QSNET

QSNET project: A network of clocks for measuring the stability of fundamental constants

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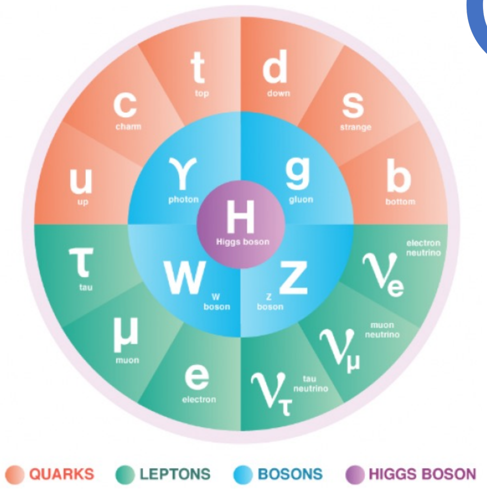
QTFP

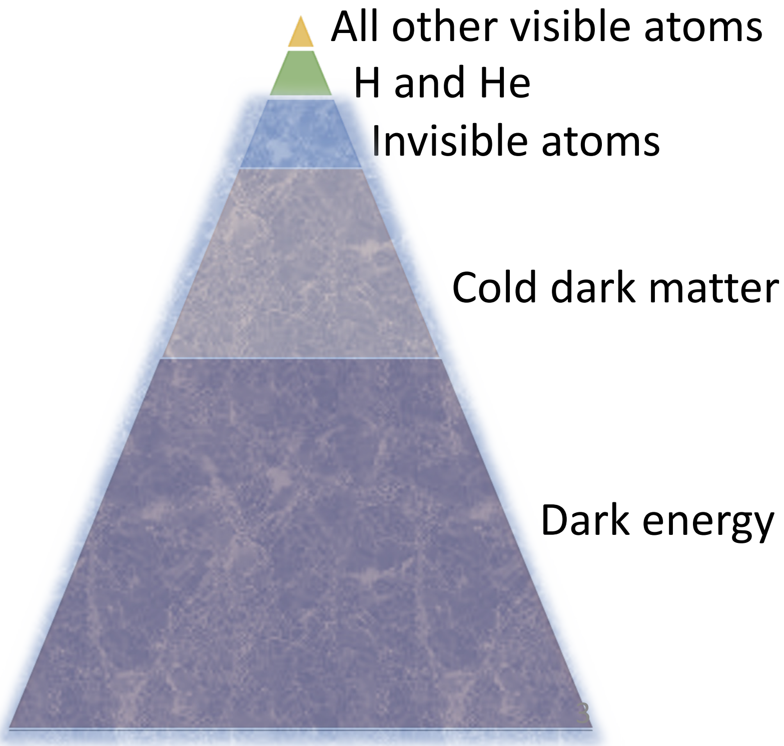
- QSNET is one of the 7 projects funded within the QTFP programme of STFC&EPSRC https://www.ukri.org/news/quantum-projects-launched-to-solve-the-universes-mysteries/

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

Background

- 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.
- 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





Choice of fundamental constants

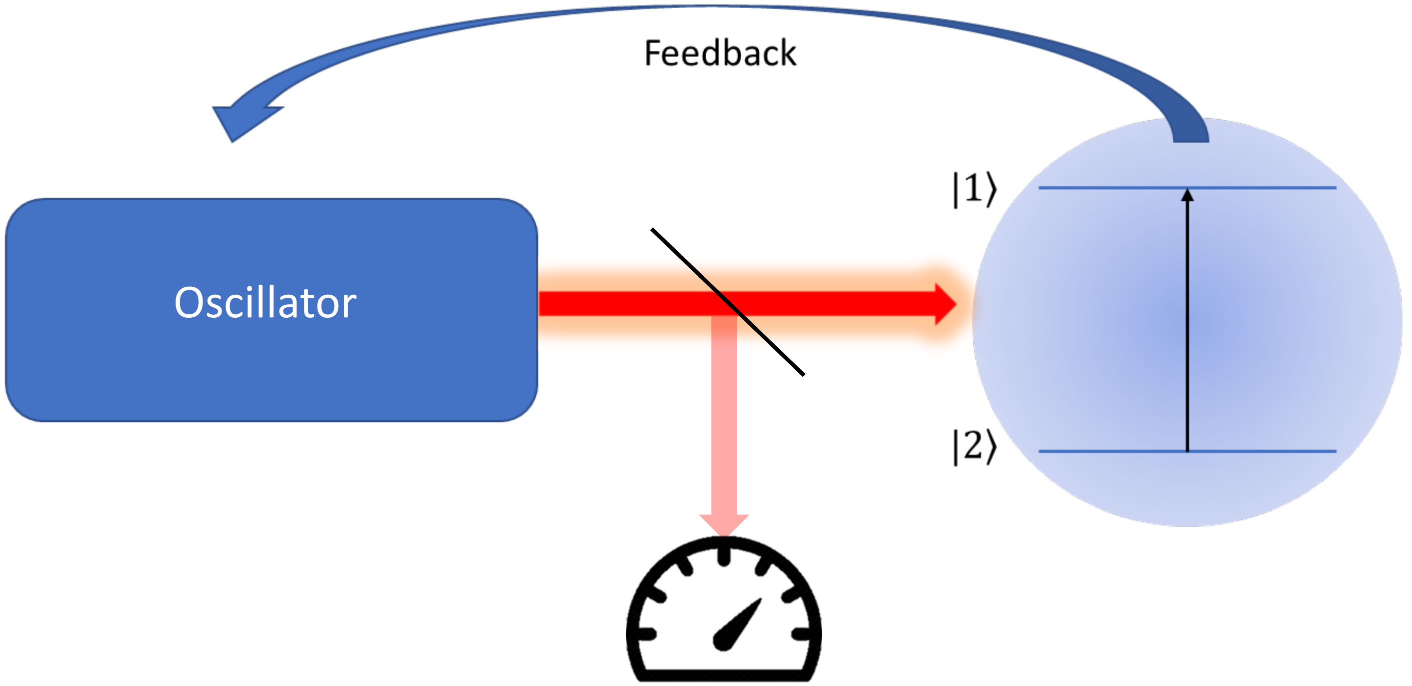
- All atomic and molecular energy spectra depend on the fundamental constants of the Standard Model
- Spectroscopy lends itself to measure variations of the fine structure constant and the electron-to-proton mass ratio:

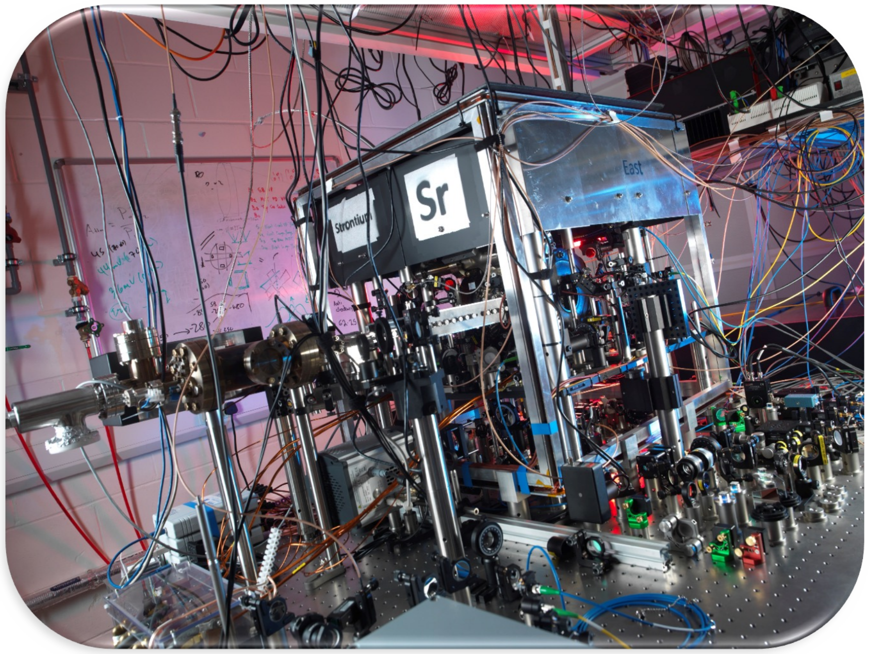
$$\alpha = \frac{1}{4\pi\varepsilon_0}\frac{e^2}{\hbar c} \qquad \mu = \frac{m_p}{m_e}$$

- 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

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

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

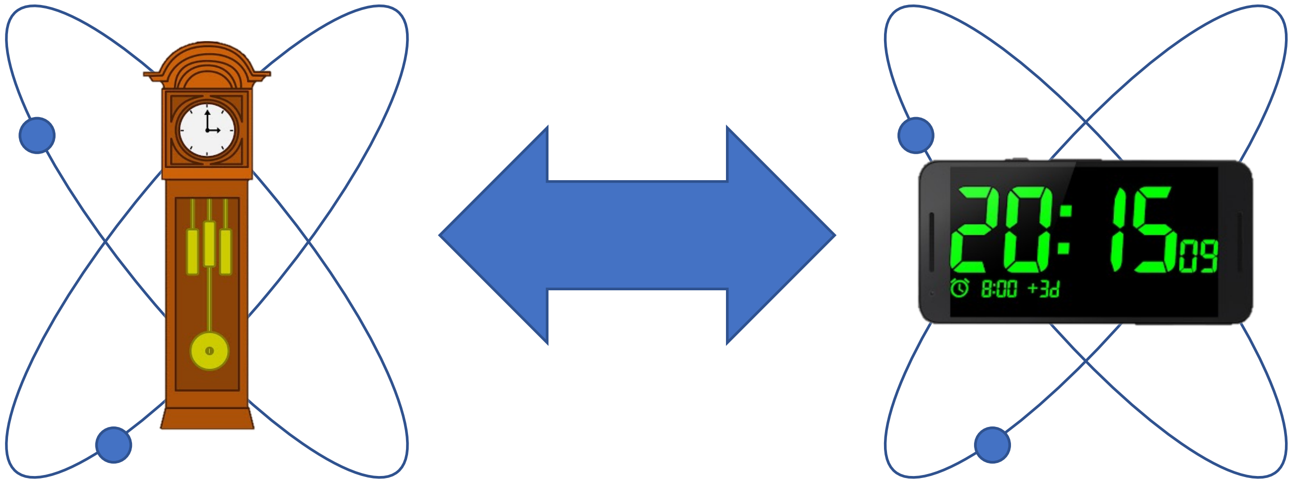
Clock	K_α	K_μ
Sr	0.06	0
Yb+	-5.95	0
Cs	2.83	1
CaF	0	0.5

How to measure variations of fundamental constants

- 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

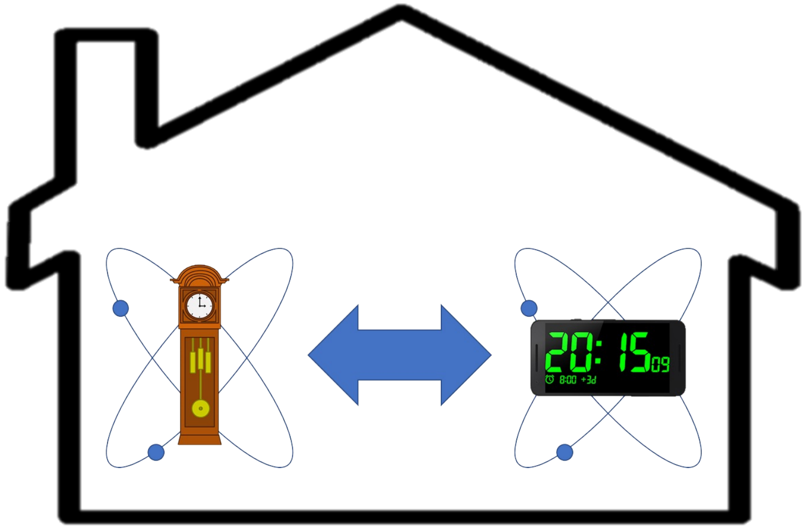
- Comparing clocks with different sensitivities to fundamental constants



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

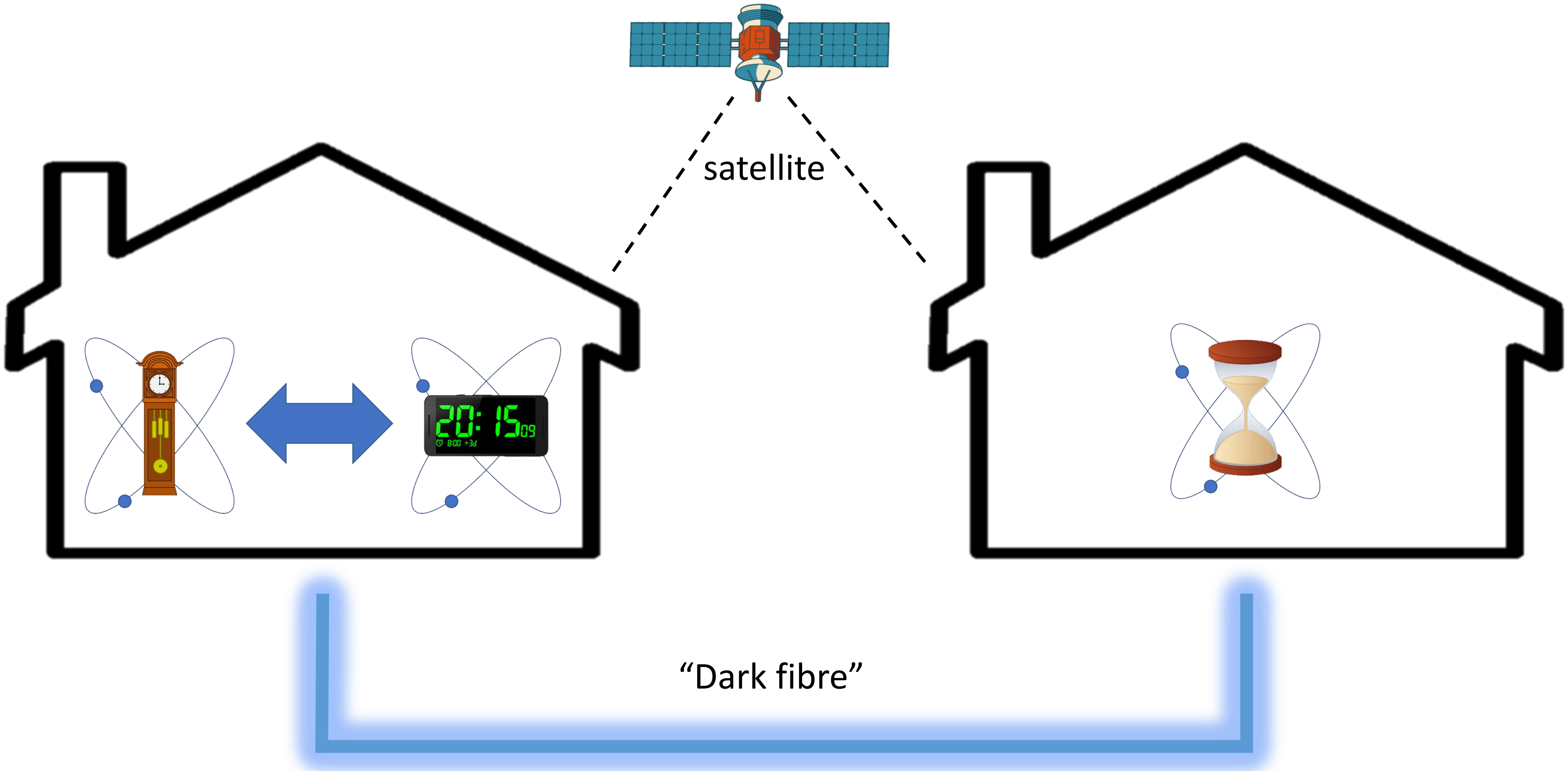
$$\frac{\Delta f1}{\Delta f2} = |K_{1x} - K_{2x}| \frac{\Delta x}{x} \qquad x = \alpha, \mu$$

How to measure variations of fundamental constants



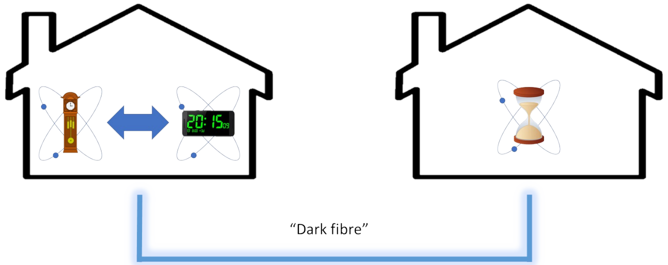
“in house” comparison

How to measure variations of fundamental constants



The network approach

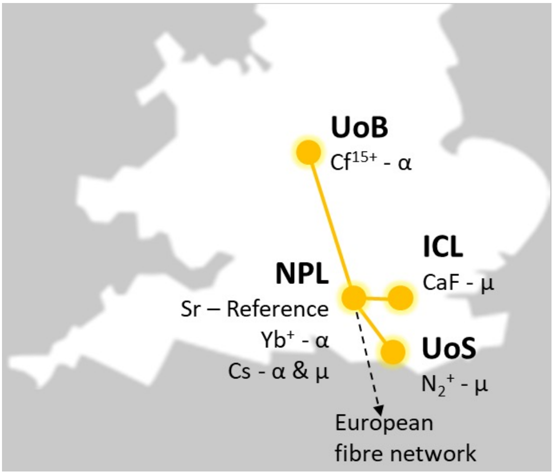
- Validation of the results: Sensors with similar sensitivities and different systematics are necessary to confirm any measurements and reject false positives



- Networks enable probing of space-time correlations

- Detecting transient events such as topological defects in dark matter fields or oscillations of dark matter

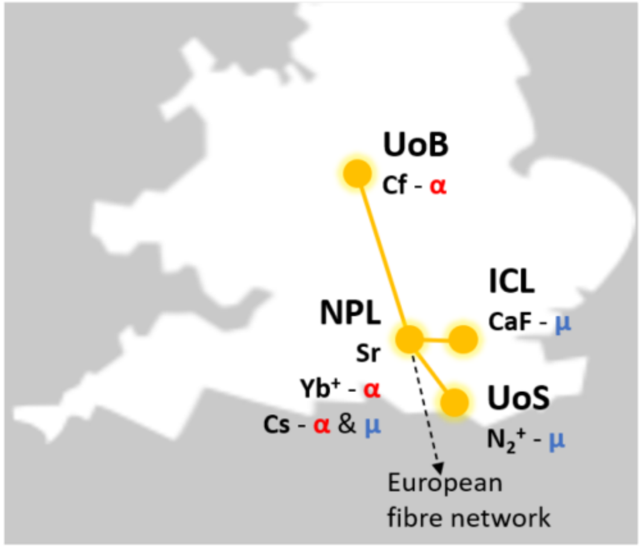
- Optimally exploit existing expertise. No single institution has the range of expertise required to run a sufficiently large and diverse set of clocks



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

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**



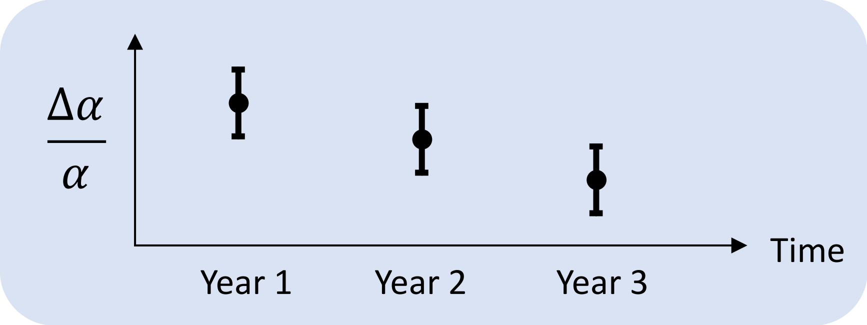
Clock	Kα	Kμ
Yb^{+} (467 nm)	-5.95	0
Sr (698 nm)	0.06	0
Cs (32.6 mm)	2.83	1
CaF (17 μm)	0	0.5
N_2^{+} (2.31 μm)	0	0.5
Cf^{15+} (618 nm)	47	0
Cf^{17+} (485 nm)	-43.5	0

- Established clock standards
- Molecular clocks
- Highly Charged ions clocks

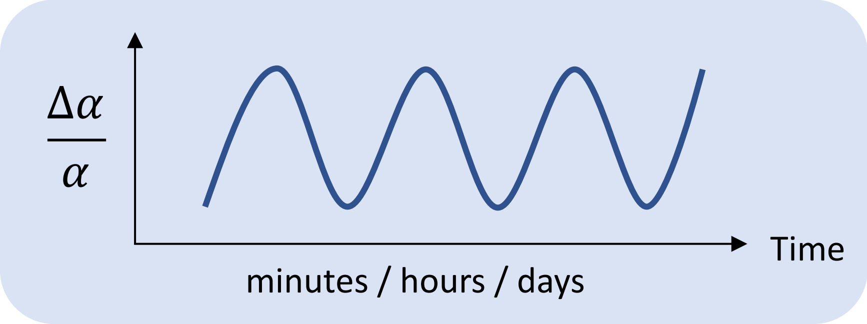
- The clocks will be linked, essential to do clock-clock comparisons

Look for variation on different timescales

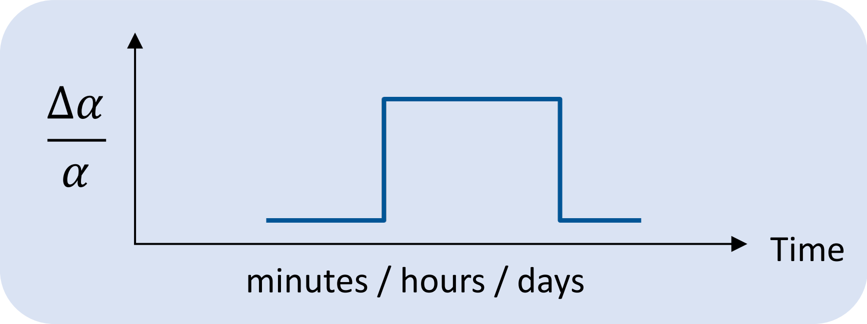
- Slow drifts



- Oscillations



- Fast transients



Scalar dark matter

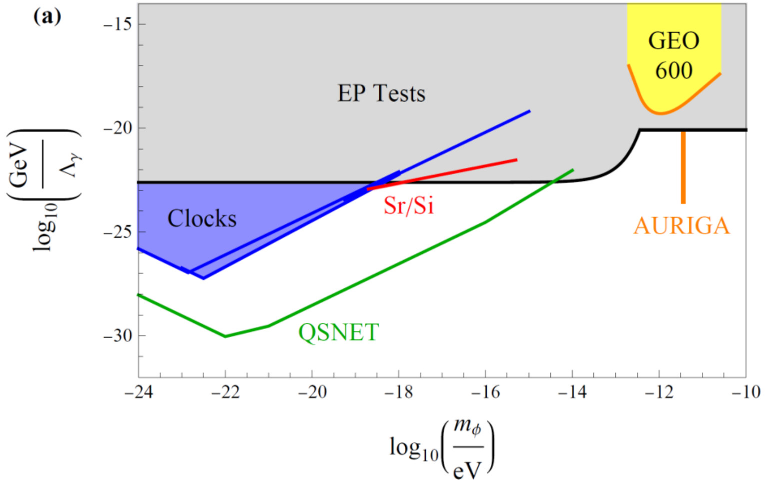
Parameter spaces for a model of an oscillating scalar dark-matter field interacting with

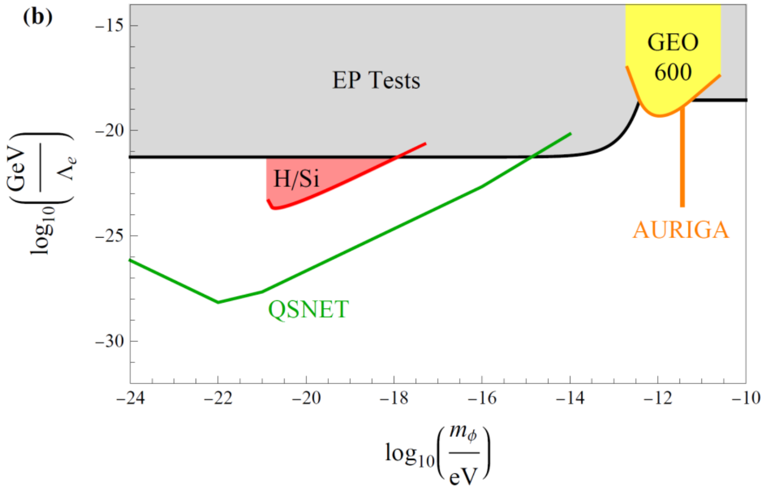
(a) the electromagnetic field and

(b) the electron via the linear-in-ϕ interactions

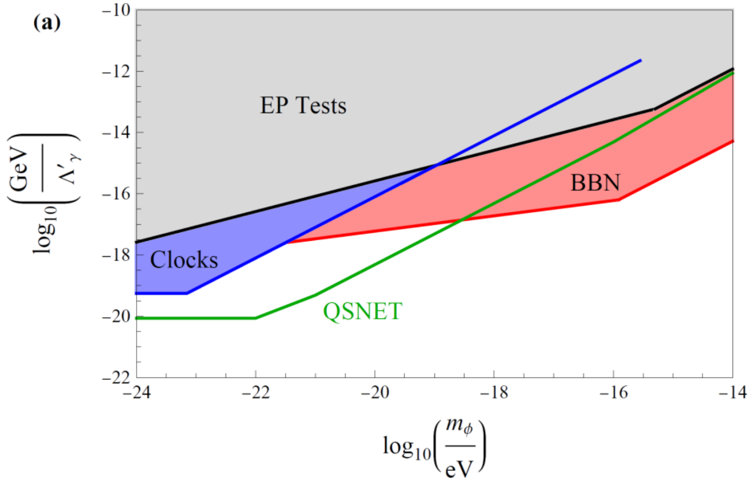
[arXiv:2112.10618]

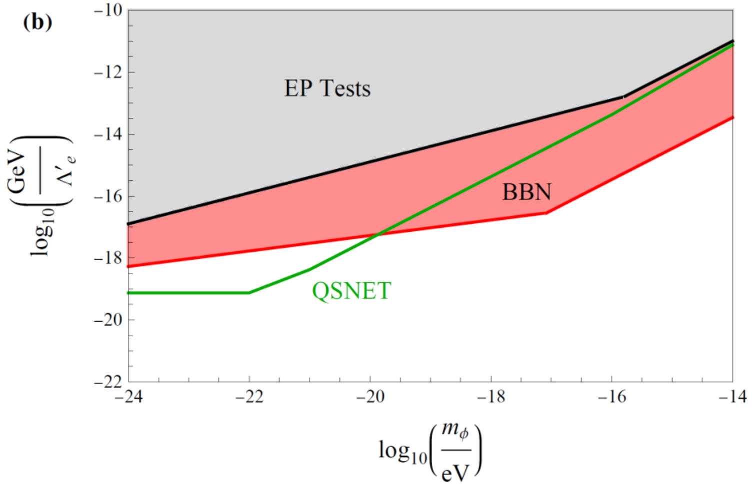
Linear





Quadratic



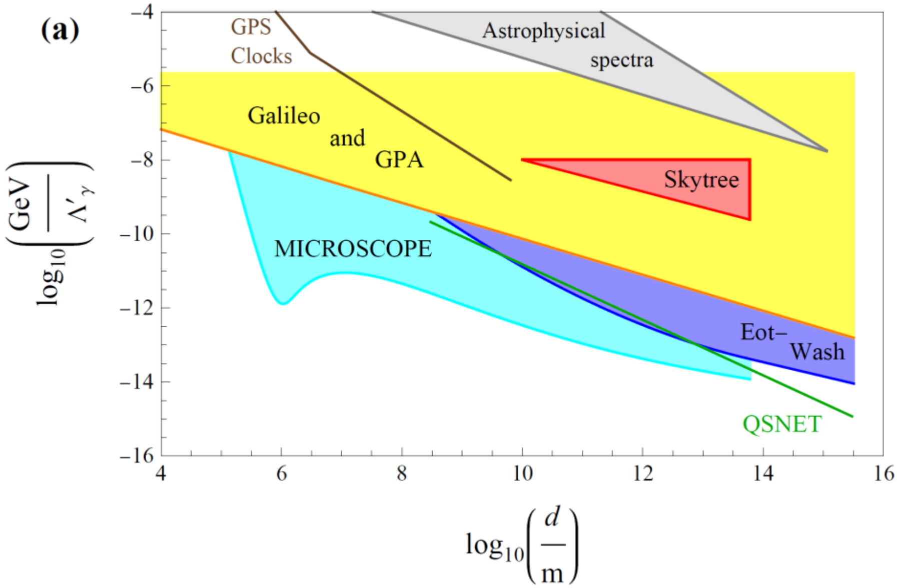


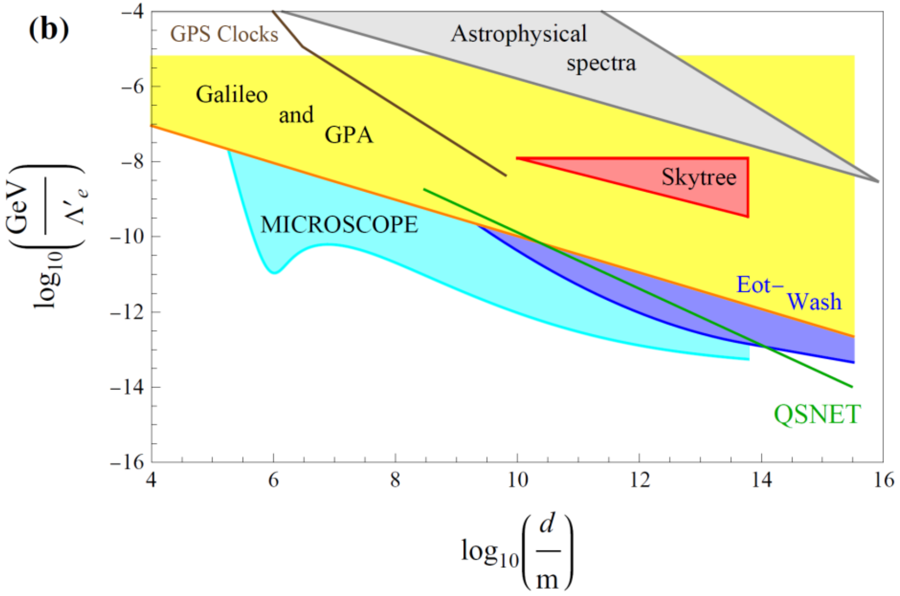
Solitons

Parameter spaces for a model of a domain-wall scalar field with the potential, interacting with

(a) the electromagnetic field and

(b) the electron via the quadratic-in-ϕ interactions





[arXiv:2112.10618]

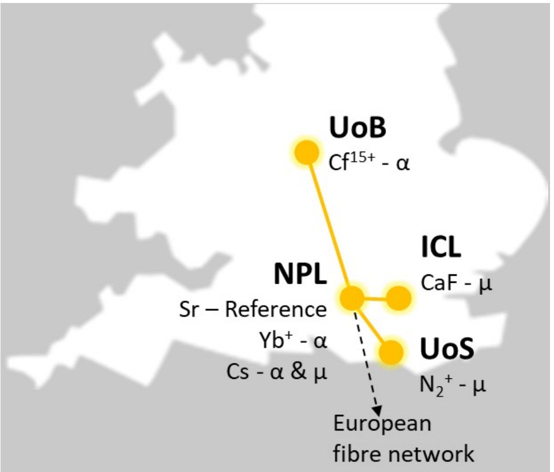
Other tests

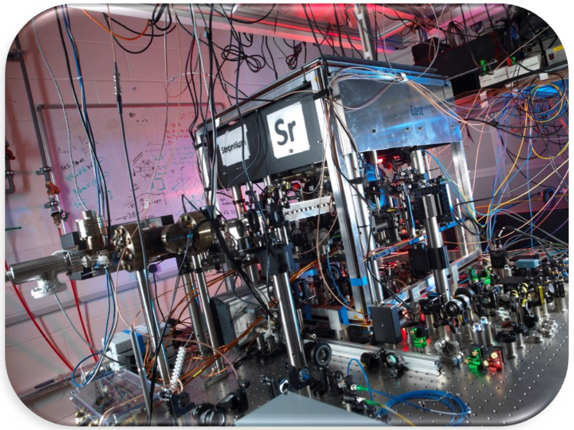
- Violation of fundamental symmetries (Lorentz invariance)
  - Space-time symmetries have been studied in a number of new-physics scenarios, some of these works suggest Lorentz-violating effects may exist and be detectable in experiments with exceptional sensitivity (Cf)
- Grand unification theories
  - 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

[arXiv:2112.10618]

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]

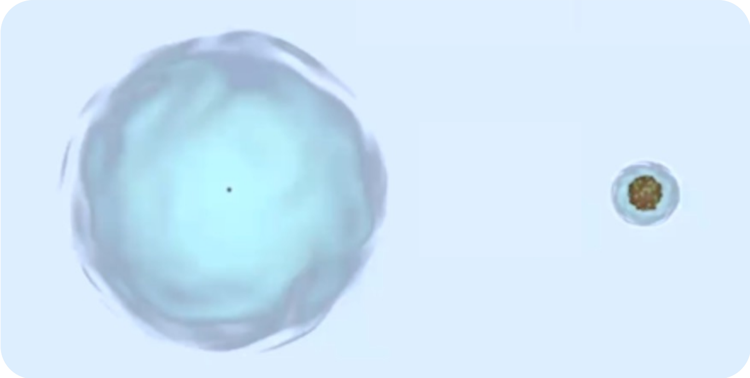




α μ

The Bham node: Highly-charged ions

Strip neutral atoms of several electrons



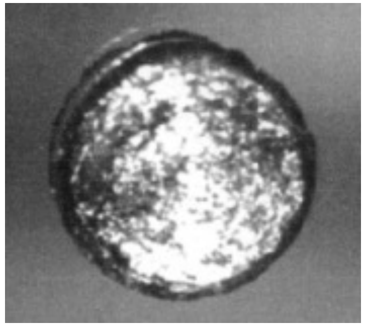
“Compressed” electronic cloud

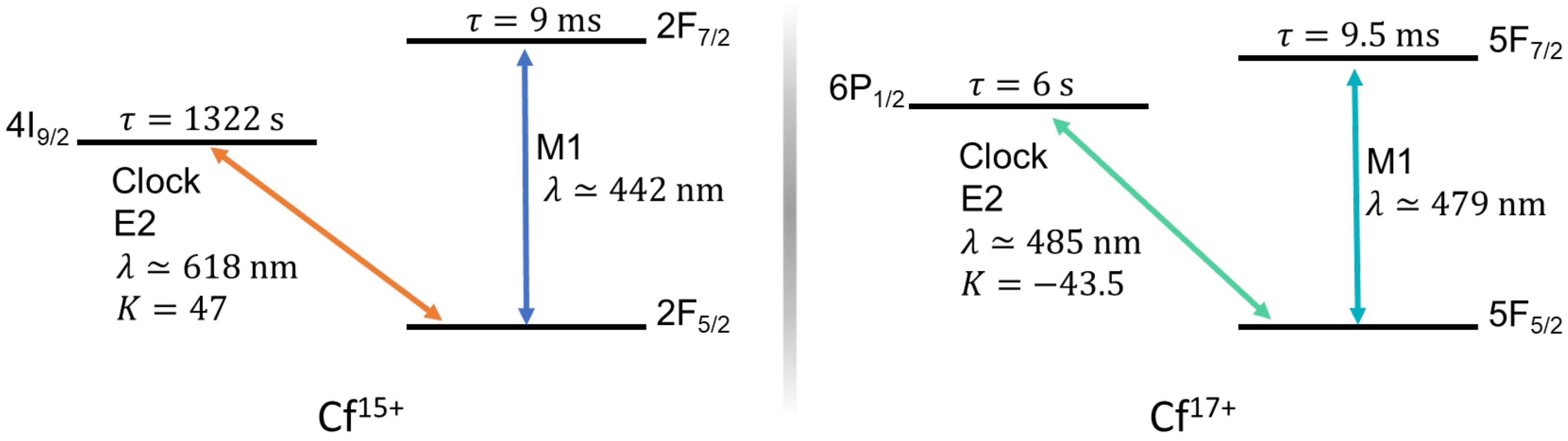
Low sensitivity to external perturbations (hopefully!) -> good for clocks

Large relativistic corrections -> high sensitivities to variations of α $(K_\alpha \sim 10 - 100)$

Cf HCIs

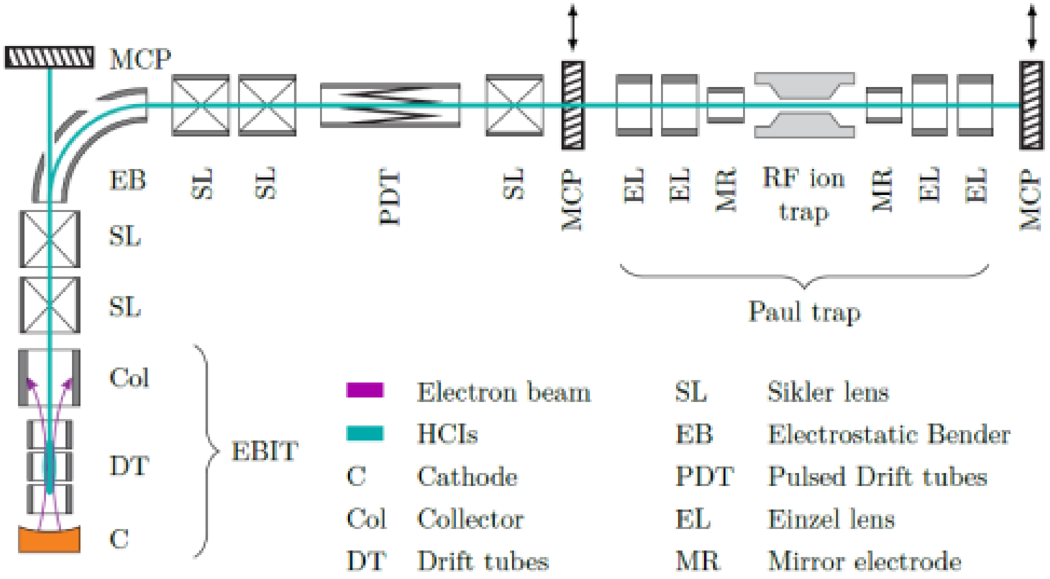
- Cf is a synthetic element produced in reactors
- ^{249}Cf has a half-life of 350 y, ^{252}Cf of 2650 y

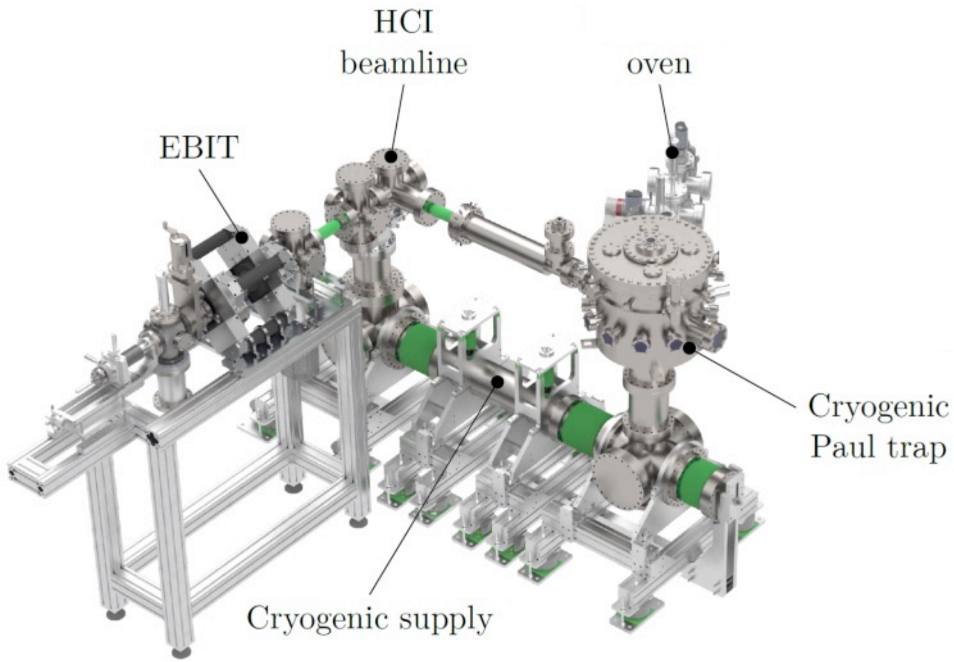




- Both ionisation states feature a clock transition in the visible range and a strong-ish transition also in the visible range
- The two clock transitions have large Ks with opposite sign

Production, cooling and trapping of HCIs

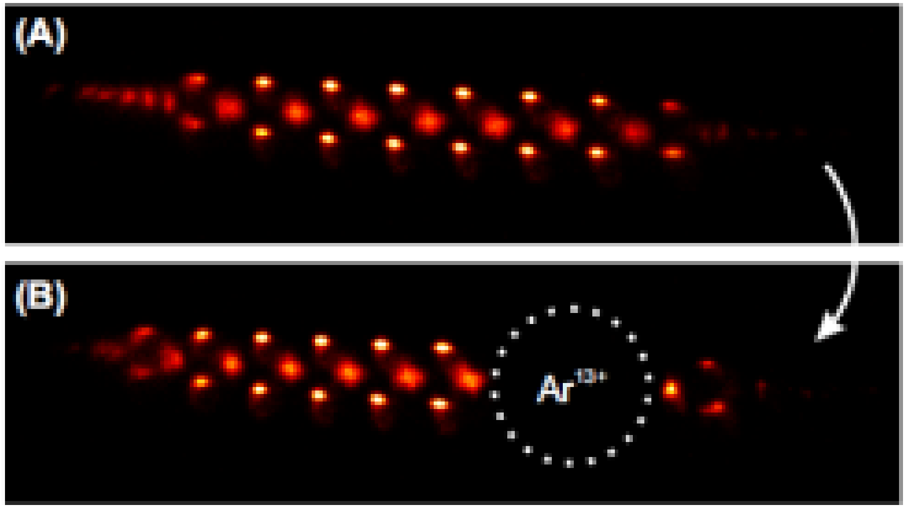




MK--->μK

MPI Heidelberg & PTB

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)]