Precision spectroscopy of highly charged ions

Update for QS4Physics

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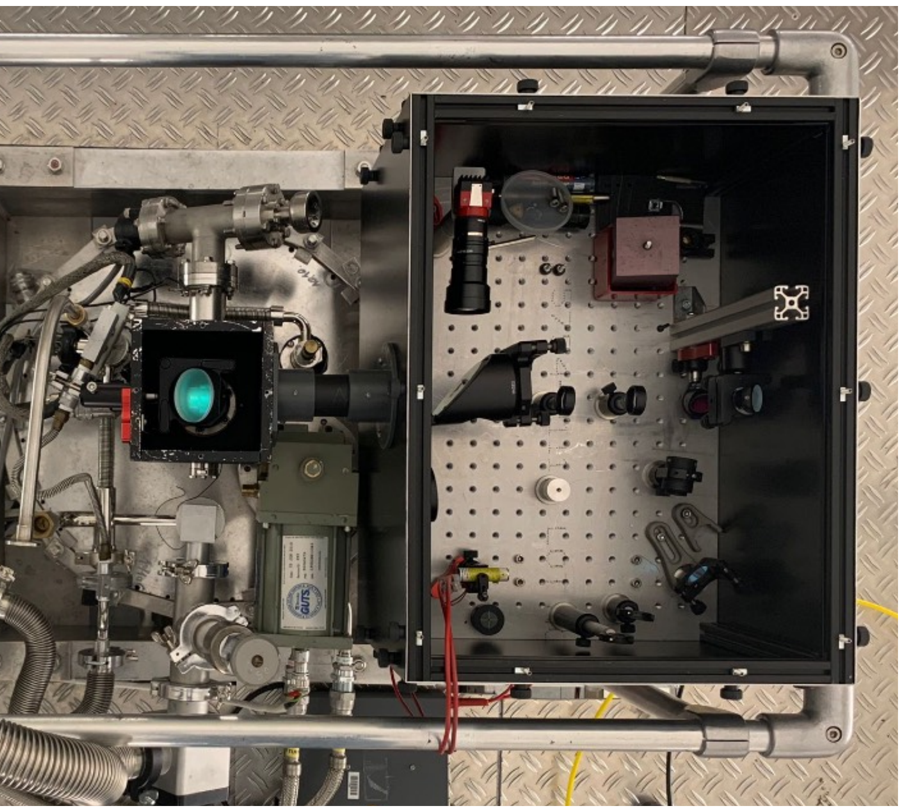
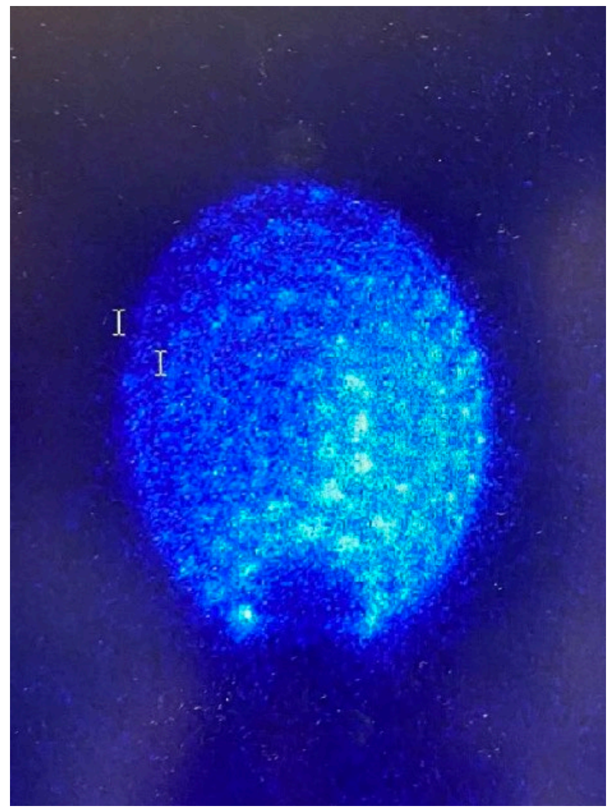
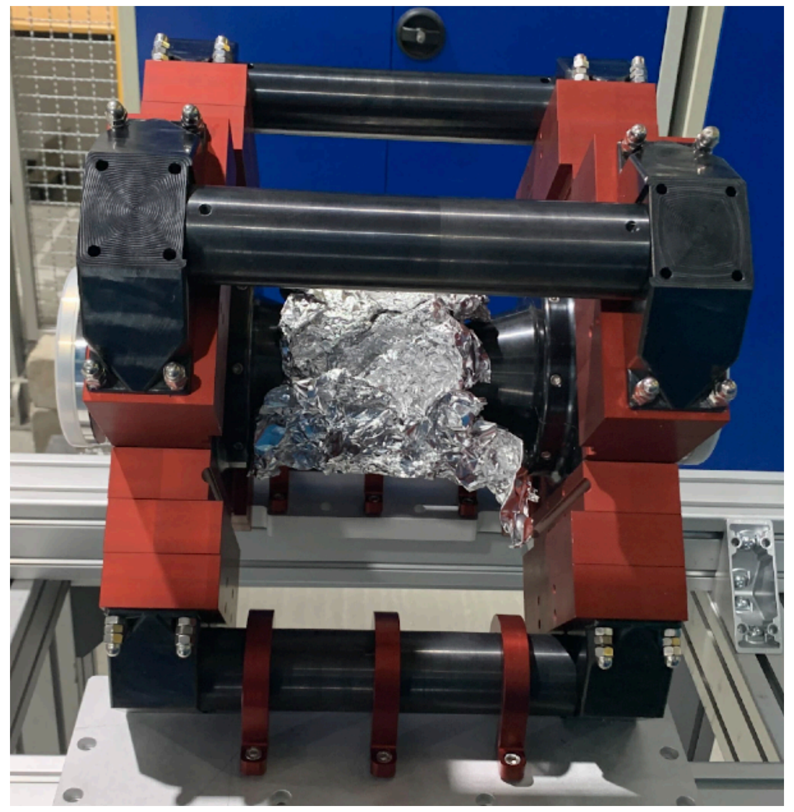
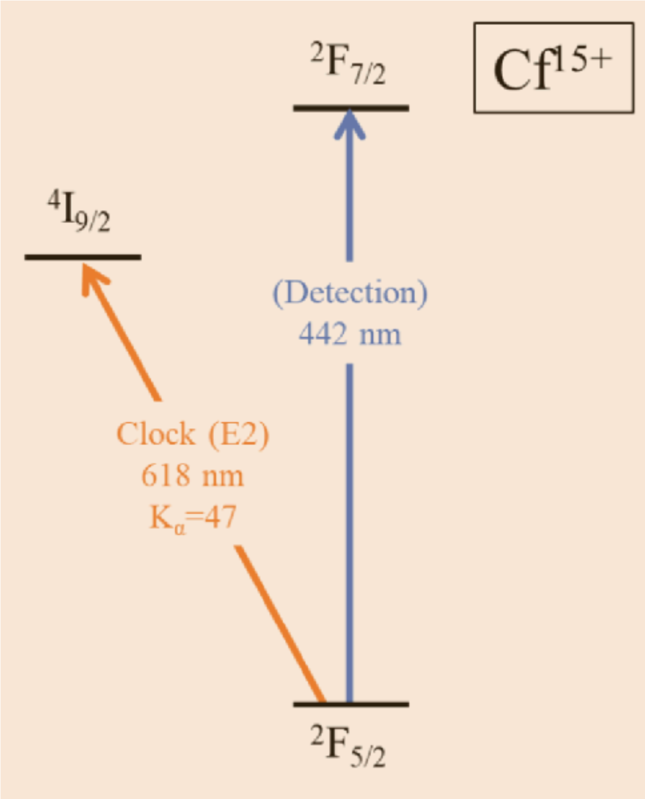
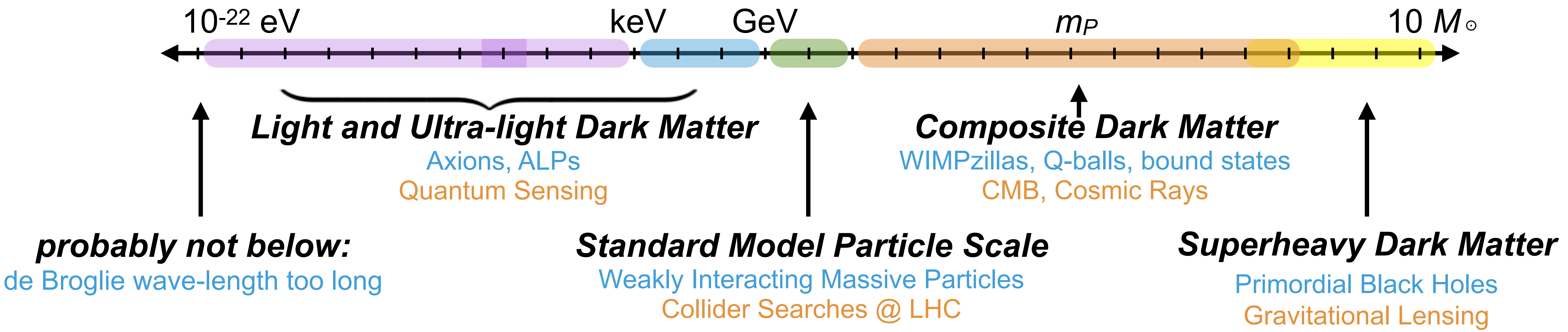
November 20, 2025


Ultralight Dark Matter + Quantum Sensing = Clock Experiments

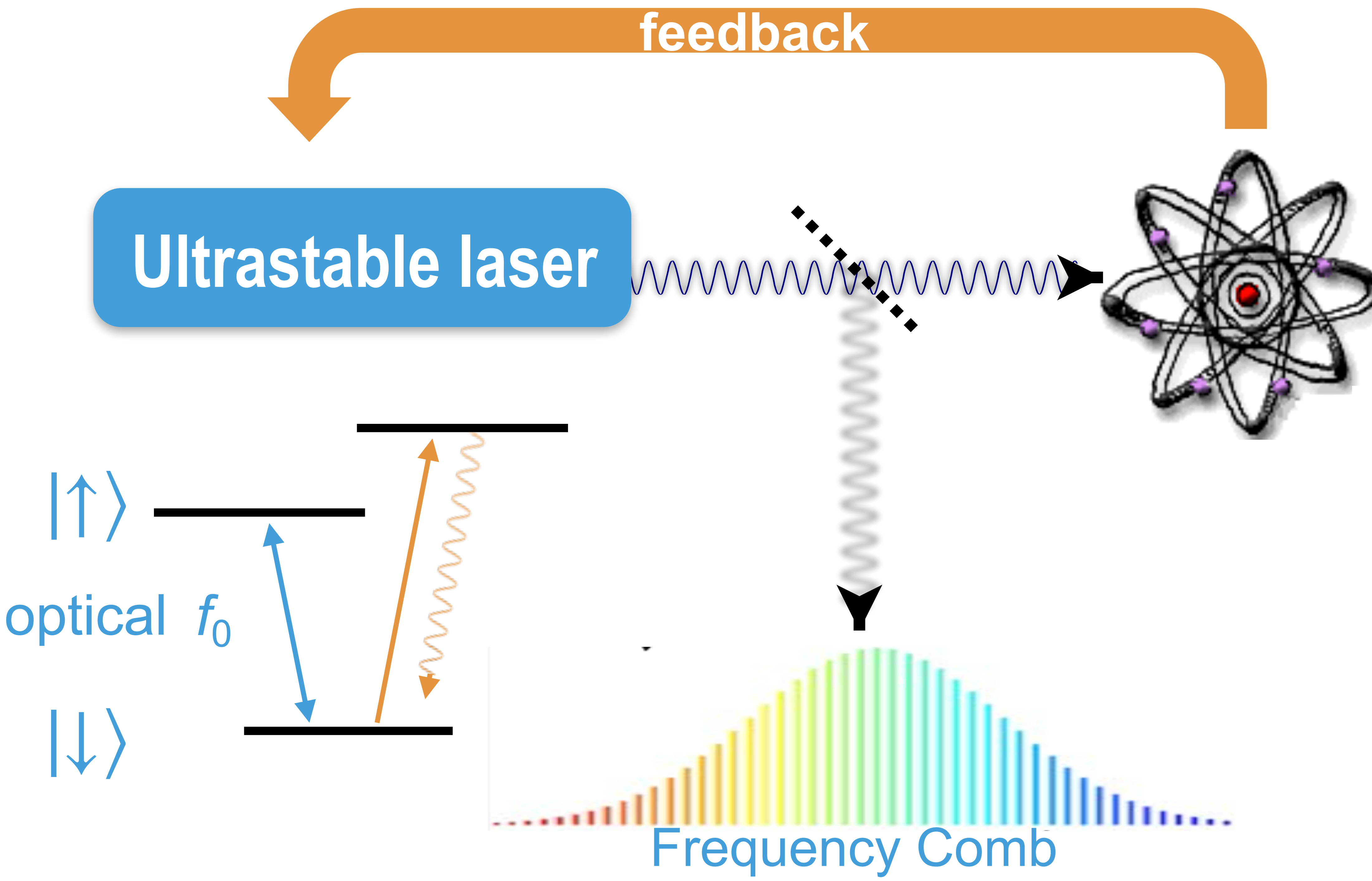
- *Quantum sensing essential* for light and ultra-light Dark Matter searches

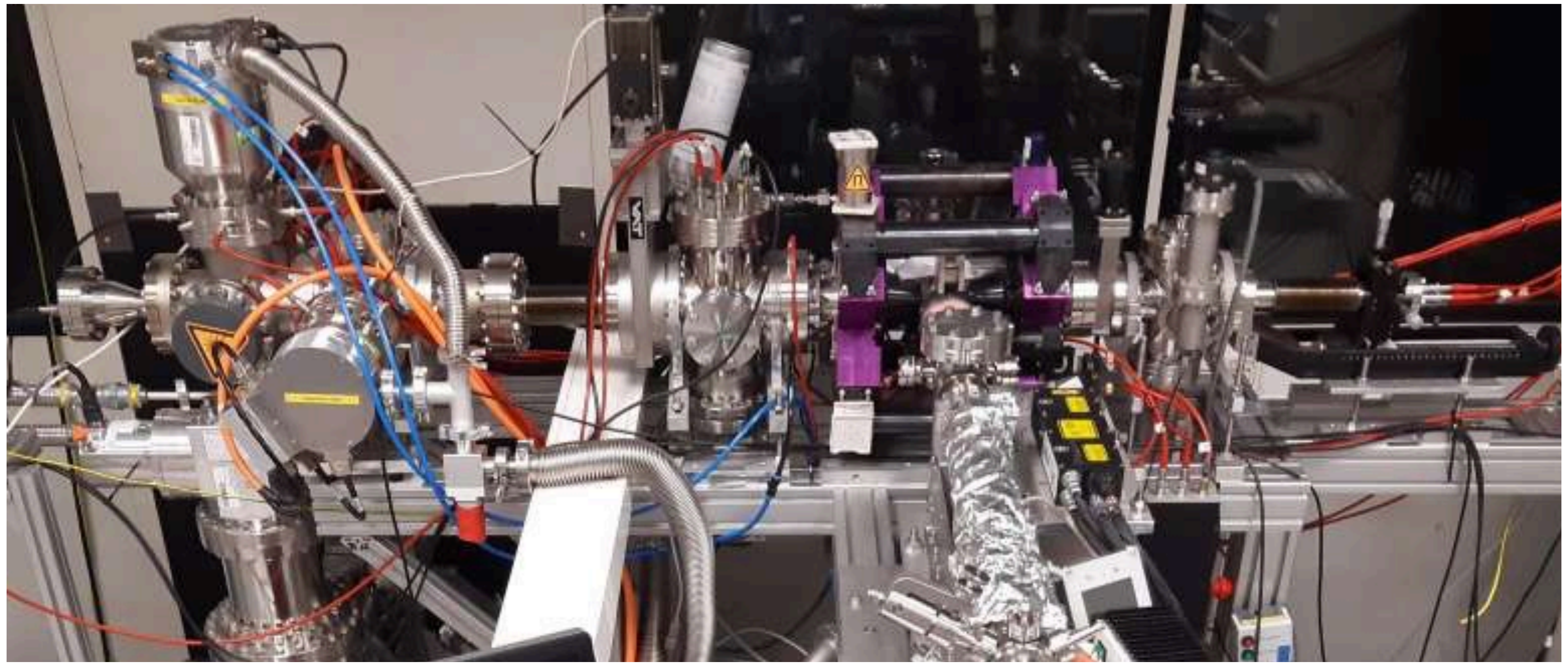


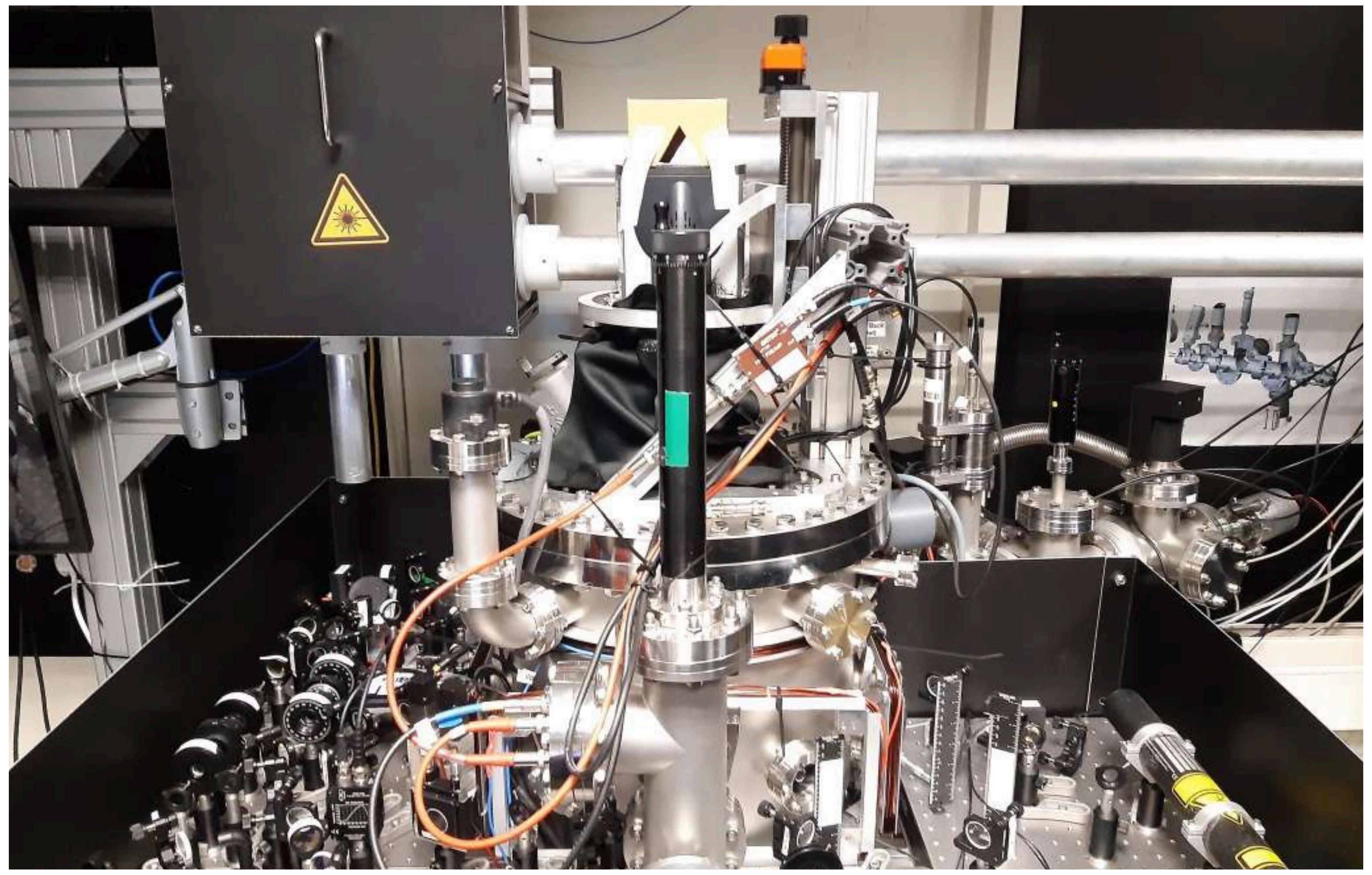
- *Optical Atomic Clock Experiments:* measure frequency ratios of two differently-sensitive clocks (α or μ)
- *More physics to explore:* topological defect Dark Matter, Local Lorentz Invariance, 5th Forces, Gravitational shift in fundamental constants, Dark Energy, Gravitational Waves

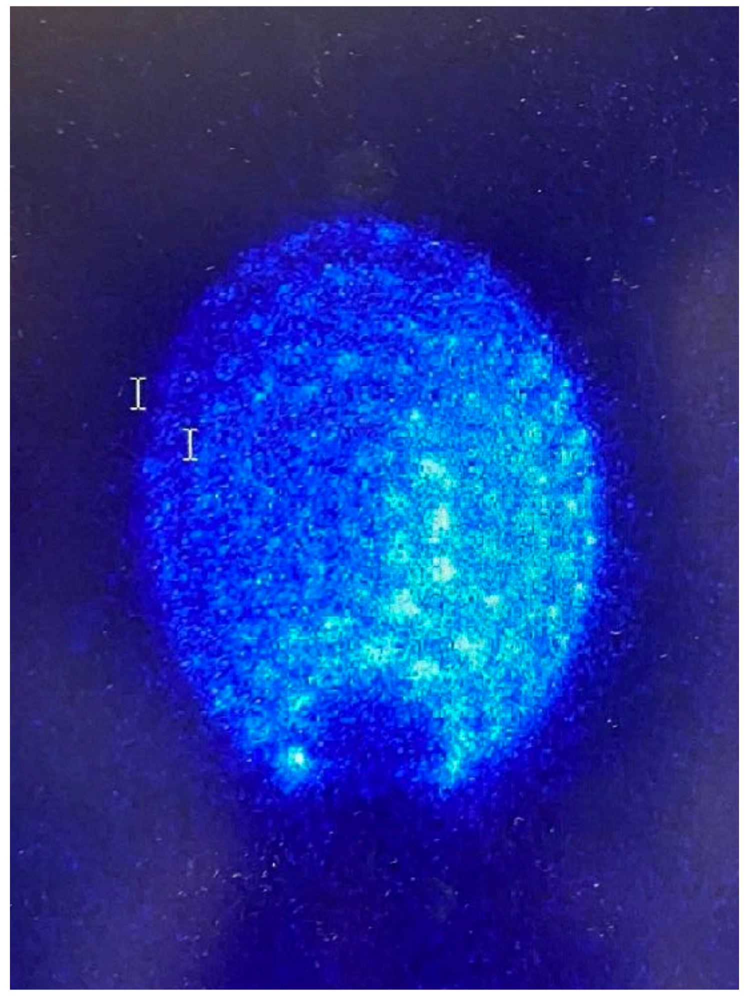
Optical Atomic Clocks w/ Ions

- Ultra-stable laser excites atomic transitions → a clock
- Frequency comb: optical → countable microwave
- Laser/sympathetic cooling with a second ion (eg Be)
- Example: Highly charged ions (HCI) for best sensitivity to $\Delta\alpha/\alpha$ for ultra-light dark matter interactions
- Half a dozen experts in this room!




EBIT test stand @MPIK

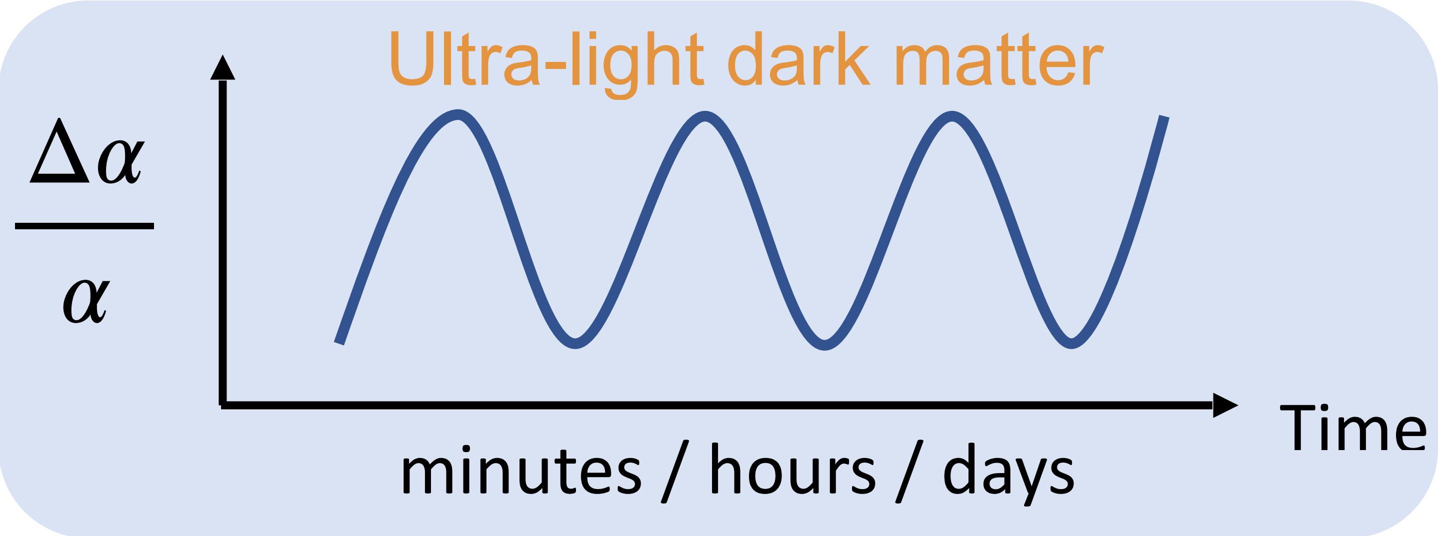

Paul trap w/ optics

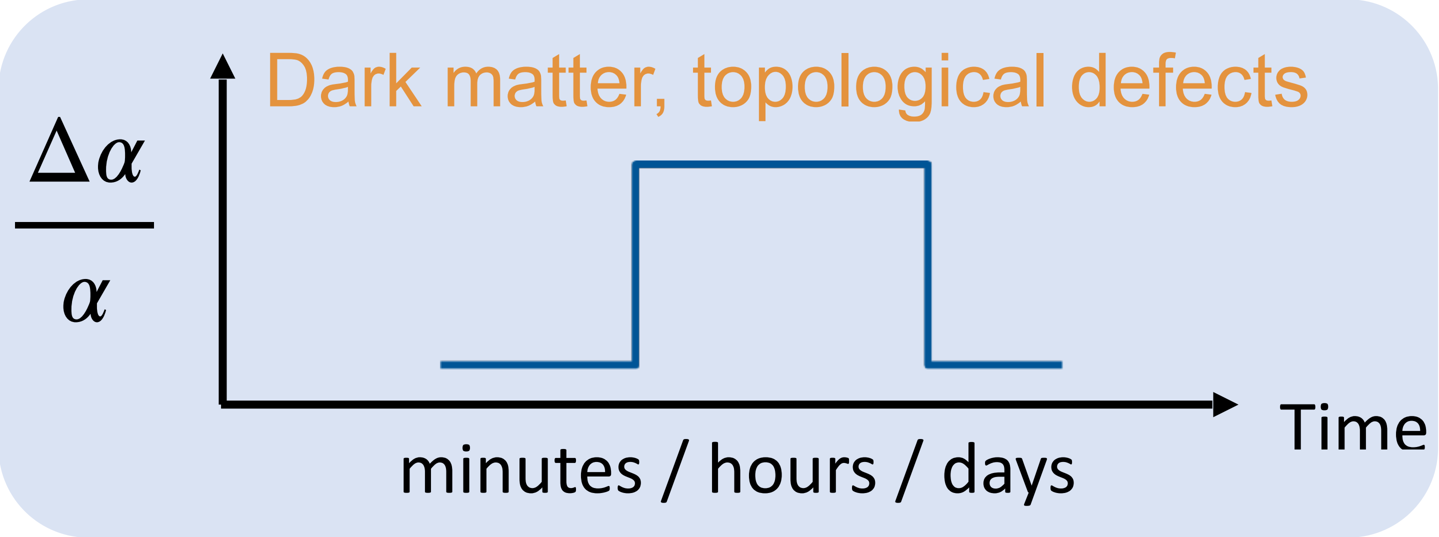

Be crystal with HCI (Ar)

[MPIK: José Crespo, also Humboldt U., DESY, UoB, PTB…]

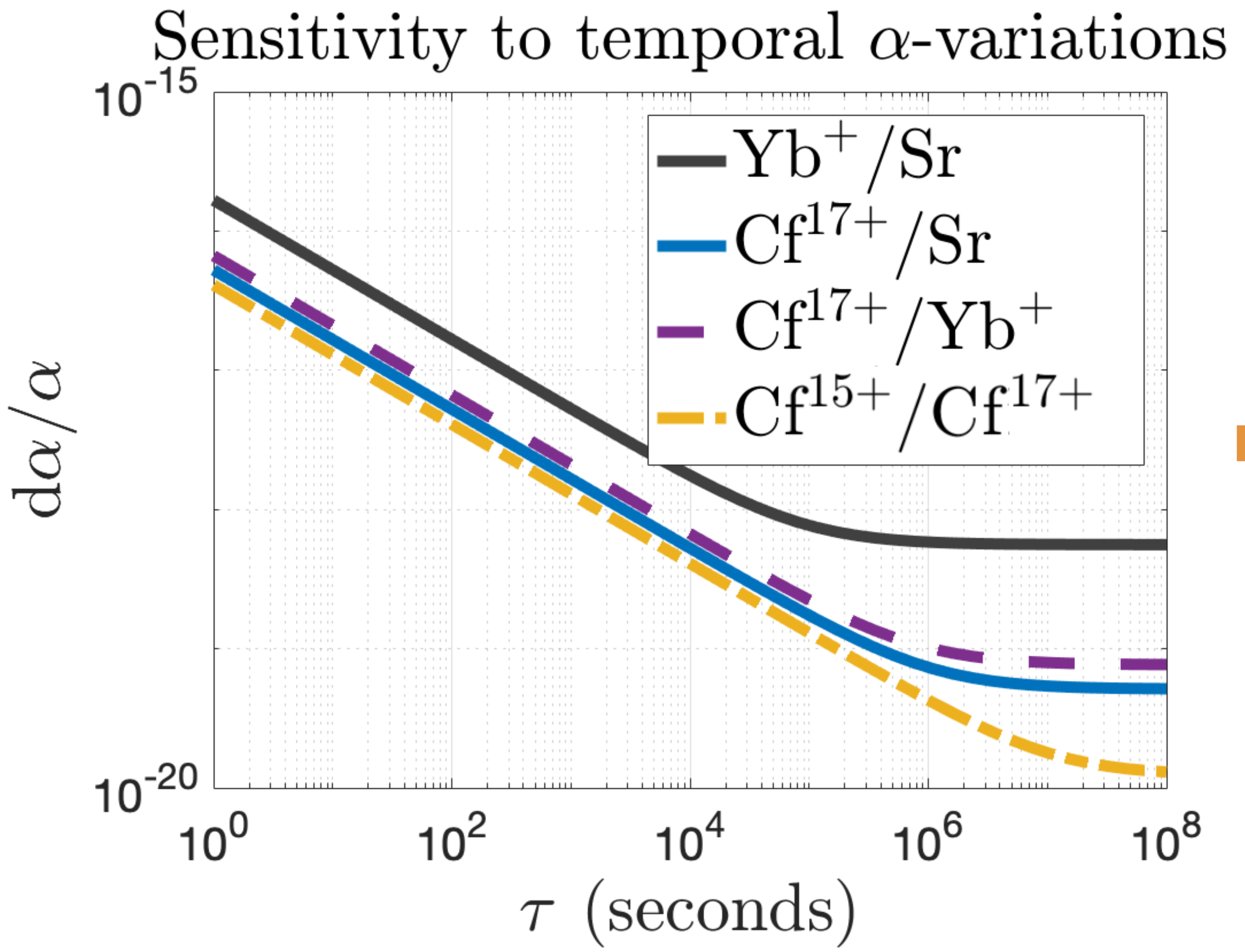
Optical Clocks and Tests of Fundamental Physics

Search for variations

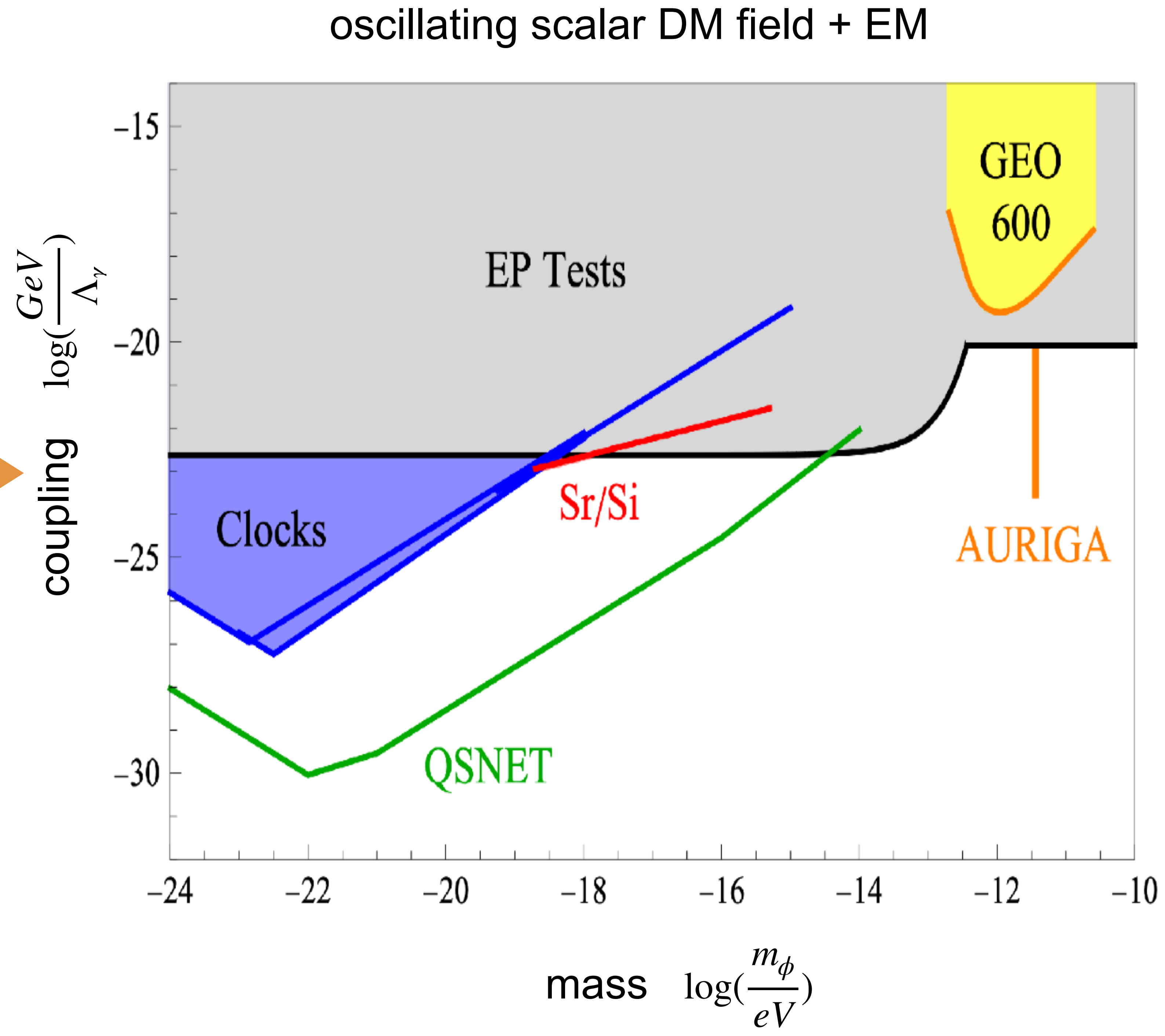




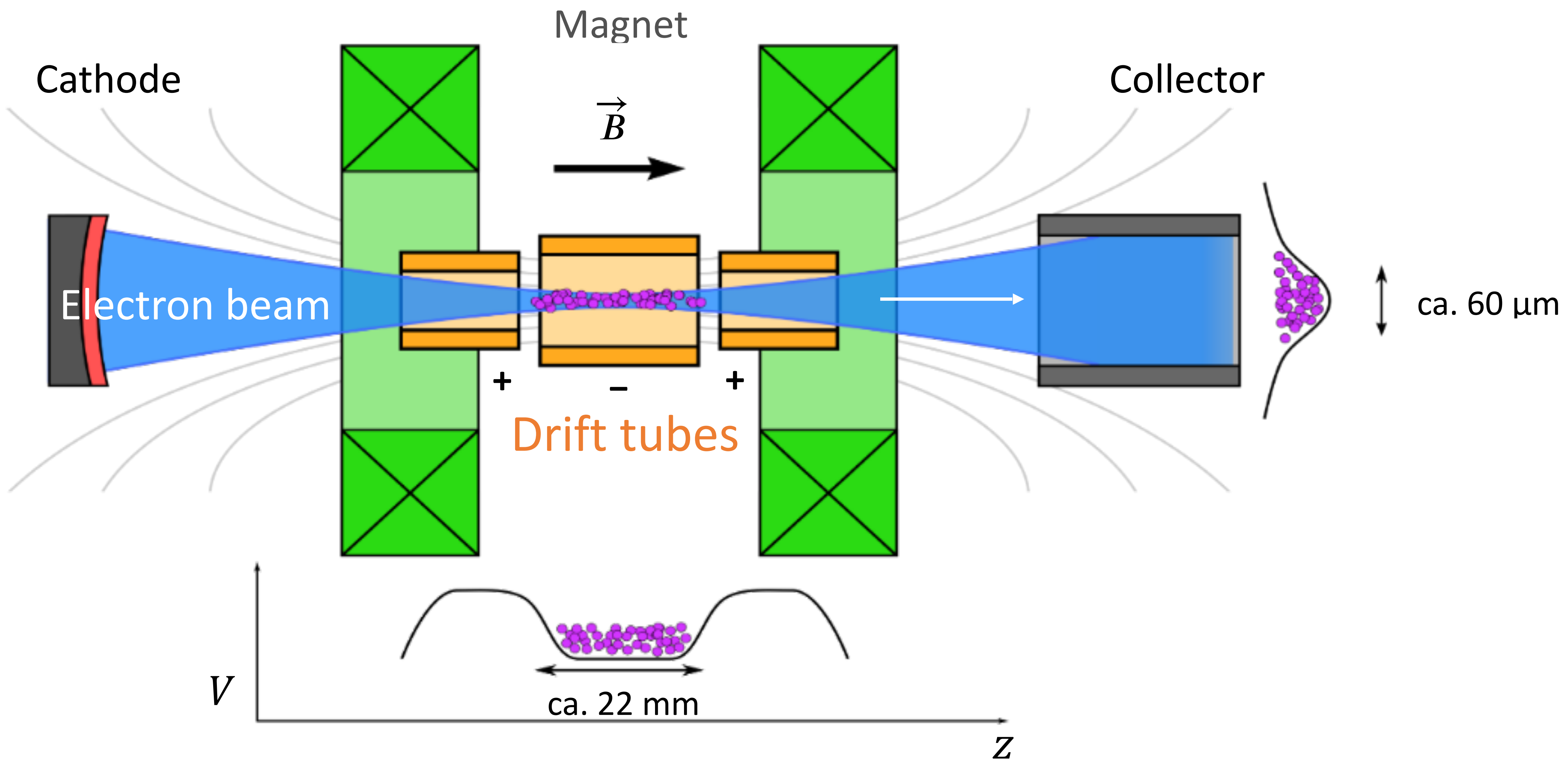
Study sensitivity

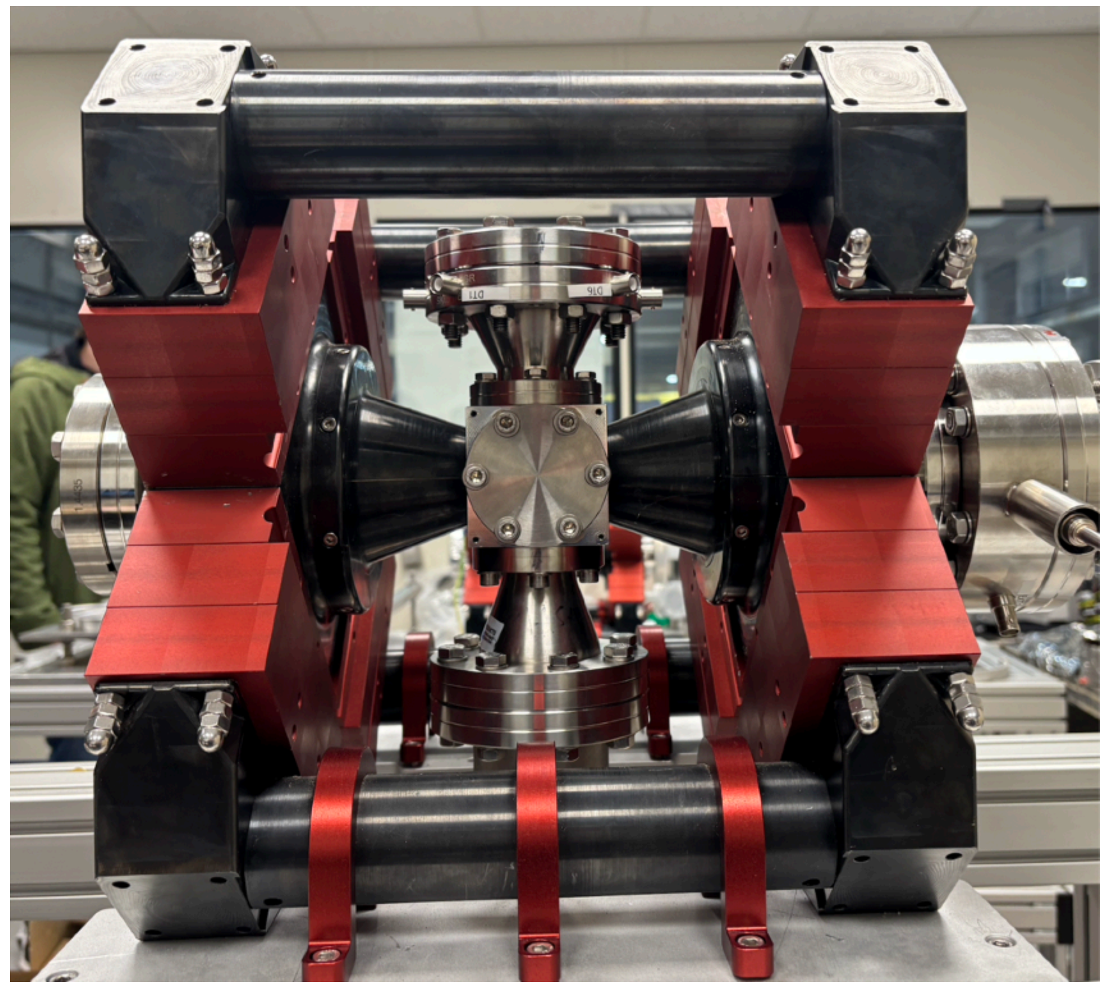


Discover DM (or limits)

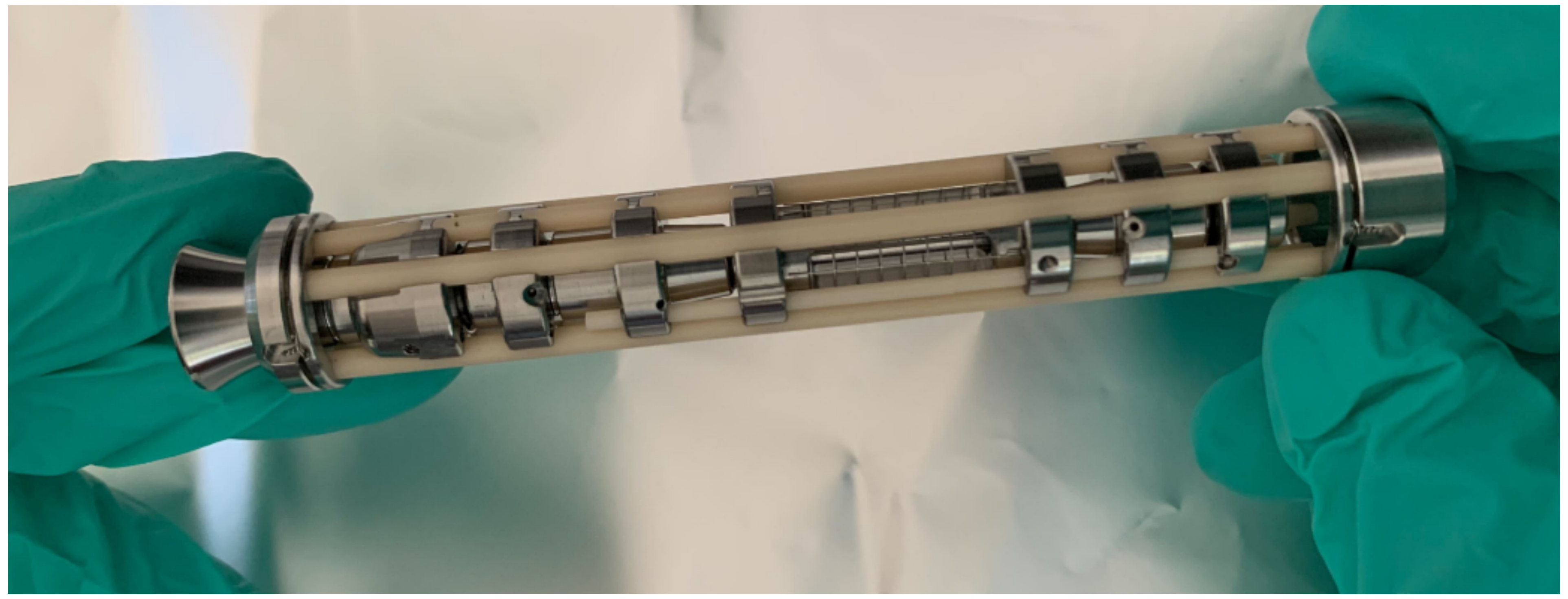


Electron Beam Ion Trap





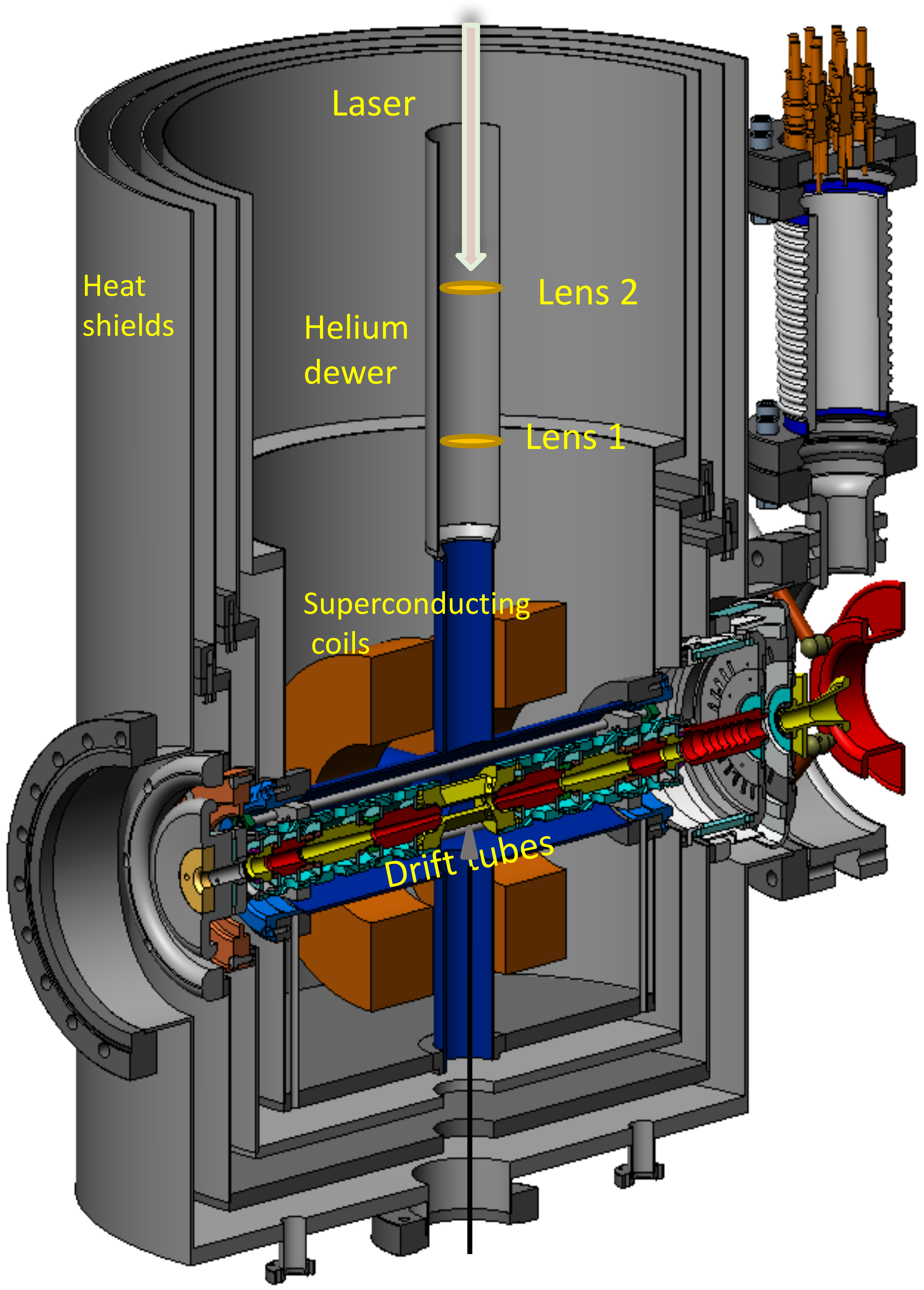
EBIT construction status



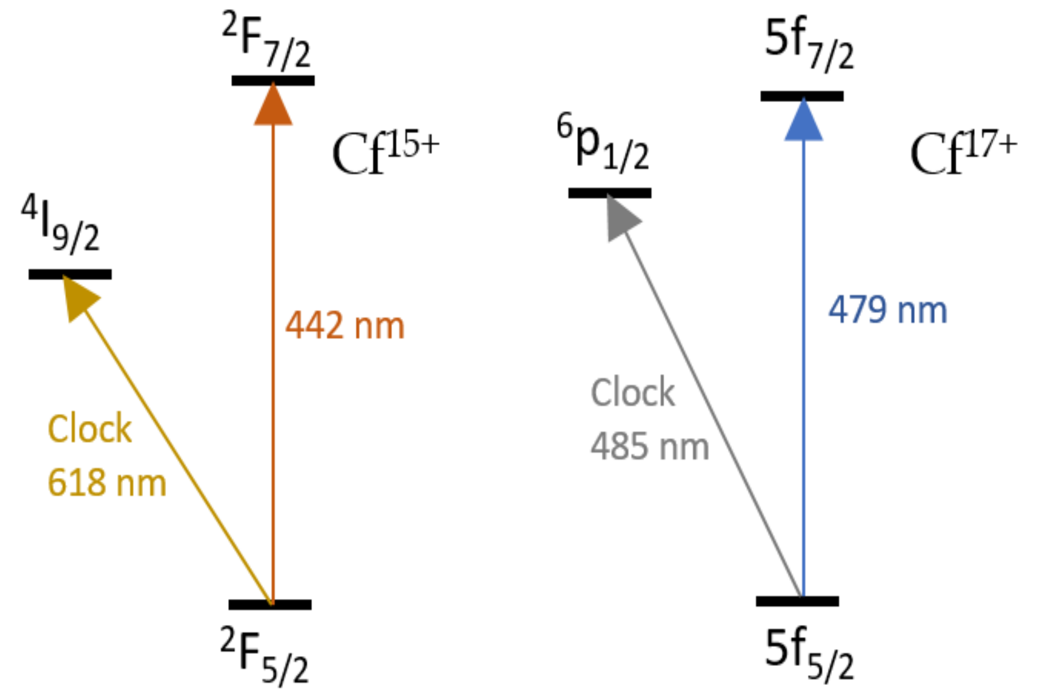
- Electron impact ionization:
  $X^{q+} + \mathrm{e}^-\left(E_\mathrm{e}\right) \rightarrow X^{(q+1)+} + \mathrm{e}^-\left(E_1\right) + \mathrm{e}^-(E_2)$
- Magnetic field in the trap center ≈ 0.9 tesla
- Axially trapped by the drift tube potential
- Radially trapped by the electron space charge

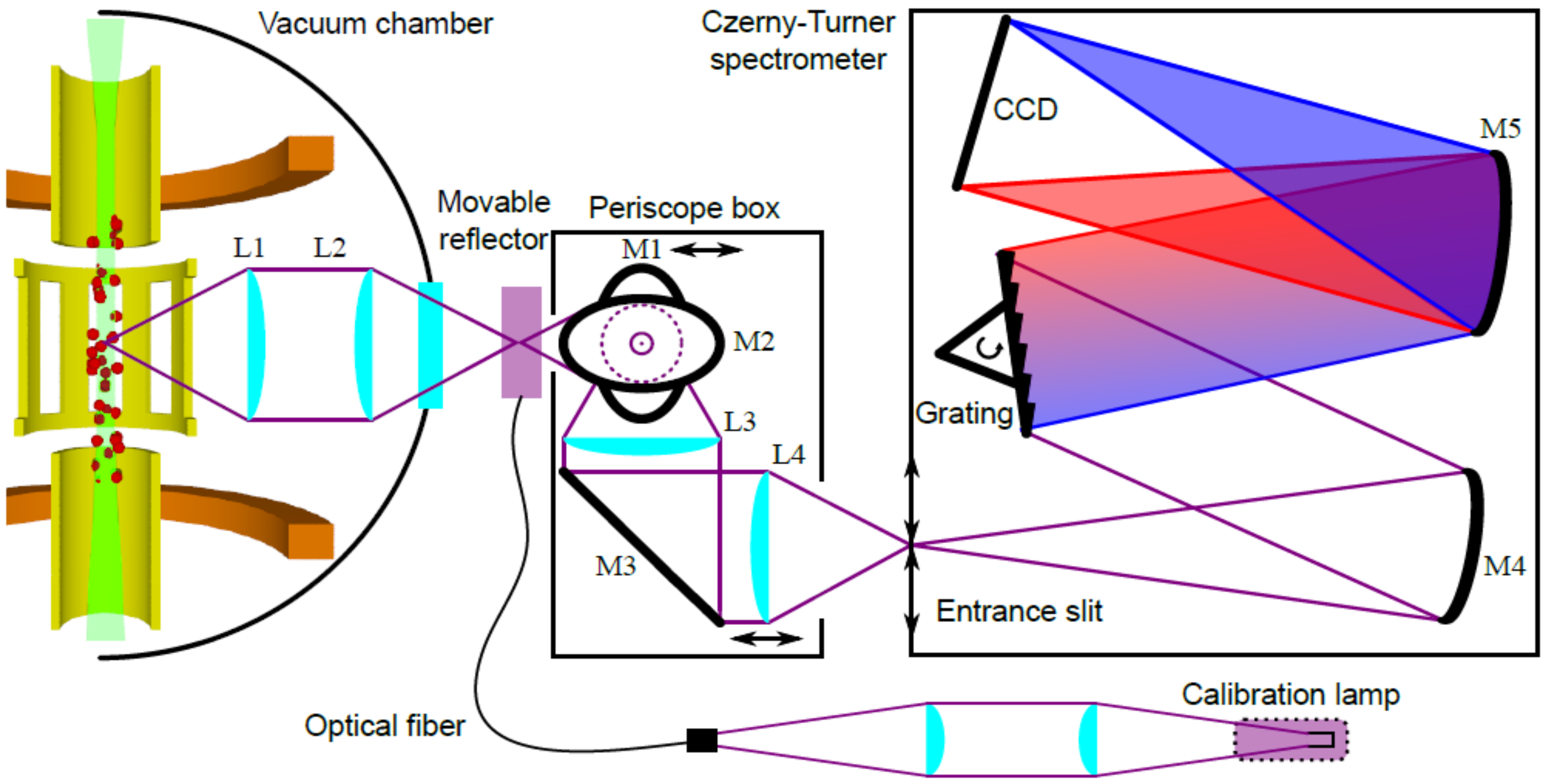
[P.Micke et al., The Heidelberg compact electron beam ion traps, Rev. Sci. Instrum. 89, 063109 (2018)]

Californium Spectroscopy in the Heidelberg EBIT



- 8T Magnetic field in the trap centre
- Heat shields cooled to 50K and 20K
- Liquid Helium filled inside the dewer = 4K

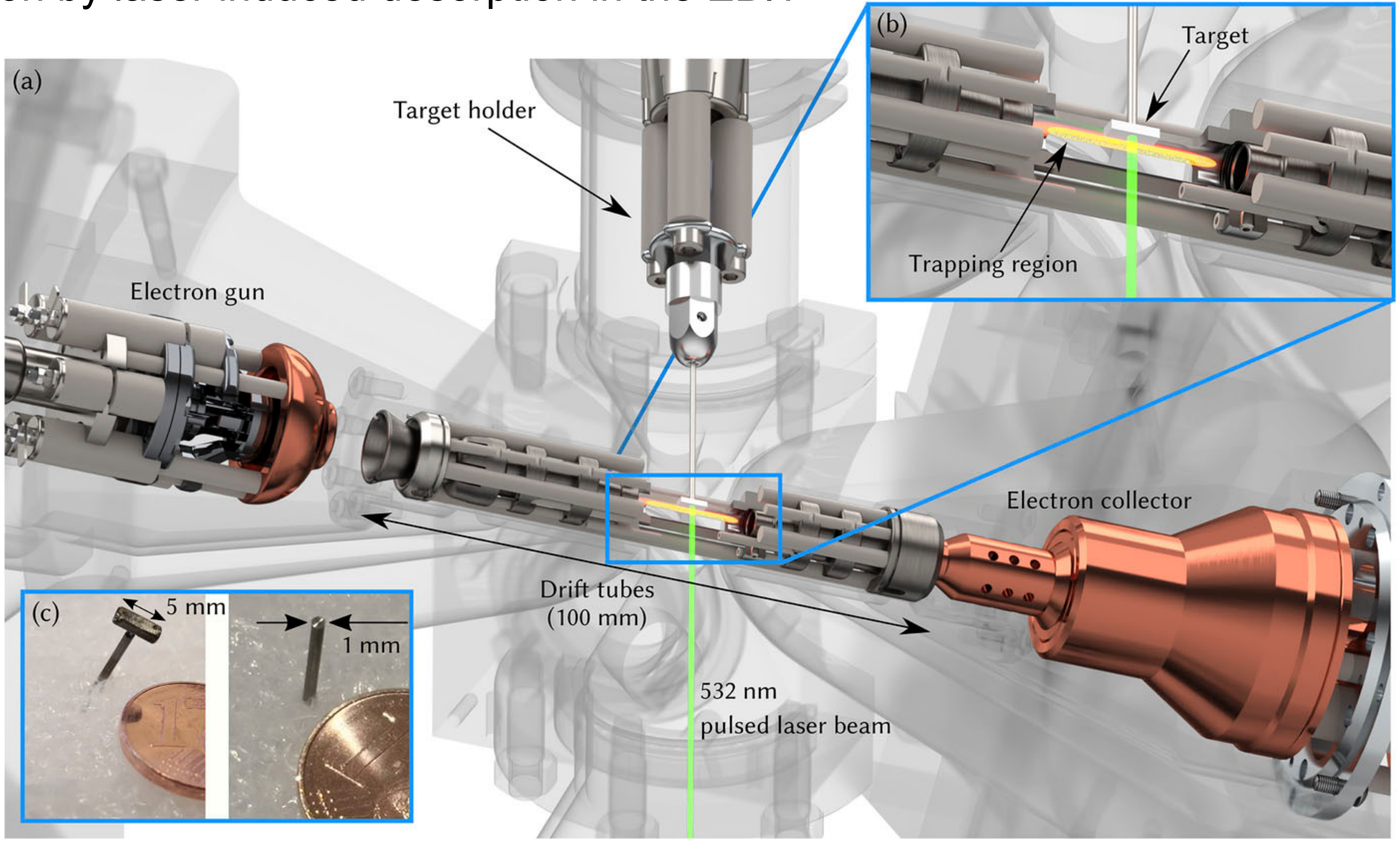




[H.Bekker, Optical and EUV spectroscopy of highly charged ions near the 4f–5s level crossing, PhD thesis]

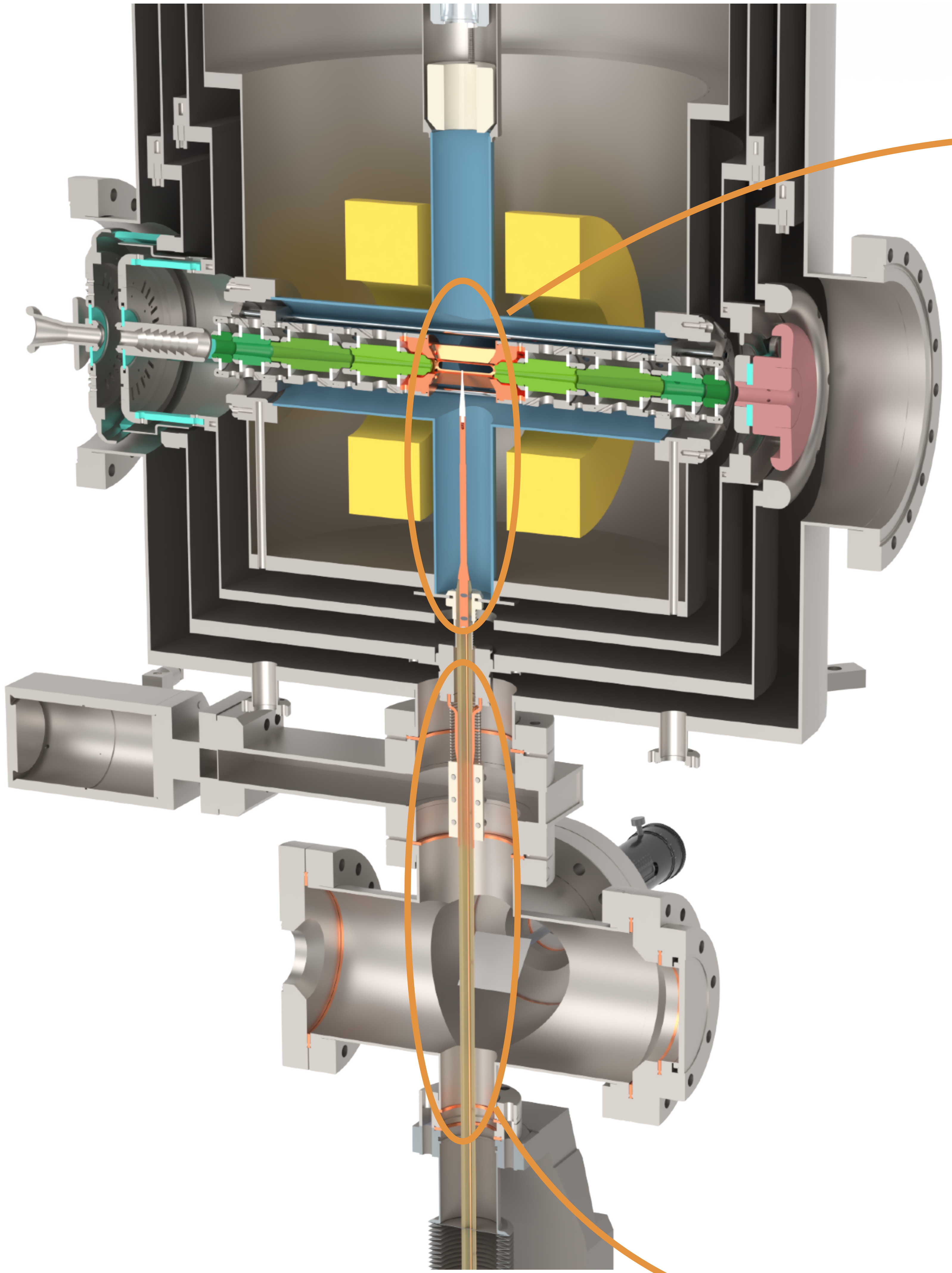
Injection of Californium

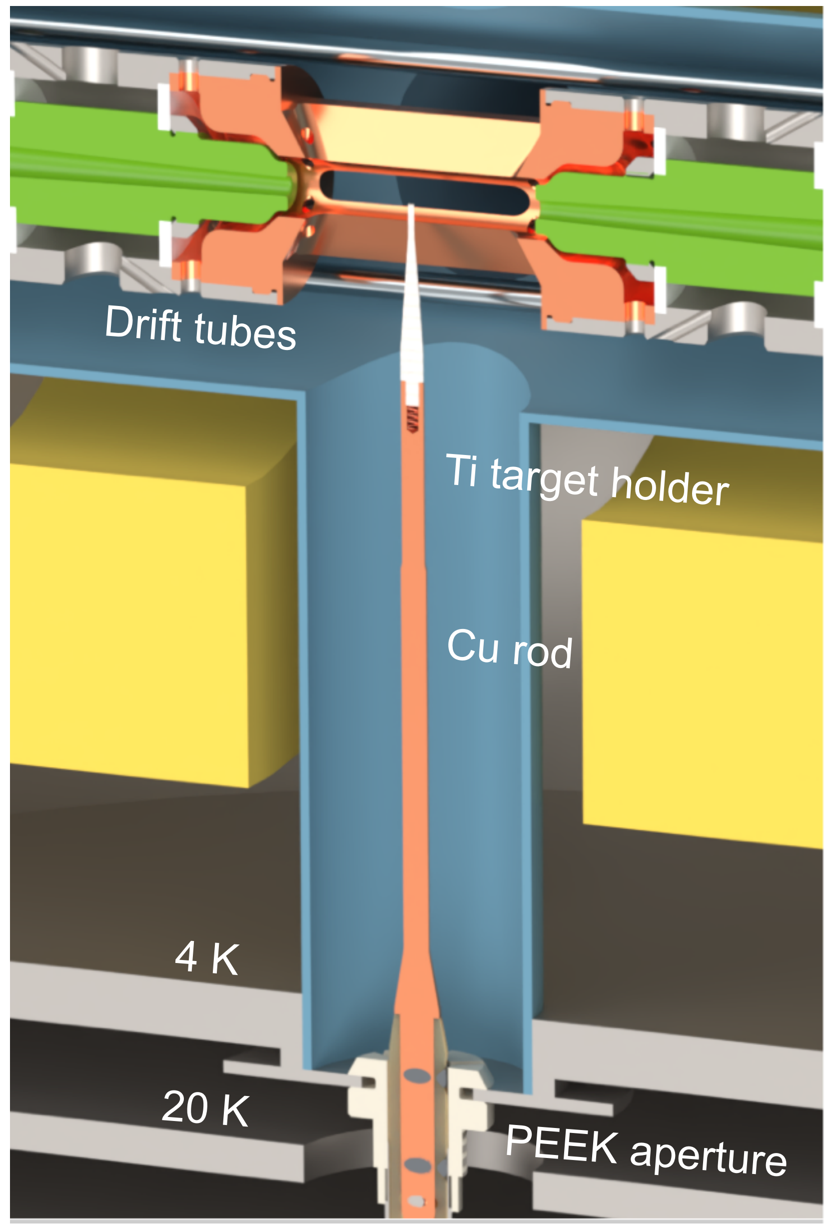
- Californium: synthetic, radioactive, rare, $£€…
- Efficient injection by laser induced desorption in the EBIT

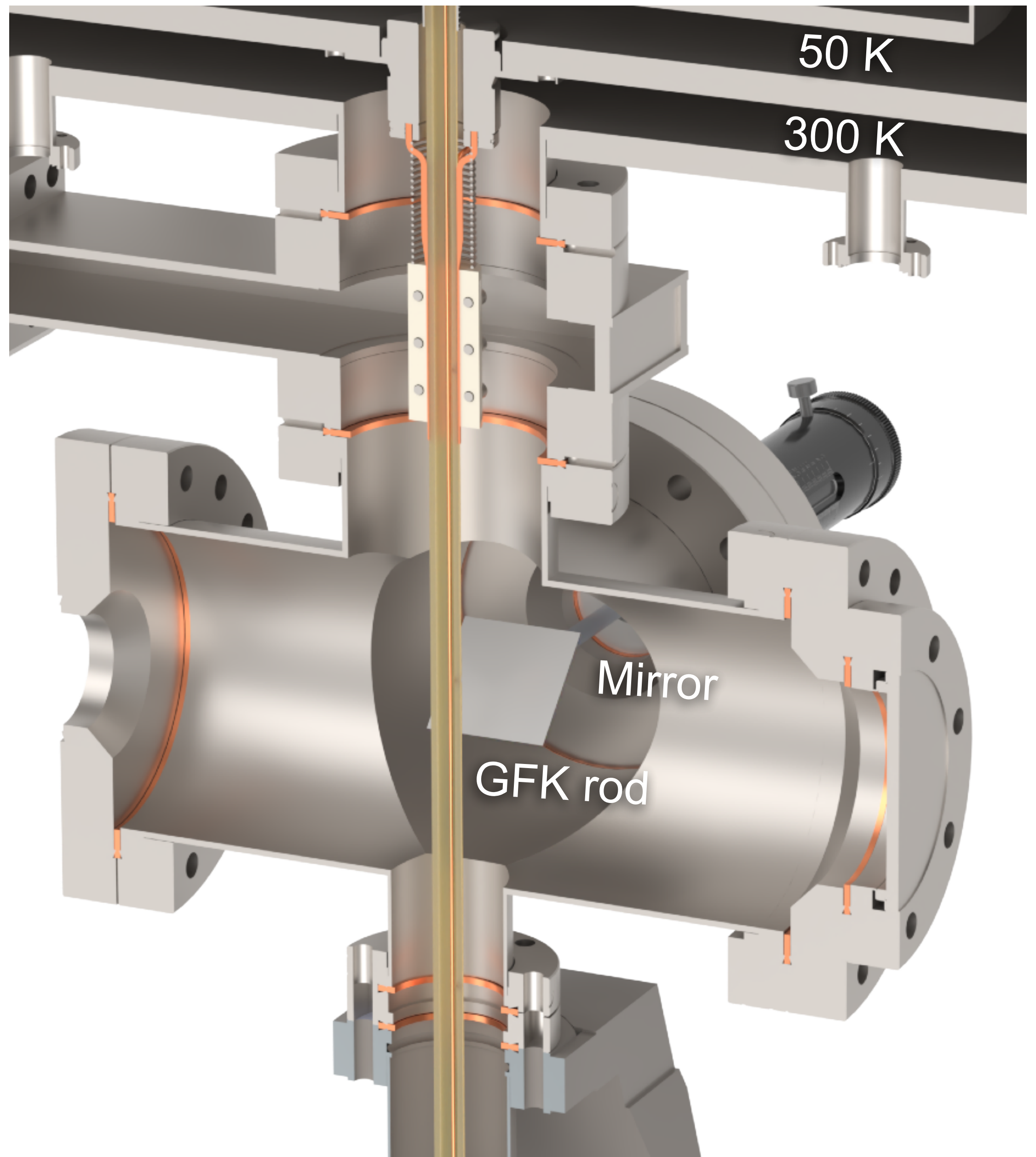


[Ch.Schweiger et al., Production of highly charged ions of rare species by laser-induced desorption…, Rev. Sci. Instrum. 90, 123201 (2019)]

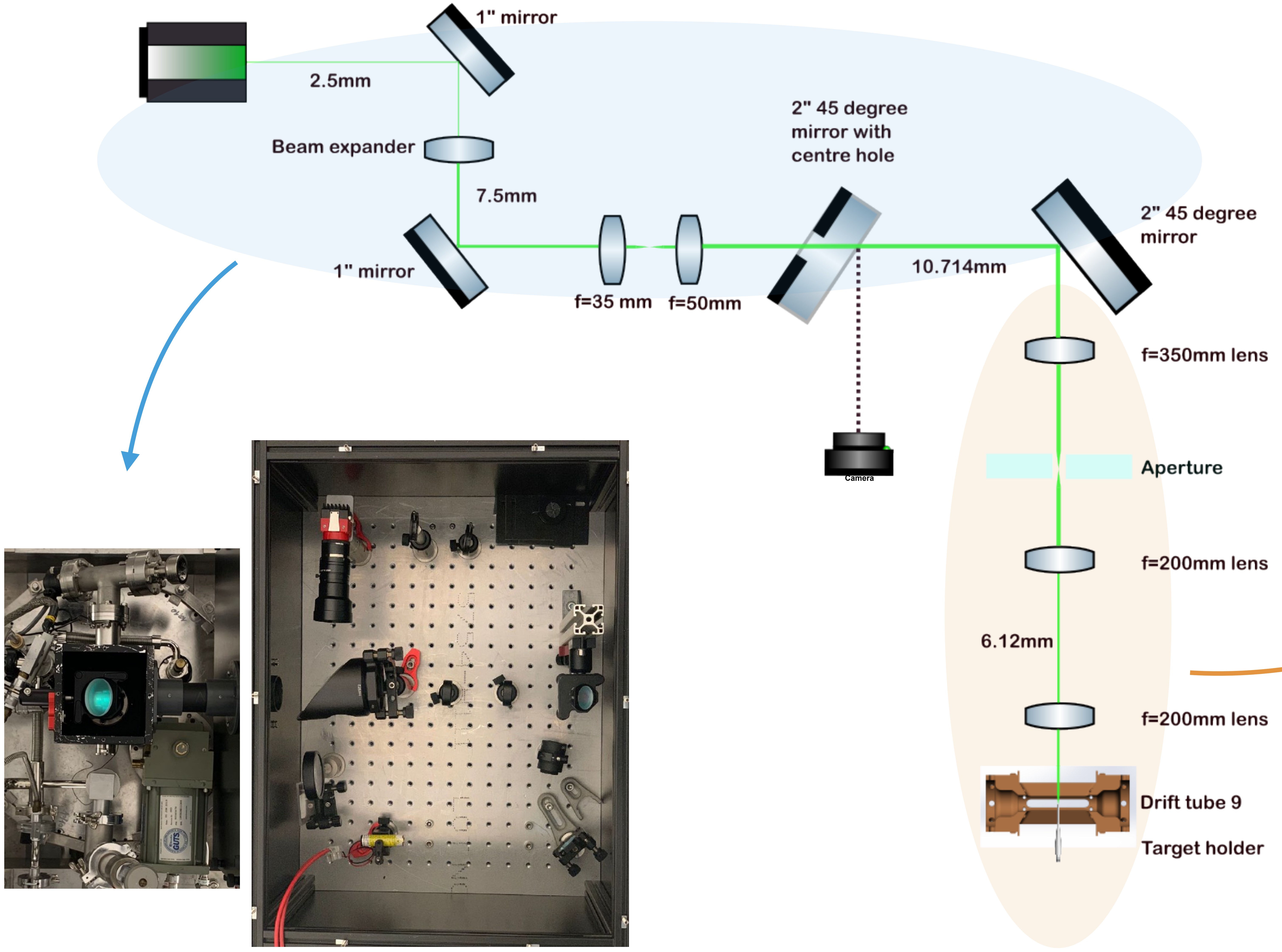
Heidelberg EBIT — Target Holder

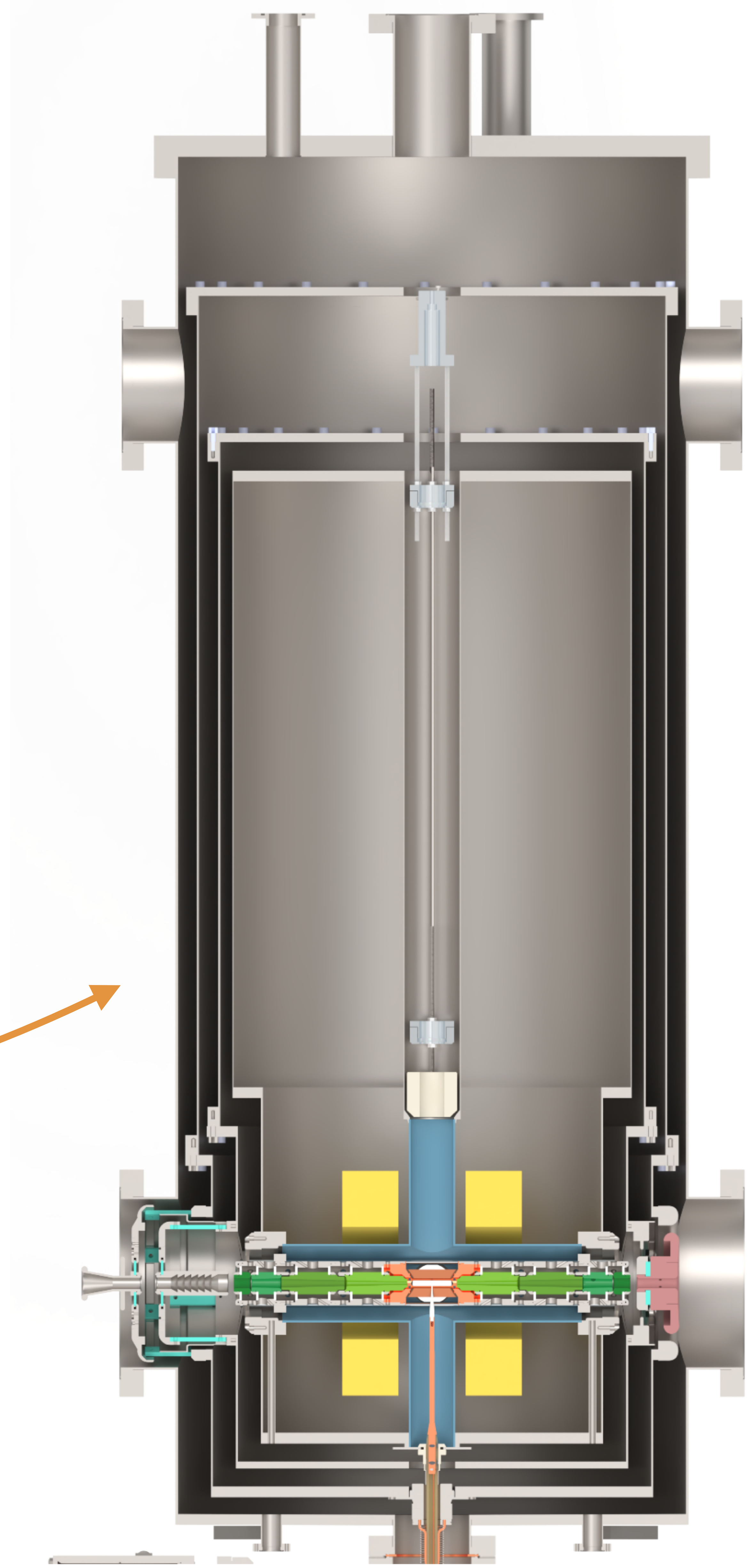






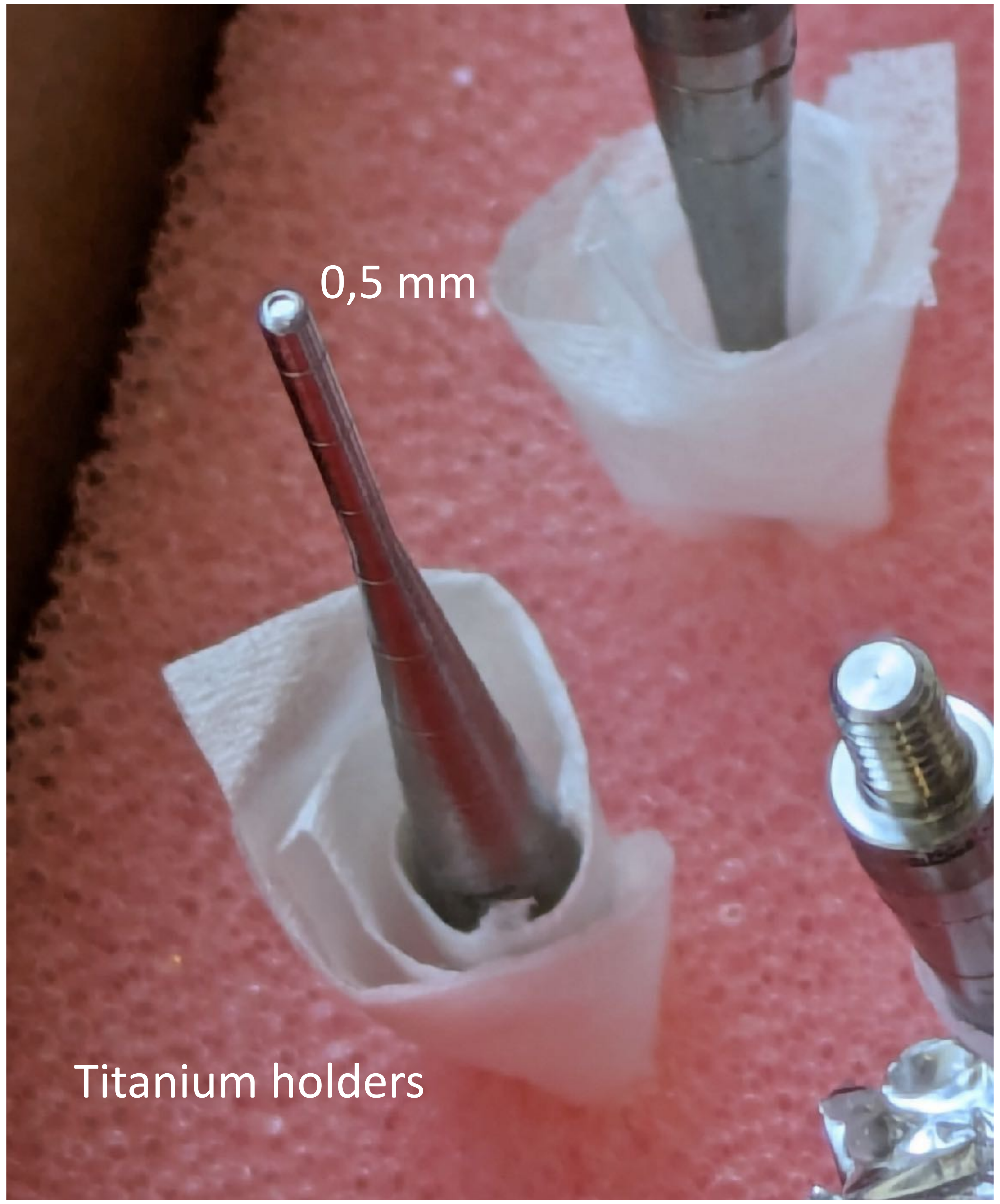
Heidelberg EBIT — Optical System

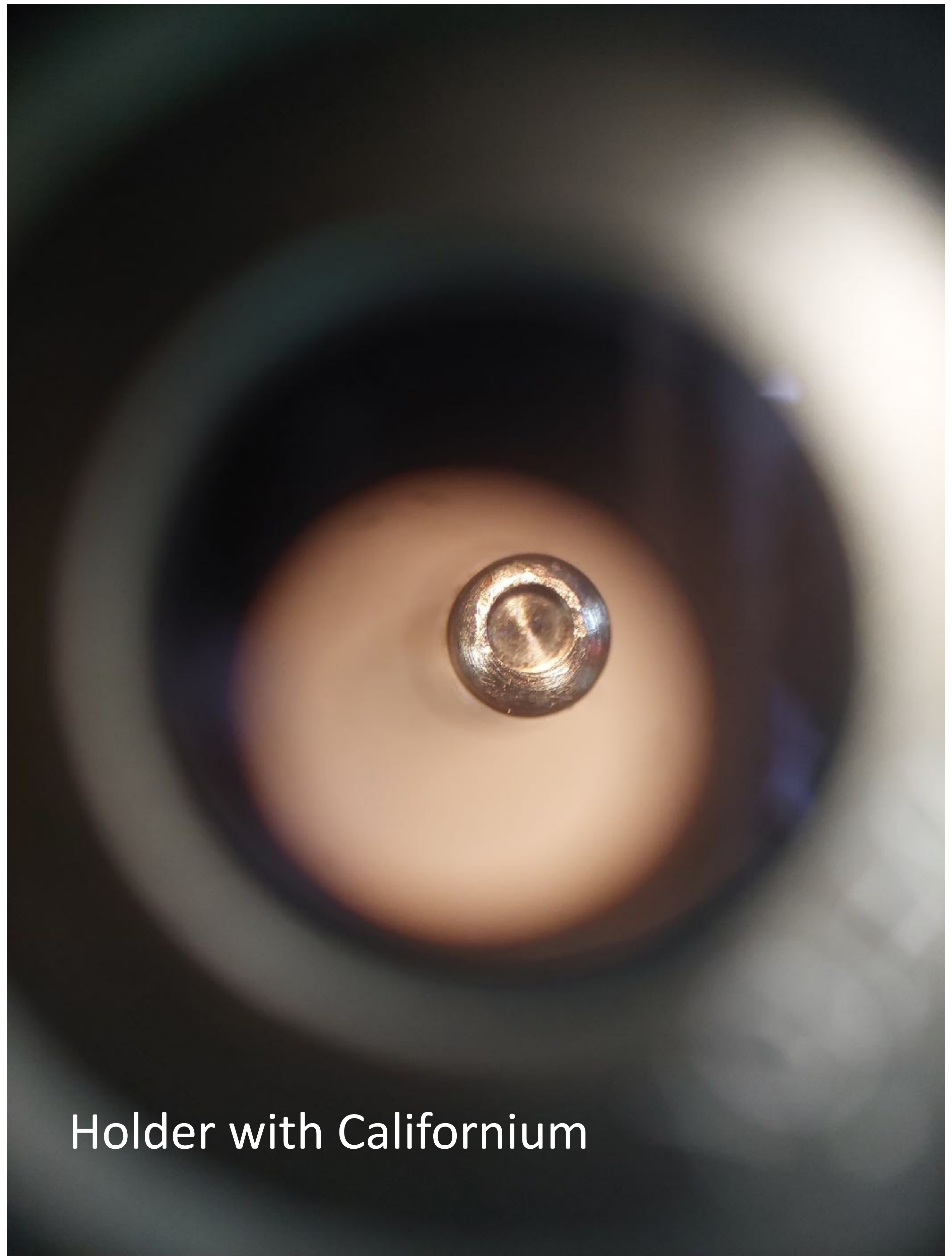




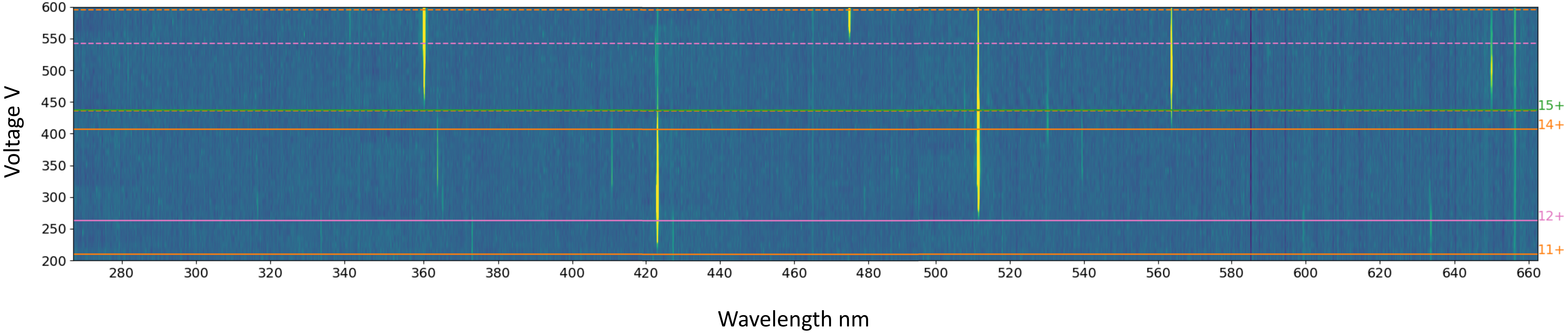
Manipulator Installation and Californium

- Manipulator and sample holder installed at the bottom of the HD EBIT
- Holders loaded with 6.6 ng of Californium, or about 1.6 x 10^{13} atoms (1k Bq)



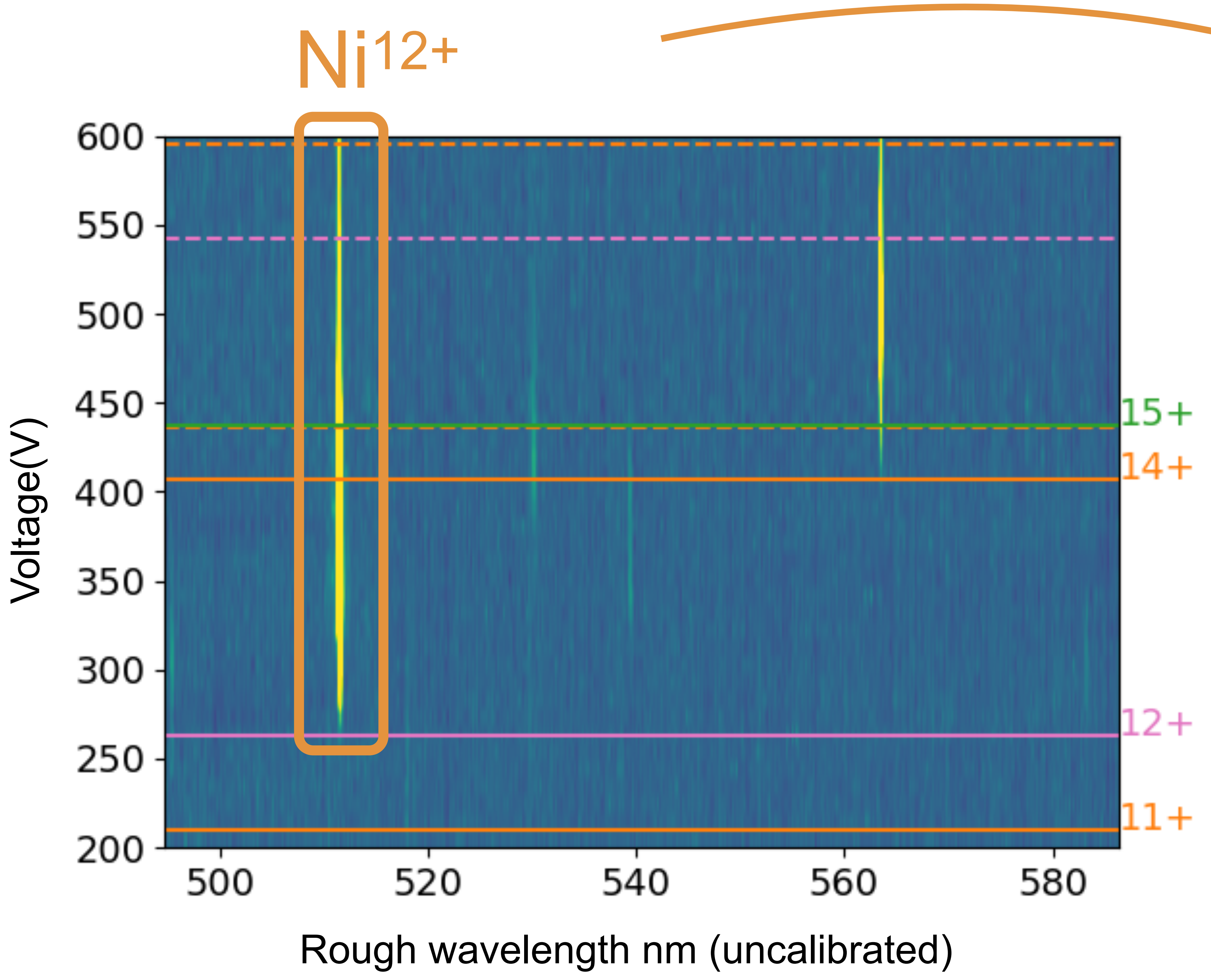


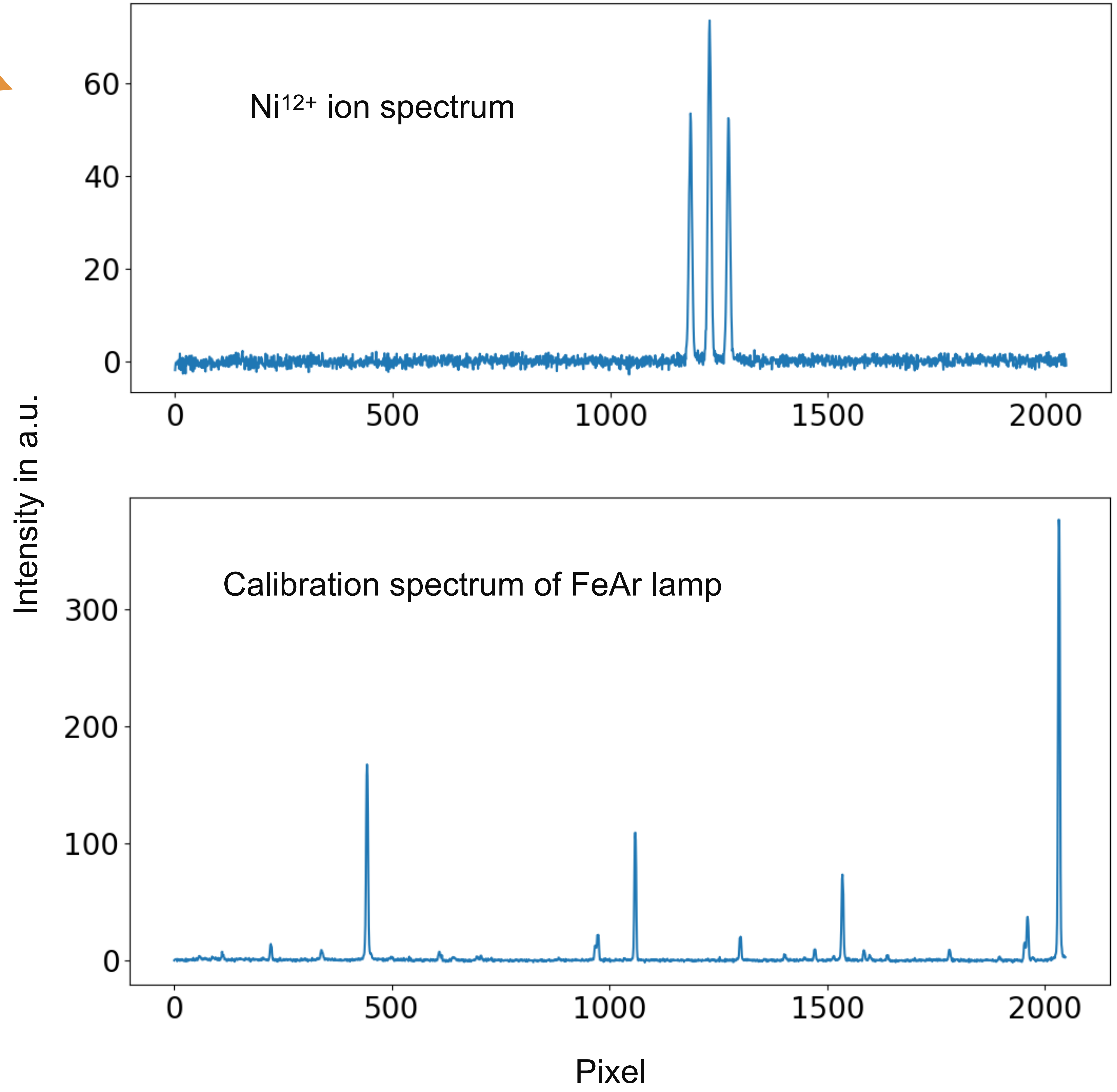
Spectroscopy Example: Nickel 12+



- Organic compound of Nickel injected into trap
- Use e-beam energy (voltage) to separate charge states
- Wavelength scan of ion source for transitions

Spectroscopy Example: Nickel 12+



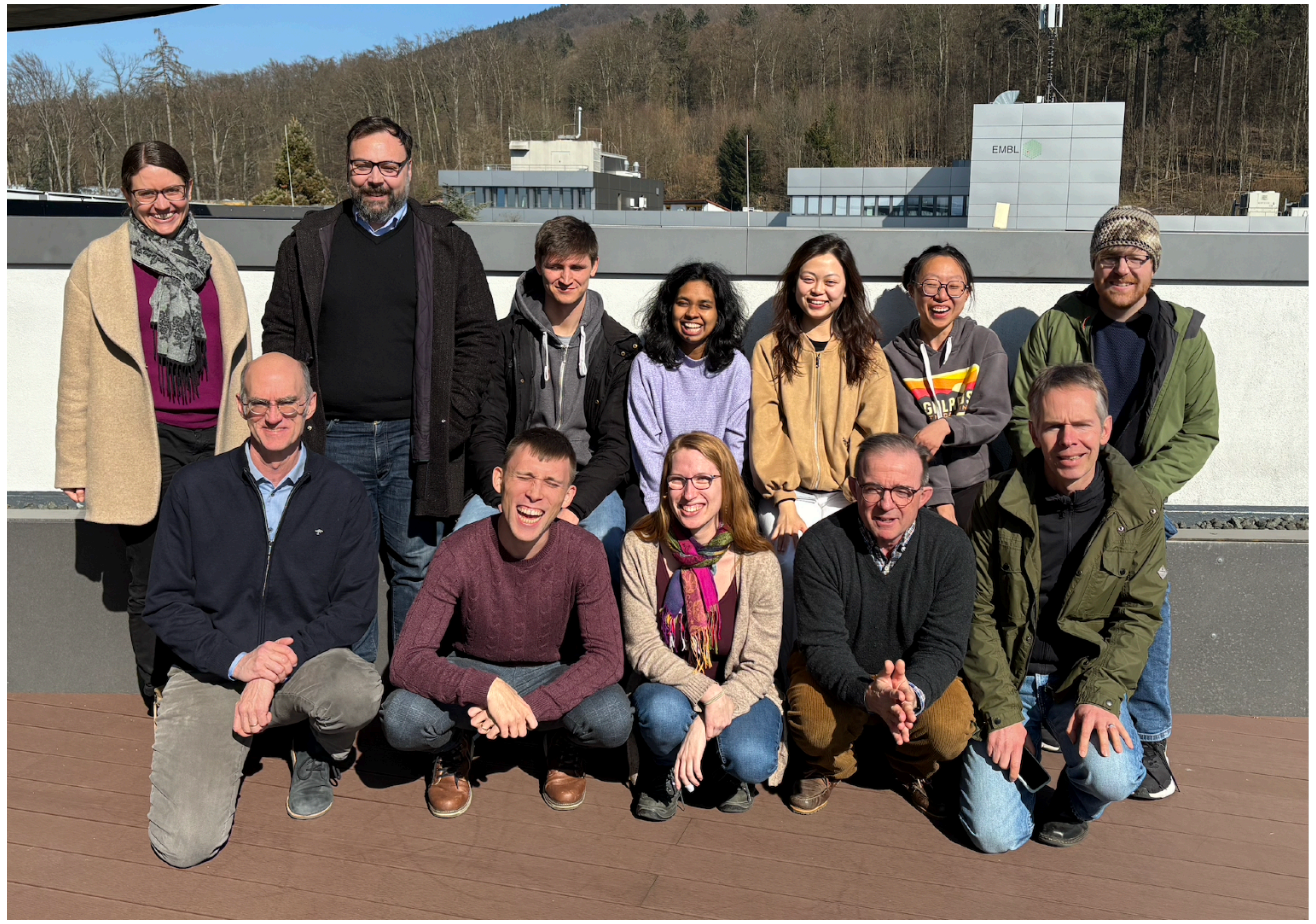


- Match with theory calculations, e.g. with AMBiT for atomic structure calculation
- Precision scan on the desired transition
- Californium is next!

[Github AMBiT documentation, arXiv: 2509.06710]

Collaborations and Support

- Collaboration with Giovanni Barontini @ Birmingham, Jose Crespo @ MPIK
- Support from German state of Brandenburg: Centre for Quantum Technology and Applications (CQTA)
- Innopool with Dmitry Budker, Hendrik Bekker (Os^{+16} spectroscopy), Elina Fuchs, Peter Micke…
- Many people waiting for HCI spectroscopy



Meeting with groups of Crespo, Barontini, Schäfer

arXiv:2509.06710v1 [physics.atom-ph] 8 Sep 2025

Study of the elusive $5s-4f$ level crossing in highly charged osmium with optical transitions suitable for physics beyond the Standard Model searches

Nils-Holger Rehbehn [1], Lakshmi Priya Kozhiparambil Sajith [1,2], Michael K. Rosner [1], Charles Cheung [3], Sergey G. Porsev [3], Marianna S. Safronova [3], Steven Worm [2], Dmitry Budker [4,5,6,7], Thomas Pfeifer [1], José R. Crespo López-Urrutia [1,*] and Hendrik Bekker [4,5,6,†]

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(Dated: September 9, 2025)

Very recently, by applying quantum logic [1] to frequency metrology [2, 3] of sympathetically cooled highly charged ions (HCI) [4], a precision close to that of state-of-the-art optical clocks [5] for neutral and singly charged atoms has been reached at the German metrology institute Physikalisch-Technische Bundesanstalt (PTB) in Braunschweig [6–12]. This enables searches for physics beyond the Standard Model (BSM) [13] using, e. g., King-plot analysis [14–16] to probe hypothetical Yukawa interactions, as just demonstrated at PTB [11]. The sensitivity of HCI to various BSM effects, such as variation of the fine-structure constant α, is highest near orbital crossings [17, 18] where the filling order changes. However, predictions for the energy levels are extremely difficult in the interesting case of the $5s-4f$ orbital crossing. Here we investigate both theoretically and experimentally one of the most promising candidates for this crossing. It was at first expected to provide laser-accessible optical transitions between fine-structure levels of the $[Pd]4f^{12}5s^2$ and $[Pd]4f^{13}5s$ configurations in the Nd-like iridium ($Z = 77$) Ir^{17+} ion. They were, however, not found, and recent predictions show that they should appear in the vacuum ultraviolet range instead [19]. In the present work, we study Nd-like Os^{16+} ($Z = 76$), which has a smaller splitting between the relevant configuration, with newer calculations predicting laser-accessible transitions there [20]. Moreover, the lowest excited state

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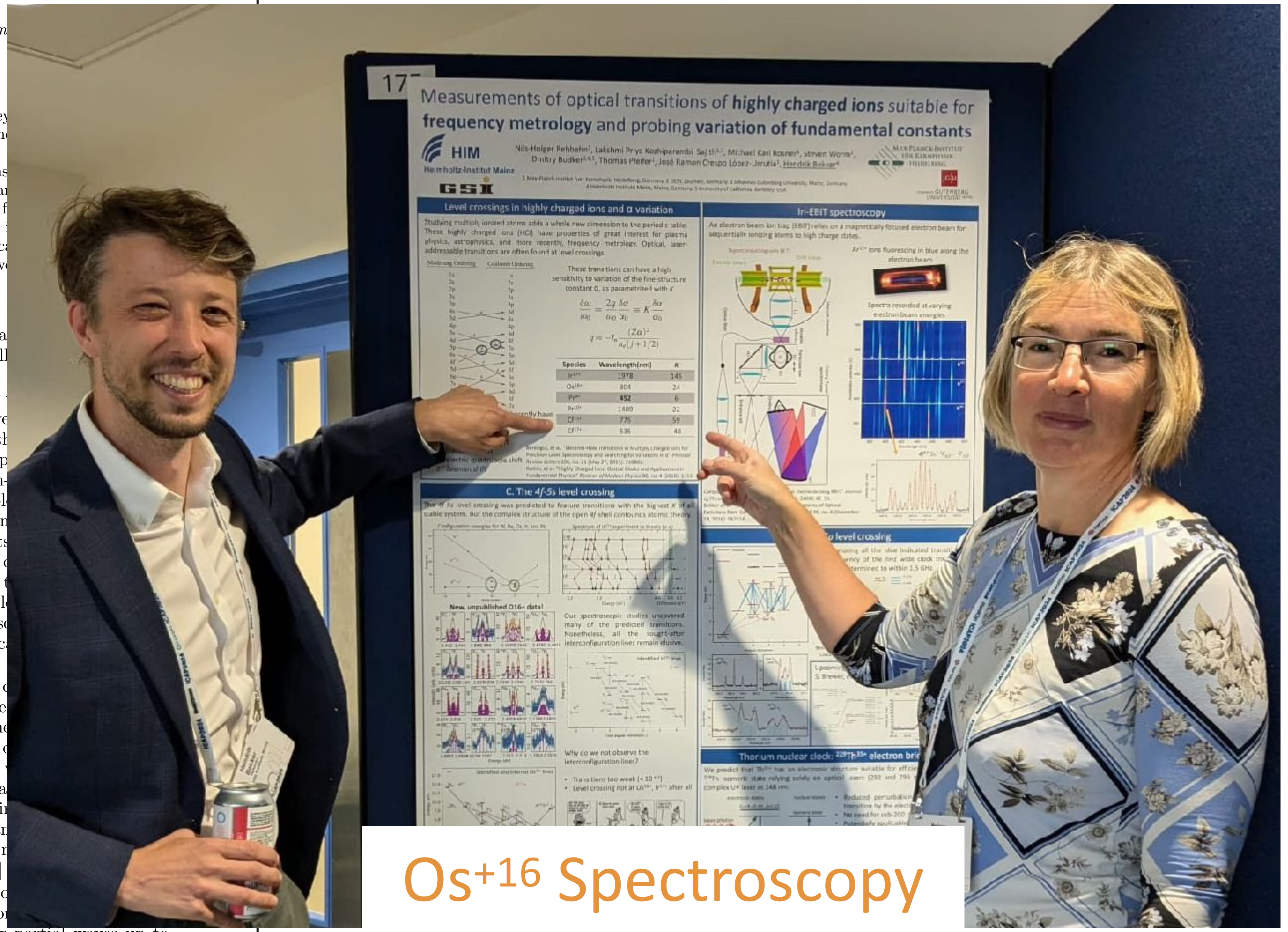

Os^{+16} Spectroscopy

Conclusion

- Precision spectroscopy of highly charged ions needed for clock experiments for new physics
- Team of people working to get it going, now with support from QS4Physics
- Lots of work from students: Lakshmi Kozhiparambil and Nutan Kumari Sah
- Spectroscopy with Heidelberg EBIT starting soon, also beam time with portable EBIT at HZB in March