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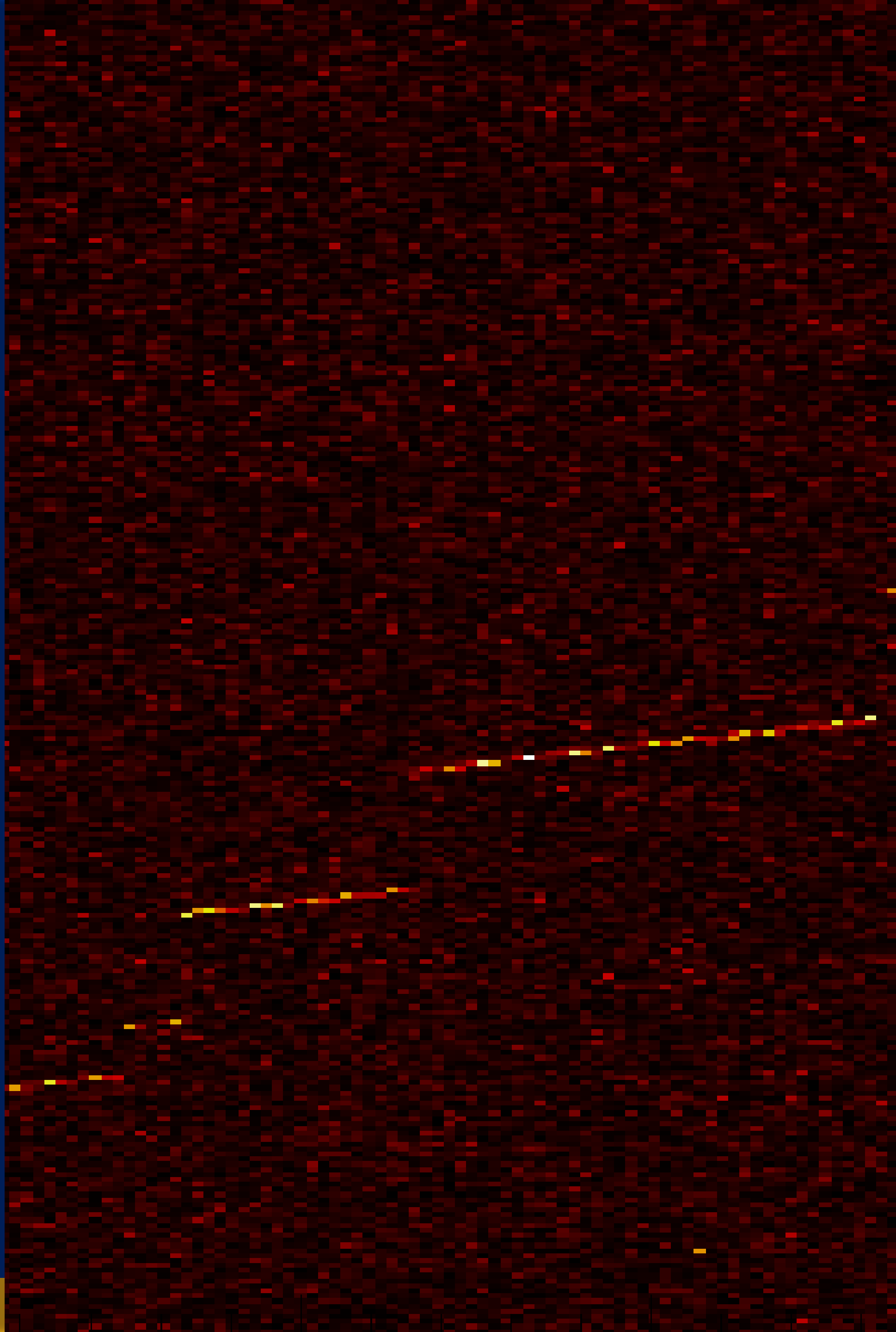
PROJECT 8

PHENO ’26 | Neutrino Physics: Masses, Exp. Signatures

Direct Neutrino Mass Measurement with Project 8

Ehteshamul Karim (on behalf of Project 8 collaboration)

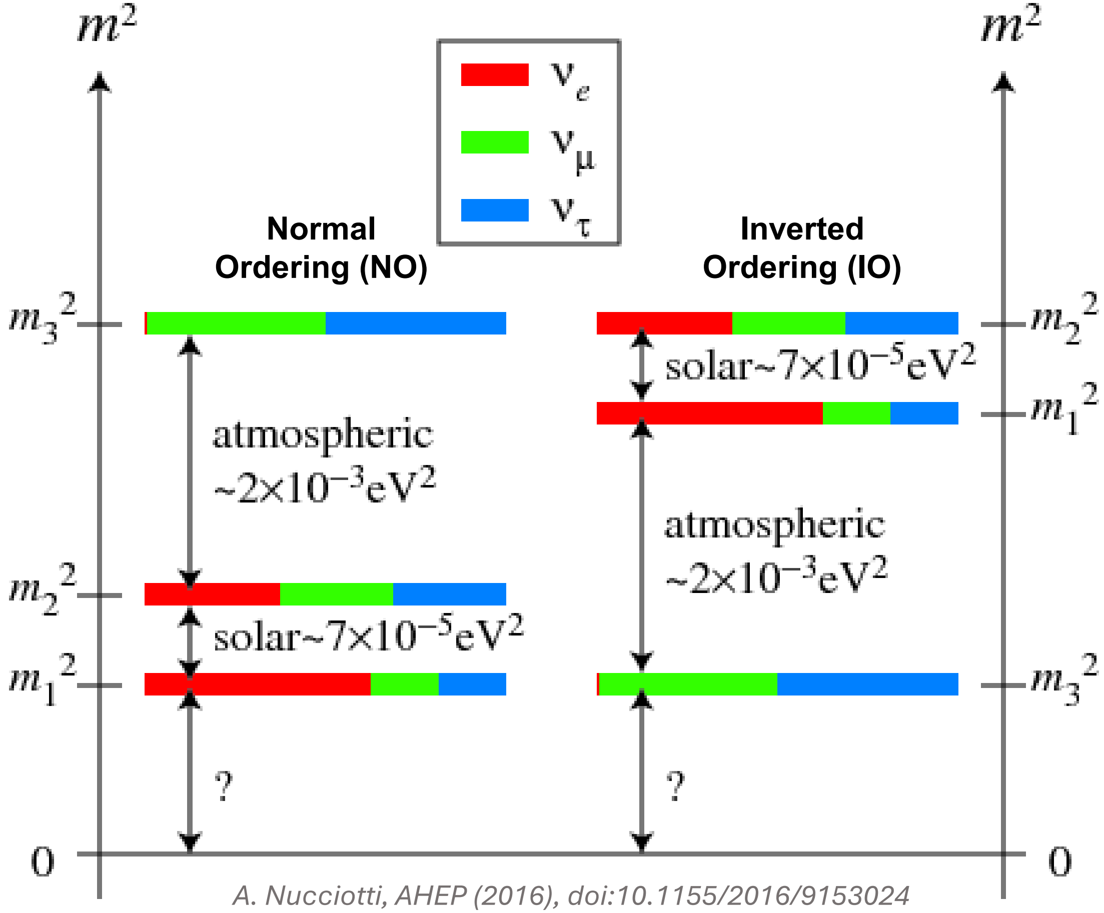
Monday, May 11th, 2026



Neutrino mass with β-decay spectroscopy

- Neutrinos oscillate as they travel distance → neutrinos have non-zero mass!
- What is the absolute mass scale? What is the mass ordering?

$$P(\nu_\alpha \to \nu_\beta) = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2}{4E}L\right)$$



A. Nucciotti, AHEP (2016), doi:10.1155/2016/9153024

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Neutrino mass with β-decay spectroscopy

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- Tritium β-spectroscopy is the leading technique for direct neutrino mass measurement

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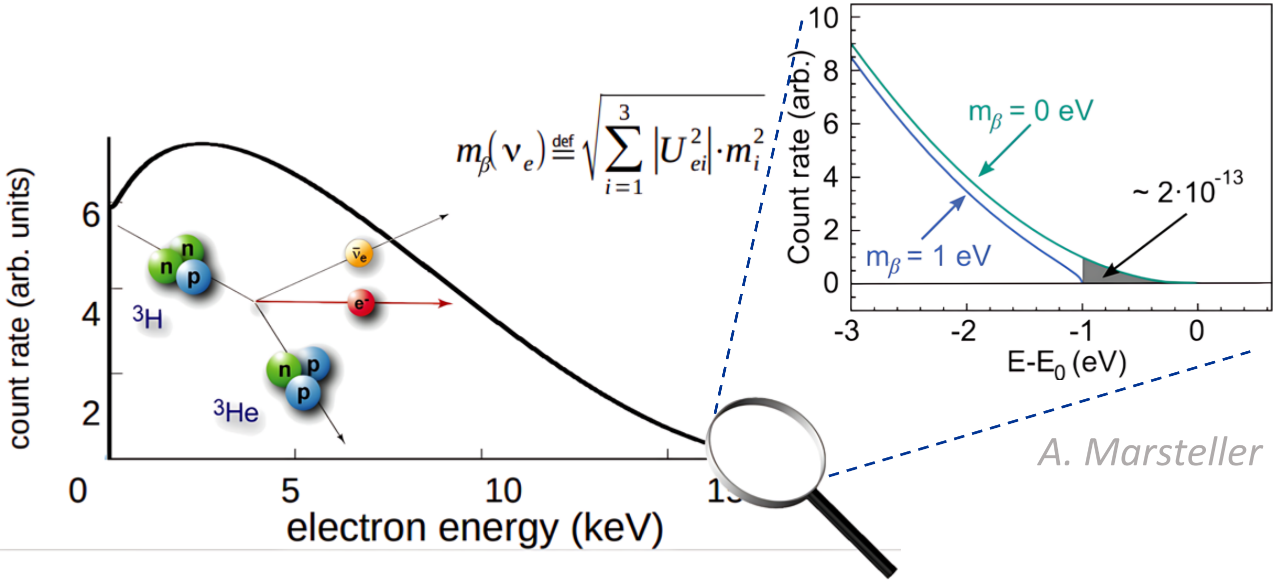

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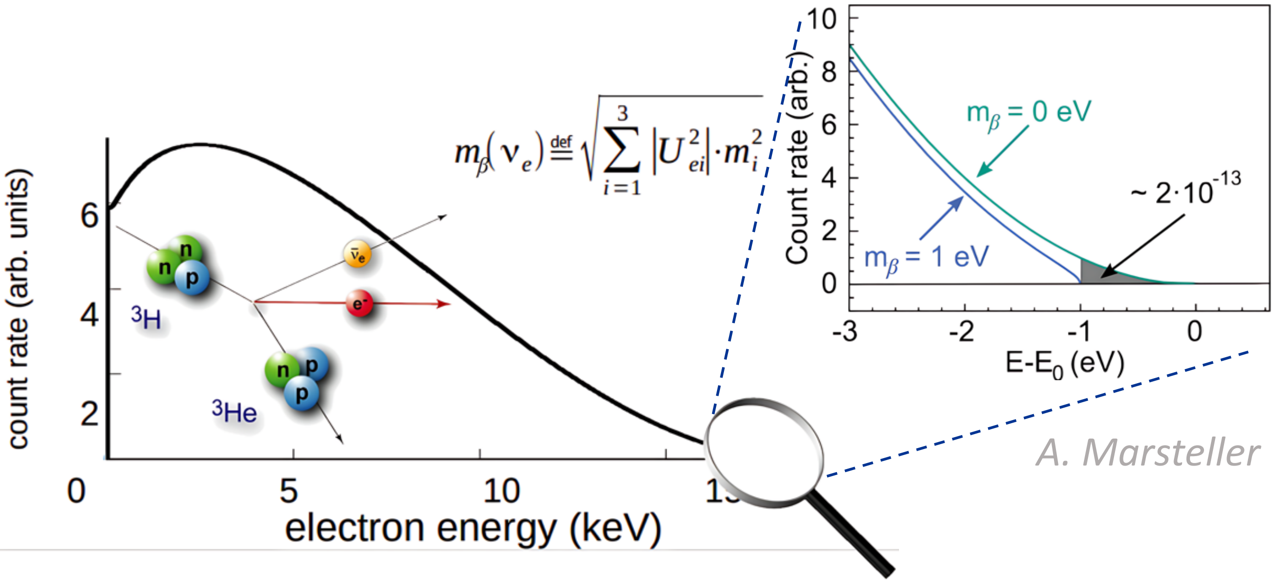
Neutrino mass with β-decay spectroscopy

$$P(\nu_\alpha \to \nu_\beta) = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2}{4E}L\right)$$

- Neutrinos oscillate as they travel distance → neutrinos have non-zero mass!
- What is the absolute mass scale? What is the mass ordering?
- Tritium β-spectroscopy is the leading technique for direct neutrino mass measurement
  - Best limits from KATRIN: m_β < 0.45 eV/c² (90% C.L.)
  - Final sensitivity goal of 0.3 eV/c² still above cosmological and inverted ordering (IO) mass scale



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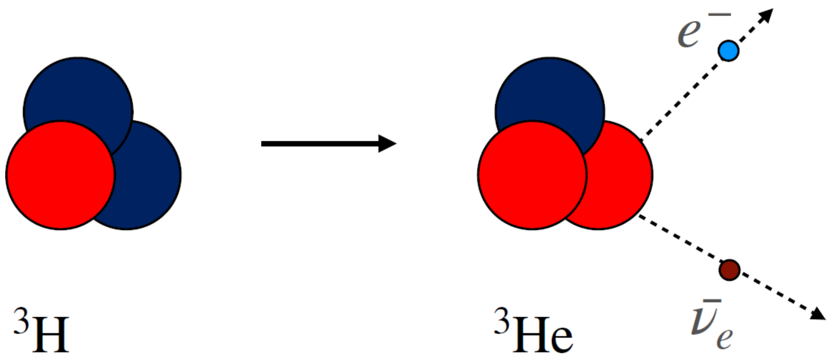
Cyclotron Radiation Emission Spectroscopy (CRES)

10.1103/PhysRevD.80.051301

❖ Place electron from β-decay (Tritium) in uniform magnetic field



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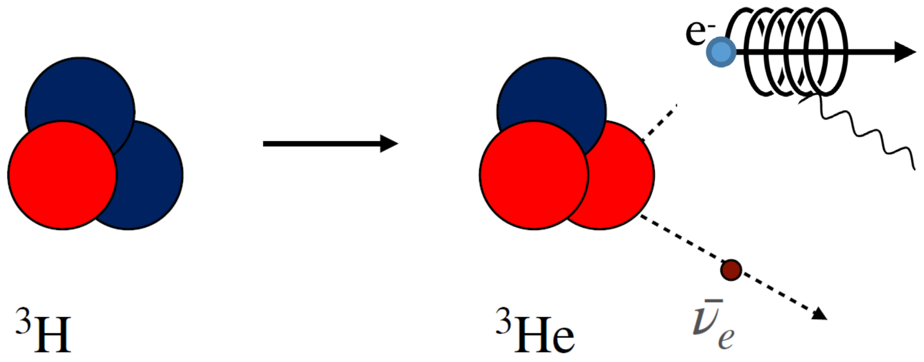
Cyclotron Radiation Emission Spectroscopy (CRES)

10.1103/PhysRevD.80.051301

- Place electron from β-decay (Tritium) in uniform magnetic field
- Undergoes cyclotron motion and emits cyclotron radiation



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Cyclotron Radiation Emission Spectroscopy (CRES)

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- Place electron from β-decay (Tritium) in uniform magnetic field
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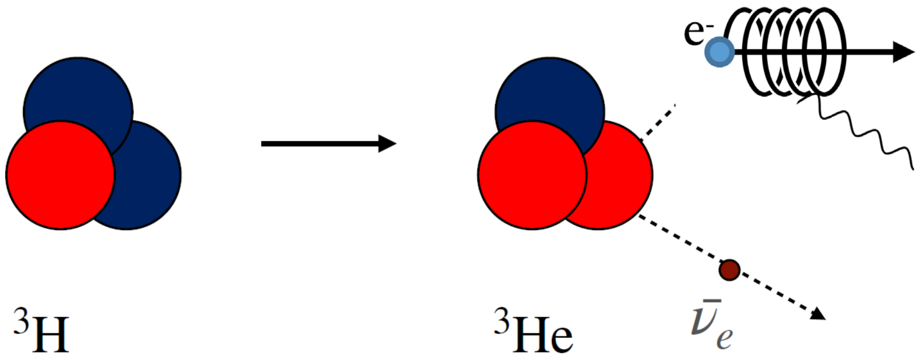
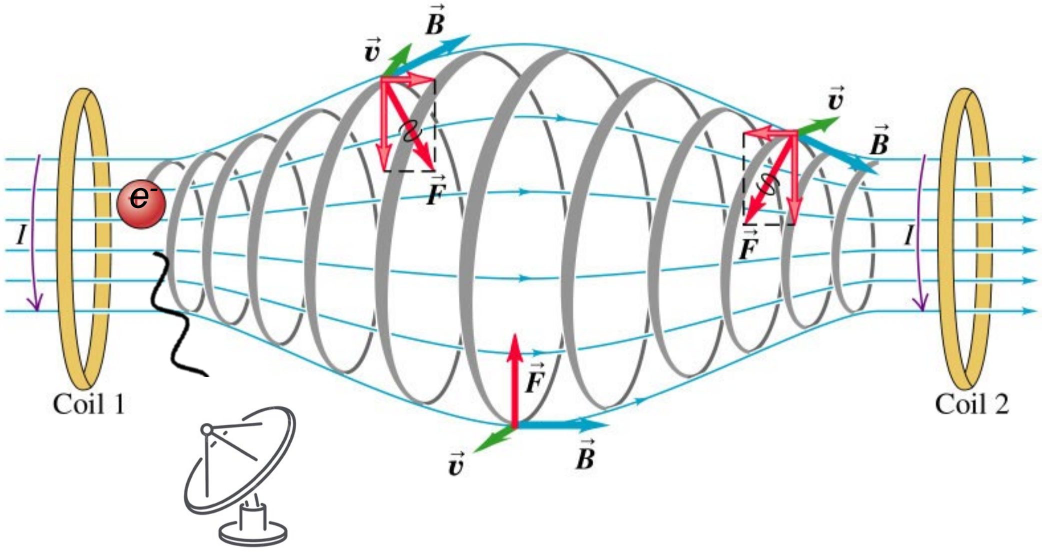
- Trap the electron long enough to measure the cyclotron frequency





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Cyclotron Radiation Emission Spectroscopy (CRES)

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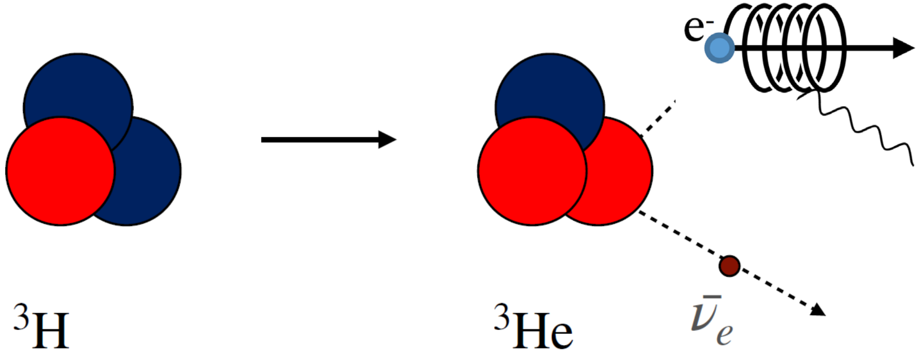
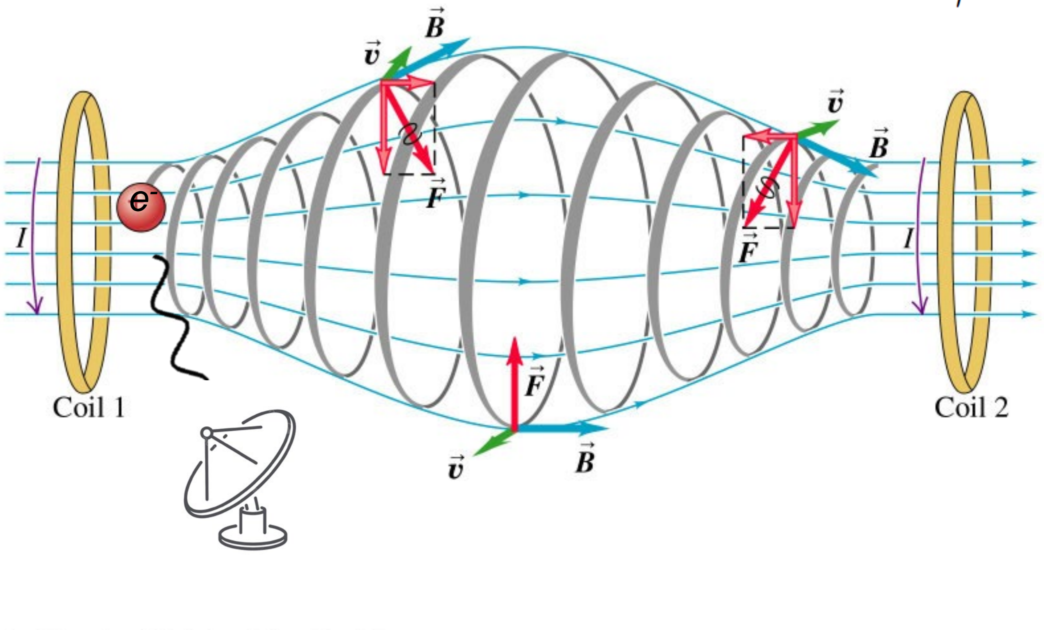
- Place electron from β-decay (Tritium) in uniform magnetic field
- Undergoes cyclotron motion and emits cyclotron radiation
- Trap the electron long enough to measure the cyclotron frequency
- Cyclotron frequency depends on electron kinetic energy

$$2\pi \boxed{f_c} = 2\pi \frac{f_{c,0}}{\gamma} = \frac{e\langle B \rangle}{m_e + \boxed{\frac{E}{c^2}}}$$





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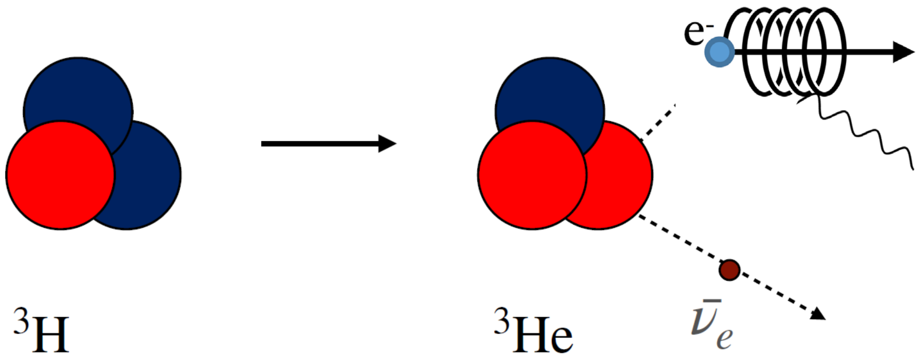

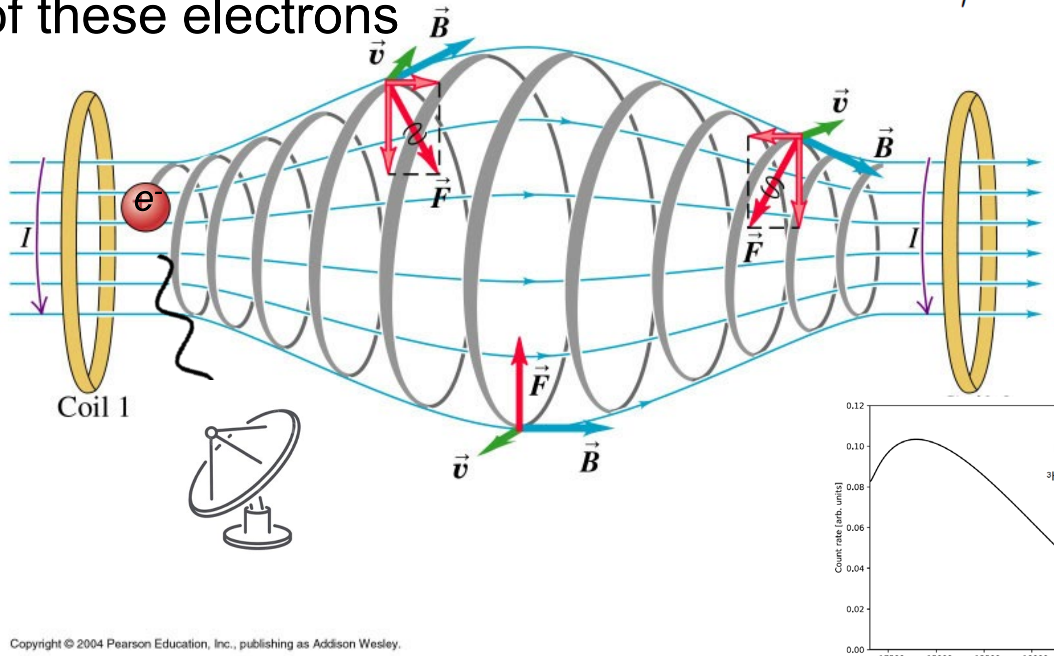

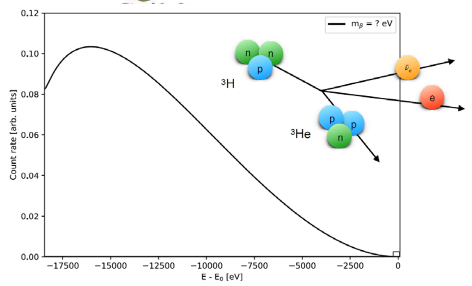

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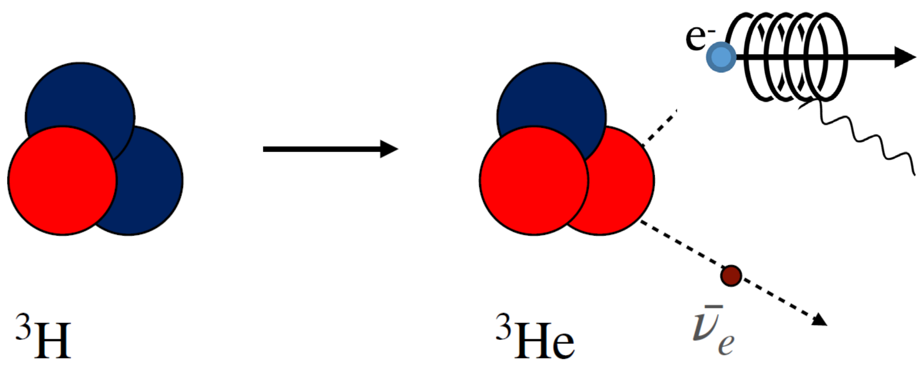

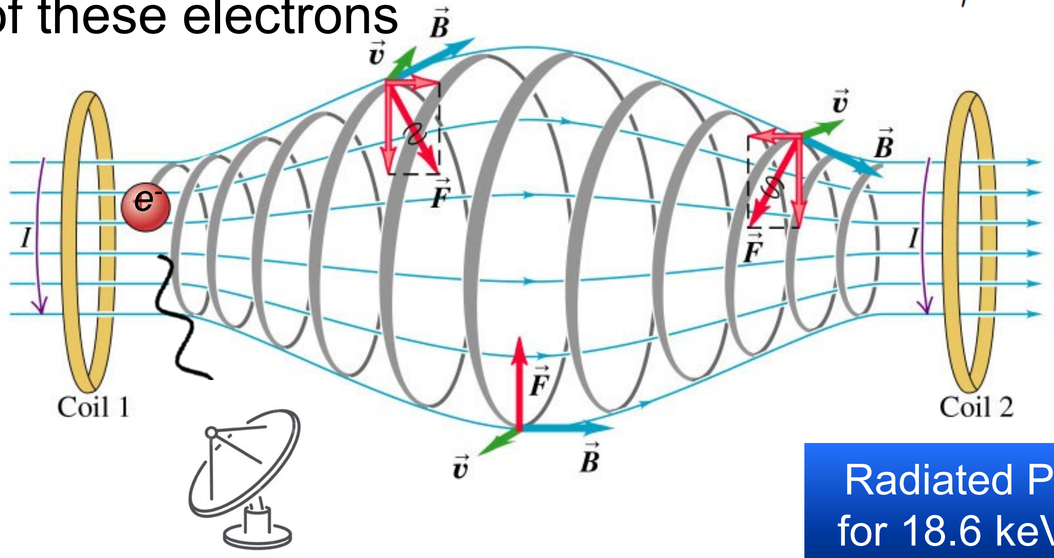

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Radiated Power ~ **1 fW** for 18.6 keV electrons in ~ 1 T B-field

Cyclotron Radiation Emission Spectroscopy (CRES)

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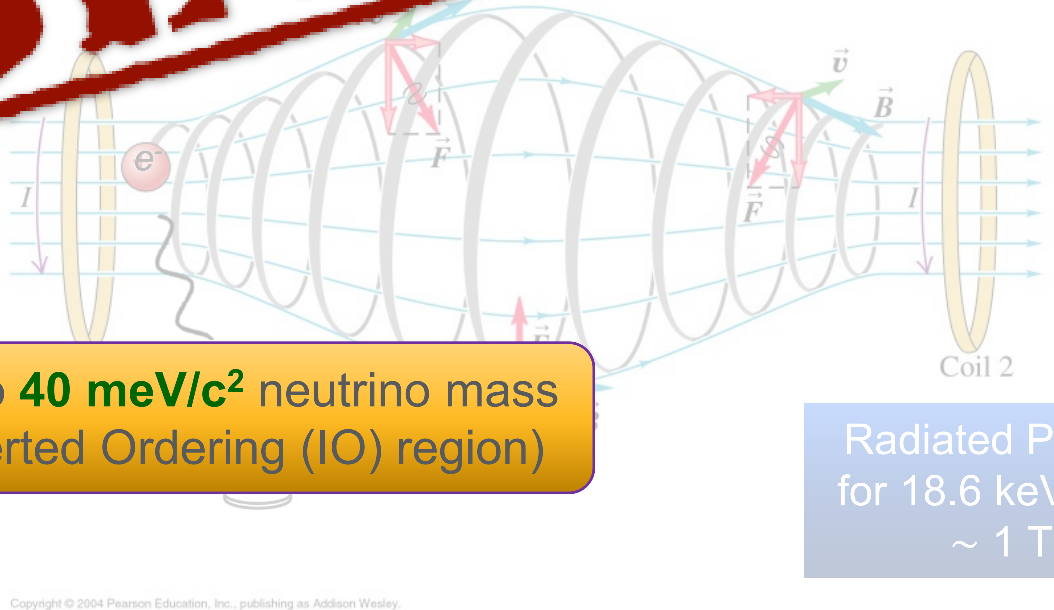

Goal: Sensitivity to **40 meV/c^2** neutrino mass (covering the Inverted Ordering (IO) region)

Radiated Power ~ **1 fW** for 18.6 keV electrons in ~ 1 T B-field

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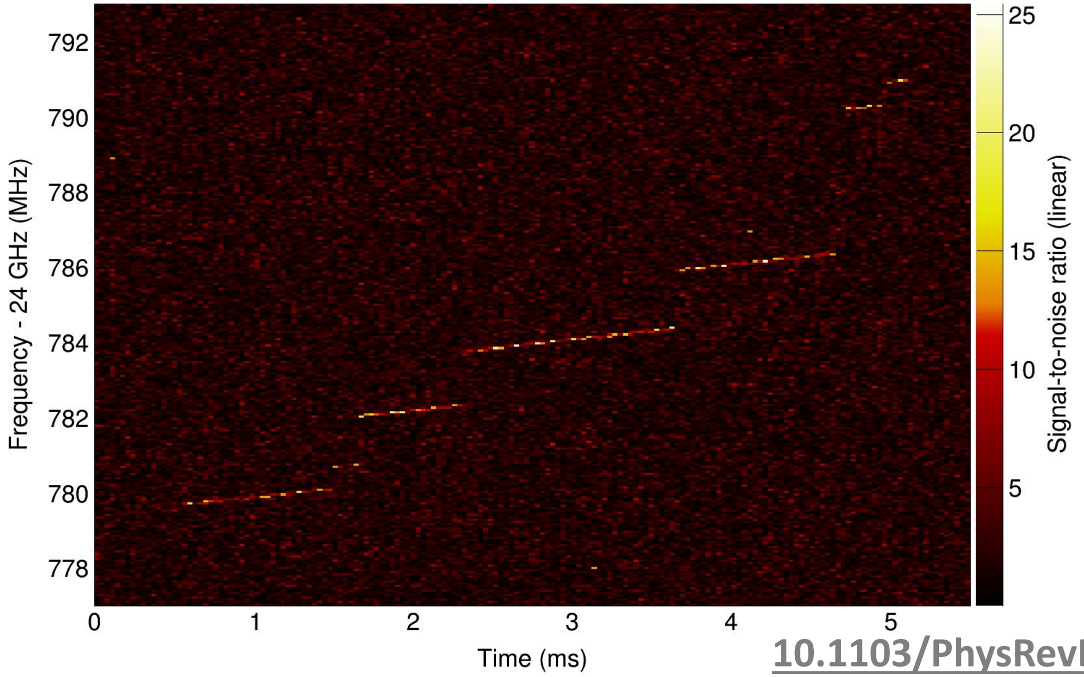
Measuring m_β using CRES with Project 8

- Phase – I:
  - First detection of single-electron cyclotron radiation spectroscopy (2015)



$$f_c = \frac{1}{2\pi}\frac{e\langle B\rangle}{m_e + E_{kin}/c^2}$$

10.1103/PhysRevLett.114.162501

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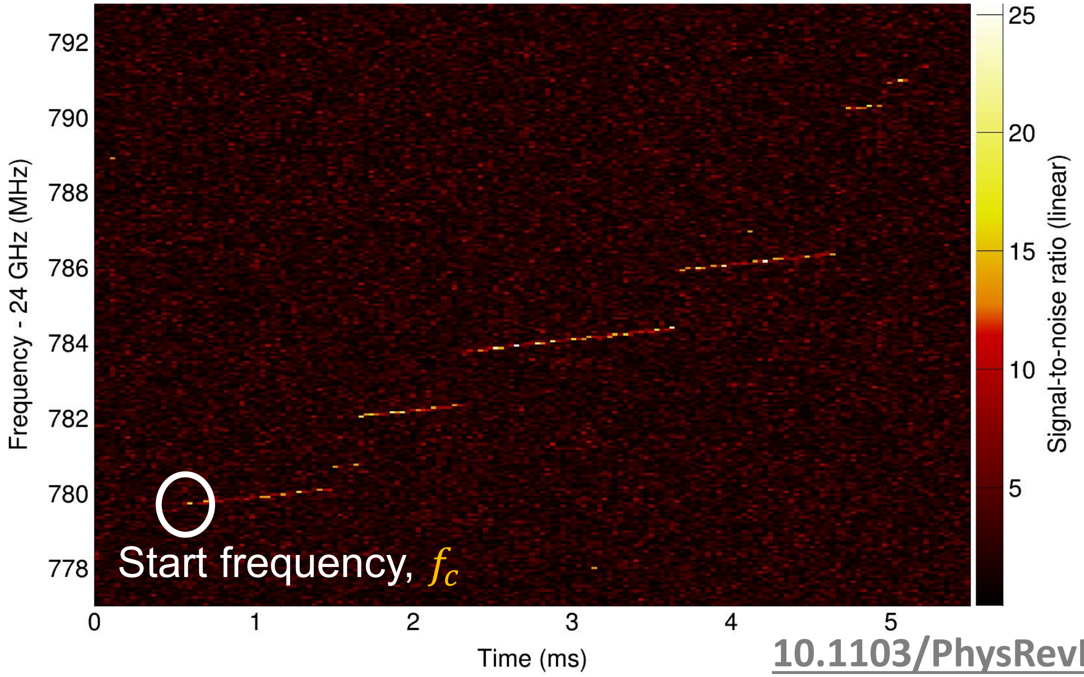

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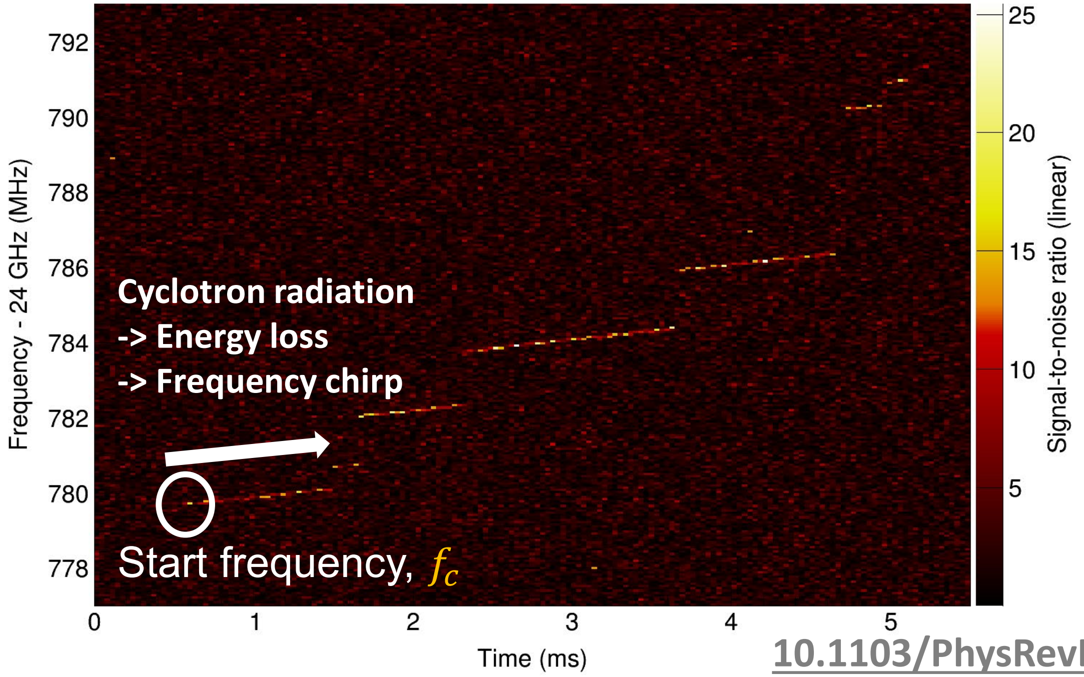

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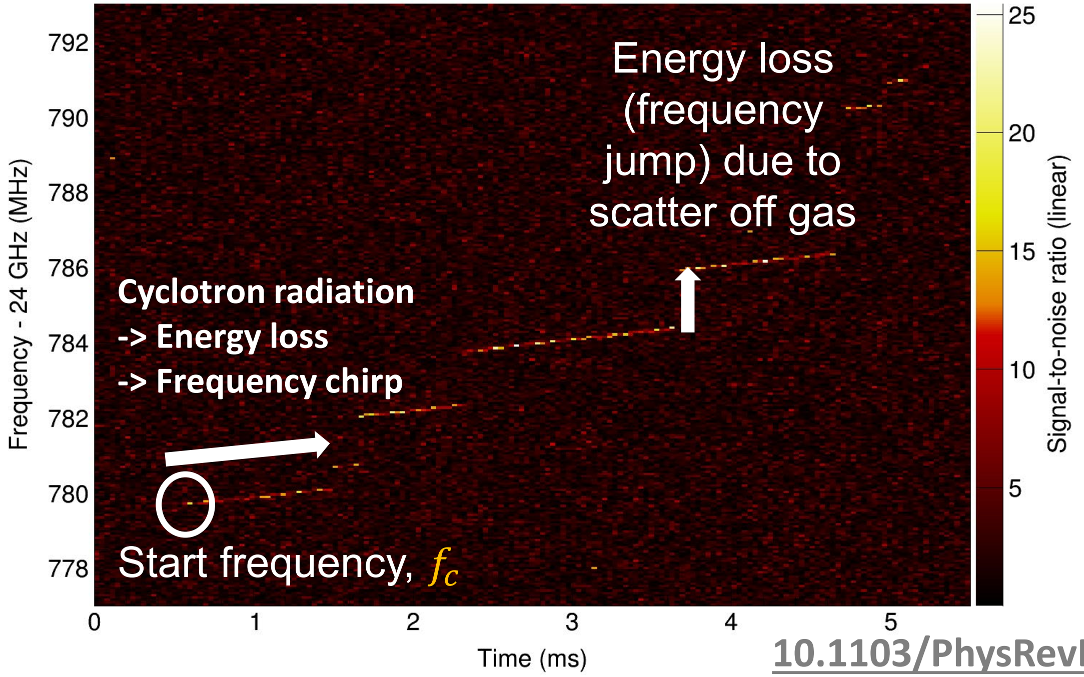

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10.1103/PhysRevLett.114.162501

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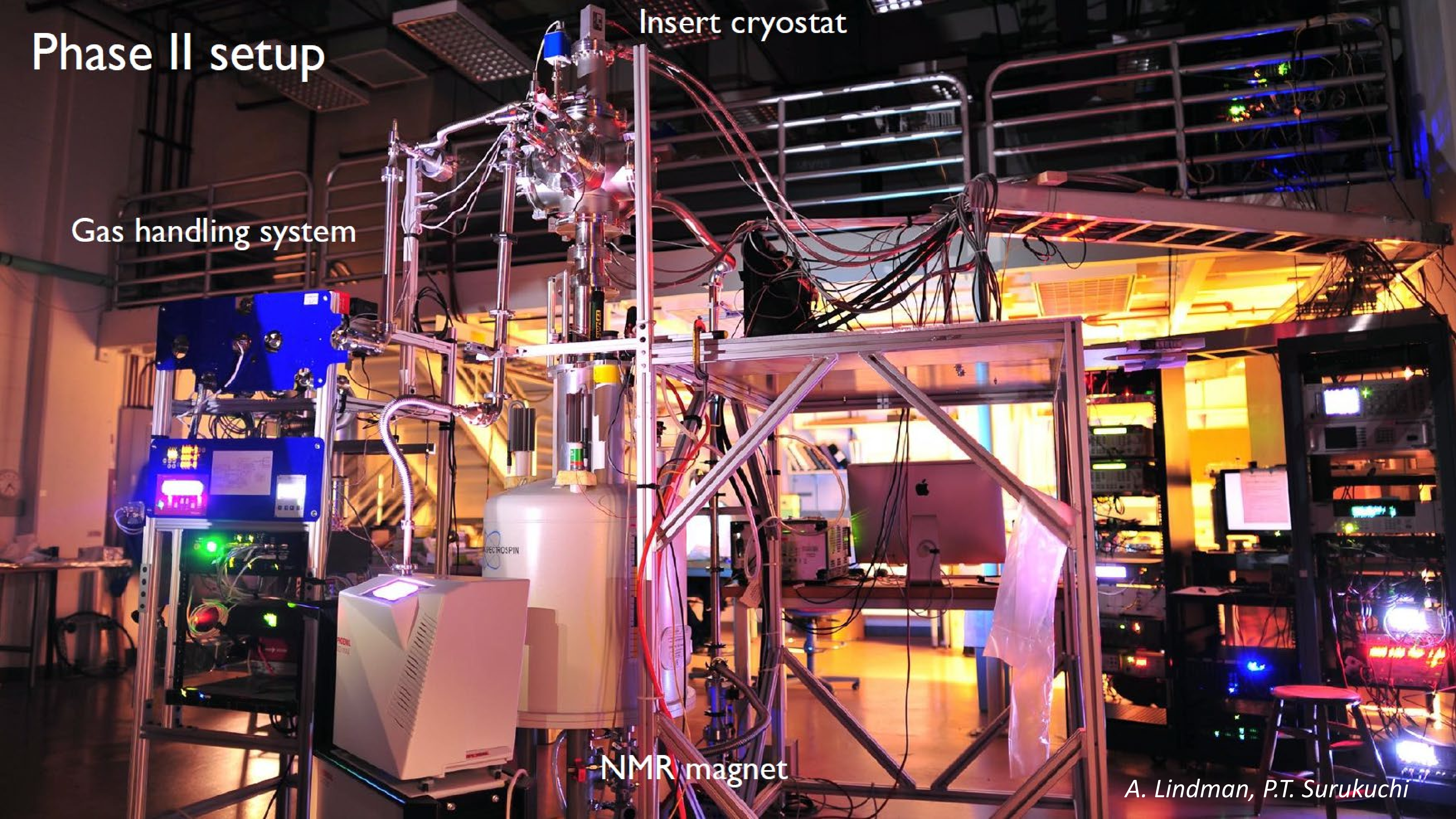
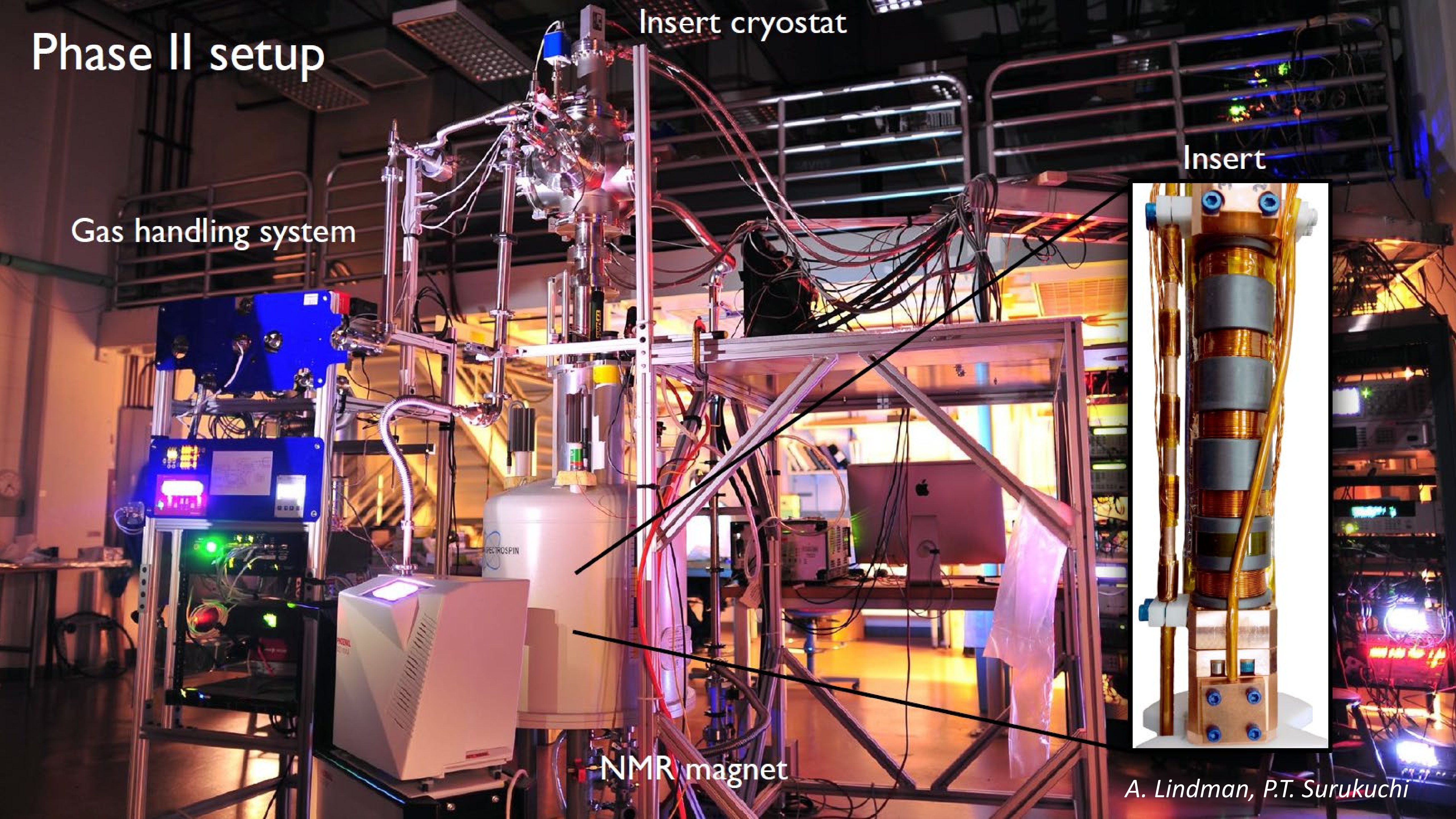
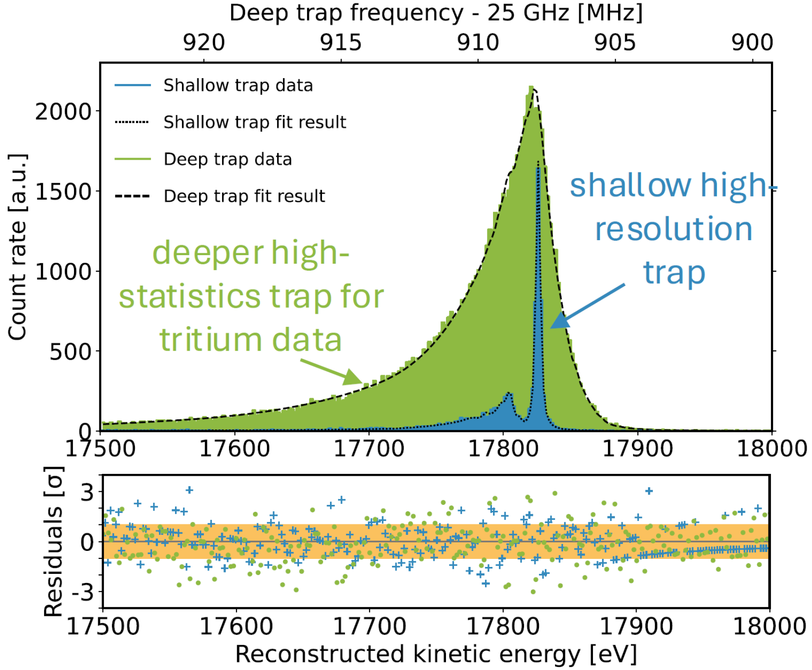
Phase II setup

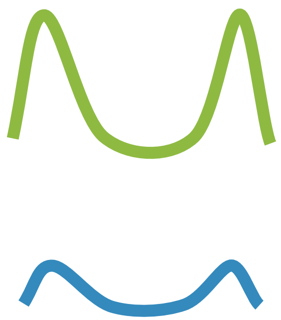


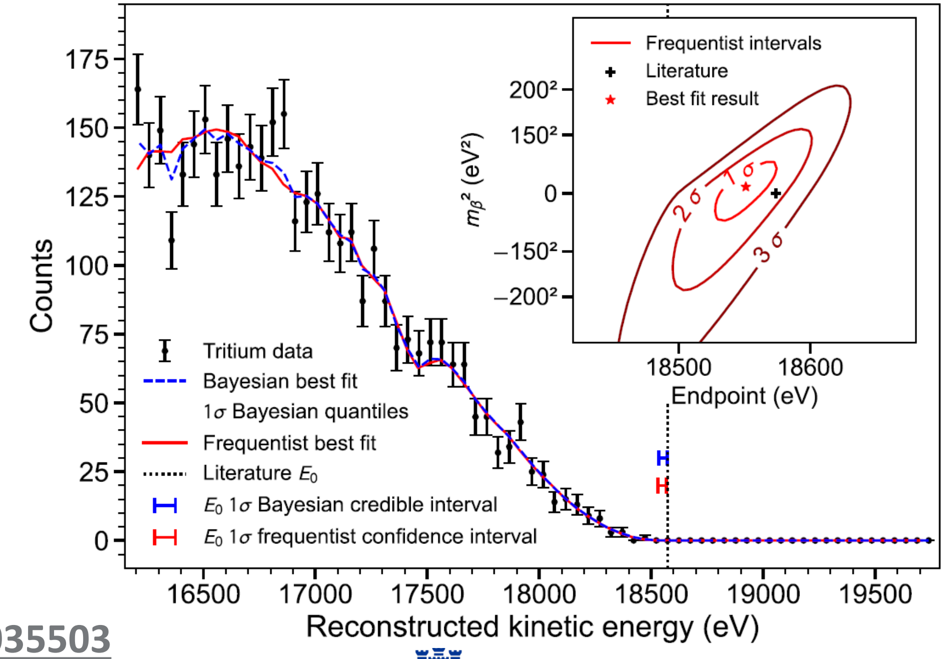

Phase II setup
Insert cryostat
Gas handling system
Insert
SPECTROSPIN
NMR magnet
A. Lindman, P.T. Surukuchi

Measuring m_β using CRES with Project 8

- Phase – I:
  - First detection of single-electron cyclotron radiation spectroscopy (2015)
- Phase – II:
  - First T_2 endpoint neutrino mass measurement using CRES ≤ 152 eV/c^2 (90% C.I.) (2023)
    - Science run - 82 days of data taking; 3770 events, **1 mm^3** effective volume
    - No events past endpoint! → set limit on background rate: ≤ 3×10^{-10} eV^{-1}s^{-1} (90% C. L.)



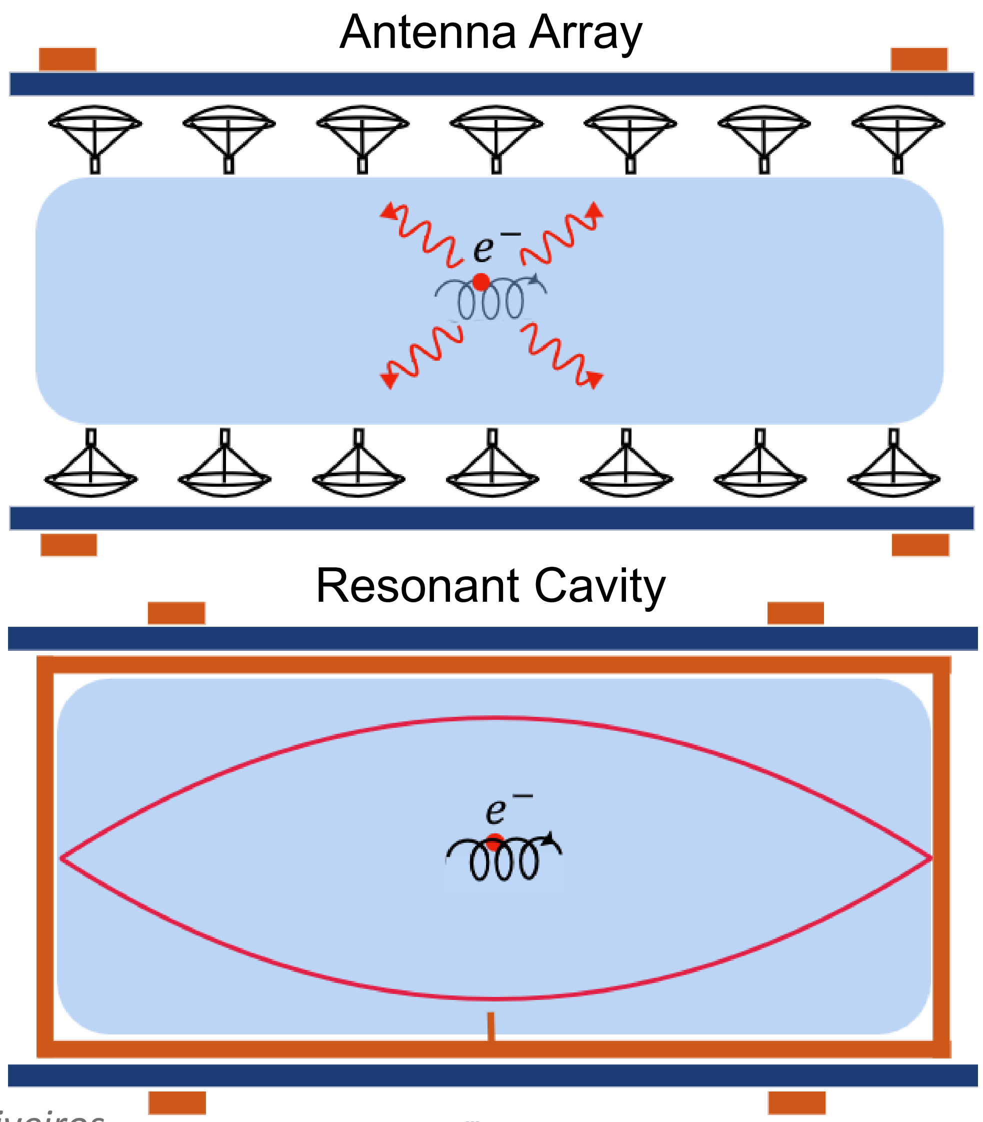




10.1103/PhysRevC.109.035503

Moving to CRES using Cavity (Phase III)

- After extensive study between antenna array (Phys. Rev. C 112 (2025) 4, 045506) and resonant cavities, resonant cavity is favorable for scaling to larger volumes to reach sensitivity goals
- Higher SNR, larger volume efficiency and low channel counts



A. Ziegler, L. de Viveiros

Moving to CRES using Cavity (Phase III)

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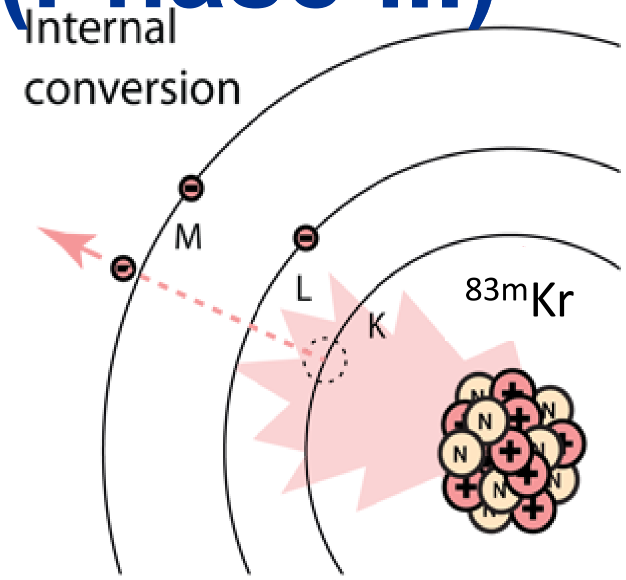
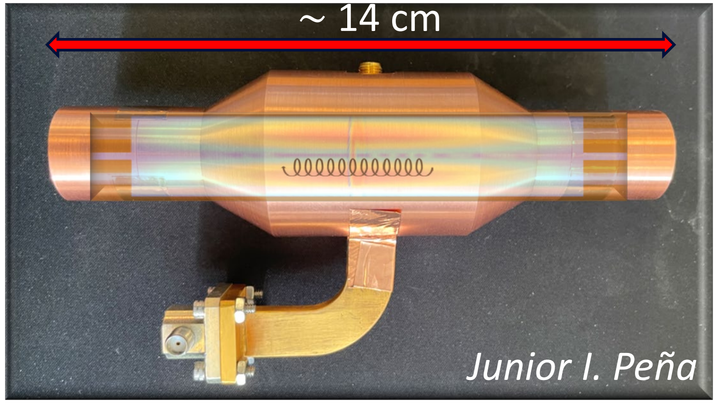
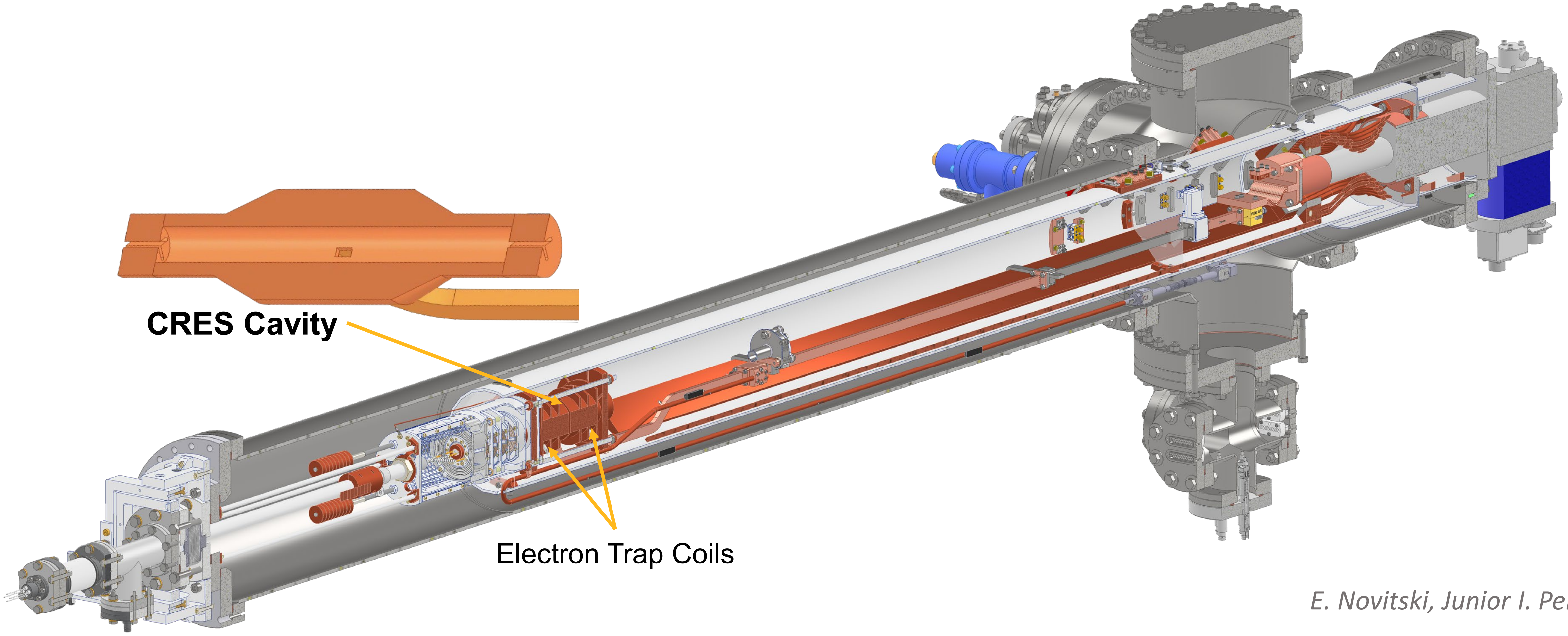
- Higher SNR, larger volume efficiency and low channel counts
- Start small: Cavity CRES Apparatus (CCA)
  - Demonstrate CRES using resonant cavity (~ cm^3)
  - Order-of-magnitude improvement in energy resolution (0.3 eV) using ^{83m}Kr internal conversion and Electron-gun calibration



Adapted from Hyperphysics, C.R. Nave

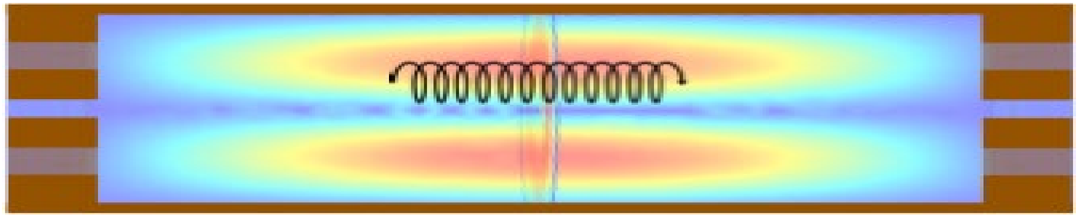


Cavity CRES Apparatus (CCA)

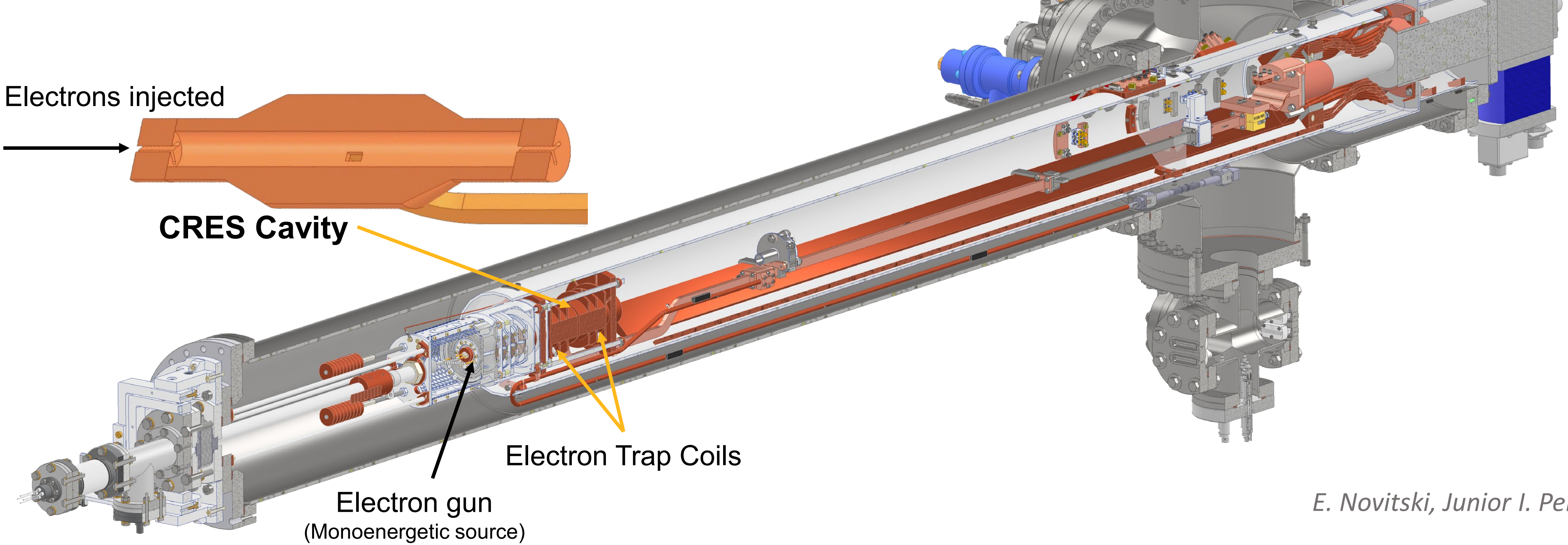


E. Novitski, Junior I. Peña

Cavity CRES Apparatus (CCA)



Electron couples to TE_{011} cavity mode



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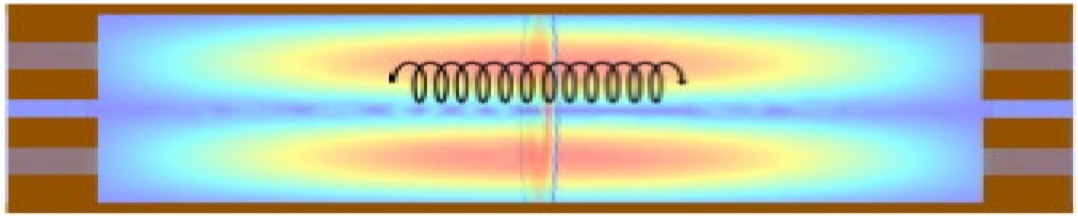
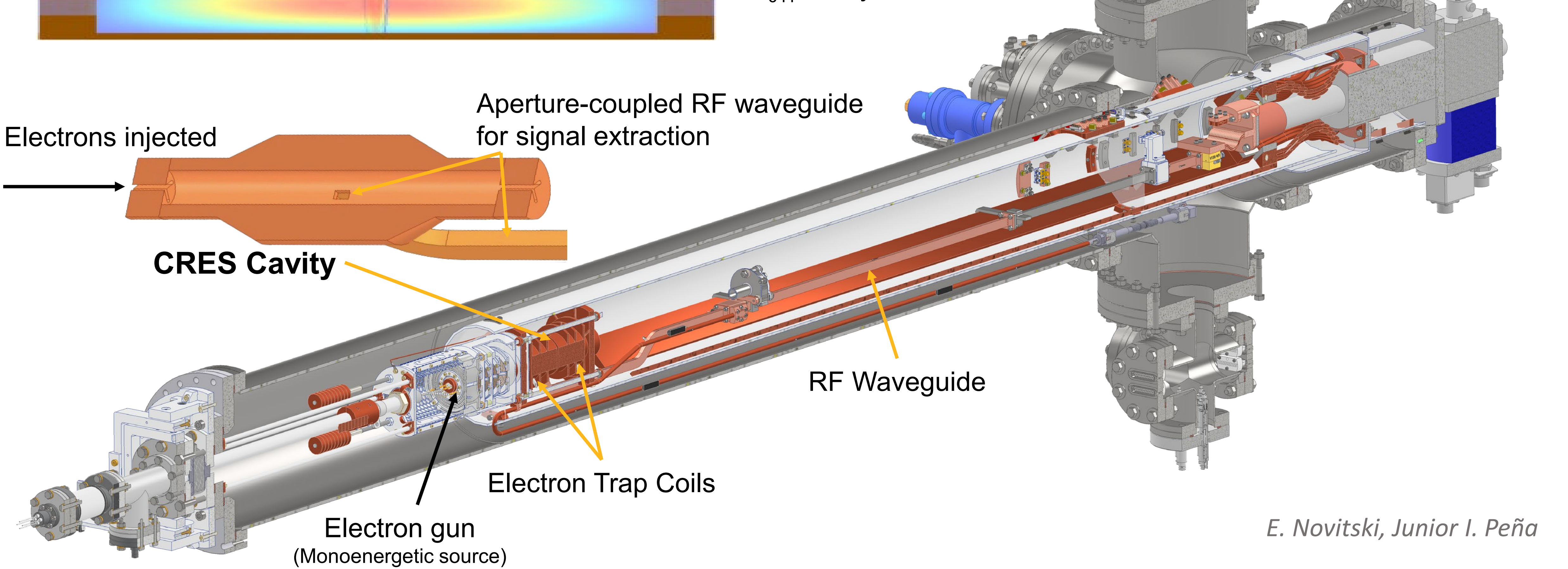
Cavity CRES Apparatus (CCA)





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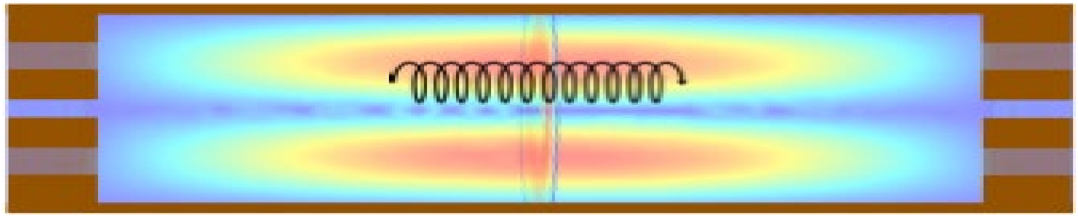

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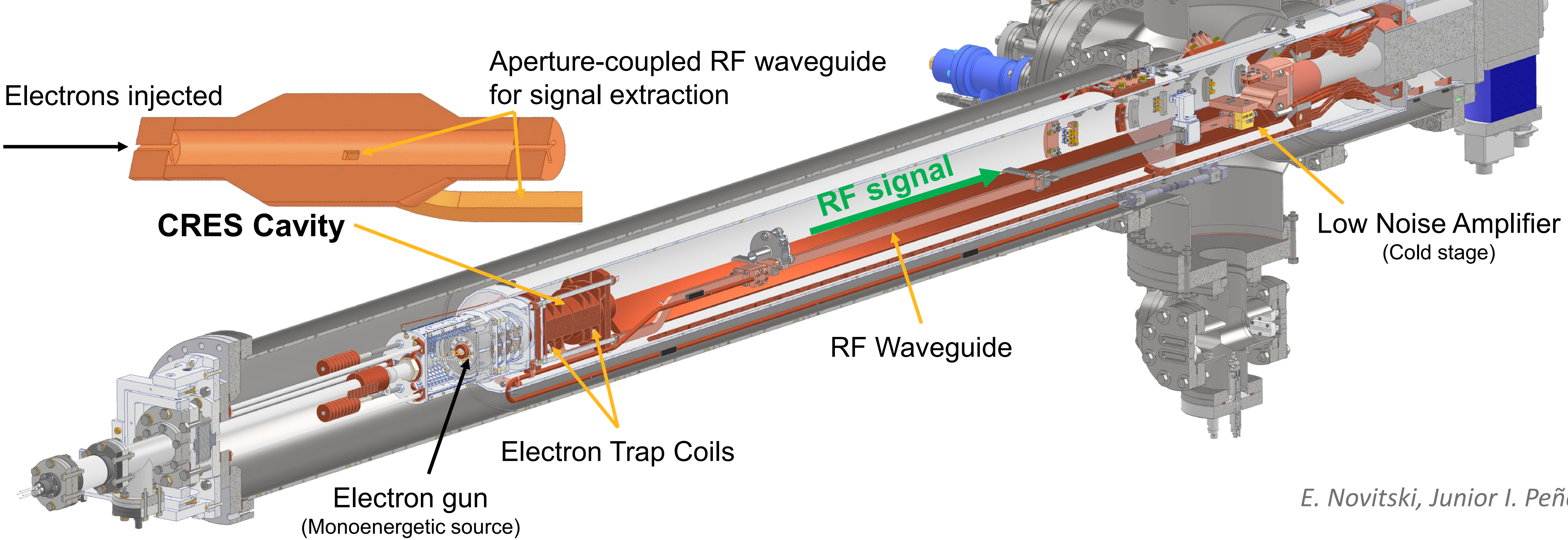

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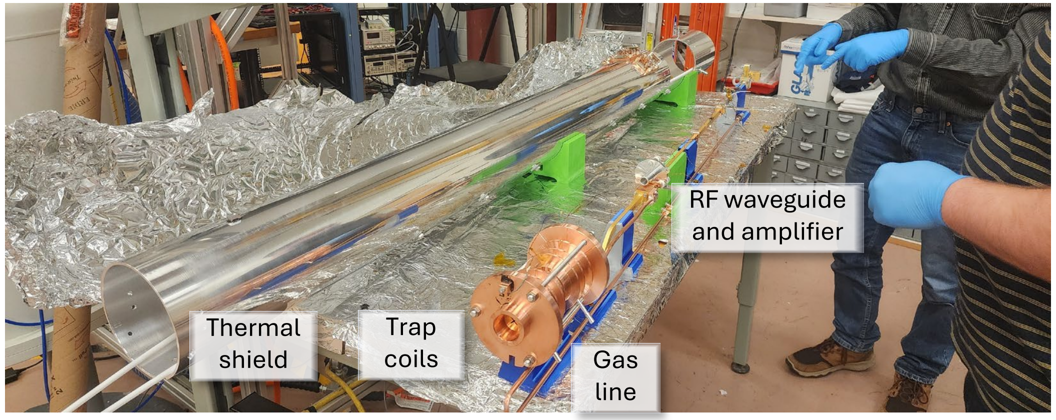
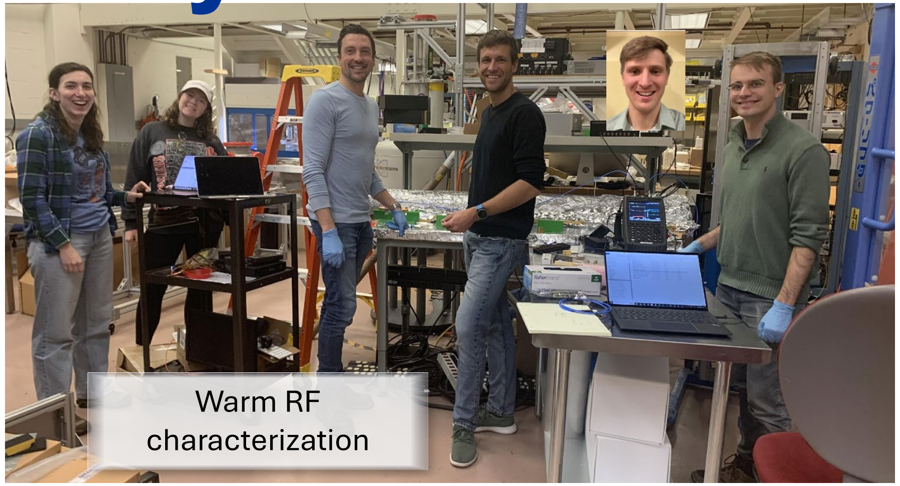
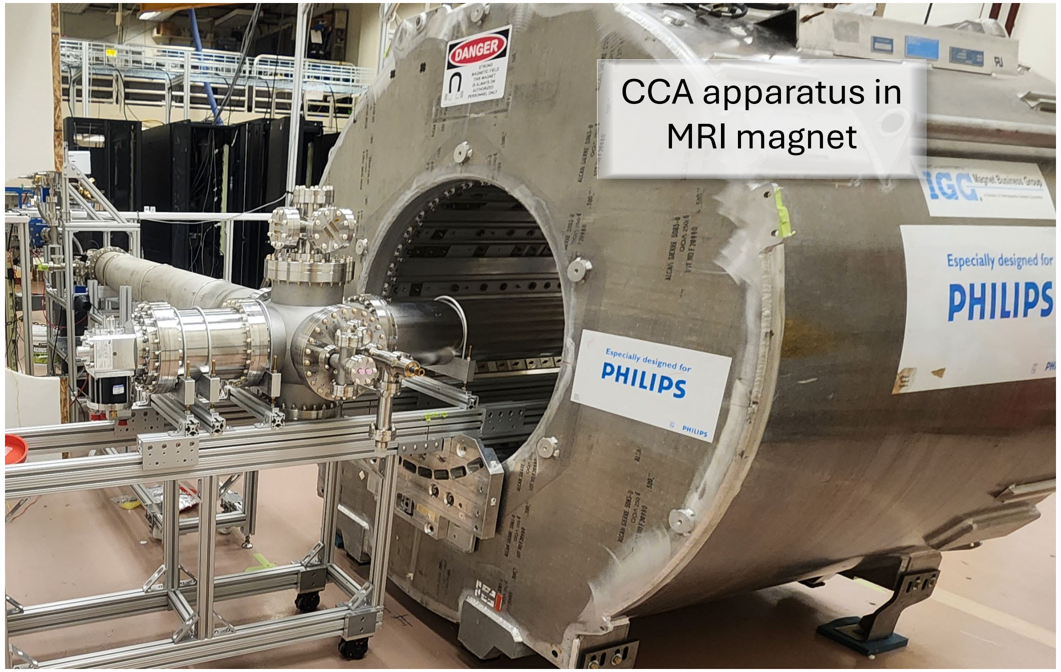
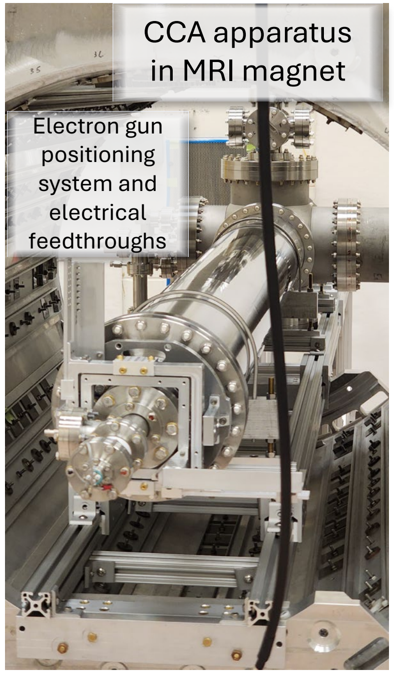
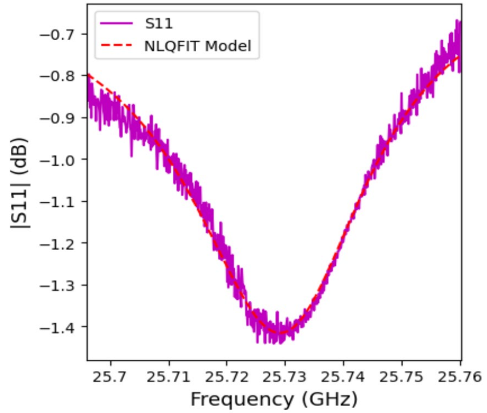
CCA commissioning underway!











First warm characterization of cavity RF resonance

Slide credit: E. Novitski

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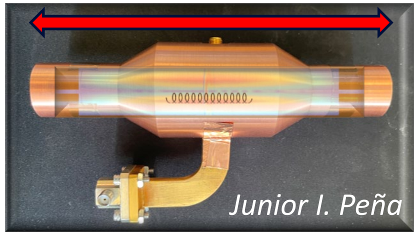
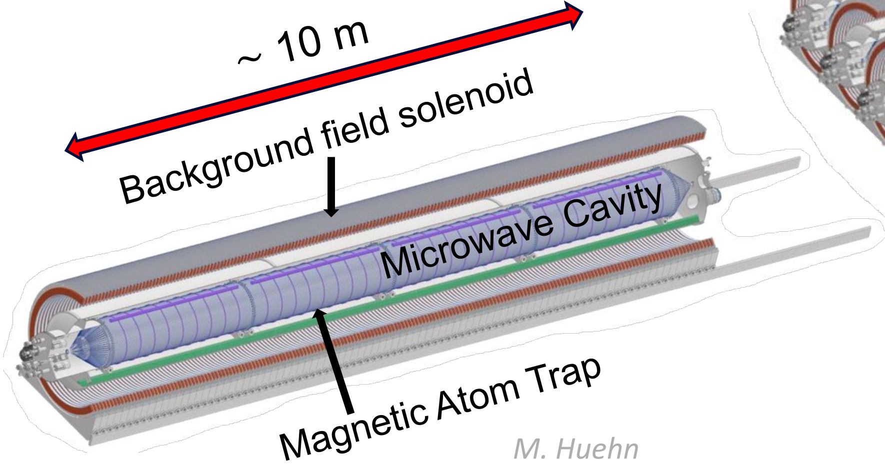
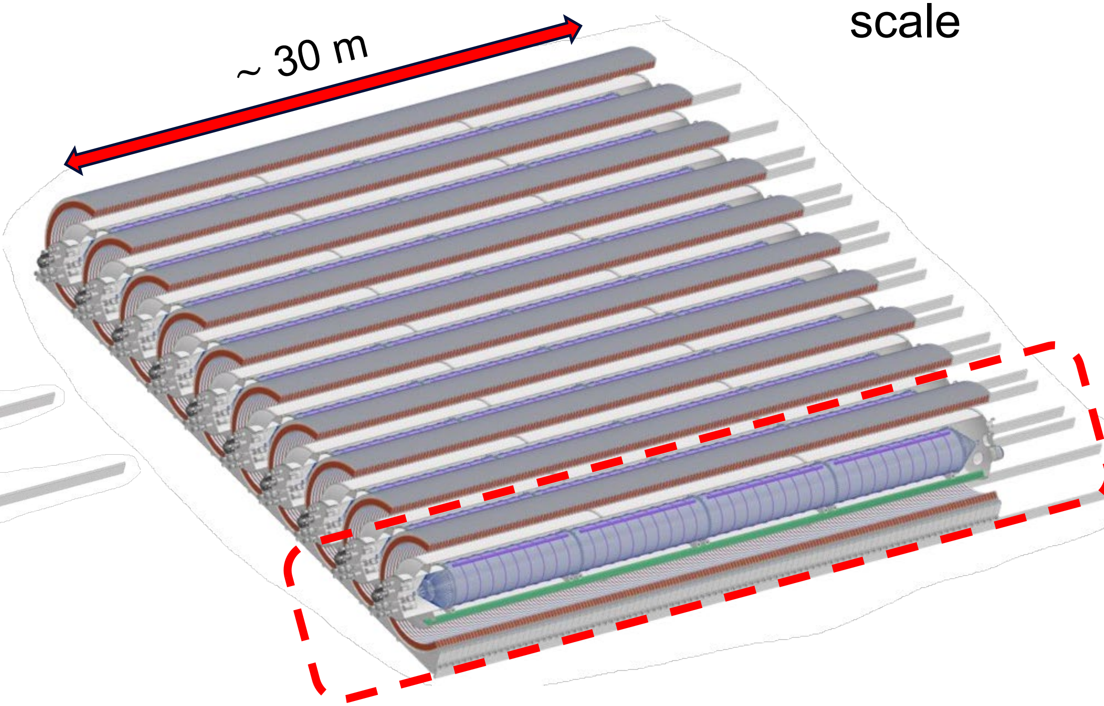
Phased approach to Cavity CRES in Project 8

*Not drawn to scale

~ 14 cm







Cavity CRES Apparatus (CCA)

Low Frequency Apparatus (LFA)

Pilot Cavity

Phase IV

26 GHz (0.96 T)

560 MHz (0.02 T)

~ 150 MHz (0.005 T)

Phase III

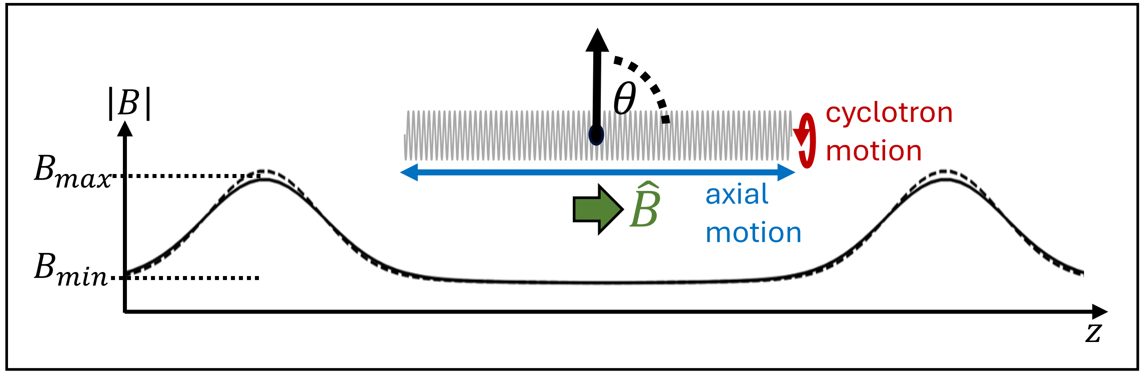
Phase IV

CRES Signal Topology

$$f_c = \frac{1}{2\pi}\frac{e\langle B\rangle}{m_e + E_{kin}/c^2}$$

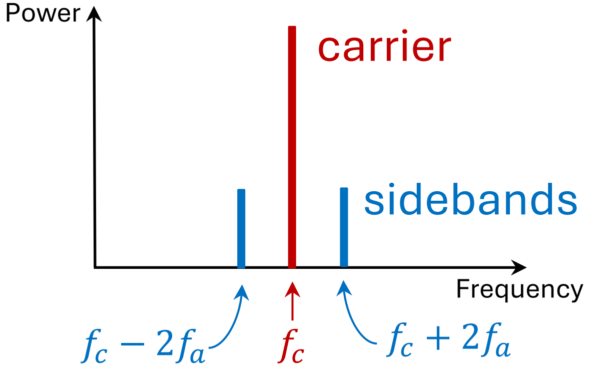
- Electrons with different kinematics experience different fields within the trap

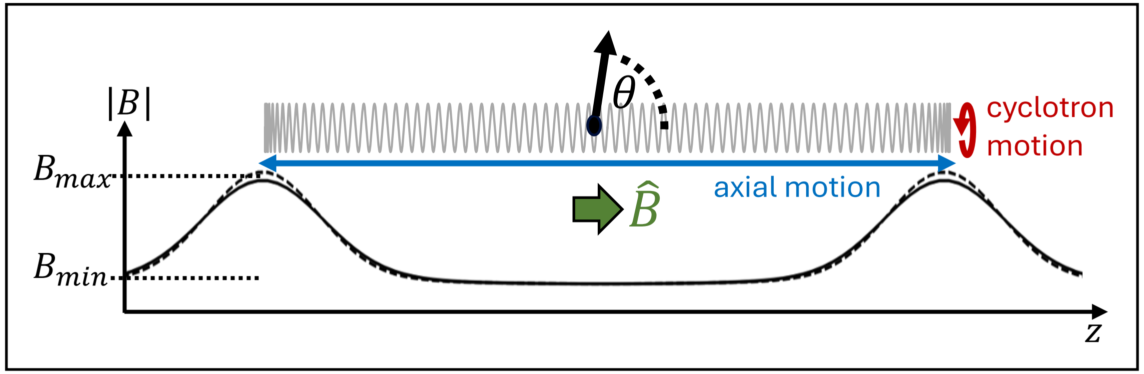
$\theta \approx 90°$



H. Binney

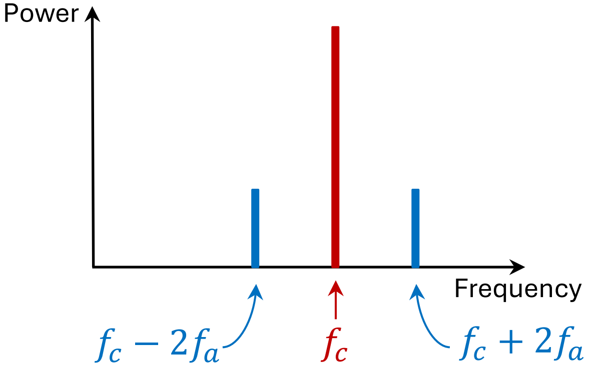
Lower average B, lower f_c, smaller f_a





H. Binney

Higher average B, higher f_c, larger f_a

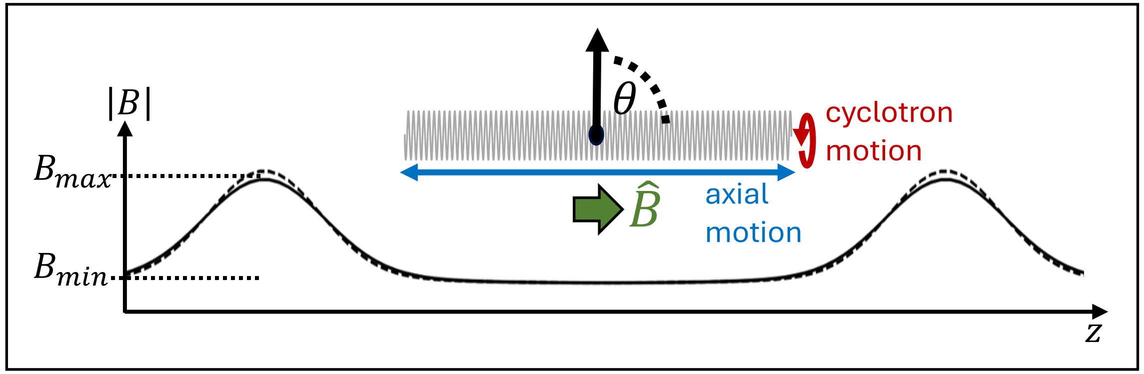


CRES Signal Topology

$$f_c = \frac{1}{2\pi}\frac{e\langle B\rangle}{m_e + E_{kin}/c^2}$$

- Electrons with different kinematics experience different fields within the trap
- Need sideband-aware reconstruction to apply event-by-event B-field correction

$\theta \approx 90°$



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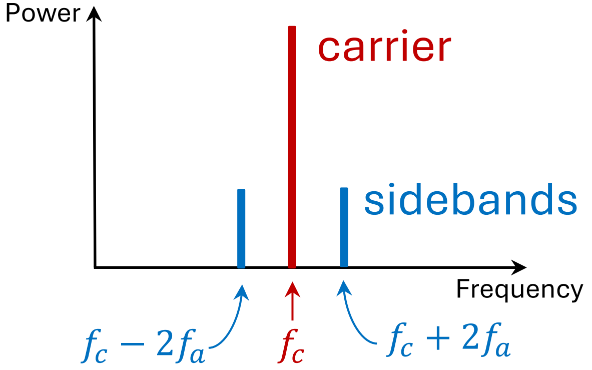

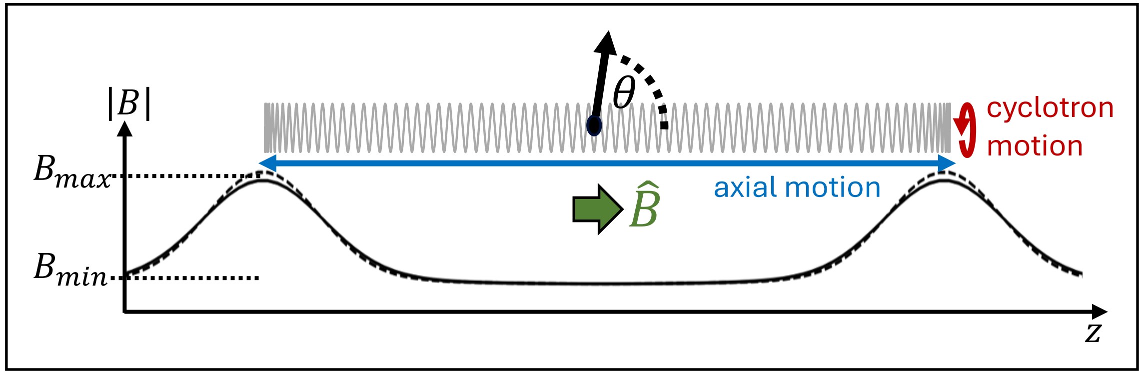

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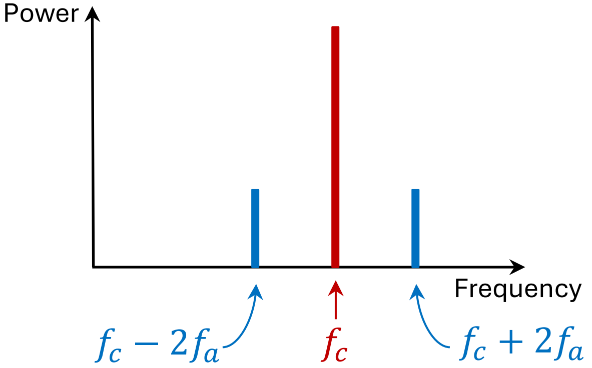
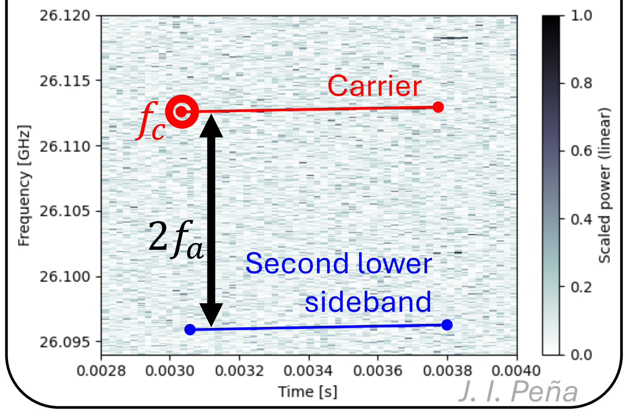


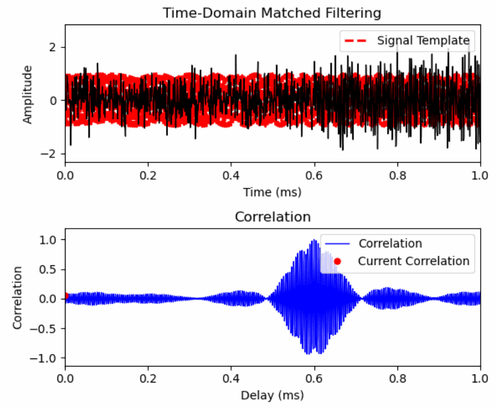
Progress in CRES Event Reconstruction

Adapting Phase II reconstruction for sidebands

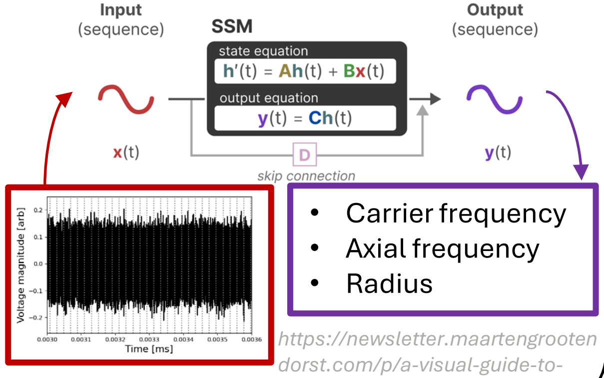


J. I. Peña

Matched filtering on time series data



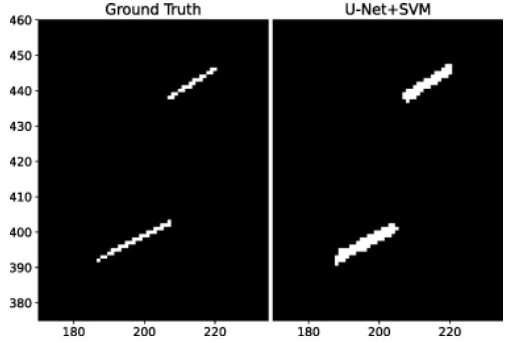
State space model on time series data



https://newsletter.maartengrootendorst.com/p/a-visual-guide-to-mamba-and-state

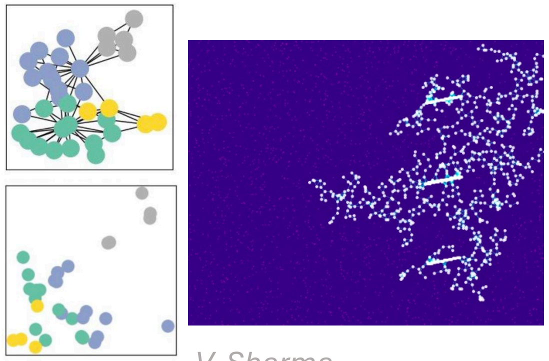
C. Reissel, H. Binney, L.F.K. Domingues

U-Net on frequency domain data



A Ashtari Esfahani et al. Mach. Learn.: Sci. Technol. (2024)

Graph neural networks on frequency domain data



V. Sharma

and more

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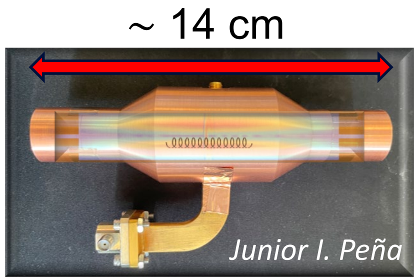
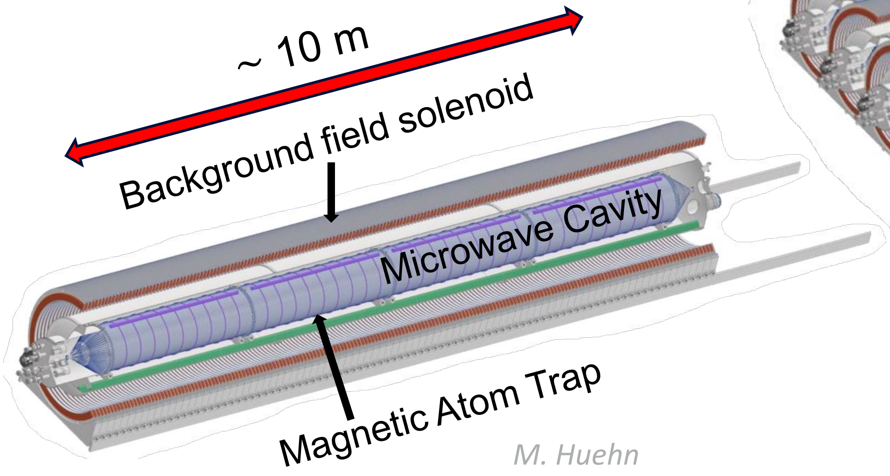
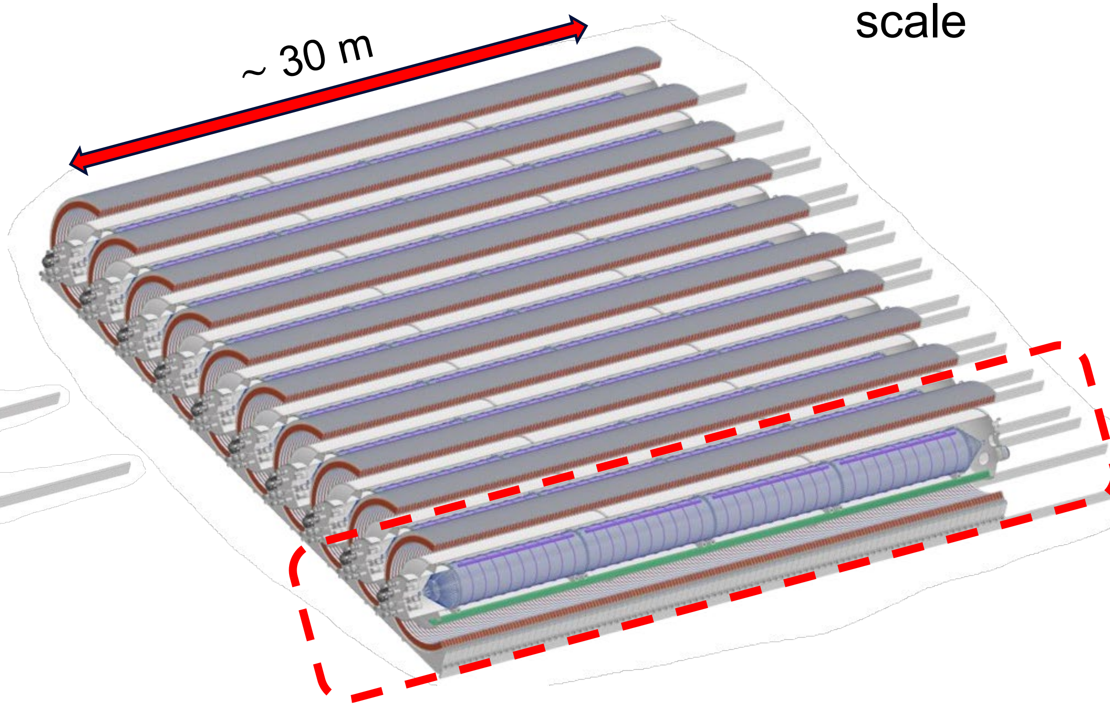
Phased approach to Cavity CRES in Project 8

*Not drawn to scale







Cavity CRES Apparatus (CCA)

Low Frequency Apparatus (LFA)

Pilot Cavity

Phase IV

26 GHz (0.96 T)

560 MHz (0.02 T)

~ 150 MHz (0.005 T)

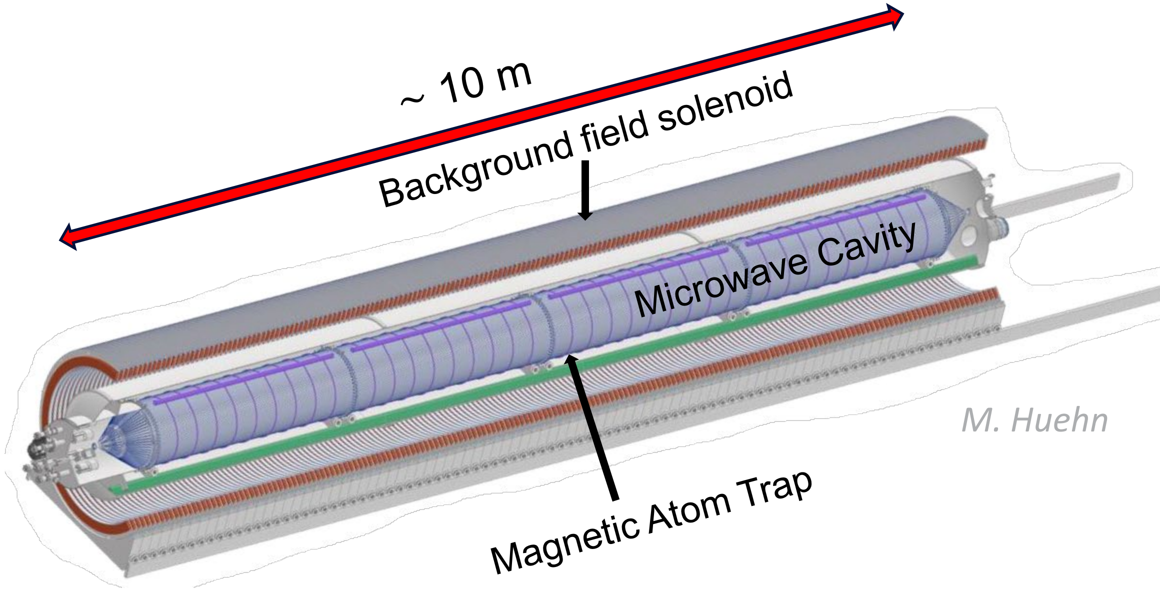
Phase III

Phase IV

Low-Frequency Apparatus (LFA)

- m^3 scale volume at lower trapping fields
  - Demonstrate CRES compatibility with large volume atomic trap
- Operating frequency ~ 560 MHz
- Electron-gun and ^{83m}Kr for calibration → upgrade source to atomic T
- Sensitivity: $m_\beta \sim \mathbf{0.3} - \mathbf{0.7}$ **eV/c²** (90% C.L.) for a year of science run
- Exploring cavity designs for SNR enhancement and energy resolution improvement
- Atomic Tritium studies also underway!

Radiated Power ~ **1 aW** for 18.6 keV electrons in ~ 0.02 T B-field



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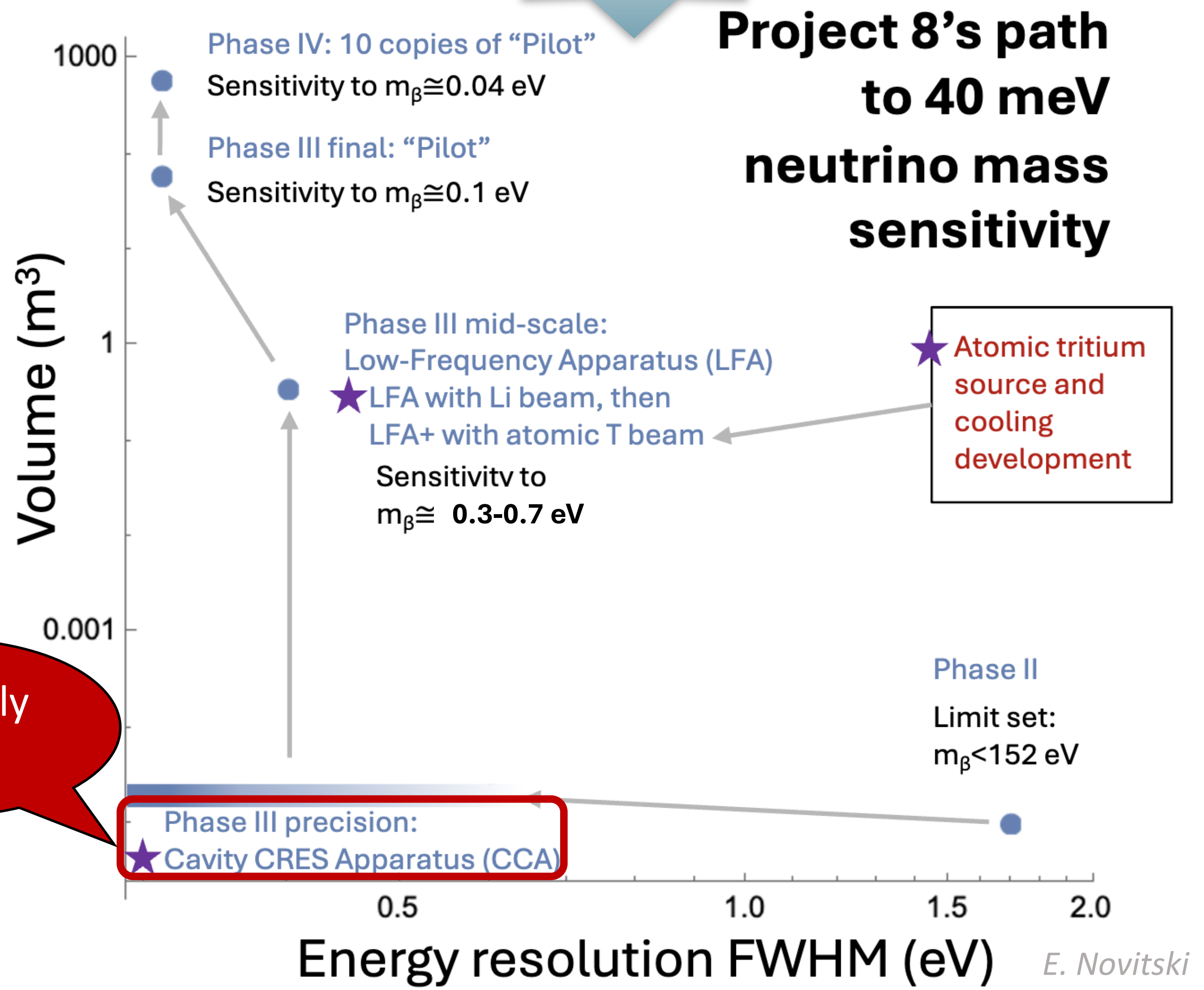
PROJECT 8

Reaching Phase IV sensitivity

See more on the next talk by Chi-Ho Lam!

- With Phase IV, Project 8's mass sensitivity goal of **40 meV/c²** will probe beyond the IO case

Currently here



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Reaching Phase IV sensitivity

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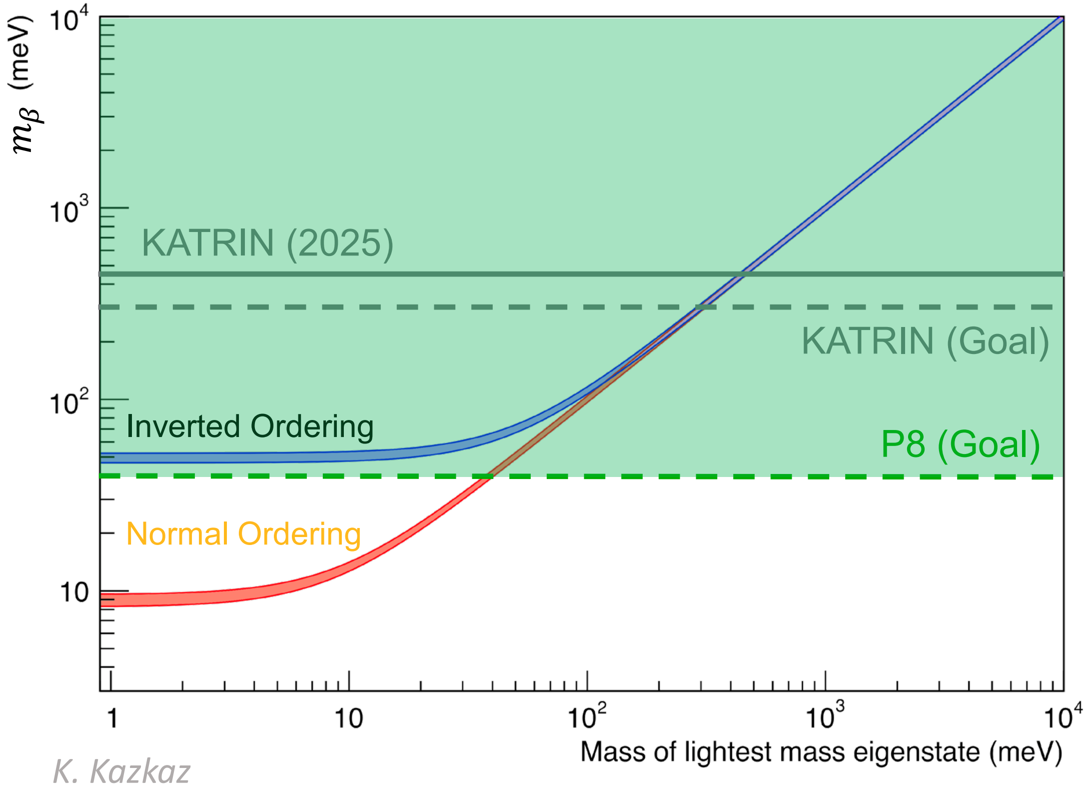
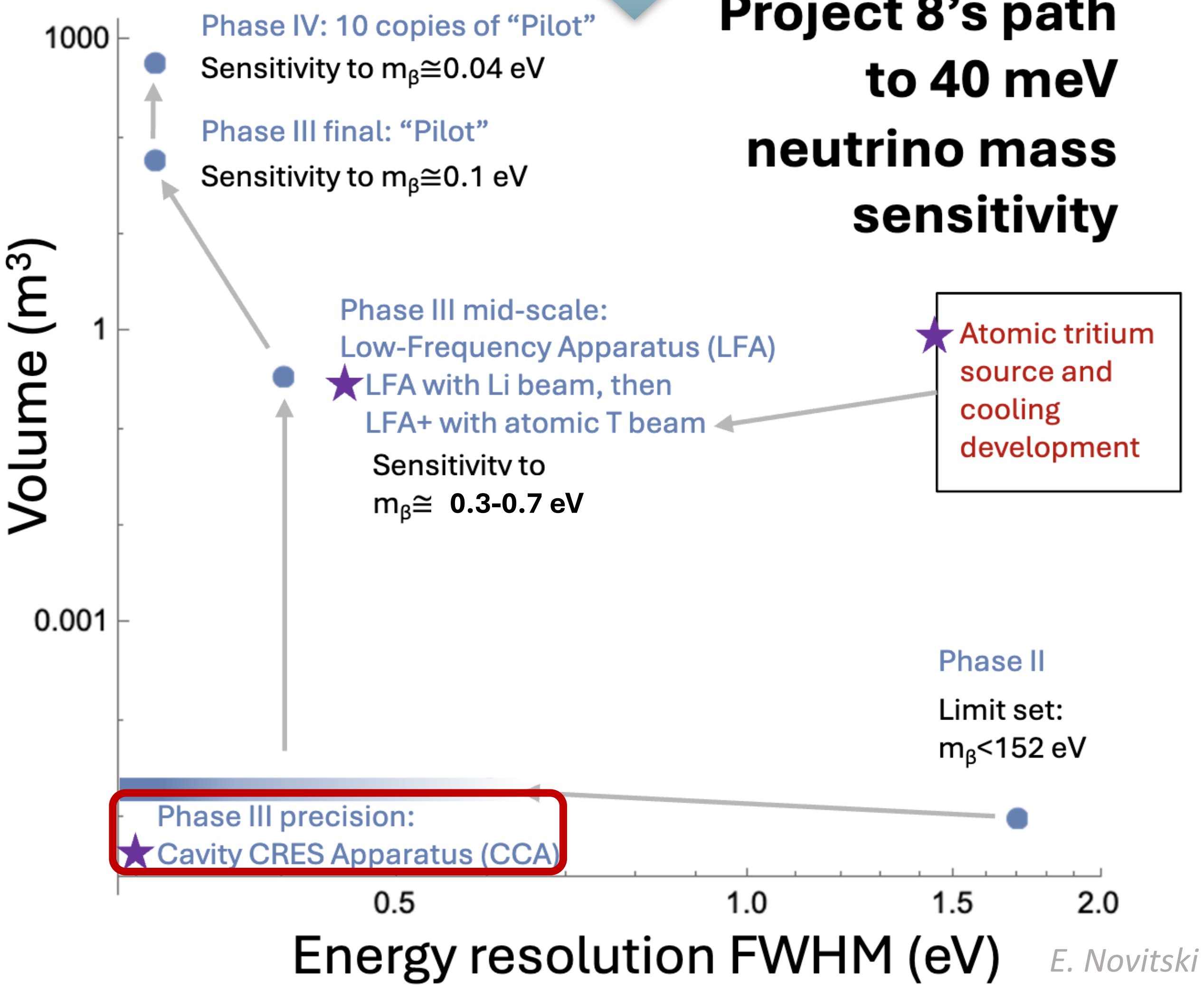


K. Kazkaz

Project 8's path to 40 meV neutrino mass sensitivity



E. Novitski

University of Pittsburgh

PROJECT 8

Thanks!

University of Pittsburgh, 2025

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

Extras

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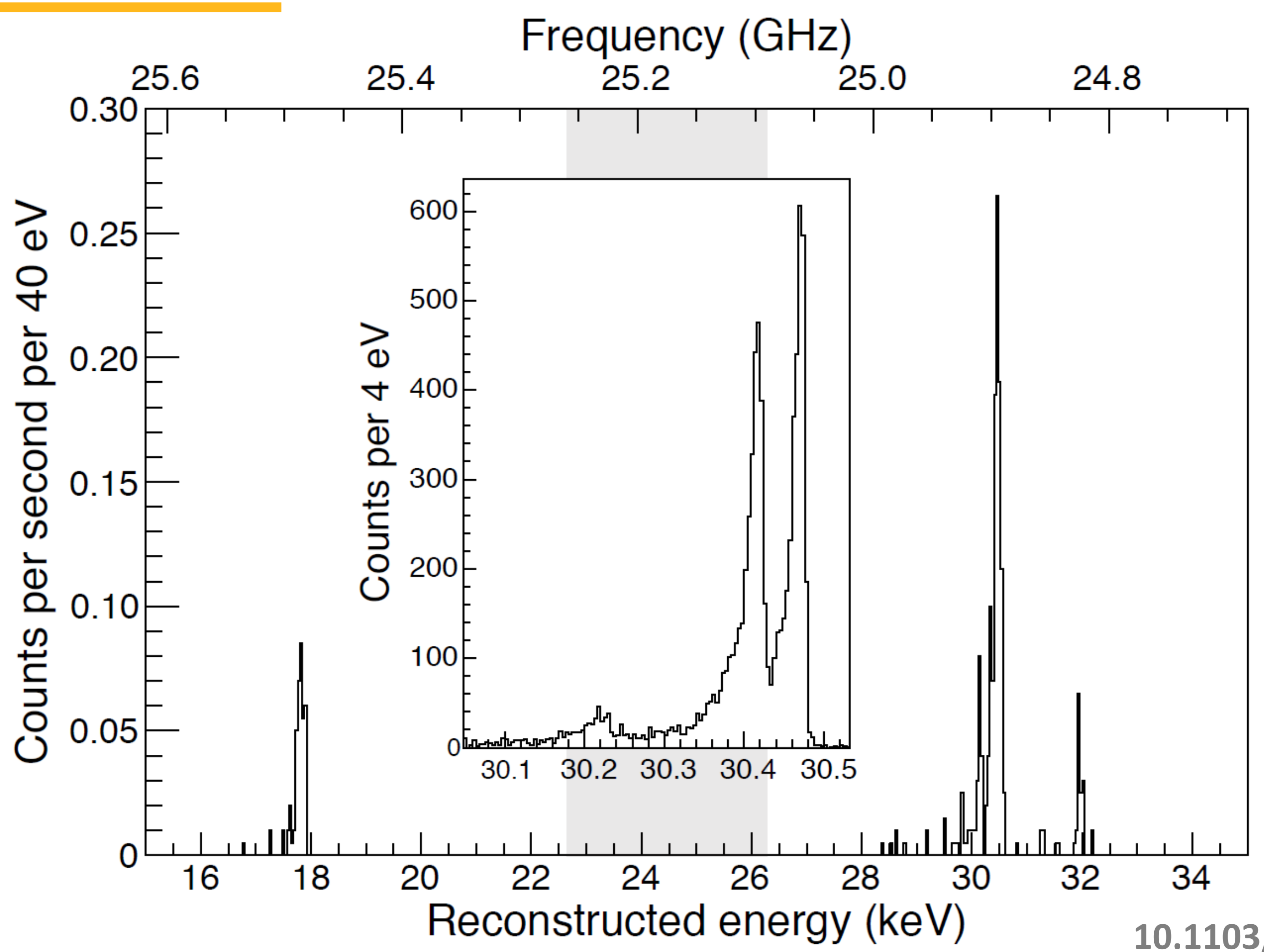
Phase-I results



10.1103/PhysRevLett.114.162501

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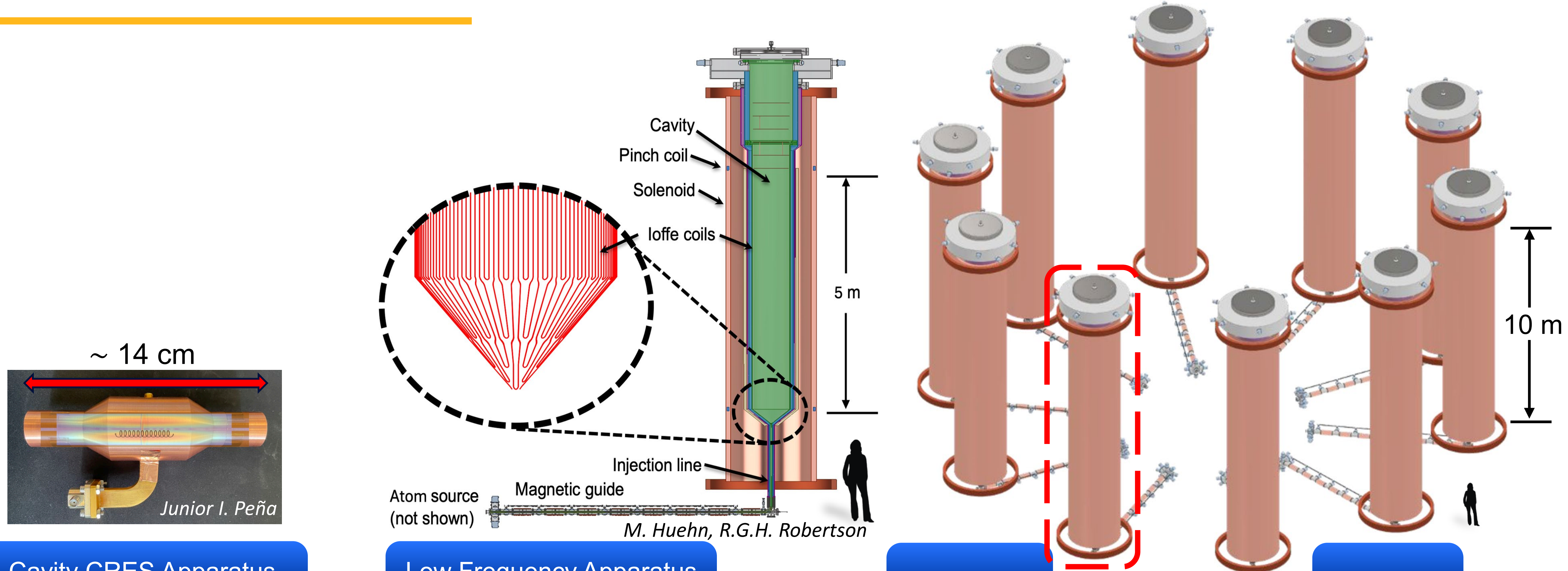
Phased approach to Cavity CRES in Project 8



Cavity CRES Apparatus (CCA)

Low Frequency Apparatus (LFA)

Pilot Cavity

Phase IV