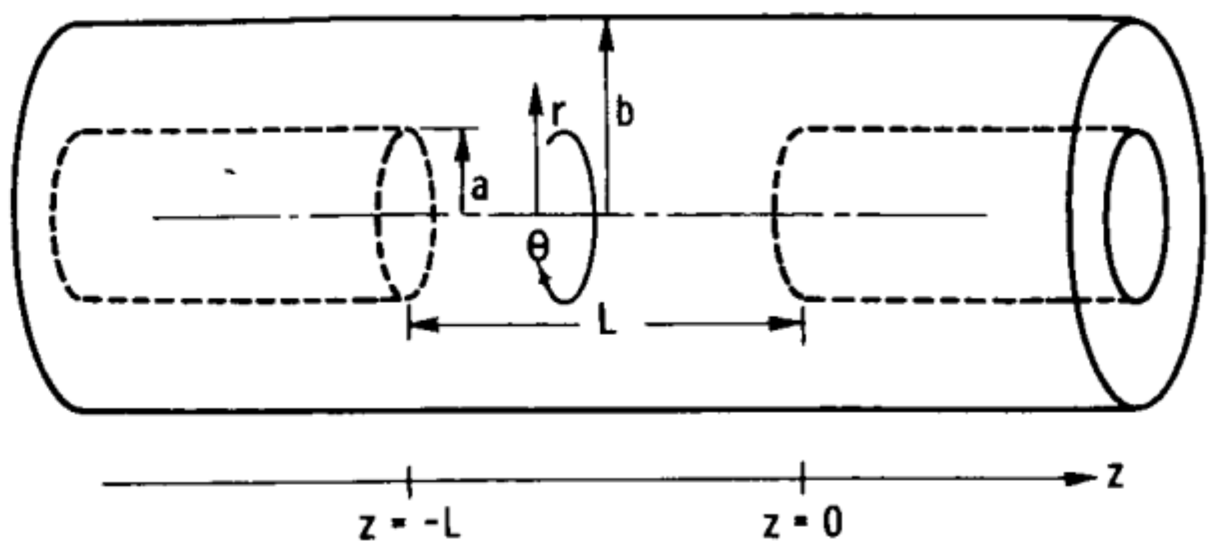
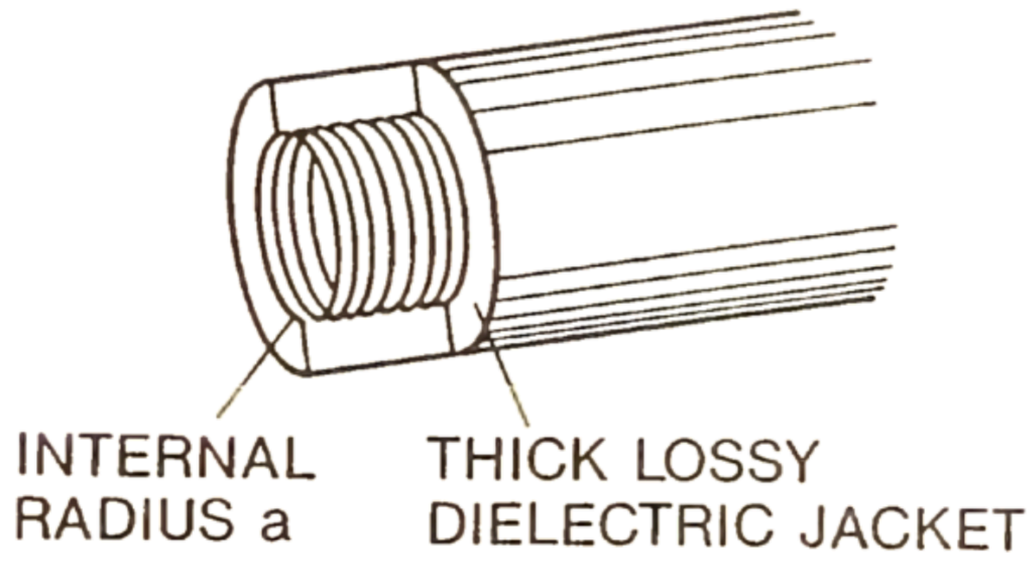


Figure 6 - Model of open-ended cavity

N. C. Wenger, NASA Technical Note (1966)

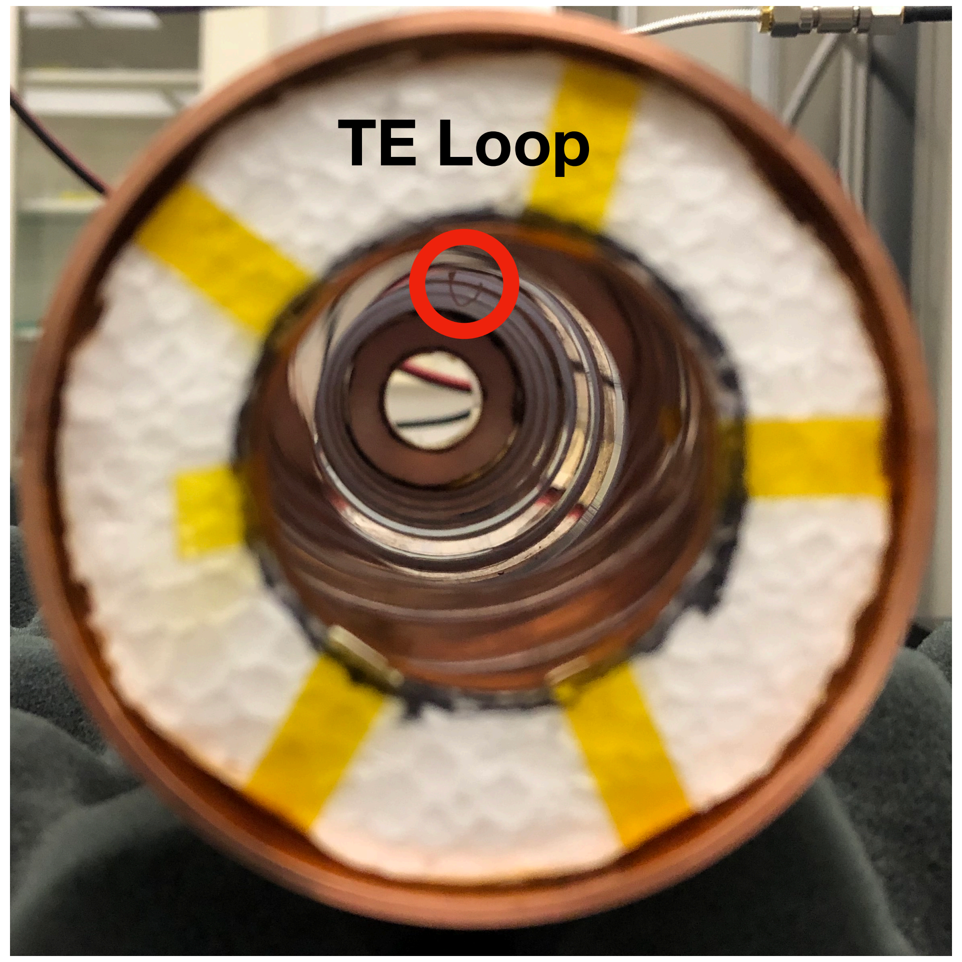


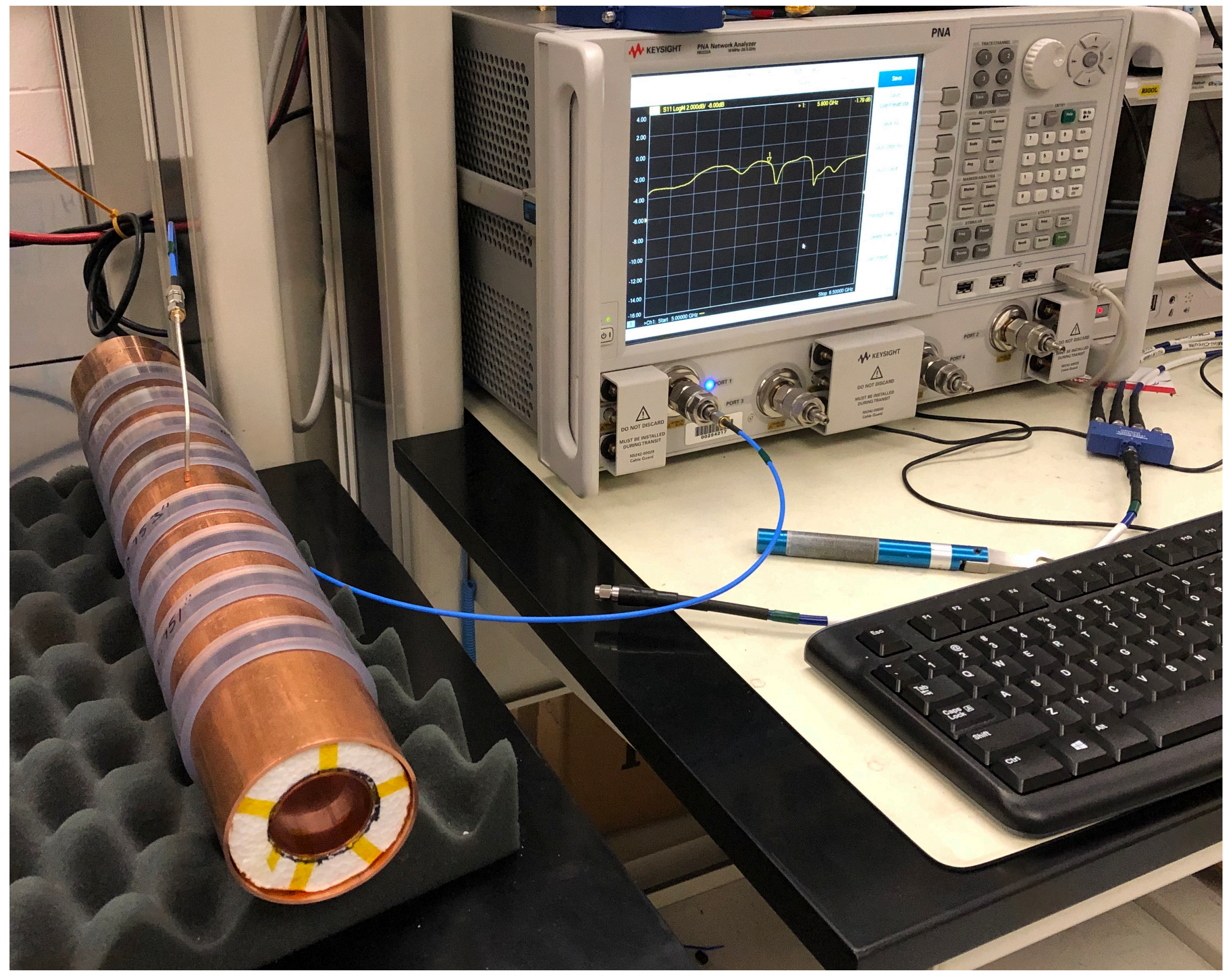
E. Venzura et al., NIST Technical Note (1993)

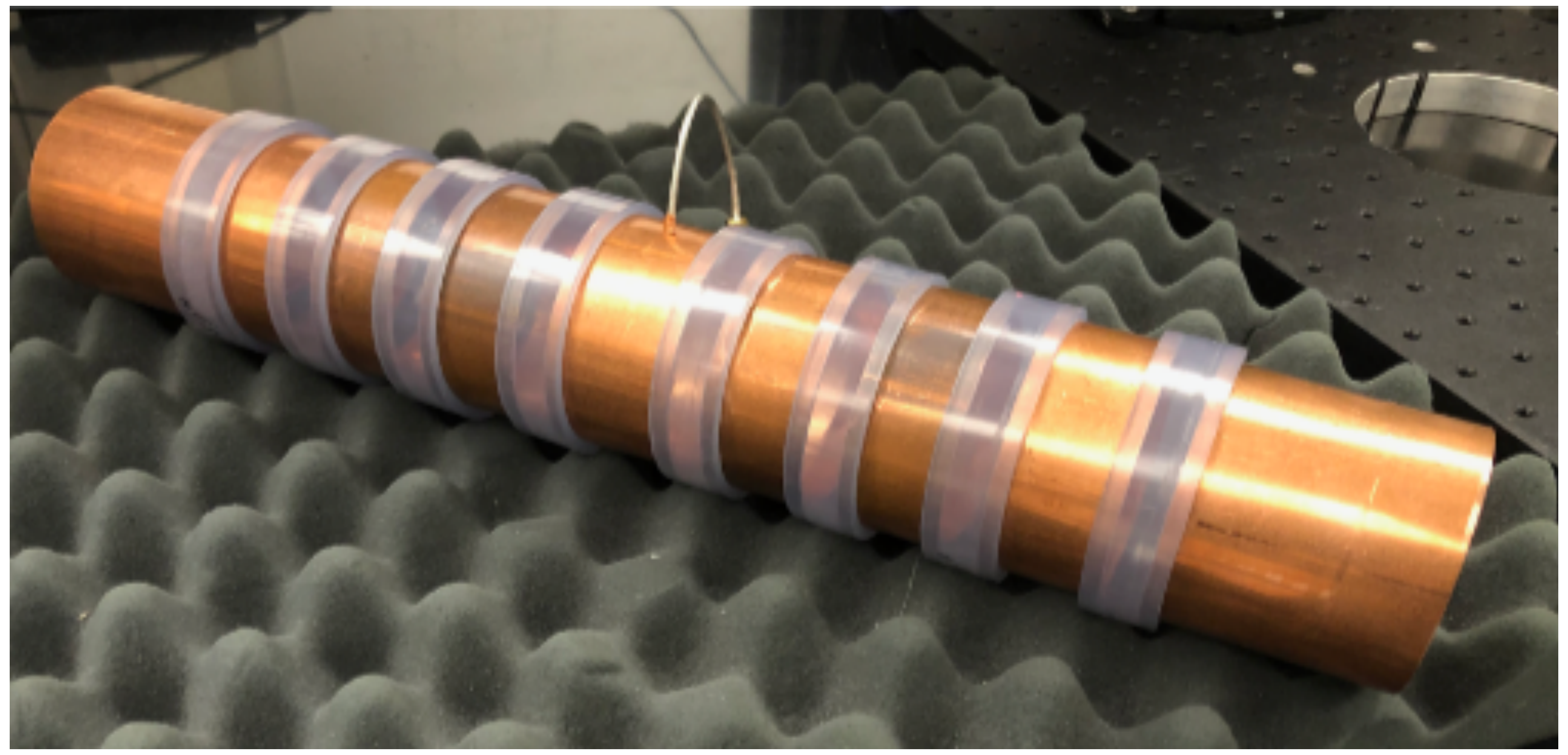
Cavity R&D - First Measurements

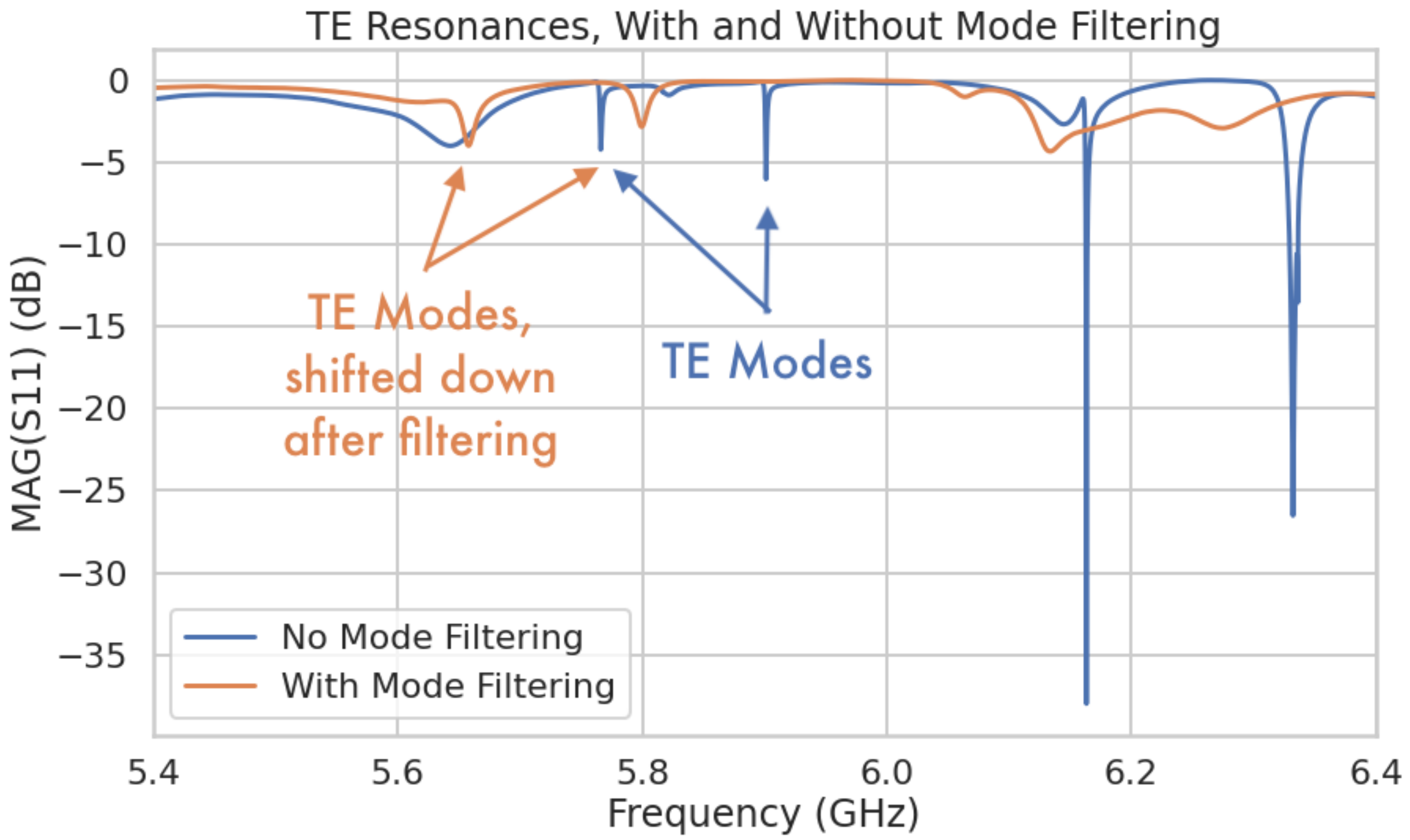
- 6 GHz Prototype
- Copper tubes connected by clear PVC rings (dielectric spacers) permit only circumferential currents
  - 1 cm spacer, 3 cm body section, 6 cm end section
- Allows only TE01p modes to propagate
- Verified mode-filtering, readout via rotatable coax loop
  - Measured with VNA

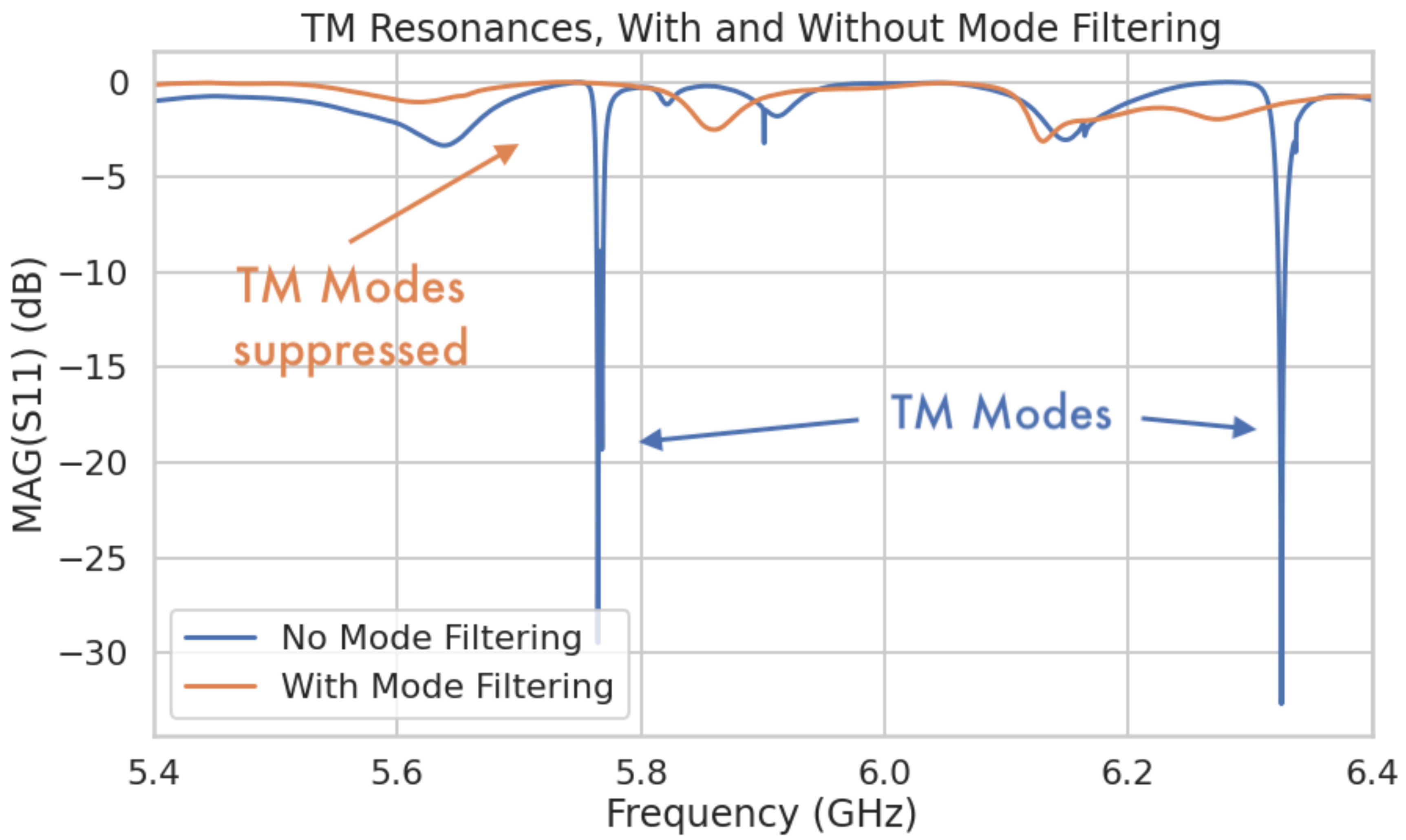
Readout









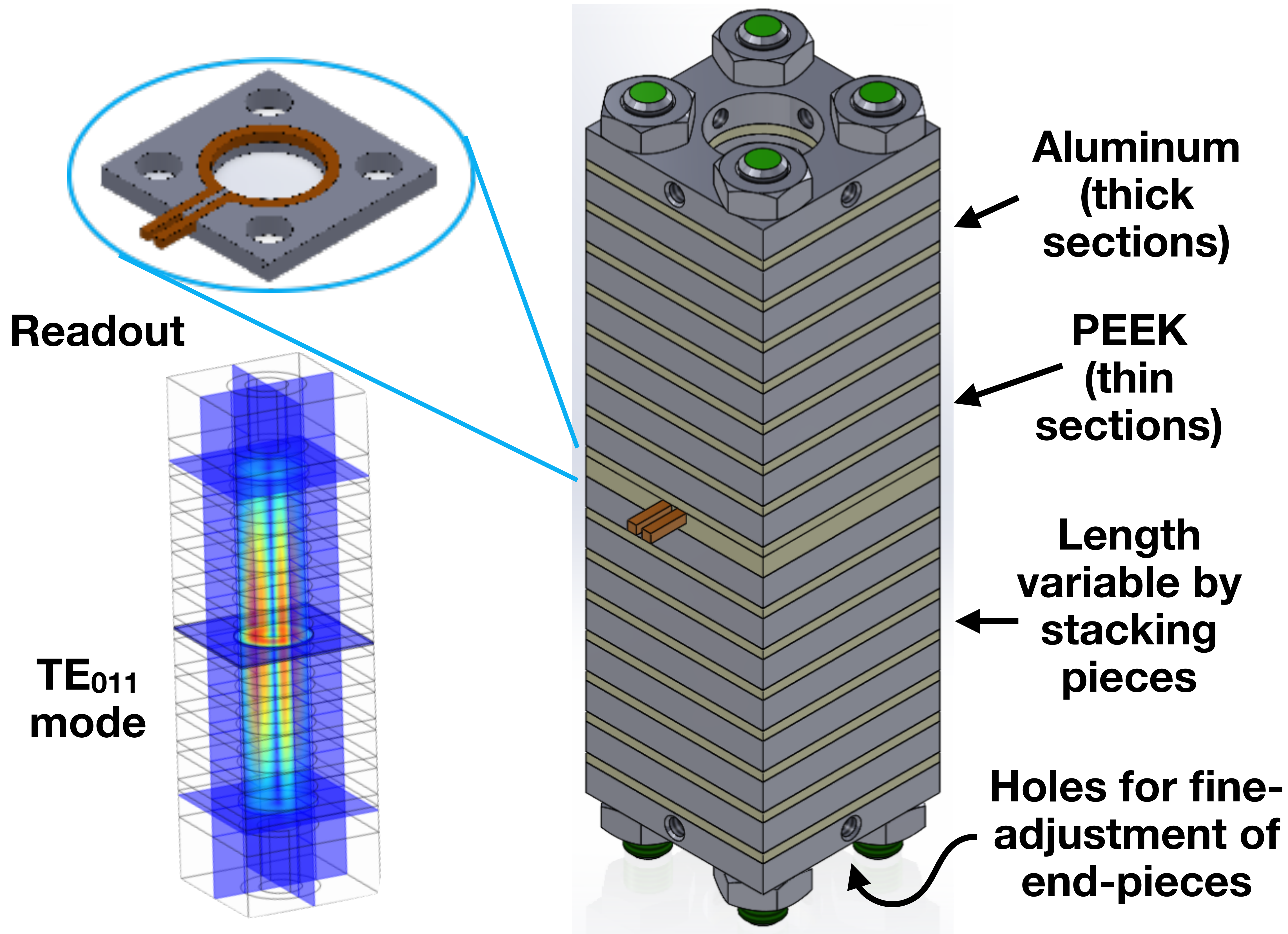


Photos and Plots by A. Ziegler, Penn State

Cavity R&D

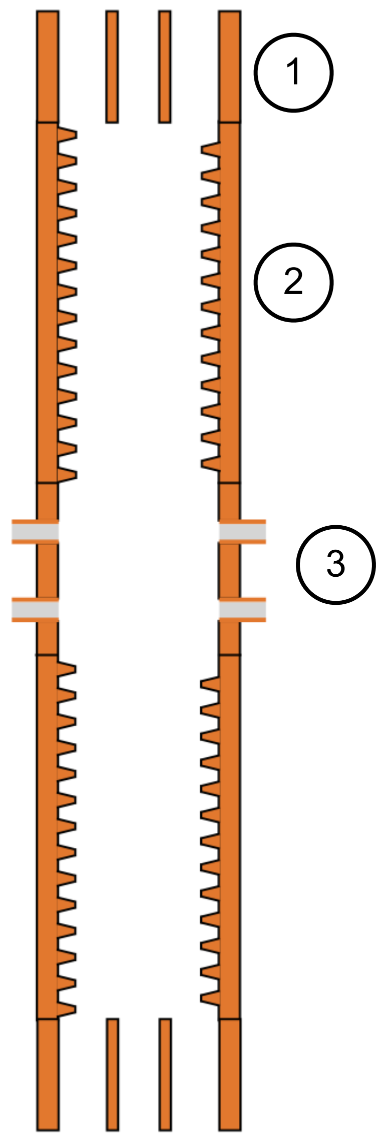
26 GHz

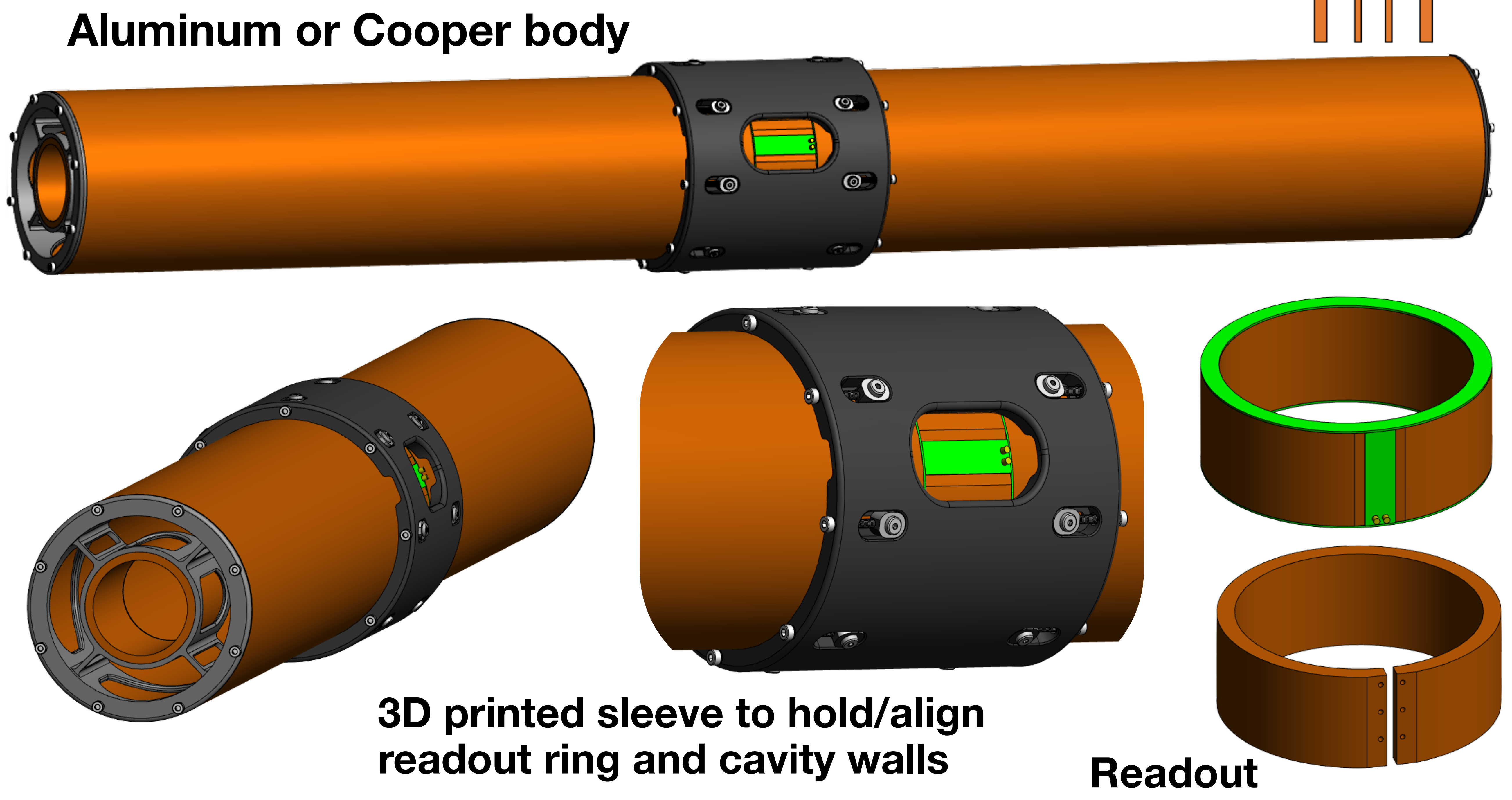
- Small Cavity for use in existing 1 T MRI magnet
  - L = 6 cm, R < 1cm, V ~ 10 cm^3
  - Trapped electrons from electron gun
- Goal: Demonstrate Cavity CRES; verify high volume and pitch angle efficiency



3 GHz

- Building towards a 1 GHz cavity
  - L = 1.15 m, R ~ 12 cm, V ~ 10^4 cm^3
- Goal: Scalability and manufacturability
  - 1 - Coaxial terminations, with open inner cylinder
  - 2 - Threaded" (helical) grooves for ease of manufacture
  - 3 - Non-invasive "cut ring" readout: insulated ring in the vertical center of the cavity, with a longitudinal cut on one side

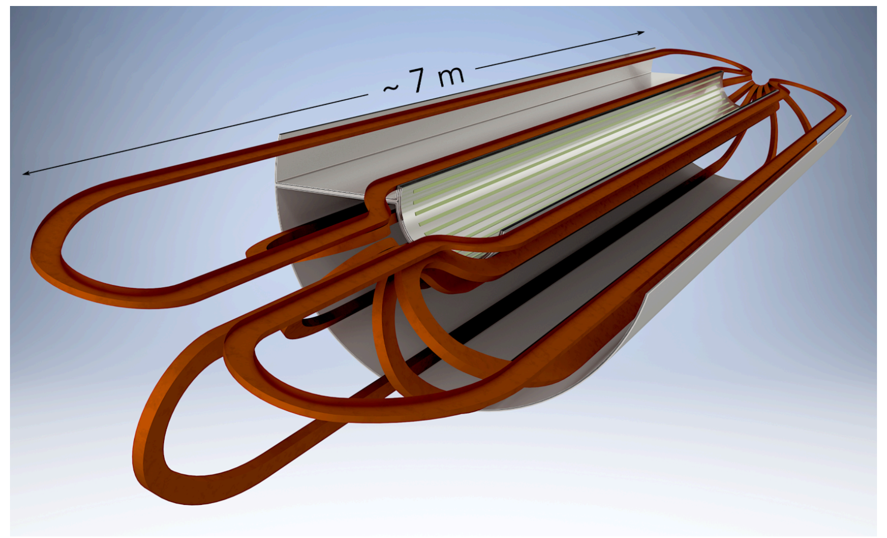




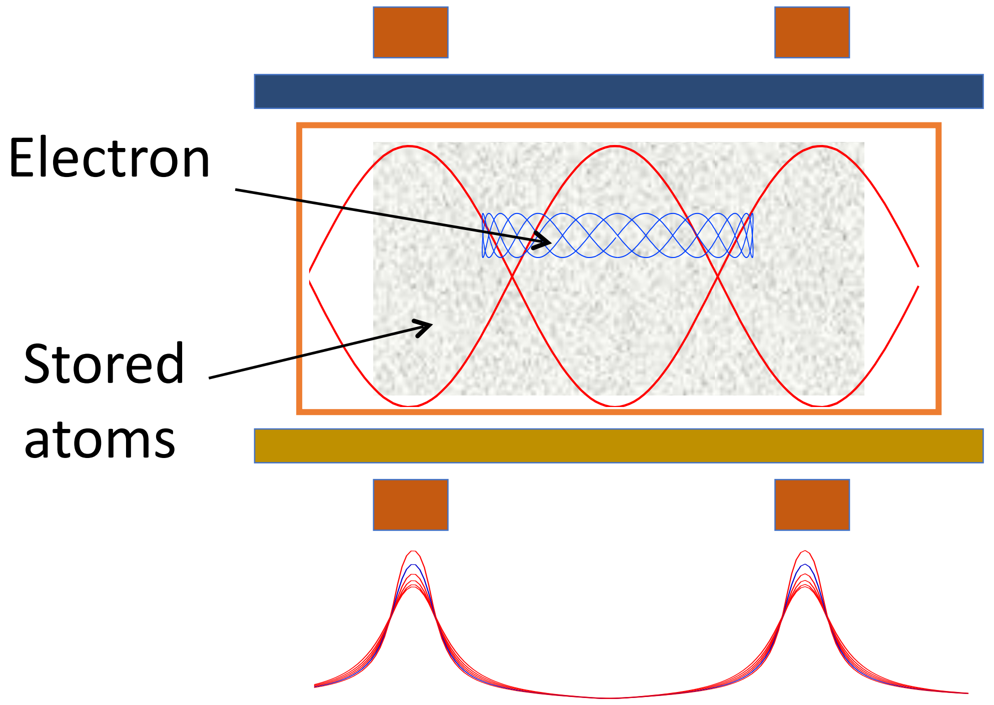
Cavity-Based Atomic Tritium Experiment

- Combine what we learned: 1 GHz Cavity with Atomic Tritium
- Atoms trapped in magnetogravitational trap
- Sensitivity calculations: 400 meV limit

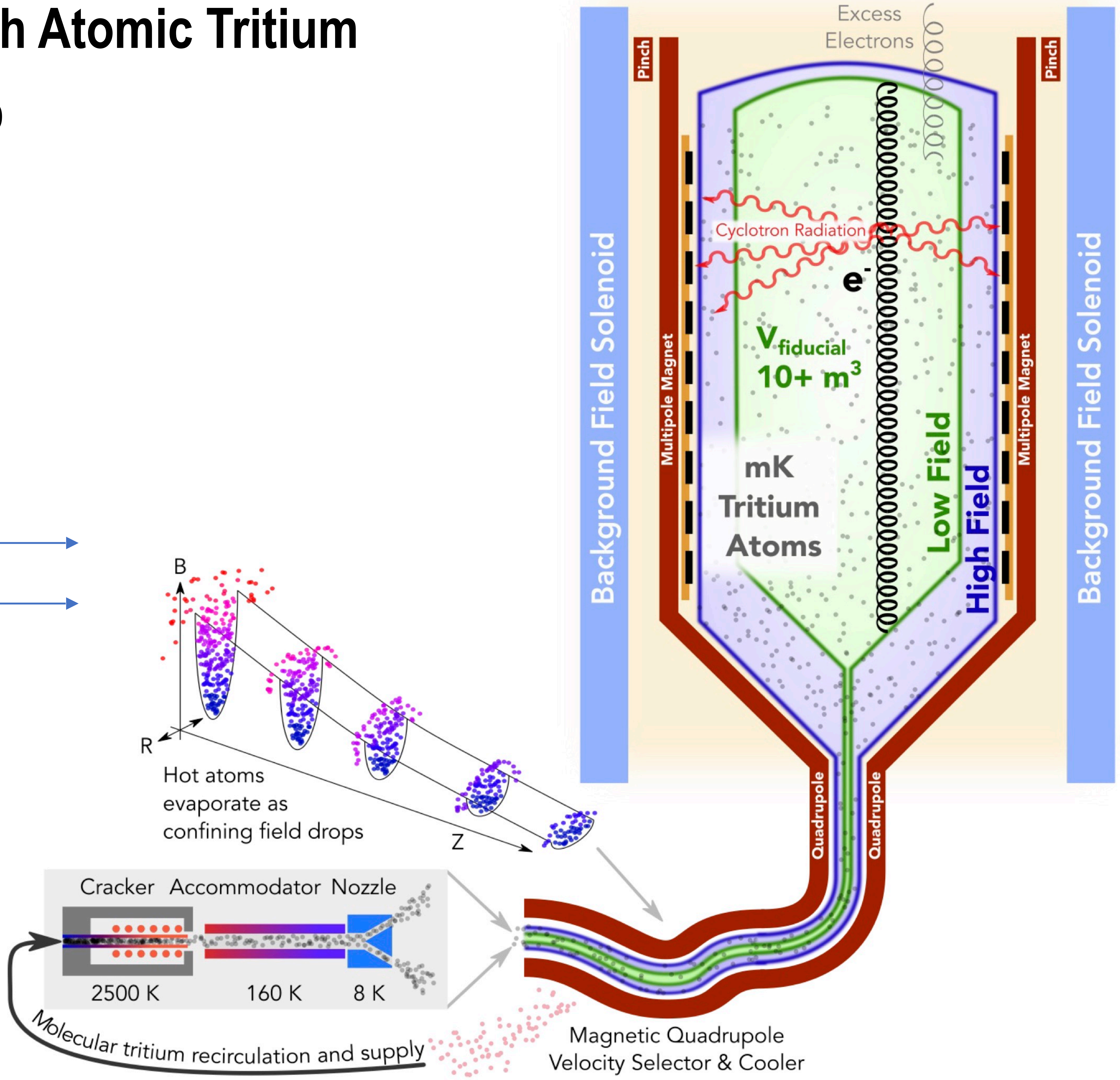
Atomic Trap Demonstrator



Large Volume (Cavity) CRES Demonstrator



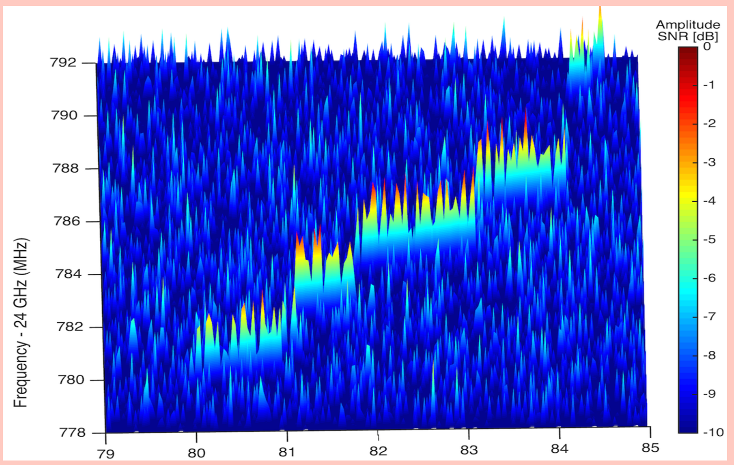
See A. Ashtari Esfahani *et al.* arXiv:2203.07349



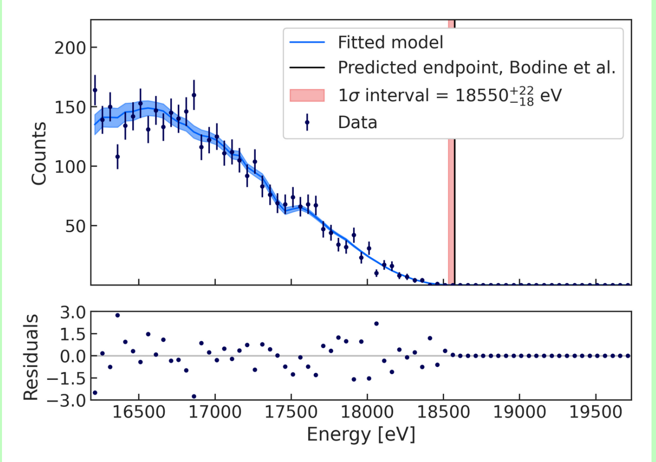
Atomic Source

The Project 8 Scientific Programme: A Phased Approach

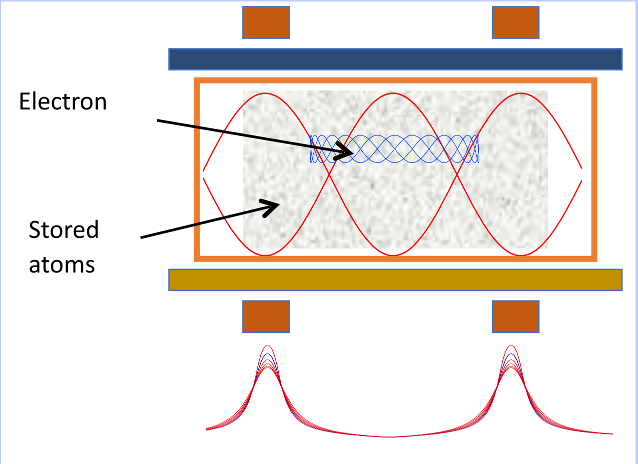
Phase I:
Demonstrate CRES technique on 83mKr mono-energetic electrons.
Status: Complete! Technique demonstrated.



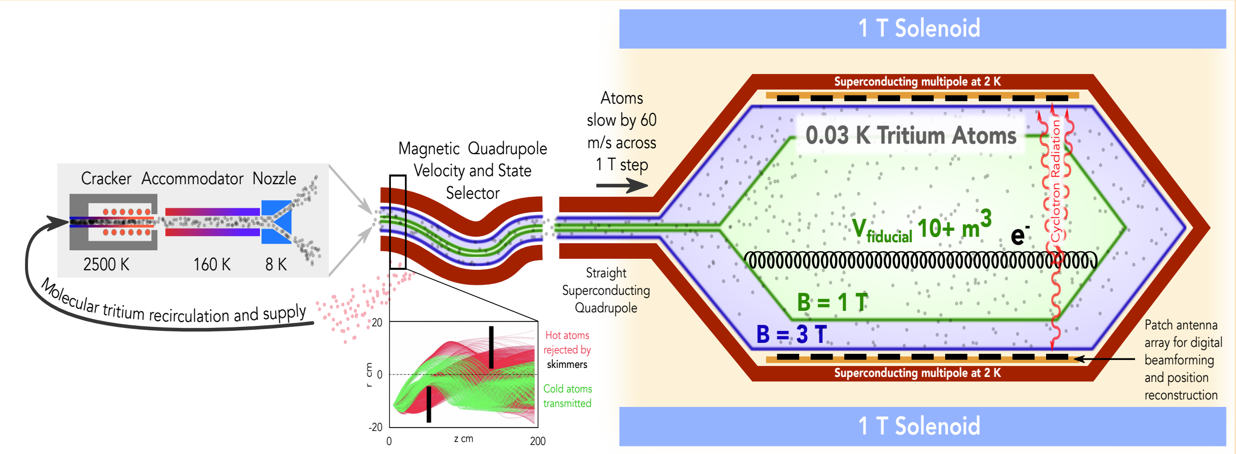
Phase II:
First T2 spectrum. Extract endpoint. Study systematics and backgrounds.
Status: Nearing completion



Phase III:
(a) “Large Volume” CRES
(b) Atomic tritium production and trapping at high densities



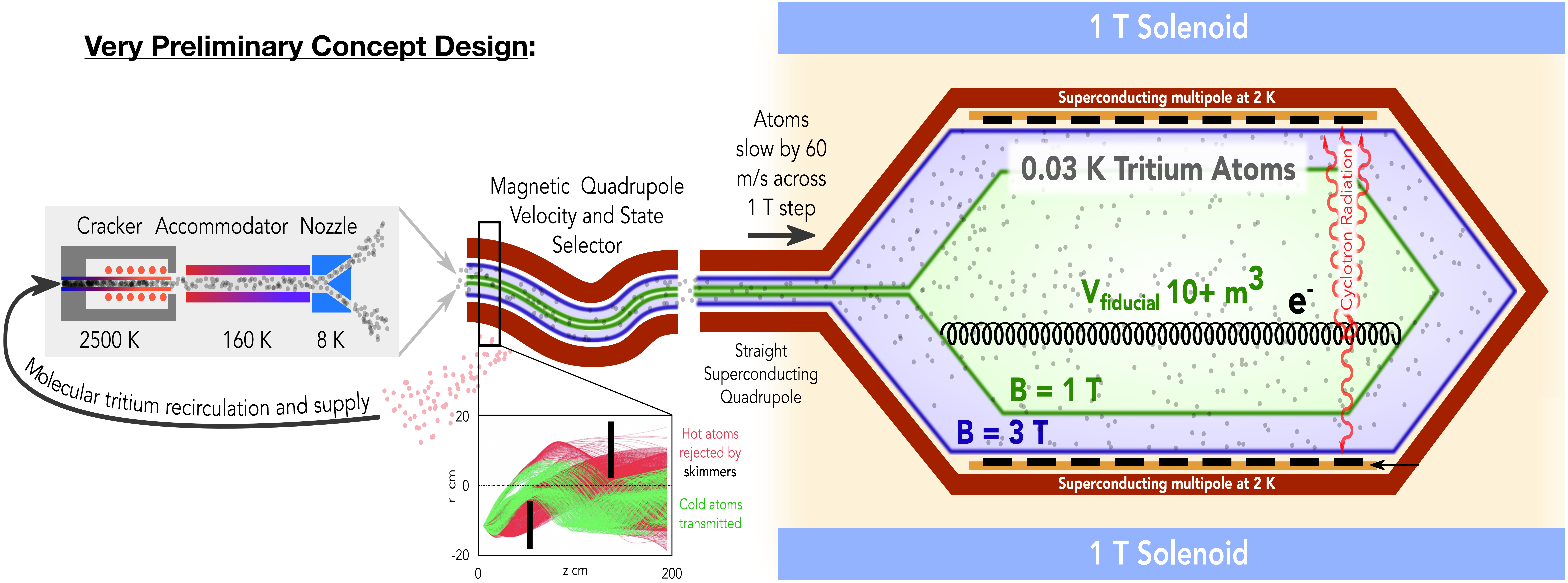
Phase IV:
Large atomic tritium experiment. Inverted mass ordering reach (40 meV)



Phase IV

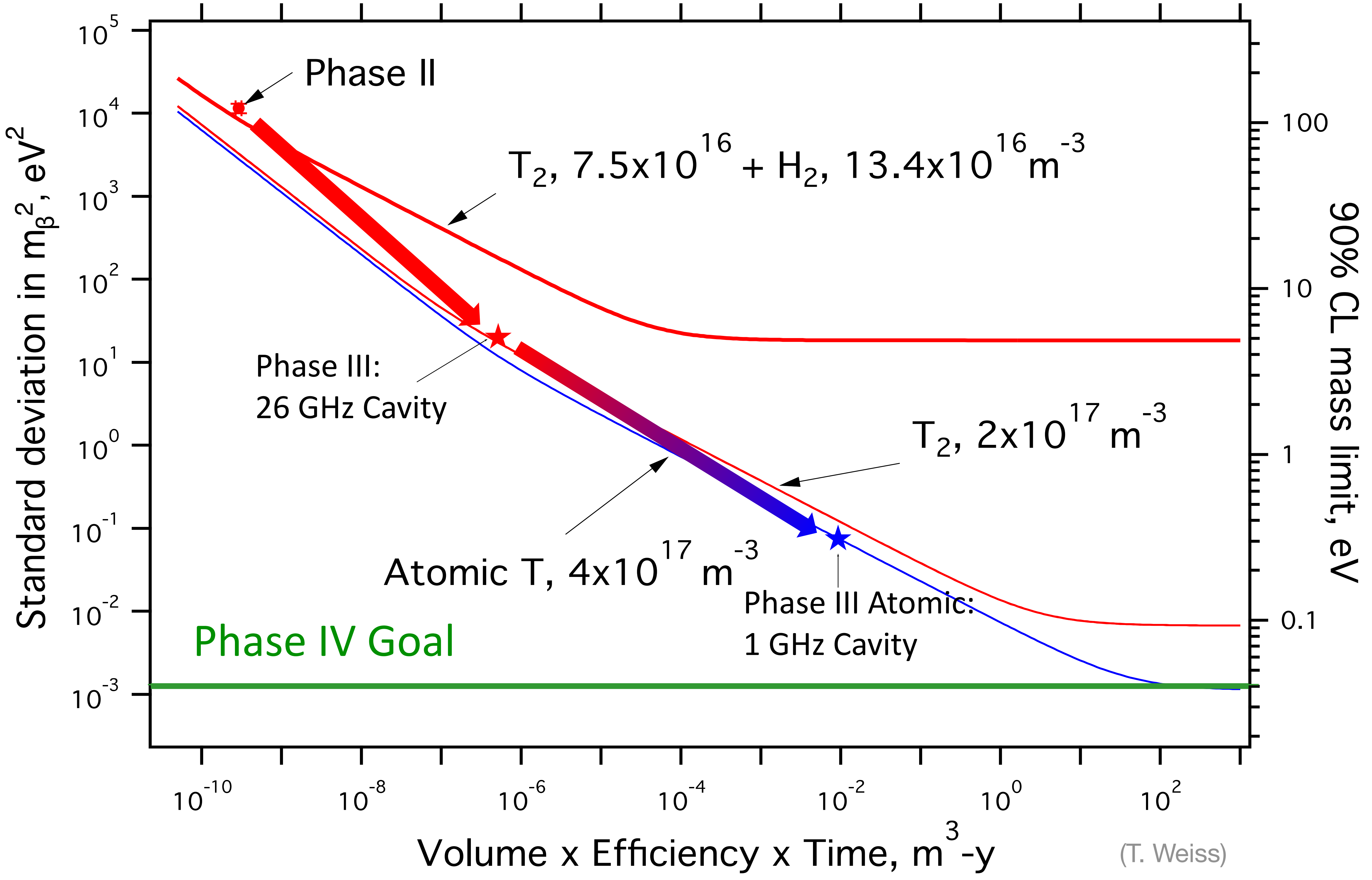
- Atomic tritium experiment combines R&D from Phase III into large tritium trap.
  - Atomic source, transport, and trap for large (>10 m^3) instrumented volume.

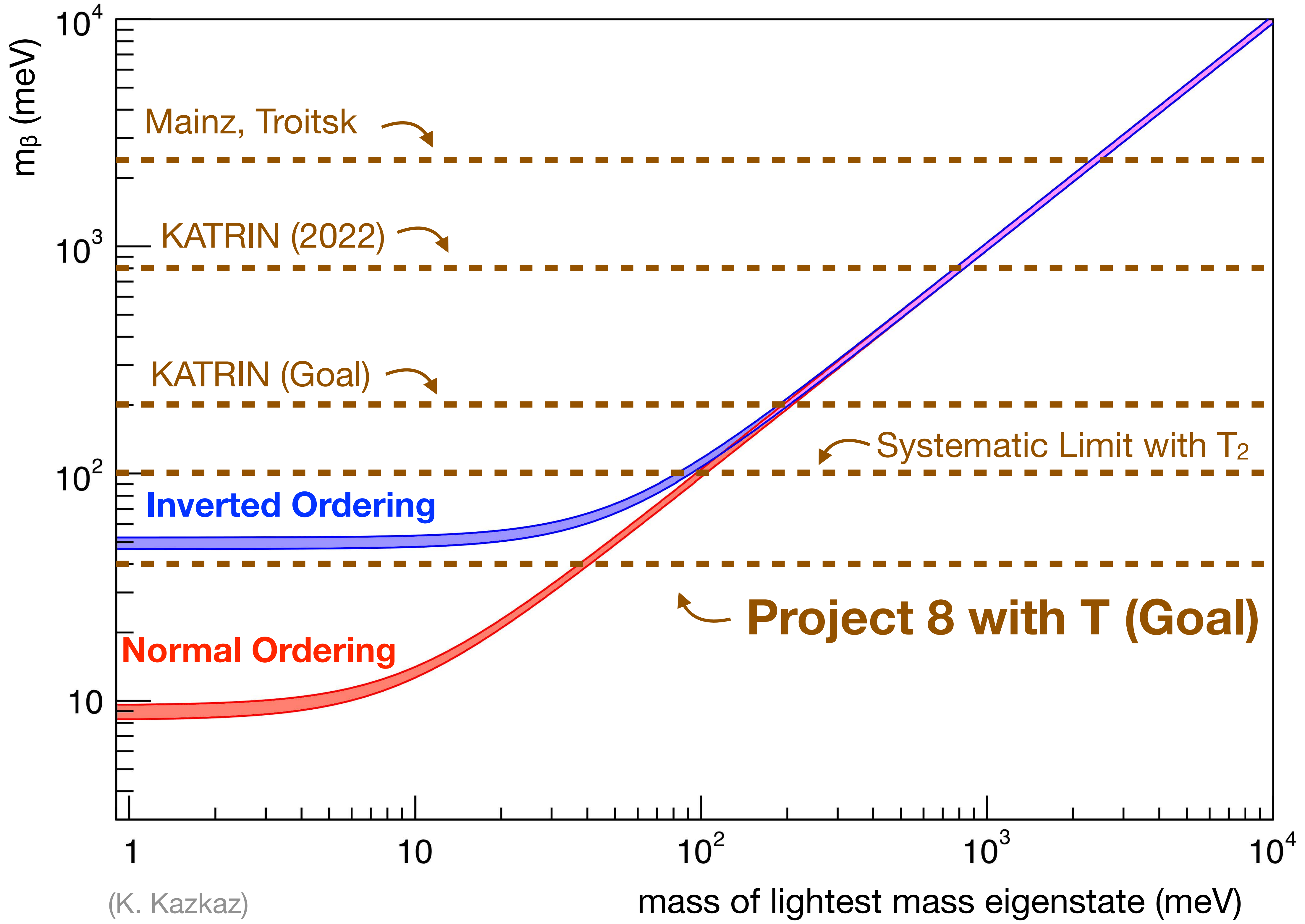
Very Preliminary Concept Design:



PHASE IV

- Target Mass Sensitivity: $m_\beta \sim 40$ meV
  - Resolve the inverted ordering case ($m_\beta \gtrsim 50$ meV)
- Collaboration is embarking on campaign to provide predictions for dependence of sensitivity against key systematics.
  - The energy resolution corresponding to the asymptote of the solid blue curve: $\sigma_E \approx 110 \pm 3$ meV





THANK YOU!

Case Western Reserve University

Indiana University

Johannes Gutenberg Universitat, Mainz

Karlsruhe Institute of Technology

Lawrence Livermore National Laboratory

Massachusetts Institute of Technology

Pacific Northwest National Laboratory

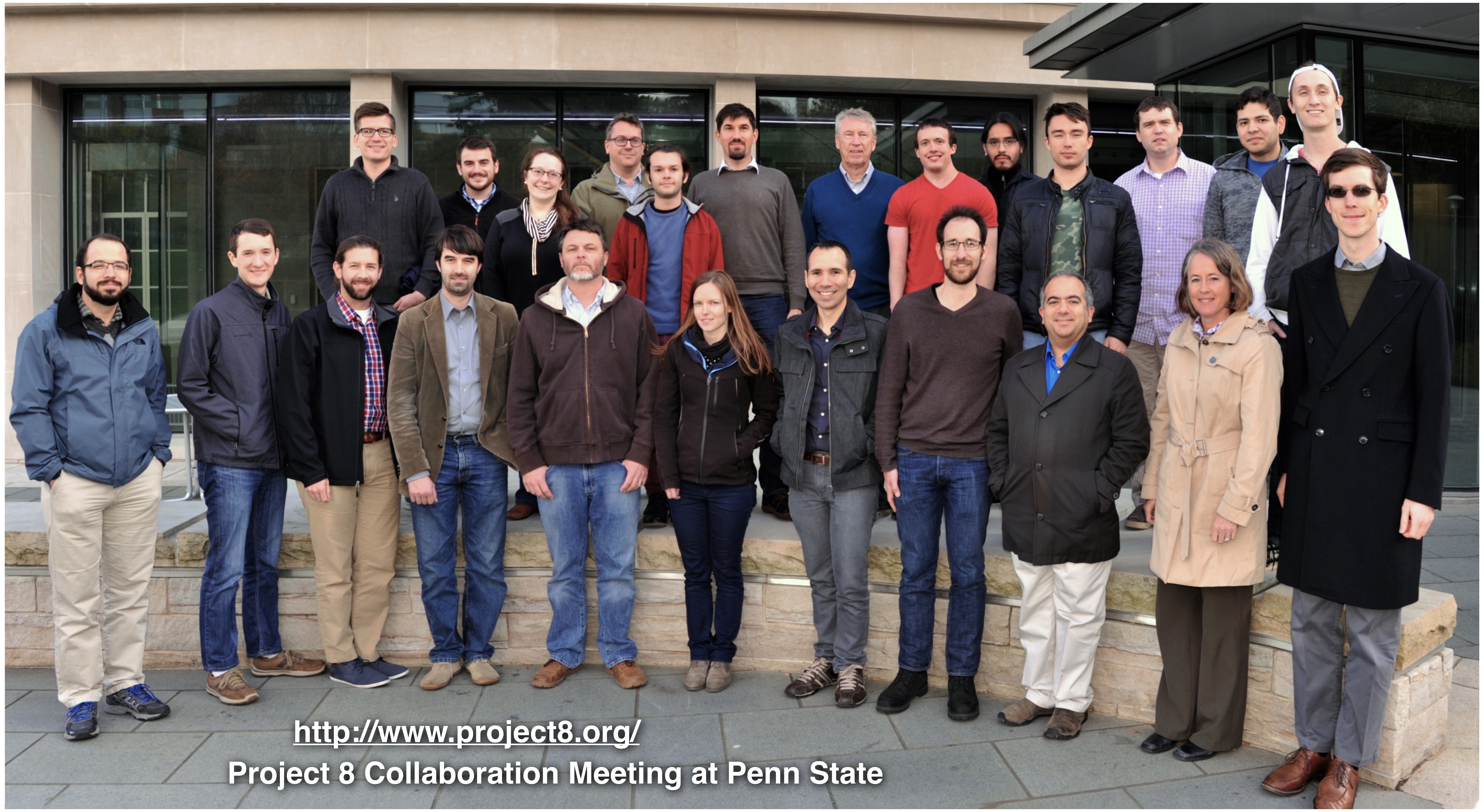
Pennsylvania State University

University of Illinois

University of Washington

Yale University

Project 8 has demonstrated the potential of the CRES technique, and charts a promising path towards a direct neutrino mass measurement!



This work is supported by the US DOE Office of Nuclear Physics, the US NSF, the PRISMA+ Cluster of Excellence at the University of Mainz, and internal investments at all institutions.

END