HCIs in Birmingham

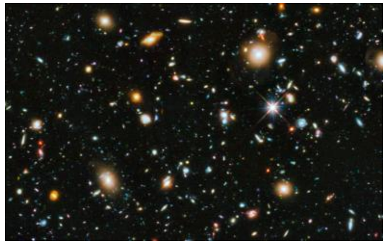
QTFP

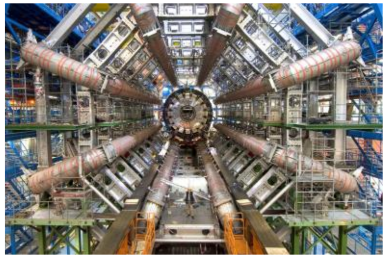
- QSFP (quantum sensors for fundamental physics) was launched in 2018
- Good timing with José's RMPs
- QSFP aimed at building a community at the interface of quantum physics and fundamental physics

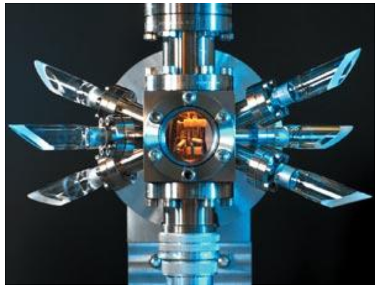
Background

- Searches for physics beyond the SM

Energy







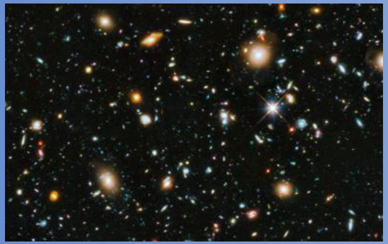
Precision

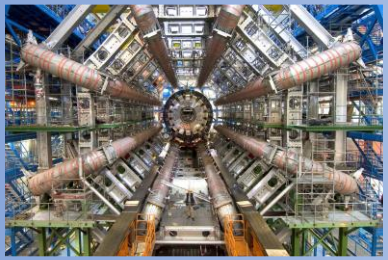
Background

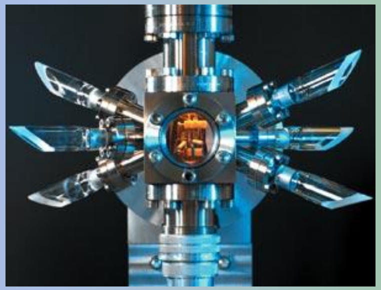
- Searches for physics beyond the SM

Science and Technology Facilities Council

Energy







Precision

Engineering and Physical Sciences Research Council

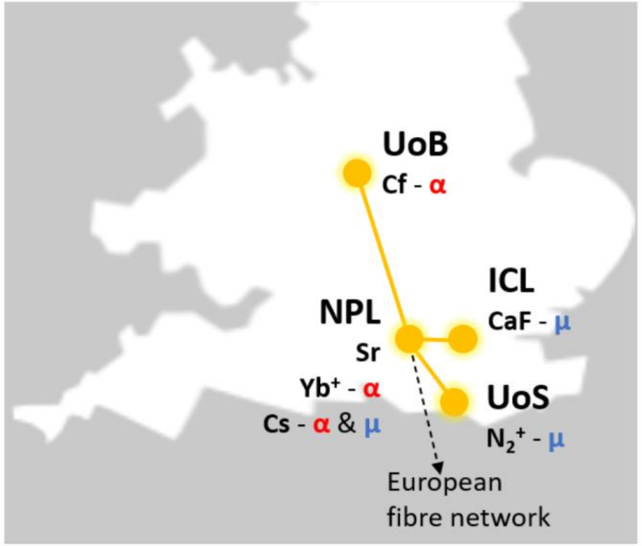
QTFP

- QTFP programme (£40M) launched in 2019
- Stevexit in 2019
- QSNET is one of the 7 projects funded, started March 2021 https://www.ukri.org/news/quantum-projects-launched-to-solve-the-universes-mysteries/

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

+ international partners

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

The QSNET project

Search for variations of fundamental constants of the Standard Model using a network of clocks

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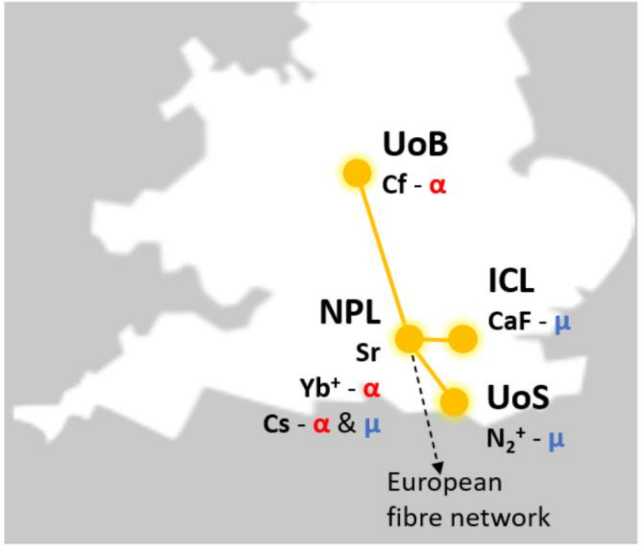

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TRL

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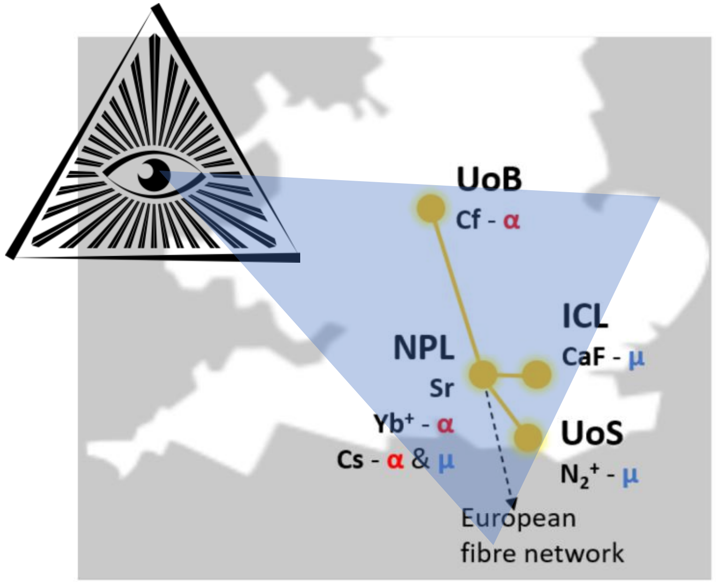

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- The clocks will be linked, essential to do clock-clock comparisons

The network approach

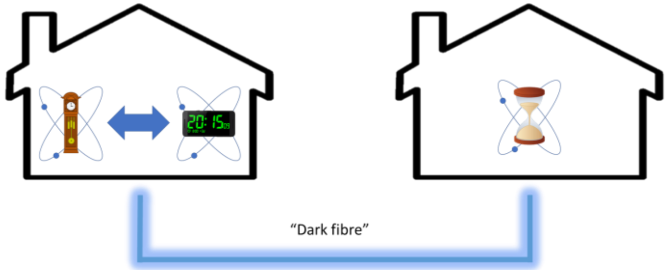
- Optimally exploit existing expertise. No single institution has the range of expertise required to run a sufficiently large and diverse set of clocks

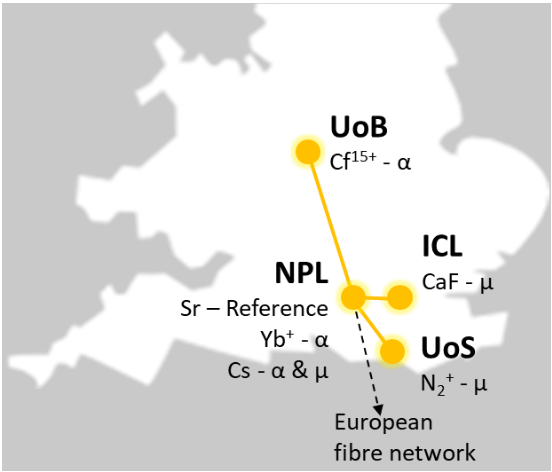
- Sensors with similar sensitivities and different systematics are necessary to confirm any measurements and reject false positives

- 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.





Phenomenology

- Coupling of “dark sector” scalar fields with standard matter [EPJ QT 9, 12 (2022)]:

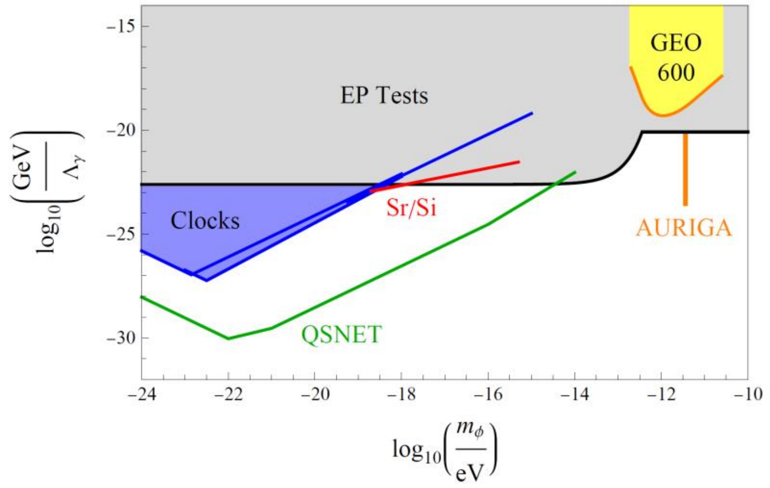
$$\mathcal{L}_{scalar} \supset \frac{\phi^n}{\Lambda_\gamma^n} F_{\mu\upsilon}F^{\mu\upsilon} - \sum_f \frac{\phi^n}{\Lambda_f^n} m_f \bar{f} f$$

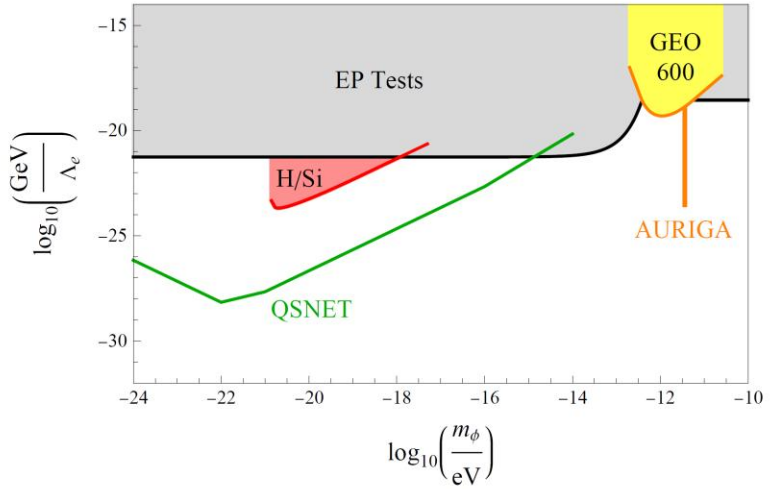
Λ_γ^n alter the fine structure constant α, Λ_f^n the fermionic masses -> manifest as effective variations of fundamental constants

- Scalar dark matter models
- Axion models
- Quintessence-like models (dark energy)
- Kaluza-Klein models/moduli models
- Dilaton field models

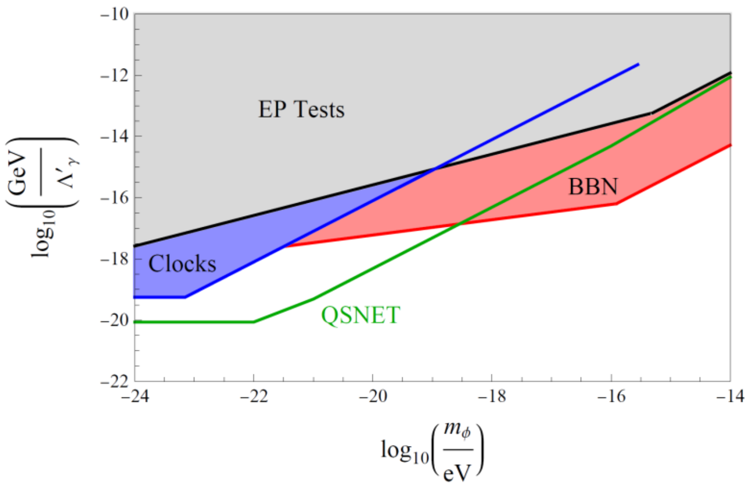
Example: scalar dark matter

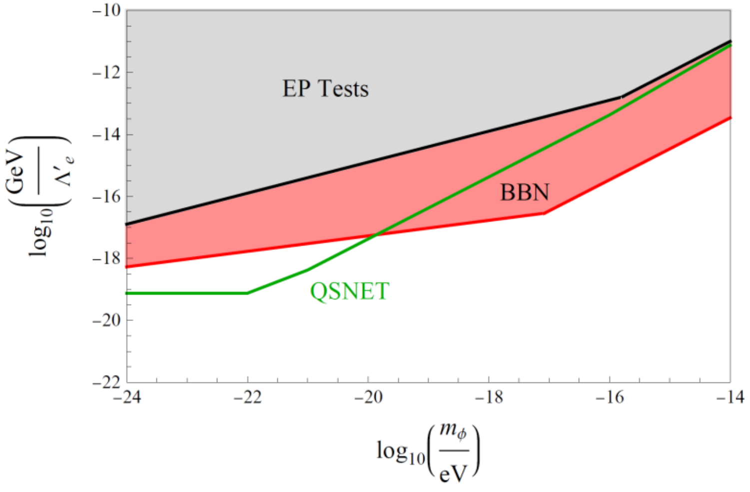
Linear





Quadratic





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

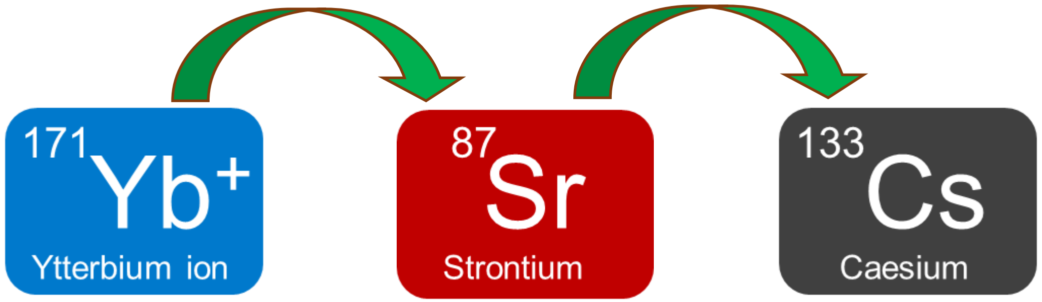
- Solitons
  - Topological solitons are made up of one or more fields that acquire stability due to the presence of two or more vacua
  - transient events, network is needed
- Violation of fundamental symmetries (Lorentz invariance)
  - Lorentz-violating effects may exist and be detectable in experiments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

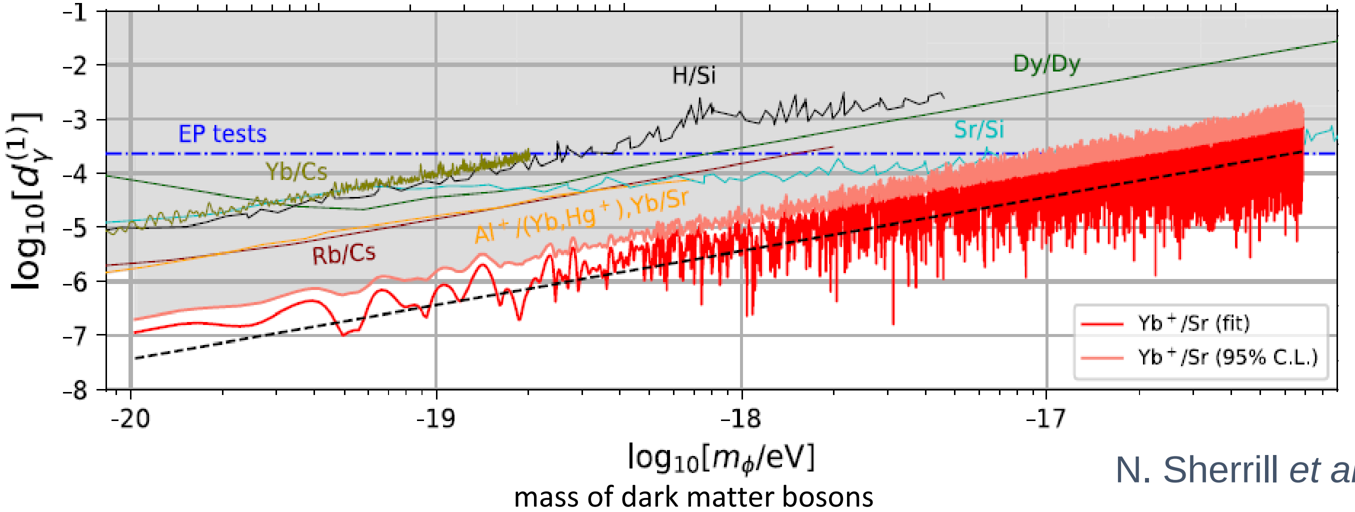
NPL optical clock measurements

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 -> now the most accurate clock in Europe!
- 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:



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

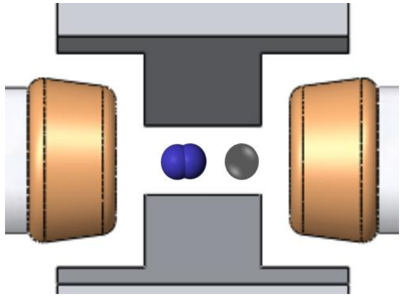
N. Sherrill *et al.*, New J. Phys. **25** 093012 (2023)

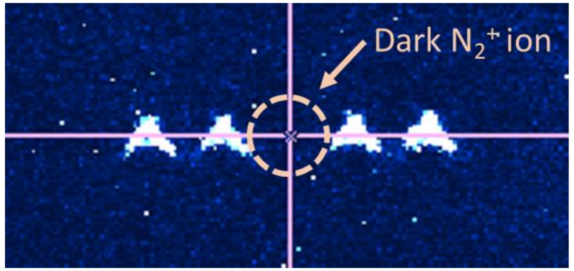
Theory at Sussex

- More than 20 published papers [qsnet.org.uk/publications]:
  - We have proposed a new framework to discuss new physics effects in clocks using effective field theory methods.
  - We have emphasized that one can obtain model independent bounds.
  - We have obtained limits for the case of dark matter and reconsidered the framework of grand unified theory.
  - Cross-fertilization of ideas, besides exciting results direct relevant to clocks
    - we made progress on dark matter deriving some theoretical bounds on their masses and in quantum gravity with some applications to the information paradox of black holes and their thermodynamics (in particular showing that they have not only a temperature but also a pressure).
    - The world, including our universe and black holes, is really quantum. The notation of macroscopic superposition is absolutely crucial in our resolution of the Hawking paradox.

N_2^+ clock at Sussex

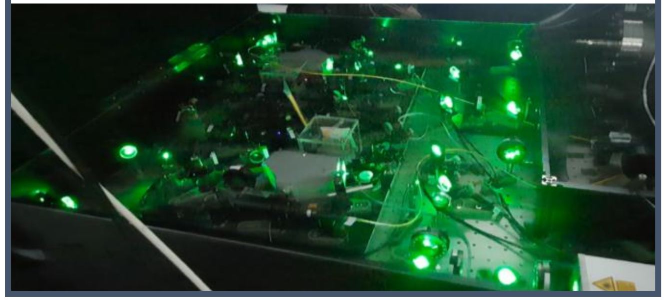
At Sussex we are building a clock system based on a vibrational transition in a trapped molecular nitrogen ion, using a calcium ion for cooling and read out.



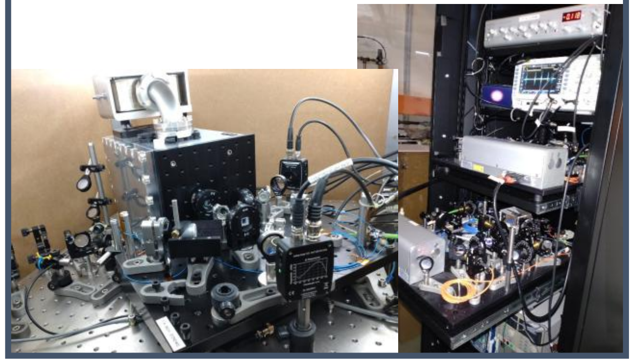


As part of QSNET, we have:

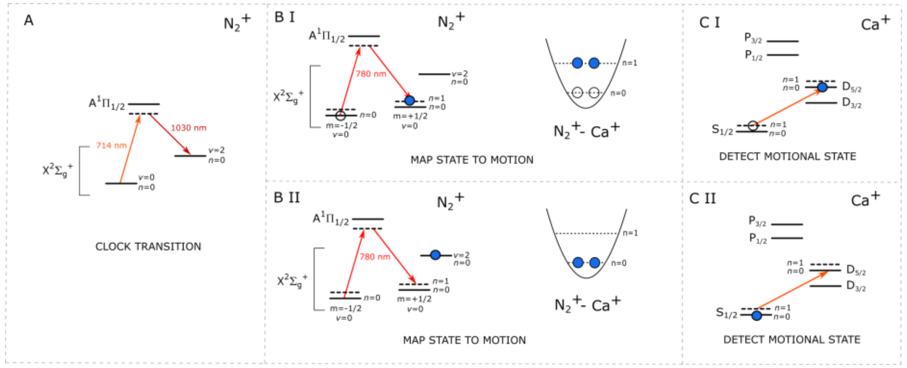
Built lasers and developed techniques for N_2 ionisation



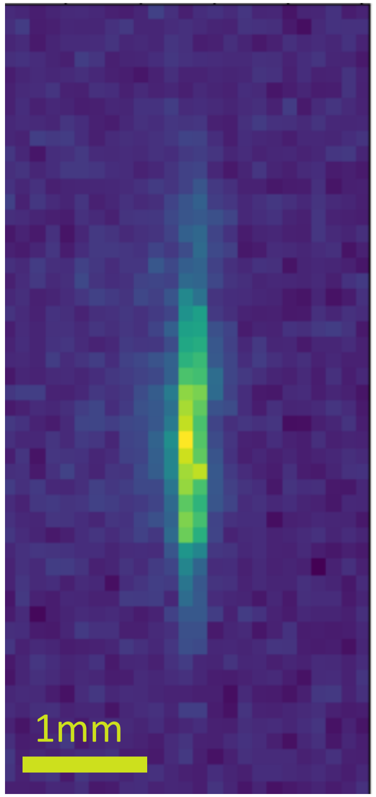
Set-up spectroscopy lasers (locked to ULE cavity)



Sideband cooled calcium and are preparing to test quantum logic spectroscopy

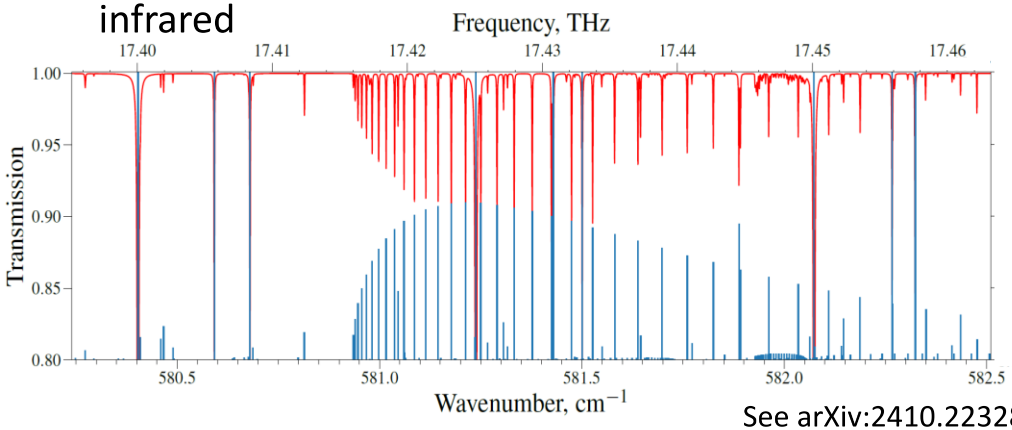


Towards a molecular lattice clock at Imperial



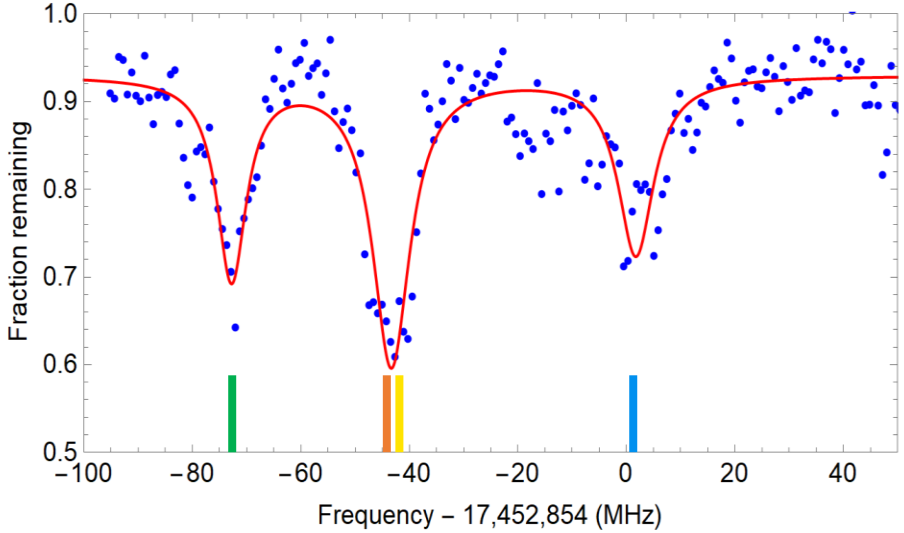
Ultracold CaF molecules trapped in an optical lattice

Spectroscopy for frequency calibration in the mid-infrared

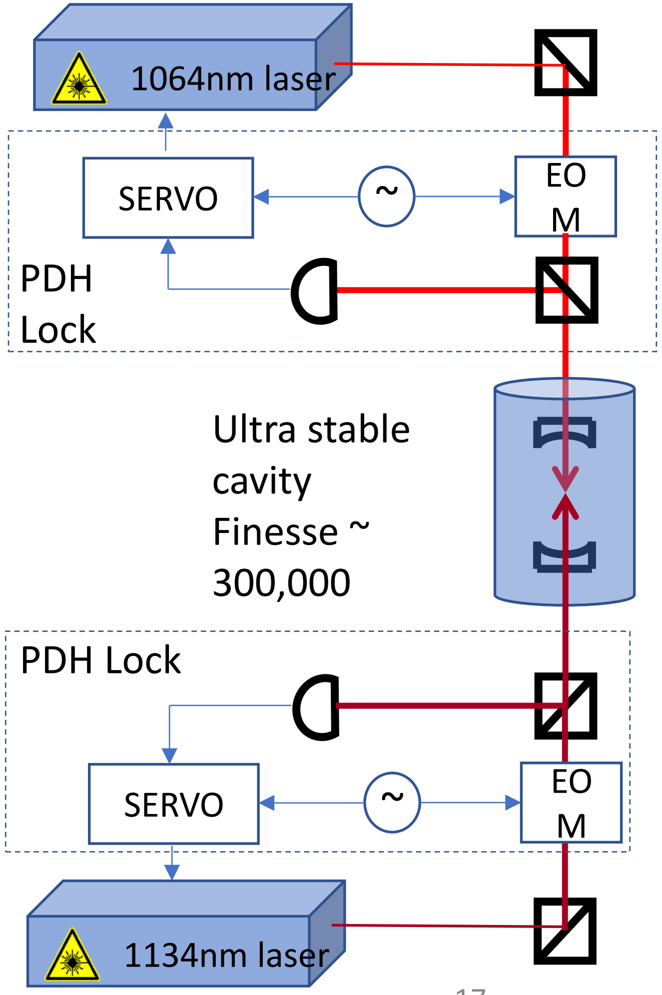


See arXiv:2410.22328

Driving mid-ir vibrational transitions in ultracold CaF

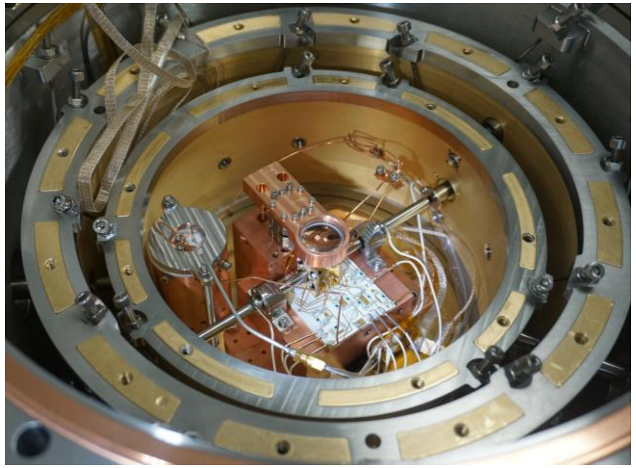


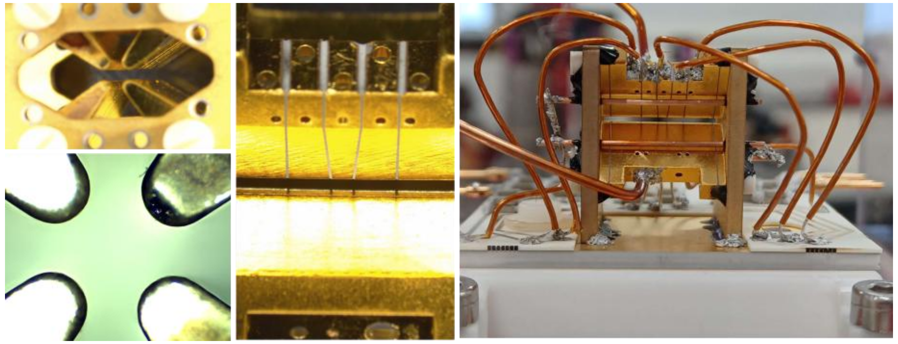
Raman laser system with a 1 Hz linewidth

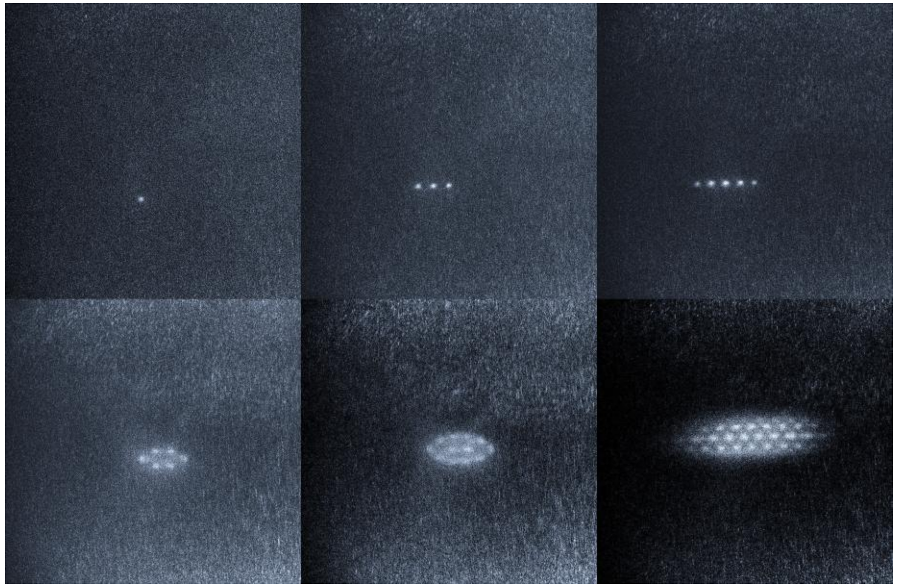


Towards Cf HCI clocks at Bham

- Compact Electron Beam Ion trap (1st in UK) [ ]
- Ion optics
- Ultra-low vibration cryogenic vacuum
- Cryogenic Paul trap [PTB]
- Laser system
- Cf samples
- Laser cooled Ca+ Coulomb crystals







Our promises

No.	Description	RAG Rating		Lead
		Previous	Current	
S1	New constraints on $\Delta\mu/\mu$ on timescales from 10-1000 s, targeting 4×10^{-15} at 1000 s	Completed	Complete	NPL
S2	Measure $\Delta\alpha/\alpha$ on fast timescales targeting 1×10^{-17} at 1000 s, exceeding current state-of-the-art sensitivity	Completed	Complete	NPL
S3	**a** Quantify impact of the new limits on unified models and dark matter models **b** Derive limits and exclusion plots for dark matter models with multiple components **c** derive an EFT framework to study new ultra light fields with clocks enabling the study of diverse phenomena such as e.g. ultra-light wavy dark matter, dark energy, extra dimensions or transient phenomena such as cosmic strings or domain walls **d** Comprehensive study to investigate the overlap in the parameter space for ultralight scalar field that can be probed by different experiments such as MAGIS, AION, EDGE, and clocks as well as fifth forces searches **e** Investigation of the possibility to discriminate between models should a signal be found. For example, can the mass, spin and interactions of the new light particle be reconstructed?	Completed	Complete	Sussex
S4	Provide first tests of model-independent parametrization for	Completed	Completed	Sussex

S4	Provide first tests of model-independent parametrization for variations of fundamental constants on data currently available, and compare with previous methods	Completed	Completed	Sussex
T1	Investigate sources of uncontrolled frequency offsets that lead to variations in frequency ratios	Green	Completed	NPL
T2	N_2^+ quantum spectroscopy	Amber	Completed	Sussex
T3	Realization of a Cf^{15+} cEBIT	Completed	Completed	Birmingham
T4	CaF molecules in optical lattices and identification of the clock transition	Green	Completed	Imperial
T5	Spectroscopy and identification of the clock line in hot Cf15+	Green	Green	Birmingham
T6	N_2^+ transition measured	Amber	Amber	Sussex

QSNET ++ 1	Realisation of a laser system for cooling and imaging Ca+ ions	Completed	Completed	Birmingham

QSNET ++ 2	Trapping and cooling Ca+ ions	Completed	Completed	Birmingham
QSNET ++ 3	Realisation of a Ca+ Coulomb crystal	Completed	Completed	Birmingham
QSNET ++4	Realisation of a Raman laser system for CaF	Completed	Completed	Imperial
QSNET ++5	Study of the CaF clock transition and coherence time	Amber	Amber	Imperial

What’s next

- STFC has announced a call to open in mid March (!)
- Similar amount of funding expected, but currently there is no funding allocated (!!)
- Second phase expected to start in October 2025

- ECFA DRD 5 (Steve knows more)
- FOREST pan-European fibre network