Search for dark matter with a highly charged californium ion clock

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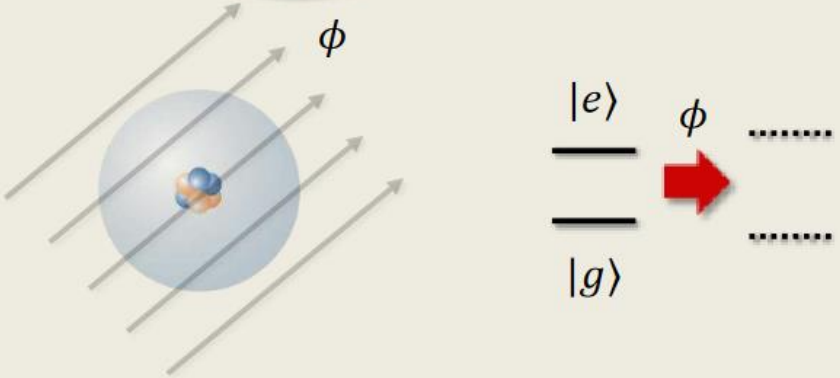
Dark matter searches & variation of constants

- dark matter candidate: e.g. ultralight scalar field ϕ
  - oscillating field: $\phi(t) = \phi_0 \cos(m_\phi t)$
  - topological field (forming „clumps“)
  - …
- weak (non-gravitational) linear coupling to matter:



$$\mathcal{L}_\phi = \frac{4\pi\phi}{M_{Pl}}\left[\frac{d_e}{4e^2}F_{\mu\nu}F^{\mu\nu} - d_{m_e} m_e \bar{e}e - \frac{d_g \beta_3}{2g_3} G^A_{\mu\nu} G^{A\mu\nu} - \sum_{i=u,d}\left(d_{m_i} + \gamma_{m_i} d_g\right) m_i \bar{\Psi}_i \Psi_i\right]$$

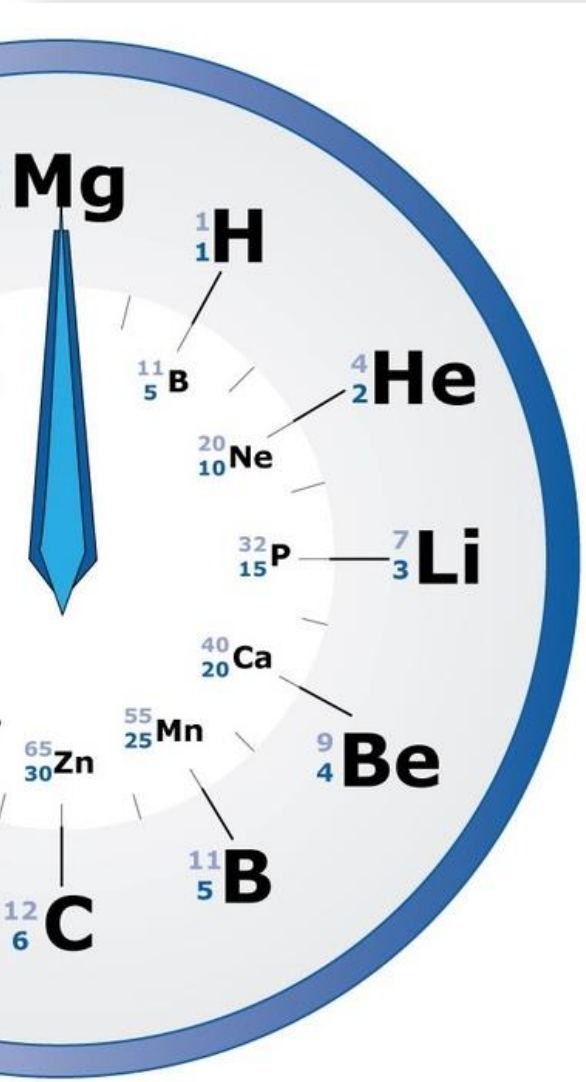
photons · electrons · gluons · quarks

➔ apparent variation of fundamental constants (α, fermionic masses, …)

[Arvanitaki *et al.*, Phys. Rev. D **91**, 015015 (2015); review: Safronova *et al.*, RMP **90**, 025008 (2018)]

Slide taken from Pete Schmidt’s talk at CERN

CLOCKS



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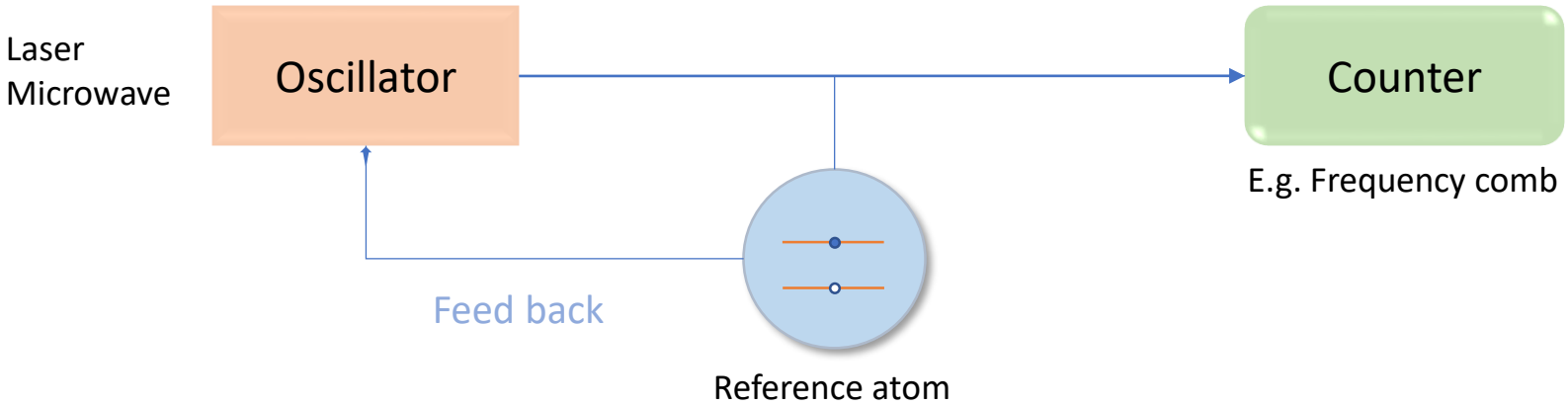
To measure time

Uses: Dark matter searches

Variation of fundamental constants



Microwave clocks (Cs)

Optical clocks (Sr, Yb+, Al+)

Stability

Statistical uncertainty: frequency, linewidth

Systematic uncertainty: small frequency shifts

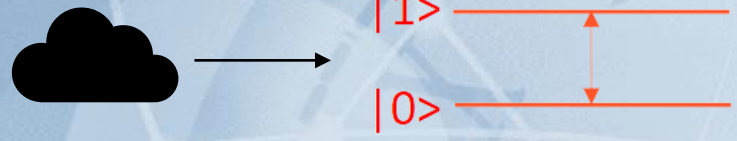
Accuracy

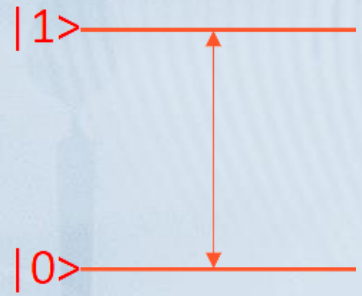
QSNET

Goal

To find possible variation in the fundamental constants ;

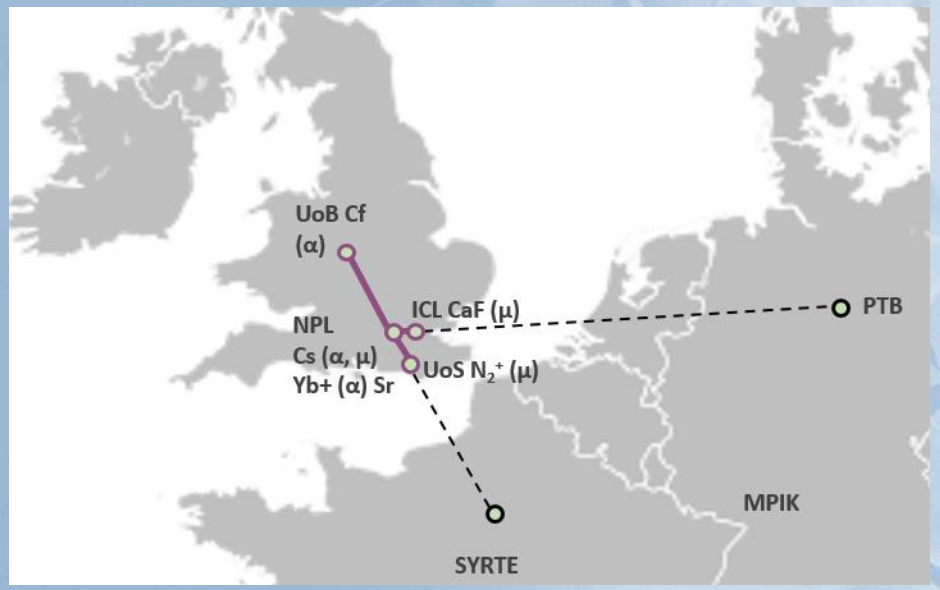
- **Fine structure constant α → Δν/ν = KΔα/α**
- **Electron to proton mass ratio μ**





Highly charged ions(HCI)

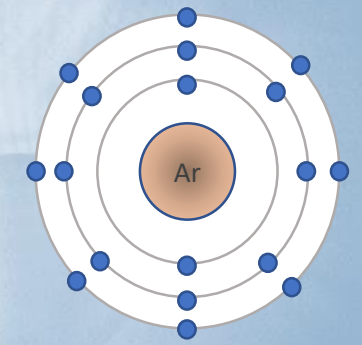
- Less sensitive to external perturbations
- Relativistic and QED effects are enhanced



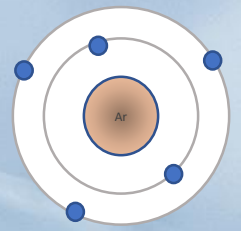
Clock	K_α	K_μ
Yb^+ (467nm)	-5.95	0
Sr (698 nm)	0.06	0
Cs (32.6 nm)	2.83	1
CaF (17 μm)	0	0.5
N_2^+ (2.31 μm)	0	0.5
Cf^{15+} (618 nm)	47	0
Cf^{17+} (485 nm)	-43.5	0

Barontini et al.

An example: Neutral Ar



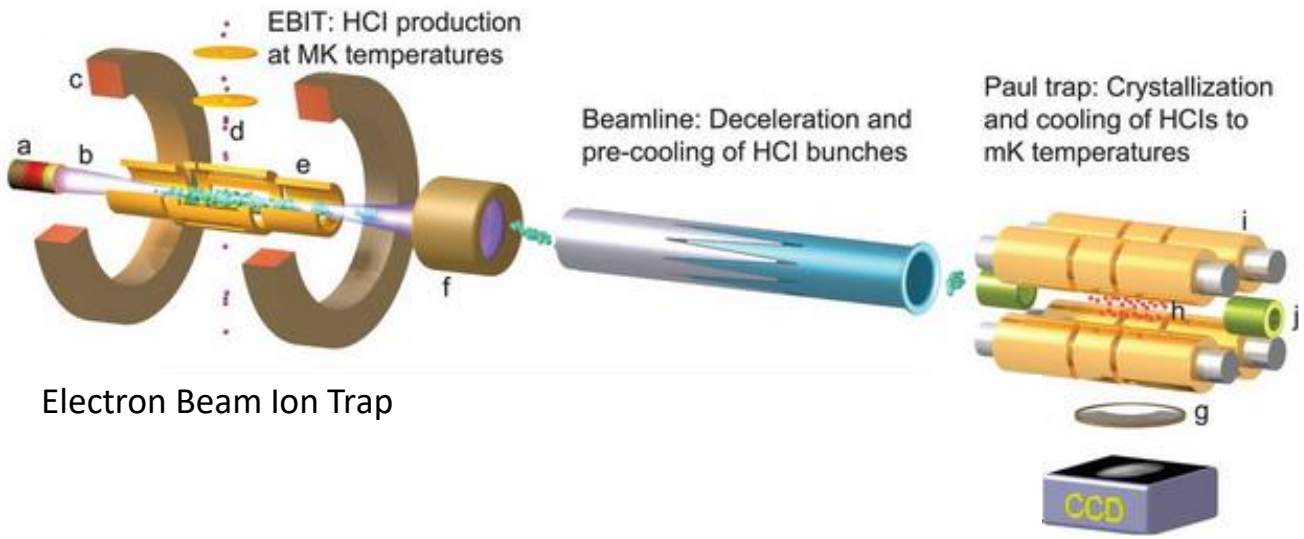
Strip e^-



Highly charged Ar

https://www.toptica-eagleyard.com/ey-application-post/atomic-clock/?_application=atomic-clock

STEPS INVOLVED

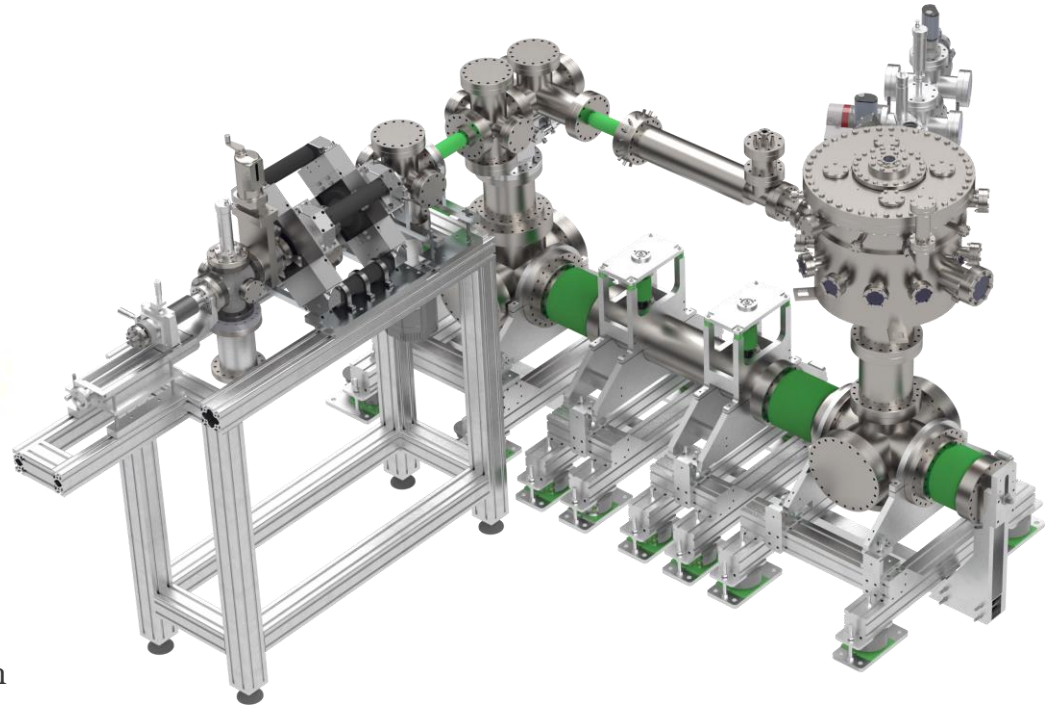


Electron Beam Ion Trap

Step 1: Heidelberg

Step 2: Heidelberg

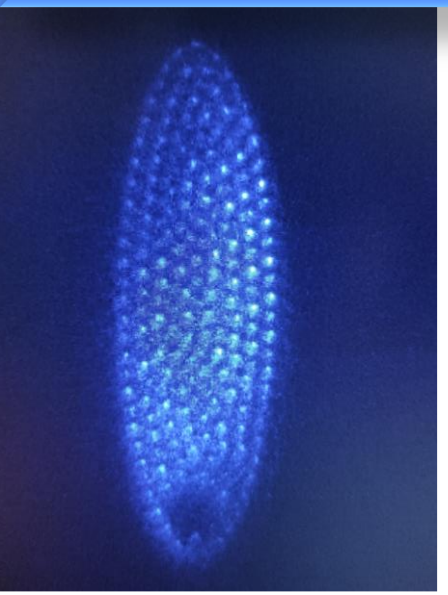
Step 3: Birmingham

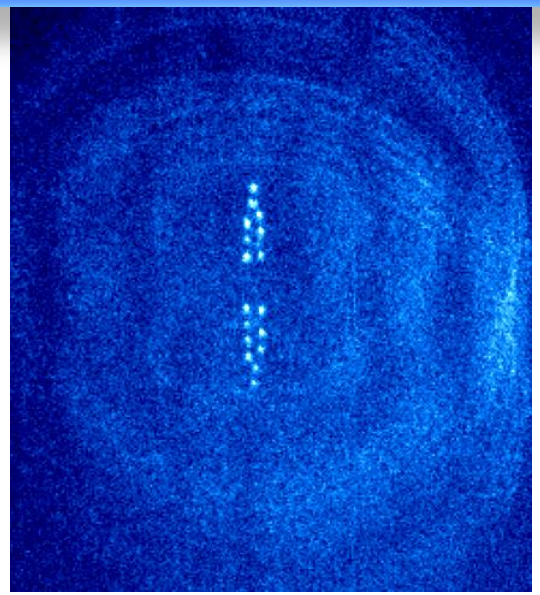


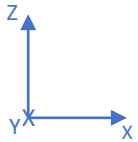
DOI: 10.1126/science.aaa2960

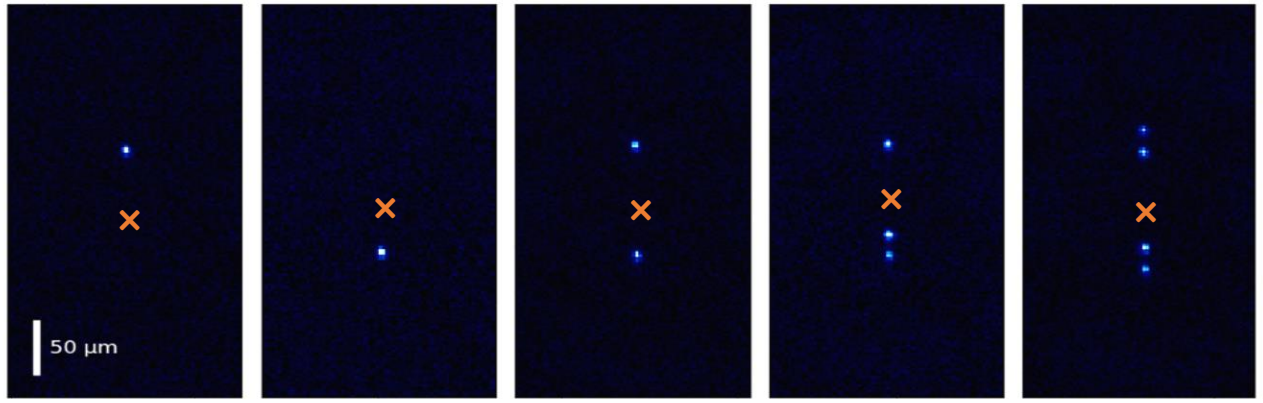
Credits: Julian Stark

Be IONS WITH 1 HIGHLY CHARGED Ar









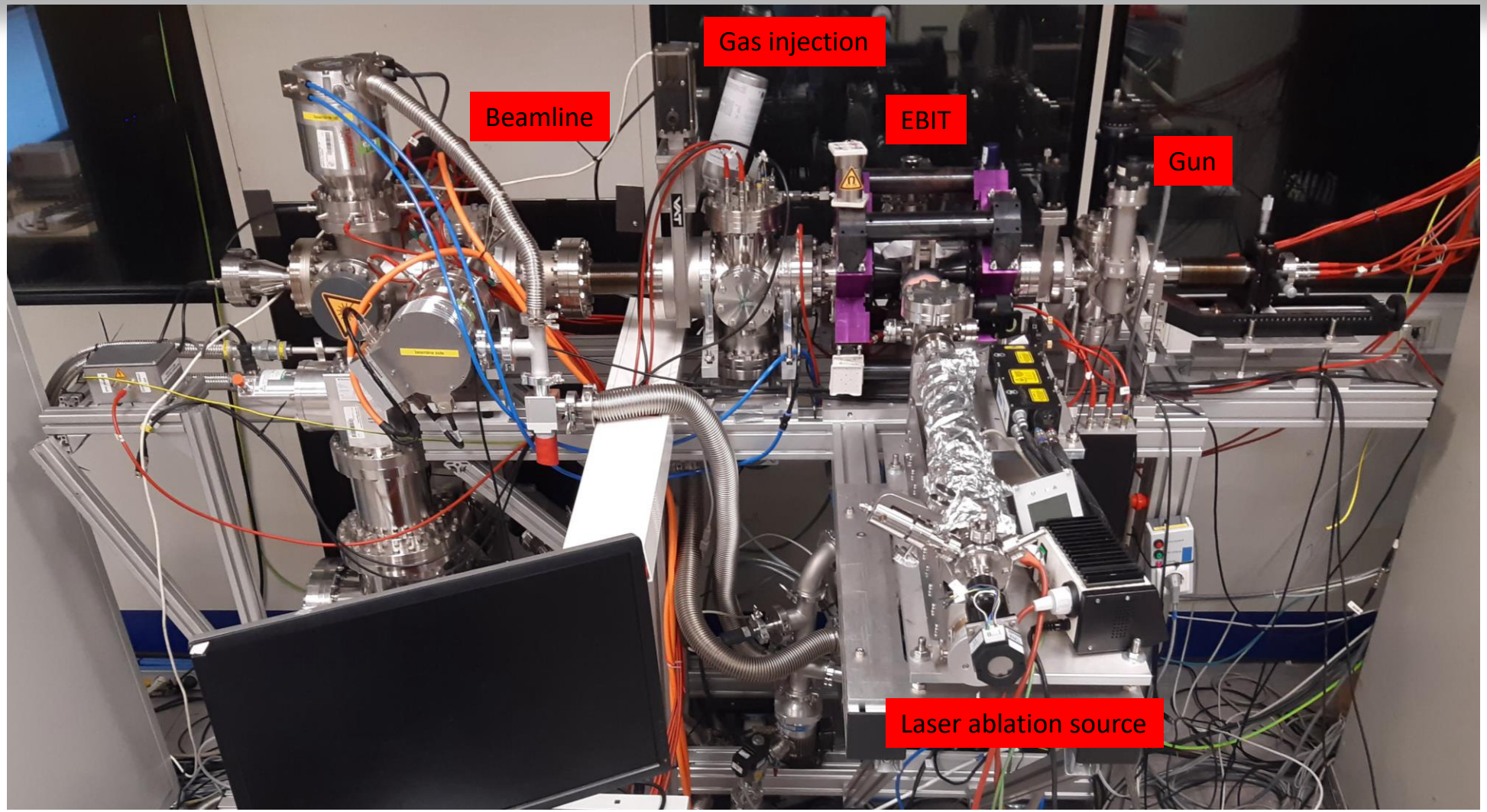
HCI ions implanted in a Coulomb crystal

- Sympathetic cooling with the crystal ions (eg $^{9}Be^{+}$)
- Clock-based experiments with highly charged ions
- Also possible: Quantum Logic Spectroscopy (QLS) using the co-trapped ions

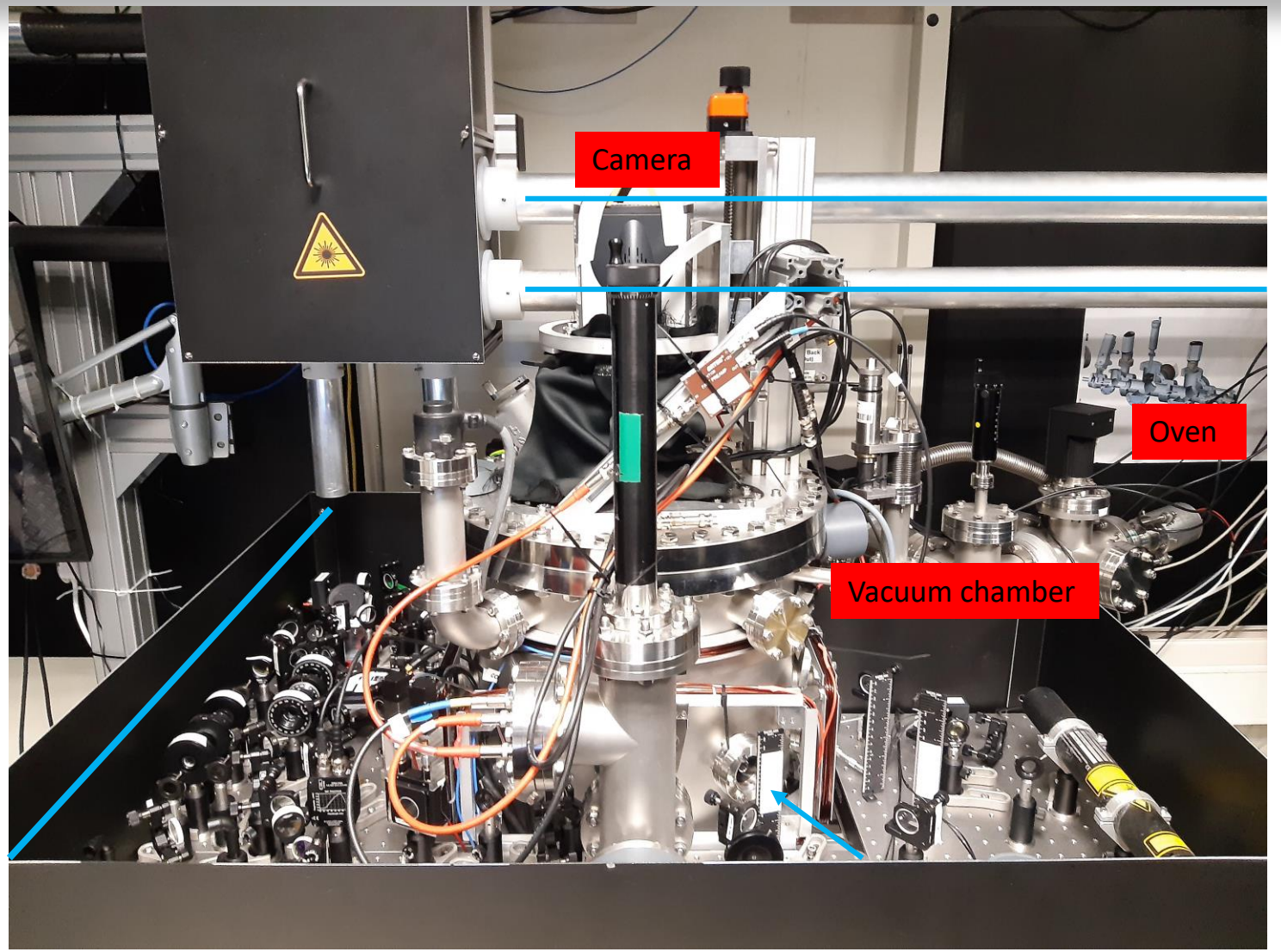
Sympathetic Resolved-Sideband Cooling

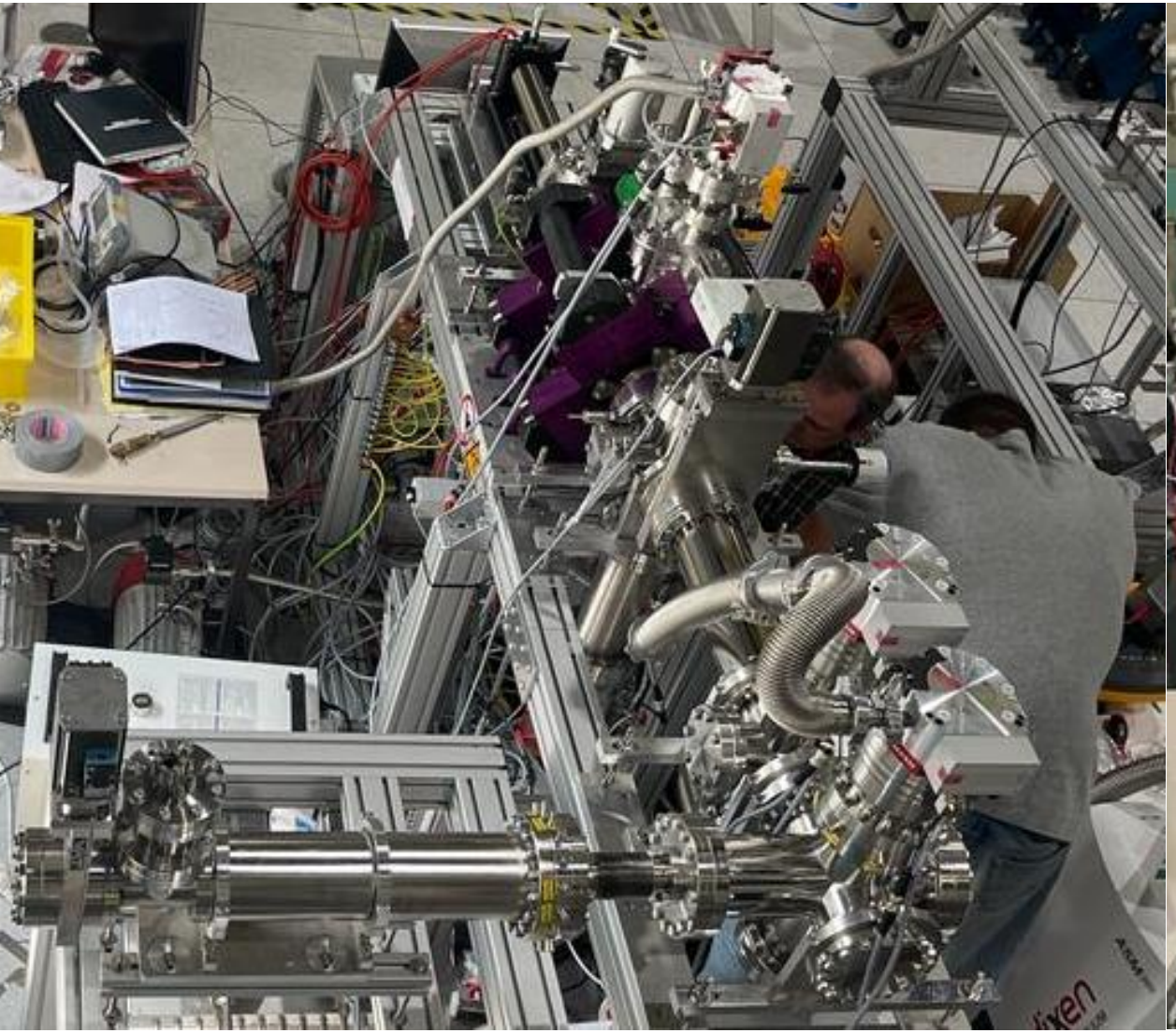
a. Laser-cooled Coulomb crystal of fluorescing $^{9}Be^{+}$ ions in the Paul trap
b. Single Ar^{+13} ion is injected, sympathetically cooled, and co-crystallized with $^{9}Be^{+}$
c. Excess $^{9}Be^{+}$ ions removed by modulating the Paul trap radio-frequency potential
d. Ar^{+13} – $^{9}Be^{+}$ two-ion crystal prepared

EBIT AND BEAMLINE



CRYOGENIC PAUL TRAP

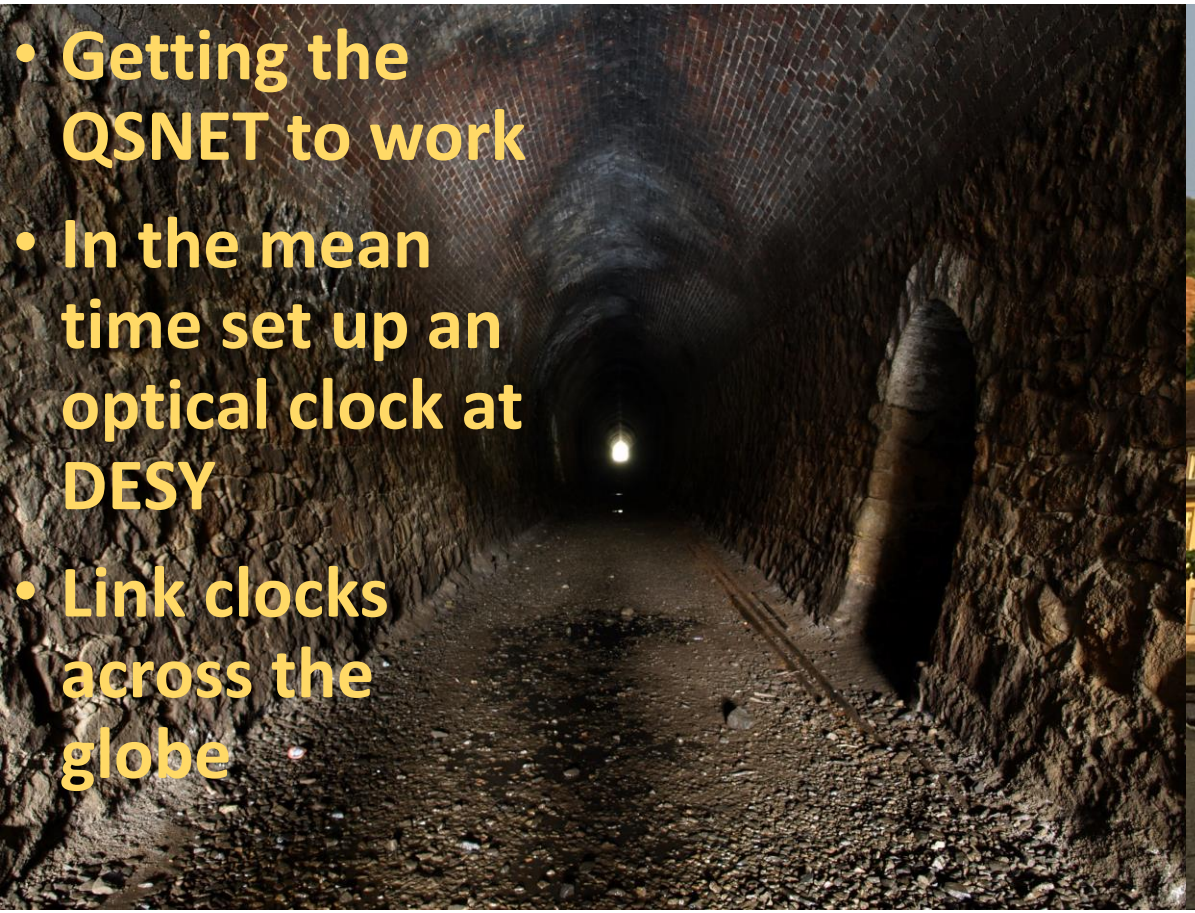




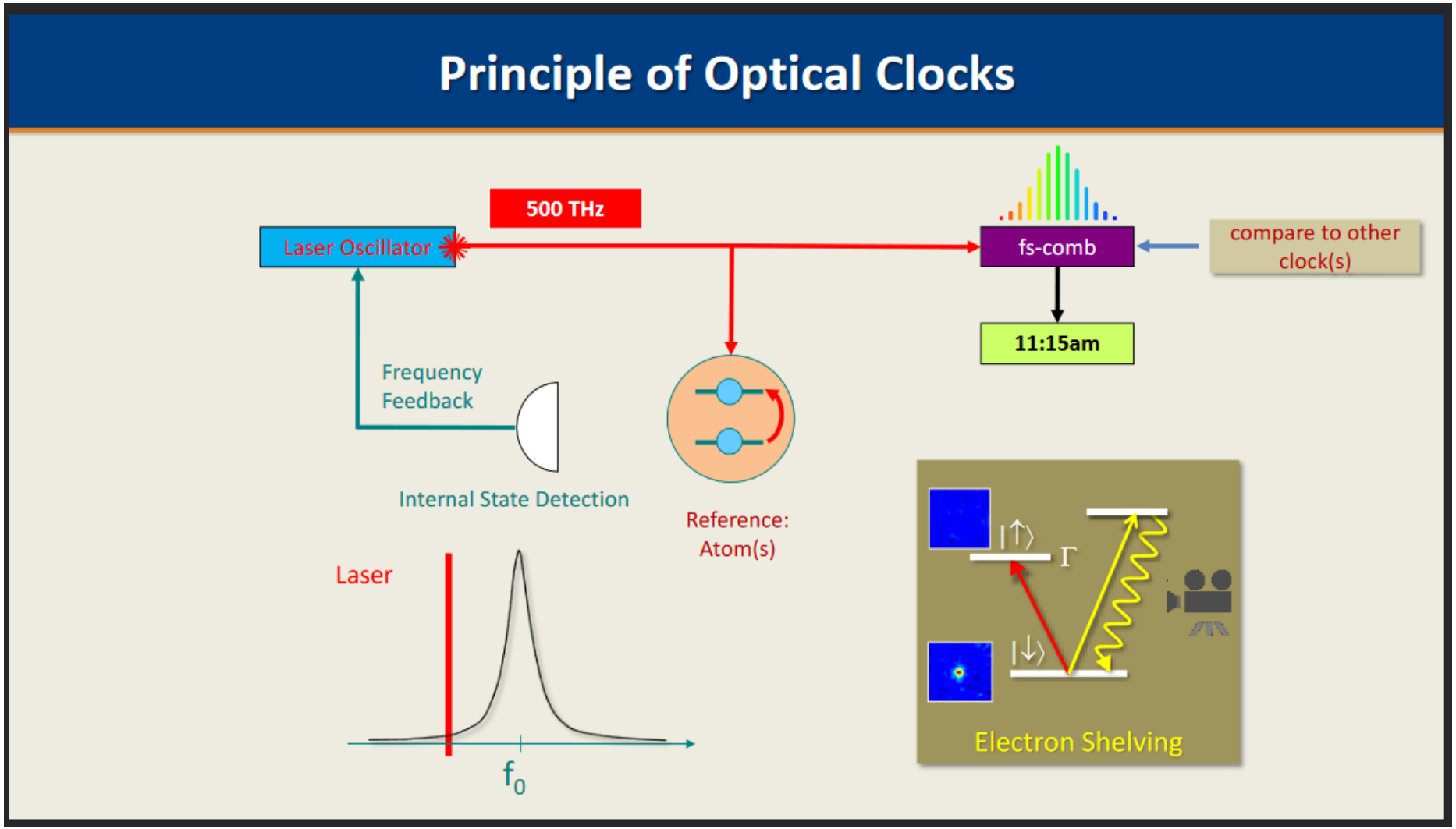
EBIT safely arrived at Birmingham !

Outlook

- Getting the QSNET to work
- In the mean time set up an optical clock at DESY
- Link clocks across the globe



https://commons.wikimedia.org/wiki/File:Swan_View_Tunnel_long_exposure.jpg



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