Title: Time And Gravity Measurement

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Abstract:

Optical atomic clocks and gravity measurements

Pierre Dubé

National Research Council Canada

PI - NRC Meeting
Perimeter Institute
Waterloo, Canada, 7–8 May 2018
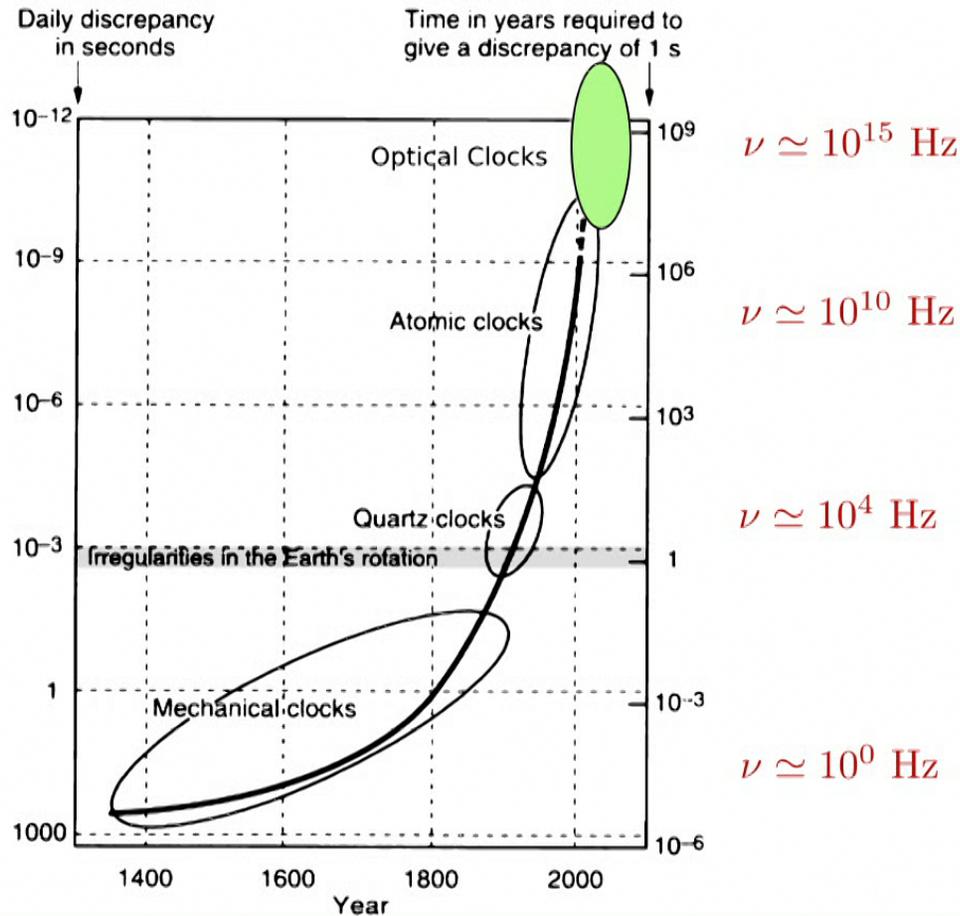
National Research Council Canada   Conseil national de recherches Canada

Canada

Outline

- Introduction to optical atomic clocks

- The $^{88}\text{Sr}^+$ ion clock at NRC

- Gravitational potential measurements

- Variation in the fundamental constants

- Outlook

Evolution of the accuracy of clocks

Daily discrepancy in seconds

Time in years required to give a discrepancy of 1 s

$$\nu \simeq 10^{15}\ \mathrm{Hz}$$

$$\nu \simeq 10^{10}\ \mathrm{Hz}$$

$$\nu \simeq 10^{4}\ \mathrm{Hz}$$

$$\nu \simeq 10^{0}\ \mathrm{Hz}$$

Optical Clocks

Atomic clocks

Quartz clocks

Irregularities in the Earth's rotation

Mechanical clocks

Year

The accuracy of clocks has historically been correlated with an increase in operating frequency...

$\Rightarrow$ Optical frequencies

This is one of several key requirements for ultra-high accuracy clock operation.

Adapted from: C. Audoin and B. Guinot, *The Measurement of Time*, and E. Peik, Tutorial, EFTF 2018.

Quantum advantage

Nature-provided frequencies:

- Quantum reference
- Frequencies determined by physical constants
  - ▶ *not artifacts*
  - ▶ *reproducible, universal references*
- SI second defined as a hyperfine transition in ^{133}Cs

Selection of a transition:

- High-frequency (optical): $\nu_0 \sim 10^{15}$ Hz
- Electric dipole forbidden: $\Delta\nu \lesssim 1$ Hz
- $Q \gtrsim 10^{15}$
- Small sensitivity to external perturbations

$$Q = \frac{\nu_0}{\Delta\nu}$$
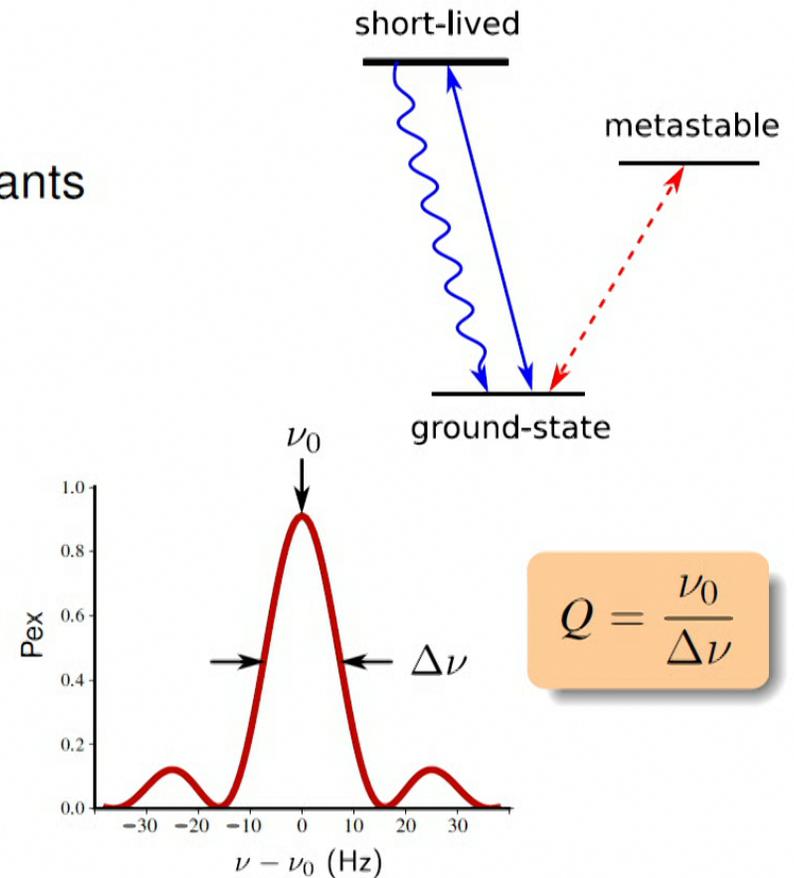
Some atomic systems investigated

Ion Clocks	Optical Lattice Clocks
^{27}Al$^+$	^{24}Mg
^{40}Ca$^+$	^{87}Sr
^{88}Sr$^+$	^{171}Yb
^{115}In$^+$	^{199}Hg
^{171}Yb$^+$	
^{199}Hg$^+$	

Challenges

- Atomic motion

- Detection of a forbidden transition

- Ultra-stable laser source

- Counting of optical frequencies

- Control and evaluation of the systematic shifts

Control of atomic motion – Laser cooling

$$T_{\min} = \frac{\hbar\gamma}{2k_B}$$

for $\omega_L - \omega_0 \simeq -\frac{\gamma}{2}$

$T_{\min} \sim$ mK
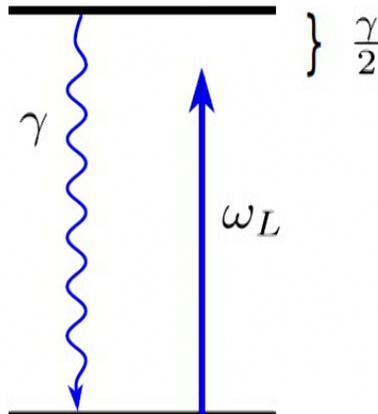
Nobel Laureates 1989 and 2012

Steve Chu

Bill Phillips

Claude Cohen-Tannoudji
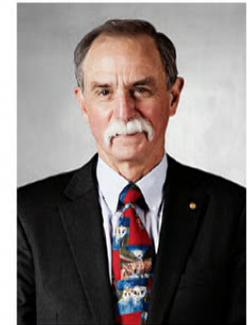
Dave Wineland

We report the first observation of radiation-pressure cooling on a system of resonant absorbers which are elastically bound to a laboratory fixed apparatus. Mg II ions confined in a Penning electromagnetic trap are cooled to <40 K by irradiating them with the 8-μW output of a frequency doubled, single-mode dye laser tuned to the low-frequency side of the Doppler profile on the ${}^2S_{1/2} \longleftrightarrow {}^2P_{3/2}$ ($M_J = +\frac{1}{2} \longleftrightarrow M_J = +\frac{3}{2}$ or $M_J = -\frac{1}{2} \longleftrightarrow M_J = -\frac{3}{2}$) transitions. Cooling to approximately 10^{-3} K should be possible.
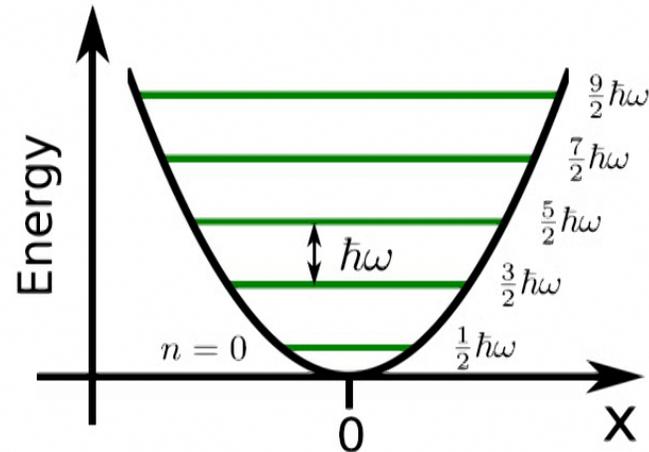
Ion trapping

Endcap

Ring

Endcap
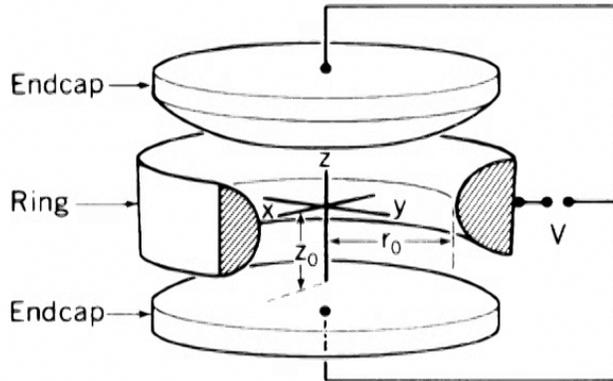
Benefits:

- No Doppler broadening
- Unlimited interaction times
- Well-controlled environment
- $\lesssim 10^{-18}$ uncertainty possible
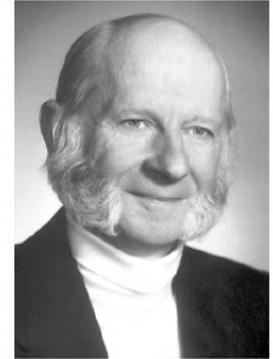
rf (ϕ) and pseudo (ψ) potentiels:

$$\phi(r, z, t) = A_0 \cos \Omega t \left(r^2 - 2z^2\right)$$

$$\psi(r, z) = \frac{k_r}{2e} \langle r \rangle^2 + \frac{k_z}{2e} \langle z \rangle^2$$

Energy

$\frac{9}{2}\hbar\omega$

$\frac{7}{2}\hbar\omega$

$\frac{5}{2}\hbar\omega$

$\hbar\omega$

$\frac{3}{2}\hbar\omega$

$n = 0$ $\frac{1}{2}\hbar\omega$

0

X

Secular frequency:
$\omega/2\pi \sim$ MHz

1989 Nobel Laureates

Hans Dehmelt

Wolfgang Paul

Atom in a box – Lamb-Dicke Confinement

Consequences:

- $\langle v \rangle = 0$ for each atom (lab bound)
- Motion modulated at secular frequencies ω_x, ω_y, ω_z
- Doppler-free carrier

Sideband intensities $= J_l^2(kx)$

$$kx = \left(\frac{2\pi}{\lambda}\right) a_0 \sqrt{2\langle n \rangle + 1}$$

$$\langle n \rangle \simeq k_B T / \hbar \omega$$

Lamb-Dicke condition:
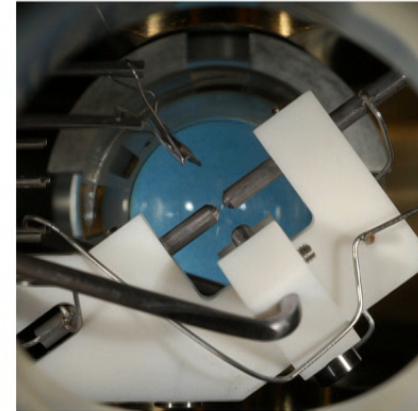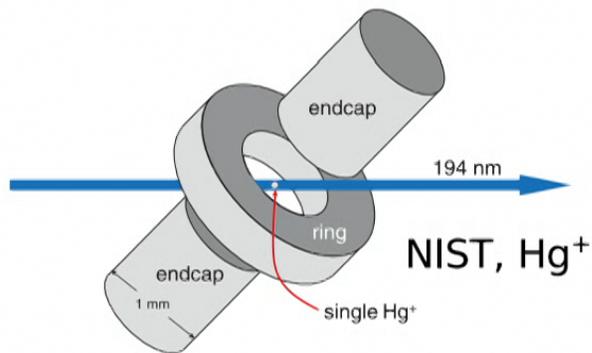
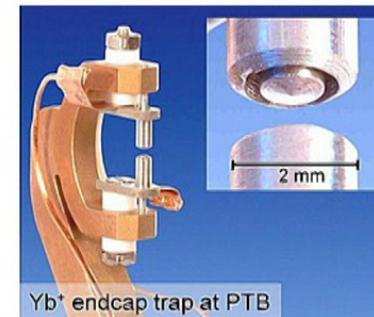$$kx \ll 1 \quad \Rightarrow \quad J_0^2(kx) \simeq 1$$

$\omega/2\pi = 0.4$ MHz
$kx = 1.6$
$T = 2.0$ mK

$\omega/2\pi = 1.0$ MHz
$kx = 0.6$

Free atom (Doppler)
Trapped atom

$\omega/2\pi = 2.0$ MHz
$kx = 0.3$

Doppler-free and recoil-free carrier

Frequency (MHz)

Common ion trap designs

Shield

Endcap

$V_0 \cos(\Omega t)$

NPL

NPL, Sr$^+$

NRC, Sr$^+$

endcap

194 nm

ring

endcap
1 mm

single Hg$^+$

NIST, Hg$^+$

Innsbruck, Ca$^+$

Yb$^+$ endcap trap at PTB

2 mm
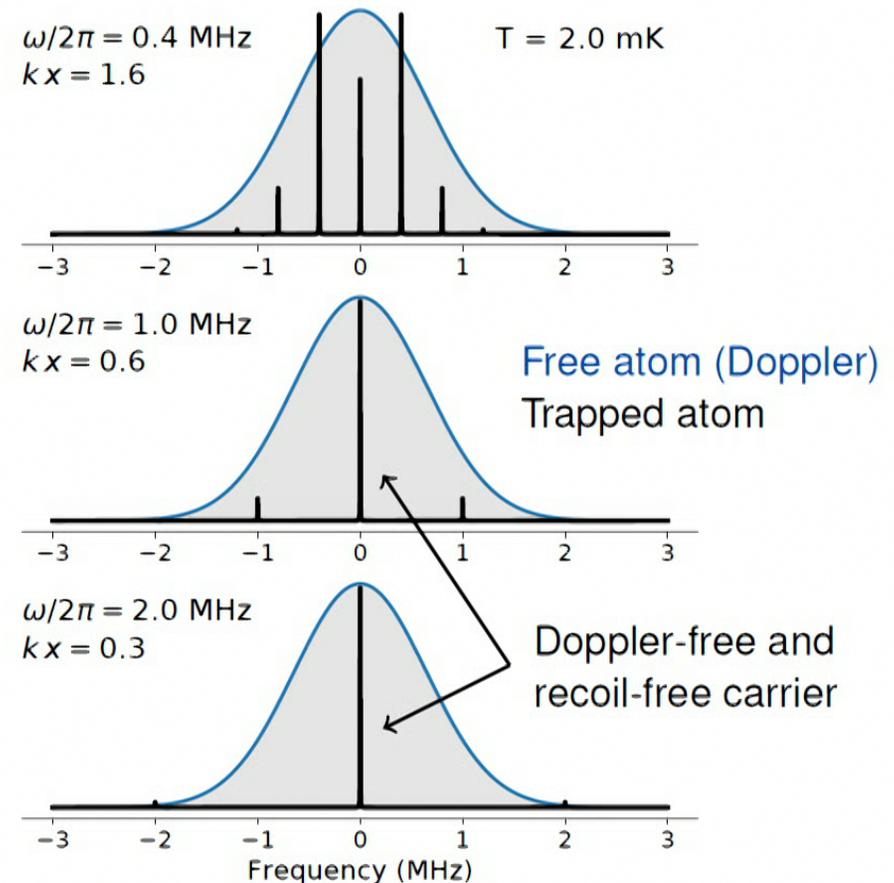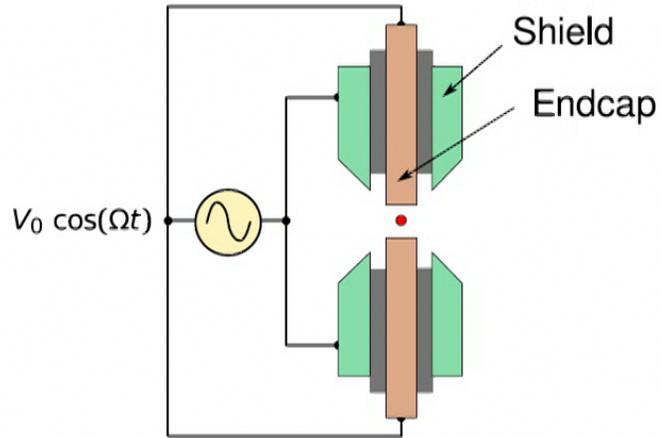
PTB, Yb$^+$

Detection of forbidden transitions
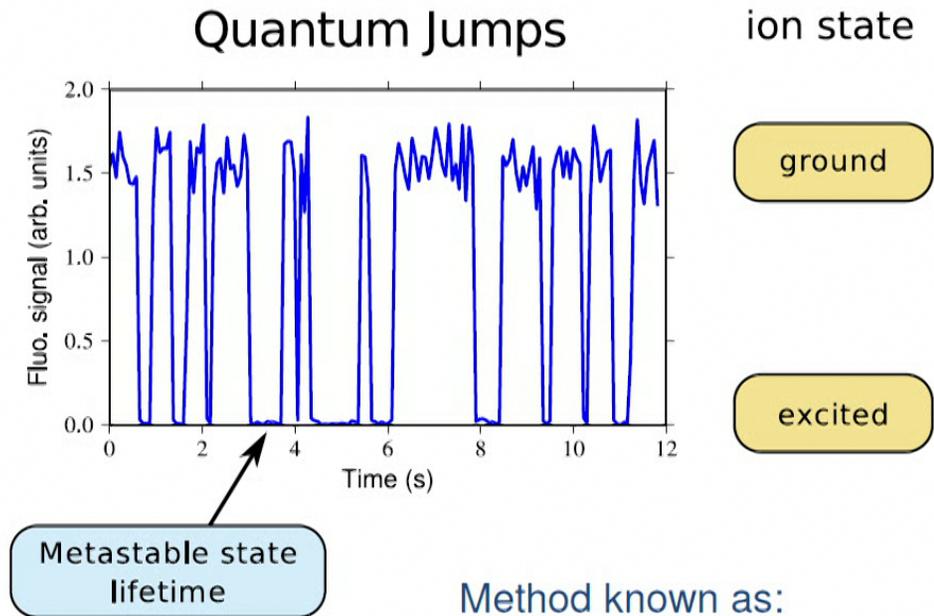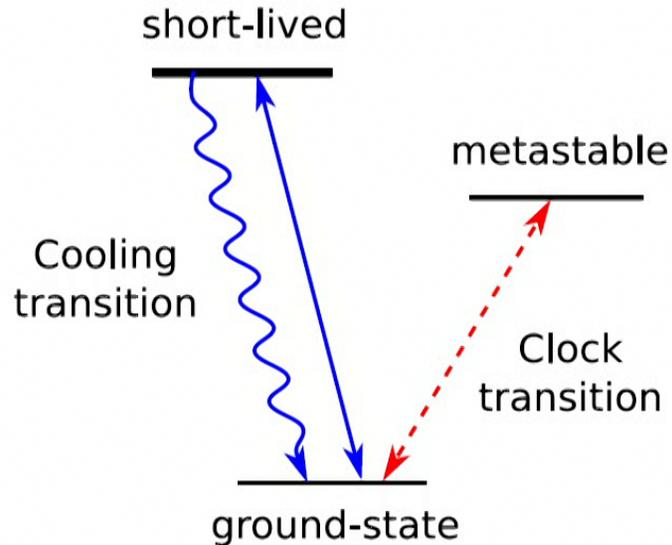
short-lived

metastable

Cooling
transition

Clock
transition

ground-state

Quantum Jumps

ion state

ground

excited

Metastable state
lifetime

Early observations of quantum jumps:

- W. Nagourney *et al.*, PRL, **56**, 2797 (1986)
- Th. Sauter *et al.*, PRL, **57**, 1696 (1986)
- J.C. Bergquist *et al.*, PRL, **57**, 1699 (1986)

Method known as:
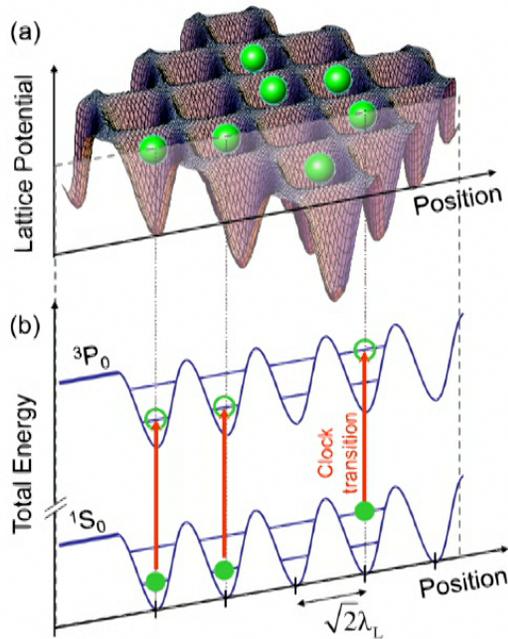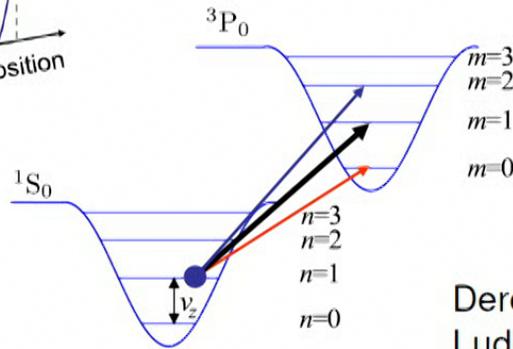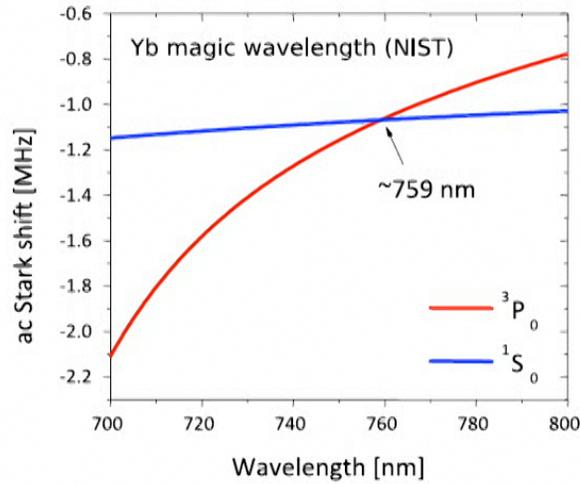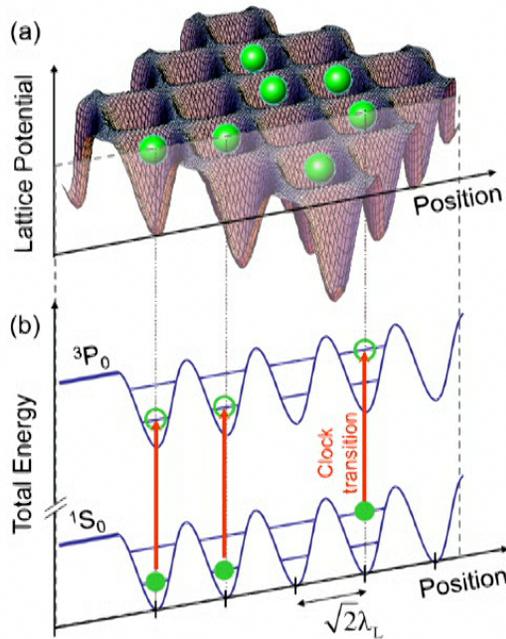
- Quantum jump
- Electron shelving

short-lived

metastable

Cooling transition

Clock transition

ground-state

Quantum Jumps

ion state

ground

excited

Metastable state lifetime

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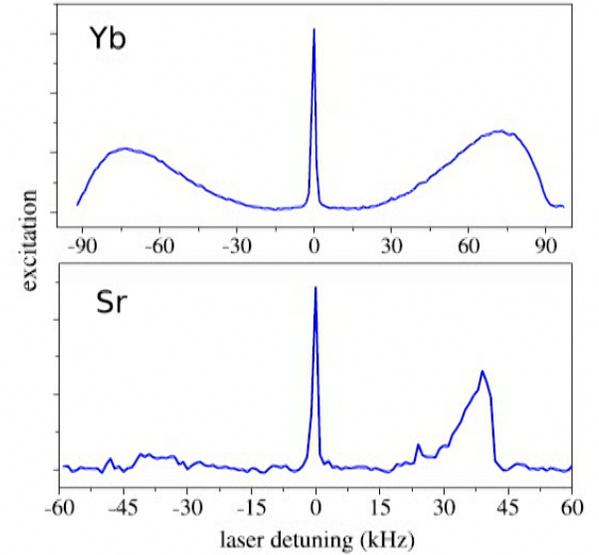- J.C. Bergquist *et al.*, PRL, **57**, 1699 (1986)

3.9 Hz

Optical lattice clocks

(a)

Lattice Potential

Position

(b)

Total Energy

$^3P_0$

Clock transition

$^1S_0$

$\sqrt{2}\lambda_L$

Position

Yb magic wavelength (NIST)

ac Stark shift [MHz]

~759 nm

$^3P_0$

$^1S_0$

Wavelength [nm]

Derevianko and Katori, Rev. Mod. Phys., **83**, 331 (2011)
Ludlow *et al.*, Rev. Mod. Phys., **87**, 637 (2015)

Optical lattice clocks

(a)

Lattice Potential

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Total Energy

$^3P_0$

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Clock transition

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$\sqrt{2}\lambda_L$

Yb magic wavelength (NIST)

ac Stark shift [MHz]

~759 nm

$^3P_0$

$^1S_0$

Wavelength [nm]

$^3P_0$

$^1S_0$

$m=3$
$m=2$
$m=1$
$m=0$

$n=3$
$n=2$
$n=1$
$n=0$

ν_z

Lamb-Dicke regime

Yb

excitation

Sr

laser detuning (kHz)

Advantage vs single ion:
number $\Rightarrow$ stability

Derevianko and Katori, Rev. Mod. Phys., **83**, 331 (2011)
Ludlow *et al.*, Rev. Mod. Phys., **87**, 637 (2015)

Optical lattice clocks vs Single ion clocks
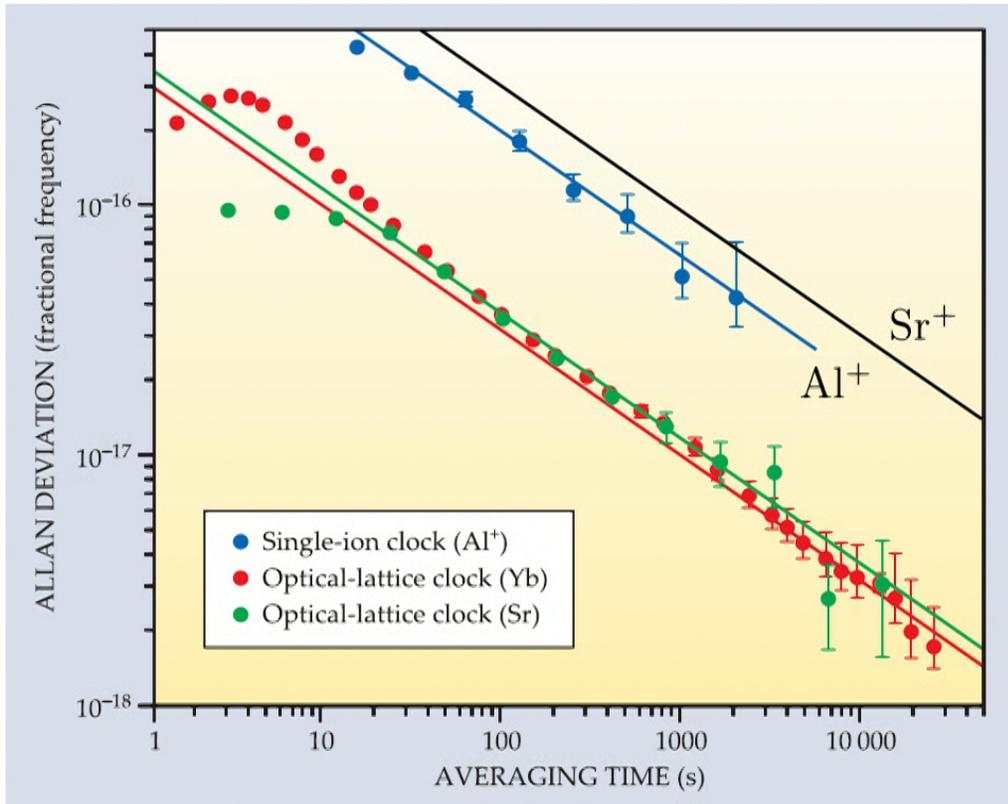
Adapted from A.G. Smart, Phys. Today 67, No. 3, 12 (2014).

Stability (Allan deviation) :

$$\sigma_y(\tau) \simeq \frac{\Delta\nu}{\nu_0}\sqrt{\frac{T_c}{N\tau}}$$

$N = 1$	Single ion
$N \sim 10^3$	Optical lattice

Accuracy records (2018):

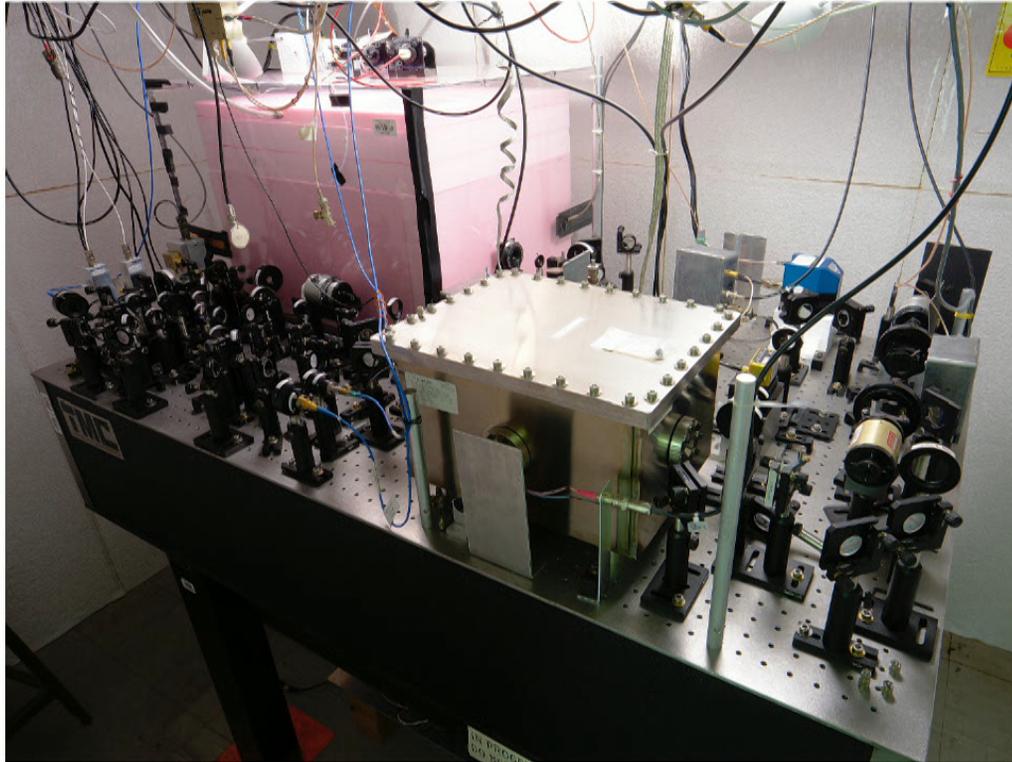|	
1×10^{-18}	$^{27}\text{Al}^+$ ion
1.2×10^{-18}	Yb olc

Pound-Drever-Hall laser stabilization
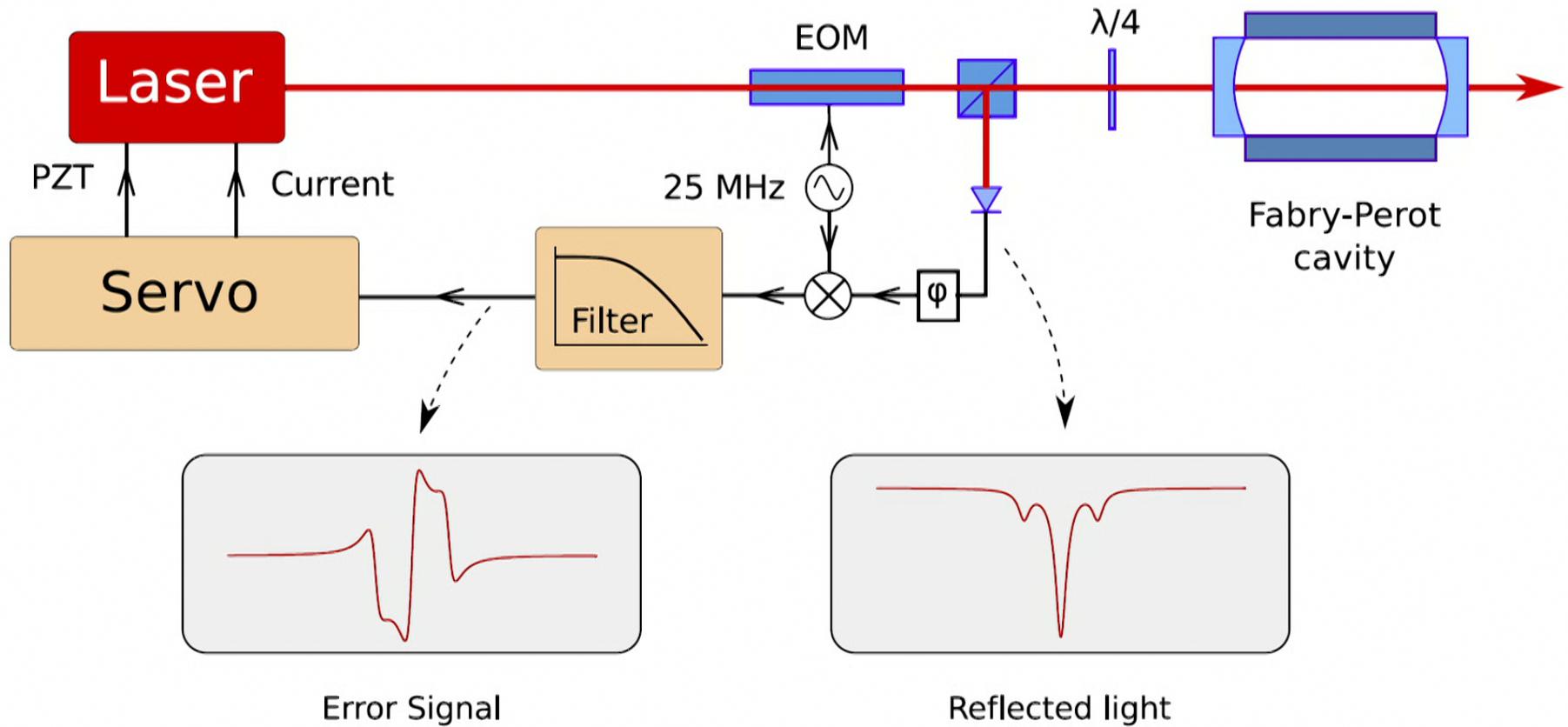
Ultra-stable reference cavities

http://www.stablelasers.com/
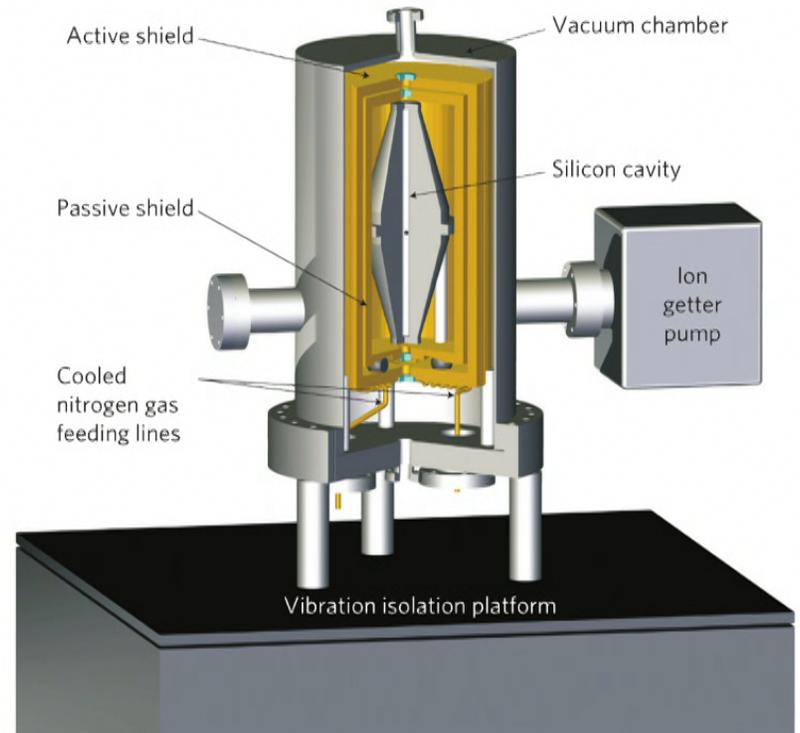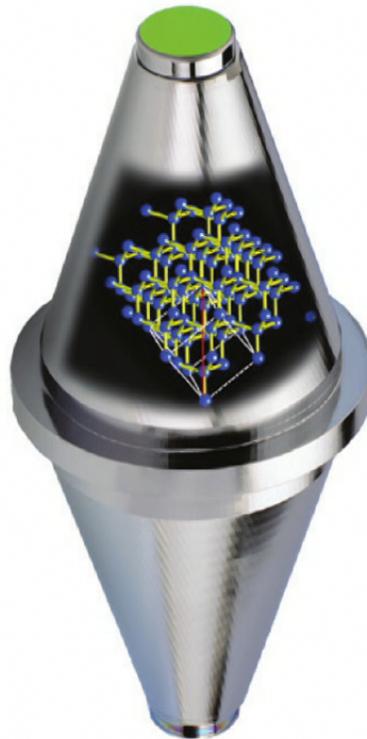
T. Kessler *et al.* Nat. Photon. 6, 687–692 (2012).

Thermal expansion
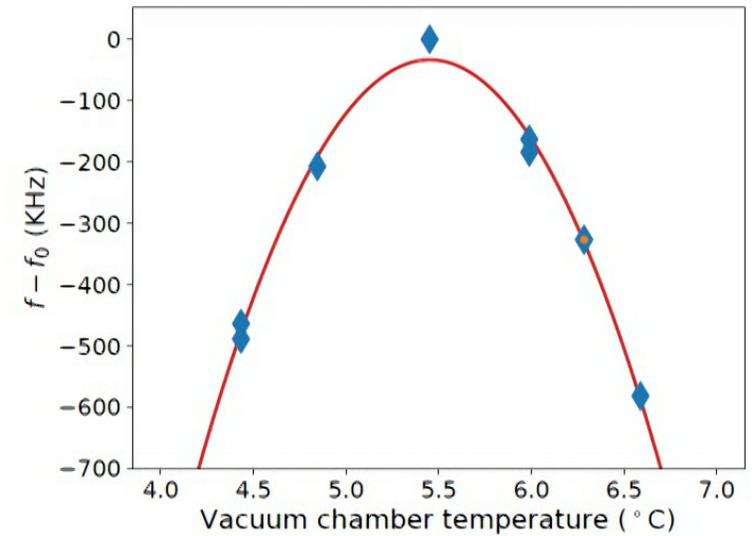
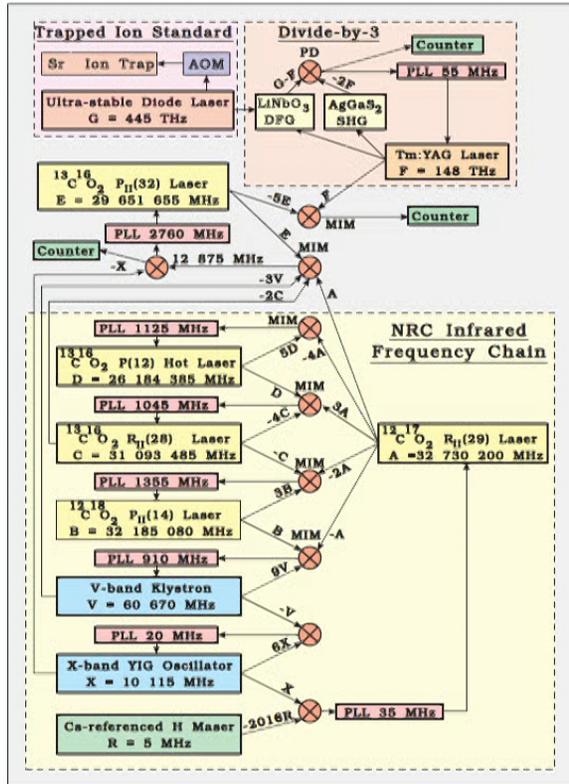**Cavity properties:**

- $T_0 = 5.45(1)\,^\circ$C
- $\alpha \lesssim 2 \times 10^{-11}/^\circ$C
- Isothermal creep $= 2 \times 10^{-17}/s$

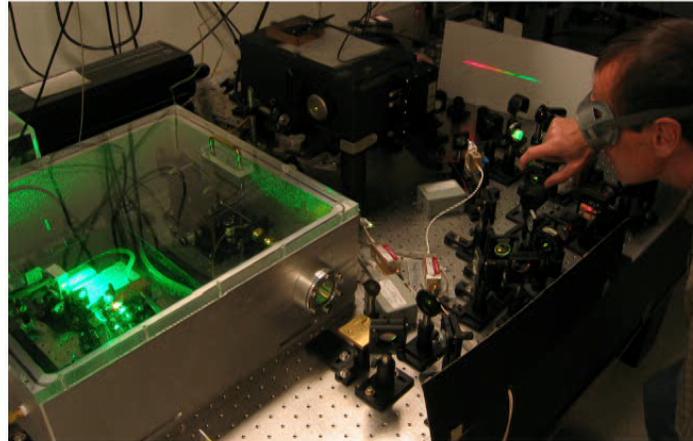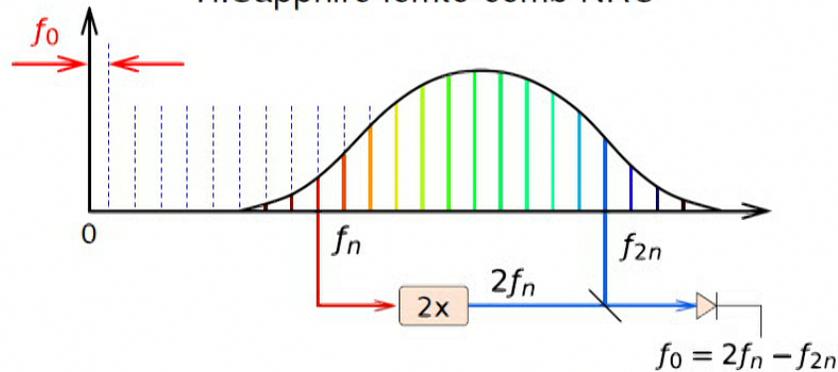# Counting optical frequencies

Before 2000

Frequency synthesis chain

Since 2000

Ti:Sapphire femto-comb NRC
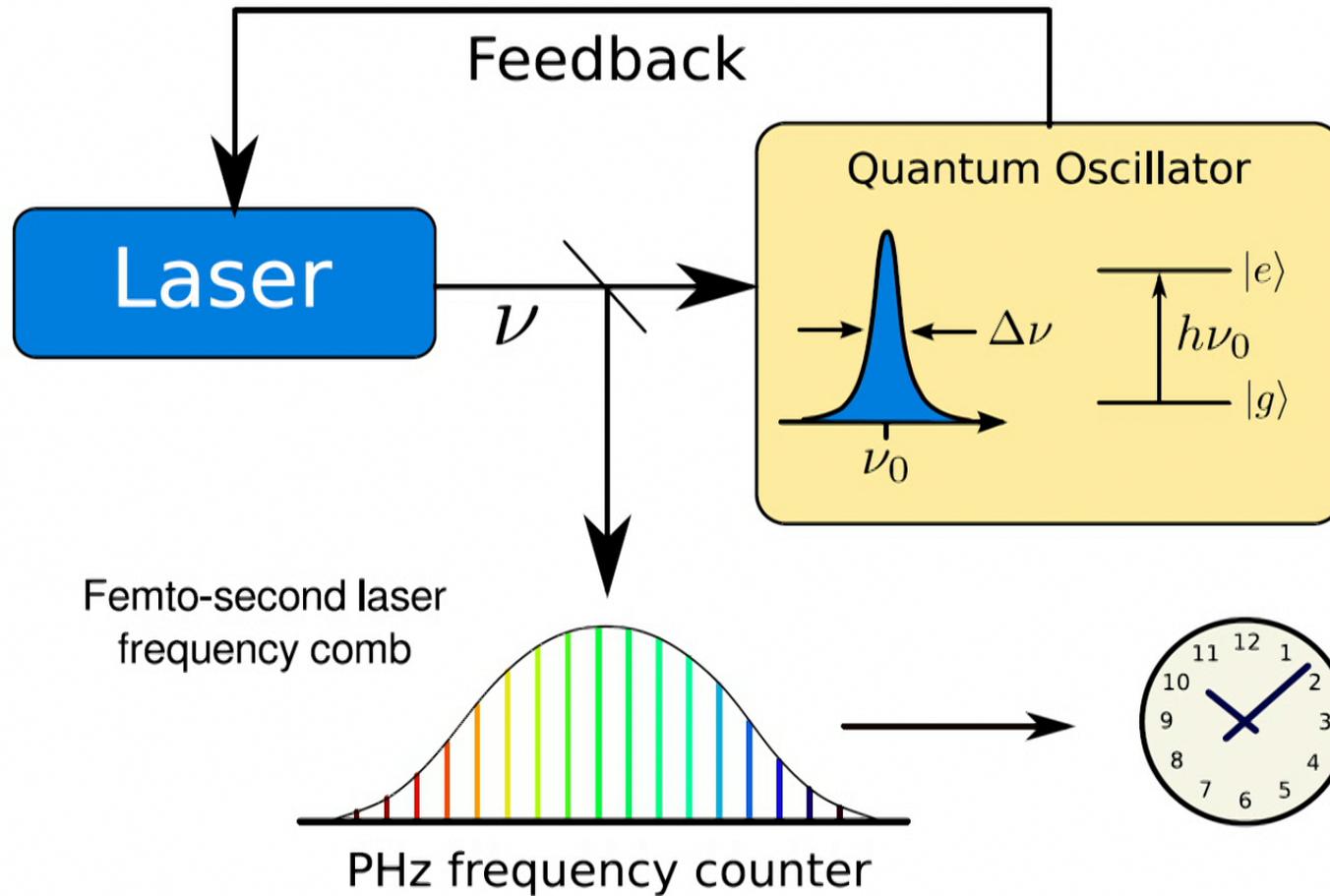

$$f_0 = 2f_n - f_{2n}$$

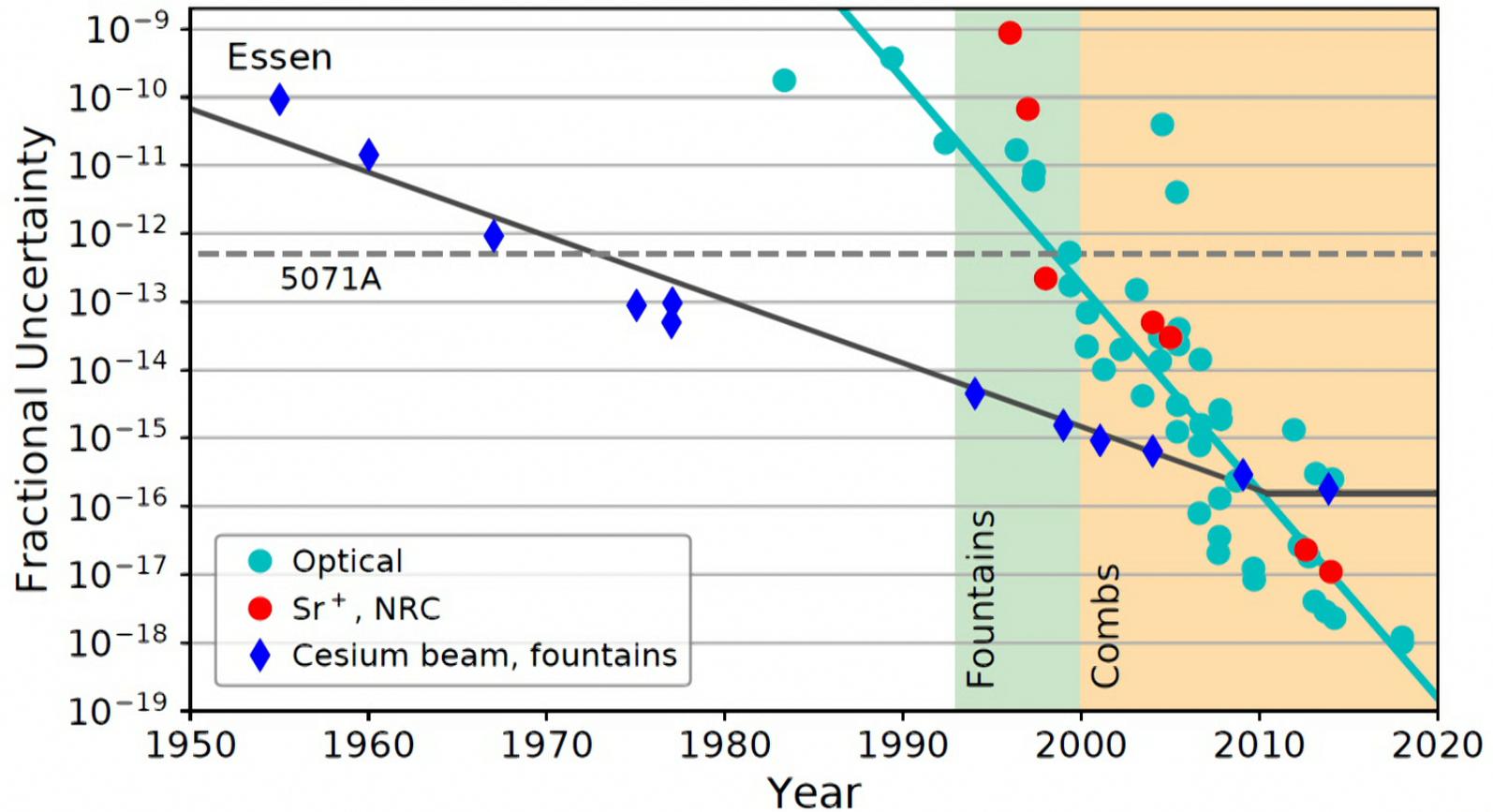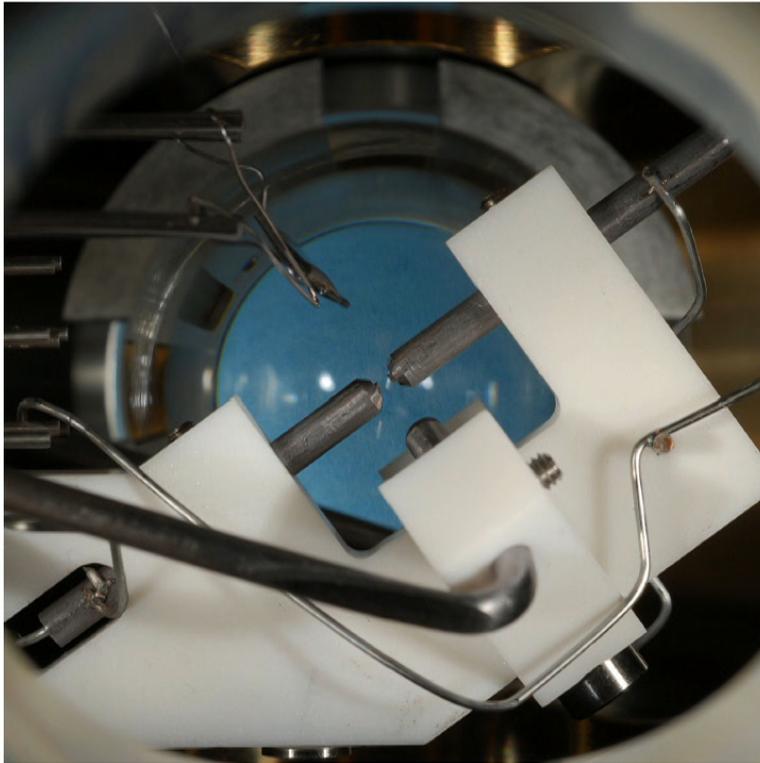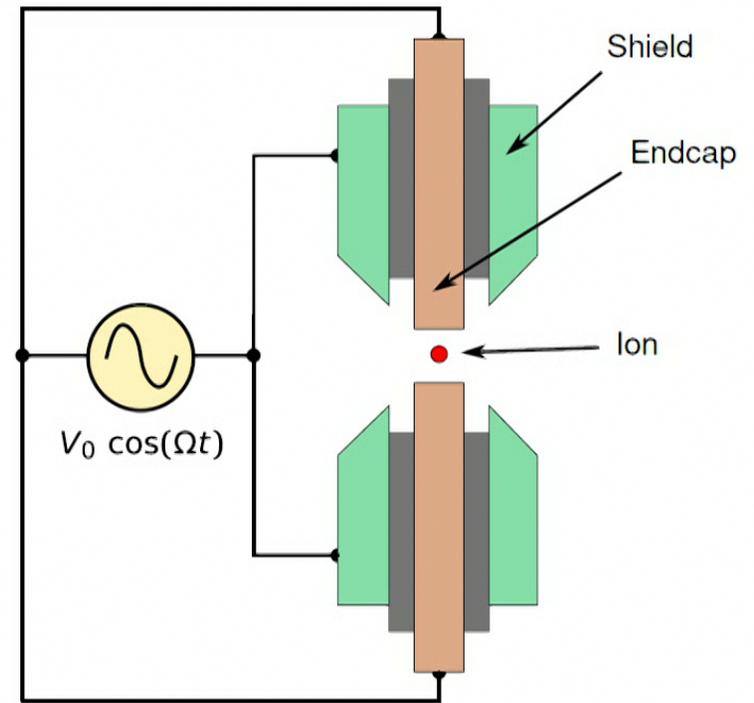**2005 Nobel Laureates**

Jan Hall

Ted Hänsch

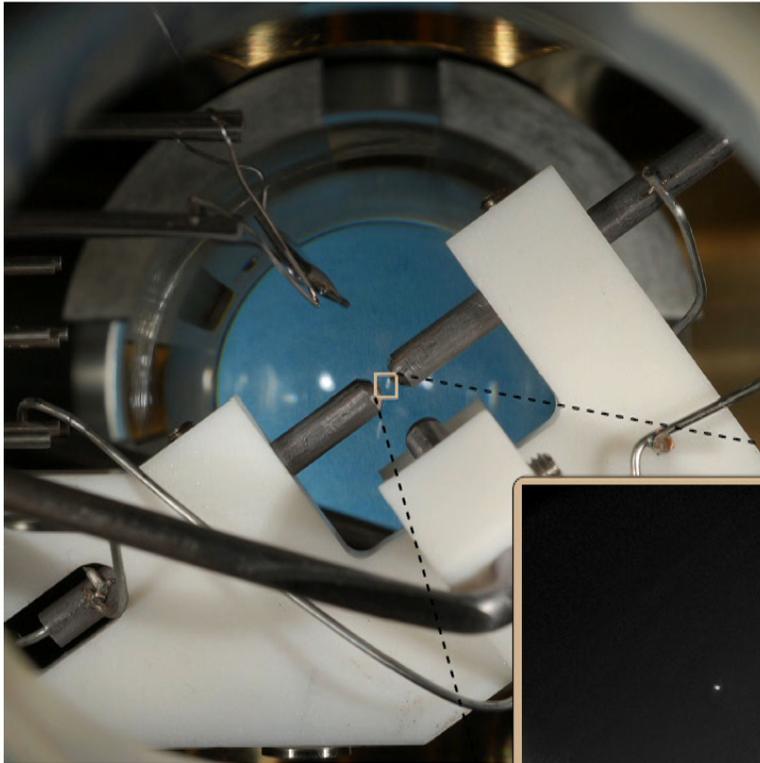# Optical clock building blocks

Atomic Clocks Uncertainties
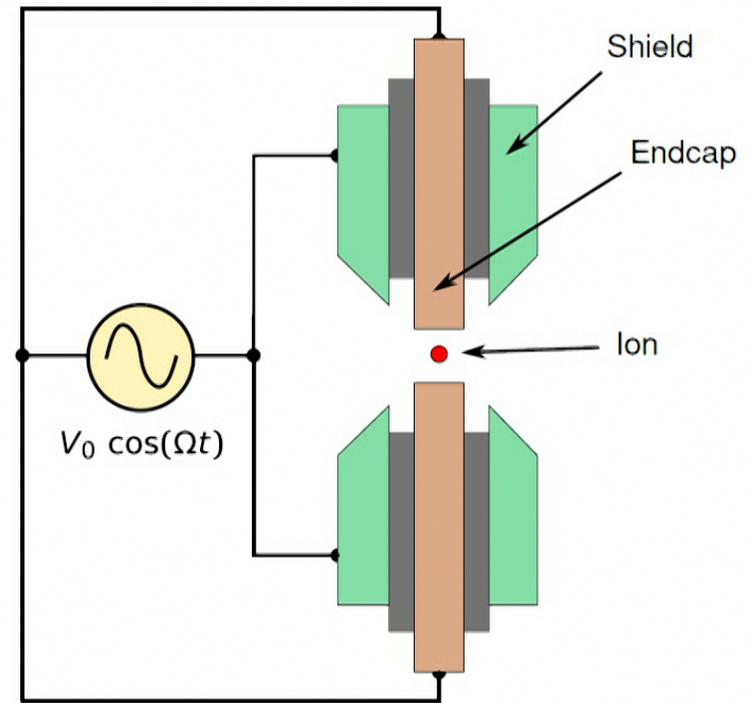
^{88}Sr$^+$ ion trap at NRC

Endcap trap, trim electrodes, and
strontium oven in vacuum chamber

$V_0 \cos(\Omega t)$

Shield

Endcap

Ion

Endcap trap, trim electro
strontium oven in vacuu

$V_0 \cos(\Omega t)$

Shield

Endcap

Ion

^{88}Sr$^+$ optical clock

S–D Zeeman Spectrum
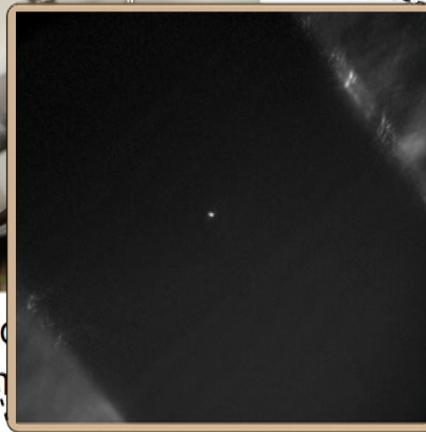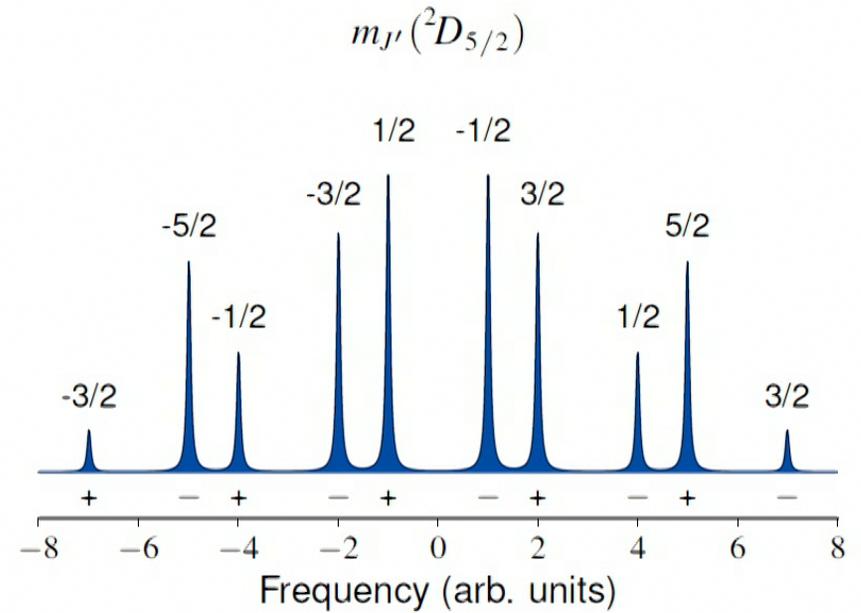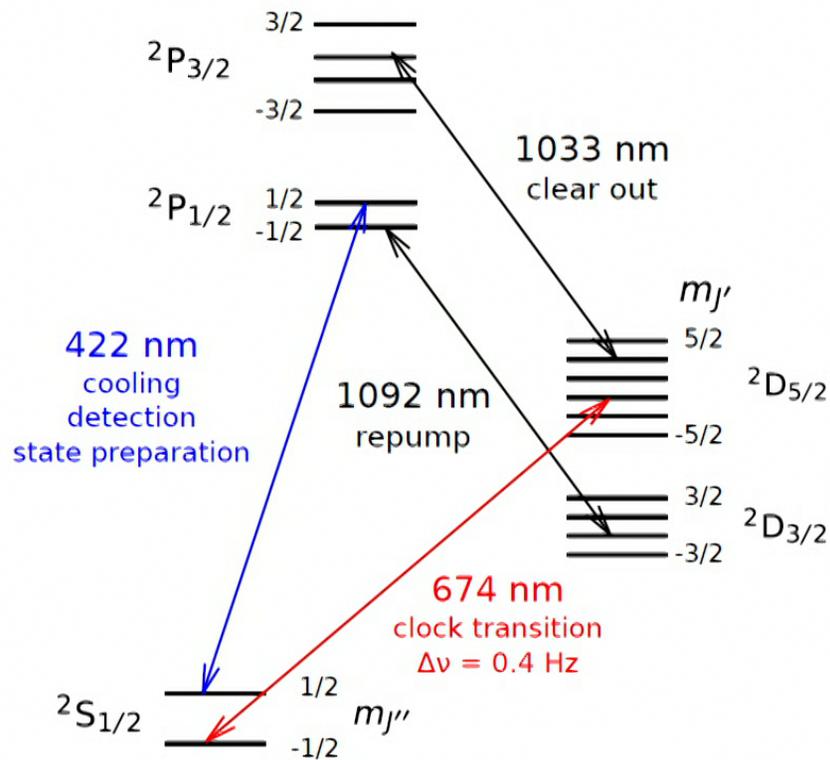
^{88}Sr$^+$ optical clock
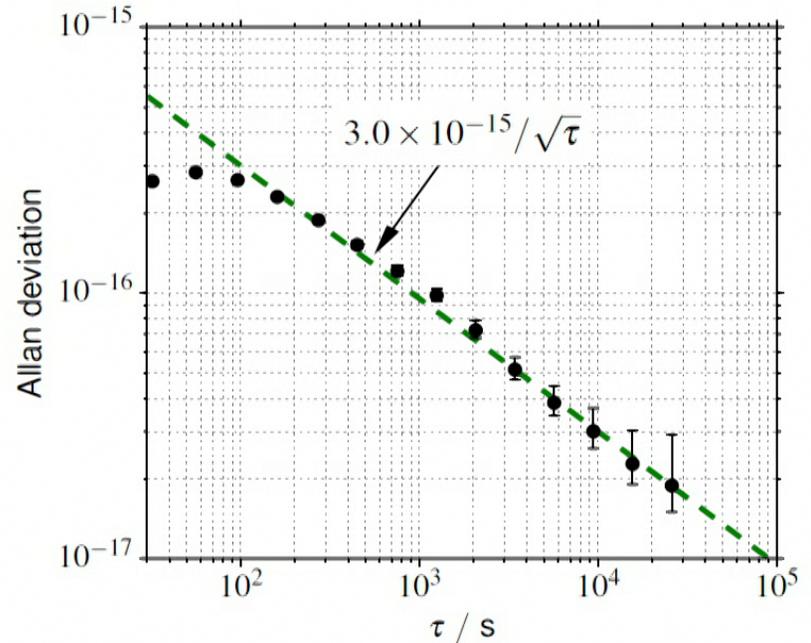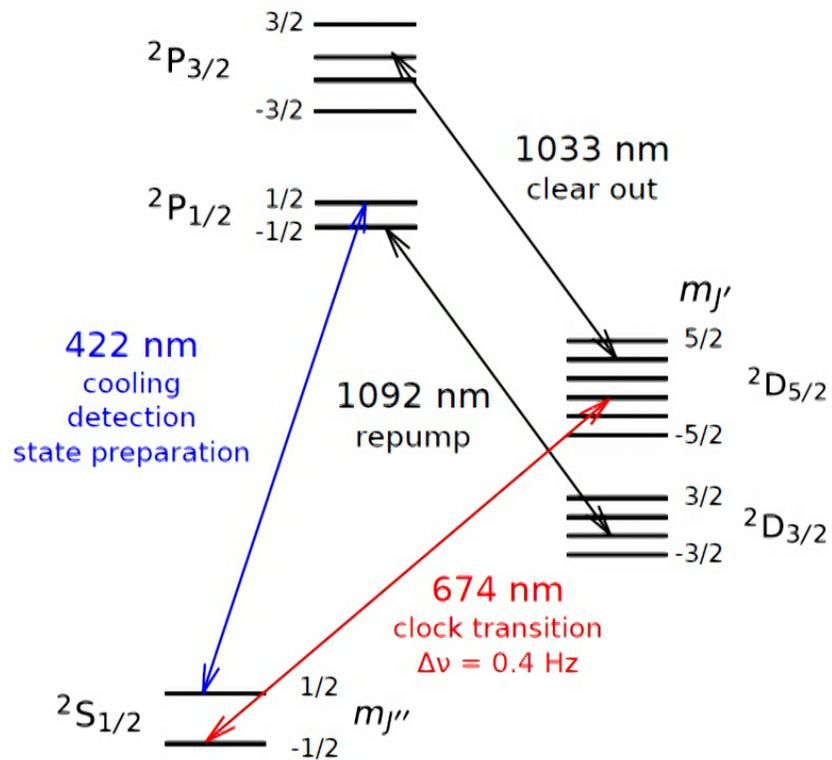
Fundamental shifts in single-ion clocks

Shift	Causes
Stark	micromotion, secular motion
	blackbody radiation
	laser light
2nd-order Doppler	micromotion, secular motion
Electric quadrupole	$\nabla \vec{E}$
Quadratic Zeeman[a]	$\langle B^2 \rangle$
Collisions	background gas

[a] For $B = 3.892(3)\ \mu$T: QZS $= 1.063(2) \times 10^{-19}$

Electric quadrupole shift (EQS)

The largest source of systematic frequency shift for the $^{88}Sr^+$ optical frequency standard arises from the electric quadrupole shift of the reference transition (17), which is due to the interaction between the electric quadrupole moment of the atomic states and any residual electric field gradient present at the position of the ion. After the treatment in (19),

H.S. Margolis *et al.*, Science, **306**, p.1355 (2004)

certainty. The largest systematic uncertainty is due to the interaction between the atomic quadrupole moment of the $^2D_{5/2}$ state and a static electric field gradient. In the cur-

Th. Udem *et al.*, Phys. Rev. Lett., **86**, p.4996 (2001)

(...)

Electric quadrupole shift (EQS)

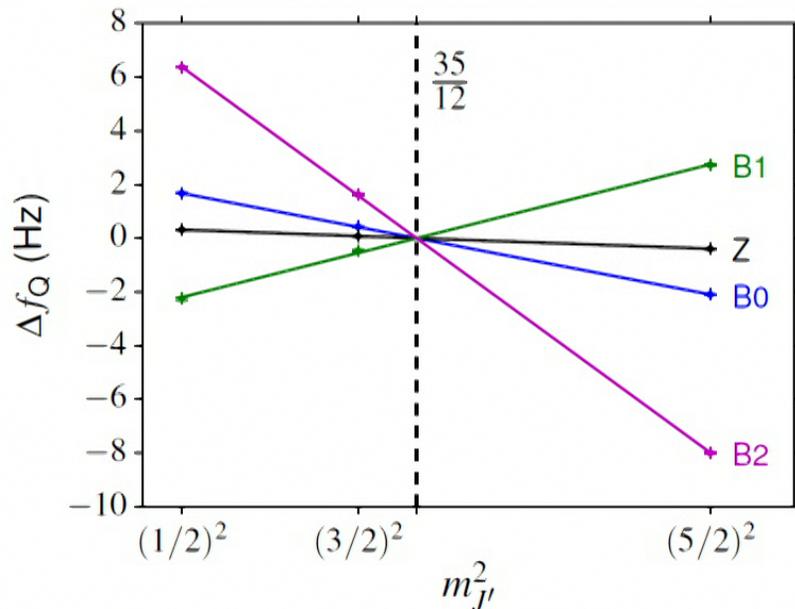$$\Delta f_Q = \frac{1}{4}\, \nu_Q \left(3\cos^2\theta - 1\right)\left[m_{j'}^2 - \frac{J'(J'+1)}{3}\right]$$

Δf_Q = frequency shift

$\nu_Q \propto \nabla\vec{E}$ and $\Theta^\dagger$

$\theta = \angle(\vec{B}, \nabla\vec{E})$

$J' = 5/2$

† Quadrupole moment measurements:
  G.P. Barwood *et al.*, PRL **93**, 133001 (2004).
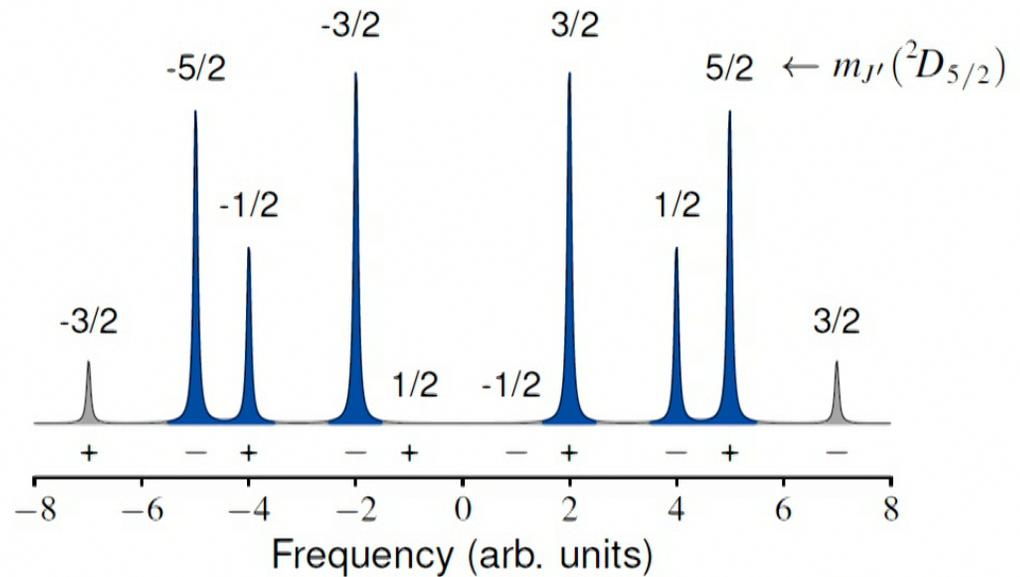 R. Shaniv *et al.*, PRL **116**, 140801 (2016).

$$\Delta f_Q = \frac{1}{4}\,\nu_Q\,(3\cos^2\theta - 1)\left[m_{J'}^2 - \frac{J'(J'+1)}{3}\right]$$

Zeeman averaging

$$\sum_{m_{J'}=-J'}^{J'}\left[m_{J'}^2 - \frac{J'(J'+1)}{3}\right] = 0$$

P. Dubé *et al.*, PRL **95**, 033001 (2005).

EQS cancellation

$$\Delta f_Q = \frac{1}{4} \nu_Q \left(3\cos^2\theta - 1\right) \left[m_{J'}^2 - \frac{J'(J'+1)}{3} \right]$$
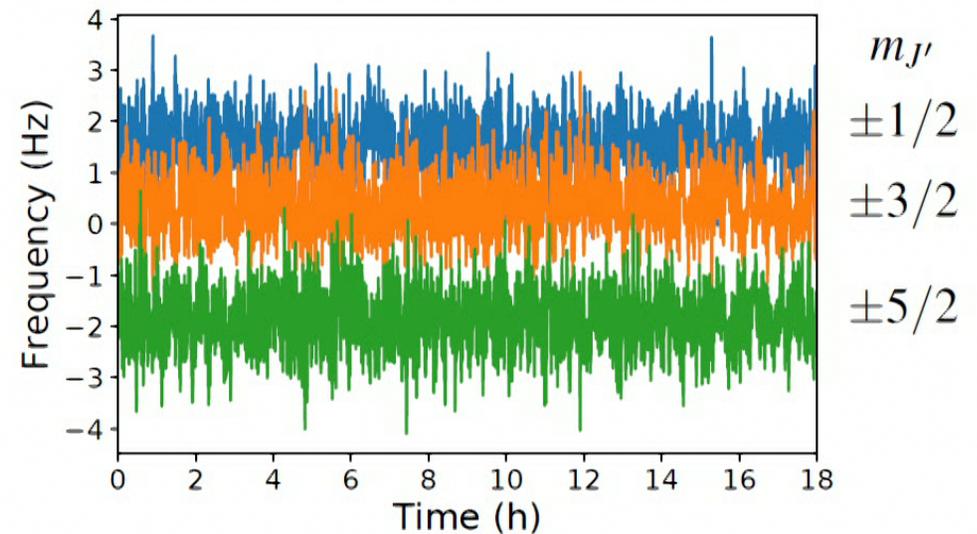
Zeeman averaging

$$\sum_{m_{J'}=-J'}^{J'} \left[m_{J'}^2 - \frac{J'(J'+1)}{3} \right] = 0$$
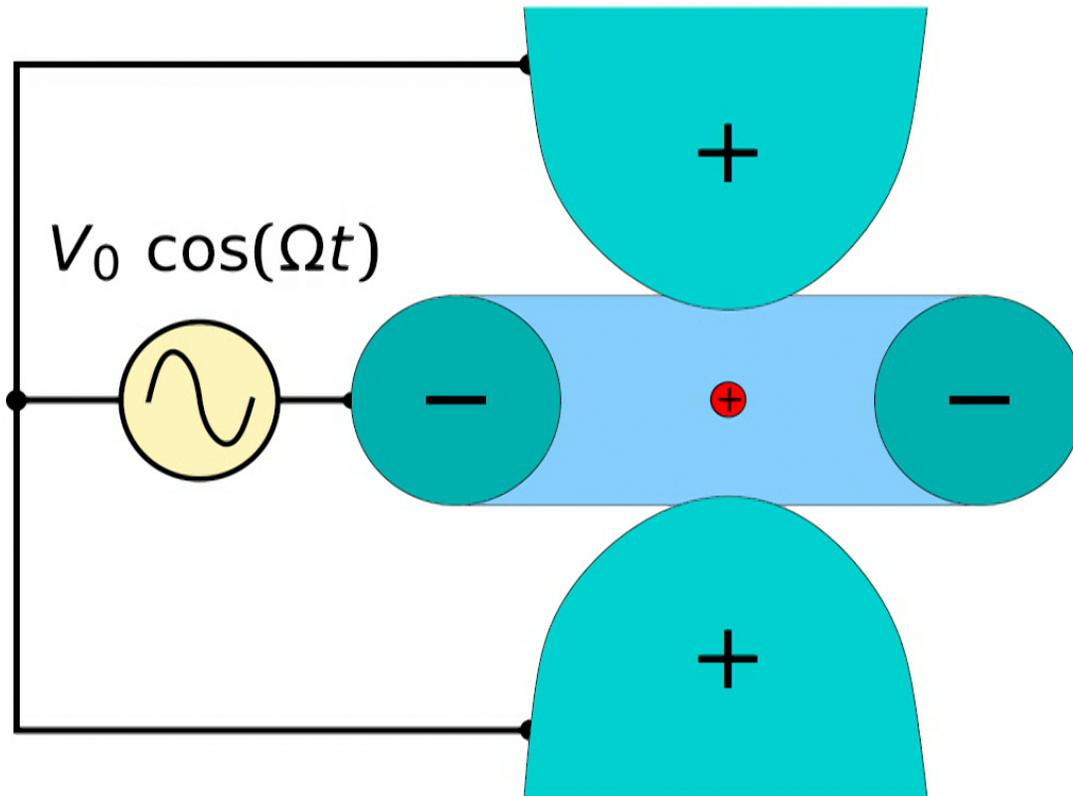
EQS uncertainty: $10^{-14} \Rightarrow 10^{-20}$

Tensor Stark shifts (TSS) also cancelled
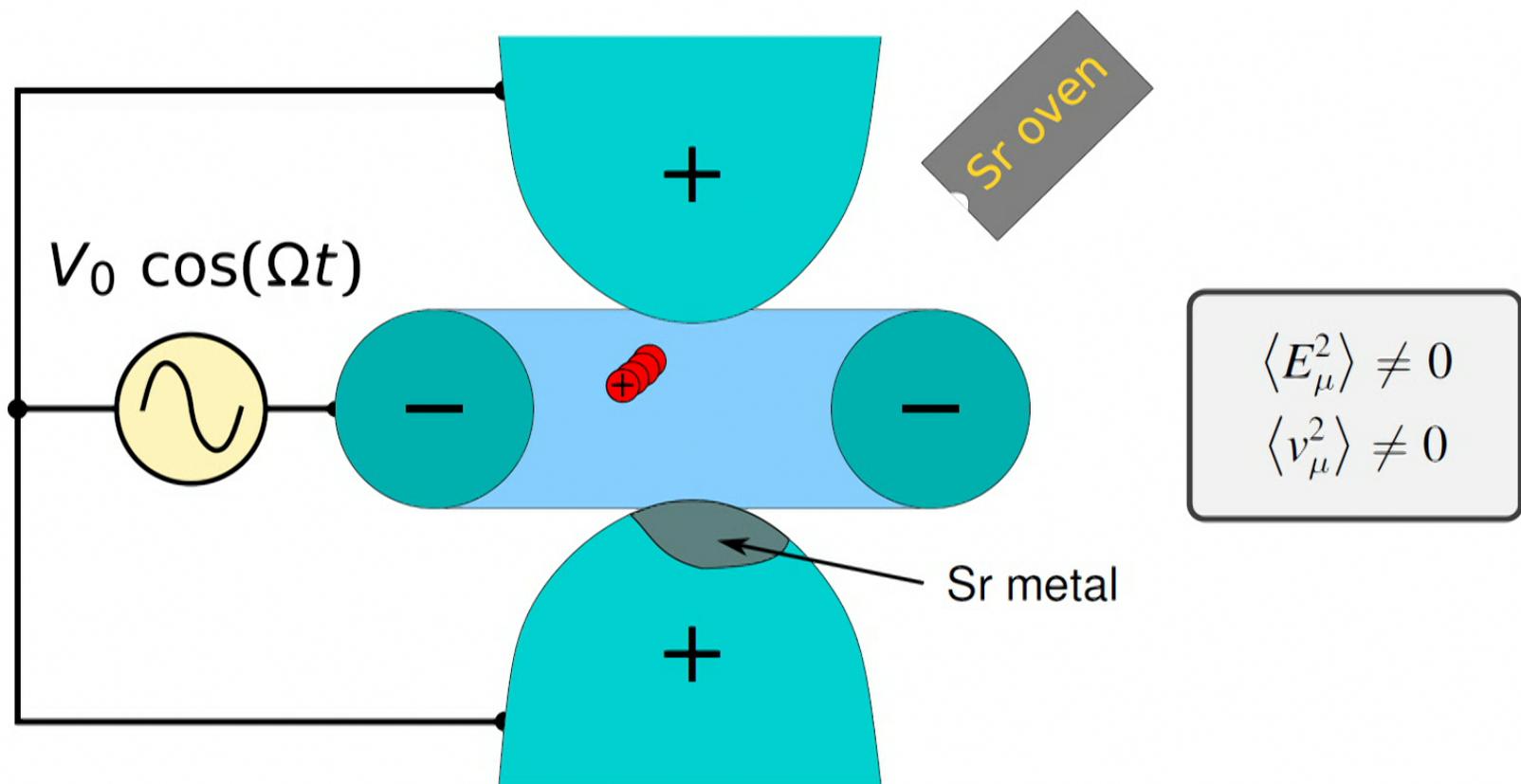
P. Dubé *et al.*, PRL **95**, 033001 (2005).

Zeeman Averaging

Micromotion

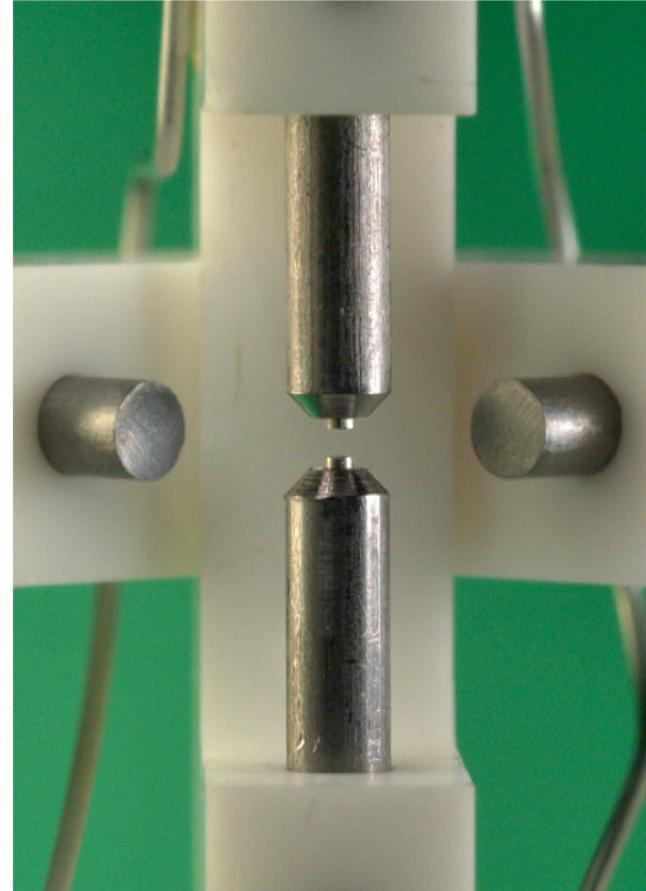

$V_0 \cos(\Omega t)$

Micromotion

Micromotion shifts
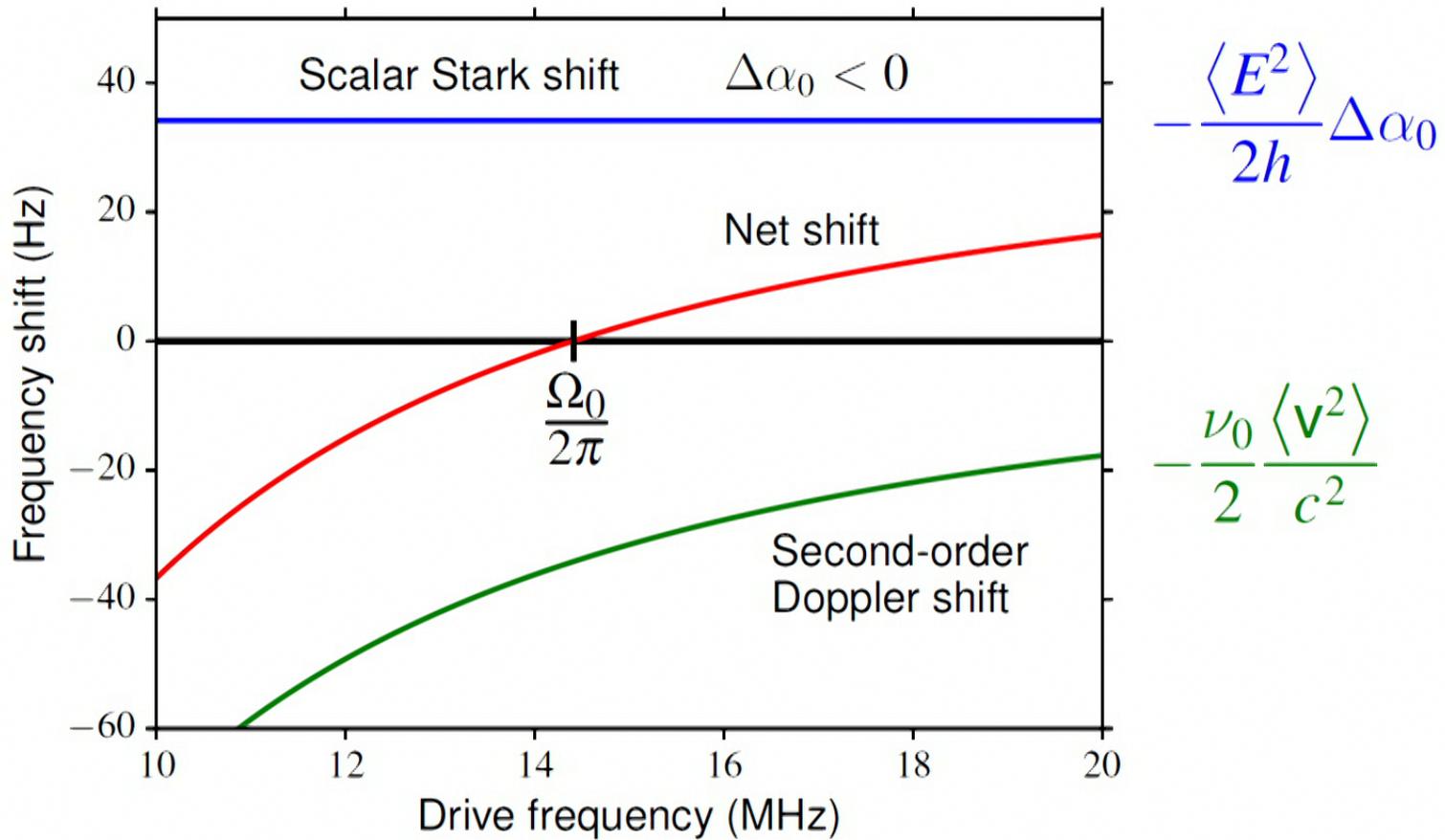
Freq. shifts caused by trap rf fields:

- Stark shifts
- Second-order Doppler shift

Control methods:

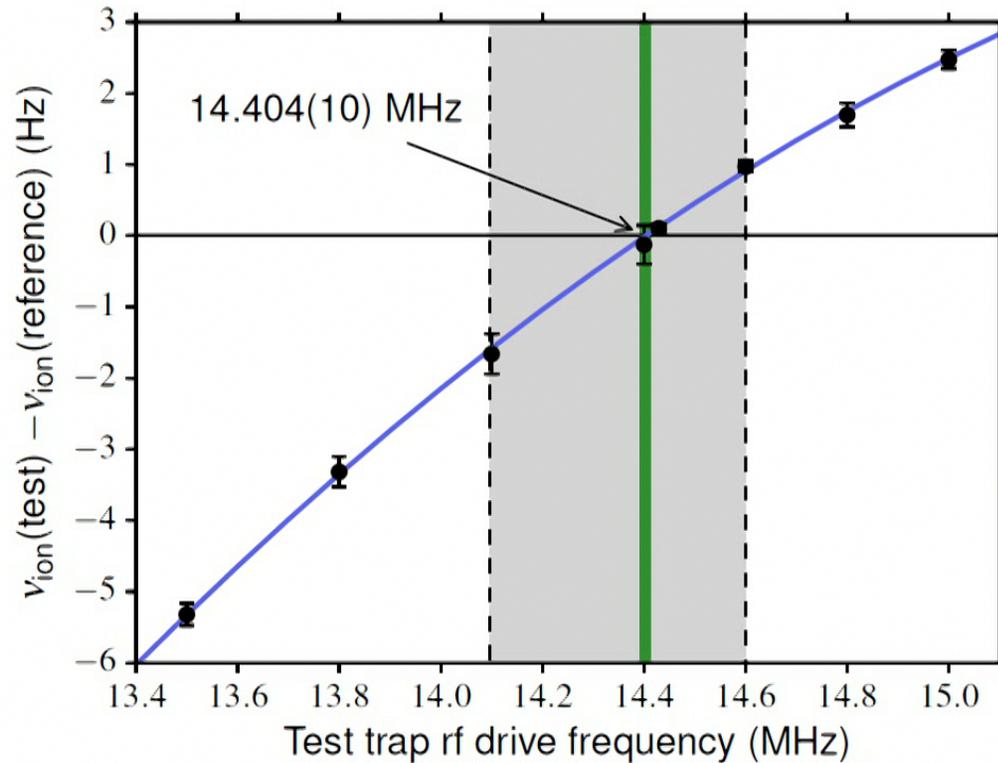- Minimization using trim electrodes
  - ▶ $10^{-14} \Rightarrow 2 \times 10^{-17}$
- Magic trap drive frequency

14.404(10) MHz

P. Dubé *et al.*, PRL, **112**, 173002 (2014).
D. Jiang *et al.*, J. Phys. B **42**, 154020 (2009).

$$\Omega_0 \simeq \frac{e}{mc}\sqrt{-\frac{h\nu_0}{\Delta\alpha_0}}$$

Unc. reductions:

$\Delta\alpha_0$ (BBR coef.)	$24\times$
Excess μ-motion	$200\times$
Thermal motion	$3\times$

$$\Delta\alpha_0 = -47.938(71) \times 10^{-41} \ \text{Jm}^2/\text{V}^2$$

$$\nu_{\text{BBR}} = 0.24799(37) \ \text{Hz}$$

Blackbody radiation Stark shift

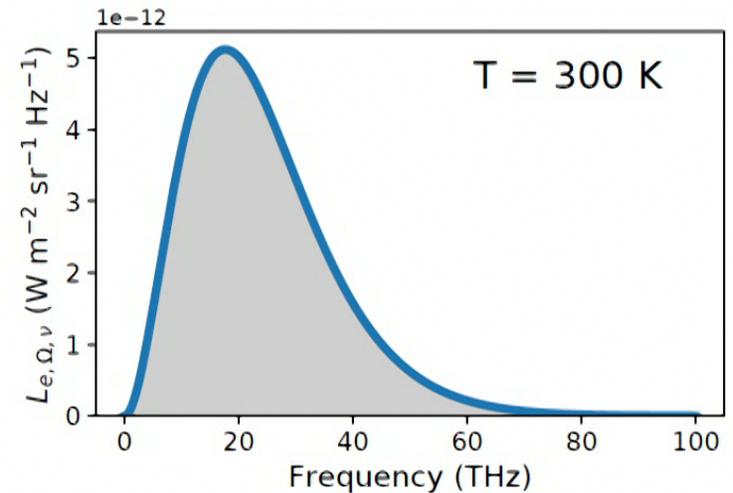$$\Delta\nu_{\text{BBR}} = -\frac{1}{2h}\langle E^2\rangle_T \, \Delta\alpha_0 \, (1+\eta)$$

- $\langle E^2\rangle_T$ 1×10^{-17}
- $\Delta\alpha_0$ measured 8×10^{-19}
- η theory 8×10^{-20}

Blackbody spectral radiance

T = 300 K

$\langle E^2\rangle_T$: P. Dubé *et al.*, Phys. Rev. A **87**, 023806 (2013).

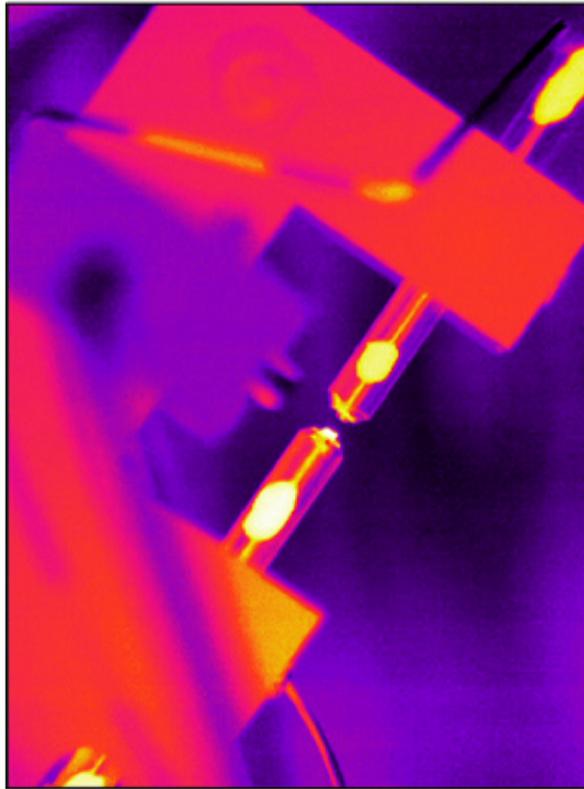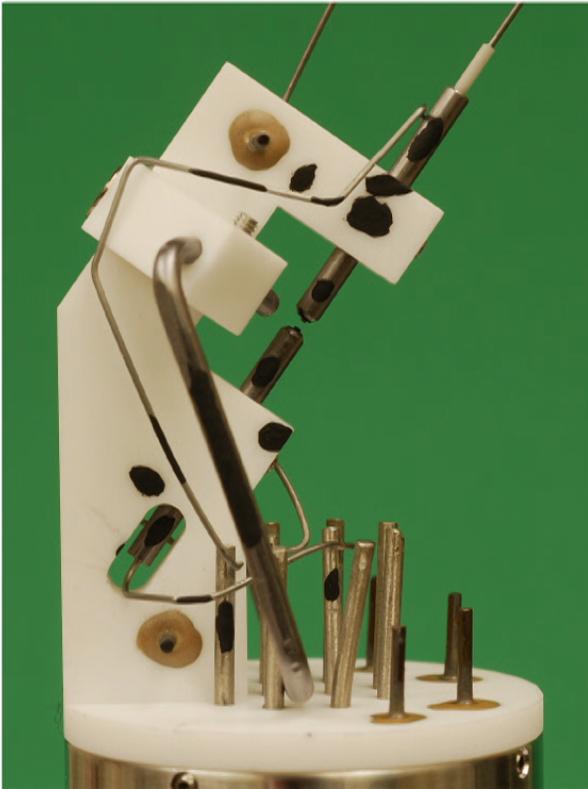$\Delta\alpha_0$: P. Dubé *et al.*, Phys. Rev. Lett. **112**, 173002 (2014).

η : D. Jiang *et al.*, J. Phys. B **42**, 154020 (2009).
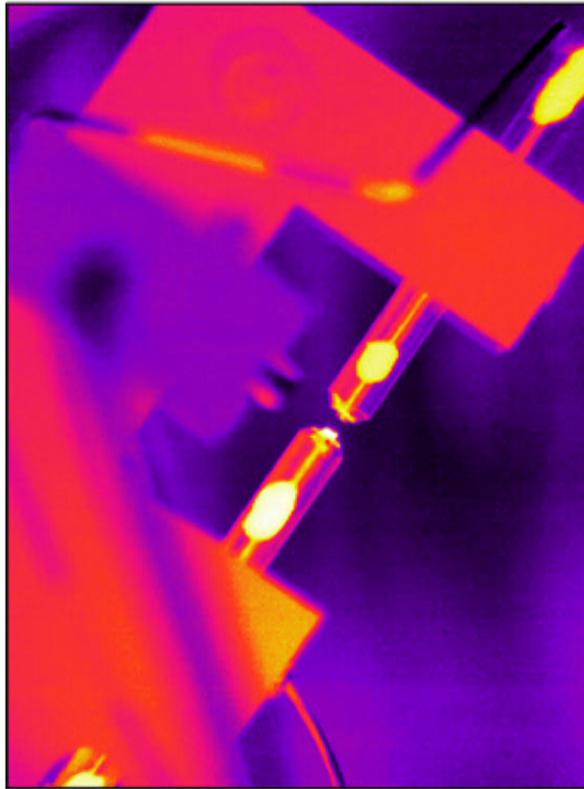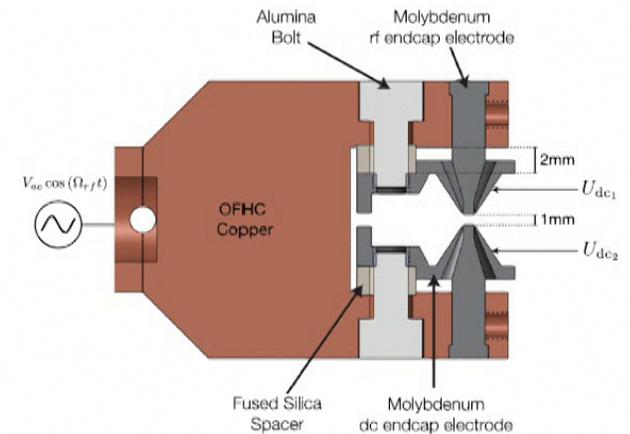
Thermal imaging of dummy ion trap

rf drive: 424 V_{pp}, 14.4 MHz

Improvements:

- Measurements + thermal modeling to determine $\langle E^2 \rangle_T$

rf drive: 424 V_{pp}, 14.4 MHz

Improvements:

- Measurements + thermal modeling to determine $\langle E^2 \rangle_T$
- New trap designs
- $< 10^{-18}$ possible

Nisbet-Jones, APB, 122:57 (2016)

^{88}Sr$^+$ current uncertainty budget

Source of shift	$\dfrac{\Delta\nu}{\nu_0}/10^{-18}$	$\dfrac{\sigma}{\nu_0}/10^{-18}$
BBR field evaluation, $\langle E^2\rangle_T$	557	11 [†]
Second-order Doppler (thermal)	−3	1
BBRS coefficient, $\Delta\alpha_0$	0	0.83
Collisional shift	−0.2	0.6 [†]
AOM chirps	0	0.3
Servo tracking errors	0	0.1
1092 nm ac Stark shift	−0.2	0.1
Excess micromotion	0	0.1
Thermal micromotion	−0.1	0.03
Electric quadrupole shift	0	0.03
Total	554	11

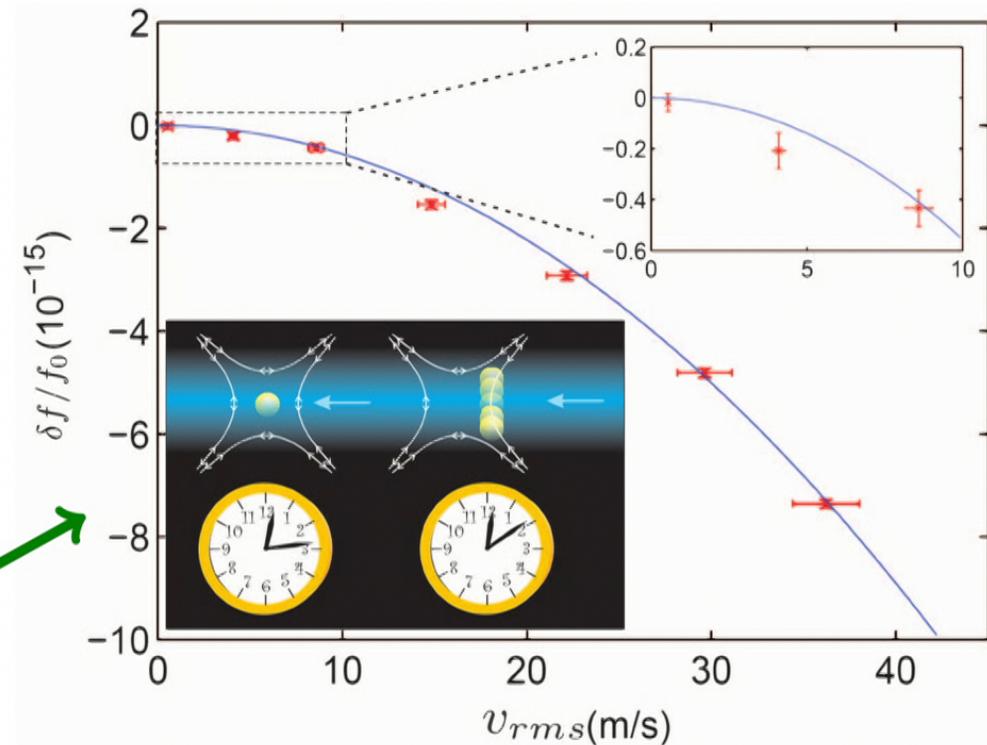[†] Preliminary estimates

Second-order Doppler shift:

$$\frac{\Delta \nu}{\nu_0} = -\frac{1}{2}\left(\frac{v}{c}\right)^2$$

Examples:

- 5.6×10^{-18} for v = 1 m/s

- Thermal (mK) $\sim 10^{-18}$

- Uncompensated ion μ-motion $\sim 10^{-14}$

Chou *et al.*, Science, **329**, 1630 (2010).

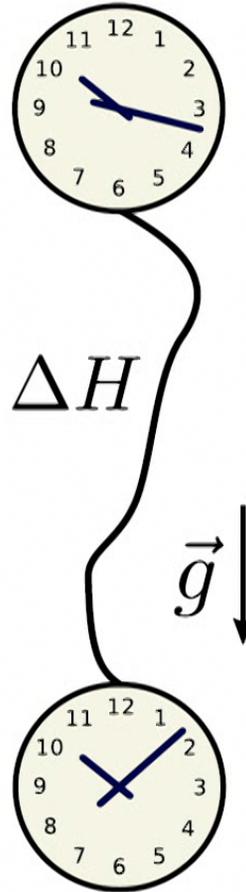# Optical clocks and general relativity

Gravitational time dilation:

$$\frac{\Delta f}{f_0} = \frac{\Delta W}{c^2} = \frac{1}{c^2} \int_{H_0}^{H_x} g \cdot dH$$

$$\approx \left(\frac{g}{c^2}\right) \Delta H \Rightarrow 10^{-16} \Delta H$$
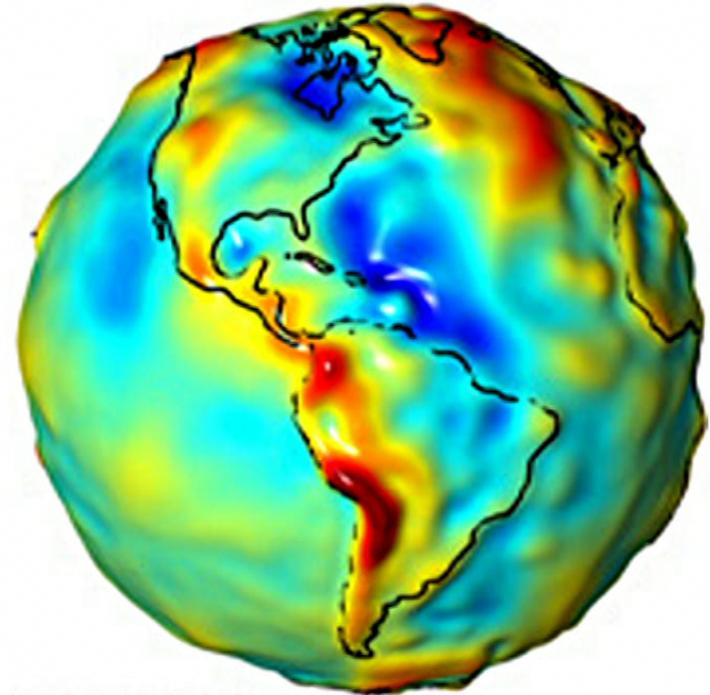
^{88}Sr$^+$ NRC clock:

- $H_{\text{Lab}} - H_{\text{Geoid}} = 95.778(24)$ m
- $f_{\text{Lab}} - f_0 = 4.648(1)$ Hz

Consequence:

Identical clocks in different

"locations" tick at different rates...

ΔH

$\vec{g}$

Gravity Anomaly Map

credit: GRACE – NASA

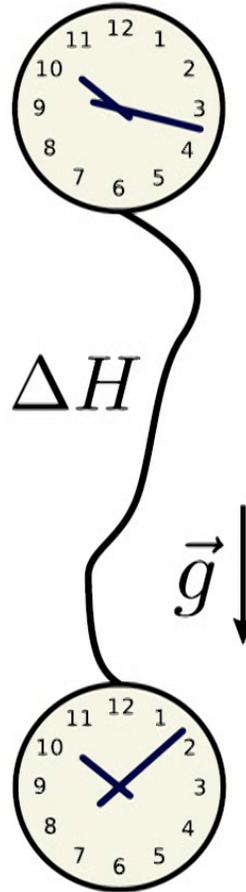# Optical clocks and general relativity

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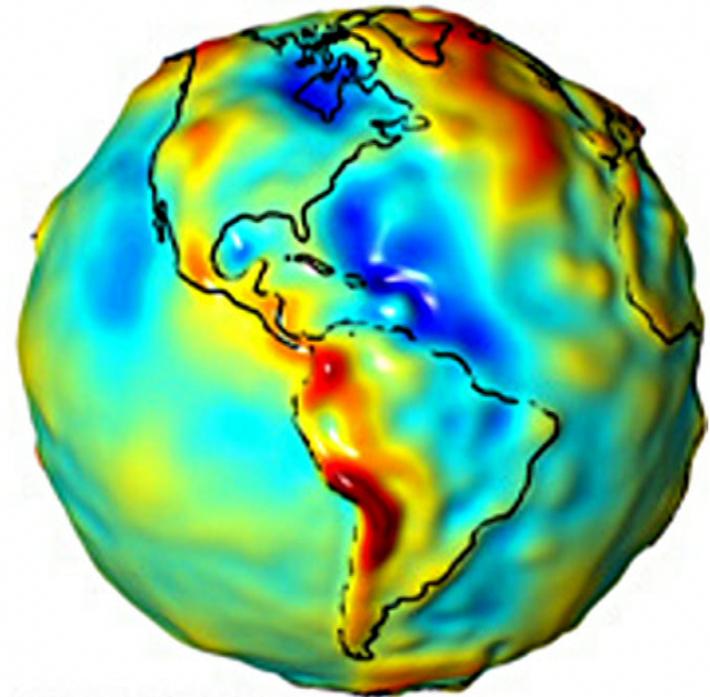
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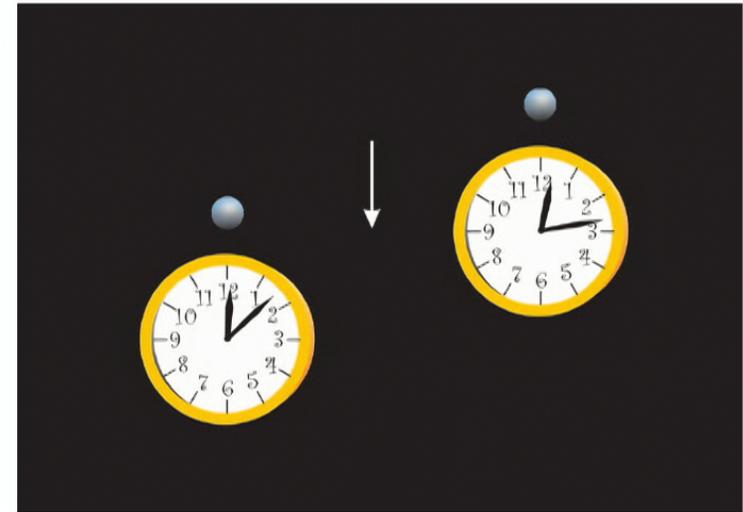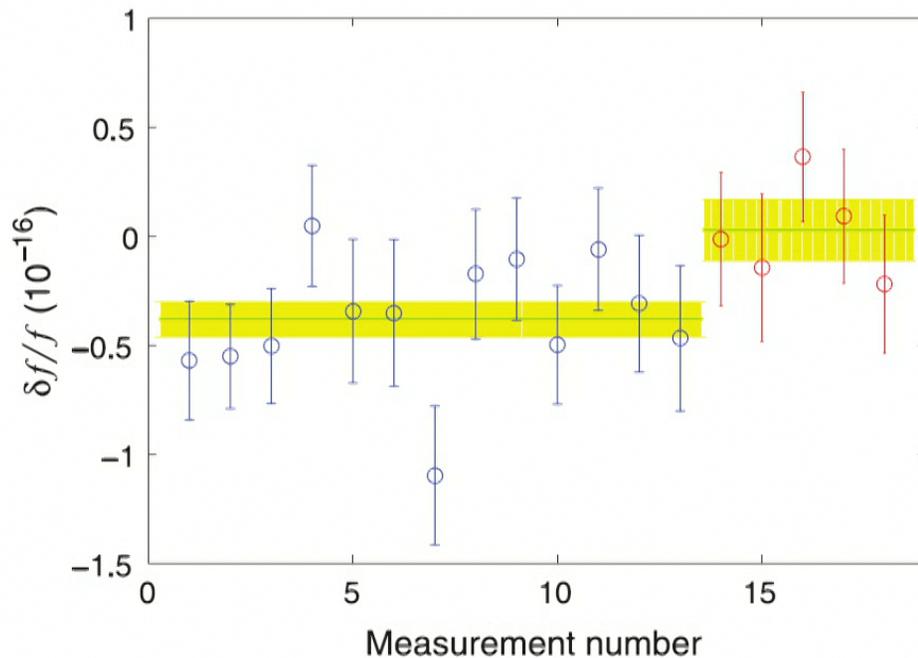Identical clocks in different

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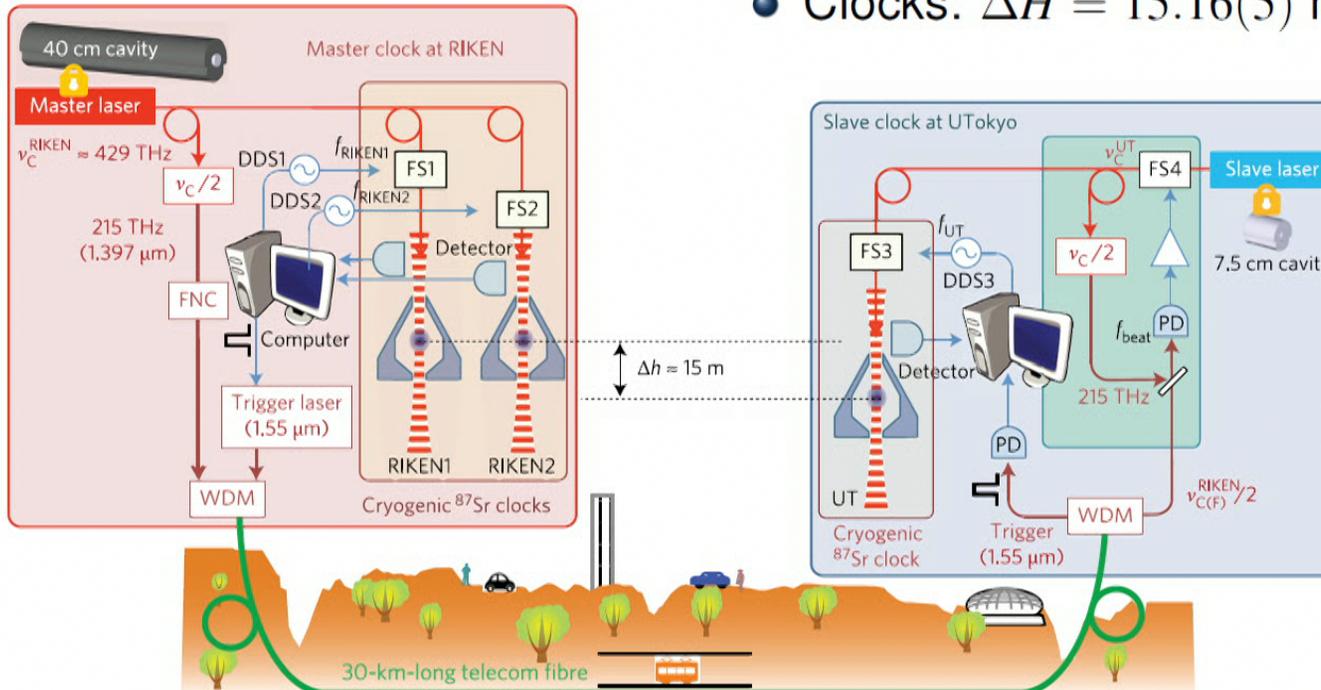
Chou *et al.*, Science, **329**, 1630 (2010).

- Measured $(4.1 \pm 1.6) \times 10^{-17}$ for $\Delta H = 33$ cm

- Gives $\Delta H = 37 \pm 15$ cm

Gravitational redshift experiment: $\Delta H = 15$ m

Takano *et al.*, Nature Photonics, **10** (2016)

- Spirit levelling: $\Delta H = 15.119(6)$ m
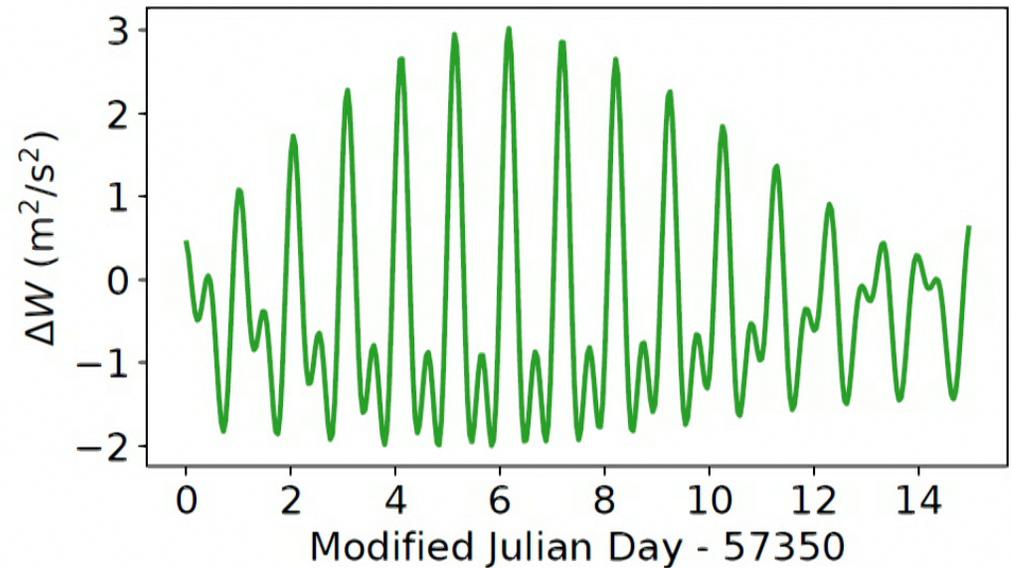- Clocks: $\Delta H = 15.16(5)$ m

$$\Delta f/f = 1652.9(5.9) \times 10^{-18}$$

Solid Earth tides

- Earth tides are caused by the Moon and the Sun

- 50 cm diurnal variations

Earth tides at NRC, Ottawa

Evaluation: Jacques Liard (NRC)

Optical frequency can be written as:

$$\omega = \omega_0 + q\left[\frac{\alpha^2}{\alpha_0^2} - 1\right]$$
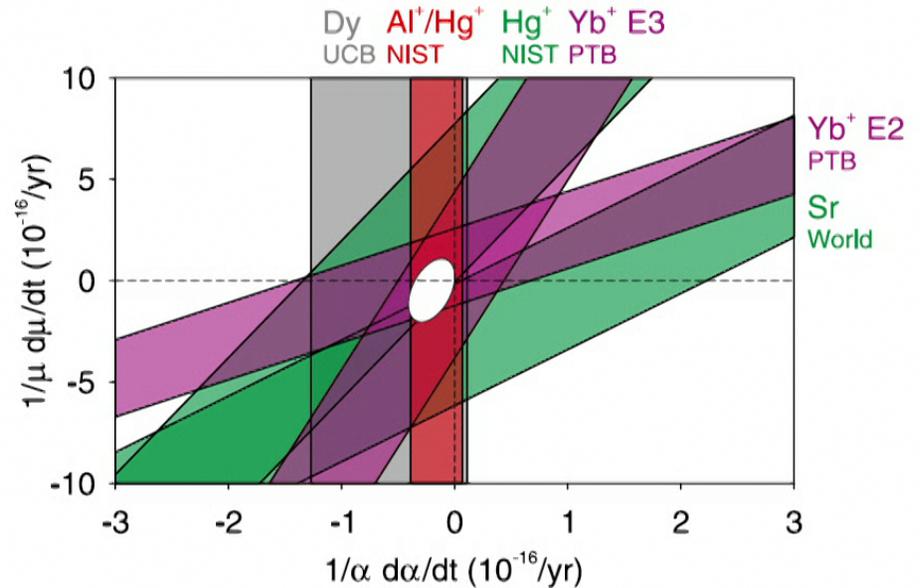
Time variation of frequency ratio:

$$\frac{\partial}{\partial t}\ln\left(\frac{\omega_2}{\omega_1}\right) = (K_2 - K_1)\frac{1}{\alpha}\frac{\partial\alpha}{\partial t}$$

Sensitivity coefficient:

$$K_i = \frac{2q}{\omega_{0i}}$$

Huntemann *et al.*, PRL **113**, 210802 (2014)

$K(Sr^+) = 0.4$
$K(Al^+) = 0.01$
$K(Hg^+) = -2.9$
$K(Yb^+\ E3) = -6$

$$\frac{1}{\alpha}\frac{\partial\alpha}{\partial t} = (-1.6 \pm 2.3) \times 10^{-17}/yr$$

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

Outlook

General advances:

- Clock performance: long-term operation and accuracy
- Transportable optical clocks
- Frequency transfer: GPS, optical fiber, free-space
- New transitions: Nuclear clock, HCI

NRC ^{88}Sr$^+$ ion:

- Evaluation of $\langle E^2 \rangle_T \Rightarrow \lesssim 5 \times 10^{-18}$
- New ion trap design for a transportable system
- ^{88}Sr$^+$ clock comparisons with
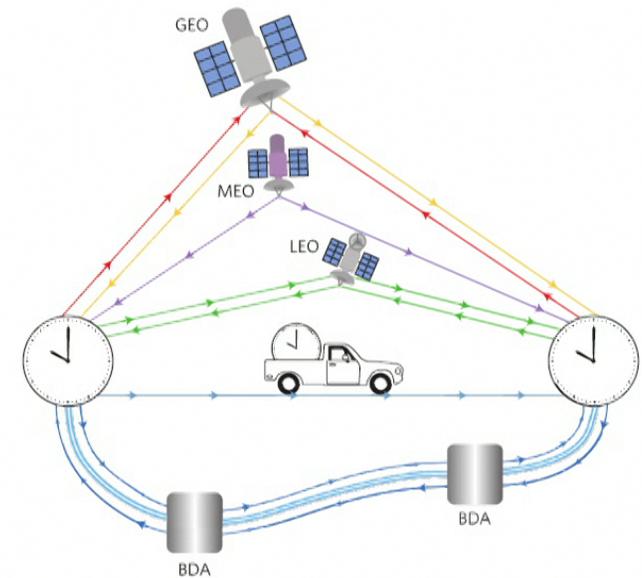 Cs, ^{88}Sr$^+$, Sr, Yb, ^{171}Yb$^+$, ...

Figure 2 | Different methods can be used to compare the frequencies of optical atomic clocks.

Nature Photonics **11**, pages 25–31 (2017)

Outlook

SI second
- Re-definition with an optical transition

Fundamental tests with optical clocks
- General relativity
- Variations of fundmantal constants
- Local position invariance
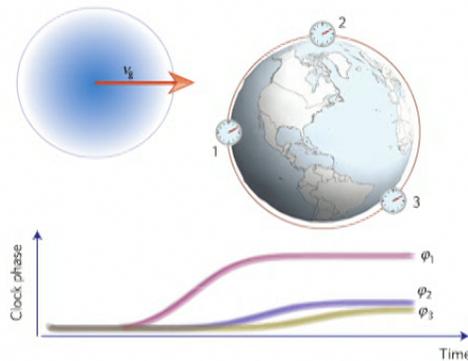- Lorentz symmmetry
- Dark matter detection, …

Figure 2 | Effect of a monopole-type defect on atomic clocks.

The measurement of time / La mesure du temps

Towards a redefinition of the second based on optical atomic clocks

Vers une redéfinition de la seconde basée sur les horloges atomiques optiques

Fritz Riehle [*]

Physikalisch-Technische Bundesanstalt (PTB), Bundesallee 100, 38116 Braunschweig, Germany

Hunting for topological dark matter with atomic clocks

A. Derevianko[1]* and M. Pospelov[2,3]