

Precision spectroscopy of highly charged ions

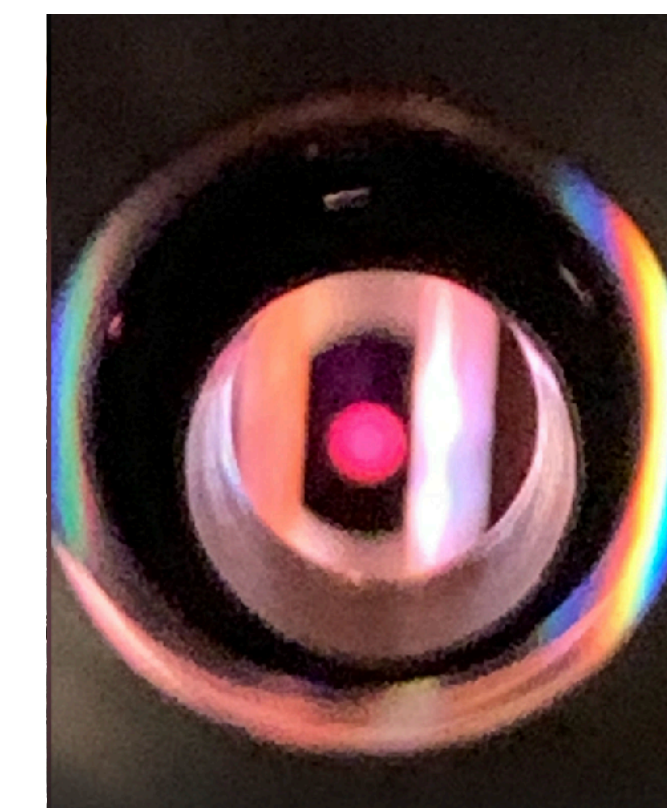
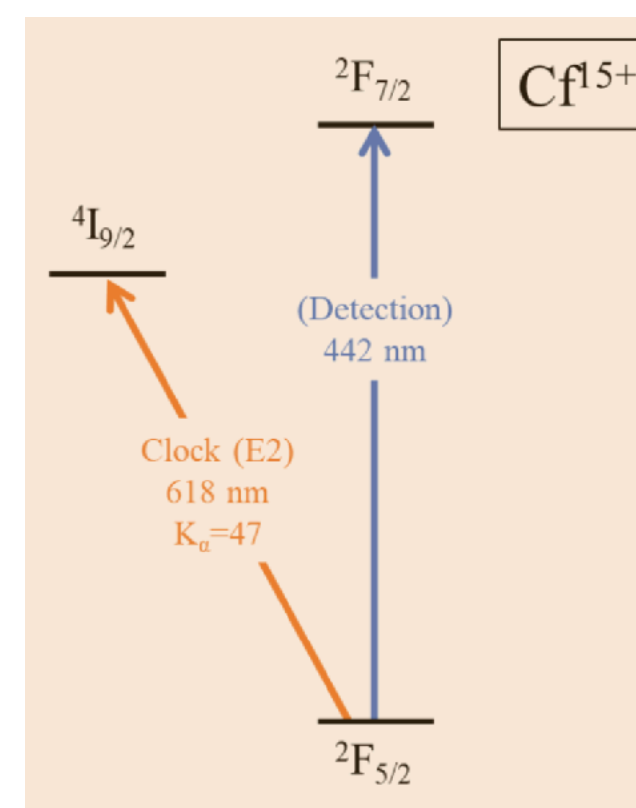
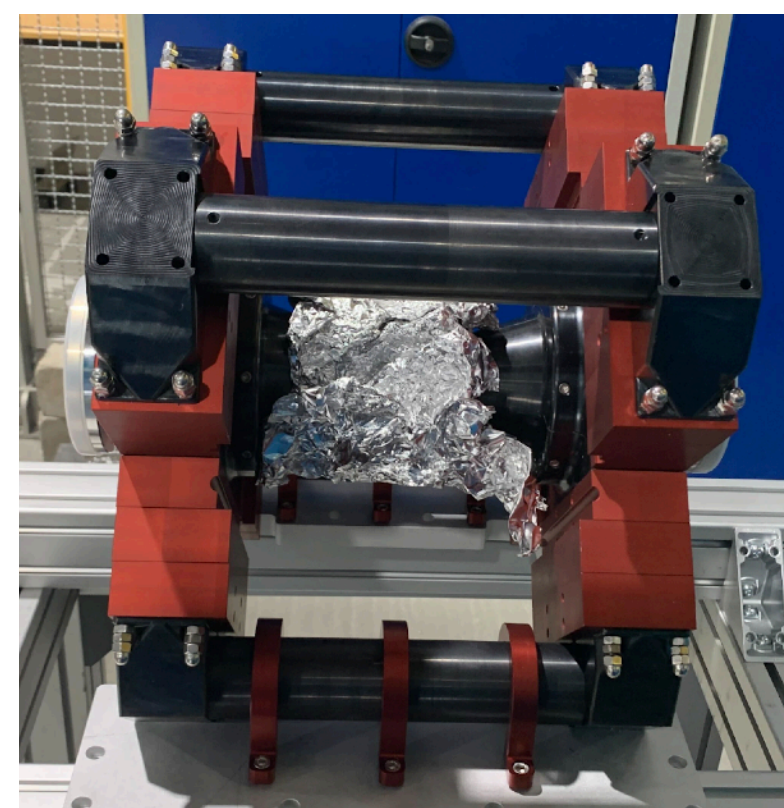
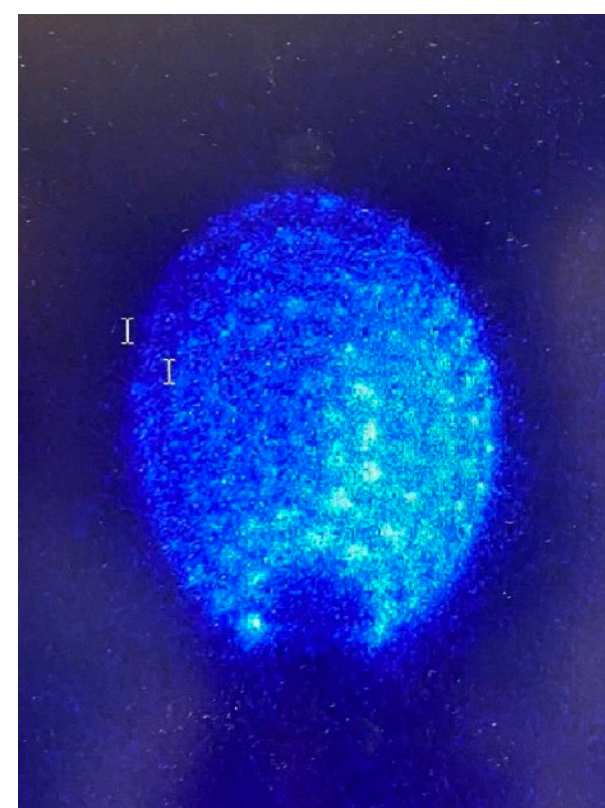
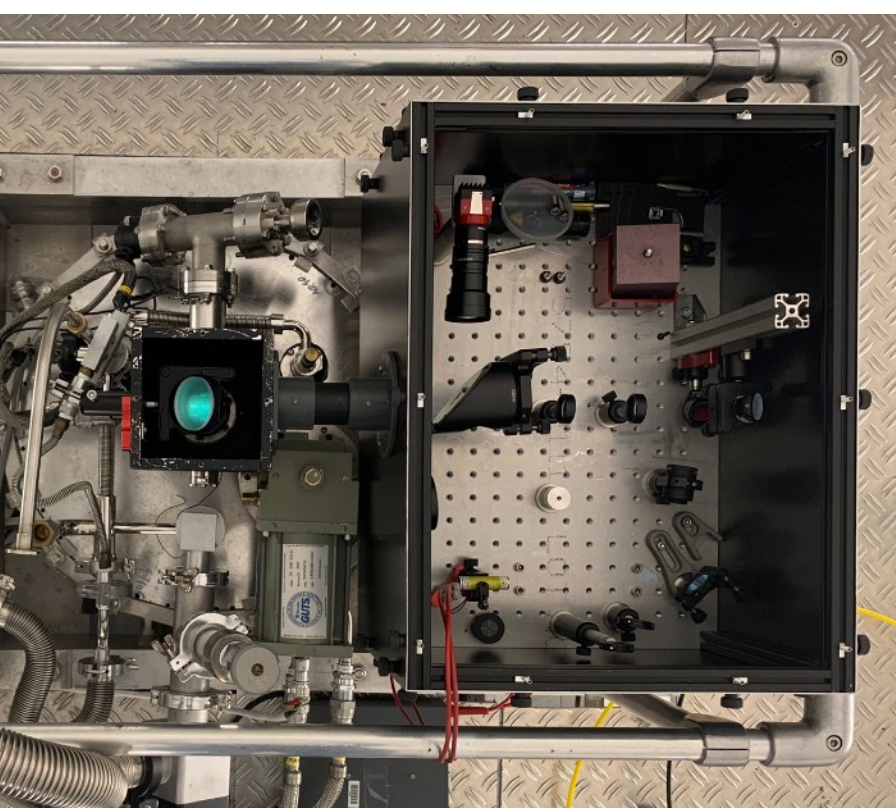


Update for QS4Physics

Steven Worm

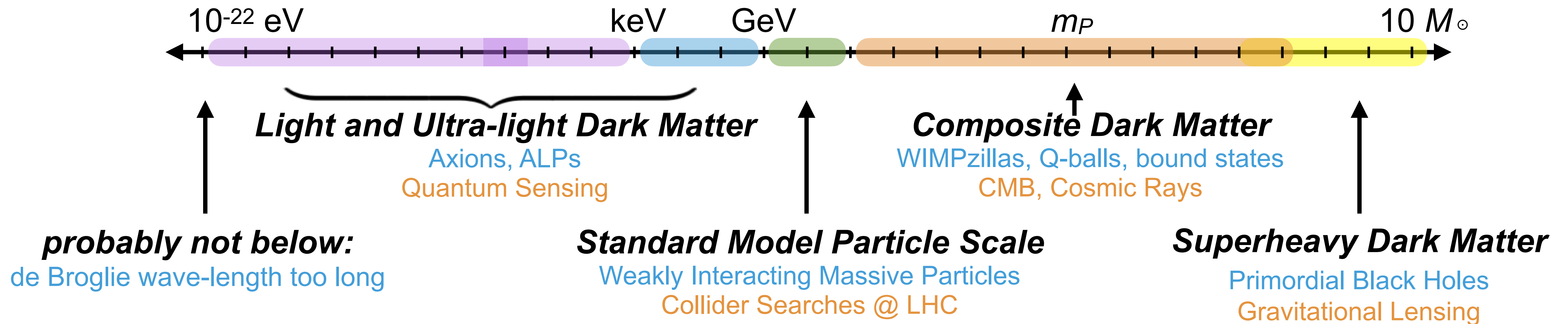
Deutsches Elektronen-Synchrotron (DESY) / Humboldt-Universität zu Berlin

November 20, 2025



Ultralight Dark Matter + Quantum Sensing = Clock Experiments

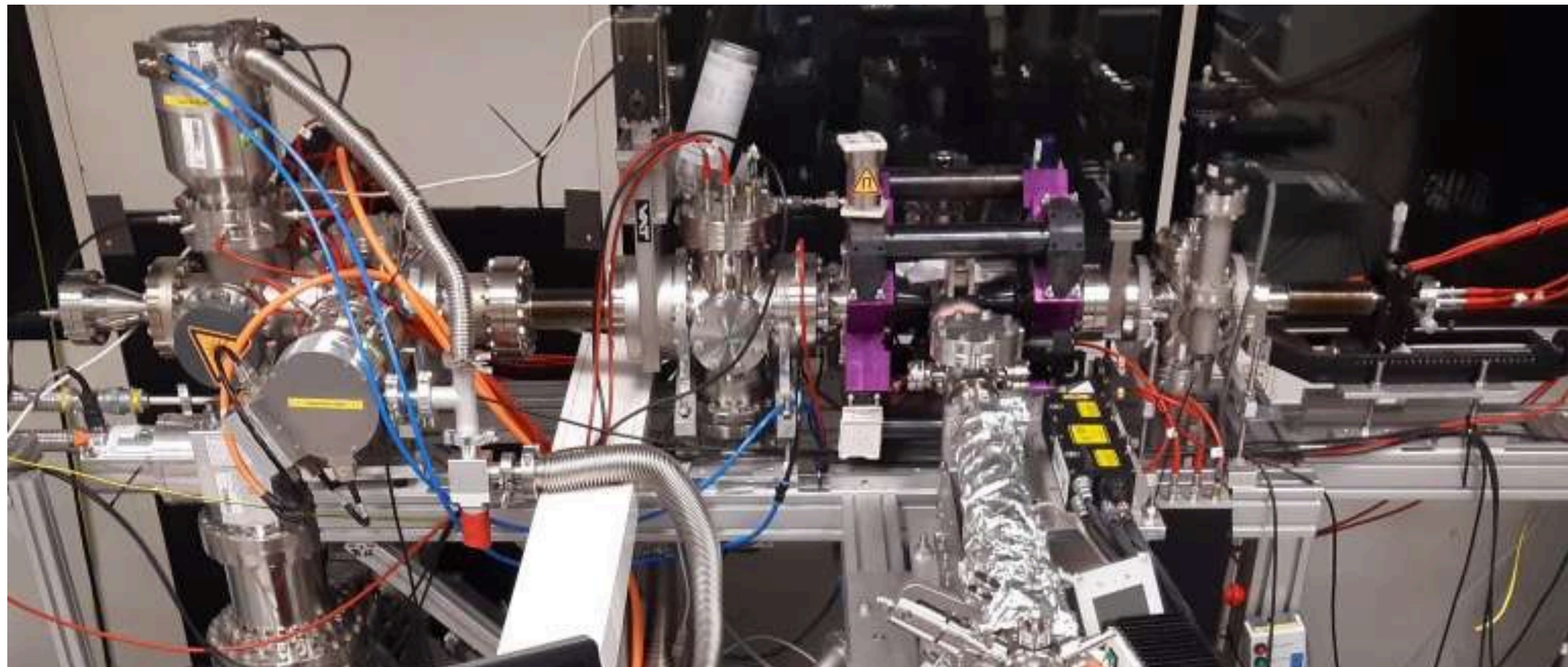
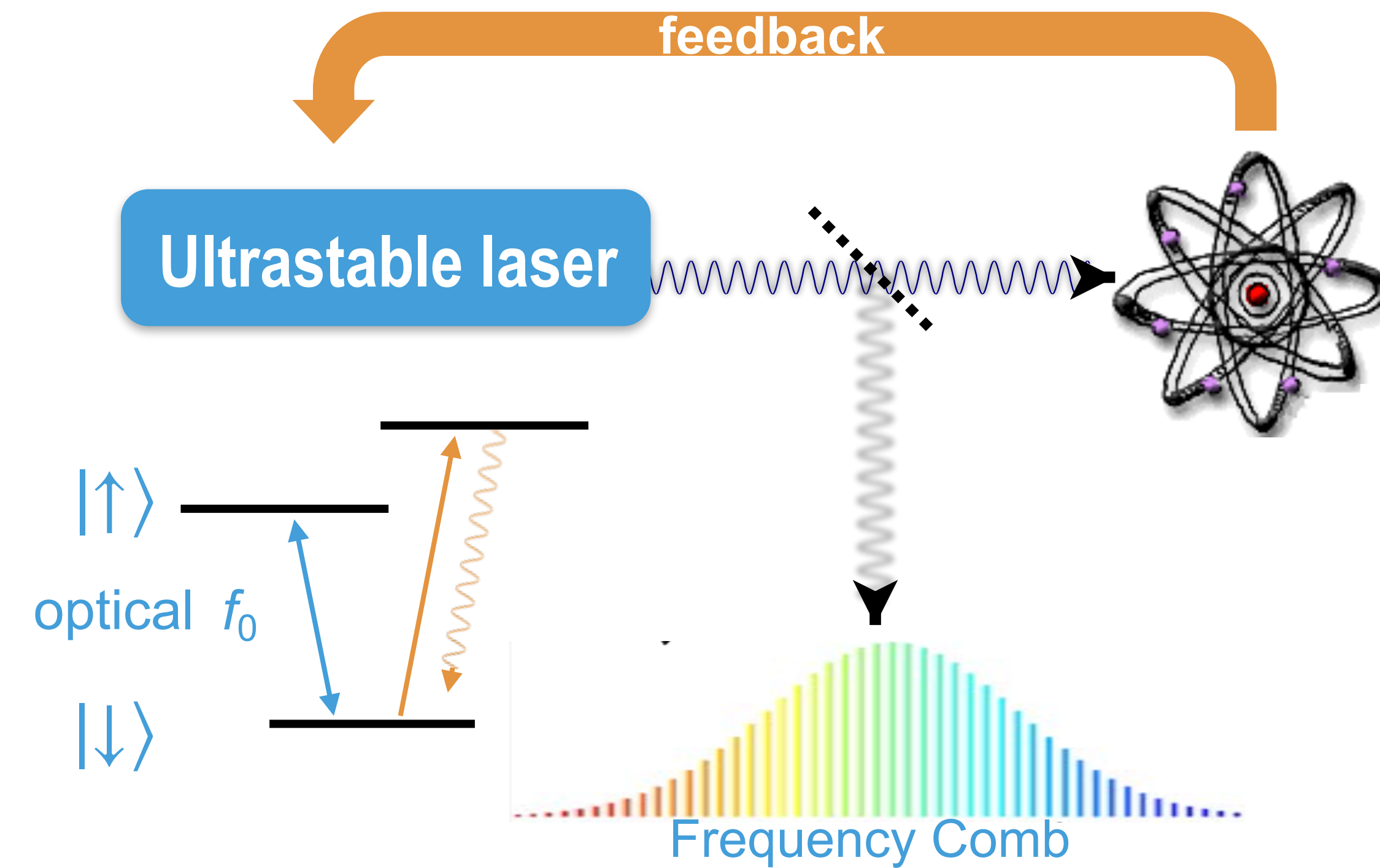
- *Quantum sensing essential* for light and ultra-light Dark Matter searches



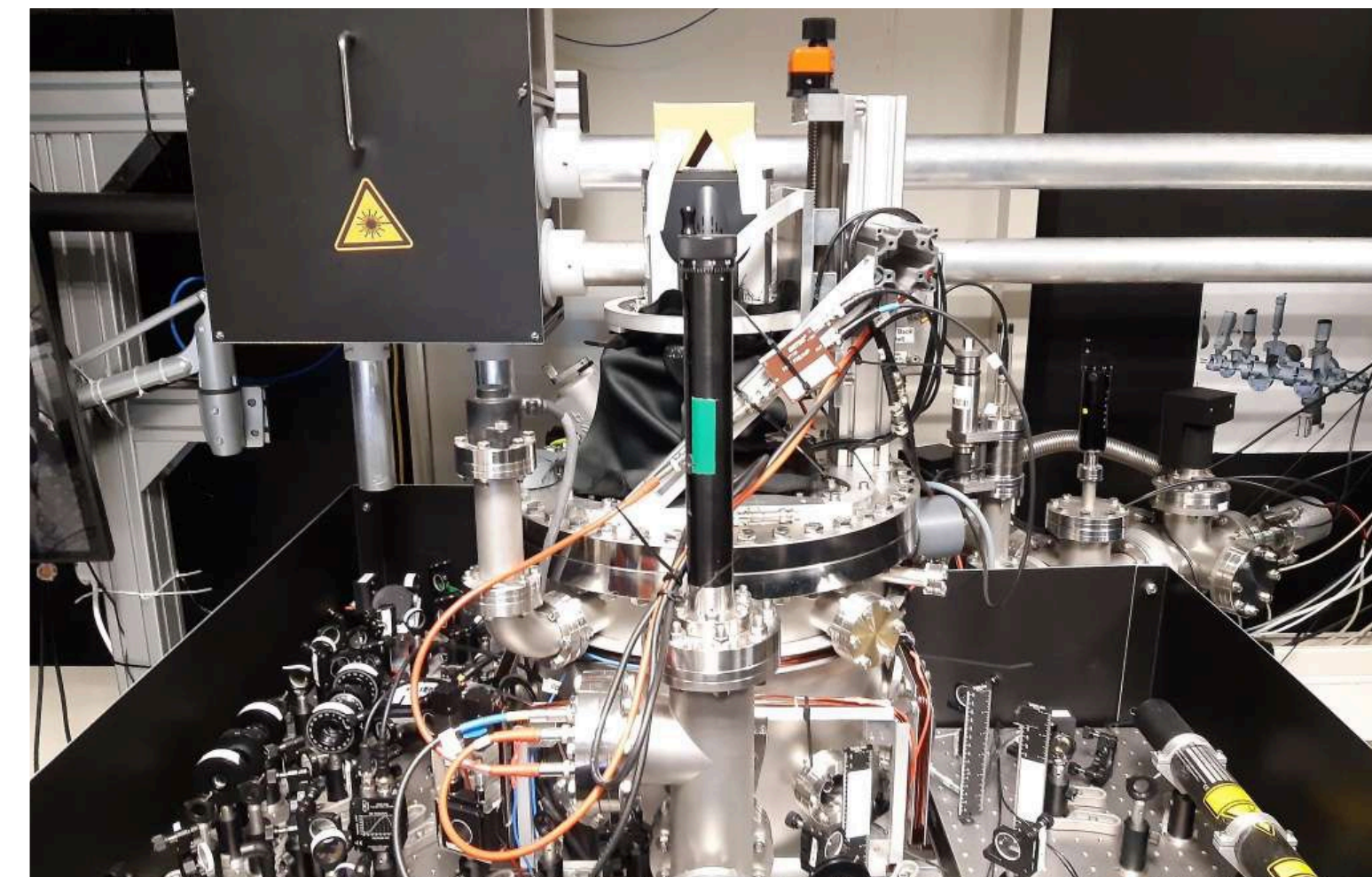
- *Optical Atomic Clock Experiments:* measure frequency ratios of two differently-sensitive clocks (α or μ)
- *More physics to explore:* topological defect Dark Matter, Local Lorentz Invariance, 5th Forces, Gravitational shift in fundamental constants, Dark Energy, Gravitational Waves

Optical Atomic Clocks w/ Ions

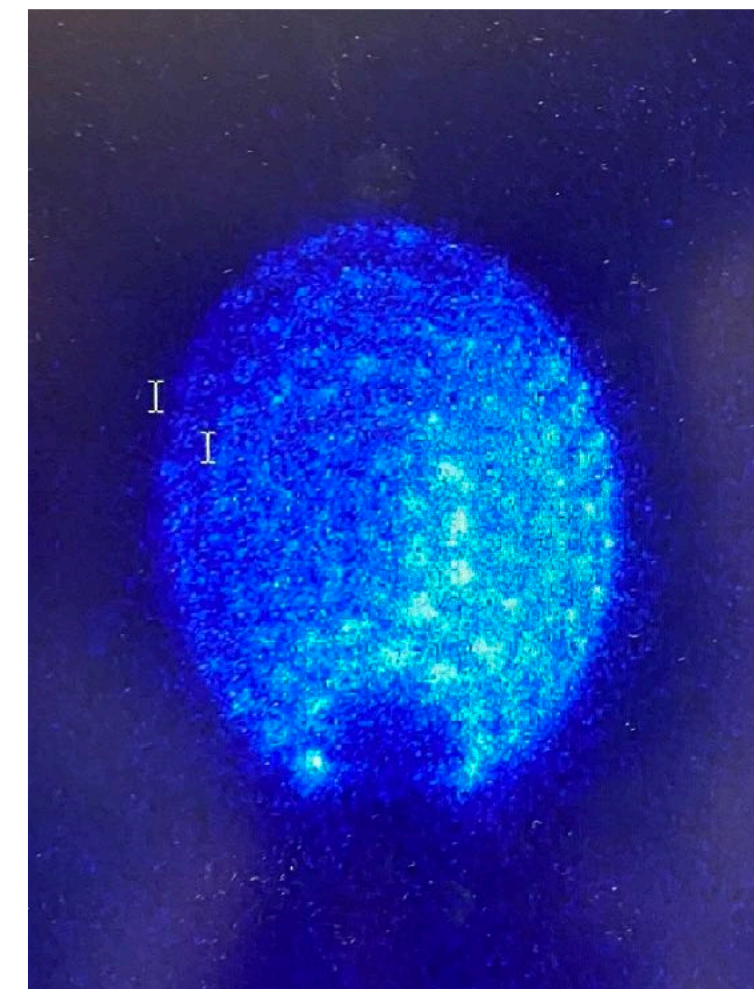
- Ultra-stable laser excites atomic transitions → a clock
- Frequency comb: optical → countable microwave
- Laser/sympathetic cooling with a second ion (eg Be)
- **Example:** Highly charged ions (HCl) for best sensitivity to $\Delta\alpha/\alpha$ for ultra-light dark matter interactions
- Half a dozen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



EBIT test stand @MPIK



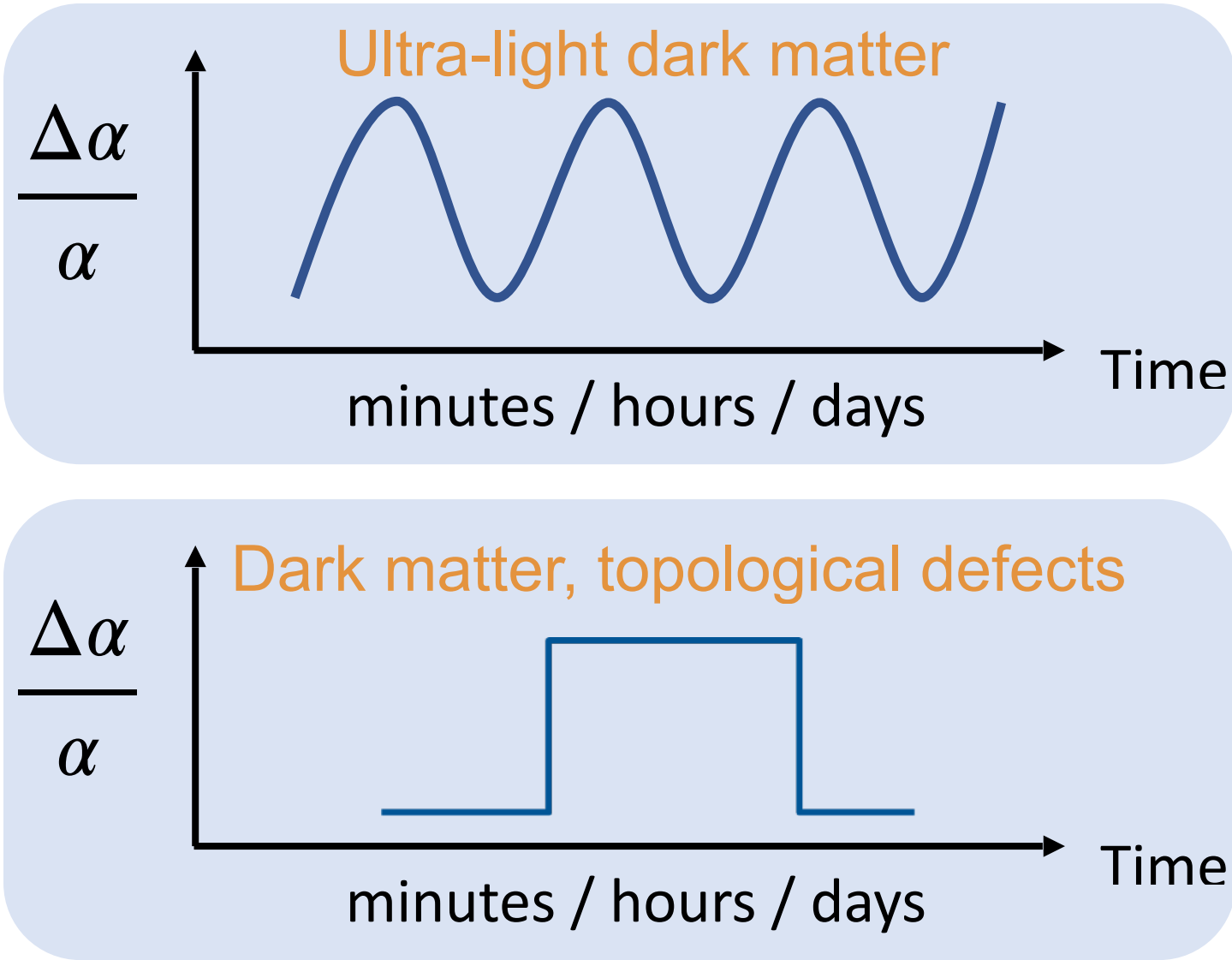
Paul trap w/ optics



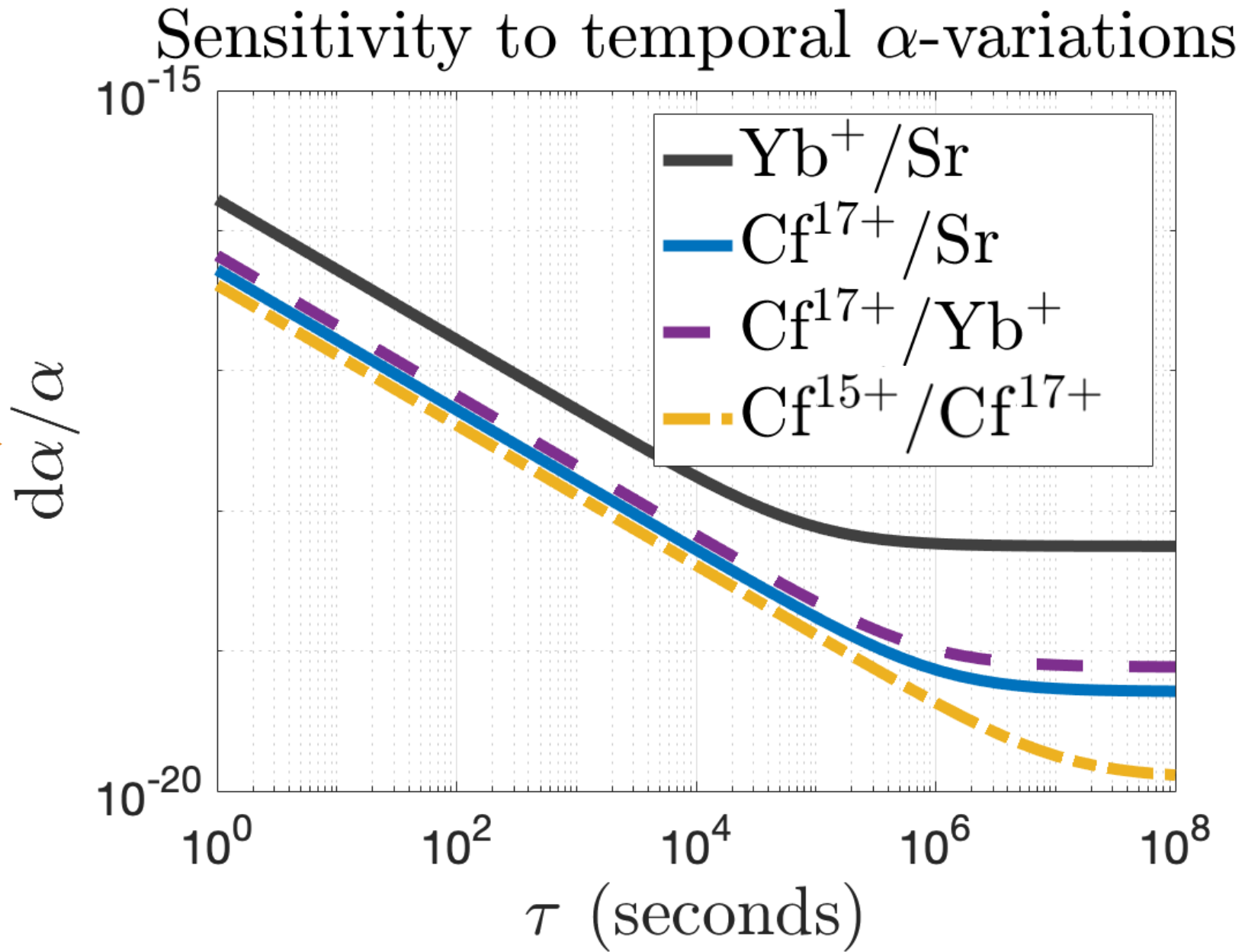
Be crystal with HCl (Ar)

Optical Clocks and Tests of Fundamental Physics

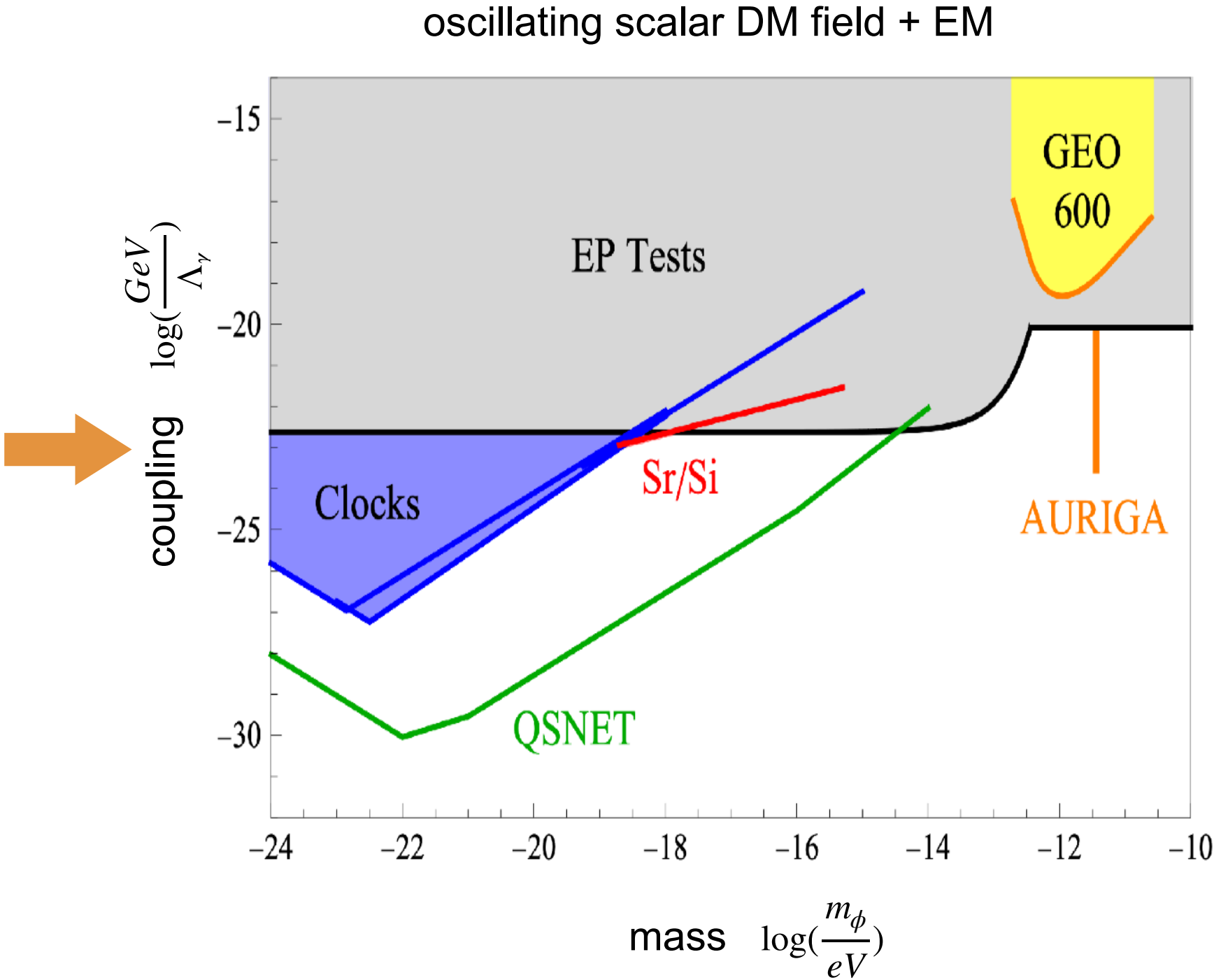
Search for variations



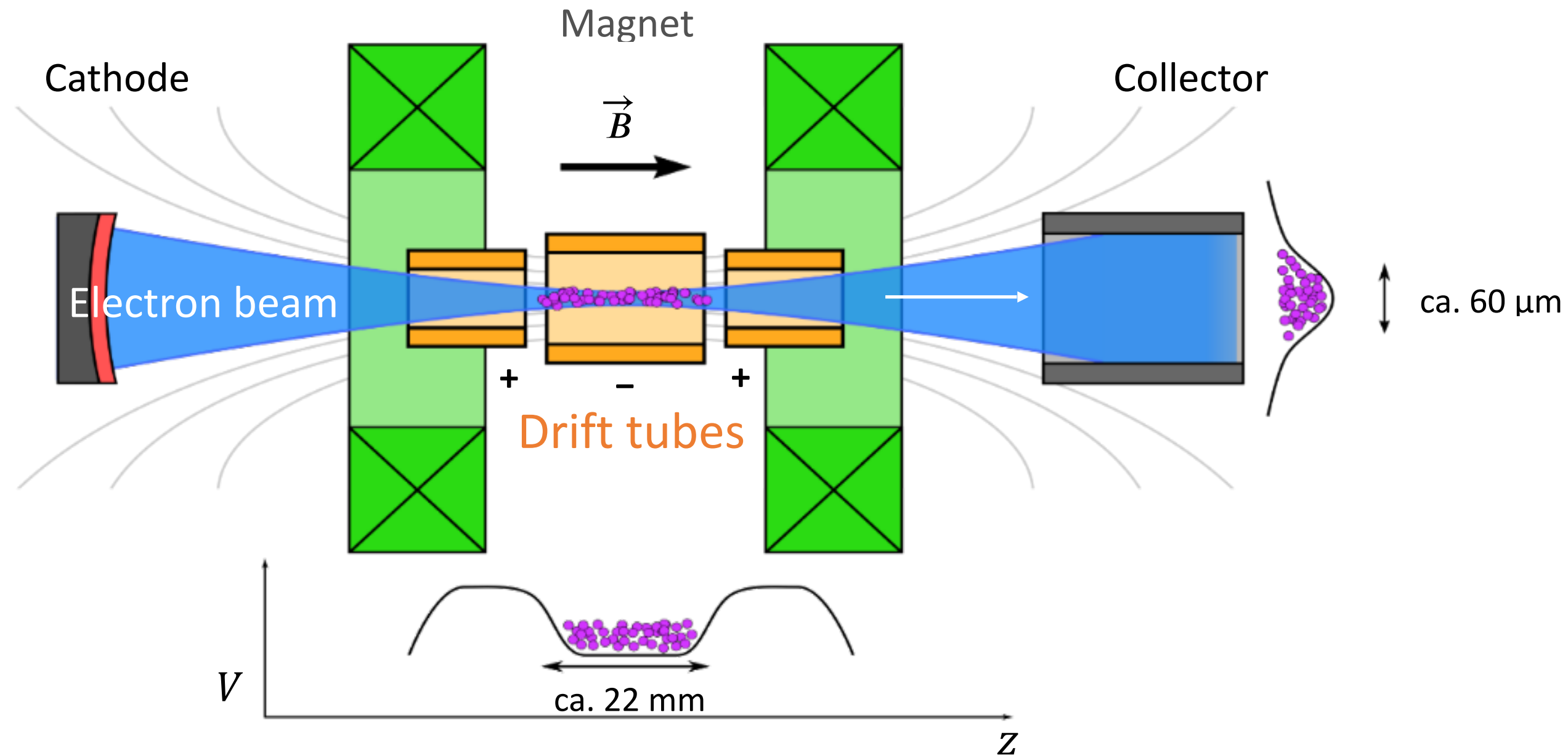
Study sensitivity



Discover DM (or limits)

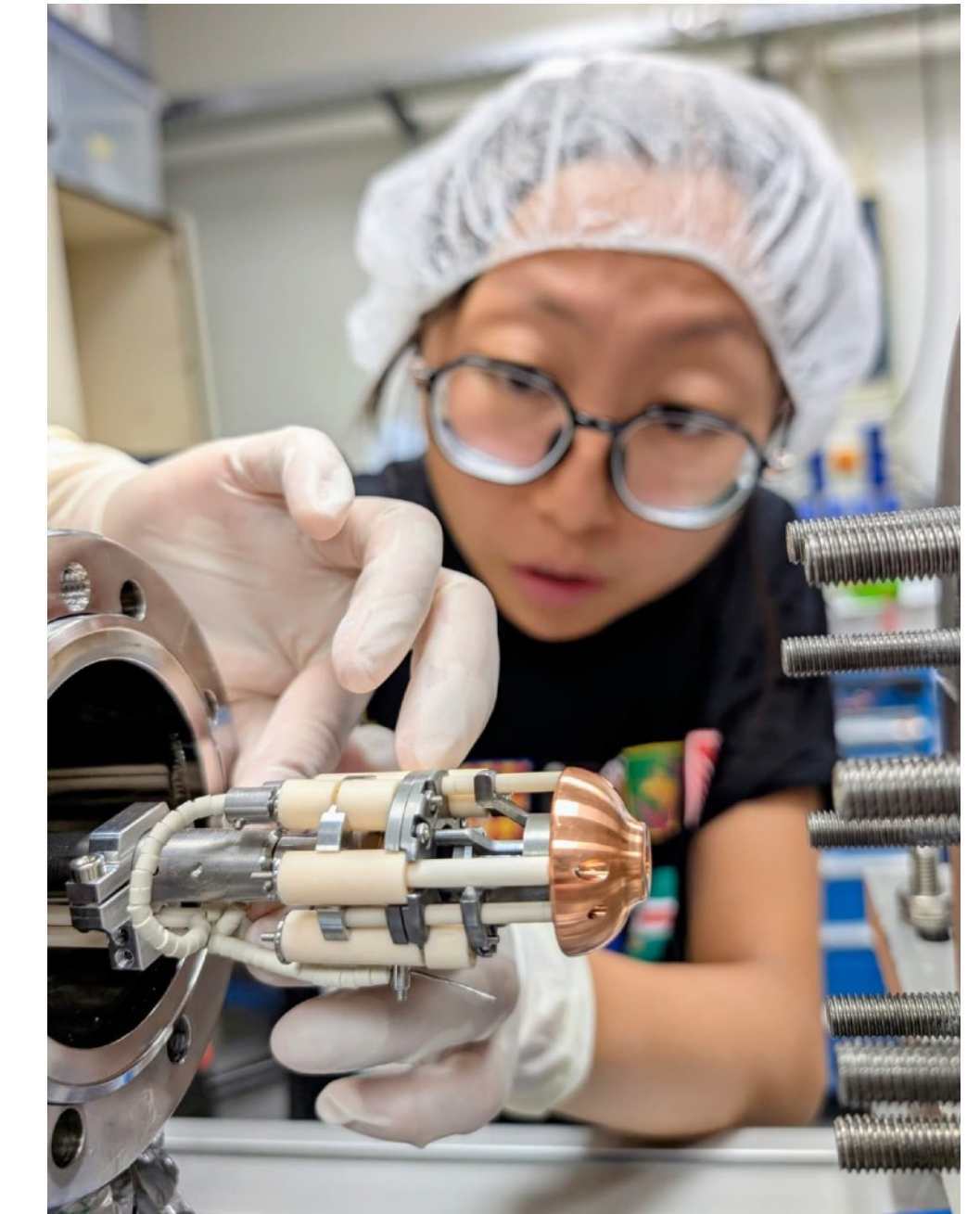
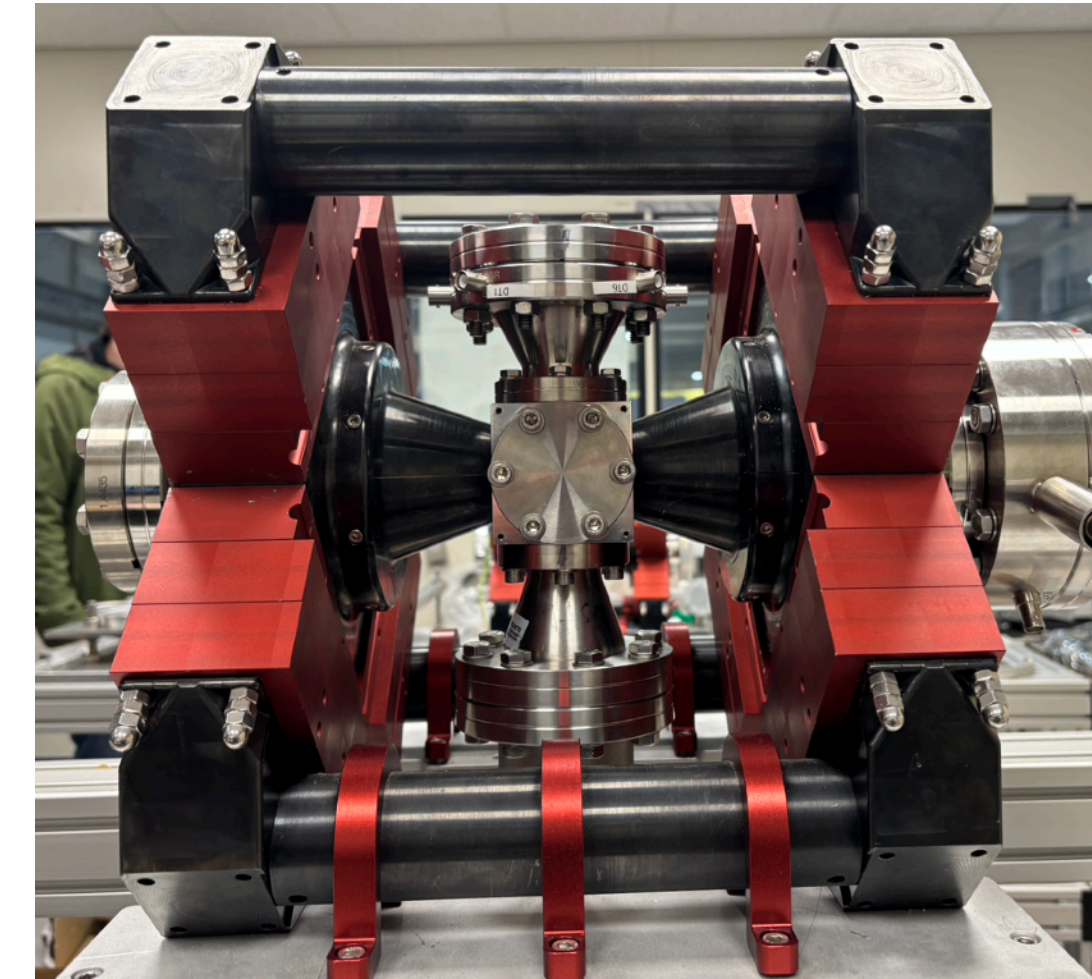


Electron Beam Ion Trap

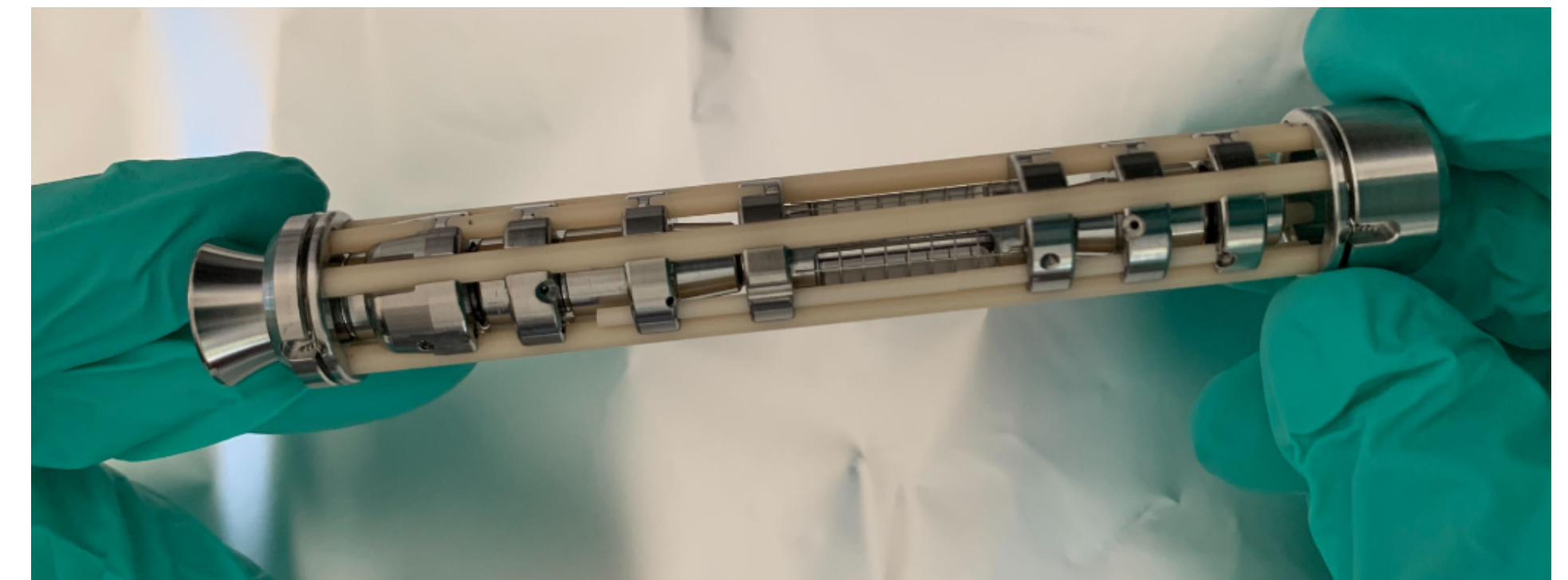


- Electron impact ionization:

$$X^{q+} + e^-(E_e) \rightarrow X^{(q+1)+} + e^-(E_1) + e^-(E_2)$$
- Magnetic field in the trap center ≈ 0.9 tesla
- Axially trapped by the drift tube potential
- Radially trapped by the electron space charge

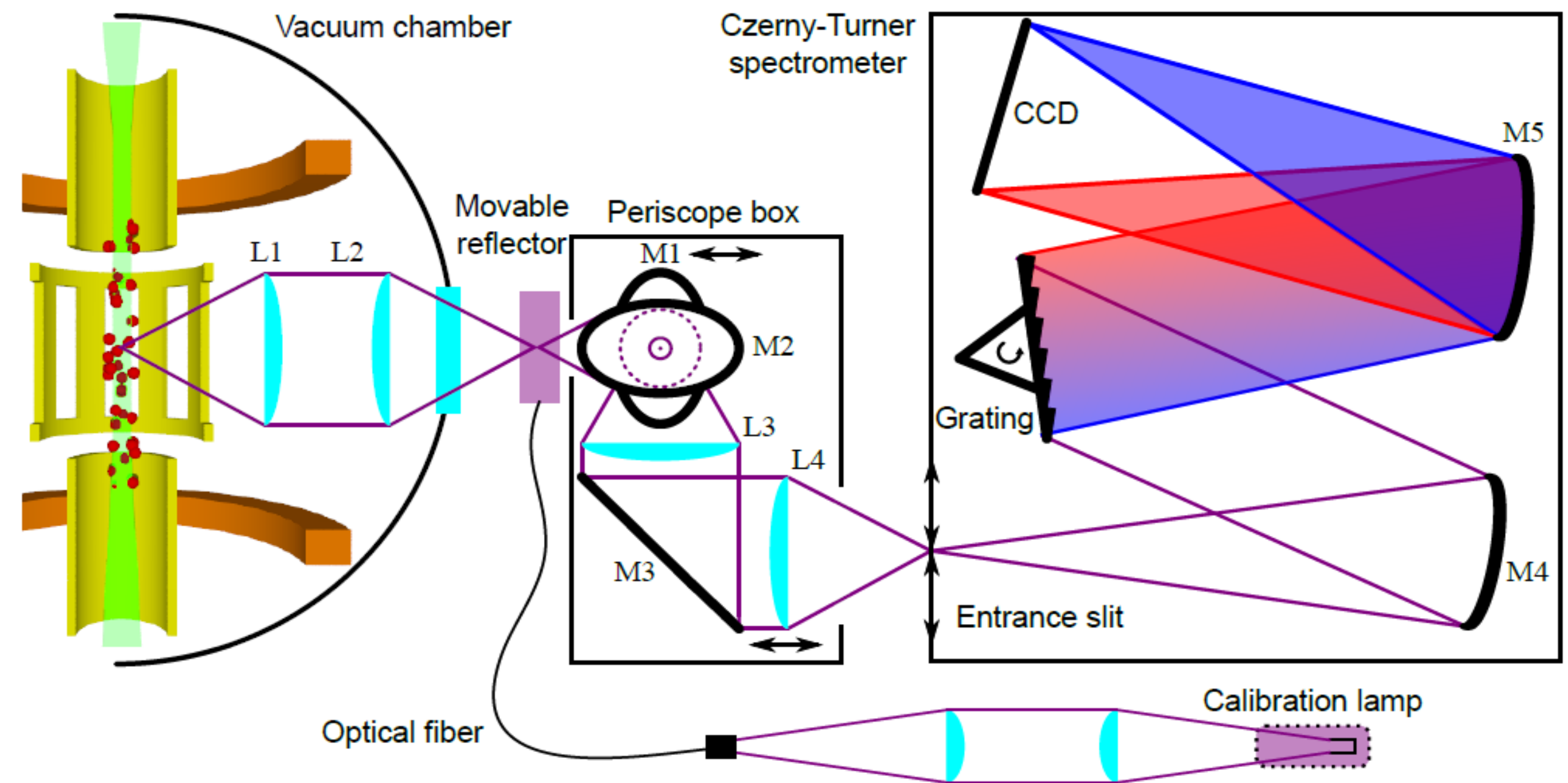
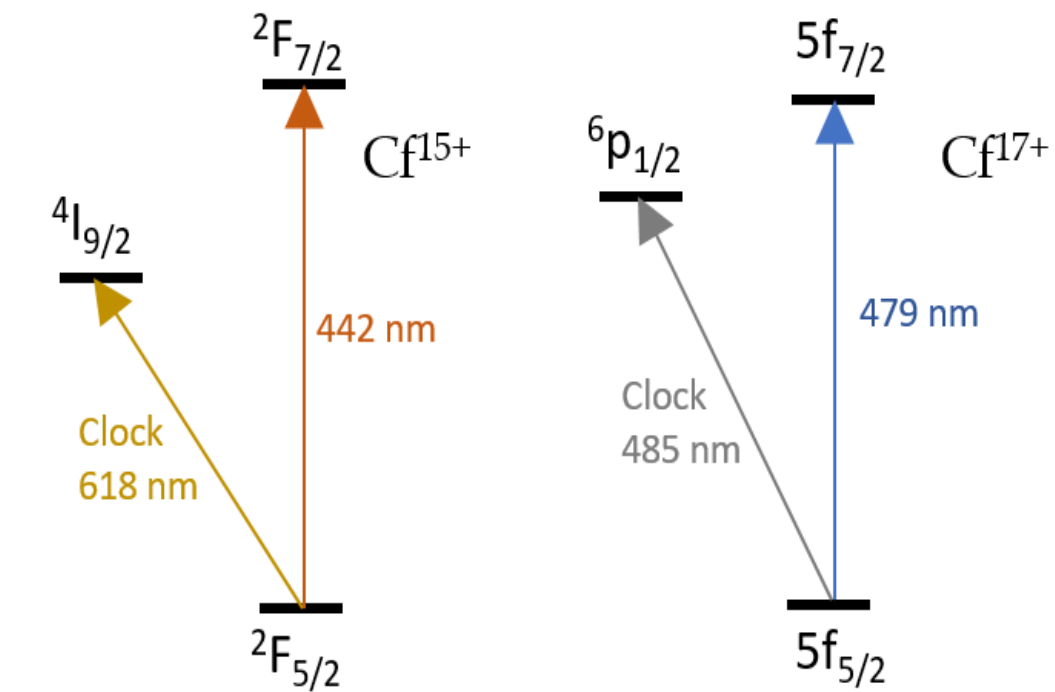
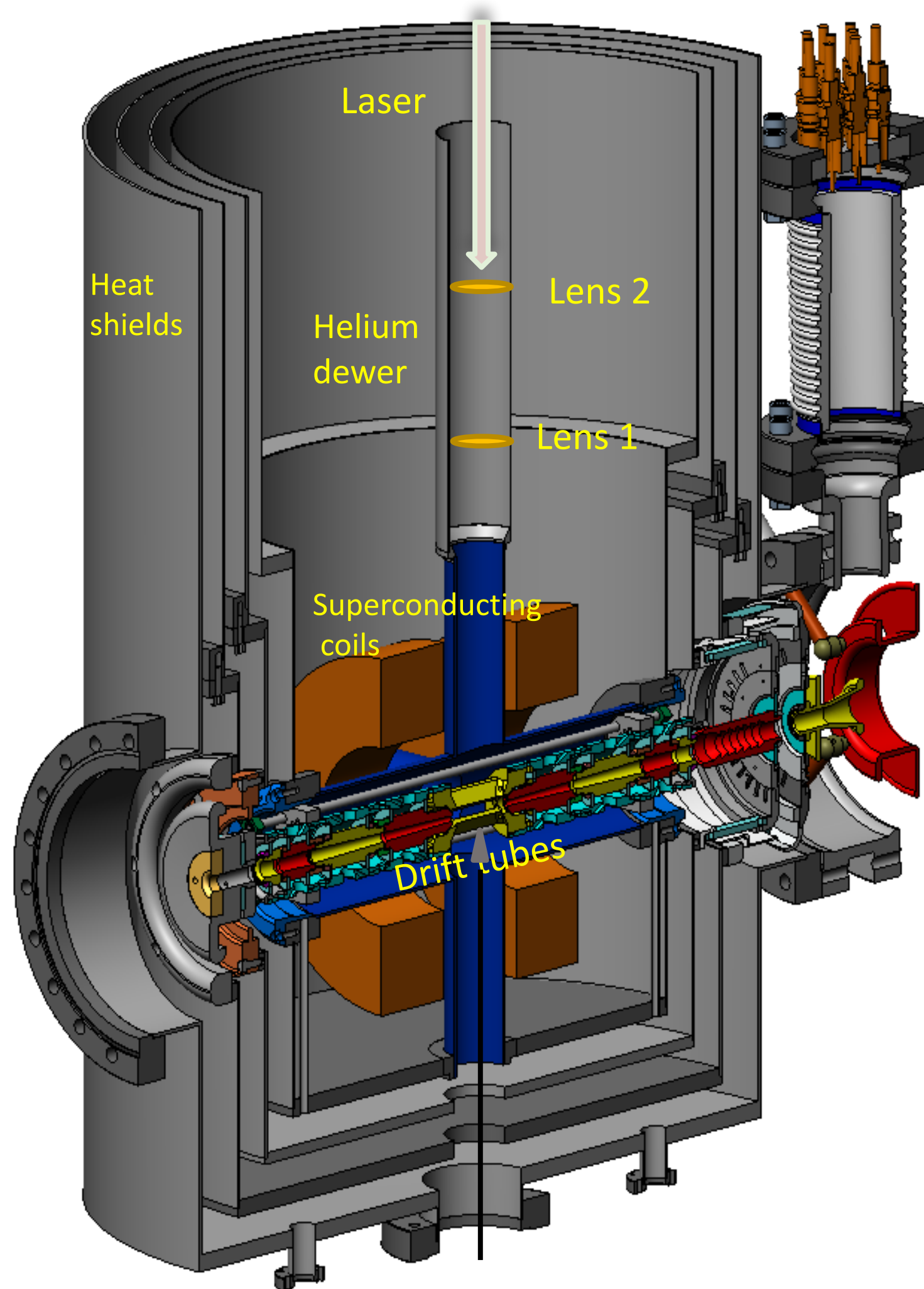


EBIT construction status



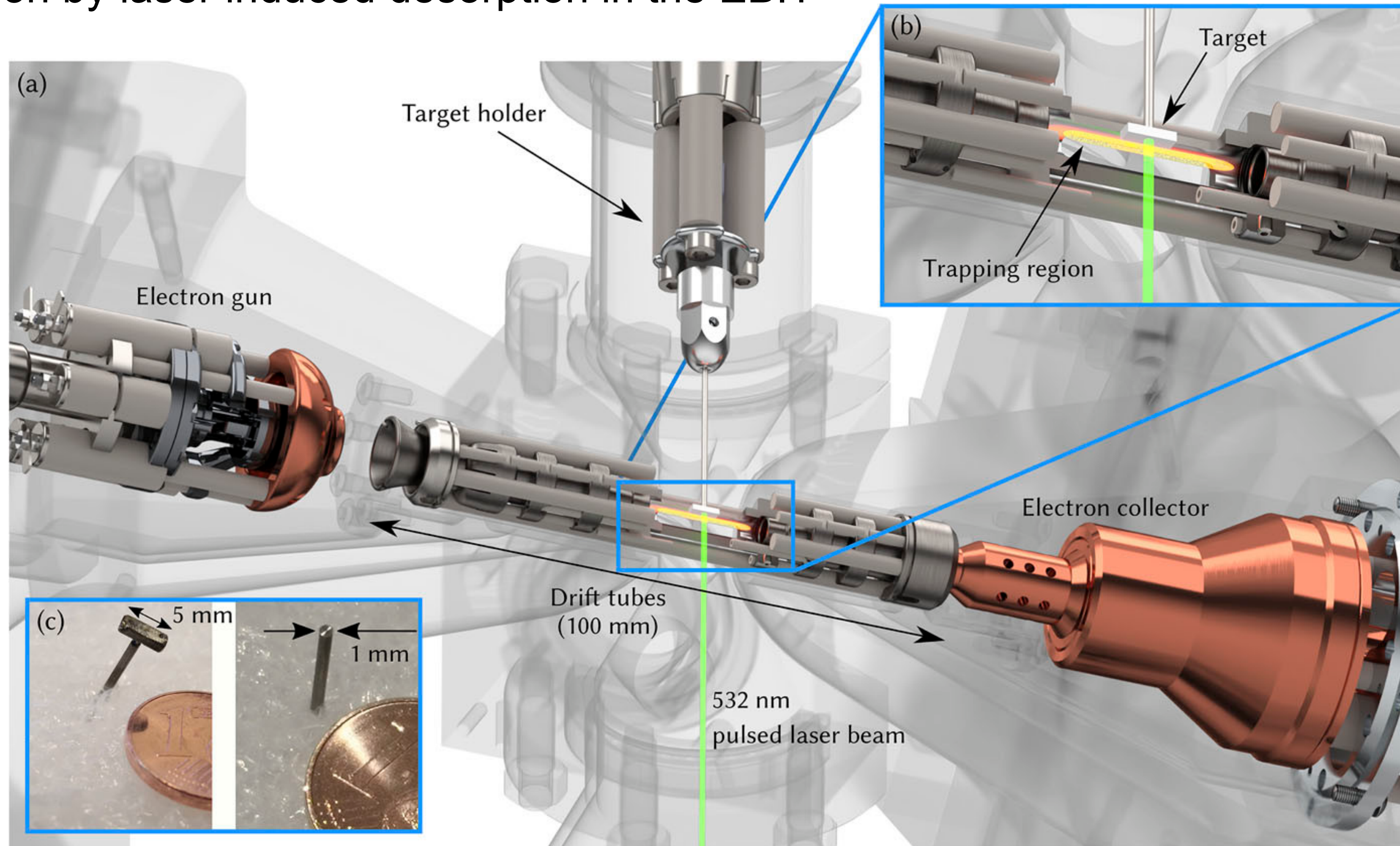
Californium Spectroscopy in the Heidelberg EBIT

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

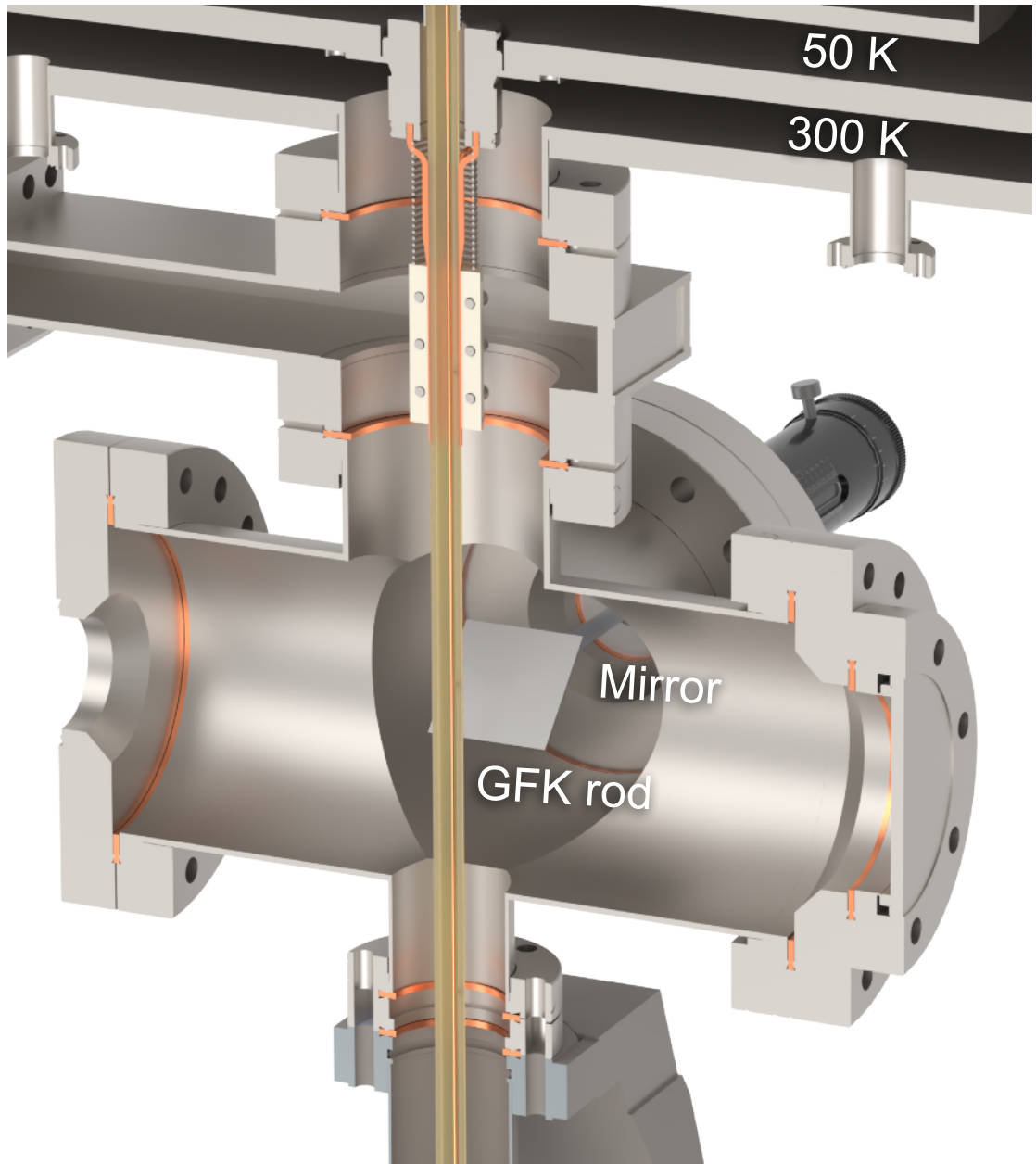
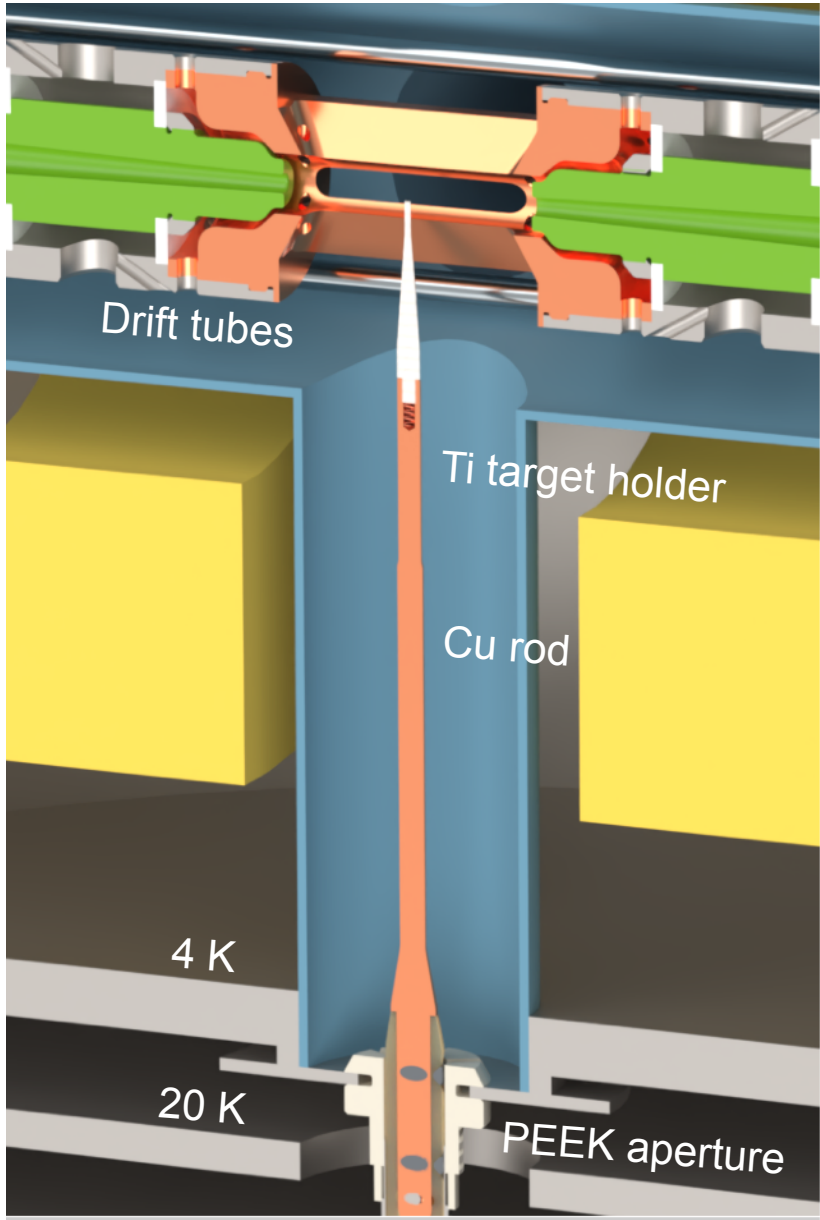
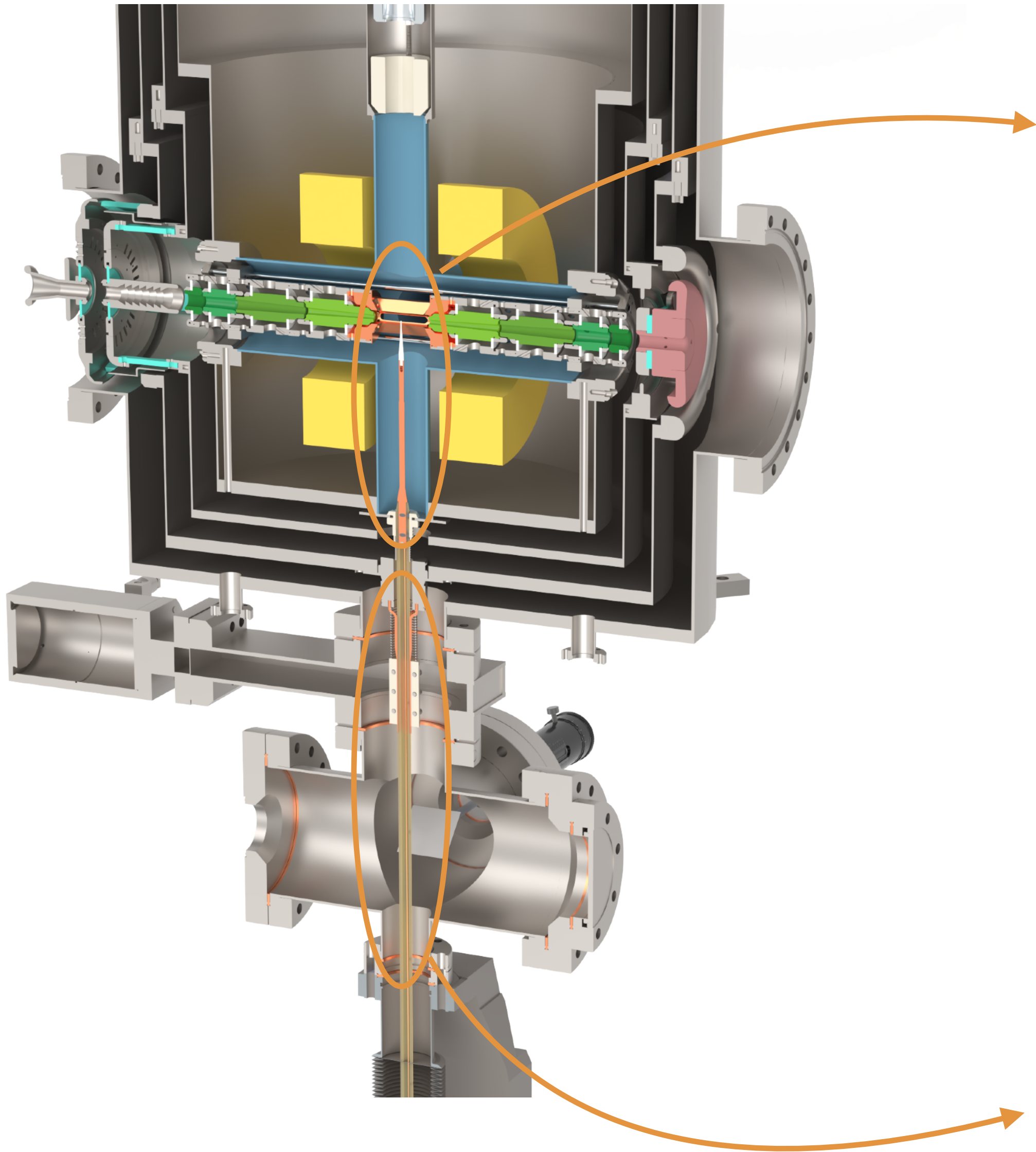


Injection of Californium

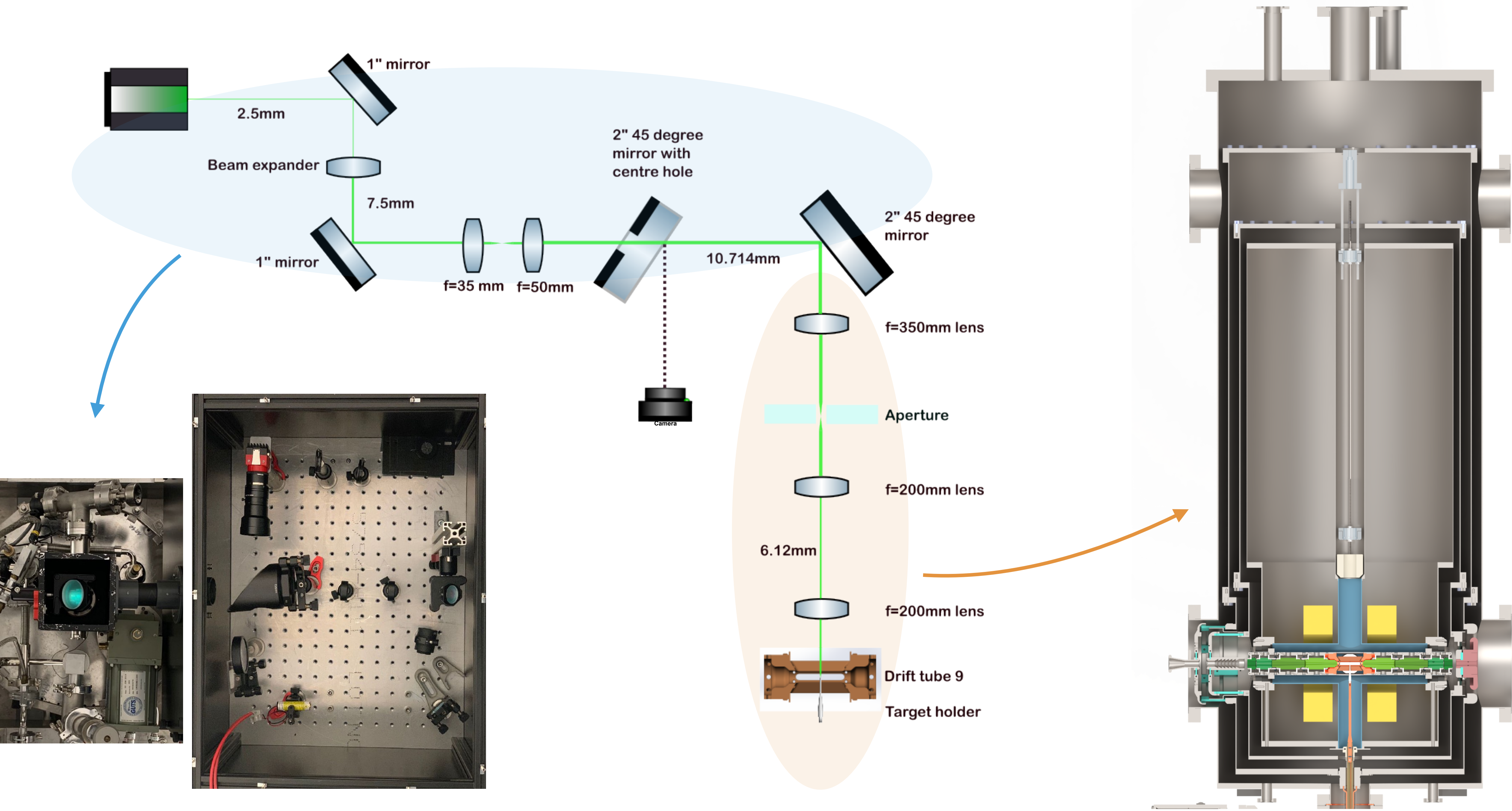
- Californium: synthetic, radioactive, rare, \$£€...
- Efficient injection by laser induced desorption in the EBIT



Heidelberg EBIT — Target Holder

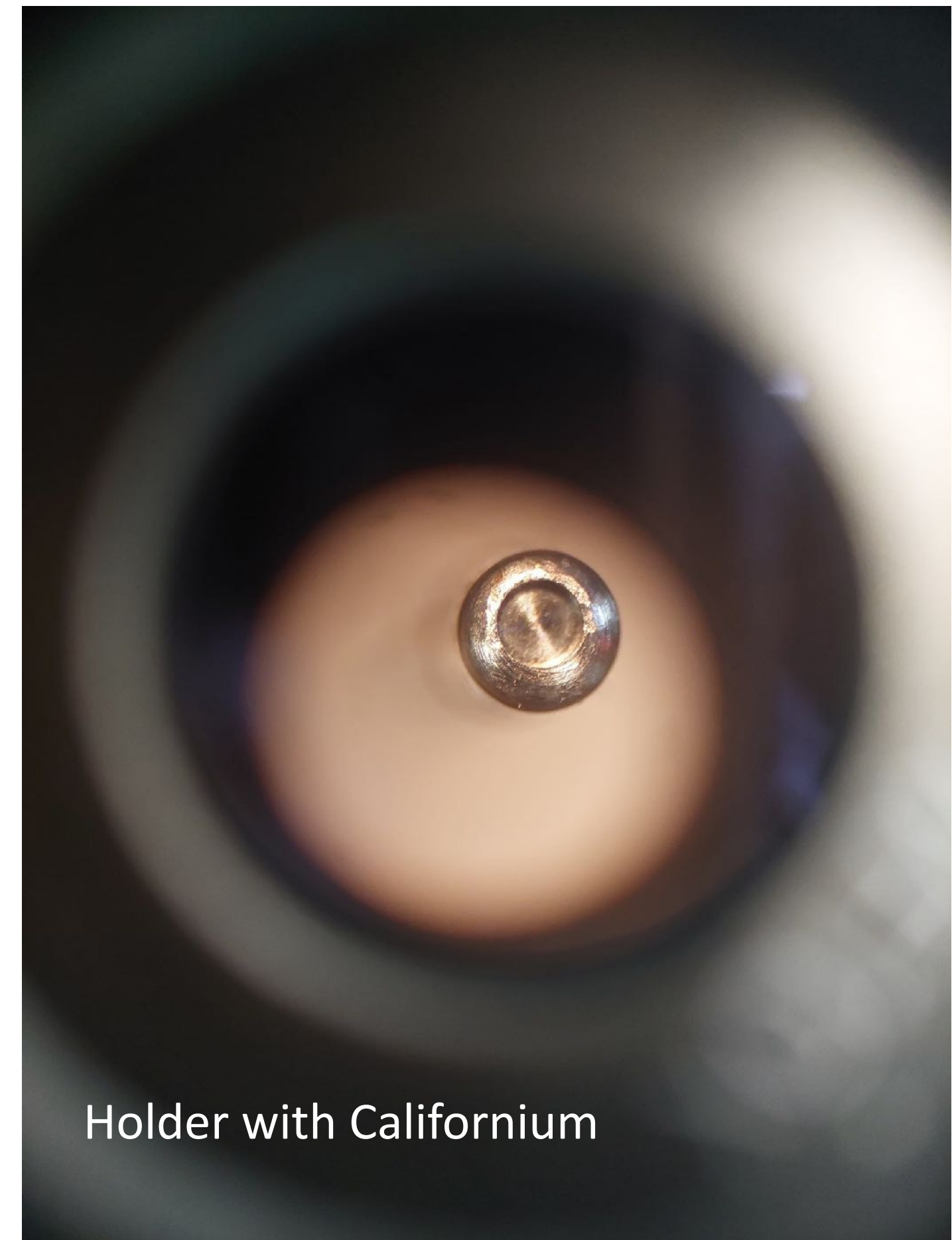
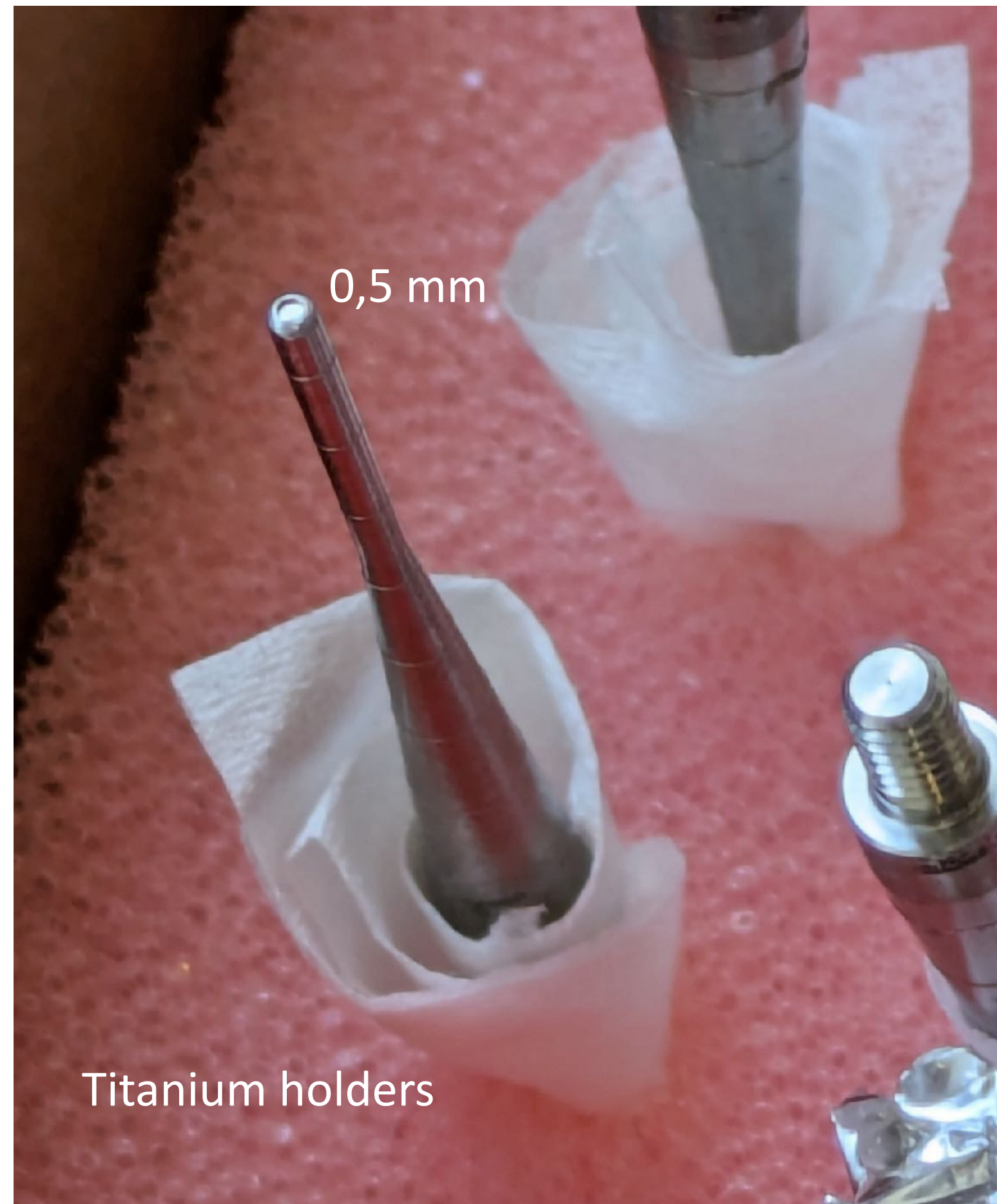


Heidelberg EBIT — Optical System

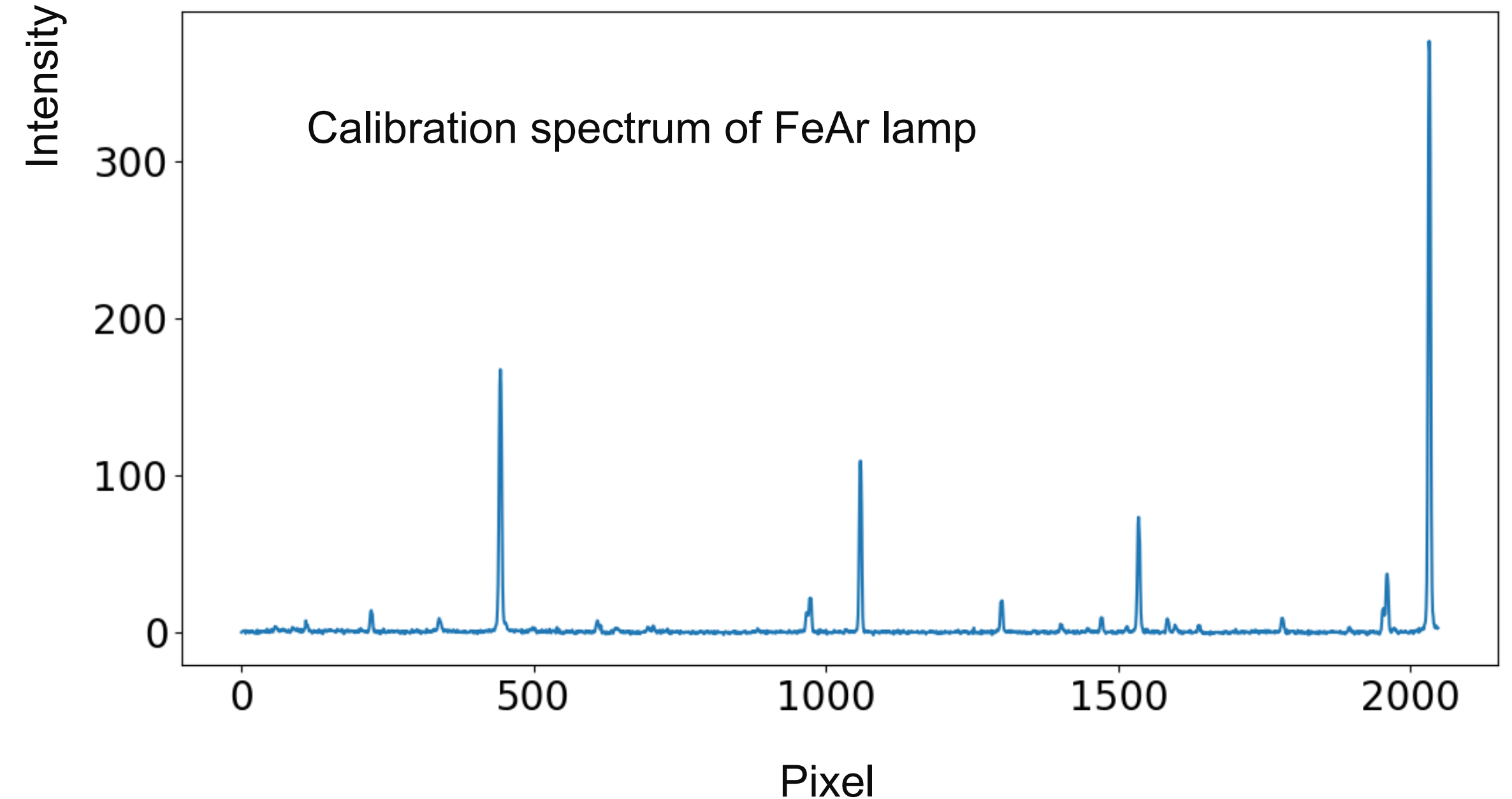
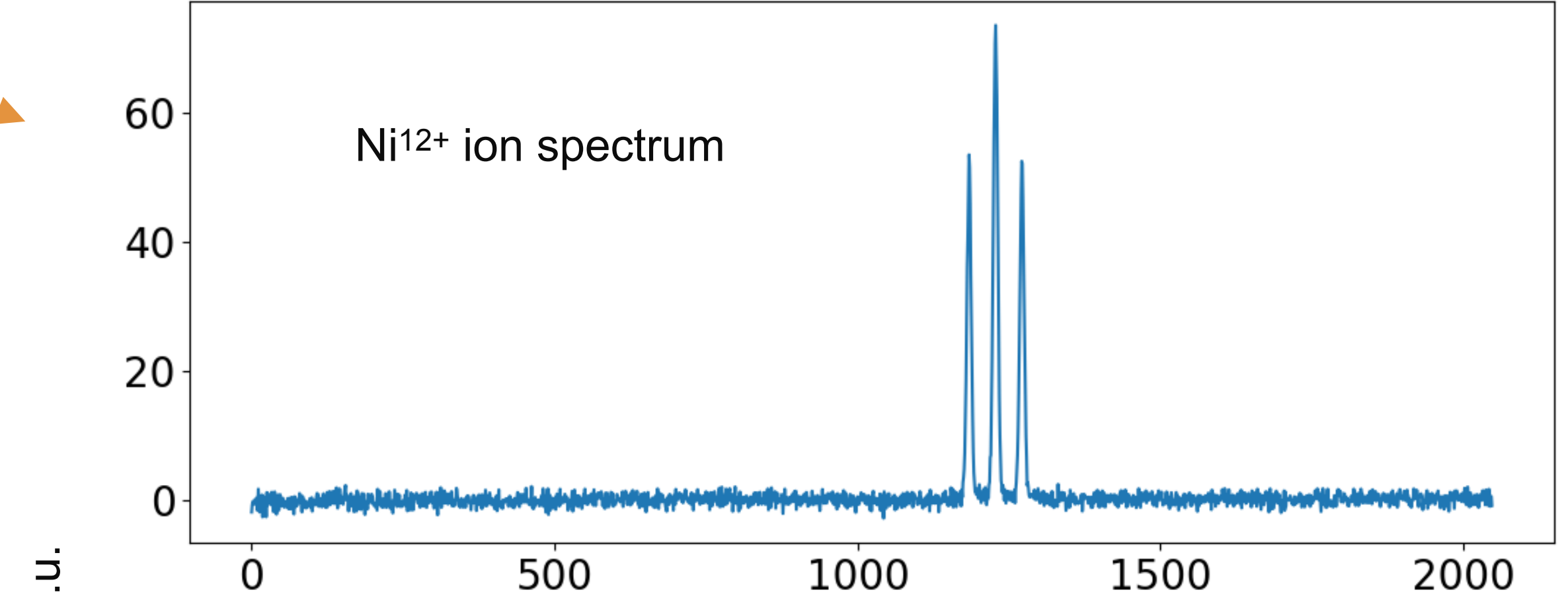
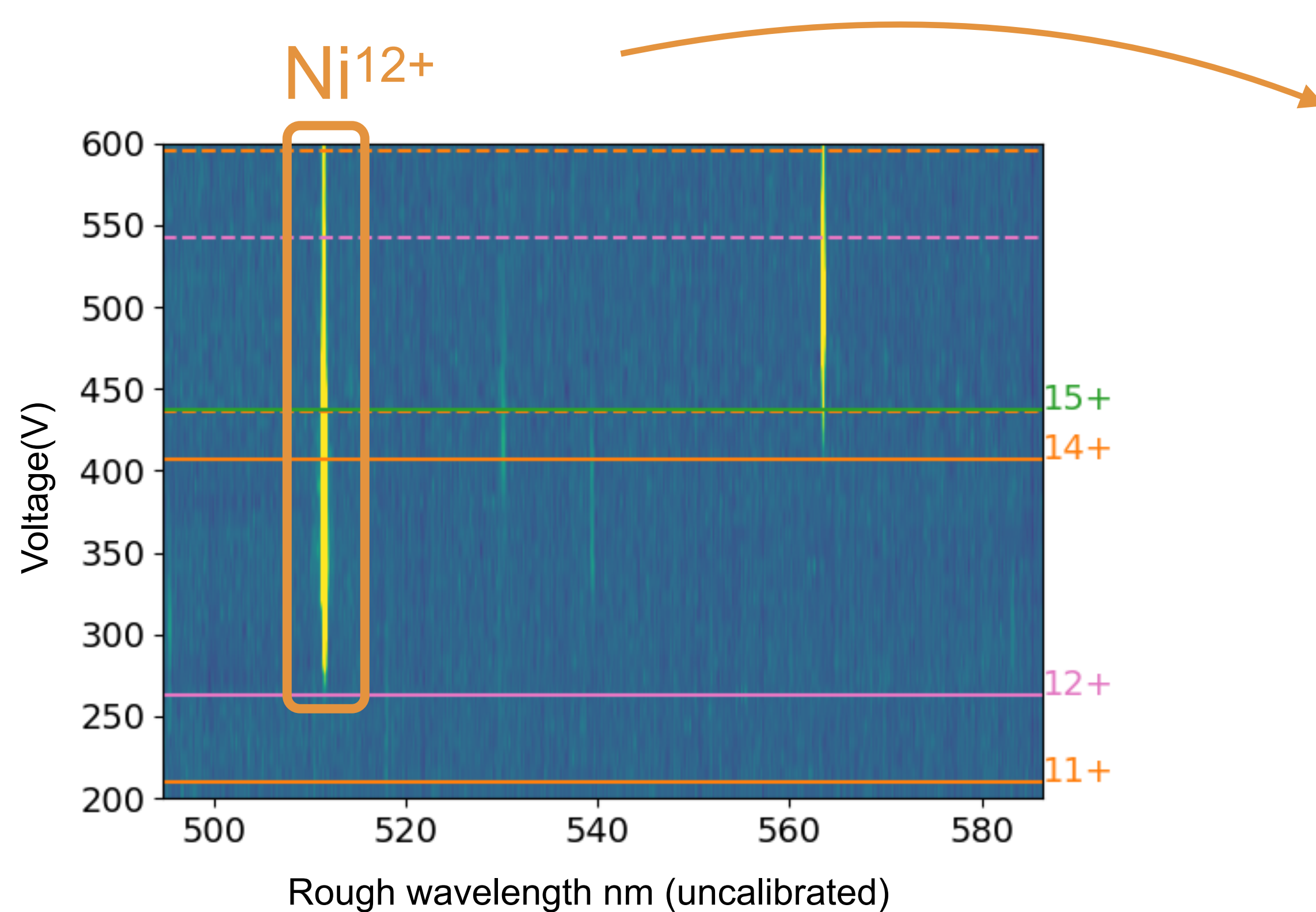


Manipulator Installation and Californium

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



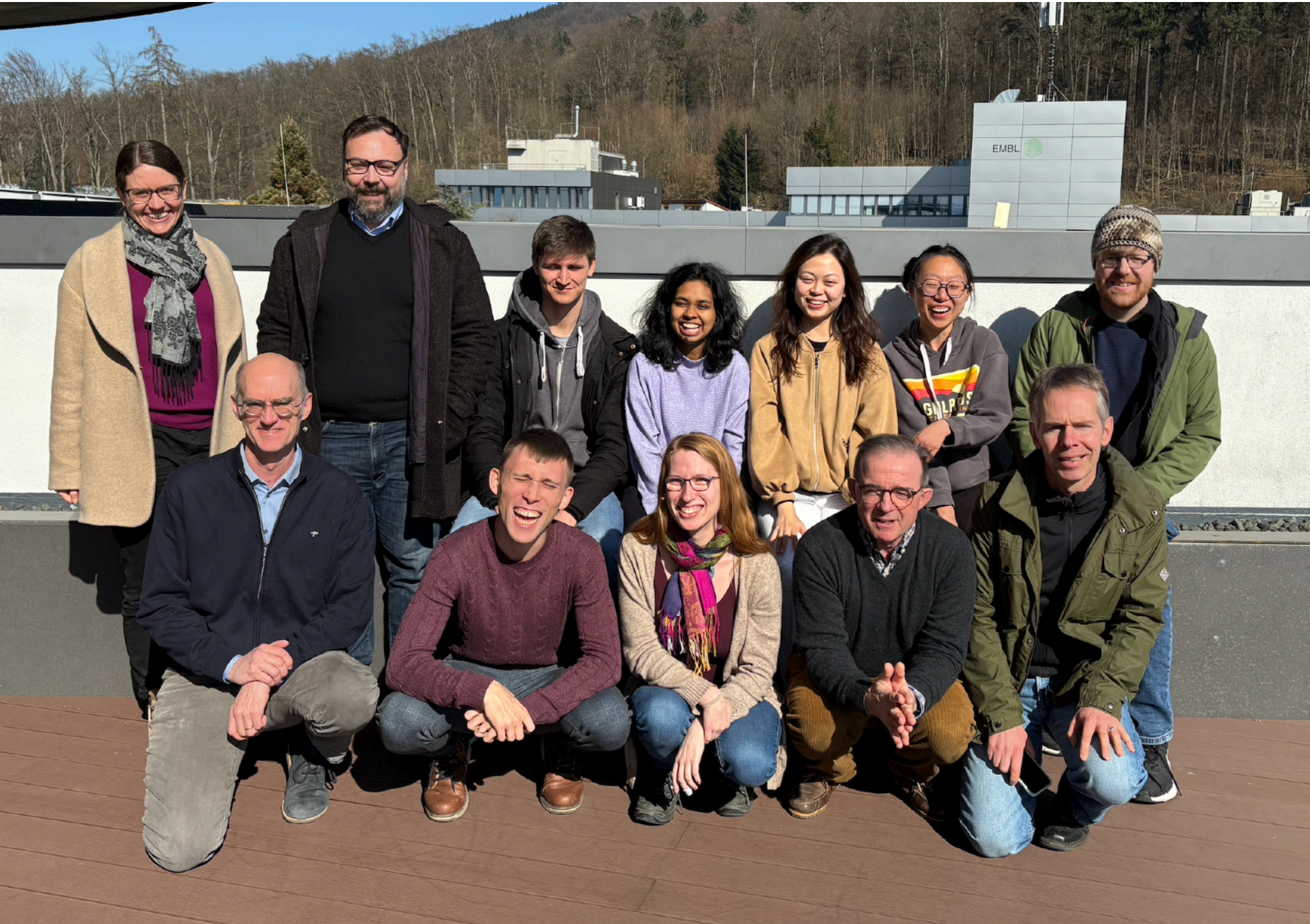
Spectroscopy Example: Nickel 12+



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

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 HCl spectroscopy



Meeting with groups of Crespo, Barontini, Schäfer

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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 Rehbehn¹,^{*} Lakshmi Priya Kozhiparambil Sajith,^{1,2} Michael K. Rosner¹,^{*} Charles Cheung,³ Sergey G. Porsev,³ Marianna S. Safronova,³ Steven Worm,² Dmitry Budker^{4,5,6,7}, Thomas Pfeifer¹,^{*} José R. Crespo López-Urrutia¹,^{*} and Hendrik Bekker¹,^{4,5,6,†}

¹Max-Planck-Institut für Kernphysik, D-69117 Heidelberg, Germany
²DESY, D-15738 Zeuthen, Germany
³Department of Physics and Astronomy, University of Delaware, Newark, Delaware 19716, USA
⁴Johannes Gutenberg-Universität Mainz, 55122 Mainz, Germany
⁵Helmholtz Institute Mainz, 55099 Mainz, Germany
⁶GSI Helmholtzzentrum für Schwerionenforschung GmbH, 64291 Darmstadt, Germany
⁷Department of Physics, University of California, Berkeley, CA 94720-7300, United States of America
(Dated: September 9, 2025)

Optical transitions of highly charged ions can be very sensitive to hypothetical beyond-Standard-Model phenomena. Those near the $5s - 4f$ level crossing, where the $5s$ and $4f$ orbitals are especially promising. We present predictions from atomic theory and measurements of $\text{Os}^{15,16,17+}$ at an electron beam ion trap for identification of several transitions for searches for a hypothetical fifth force and possible violations of local Lorentz invariance. We find electric quadrupole (E2) transitions of Os^{16+} that were found to be especially suitable for frequency metrology due to their small linewidth of 44 μHz . Our calculations show the need for enough inner-shell excitations to predict transition rates between configurations, which otherwise would be overestimated. Ultimately, the predicted interconfiguration transitions were too weak to be detected.

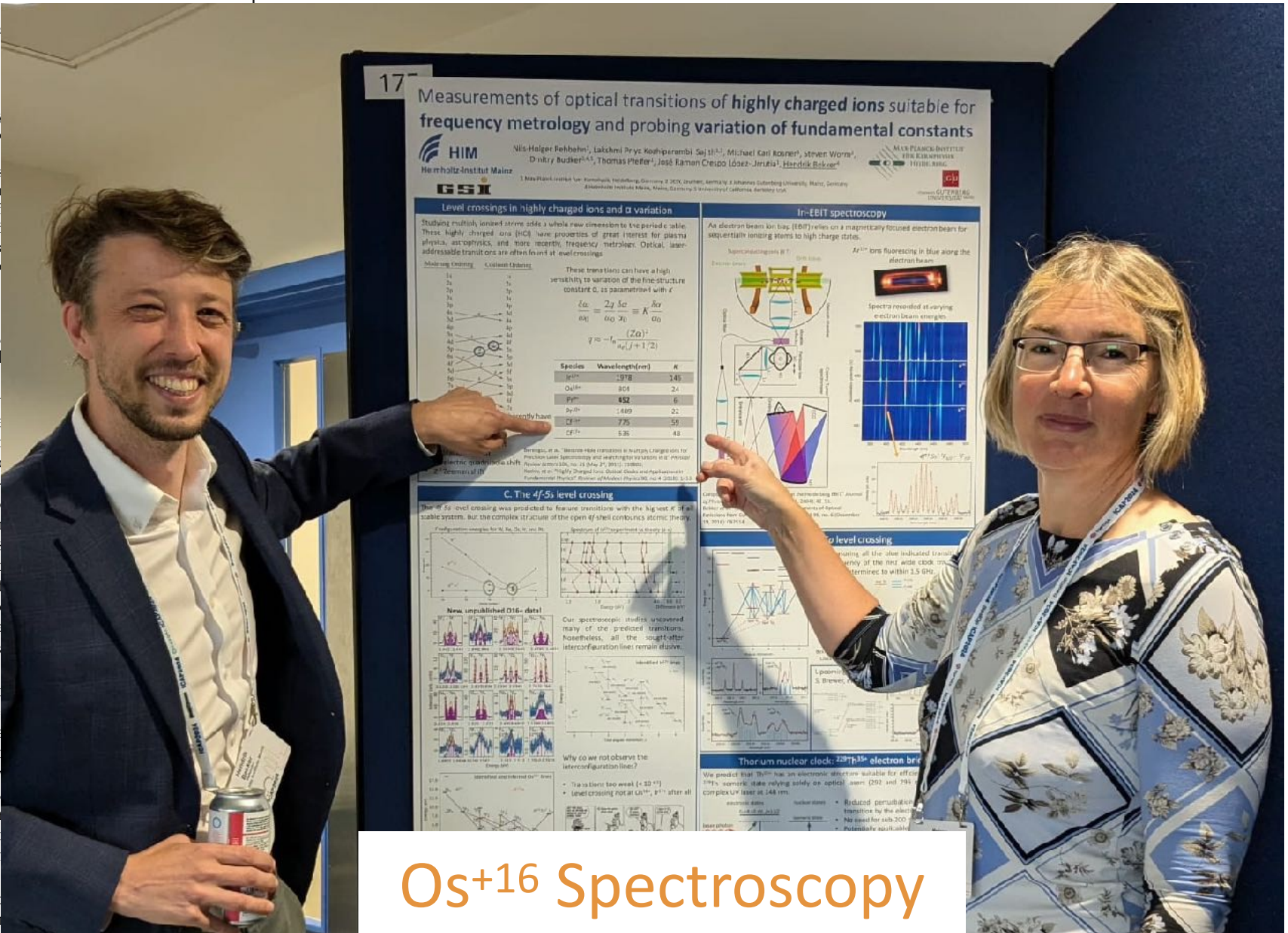
Very recently, by applying quantum logic [1] to frequency metrology [2, 3] of sympathetically cooled highly charged ions (HCI) [4], a precision close to that of state-of-the-art optical clocks [5] for neutral and singly charged atoms has been reached at the German metrology institute Physikalisch-Technische 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 $[\text{Pd}]4f^{12}5s^2$ and $[\text{Pd}]4f^{13}5s$ 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

couples to the ground state by an electric quadrupole (E2) transition well within the optical range.

One central advantage of HCI is that the outer electrons [13]. Their wave functions are affected by external perturbations such as magnetic fields. In contrast, its strong overlap with the inner shell electrons enhances hypothetical BSM electron-positron interactions accessible to the generalized King plot [13]. Its seven stable, naturally occurring isotopes have nuclear spin $I = 0$, and its high ionization energy and resulting relativistic effects, make it well suited for such studies. In Os^{16+} , the $5s$ and $4f$ orbitals are very different for s - and f -electrons, yielding a large variation in the orbital angular momentum quantum number l and an outstanding sensitivity to a variation and to hypothetical Lorentz invariance [20].

Theory—We perform large-scale configuration interaction (CI) calculations for Os^{16+} treating the closed-shell core electrons and the valence electrons with systematic accounting of the correlation energy. The vast number of configurations and the large number of weights requires the inclusion of many-body effects. To support these demands, we have developed a threefold the Hamiltonian bitstring-determinant storage and the corresponding CI package [22].

We construct our basis set based on the Ir^{17+} [19] expanding it to include the $5p$ orbitals up to $n = 13$ for partial waves up to $l = 7$, and comprising all orbitals up to $13g$, $12h$, $11i$, and $10k$. We gradually expand the basis set until conver-



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

