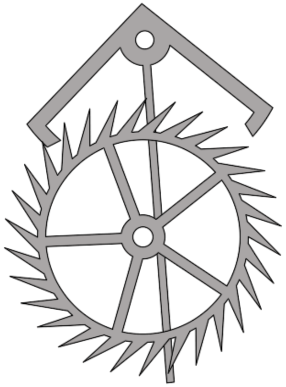
Optical Atomic Clocks

David Hanneke

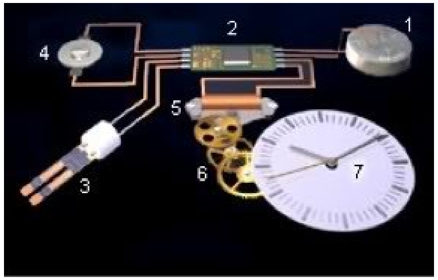
Michelson Postdoctoral Prize Lectures
11 May 2010

What is a clock?

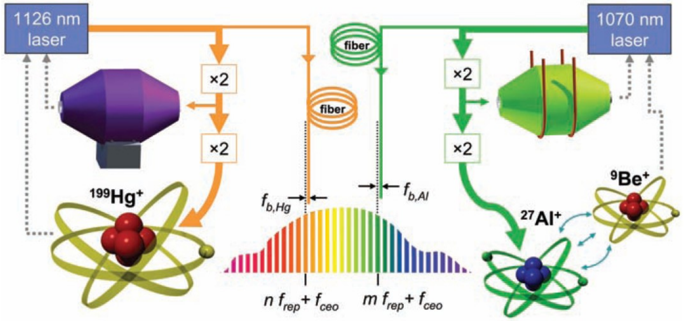
	Ticker	Counter
Earth's orbit	1 yr $^{-1}$ ≈ 32 nHz	Calendar
Pendulum clock	1 Hz	Escapement, gears
Quartz watch	32 768 Hz = 2^{15} Hz	Microchip
Optical atomic clock	1 PHz = 10^{15} Hz	Frequency comb



http://en.wikipedia.org/wiki/File:Scappamento.gif



http://www.fhs.ch/en/work.php

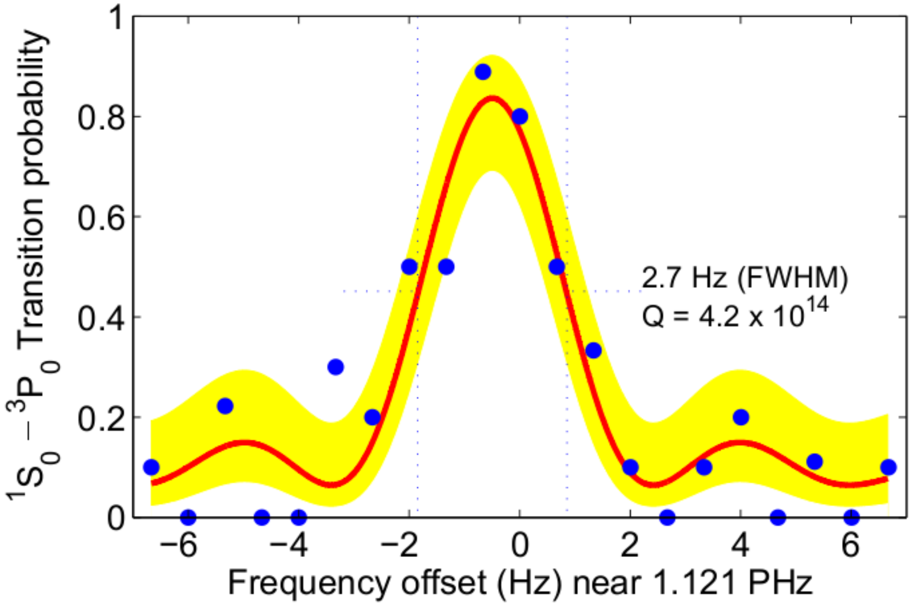


T. Rosenband, *et al.*, *Science* **319** 1808 (2008)

What makes a good clock?

$$\sigma \propto \frac{\Delta\nu}{\nu_0} \frac{1}{\mathrm{S/N}}$$

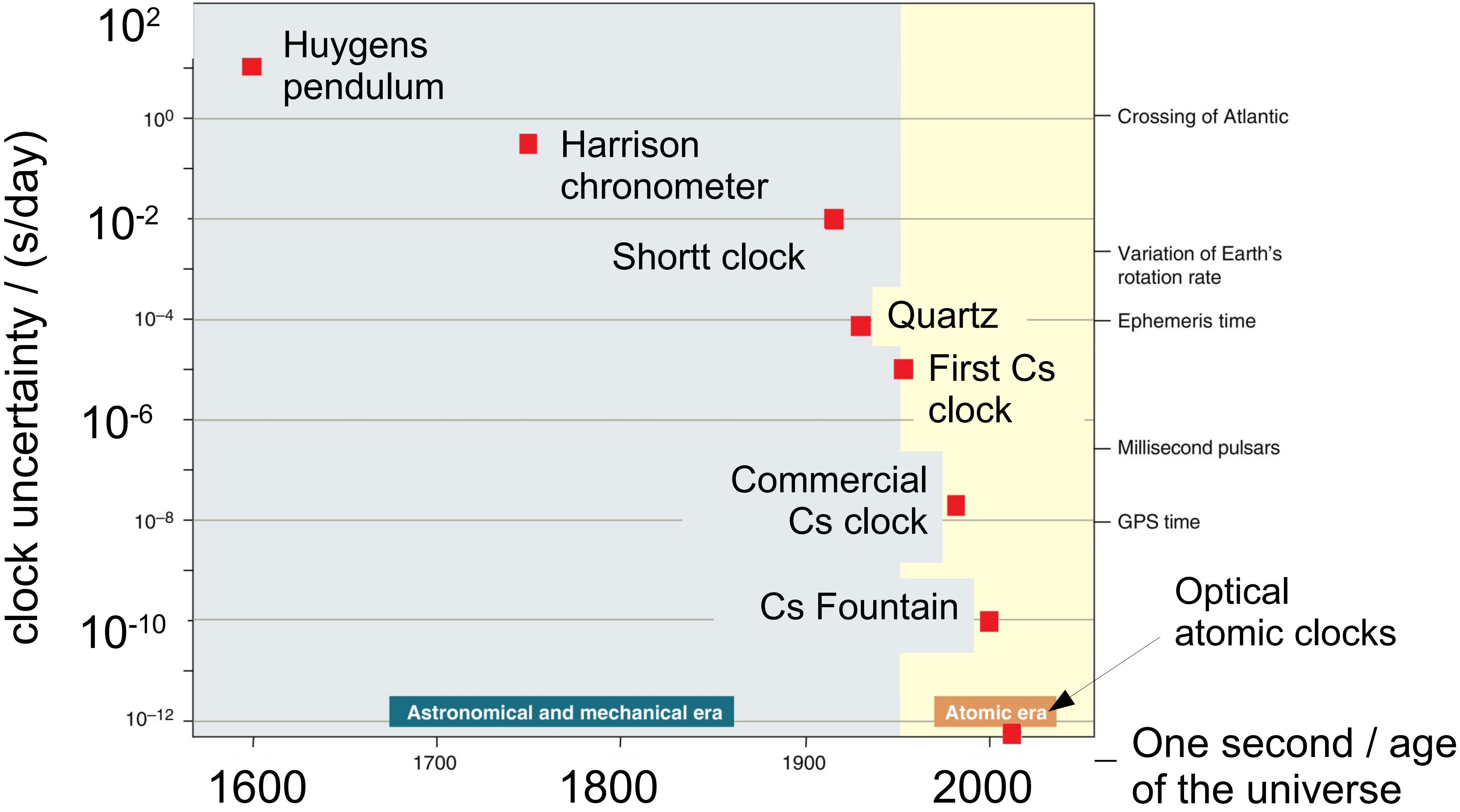
$\nwarrow$ 1/*Q*



C. W. Chou, *et al.*, *To be published* (2010)

	Q
Pendulum clock	10^3
Quartz watch	10^5
Optical atomic clock	10^{14}

Historic accuracy



Adapted from S. A. Diddams, *et al*., *Science* **306** 1318 (2004)

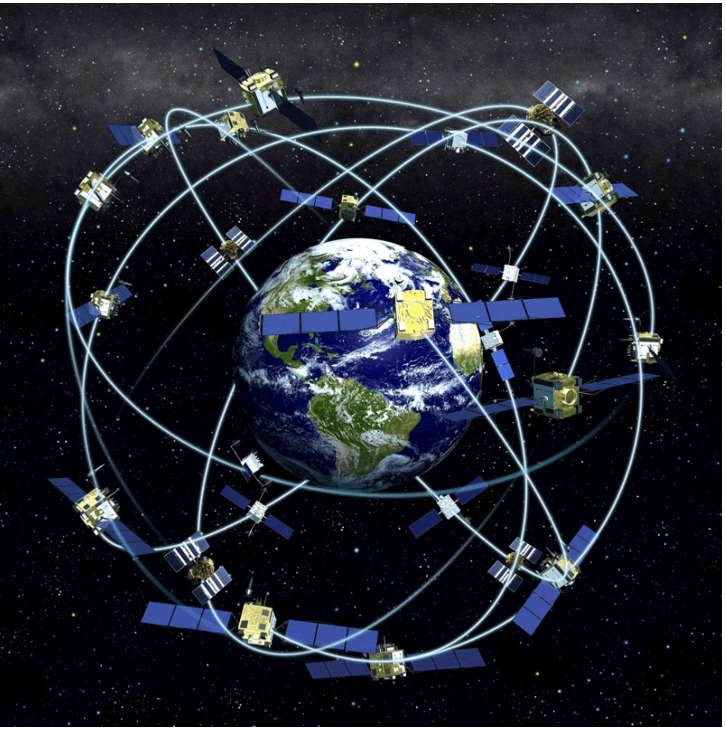
Motivation for clocks

- Navigation
- Network synchronization
- Geodesy
- Astronomy
  - Pulsar timing
  - Very long baseline interferometry
- Fundamental physics
  - Variation of the fundamental constants
  - Local position invariance

Navigation

- Longitude prize (1714): navigate better than 1 degree

  (24h/360 deg) → 4 min
- GPS



<u>GPS relativistic effects</u>

Special relativity:

7.2 μs / day slow

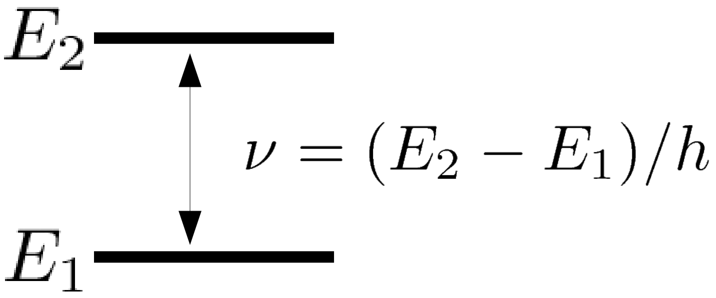
General relativity:

46 μs / day fast

> 11 km / day !

N. Ashby, *Physics Today*, May 2002, p. 41-47

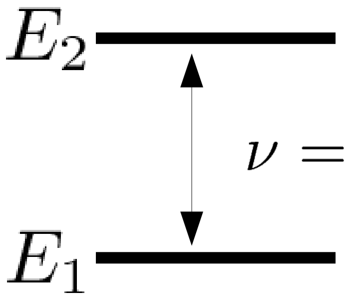
Atomic clocks



$$\nu = (E_2 - E_1)/h$$

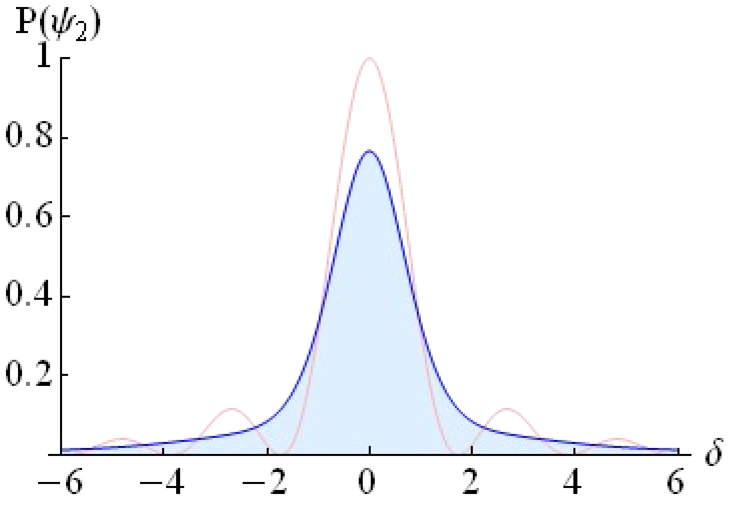
- *Identical* copies
- Typically reference an external oscillator to the atomic transition (exception H-maser)
- How to pick an atomic transition
    - Narrow linewidth (high *Q*)
    - Insensitive to environment

Frequency Probes



$$\nu = (E_2 - E_1)/h$$

Rabi interrogation
“π”-pulse



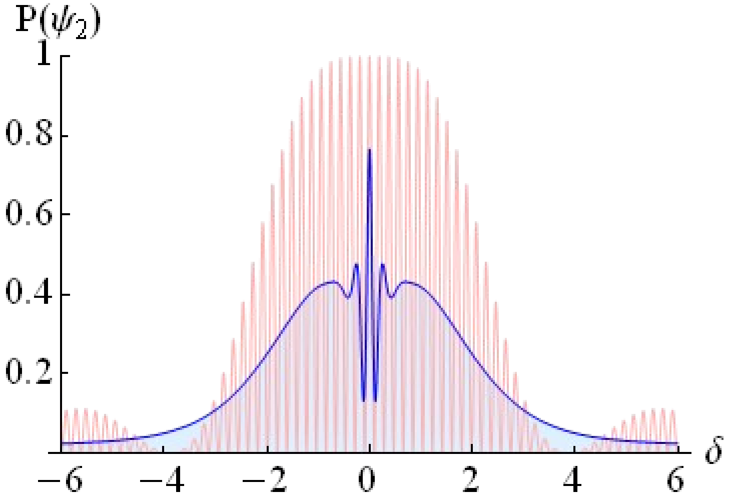
Free precession

$$|\psi\rangle = \alpha\,|\psi_1\rangle + e^{-i\omega t}\beta\,|\psi_2\rangle$$

Coherent drive

$$H' = V_{1,2}\cos[(\omega+\delta)\,t+\phi]$$

Ramsey interrogation
“π/2”-pulse
Free precession
“π/2”-pulse



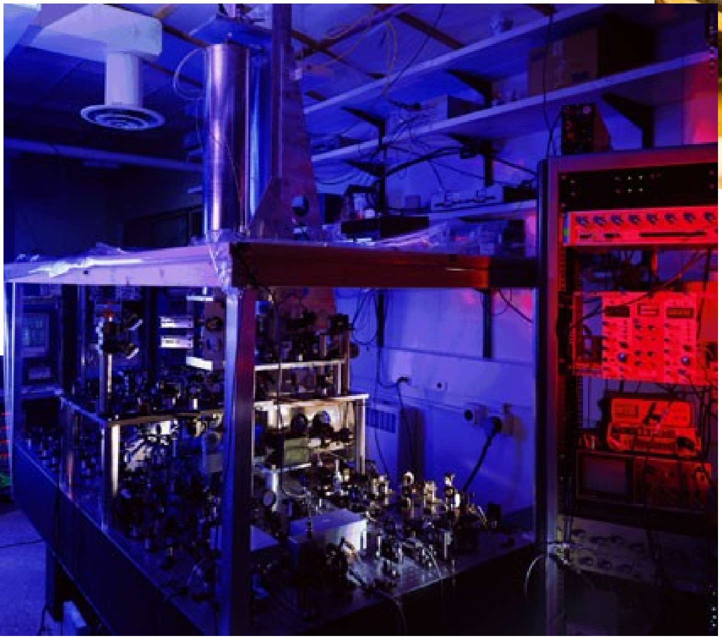
Three examples

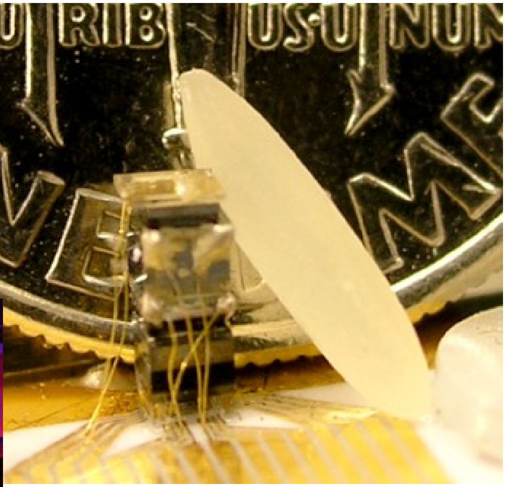
- Cesium – 9.2 GHz (33 mm)
  the current workhorse
- Strontium – 0.43 PHz (698 nm)
  neutral atoms
- Aluminum – 1.1 PHz (267 nm)
  single trapped ion

Cesium clocks

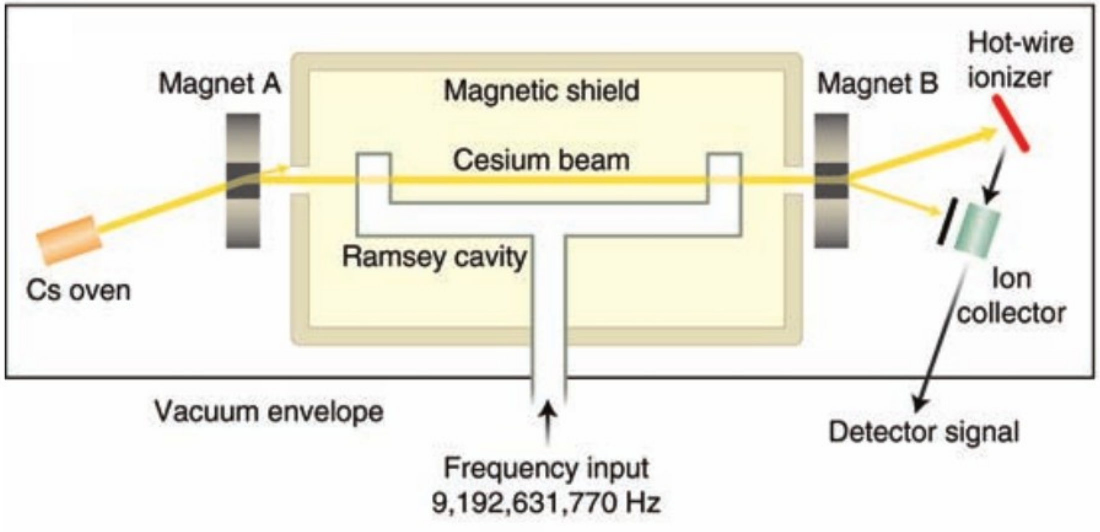
9,192,631,770 Hz (exact)

$$^{133}\mathrm{Cs}\ 6\ ^2S_{1/2}\,|F=3\rangle \leftrightarrow |F=4\rangle$$





Commercial Cesium clocks



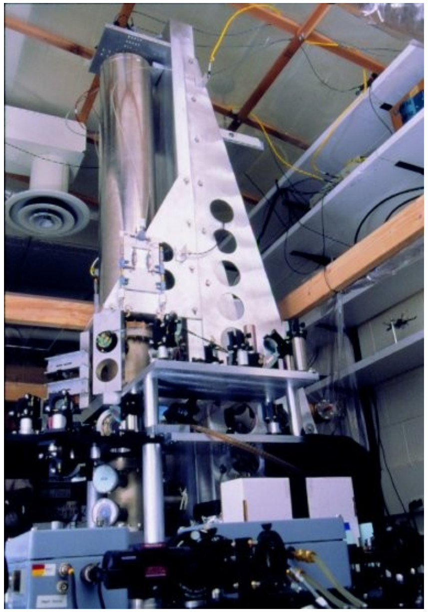
- Thermal source (350 K, 250 m/s)
- Magnetic state selection
- Separated oscillatory fields (10 ms interrogation)
- As good as $\delta f / f_0 = 5 \times 10^{-13}$

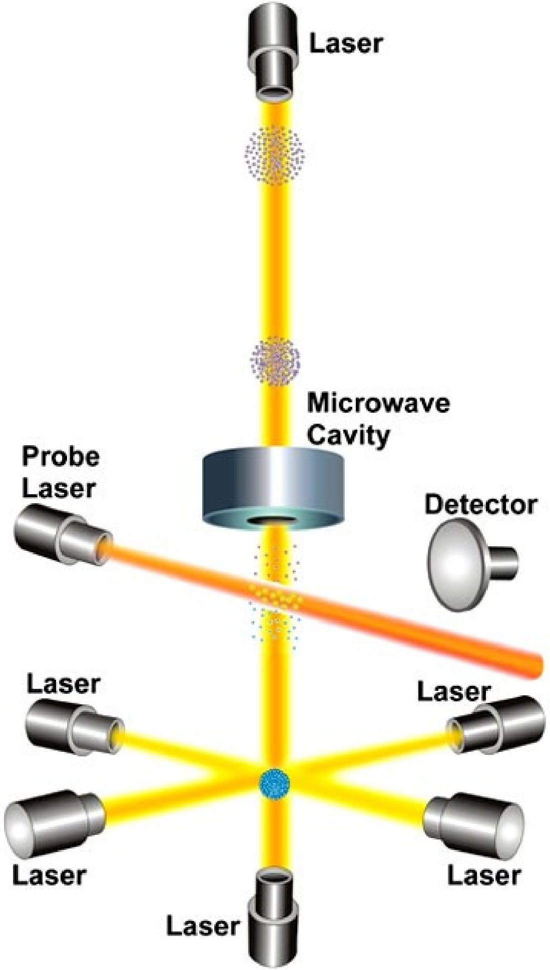
Cesium fountain clock

- Cold (1.3 μK), slow (4 m/s) atoms
- Optical state preparation/read-out
- 0.5 – 1 s interrogation time
- Precision limited by shot noise
- Accuracy limited by

  BBR & collisions
- $\delta f / f_0 = 3 \times 10^{-16}$

S. R. Jefferts, *et al.*, *Metrologia* **39** 321-336 (2002)





Optical clocks

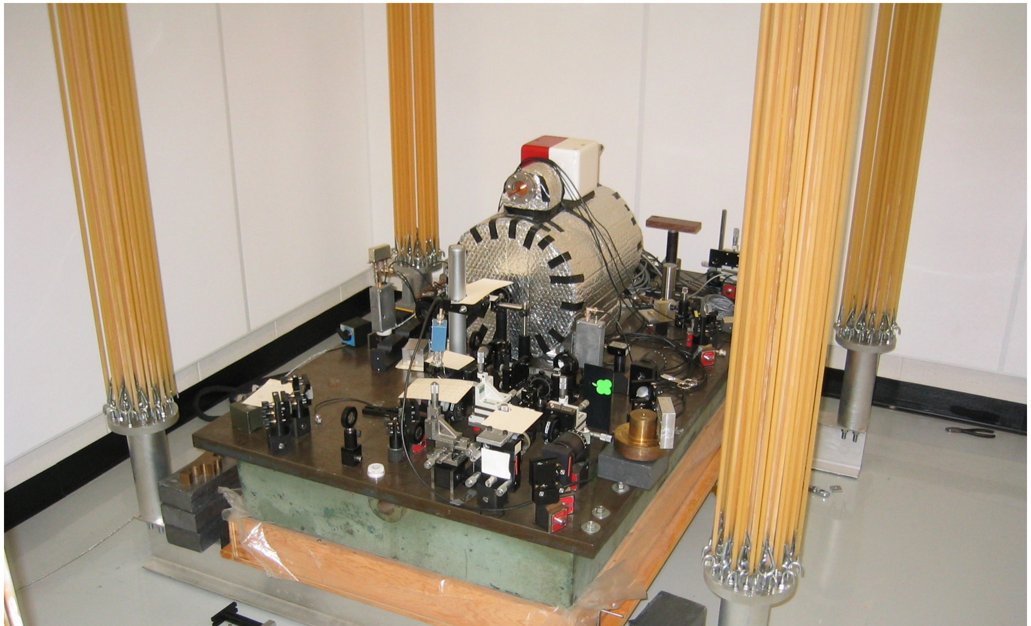
$$\sigma \propto \frac{\Delta\nu}{\nu_0} \frac{1}{\mathrm{S/N}}$$

- GHz → PHz
- Quartz / maser → Laser
- Electronic counter → frequency comb

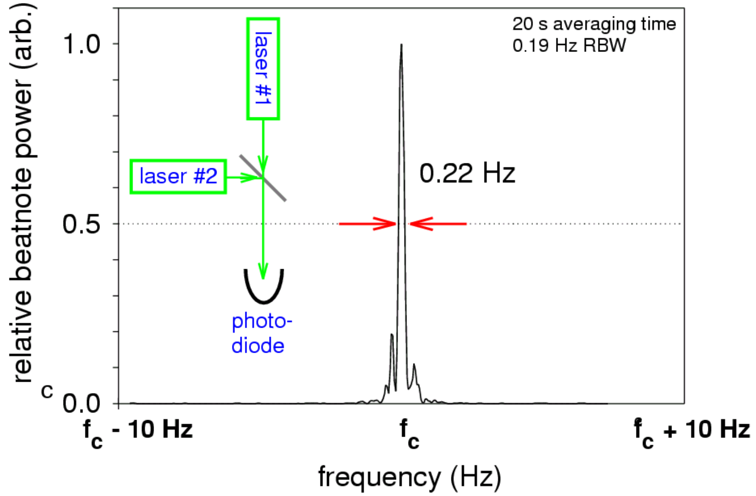
Lasers for optical clocks

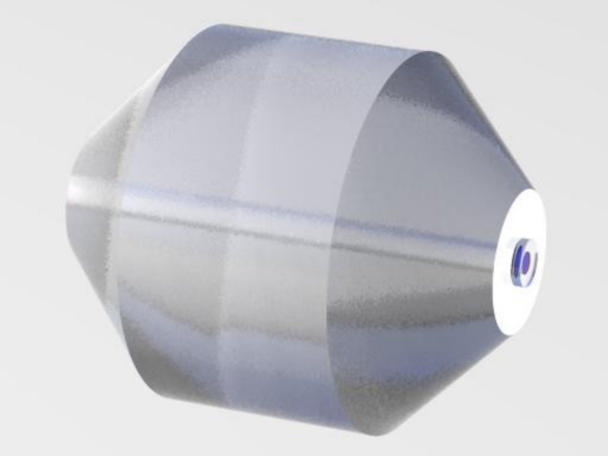
- Commercial laser
- External cavity

$$\frac{\delta f}{f_0} = \frac{\delta l}{l_0}$$



Beatnote of two lasers locked to separate cavities





B. C. Young, *et al*., *Phys. Rev. Lett.* **82** 3799-3802 (1999)

Frequency Comb

f_{rep} ~ MHz – GHz

τ ~ 10 fs

$$2\pi f_0 = f_{rep}\,\Delta\phi$$
$$2 f_n - f_{2n} = f_0$$

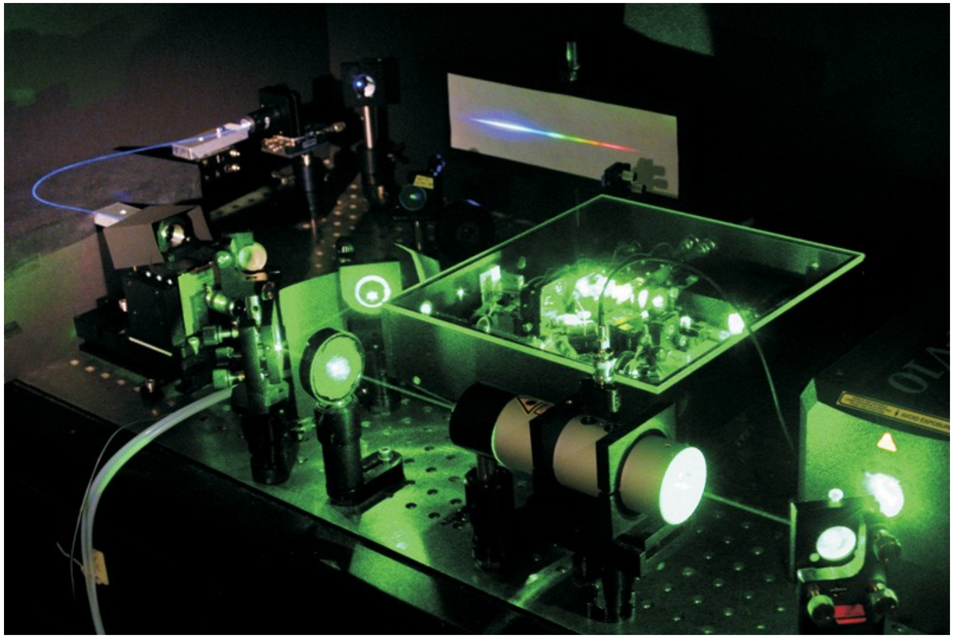
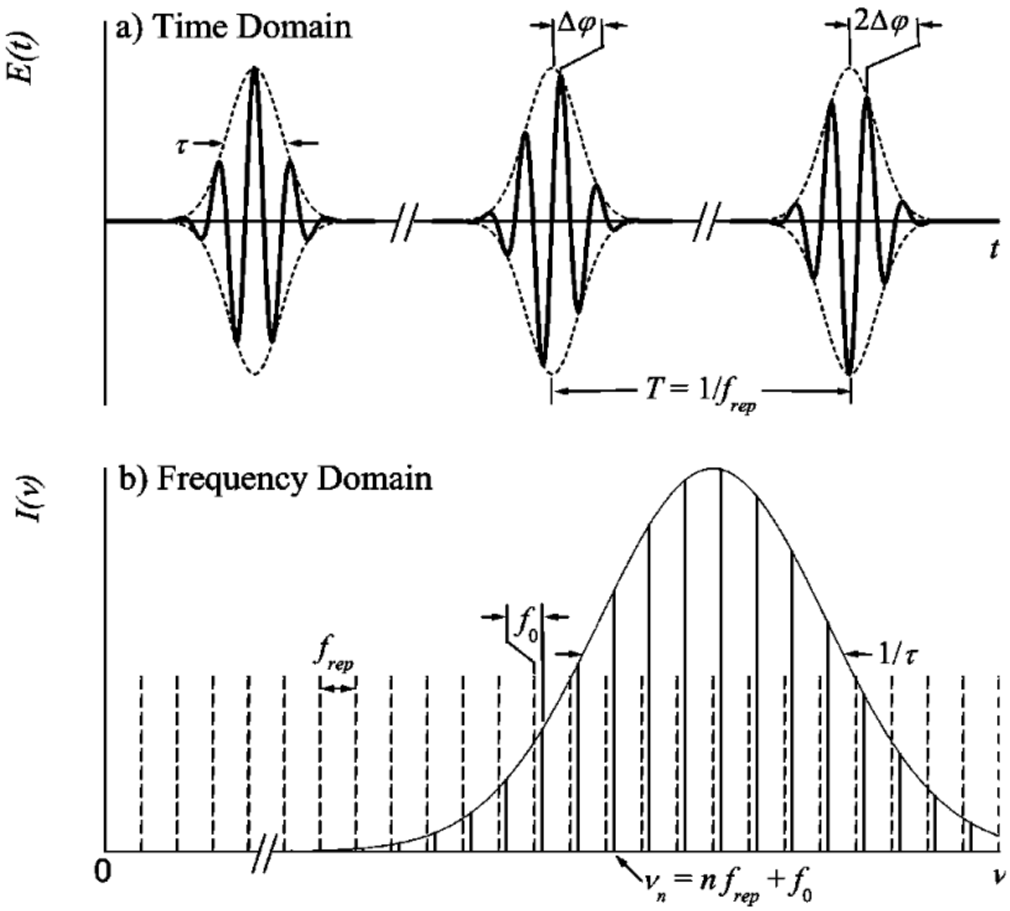


Image: Max Planck Institute of Quantum Optics



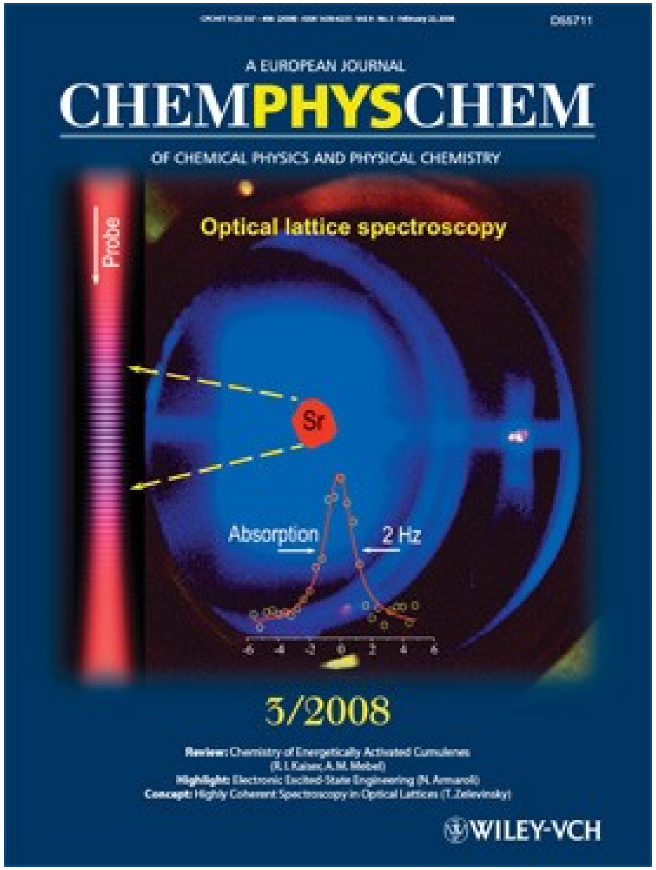
Many references, e.g., S. T. Cundiff & J. Ye, *Rev. Mod. Phys.* **75** 325 (2003)

Strontium

429 228 004 229 873.65 (37) Hz

$$^{87}\mathrm{Sr}\ 5\ ^1S_0 \leftrightarrow {}^3P_0$$

- JILA, Boulder, CO
- Paris Observatory, France
- University of Tokyo, Japan



A EUROPEAN JOURNAL

CHEMPHYSCHEM

OF CHEMICAL PHYSICS AND PHYSICAL CHEMISTRY

Optical lattice spectroscopy

3/2008

Review: Chemistry of Energetically Activated Cumulenes (R. I. Kaiser, A.M. Mebel)

Highlight: Electronic Excited-State Engineering (N. Armaroli)

Concept: Highly Coherent Spectroscopy in Optical Lattices (T. Zelevinsky)

WILEY-VCH

- Laser cooling *and* trapping of neutral atoms
- Single-pulse (Rabi) spectroscopy
- $\delta f / f_0 = 1.5 \times 10^{-16}$

Strontium clock

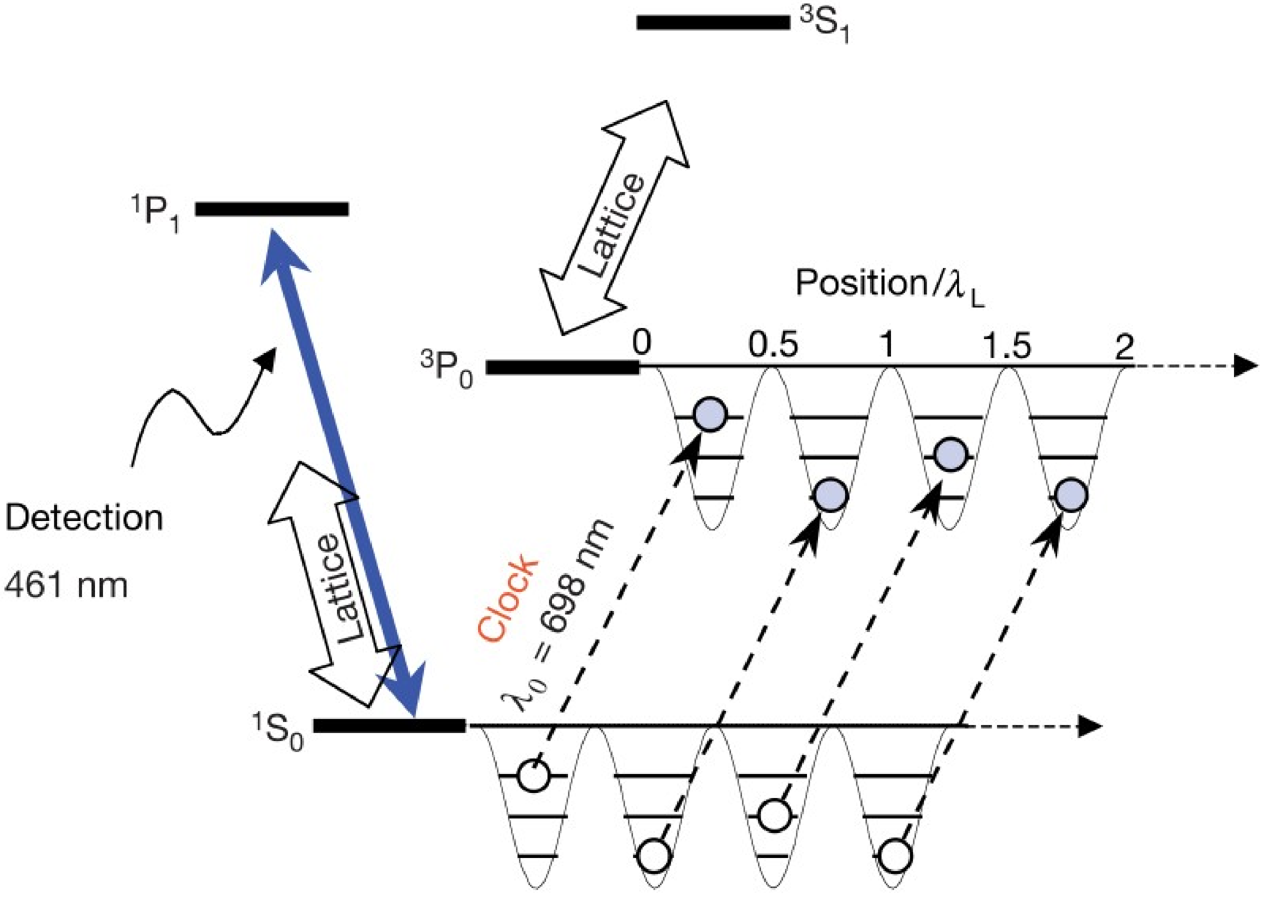


Figure from M. Takamoto, *et al*., *Nature* **435** 321-324 (2005)

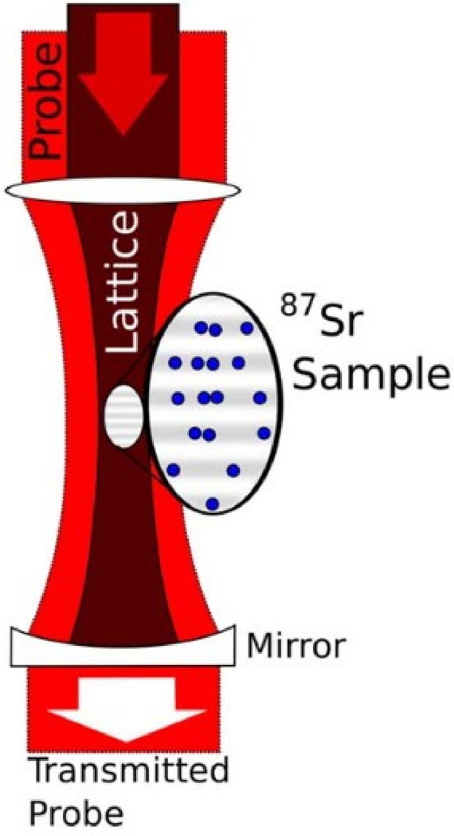
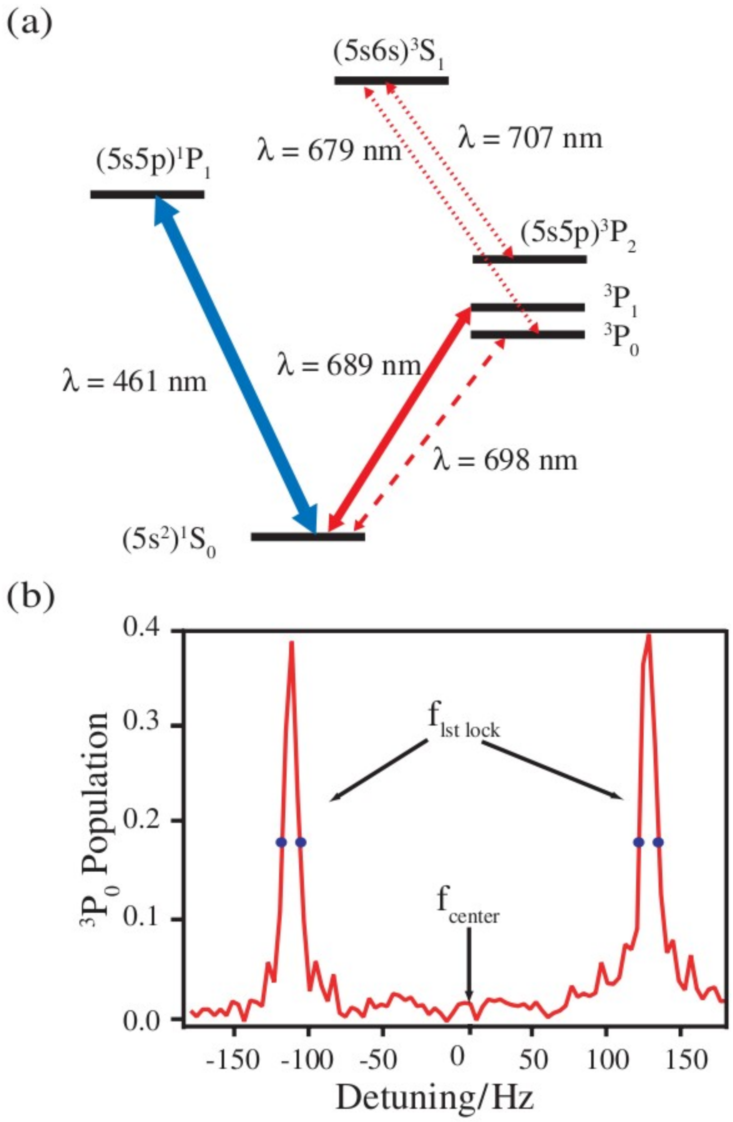


Figure from S. Blatt, *et al*.,
Phys. Rev. A **80** 052703 (2009)

Strontium clock



Duty Cycle: 80 ms probing / 1 s cycle

- Laser-cool and trap atoms in a magneto-optical trap (MOT)
- Ramp up the lattice to get 10^4 atoms at 2.5 μK
- Optically pump to hyperfine stretched states (virtual B-field-insensitive state)
- Single pulse on clock state
- Destructively measure failed population
- Repump and measure success population

Figure from G. K. Campbell, *et al.*, *Metrologia* **45** 539-548 (2008)

Strontium clock

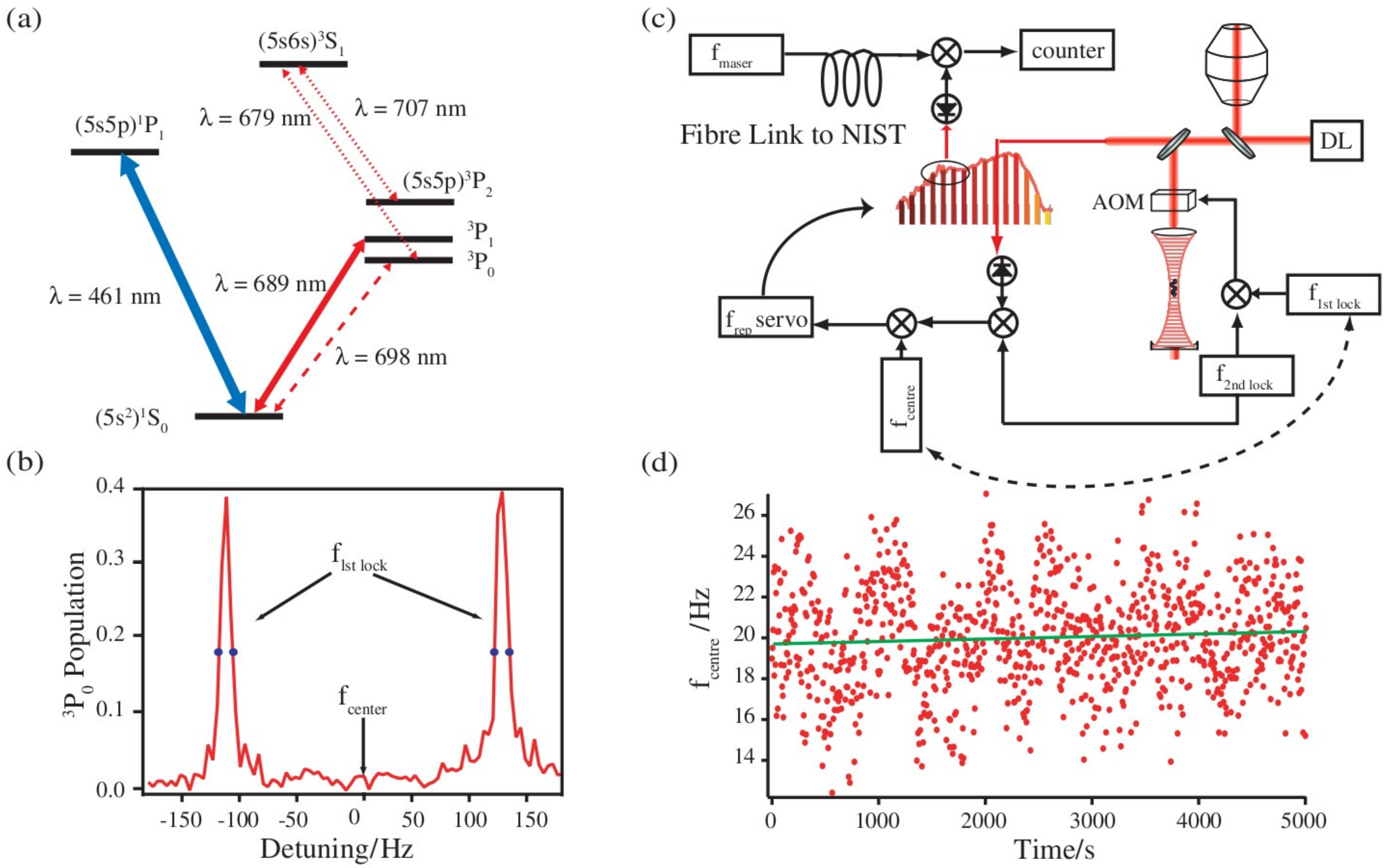


Figure from G. K. Campbell, *et al.*, *Metrologia* **45** 539-548 (2008)

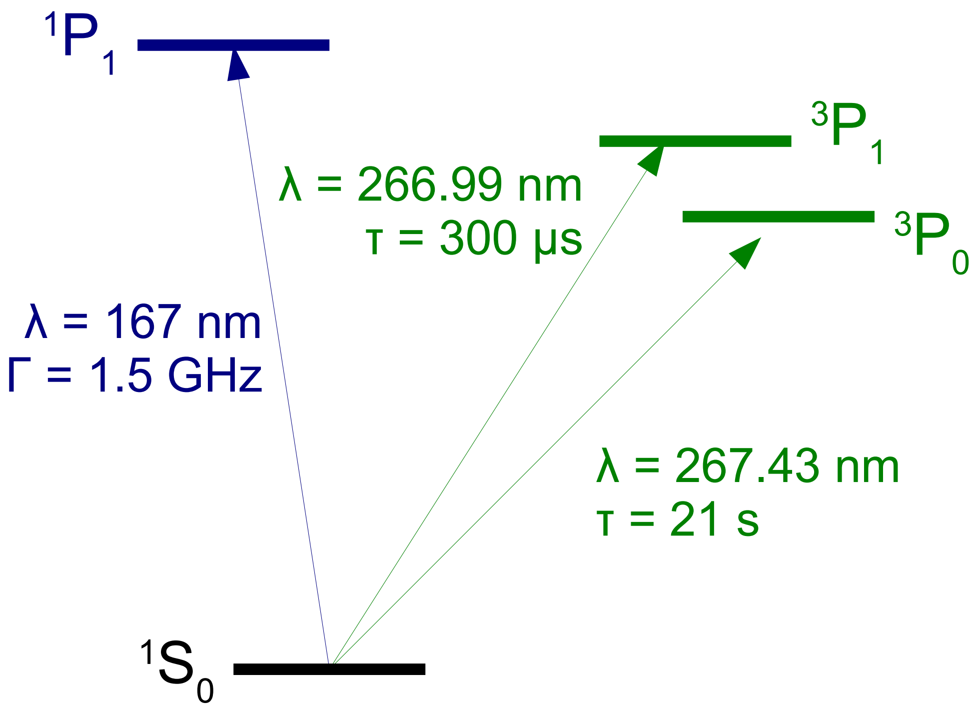
Aluminum

1 121 015 393 207 857.4(7) Hz

$$^{27}\mathrm{Al}^+ \; 3\;{}^1S_0 \leftrightarrow {}^3P_0$$

- NIST, Boulder, CO (Rooms 2108, 2034)

- Single trapped charged atom
- Single-pulse (Rabi) spectroscopy
- Smallest known blackbody shift
- $\delta f / f_0 = 8.6 \times 10^{-18}$



Quantum Logic Spectroscopy

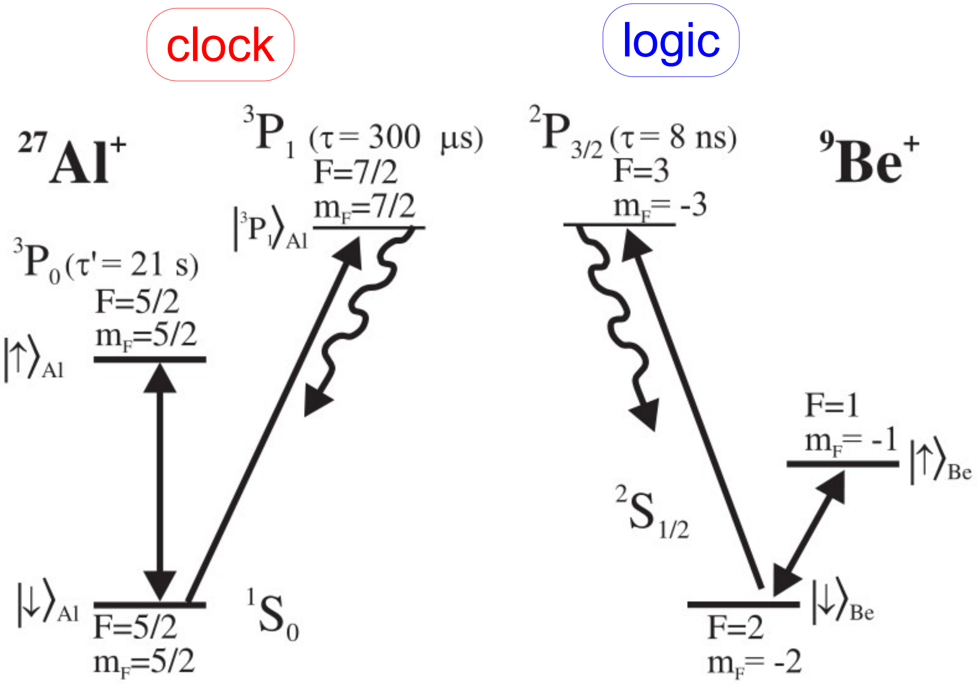
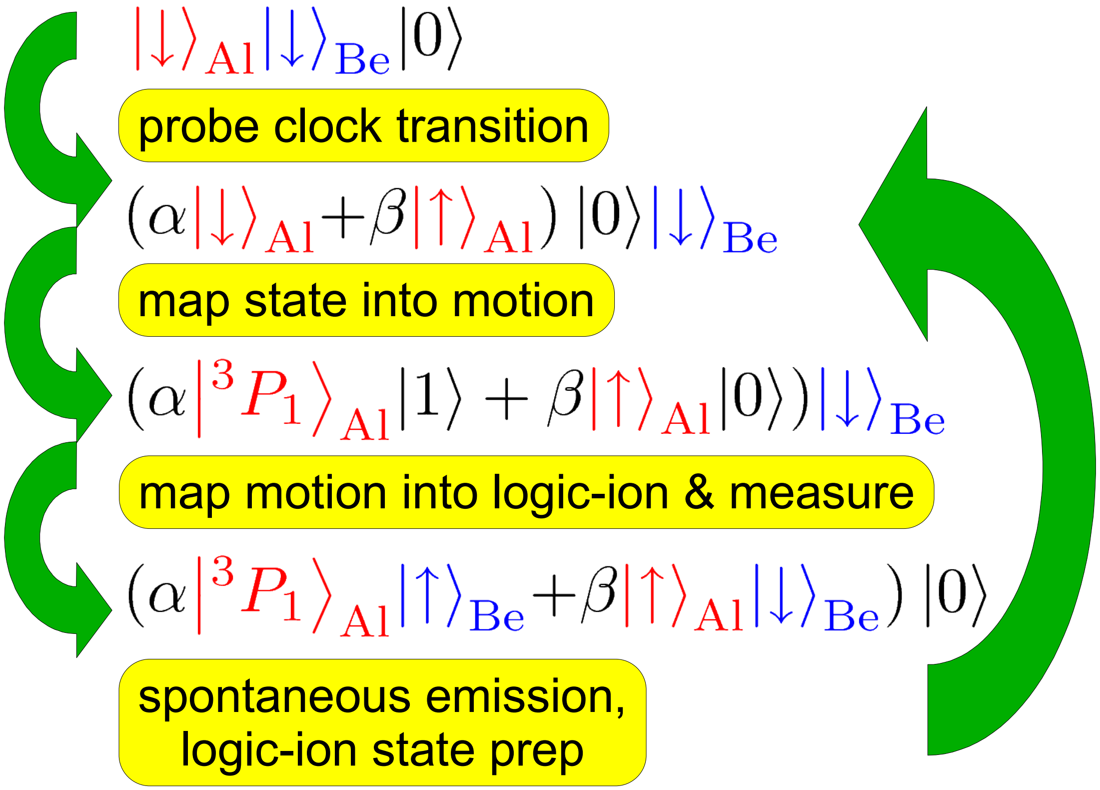


Figure from D. B. Hume, *et al.*, *Phys. Rev. Lett.* **99** 120502 (2007)
See also, P. O. Schmidt, *et al.*, *Science* **309** 749-752 (2005)



$|\downarrow\rangle_{\mathrm{Al}}|\downarrow\rangle_{\mathrm{Be}}|0\rangle$

probe clock transition

$(\alpha|\downarrow\rangle_{\mathrm{Al}}+\beta|\uparrow\rangle_{\mathrm{Al}})\,|0\rangle|\downarrow\rangle_{\mathrm{Be}}$

map state into motion

$(\alpha\left|{}^3P_1\right\rangle_{\mathrm{Al}}|1\rangle + \beta|\uparrow\rangle_{\mathrm{Al}}|0\rangle)|\downarrow\rangle_{\mathrm{Be}}$

map motion into logic-ion & measure

$(\alpha\left|{}^3P_1\right\rangle_{\mathrm{Al}}|\uparrow\rangle_{\mathrm{Be}}+\beta|\uparrow\rangle_{\mathrm{Al}}|\downarrow\rangle_{\mathrm{Be}})\,|0\rangle$

spontaneous emission,
logic-ion state prep

- Co-trap “clock” and “logic” ion species
- Use motion as an information bus
- Quantum nondemolition measurement

Al^+ clocks

Duty Cycle: 150 ms probing /
230 ms cycle

- Laser cool
- State preparation
- Probe clock transition
- Quantum logic spectroscopy

Current limitations: motion in trap

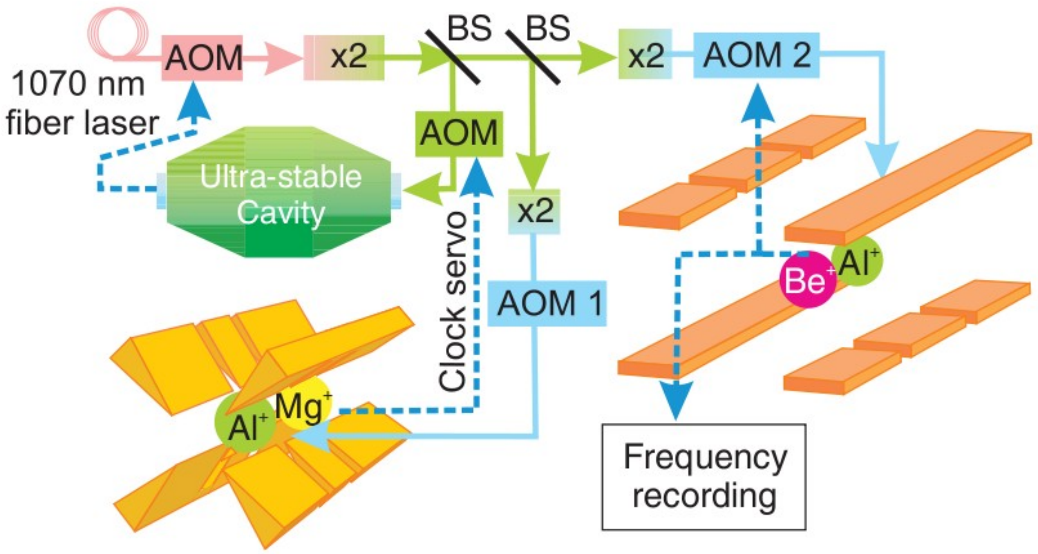


Figure from C. W. Chou, *et al.*, *Phys. Rev. Lett.* **104** 070802 (2010)

Variation of fundamental constants

	Timescale	Precision
Quasar absorption spectra	10^{10} yr $z = 0.5 – 3.5$	10^{-16} yr^{-1}
Oklo natural fission reactor	2 x 10^{9} yr $z = 0.2$	10^{-17} yr^{-1}
Laboratory spectroscopy	10 yr $z = 10^{-10}$	10^{-17} yr^{-1}

See e.g., J.-P. Uzan, *Rev. Mod. Phys.* **75** 403-455 (2003)

$$\frac{\dot{\alpha}}{\alpha}$$

Variation of fundamental constants

Transitions have different dependence on *α* (relativistic corrections)

$$\nu_{el,j} = R_y F_j(\alpha) \qquad \Rightarrow \qquad \frac{\dot{\nu}_{el,j}}{\nu_{el,j}} = \frac{\dot{R}_y}{R_y} + N_j \frac{\dot{\alpha}}{\alpha}$$

$$\nu_{FS,j} = \alpha^2 R_y F_j(\alpha) \qquad \Rightarrow \qquad \frac{\dot{\nu}_{FS,j}}{\nu_{FS,j}} = \frac{\dot{R}_y}{R_y} + (2 + N_j) \frac{\dot{\alpha}}{\alpha}$$

$$\nu_{HFS,j} = \alpha^2 \frac{\mu}{\mu_B} R_y F_j(\alpha) \qquad \Rightarrow \qquad \frac{\dot{\nu}_{HFS,j}}{\nu_{HFS,j}} = \frac{\dot{R}_y}{R_y} + \frac{d \ln(\mu/\mu_B)}{dt} + (2 + N_j) \frac{\dot{\alpha}}{\alpha}$$

$N_{Cs} = 0.8$

$N_{Al+} = 0$

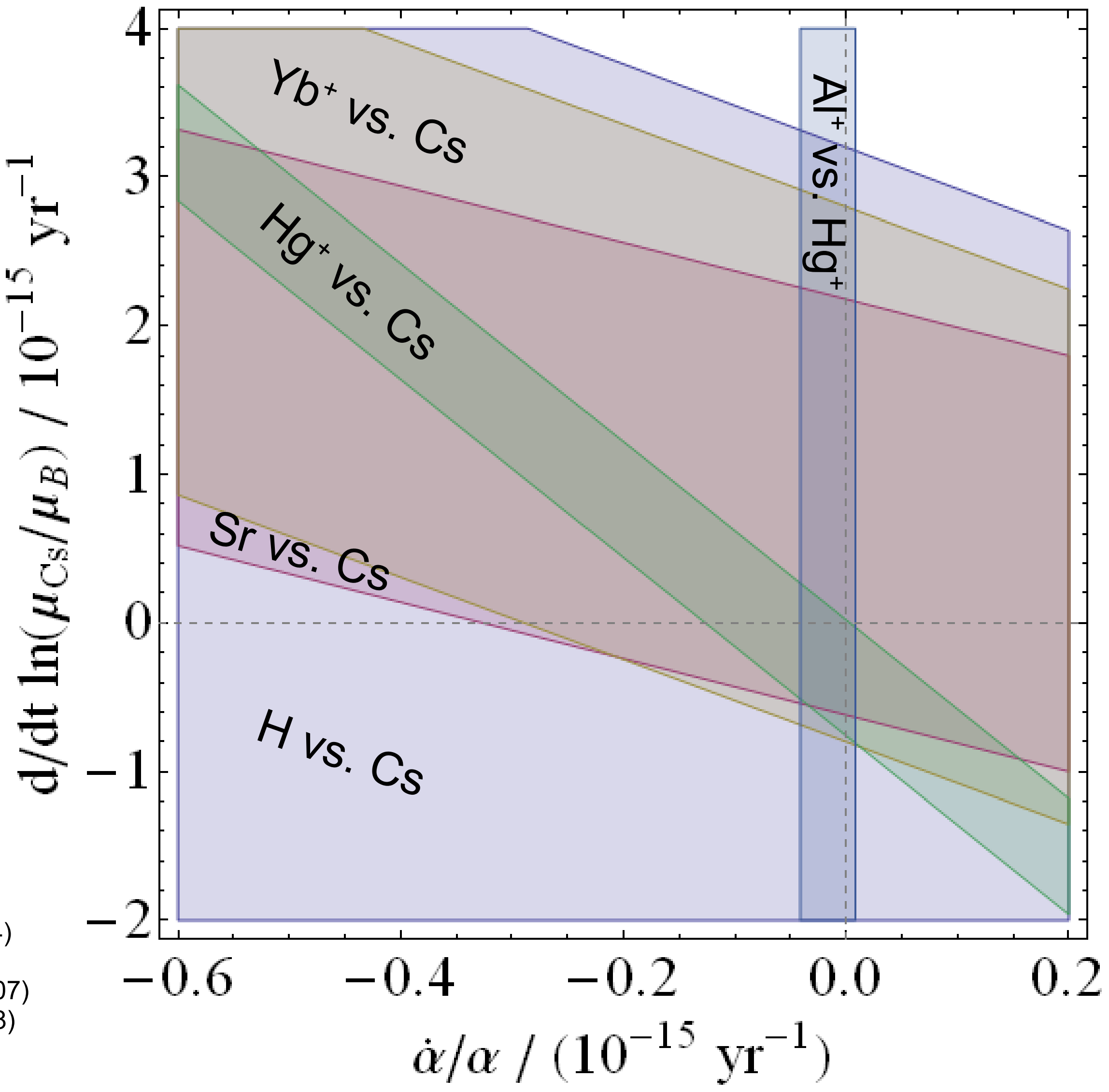
$N_{Sr} = 0$

$N_{Hg+} = -3.2$

$N_{H} = 0$

$N_{Yb+} = 0.9$

Variation of fundamental constants



M. Fischer, *et al.*, *Phys. Rev. Lett.* **92** 230802 (2004)
E. Peik, *et al.*, arXiv:physics/0611088
T. M. Fortier, *et al.*, *Phys. Rev. Lett.* **98** 070801 (2007)
T. Rosenband, *et al.*, *Science* **319** 1808-1812 (2008)
S. Blatt, *et al.*, *Phys. Rev. Lett.* **100** 140801 (2008)

Local position invariance

$$\frac{\Delta\nu}{\nu} = -\frac{\Delta U}{c^2}$$

model of violation: $(1+\beta)$

$$\Delta\beta \lesssim 10^{-6}$$

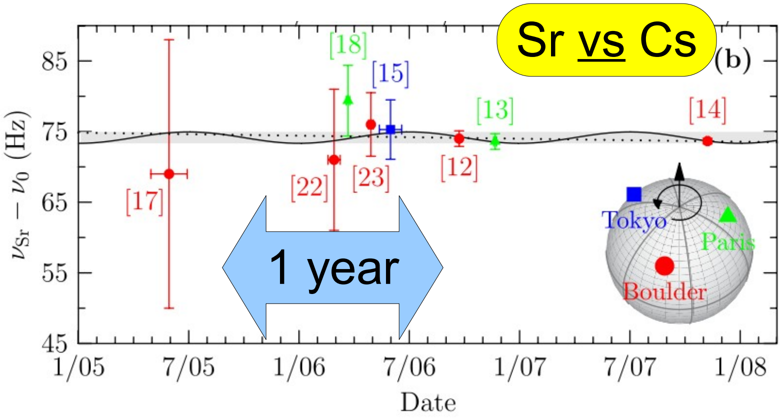


Figure from S. Blatt, *et al.*, *Phys. Rev. Lett.* **100** 140801 (2008)

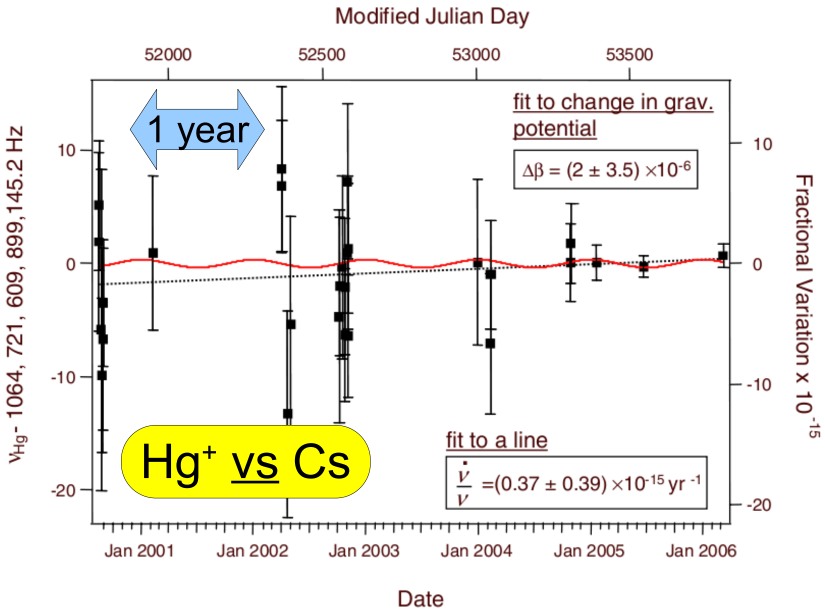
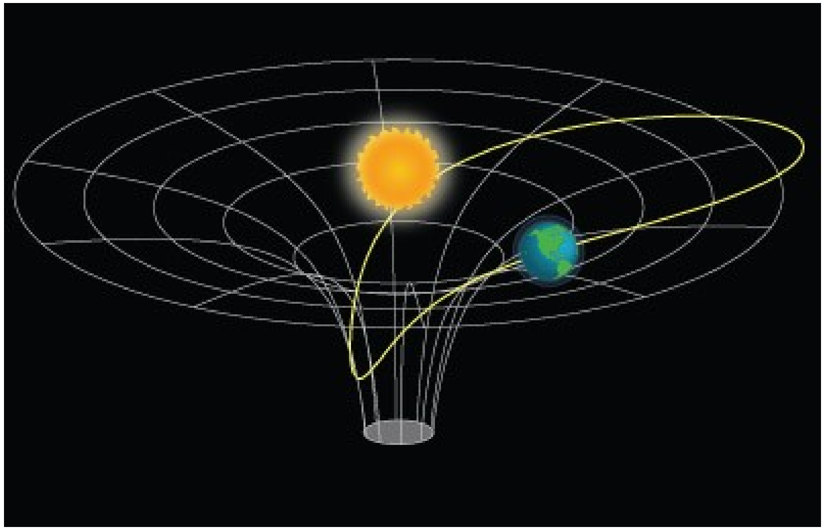
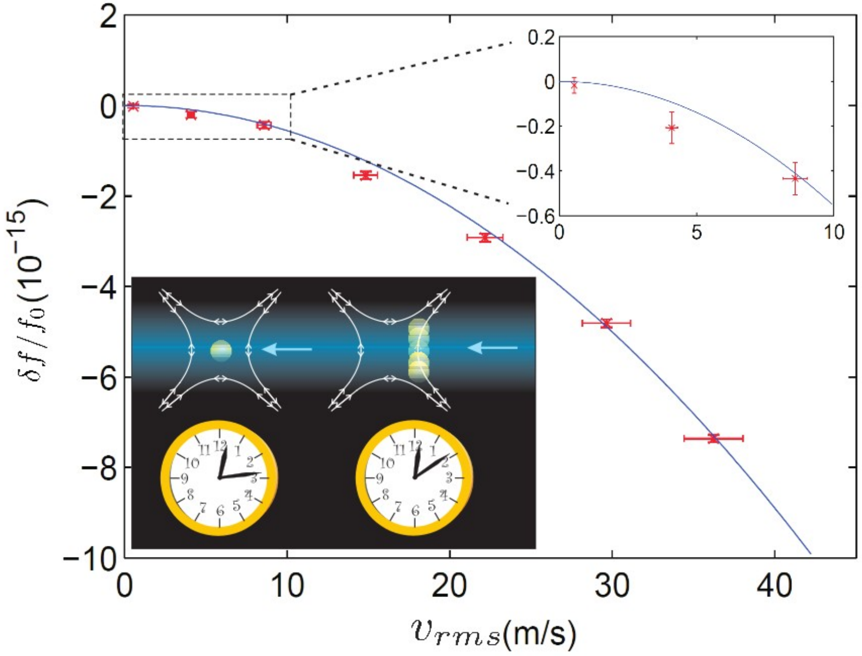


Figure from T. M. Fortier, *et al.*, *Phys. Rev. Lett.* **98** 070801 (2007)



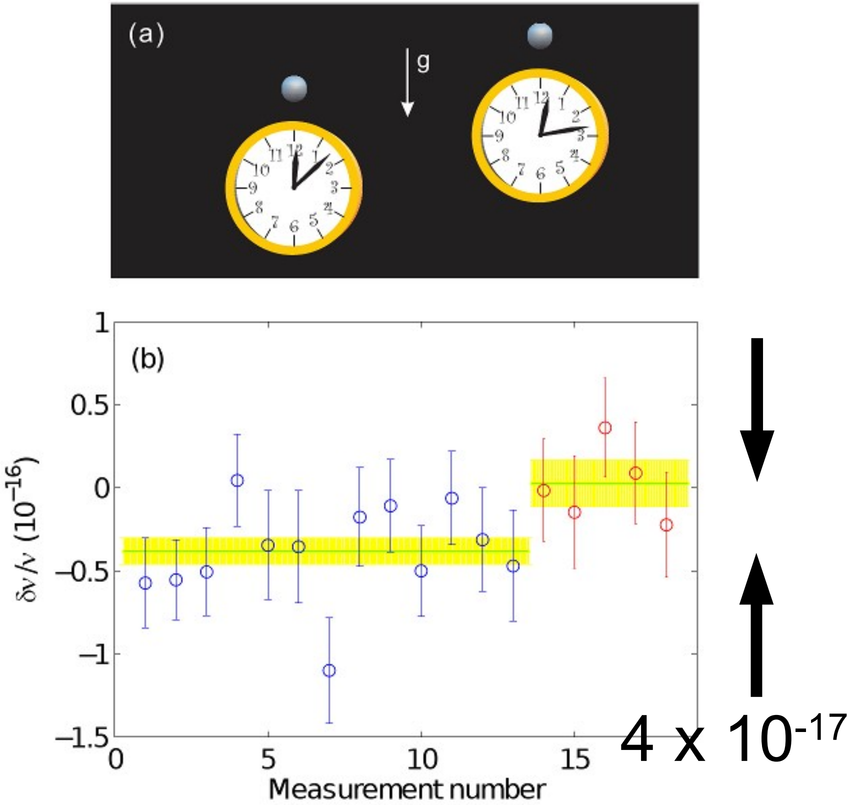
$$\frac{\Delta U_{\max}}{c^2} = 3.3 \times 10^{-10}$$

Relativity demonstrations on human scales



time dilation at 10 m/s = 36 km/h ≈ 22 mph

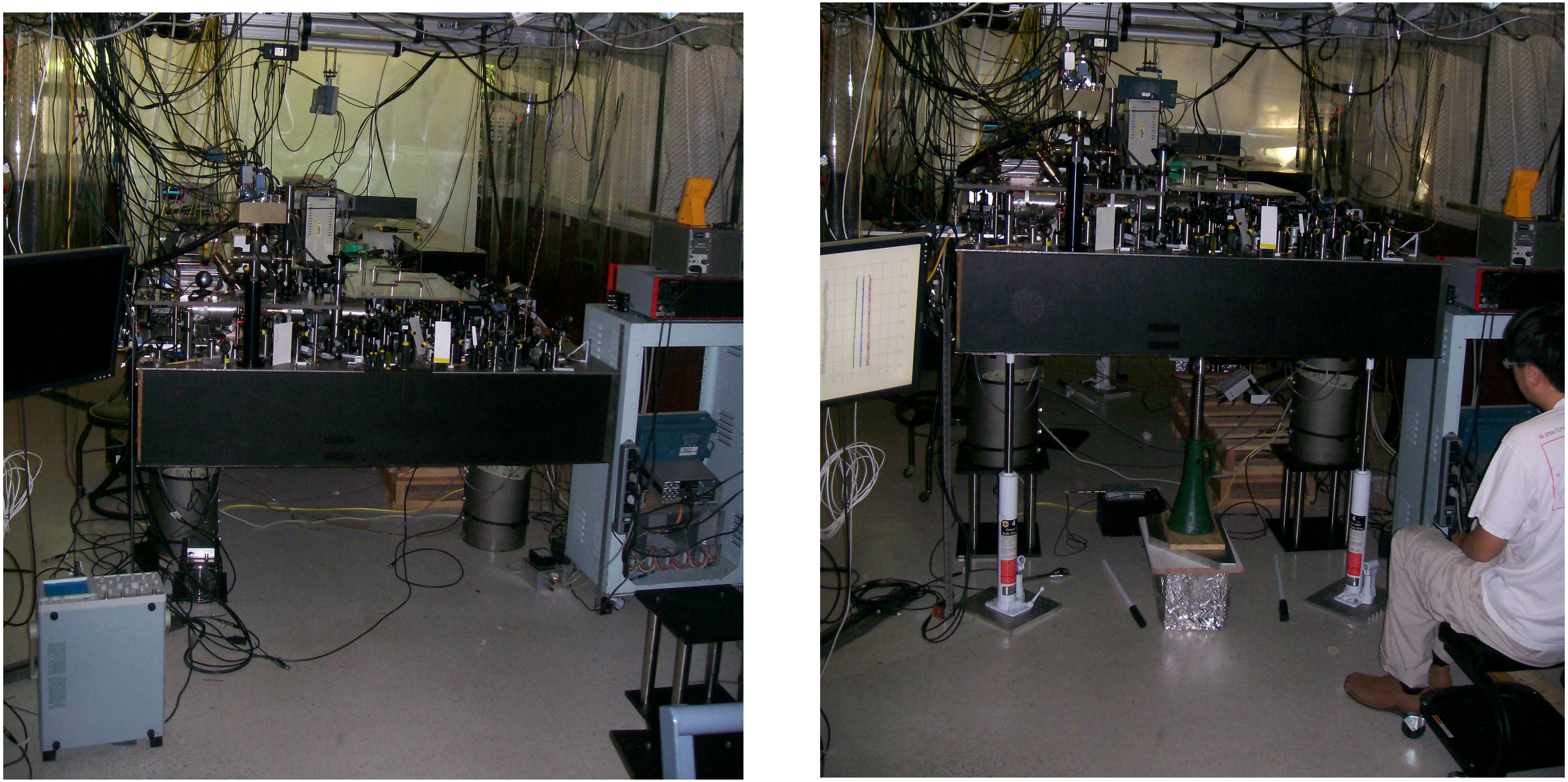
C. W. Chou, *et al.*, *To be published* (2010)



4×10^{-17}

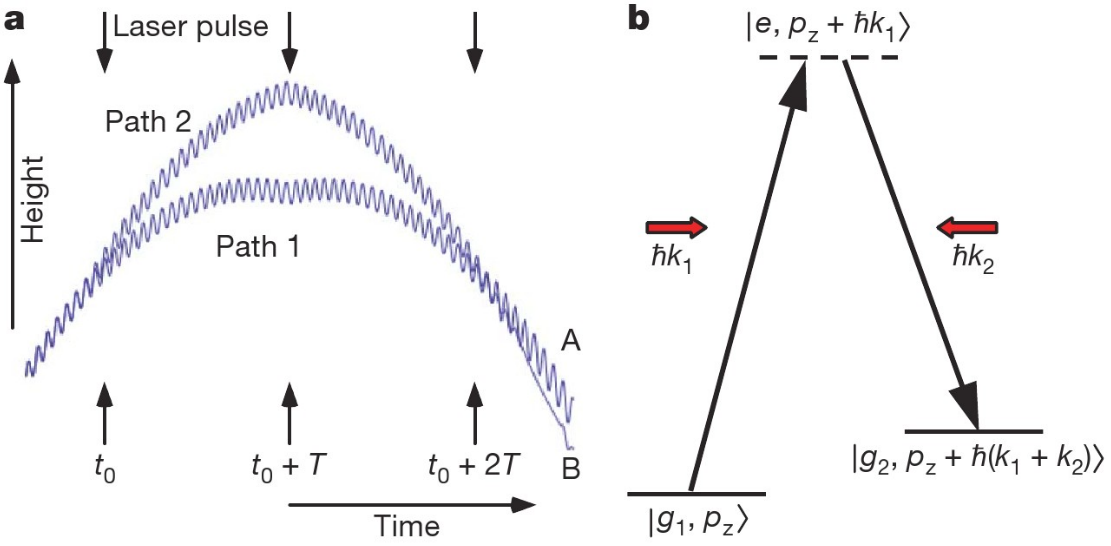
gravitational redshift with a
33 cm height change

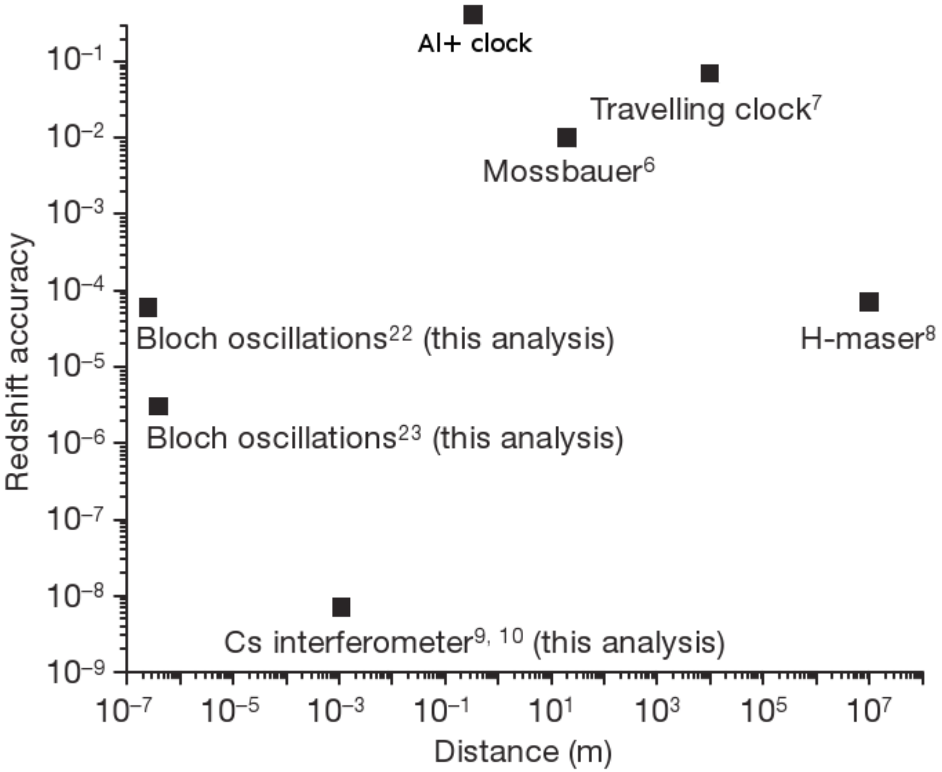
Relativity demonstrations on human scales



33 cm → 4 x 10^{-17}

GR in a fountain





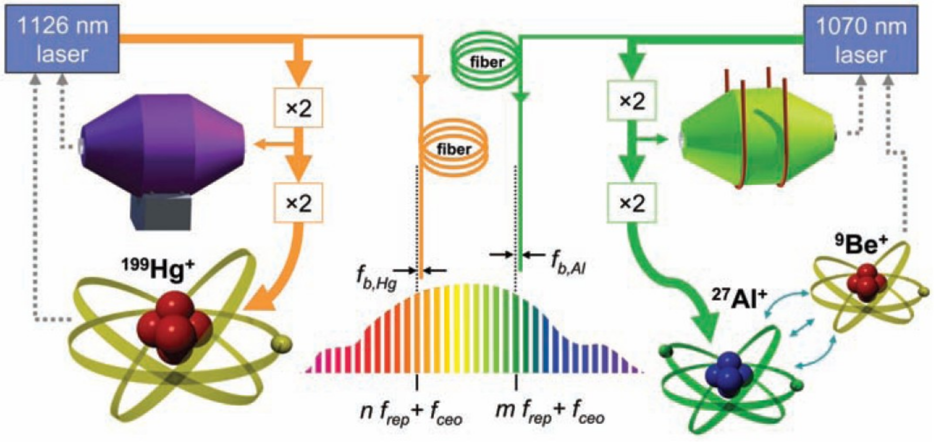
- Atom interferometry
- 7 ppb over 120 µm
- $\nu = M_{\mathrm{Cs}} c^2 / h = 3.2 \times 10^{25}\ \mathrm{Hz}$

$$\frac{\Delta\nu}{\nu} = -\frac{\Delta U}{c^2}$$

H. Muller, *et al.*, *Nature* **463** 926-929 (2010)

Conclusions

- Optical atomic clocks are now more precise than radiofrequency clocks
- Narrow linewidth lasers / frequency combs
- Two approaches: collections of neutral atoms, individual trapped ions
- Already contributing to fundamental physics



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

Thank you

General references

From NIST: http://tf.nist.gov/timefreq/general/generalpubs.htm

For the layman: *From Sundials to Atomic Clocks*, J. Jespersen and J. Fitz-Randolph (Dover Books or NIST website)

S. A. Diddams, *et al.*, *Standards of Time and Frequency at the Outset of the 21st Century*, *Science* **306** 1318-1324 (2004)

Next Lectures

Cavity Control in a Single-Electron Quantum Cyclotron
Thursday, May 13, 4:15pm, Rock 301

High-Energy Physics with Low-Energy Symmetry Studies
Friday, May 14, 12:30pm, Miller Room

Hydrogen maser

1 420 405 751.768(2) Hz (21 cm)

$$\mathrm{H}\ 1\ {}^2S_{1/2}\,|F=1\rangle \leftrightarrow |F=0\rangle$$

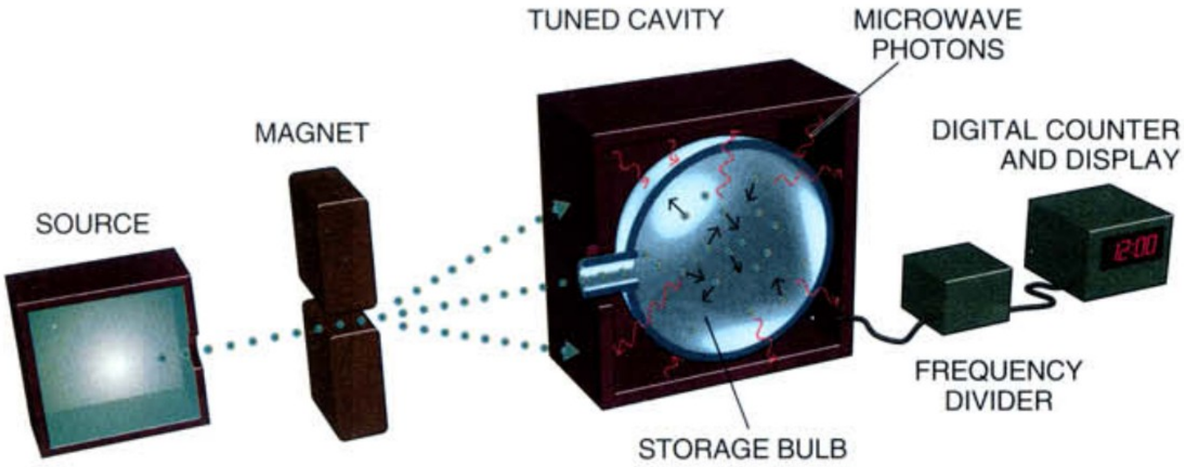


Figure from Wayne M. Itano and Norman F. Ramsey, *Scientific American*, July 1993, 56-65