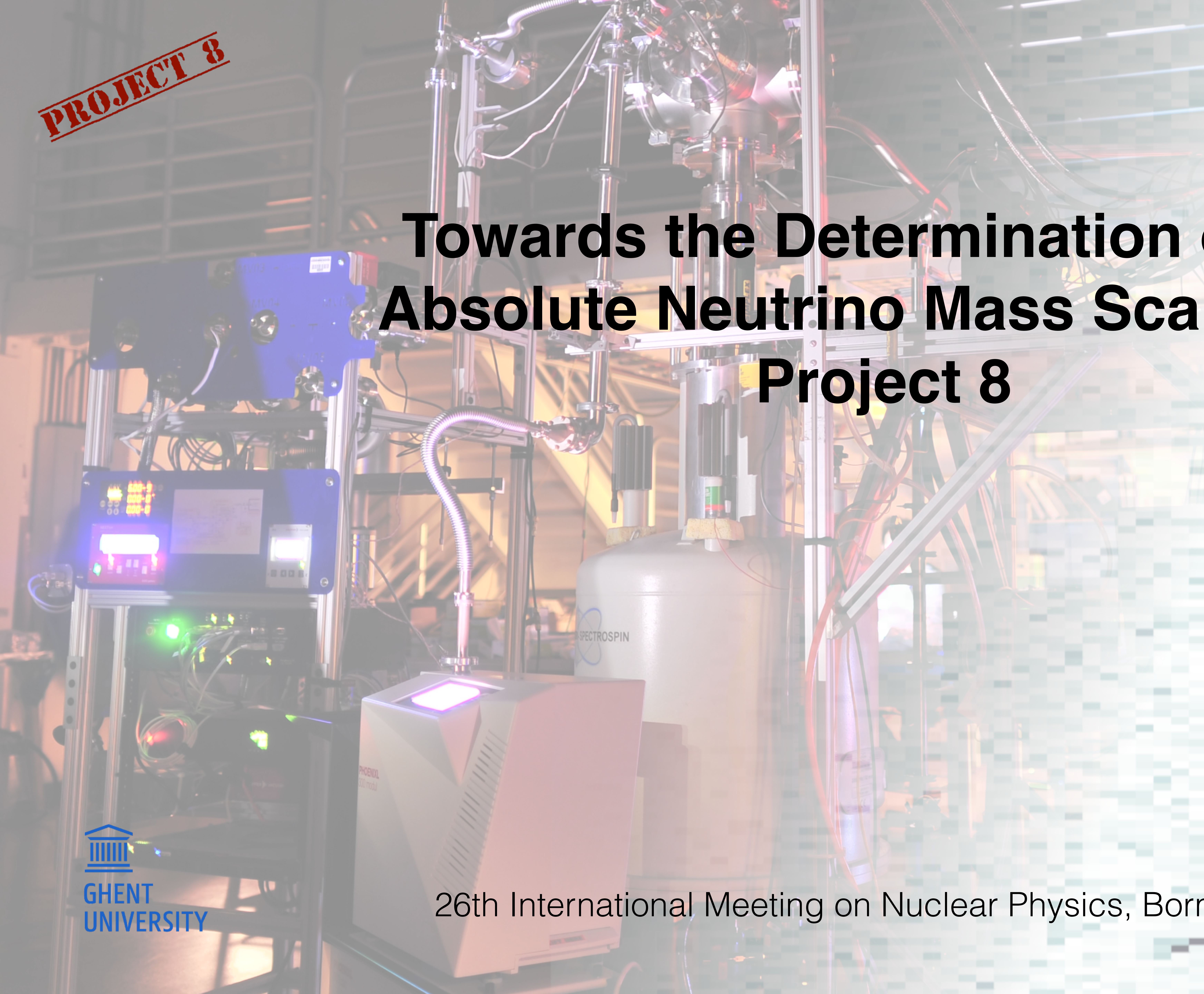
PROJECT 8



Towards the Determination of the Absolute Neutrino Mass Scale with Project 8

26th International Meeting on Nuclear Physics, Bormio 2026

Juliana Stachurska

GHENT UNIVERSITY

Neutrino Mass Basics

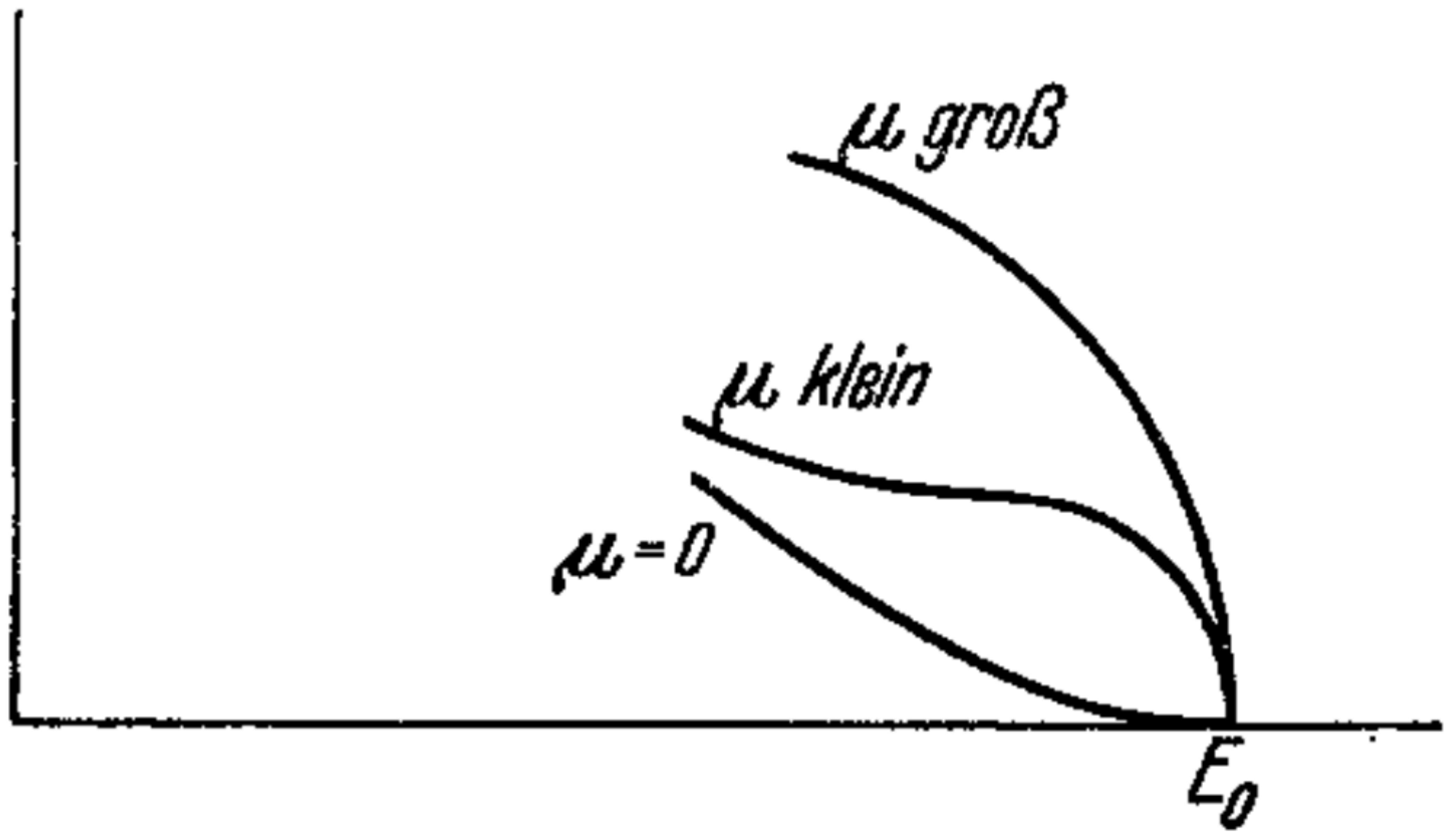
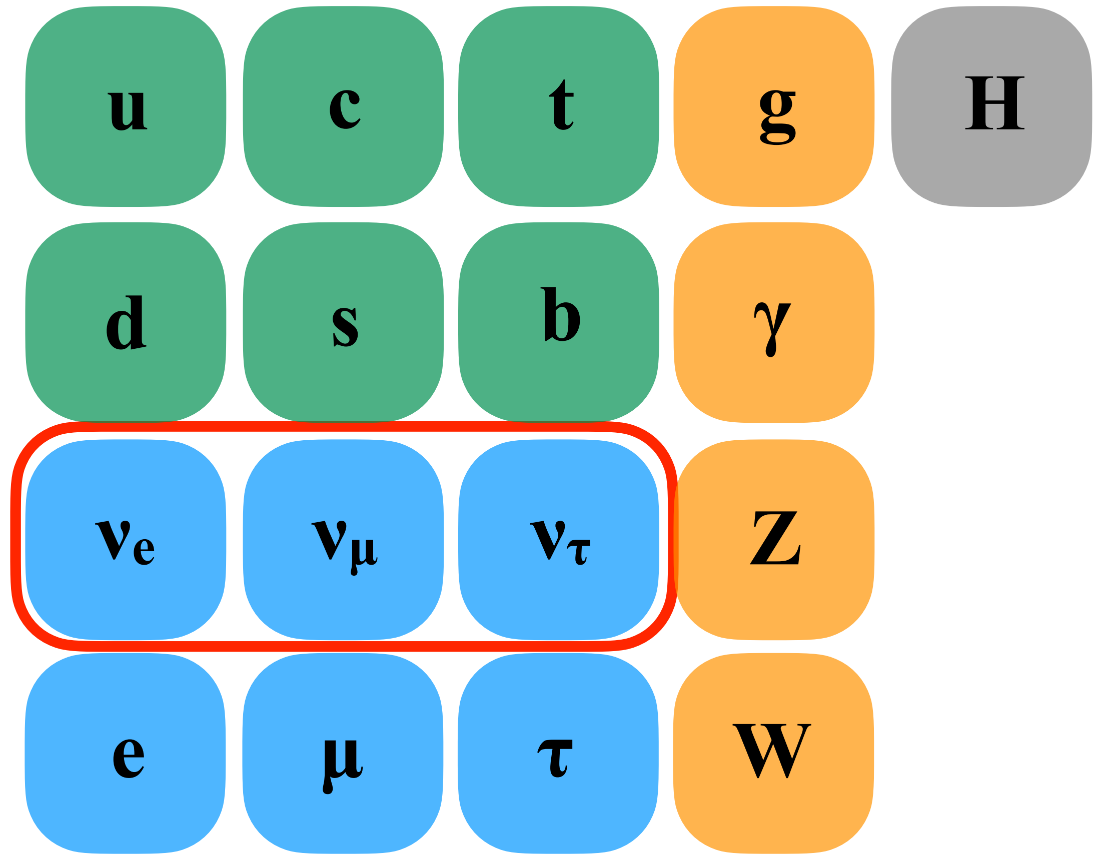
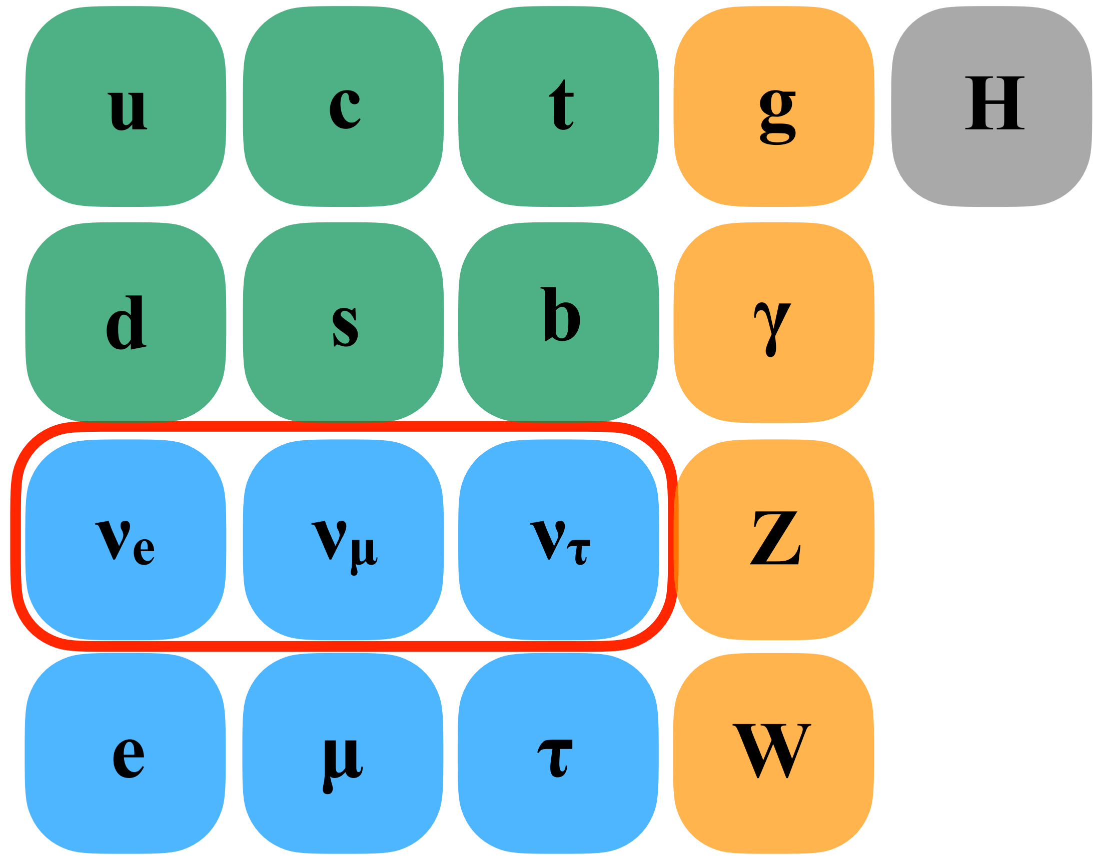


Fig. 1.



SM: massless neutrinos



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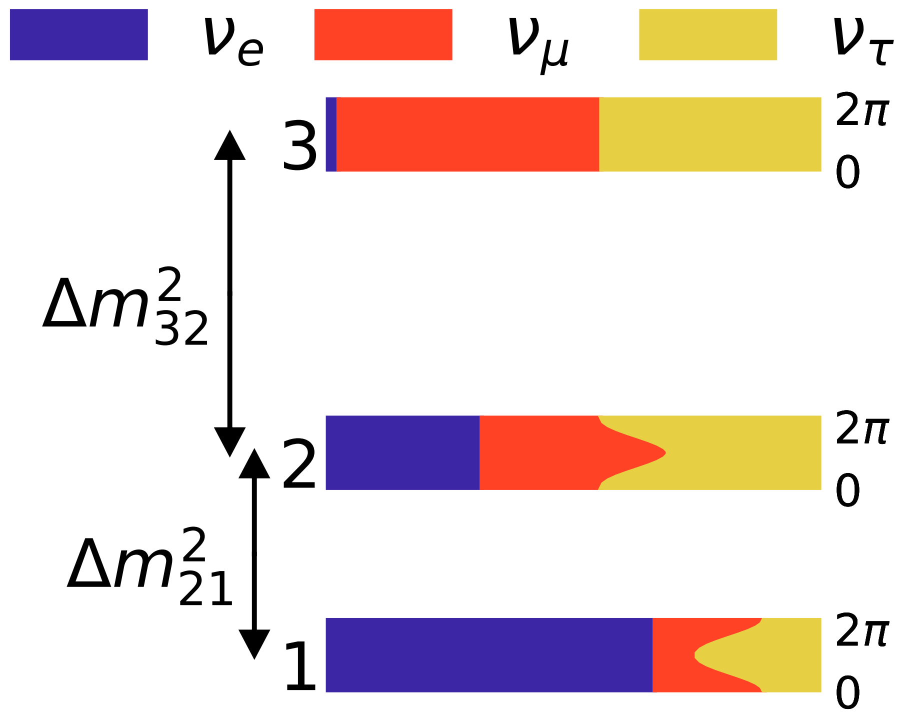
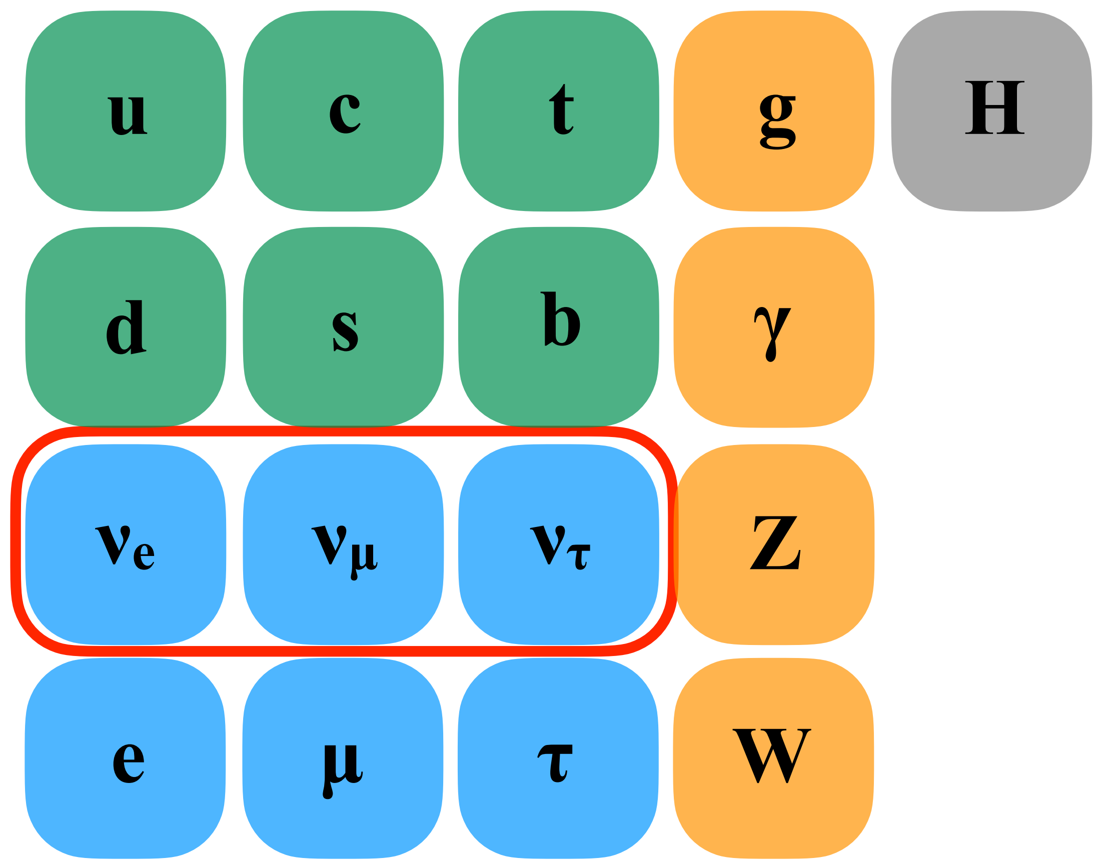


Neutrino oscillations → neutrino mass differences

$\Sigma m_i > 0.059\,\mathrm{eV}$

JHEP 12, 216 (2024)



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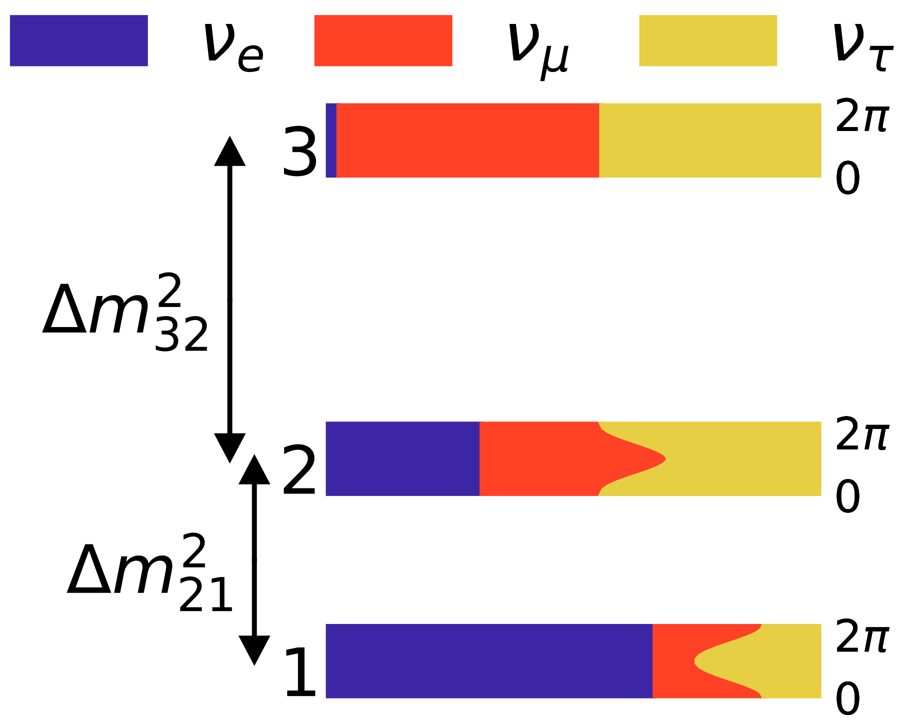
←



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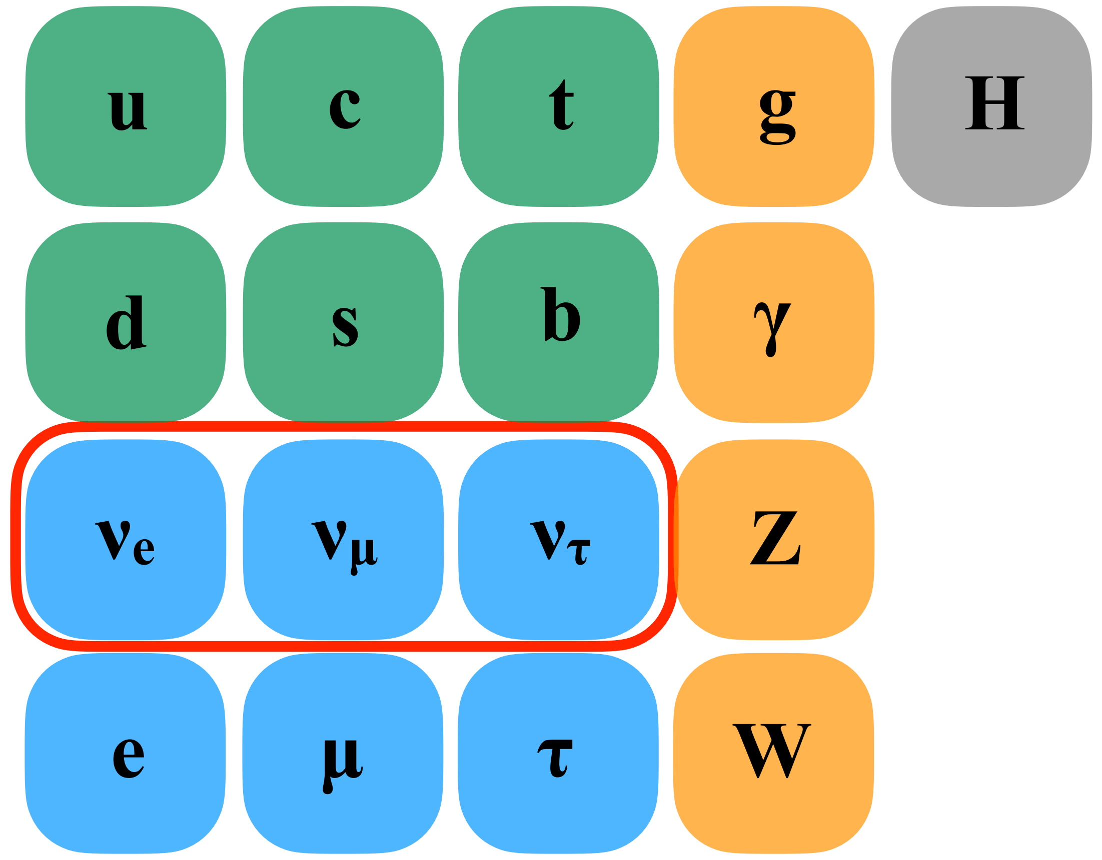

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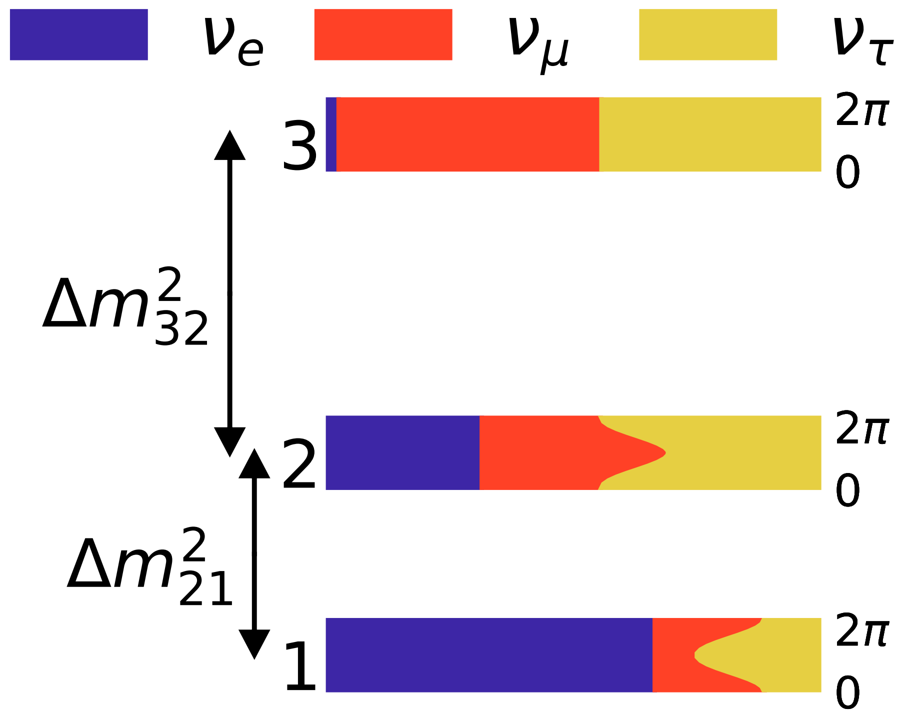

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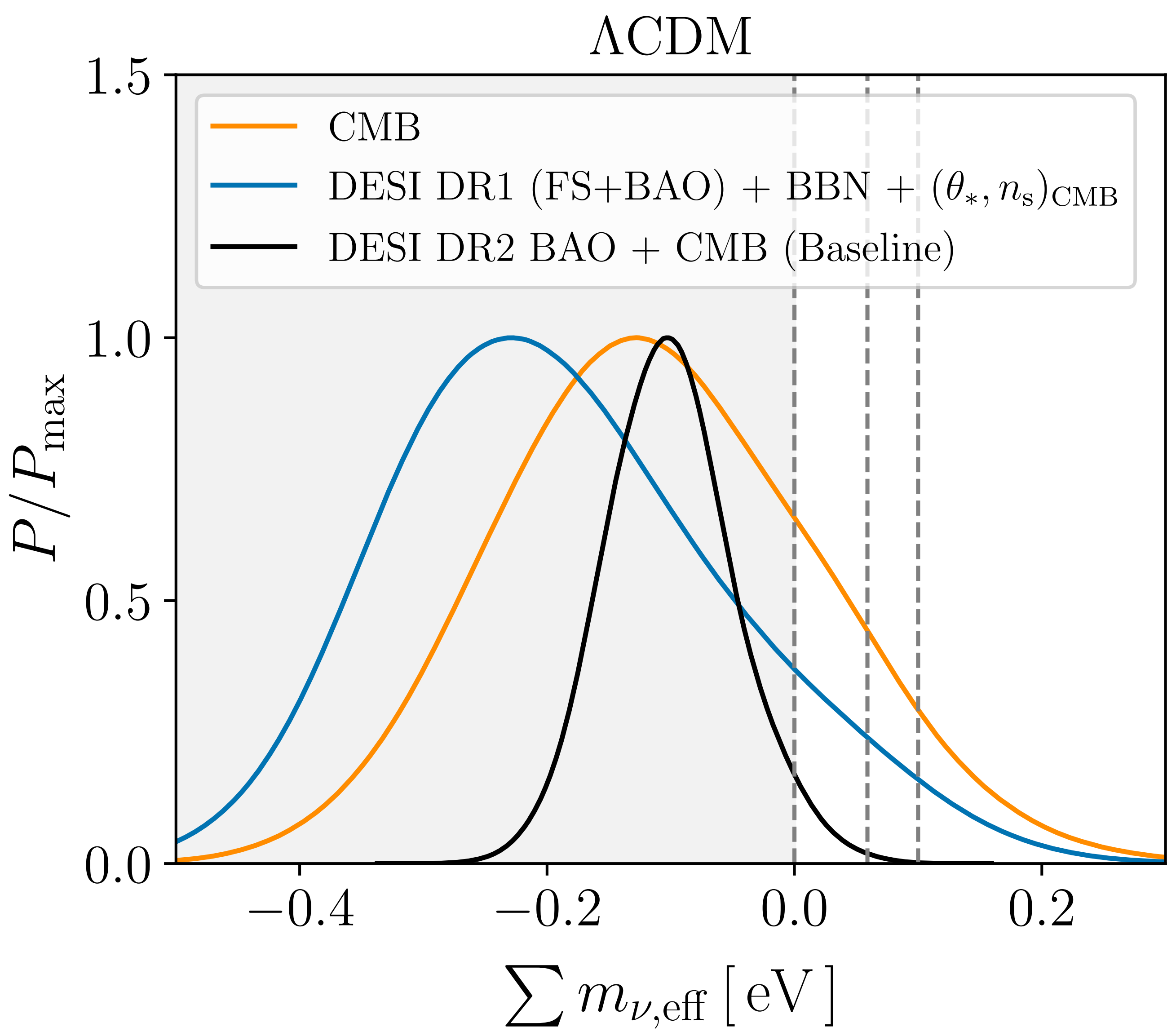

Cosmic surveys:
Indirect neutrino mass sensitivity

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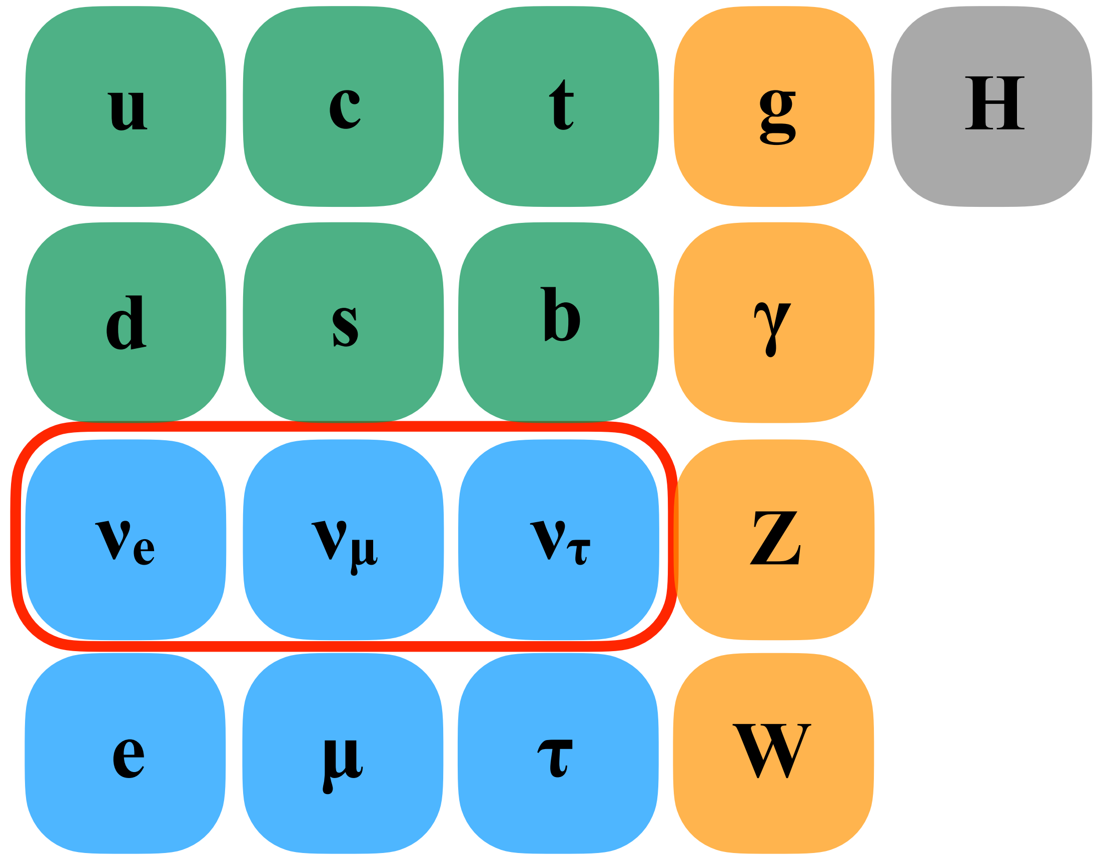
PRD 112, 083513 (2025)



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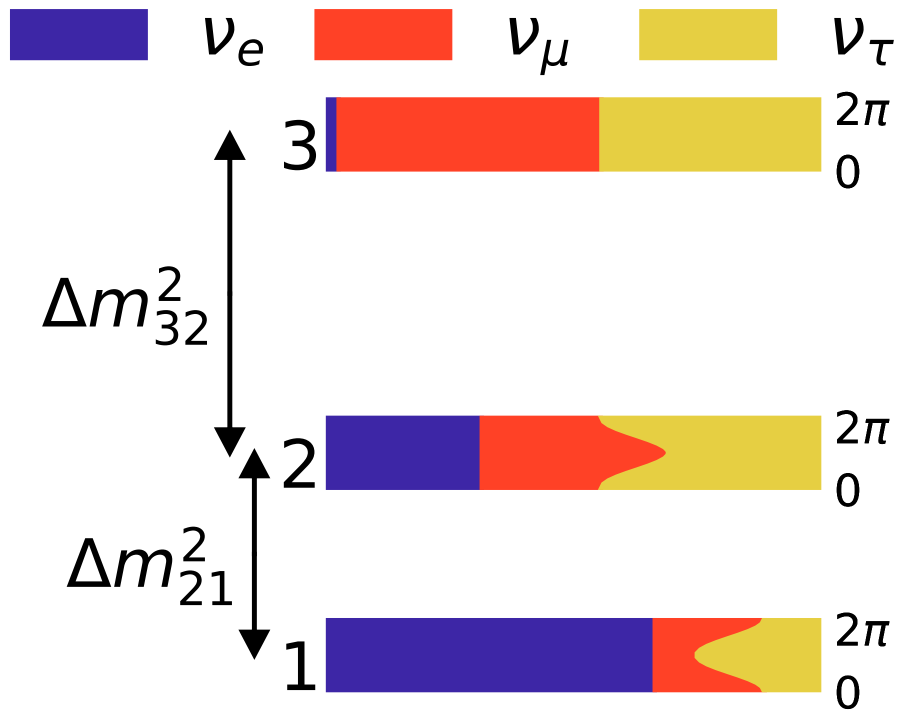

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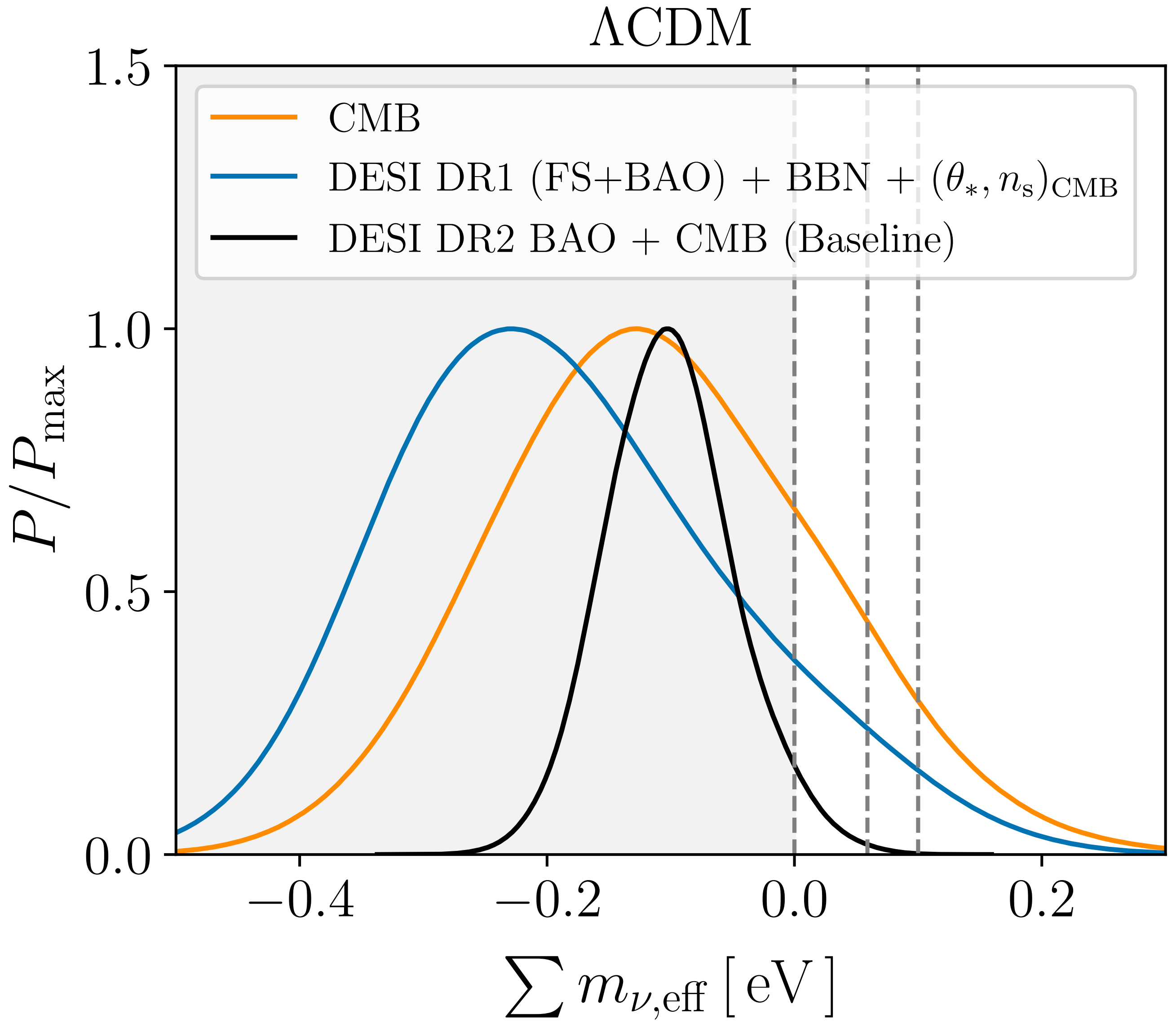

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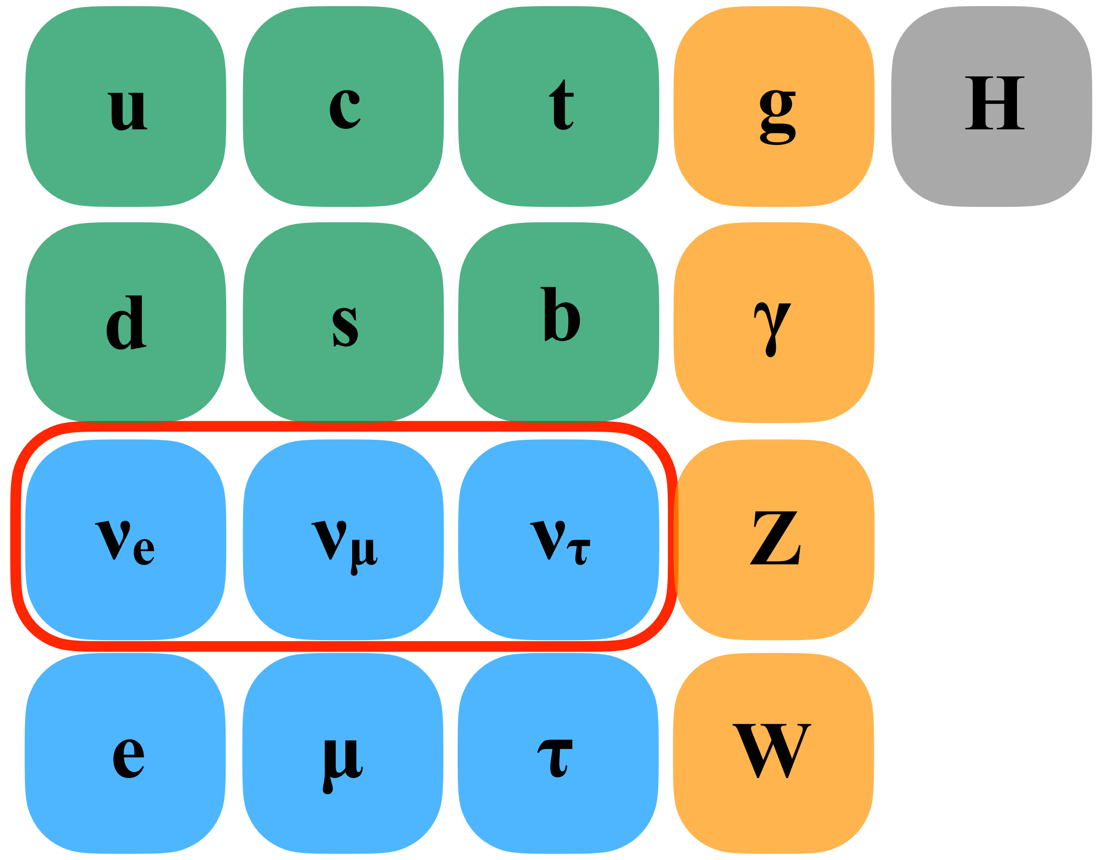

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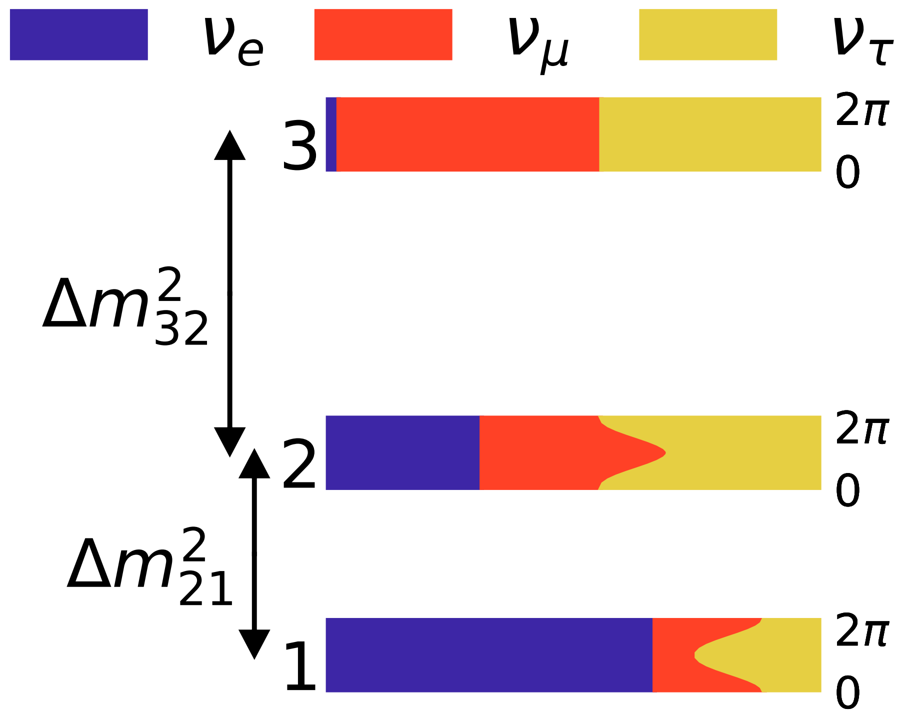

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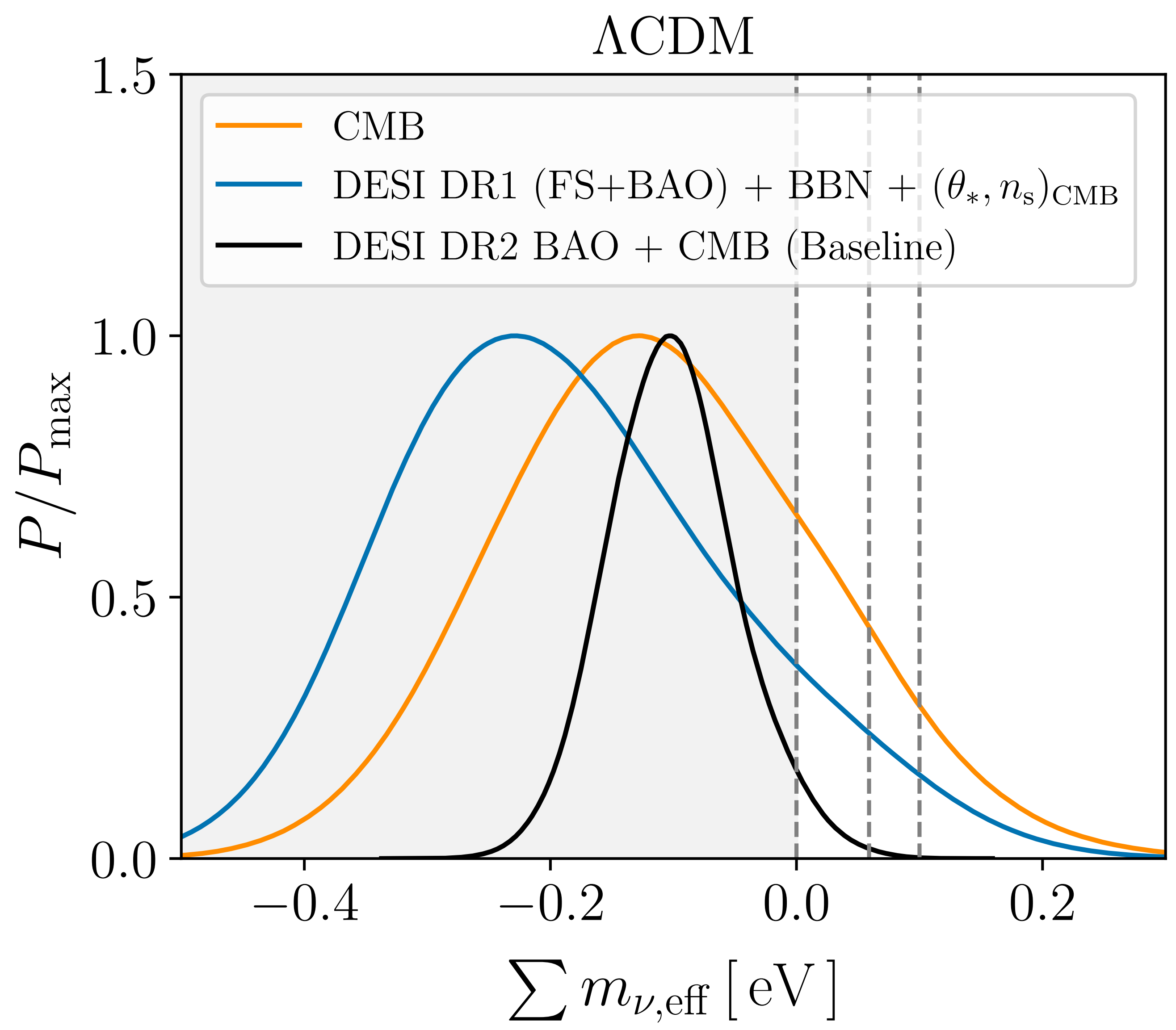

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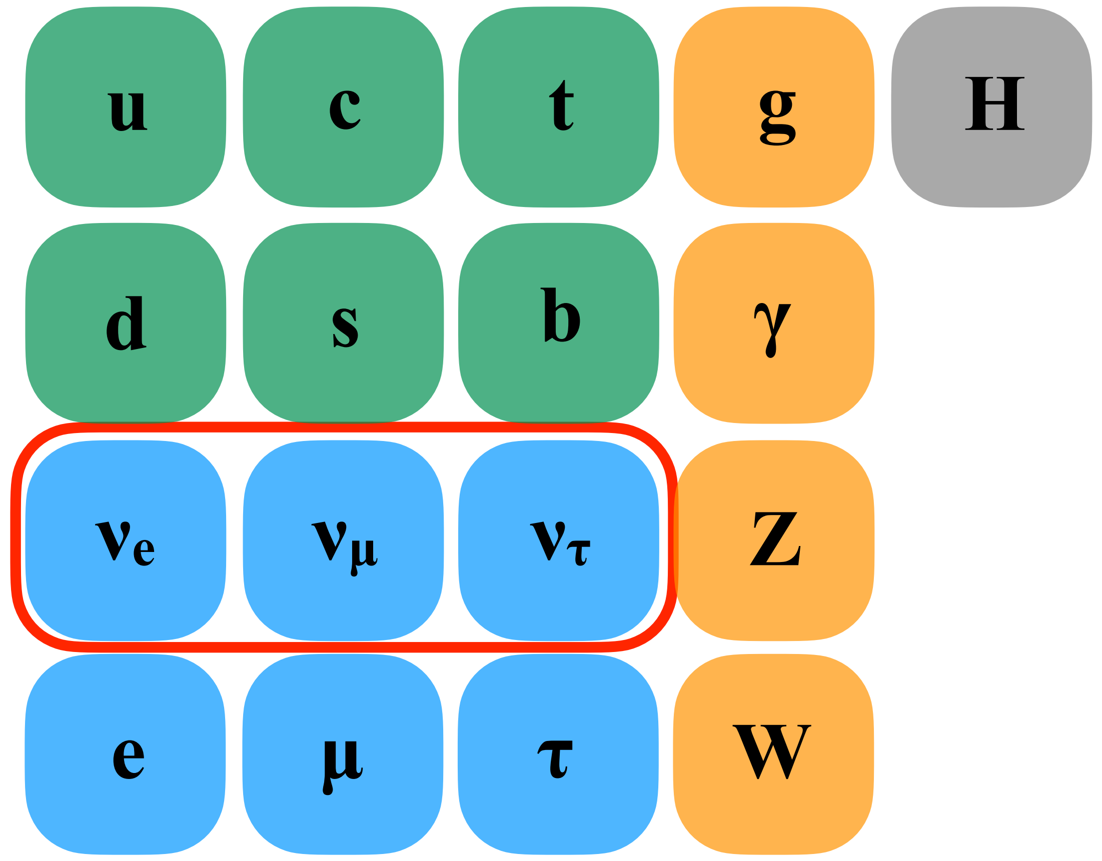

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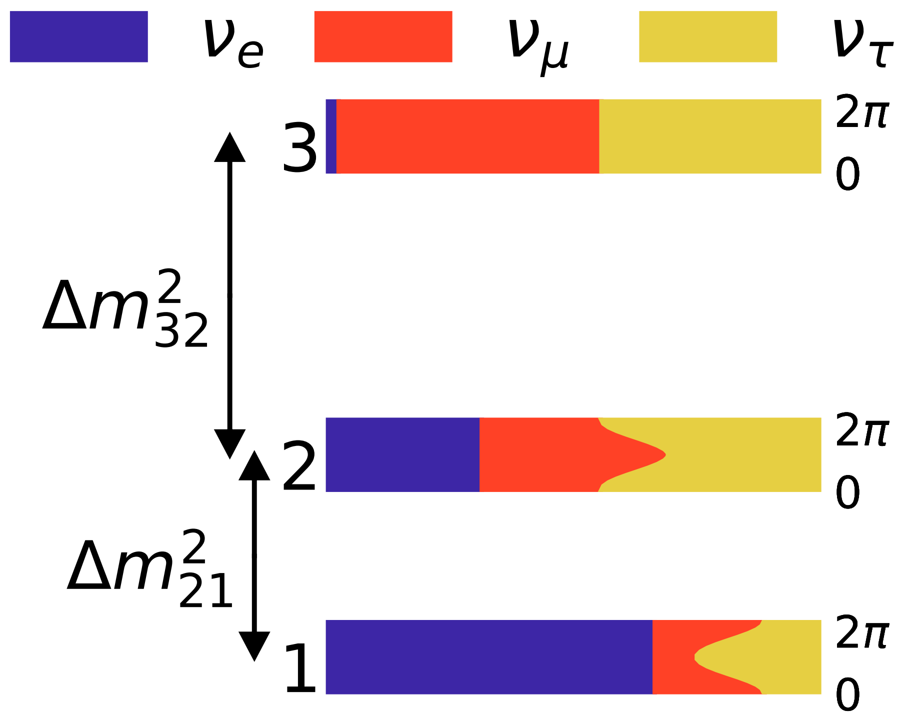

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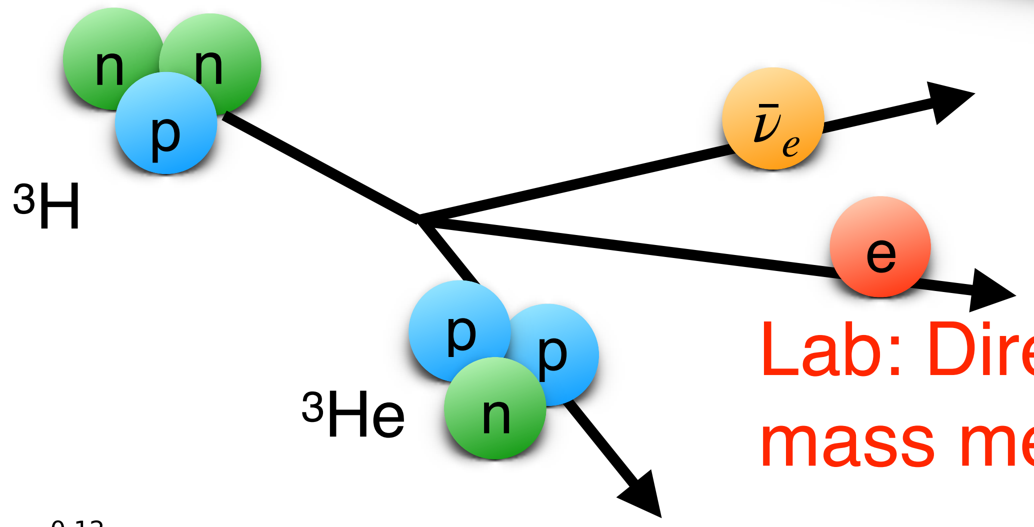
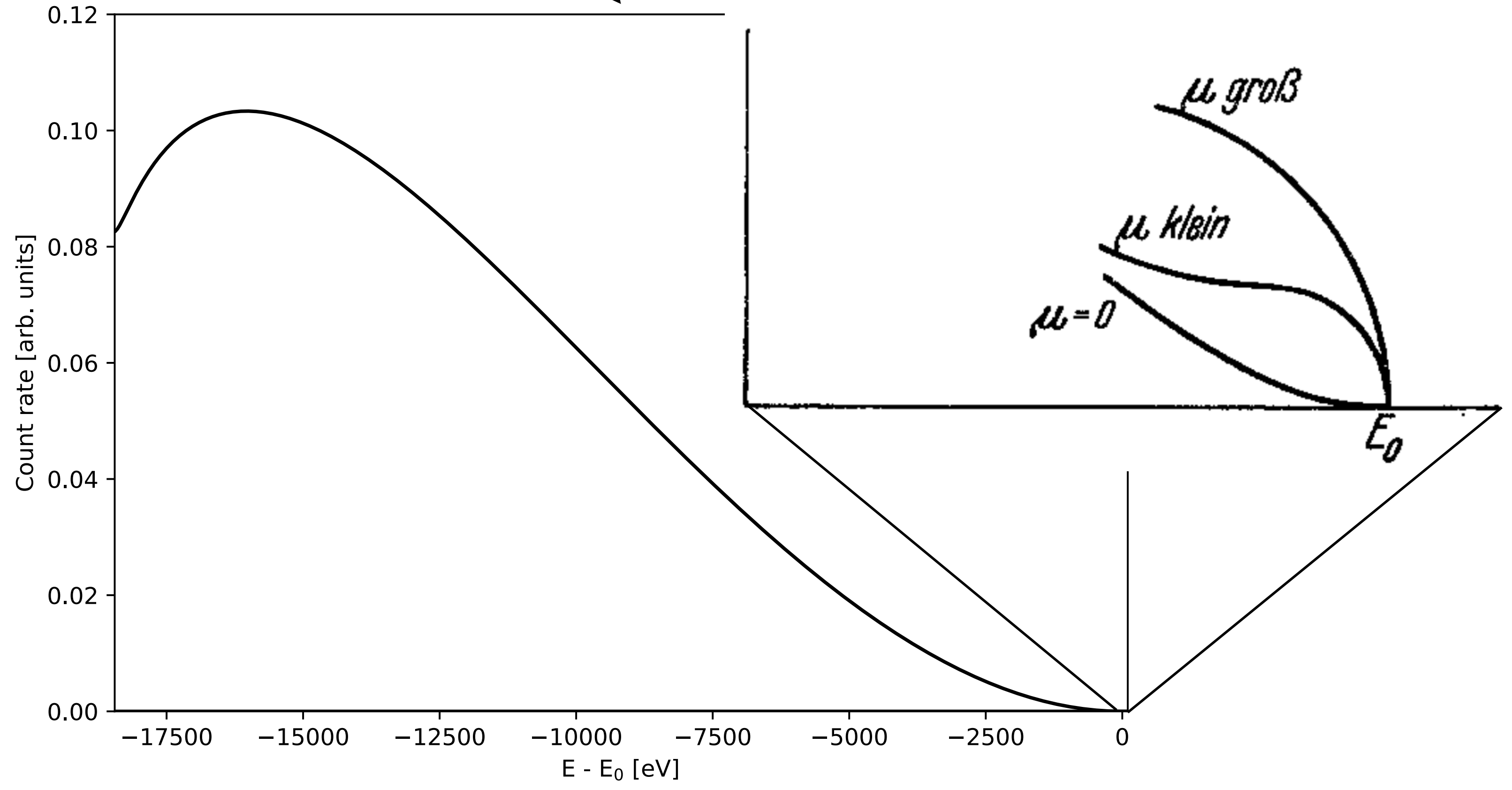
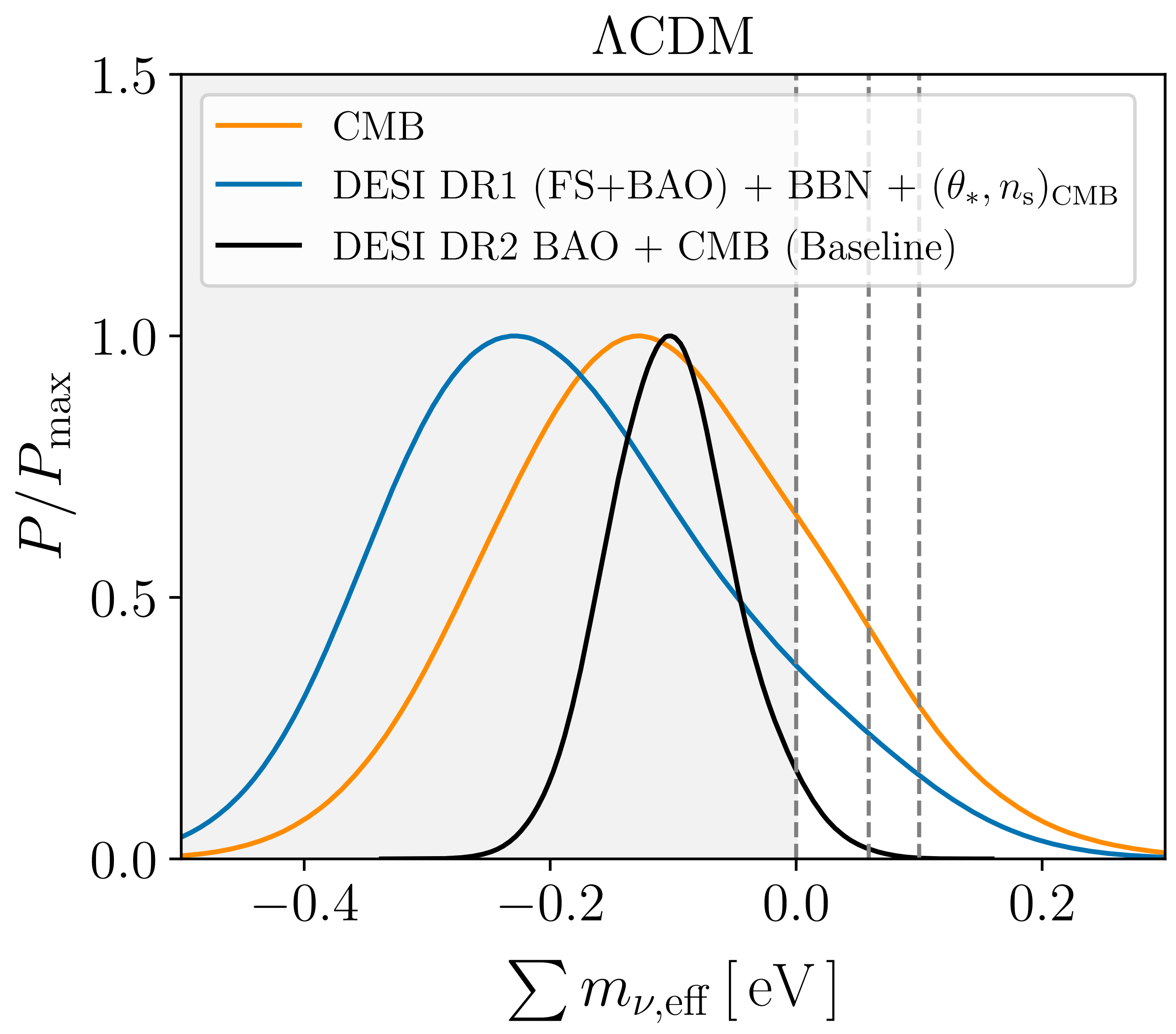


Lab: Direct neutrino mass measurement





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PRD 112, 083513 (2025)

Direct Neutrino Mass Measurement

- Sensitive to electron-weighted neutrino mass:
  $m^2_{\nu_e,\mathrm{eff}} = \sum |U_{ei}|^2 m_i^2$

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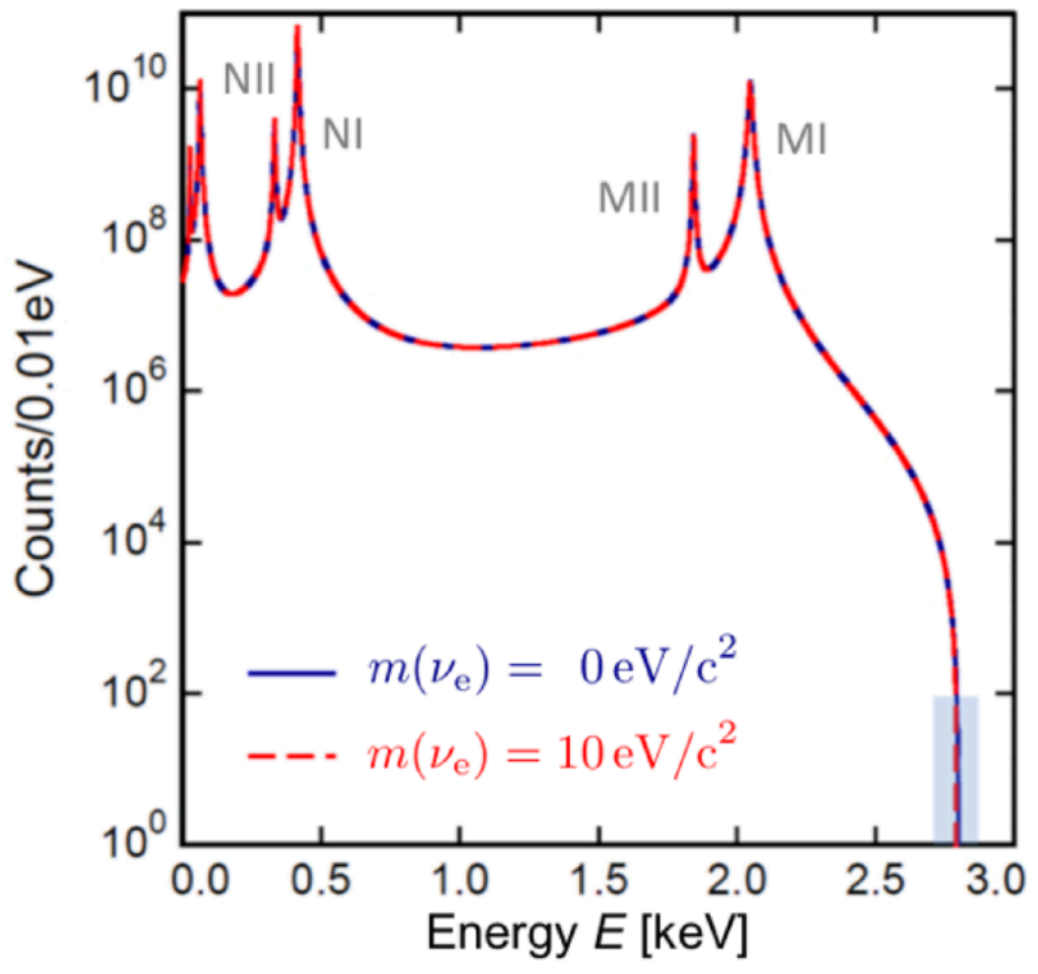

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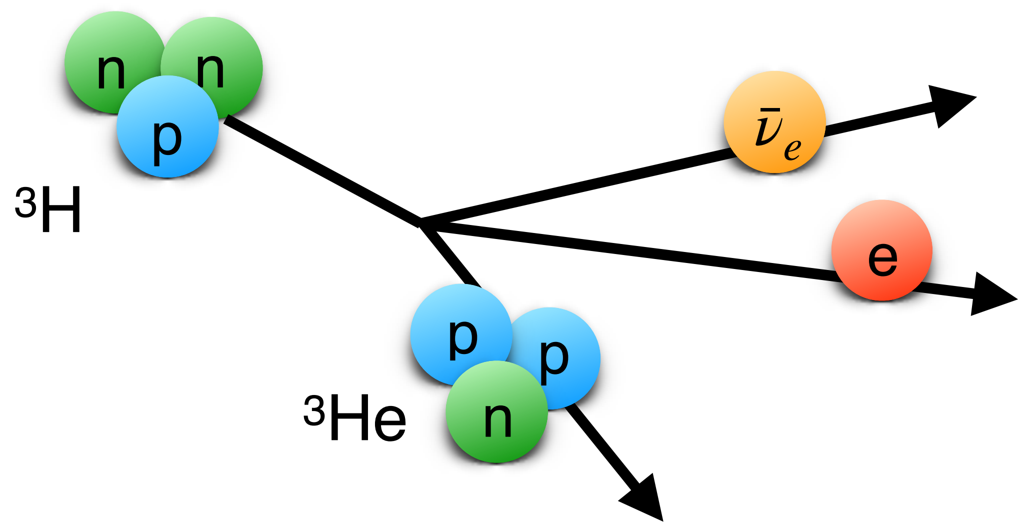

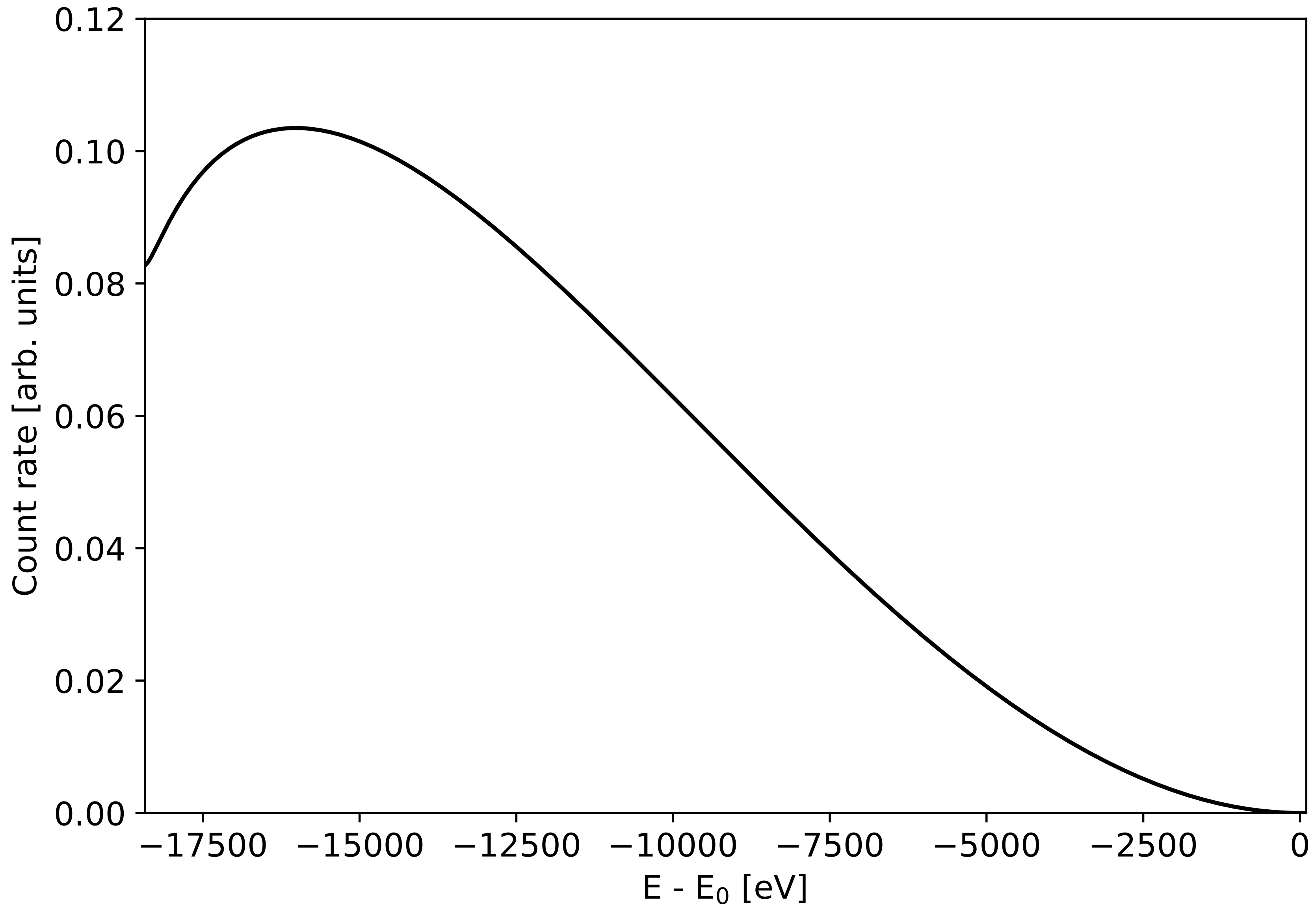

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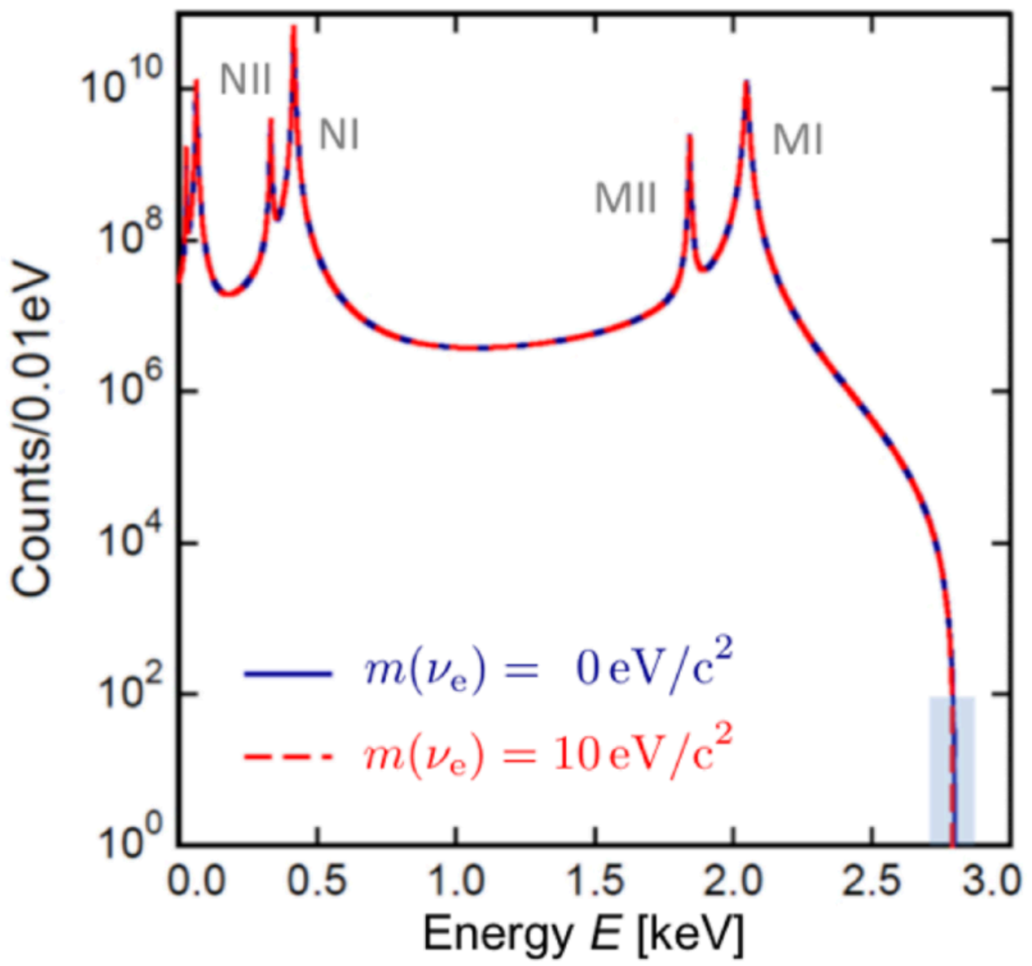

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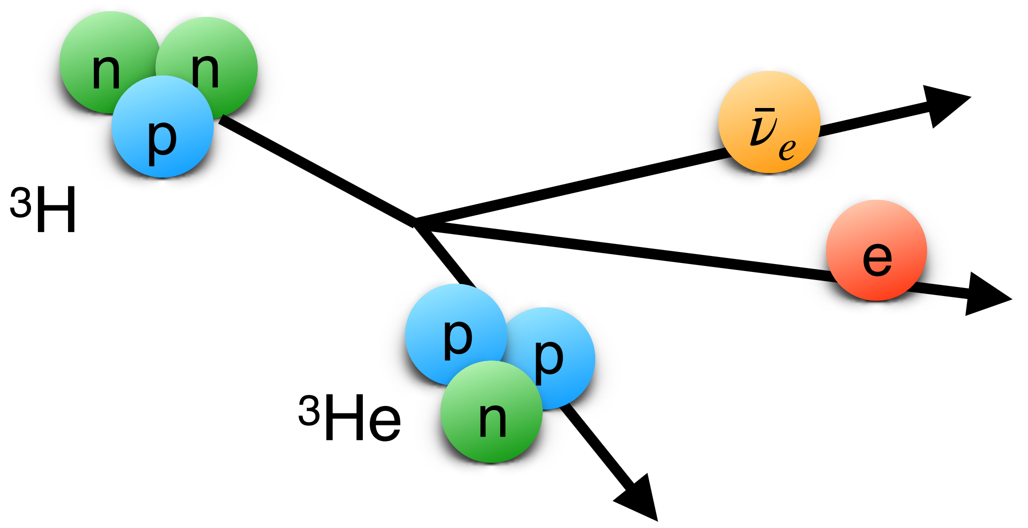

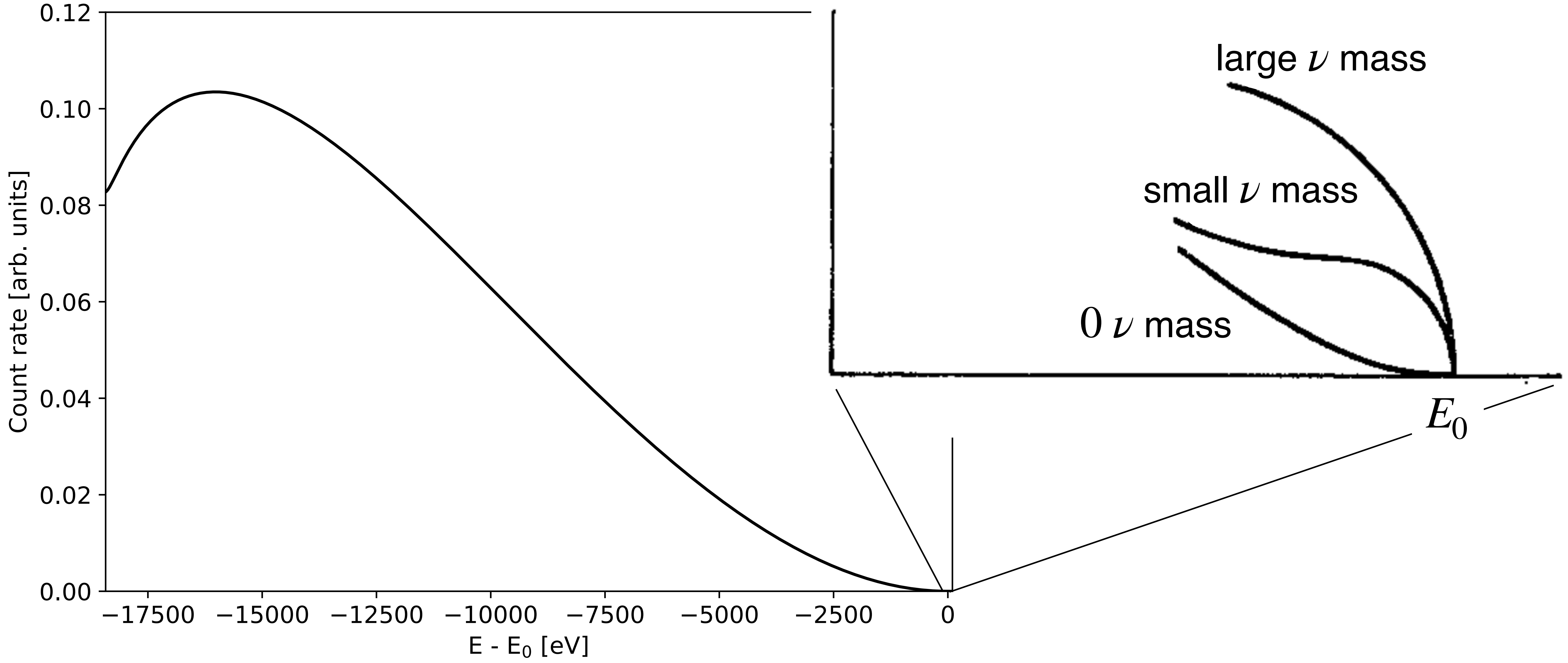

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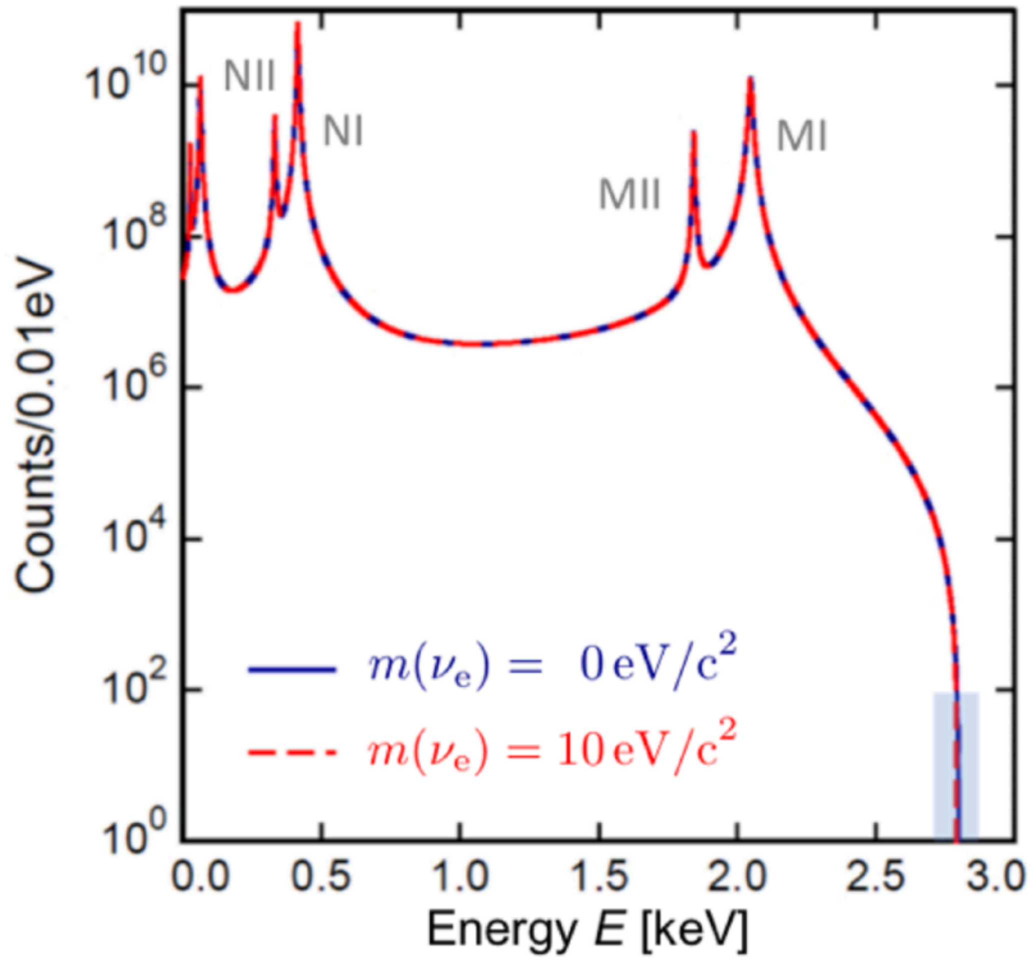
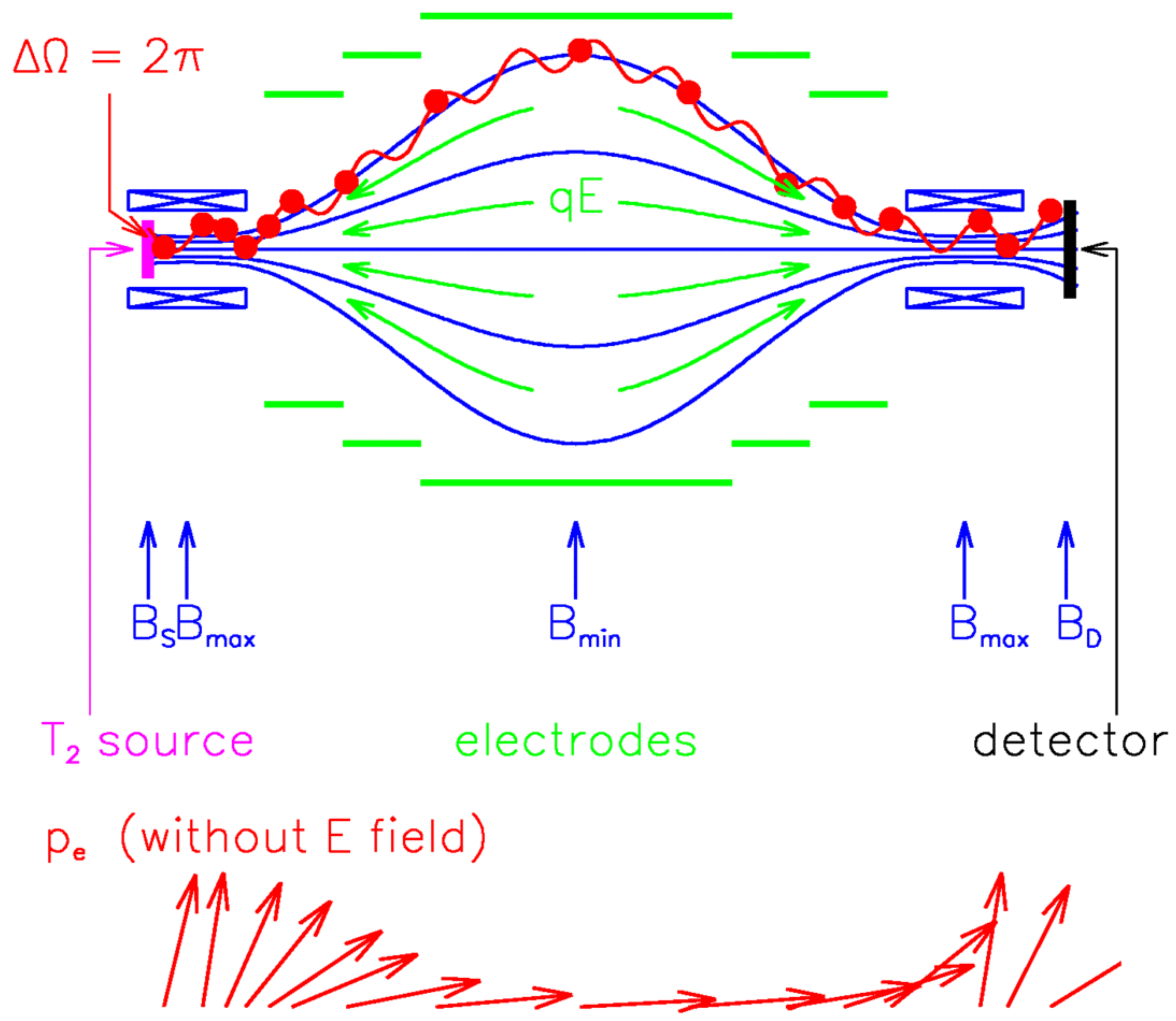


State-of-the-Art: KATRIN



- Running 2018-2025 at TLK
- Molecular T_2 source
- 1/2 of decays into forward direction
- MAC-E filter: Magnetic Adiabatic Collimation with Electrostatic filter = high-pass filter
- Electrons above filter energy counted: integrated spectrum

[KATRIN, https://www.katrin.kit.edu/]

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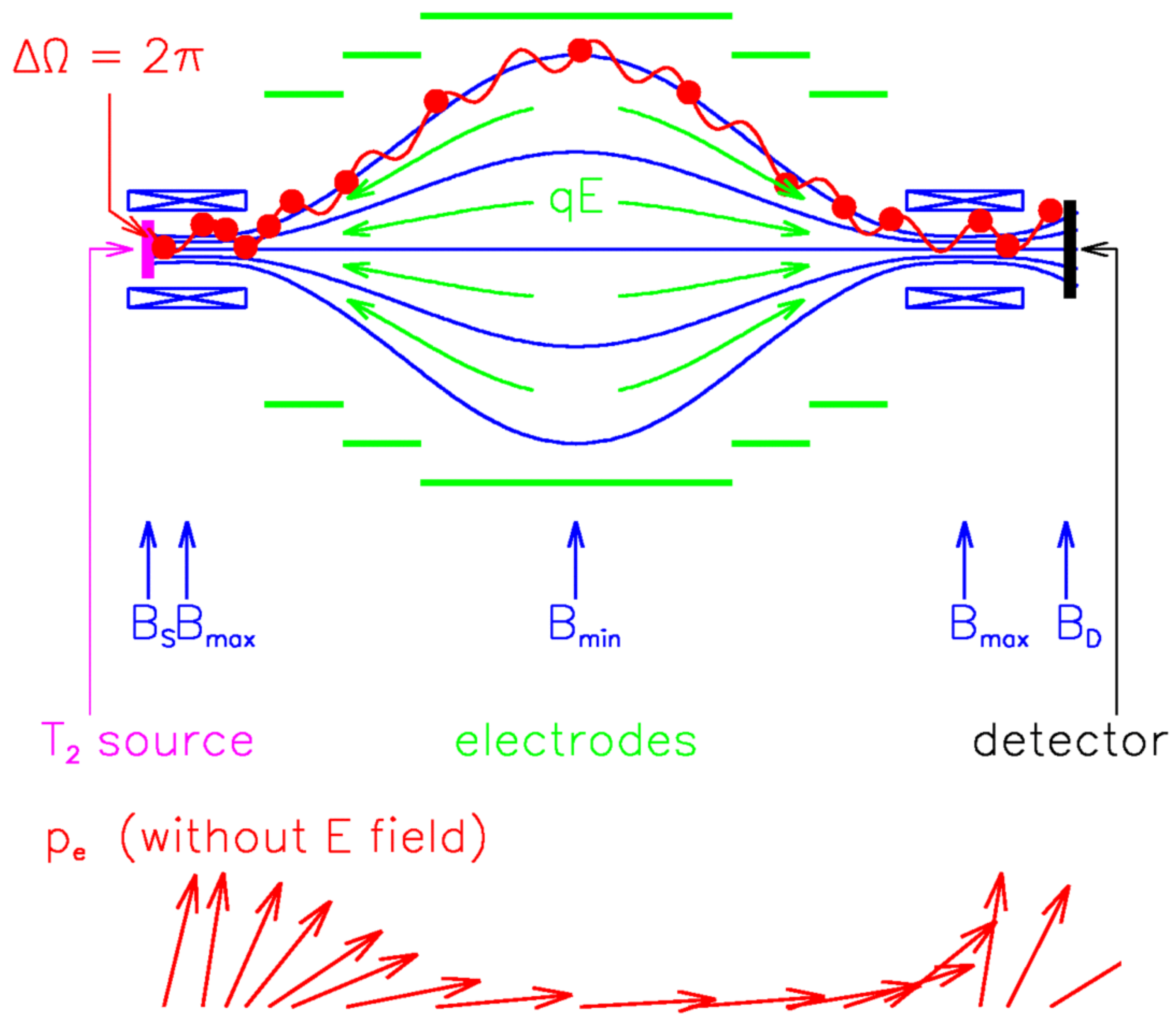

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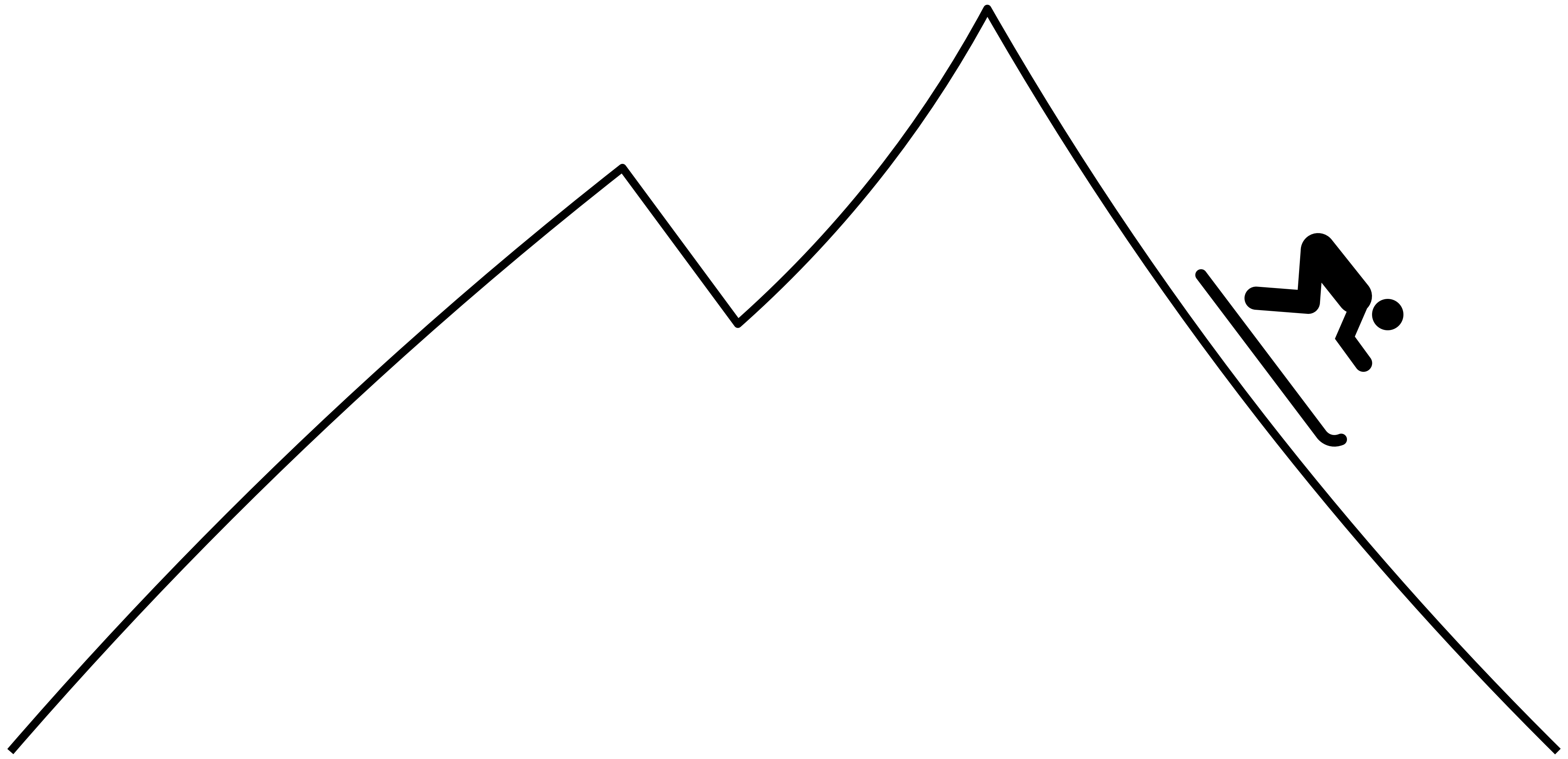
- Current best limit: $m_{\nu_e,\mathrm{eff}} < 0.45\,\mathrm{eV}$
    - Design sensitivity: 0.2 eV
    - Technology not further scalable

[KATRIN, Science 388, 6743 (2025)]

[KATRIN, https://www.katrin.kit.edu/]

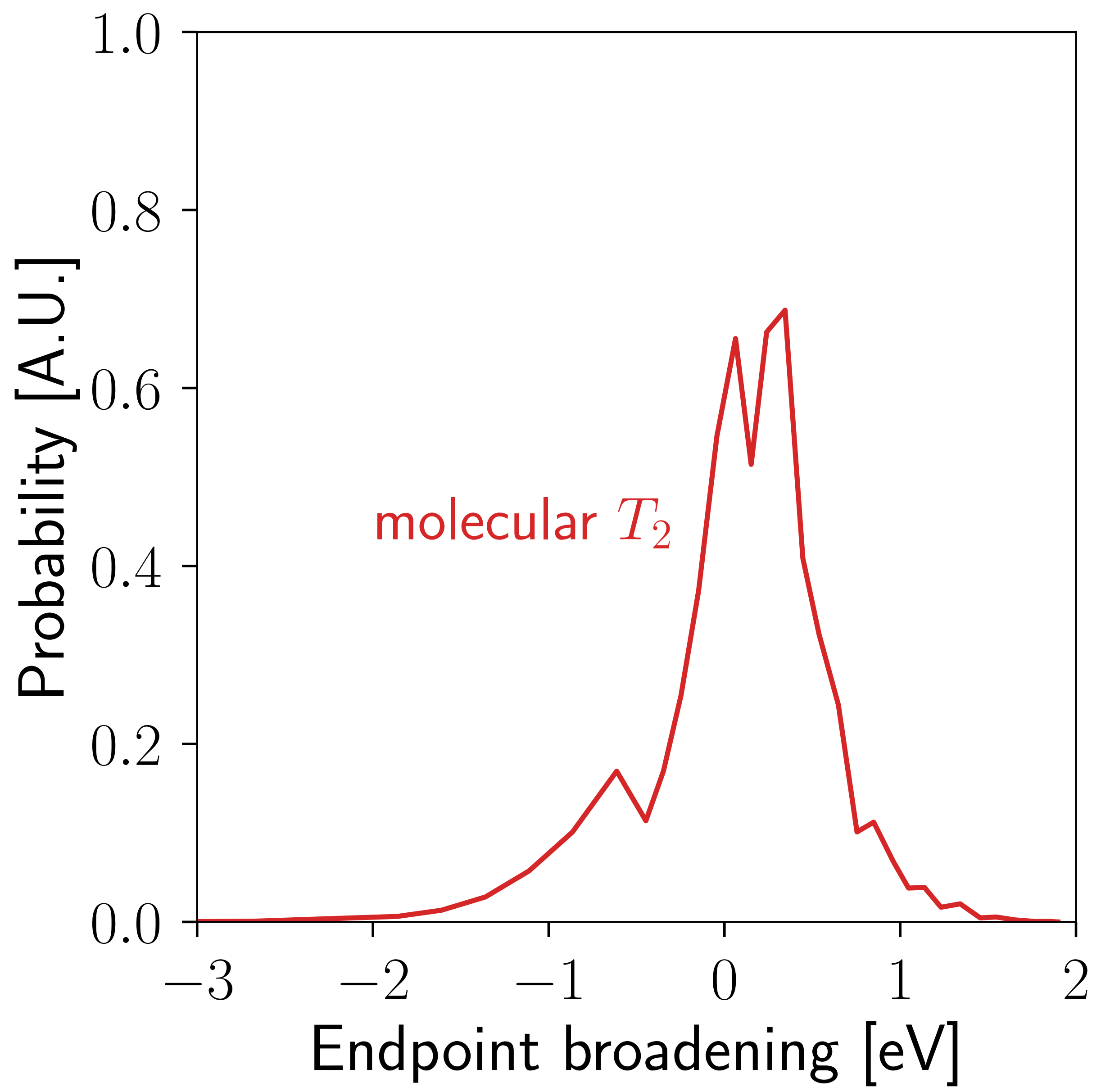
Project 8 Concept



Next Neutrino Mass Experiment: Project 8

Necessary key technology developments:

- Strong atomic tritium source



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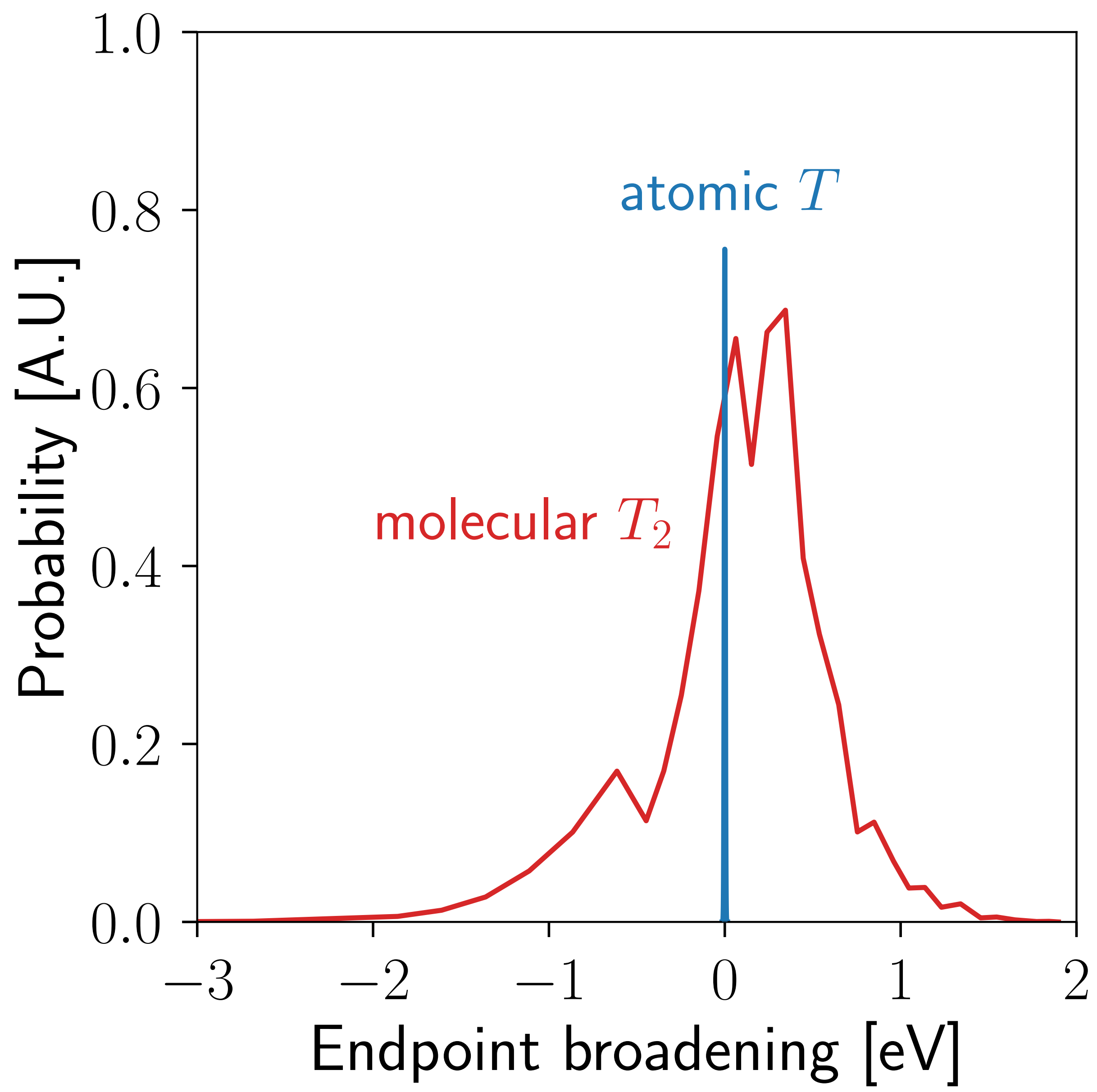

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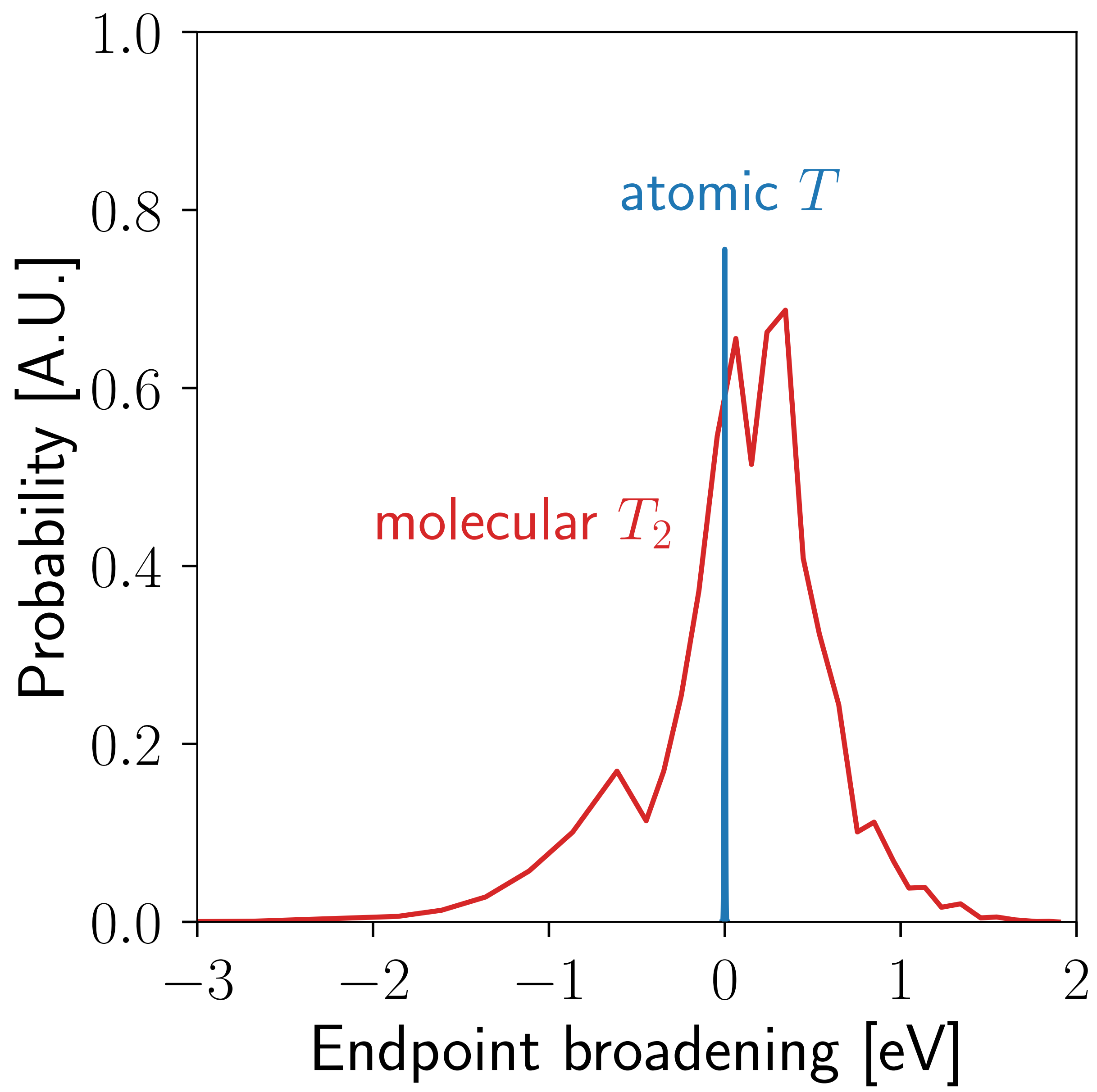

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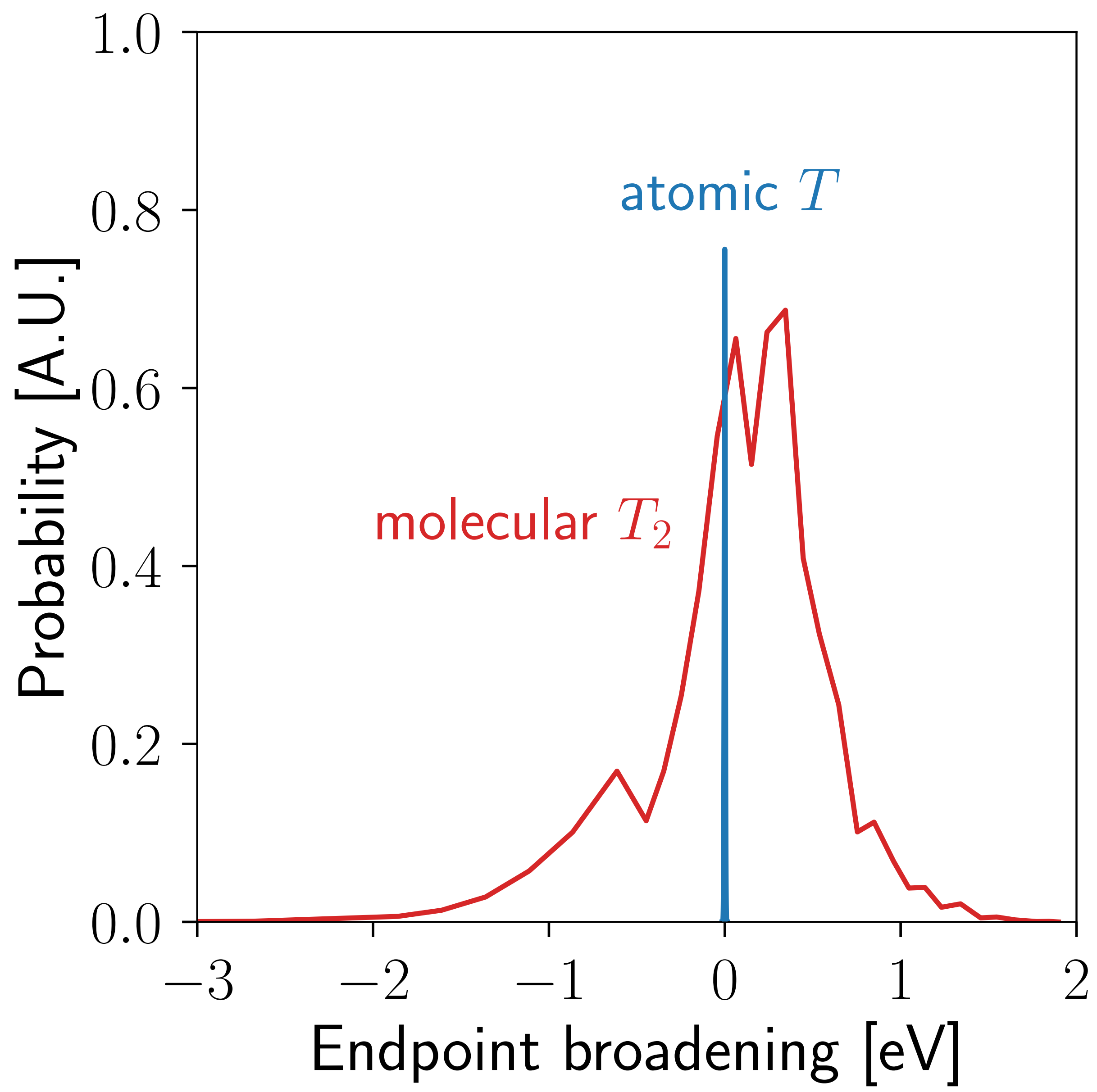
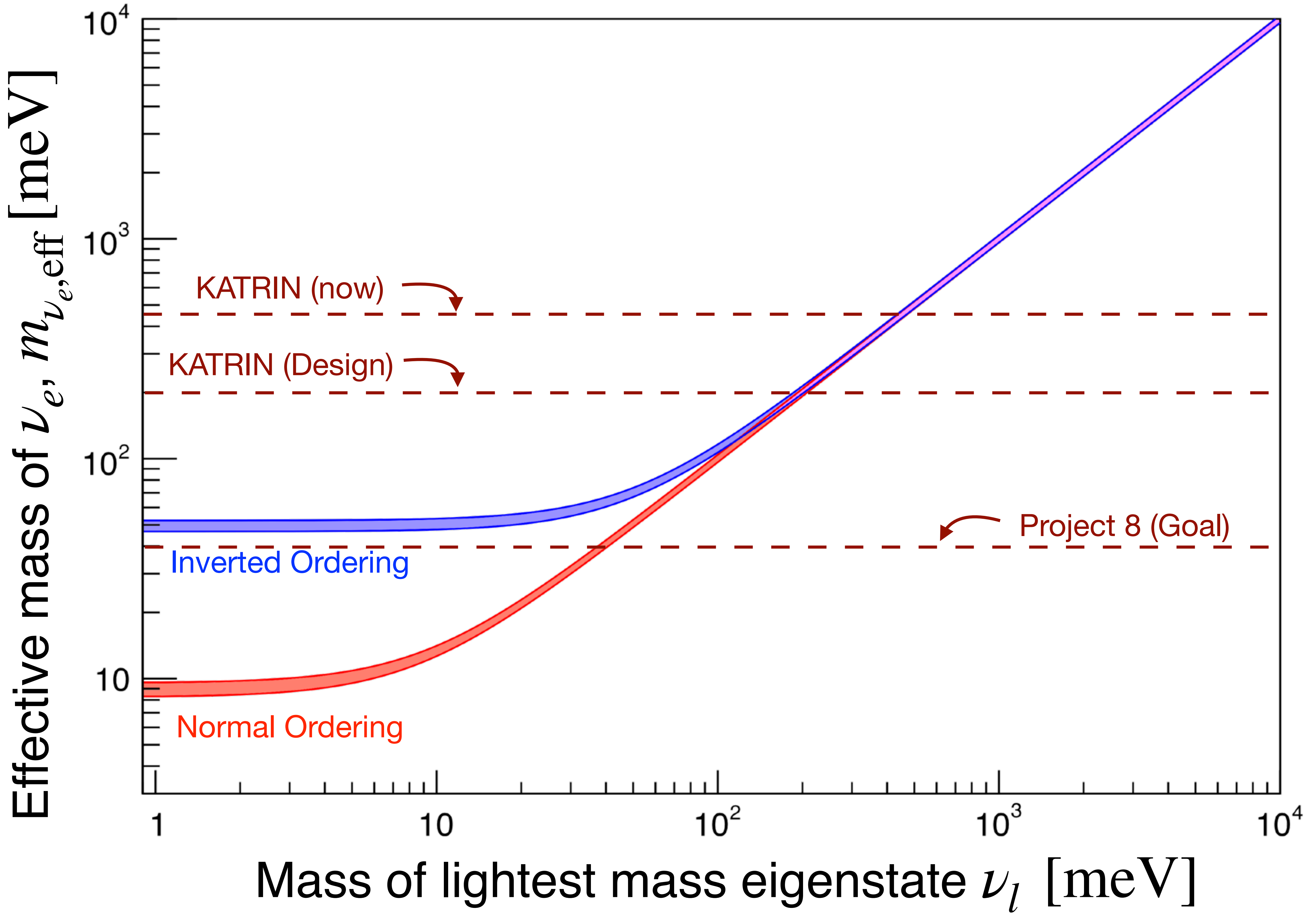
- Project 8 goal: $40\mathrm{meV}$ sensitivity to $m_{\nu_e,\mathrm{eff}}$





PROJECT 8

Cyclotron Radiation Emission Spectroscopy (CRES)

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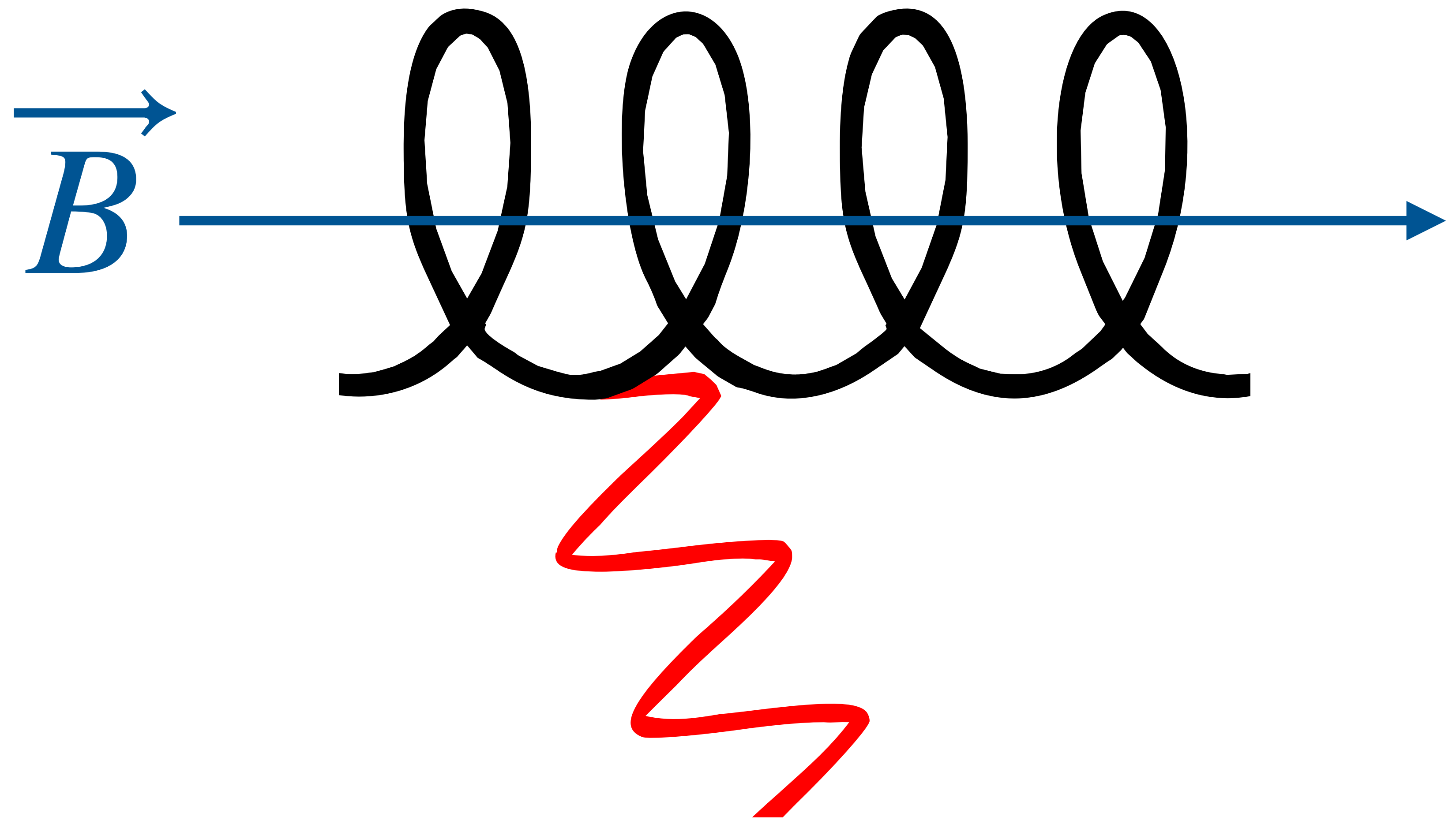
- Electron in B-field: cyclotron motion & radiation

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



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

[PRD 80, 051301 (2009)]

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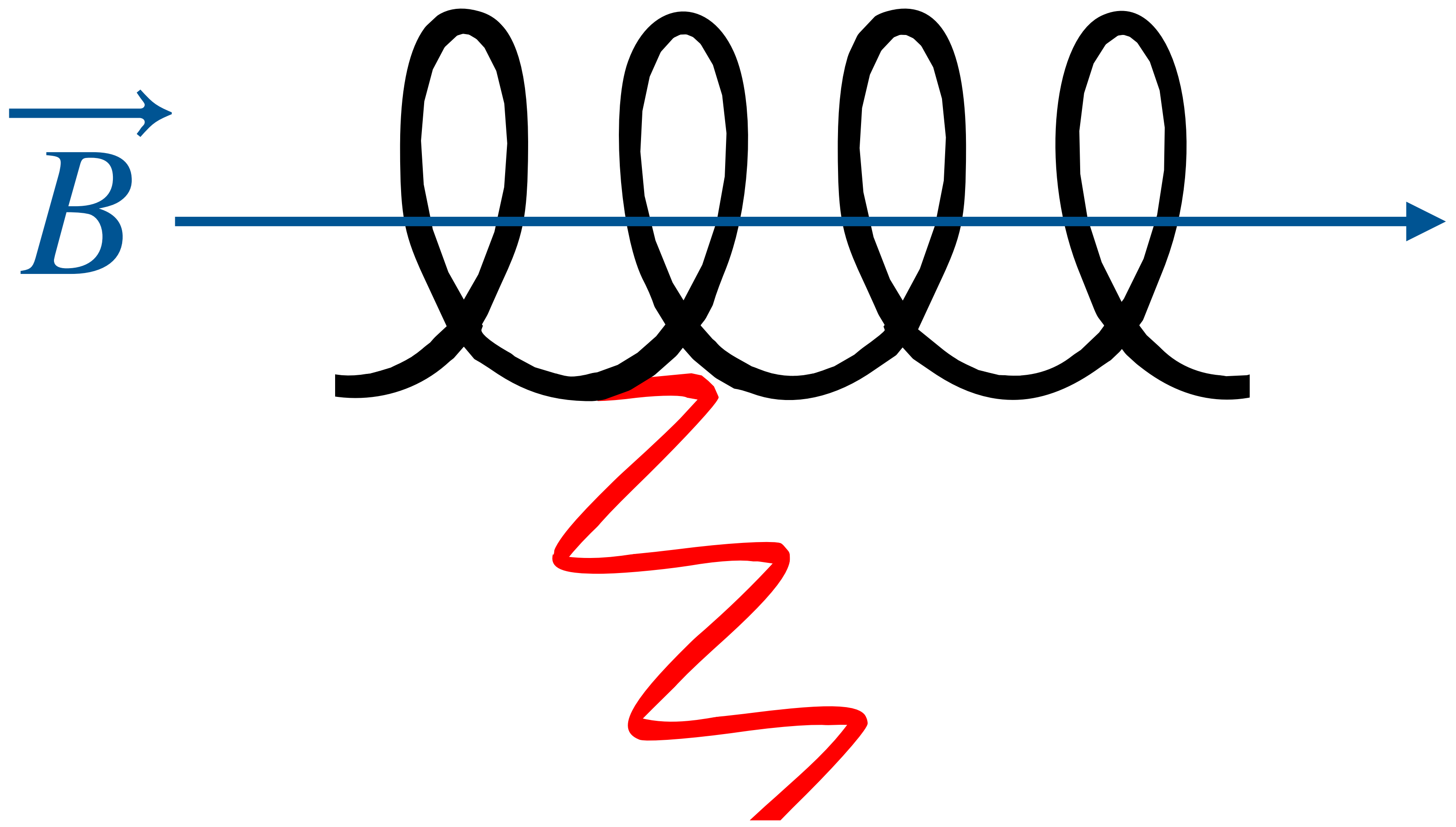

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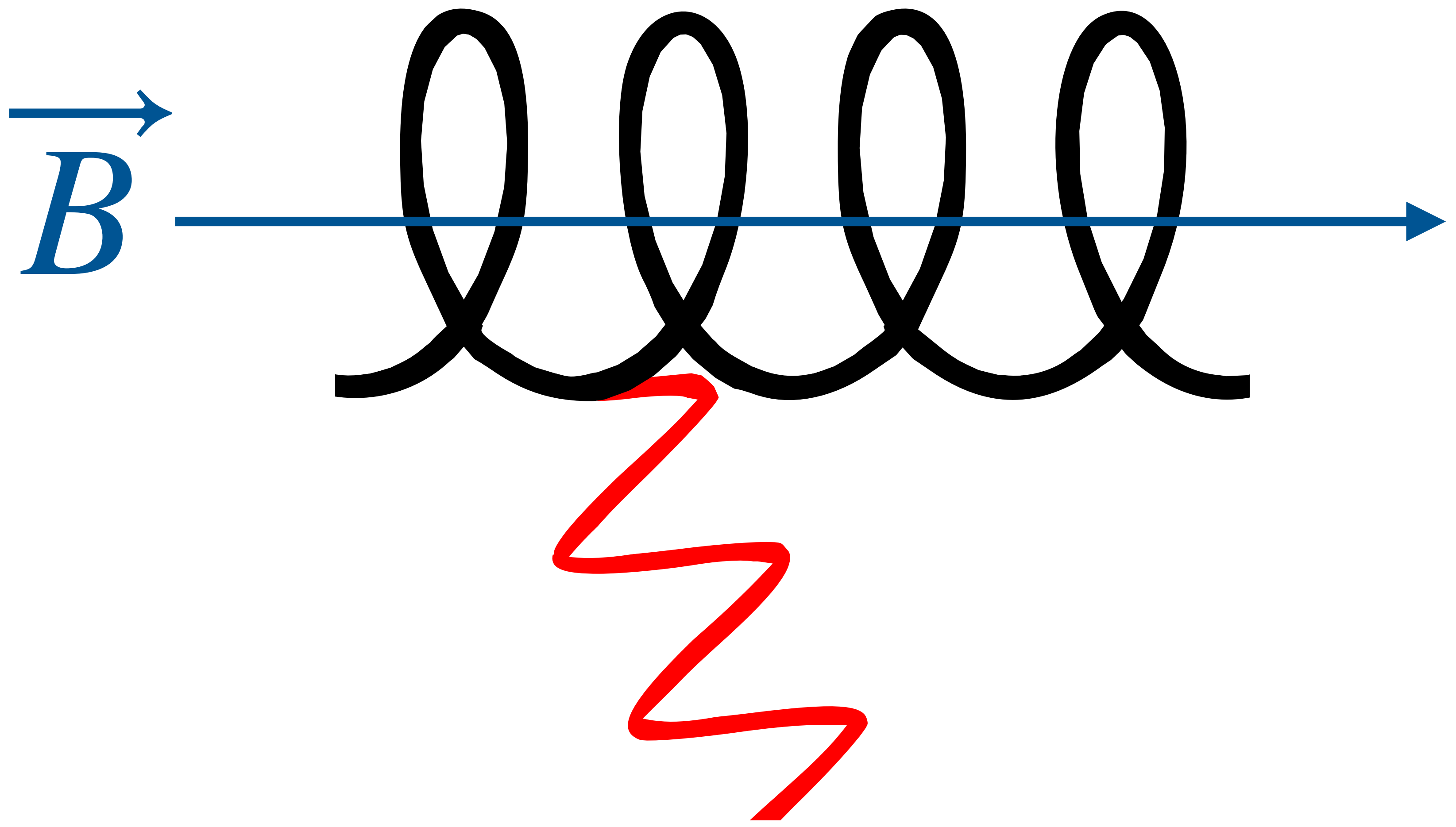

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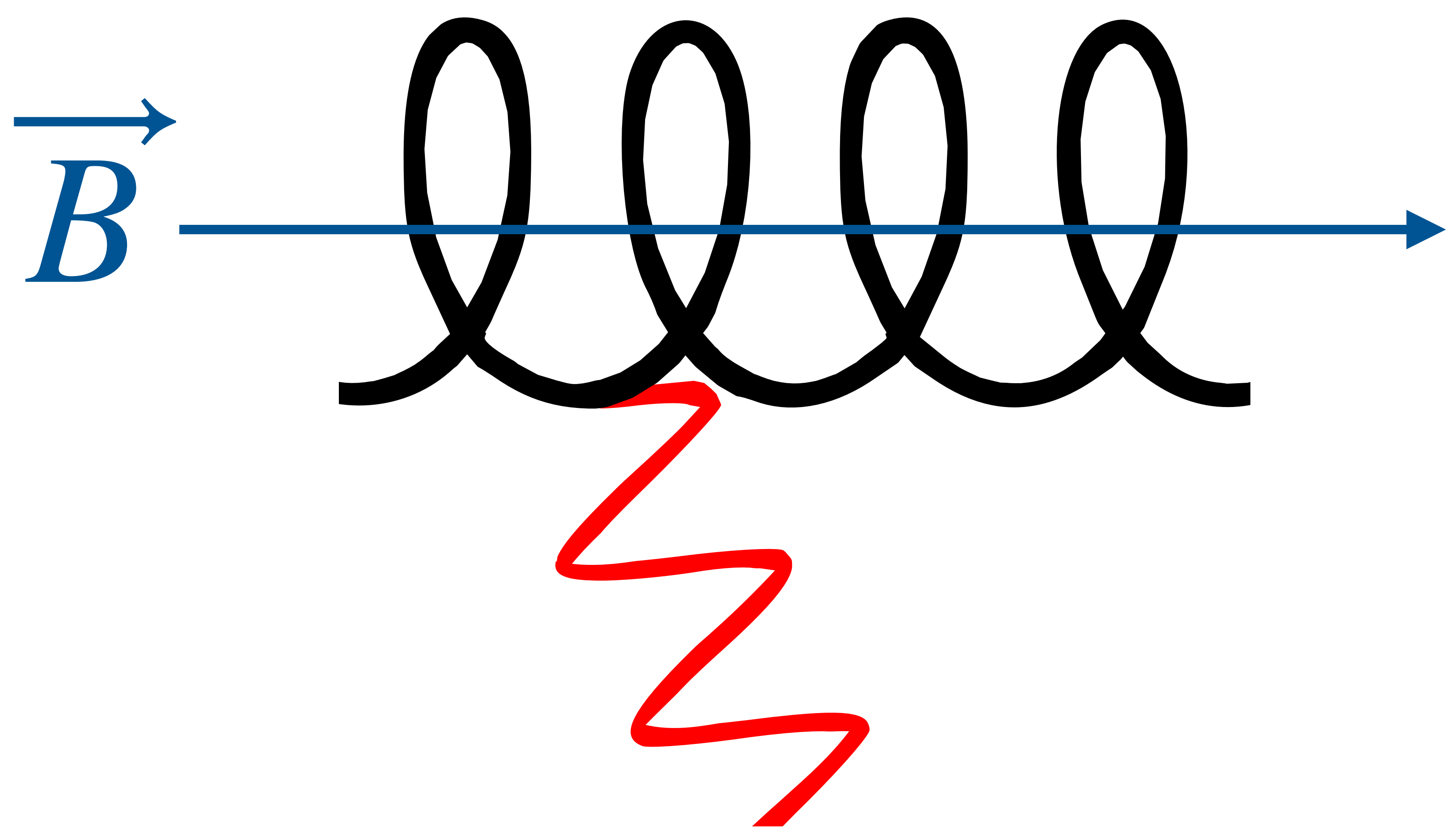

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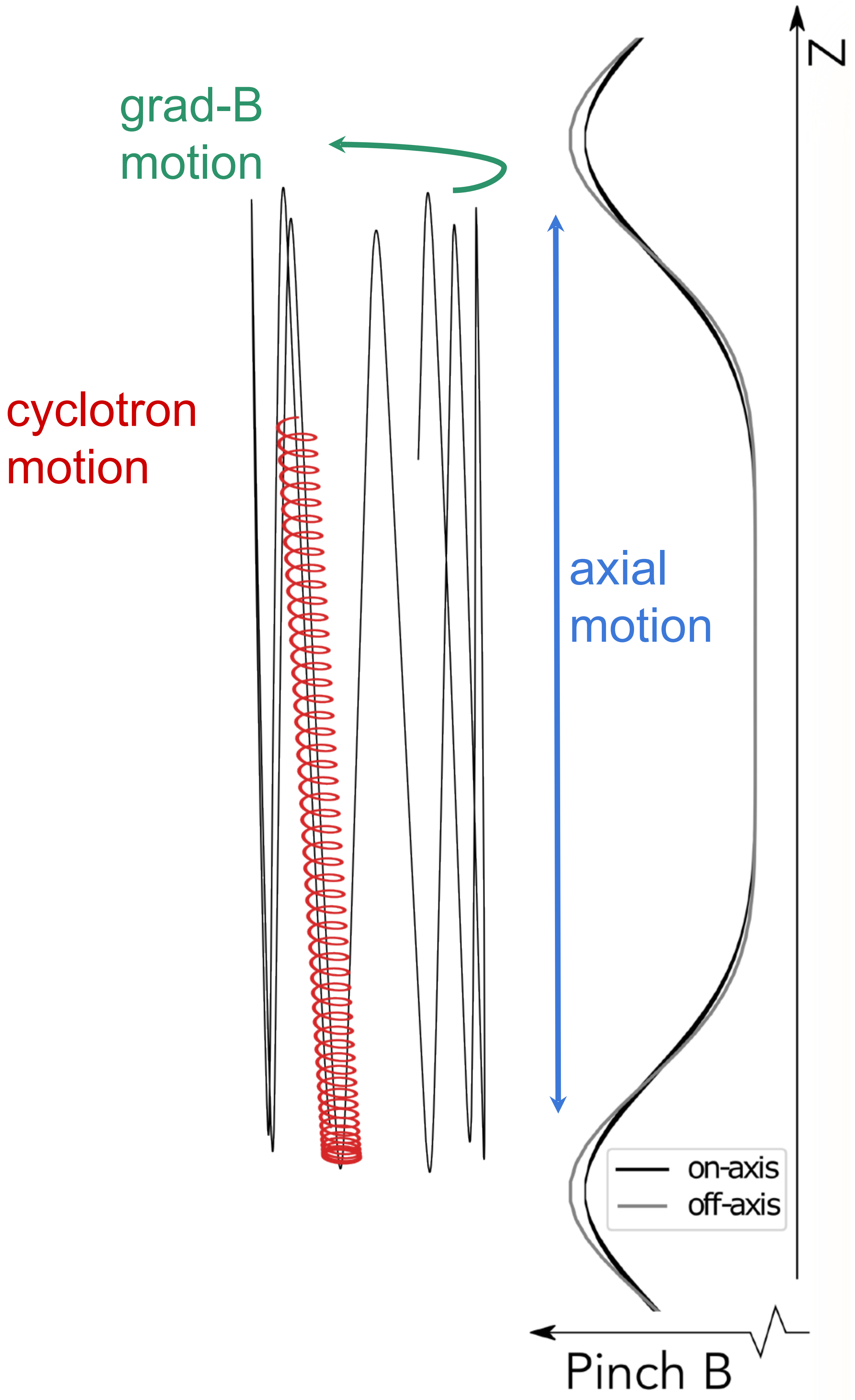
CRES advantages

+ high precision
+ T transparent to radiation
+ no electron transport: no losses, no backgrounds
+ differential - high statistics

[PRD 80, 051301 (2009)]

CRES Electron Motion



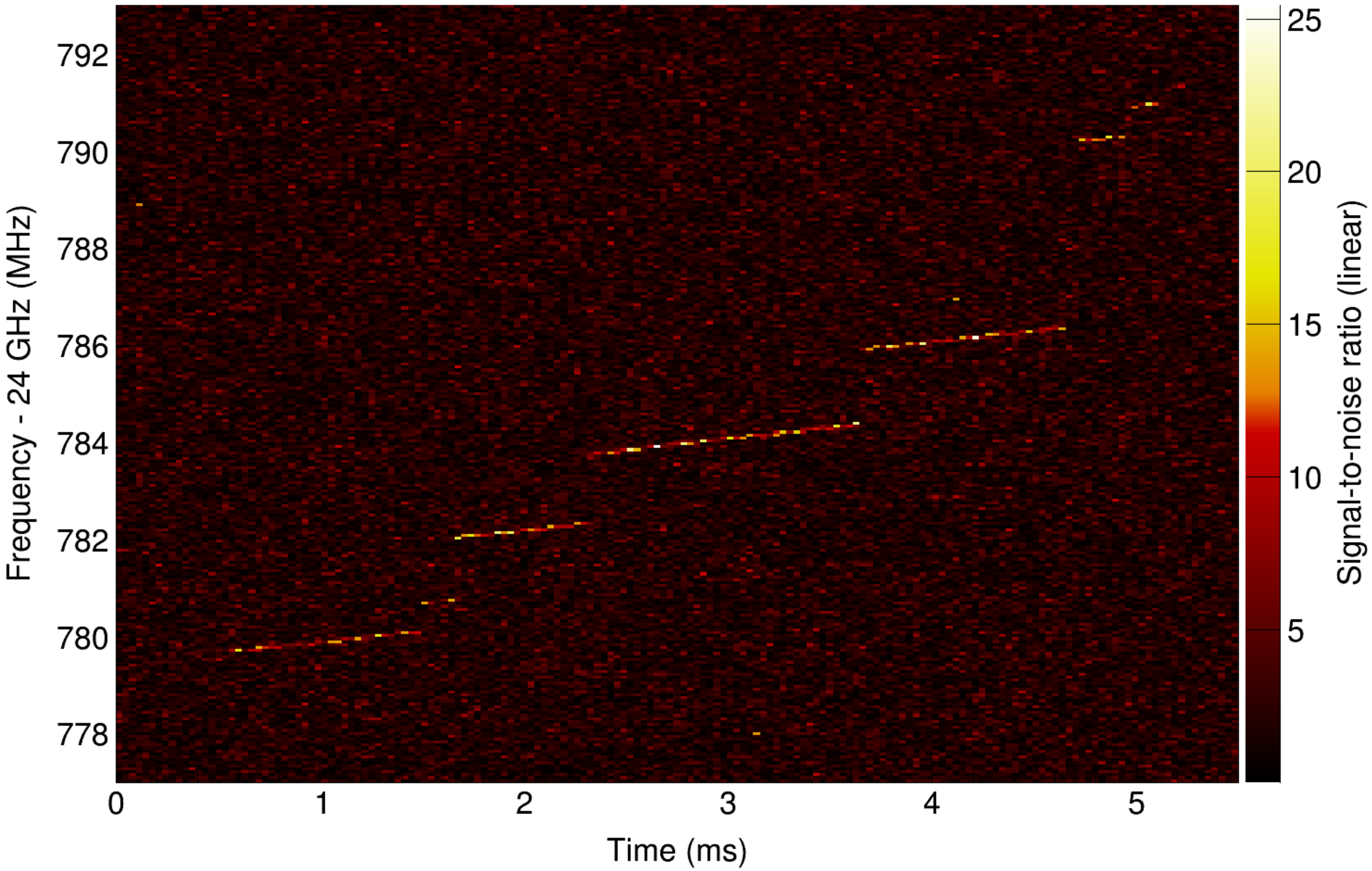
- Electron trapped in magnetic field
- Three superimposed motions:
  - Cyclotron motion with frequency

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

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



* so far

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[PRL 114, 162501 (2015)]

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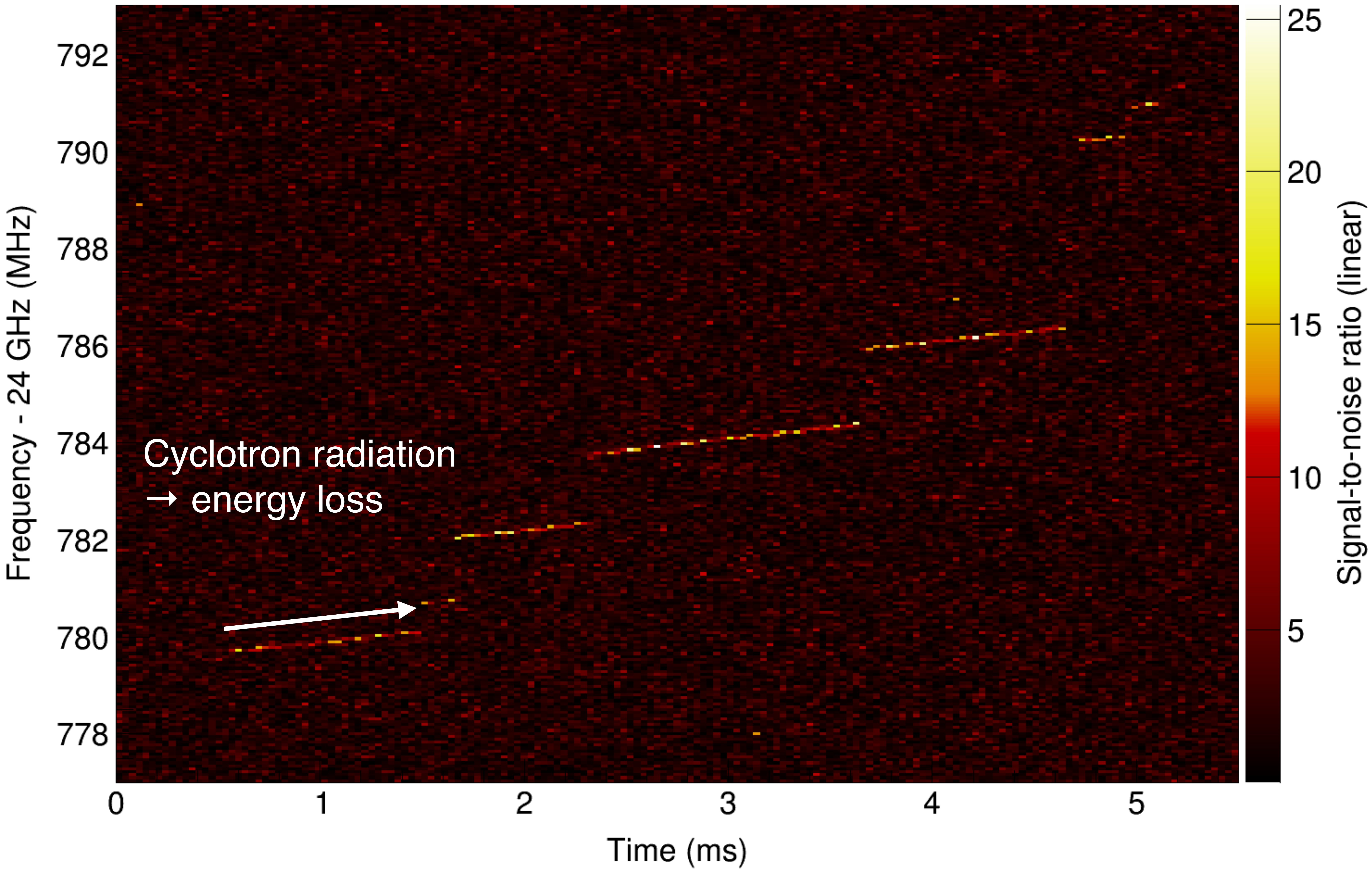

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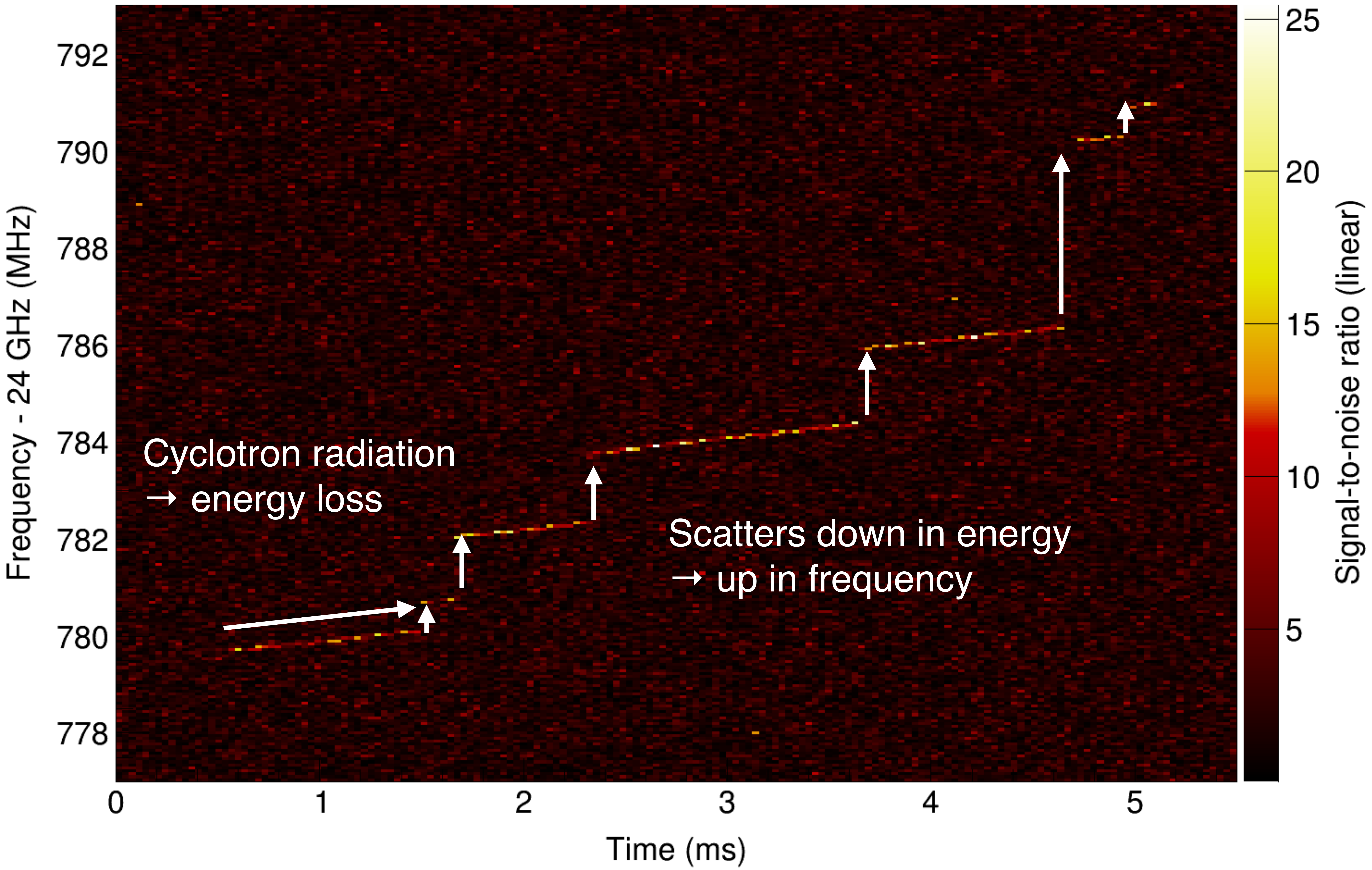

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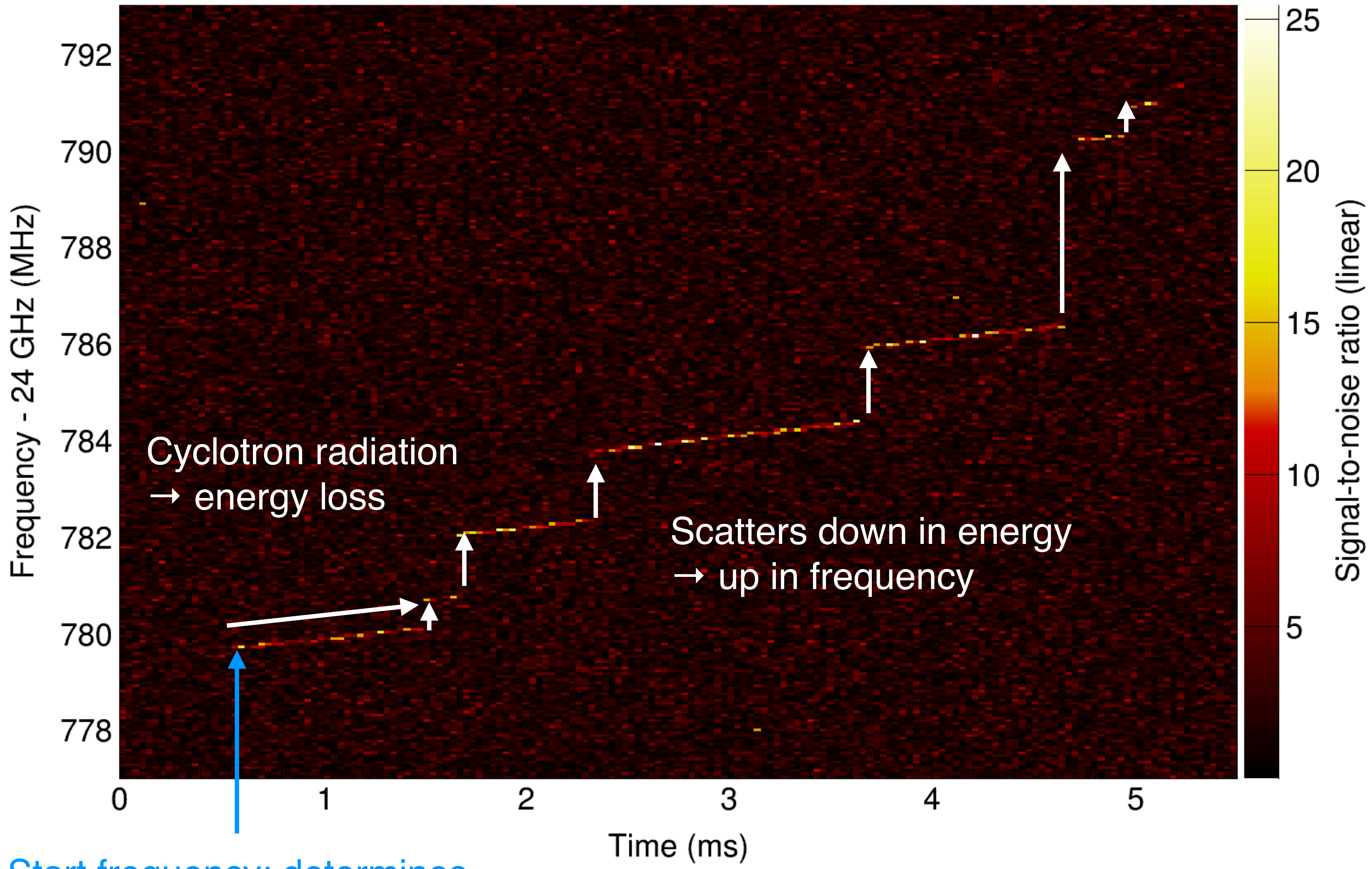

Start frequency: determines electron energy before losses

* so far

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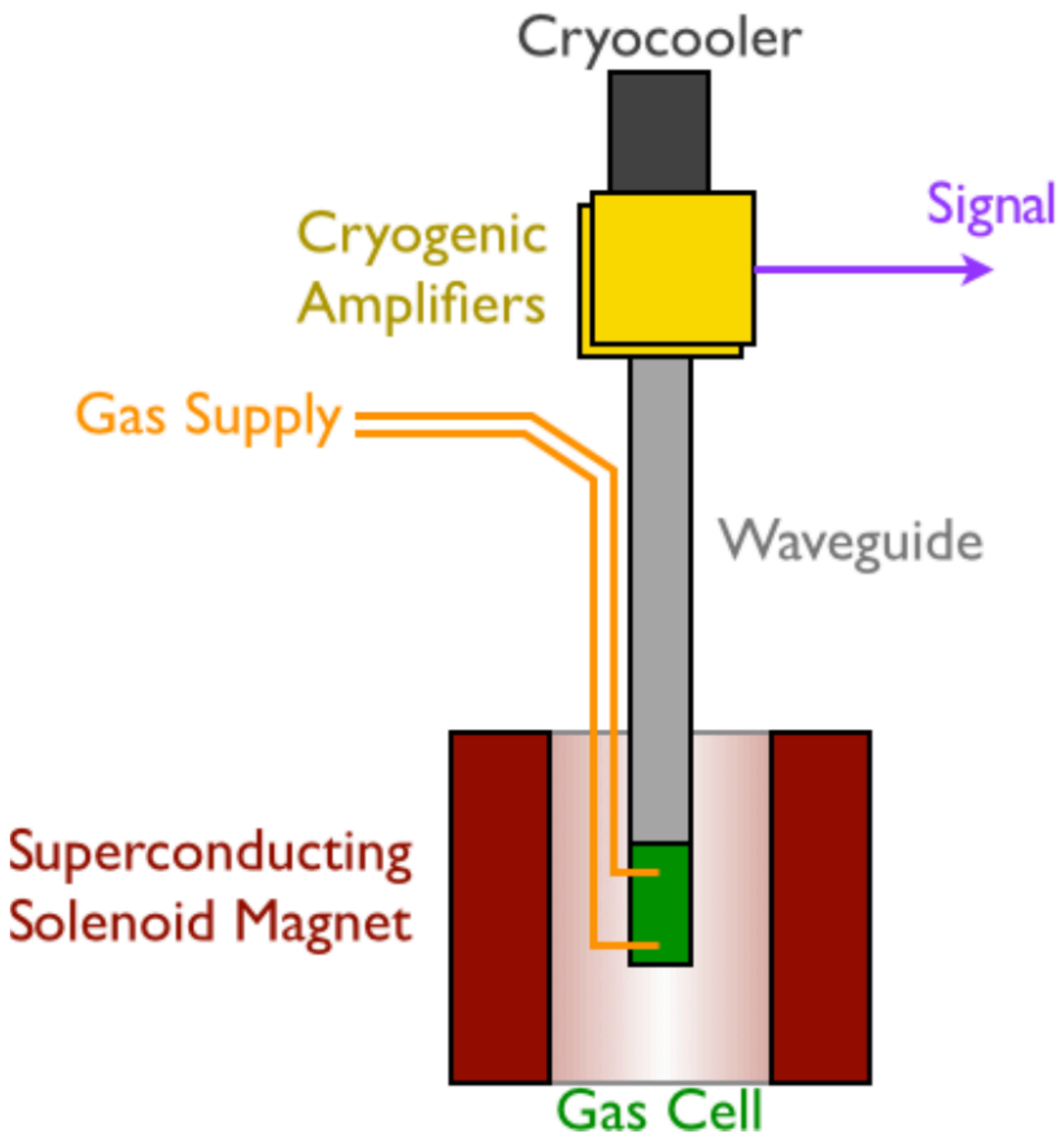
[PRL 114, 162501 (2015)]

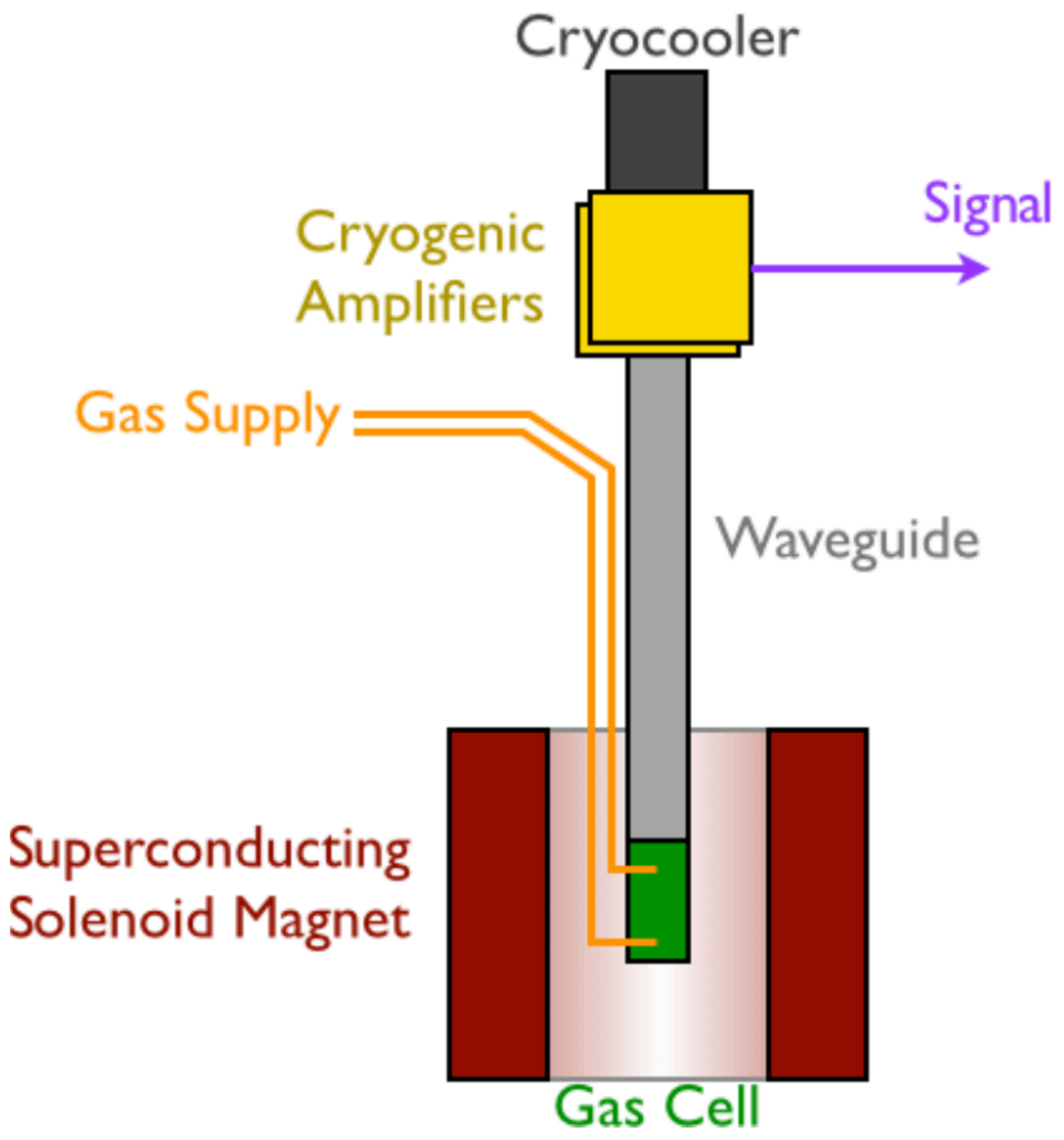
Phase I & II Results

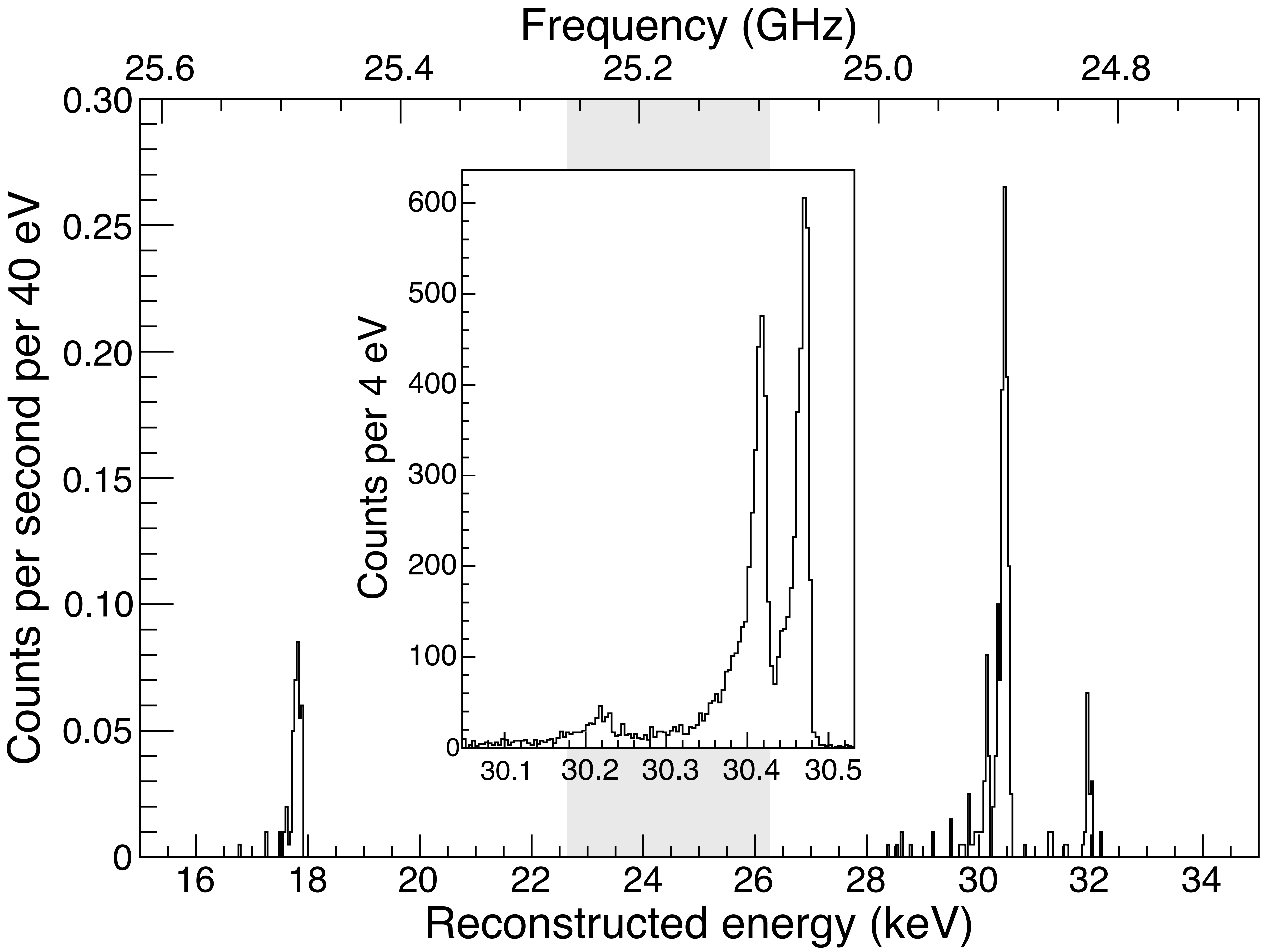
Phase I: CRES Demonstration



[PRL 114, 162501 (2015)]

Phase I: CRES Demonstration





- ^{83m}Kr: electron conversion lines at 18 keV, 30 keV and a 32 keV
- Demonstrated energy measurement of single trapped electrons via CRES, resolution: 15 eV (FWHM)

[PRL 114, 162501 (2015)]

PROJECT 8

Phase II: First CRES Neutrino Mass Extraction

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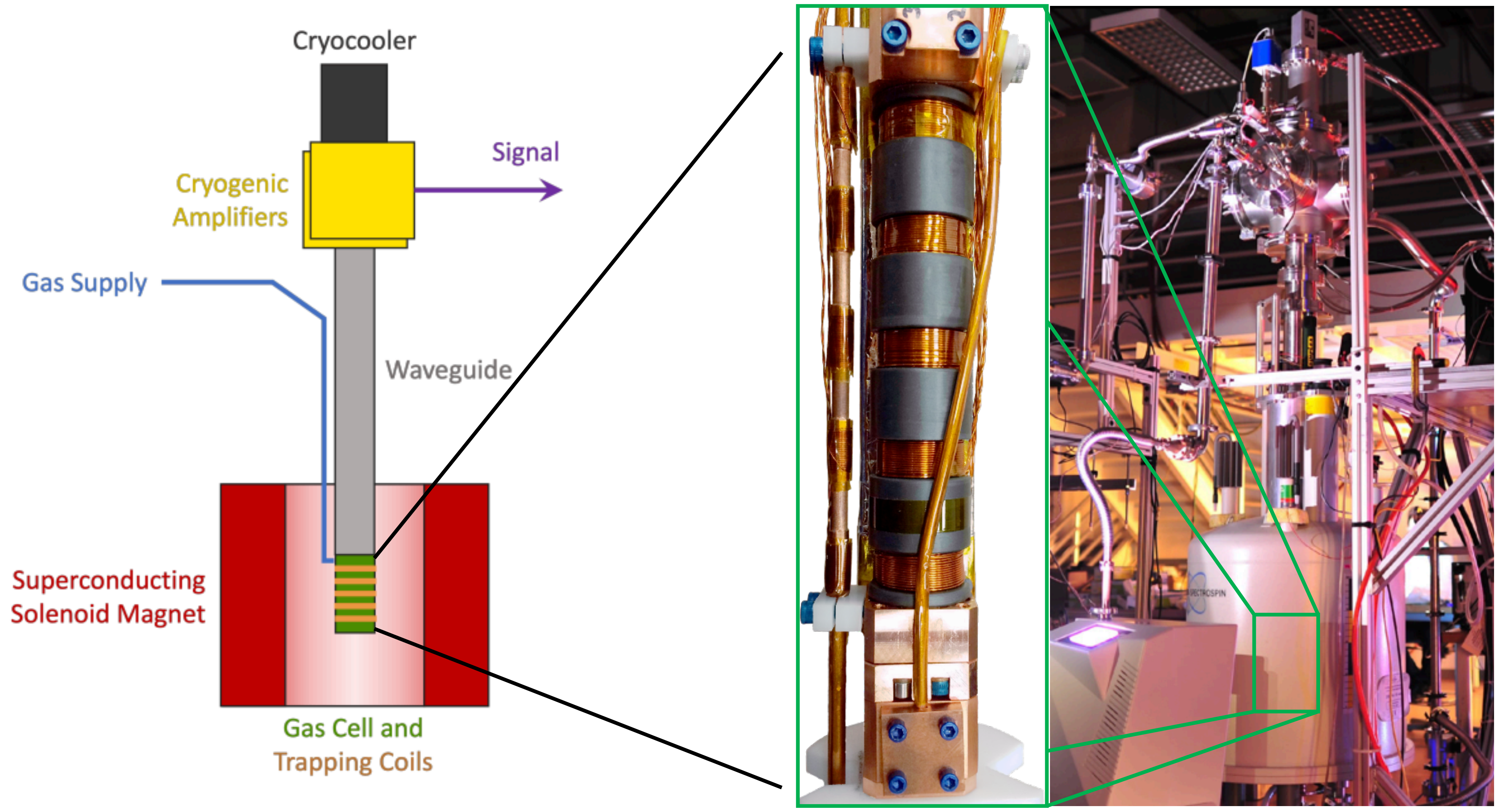

Credit: A. Lindman, E. Novitski

- Effective volume: 1mm^3
- Demonstrated CRES on continuous tritium spectrum

[PRL 131, 102502 (2023)]

PROJECT 8

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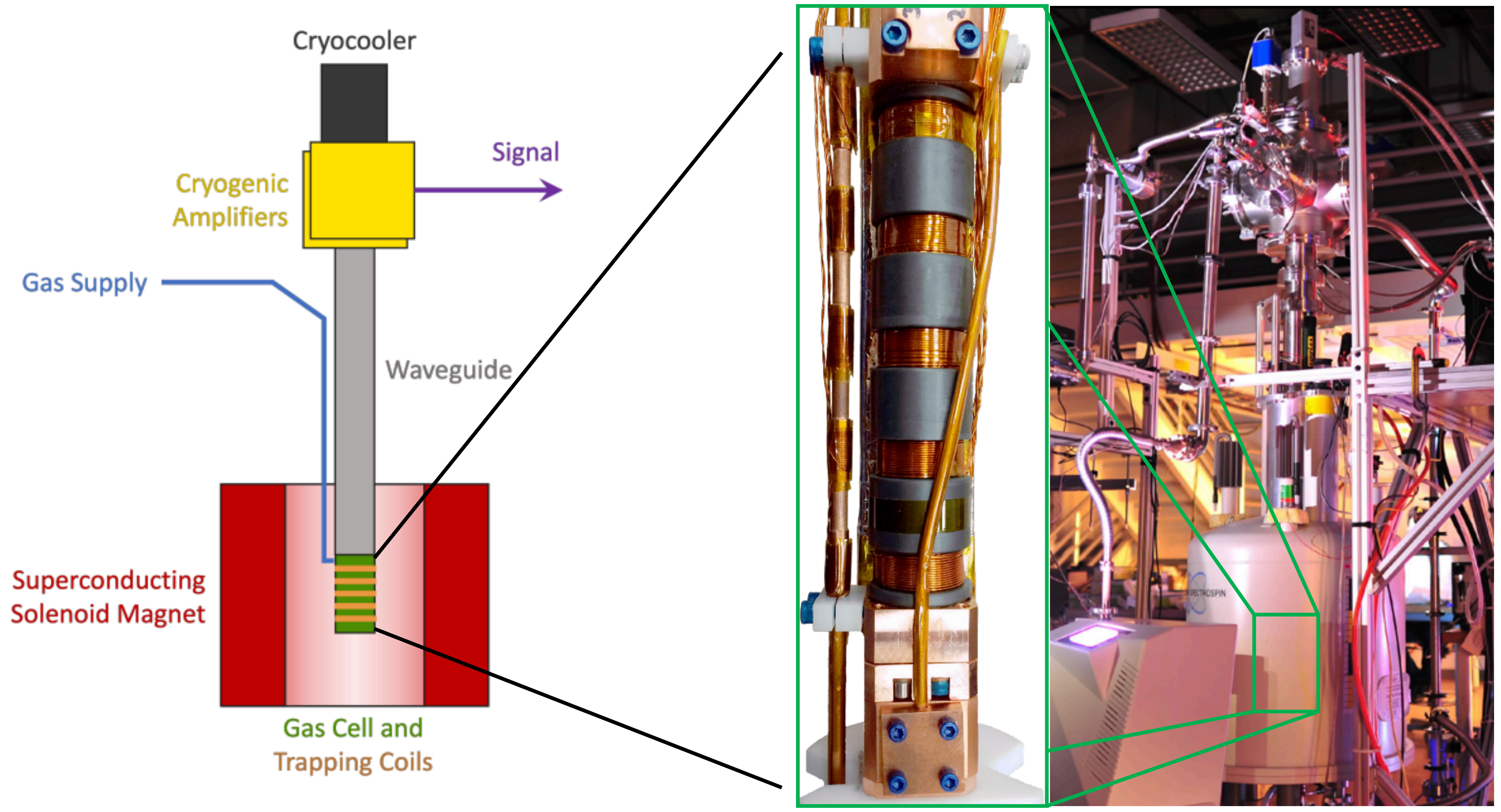

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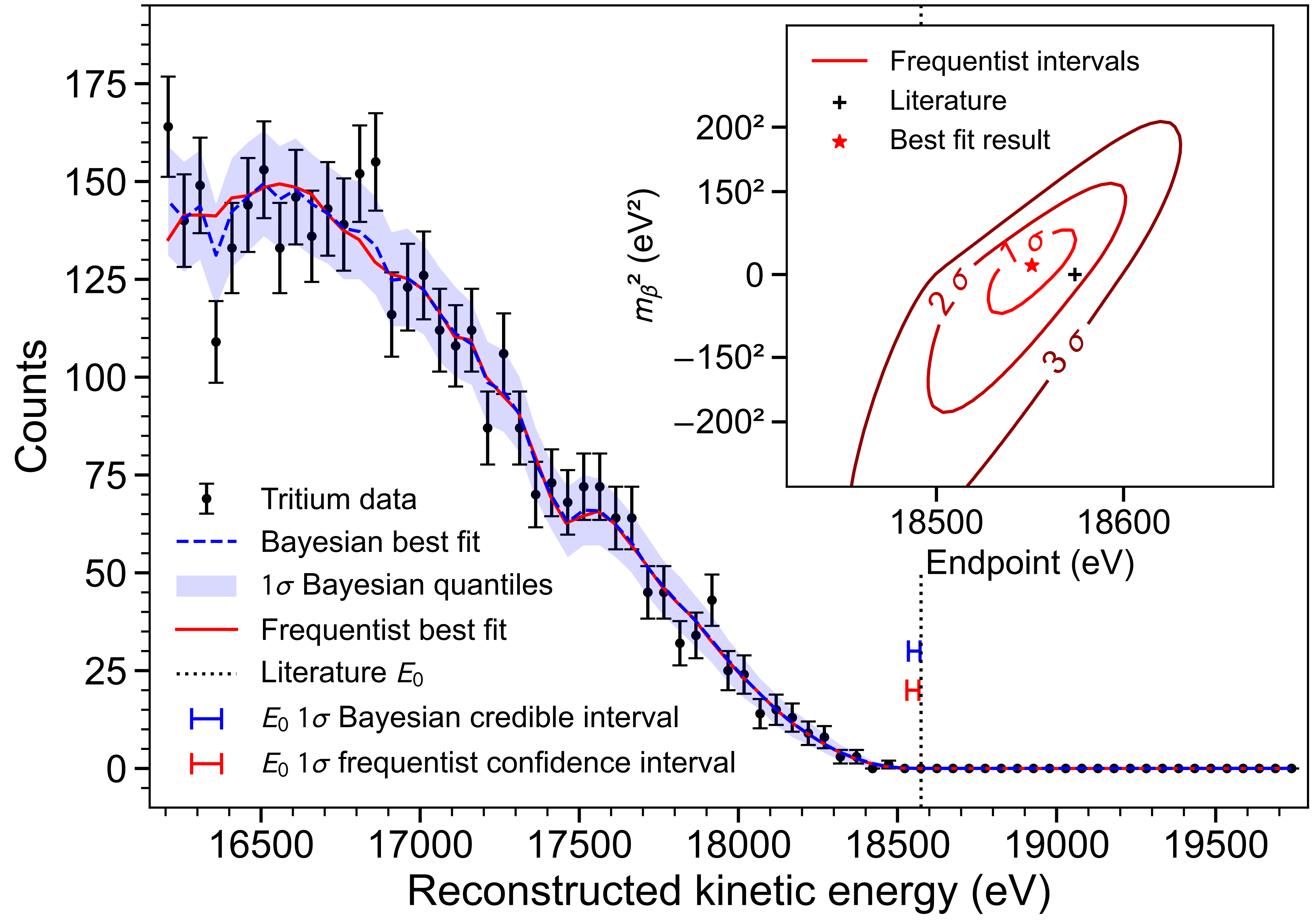

- Effective volume: 1mm^3
- Demonstrated CRES on continuous tritium spectrum
- First neutrino mass upper limit extraction with CRES: $m_{\nu_e,\mathrm{eff}} \leq 155\,\mathrm{eV}/c^2\,(90\,\%\,\mathrm{C.L.})$
- Zero background observed → background rate $\leq 3 \times 10^{-10}\,\mathrm{eV}^{-1}s^{-1}\,(90\,\%\,\mathrm{C.L.})$
- High energy resolution: $1.7 \pm 0.2\,\mathrm{eV}\,(\mathrm{FWHM})$

[PRL 131, 102502 (2023)]

Phase III R&D: Atomic Tritium

PROJECT 8

Atom Production

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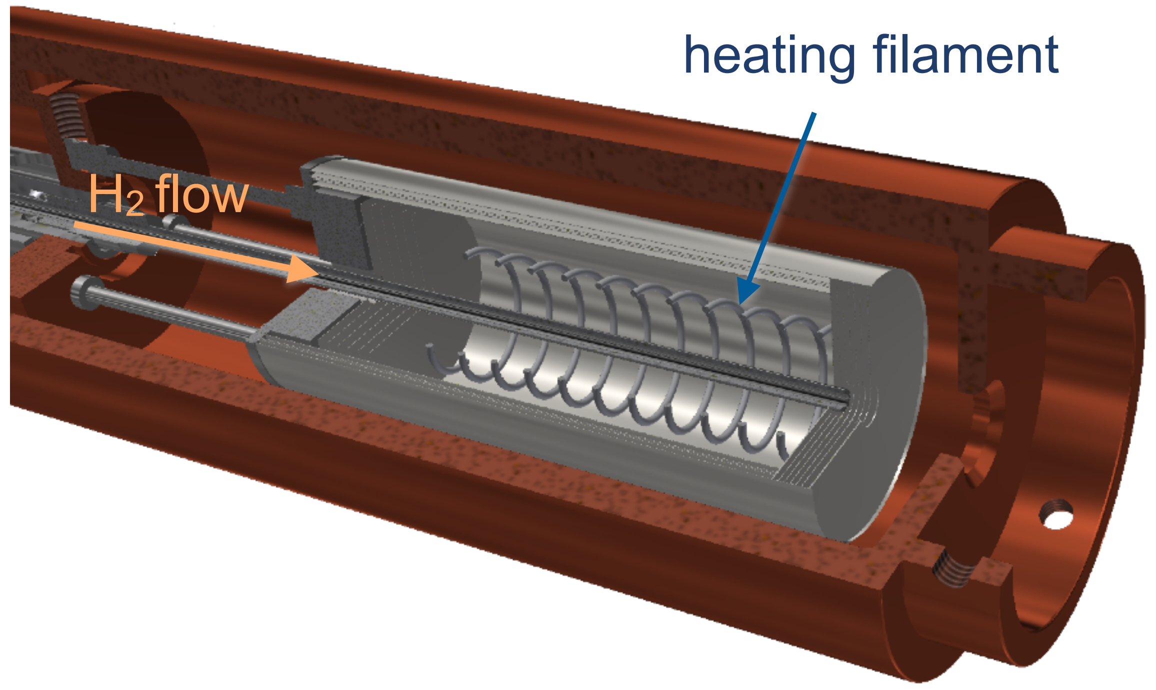
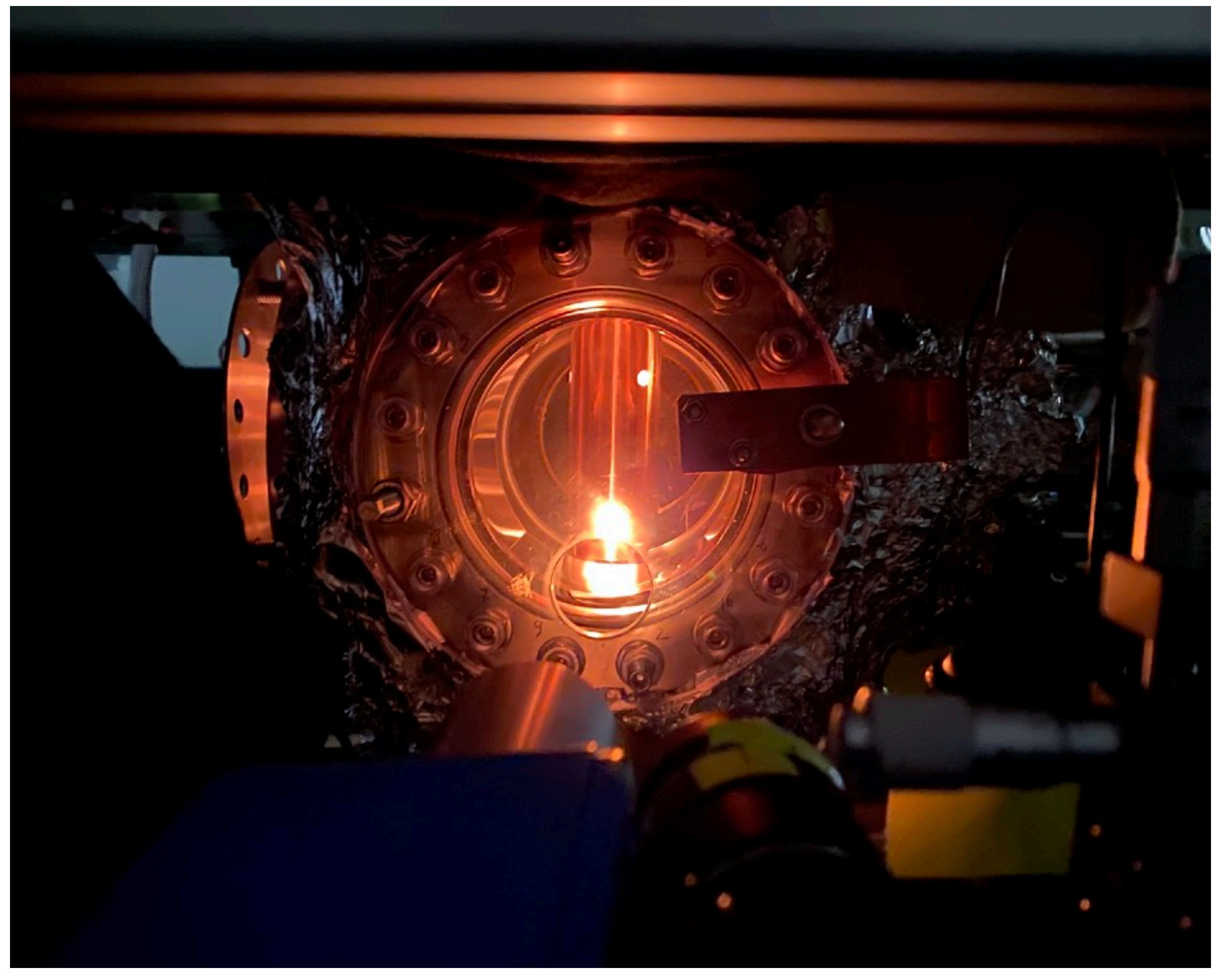
- Prototype with Hydrogen / Deuterium
- Thermal dissociation:
  - Hot Tungsten surface (2200K-2500K)
  - Hydrogen Atomic Beam Source (HABS) @ JGU Mainz

Credit: A. Lindman





Credit: L. Thorne

Atom Production

- Prototype with Hydrogen / Deuterium
- Thermal dissociation:
  - Hot Tungsten surface (2200K-2500K)
  - Hydrogen Atomic Beam Source (HABS) @ JGU Mainz

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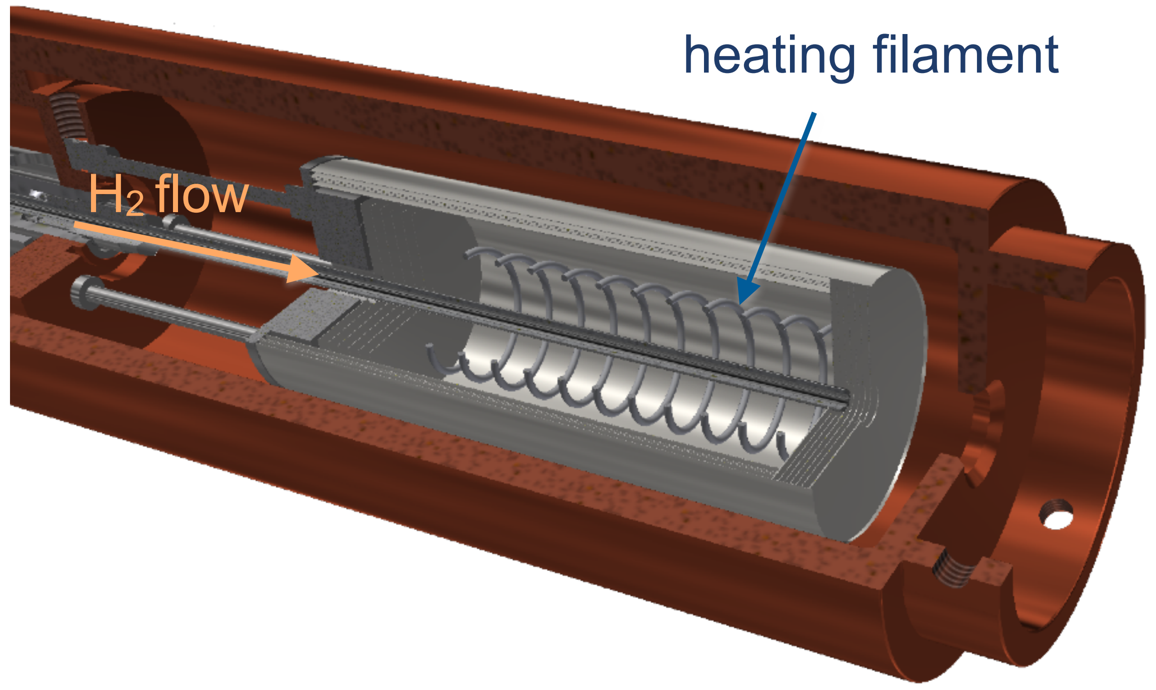
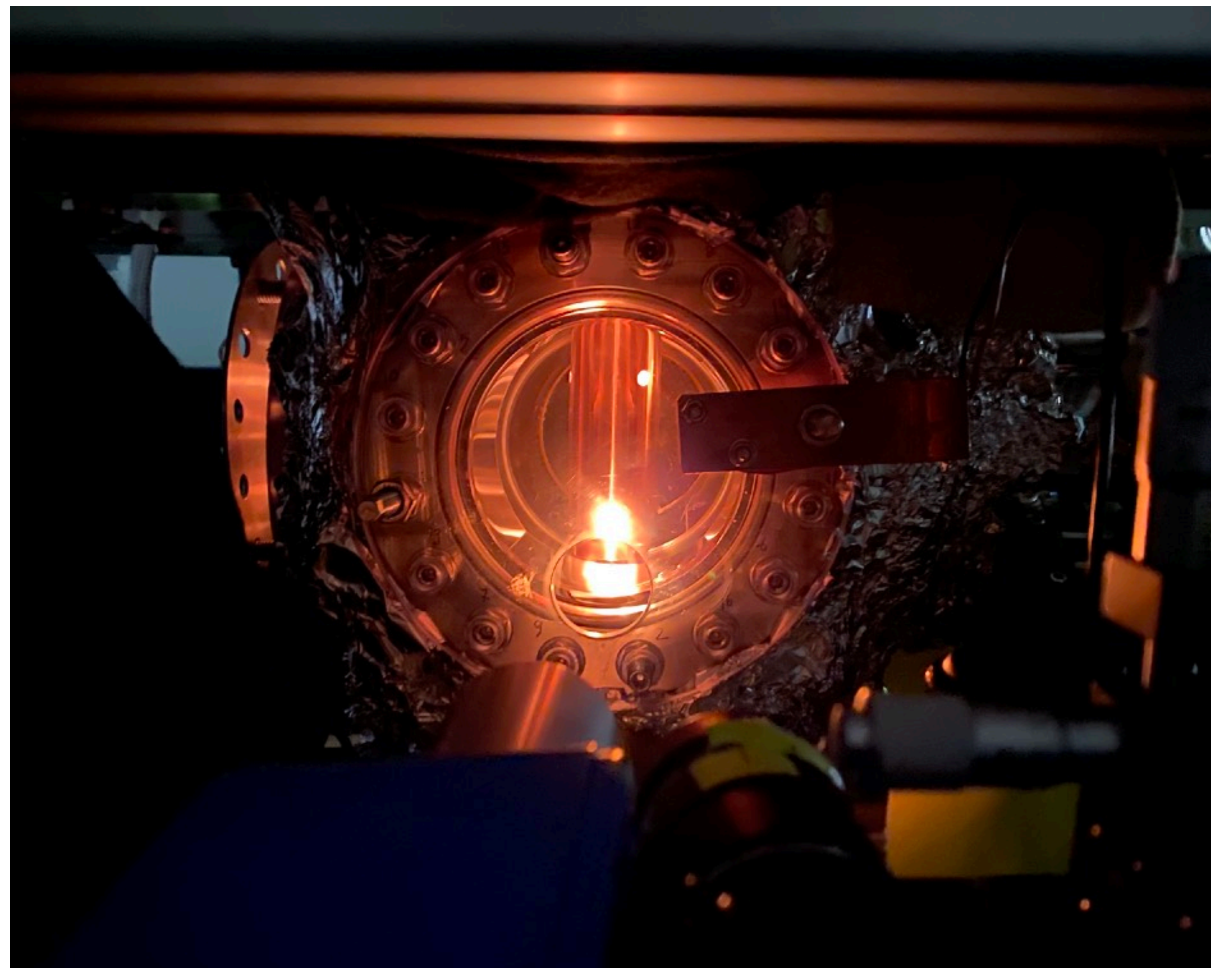


- Plasma dissociation
  - Initially discarded due to T_2O formation
  - Revisiting new quartzless cavities @ Indiana U



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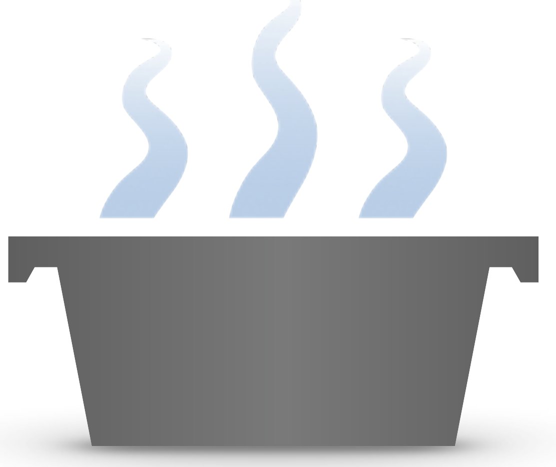

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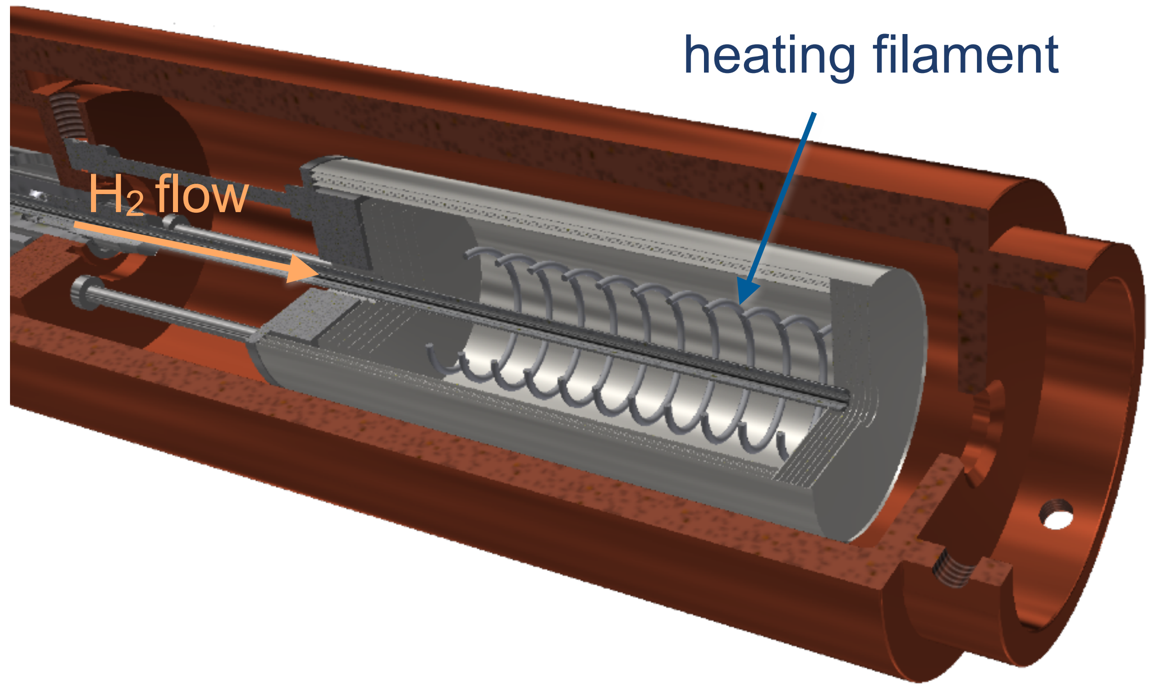
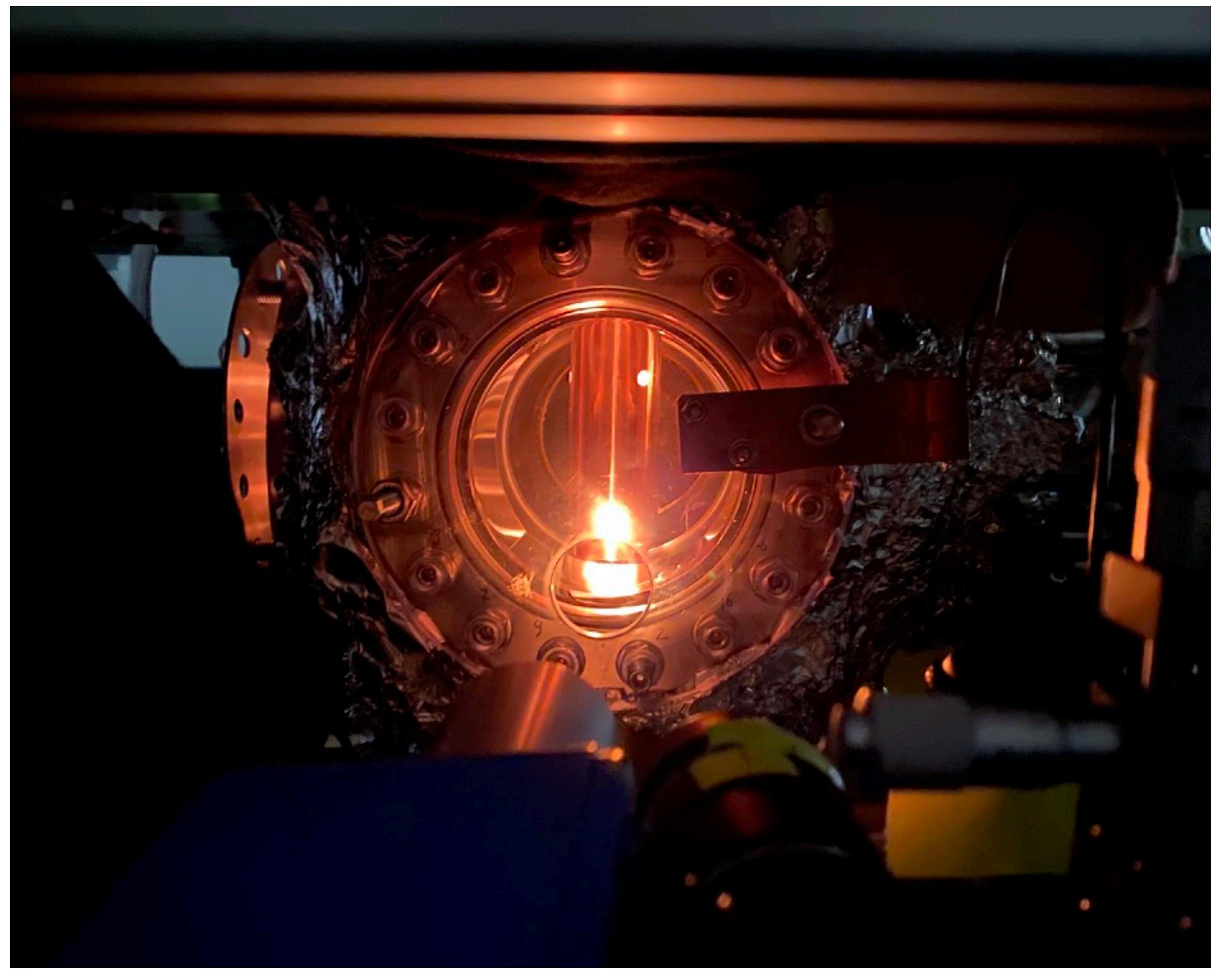
- HABS rebuilt for Tritium @ TLK

Credit: A. Lindman





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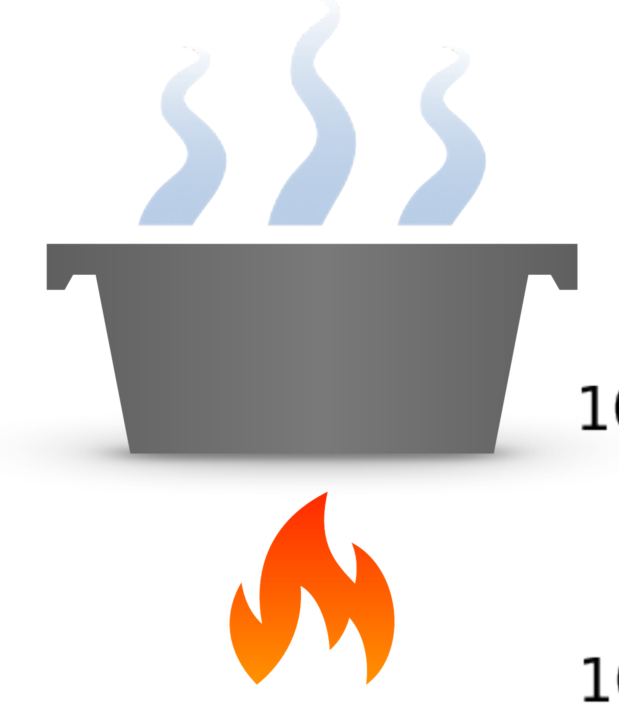
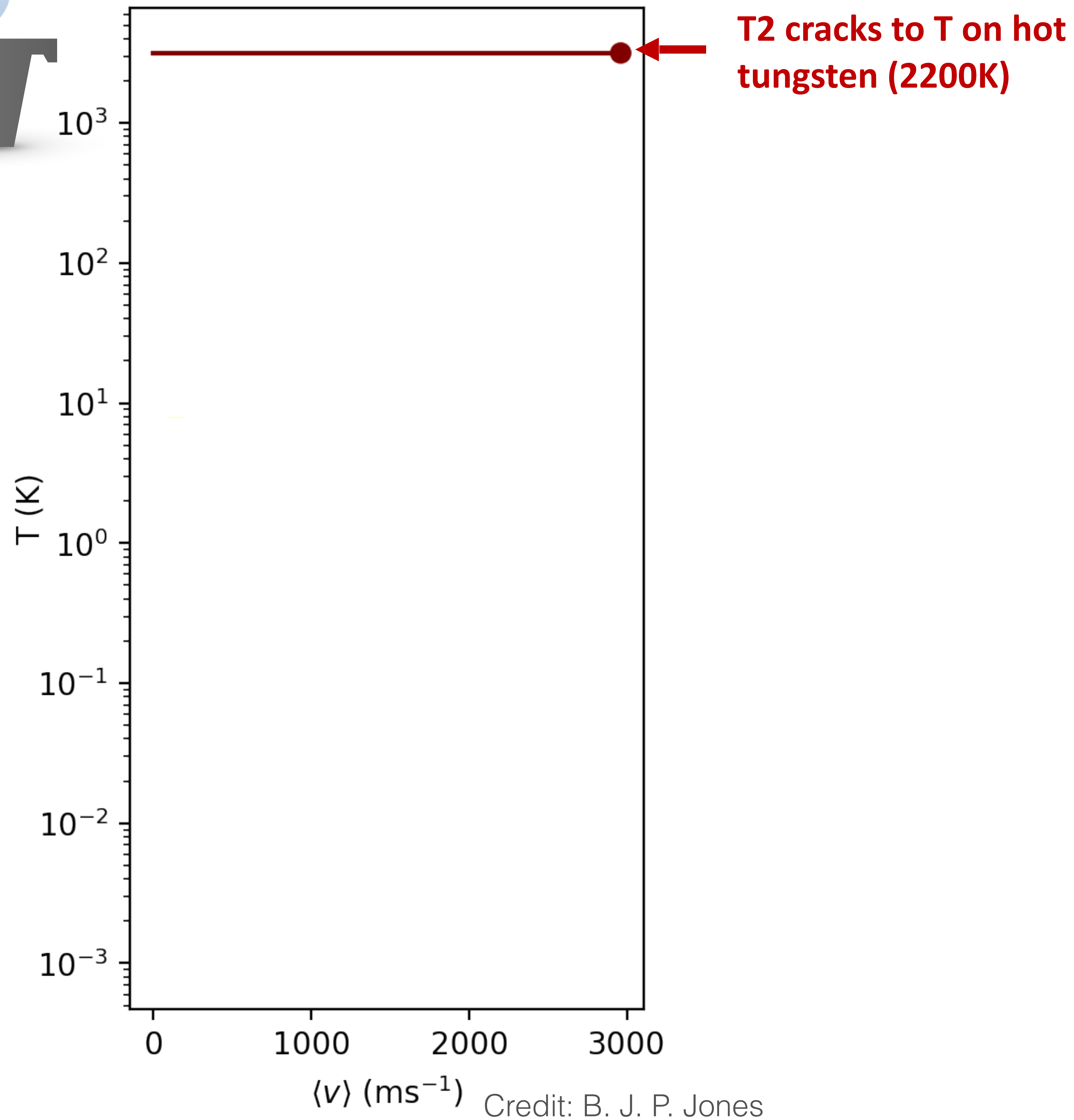
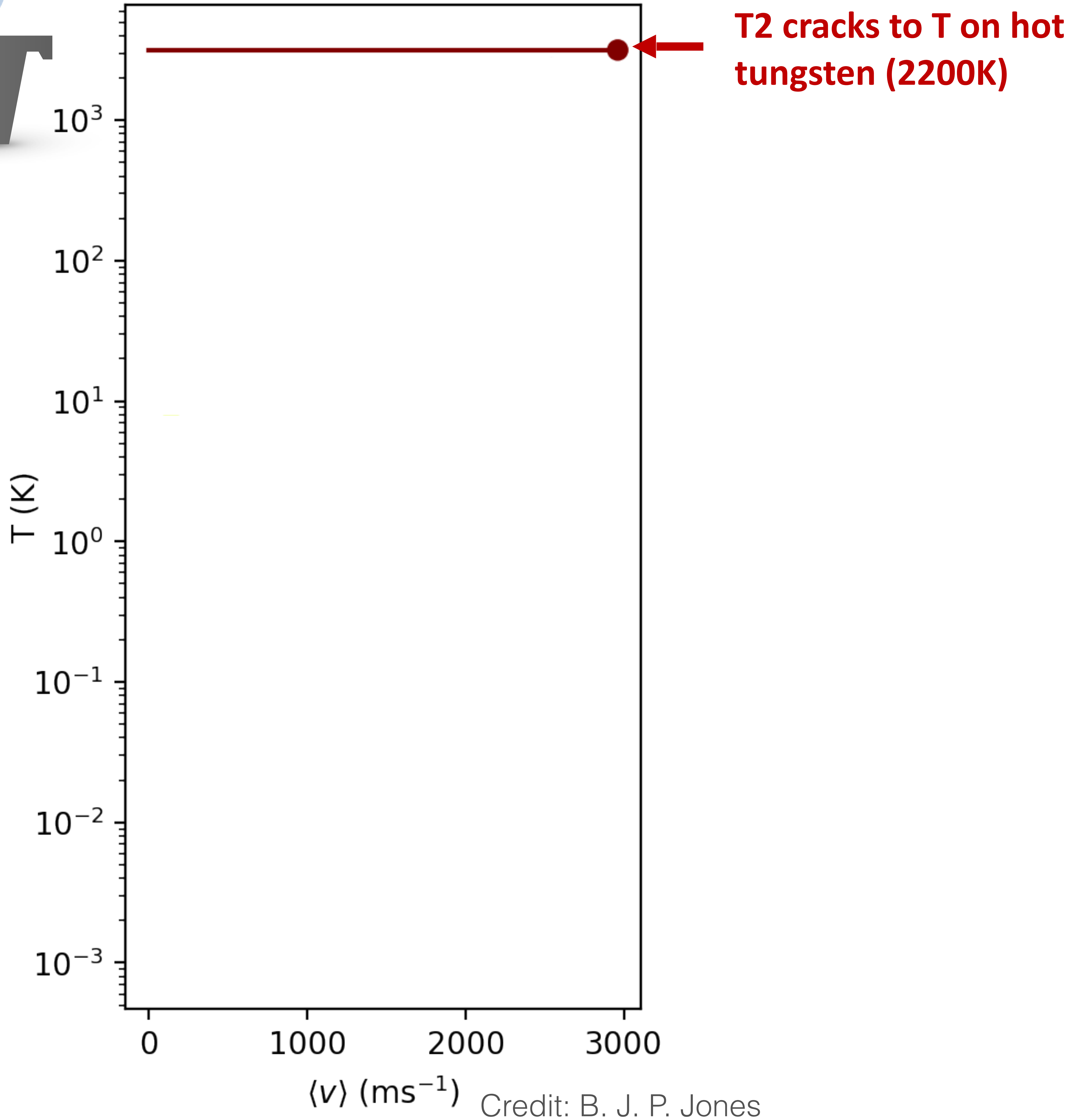
Atom Cooling





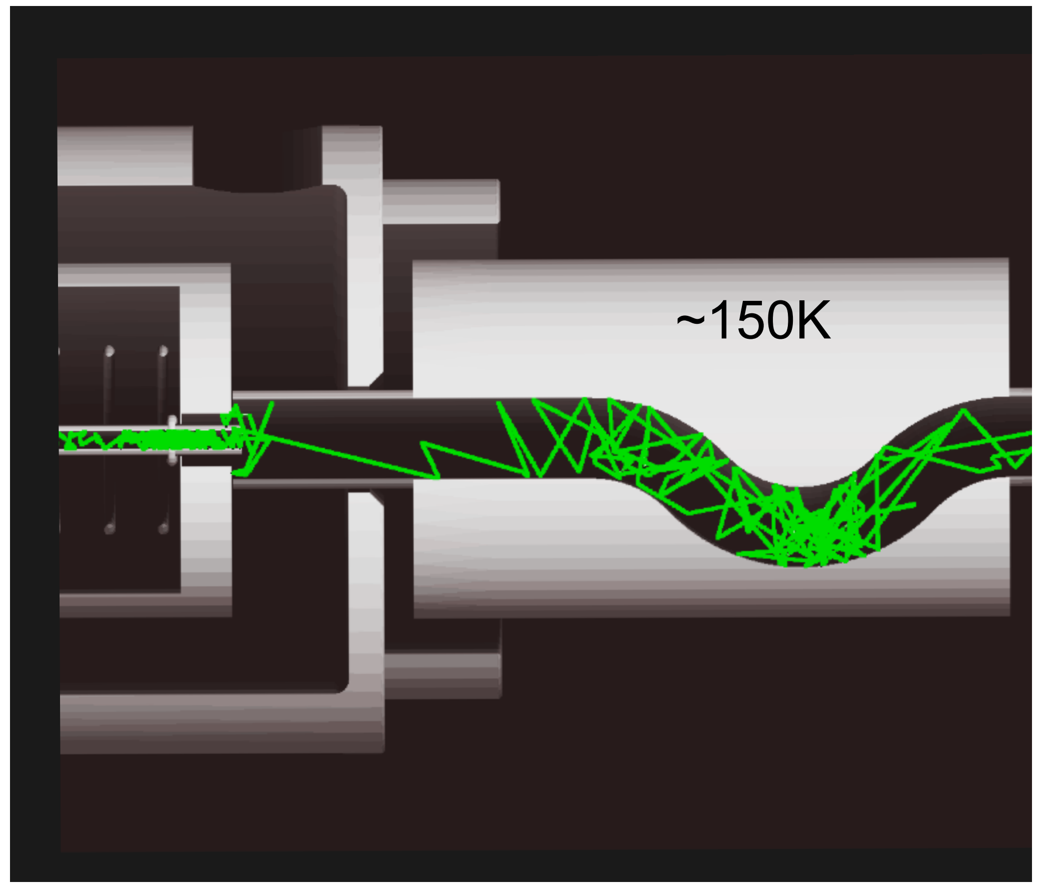
Credit: B. J. P. Jones

Atom Cooling



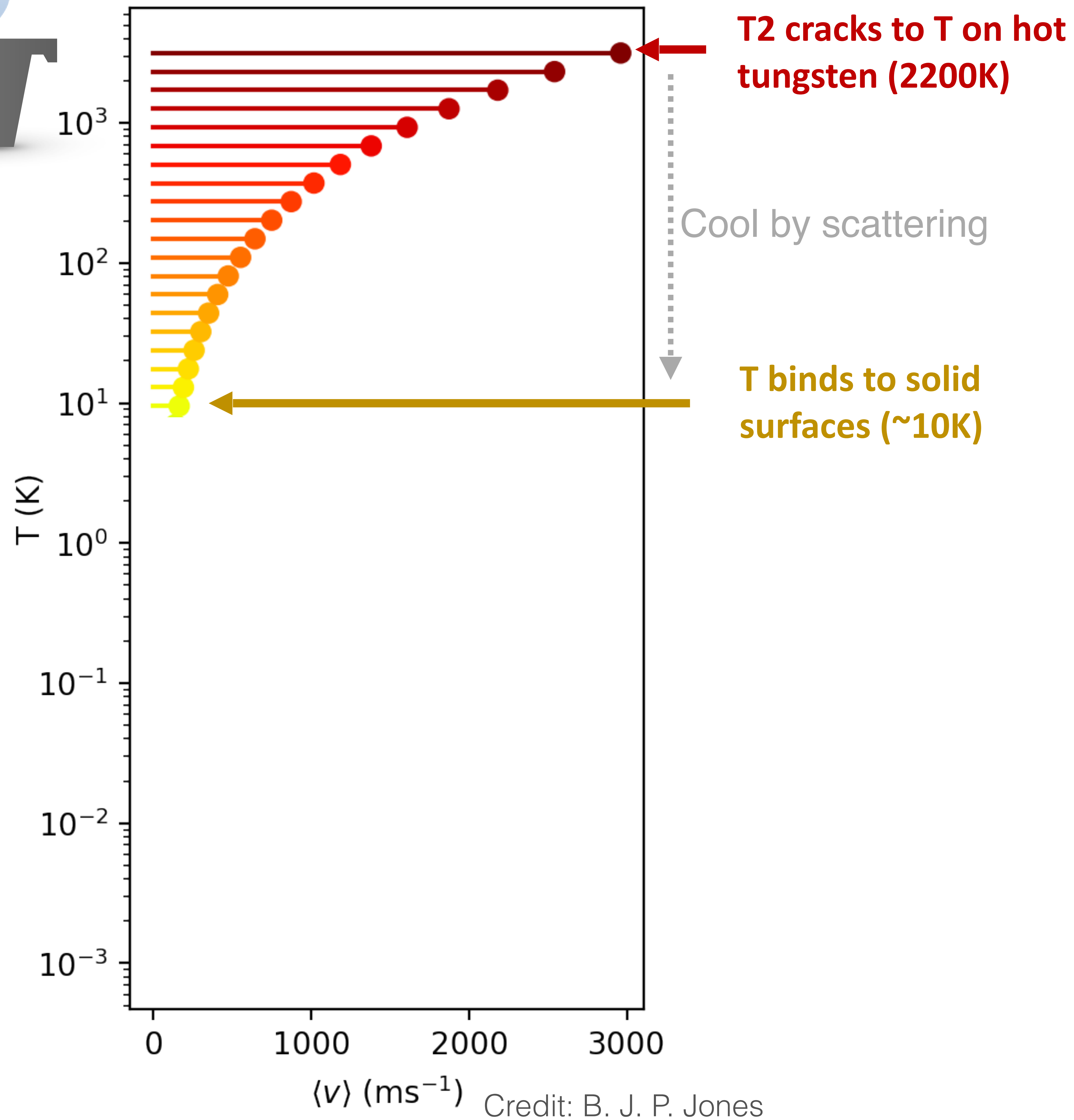
Credit: B. J. P. Jones

1. Accommodator: cool to 150K with multiple bounces at low recombination rate



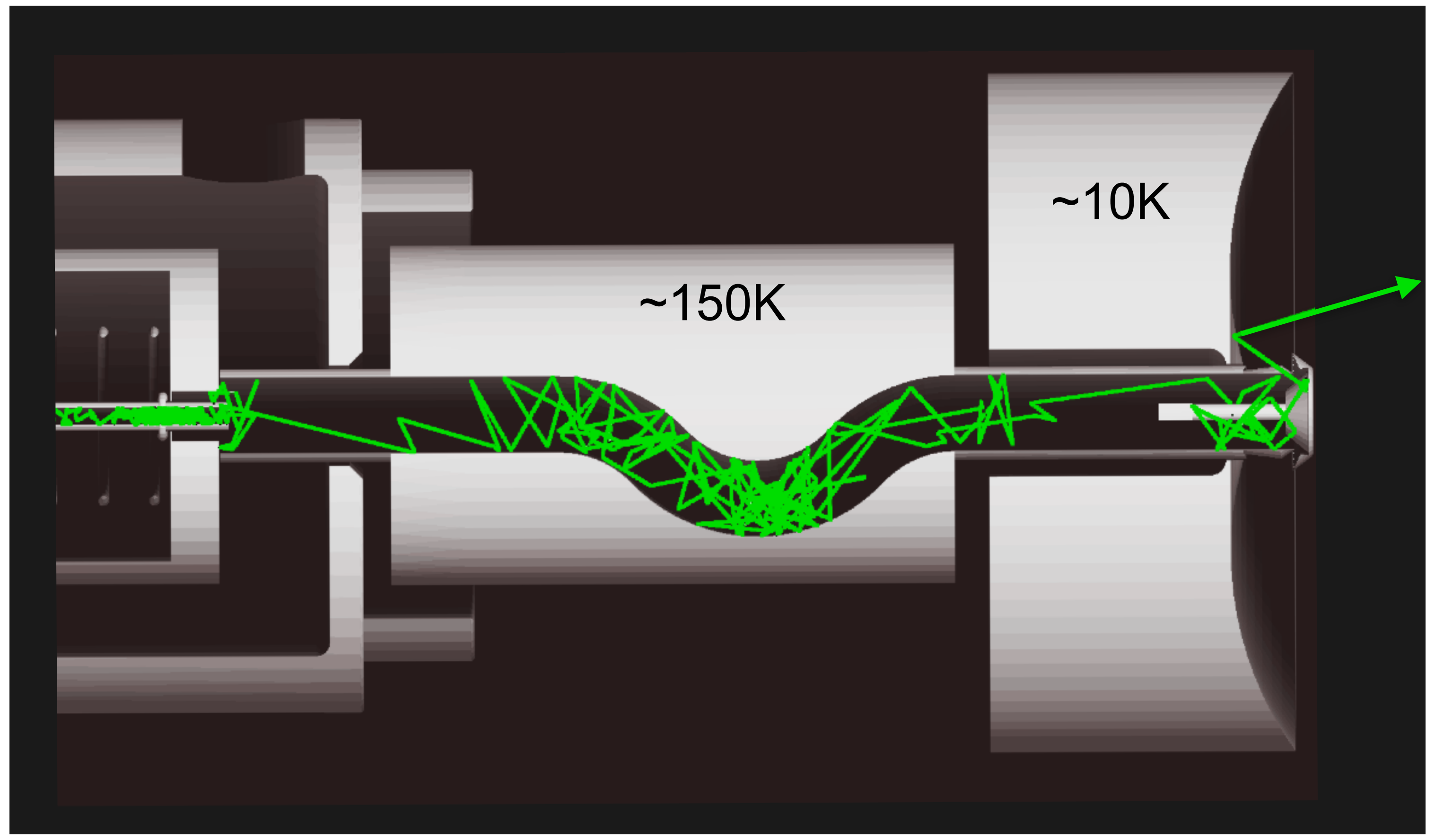
Credit: A. Lindman

Atom Cooling



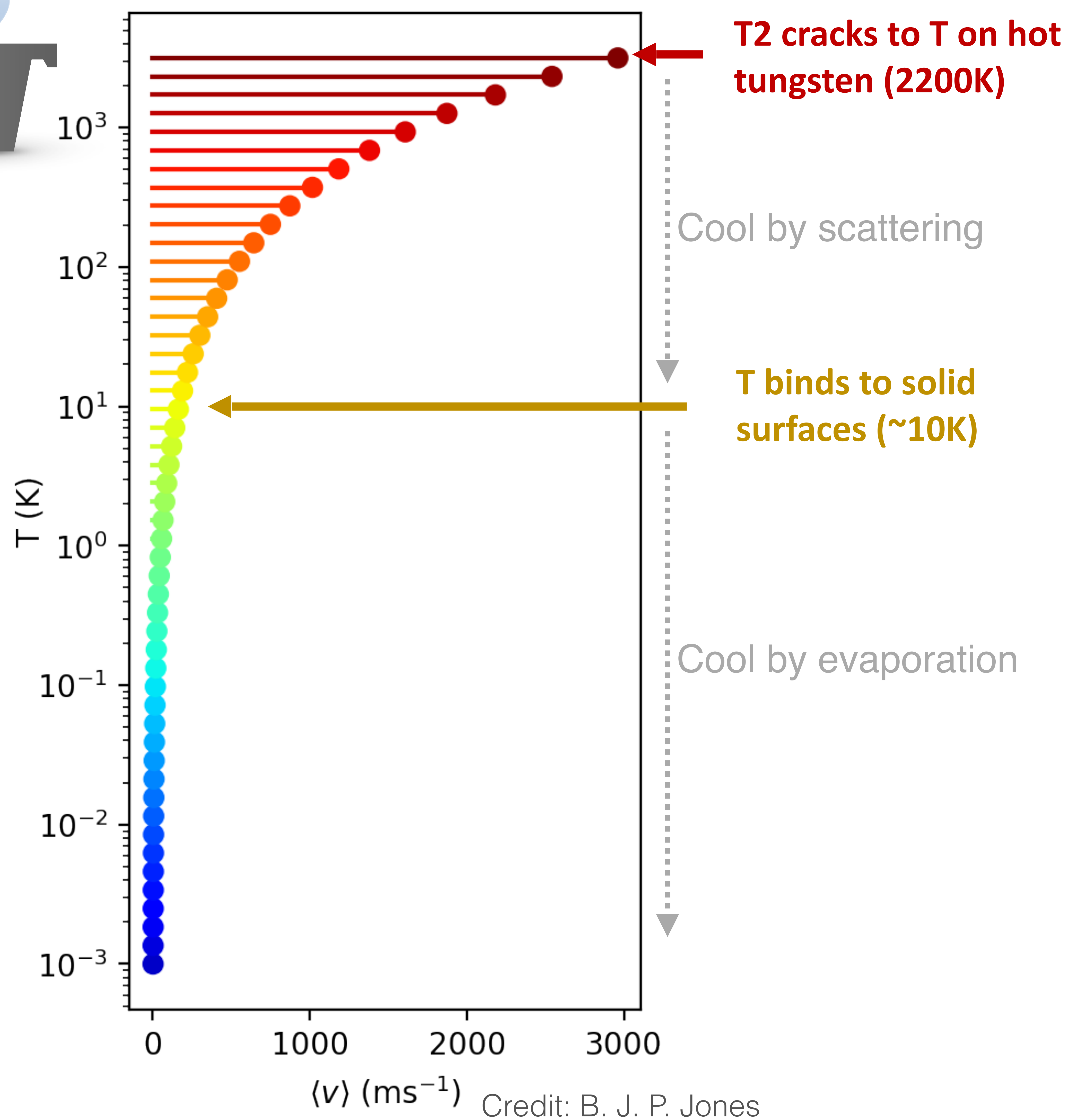
Credit: B. J. P. Jones

1. Accommodator: cool to 150K with multiple bounces at low recombination rate
2. One-bounce nozzle to cool to 10K



Credit: A. Lindman

Atom Cooling



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1. Accommodator: cool to 150K with multiple bounces at low recombination rate
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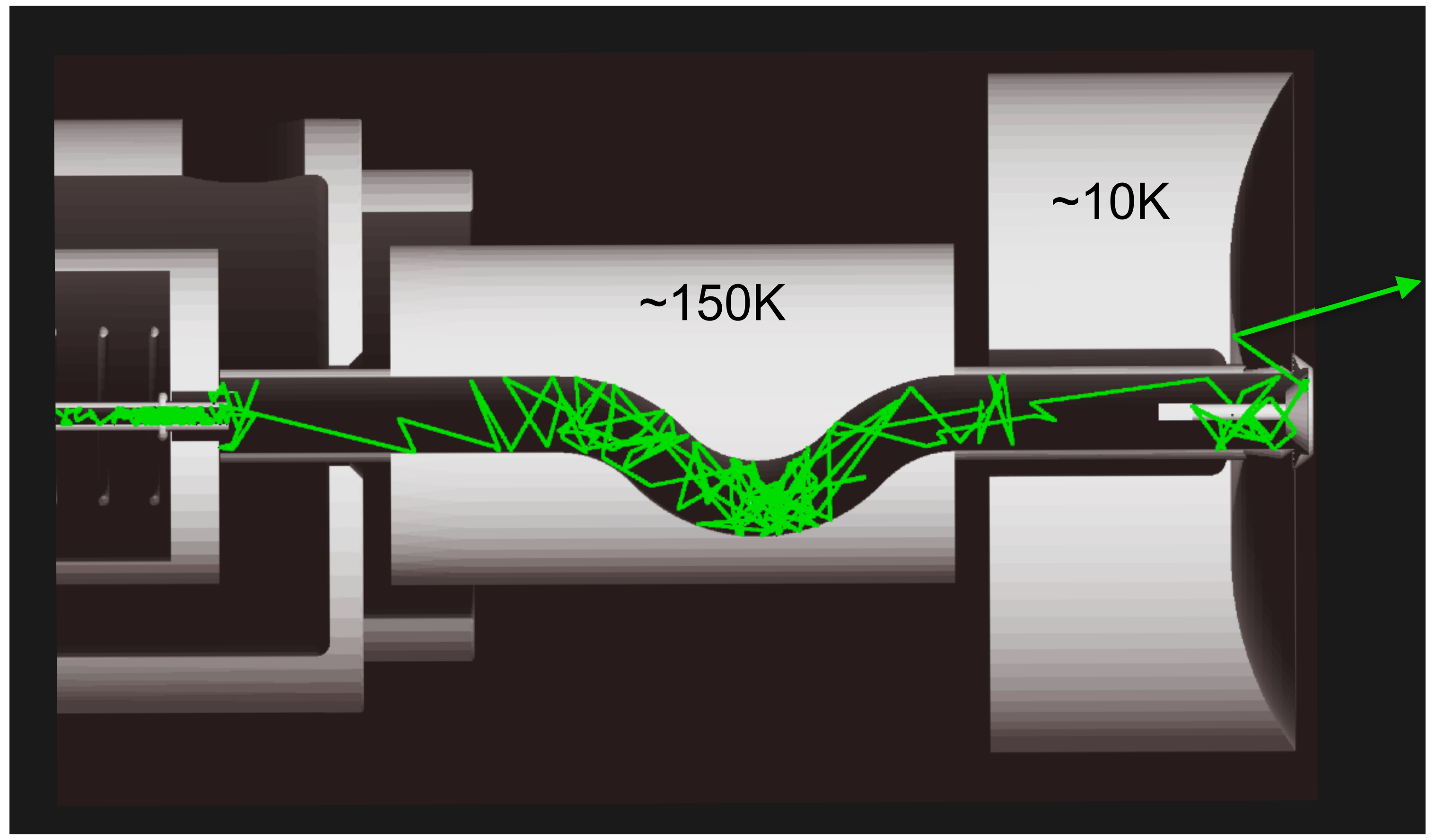
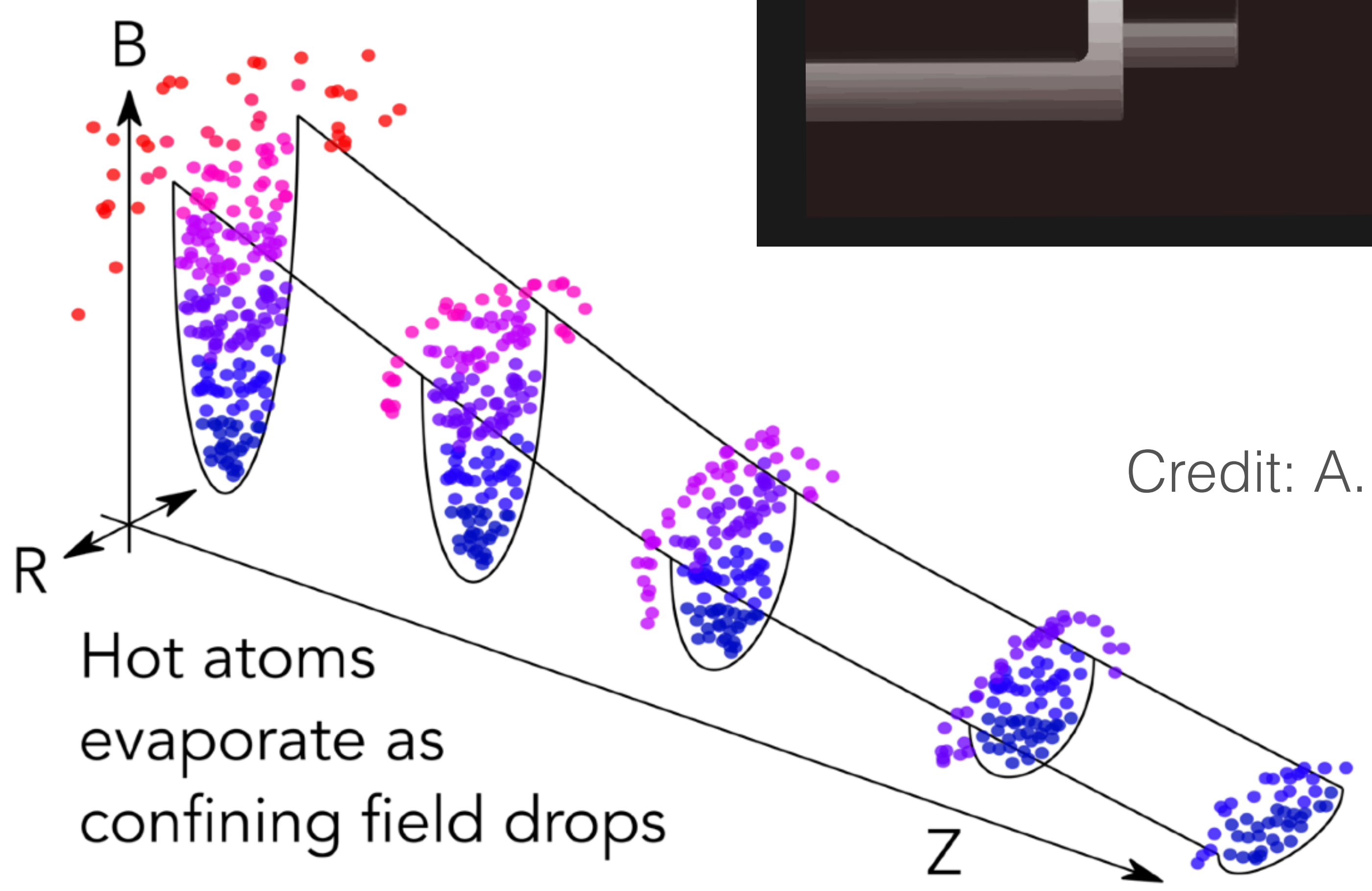
3. Cool by evaporation of hottest atoms





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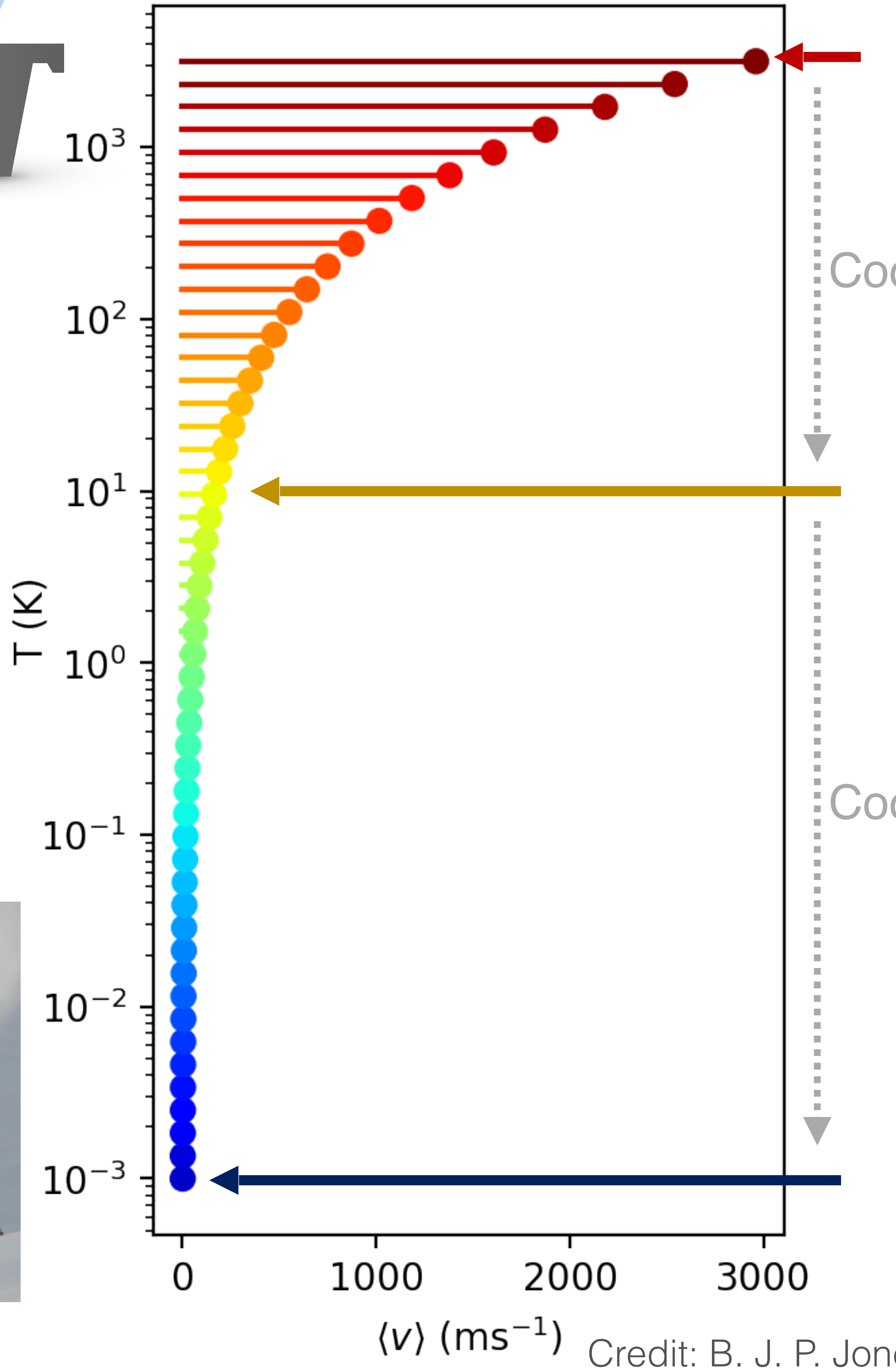
Atom Cooling



T2 cracks to T on hot tungsten (2200K)

Cool by scattering

T binds to solid surfaces (~10K)

Cool by evaporation

T gravitationally storable in 3m high trap (~1mK)

Credit: B. J. P. Jones

1. Accommodator: cool to 150K with multiple bounces at low recombination rate
2. One-bounce nozzle to cool to 10K
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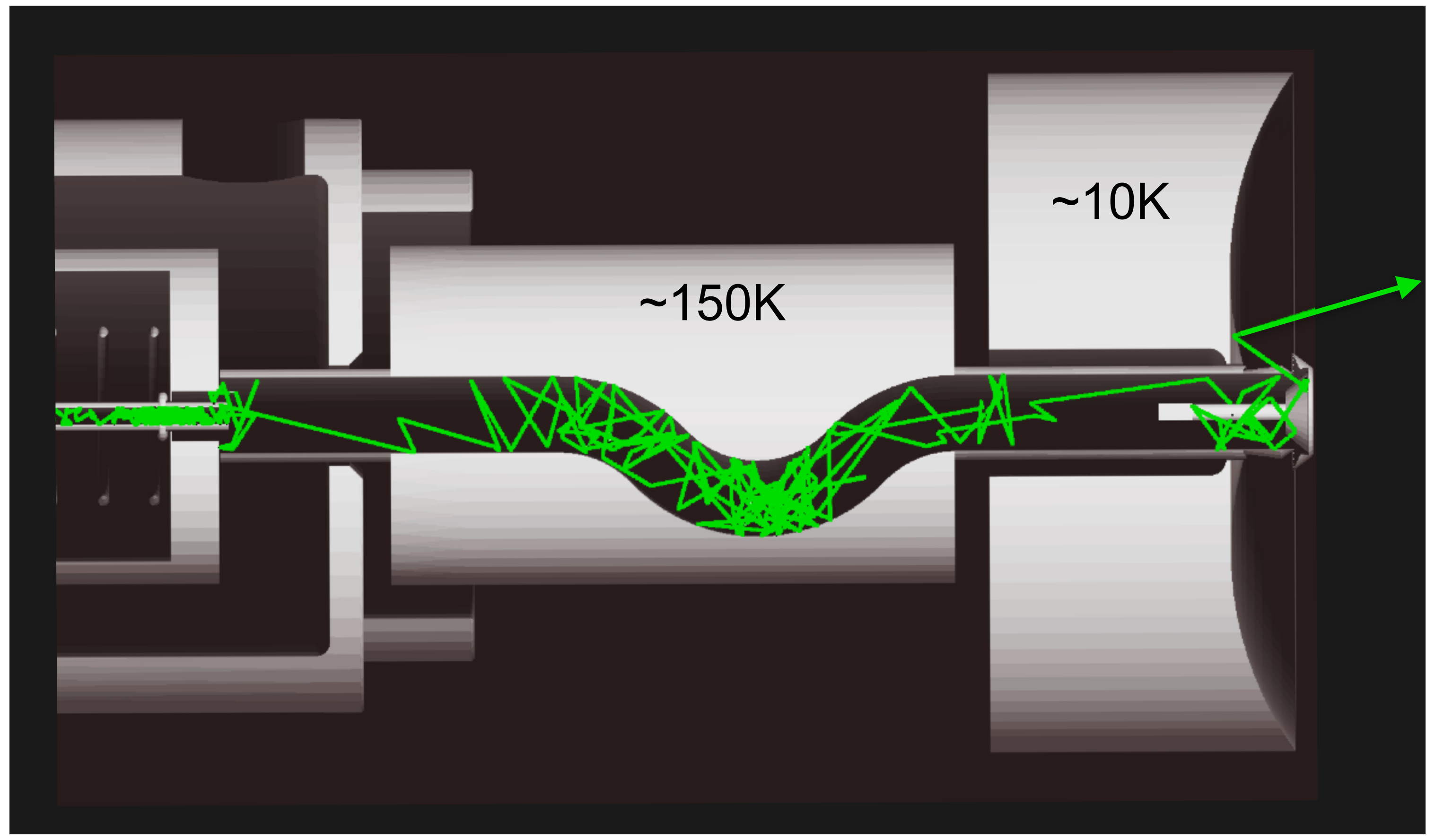
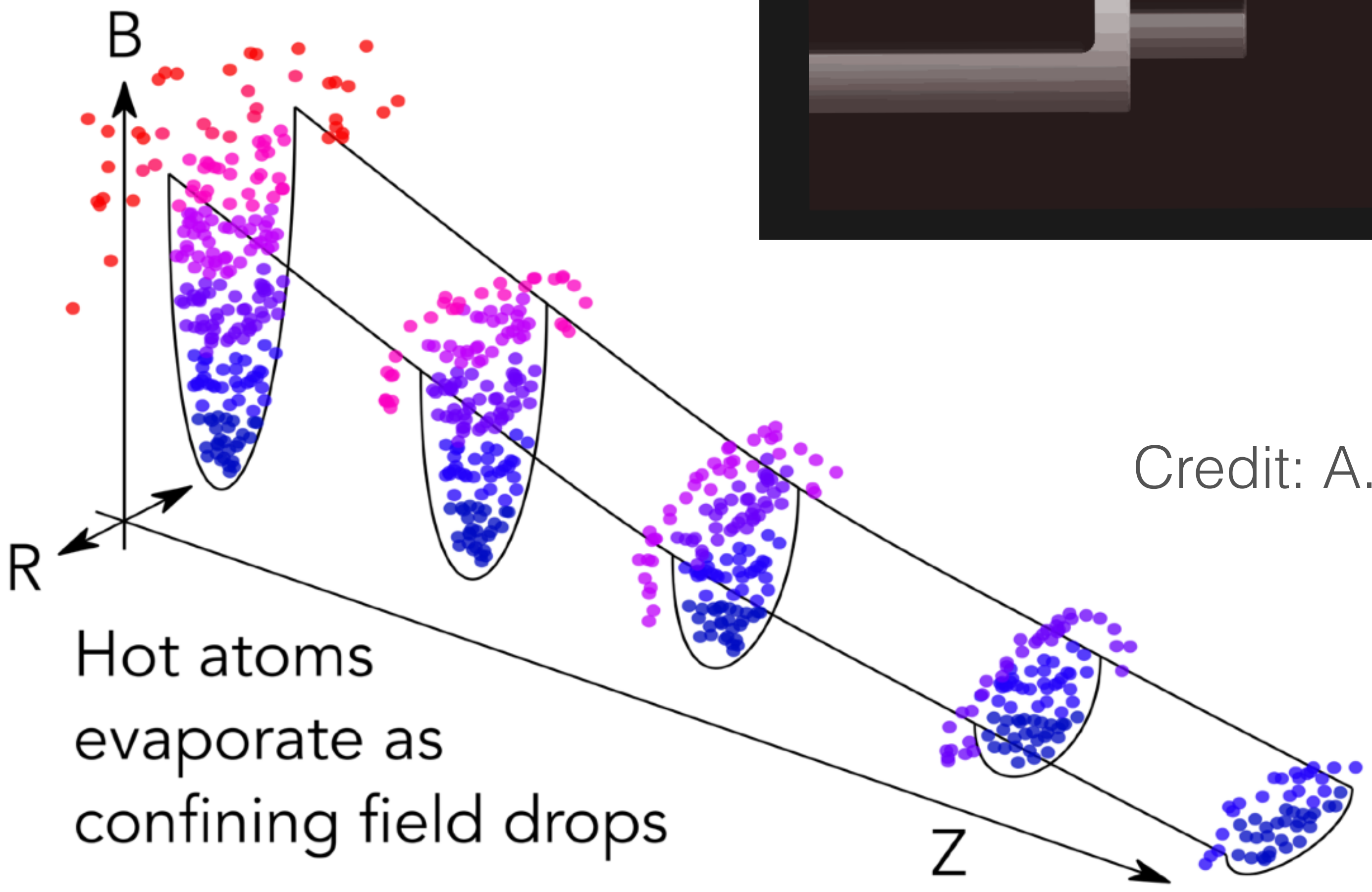
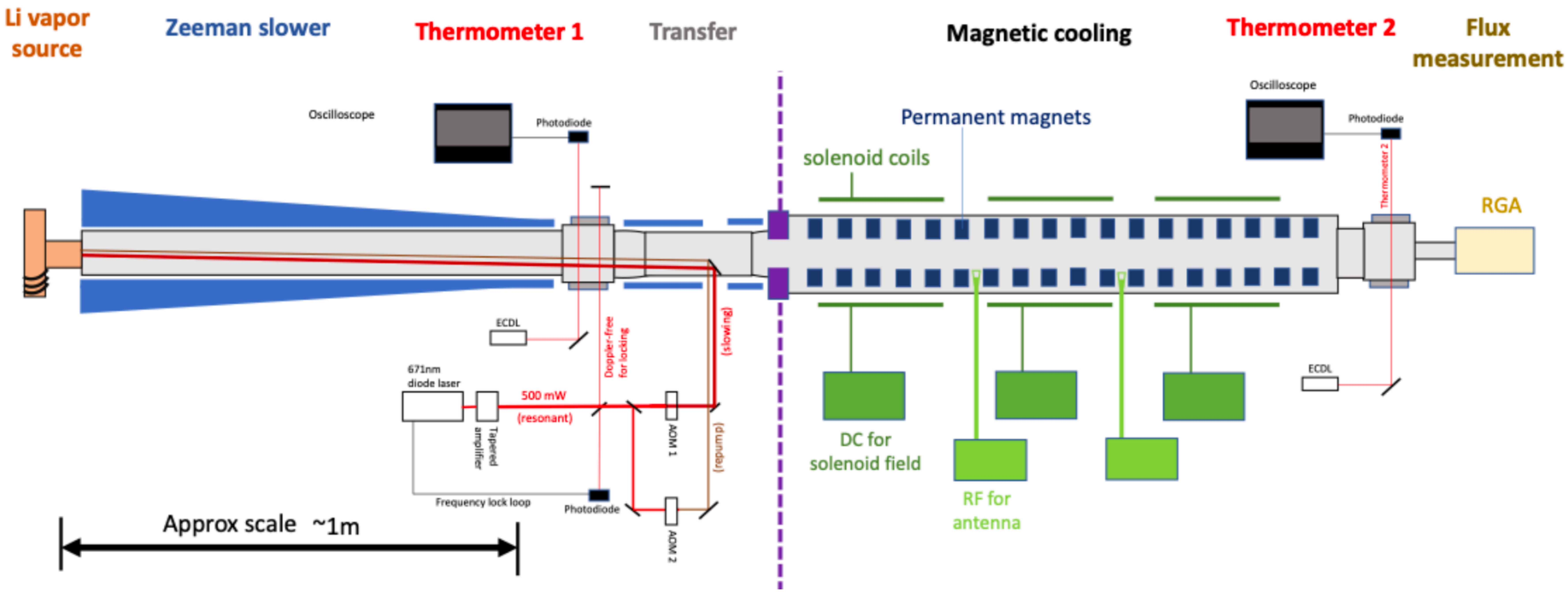




Credit: A. Lindman

Magnetic Evaporative Cooling Beamline

- Can cooling be done in a beamline?
- Prototype with Lithium-6 @ UT Arlington / U Manchester

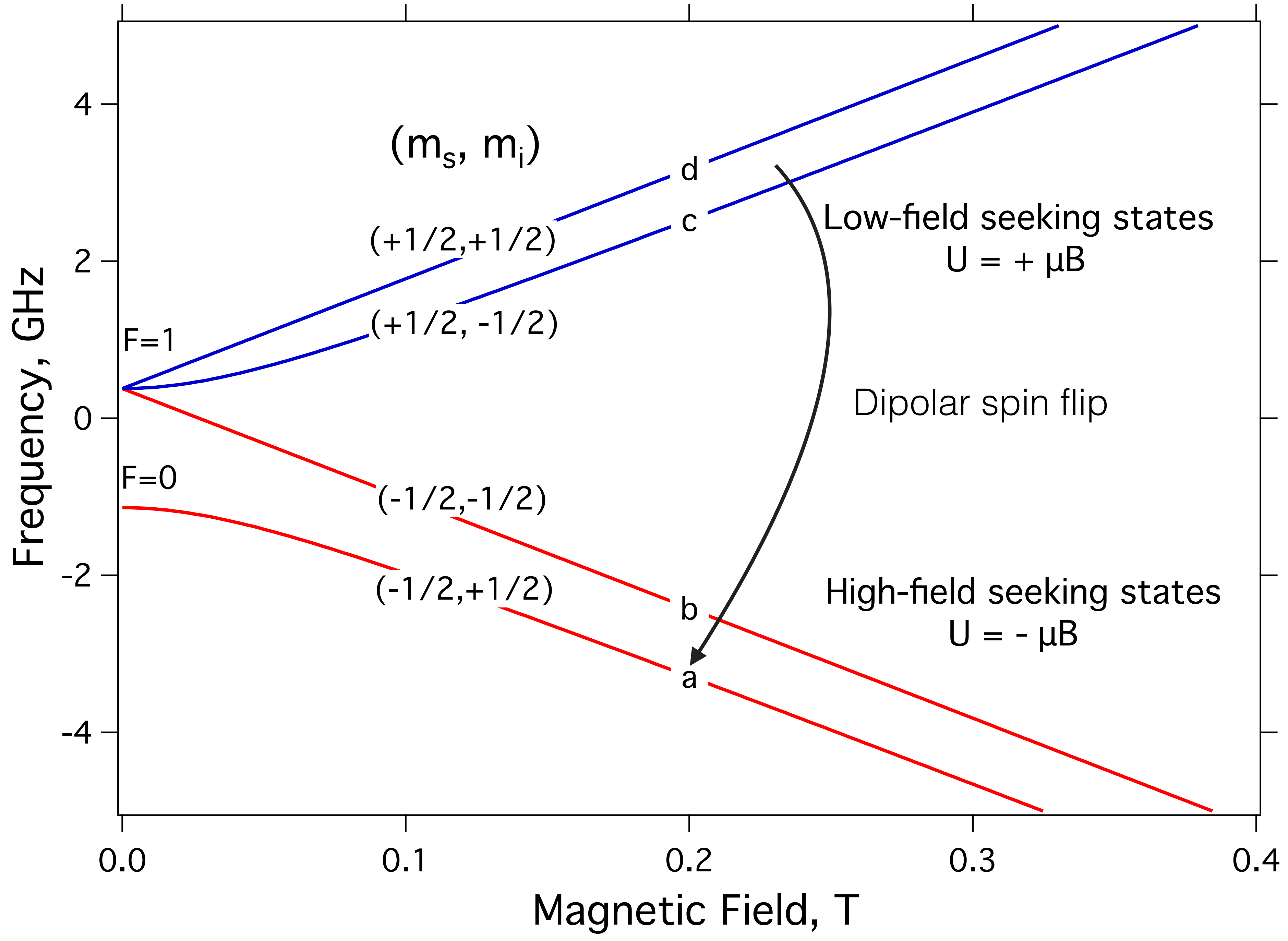


This side is beam prep to 5K
(uses visible lasers to slow Li)

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

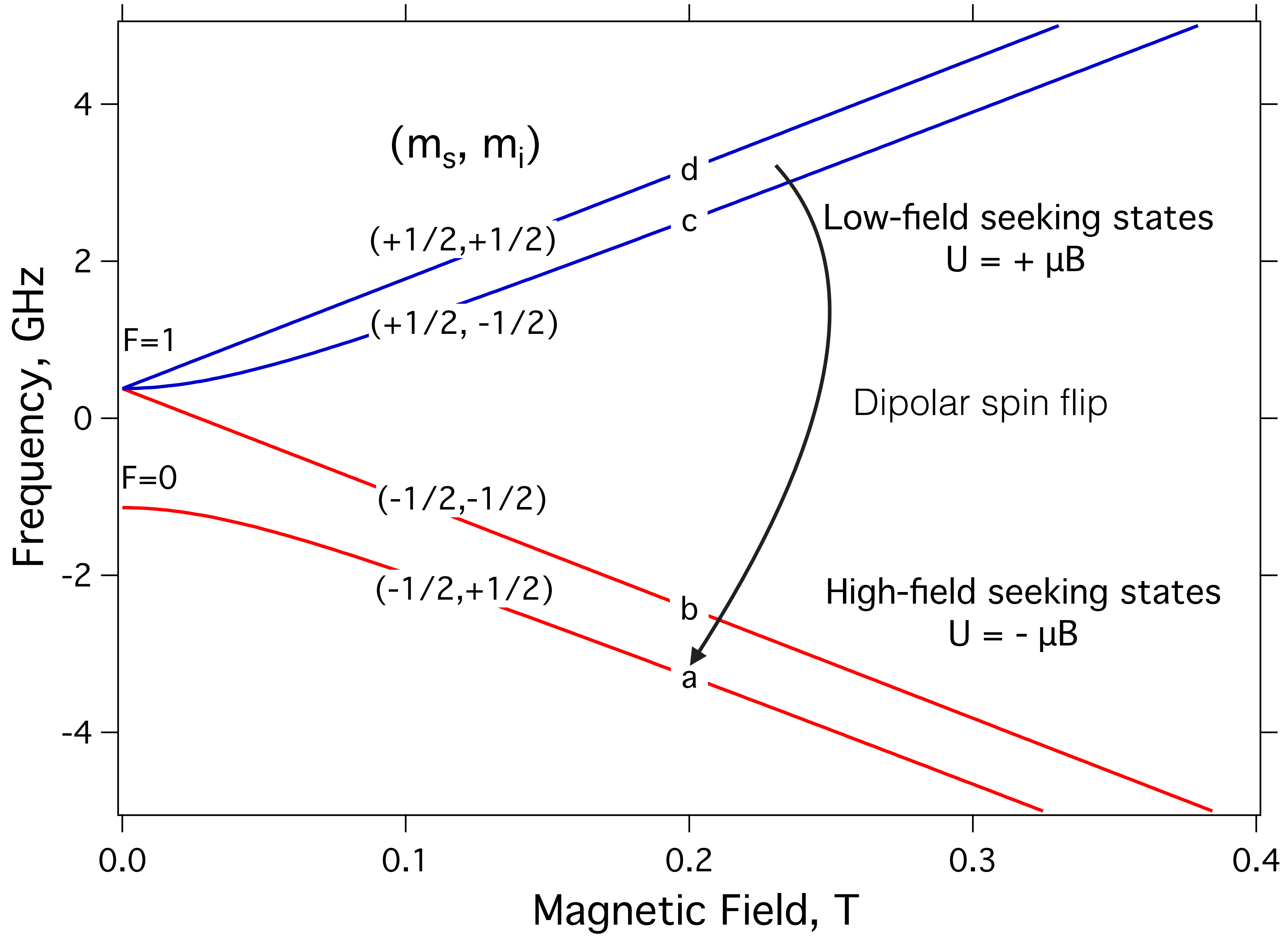
[PRA 112, 033311 (2025)]

Atom Trapping

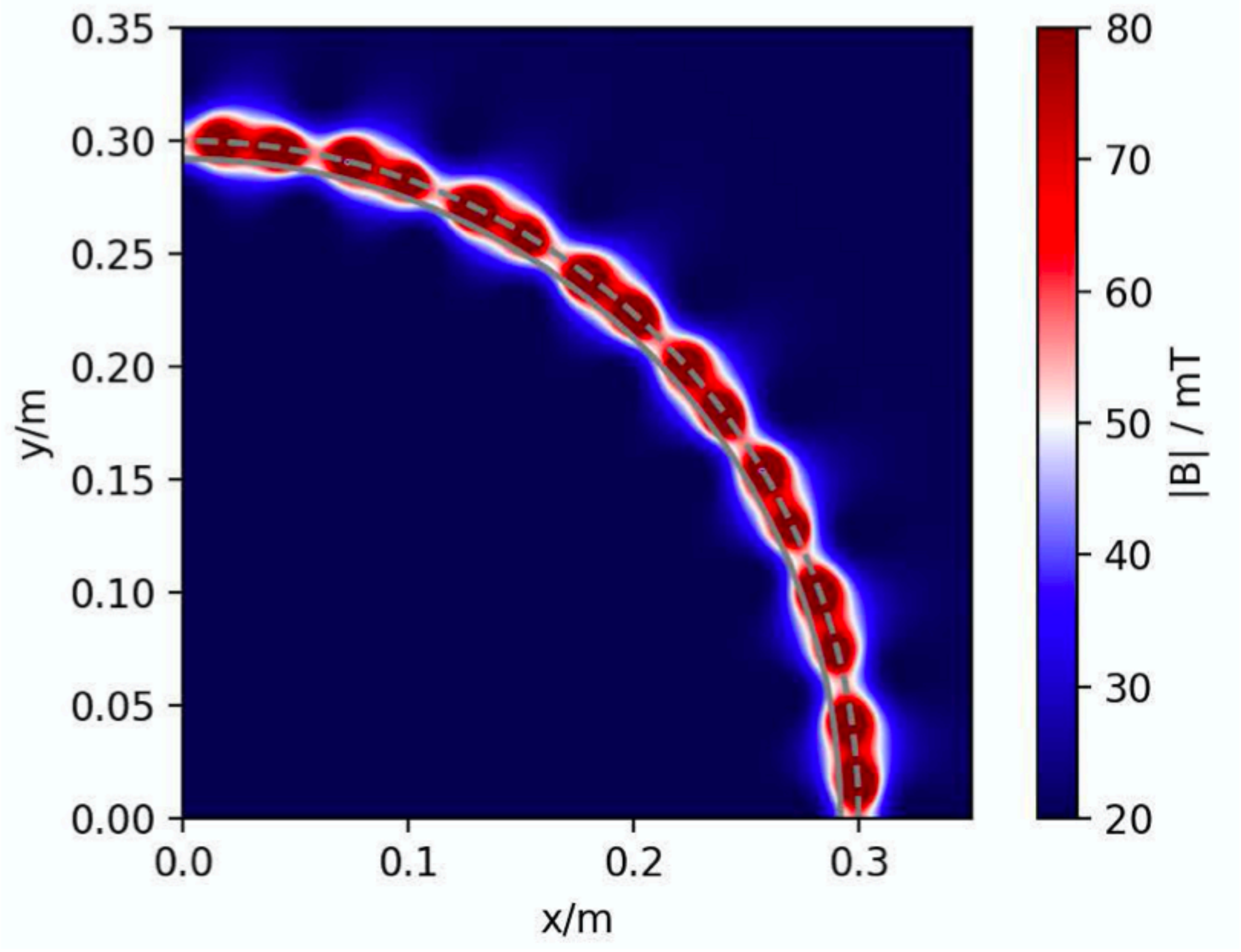


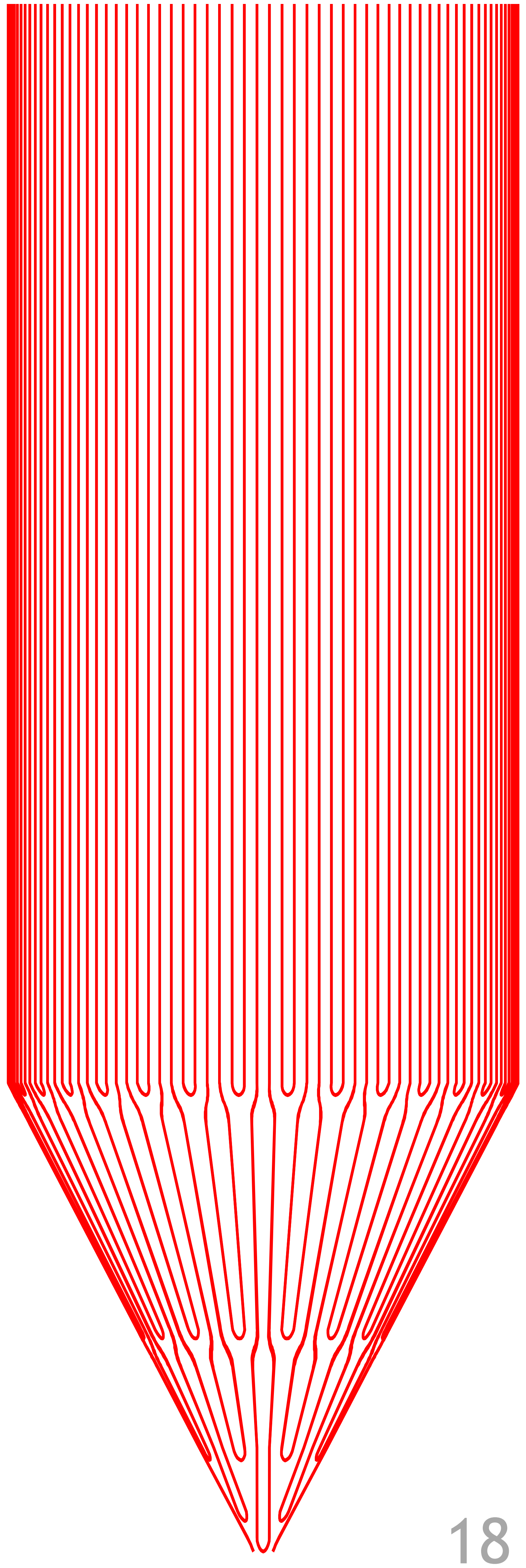
- Confine atoms in low-field seeking state magnetically

Atom Trapping



- Confine atoms in low-field seeking state magnetically
- Ioffe trap creates magnetic wall
- Central part free of field variations for CRES

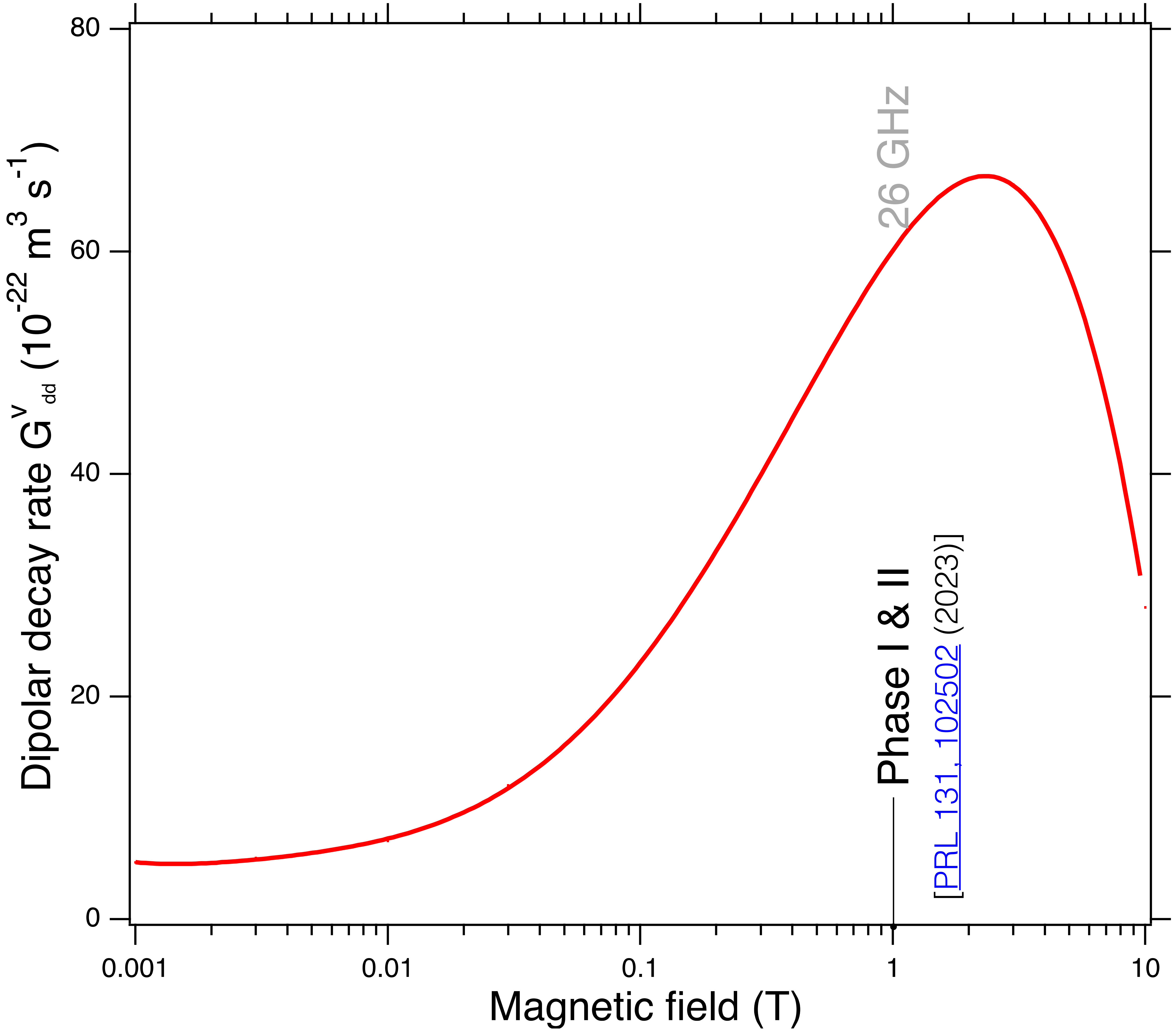




Phase III R&D: CRES Detection

Challenge: Large-Volume CRES

- Low CRES fields for atomic tritium trapping
  → low emitted powers



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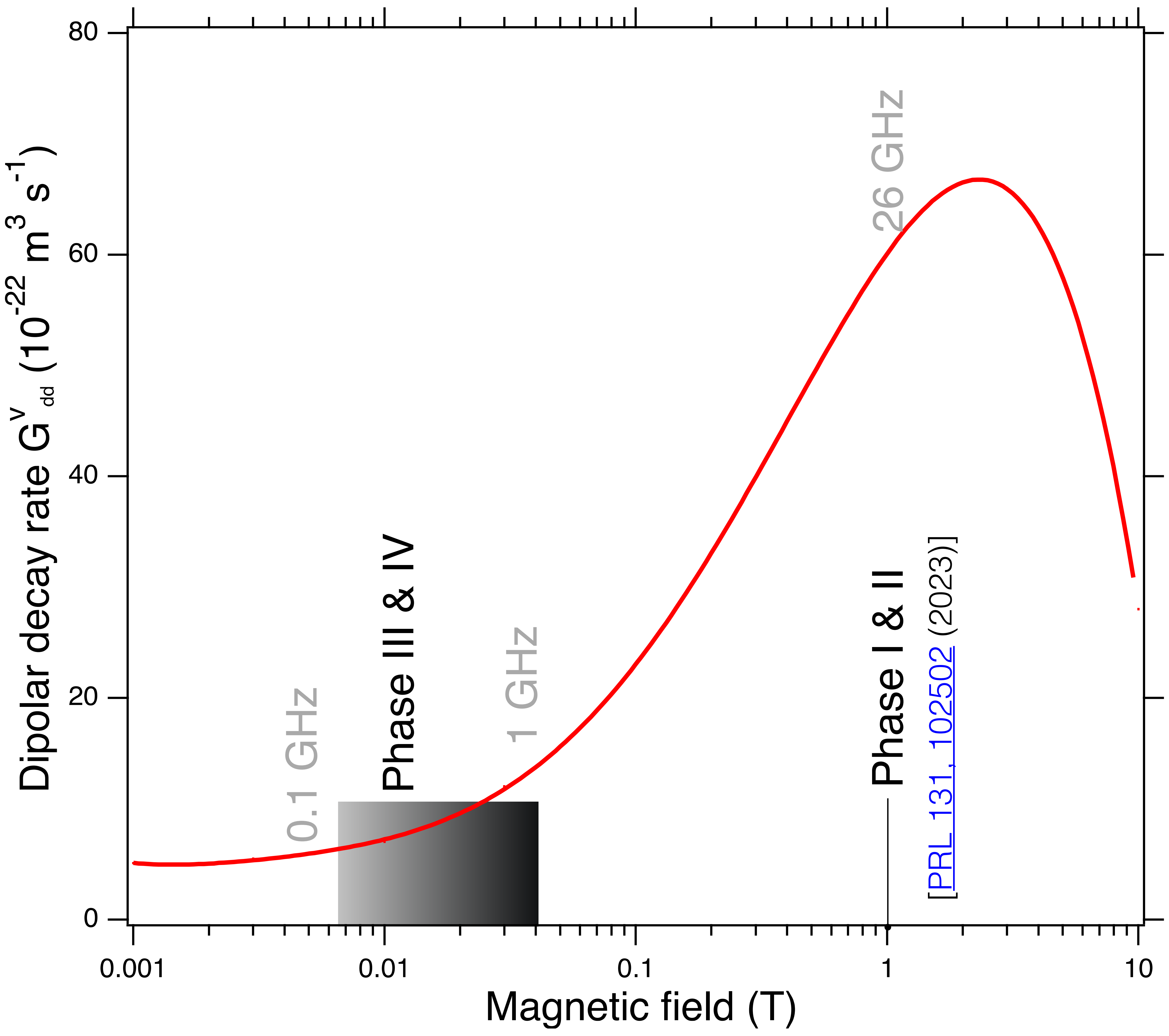

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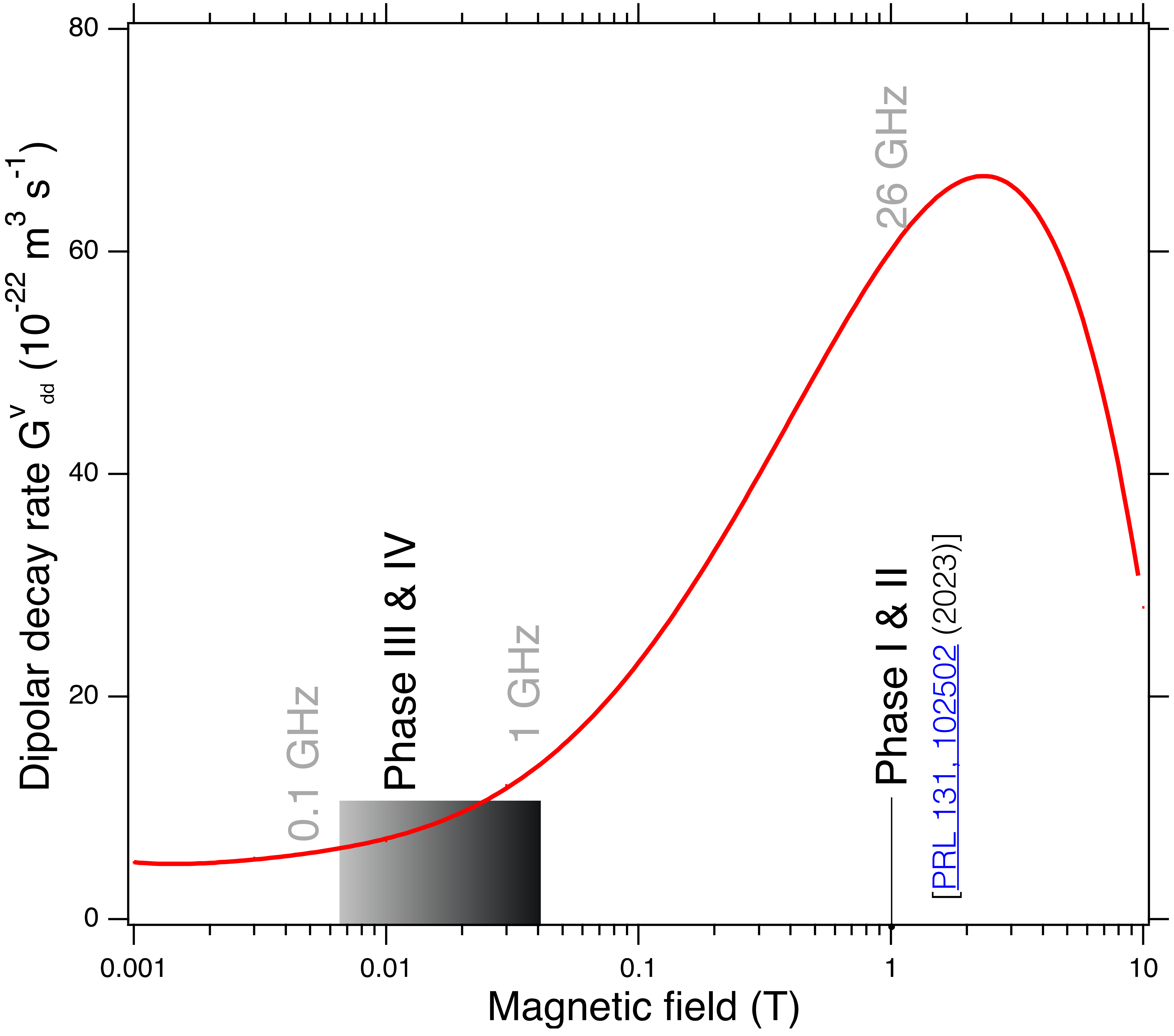
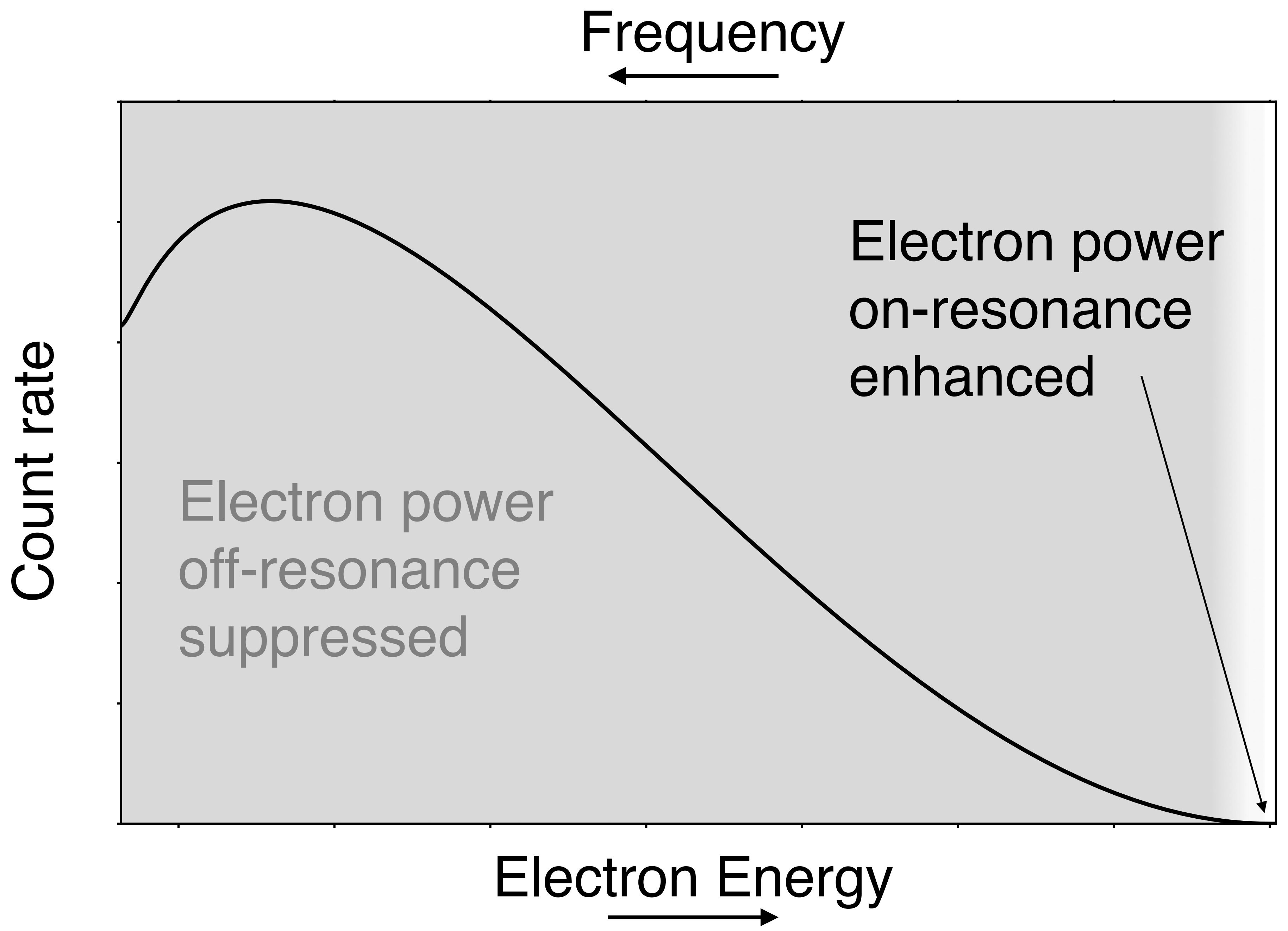
- Large volumes for high statistics



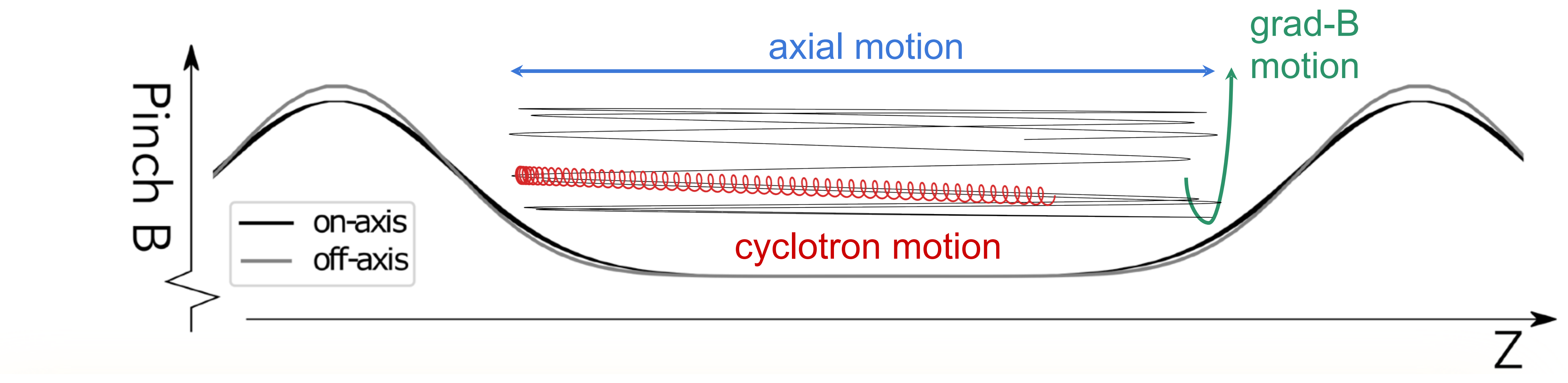
Challenge: Large-Volume CRES

- Low CRES fields for atomic tritium trapping
  → low emitted powers
- Large volumes for high statistics

- Solution are large resonant cavities:
  - Large volumes at low frequencies
  - Resonant enhancement of electron signal
  - Compatible with atomic tritium



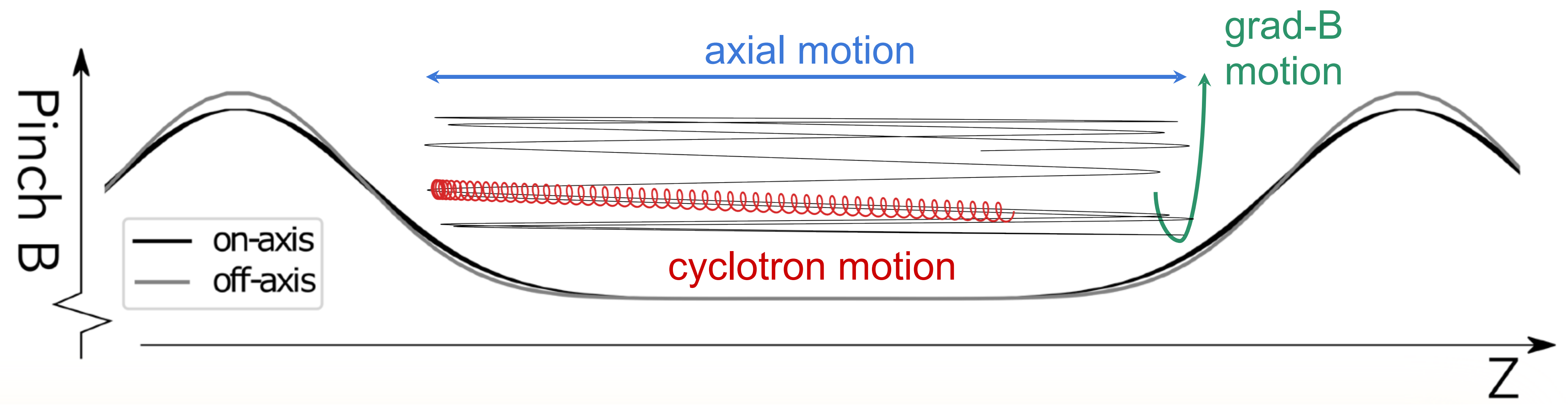
CRES in Cavities



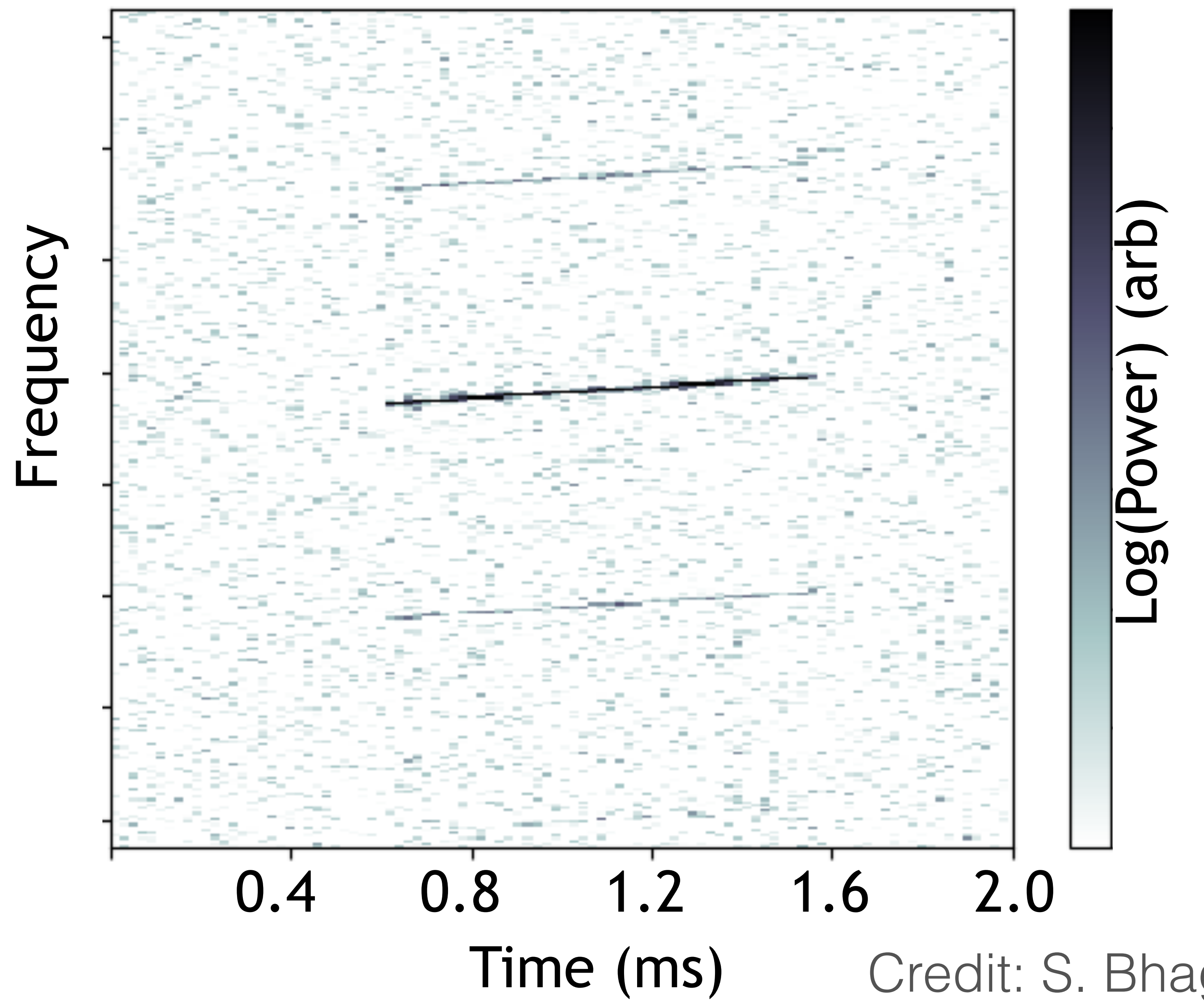
- Cyclotron motion gets modulated by axial motion
  → $\langle B \rangle$ experienced by electrons depends on pitch angle

[Arxiv 2601.07848 (2026)]

CRES in Cavities



- Cyclotron motion gets modulated by axial motion
  → $\langle B \rangle$ experienced by electrons depends on pitch angle
- Necessitates the detection of the carrier frequency and a lower sideband
  → accurately links $\langle B \rangle$ to individual electron
  → allows accurate energy reconstruction



Credit: S. Bhagvati

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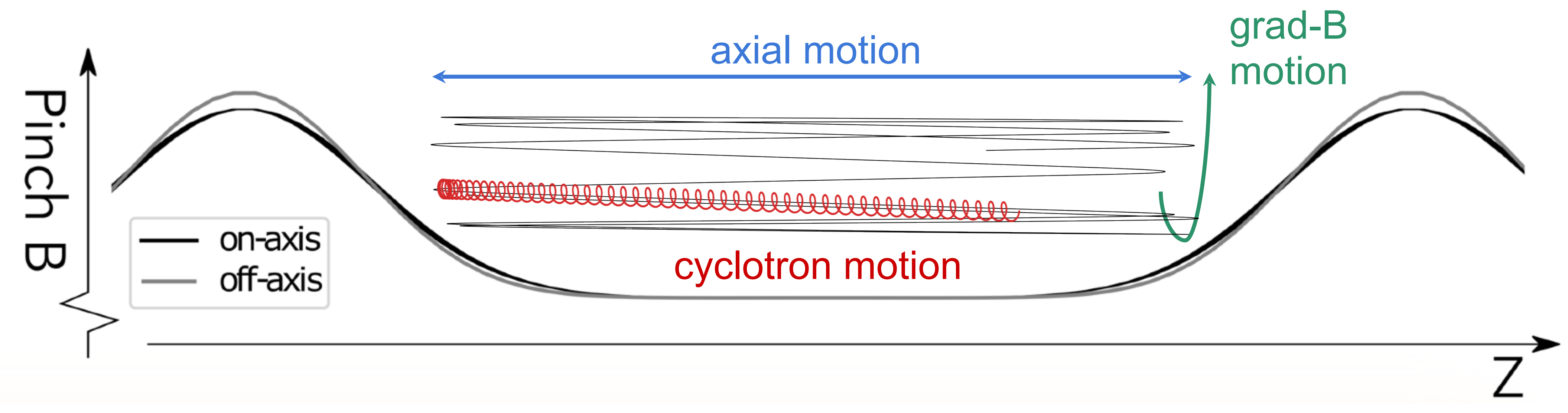
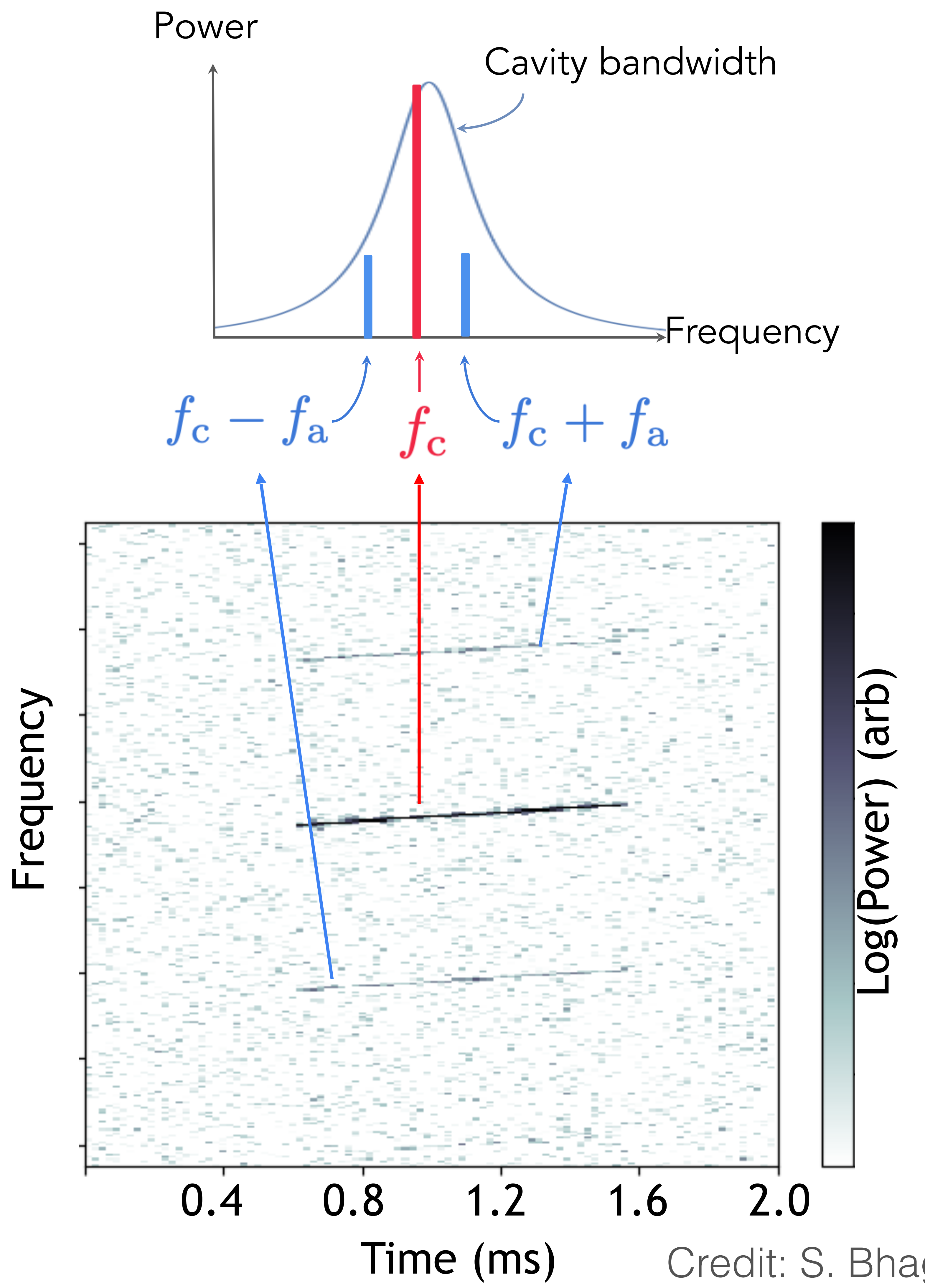
CRES in Cavities





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  → $\langle B \rangle$ experienced by electrons depends on pitch angle
- Necessitates the detection of the carrier frequency and a lower sideband
  → accurately links $\langle B \rangle$ to individual electron
  → allows accurate energy reconstruction
- Range of axial motions sets bandwidth requirements for the cavity design

[Arxiv 2601.07848 (2026)]

The Cavity CRES Apparatus

- Cavity at 26 GHz:
  $L = 14\,\mathrm{cm}, R = 0.7\,\mathrm{cm}, V \sim 20\,\mathrm{cm}^3$
- Inserted into 1 T MRI magnet @ U of Washington
  - Same frequency as Phase II
- Small-scale cavity-CRES demonstration
  - Aim: 0.3 eV energy resolution

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The Cavity CRES Apparatus

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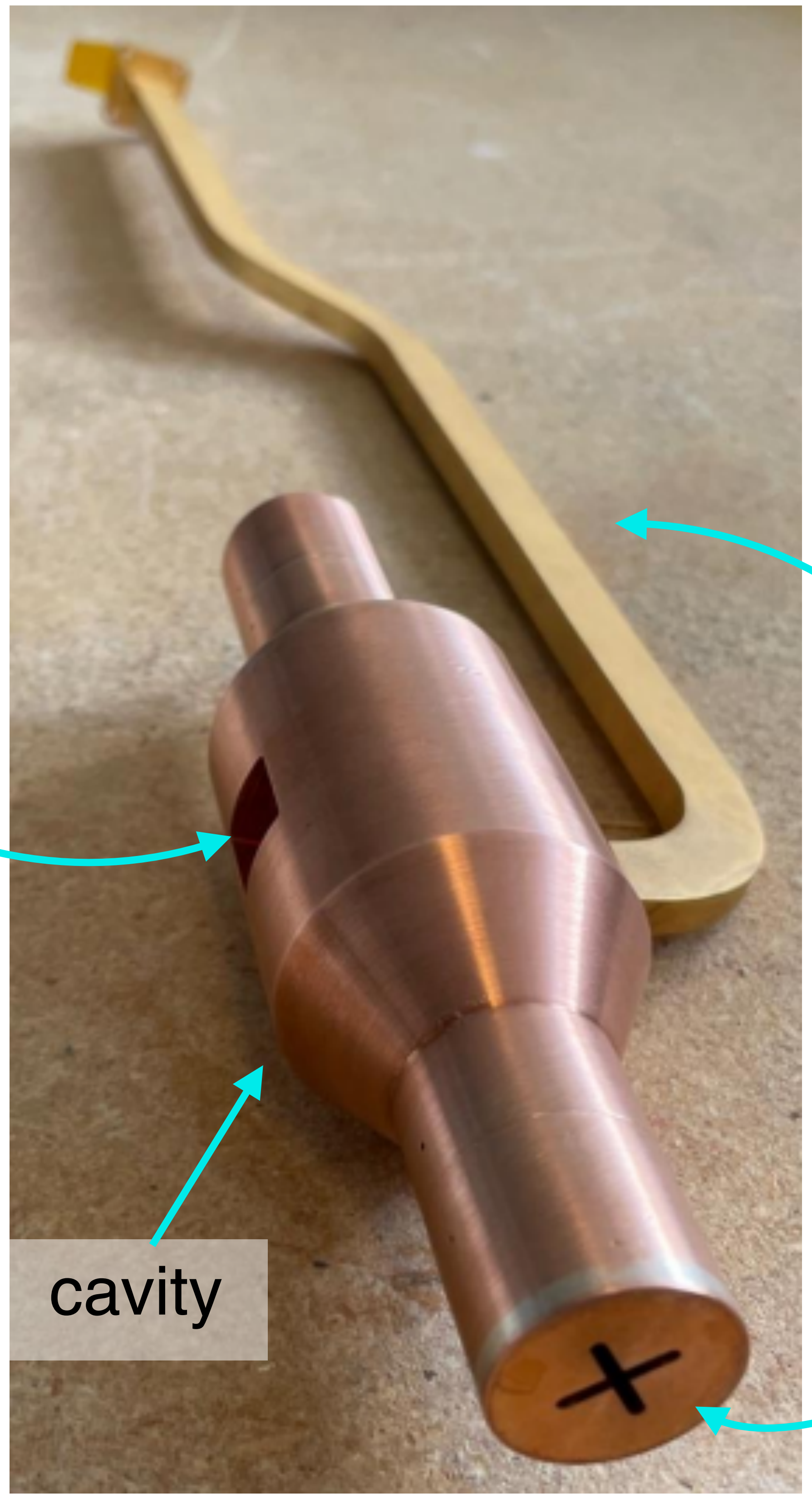
CCA - Commissioning



- Status: Commissioning ongoing
- Expect first cavity CRES data soon

CCA - Commissioning

Photo: M. Huehn

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CCA - Commissioning

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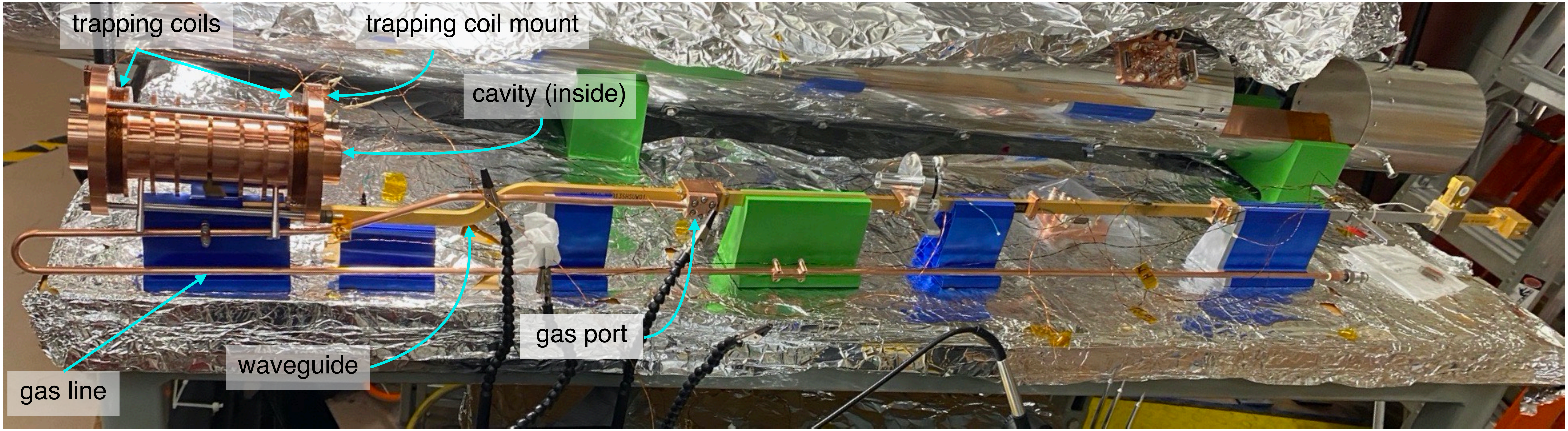

Photo: T. E. Weiss

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CCA - Commissioning

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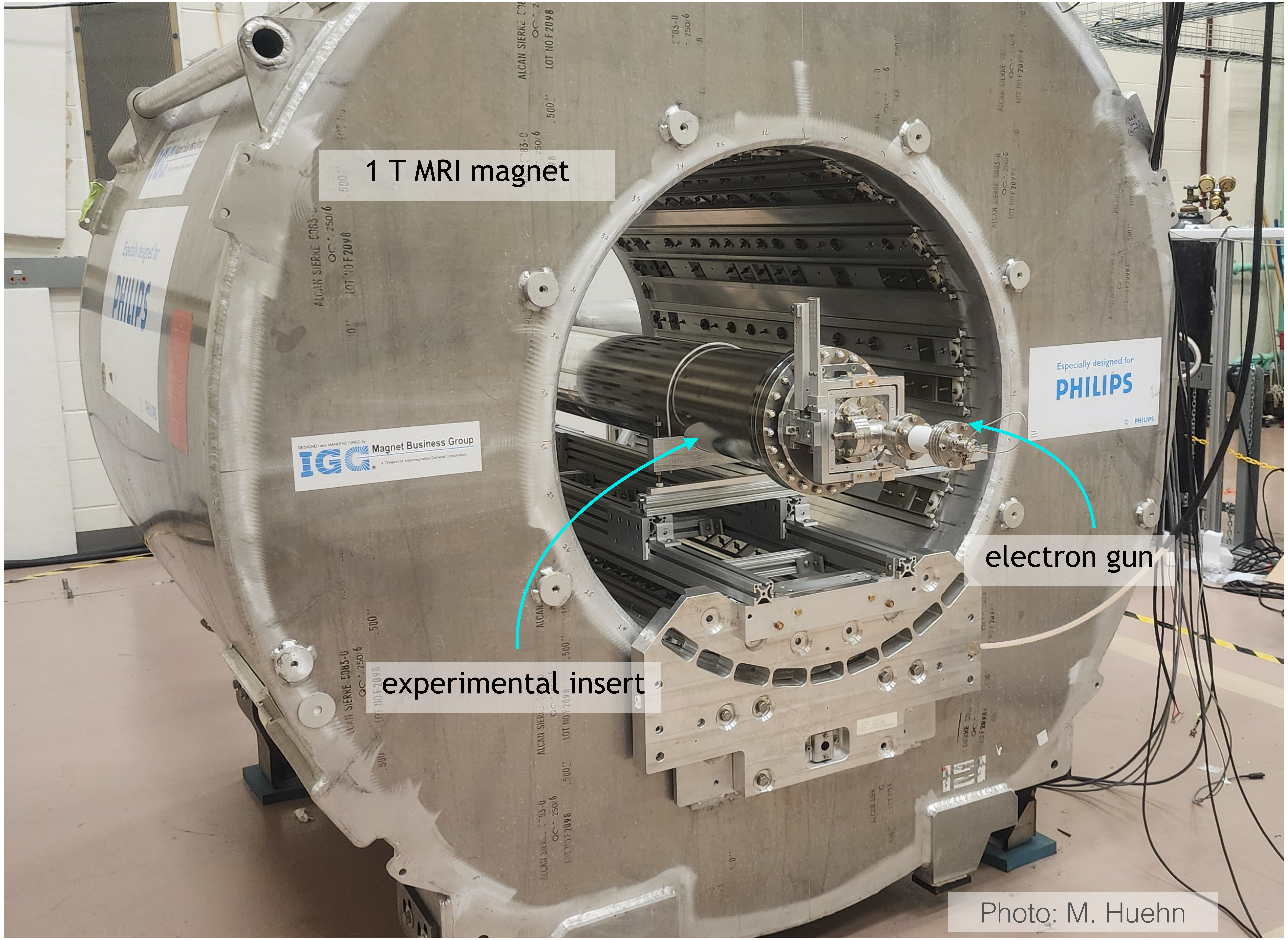

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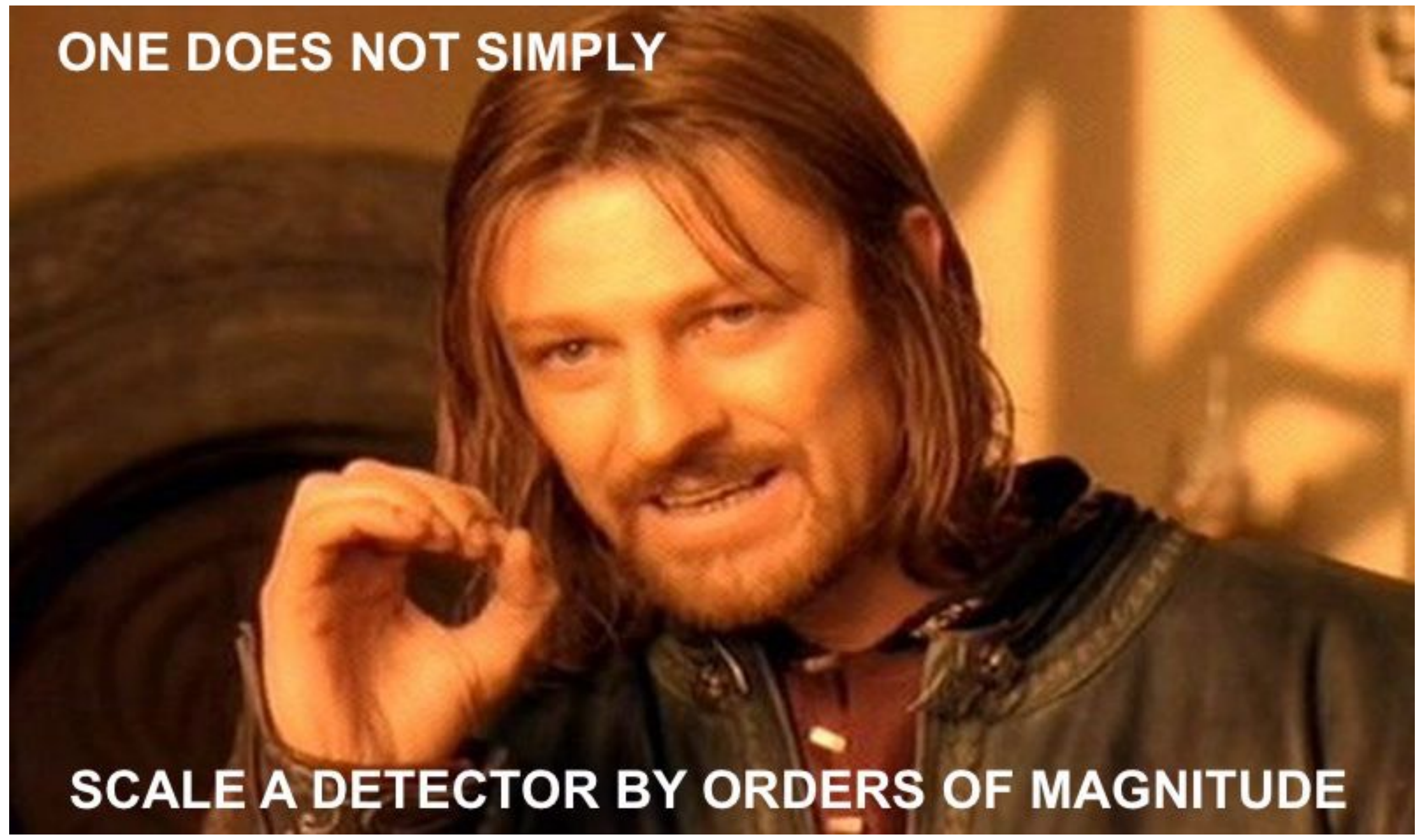
The Low Frequency Apparatus

- Scale up in volume:
  - $f = 560\,\mathrm{MHz}, B = 0.02\,\mathrm{T}, V \sim 1.5\,\mathrm{m}^3 \rightarrow \mathcal{O}(10^5)$ larger than CCA
- Scale down in collected power:
  - $P \propto B^2 \rightarrow$ 0.5% of radiated power compared to Phase II



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Work @UGent supported by ERC Starting Grant

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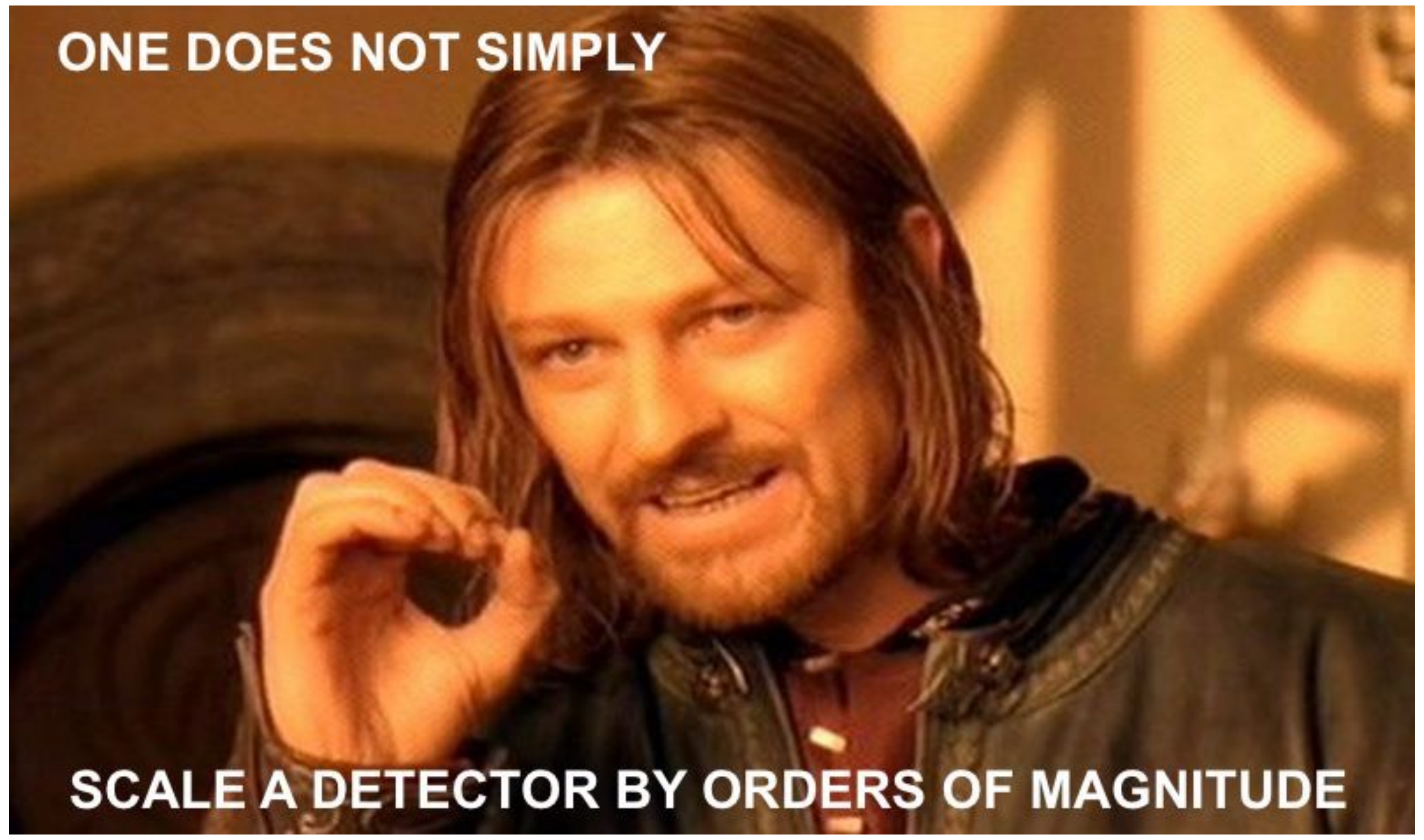

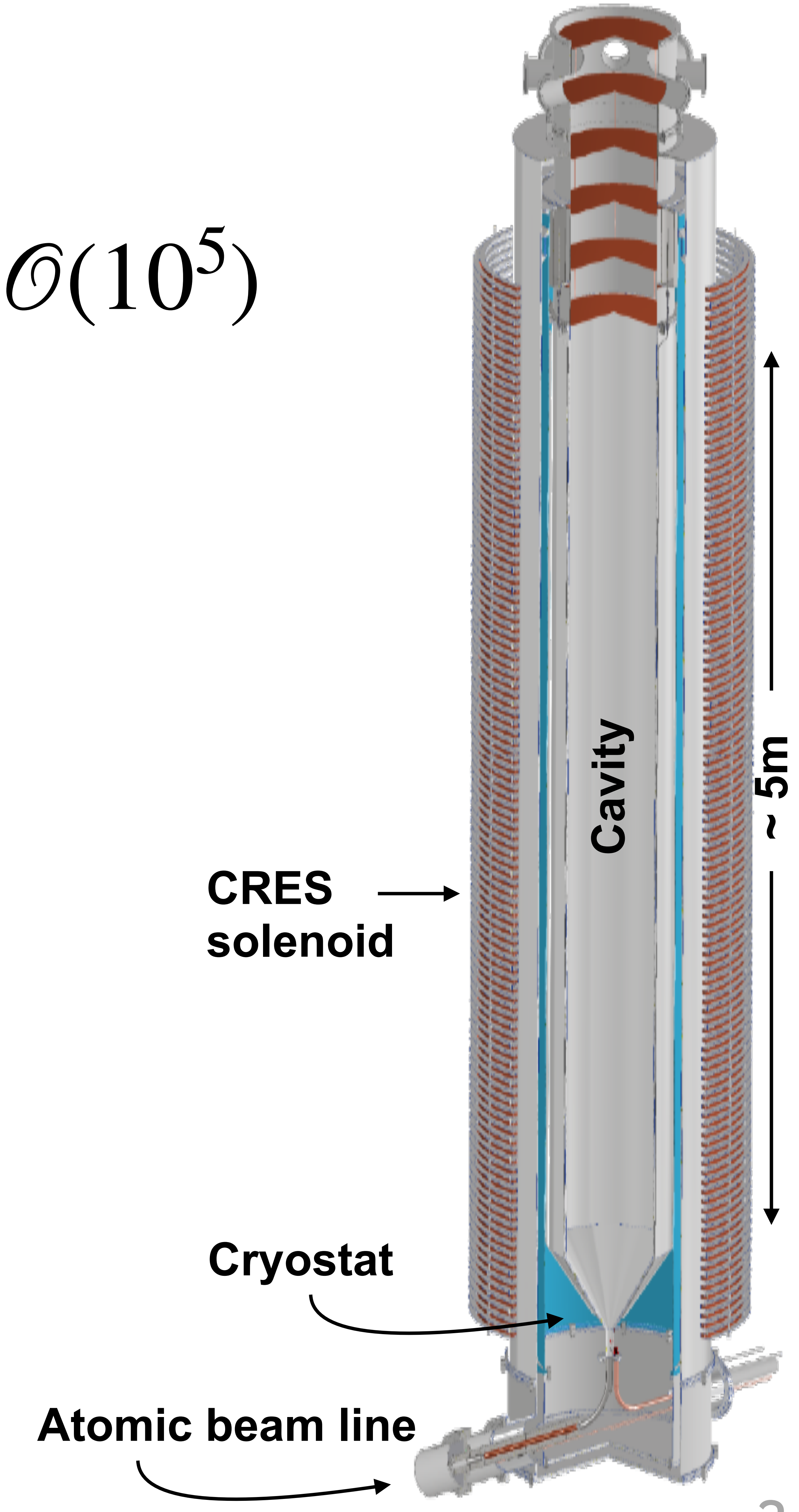

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- Scale down in collected power:
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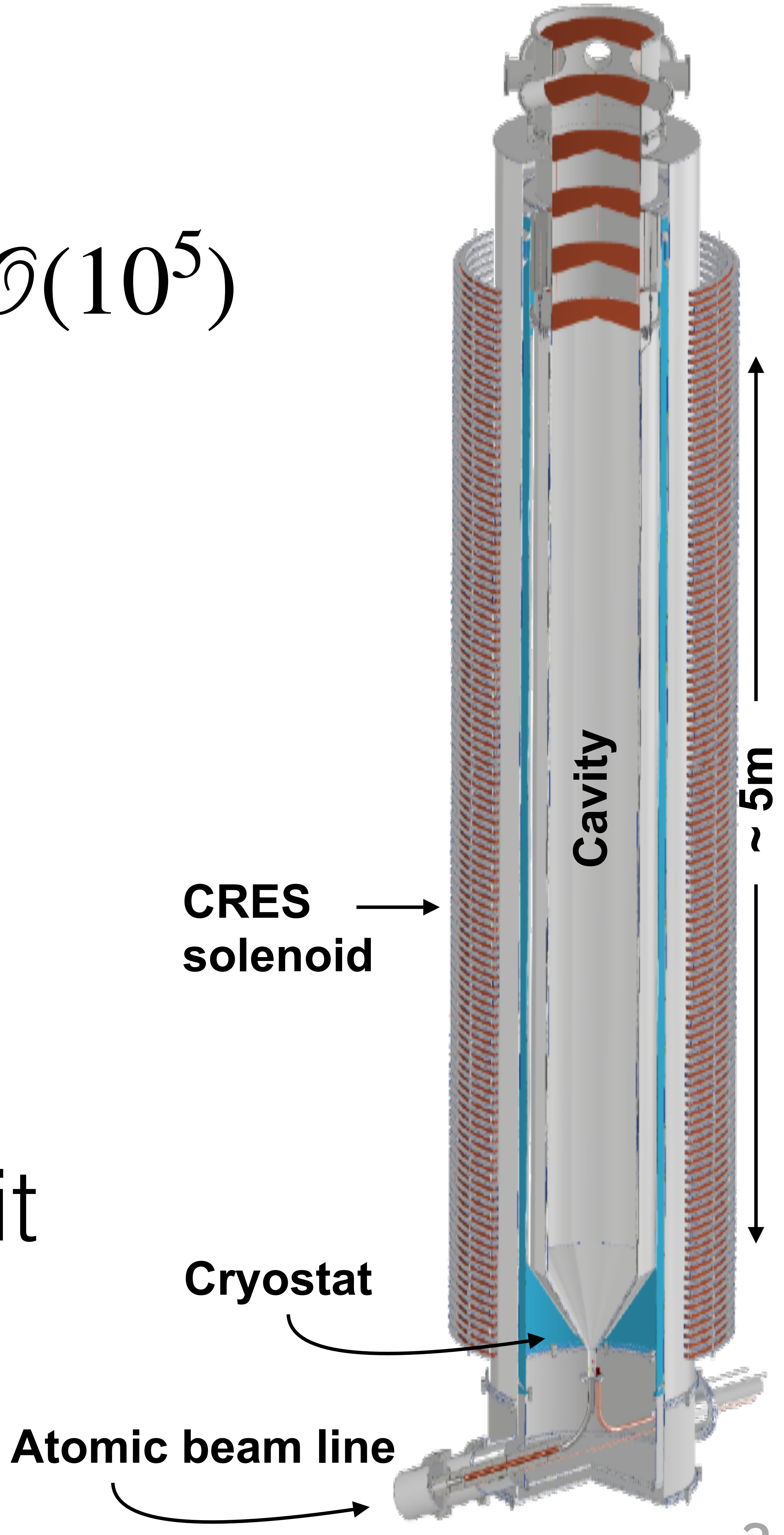
- Integrated magnet design
- Upgrade with atomic tritium beam for competitive, sub-eV neutrino mass limit



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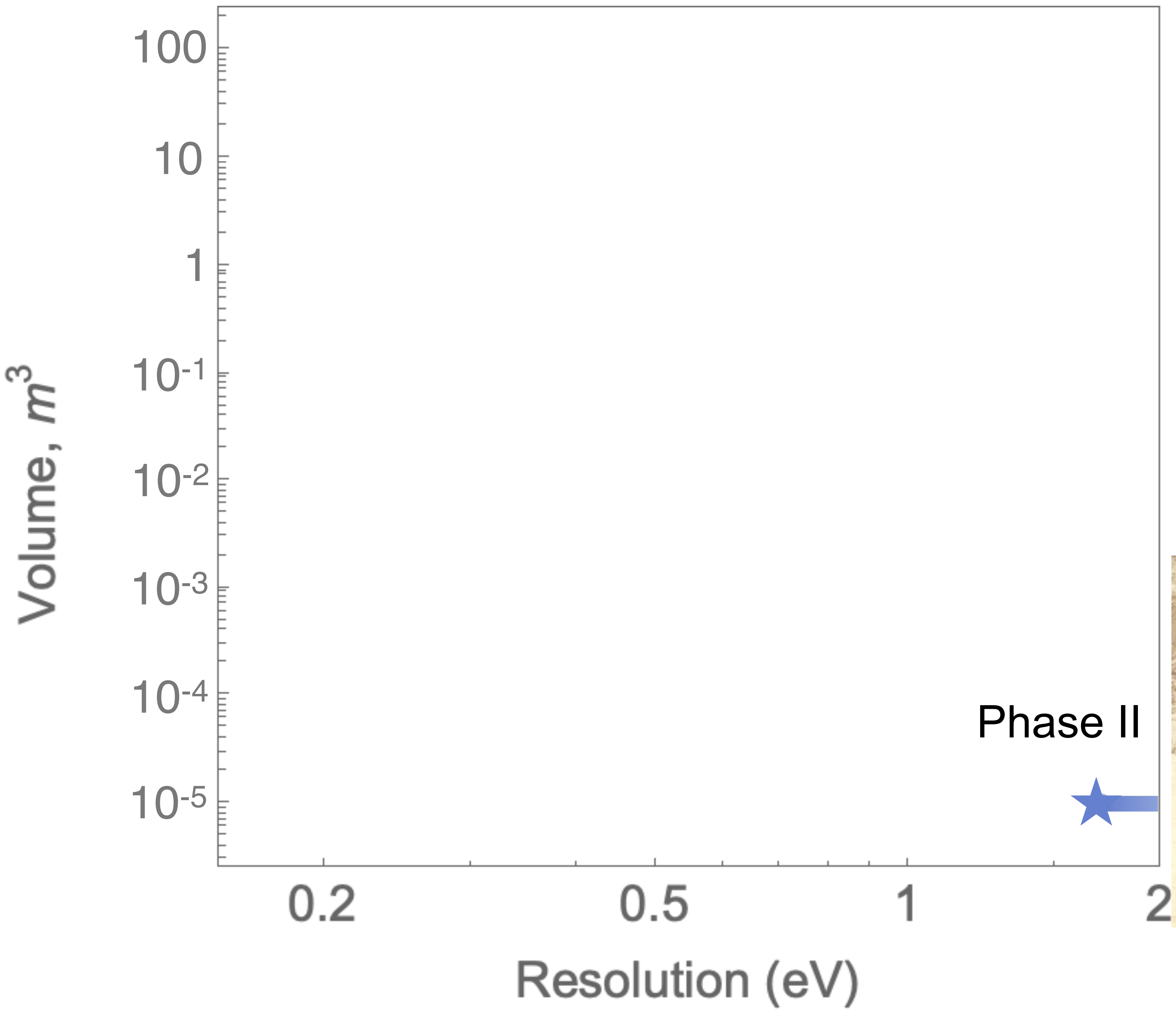
Phased Approach



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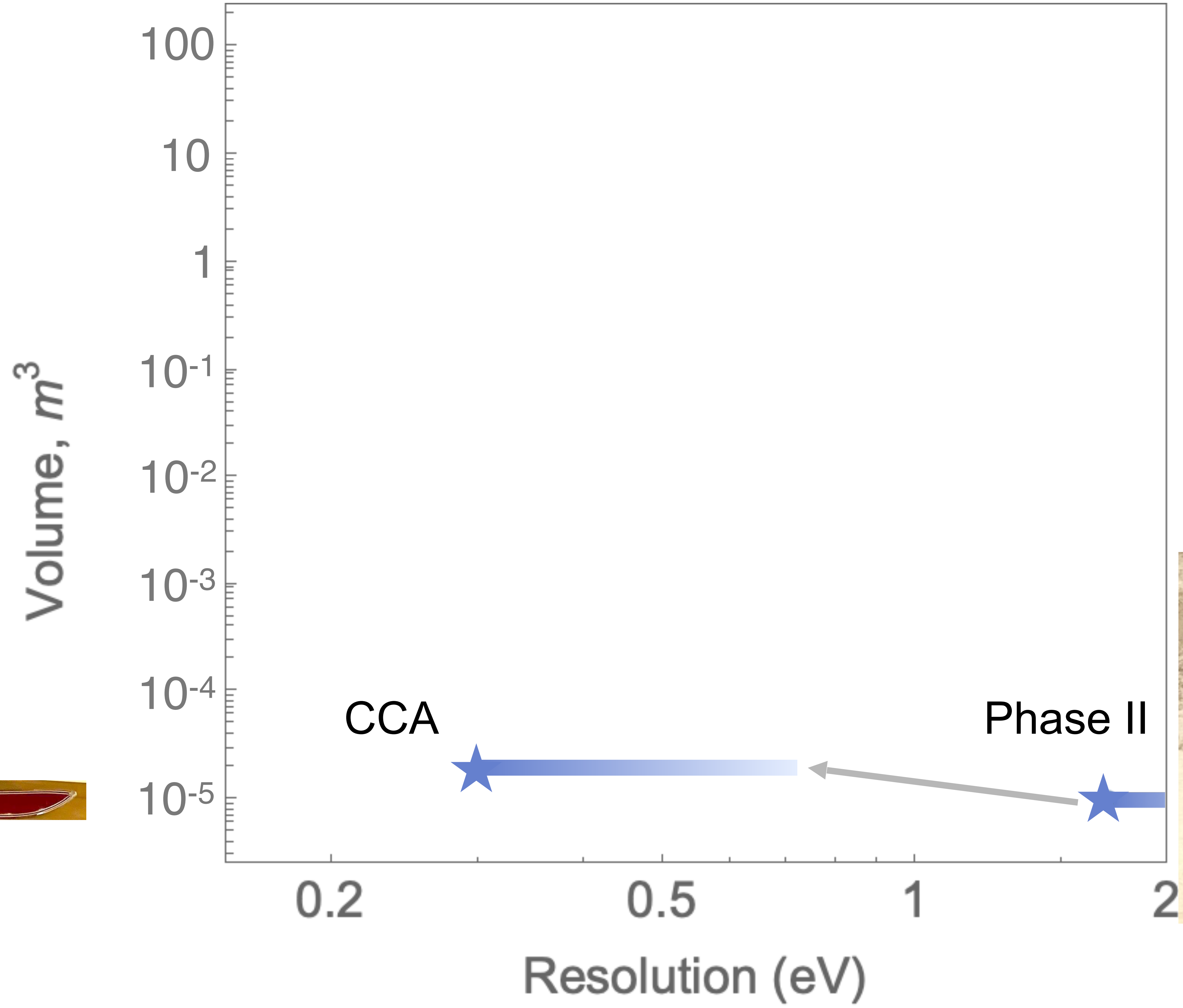
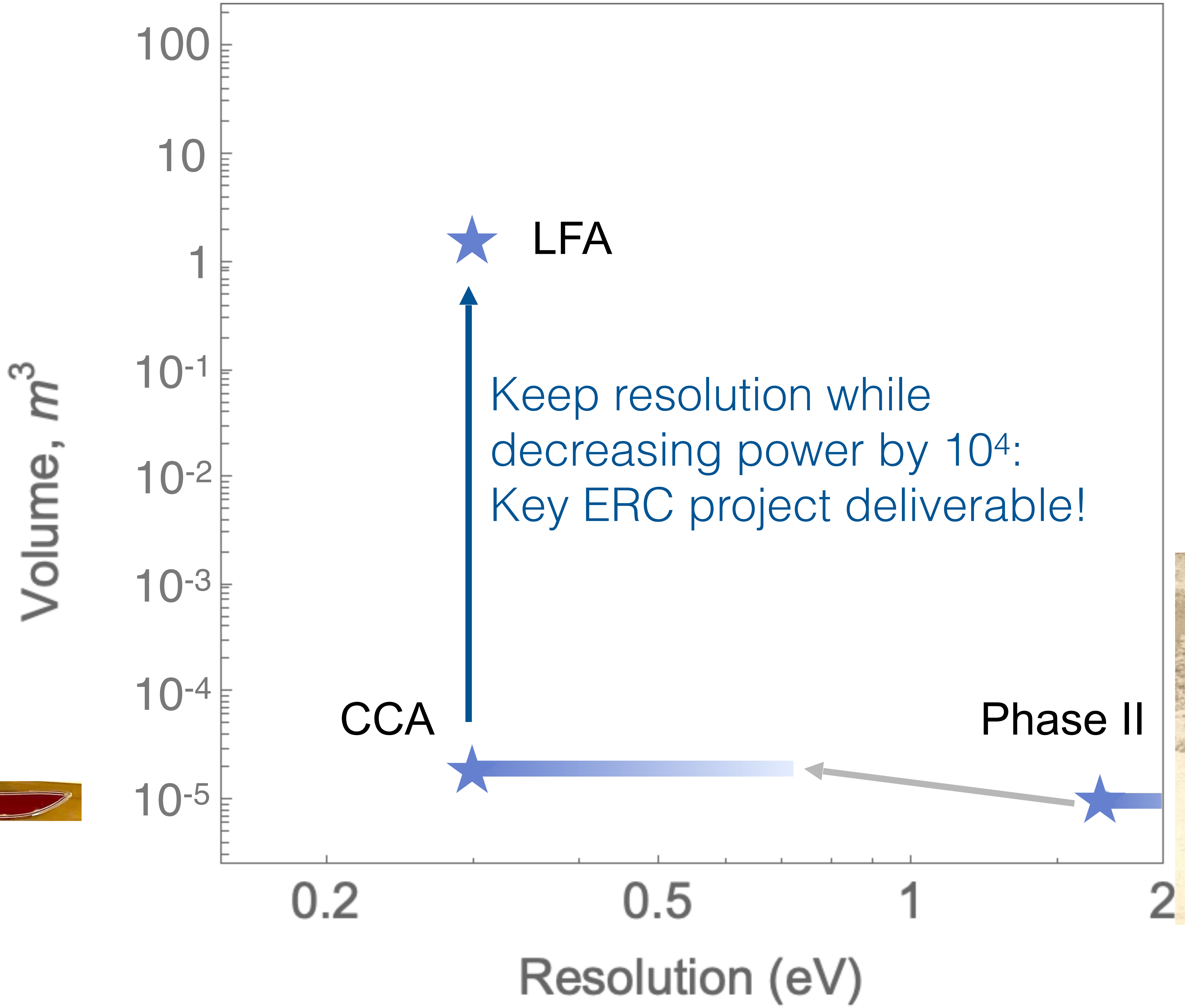


Phased Approach



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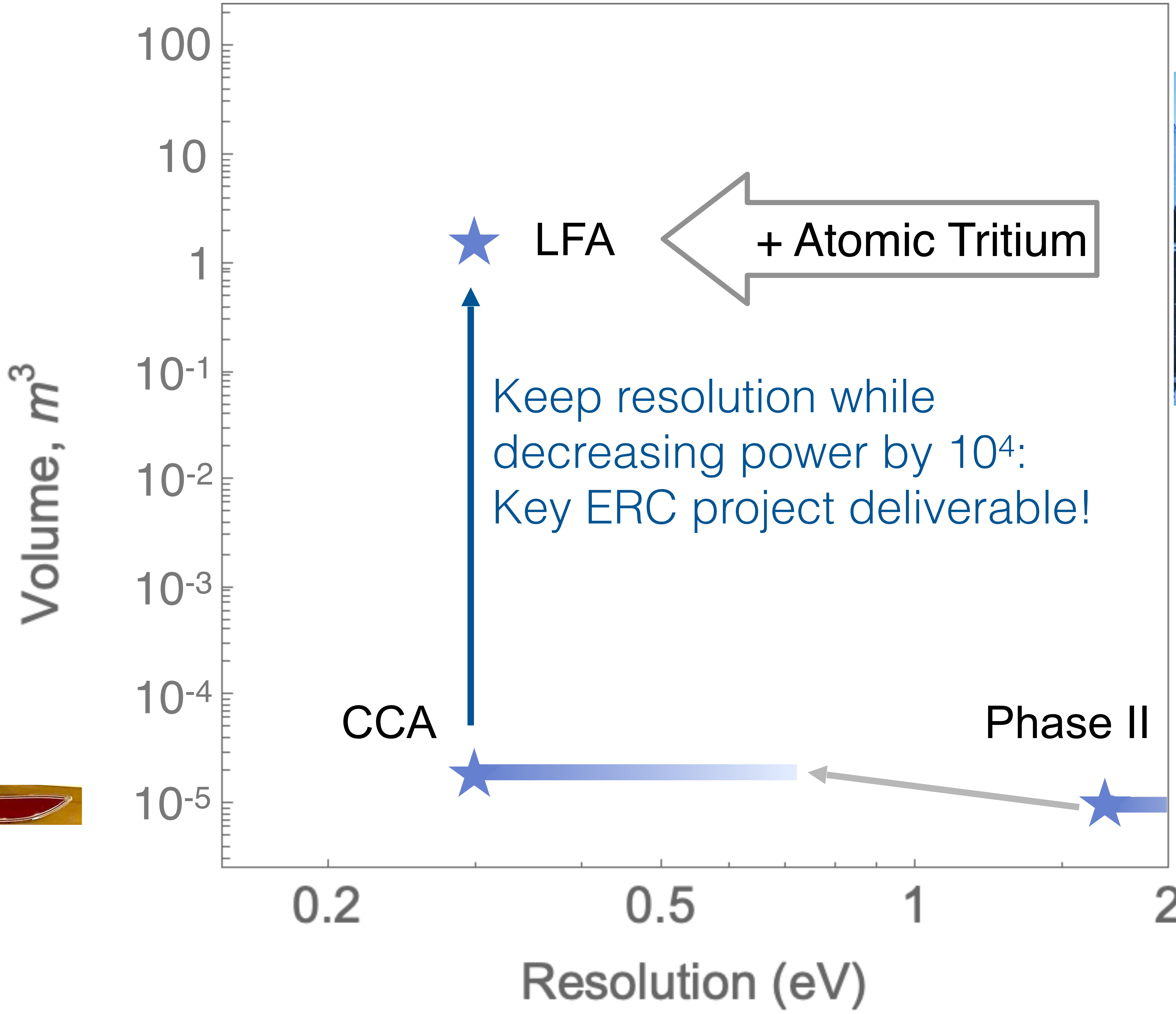

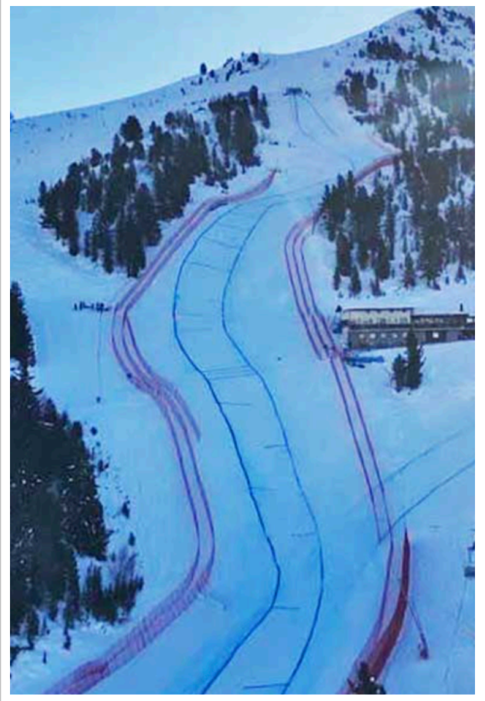

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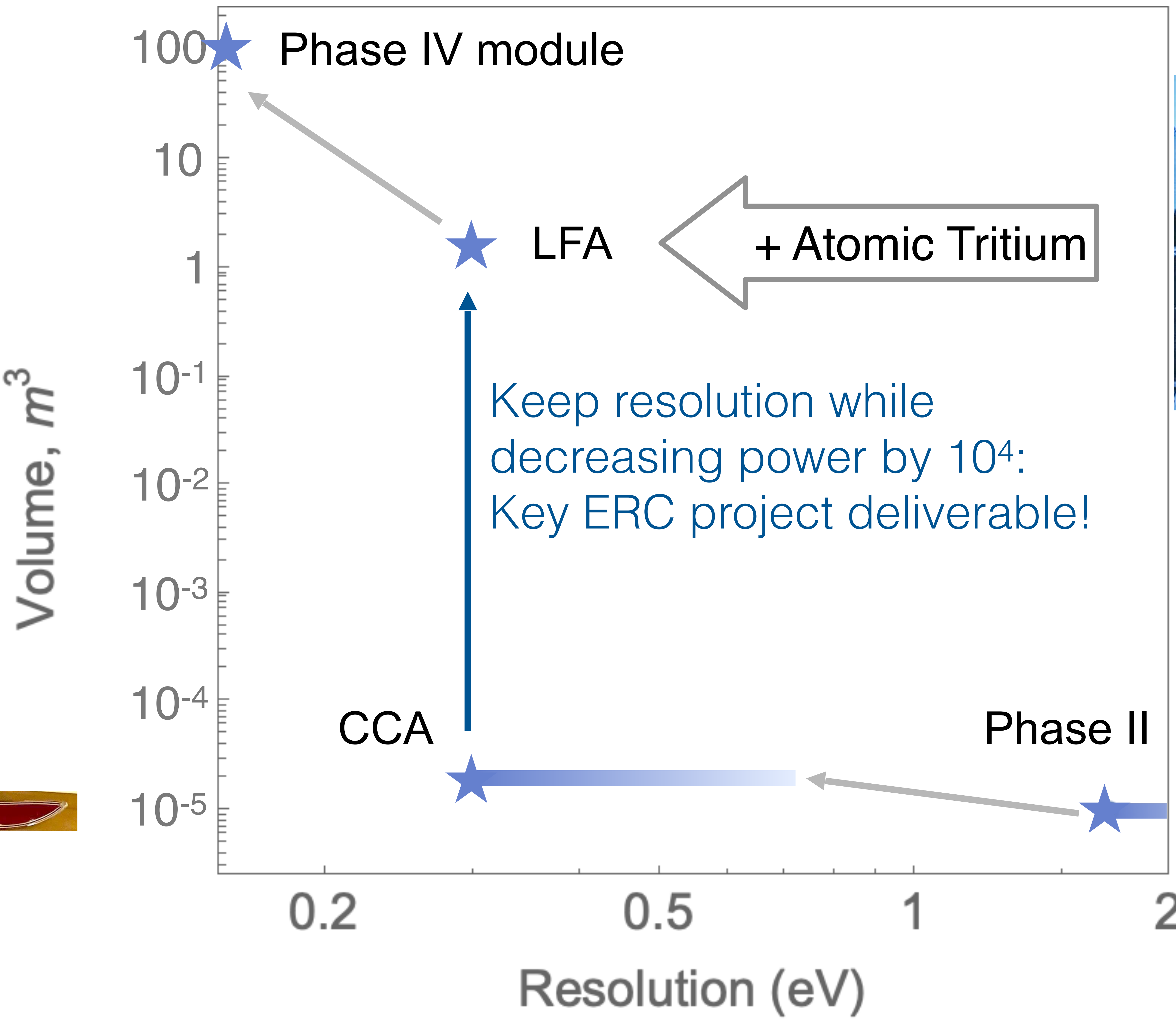
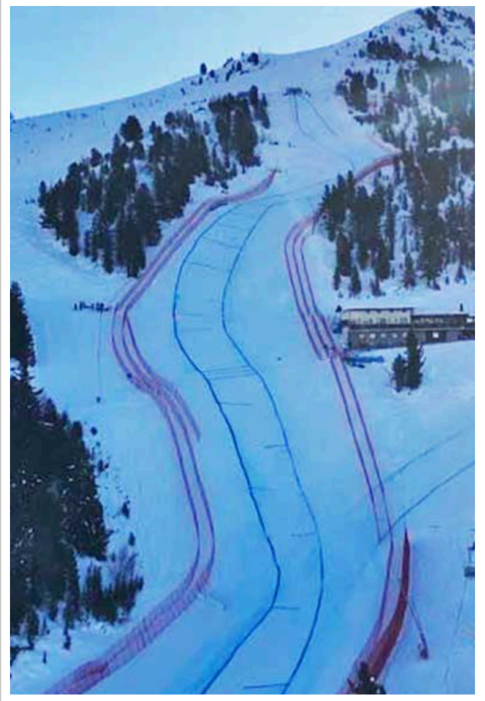




Phase IV


2255 m.
START Praimont
1740 m. Carcentina
1550 m. M. S.Pietro
1467 m. La Konta
1245 m.
FINISH Bormio
BORMIO 3000
BORMIO 2000
CIUK
S. PIETRO
BORMIO

Phase IV concept

Source gas density

Uncertainties on response function

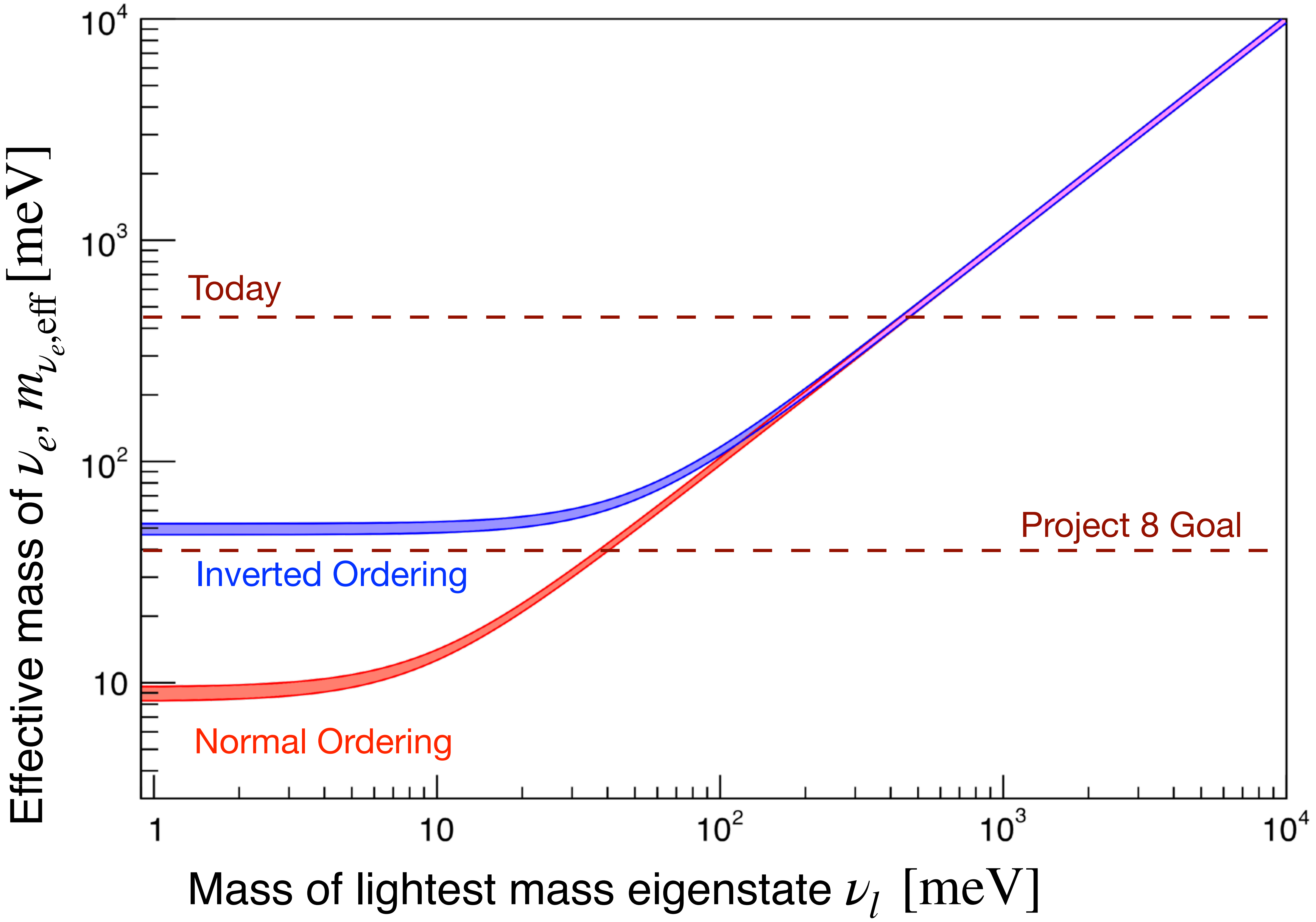
$$\sigma_{m_\beta^2} = 4\sqrt{\frac{1}{(6\,C_T\,V_{\text{eff}}\,n\,t)^2}\left[C_T\,V_{\text{eff}}\,n\,t\,\Delta E + \frac{b\,t}{\Delta E}\right] + \sum_i \sigma_i^2(n)\cdot\delta\sigma_i^2}$$

Effective volume (volume × efficiency)

Runtime

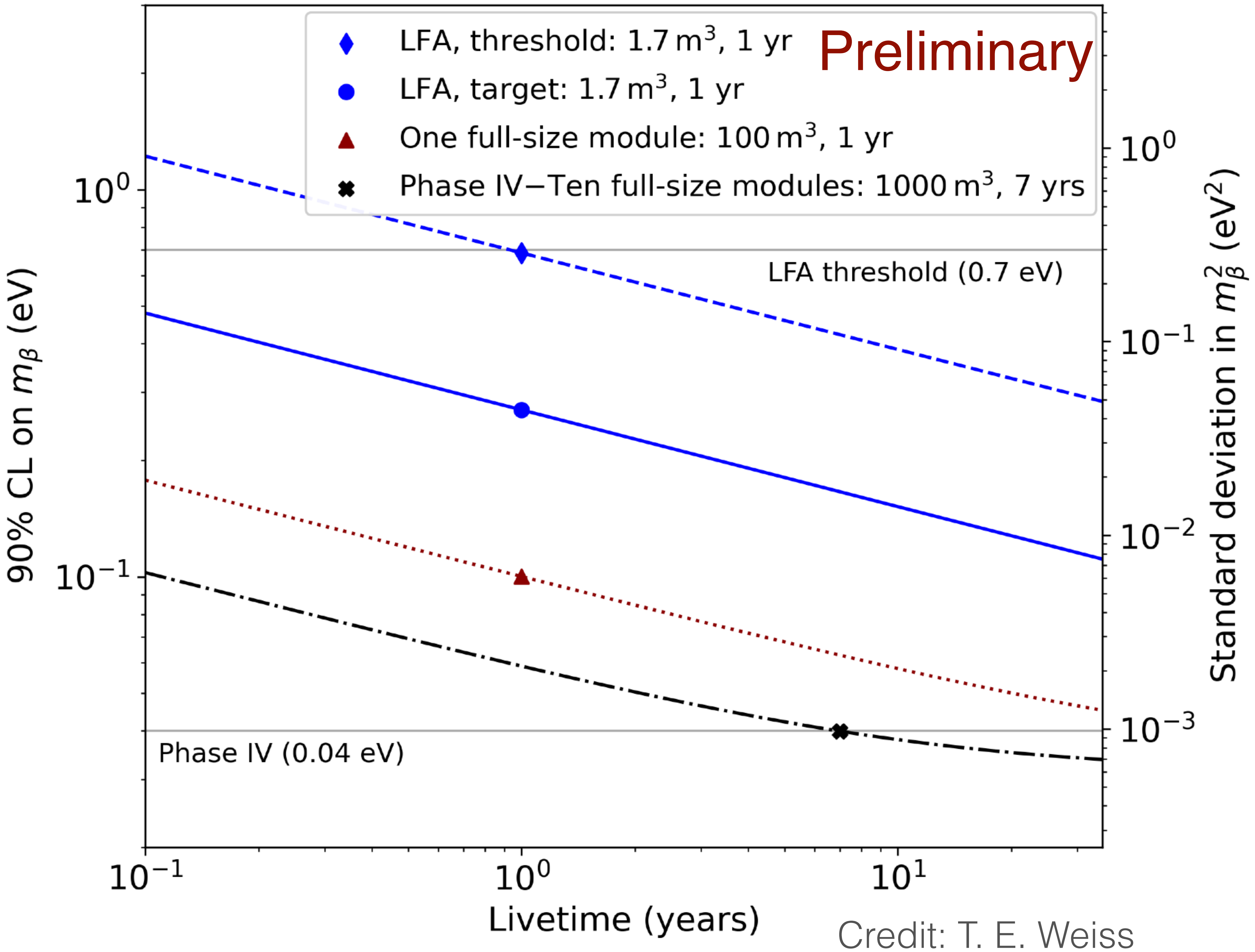
Background

Response function stdevs. (resolution)

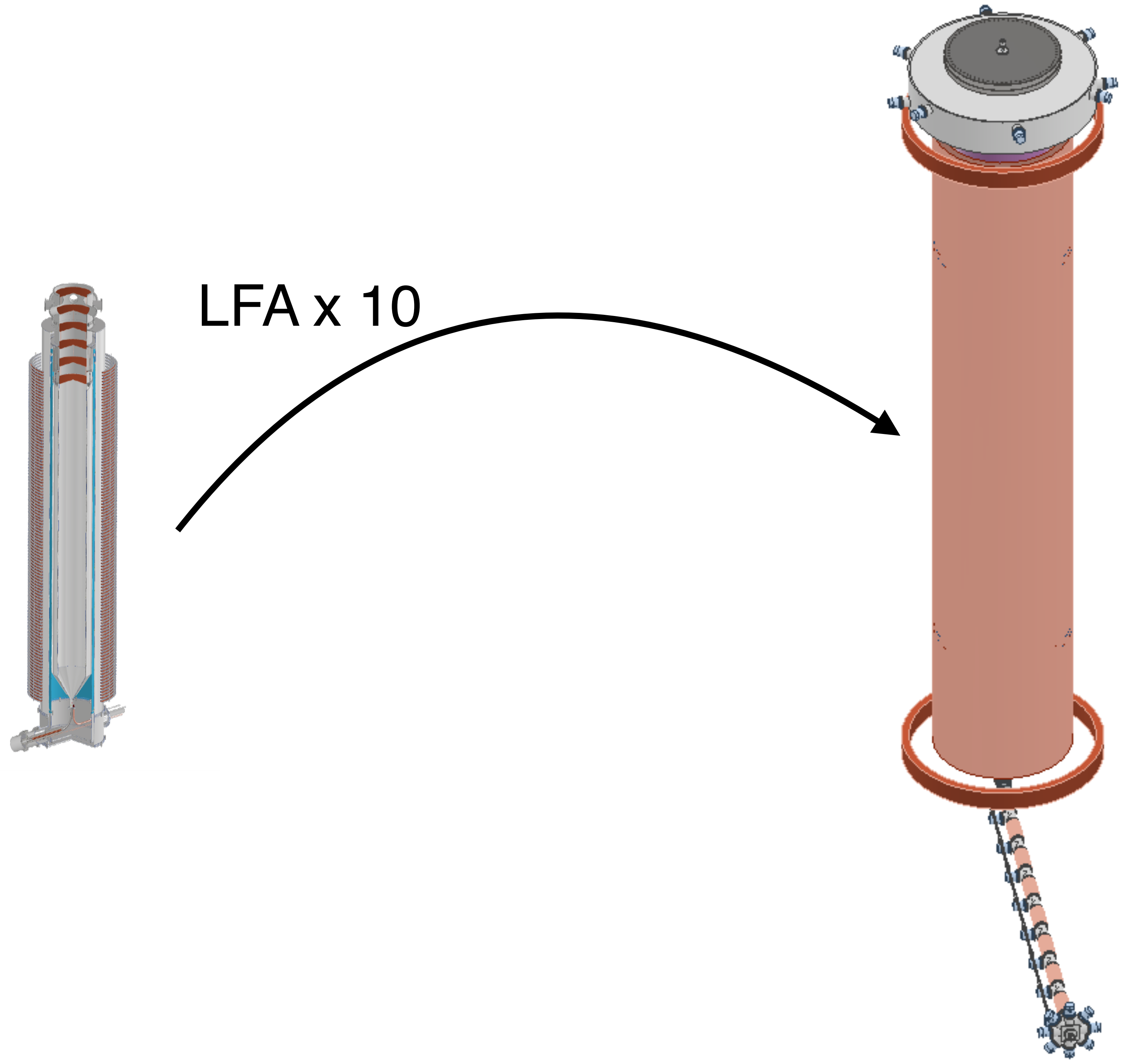


Phase IV concept

- Even bigger: $f = 150\,\mathrm{MHz}$, $V \sim 100\,\mathrm{m}^3$



Credit: T. E. Weiss



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Phase IV concept

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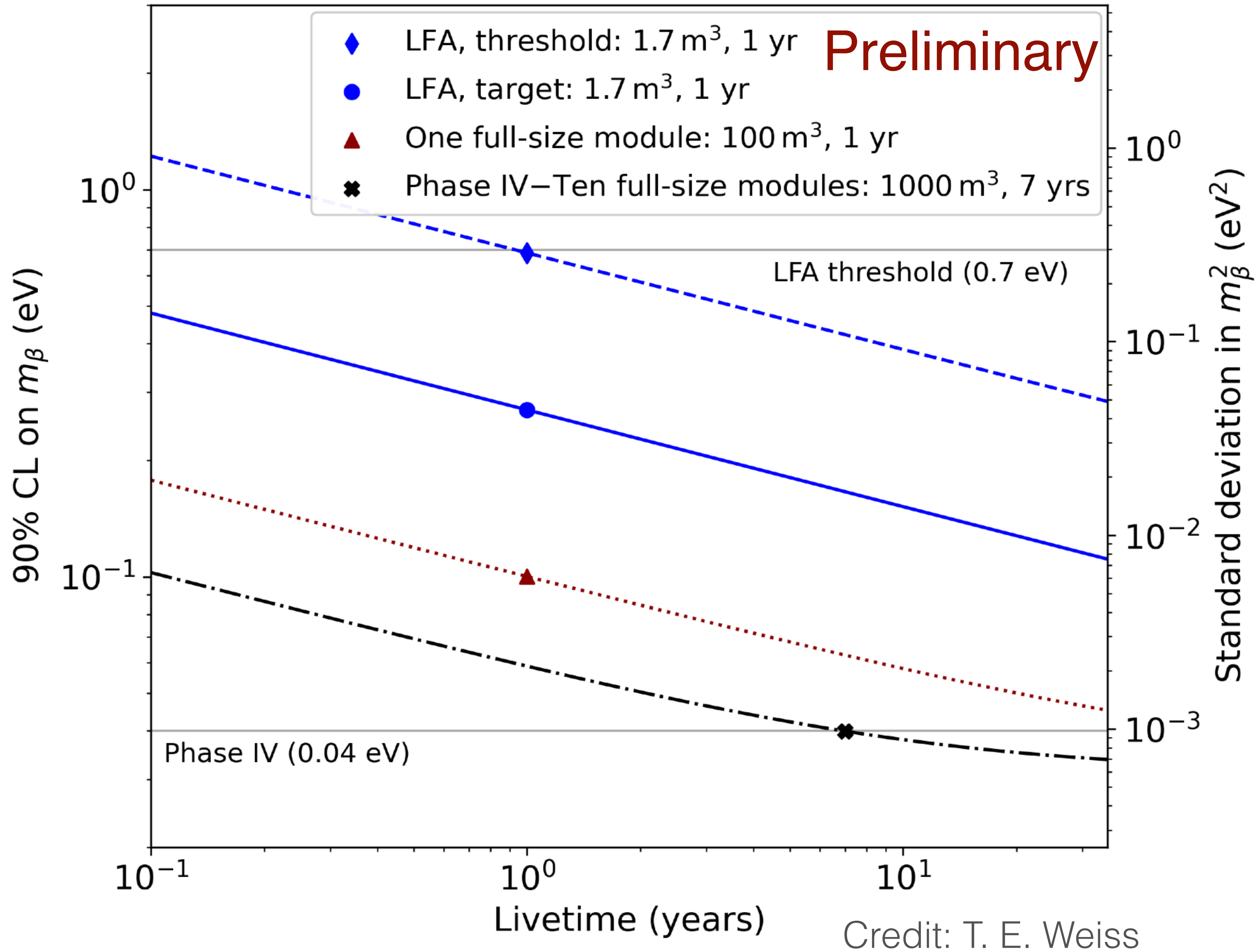
- Even bigger: $f = 150\,\mathrm{MHz}, V \sim 100\,\mathrm{m}^3$
- 10 detector modules
- $40\mathrm{meV}$ sensitivity



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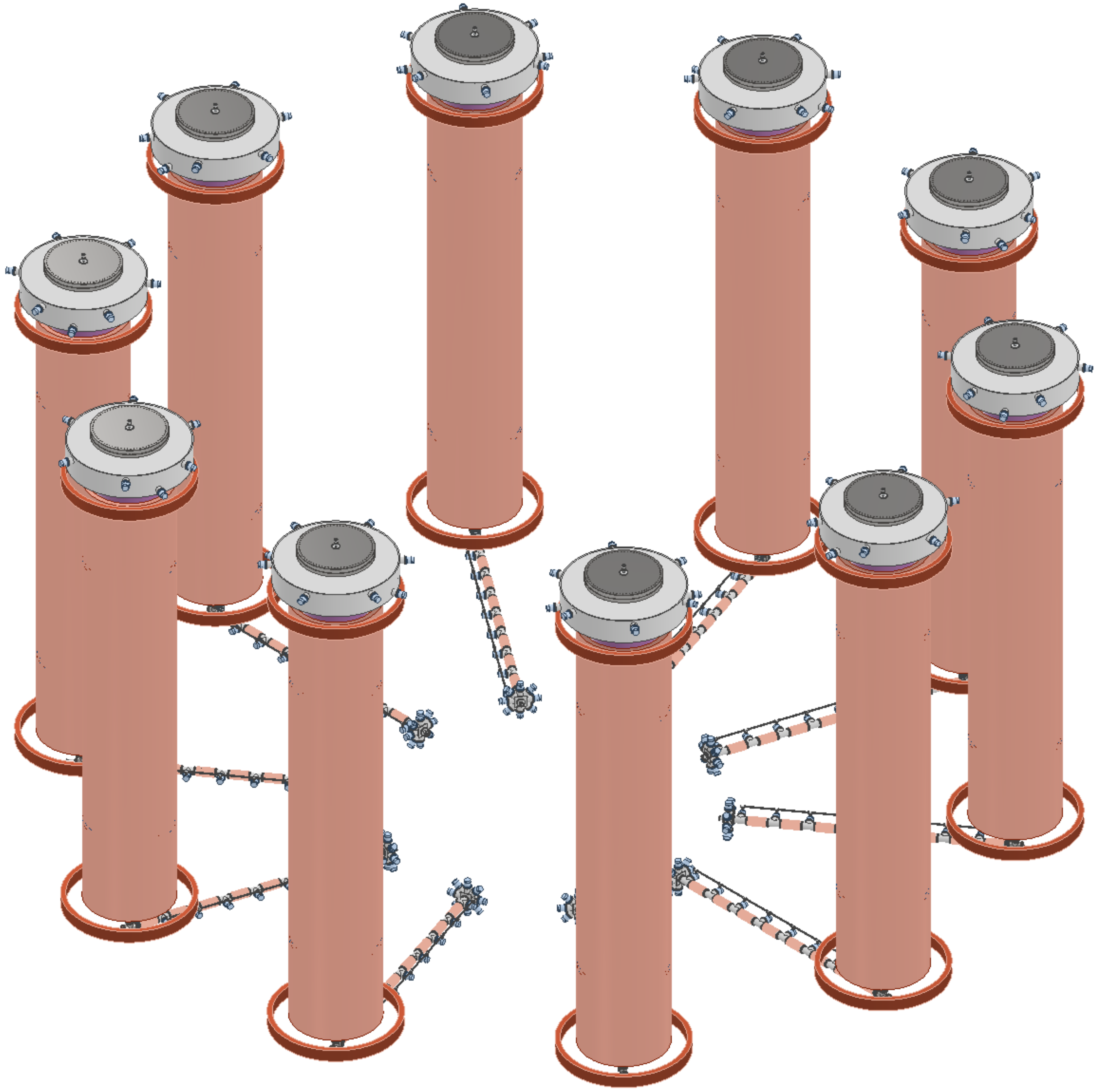
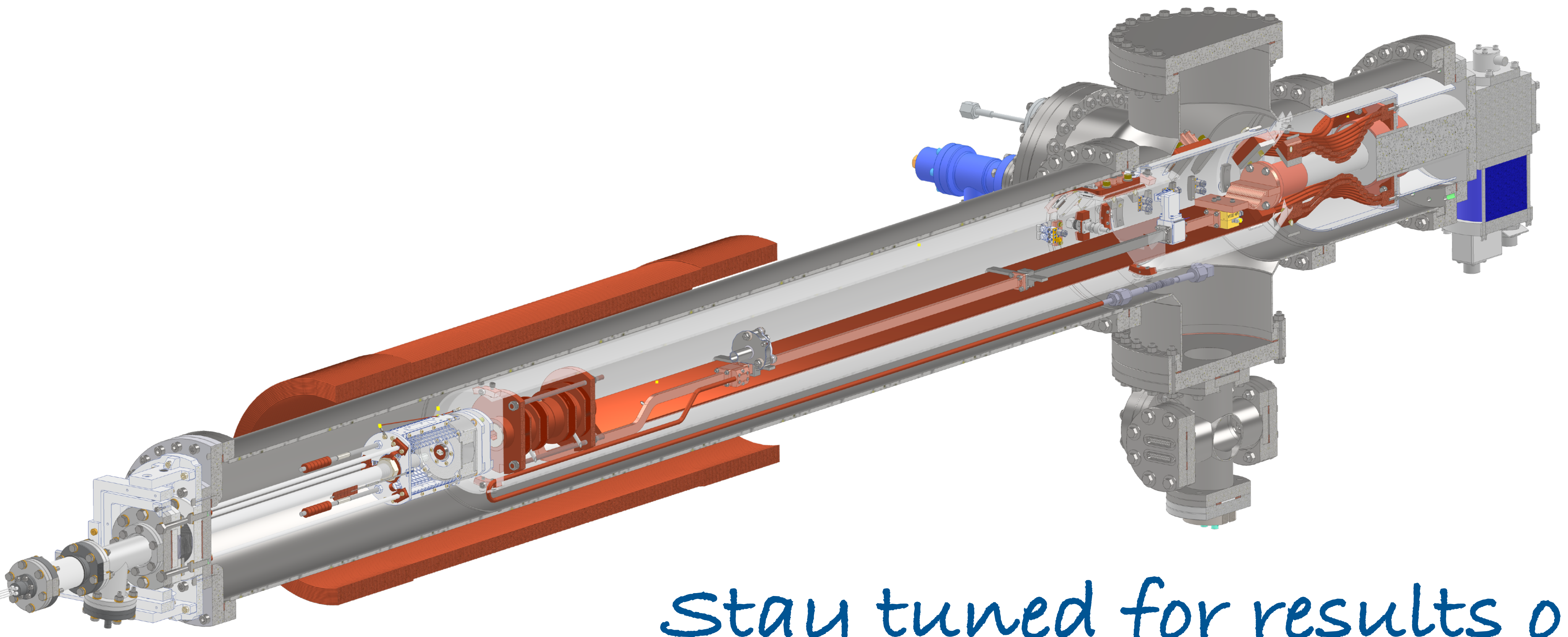
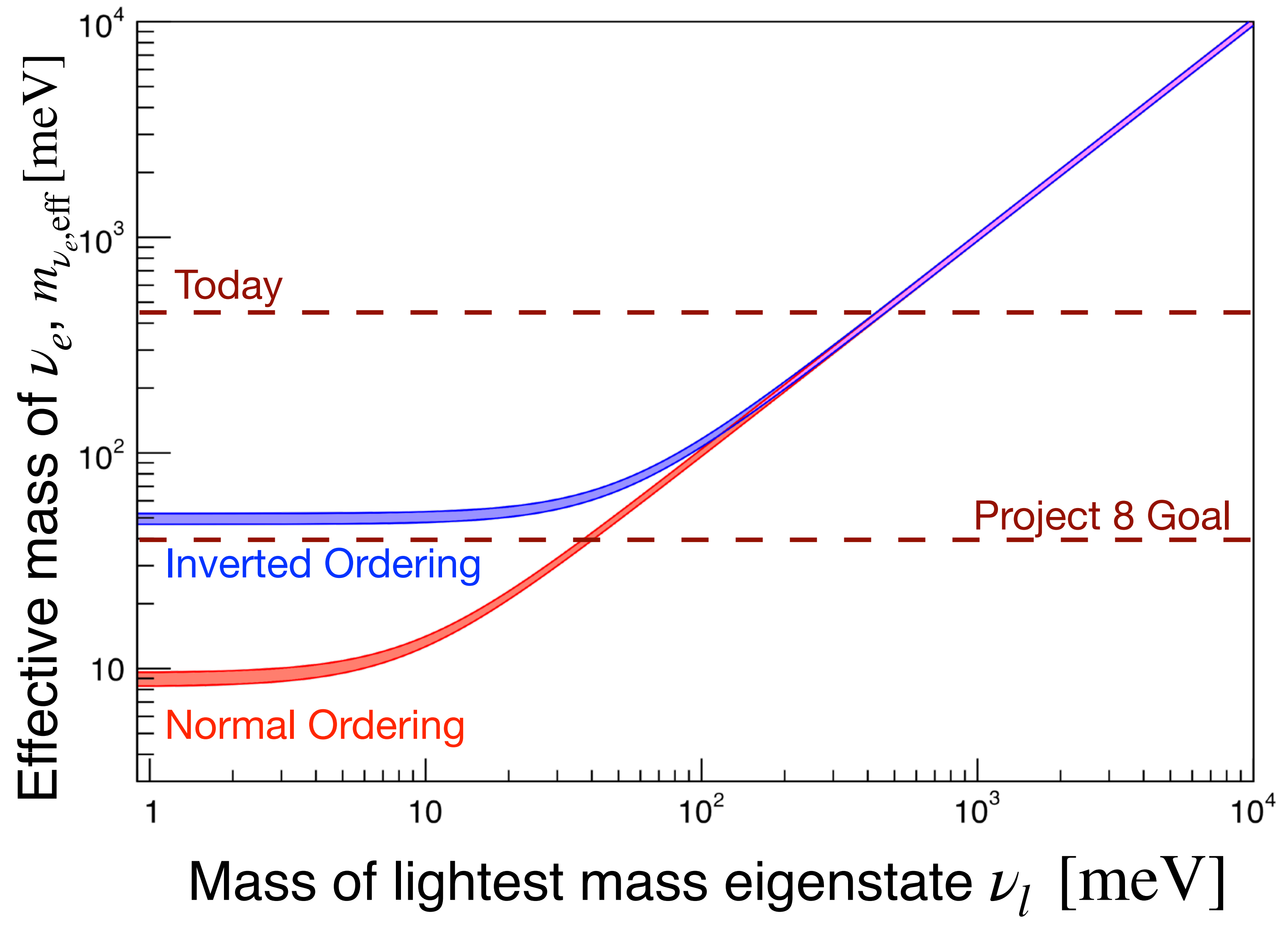


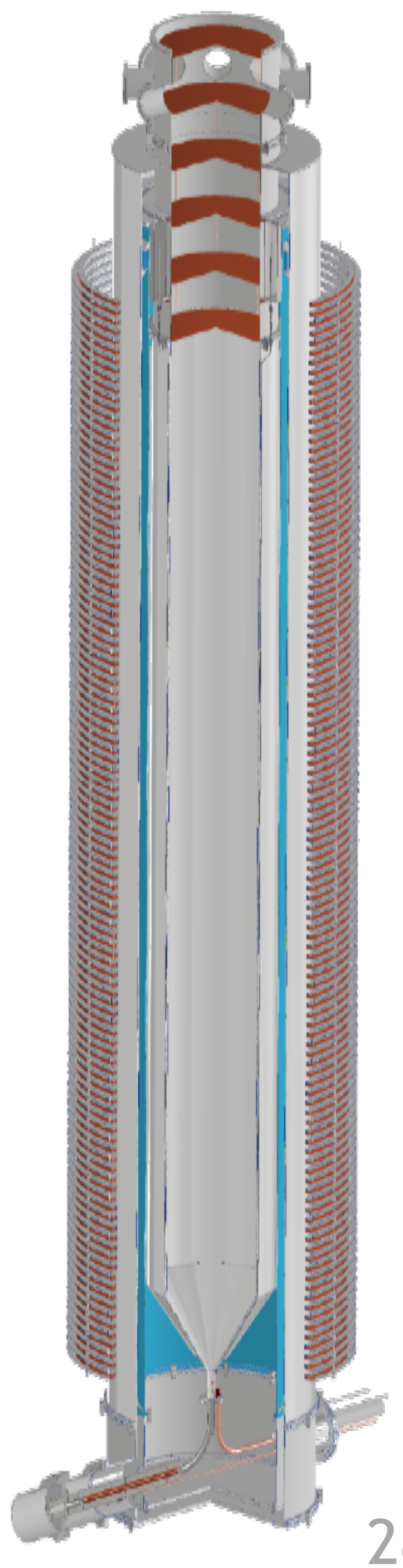
Take-Home Message

- Neutrino mass remains one of the outstanding unknowns in both particle physics and cosmology
- Next neutrino mass experiment to have $40\mathrm{meV}$ sensitivity to $m_{\nu_e,\mathrm{eff}}$
- Project 8 is developing key technologies:
  - CRES for high-precision, differential electron spectroscopy
  - Atomic tritium for higher statistics, lower systematic uncertainties
  - Resonant cavities as scalable detectors compatible with atomic tritium
- Many exciting results along the way: competitive mass limit with the LFA!



Stay tuned for results on cavity CRES, atomic tritium, and more!





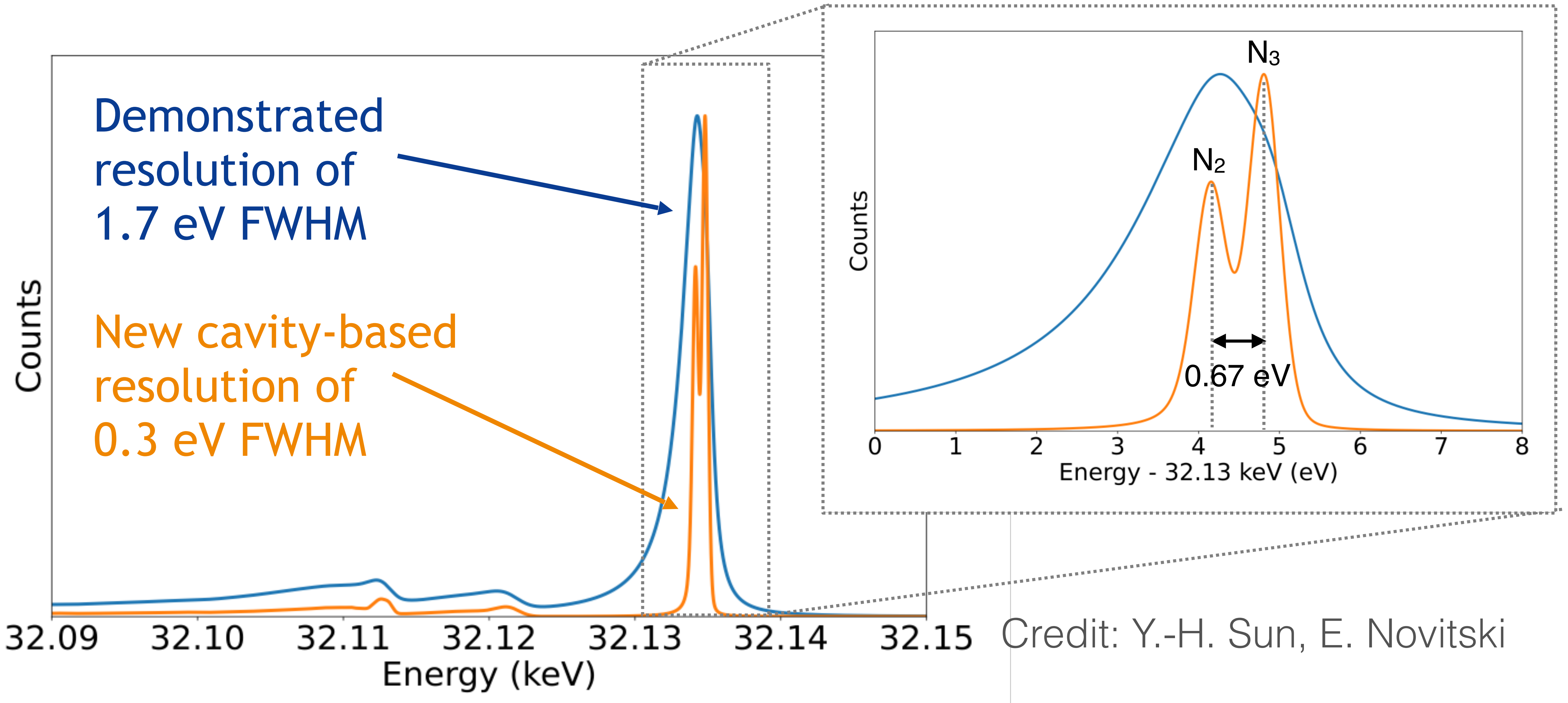
Thank you!

Thank you!

Goals of the CCA

Technology goals:

- Demonstrate CRES in cavities, allowing for orders-of-magnitude increase in detector volume
- Improve energy resolution to 0.3 eV
- Demonstrate new electron gun calibration source



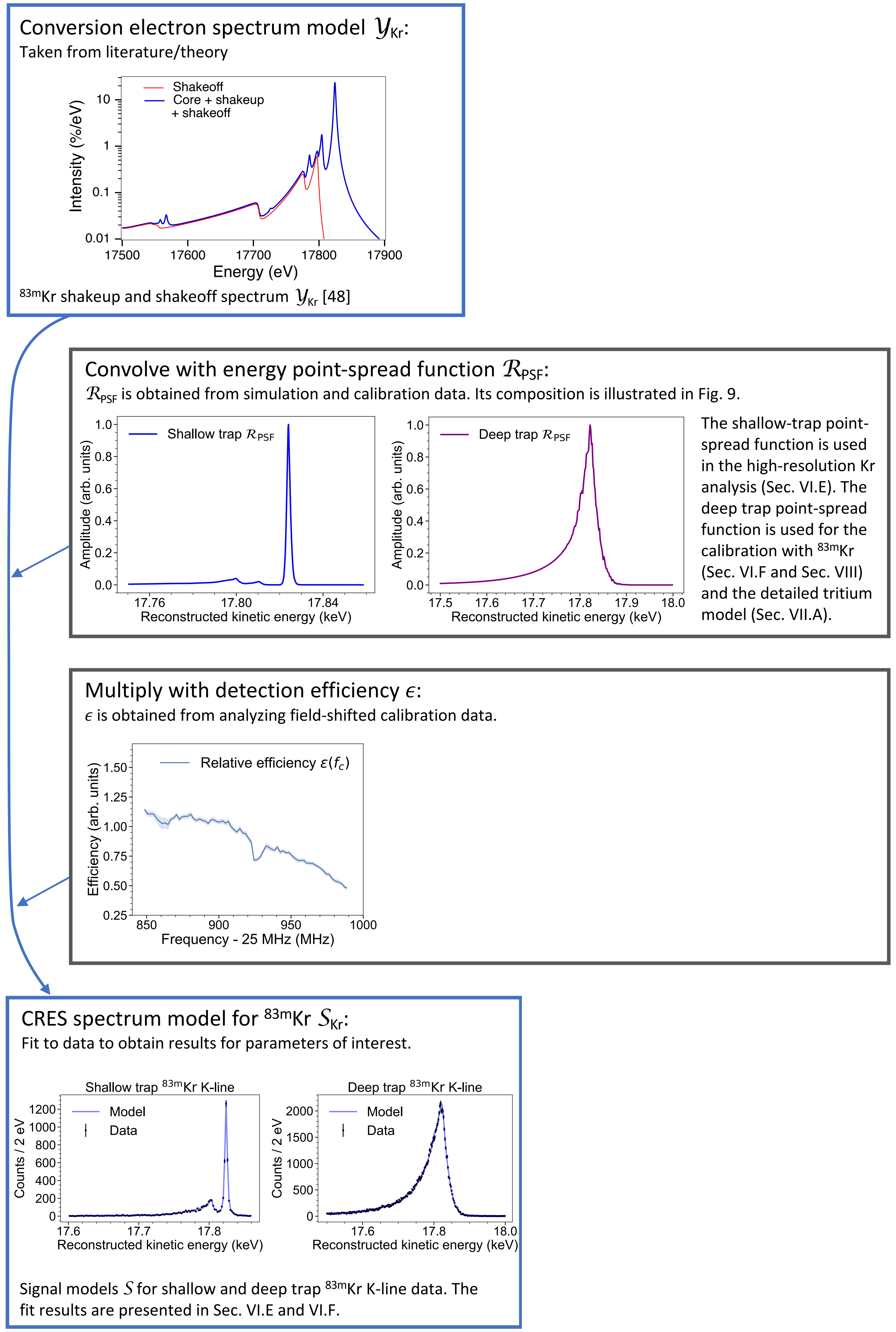
Credit: Y.-H. Sun, E. Novitski

Physics goals:

- Most precise measurement of ^{83m}Kr conversion electrons
  - K-, L-, M-, N- lines
  - Shakeup and shakeoff

Analysis Overview: Krypton

- Spectrum model
  - From literature
  - Underlying physics
- Energy point-spread function
  - From simulation and calibration data
- Detection efficiency
  - From field-shifted data
  - Efficiency depends on frequency and energy
- CRES spectrum model for ^{83m}Kr
  - In shallow and deep trap
  - Fit to data



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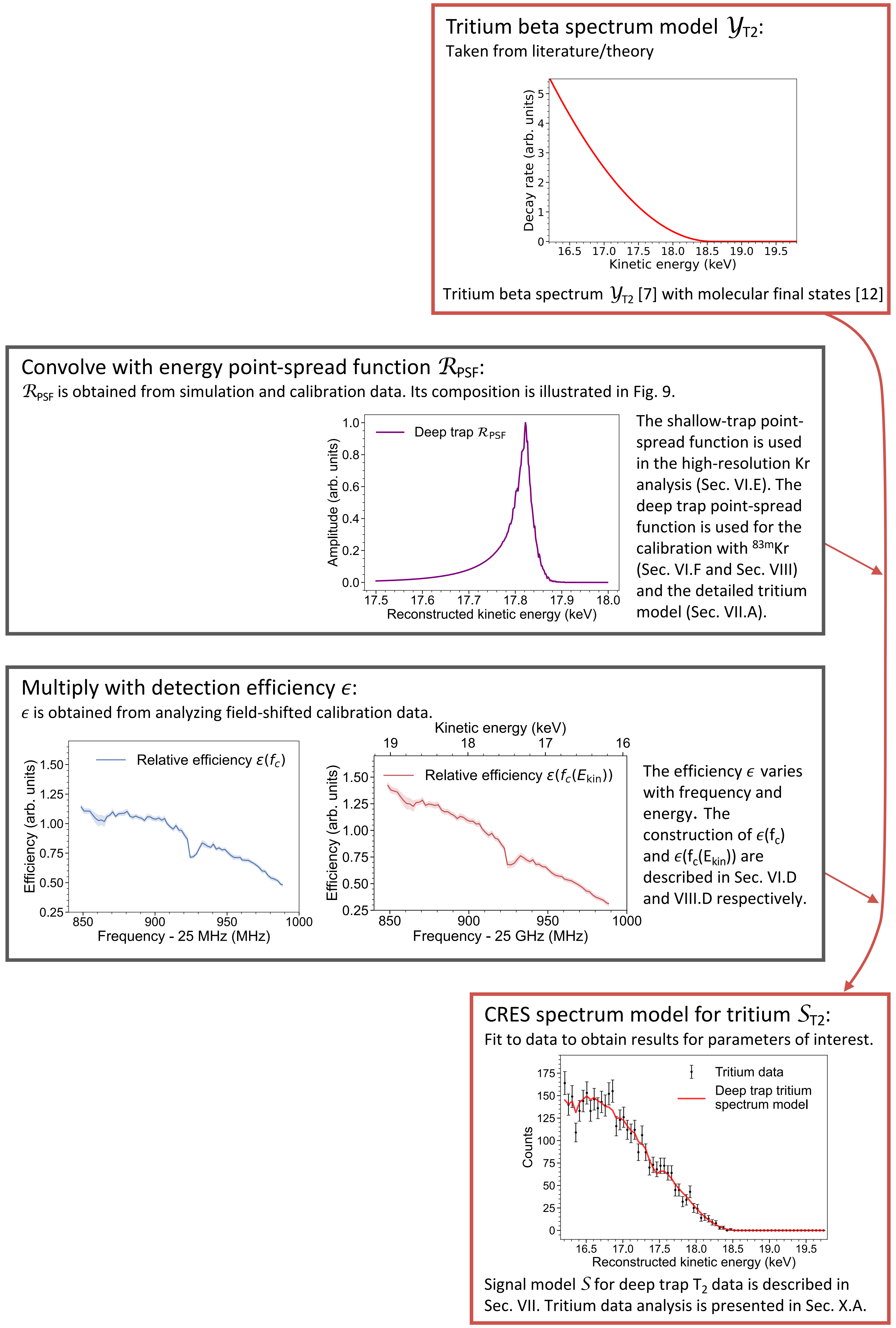
Analysis Overview: Tritium

- Spectrum model
  - From literature
  - Underlying physics
- Energy point-spread function
  - From simulation and calibration data
- Detection efficiency
  - From field-shifted data
  - Efficiency depends on frequency and energy
- CRES spectrum model for tritium
  - Fit to data
  - Extract endpoint, neutrino mass upper limit, background rate



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