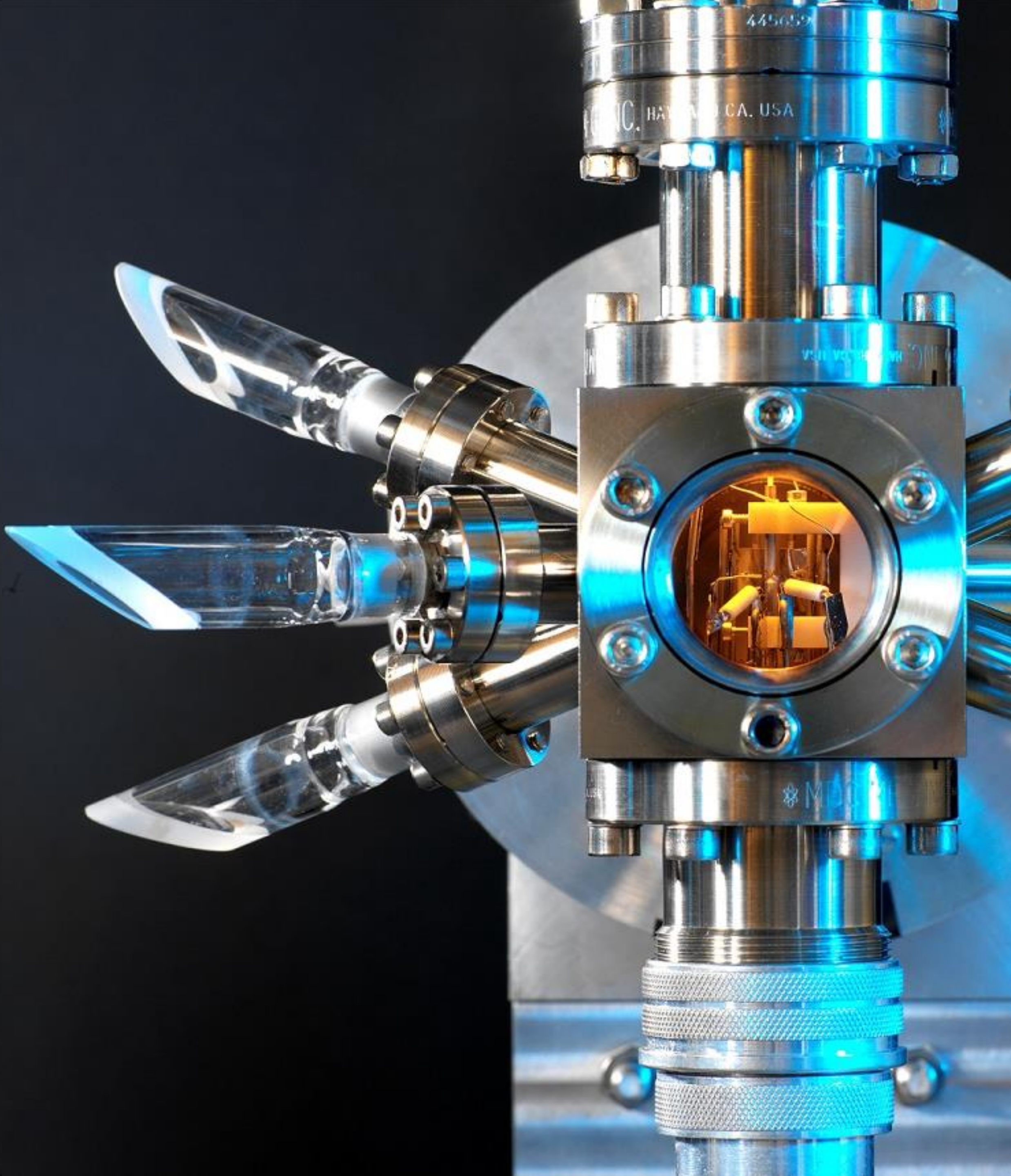
National Physical Laboratory

QSNET lecture 2: Optical atomic clocks in search of new physics

QTFP School 2023

Dr Rachel Godun

13th January 2023, Cambridge



Key messages from QSNET lecture 1 (Nathaniel Sherrill)

✓ QSNET project is using atomic clocks to search for variations in fundamental constants

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

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

✓ Can use Effective Field Theory to describe New Physics through interactions with known Low Energy physics

$$\mathscr{L}_{\mathrm{NP}}(F) = \underbrace{F}_{=\,\text{(coupling strength, new field)}} \cdot \mathscr{O}_{\mathrm{LE}} \Rightarrow \boxed{\mathscr{L}_{\mathrm{EFT}} = \mathscr{L}_{\mathrm{LE}} + \sum_F \mathscr{L}_{\mathrm{NP}}(F)}$$

✓ Model-independent approaches allow the study of a wide variety of well-motivated New Physics signals, e.g.

- Ultralight Dark Matter
- Fundamental symmetry violations

Learning objectives for QSNET lecture 2

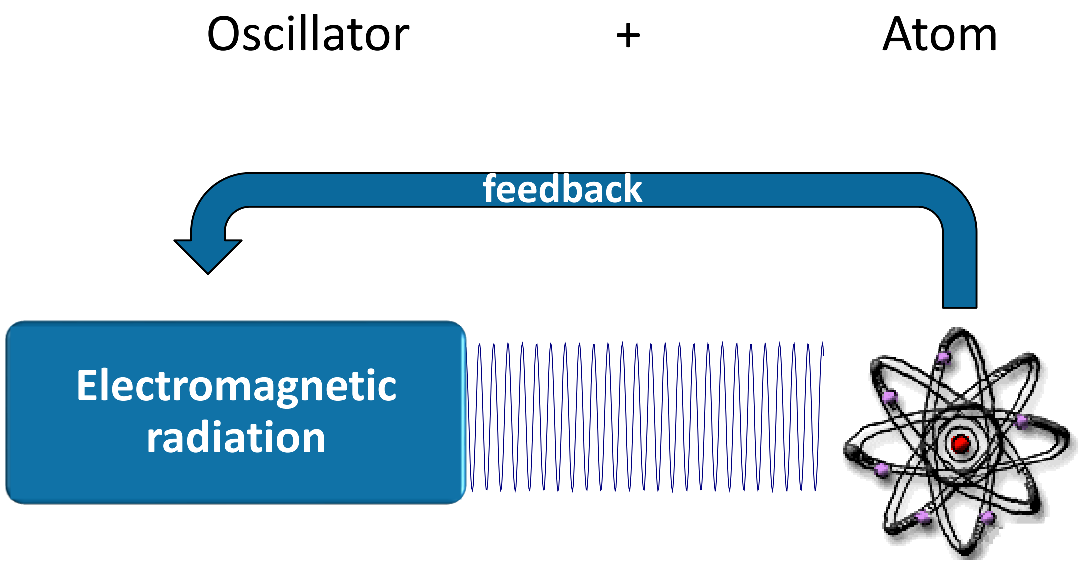
- Understand the basic principles of atomic clocks
  - how they work
  - characterisation in terms of inaccuracy / instability

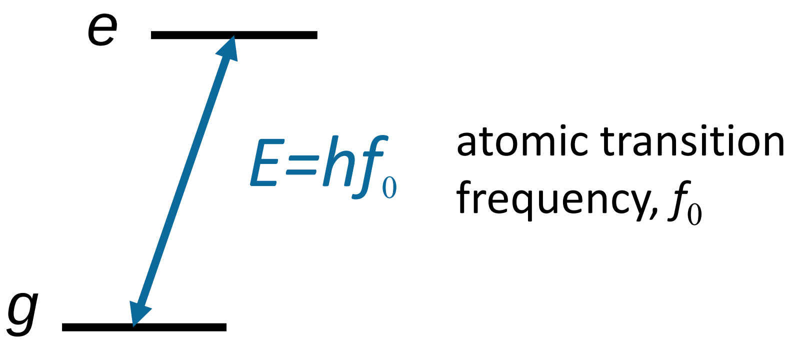
- Meet some practicalities of ion clocks vs lattice clocks

- Understand why certain clocks are good for measuring variations of α and μ
  - slow drifts / oscillations / transients

- Meet the clocks in the QSNET consortium

Components of an atomic clock

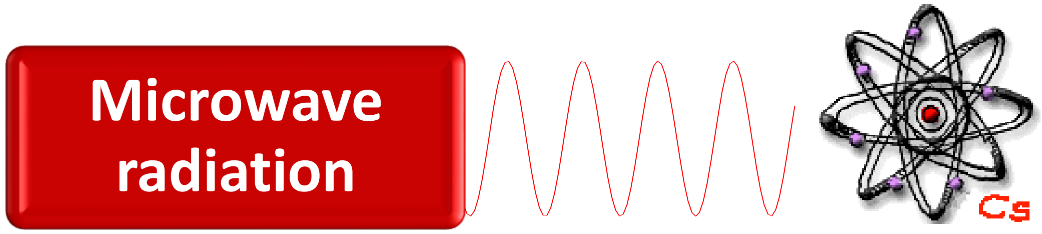




The output from the clock is an electromagnetic wave at a fixed frequency

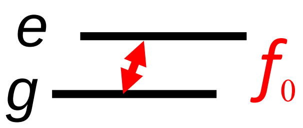
Strictly speaking, this is a frequency standard, not a clock

Clocks can operate at many different frequencies

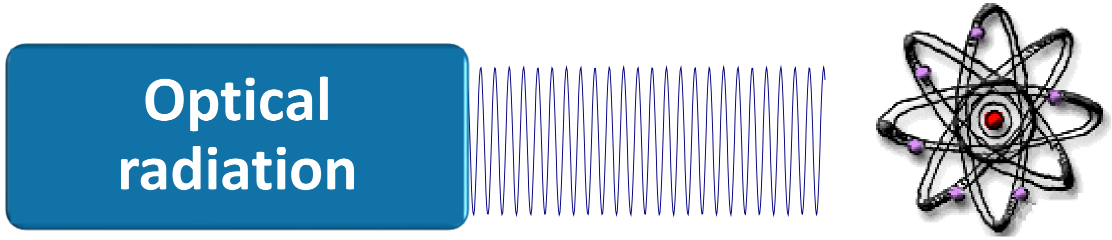


Microwave radiation

few GHz ~ 10^9 Hz

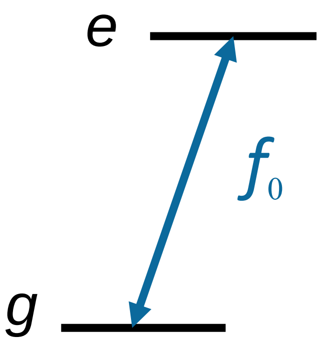


microwave frequency



Optical radiation

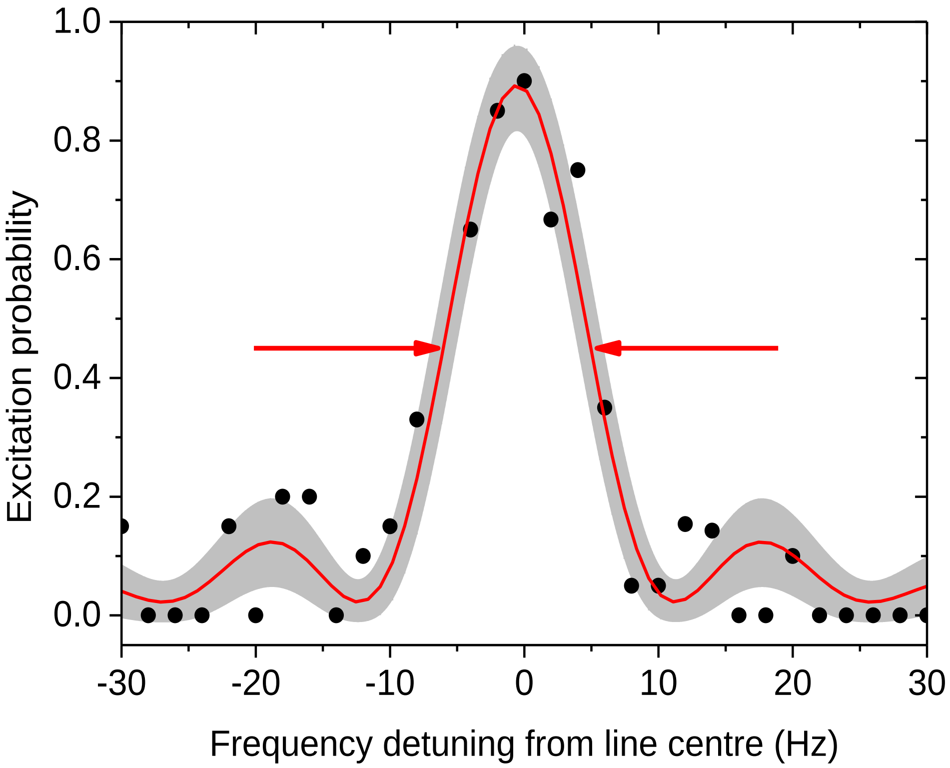
few hundred THz ~ 10^{14} Hz



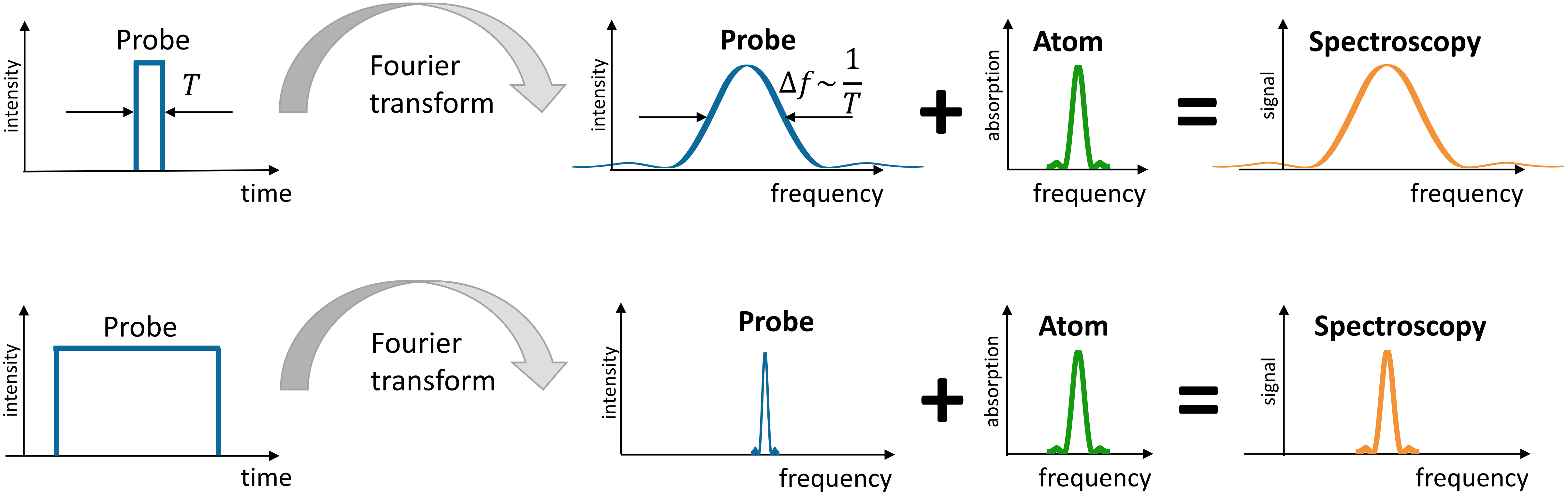
optical frequency

Can any atomic transition be used to form a clock?

- Need an atomic transition with a narrow linewidth
- It is then a good discriminator for tuning the electromagnetic radiation



Fourier transform limit



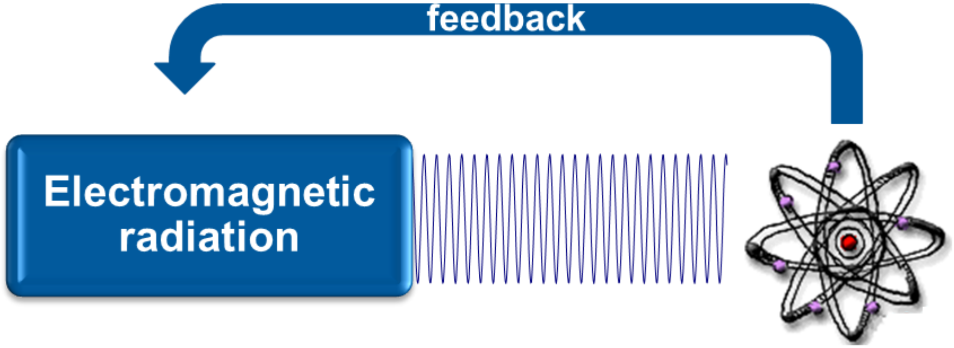
- In practice, you therefore want:
  - Probe time to be as long as possible
  - Atomic transition to be narrow enough not to limit the spectral signal

Summary so far

✓ Understand the basic principles of optical atomic clocks

- how they work

Oscillator + Atom

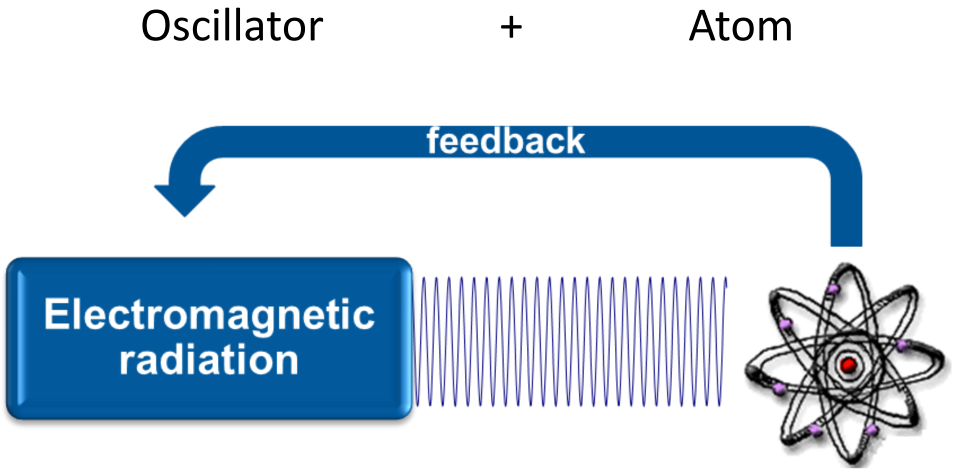


- Long probe times
- Narrow linewidths

Summary so far

✓ Understand the basic principles of optical atomic clocks

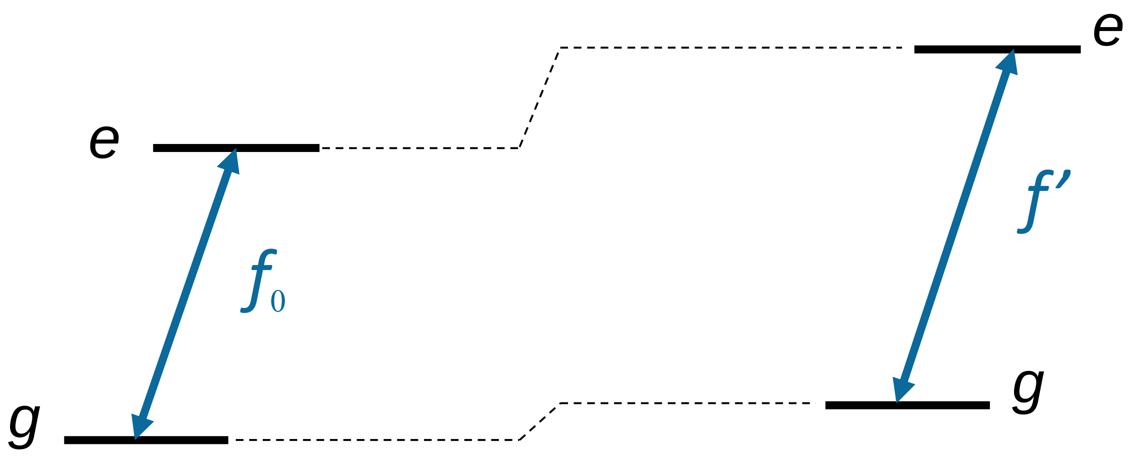
- how they work
- characterisation in terms of inaccuracy / instability



- Long probe times
- Narrow linewidths

Systematic frequency shifts

- In practice, the atomic transition is disturbed by external fields
- Changes in the atomic energy levels cause changes in the clock frequency



The goal is to have the clock output at the ***unperturbed*** atomic frequency

Unperturbed atomic transition frequency

Perturbed frequency that is seen by the probe

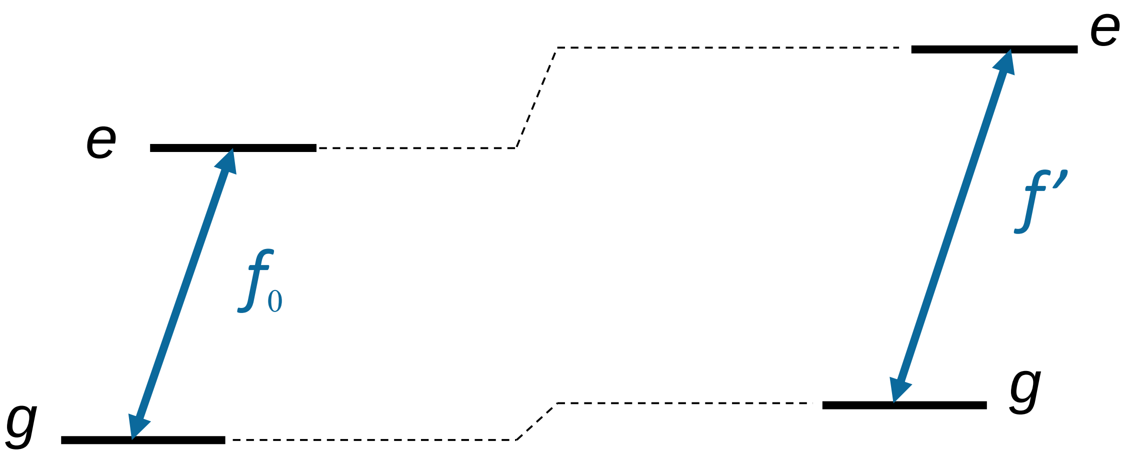
Systematic frequency shifts – sources of disturbance

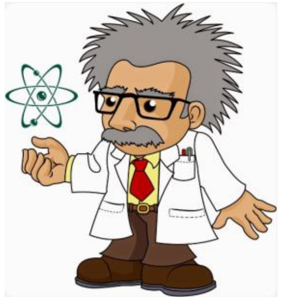
Magnetic fields ⇩ Zeeman shift

Electric fields ⇩ Stark shift

Motion of atom ⇩ Doppler shift

Gravitational fields ⇩ Gravitational red-shift

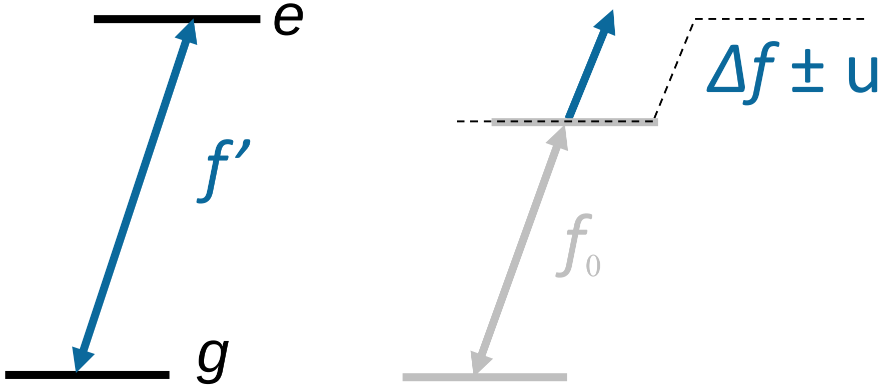




10^{-16} fractional frequency change for every 1 m change in height at Earth's surface

- Need to characterise the size of all shifts, and subtract them from the clock's output frequency
- There is an associated uncertainty with this correction, which gives the clock an inaccuracy

Inaccuracy in clock frequency



$f_{\text{output}} = f' - (\Delta f \pm u)$

$\boxed{f_{\text{output}} = f_0 \pm u}$

Deduce systematic frequency shift, Δf with uncertainty, u

Correct the clock's output frequency

Clock's output frequency is f_0 with an inaccuracy of u

- The clock's inaccuracy is the uncertainty with which the clock's output frequency matches the unperturbed transition frequency

Inaccuracy in clock frequency – uncertainty budgets

- Example uncertainty budget

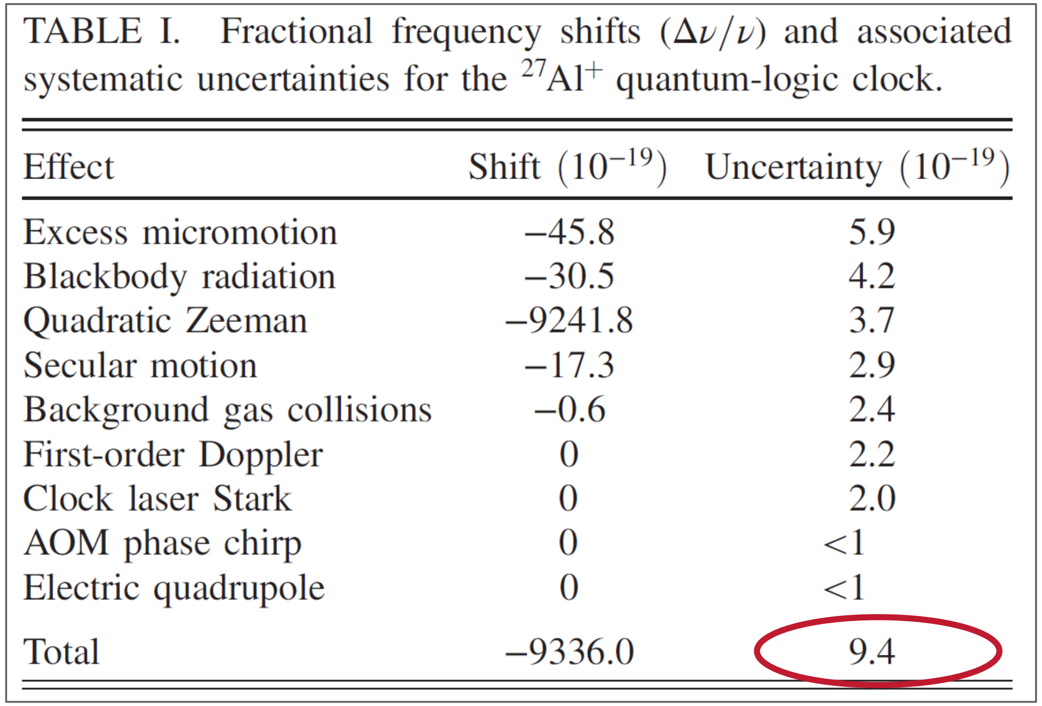


TABLE I. Fractional frequency shifts ($\Delta\nu/\nu$) and associated systematic uncertainties for the $^{27}\mathrm{Al}^+$ quantum-logic clock.

Effect	Shift (10^{-19})	Uncertainty (10^{-19})
Excess micromotion	−45.8	5.9
Blackbody radiation	−30.5	4.2
Quadratic Zeeman	−9241.8	3.7
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Background gas collisions	−0.6	2.4
First-order Doppler	0	2.2
Clock laser Stark	0	2.0
AOM phase chirp	0	<1
Electric quadrupole	0	<1
Total	−9336.0	9.4

Brewer *et al.*, Phys. Rev. Lett. **123**, 033201 (2019)

Size of total shift doesn't matter – it will be subtracted.
It's the total uncertainty (i.e. inaccuracy) that must be minimised

Inaccuracy is an important figure of merit when assessing a clock's performance

Inaccuracy expressed as fraction of f_0

- Frequencies can be readily multiplied or divided

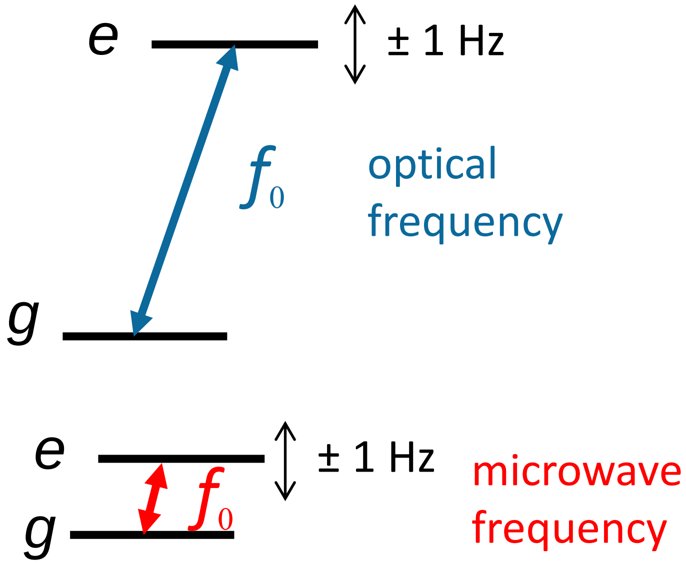
- <u>Example</u>

  optical clock operates at $(10^{15} \pm 1)$ Hz, with fractional inaccuracy of 10^{-15}

  divide down to microwave frequency

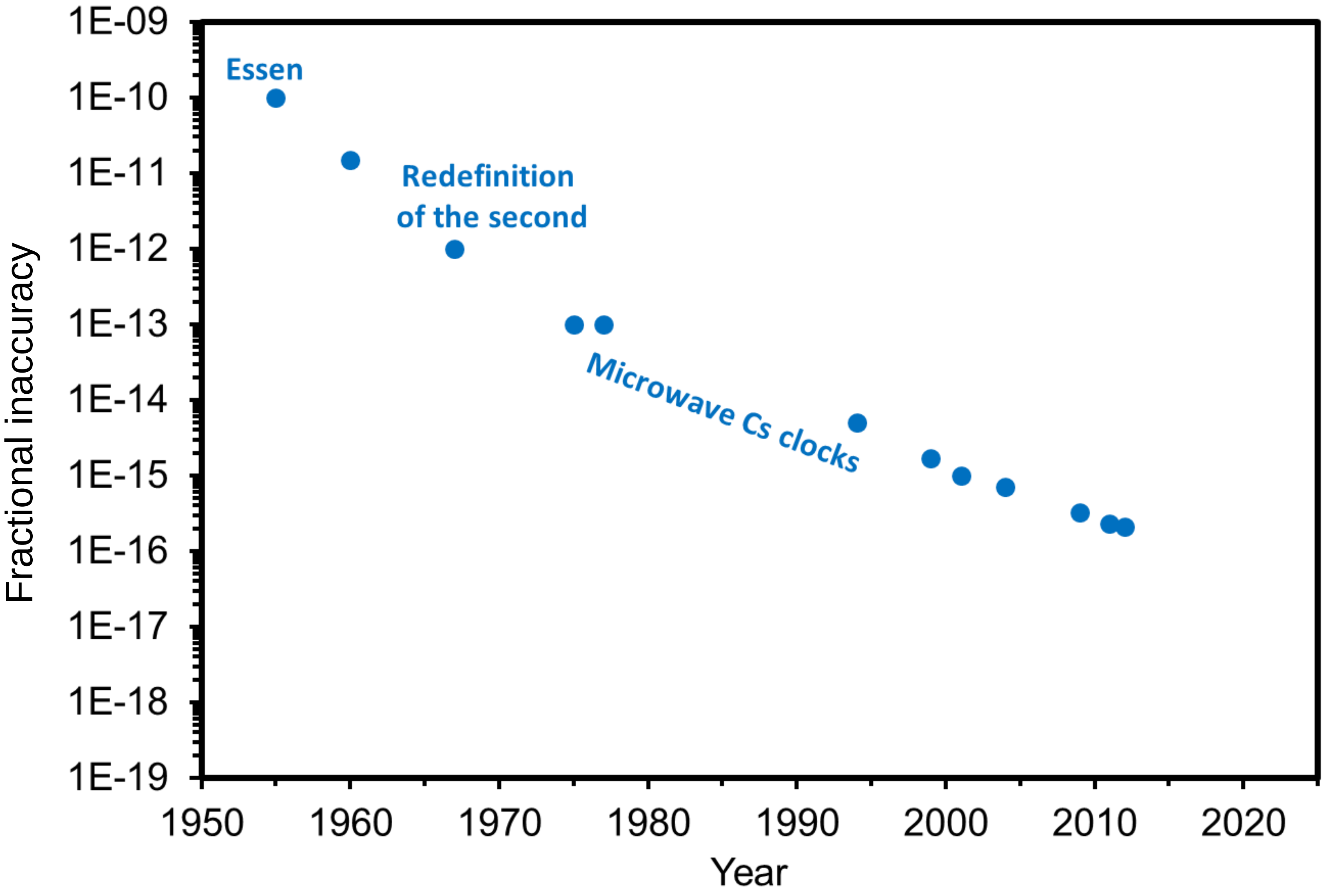
  → microwave frequency of $(10^{10} \pm 10^{-5})$ Hz

- Note how this is significantly better than operating a microwave clock with 1 Hz uncertainty



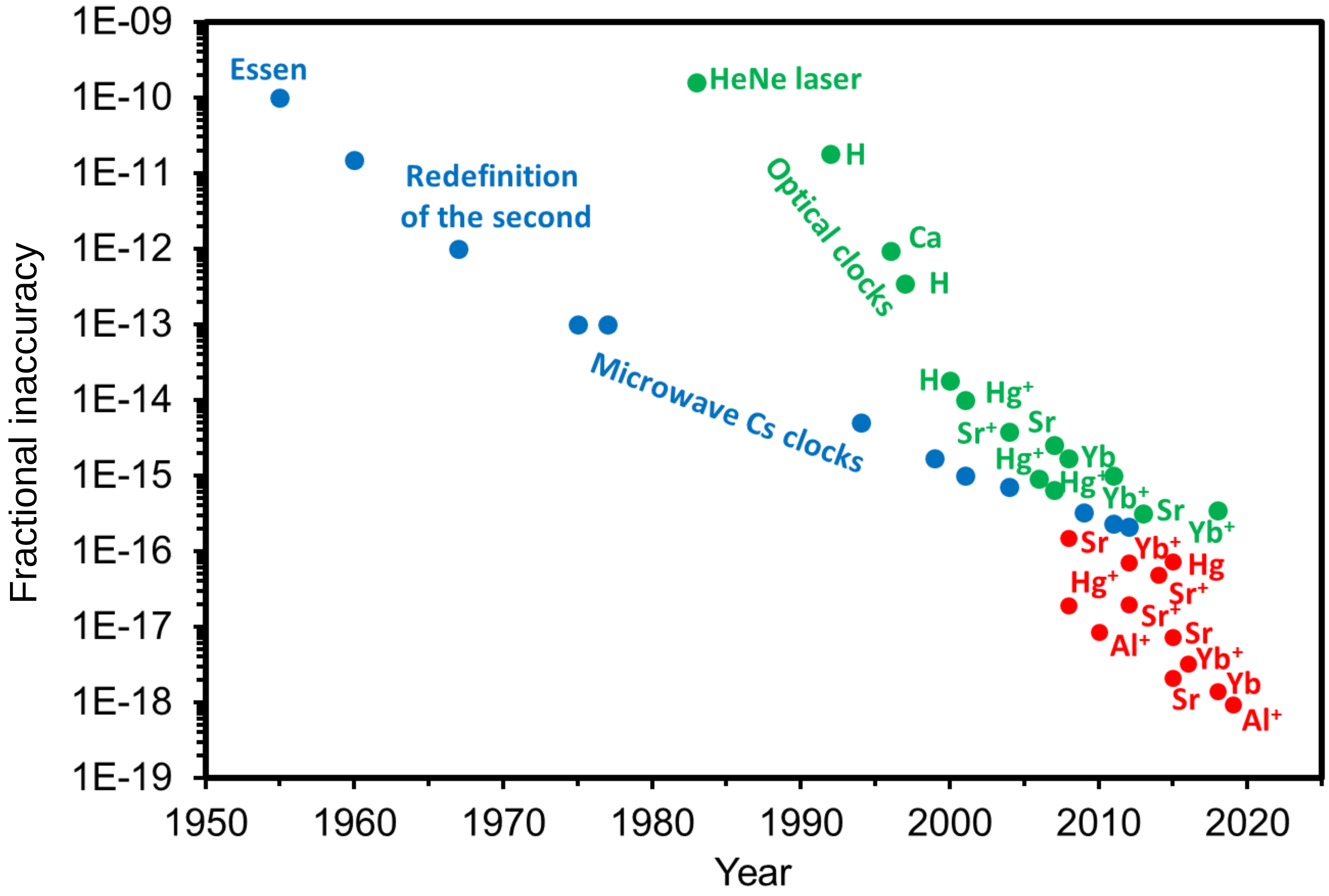
Generally better to operate clocks at higher frequencies to have smaller fractional inaccuracies.

Progress in atomic clock measurements



The best Cs fountain clocks are reaching inaccuracies of 10^{-16}

Progress in atomic clock measurements

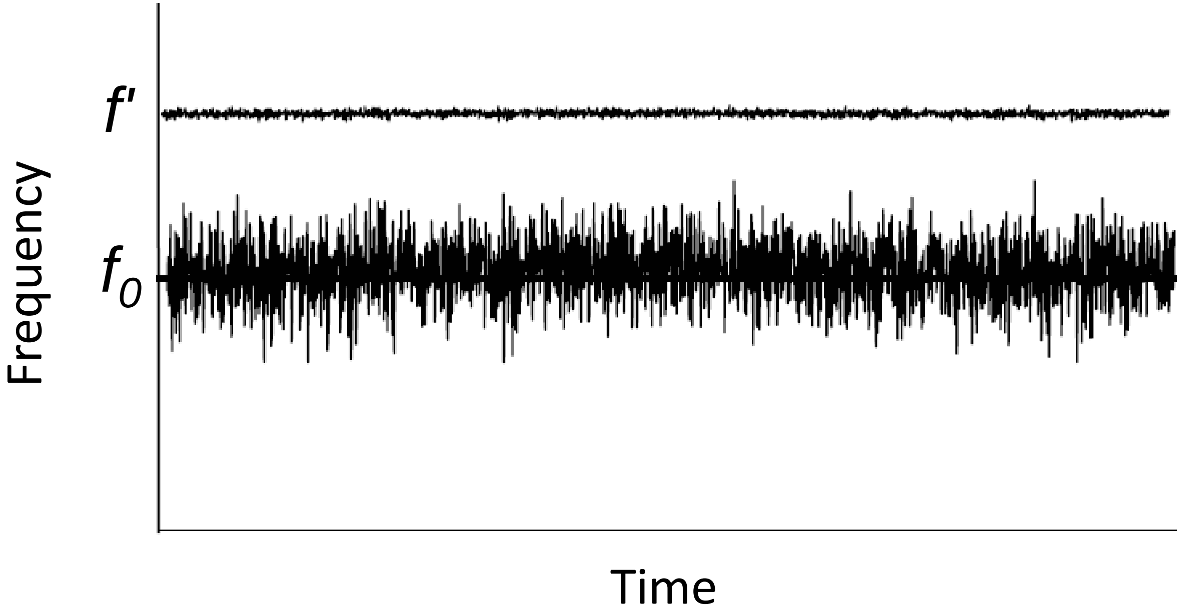


Optical clocks have now demonstrated inaccuracies two orders of magnitude beyond those of Cs

Instability – another important figure of merit

- Inaccuracy is the level of uncertainty associated with how well the clock can be corrected back to f_0 (uncertainty in systematic shift)
- Instability is the level of frequency fluctuations over time (statistical uncertainty)

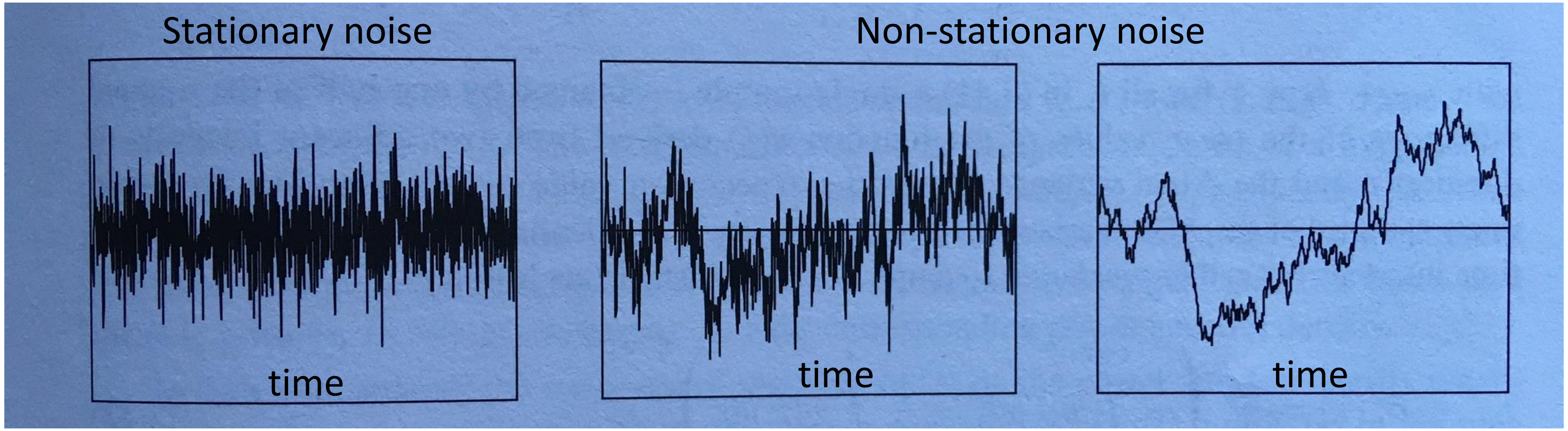
Example: white frequency noise



Instability determines the required averaging time to reach a particular level of uncertainty

Instability - Allan deviation

- Standard variance is the mean square deviation from the mean frequency value
- Mean frequency not always constant over time



- Use Allan deviation, $\sigma_y(\tau)$ to characterise instability
- Allan variance is the mean square deviation between adjacent frequency values

F. Riehle, "Frequency Standards," Wiley-VCH

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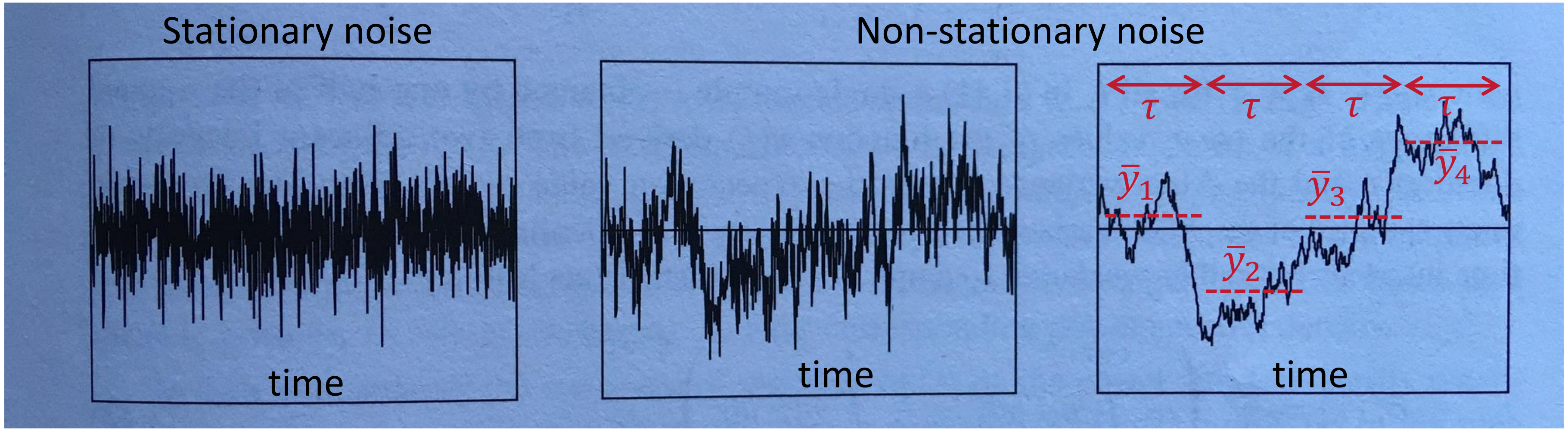
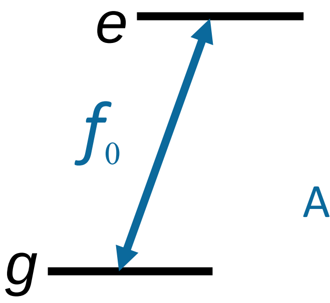


- Use Allan deviation, $\sigma_y(\tau)$ to characterise instability
- Allan variance is the mean square deviation between adjacent frequency values

Allan variance, $\sigma_y^2(\tau) = \frac{1}{2}\langle(\bar{y}_{i+1} - \bar{y}_i)^2\rangle$

F. Riehle, “Frequency Standards,” Wiley-VCH

Instability in clock frequency – Allan deviation plots



Linewidth = Δf
Probe time = T
Averaging time = τ

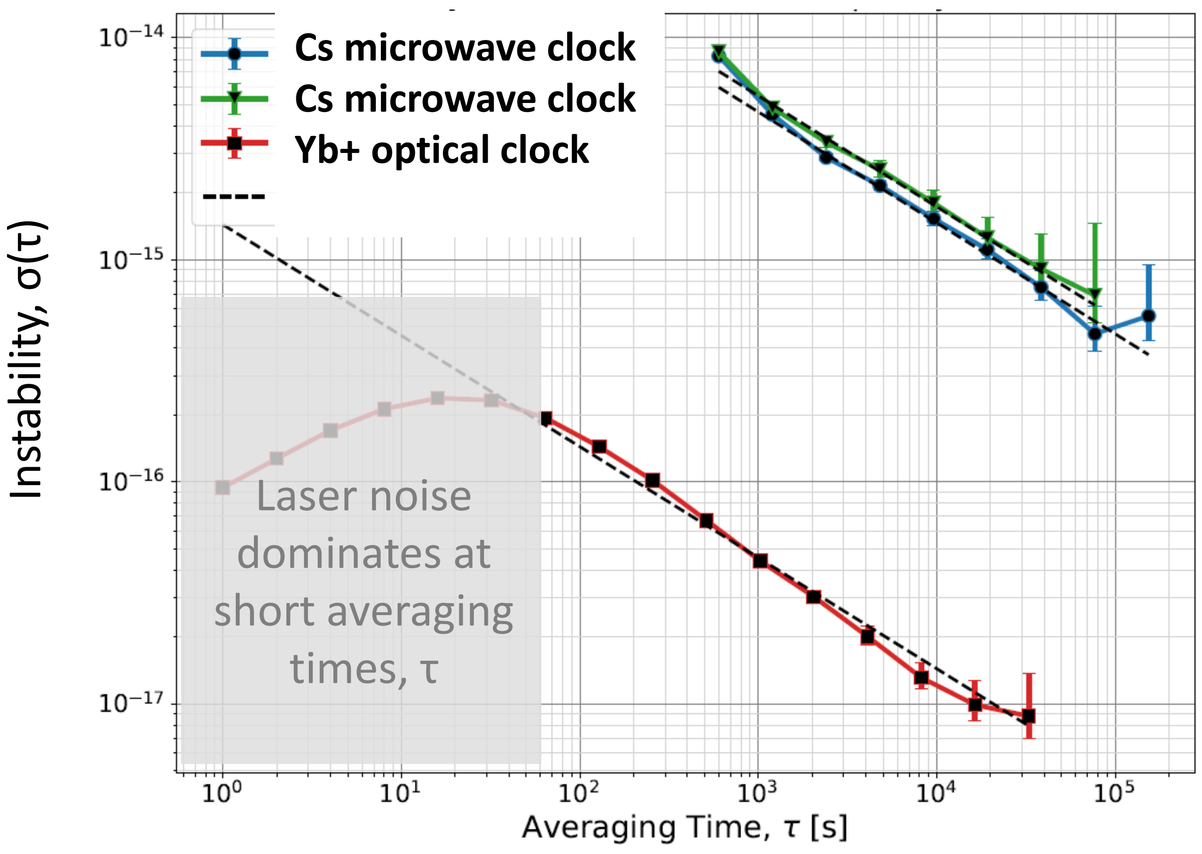
Fractional instability $$\sigma(\tau)\sim\frac{\Delta f}{f_0}\frac{1}{(\mathrm{SNR})}\sqrt{\frac{T}{\tau}}$$

$$\Delta f\sim\frac{1}{T}$$ Assuming Fourier-transform limited probing

Fractional instability $$\sigma(\tau)\sim\frac{1}{f_0}\frac{1}{(\mathrm{SNR})}\sqrt{\frac{1}{T\tau}}$$

Operate clocks with high f_0 and long probe time T to minimise instability

- Example instability, shown on Allan deviation plot



Laser noise dominates at short averaging times, τ

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- ○ how they work
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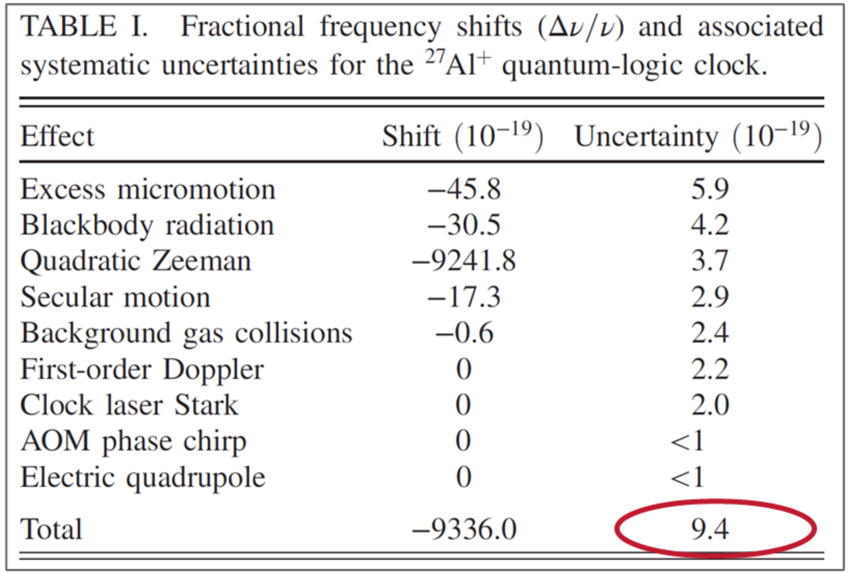

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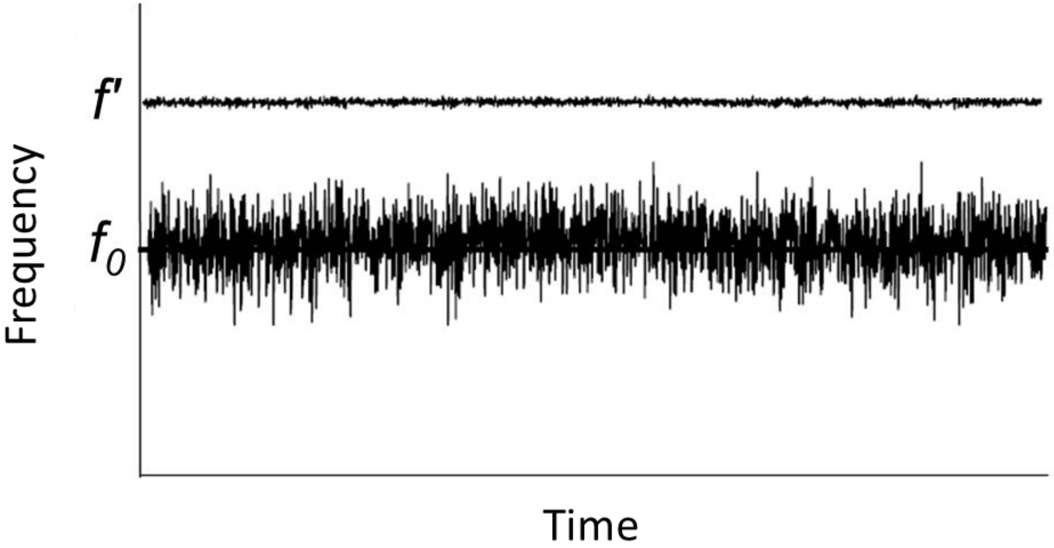

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✓ Understand the basic principles of optical atomic clocks
  - how they work
  - characterisation in terms of instability / inaccuracy

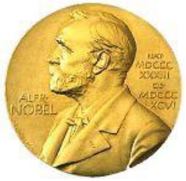
- Meet some practicalities of ion clocks vs lattice clocks

Trapped-ion optical clocks

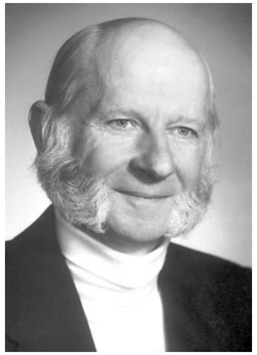
- In pursuit of the lowest instability, want to probe atoms with high f_0, high SNR and long T

Fractional instability $\sigma(\tau) = \frac{1}{f_0} \frac{\eta}{(SNR)} \sqrt{\frac{1}{T\tau}}$

- Need to trap atoms while avoiding disturbances from external fields

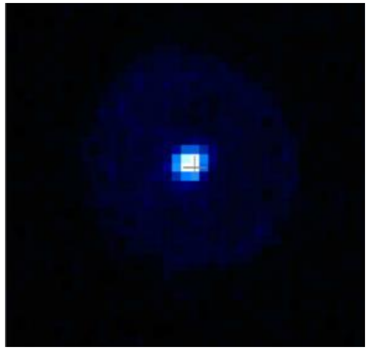


1989



Hans Dehmelt

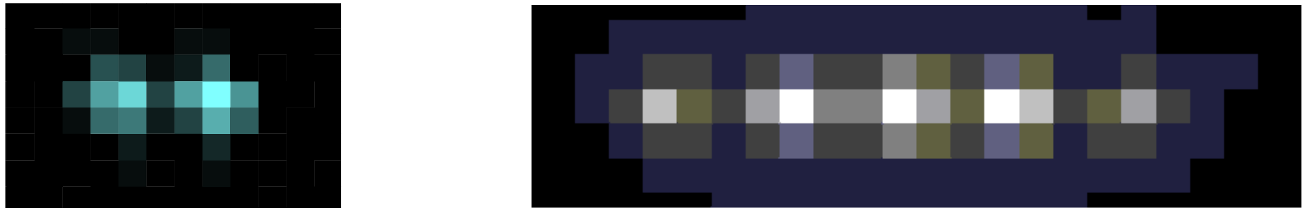
- Dehmelt and Paul proposed and developed single-ion traps
  - Charges can be trapped in a weak electric field
  - Single ion in vacuum system
  - Close to ideal of isolated reference



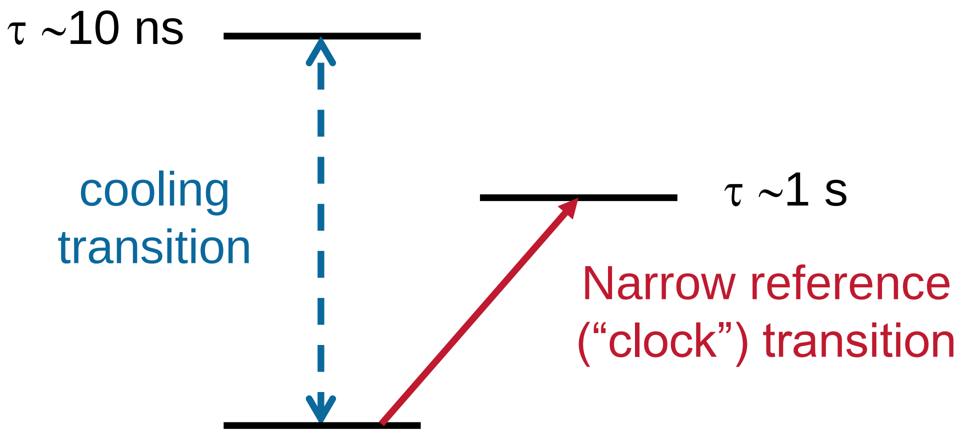
Wolfgang Paul

Ion clocks allow sympathetic cooling

- Can create multi-ion traps



- This can help improve signal-to-noise ratio (SNR), and reduce instability
- Can also trap different species together and use sympathetic cooling for ions that don’t have a readily accessible cooling transition



τ ~10 ns

cooling transition

τ ~1 s

Narrow reference (“clock”) transition

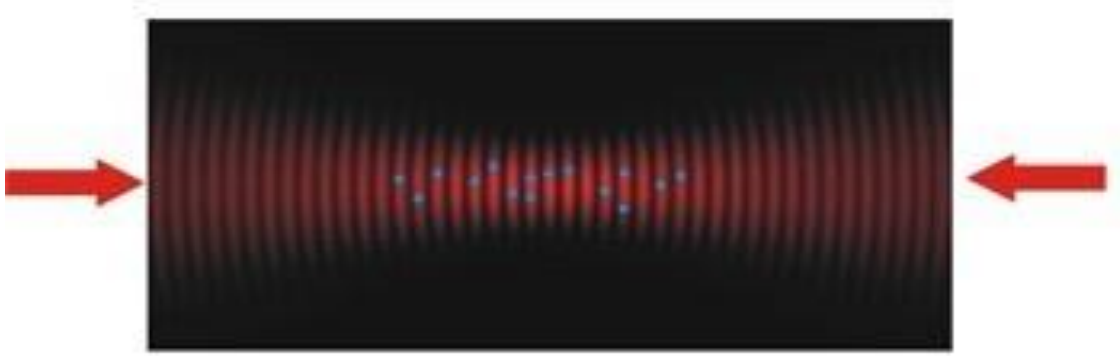
- Allows a greater variety of clock species to be used, e.g. molecular ions, highly-charged ions

Optical lattice clocks – clouds of neutral atoms

- Trapped neutral atoms could allow long probe times **and** good (SNR)

Fractional instability $\sigma(\tau) = \frac{1}{f_0} \frac{\eta}{(\mathrm{SNR})} \sqrt{\frac{1}{T\tau}}$

- Optical dipole trapping in standing wave of light provides tight confinement

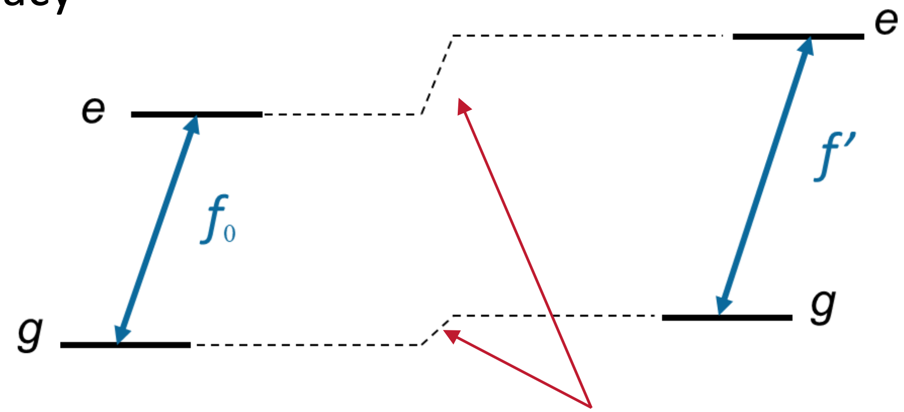


Optical lattice trap

- Number of atoms ~ 10,000, so instability is greatly reduced

Optical lattice clocks – clouds of neutral atoms

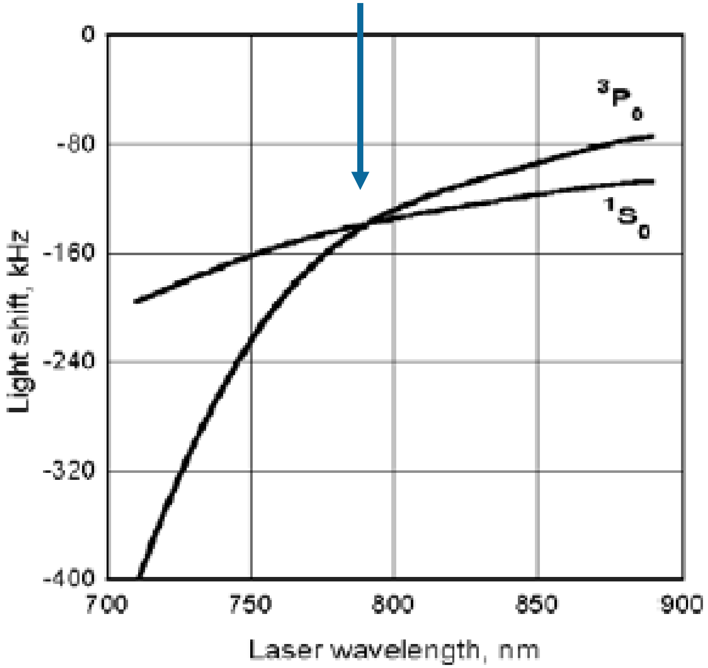
- BUT … optical dipole trapping works by shifting internal energy levels → increases inaccuracy



ac Stark shift from standing wave

- Standing wave at ‘magic’ wavelength produces same shift on ground and excited states, so clock transition is still at f_0 … to first order
- Disadvantage of lattice traps: need to reload atoms after every probe, which introduces dead time and increases instability

‘magic’ wavelength



(credit: Katori, 2001)

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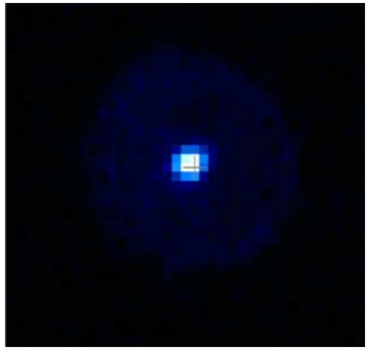
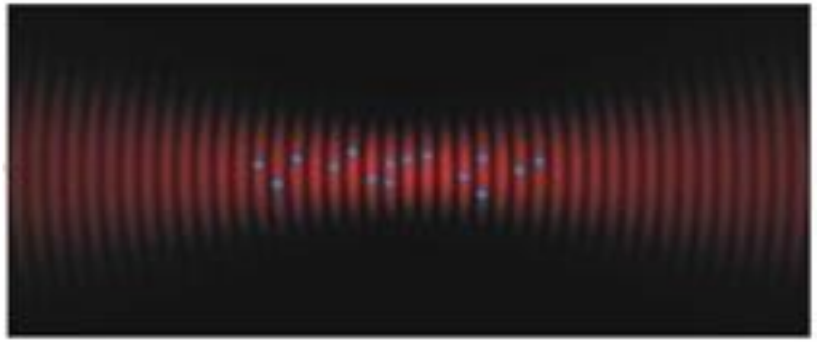
✓ Meet some practicalities of ion clocks vs lattice clocks





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✓ Meet some practicalities of ion clocks vs lattice clocks

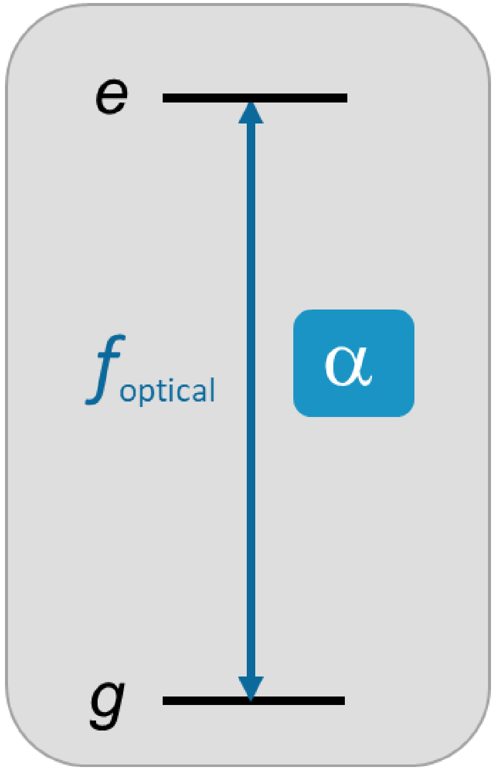
- Understand why certain clocks are good for measuring variations of α and μ

Clocks for measuring variations in fundamental constants

- Atomic transitions can be sensitive to changes in
  - fine structure constant (α)
  - proton-to-electron mass ratio (μ)

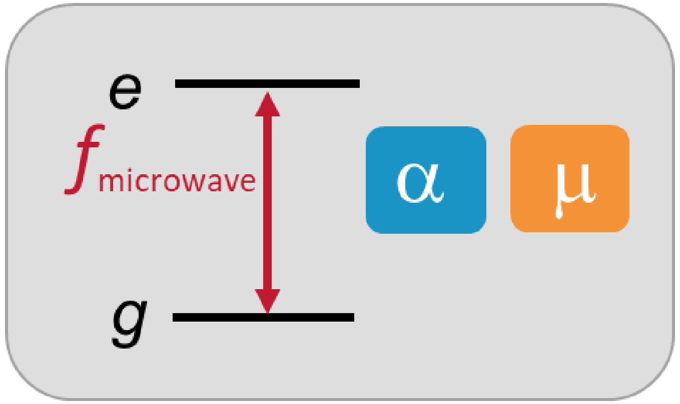
$$\alpha = \frac{1}{4\pi\varepsilon_0}\frac{e^2}{\hbar c}$$

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



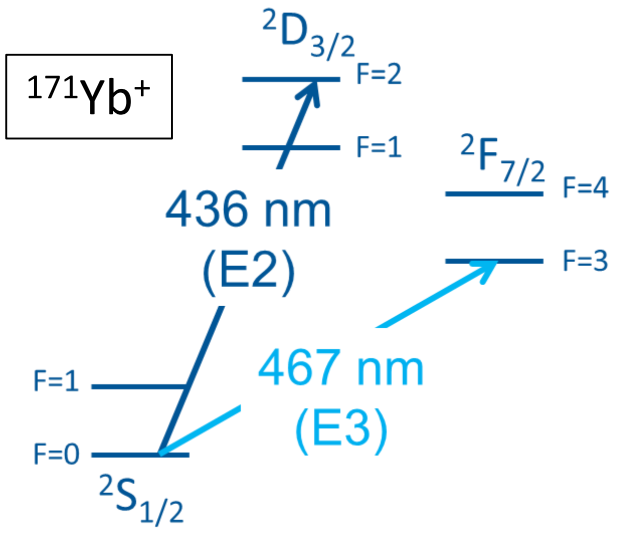
Atomic energy	Scaling with α and μ
Gross structure	$\sim R_\infty$
Fine structure	$\sim R_\infty \alpha^{K}$
Hyperfine structure	$\sim R_\infty \alpha^{2+K} \mu^{-1}$
Molecular rotation	$\sim R_\infty \mu^{-1}$
Molecular vibration	$\sim R_\infty \mu^{-0.5}$

K depends on relativistic many-body corrections, so is different for different atoms



Different sensitivities in different atoms

Species	Wavelength	K_α	K_μ
$^{171}Yb^+$	467 nm (E3)	-5.95	
$^{171}Yb^+$	436 nm (E2)	1.00	
^{87}Sr	698 nm	0.06	
^{133}Cs	32.6 mm	2.83	-1



- Take frequency ratios between clocks with different sensitivities

$$r = \frac{f_1}{f_2}$$

$$\frac{\dot{r}}{r} = [A_1 - A_2]\frac{\dot{\alpha}}{\alpha} + [B_1 - B_2]\frac{\dot{\mu}}{\mu}$$

Measure fractional change in frequency ratio → Deduce fractional change in constants

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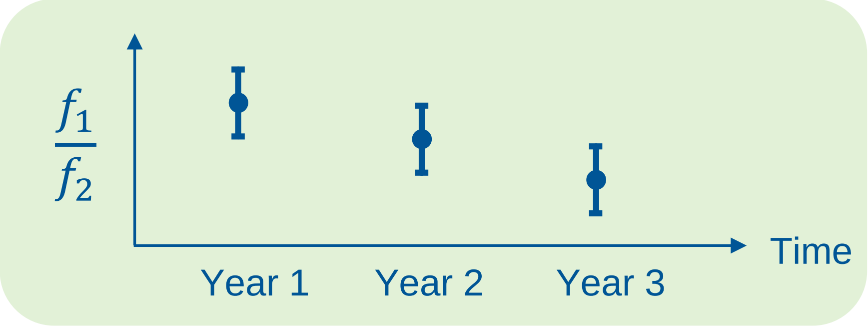
- slow drifts / oscillations / transients

$$\boxed{\frac{\dot{r}}{r}} = \boxed{[A_1 - A_2]}\,\frac{\dot{\alpha}}{\alpha} + \boxed{[B_1 - B_2]}\,\frac{\dot{\mu}}{\mu}$$

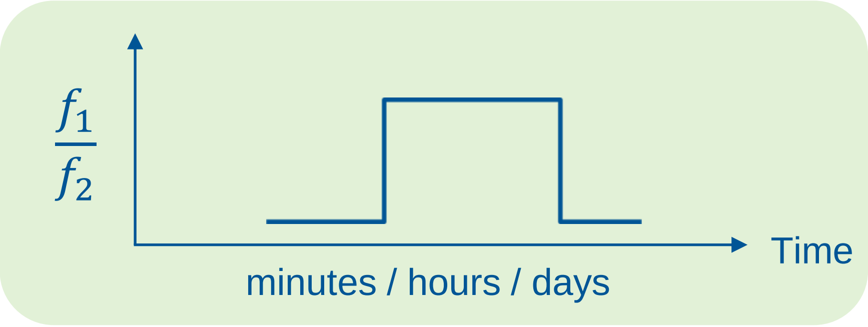
Variations over different timescales

Slow drifts



Oscillations

Fast transients



Aside:
Some astrophysical measurements revealed α few ppm different 10 billion yrs ago at 4σ level

Webb *et al.*
PRL 87 091301 (2001)

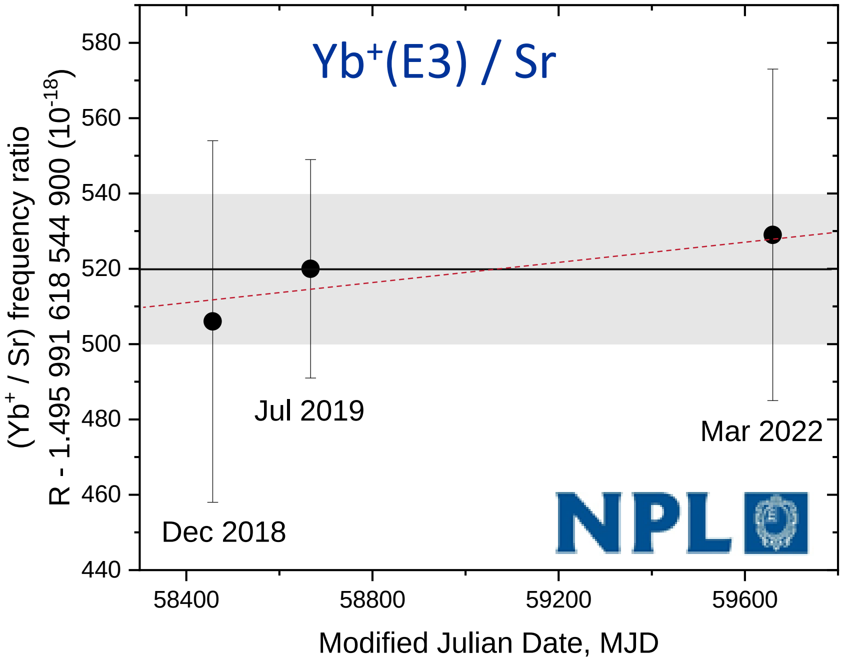
Could be a signature of dark matter interacting non-gravitationally with SM fields

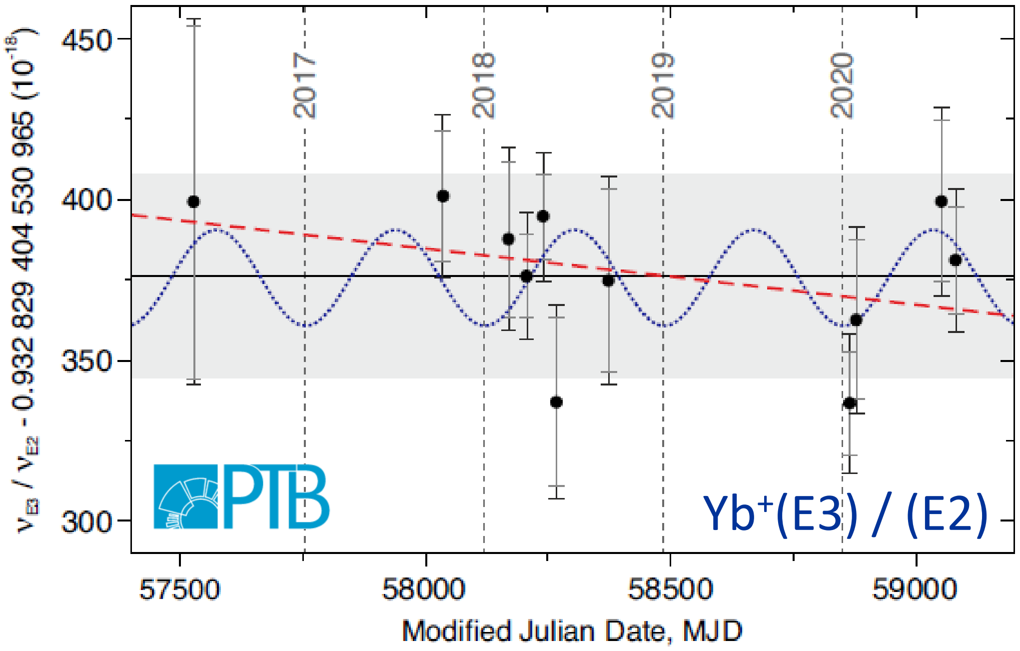
Derevianko *et al.*
Nat. Phys. 10 933 (2014)

Slow-drift constraint on changes in α

$$\frac{1}{\alpha}\frac{\Delta\alpha}{\Delta t} = -0.6(1.9)\times 10^{-18} \text{ / year}$$

$$\frac{1}{\alpha}\frac{\Delta\alpha}{\Delta t} = 1.0(1.1)\times 10^{-18} \text{ / year}$$

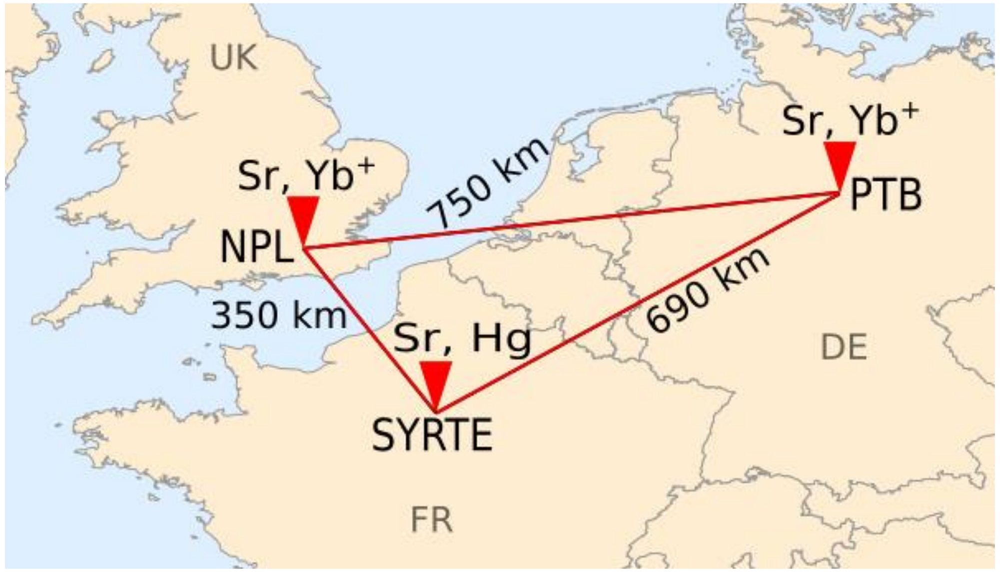


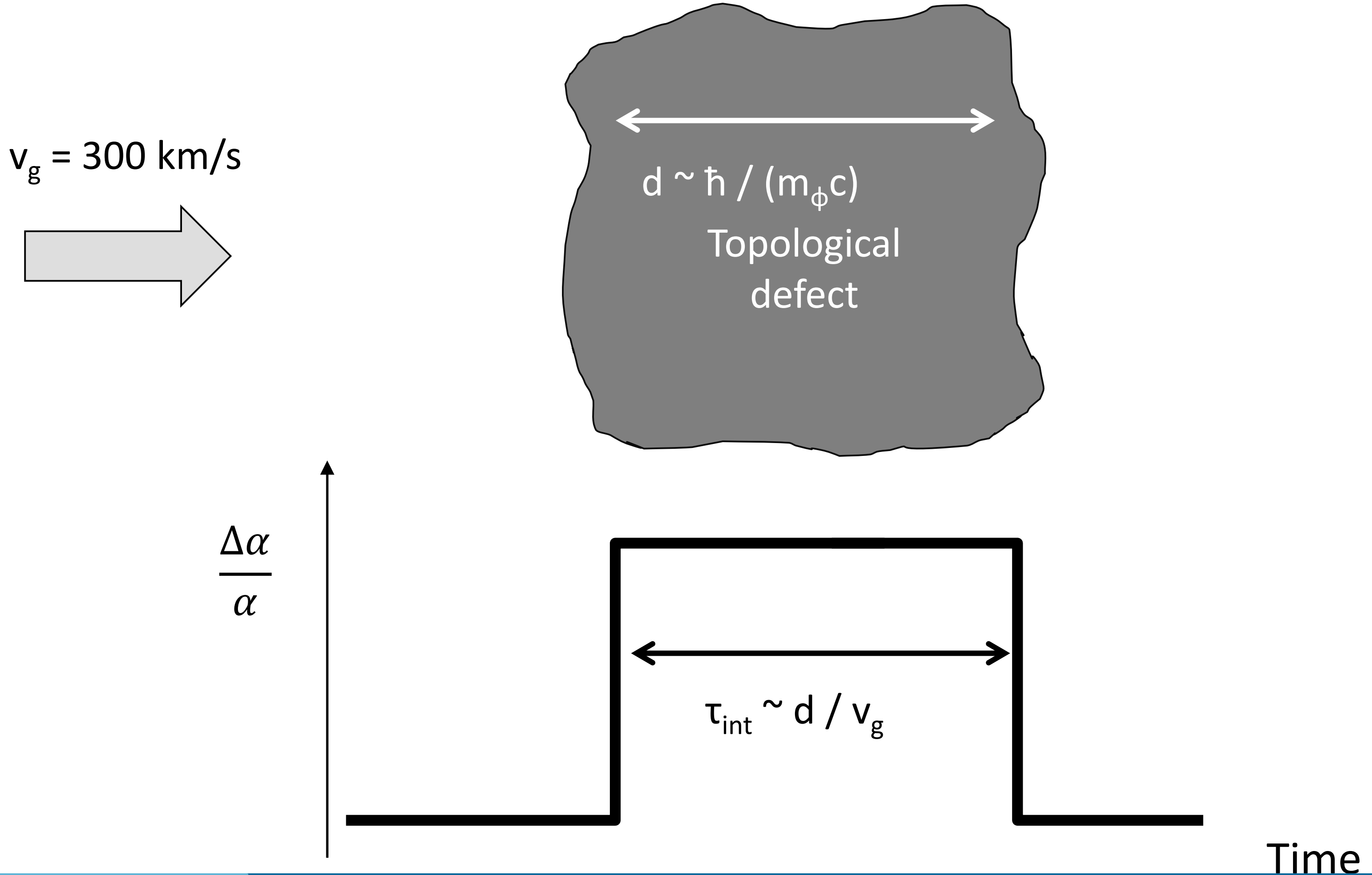


R. Lange *et. al*. PRL **126**, 011102 (2021)

- Drift of α is consistent with zero
- Yb⁺ clocks enable constraint on present-day drift in α at 10^{-18} / year

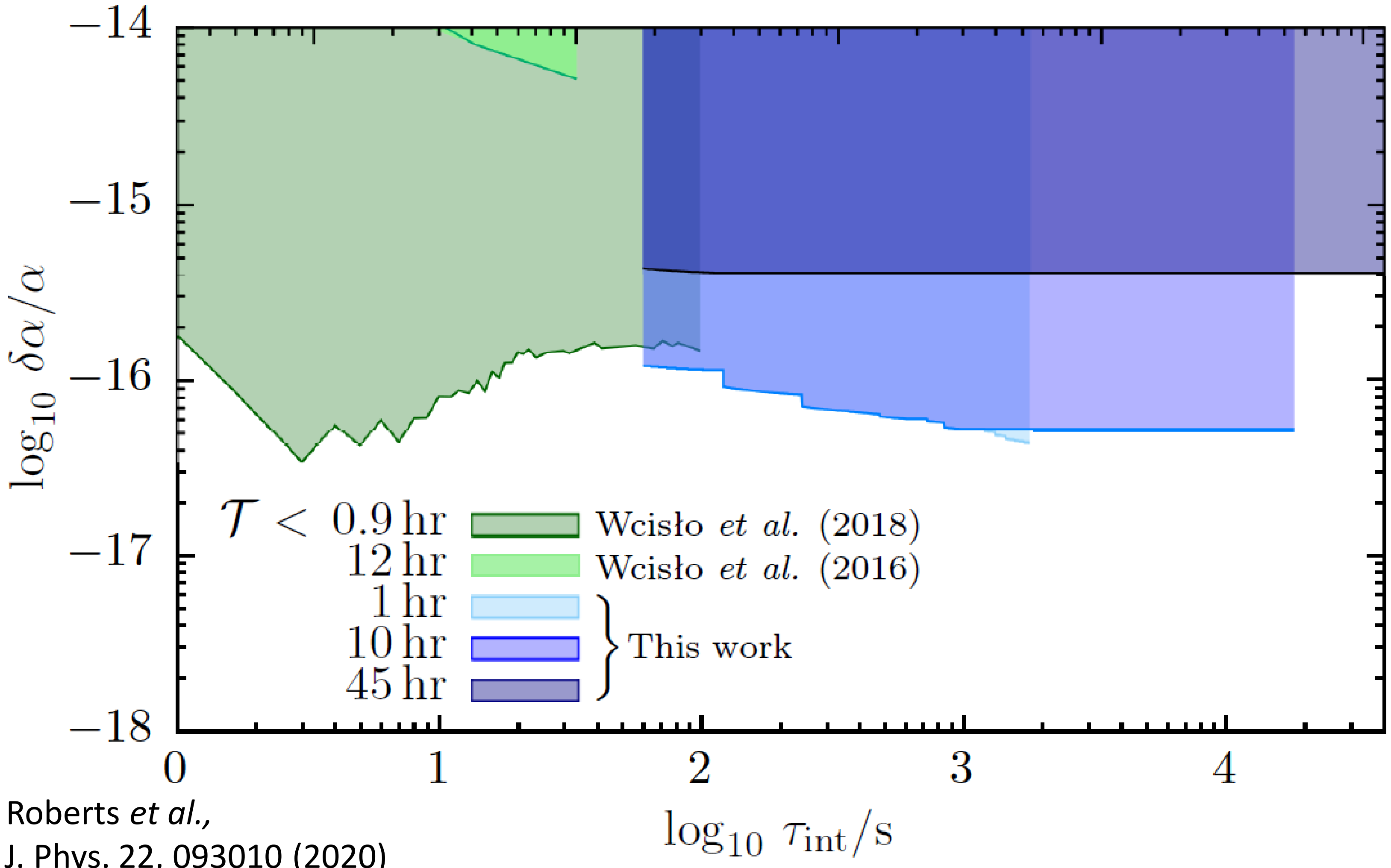
Transient changes in α: Topological defect dark matter



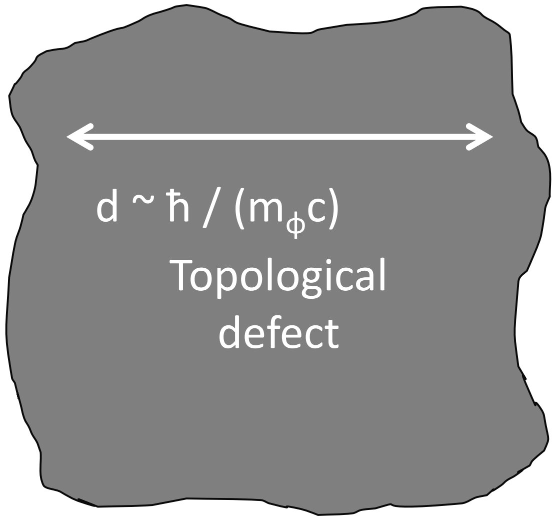


B.M. Roberts *et al.*,
New J. Phys. 22, 093010 (2020)

Constraints on transients in α



B.M. Roberts *et al.*,
New J. Phys. 22, 093010 (2020)



$\tau_{\rm int} \sim d / v_g$

Summary so far

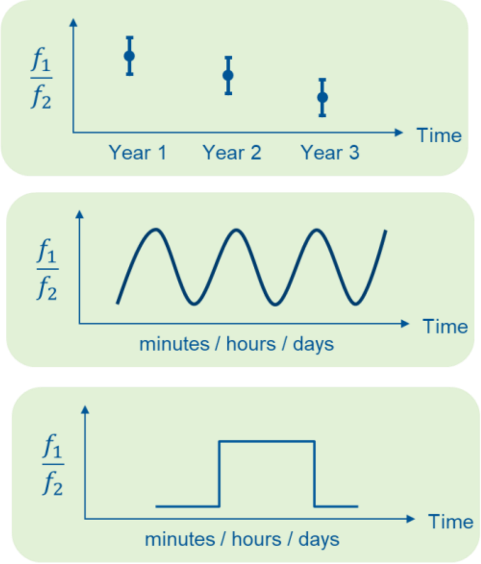
✓ Understand the basic principles of optical atomic clocks

- ○ how they work
- ○ characterisation in terms of inaccuracy / instability

✓ Meet some practicalities of ion clocks vs lattice clocks

✓ Understand why certain clocks are good for measuring variations of α and μ

- ○ slow drifts / oscillations / transients



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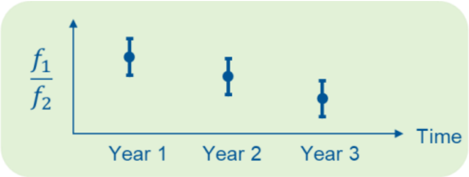
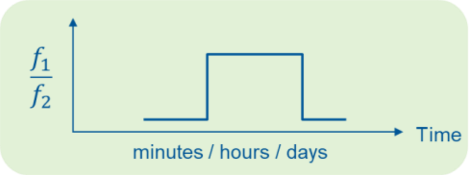
- Meet the clocks in the QSNET consortium





How to reach new levels of sensitivity

QSNET

“A network of optical clocks for measuring the stability of fundamental constants”

University of Birmingham
(Giovanni Barontini)

Imperial College London

University of Sussex

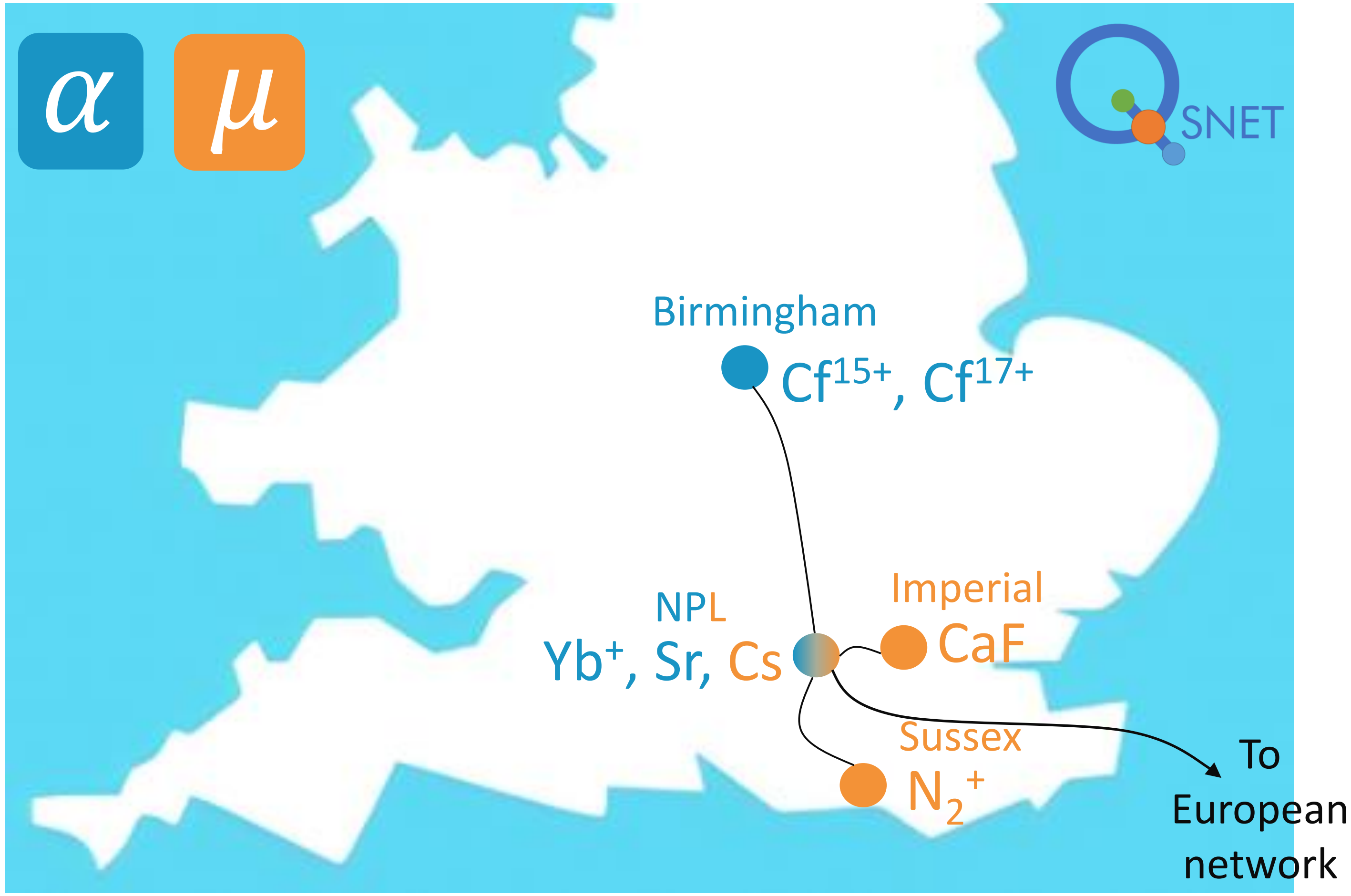
National Physical Laboratory

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

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

	Species	Wavelength	K_α	K_μ
existing	$^{171}Yb^{+}$	467 nm (E3)	-5.95	
	$^{171}Yb^{+}$	436 nm (E2)	1.00	
	^{87}Sr	698 nm	0.06	
	^{133}Cs	32.6 mm	2.83	-1
new	$^{251}Cf^{17+}$	485 nm	-43.5	
	$^{251}Cf^{15+}$	618 nm	47.0	
	CaF	17 µm		-0.5
	N_2^{+}	2.31 µm		-0.5

UK network of clocks – QSNET project



Phase 1

- Investigate measurement & theory with the existing clocks at NPL
- Build the new clocks

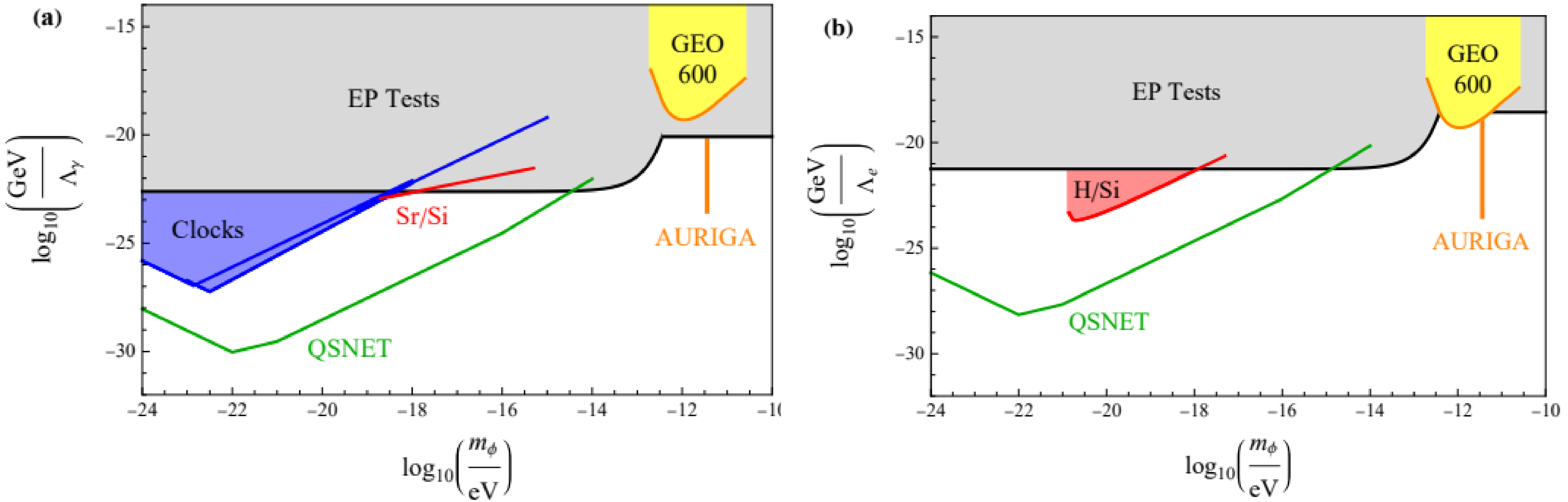
Phase 2

- Connect the clocks with optical fibre links
- Begin measuring frequency ratios with new clocks to achieve greater sensitivities

G. Barontini *et. al*. EPJ Quantum Technology **9**, 12 (2022)

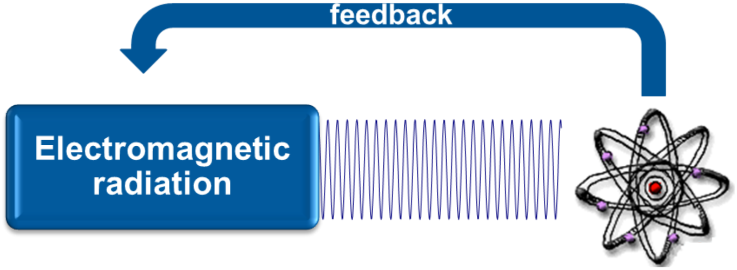
Exclusion plot examples – oscillating scalar dark matter fields

- Clocks with increased sensitivities to α, μ variation are expected to improve constraints in many theories
- One example is couplings between oscillating scalar dark-matter fields interacting linearly with (a) the electromagnetic field and (b) the electron:



G. Barontini *et. al*. EPJ Quantum Technology **9**, 12 (2022)

Conclusion

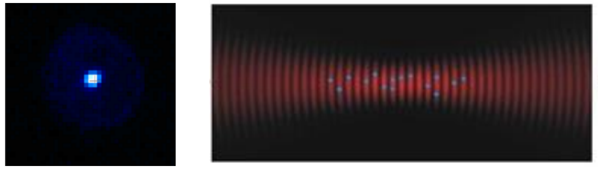


feedback

Electromagnetic radiation

✓ Understand the basic principles of optical atomic clocks

- ○ how they work
- ○ characterisation in terms of inaccuracy / instability



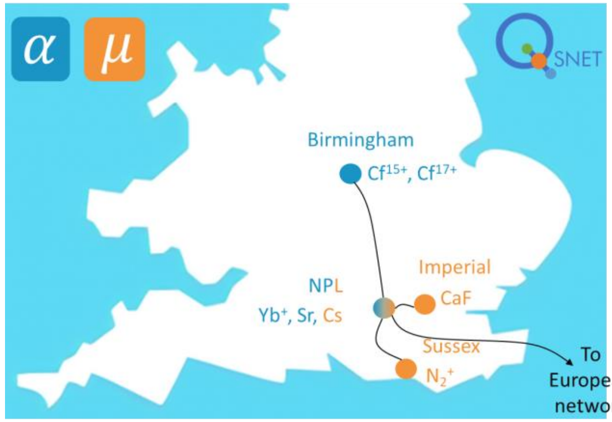
✓ Meet some practicalities of ion clocks vs lattice clocks

✓ Understand why certain clocks are good for measuring variations of α and μ

- ○ slow drifts / oscillations / transients

$$\frac{\dot{r}}{r} = [A_1 - A_2]\frac{\dot{\alpha}}{\alpha} + [B_1 - B_2]\frac{\dot{\mu}}{\mu}$$

✓ Meet the clocks in the QSNET consortium



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Rachel.Godun@npl.co.uk

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