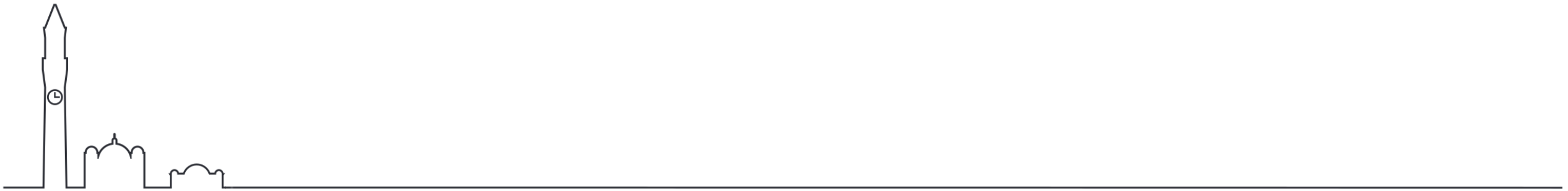
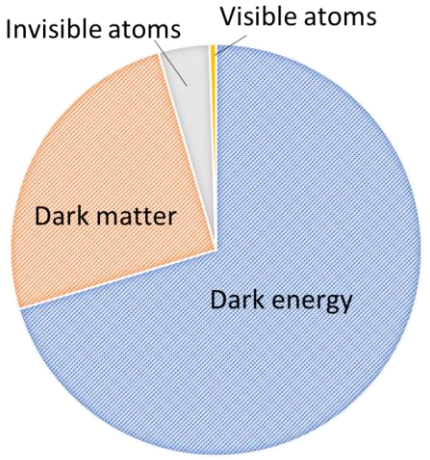
Searching for ultralight dark matter using highly charged ion clocks

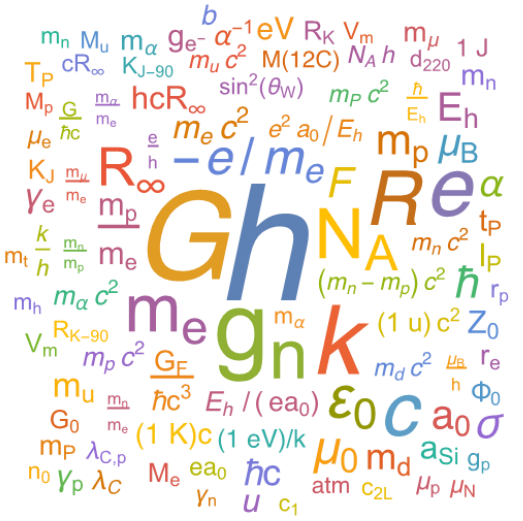
Mingyao Xu, Leonid Prokhorov, Aaron Smith, Vera Guarrera, and Giovanni Barontini



Motivation

- The Standard Model and ΛCDM are very successful theories but…
- The ΛCDM model postulates that 95% of the energy content of the universe is dark matter and dark energy. Their exact nature is unknown. Only the remaining 5% is described by the SM.
- Both models have several parameters, supposed to be immutable, called fundamental constants.
- **Challenging this assumption could be the key to solving the dark matter and dark energy enigmas**

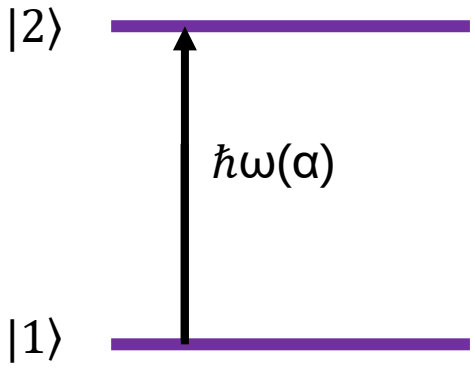




Why clocks?

- All atomic and molecular energy spectra depend on the fundamental constants of the Standard Model
- Spectroscopy lends itself to measure variations of:

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

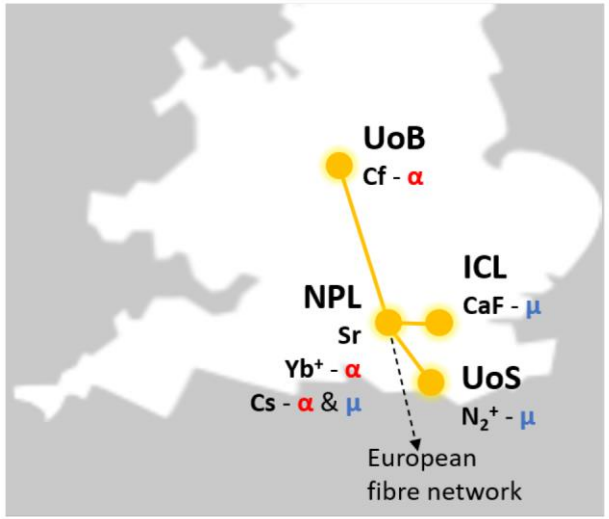


- Atomic and molecular spectra can be measured with extreme precision using atomic clocks

- Grand unification physics fixes relations between fundamental constants (if one changes with time, others will as well)

The QSNET project

- **Search for variations of fundamental constants of the Standard Model, using a network of clocks**
- A unique network of clocks chosen for their different sensitivities to variations of **α** and **μ**



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

- The clocks will be linked, essential to do clock-clock comparisons

$$\frac{\Delta f1}{\Delta f2} = |K_{1x} - K_{2x}| \frac{\Delta x}{x} \qquad x = \alpha, \mu$$

Barontini et al., Measuring the stability of fundamental constants with a network of clocks, EPJ Quantum Technol. 9, 12 (2022)

Scalar dark matter detection

- Coupling of “dark sector” scalar fields with standard matter [EPJ QT 9, 12 (2022)]:

$$\mathcal{L}_{scalar} \supset \frac{\phi^n}{\Lambda_\gamma^n} F_{\mu\upsilon}F^{\mu\upsilon} - \sum_f \frac{\phi^n}{\Lambda_f^n} m_f \bar{f} f$$

Λ_γ^n alter the fine structure constant α, Λ_f^n alter the fermionic masses -> manifest as effective variations of fundamental constants

$$\alpha \to \alpha[1 \pm \frac{\phi^n}{\Lambda_\gamma^n}] \qquad m_f \to m_f[1 \pm \frac{\phi^n}{\Lambda_f^n}]$$

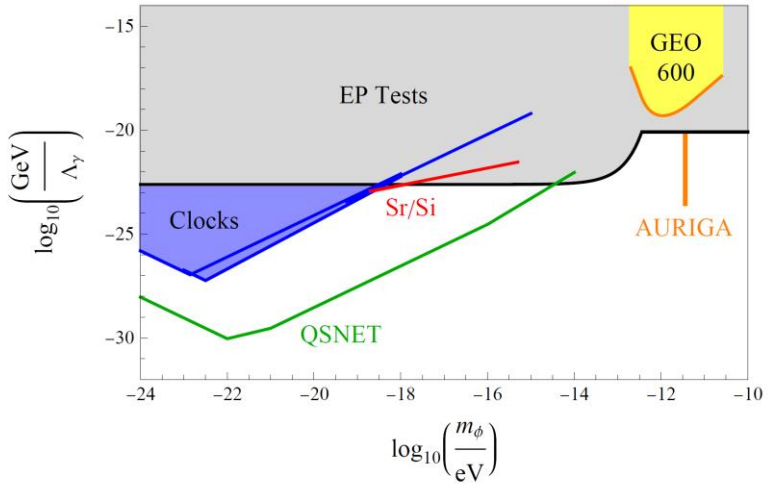
- Scalar dark matter models
- Axion models
- Quintessence-like models (dark energy)
- Kaluza-Klein models/moduli models
- Dilaton field models

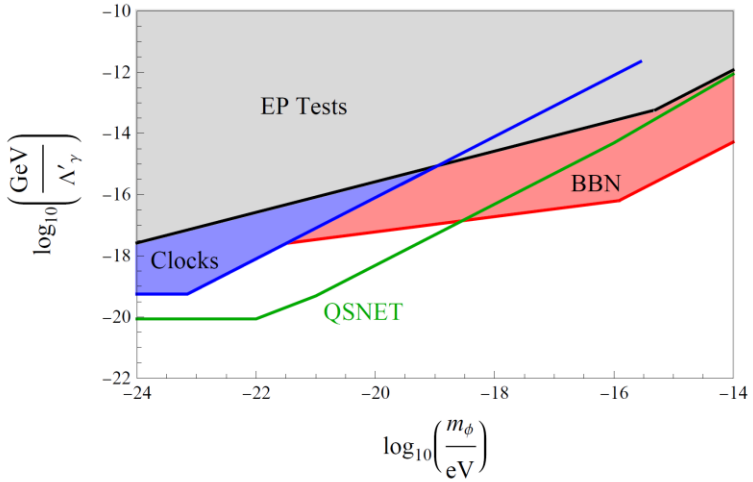
The QSNET estimated constraint

Linear

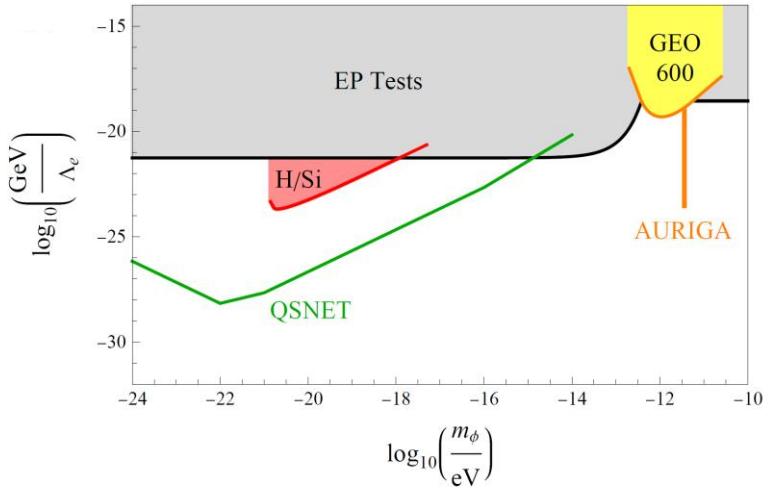
Quadratic

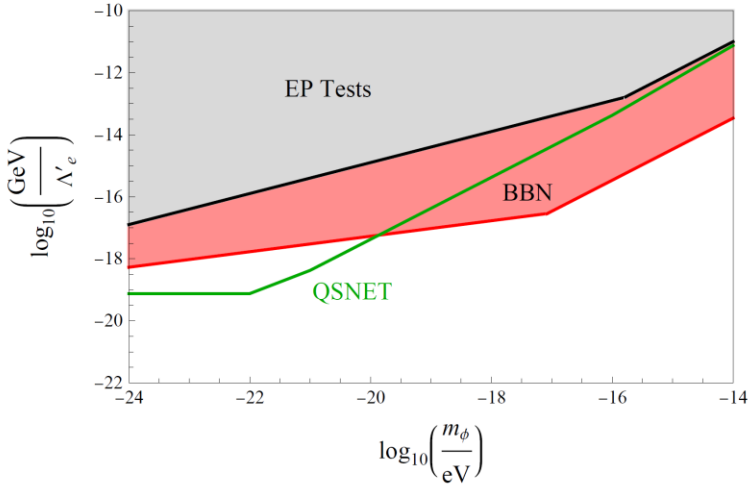
α





μ

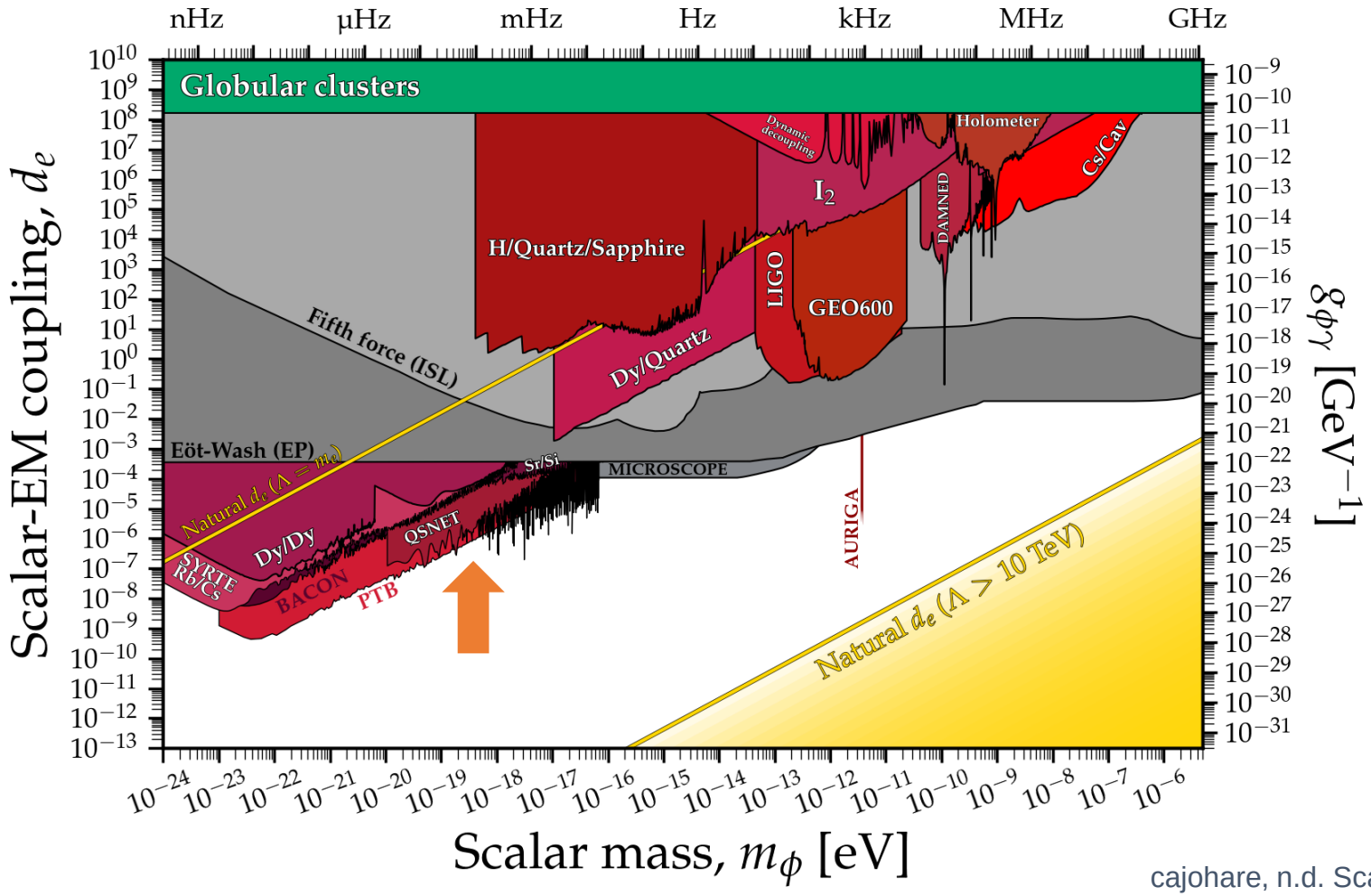




Barontini et al., Measuring the stability of fundamental constants with a network of clocks, EPJ Quantum Technol. 9, 12 (2022)

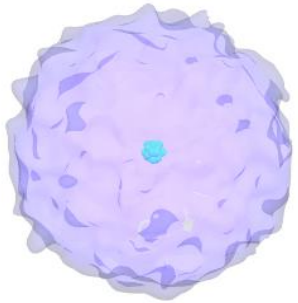
The QSNET results

α

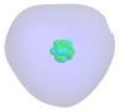


cajohare, n.d. ScalarPhoton. GitHub. Available at: https://raw.githubusercontent.com/cajohare/AxionLimits/master/plots/plots_png/ScalarPhoton.png
N. Sherrill et al., New J. Phys. 25 093012 (2023)

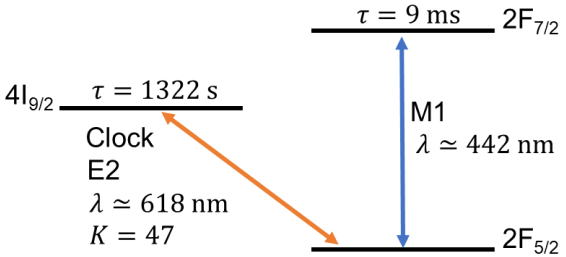
The Bham node: Cf highly charged ions (HCIs)



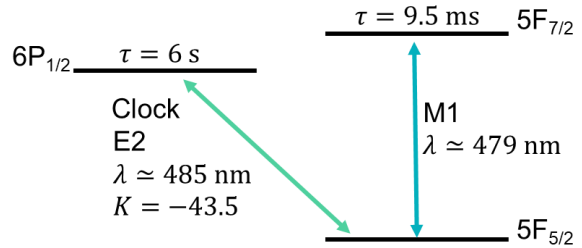
Cf



Cf^{15+}



Cf^{15+}



Cf^{17+}

- Strip neutral atoms of several electrons
- “Compressed” electronic cloud
- Low sensitivity to external perturbations (hopefully!) -> good for clocks
- Large relativistic corrections -> high sensitivities to variations of α $(K_\alpha \sim 10 - 100)$

- Cf is a synthetic element produced in reactors
- ^{249}Cf has a half-life of 350 y, ^{252}Cf of 2.65 y
- Both ionisation states feature a clock transition in the visible range and a strong-ish transition also in the visible range
- The two clock transitions have large Ks with opposite sign

Production, cooling and trapping of HCIs

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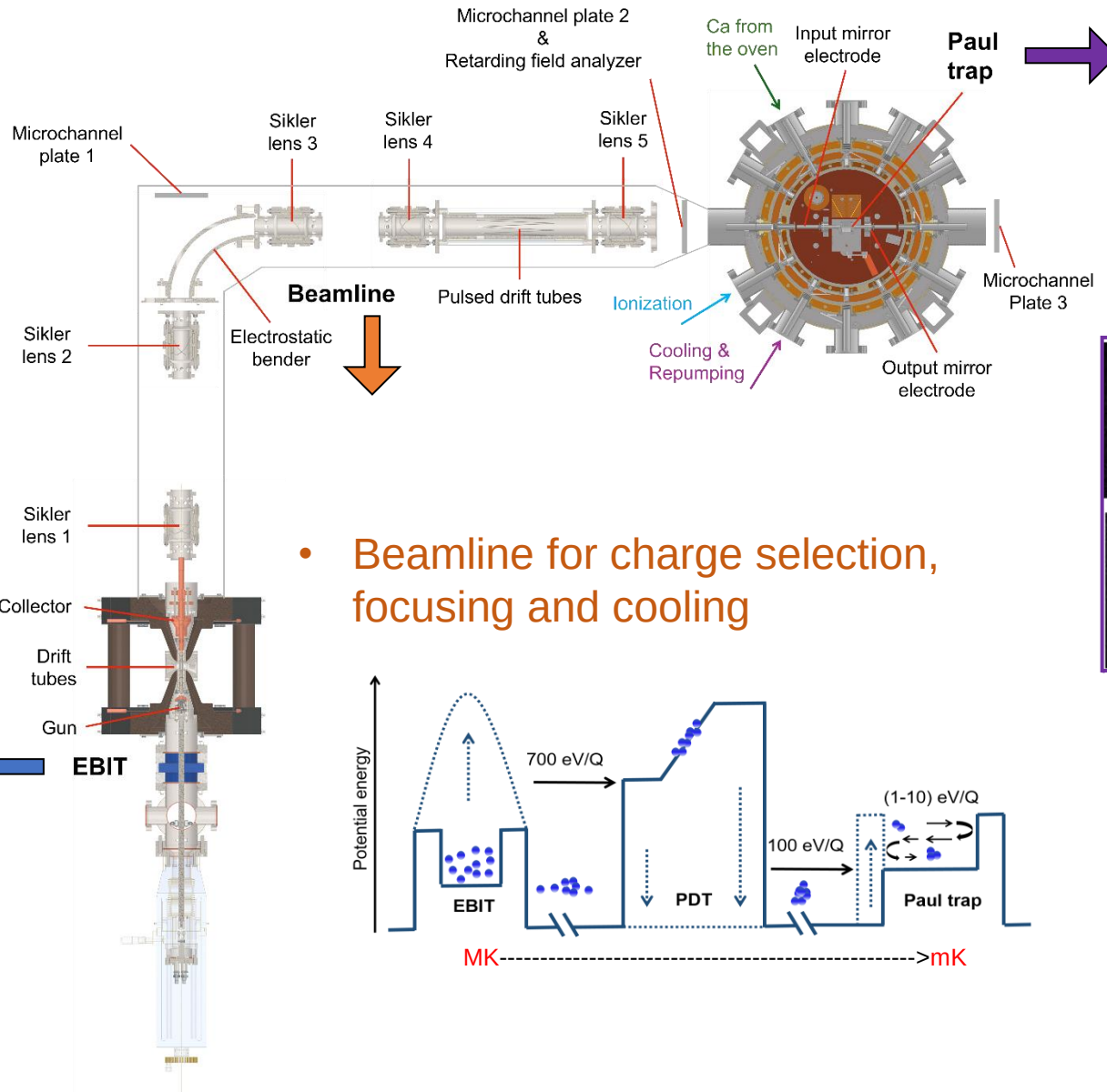
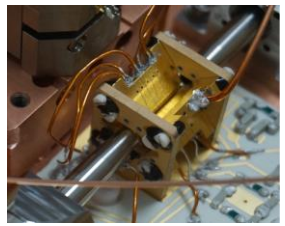
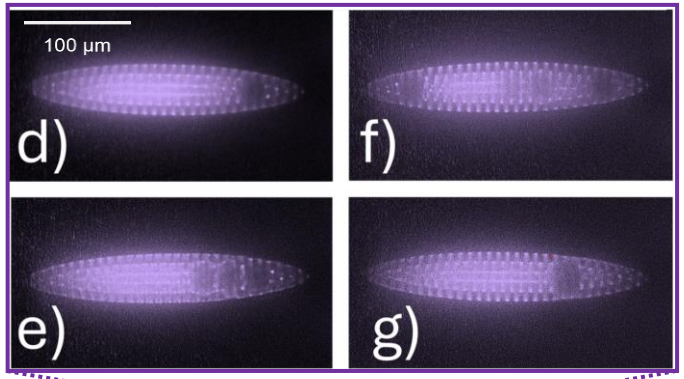


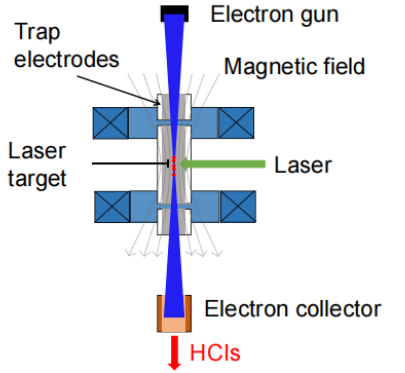
- Cryogenic Paul trap:



In collaboration with PTB

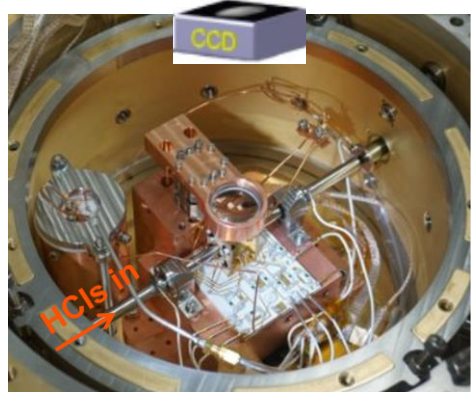


- EBIT produces HCIs



Compact EBIT
In collaboration with

- Beamline for charge selection, focusing and cooling



Current status & Next steps

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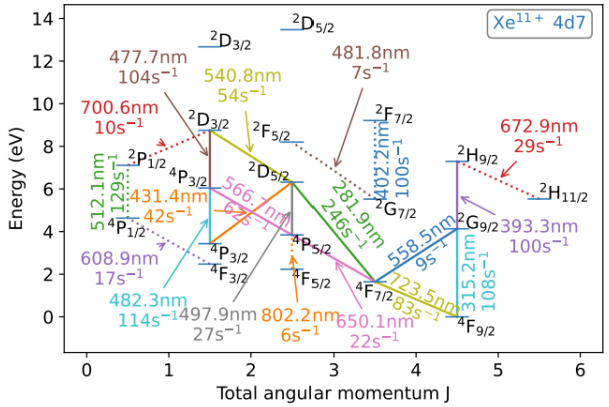
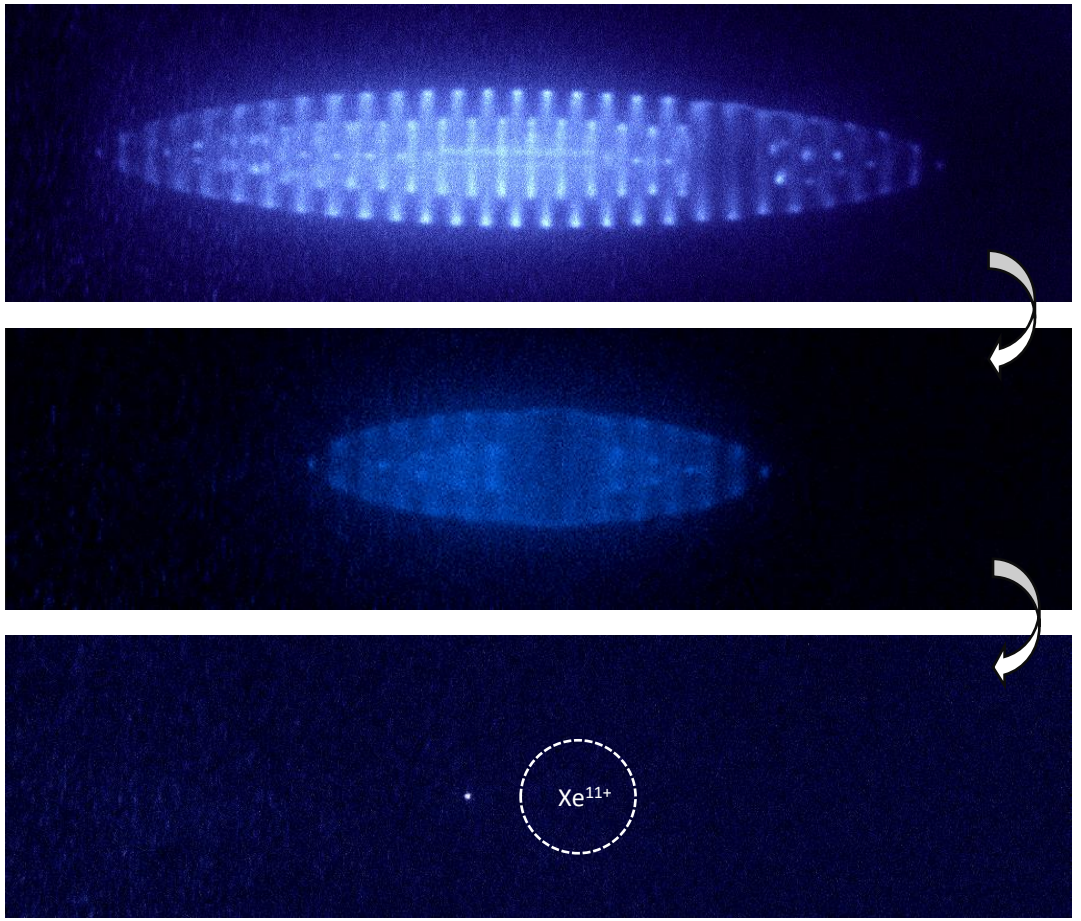
- We produced Xe HCIs and sympathetically cooled them with a Ca^+ Coulomb crystals.



- Xe HCI Quantum Logic Spectroscopy -> lead us to clocks.
- Towards Cf HCI clocks.

Cf-249 sample

Ca^+ Coulomb crystals with an Xe^{11+} HCI implanted



Nils-Holger Rehbehn et al. (2023). Narrow and Ultranarrow Transitions in Highly Charged Xe Ions as Probes of Fifth Forces. Physical Review Letters, 131(16).
Micke et al., Coherent laser spectroscopy of highly charged ions using quantum logic, Nature 578, 60 (2020)

Summary

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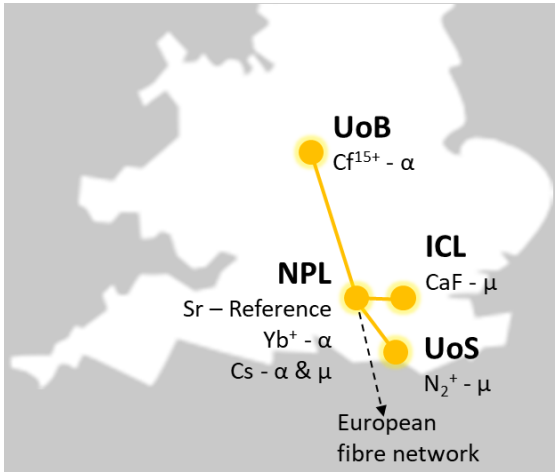
QSNET

- A world-unique network of next-generation clocks.
- Delivered world leading constraints on detecting scalar ultra-light dark matter.

- At Birmingham, we are developing the 1st HCI clock in the UK, 3rd worldwide.
- Succeeded in producing Xe HCIs and trapping them in a Ca^+ Coulomb crystal. The only one uses Ca^+ ions.



- Working to Xe HCI Quantum Logic Spectroscopy.
- Working towards Cf HCI clocks.

Thankyou!

Appendix

How to measure variations of fundamental constants

- Different clock transitions have different sensitivities to fundamental constants

- Hyperfine transitions
  $\upsilon_{Hf} = A\mu\alpha^2 F_{Hf}(\alpha) R_\infty$
- Optical transitions
  $\upsilon_{Opt} = B F_{Opt}(\alpha) R_\infty$
- Vibrational transitions
  $\upsilon_{vib} = C\mu^{1/2} R_\infty$

$$\frac{dE}{E_0} = K_X \frac{dX}{X_0}$$

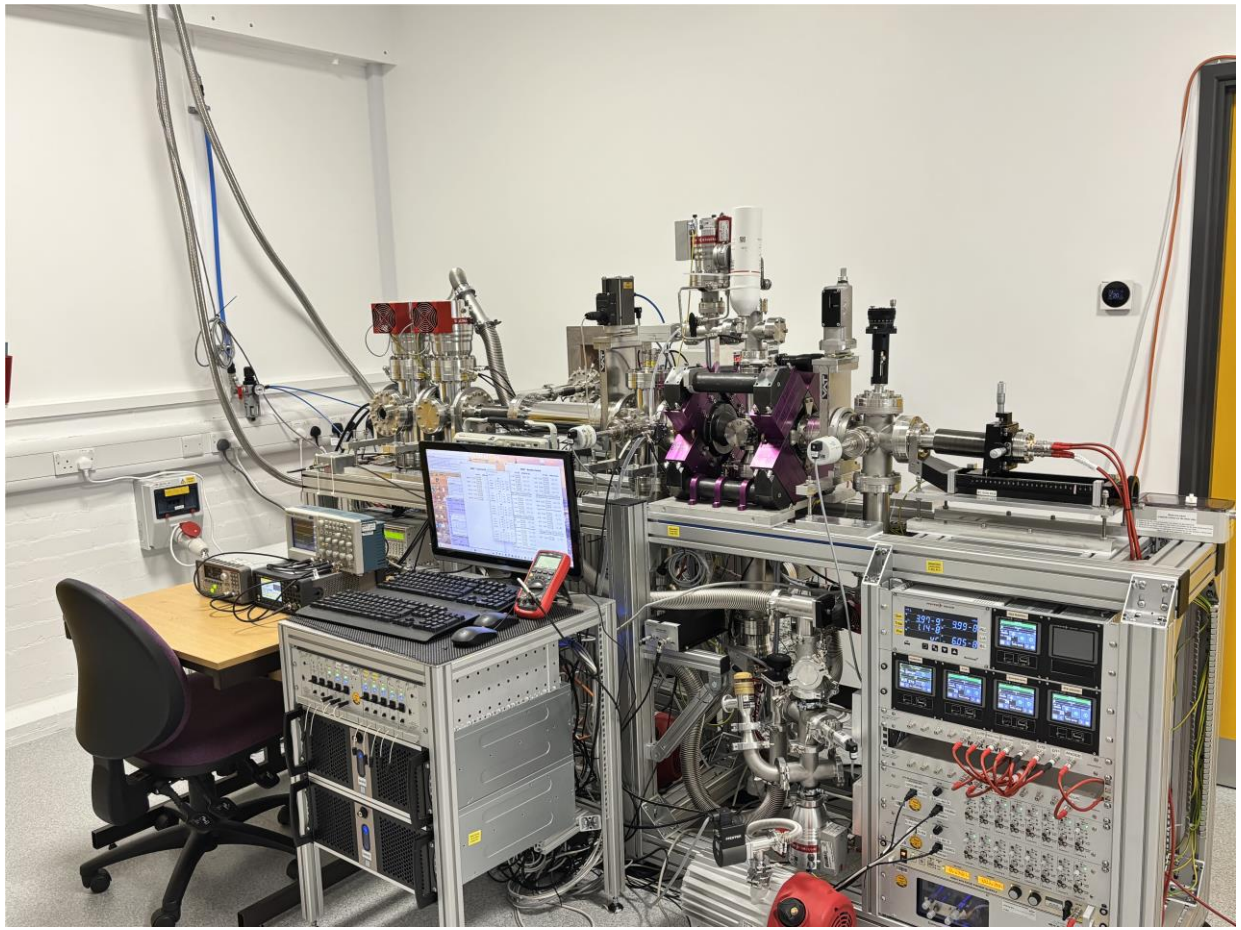
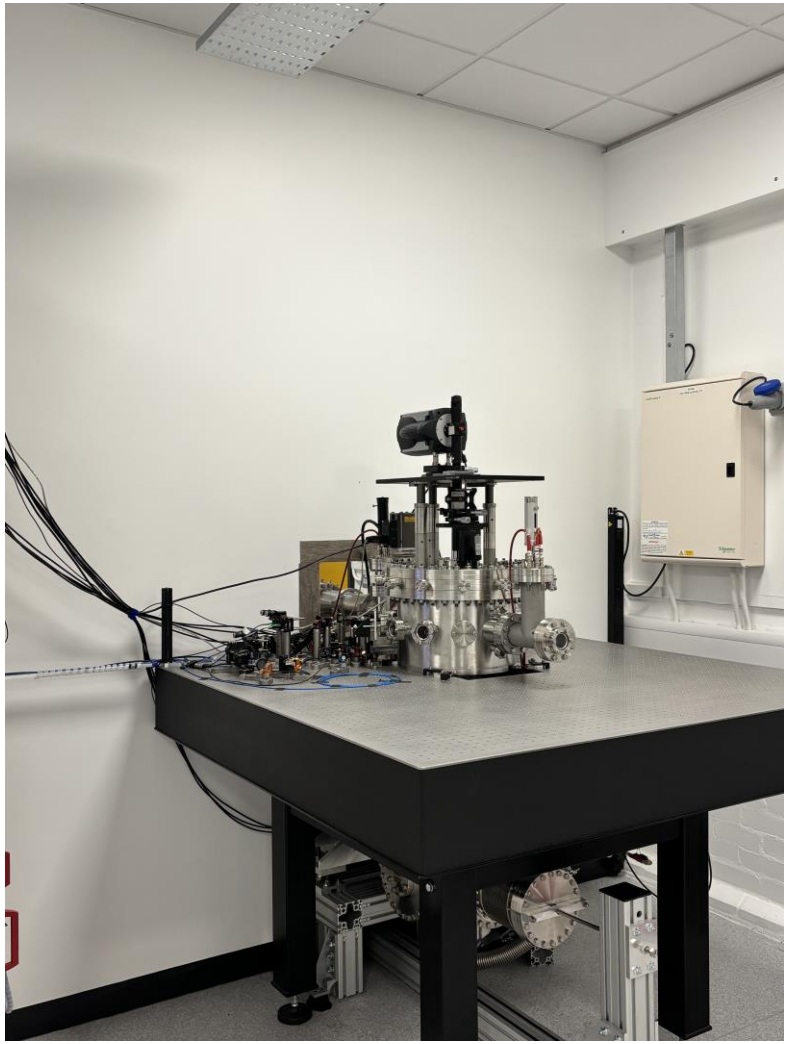
Clock	K_α	K_μ
Sr	0.06	0
Yb+	-5.95	0
Cs	2.83	1
CaF	0	0.5

HCIs and variations of α

- ✓Visible range
- ✓High values of K
- ❖Other groups too unstable

Ion	Level	Energy	q	K	λ	τ
Nd^{13+}	$5s_{1/2}$	0				
	~~$4f_{5/2}$~~	~~55 706~~	~~104 229~~	~~3.7~~	~~179~~	~~1.3×10^{6}[a]~~
	~~$4f_{7/2}$~~	~~60 134~~	~~108 243~~	~~3.6~~	~~166~~	~~0.996~~
Sm^{15+}	$4f_{5/2}$	0				
	~~$4f_{7/2}$~~	~~6 444~~	~~5 910~~	~~1.8~~	~~1526~~	~~0.308~~
	~~$5s_{1/2}$~~	~~60 517~~	~~134 148~~	~~4.4~~	~~166~~	~~3.1×10^{5}~~
$*Cf^{17+}$	$5f_{5/2}$	0				
	$6p_{1/2}$	18 686	−449 750	−48	535	
	~~$5f_{7/2}$~~	~~21 848~~	~~17 900~~	~~1.6~~	~~458~~	
Nd^{12+}	$5s^2\ {}^1S_0$	0				
	~~$5s4f\ {}^3F_2$~~	~~79 469~~	~~101 461~~	~~2.6~~	~~126~~	~~8.5×10^{10}~~
	~~$5s4f\ {}^3F_3$~~	~~80 769~~	~~102 325~~	~~2.4~~	~~124~~	~~19.7~~
Sm^{14+}	$4f^2\ {}^3H_4$	0				
	~~$5s4f\ {}^3F_2$~~	~~2 172~~	~~−127 720~~	~~−118~~	~~4600~~	~~5.6×10^{13}[b]~~
	~~$5s4f\ {}^3F_3$~~	~~3 826~~	~~−126 746~~	~~−66~~	~~2614~~	~~8.51~~
$*Es^{17+}$	$5f^2\ {}^3H_4$	0				
	$5f6p\ {}^3F_2$	7 445	−46 600	−13	1343	11 000

Ion	Level		Energy	q	K	λ
Ir^{16+}	$4f^{13}5s^2$	$^2F_{7/2}$	0			
	~~$4f^{13}5s^2$~~	~~$^2F_{5/2}$~~	~~25 898~~	~~23 652~~	~~1.8~~	~~386~~
	$4f^{14}5s$	$^2S_{1/2}$	37 460	367 315	20	267
Ir^{17+}	$4f^{13}5s$	$^3F_4$	0			
	~~$4f^{13}5s$~~	~~$^3F_3$~~	~~4 838~~	~~2 065~~	~~0.9~~	~~2067~~
	~~$4f^{13}5s$~~	~~$^3F_2$~~	~~26 272~~	~~24 183~~	~~1.8~~	~~381~~
	~~$4f^{14}$~~	~~$^1S_0$~~	~~5 055~~	~~367 161~~	~~145~~	~~1978~~
	$4f^{12}5s^2$	$^3H_6$	35 285	−385 367	−22	283
	$4f^{12}5s^2$	$^3F_4$	45 214	−387 086	−17	221
Ho^{14+}	$4f^{6}5s$	$^8F_{1/2}$				
	$4f^{5}5s^2$	$^6H_{5/2}$	23 823	−186 000	−16	420

Ion	Level	Energy	q	K	λ	τ
Ce^{9+}	$5s^25p_{1/2}$	0				
	~~$5s^25p_{3/2}$~~	~~33 450~~	~~37 544~~	~~2.2~~	~~299~~	~~0.0030~~
	~~$5s^24f_{5/2}$~~	~~54 683~~	~~62 873~~	~~2.3~~	~~182~~	~~0.0812~~
	~~$5s^24f_{7/2}$~~	~~57 235~~	~~65 150~~	~~2.3~~	~~174~~	~~2.18~~
Pr^{10+}	$5s^25p_{1/2}$	0				
	~~$5s^24f_{5/2}$~~	~~3 702~~	~~73 849~~	~~40~~	~~2700~~	~~8.5×10^{4}~~
	~~$5s^24f_{7/2}$~~	~~7 031~~	~~76 833~~	~~22~~	~~1422~~	~~2.35~~
	~~$5s^25p_{3/2}$~~	~~39 141~~	~~44 098~~	~~2.3~~	~~256~~	~~0.0018~~
Nd^{11+}	$5s^24f_{5/2}$	0				
	~~$5s^24f_{7/2}$~~	~~4 180~~	~~3 785~~	~~1.8~~	~~2392~~	~~1.19~~
	~~$5s^25p_{1/2}$~~	~~53 684~~	~~−85 692~~	~~−3.2~~	~~186~~	~~0.061~~
Sm^{13+}	$5s^24f\ {}^2F_{5/2}$	0				
	~~$5s^24f\ {}^2F_{7/2}$~~	~~6 203~~	~~5 654~~	~~1.8~~	~~1612~~	~~0.367~~
	$4f^25s\ {}^4H_{7/2}$	20 254	123 621	12	494	0.133
Eu^{14+}	$4f^25s\ J=7/2$	0				
	~~$4f^3\ J=9/2$~~	~~1 262~~	~~137 437~~	~~218~~	~~7924~~	
	~~$4f^25s\ J=9/2$~~	~~2 594~~	~~1 942~~	~~1.5~~	~~3855~~	
	~~$4f^3\ J=11/2$~~	~~5 388~~	~~141 771~~	~~53~~	~~1856~~	
$*Cf^{15+}$	$5f6p^2\ {}^2F_{5/2}$	0				
	$5f^26p\ {}^4I_{9/2}$	12 898	380 000	59	775	6900
	$5f6p^2\ {}^2F_{7/2}$	22 018			454	0.012
$*Es^{16+}$	$5f^26p\ {}^4I_{9/2}$	0				
	~~$5f^26p\ {}^2F_{5/2}$~~	~~6 994~~	~~−184 000~~	~~−53~~	~~1430~~	~~16 000~~
	$5f^3\ {}^2H_{9/2}$	10 591			944	3.4
Pr^{9+}	$5s^25p^2\ {}^3P_0$	0				
	~~$5s^25p4f\ {}^3G_3$~~	~~20 216~~	~~42 721~~	~~4.2~~	~~475~~	~~6.6×10^{14}~~
	~~$5s^25p4f\ {}^3F_2$~~	~~22 772~~	~~42 865~~	~~3.8~~	~~426~~	~~59.0~~
	~~$5s^25p4f\ {}^3F_3$~~	~~25 362~~	~~47 076~~	~~3.7~~	~~382~~	~~5.33~~
Nd^{10+}	$5s^24f^2\ J=4$	0				
	$5s^25p4f\ J=3$	1 564	−81 052	−104		16 000
	$5s^24f^2\ J=5$	3 059	3 113	2.0		1.4
	~~$5s^25p4f\ J=2$~~	~~5 060~~	~~−60 350~~	~~−24~~	~~2200~~	~~25~~

The Bham EBIT + Beamline + Cryogenic Paul trap