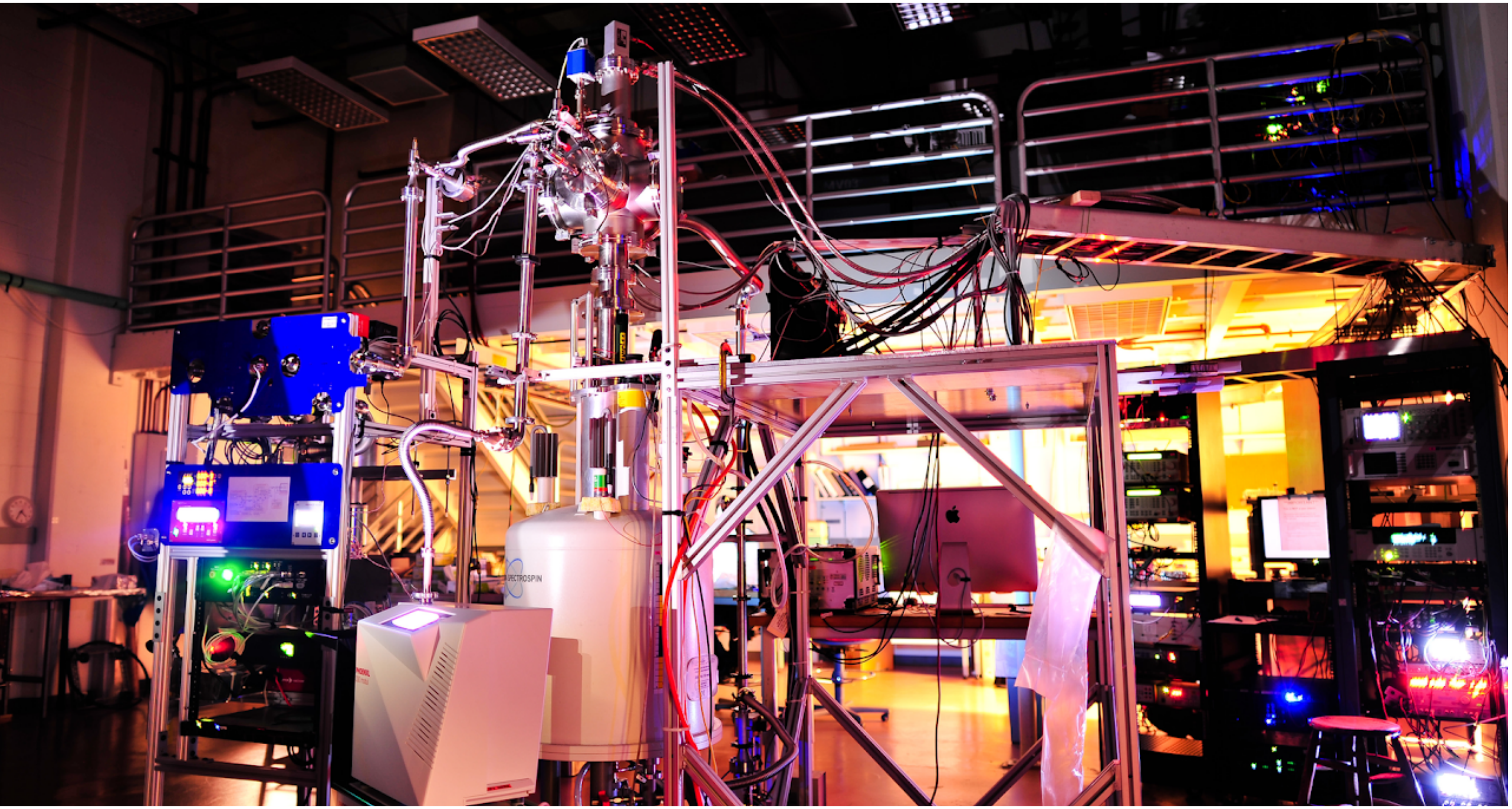
Project 8

Towards a Precise Measurement of the Neutrino Mass



Karsten Heeger
Yale University

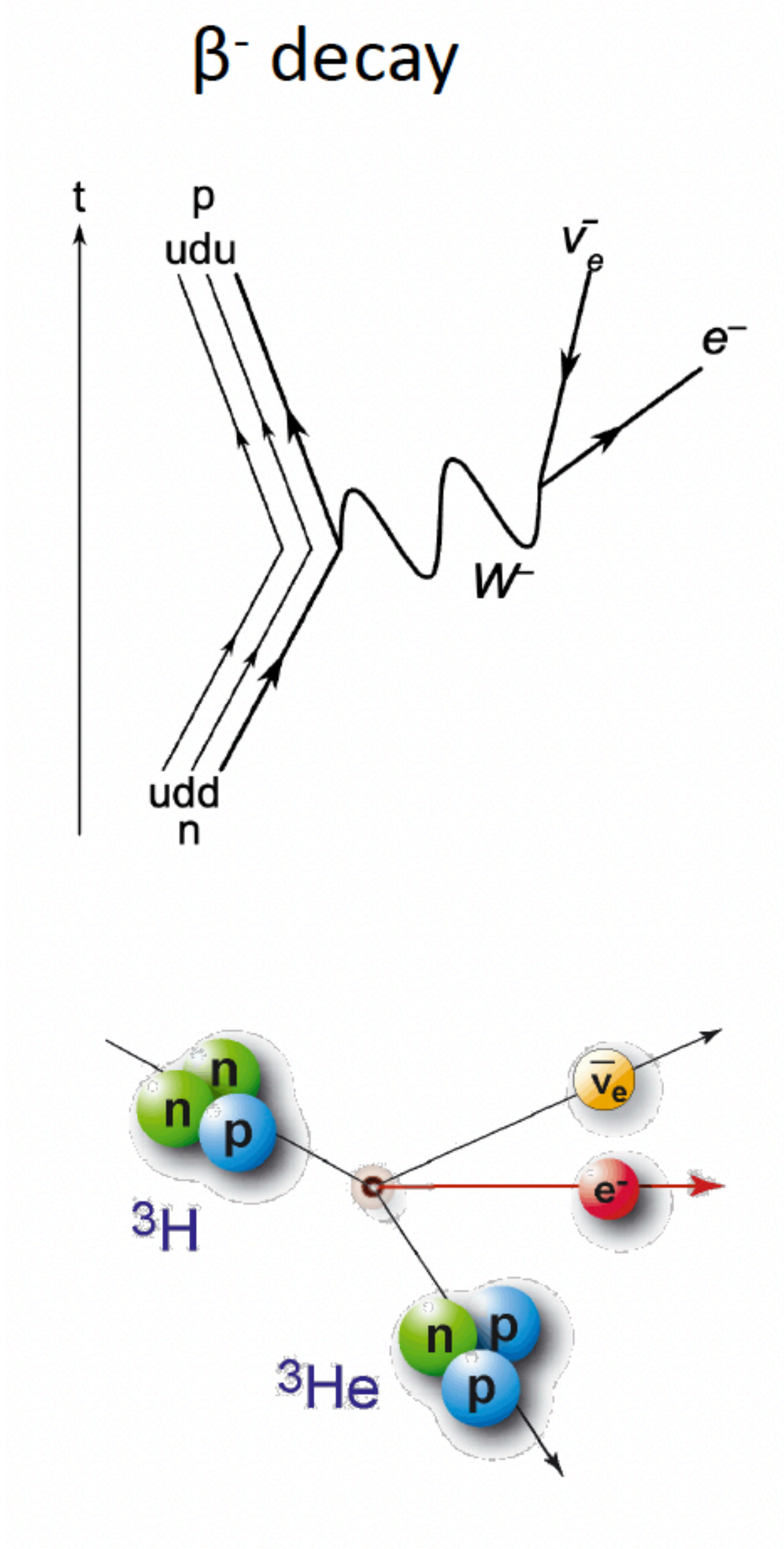
On behalf of the Project 8 collaboration

NPB 2024
February 19, 2024

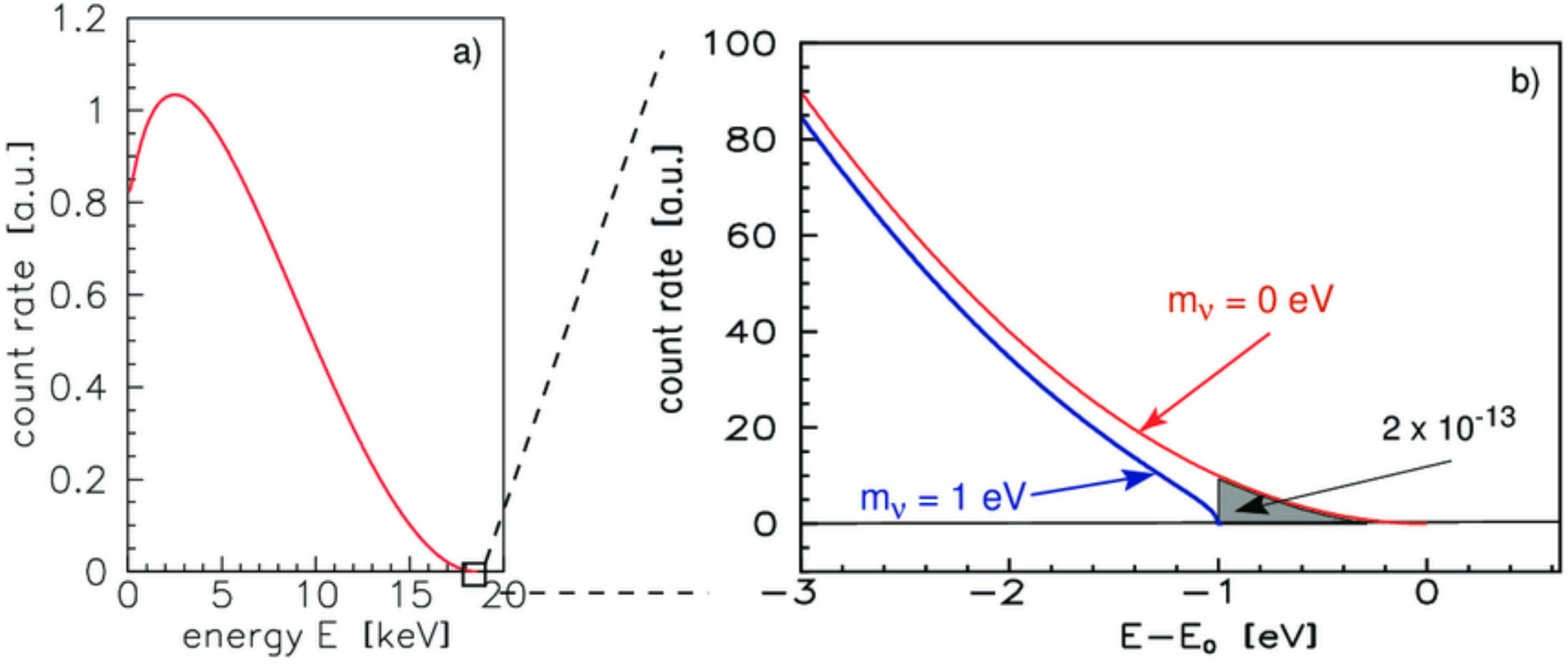
Yale

Neutrino Mass from Tritium β^- Spectroscopy

Tritium β^- spectroscopy is the leading technique for direct neutrino mass measurements



Energy spectrum of electrons emitted from tritium β- decay



Why tritium? Q = 18.6 keV

- Well understood spectral shape
- Relatively low endpoint of 18.6 keV and short half-life of 12.3 years
- 2×10^{-13} within 1eV below endpoint

Project 8 Collaboration

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Ruprecht Karls-Universität Heidelberg
- Felix Spanier

University of Illinois Urbana-Champaign
- Chen-Yu Liu

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Karlsruher Institut für Technologie
- Thomas Thümmler

Lawrence Berkeley National Laboratory
- Alan Poon

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Massachusetts Institute of Technology
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University of Pittsburgh
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Yale University
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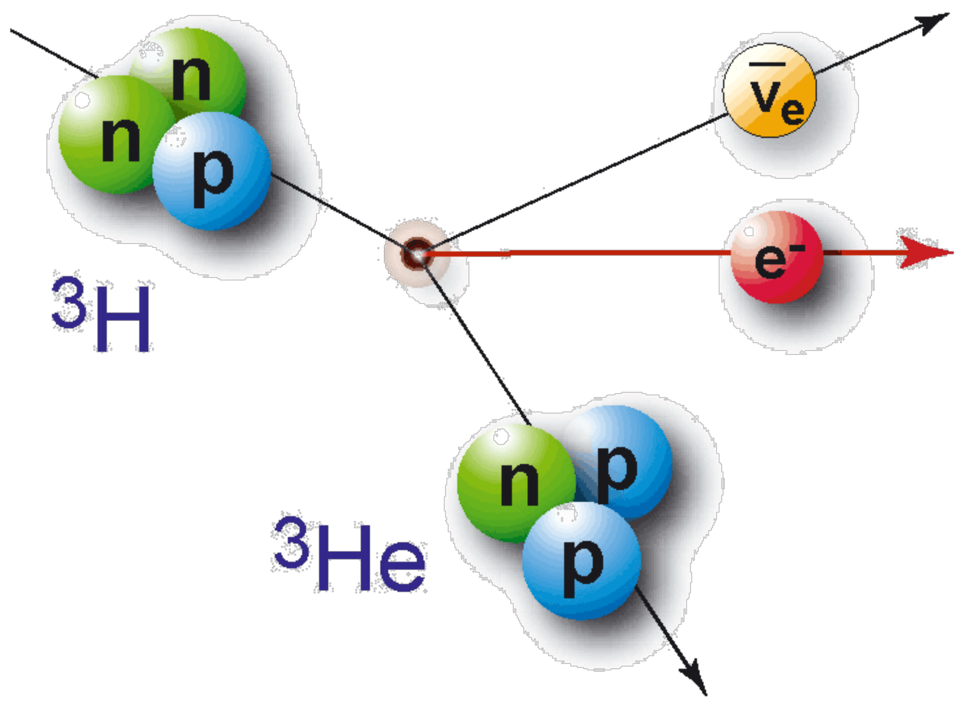
www.project8.org

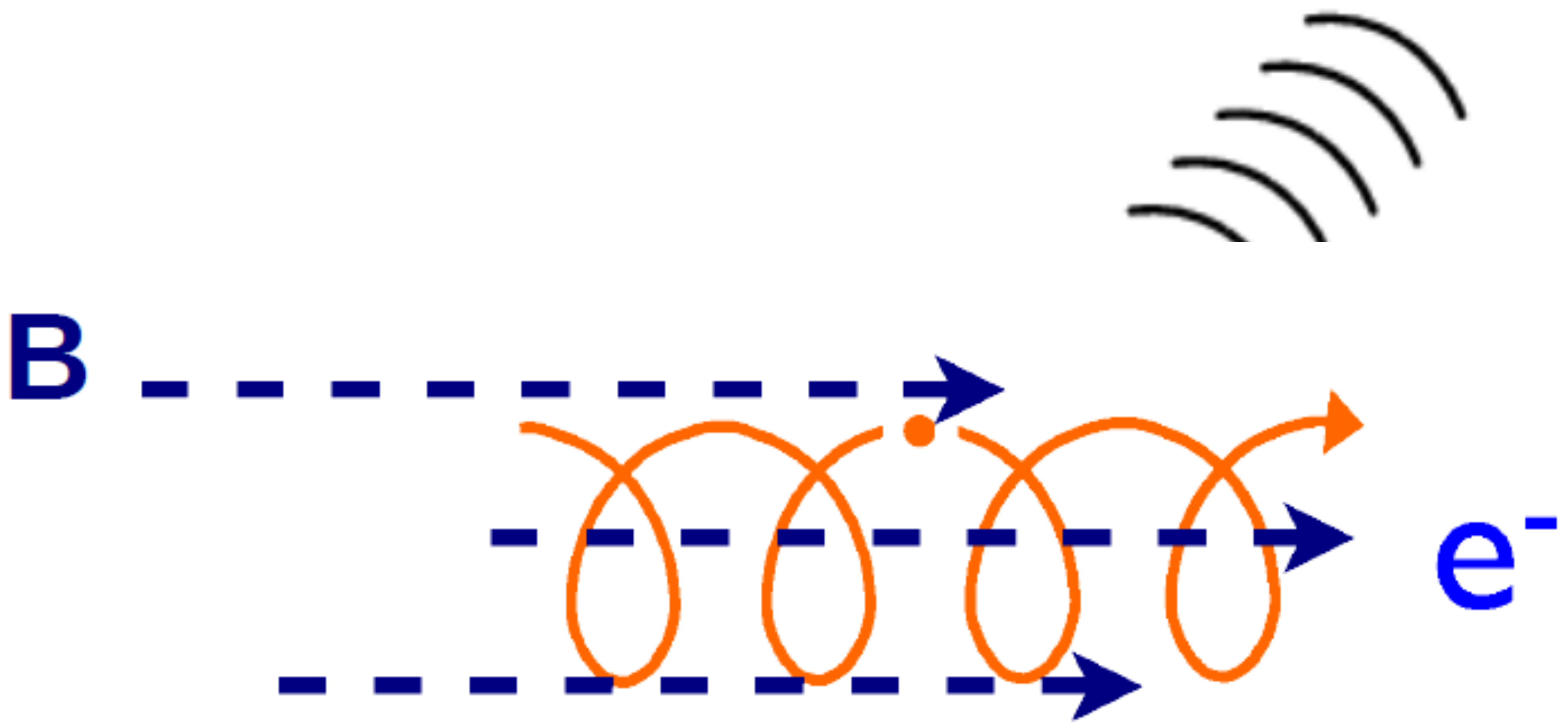
Cyclotron Radiation Emission Spectroscopy (CRES)

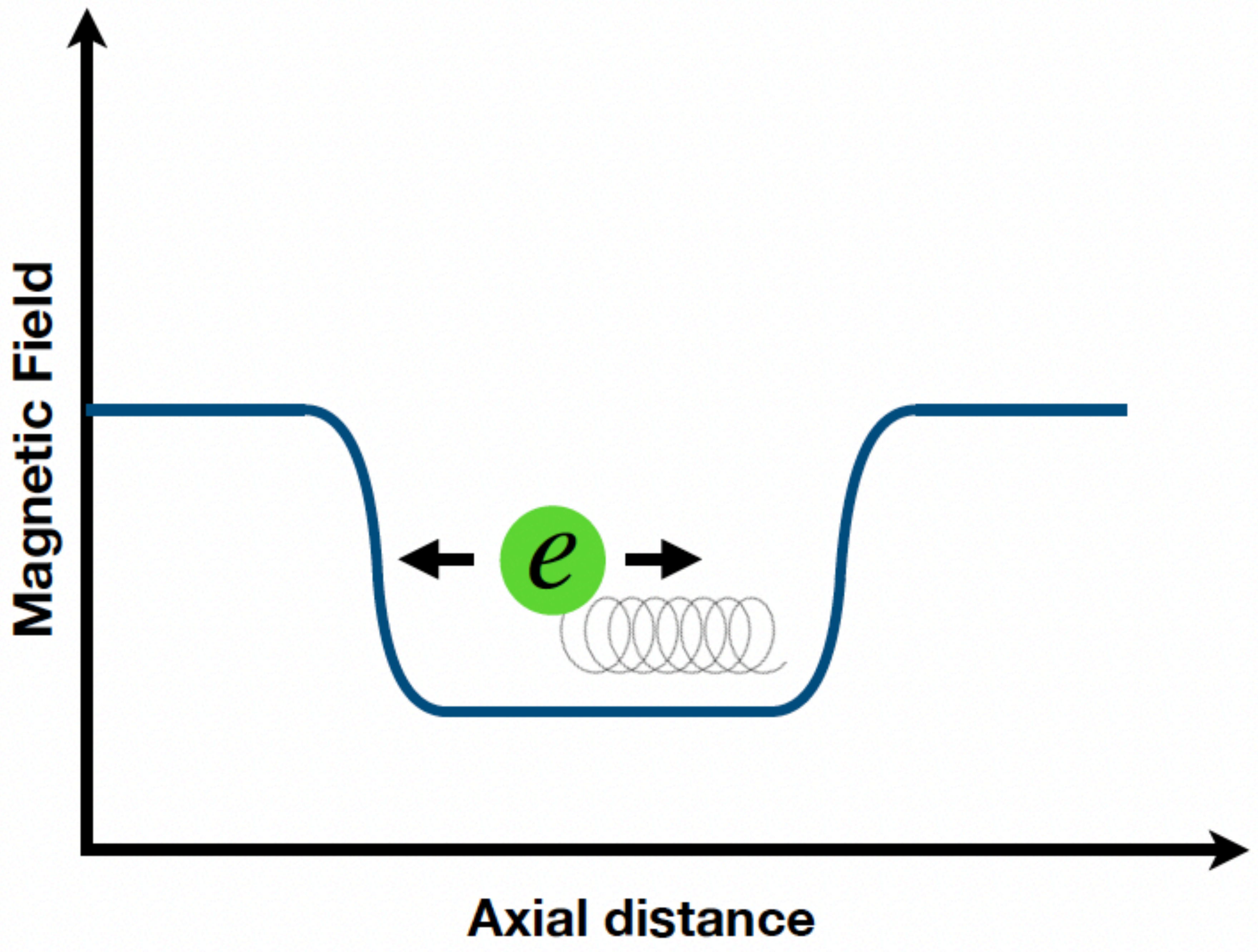


In uniform magnetic field, a charged particle will have a helical trajectory

Accelerating electron will radiate EM waves at frequency:

$$f_{Cyc} = \frac{1}{2\pi}\frac{qB}{m\gamma} = \frac{1}{2\pi}\frac{qB}{m_e + E_e}$$

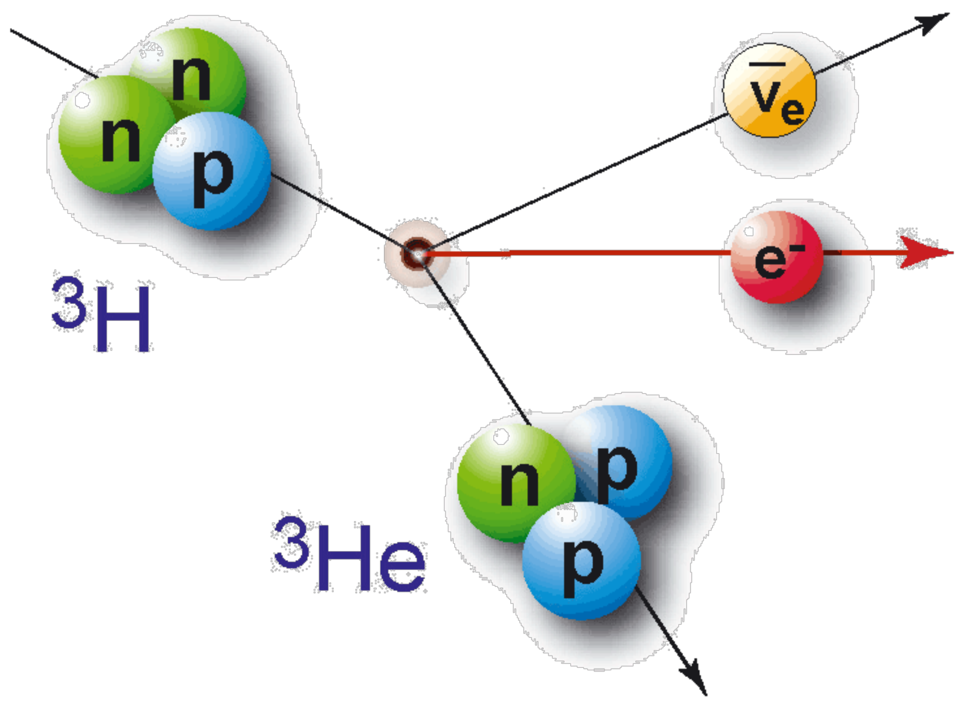


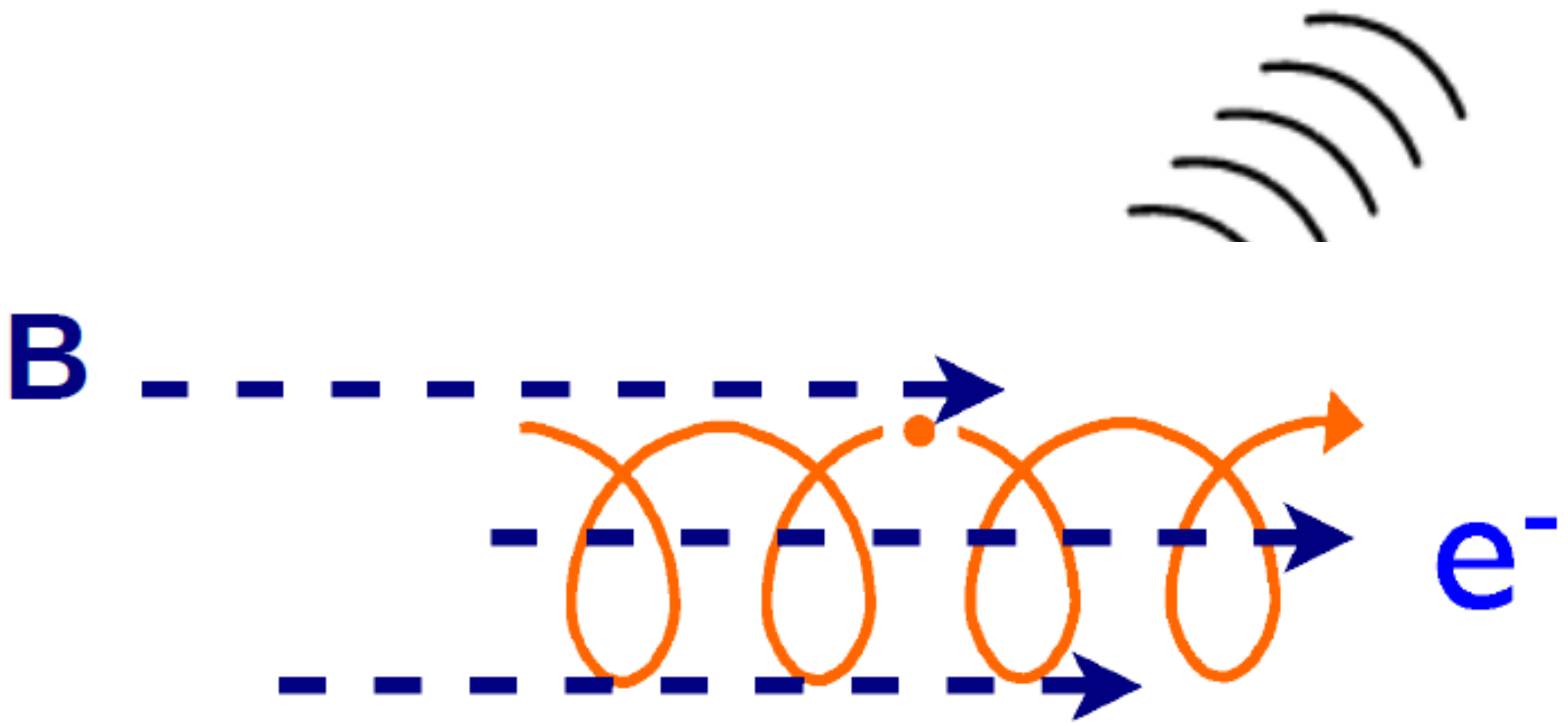


Working principle

- Source gas in a strong homogeneous magnetic field
- Trap electron in magnetic bottle trap
- Electrons emit cyclotron radiation
- Detect radiation and reconstruct kinetic energy

Cyclotron Radiation Emission Spectroscopy (CRES)





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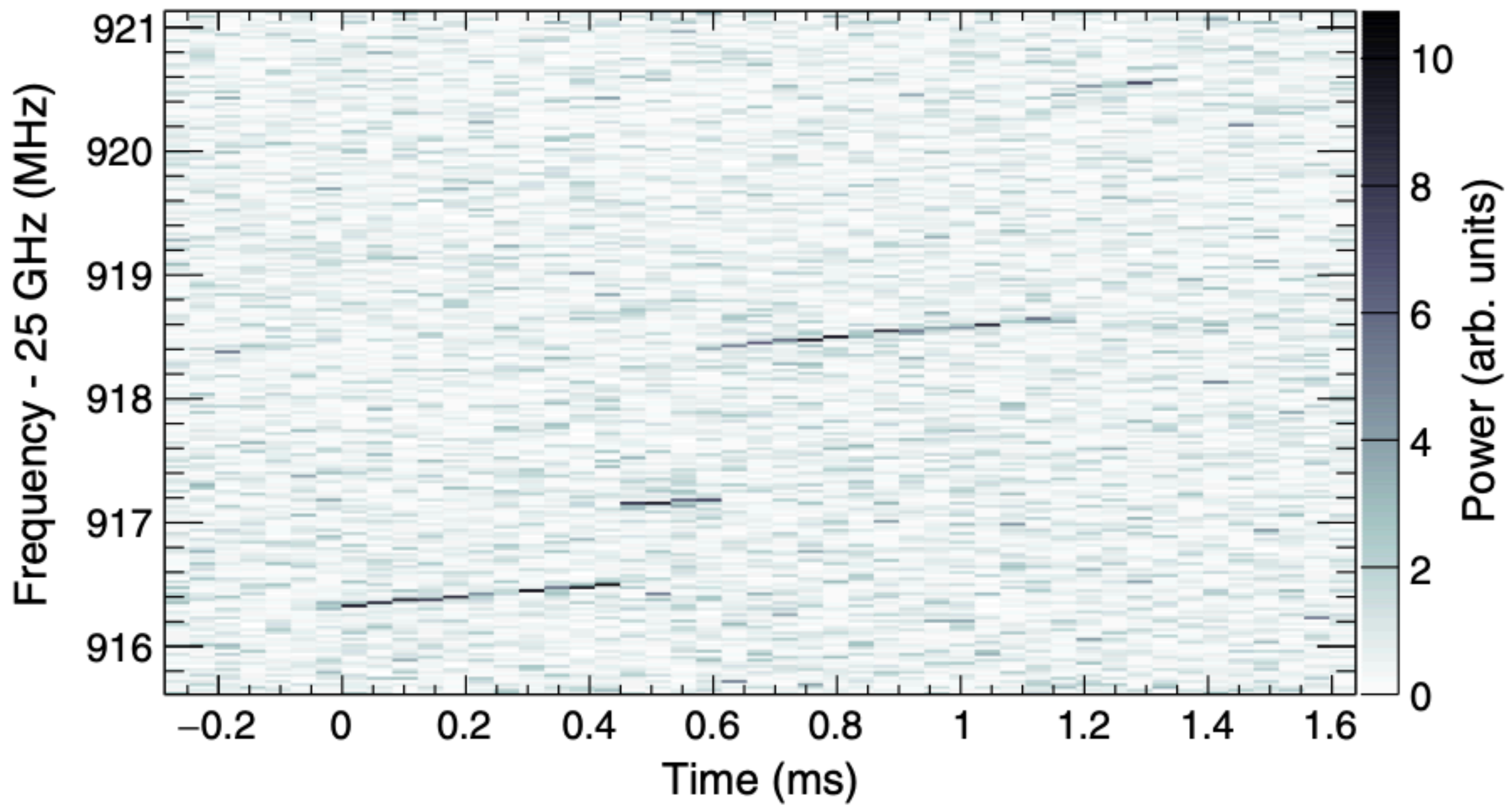

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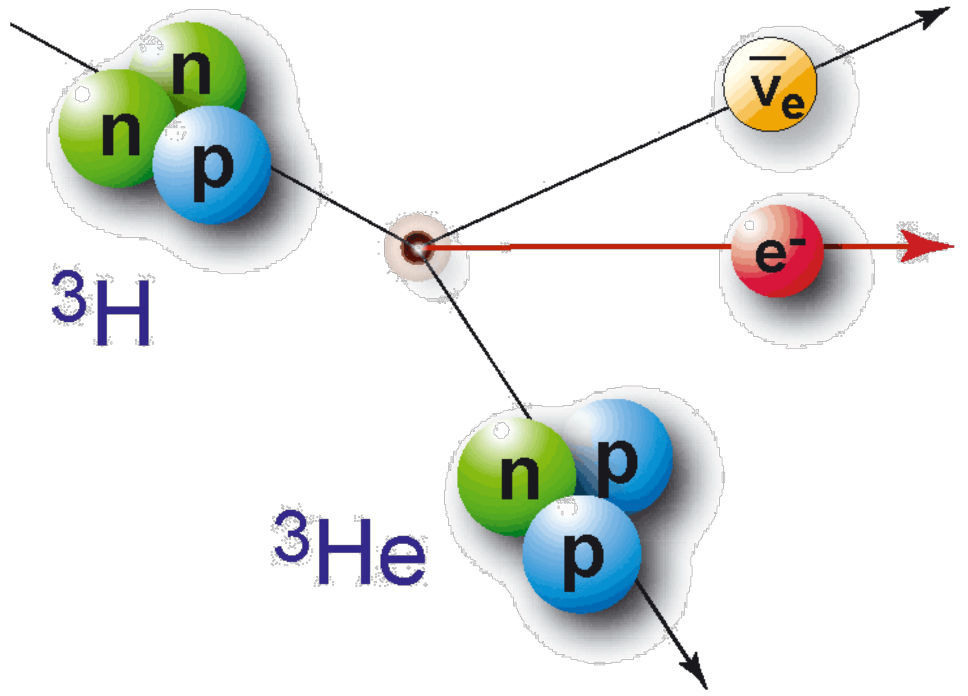

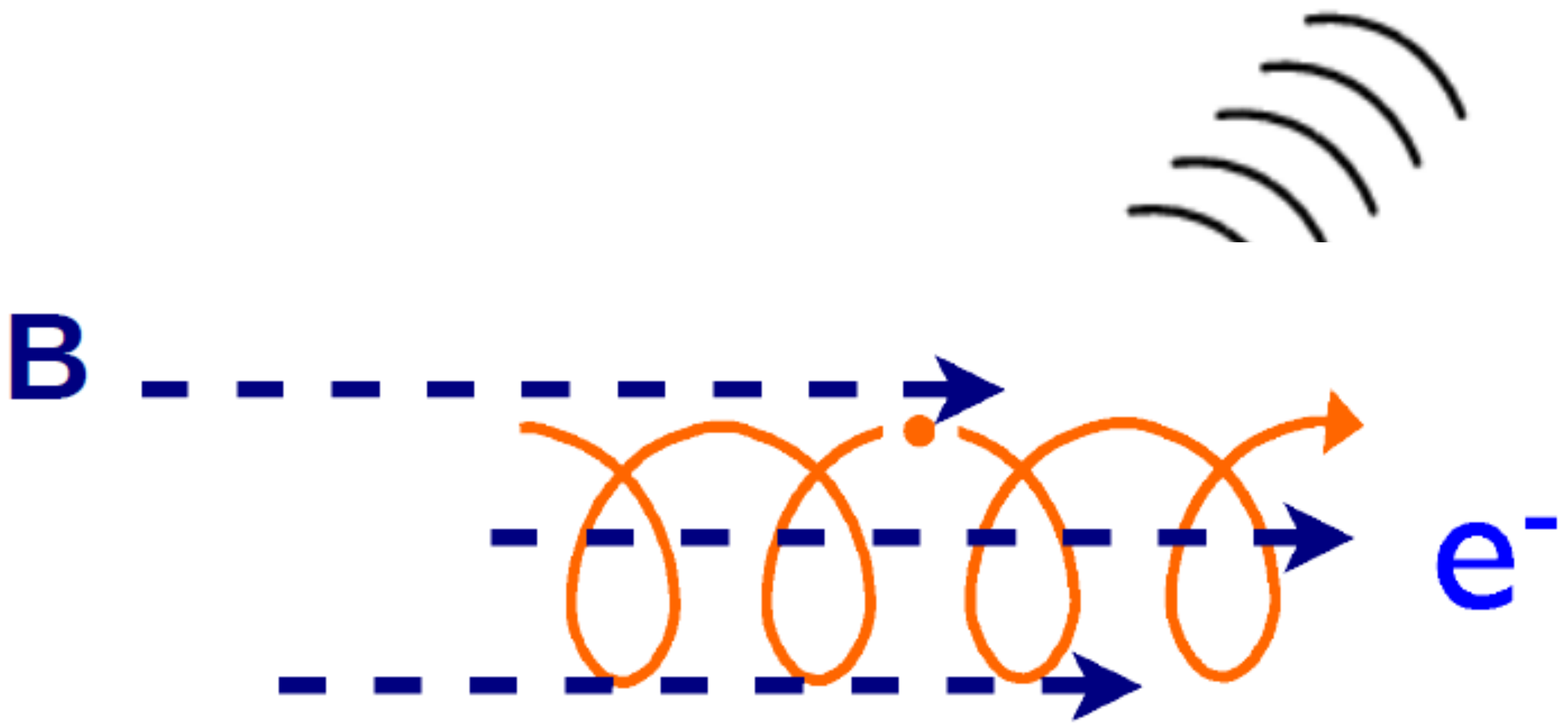

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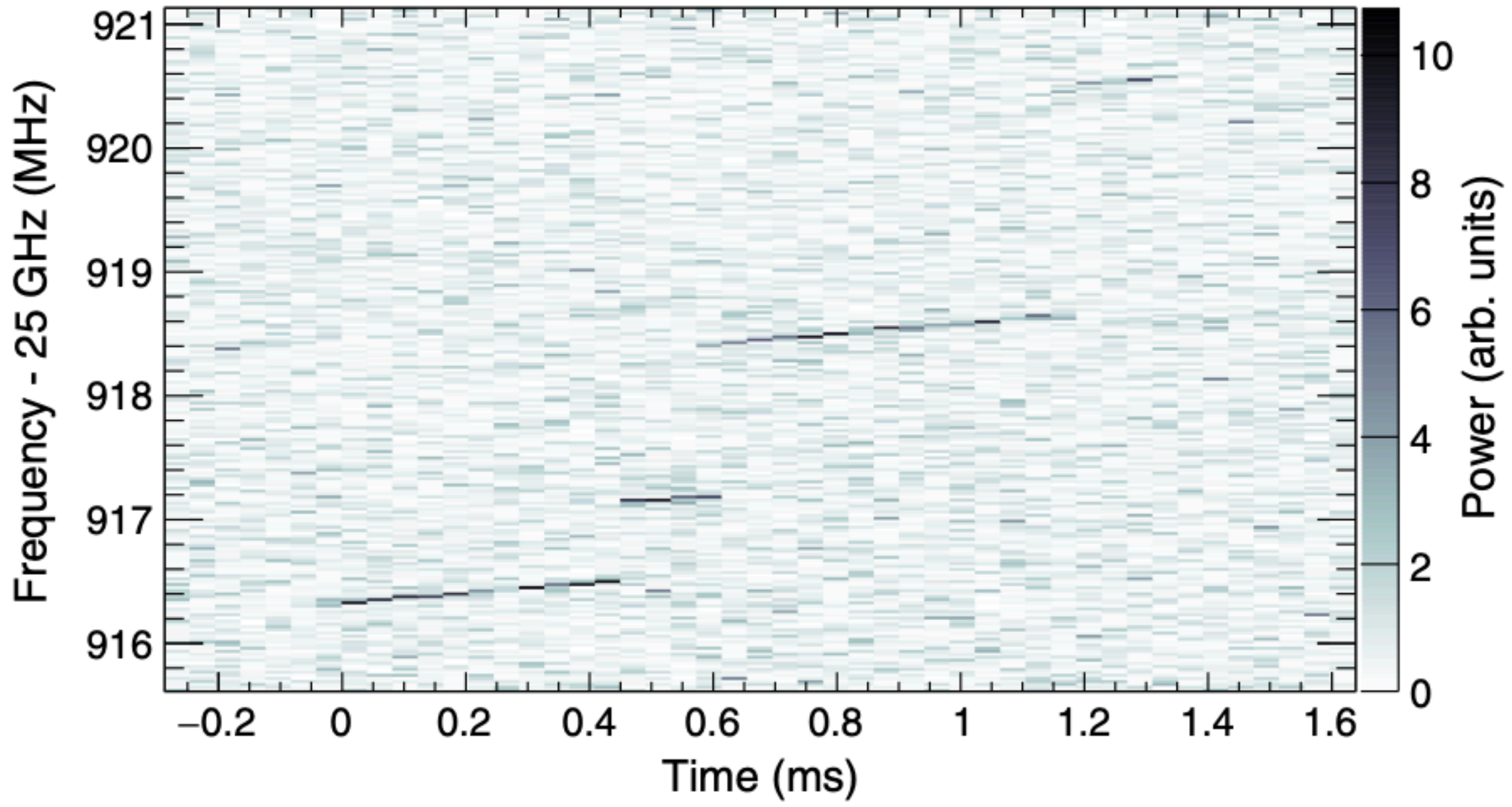

- Magnetic trap (no energy change)
- Extends observation time of electron (*time)
- Knowledge of B places limit on energy resolution

$$\triangle E = \frac{\triangle B}{B}(m_e c^2 + E_{kin})$$

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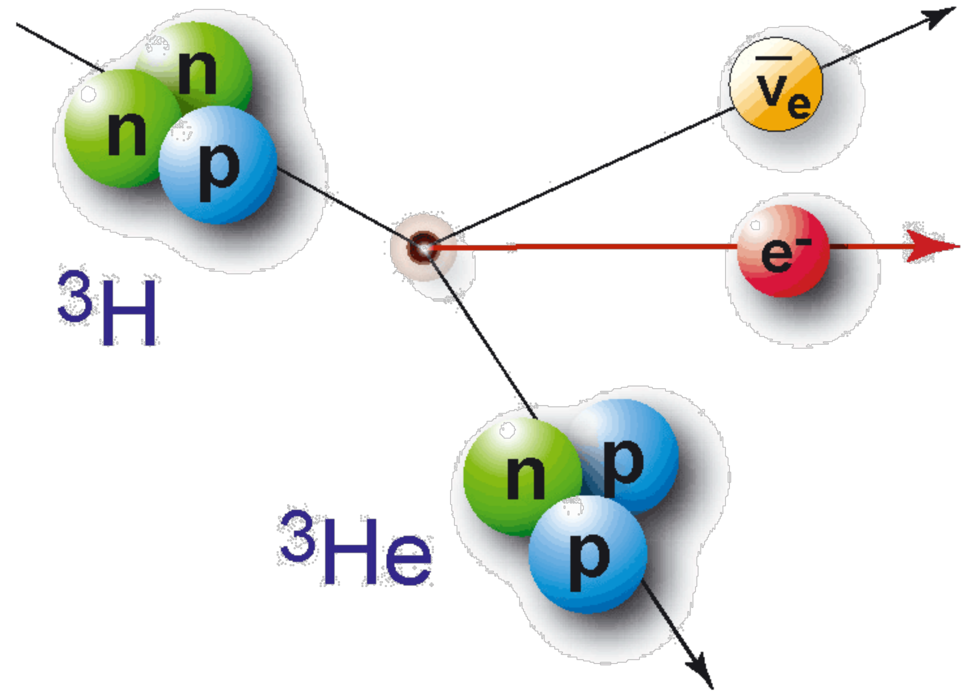
Cyclotron Radiation Emission Spectroscopy (CRES)



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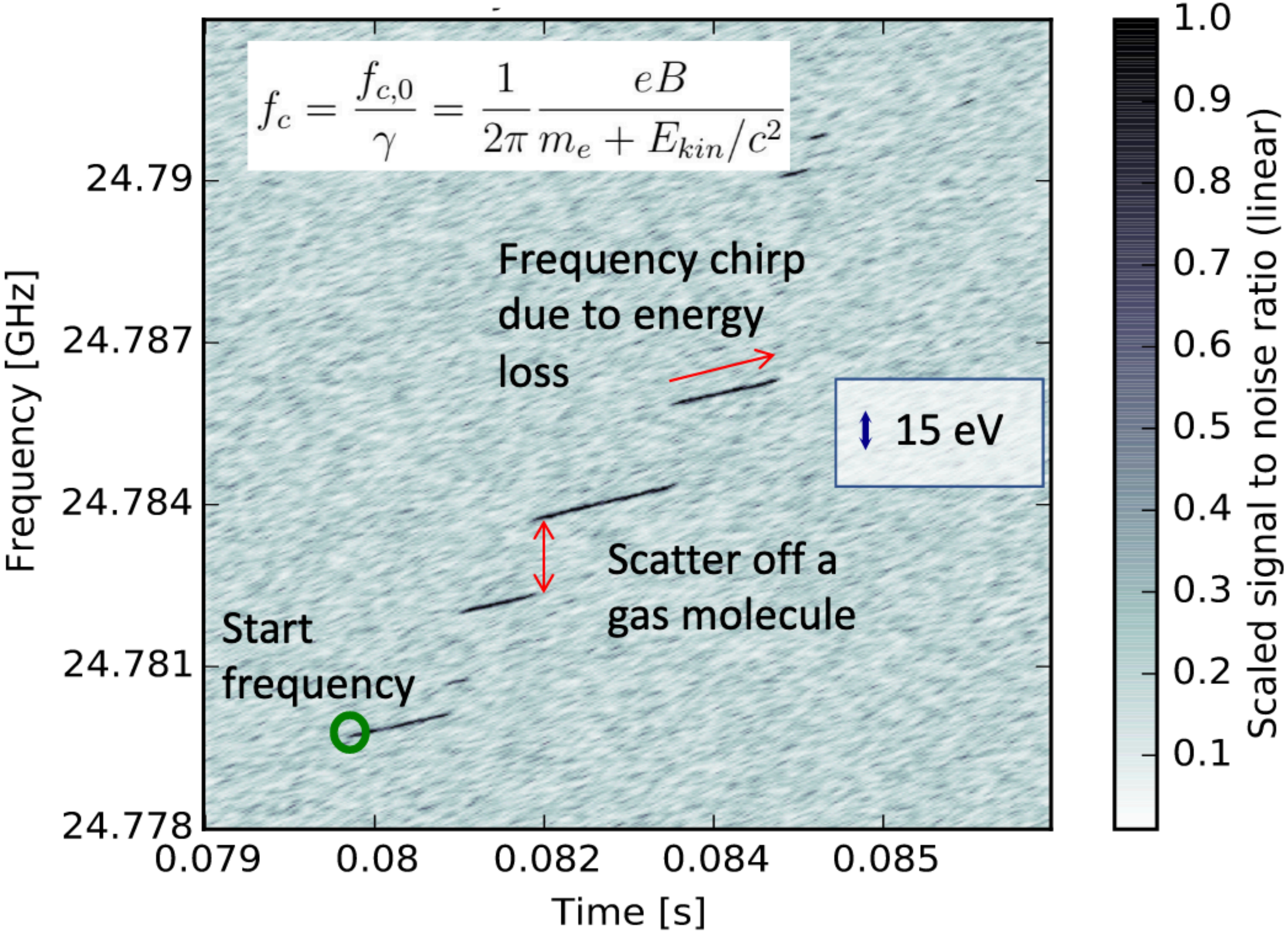

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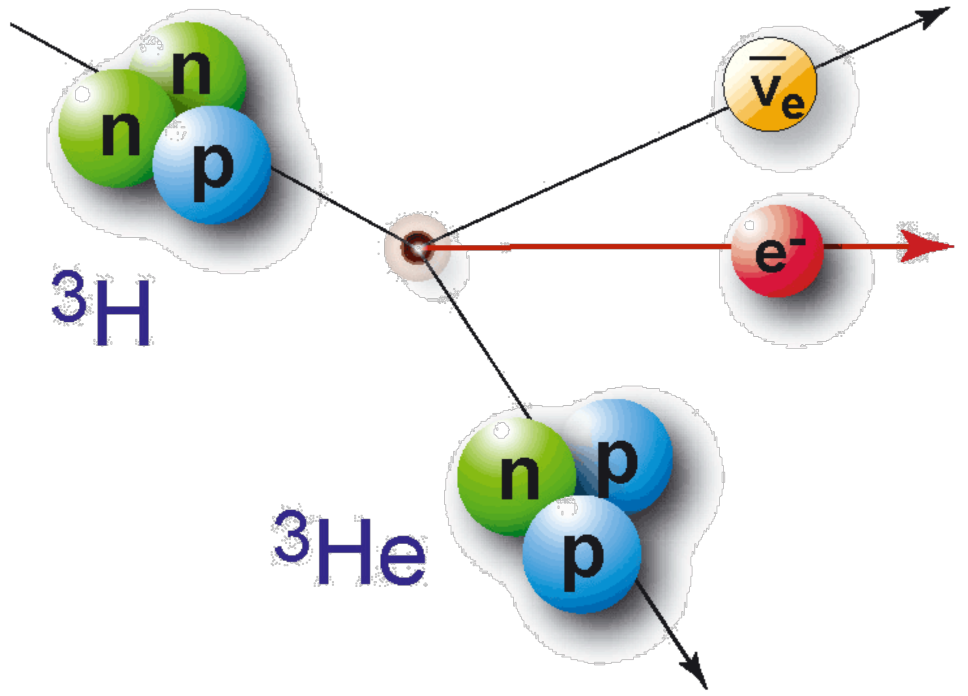

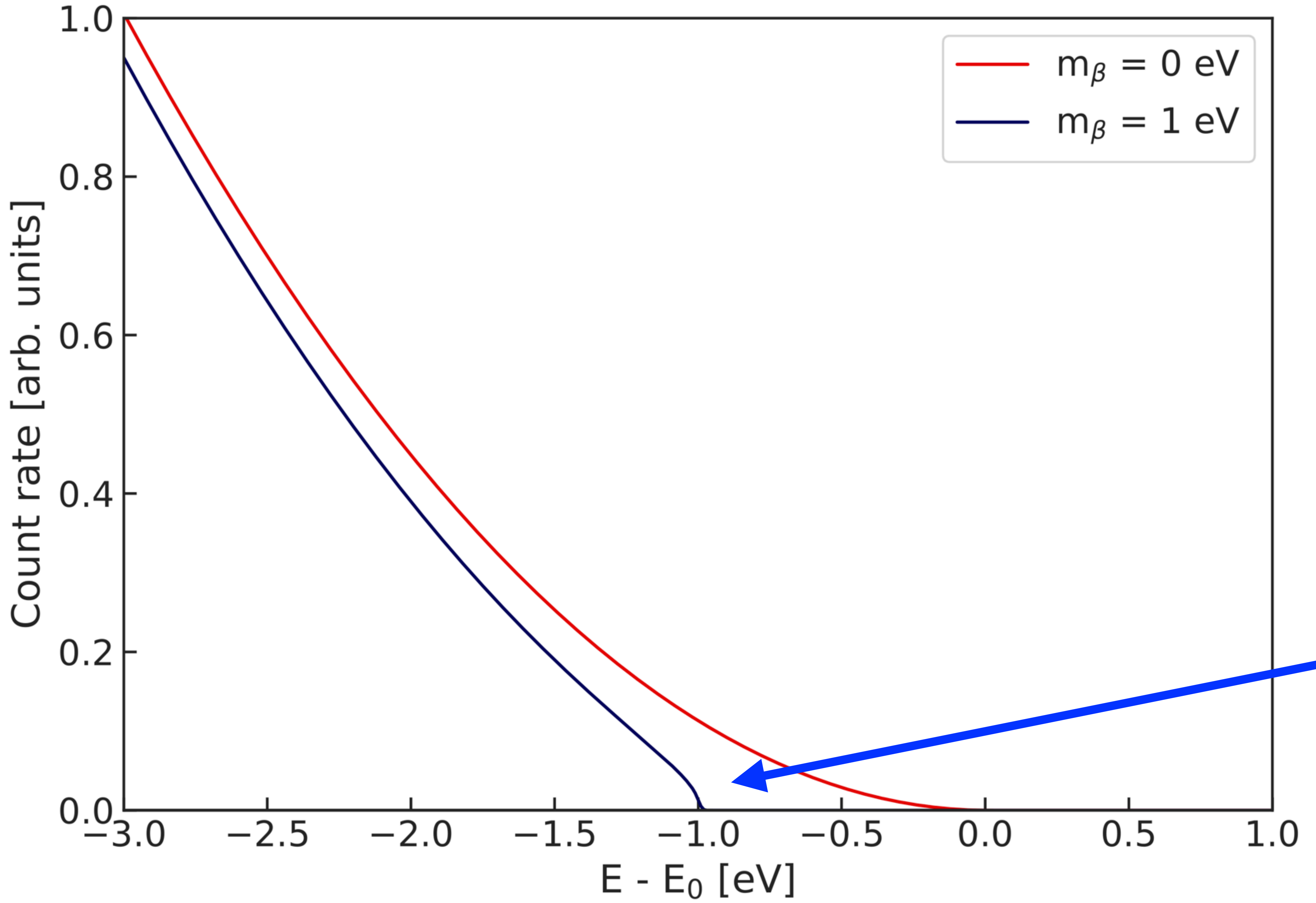

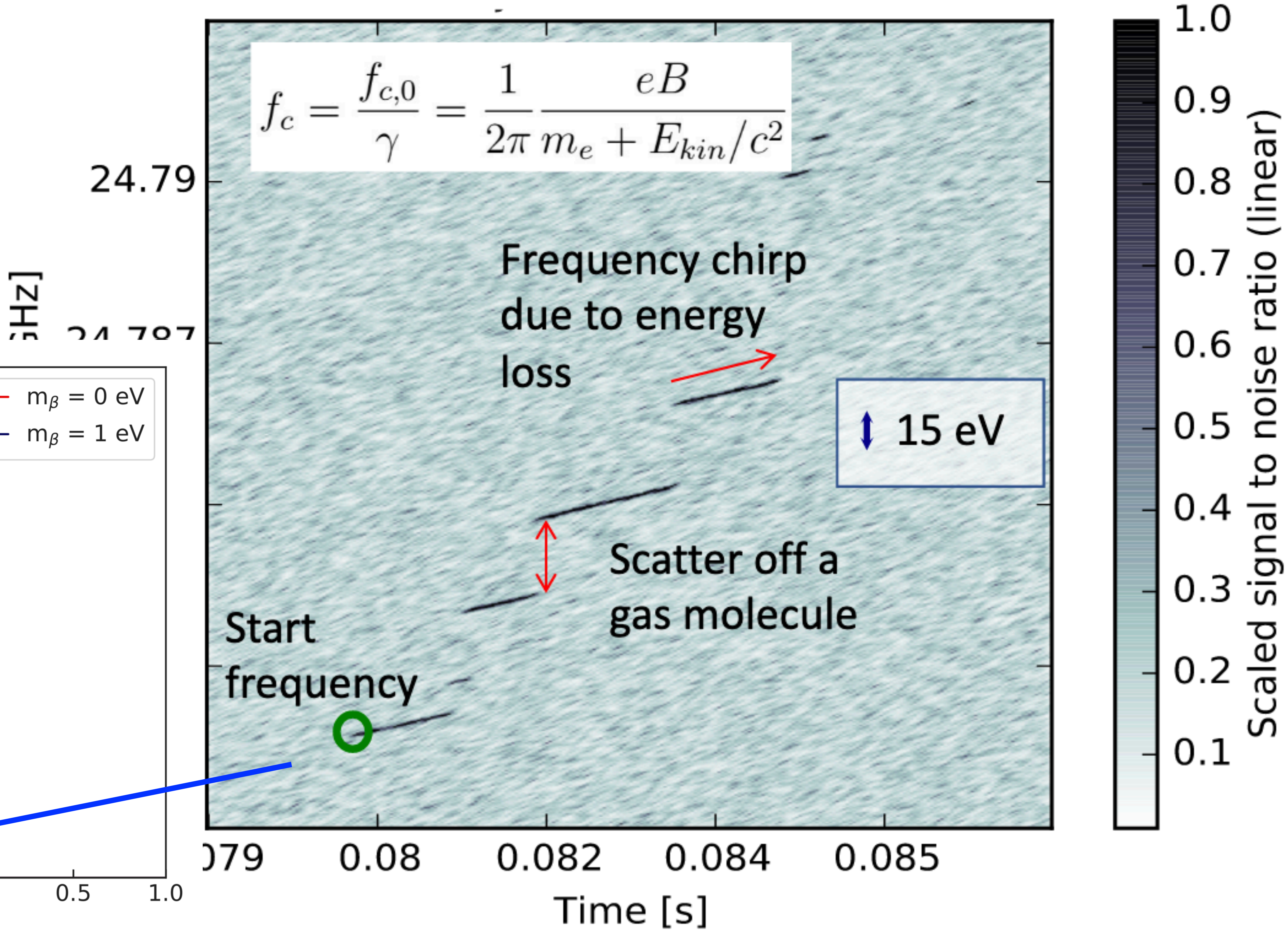

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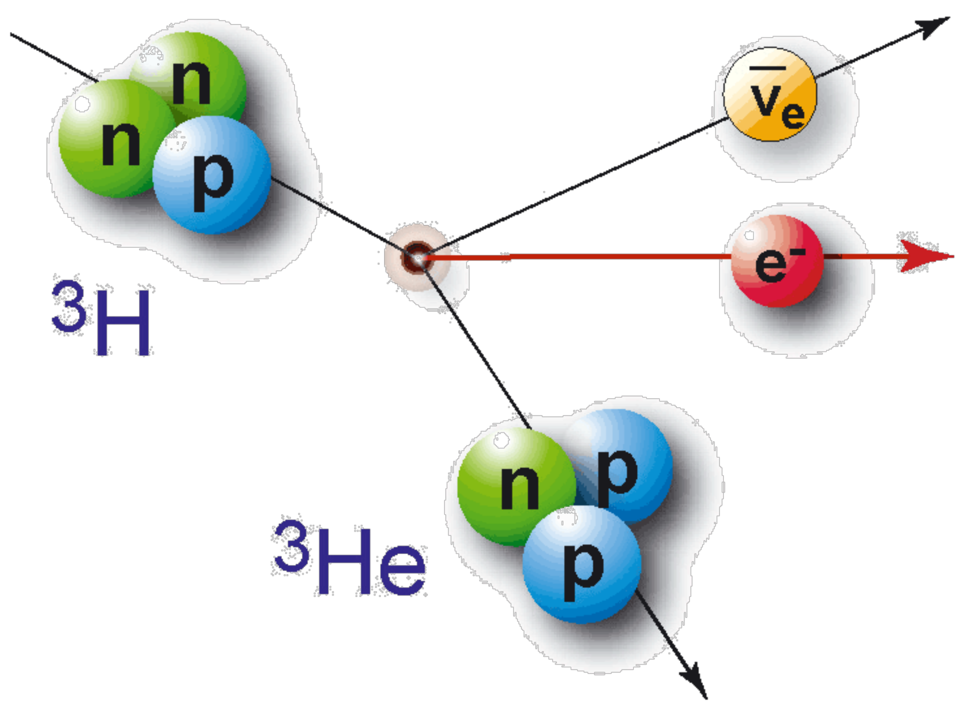

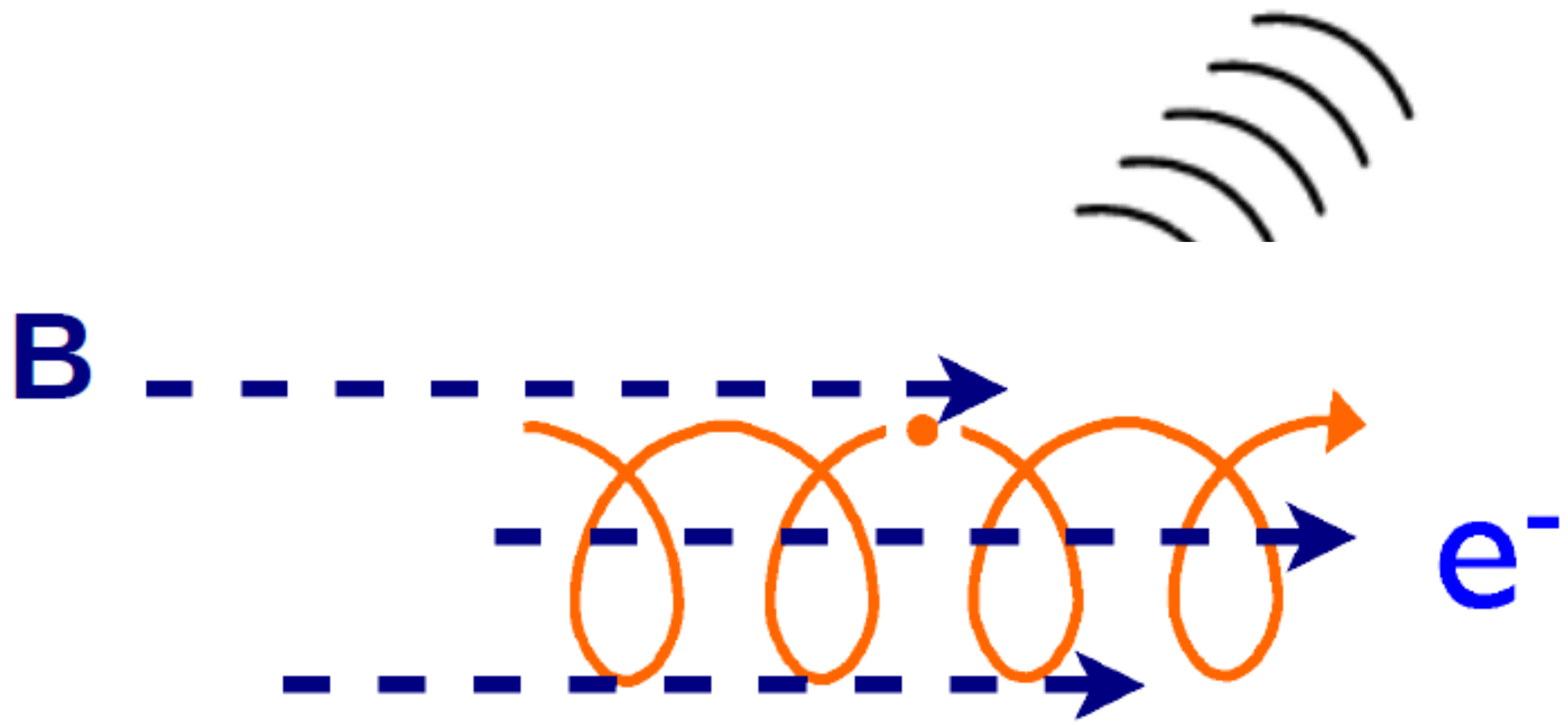

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Frequency measurement ➡	High precision
Source is transparent to microwave radiation ➡	No electron transport; volume scaling
Differential spectrometer ➡	Increased statistical efficiency
Compatible with atomic tritium ➡	Avoids T_2 final-state broadening
Low background ➡	More info near endpoint

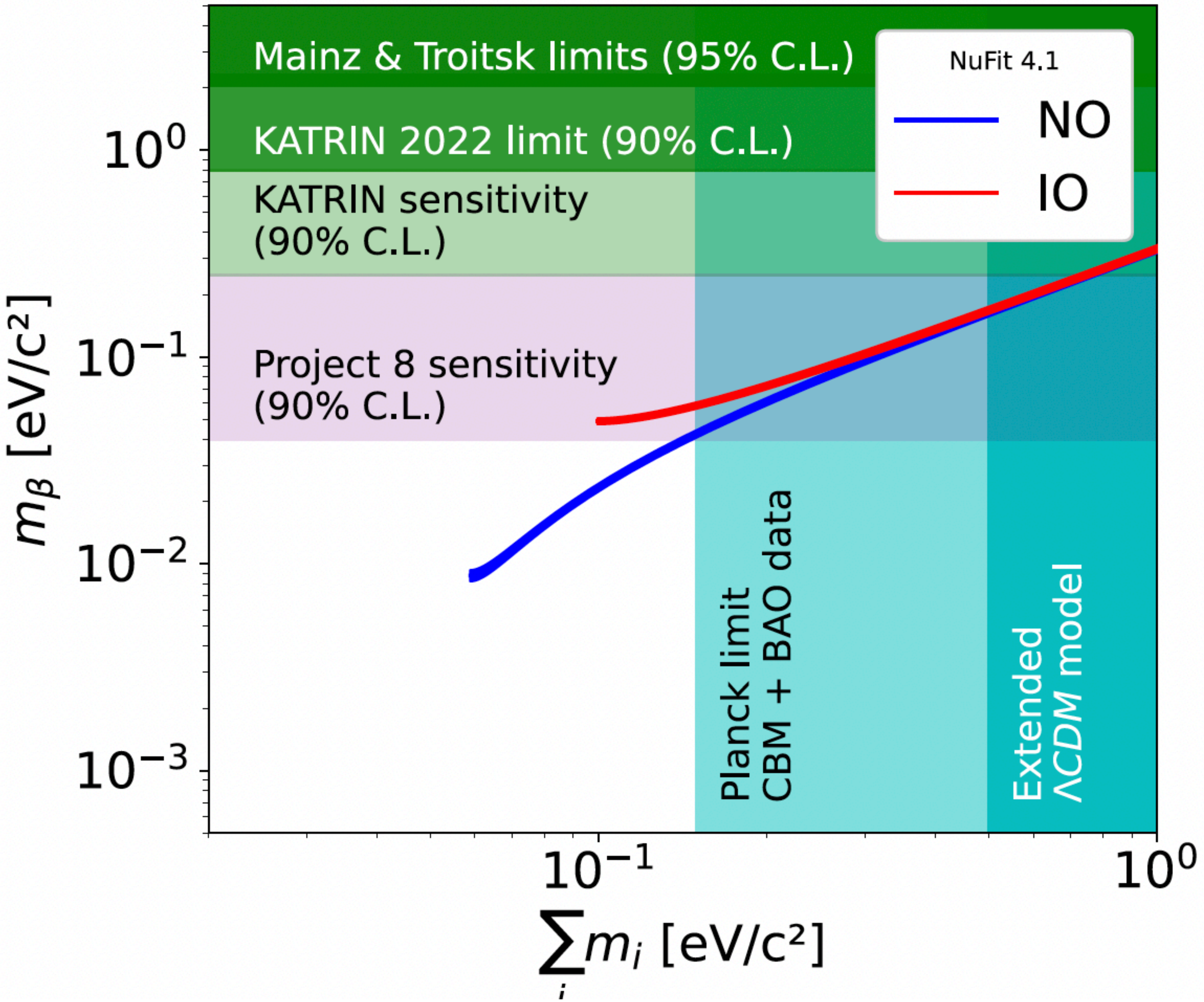
Project 8 - Sensitivity Goal

Goals

Sensitivity to 0.04 eV/c² neutrino mass

Measure neutrino mass or exclude inverted hierarchy

Simultaneous sensitivity to active and sterile neutrinos

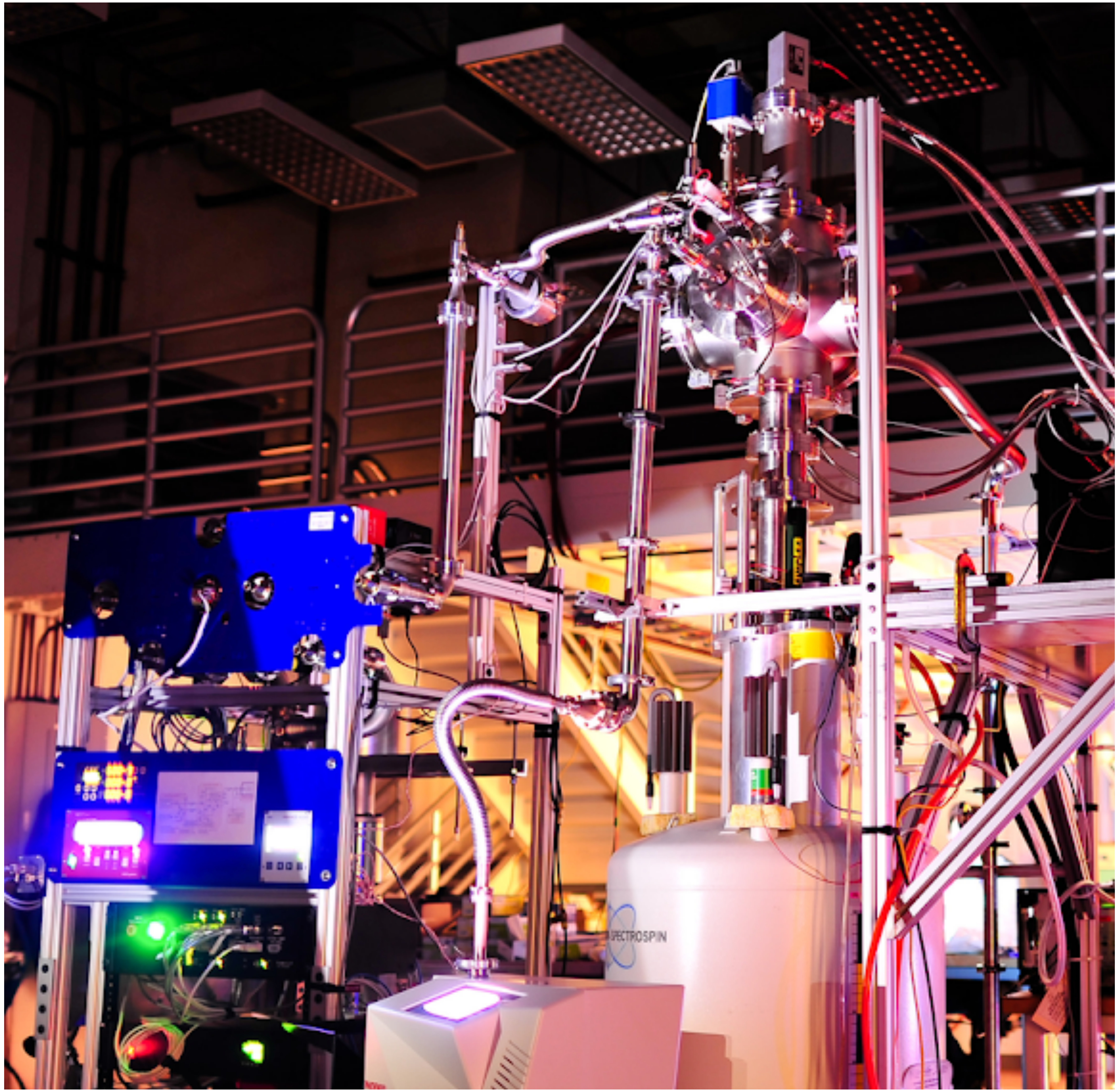


Project 8

Phase I first demonstration of CRES

Phase II first CRES experiment with molecular tritium, sensitivity to neutrino mass

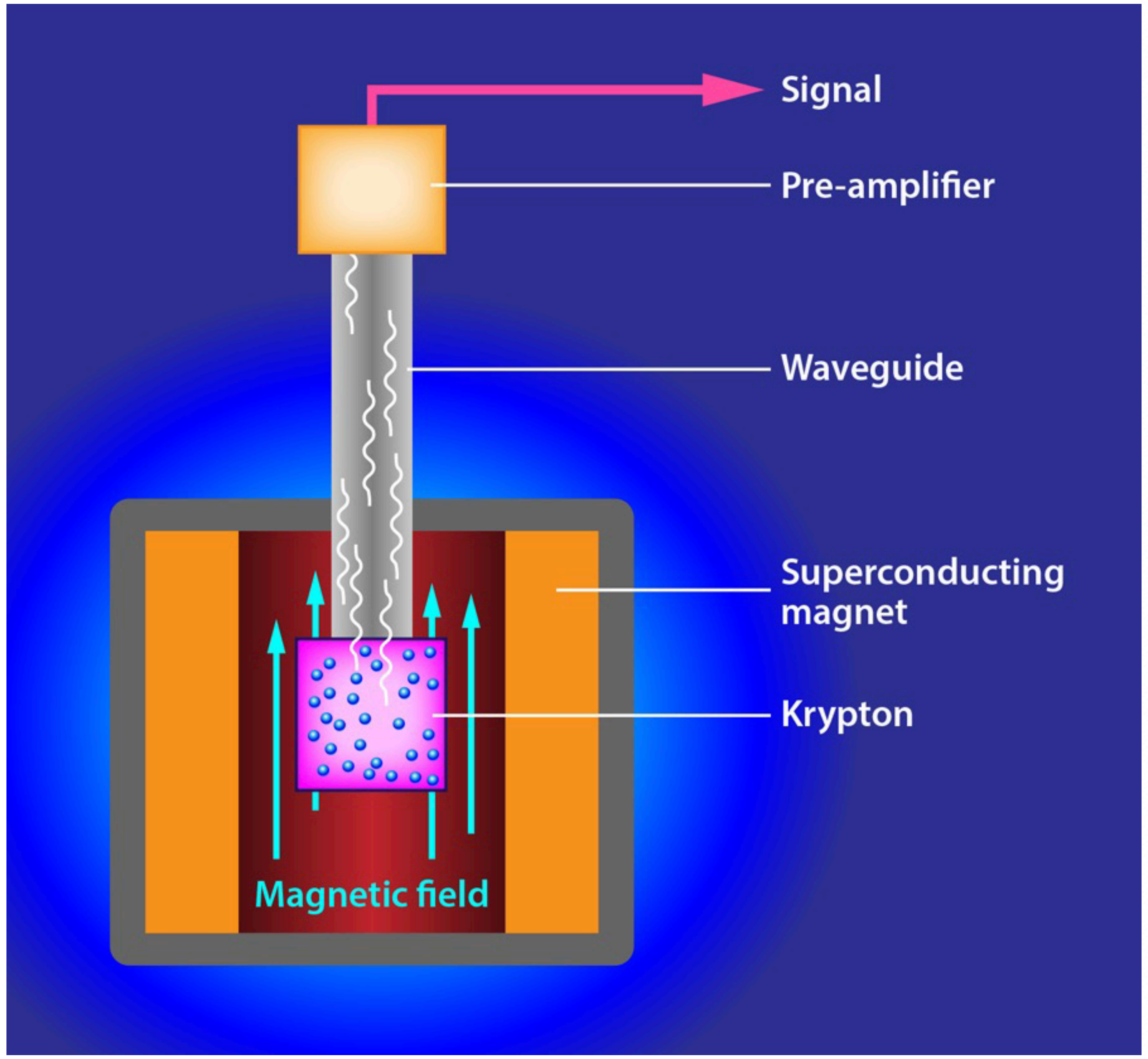
~mm^3 effective volume

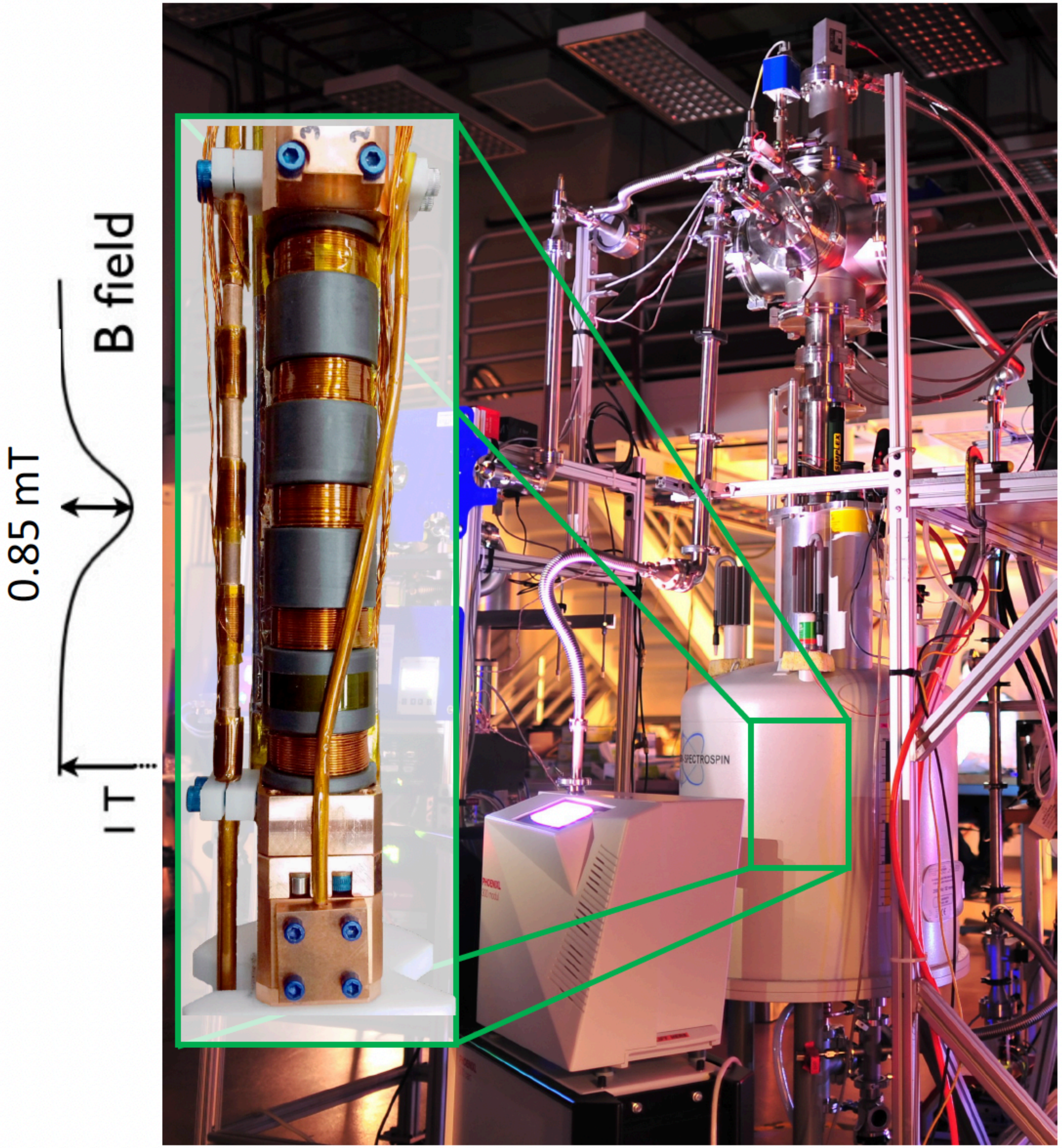


PROJECT 8

Project 8 - Phase II

Wave guide experiment for molecular tritium

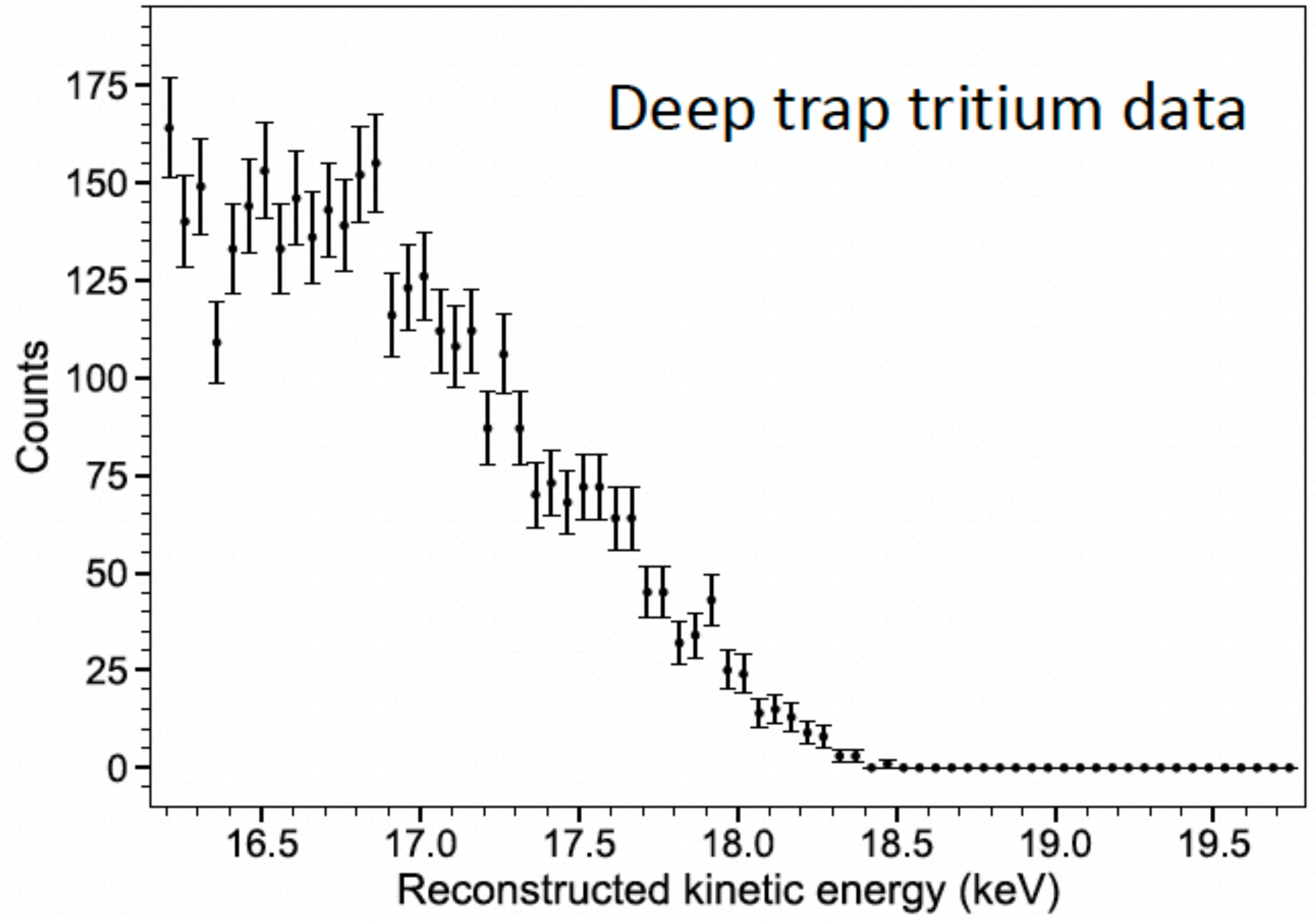




Project 8 - Phase II

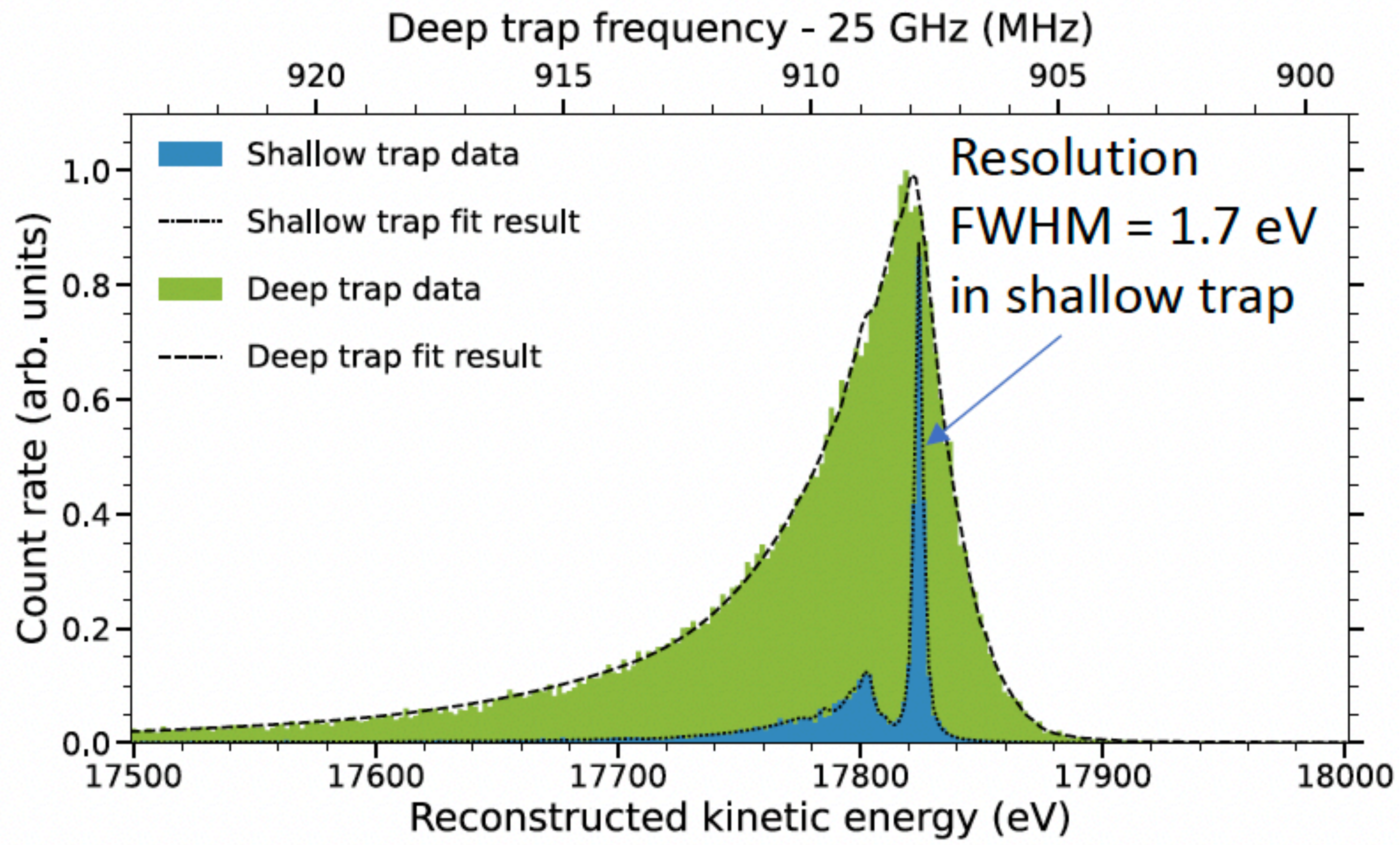
First molecular tritium spectrum recorded with CRES

- 3770 events after all cuts
- Frequency range corresponds to 16.2 – 19.7 keV
- No background events beyond the endpoint



^{83m}Kr data for systematic studies and calibration

- Quasi-monoenergetic internal conversion lines
- 17.8 keV is close to tritium endpoint (18.6 keV)
- Ideal for calibration and systematic studies
- Resolution width depends on magnetic trap depth



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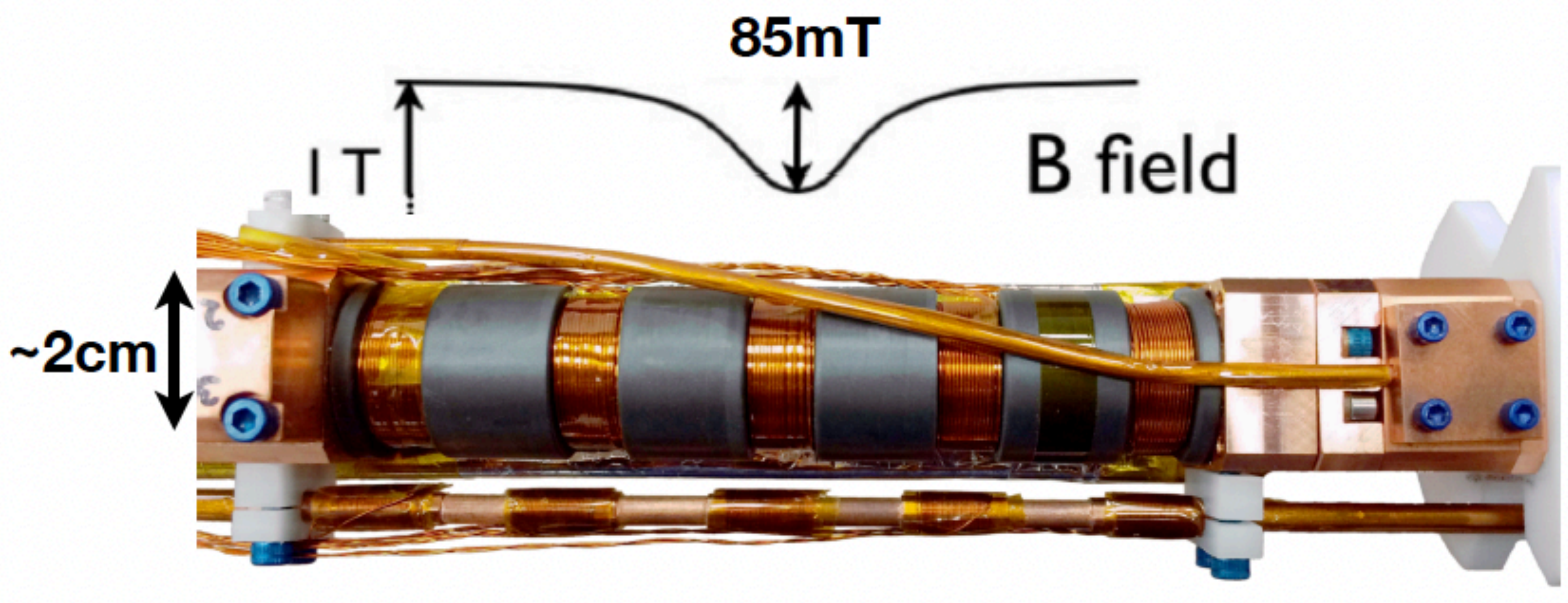
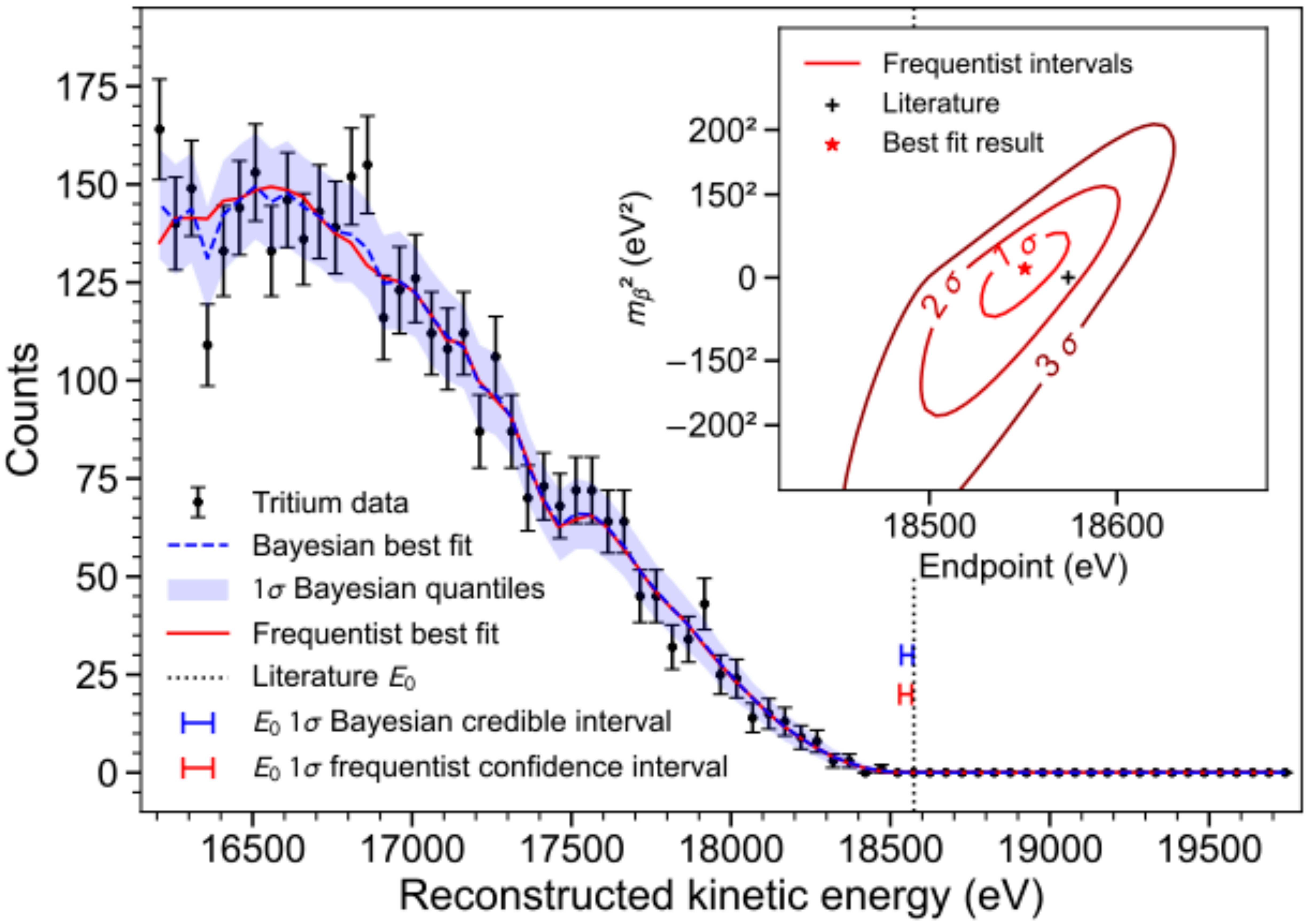
Project 8 - Phase II



- Count rate: 3770 events over 82 days. T_2 at 10^{-6} mbar
- Resolution: 54.3 eV (FWHM)
- Effective volume: 1.20 ± 0.09 mm^3



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Project 8 - Phase II

Demonstrated understanding of **detector response,** control of systematic effects from scattering & field inhomogeneity (statistics-limited)

Stringent **background limit,** no events above endpoint!

T_2 endpoint measurement in agreement with literature

First **neutrino mass** measurement using CRES

Background rate

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

T_2 endpoint

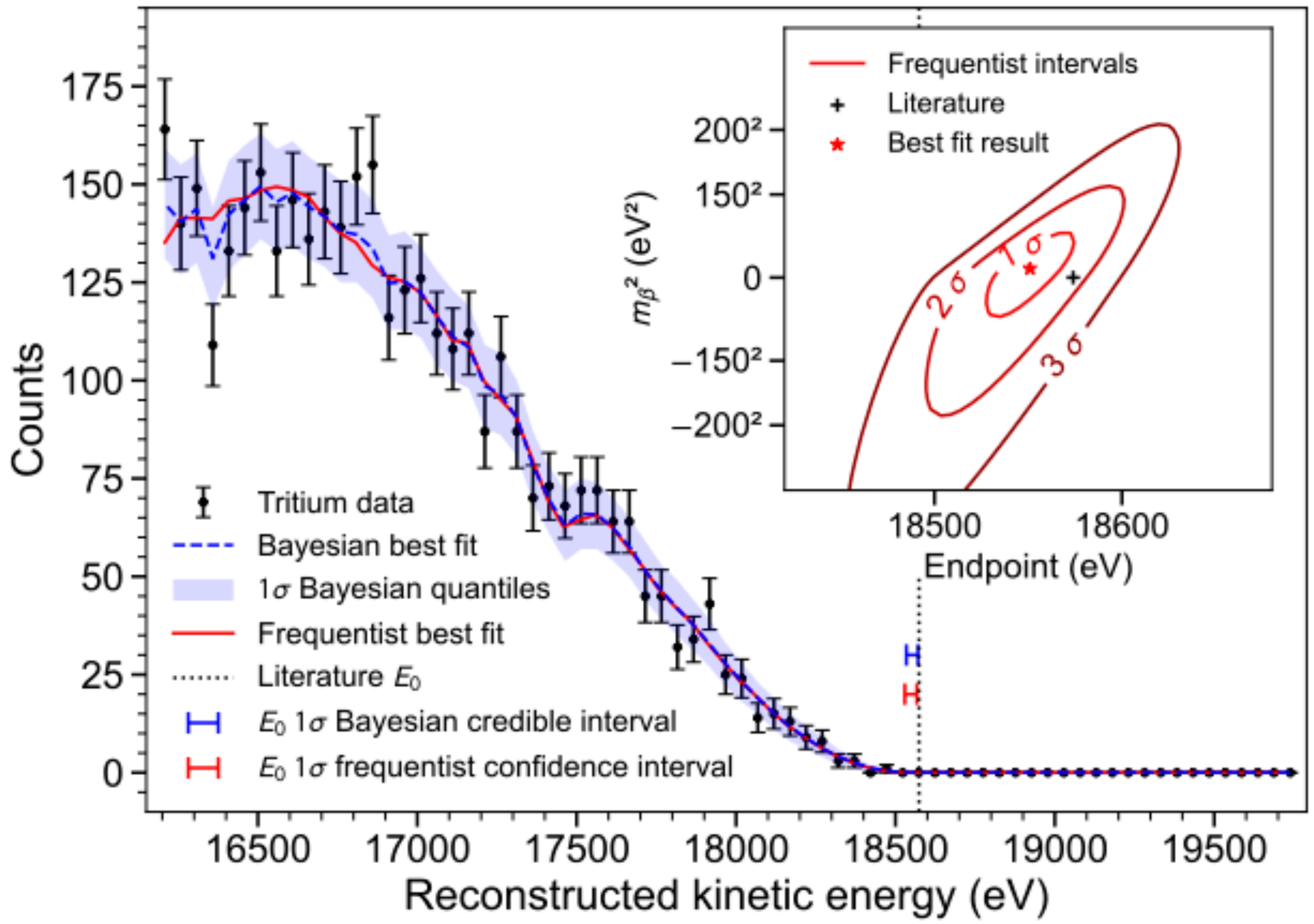
Frequentist: $E_0 = (18548^{+19}_{-19})$ eV (1σ)

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

Neutrino mass

Frequentist: $\leq$ 152 eV/c² (90% C.L.)

Bayesian: $\leq$ 155 eV/c² (90% C.L.)



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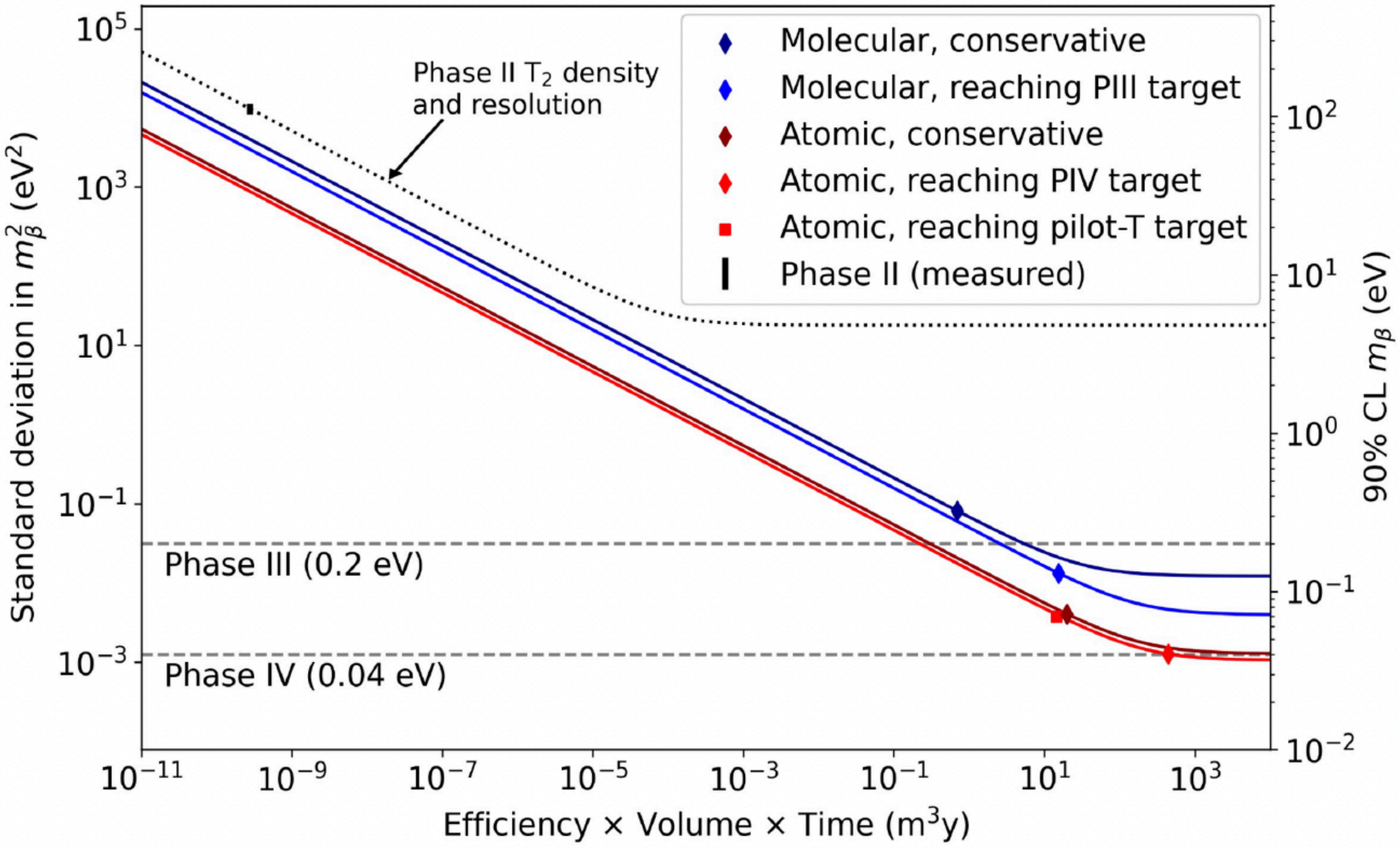
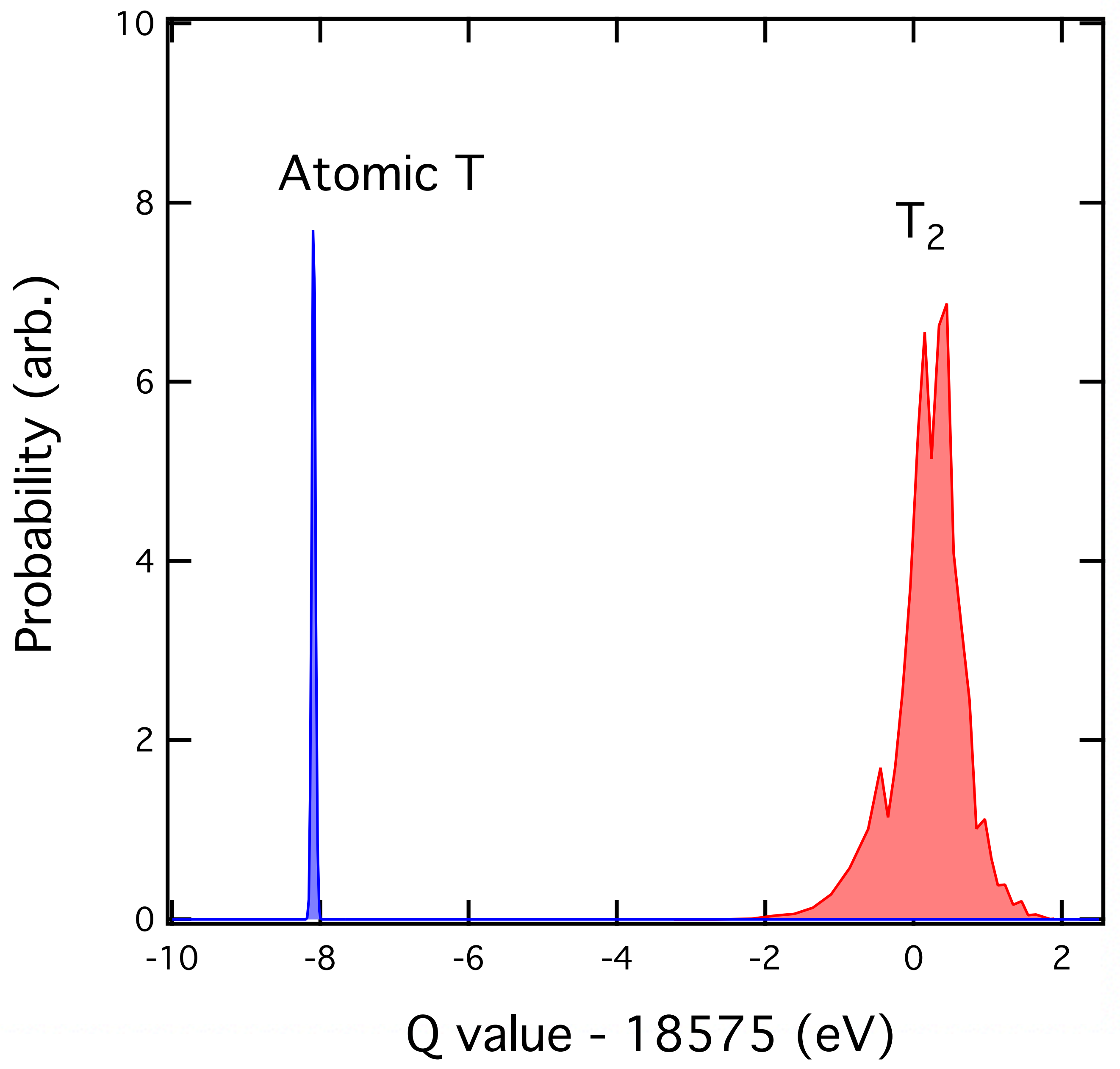
Beyond Phase II - Path Towards 40 meV



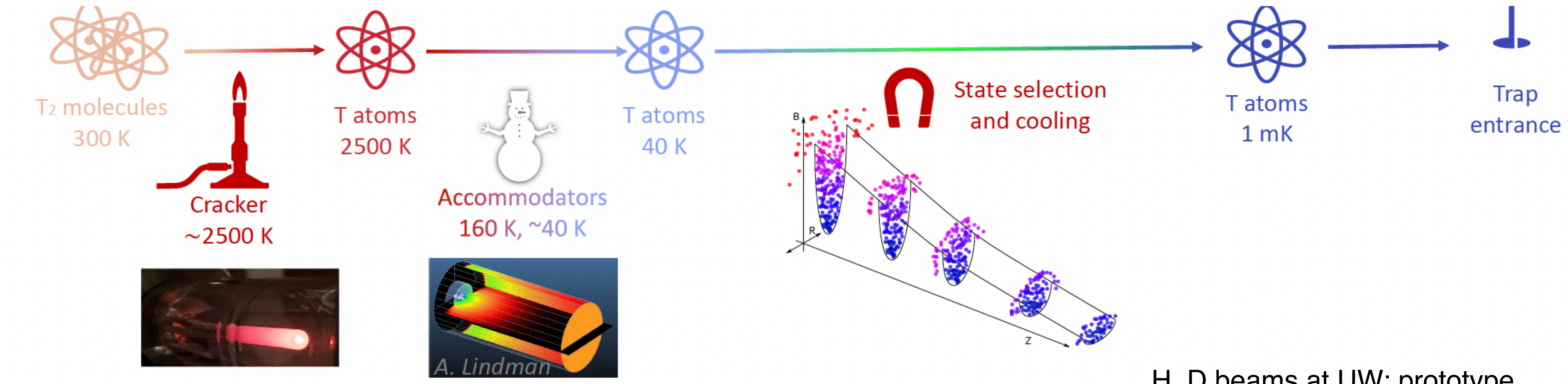
- Develop atomic tritium source
  - Overcome systematic of molecular final states

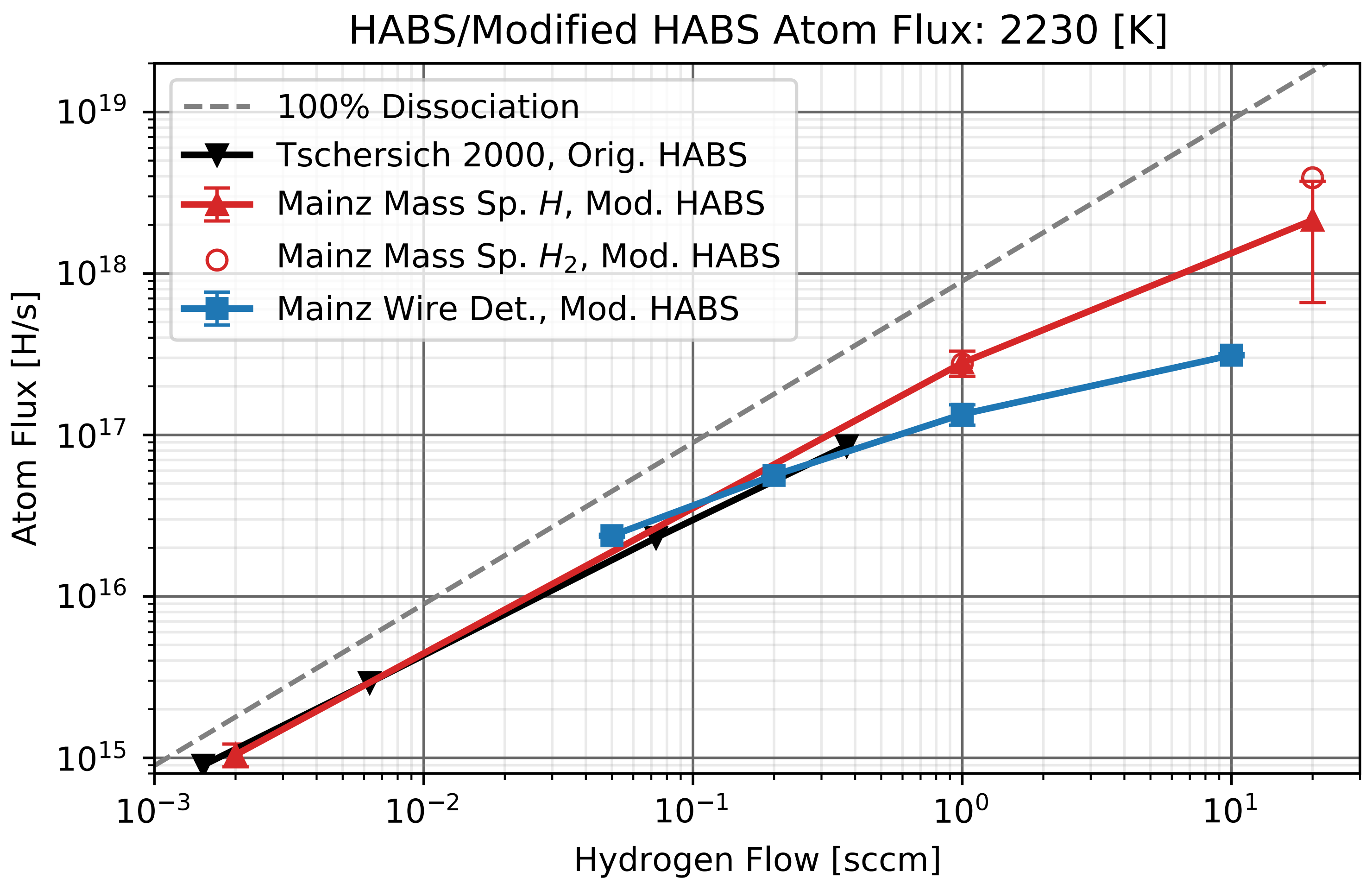


Atomic Tritium Development

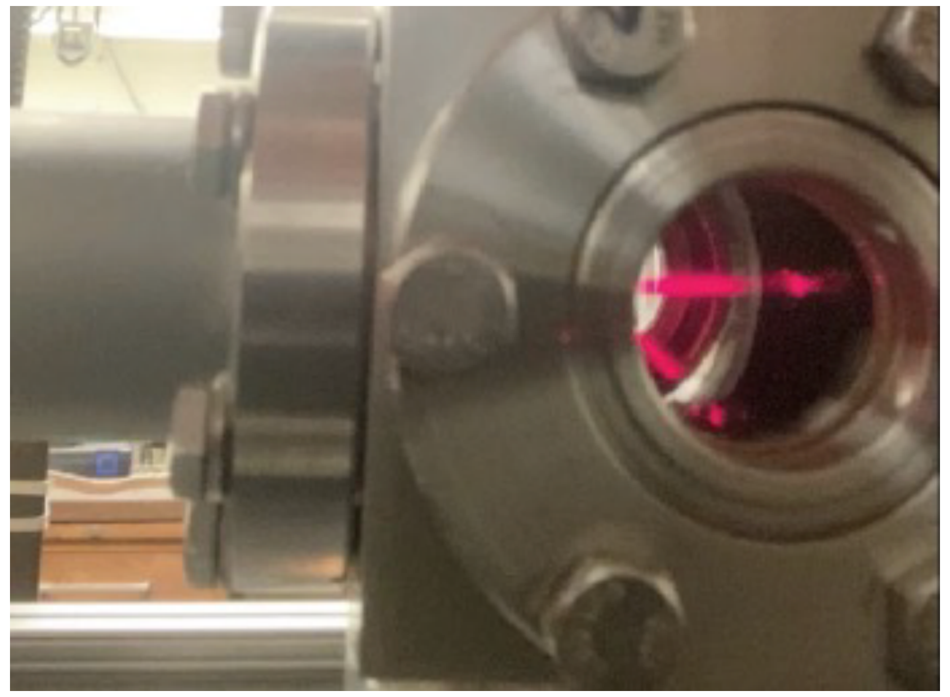
Atomic T for Project 8: 10^{14} atoms/s at ~2 mK

- Theoretical and computational basis for evaporative cooling in a beam.
- Demonstrations in progress now. Developing all steps of atomic tritium production and cooling to 50mK

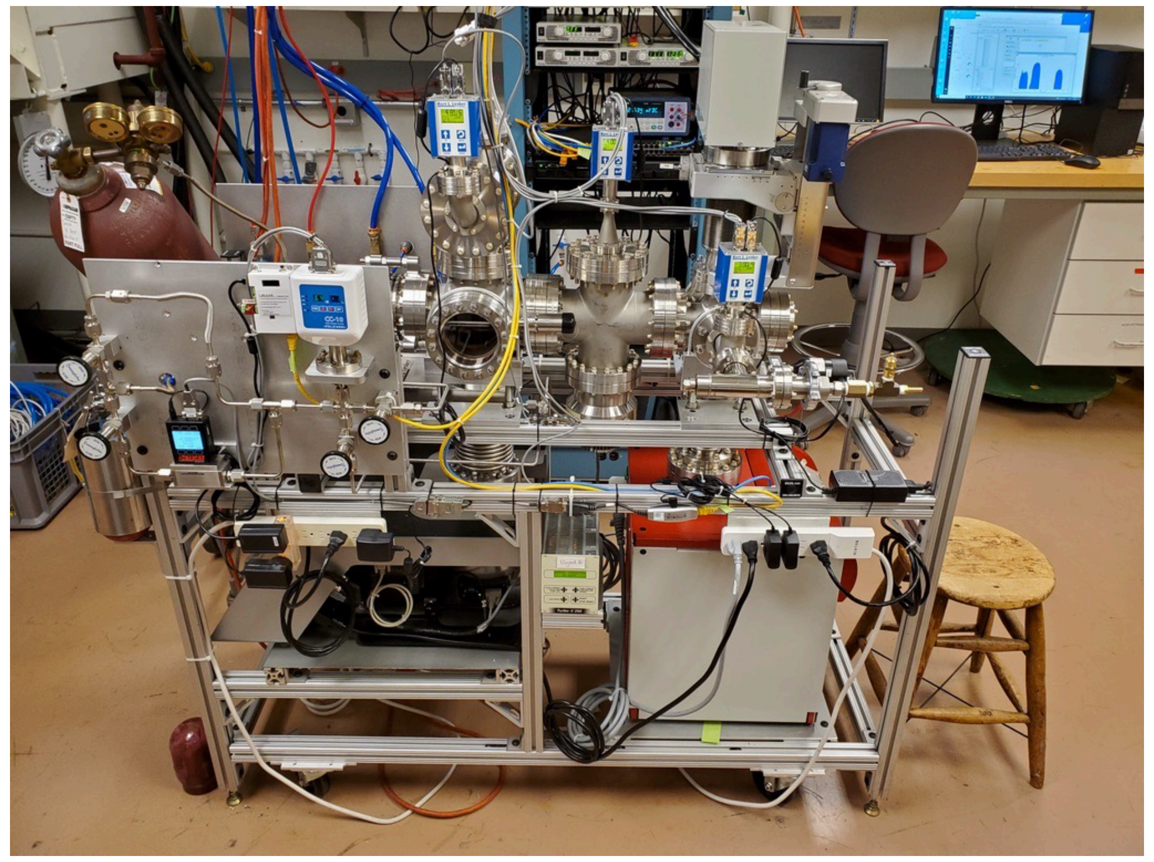




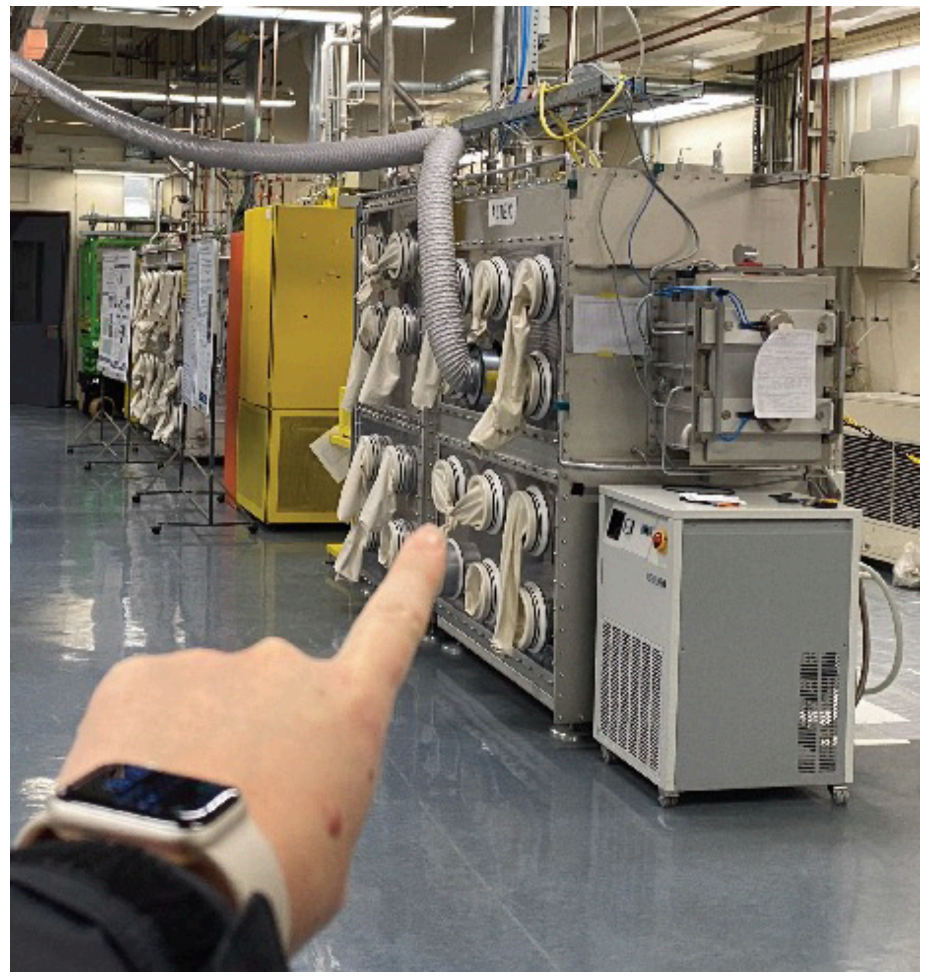
Li beam at UTA: Evaporative cooling dynamics.



H, D beams at UW: prototype dissociation, accommodation, cooling

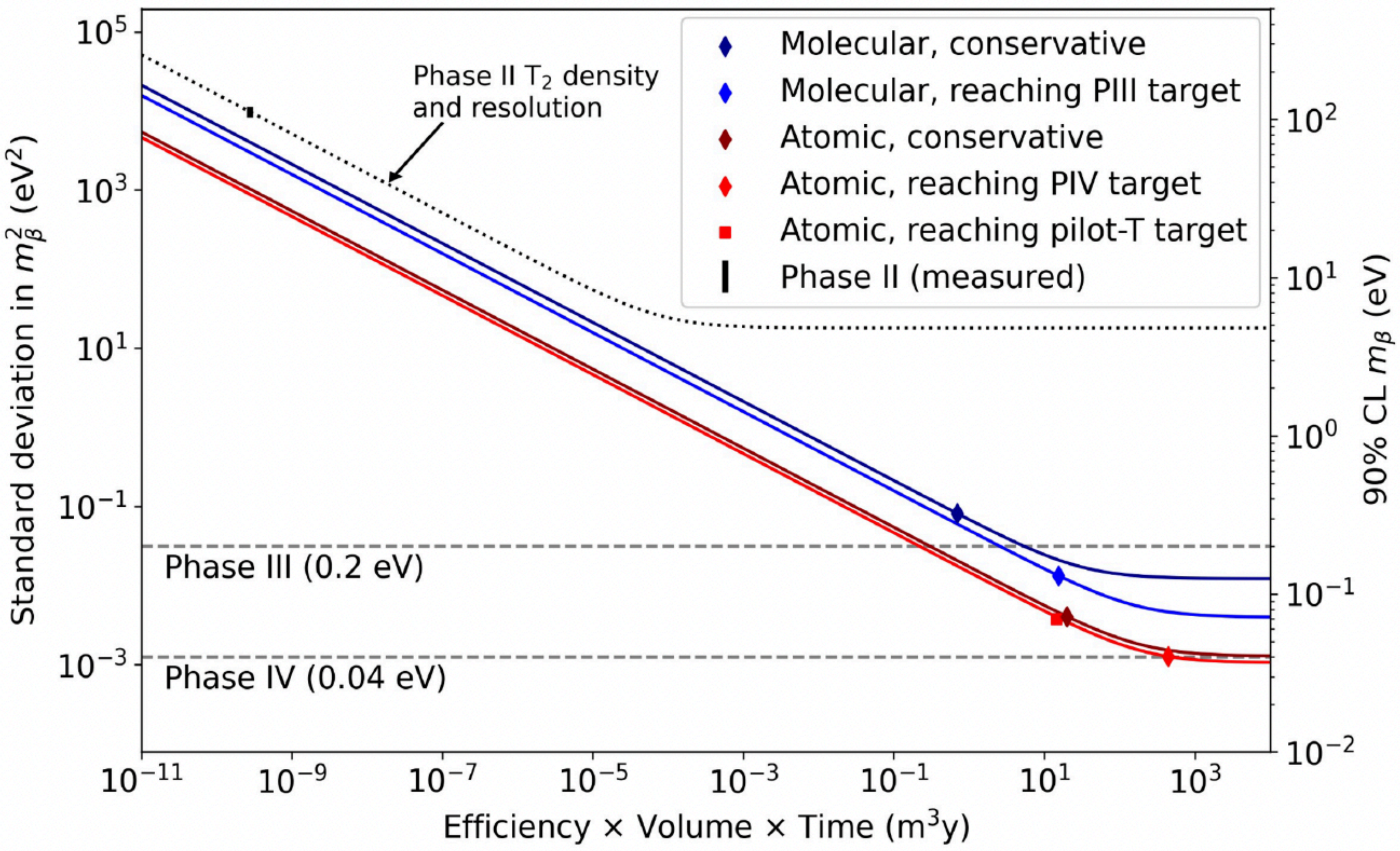


H, D beams at Mainz, preparation for full-scale T line at KIT



Beyond Phase II - Path Towards 40 meV

PROJECT 8



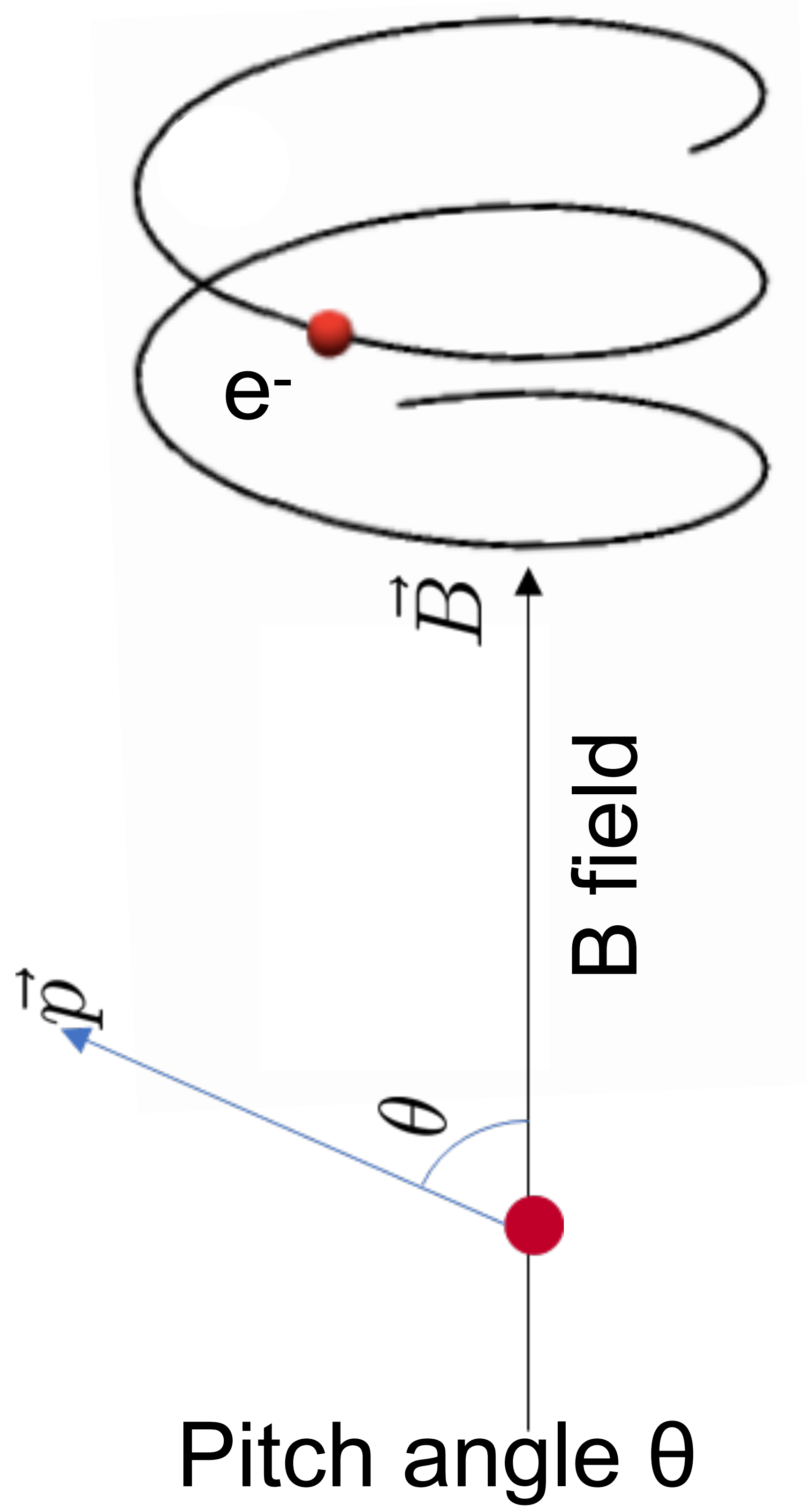
- Develop atomic tritium source
    - Overcome systematic of molecular final states
- Improve resolution, control of systematics, field homogeneity, scattering effects
- Increase event rate
    - Larger volume
    - Higher efficiency

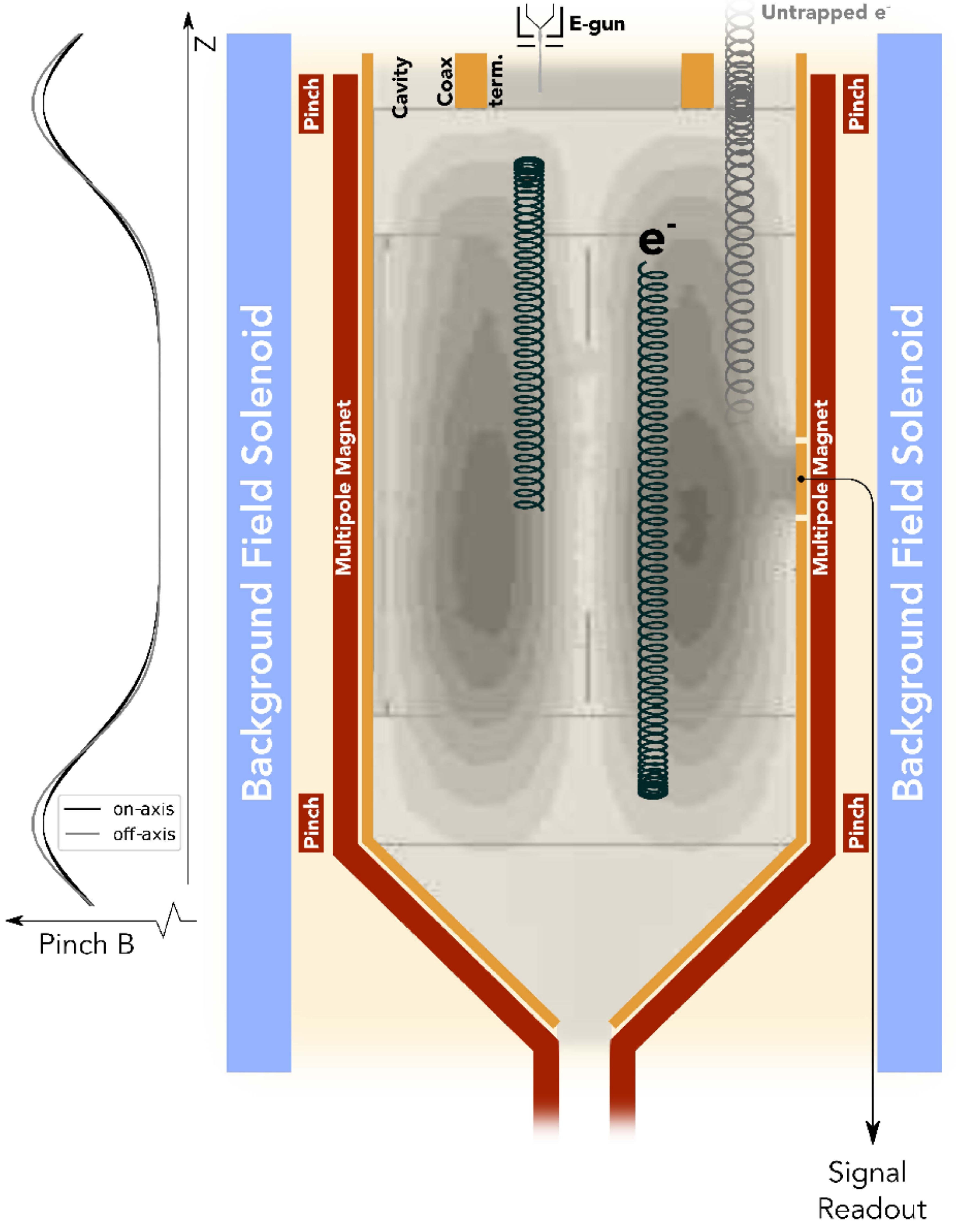
Cavity CRES in Project 8

Key Elements of CRES

- Tritium
- Atomic source
- Magnetic trap for atoms

- Uniform magnetic field
- Magnetic trap for e-
- Cavity
- Sensitive receiver





Cavity CRES in Project 8

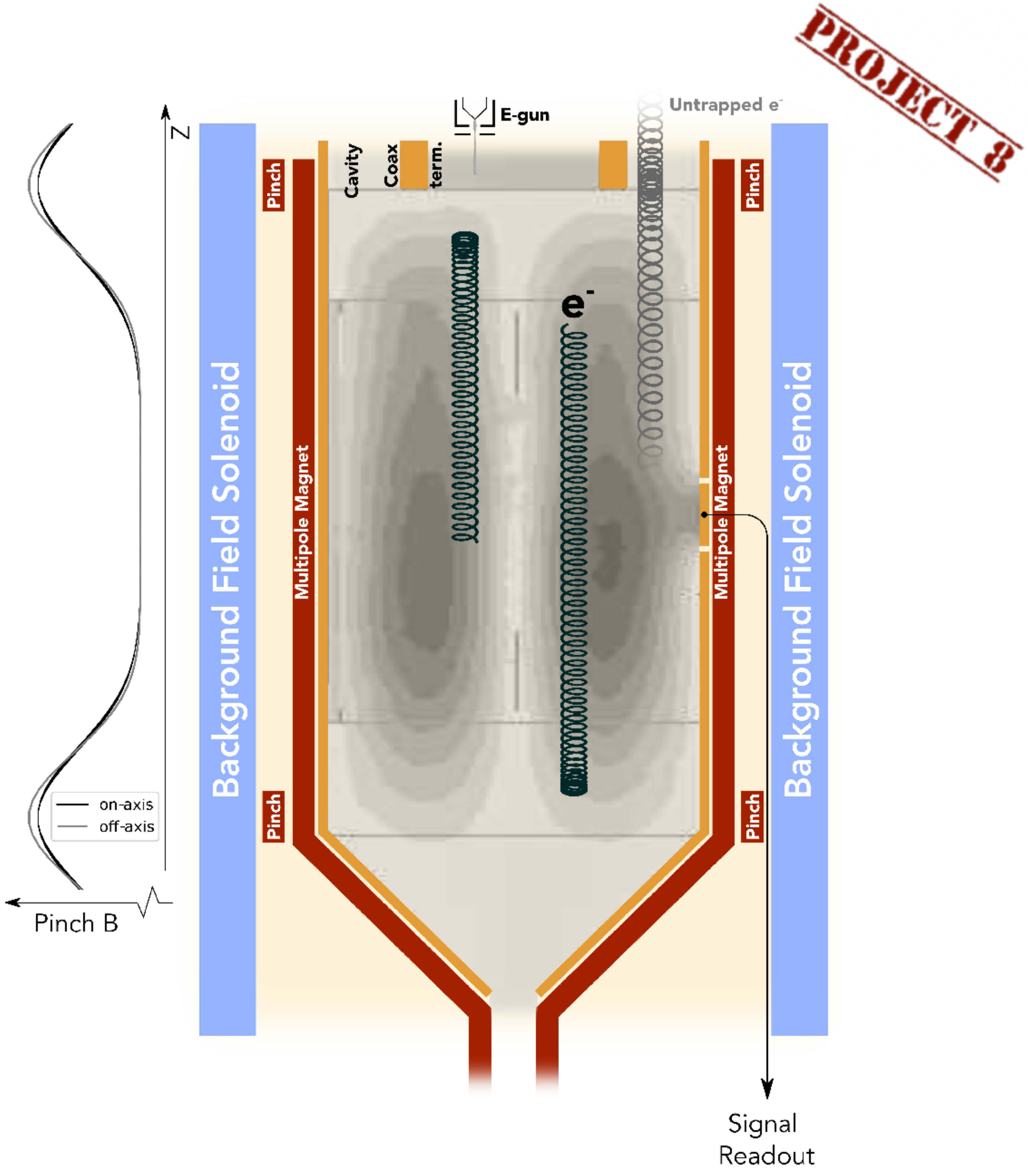
A Low-Frequency Cavity Experiment

Low field

- smaller losses of atomic tritium
- Need spin selected atomic tritium to trap magnetically

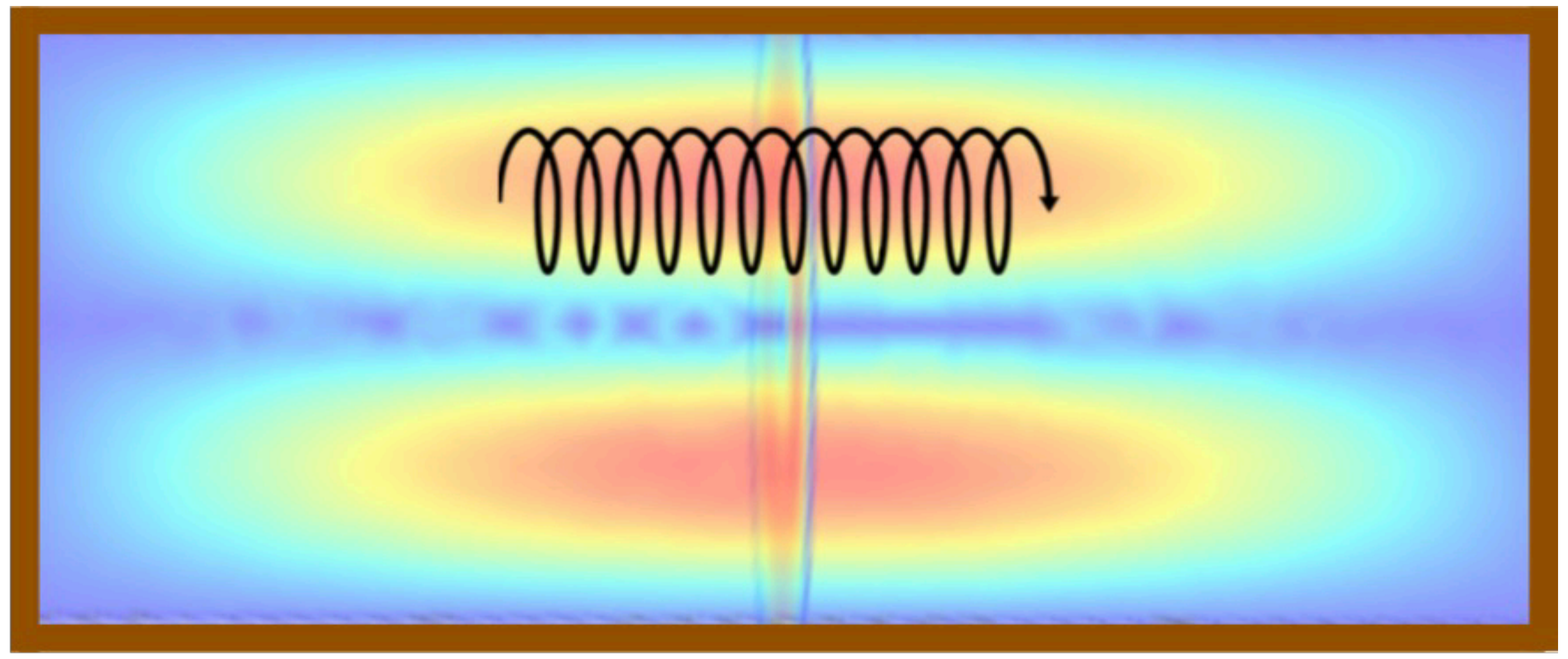
Low frequency

- Large cavity volume scales with $1/f^3$
- Simpler mode structure

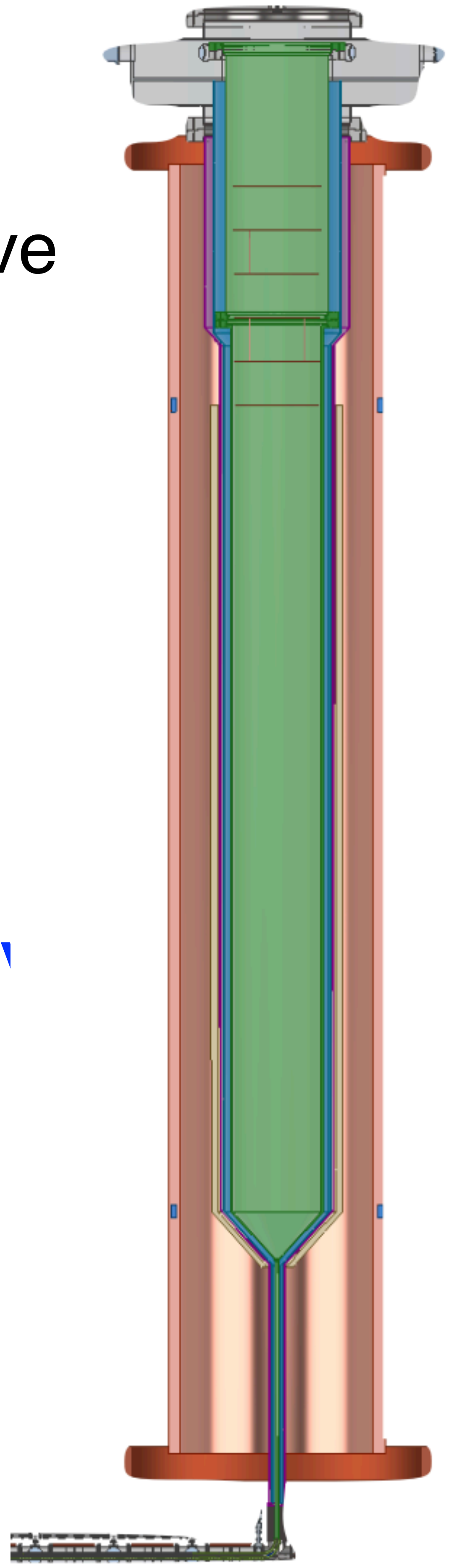


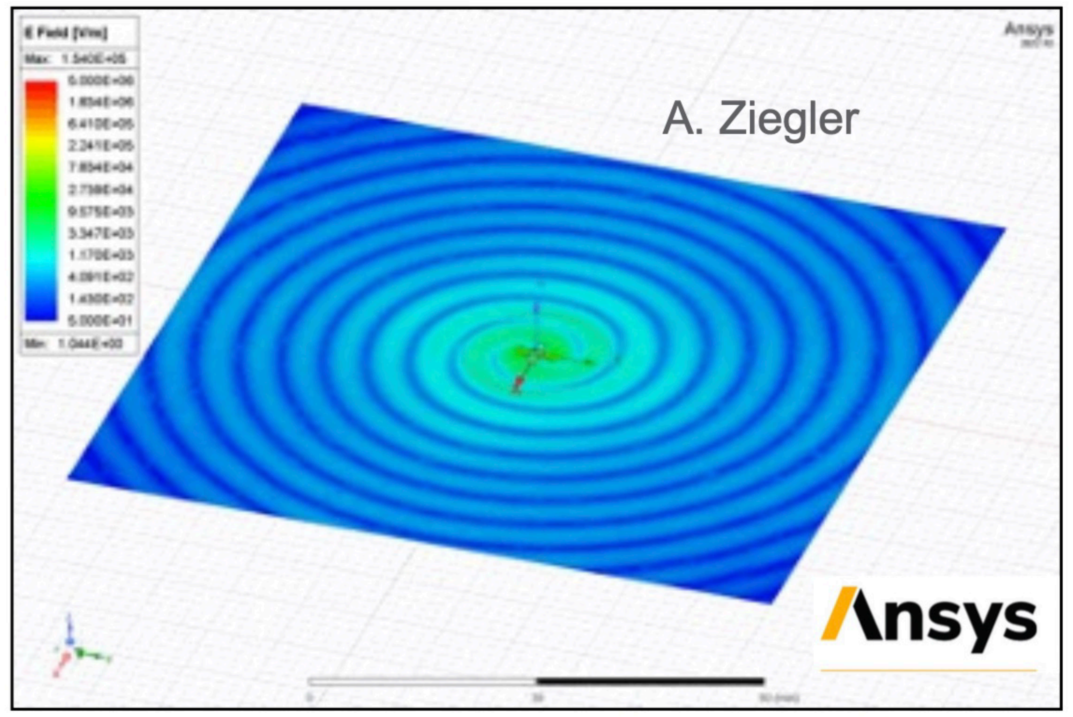
Developing CRES Techniques

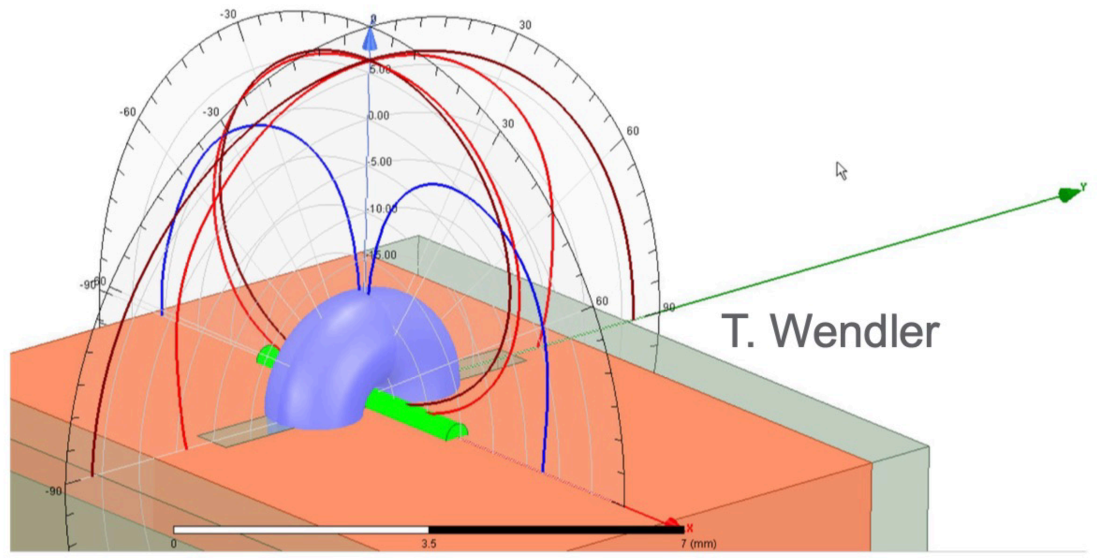
Increasing volume and efficiencies with cavities



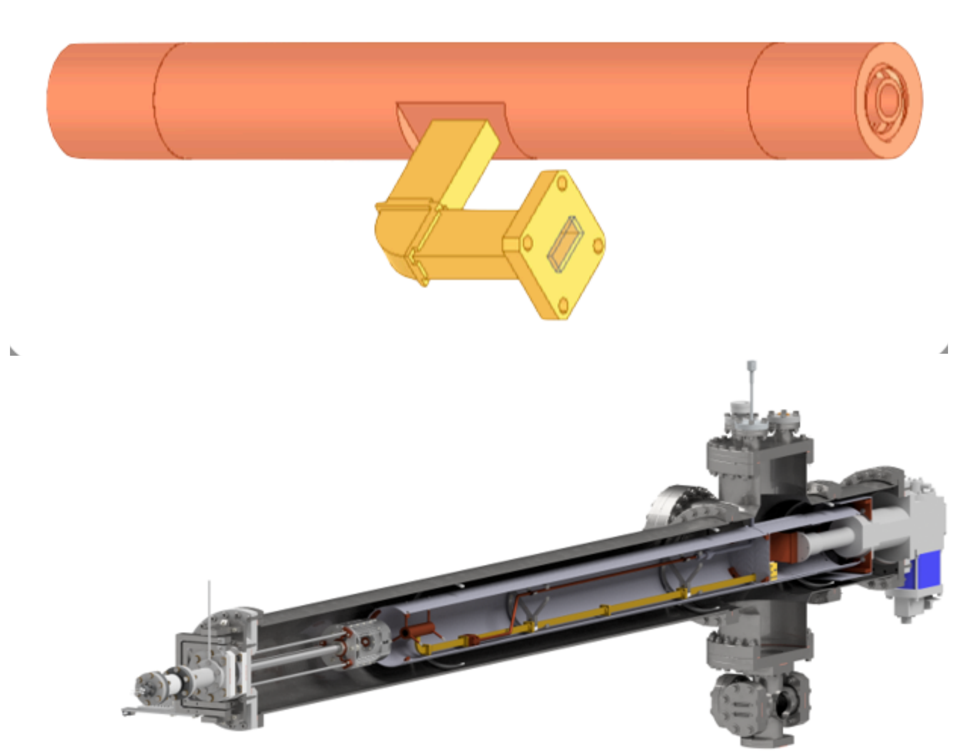
m³-scale effective volume

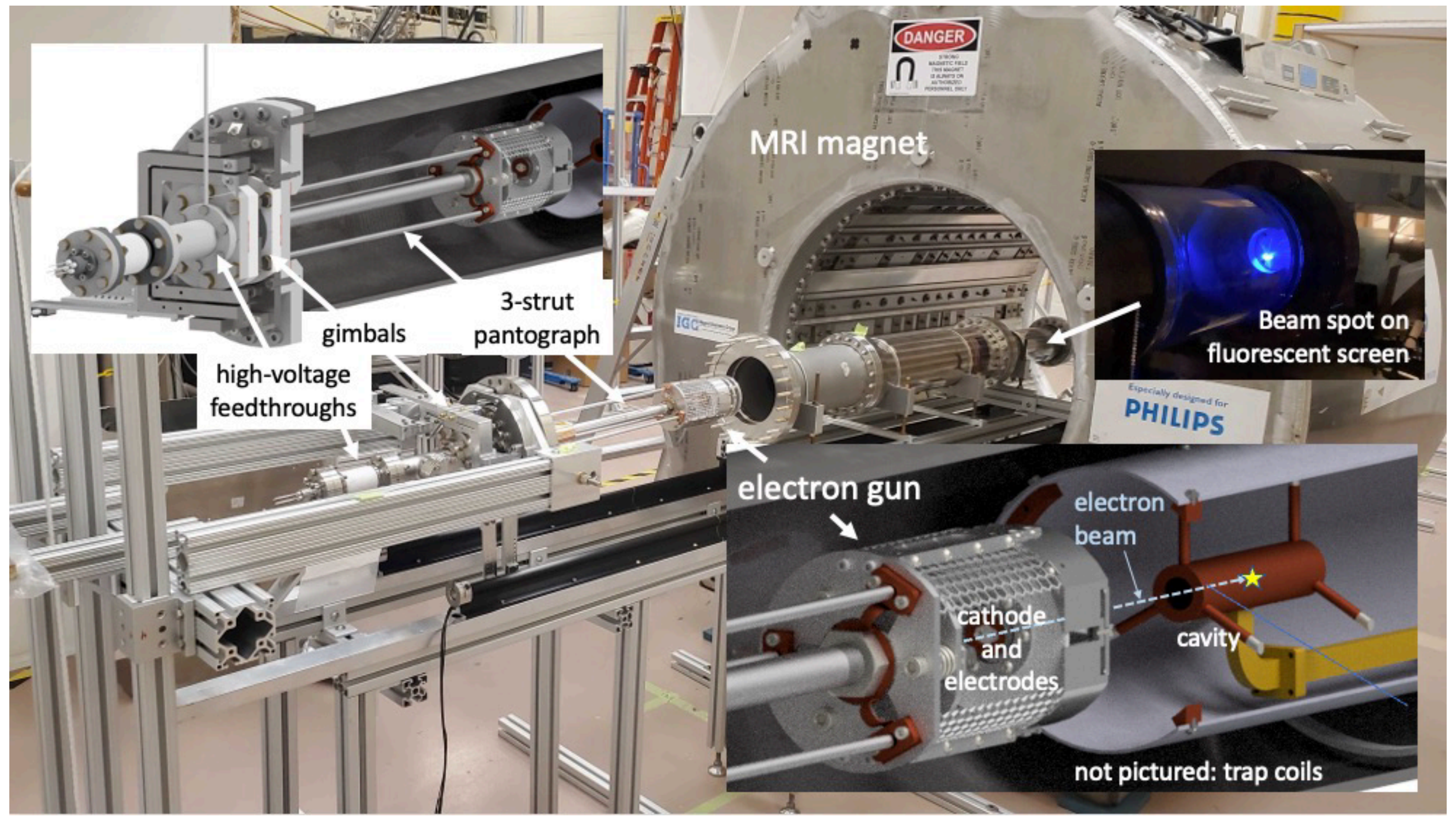






First cavity geometry demonstrator:**mm³-scale** effecti





Position-sensitive reconstruction for better resolution; improved simulations

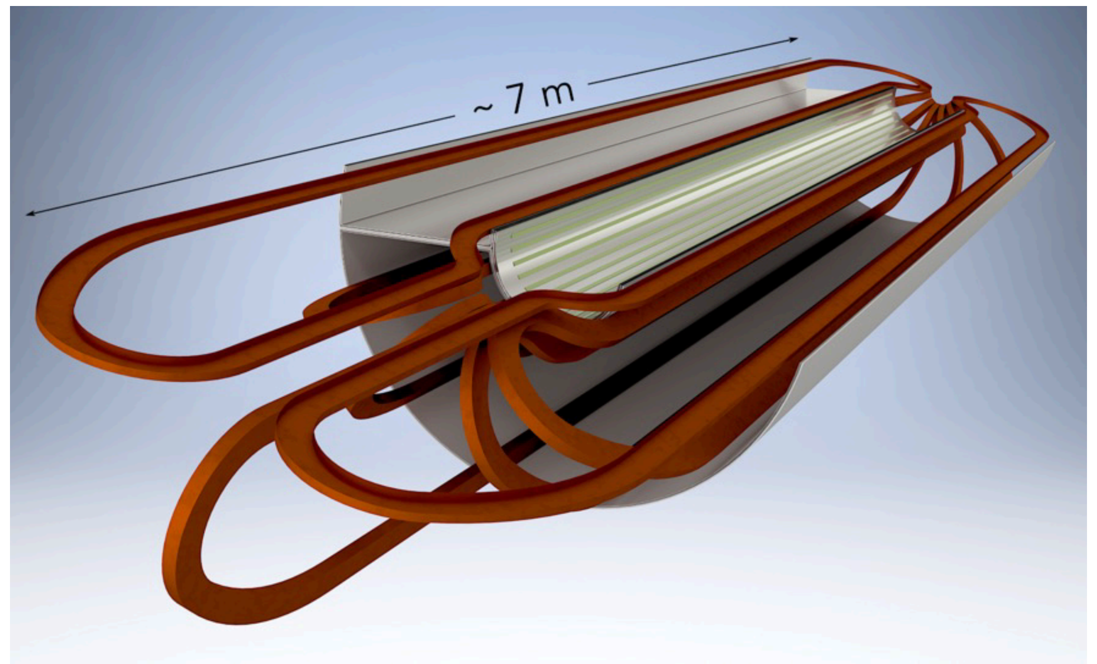
Improved signal with quantum amplifiers

New calibration techniques and optimized magnetic trapping field shape for higher resolution

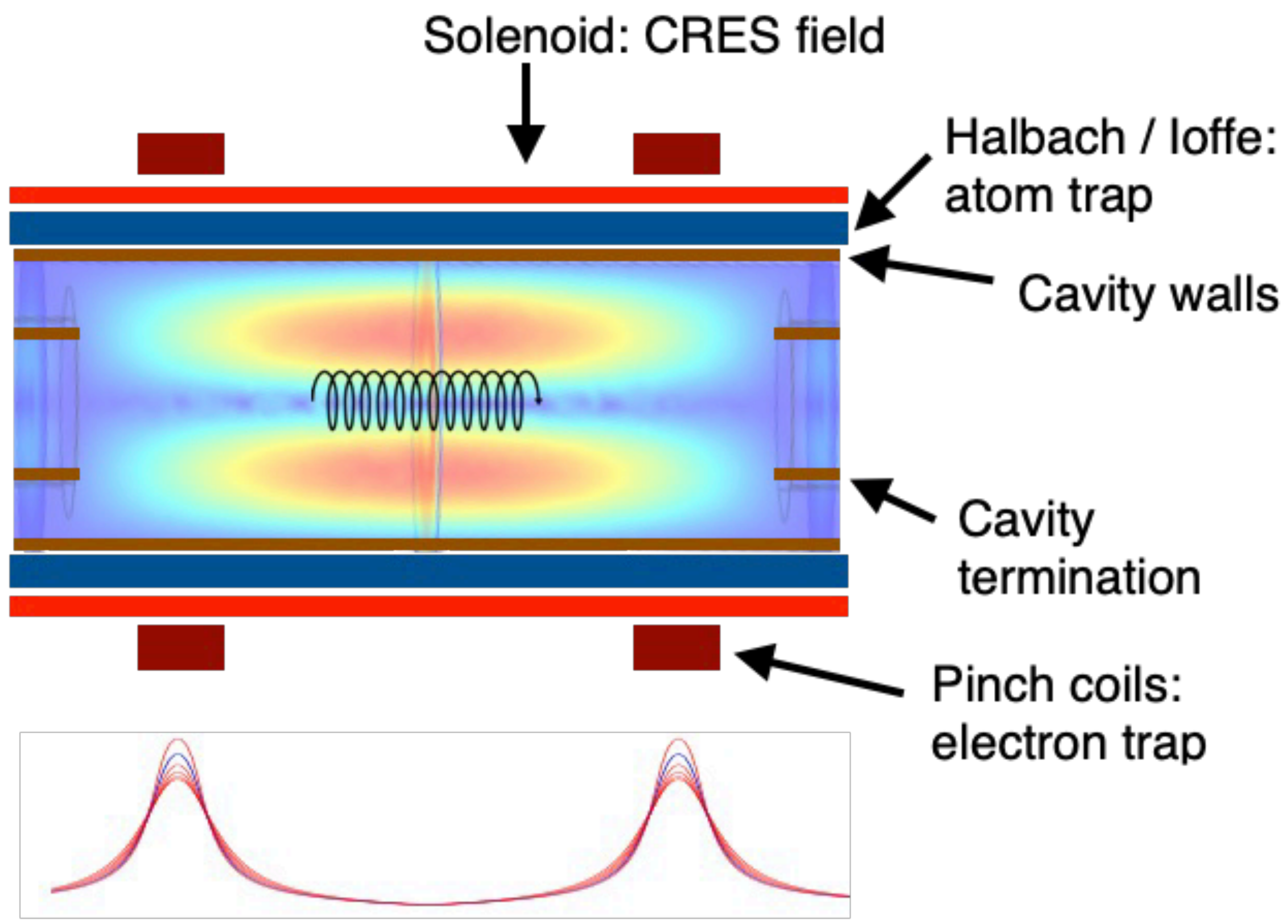
Demonstrating Key Technologies

PROJECT 8

Atomic trap demonstrator

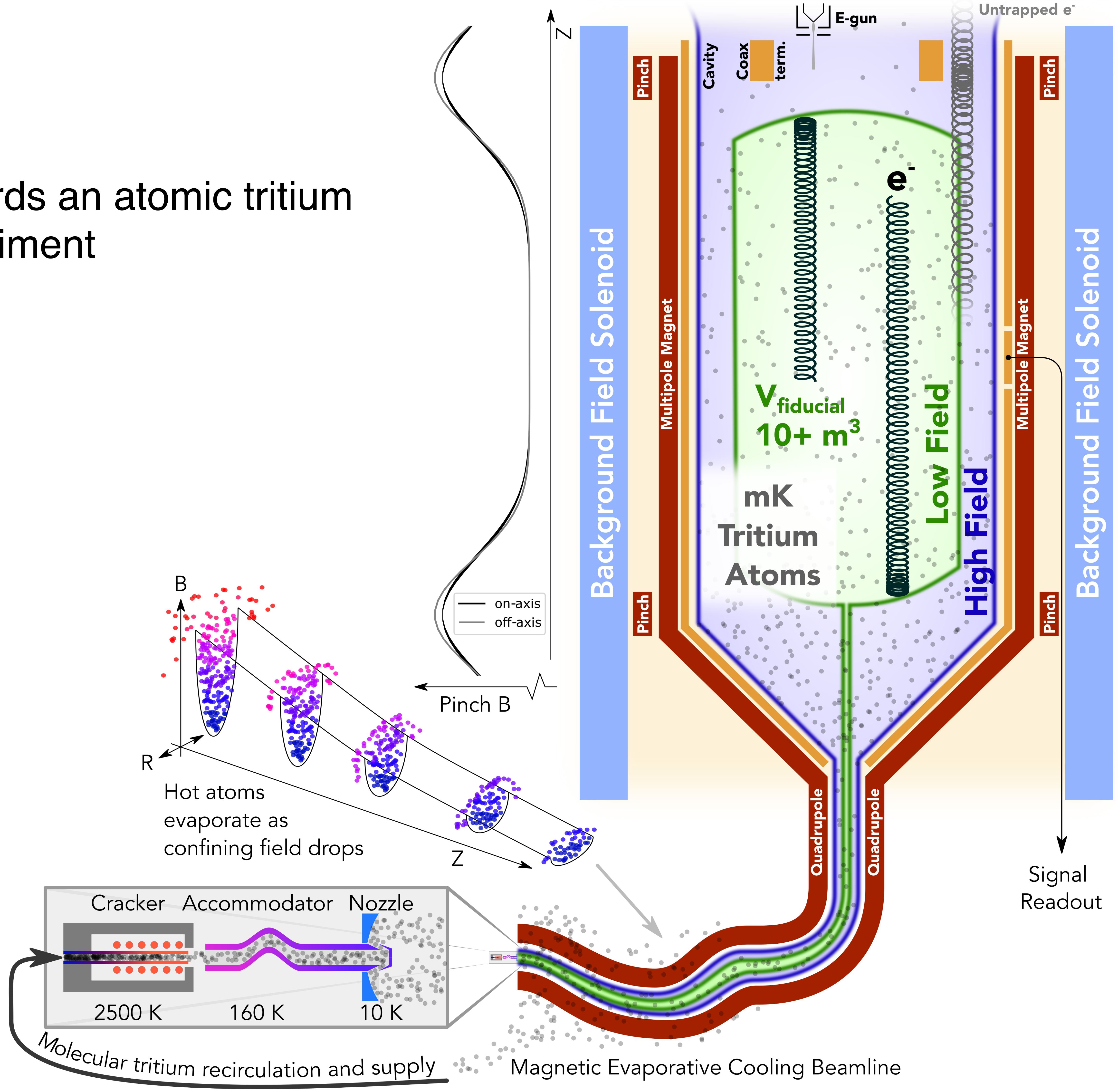


Large-volume cavity-based CRES



Field from pinch coils

Towards an atomic tritium experiment



Project 8 Collaboration, Contribution to Snowmass 2021, arXiv:2203.07349 (2022).

Future of Project 8

Phase III

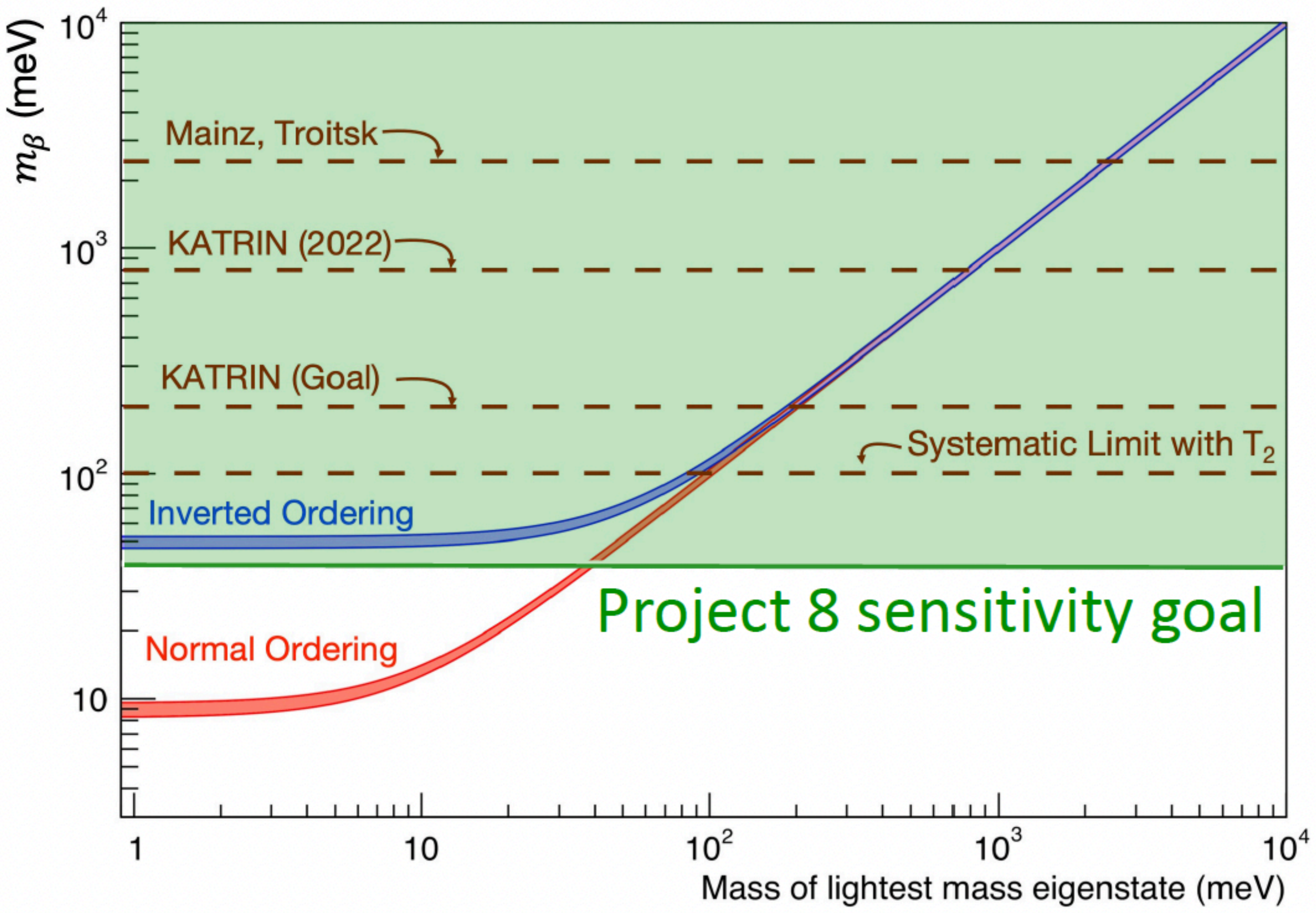
- Sensitivity to ~ 0.1 eV/c^2 neutrino mass

- Leading sensitivity to eV-scale sterile neutrinos

Phase IV

- Sensitivity to 0.04 eV/c^2 (40 meV/c^2) neutrino mass

- Measure neutrino mass or exclude inverted ordering



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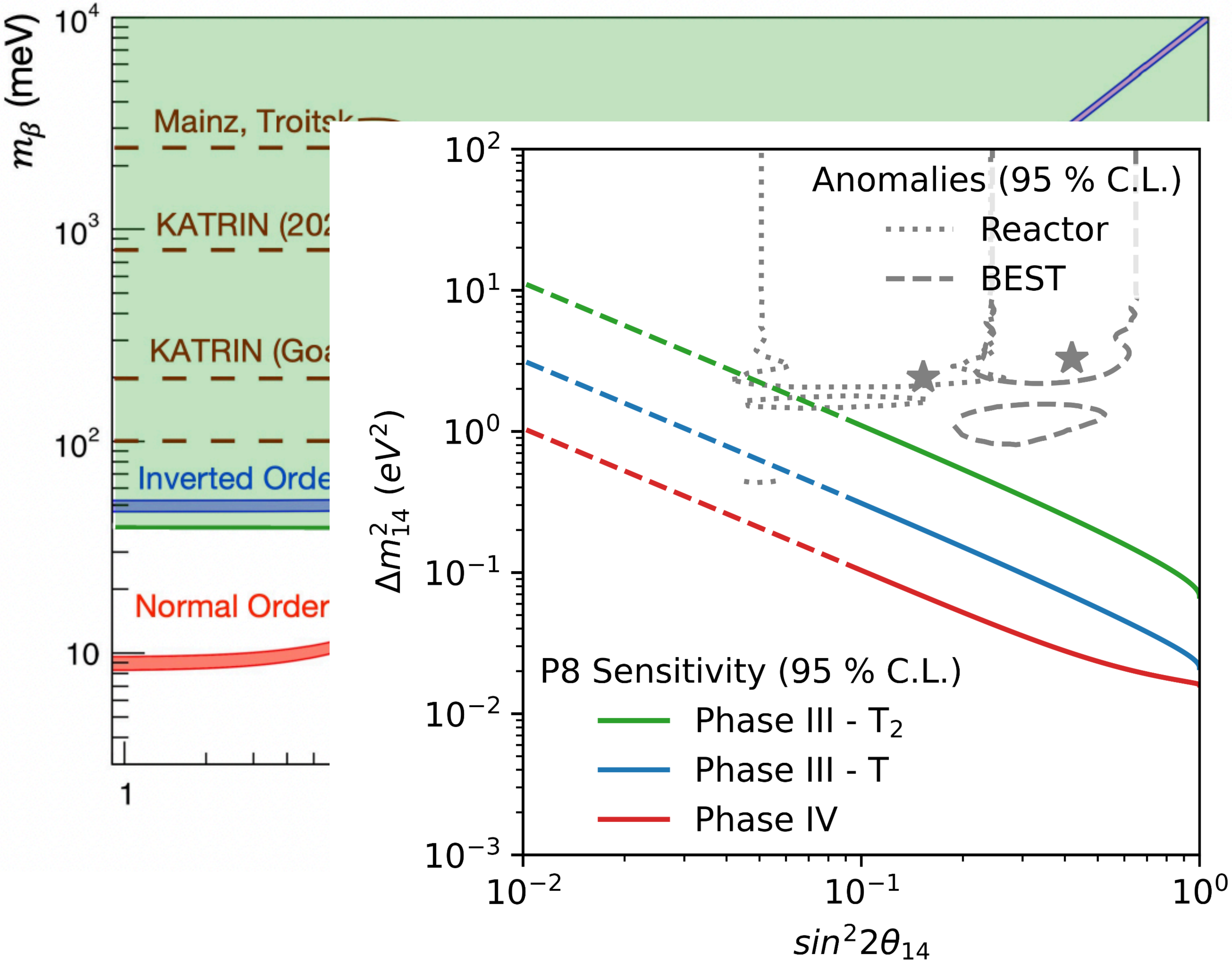
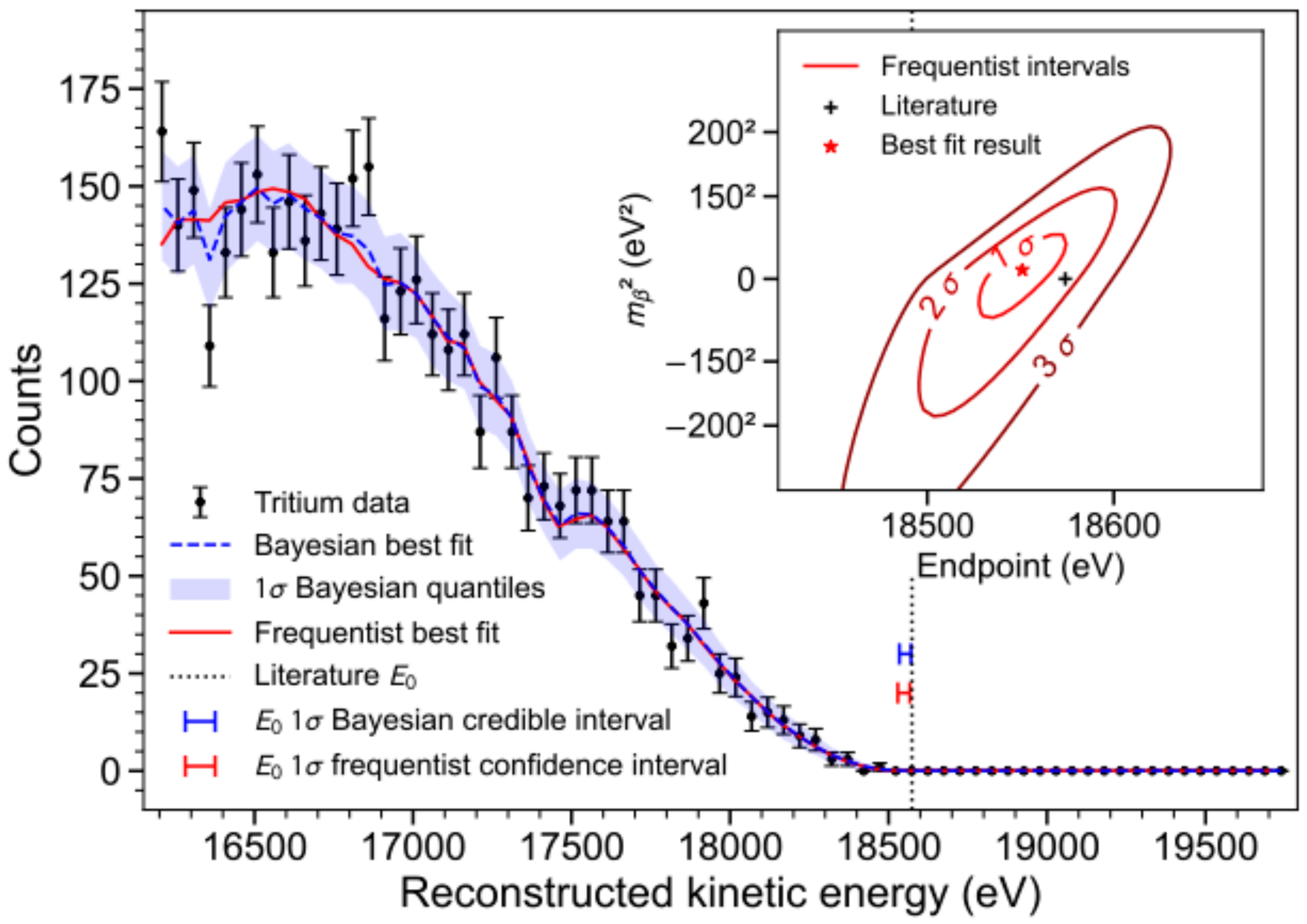
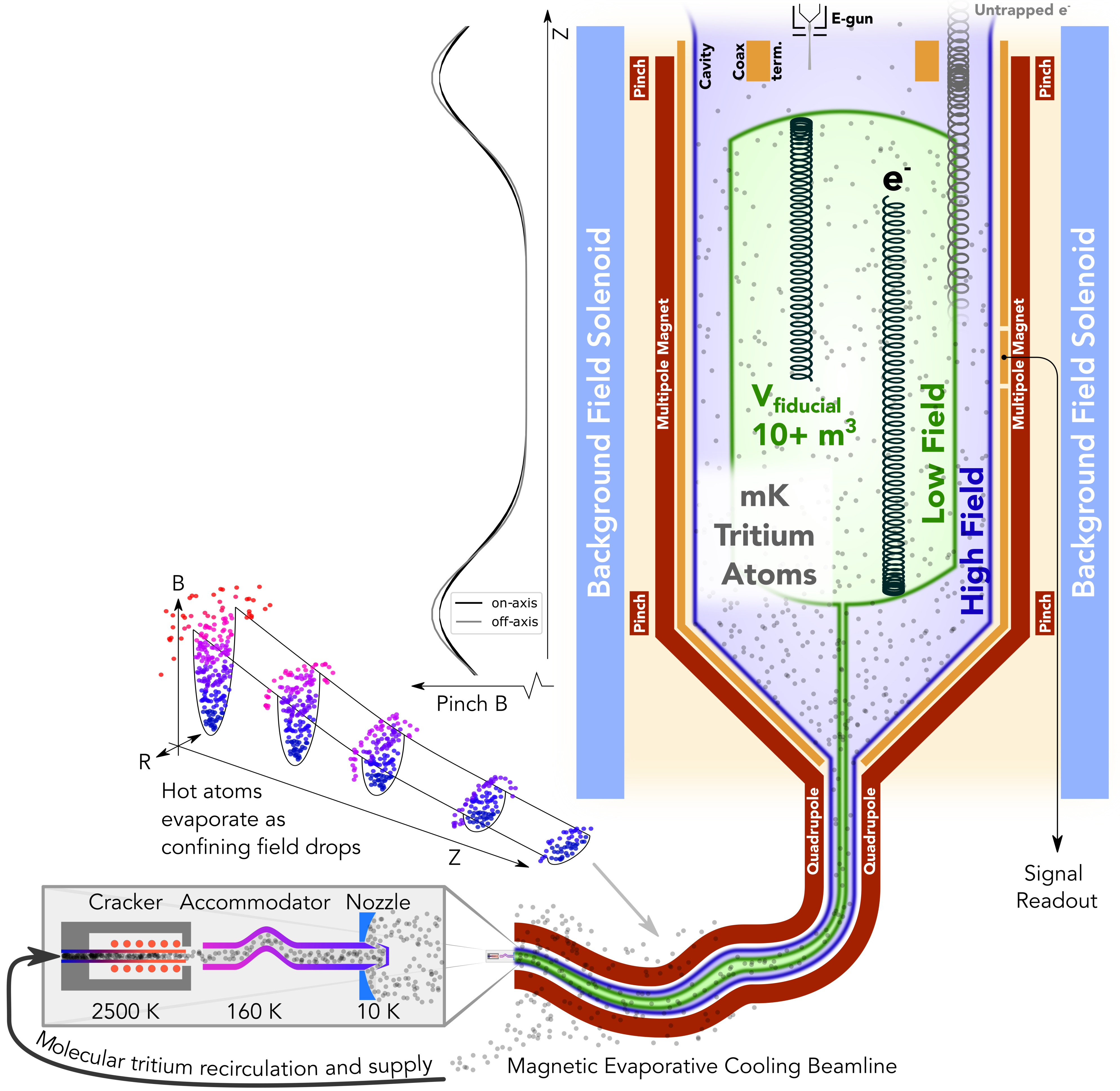


Summary and Outlook





CRES established as a promising technique for a neutrino mass experiment

Phase II demonstrated background-free operation, control of systematics, first CRES limit

Progress toward key technology demonstrations, sub-eV neutrino mass sensitivity, and the path to the 40 meV experiment. Stay tuned!