PROJECT 8

Massachusetts Institute of Technology

Project 8: Recent Results and Future Plans

PTOLEMY @ Princeton, 11/06/2023

Juliana Stachurska

Project 8 Basics

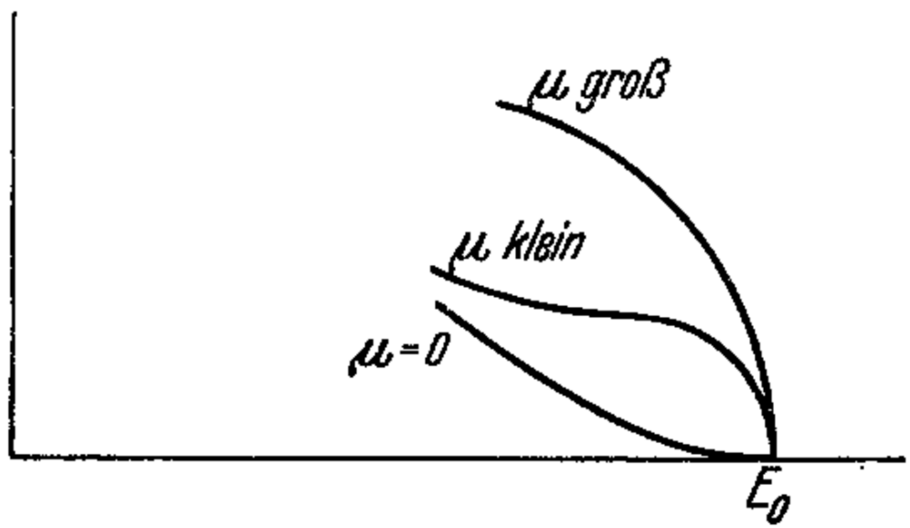
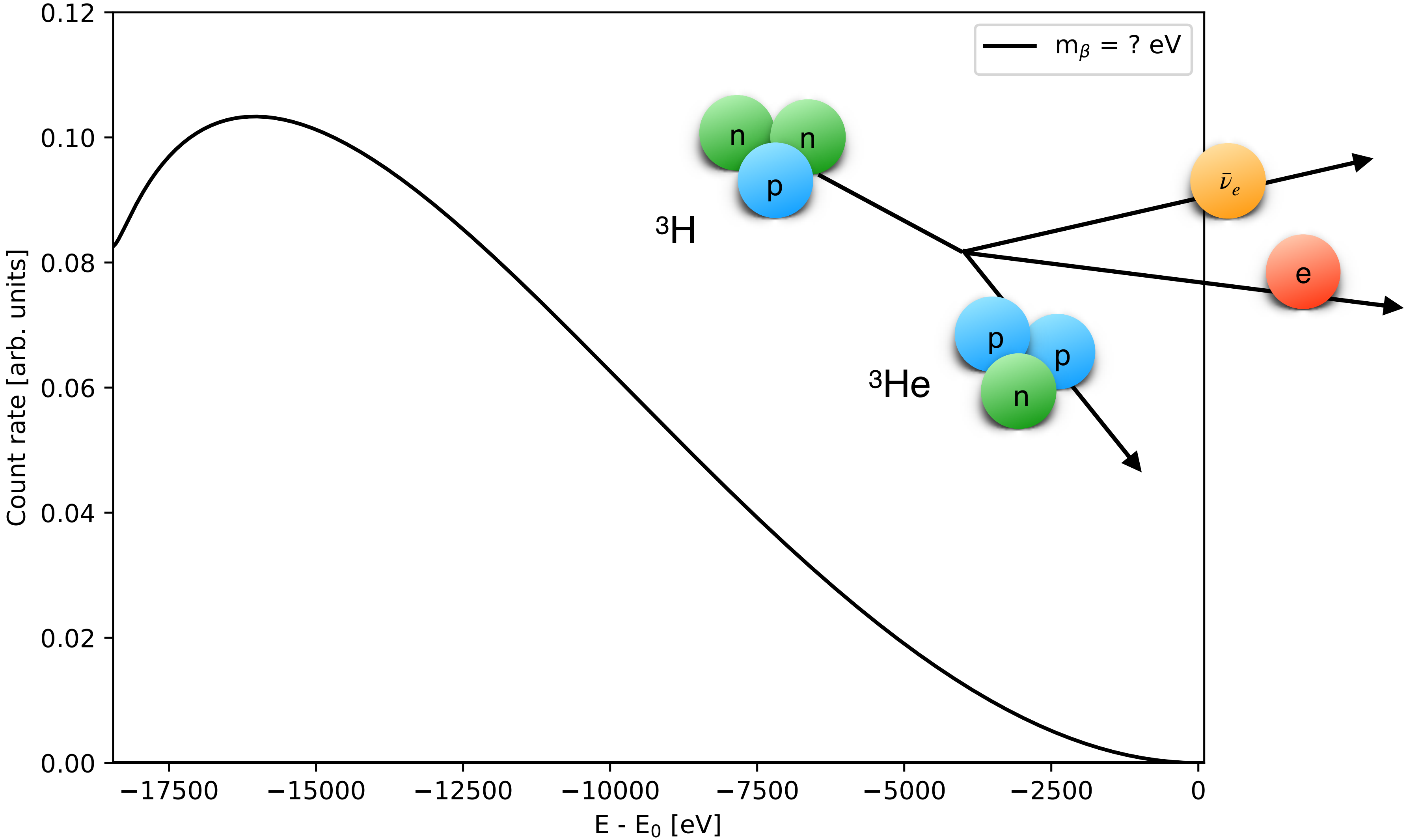


Fig. 1.

Beta Decay Spectrum



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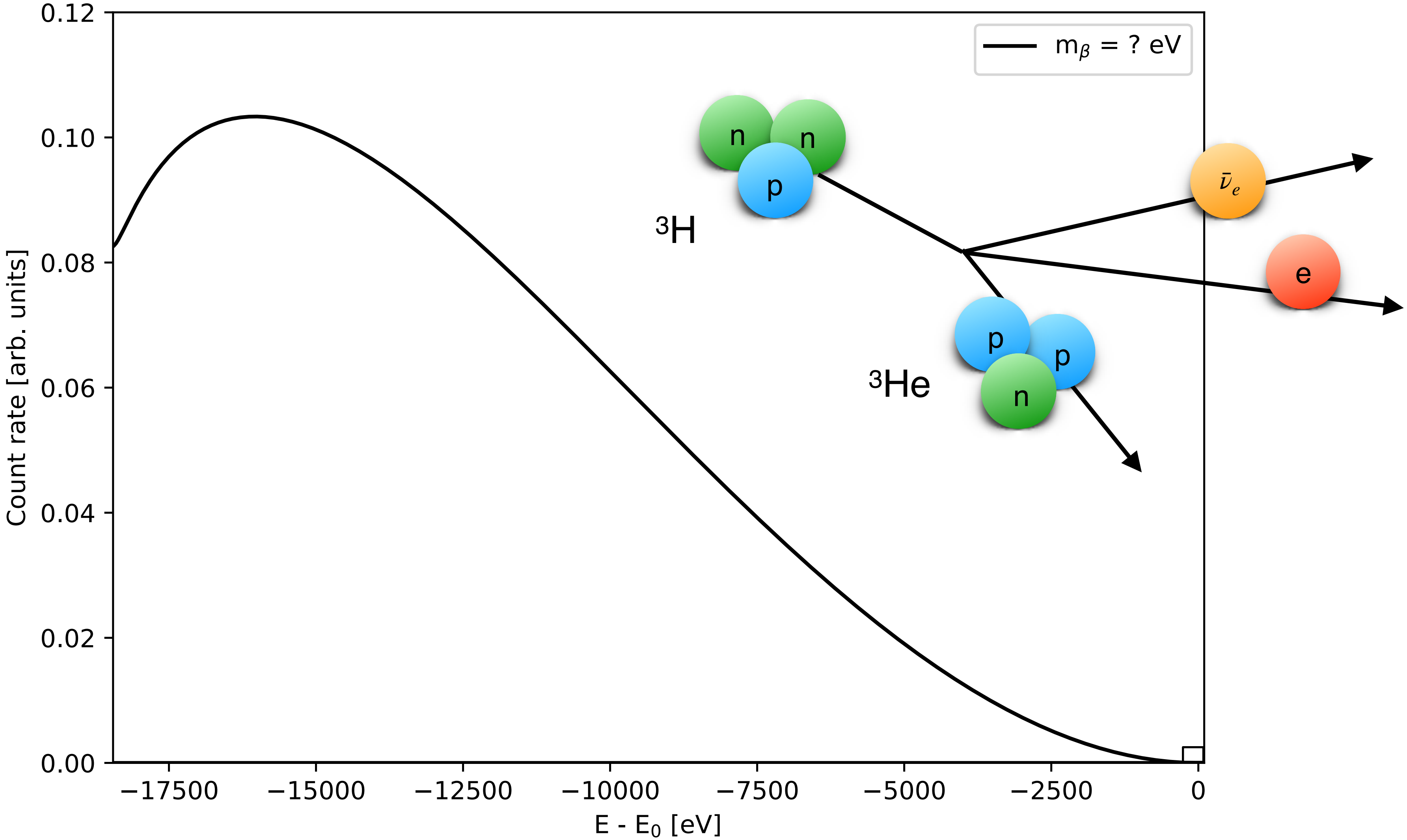

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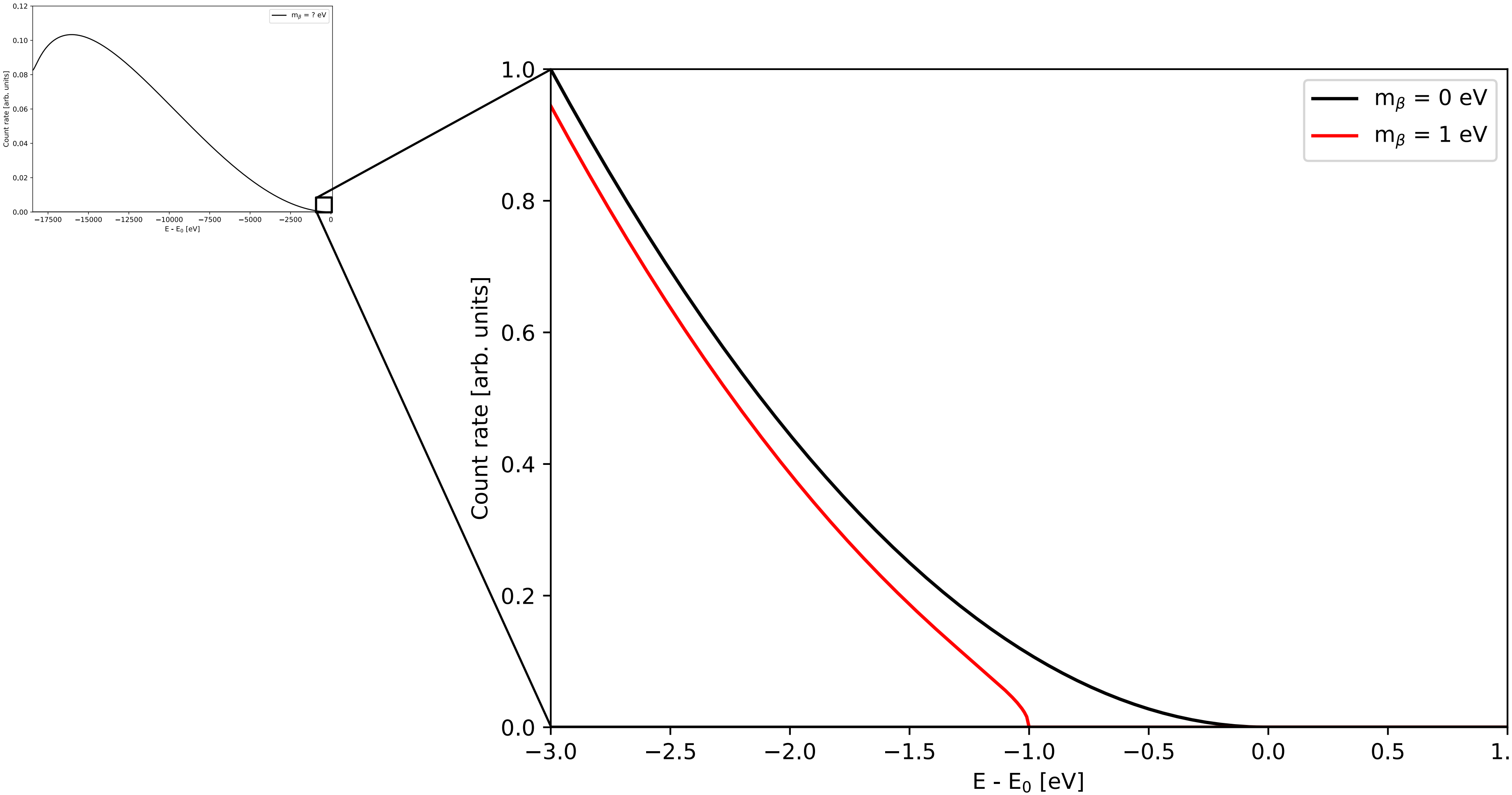

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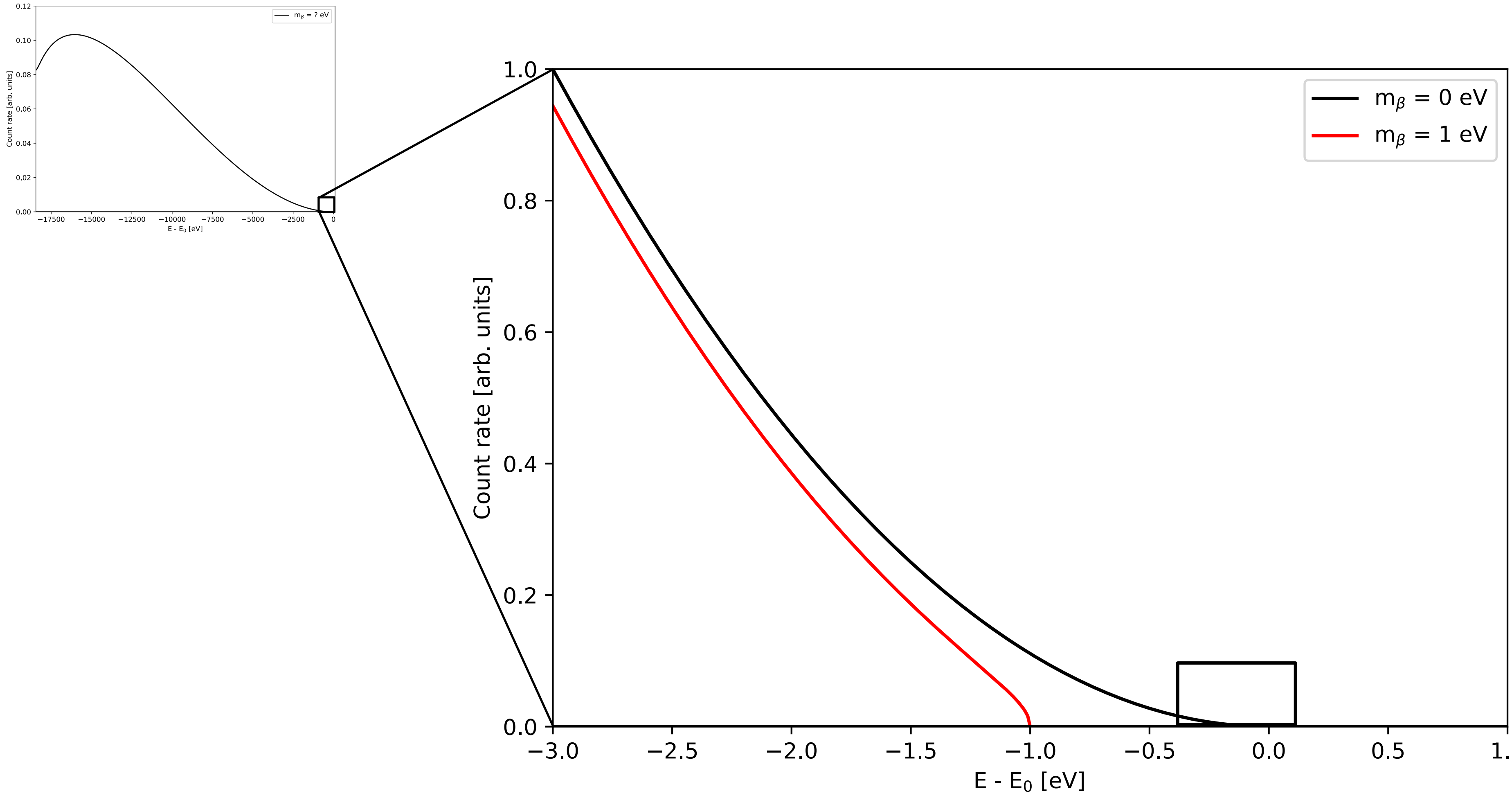

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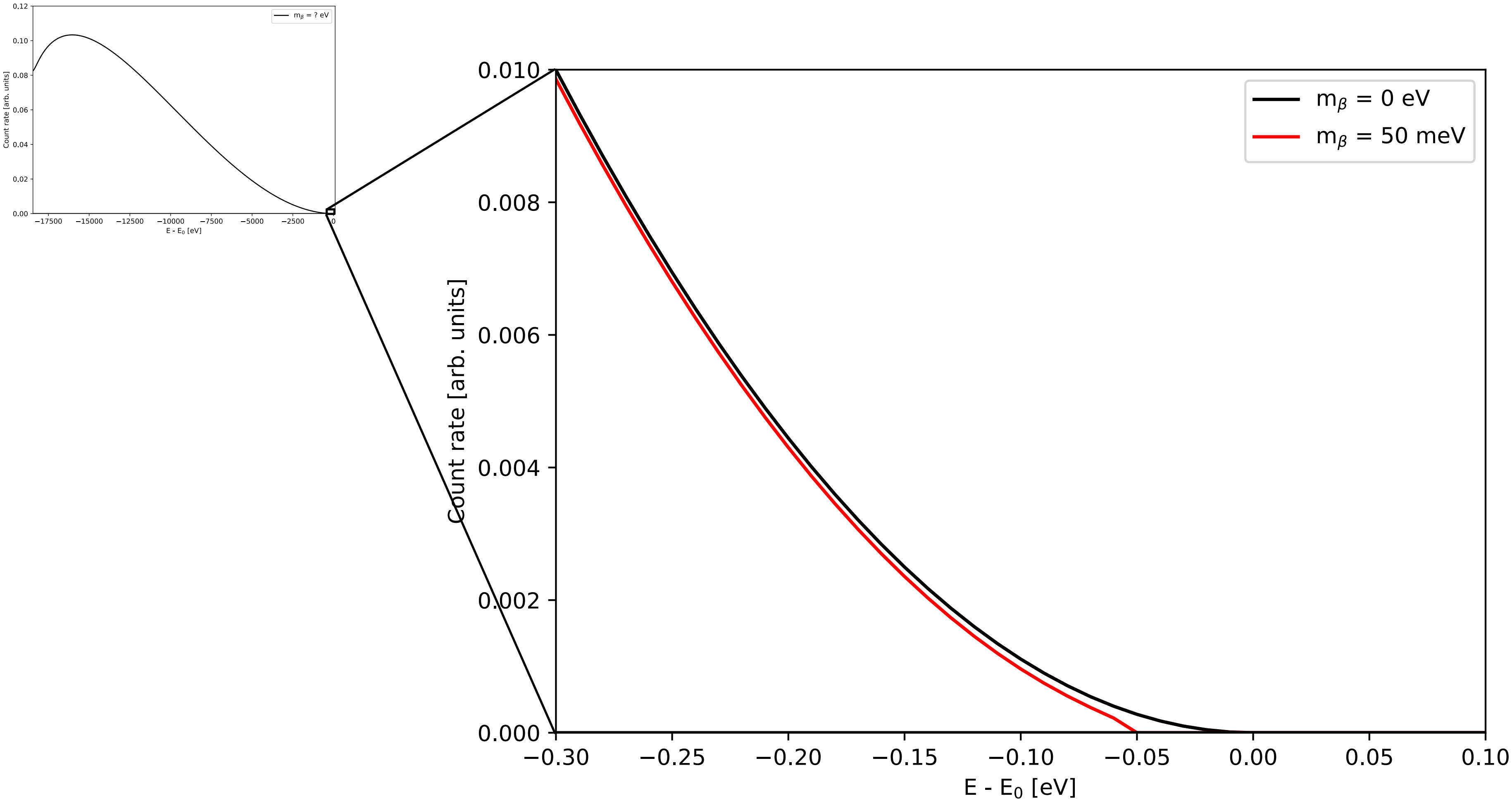
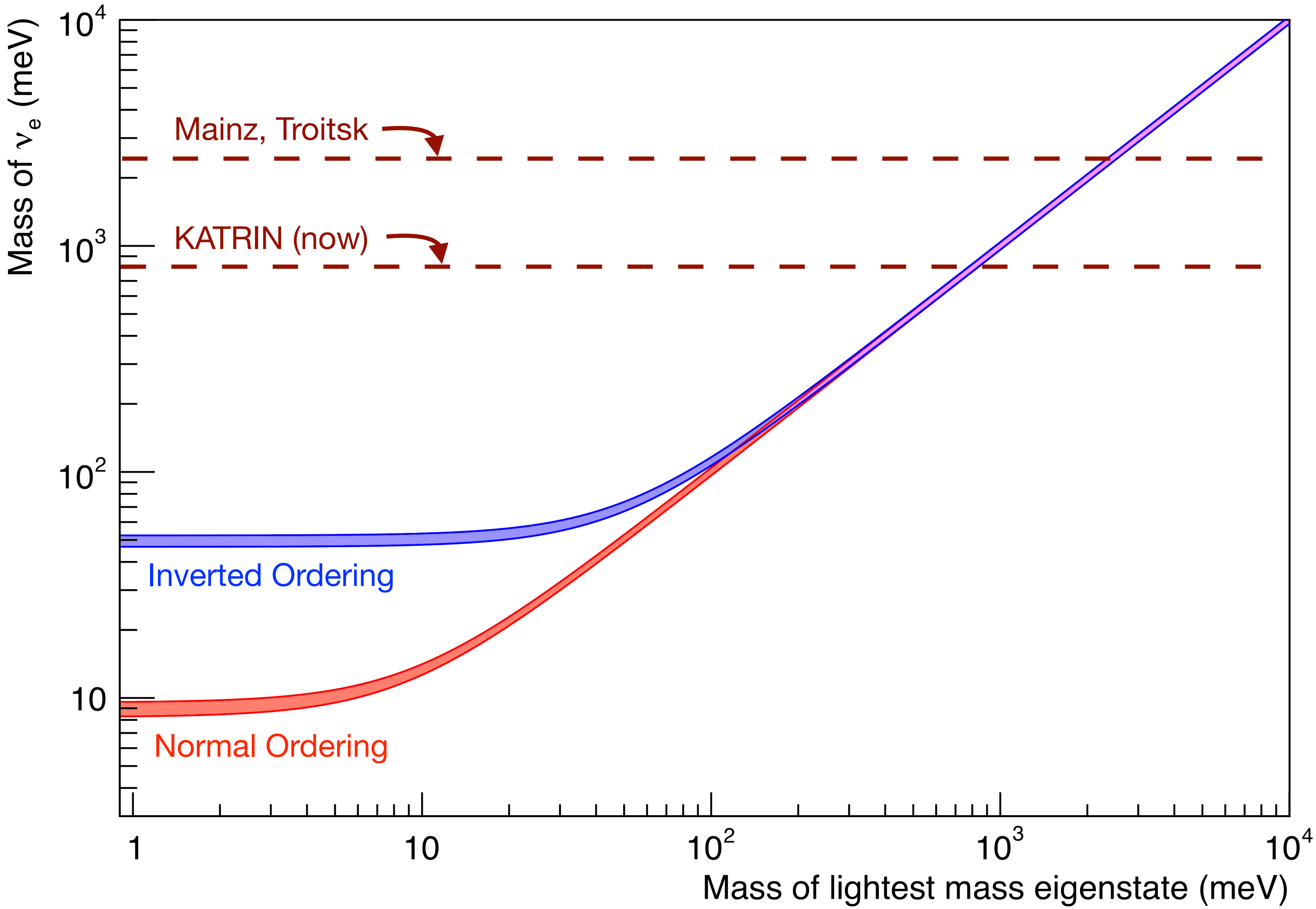


Project 8 Goal



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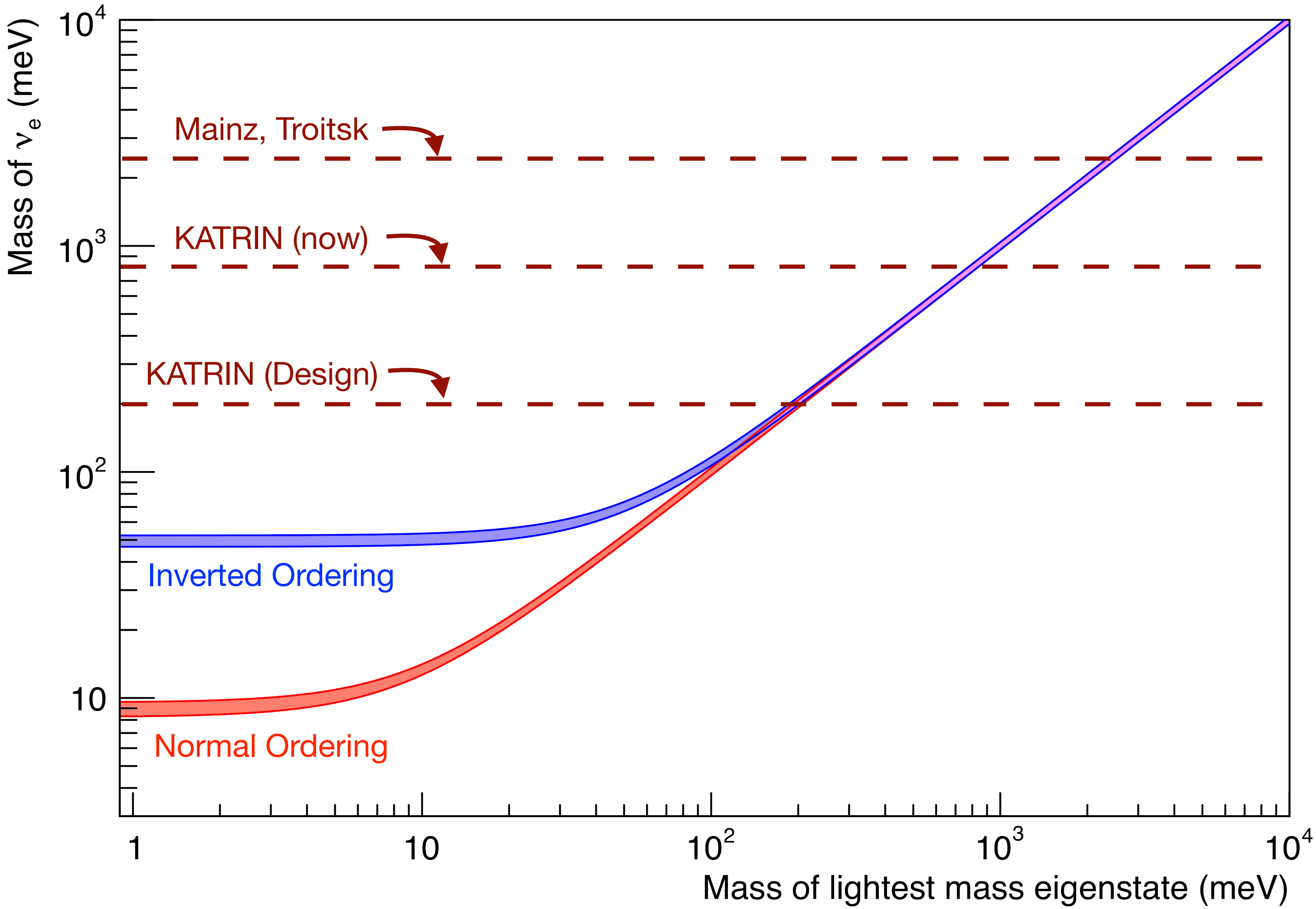

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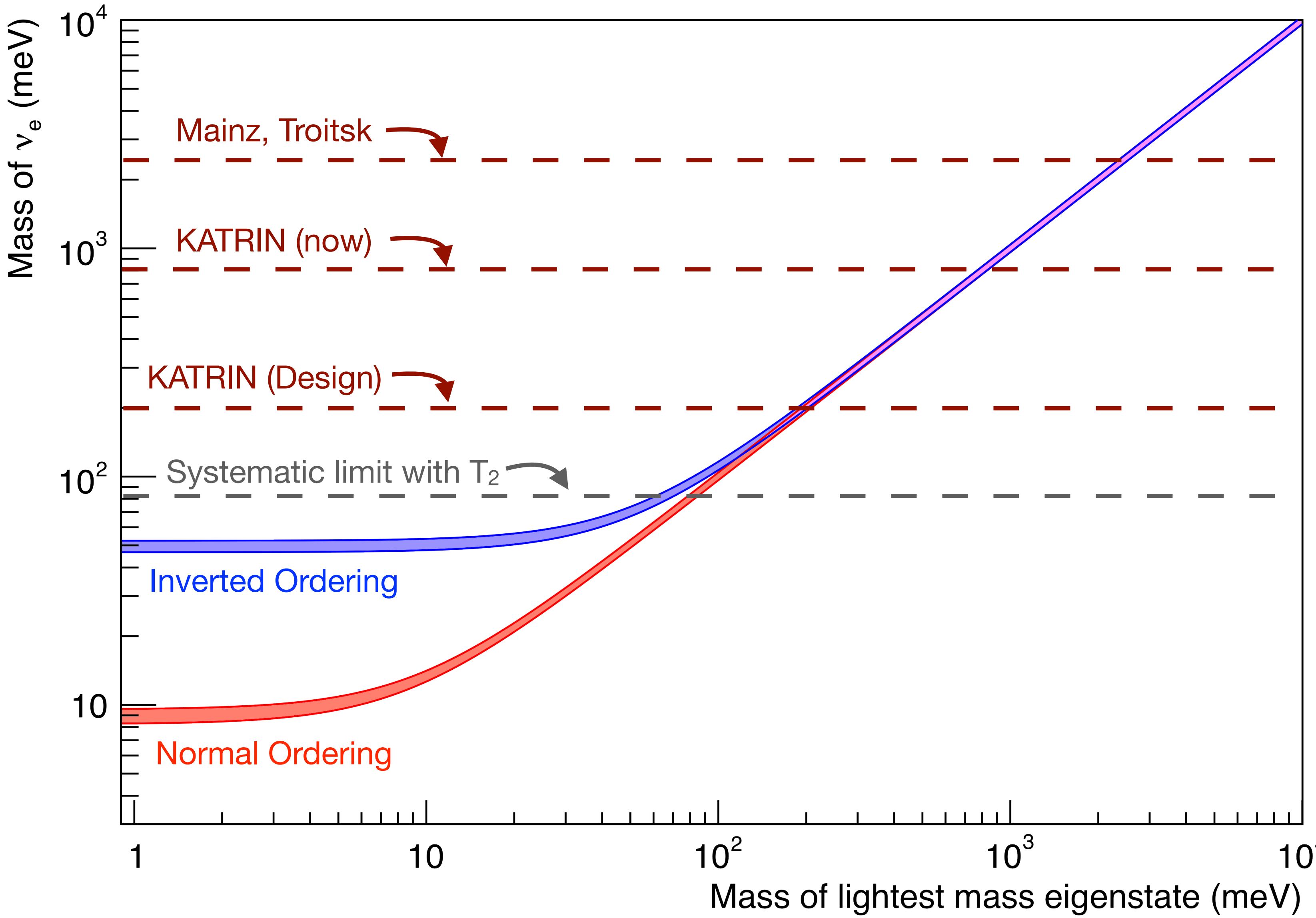

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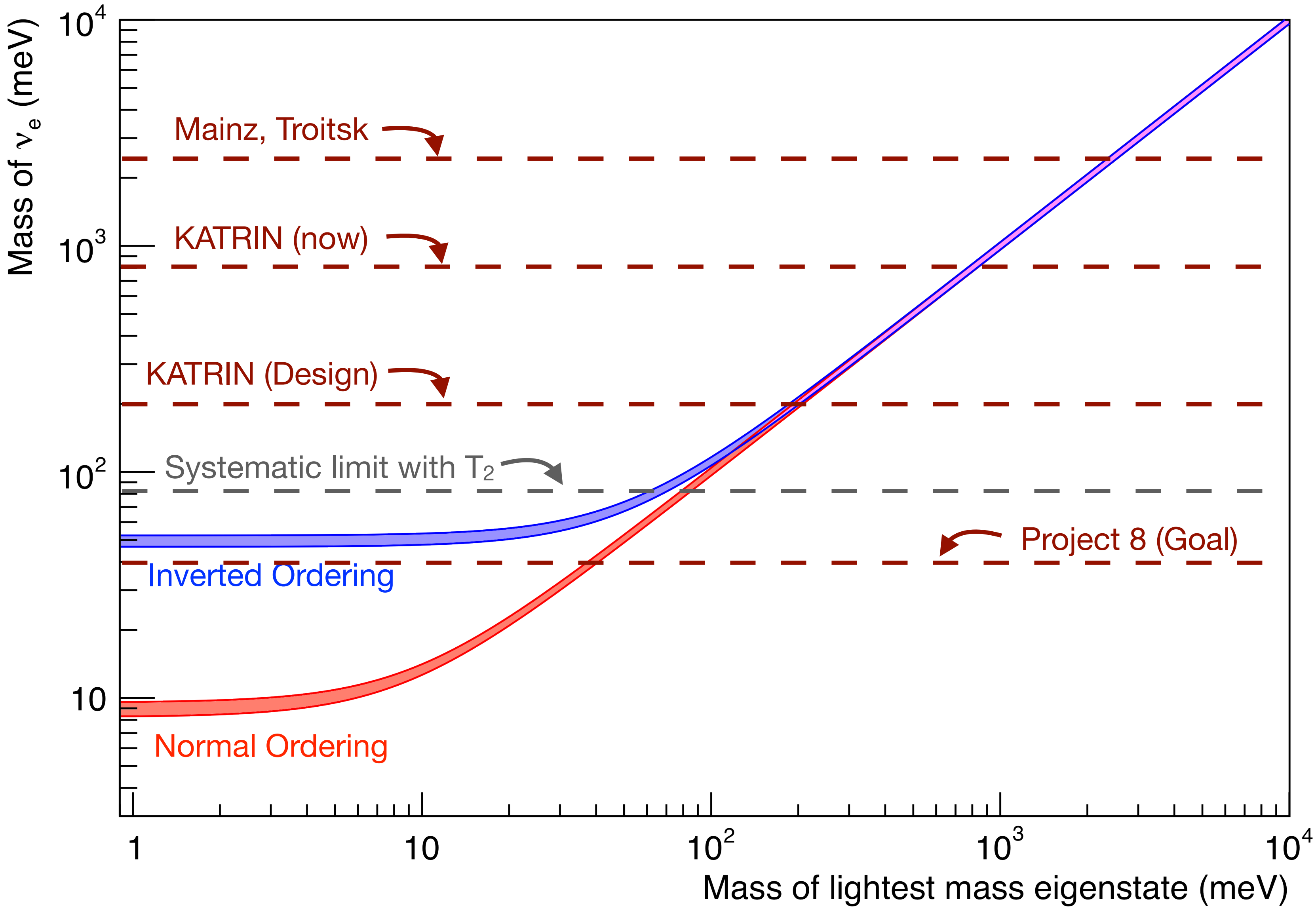

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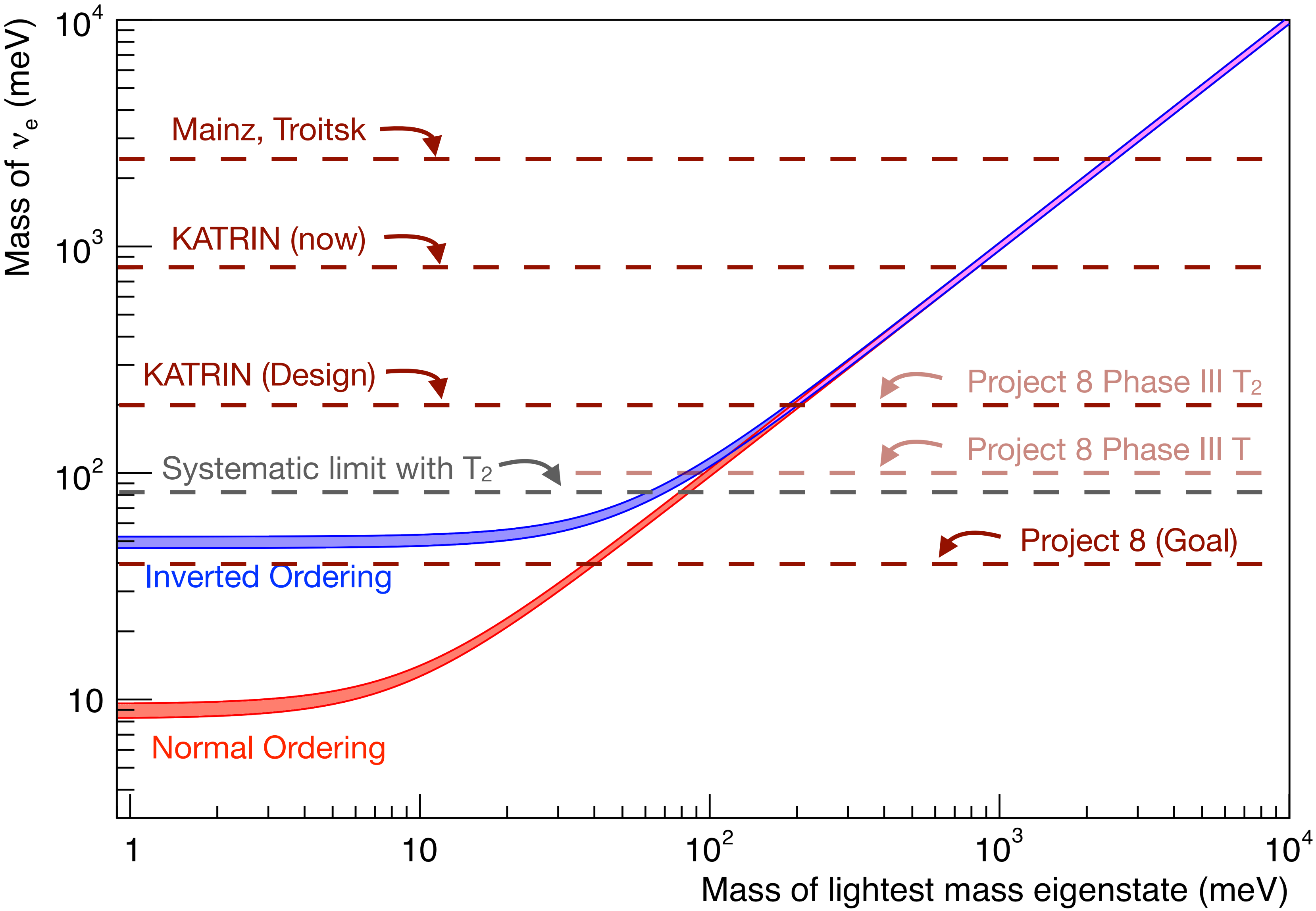


CRES

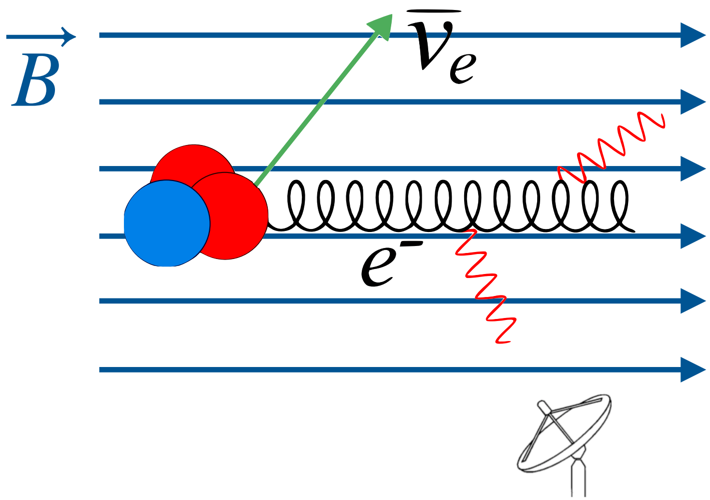
- Cyclotron Radiation Emission Spectroscopy
- Electron in B-field: cyclotron motion & radiation:

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

- Energy resolution:

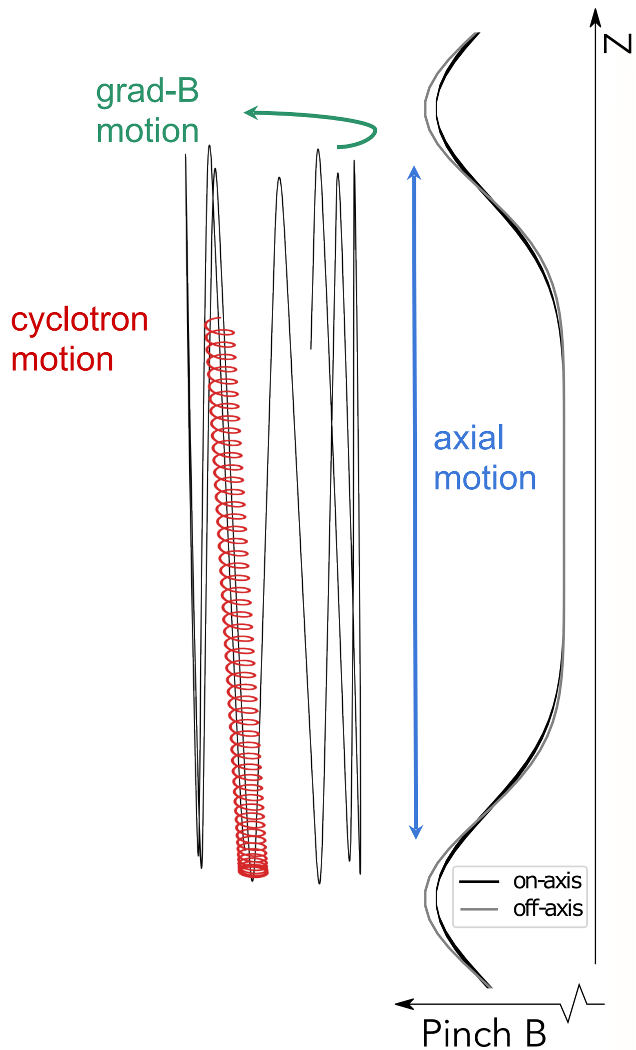
$$\frac{\Delta E}{m_e} \approx \frac{\Delta f}{f}$$

"Never measure anything but frequency!" — A. L. Schawlow



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

CRES Electron Motion



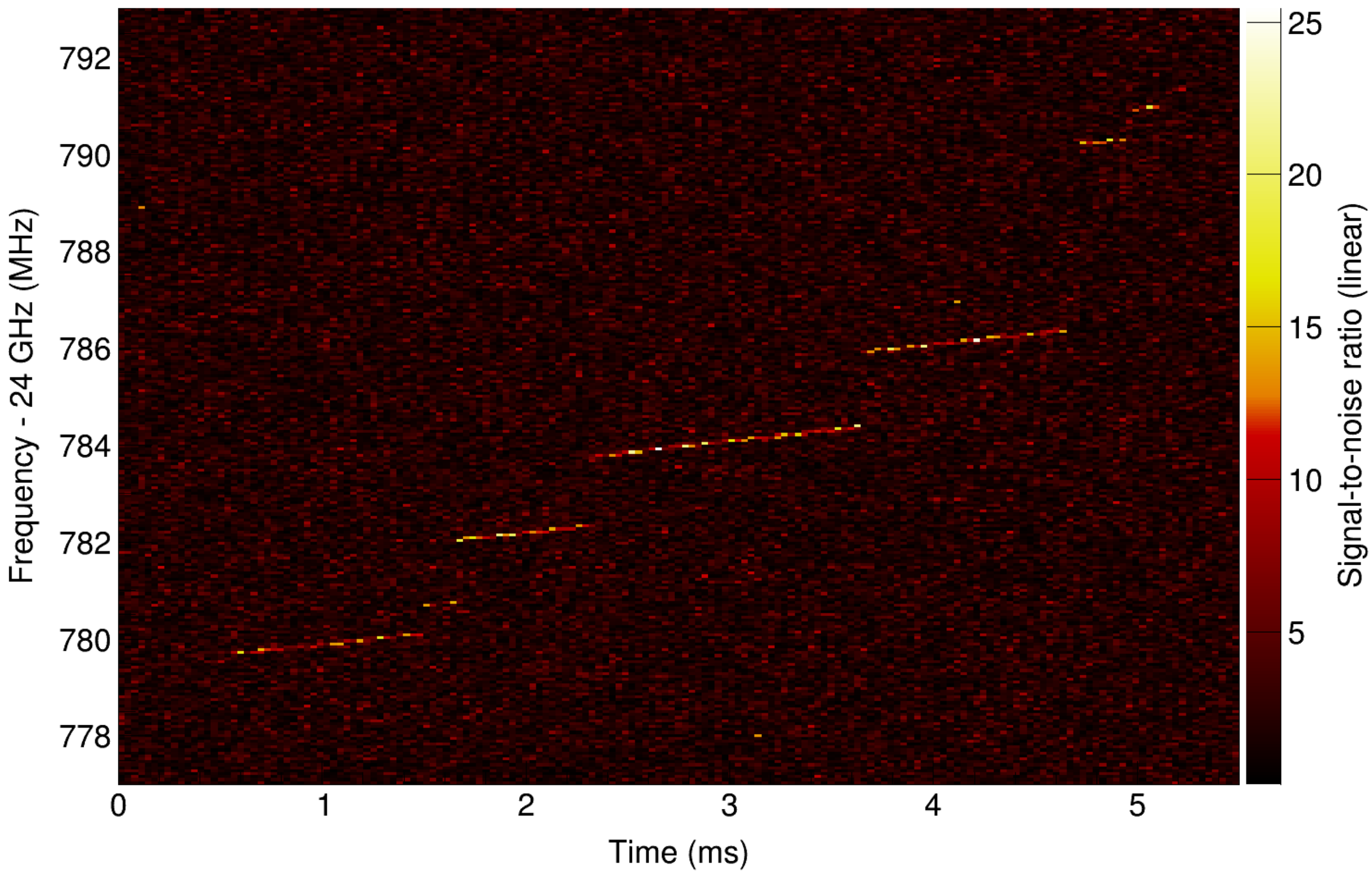
- Electron trapped in magnetic field
- Three superimposed motions:
  - Cyclotron motion with frequency

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

average magnetic field along electron trajectory

  - 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



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

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

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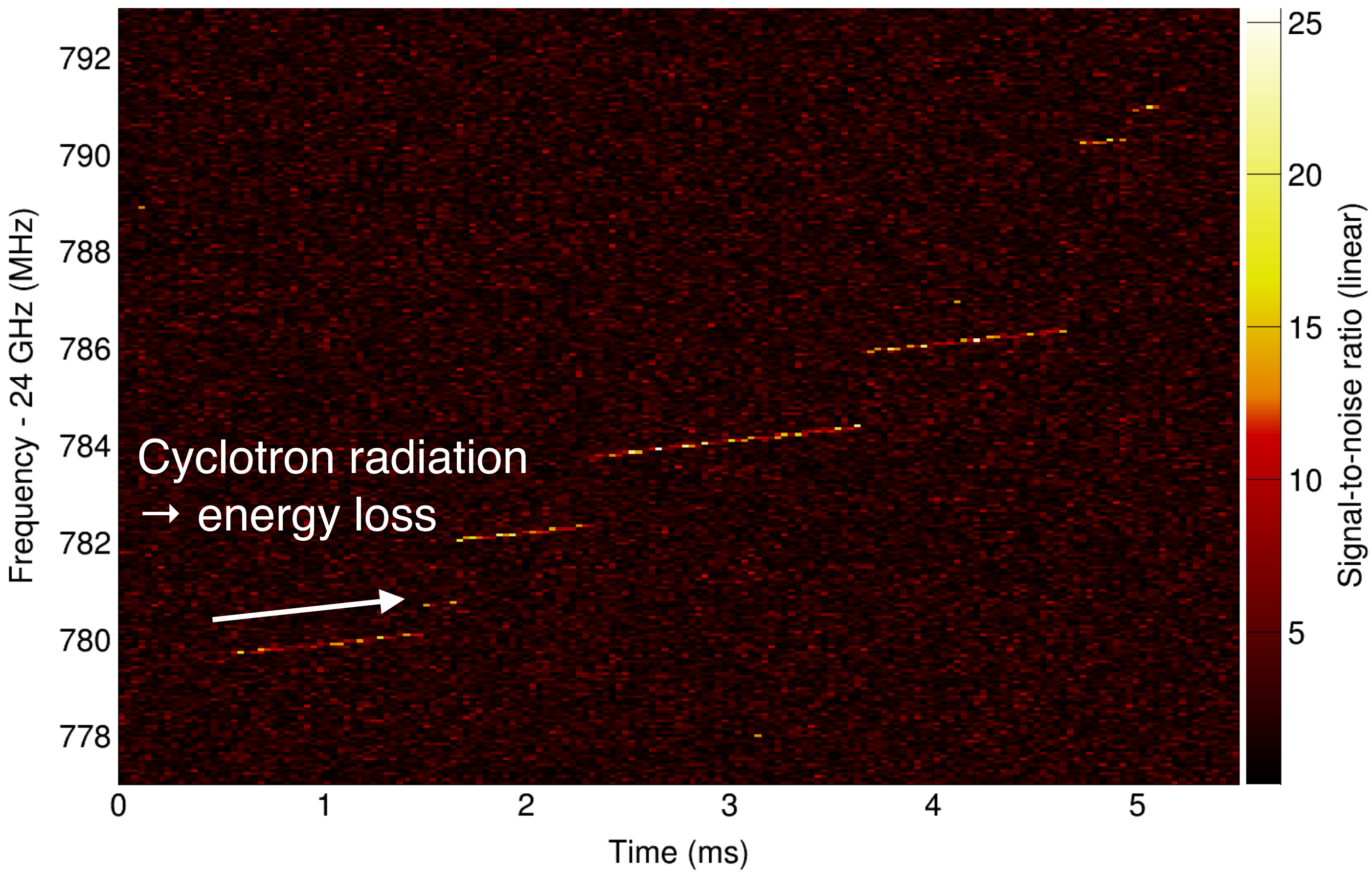

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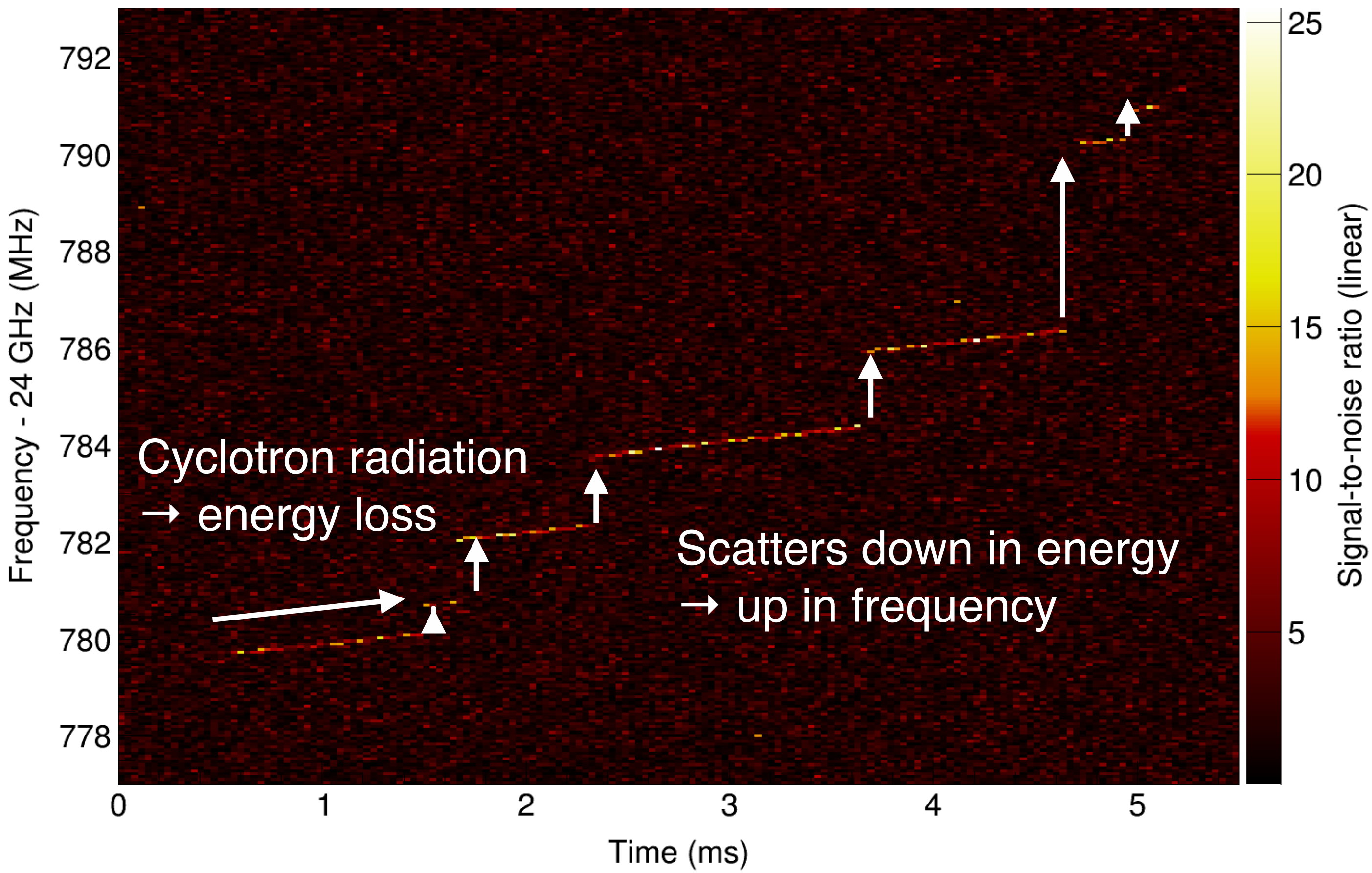

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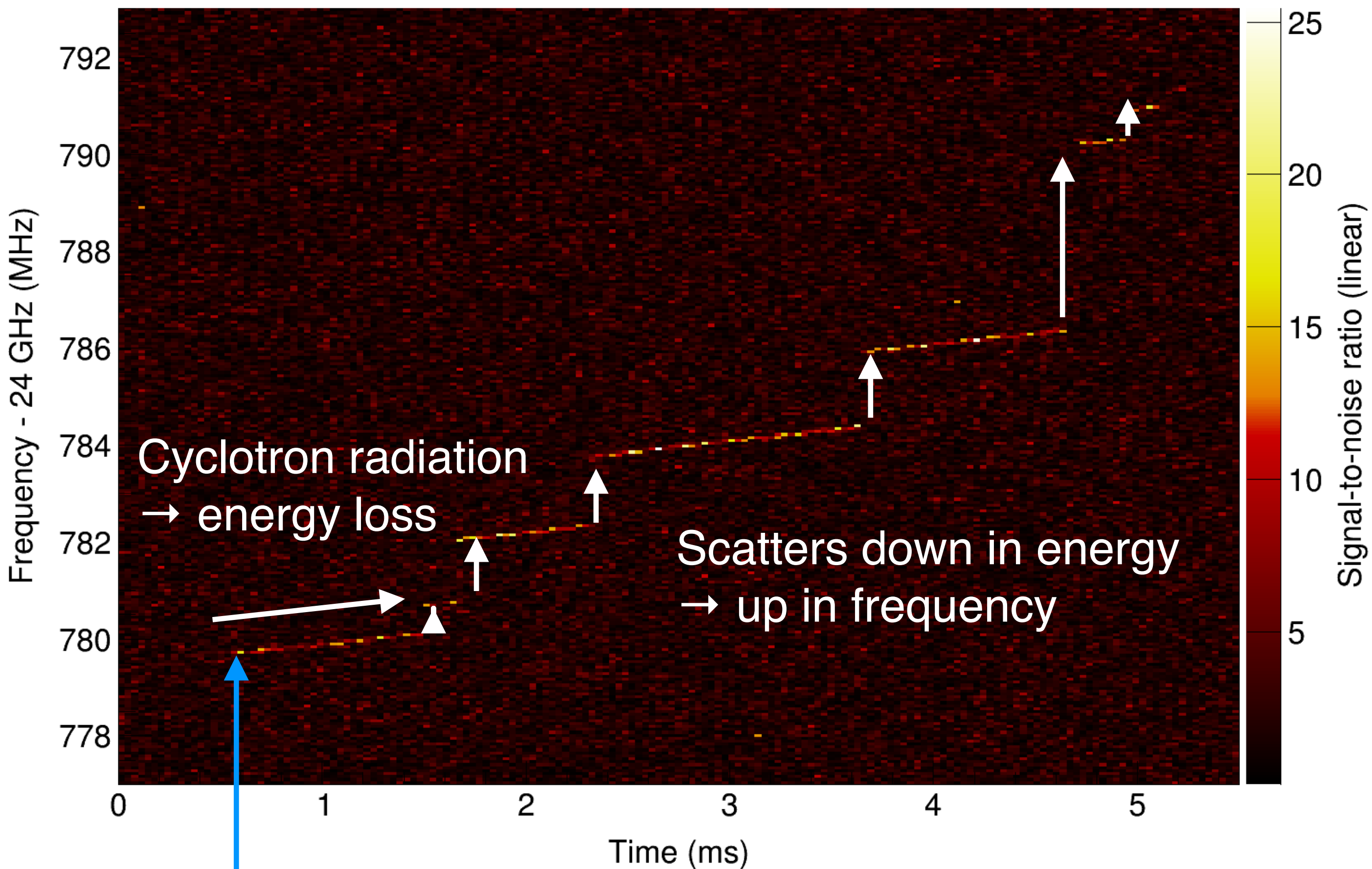


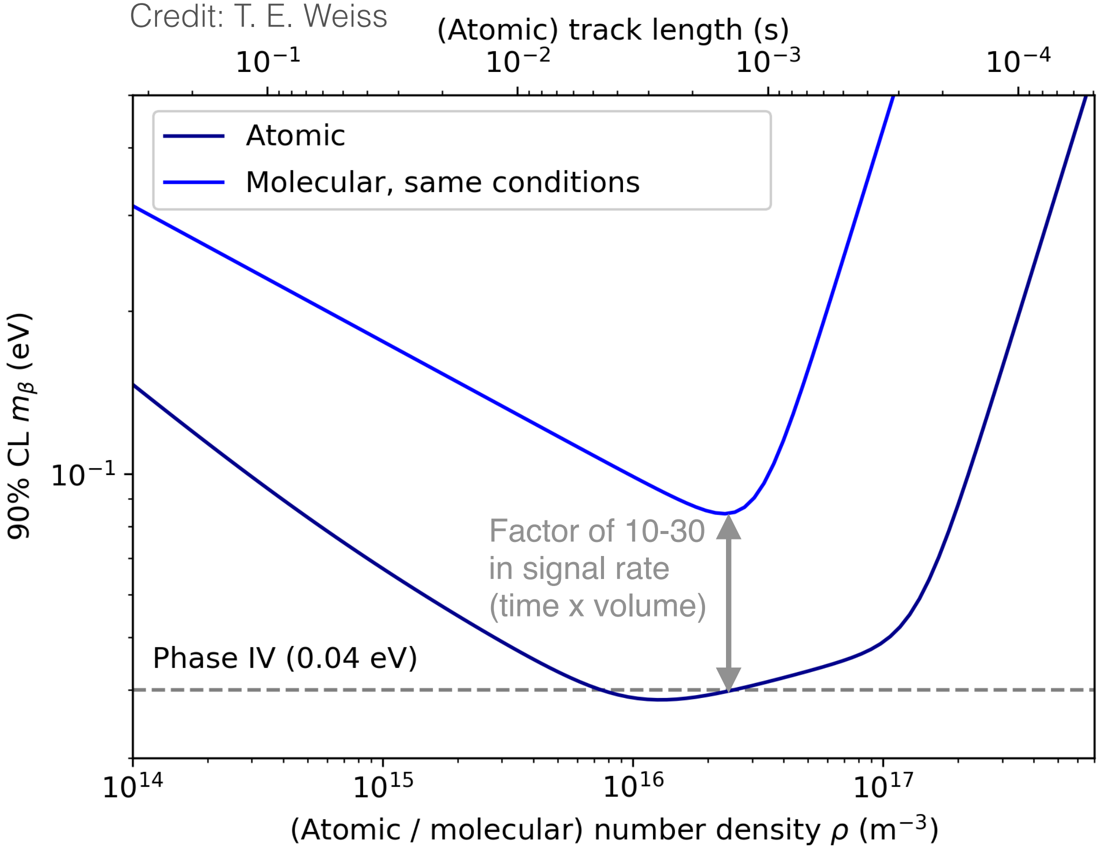
Start frequency: determines electron energy before losses

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

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

Why Go Atomic?

Credit: T. E. Weiss



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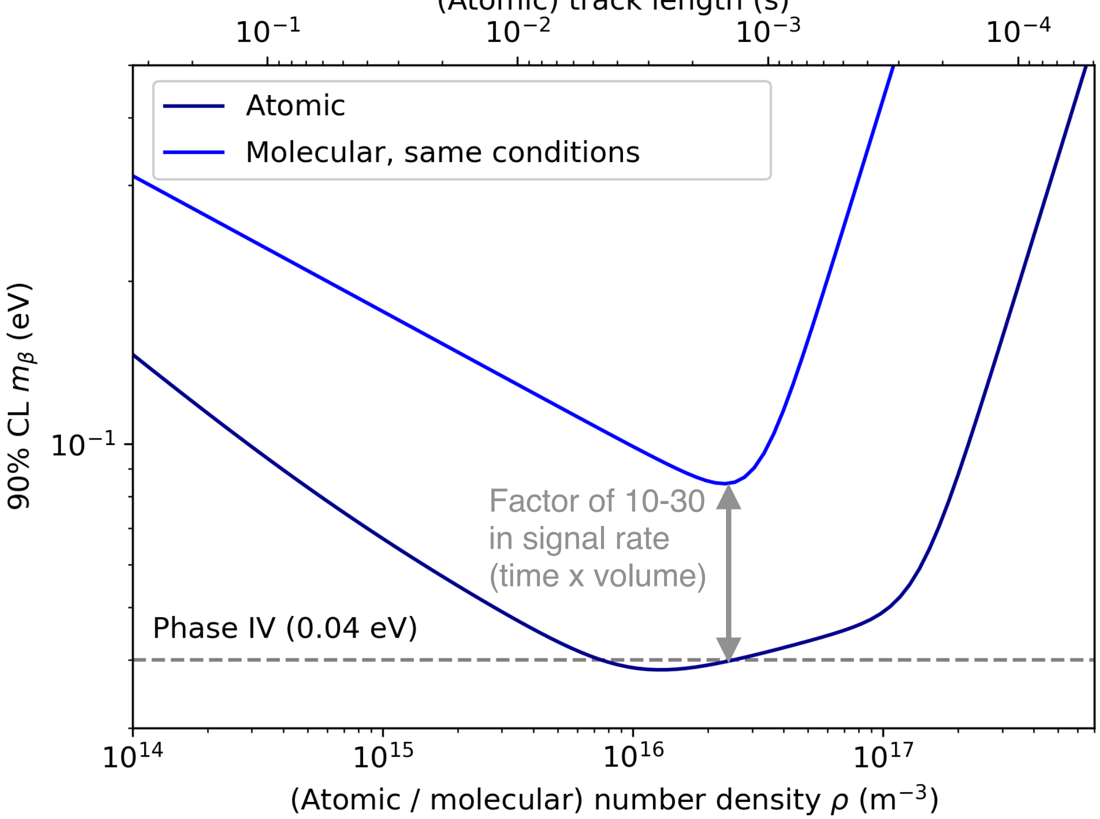

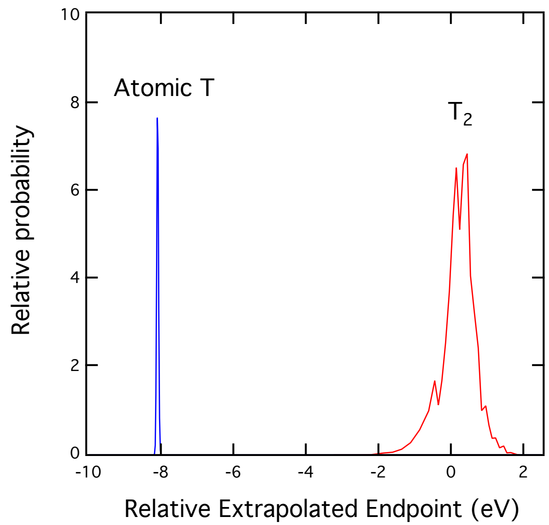

Phys. Rep. **914**, 1-54 (2021)

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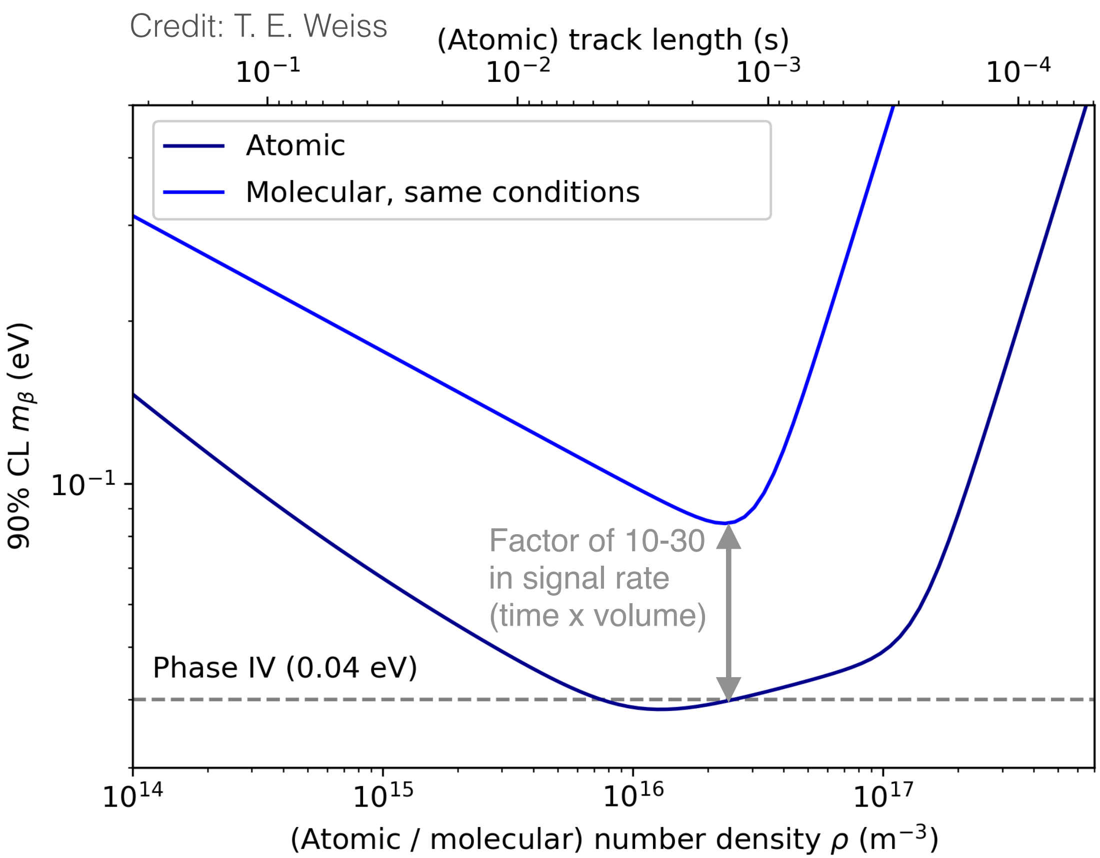

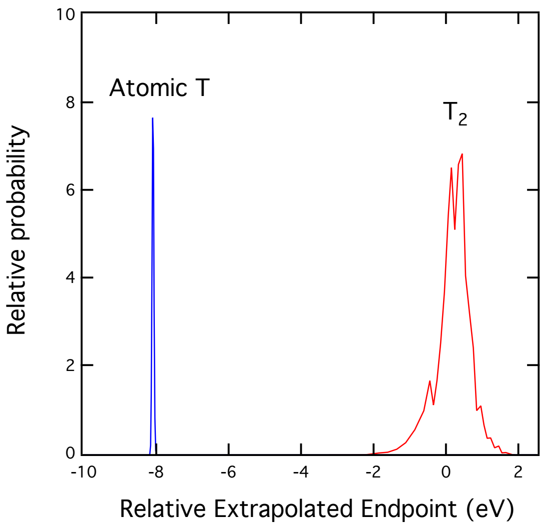

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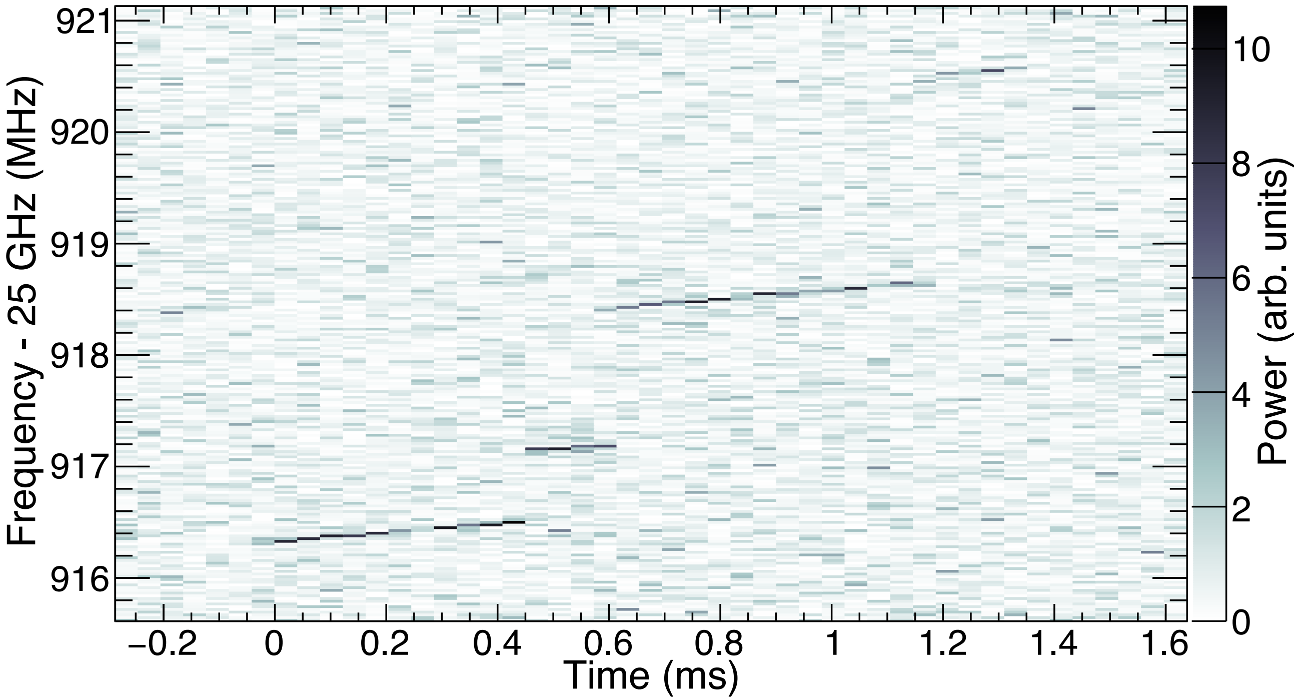
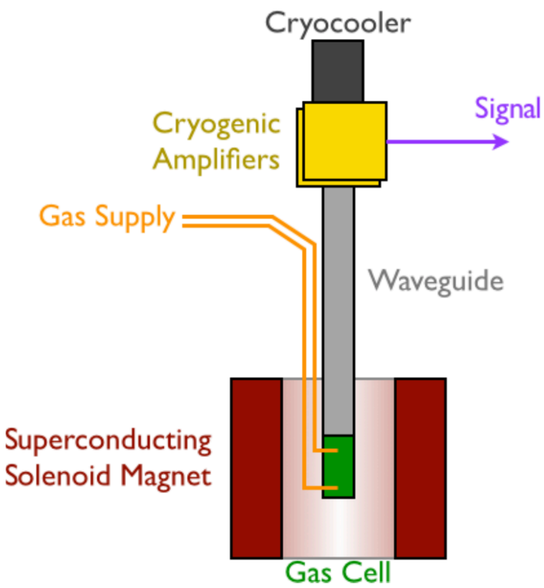
+ Uncertainties in molecular final states distribution!

Phase I & II Results



Phase I



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

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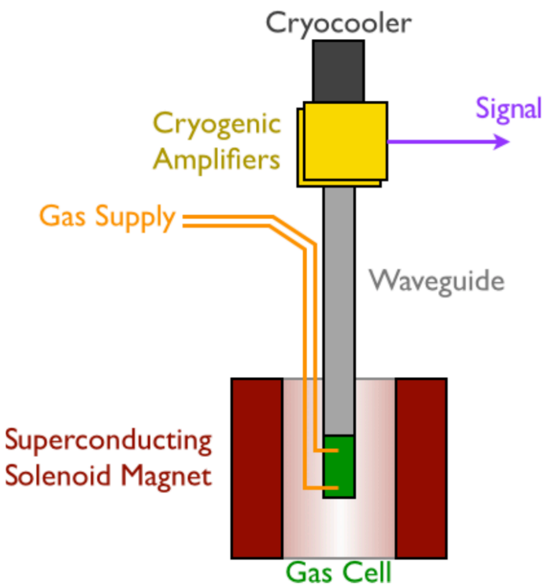

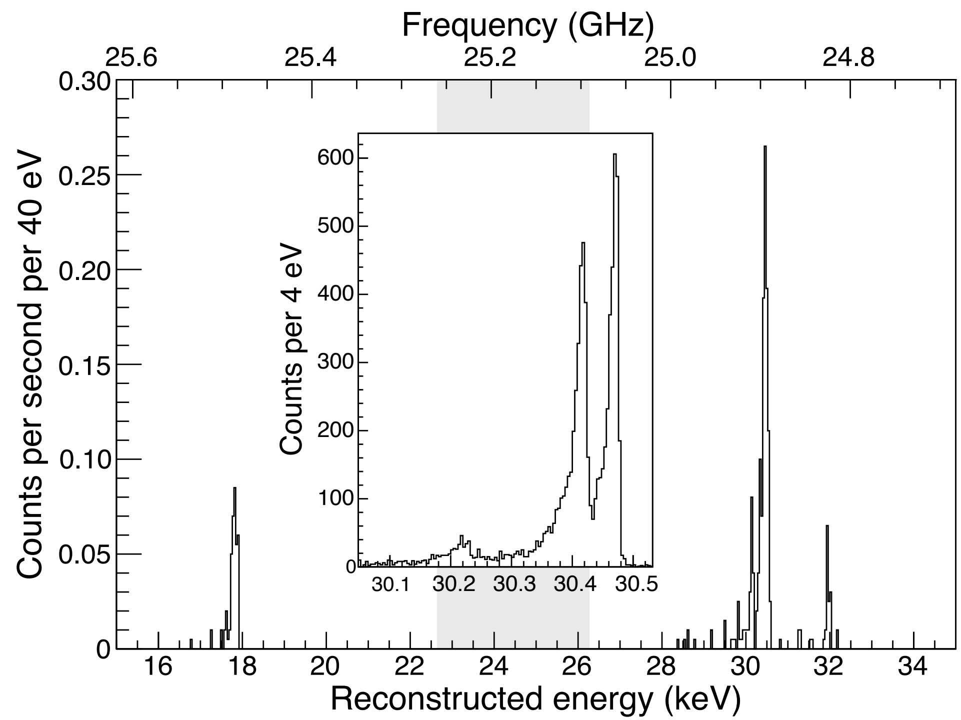

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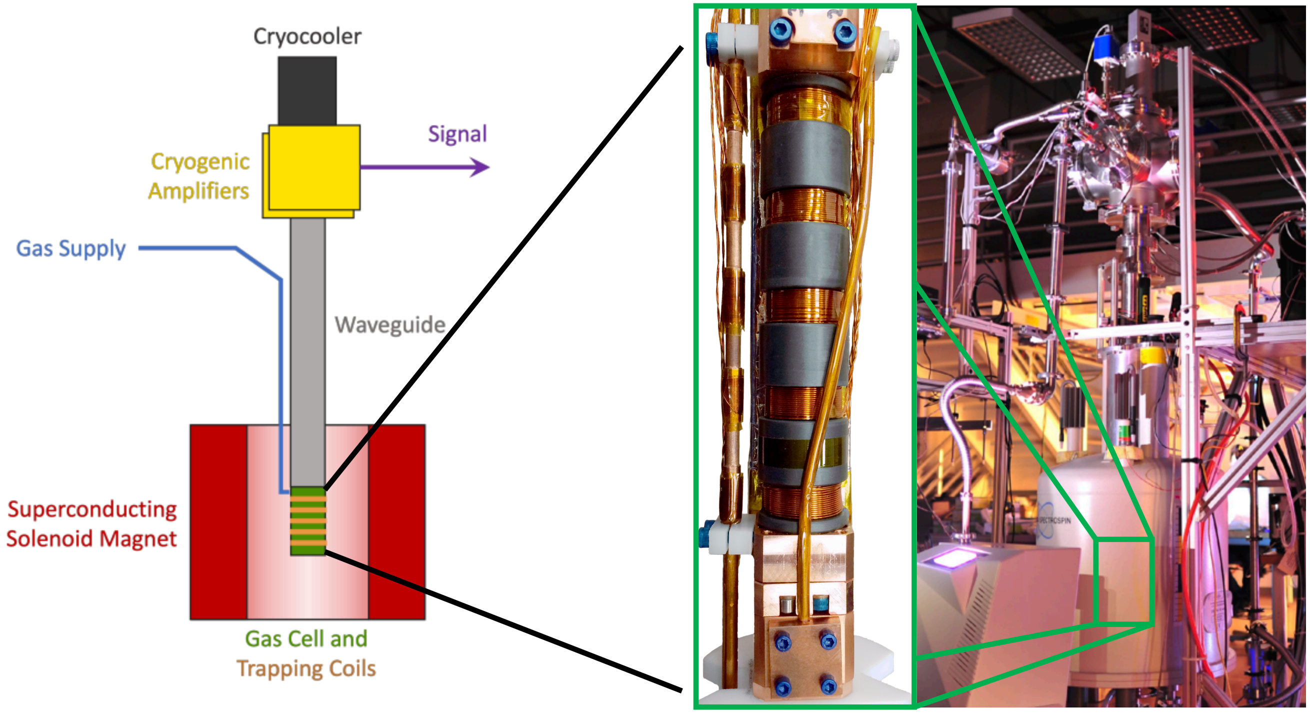
Phase II

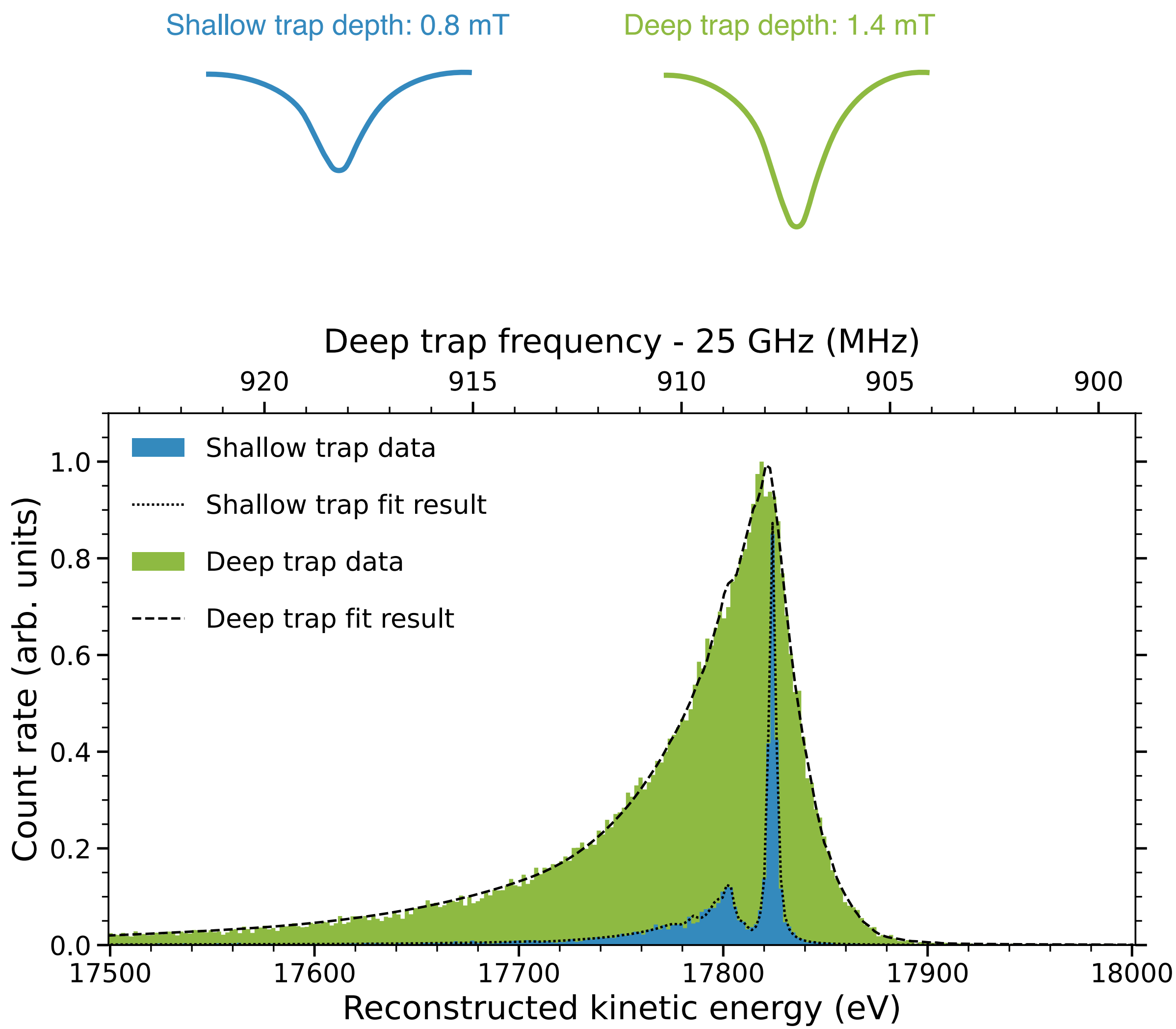


Credit: E. Novitski

- Effective volume: 1mm^3
- Demonstrated CRES on continuous tritium spectrum
- First neutrino mass upper limit extraction
- Zero background observed
- Improved energy resolution

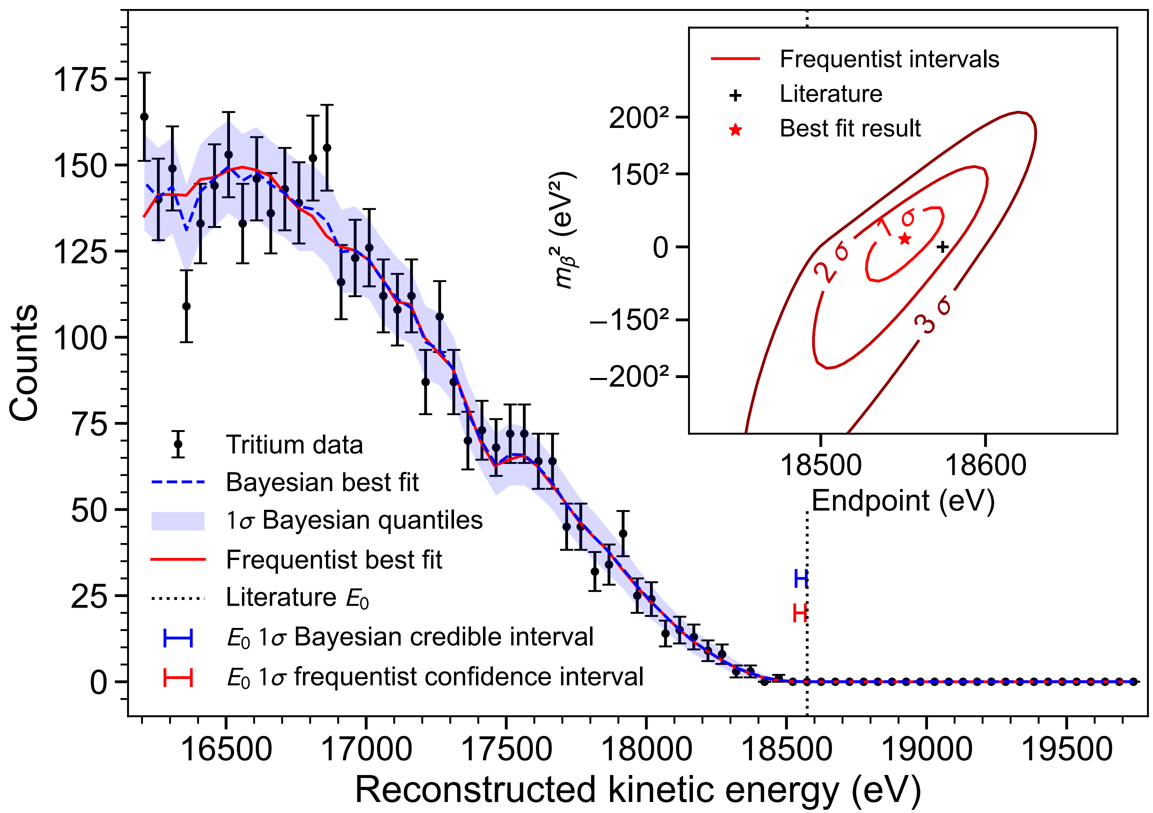
^{83m}Kr Measurements

- “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)

Phase II



T_2 endpoint:

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

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

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:

$\leq 3\times10^{-10}\,\mathrm{eV}^{-1}s^{-1}\,(90\,\%\,\mathrm{C.L.})$

Published September 6! Editor's Suggestion :)

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

Long-form paper: arXiv:2303.12055

Project 8: Phased Approach

- 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_β upper limit with CRES [2]

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- Phase II:
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  - First m_β upper limit with CRES [2]
- Phase III:

  - Atomic source development
  - Large-volume CRES

} Sensitivity: $m_\beta < 100\,\mathrm{meV}\ (90\,\%\ \mathrm{C.L.})$

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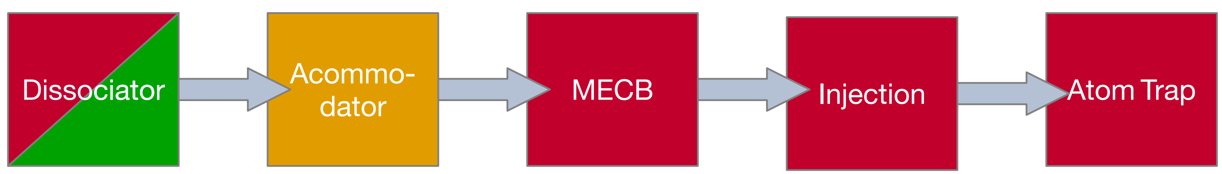
- Phase IV:
  - Neutrino mass measurement if $m_\beta \geq 40\,\mathrm{meV}$

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

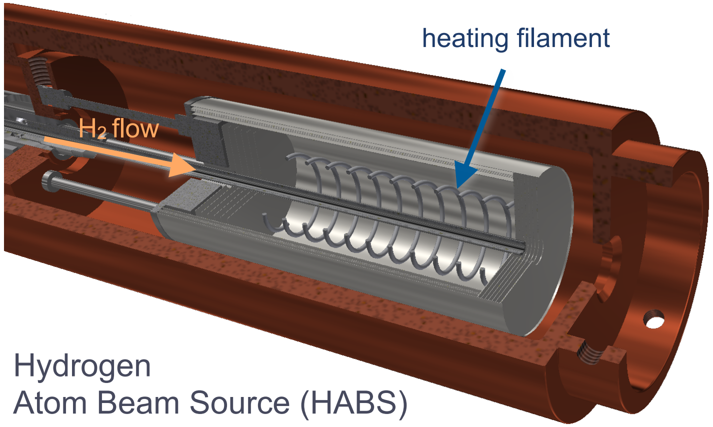
[2] Phys.Rev.Lett. 131, 102502 (2023)

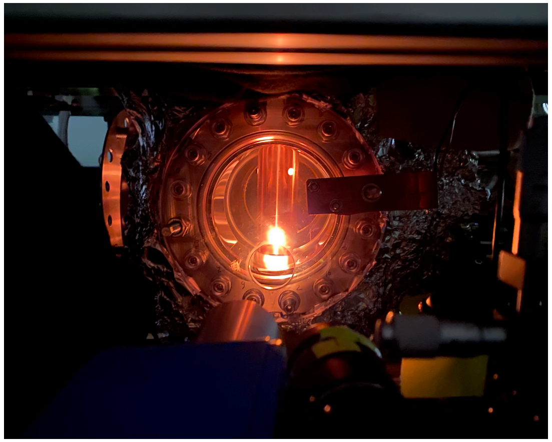
Phase III R&D: Atomic Tritium



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
  - New developments
  - Currently revisiting





Credit: L. Thorne

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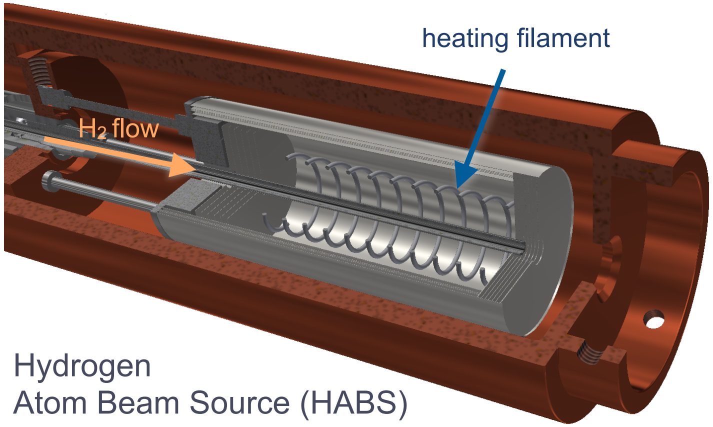

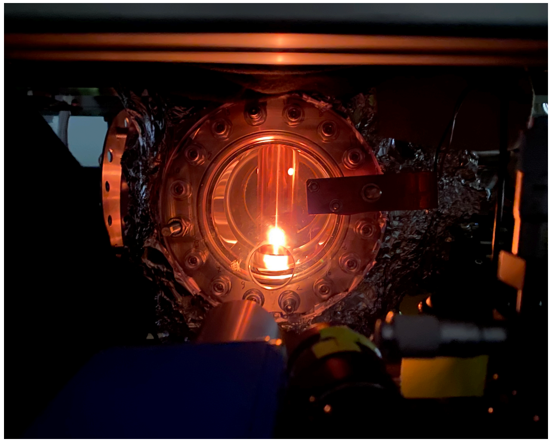

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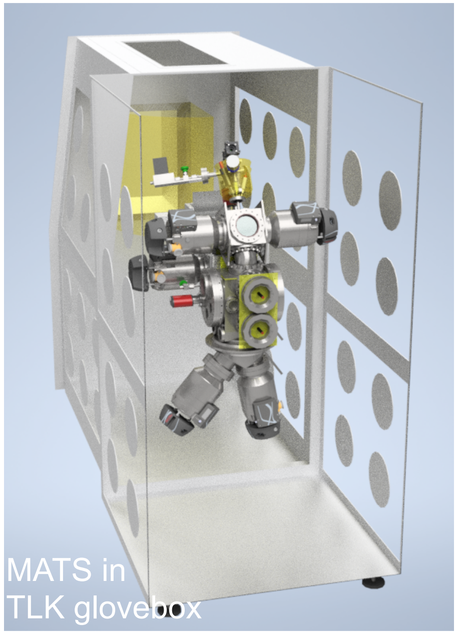

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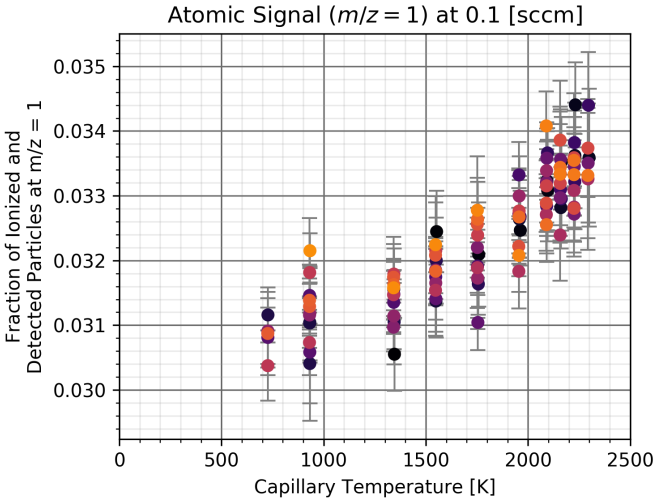
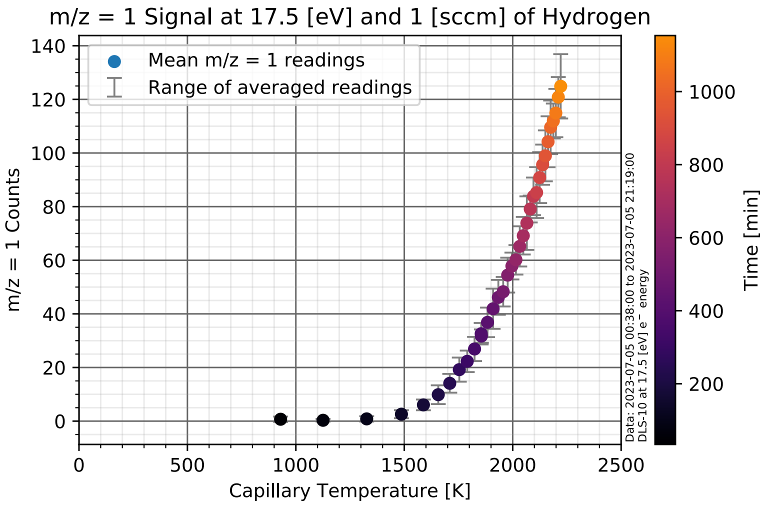


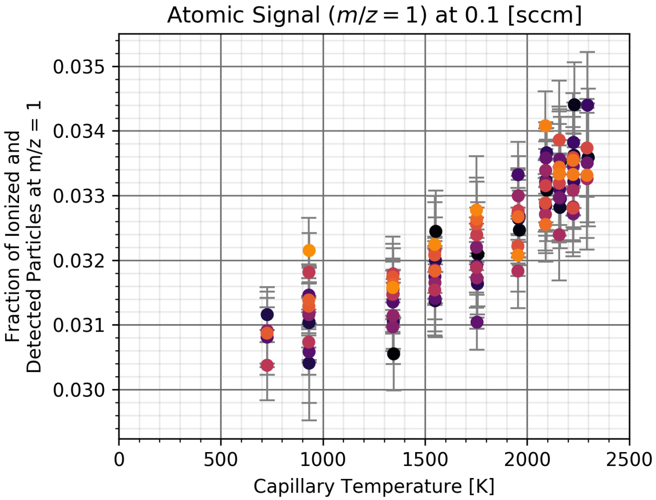


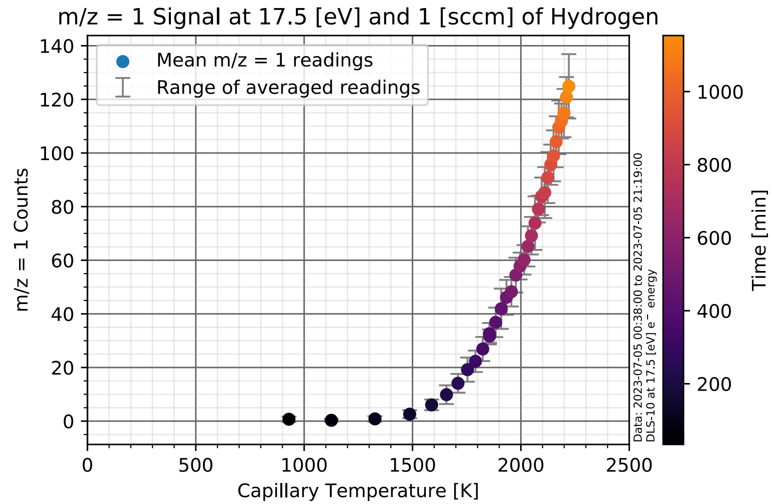
- Atom cracking using mass spectrometer proven

Credit: A. Lindmann

PROJECT 8

Hydrogen Atom Production





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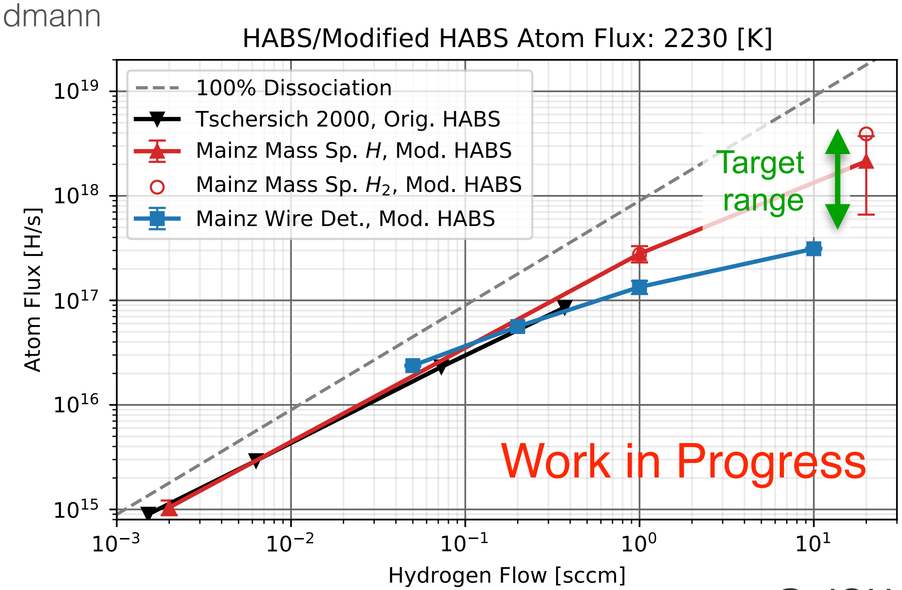
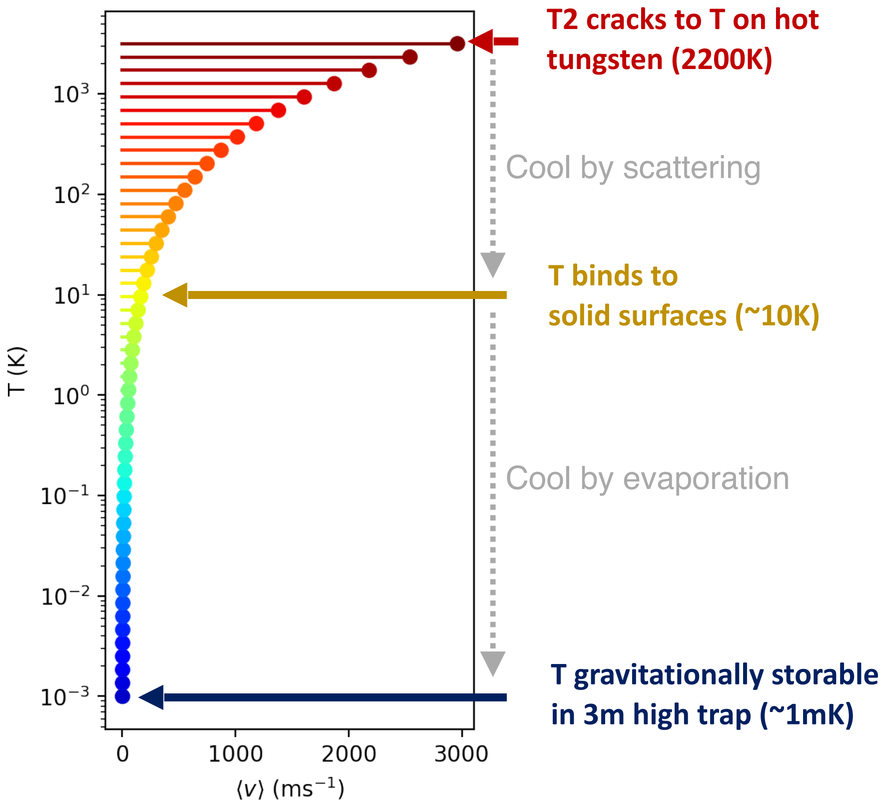


- Atomic hydrogen beam characterization in progress

@ JGU Mainz

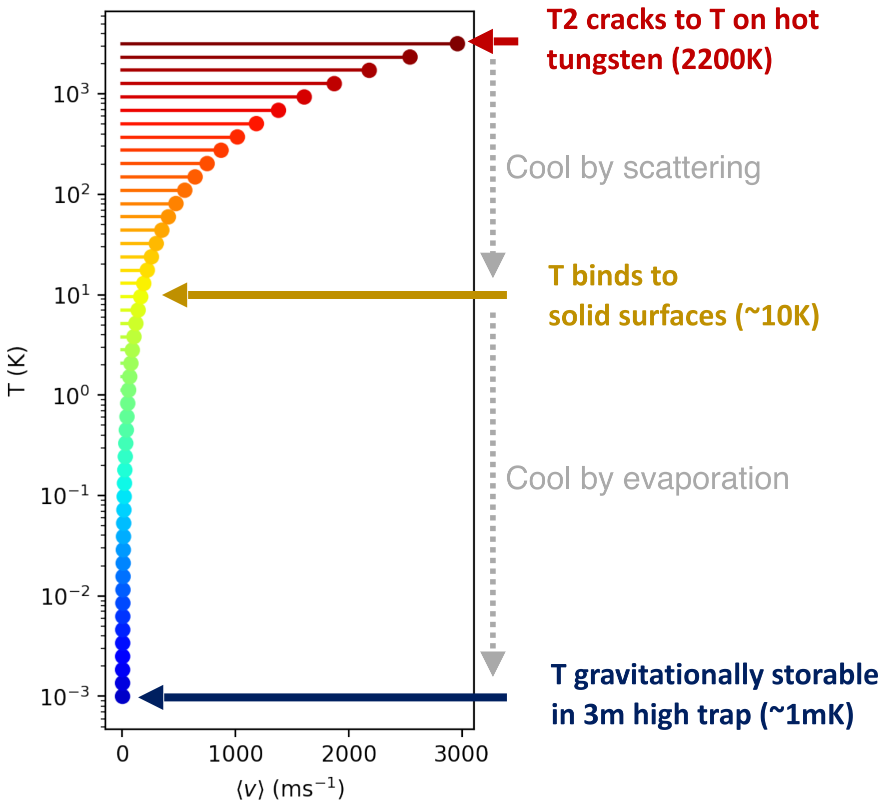
Atom Cooling

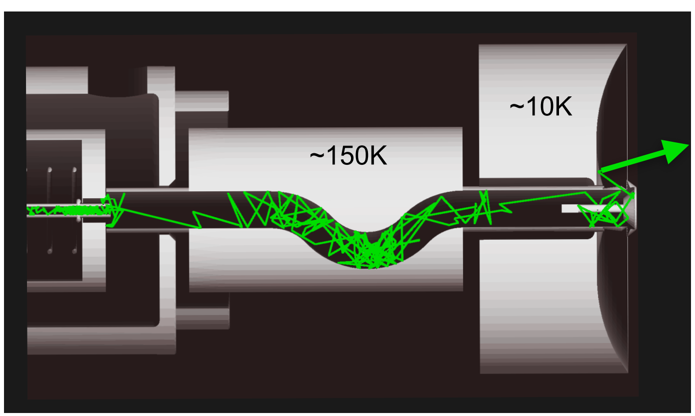


1. Accommodator: cool to 150K with multiple bounces at low recombination rate
2. One-bounce nozzle to cool to 10K
3. Cool by evaporation of hottest atoms

PROJECT 8

Atom Cooling





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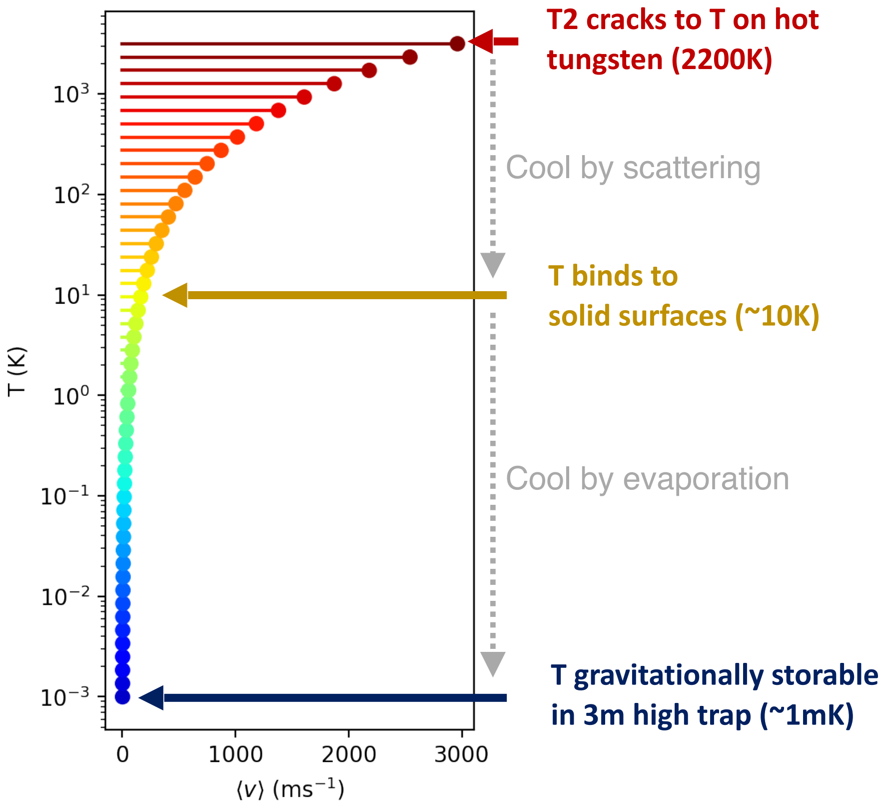

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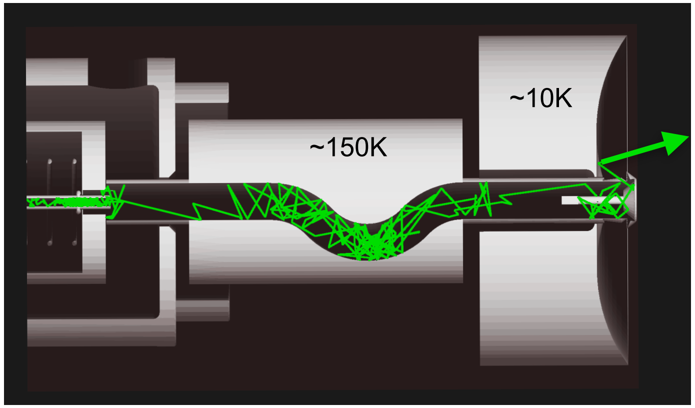
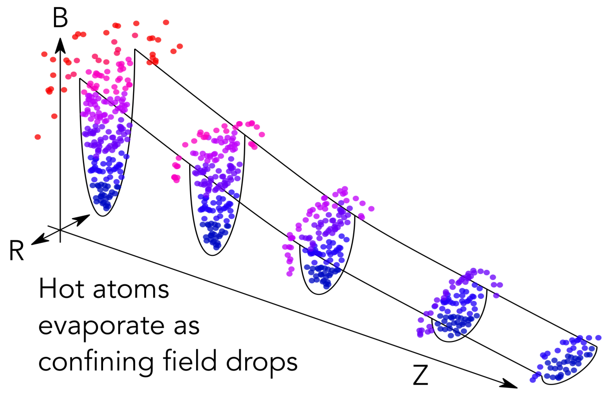
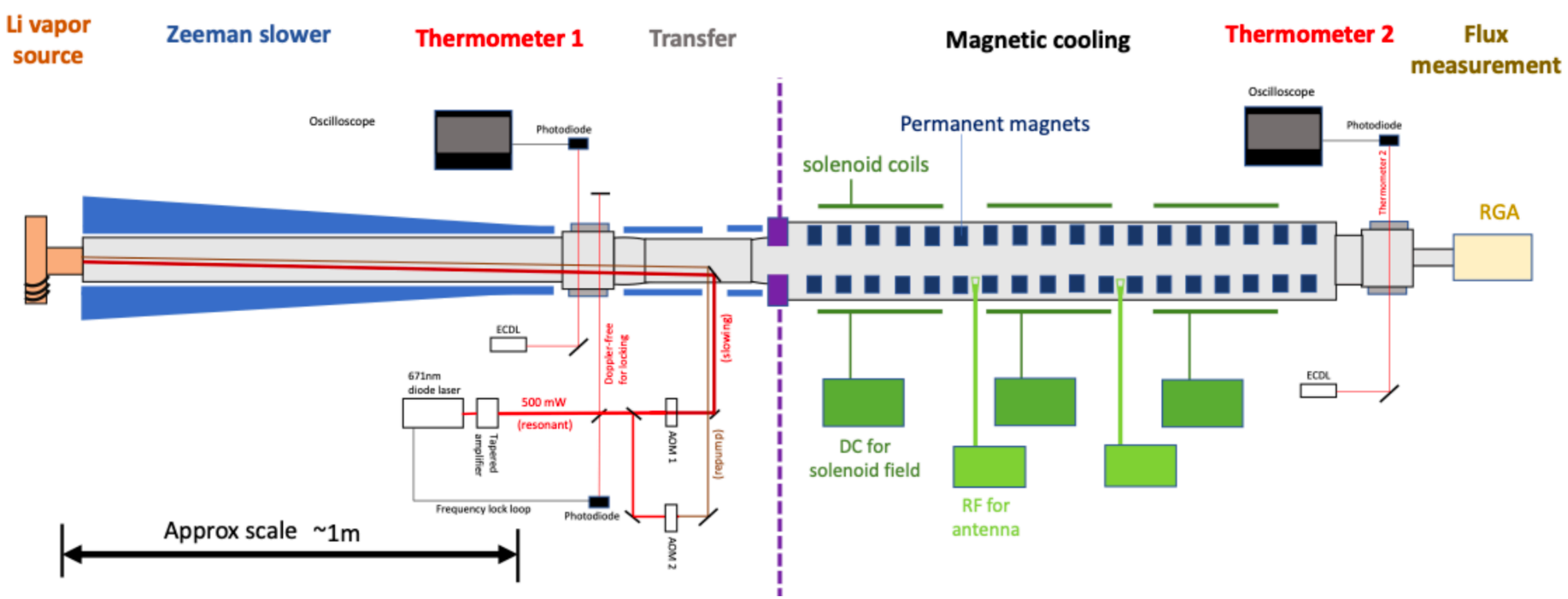




Credit: A. Lindmann

Magnetic Evaporative Cooling Beamline

- Can this be done in a beam line?
- Prototype with Lithium-6 @ UT Arlington
  - Don’t need to wait for cracker-accommodator-nozzle development to conclude
- Then H/D beam line cooling, finally T

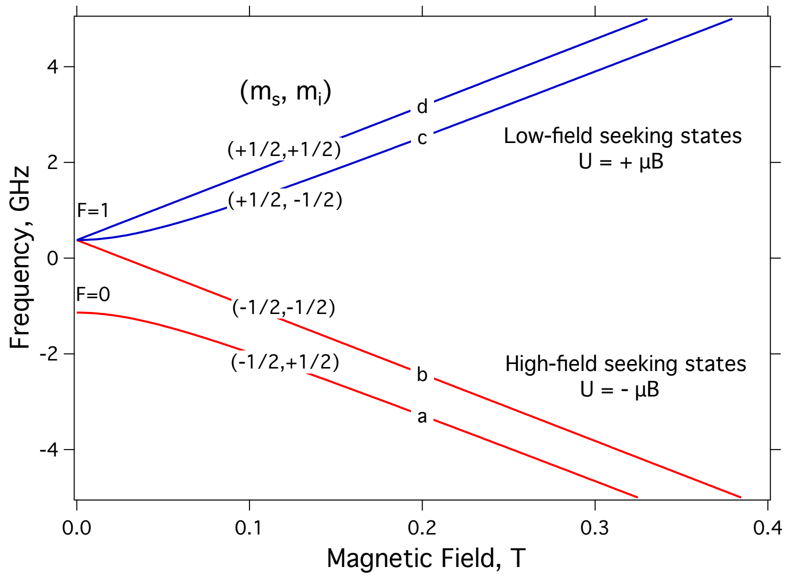


This side is beam prep to 5K
(uses visible lasers to slow Li)

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

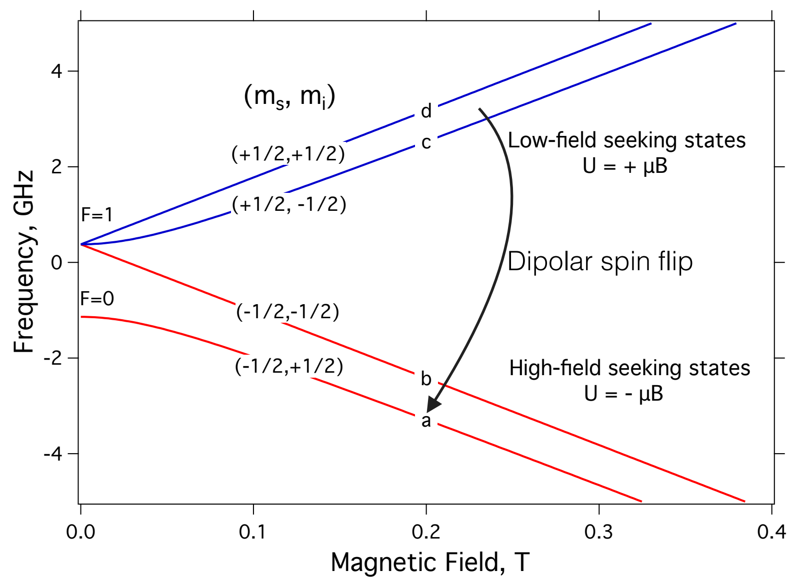
Credit: B. J. P. Jones

Atom Trap



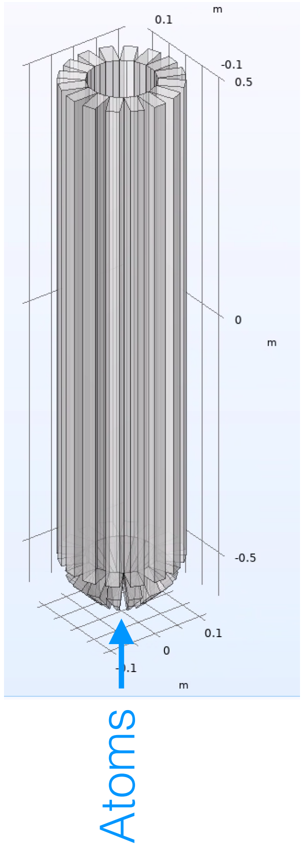
(m_s, m_i)
d
c
(+1/2,+1/2)
(+1/2, -1/2)
F=1
F=0
(-1/2,-1/2)
(-1/2,+1/2)
b
a
Low-field seeking states
U = + μB
High-field seeking states
U = - μB
Frequency, GHz
Magnetic Field, T
4
2
0
-2
-4
0.0
0.1
0.2
0.3
0.4

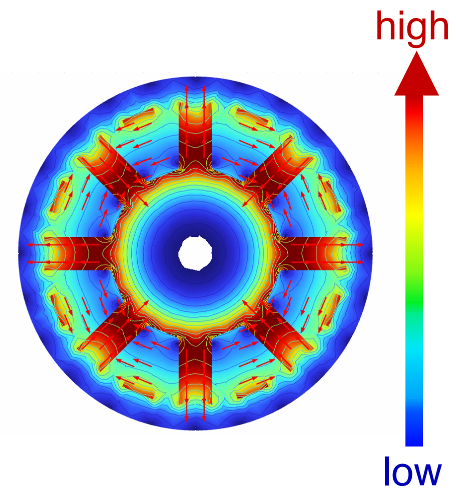
Atom Trap


(m_s, m_i)
d
c
b
a
(+1/2,+1/2)
(+1/2, -1/2)
(-1/2,-1/2)
(-1/2,+1/2)
F=1
F=0
Low-field seeking states
U = + μB
Dipolar spin flip
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

Halbach array: permanent magnets

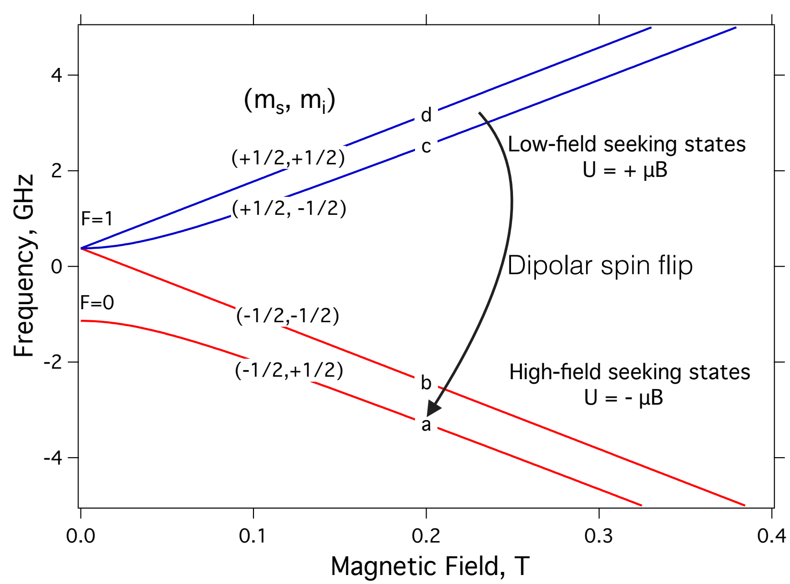




Magnetic field strength

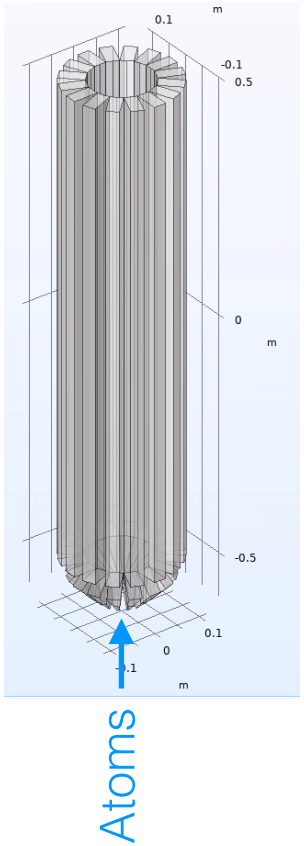
Credit: C.-Y. Liu

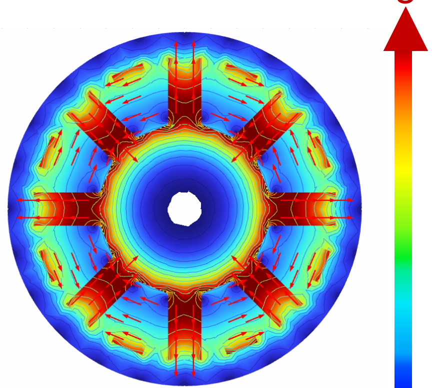
@ U Illinois



Atom Trap

Halbach array: permanent magnets



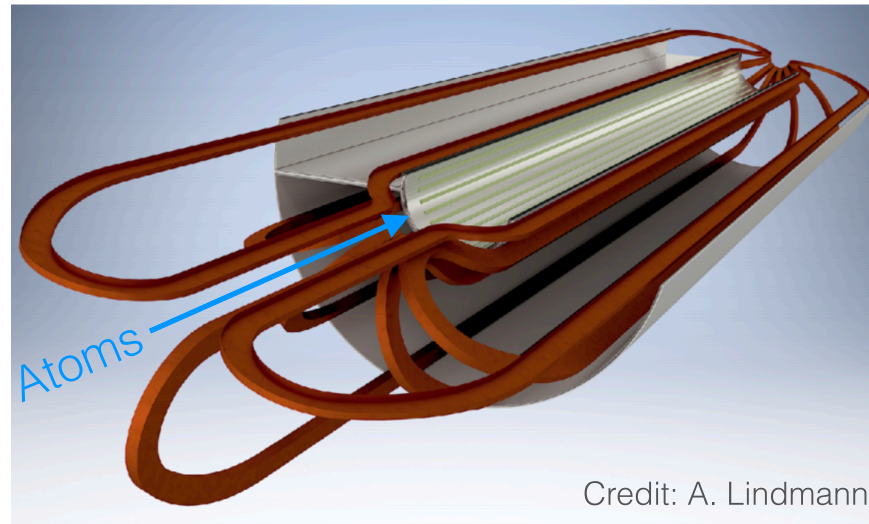


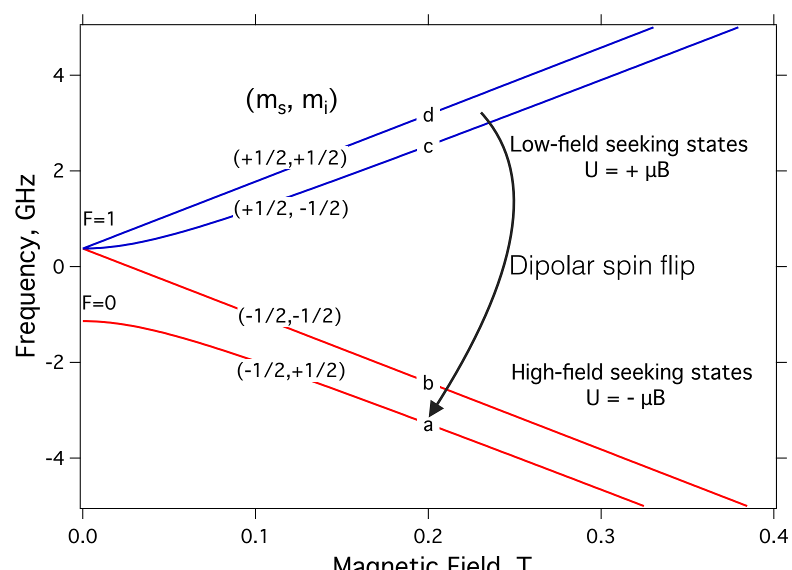
Magnetic field strength

Credit: C.-Y. Liu

@ U Illinois

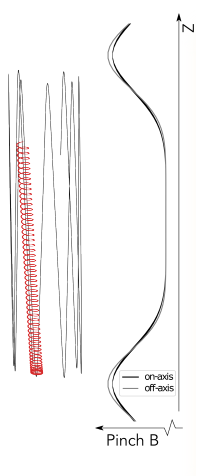
Ioffe trap: superconducting coils

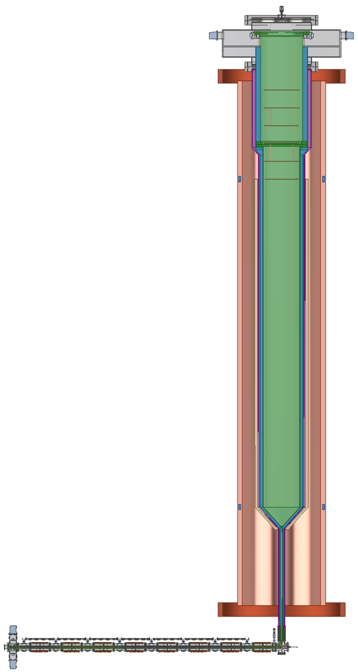




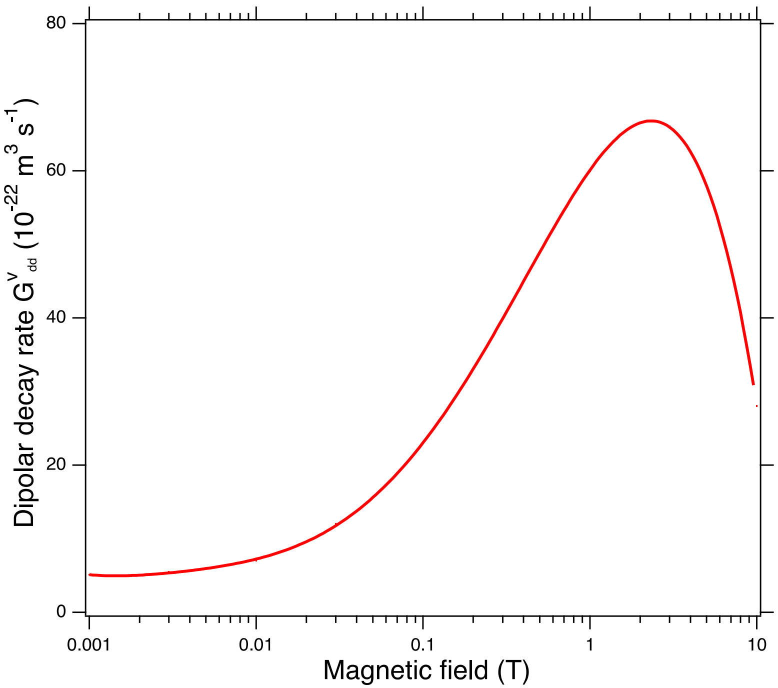
PROJECT 8

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

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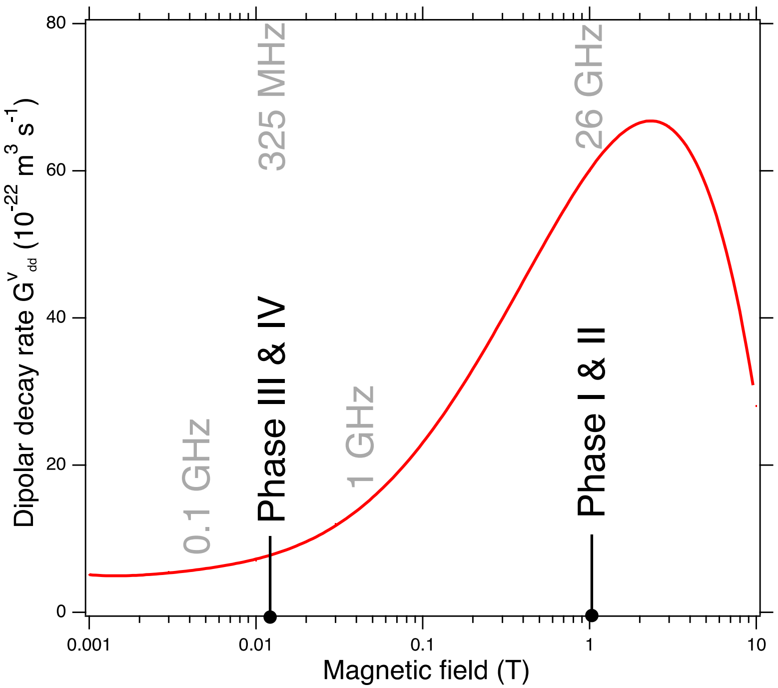

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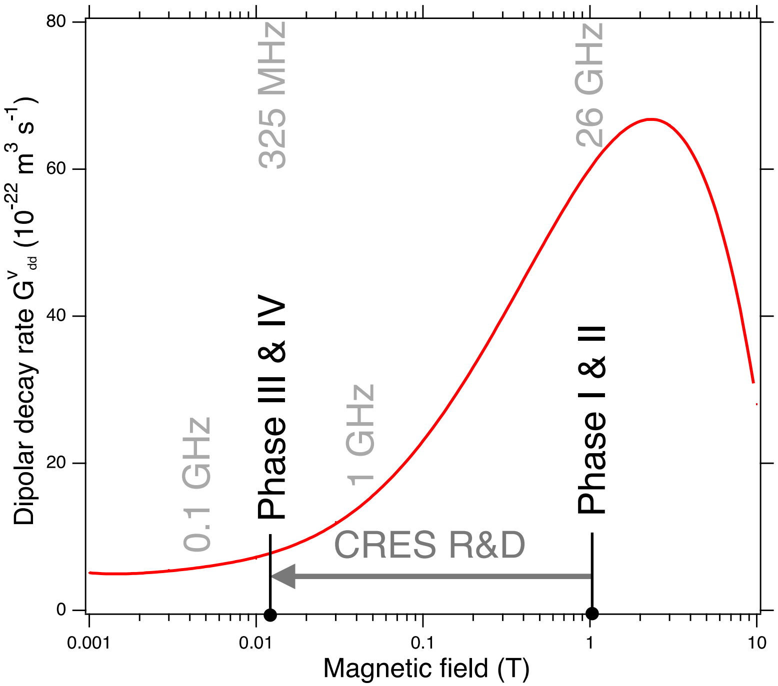

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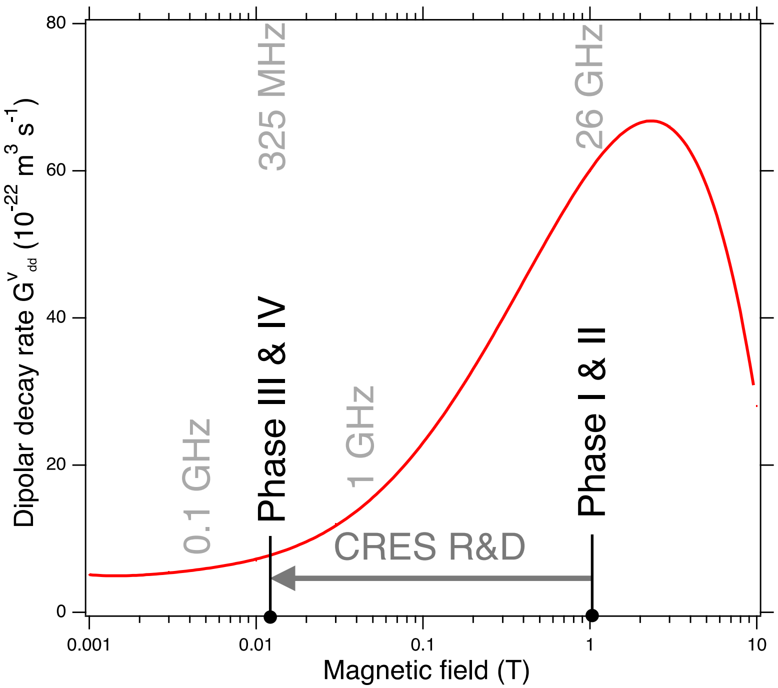
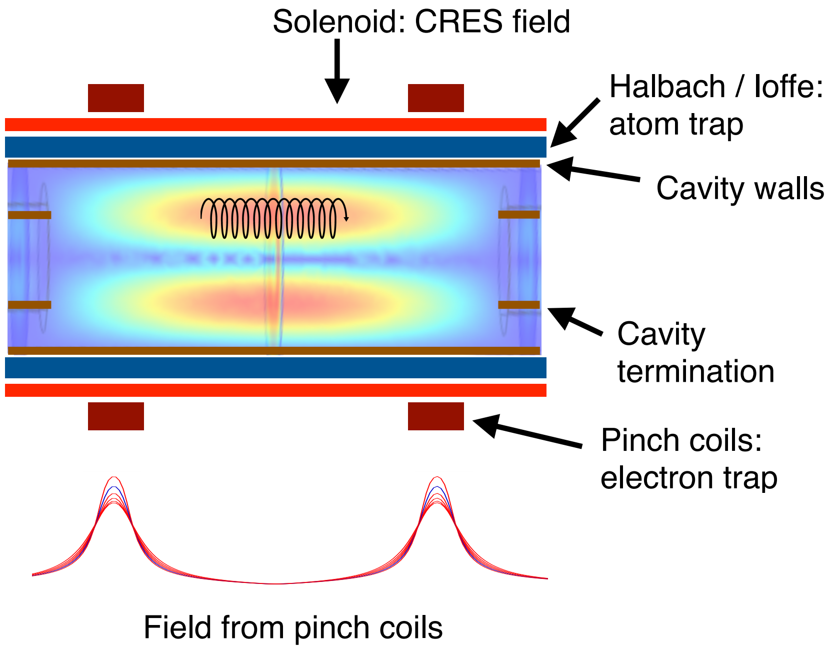




- Dipolar decay rate can be greatly reduced by lowering magnetic field for longer trapping life times

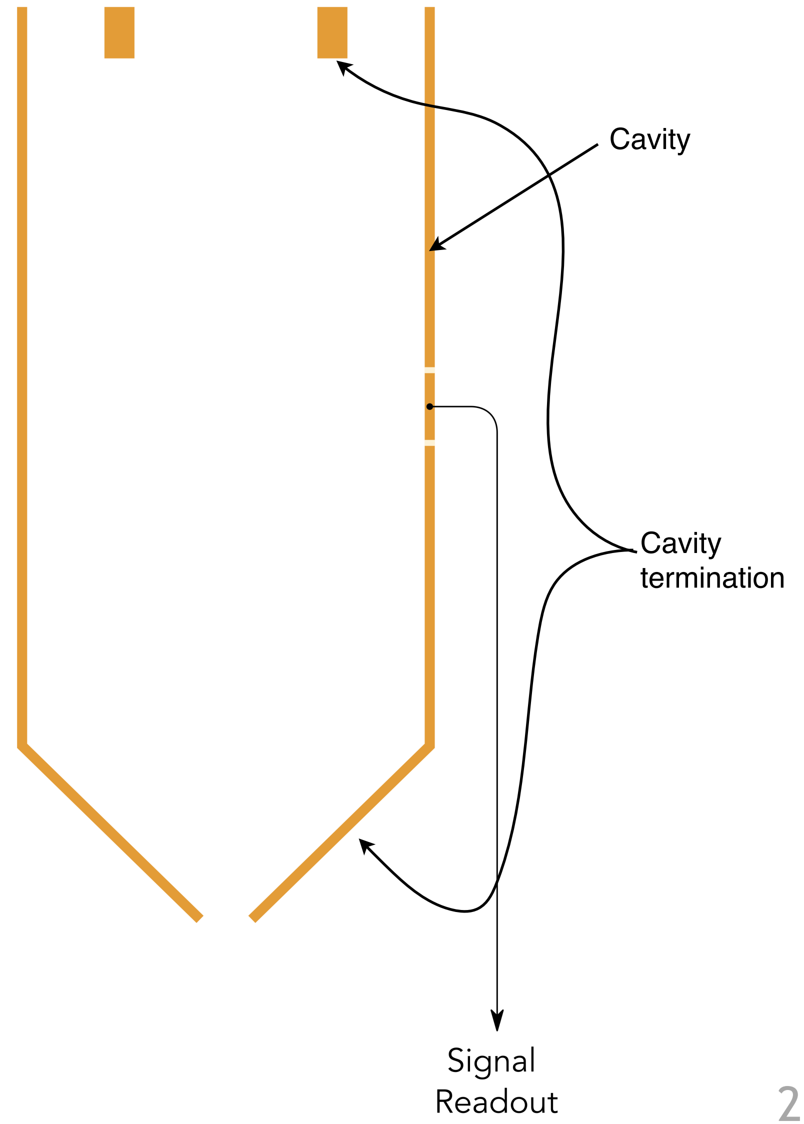
- Cavity volume scales as $1/f^3$
- Lower frequency makes resonant cavity desirable
- Open-ended, single-mode?

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

PROJECT 8

A Cavity-Based CRES Experiment

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



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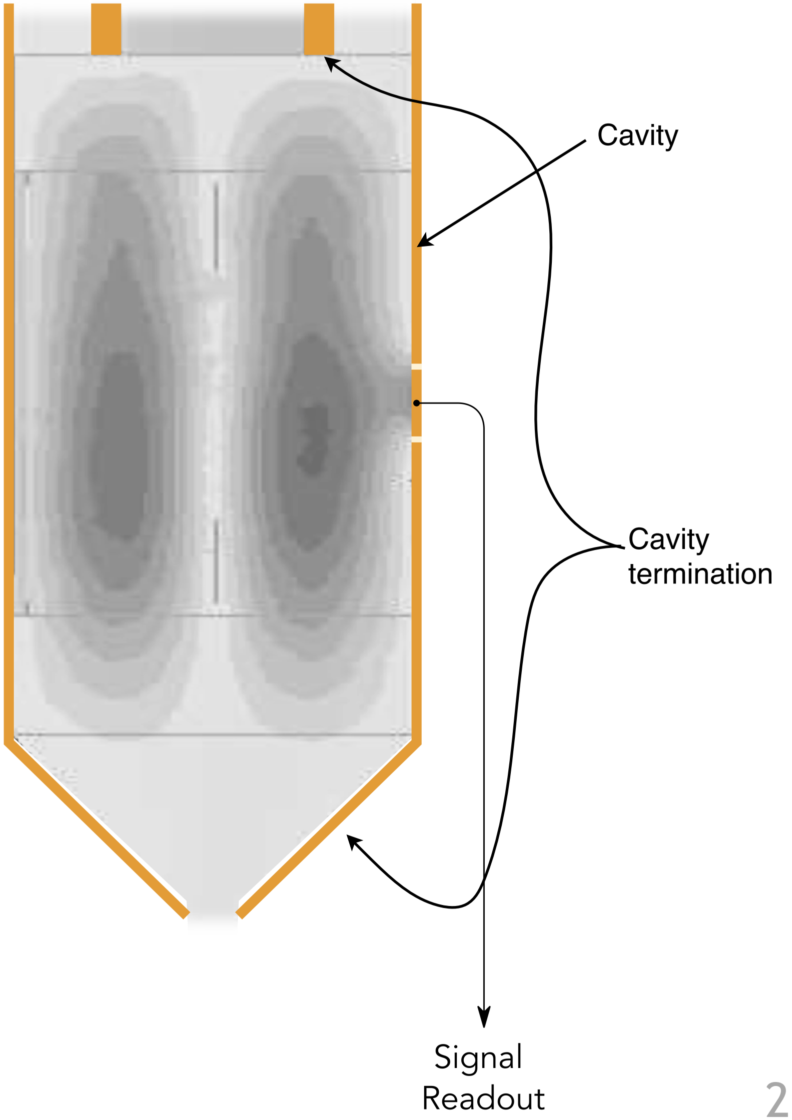

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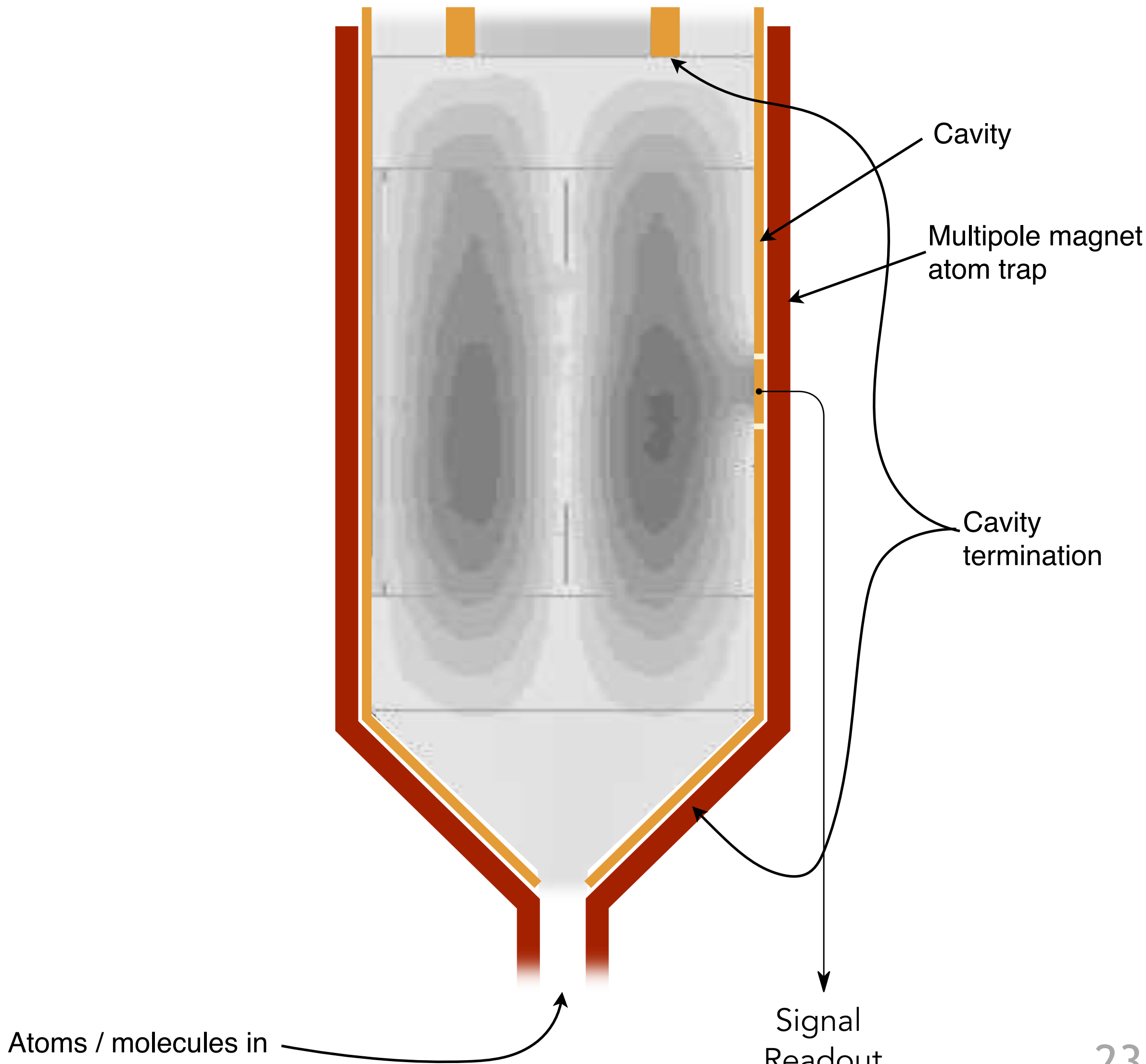

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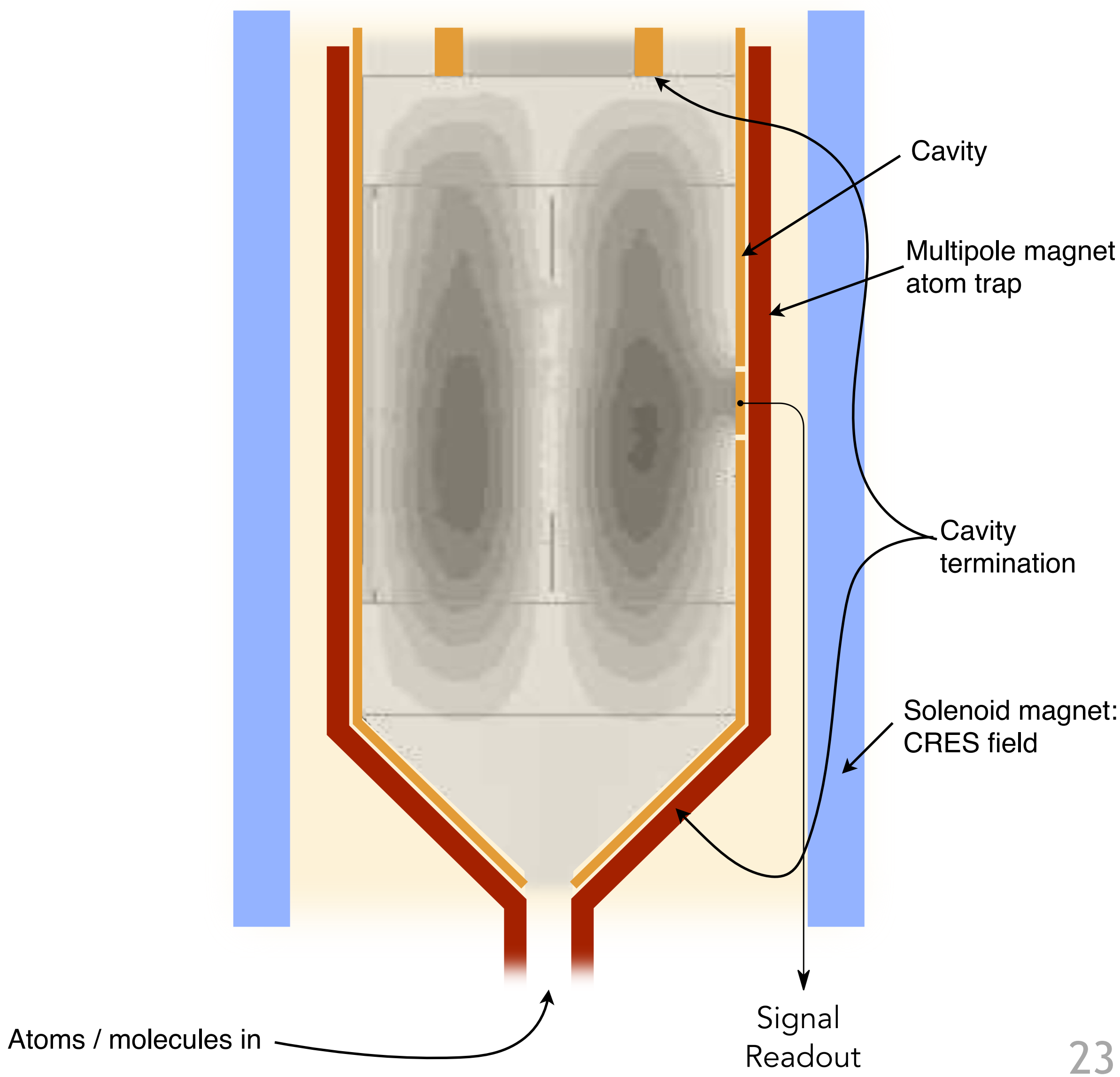

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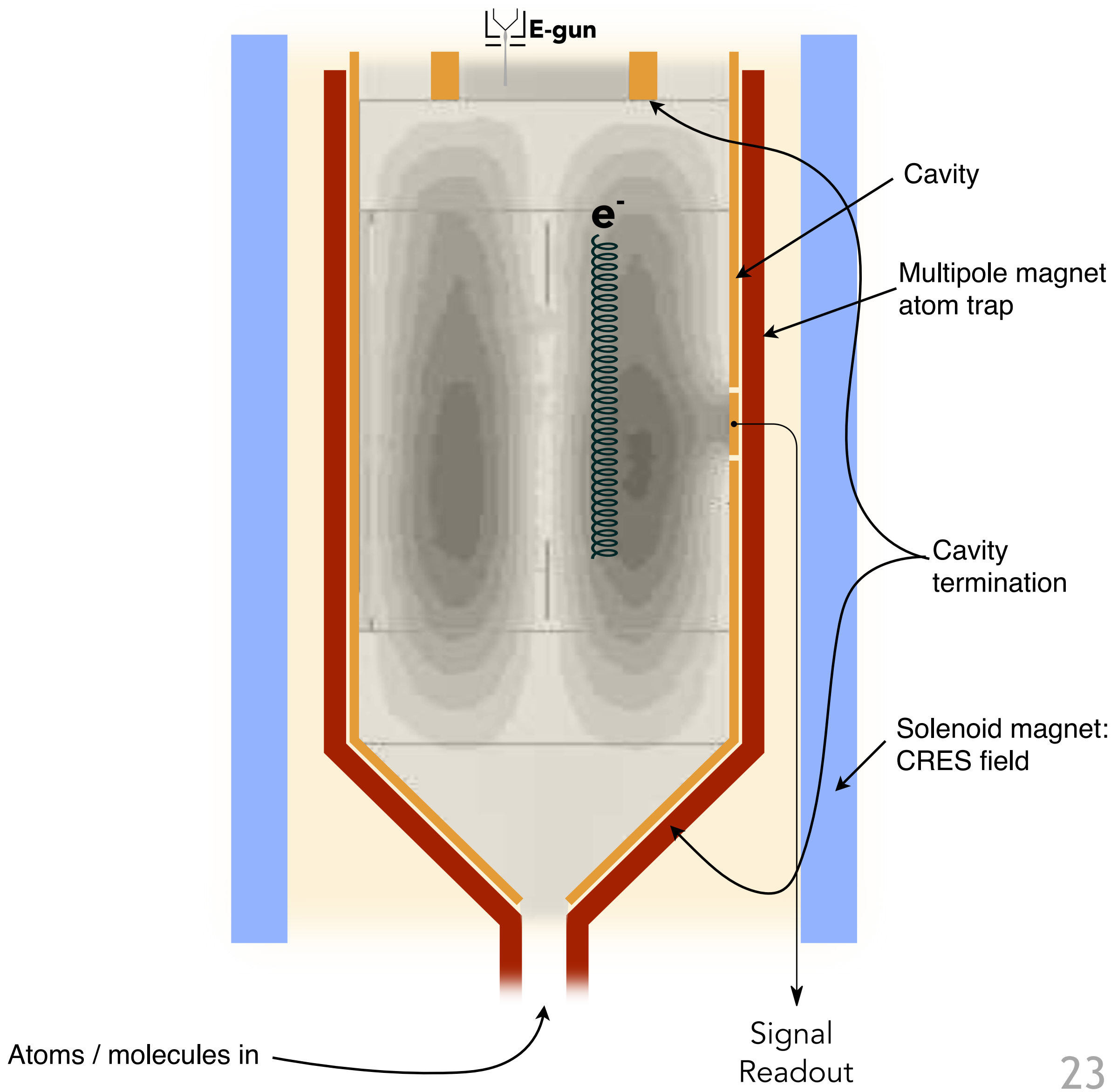

A Cavity-Based CRES Experiment

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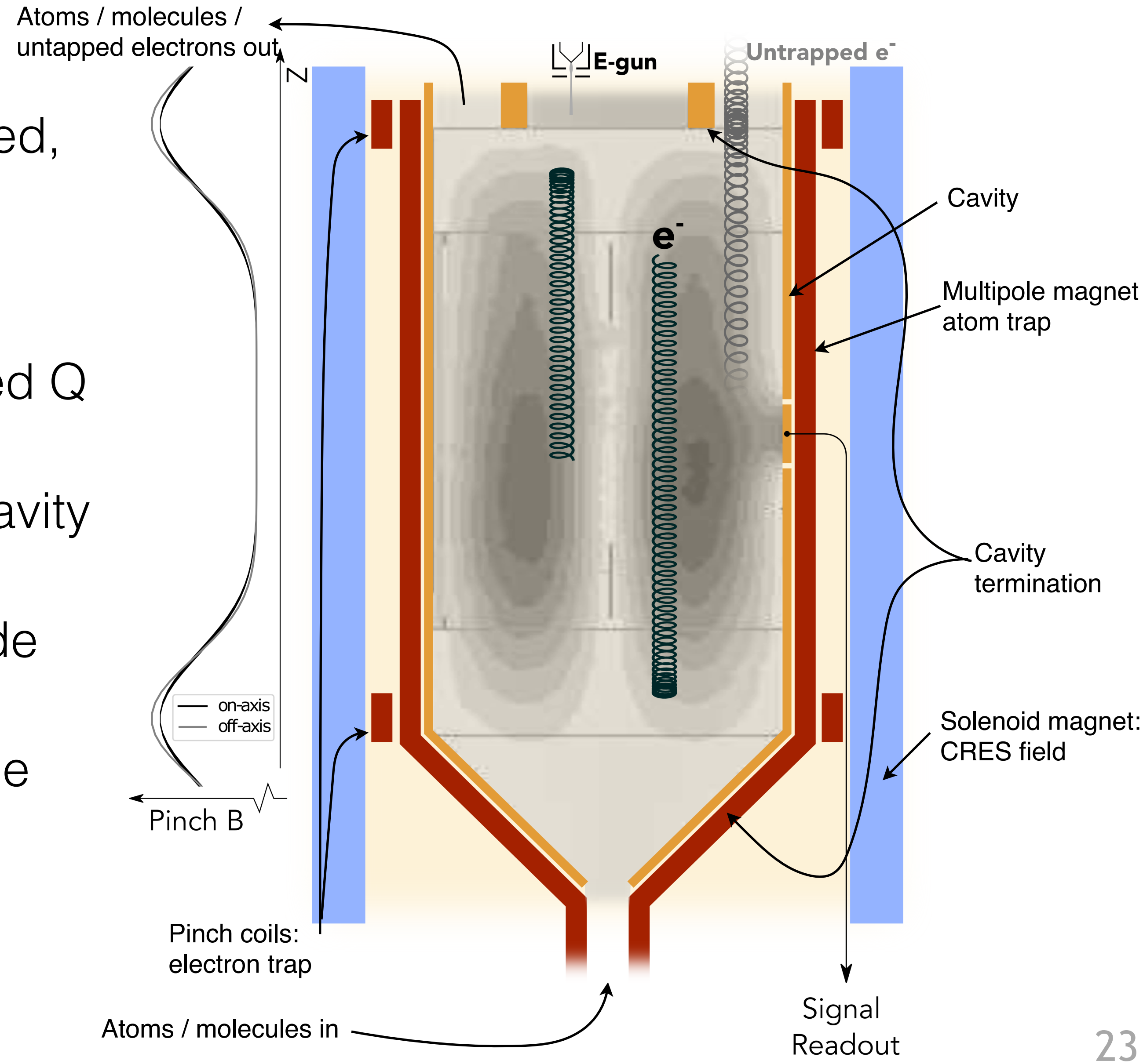
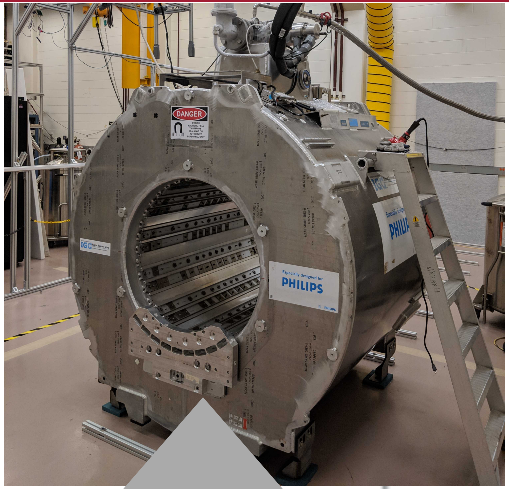
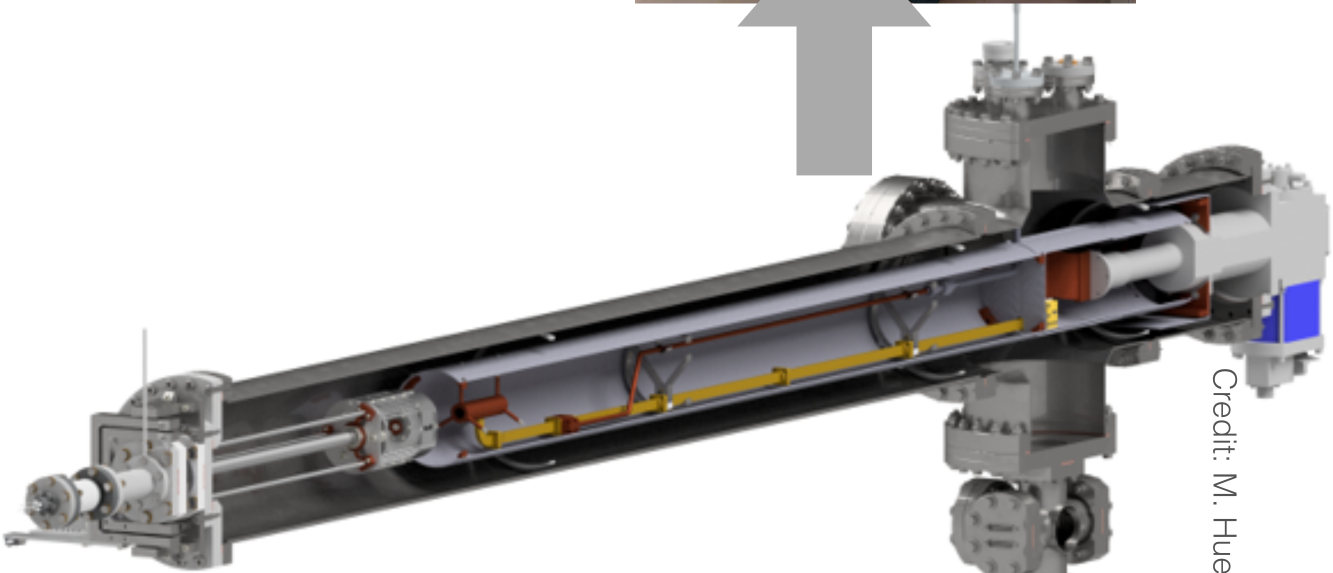
- Solenoid to provide CRES field
- Pinch coils provide electron trapping



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 reuse RF setup, waveguide





Credit: M. Huehn

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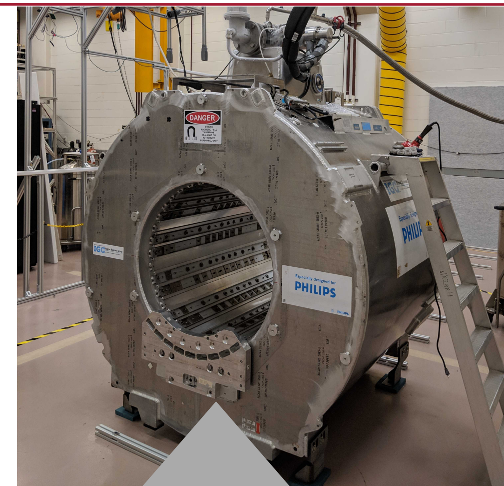

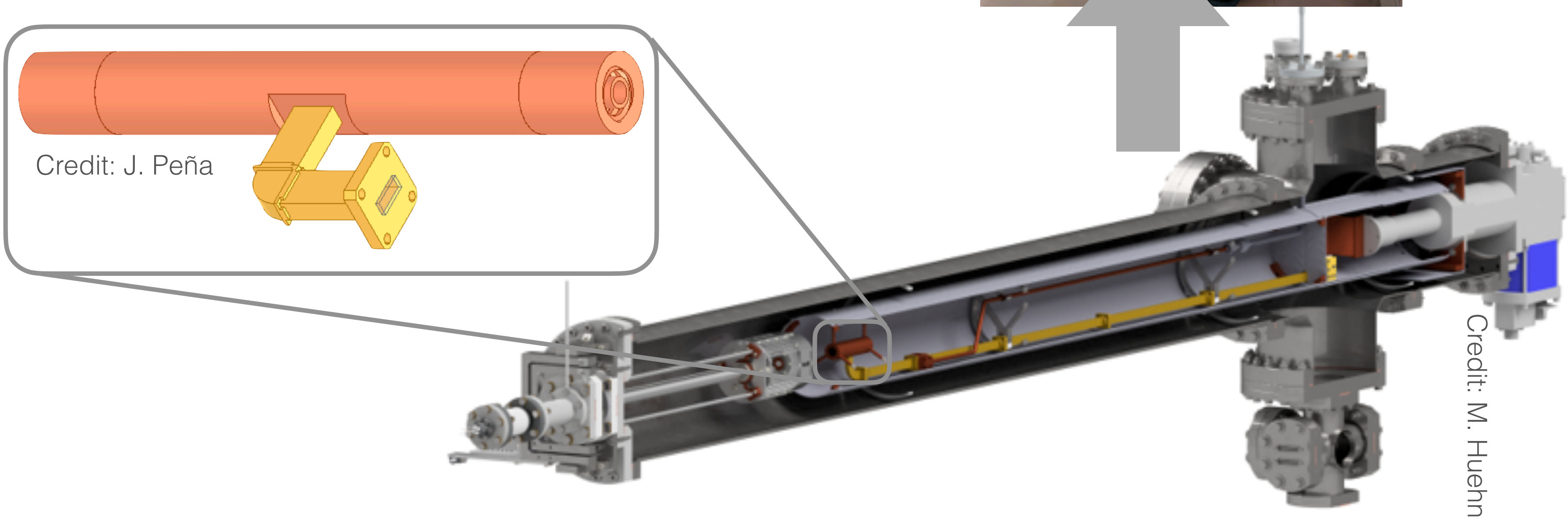

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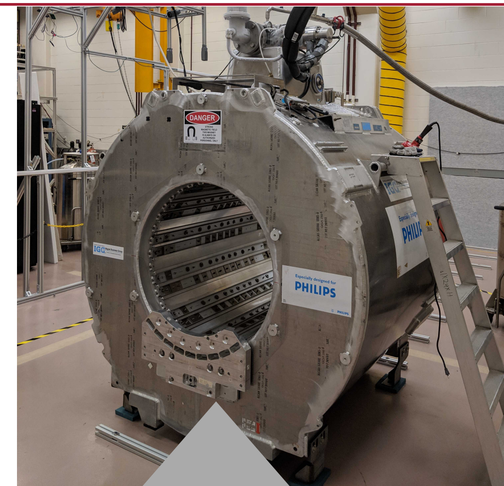

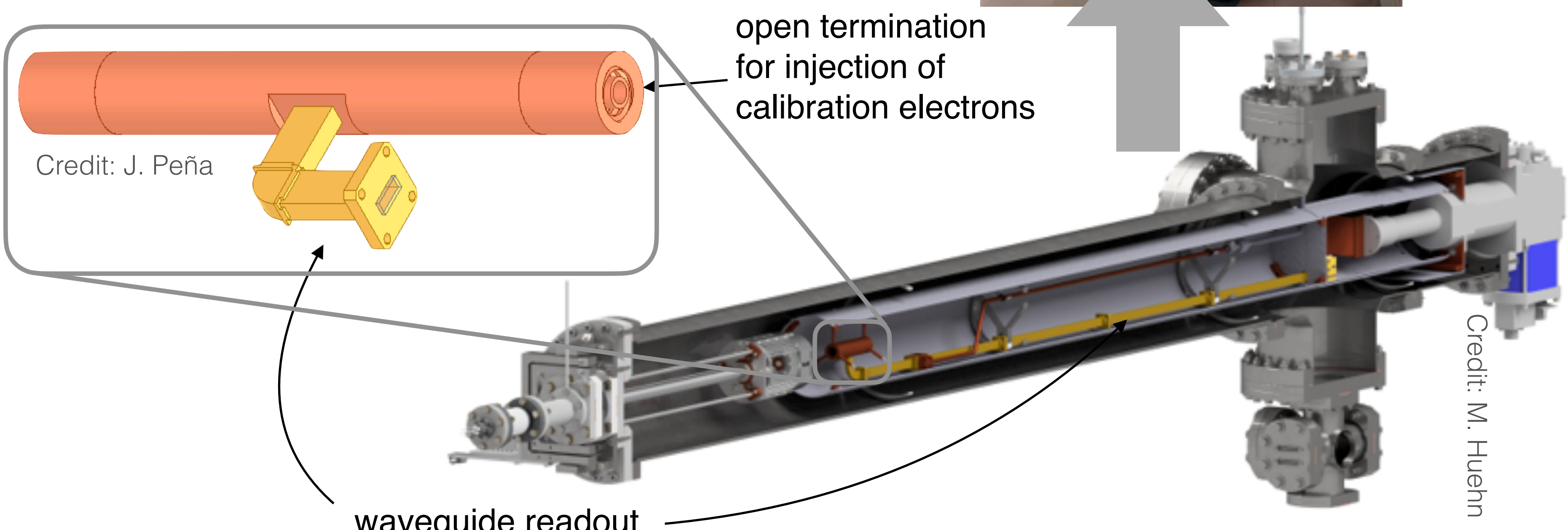

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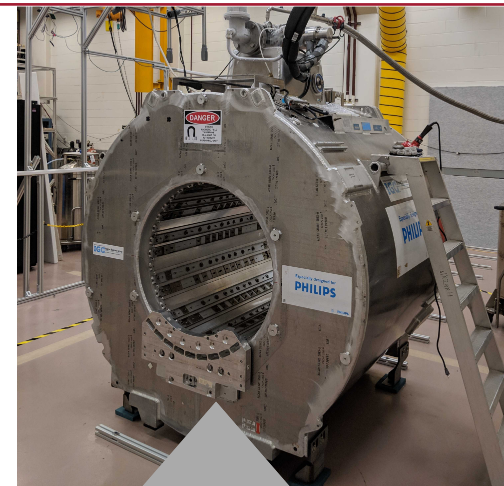
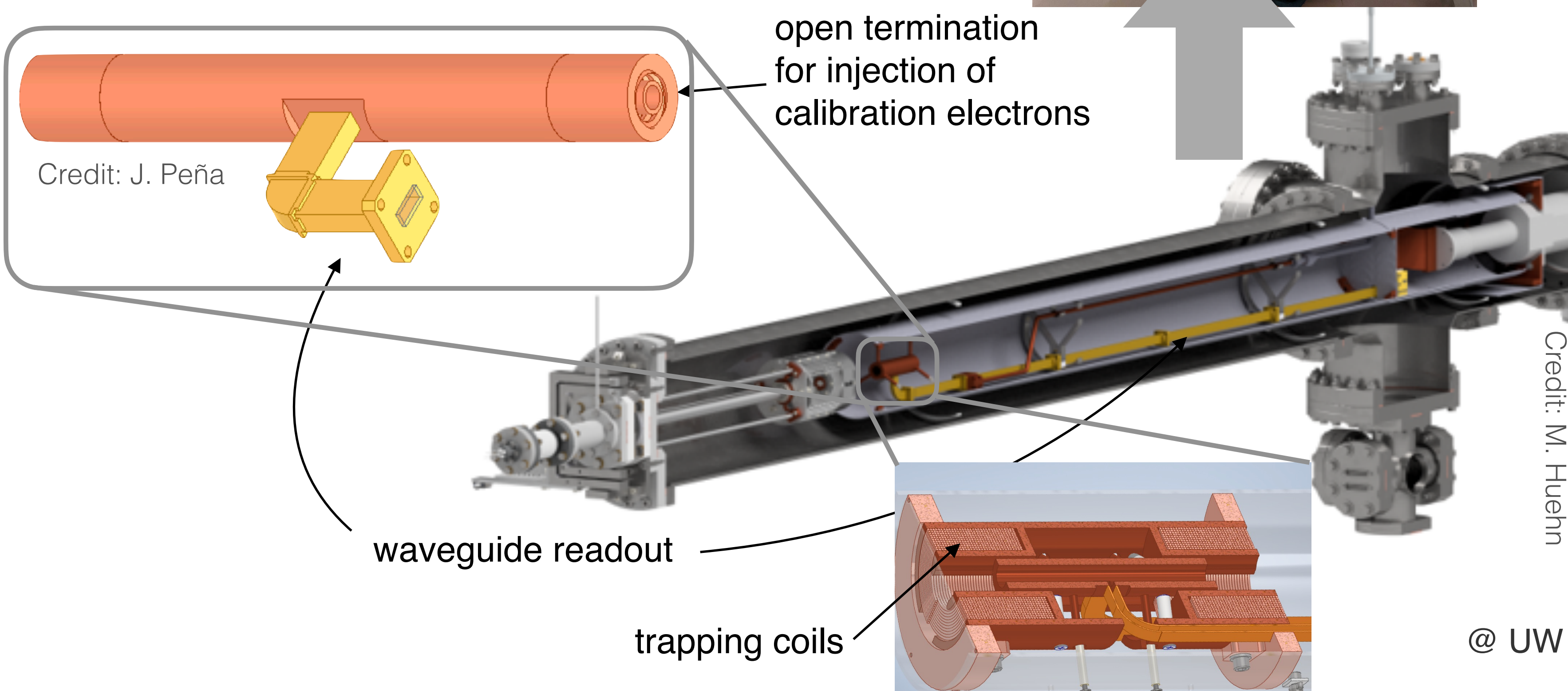
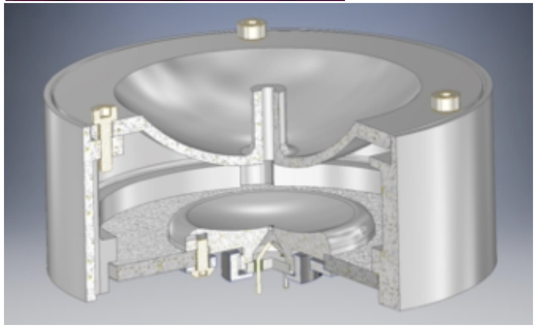




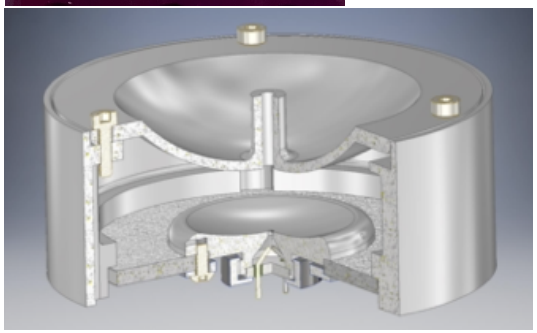
Electron Source



Credit: R. Roehnelt

- LaB6 / Y2O3 cathode, Pierce design
- Excellent energy spread (simulated)
- Powered by LEDs & solar panels
- Test stand & magnet tests at UW

Electron Source



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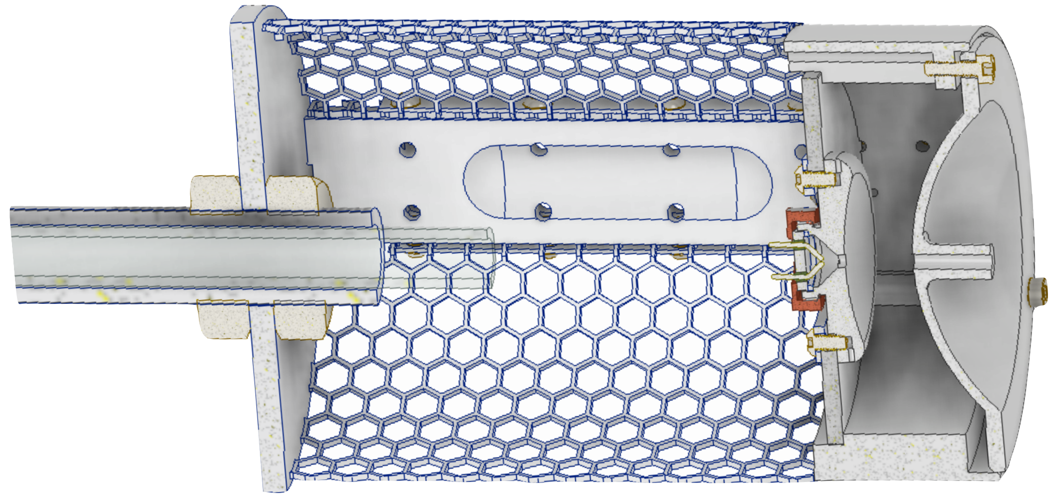

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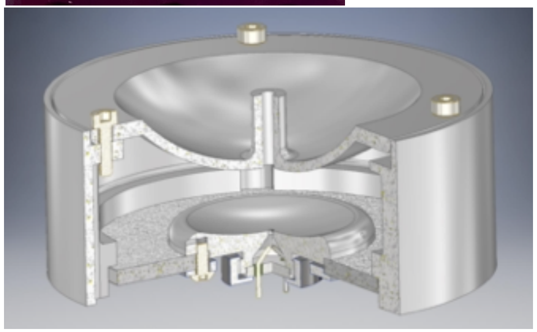

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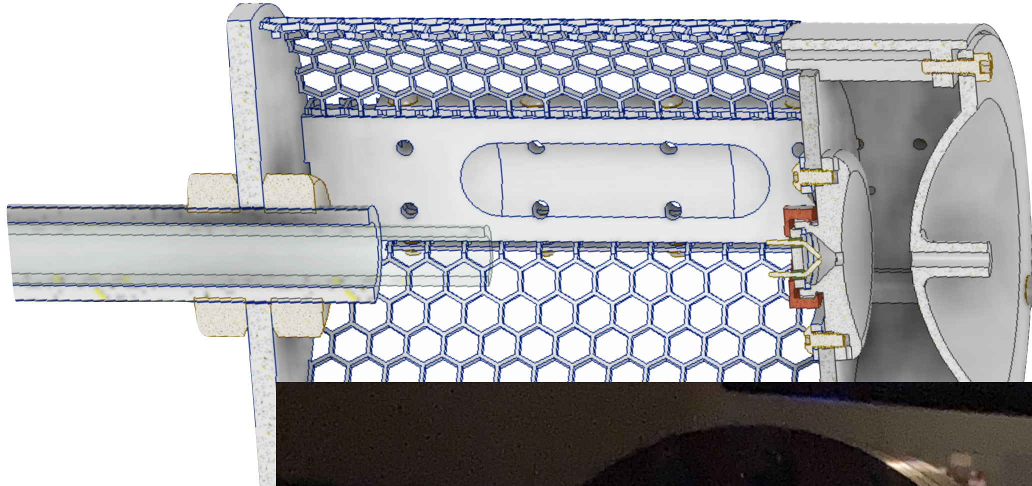

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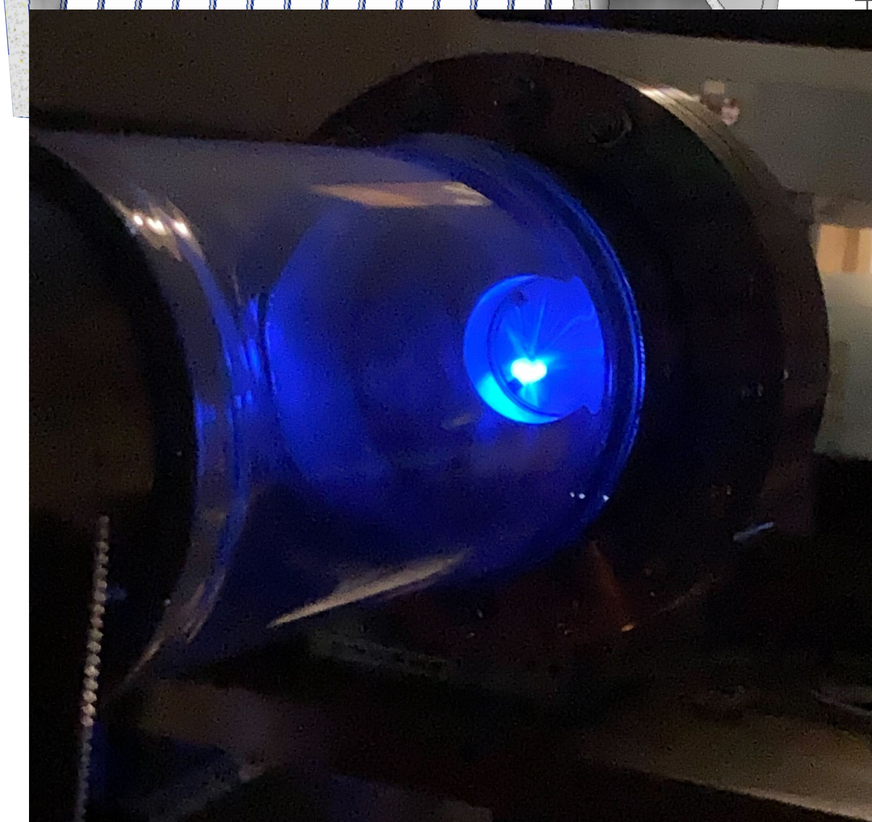

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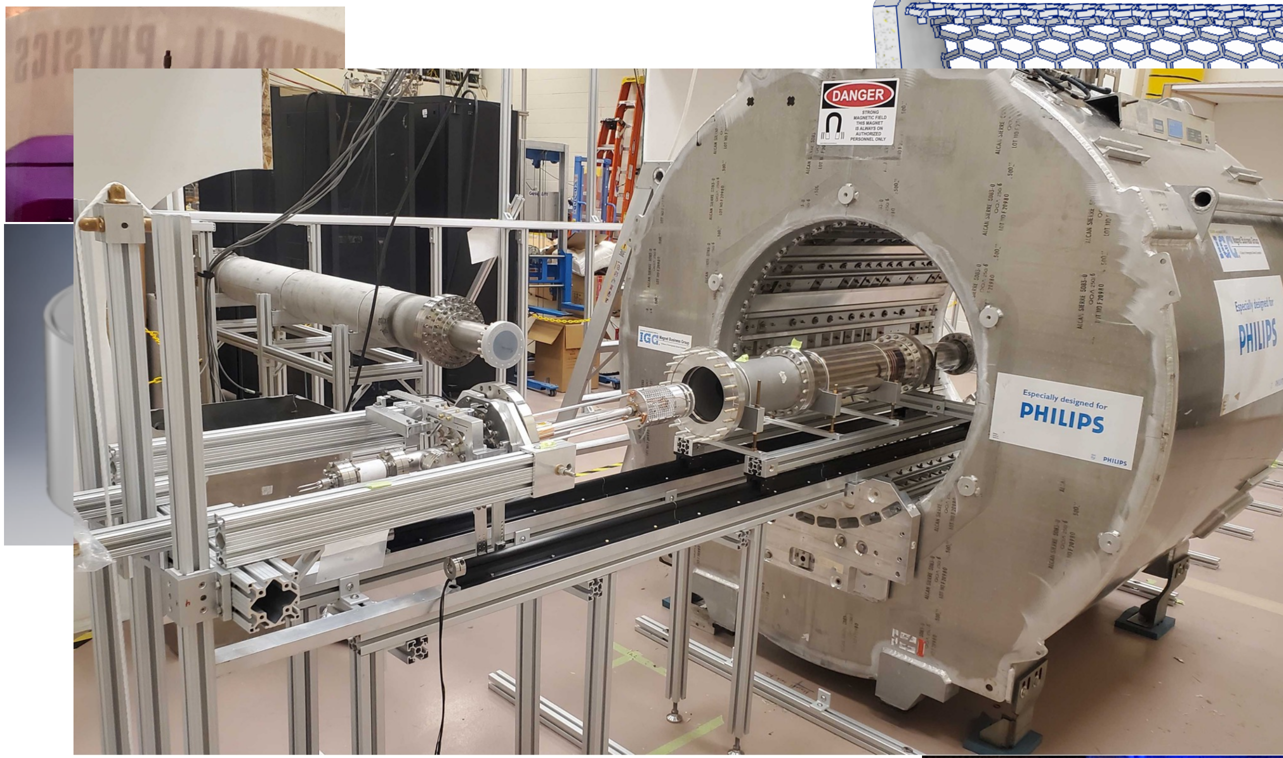

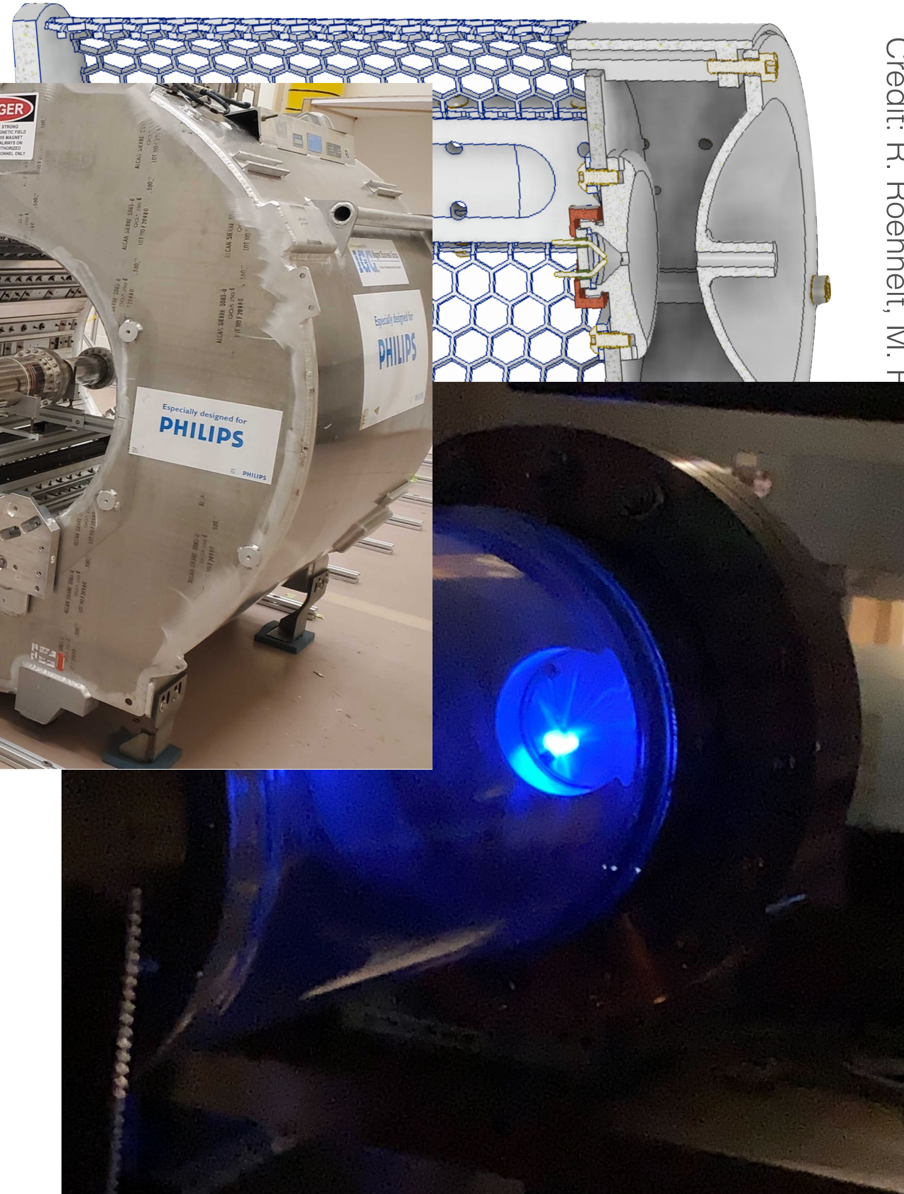

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CCA Goals

- Verify CRES phenomenology in resonant cavity with high SNR
  - Simulation verification
  - Reconstruction with event-by-event magnetic field corrections
  - Verify high volume & pitch angle efficiency
- Calibration development: electron gun
  - Main calibration device going forward
- High resolution of $0.3\,\mathrm{eV}$ in small volume
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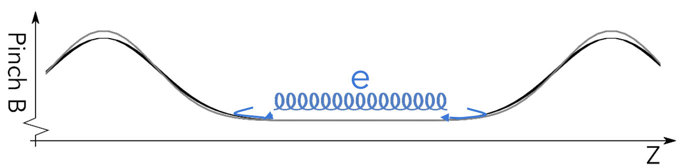

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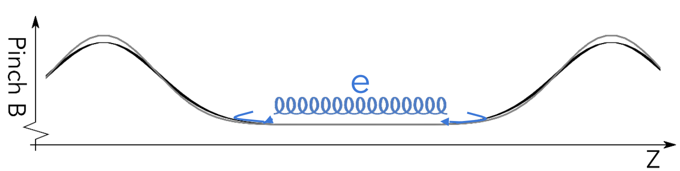

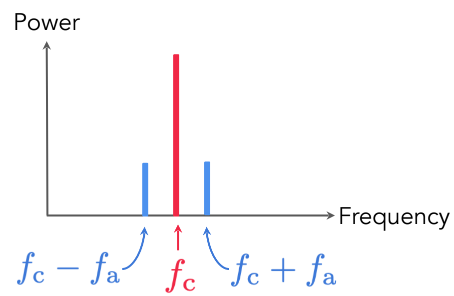

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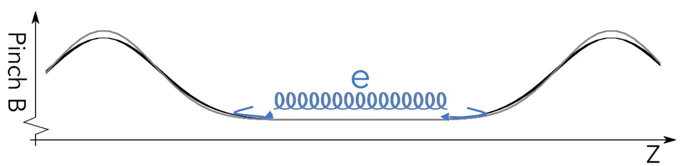
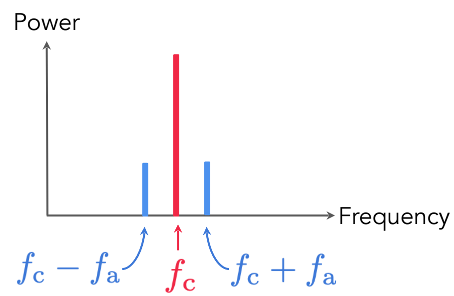
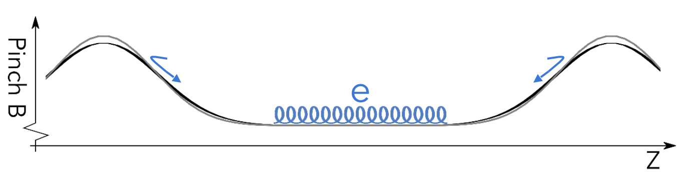




“Small” pitch angle, $\theta \rightarrow \theta_{min}$:



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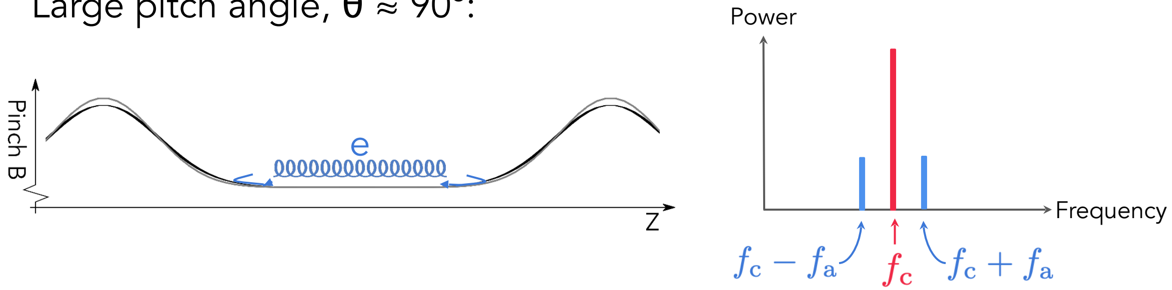

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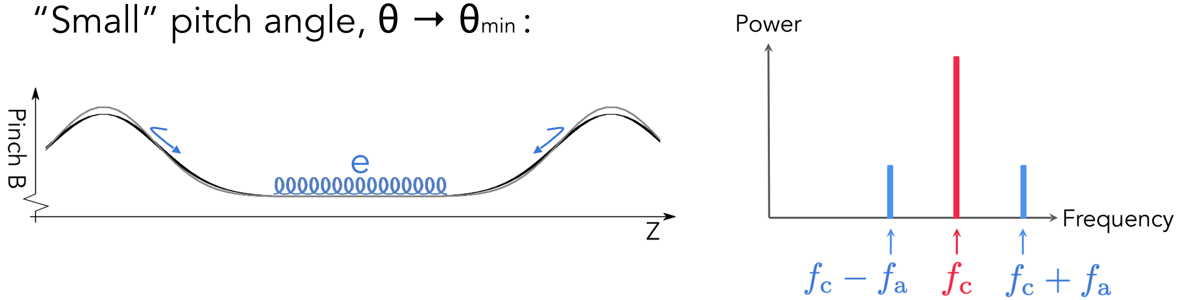

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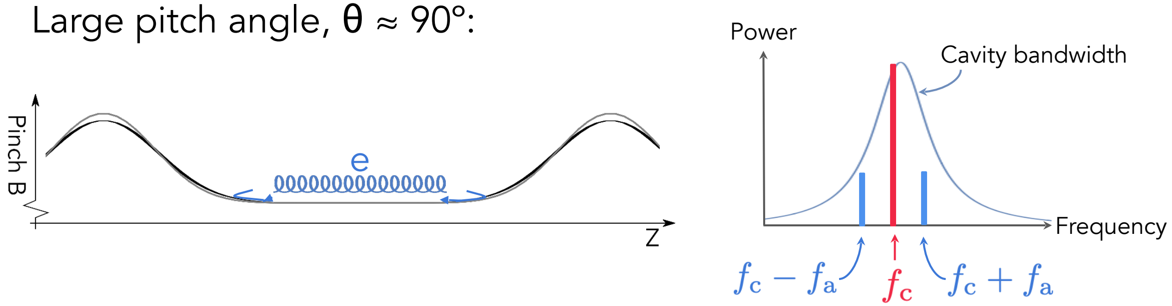

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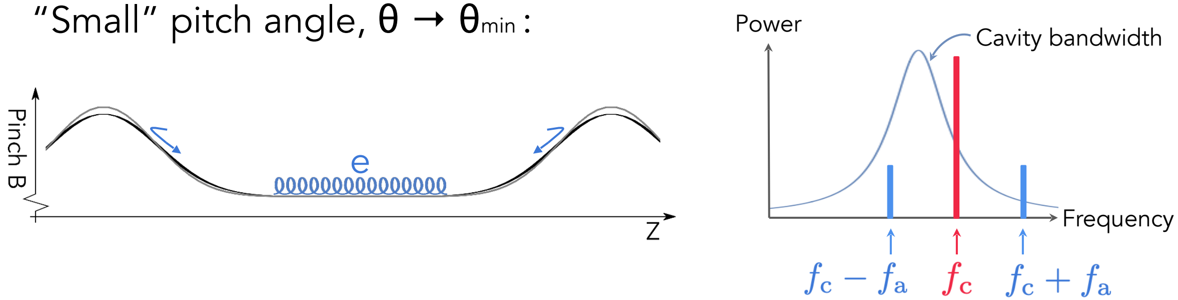

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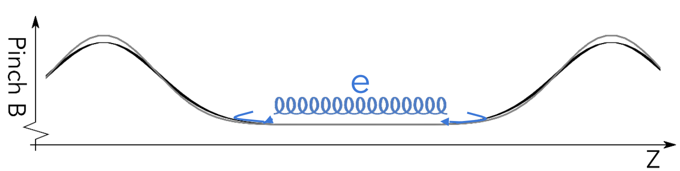

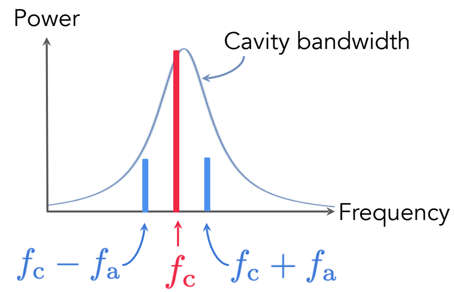

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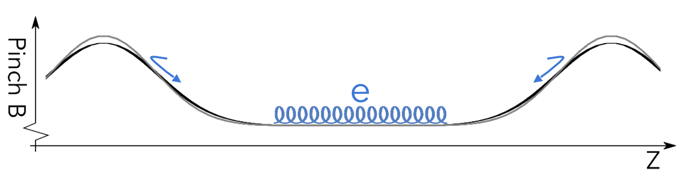
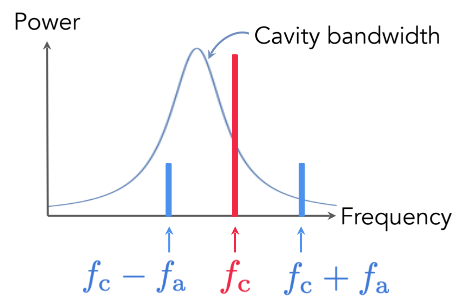
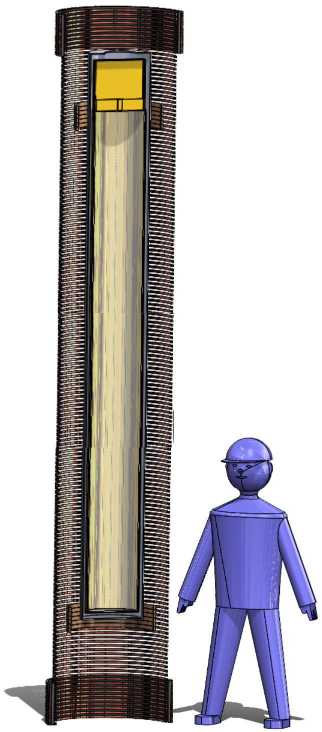




- Sidebands due to axial motion
- Axial motion leads to variation in magnetic field along electron track
- Larger average magnetic field and higher carrier frequency
- Sideband detection for magnetic field correction

Low Frequency Apparatus

- Goal: Prove feasibility of CRES in large volumes $V \approx 0.3\,\mathrm{m}^3$, low fields $B \approx 0.035\,\mathrm{T}$, and frequencies $f_c \approx 1\,\mathrm{GHz}$
  - $P \propto V^{-1} f^{-1} \propto f^2$ for cavities
  - Collected power is $\mathcal{O}(\mathrm{aW})$ $(1\,\mathrm{aW} = 10^{-18}\,\mathrm{W})$



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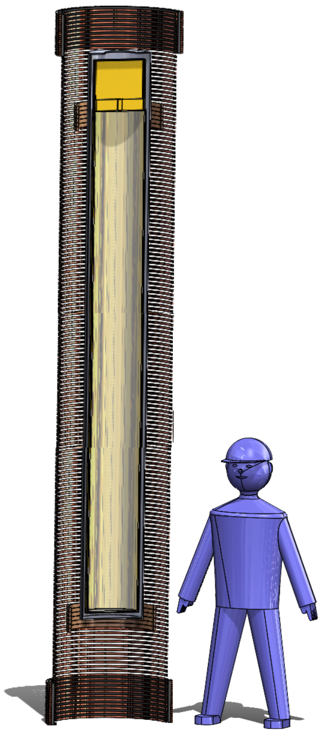

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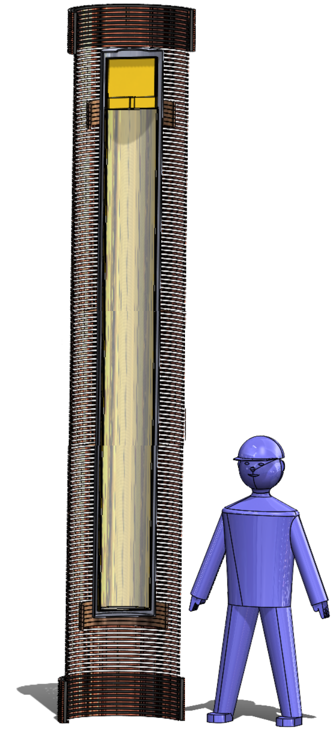
- Custom-designed high-uniformity magnet
- First low-field prototype LUCKEY at $1.5\,\mathrm{GHz}$, optimized for maximum power:
    - shorter, lower volume $V \approx 0.025\,\mathrm{m}^3$
    - Low field CRES detection
    - First work on custom magnet design



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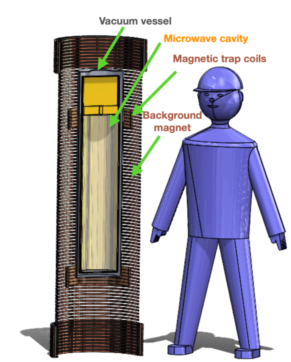
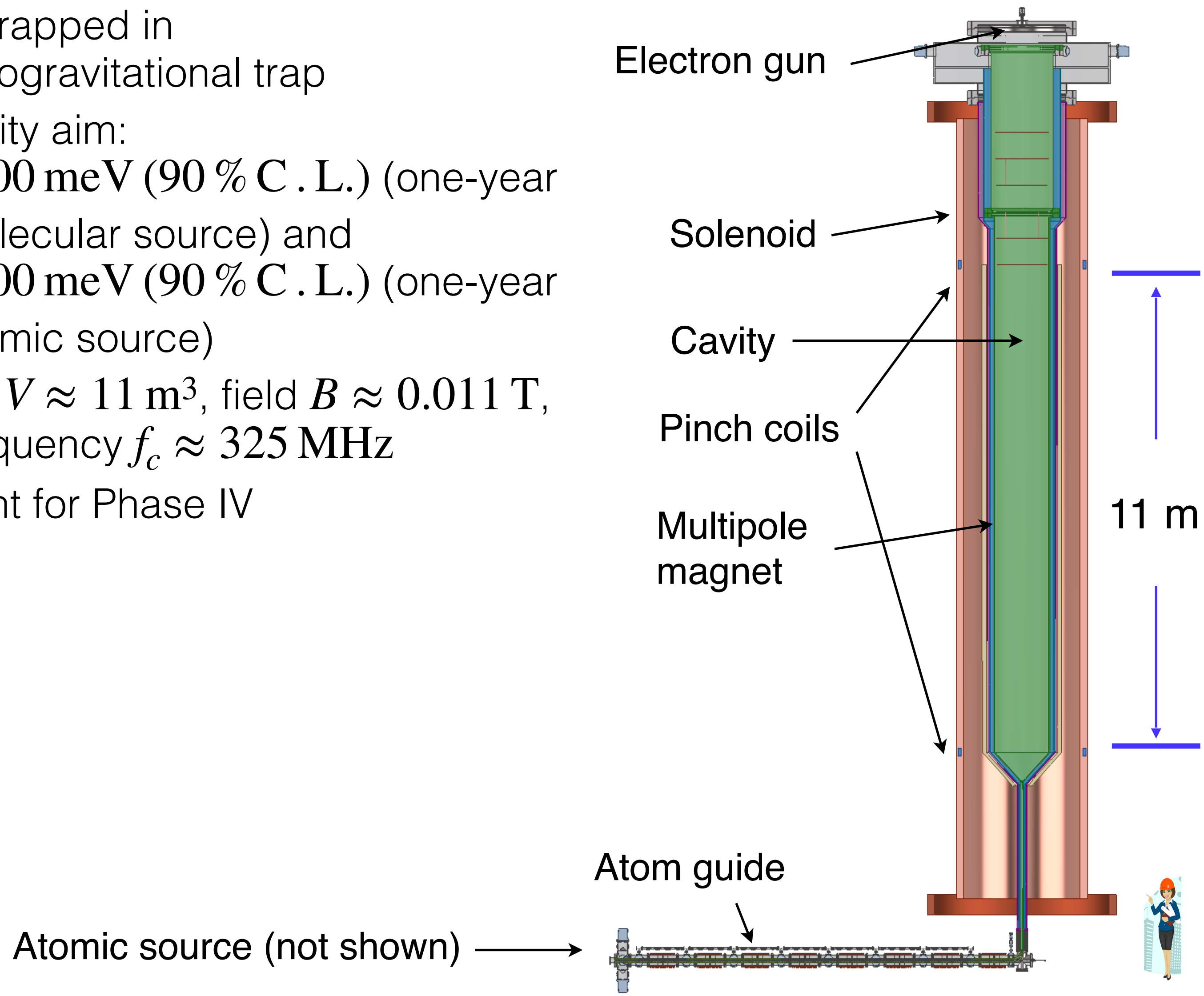


Cavity-based Phase III

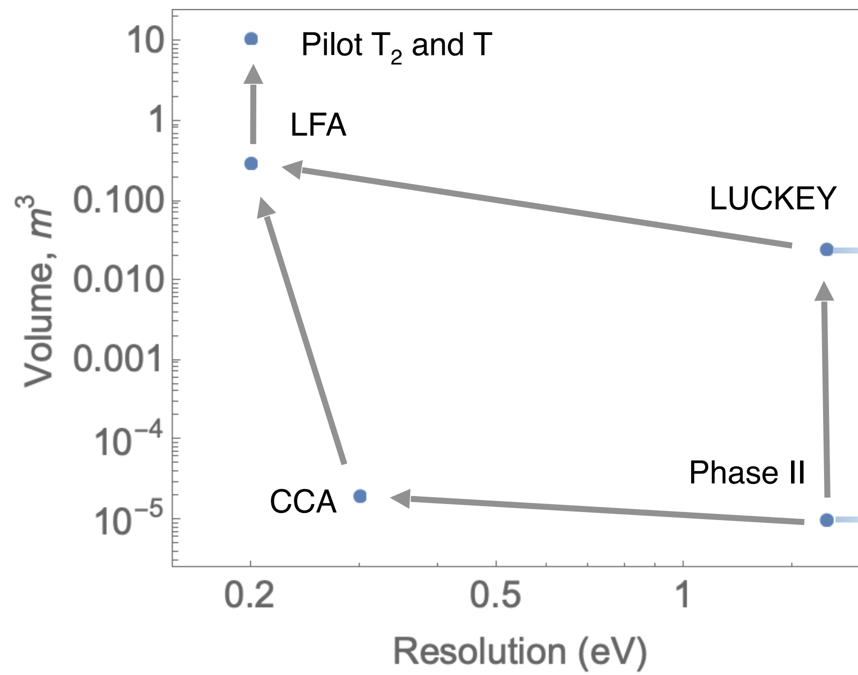
- Atoms trapped in magnetogravitational trap
- Sensitivity aim:
  $m_\beta < 200\,\mathrm{meV}\ (90\,\%\ \mathrm{C.L.})$ (one-year with molecular source) and
  $m_\beta < 100\,\mathrm{meV}\ (90\,\%\ \mathrm{C.L.})$ (one-year with atomic source)
- Volume $V \approx 11\,\mathrm{m}^3$, field $B \approx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



Credit: M. Huehn

Phase III CRES Development

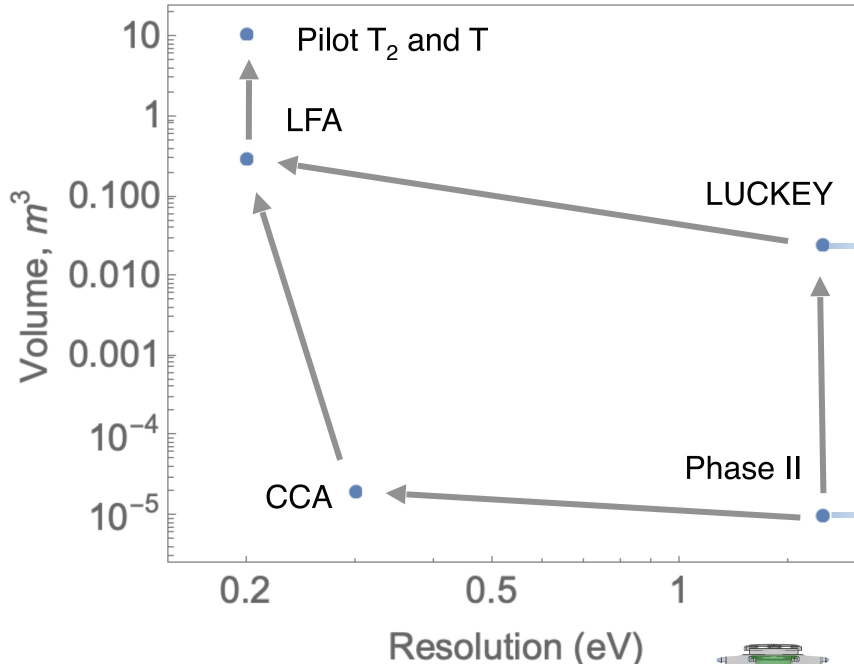
- Resonant cavities provide an attractive way of scaling Project 8 to large volumes
    - High volume efficiency
    - High pitch angle efficiency
- Set of demonstrators:
    - High resolution (CCA)
    - Large volume (LUCKEY)
    - High resolution and large volume (LFA)
- Phase III: First atomic tritium neutrino mass extraction: 100 meV sensitivity → blueprint for full 40 meV experiment



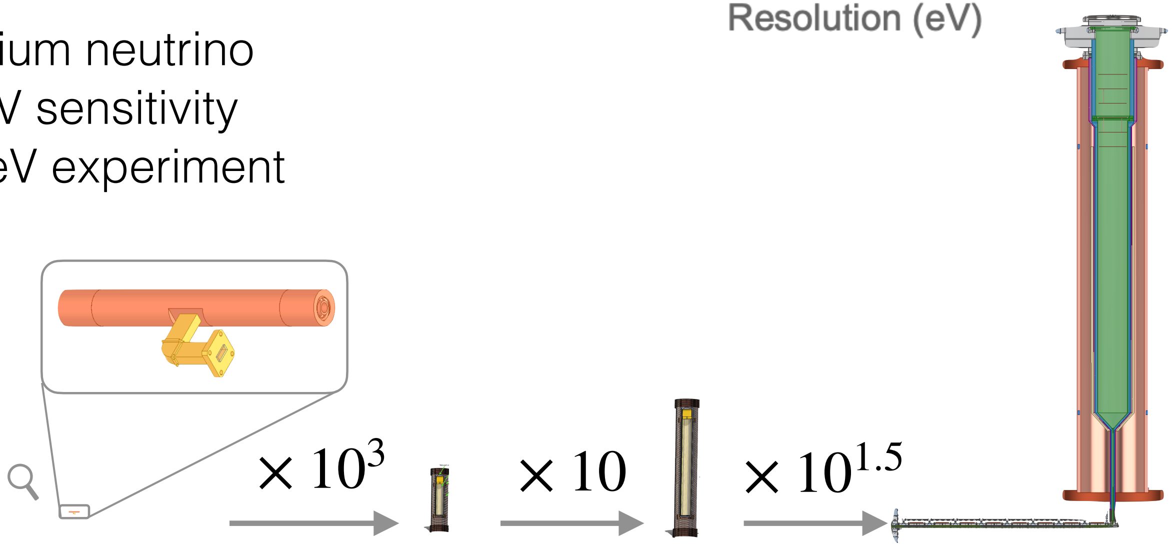
Credit: E. Novitski

Phase III CRES Development

- Resonant cavities provide an attractive way of scaling Project 8 to large volumes
  - High volume efficiency
  - High pitch angle efficiency
- Set of demonstrators:
  - High resolution (CCA)
  - Large volume (LUCKEY)
  - High resolution and large volume (LFA)
- Phase III: First atomic tritium neutrino mass extraction: 100 meV sensitivity → blueprint for full 40 meV experiment

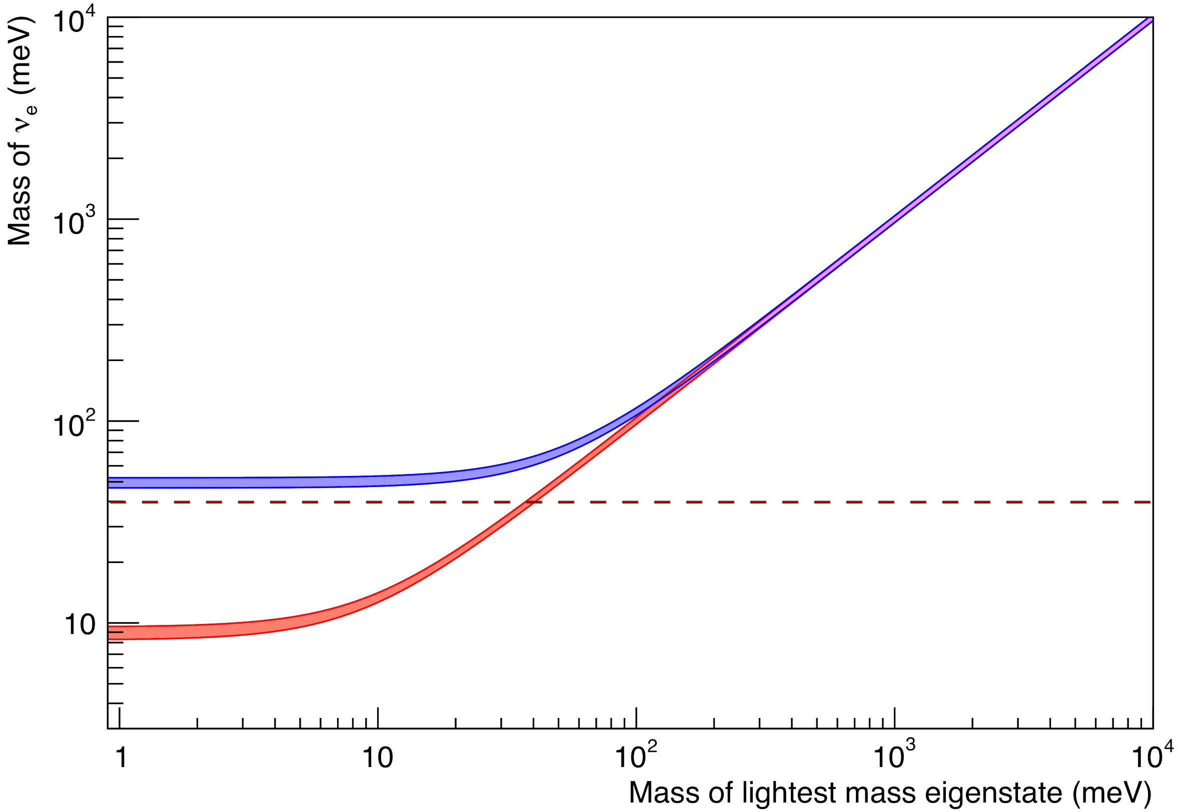


Credit: E. Novitski



PROJECT 8

Phase IV



Project 8 Concept

Energy of cold atomic beam:

$E_k = k_B T \rightarrow$ 3 μeV at 30 mK

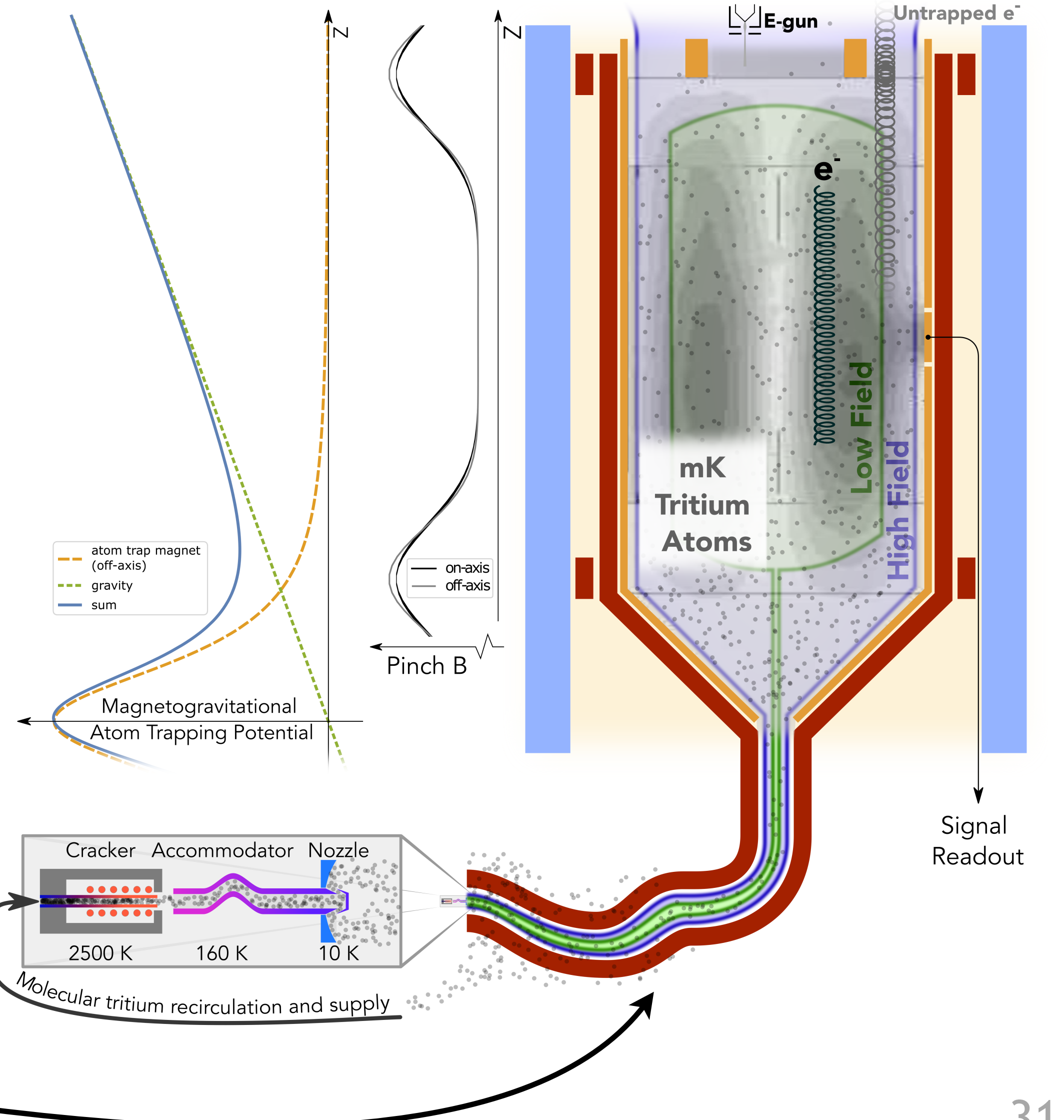
Gravitational trapping:

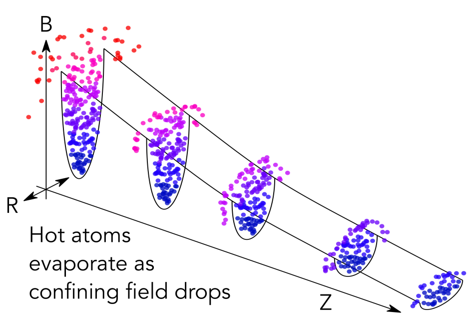
$E_g / h = mg \rightarrow$ 3 μeV / 10 m

Magnetic trapping:

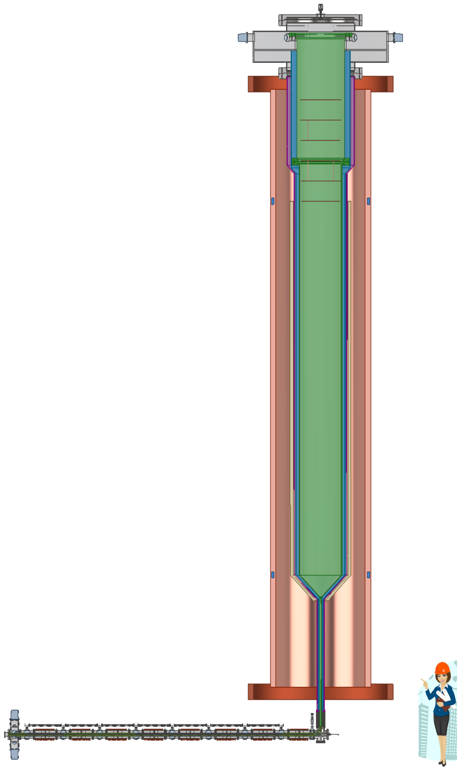
$E_B / B = \mu_B \rightarrow$ 3 μeV / 0.05 T

Setting $mgh \simeq \mu B \gtrsim 20 k_B T \rightarrow$ 2 mK cold injected atoms

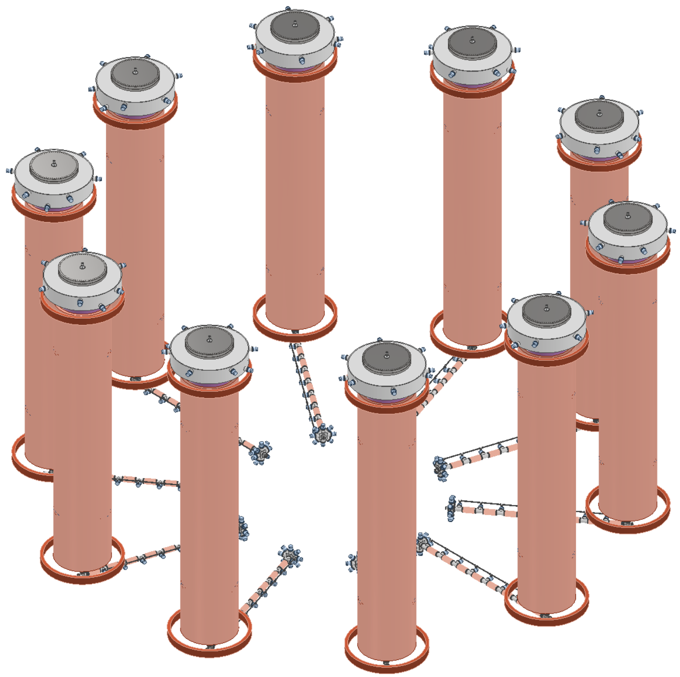




Phase IV Concept



Phase IV =
Phase III x 10



Credit: M. Huehn

Sensitivity

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

Source gas density

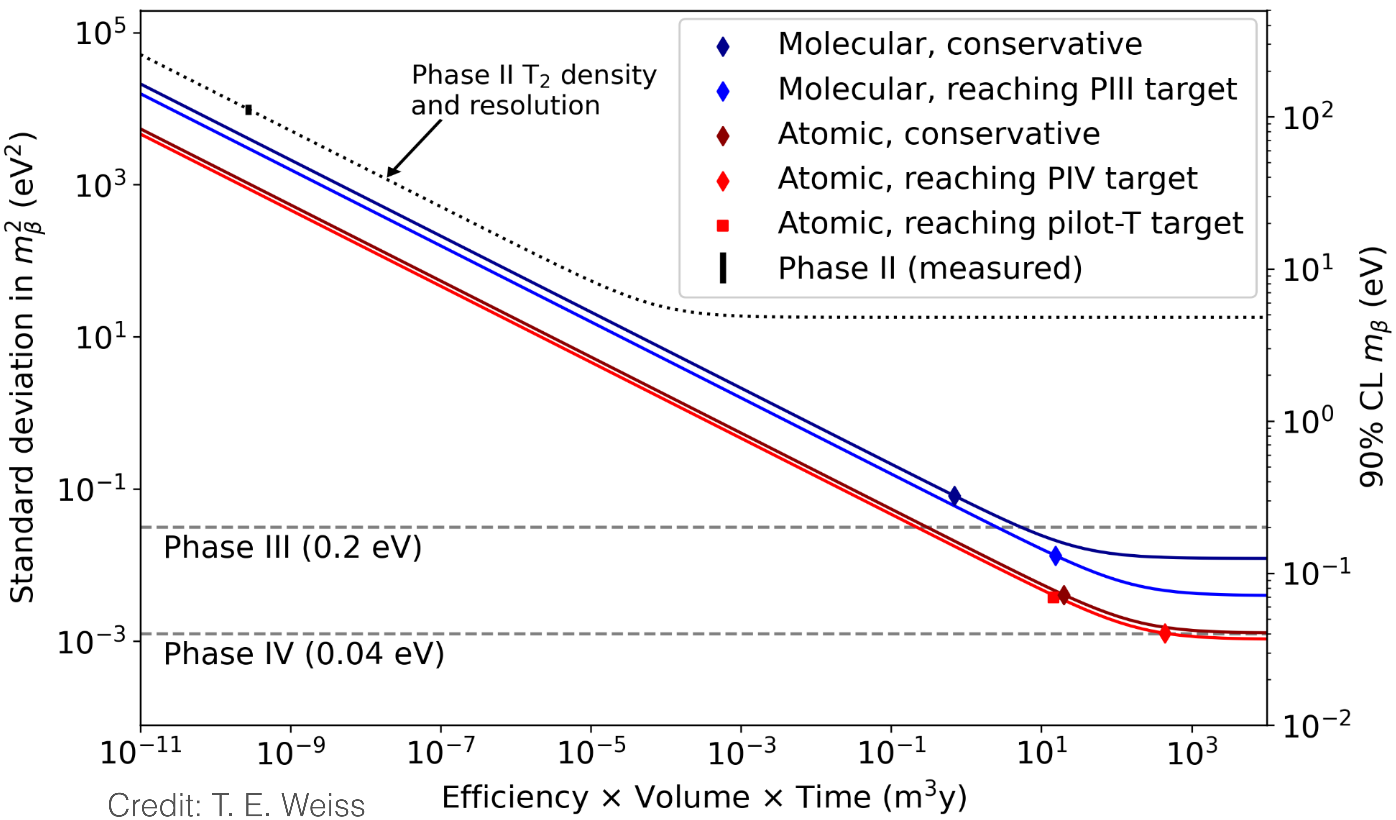
Uncertainties on response function

Effective volume (volume × efficiency)

Runtime

Background

Response function stdevs. (resolution)



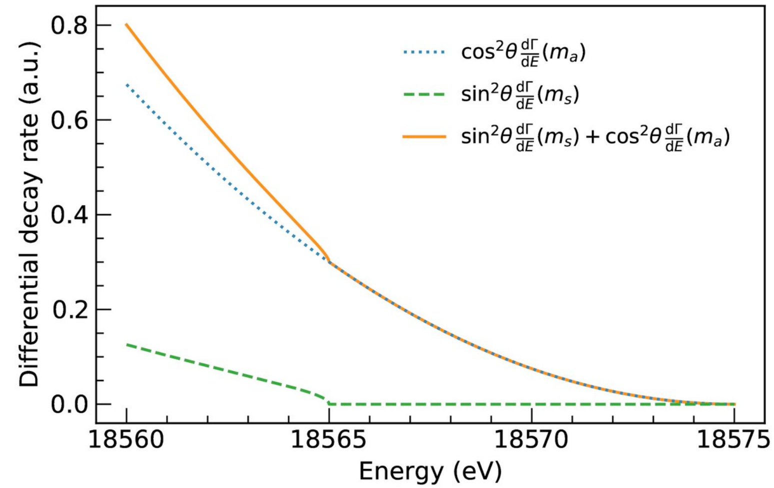
Credit: T. E. Weiss

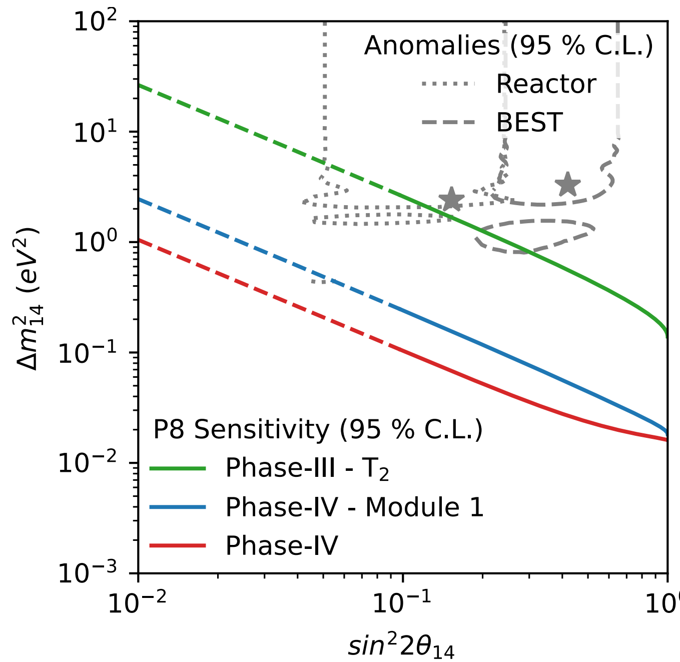
Conservative:
What we think we can do if building today

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 neutrino sensitivity under investigation
- Also sensitive to relic neutrino overdensity from neutrino capture on tritium





Credit: P. T. Surukuchi

PROJECT 8

Take Aways

- The Project 8 approach to neutrino mass measurement:
    - High precision frequency measurement
    - Source = detector concept
    - 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: World-leading neutrino mass limit with molecular tritium
- 2030s: First atomic tritium neutrino mass extraction
- Final experiment: 40 meV neutrino mass sensitivity

Project 8 Simulation Development: Tomorrow (P. Slocum)

Case Western Reserve University
think beyond the possible

Universität Heidelberg
Zukunft seit 1386

Karlsruher Institut für Technologie

Berkeley Lab

Pacific Northwest
National Laboratory

Yale