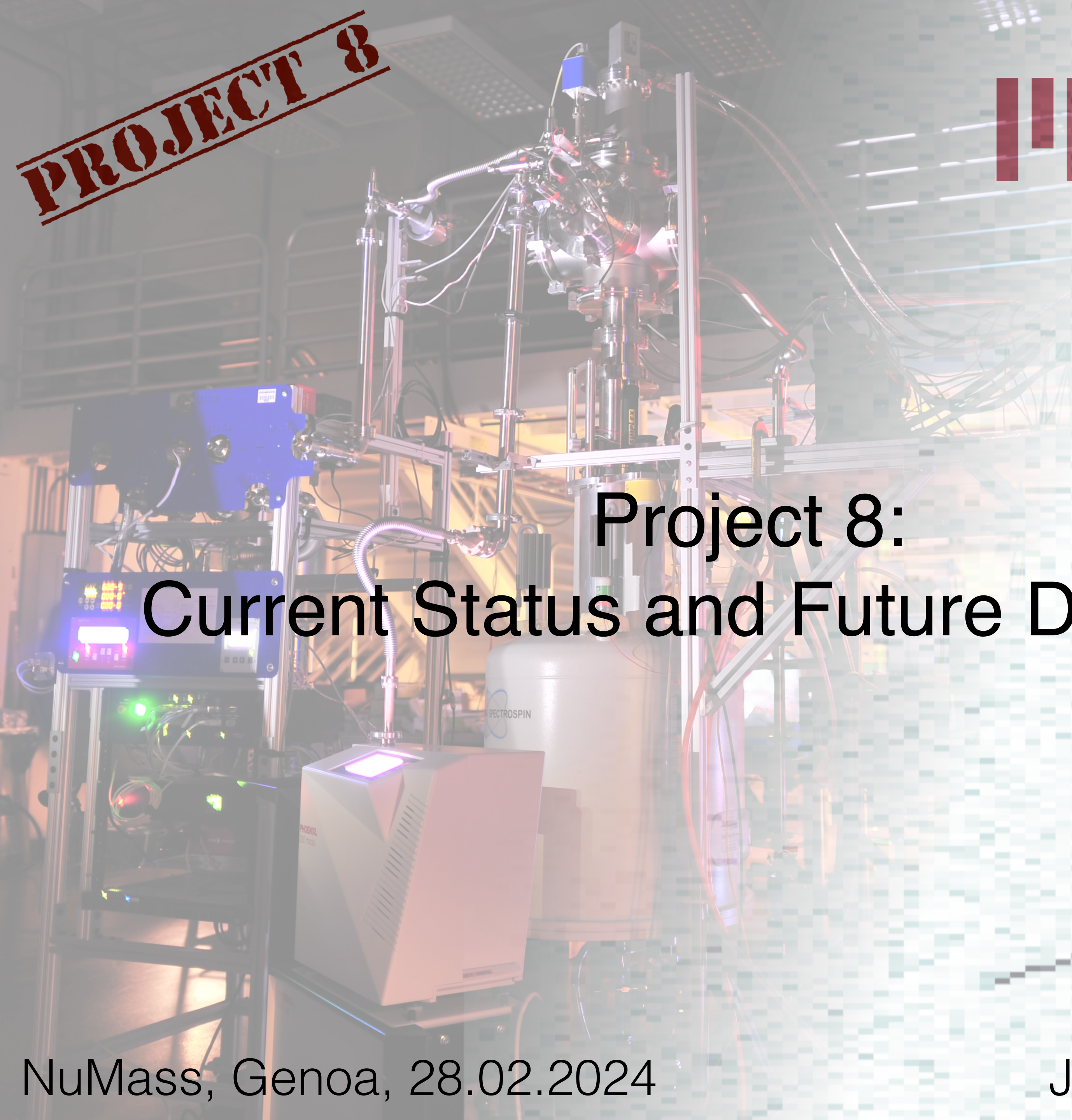


PROJECT 8

Massachusetts Institute of Technology

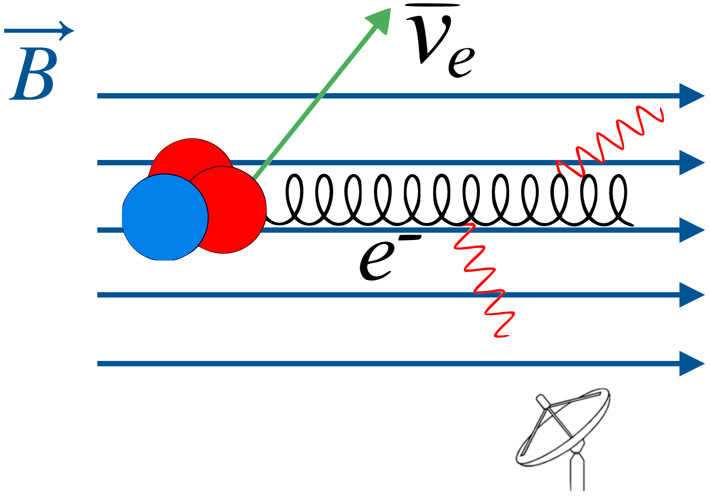
# Project 8: Current Status and Future Directions

NuMass, Genoa, 28.02.2024

Juliana Stachurska

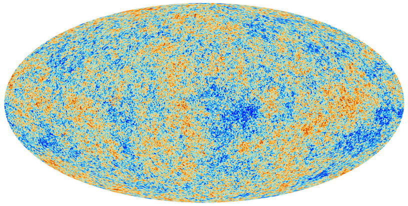
PROJECT 8

# Project 8 Concept



# Neutrino Mass Probes

- Cosmology: indirect, model-dependent, probe of sum of masses



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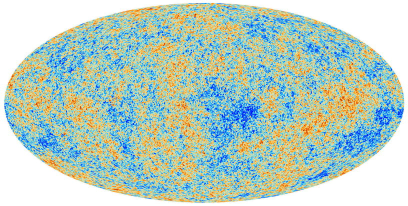

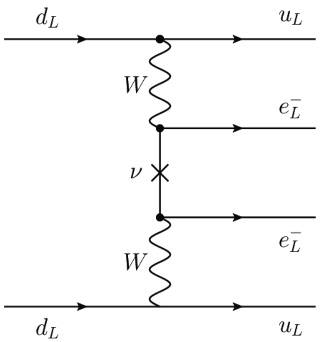

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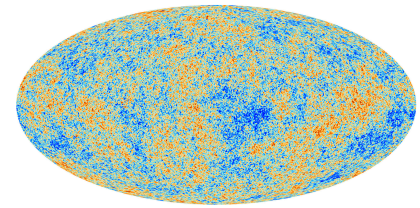

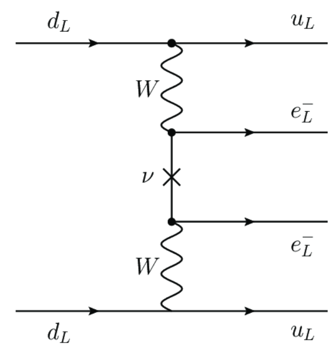


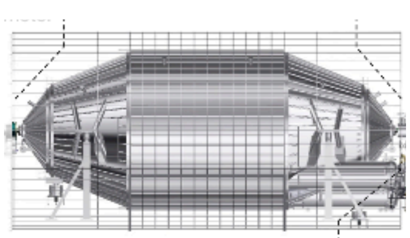

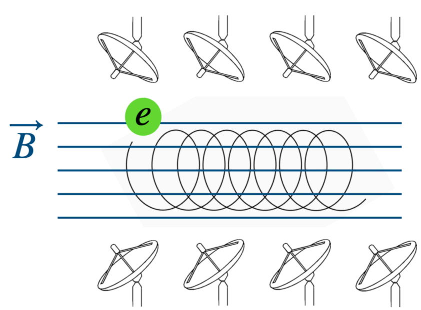


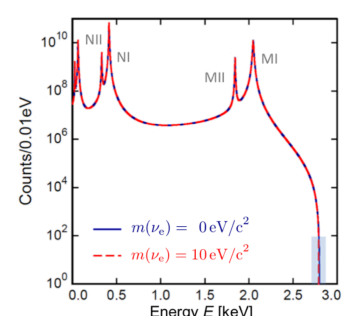

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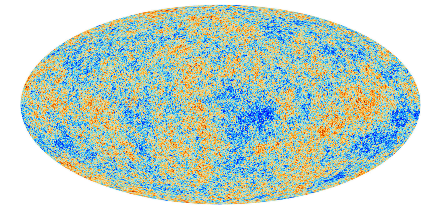

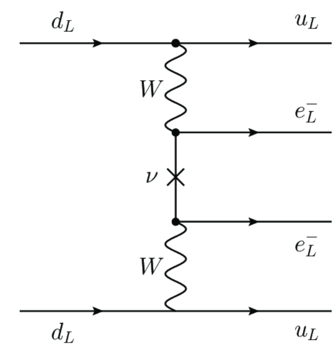


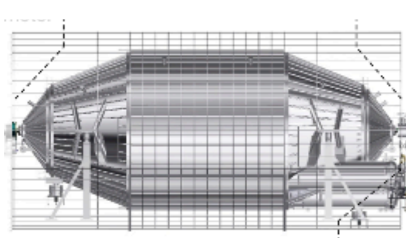

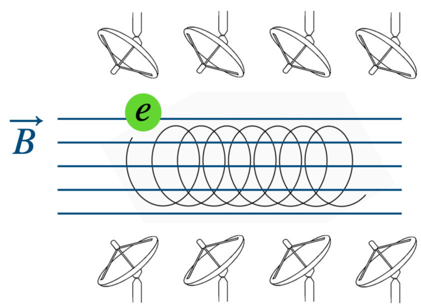


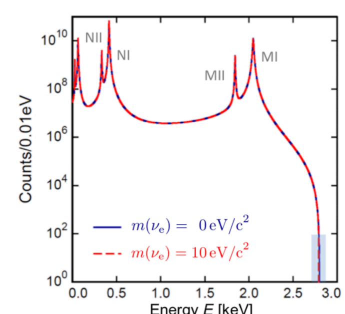

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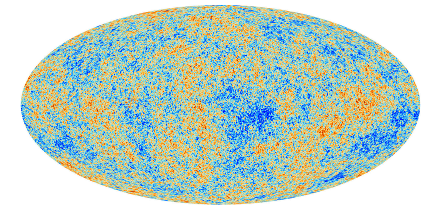

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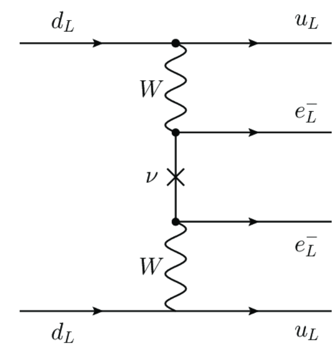


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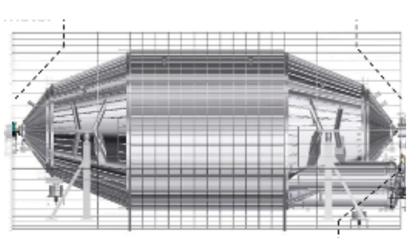
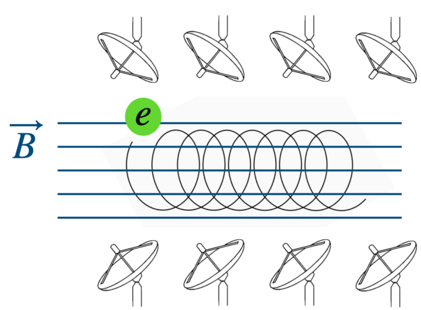
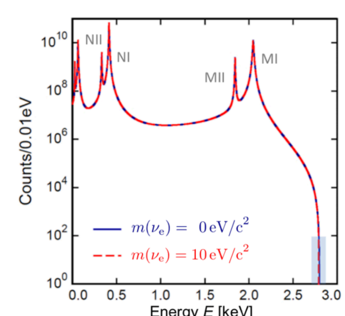
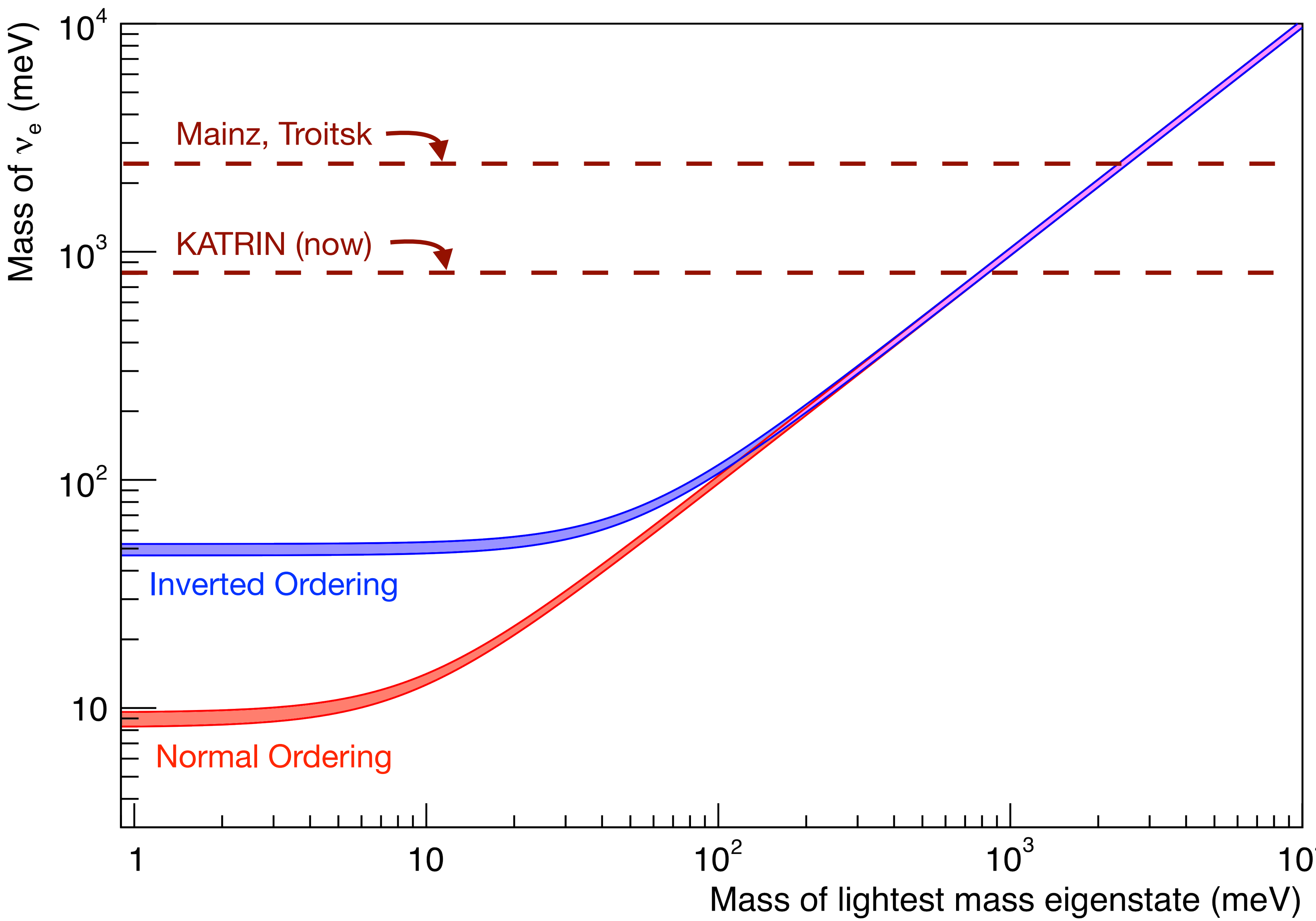




# Project 8 Goal



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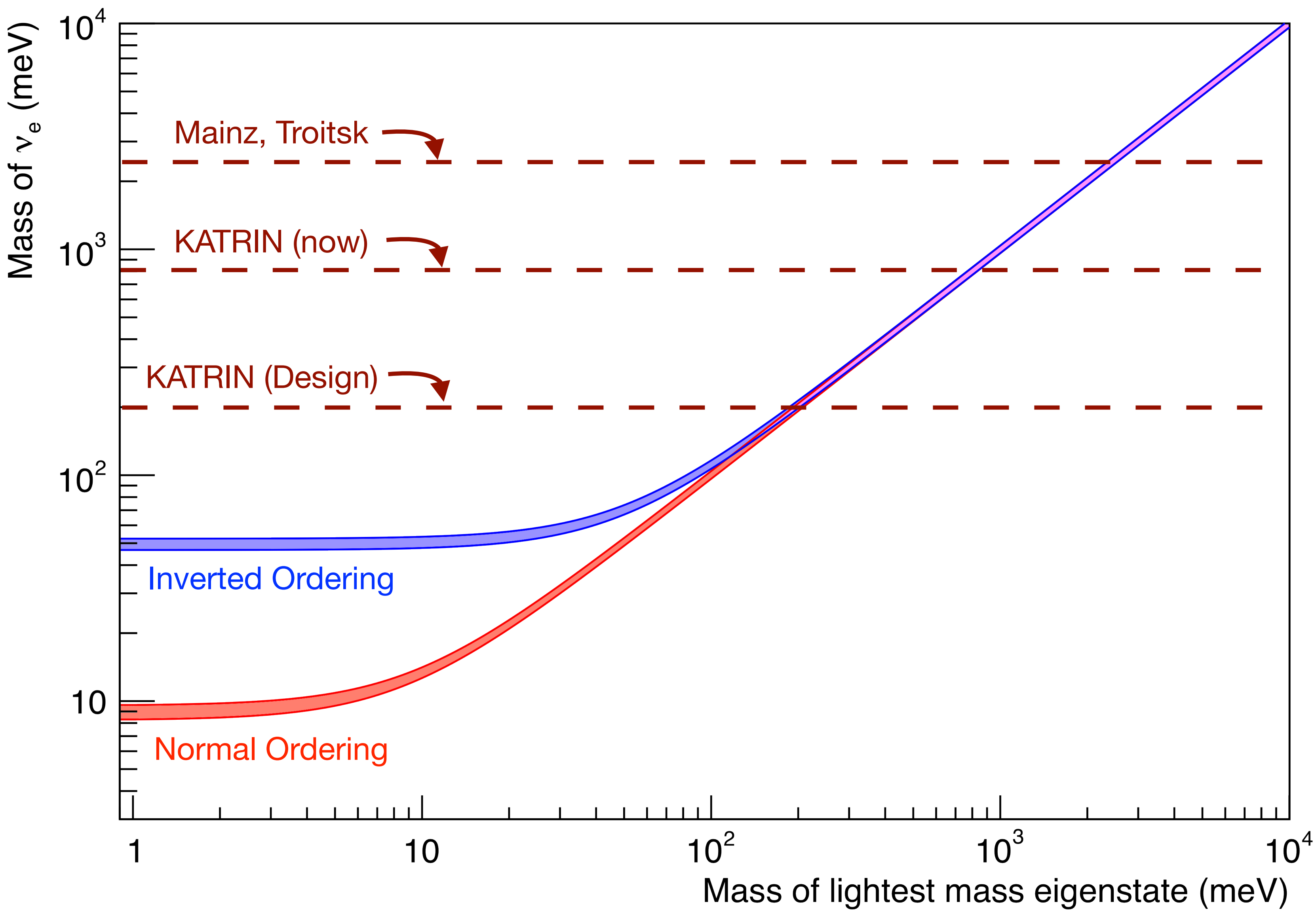

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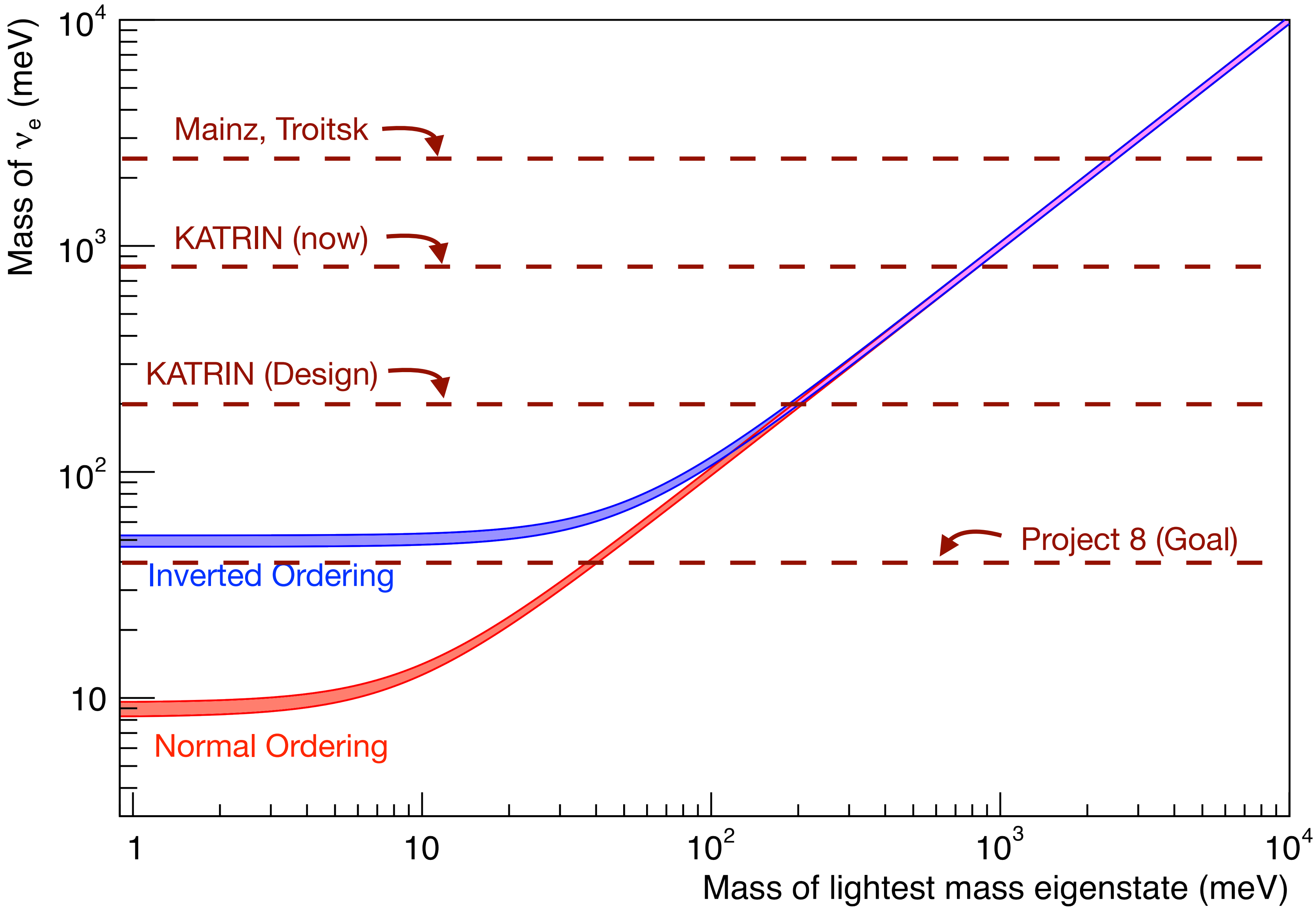

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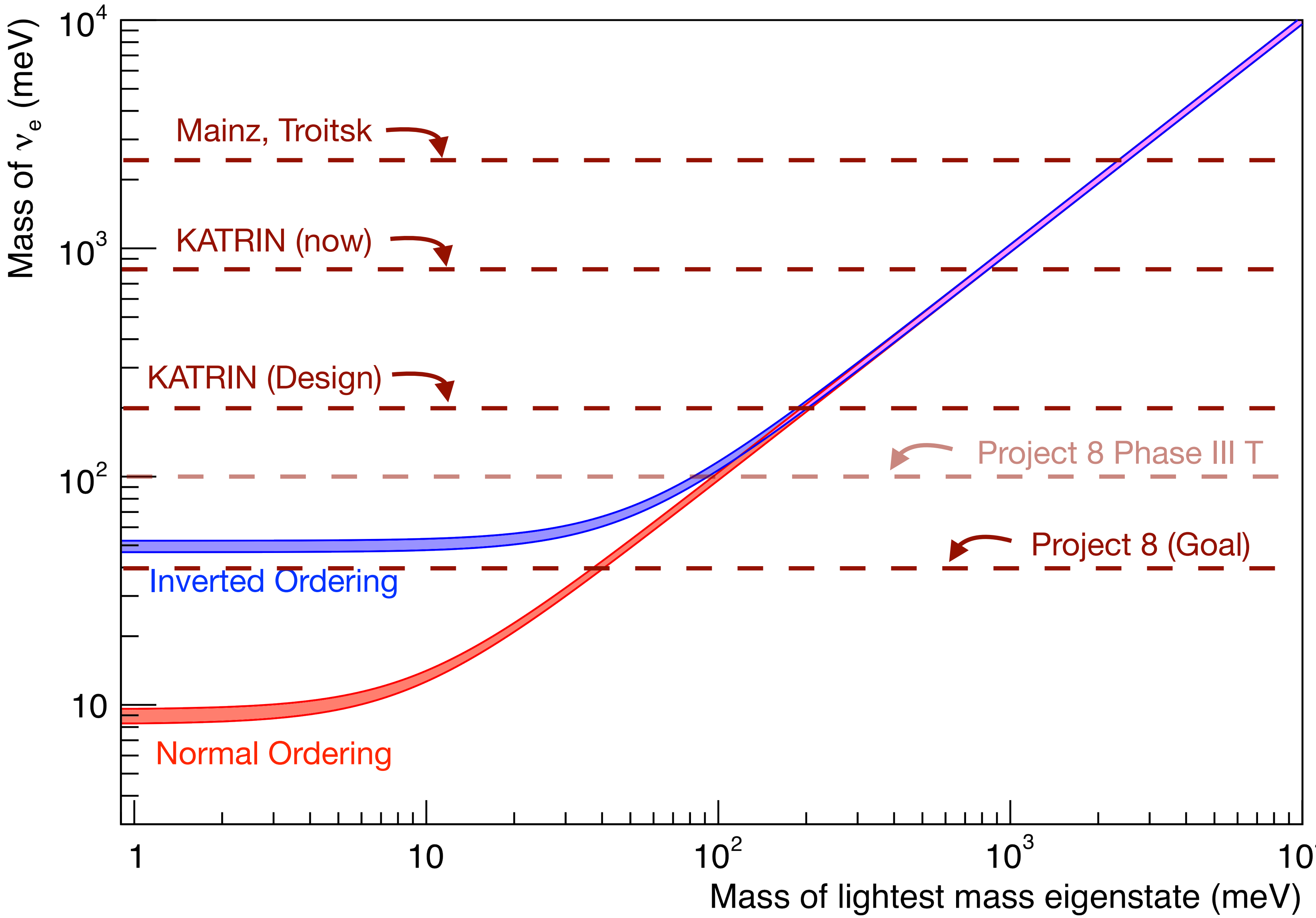

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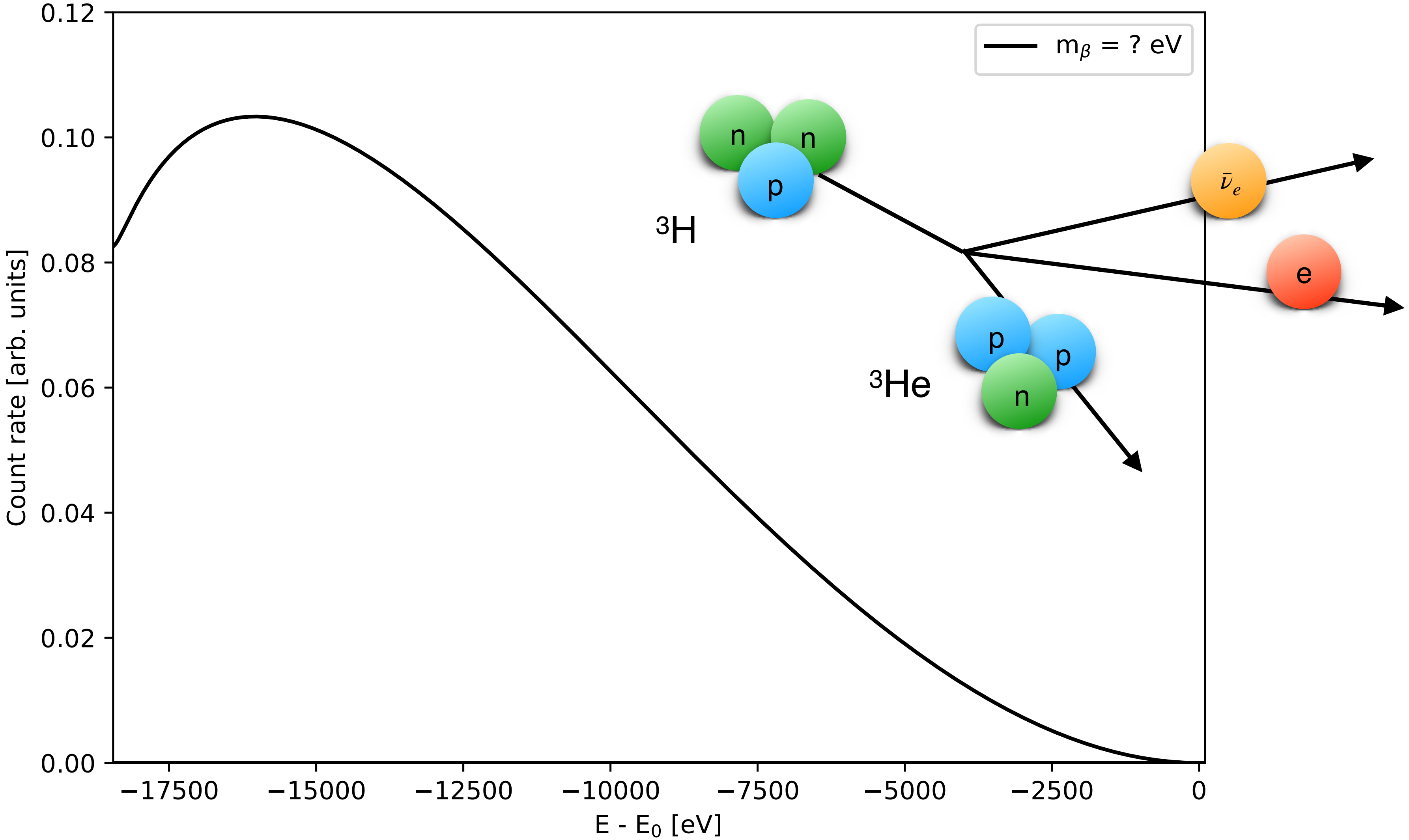

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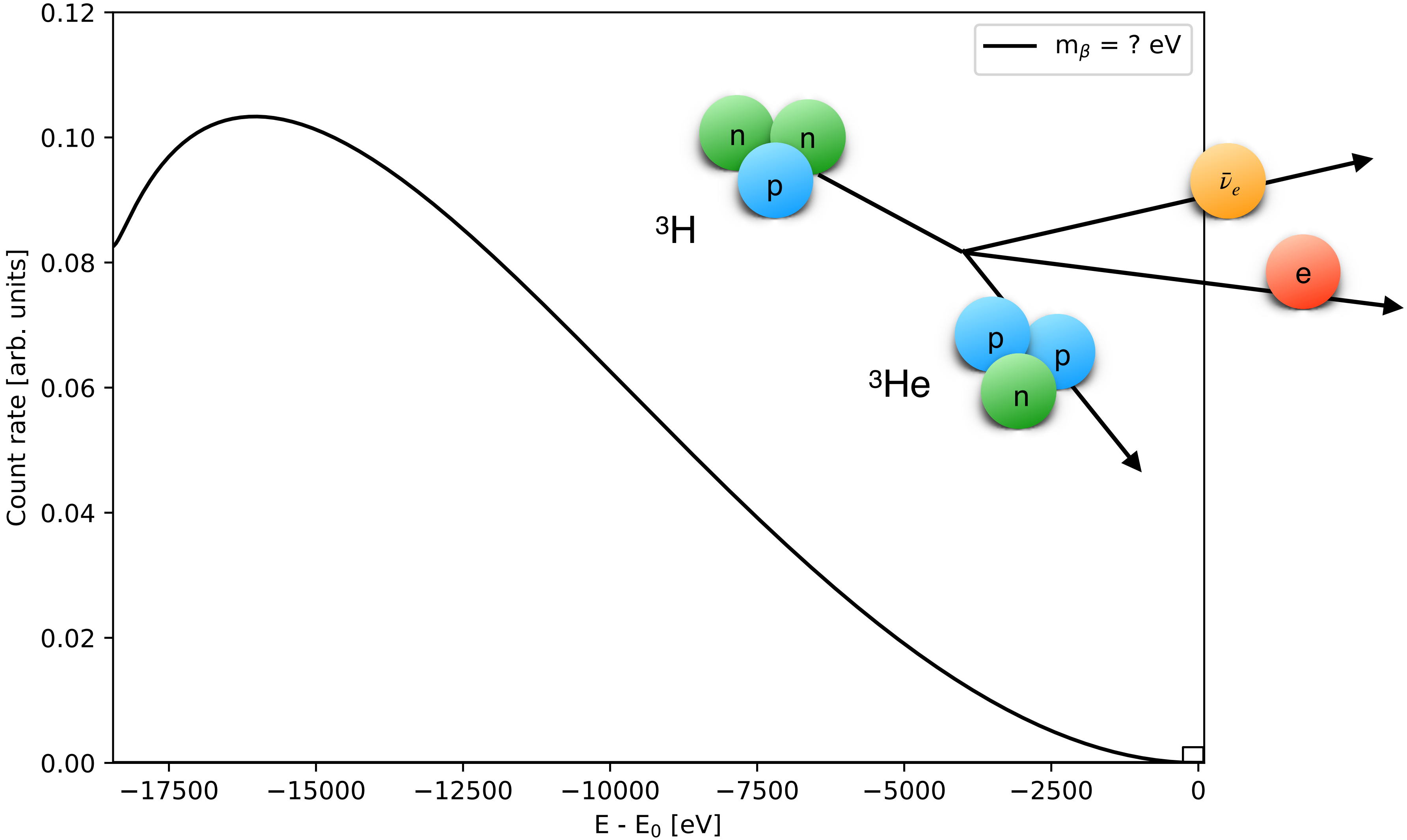

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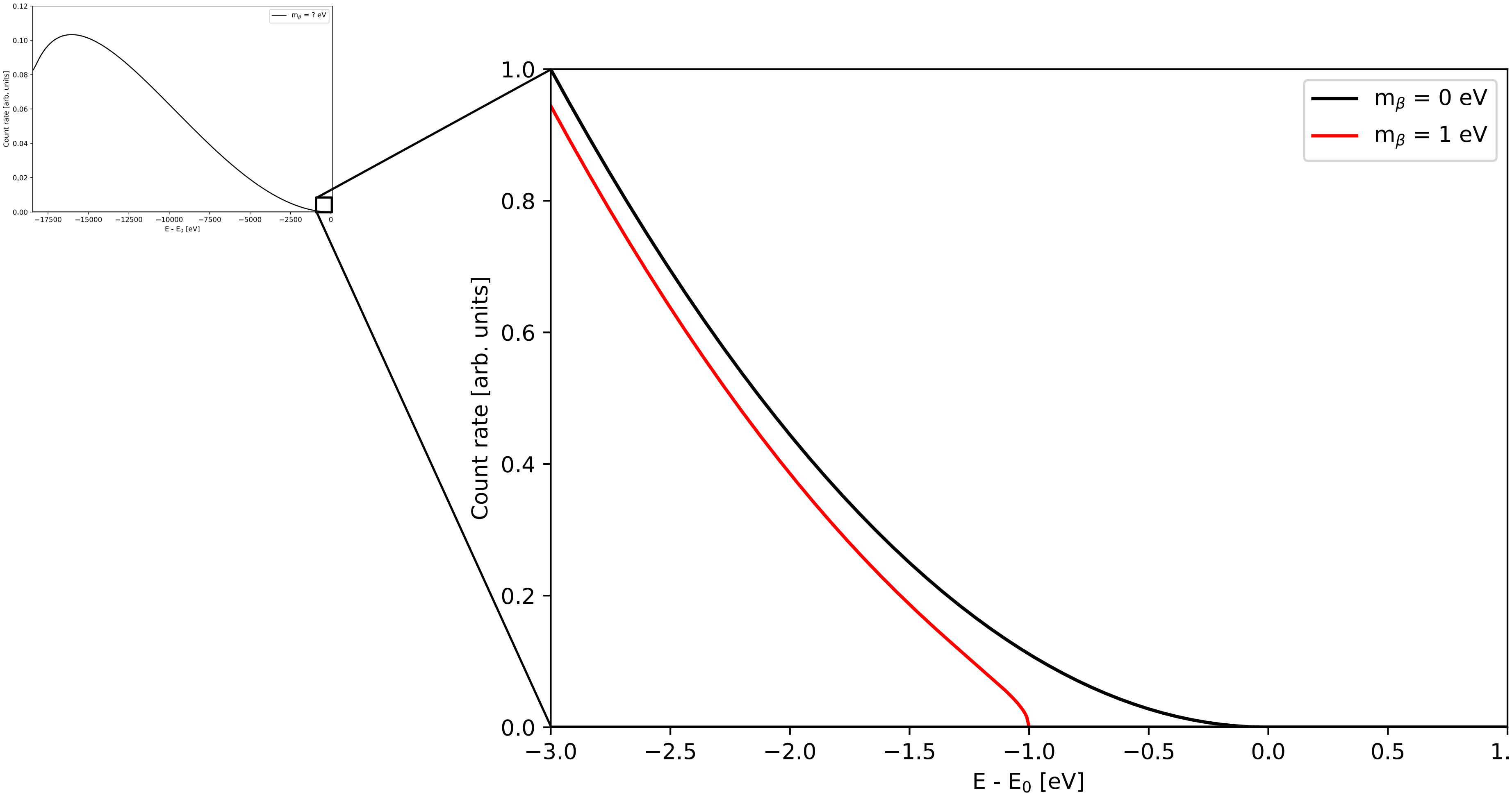

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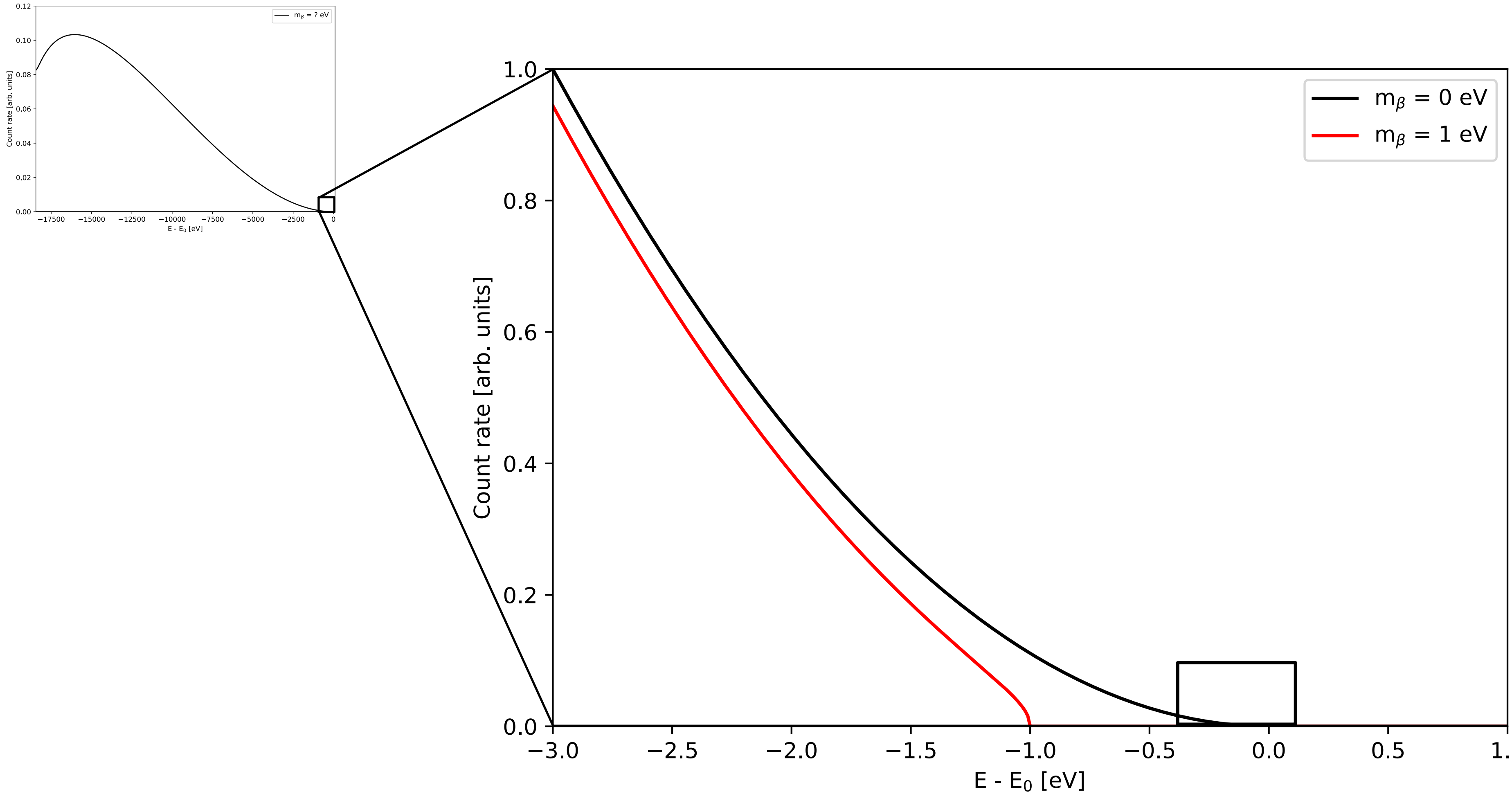

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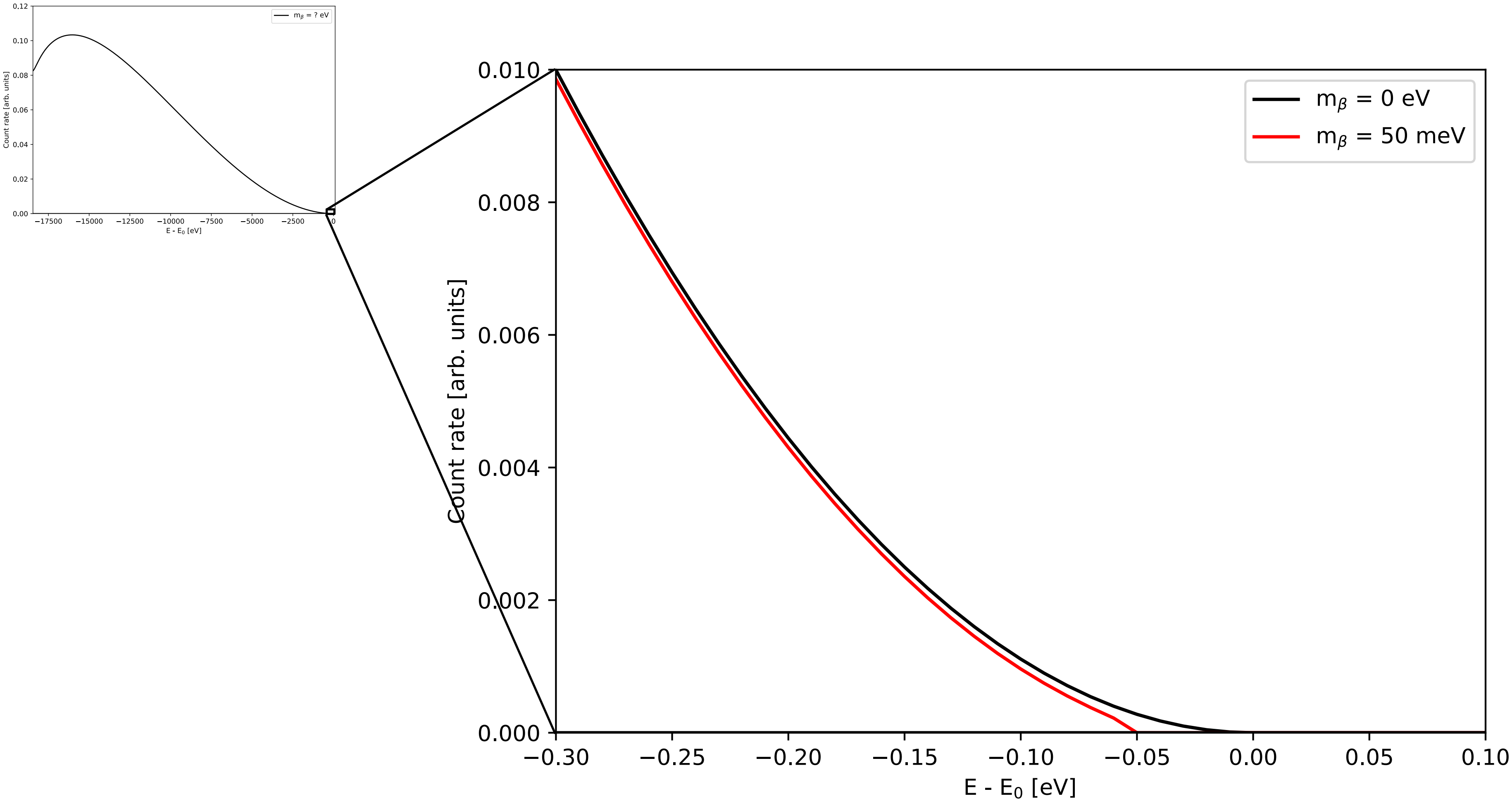
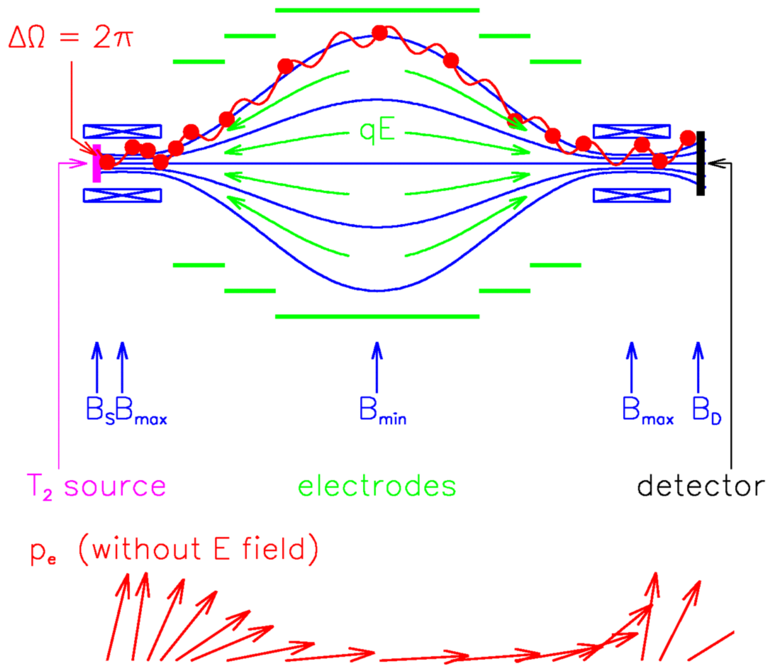


# Measuring Neutrino Mass (Now)




- KATRIN sensitivity: 200 meV
  Current results:
  $m_\beta < 0.8\,\mathrm{eV}\,(90\,\%\,\mathrm{C.L.})$

Nat. Phys. **18**, 160–166 (2022)
https://www.katrin.kit.edu/

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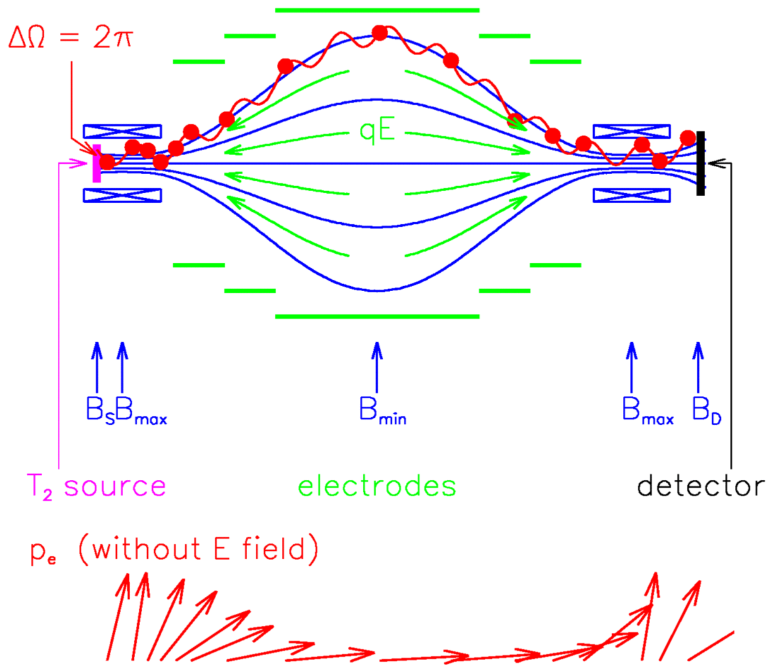


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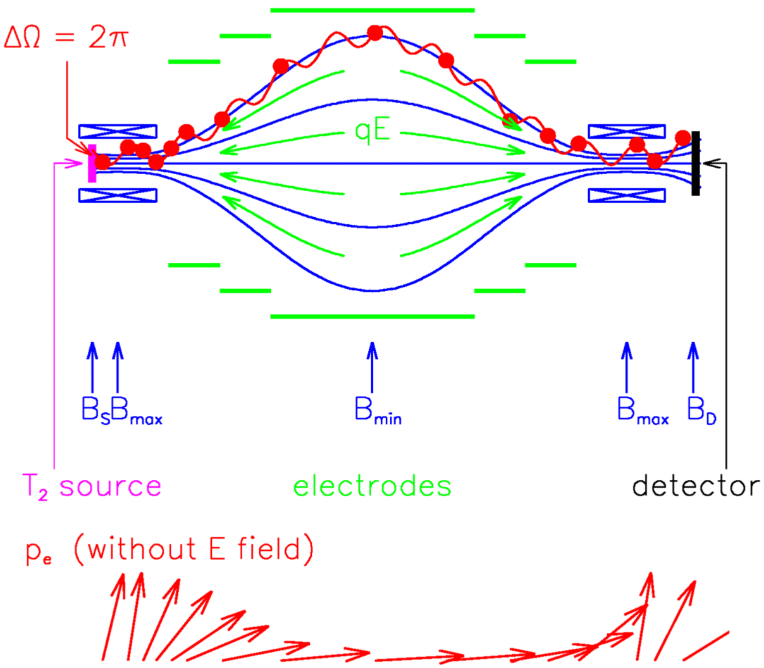


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- Systematics from molecular final states greatly reduced
- Sensitivity to $m_\beta$ scales as $N^{-1/4}$
- Energy resolution:

$$\frac{\Delta E}{E} = \frac{B_{min}}{B_{max}}$$

defined by size of spectrometer

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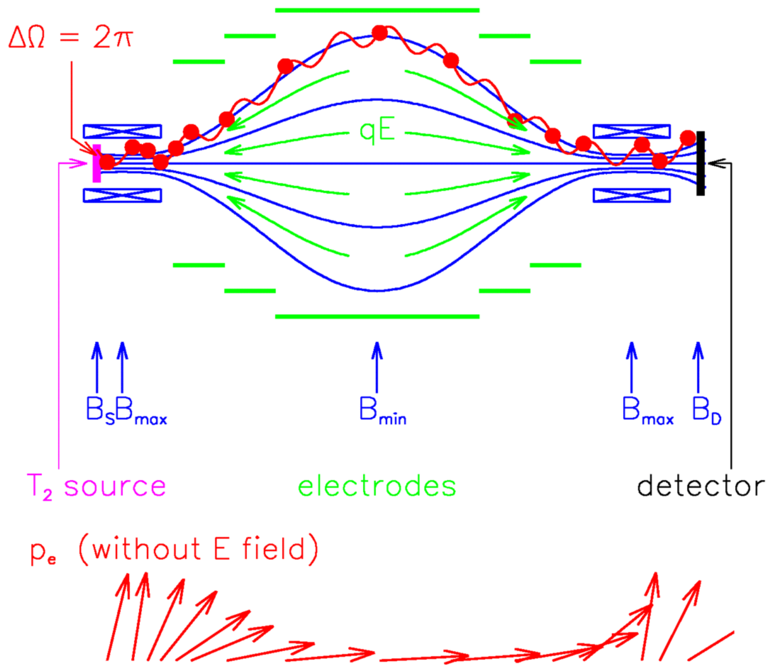


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# CRES

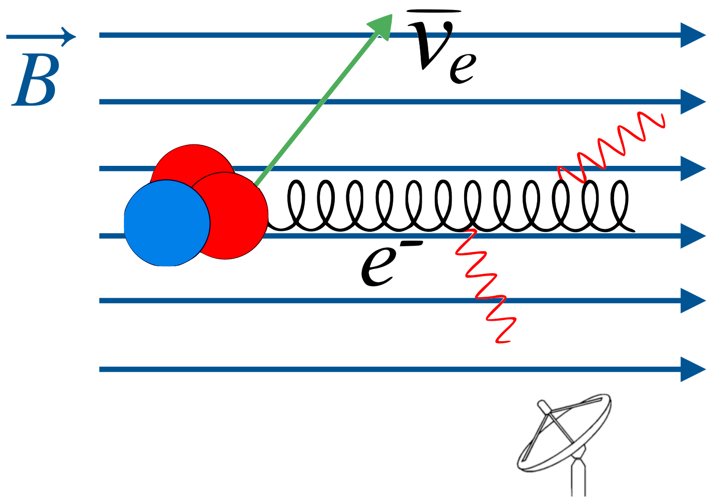
- Cyclotron Radiation Emission Spectroscopy
- Electron in B-field: cyclotron motion & radiation:

$$2\pi f = \frac{e\langle B\rangle}{m_e + K_e/c^2} = \frac{e\langle B\rangle}{\gamma m_e}$$

- Energy resolution:

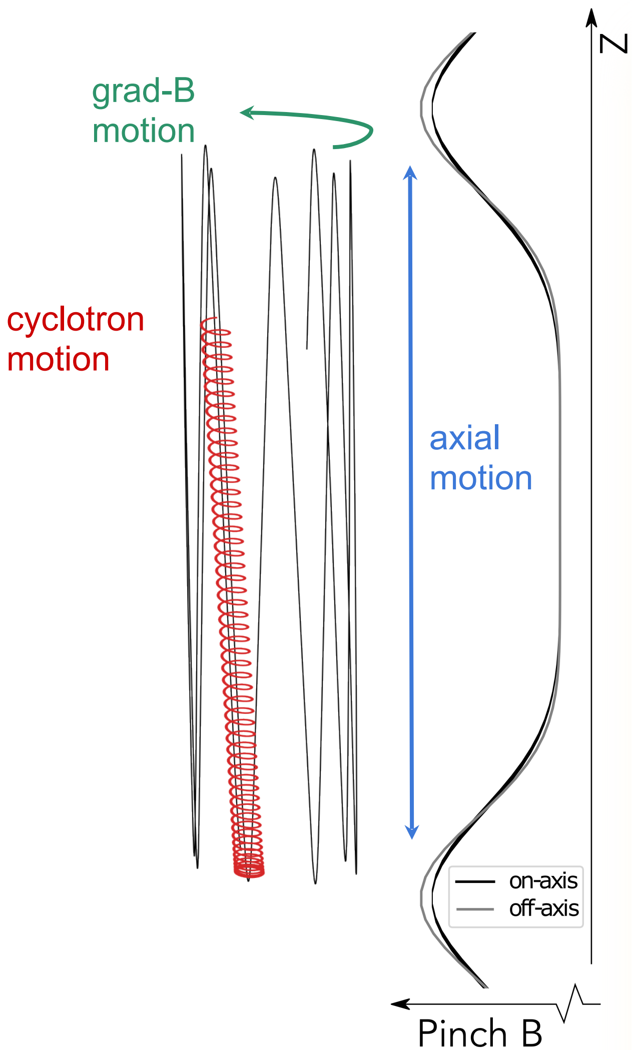
$$\frac{\Delta E}{m_e} = \frac{\Delta f}{f}$$

“Never measure anything but frequency!” — A. L. Schawlow



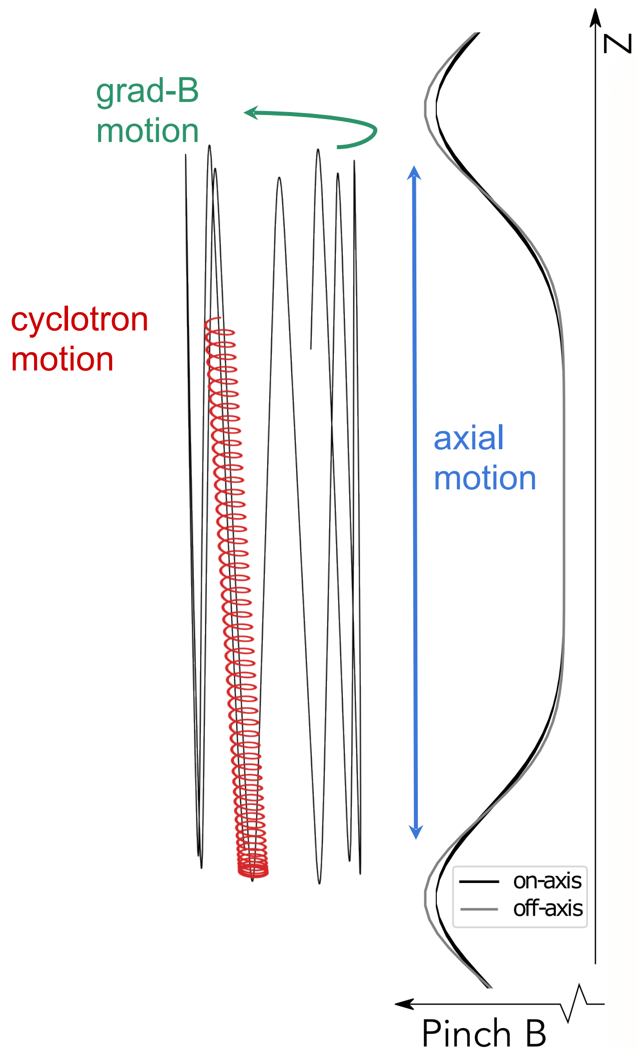

Phys. Rev. D **80**, 051301 (2009)

# CRES Electron Motion




- Electron trapped in magnetic field

# CRES Electron Motion



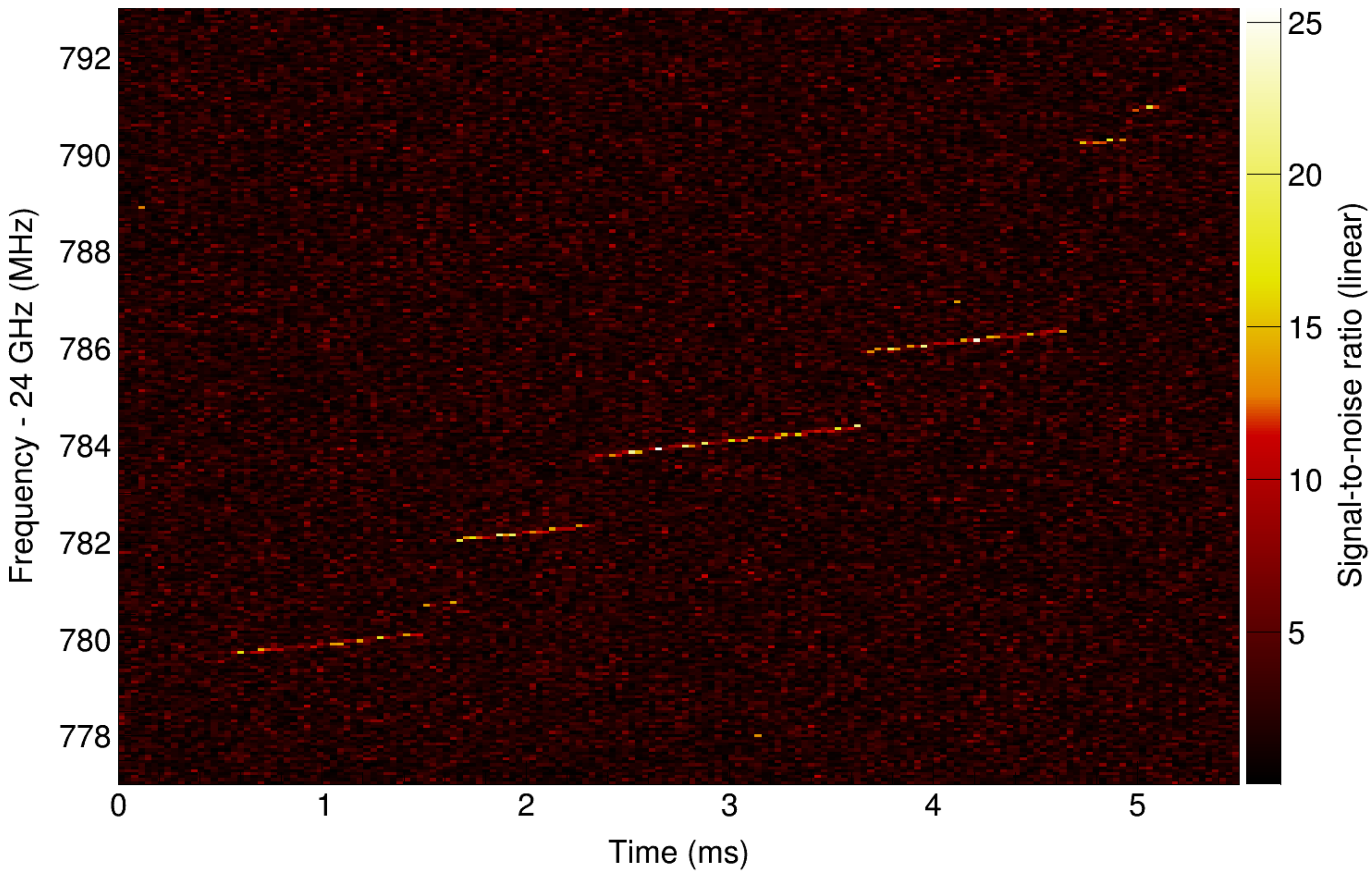

- Electron trapped in magnetic field
- Three superimposed motions:
  - Cyclotron motion with frequency

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



  - Axial motion with frequency $f_a$ that depends on trap design and electron's pitch angle
  - Grad-B motion $f_{\nabla B}$ from magnetic trapping field gradient

# A Typical CRES Event

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

PROJECT 8

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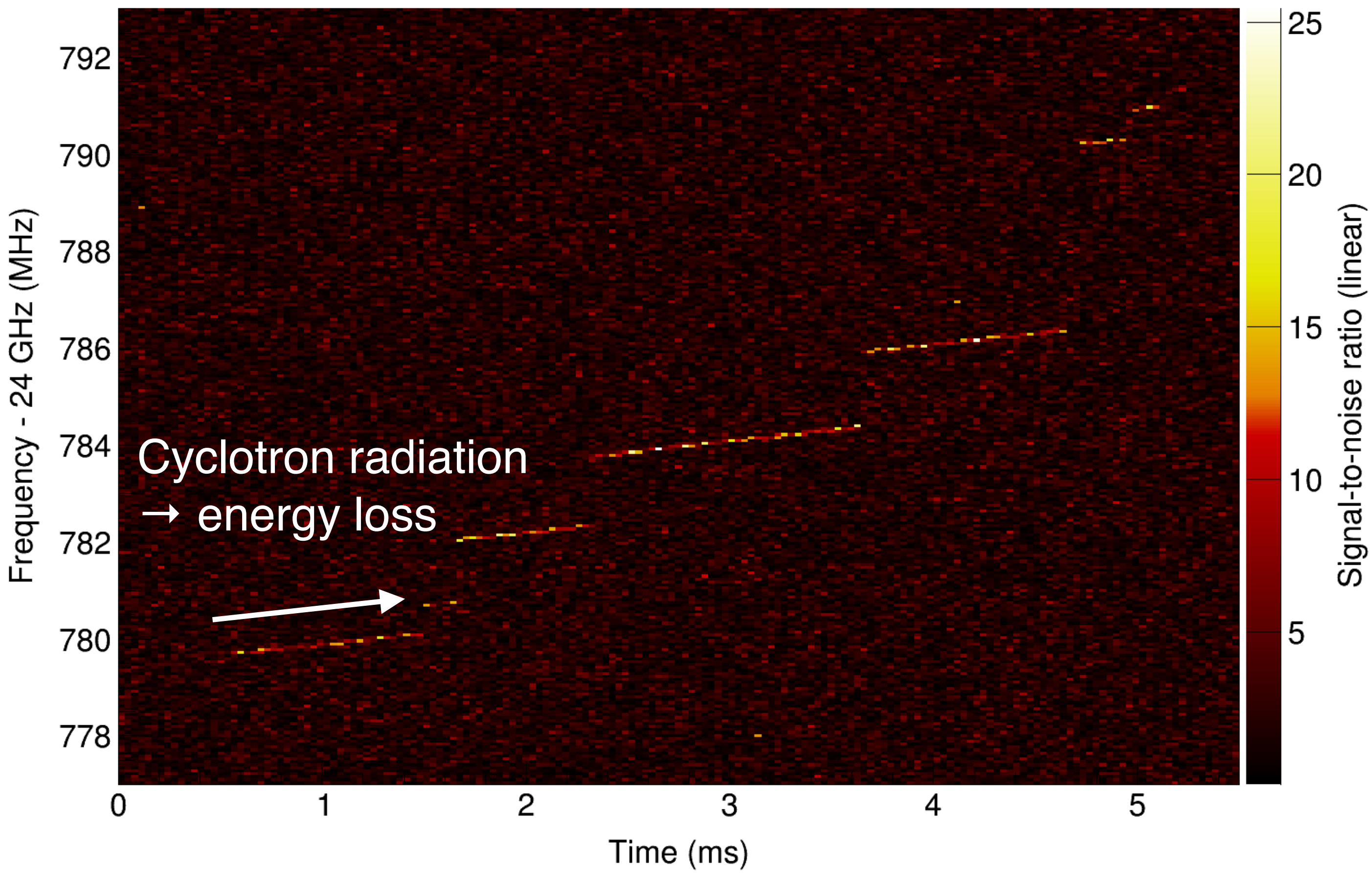


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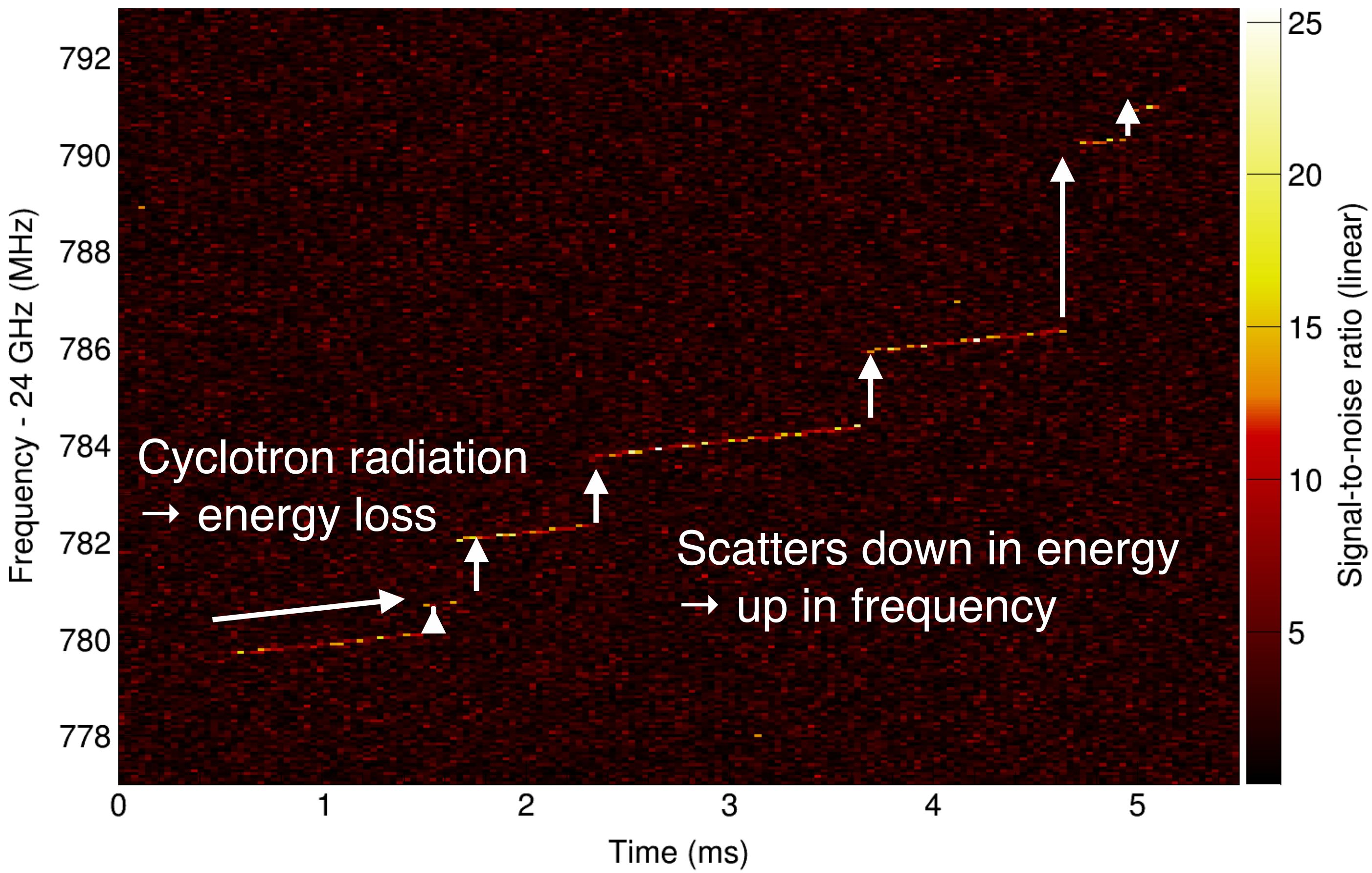


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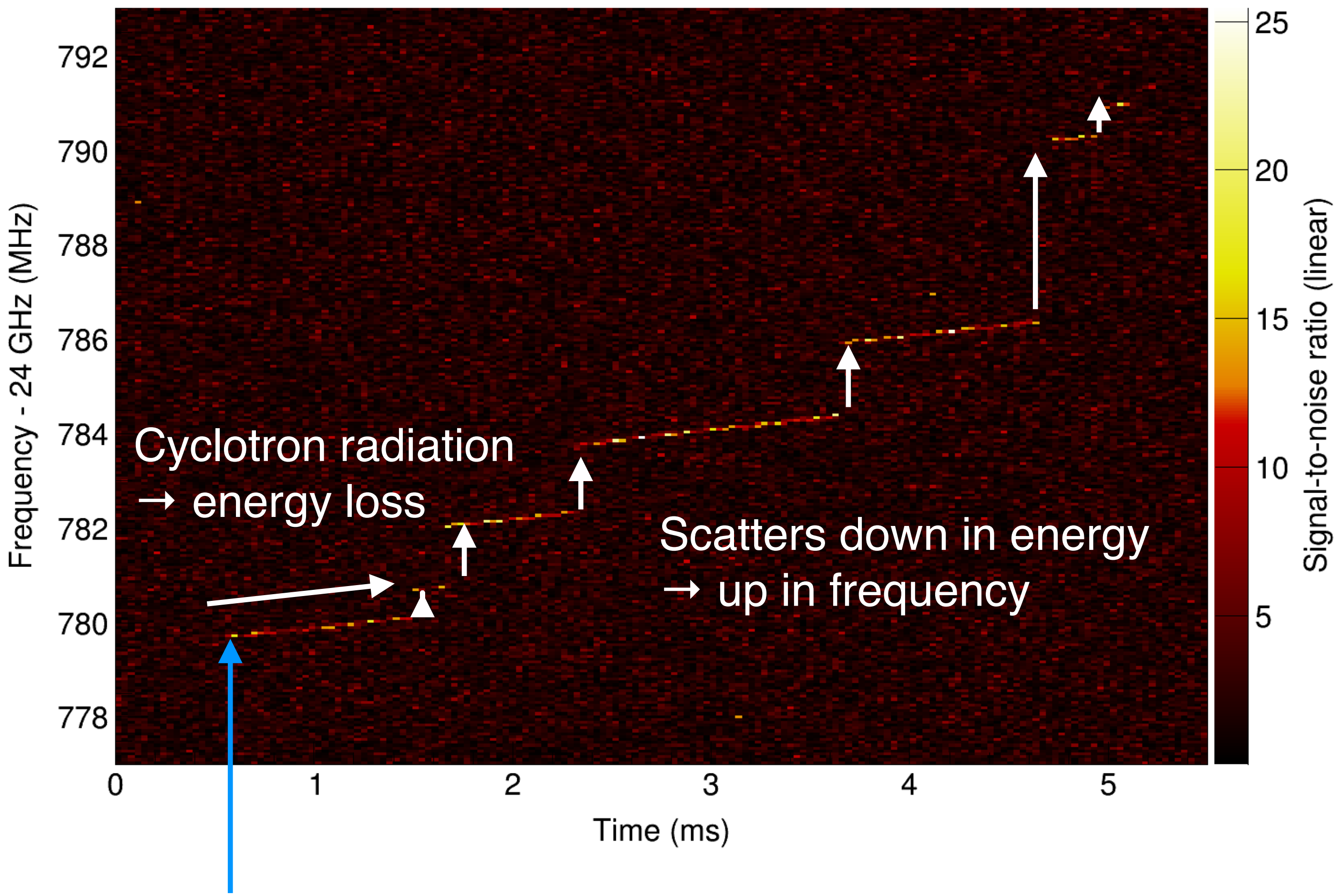
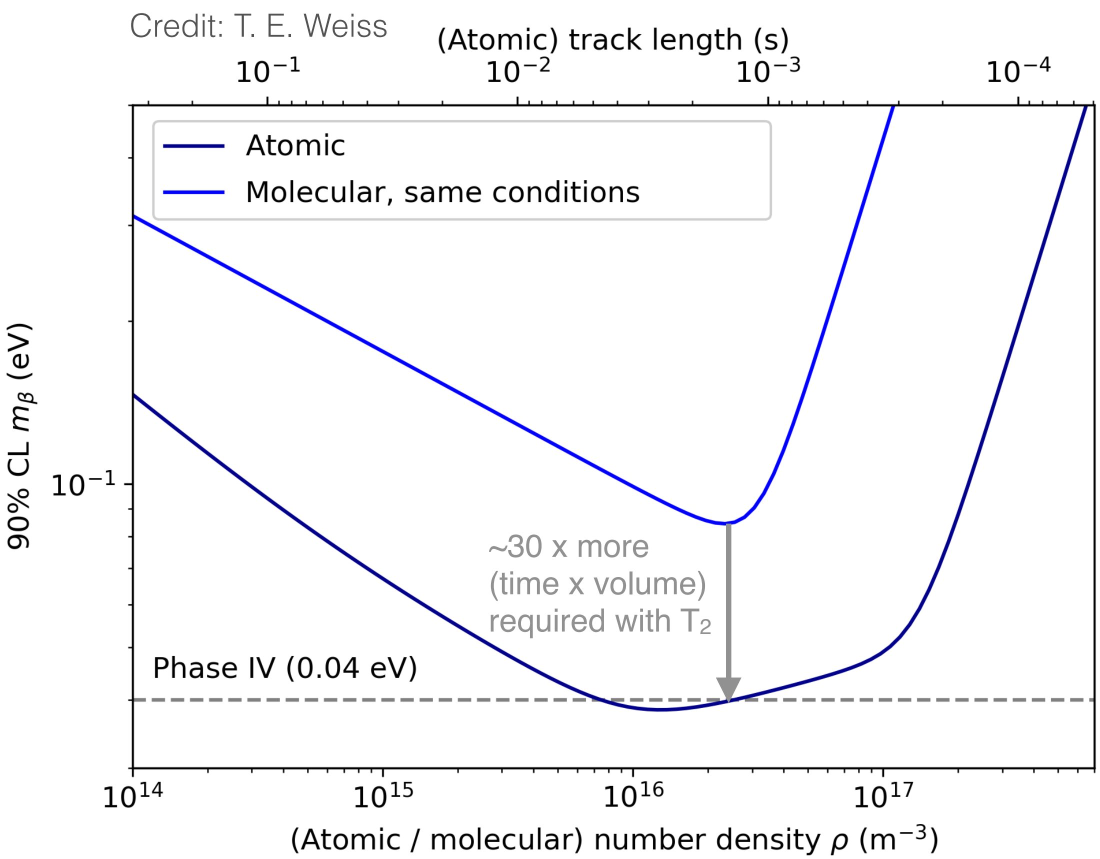



Start frequency: determines electron energy before losses

$$2\pi f = \frac{e\langle B\rangle}{m_e + K_e/c^2} = \frac{e\langle B\rangle}{\gamma m_e}$$

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

# Why Go Atomic?



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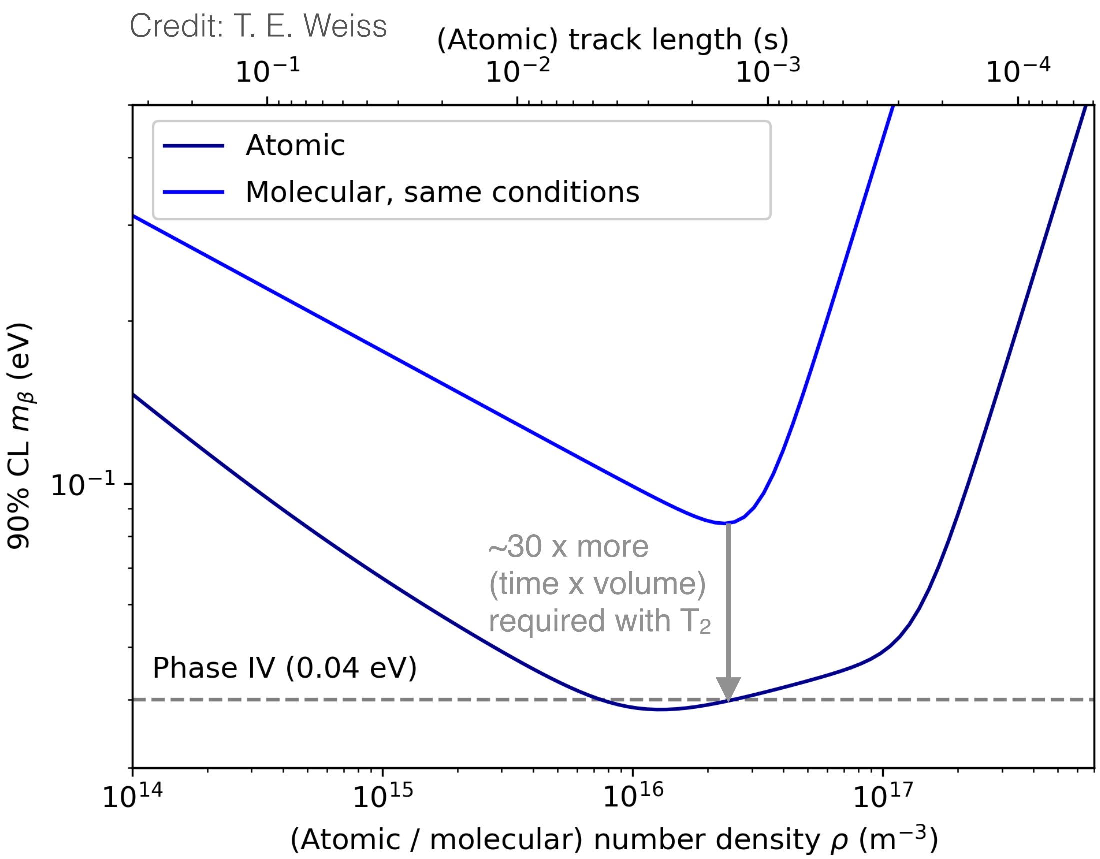


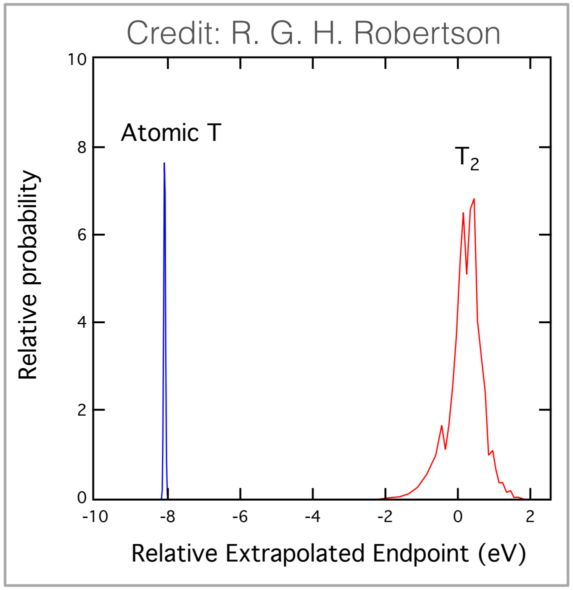

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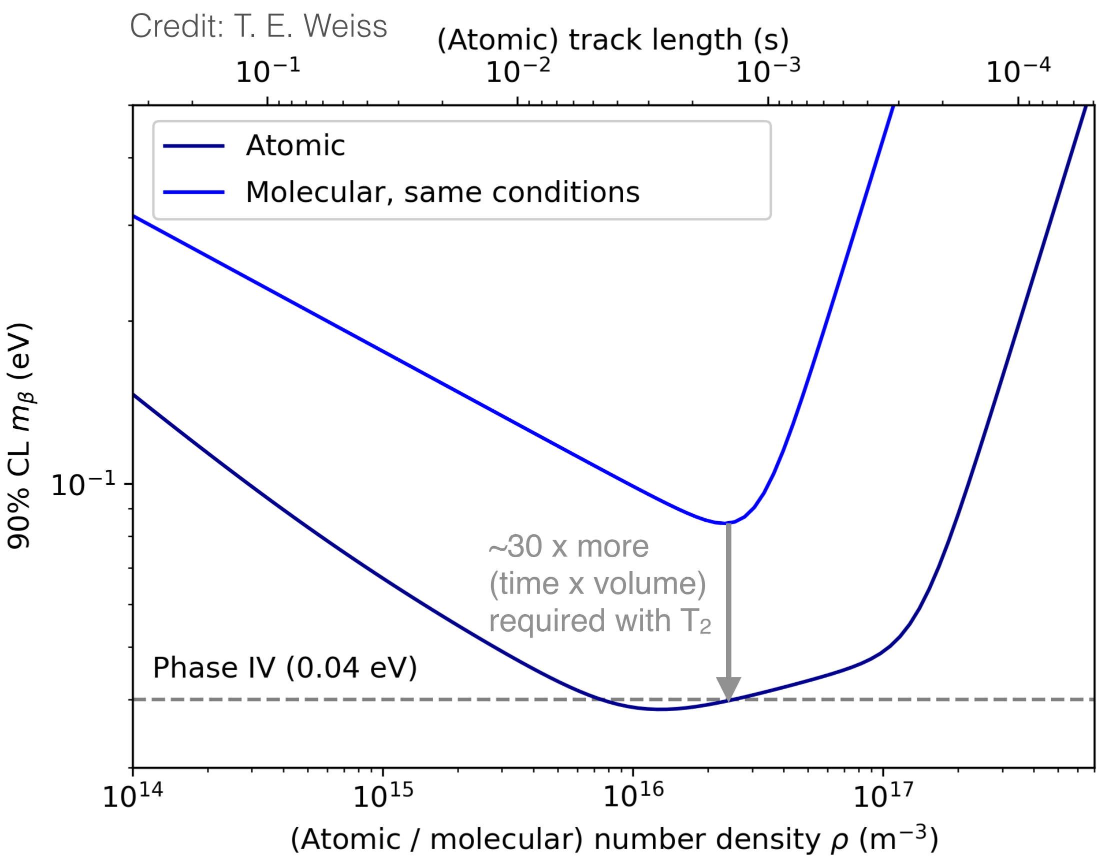
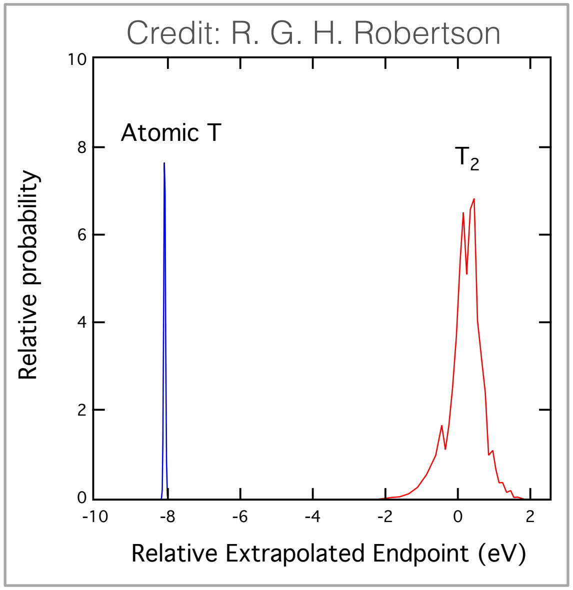
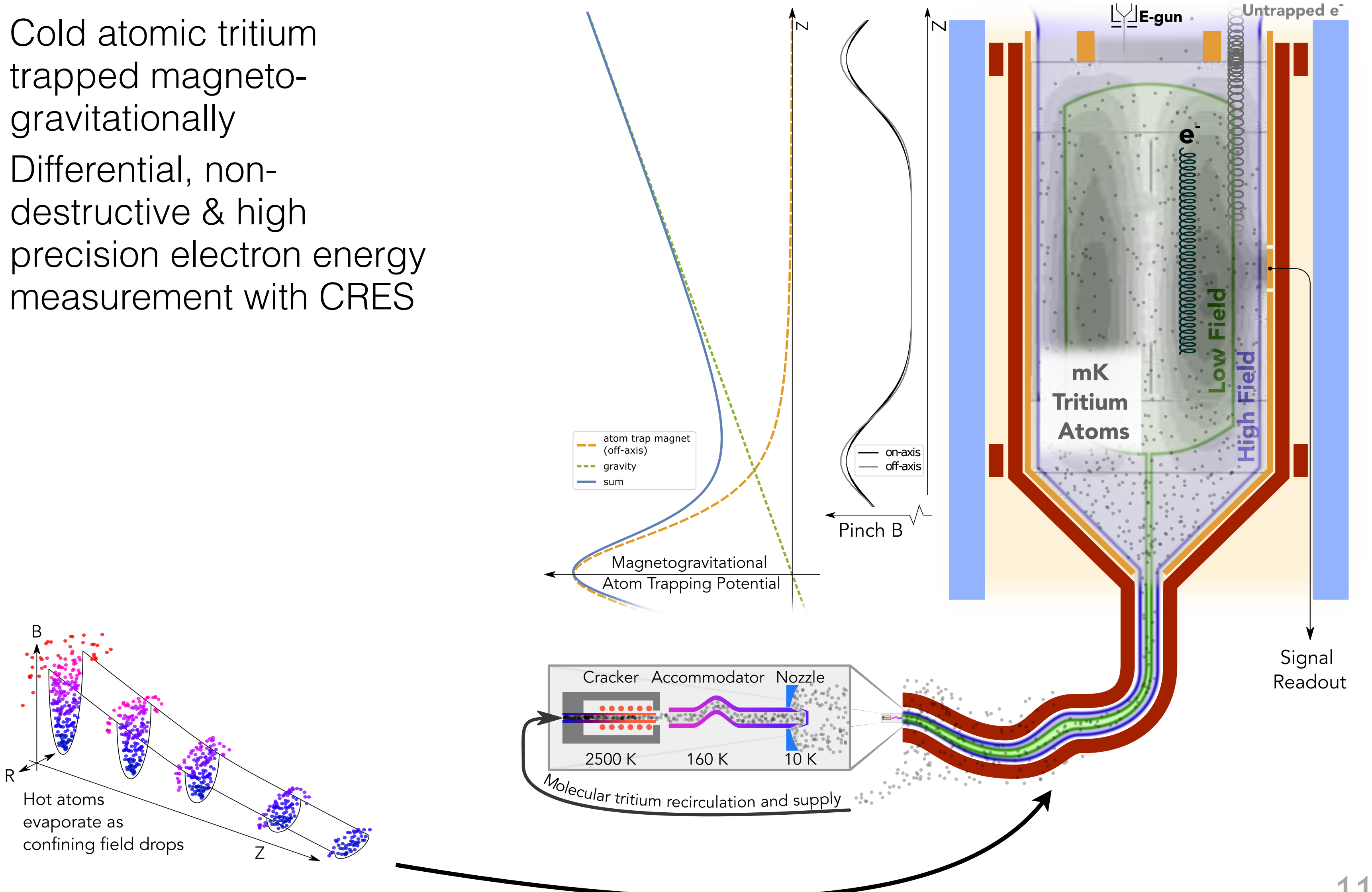



+ Uncertainties in molecular final states distribution!

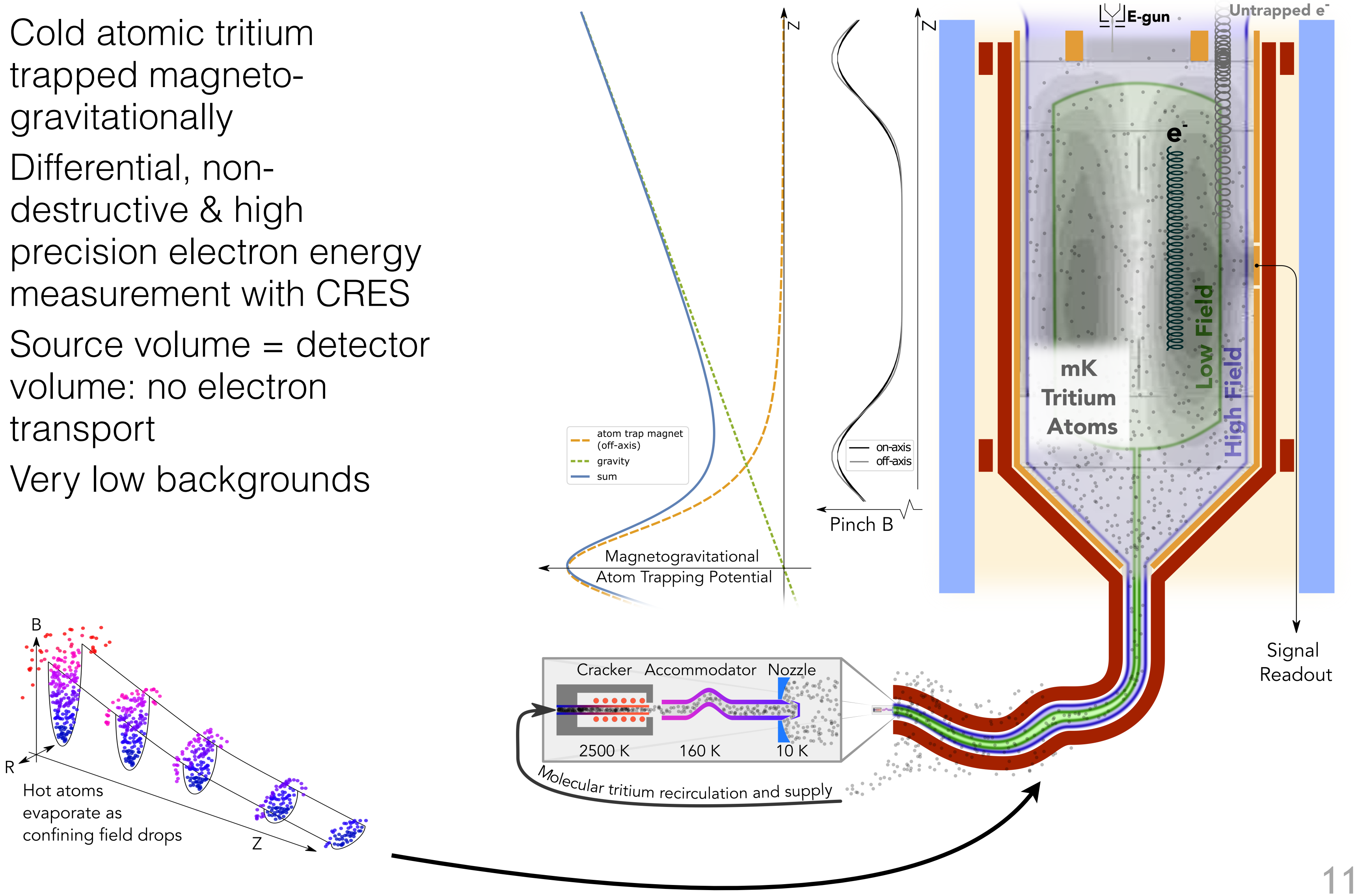
# Project 8 Concept

- Cold atomic tritium trapped magneto-gravitationally
- Differential, non-destructive & high precision electron energy measurement with CRES

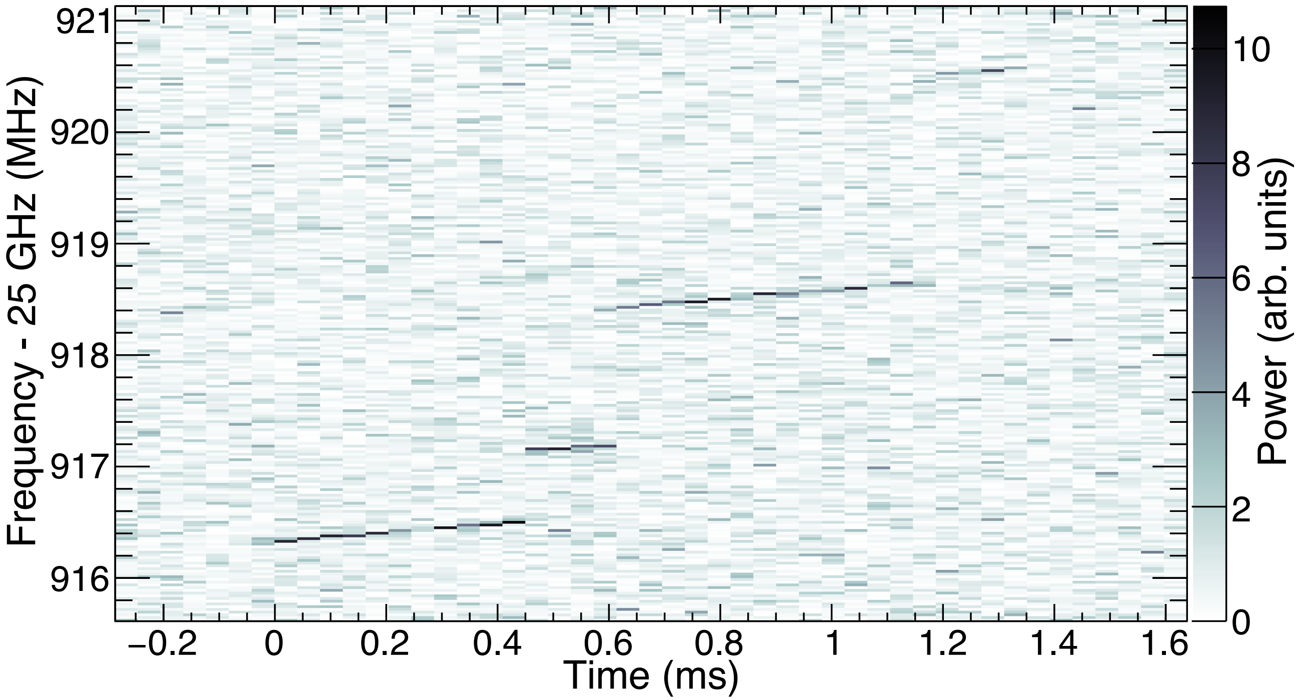


# Project 8 Concept

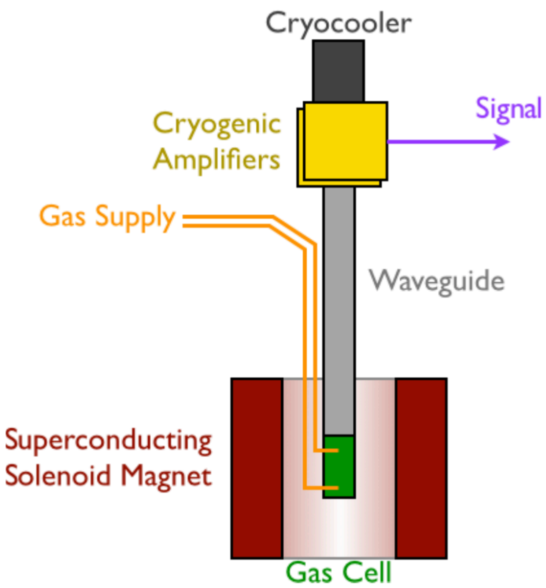
- Cold atomic tritium trapped magneto-gravitationally
- Differential, non-destructive & high precision electron energy measurement with CRES
- Source volume = detector volume: no electron transport
- Very low backgrounds



# Phase I & II Results



# Phase I




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

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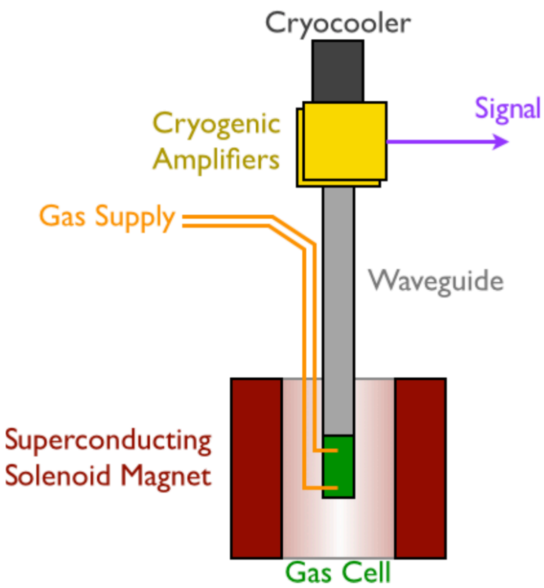
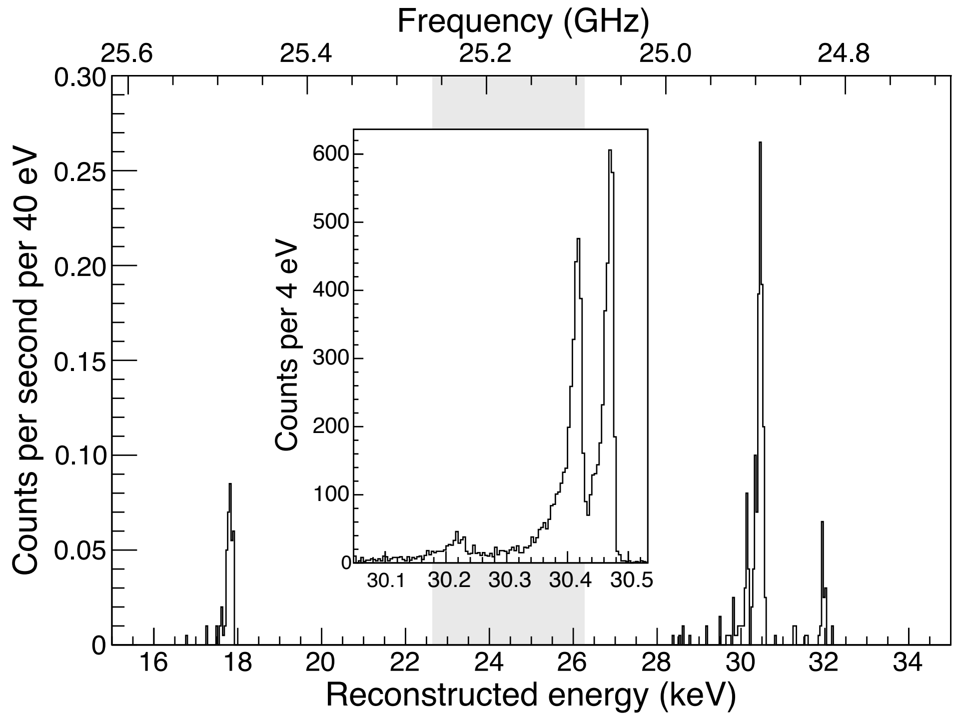
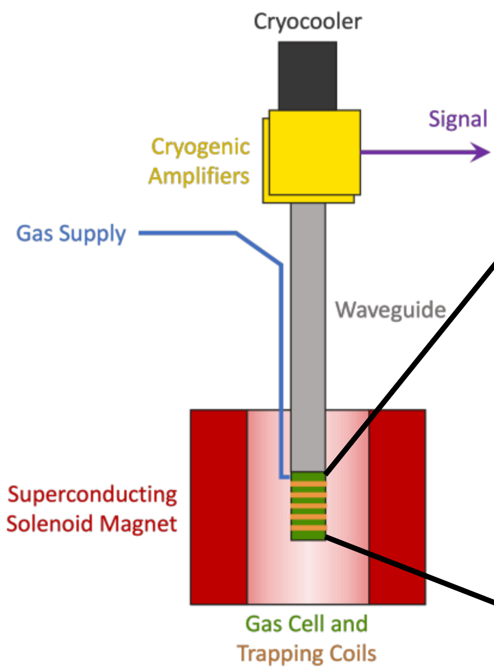


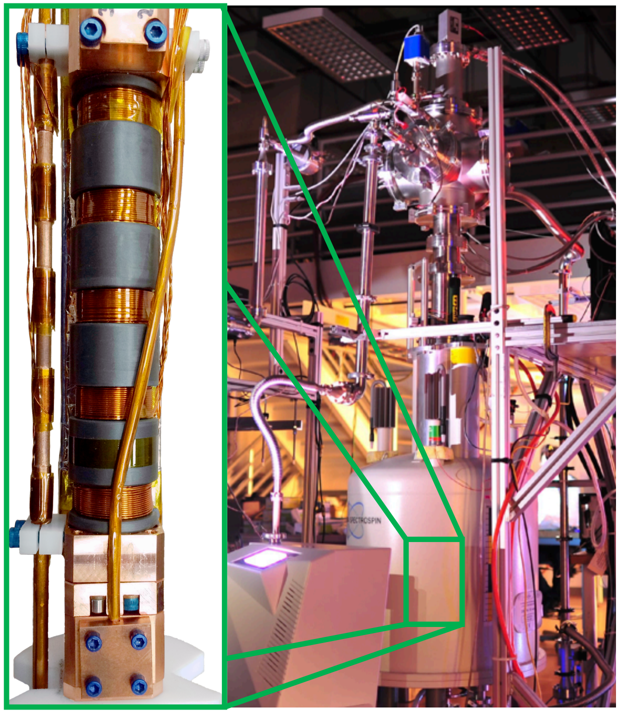




- $^{83m}$Kr: electron conversion lines at 18 keV, 30 keV and a 32 keV
- Demonstrated energy measurement of single trapped electrons via CRES, resolution: 3.3 eV

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

# Phase II



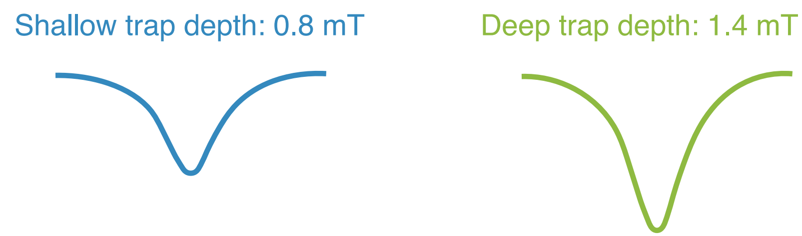



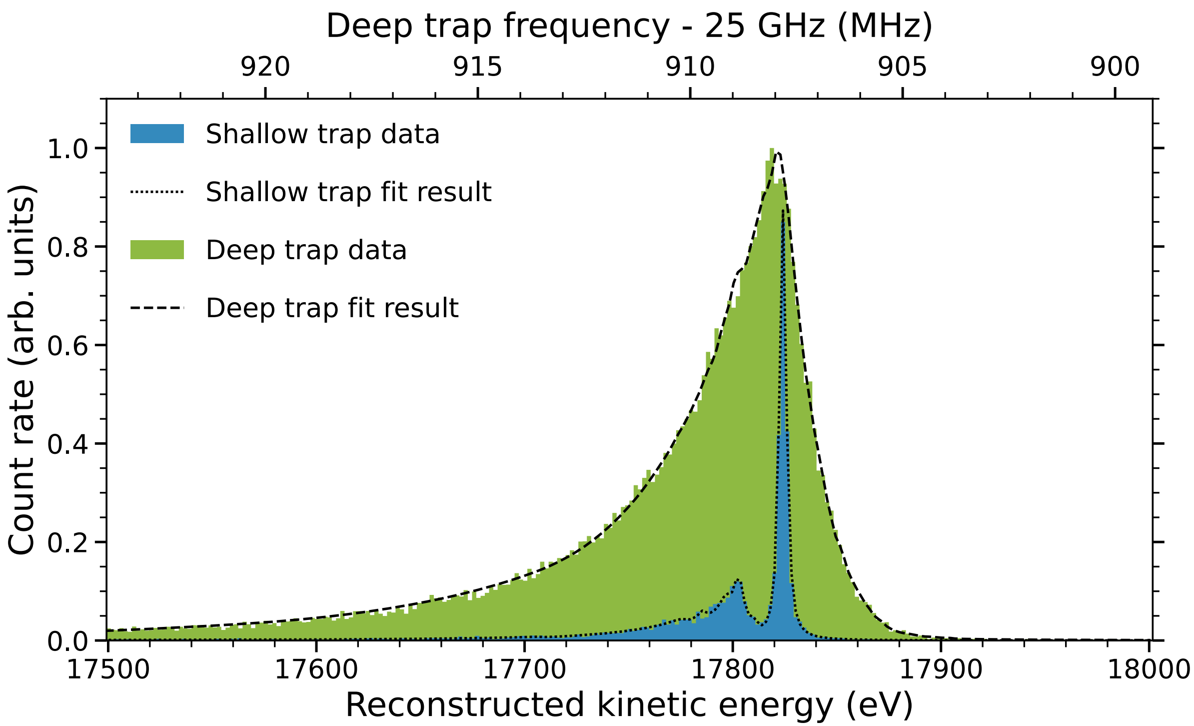
Credit: A. Lindman, E. Novitski

- Effective volume: 1mm$^3$
- Demonstrated CRES on continuous tritium spectrum
- First neutrino mass upper limit extraction
- Zero background observed → background rate $\leq 3 \times 10^{-10}\,\mathrm{eV}^{-1}s^{-1}$ (90 % C . L.)
- Improved energy resolution

# $^{83m}$Kr Measurements

- "Shallow trap":
  - magnetic field calibration via Kr K-line
  - 1.7 ± 0.2 eV (FWHM) energy broadening (2.8 ± 0.1 eV natural linewidth)
- "Deep trap":
  - Increased statistics
  - Used for tritium run
  - 54 eV (FWHM) energy broadening




Phys.Rev.Lett. 131, 102502 (2023)

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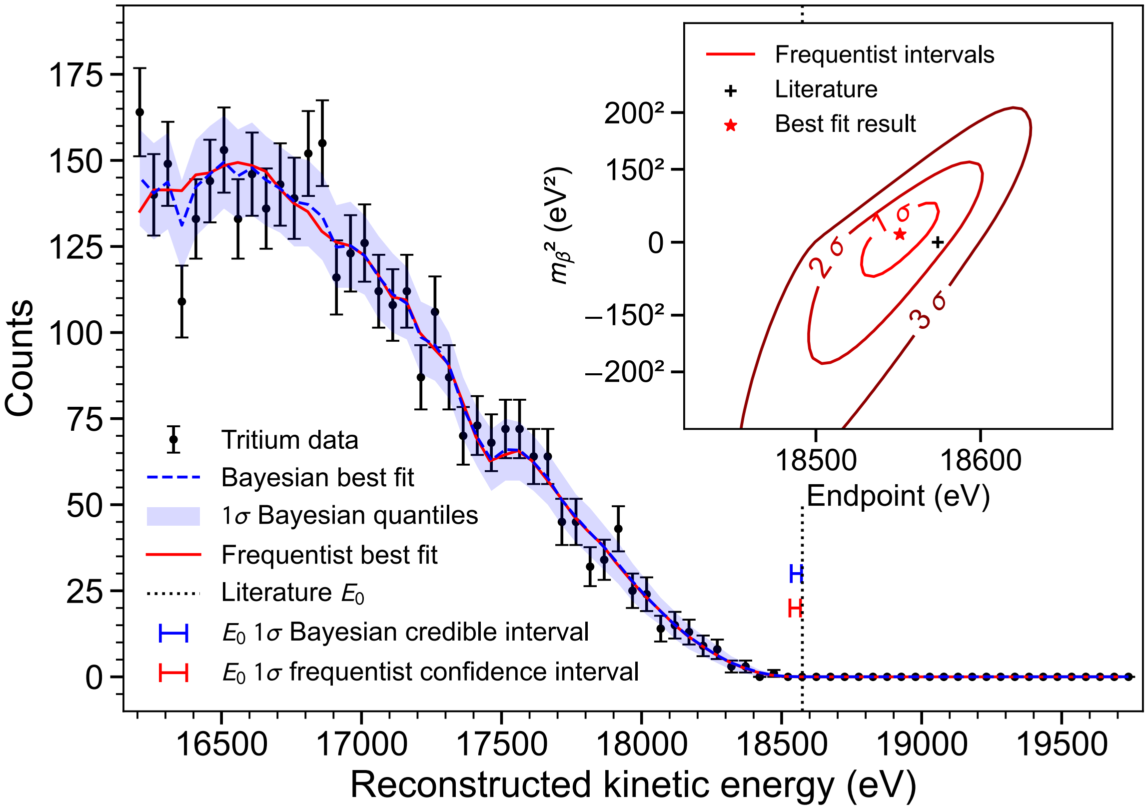


**$T_2$ endpoint:**

Frequentist: $E_0 = \left(18548^{+19}_{-19}\right)$ eV $(1\sigma)$

Bayesian: $E_0 = \left(18553^{+18}_{-19}\right)$ eV $(1\sigma)$

**Neutrino mass:**

Frequentist: $\leq 152\,\mathrm{eV}/c^2\,(90\,\%\,\mathrm{C.L.})$

Bayesian: $\leq 155\,\mathrm{eV}/c^2\,(90\,\%\,\mathrm{C.L.})$

**Background rate:**

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

**Published September 2023! Editor's Suggestion**

PROJECT 8

# Project 8: Phased Approach

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- Phase I:
  - First electron spectroscopy with CRES [1]

[1] Phys.Rev.Lett. 114, 162501 (2015)

# Project 8: Phased Approach

- Phase I:
  - First electron spectroscopy with CRES [1]
- Phase II:
  - First continuous spectrum measured with CRES [2]
  - First $m_\beta$ upper limit with CRES [2]

[1] Phys.Rev.Lett. 114, 162501 (2015)
[2] Phys.Rev.Lett. 131, 102502 (2023)

PROJECT 8

# Project 8: Phased Approach

- Phase I:
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- Phase III:

  - Atomic source development
  - Large-volume CRES

} First $m_\beta$ limit obtained from atomic tritium

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# Project 8: Phased Approach

- Phase I:
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- Phase III:

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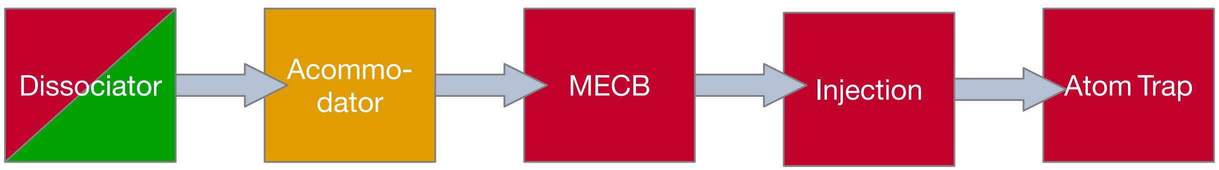
  - Large-volume CRES

  } First $m_\beta$ limit obtained from atomic tritium
- Phase IV:
  - Neutrino mass measurement if $m_\beta \geq 40\,\mathrm{meV}$

[1] Phys.Rev.Lett. 114, 162501 (2015)
[2] Phys.Rev.Lett. 131, 102502 (2023)

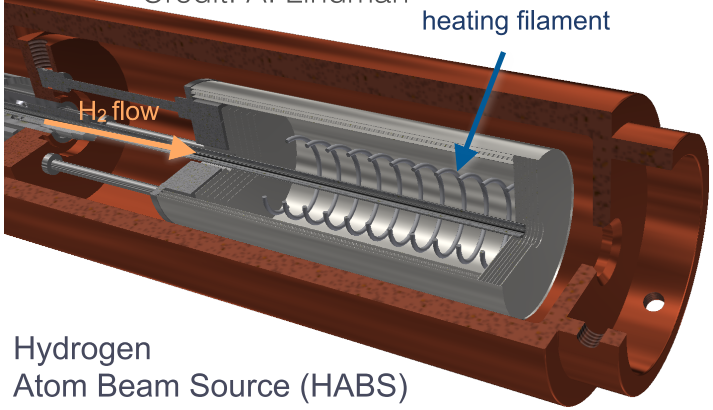
PROJECT 8

# Phase III R&D:
# Atomic Tritium

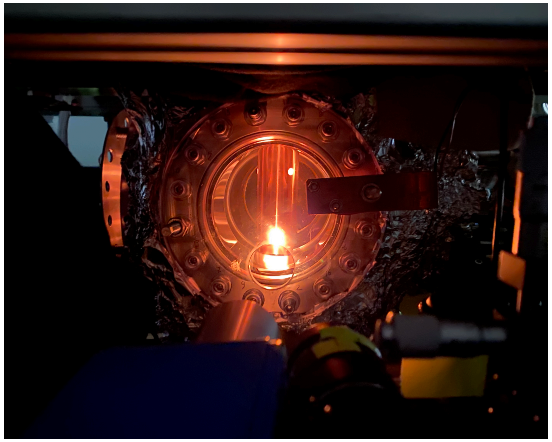


# Hydrogen Atom Production

- Hydrogen / Deuterium first
- Thermal dissociation:
  - Hot Tungsten surface
  - Temperature 2200K-2500K
  - Test stand at Mainz
  - To be rebuilt at TLK for Tritium
- Plasma dissociation
  - Initially discarded due to $T_2O$ formation
  - New developments: quartzless cavities
  - Currently under investigation




Credit: A. Lindman



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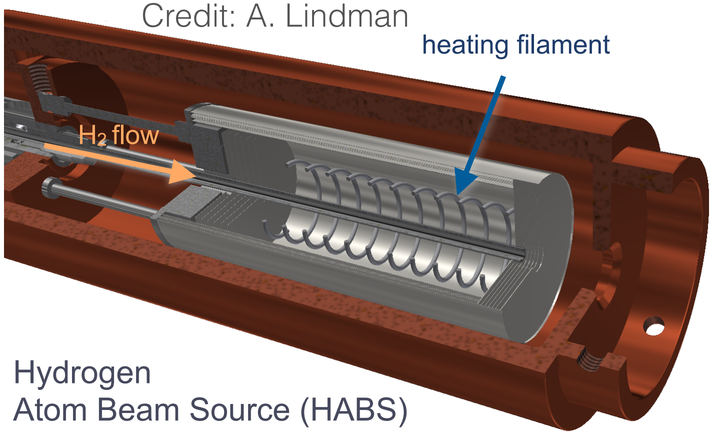
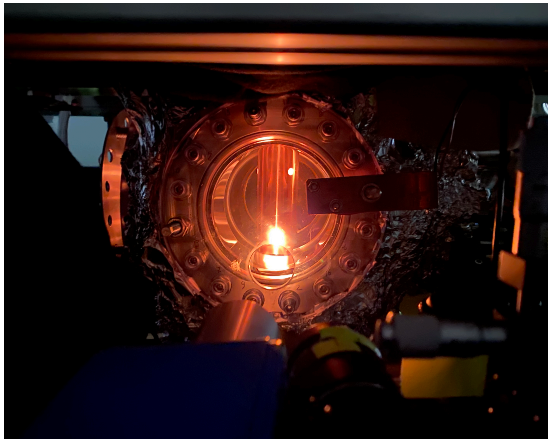
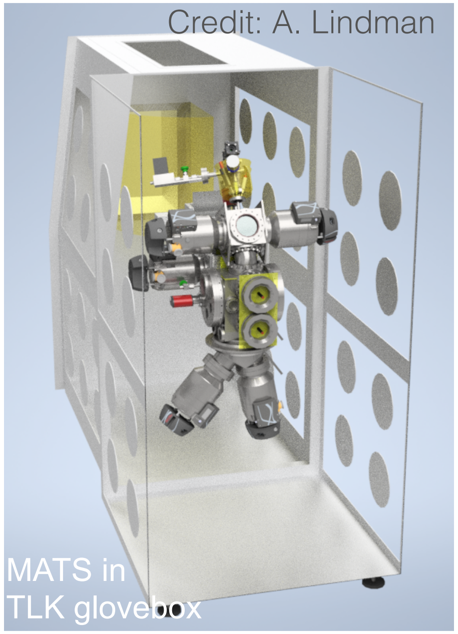



Hydrogen Atom Beam Source (HABS)



Credit: L. Thorne

Credit: A. Lindman



PROJECT 8

# Hydrogen Atom Production

See talk by Alec Lindman today

- Hydrogen / … first
- Therm… …ation:
  - …ngsten surface
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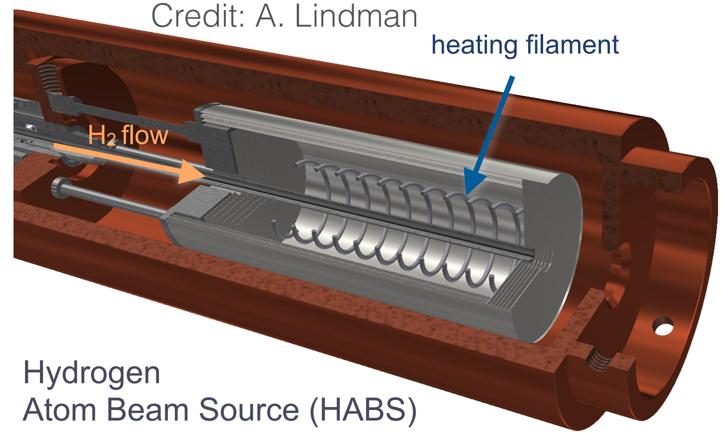


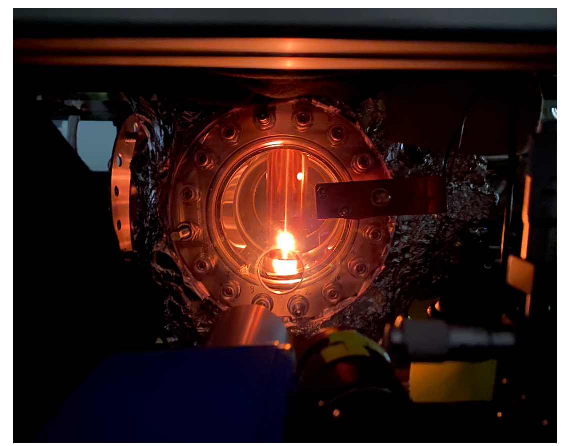

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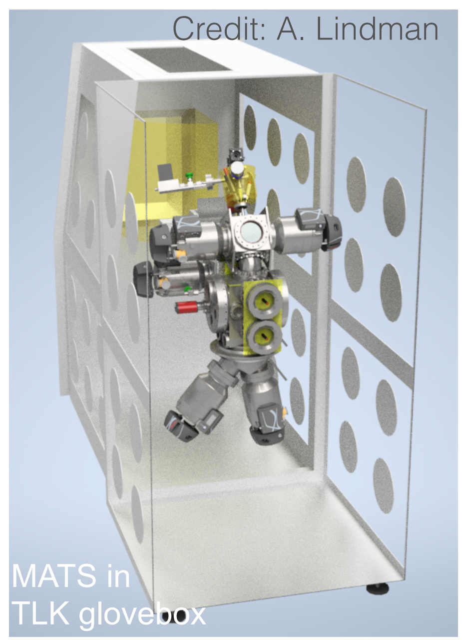
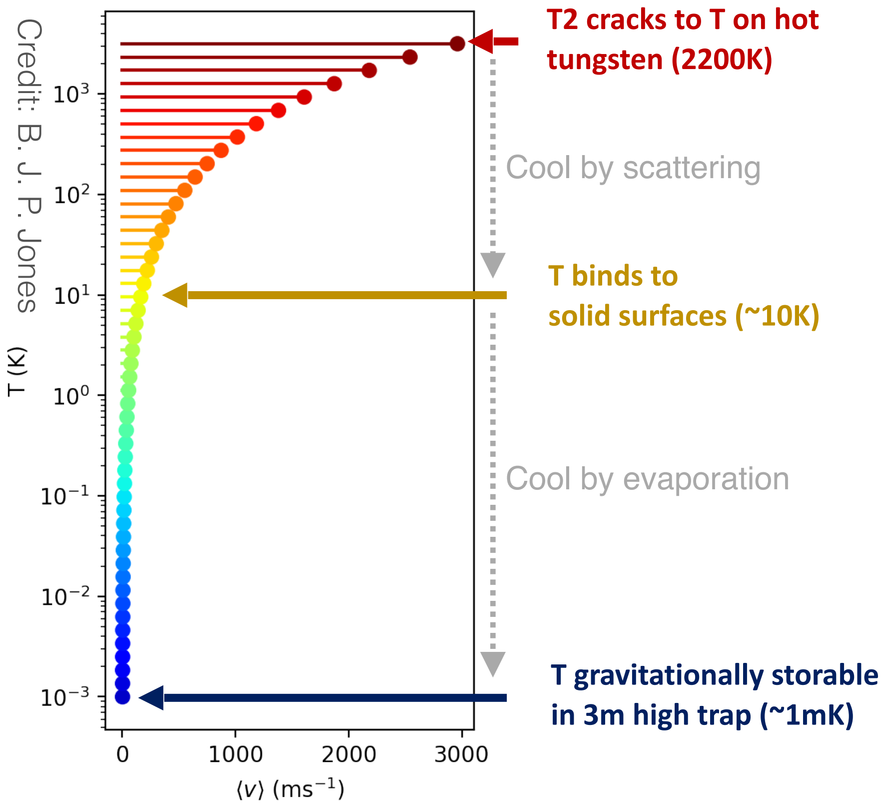


# Atom Cooling




1. Accommodator: cool to 150K with multiple bounces at low recombination rate
2. One-bounce nozzle to cool to 10K
3. Cool by evaporation of hottest atoms

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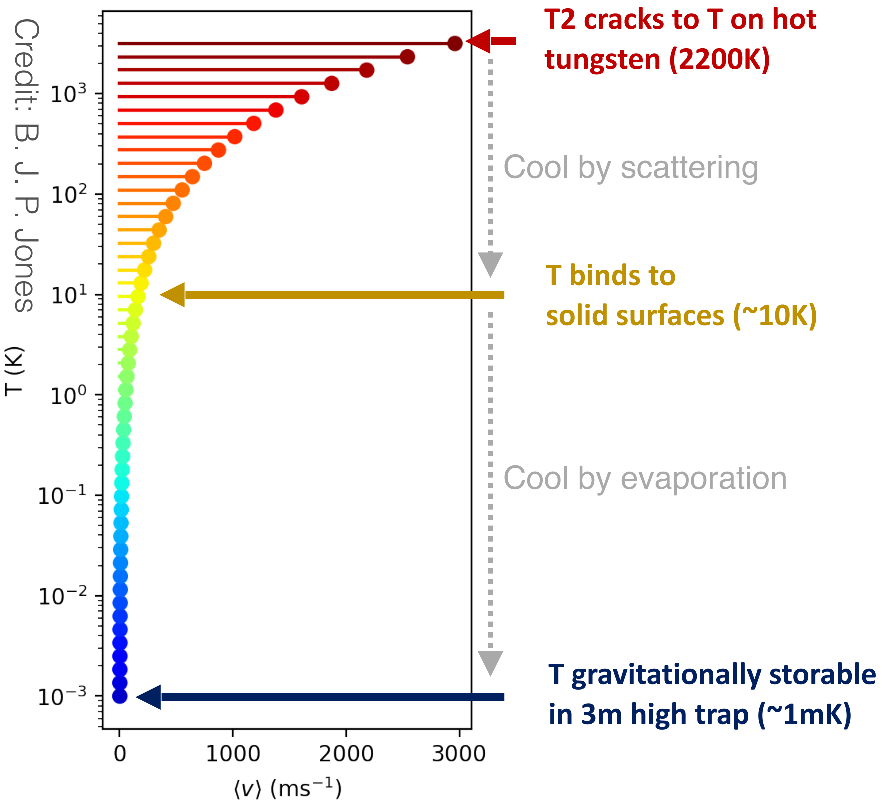


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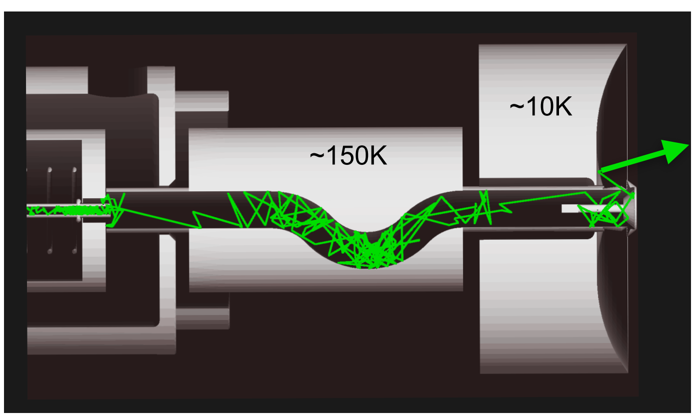


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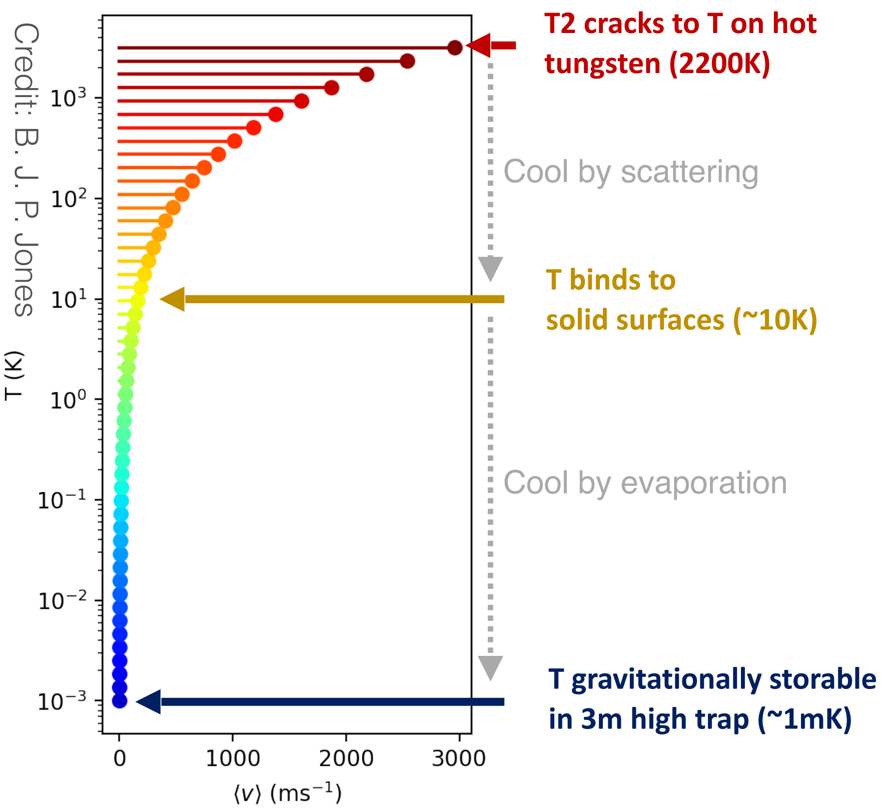


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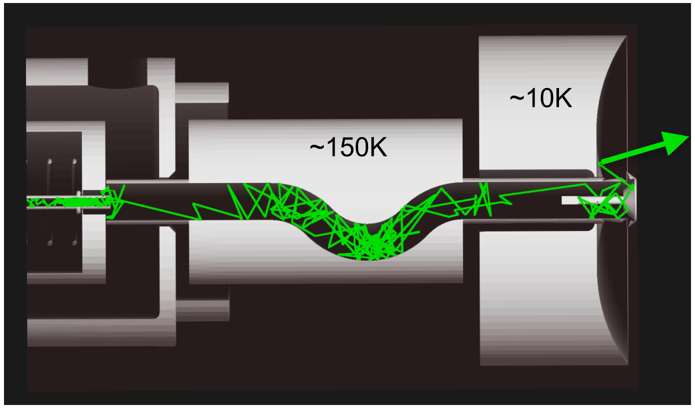


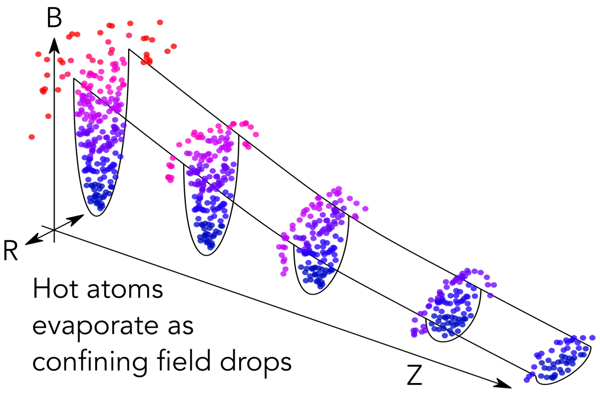


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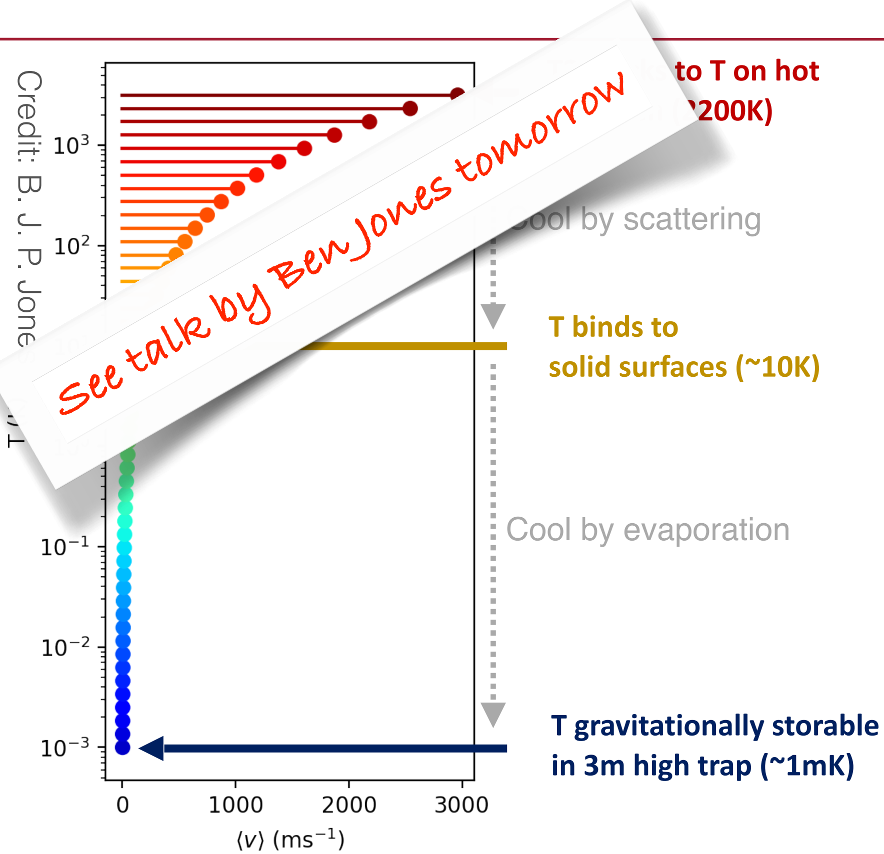


See talk by Ben Jones tomorrow

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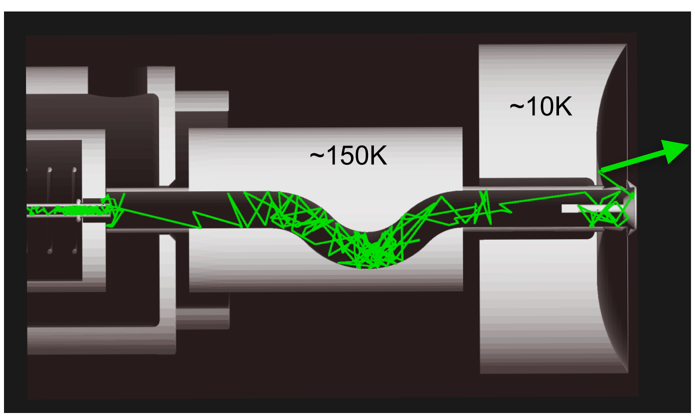
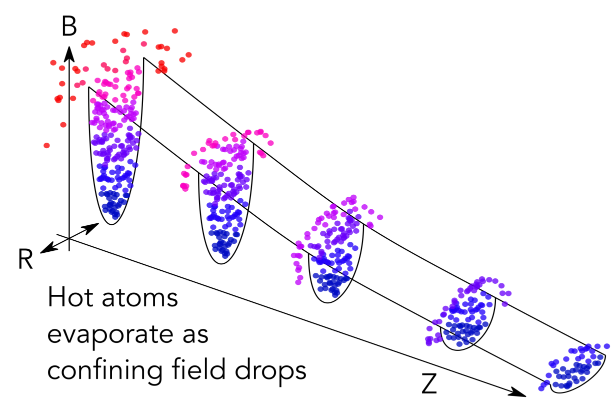
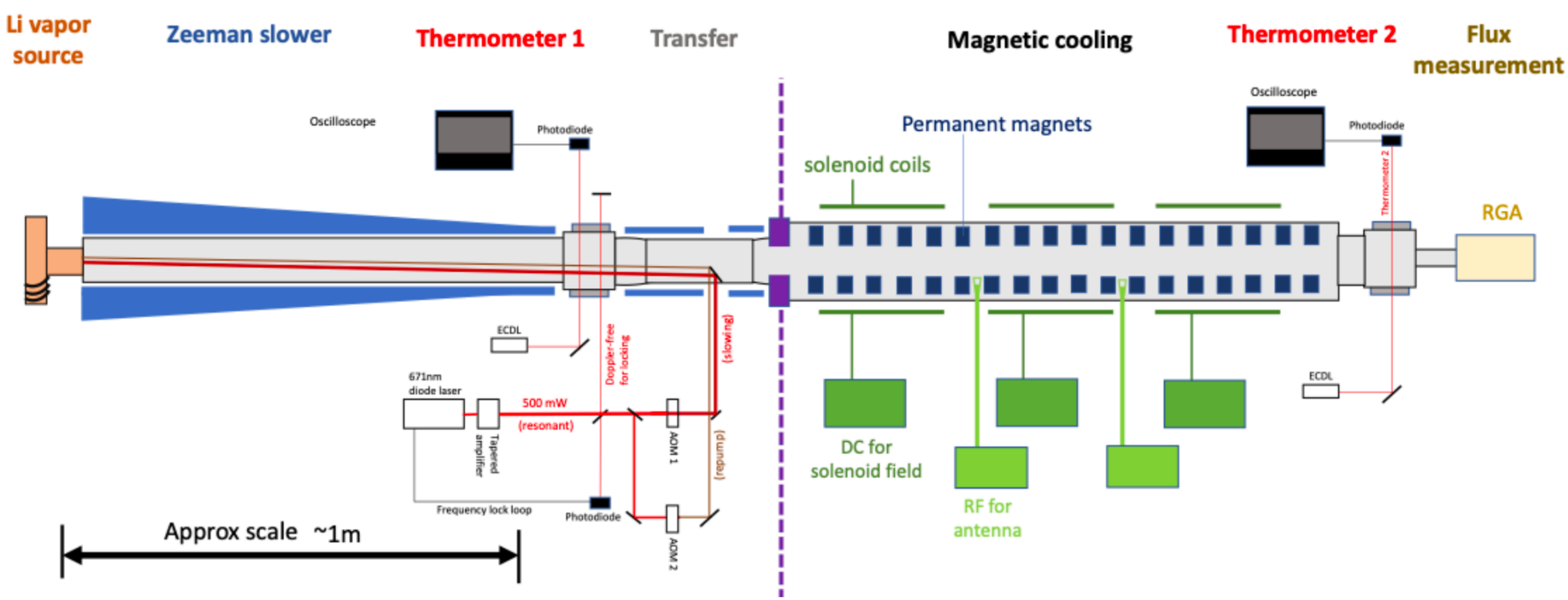



Credit: A. Lindman

# Magnetic Evaporative Cooling Beamline

- Can this be done in a beamline?
- Prototype with Lithium-6 @ UT Arlington
  - Don't need to wait for cracker-accommodator-nozzle development to conclude
- Will inform design of tritium cooling beamline




Credit: B. J. P. Jones

**This side is beam prep to 5K**
***(uses visible lasers to slow Li)***

**This side is P8 Prototype MECB**
***(no lasers, except for thermometers)***

PROJECT 8

# Magnetic Evaporative Cooling Beamline

See talk by Ben Jones tomorrow

- Can this be d… …mline?
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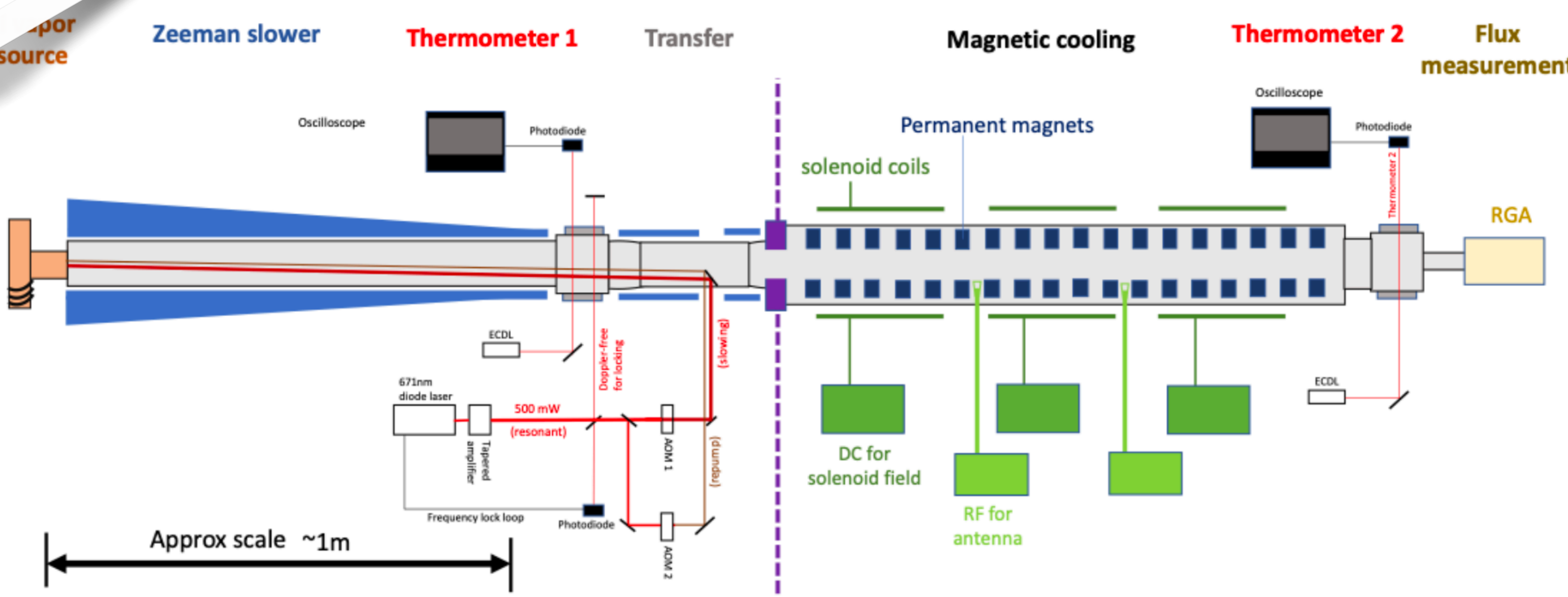


Credit: B. J. P. Jones

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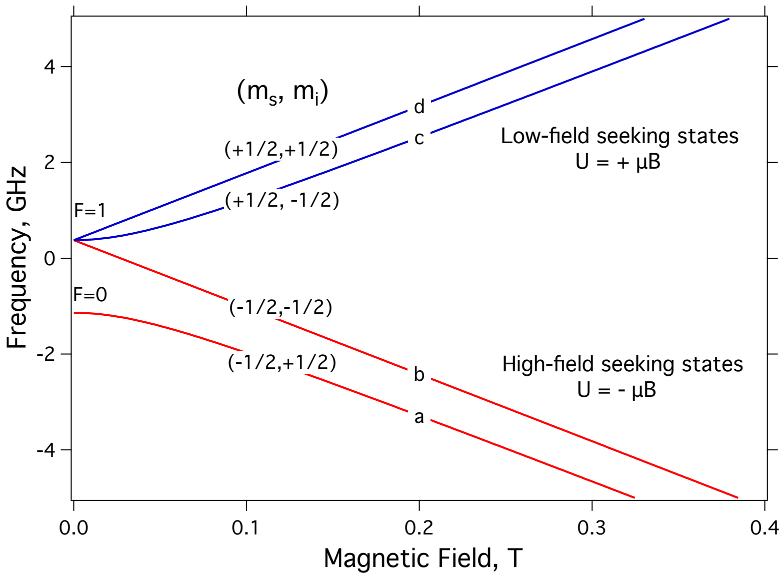
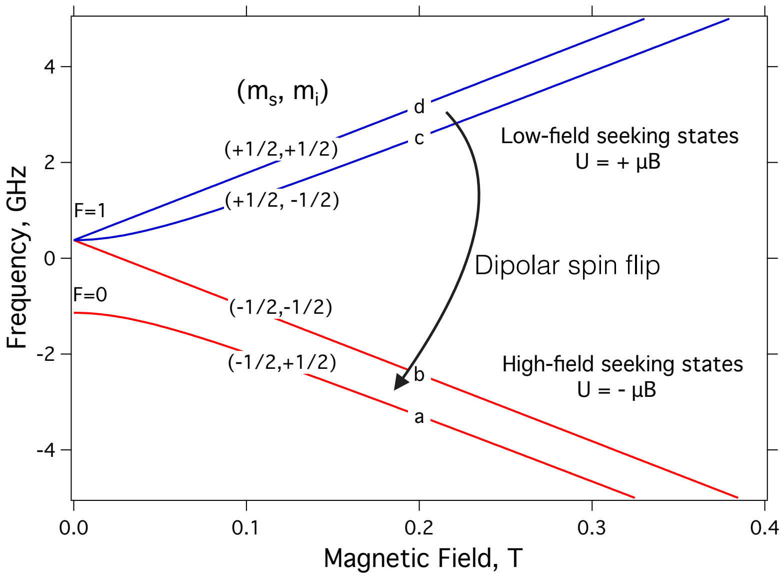
# Atom Trap


(m_s, m_i)
d
c
(+1/2,+1/2)
(+1/2, -1/2)
Low-field seeking states
U = + μB
F=1
F=0
(-1/2,-1/2)
(-1/2,+1/2)
b
a
High-field seeking states
U = - μB
Frequency, GHz
4
2
0
-2
-4
0.0
0.1
0.2
0.3
0.4
Magnetic Field, T

# Atom Trap



(m_s, m_i)
d
c
b
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(+1/2,+1/2)
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(-1/2,+1/2)
F=1
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Low-field seeking states
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Dipolar spin flip
High-field seeking states
U = - μB
Frequency, GHz
Magnetic Field, T
4
2
0
-2
-4
0.0
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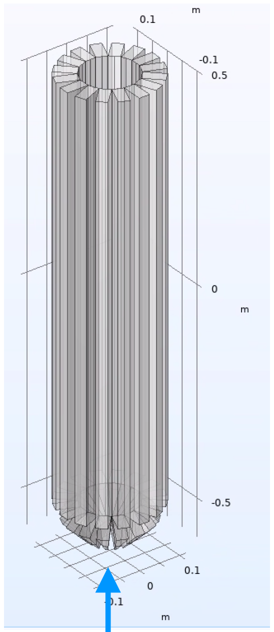
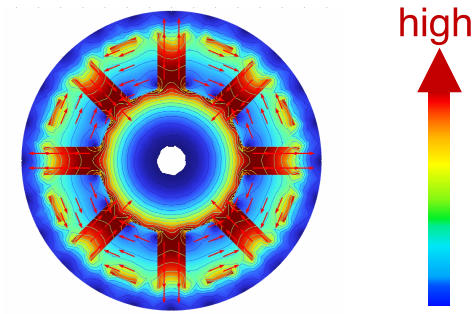
0.2
0.3
0.4

# Atom Trap

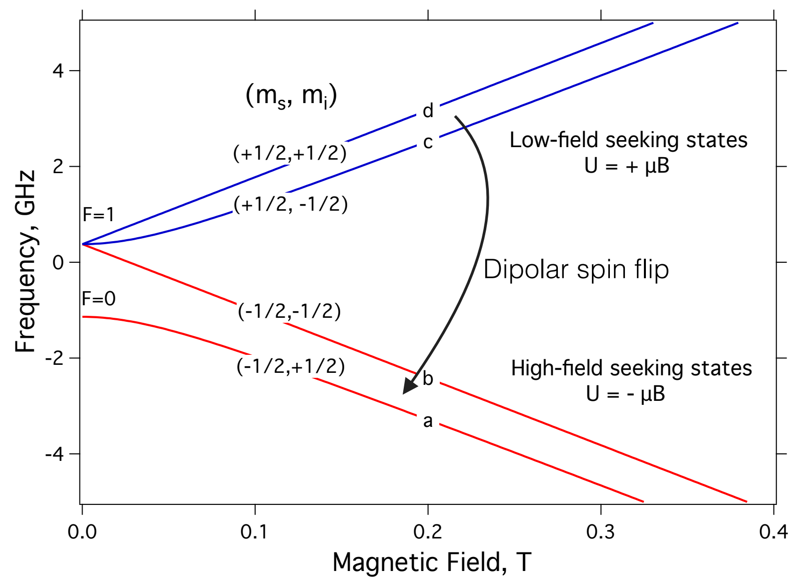
Halbach array: permanent magnets



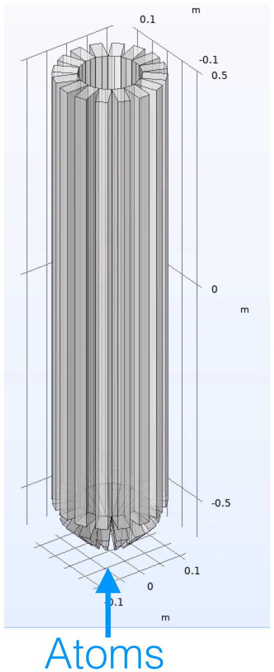

Magnetic field strength

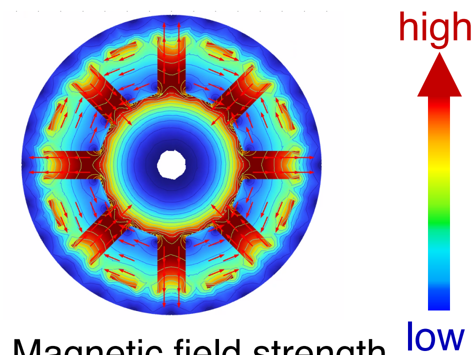
Credit: C.-Y. Liu



# Atom Trap

## Halbach array: permanent magnets

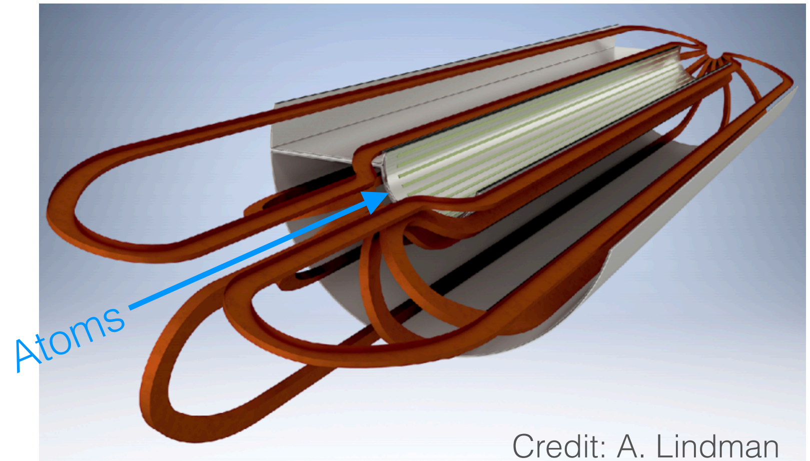


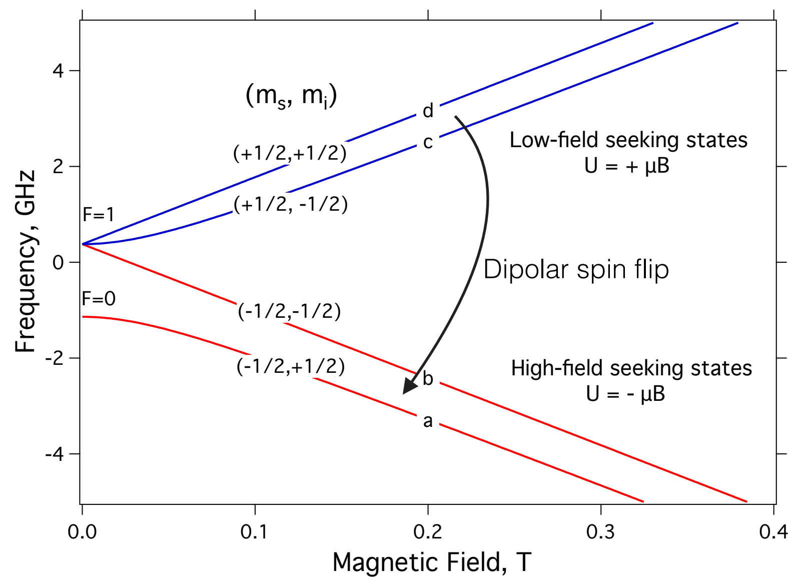




Magnetic field strength

Credit: C.-Y. Liu

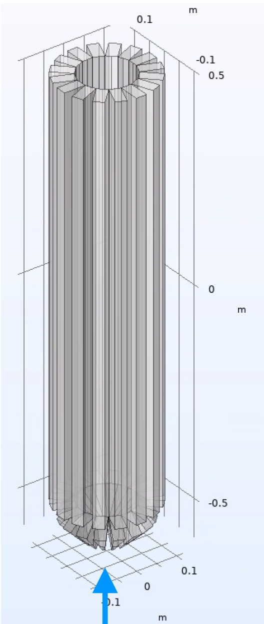
## Ioffe trap: superconducting coils



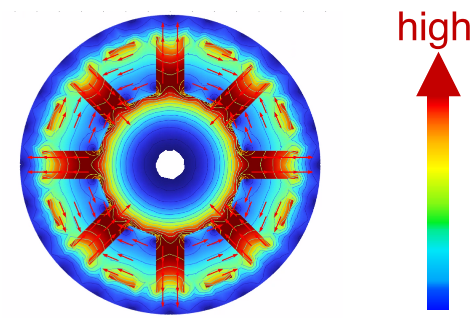



# Atom Trap

## Halbach array: permanent magnets



Atoms

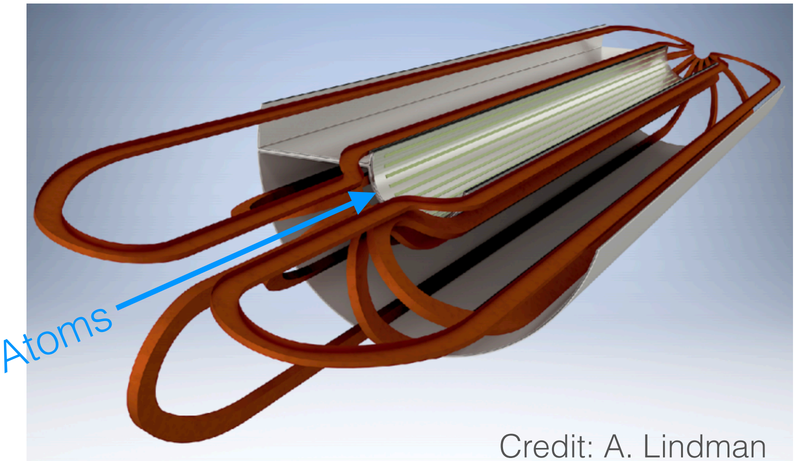



low

Magnetic field strength

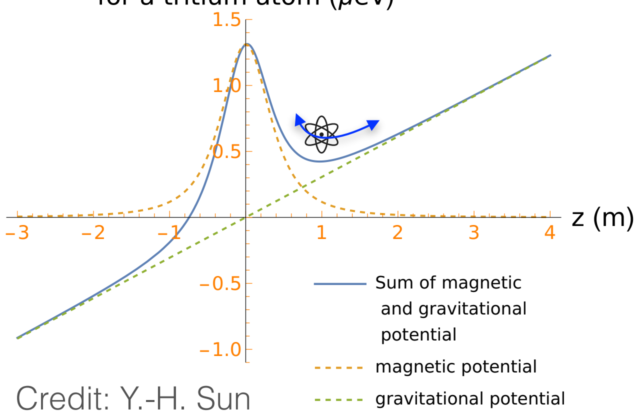
Credit: C.-Y. Liu

## Ioffe trap: superconducting coils

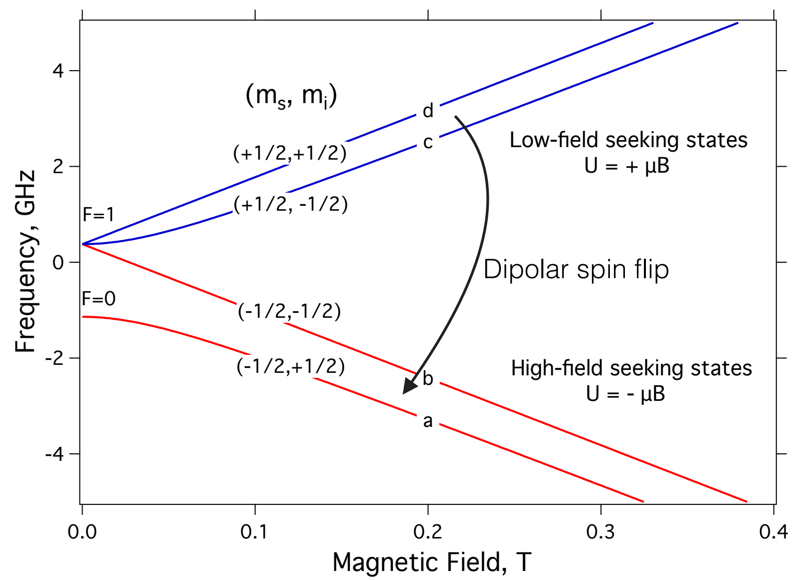



Credit: A. Lindman

Potential energy
for a tritium atom ($\mu$eV)

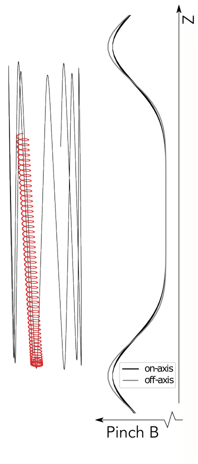


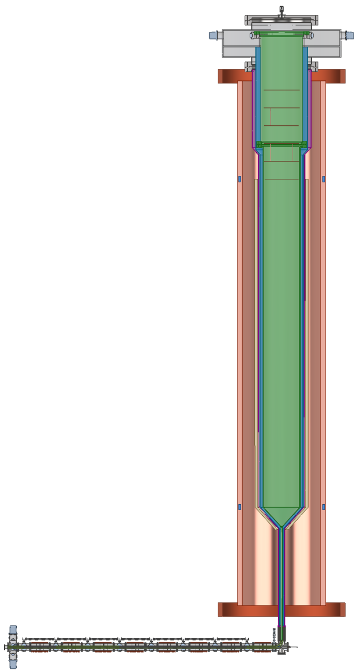

Credit: Y.-H. Sun



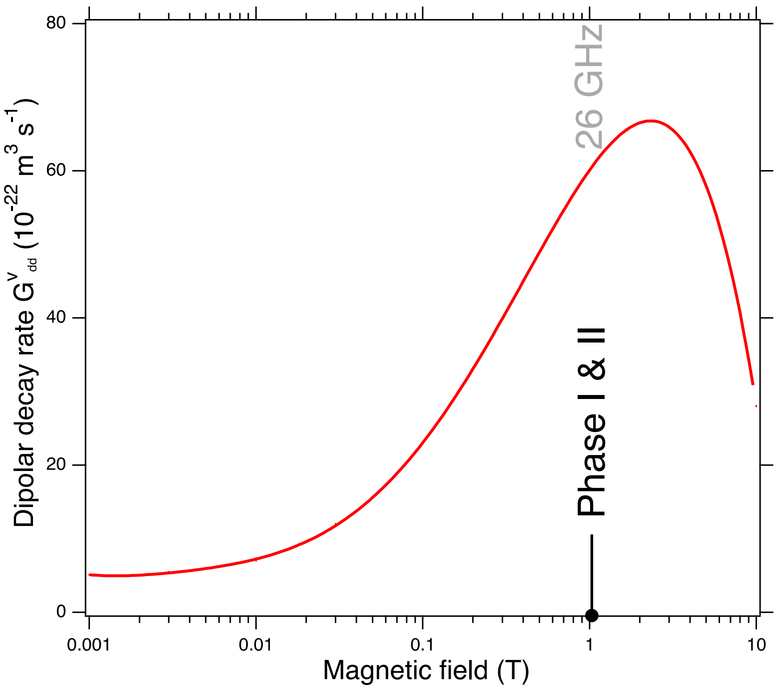
PROJECT 8

# Phase III R&D:
# CRES Detection



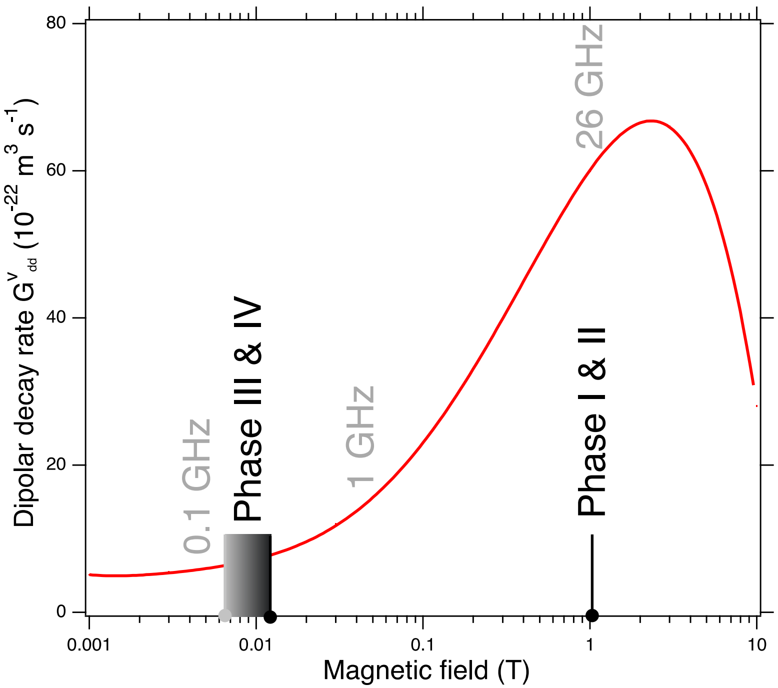
# Cavity As CRES Volume




- Dipolar decay rate can be greatly reduced by lowering magnetic field for longer trapping life times

Data from Phys. Rev. B, 33:626–628,1986

# Cavity As CRES Volume

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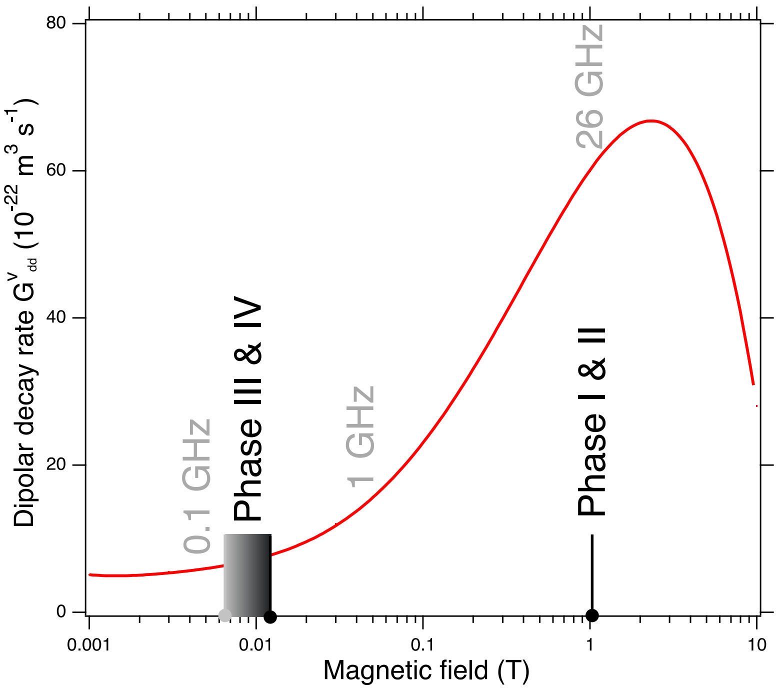
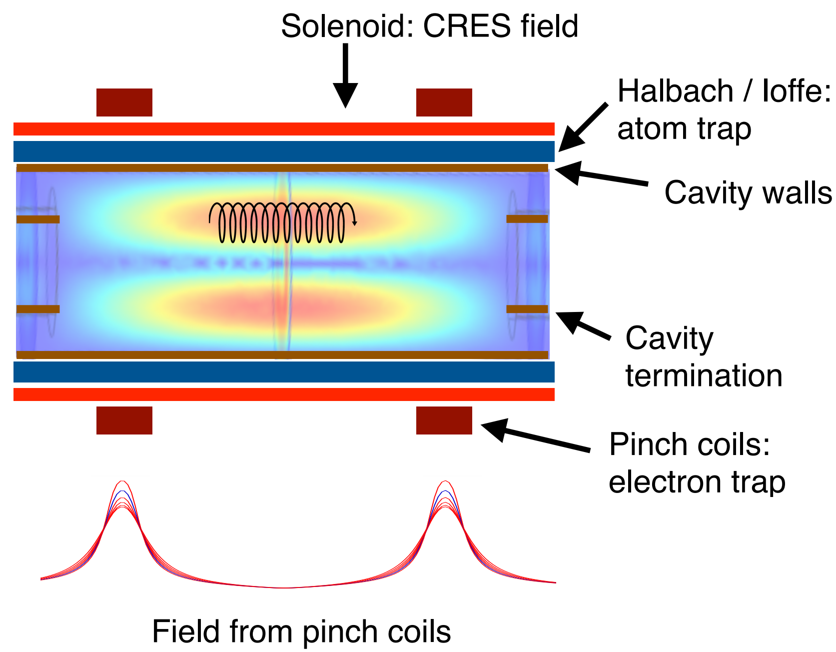


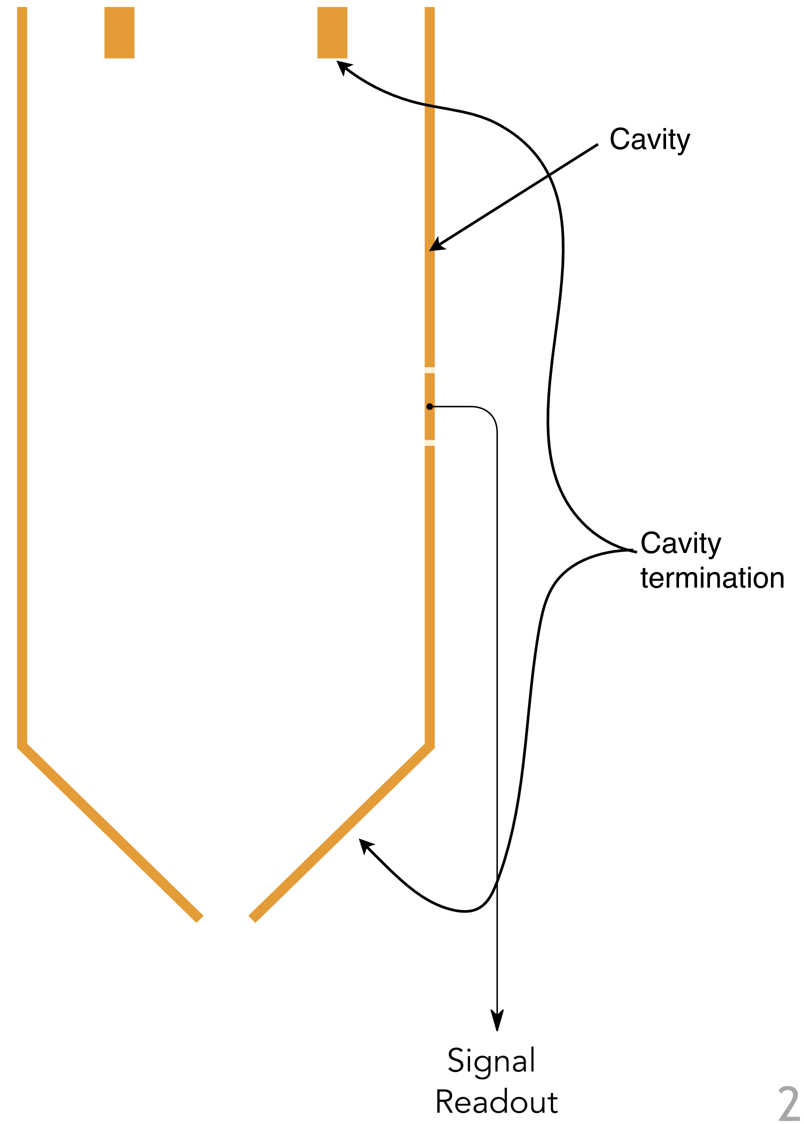

- Dipolar decay rate can be greatly reduced by lowering magnetic field for longer trapping life times

- Cavity volume scales as $1/f^3$
- Resonant enhancement of electron signal
- Lower frequency makes resonant cavity desirable

Data from Phys. Rev. B, 33:626–628,1986

# A Cavity-Based CRES Experiment

- Cavity: open-ended, specific mode structure
- Cavity coupling: appropriate loaded Q



PROJECT 8

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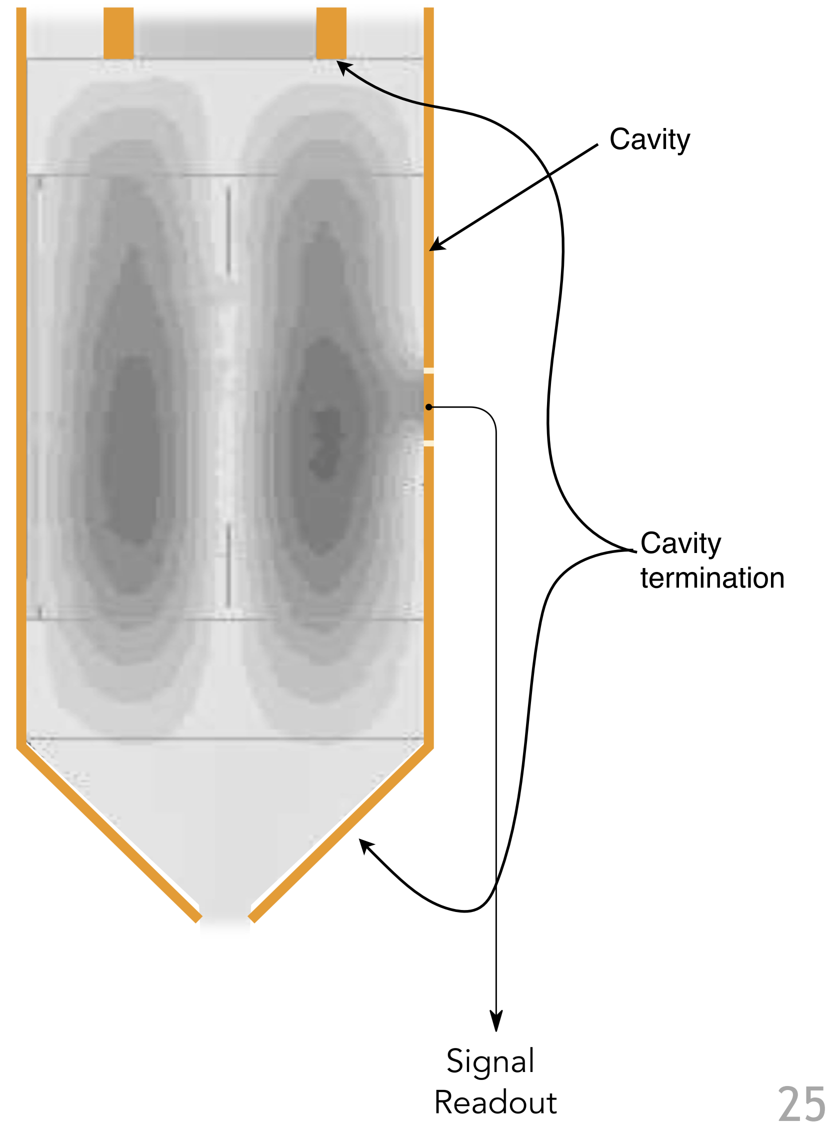

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- Cavity: open-ended, specific mode structure
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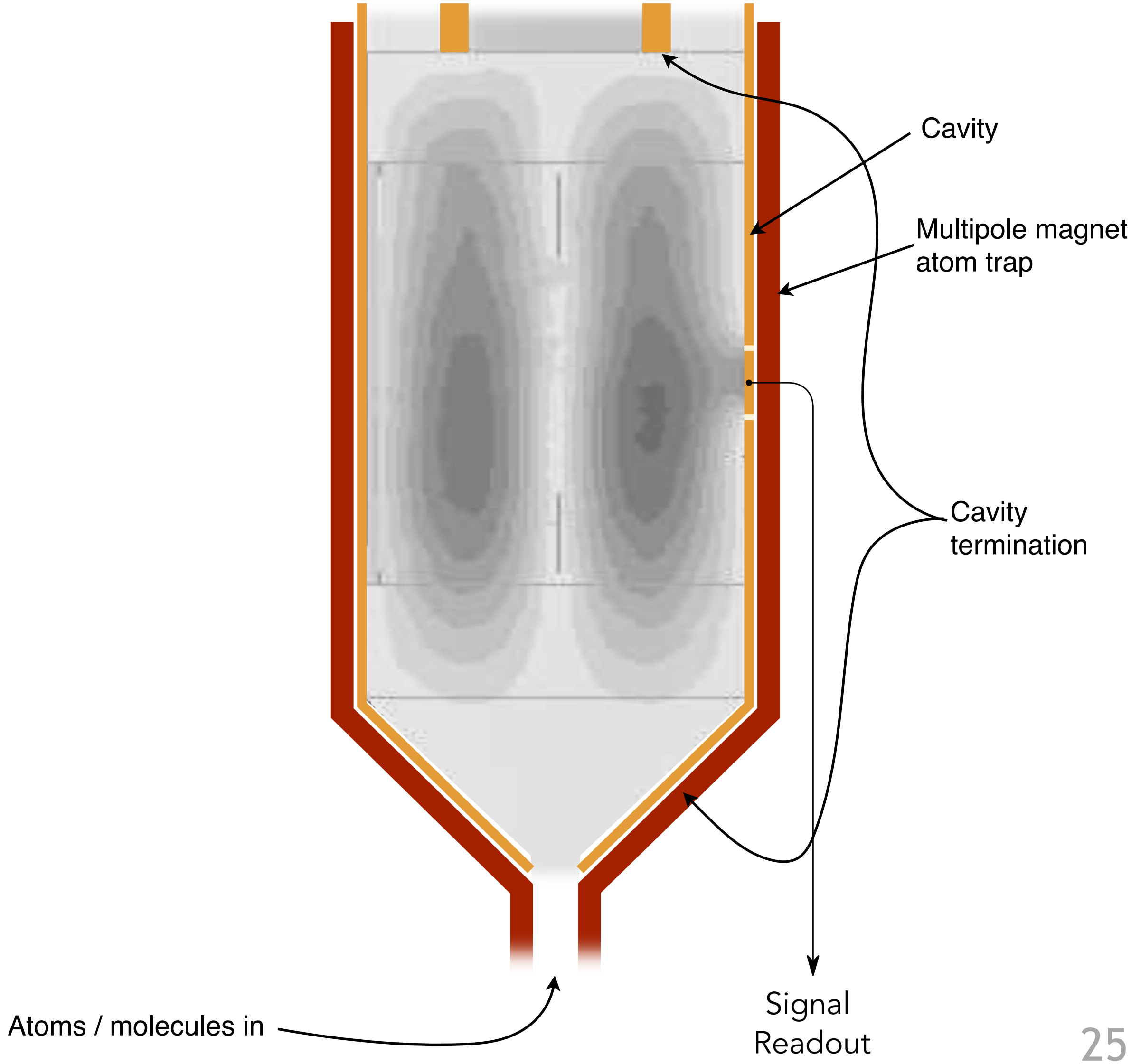

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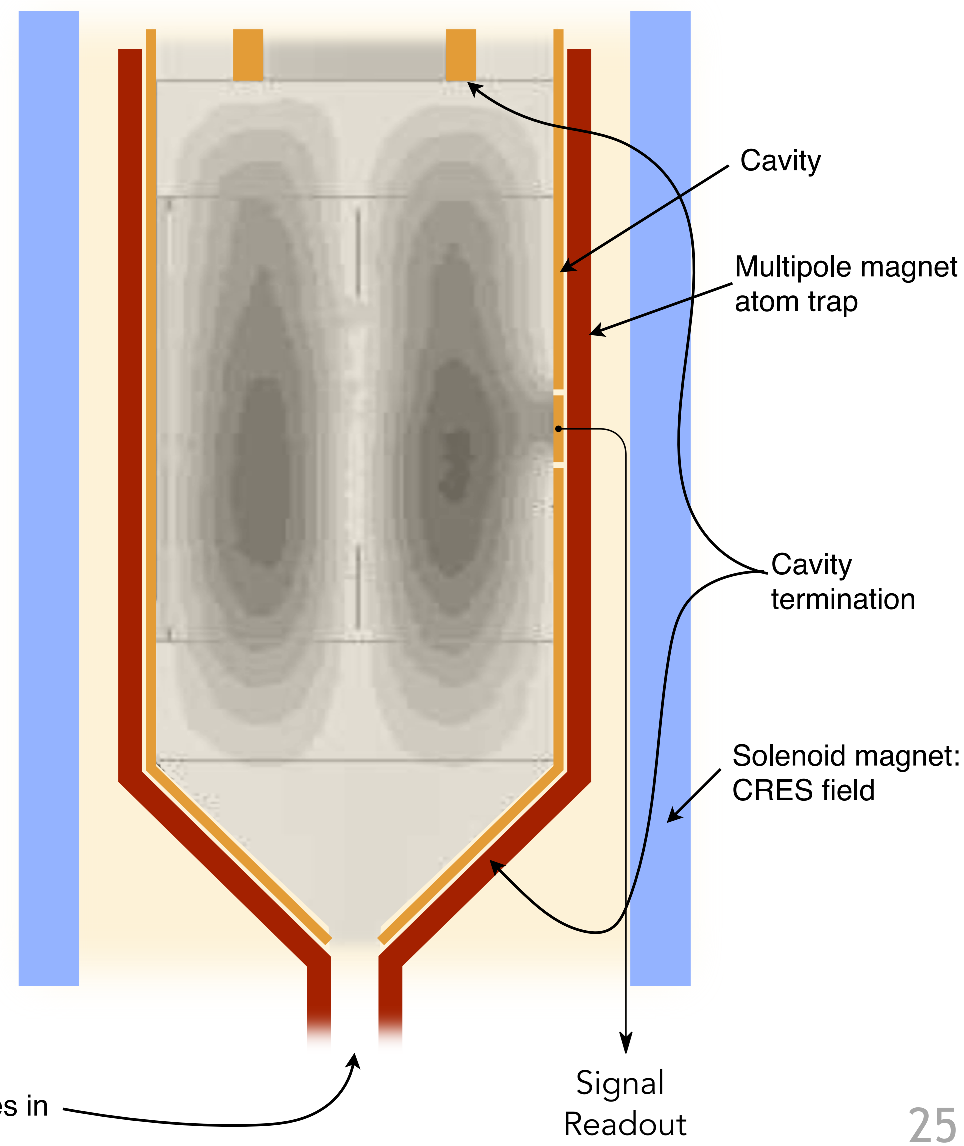

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PROJECT 8

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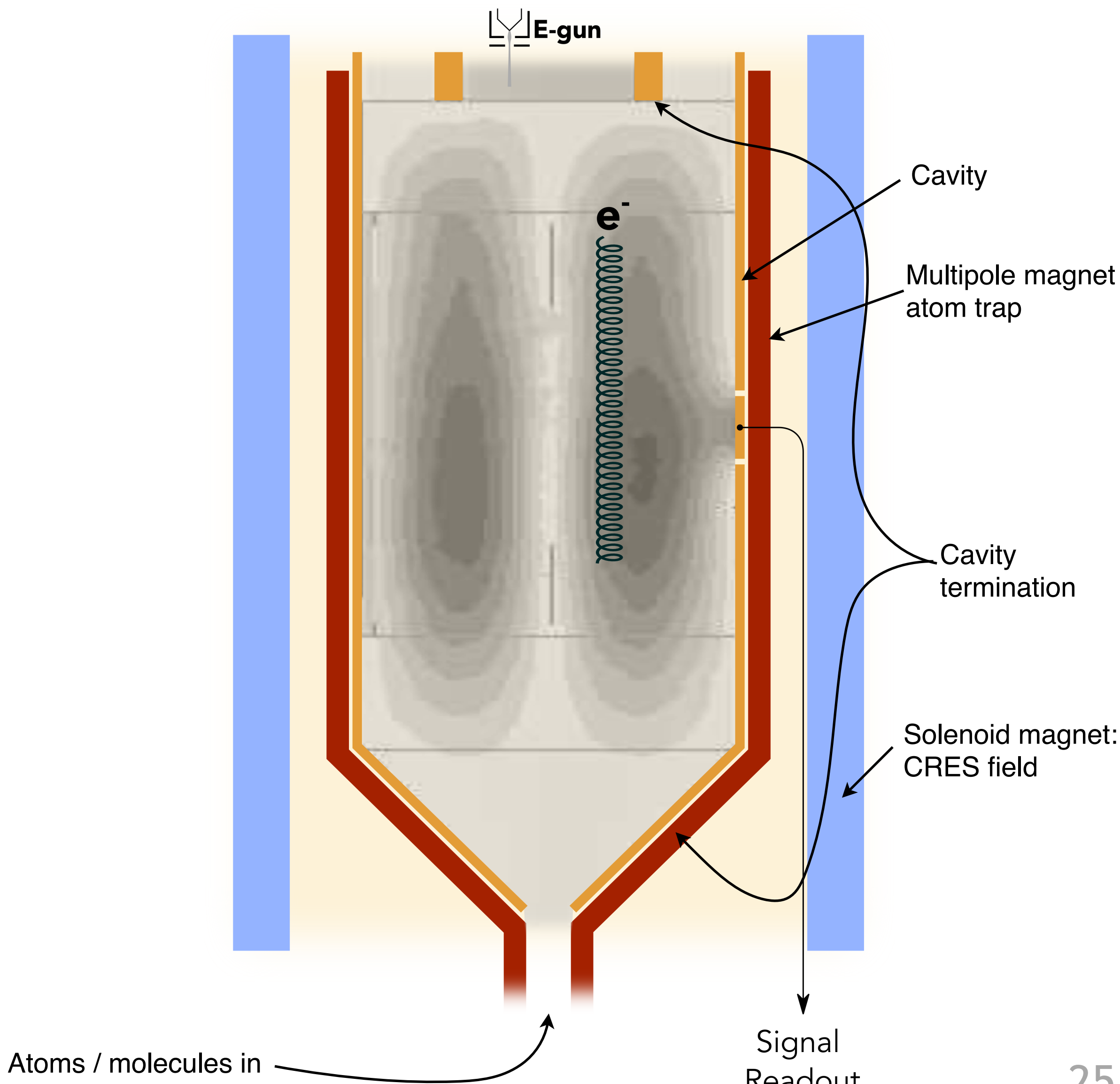

# A Cavity-Based CRES Experiment

- Cavity: open-ended, specific mode structure
- Cavity coupling: appropriate loaded Q
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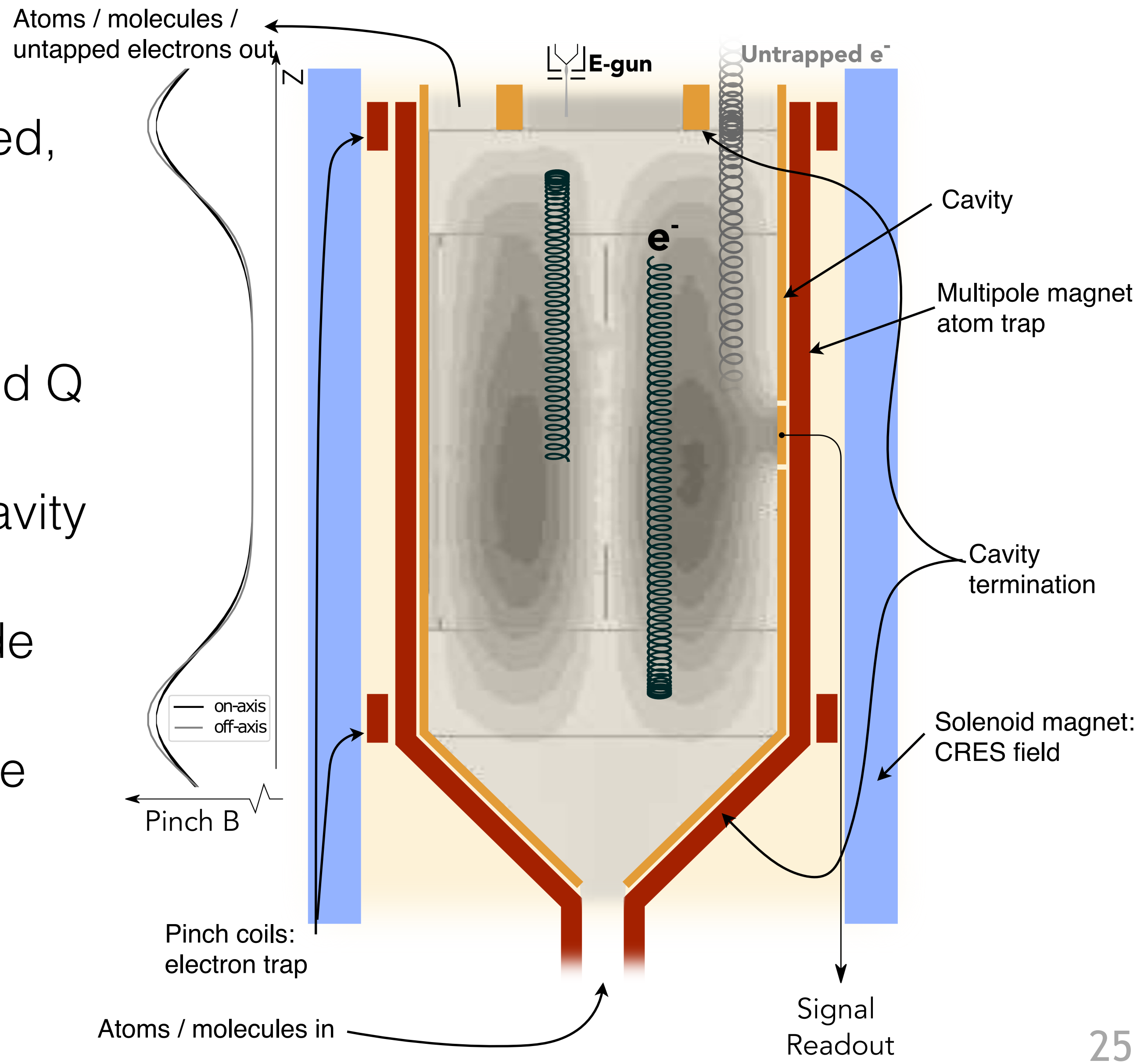
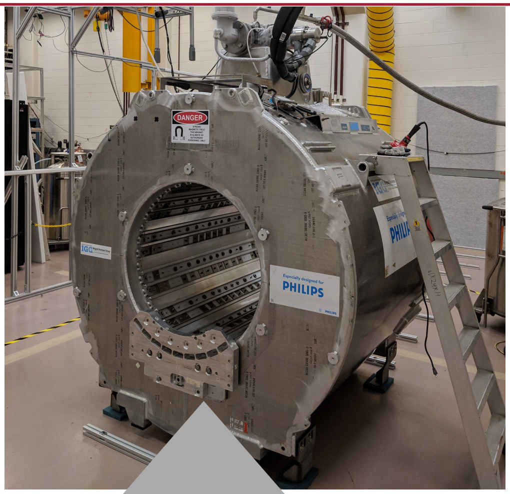
- Solenoid to provide CRES field
- Pinch coils provide electron trapping

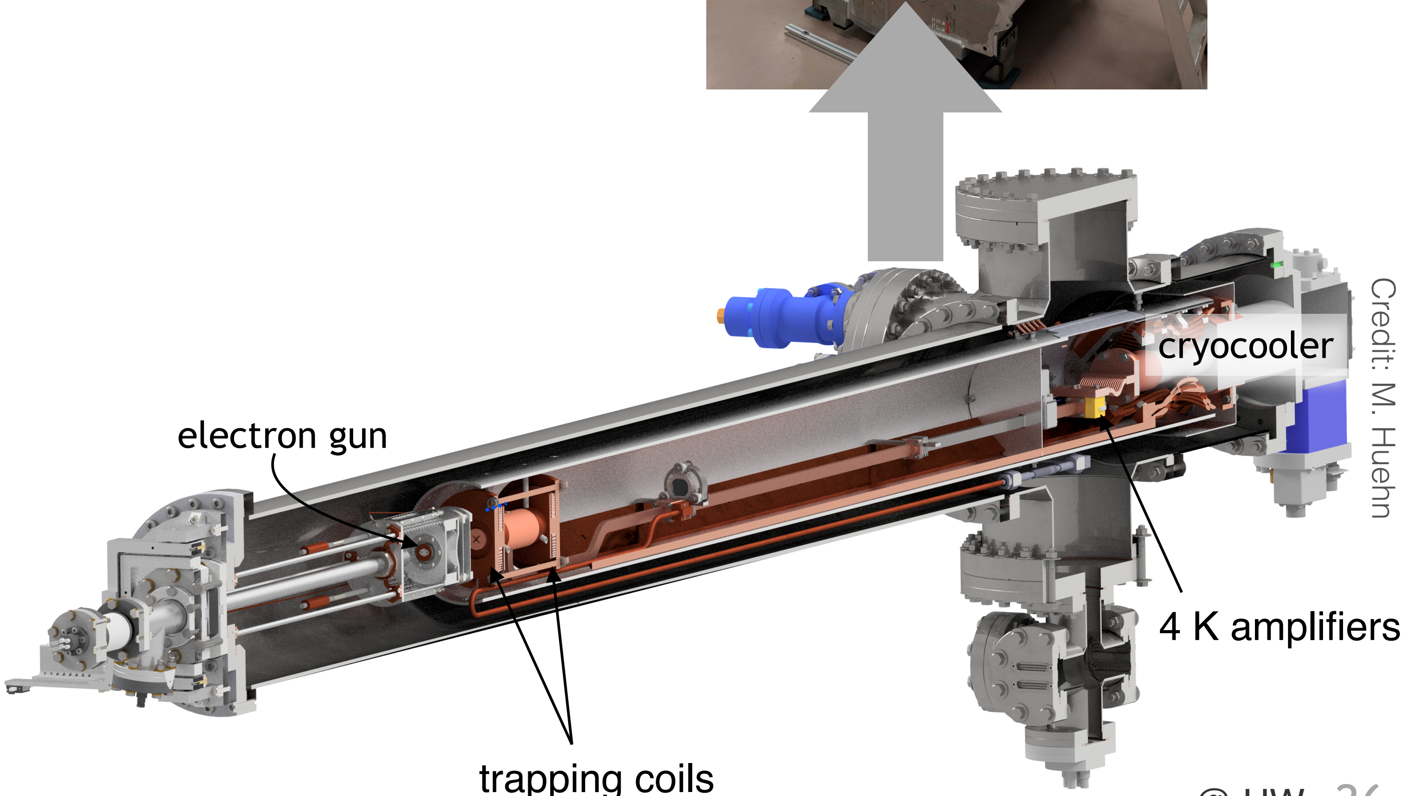


PROJECT 8

# Cavity CRES Apparatus

- Cavity at 26 GHz: $L = 14\,\mathrm{cm}, R = 0.7\,\mathrm{cm}, V \sim 20\,\mathrm{cm}^3$ using $TE_{011}$ mode
- Inserted into 1 T MRI magnet
  - Same frequency as Phase II: can build on expertise with RF setup, waveguide, DAQ …



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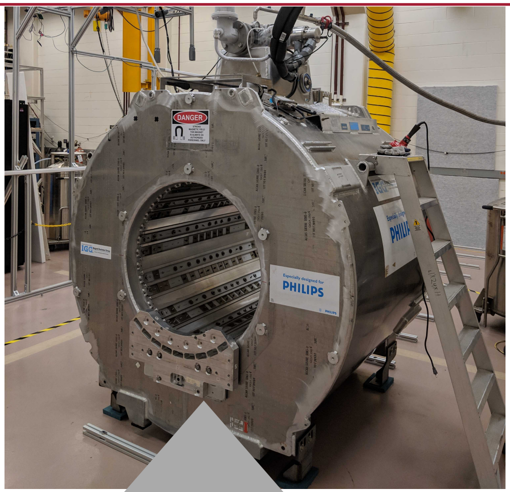


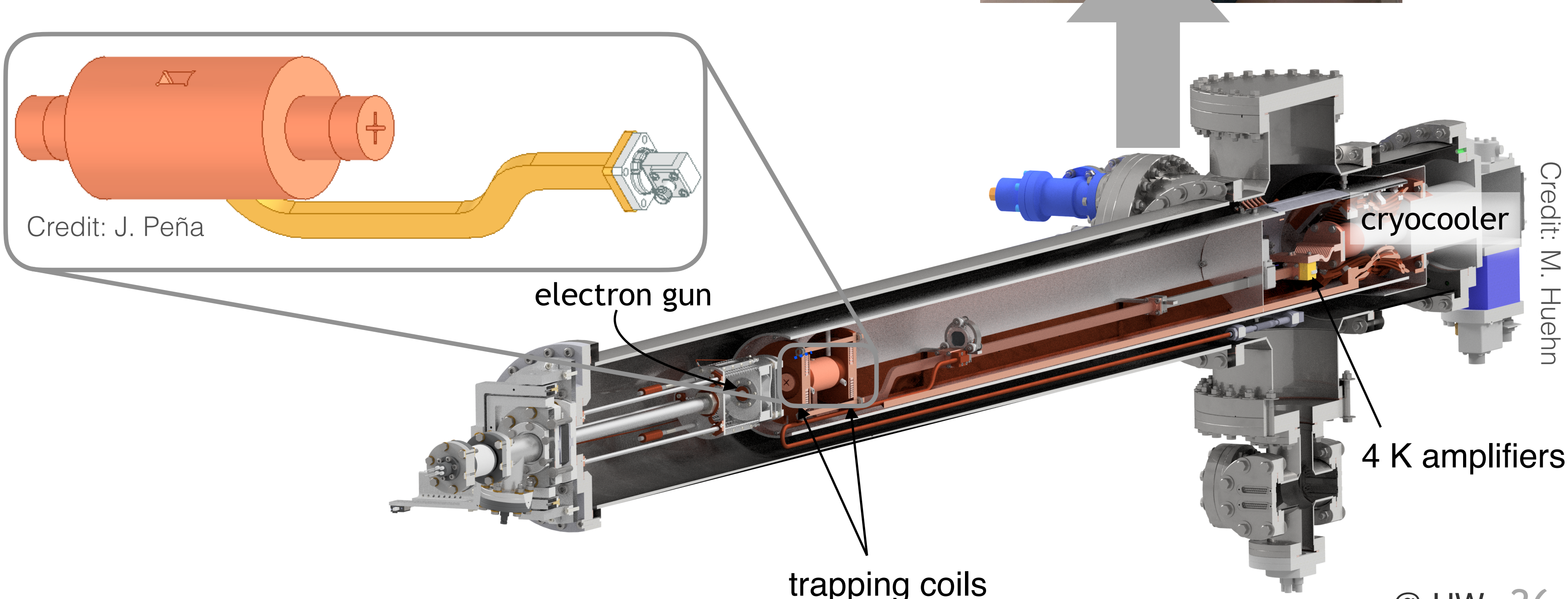

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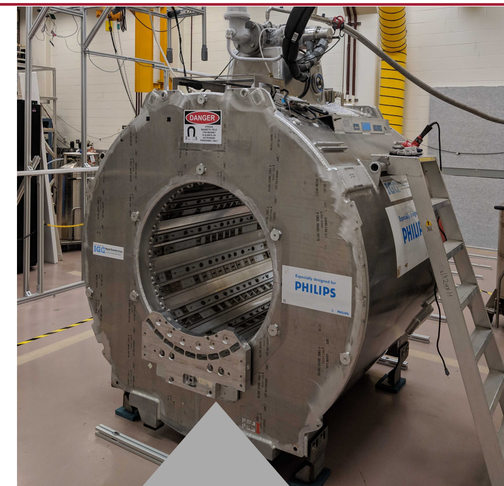
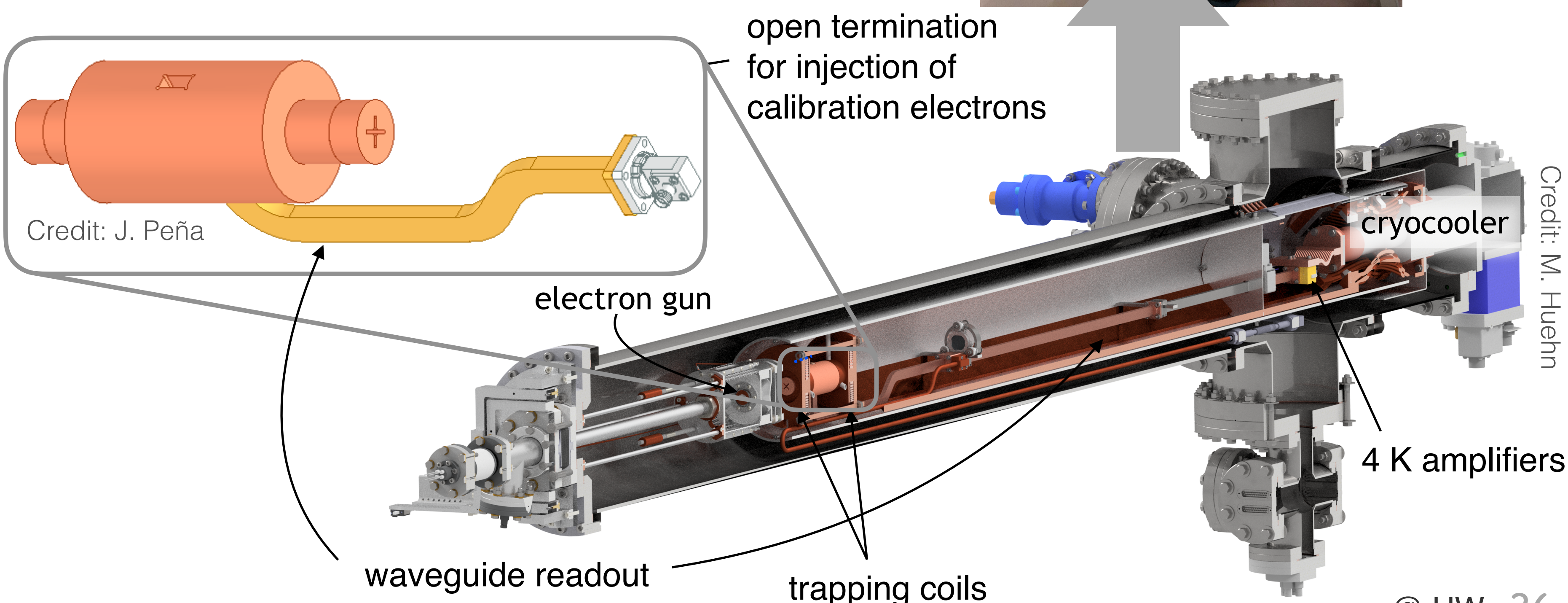
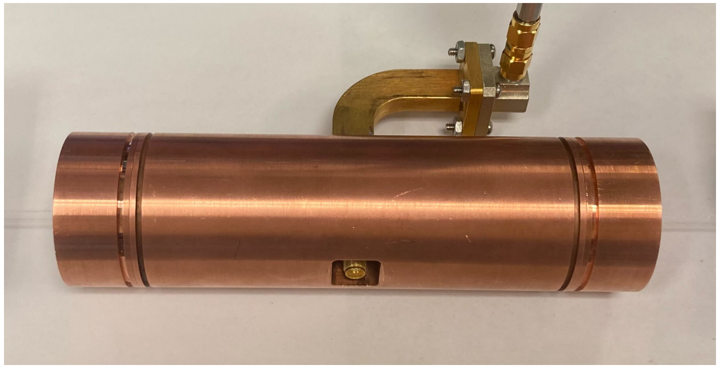


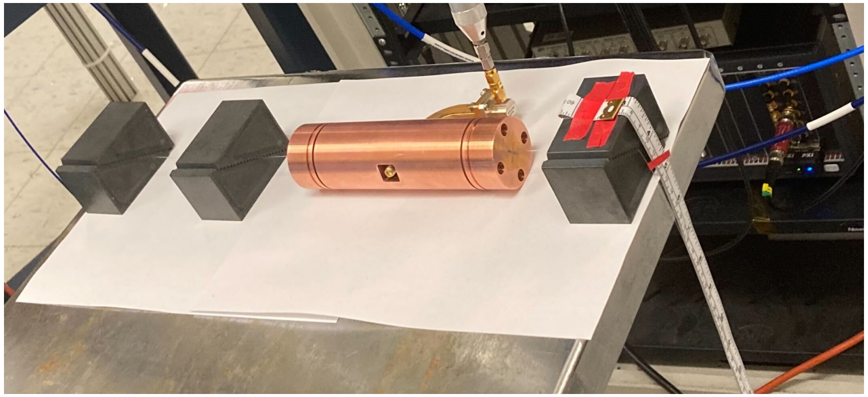



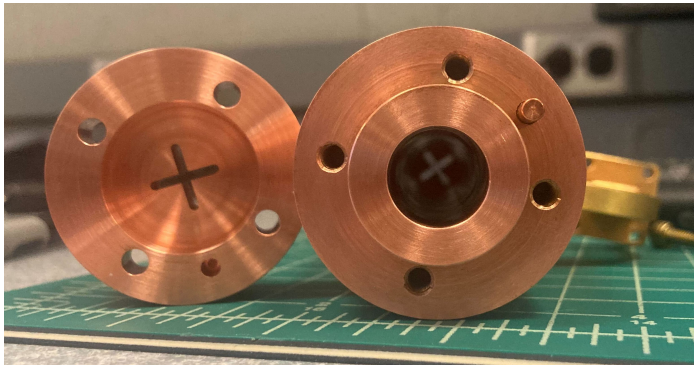
# Cavity Prototype Development

- Built in-house, without connected custom pieces
  → verify design and fix arising issues
- $TE_{011}$ mode at ~26 GHz
- Length : Diameter = 10 : 1
- Readout via waveguide from center
  - Overcoupled to increase bandwidth
- Injection port with small loop antenna
- Status: Fixing machining issues
- Next: Remapping mode structure with bead pull
- Bead shifts resonant frequency as

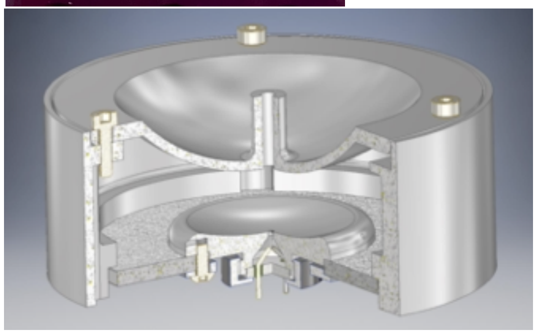
$$\frac{\Delta\omega}{\omega} = \frac{-(\epsilon - 1)}{2} \frac{V_{\text{bead}}}{V_{\text{cavity}}} \frac{E(\vec{x})^2}{\langle E(\vec{x})^2 \rangle}$$







# Electron Source



Credit: R. Roehnelt

- $LaB_6$ / $Y_2O_3$ cathode, Pierce design
- Excellent energy spread (simulated)
- Powered by LEDs & solar panels
- Test stand & magnet tests at UW

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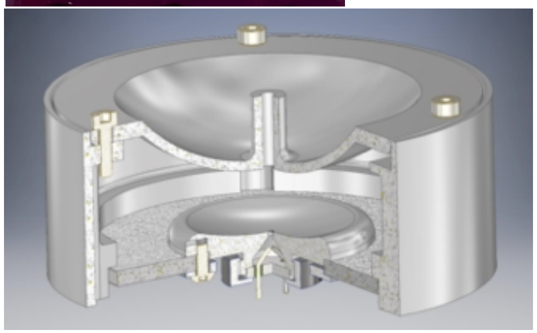

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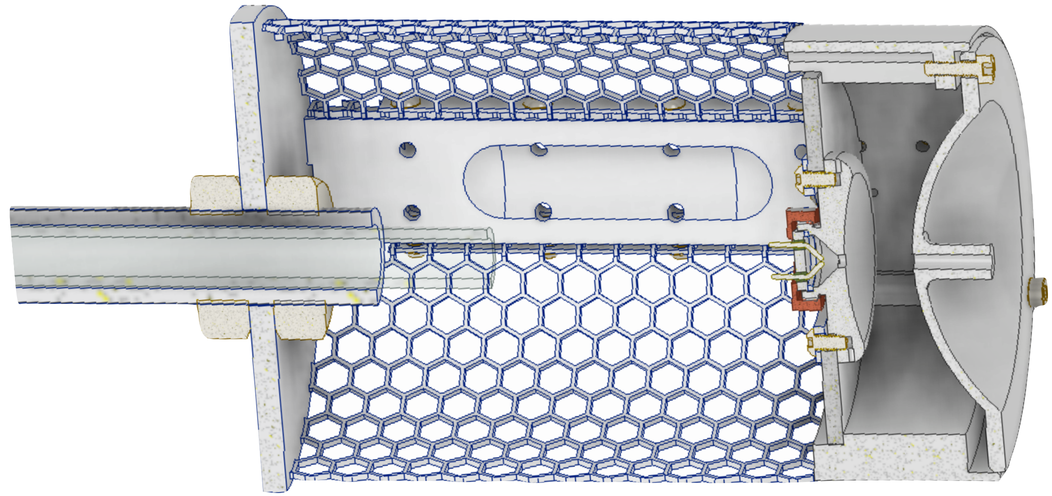

Credit: R. Roehnelt, M. Huehn

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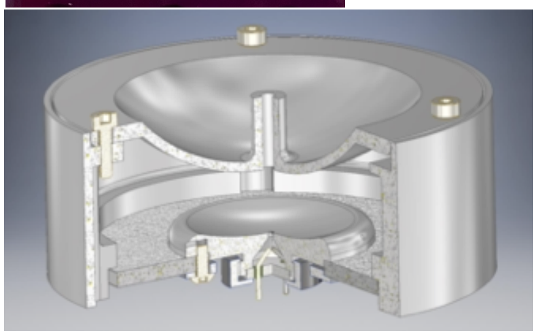

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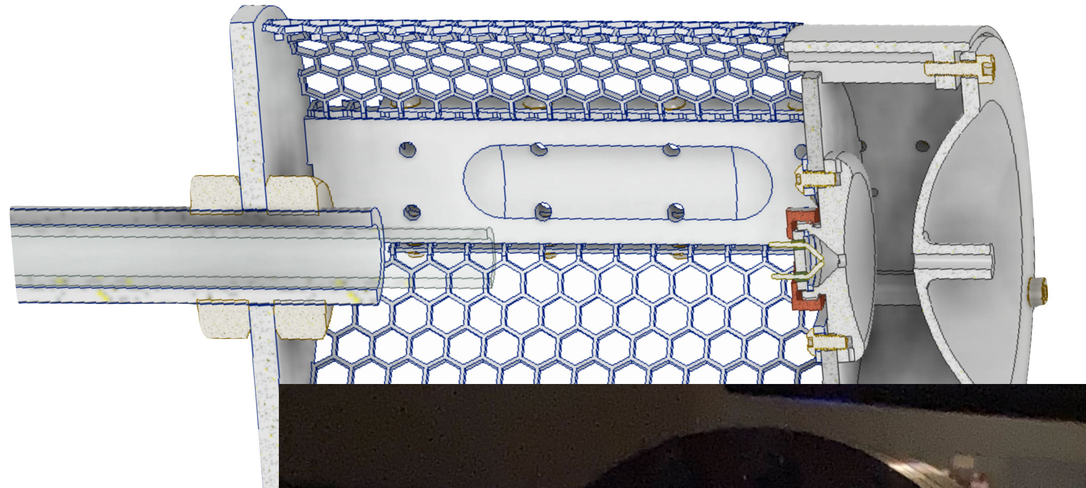

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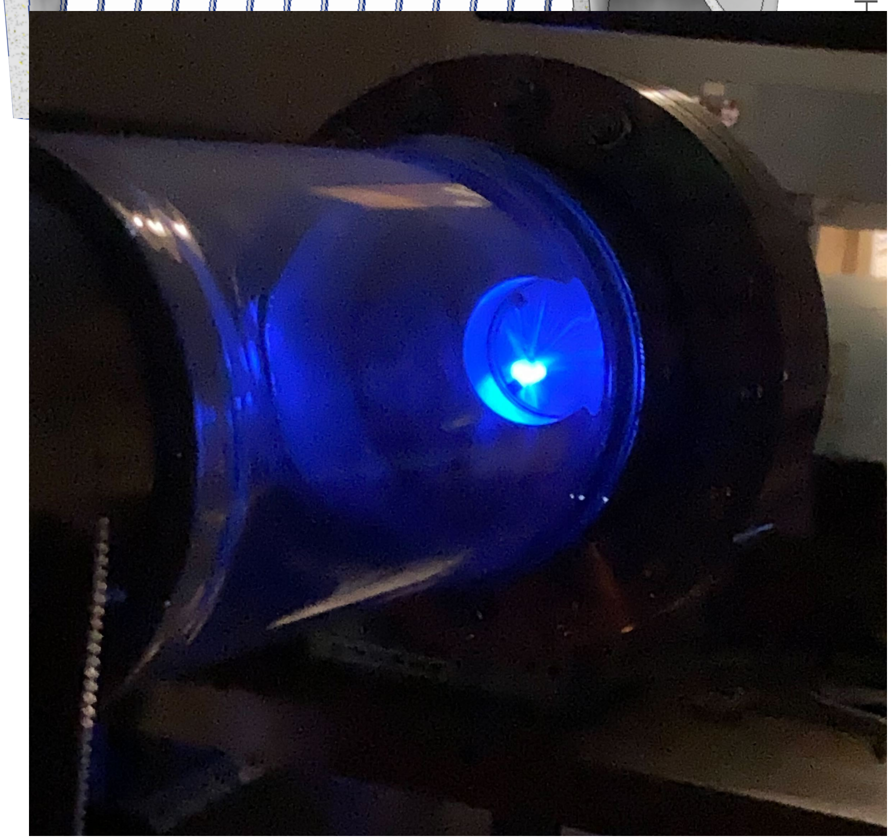

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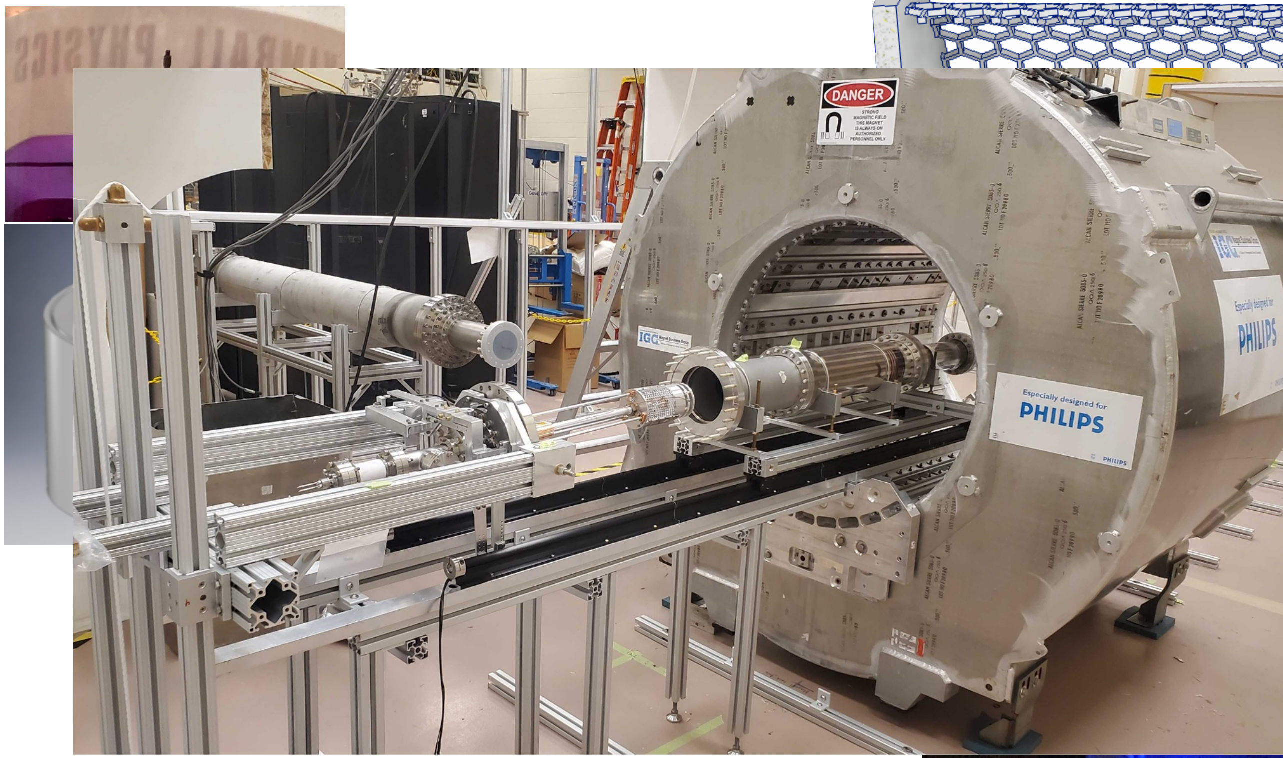


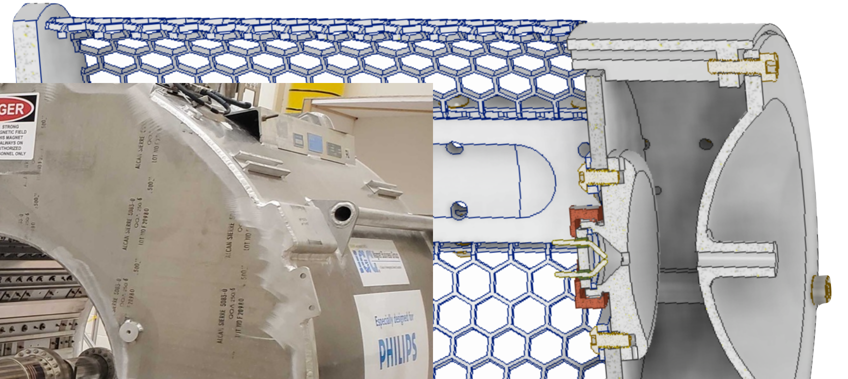

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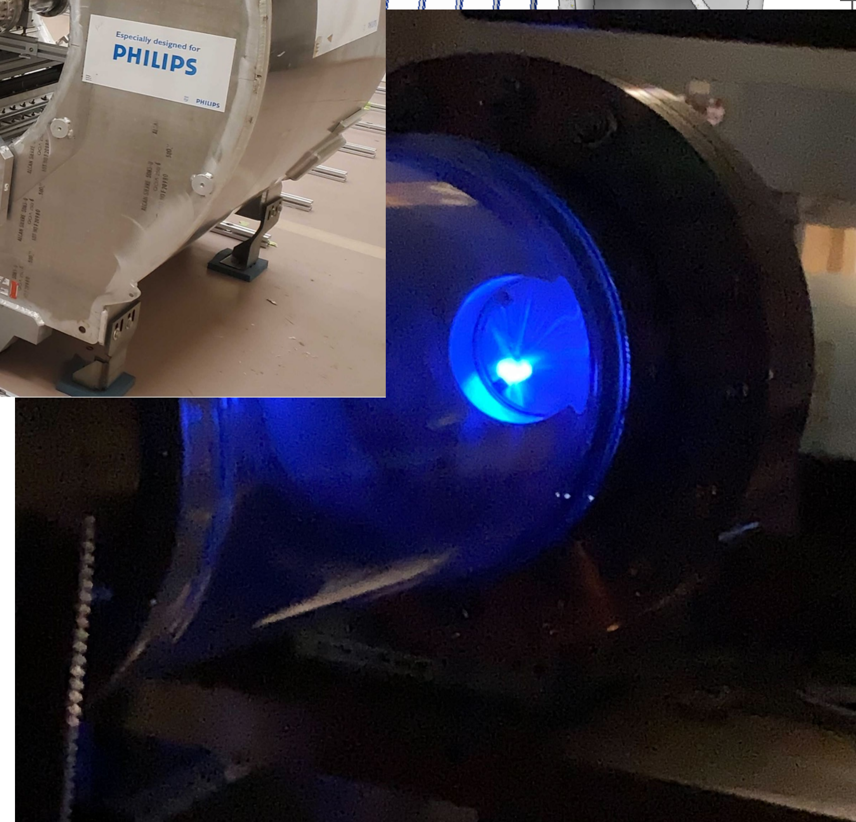

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- Verify CRES phenomenology in resonant cavity with high SNR
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  - Reconstruction with event-by-event magnetic field corrections
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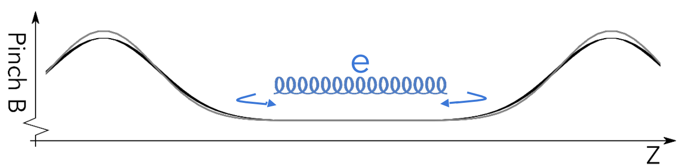

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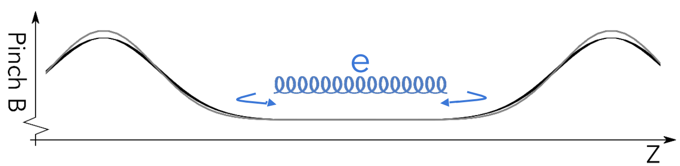


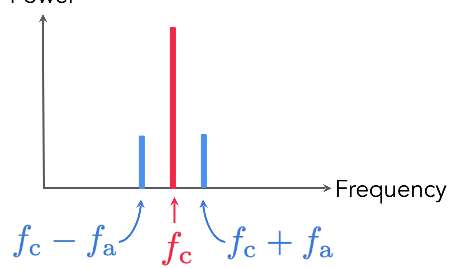

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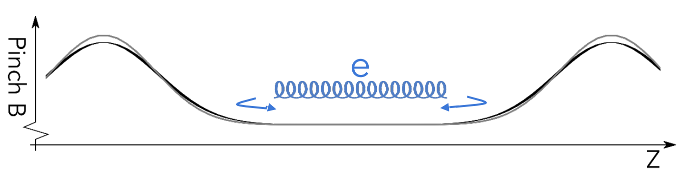


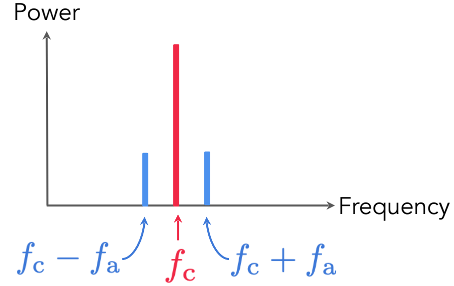


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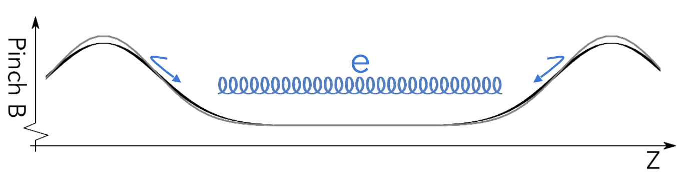

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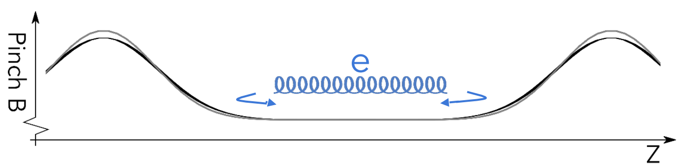


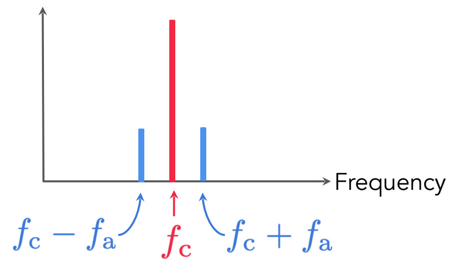


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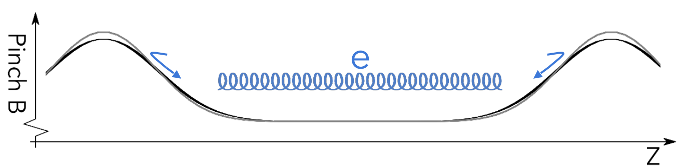


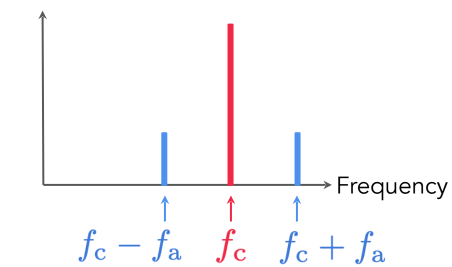

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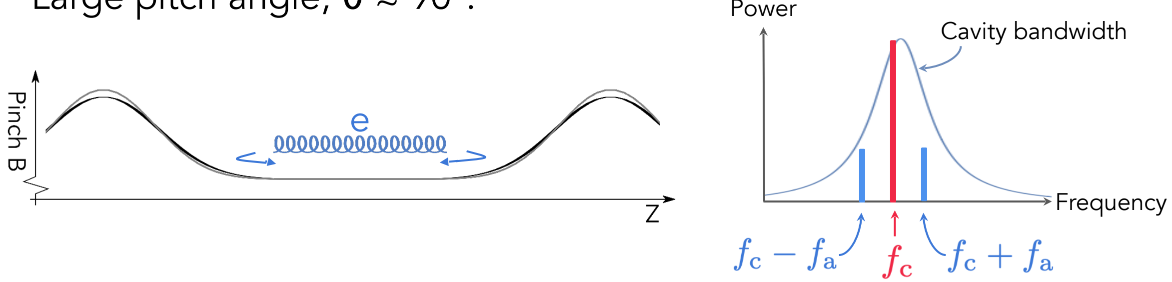


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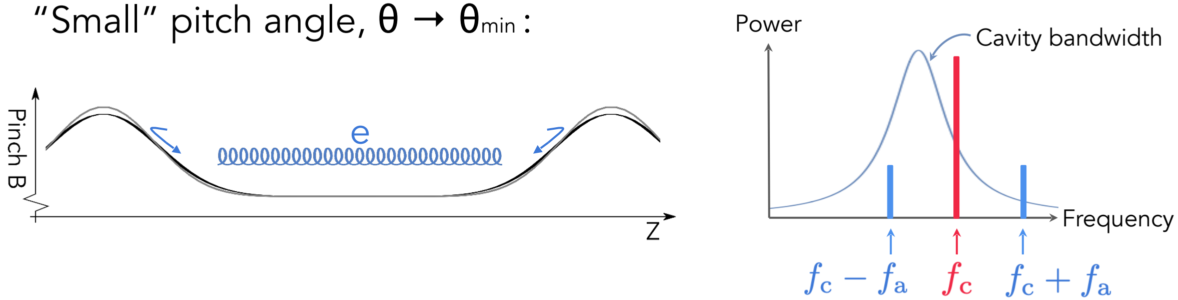

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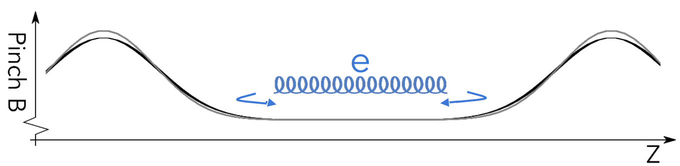


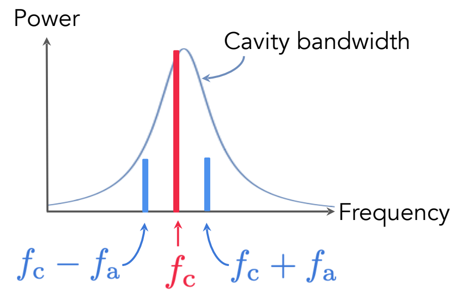


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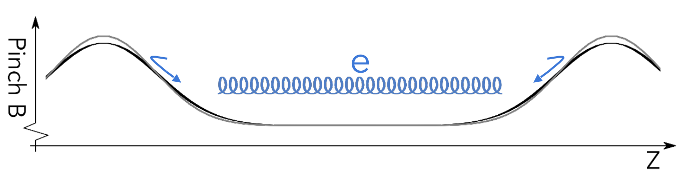
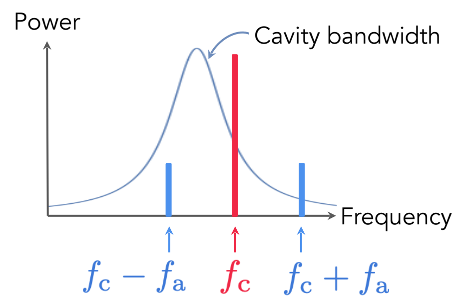
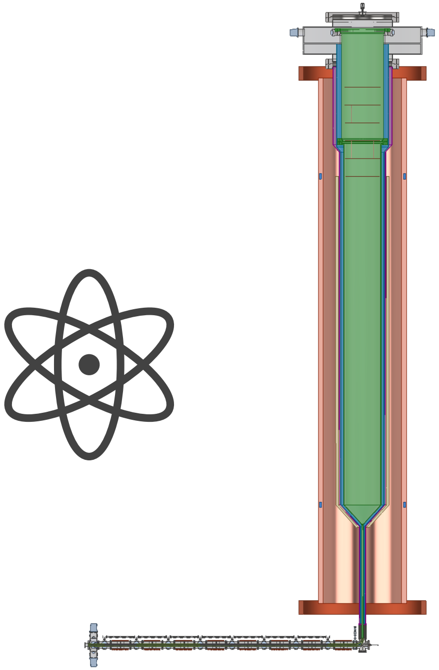


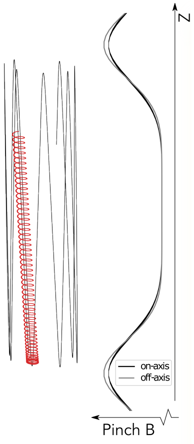




- Sidebands due to axial motion
- Axial motion leads to variation in magnetic field along electron track
- Larger average magnetic field and higher carrier frequency
- Sideband detection for magnetic field correction

PROJECT 8

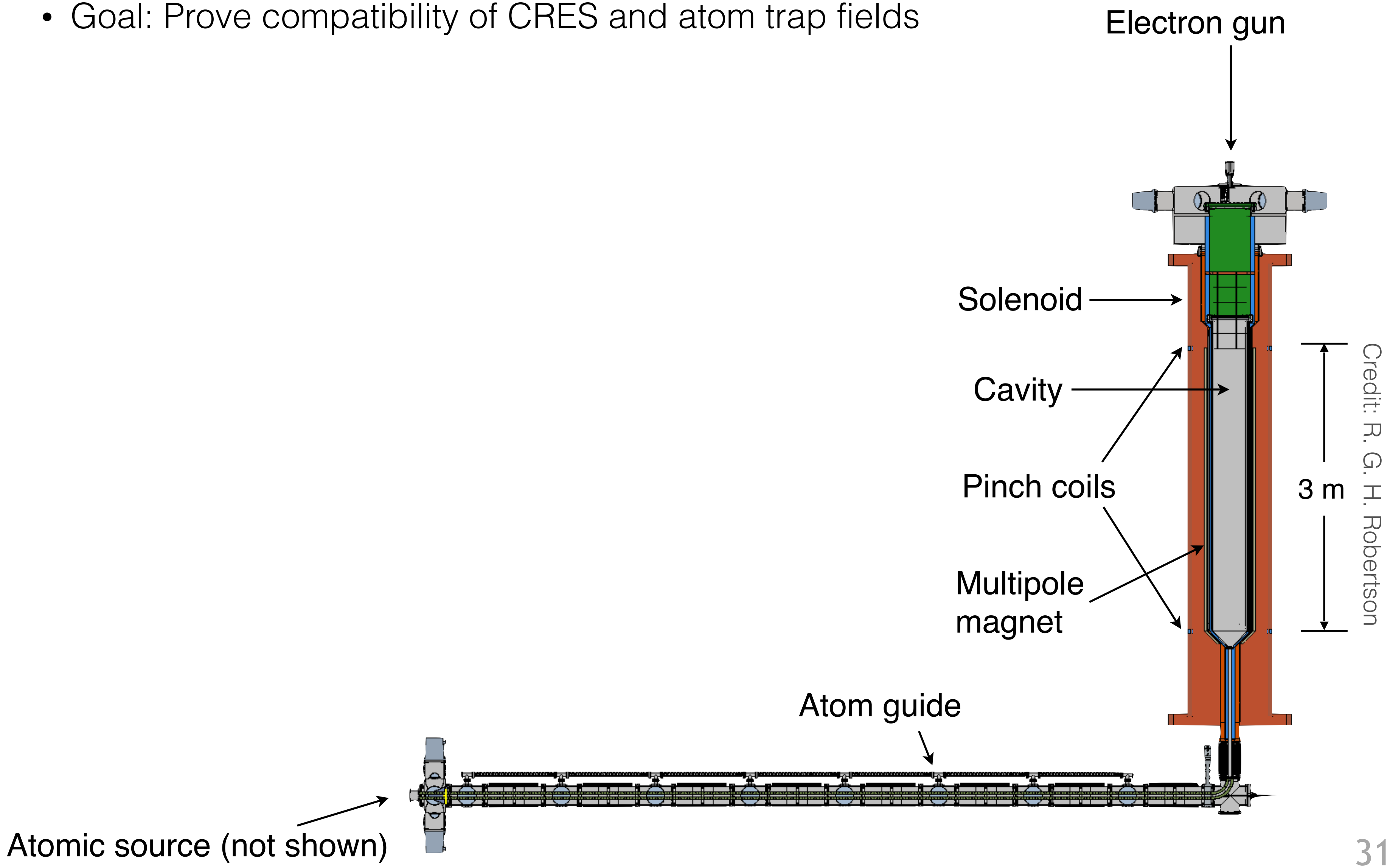
# Finalizing Phase III: CRES ♥ Atoms





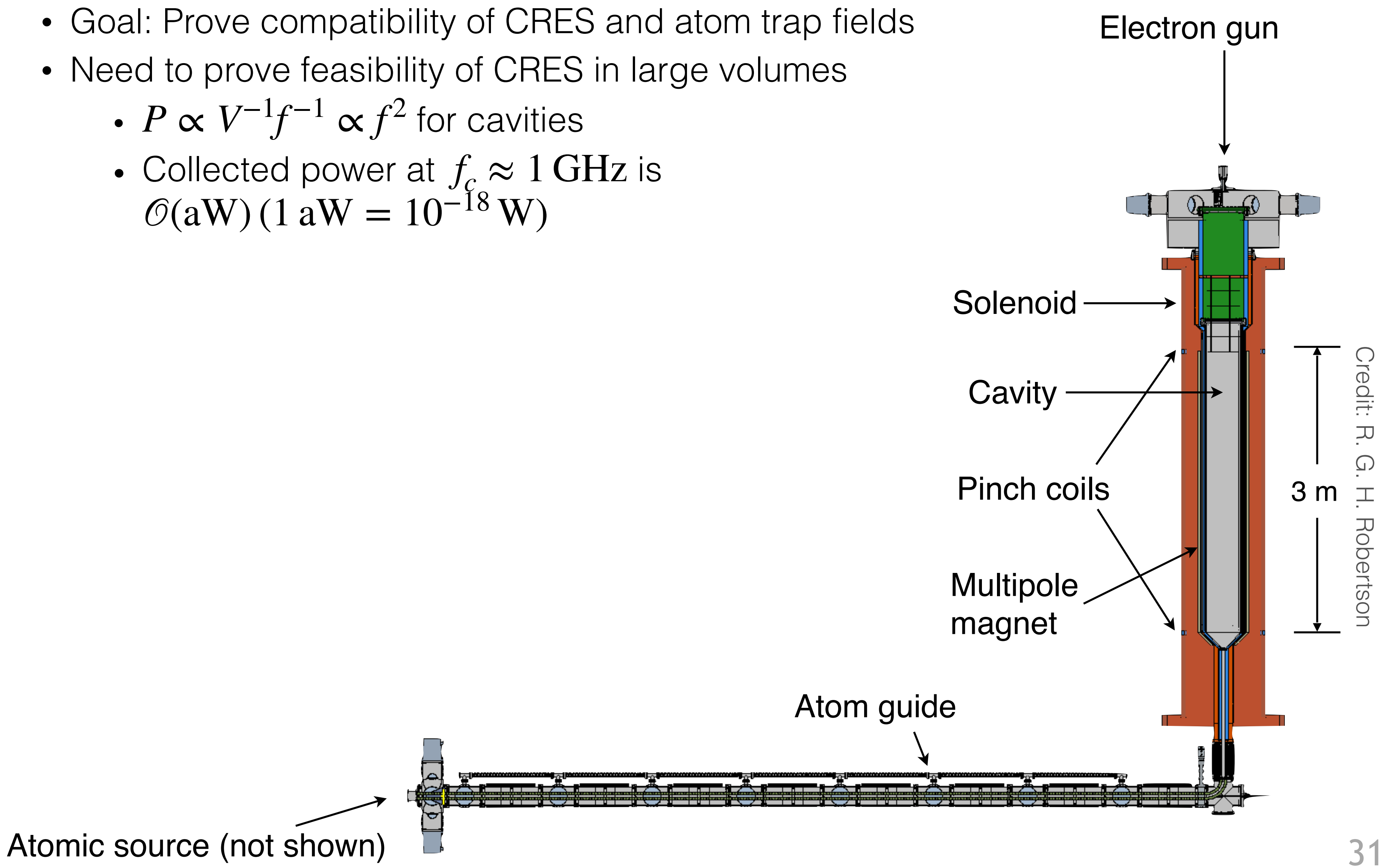
# CRES In Atomic Trap

- Goal: Prove compatibility of CRES and atom trap fields



# CRES In Atomic Trap

- Goal: Prove compatibility of CRES and atom trap fields
- Need to prove feasibility of CRES in large volumes
  - $P \propto V^{-1} f^{-1} \propto f^2$ for cavities
  - Collected power at $f_c \approx 1\,\mathrm{GHz}$ is $\mathcal{O}(\mathrm{aW})$ $(1\,\mathrm{aW} = 10^{-18}\,\mathrm{W})$



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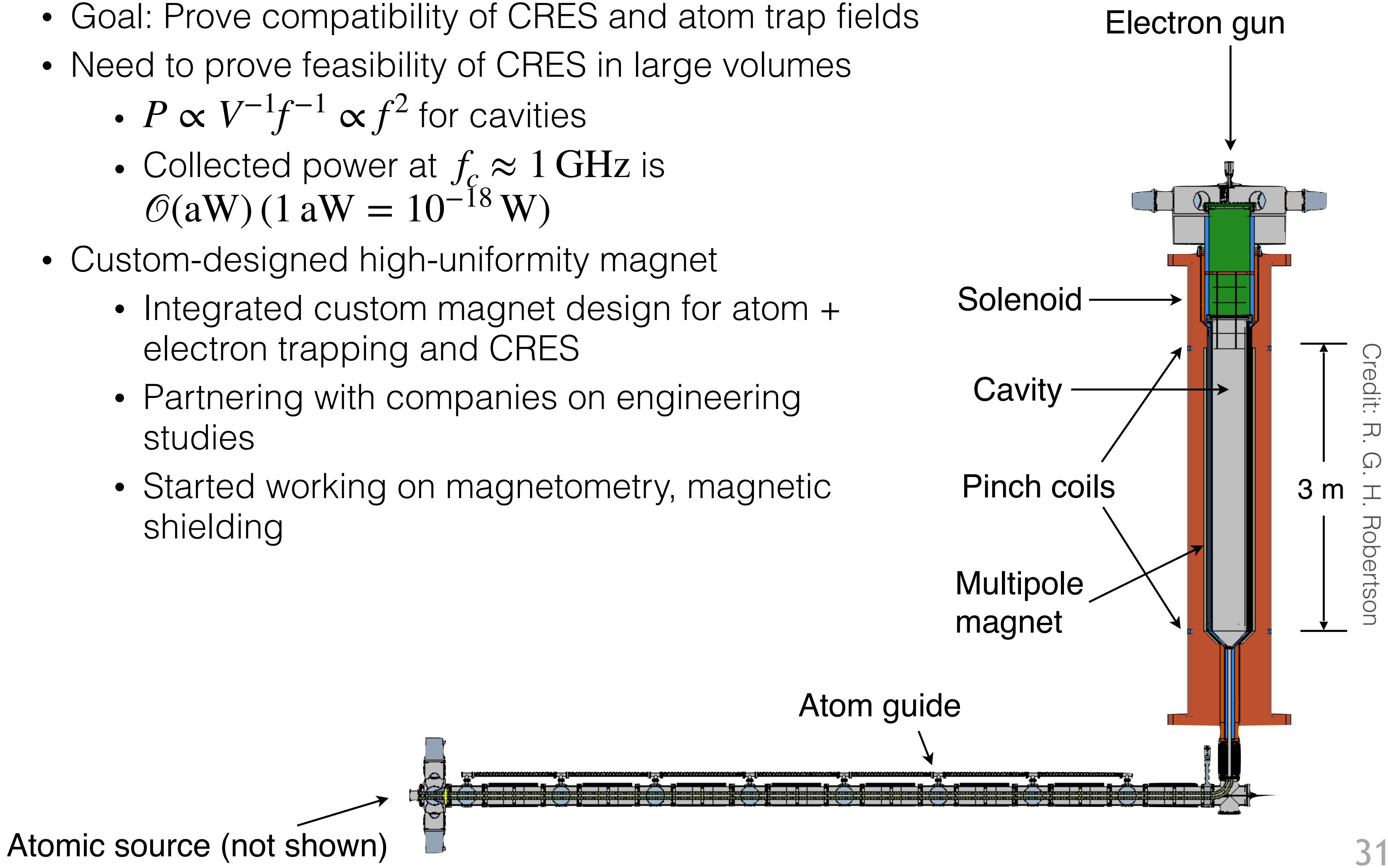
- Custom-designed high-uniformity magnet
  - Integrated custom magnet design for atom + electron trapping and CRES
  - Partnering with companies on engineering studies
  - Started working on magnetometry, magnetic shielding



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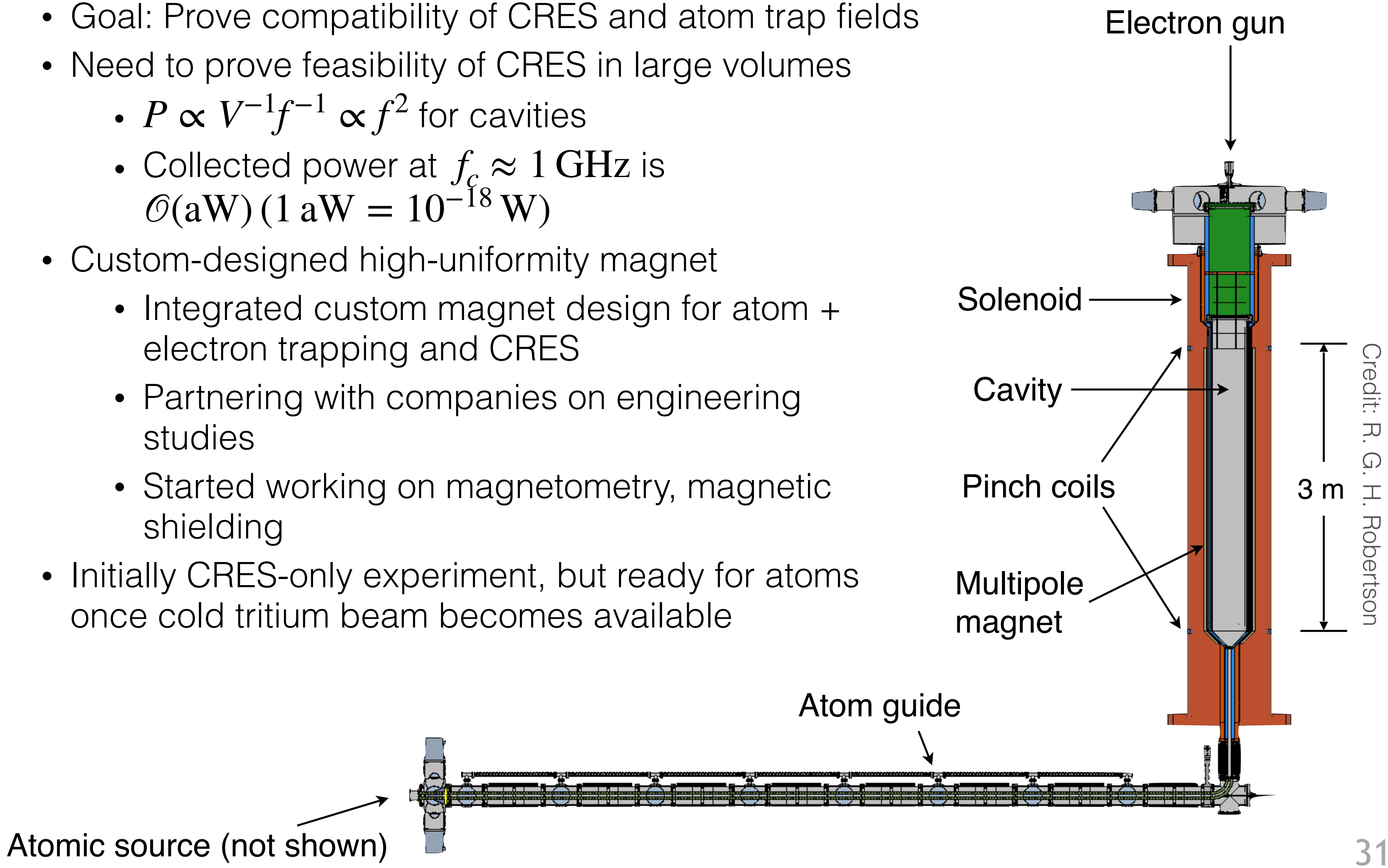
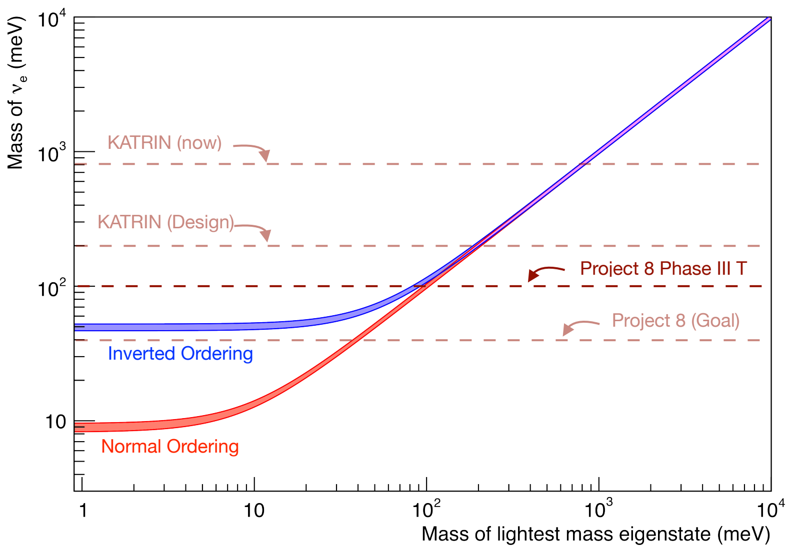
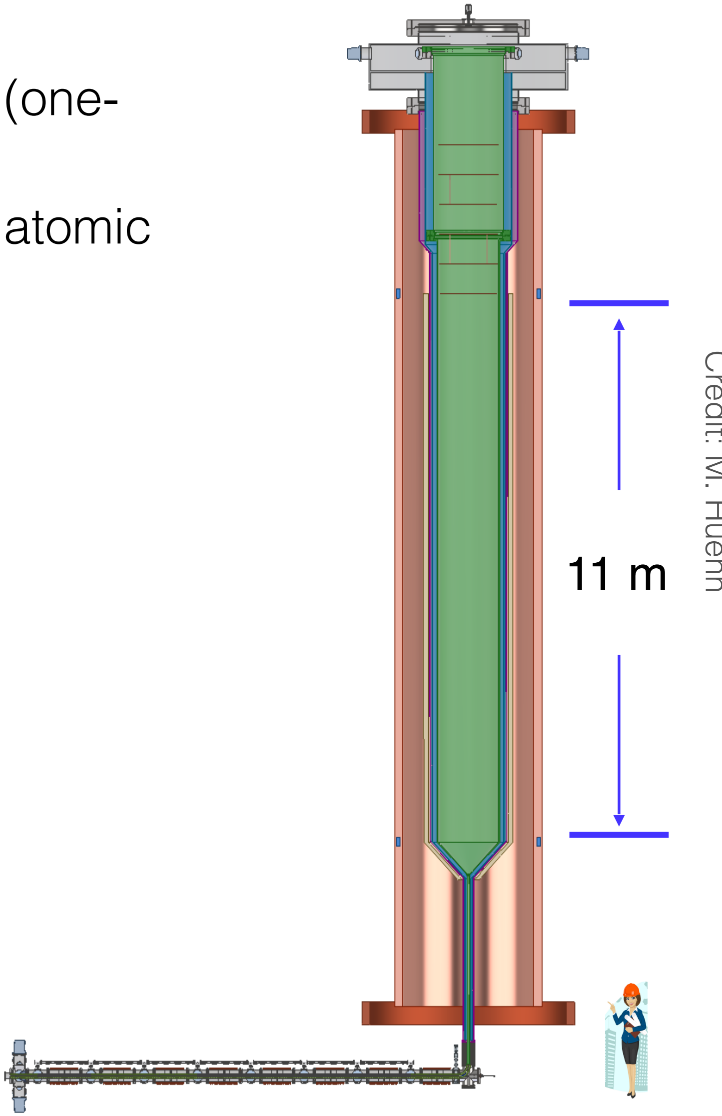
- Initially CRES-only experiment, but ready for atoms once cold tritium beam becomes available



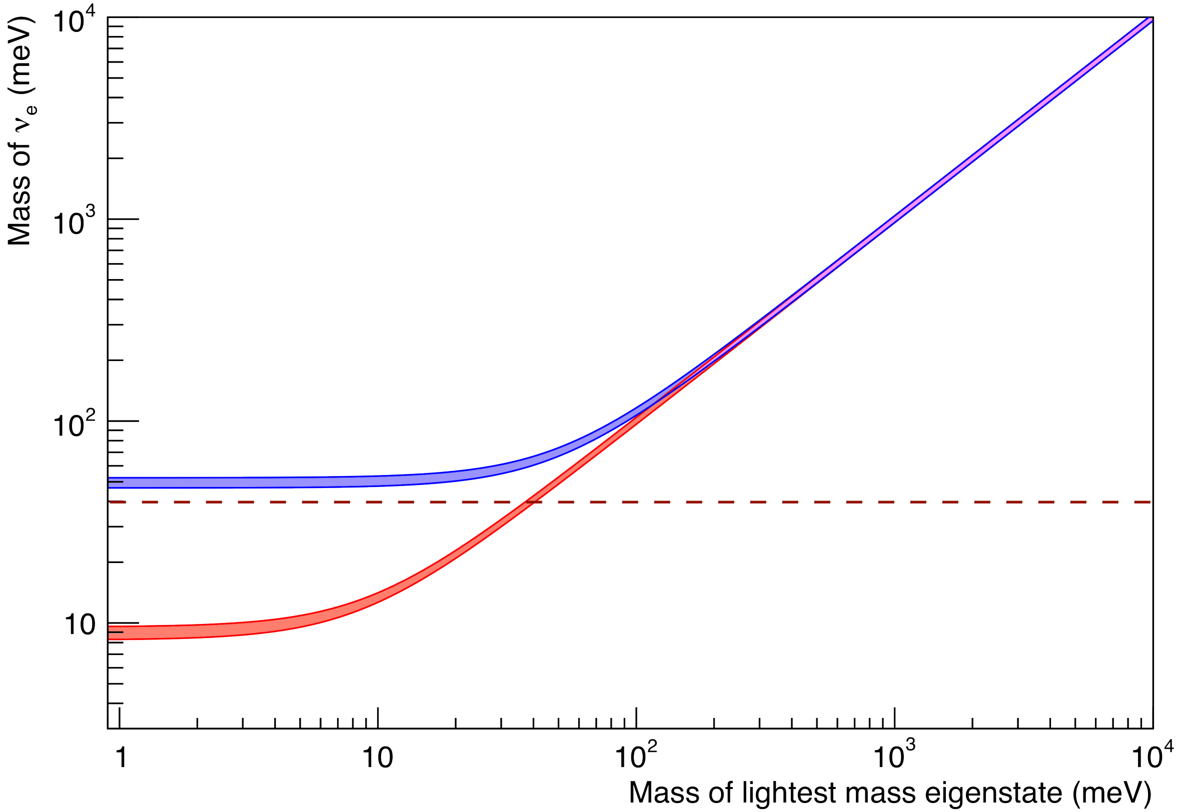
# Cavity-based Phase III

- Atoms trapped in magnetogravitational trap
- Sensitivity aim: $m_\beta < 200\,\mathrm{meV}\ (90\,\%\ \mathrm{C.L.})$ (one-year with molecular source) and $m_\beta < 100\,\mathrm{meV}\ (90\,\%\ \mathrm{C.L.})$ (one-year with atomic source)
- Volume $V \approx 11\,\mathrm{m}^3$, field $B \lesssim 0.011\,\mathrm{T}$, and frequency $f_c \lesssim 325\,\mathrm{MHz}$
- Blueprint for Phase IV



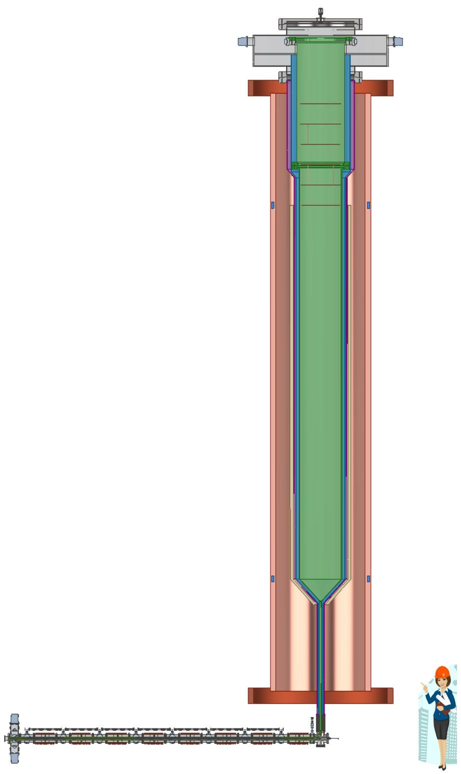



# Phase IV

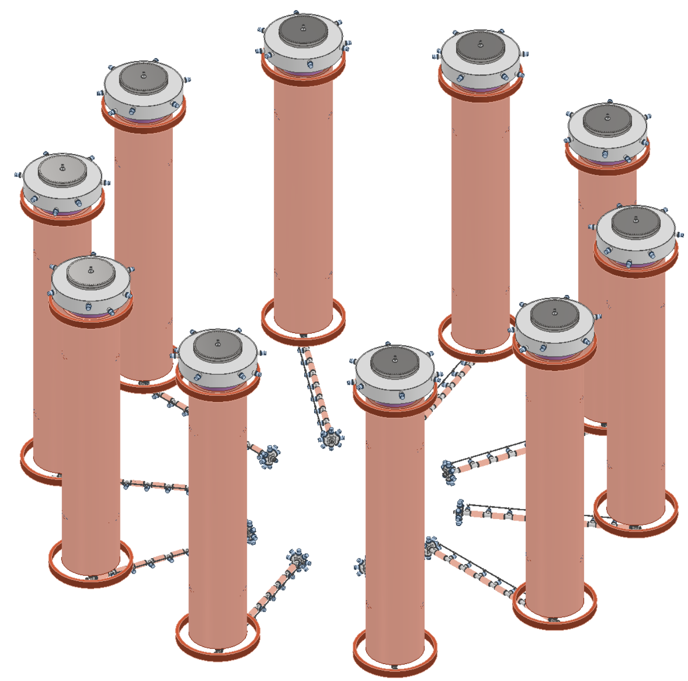


Mass of $\nu_e$ (meV)
$10^4$
$10^3$
$10^2$
10
1
10
$10^2$
$10^3$
$10^4$
Mass of lightest mass eigenstate (meV)

# Phase IV Concept



Phase IV =
Phase III x 10



Credit: M. Huehn

# Sensitivity

PROJECT 8

Source gas density

Uncertainties on response function

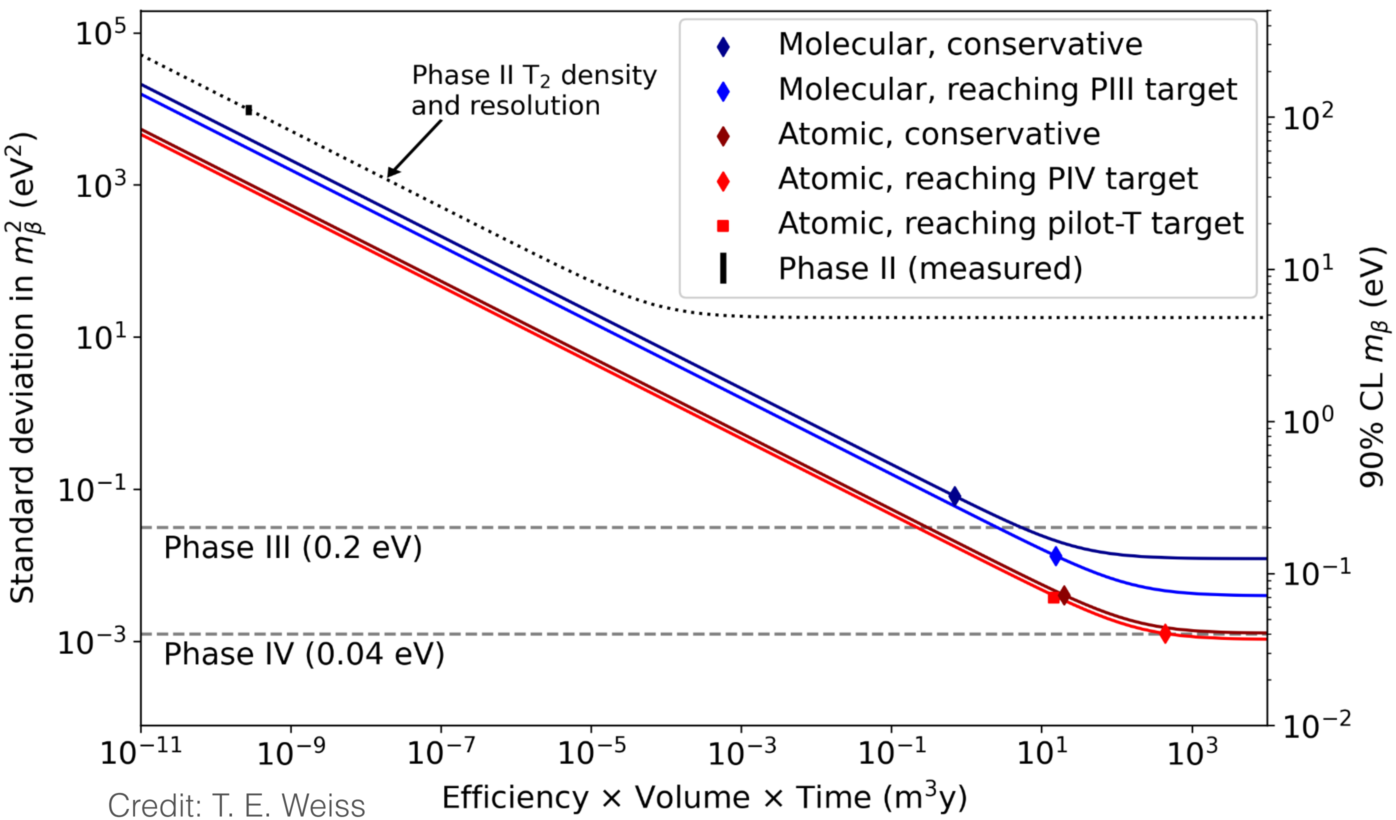
$$\sigma_{m_\beta^2} = 4\sqrt{\frac{1}{(6\, C_T\, V_{\mathrm{eff}}\, n\, t)^2}\left[C_T\, V_{\mathrm{eff}}\, n\, t\, \Delta E + \frac{b\, t}{\Delta E}\right] + \sum_i \sigma_i^2(n) \cdot \delta\sigma_i^2}$$

Effective volume (volume × efficiency)

Runtime

Background

Response function stdevs. (resolution)



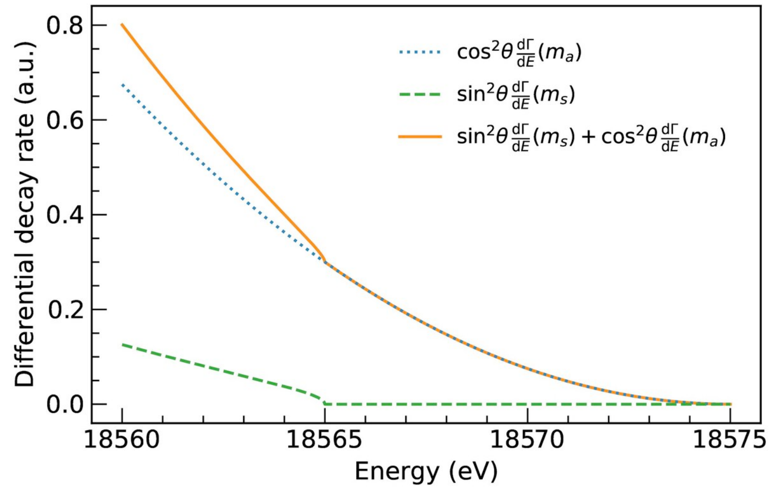

Credit: T. E. Weiss

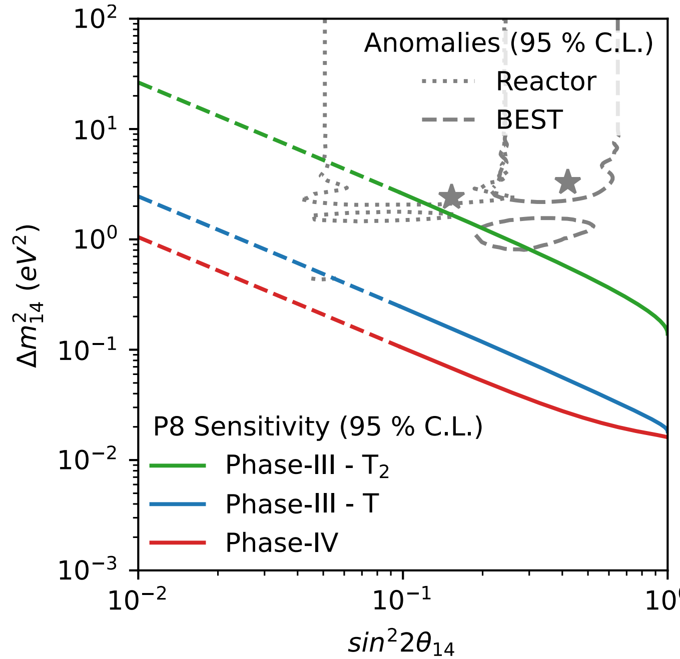
**Conservative:** What we think today we can do

**Reaching target:** What we need to do

# Sterile Neutrino Sensitivity

- Simultaneous active and sterile mass measurements possible
- eV-scale sterile search planned
- Higher mass sterile sensitivity under investigation
- Also sensitive to relic neutrino overdensity from neutrino capture on tritium




Credit: P. T. Surukuchi

# Take Aways

- The Project 8 approach to neutrino mass measurement:
  - High precision frequency measurement
  - Source volume = detector volume
  - Differential spectrum measurement for high statistics
  - Low background
- Next challenges:
  - Atomic tritium handling
  - Large CRES detection volumes
- Near future: cavity CRES characterization with electron source & Krypton, Krypton measurements
- ~2030: CRES & atomic trapping compatibility demonstrated
- 2030s: First atomic tritium neutrino mass extraction
- Final experiment: 40 meV neutrino mass sensitivity

# 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.