Optical clocks for testing fundamental physics

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Oxford – Quantum Sensors for Fundamental Physics
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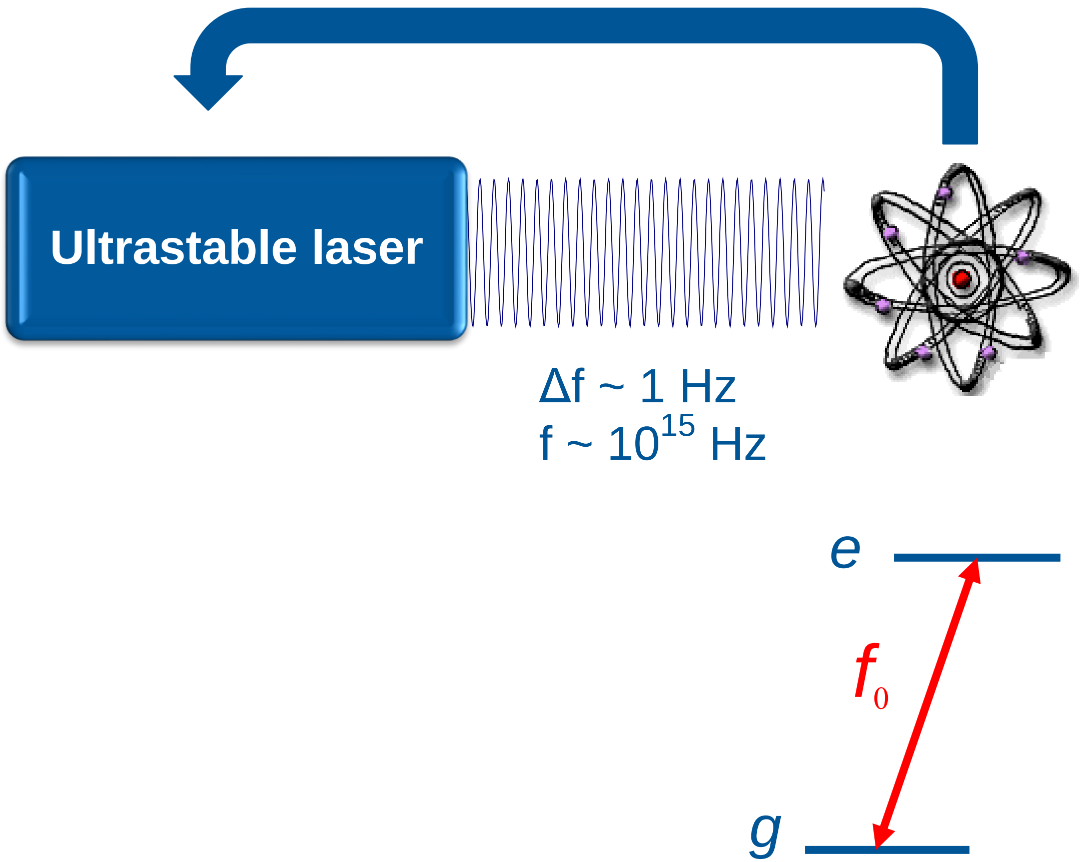
Outline

- Optical clock performance

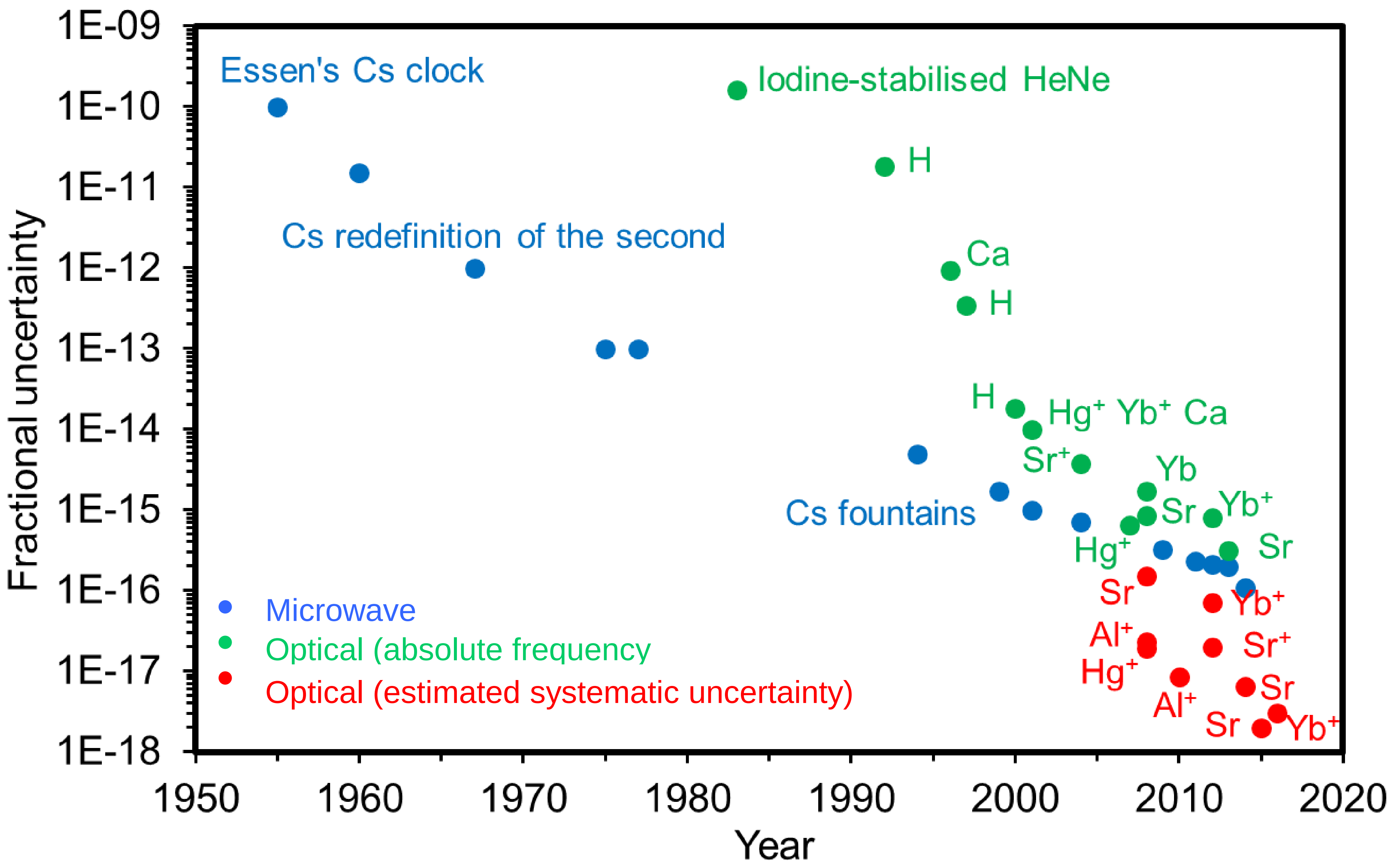
- Two fundamental physics experiments with NPL clocks

  1. Search for variation of fundamental constants
  2. Test of Special Relativity

Optical clock basics



Improvements in optical clocks



Optical clocks at NPL

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Sr lattice
optical clock

Sr+ ion
optical clock

Yb+ ion
optical clock

- All 3 clocks have frequency uncertainties in the 10^{-17} – 10^{-18} range

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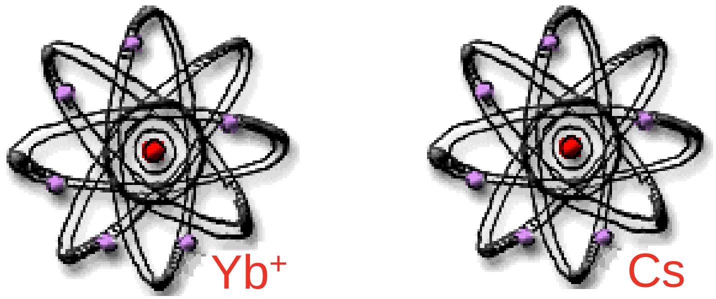
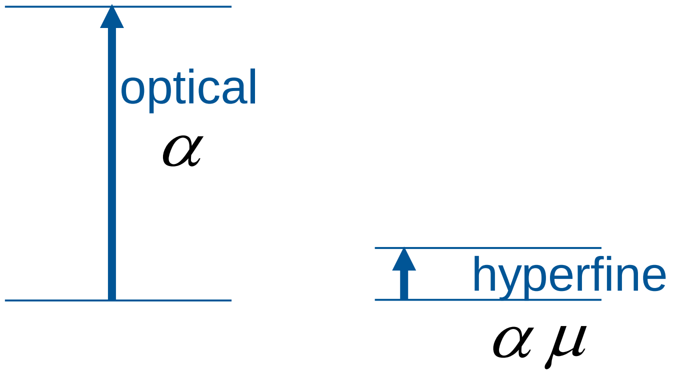
Atomic clocks to investigate Δα

- If α varies, so will the atomic frequency f
- Beware that other quantities may also be varying
- For α variation, use optical ratio $f_1^{\mathrm{opt}} / f_2^{\mathrm{opt}} = r$



$$\frac{\dot{r}}{r} = [A_1 - A_2]\frac{\dot{\alpha}}{\alpha}$$

sensitivity factors



Measure fractional rate of change in frequency ratio → Deduce fractional rate of change in fine structure constant

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

Dimensionless constants

NIST - Hg^+/ Al^+ optical frequency ratio

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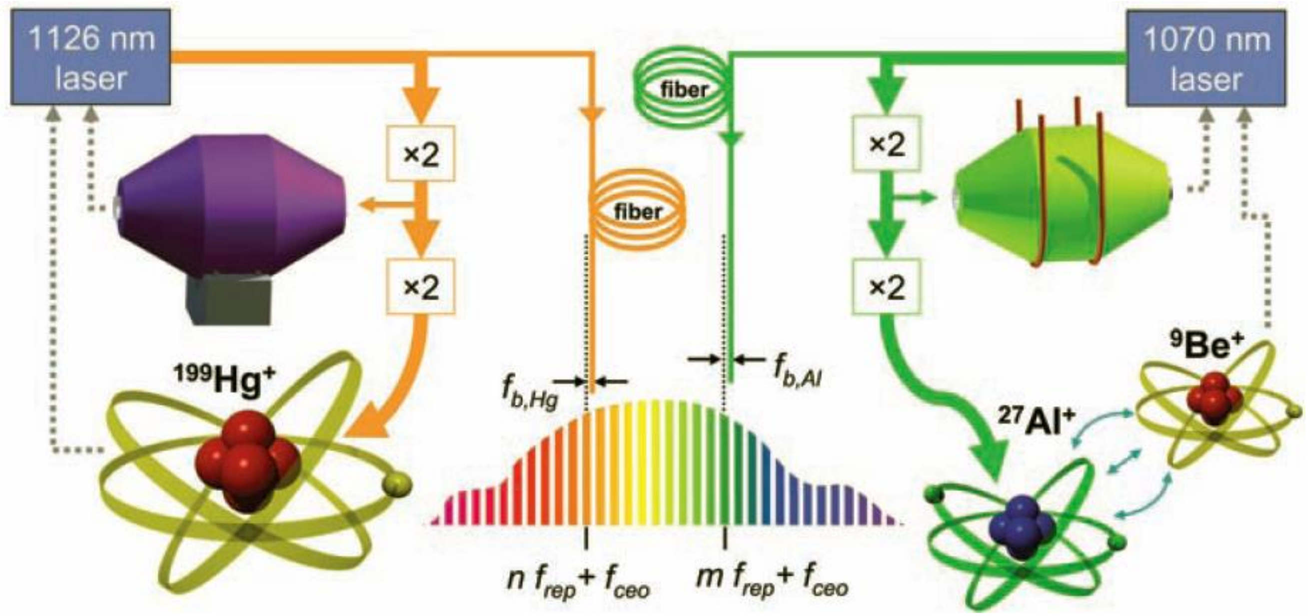
- Most accurate single test of alpha-only variation



	Clock transition	*A*
Hg^+	$^2S_{1/2} - {}^2D_{5/2}$	-2.94
Al^+	$^1S_0 - {}^3P_0$	0.008
Yb^+(E3)	$^2S_{1/2} - {}^2F_{7/2}$	-5.95
Yb^+(E2)	$^2S_{1/2} - {}^2D_{3/2}$	1.00
Sr^+	$^2S_{1/2} - {}^2D_{5/2}$	0.43
Ca^+	$^2S_{1/2} - {}^2D_{5/2}$	0.15
Sr	$^1S_0 - {}^3P_0$	0.06

V.V. Flambaum and V.A. Dzuba, Can. J. Phys. **87**, 25 (2009)

$$\frac{\dot{r}}{r} = [A_1 - A_2]\frac{\dot{\alpha}}{\alpha}$$

$$\frac{\dot{r}}{r} = 2.95\frac{\dot{\alpha}}{\alpha}$$

T. Rosenband *et al.*, Science, **319** 1808 (2008)

The advantage of Yb^+ for laboratory tests

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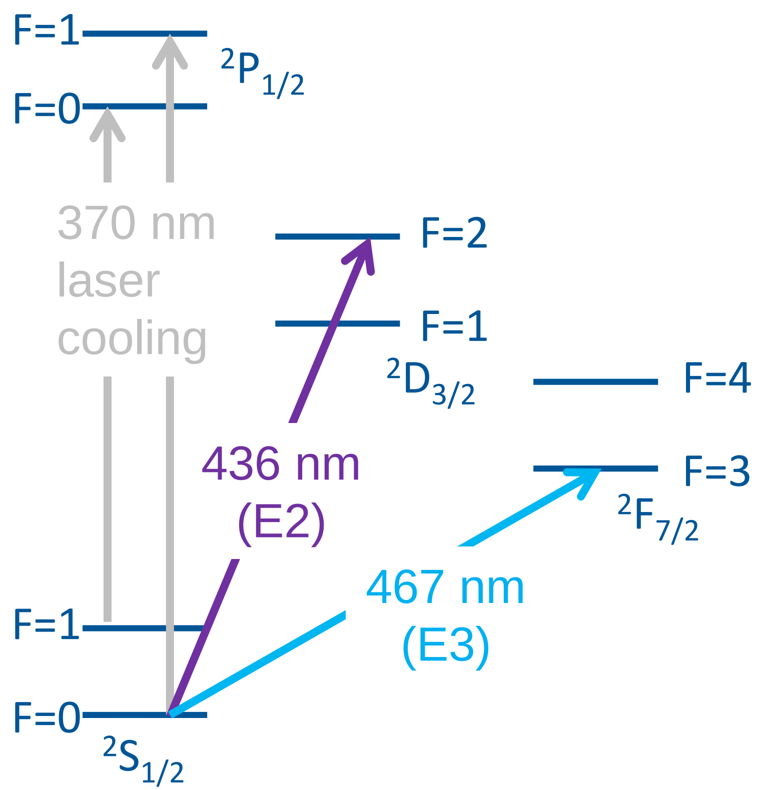

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V.V. Flambaum and V.A. Dzuba, Can. J. Phys. **87**, 25 (2009)

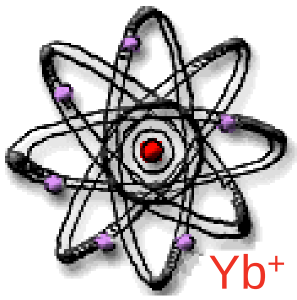
- Increased sensitivity to α variation
- Two clock transitions in the same ion in same environment

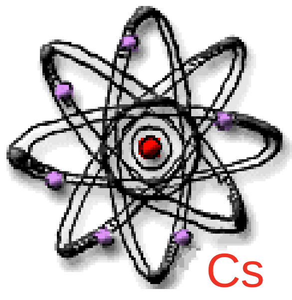
$$\frac{\dot{r}}{r} = [A_1 - A_2]\frac{\dot{\alpha}}{\alpha}$$

$$\frac{\dot{r}}{r} = 6.95\frac{\dot{\alpha}}{\alpha}$$

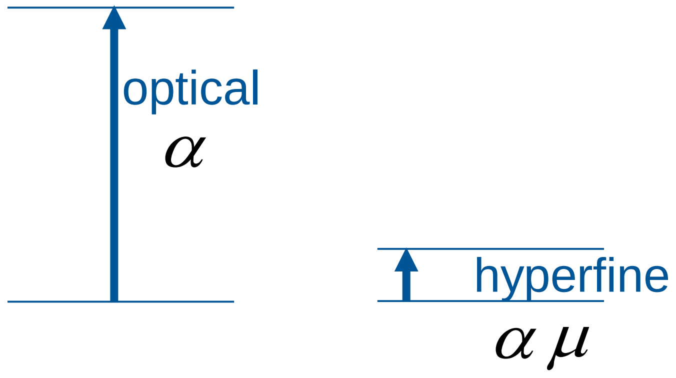
Frequency ratios between Yb$^+$ and Cs

- Can also investigate variation in μ as well





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

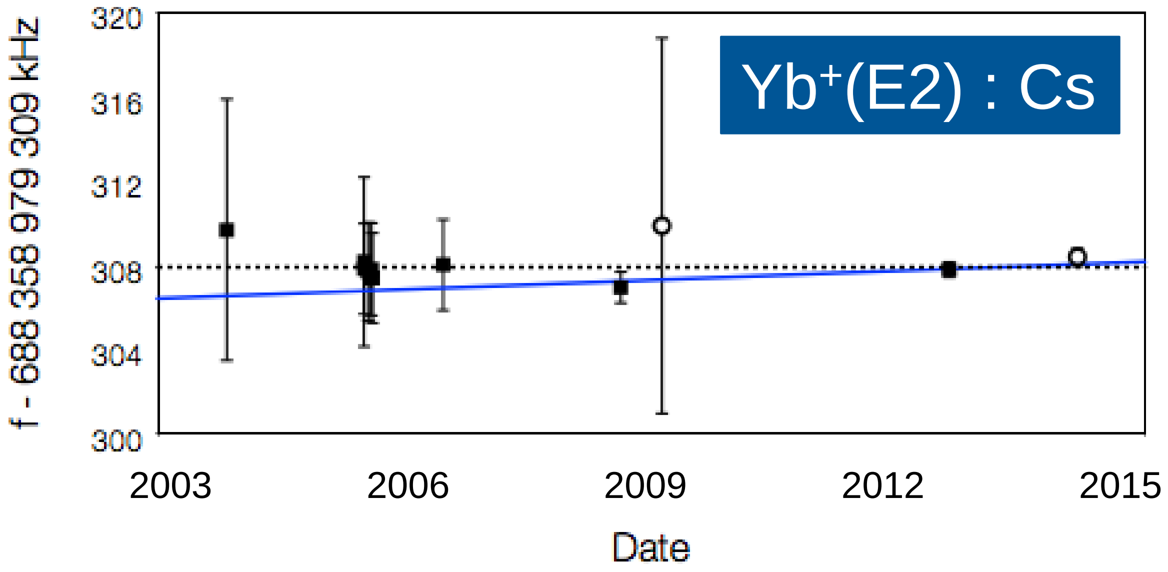


Ion	Clock transition	*A*	*B*
Yb$^+$	$^2S_{1/2} - {}^2D_{3/2}$	1.00	0
Yb$^+$	$^2S_{1/2} - {}^2F_{7/2}$	-5.95	0
Cs	$^2S_{1/2}$ F=3-4	2.83	1

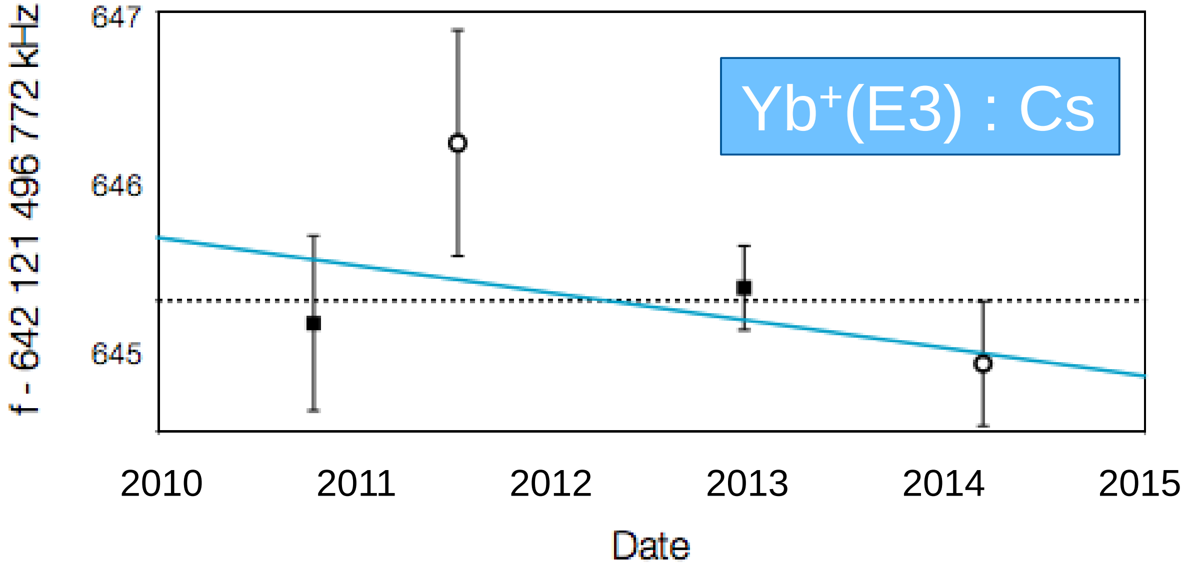
$$\alpha = \frac{e^2}{4\pi\varepsilon_0 \hbar c}$$

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

History of Yb⁺ E3 and E2 against Cs

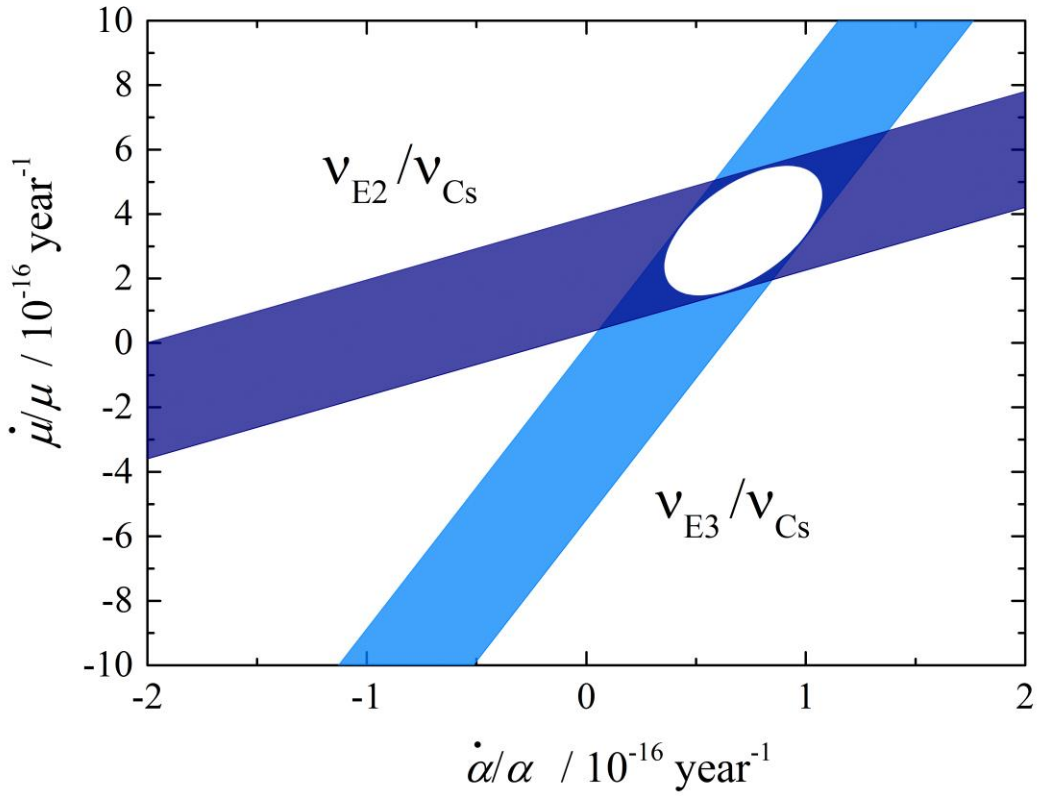


$$\frac{d}{dt}\ln\left(\frac{\nu_{\mathrm{E2}}}{\nu_{\mathrm{Cs}}}\right) = (2.3 \pm 1.5) \times 10^{-16}\,\mathrm{yr}^{-1}$$



$$\frac{d}{dt}\ln\left(\frac{\nu_{\mathrm{E3}}}{\nu_{\mathrm{Cs}}}\right) = (-2.5 \pm 2.7) \times 10^{-16}\,\mathrm{year}^{-1}$$

Yb$^+$ limits on α and μ time-variation

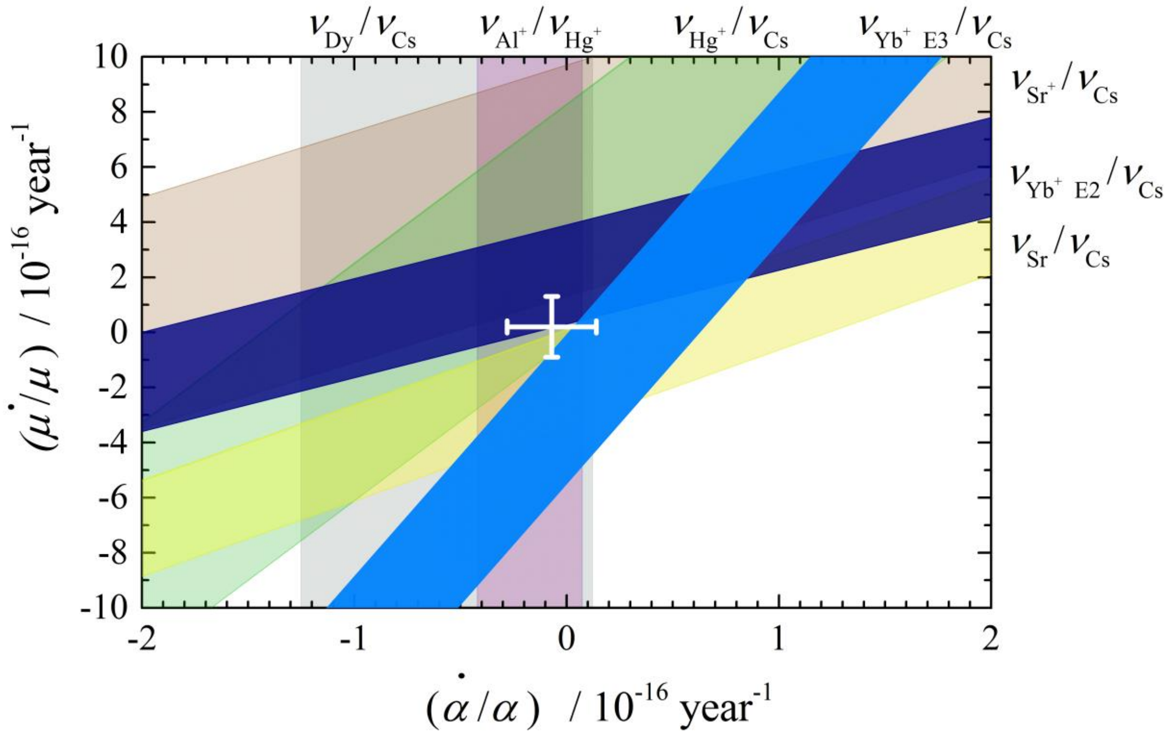


$$[\dot{\alpha}/\alpha]_{Yb^+/Cs} = 7.2(4.7) \times 10^{-17}\ \mathrm{yr}^{-1}$$

$$[\dot{\mu}/\mu]_{Yb^+/Cs} = 3.5(2.4) \times 10^{-16}\ \mathrm{yr}^{-1}$$

R.M. Godun *et al.*, Phys. Rev. Lett., **113** 210801 (2014)

Combined limits on α and μ variation



$$\dot{\mu}/\mu = 0.2(1.1) \times 10^{-16}\,\text{year}^{-1}$$
$$\dot{\alpha}/\alpha = -0.7(2.1) \times 10^{-17}\,\text{year}^{-1}$$

- Three-fold improvement on best previous constraint on $\dot{\mu}$
- Improvements to the clock will allow even more stringent searches for present-day changes
  - Slow variations
  - Transients
  - Oscillations

R.M. Godun *et al.*, Phys. Rev. Lett., **113** 210801 (2014)

Outline

- Optical clock performance

- Three fundamental physics experiments with NPL clocks

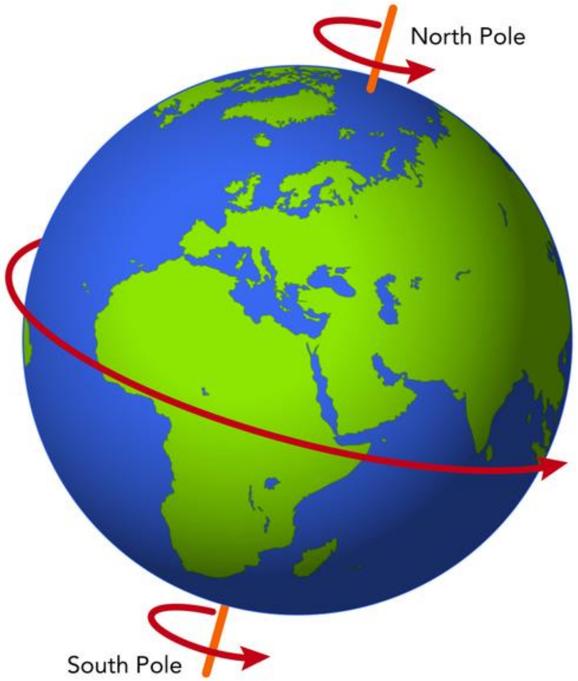
 1. Search for variation of fundamental constants
 2. Test of Special Relativity

Test of Special Relativity

- Lorentz Invariance is an assumption of Special Relativity: *the outcome of an experiment does not depend on the velocity or orientation of the inertial frame in which it is performed*

- If true, atomic clocks in different inertial frames will have the same frequency

- Compare clocks in different locations and look for daily variations in their frequency differences



P. Delva *et al.*, Phys. Rev. Lett., **118** 221102 (2017)

European network of optical clocks

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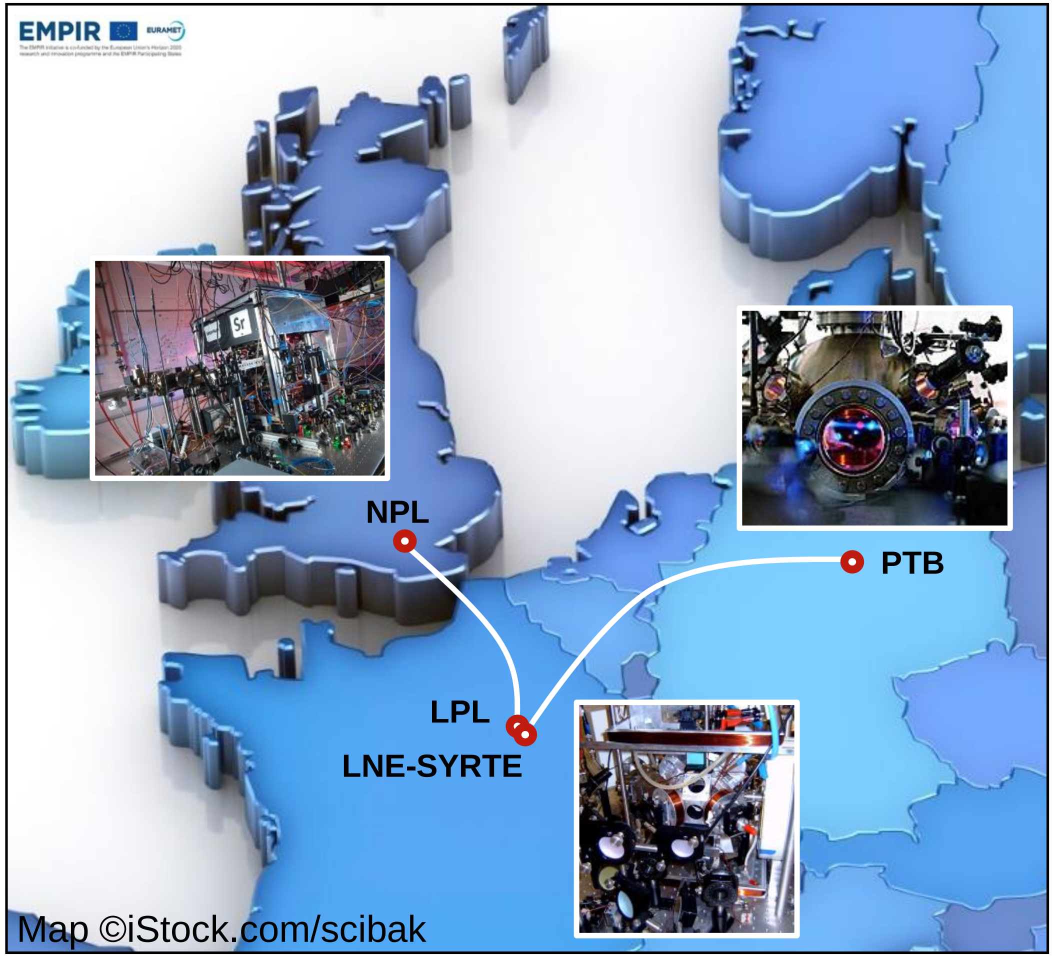

- Comparison of Sr optical lattice clocks, linked via optical fibres

P. Delva *et al.*, Phys. Rev. Lett., **118** 221102 (2017)

Test of Special Relativity

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- Need to account for gravitational redshifts due to tides
- Analysis of clock frequency differences shows that

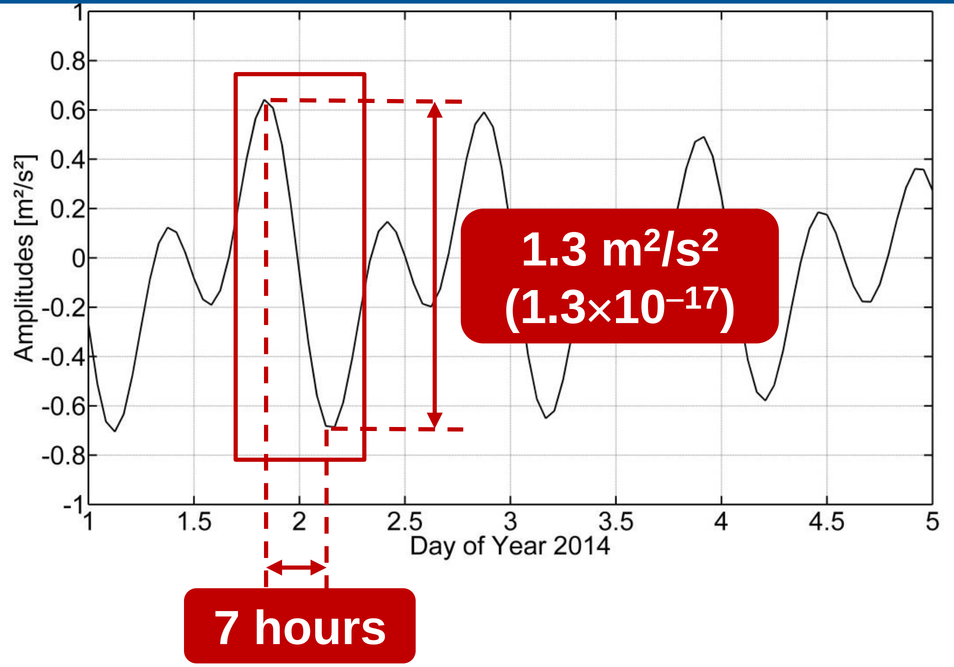
violation of Lorentz Invariance

Robertson-Mansouri-Sexl parameter

$< 1.1 \times 10^{-8}$

- Factor of 2 improvement on best previous constraint

Gravity potential differences between NPL and PTB

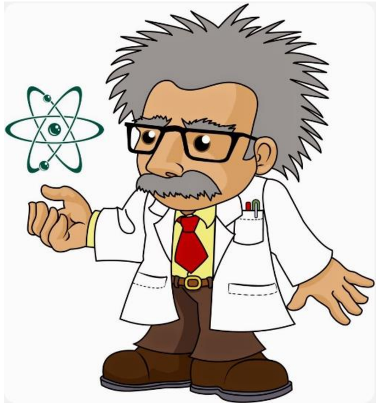


P. Delva *et al.*, Phys. Rev. Lett., **118** 221102 (2017)

Summary

- NPL Sr, Sr^+ and Yb^+ optical clocks have frequency uncertainties in the 10^{-17} – 10^{-18} range

- Can use optical clocks to test fundamental physics at unprecedented levels
  - Variations in α and μ
  - Lorentz Invariance tests



With thanks to…

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Time and Frequency group at NPL

European collaborators

LNE Le progrès, une passion à partager

PTB Physikalisch-Technische Bundesanstalt Braunschweig und Berlin

l'Observatoire de Paris SYRTE Systèmes de Référence Temps-Espace

LPL Laboratoire de physique des lasers

cnrs

Department for Business, Energy & Industrial Strategy

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