

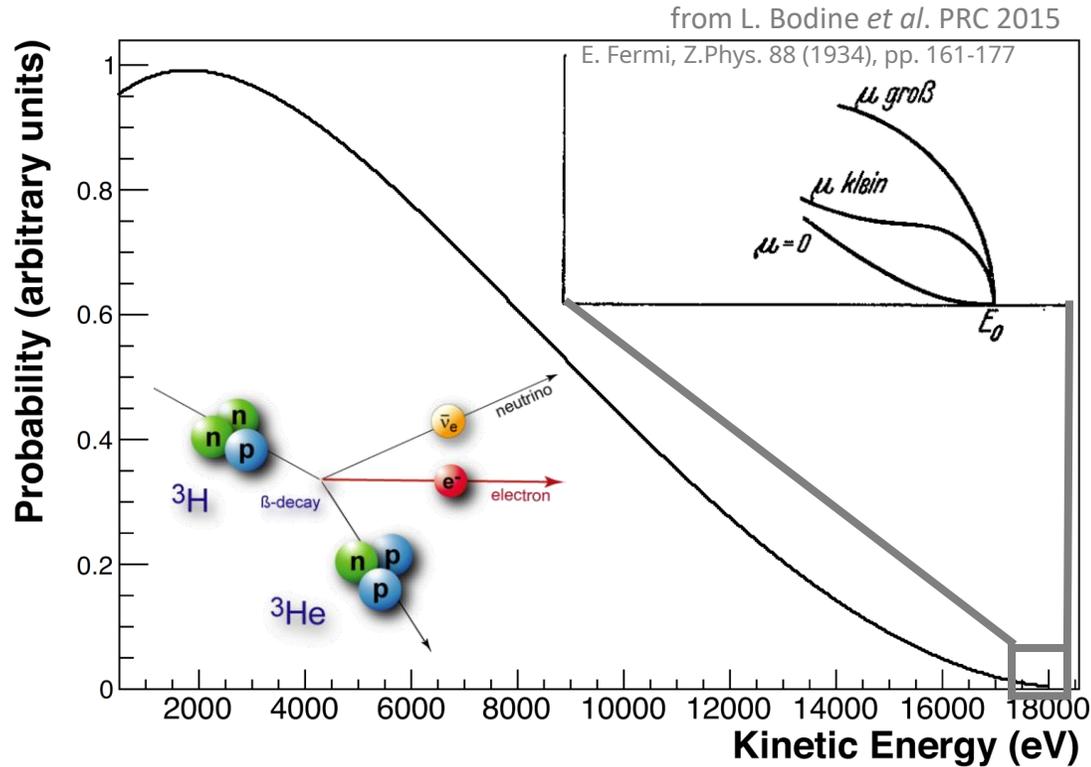
# Combining Atom Trapping & Cyclotron Radiation Emission Spectroscopy for Next-generation Neutrino Mass Experiment

René Reimann for the Project 8 collaboration

WIN 2025, Jun 12<sup>th</sup>, Brighton

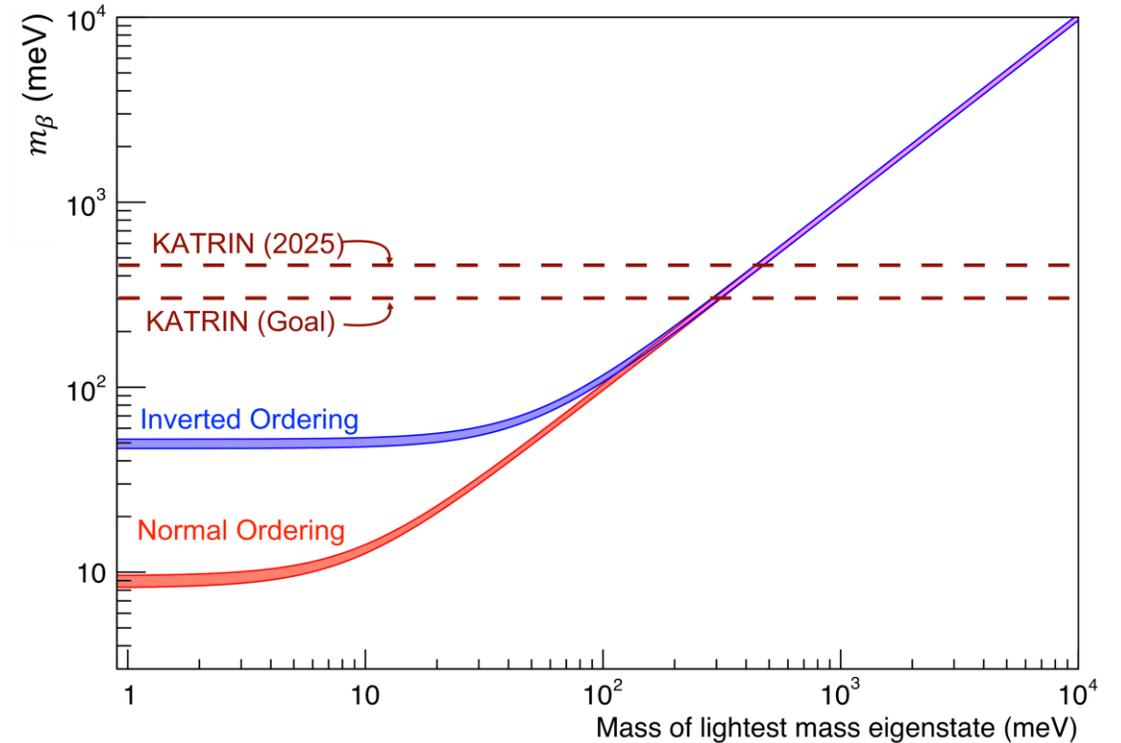
**PROJECT 8**

# Direct Kinematic Approach



No model dependence, pure kinematic effect

KATRIN experiment and sets current best limit with MAC-E filter technique



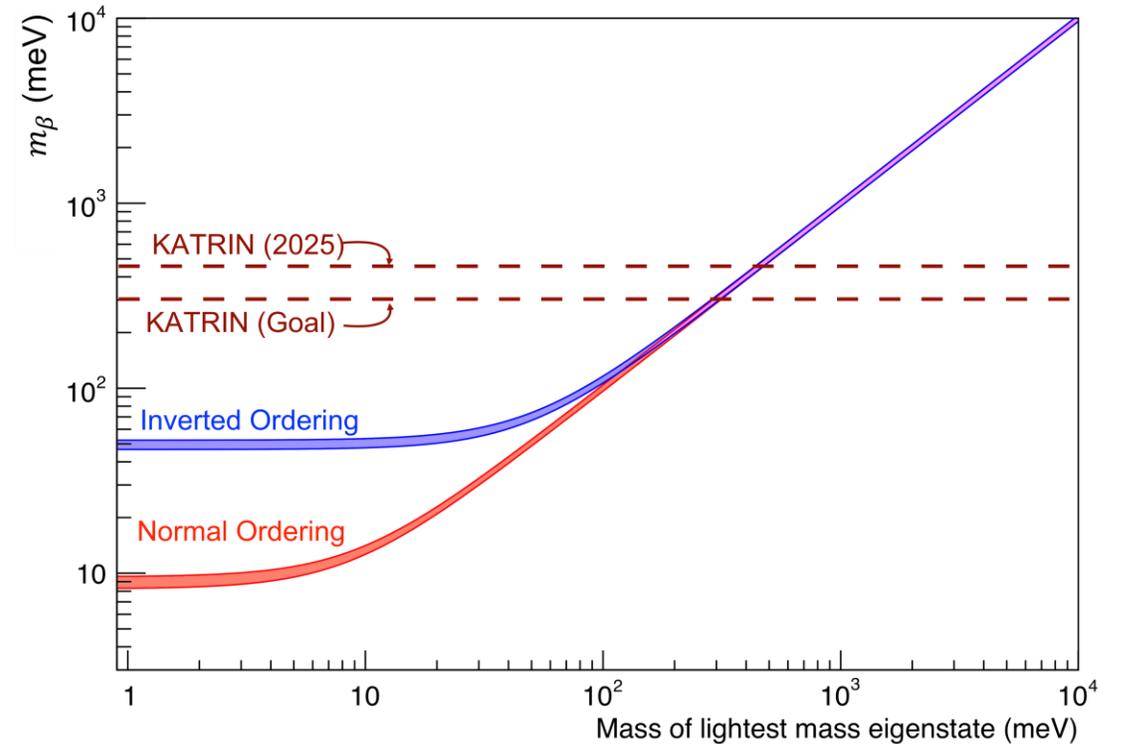
# Challenges

## Statistics

- Sensitivity scales with  $\sqrt[4]{N}$
- MAC-E filter technique not scalable



KATRIN experiment and sets current best limit with MAC-E filter technique

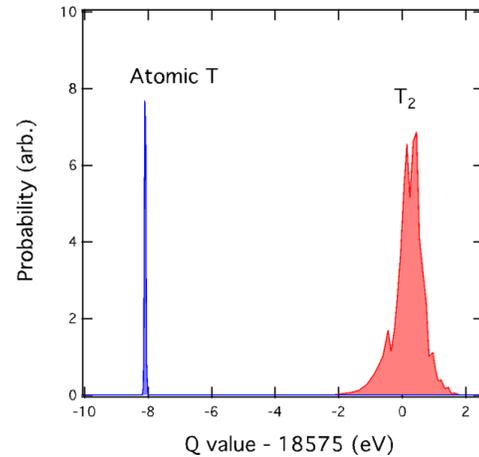


Branching ratio into last 1eV of spectrum  $\sim 10^{-13}$   
Relative energy resolution:  $0.3 \text{ eV} / m_e = 6 \times 10^{-7}$

# Challenges

## Statistics

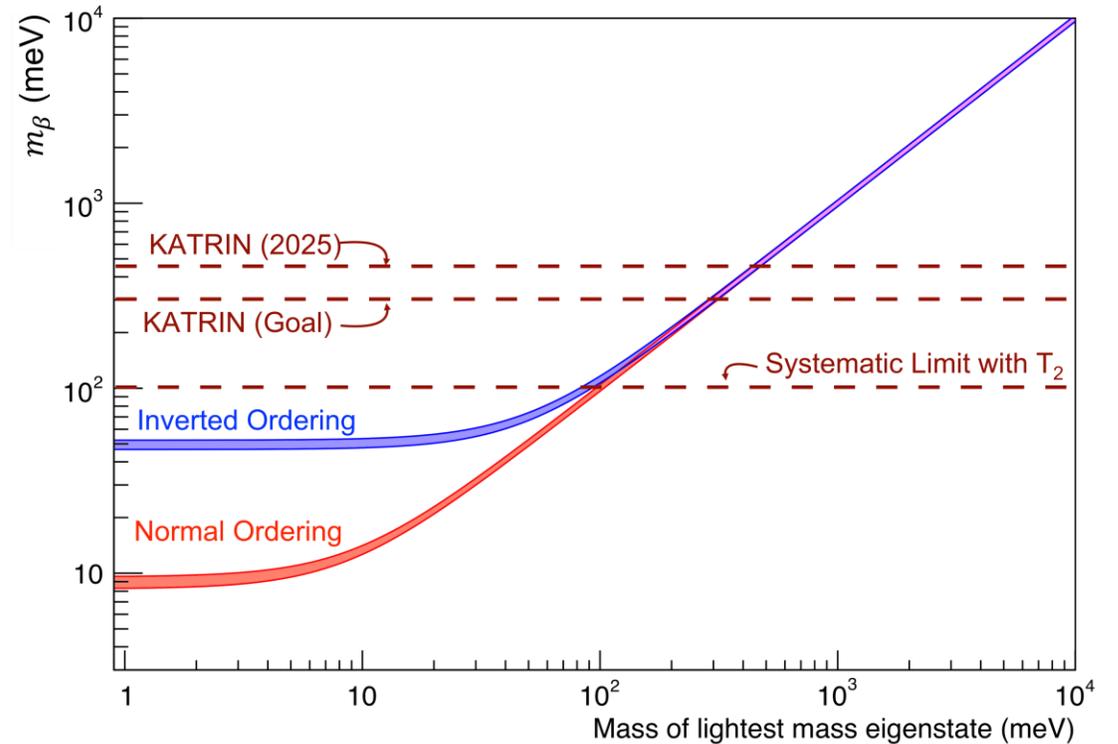
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## Final State Excitation

- Rotational and vibrational states of daughter molecule leads to energy broadening

KATRIN experiment and sets current best limit with MAC-E filter technique

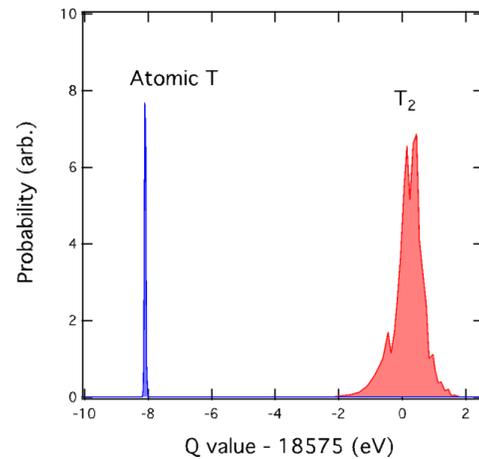


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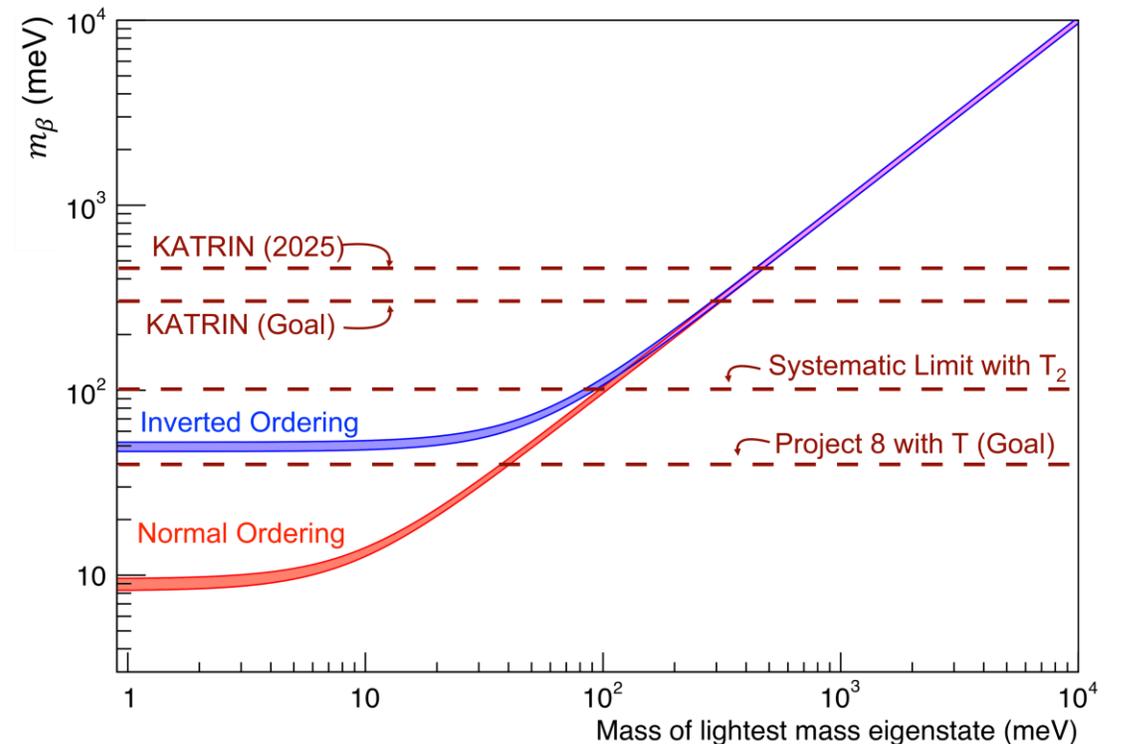


## Final State Excitation

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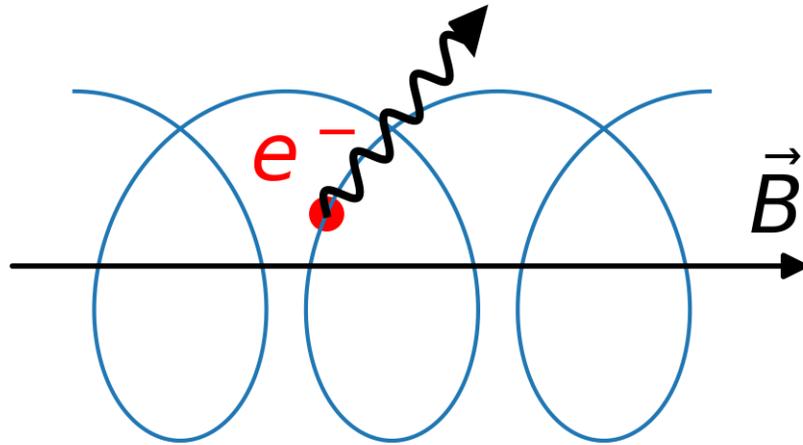
**Project 8**  
novel detection method & atomic tritium

KATRIN experiment and sets current best limit with MAC-E filter technique



Branching ratio into last 1eV of spectrum  $\sim 10^{-13}$   
Relative energy resolution:  $0.3 \text{ eV} / m_e = 6 \times 10^{-7}$

# Cyclotron Radiation Emission Spectroscopy



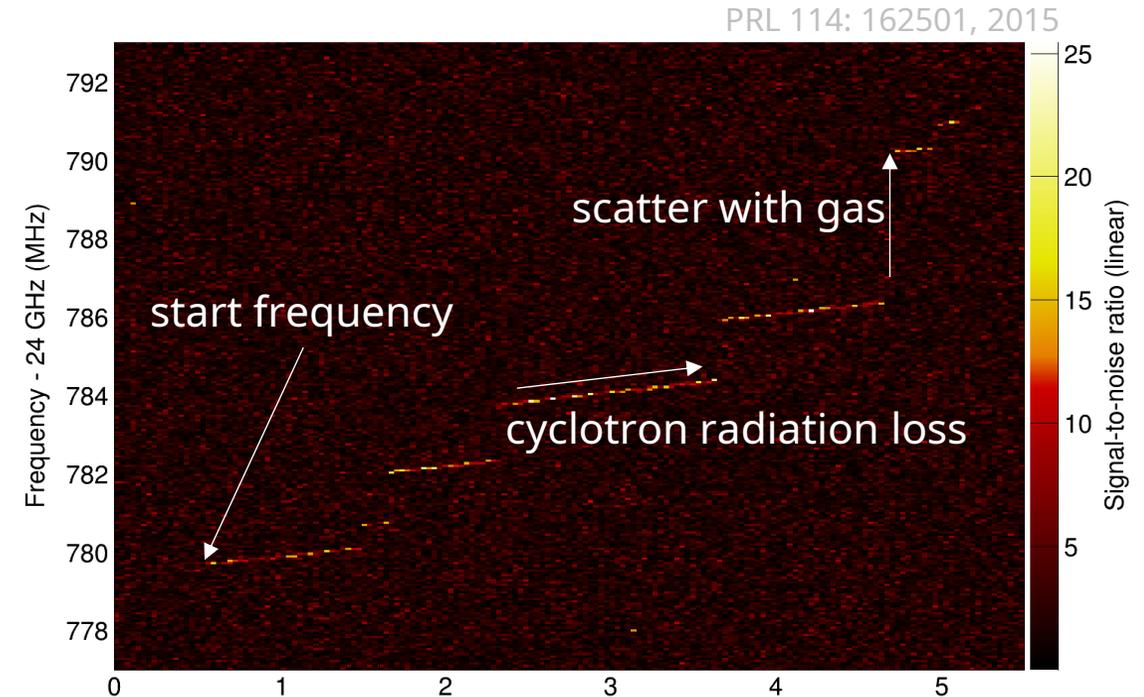
Frequency measurement  
Cavities or Antennas

Background  
magnetic field

$$f_c = \frac{f_{c,0}}{\gamma} = \frac{1}{2\pi} \frac{eB}{m_e + E_{\text{kin}}/c^2}$$

Physics spectrum

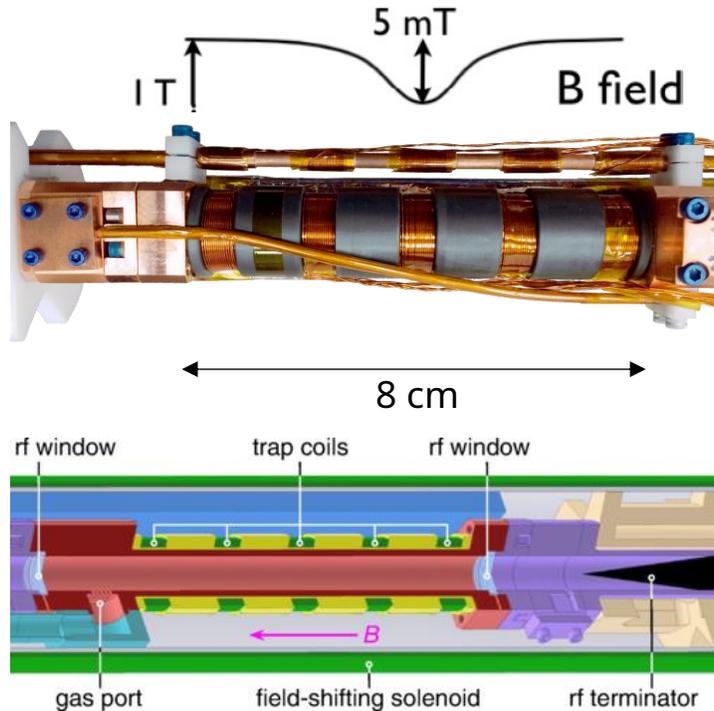
Challenge: Radiated power in aW to fW range



CRES demonstrated on <sup>83m</sup>Kr and T<sub>2</sub> in small waveguide

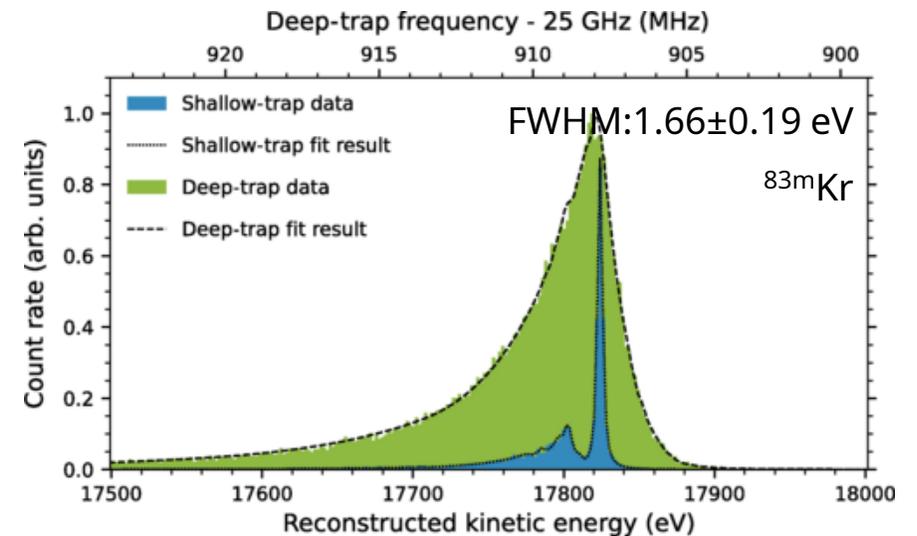
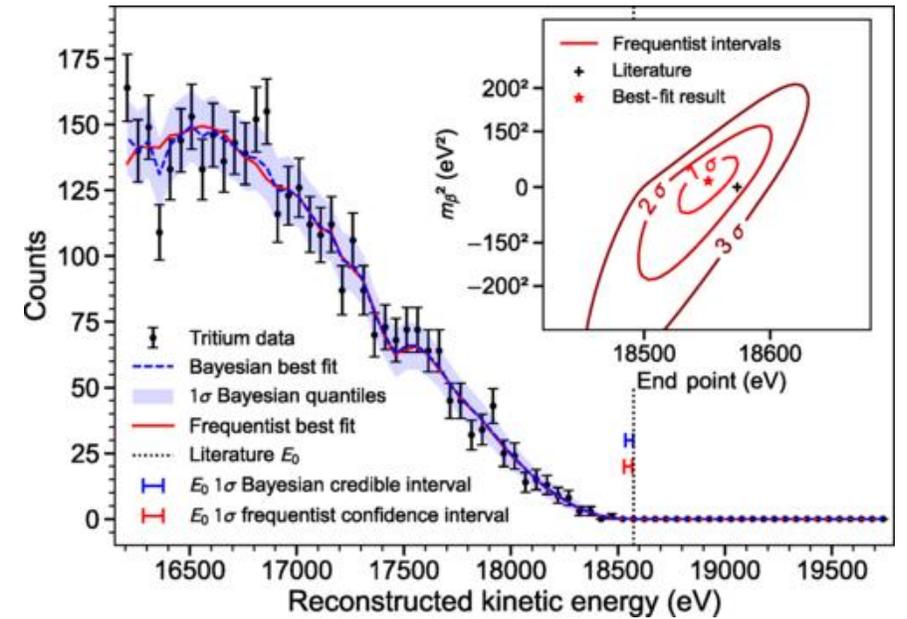
# CRES with Molecular Tritium

- First tritium spectroscopy ✓
- First neutrino mass limit ( $\leq 155$  eV) ✓
- Demonstration energy resolution ✓
- Demonstration zero-background ✓
- Control of systematic effects ✓



waveguide  
 $\sim 1 \text{ mm}^3$  effective volume

need to scale up

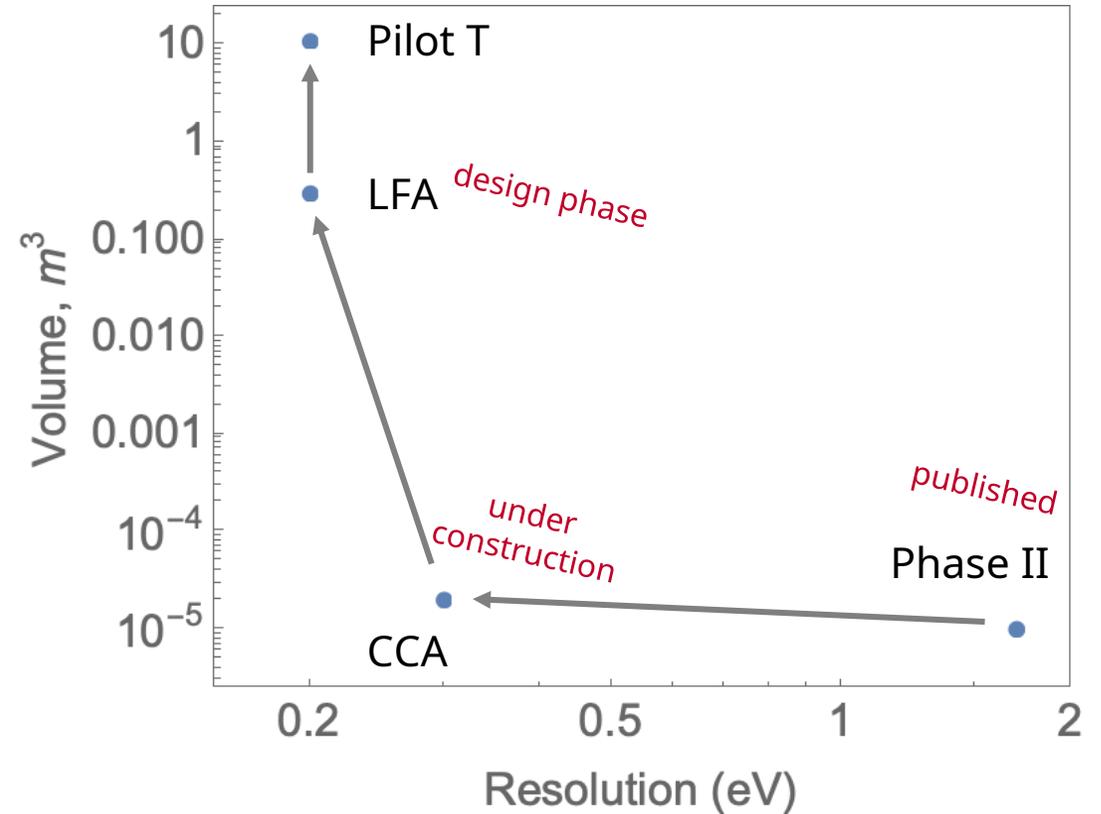


# Project 8 – Phased Approach

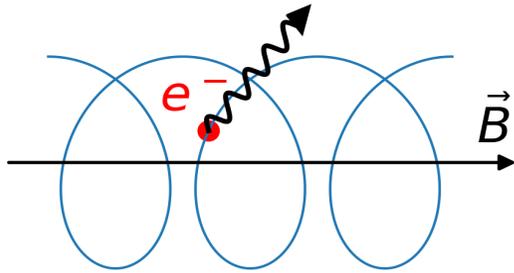
- Phase II
  - Demonstration of neutrino mass analysis with molecular tritium in waveguide
- Cavity RES Apparatus (CCA)
  - Demonstrate resonant cavity readout
  - Demonstrate ~0.3 eV energy resolution
  - Under construction
- Low Frequency Apparatus (LFA)
  - Demonstrate volume scaling and low magnetic field
  - Demonstrate compatibility with atom trapping
- Pilot T
  - First module of final scale experiment

*J. Stachurska  
Tue 11:45 AM*

*this talk*



# Magnetic Fields in CRES

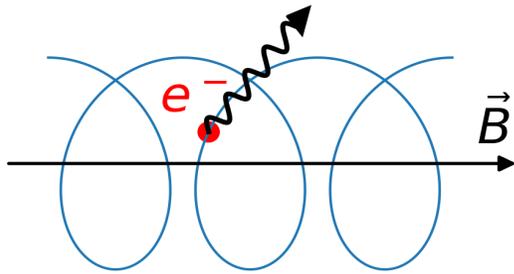


## Background Field

Strong, homogeneous field  
needed for cyclotron motion

$$B = 20 \text{ mT}$$

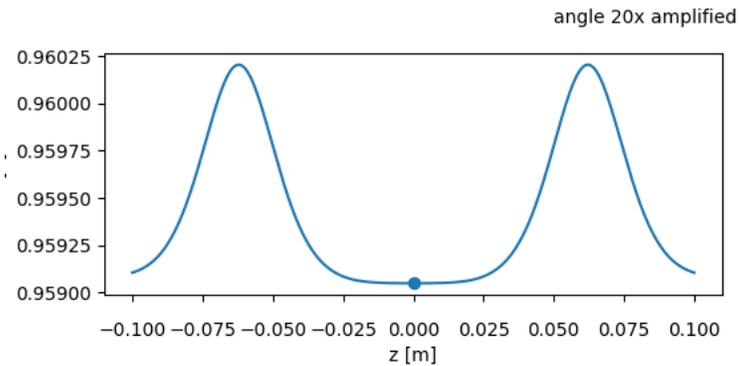
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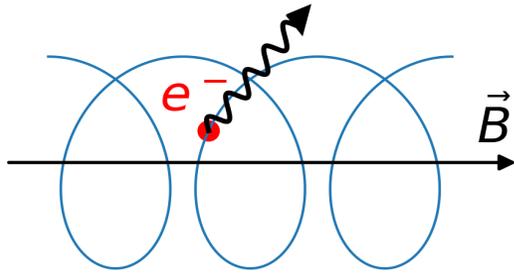


## Electron Trap

Confine  $\beta$ -decay electrons in readout region

$$\Delta B = 0.057 \text{ mT}$$

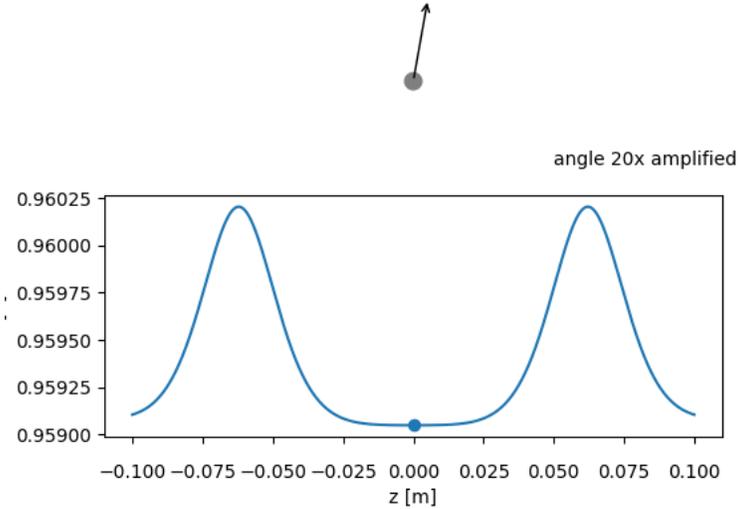
# Magnetic Fields in CRES



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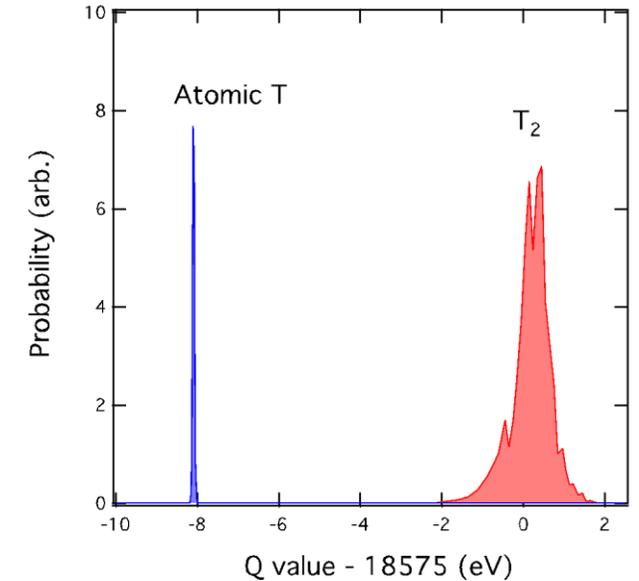
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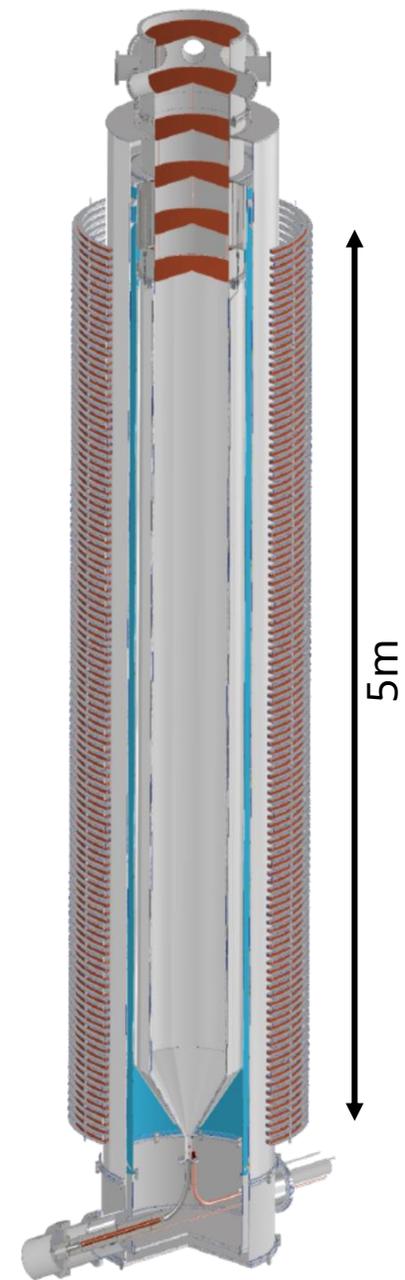
## Atom Trap

Avoid recombination of atomic tritium at physical walls

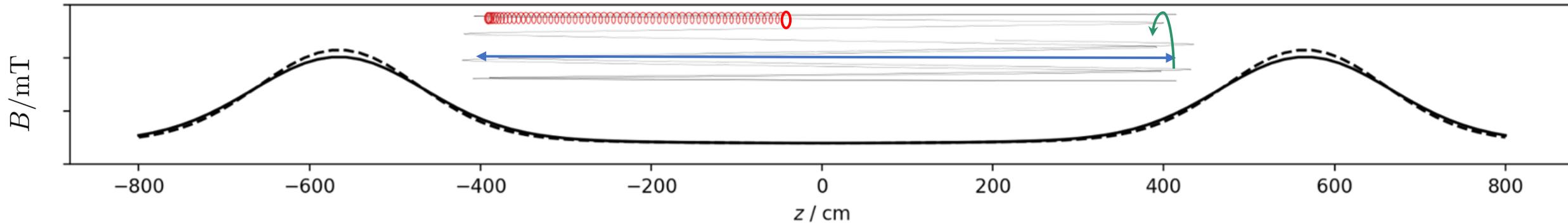
$$\Delta B = 50 \text{ mT}$$

# Background Field

- Background field strength: 20 mT
  - Cyclotron radiation at  $f = 560$  MHz
  - Cavity diameter 654 mm for TE011 mode
- Solenoid field
  - Stack of 101 individual coils
  - Current-turns optimized for each coils
  - Individual coils have 70 cm radius and are spaced 5 cm
- Targeting  $<10^{-6}$  precision in detection volume
- Need for Earth field compensation and active stabilization



# Electron Motion in Magnetic Bottle



## Cyclotron motion

- background field dominates
- trapping field correction

## Axial motion

- trap shape dependent
- pitch angle dependent

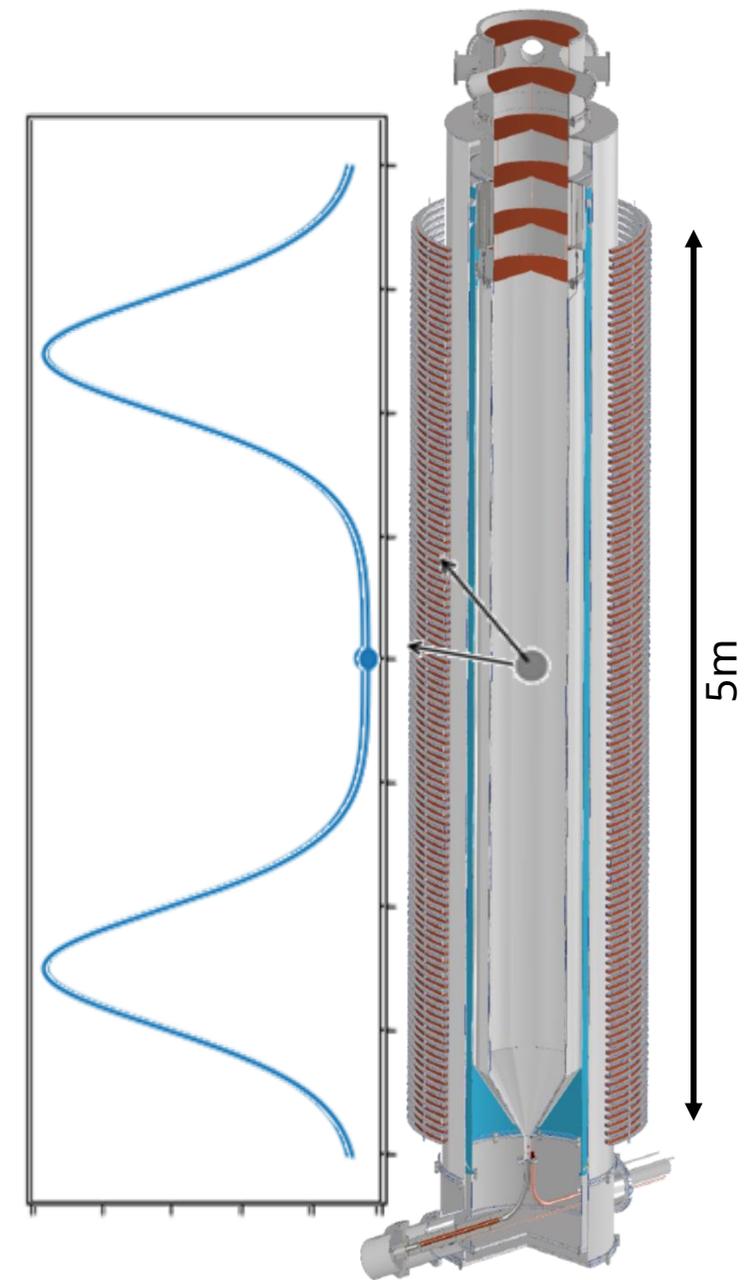
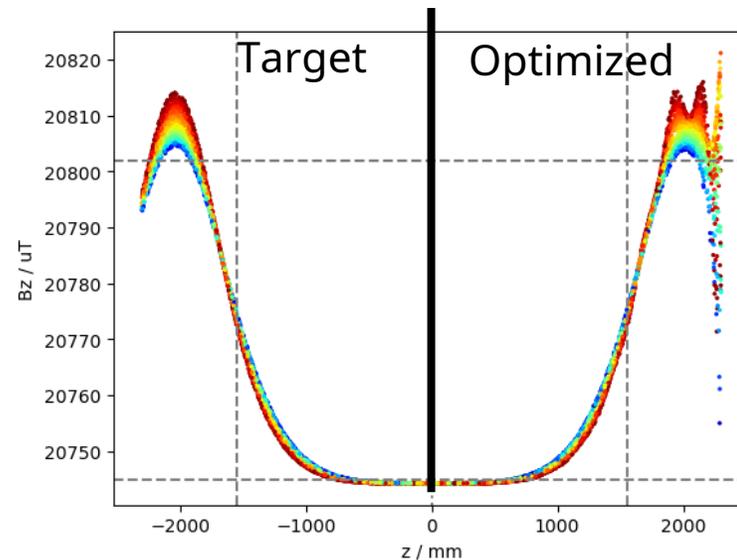
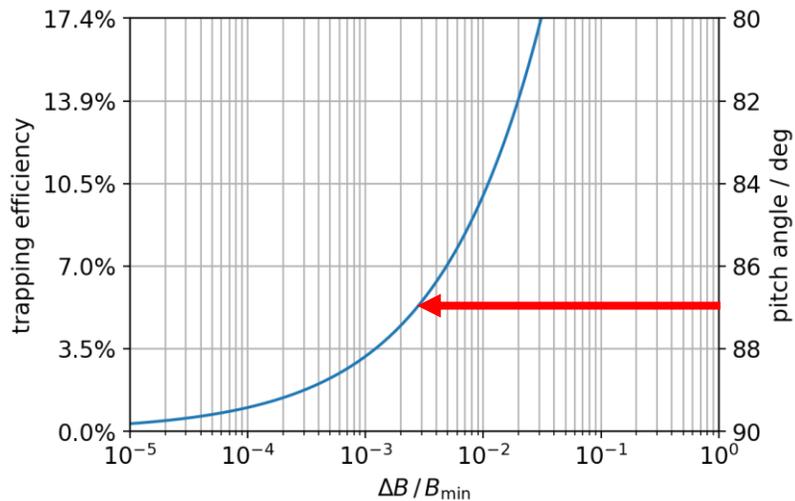
## Grad-B motion

- rotation around trap axis
- trap gradient dependent

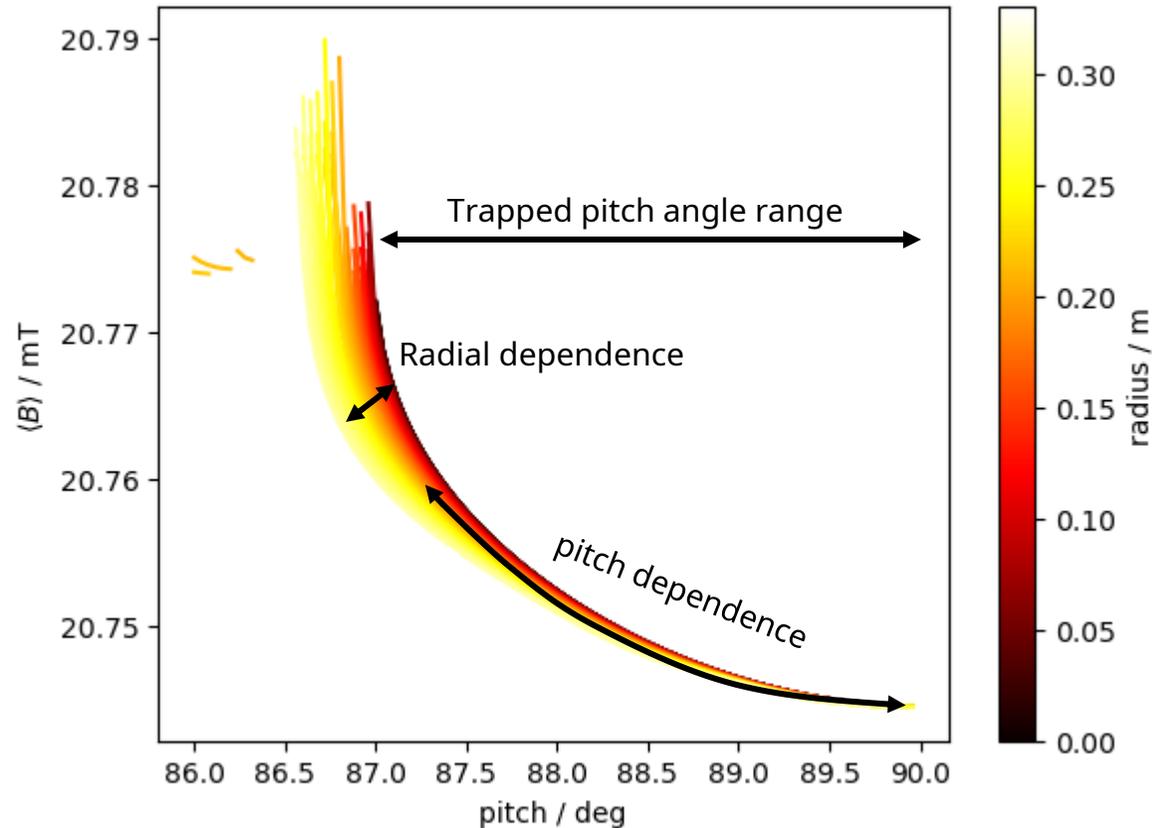
trap shape influences all frequencies  
→ signal information

# Electron Trap

- Double magnetic mirror trap (adiabatic motion)
- Electron trap provided by same coil stack
  - Re-tune currents to provide electron trap
- Trap length  $\sim 4$  m
- Trap depth of  $57 \mu\text{T}$  traps electrons with pitch angle  $> 87^\circ$ 
  - Trapping efficiency  $\sim 4.7\%$



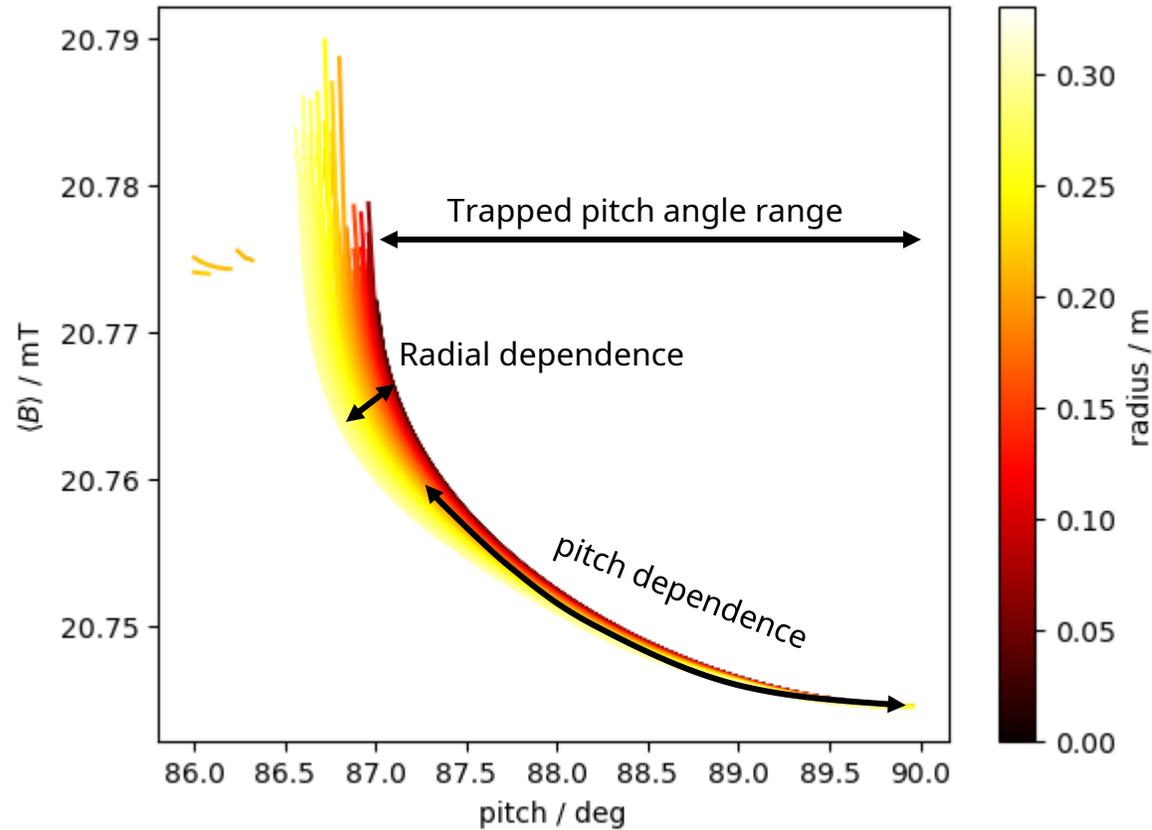
# Electron Trap - Energy Resolution



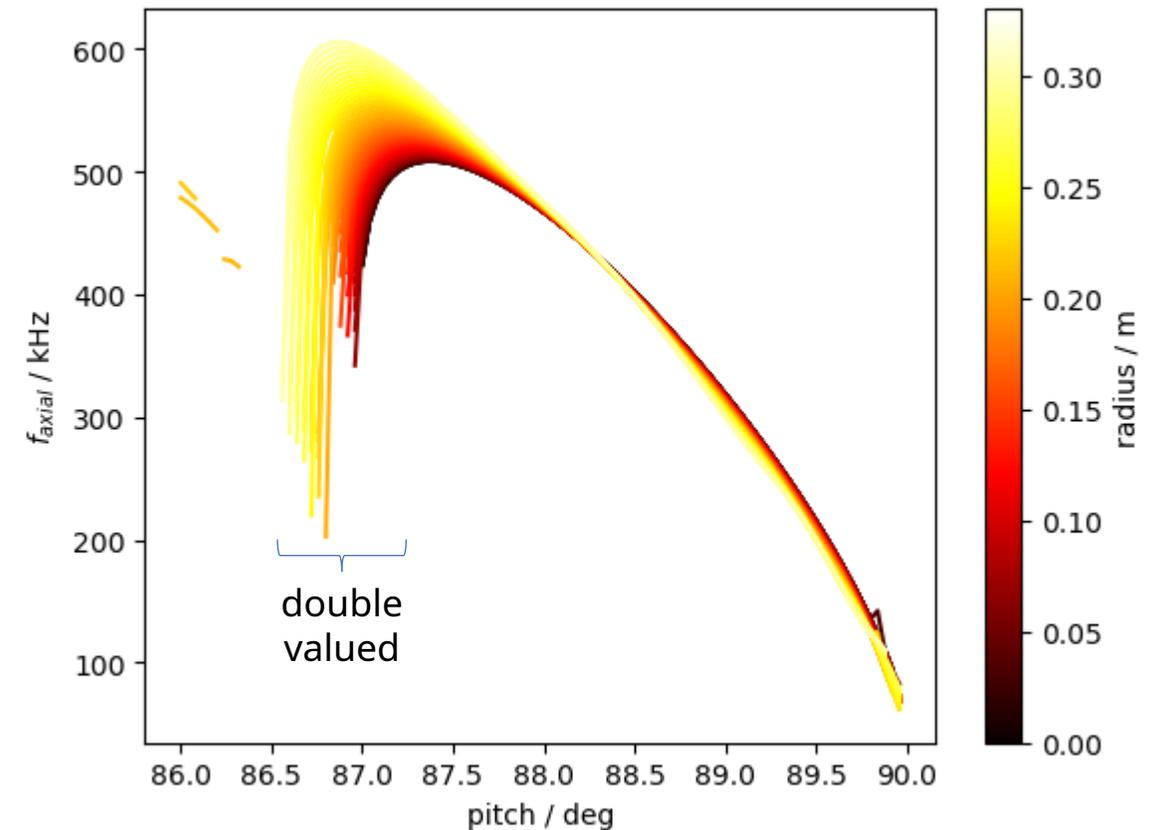
Averaged field seen by electron  
 → shifts cyclotron frequency

$$f_c = \frac{f_{c,0}}{\gamma} = \frac{1}{2\pi} \frac{eB}{m_e + E_{\text{kin}}/c^2}$$

# Electron Trap - Energy Resolution

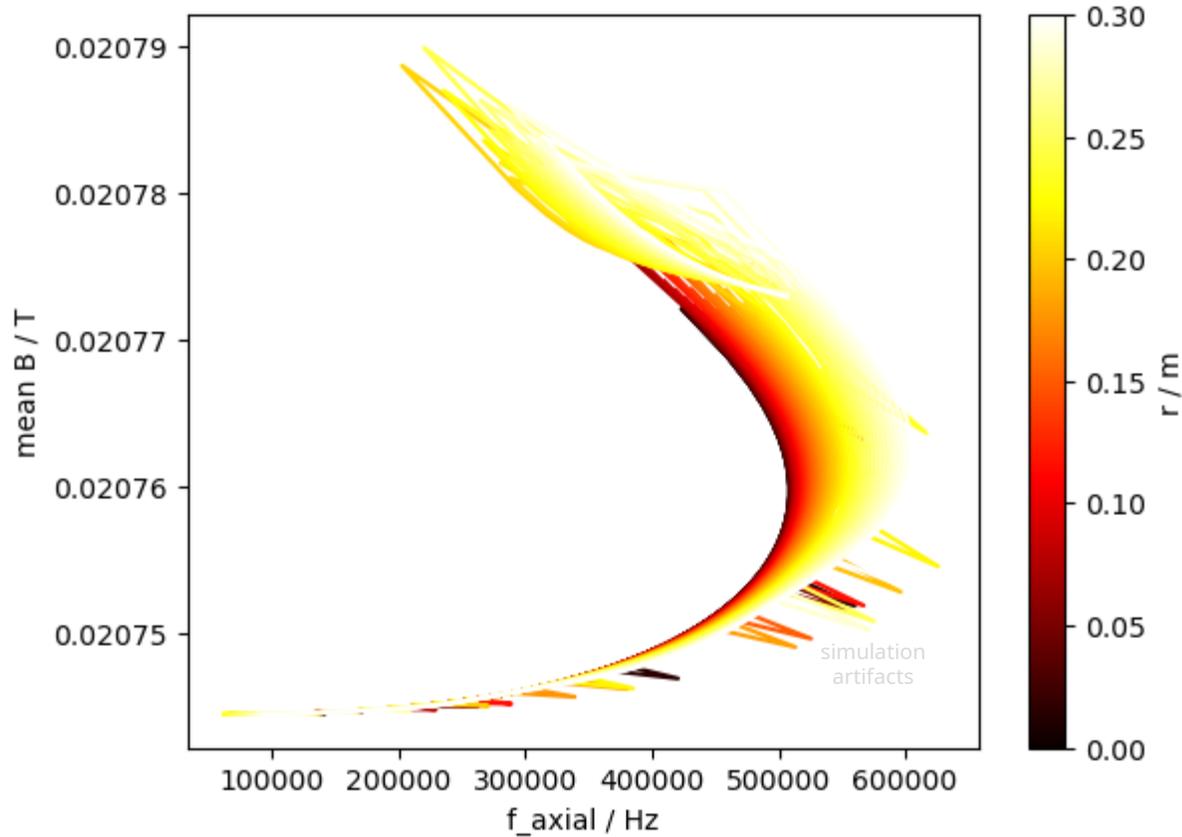


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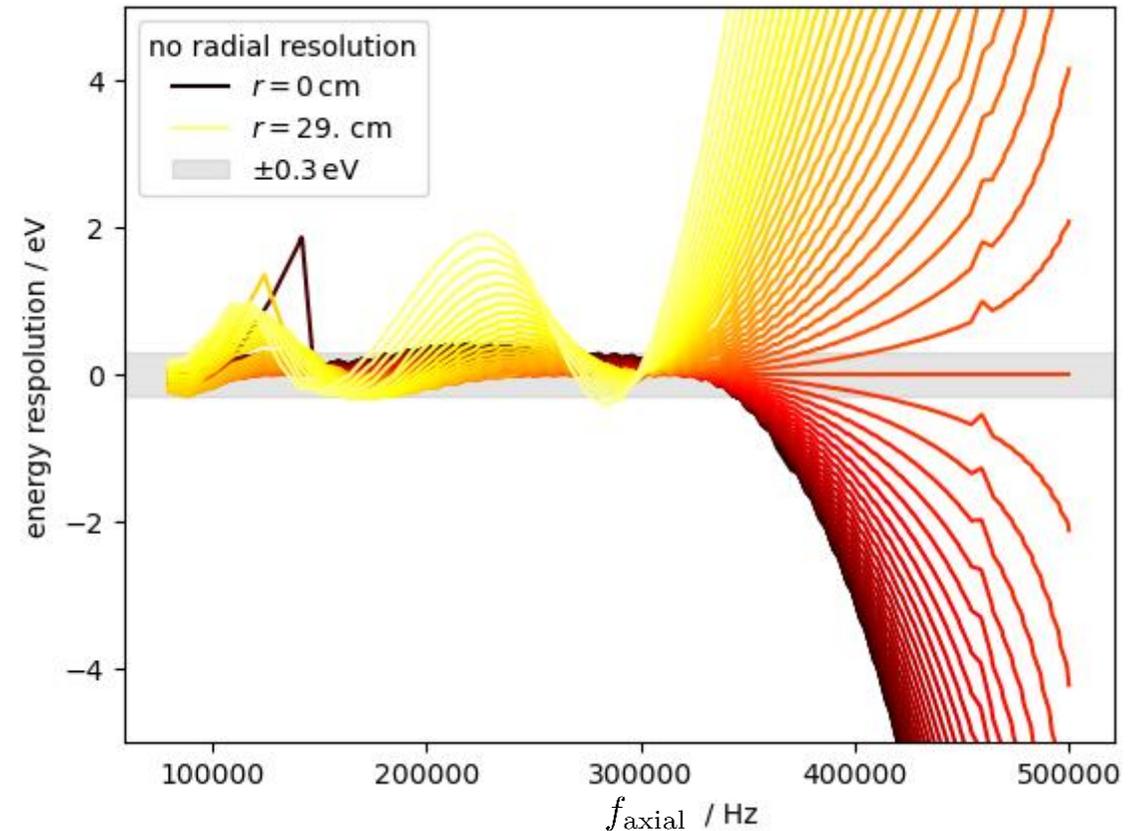


Axial frequency is a proxy for pitch angle

# Electron Trap - Energy Resolution



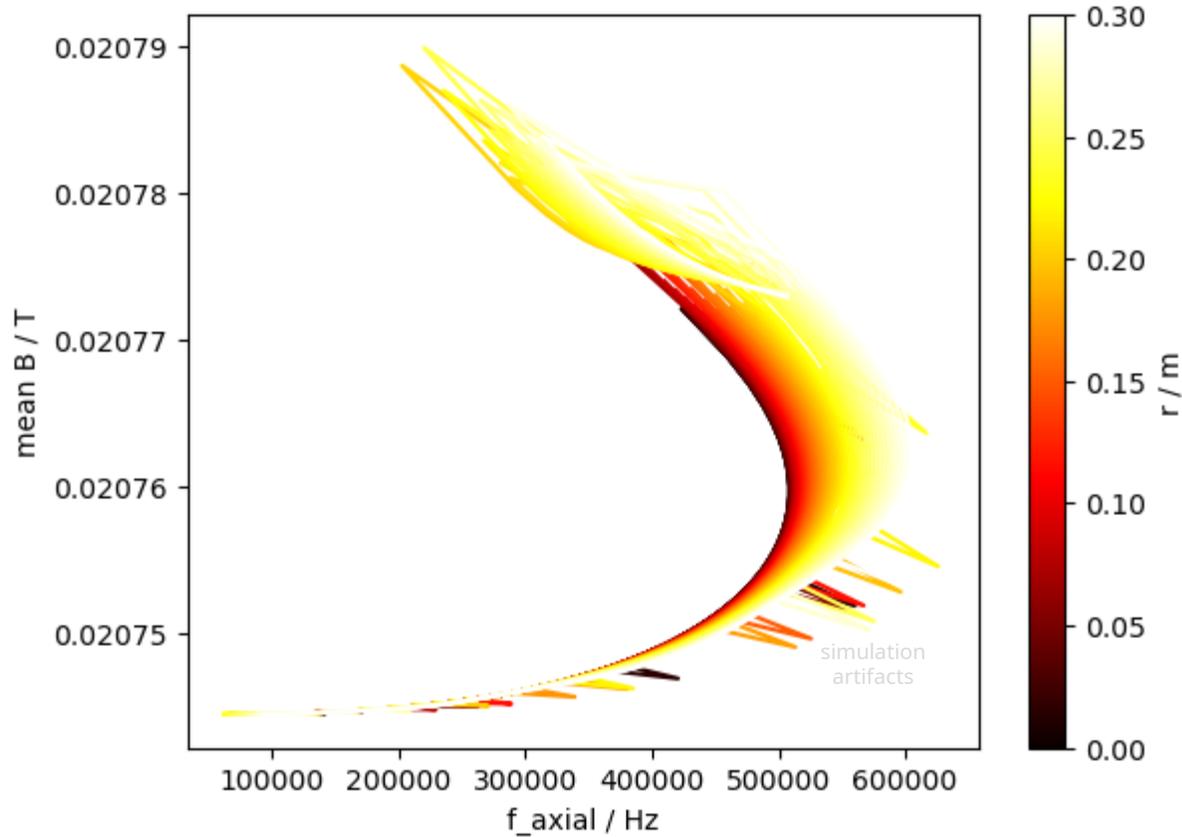
Observable frequencies



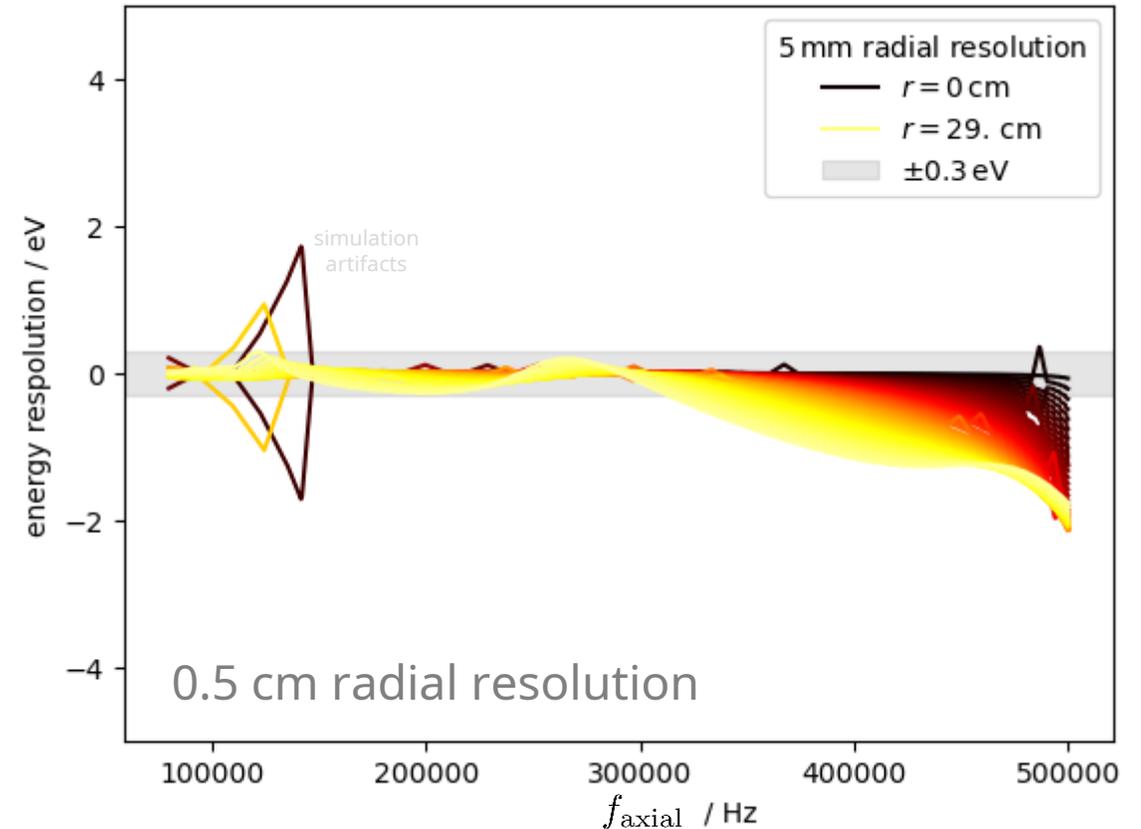
Reconstructed energy just from frequencies

$$\langle B \rangle(r, f_{\text{axial}}) - \langle B \rangle(f_{\text{axial}} | r_{\text{ref}})$$

# Electron Trap - Energy Resolution



Observable frequencies

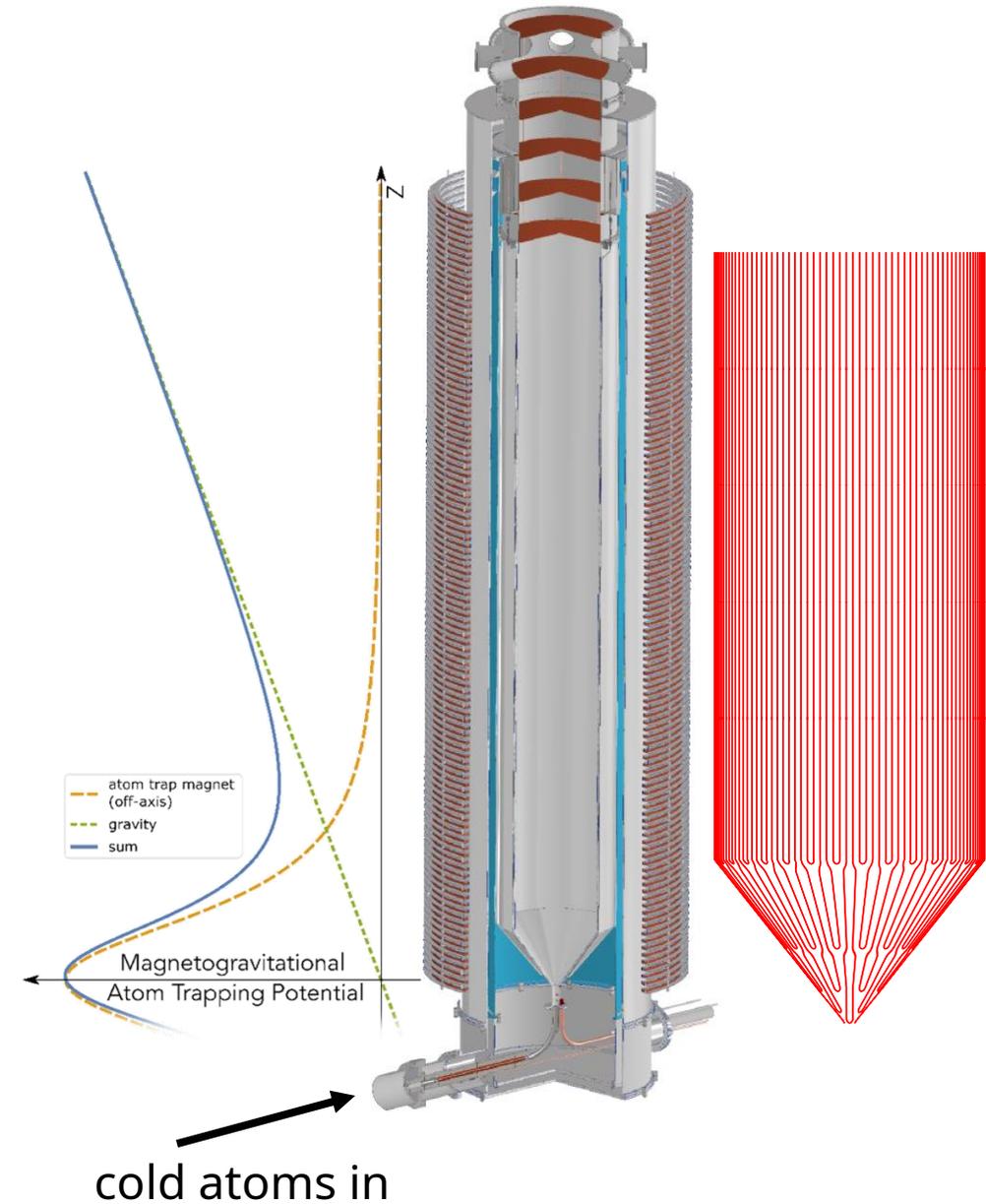
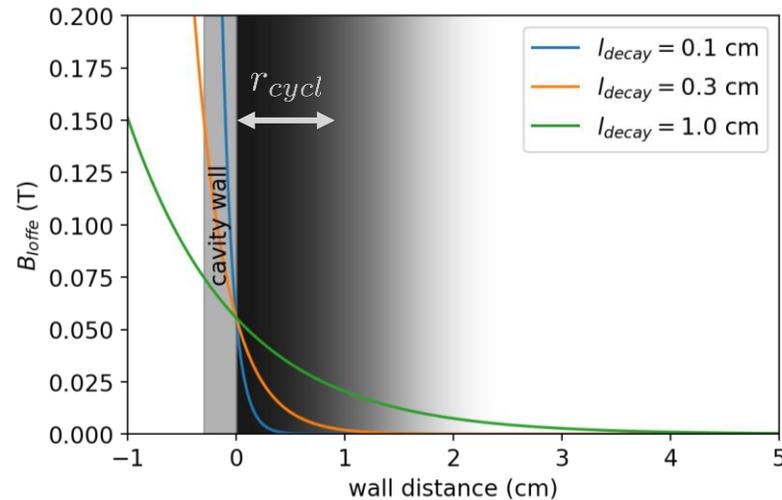
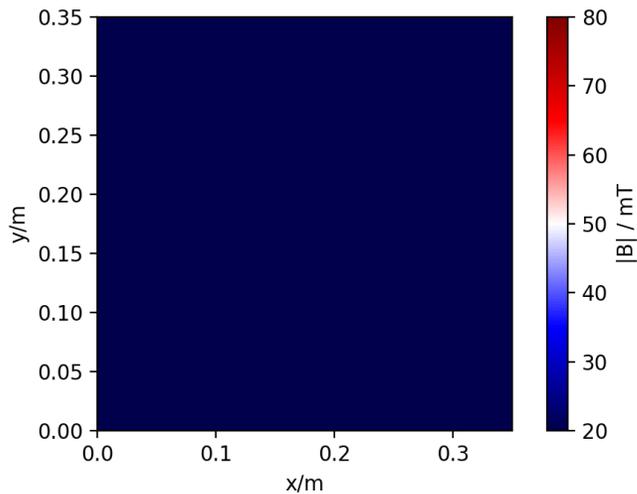


Reconstructed energy just from frequencies

$$\langle B \rangle(r, f_{\text{axial}}) - \langle B \rangle(f_{\text{axial}} | r_{\text{ref}})$$

# Atom Trap

- Magneto-gravitational trap  $mgh \simeq \mu B_{\max} \geq 20k_B T$
- need  $\sim 50\text{mT}$  trapping field to confine  $1\text{mK}$  atomic tritium
- Ioffe coil with 64 loops on outside of cavity
- Field decays rapidly with radius  
→ Little disturbance in detection volume



# Summary

- Low Frequency Apparatus should demonstrate all critical techniques for full scale neutrino mass experiment
  - CRES experiment in huge volume at low magnetic field
  - Co-existence of atomic trap and CRES
- Demonstrates all critical techniques for full scale neutrino mass experiment
- Composition of three magnetic fields
  - Background field → cyclotron radiation
  - CRES electron trap → confinement in readout region
  - Atom trap → avoid recombination at physical walls
- Magnetic fields influence each other and are partly in contradiction  
→ Optimize for efficiency and energy resolution
- Additional shielding from Earth magnetic field and other stray fields needed



# Thank you for your attention



This work was 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 collaborating institutions.

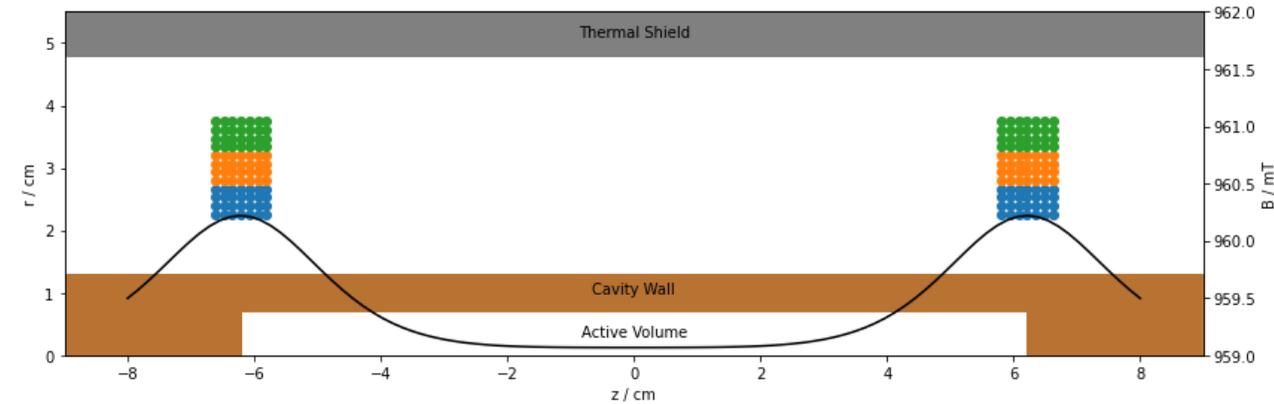


# Experimental Setup

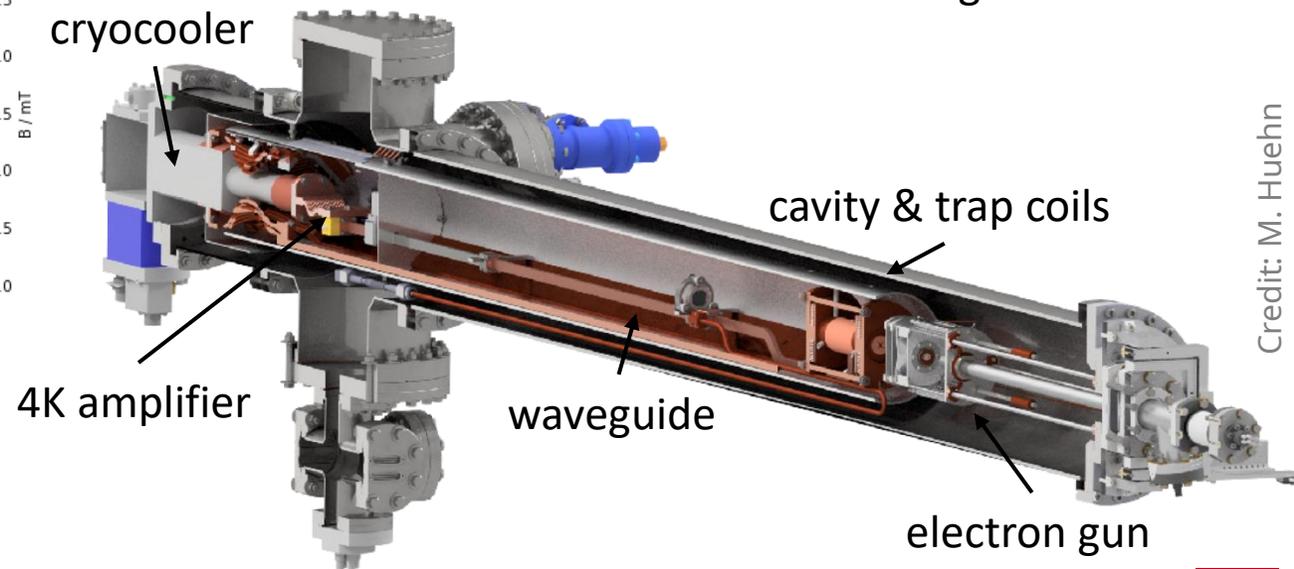
- MRI magnet provides 1T background field
- Cavity with TE011 mode at 26 GHz
- Trap Coils around end of cavity
- Demonstrate CRES in cavity, sub-eV resolution through event-by-event reconstruction
- scale up volume to few  $\text{cm}^3$



MRI magnet



Credit: J. Pena & J. Stachurska



Credit: M. Huehn

# Magnetic Trap Shape

$$2\pi f_{\text{meas}} = \frac{e\langle B \rangle}{m_e + E_{\text{kin}}/c^2}$$

## Box trap

- $\langle B \rangle$  independent of pitch angle
- Axial frequency  $\propto \cos(\theta)$
- Independent of pitch angle
- Unphysical (Maxwell's equations)



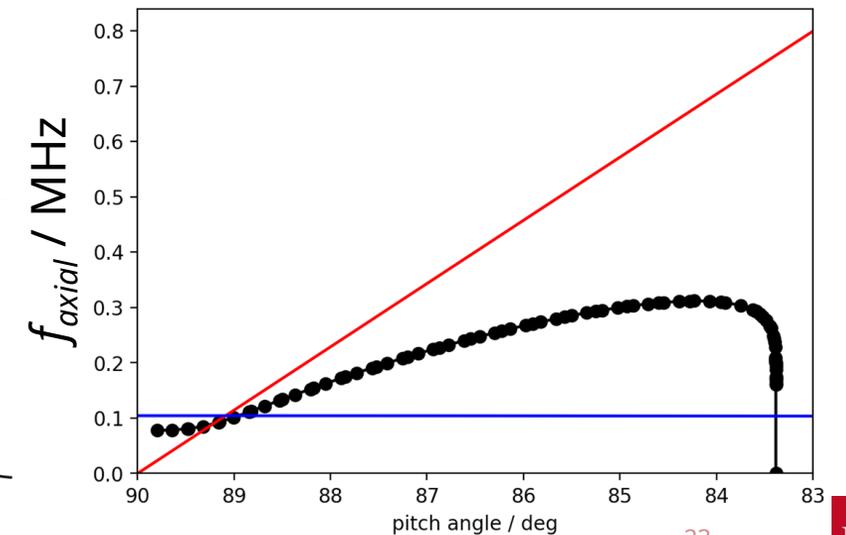
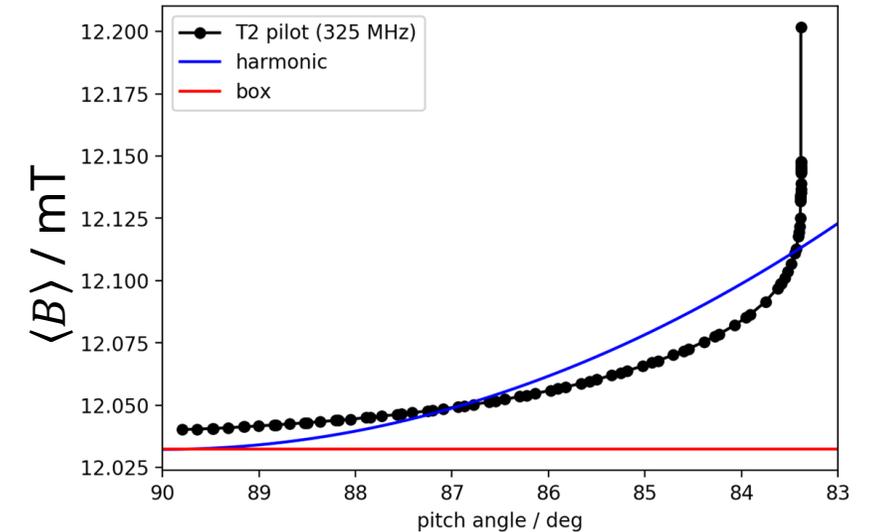
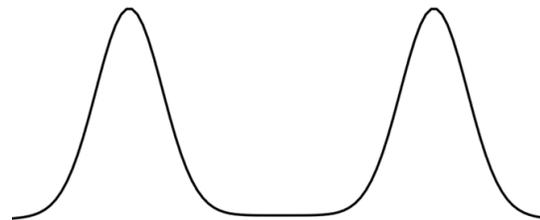
## Harmonic trap

- $\langle B \rangle \propto 1 + \sin^2(\theta)$
- Axial frequency  $\propto \sin(\theta) \cong \text{const}$
- Energy and pitch angle are degenerate



## Real trap

- Finite walls  
→ finite trap pitch angle
- Radial and axial gradients related
- Turn over in axial frequency

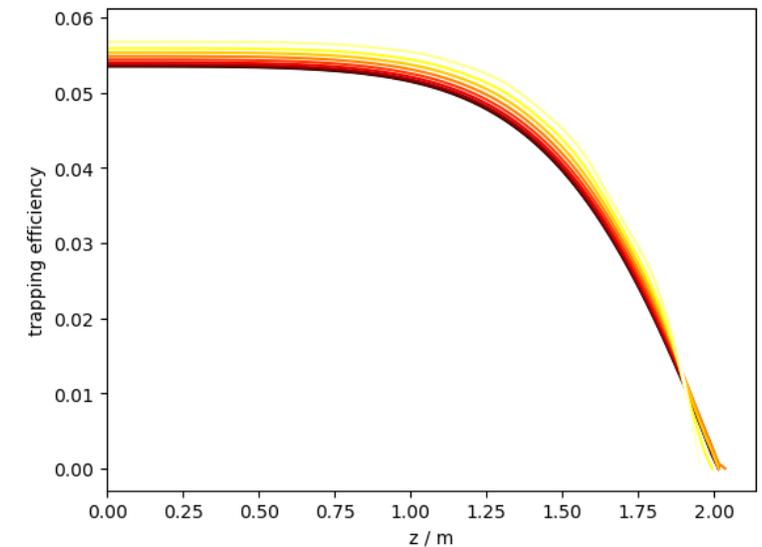
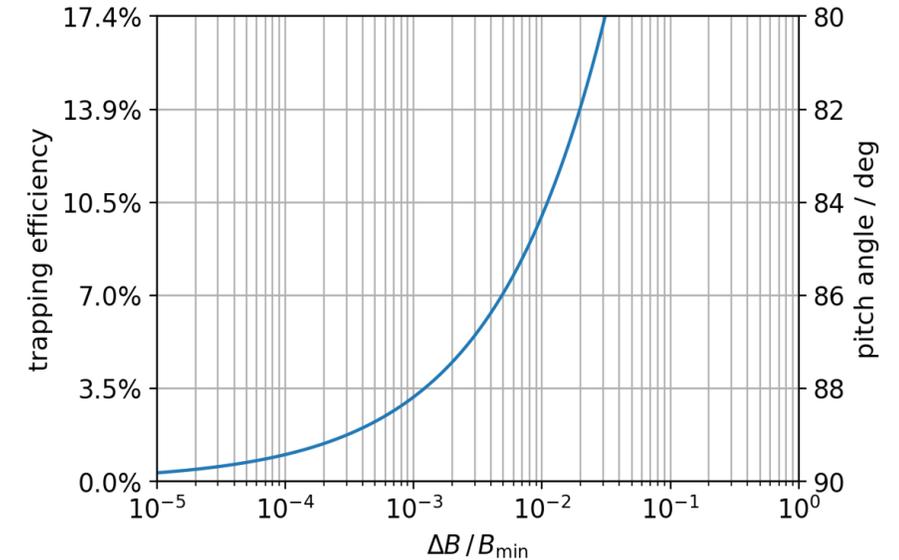
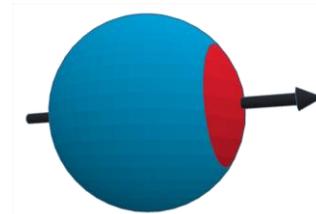


# Trapping Efficiency

- Adiabatic motion  $\rightarrow \frac{\sin^2 \theta(t)}{B(t)}$  conserved
- Trappable pitch angle  

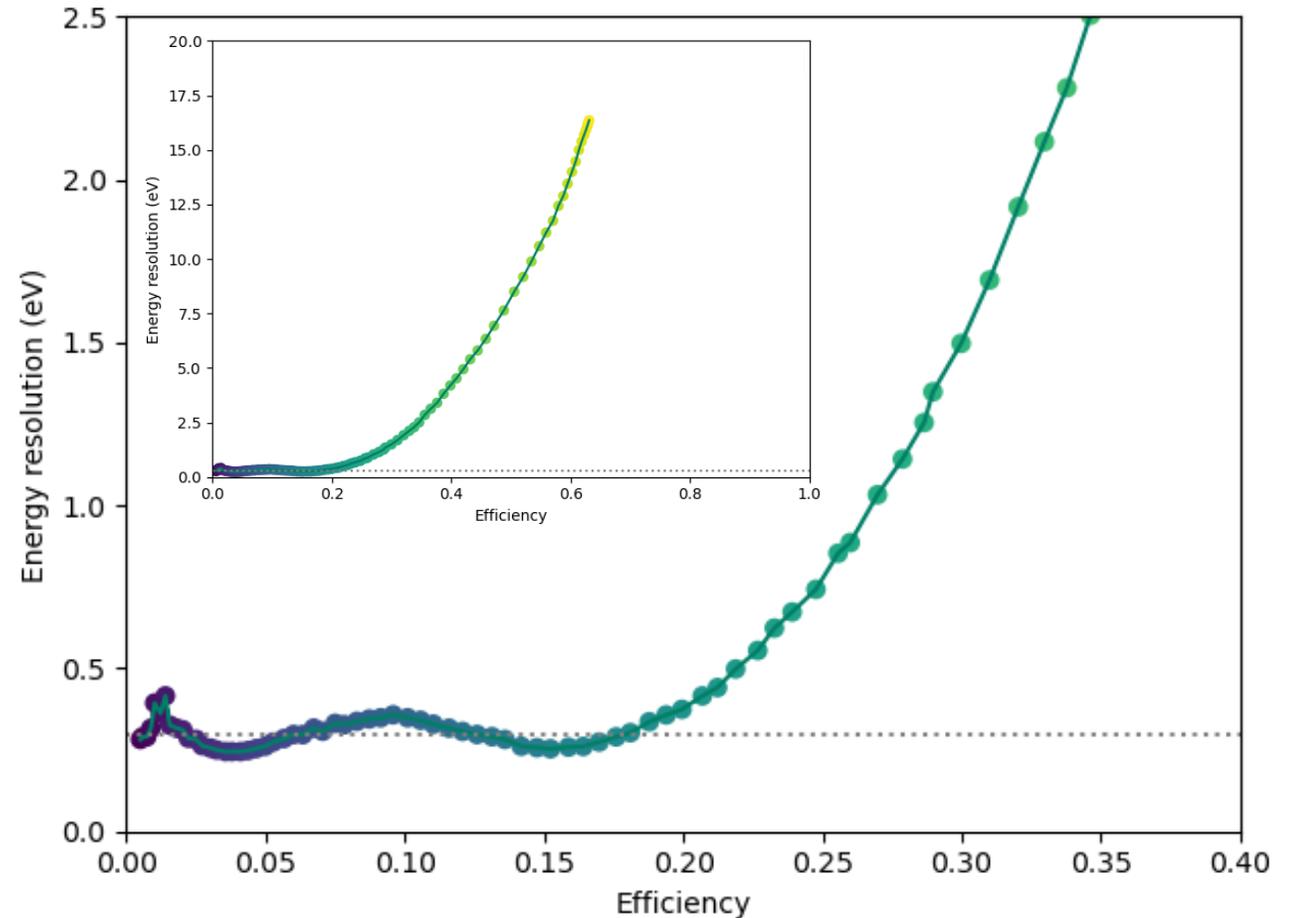
$$\theta_{\text{trap}} = \arcsin \sqrt{\frac{B(r, z)}{B_{\text{max}}(r)}}$$
- **Trapping efficiency**  

$$\eta_{\text{trap}} = \cos \theta_{\text{min}}$$
  - position dependence  
 $\rightarrow$  trap shape dependence
- **Deeper traps increase efficiency**



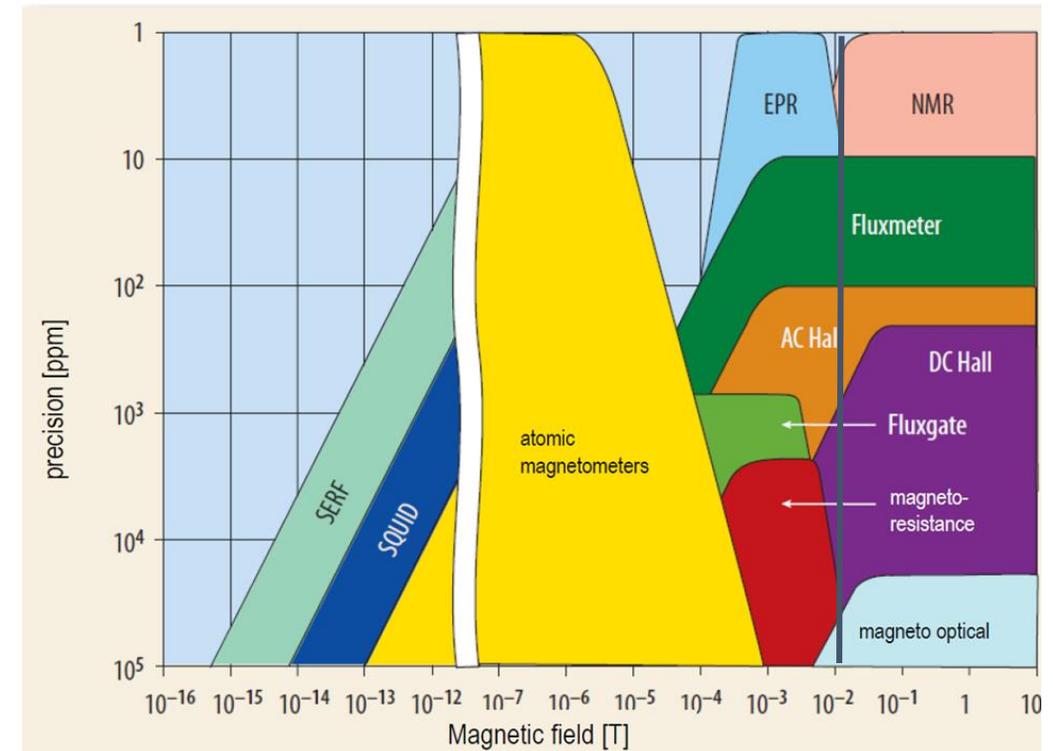
# Performance

- Phase space is
  - larger at larger radius
  - larger for lower pitch angles
- Calculate phase space weighted energy resolution (std)
- apply cut on axial frequency (color of dots)
- Here no radial information used



# Magnetometry

- Magnetometer array surrounding cavity for monitoring
  - online and offline correction
- EPR and NMR magnetometers yield sufficient resolution at  $\sim 20\text{mT}$  fields (560MHz)
- Shimming ([homogeneity](#))
  - special materials needed for passive shimming
  - correction coils for active shimming
- Shielding ([homogeneity](#))
  - Earth magnetic field relevant at low magnetic fields
  - Shielding by several layers of mu-metal



L. Bottura, K.N. Henrichsen CERN, Geneva, Switzerland

# Coil Current Optimization

- 101 individual coils → 101D space
- Energy resolution & efficiency calculation computing intense → not a feasible metric

- Define target field
  - Solve for best current to achieve target field
  - Straight forward
  - BUT what is a good target field?

$$\begin{pmatrix} B(\vec{r}_1) \\ B(\vec{r}_2) \\ B(\vec{r}_3) \\ \dots \end{pmatrix} = \begin{pmatrix} \frac{B_1(\vec{r}_1)}{I_{ref}} & \frac{B_2(\vec{r}_1)}{I_{ref}} & \frac{B_3(\vec{r}_1)}{I_{ref}} & \dots \\ \frac{B_1(\vec{r}_2)}{I_{ref}} & \frac{B_2(\vec{r}_2)}{I_{ref}} & \frac{B_3(\vec{r}_2)}{I_{ref}} & \dots \\ \frac{B_1(\vec{r}_3)}{I_{ref}} & \frac{B_2(\vec{r}_3)}{I_{ref}} & \frac{B_3(\vec{r}_3)}{I_{ref}} & \dots \\ \dots & \dots & \dots & \dots \end{pmatrix} \cdot \begin{pmatrix} I_1 \\ I_2 \\ I_3 \\ \dots \end{pmatrix}$$

Solution:  $\vec{I} = M^{-1}\vec{B}$

- Define requirements on field and optimize a  $\chi^2$

- Trap depth
- Trap length
- Z-symmetry
- Flatness of trap
- ...

$$\chi_{total}^2 = \chi_{req.1}^2 + \chi_{req.2}^2 + \chi_{req.3}^2 + \dots$$

target  $\chi_{req}^2 = \left( \frac{value - target}{tolerance} \right)^2$

limit  $\chi_{req}^2 = \begin{cases} \left| \frac{value - target}{tolerance} \right|^3 & \text{if } value > target \\ 0 & \text{otherwise} \end{cases}$

How to quantify numerically?  
Limit on field gradients,  
length below 10% of trap depth, ...

Not easy to converge

