Title: David Wineland: Keeping Better Time: The Era of Optical Atomic Clocks

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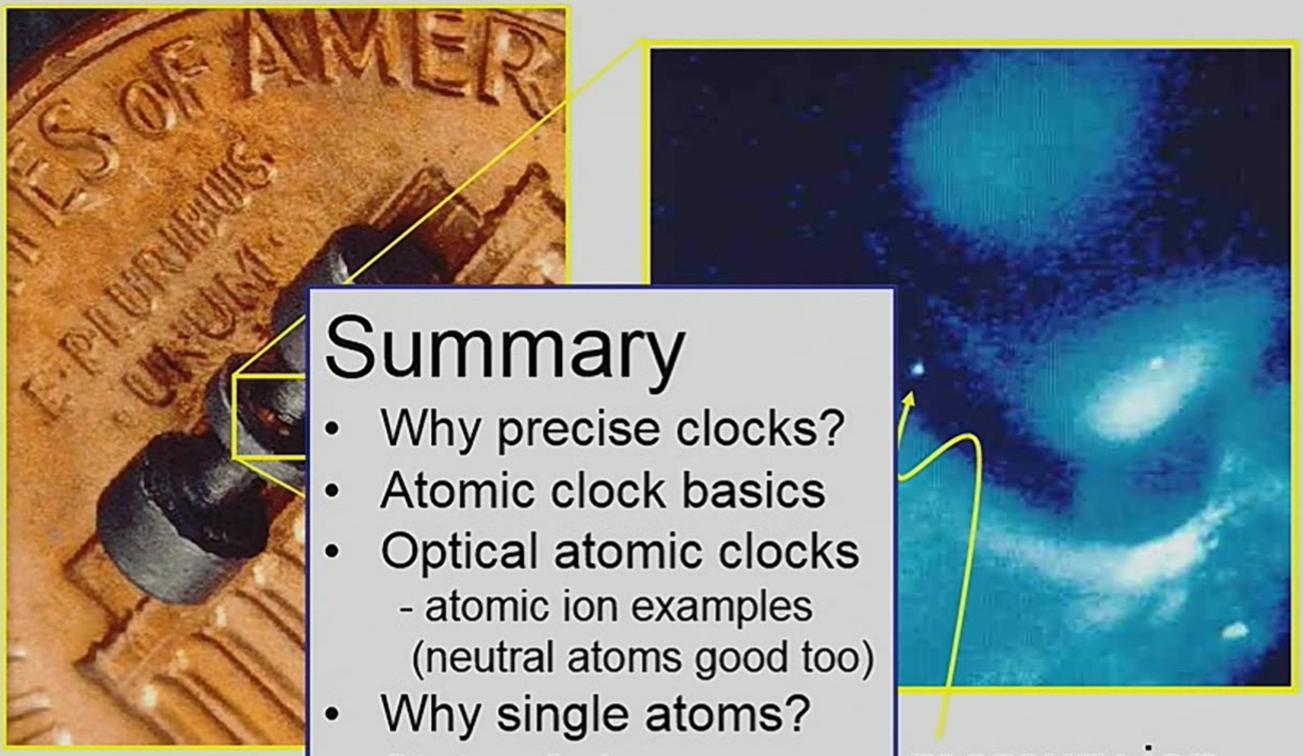
Abstract: <p>Atomic clocks are the most precise timekeepers ever built. If you could keep an advanced atomic clock running long enough, it would neither gain nor lose a single second over the entire lifespan of the universe. With the availability of spectrally pure lasers and the ability to precisely measure optical frequencies, it appears the era of optical atomic clocks has begun. Advances in atomic clocks are expected to be important in a range of emerging technological applications, including quantum computers. Dr. David Wineland, 2012 Nobel Laureate in Physics, will explore the theoretical and technological know-how needed to build these ultra-precise timepieces during his Perimeter Institute Public Lecture on Wednesday, Nov. 4. </p>

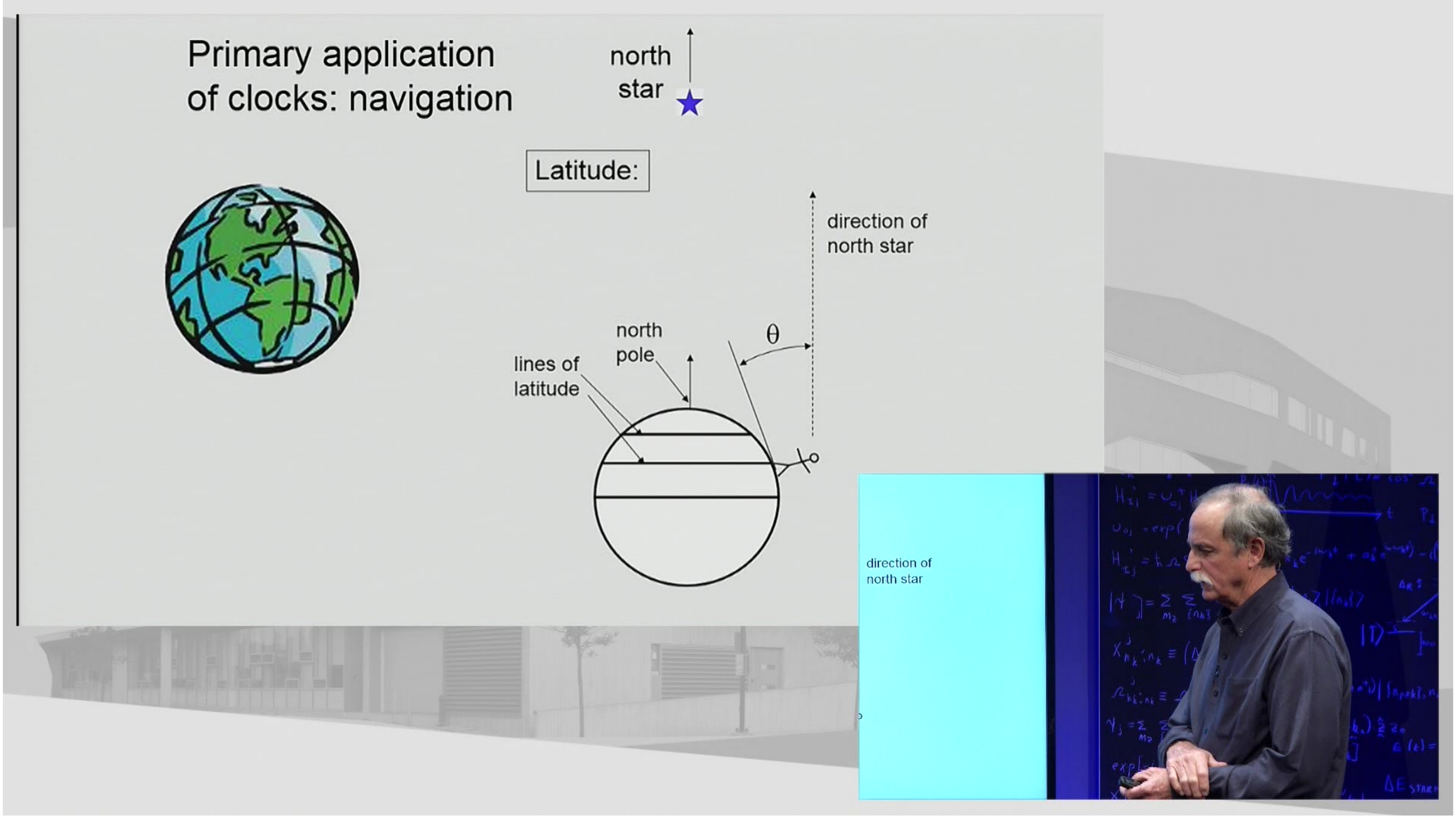
Keeping Better Time: The Era of Optical Atomic Clocks

D. J. Wineland, NIST, Boulder



Summary

- Why precise clocks?
- Atomic clock basics
- Optical atomic clocks
  - atomic ion examples (neutral atoms good too)
- Why single atoms?
- State of play
- Future



Primary application of clocks: navigation

north star

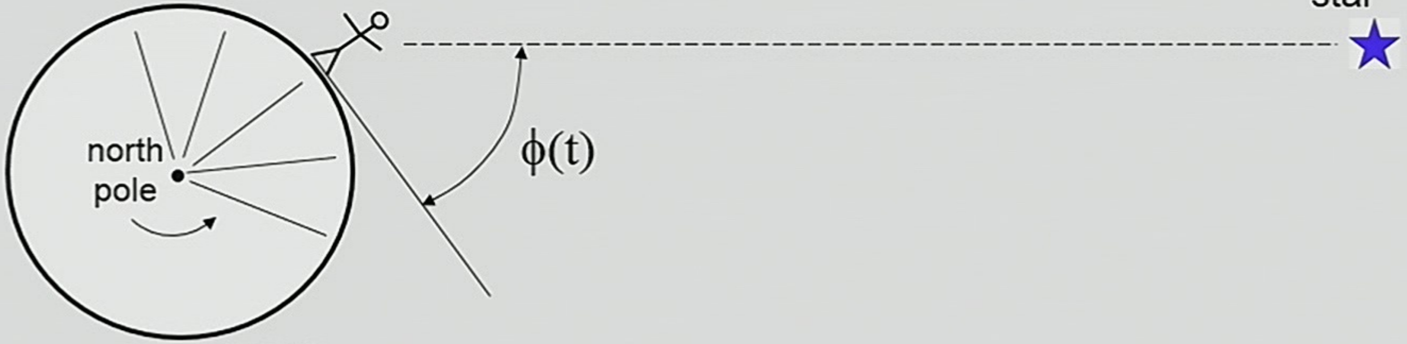
Latitude:

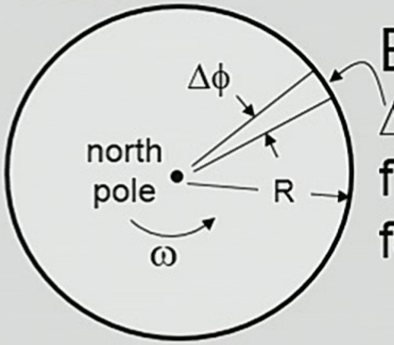
direction of north star

direction of north star

Clocks and navigation

Longitude:





Errors:

$\Delta d = R\Delta\phi = R2\pi f\Delta t$

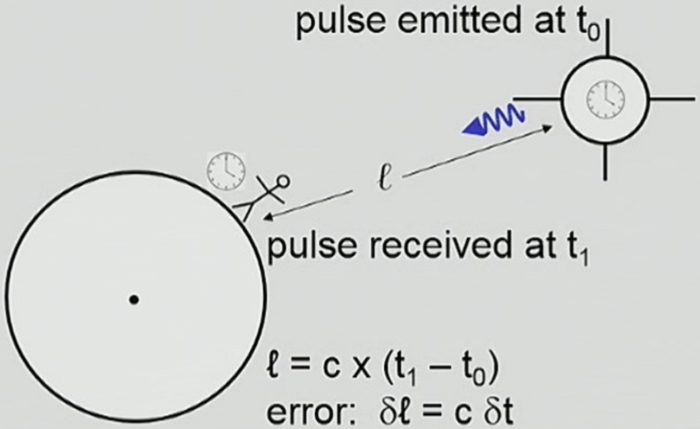
$f = 1/\text{day}$, $R \cong 3960$ mi $\cong 6370$ km

for $\Delta t = 1$ s, $\Delta d \cong 0.463$ km $\cong 0.25$ naut. mi

some history: naval disasters ⇒ prizes:

- ◊ e.g., British parliament (1714) "Longitude act"
- ◊ accuracy of 30 nautical miles (⇔ 120 s) ⇒ 20,000 £
- ◊ John Harrison (1693 – 1776)

More precise navigation
e.g. satellite navigation (GPS)


pulse emitted at t_0

ℓ

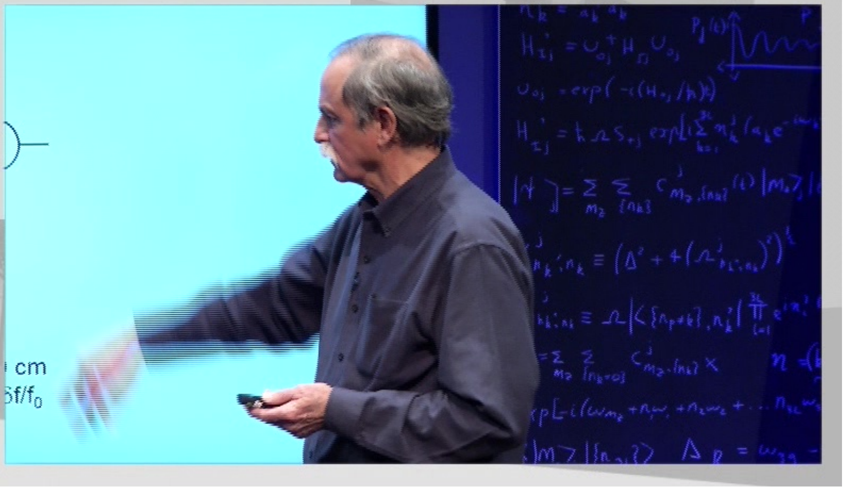
pulse received at t_1

$\ell = c \times (t_1 - t_0)$

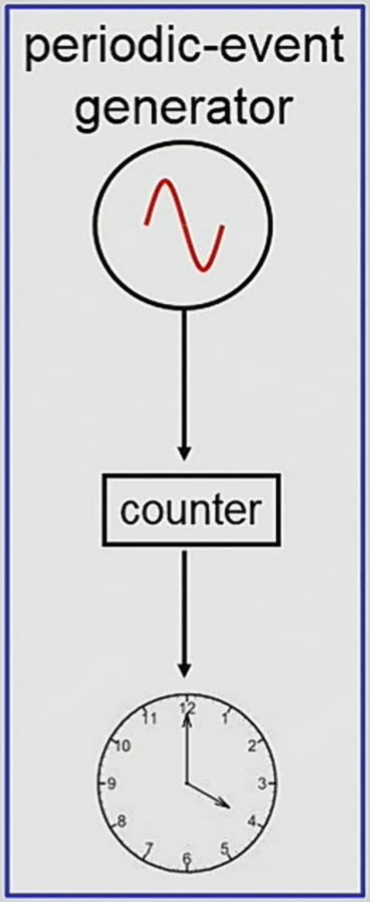
error: $\delta\ell = c\,\delta t$

for $\delta t = 10^{-9}$ s, $\delta\ell \cong 30$ cm

$(\delta t)/(1\text{ day}) = 10^{-14} \cong \delta f/f_0$

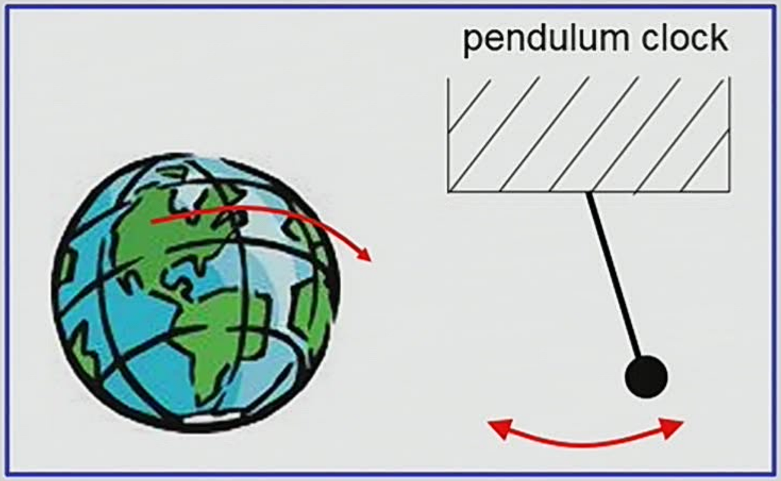


Clocks

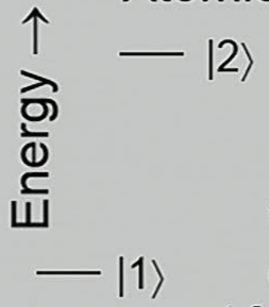

periodic-event generator

counter

Traditional periodic event-generators, or frequency references:

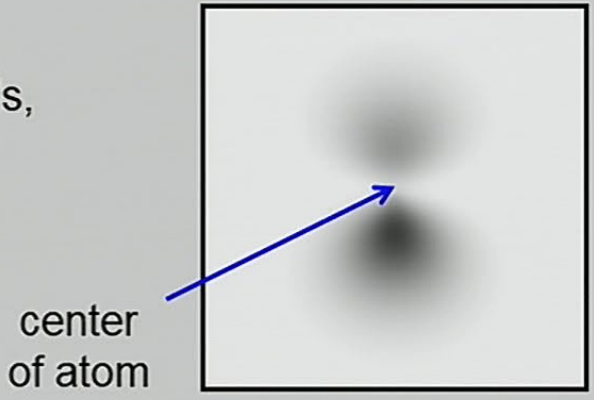


Atomic energy state superpositions act like pendulum clock

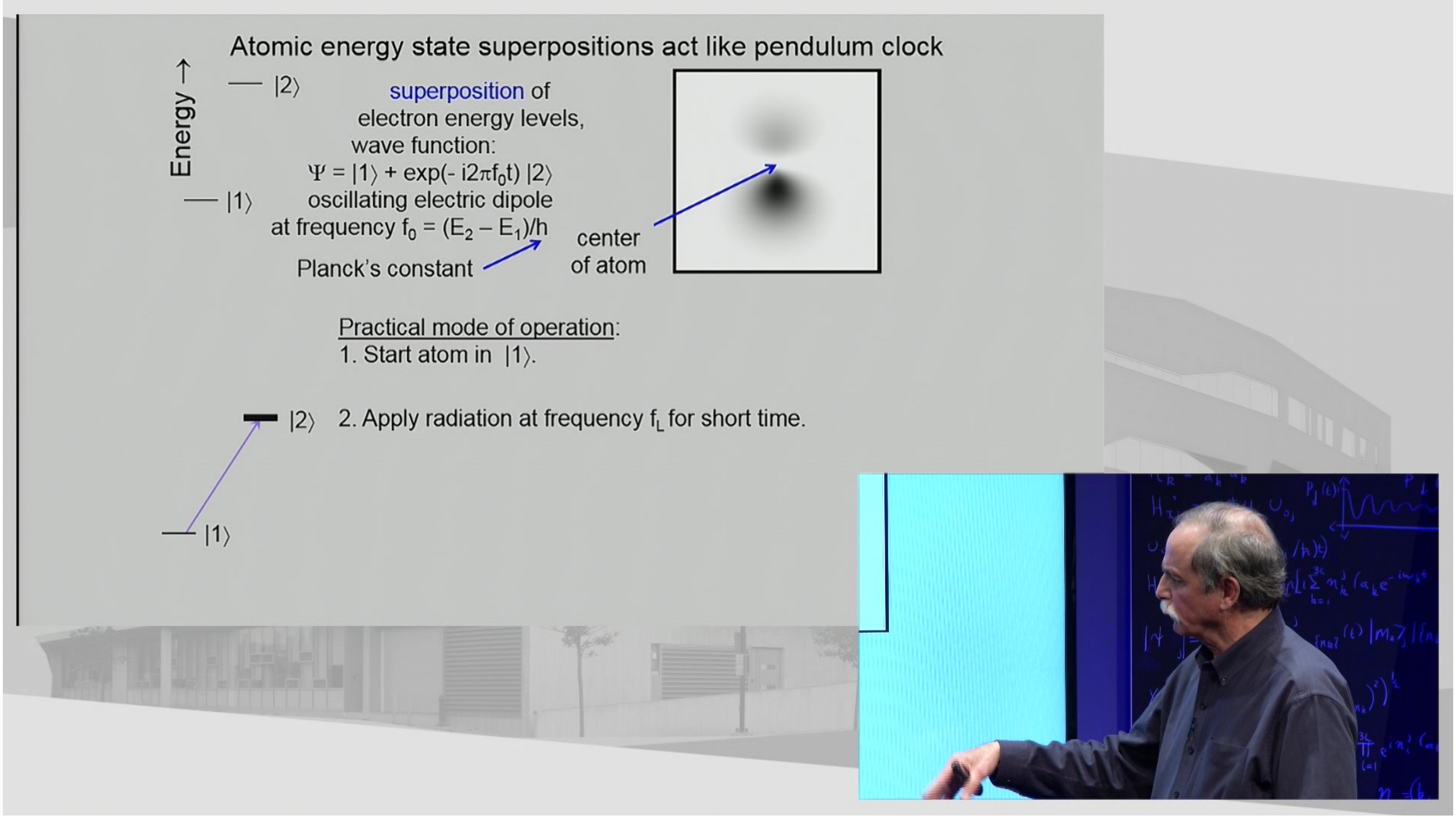


superposition of
electron energy levels,
wave function:
$\Psi = |1\rangle + \exp(-i2\pi f_0 t)\,|2\rangle$
oscillating electric dipole
at frequency $f_0 = (E_2 - E_1)/h$

Planck's constant



oscillating electron density



Atomic energy state superpositions act like pendulum clock

superposition of electron energy levels, wave function:

$\Psi = |1\rangle + \exp(-i2\pi f_0 t)\,|2\rangle$

oscillating electric dipole at frequency $f_0 = (E_2 - E_1)/h$

Planck's constant

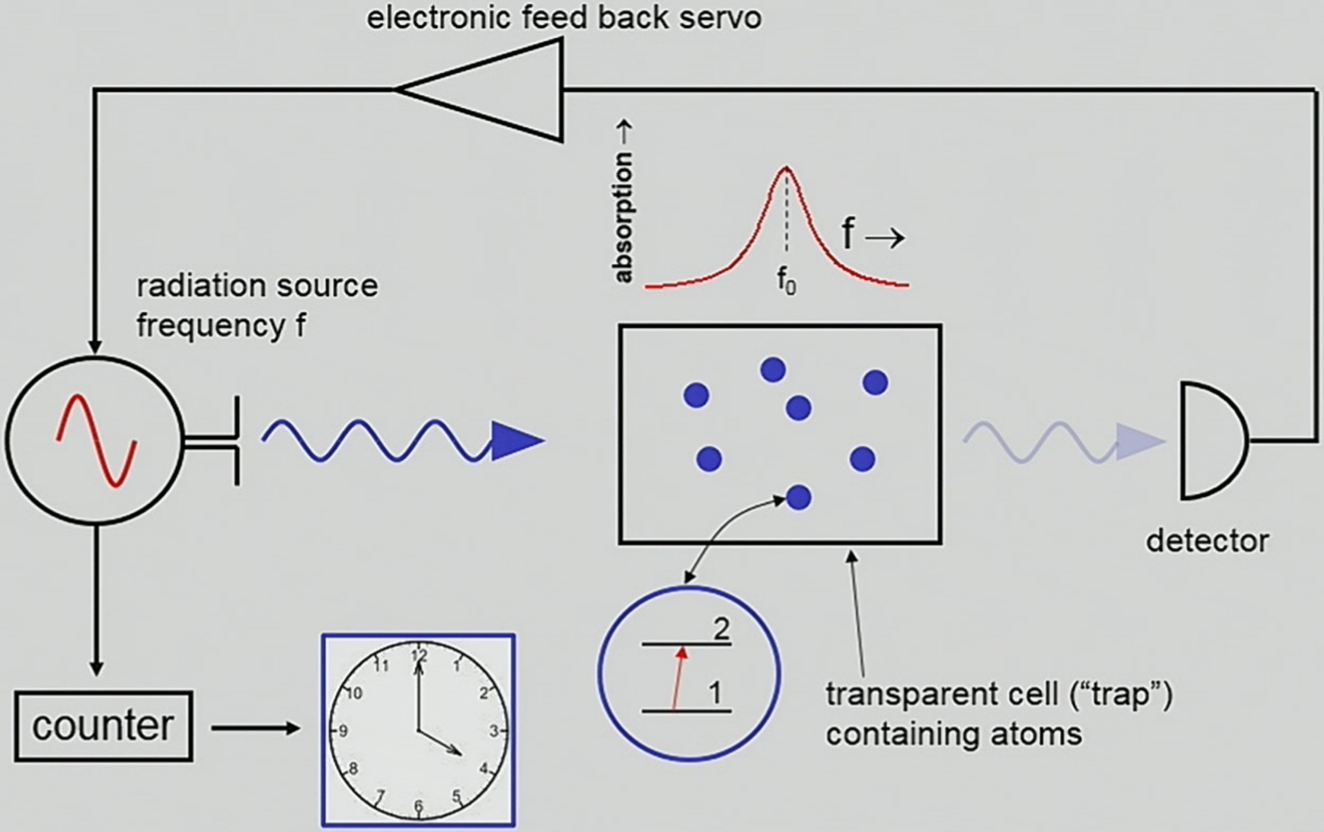
center of atom

Practical mode of operation:

1. Start atom in $|1\rangle$.

2. Apply radiation at frequency f_L for short time.

Atomic clock recipe



electronic feed back servo

absorption →

f →

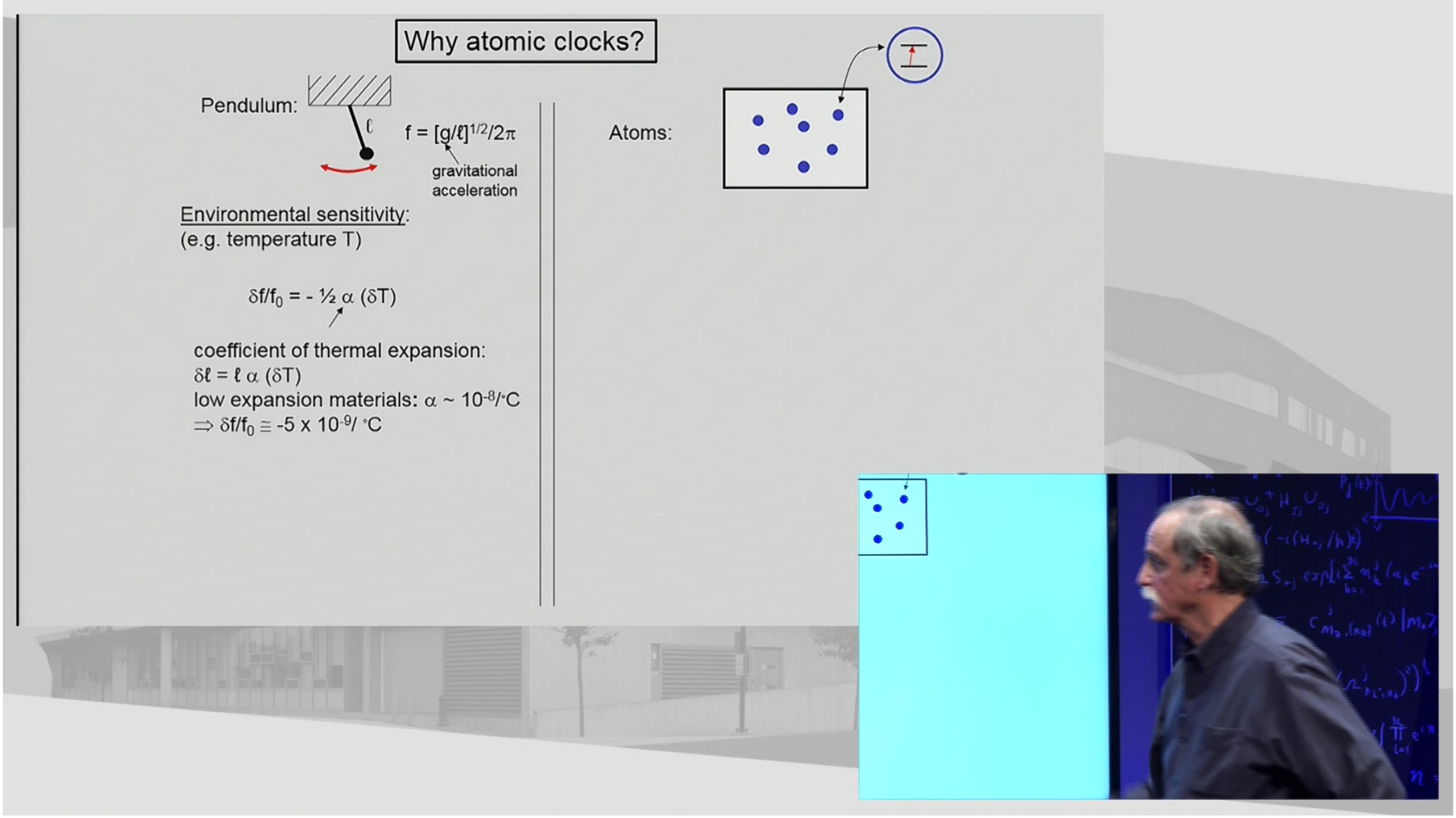
f_0

radiation source
frequency f

detector

counter

transparent cell ("trap")
containing atoms



Why atomic clocks?

Pendulum:

$f = [g/\ell]^{1/2}/2\pi$

gravitational acceleration

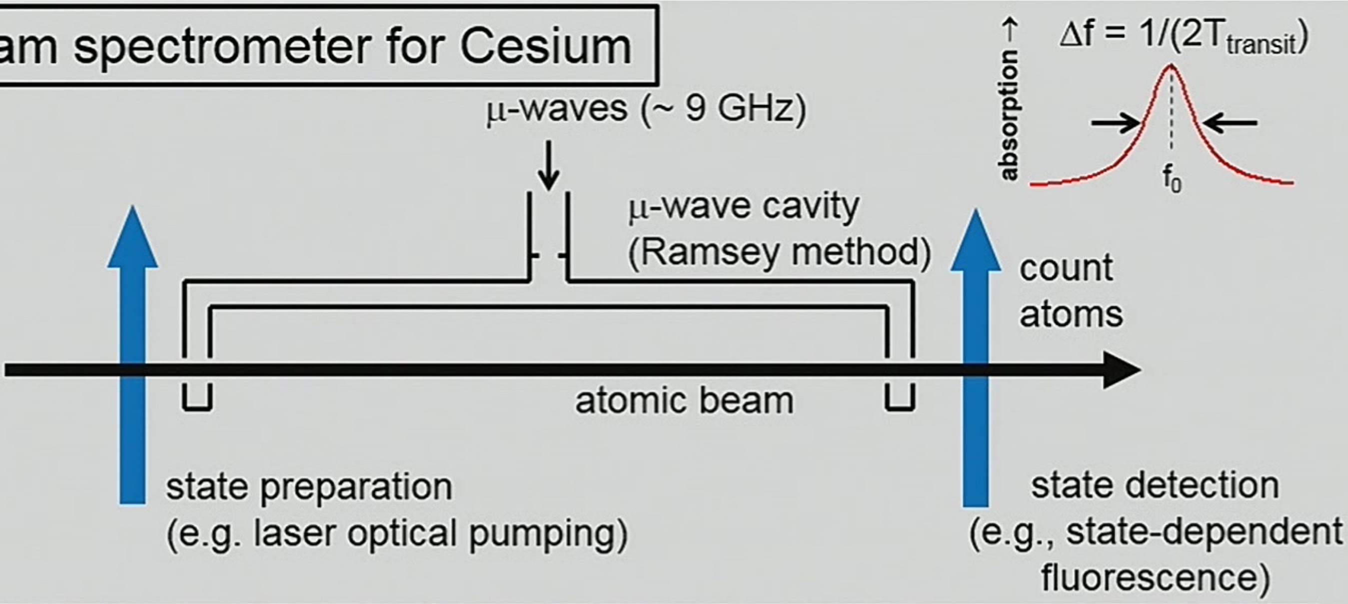
Environmental sensitivity:
(e.g. temperature T)

$$\delta f/f_0 = -\tfrac{1}{2}\,\alpha\,(\delta T)$$

coefficient of thermal expansion:
$\delta\ell = \ell\,\alpha\,(\delta T)$
low expansion materials: $\alpha \sim 10^{-8}/{}^\circ C$
$\Rightarrow \delta f/f_0 \cong -5 \times 10^{-9}/{}^\circ C$

Atoms:

Atomic beam spectrometer for Cesium



μ-waves (~ 9 GHz)

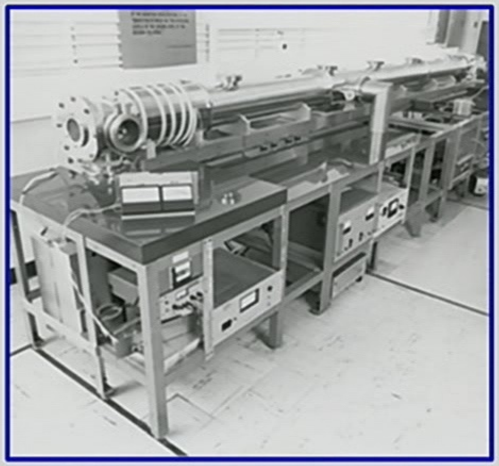
μ-wave cavity
(Ramsey method)

count
atoms

atomic beam

state preparation
(e.g. laser optical pumping)

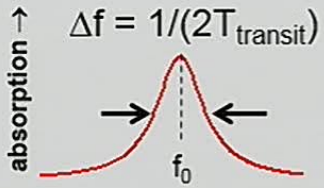
state detection
(e.g., state-dependent
fluorescence)



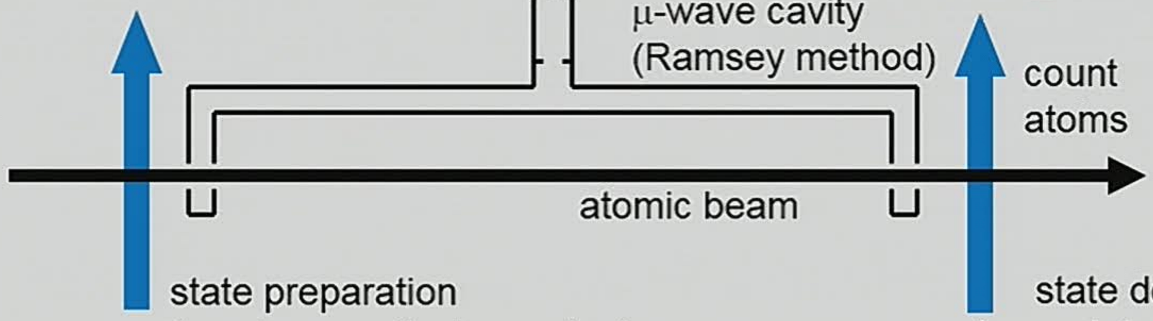
$\Delta f \sim 1/(2T_{transit})$

e.g., Cesium beam clock (hyperfine trans.)
$f_0 \equiv 9\,192\,631\,770$ Hz (microwaves)
e.g., NBS-6 (~ 1976)
L = 3.75 m, $\Delta f \cong 30$ Hz ($T_{transit} \sim 16$ ms)

Atomic beam spectrometer for Cesium



μ-waves (~ 9 GHz)



μ-wave cavity
(Ramsey method)

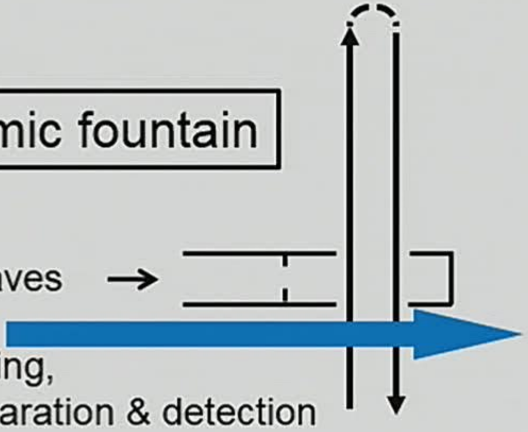
count
atoms

atomic beam

state preparation
(e.g. laser optical pumping)

state detection
(e.g., state-dependent
fluorescence)

Atomic fountain



μ-waves

atom cooling,
state preparation & detection

NIST F-1

$T_{transit} \cong 1$ s

Why optical atomic clocks?

- tick rate can be fast; e.g., for $^{199}Hg^{+}$ ($^{2}S_{1/2} \leftrightarrow {}^{2}D_{5/2}$)
  f_0 = 1 064 721 609 899 144.94 (97) Hz
- absorption range very narrow
  e.g., for $^{199}Hg^{+}$, $\Delta f_0 \cong 1.6$ Hz

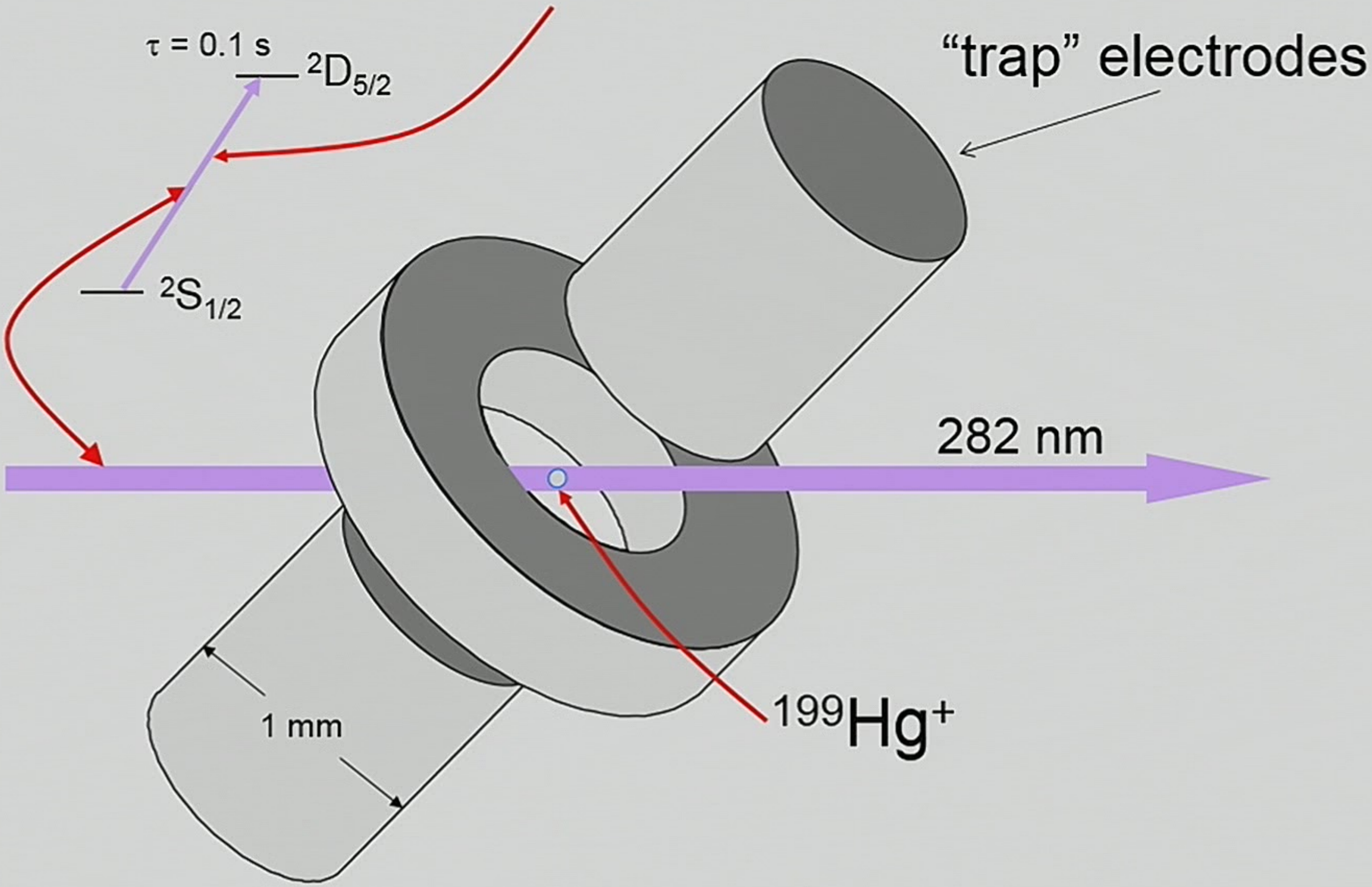
New idea?

From 1879 text written by Thompson (Lord Kelvin) and Tate,
(Idea attributed to Maxwell)

``The recent discoveries … indicate to us *natural standard* pieces of matter such as atoms of hydrogen or sodium, ready made in infinite numbers, all absolutely alike in every physical property. The time of vibration of a sodium particle corresponding to any one of its modes of vibration is known to be absolutely independent of its position in the universe, and it will probably remain the same so long as the particle itself exists."

W. F. Snyder, “Lord Kelvin on atoms as fundamental natural standards (for base units)” *IEEE Trans. Instrum. Meas.*, 99, 1973.

Hg^+ ion optical clock experiments at NIST (1981 →)



"optical clock" transition $\lambda = 282$ nm

$\tau = 0.1$ s

$^2D_{5/2}$

$^2S_{1/2}$

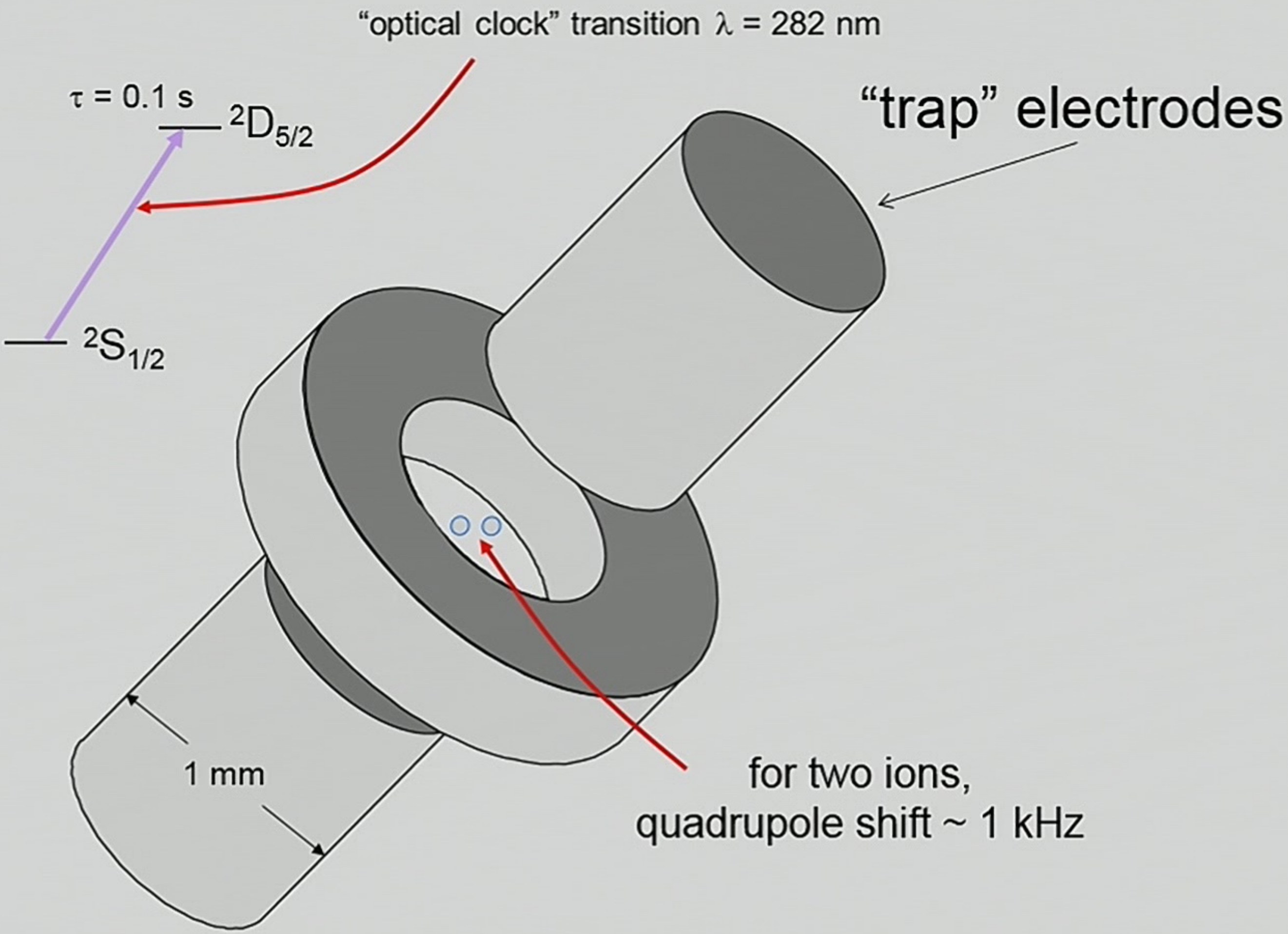
"trap" electrodes

282 nm

1 mm

$^{199}Hg^+$

Why just one ion? (single ions ⇒ smallest frequency shifts)



“optical clock” transition λ = 282 nm

τ = 0.1 s

$^2D_{5/2}$

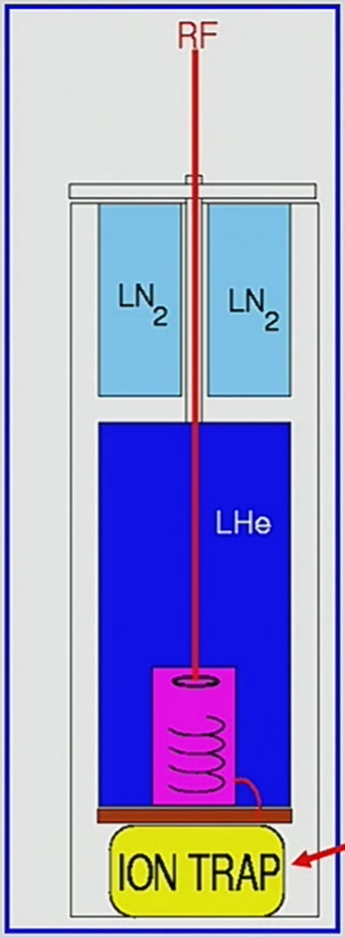
$^2S_{1/2}$

“trap” electrodes

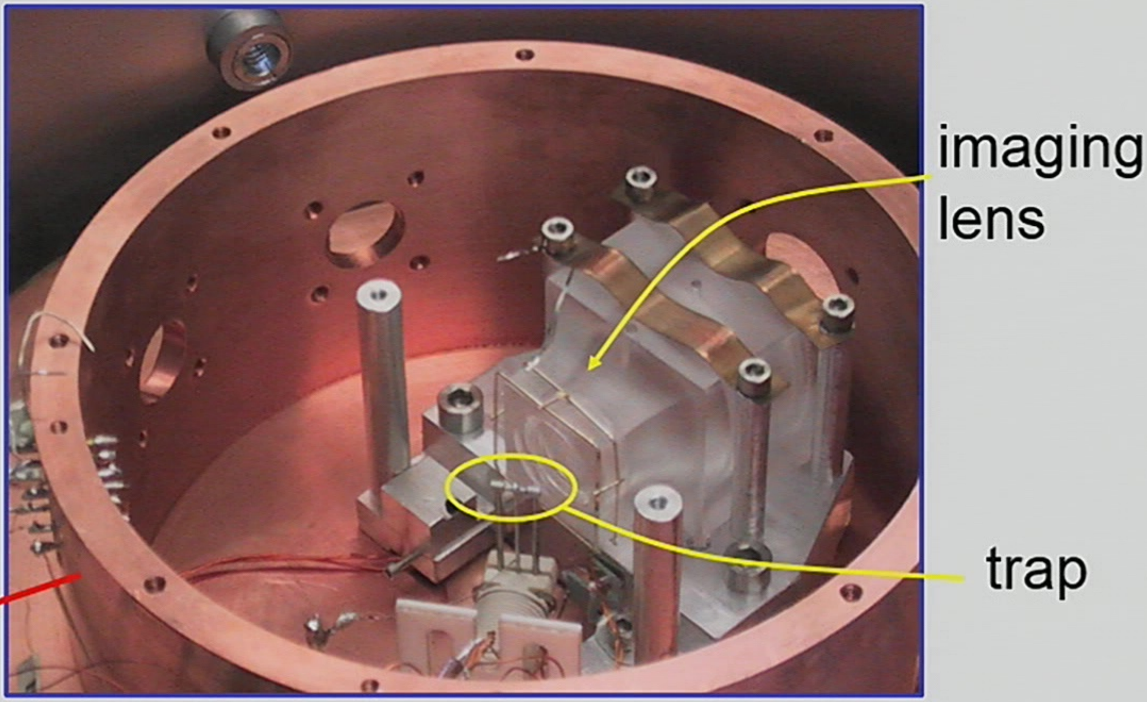
1 mm

for two ions,
quadrupole shift ~ 1 kHz

Ion "trap" in vacuum at liquid Helium temperature (4 K)

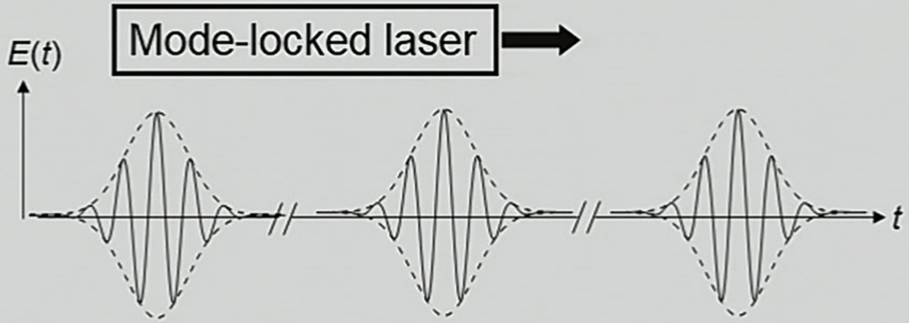


- suppresses ion loss ($T_{storage}$ ~ 6 months)
- suppresses heating, perturbations from collisions
- reduces blackbody radiation shifts



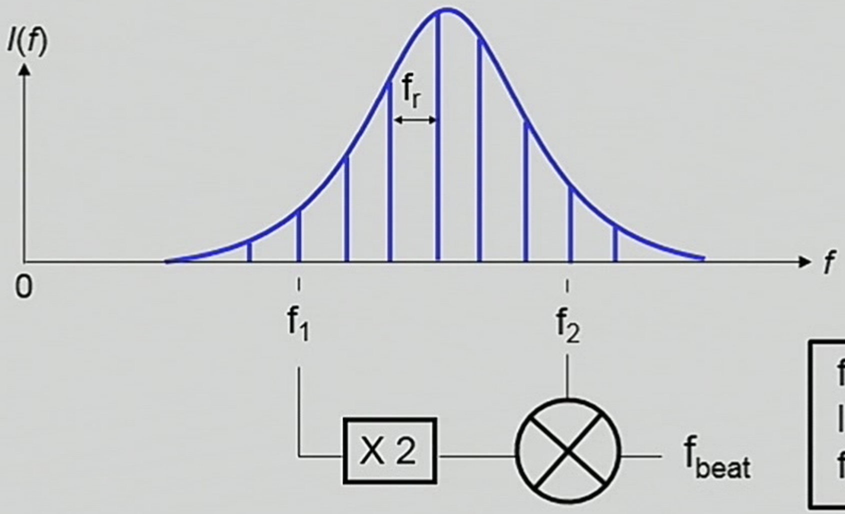
Frequency counters, after 2000

Mode-locked laser ➡



synchronize carrier
phase with pulse phase

Frequency domain



feed back on
laser to make
$f_{beat} \to 0$

$f_2 = 2 f_1$

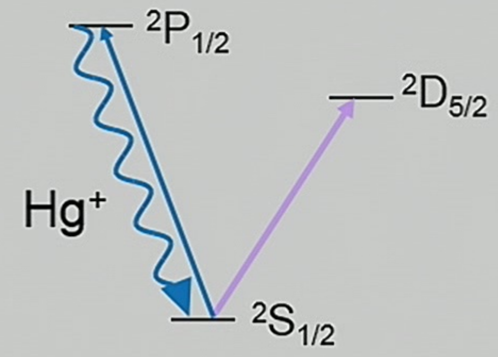
$f_1 = M f_r$

!

T. Hänsch, J. Hall *et al.*

Single $^{199}Hg^+$ ions for (optical) clocks:

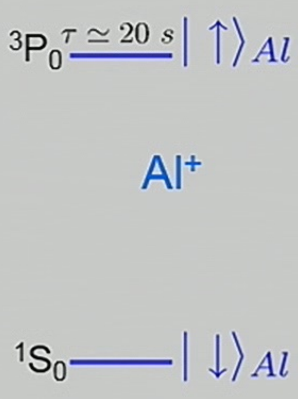
J. C. Bergquist et al., (NIST)1981 →



Jim Bergquist

- trapping ⇒ first-order Doppler shift → 0
- laser cooling ⇒ time dilation small
- trapping in high vacuum at 4 K
  ⇒ small environmental perturbations (collisions, black body shifts, etc.)

Al$^+$ “quantum-logic clock” (T. Rosenband, D. Lebrandt et al.)



$^3P_0$ $\tau \simeq 20\ s$ $|\uparrow\rangle_{Al}$

Al$^+$

$^1S_0$ $|\downarrow\rangle_{Al}$

Till Rosenband

David Leibrandt

Systematic frequency shifts

Example: relativistic effects in measurement

Doppler shifts: $\Delta f/f_0 = \langle v\rangle/c - \frac{1}{2}\langle v^2\rangle/c^2$

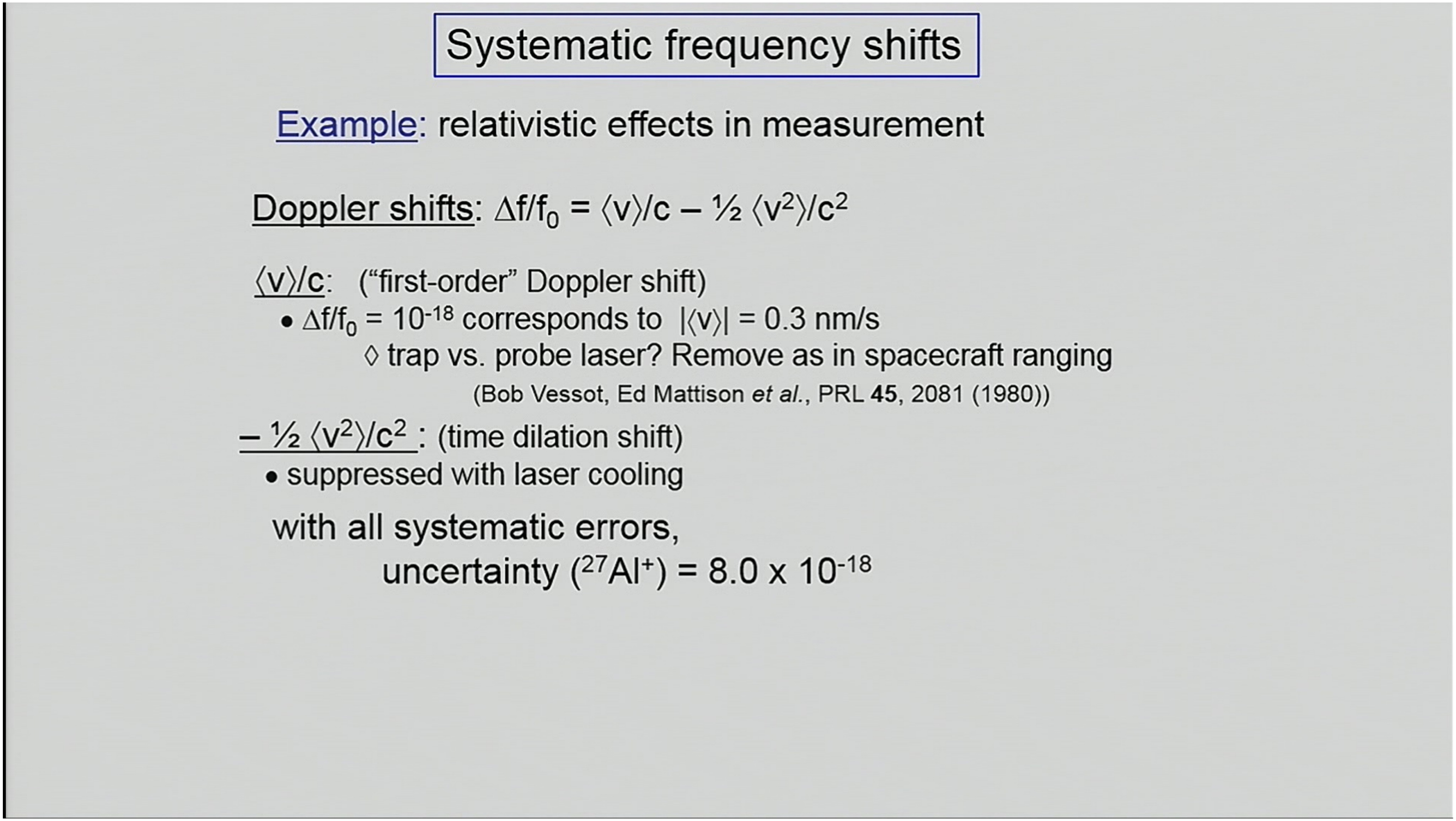
$\langle v\rangle/c$: ("first-order" Doppler shift)

- $\Delta f/f_0 = 10^{-18}$ corresponds to $|\langle v\rangle| = 0.3$ nm/s
  - ◊ trap vs. probe laser? Remove as in spacecraft ranging

    (Bob Vessot, Ed Mattison *et al.*, PRL **45**, 2081 (1980))

$-\frac{1}{2}\langle v^2\rangle/c^2$: (time dilation shift)

- suppressed with laser cooling



Systematic frequency shifts

Example: relativistic effects in measurement

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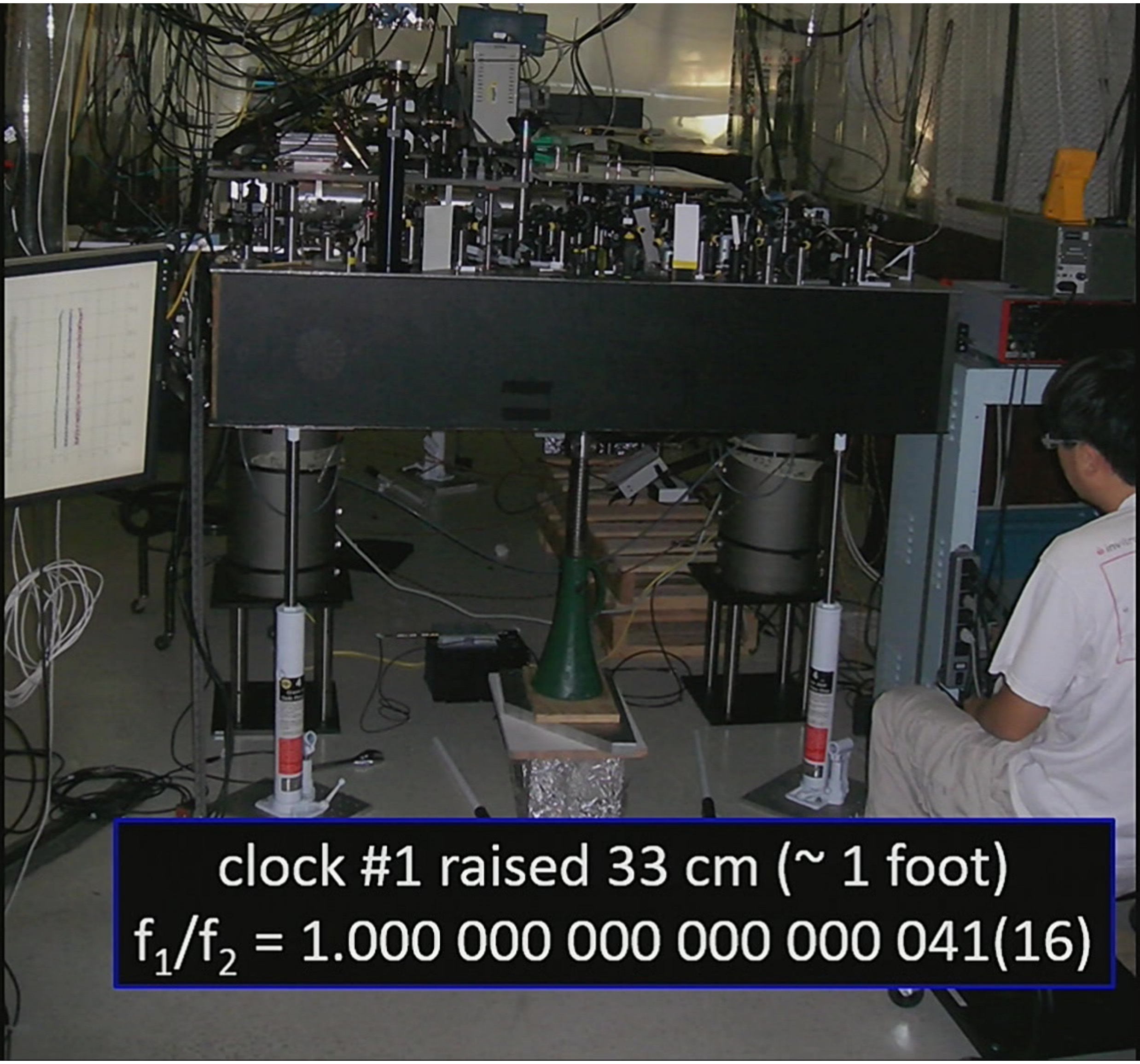
(Bob Vessot, Ed Mattison *et al.*, PRL **45**, 2081 (1980))

$- \frac{1}{2}\langle v^2\rangle/c^2$: (time dilation shift)

- suppressed with laser cooling

with all systematic errors,

uncertainty ($^{27}Al^+$) = 8.0×10^{-18}



clock #1 raised 33 cm (~ 1 foot)

$f_1/f_2 = 1.000\,000\,000\,000\,000\,041(16)$

Moving target!

Jun Ye's group (JILA), Sr neutral atoms in optical lattice:

$\Delta f/f_0$(systematic) = ~~6.4~~ 2.1 x 10^{-18}

(B. J. Bloom et al., *Nature* **506**, 71 (2014))

$\Delta T \approx 30$ mK

PTB, Braunschweig, Germany

$\Delta f/f_0$(systematic) = 3.3 x 10^{-18}

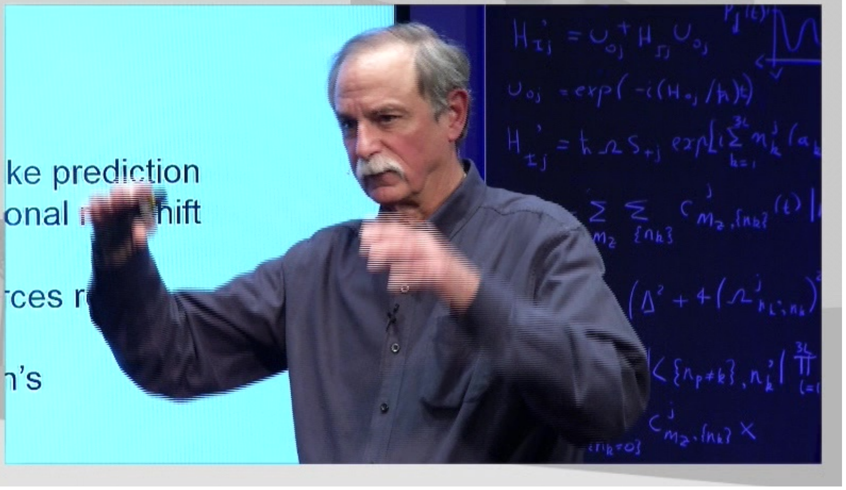
weak (octupole) transition, laser Stark shifts, …

H. Katori group (Riken) Sr neutral atoms in optical lattice

$\Delta f/f_0$(systematic) = 7.2 x 10^{-18} (arXiv:1405.4071)

Future?

- “Navigation” at < 1 cm scale:
  - Measure earth strain – earthquake prediction
  - geodesy: map earth via gravitational red shift
- Fundamental science:
  - are the strengths of the basic forces really constant in time?
  - possible deviations from Einstein’s general relativity?



NIST “IONS” June 2014

Jim Bergquist, John Bollinger, Joe Britton, Justin Bonet, Ryan Bowler, John Gaebler, Andrew Wilson, Dave Wineland, David Leibrandt, Peter Burns, Raghu Srinivas, Shon Cook, Robert Jordens

David Hume Ting Rei Tan

Shlomi Kotler, Dustin Hite, Katie McCormick ,Susanna Todaro, Leif Waldner, Yiheng Lin, Daniel Slichter, James Chou, David Allcock, Didi Leibfried, Jwo-Sy Chen, Sam Brewer, Kyle McKay

Not pictured: Brian Sawyer, Till Rosenband, Wayne Itano, Dave Pappas, Bob Drullinger