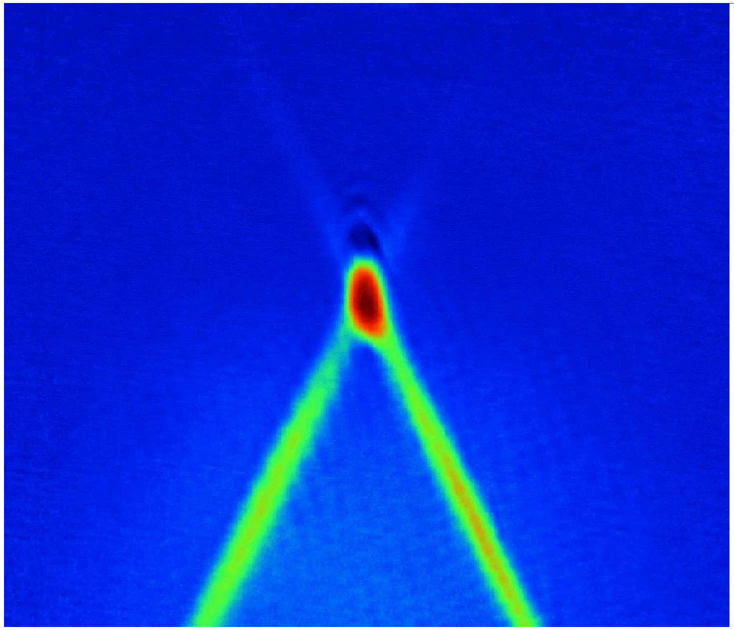
Optical Clocks at 10^{-18} accuracy: challenges and applications



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Physique quantique et applications

CGPM 2022, Versailles, November 17, 2022

An Adage !

Never measure anything but frequency !

Arthur Schawlow advice to his students at Stanford

1981 Nobel prize laureate

Clock concept

Find a periodic phenomenon

1) Nature:

observation: Earth rotation, pulsars,…

2) Human realization: example Galileo pendulum

simple phenomenon described by a small number of parameters

$$T = 2\pi\sqrt{l/g}$$

Counting oscillations !

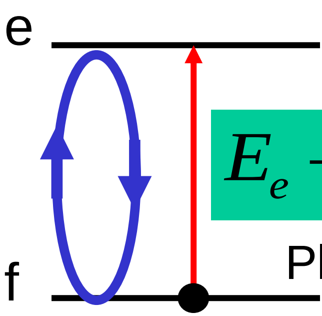
The shorter the period, the better is the precision of a time interval measurement

3) Optical clocks use electromagnetic signals oscillating with 10^{15} cycles per second.

The physical signal is locked onto an atomic transtion

Atomic Clock

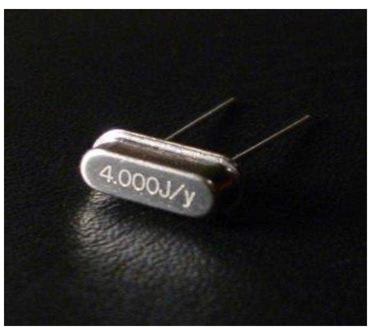
Atom



$$E_e - E_f = h\nu_A$$

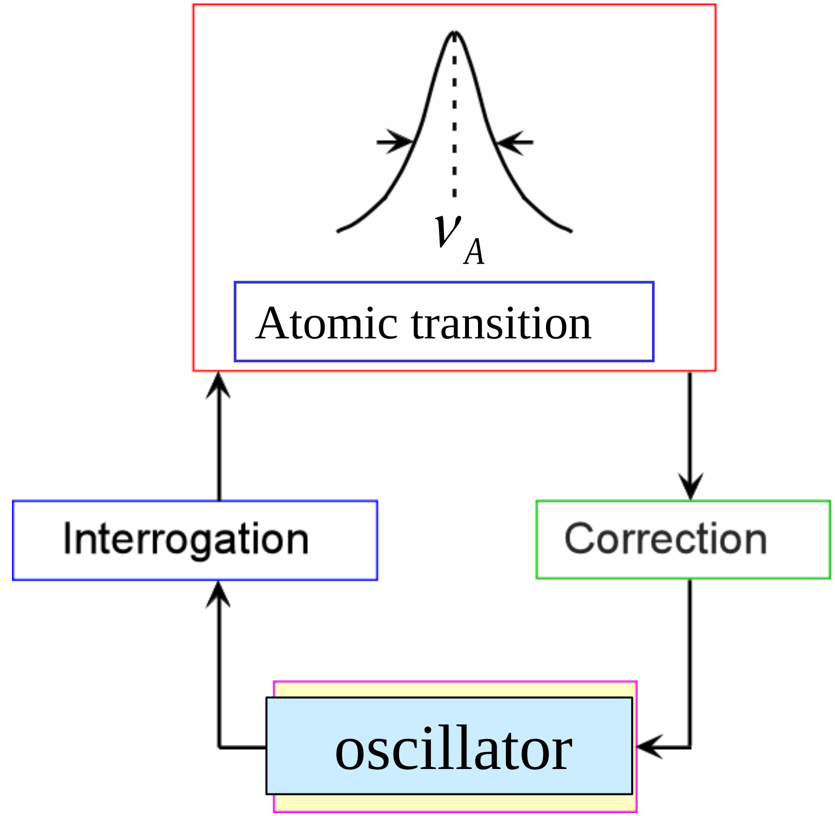
Planck-Einstein

Oscillator



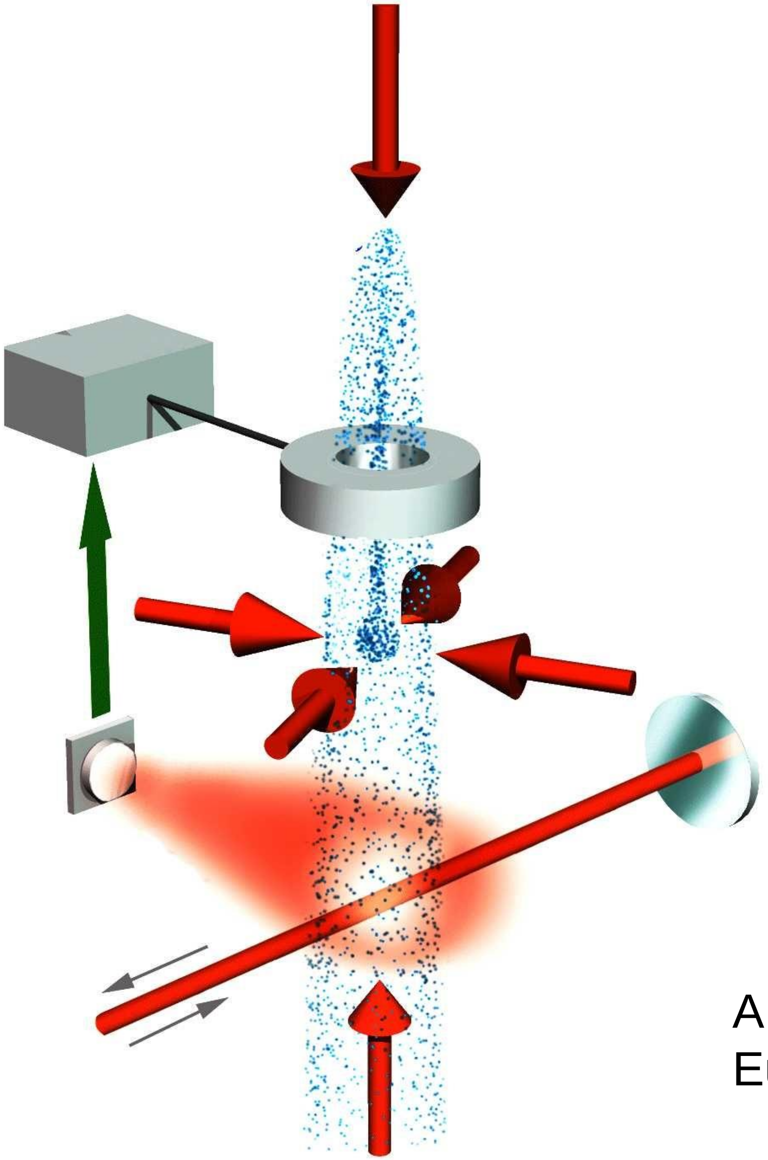
Quartz

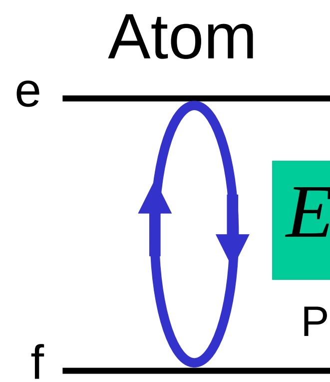
Laser



The oscillator of frequency ν is locked to the frequency ν_A of a transition between two energy levels in an atom

Current definition of the second: Cesium atomic fountain





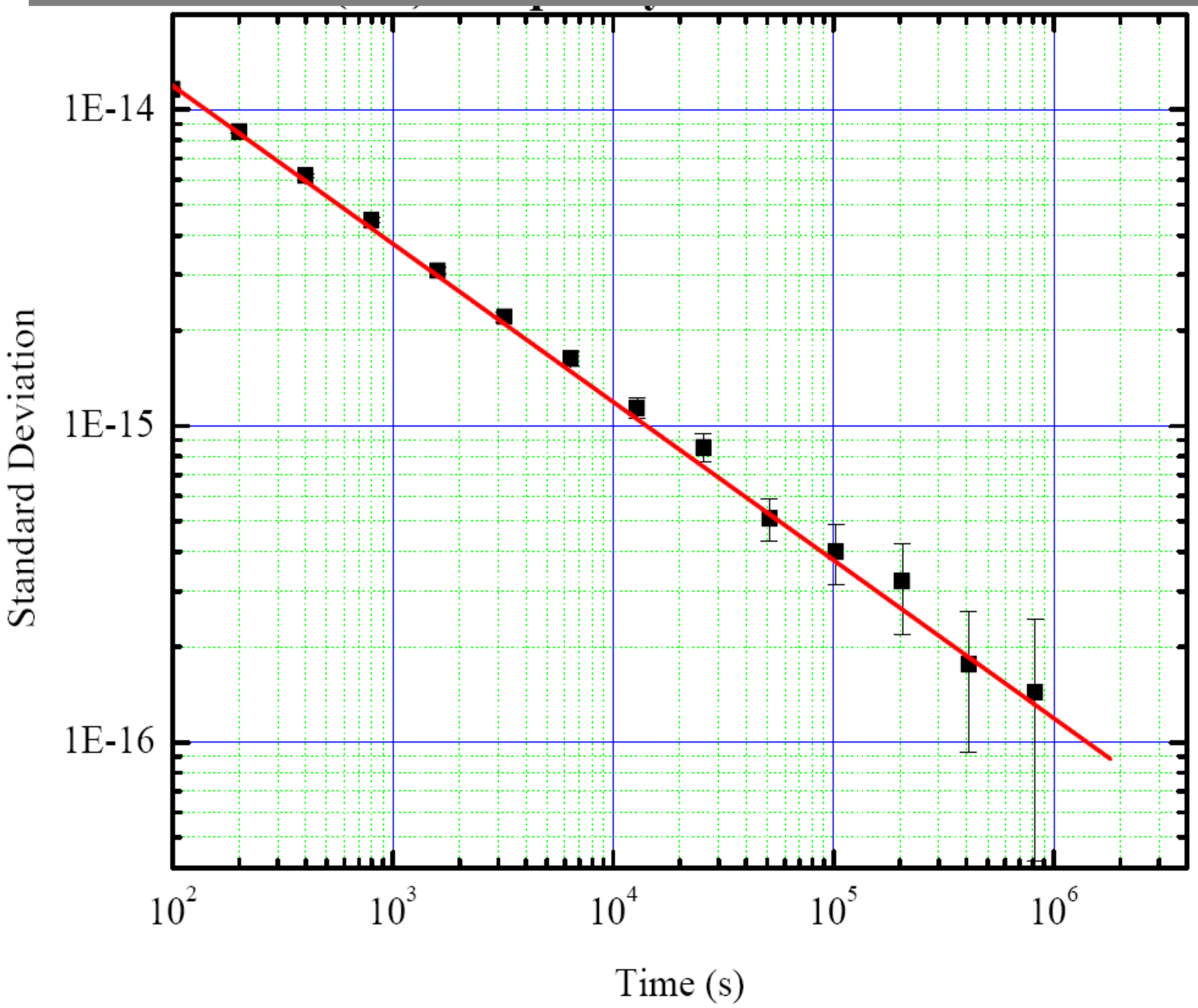
$$E_e - E_f = h\nu_A$$

Planck –Einstein relation

Hyperfine transition at 9.2 GHz
Atoms at 1 microKelvin

A. Clairon, C. Salomon, S. Guellati, W. Phillips, Europhys. Lett., **16** (1991)

Comparison between two fountains Paris Observatory



S. Bize
et al.
EFTF'08
J. Phys. B 2005
SYRTE

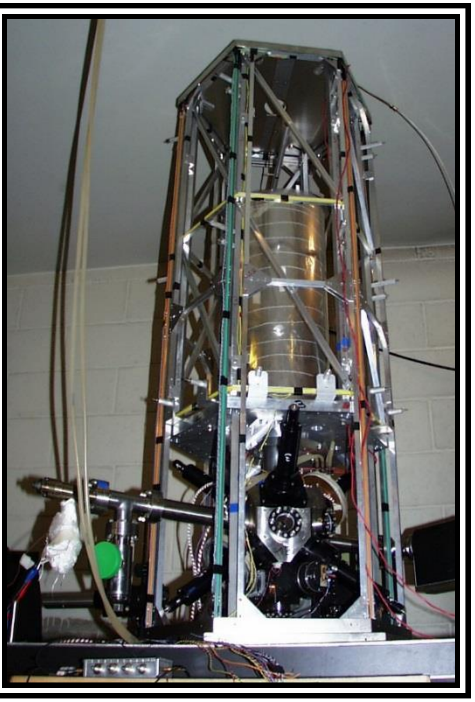
1 m of gravitational shift

Frequency stability at 10^{-16} after 5 to10 days of averaging

Accuracy: agreement between the cesium frequencies: 2 10^{-16}

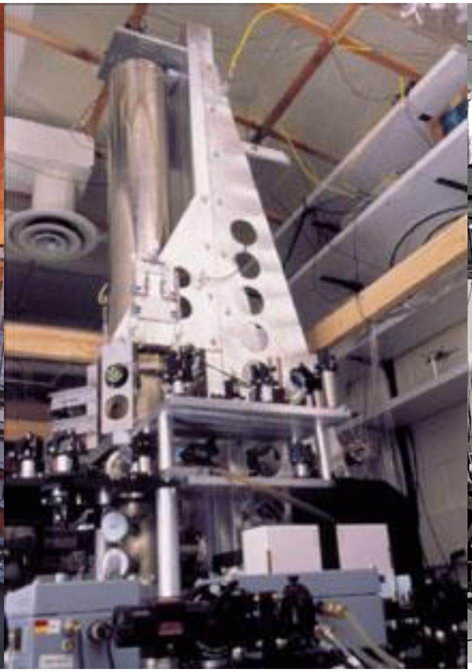
Fountains and Temps Atomique International

~ 12 fountains in the world are compared by GPS and optical fibers.
Steer TAI computed by BIPM with an accuracy of 2 10^{-16}



LNE-SYRTE, FR

PTB, D



NIST, USA

INRIM, IT

Clock Figure of Merit

- Frequency: ν
- Resonance width and interaction time T
  $\Delta\nu = 1/2T$
- Signal to Noise ratio: $S/N \sim N_{at}^{1/2}$

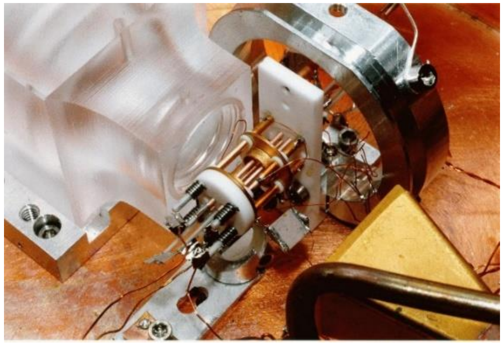
$$\mathcal{F} = \nu / \Delta\nu \times S/N = 2\,\nu\,T\,S/N$$

Microwave cesium fountain: $\mathcal{F} = 2\ 10^{10} \times 0.5 \times 5000 = 5\ 10^{13}$

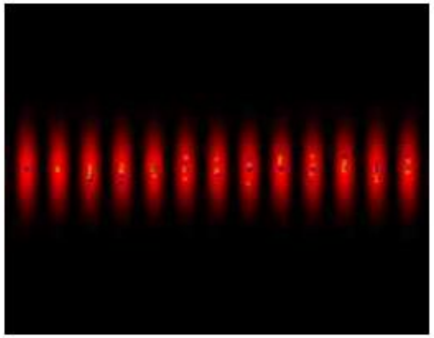
Optical clocks: $\mathcal{F} = 2\ 5\ 10^{14} \times 1 \times 100 = 5\ 10^{17}$

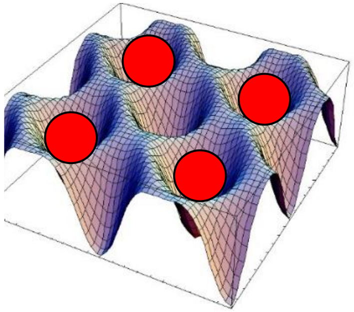
Trapped ion

Al^+, Yb^+, Hg^+, Ca^+, Lu^+,…..



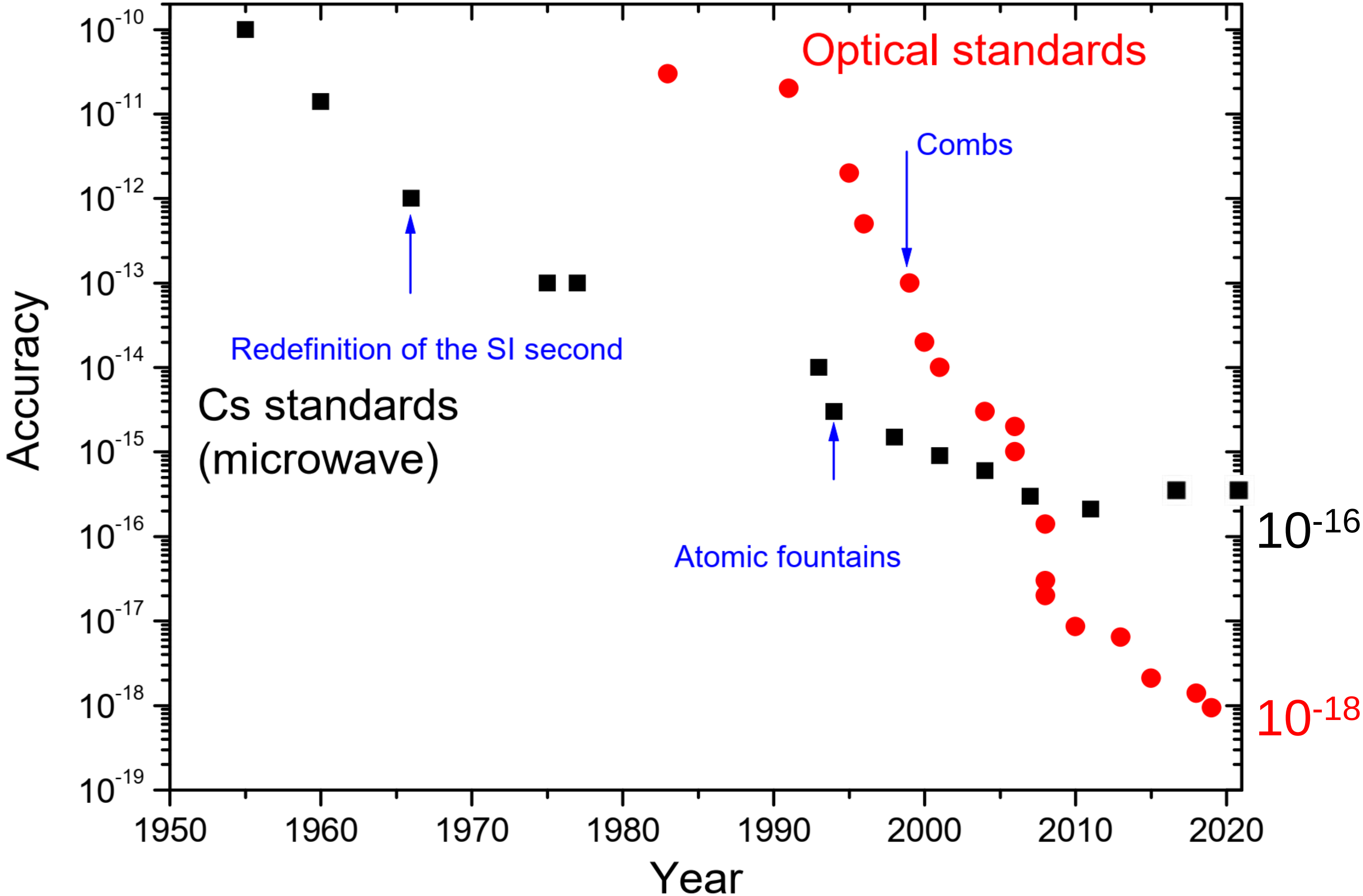
Neutral atoms Sr, Yb, Hg, Ca, Cd



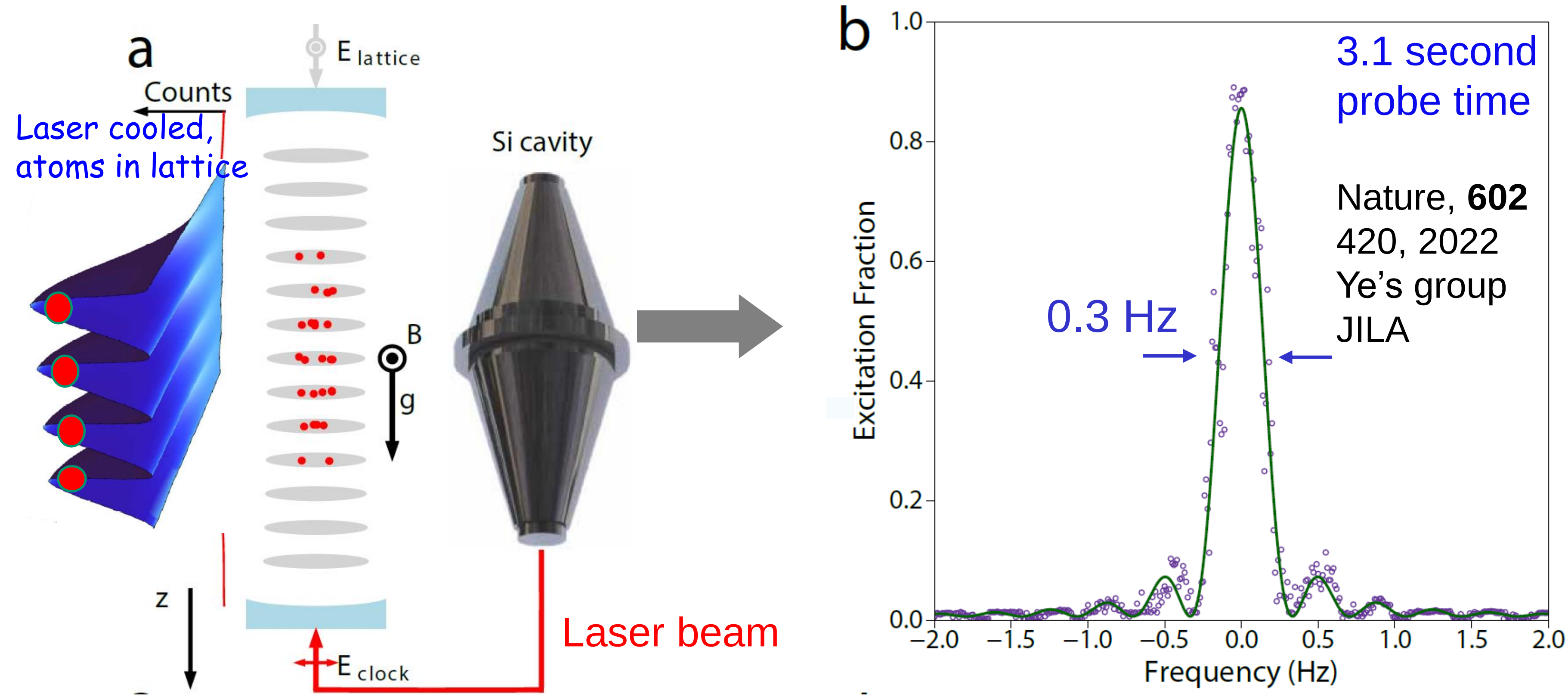


NIST, PTB, NPL, SYRTE, NPL, RIKEN, NICT, Innsbruck, Seoul, Singapore,….

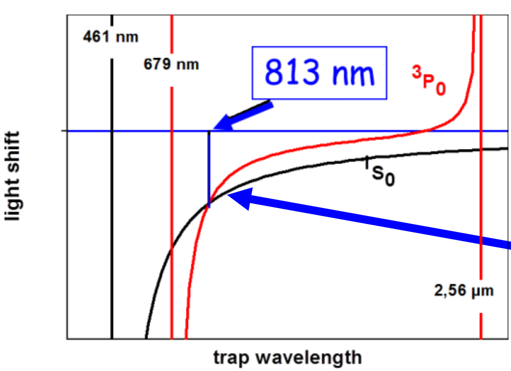
Optical Clocks surpass cesium clocks by two orders of magnitude



^{87}Strontium Optical Clocks

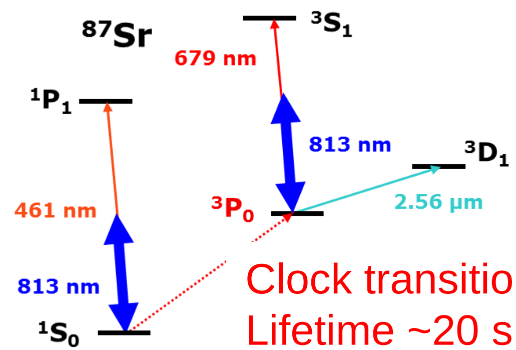


Non-perturbing lattice trap at magic wavelength: light shift of the clock transition vanishes



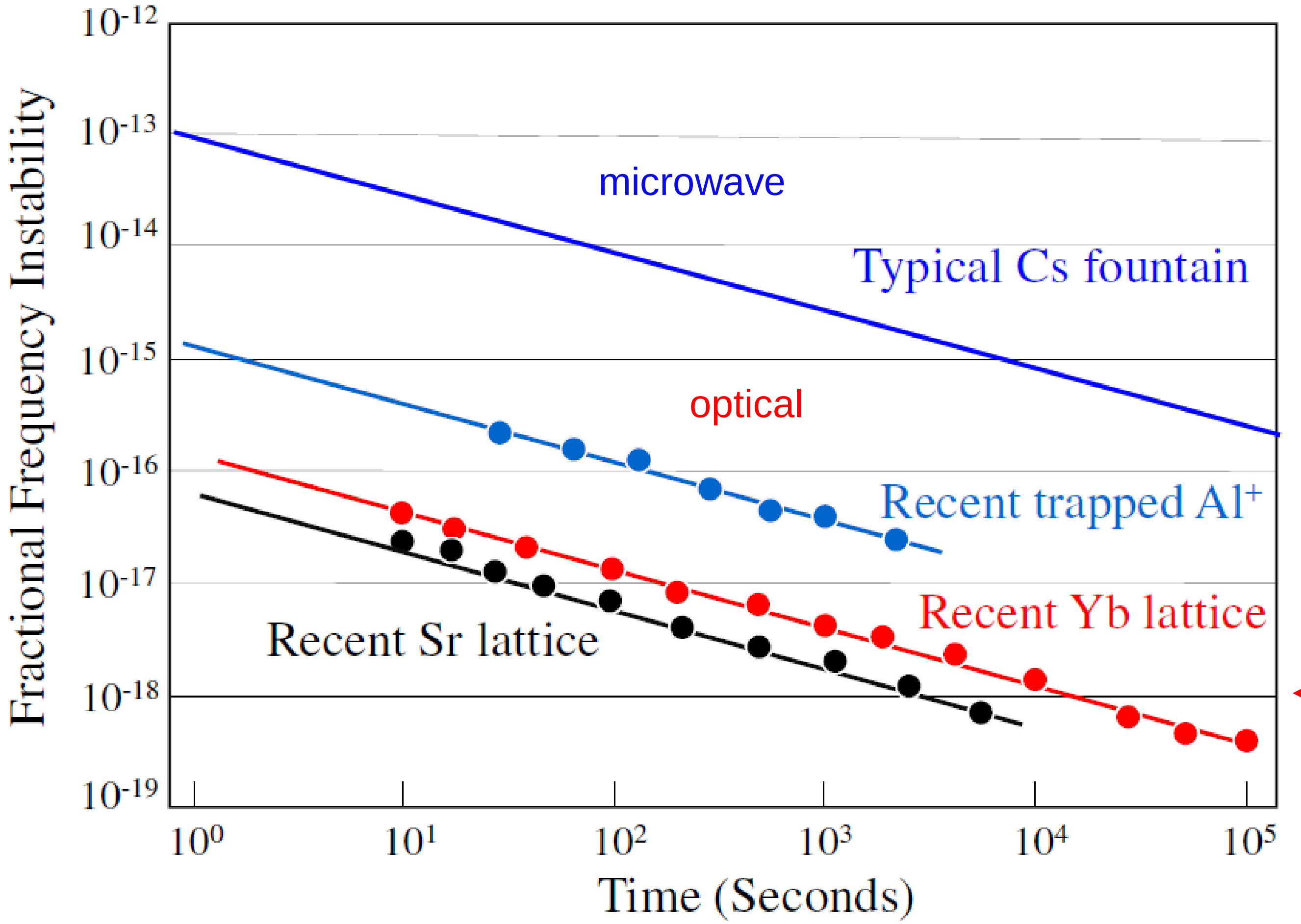
Magic wavelength λ_{magic}: polarizabilities are equal for both clock states

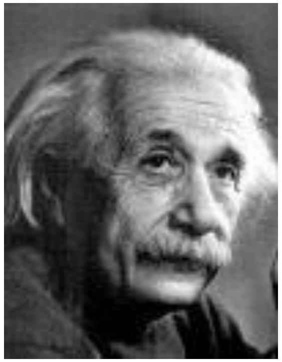
H. *Katori, PRL (2003)*



Clock transition: 698 nm
Lifetime ~20 s

Frequency Stability of Optical Atomic Clocks



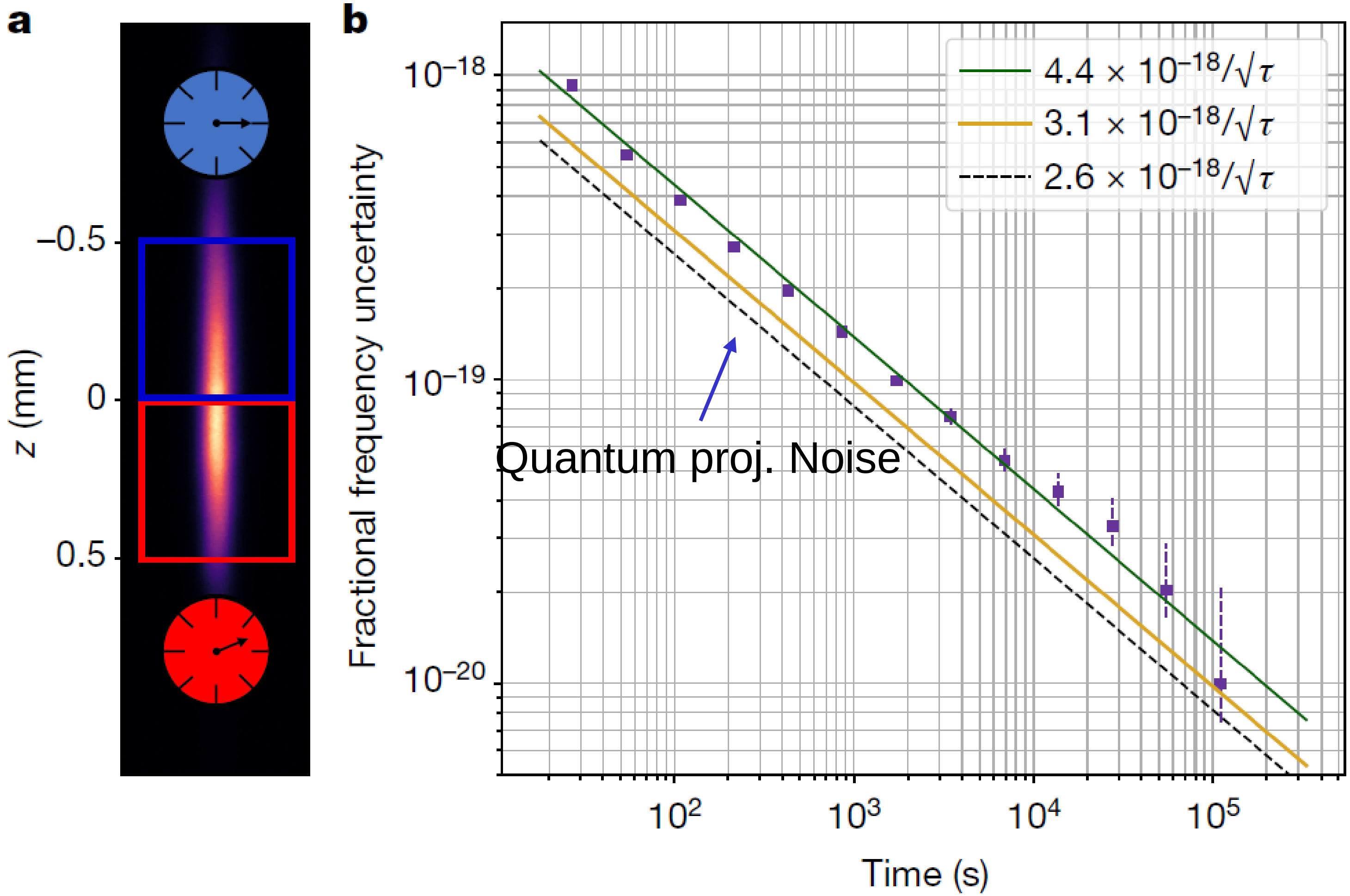


1 cm of gravitational red shift

Applications in Earth geodesy

Graph from C. Oates, NIST, Oct '19

JILA ^{87}Sr OLC: measuring the differential gravitational shift over 1 mm sample



T. Bothwell,… J. Ye, JILA, Nature, 602 420, 2022

Two trap areas on same image: laser noise is common mode

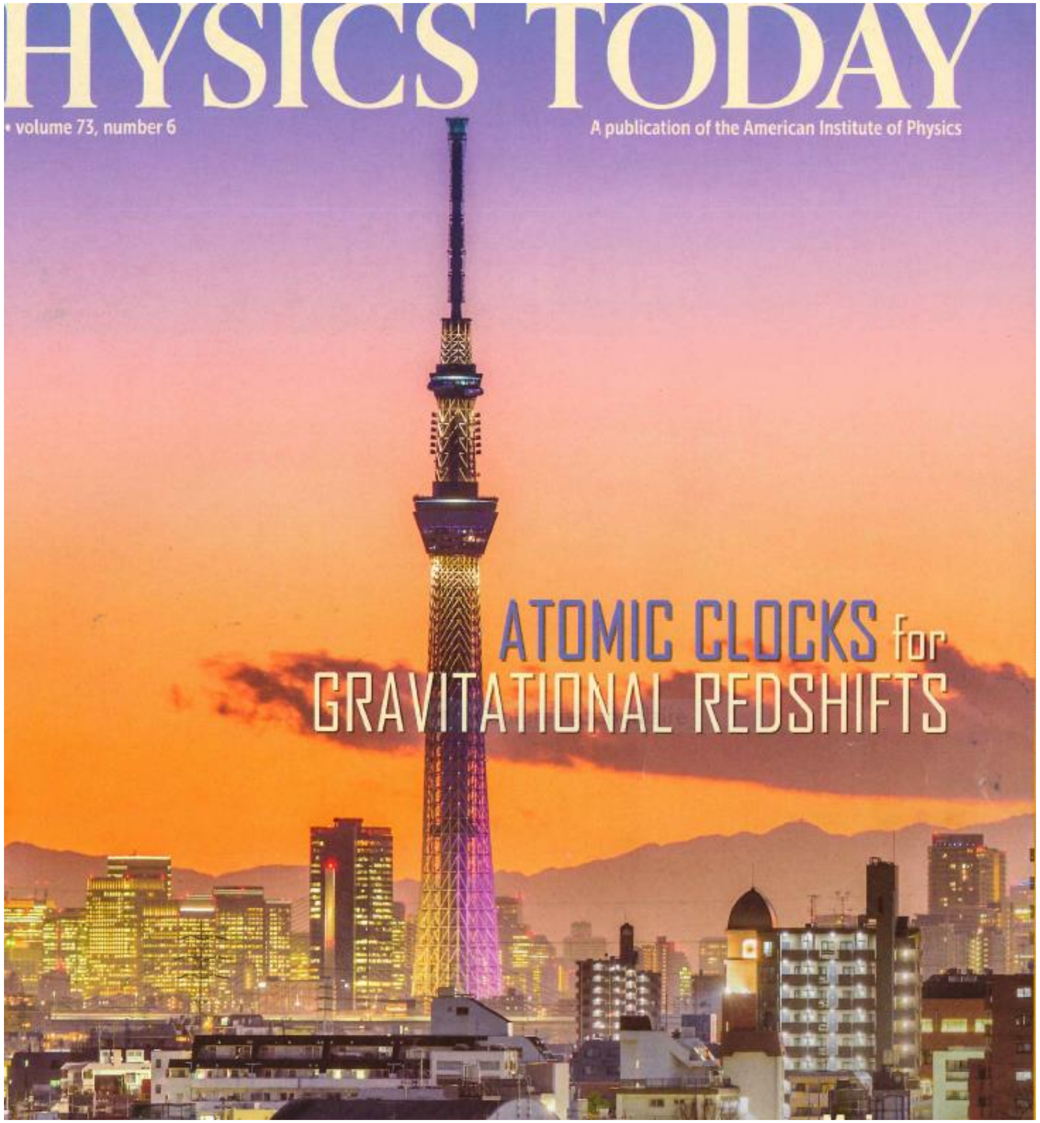
Differential sensibility: 4.4 10^{-18} @1s et 1 10^{-19} @2000 s

Testing the Einstein effect with transportable optical clocks

$$\frac{\nu_2}{\nu_1} = \left(1 + \frac{U_2 - U_1}{c^2}\right)$$

Tokyo skytree
450 m radio tower

Katori et al., 2020

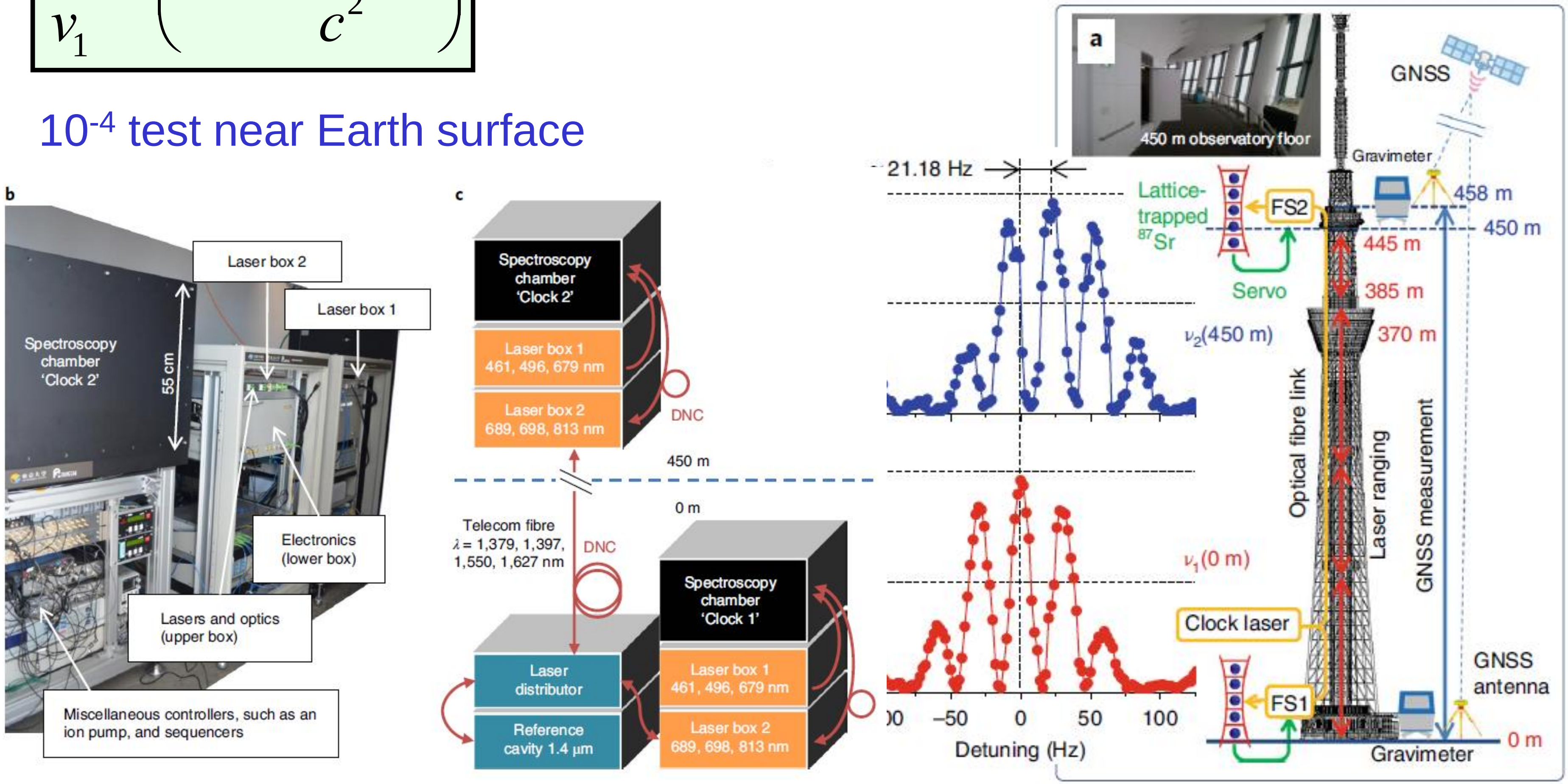


Testing the Einstein effect with transportable optical clocks

$$\frac{\nu_2}{\nu_1} = \left(1 + \frac{U_2 - U_1}{c^2}\right)$$

NATURE PHOTONICS Katori, 2020

10^{-4} test near Earth surface



Quantum metrology: towards Heisenberg limit

The signal to noise ratio in fountains and OL clocks is at the quantum projection noise:
Uncorretaled atoms: frequency instability scales as $1/N^{1/2}$

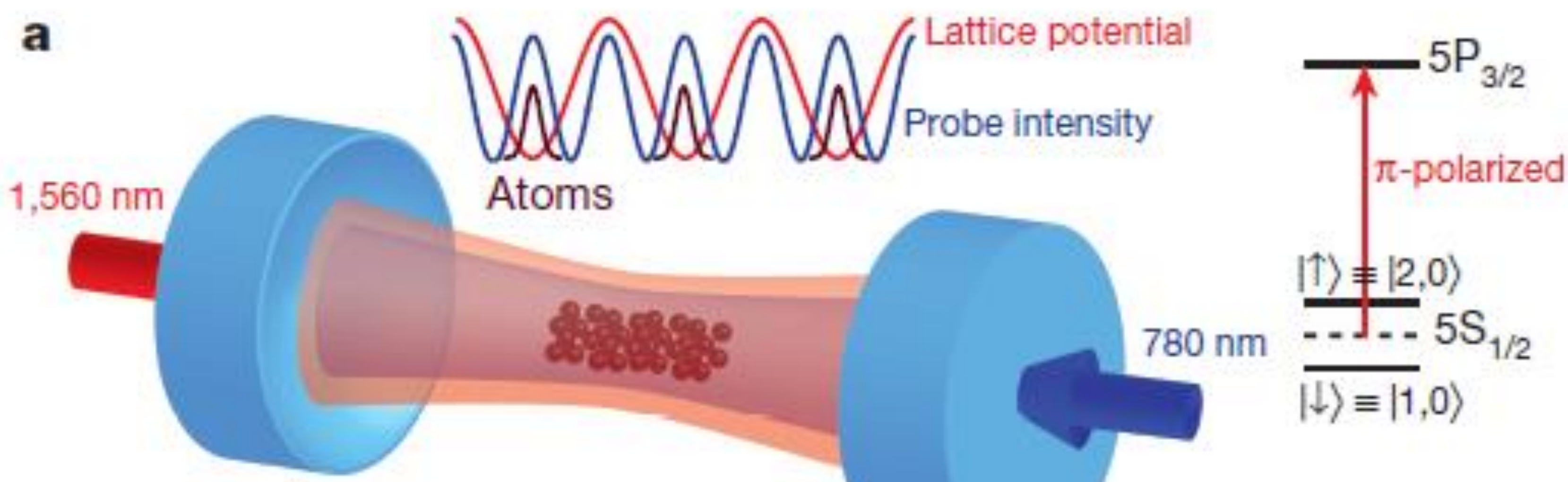
N two-level atoms: spin ½ ensemble forming a collective spin $|J| = N/2$

$$\Delta J_z . \Delta J_y \geq |J_x / 2|$$

Spin squeezing: reduce variance in one direction, useful for measurement sensitivity
Kitagawa et Ueda, 1993, Wineland et al. 1994, approach $1/N$

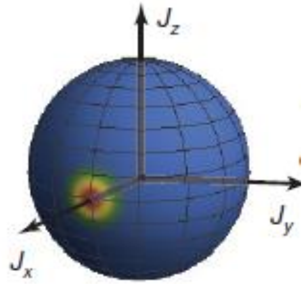
LETTER Nature 2016

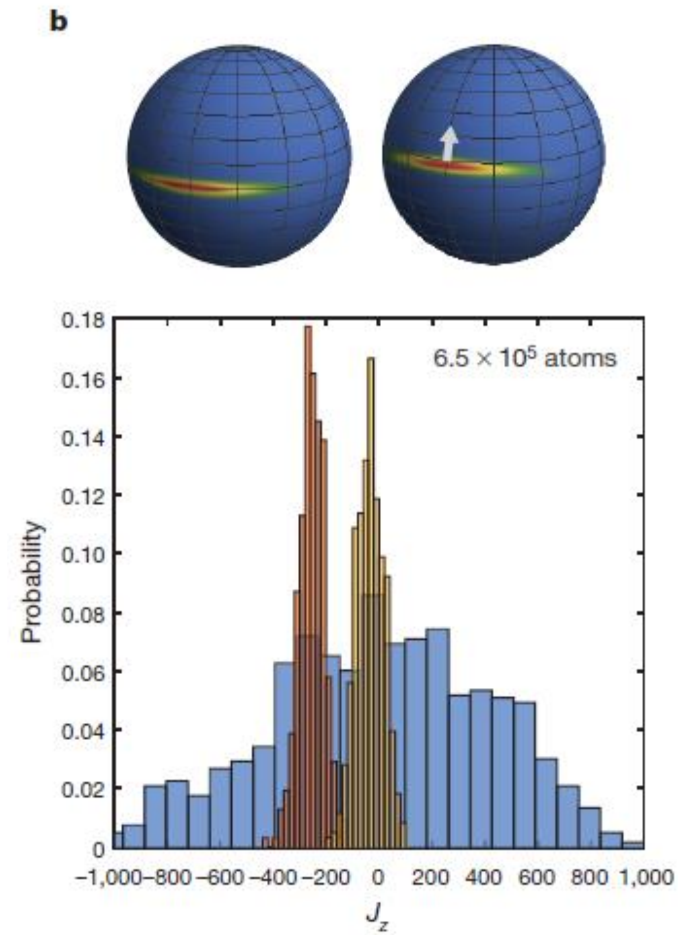
doi:10.1038/nature16176



Non destructive measurement of index of refraction of atoms in cavity mode: J_z

Quantum metrology

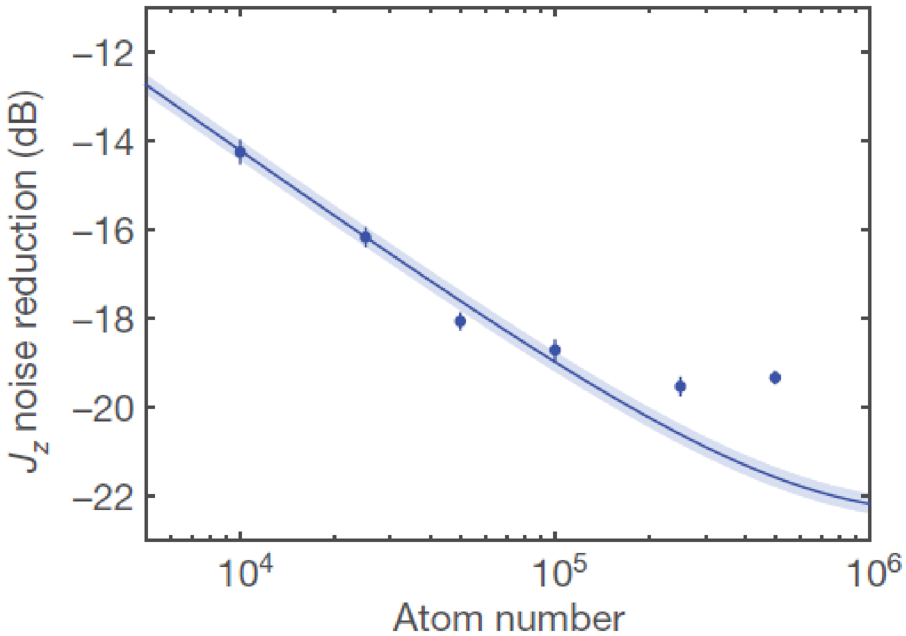




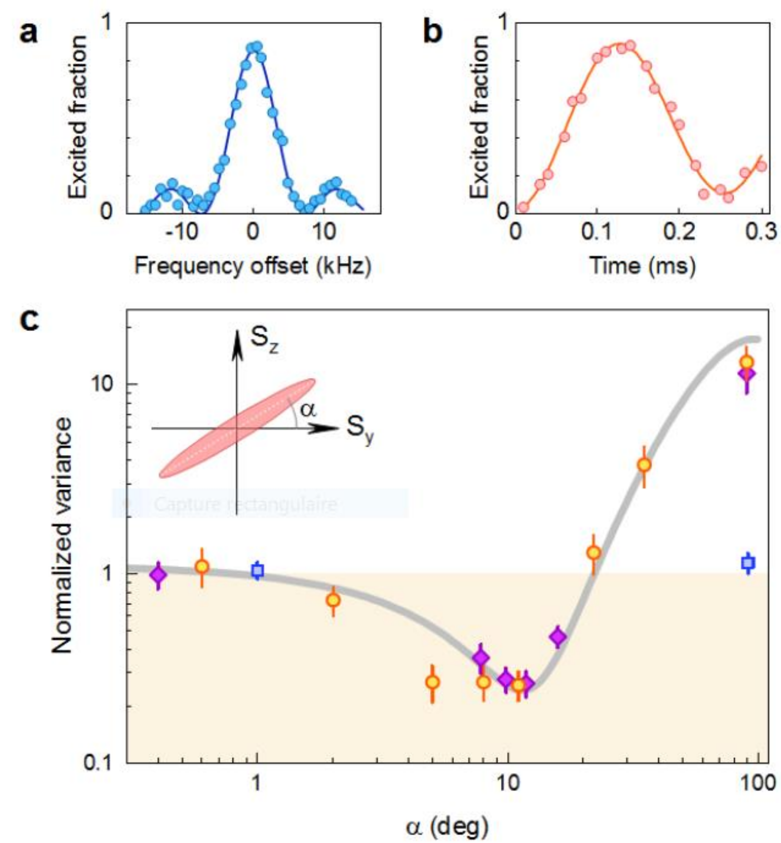
Rotation of 660 μrad

Gain in signal to noise : factor 10 for 5 10^5 atoms
Phase sensitivity: 147 microradians per cycle
This implies that at least 680 particles are entangled

20 dB noise reduction on variance
Towards an optical clock with correlated atoms



Entanglement-Enhanced ^{171}Yb Optical Atomic Clock
Nature , **588**, 414 (2020)



The current challenge: increase interaction time beyond 228 μs while preserving quantum correlations

Vuletic, MIT Metrological gain:4.4 dB

Perspectives 1

Optical clocks surpass microwave clocks by two orders of magnitude. They have daily fluctuations ~ 0.1 - 1 picosecond. New definition of the second is required.

3 options:

- One atomic species
- A combination of atomic transitions

See J. Lodewyck, Metrologia 56, 055009 (2019)

- Fixing another fundamental constant such as electron mass

See presentation of draft resolution E
by N. Dimarcq

Perspectives 2

1) Optical fiber links and frequency combs enable *continental* optical clock comparisons at adequate level. Satellite missions like ACES will enable in 2025 *intercontinental* clock comparisons at 10^{-17} -10^{-18}.

2) Einstein effect: a new relativistic geodesy with optical clocks.

3) Earth potential fluctuations will limit the precision of time on ground at 10^{-18}-10^{-19} (ie. cm - mm). Solution: have reference clock(s) in high Earth orbit where fluctuations are reduced.

4) Quantum Metrology will improve clock performance through quantum correlations.