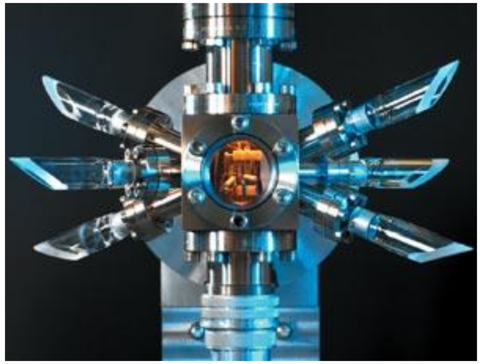
Multisensor and networked detection

Giovanni Barontini

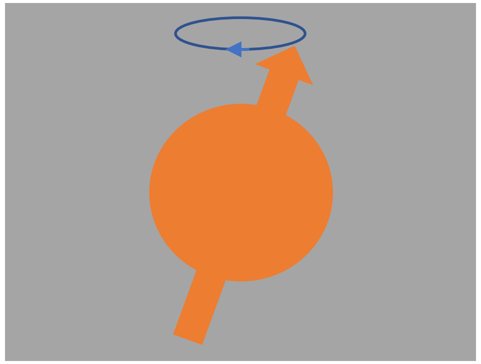
University of Birmingham

ECFA symposium

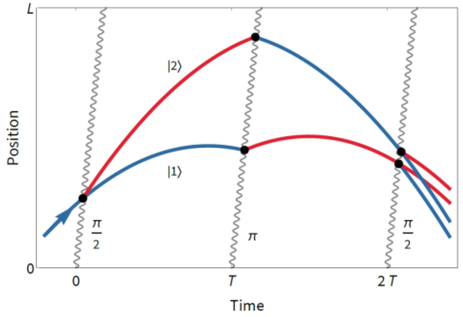
Networked AMO quantum sensors



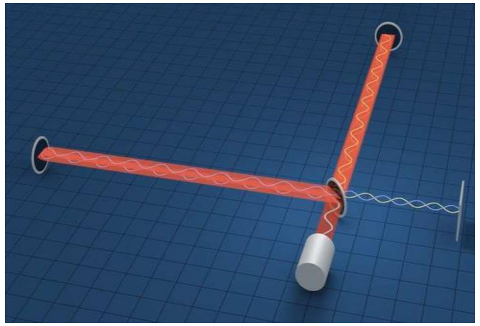
Atomic clocks



Magnetometers

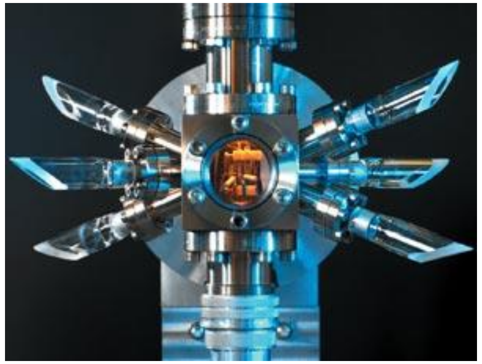


Atom interferometers

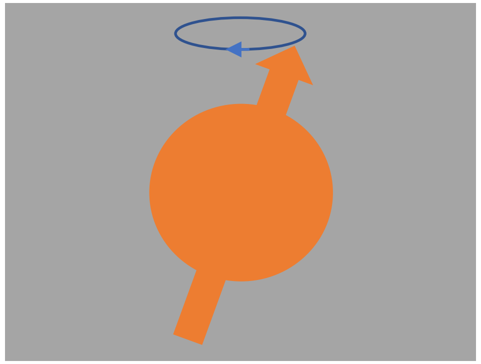


Light interferometers

Networked AMO quantum sensors



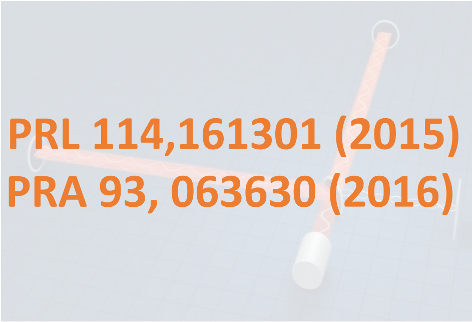
Atomic clocks



Magnetometers

->Jason @ 17:15

Atom interferometers



PRL 114,161301 (2015)
PRA 93, 063630 (2016)

Light interferometers

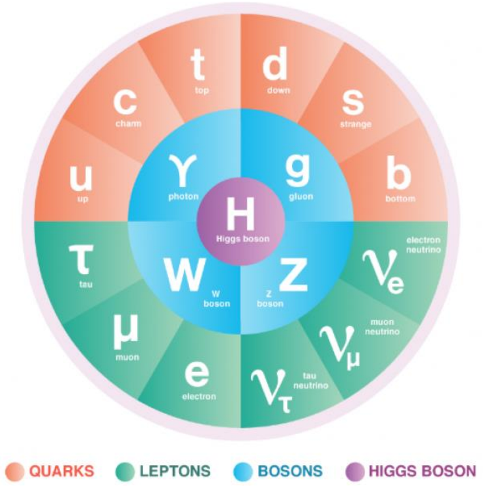
Background

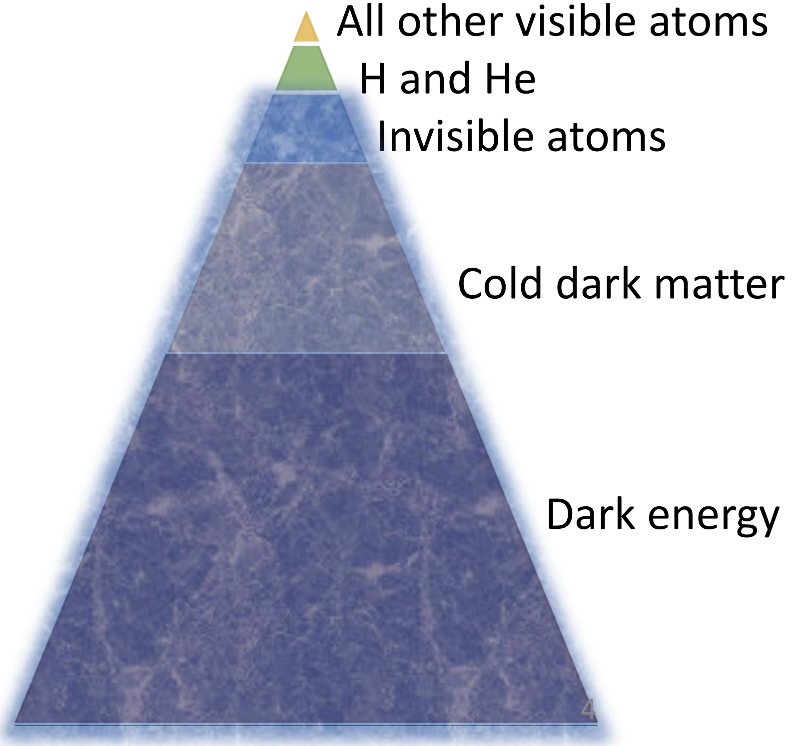
- The Standard Model and General Relativity are very successful theories, but the SM only accounts for 5% of the energy balance of the Universe

- We don't know much: DM searches in the laboratory should be unbiased and as wide as possible

- WIMP searches have been unsuccessful so far, DM searches are then moving towards well-motivated DM candidates with smaller masses

- Precision measurement techniques based on AMO quantum sensors are well suited to look for DM candidate with masses $<10^{-9}$ eV





Background

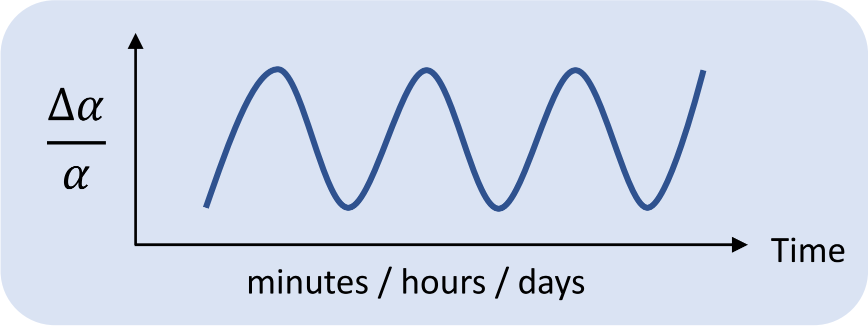
- Light DM candidate have large mode volume occupation number -> can be treated as classical fields

- QCD Axions and ALPs $\mathcal{L}_{axion} \supset \sum_f \frac{c_f}{\Lambda} \partial_\mu a \, \bar{f} \gamma^\mu \gamma^5 f \;\rightarrow\; \mathrm{H} \propto \sum_f \boldsymbol{\nabla} a \cdot \boldsymbol{S}_f$
  - $\boldsymbol{\nabla} a$ acts as a pseudo magnetic field -> can be detected by atomic magnetometers

- Scalar fields $\mathcal{L}_{scalar} \supset \frac{\phi^n}{\Lambda_\gamma^n} F_{\mu\upsilon} F^{\mu\upsilon} - \sum_f \frac{\phi^n}{\Lambda_f^n} m_f \bar{f} f$
  - Λ_γ^n alter the fine structure constant α, Λ_f^n the fermionic masses -> manifest as variations of fundamental constants

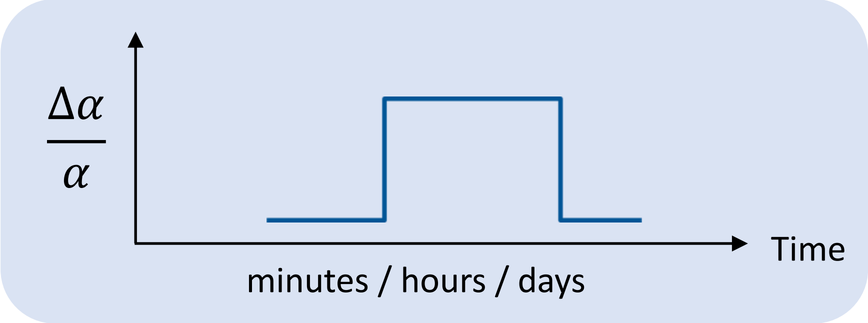
Look for variations on different timescales

- Oscillations



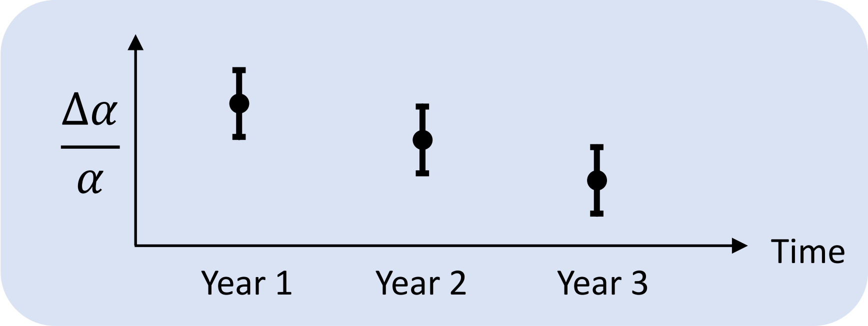
Very light DM

- Fast transients



DM- topological defects

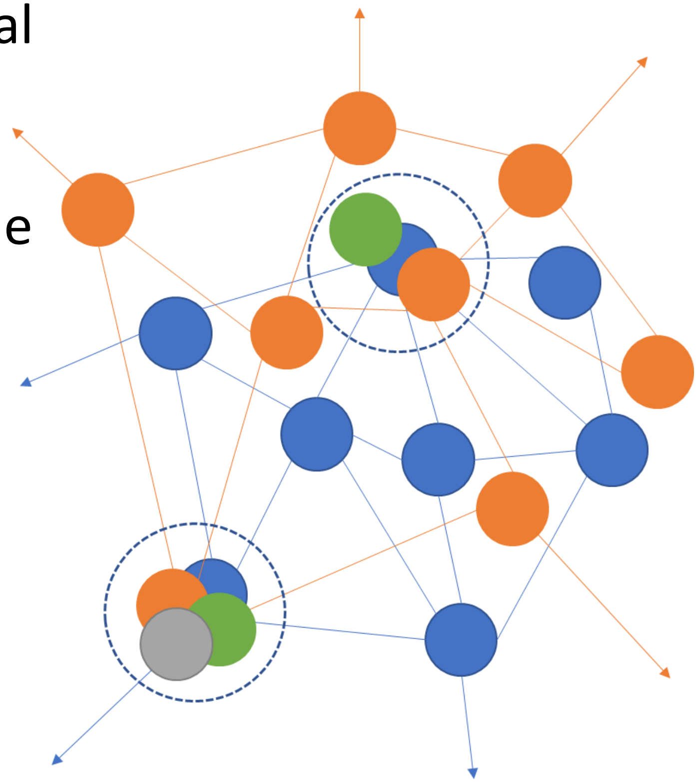
- Slow drifts



New physics

Networking quantum sensors

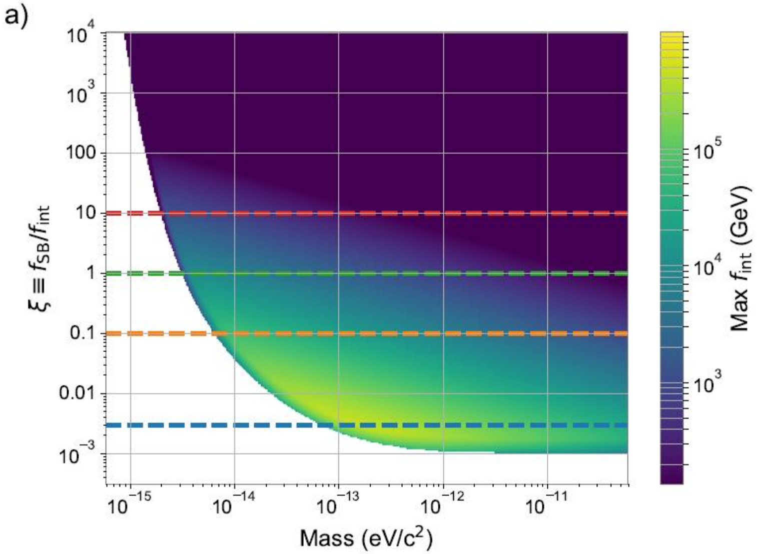
- The only possibility of detecting transient events such as topological defects, solitons, Q balls and dark stars
- Oscillations of dark matter fields at different locations as long as the distance is below the coherence length (100 km: mass ~10^{-9} eV)
- Sensors with similar sensitivities and different systematics are necessary to confirm any measurements and reject false positives
- Using multiple sensors increases the detection confidence and sensitivity
- Multimessenger detection, discriminating between different couplings

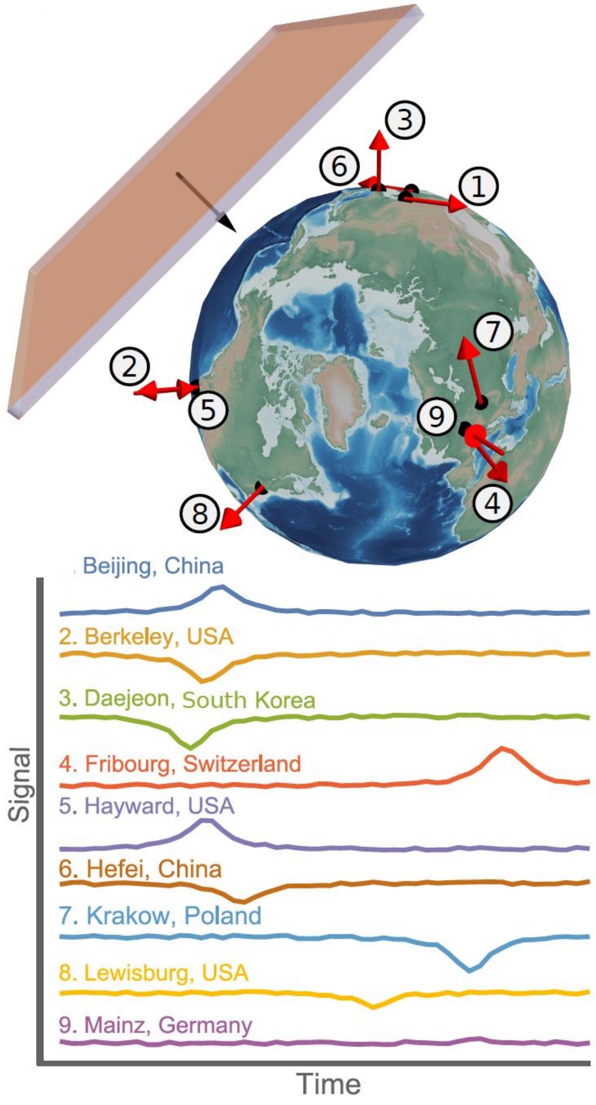


Networked magnetometers

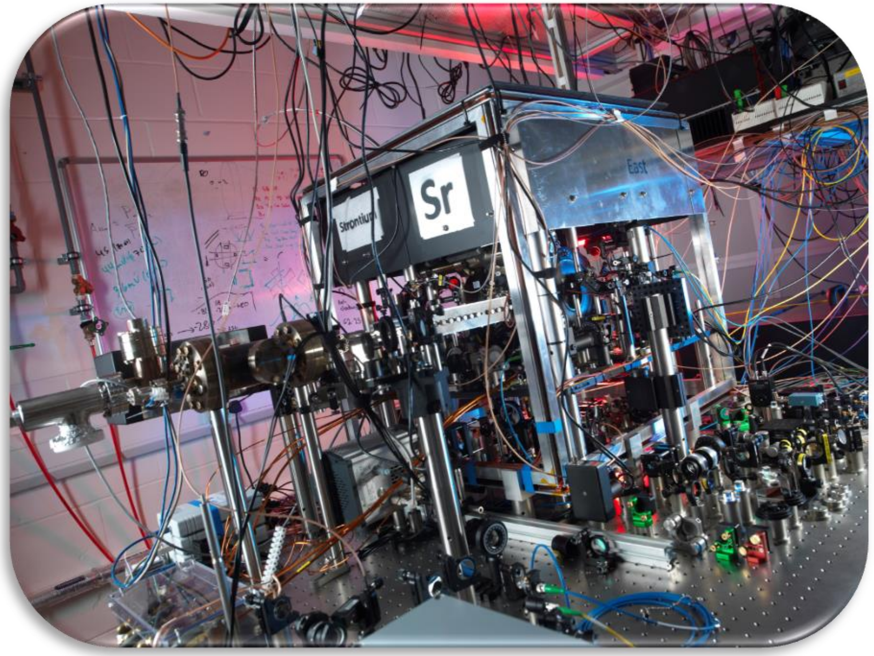
GNOME ->Dima @ 11:30

- A global network of magnetometers to look for transient events on the global scale [Afach et al, arXiv:2102.13379v2]
- Synchronisation with GPS
- Grown and developed in the last ~10 years
- 9 magnetometers, ~ 1 month measurement campaign
- Topological defects in ultralight DM fields with size $\mathrm{d} = \frac{\hbar}{m_a c}$





Networked Atomic clocks



->Marianna @ 12:00

->David @ 12:30

Which fundamental constants?

- Atomic clocks measure with extreme precision atomic and molecular spectra

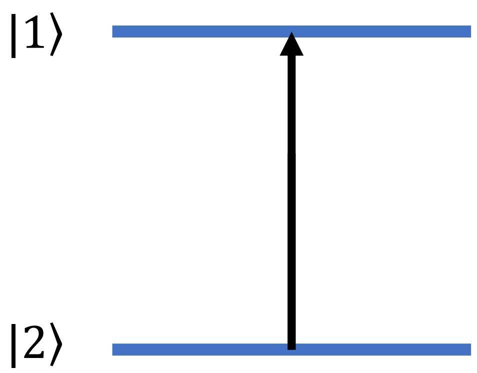
- Spectroscopy lends itself to measure variations of:

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

- Different clocks have different sensitivities to variations of α and μ

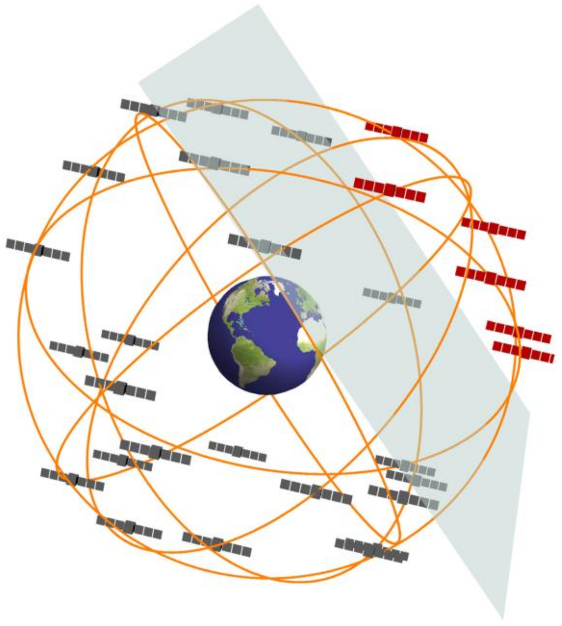
$$\frac{\delta\omega}{\omega} = K_\alpha \frac{\delta\alpha}{\alpha} + K_\mu \frac{\delta\mu}{\mu}$$

- Clocks are “naturally” networked, need to compare at least 2

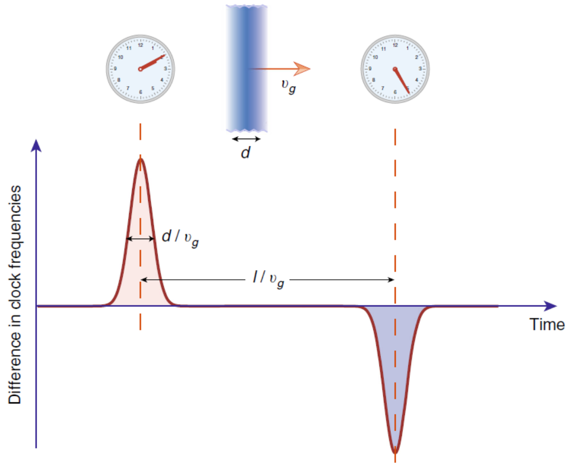


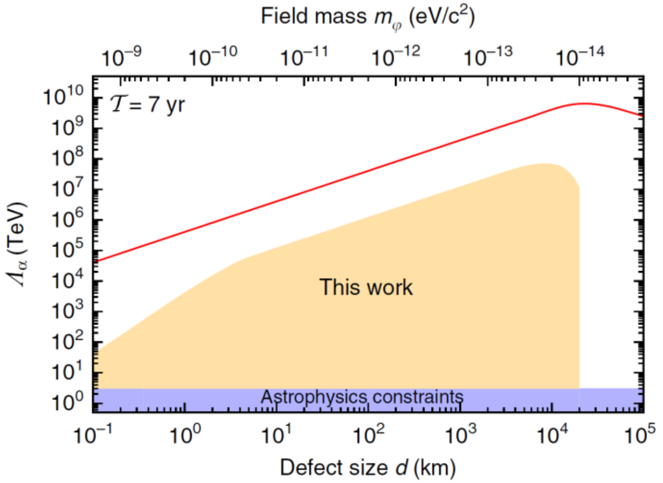
α

Fast transients (satellites)



- GPS.DM: Use the GPS constellation to look for transient events on the global scale [Roberts et al, Nat. Comm. 8, 1195 (2017)]

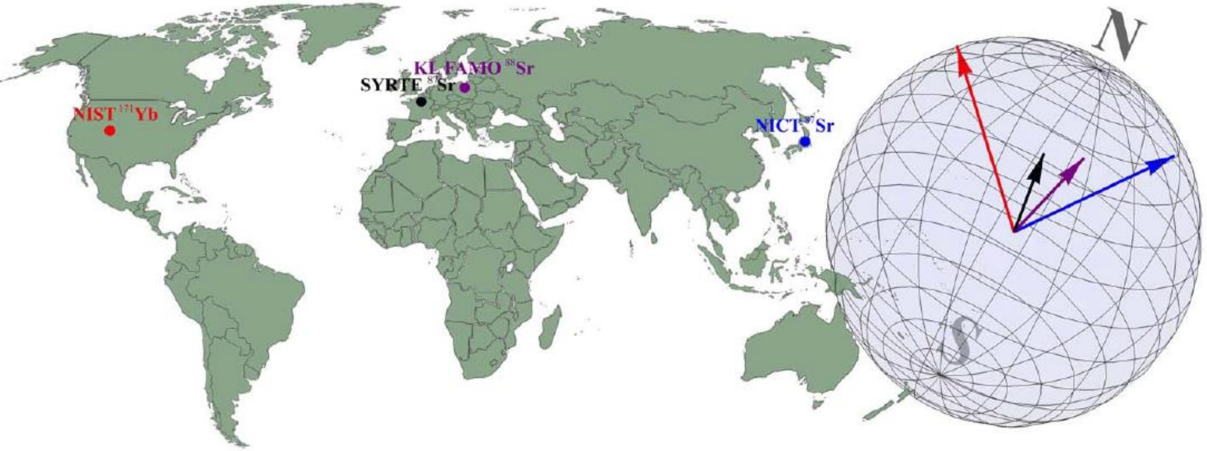




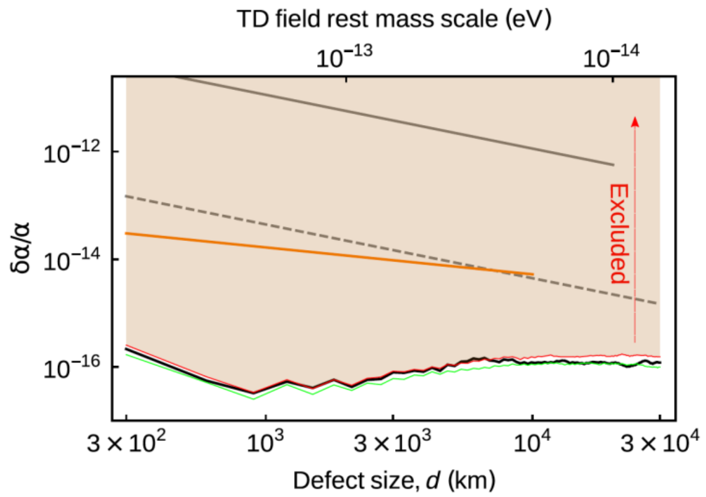
- Topological defects in scalar DM fields with size $\mathrm{d} = \frac{\hbar}{m_\phi c}$, quadratic coupling $\phi^2 \mathcal{O}_{SM}$
- Huge set of data to look at, also for oscillating DM fields
- Integrate with other satellite constellations and terrestrial clocks (check atmospheric shielding [Wolf et al. PRD 99, 095019 (2019)])

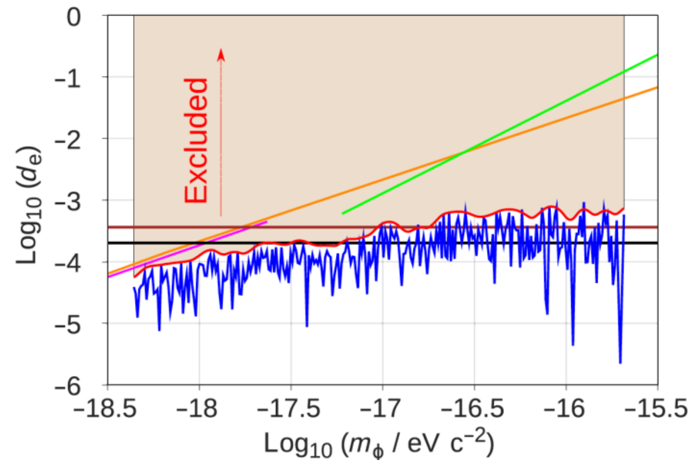
Fast transients/oscillations (“offline”)

- NIST-SYRTE-KL FAMO-NICT: measurements time stamped and correlated “offline” [Wcislo et al, Sci. Adv. 4, 4869 (2018)]



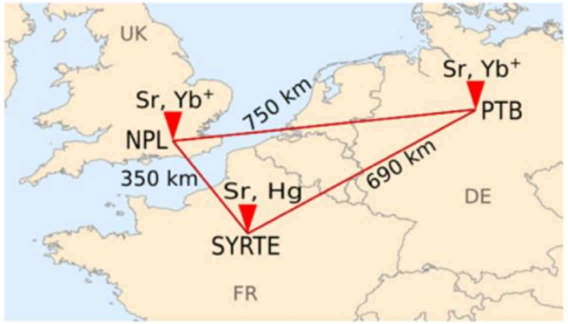
- Local atom-cavity comparison (different sensitivity to variations of α)
- Quadratic coupling for transients, linear for oscillations, two orders of magnitude improvements on previous constraints
- Easy kind of network to expand. Signals are weighted by their inverse variances.
- Considerable scope to do better with high precision clocks that run for longer (the current four clocks only ran for between 11 and 54 days over the course of a year)



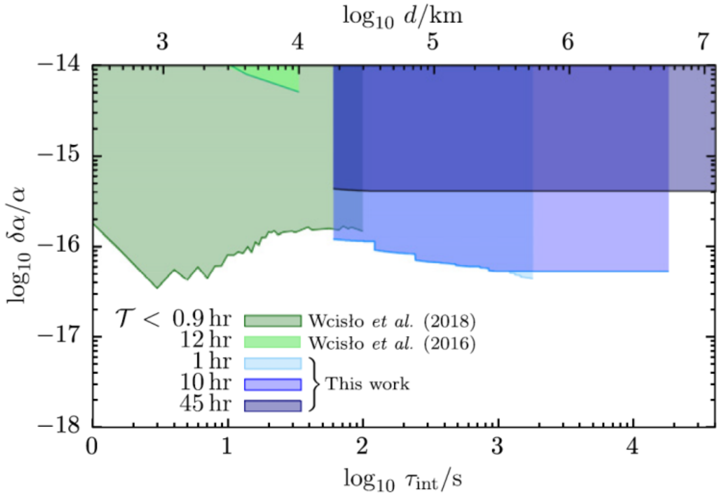


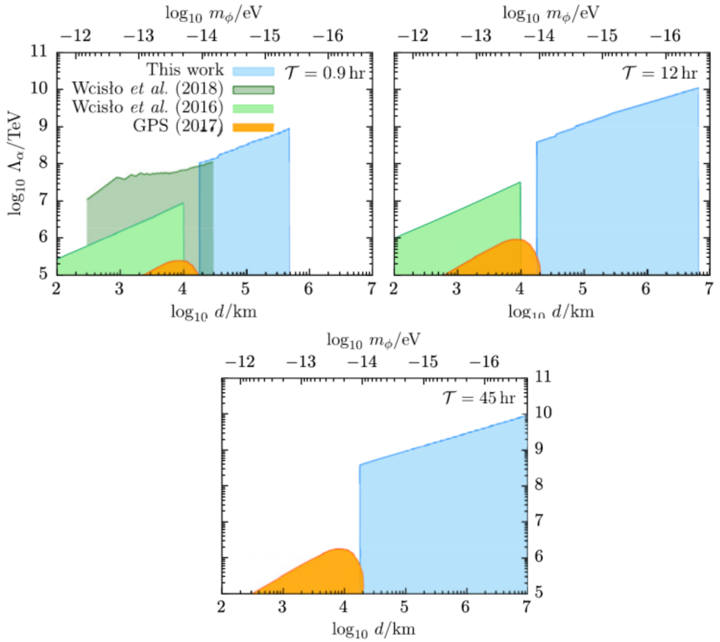
Fast transients (optical fibre network)

- NPL-SYRTE-PTB: realising a "superdetector" connecting clocks with dark fibres [Roberts et al, New J. Phys. 22, 093010 (2020)]



- Comparing clocks with different sensitivities to variations of α
- Clock-clock comparisons over optical fibres features excellent long-term stability
- Previously unconstrained parameter space for quadratic coupling
- Longer measurement time (40 days so far), nested networks

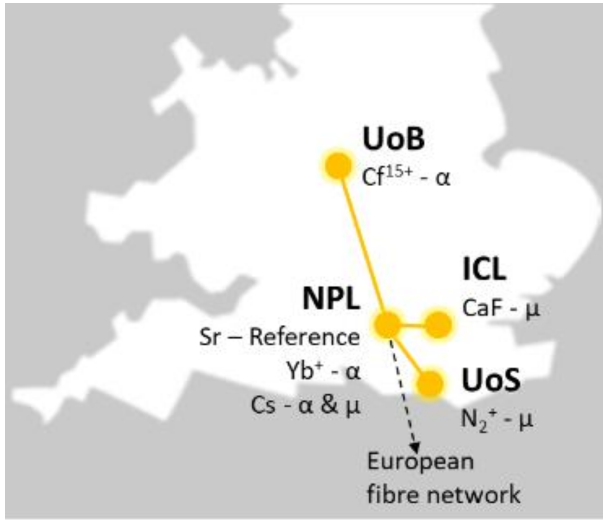




QSNET (fibre network)

- NPL-UoB-ICL-UoS: a network of clocks with enhanced sensitivity to variations of fundamental constants [https://qsnet19.wixsite.com/home]
- “Exotic” clocks: HCI, molecules -> Marianna @ 12

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



- “Disentangle” and identify correlations between variations of α and μ
- A common, stable, and insensitive frequency reference (the Sr clock at NPL), against which all the clocks of the network can measure variations

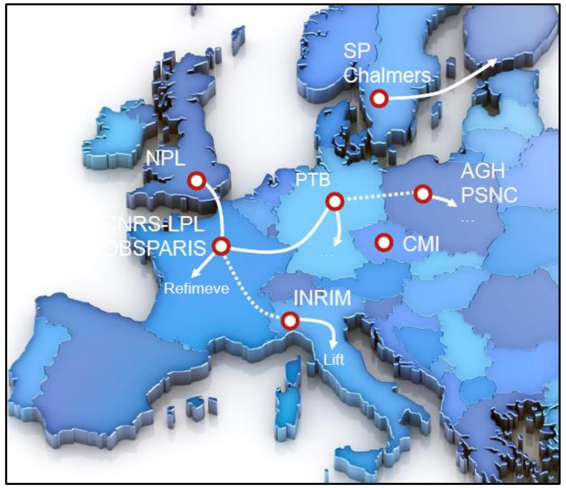
Possibilities and challenges

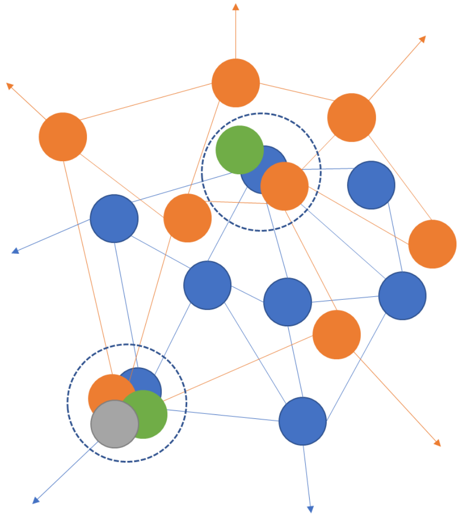
Investigate very light scalar and pseudo-scalar DM candidates over ~10 orders of magnitude in mass and different couplings

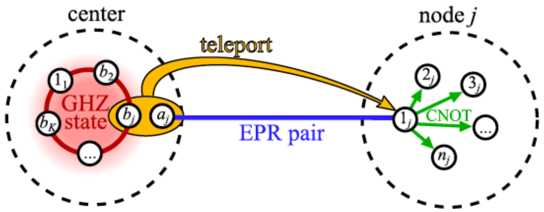
- Expand the networks
  - Increase number of clocks and duty cycle to get better statistics. Sensitivity scales ad $\sqrt{N}$
  - Expand fibre networks, longer distances
  - Longer measurement campaigns, dedicated programmes
  - Next generation sensors, with enhanced sensitivity to detection of physics BSM

- Connect the networks
  - Multimessenger detection

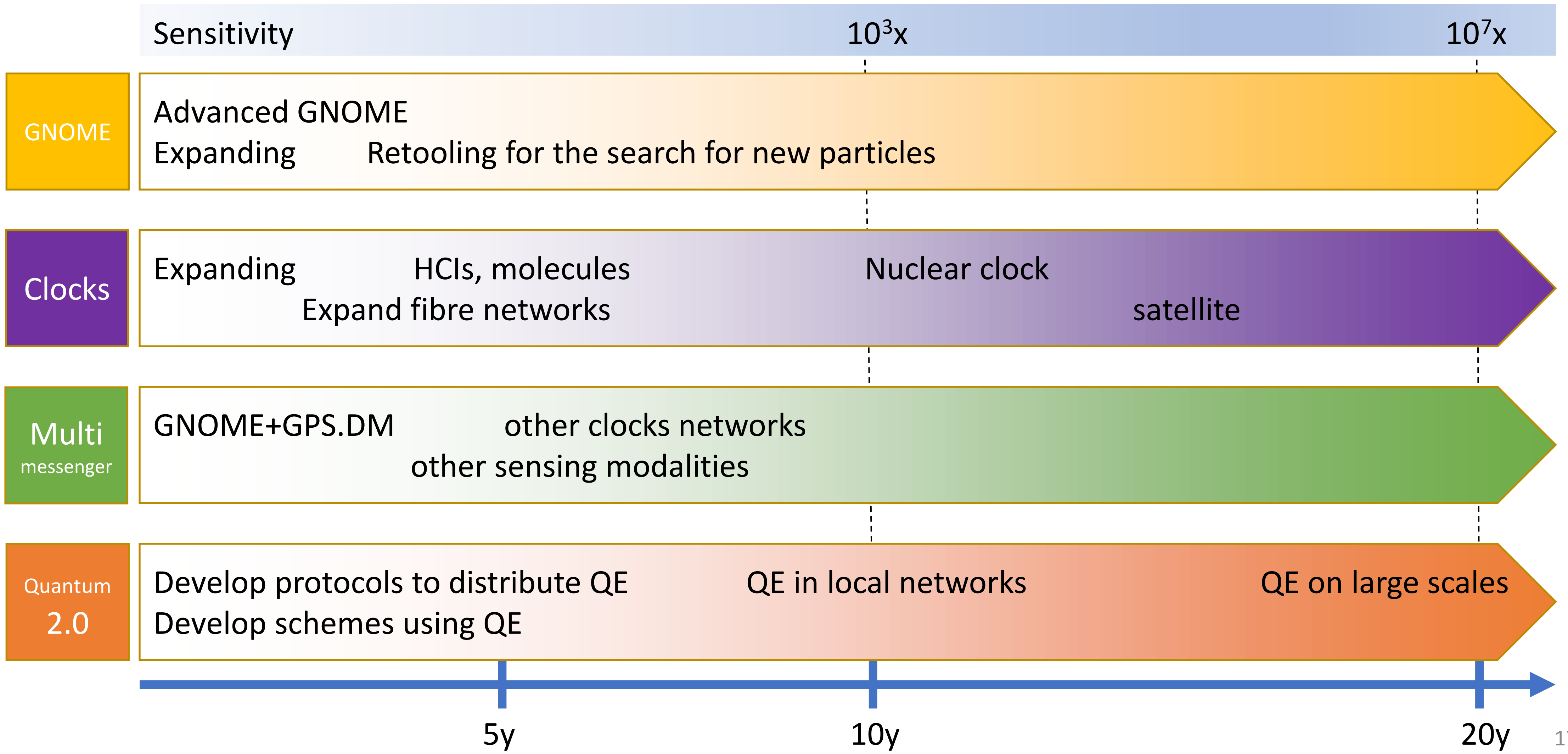
- Quantum 2.0
  - Entanglement between sensors can give an advantage when measuring multiple non-commuting parameters of dealing with “nuisance” parameters [PRA 95, 012326 (2017)]
  - Creating a super-stable global network of clocks synchronized with entanglement [Nat. Phys. 10, 582 (2014)]
  - Need more measurement schemes







Timeline



Sensitivity
10^3x
10^7x
GNOME
Advanced GNOME
Expanding
Retooling for the search for new particles
Clocks
Expanding
HCIs, molecules
Expand fibre networks
Nuclear clock
satellite
Multi
messenger
GNOME+GPS.DM
other clocks networks
other sensing modalities
Quantum
2.0
Develop protocols to distribute QE
Develop schemes using QE
QE in local networks
QE on large scales
5y
10y
20y

Related topics

- Atomic clocks -> David
- Magnetometers -> Dima
- New clocks: HCIs, molecules -> Marianna
- Nuclear clocks
- Dark fibre networks
- Other kind of detectors (AI, LI…)
- Space missions
- Entanglement (both local and remote)
- Other couplings
- Other implications of varying fundamental constants
- Data analysis/mining

Thank you