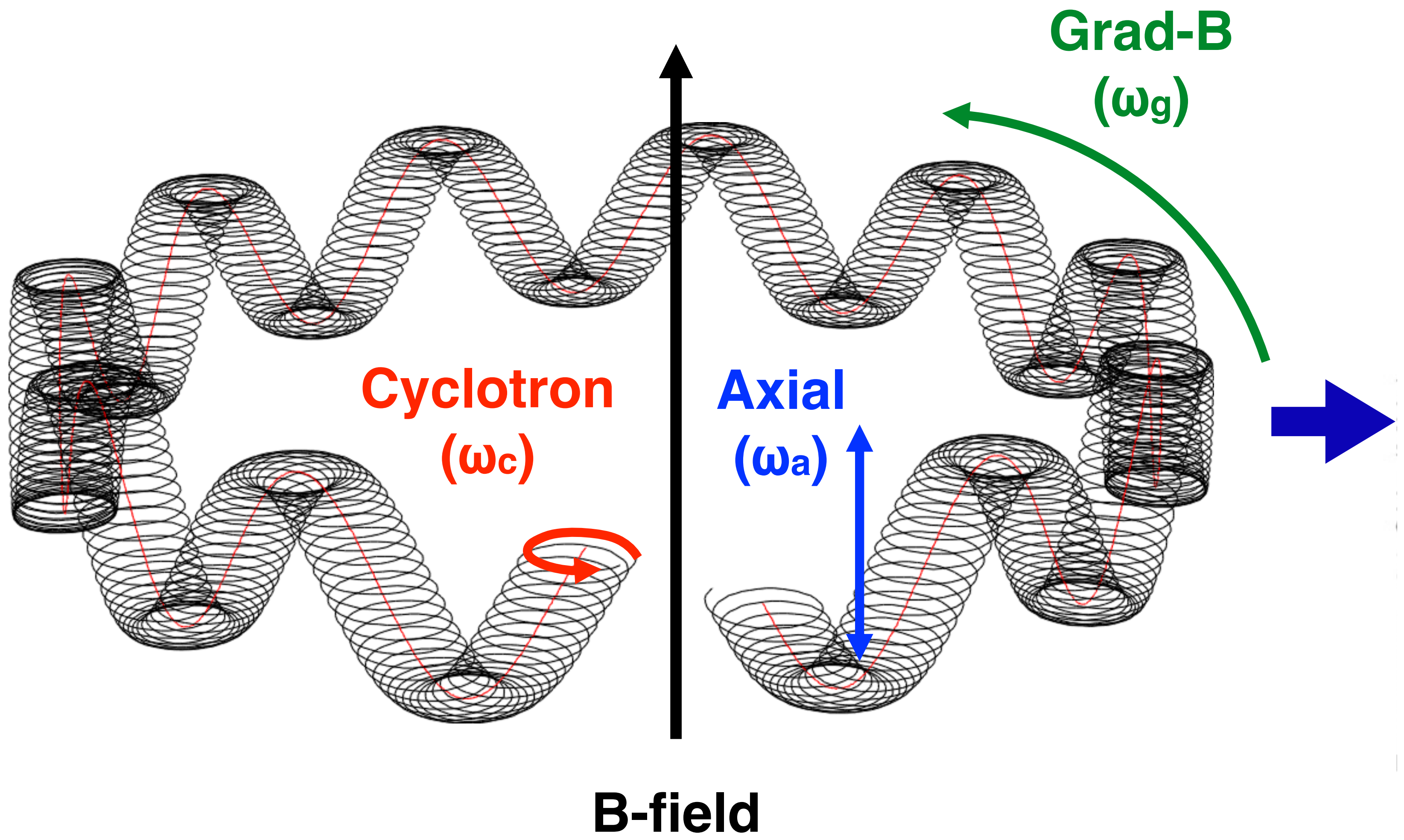
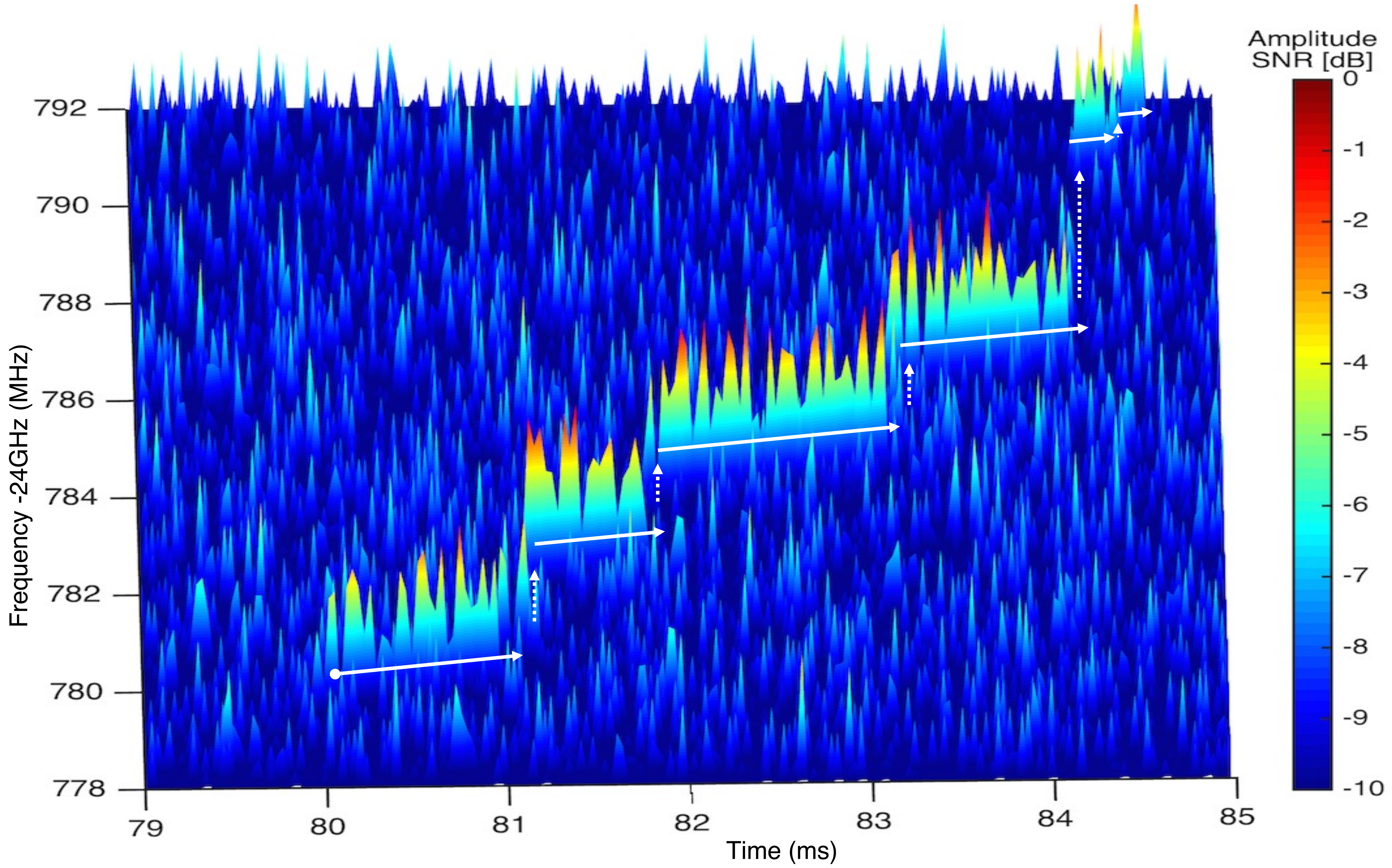
Project 8: Measuring the Neutrino Mass Using Cyclotron Radiation Emission Spectroscopy

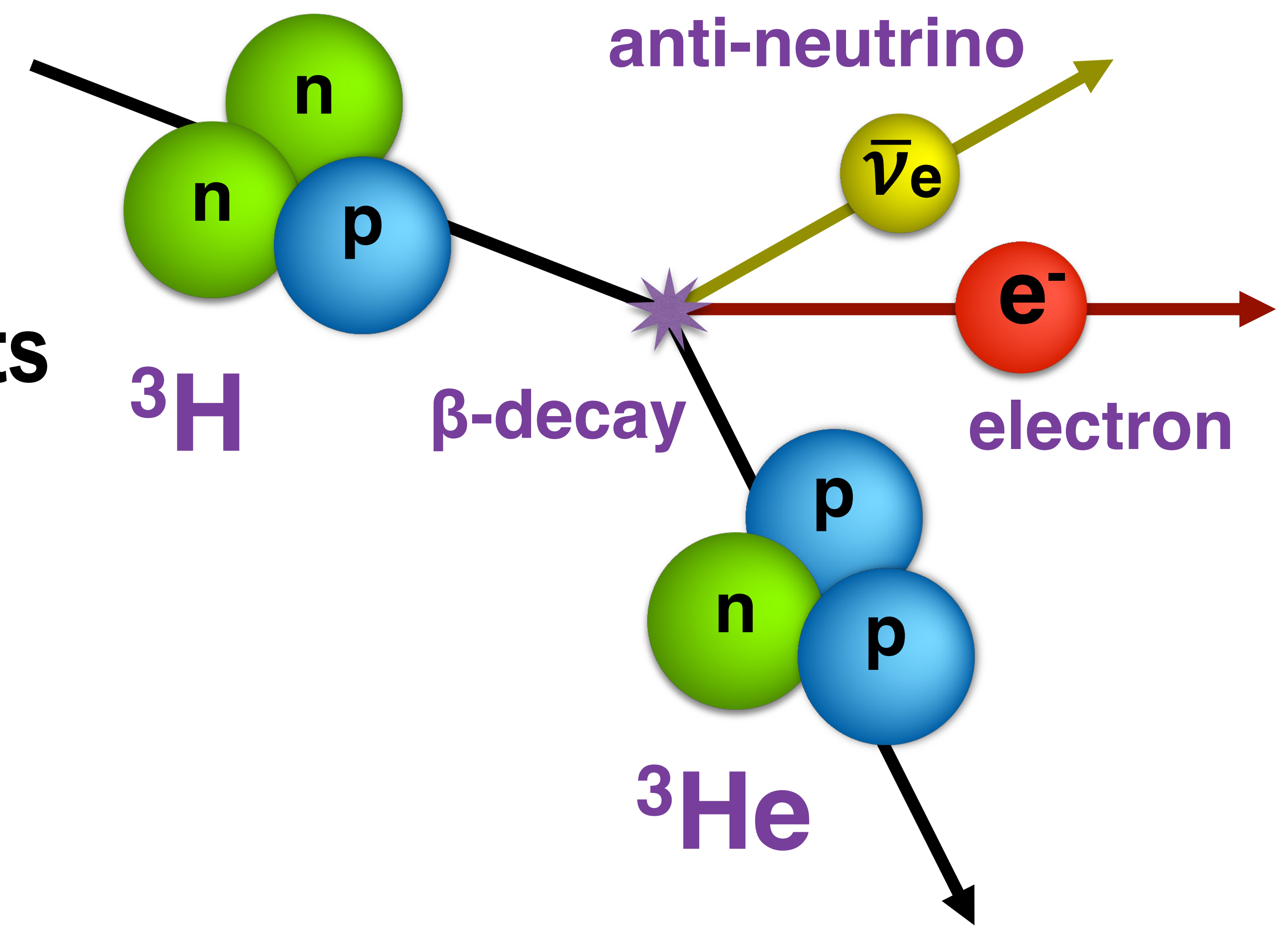


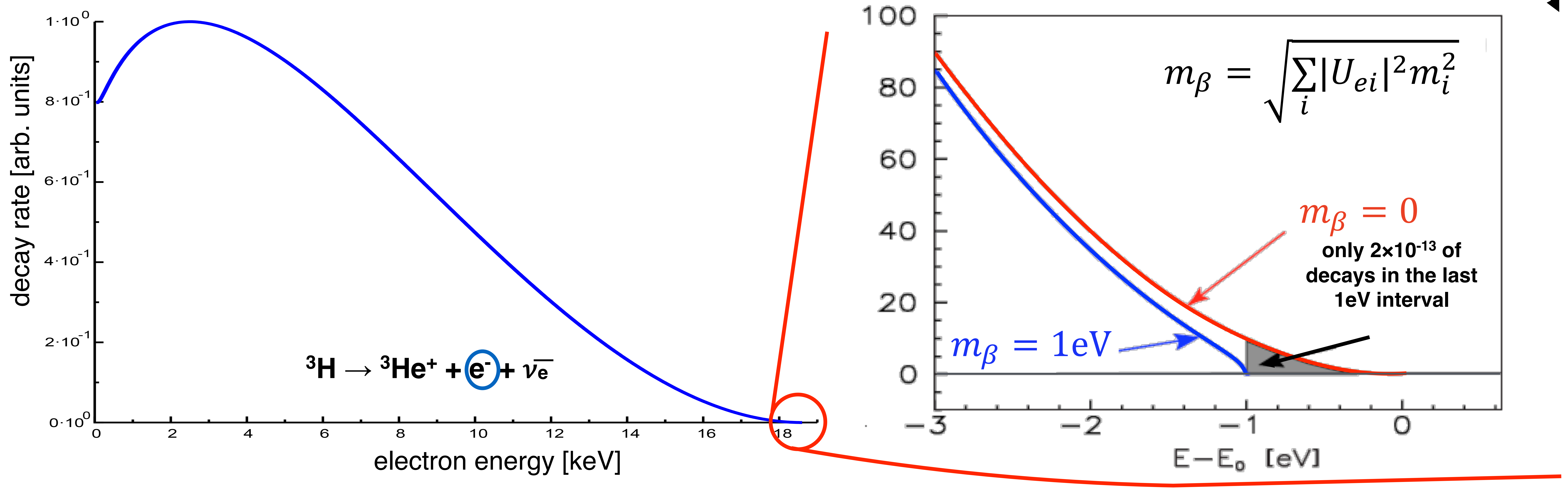


Luiz de Viveiros - Penn State
Project 8 Collaboration

Beta Decays and the Neutrino Mass

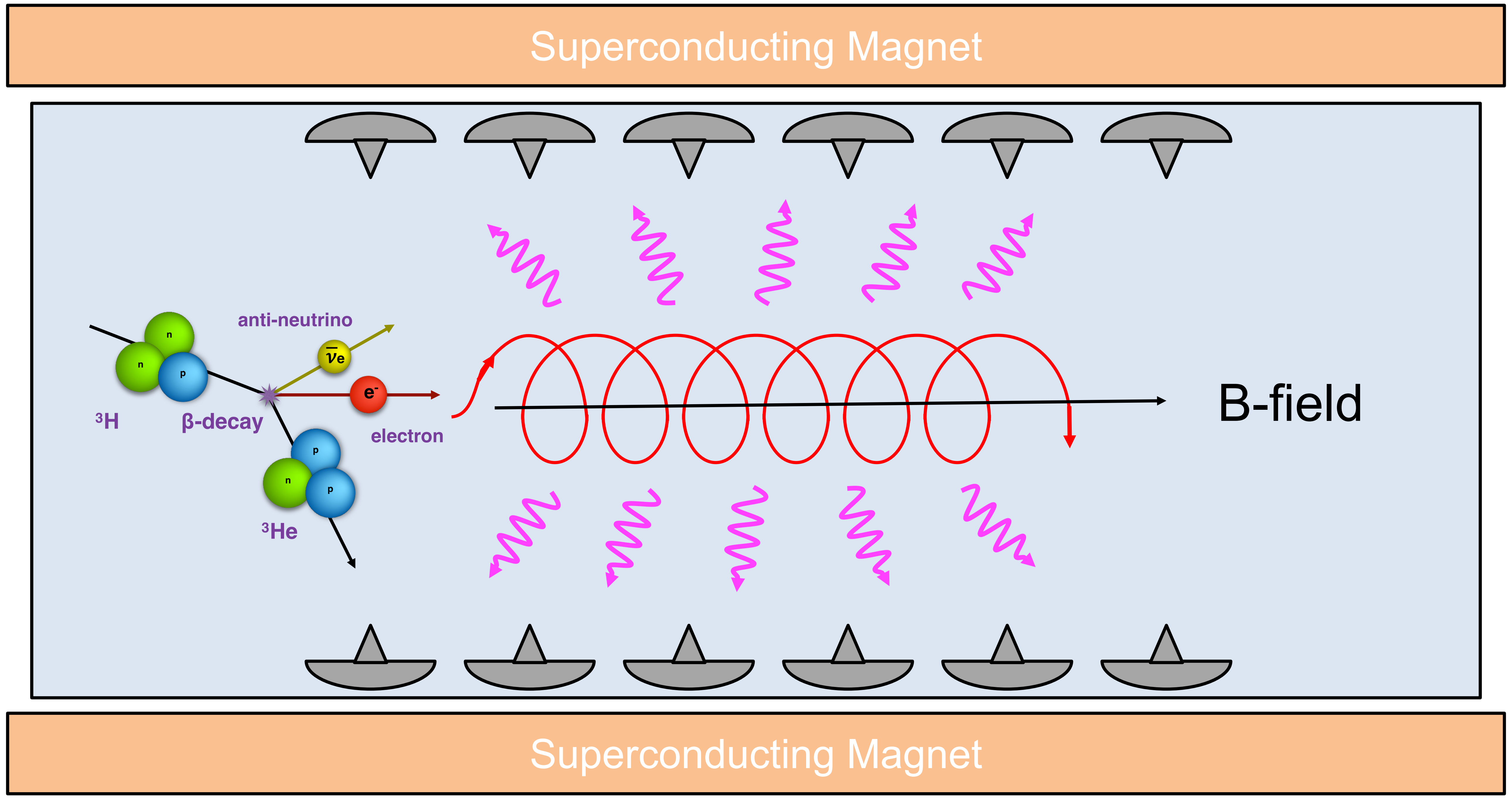
- Neutrino flavor oscillations ⇒ neutrino masses > 0 eV/c^2
- Absolute mass scale and ordering are still unknown
- Tritium β- spectroscopy is the leading technique for direct neutrino mass measurements
  - Beta decay endpoint should match the mass difference (~18.6 keV) for $m_{\nu_e} = 0$
  - Determine 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!

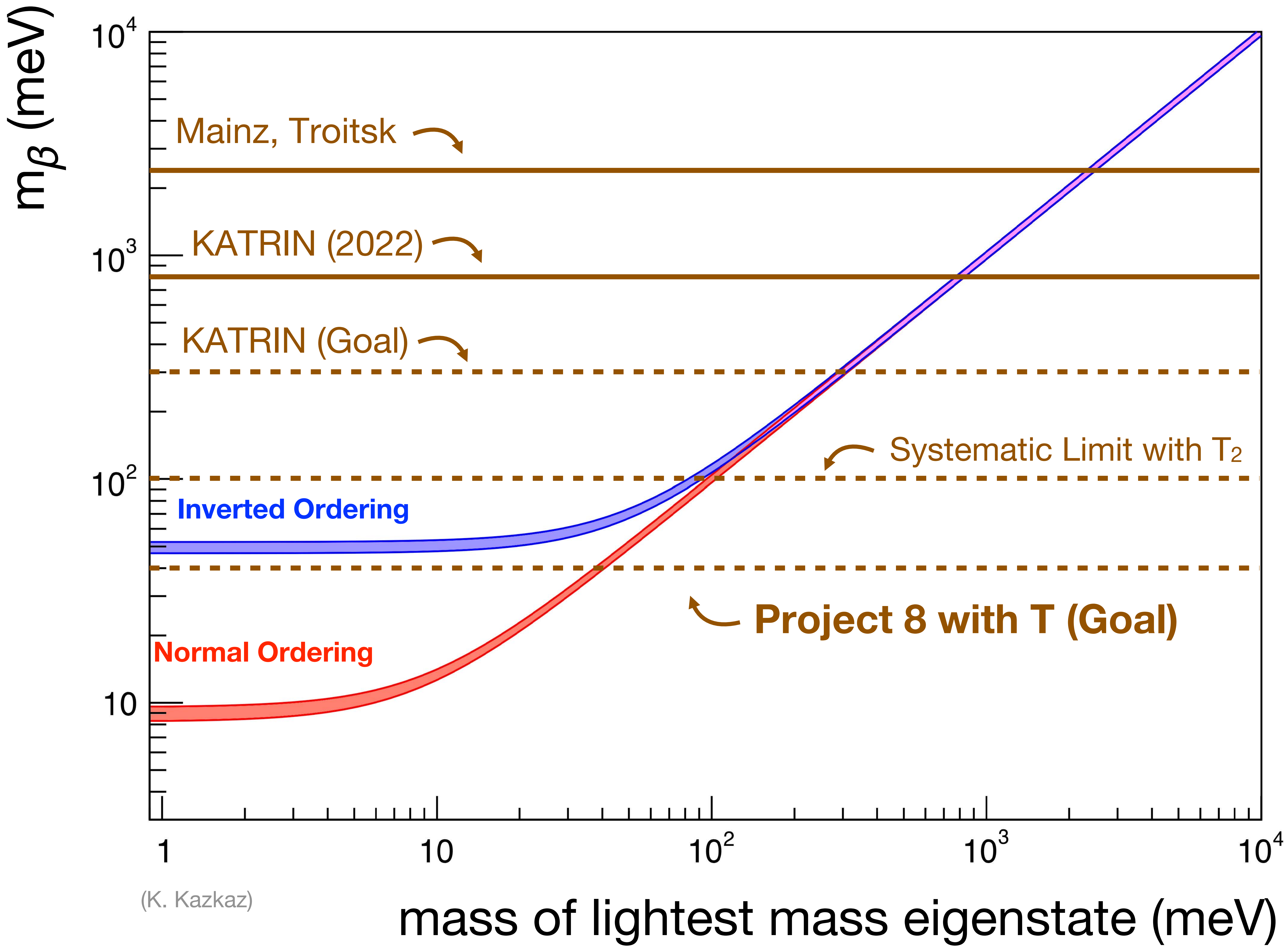


$$f_\gamma = \frac{eB}{2\pi(m_e + K/c^2)}$$

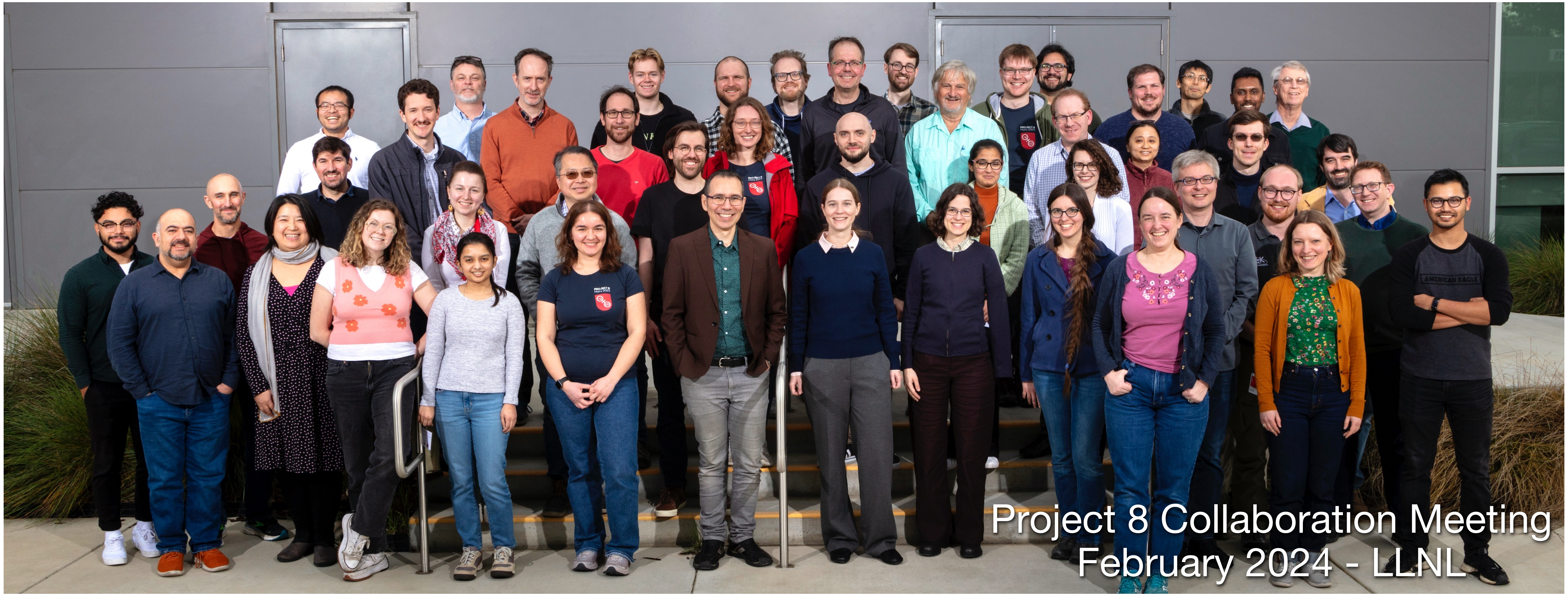
kinetic energy factor

PROJECT 8 SENSITIVITY GOALS

- Sensitivity to 40 meV/c^2 neutrino mass
- Measure neutrino mass or exclude inverted ordering



PROJECT 8



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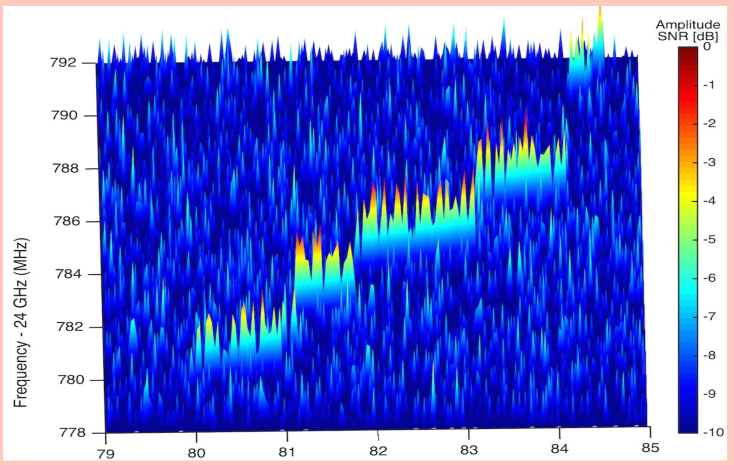
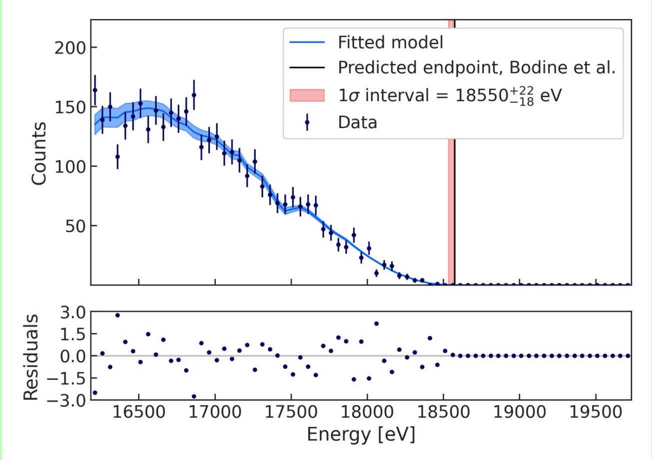
THE PROJECT 8 SCIENTIFIC PROGRAMME: A PHASED APPROACH

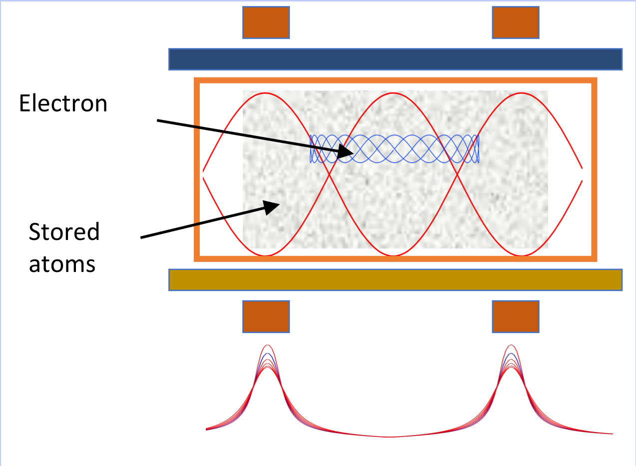
Phase I:
Demonstrate CRES technique on 83mKr mono-energetic electrons.



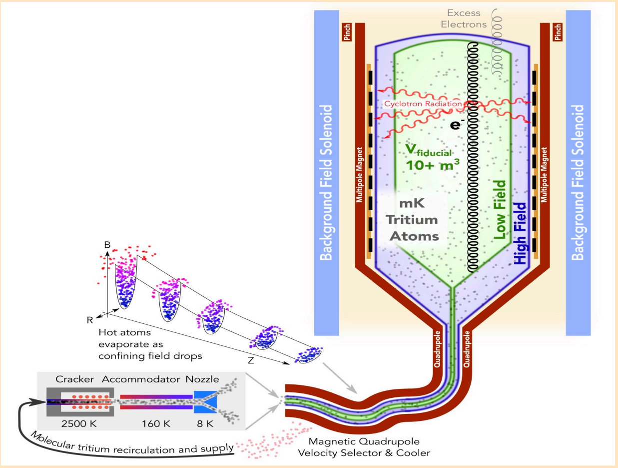
Phase II:
Acquire Tritium spectrum. Extract endpoint. Study systematics and backgrounds.



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

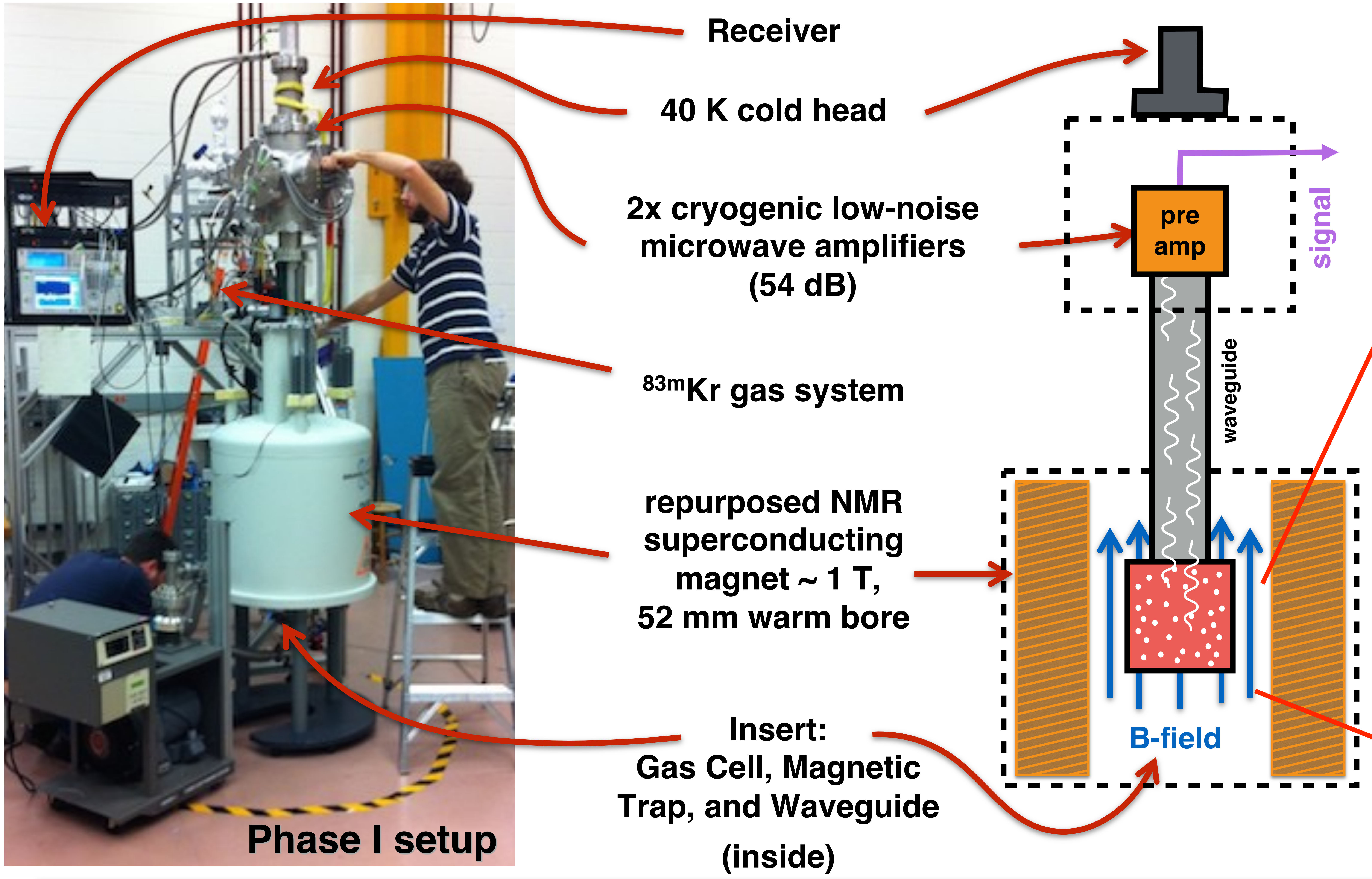


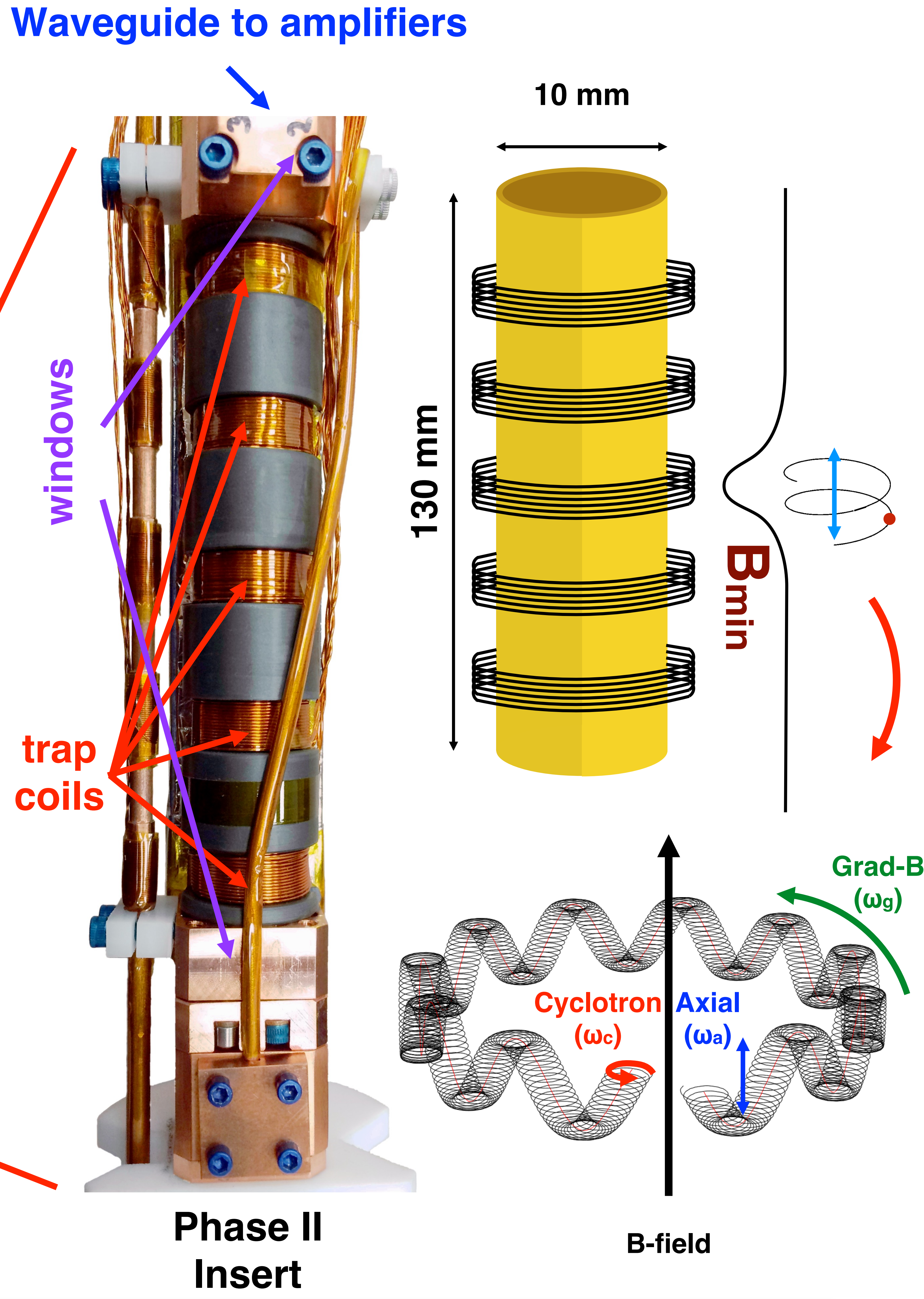
Phase IV:
Large atomic tritium experiment. Inverted mass ordering reach (40 meV)



Phases I and II - The Detector

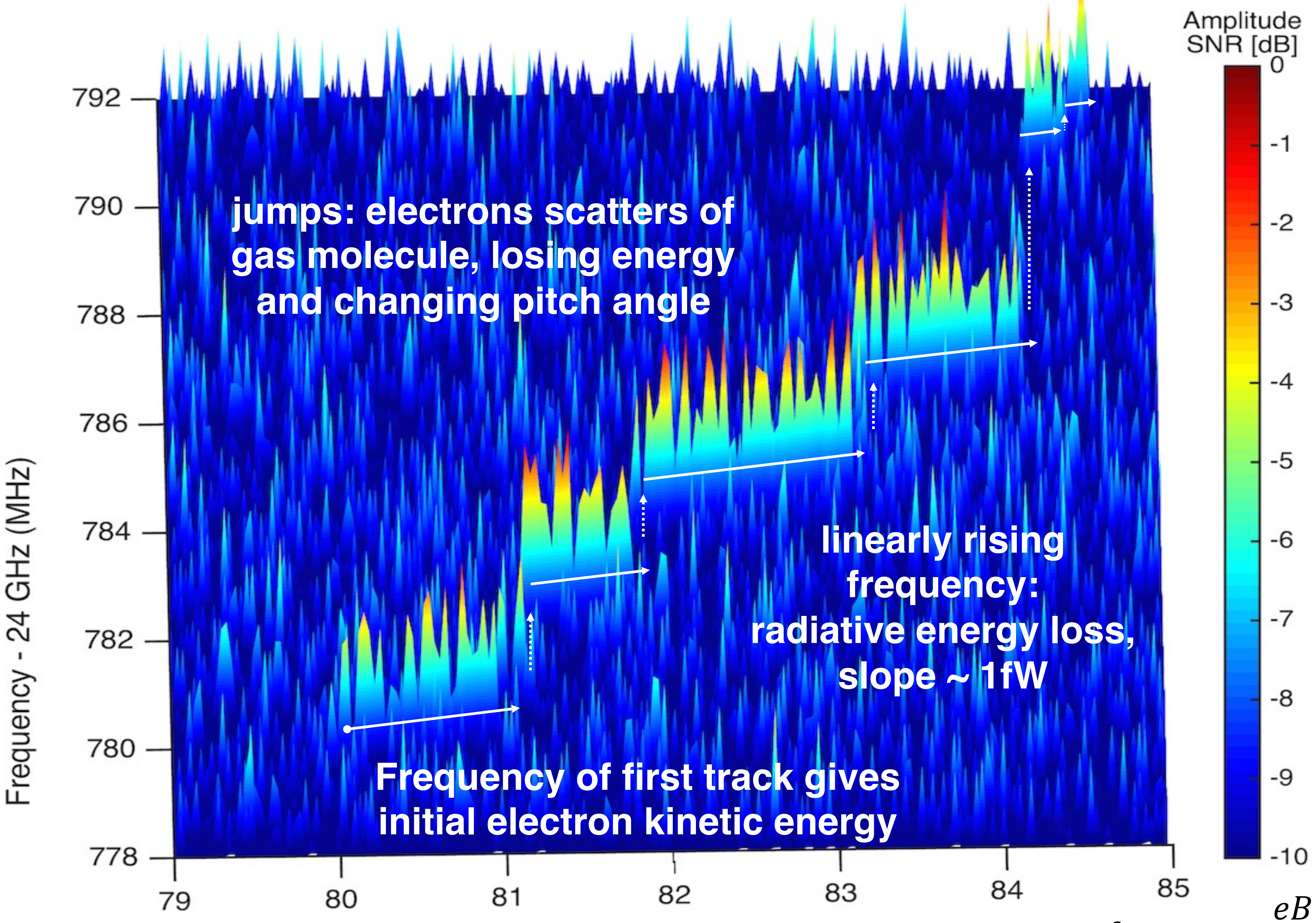
- Assembled at the University of Washington in Seattle, WA
- Phase I: ^{83m}Kr only (2016); Phase II: ^{83m}Kr and T_2 (analysis being completed now)





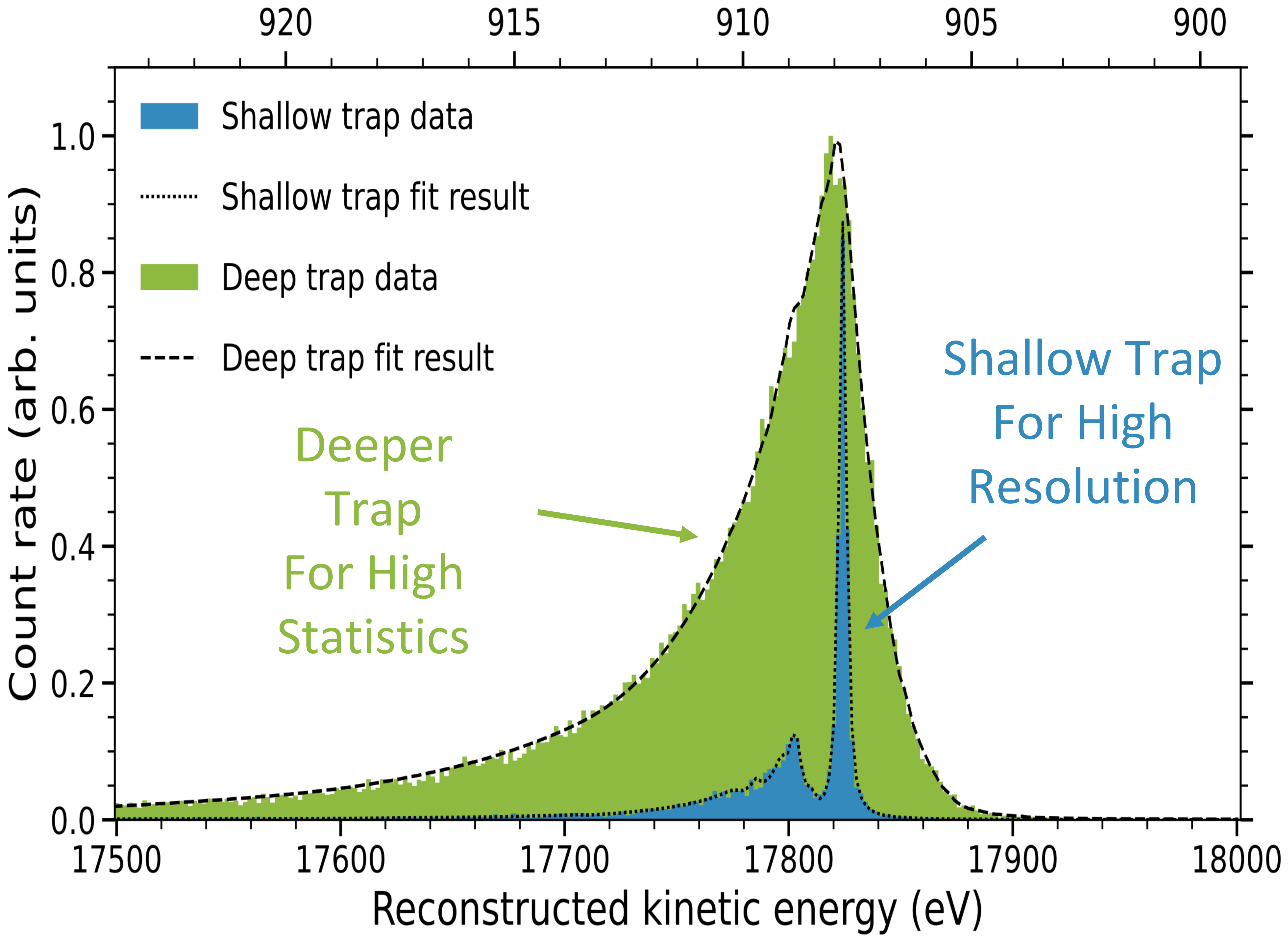
MEASURING THE CYCLOTRON RADIATION

- First detection of single-electron cyclotron radiation - Phys. Rev. Lett. 114, 162501 (2015)
- Shallow harmonic trap for high precision scans, deep harmonic trap for high statistics
- Best demonstrated resolution in ROI: FWHM = 1.7 ± 0.2 eV for 17.8keV ^{83m}Kr line (during Phase II)



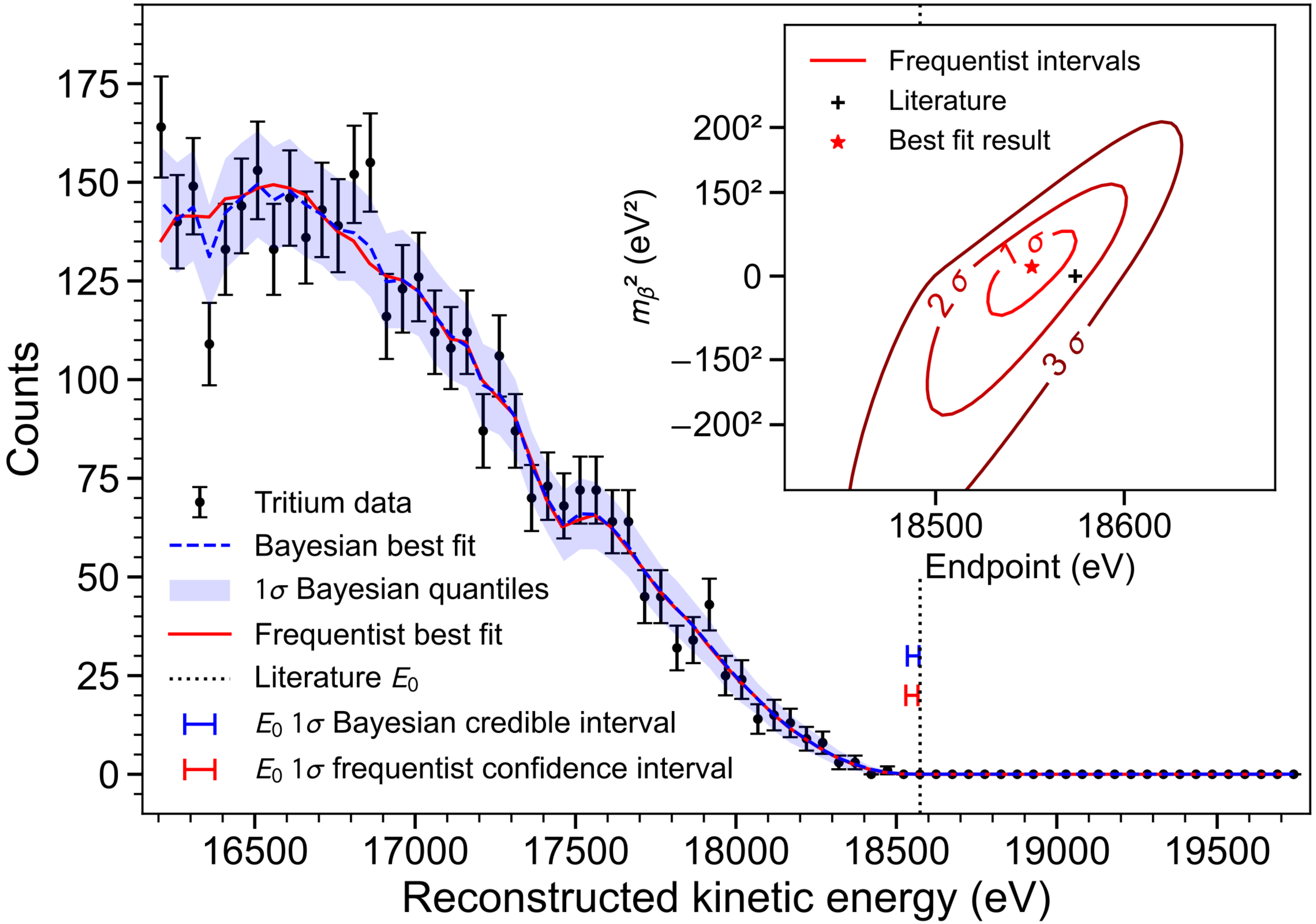
scale: 1 MHz ~ 20 eV

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



Phase II Tritium Results

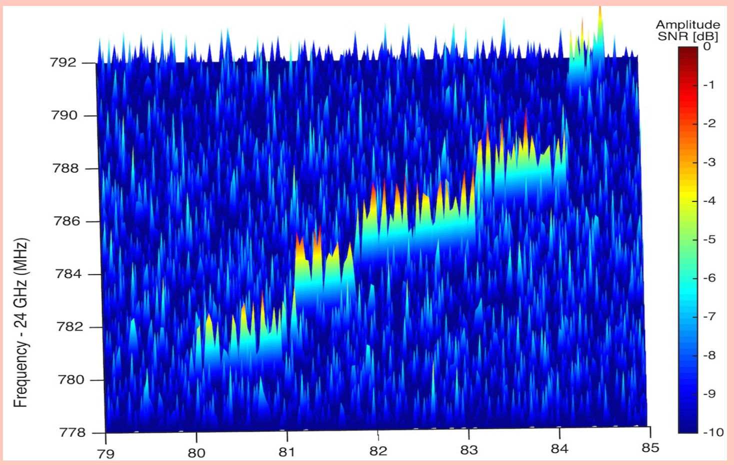
- **Long science run completed in 2020**
  - 82 net days of data taking, 3770 events
  - 4 trapping coils, 1 mm^3 effective volume
- **T_2 endpoint measurement in agreement with literature**
  - Frequentist: $E_0 = (18548^{+19}_{-19})\mathrm{eV}(1\sigma)$
  - Bayesian: $E_0 = (18553^{+18}_{-19})\mathrm{eV}(1\sigma)$
- **First neutrino mass measurement using CRES !**
  - Frequentist: $\leq 152\ \mathrm{eV/c^2}\ (90\%\mathrm{C.L})$
  - Bayesian: $\leq 155\ \mathrm{eV/c^2}\ (90\%\mathrm{C.L})$
- **No events past endpoint**
  ⇒ sets limit on background rate:
  $\leq 3\times10^{-10}\mathrm{eV^{-1}s^{-1}}(90\%\mathrm{C.L.})$



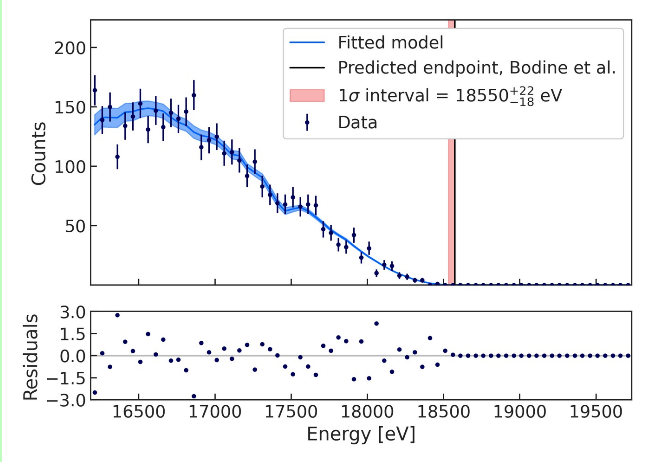
Phys. Rev. Lett. 131, 102502 (2023) [arXiv:2212.05048]
Phys. Rev. C 109, 035503 (2024) [arXiv:2303.12055]

The Project 8 Scientific Programme: A Phased Approach

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



Phase II:
Acquire Tritium spectrum. Extract endpoint. Study systematics and backgrounds.
Status: Complete! First Tritium spectrum!



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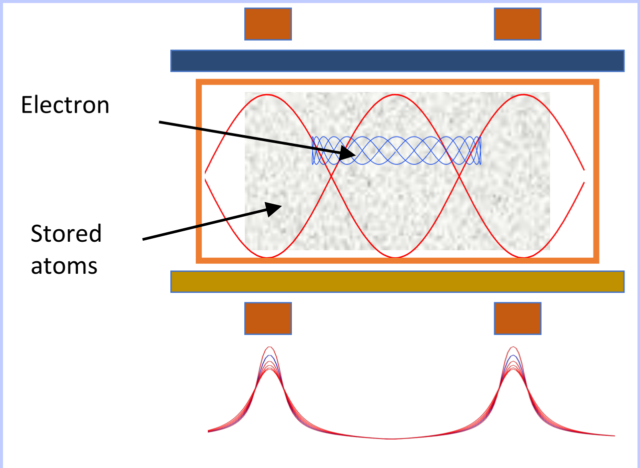
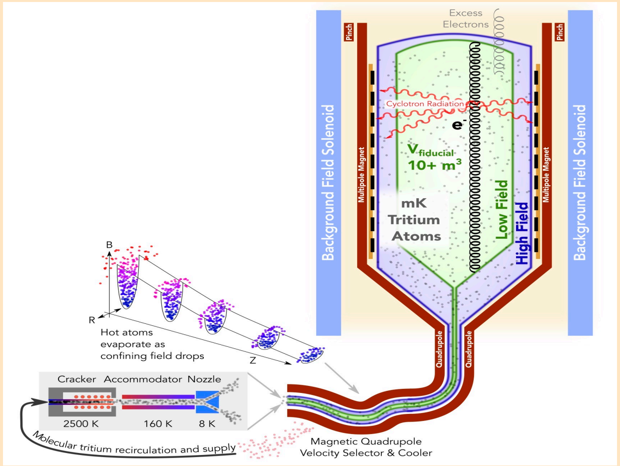
(a) “Large Volume” CRES
(b) Atomic tritium production and trapping at high densities



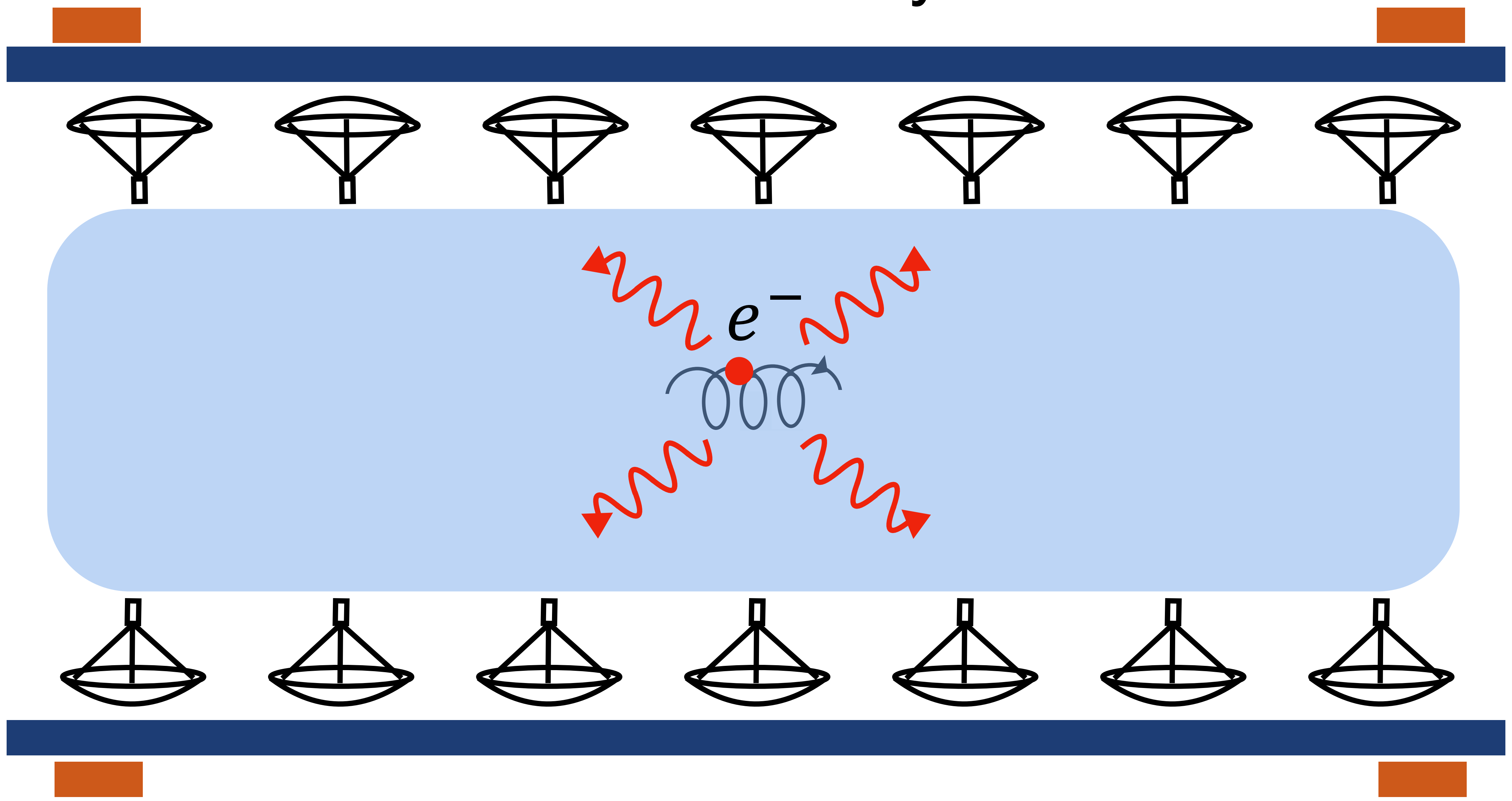
Phase IV:
Large atomic tritium experiment. Inverted mass ordering reach (40 meV)



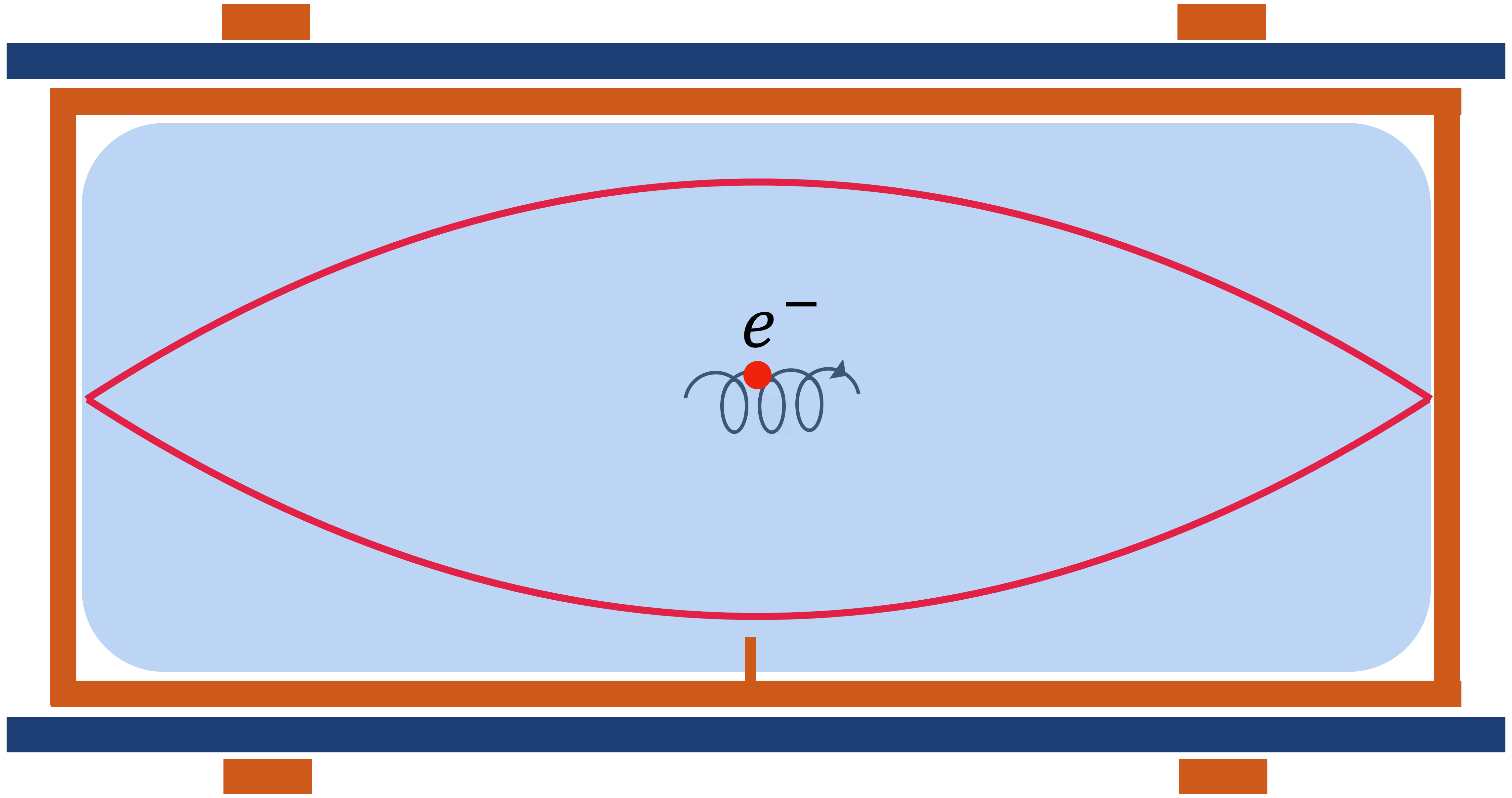
LARGE VOLUME CRES

- We need a new CRES technology to reach cubic meter volumes.
  - Waveguide-centric design no longer suitable
- Project 8 has considered and investigated an *antenna array* design significantly in the last few years. A number of challenges identified during R&D have given rise to a new option: *resonant cavities*

Antenna Arrays

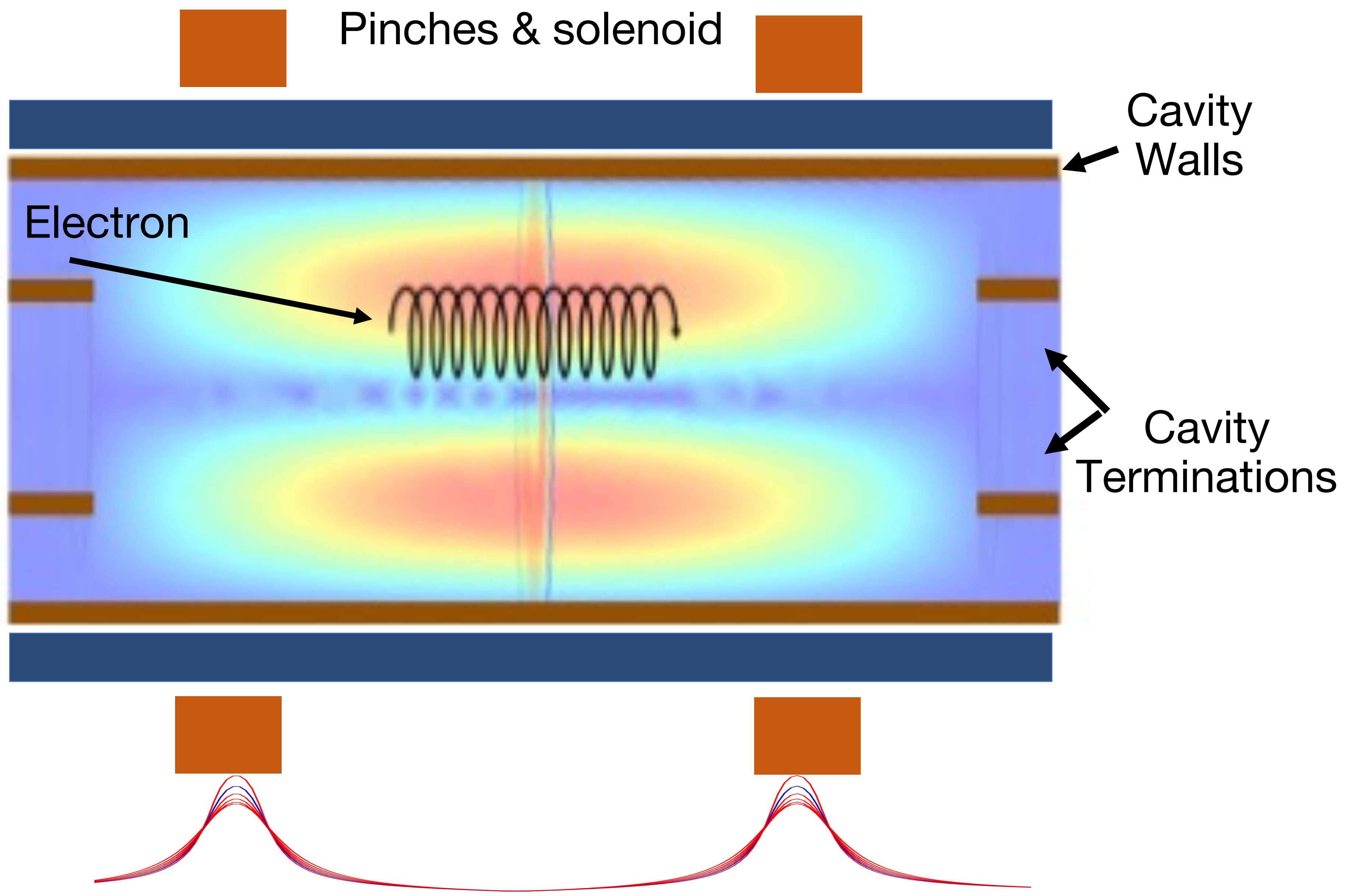


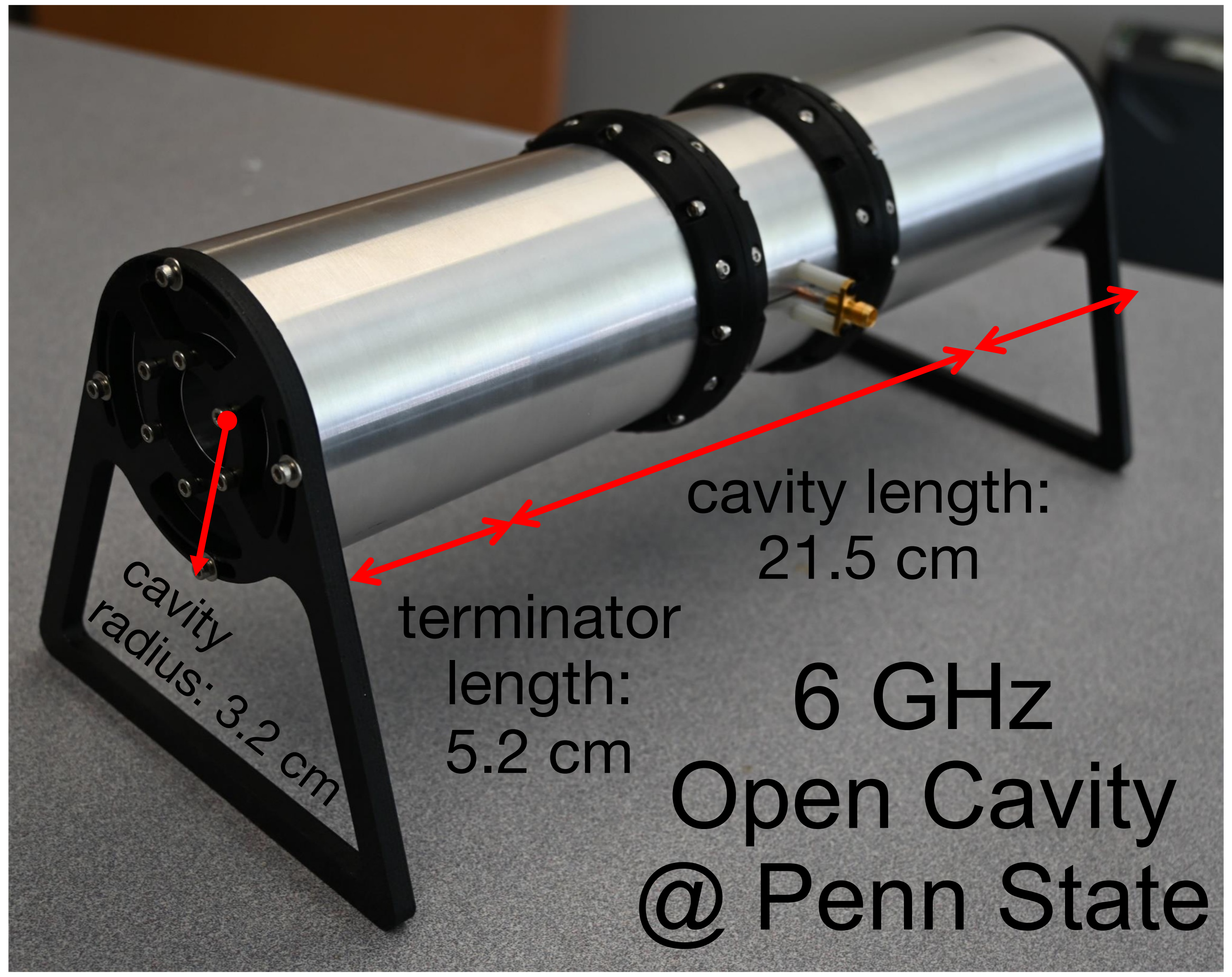
Cavities

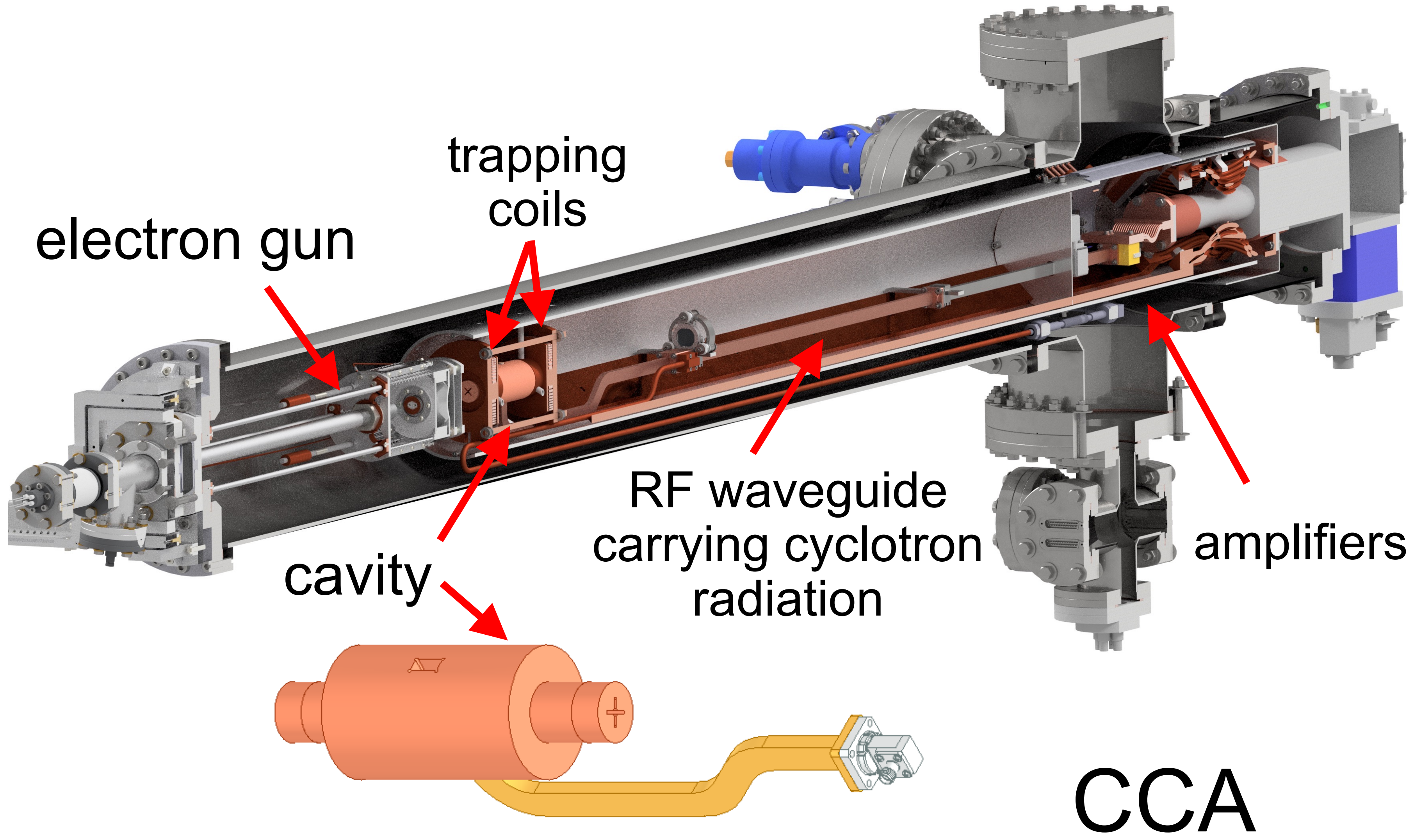


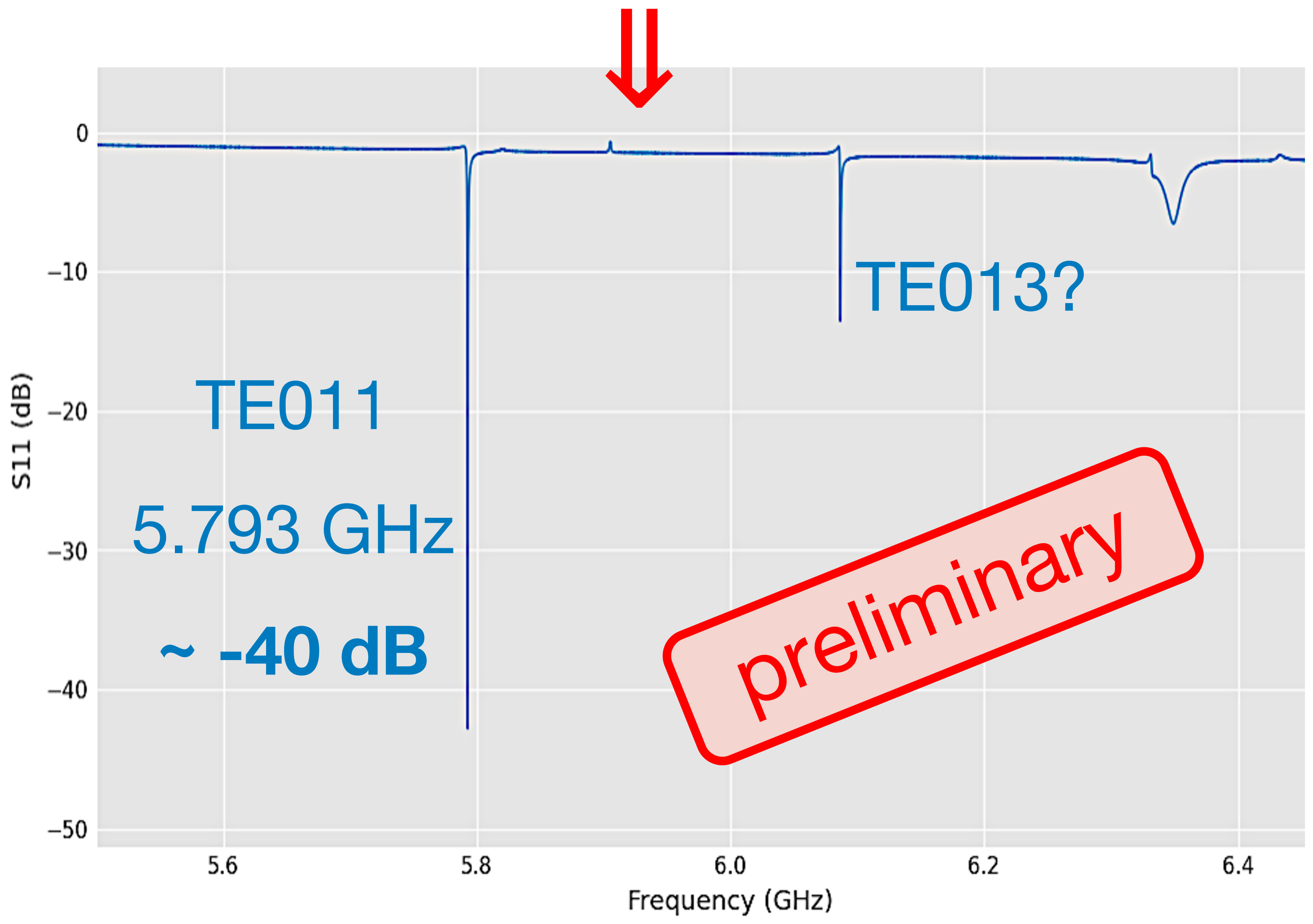
Large Volume CRES with Resonant Cavities

- Electron couples to filtered T_{0np} mode in cylindrical cavity
  - Radiation is not lost ⇒ large effective volume
  - Volume scales with wavelength
  - Improved SNR
  - Small channel count
- Challenges:
  - Ensuring radioactive gas can be injected and removed
  - Understanding signal coupled to cavity modes
- 6 GHz Open Cavity Prototype
  - Demonstrate scaling, test strategies for large volume cavity design and readout
  - First prototype: aluminum body, modular design
  - Measured S11 of ~40 dB, Q = 3789 for TE011 mode
- Cavity CRES Apparatus (CCA):
  - Demonstrate small scale cavity at high frequency (26 GHz) with large SNR
  - Electron gun source



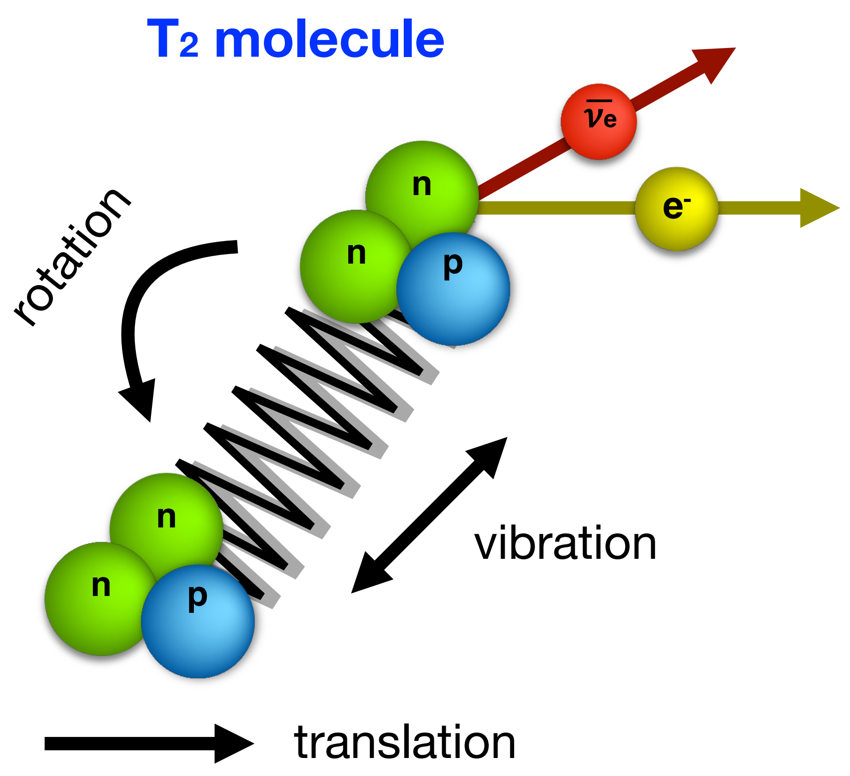


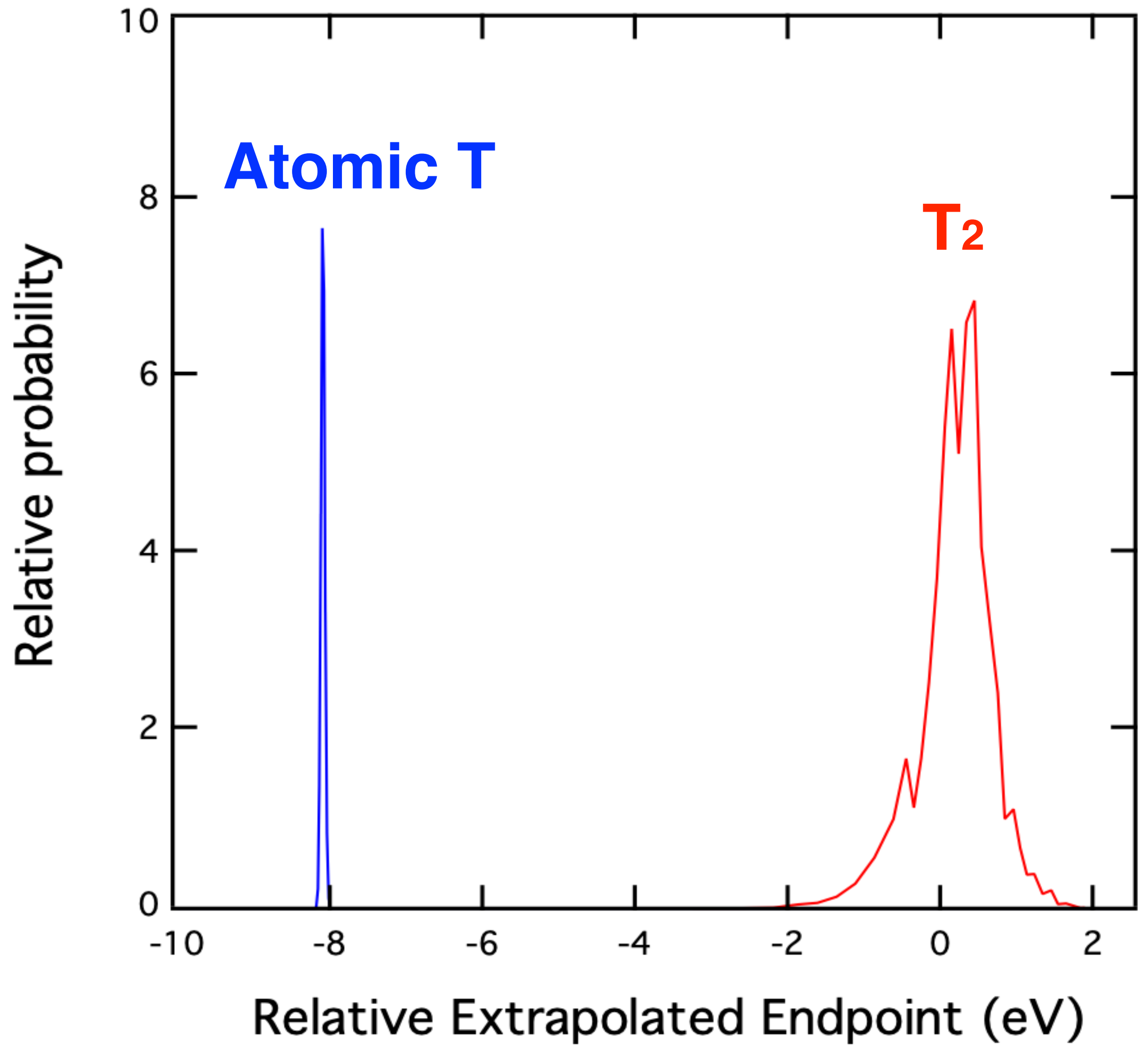


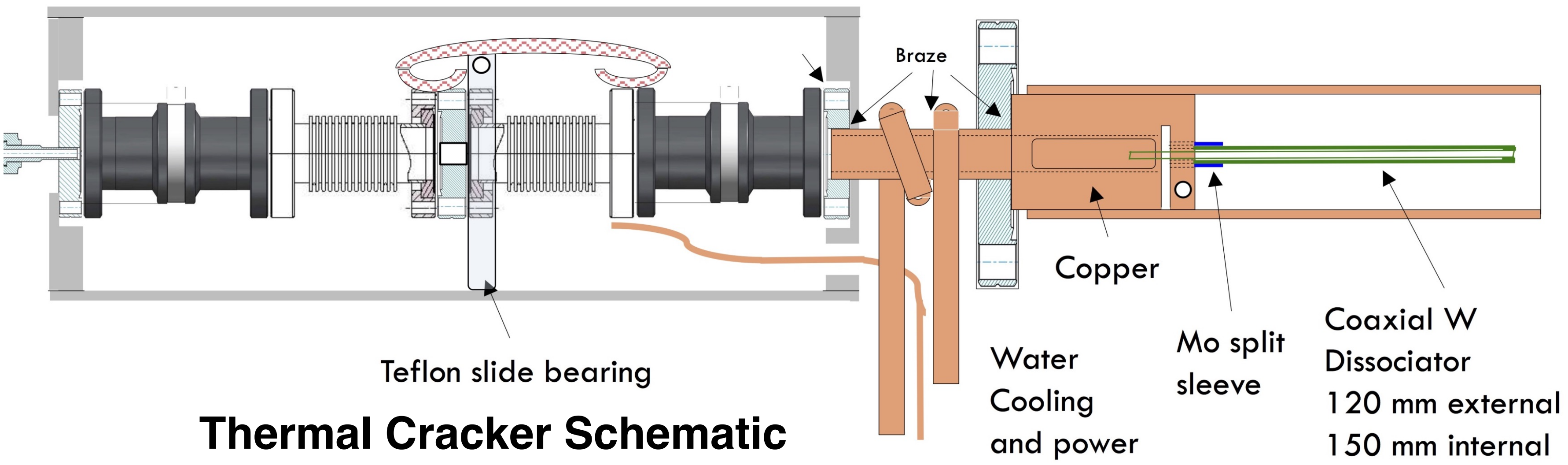


ATOMIC TRITIUM

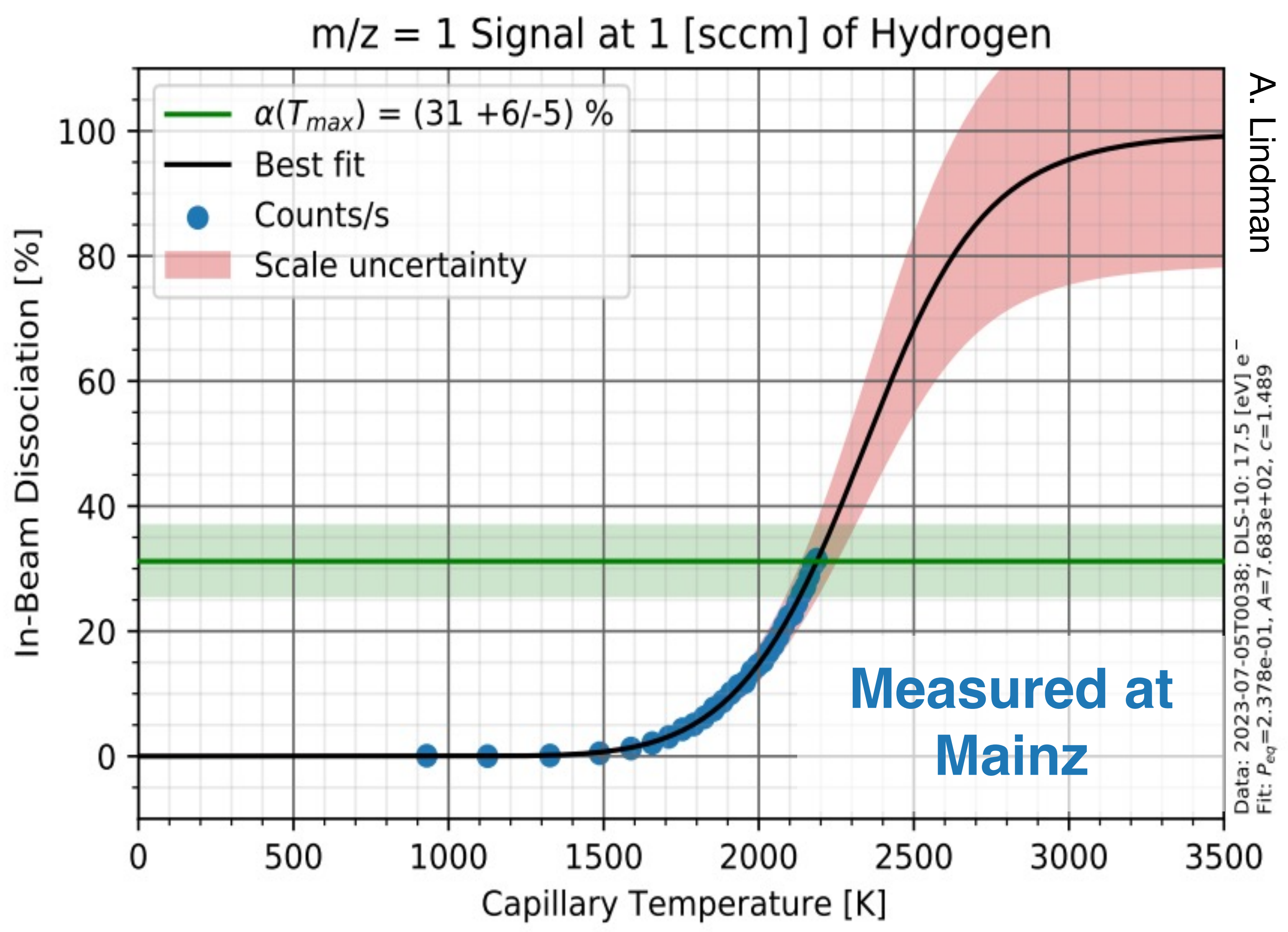
- The irreducible uncertainty on distribution of the ^{3}HeT+ final states after the decay of molecular tritium complicates the extraction of neutrino mass
  - Limits all future tritium-based experiments to ~100 meV sensitivity!
- Switch to Atomic Tritium to improve mass sensitivity: 40 meV!
- Challenges: How to produce atomic T? How to trap?
- Design: Cool and trap polarized atomic tritium in Ioffe magnetic trap
  - Alternative: Halbach array (permanent magnets)

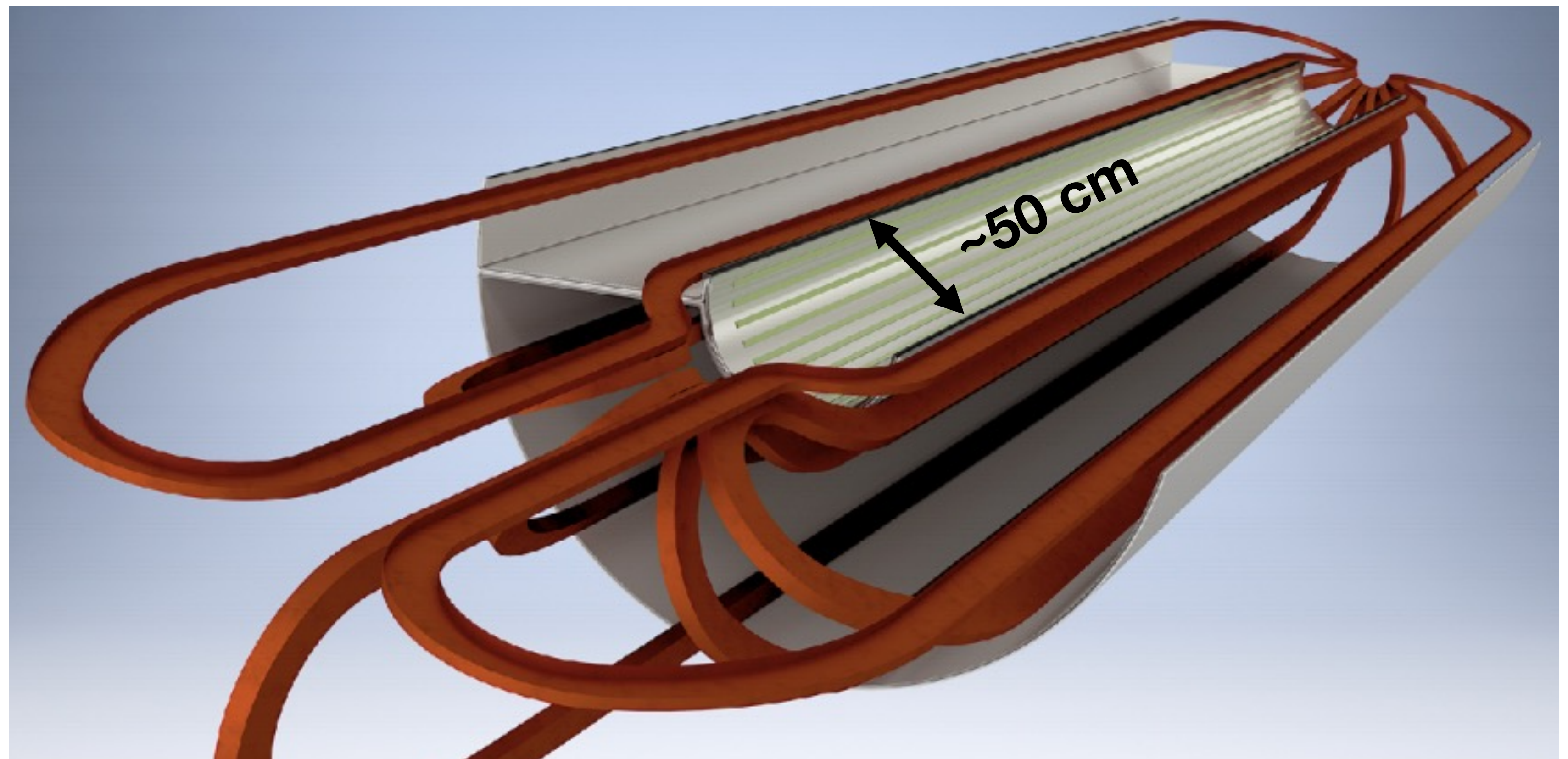






Thermal Cracker Schematic

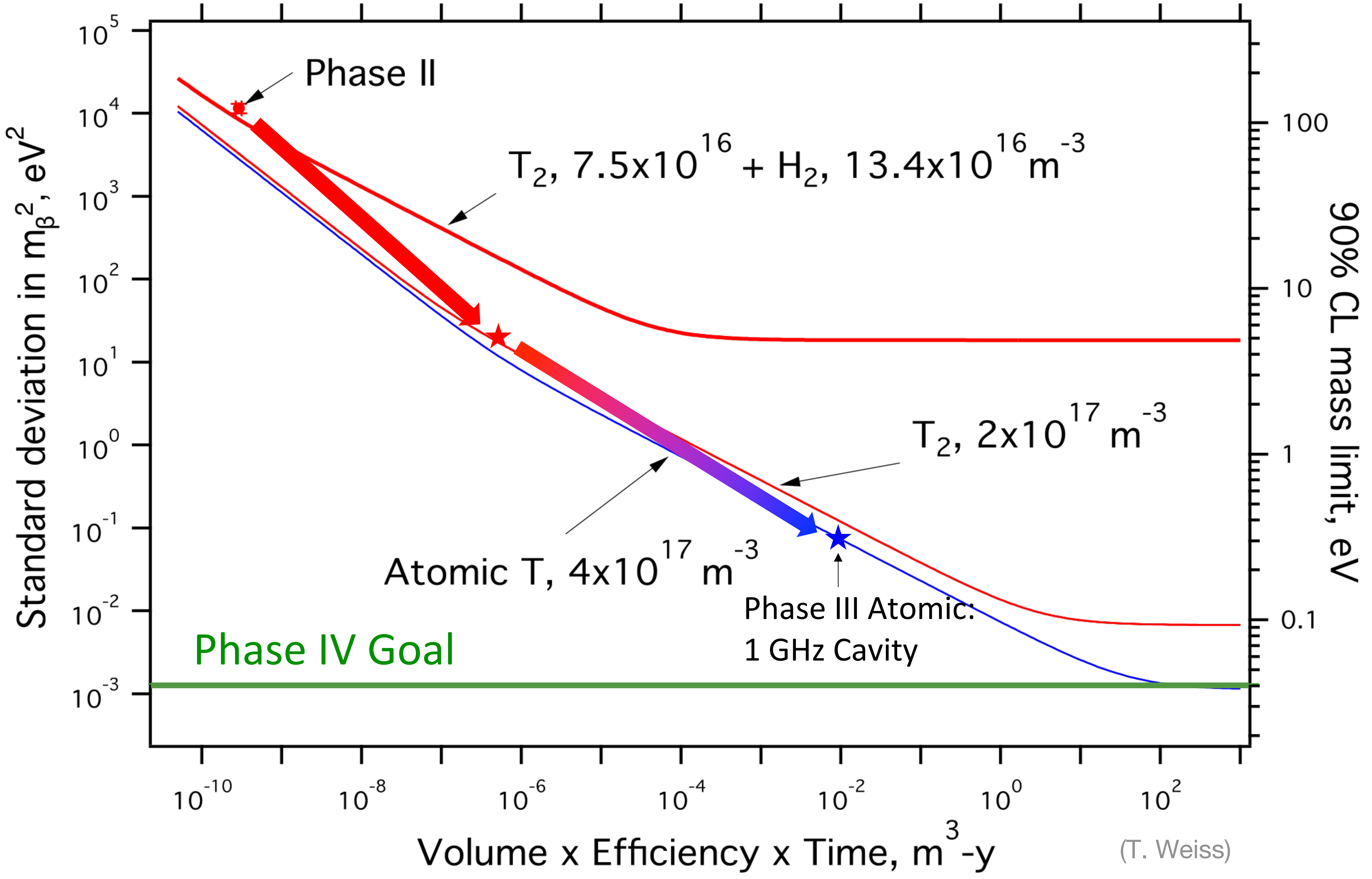


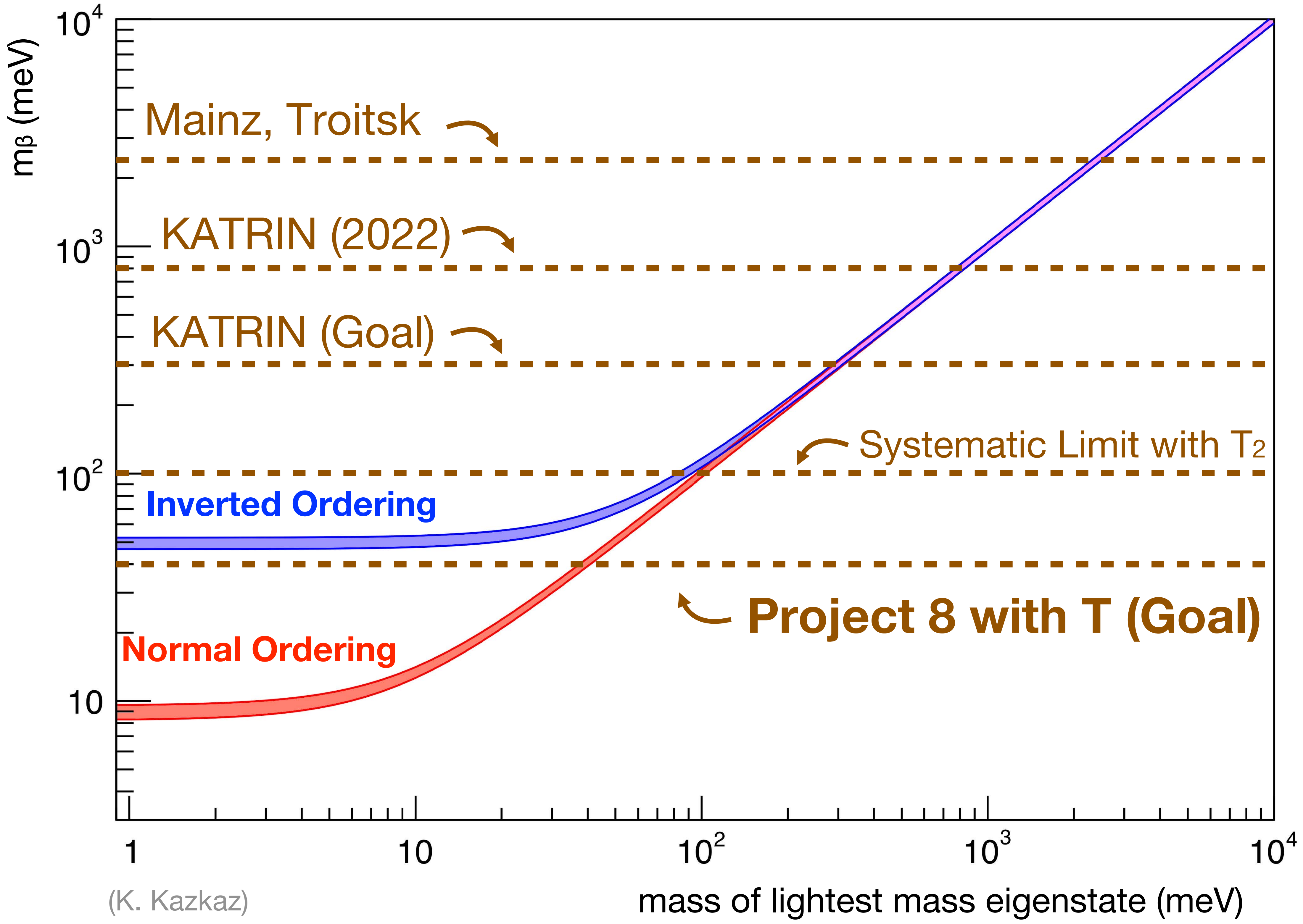


Design Concept: Ioffe magnetic trap
(Image: A. Lindman)

PHASE IV

- Atomic tritium experiment with large (>10 m^3) instrumented volume ⇒ 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!

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

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Lawrence Berkeley National Laboratory
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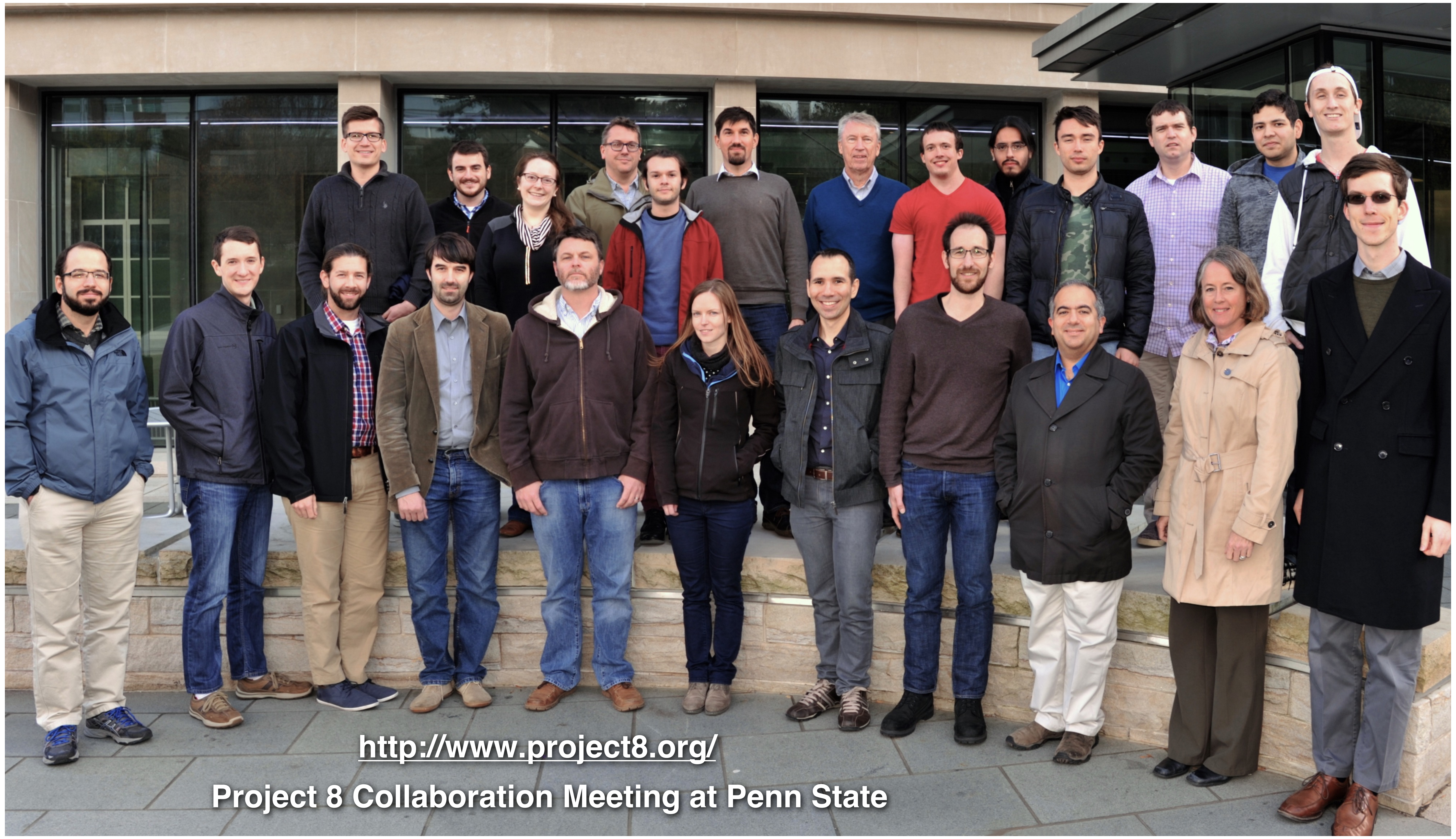
University of Washington
Yale University



Interested in joining Project 8?
We are looking for a Postdoc at Penn State !
Please contact ldeviveiros@psu.edu !

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