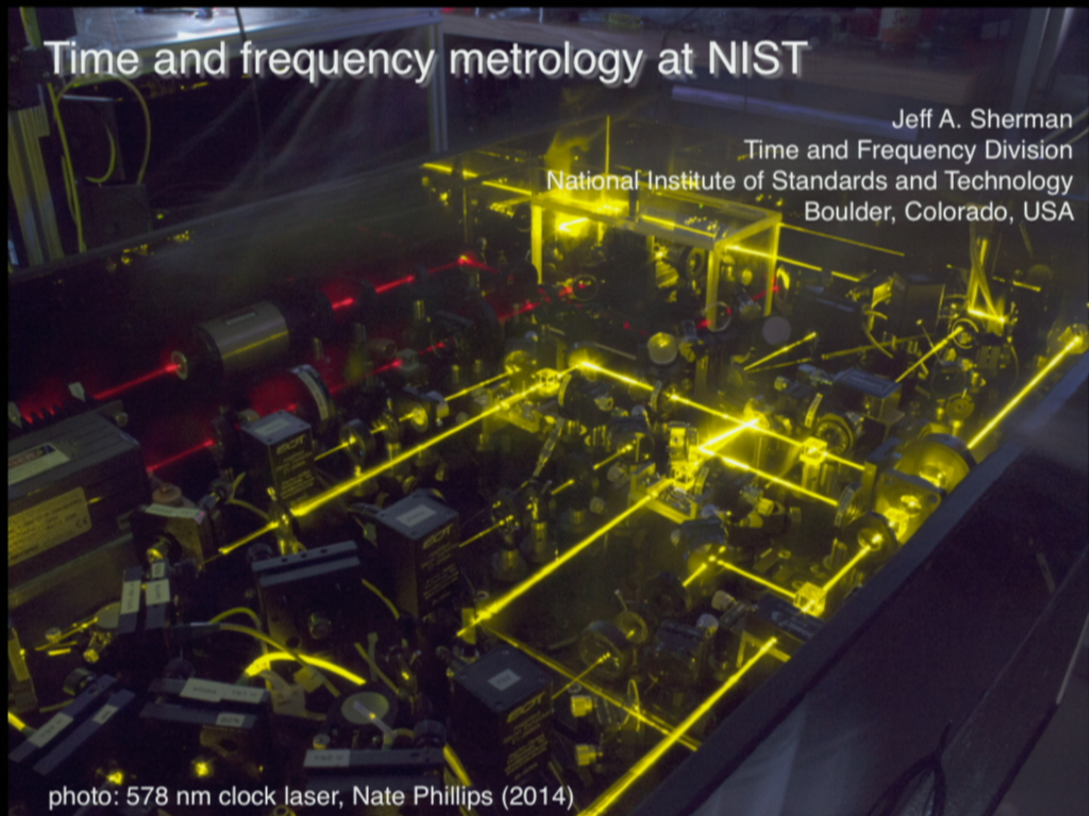
Title: Time and frequency metrology at NIST

Date: Jun 16, 2014 03:30 PM

URL: http://pirsa.org/14060011

Abstract: Official U.S. time is currently realized by an ensemble of commercial cesium-beam atomic clocks and hydrogen masers. Cesium-fountain devices presently serve as ultimate frequency references and help to define the SI second. The present quandary is: these microwave-based standards are rapidly becoming outmatched by new optical atomic frequency references---by a factor of 1,000 in stability, and perhaps a factor of 100 in accuracy. I will survey the ongoing optical atomic clock projects at NIST and highlight related work in optical time and frequency measurement and transfer.


Time and frequency metrology at NIST
Jeff A. Sherman
Time and Frequency Division
National Institute of Standards and Technology
Boulder, Colorado, USA
photo: 578 nm clock laser, Nate Phillips (2014)

Outline

- Atomic clocks as official source of U.S. time and frequency

  one dilemma: optical atomic clocks will surpass
  the current SI definition of time/frequency.

- Selection of recent progress on optical clockwork

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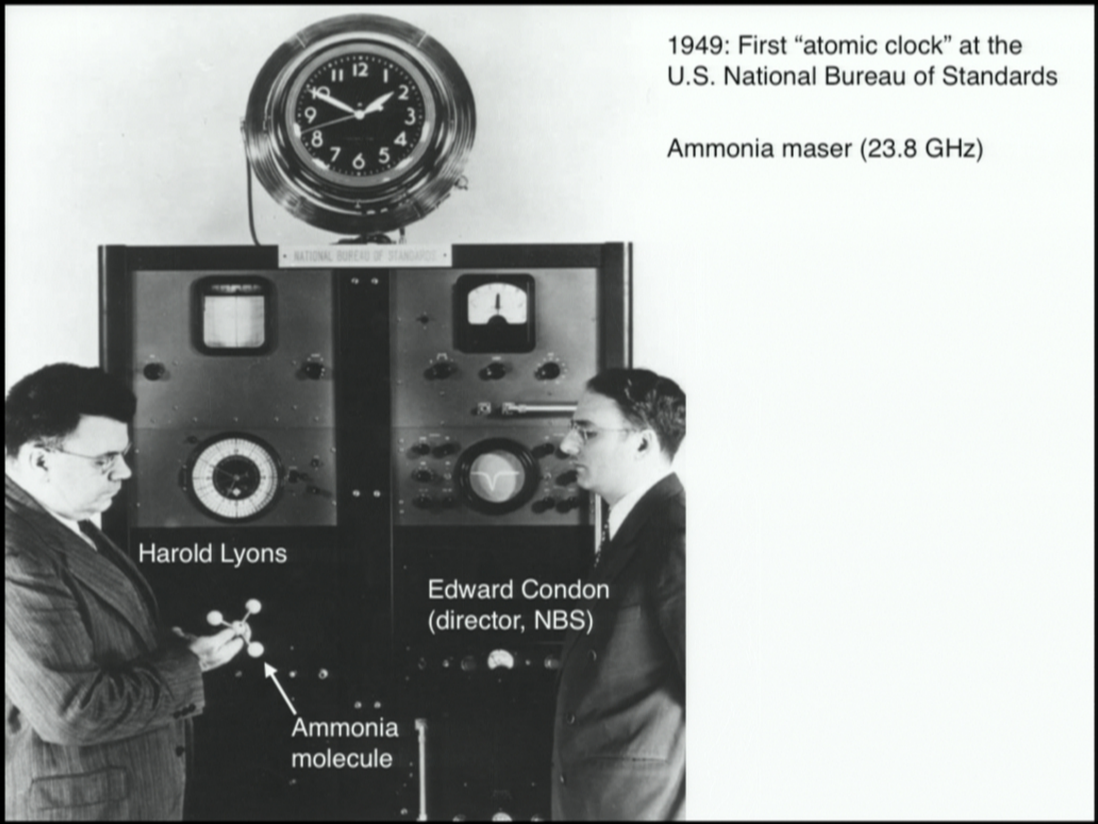
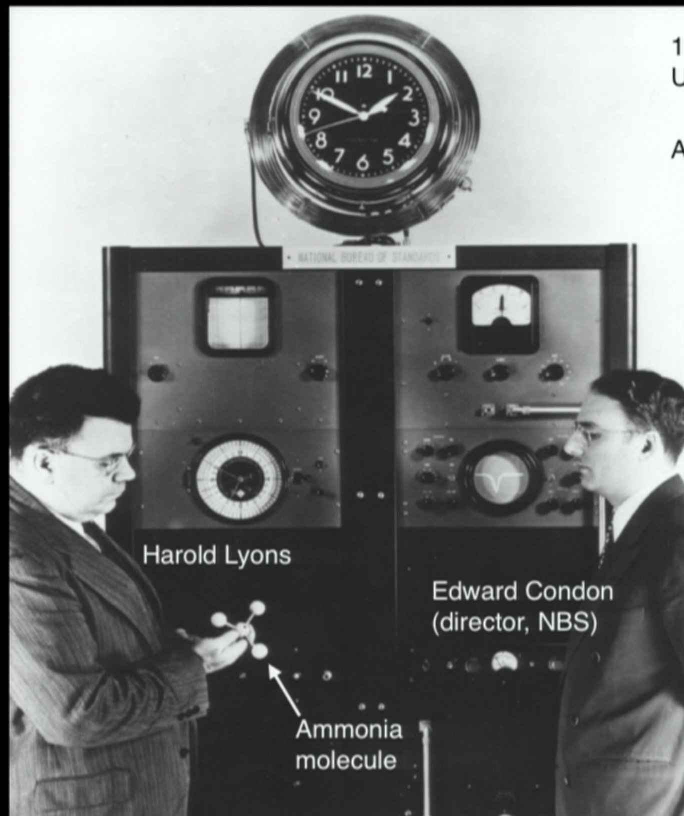

1949: First “atomic clock” at the
U.S. National Bureau of Standards
Ammonia maser (23.8 GHz)
Harold Lyons
Edward Condon
(director, NBS)
Ammonia
molecule



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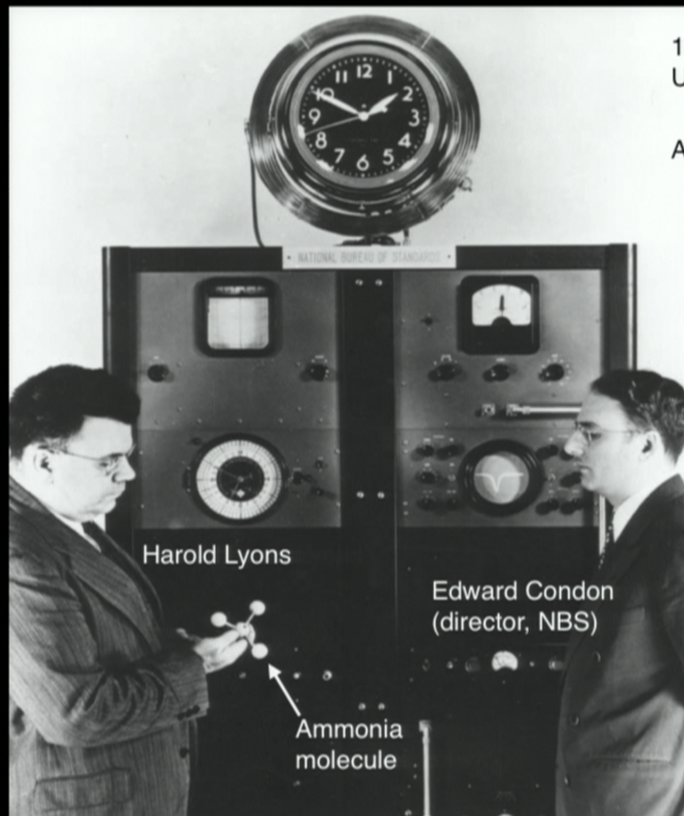
"Dr. Condon, it says here that you have been at the forefront of a revolutionary movement in physics called...quantum mechanics.

It strikes [us] that if you could be at the forefront of one revolutionary movement... you could be at the forefront of another."

—Carl Sagan’s reporting of a closed-door HUAC committee statement



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Atomic clocks as official source of U.S. time and frequency

BIPM

The **second** is the duration of **9 192 631 770 periods** of the radiation corresponding to the transition between two **hyperfine levels of the ground state of the cesium-133 atom**... at rest and at a temperature of 0 K.

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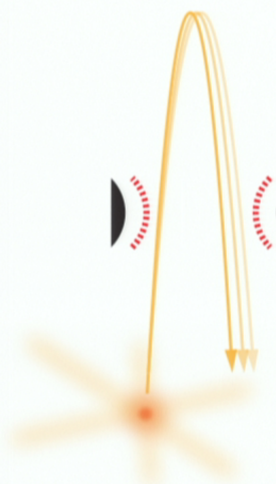

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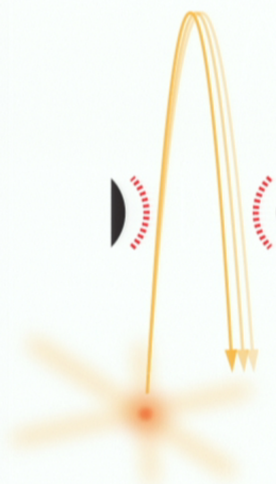
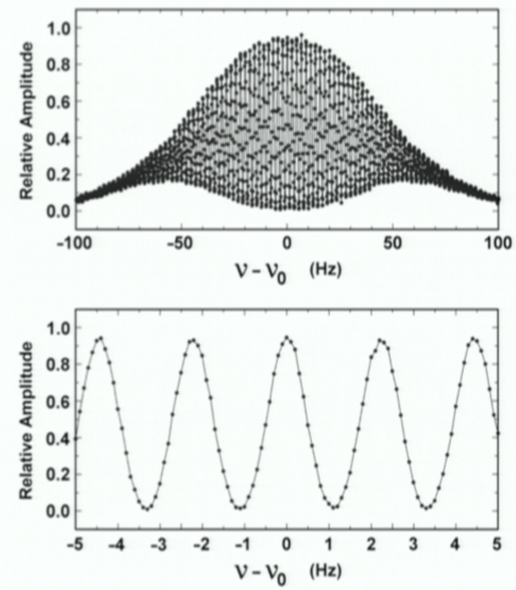
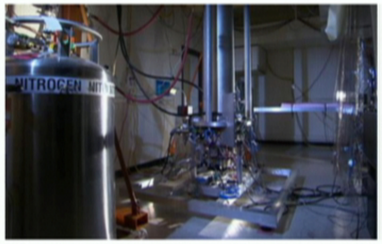
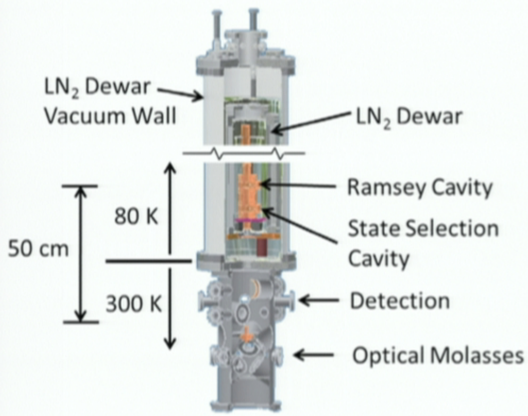




DB Sullivan, JC Bergquist, JJ Bollinger, et al., *J. Res. NIST* **106**, 47–63 (2011)

April 2014: NIST launches cryogenic Cs-fountain, NIST-F2





Frequency uncertainty sources (mostly "type B")

$\times 10^{-15}$

Physical effect	Magnitude	Uncertainty
Gravitational redshift	+179.87	0.03
Second-order Zeeman	+286.06	0.02
Blackbody radiation	−0.087	0.005
Spin-exchange (low density)	(−0.71)[a]	(0.24)[a]
Spin-exchange non-linearity	0	0.02
Microwave amplitude effects		
Distributed cavity phase shift (DCPS)		
$m = 0$	<0.01	<0.01
$m = 1$	0	0.028
$m = 2$	0	0.02
Microwave power	<0.01	0.08
Microwave spurious	0	0.05
Cavity pulling	0.015	0.015
Rabi pulling	<0.01	<0.01
Ramsey pulling	<0.01	<0.01
Majorana transitions	<0.01	<0.01
Fluorescence light shift	<0.01	<0.01
Dc Stark effect	<0.01	<0.01
Background gas collisions	<0.01	<0.01
Bloch–Siegert	<0.01	<0.01
Integrator offset	<0.01	<0.01
Total type B Standard uncertainty		0.11 $\times 10^{-15}$

[a] For information purposes only. Not used in the total. See section 3.3 and [16] for details.

TP Heavner, EA Donley, Filippo Levi, et al., *Metrologia* **51**, 174–182 (2014)

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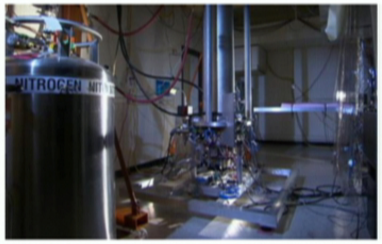

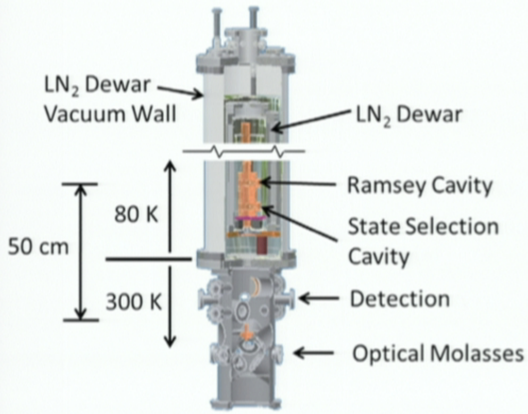

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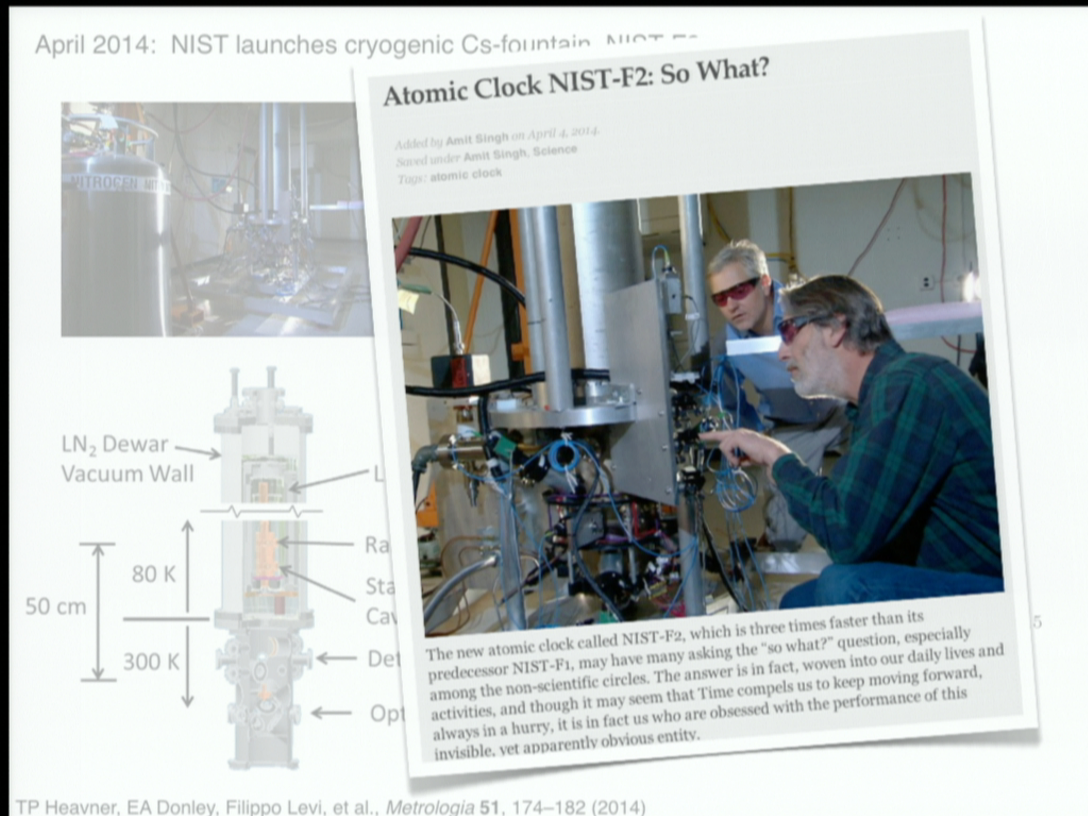
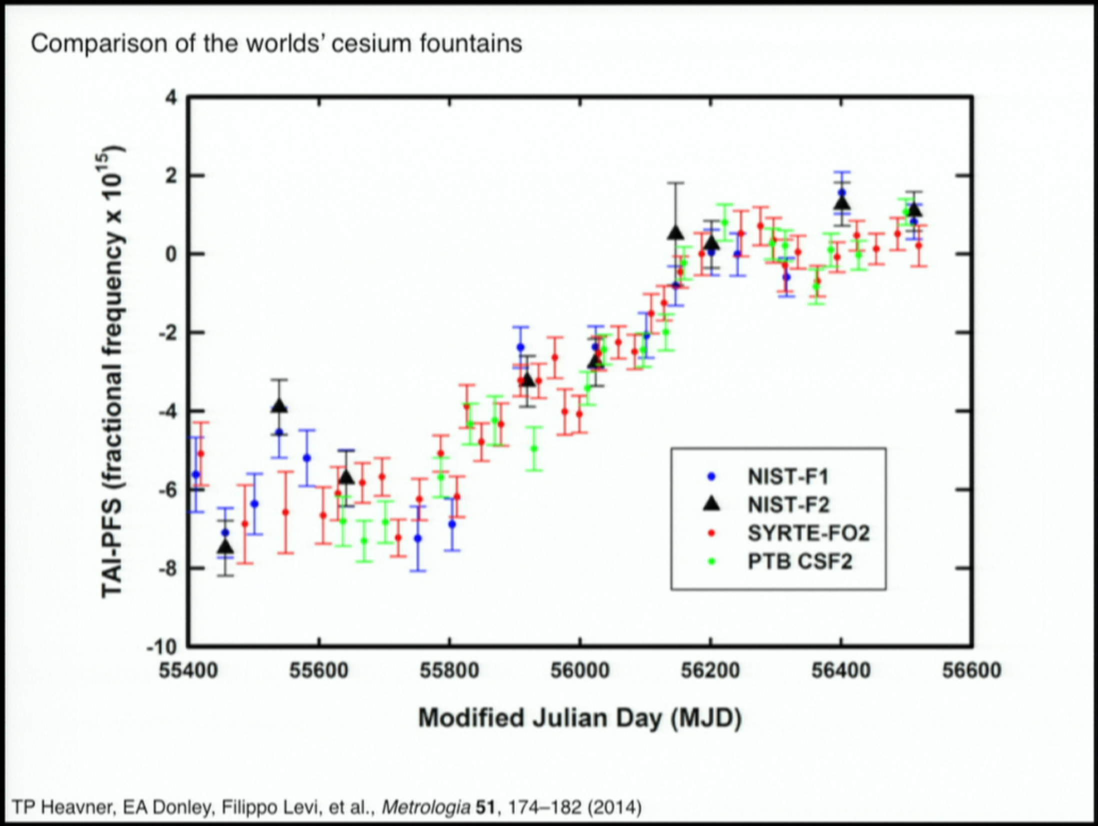

April 2014: NIST launches cryogenic Cs-fountain
LN$_2$ Dewar
Vacuum Wall
80 K
50 cm
300 K
Atomic Clock NIST-F2: So What?
Added by Amit Singh on April 4, 2014.
Saved under Amit Singh, Science
Tags: atomic clock
The new atomic clock called NIST-F2, which is three times faster than its predecessor NIST-F1, may have many asking the "so what?" question, especially among the non-scientific circles. The answer is in fact, woven into our daily lives and activities, and though it may seem that Time compels us to keep moving forward, always in a hurry, it is in fact us who are obsessed with the performance of this invisible, yet apparently obvious entity.
TP Heavner, EA Donley, Filippo Levi, et al., Metrologia 51, 174–182 (2014)


Comparison of the worlds' cesium fountains
TAI-PFS (fractional frequency x 10^15)
Modified Julian Day (MJD)
NIST-F1
NIST-F2
SYRTE-FO2
PTB CSF2
4
2
0
-2
-4
-6
-8
-10
55400
55600
55800
56000
56200
56400
56600
TP Heavner, EA Donley, Filippo Levi, et al., Metrologia 51, 174–182 (2014)

Commercial atomic clocks are the operational source of official U.S. time.

Commercial cesium beam clocks (x8)

Commercial hydrogen masers (x4)

DB Sullivan, JC Bergquist, JJ Bollinger, et al., *J. Res. NIST* **106**, 47–63 (2011)

photos: ESA

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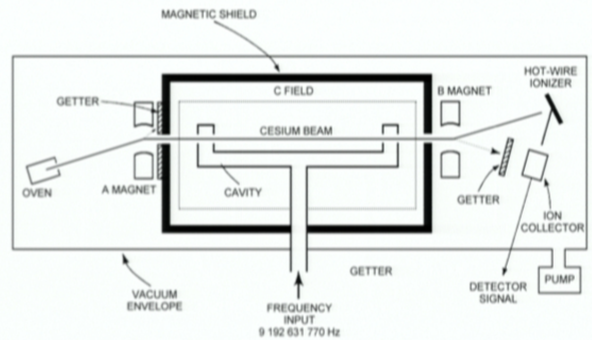
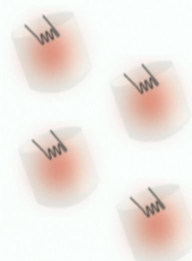


Commercial hydrogen masers (x4)



DB Sullivan, JC Bergquist, JJ Bollinger, et al., *J. Res. NIST* **106**, 47–63 (2011) photos: ESA

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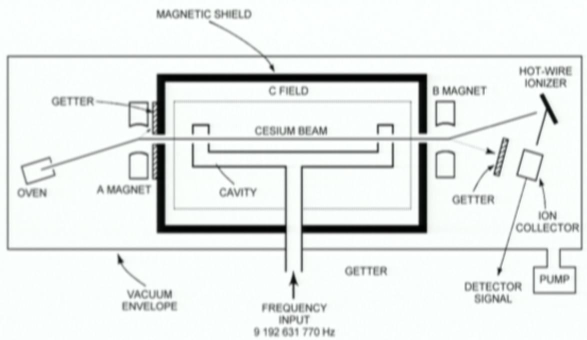
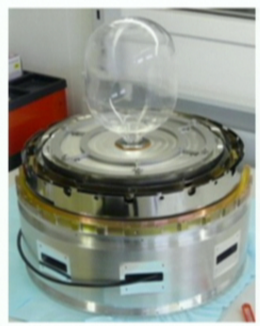
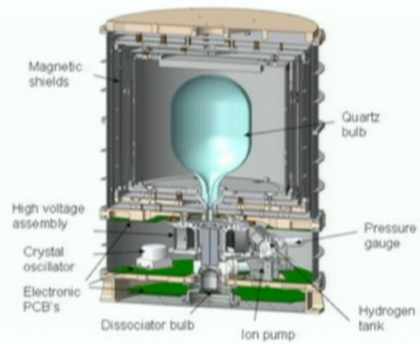


Commercial hydrogen masers (x4)





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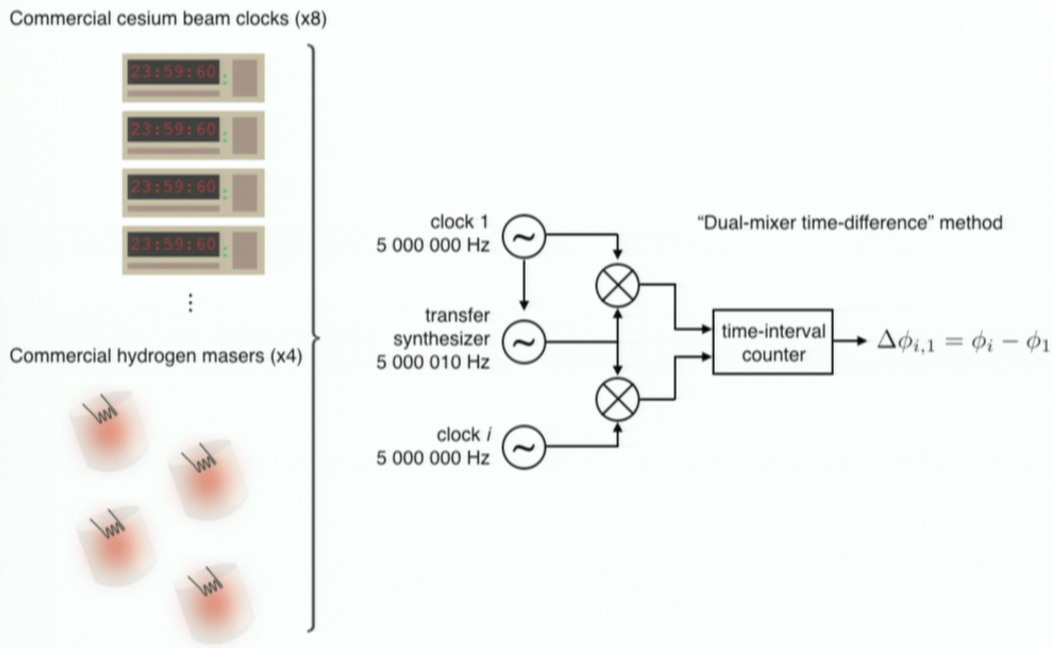

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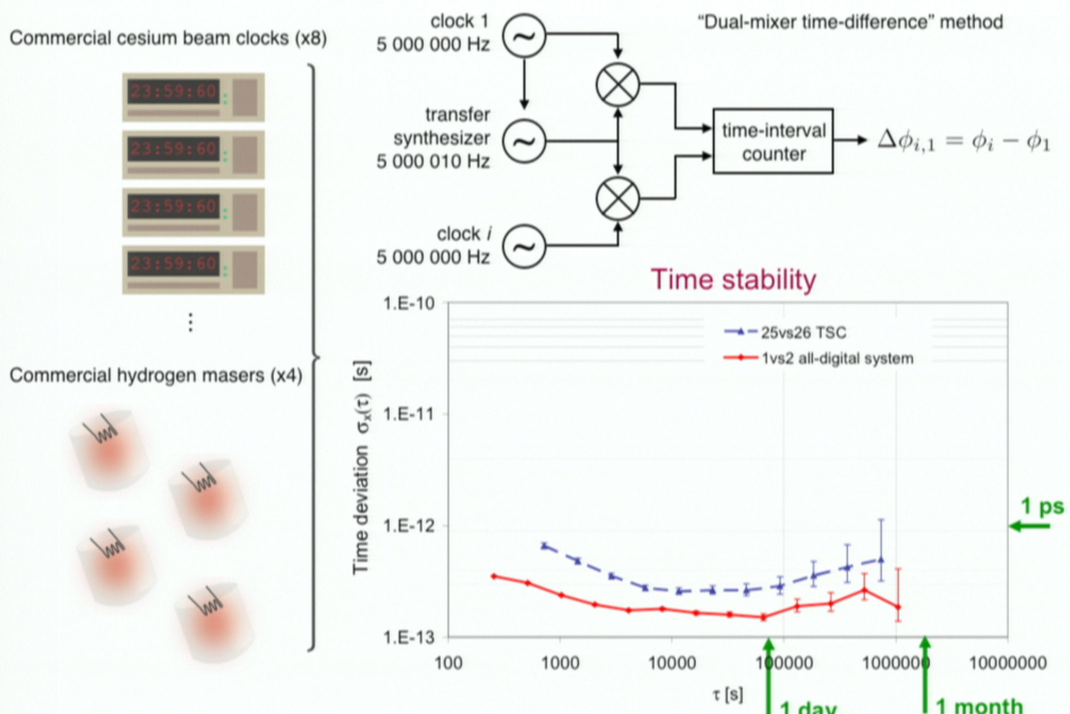
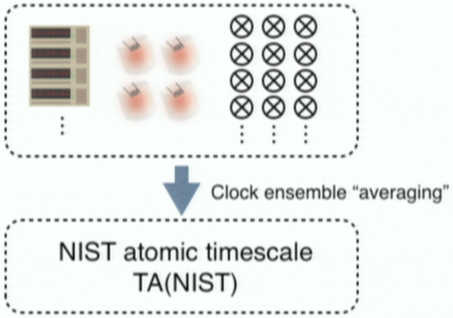
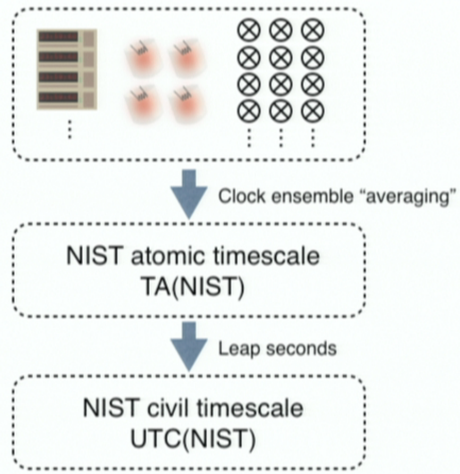
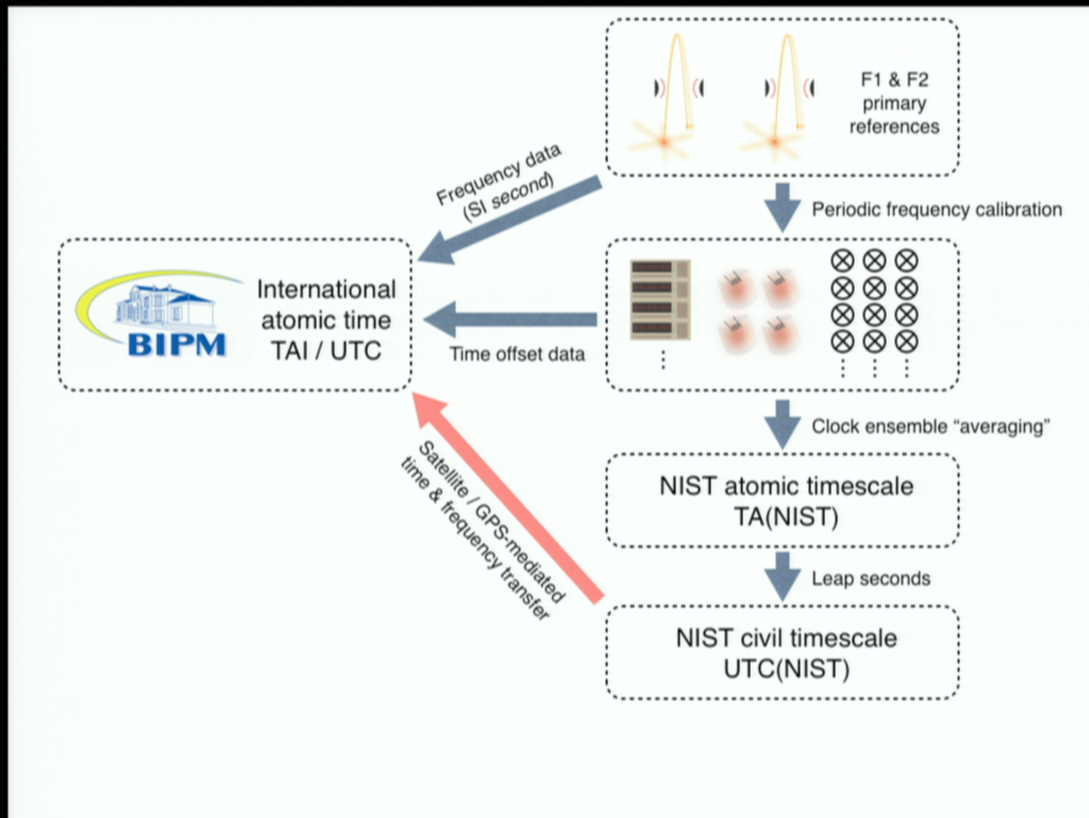
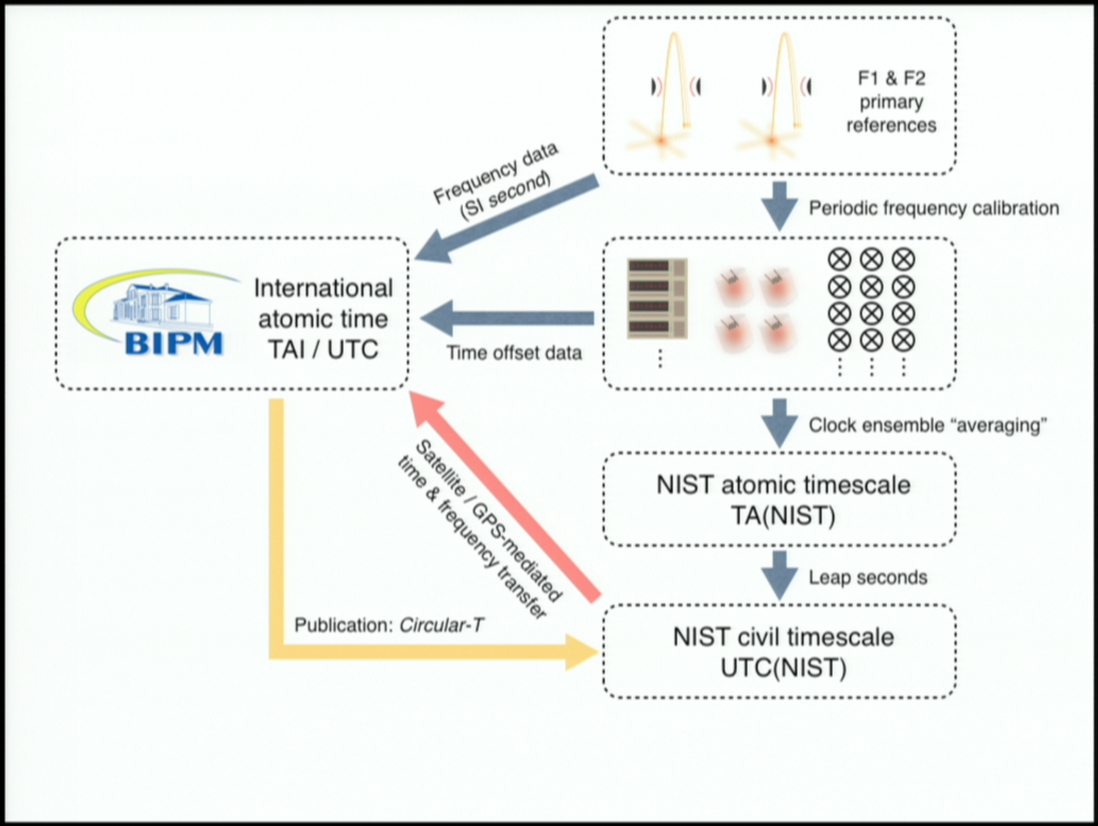


S. Romisch, S.R. Jefferts, T.E. Parker, *Proc. XXXth Gen. Assem. URSI* (2011)


Clock ensemble "averaging"
NIST atomic timescale
TA(NIST)


Clock ensemble "averaging"
NIST atomic timescale
TA(NIST)
Leap seconds
NIST civil timescale
UTC(NIST)


F1 & F2
primary
references
Frequency data
(SI *second*)
Periodic frequency calibration
BIPM
International
atomic time
TAI / UTC
Time offset data
Clock ensemble "averaging"
NIST atomic timescale
TA(NIST)
Satellite / GPS-mediated
time & frequency transfer
Leap seconds
NIST civil timescale
UTC(NIST)



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NIST civil timescale
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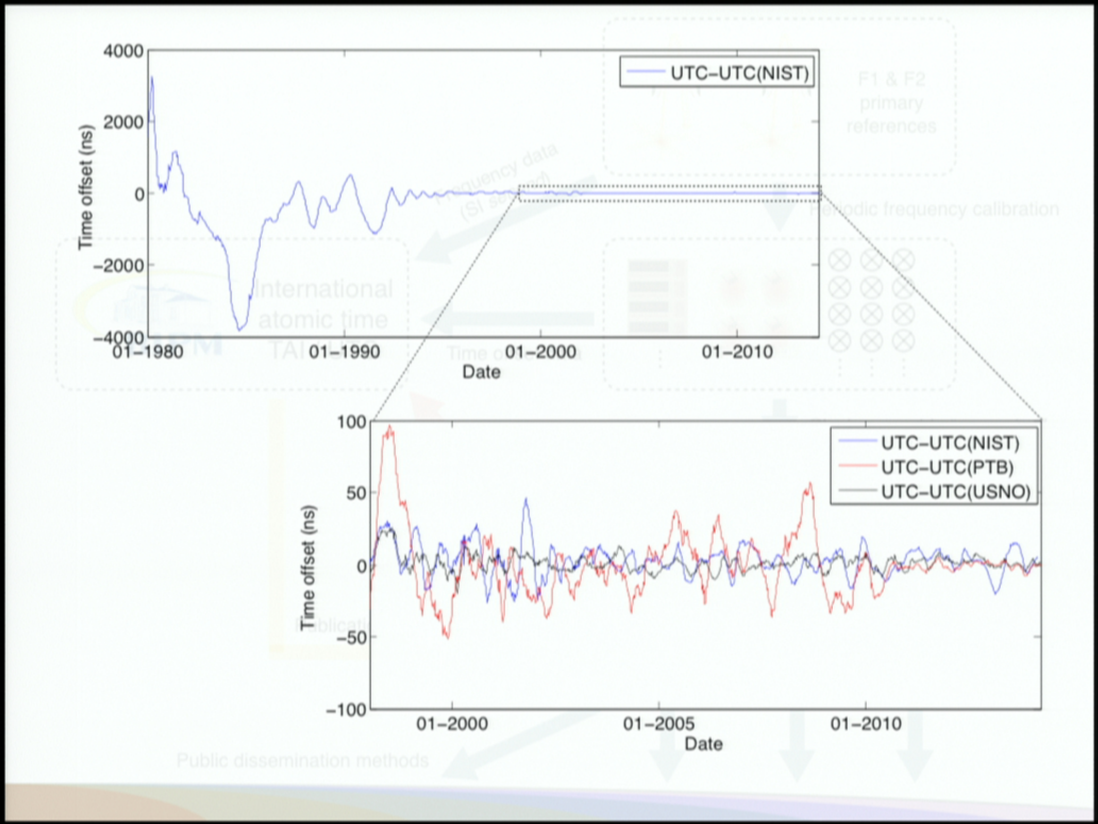
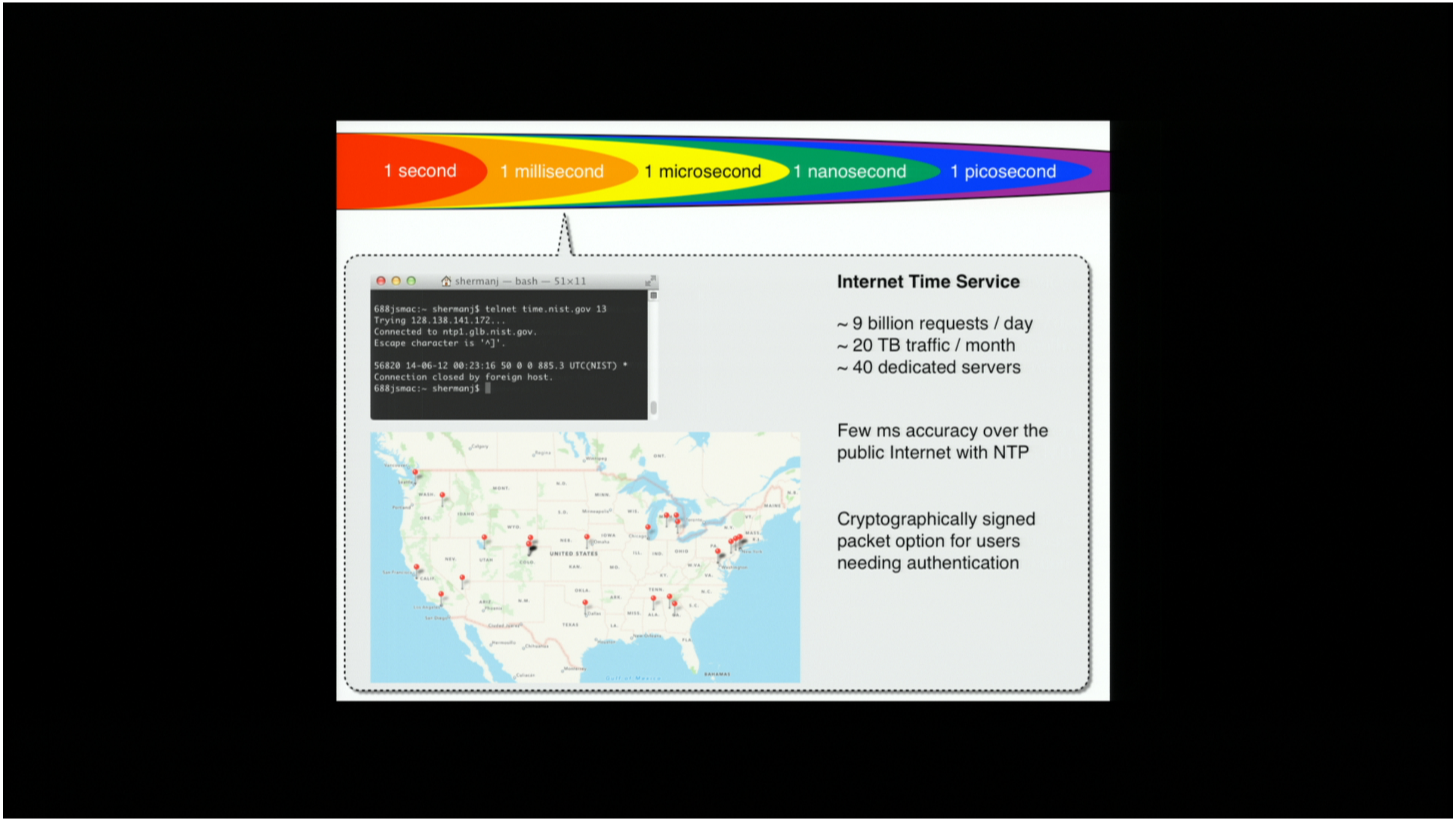
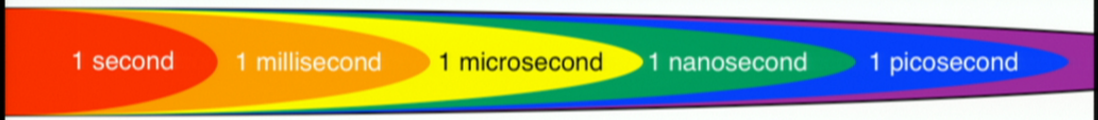


UTC−UTC(NIST)
Time offset (ns)
4000
2000
0
−2000
−4000
01−1980
01−1990
01−2000
01−2010
Date
UTC−UTC(NIST)
UTC−UTC(PTB)
UTC−UTC(USNO)
100
50
0
−50
−100
01−2000
01−2005
01−2010


1 second
1 millisecond
1 microsecond
1 nanosecond
1 picosecond
shermanj — bash — 51×11
688jsmac:~ shermanj$ telnet time.nist.gov 13
Trying 128.138.141.172...
Connected to ntp1.glb.nist.gov.
Escape character is '^]'.
56820 14-06-12 00:23:16 50 0 0 885.3 UTC(NIST) *
Connection closed by foreign host.
688jsmac:~ shermanj$
UNITED STATES
Internet Time Service
~ 9 billion requests / day
~ 20 TB traffic / month
~ 40 dedicated servers
Few ms accuracy over the public Internet with NTP
Cryptographically signed packet option for users needing authentication



WWV / WWVH

Radio stations in
Colorado and Hawaii

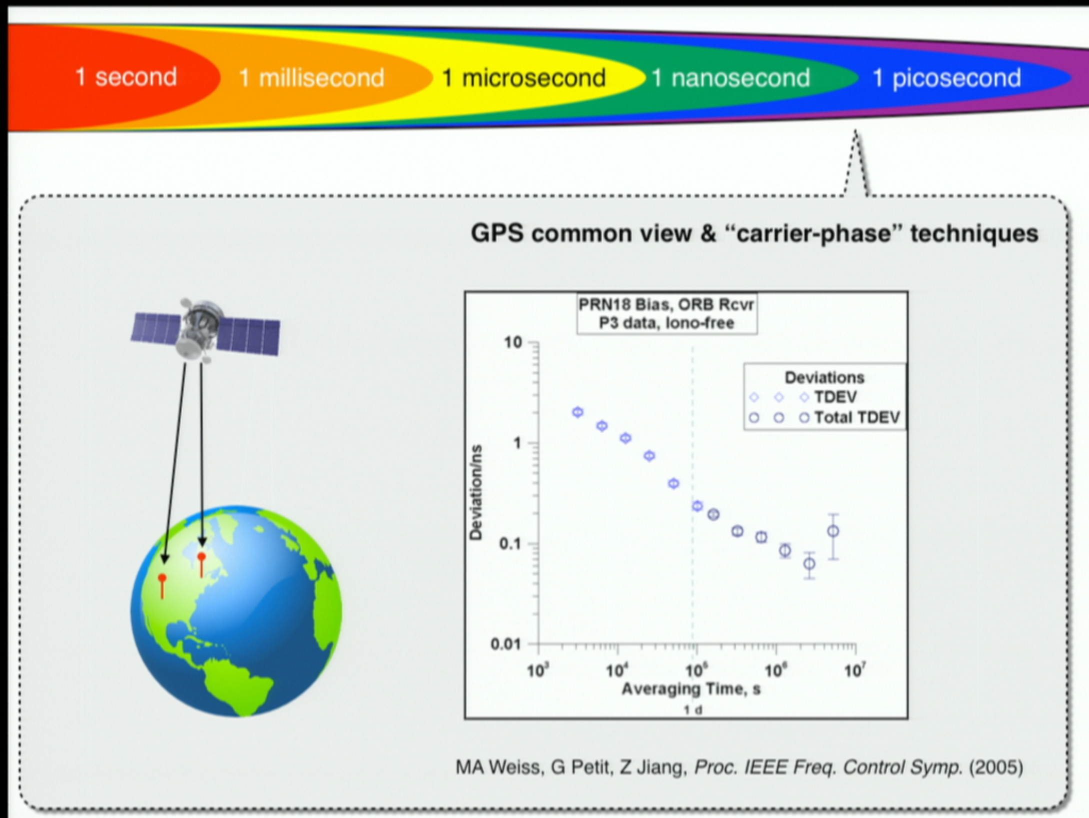
Power: 10 kW
2.5 MHz, 5 MHz, 10 MHz
15 MHz, 20 MHz

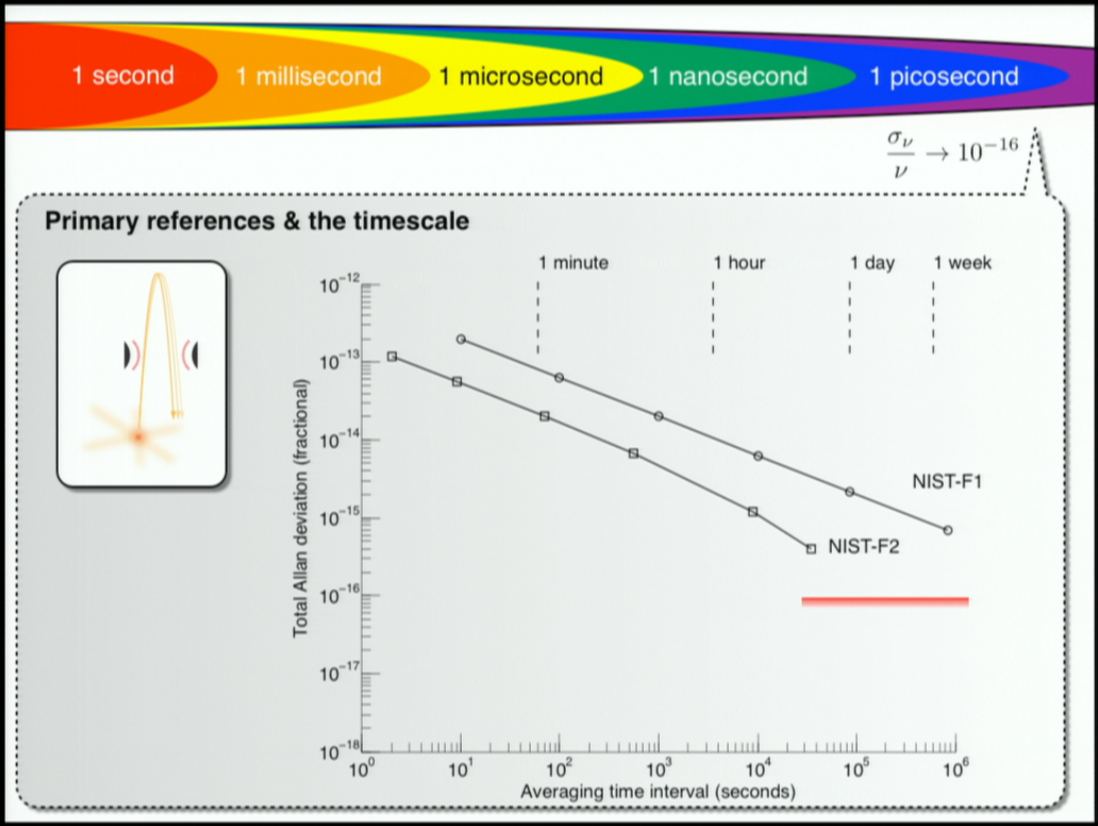
WWVB

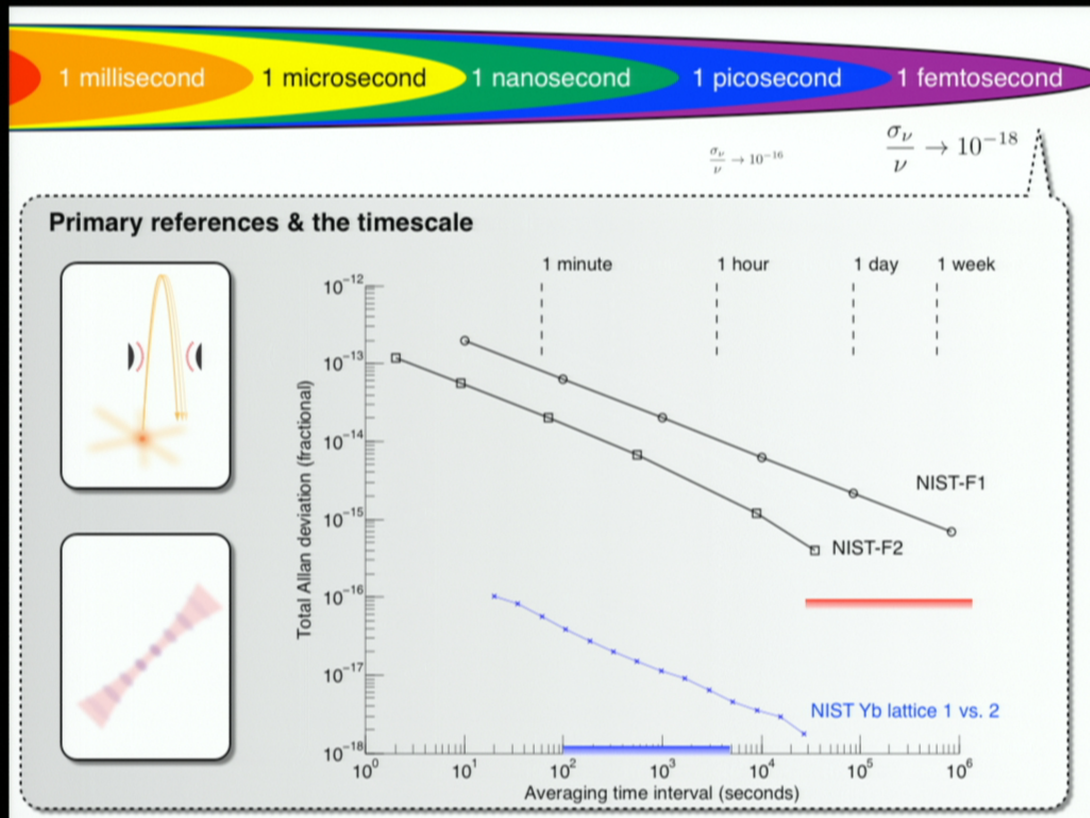
Ft. Collins, Colorado

Power: 75 kW
60 kHz (5 km wavelength!)

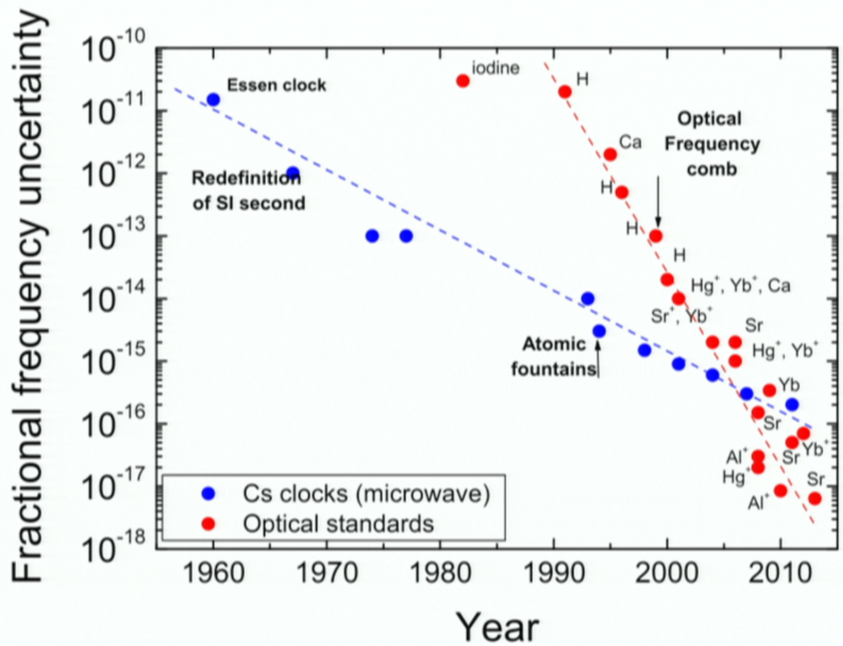
Main limitations
1 ms delay / 300 km
Day/night signal variation


1 second
1 millisecond
1 microsecond
1 nanosecond
1 picosecond
GPS common view & "carrier-phase" techniques
PRN18 Bias, ORB Rcvr
P3 data, Iono-free
Deviations
TDEV
Total TDEV
Deviation/ns
Averaging Time, s
1 d
MA Weiss, G Petit, Z Jiang, *Proc. IEEE Freq. Control Symp.* (2005)


1 second
1 millisecond
1 microsecond
1 nanosecond
1 picosecond
$\frac{\sigma_\nu}{\nu} \to 10^{-16}$
Primary references & the timescale
1 minute
1 hour
1 day
1 week
NIST-F1
NIST-F2
Total Allan deviation (fractional)
Averaging time interval (seconds)



1 millisecond
1 microsecond
1 nanosecond
1 picosecond
1 femtosecond
$\frac{\sigma_\nu}{\nu} \to 10^{-16}$
$\frac{\sigma_\nu}{\nu} \to 10^{-18}$
Primary references & the timescale
1 minute
1 hour
1 day
1 week
Total Allan deviation (fractional)
Averaging time interval (seconds)
NIST-F1
NIST-F2
NIST Yb lattice 1 vs. 2



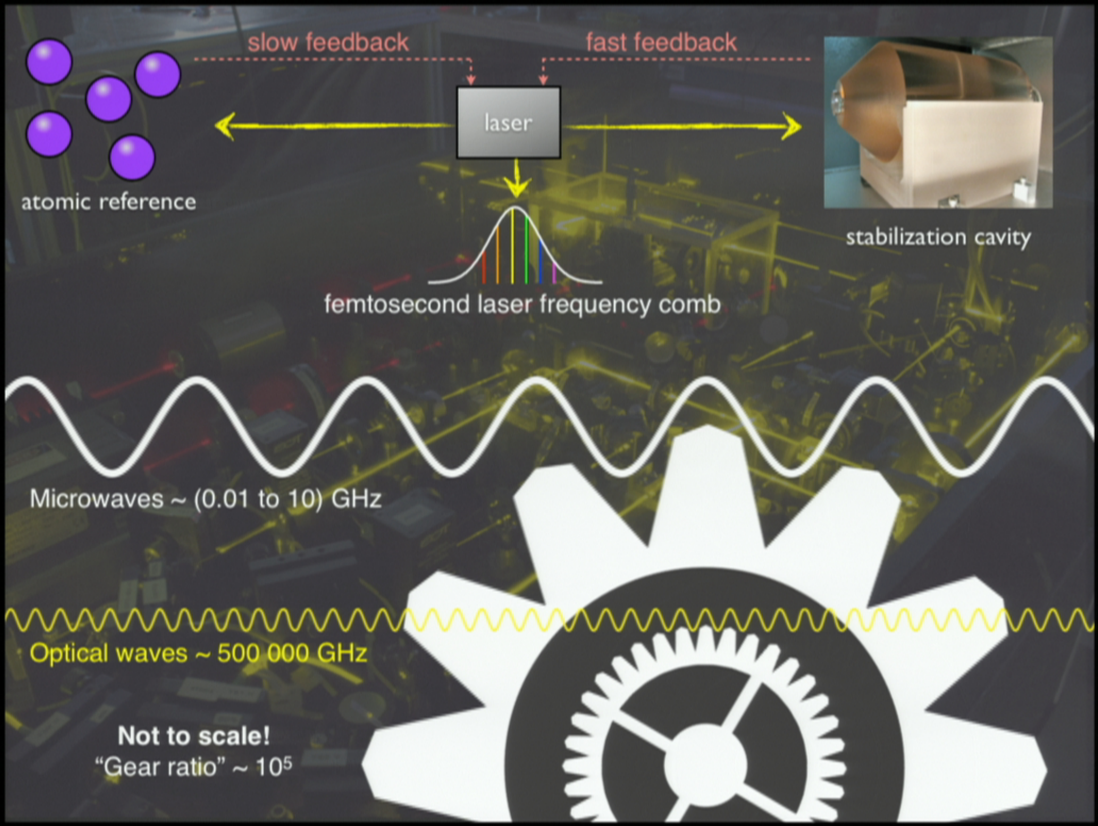
N Poli, CW Oates, P Gill, GM Tino, "Optical atomic clocks", *Riv. Nuovo Cimento* **36**, 555-624 (2013)

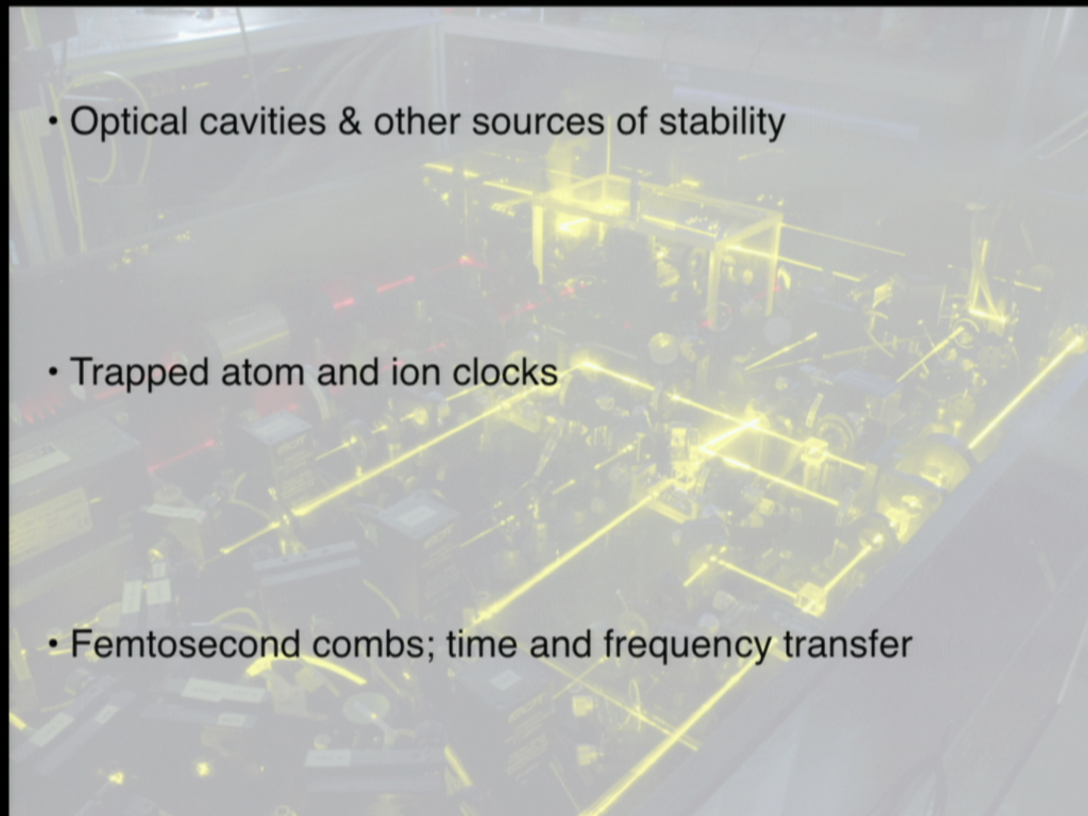
... meanwhile, **almost everything else** in life is getting **exponentially worse** with time.

probably by Rob Beschizza (boingboing.net)

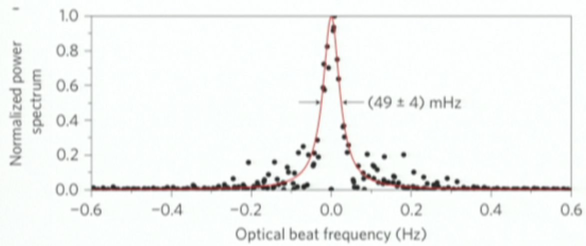

fast feedback
laser
stabilization cavity

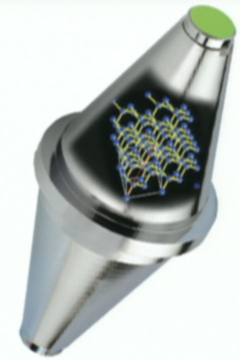

slow feedback
fast feedback
laser
atomic reference
stabilization cavity

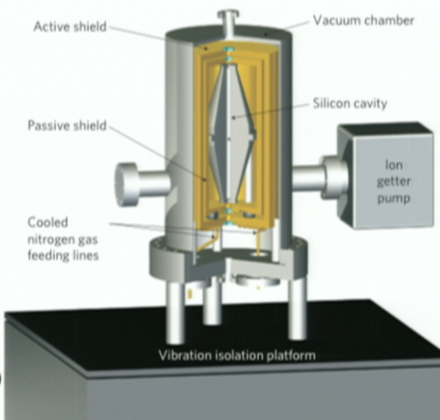

slow feedback
fast feedback
laser
atomic reference
stabilization cavity
femtosecond laser frequency comb
Microwaves ~ (0.01 to 10) GHz
Optical waves ~ 500 000 GHz
Not to scale!
"Gear ratio" ~ 10^5


• Optical cavities & other sources of stability
• Trapped atom and ion clocks
• Femtosecond combs; time and frequency transfer

State of the art in cavities



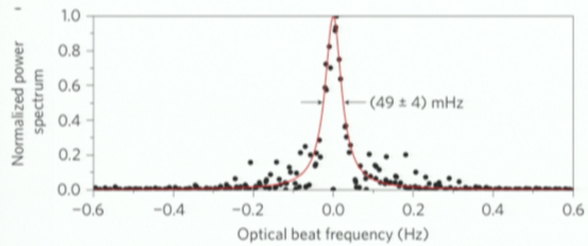


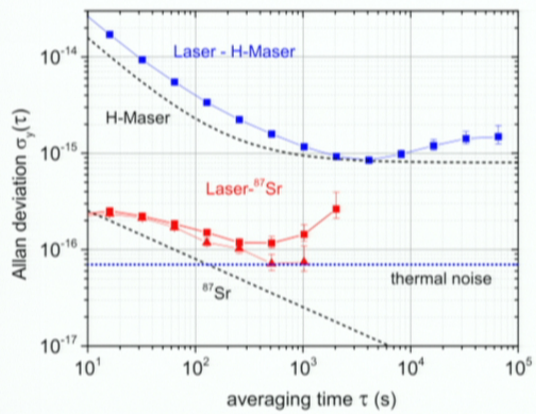


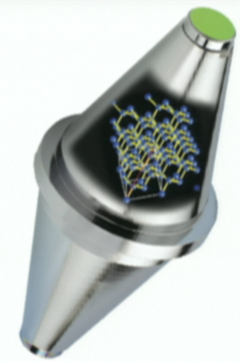
T Kessler, C Hagemann, C Grebing, et al., *Nature Photonics* **6**, 687 (2012)

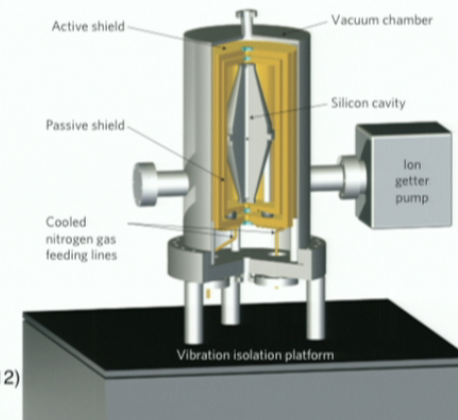
C Hagemann, C Grebing, C Lisdat, et al., **arXiv**:1405.1759 (2014)

State of the art in cavities









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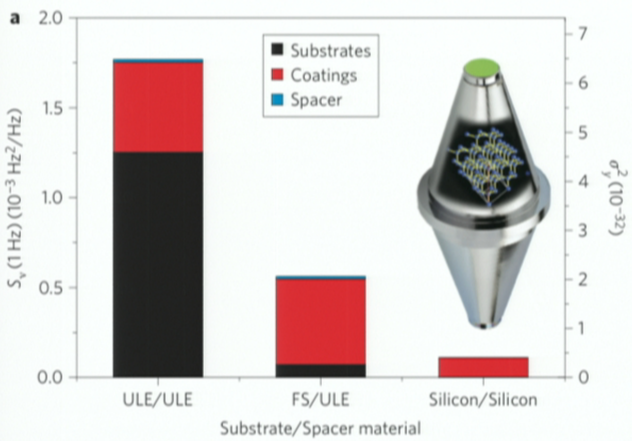
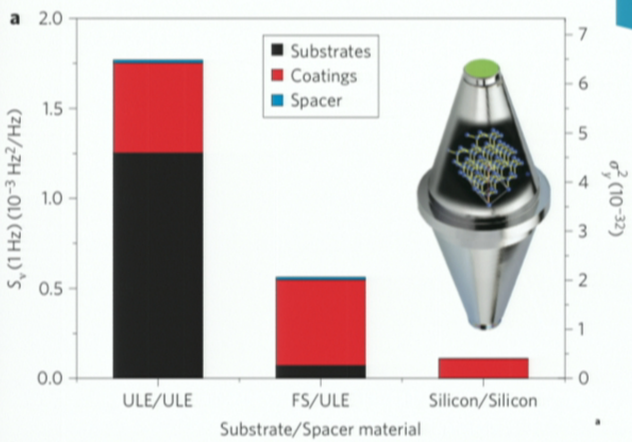
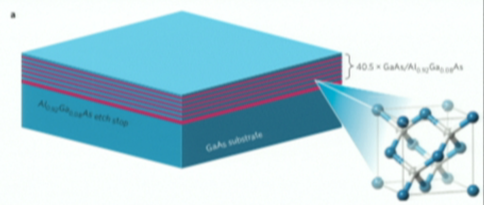
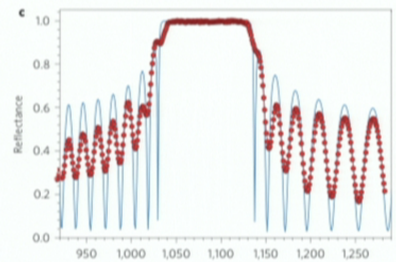


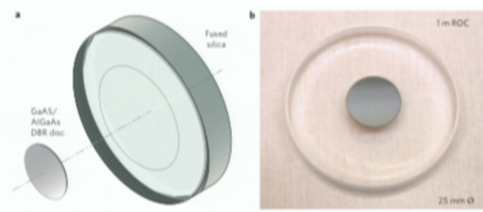
T Kessler, C Hagemann, C Grebing, et al., *Nature Photonics* **6**, 687 (2012)
GD Cole, W Zhang, M Martin, et al., *Nature Photonics* **7**, 644 (2013)

State of the art in cavities









T Kessler, C Hagemann, C Grebing, et al., *Nature Photonics* **6**, 687 (2012)

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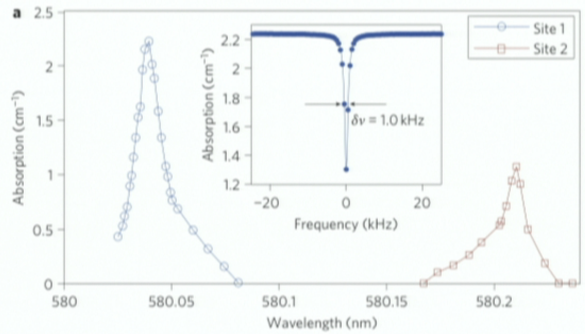
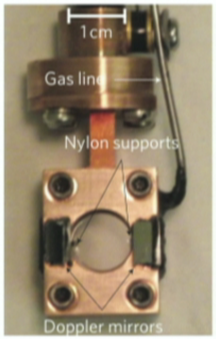
Laser stabilization to spectral holes in $Eu^{3+}:Y_2SiO_5$





MJ Thorpe, L Rippe, TM Fortier, et al., *Nature Photonics* **5**(11), 688 (2011)
DR Leibrandt, MJ Thorpe, CW Chou, et al., *PRL* **111**, 237402 (2013)

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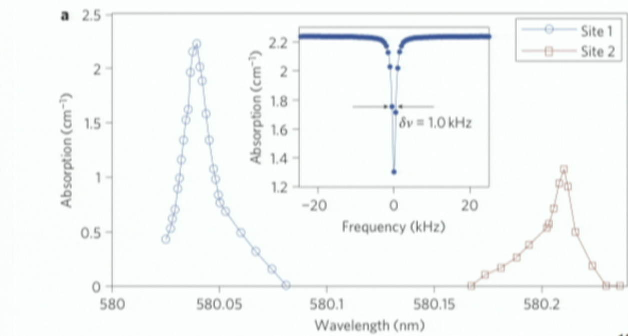

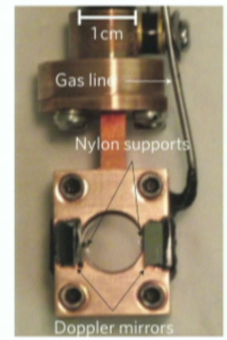

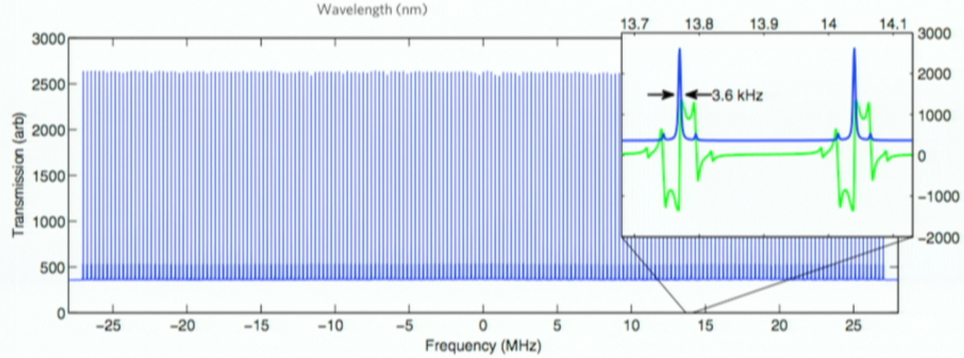

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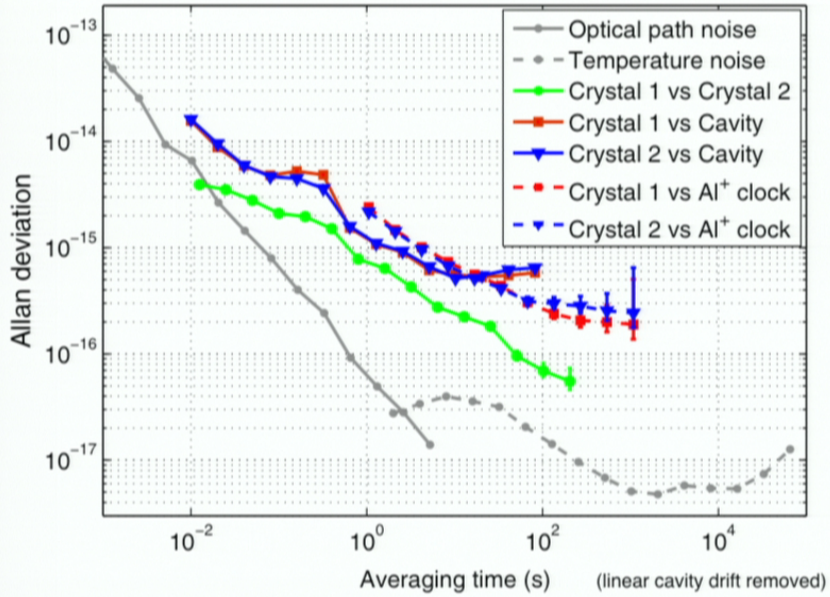

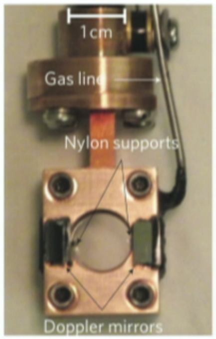

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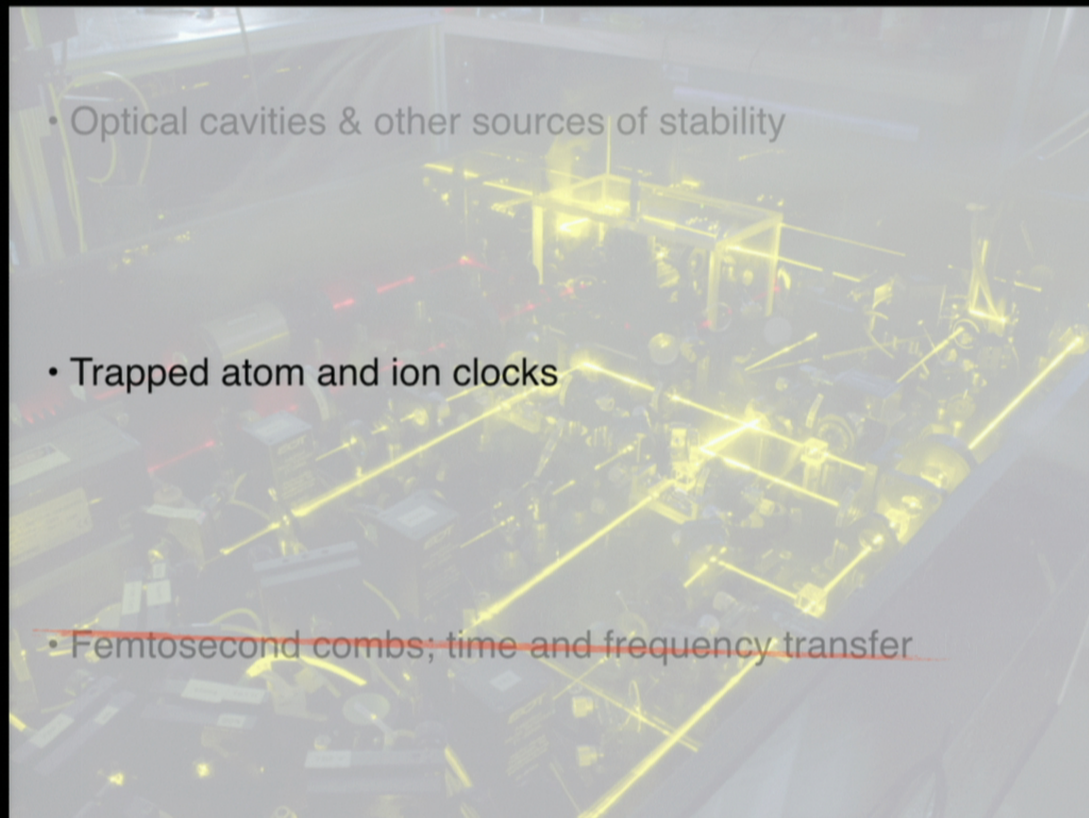
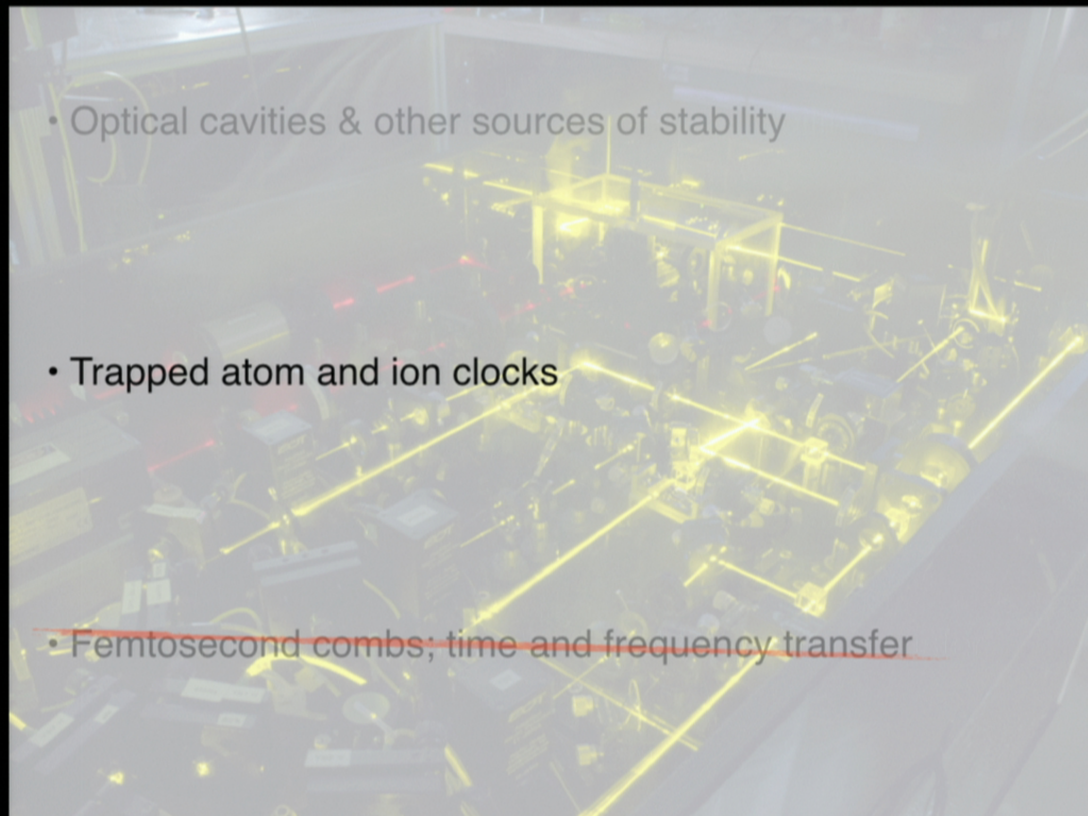

• Optical cavities & other sources of stability
• Trapped atom and ion clocks
• Femtosecond combs; time and frequency transfer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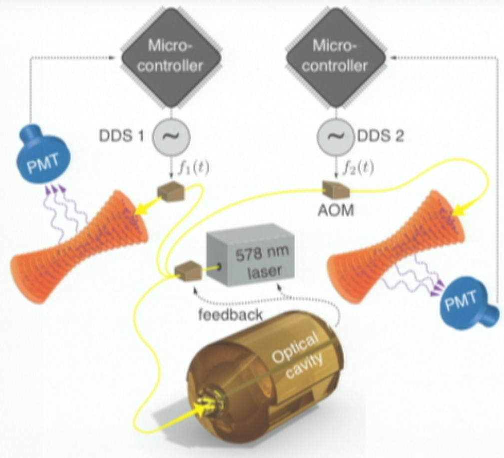
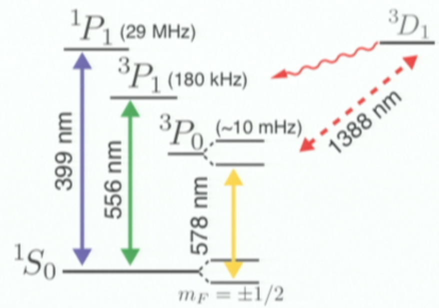
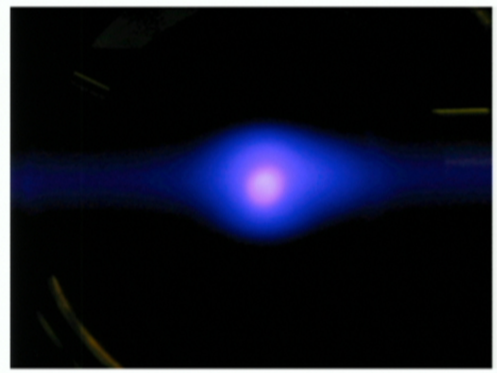
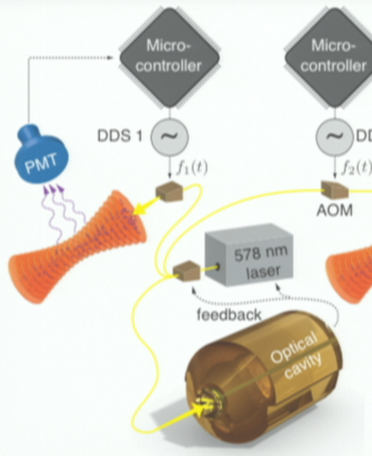
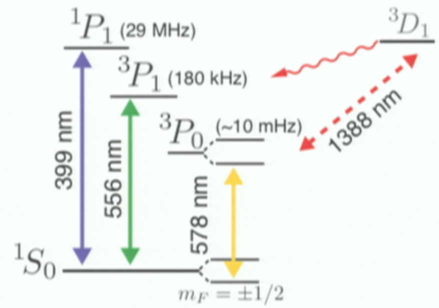


N Hinkley, JA Sherman, NB Phillips, et al.,
Science **341**, 1215–1218 (2013)









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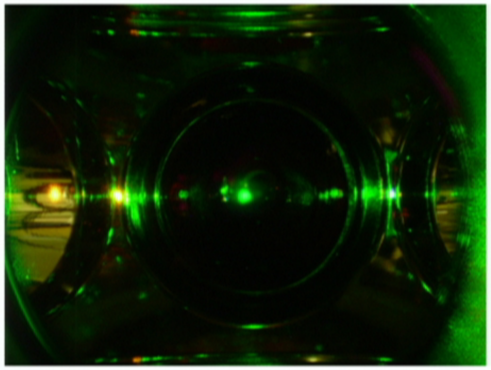

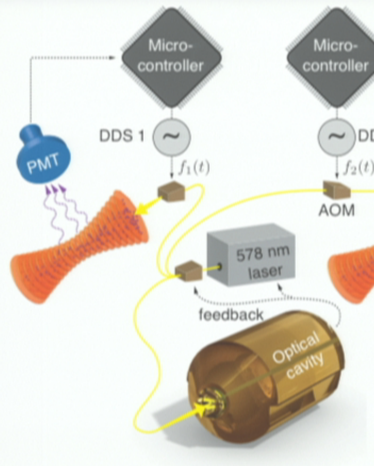

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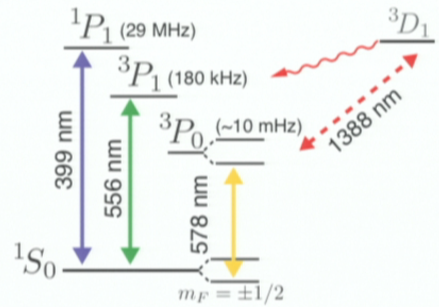

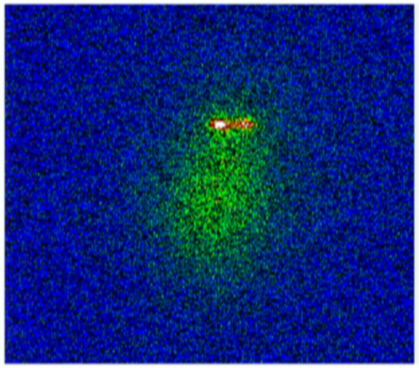

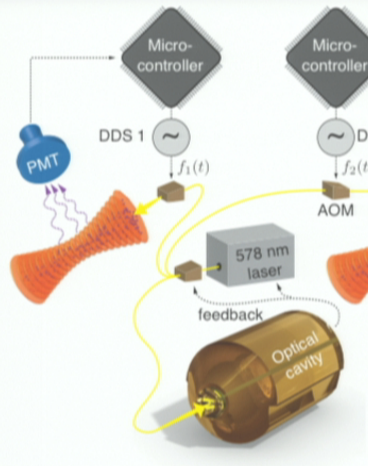

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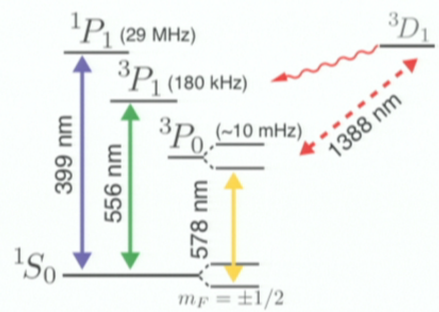

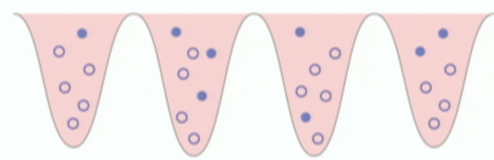

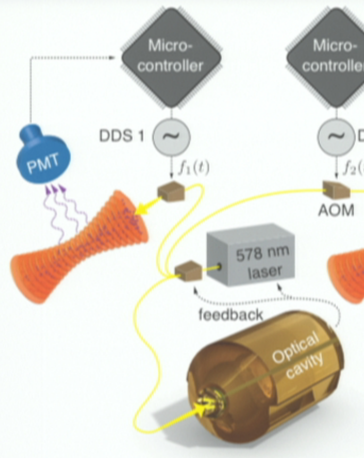

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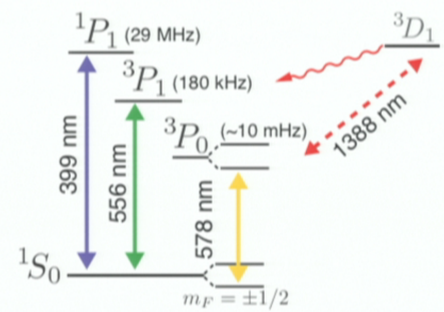

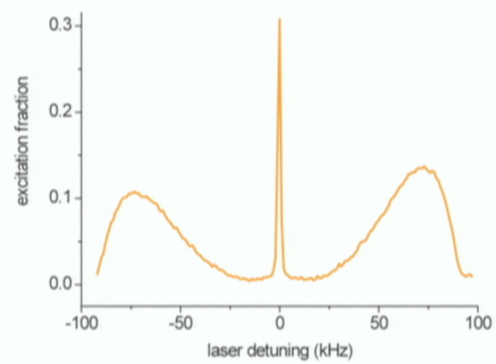

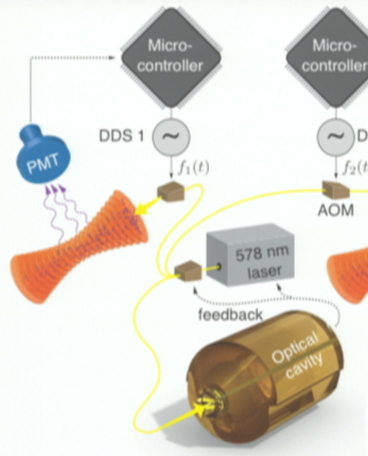

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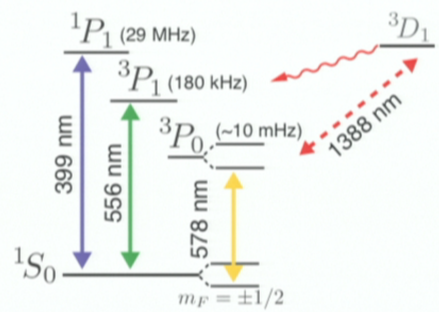

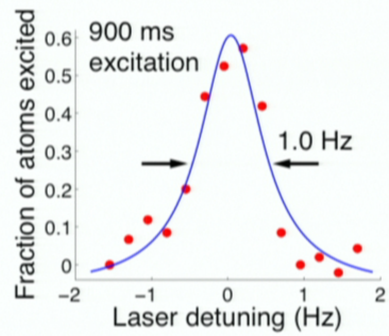

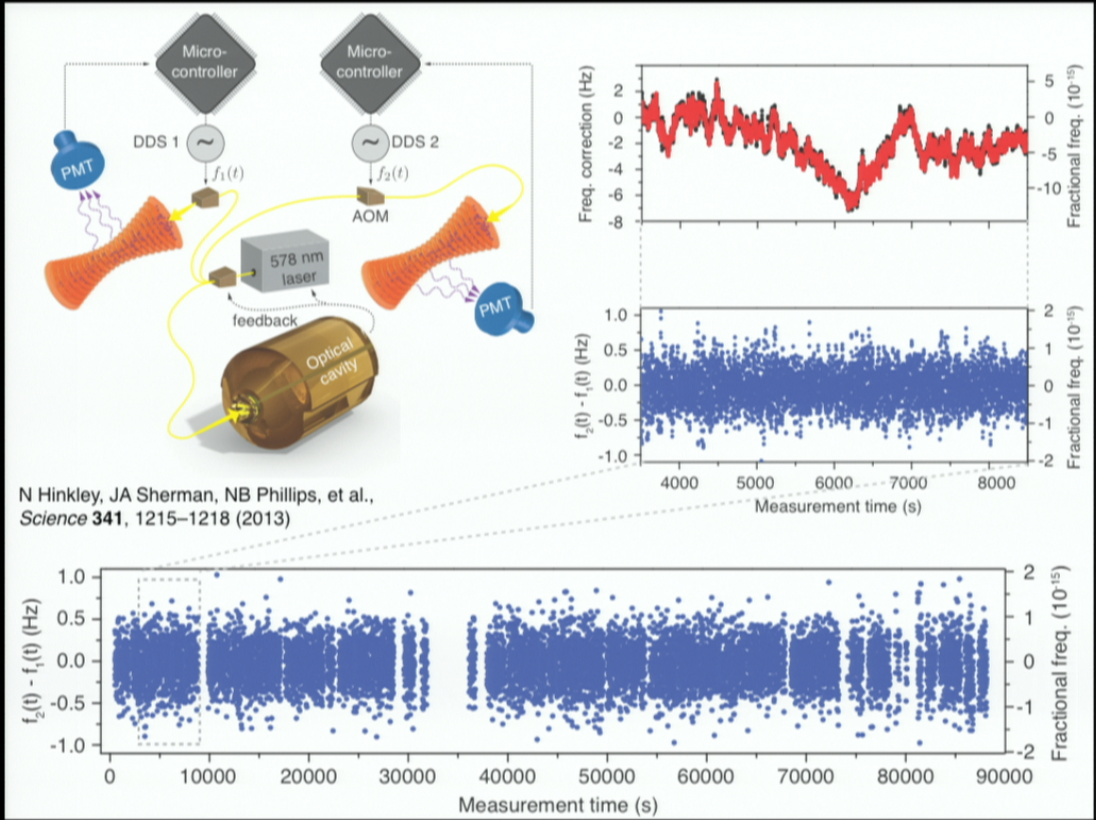

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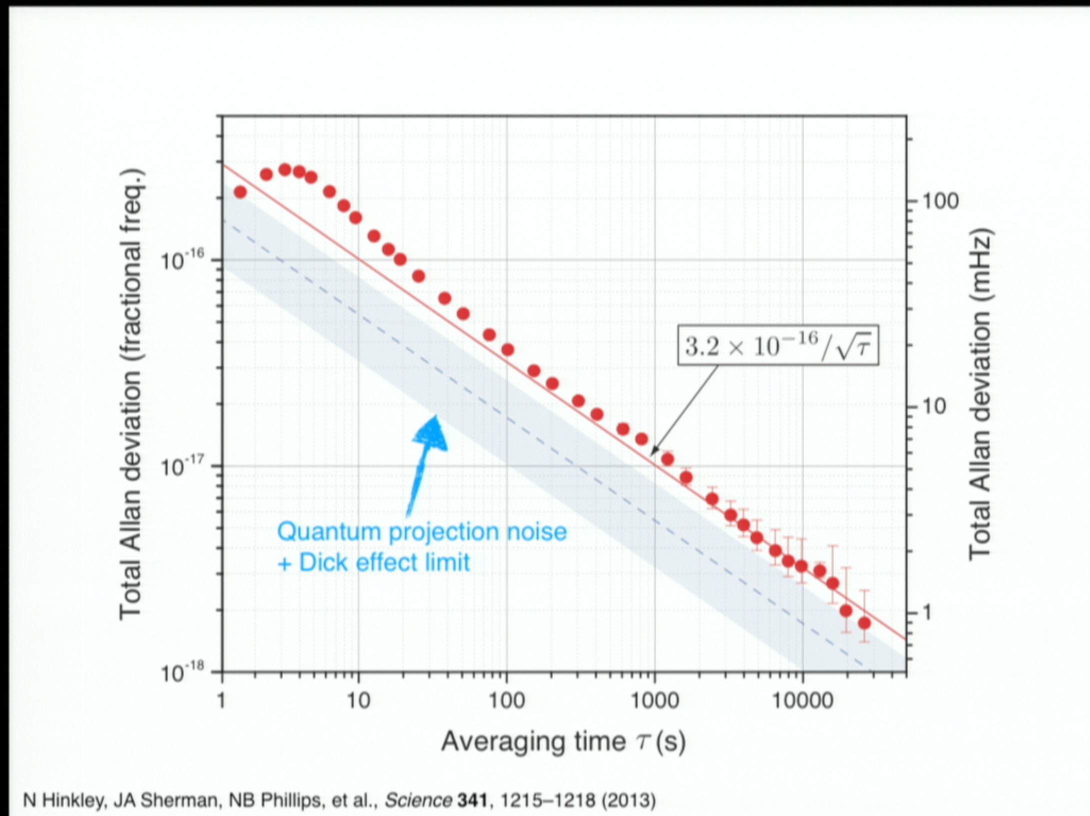
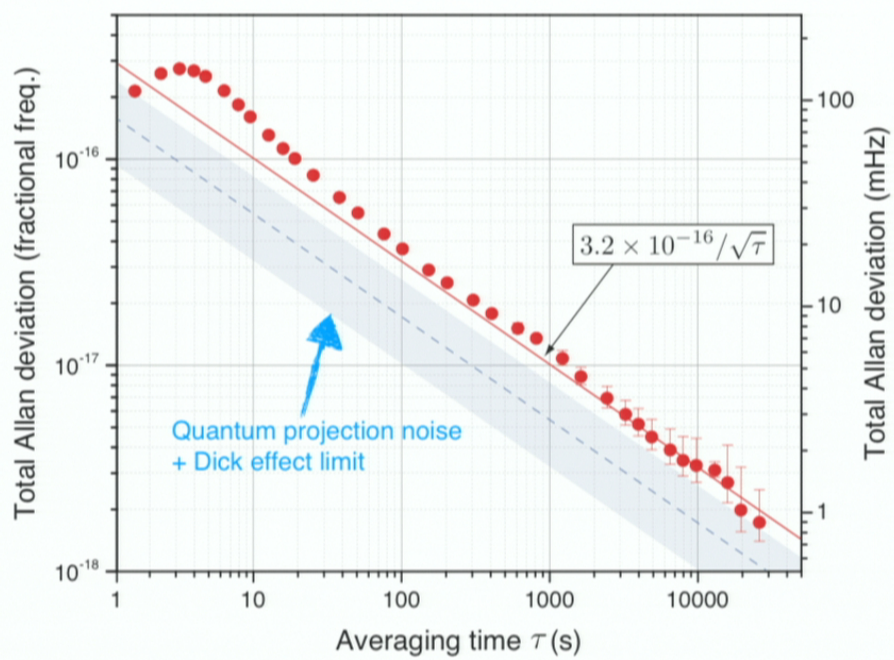
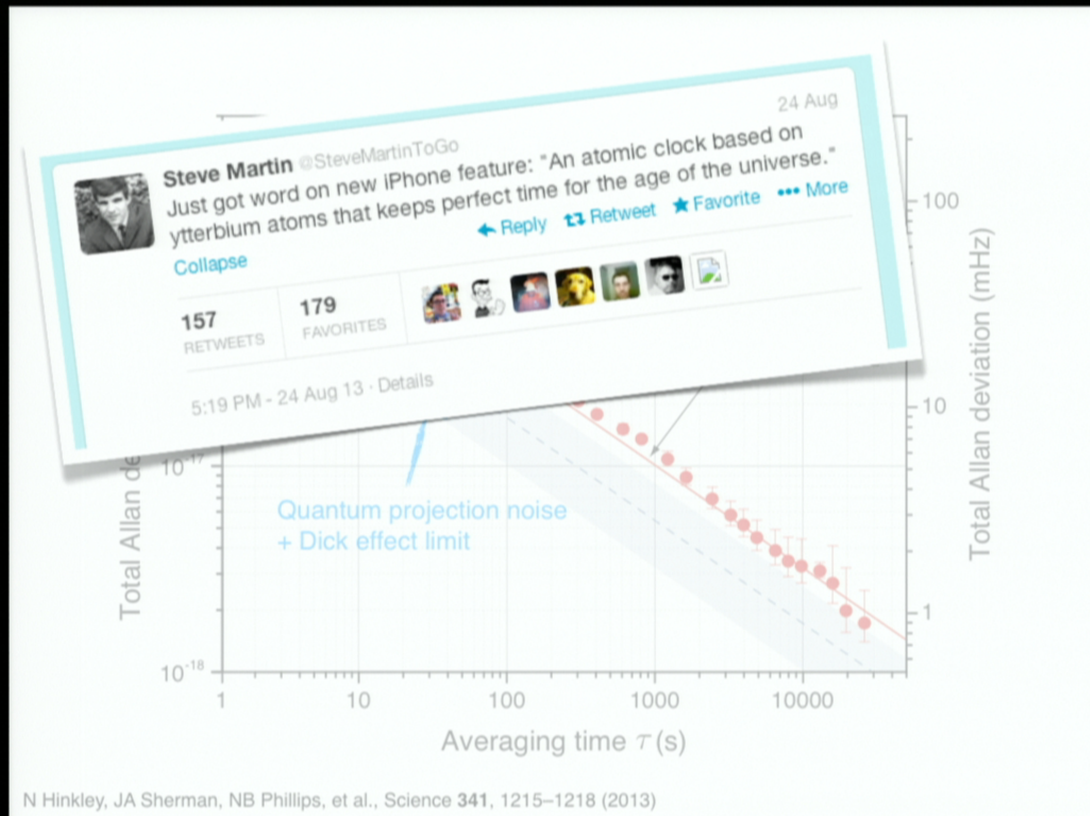

Total Allan deviation (fractional freq.)
10^{-16}
10^{-17}
10^{-18}
Total Allan deviation (mHz)
100
10
1
1
10
100
1000
10000
Averaging time τ (s)
$3.2 \times 10^{-16}/\sqrt{\tau}$
Quantum projection noise
+ Dick effect limit
N Hinkley, JA Sherman, NB Phillips, et al., *Science* **341**, 1215–1218 (2013)



N Hinkley, JA Sherman, NB Phillips, et al., *Science* **341**, 1215–1218 (2013)


Steve Martin @SteveMartinToGo
24 Aug
Just got word on new iPhone feature: "An atomic clock based on ytterbium atoms that keeps perfect time for the age of the universe."
Reply
Retweet
Favorite
More
Collapse
157 RETWEETS
179 FAVORITES
5:19 PM - 24 Aug 13 · Details
Quantum projection noise
+ Dick effect limit
Total Allan deviation (mHz)
100
10
1
10^{-17}
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5:19 PM - 24 Aug 13 · Details
Stank JJ · 4 days ago
Amazing. This is going to revolutionize....pretty much nothing
Reply
Share ›
Total Allan deviation (mHz)
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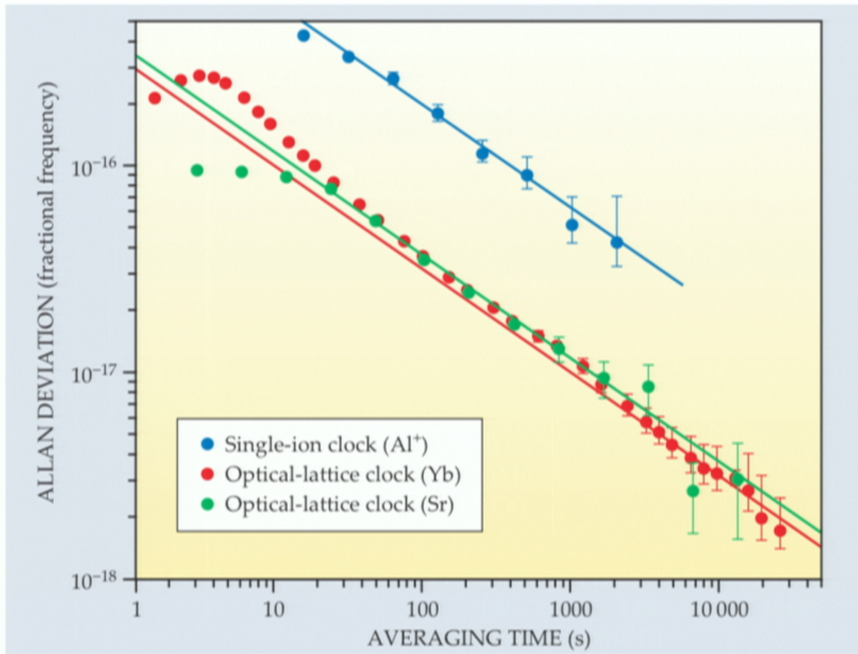
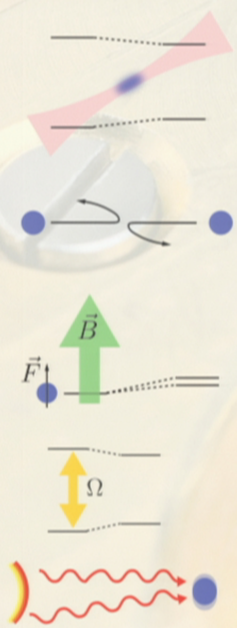
N Hinkley, JA Sherman, NB Phillips, et al., Science 341, 1215–1218 (2013)

$$\sigma(\tau) \propto \frac{\Delta\nu}{\nu} \frac{1}{\sqrt{N_{\text{atoms}}}} \sqrt{\frac{T_{\text{meas}}}{\tau}}$$



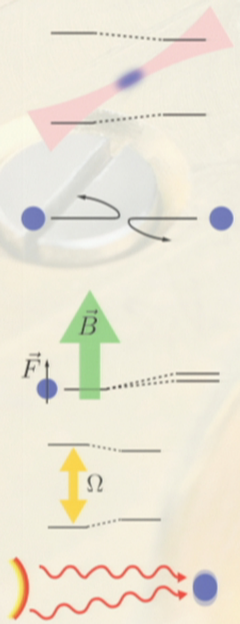
A Smart, *Physics Today* **67**(3), 12 (2014)

Adapted from Lemke *et al.*, *PRL* **103**, 063001 (2009)



Dominant systematic shifts	Correction (x 10^{-17})	Uncertainty (x 10^{-17})
Lattice polarizability & M1-E2 interference	4	2
Hyper-polarizability	33	7
Collisions (“density shift”)	-161	8
Uncanceled linear Zeeman (and line-centering)	4	4
Quadratic Zeeman	-17	1
Light shift: probe	0.5	2
Blackbody radiation	-250	25
Total (2009 evaluation)		**34**

Adapted from Lemke *et al.*, *PRL* **103**, 063001 (2009)



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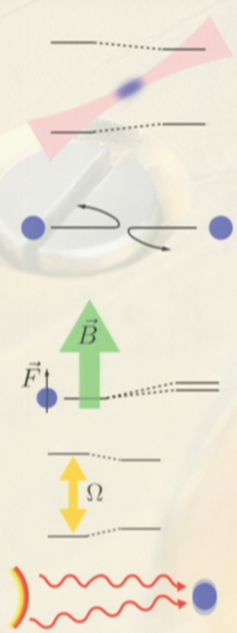
N.D. Lemke et al., *PRL* **107** 103902 (2011)
A.D. Ludlow et al., *PRA* **84** 052724 (2011)

Adapted from Lemke *et al.*, *PRL* **103**, 063001 (2009)



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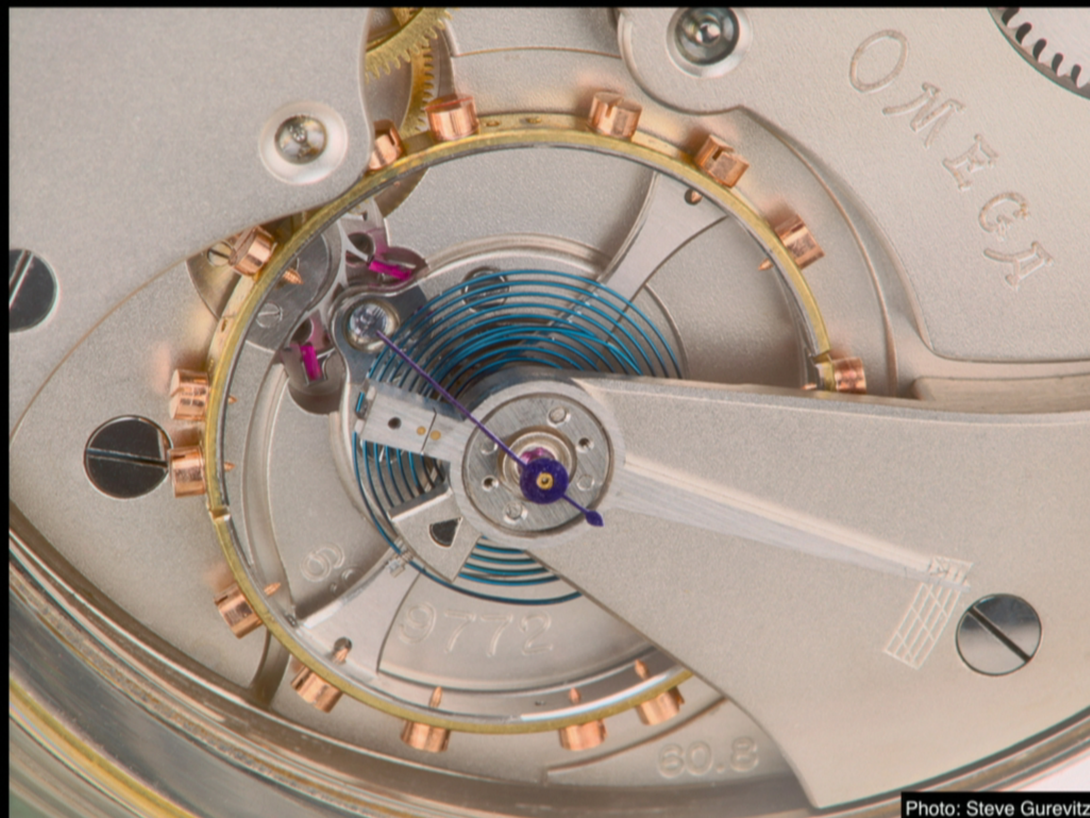
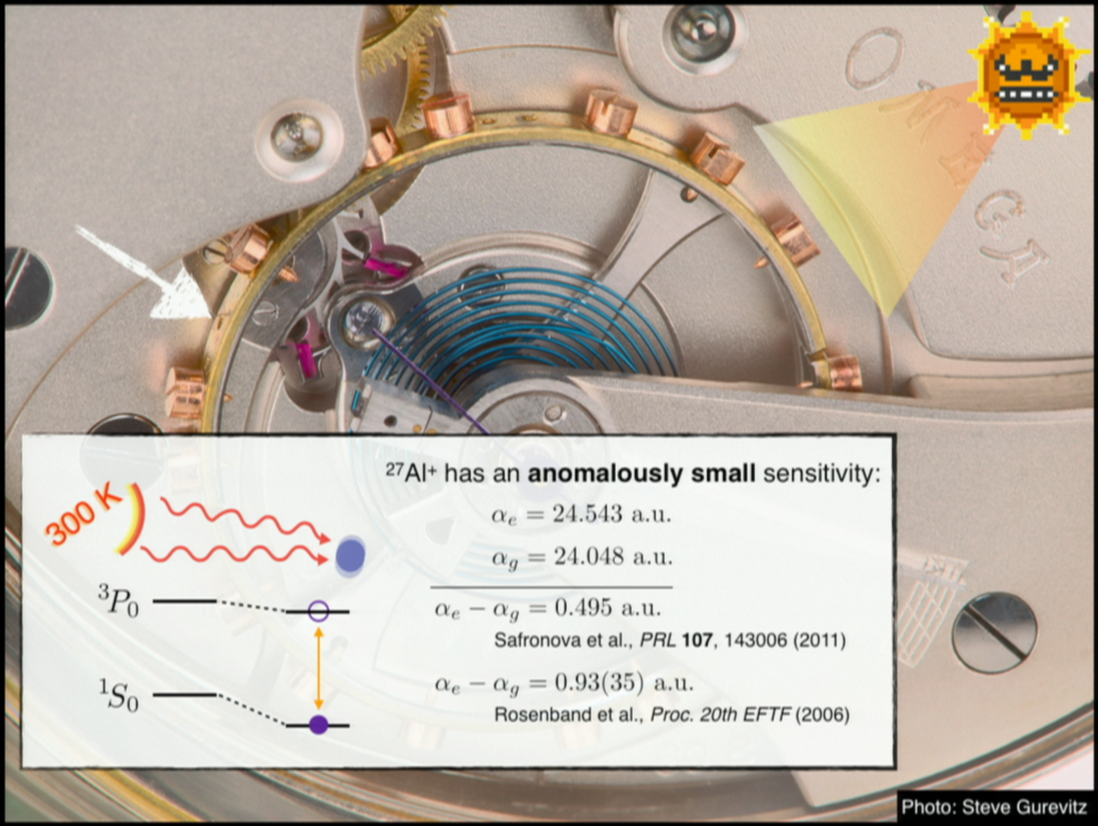
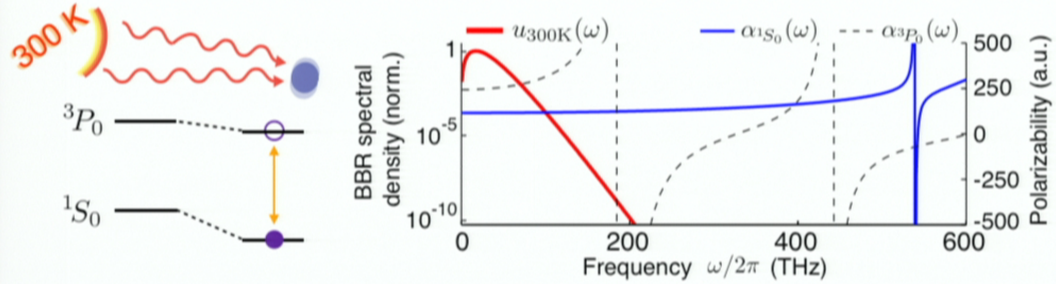

OMEGA
9772
60.8
Photo: Steve Gurevitz



300 K
$^3P_0$
$^1S_0$
^{27}Al$^+$ has an **anomalously small** sensitivity:
$\alpha_e = 24.543$ a.u.
$\alpha_g = 24.048$ a.u.
$\alpha_e - \alpha_g = 0.495$ a.u.
Safronova et al., *PRL* **107**, 143006 (2011)
$\alpha_e - \alpha_g = 0.93(35)$ a.u.
Rosenband et al., *Proc. 20th EFTF* (2006)
Photo: Steve Gurevitz

Ytterbium: no such temperature compensating “bi-metallic strip”



$$\Delta\nu_{\rm BBR} = -\frac{1}{2}\left(\alpha_e^{(0)} - \alpha_g^{(0)}\right)(1+\eta_{\rm clock})\langle E^2\rangle_T \approx -1.277\ {\rm Hz}\left(\frac{T}{300\ {\rm K}}\right)^4$$

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Clock's static polarizability

JA Sherman, ND Lemke, N Hinkley, et al., *PRL* **108**(15), 153002 (2012)
T Middelmann, S Falke, C Lisdat, et al., *PRL* **109**(26), 236004 (2012)

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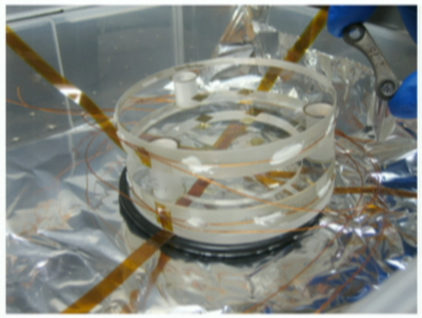

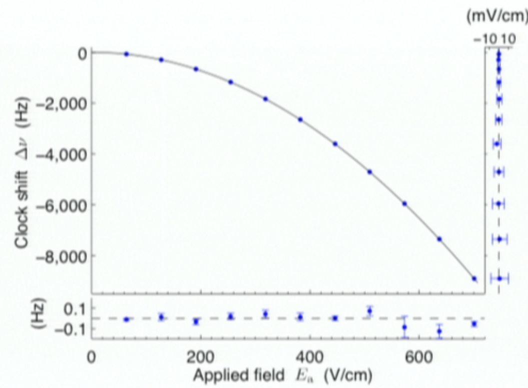

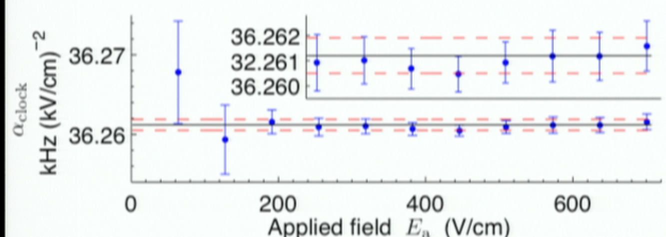

$$\Delta\nu_{\mathrm{Stark}} = -\frac{1}{2}\alpha_{\mathrm{clock}} E_a^2$$

36.2612(7) kHz (V/cm)$^{-2}$

19 ppm total uncertainty!

JA Sherman, ND Lemke, N Hinkley, et al., *PRL* **108**(15), 153002 (2012)

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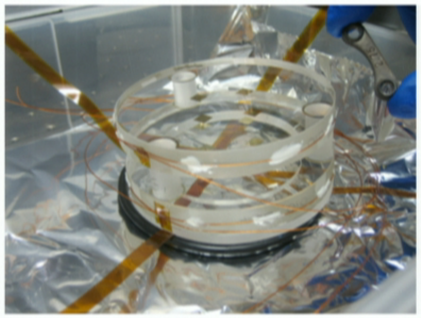
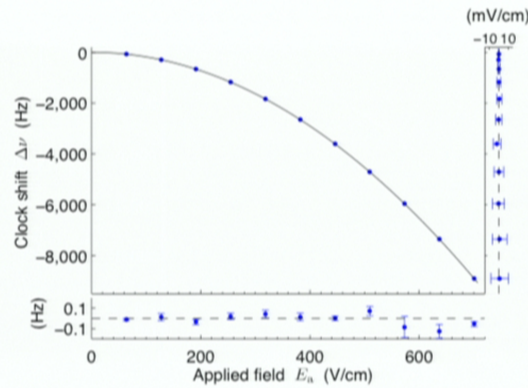
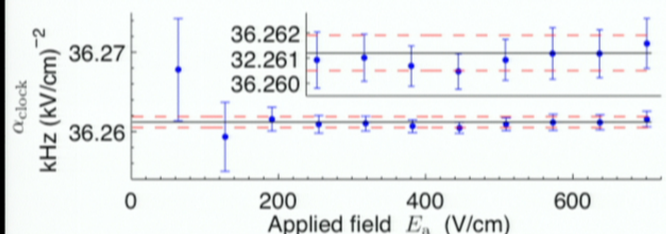
Clock's static polarizability







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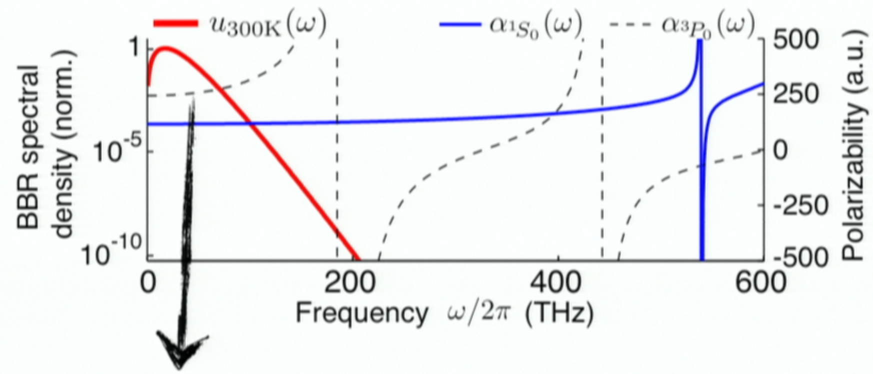
Clock's "dynamic polarizability"



Frequency dependence almost totally determined by one dipole matrix element:

$$\mathcal{D} \equiv \left|\langle 5d6s\,^3D_1||\mathbf{D}||6s6p\,^3P_0\rangle\right|$$

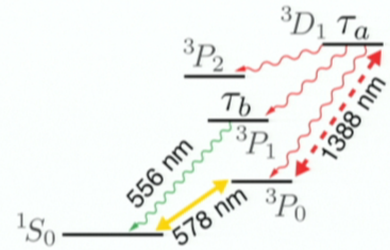
K Beloy, JA Sherman, ND Lemke, et al., *PRA* **86**(5), 051404 (2012)

Let's measure the matrix element...

$$\mathcal{D} \equiv \left| \langle 5d6s\,^3D_1 || \mathbf{D} || 6s6p\,^3P_0 \rangle \right|$$

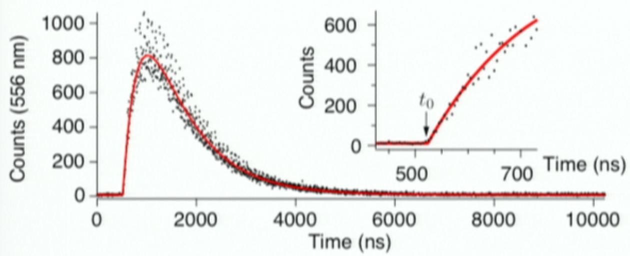
...via an excited state lifetime

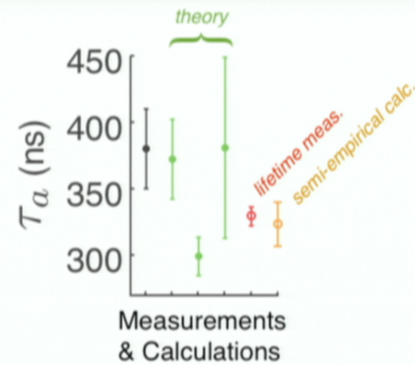
$$\mathcal{D}^2 = 3\pi\epsilon_0\hbar c^3 \frac{(2J'+1)}{\omega_0^3}\frac{\zeta_0}{\tau_a}$$

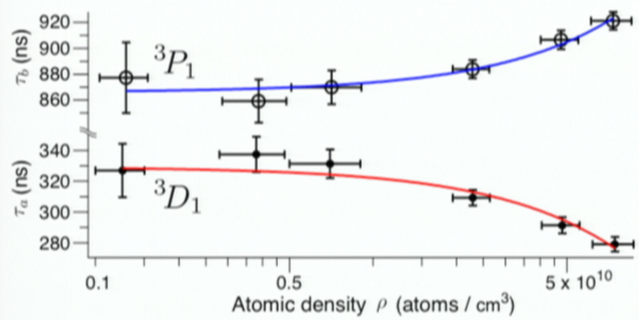


K Beloy, JA Sherman, ND Lemke, et al., *PRA* **86**(5), 051404 (2012)
following method of: CJ Bowers, D Budker, ED Commins, et al., *PRA* **53**(5), 3103 (1996)

$$y(t) \propto \left[e^{-(t-t_0)/\tau_a} - e^{-(t-t_0)/\tau_b}\right]$$







$$\Rightarrow \mathcal{D} = 2.77(4) \text{ a.u.}$$

Systematic uncertainty	$u(\tau_a)$ (ns)
Atomic interactions	4.3
Fit biases	0.9
Zeeman quantum oscillations	3.0
1388 nm finite excitation duration	3.3
1388 nm stray light	3.4
Event counter timing	0.2
Total (in quadrature)	**7.1**

K Beloy, JA Sherman, ND Lemke, et al., *PRA* **86**(5), 051404 (2012)

$$\Delta\nu_{\mathrm{BBR}} = -\frac{1}{2}\left(\alpha_e^{(0)} - \alpha_g^{(0)}\right)(1+\eta_{\mathrm{clock}})\langle E^2\rangle_T \approx -1.277\ \mathrm{Hz}\left(\frac{T}{300\ \mathrm{K}}\right)^4$$

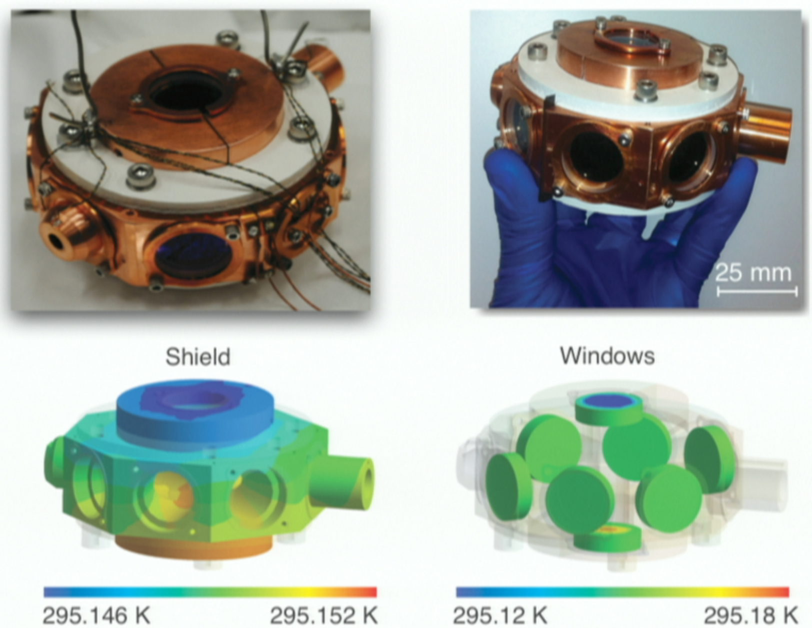
Clock's blackbody radiation polarizability terms

Author	$\alpha_e^{(0)} - \alpha_g^{(0)}$ [a.u.]	η_{clock}
Porsev, Rakhlina, Kozlov (1999)	134(51)	
Porsev, Derevianko (2006)	161(15)	0.0145(15)
Dzuba, Derevianko (2010)	155(16)	
Safronova, Porsev, Clark (2012)	152(10)	0.0179(6)
our experimental results (2012)	145.726(3)	0.0179(5)

...supports a clock BBR uncertainty of ~ 1.2 x 10^{-18} at 300 K

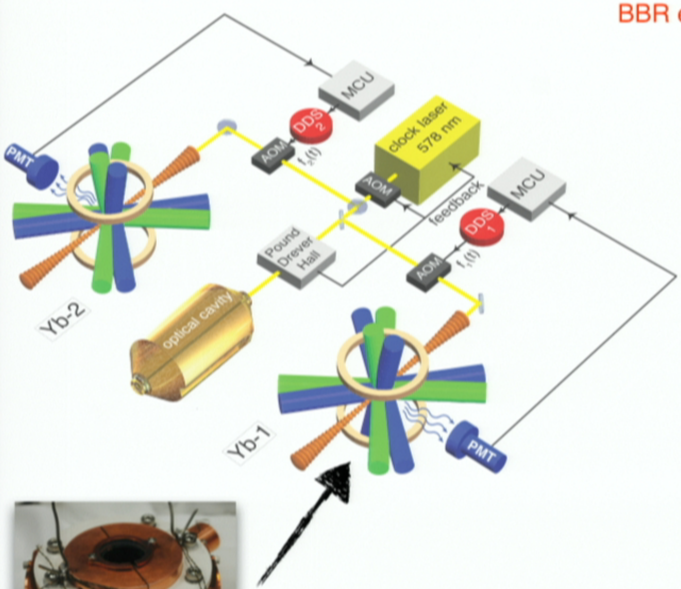
$$\Delta\nu_{\mathrm{BBR}} = -\frac{1}{2}\left(\alpha_e^{(0)} - \alpha_g^{(0)}\right)(1+\eta_{\mathrm{clock}})\langle E^2\rangle_T \approx -1.277\ \mathrm{Hz}\left(\frac{T}{300\ \mathrm{K}}\right)^4$$

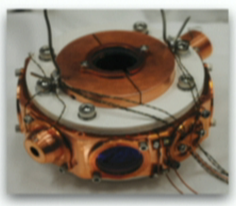
BBR electric field intensity



$$\Delta\nu_{\rm BBR} = -\frac{1}{2}\left(\alpha_e^{(0)} - \alpha_g^{(0)}\right)(1+\eta_{\rm clock})\underline{\langle E^2\rangle_T} \approx -1.277\ \text{Hz}\left(\frac{T}{300\ \text{K}}\right)^4$$

BBR electric field intensity





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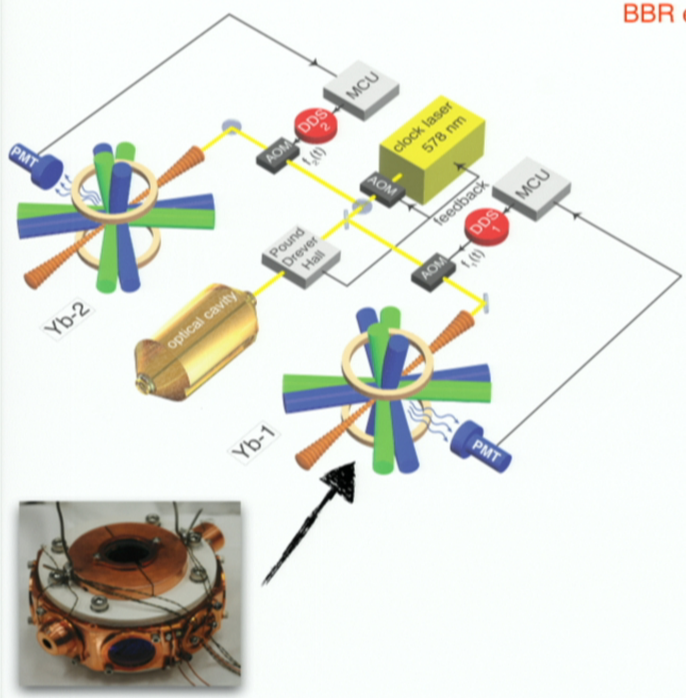

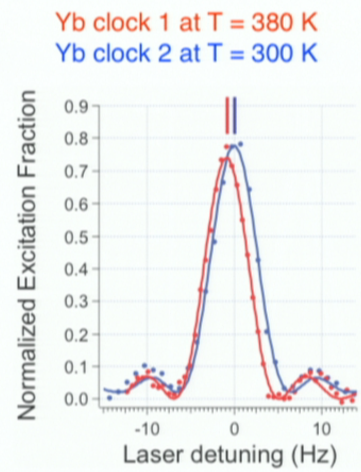

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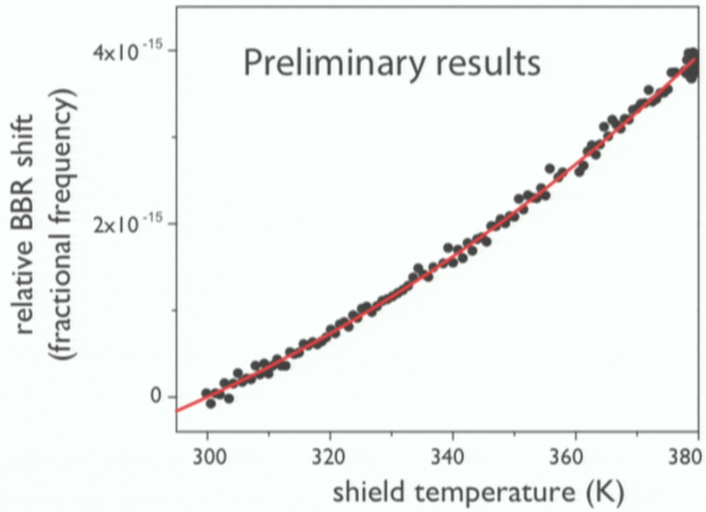


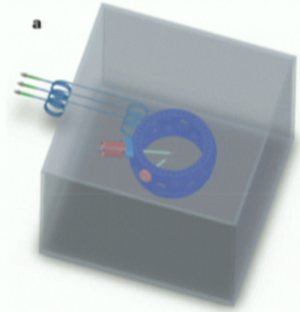
T^4 fit consistent with measured polarizability parameters

Preliminary blackbody radiation systematic uncertainties, Yb optical lattice

	Room-temperature T ~ 300 K Correction (× 10^{-19})	± Unc.	Cryogenic T ~ 90 K Correction (× 10^{-19})	± Unc.
Atomic response:				
Static polarizability	-24,270	1	-197	0
Dynamic polarizability	-433	12	-1	0
Thermal environment:				
RTD measurement		10		0
T gradient–shield		1		13
T gradient–window		3		2
Ambient BBR leakage	< 1	4	-60	4
Atomic position		0		5
Coating emissivity		0		2
Window emissivity		0		0
Shield geometry		0		0
Window transmittance		0		0
Vector/tensor coupling		0		0
Total (fractional):	**-24,703**	**16**	**-258**	**15**
Total (mHz):	**-1277**	**1**	**-13.3**	**1**

JILA grabs the brass ring...

a



b

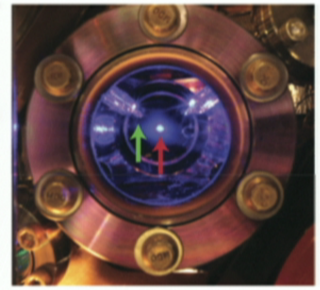


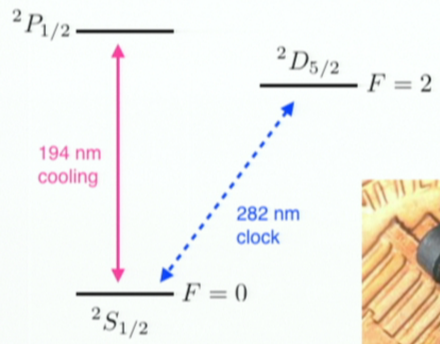
Table 1 | Frequency shifts and related uncertainties for SrI and SrII

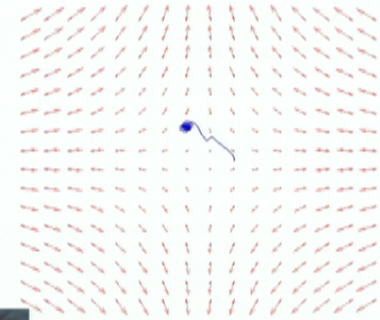
Sources for shift	Δ_{SrI}	σ_{SrI}	Δ_{SrII}	σ_{SrII}
BBR static	−4,832	45	−4,962.9	1.8 $\times 10^{-18}$
BBR dynamic	−332	6	−345.7	3.7
Density shift	−84	12	−4.7	0.6
Lattice Stark	−279	11	−461.5	3.7
Probe beam a.c. Stark	8	4	0.8	1.3
First-order Zeeman	0	<0.1	−0.2	1.1
Second-order Zeeman	−175	1	−144.5	1.2
Residual lattice vector shift	0	<0.1	0	<0.1
Line pulling and tunnelling	0	<0.1	0	<0.1
d.c. Stark	−4	4	−3.5	2.1
Background gas collisions	0	0.07	0	0.6
AOM phase chirp	−7	20	0.6	0.4
Second-order Doppler	0	<0.1	0	<0.1
Servo error	1	4	0.4	0.6
Totals	−5,704	53	−5,921.2	6.4 $\times 10^{-18}$

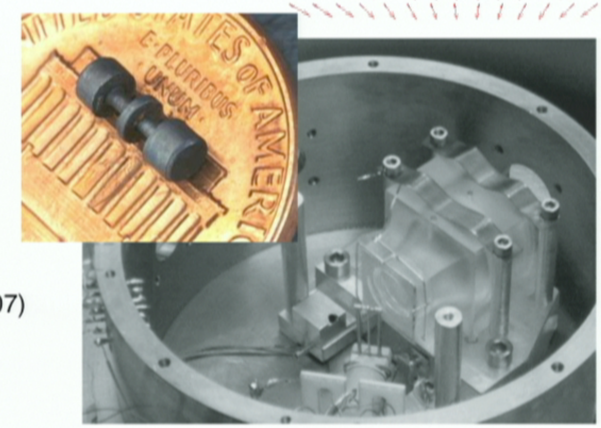
B Bloom, TL Nicholson, JR Williams, et al., *Nature* **506,** 71 (2014)

State of the NIST ion clocks...

$^{199}Hg^{+}$





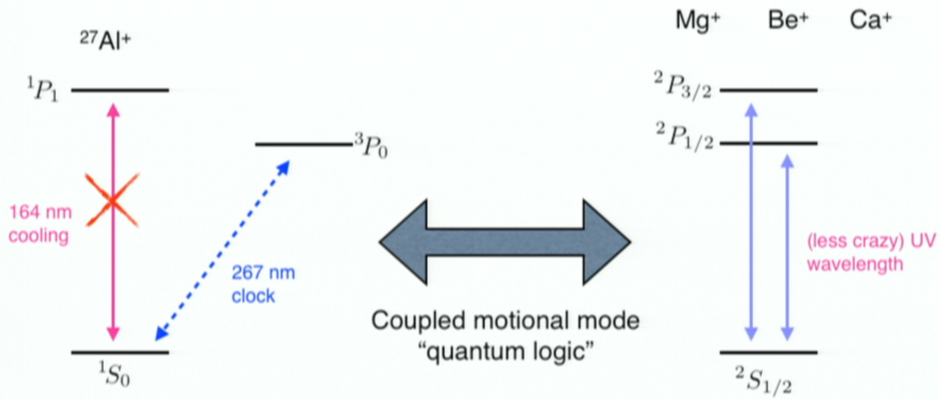


Frequency uncertainty (c.a. 2007)

$$\frac{\sigma_\nu}{\nu} = 1.9 \times 10^{-17}$$

L Lorini, N Ashby, A Brusch, et al., *Eur. Phys. J. Special Topics* **163,** 19–35 (2008)

State of the NIST ion clocks...

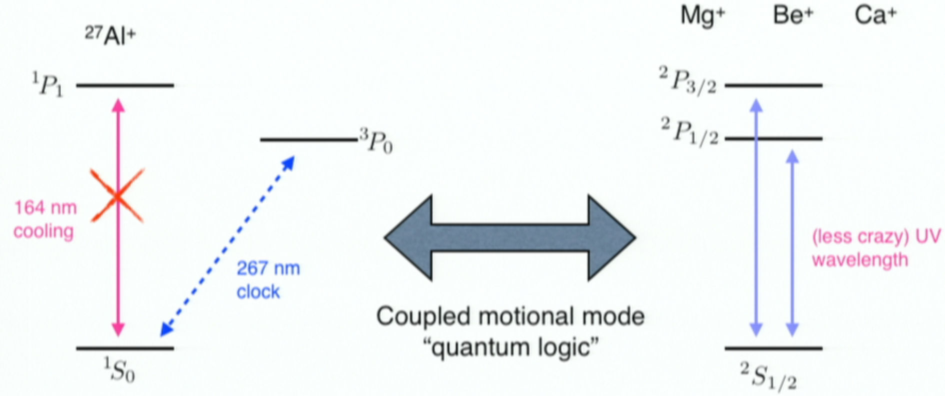


$$\frac{\sigma_\nu}{\nu} = 8.6 \times 10^{-18}$$

Effect	Shift (10^{-18})	Uncertainty (10^{-18})
Excess micromotion	−9	6
Secular motion	−16.3	5
Blackbody radiation shift	−9	3
Cooling laser Stark shift	−3.6	1.5
Quad. Zeeman shift	−1079.9	0.7
Linear Doppler shift	0	0.3
Clock laser Stark shift	0	0.2
Background-gas collisions	0	0.5
AOM freq. error	0	0.2
Total	−1117.8	8.6

CW Chou, DB Hume, JCJ Koelemeij, et al., *PRL* **104**, 070802 (2010)

State of the NIST ion clocks...



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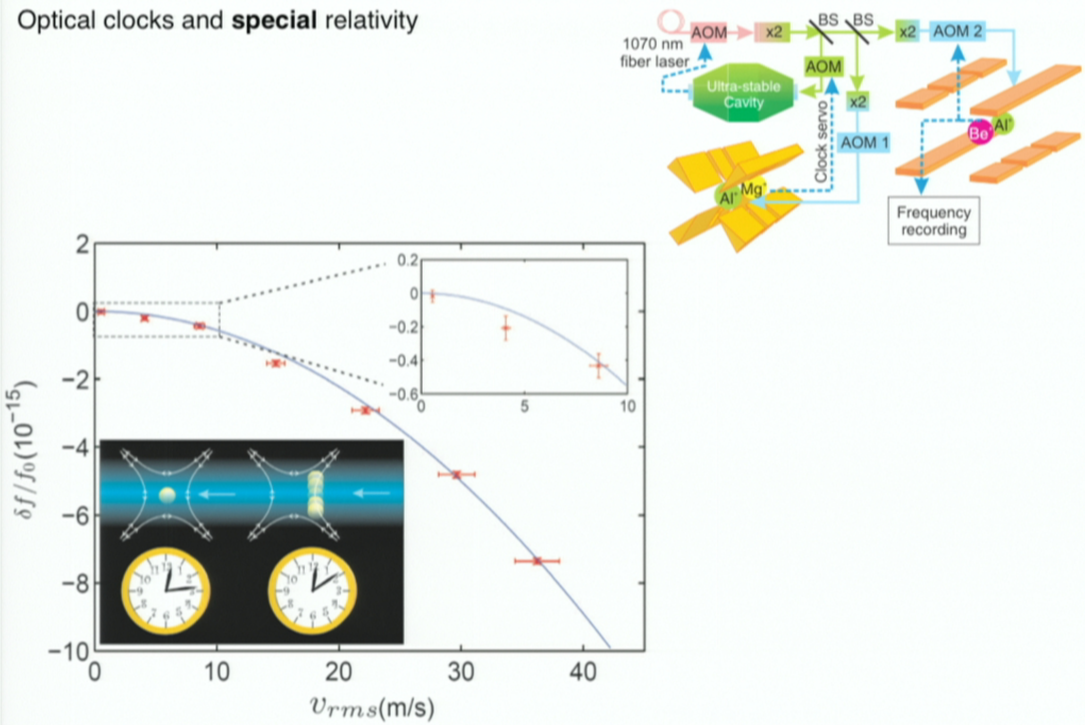
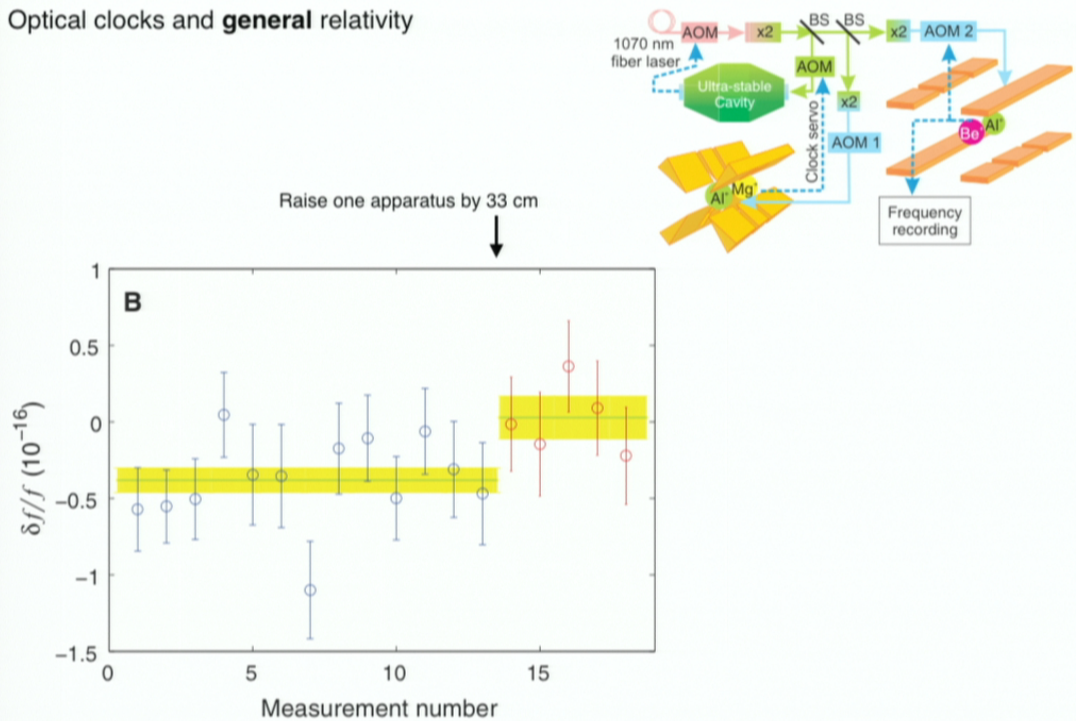
Optical clocks and **special** relativity



CW Chou, DB Hume, JCJ Koelemeij, et al., *PRL* **104**, 070802 (2010)
CW Chou, DB Hume, T Rosenband, DJ Wineland, *Science* **329**, 1630–1633 (2010)

Optical clocks and **general** relativity



CW Chou, DB Hume, JCJ Koelemeij, et al., *PRL* **104**, 070802 (2010)
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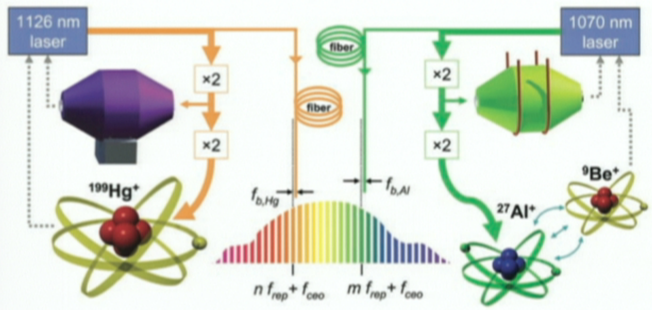
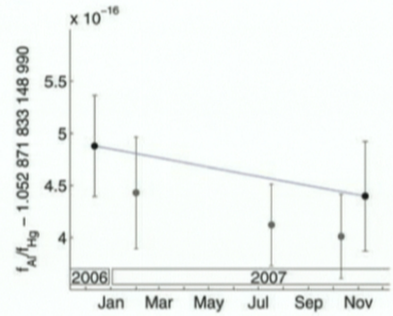
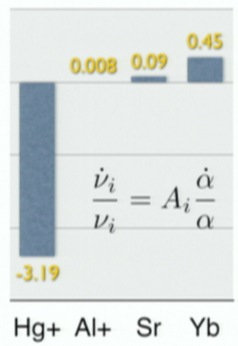
Optical frequency ratios: search for varying fundamental "constants"





Clock differential sensitivity to varying "constants":



VA Dzuba, VV Flambaum, JK Webb, *PRA* **59**(1), 230 (1999)

T Rosenband, DB Hume, PO Schmidt, et al., *Science* **319**, 1808–1812 (2008)

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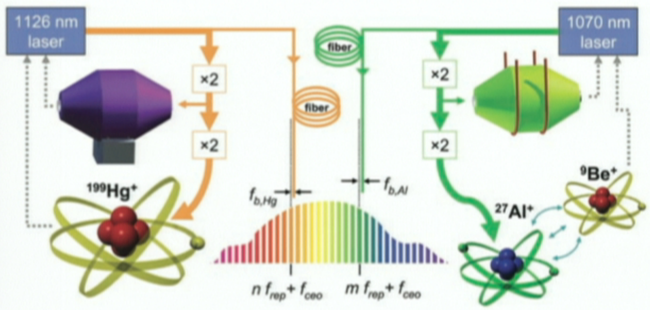
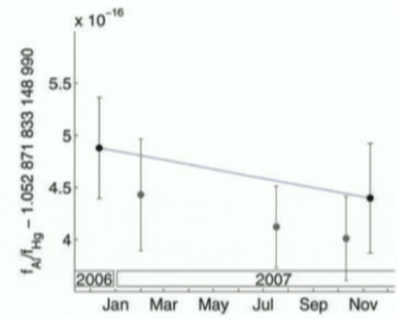
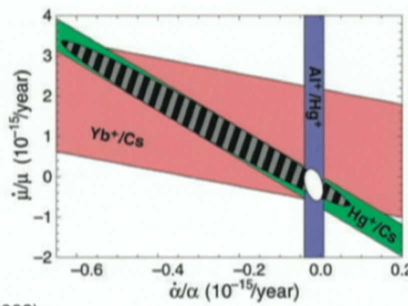




Current constraint:

$$\frac{\dot{\alpha}}{\alpha} = (-1.6 \pm 2.3) \times 10^{-17} \ \mathrm{yr}^{-1}$$



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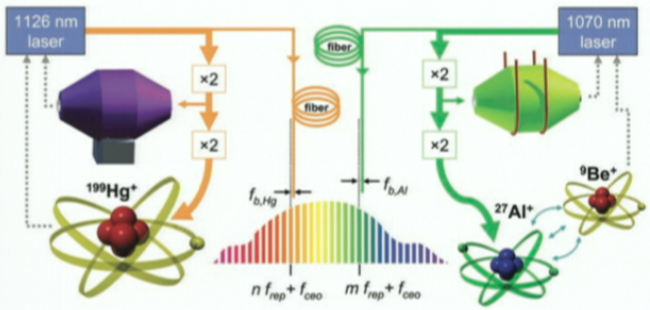

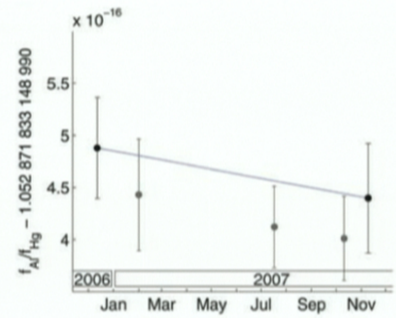

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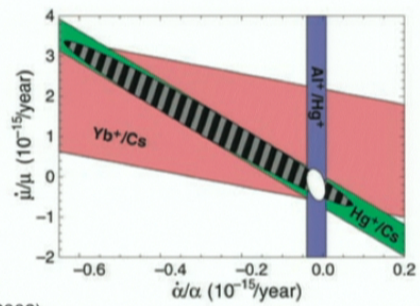

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Summary

- Atomic clocks as official source of U.S. time and frequency

  dilemma/opportunity: optical atomic clocks will surpass the current SI definition of time/frequency.

- Selection of recent progress on optical clockwork

  optical cavities now surpassing H-maser performance

  optical atomic clock stabilities near 1 x 10^{-18}
  accuracies near 5 x 10^{-18}

- What's next? A new round of multi-clock comparisons!
  Better optical time/frequency infrastructure