Highly-charged Ion Atomic Clock and Ultra-light Dark Matter

Quantum Sensors for Fundamental Physics, and Plans for the Future

Steven Worm
DESY Zeuthen and Humboldt-Universität zu Berlin

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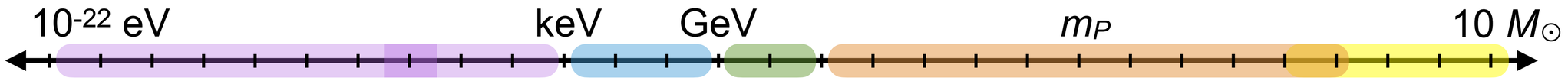
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY.

Particle Physics Example: Mass Scales for Dark Matter

Quantum Sensing needed for Light/Ultralight Dark Matter



Light and Ultra-light Dark Matter
Axions, ALPs
Quantum Sensing

Composite Dark Matter
WIMPzillas, Q-balls, bound states
CMB, Cosmic Rays

probably not below:
de Broglie wavelength too long

Standard Model Particle Scale
Weakly Interacting Massive Particles
Collider Searches

Superheavy Dark Matter
Primordial Black Holes
Gravitational Lensing

Example: Light Bosonic Dark Matter Couplings

Bosons

Scalar (Spin = 0)
Axions and other Goldstone Bosons

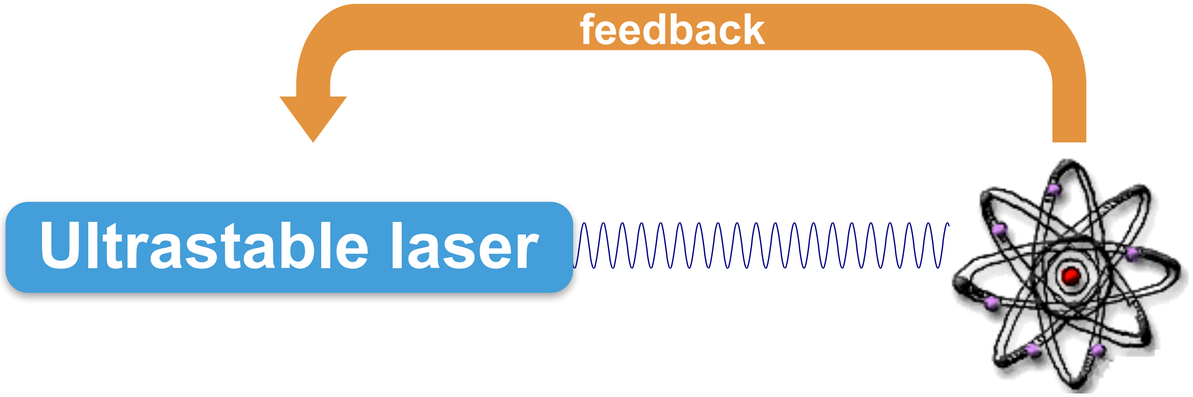
Pseudoscalar (Spin = 1)
Investigate anomaly-free couplings

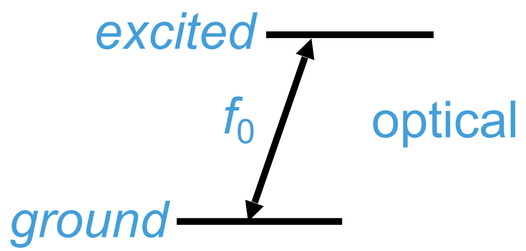
Electro-magnetism	Nuclear Spin	Nuclear Force	Electro-magnetism	Nuclear Spin	Nuclear Current
$\left(\frac{a}{f_a}F\tilde{F}\right)$ $\left(\sim \frac{a}{f_a}\vec{E}.\vec{B}\right)$	$\left(\frac{\partial_\mu a}{f_a}\bar{N}\gamma^\mu\gamma_5 N\right)$	$\left(\frac{a}{f_a}G\tilde{G}\right)$	$\left(\epsilon F' F\right)$	$\left(\frac{F'_{\mu\nu}}{f_a}\bar{N}\sigma^{\mu\nu}N\right)$	$\left(gA'_\mu J^\mu_{B-L}\right)$
	General Axions	QCD Axions	Kinetic Mixing	Dipole Moment	B-L

- New boson fields for Dark Matter can change fixed, fundamental constants into dynamic variables
- For example: α = fine structure constant, and μ = proton to electron mass ratio, no longer constants

Search for Dark Matter by looking for spatial and temporal violations of α, μ

Optical Atomic Clocks





$$\alpha = \frac{1}{4\pi\varepsilon_0}\frac{e^2}{\hbar c}$$

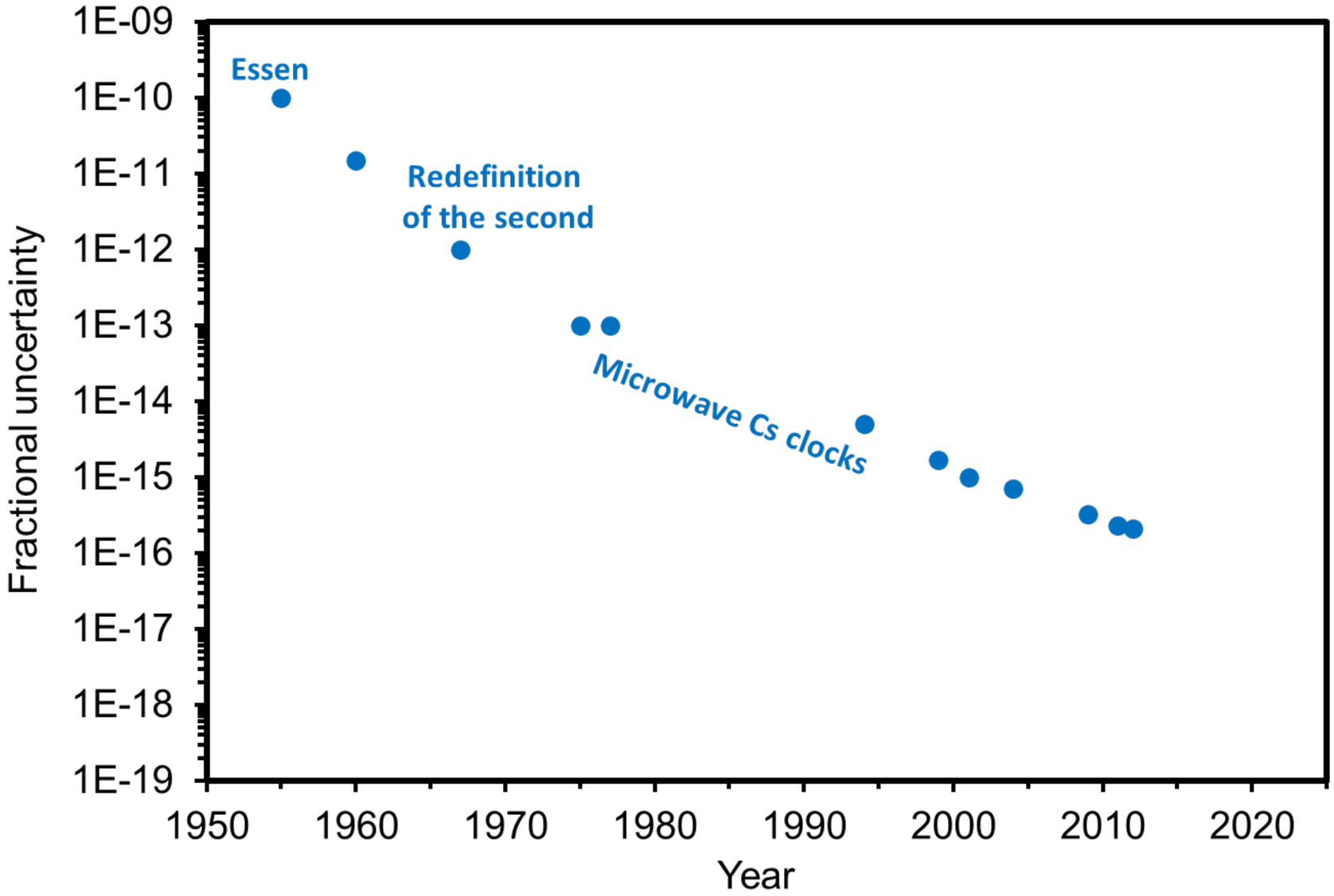
$$\mu = \frac{m_p}{m_e}$$

Electron transition frequency stabilisation for timekeeping element

- Recent (2000) innovation of using high-frequency mode-locked laser for optical transitions
- Stabilisation technique led to Nobel Prize in Physics for Hall and Hänsch in 2005

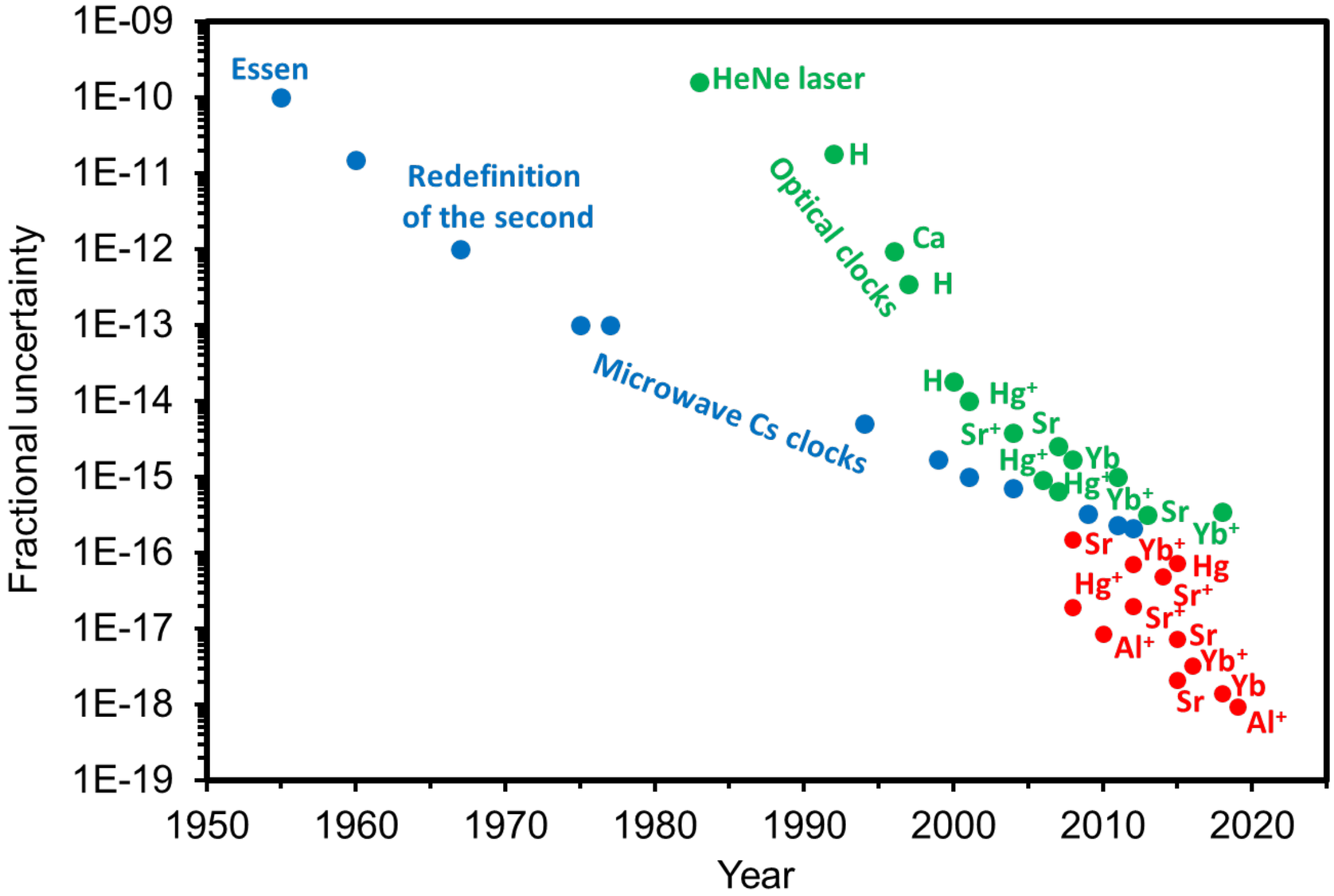
***Ultra-sensitive**, e.g. to Dark Matter variations in fine structure constant α or proton/electron mass ratio μ*

Accuracy of Atomic Clocks: Microwave



[Godon]

Accuracy of Atomic Clocks: Optical



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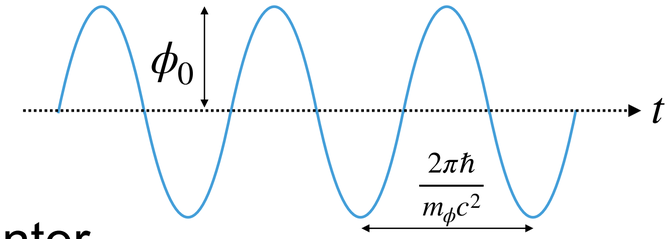
Ultra-Light Dark Matter: Phenomenology



- Starting with Standard Model Lagrangian, adding new DM field
- **Bosonic:** Ultra-light DM must be bosonic in nature
- **Non-relativistic** ($\sim 10^{-3}c$): so it neither leaves the galaxy or clumps near the center
- **Oscillating classical field:** coherent, practically monochromatic → wave-like

$$\phi(t) \approx \phi_0 \cos(m_\phi c^2 t/\hbar)$$

$$\mathscr{L} = \frac{4\pi\phi}{M_{pl}}\left(\frac{d_e}{4e^2}F_{\mu\nu}F^{\mu\nu} - d_{m_e}m_e\bar{e}e - \frac{d_g\beta_3}{2g_3}G^A_{\mu\nu}G^{A\mu\nu} - \sum_{i=u,d}(d_{m_i}+\gamma_{m_i}d_g)m_i\bar{\psi}_i\psi_i\right)$$

- Coupling to Lagrangian is linear (in ϕ) for lowest order interaction w/ scalar field (or quadratic with $\phi \to -\phi$ symmetry)

$$\mathscr{L} = \frac{\phi}{\Lambda_\gamma}\frac{F_{\mu\nu}F^{\mu\nu}}{4} - \frac{\phi}{\Lambda_e}m_e\bar{\psi}\psi \qquad \mathscr{L} = \frac{\phi^2}{(\Lambda'_\gamma)^2}\frac{F_{\mu\nu}F^{\mu\nu}}{4} - \frac{\phi^2}{(\Lambda'_e)^2}m_e\bar{\psi}\psi$$

- At the effective new physics energy scales Λ_α and Λ_e, α and m_e appear to **oscillate**

$$\frac{d\alpha}{\alpha} \approx \frac{\phi_0\cos(m_\phi t)}{\Lambda_\gamma}, \quad \frac{dm_e}{m_e} \approx \frac{\phi_0\cos(m_\phi t)}{\Lambda_e} \qquad \frac{d\alpha}{\alpha} \approx \frac{\phi_0^2\cos^2(m_\phi t)}{(\Lambda'_\gamma)^2}, \quad \frac{dm_e}{m_e} \approx \frac{\phi_0^2\cos^2(m_\phi t)}{(\Lambda'_e)^2}$$

[Phys. Rev. D 91, 015015 (2015), RMP 90, 025008 (2018)]

Clock Transitions and Sensitivities

- Atomic transition scale set by Rydberg constant $R_\infty = \alpha^2 m_e c/4\pi\hbar$, also fine structure constant α and proton-to-electron mass ratio μ

  Hyperfine transitions: $\nu_{\mathrm{hf}} = A \cdot \mu\alpha^2 F_{\mathrm{hf}}(\alpha) \cdot R_\infty$

  Optical transitions: $\nu_{\mathrm{opt}} = B \cdot F_{\mathrm{opt}}(\alpha) \cdot R_\infty$

  Vibrational transitions: $\nu_{\mathrm{vib}} = C \cdot \mu^{1/2} \cdot R_\infty$

Clock	Kα	Kμ
Yb^+ (467 nm)	-5.95	0
Sr (698 nm)	0.06	0
Cs (32.6 mm)	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

- Transitions have different sensitivities to variations in α or μ, given by K_α and K_μ
- Measure ratios of frequencies of two transitions ($R = \nu_1/\nu_2$)
- So for α and simple case of scalar field ϕ and linear coupling, ratio oscillates with frequency $f = m_\phi c^2/h$

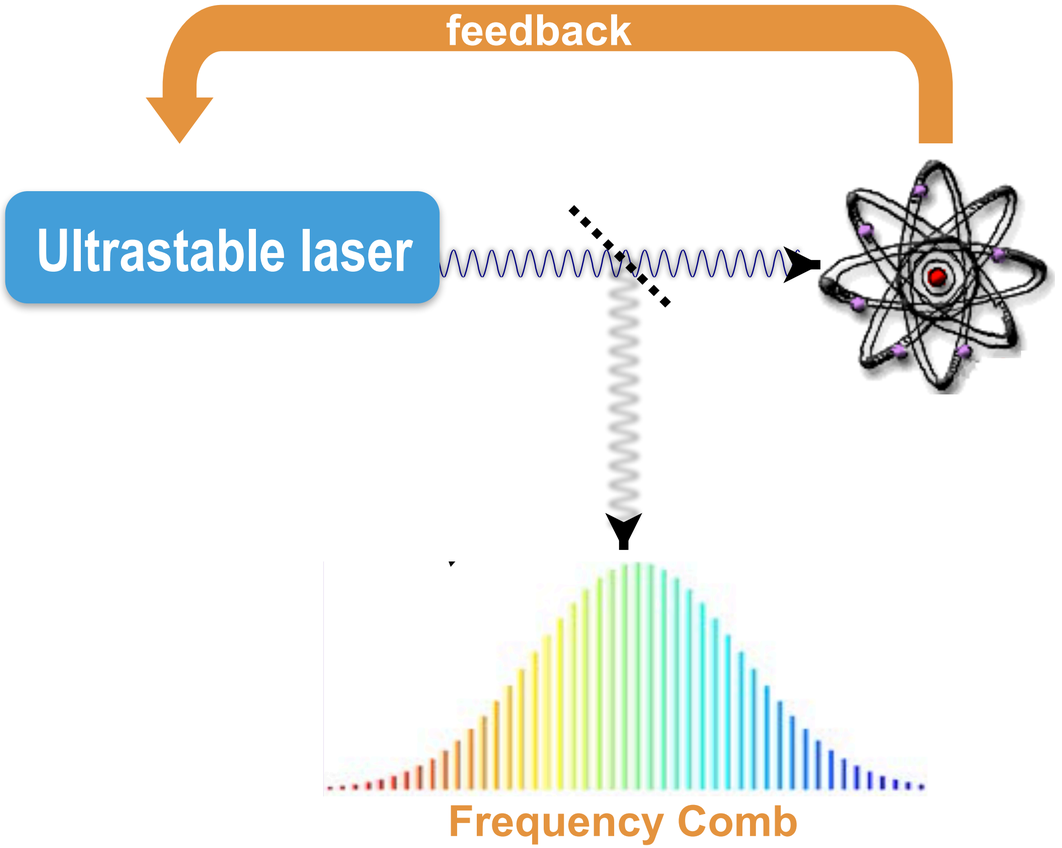
$$\frac{dR}{R} = [K_{\alpha,1} - K_{\alpha,2}]\frac{d\alpha}{\alpha}$$

$$\propto [K_{\alpha,1} - K_{\alpha,2}]\cos(2\pi f t)$$

Optical Atomic Clocks

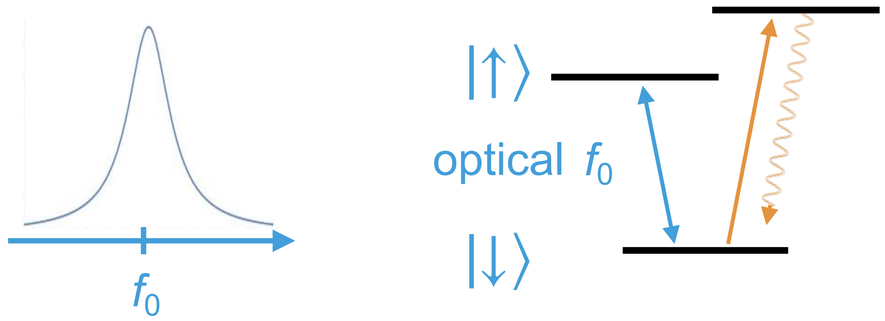
Operational Considerations

- Ultra-stable laser provides local oscillator for atomic transitions
- Feedback loop established for staying on resonance
- Frequency comb divides optical frequencies into countable microwave
- Fluorescence monitor 3-state systems (electron shelving)
- Can use laser cooling, sympathetic cooling with a second ion species (eg Be)

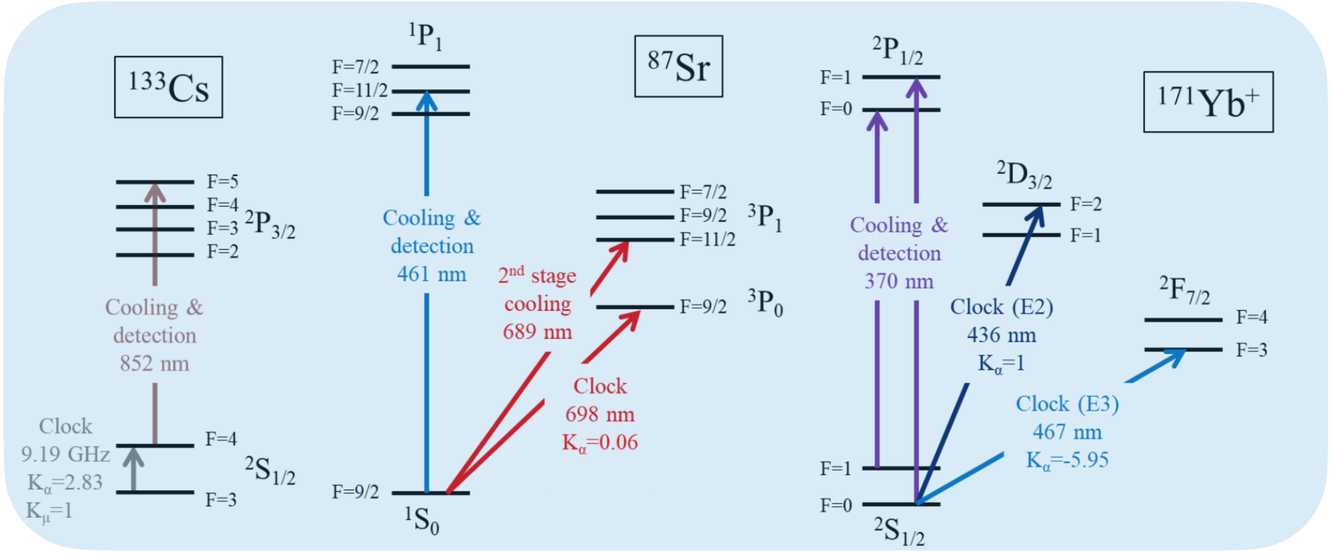


Uncertainties and Improvements

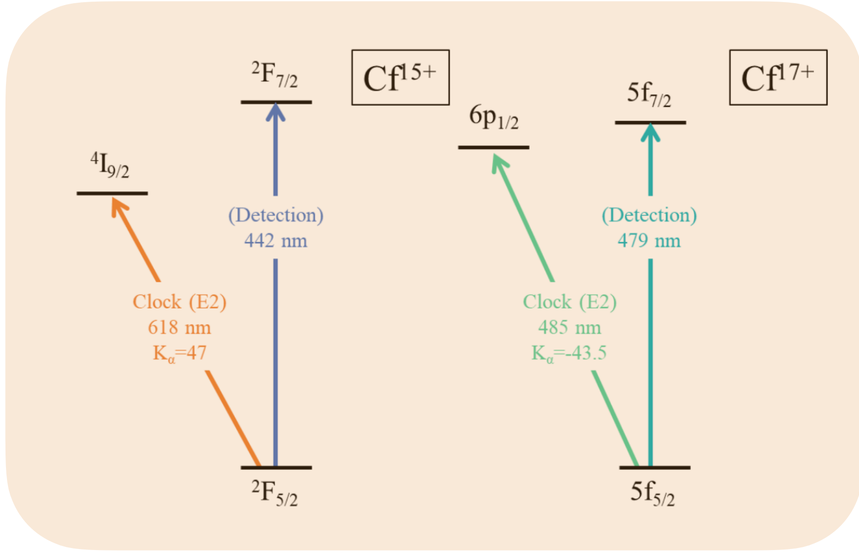
- Systematic effects: Doppler shift, collisions (vacuum), stability of magnetic/electric fields (eg trap)
- Statistical effects: optical (vs microwave) frequencies, narrow transition widths, long probe times



QSNET Clocks

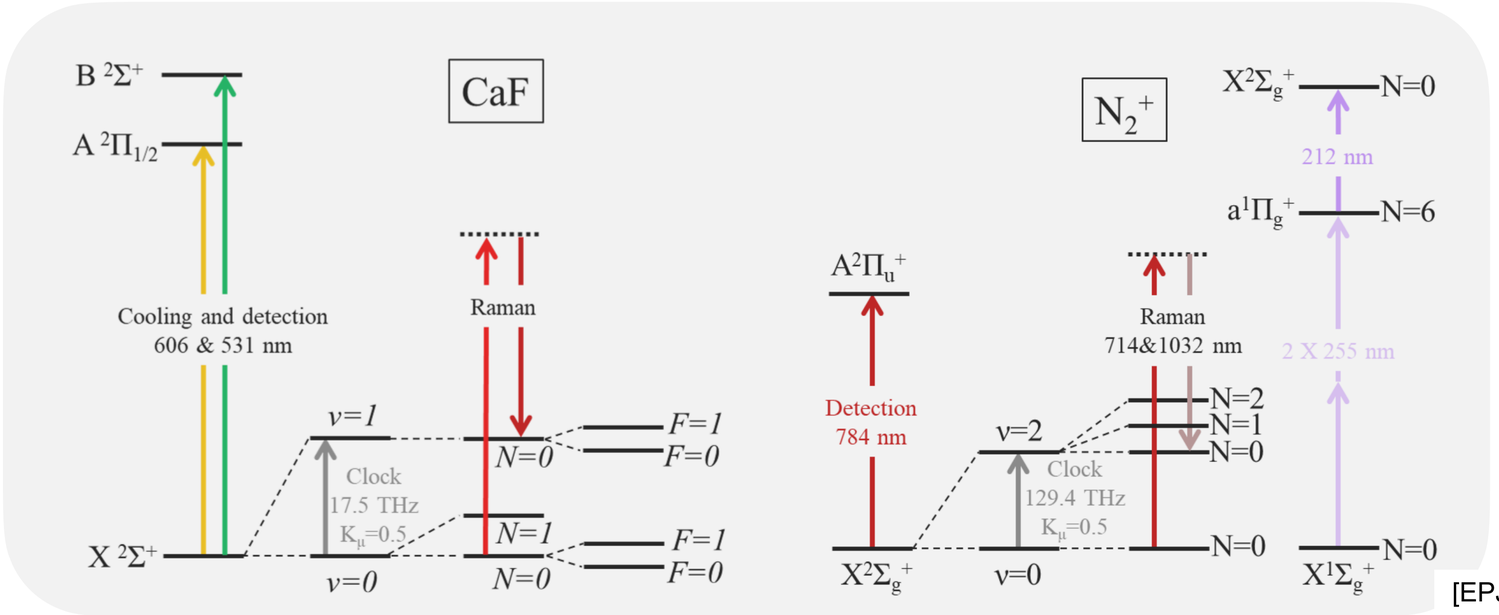


Atomic Clocks



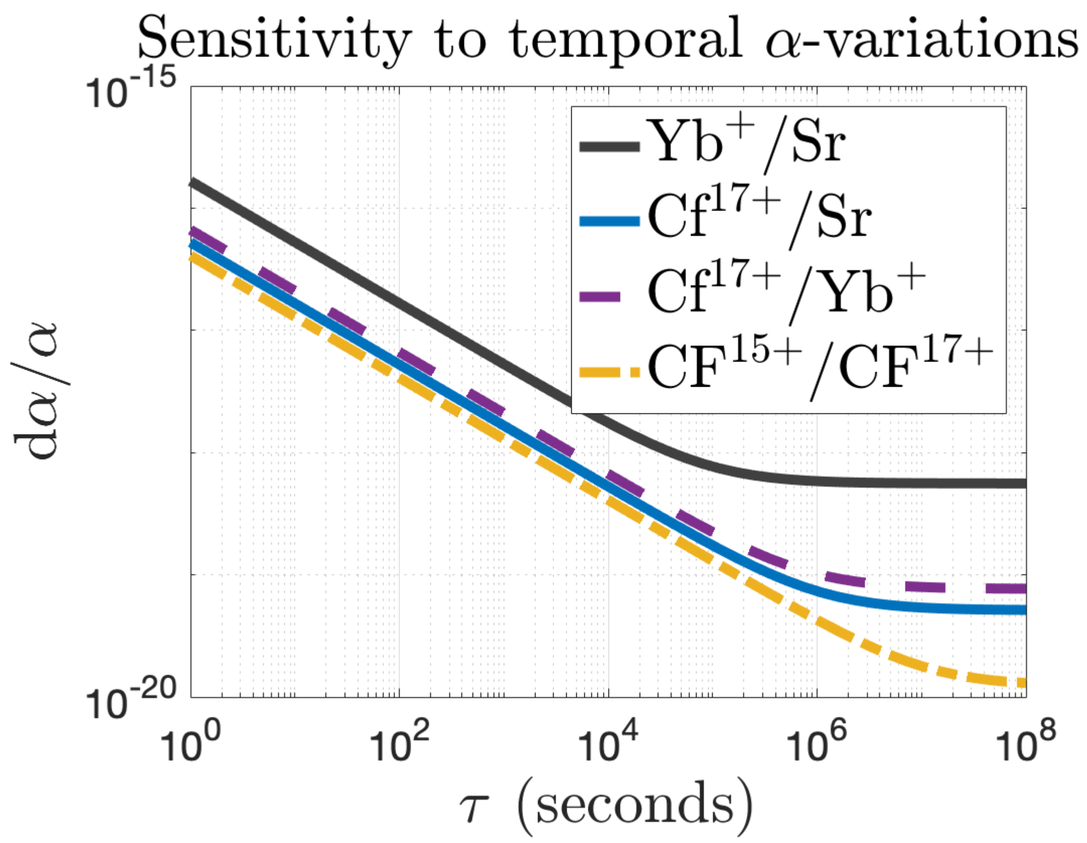
Highly Charged Ion Clock

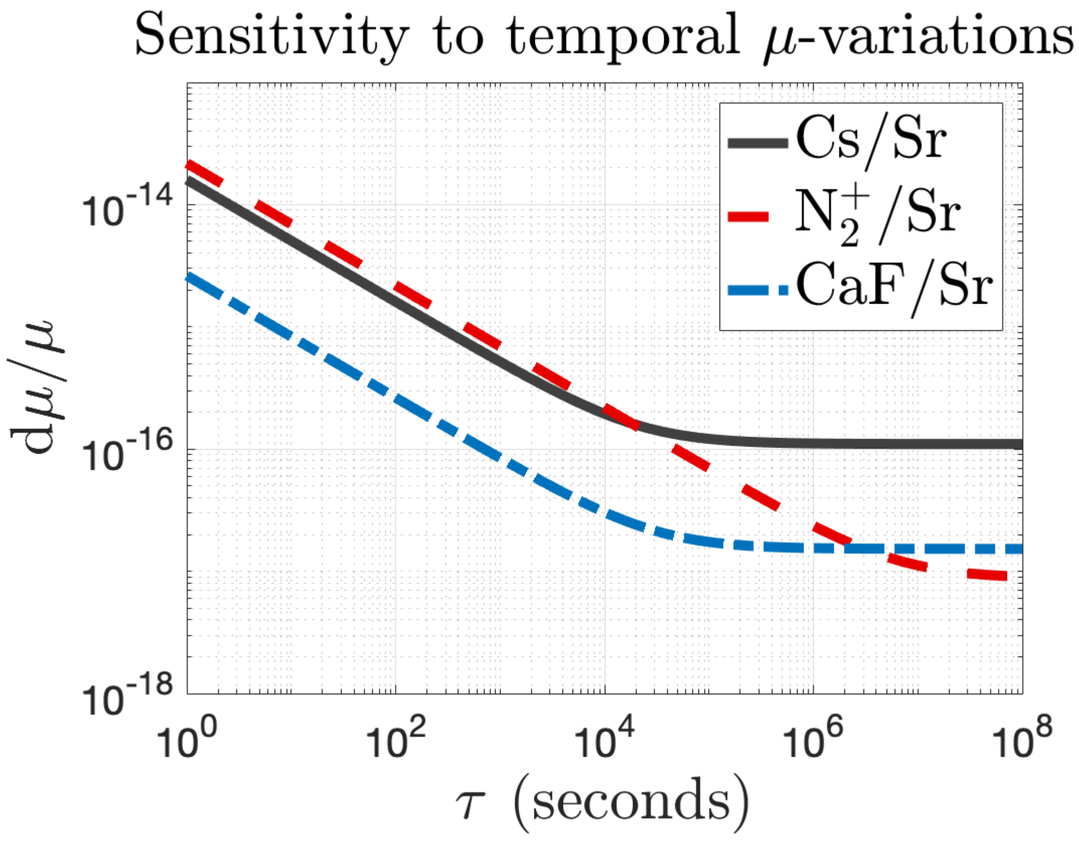
Molecular Clocks



[EPJ Quant.Technol. 9 (2022) 1,12]

Sensitivities to Temporal Variations of α, μ

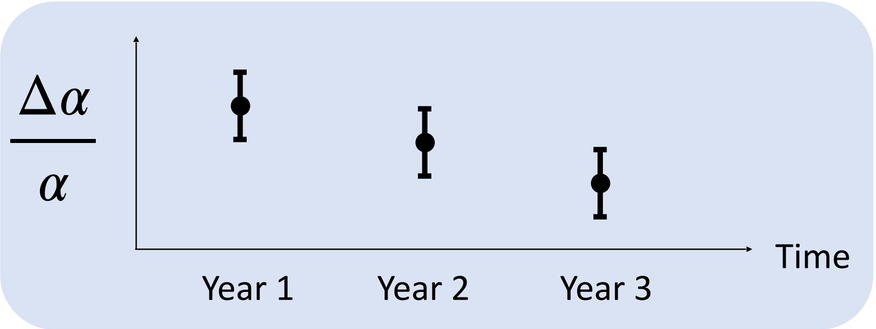




[EPJ Quant.Technol. 9 (2022) 1,12]

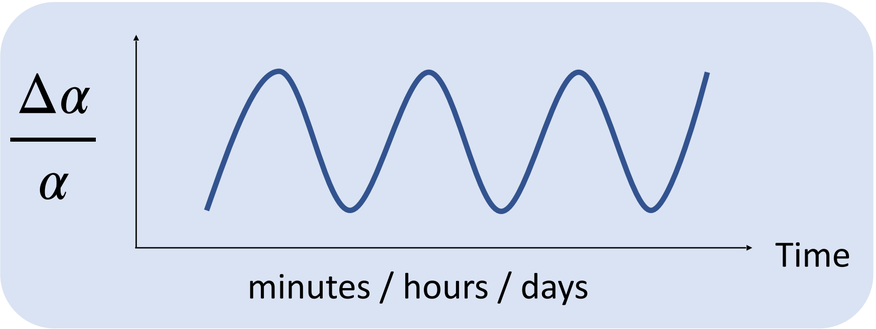
Search for Variations at Different Timescales

- Slow drifts



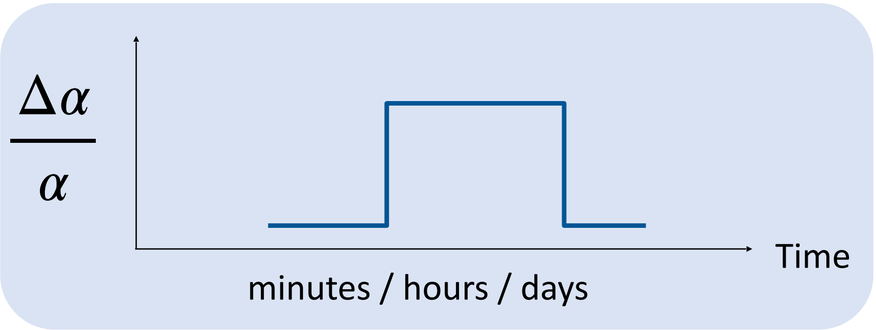
New physics

- Oscillations



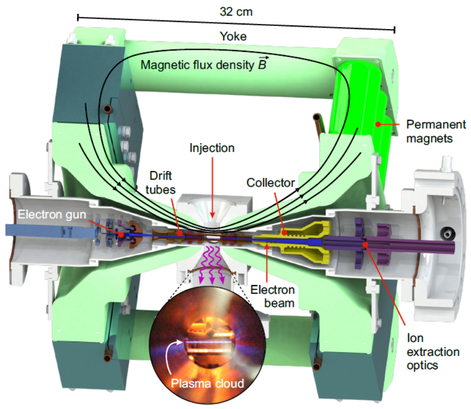
Very light dark matter

- Fast transients

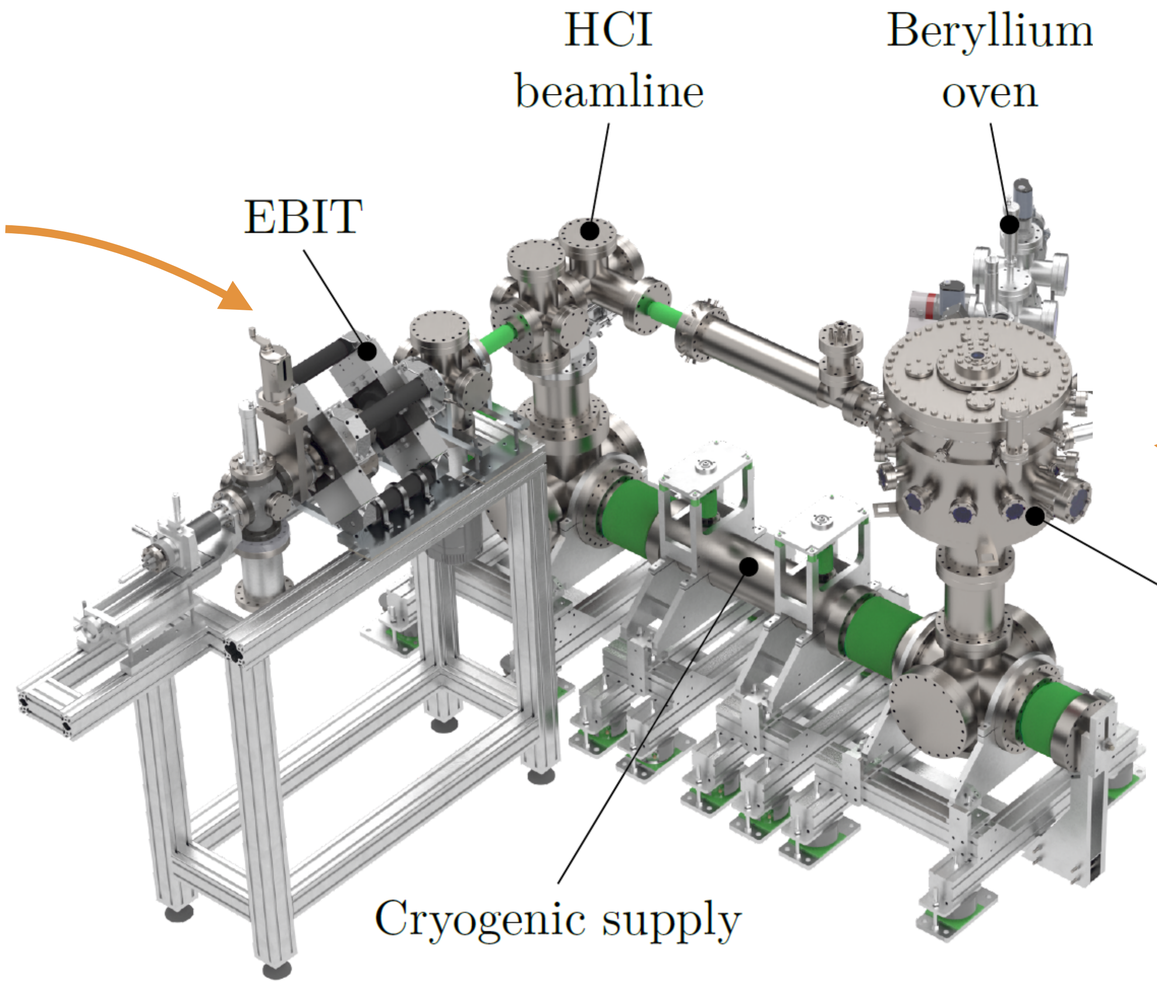


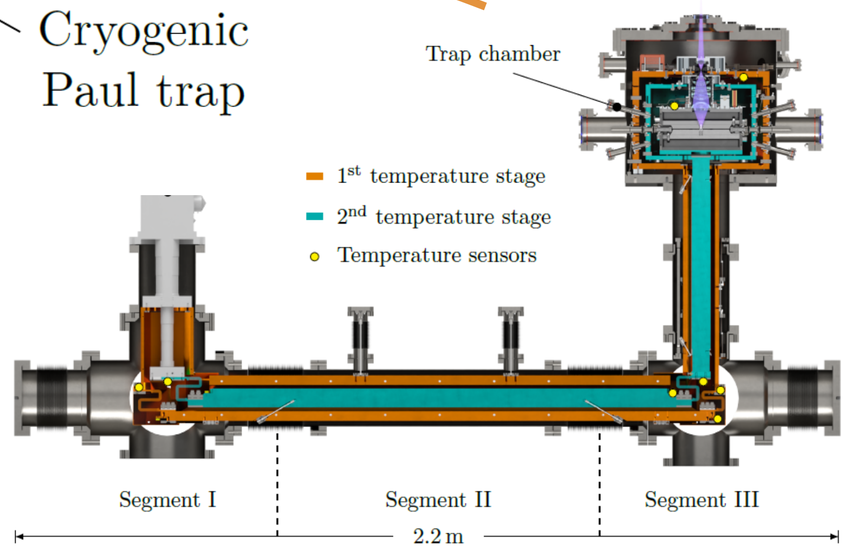
Dark matter, topological defects

Highly Charged Ions: Production, cooling and trapping



Compact EBIT @ MPIK

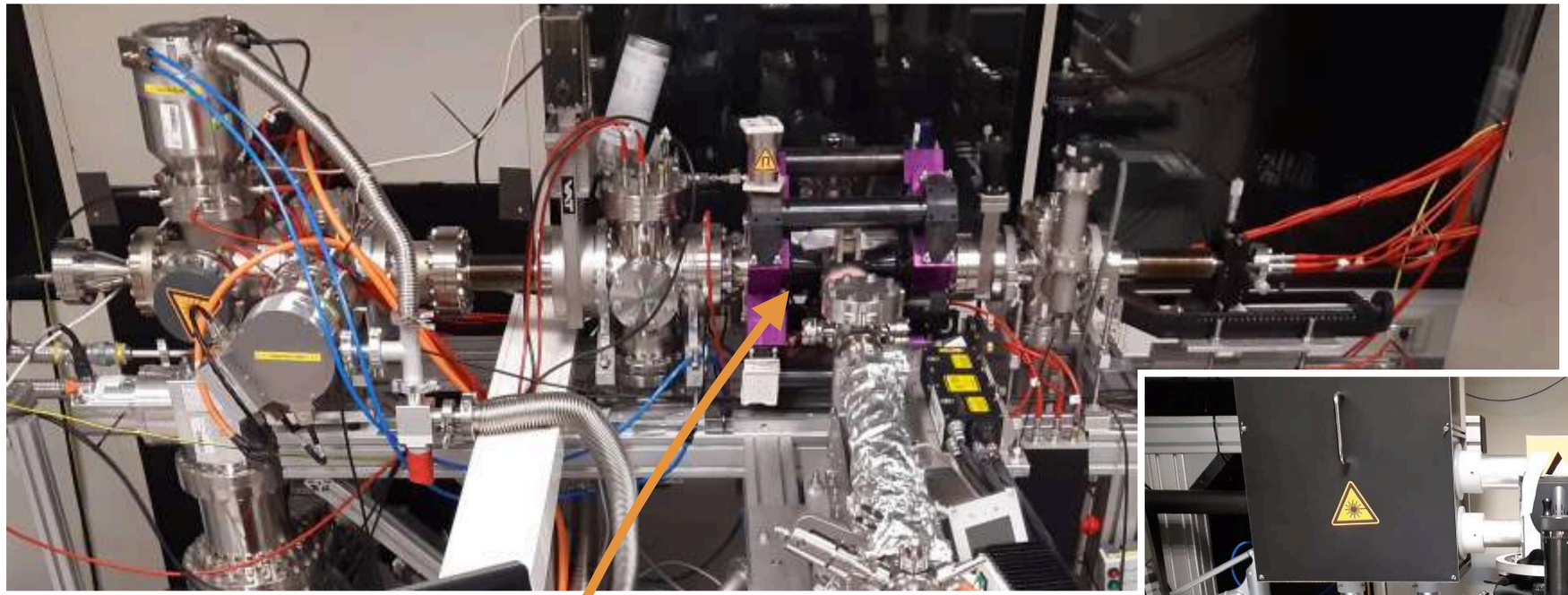




Ultra-low vibration cryogenic vacuum

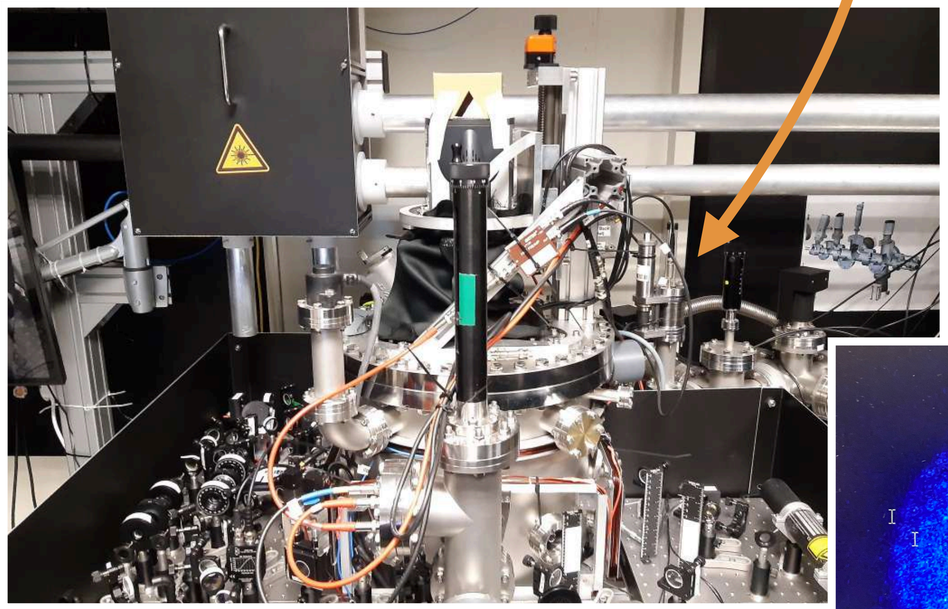
mK → μK

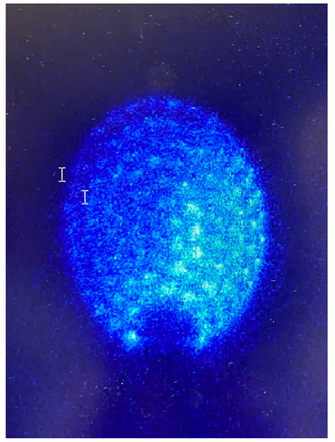
Highly Charged Ions: Production, cooling and trapping



EBIT test stand @MPIK

Paul trap w/ optics





Be crystal with highly charged ion (Ar)

[MPIK: José R. Crespo López-Urrutia]

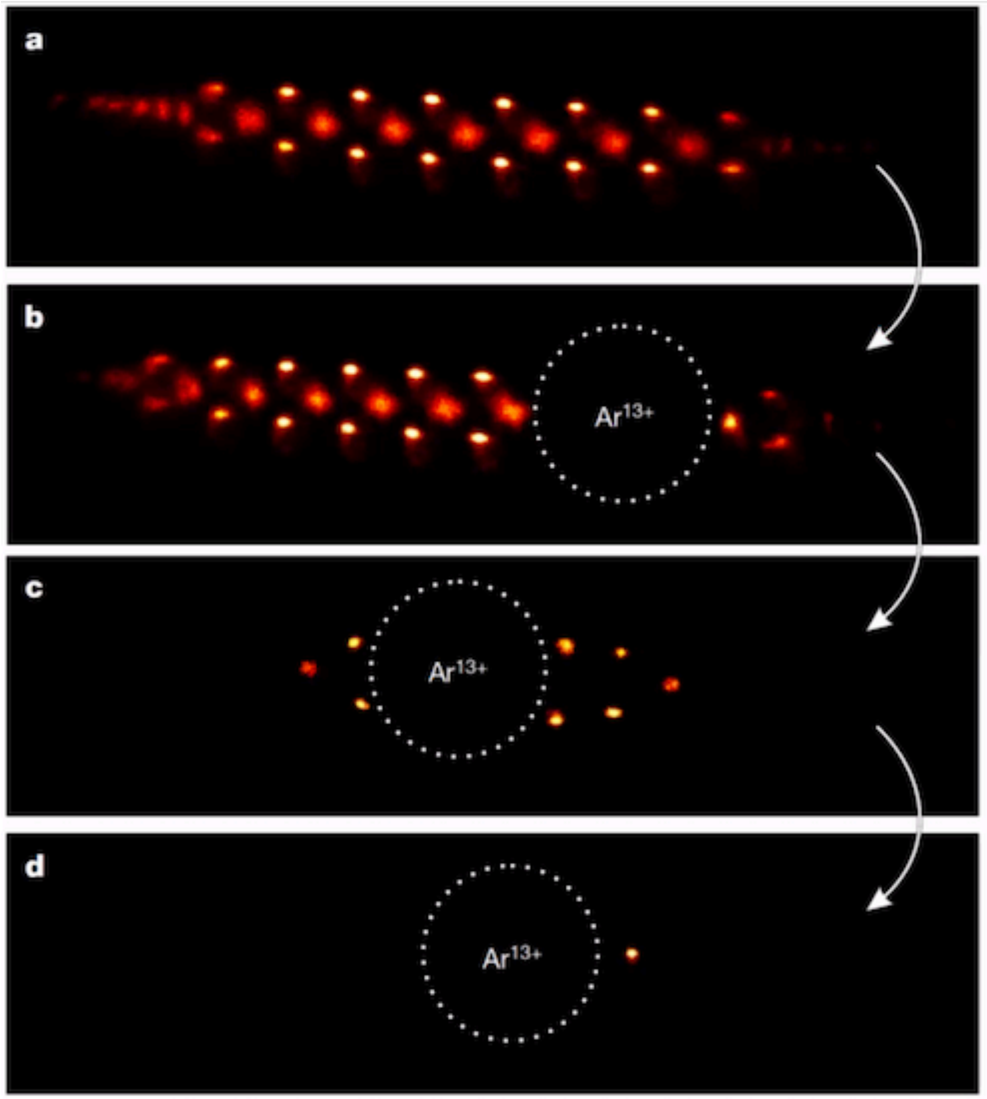
Highly Charged Ions: Production, cooling and trapping

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

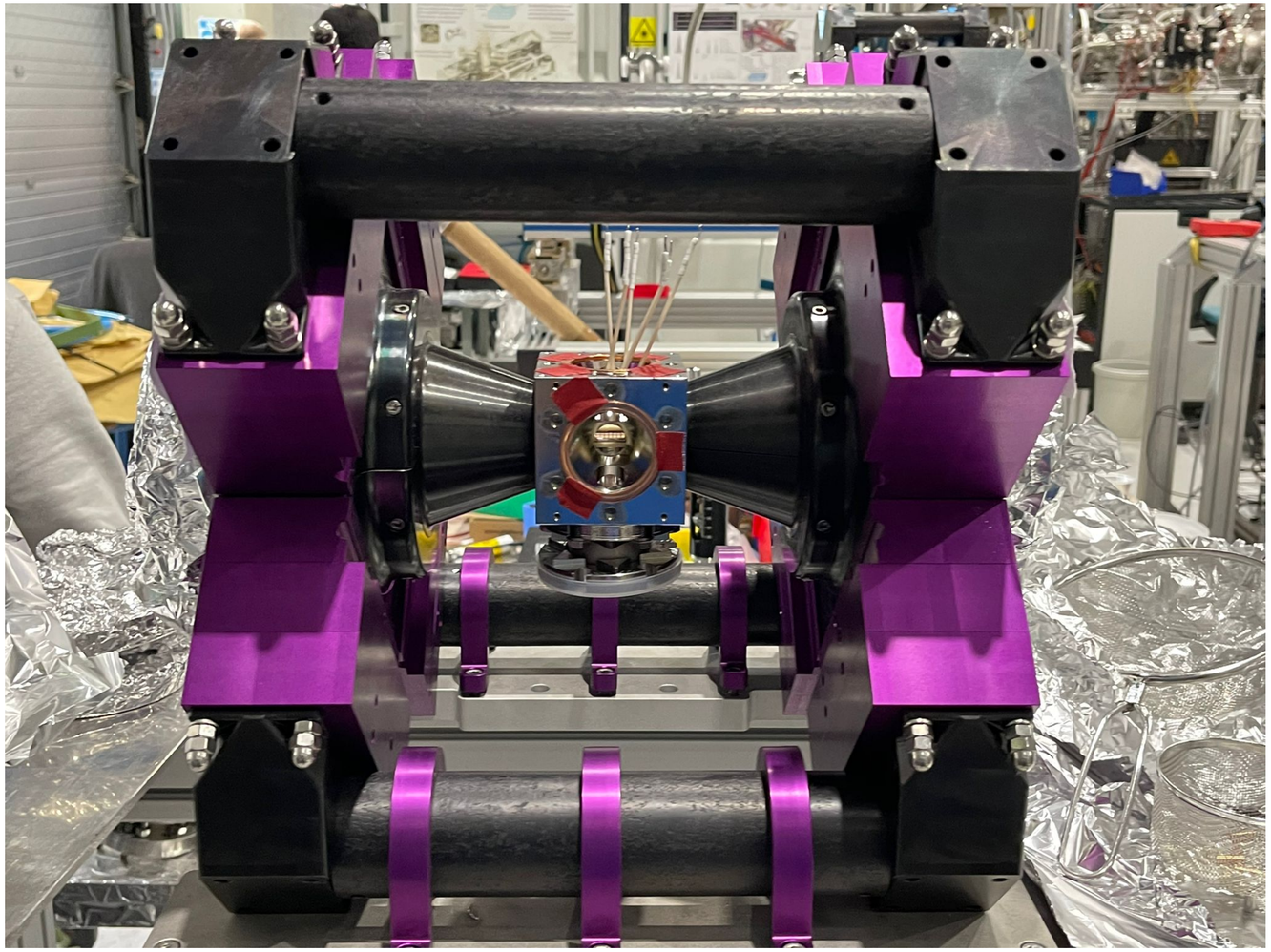
a. Laser-cooled Coulomb crystal of fluorescing $^{9}Be^{+}$ ions in the Paul trap
b. Single Ar^{+13} ion is injected, sympathetically cooled, and co-crystallized with $^{9}Be^{+}$
c. Excess $^{9}Be^{+}$ ions removed by modulating the Paul trap radio-frequency potential
d. Ar^{+13} – $^{9}Be^{+}$ two-ion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



[Science 347 (6227), 1233-1236 (2015), Nature 578 (7793), 60-65 (2020)]

Californium HCI EBIT Construction

- Drift tubes and Magnet



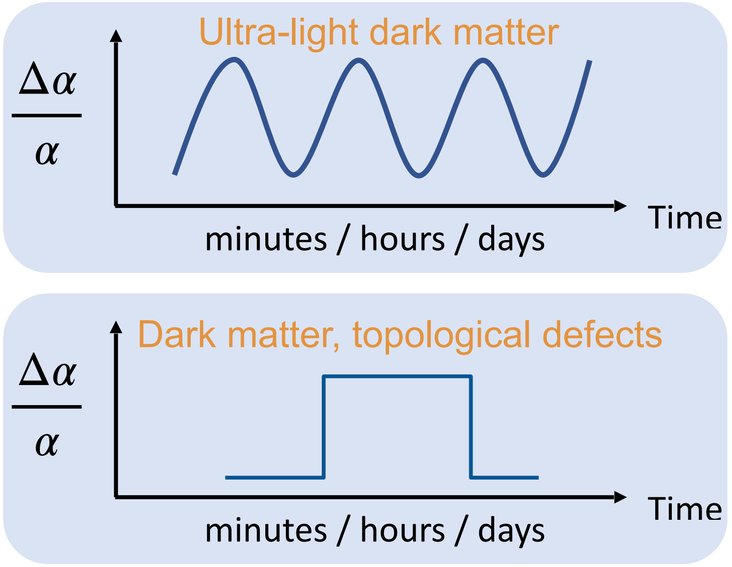
Californium HCI EBIT Construction

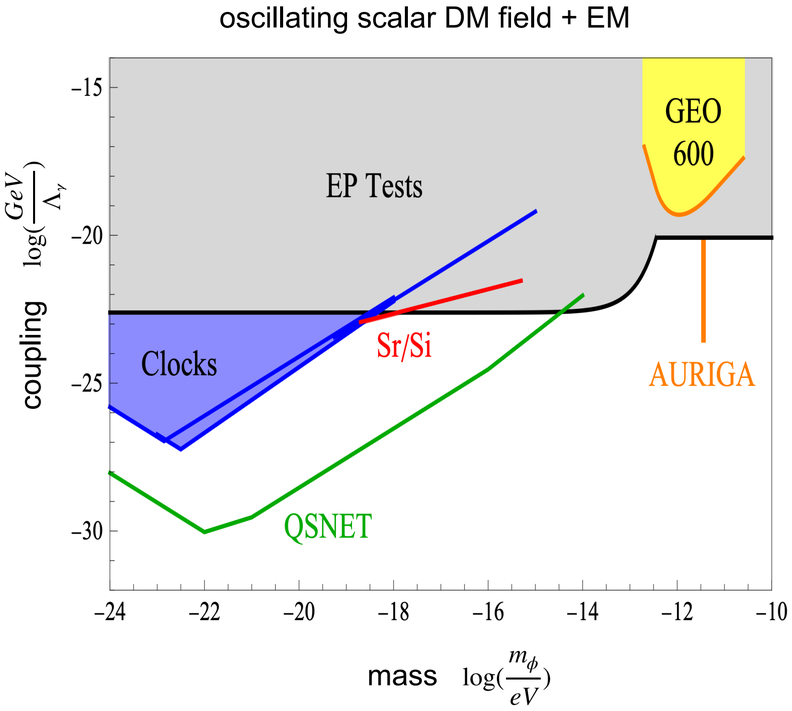
- Electron collector, turbo pump installation

Optical Clocks and Tests of Fundamental Physics

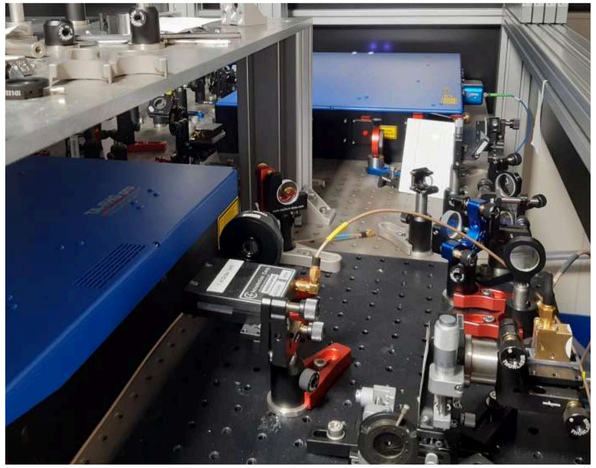
Atomic energy	Scaling
Gross structure	$\sim \alpha^2$
Fine structure	$\sim \alpha^4$
Hyperfine structure	$\sim (\alpha^4/\mu)$

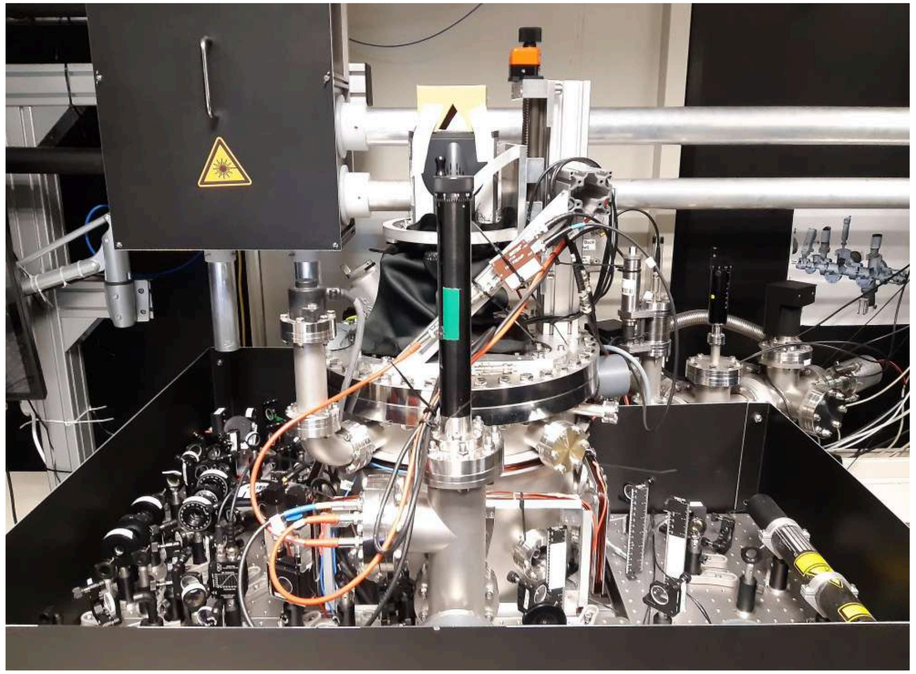
Molecular energy	Scaling
Vibrational levels	$\sim \mu$

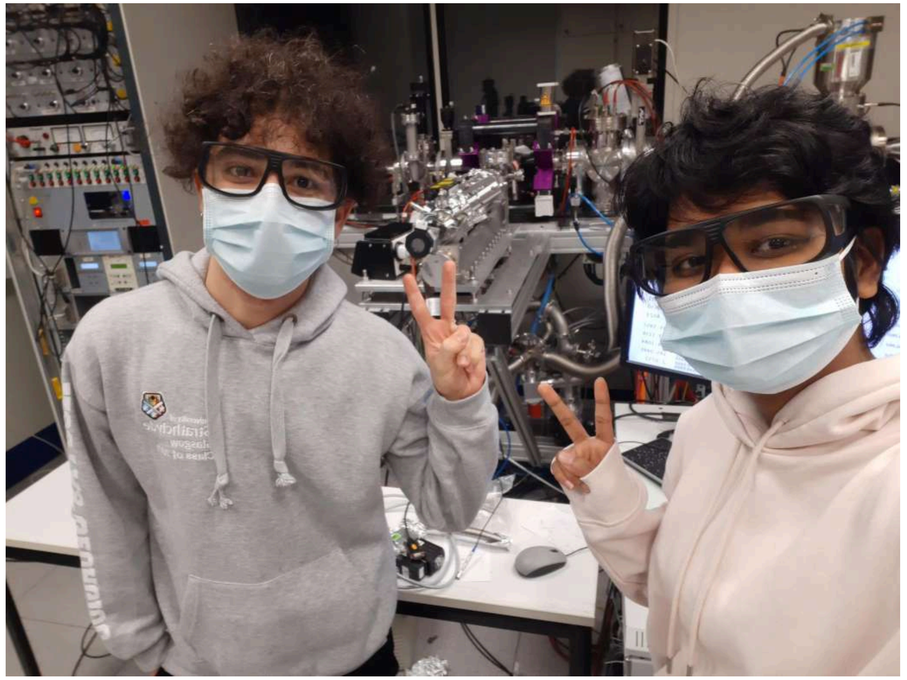


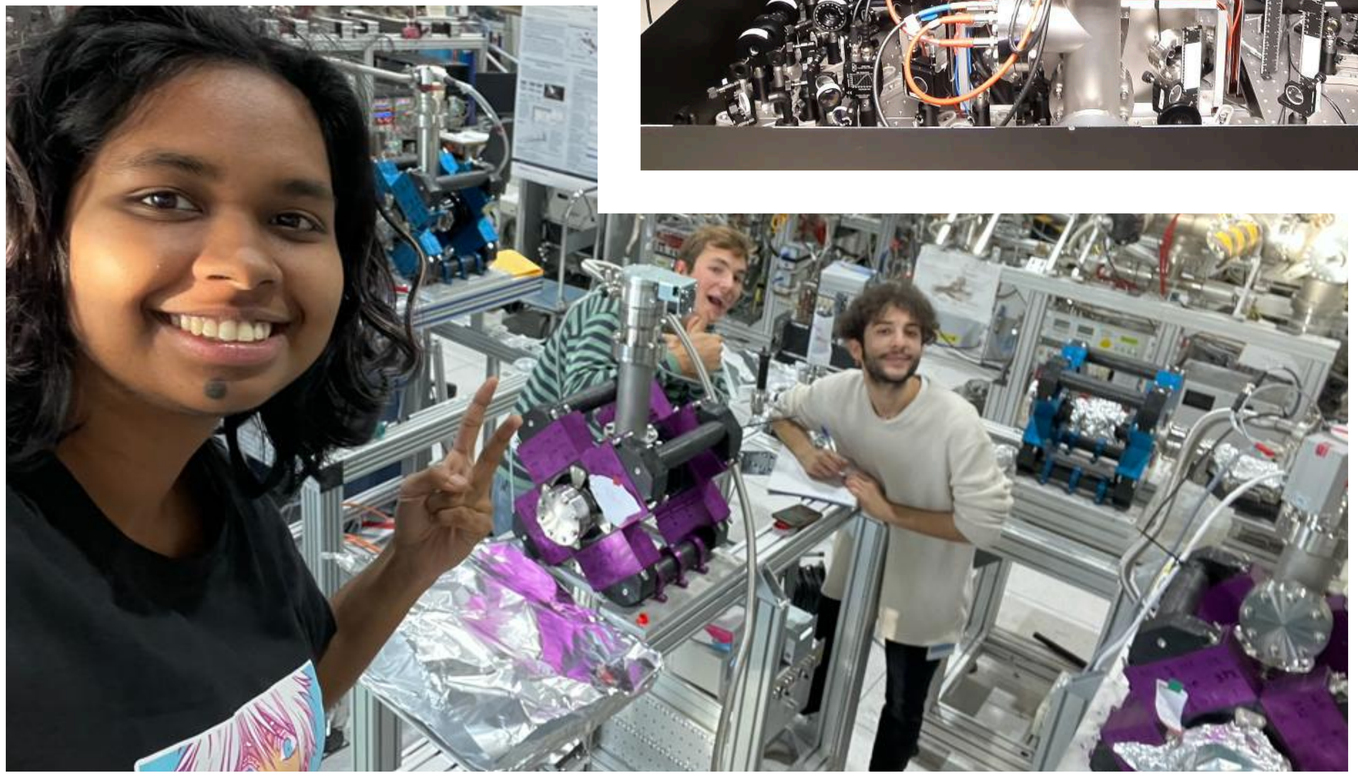


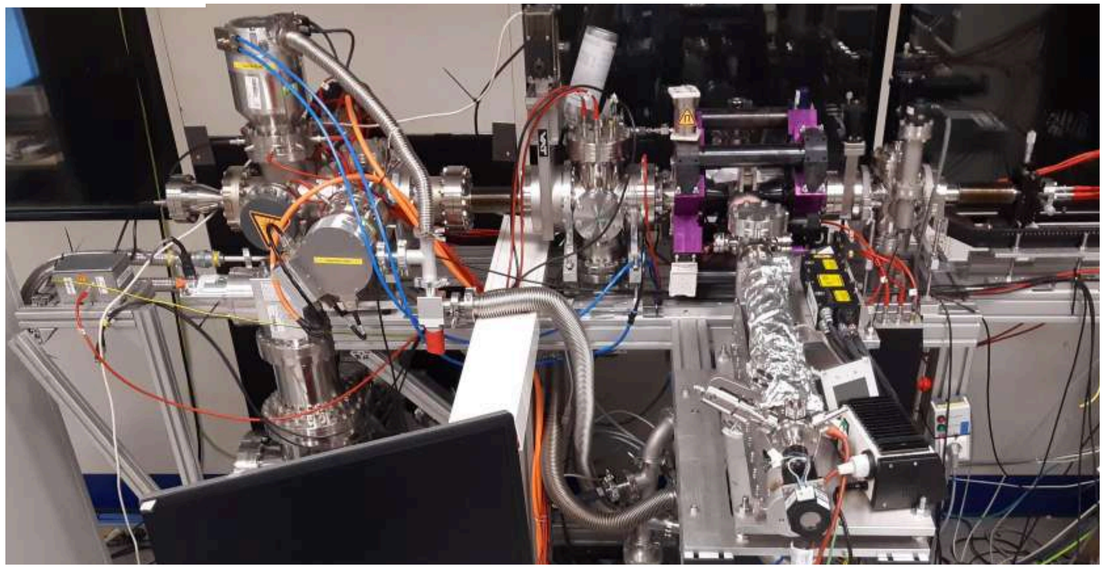
- Oscillating variations: ultra-light Dark Matter
- Topological defect Dark Matter
- Local Lorentz Invariance
- 5th Forces
- Gravitational shift in fundamental constants
- Dark Energy…







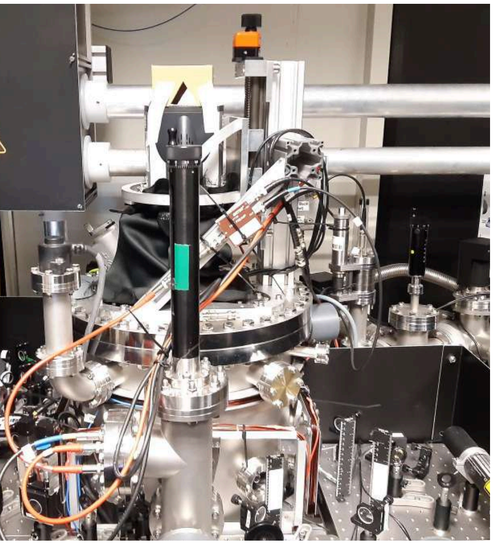


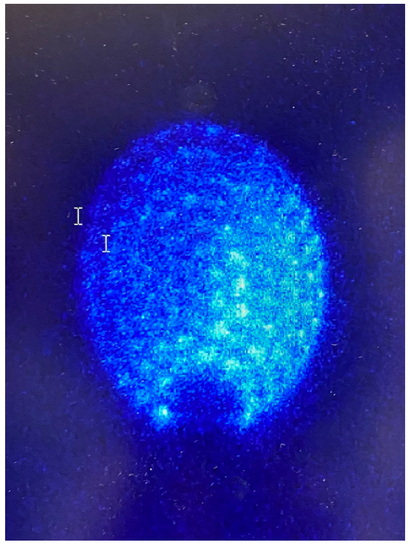


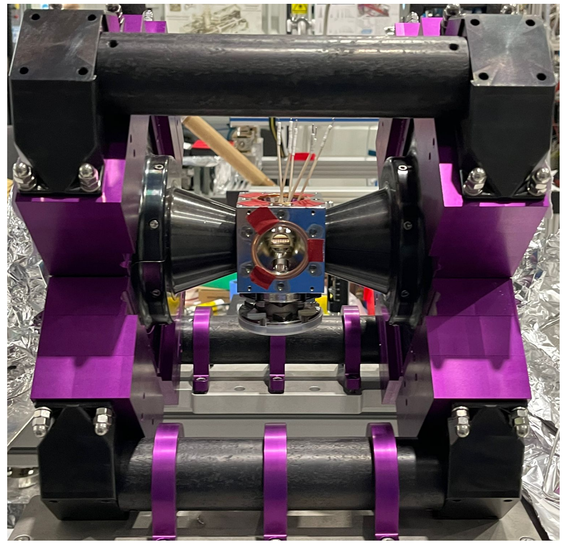
Conclusion

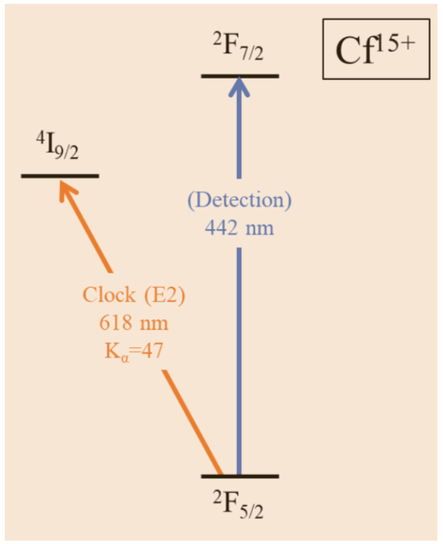
Optical atomic clocks: *Game-changing* sensitivity for new physics

- Important new direction for Particle Physics, e.g. to extend search for Dark Matter
- New way of working: multidisciplinary collaborative links are essential to incorporate new technologies
- Proof-of-principle with existing clocks; dedicated experiments/networks like QSNET under construction
- Californium-based highly charged ion clock being set up now









Thank you

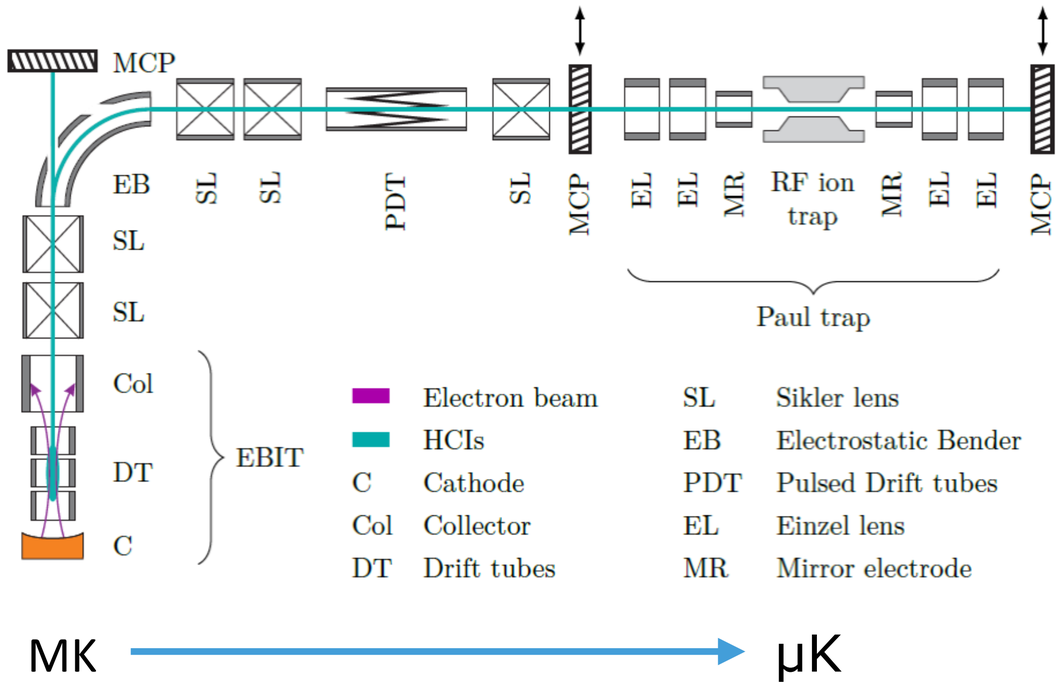
Contact

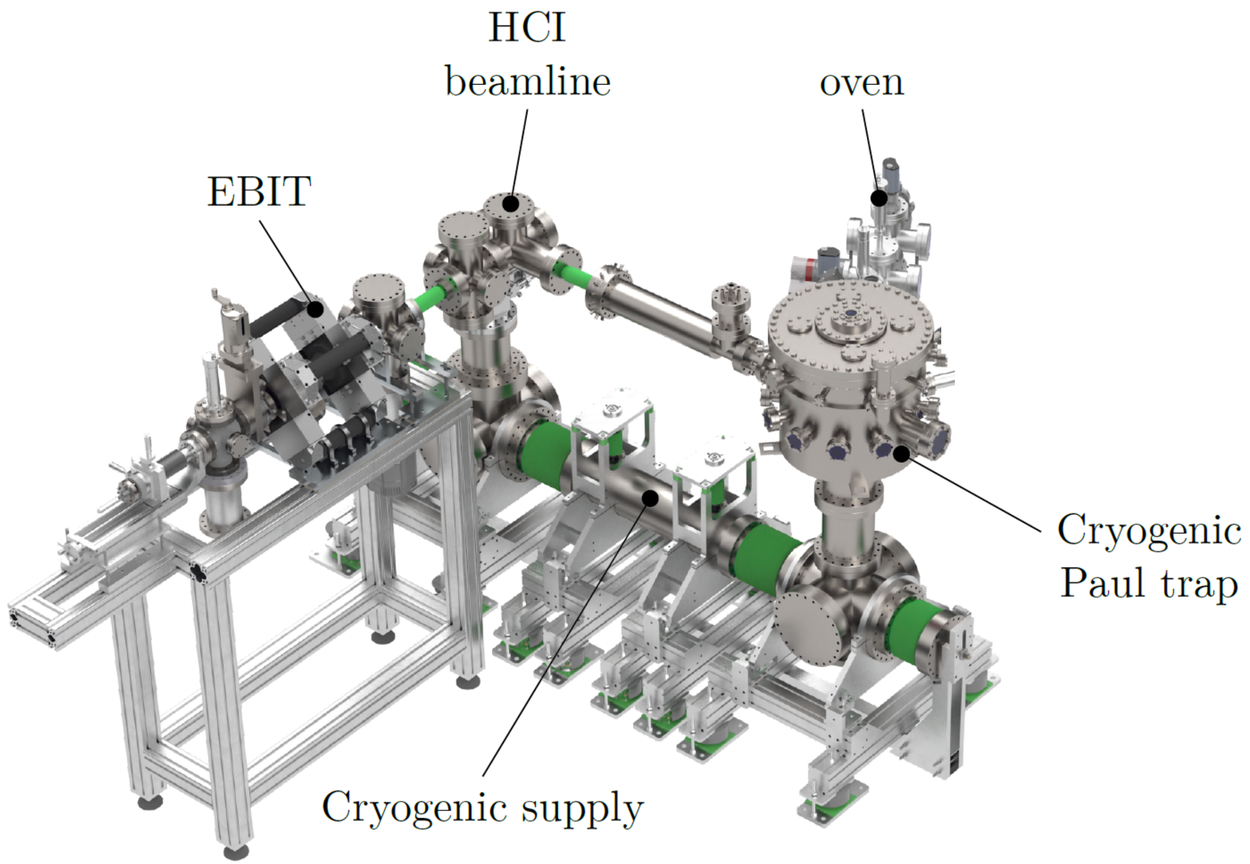
DESY. Deutsches
Elektronen-Synchrotron

www.desy.de

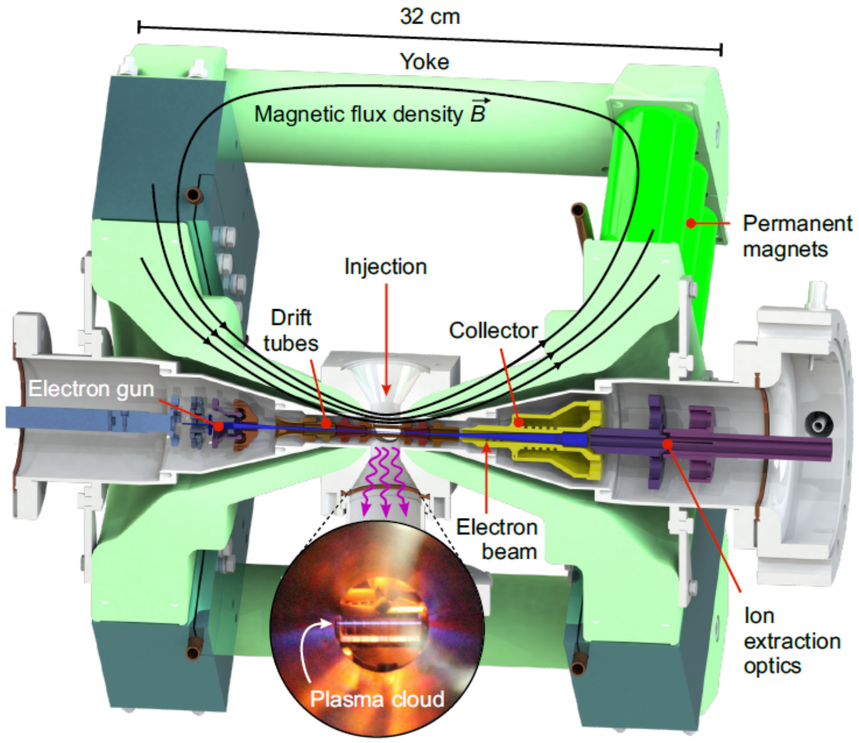
Steven Worm
Head of Astroparticle Detectors
Detector R&D DESY Zeuthen
steven.worm@desy.de

Highly Charged Ions: Production, cooling and trapping

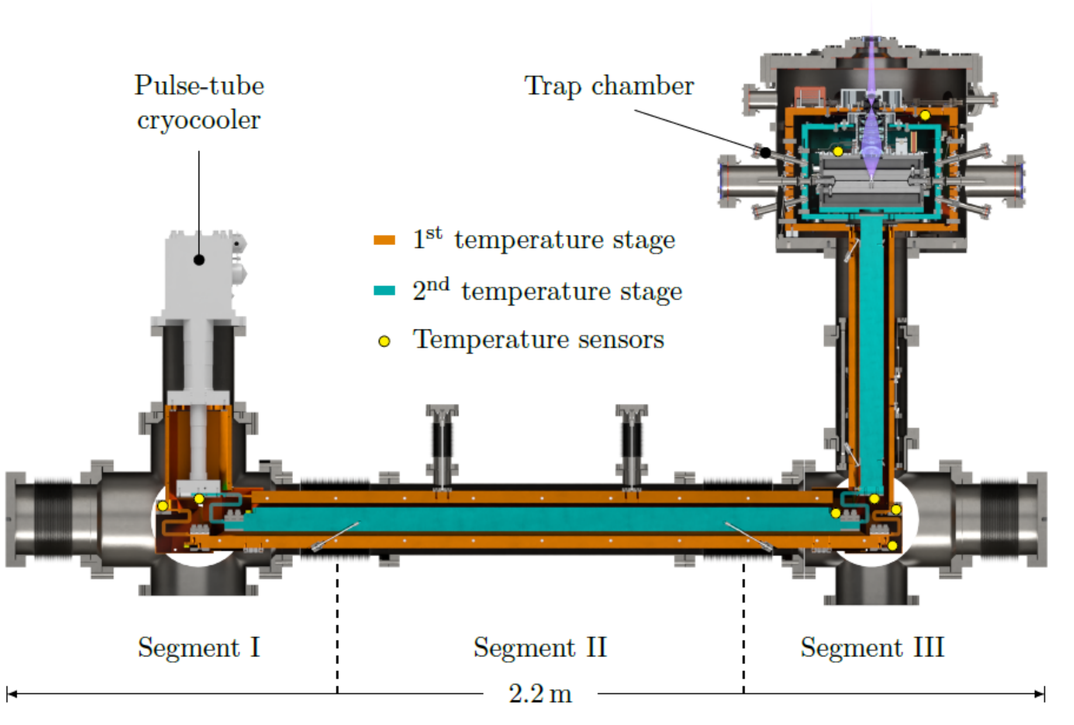




Highly Charged Ions: Production, cooling and trapping

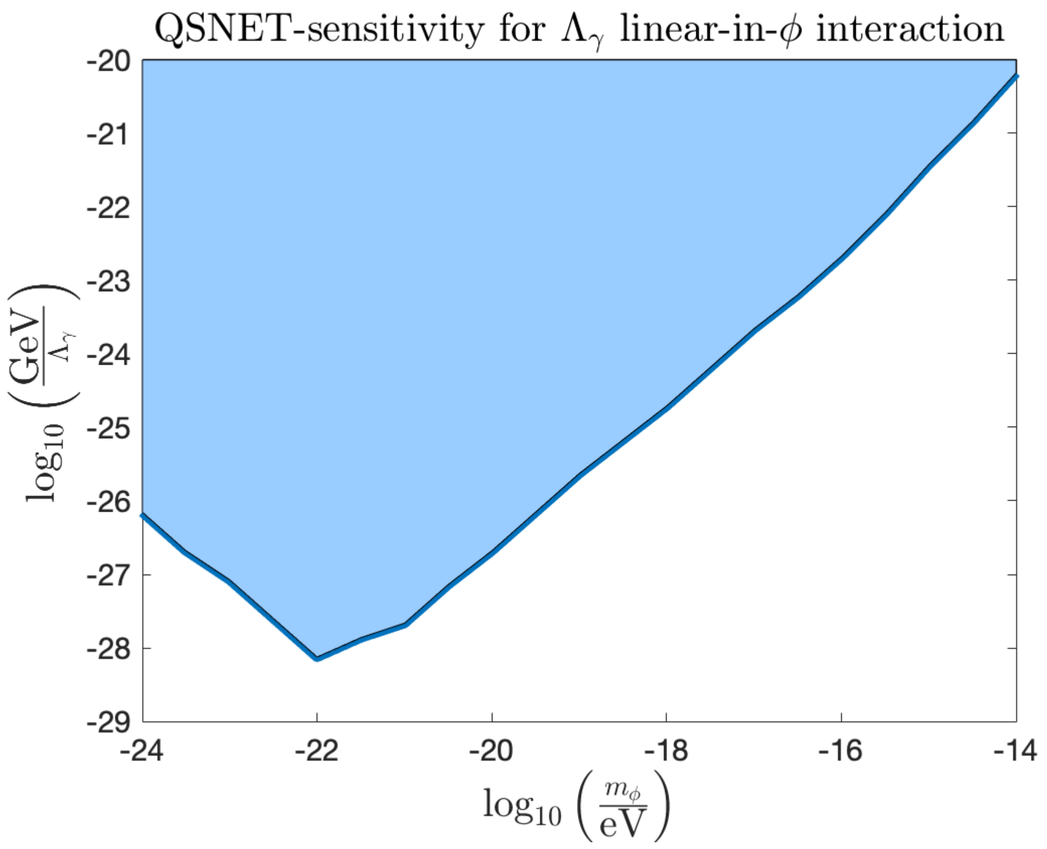


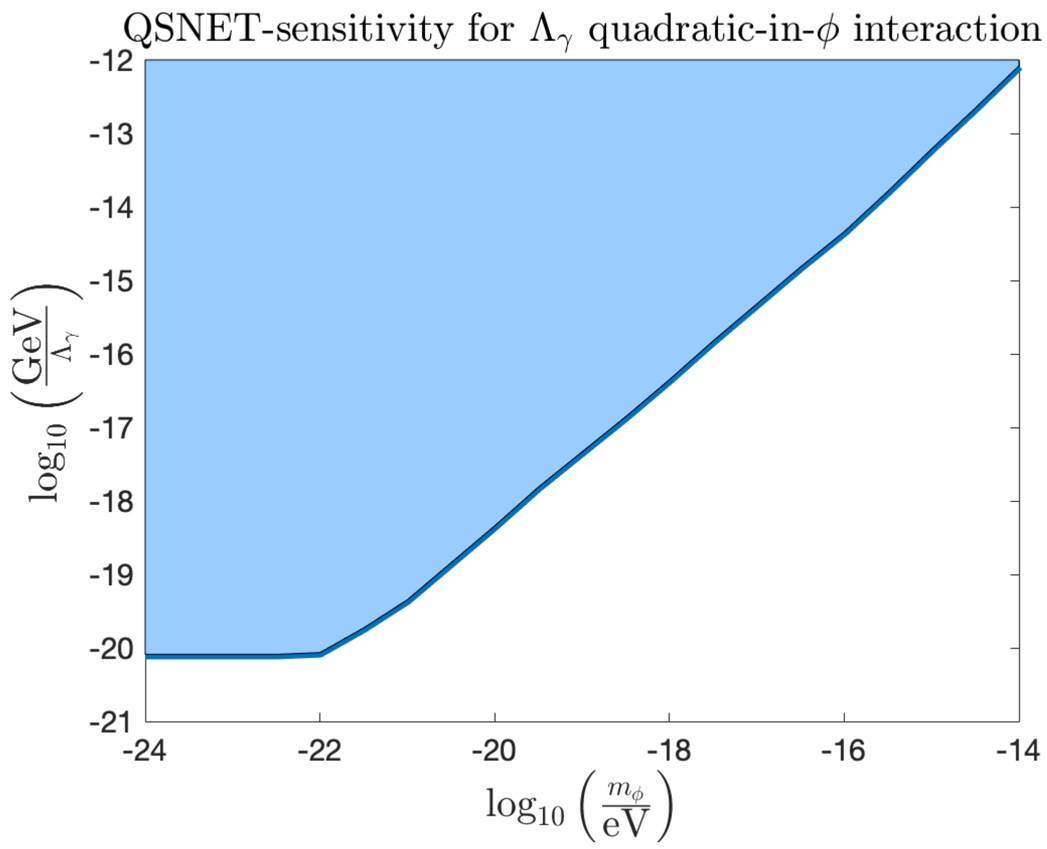
Compact EBIT
@ MPI Heidelberg



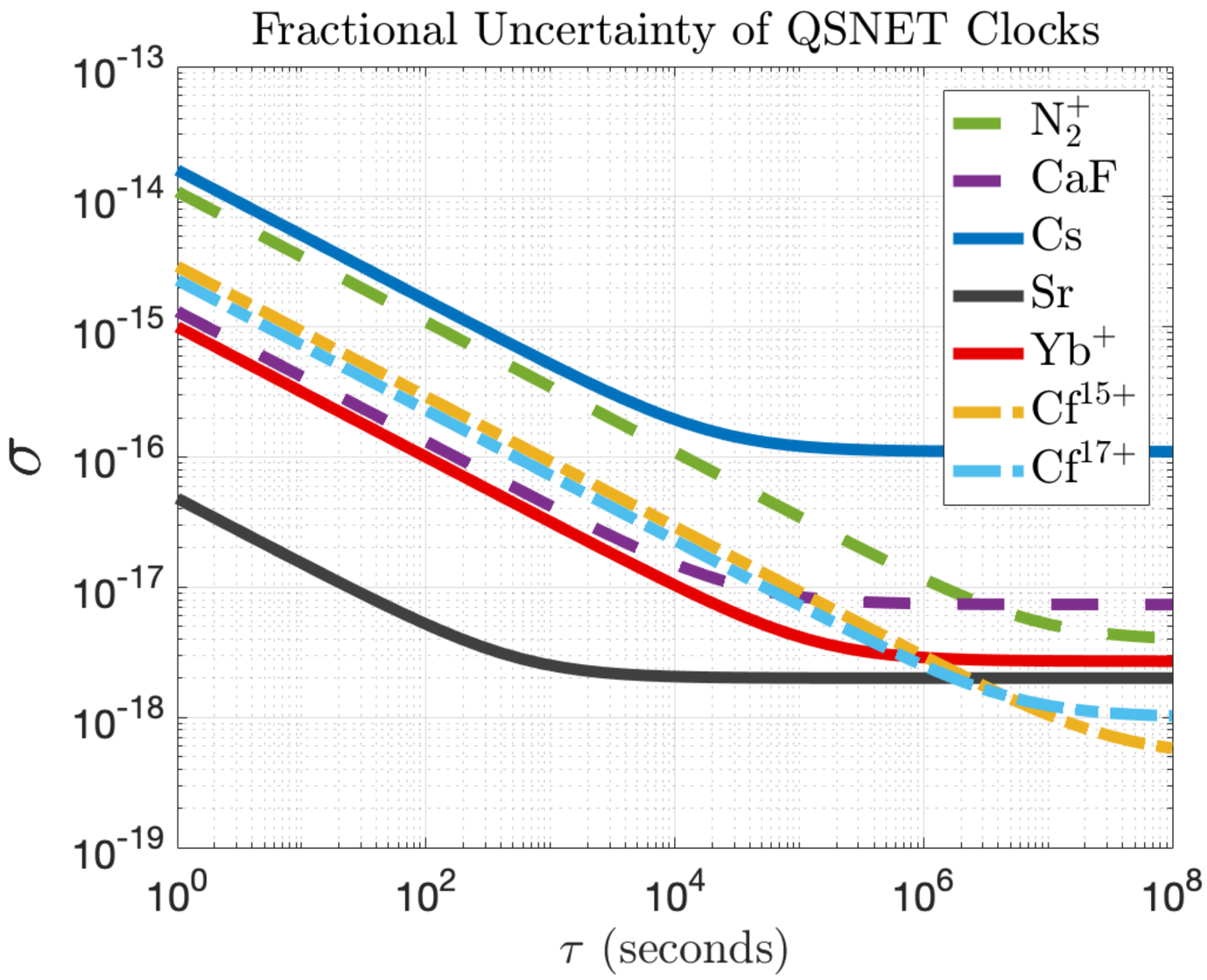
Ultra-low vibration
cryogenic vacuum

QSNET Sensitivity



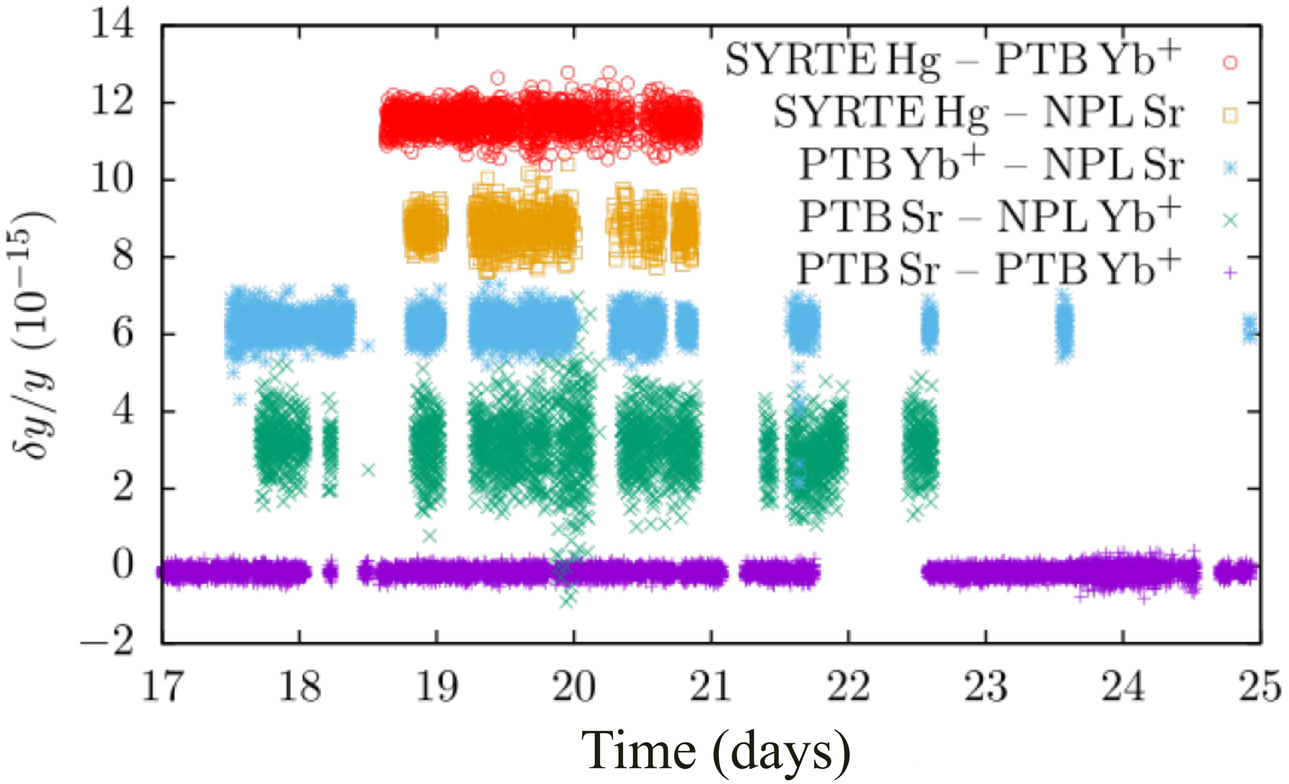


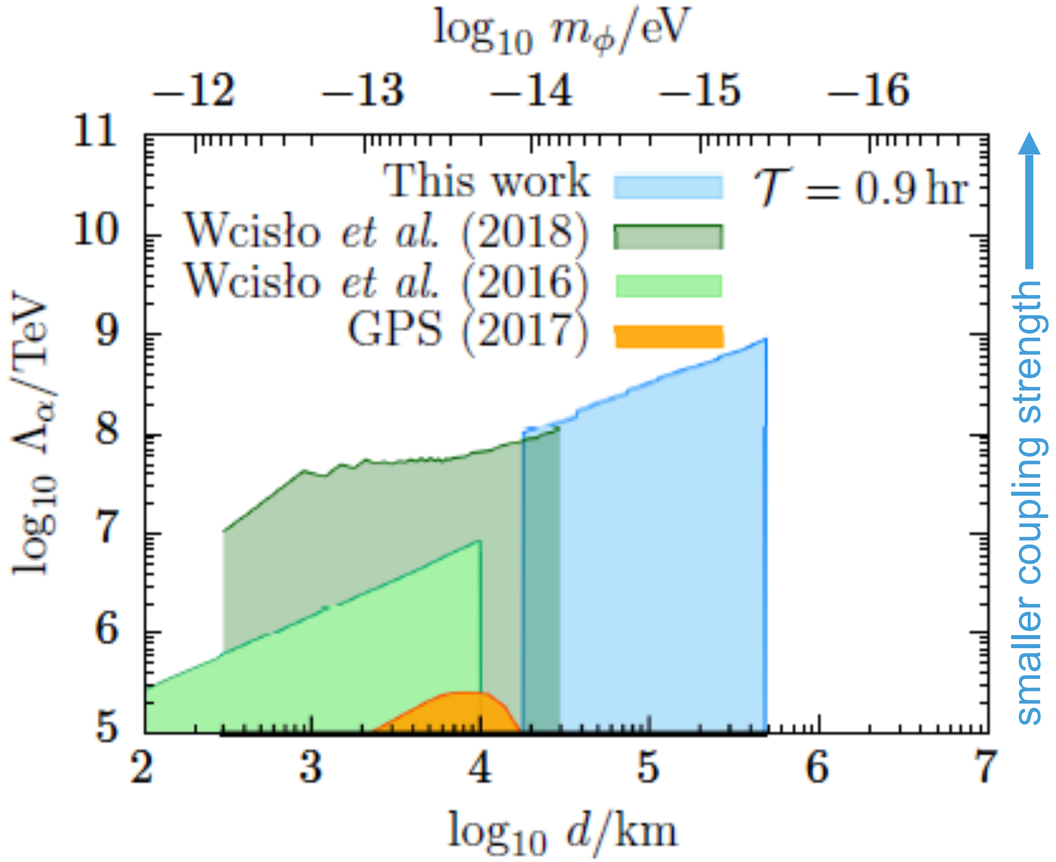
QSNET Clock Fractional Uncertainty



International Clock Comparison Data

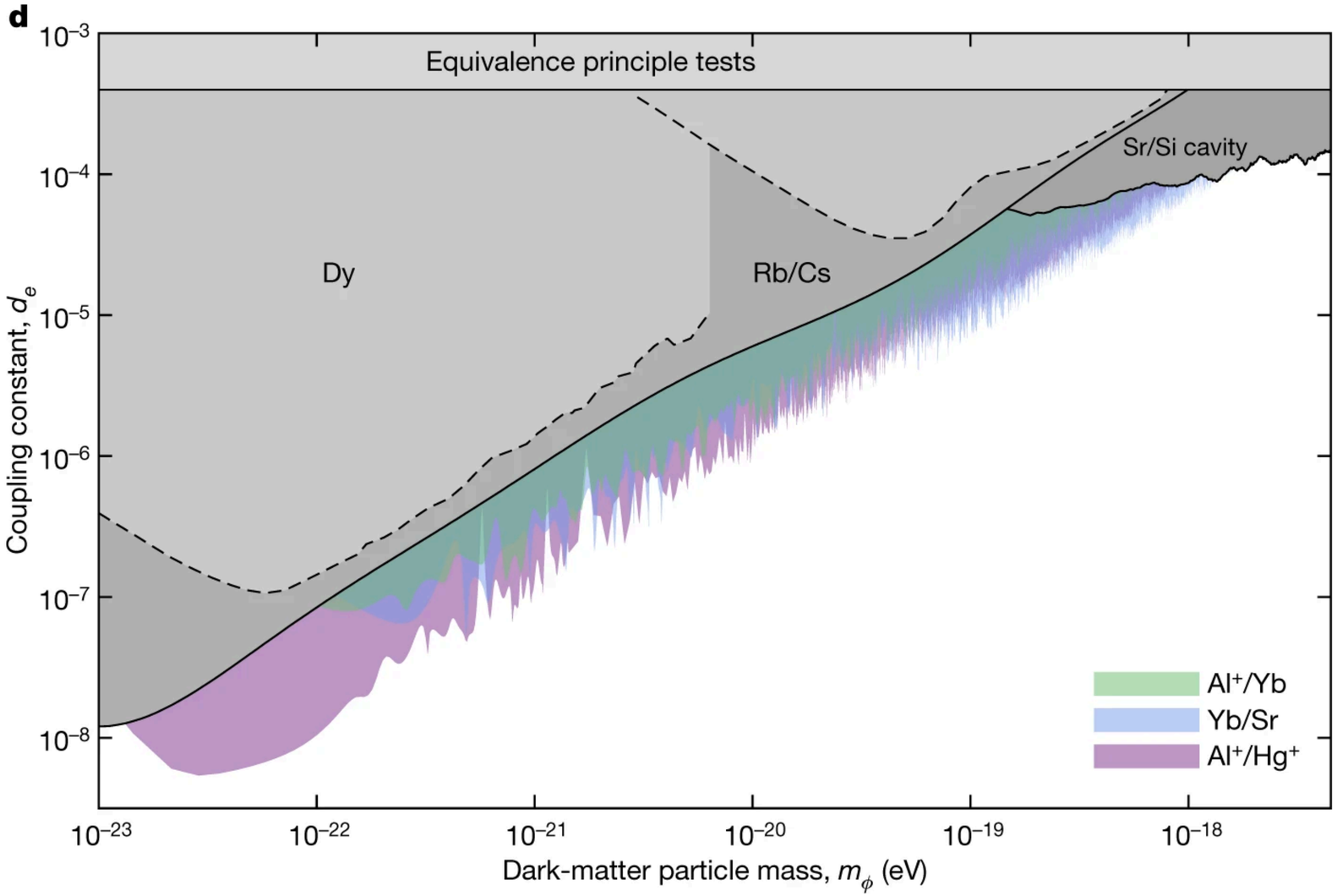
- Constraints on energy scale, Λ_α of dark matter interactions
- Results for T = 0.9, 12, 45 hours
- Collaboration between PTB, SYRTE and NPL





[B.M. Roberts *et al.* arXiv:1907.02661]

Clock Comparisons: Recent Results



[Nature **591**, 564–569 (2021)]