Quantum Technologies for Neutrino Mass

Stephen Hogan

Department of Physics and Astronomy
University College London

(on behalf of the QTNM collaboration)

21.1.2025

Neutrino mass

- Neutrinos are the most abundant particles with mass in Universe

- Neutrinos are *massless in Standard Model*

  Neutrinos are known to have non-zero mass

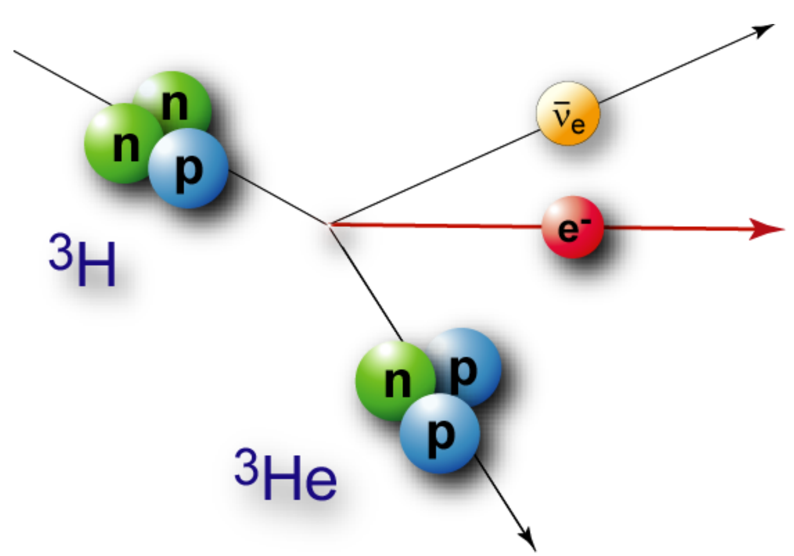
  Absolute mass scale not precisely known: $9 \text{ meV/c}^2 < m_\nu < 450 \text{ meV/c}^2$

KATRIN Collaboration, Nat. Phys. **18**, 160 (2022)
arXiv:2406.13516 (2024)

- Experimental determination of absolute neutrino mass

  Measure electron spectrum following β-decay of tritium: T_2 or T

$$T \rightarrow {}^3He^+ + e^- + \overline{\nu}_e$$



Mertens, *Absolute Neutrino Mass Workshop* (2019)

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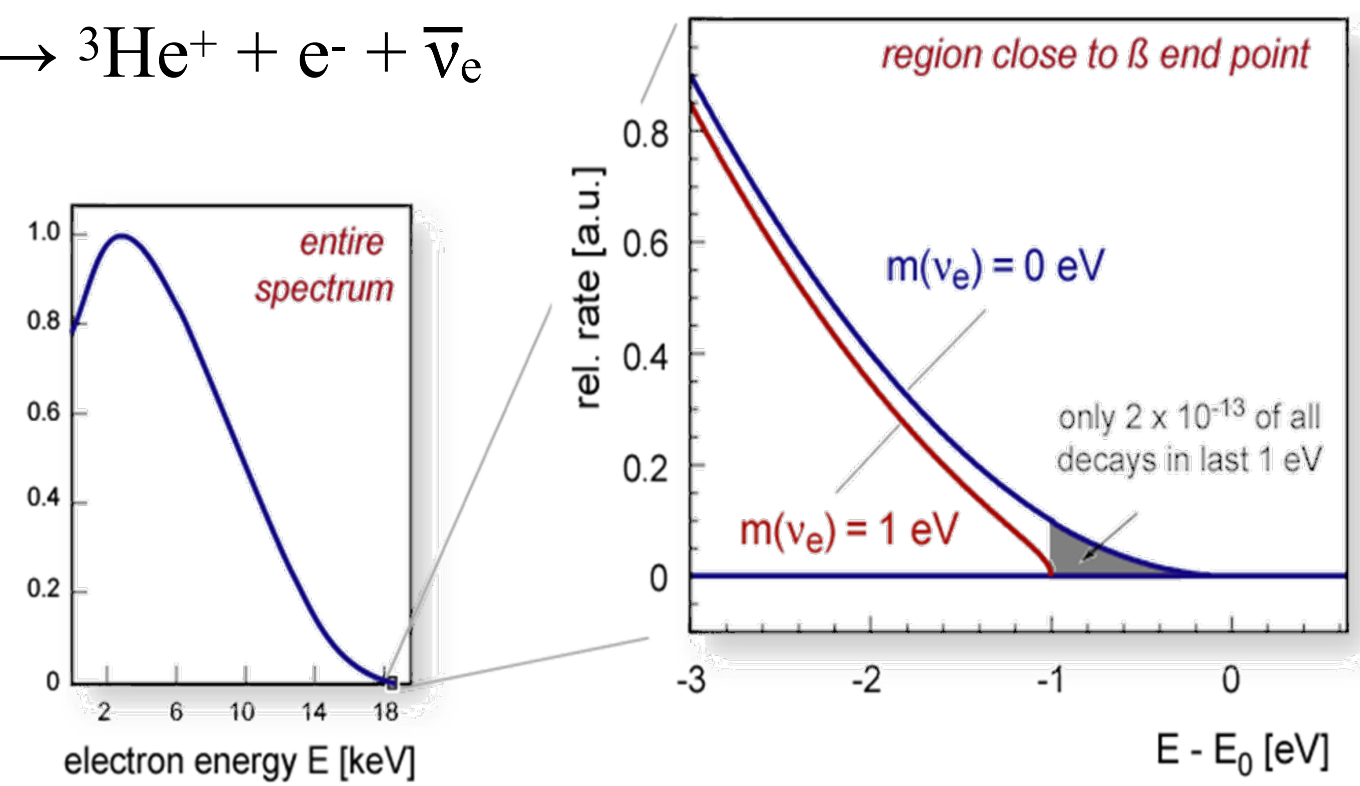
β-decay-electron spectrum



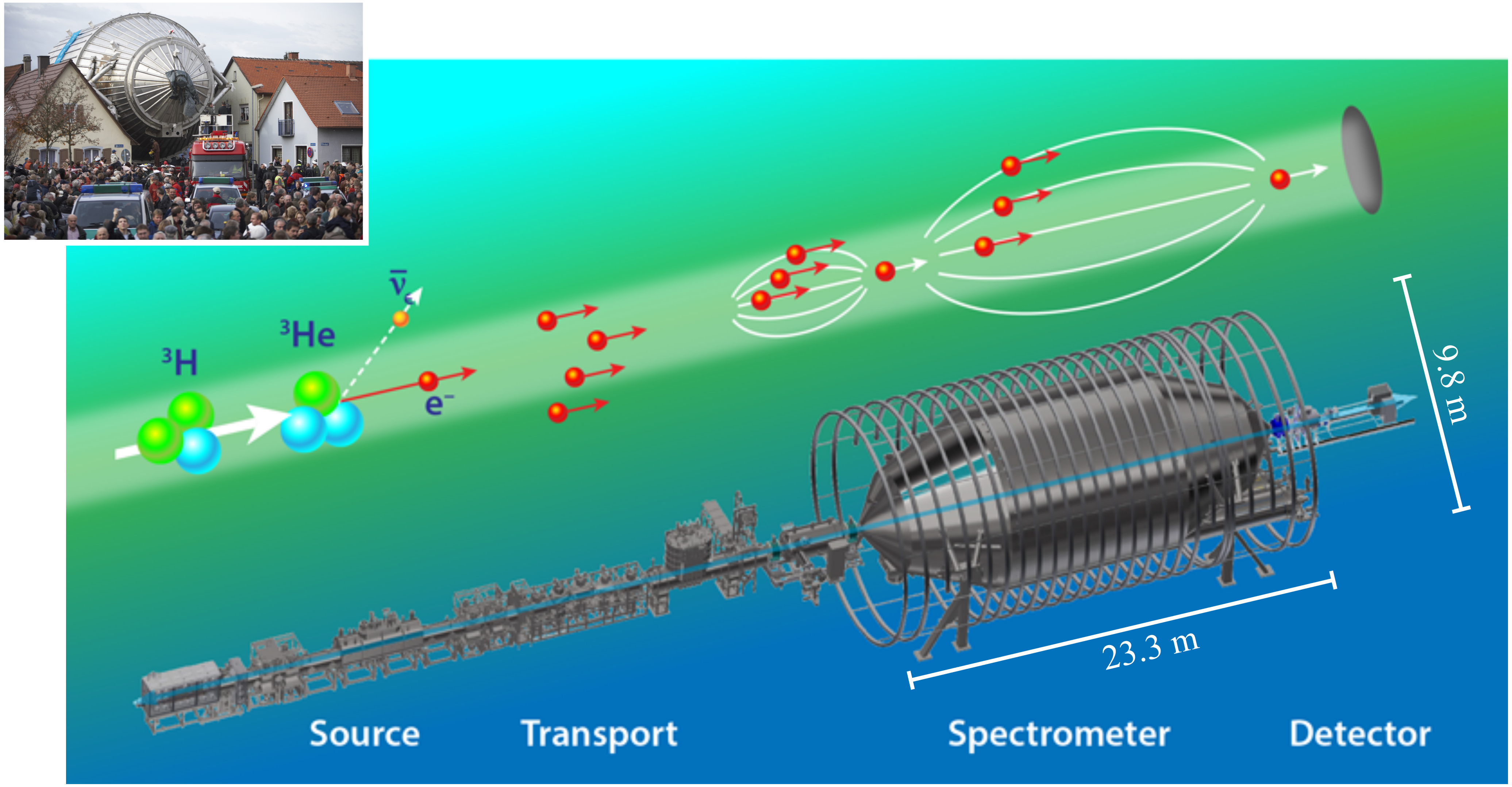
Mertens, *Absolute Neutrino Mass Workshop* (2019)

KATRIN experiment

- KATRIN electron spectrometer

  Magnetic Adiabatic Collimation + Electrostatic Filter (MAC-E filter)

  Experiment with T_2 molecules



Brugnera, *Physics* **12**, 129 (2019)
KATRIN Collaboration, Nat. Phys. 18, 160 (2022)

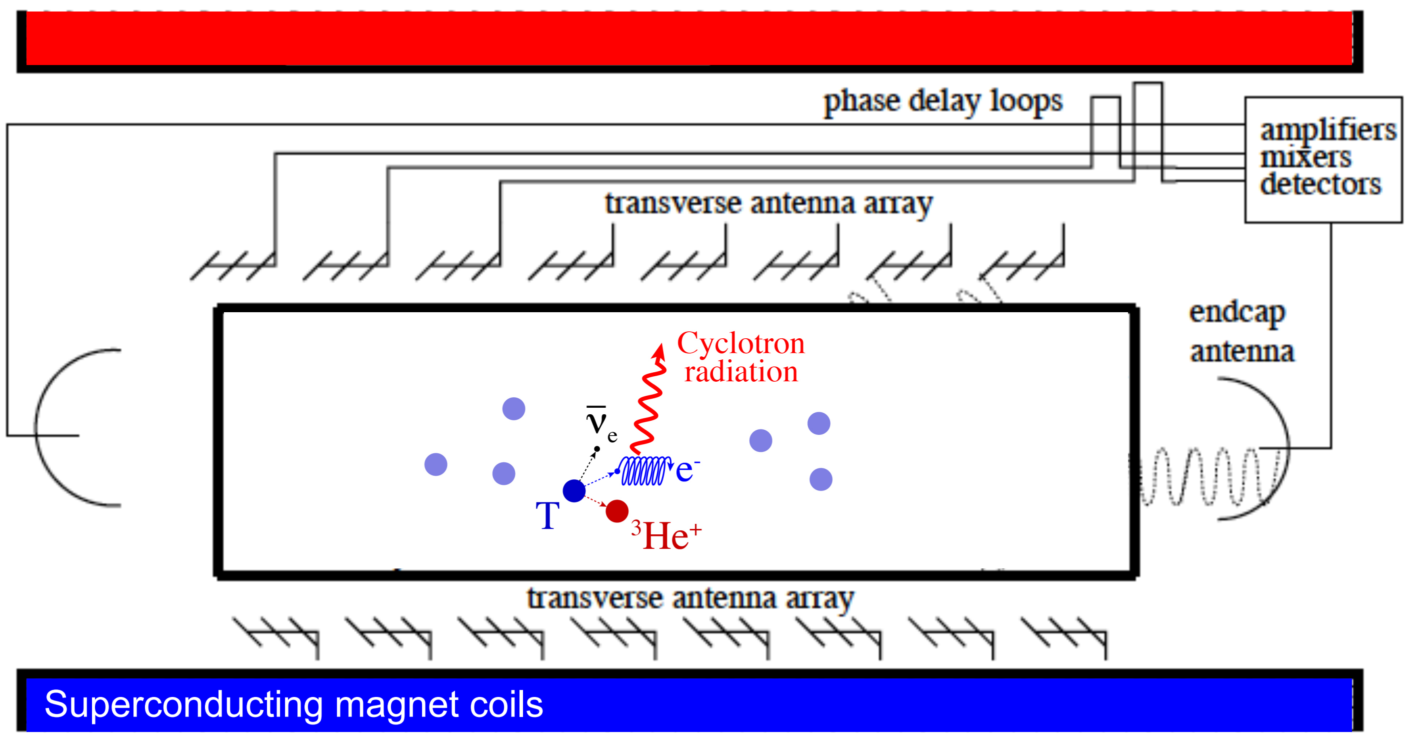
Next generation experiment

- Requirements of next generation experiment

  Atomic tritium — requires magnetic confinement/magnetic trapping

  Electron spectrometer — quantum limited sensors

- Cyclotron radiation emission spectroscopy (CRES) — Project 8



- Frequency of cyclotron radiation:

$$\nu_{CR} = \frac{e\,B}{2\pi\left(m_e + E_{kin}/c^2\right)}$$

Monreal and Formaggio, *Phys. Rev D* **80** 051301 (2009)
Asner et al. (Project 8), *Phys. Rev Lett.* **114** 162501 (2015)

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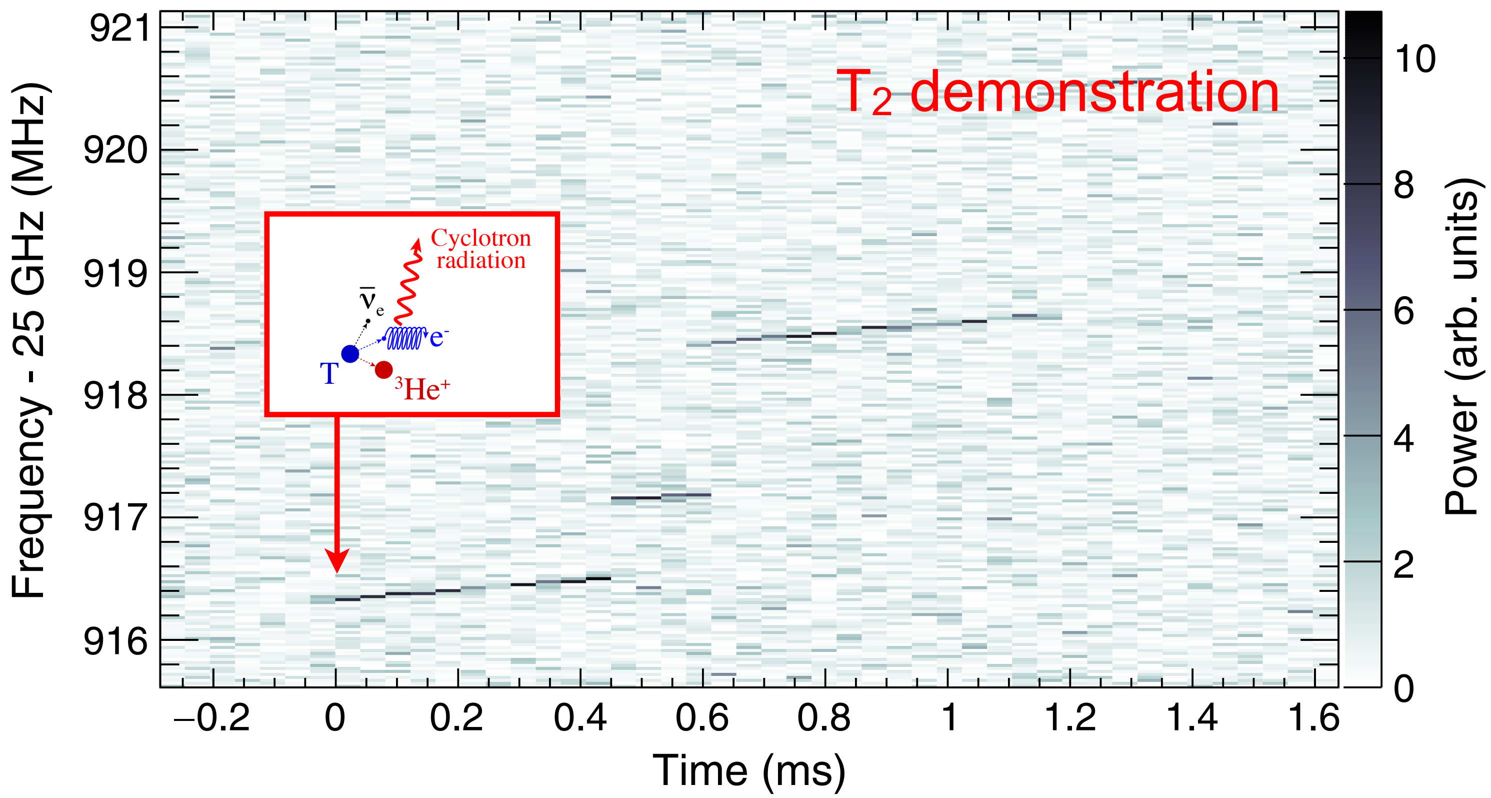

Ashtari Esfahani et al. (Project 8)
Phys. Rev Lett. **131** 102502 (2023)

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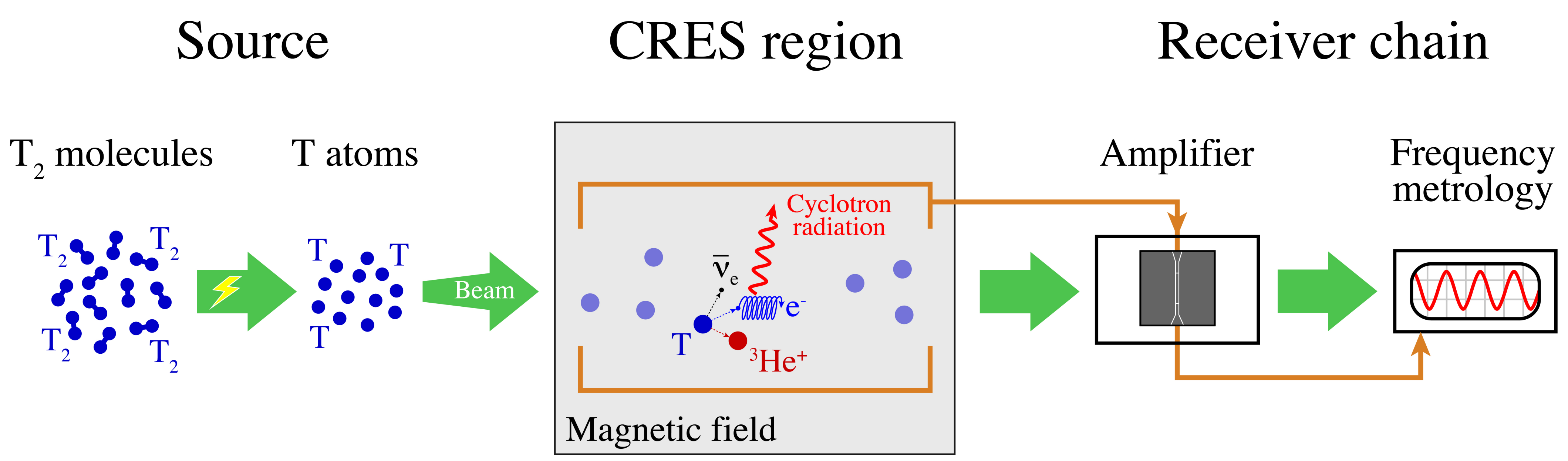
The QTNM project

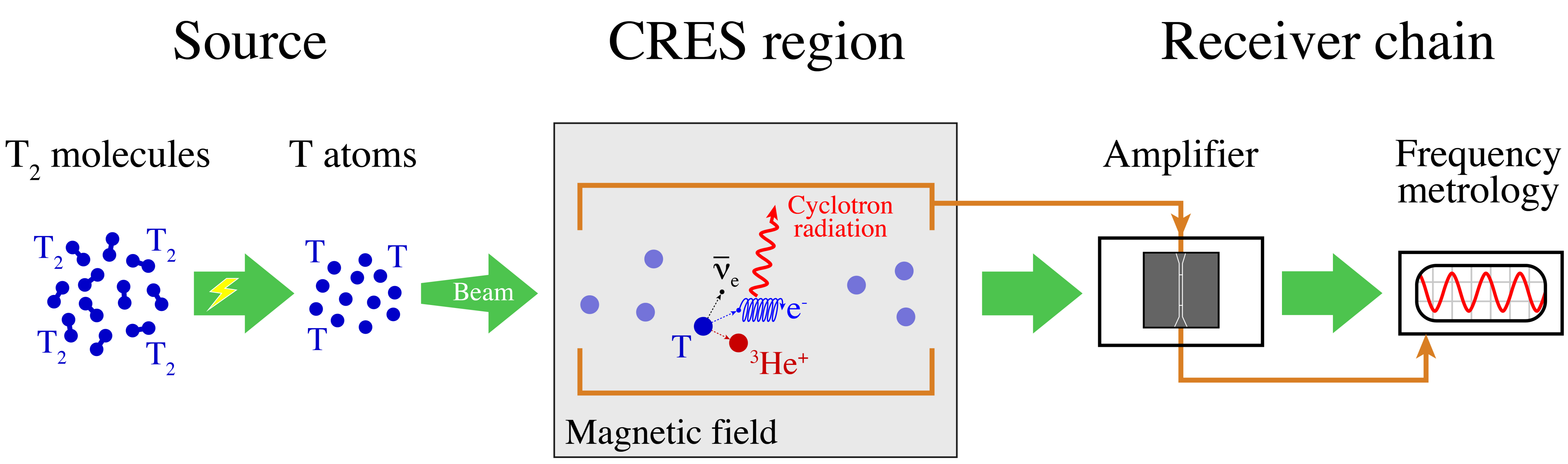
- Quantum Technologies for Neutrino Mass (QTNM)



- Magnetic field in CRES region: 0.6 — 0.7 T
- Operating microwave frequency: 18 GHz
- Radiated power from single electron: ~1 fW

The QTNM project

- Quantum Technologies for Neutrino Mass (QTNM)

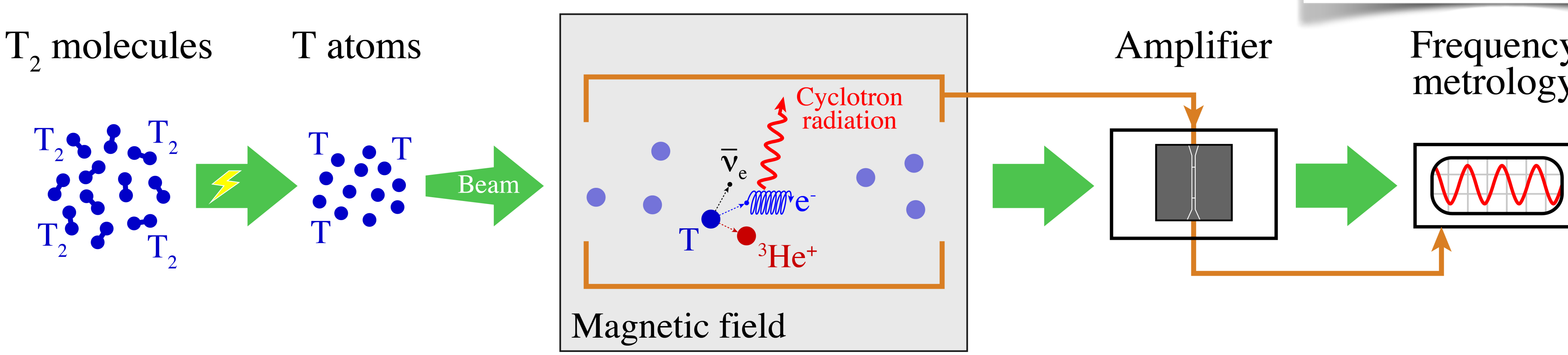


- Key objectives — Phase 1
  - Development of high density cryogenic ***sources*** of **H, D** (and T) atoms
  - Rydberg atom ***magnetometry*** and ***electrometry*** to characterise of CRES region
  - Development of ***quantum-limited microwave amplifiers***
  - Design and development of a ***prototype microwave receiver*** + ***test electron source***
  - Development of ***data acquisition, analysis and simulation software***

The QTNM project

- Quantum Technologies for Neutrino Mass (QTNM)

Collaboration meeting
Spring 2023



UCL
WARWICK THE UNIVERSITY OF WARWICK
Queen Mary University of London
Prifysgol Abertawe Swansea University
UNIVERSITY OF OXFORD
NPL National Physical Laboratory

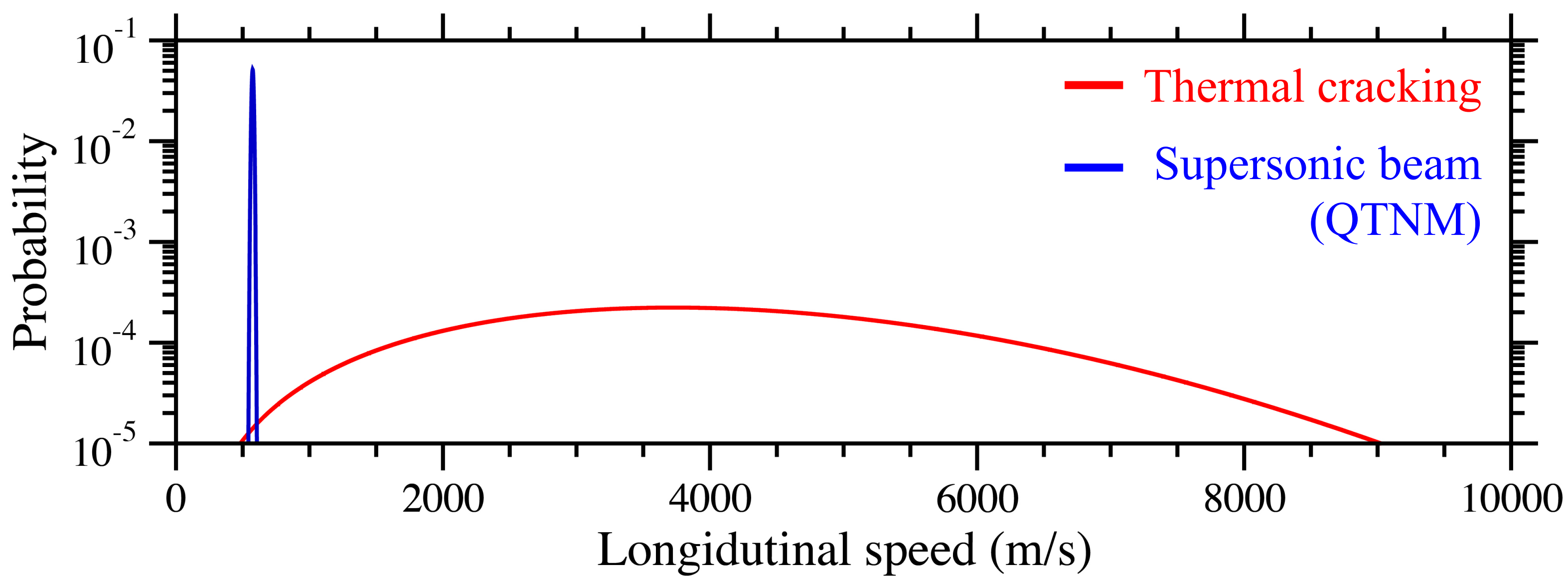
Alan Amad, Jon Breeze, Frank Deppisch, Markus Fleck, John Gallop, Tom Goffrey, **Ling Hao**, Nathan Higginbotham, **Stephen Hogan**, Seb Jones, **Lijie Li**, **Nicola McConkey**, Vincenzo Monachello, **Ryan Nichol**, Jamie Potter **Yorck Ramachers**, **Ruben Saakyan**, Emilia Sedzielewski, Daniel Swinnock, **David Waters**, **Stafford Withington** Songyang Zhao, Junwen Zou

Atomic hydrogen sources

- Thermal cracking
  - Heat H_2 gas so that thermal energy equal to dissociation energy (~4.5 eV)
  - T ~ 2500 K: v = 7000±3000 m/s

Olmstead and Compton, *Phys. Rev.* **22** 559 (1923)

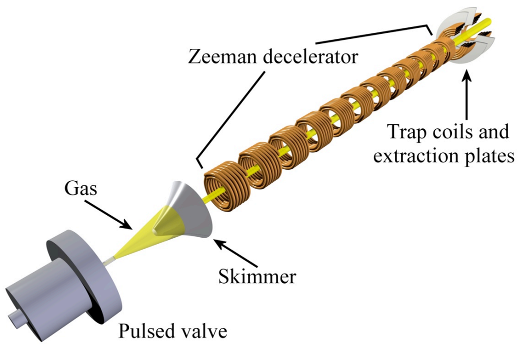
- Supersonic beams
  - Adiabatic expansion from high pressure reservoir into vacuum
    - High number densities, narrow speed distributions
    - Electric discharge to dissociation molecules



  - Motion of ground-state atoms controlled using in homogeneous magnetic fields

Deceleration and magnetic trapping H and D atoms

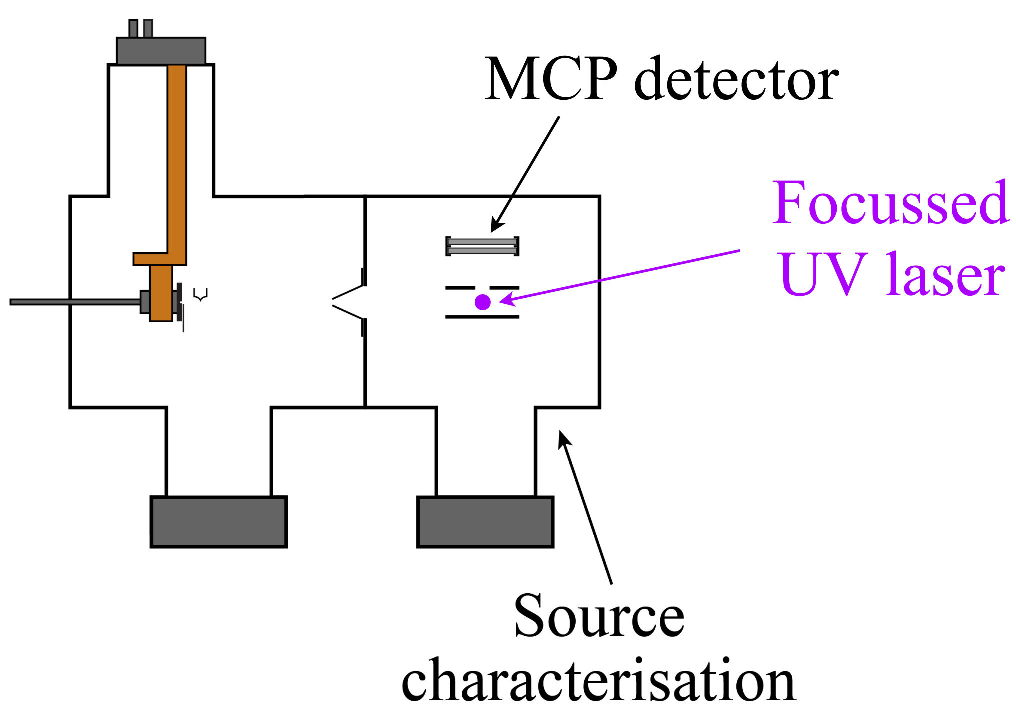
Hogan, Wiederkehr, Schmutz and Merkt, *Phys. Rev. Lett.* **101** 143001 (2008)
Wiederkehr, et al., *Phys. Rev. A* **81** 021402(R) (2010)

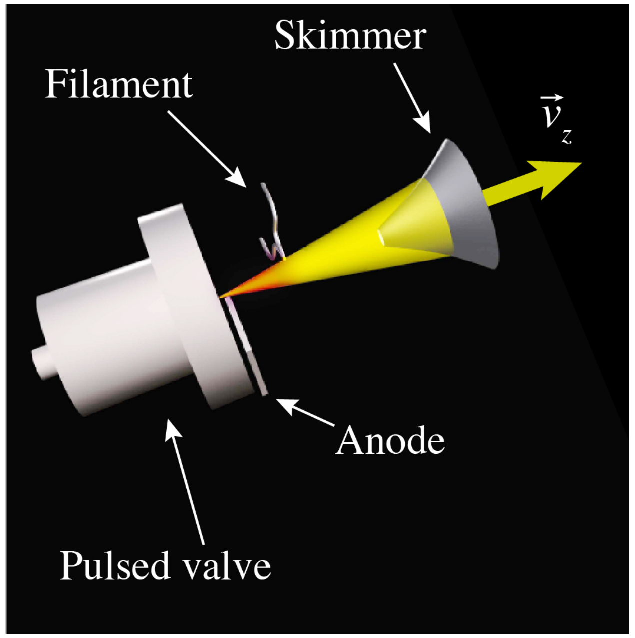


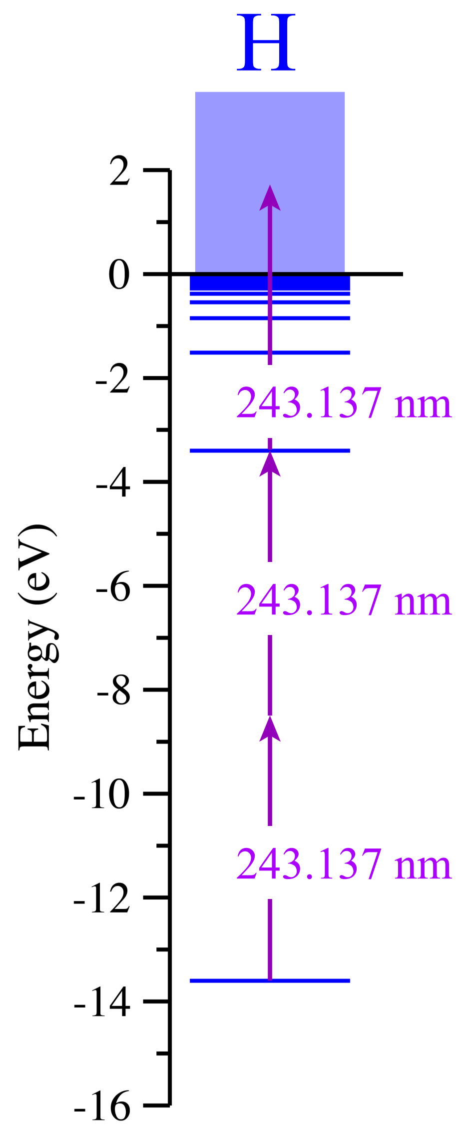
QTNM atomic beam source

- Supersonic beam source of H, D (or T)
  - DC electric discharge at exit of valve — dissociation of molecules occurs in vacuum
  - Thermalisation of atoms by collisions with molecules

H/D/T atom supersonic beam discharge source







D: $\lambda_{uv} = 243.071$ nm

T: $\lambda_{uv} = 243.049$ nm

- Pulsed solenoid valve — Even Lavie (10 Hz rep. rate)
- Operating temperature 300 K — 30 K
- H_2 gas pressure in reservoir: ~6 bar
- Background pressure of vacuum system: ~10^{-8} mbar

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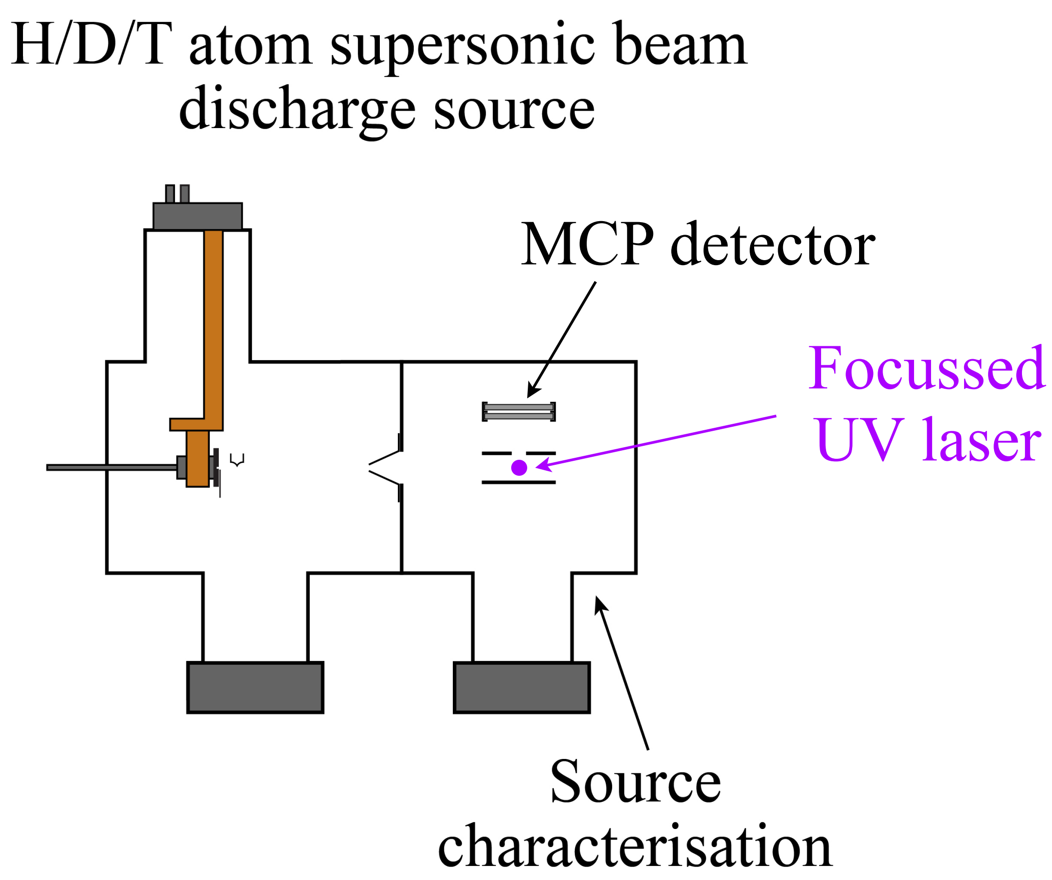

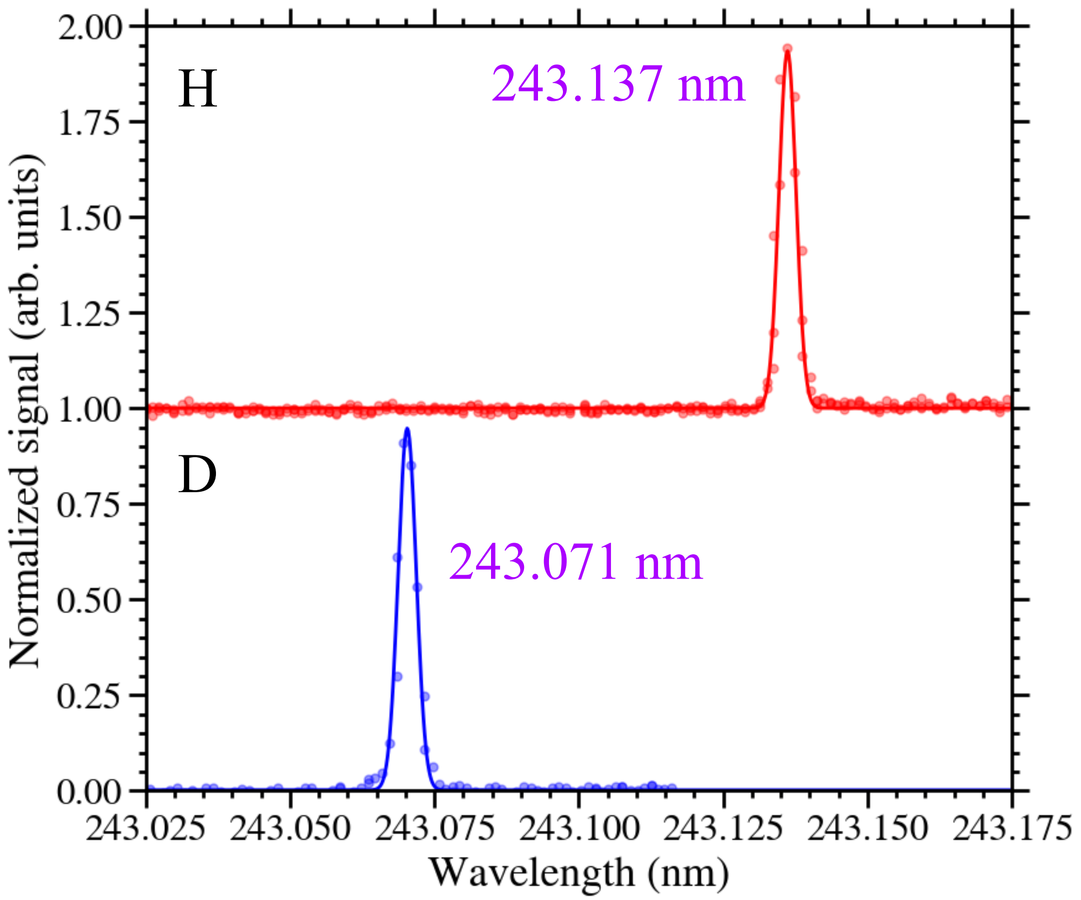

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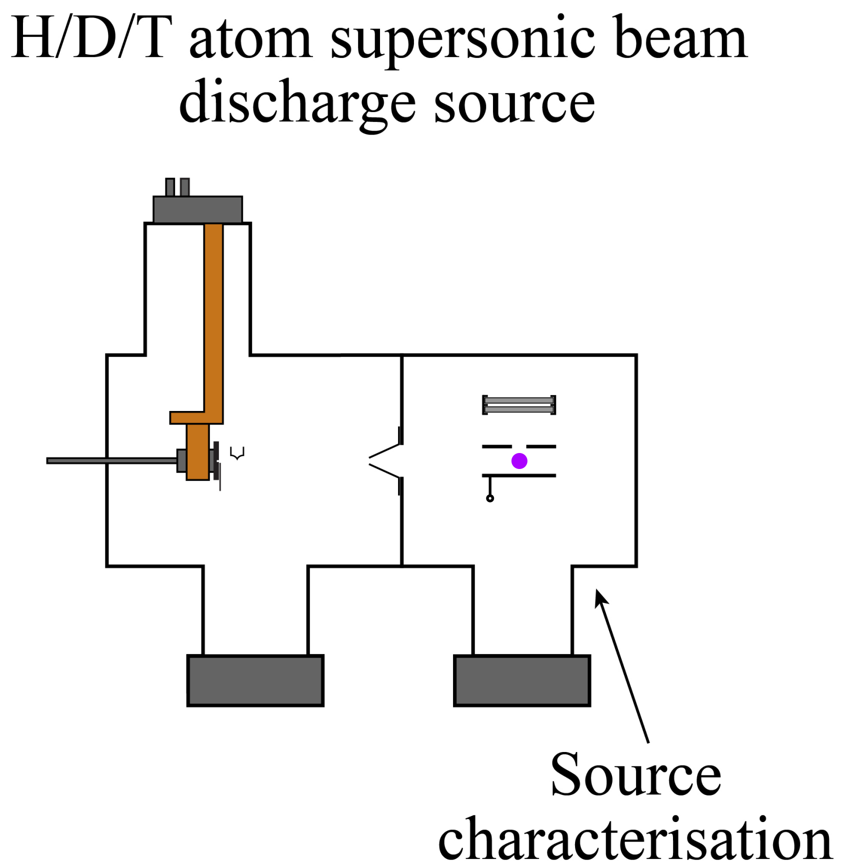
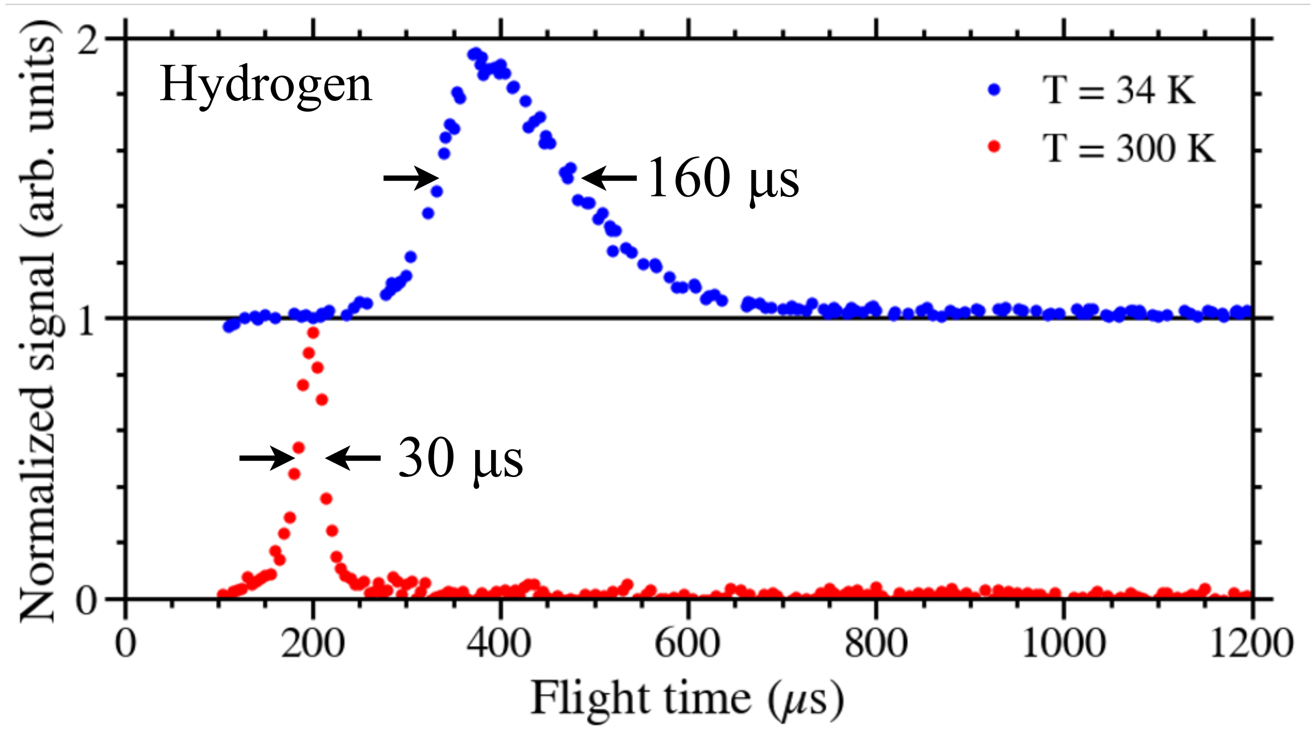
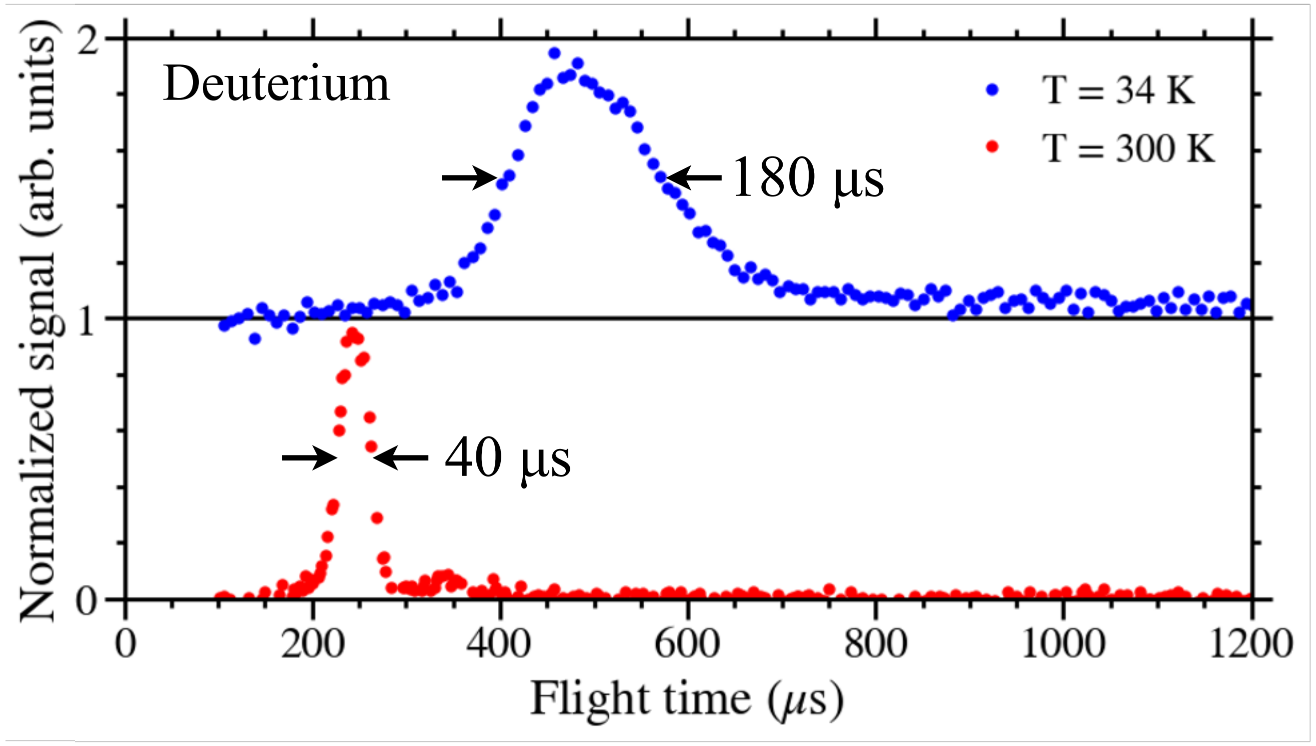
Time of flight distributions

- H and D atom beams

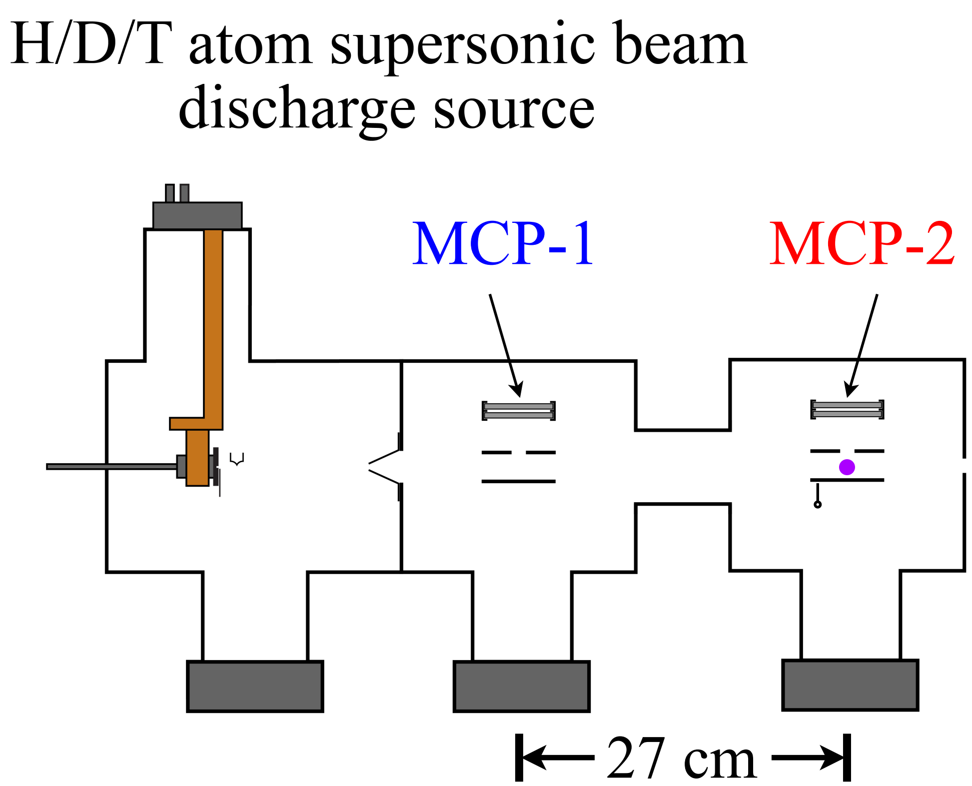


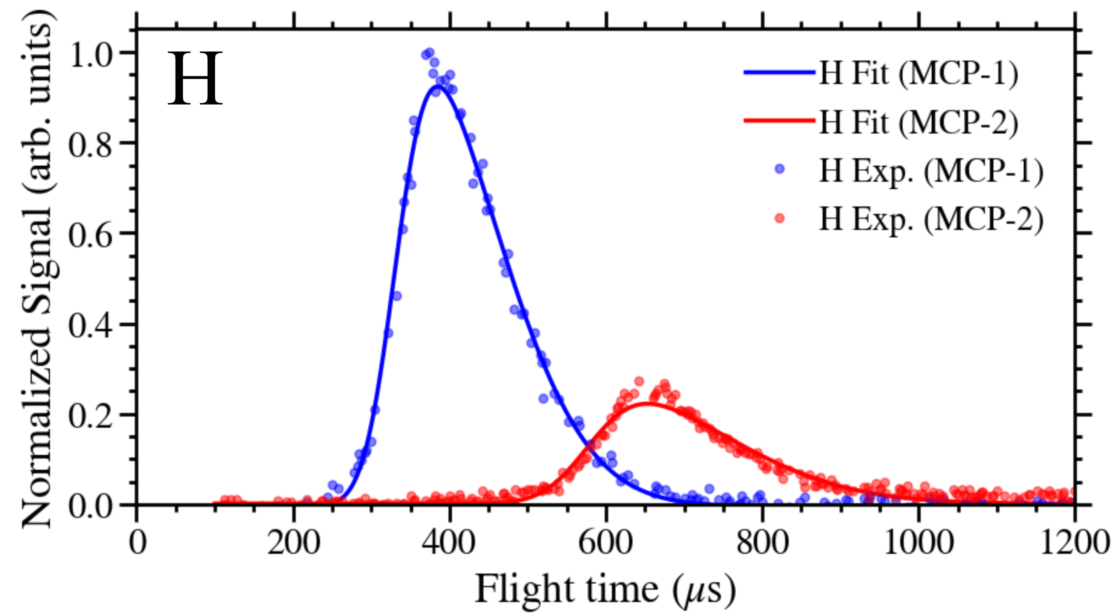


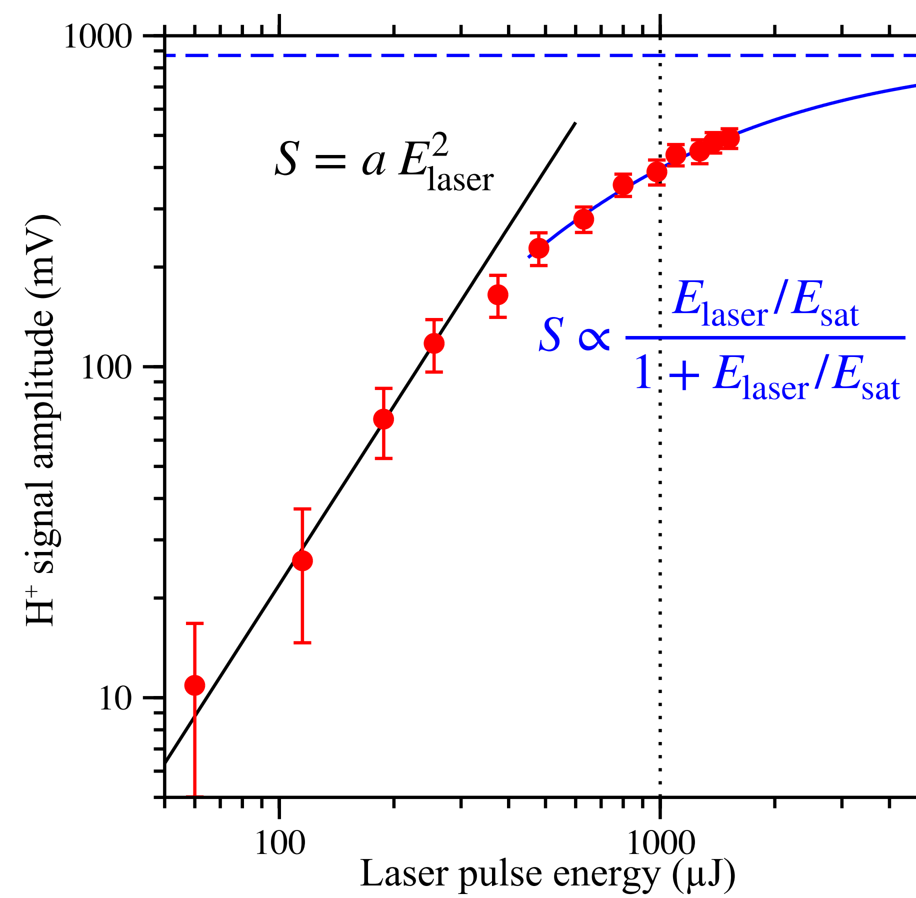


Speed distributions

- H atom beams



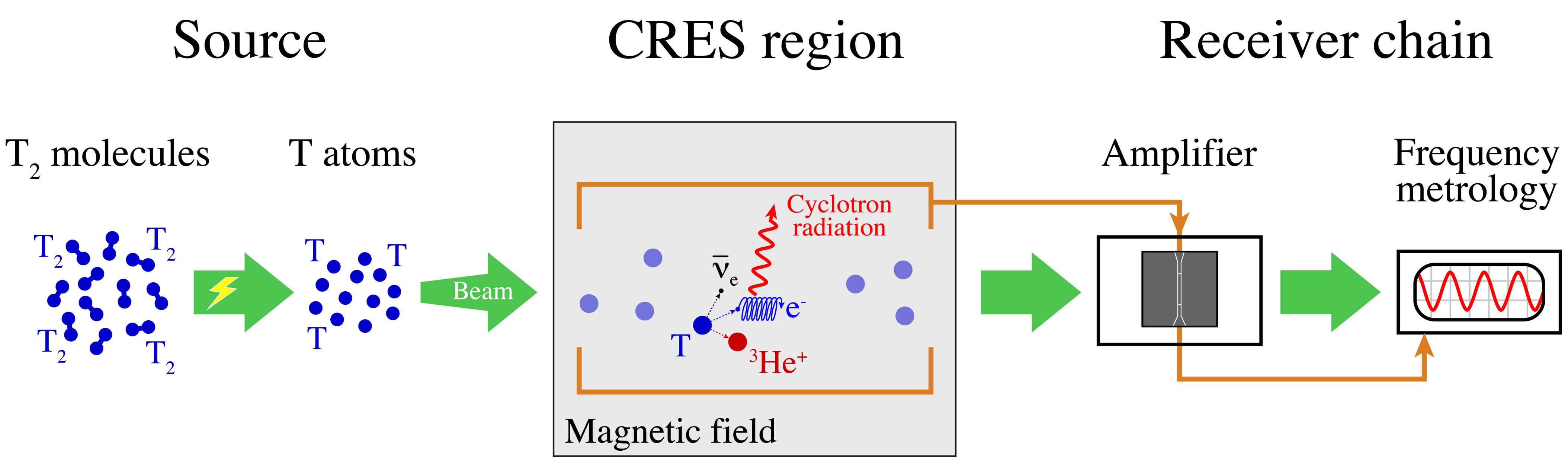




- Phase space properties
  - $\bar{v}_{\mathrm{H}} = 1000$ m/s; $\sigma_{\mathrm{H}} = 30$ m/s; $T_{\mathrm{trans}} = 50$ mK
  - $\bar{v}_{\mathrm{D}} = 750$ m/s; $\sigma_{\mathrm{D}} = 20$ m/s; $T_{\mathrm{trans}} = 50$ mK
  - Density at ***detection position***: ~1 x 10^7 cm^{-3}
  - Estimated density at ***skimmer***: 10^9 cm^{-3}
  - ***Flux*** from source: 10^{15} — 10^{16} atoms s^{-1}

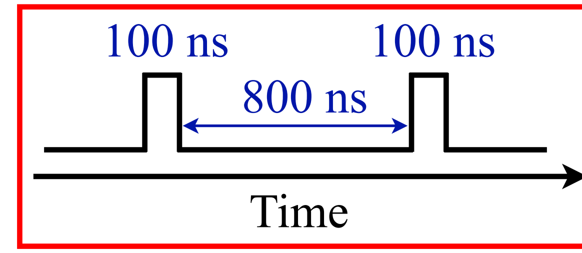
Magnetometry/electrometry

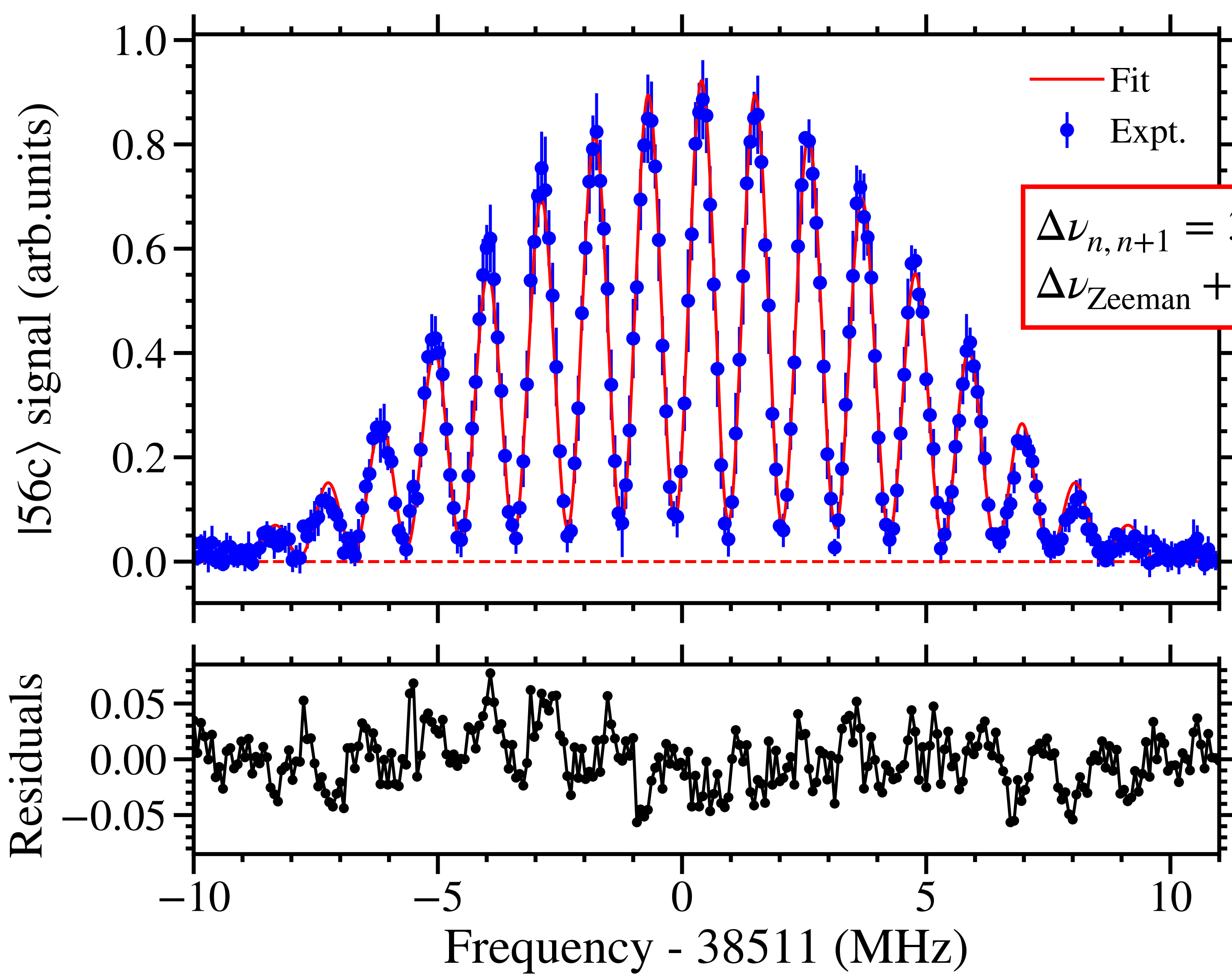
- Atoms in superpositions of circular Rydberg states as quantum sensors
  - Static magnetic field mapping
  - Individual vector components of stray electric fields
  - Can be implemented *in situ* in CRES spectrometry at cryogenic temperature



Ramsey spectroscopy

- Microwave spectroscopy of n = 55 → n = 56 transition
- Ramsey pulse duration 100 ns
- Free-evolution time 800 ns
- Uncertainty in determination of resonance frequency ±1.5 kHz





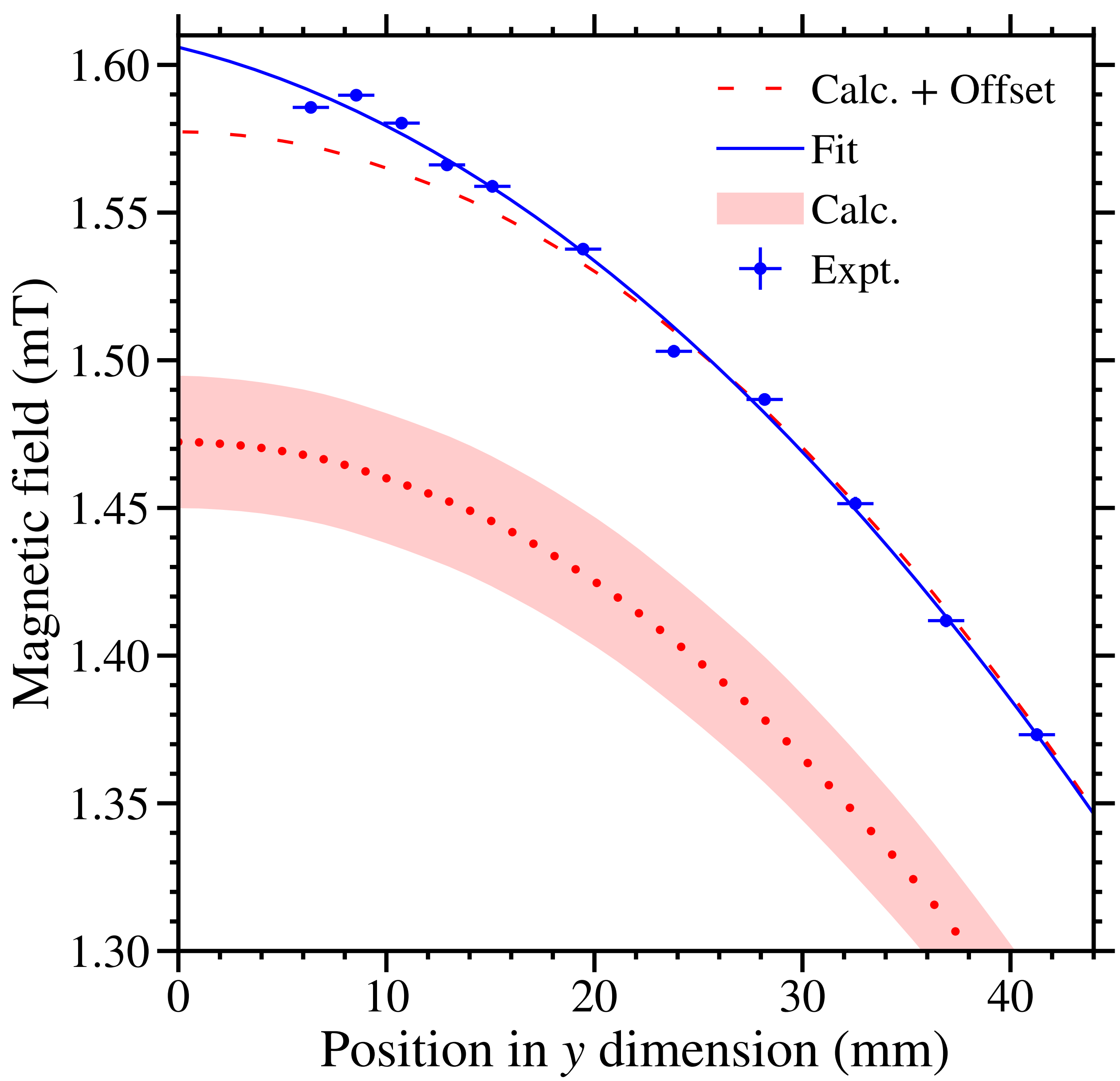
$$\Delta\nu_{n,n+1} = 38489.038 \text{ MHz}$$
$$\Delta\nu_{\text{Zeeman}} + \Delta\nu_{\text{Stark}} + \Delta\nu_{\text{Doppler}} = 22.3638 \text{ MHz}$$

$$\Delta\nu_{\text{Doppler}} = +50.91 \pm 21.65 \text{ kHz}$$

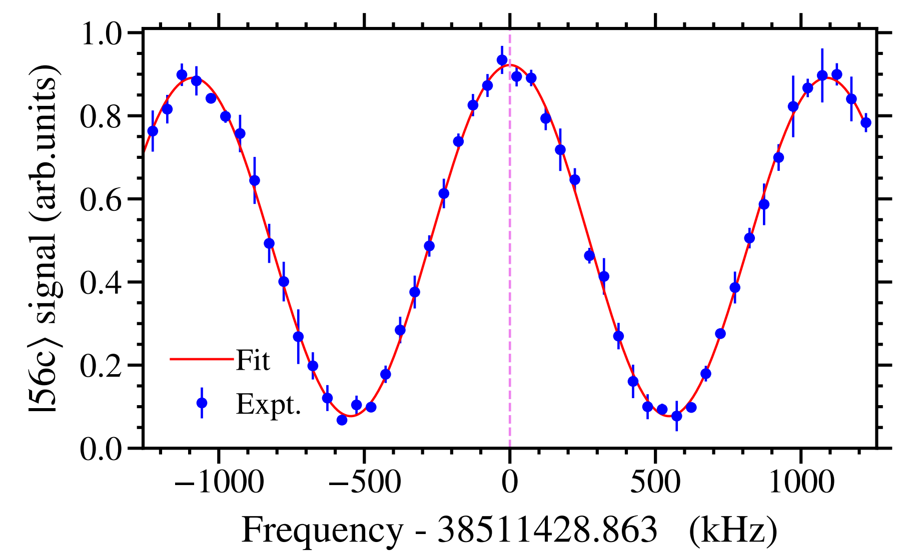
Zou and Hogan
Phys. Rev. A **207** 062820 (2023)

Static field mapping

- Spatial resolution: ±0.87 mm
- Absolute precision of **magnetic field**: ±2.0 μT
- Precision of **magnetic field gradient**: ±53 nT/mm over 35 mm baseline
- Residual **electric field**: (±85 μV/cm, 15.47±0.75 mV/cm, ±100 μV/cm)



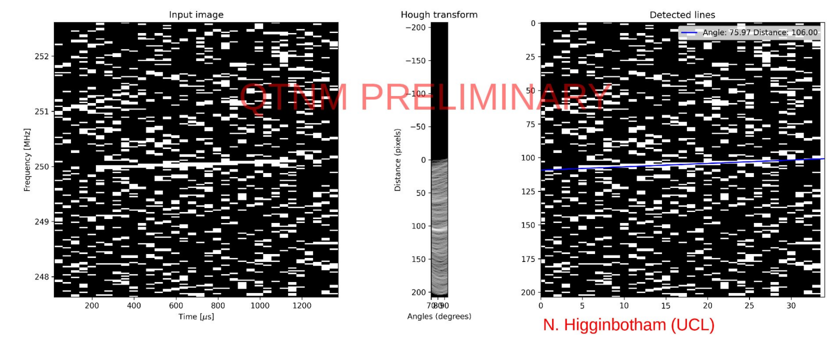
Short Ramsey spectrum

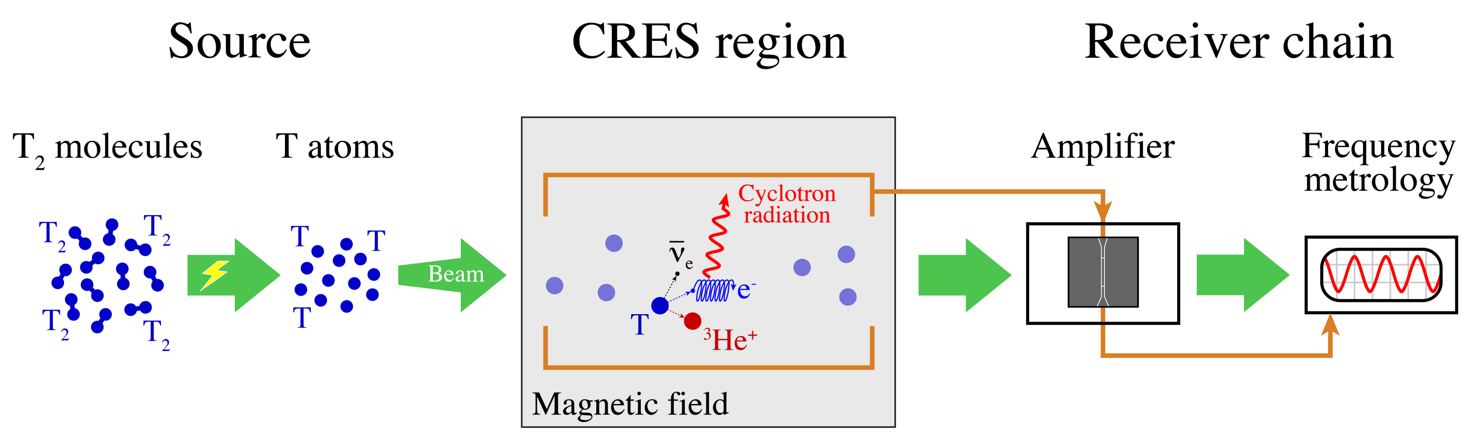


Zou and Hogan
Phys. Rev. A **207** 062820 (2023)

CRES components & simulations

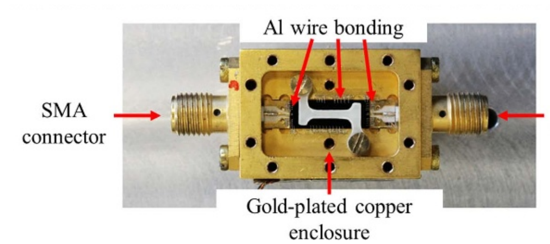
- Simulation and analysis software
  - Cyclotron radiation field distributions & antenna response
  - Read-out chain
  - Signal analysis/event reconstruction:
    - Power cuts, Hough transforms, matched filtering, …

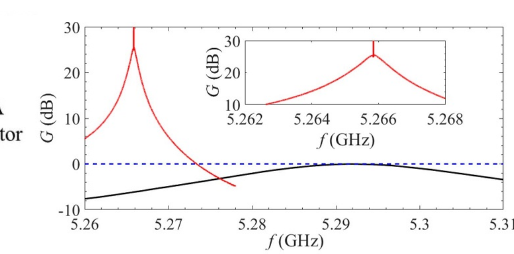




- Quantum limited microwave electronics
  - Superconducting parametric amplifiers

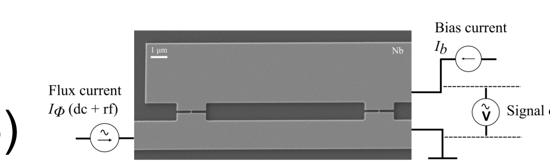
    Zhao, Withington and Thomas
    Supercond. Sci. Technol. **36** 105010 (2023)





  - **S**uperconducting **L**ow-inductance **U**ndulatory **G**alvanometer

    Chapman et al., *IEEE Trans. Appl. Supercond.*, **34** 1500505 (2024)



  - Antenna arrays in CRES spectrometer

    Withington, Thomas and Zhao, *arXiv:2401.03247* (2024)

Songyuan Zhao, Wed. 22nd 11:00

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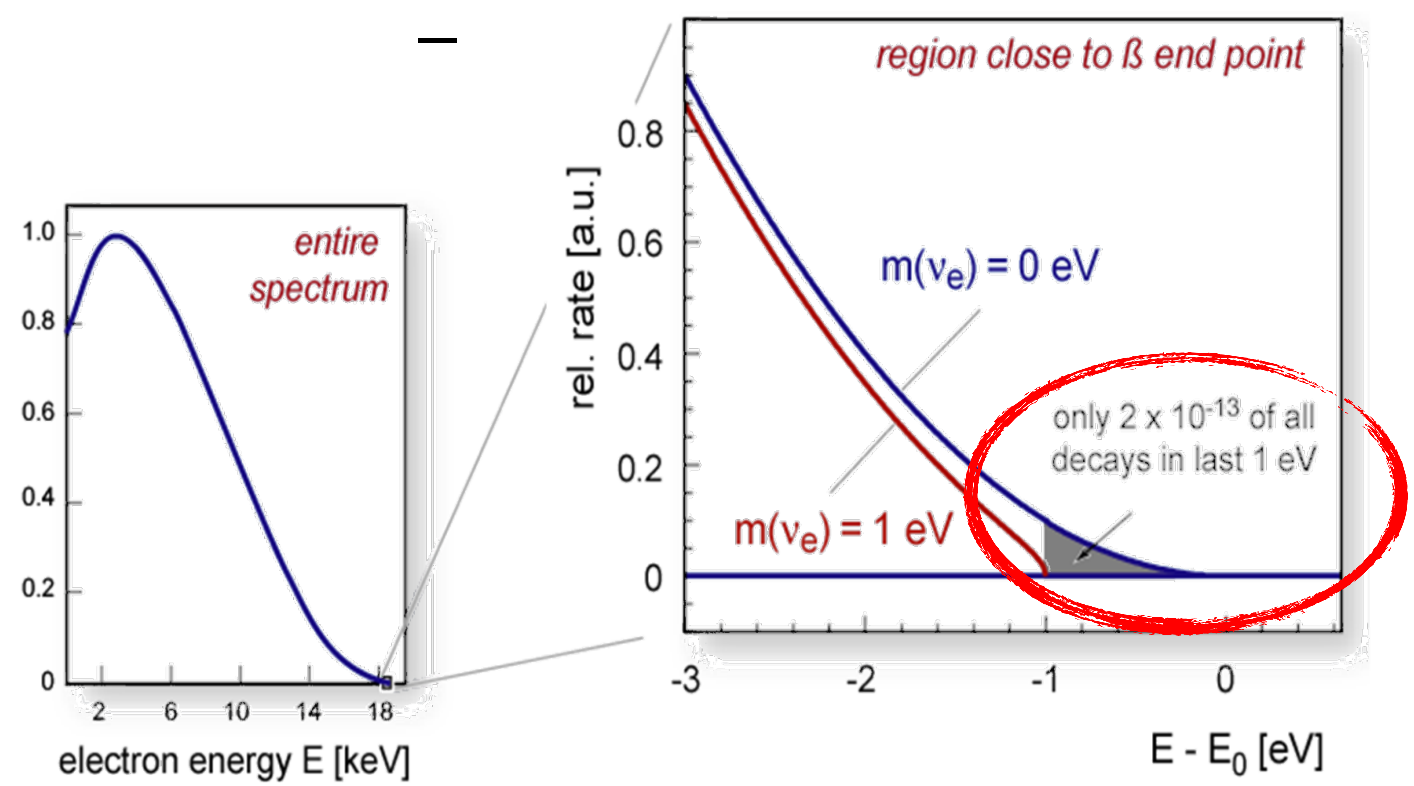
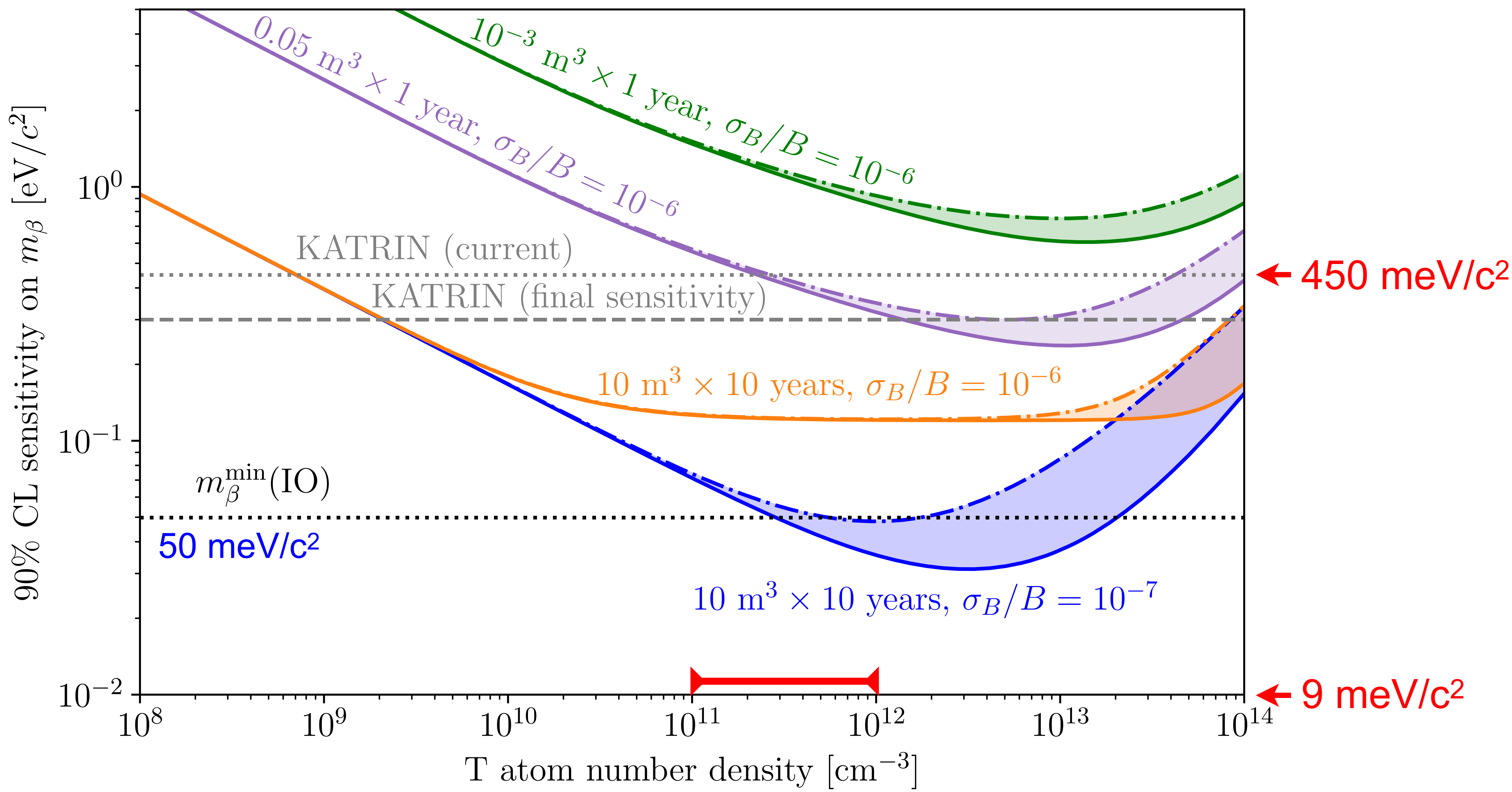
β-decay-electron spectrum



Mertens, *Absolute Neutrino Mass Workshop* (2019)

Absolute neutrino mass

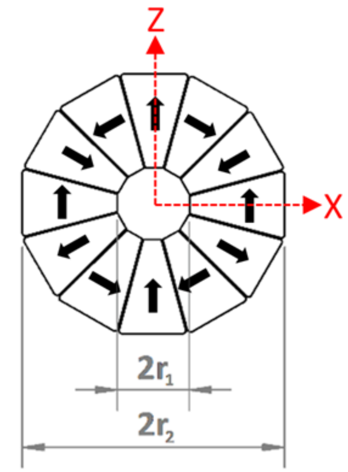
- Sensitivity targets

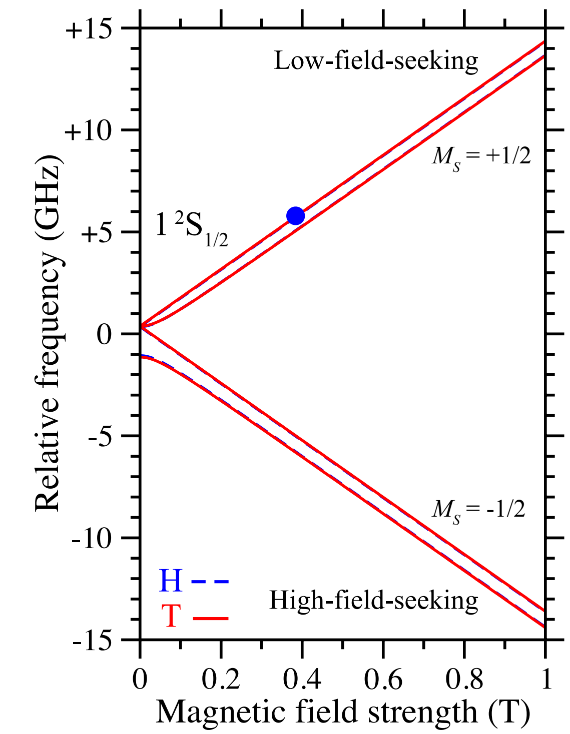


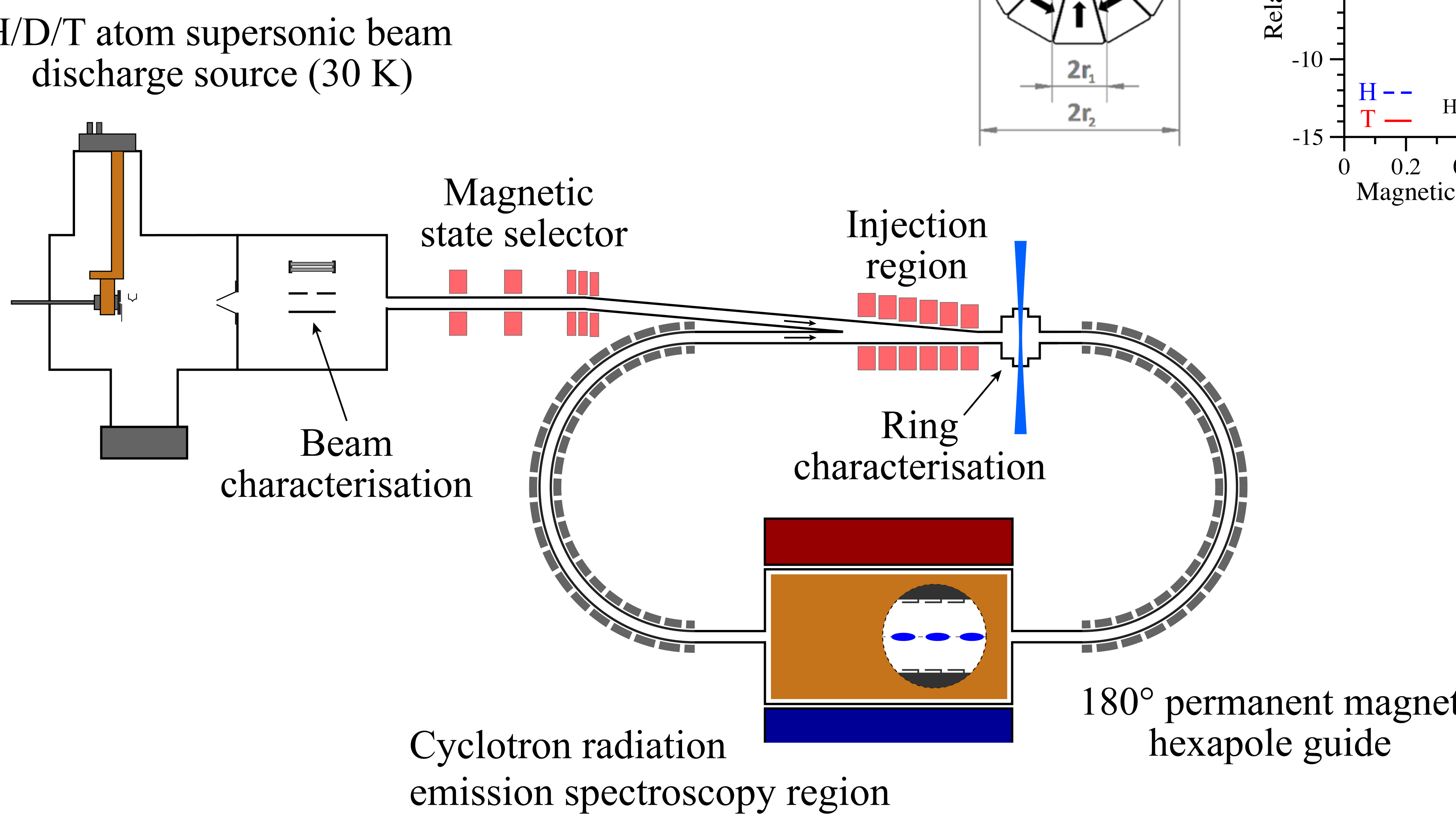
Amed et al. (QTNM), arXiv:2412.06338 (2024)

Magnetic confinement of atoms

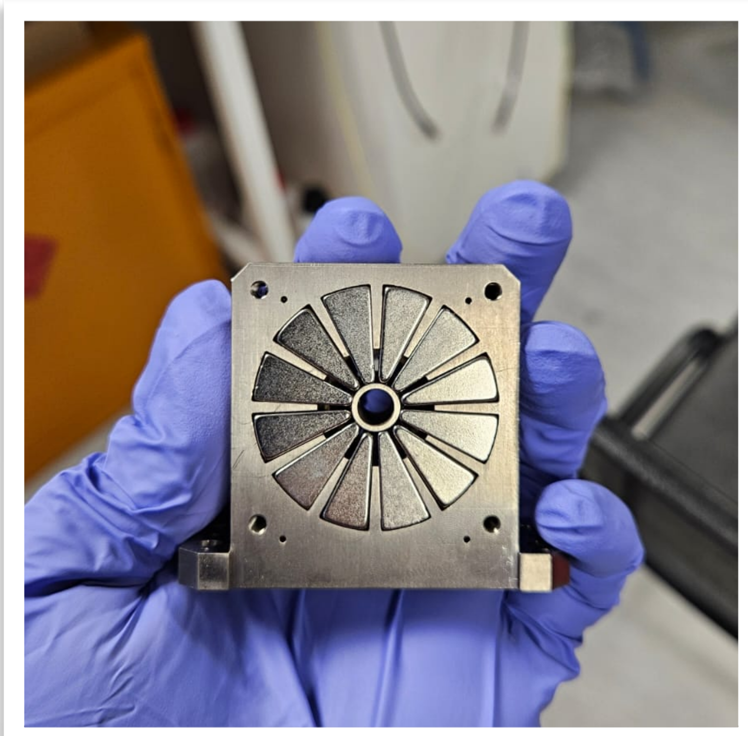
- Magnetic storage ring for ground state H or T atoms
  - 120 permanent hexapole Halbach arrays (full ring)
  - Ring radius of curvature 0.6 m
  - Inner guide diameter 4 mm

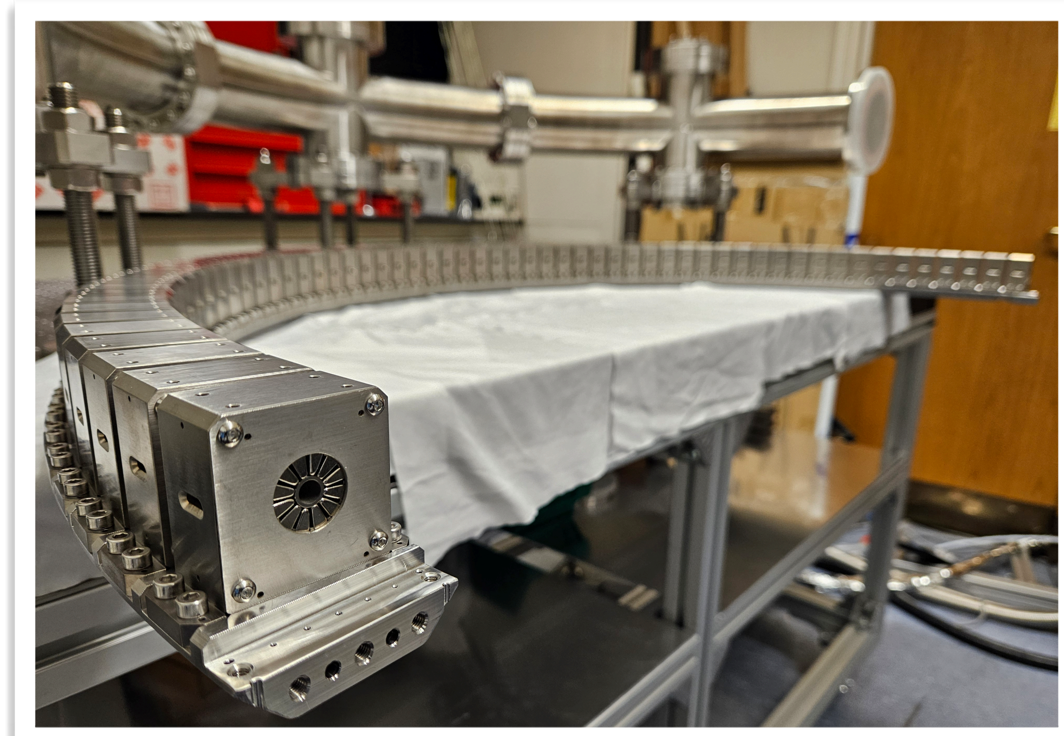


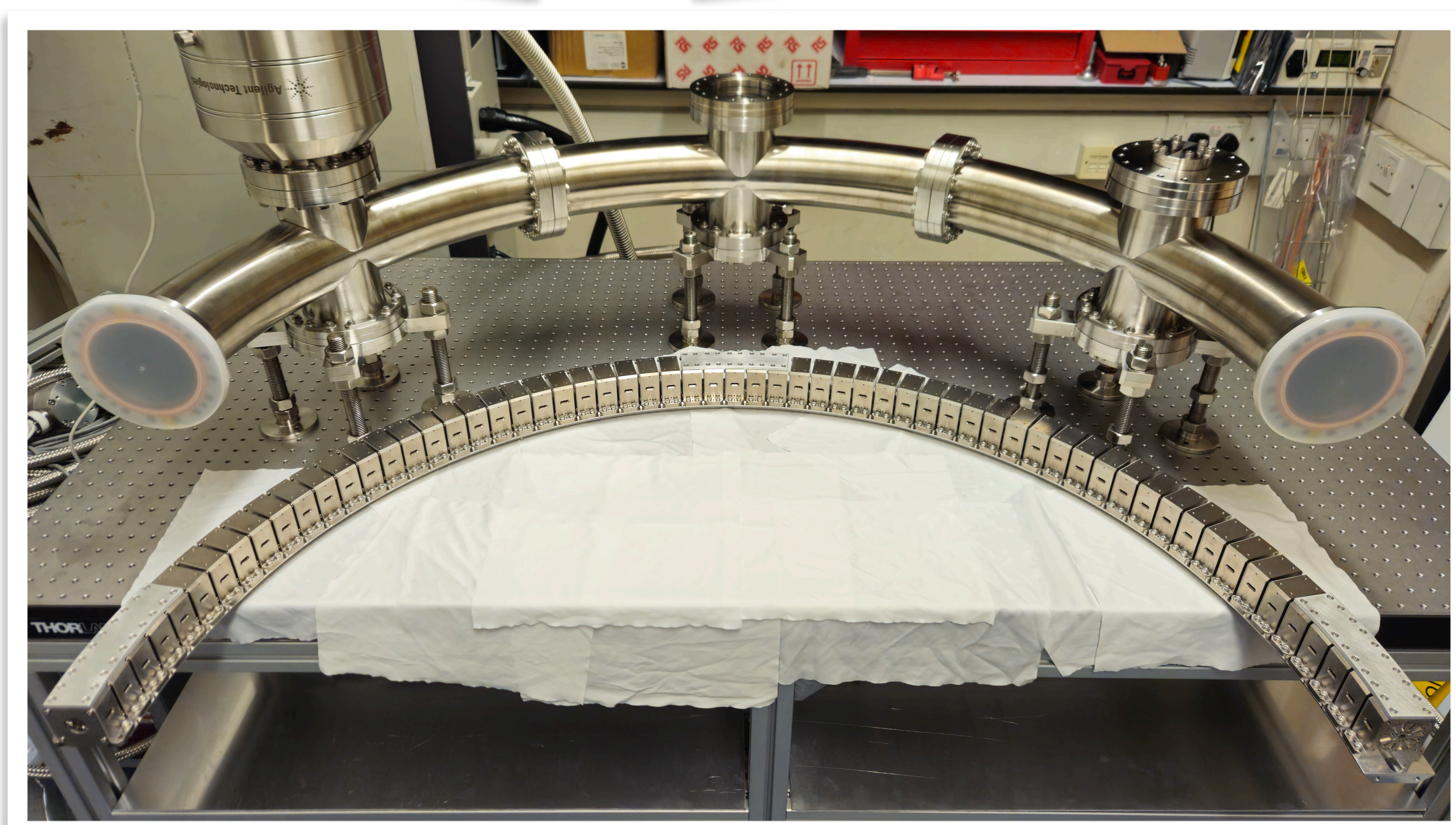




Storage ring construction







Dr Vincenzo Monachello
(UCL)

Future scaling

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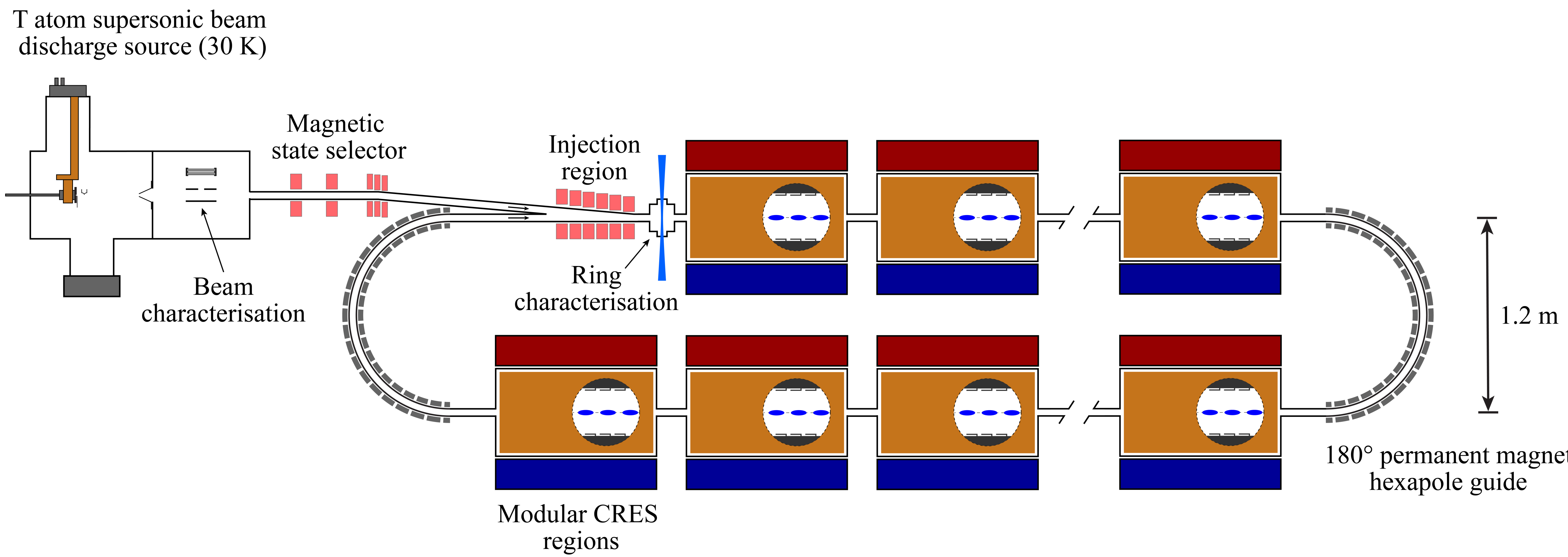
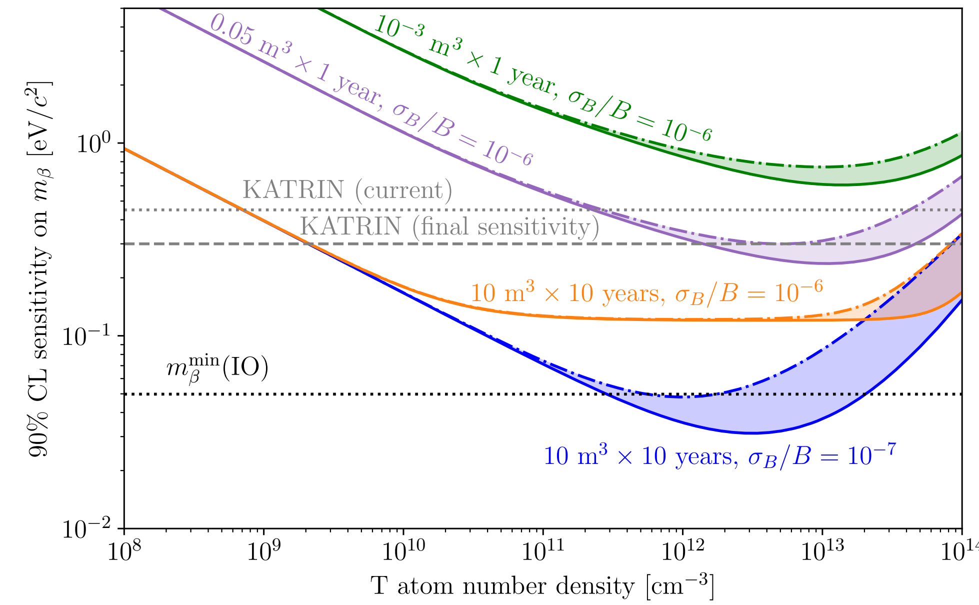
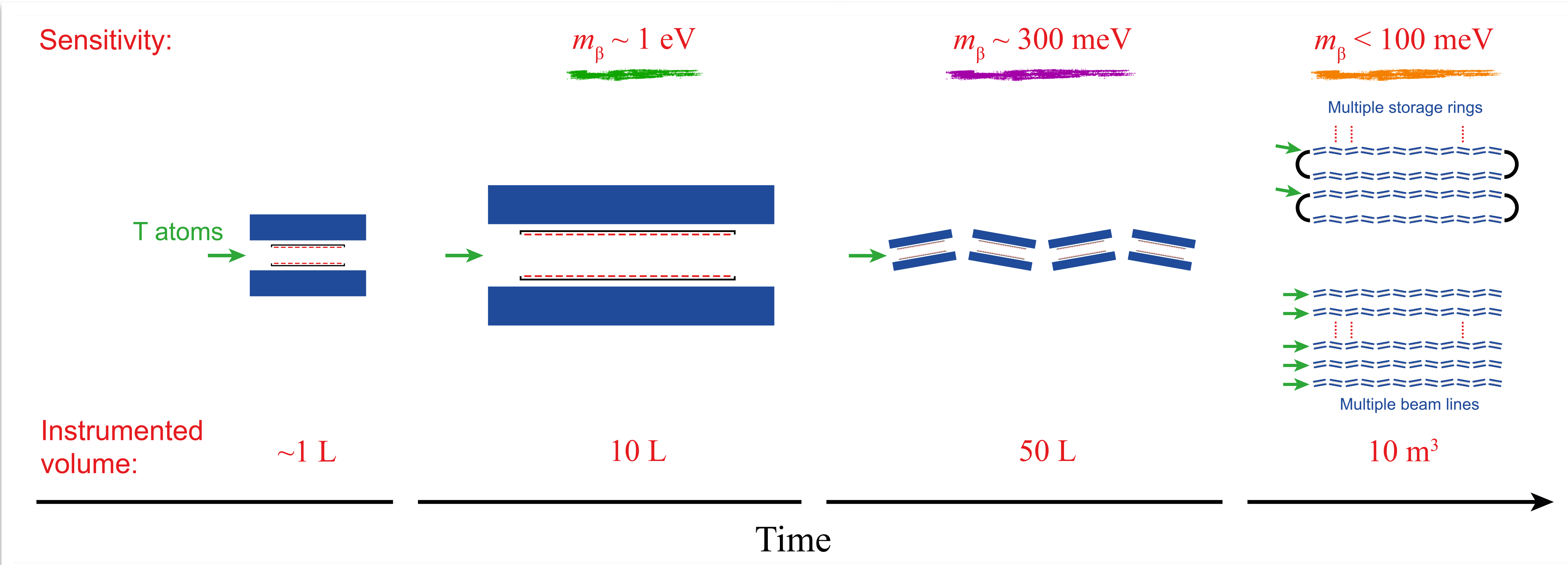
  - Inner diameter 4 mm



Future scaling

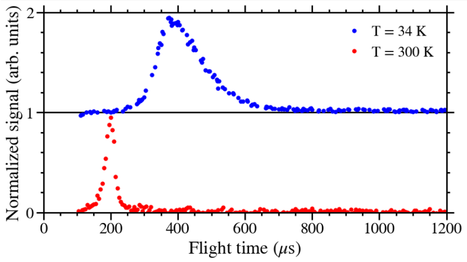
- Sensitivity targets

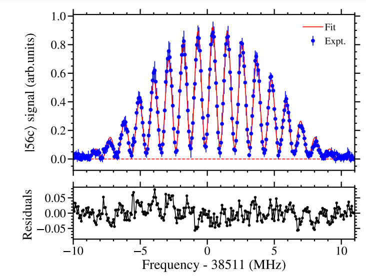




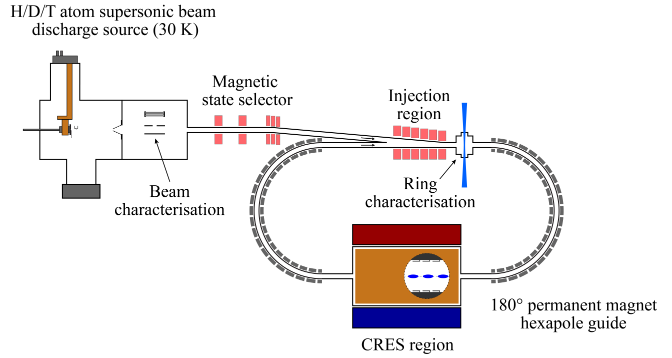
Summary

- Supersonic beam sources of H and D atoms
  - Operation from 300 K to 34 K
  - High phase-space densities
  - Suitable for production of T atoms





- CRES spectrometer
  - Quantum limited microwave amplifiers
  - Superpositions of circular Rydberg states — electric/magnetic field sensing
  - Prototype CRES receiver - development, simulation + analysis software
- Outreach
  - Follow-on funding for impact and engagement
    incl. secondary school ‘quantum club’, Tower Hamlets



- Toward experiments with T atoms
  - Culham Centre for Fusion Energy — large T_2 inventory (H3AT)
  - Tritium Laboratory Karlsruhe (TLK)
  - Joint Atomic Tritium Working Group — KATRIN++, Project 8, QTNM

CCFE CULHAM CENTRE FOR FUSION ENERGY

KIT Karlsruher Institut für Technologie