QSNET

A network of clocks for measuring the stability of fundamental constants

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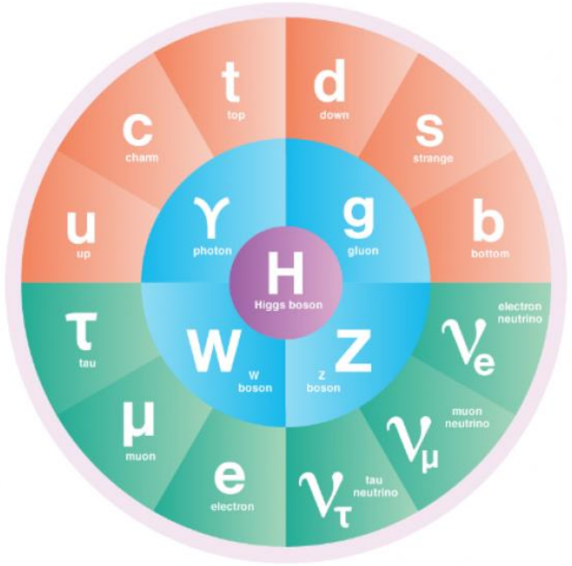
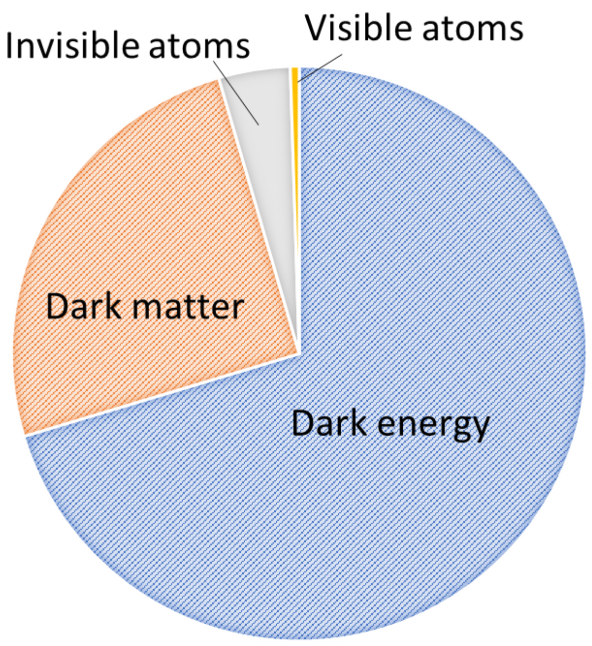
qsnet.org.uk

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 ΛCDM model postulates that 95% of the energy content of the universe is dark matter and dark energy. Their exact nature is unknown.





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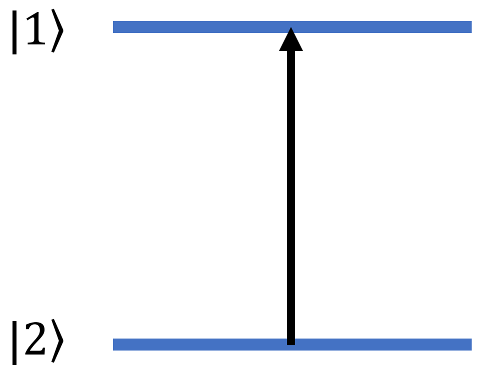
- Both models have several parameters, supposed to be immutable, called fundamental constants.
- Challenging this assumption could be the key to solving the dark matter and dark energy enigmas
- Any variations of fundamental constants would give us evidence of revolutionary new physics

Why clocks?

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

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

$$\mu = \frac{m_p}{m_e}$$



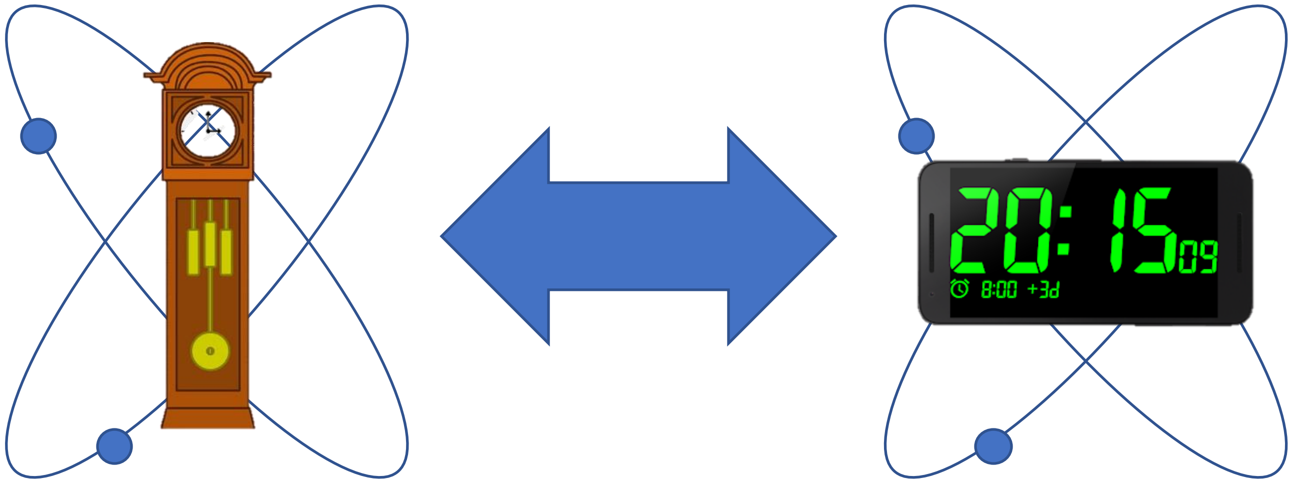
- Atomic and molecular spectra can be measured with extreme precision using atomic clocks

α

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

How to measure variations of fundamental constants

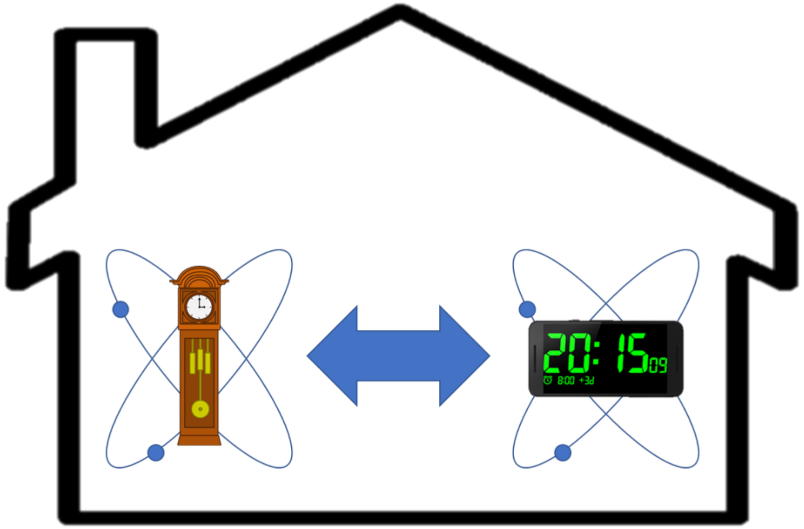
- Comparing clocks with different sensitivities to fundamental constants



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

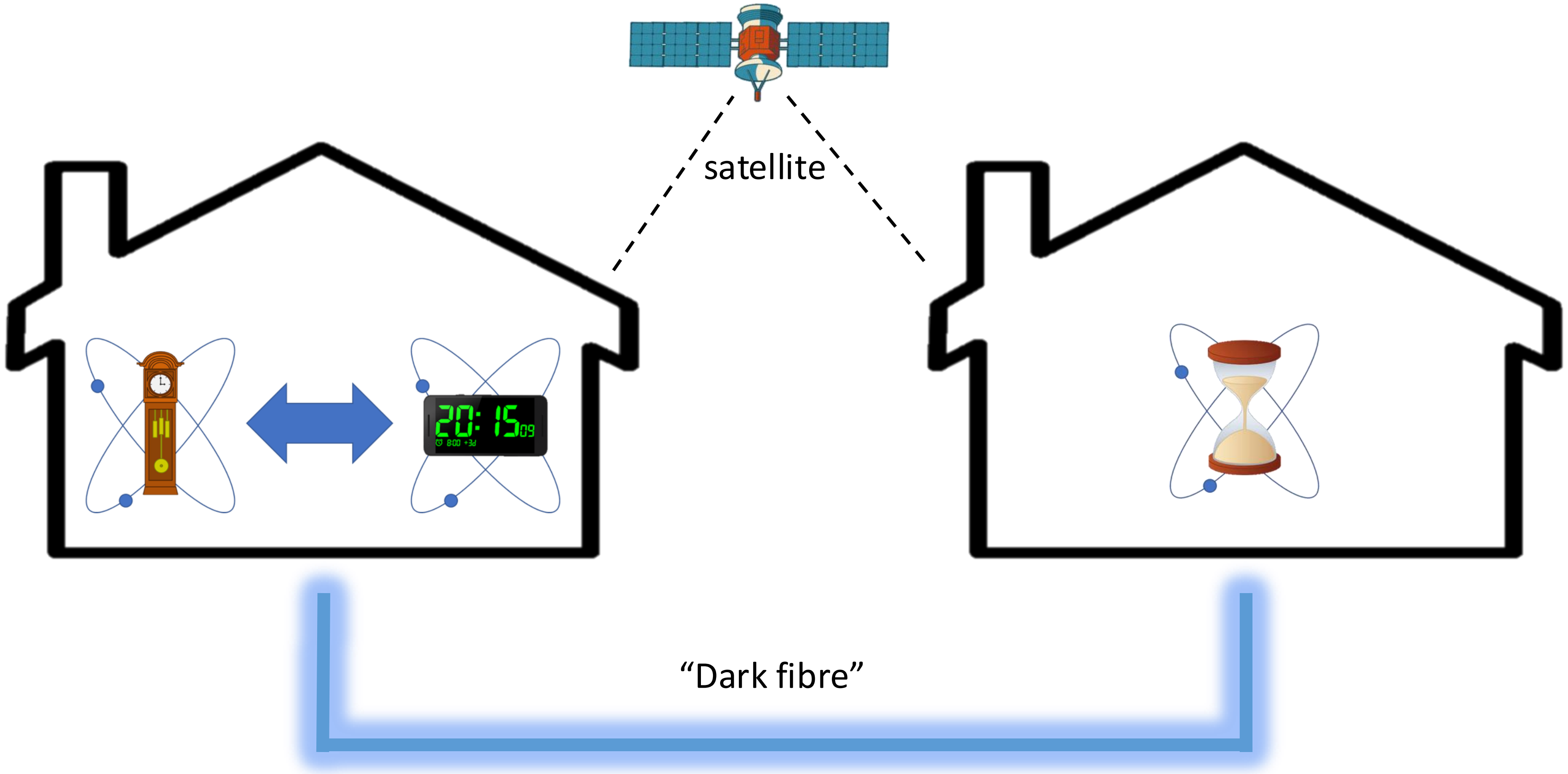
$$\frac{\Delta f1}{\Delta f2} = |K_{1x} - K_{2x}| \frac{\Delta x}{x} \qquad x = \alpha, \mu$$

How to measure variations of fundamental constants



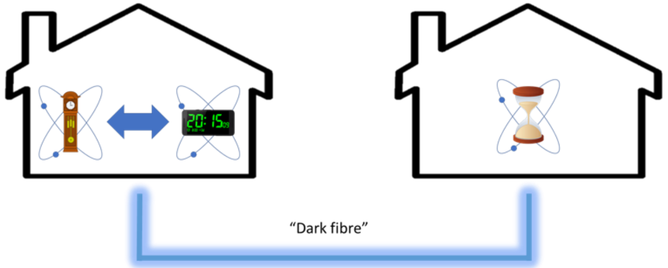
"in house" comparison

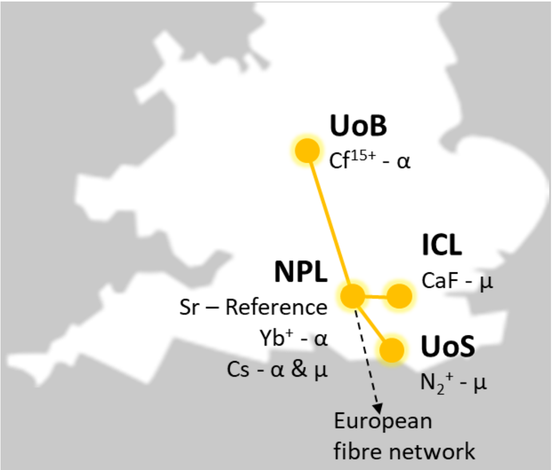
How to measure variations of fundamental constants



The network approach

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





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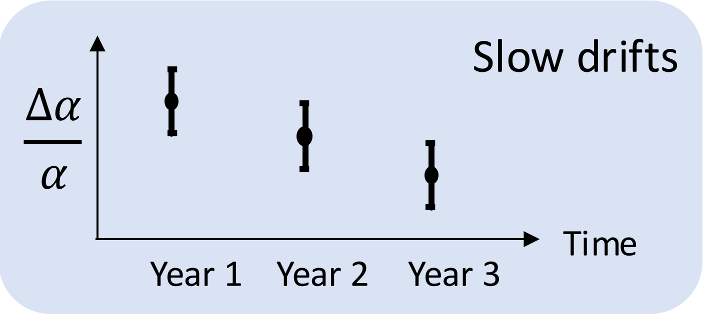
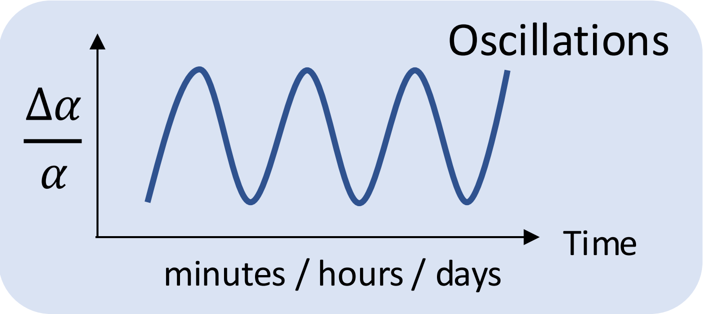
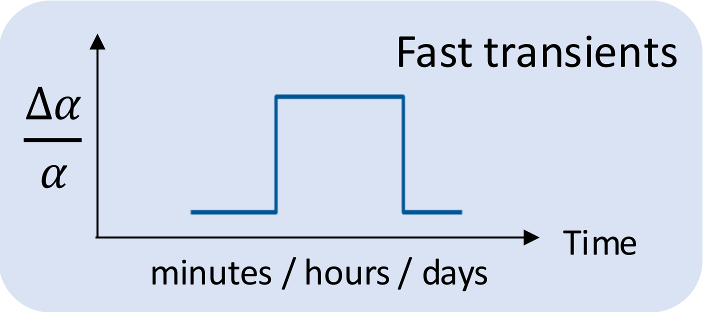


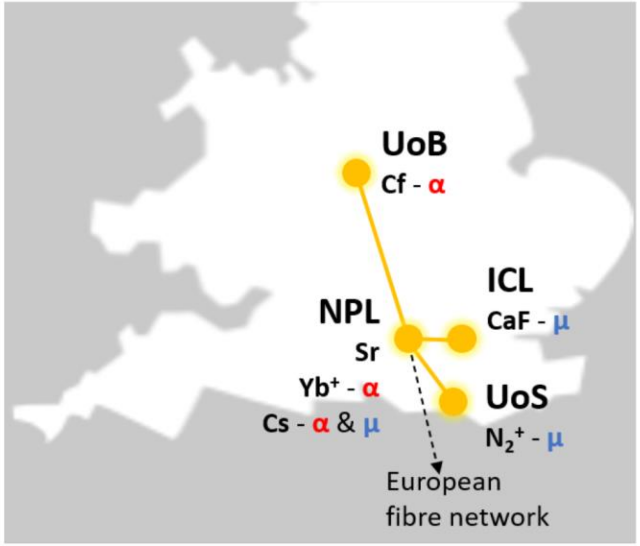




The QSNET project

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

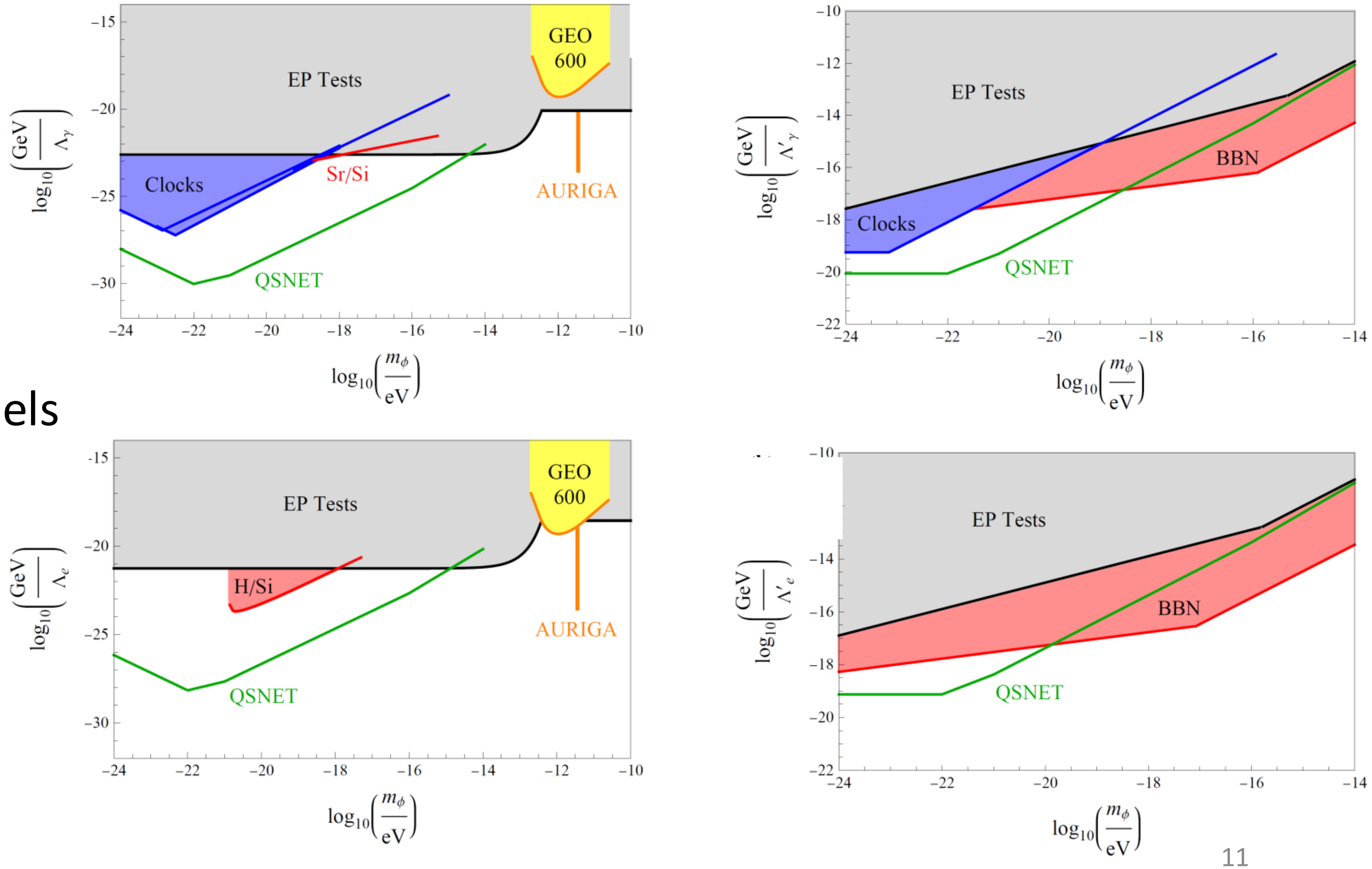
Sensitivity discussed in [EPJ QT 9, 12 (2022)]

- Coupling of dark sector scalar fields with standard matter
- Scalar dark matter models
- Axion models
- Quintessence-like models (dark energy)
- Kaluza-Klein models/moduli models
- Dilaton field models

Example: scalar dark matter

Linear

Quadratic



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

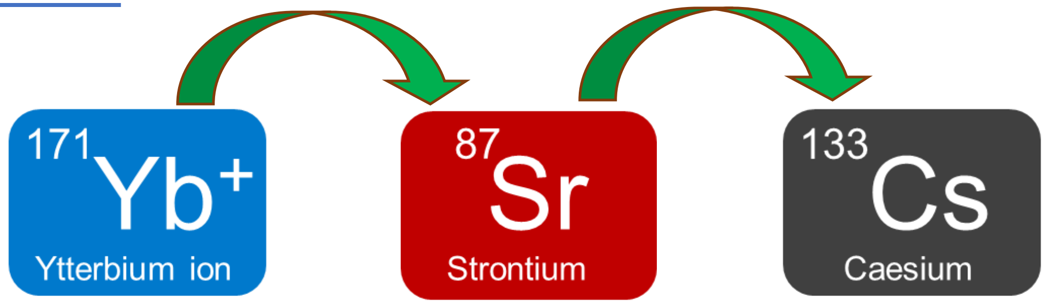
- Solitons
  - Topological solitons are made up of one or more fields that acquire stability due to the presence of two or more vacua
  - transient events, network is needed
- Violation of fundamental symmetries (Lorentz invariance)
  - Lorentz-violating effects may exist and be detectable in experiments 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

Our results

QSNET

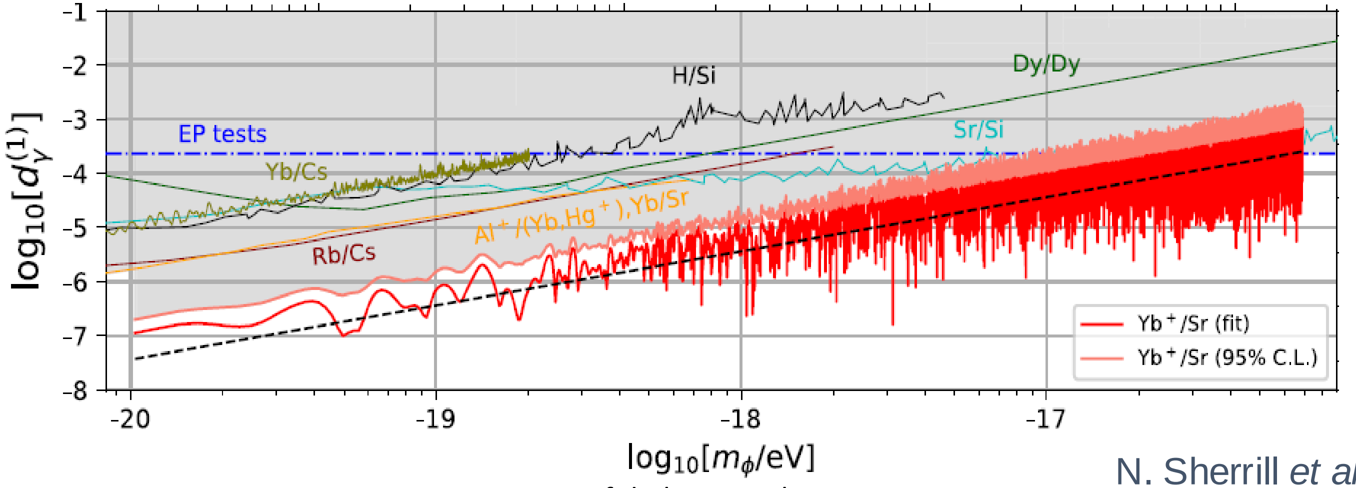
NPL optical clock measurements

Frequency ratios between NPL's optical clocks and Cs fountain have allowed limits to be placed on variations in the fine structure constant, α and the proton-to-electron mass ratio, μ.



During QSNET, we have:

- Improved the stability, accuracy and automation of the optical clocks
- Carried out several month-long measurement campaigns to search for variations in fundamental constants
- Worked with the theory team at Sussex to interpret the results for fundamental physics, e.g:



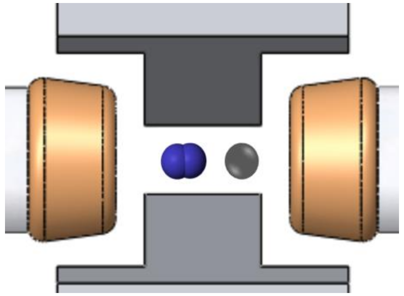
mass of dark matter bosons

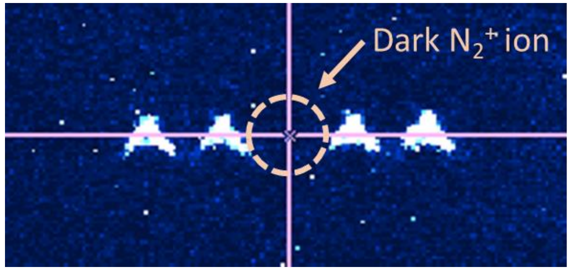
New data from NPL (red and pink lines) improved the constraint on the coupling strength between dark matter and photons by an order of magnitude compared to any previous measurements

N. Sherrill *et al*., New J. Phys. **25** 093012 (2023)

N_2^+ clock at Sussex

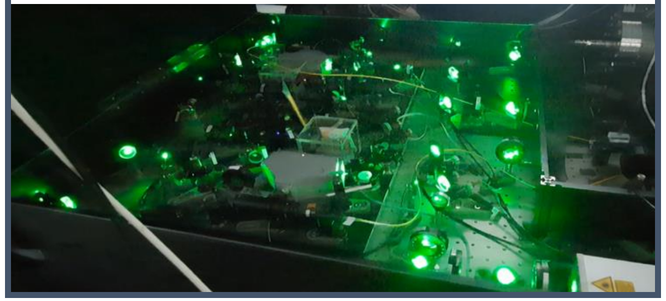
At Sussex we are building a clock system based on a vibrational transition in a trapped molecular nitrogen ion, using a calcium ion for cooling and read out.



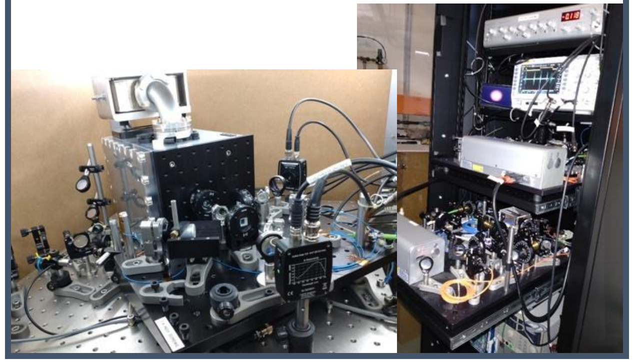


As part of QSNET, we have:

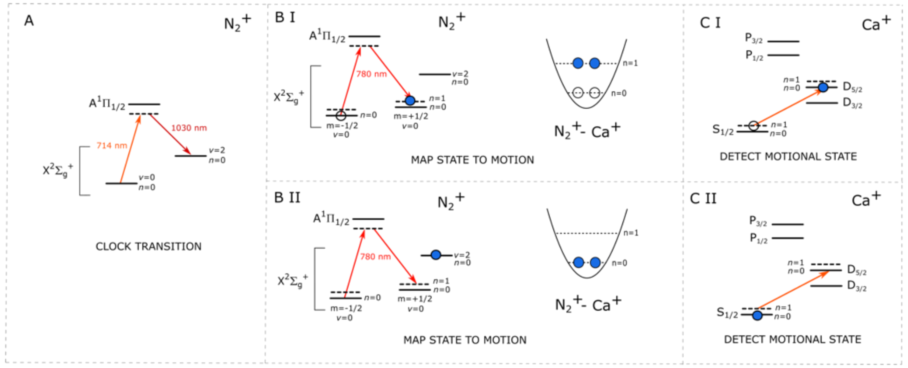
Built lasers and developed techniques for N_2 ionisation



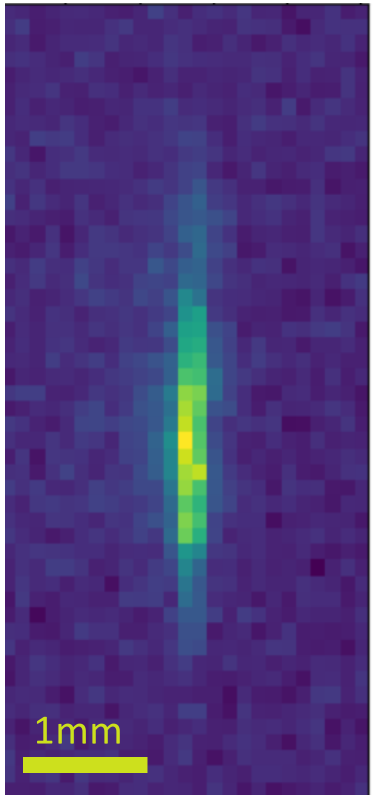
Set-up spectroscopy lasers (locked to ULE cavity)



Sideband cooled calcium and are preparing to test quantum logic spectroscopy

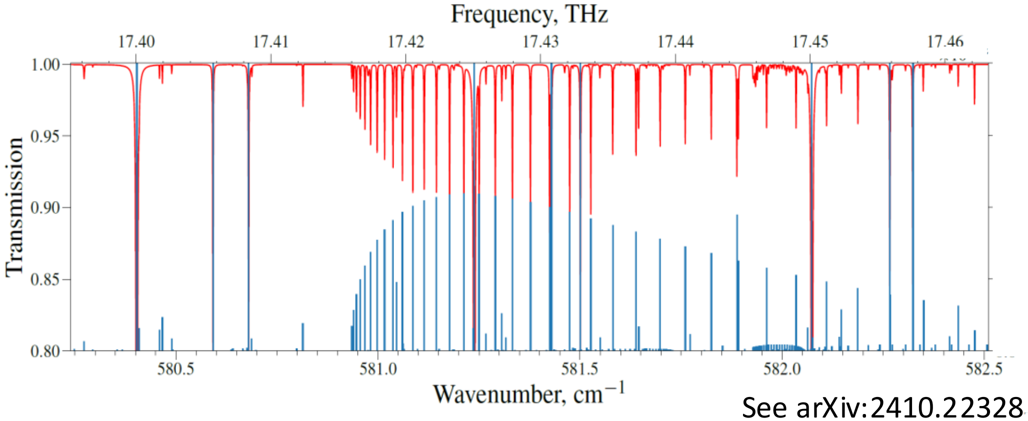


Towards a molecular lattice clock at Imperial



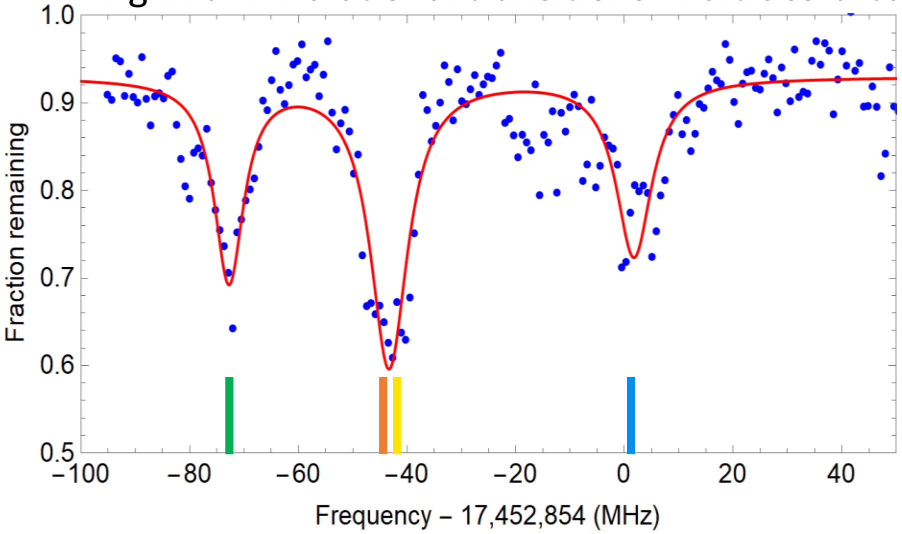
Ultracold CaF molecules trapped in an optical lattice

Spectroscopy for frequency calibration in the mid-infrared

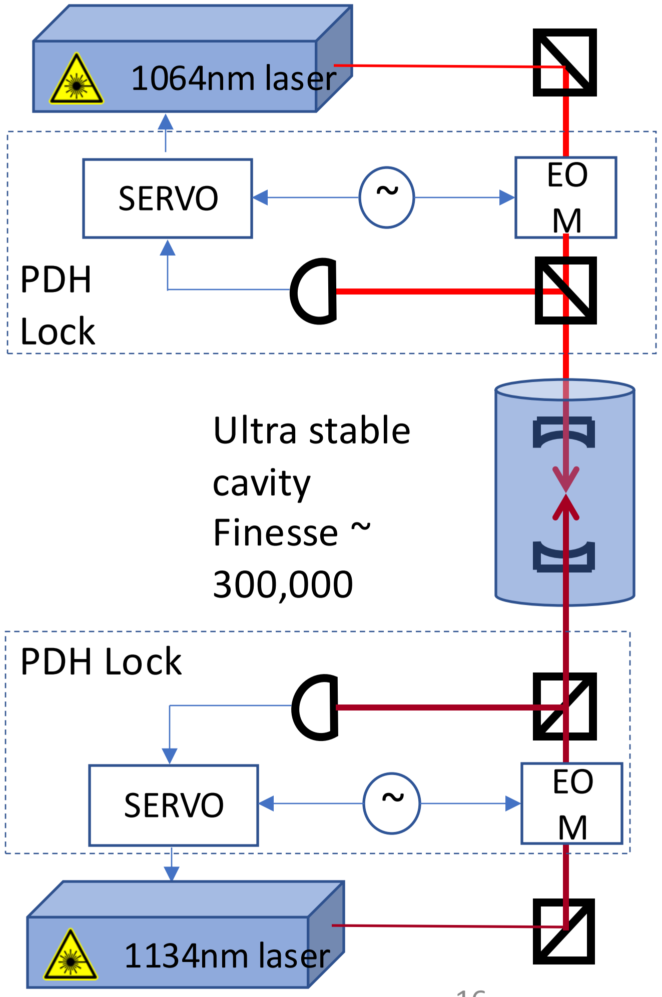


See arXiv:2410.22328

Driving mid-ir vibrational transitions in ultracold CaF

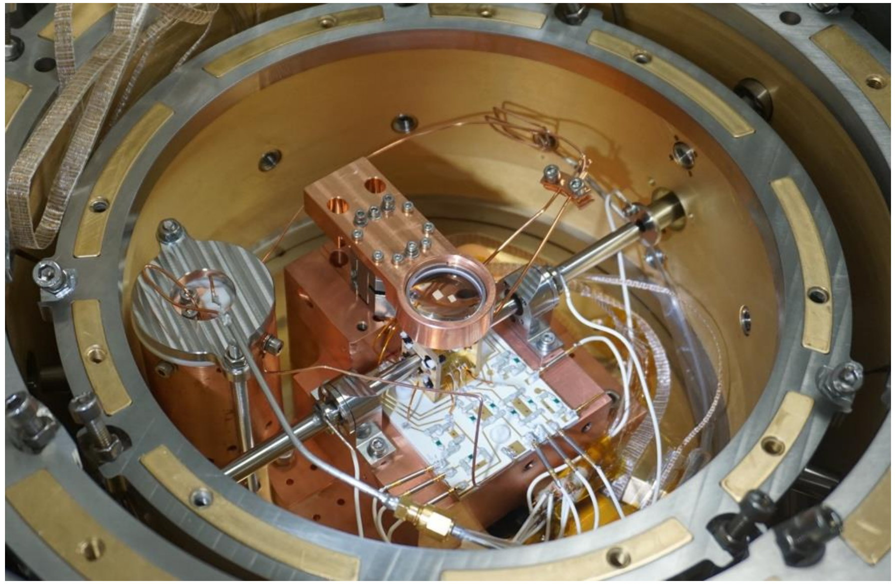


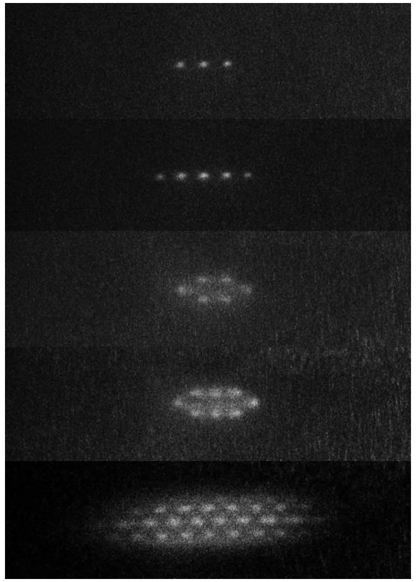
Raman laser system with a 1 Hz linewidth

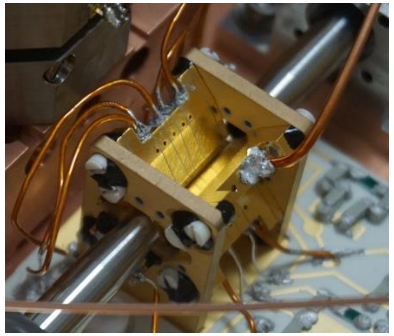


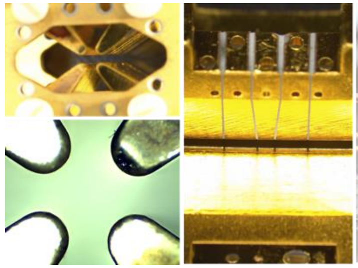
Towards Cf HCI clocks at Birmingham

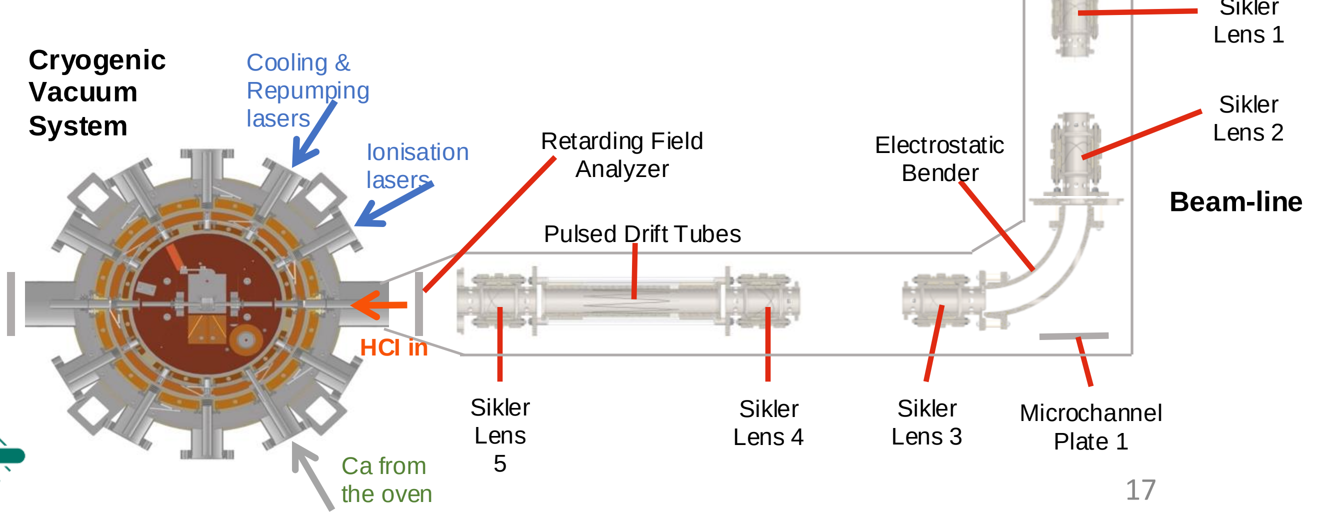
- Compact Electron Beam Ion trap
- Ion optics
- Ultra-low vibration cryogenic vacuum
- Cryogenic Paul trap
- Laser system
- Cf samples
- Laser cooled Ca+ Coulomb crystals











Collaboration with PTB, Max-Planck-Institut für Kernphysik

Summary

- An inter-disciplinary community gathered around a new (expandable) national infrastructure
- Exploited and enhanced world-class expertise and capabilities developed in NQTP
- Over 30 publications/preprints, over 100 invitations to give plenary talks, colloquia and seminars. Seminar series with more than 45 speakers -> **https://qsnet.org.uk/**

- Crucial milestones towards world-unique network of next-generation clocks
- Competitive constraints on variations of fundamental constants