Atom-based Frequency Metrology: Real World Applications

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Outline

- Introduction to atom-based frequency metrology
- “Practical Uses”
  - Tests of fundamental physics
  - Space-based optical clocks

Why do we need clocks?

Why do we need better and better clocks?

Navigation

- transatlantic voyages
- missile guidance systems
- GPS + satellite control
- deep space missions

Synchronisation

- global economy
- very long base-line interferometry and arrays

Standards

- economic and public needs (NBS)

NPL

What is a clock?

Oscillator

something periodic
(pendulum, electromagnetic radiation)

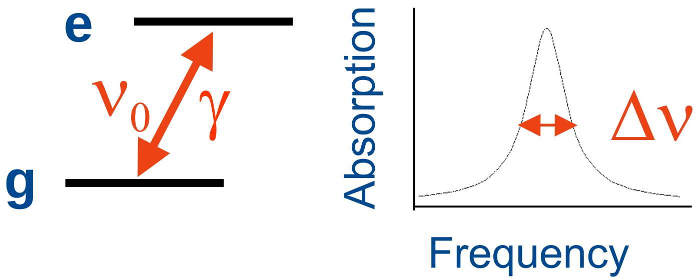
Counter

something that can measure the oscillations

Why do atoms make good clocks?

All atoms are identical

-atomic transitions are excited
by electromagnetic radiation
(oscillation!)



ν_0 = excitation frequency

$$\boxed{Q = \nu_0/\Delta\nu}$$

Aside on Q (Quality factor)

- resonance phenomenon: coupled pendulums, cavities, atoms all have similar properties

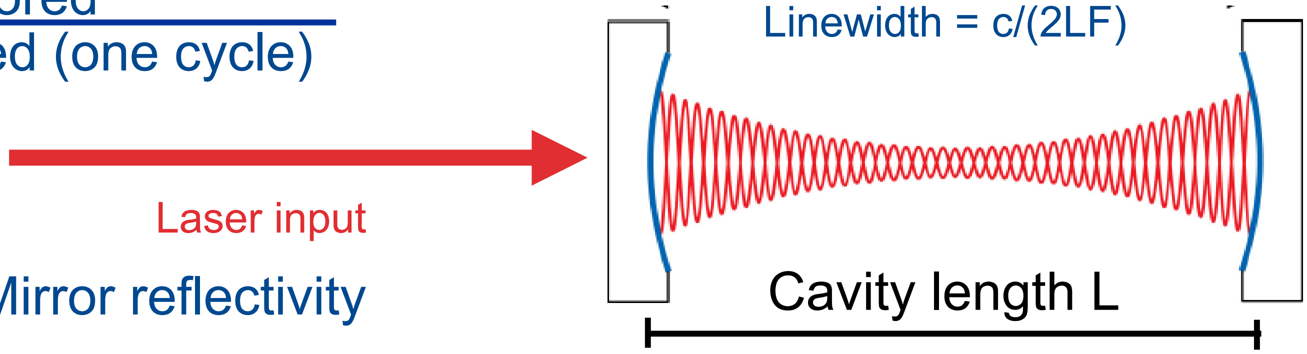
$$Q = 2\pi \frac{\text{energy stored}}{\text{energy dissipated (one cycle)}}$$

Only modes fulfilling the boundary conditions will add constructively

Resonance frequencies

f_n=nc/2L

Linewidth = c/(2LF)



Laser input

Mirror reflectivity

What makes a good atomic clock?

Stability

Figure of merit:

Fractional frequency instability

$$\sigma(\tau) \sim \frac{\Delta\nu}{\nu_0 \cdot S/N(\tau)}$$

optical or microwave?

- ratio $\frac{\nu_{opt}}{\nu_{\mu wave}} \sim 10^5$

-microwave engineering mature field (measurement, transport of signal)

But how to measure optical frequencies?

Accuracy

- Insensitive to external perturbations (accuracy)
- Long interrogation times (laser cooling and trapping)

ions and atoms

<u>Laboratory realities</u>: What makes a good atomic clock?

Reproducibility

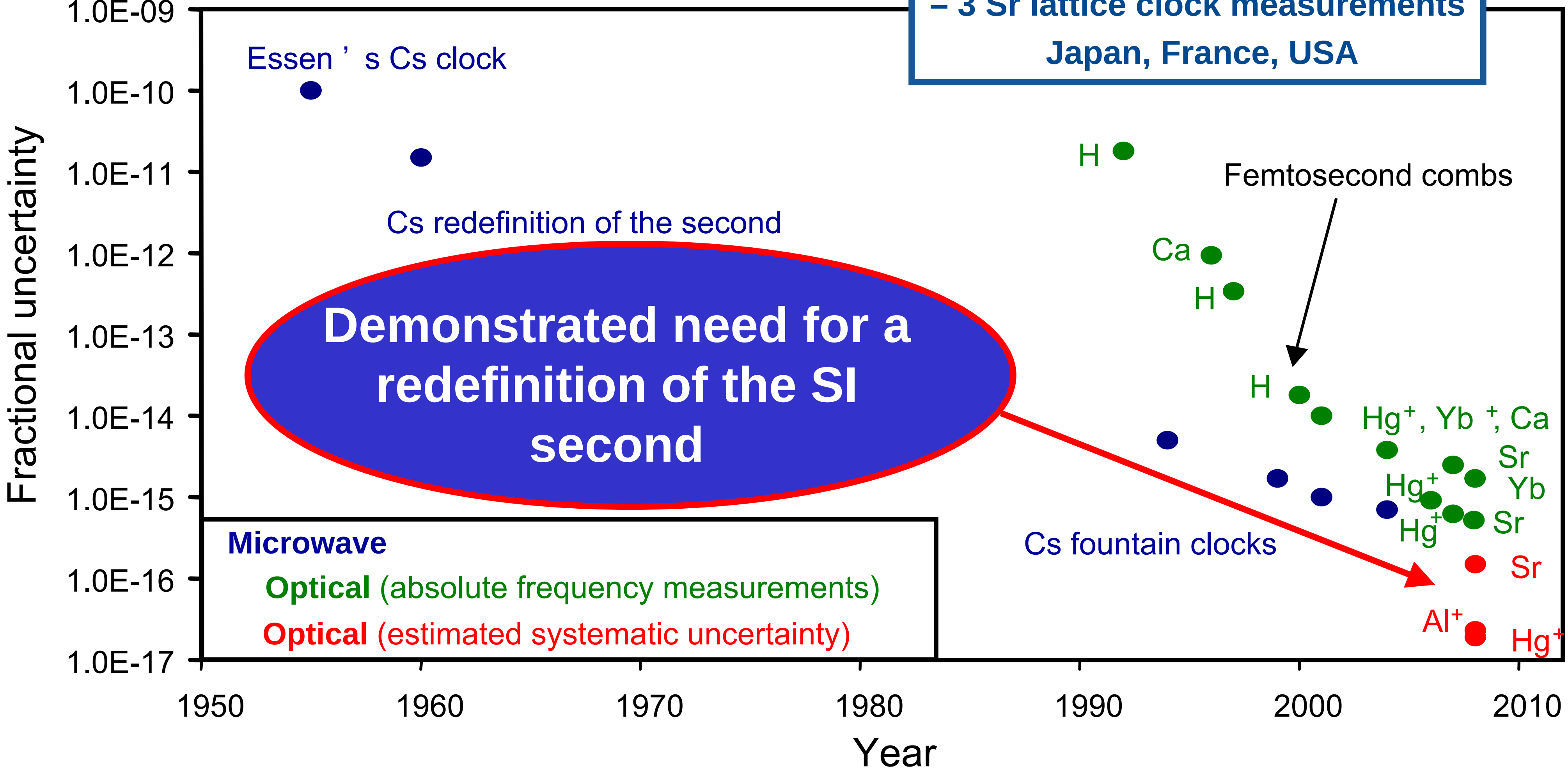
- Accessible cooling and clock transitions
- Experimental possibilities for assessing systematics

Improvements in accuracy

Best accuracy – Hg^+ and Al^+

Best short-term stability – neutral atoms

Best reproducibility – 3 Sr lattice clock measurements Japan, France, USA



Demonstrated need for a redefinition of the SI second

Evaluation of systematic uncertainties at 10^{-16} – needs optical-optical measurement.

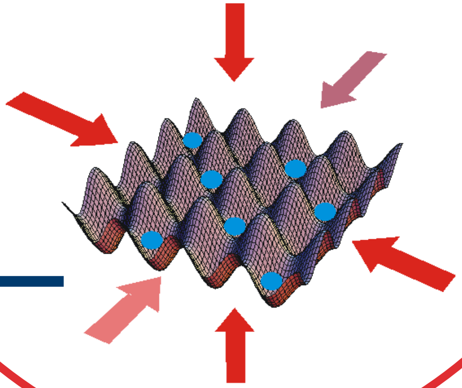
Components of an optical clock

Oscillator
(Ultra-stable laser)

\+

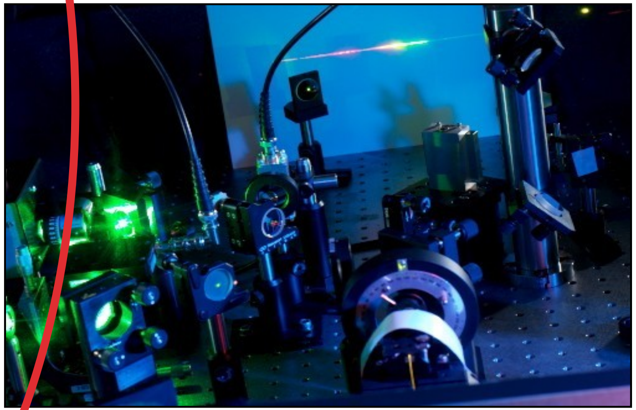
Reference
(narrow optical transition in an atom or ion)

or

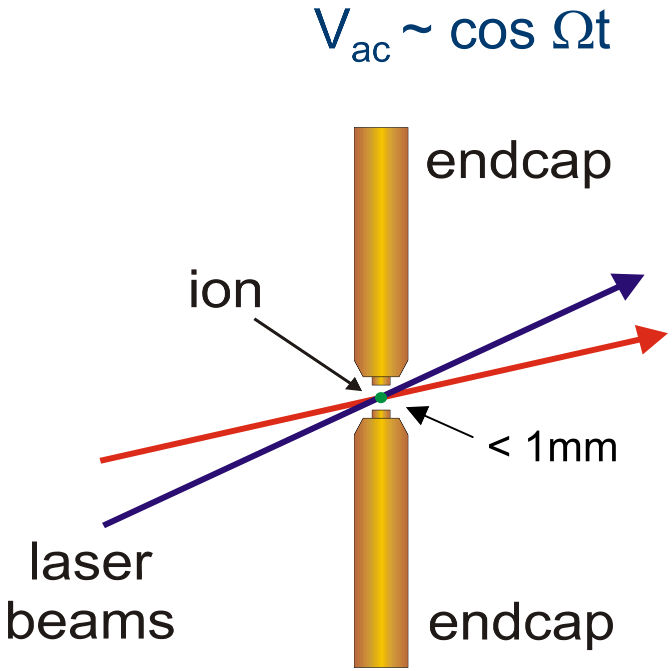


\+

Counter
(Femtosecond comb)

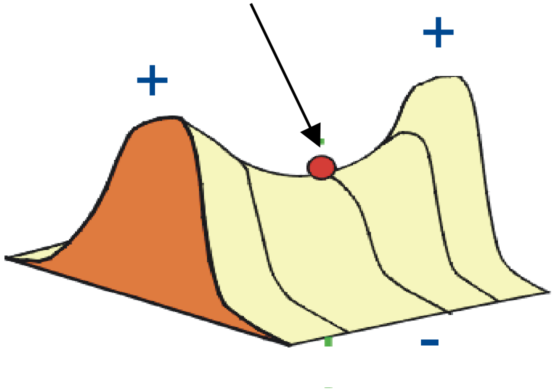


Trapped ion optical frequency standards



- Laser-cooled single trapped ion
- High-Q optical clock transitions (10^{15} or higher)
- Low perturbation environment
- Laser cool to Lamb-Dicke regime (low energy vibrational states)

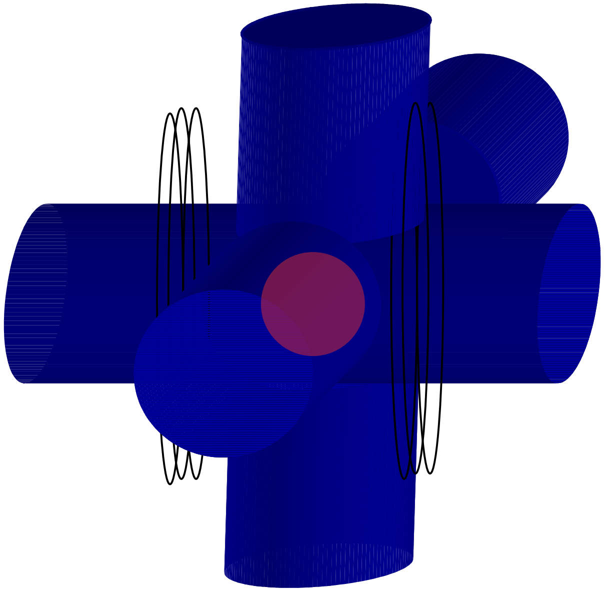
Positively charged ion

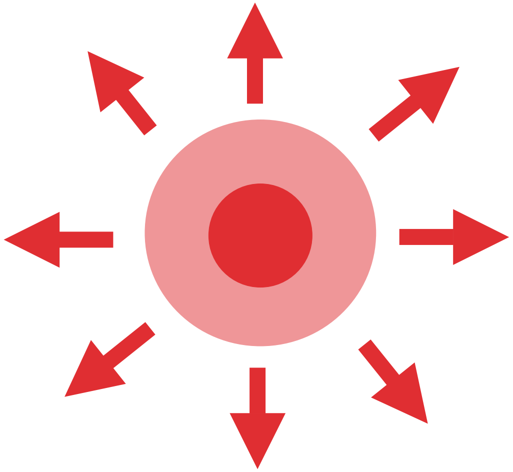


- No 1st-order Dopper shift
- Minimum 2nd-order Doppler shift
- Field perturbations minimised at trap centre
- Background collision rate low
- No other ions to perturb clock ion

Neutral atom optical frequency standards

- Laser-cooled ensemble of atoms (~10 million atoms)
- High-Q optical clock transitions (10^{15} or higher)
- More perturbative environment than ions,
  but make up for this in signal-to-noise

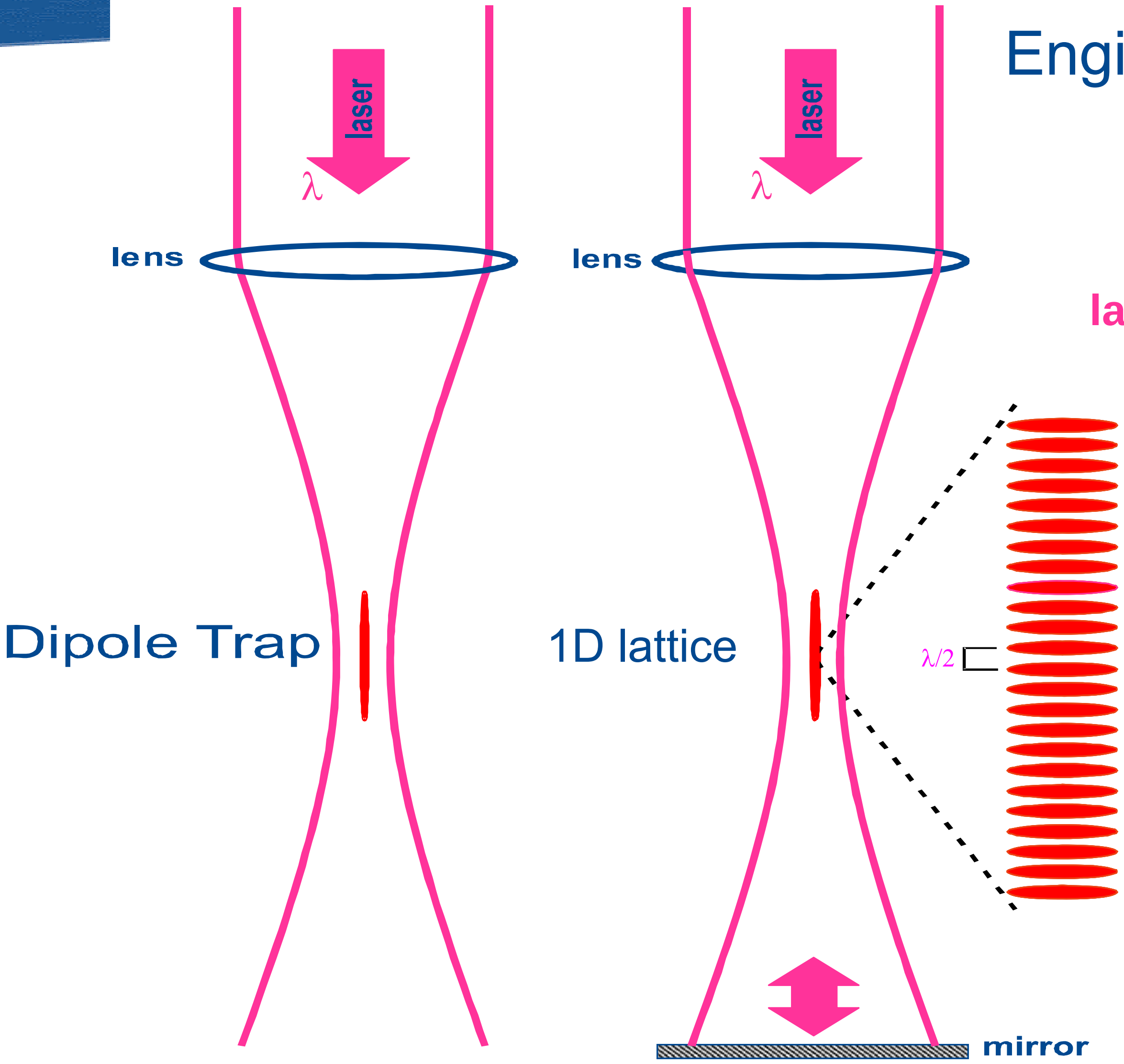




Systematic effects (ballistic expantion):

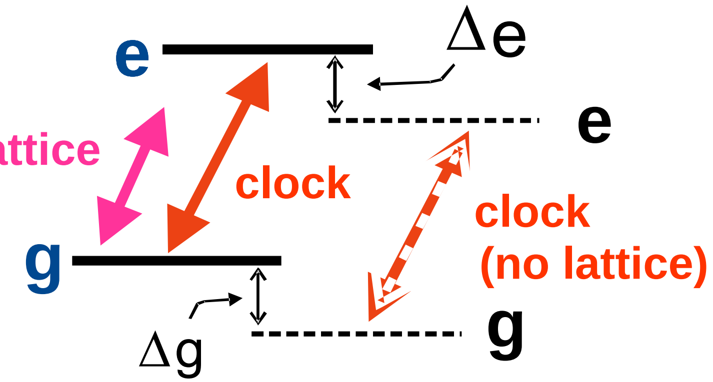
- Velocity-related systematics
- Probe beam overlap and angle
- Blackbody radiation shift

Optical Lattice Clock Revolution!



reflection from mirror
causes interference fringes

Engineered light shift trap



$$\boxed{\Delta g = \Delta e}$$

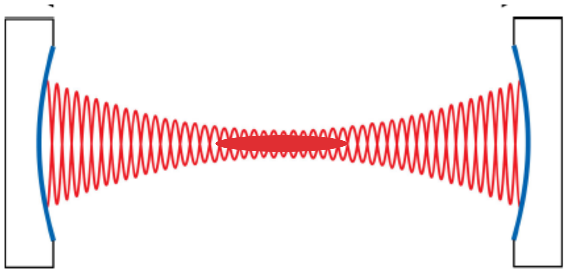
No shift in the clock frequency!

Neutral atom lattice trap optical frequency standards

- Laser-cooled, lattice trapped ensemble of atoms
- High-Q optical clock transitions (10^{15} or higher)
- More perturbative environment than ions, b
  make up for this in signal-to-noise

Lattice trapped atoms have similar properties to trapped ions, but win in stability by ⌦N

* In lattice, eliminate recoil effects (Lamb-Dicke regime)



Systematic effects (lattice trap):

- Polarisation issues with lattice trap
- Collisional shifts
- Blackbody radiation shift

Practical Applications

Space-borne optical clocks will be needed because:

- Precision measurements in space need very good clocks
- Terrestrial clocks will not be good enough

Gravitational effects

Fundamental physics

See e.g. D. Kleppner, “Time Too Good to Be True”,
Physics Today, March 2006

Gravitational Redshift

$$\frac{\nu_1 - \nu_2}{\nu} = \frac{U(r_1) - U(r_2)}{c^2}$$

Problem:

Knowing the distance of the clock from the geoid (gravitational equipotential surface)

- uncertainty at present of 30 – 50 cm
- 3 parts in 10^{17} for present clock experiments
- need 1 cm accuracy for part in 10^{18} measurements

Fundamental problem:

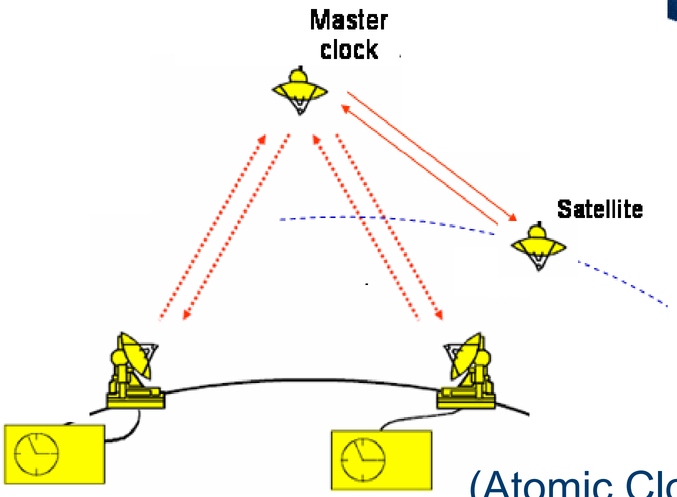
Earth is always changing (solid earth tides, tectonic plate motion, etc.)

Solution:

Optical atomic clock in space

- spatial and temporal variations of Earth's gravity field smooth out
- new, space-referenced timescale possible
- great environment for studies of fundamental physics

Optical “master” clock in space



- Requirement for high accuracy (10^{-18} level) intercomparison of remote ground-based optical clocks
- ACES target of 10^{-16} @ 1 day not sufficient (Atomic Clock Ensemble in Space – Hydrogen Maser + Cs clock on ISS after 2010)
- Common-view comparison via optical master clock
- Geostationary orbit for ease of orbit determination and reduction of tracking requirements
- Altitude determination of master clock to 40 cm required for 10^{-18} accuracy (laser ranging sufficient)
- Also available for fundamental physics (e.g. gravitational redshift), geodesy and as a clock reference for satellites in lower orbits

Fundamental Physics: General Relativity

Einstein Equivalence Principle (EEP)

- Local Lorentz invariance (LLI)
  - -Local measurement independent of velocity of freely- falling reference frame
- Local position invariance (LPI)
  - - Local measurement independent of location and time (non-gravitational experiments)
- Weak equivalence principle (WEP)

$$\frac{\Delta\nu}{\nu} = \frac{\Delta U}{c^2} \rightarrow (1+\beta)\,\frac{\Delta U}{c^2}$$

Consequence of LPI

Universal redshift of clocks

- make absolute gravitational redshift measurements

Violations of EEP?

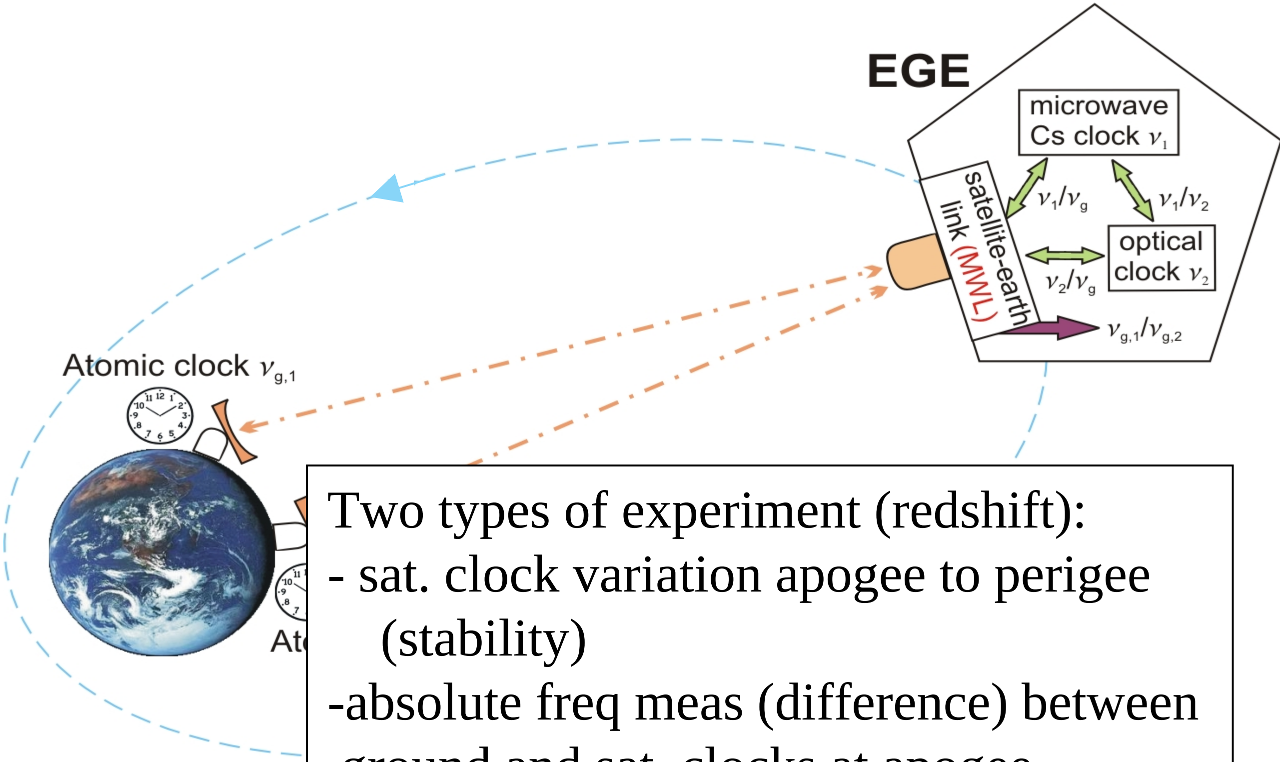
- predicted by theories attempting to unify Gravitation and Quantum Mechanics

Einstein Gravity Explorer

Schiller, Tino, Gill,
Salomon, et al. (2007)

Primary Goals:

- Study space-time structure with high accuracy
- Search for hints of quantum effects in gravity



Two types of experiment (redshift):
- sat. clock variation apogee to perigee (stability)
-absolute freq meas (difference) between ground and sat. clocks at apogee (accuracy)

Local Lorentz invarience:
- large Δ velocity
- measure clock frequencies

- Highly elliptic earth orbit
- 2 atomic clocks on board, one optical, one microwav
- Microwave link (MWL) to earth
- Comparison between on-board and ground clocks (≥2 ground stations)
- Common-view comparisons of ground clocks
- ~ 2 year mission duration

Opportunities for space-based optical clocks

Optical master clock in space

Necessary for intercomparison of ground-based optical clocks

Fundamental physics

Tests of general relativity, e.g. EGE

Geoscience

Direct measurement of earth's geopotential with high resolution

Tracking tectonic plate movement

Navigation

Upgrade of GPS/Galileo to optical clocks

VLBI

Very Long Baseline interferometry (LISA gravity wave detection)

VLA

Very Large (telescope) Arrays (Radio astronomy – timing)

Deep space missions

Communications

The better the clock, the longer the list….

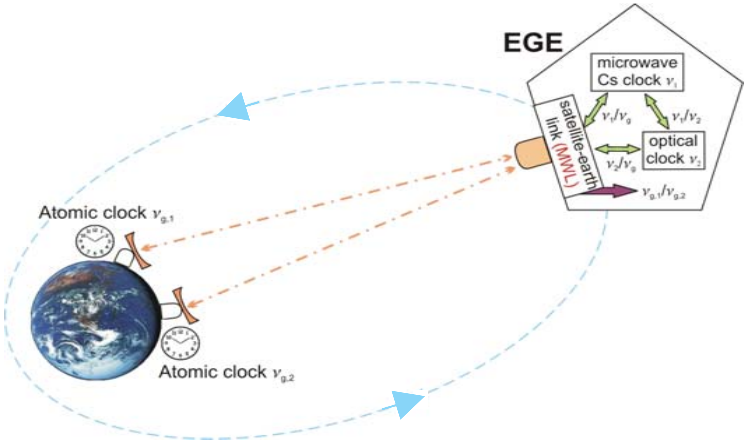
Tests of general relativity: gravitational redshift

Frequency shift

$$Z \equiv \frac{\Delta f}{f} = (1 + \alpha')\frac{\Delta U}{c^2}$$

non-zero if local position invariance is not valid

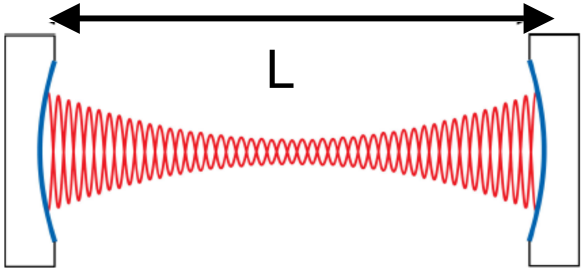
Tested at the 70 ppm level by Gravity Probe A (comparison of ground and space-borne hydrogen masers).



Proposed Einstein Gravity Explorer (EGE) mission (including an optical clock) would provide a test at the 25 ppb level.

Class M Cosmic Vision proposal:
Schiller, Tino, Gill, Salomon *et al*. (2007)

Optical Cavities
- laser stabilisation

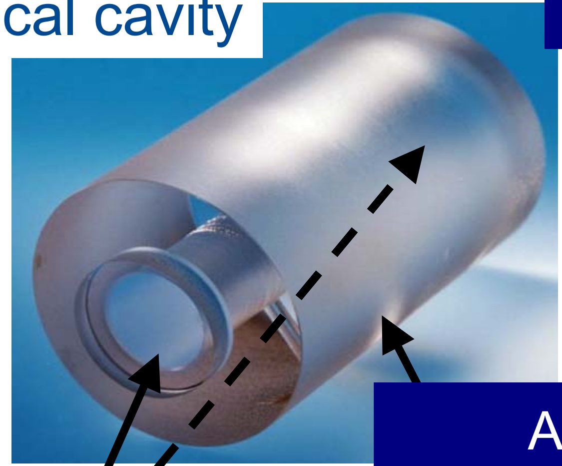


Resonance frequencies

$f_n = nc/2L$

Clock linewidths can be < 1 Hz!

Typical cavity



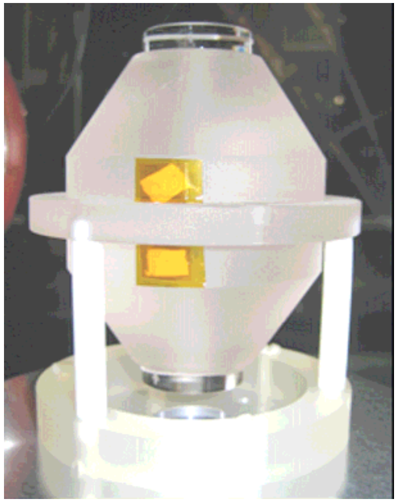
High reflectivity mirrors (>99.99%)

Ultra-low expansion material (ULE)

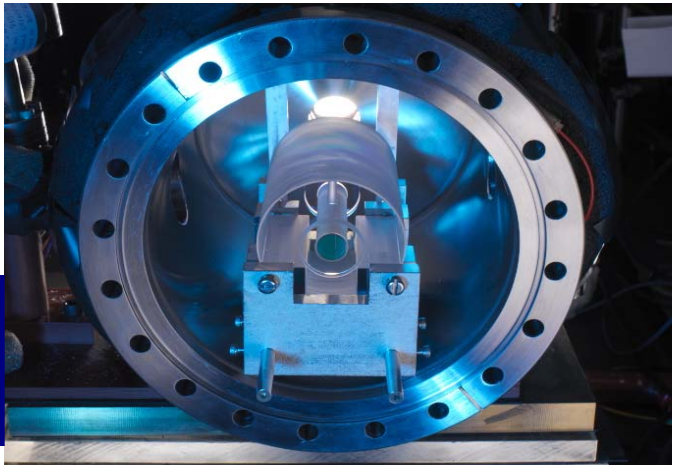
Linewidth = c/(2LF)
where the Finesse, F
Is directly related to
the mirror reflectivity

At optical frequencies:
$\Delta\nu$ of 1Hz = 2 <u>fm</u> change in L

New designs:

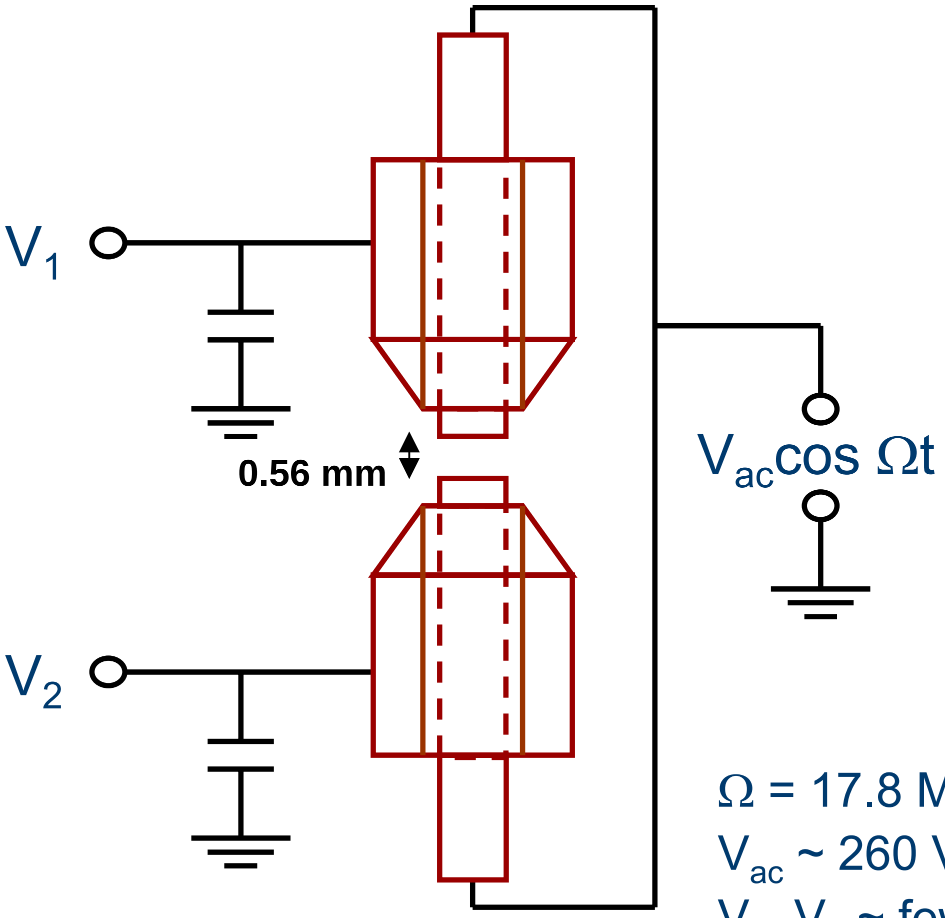


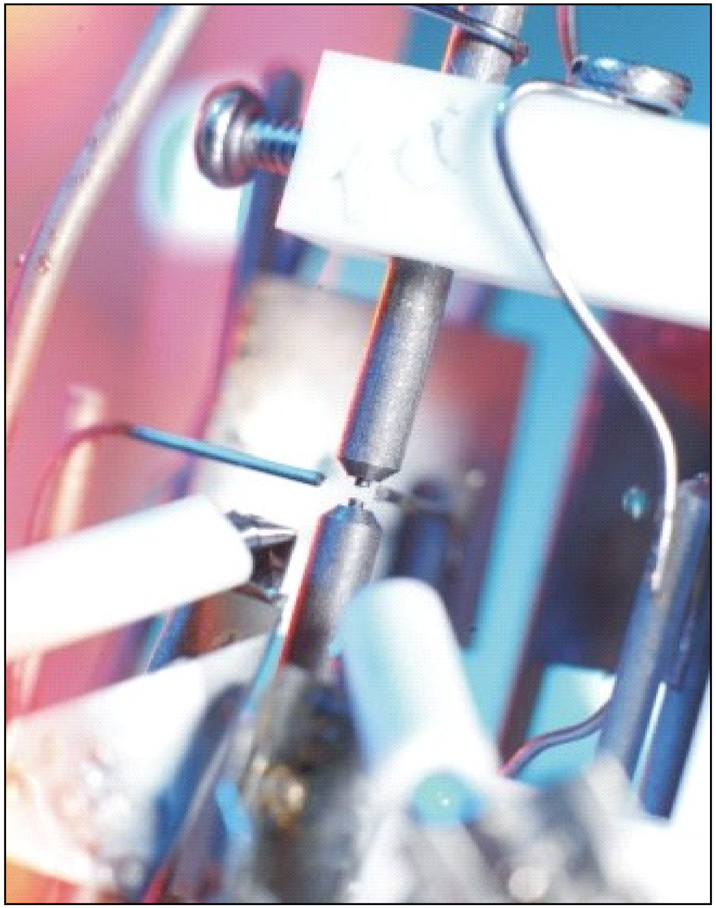
JILA vertical cavity
(Notcutt, *et al.*)
"Compact, thermal-noise-limited optical cavity for diode laser stabilization at 1 x 10^{-15},"
Ludlow, *et al.*,
Optics Letters 32, 641-643 (2007).



NPL cut-out cavity (Webster, *et al.*)
"Vibration insensitive optical cavity,"
Webster, *et al.*, Phys. Rev. A 75, 011801(R) (2007).

NPL strontium ion trap





Ω = 17.8 MHz

V_{ac} ~ 260 V

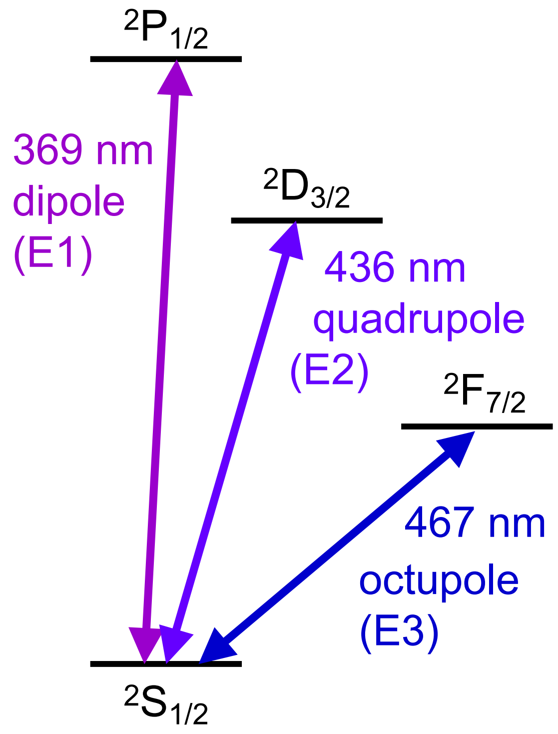
V_1, V_2 ~ few V

Time variation of the fine structure constant

Sensitivity of time variation of the fine structure constant α for various transitions is given by S, where

$$\frac{\dot{\nu}}{\nu} = S\,\frac{\dot{\alpha}}{\alpha}$$

Ion or atom	Clock transition	*S*
Sr^+	${}^2S_{1/2} - {}^2D_{5/2}$	0.43
Yb^+	${}^2S_{1/2} - {}^2D_{3/2}$	0.88
Yb^+	${}^2S_{1/2} - {}^2F_{7/2}$	− 5.30
Hg^+	${}^2S_{1/2} - {}^2D_{5/2}$	− 3.19
In^+	${}^1S_0 - {}^3P_0$	0.18
Al^+	${}^1S_0 - {}^3P_0$	0.008
Ca	${}^1S_0 - {}^3P_1$	0.02
Sr	${}^1S_0 - {}^3P_0$	0.06
Yb	${}^1S_0 - {}^3P_0$	0.31
Hg	${}^1S_0 - {}^3P_0$	0.81

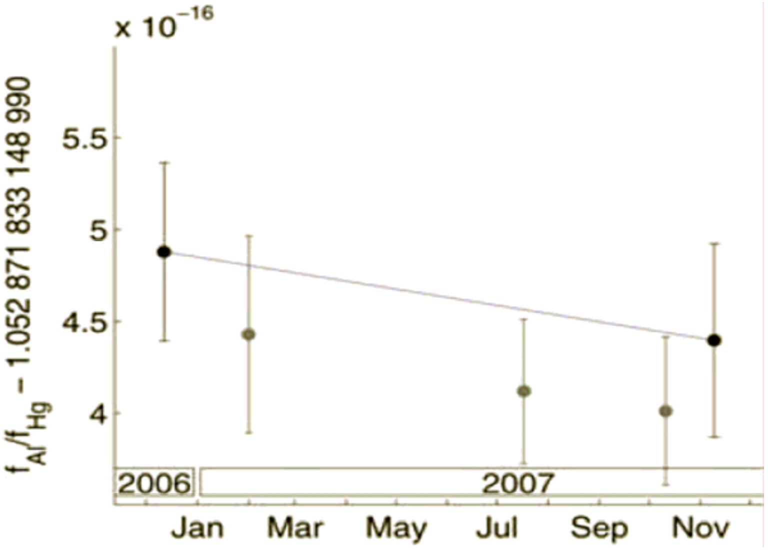


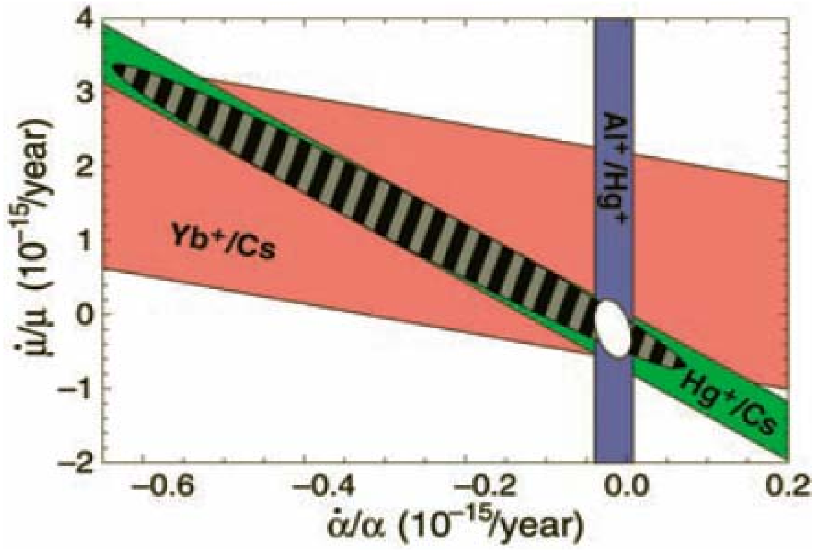
Ratio of 435 nm quadrupole and 467 nm octupole transition frequencies in $^{171}Yb^+$ has a total sensitivity $S = 6.2$

Status of laboratory tests

Comparison between $^{199}\mathrm{Hg}^+$ and $^{27}\mathrm{Al}^+$ standards over 1 year:

$$\frac{\dot{\alpha}}{\alpha} = (-1.6 \pm 2.3) \times 10^{-17} \text{ / year}$$



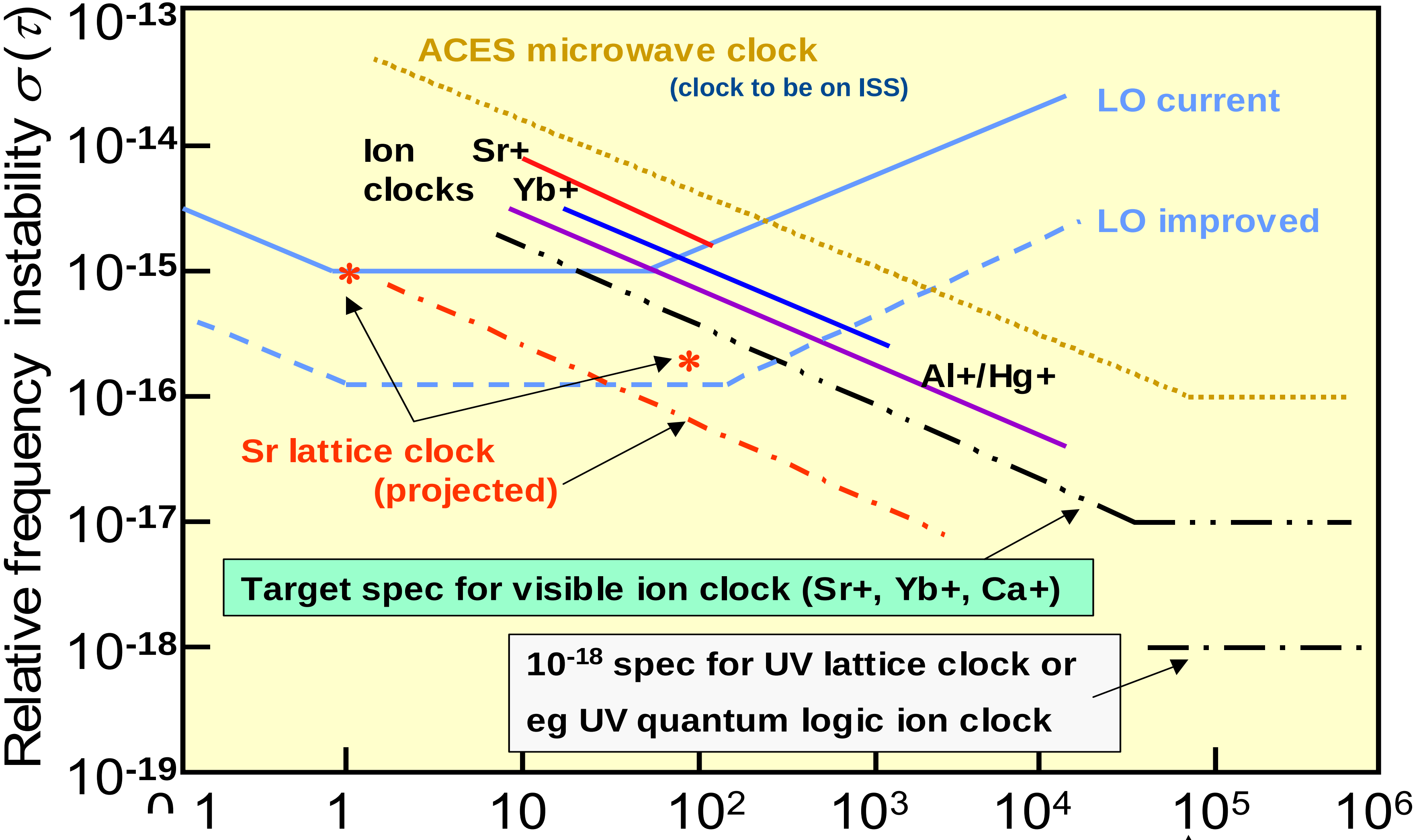


Rosenband *et al*., Science 319, 1808 (2008)

Yb$^+$ after 1 year:

$$\frac{\dot{\alpha}}{\alpha} < \frac{\Delta\nu}{\nu} \sim 2 \times 10^{-18}\,\text{year}^{-1}$$

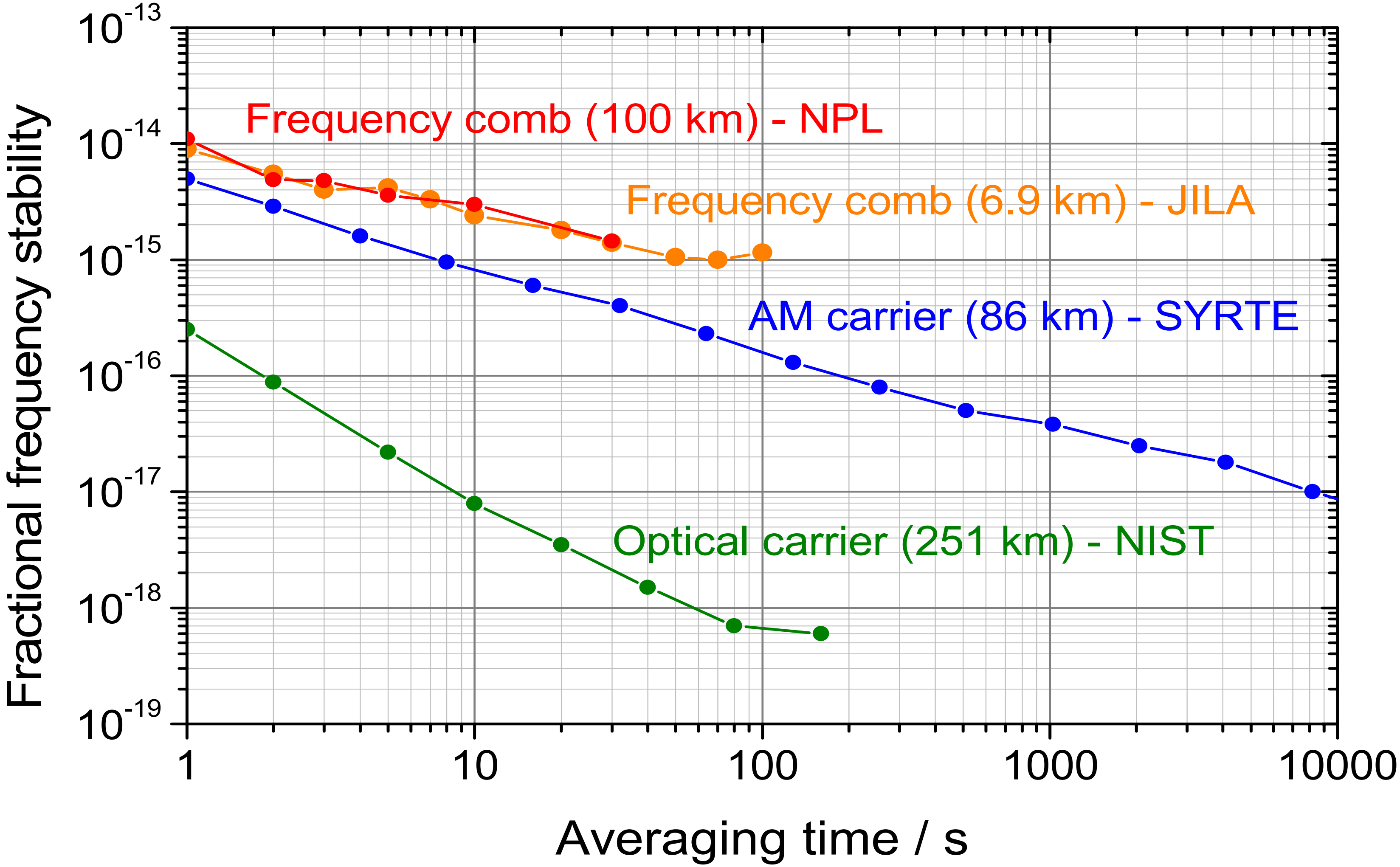
Optical clock current performance & target specification



How can we send this time to others?

1 day

Optical clock comparison: state of the art

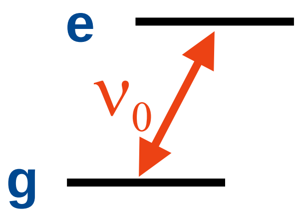


Challenge:

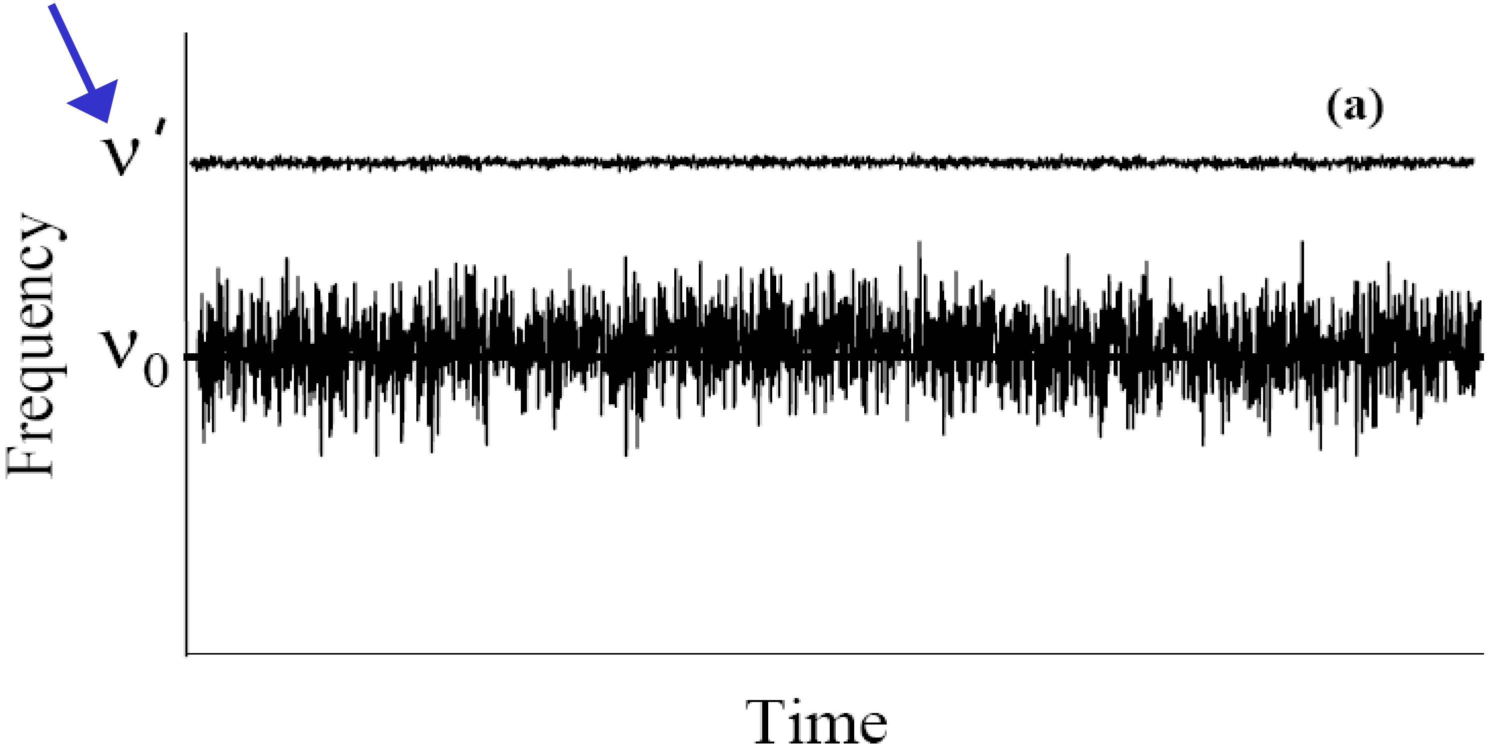
comparison over longer distances.

Stability vs. Accuracy

Trying to measure frequency ν_0



What causes this deviation?



Accuracy: Evaluation of systematic uncertainties

Stability: Evaluation of frequency fluctuations over time