A network of clocks for measuring the stability of fundamental constants

Birmingham NPL Sussex Imperial

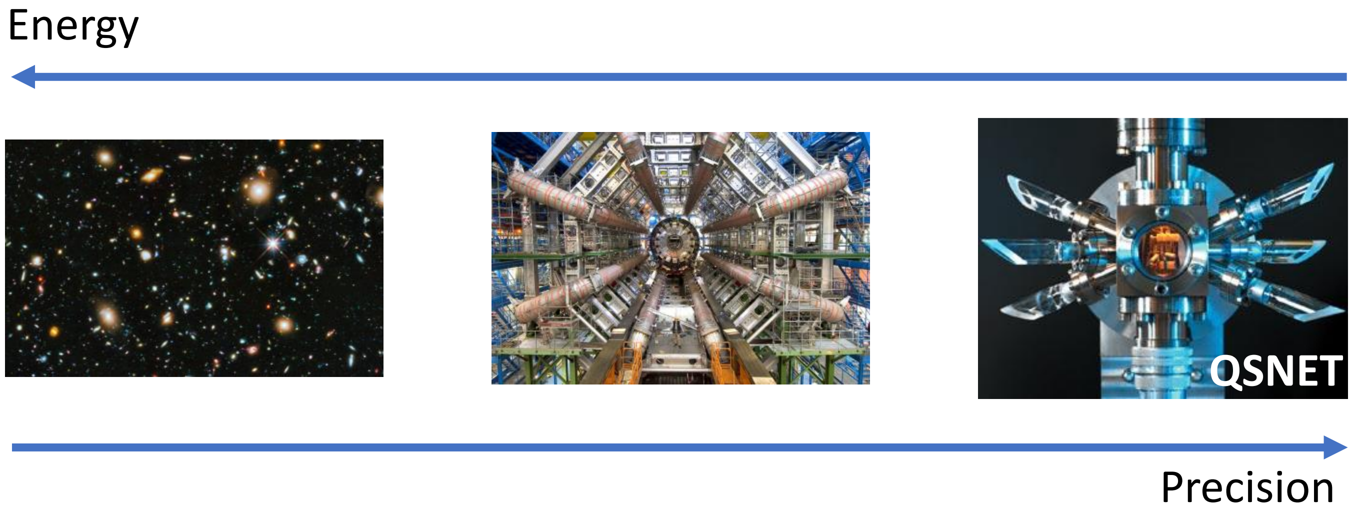
QTFP

- QSNET is one of the 7 projects funded within the QTFP programme of STFC&EPSRC https://www.ukri.org/news/quantum-projects-launched-to-solve-the-universes-mysteries/

- QTFP aims at building a community at the interface of quantum physics and fundamental physics

Background

- Searches for physics beyond the SM



Background

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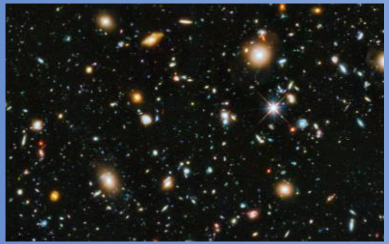
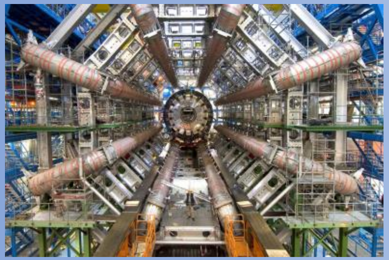
Science and Technology Facilities Council

Energy





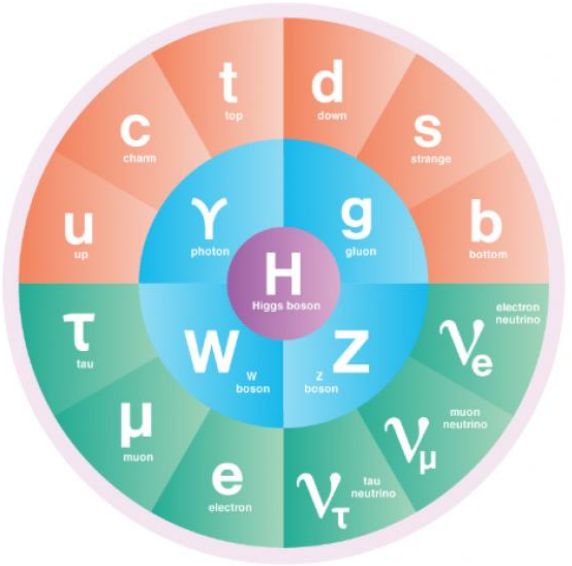
Precision

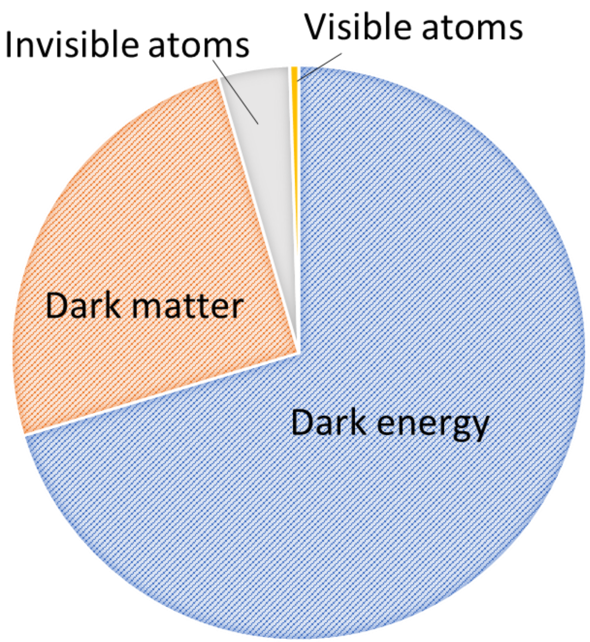
Engineering and Physical Sciences Research Council

Background

- 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.





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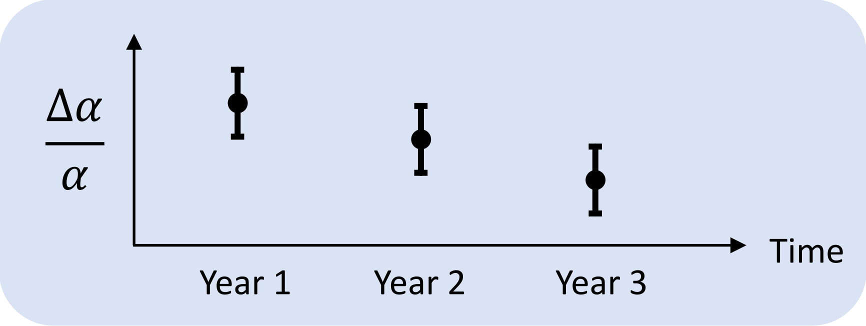
- Both models have several parameters, supposed to be immutable, called fundamental constants.

- Challenging this central assumption could be the key to solving the dark matter and dark energy enigmas

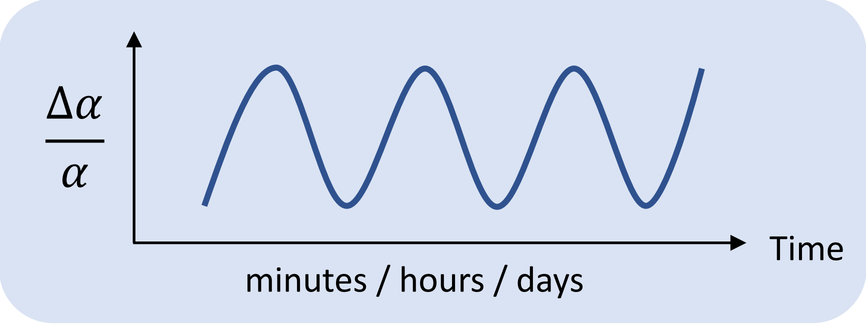
- Any variations of fundamental constants would give us evidence of revolutionary new physics

Look for variation on different timescales

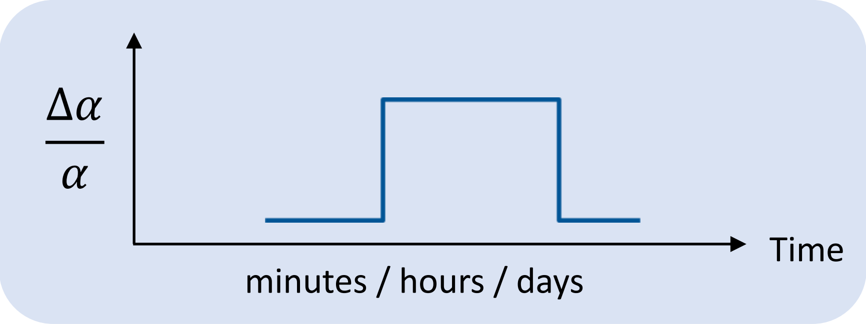
- Slow drifts



- Oscillations



- Fast transients



And any combination…

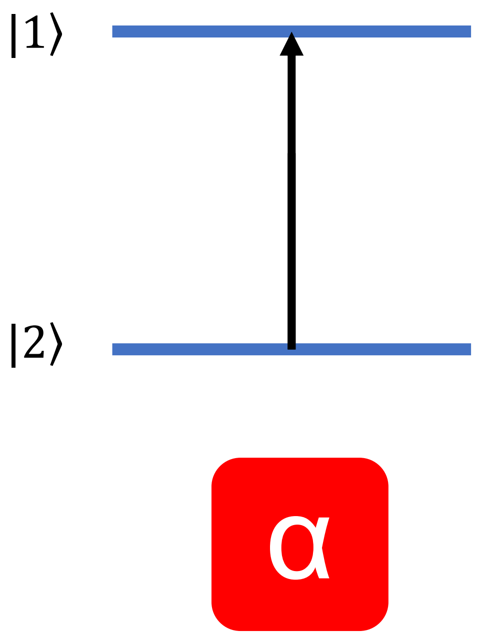
Why clocks?

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

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

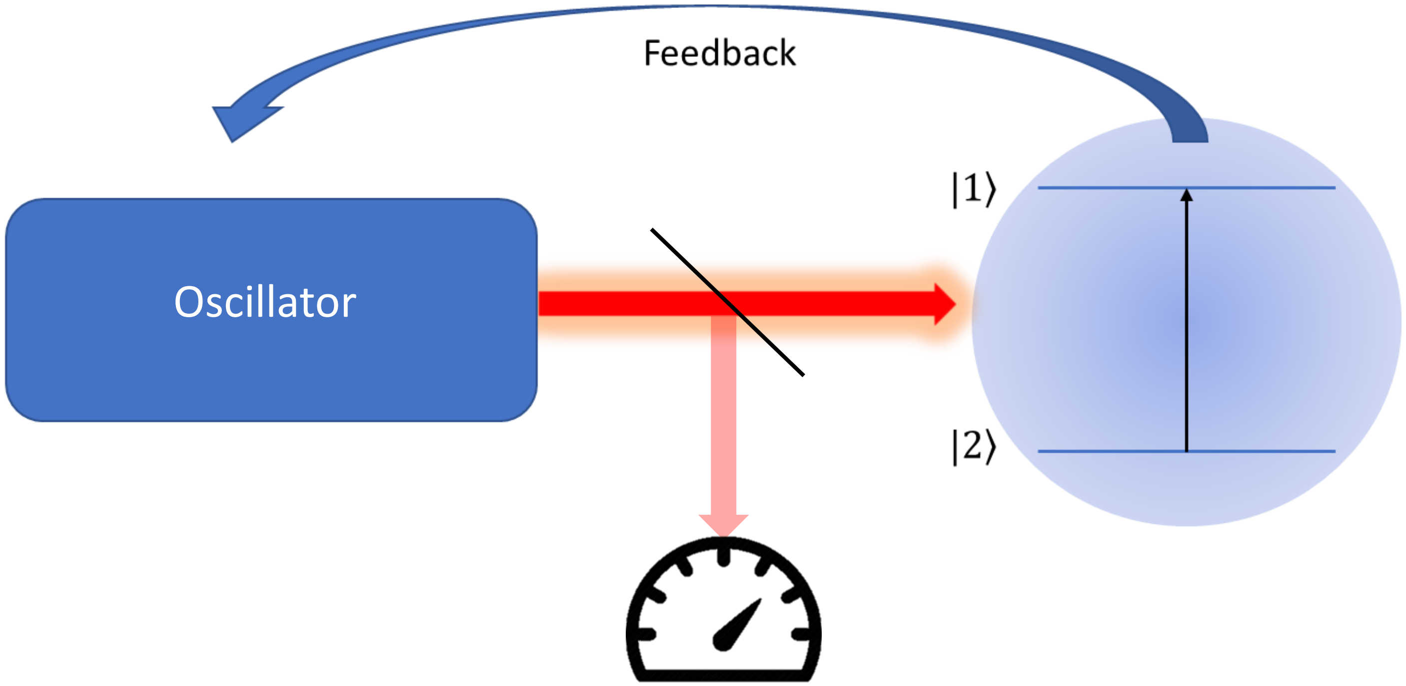
- Atomic an molecular spectra can be measured with extreme precision using atomic clocks

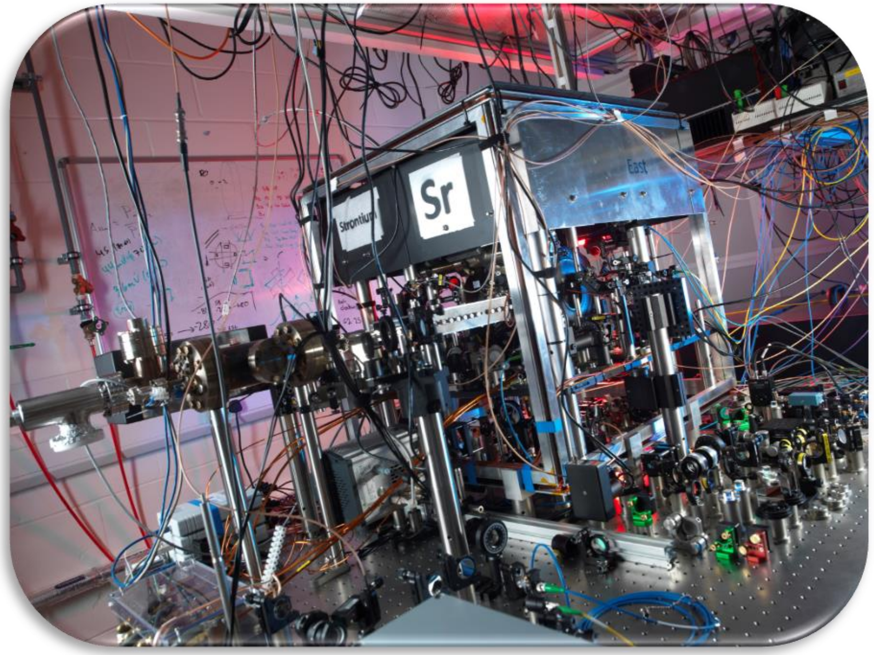
- Grand unification physics fixes relations between fundamental constants (if one changes with time, others will as well)



Atomic clocks

- Extremely high-precision spectroscopy





- Stability and accuracy at the 10^{-18} level

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
  $\upsilon_{Opt} = BF_{Opt}(\alpha)R_\infty$

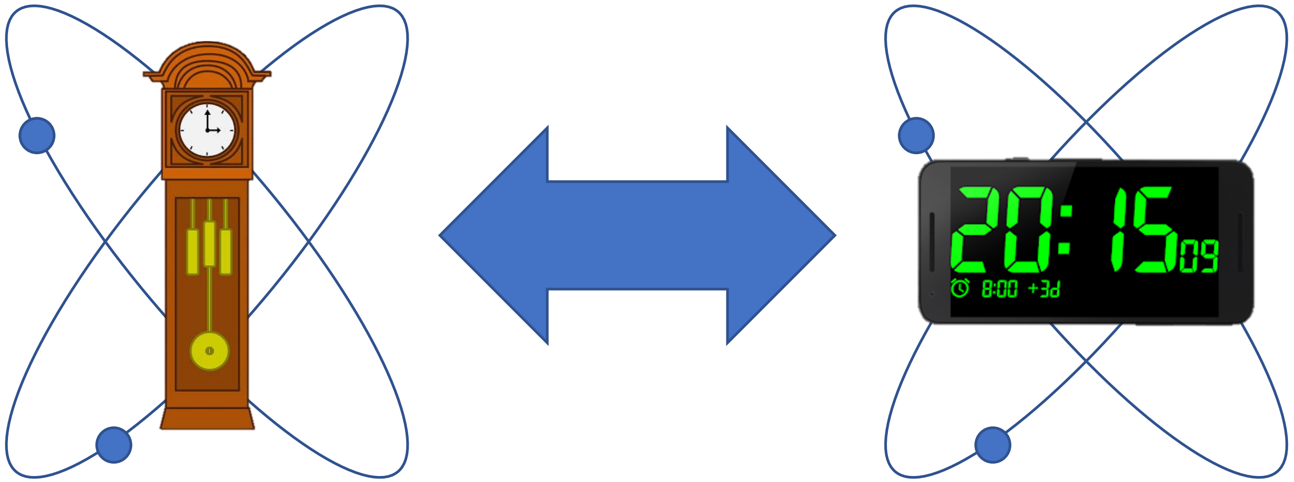
- Vibrational transitions
  $\upsilon_{vib} = C\mu^{1/2}R_\infty$

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

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

How to measure variations of fundamental constants

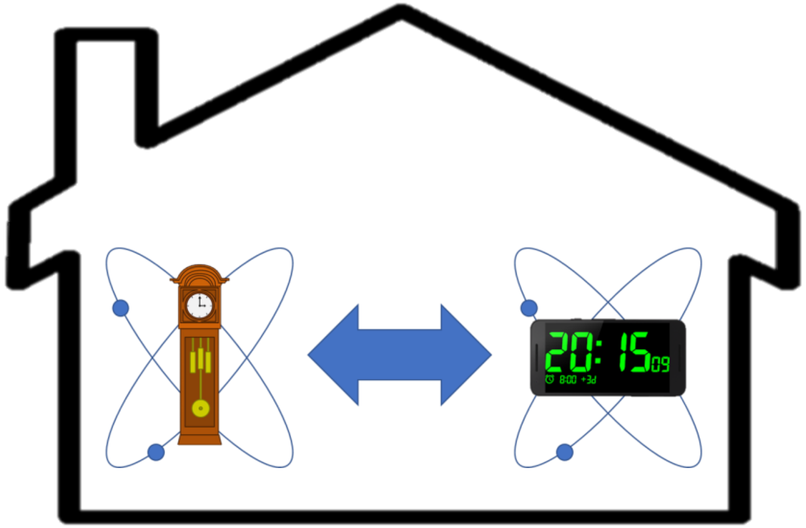
- Comparing clocks with different sensitivities to fundamental constants



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

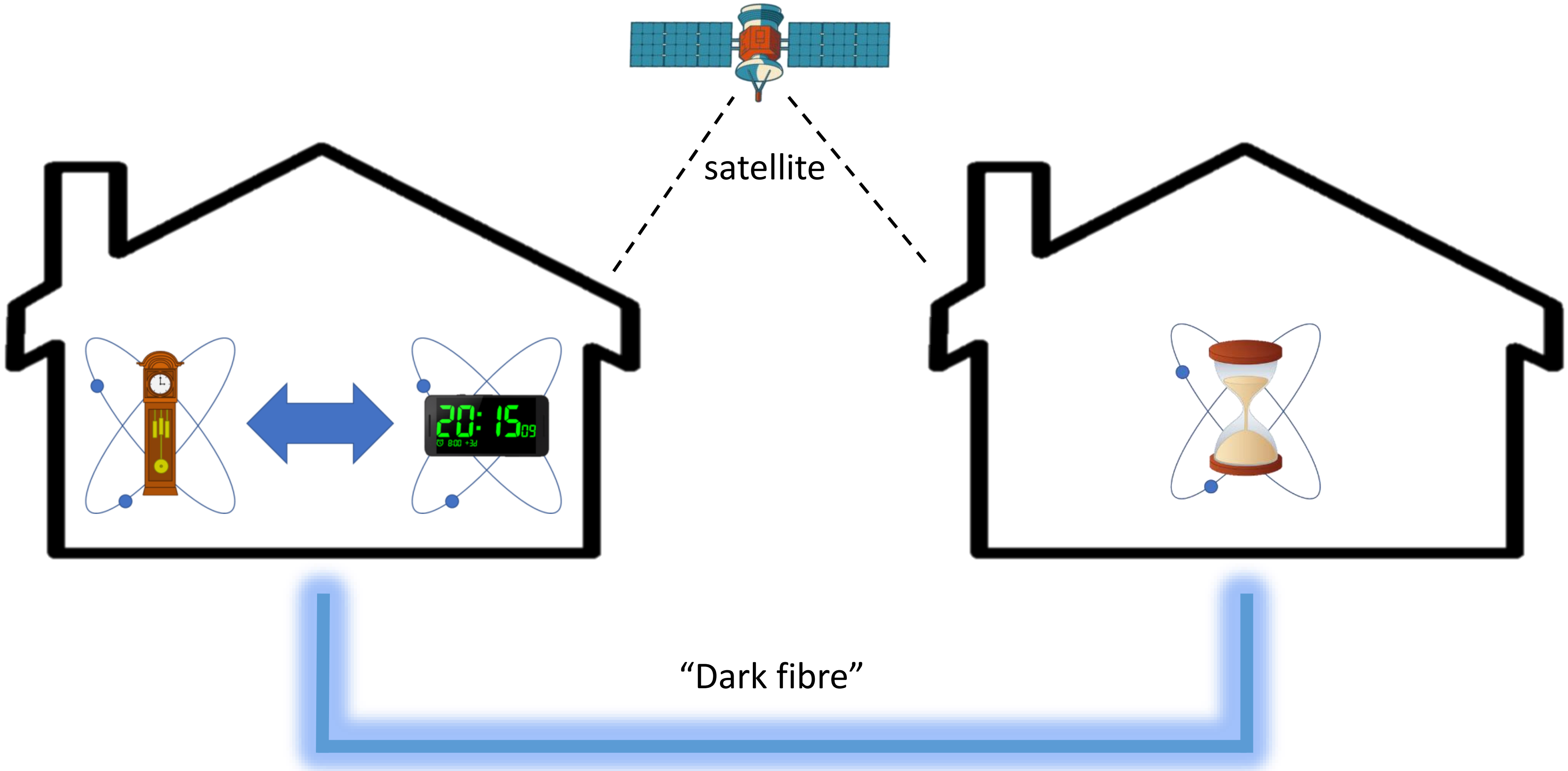
$$\frac{\Delta f1}{\Delta f2} = |K_{1x} - K_{2x}| \frac{\Delta x}{x} \qquad x = \alpha, \mu$$

How to measure variations of fundamental constants



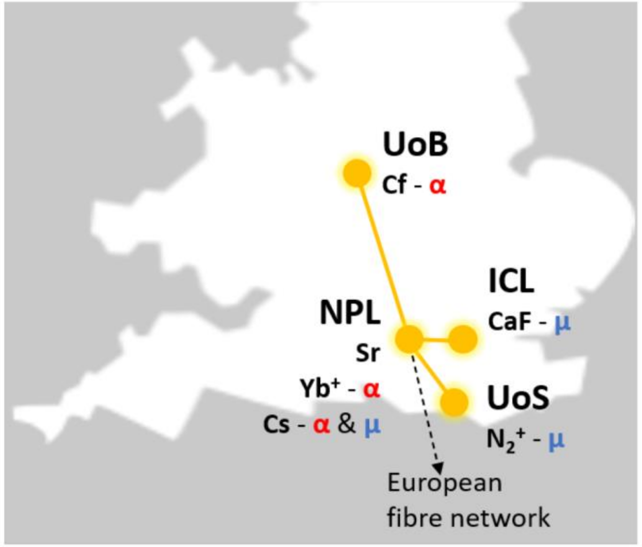
“in house” comparison

How to measure variations of fundamental constants



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

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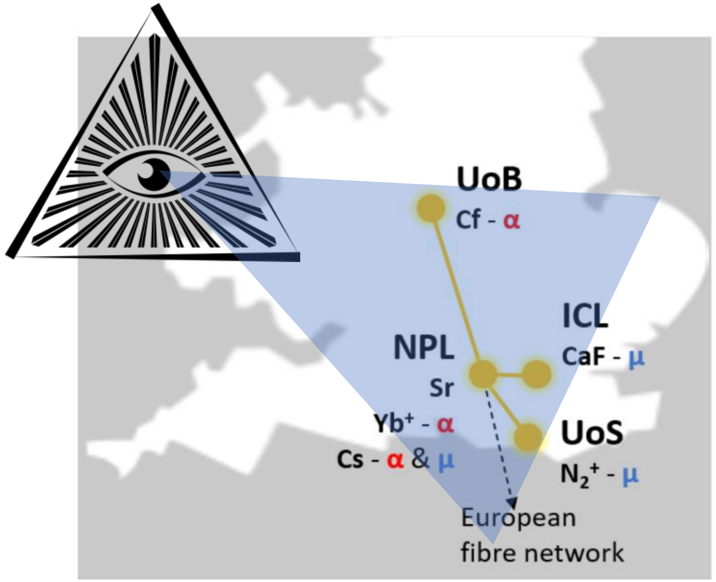

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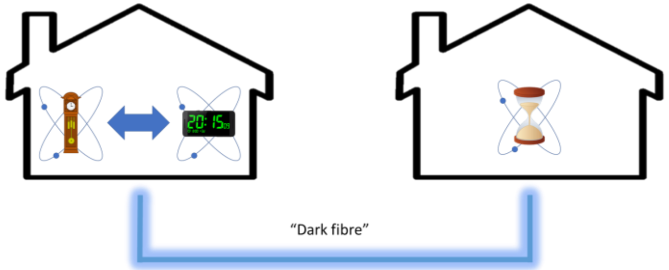
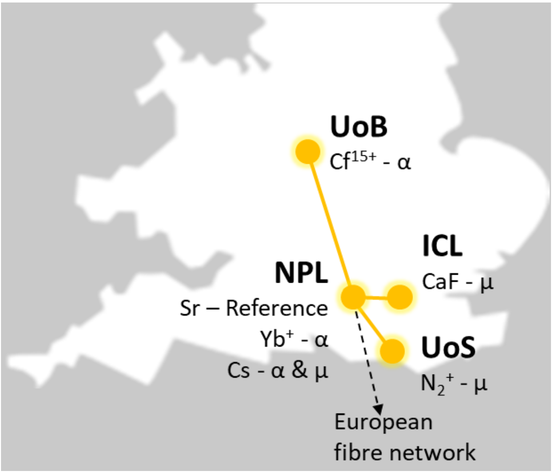
The network approach

- 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

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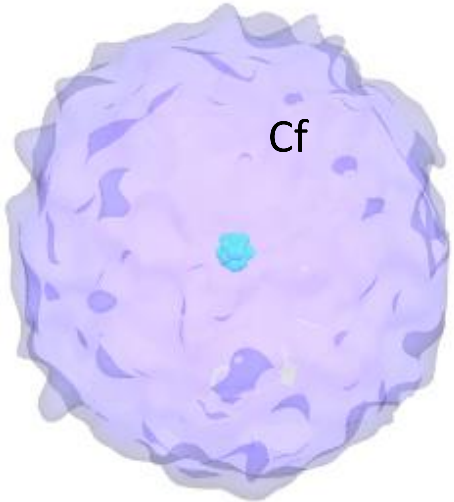
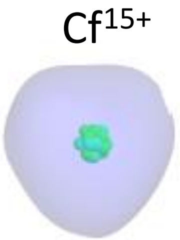
The Bham node: Highly-charged ions

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 α $(K_{\alpha} \sim 10 - 100)$

Highly-charged ions

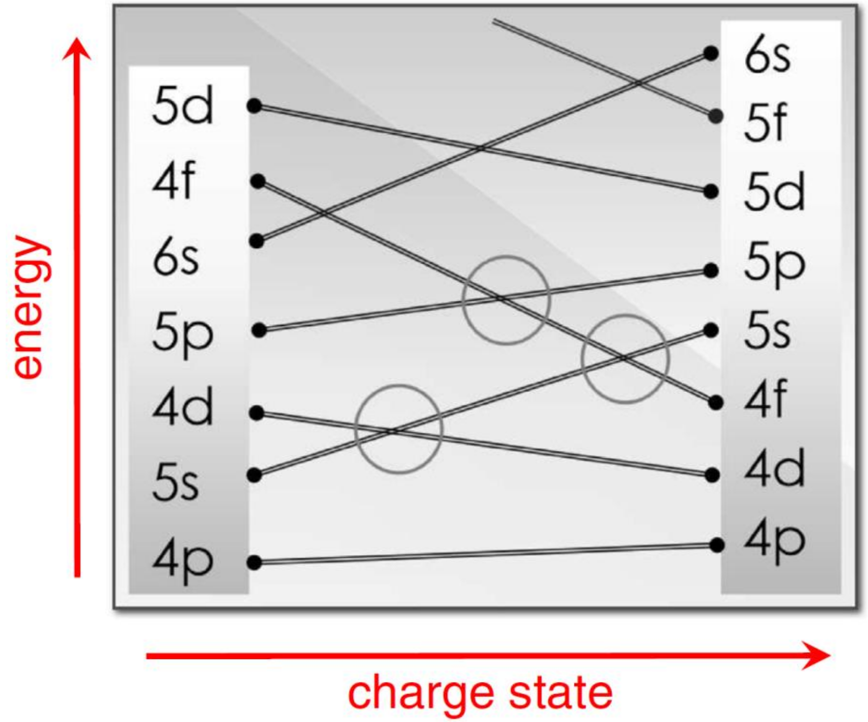
The energy scale for electronic transitions scales as

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

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 α

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
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	$5s^24f\ ^2F_{7/2}$	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				
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	$5s^24f^2\ J = 5$	3 059	3 113	2.0		1.4
	$5s^25p4f\ J = 2$	5 060	−60 350	−24	2200	25

HCIs and variations of α

✓Visible range

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HCIs and variations of α

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✓High values of K

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

HCIs and variations of α

- ✓Visible range
- ✓High values of K

Ion	Level	Energy	q	K	λ	τ
$*Cf^{17+}$	$5f_{5/2}$	0				
	$6p_{1/2}$	18 686	−449 750	−48	535	
	$5f_{7/2}$	21 848	17 900	1.6	458	
$*Es^{17+}$	$5f^2\,{}^3H_4$	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
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Sm^{13+}	$5s^2 4f\,{}^2F_{5/2}$	0				
	$5s^2 4f\,{}^2F_{7/2}$	6 203	5 654	1.8	1612	0.367
	$4f^2 5s\,{}^4H_{7/2}$	20 254	123 621	12	494	0.133
$*Cf^{15+}$	$5f6p^2\,{}^2F_{5/2}$	0				
	$5f^2 6p\,{}^4I_{9/2}$	12 898	380 000	59	775	6900
	$5f6p^2\,{}^2F_{7/2}$	22 018			454	0.012
$*Es^{16+}$	$5f^2 6p\,{}^4I_{9/2}$	0				
	$5f^2 6p\,{}^2F_{5/2}$	6 994	−184 000	−53	1430	16 000
	$5f^3\,{}^2H_{9/2}$	10 591			944	3.4

HCIs and variations of α

- ✓Visible range
- ✓High values of K

- ❖Other groups
- ❖ Too unstable

Ion	Level	Energy	q	K	λ	τ
Sm^{13+}	$5s^2 4f\ ^2F_{5/2}$	0				
	$5s^2 4f\ ^2F_{7/2}$	6 203	5 654	1.8	1612	0.367
	$4f^2 5s\ ^4H_{7/2}$	20 254	123 621	12	494	0.133
$*Cf^{15+}$	$5f6p^2\ ^2F_{5/2}$	0				
	$5f^2 6p\ ^4I_{9/2}$	12 898	380 000	59	775	6900
	$5f6p^2\ ^2F_{7/2}$	22 018			454	0.012
$*Es^{16+}$	$5f^2 6p\ ^4I_{9/2}$	[illegible]				
	$5f^2 6p\ ^2F_{5/2}$	[illegible]	[illegible]	−53	1430	16 000
	$5f^3\ ^2H_{9/2}$	[illegible]	[illegible]	[illegible]	944	3.4

Ion	Level	Energy	q	K	λ	τ
$*Cf^{17+}$	$5f_{5/2}$	0				
	$6p_{1/2}$	18 686	−449 750	−48	535	
	$5f_{7/2}$	21 848	17 900	1.6	458	
$*Es^{17+}$	$5f^2\ ^3H_4$	[illegible]				
	$5f6p\ ^3F_2$	[illegible]	[illegible]	−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
	[illegible]	$^2S_{1/2}$	37 460	367 315	[illegible]	267
Ir^{17+}	[illegible]	[illegible]	0			
	[illegible]	[illegible]	[illegible]	[illegible]	0.9	2067
	$4f^{13}5s$	[illegible]	[illegible]	[illegible]	1.8	381
	[illegible]	[illegible]	[illegible]	[illegible]	145	1978
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	283
	[illegible]	[illegible]	45 214	[illegible]	[illegible]	221
Ho^{14+}	[illegible]	$^8F_{1/2}$				
	$4f^5 5s^2$	$^6H_{5/2}$	23 823	−186 000	−16	420

HCIs and variations of α

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$*Cf^{17+}$	$5f_{5/2}$	0				
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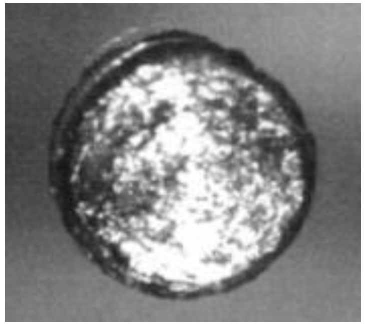
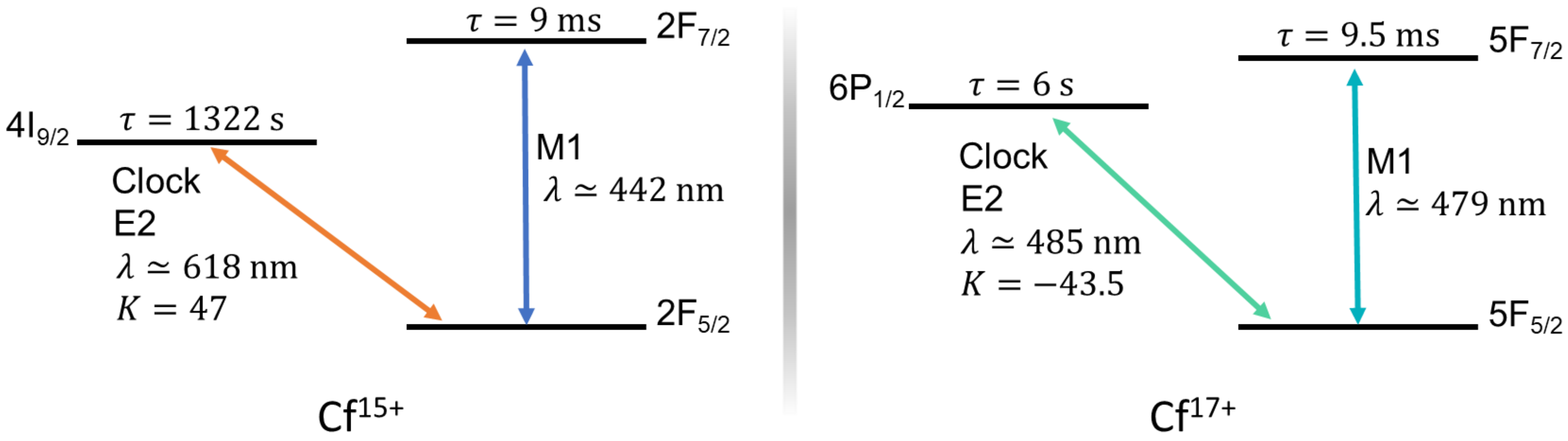
	$5f_{7/2}$	21 848	17 900	1.6	458	

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

Cf HCIs

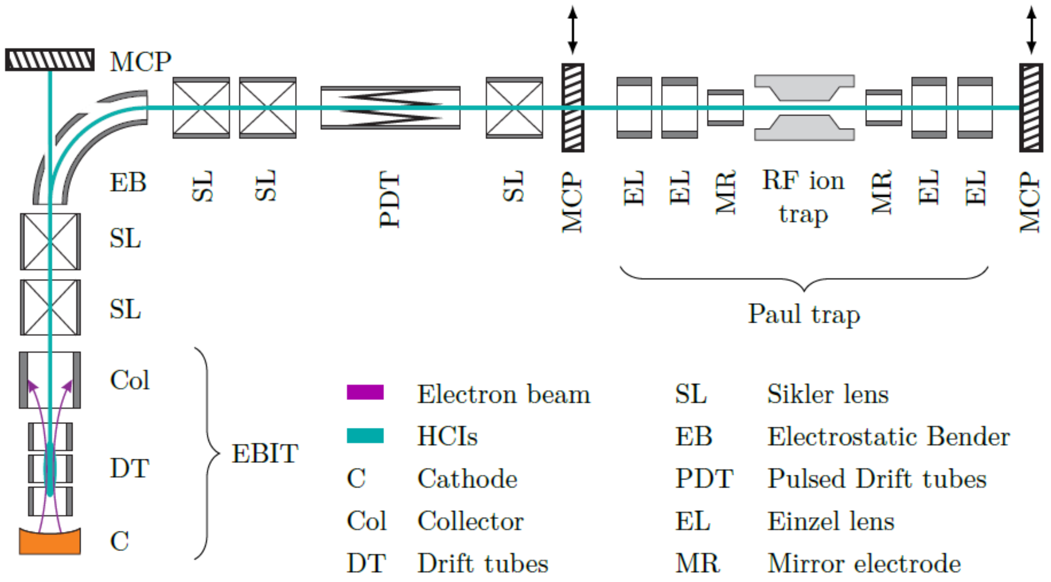
- Cf is a synthetic element produced in reactors
- ^{249}Cf has a half-life of 350 y, ^{252}Cf of 2650 y
- It costs ~$7,350,000 / g (!)

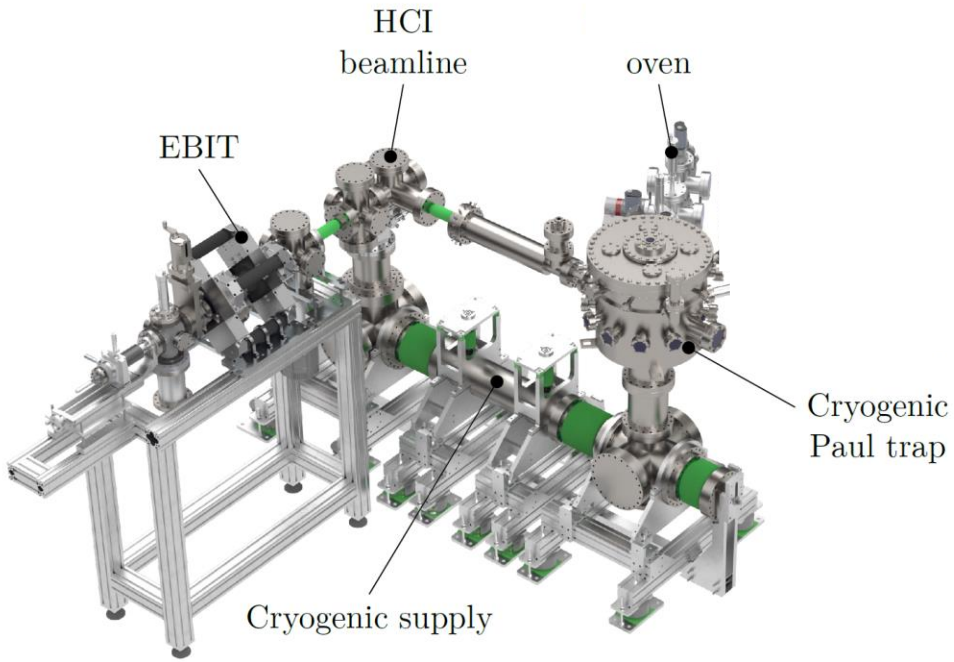




- Both ionisation states feature a clock transition in the visible range and a strong-ish transition also in the visible range
- The two clock transitions have large Ks with opposite sign

Production, cooling and trapping of HCIs

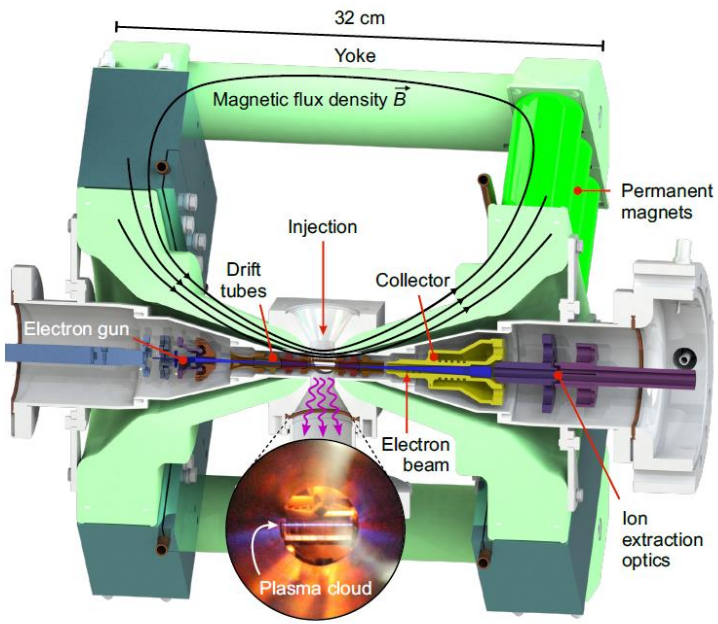




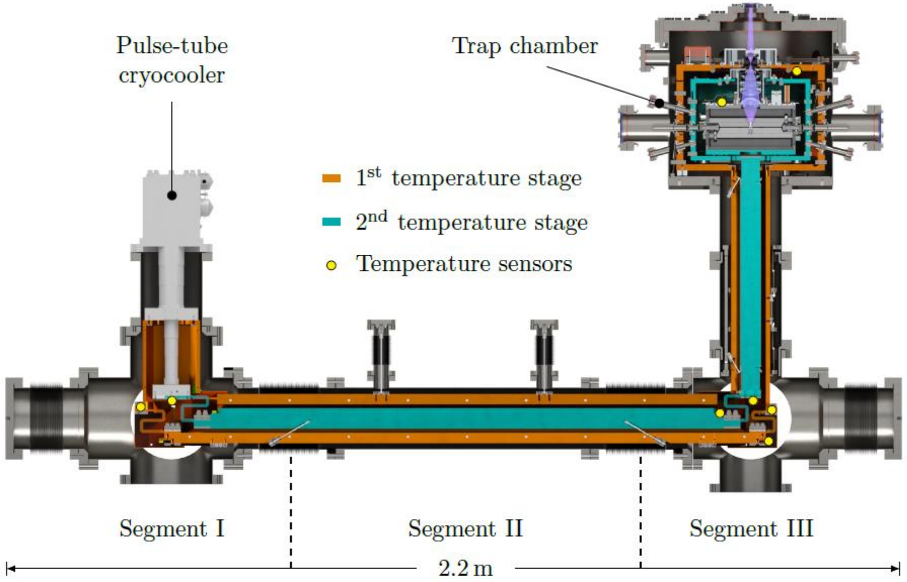
MK--->μK

MPI Heidelberg & PTB

Production, cooling and trapping of HCIs

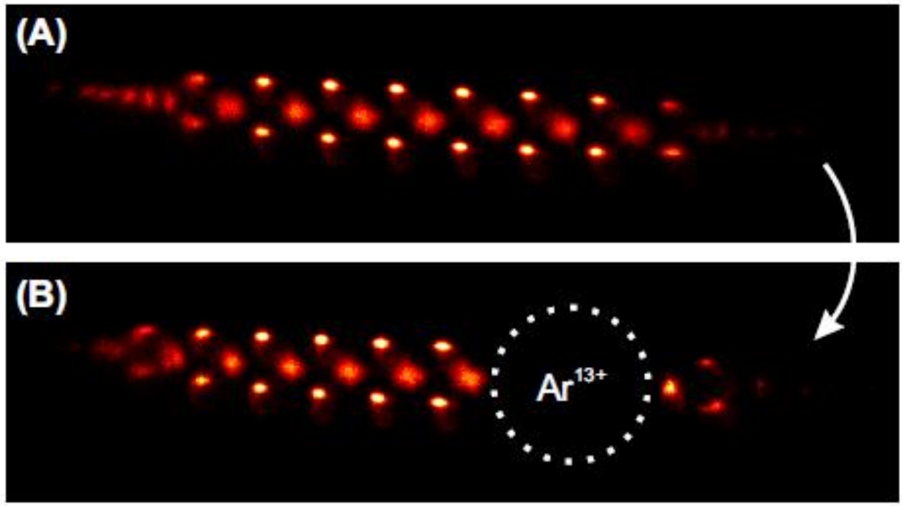


Compact EBIT
@ MPI Heidelberg



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 singly-charged 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)]:

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

Λ_γ^n alter the fine structure constant α, Λ_f^n 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

$$\frac{d\alpha}{\alpha} \approx \frac{\phi_0 \cos(m_\phi t)}{\Lambda_\gamma}, \qquad \frac{dm_e}{m_e} \approx \frac{\phi_0 \cos(m_\phi t)}{\Lambda_e}$$

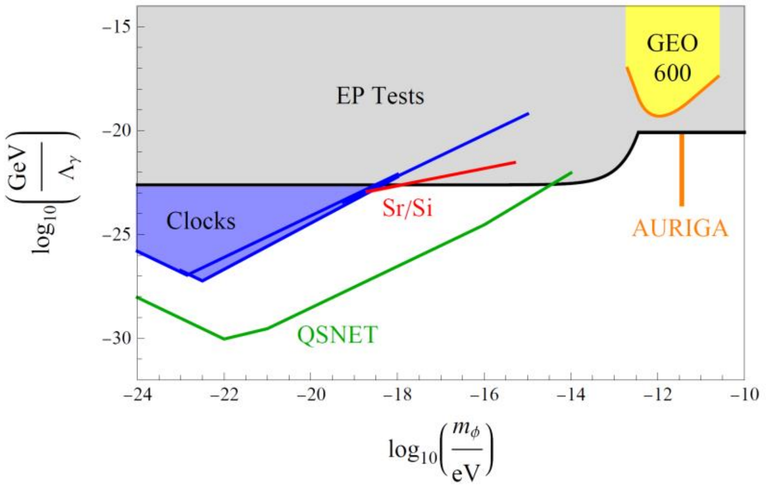
$$\frac{d\alpha}{\alpha} \approx \frac{\phi_0^2 \cos^2(m_\phi t)}{(\Lambda'_\gamma)^2}, \qquad \frac{dm_e}{m_e} \approx \frac{\phi_0^2 \cos^2(m_\phi t)}{(\Lambda'_e)^2}$$

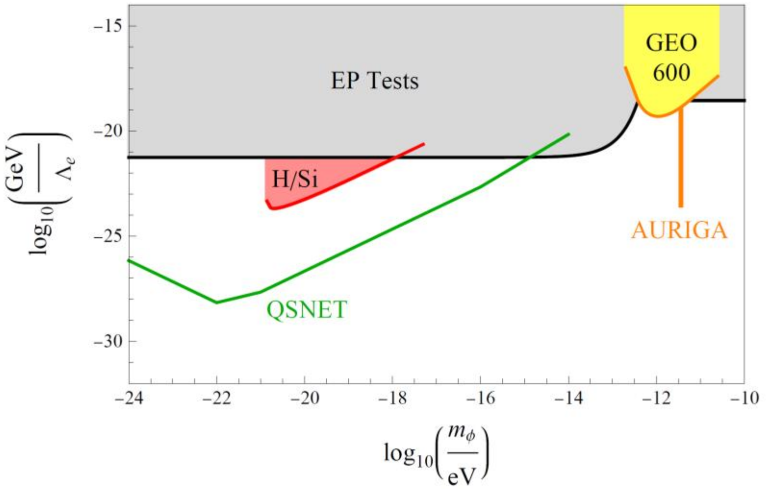
Therefore we would observe atomic frequencies undergoing small oscillations in time around their mean value:

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

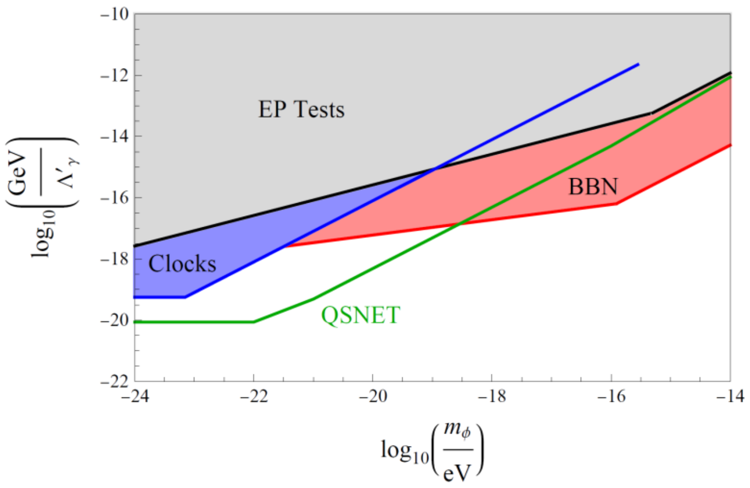
Scalar dark matter

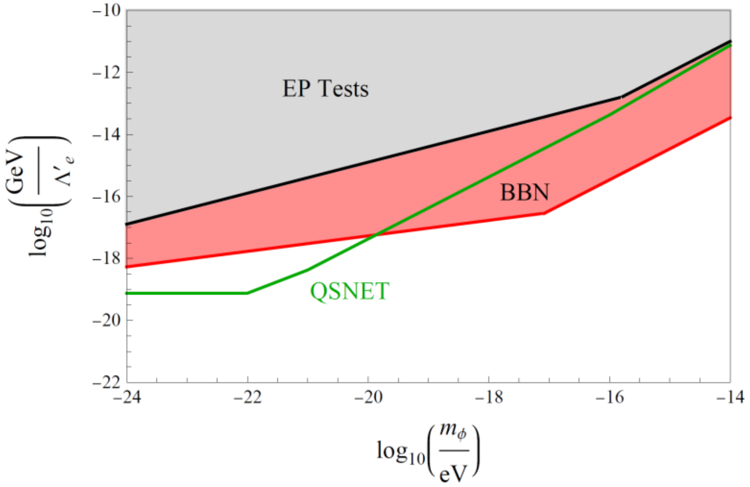
Linear





Quadratic





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.

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

- 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 $m_\phi \sim H_0 \sim 10^{-33}$eV

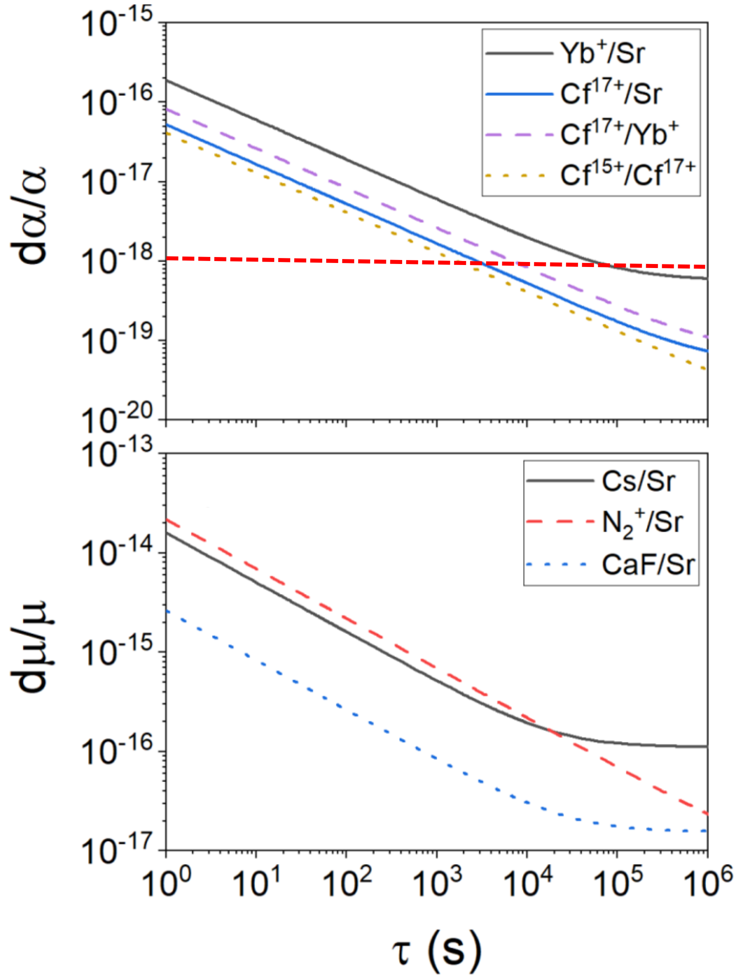
If the quintessence field couples to visible matter, fundamental constants could be slowly evolving with cosmological time

Dark energy

Linear drifts in α

Current limits:

Measurement type	$\lvert d\ln(\alpha)/dt \rvert/\mathrm{yr}$
Yb^+ clocks	$\sim 10^{-18}$
Oklo phenomenon	$\sim 10^{-17}$
Meteorite dating	$\sim 10^{-16}$
MICROSCOPE (indirect limits)	$\sim 10^{-17} - 10^{-23}$



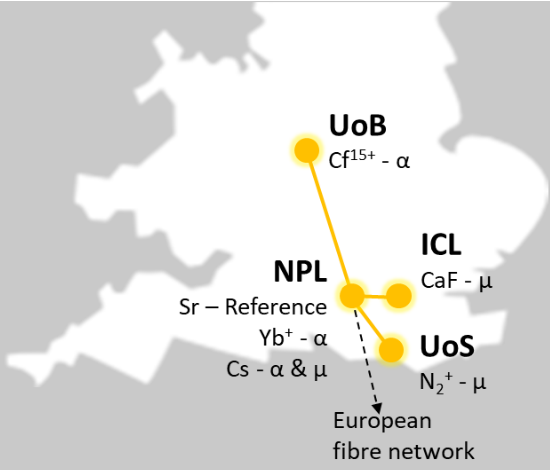
Other tests [EPJ QT 9, 12 (2022)]

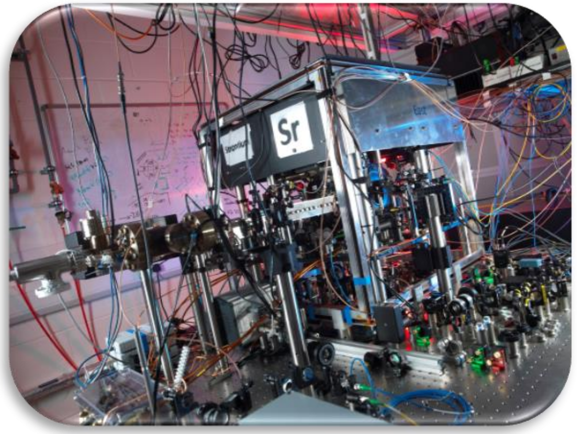
- Solitons
  - Topological solitons are made up of one or more fields that acquire stability due to the presence of two or more vacua
  - transient events, network is needed

- 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 **α** and **μ**, 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 α and μ by orders of magnitude
    - Cosmology
    - Astrophysics
    - High-energy theory
    - Fundamental symmetries
    - …





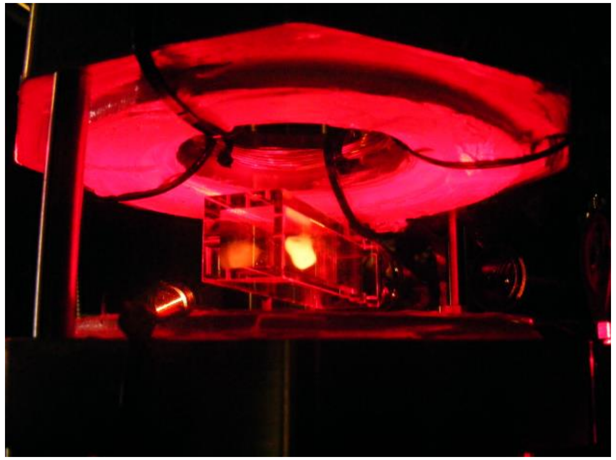
α

μ

Thanks

- White paper: EPJ Quantum Technology 9, 12 (2022)
  [arXiv:2112.10618]

- Website: qsnet.org.uk



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