QSNET

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

Birmingham NPL Sussex Imperial

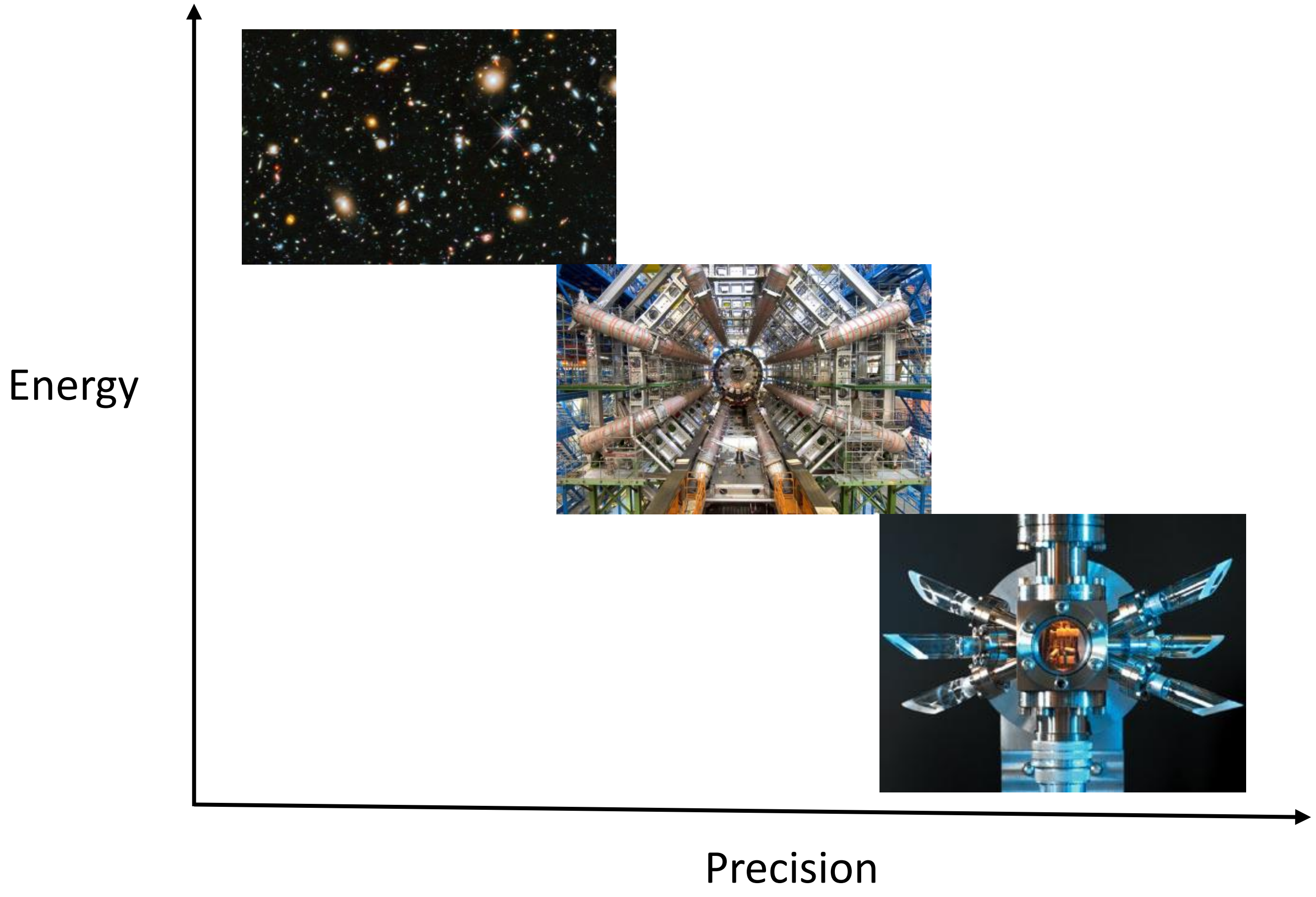
# QTFP

- 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

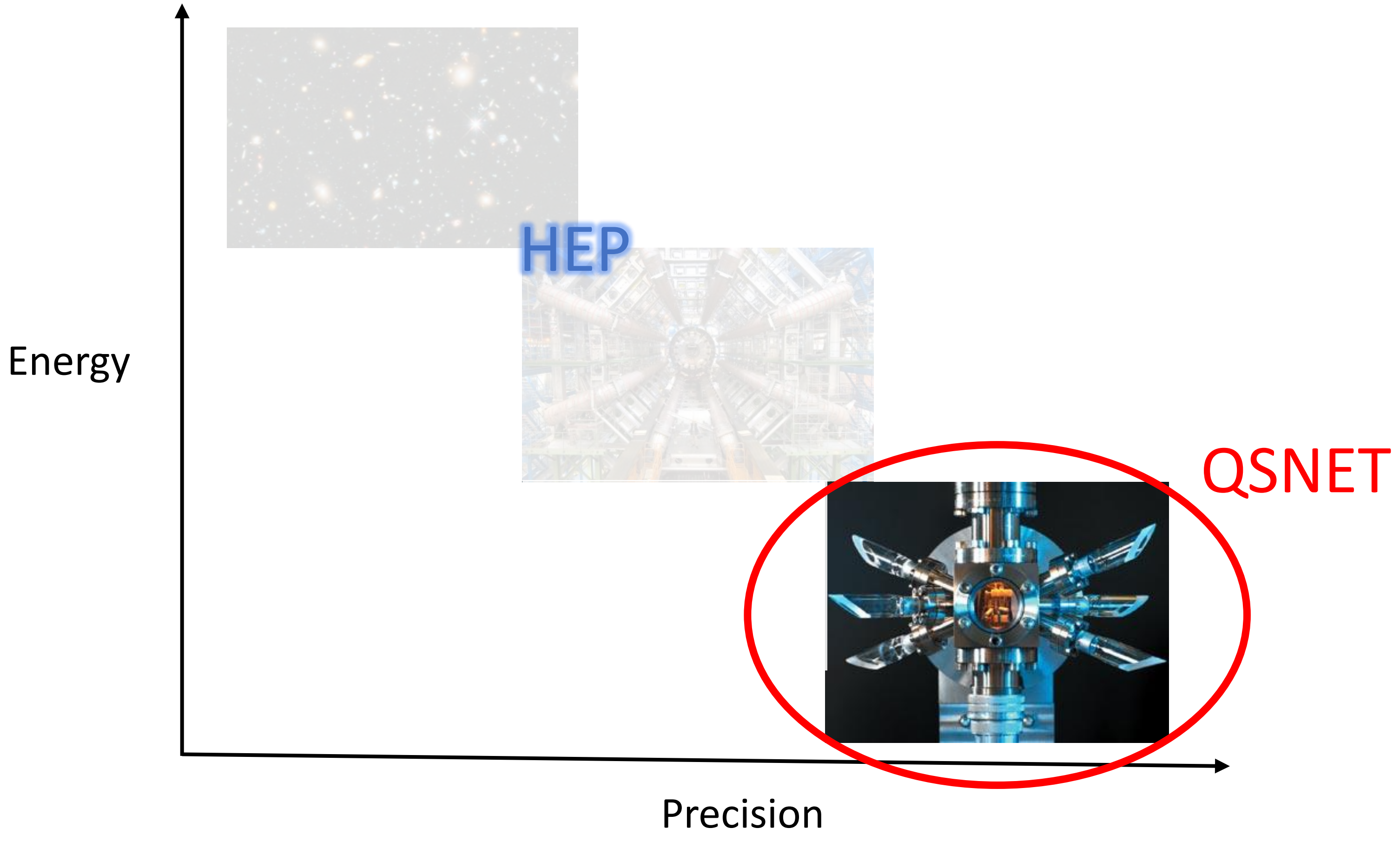
# Background

- Searches for physics beyond the SM



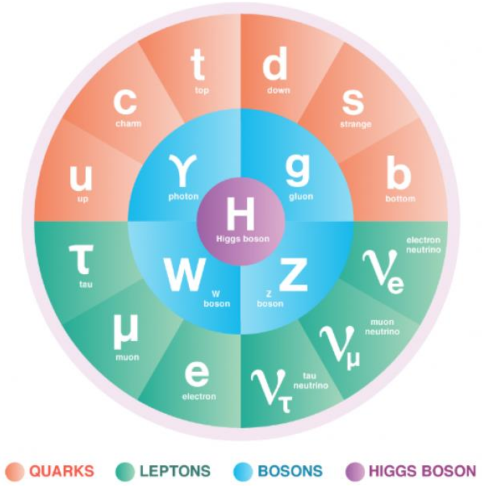
# Background

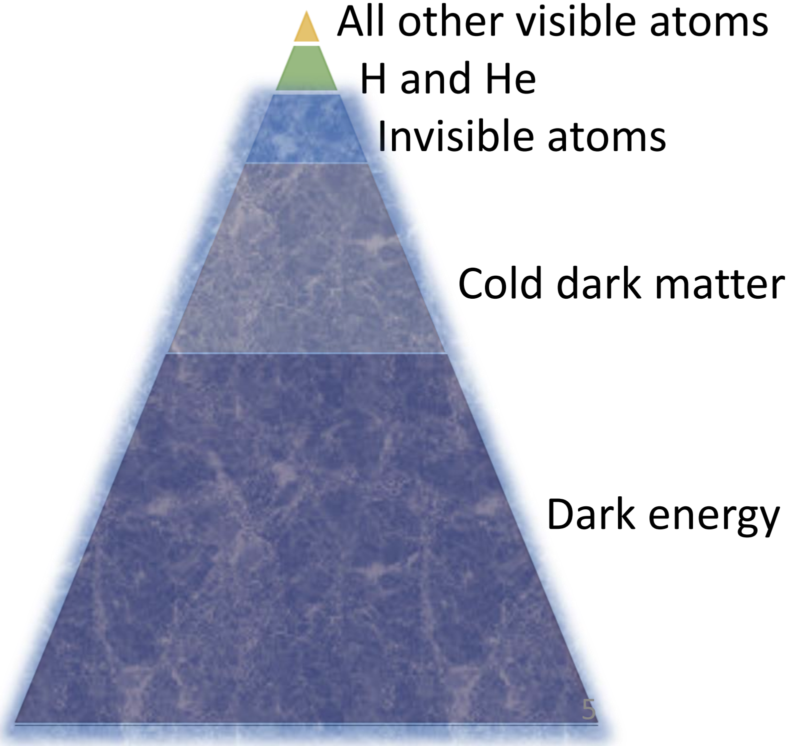
- Searches for physics beyond the SM



# Background

- The Standard Model and ΛCDM are very successful theories but…
- The SM only accounts for 5% of the energy balance of the Universe. The exact nature of the remaining 95% -dark matter and dark energy- is unknown
- The SM has several (~20) parameters, supposed to be immutable, referred to as fundamental constants.
- <u>Challenging this central assumption could be the key to solving the dark matter and dark energy enigmas</u>
- Any variations of fundamental constants would give us evidence of revolutionary new physics

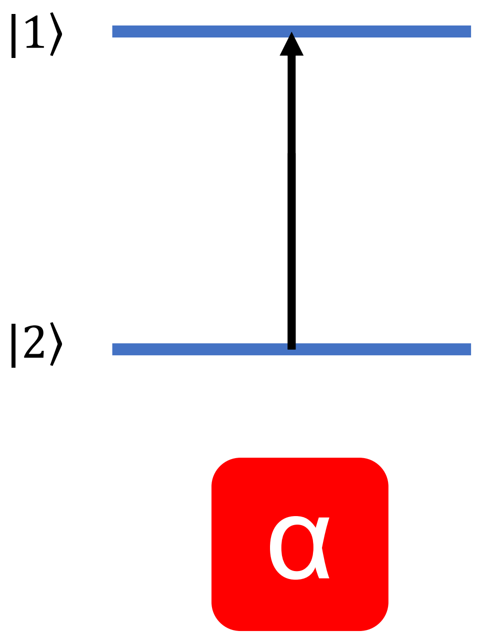


# Choice of fundamental constants

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

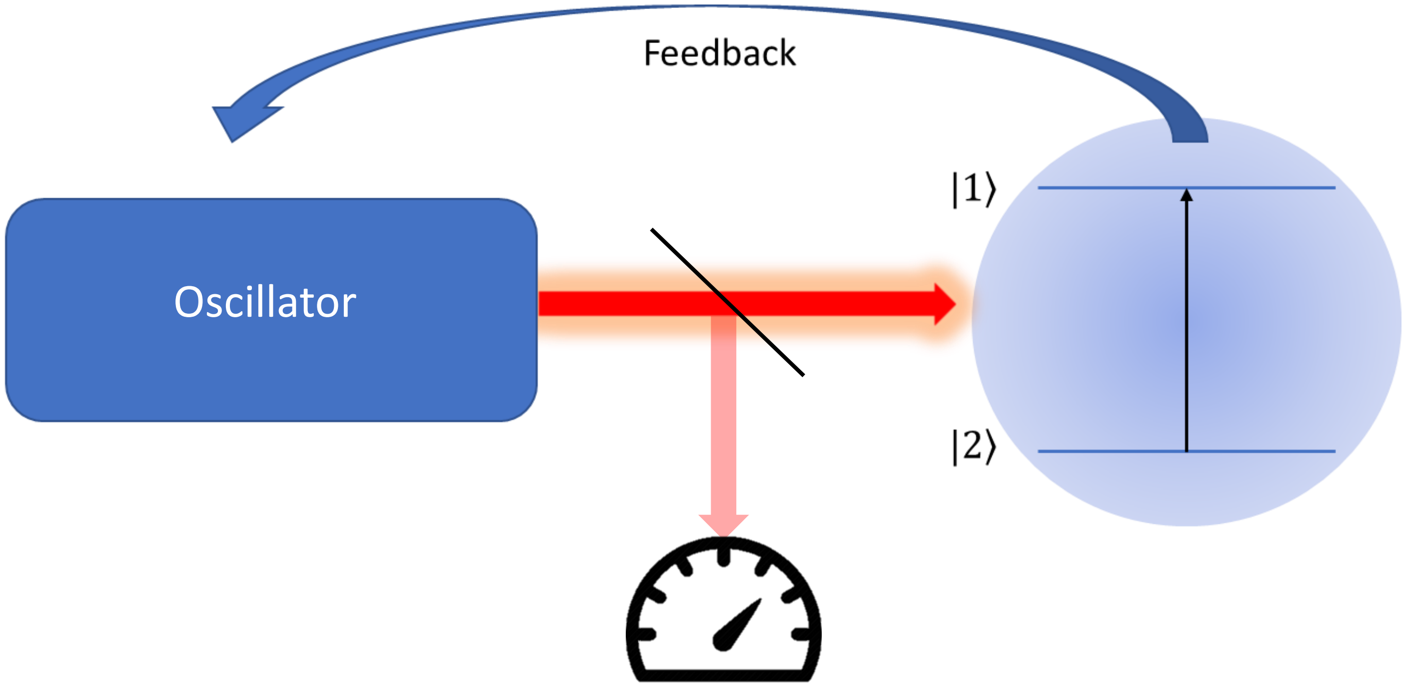
$$\alpha = \frac{1}{4\pi\varepsilon_0}\frac{e^2}{\hbar c} \qquad \mu = \frac{m_p}{m_e}$$

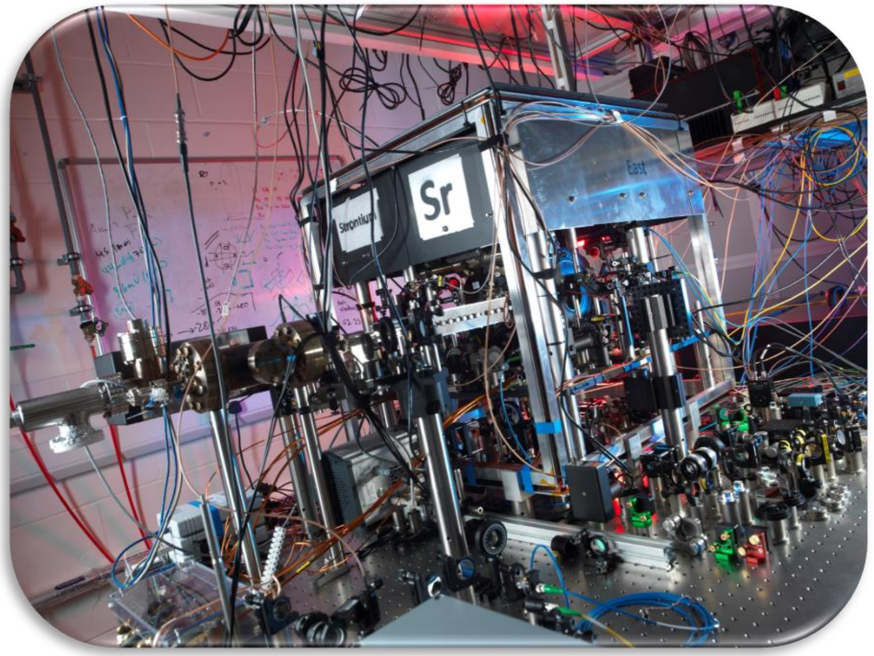



- Atomic an molecular spectra can be measured with extreme precision using atomic clocks
- Grand unification physics fixes relations between fundamental constants (if one changes with time, others will as well)

# 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
  $\upsilon_{Opt} = B F_{Opt}(\alpha) R_\infty$

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

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

| Clock | $K_\alpha$ | $K_\mu$ |
|---|---|---|
| Sr | 0.06 | 0 |
| Yb+ | -5.95 | 0 |
| Cs | 2.83 | 1 |
| CaF | 0 | 0.5 |

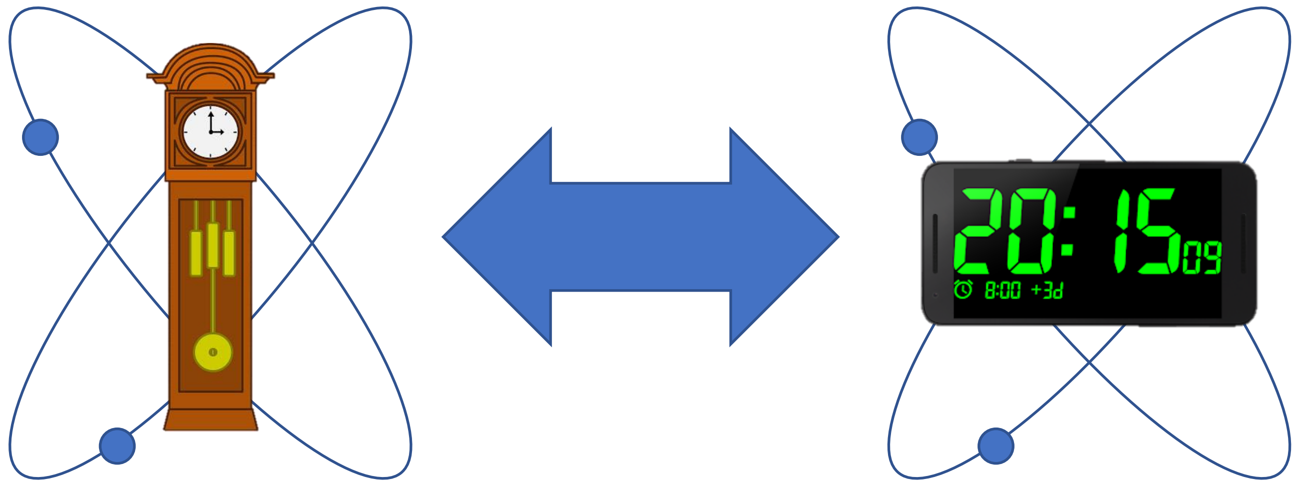
# How to measure variations of fundamental constants

- In general atomic clocks are insensitive to external perturbations (magnetic & electric fields, BB radiation et…)

- Choose two (or more) clocks with DIFFERENT sensitivity to the variation of fundamental constants and compare them

# How to measure variations of fundamental constants

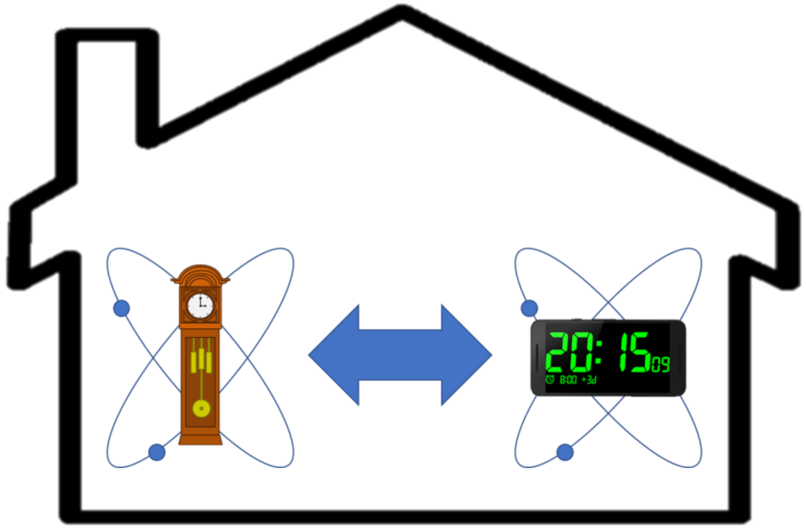
- Comparing clocks with different sensitivities to fundamental constants




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

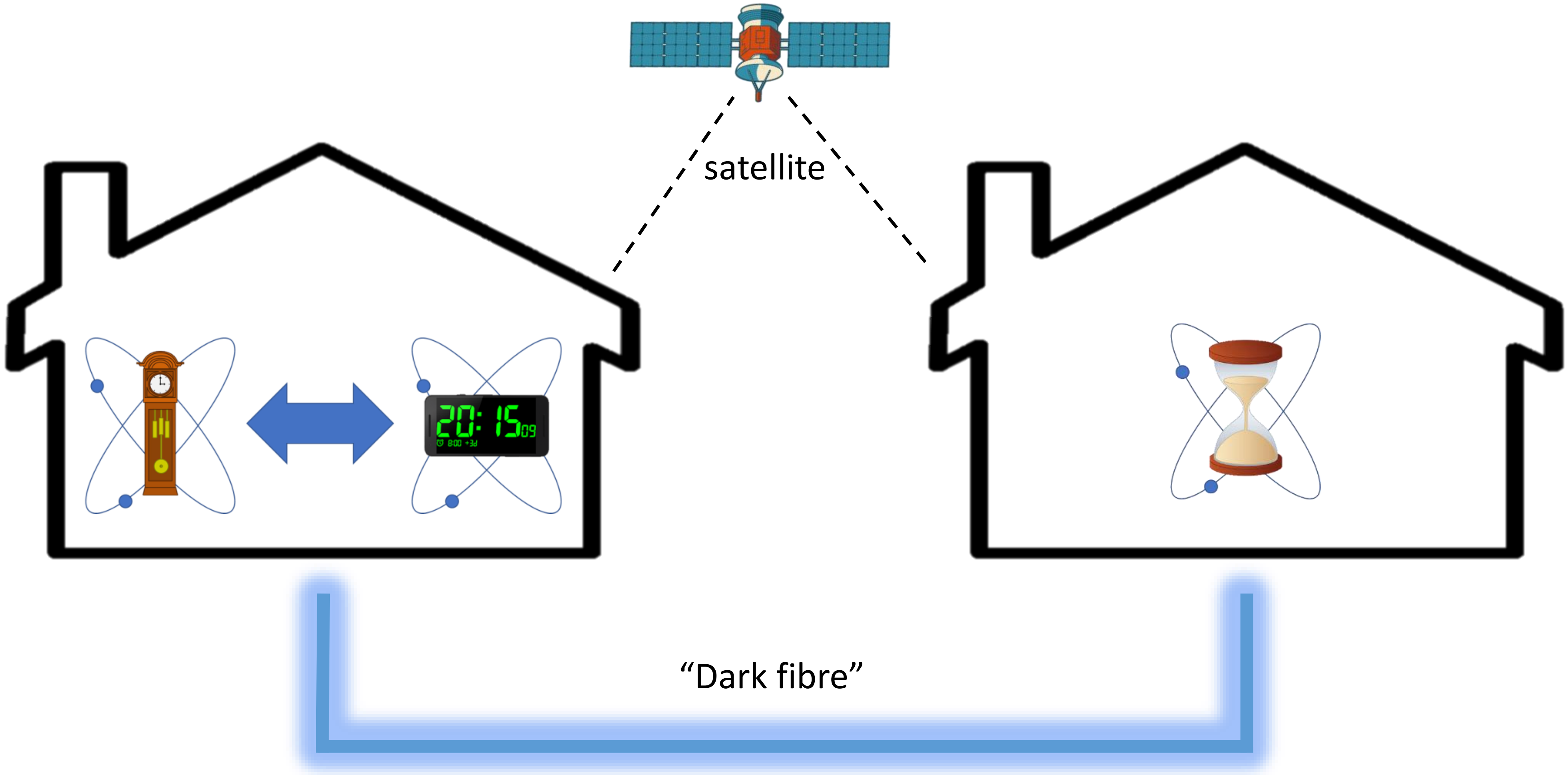
$$\frac{\Delta f1}{\Delta f2} = |K_{1x} - K_{2x}| \frac{\Delta x}{x} \qquad x = \alpha, \mu$$

# How to measure variations of fundamental constants



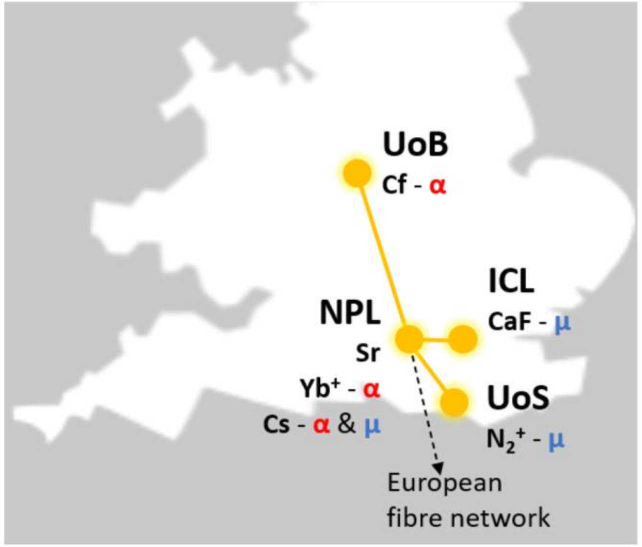

"in house" comparison

# 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**

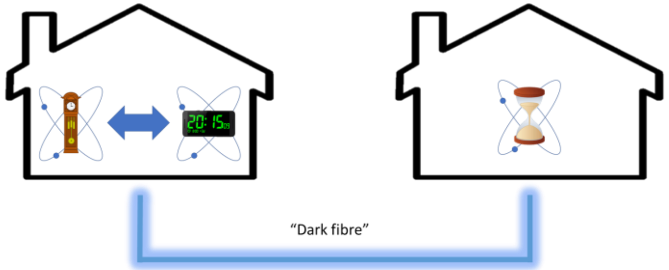



| Clock | Kα | Kμ |
|---|---|---|
| $Yb^+$ (467 nm) | -5.95 | 0 |
| Sr (698 nm) | 0.06 | 0 |
| Cs (32.6 mm) | 2.83 | 1 |
| CaF (17 μm) | 0 | 0.5 |
| $N_2^+$ (2.31 μm) | 0 | 0.5 |
| $Cf^{15+}$ (618 nm) | 47 | 0 |
| $Cf^{17+}$ (485 nm) | -43.5 | 0 |

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

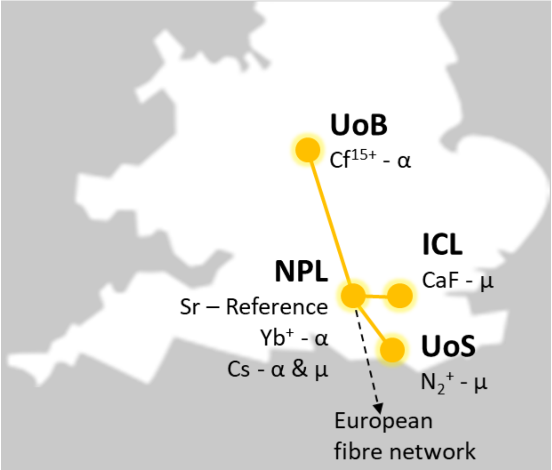
# The network approach

- 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

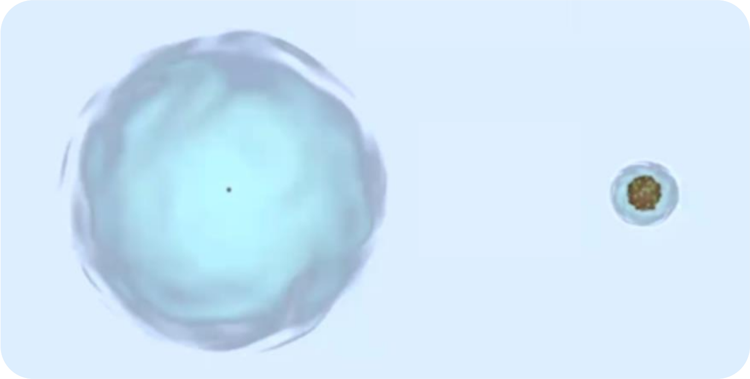



- The possibility of detecting transient events such as topological defects in dark matter fields or oscillations of dark matter

- A new versatile and expandable national infrastructure with possible further applications in and beyond fundamental physics.

# The Bham node: 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 $\alpha$ $(K_{\alpha}\sim 10-100)$

# Highly-charged ions

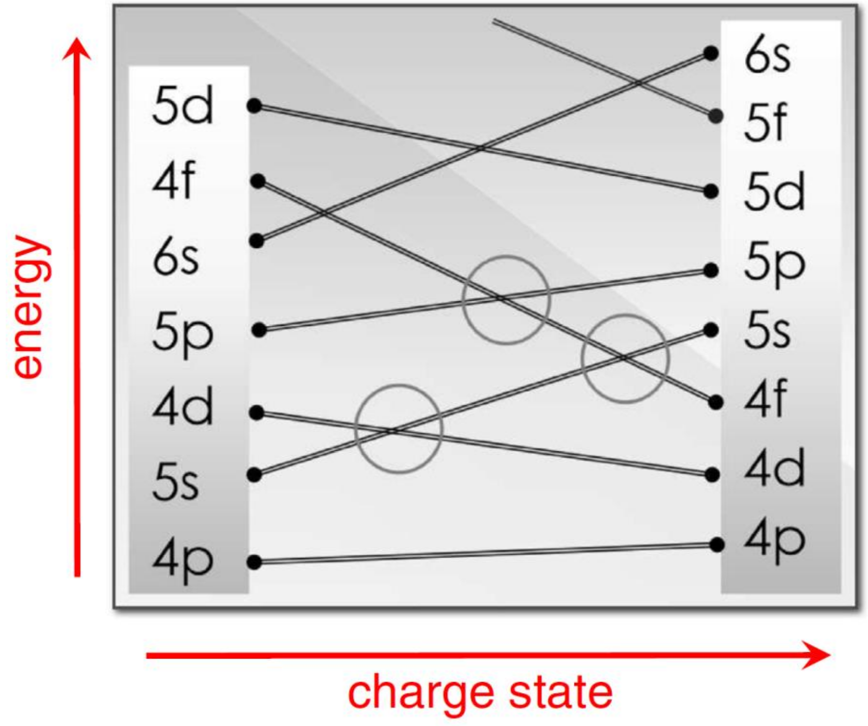
The energy scale for electronic transitions scales as

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

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 $\alpha$

| Ion | Level | Energy | $q$ | $K$ | $\lambda$ | $\tau$ |
|---|---|---|---|---|---|---|
| $Nd^{13+}$ | $5s_{1/2}$ | 0 | | | | |
| | $4f_{5/2}$ | 55 706 | 104 229 | 3.7 | 179 | $1.3 \times 10^{6}$[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 | $3.1 \times 10^{5}$ |
| $*Cf^{17+}$ | $5f_{5/2}$ | 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 | $8.5 \times 10^{10}$ |
| | $5s4f\ ^3F_3$ | 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 | $5.6 \times 10^{13}$[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 | $q$ | $K$ | $\lambda$ |
|---|---|---|---|---|---|---|
| $Ir^{16+}$ | $4f^{13}5s^2$ | $^2F_{7/2}$ | 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 | $q$ | $K$ | $\lambda$ | $\tau$ |
|---|---|---|---|---|---|---|
| $Ce^{9+}$ | $5s^2 5p_{1/2}$ | 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 | $8.5 \times 10^{4}$ |
| | $5s^2 4f_{7/2}$ | 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 | $6.6 \times 10^{14}$ |
| | $5s^2 5p4f\ ^3F_2$ | 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 $\alpha$

✓Visible range

✓High values of K

❖Other groups

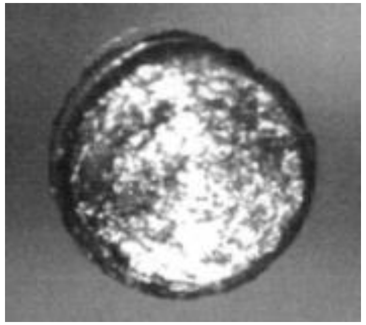
❖ Too unstable

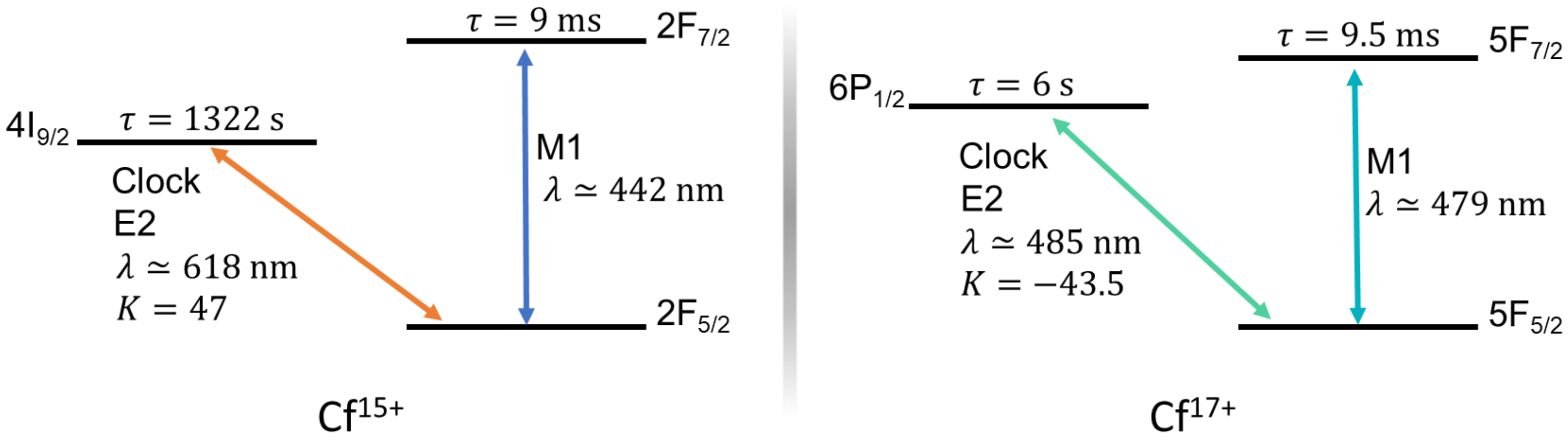
| Ion | Level | Energy | q | K | λ | τ |
|---|---|---|---|---|---|---|
| * $Cf^{17+}$ | $5f_{5/2}$ | 0 | | | | |
| | $6p_{1/2}$ | 18 686 | −449 750 | −48 | 535 | |
| | $5f_{7/2}$ | 21 848 | 17 900 | 1.6 | 458 | |

| 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

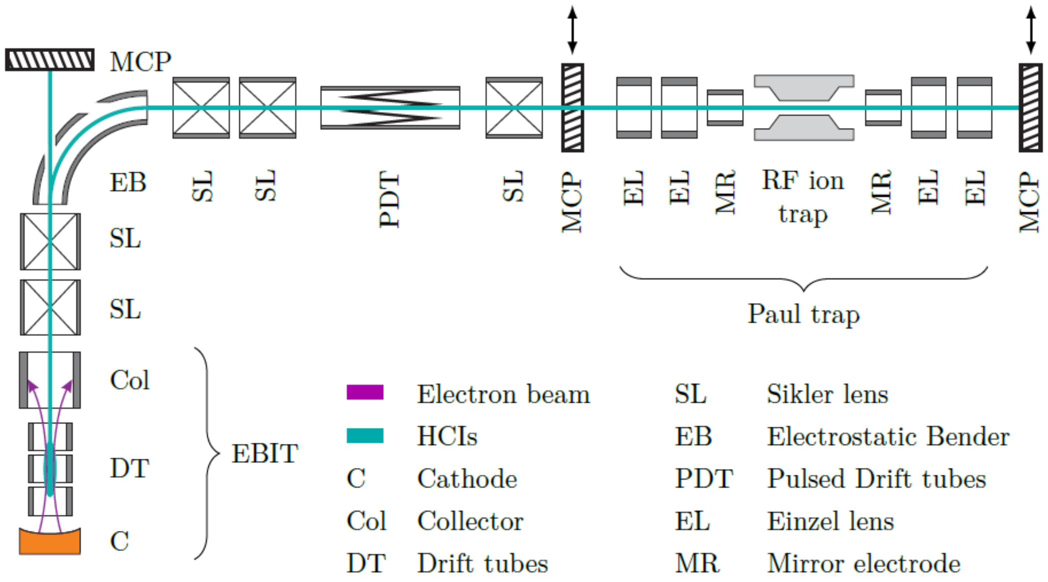
- Cf is a synthetic element produced in reactors
- $^{249}$Cf has a half-life of 350 y, $^{252}$Cf of 2650 y
- It costs ~$7,350,000 / g (!)



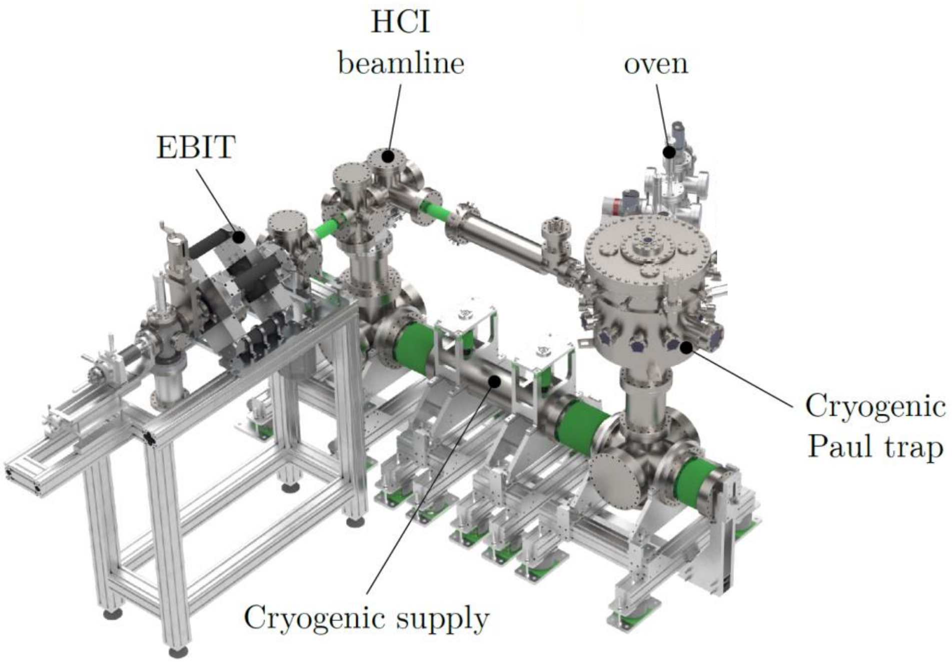



- Both ionisation states feature a clock transition in the visible range and a strong-ish transition also in the visible range
- The two clock transitions have large Ks with opposite sign

# Production, cooling and trapping of HCIs

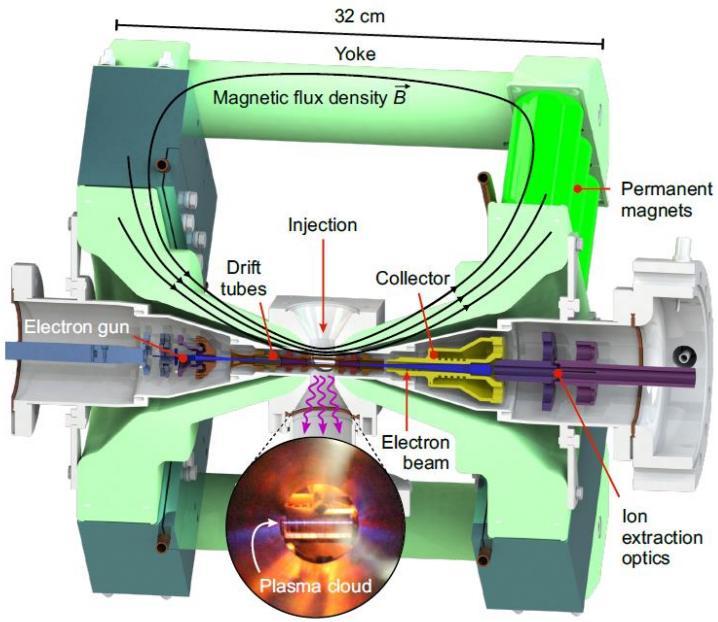



MK------------------------------------------------->μK

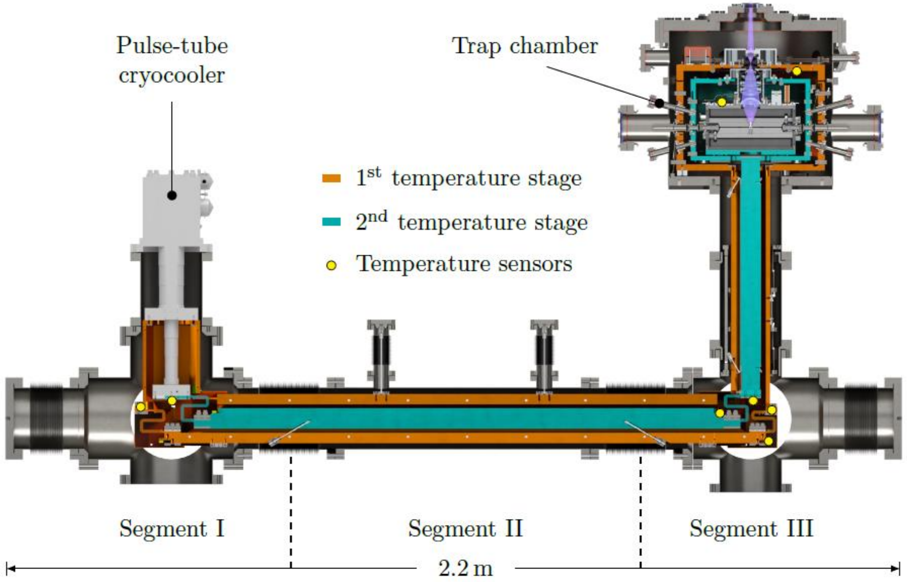



MPI Heidelberg & PTB

# Production, cooling and trapping of HCIs

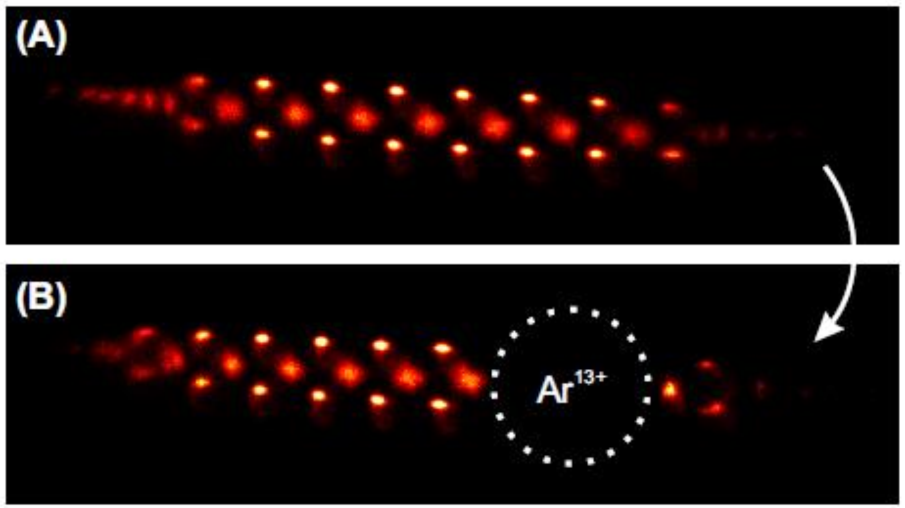



Compact EBIT
@ MPI Heidelberg




Ultra-low vibration
cryogenic vacuum

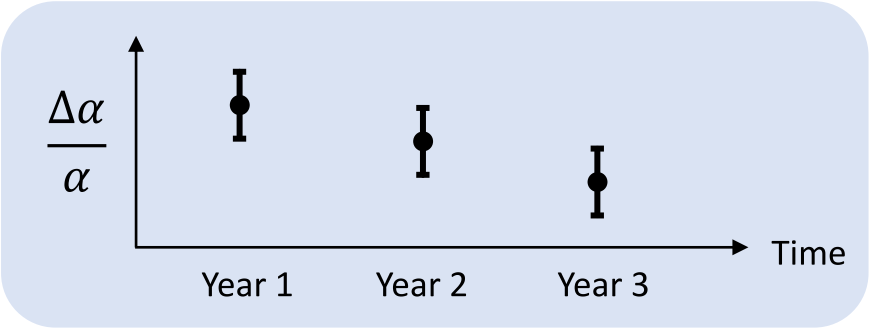
# Production, cooling and trapping of HCIs



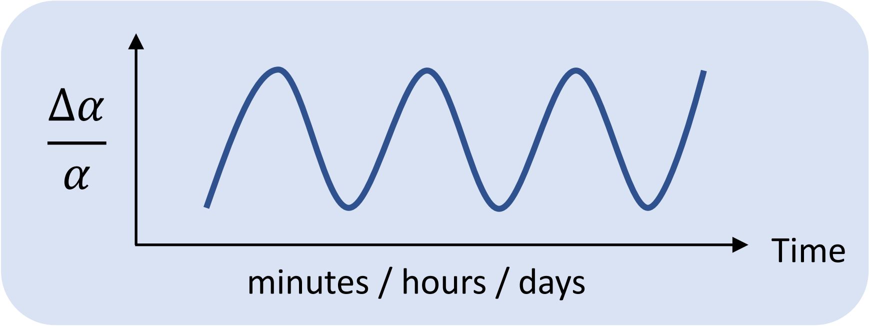

- Once produced and pre-cooled, the ions are implanted into a Coulomb crystal of singly-charged ions
- Sympathetic cooling with the crystal [Science 347 (6227), 1233-1236 (2015)]
- QLS using the co-trapped ions [Nature 578 (7793), 60-65 (2020)]

# Look for variation on different timescales

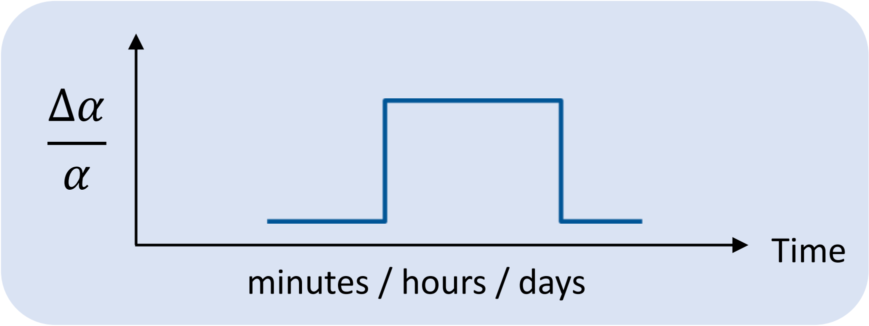
- Slow drifts




- Oscillations




- Fast transients



# Phenomenology

- Coupling of scalar fields with standard matter [arXiv:2112.10618]:

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

$\Lambda_\gamma^n$ 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 (including Brans-Dicke fields and scalar fields that are coupled non-minimally to the Ricci scalar)
- 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

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

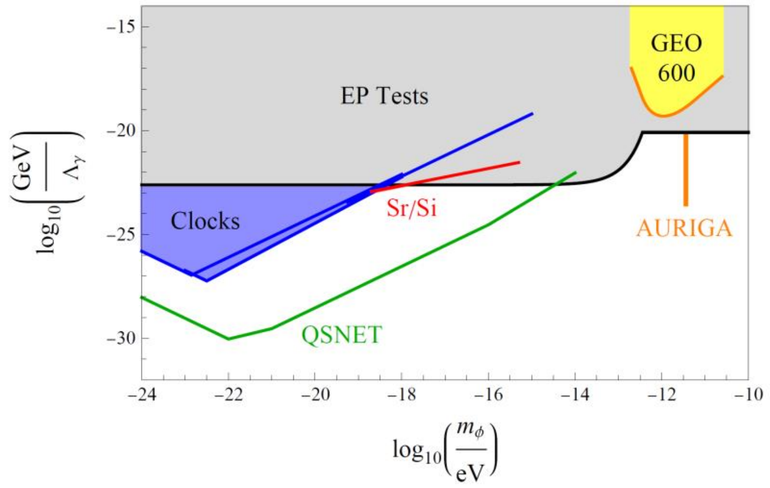
$$\frac{d\alpha}{\alpha} \approx \frac{\phi_0^2 \cos^2(m_\phi t)}{(\Lambda'_\gamma)^2}, \quad \frac{dm_e}{m_e} \approx \frac{\phi_0^2 \cos^2(m_\phi t)}{(\Lambda'_e)^2}$$

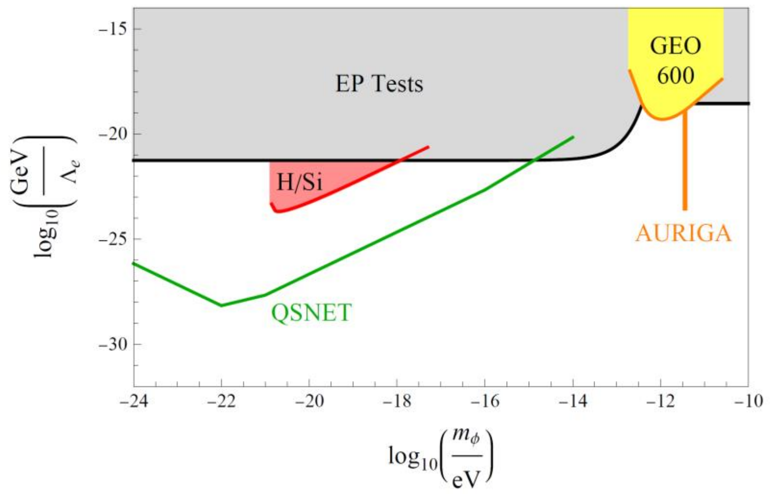
Therefore we would observe atomic frequencies undergoing small oscillations in time around their mean value:

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

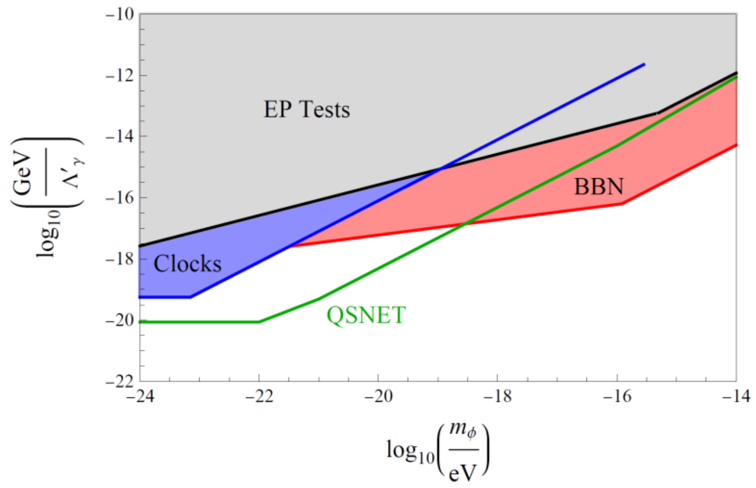
# Scalar dark matter

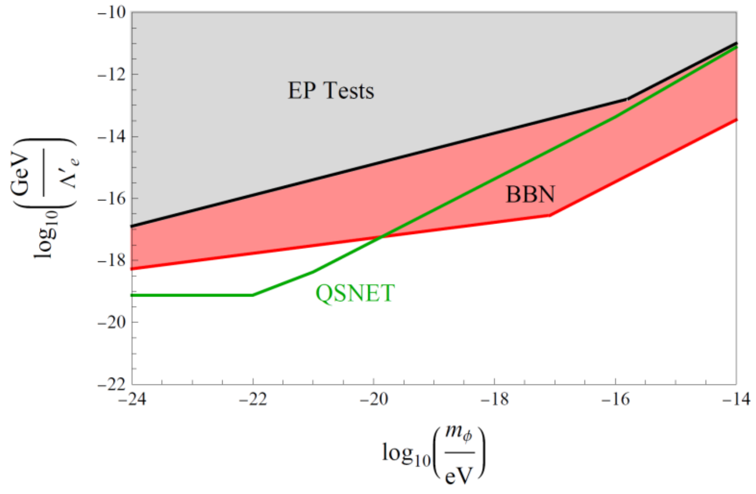
Linear




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.

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

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

Appreciable changes in the scalar field compatible with dark matter occur when $m_\phi \sim H_0 \sim 10^{-33}$eV

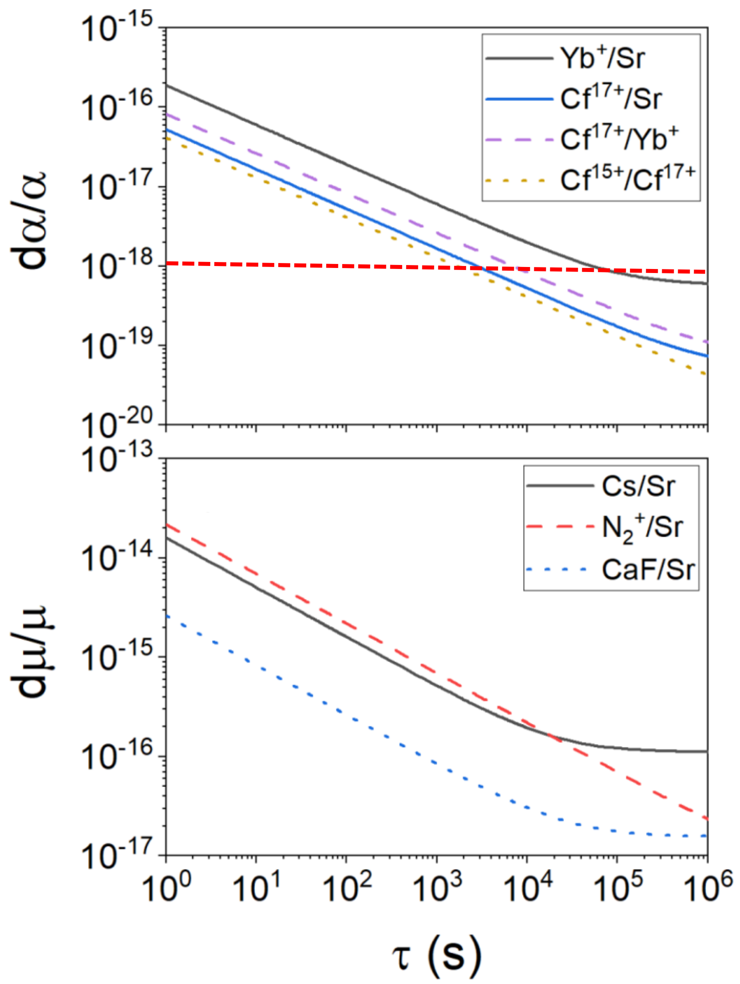
-> very slow drifts

# Dark energy

Linear drifts in α

Current limits:

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



# Solitons

Solitons can be either topological or non-topological in nature.

Topological solitons are made up of one or more fields that acquire stability due to the presence of two or more vacua, which are energetically equivalent but topologically distinguishable

Many different dimensionalities are possible

Simple model

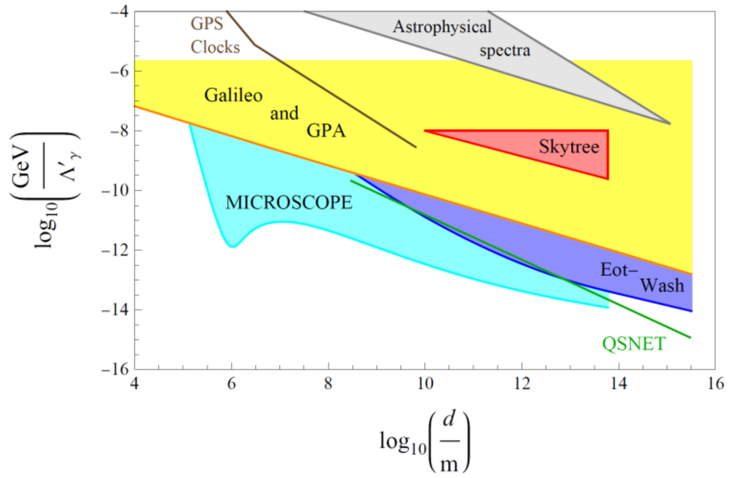
$$\phi(x) = \phi_0 \tanh(x/d) \qquad \phi_0^2 \sim \rho_{\rm walls} v_{\rm wall} \mathcal{T} d$$

Lead to apparent variations of fundamental constants:

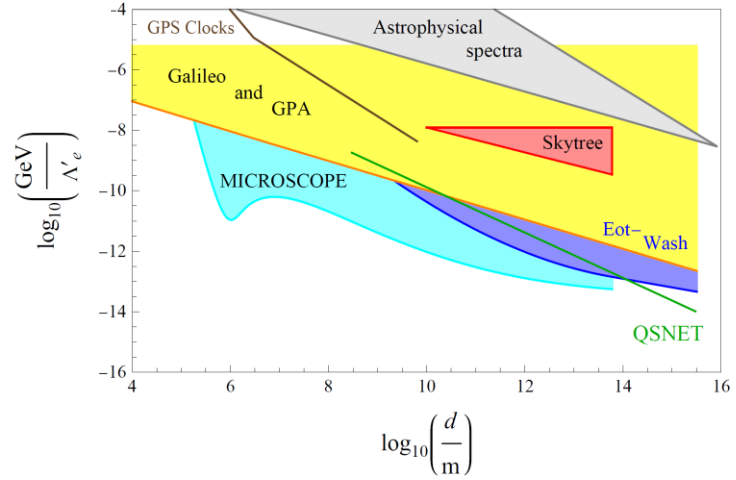
$$\alpha(\phi^2) \approx \alpha_0 \left[1 + \left(\frac{\phi}{\Lambda'_\gamma}\right)^2\right], \quad m_e(\phi^2) = m_{e,0}\left[1 + \left(\frac{\phi}{\Lambda'_e}\right)^2\right]$$

-> transient events, network is needed

# Solitons



GPS
Clocks
Astrophysical
spectra
Galileo
and
GPA
Skytree
MICROSCOPE
Eot–
Wash
QSNET
$\log_{10}\left(\frac{\text{GeV}}{\Lambda'_\gamma}\right)$
$\log_{10}\left(\frac{d}{\text{m}}\right)$

GPS Clocks
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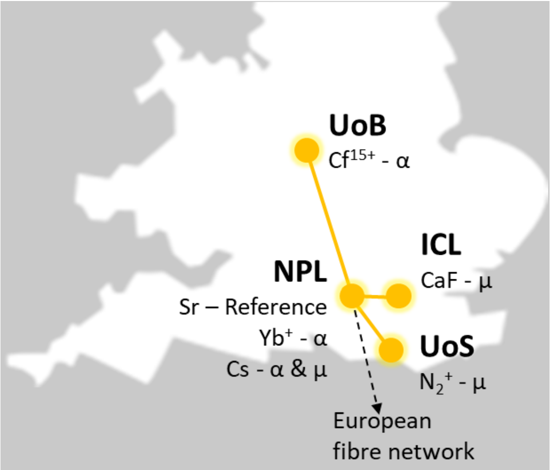
Wash
QSNET
$\log_{10}\left(\frac{\text{GeV}}{\Lambda'_e}\right)$
$\log_{10}\left(\frac{d}{\text{m}}\right)$

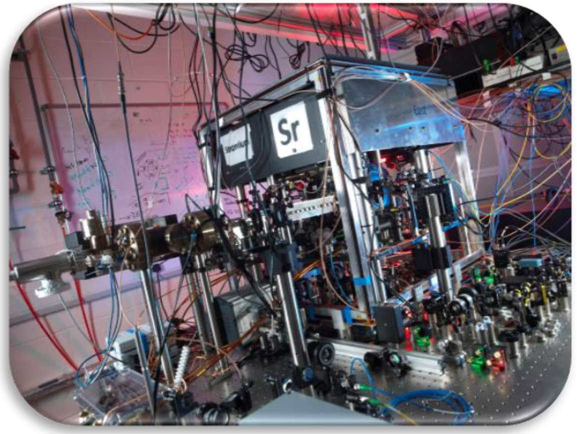
# Other tests [arXiv:2112.10618]

- 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

# QSNET in a nutshell

- 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
    - …
- White paper: [arXiv:2112.10618]




α μ