QSNET

A network of clocks for measuring the stability of fundamental constants

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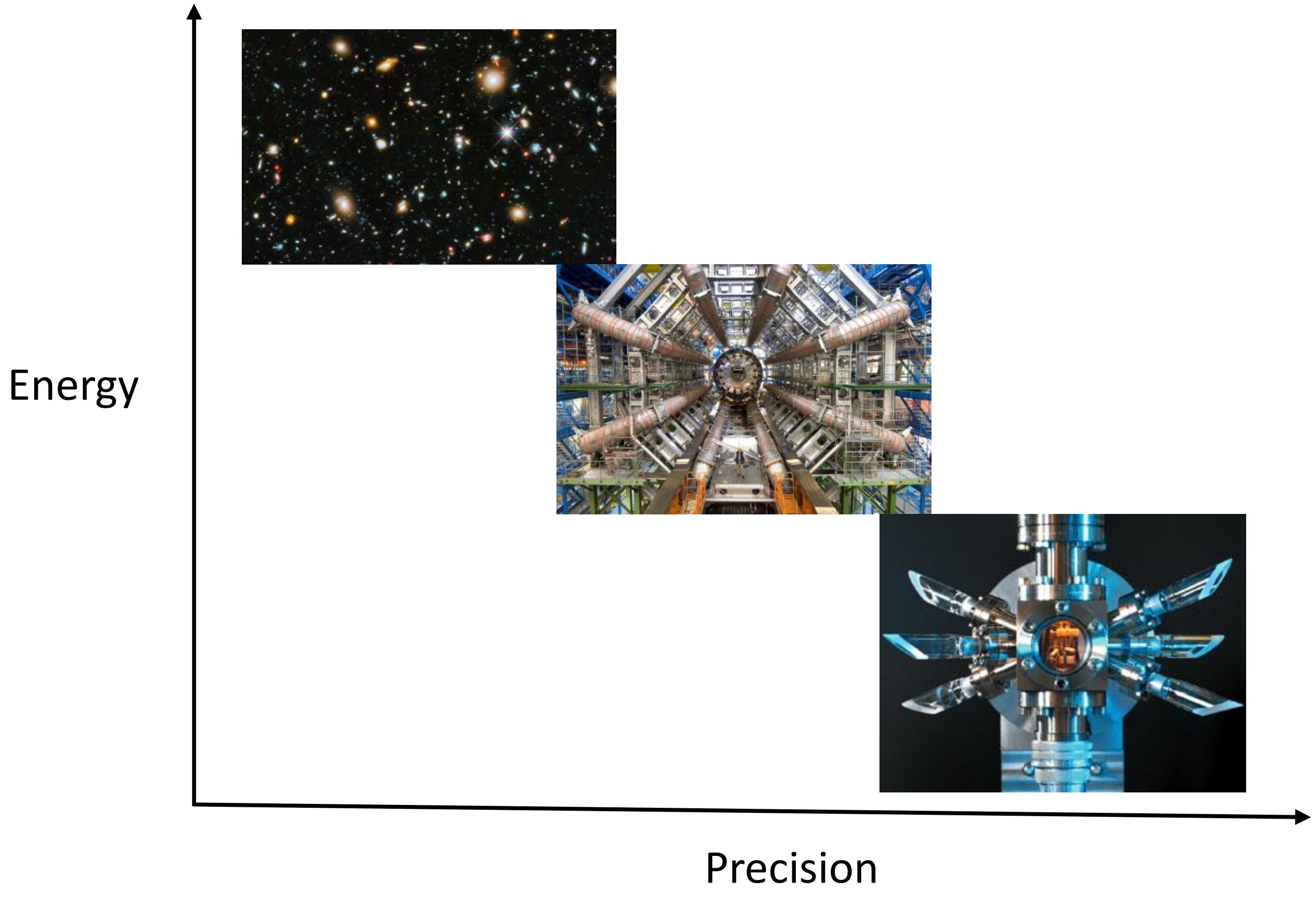
Birmingham NPL Sussex Imperial

Background

- Searches for physics beyond the SM



Background

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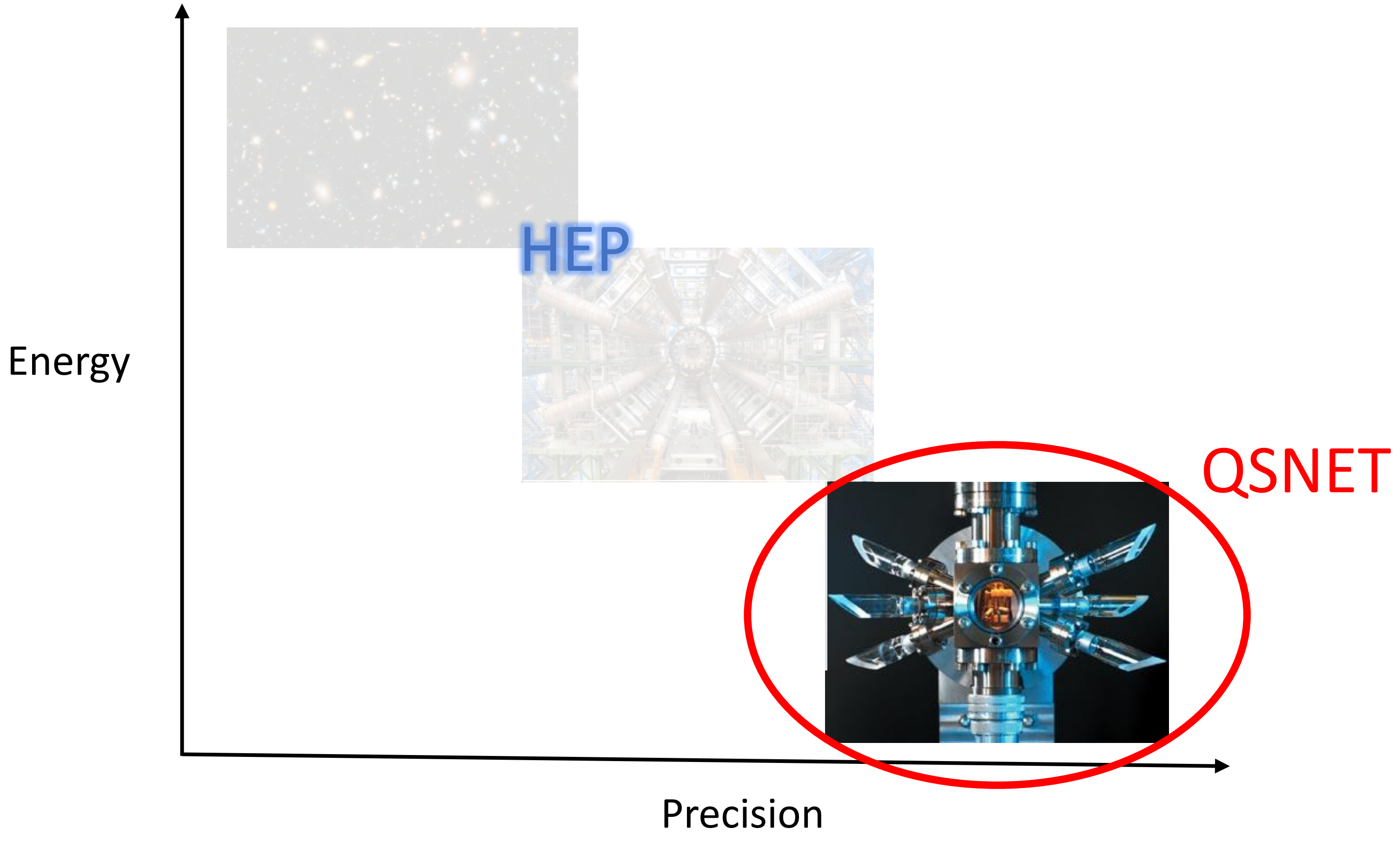


Background

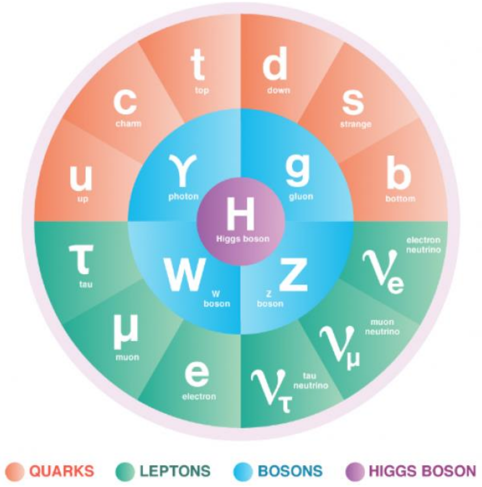
- The Standard Model and General Relativity are very successful theories, but the SM only accounts for 5% of the energy balance of the Universe

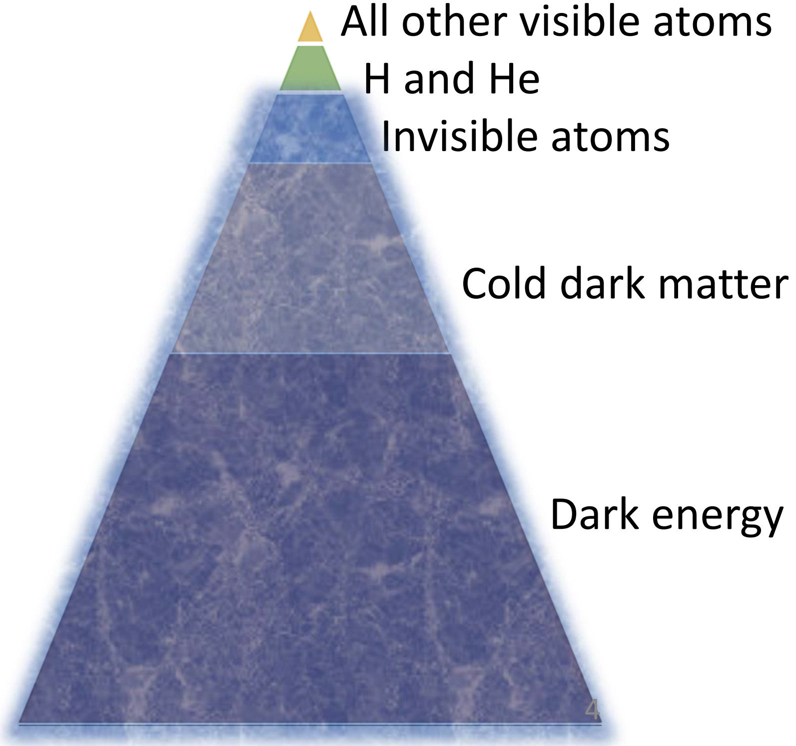
- The SM has 19 parameters: 6 quark masses, 3 lepton masses, 3 quark mixing angles and phases, 3 electroweak parameters, the Higgs mass, strong combined charge conjugation and parity violating phase, and the QCD coupling constant (+Newtonian constant of gravitation of general relativity, the speed of light in vacuum, and the Planck constant).

- These parameters are supposed to be immutable and are referred to as fundamental constants.

- <u>This assumption needs to be tested.</u>

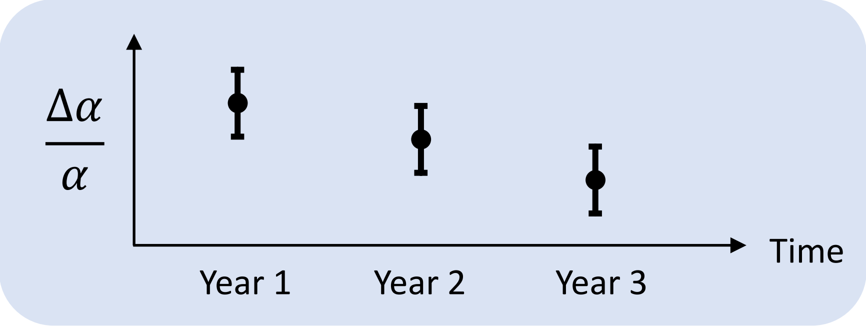
- Any variations of fundamental constants would give us evidence of revolutionary new physics





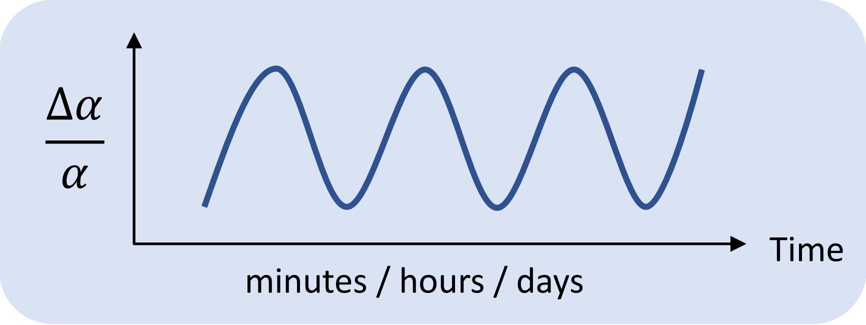
Look for variation on different timescales

- Slow drifts



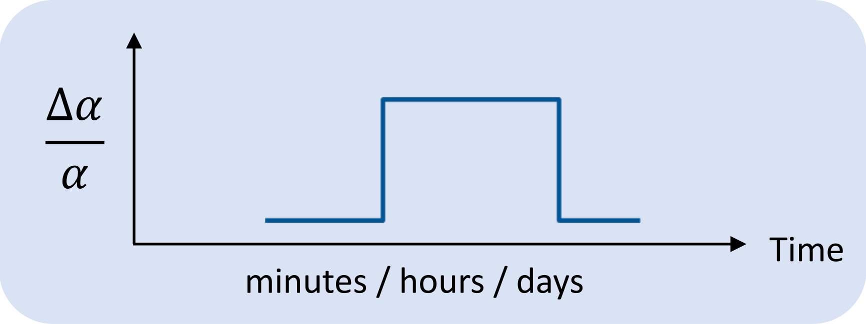
New physics

- Oscillations



Very light dark matter

- Fast transients



Dark matter - topological defects

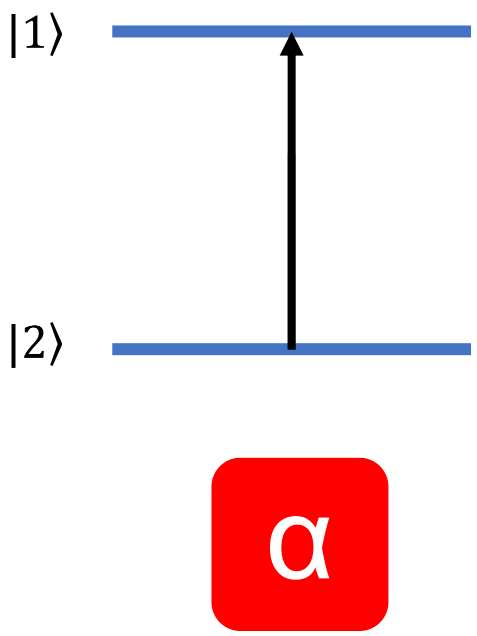
Choice of fundamental constants

- Need to measure dimensionless constants

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

- Spectroscopy lends itself to measure variations of:

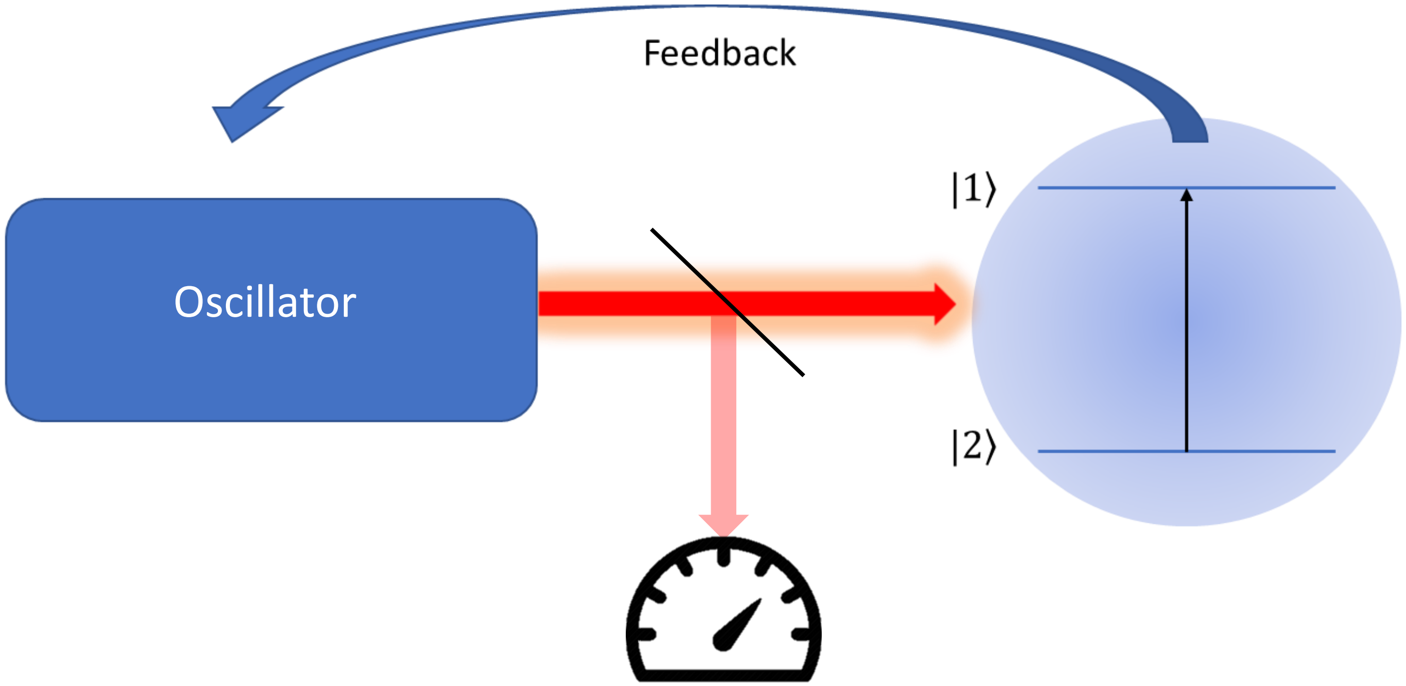
$$\alpha = \frac{1}{4\pi\varepsilon_0}\frac{e^2}{\hbar c} \qquad \mu = \frac{m_p}{m_e}$$

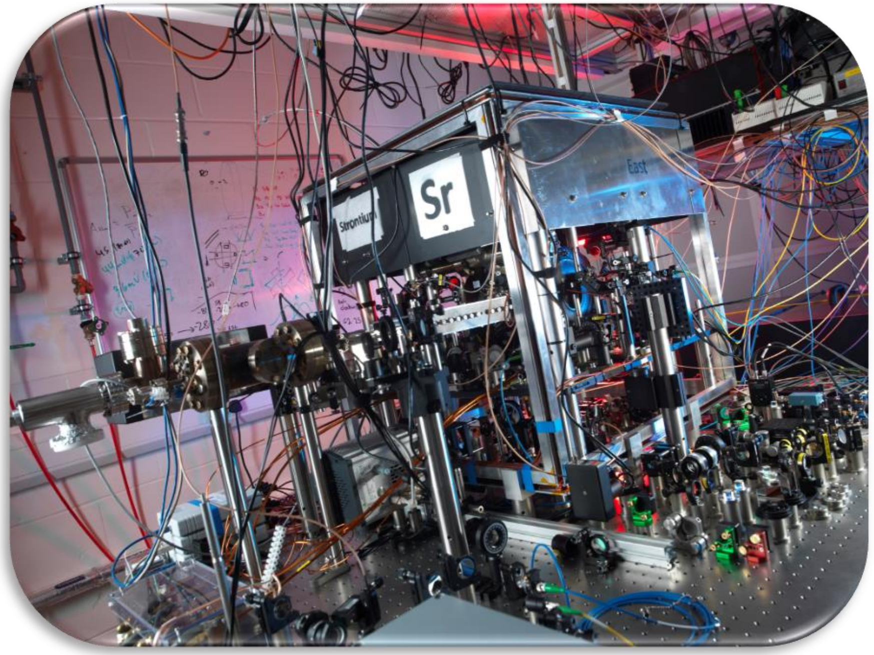


- Grand unification physics fixes relations between fundamental constants (if one changes with time, others will as well)

Atomic clocks

- Extremely high-precision spectroscopy





- Stability and accuracy at the 10^{-19} level

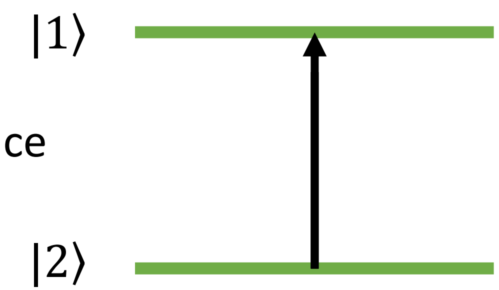
How to measure variations of fundamental constants

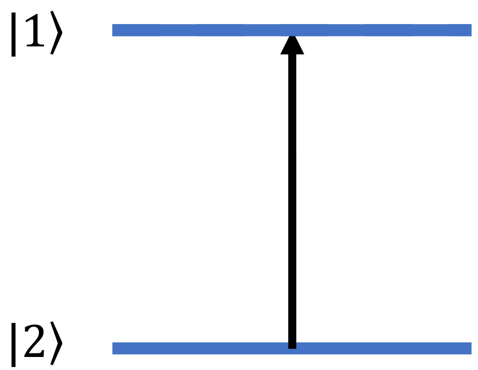
- How can we be sure that if we measure a variation of the energy spacing of our clock this is due to variations of fundamental constants?

  - 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

Reference





α

How to measure variations of fundamental constants

- Different clock transitions have different sensitivities to fundamental constants

Atomic energy	Scaling
Gross structure	$\sim \alpha^2$
Fine structure	$\sim \alpha^4$
Hyperfine structure	$\sim (\alpha^4/\mu)$

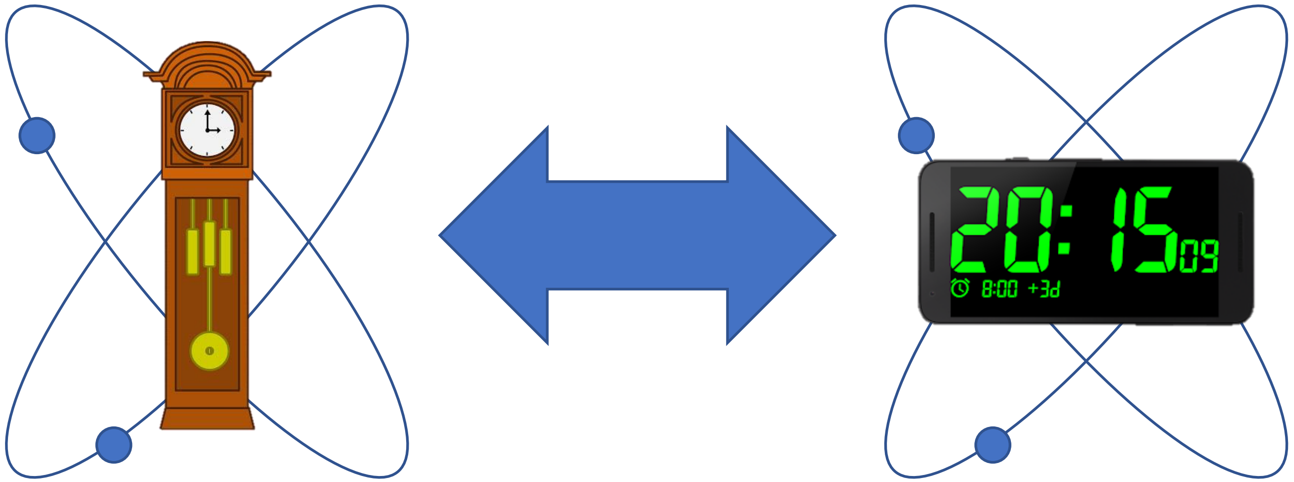
Molecular energy	Scaling
Vibrational levels	$\sim \mu$

Sensitivity

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

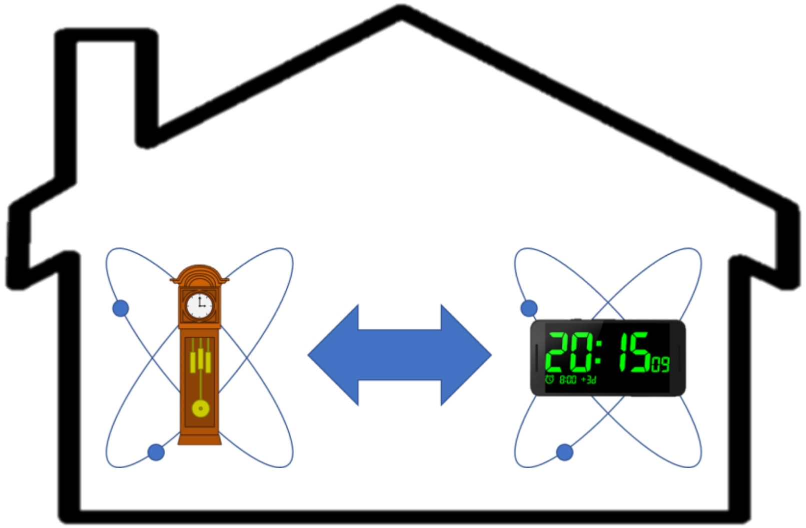
- Different clock transitions have different sensitivities to fundamental constants



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

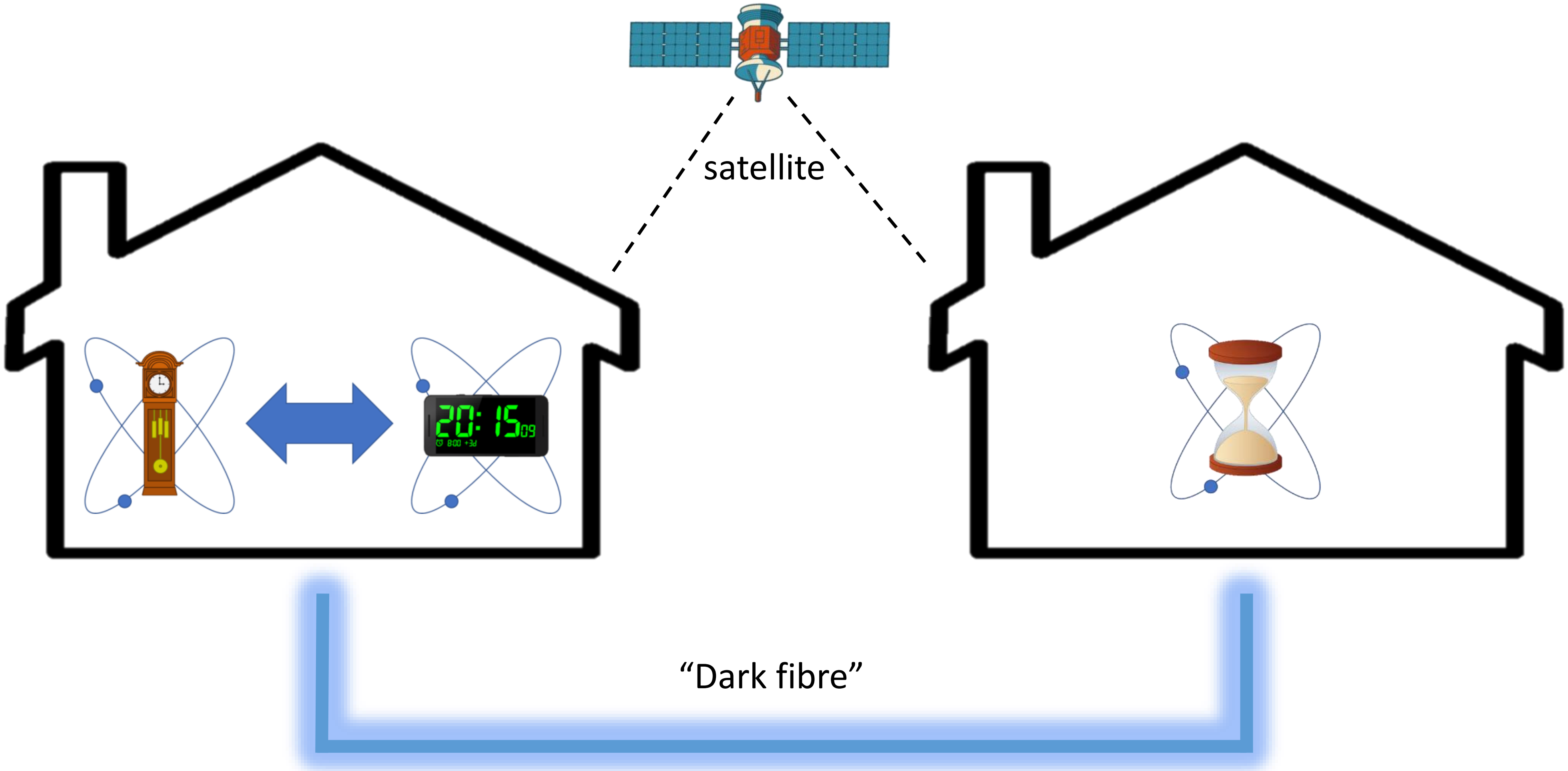
$$\frac{\Delta f1}{\Delta f2} = |K_{1x} - K_{2x}| \frac{\Delta x}{x} \qquad x = \alpha, \mu$$

How to measure variations of fundamental constants



“in house” comparison

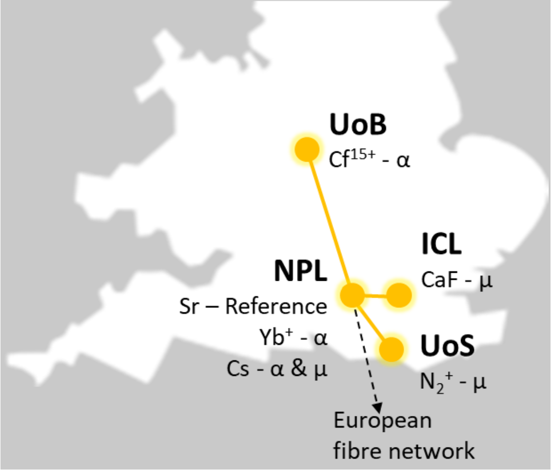
How to measure variations of fundamental constants



The QSNET project

- **Search for variations of fundamental constants of the Standard Model, using a network of quantum clocks**

- A unique network of clocks chosen for their enhanced sensitivities to variations of **α** and **μ**



Clock		Kα	Kμ
Higly-charged ion clock	Cf^{15+} (775 nm)	59	0
Atomic clock	Yb^{+} (467 nm)	-5.95	0
Molecular ion clock	N_2^{+} (2.31 μm)	0	0.5
Molecular clock	CaF (17 μm)	0	0.5
Atomic clock	Sr (698 nm)	0.06	0
	Cs (32.6 mm)	2.83	1

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

The network approach

- Needed to perform clock-clock comparison at the ultimate level of accuracy and optimally exploit existing expertise

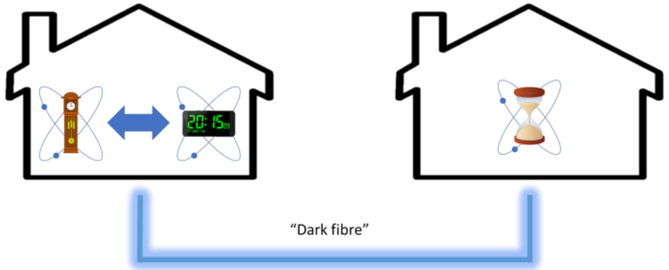
- A common, stable, and insensitive frequency reference (the Sr clock at NPL), against which all the clocks of the network can measure variations, is cost effective and allows all the members of the consortium to benefit from the clocks at NPL

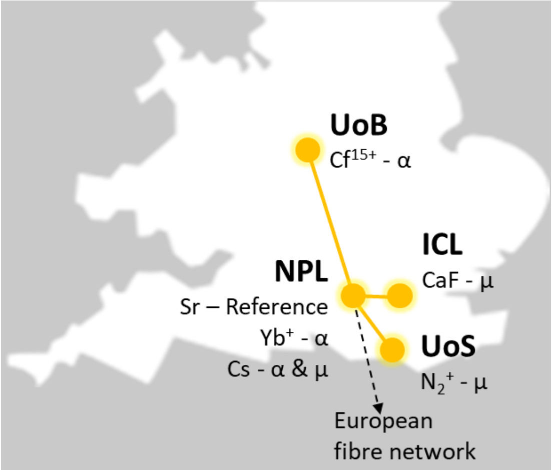
- Sensors with similar sensitivities and different systematics are necessary to confirm any measurements and reject false positives

- The possibility of detecting transient events such as topological defects in dark matter fields or oscillations of dark matter fields at different locations as long as the distance is below the coherence length (dark matter mass $<10^{-9}$ eV)

- A strong national network will allow the UK to join existing global networks with a critical mass

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





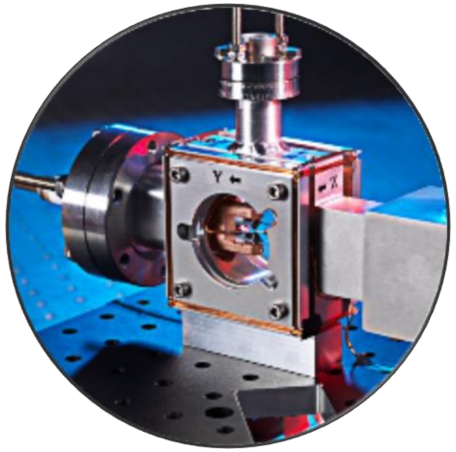
The nodes - NPL

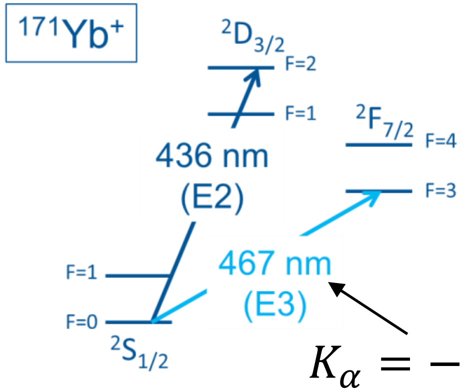
Sr lattice
optical clock

Insensitive to variations
of α and μ

[Network Reference]

Yb^{+} ion
optical clock





$K_{\alpha} = -5.95$

Cs
fountain clock

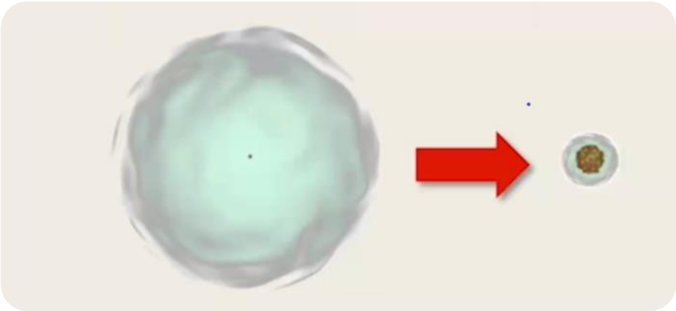
Primary frequency standard
MW clock
fast oscillations of μ

The nodes - NPL

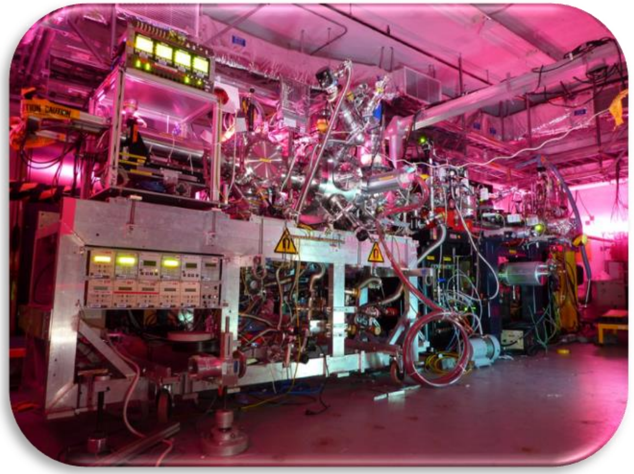
Part of the EU “dark fibre” network

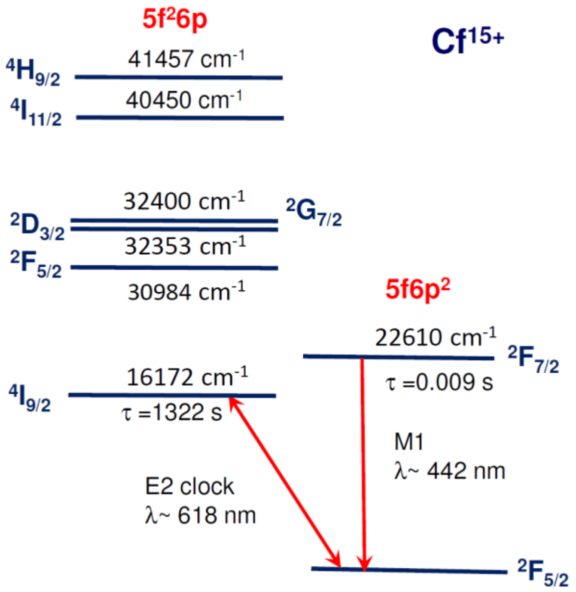
The nodes - Birmingham

Highly-charged ion clock of Cf^{15+}



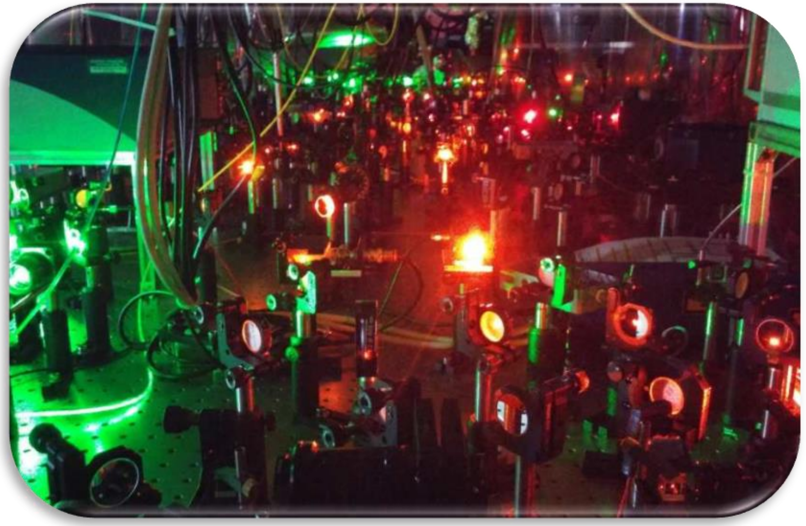
- “Compressed” electronic wf
  - low sensitivity
    to external perturbations
  - High sensitivity to variations of α ($K_\alpha = 59$)

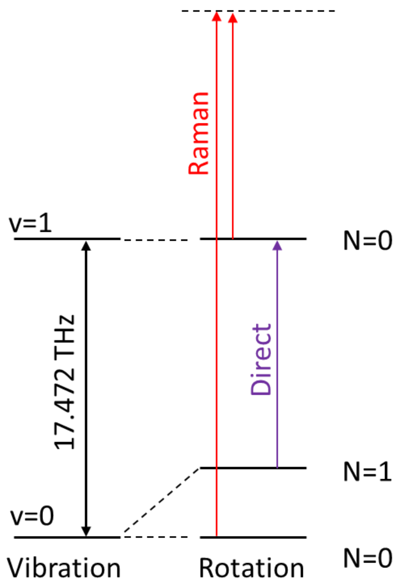




The nodes – Imperial College

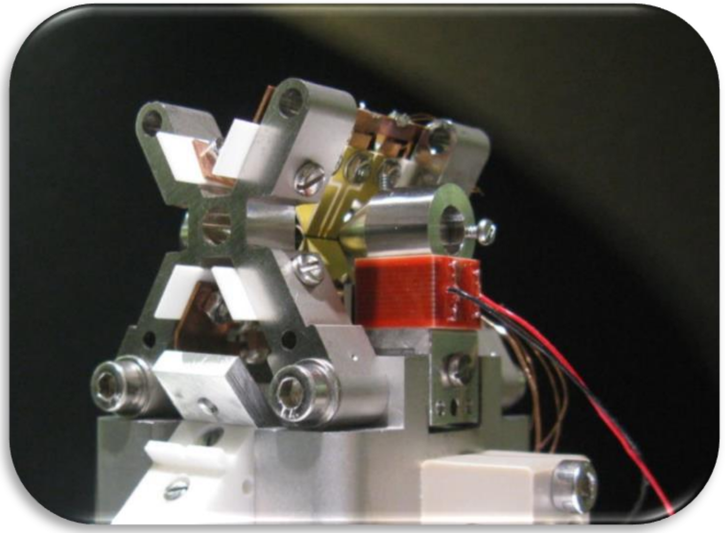
- 17 μm vibrational transition frequency in CaF
- CaF cooled to a few micro-K available at Imperial
- Magic-frequency optical lattice
- $K_\mu = 0.5$

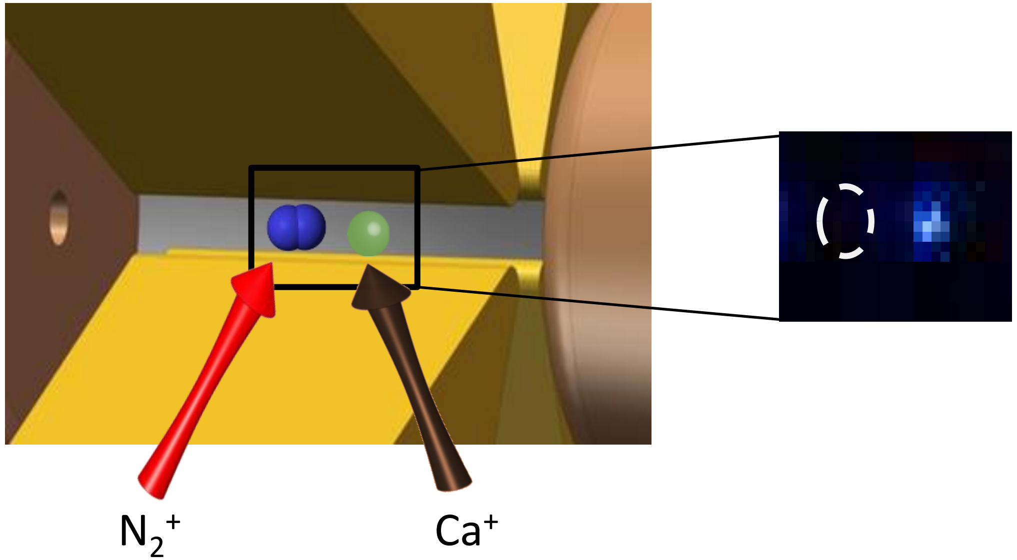




The nodes - Sussex

- 2.31 μm vibrational frequency in N_2^+ molecular ions
- Cooling by atomic Ca^+ ion
- Quantum logic spectroscopy
- $K_\mu = 0.5$





The QSNET community

QT Hubs
- Sensors & timing
- Communications
- Computing & simulation

PTB

SYRTE

INRIM

Birmingham

Cold atoms
Spectroscopy
Vib isolation
Detection
Cryogenics

NPL

Metrology
Cold atoms
Ion trapping
Fibre links

Sussex

Ion trapping
Metrology
Cold atoms
High-energy theory

Imperial

Precision measurements
Cold atoms and molecules

Tokyo

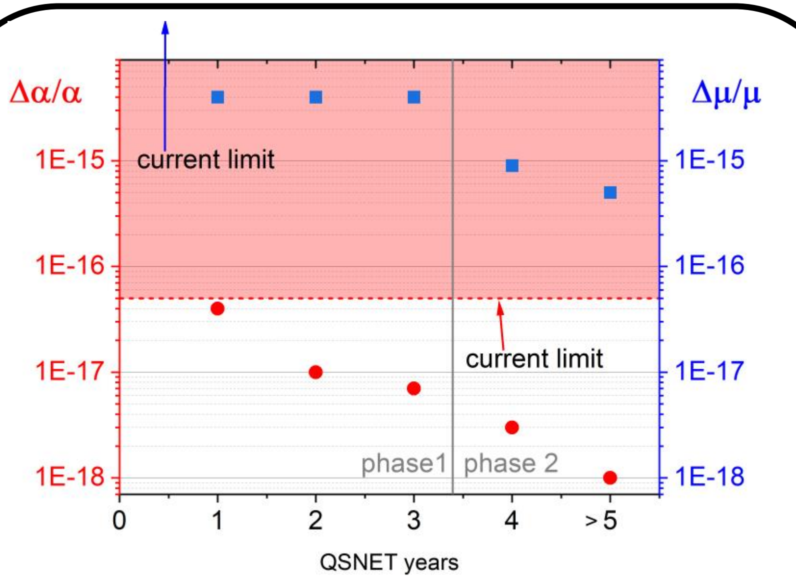
Delaware

MPI Heidelberg

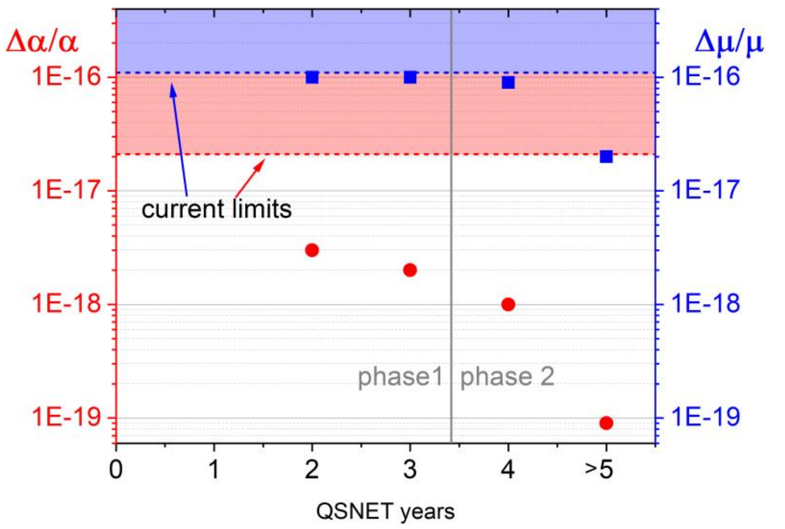
LPL Paris

Expected performance

- A mix of mature and nascent technological platforms: we will be able to deliver results from the first year. We can immediately initiate measurement campaigns and start to build sophisticated devices.



FAST OSCILLATIONS (1000 s)



SLOW DRIFTS (PER YEAR)

- Either we will discover new physics or we will set new boundaries to existing models and mass of dark matter in the 10^{-17}-10^{-24} eV range

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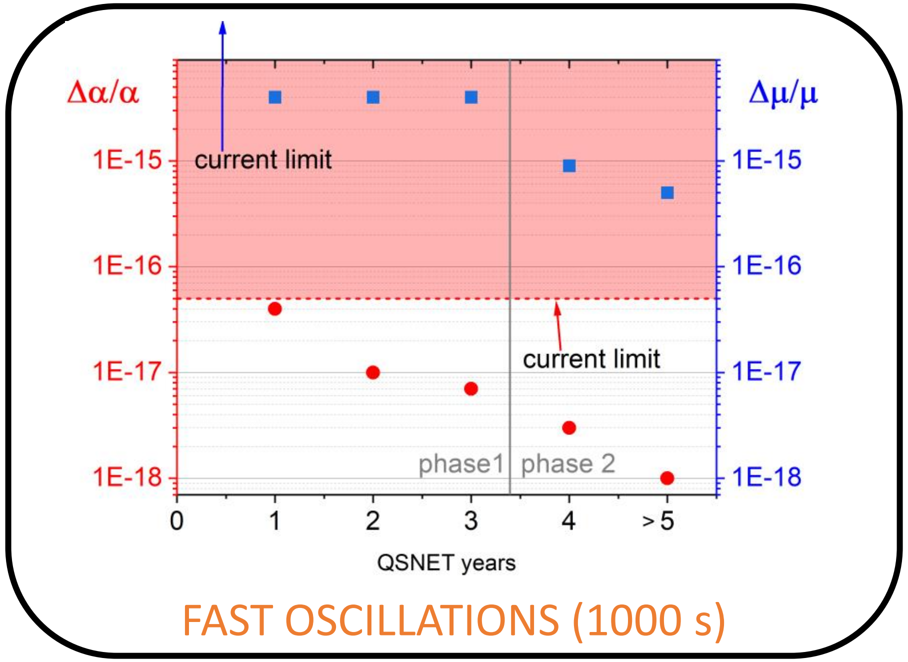

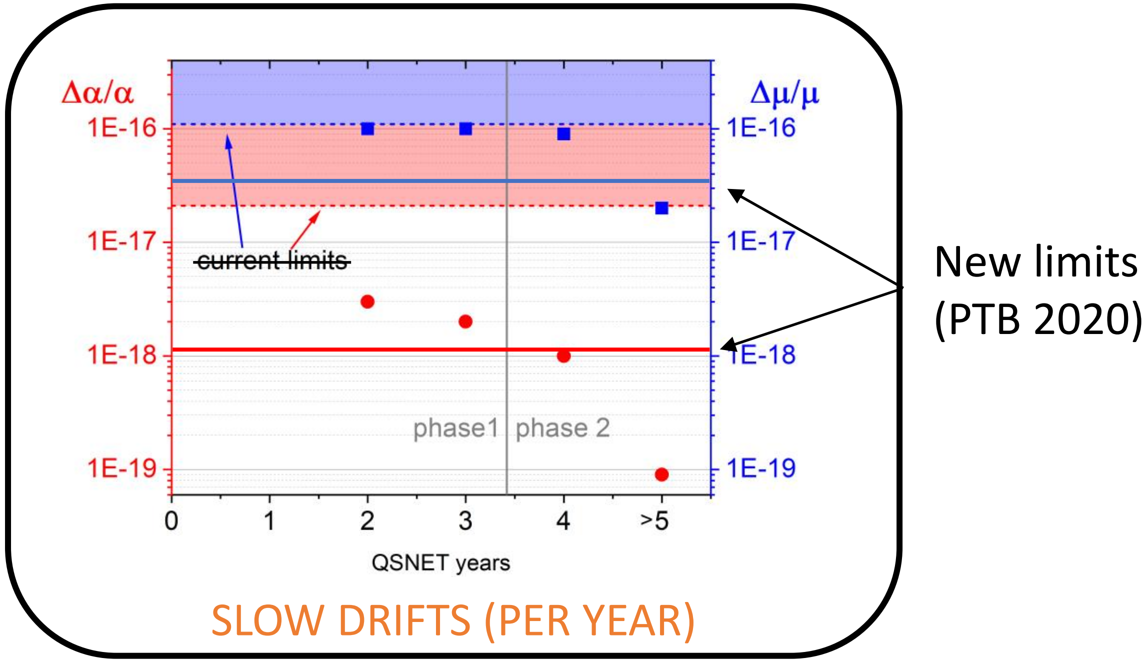

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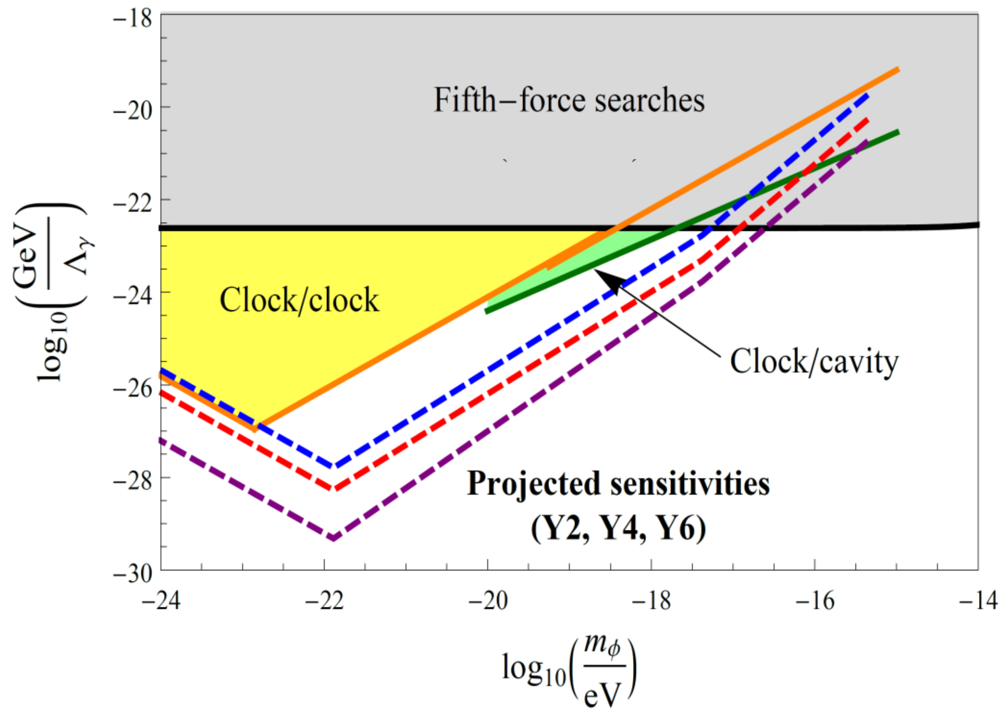
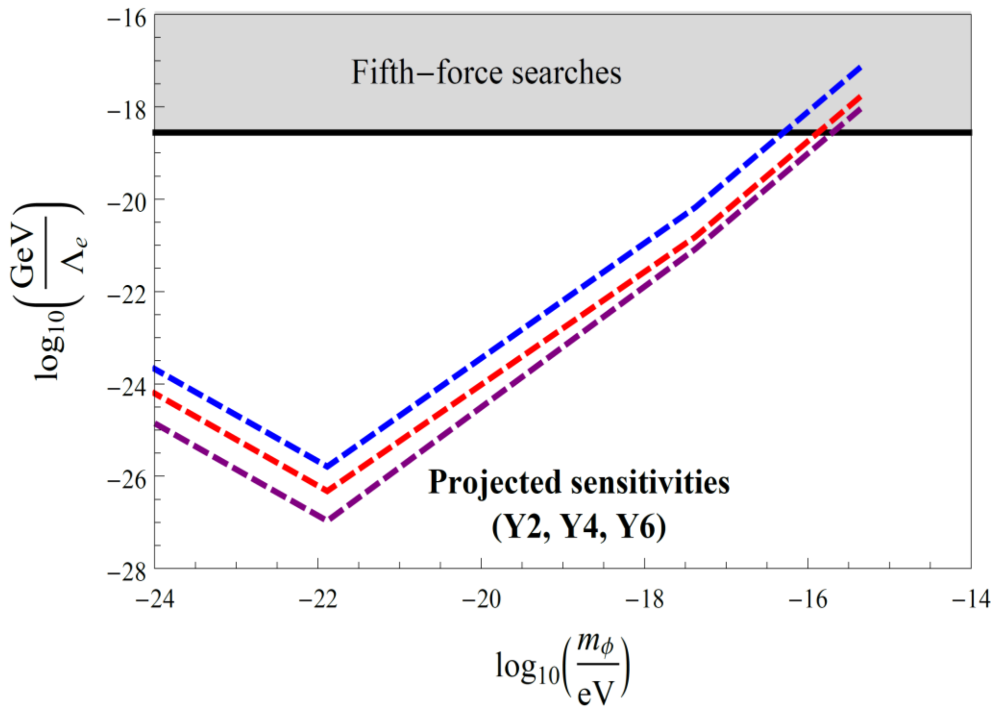
QSNET Dark matter exclusion diagrams



Scalar-photon

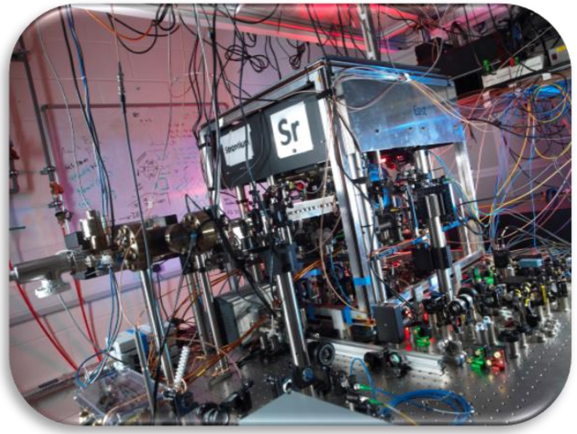


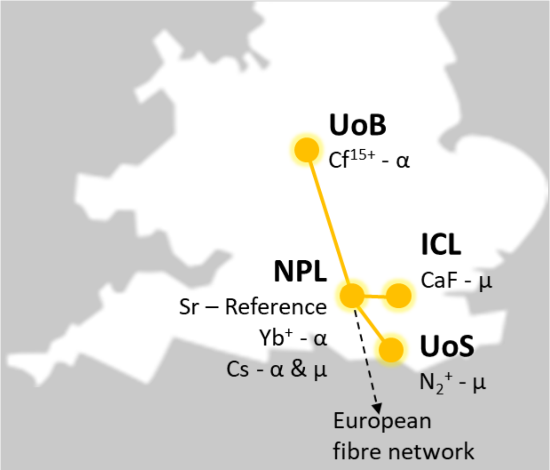
Scalar-electron

QSNET in a nutshell

α μ

- A unique opportunity for discovery, improving current limits on variations of α and μ by orders of magnitude
- Extending and exploiting world-class expertise and capabilities developed in NQTP
- A new inter-disciplinary community gathered around a new (expandable) national infrastructure
- National and international collaborations to promote the UK as world leader in the field





Thank you

- QSNET website (outdated!):
  https://qsnet19.wixsite.com/home
- New physics with AMO systems:
  RMP 90 025008 (2018)
- NPL time&frequency:
  https://eprintspublications.npl.co.uk/view/subjects/TF.html
- Imperial cold CaF molecules:
  https://www.imperial.ac.uk/centre-for-cold-matter/publications/papers/
- Sussex ion traps:
  http://itcm-sussex.com/?page_id=34
- Sussex theory:
  https://scholar.google.com/citations?user=Y4Ca4hgAAAAJ
- Highly-Charged Ions:
  RMP 90 045005 (2018)

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