# Making a more precise neutrino mass measurement, with Project 8

## Colloquium @ Paul Scherrer Institut
## 30 Oct 2025

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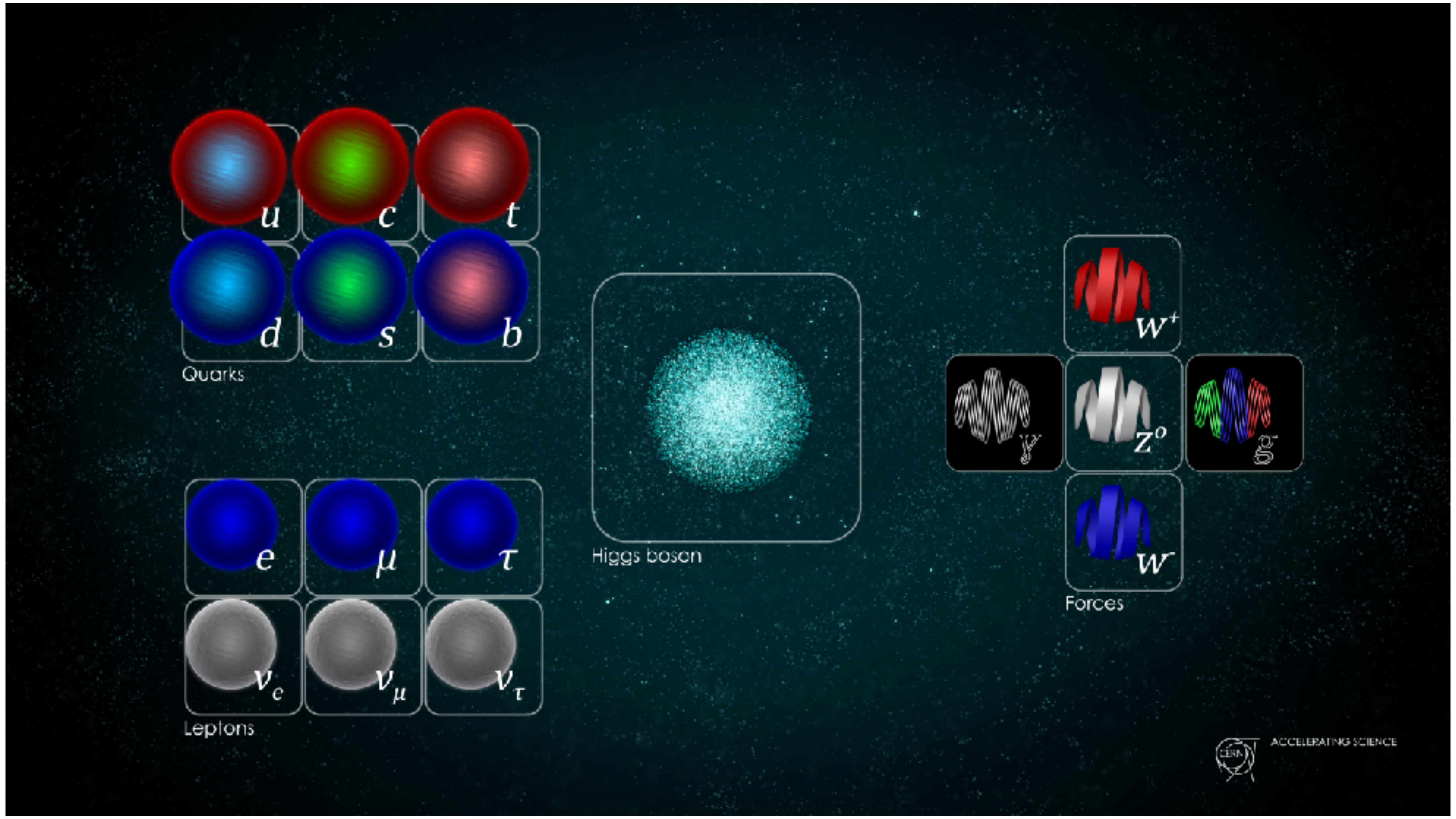
Johannes Gutenberg University Mainz (Germany)

# Outline

- A primer on neutrinos
- Neutrino mass measurement methods
- The Project 8 experiment
    - Overview
    - R&D progress towards full-scale experiment
        - *Special focus:* development efforts at Mainz
- Summary

# Neutrino primer

- Neutrinos are Standard Model particles




Source: CERN

# Neutrino primer

- Neutrinos are Standard Model particles
- Interesting properties:
    1. Oscillation

PMNS mixing matrix

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

Flavor eigenstate $|\nu_\ell>$

$$n \rightarrow p + e^- + \bar{\nu}_e$$

Mass eigenstate $|\nu_i>$

# Neutrino primer

- Neutrinos are Standard Model particles
- Interesting properties:
    1. Oscillation
    2. Mass ordering

Eigenstate $\nu_3$,

Eigenvalue $m_3$

Source: JUNO coll/JGU Mainz

# Neutrino primer

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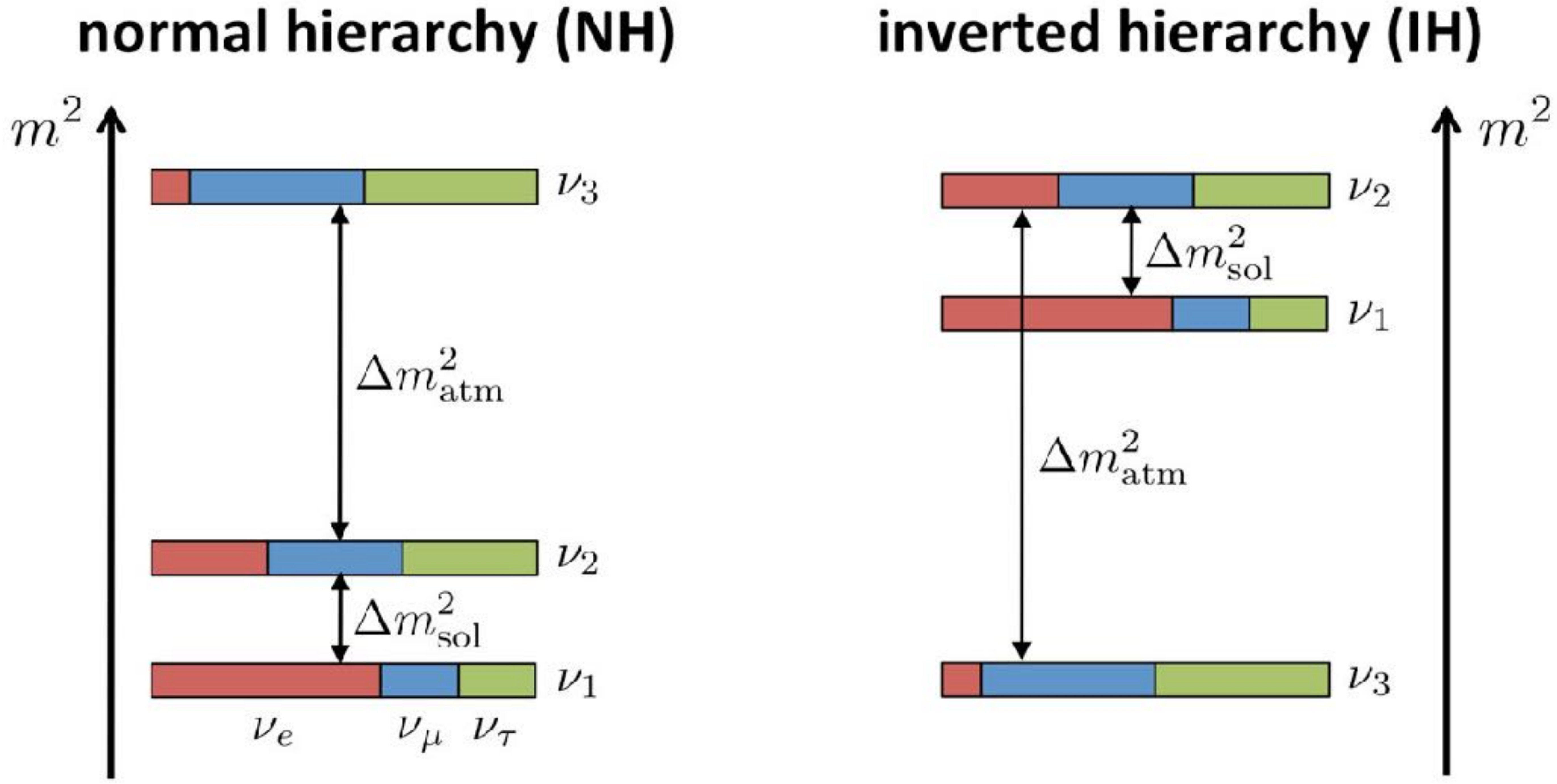
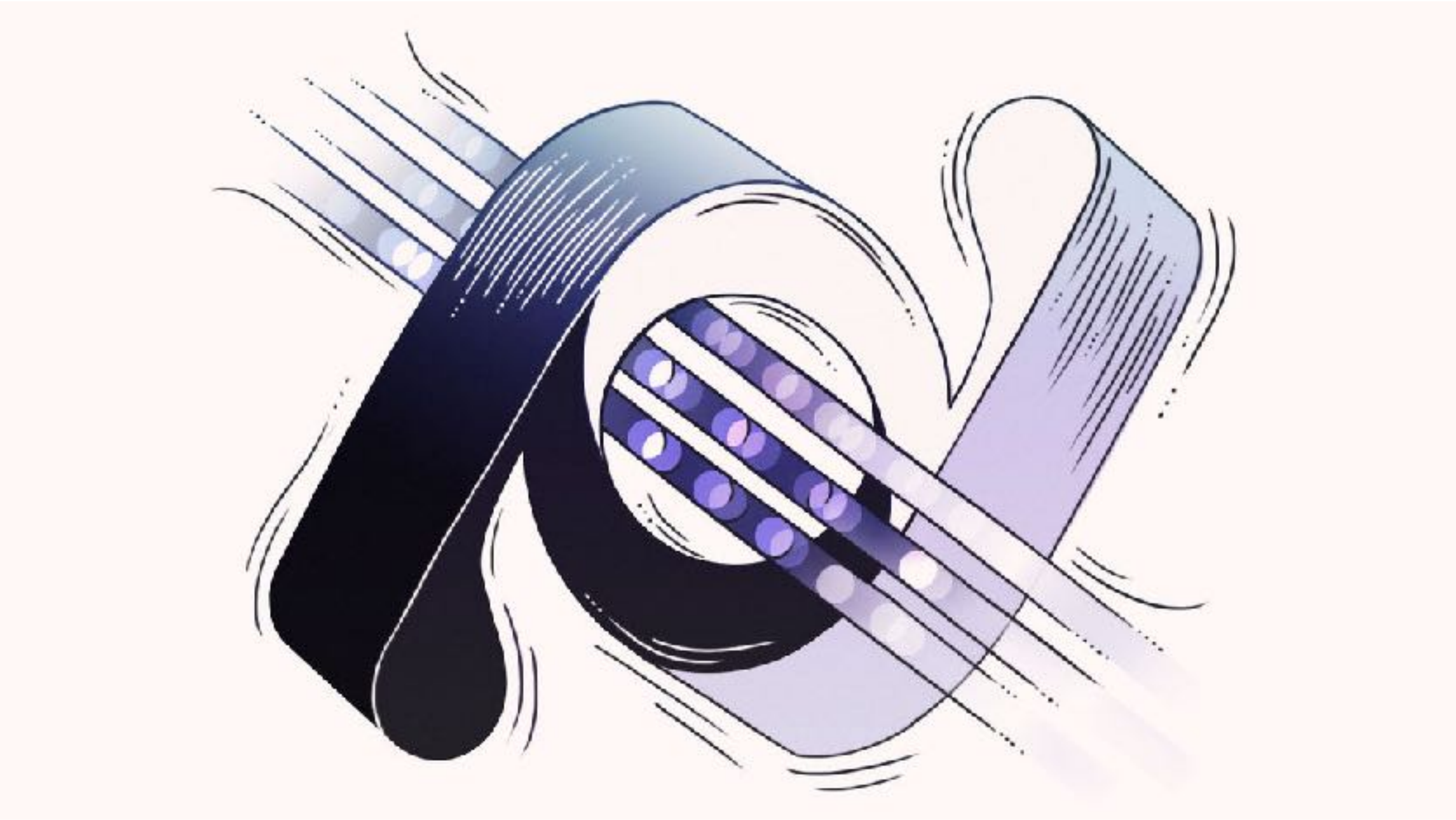



Source: JUNO coll/JGU Mainz

# Neutrino primer

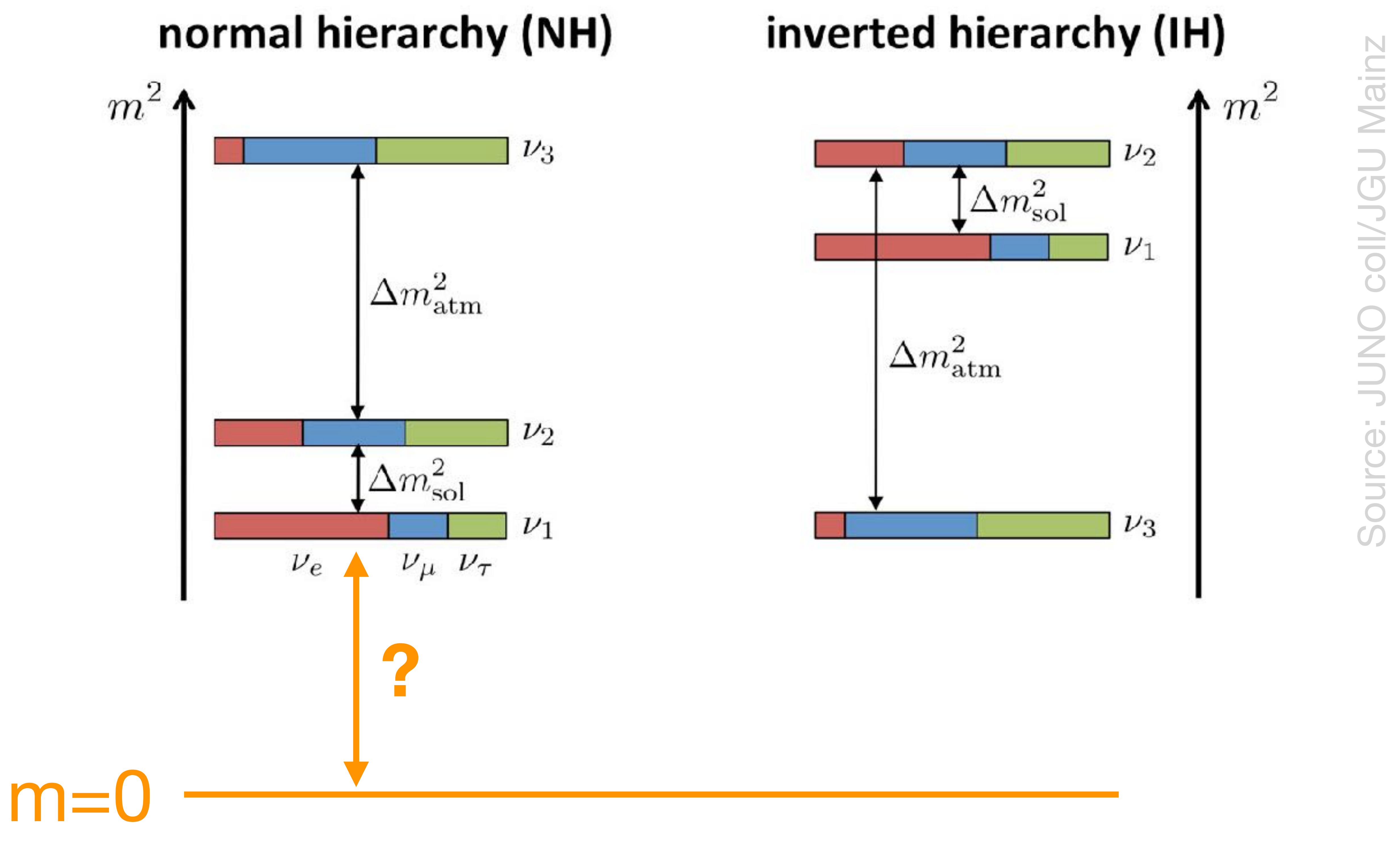
- Neutrinos are Standard Model particles
- Interesting properties:
    1. Oscillation
    2. Mass ordering
    3. Lepton number conservation



Source: Symmetry Magazine

# Neutrino primer

- Neutrinos are Standard Model particles
- Interesting properties:
    1. Oscillation
    2. Mass ordering
    3. Lepton number conservation
    4. Absolute mass scale



# Neutrino primer

- Neutrinos are Standard Model particles
- Interesting properties:
    1. Oscillation
    2. Mass ordering
    3. Lepton number conservation
    4. Absolute mass scale
    5. … steriles? Interaction cross-section? Mass mechanism? Influence on large-scale structure of the universe? New astronomy tool? Etc…

# Neutrino mass measurement methods

1. Cosmic microwave background
2. Supernove time-of-flight
3. Neutrino-less double beta decay
4. Single beta decay

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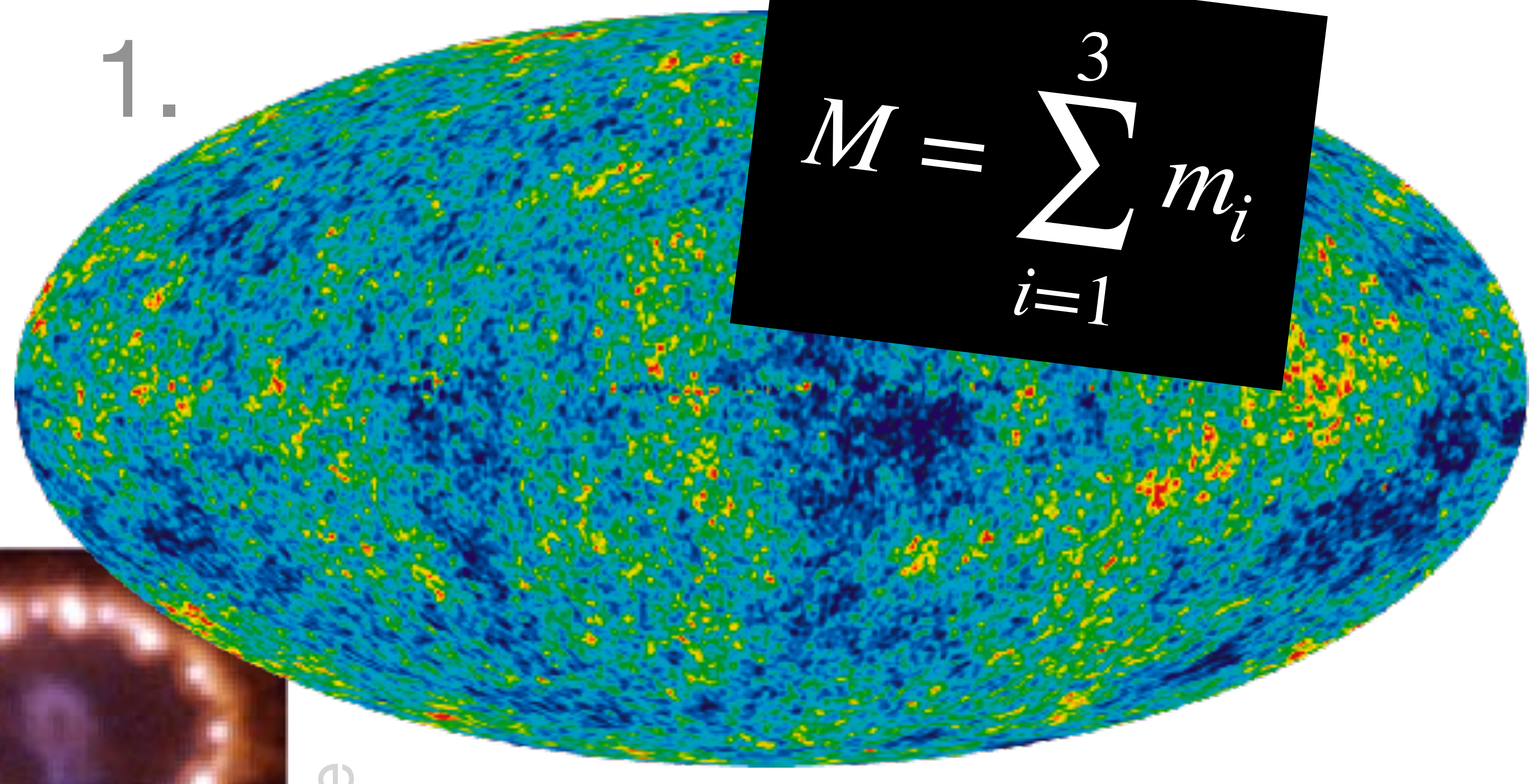
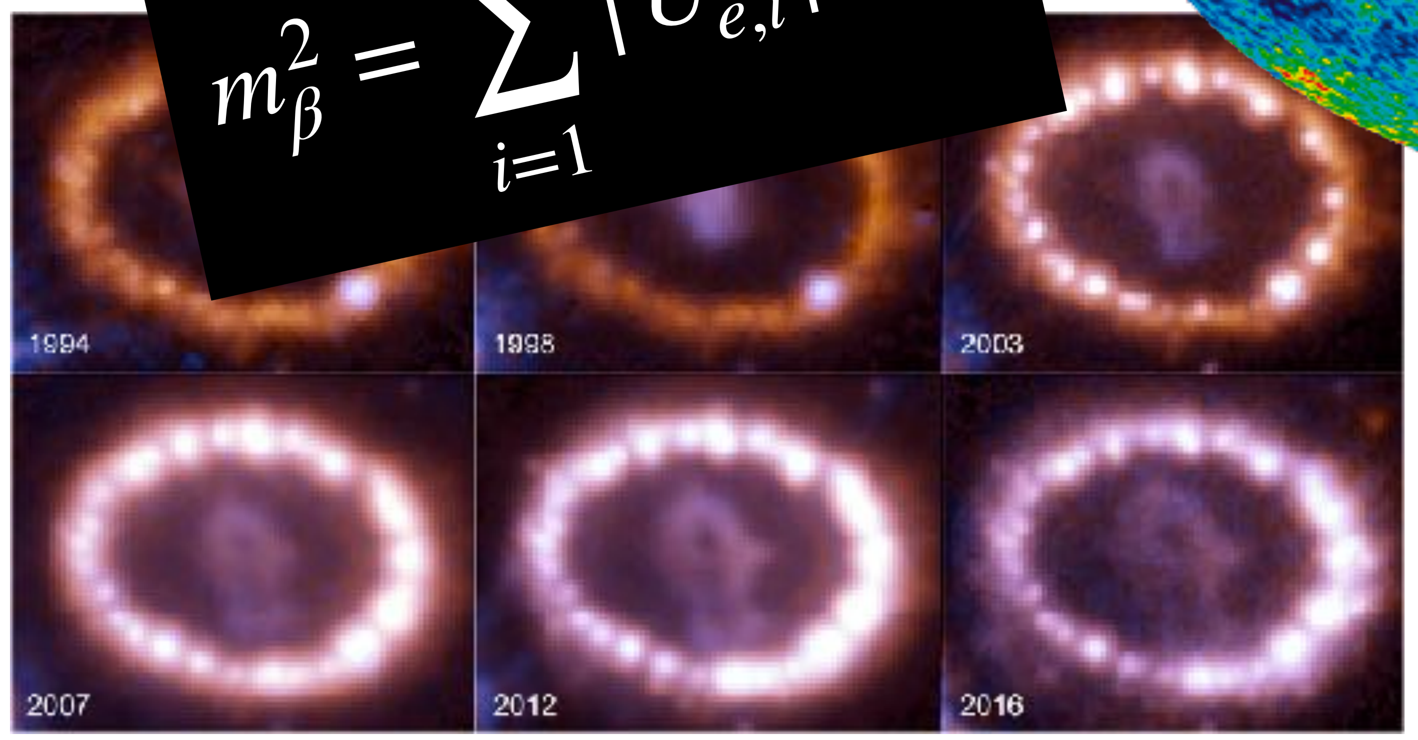
1.



$$M = \sum_{i=1}^{3} m_i$$

Source: WMAP2012

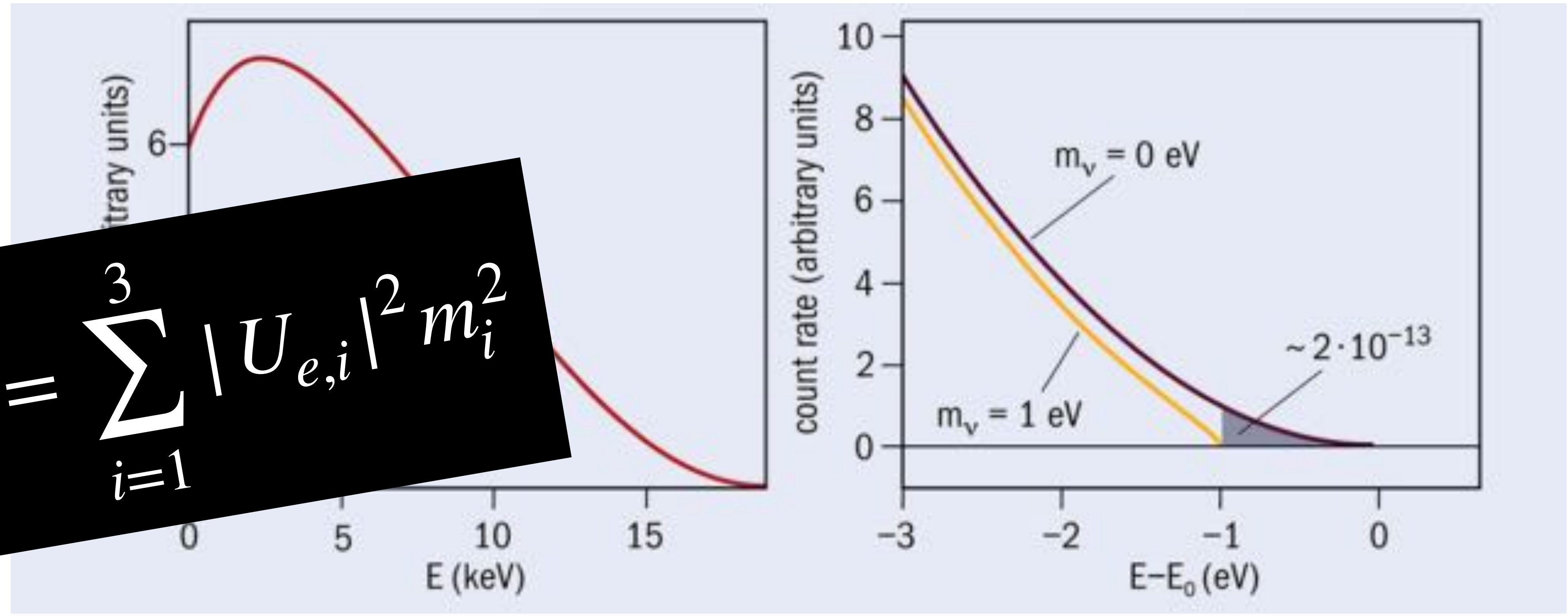
2.




$$m_\beta^2 = \sum_{i=1}^{3} |U_{e,i}|^2 m_i^2$$

Source: Hubble

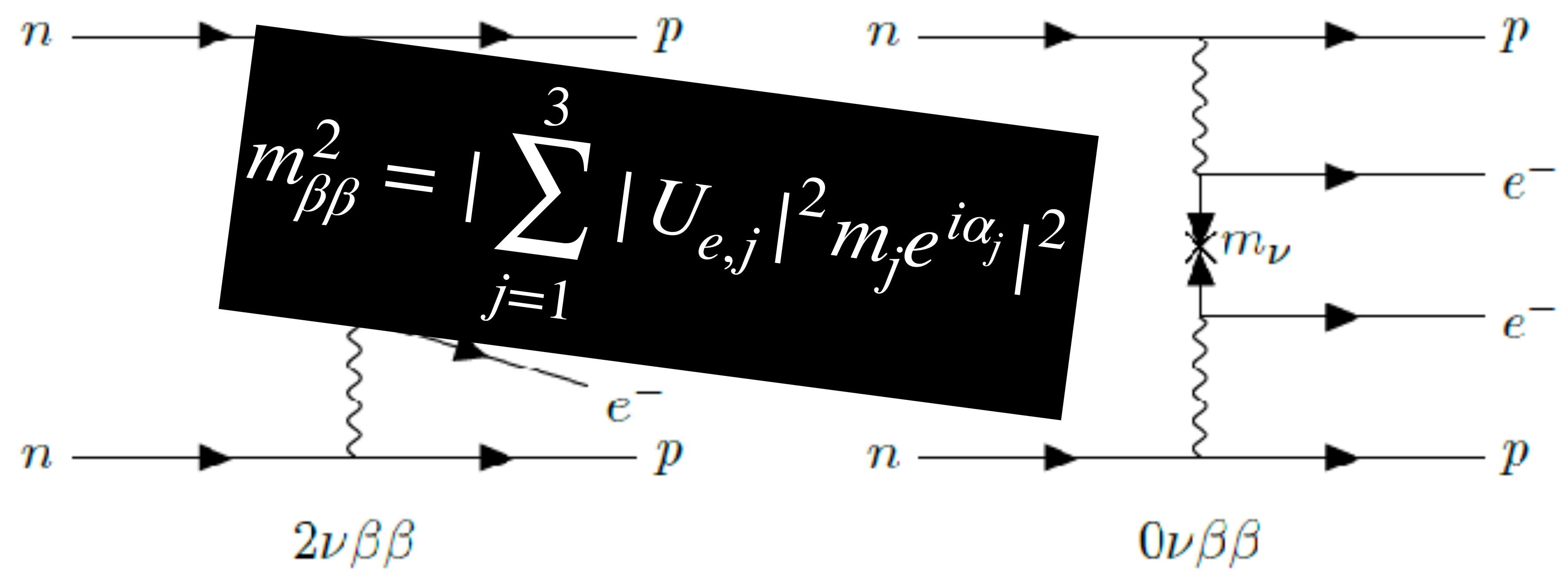
4.




$$m_\beta^2 = \sum_{i=1}^{3} |U_{e,i}|^2 m_i^2$$

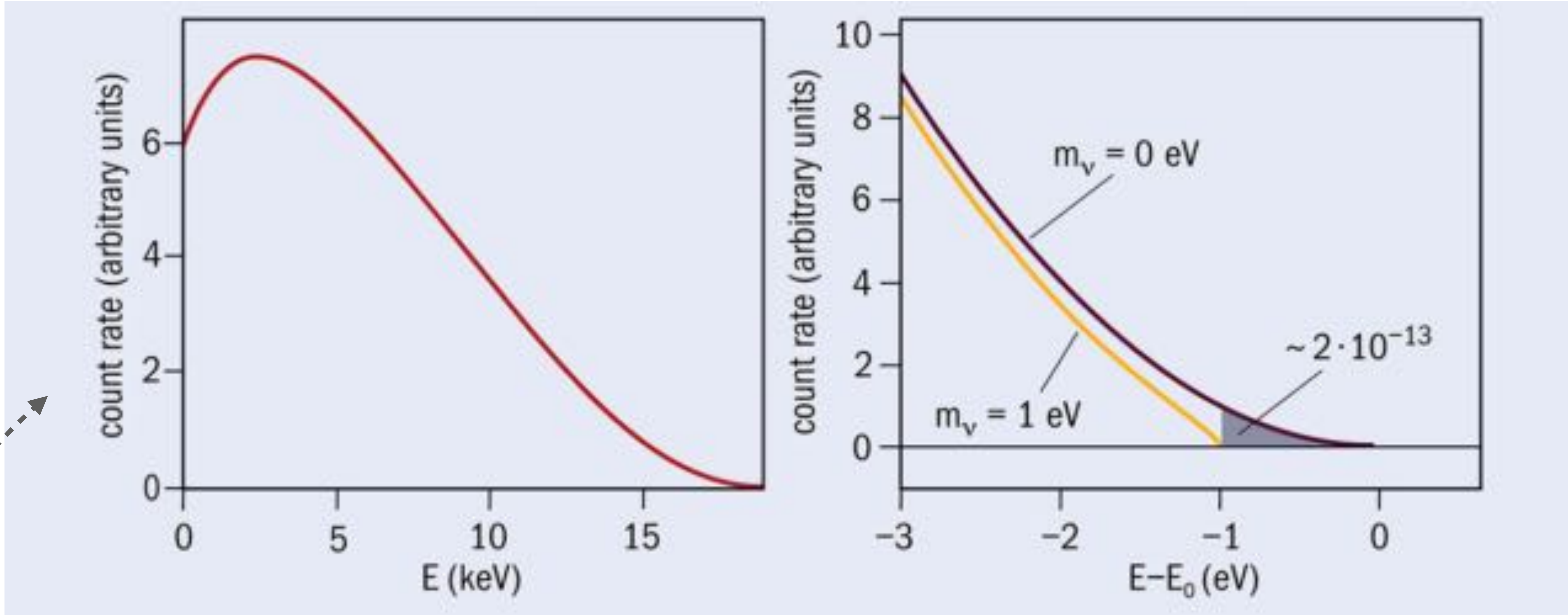
Source: CERN

3.




$$m_{\beta\beta}^2 = |\sum_{j=1}^{3} |U_{e,j}|^2 m_j e^{i\alpha_j}|^2$$

# Neutrino mass measurement using Tritium




Credit: CERN

$$^3\text{H} \rightarrow ^3\text{He}^+ + e^- + \bar{\nu}_e$$

$$\frac{d^2N}{dEdt} = \frac{G_F |V_{ud}|^2}{2\pi^3} |\mathscr{M}_{nuc}|^2 F(Z,E) p_e (E + m_e) \sum_f G_f P_f \epsilon_f \sqrt{\epsilon_f^2 - m_\beta^2}\,\Theta(\epsilon_f - m_\beta)$$

# Neutrino mass: current status?

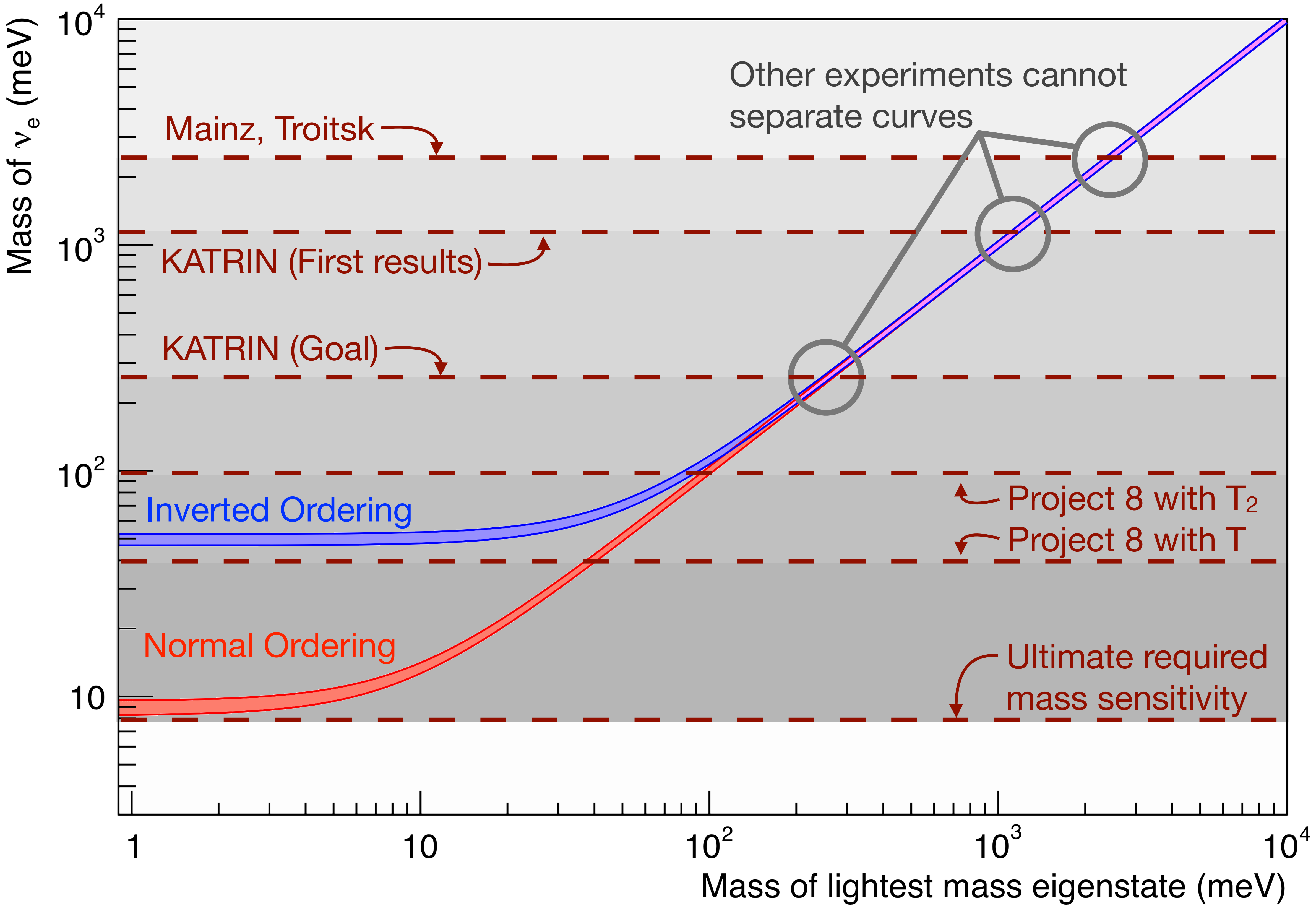
- No measurement *yet* → set upper limit
- Current limits:
  - Cosmology (DESI + Planck): $\sum m_i \leq 0.13$eV ($0.16$eV) for NH (IH)
  - Neutrino-less double beta decay (Kamland-Zen): $m_{\beta\beta} \leq 28 - 122$ meV
  - Single beta decay (KATRIN): $m_\beta \leq 0.45$ eV

Full 1000-day dataset collected, as of last week!

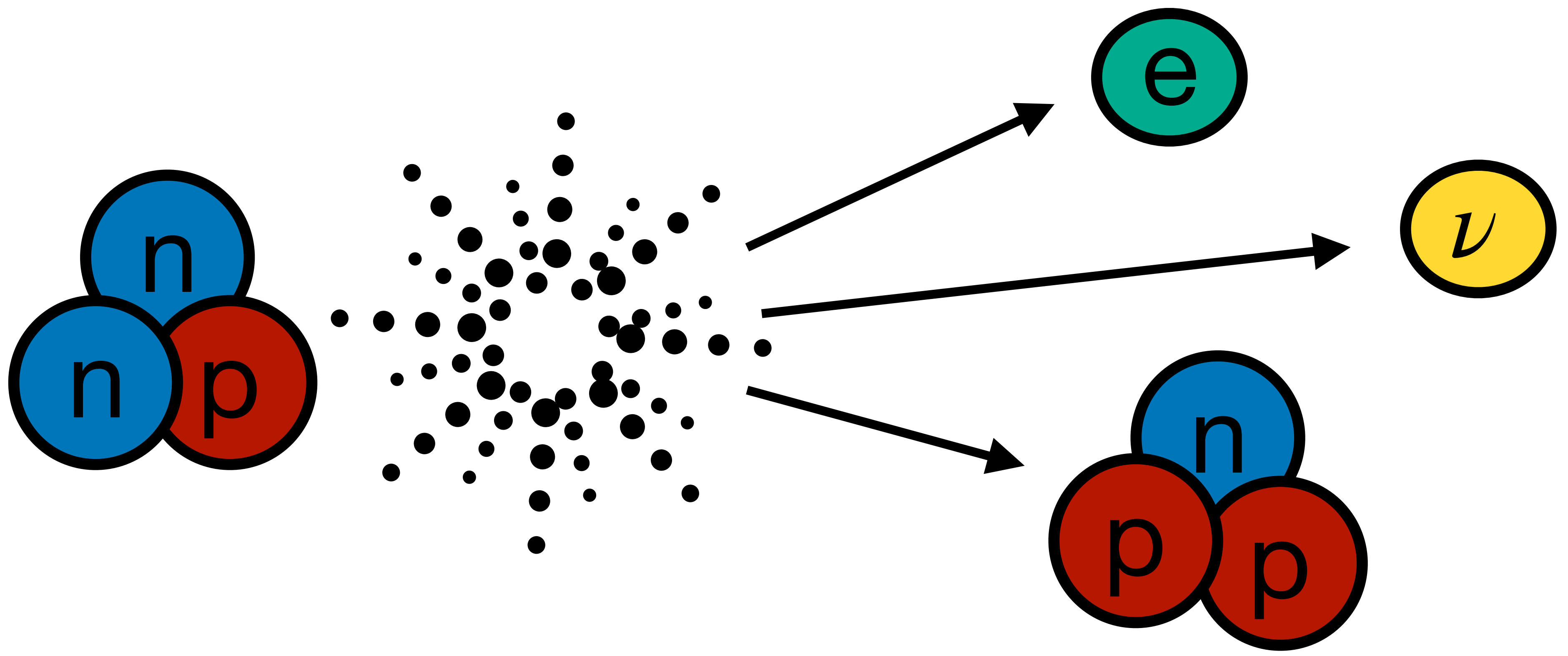
# What if it's not enough?

# Next generation experiment: Project 8

- Goal neutrino mass sensitivity:
  $m_\beta \leq 0.04$ eV @ 90% C.L.
- Differential measurement of electron energies using Cyclotron Radiation Emission Spectroscopy (CRES)
- Beta decay source is atomic tritium
- Webpage:



# Next generation experiment: Project 8

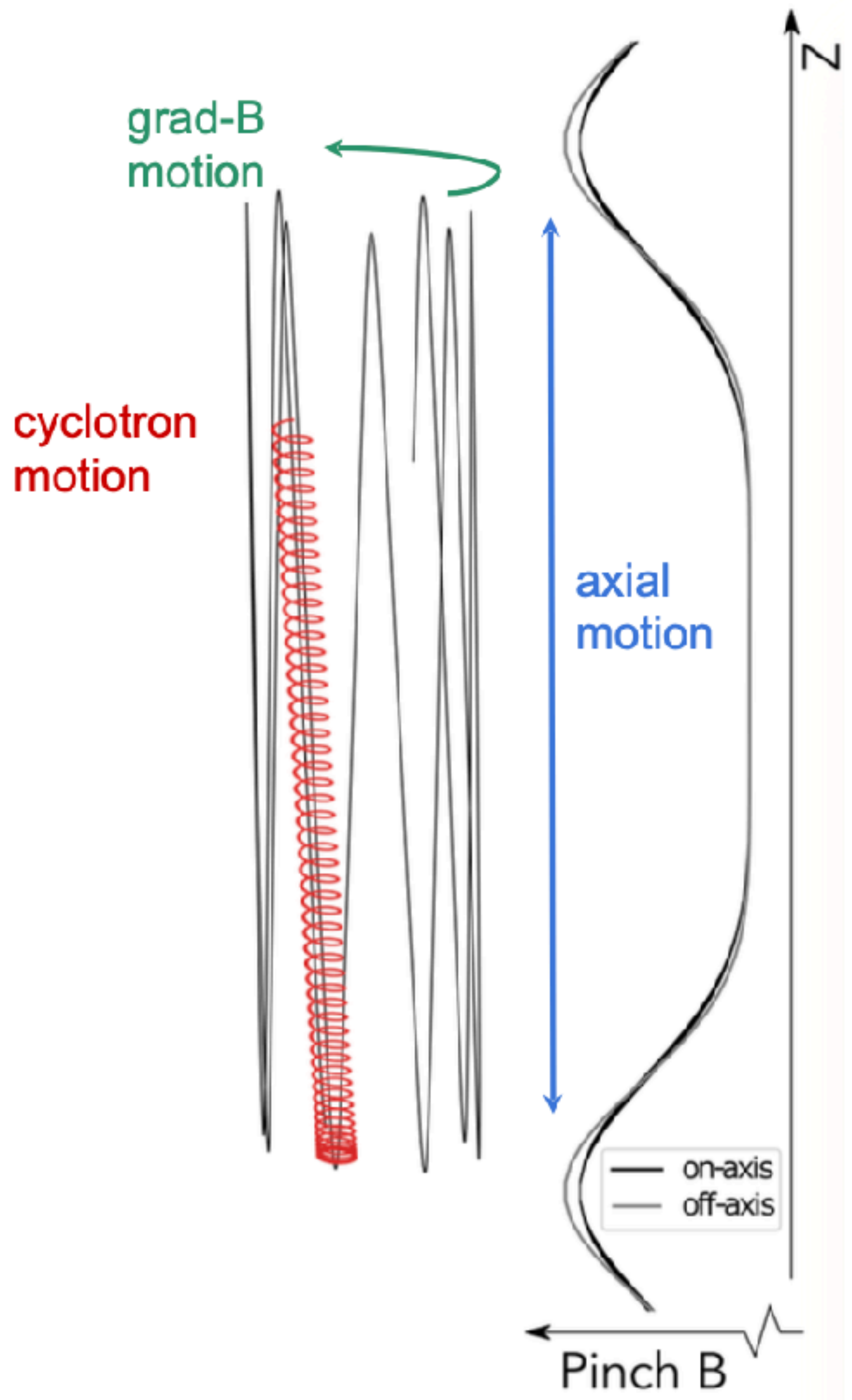



$$f_{cyc} = \frac{1}{2\pi}\frac{qB}{m_e + E/c^2}$$

0.1 T

1 GHz

18.6 keV



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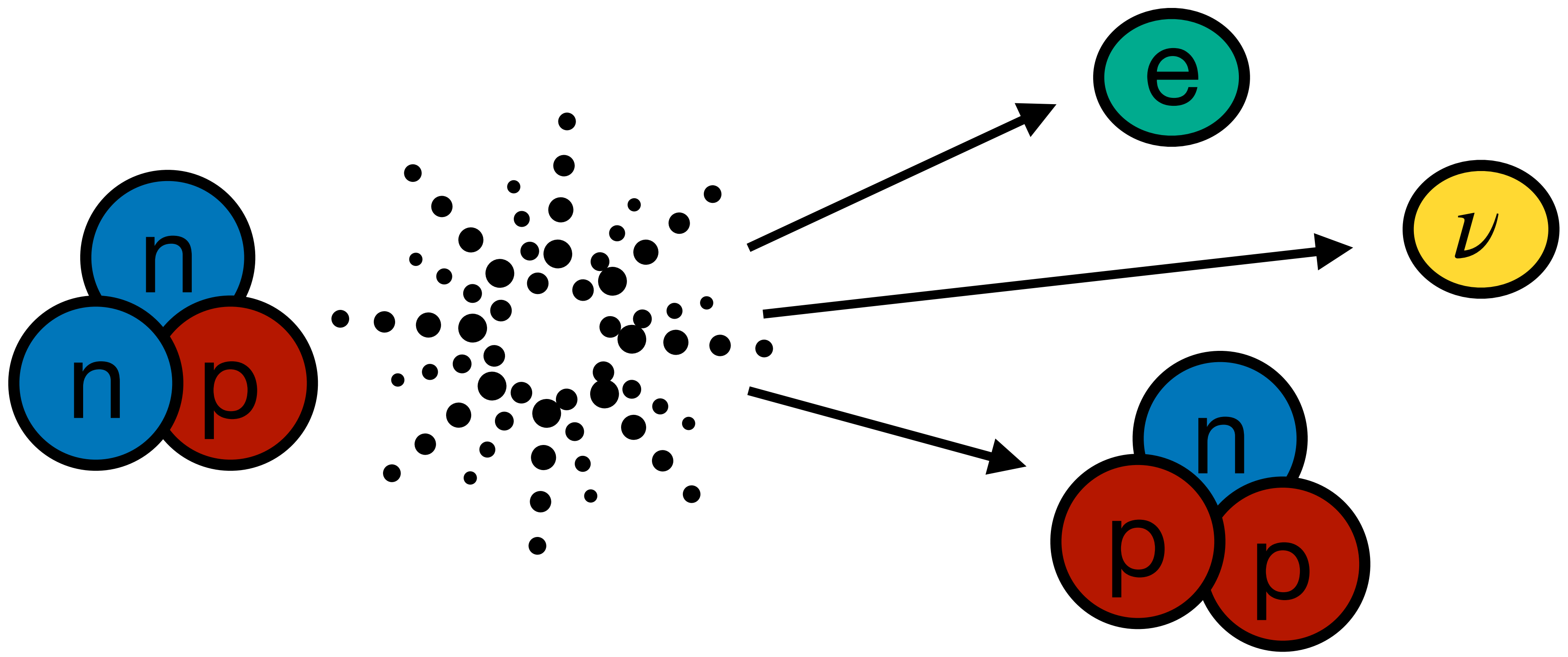
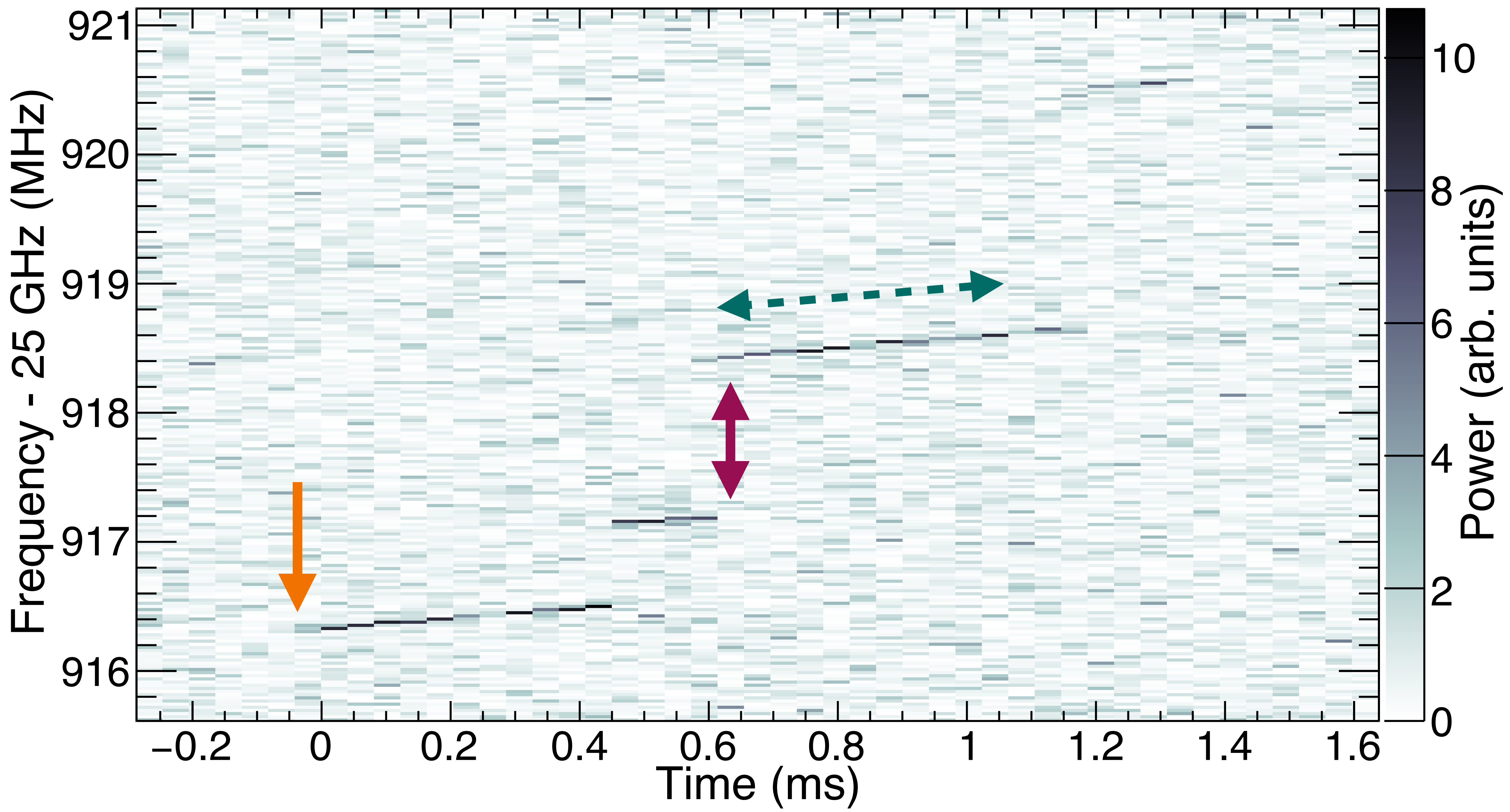
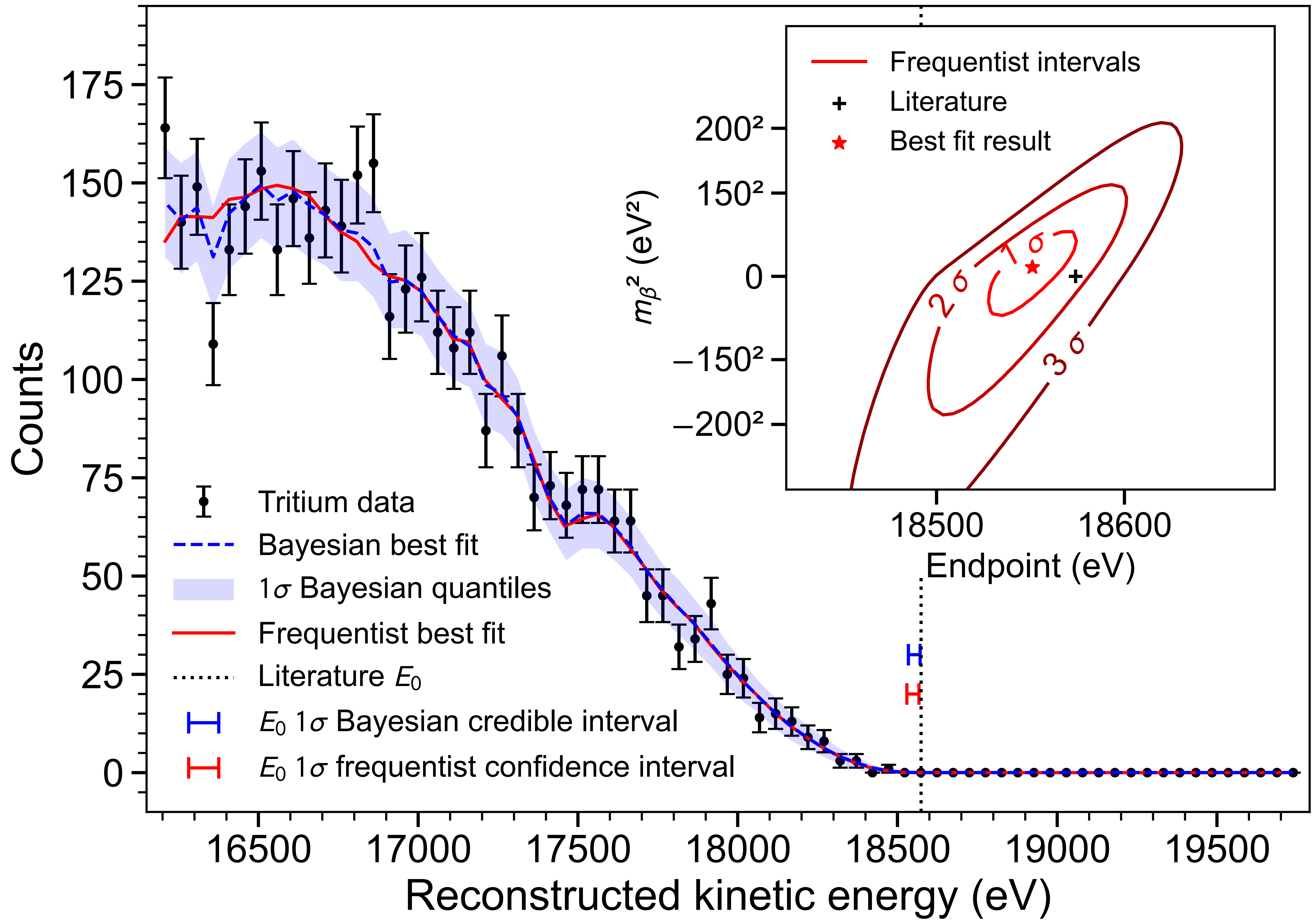



$$f_{cyc} = \frac{1}{2\pi}\frac{qB}{m_e + E/c^2}$$

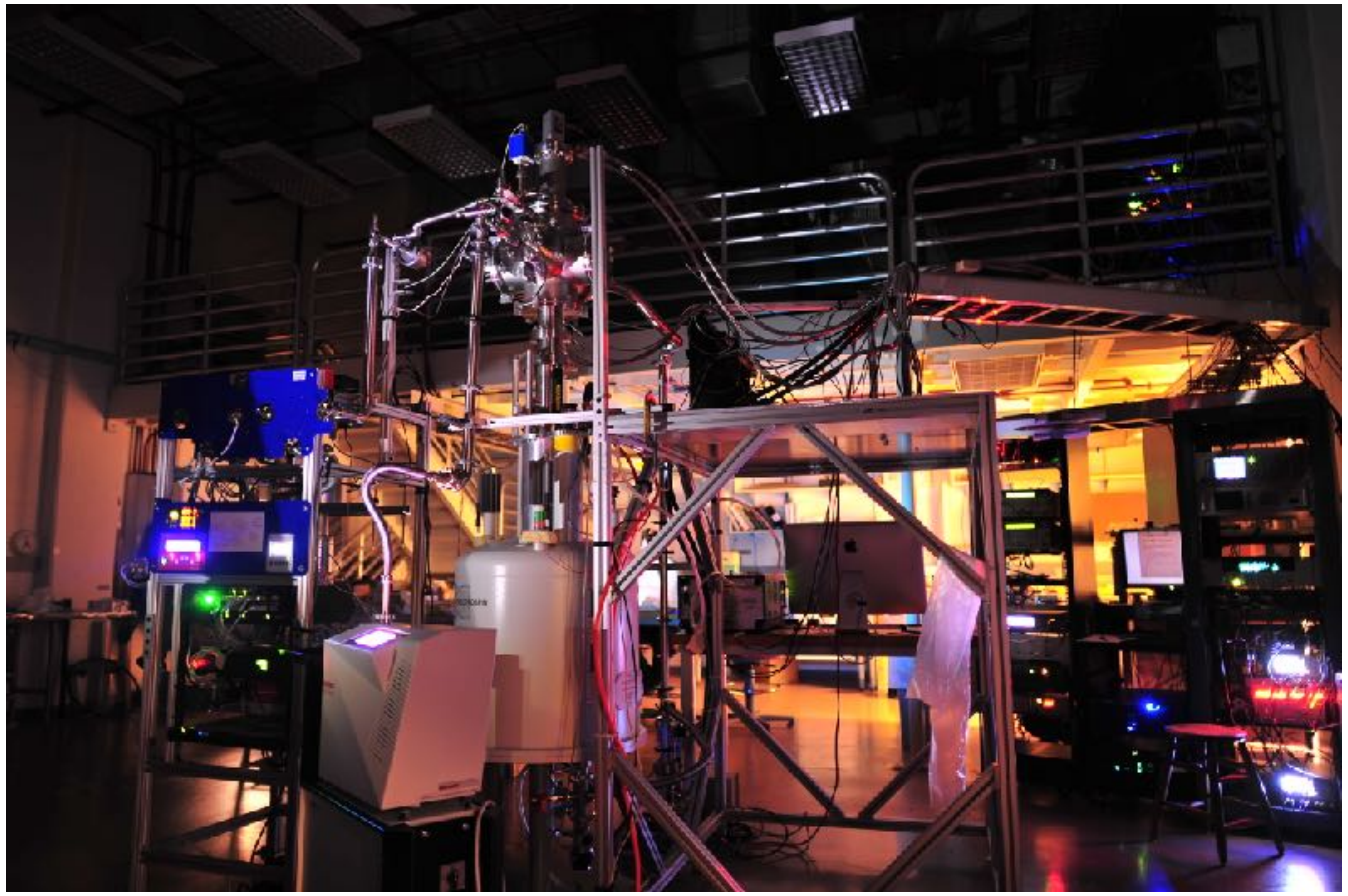
Source: Snowmass 2021

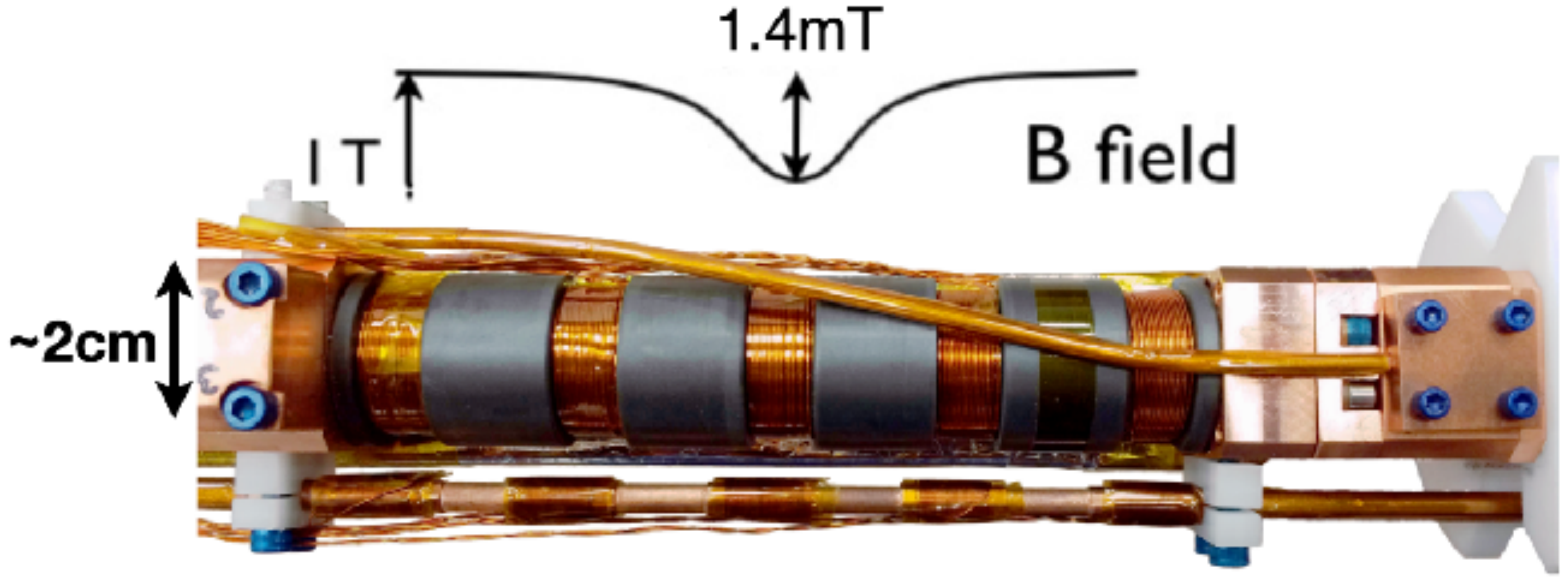


# Next generation experiment: Project 8

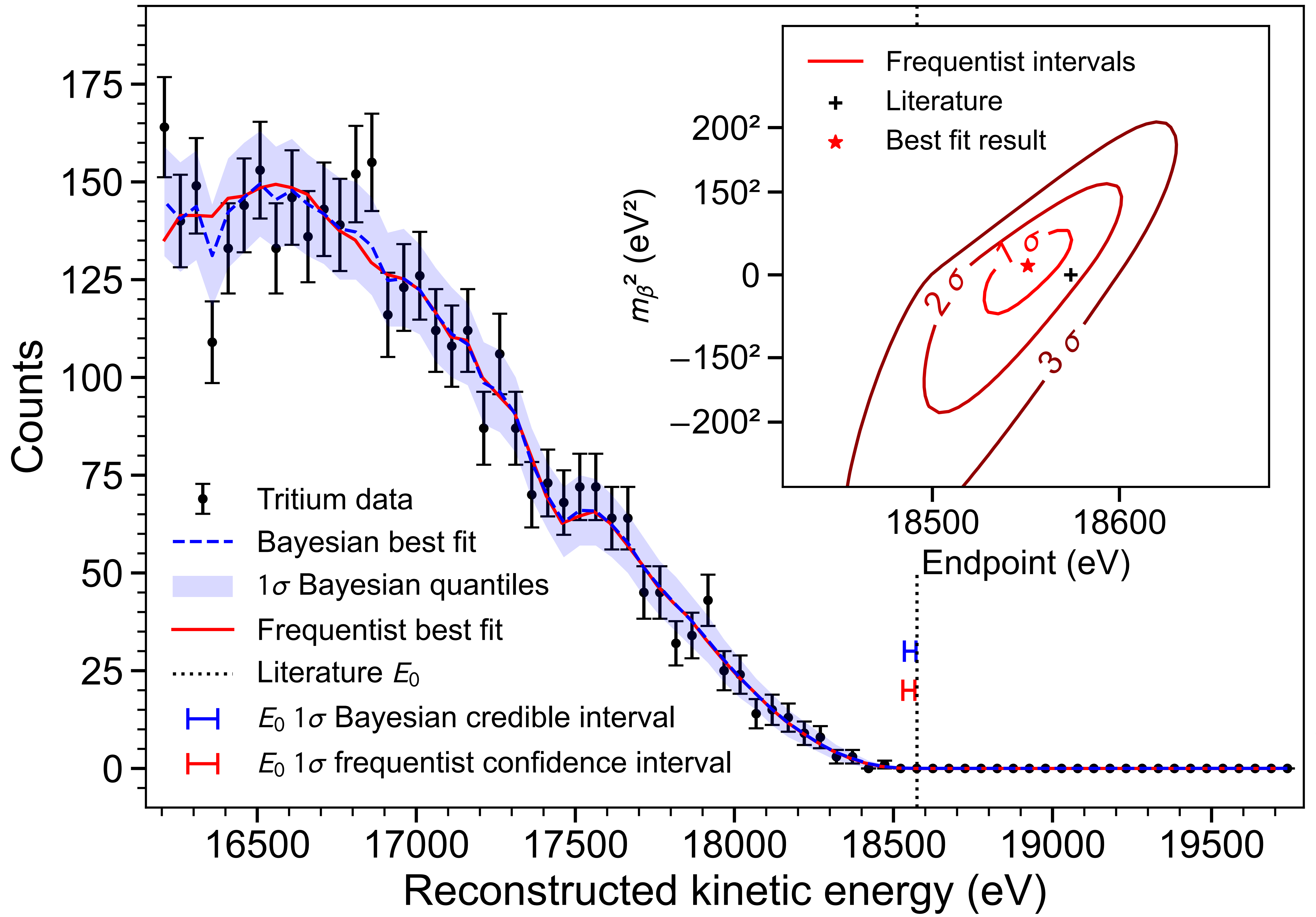



Source: PRL 2023





# Next generation experiment: Project 8



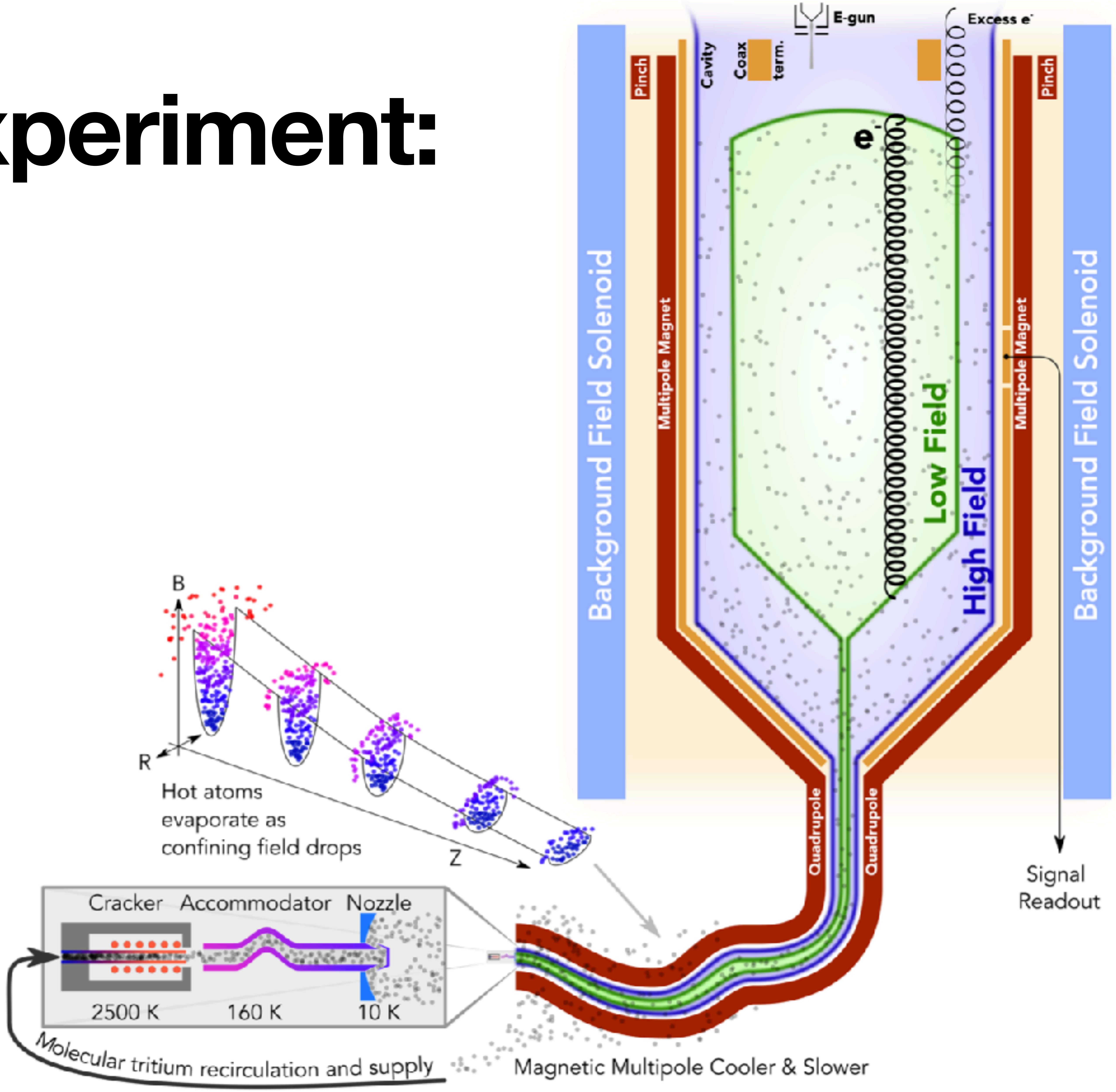

Source: PRL 2023

- First detection of single $^{83m}$Kr electrons using CRES: PhysRevLett.114.162501
- First results with tritium ($T_2$): PhysRevLett.131.102502
  - $m_\beta \leq 155$ eV $(152$ eV$)$
  - Background rate: $\leq 3 \times 10^{-10}$ cps/eV
  - Resolution: 54.3 eV FWHM
  - Effective volume: $1.20 \pm 0.09$ mm$^3$ eV

# Path to full-scale experiment:

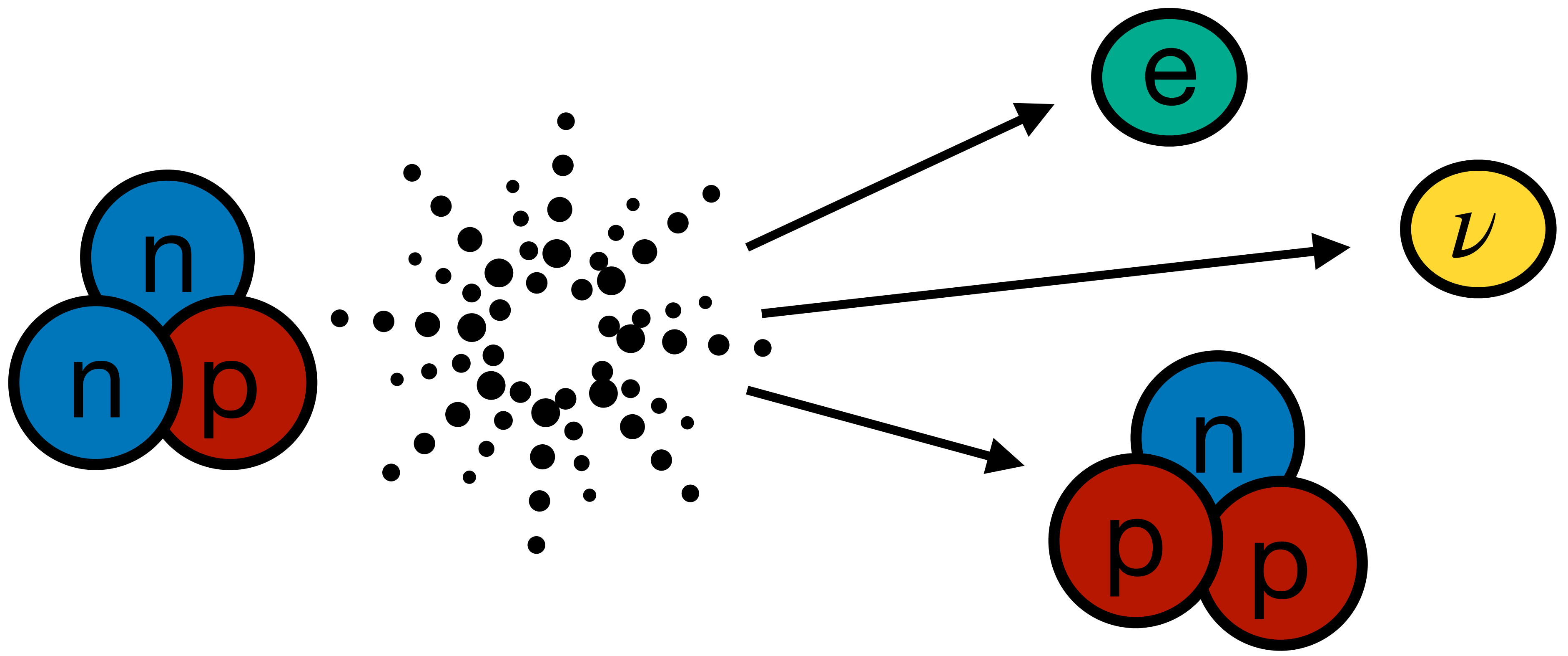
Largest sensitivity gains:

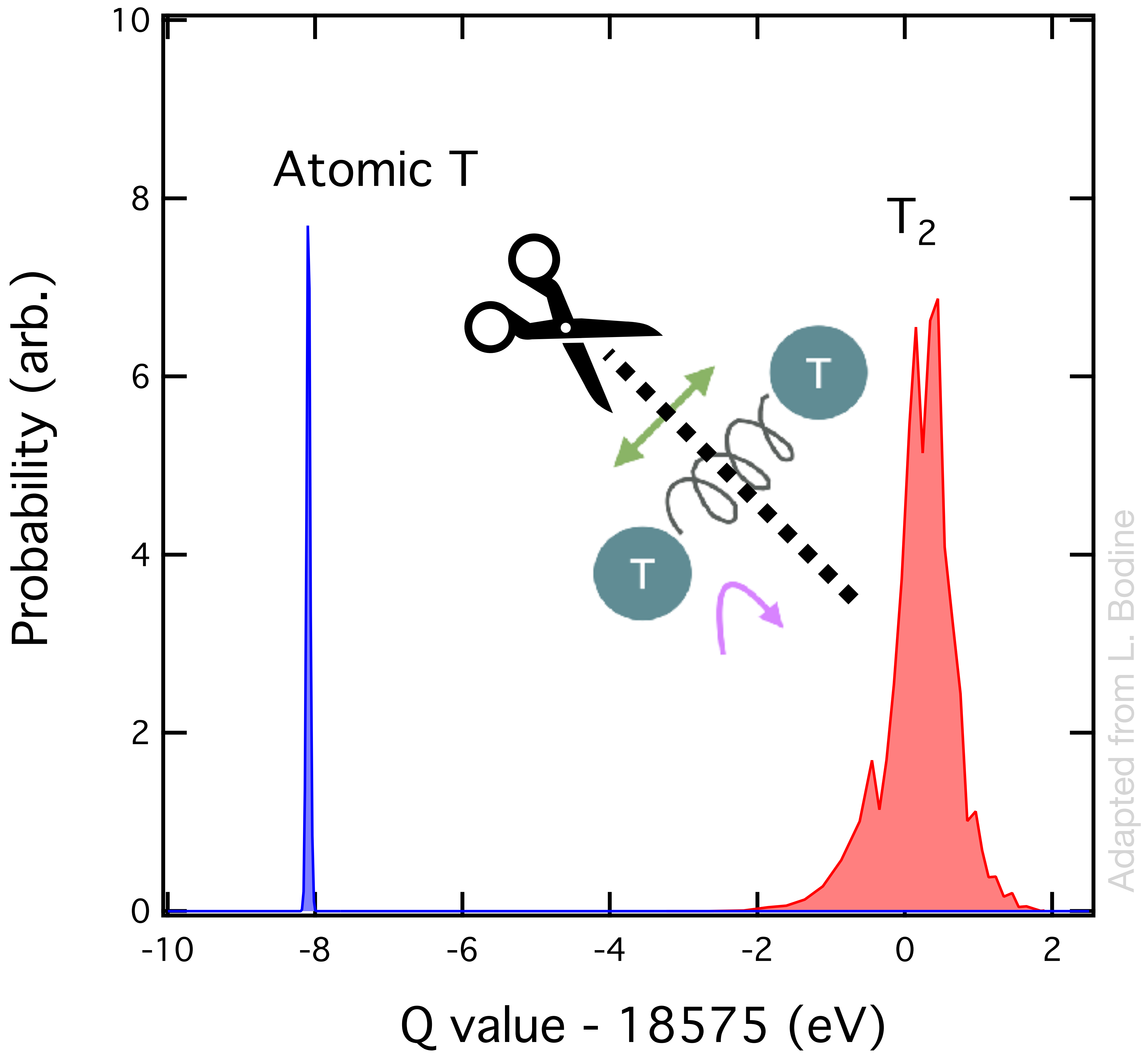
- Molecular →atomic tritium
- Scale up CRES volume




Adapted from B. Jones

# 1. Atomic source preparation



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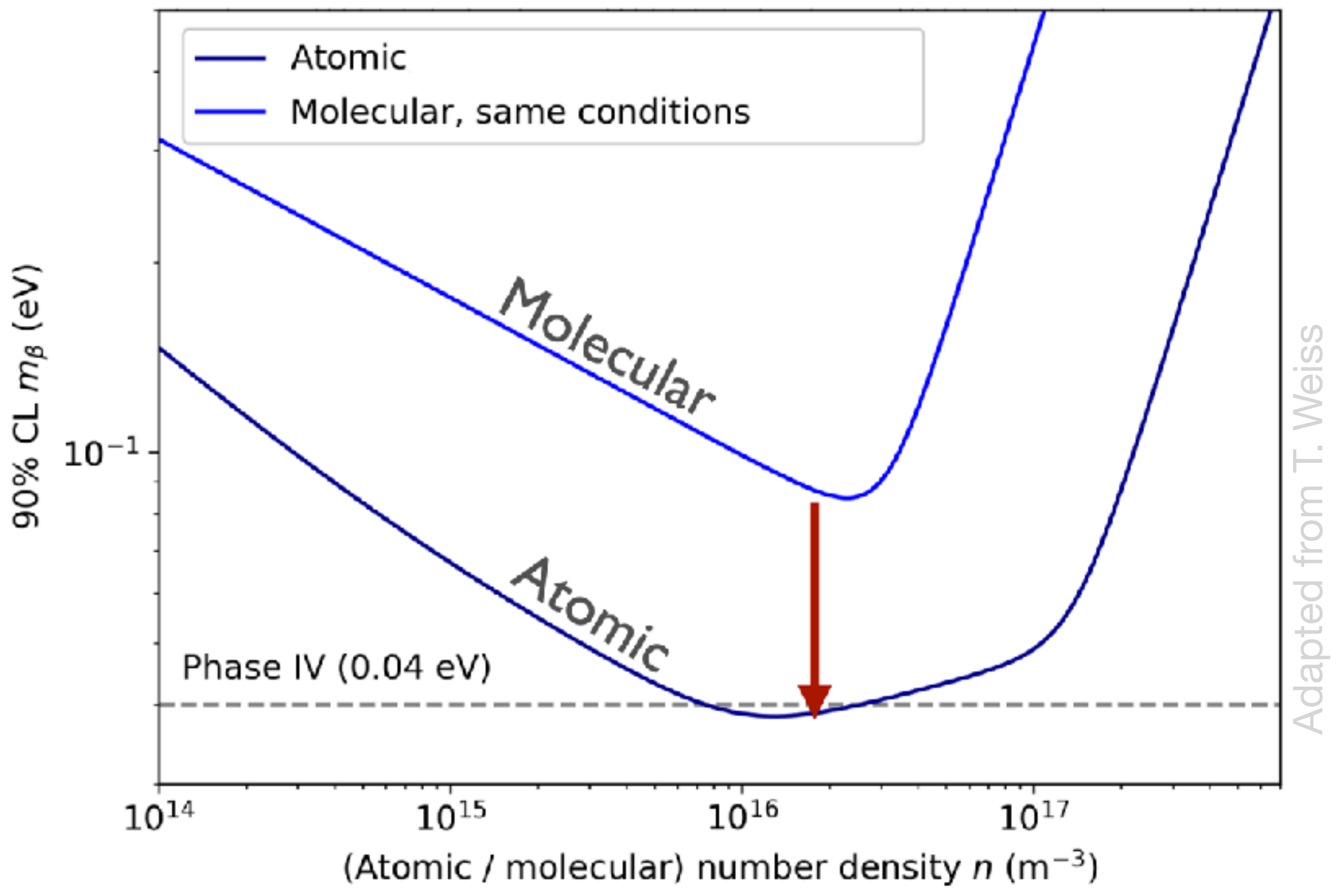
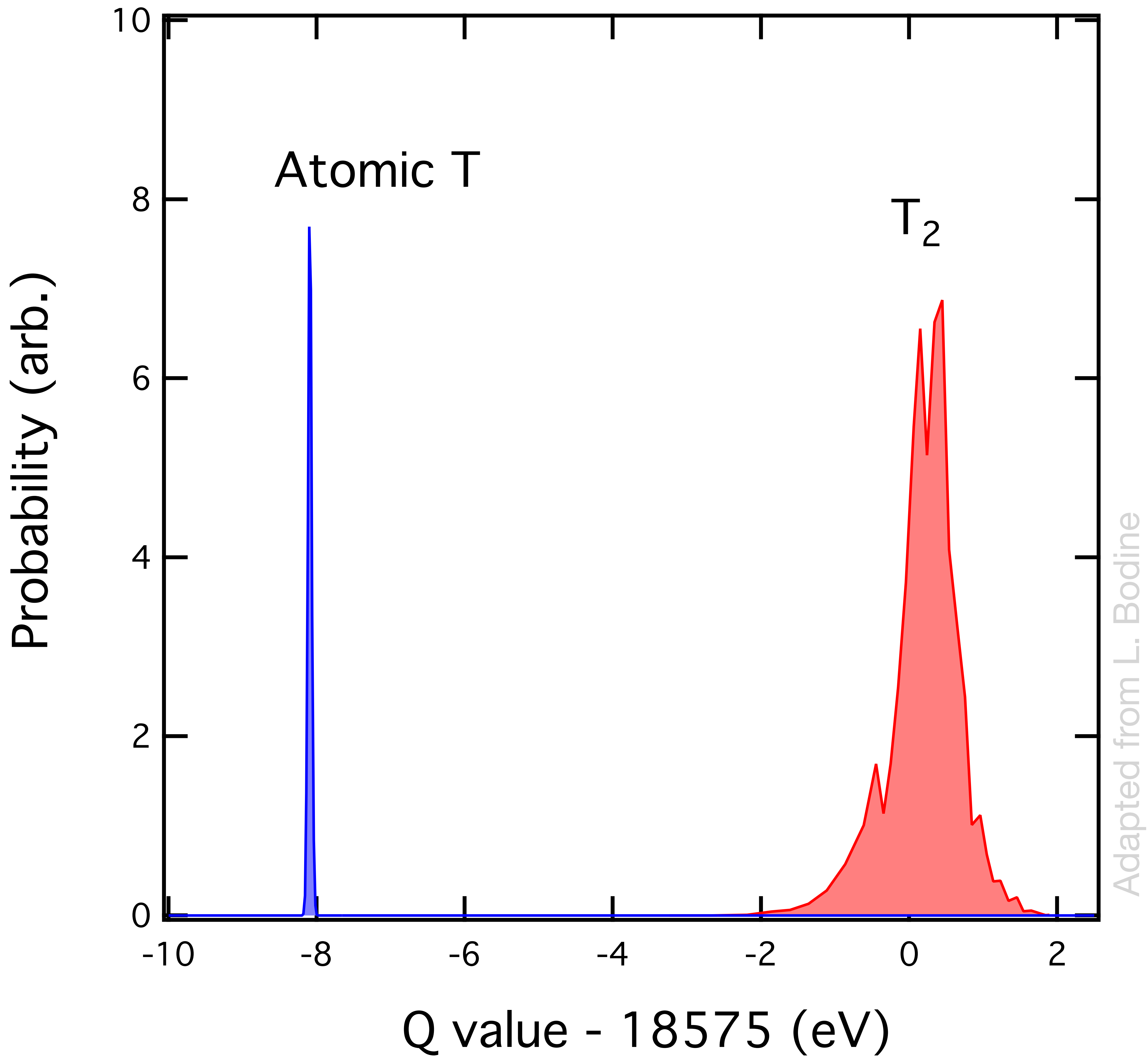


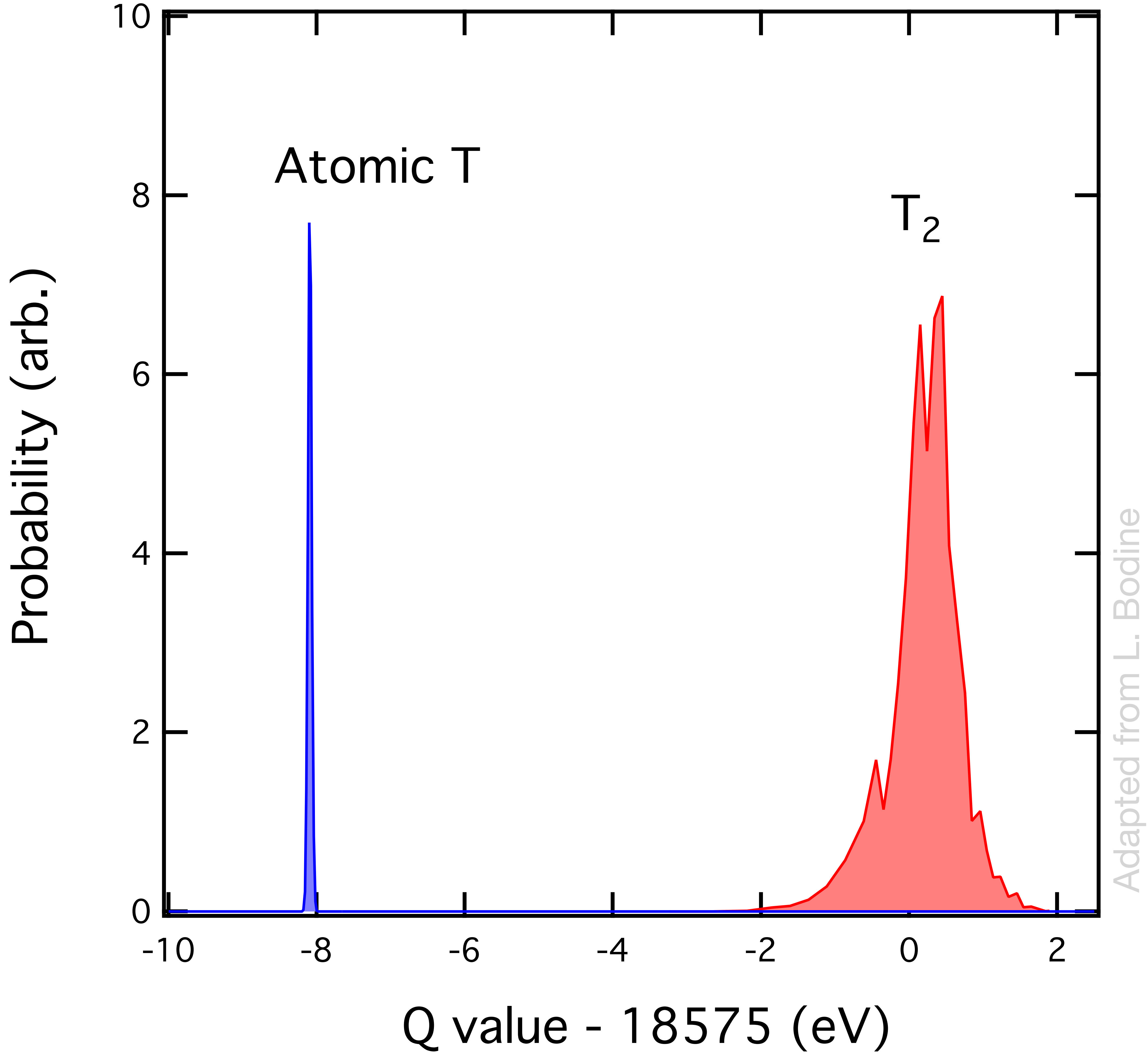
# 1. Atomic source preparation

Key performance parameters:

**Density**: 1e17 tritons/m^3

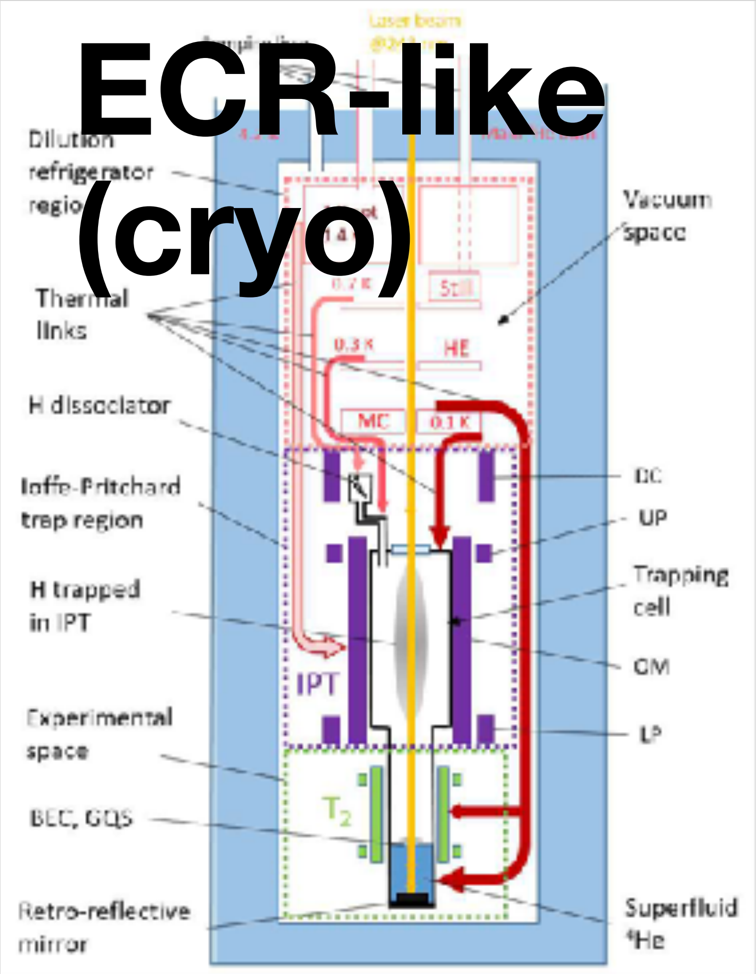
**Temperature**: ~1mK

**Purity**: 1e-4 molecular contamination



# 1. Atomic source preparation (status)

## Dissociation:





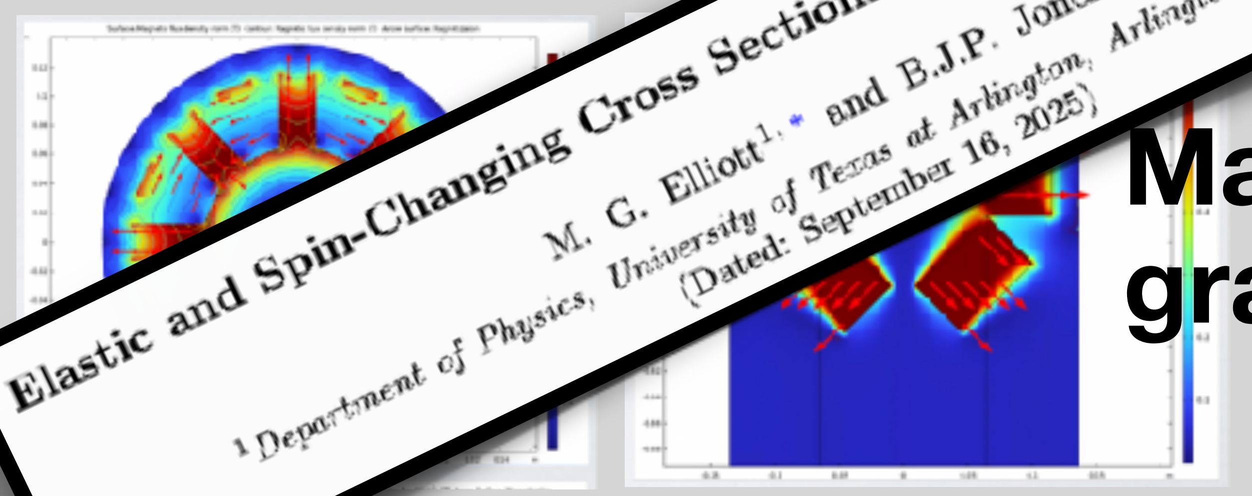



Dynamics of Magnetic Evaporative Beamline Cooling for Preparation of Cold Atomic Beams

(Project 8 Collaboration)

4 Sep 2025

## Trappi[ng]

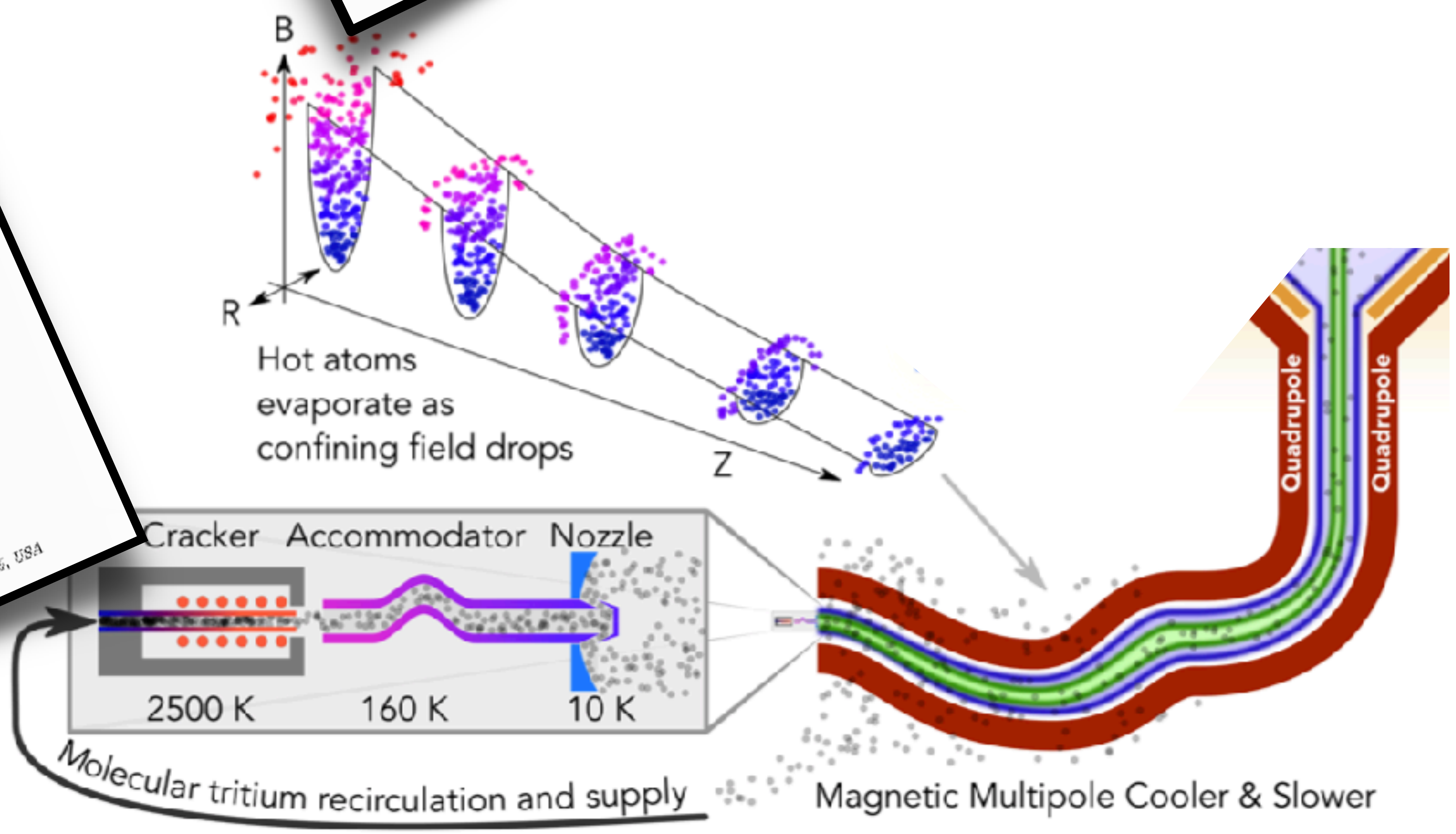



Elastic and Spin-Changing Cross Sections of Spin-Polarized Atomic Tritium

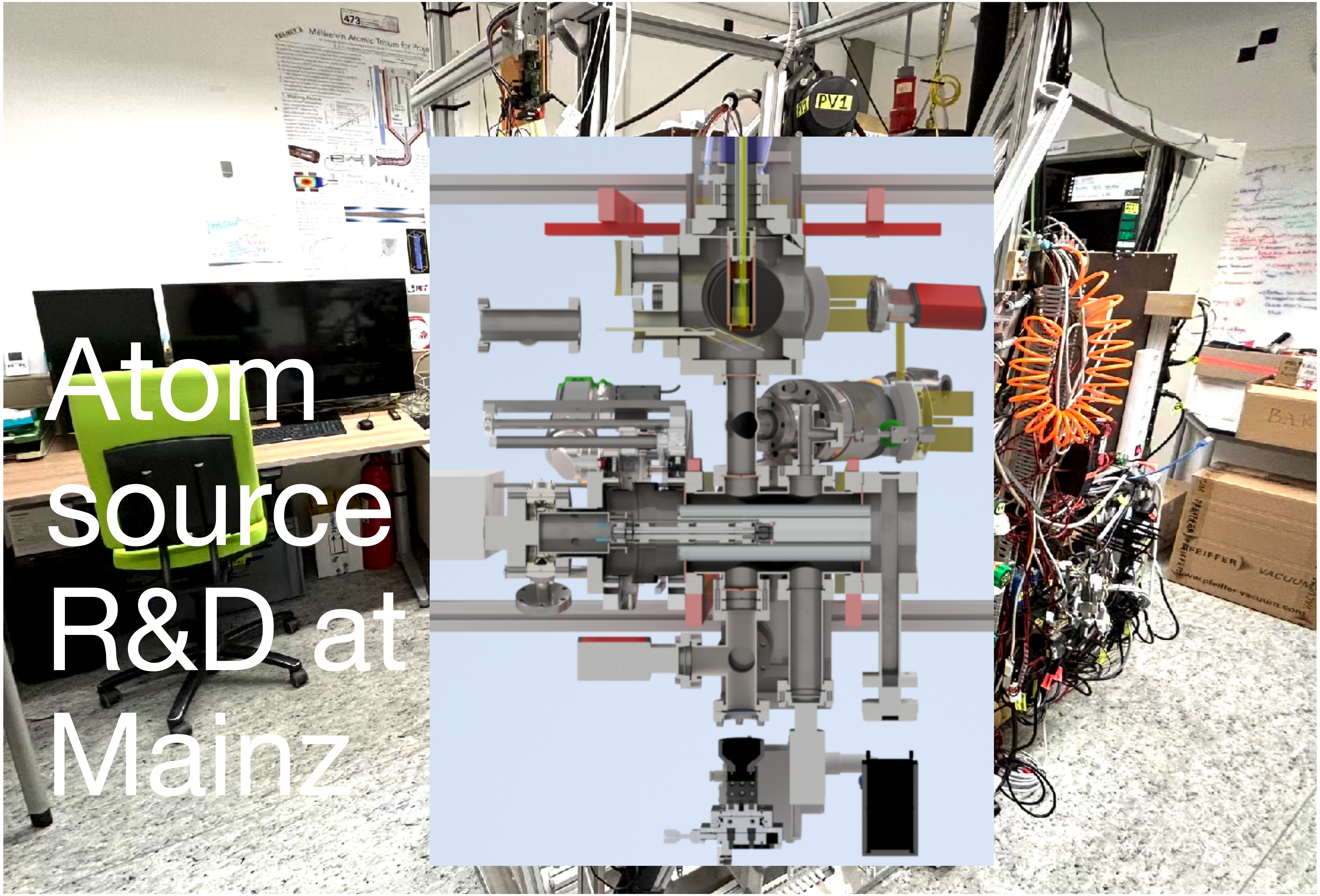
M. G. Elliott[1,*] and B.J.P. Jones[1,†]

[1] Department of Physics, University of Texas at Arlington, Arlington, TX 76019, USA

(Dated: September 16, 2025)

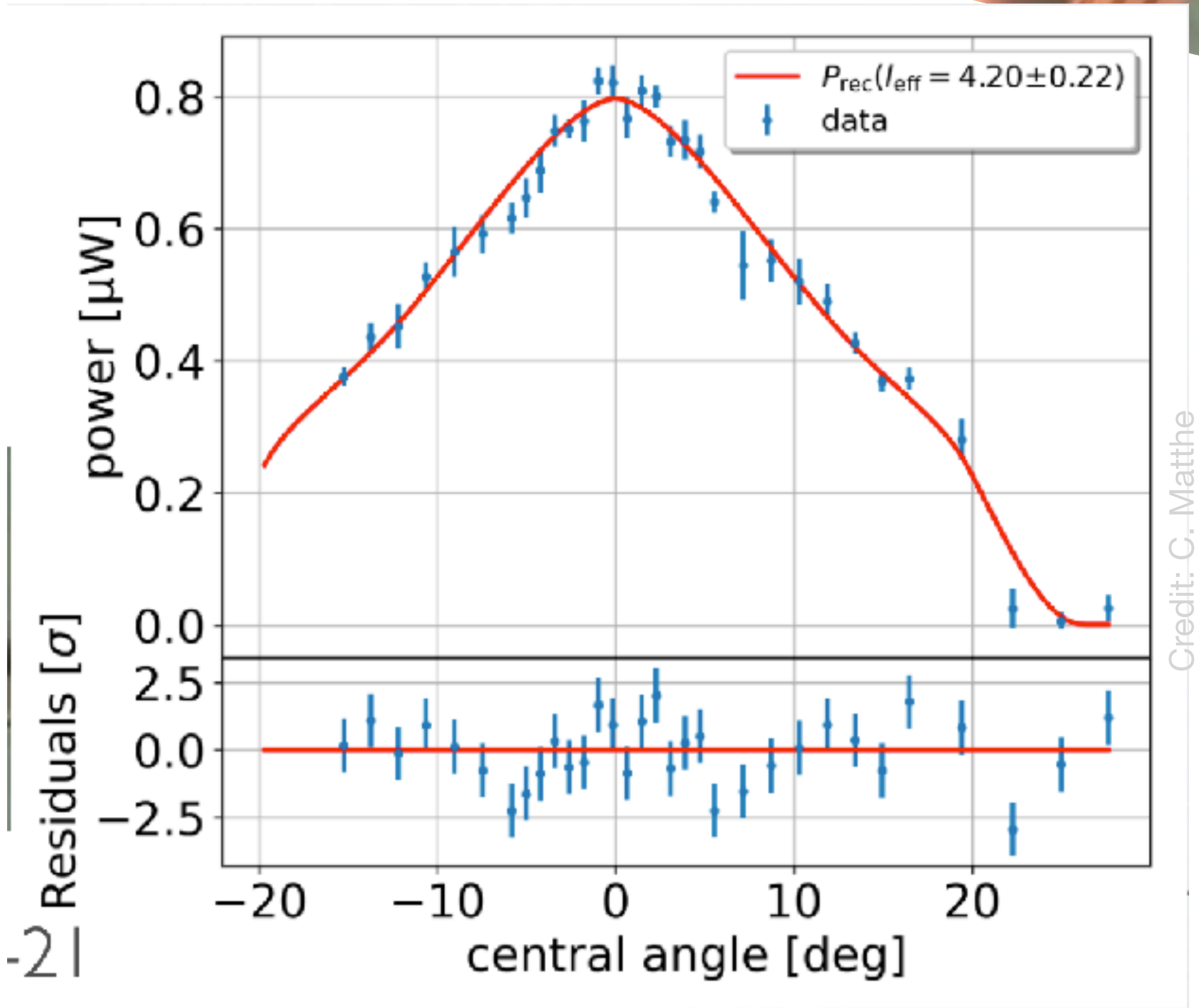


# Atom source R&D at Mainz

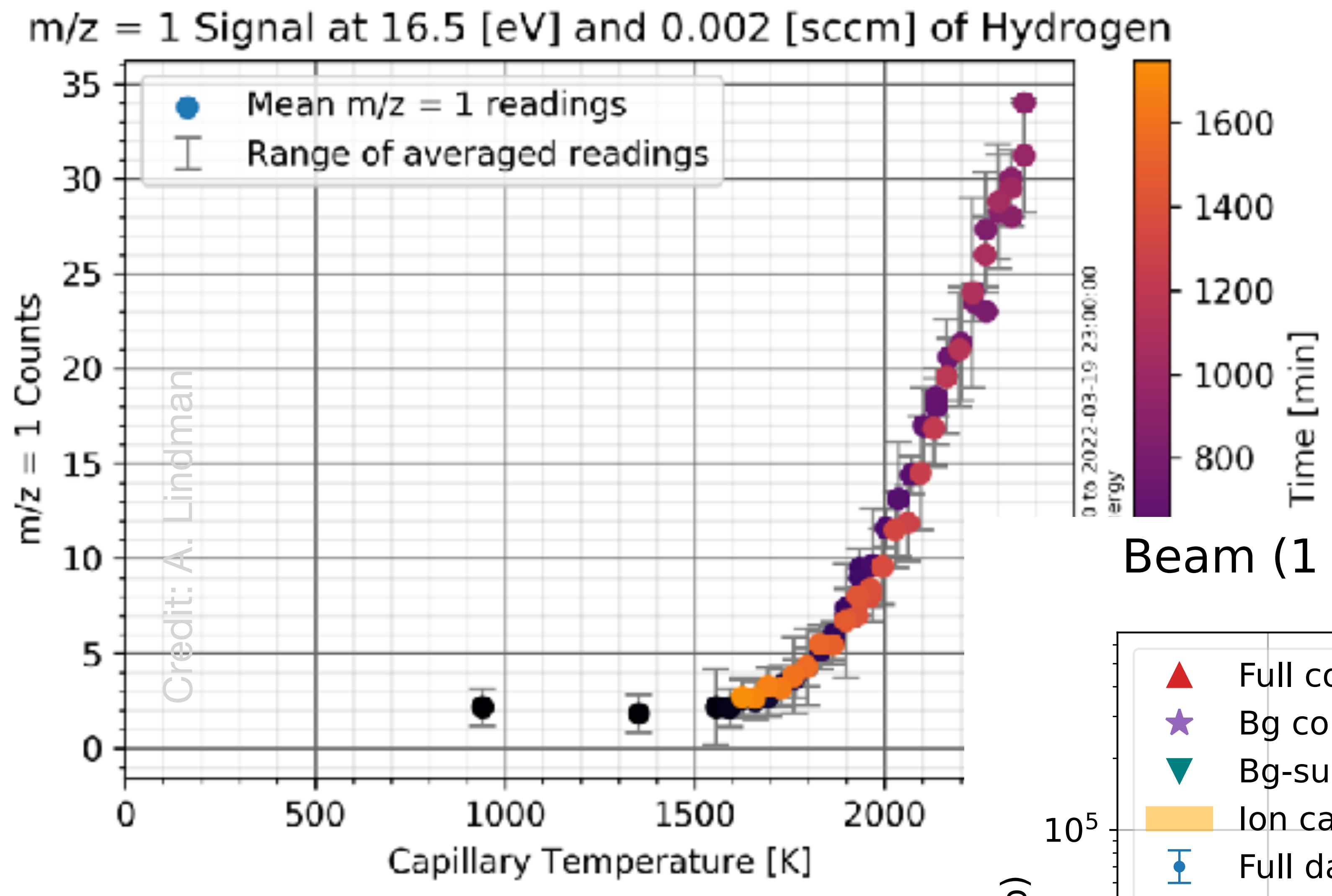


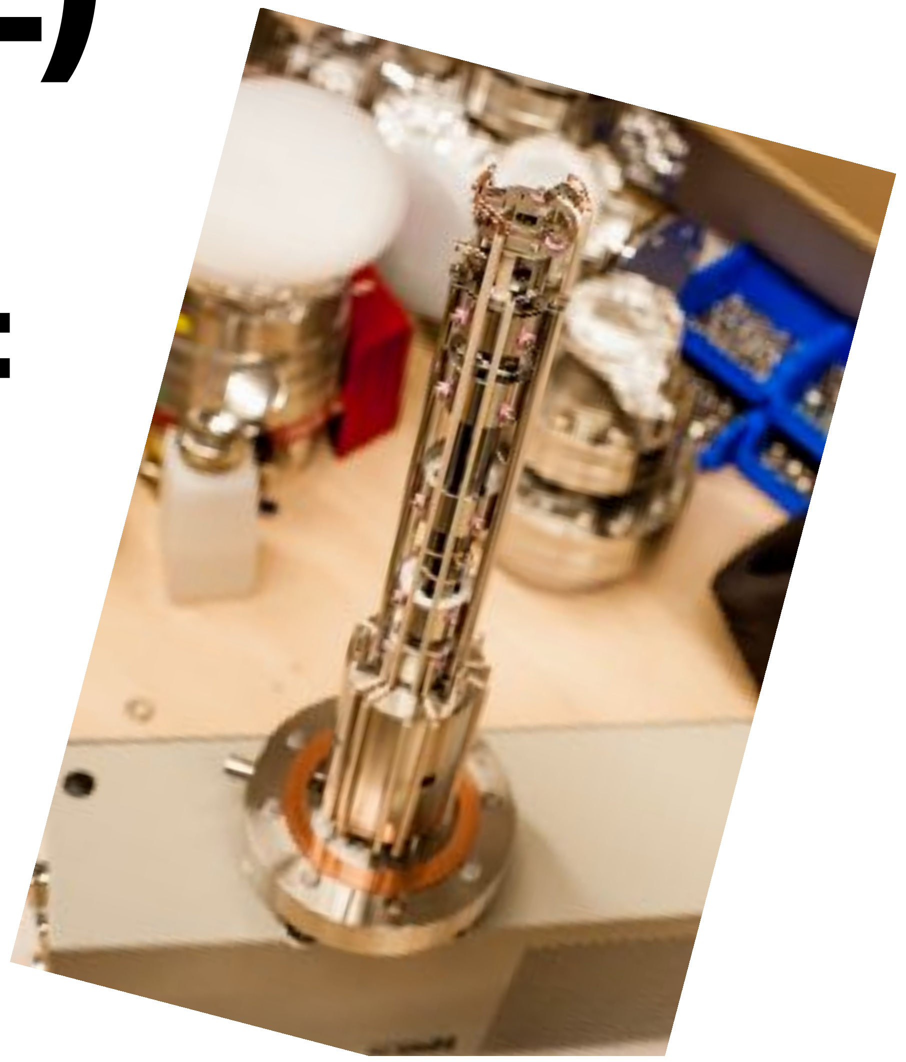
# 1. Atomic source preparation (Mainz)

## Calorimetry:

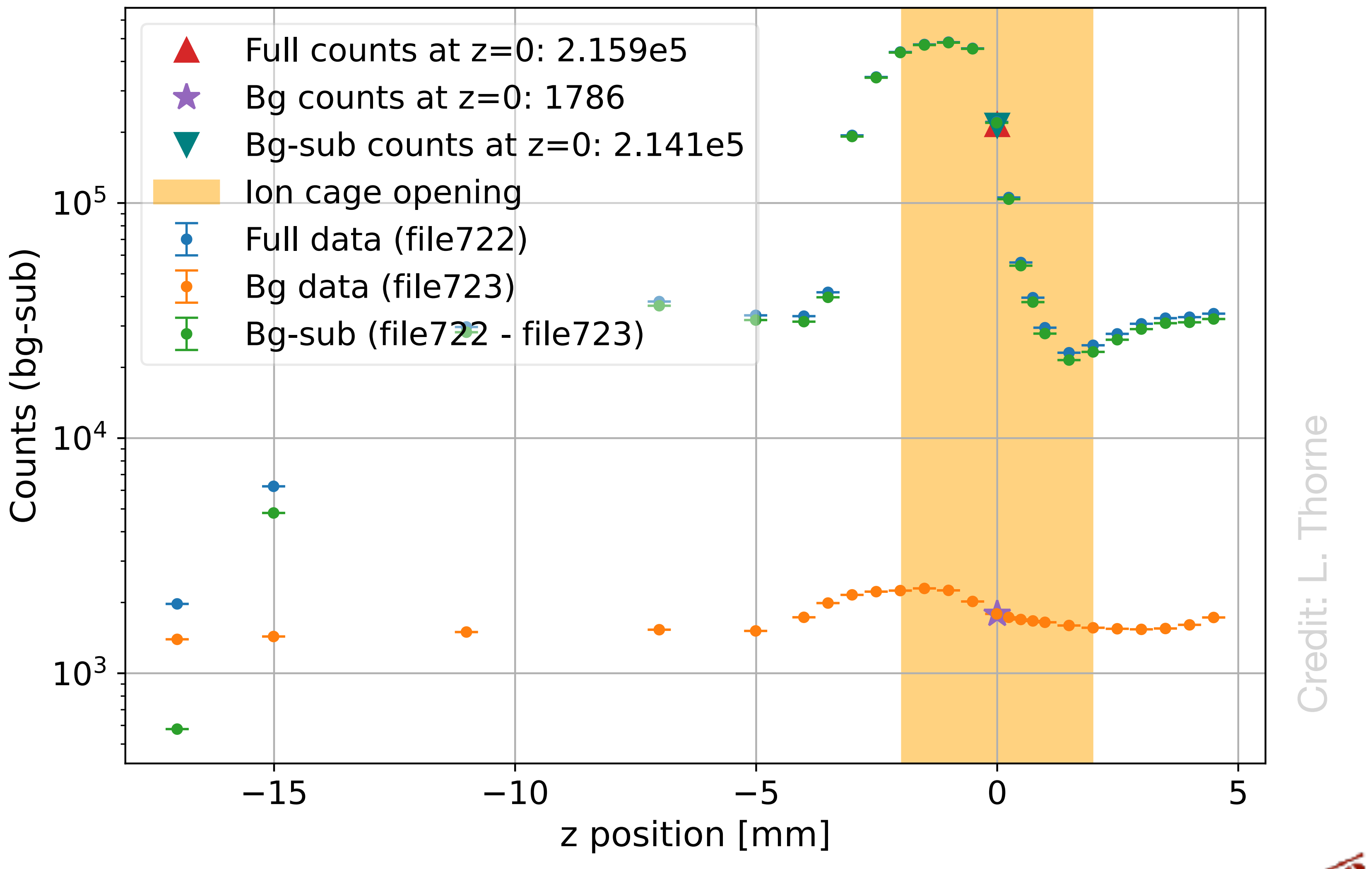



## Mass spectrometry:



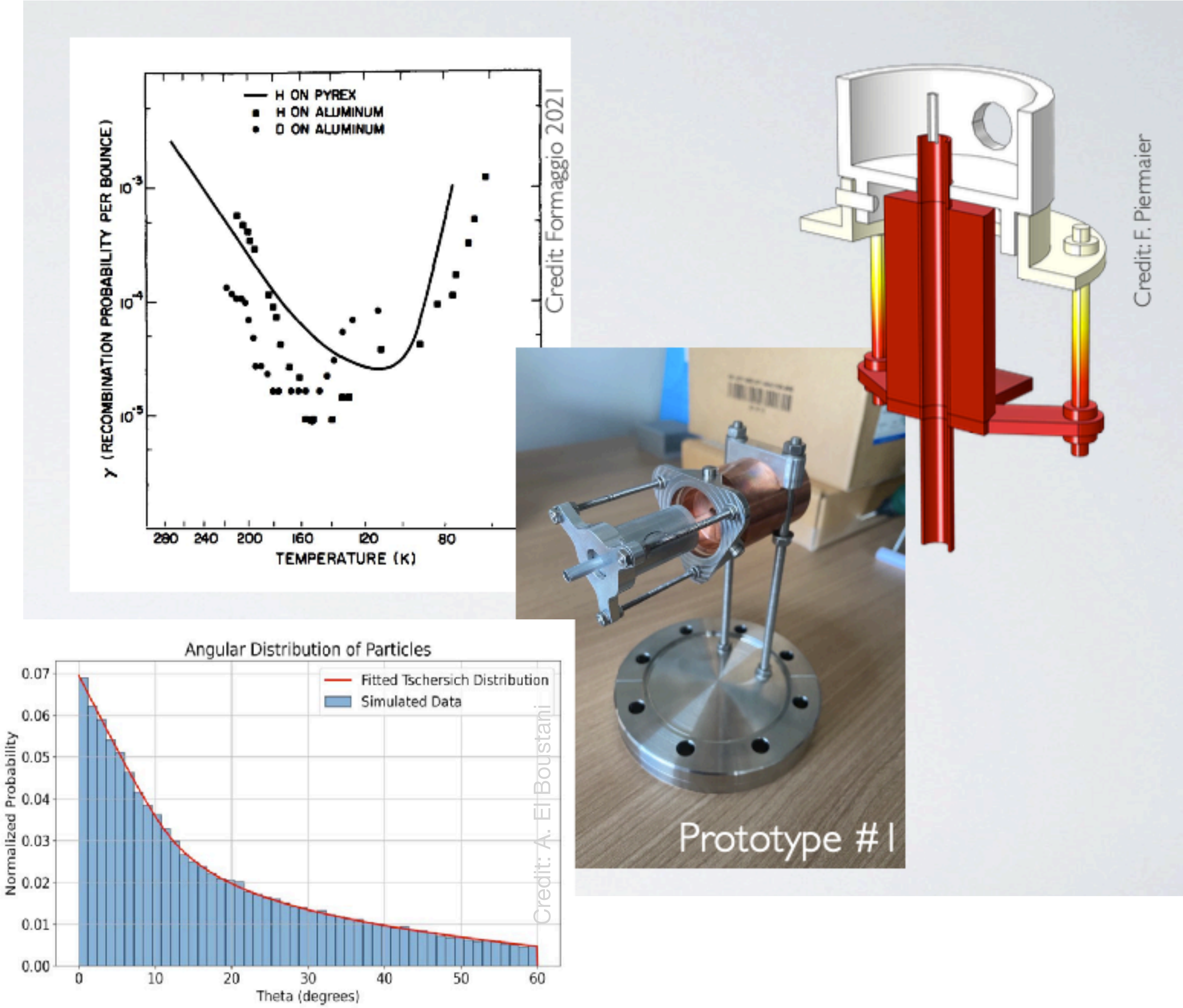



Beam (1 sccm; 0 A) background subtraction

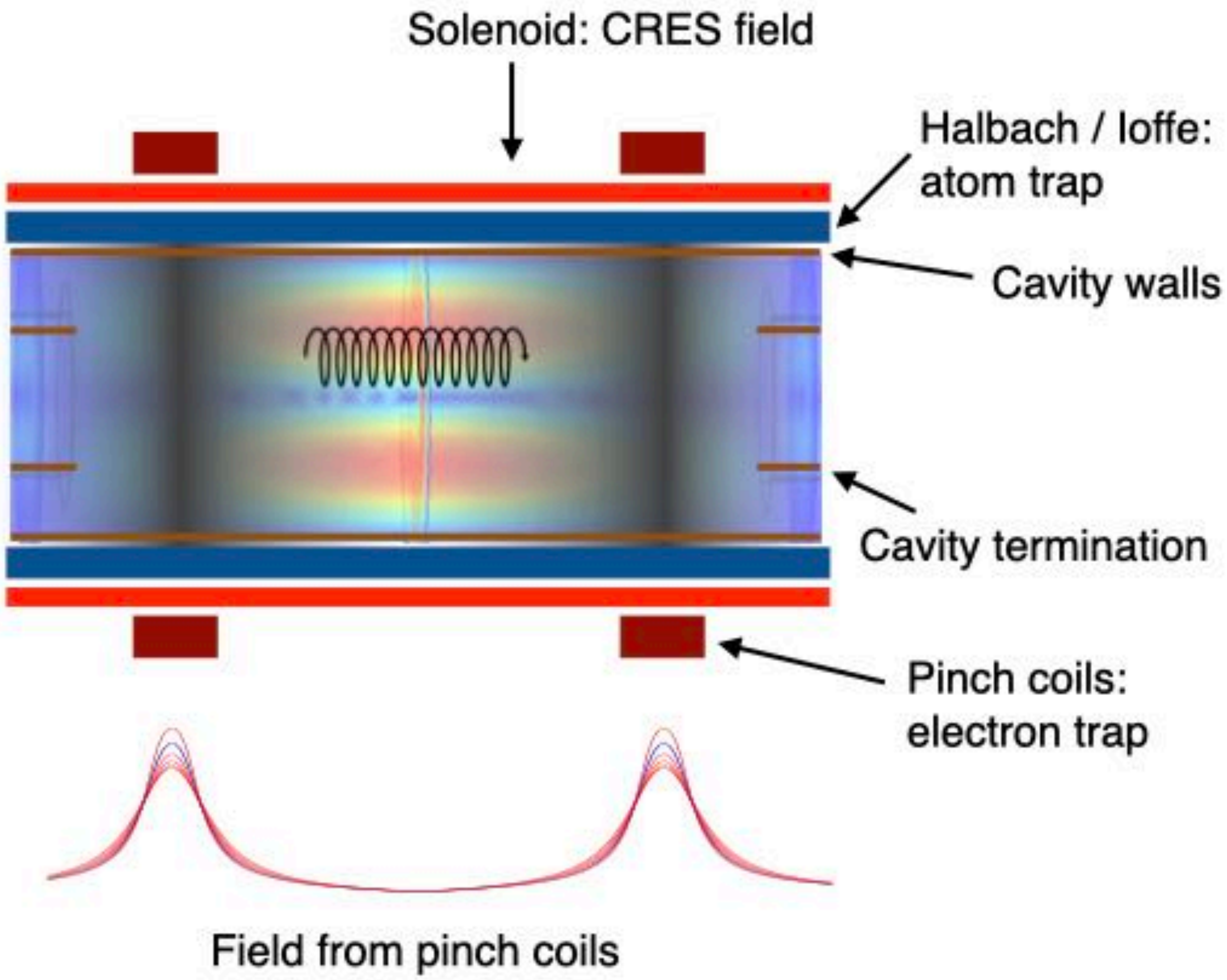


# 1. Atomic source preparation (Mainz)

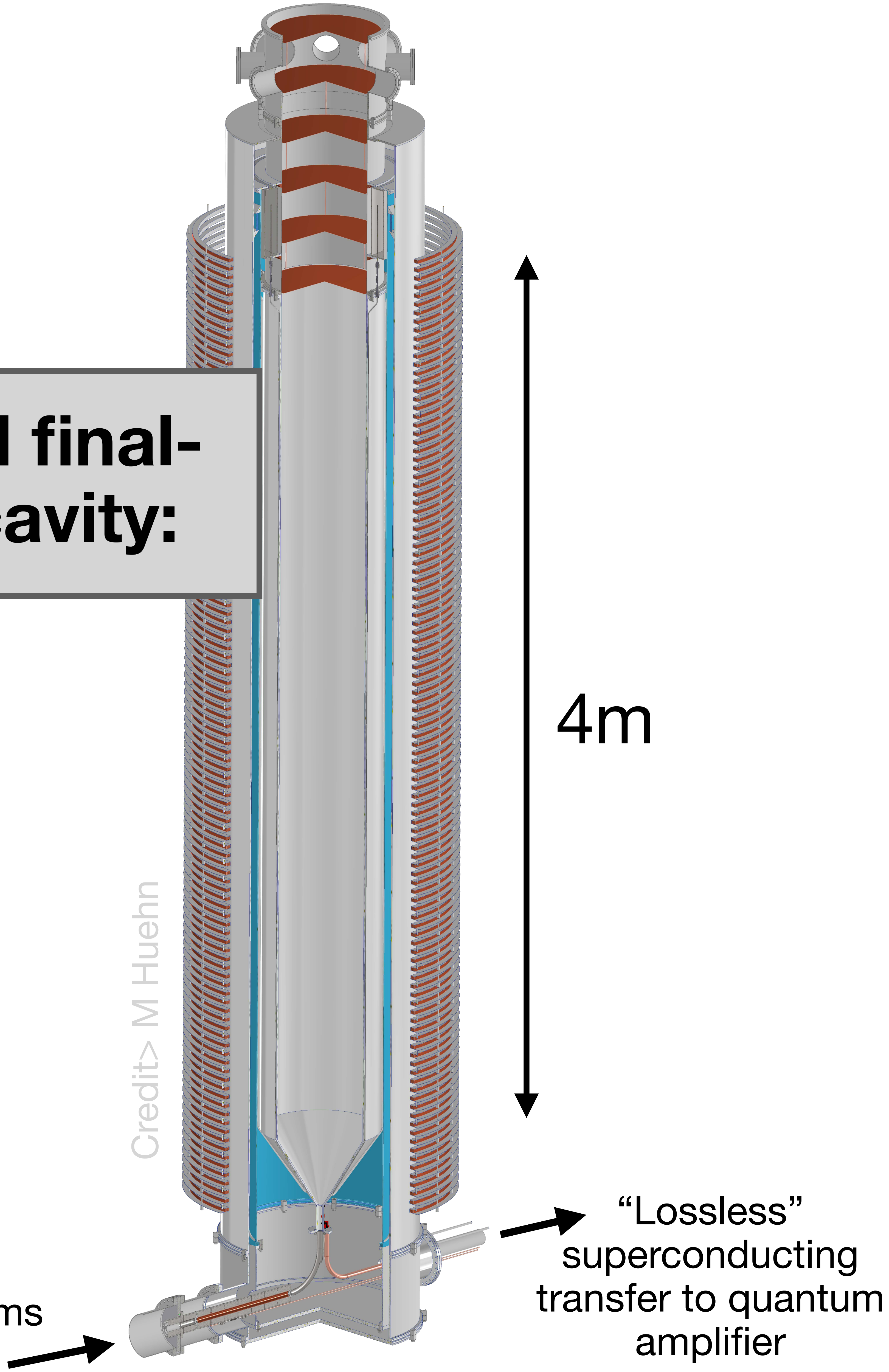
- Surface cooling concept
- Challenge: recombination
- Surface cooling at recombination minimum (~150K):
    - Estimated LN2 cooling needed (COMSOL)
    - First prototype ready for tests
    - Model gas dynamics with Sparta



# 2. Detection scheme

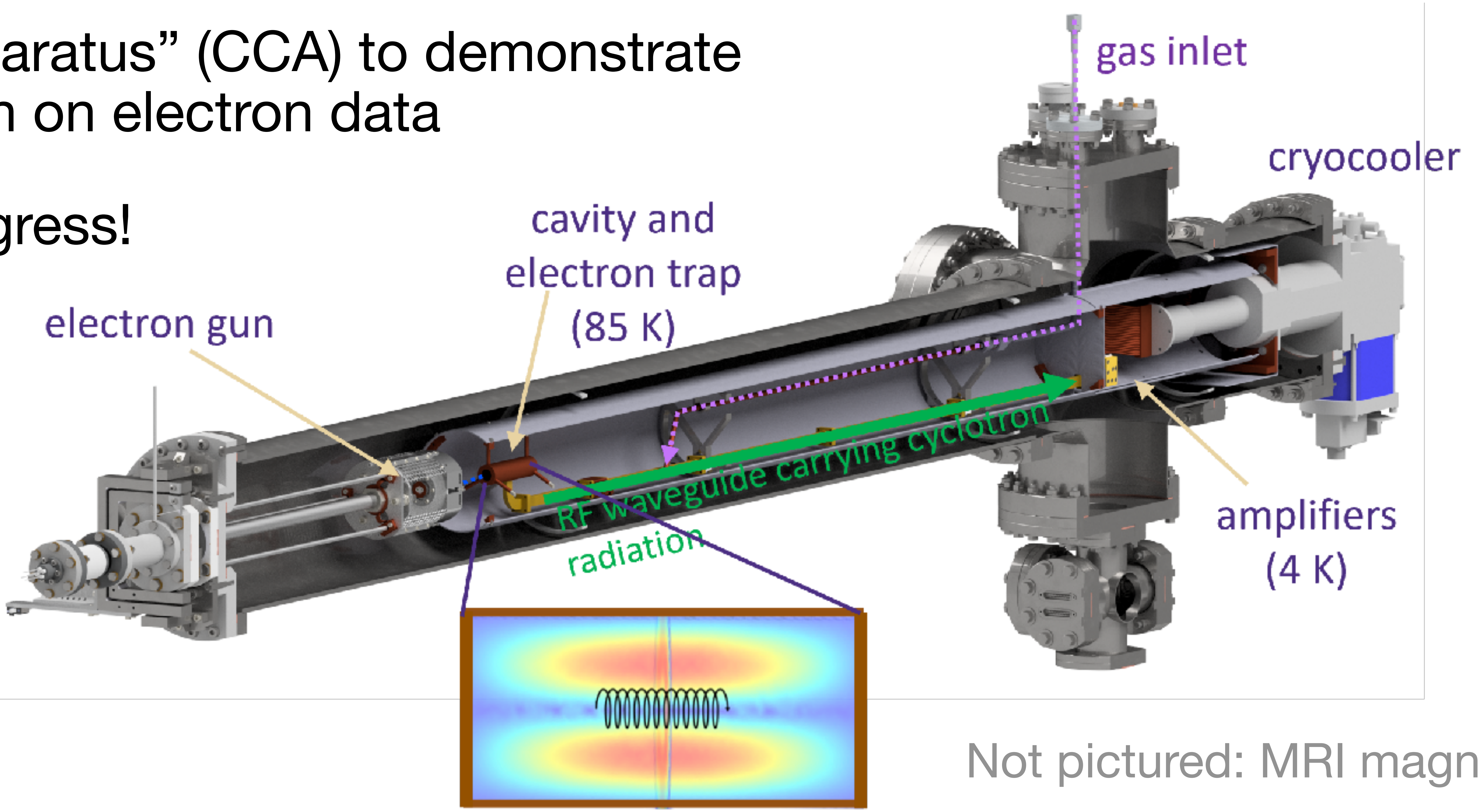



**Planned final-phase cavity:**



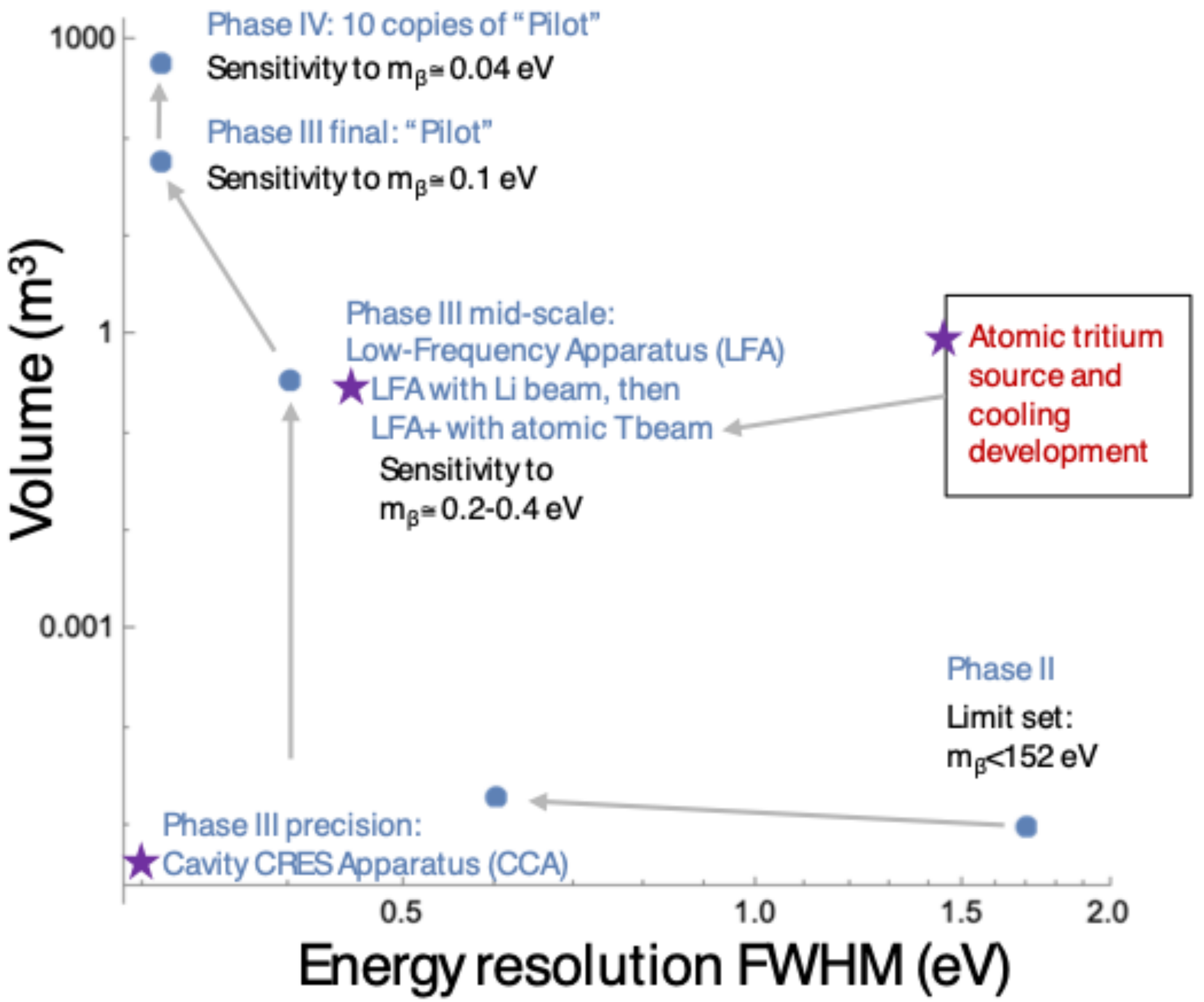
# 2. Detection scheme

- "Cavity CRES Apparatus" (CCA) to demonstrate feasibility of design on electron data
- Pumpdown in progress!



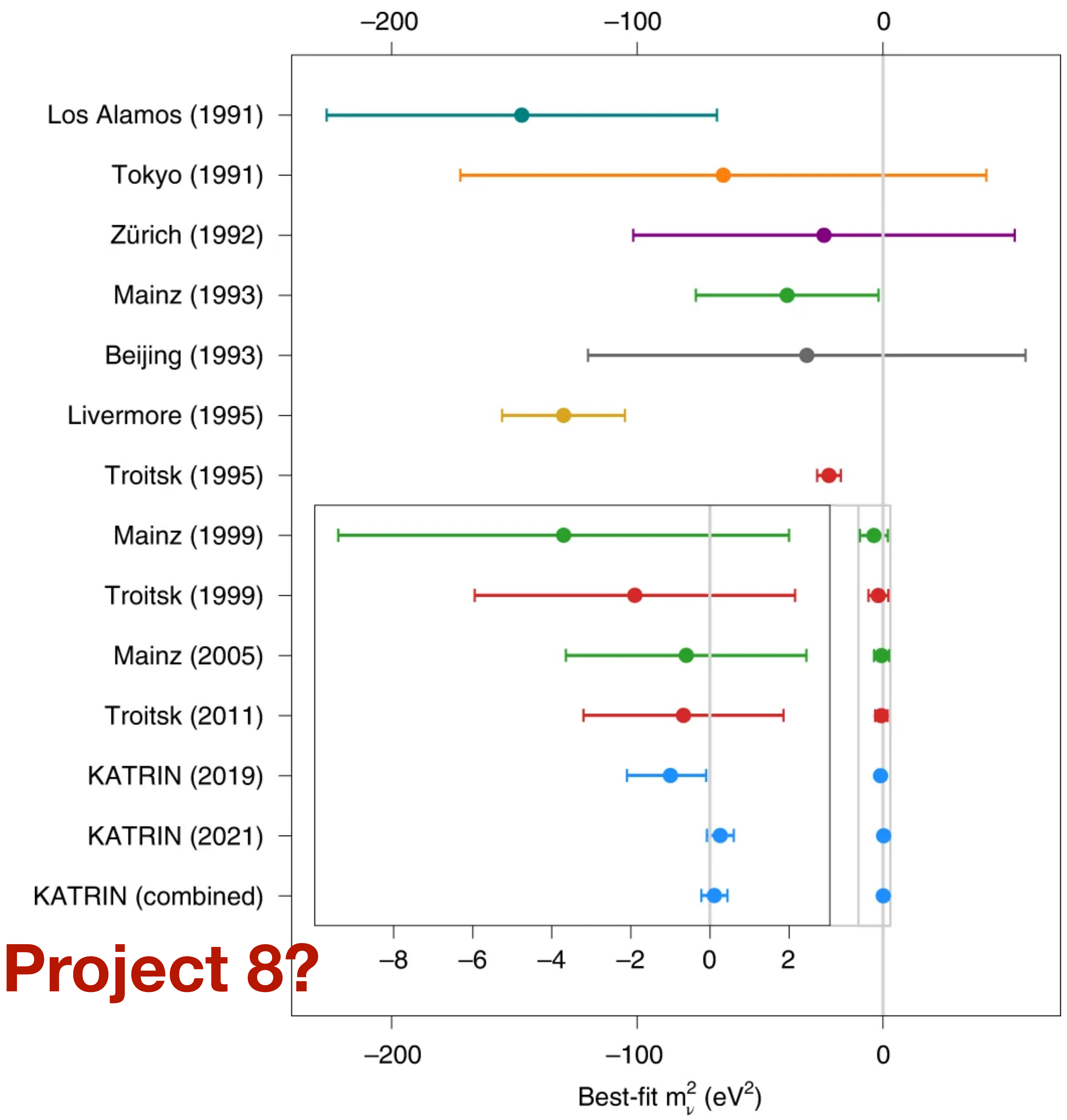

Not pictured: MRI magnet

# 2. Detection scheme: future



# Summary

- State of neutrino mass physics
- Crucial R&D for Project 8 in progress
  - Next CRES demonstrator ("CCA") soon operational
- Atomic diagnostic tools development at Mainz:
  - Flux, via mass spectrometry & calorimetry
  - Atom cooling prototype ready to test



# Thank you.

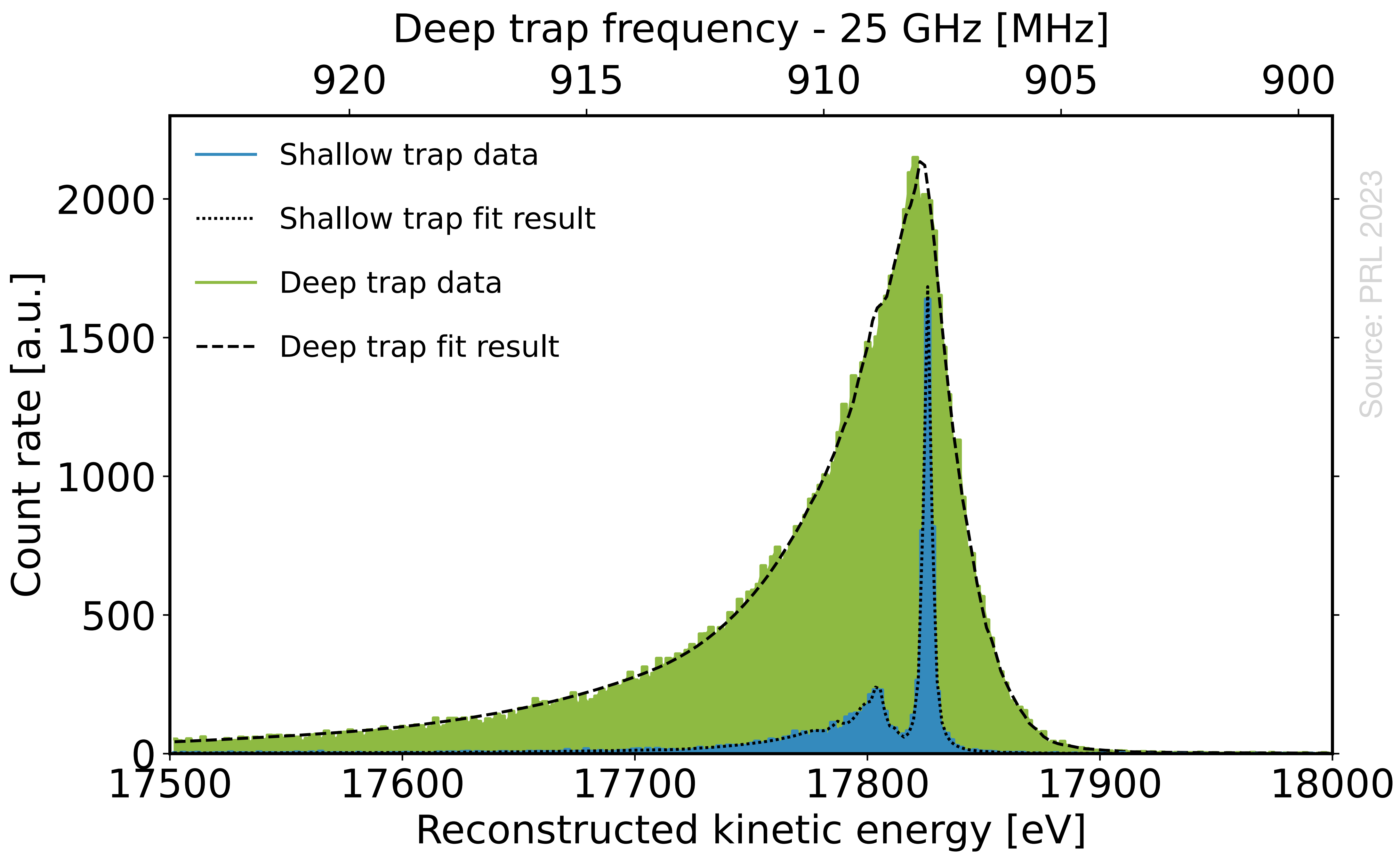



FIG. 3. Data and fits of the 17.8 keV $^{83m}$Kr conversion electron K-line, as measured in the shallow (high-resolution) and the deep (high-statistics) electron trapping configurations. The shallow trap exhibits an instrumental resolution of 1.66±0.16 eV (FWHM), while the deep trap provides direct calibration of the tritium data-taking conditions.

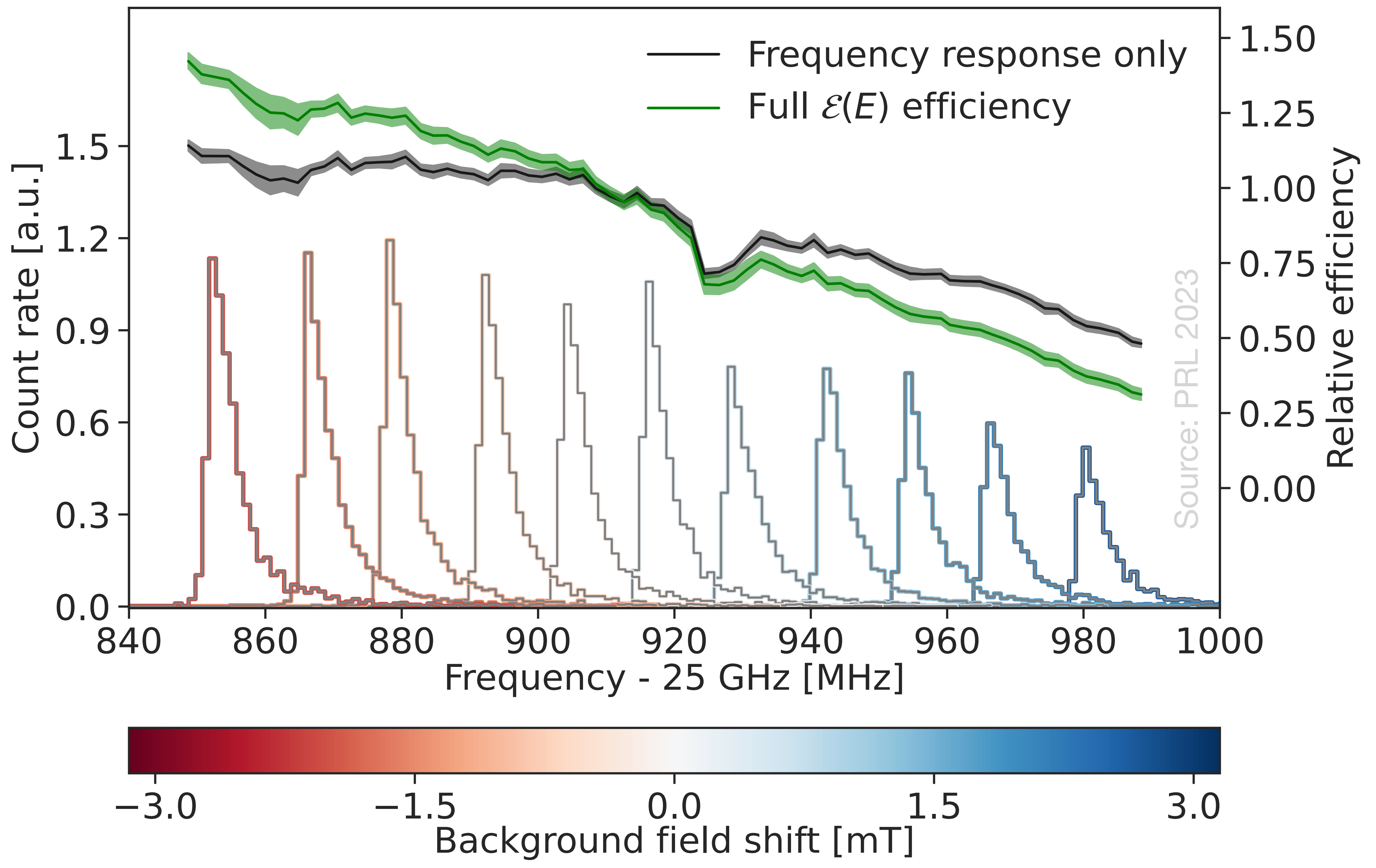



FIG. 4. The 17.8 keV $^{83m}$Kr conversion electron line recorded in the deep trap with varying magnetic background fields (red to blue). The gray curve shows the efficiency response to frequency variation, extrapolated from single trap data. The green curve is corrected for energy dependence and shows the relative efficiency predicted for tritium data.