

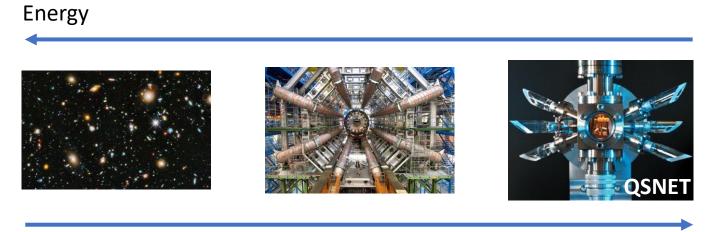
## A network of clocks for measuring the stability of fundamental constants



#### QTFP

- QSNET is one of the 7 projects funded within the QTFP programme of STFC&EPSRC <u>https://www.ukri.org/news/quantum-projects-launched-to-solve-the-universes-mysteries/</u>
- QTFP aims at building a community at the interface of quantum physics and fundamental physics

• Searches for physics beyond the SM



Precision

#### • Searches for physics beyond the SM

Energy

## RK

Science and Technology Facilities Council



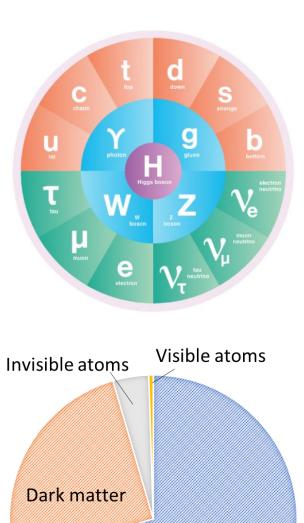






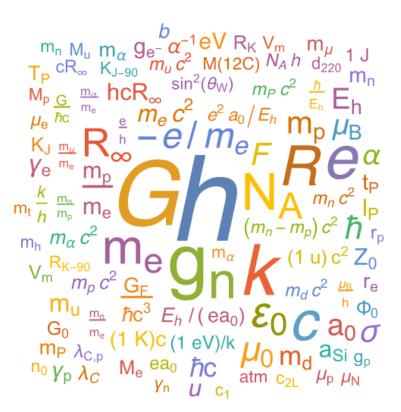
Precision

- 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.

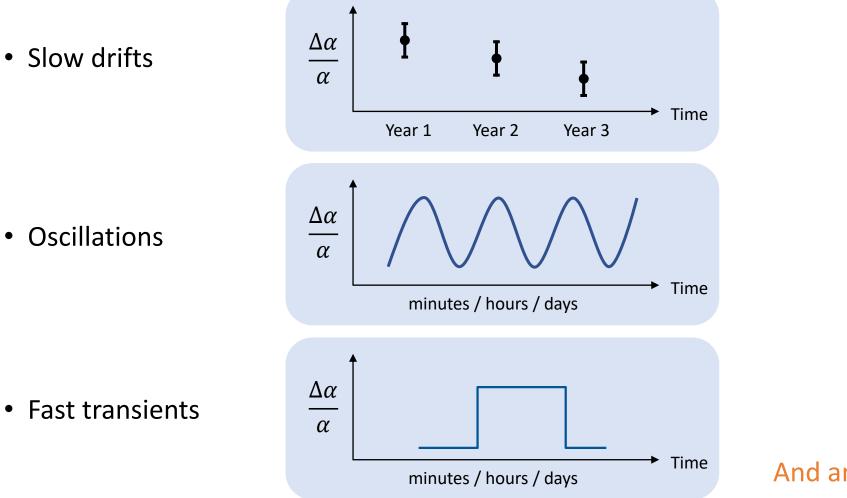


Dark energy

- The Standard Model and  $\Lambda$ CDM are very successful theories but...
- The  $\Lambda$ CDM 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.
- <u>Challenging this central assumption could be the key to solving the</u> <u>dark matter and dark energy enigmas</u>
- Any variations of fundamental constants would give us evidence of revolutionary new physics



#### Look for variation on different timescales



And any combination...

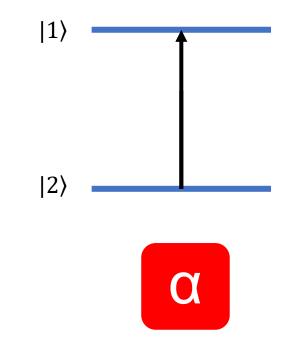
Oscillations

## Why clocks?

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

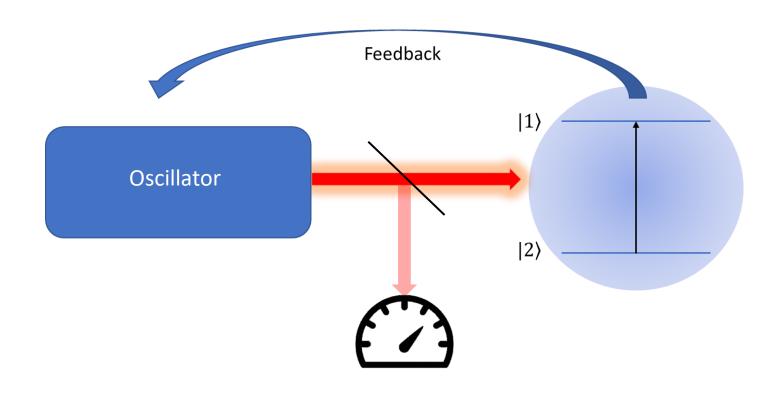
$$\mathbf{Q} = \frac{1}{4\pi\varepsilon_0} \frac{e^2}{\hbar c} \qquad \qquad \mathbf{\mu} = \frac{m_p}{m_e}$$

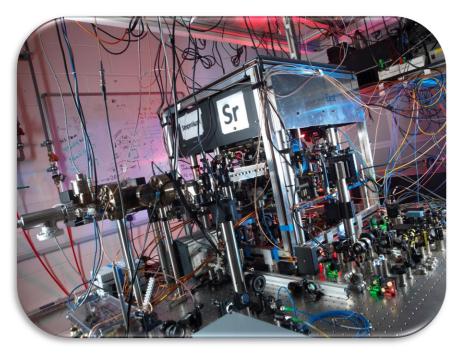
- Atomic an molecular spectra can be measured with extreme precision using atomic clocks
- Grand unification physics fixes relations between fundamental constants (if one changes with time, others will as well)



### Atomic clocks

• Extremely high-precision spectroscopy



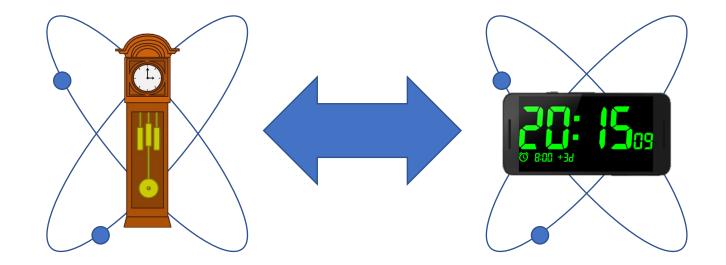


• Stability and accuracy at the 10<sup>-18</sup> level

- Different clock transitions have different sensitivities to fundamental constants
- Hyperfine transitions  $v_{Hf} = A\mu \alpha^2 F_{Hf}(\alpha) R_{\infty}$
- Optical transitions  $v_{Opt} = BF_{Opt}(\alpha)R_{\infty}$
- Vibrational transitions  $v_{vib} = C \mu^{1/2} R_{\infty}$

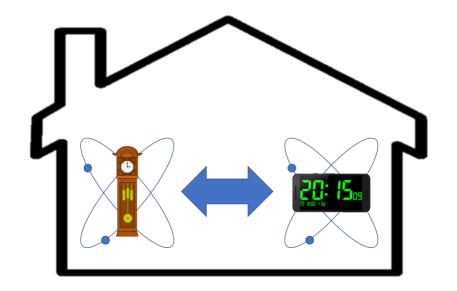
	Clock	K <sub>α</sub>	$K_{\mu}$
	Sr	0.06	0
$\frac{dE}{E_0} = K_X \frac{dX}{X_0}$	Yb+	-5.95	0
$L_0 \qquad \Lambda_0$	Cs	2.83	1
	CaF	0	0.5

• Comparing clocks with different sensitivities to fundamental constants

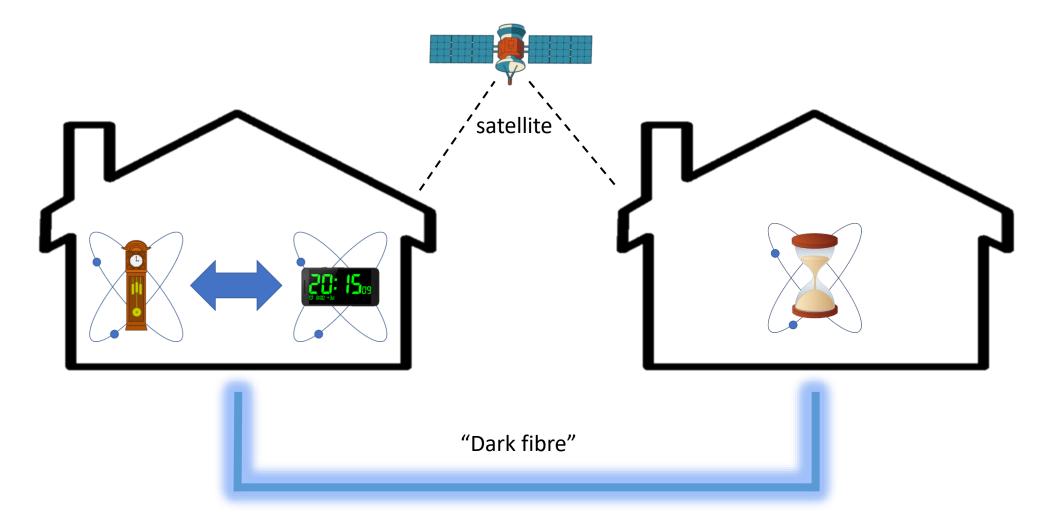


- Measure ratio  $f_1/f_2$
- Look for changes over time

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



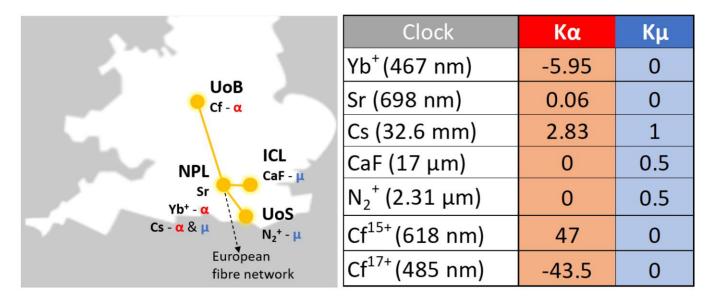
"in house" comparison



## The QSNET project

 Search for variations of fundamental constants of the Standard Model, using a <u>network of clocks</u>

• A unique network of clocks chosen for their different sensitivities to variations of  $\alpha$  and  $\mu$ 

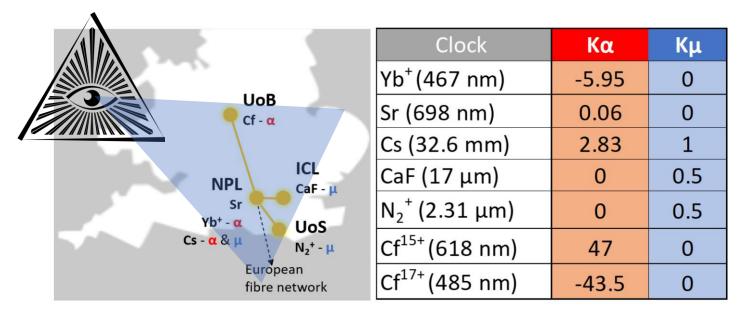


• The clocks will be linked, essential to do clock-clock comparisons

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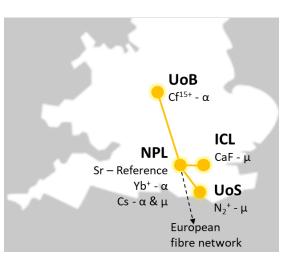
• The clocks will be linked, essential to do clock-clock comparisons

## The network approach

- Optimally exploit existing expertise. No single institution has the range of expertise required to run a sufficiently large and diverse set of clocks
- Sensors with similar sensitivities and different systematics are necessary to confirm any measurements and reject false positives



- Networks enable probing of space-time correlations
- The possibility of detecting transient events such as topological defects in dark matter fields or oscillations of dark matter
- A new versatile and expandable national infrastructure with possible further applications in and beyond fundamental physics.



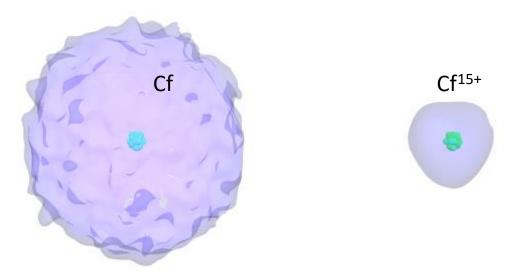
### The Bham node





## The Bham node: Highly-charged ions

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  $\alpha (K_{\alpha} \sim 10 - 100)_{18}$ 

## Highly-charged ions

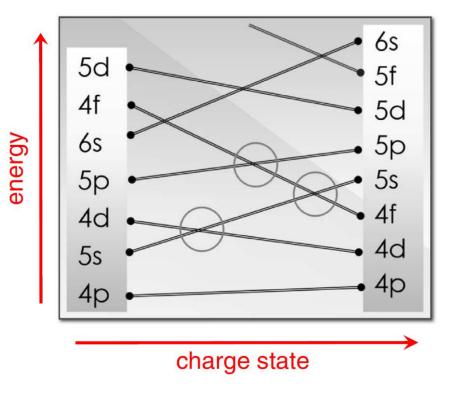
The energy scale for electronic transitions scales as

 $E \propto (q+1)^2 R_{\infty}$ 

So HCIs normally feature transitions in the XUV and x-ray regions

However there are some level crossings going from the Madelung ordering to the hydrogen-like ordering

Some HCIs feature ground-state transitions in the visible range -> good for clocks



Phys. Rev. Lett. 109, 070802 (2012)

HCIS	and	variations	of $\alpha$
	und	variations	$O$ $\alpha$

Energy

60134

0 6444

0

0

0

0

7 445 -46 600

21 848

79 469

80769

18 686 -449 750

0 55 706

Level

 $5s_{1/2}$ 

 $4f_{5/2}$ 

 $4f_{7/2}$ 

 $4f_{5/2}$ 

 $4f_{7/2}$ 

 $5s_{1/2}$ 

 $6p_{1/2}$ 

 $5f_{7/2}$ 

 $5s4f^{3}F_{2}$ 

 $5s4f^{3}F_{3}$ 

 $5s4f^{3}F_{2}$ 

 $5s4f^{3}F_{3}$ 

 $5f6p^{3}F_{2}$ 

 $*Cf^{17+}$  5 $f_{5/2}$ 

 $Nd^{12+} 5s^{2} S_0$ 

Sm<sup>14+</sup>  $4f^{2} {}^{3}H_{4}$ 

 $*Es^{17+}$  5 $f^{2}{}^{3}H_{4}$ 

Ion

 $Nd^{13+}$ 

 $\mathrm{Sm}^{15+}$ 

Κ

3.7

3.6

 $60\,517 \quad -134\,148 \quad -4.4 \quad 166 \quad 3.1\times10^5$ 

-48

2.4

2 172 -127 720 -118 4600  $5.6 \times 10^{13b}$ 

-13 1343

q

104 229

108 243

5910

17 900

101 461

102 325

3826 -126746 -66 2614

λ

179

166

535

124

2.6 126  $8.5 \times 10^{10}$ 

1.8 1526

1.6 458

au

 $1.3 \times 10^{6a}$ 

0.996

0.308

19.7

8.51

11 000

Ion

 $Ir^{16+}$ 

 $Ir^{17+}$ 

 $Ho^{14+}$ 

						Ion	Level	Energy	q	K	λ	τ
on	S (	of	α			Ce <sup>9+</sup>	$5s^{2}5p_{1/2} \\ 5s^{2}5p_{3/2} \\ 5s^{2}4f_{5/2} \\ 5s^{2}4f_{7/2} \\$	0 33 450 54 683 57 235	37 544 62 873 65 150	2.2 2.3 2.3	299 182 174	0.0030 0.0812 2.18
						Pr <sup>10+</sup>	$5s^{2}5p_{1/2} \\ 5s^{2}4f_{5/2} \\ 5s^{2}4f_{7/2} \\ 5s^{2}5p_{3/2}$	0 3 702 7 031 39 141	73 849 76 833 44 098	40 22 2.3	2700 1422 256	$8.5 \times 10^4$ 2.35 0.0018
						Nd <sup>11+</sup>	$\frac{5s^2 4f_{5/2}}{5s^2 4f_{7/2}}$ $\frac{5s^2 5p_{1/2}}{5s^2 5p_{1/2}}$	0 4 180 53 684	3 785 -85 692	1.8 -3.2	2392 186	1.19 0.061
						Sm <sup>13+</sup>	$5s^{2}4f  {}^{2}F_{5/2} \\ 5s^{2}4f  {}^{2}F_{7/2} \\ 4f^{2}5s  {}^{4}H_{7/2}$	0 6 203 20 254	5 654 123 621	1.8 12	1612 494	0.367 0.133
						Eu <sup>14+</sup>	$4f^{2}5s \ J = 7/2 4f^{3} \ J = 9/2 4f^{2}5s \ J = 9/2 4f^{3} \ J = 11/2$	0 1 262 2 594 5 388	137 437 1 942 141 771	218 1.5 53	7924 3855 1856	
Lev	vel	Energy	<i>q</i>	K	λ	*Cf <sup>15+</sup>	$5f6p^2 {}^2F_{5/2}$ $5f^26p {}^4I_{9/2}$ $5f6p^2 {}^2F_{7/2}$	0 12 898 22 018	380 000	59	775 454	6900 0.012
$4f^{13}5s^2 4f^{13}5s^2 4f^{14}5s$	${}^{2}F_{7/2}$ ${}^{2}F_{5/2}$ ${}^{2}S_{1/2}$	0 25 898 37 460	23 652 367 315	1.8 20	386 267	*Es <sup>16+</sup>	$5f^26p  {}^4I_{9/2} \\ 5f^26p  {}^2F_{5/2} \\ 5f^3  {}^2H_{9/2}$	0 6 994 10 591	-184 000	-53	1430 944	16 000 3.4
$4f^{13}5s$ $4f^{13}5s$ $4f^{13}5s$ $4f^{14}$ $4f^{12}5s^{2}$ $4f^{12}5s^{2}$	${}^{3}F_{4}$ ${}^{3}F_{3}$ ${}^{3}F_{2}$ ${}^{1}S_{0}$ ${}^{3}H_{6}$	0 4 838 26 272 5 055 35 285	2 065 24 183 367 161 -385 367	0.9 1.8 145 -22	2067 381 1978 283	Pr <sup>9+</sup> Nd <sup>10+</sup>	$5s^{2}5p^{2} {}^{3}P_{0}$ $5s^{2}5p4f {}^{3}G_{3}$ $5s^{2}5p4f {}^{3}F_{2}$ $5s^{2}5p4f {}^{3}F_{3}$ $5s^{2}4f^{2} J = 4$	0 20 216 22 772 25 362 0	42 721 42 865 47 076	4.2 3.8 3.7	475 426 382	$6.6 \times 10^{14}$ 59.0 5.33
$4f^{12}5s^2$ $4f^65s$ $4f^55s^2$	${}^{3}F_{4}$ ${}^{8}F_{1/2}$ ${}^{6}H_{5/2}$	45 214 23 823	-387 086 -186 000	-17 -16	420		$5s^{2}4f^{2}J = 4$ $5s^{2}5p4f J = 3$ $5s^{2}4f^{2} J = 5$ $5s^{2}5p4f J = 2$	1 564 3 059	-81 052 3 113 -60 350	-104 2.0 -24	2200	16 000 1.4 25

	HC	ls	an	d	Va	aria	ati	on	S (	of	α		Ion Ce <sup>9+</sup>	Level $5s^25p_{1/2}$ $5s^25p_{3/2}$ $5s^24f_{5/2}$ $5s^24f_{7/2}$	Energy 0 33 450 54 683 57 235	<i>q</i> 37 544 62 873 65 150	<i>K</i> 2.2 2.3 2.3	λ 299 182 174	τ 0.0030 0.0812 2.18
	✓ Vis	sible	e rar	ige	2								Pr <sup>10+</sup>	$5s^{2}5p_{1/2}$ $5s^{2}4f_{5/2}$ $5s^{2}4f_{7/2}$ $5s^{2}5p_{3/2}$	0 <u>3 702</u> 7 031 39 141	<del>73 849</del> <del>76 833</del> 44 098	40 22 2.3	2700 1422 256	$\frac{8.5 \times 10^4}{2.35}$ 0.0018
														$5s^{2}4f_{5/2}$ $5s^{2}4f_{7/2}$ $5s^{2}5p_{1/2}$ $5s^{2}4f^{2}F_{5/2}$	0 4 180 53 684 0	<del>3 785</del> -85 692	<del>1.8</del> -3.2	2392 186	1.19 0.061
Ion Nd <sup>13+</sup>	Level 5 <i>s</i> <sub>1/2</sub>	Energy 0	q	K	λ	τ								$5s^{2} 4f^{2}F_{7/2}$ $4f^{2}5s^{4}H_{7/2}$ $4f^{2}5s J = 7/2$ $4f^{3} J = 9/2$	6 203 20 254 0 1 262	5 654 123 621 137 437	1.8 12 218	<del>1612</del> 494 7924	0.367 0.133
Sm <sup>15+</sup>	$\begin{array}{c} 4f_{5/2} \\ 4f_{7/2} \\ 4f_{5/2} \\ 4f_{7/2} \end{array}$	55 706 60 134 0 6 444	104 229 108 243 5 910		179 166 1526	$1.3 \times 10^{6a}$ 0.996 0.308							*Cf <sup>15+</sup>	$ \begin{array}{l} 4f^{2} 5s \ J = 9/2 \\ 4f^{2} \ J = 11/2 \\ 5f6p^{2} \ ^{2}F_{5/2} \\ 5f^{2}6p^{4}I_{9/2} \end{array} $	2 594 5 388 0 12 898	<u>1942</u> <u>141771</u> 380 000	1.5 53	3855 1856 775	6900
*Cf <sup>17+</sup>	$5f_{5/2} \\ 5f_{5/2} \\ 6p_{1/2} \\ 5f_{7/2}$	60 517 0 18 686 21 848	<u>134 148</u> -449 750 17 900	4.4 -48 1.6	166 535 458		Ion Ir <sup>16+</sup>	Leve $4f^{13}5s^2$ $4f^{13}5s^2$ $4f^{14}5s$	el	Energy 0 25 898 37 460	<i>q</i> 23 652 367 315		$\frac{\lambda}{386} \xrightarrow{*\text{Es}^{16+}}_{267}$	$5f6p^2 {}^2F_{7/2}$	22 018 0 <u>6 994</u> 10 591	<del>-184 000</del>	-53	454 1430 944	0.012 
Nd <sup>12+</sup>	$5s^{2} {}^{1}S_{0}$ $5s4f {}^{3}F_{2}$ $5s4f {}^{2}F_{3}$ $4f^{2} {}^{3}H_{4}$	0 79 469 80 769 0	101 461 102 325	2.6 2.4	<del>- 126</del> - 124	$\frac{8.5 \times 10^{10}}{19.7}$	Ir <sup>17+</sup>	$4f^{13}5s  4f^{13}5s  4f^{13}5s  4f^{13}5s  4f^{14}$	${}^{3}F_{4}$ ${}^{3}F_{3}$ ${}^{3}F_{2}$ ${}^{1}S_{0}$	0 <u>4 838</u> 26 272 <u>5 055</u>	2 065 24 183 367 161	<del>- 0.9 - 2</del> 1.8	Pr <sup>9+</sup> 2067 381 1978	$5f H_{9/2}$ $5s^25p^2 {}^{3}P_0$ $5s^25p4f {}^{3}G_3$ $5s^25p4f {}^{3}F_2$ $5s^25p4f {}^{3}F_3$	0 20 216 22 772 25 362	42 721 42 865 47 076	4.2 3.8 3.7		$6.6 \times 10^{14}$ 59.0 5.33
*Es <sup>17+</sup>	$\begin{array}{r} 4f^{-1}H_{4} \\ 5s4f^{-3}F_{2} \\ 5s4f^{-3}F_{3} \\ 5f^{2}{}^{-3}H_{4} \\ 5f6p^{-3}F_{2} \end{array}$	0 2 172 3 826 0 7 445	<u>-127 720</u> -126 746 -46 600	-118 -66 -13	4600 2614 1343	$\frac{5.6 \times 10^{13b}}{8.51}$ 11 000	Ho <sup>14+</sup>	$     4f^{12}5s^2      4f^{12}5s^2      4f^65s      4f^55s^2 $	${}^{3}H_{6}$ ${}^{3}F_{4}$ ${}^{8}F_{1/2}$ ${}^{6}H_{5/2}$	35 285 45 214 23 823	-385 367 -387 086 -186 000	-22	283 221 Nd <sup>10+</sup>	$5s^{2}5p^{4}f^{2}J = 4$ $5s^{2}5p^{4}fJ = 3$ $5s^{2}4f^{2}J = 5$ $5s^{2}5p^{4}fJ = 2$	0	-81 052 3 113 -60 350		2200	16 000 1.4 25

	HC	:ls	an	d	Va	aria	ati	on	S (	of	α		Ion Ce <sup>9+</sup>	Level $5s^25p_{1/2}$ $5s^25p_{3/2}$ $5s^24f_{5/2}$ $5s^24f_{7/2}$	Energy 0 33 450 54 683 57 235	q 37 544 62 873 65 150	<i>K</i> 2.2 2.3 2.3	λ 299 182 174	τ 0.0030 0.0812 2.18
			e rar										Pr <sup>10+</sup>	$\frac{5s^25p_{1/2}}{5s^24f_{5/2}}$ $\frac{5s^24f_{5/2}}{5s^24f_{7/2}}$ $\frac{5s^25p_{3/2}}{5s^25p_{3/2}}$	0 <u>3 702</u> 7 031 39 141	73 849 76 833 44 098	40 22 2.3	2700 1422 256	$\frac{8.5 \times 10^4}{2.35}$
•	✓ Hi	gh v	value	es o	of I	<								+ $5s^24f_{5/2}$ $5s^24f_{7/2}$ $5s^25p_{1/2}$ + $5s^24f^2F_{5/2}$	0 <u>4 180</u> 53 684 0	<del>3 785</del> 	<del>-1.8</del> -3.2	2392 186	<u> </u>
Ion	Level	Energy			λ	τ							5111	$\frac{5s^{2}4f^{2}F_{7/2}}{4f^{2}5s^{4}H_{7/2}}$	6 203 20 254	<del>5 654</del> 123 621	1.8 12	<del>1612</del> 494	0.367 0.133
Nd <sup>13+</sup>	$\frac{5s_{1/2}}{4f_{5/2}}$	0 55 706 60 134	<i>q</i> 104 229 108 243	3.7 3.6	λ 179 166	$\frac{1.3 \times 10^{6a}}{0.996}$							Eu <sup>14+</sup>	$\begin{array}{r} 4f^25s \ J = 7/2 \\ 4f^3 \ J = 9/2 \\ 4f^25s \ J = 9/2 \\ 4f^2 \ J = 11/2 \end{array}$	0 <u>1 262</u> 2 594 5 388	137 437 1 942 141 771	218 1.5 53	7924 3855 1856	
Sm <sup>15+</sup>	$\begin{array}{c} 4f_{5/2} \\ 4f_{7/2} \\ 5s_{1/2} \end{array}$	0 <del>6 444</del> <del>60 517</del>	5 910 134 148	1.8 4.4	1526 166	$\frac{0.308}{3.1 \times 10^5}$	Ion	Lev	el	Energy	q	K	${\lambda}$ *Cf <sup>15</sup>	$ \begin{array}{r} 5 \\ 5 \\ 5 \\ f^2 6 \\ p \\ 4 \\ I_{9/2} \\ 5 \\ f^2 6 \\ p^2 \\ F_{7/2} \end{array} $	0 12 898 22 018	380 000	59	775 454	6900 0.012
*Cf <sup>17+</sup>	$5f_{5/2} \\ 6p_{1/2} \\ 5f_{7/2}$	0 18 686 21 848	-449 750 17 900	-48 	535 458		Ir <sup>16+</sup>	$4f^{13}5s^2 \\ 4f^{13}5s^2 \\ 4f^{14}5s$	${}^{2}F_{7/2}$ ${}^{2}F_{5/2}$ ${}^{2}S_{1/2}$	0 25 898 37 460	<u>23 652</u> 367 315	1.8 20	*Es <sup>16</sup> 267	$ \begin{array}{r} + 5f^2 6p  {}^4I_{9/2} \\ \hline 5f^2 6p  {}^2F_{5/2} \\ 5f^3  {}^2H_{9/2} \end{array} $	0 <del>6 994</del> 10 591	<del>-184<i>0</i>00</del>	-53	<del>-1430</del> 944	<del>- 16 000 -</del> 3.4
Nd <sup>12+</sup>	$\frac{5s^{2} {}^{1}S_{0}}{5s4f {}^{3}F_{2}}}{5s4f {}^{3}F_{3}}$	0 79 469 80 769	<u>-101 461</u> 102 325	2.6 2.4	126 124	$\frac{8.5 \times 10^{10}}{19.7}$	Ir <sup>17+</sup>	$4f^{13}5s$ $4f^{13}5s$ $4f^{13}5s$	$3F_4$ $3F_3$ $3F_2$	0 <u>4 838</u> 26 272	<del>2 065</del> 24 183	0.9 1.8	$\frac{-2067}{-381}$ Pr <sup>9+</sup>	$\frac{5s^2 5p^2 {}^3P_0}{5s^2 5p 4 \int {}^3G_3}$	0 20 216 22 772	42 721 42 865	4.2	475 (	$\frac{5.6 \times 10^{14}}{59.0}$
Sm <sup>14+</sup>	$\frac{4f^{2} {}^{3}H_{4}}{5s4f {}^{3}F_{2}}}{5s4f {}^{2}F_{3}}$	0 2 172 3 826	<u>-127 720</u> -126 746	-118 -66	4600 2614	$\frac{5.6 \times 10^{13^{b}}}{8.51}$		$\frac{4f^{14}}{4f^{12}5s^2}$ $4f^{12}5s^2$	${}^{1}S_{0}$ ${}^{3}H_{6}$ ${}^{3}F_{4}$	5 055 35 285 45 214	367 161 -385 367 -387 086	145 -22 -17	1978 283 221 Nd <sup>10-</sup>	$5s^25p4f^3F_3$	25 362 0	-81 052	<u> </u>	382	5.33
*Es <sup>17+</sup>	$5f^{2} {}^{3}H_{4}$ $5f6p {}^{3}F_{2}$	0 7 445	-46 600	-13	1343	11 000	Ho <sup>14+</sup>	$4f^65s$ $4f^55s^2$	${}^{8}F_{1/2}$ ${}^{6}H_{5/2}$	23 823	-186 000	-16	420	$5s^{3} p + f^{2} J = 5$ $5s^{2} 4f^{2} J = 5$ $5s^{2} 5p + f^{2} J = 2$	3 059 5 060	3 113 -60 350	2.0 -24	2200	1.4 25

Ion Level Energy	q	Κ.	λ	τ
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#### HCIs and variations of $\alpha$

## ✓ Visible range✓ High values of K

${\rm Sm}^{13+}$	$5s^24f^2F_{5/2}$	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

Ion Level Energy q K  $\lambda$   $\tau$ 

														*Cf <sup>15+</sup>	$5f6p^2 {}^2F_{5/2} \\ 5f^26p {}^4I_{9/2}$	0 12 898	380 000	59	775	6900
							Ion	Leve	el	Energy	q	K	λ		$5f6p^2 {}^2F_{7/2}$	22 018			454	0.012
$*Cf^{17+}$	$5f_{5/2}$	0					$Ir^{16+}$	$4f^{13}5s^2$	${}^{2}F_{7/2}$	0				*Es <sup>16+</sup>	$5f^26p  {}^4\!I_{9/2}$	0				
	$6p_{1/2}$	18 686	-449 750	-48	535			$4f^{13}5s^2$	${}^{2}F_{5/2}$	25 898	23 652	1.8	386	. 10	$5f^{2}6p^{2}F_{5/2}$		-184000	-53	1430	16 000
	$5f_{7/2}$	21 848	17 900	1.6	458			$4f^{14}5s$	${}^{2}S_{1/2}$	37 460	367 315	20	267		$5f^{3}{}^{2}H_{9/2}$	10 591			944	3.4
							$Ir^{17+}$	$4f^{13}5s$	${}^{3}F_{4}$	0										
								$4f^{13}5s$	${}^{3}F_{3}$	4 8 3 8	2 065	0.9	2067							
								$4f^{13}5s$	${}^{3}F_{2}$	26 272	24 183	1.8	381							
								$4f^{14}$	${}^{1}S_{0}$	5 0 5 5	367 161	145	1978							
								$4f^{12}5s^2$	${}^{3}H_{6}$	35 285	-385 367	-22	283							
								$4f^{12}5s^2$	${}^{3}F_{4}$	45 214	-387 086	-17	221							
*Es <sup>17+</sup>	$5f^{2}{}^{3}H_{4}$	0					$\mathrm{Ho}^{14+}$	$4f^{6}5s$	${}^{8}F_{1/2}$											
	$5f6p^{3}F_{2}$	7 445	-46 600	-13	1343	11 000		$4f^55s^2$	${}^{6}H_{5/2}$	23 823	-186 000	-16	420							

Ion	Level	Energy	q	K	λ	au
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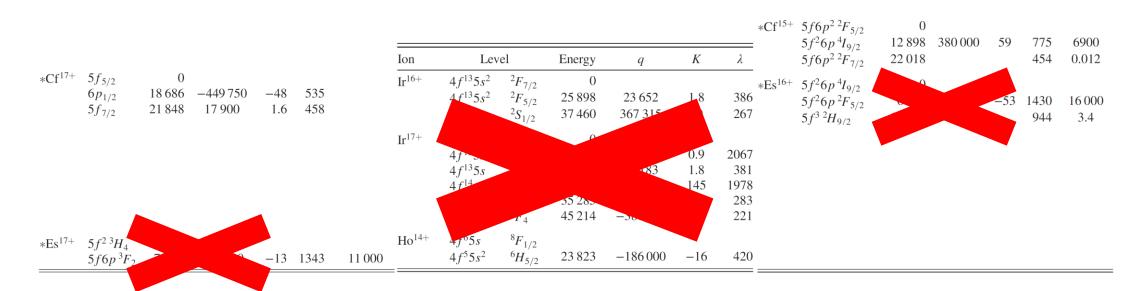
#### HCIs and variations of $\alpha$

✓ Visible range ✓ High values of K Too unstable

#### Other groups

$\mathrm{Sm}^{13+}$	$5s^24f^2F_{5/2}$	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

Energy Level Κ λ Ion q $\tau$ 



1011 Level Lifety $q$ $R$ $h$ $t$	Ion	Level	Energy	q	K	λ	τ
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#### HCIs and variations of $\alpha$

✓ Visible range ◆ Other groups ✓ High values of K ◆ Too unstable

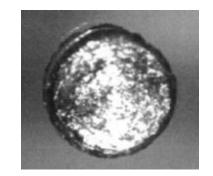
K  $\lambda$ Ion Level Energy qau

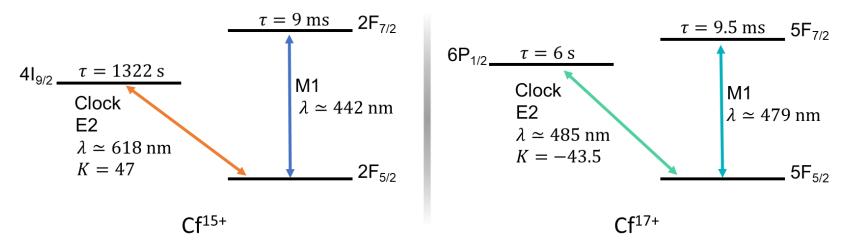
$*Cf^{15+} 5f6p^2 {}^2F_{5/2}$	0				
$5f^26p  {}^4\!I_{9/2}$	12 898	380 000	59	775	6900
$5f6p^2 {}^2F_{7/2}$	22 018			454	0.012

 $*Cf^{17+}$  5 $f_{5/2}$ 0  $6p_{1/2}$ 18 686 -449 750 -48535  $5f_{7/2}$ 21 848 17 900 458 1.6

### Cf HCls

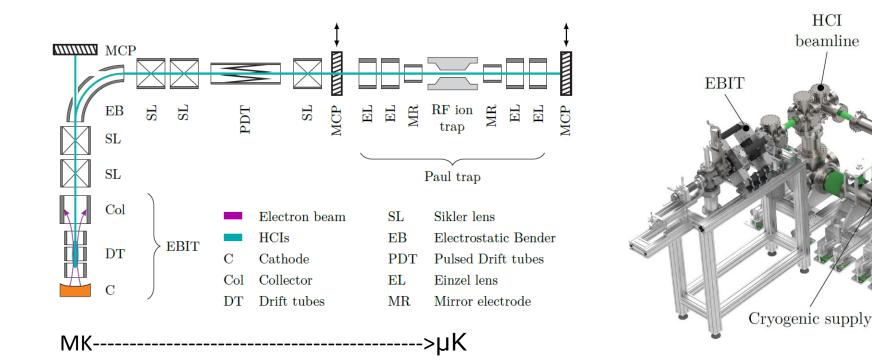
- Cf is a synthetic element produced in reactors
- <sup>249</sup>Cf has a half-life of 350 y, <sup>252</sup>Cf of 2650 y
- It costs ~\$7,350,000 / g (!)





- 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

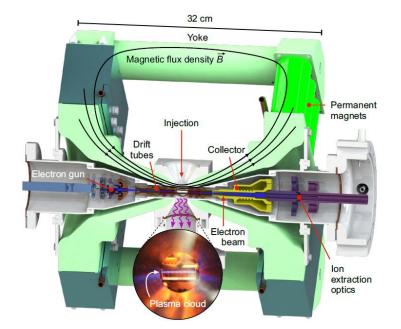


Cryogenic Paul trap

oven

MPI Heidelberg & PTB

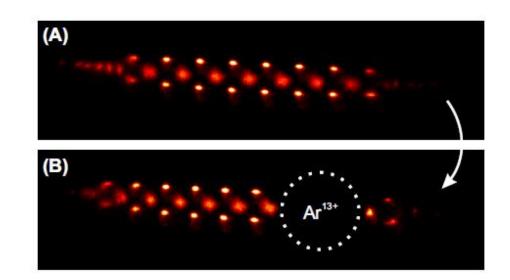
## Production, cooling and trapping of HCIs



Pulse-tube cryocooler - 1<sup>st</sup> temperature stage - 2<sup>nd</sup> temperature stage - Temperature sensors - Temperature sensors - Segment I - Segment II - Segment II - Segment II

Compact EBIT @ MPI Heidelberg Ultra-low vibration cryogenic vacuum

## Production, cooling and trapping of HCIs



- Once produced and pre-cooled, the ions are implanted into a Coulomb crystal of singlycharged ions
- Sympathetic cooling with the crystal [Science 347 (6227), 1233-1236 (2015)]
- QLS using the co-trapped ions [Nature 578 (7793), 60-65 (2020)]

## **QSNET** Phenomenology



## Phenomenology

• Coupling of scalar fields with standard matter [EPJ QT 9, 12 (2022)]:

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

 $\Lambda_{\gamma}^{n}$  alter the fine structure constant  $\alpha$ ,  $\Lambda_{f}^{n}$  the fermionic masses -> manifest as effective variations of fundamental constants

- Scalar dark matter models
- Quintessence-like models
- A generic hidden sector scalar field
- Kaluza-Klein models/moduli models
- Dilaton field models
- Soliton models, transient phenomena, cosmic strings, domain walls, and kink solutions

#### Scalar dark matter

Low-mass spinless bosons may form a coherently oscillating classical field, which in the rest frame is given by:

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

This would induce apparent oscillations of the fine structure constant and electron mass

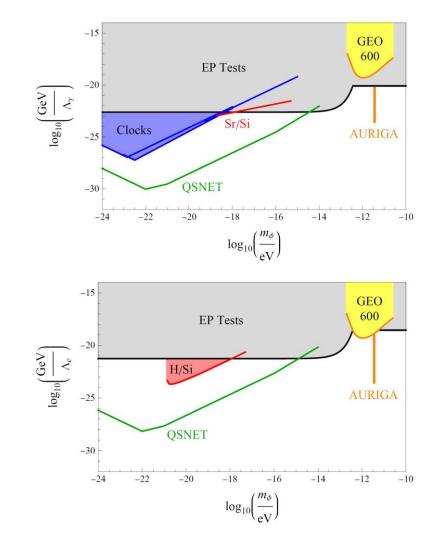
$$\frac{d\alpha}{\alpha} \approx \frac{\phi_0 \cos(m_\phi t)}{\Lambda_\gamma}, \quad \frac{dm_e}{m_e} \approx \frac{\phi_0 \cos(m_\phi t)}{\Lambda_e}$$
$$\frac{d\alpha}{\alpha} \approx \frac{\phi_0^2 \cos^2(m_\phi t)}{(\Lambda_\gamma')^2}, \quad \frac{dm_e}{m_e} \approx \frac{\phi_0^2 \cos^2(m_\phi t)}{(\Lambda_e')^2}$$

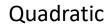
Therefore we would observe atomic frequencies undergoing small oscillations in time around their mean value:

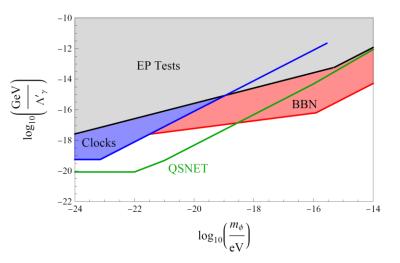
$$\frac{dR}{R} = (K_{X,1} - K_{X,2}) \frac{dX}{X} \propto (K_{X,1} - K_{X,2}) \cos(2\pi f_{\text{signal}} t)$$

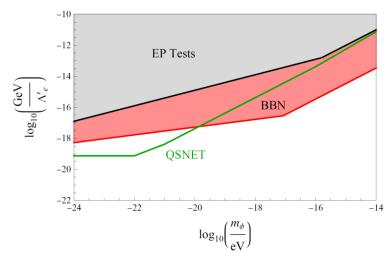
#### Scalar dark matter

Linear









## Dark energy

Dark energy, usually in the form of a cosmological constant, is postulated to explain the observed accelerated expansion of the universe.

In quintessence models, the matter content of the universe consists of radiation, dark matter, visible matter and quintessence, which is a scalar field that evolves on a cosmological time scale.

$$\ddot{\phi} + 3H\dot{\phi} + \frac{\partial V}{\partial \phi} = \frac{\partial \mathcal{L}_{\text{int}}}{\partial \phi} \quad \longrightarrow \quad \ddot{\phi} + 3H\dot{\phi} + m_{\phi}^2 \phi \approx 0$$

- Overdamped regime, very low masses, no appreciable change
- Underdamped regime, large masses, oscillations similar to DM
- Appreciable changes in the scalar field compatible with dark energy occur when  $m_{\phi} \sim H_0 \sim 10^{-33} \text{eV}$

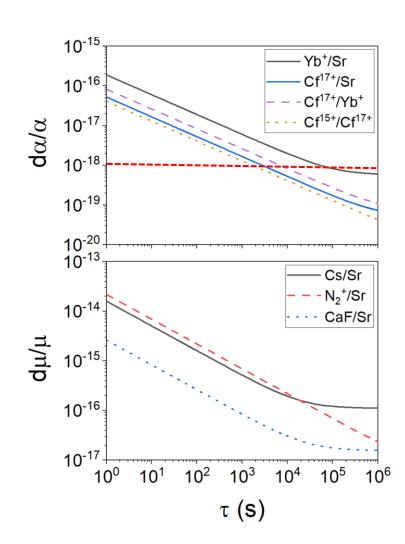
If the quintessence field couples to visible matter, fundamental constants could be slowly evolving with cosmological time

## Dark energy

Linear drifts in  $\boldsymbol{\alpha}$ 

Current limits:

Measurement type	$ d\ln(lpha)/dt /{ m yr}$
Yb <sup>+</sup> clocks	$\sim 10^{-18}$
Oklo phenomenon	$\sim 10^{-17}$
Meteorite dating	$\sim 10^{-16}$
MICROSCOPE (indirect limits)	$\sim 10^{-17} - 10^{-23}$

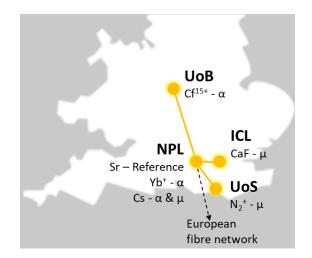


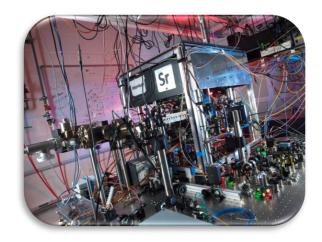
## Other tests [EPJ QT 9, 12 (2022)]

- Solitons
  - Topological solitons are made up of one or more fields that acquire stability due to the presence of two or more vacua
  - transient events, network is needed
- Violation of fundamental symmetries (Lorentz invariance)
  - Space-time symmetries have been studied in a number of new-physics scenarios, some of these works suggest Lorentz-violating effects may exist and be detectable in experiments with exceptional sensitivity (Cf)
- Grand unification theories
  - QSNET is sensitive both to variations of  $\alpha$  and  $\mu$ , can discriminate between GUTs:  $\dot{\mu}/\mu = R \dot{\alpha}/\alpha$ , with R strongly model dependent
- Quantum gravity
  - If light scalar field is detected, coupling operators between dark and standard matter are not generated by quantum gravity

## Summary

- A new inter-disciplinary community gathered around a new (expandable) national infrastructure
- Extending and exploiting world-class expertise and capabilities developed in NQTP
- A unique opportunity for discovery, improving current limits on variations of  $\alpha$  and  $\mu$  by orders of magnitude
  - Cosmology
  - Astrophysics
  - High-energy theory
  - Fundamental symmetries
  - ...







## Thanks

- White paper: EPJ Quantum Technology 9, 12 (2022) [arXiv:2112.10618]
- Website: <a href="mailto:qsnet.org.uk">qsnet.org.uk</a>



- Quantum systems: quantumsystemsbham.wixsite.com
  - Quantum simulations [arXiv:2112.10648]
  - Quantum thermodynamics [arXiv:2204.11816, PRX Quantum tbp]
  - Quantum sensors for neuroscience [NeuroImage tbp]

