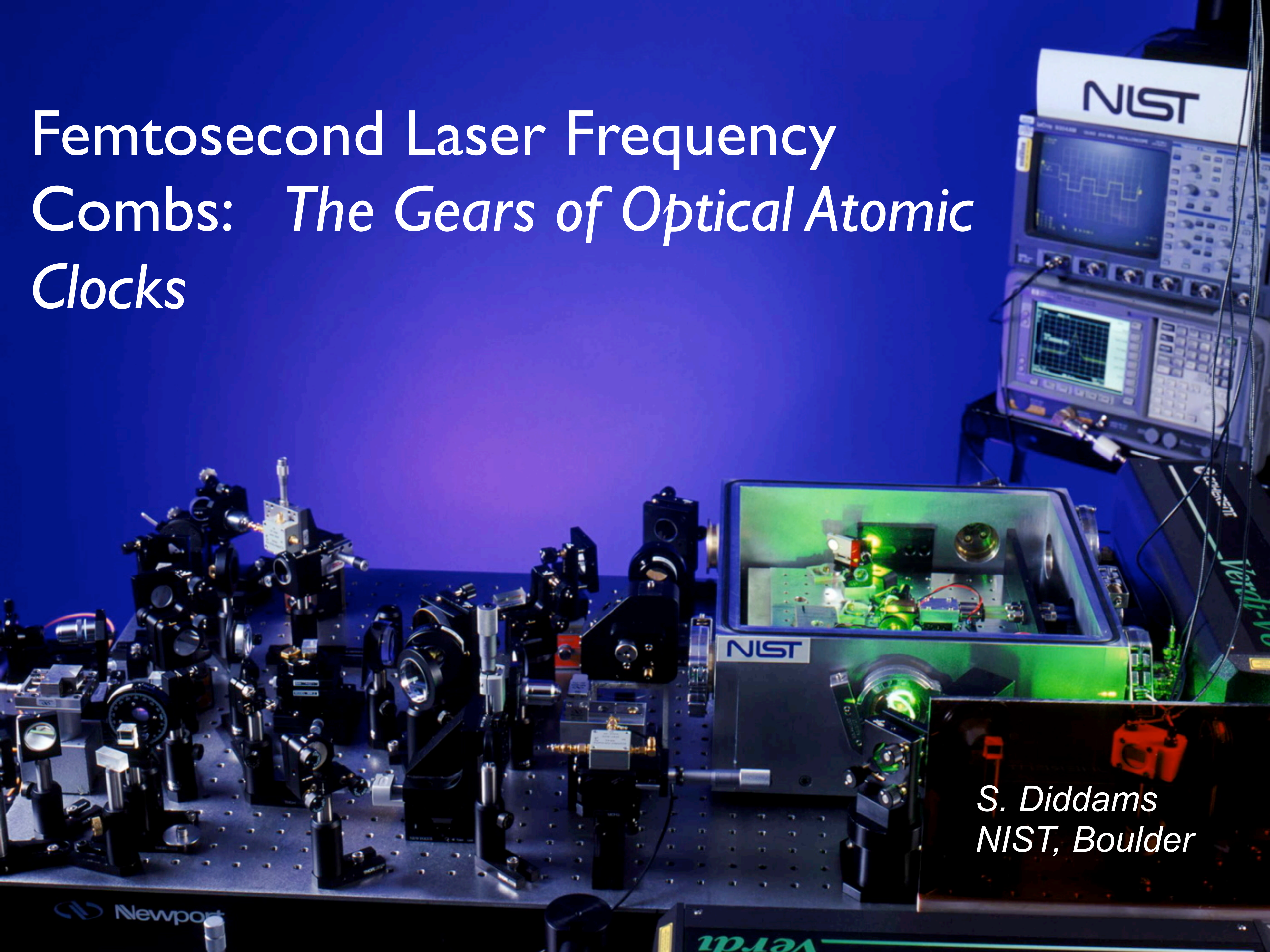
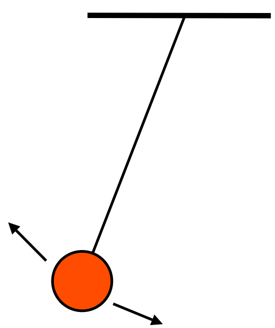
Femtosecond Laser Frequency Combs: *The Gears of Optical Atomic Clocks*

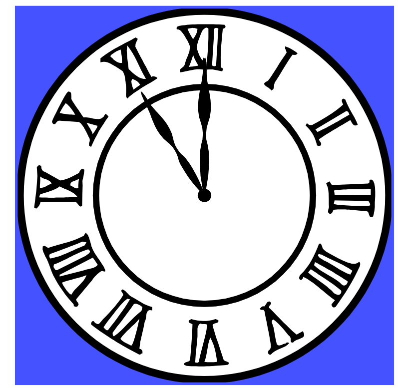


S. Diddams
NIST, Boulder

What Makes a Clock?

Oscillator + **Counting Mechanism**





Earth Rotation
Pendulum
Quartz Crystal

Sundial
Clock Gears/Hands
Electronic Counter

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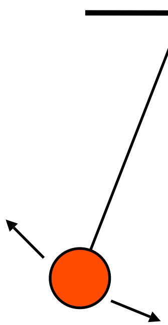

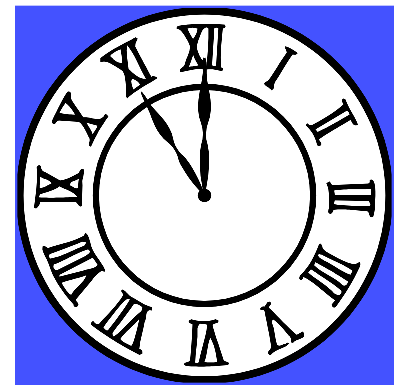

Earth Rotation
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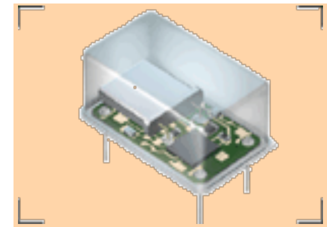
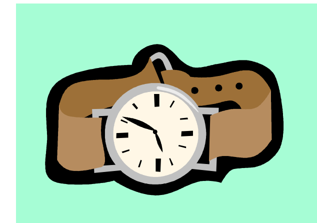
Electronic Counter

ATOMIC CLOCKS
Microwave Transition + Oscillator
Optical Transition + Laser

Electronic Counter
Femtosecond Laser

Types of Clocks

"Better" ←

				
	Primary Standard	Compact Atomic Clock	Precision Quartz Crystal	Wristwatch Quartz Crystal
Loses 1 sec. in:	10^8 yrs	1000 yrs	1 yr	1 day
Size:	10^7 cm^3	100 cm^3	1 cm^3	10^{-3} cm^3
Stability (1s):	10^{-13}	10^{-10}	10^{-11}	10^{-6}
Cost:	$1 M	$1,000	$100	$1

→ "Smaller"

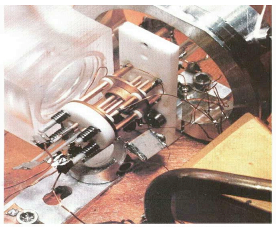
All atomic clocks have:

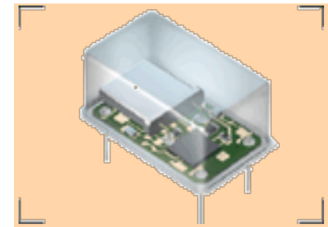
- Reference atom
- Local oscillator (pendulum)
- Counter/gears

Figure: J. Kitching, (NIST)

Types of Clocks

"Better" ←




	Optical Clock	Primary Standard	Compact Atomic Clock	Precision Quartz Crystal	Wristwatch Quartz Crystal
Loses 1 sec. in:	**10^{10} yrs??**	10^{8} yrs	1000 yrs	1 yr	1 day
Size:	laboratory	10^{7} cm^{3}	100 cm^{3}	1 cm^{3}	10^{-3} cm^{3}
Stability (1s):	**10^{-15}**	10^{-13}	10^{-10}	10^{-11}	10^{-6}
Cost:		\$1 M	\$1,000	\$100	\$1

→ "Smaller"

All atomic clocks have:

- Reference atom
- Local oscillator (pendulum)
- Counter/gears

Figure: J. Kitching, (NIST)

Why Measure Time/Frequency?

1. Frequency & time interval are the most accurately measured physical quantities
   - Cesium fountain clock: ~3×10^{-16}
   - Define other quantities with respect to time/frequency (meter, kilogram??)

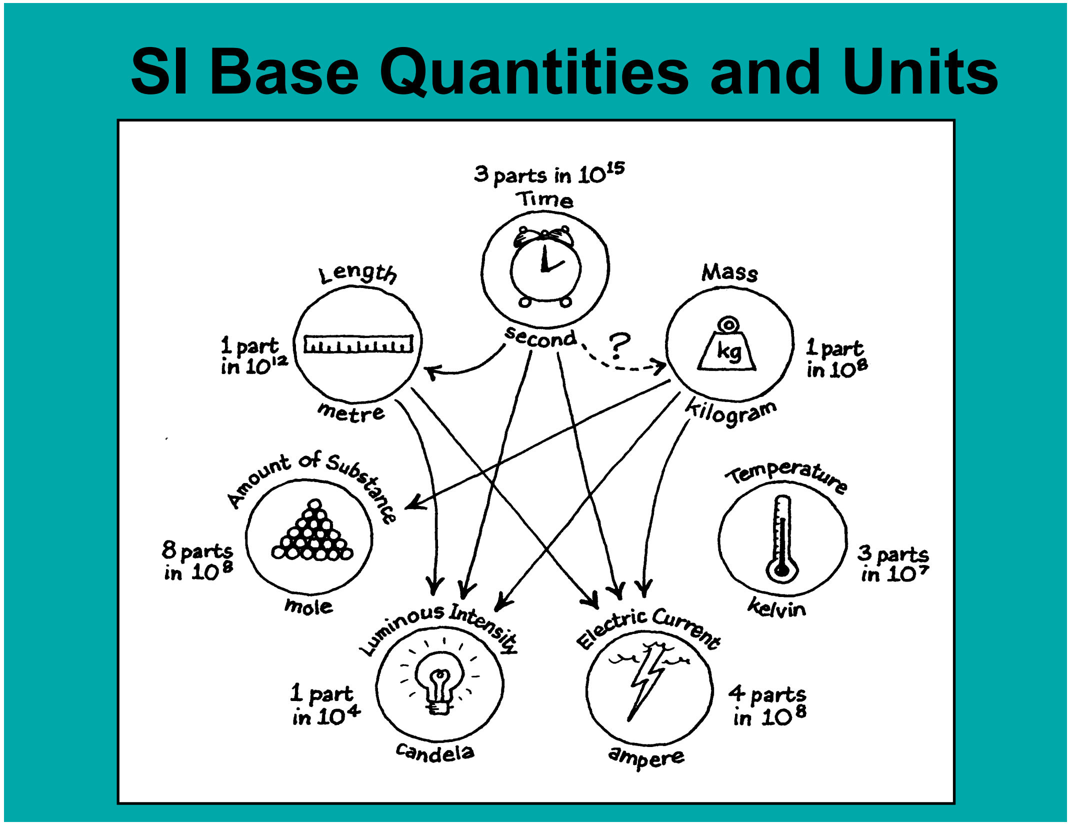


Figure from:
Tony Jones "Splitting the second" IOP Publishing (2000).

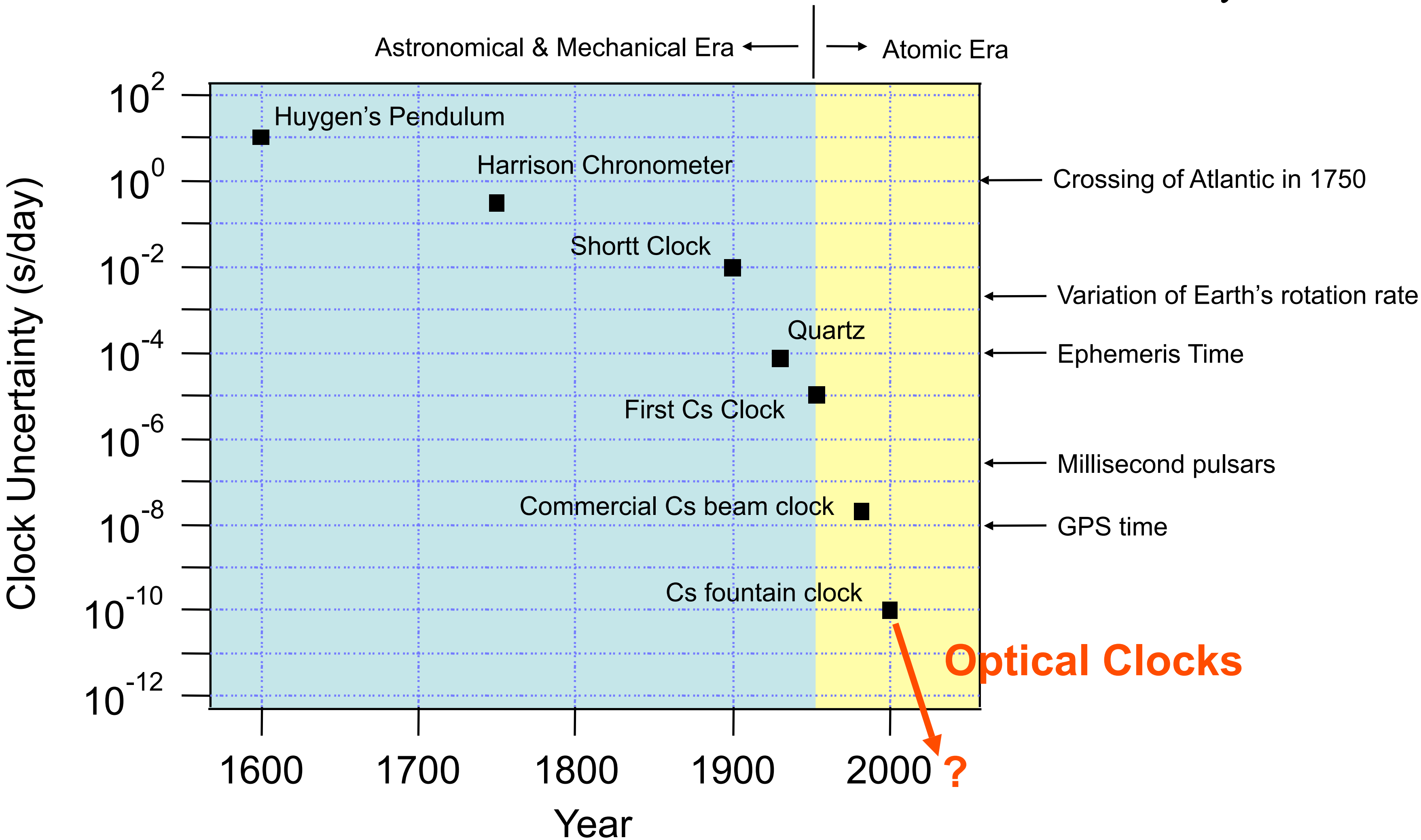
Why Measure Time/Frequency….. (2)

2. Interesting physics
   - Measurement and variation (?) of fundamental physical constants
     --speed of light, α, Rydberg constant)
   - Tests of relativity, Lorentz invariance
   - Precision Spectroscopy
   - Measurements & calculations for "simple" atoms (hydrogen and helium)
   - Astrophysics: millisecond pulsars, very-long baseline observatories

3. Commercial and technological applications
   - Navigation (GPS), Radar
   - Communications, Network synchronization

The times they are a-changin'…

Bob Dylan



Time & Frequency Division

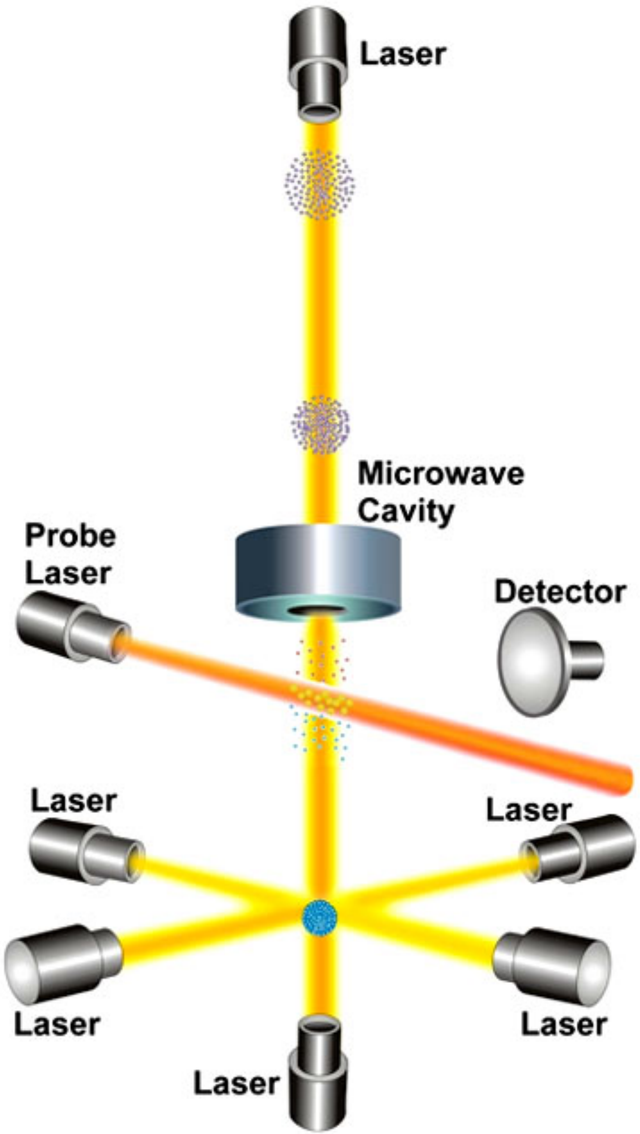
NIST

Nobel Laureates Contributing to Atomic Timekeeping

Year	Nobel Laureate	Contribution
1944	Isidor Rabi	Developed the “atomic beam resonance method” and proposed the cesium atomic clock
1955	Polykarp Kusch	Early practical design of cesium atomic clock
1964	Nikolai Basov, Aleksander Prochorov, Charles Townes	Masers and lasers
1966	Alfred Kastler	Optical pumping
1981	Nicolaas Bloembergen, Arthur Schawlow	Laser spectroscopy
1989	Norman Ramsey	Developed the “separated oscillatory fields method” and the hydrogen maser
1989	Hans Dehmelt, Wolfgang Paul	Single ion trapping and proposal of ion-based clocks
1997	Steve Chu, Claude Cohen-Tannoudji, Bill Phillips	Laser cooling and trapping
2005	Ted Haensch, John Hall	Precision frequency measurements & femtosecond laser comb

Tony Jones “Splitting the second” IOP Publishing (2000).

Cs Fountain Clock: The Current Standard and the Definition of the Second



f_{Cs}=9,192,631,770 Hz

Total Uncertainty ~3×10^{-16}

Cold Atoms allow long interaction times

S. Jefferts, T. Heavner, T. Parker (NIST)

Time & Frequency Division NIST

Optical Clocks

What are they?

- Atomic clocks based on optical transitions

  "tick period" ~ 1 femtosecond (10^{-15} s)

Why are they interesting?

- Optical standards have low instability:

$$\sigma(\tau) \sim \frac{\Delta f}{f_o \sqrt{N}} \frac{1}{\sqrt{\tau}}$$

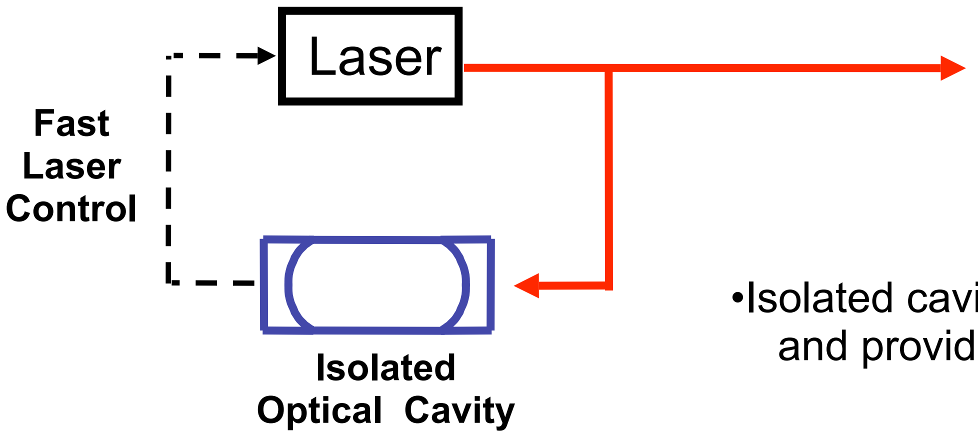
e.g. Ca optical standard

<2×10^{-16} at 1 s

- Optical standards have the potential for greatly improved accuracy: e.g. approaching **1×10^{-18}**

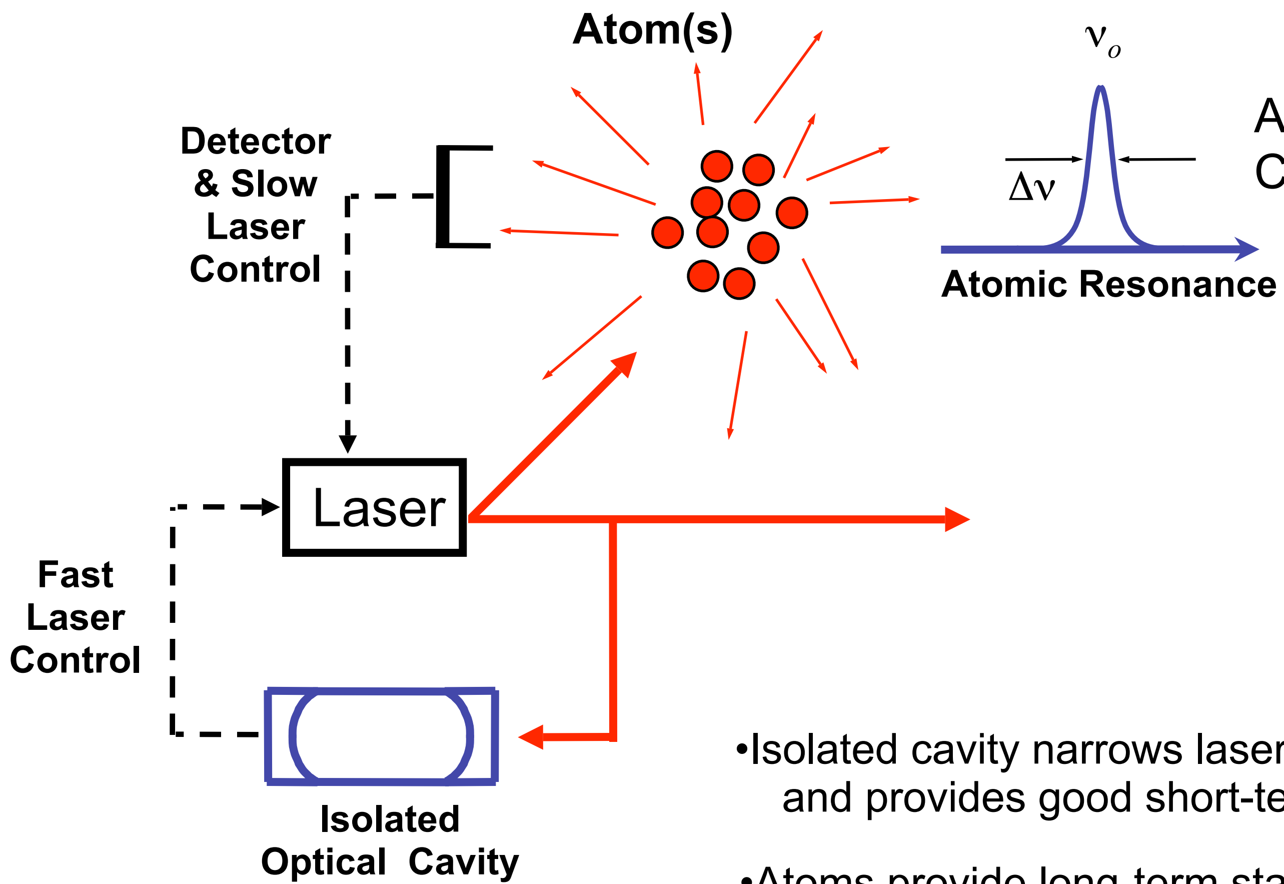
Components of an Optical Clock

Components of an Optical Clock



- Isolated cavity narrows laser linewidth and provides good short-term stability

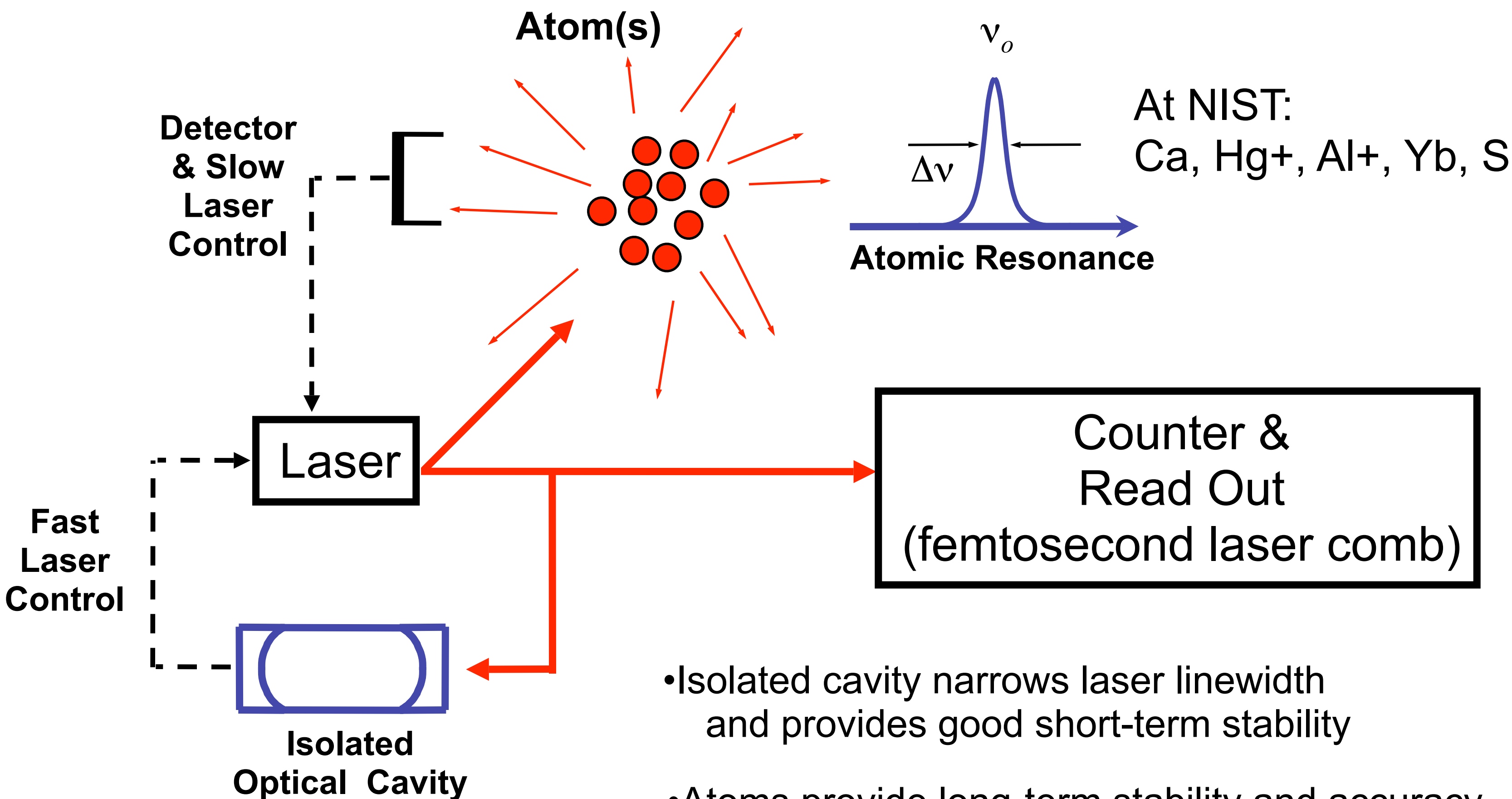
Components of an Optical Clock



At NIST:
Ca, Hg+, Al+, Yb, Sr

- Isolated cavity narrows laser linewidth and provides good short-term stability
- Atoms provide long-term stability and accuracy

Components of an Optical Clock



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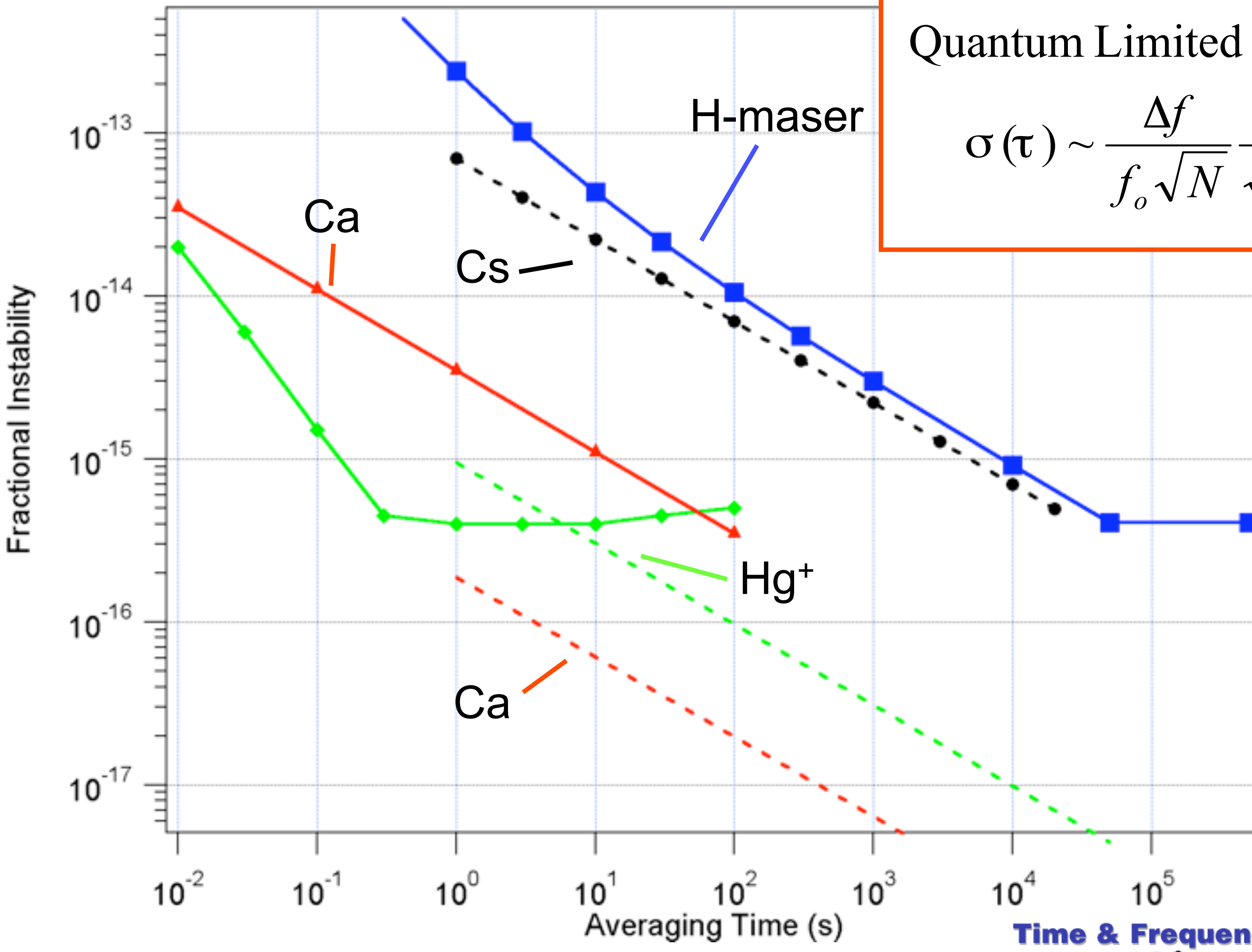
- Counter accumulates cycles to generate 1 sec

Time & Frequency Division
NIST

Oscillator (In)stability



Quantum Limited Instability

$$\sigma(\tau) \sim \frac{\Delta f}{f_o \sqrt{N}} \frac{1}{\sqrt{\tau}}$$

Time & Frequency Division

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Approaches to optical frequency standards (advantages and disadvantages)

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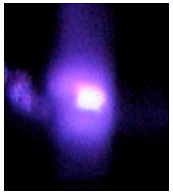
1. Freely expanding laser-cooled neutral atoms (e.g. Ca, Sr, H)
   - high signal-to-noise
   - troublesome Doppler effects
   - limited interaction times (~ 10 ms)



F. Riehle,
H. Katori,
J. Hall,
T. Hänsch

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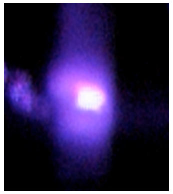

F. Riehle, H. Katori, J. Hall, T. Hänsch

2. Single trapped ions (e.g. Hg^+, Yb^+, Sr^+, In^+, Al^+)
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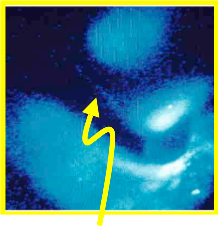
   - long interaction times (high Q)
   - limited signal-to-noise
   - challenging technology



H. Dehmelt, D. Wineland

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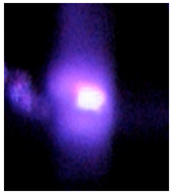

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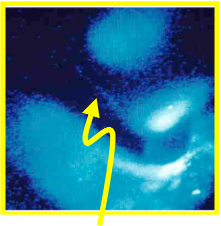
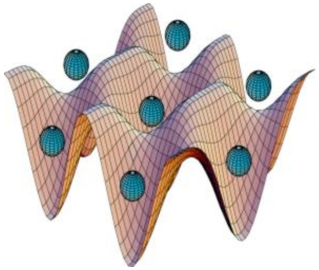


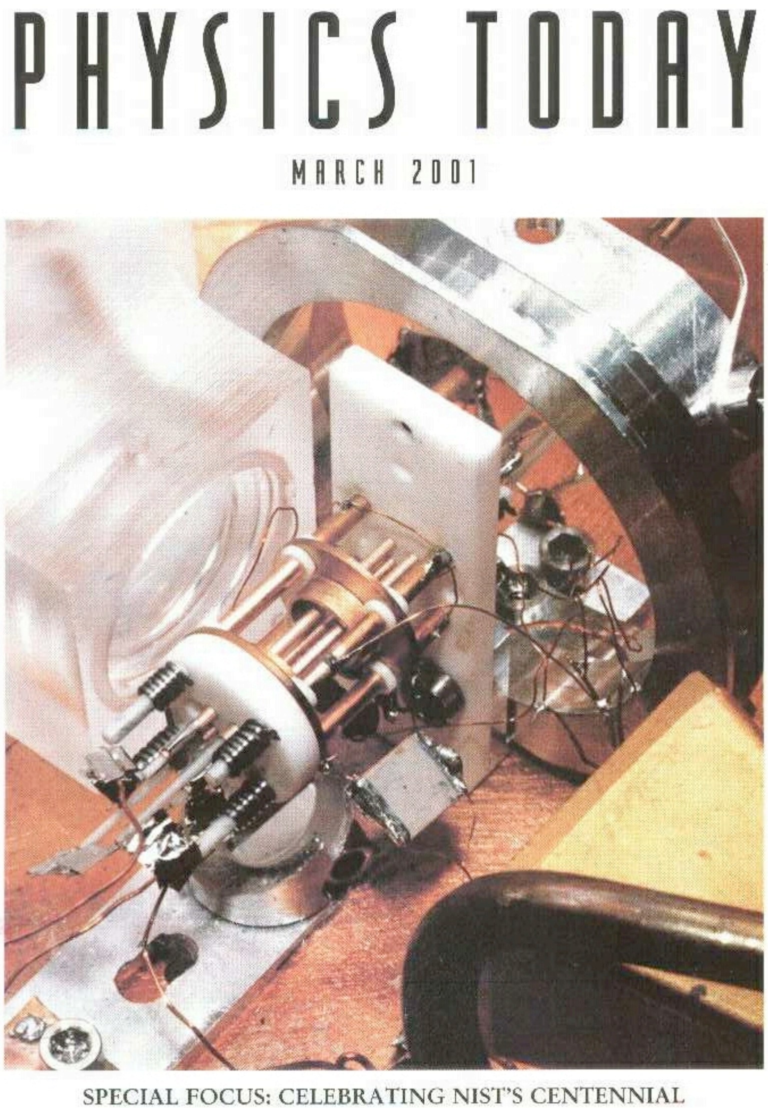
H. Dehmelt, D. Wineland

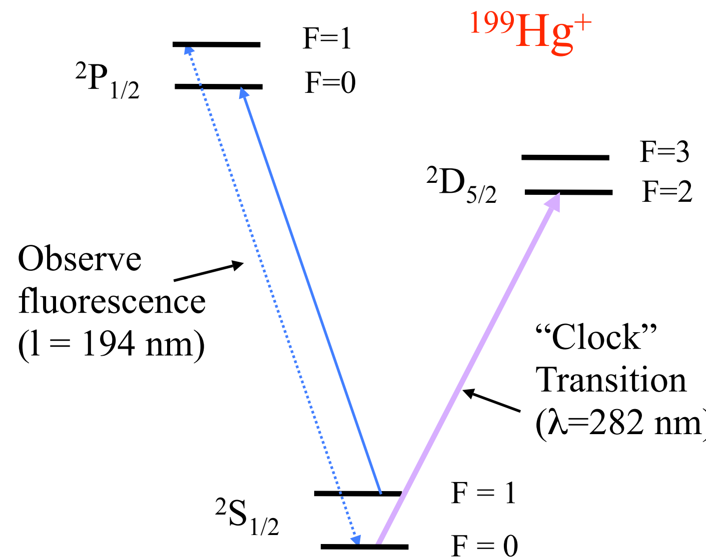
3. Neutral atoms held in an optical lattice (Yb, Sr, Hg)
   - good signal-to-noise
   - Doppler-free
   - long interaction times
   - lattice shifts? (predicted to be 10^{-17} or less)



H.Katori

Single Ion Optical Clock





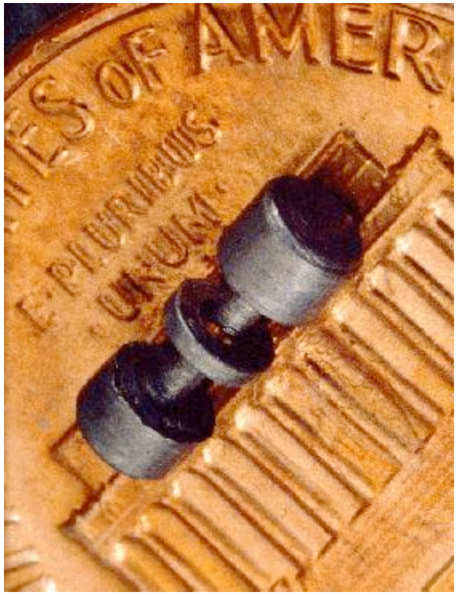
"clock" transition @
$f_o \approx 1.06 \times 10^{15}$ Hz

J. Bergquist, et al. (NIST)

Time & Frequency Division
NIST

Ion clock example: Single $^{199}Hg^+$

Jim Bergquist *et al*.



Time & Frequency Division
NIST

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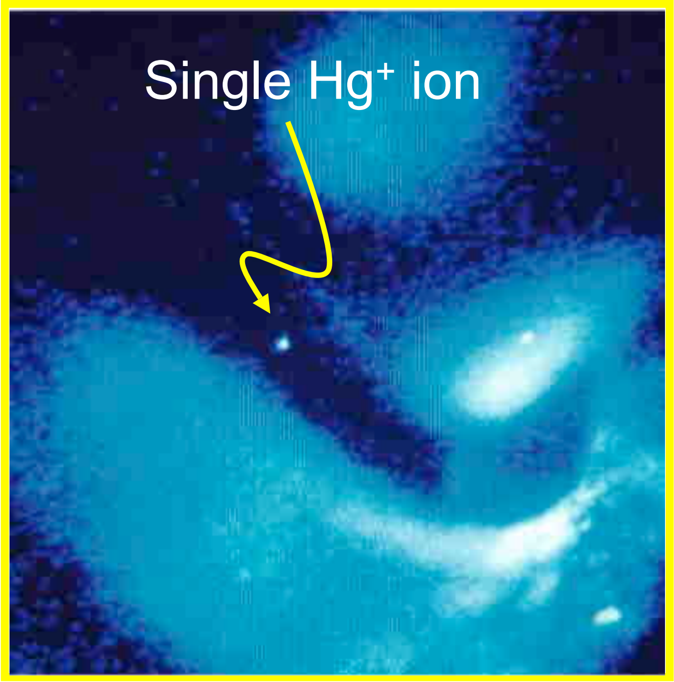

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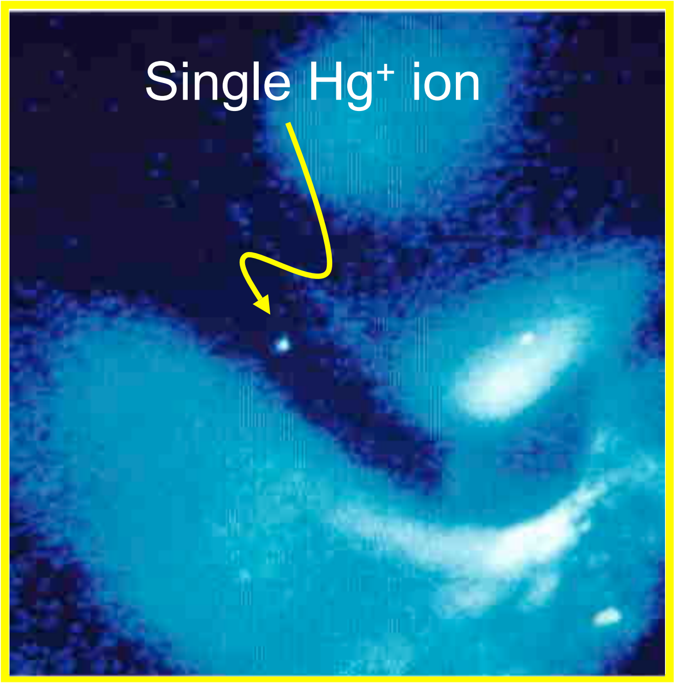

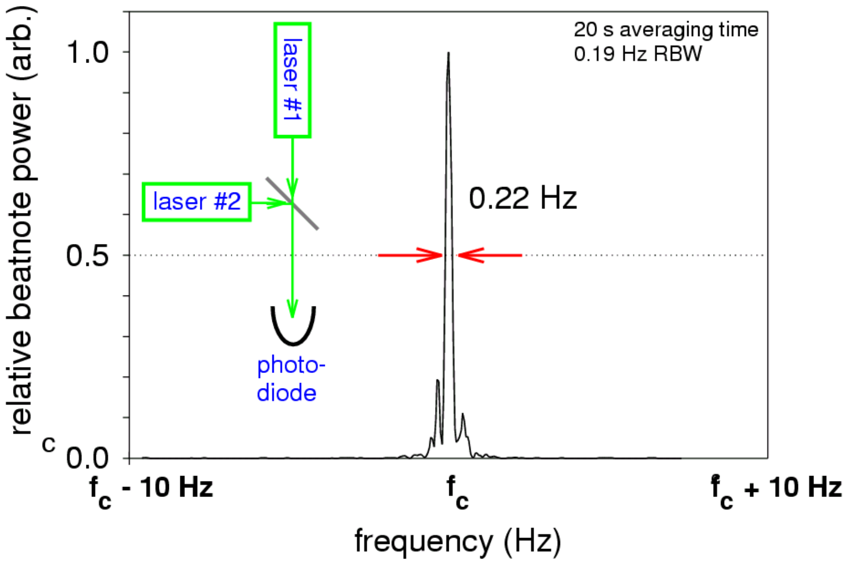

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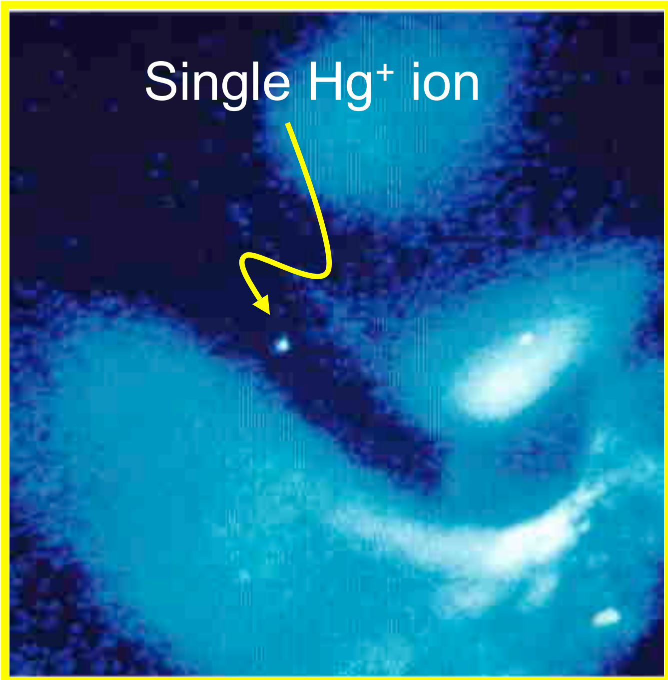

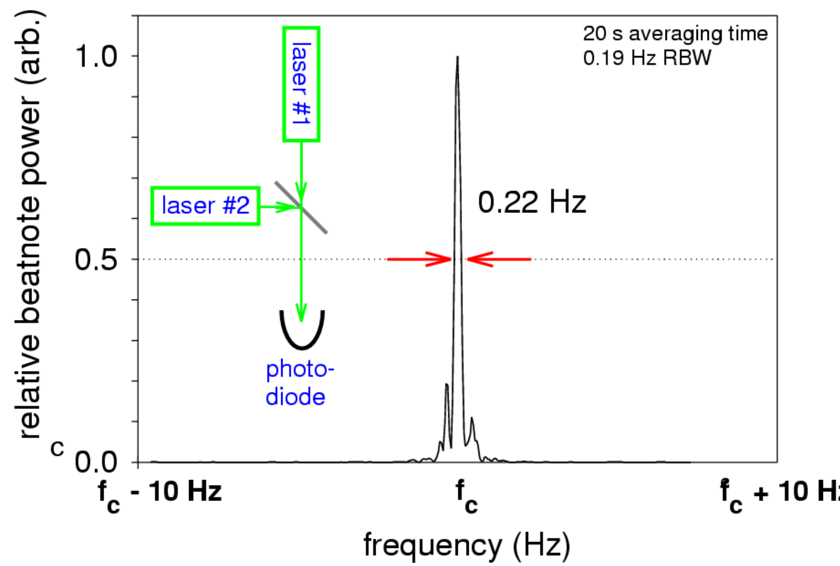

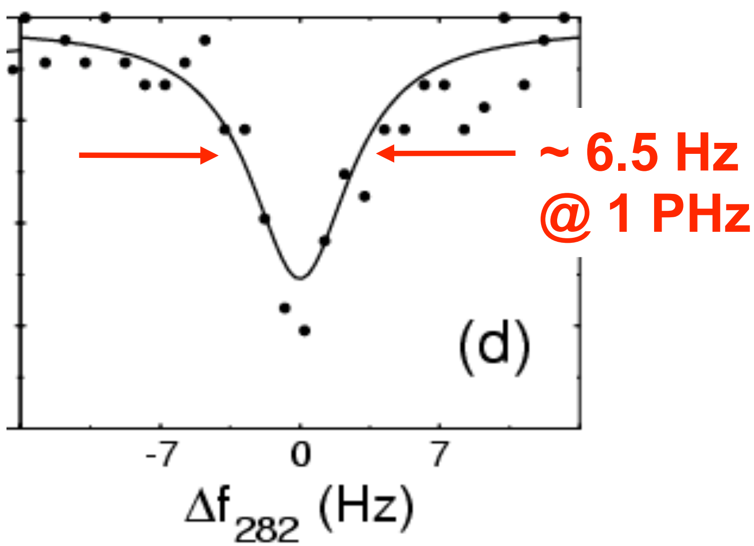

Time & Frequency Division

NIST

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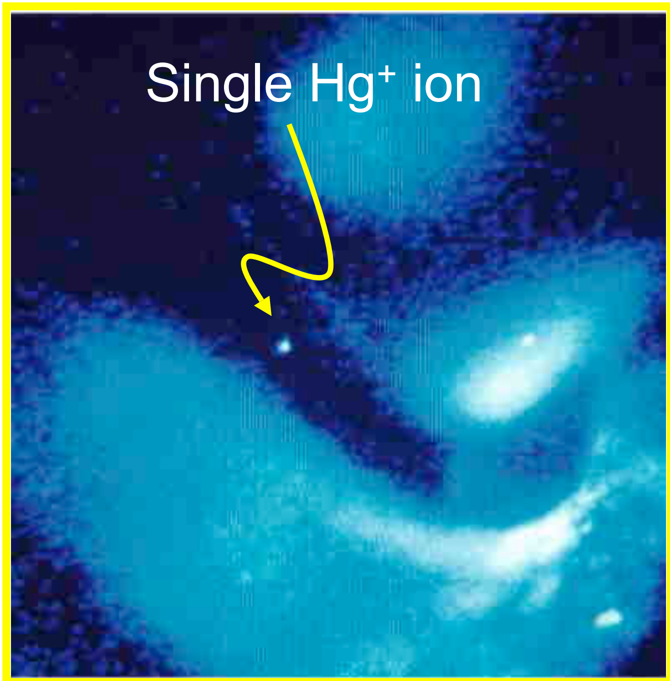
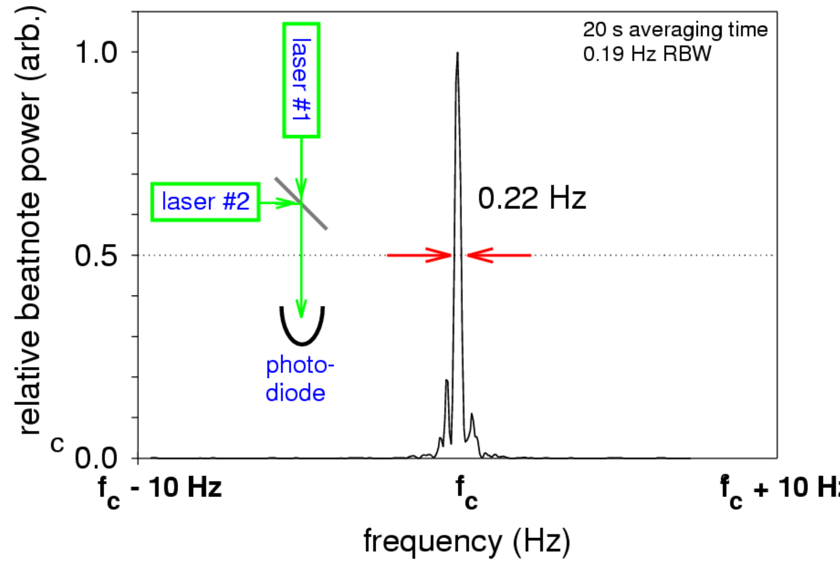
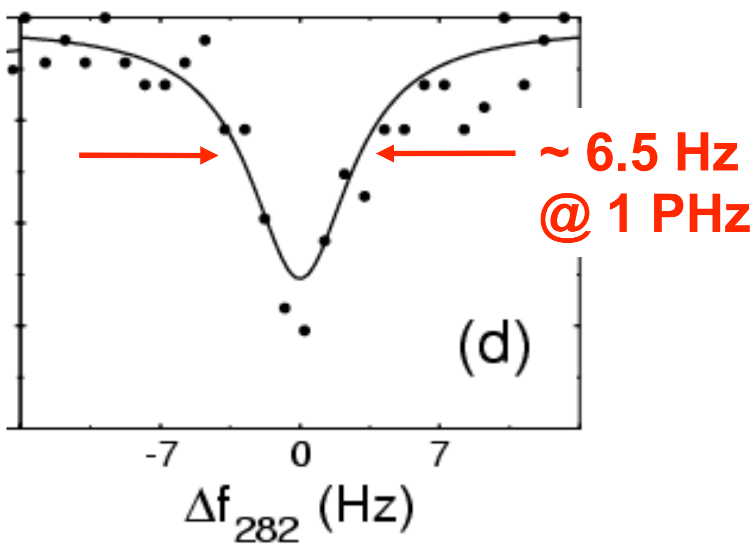






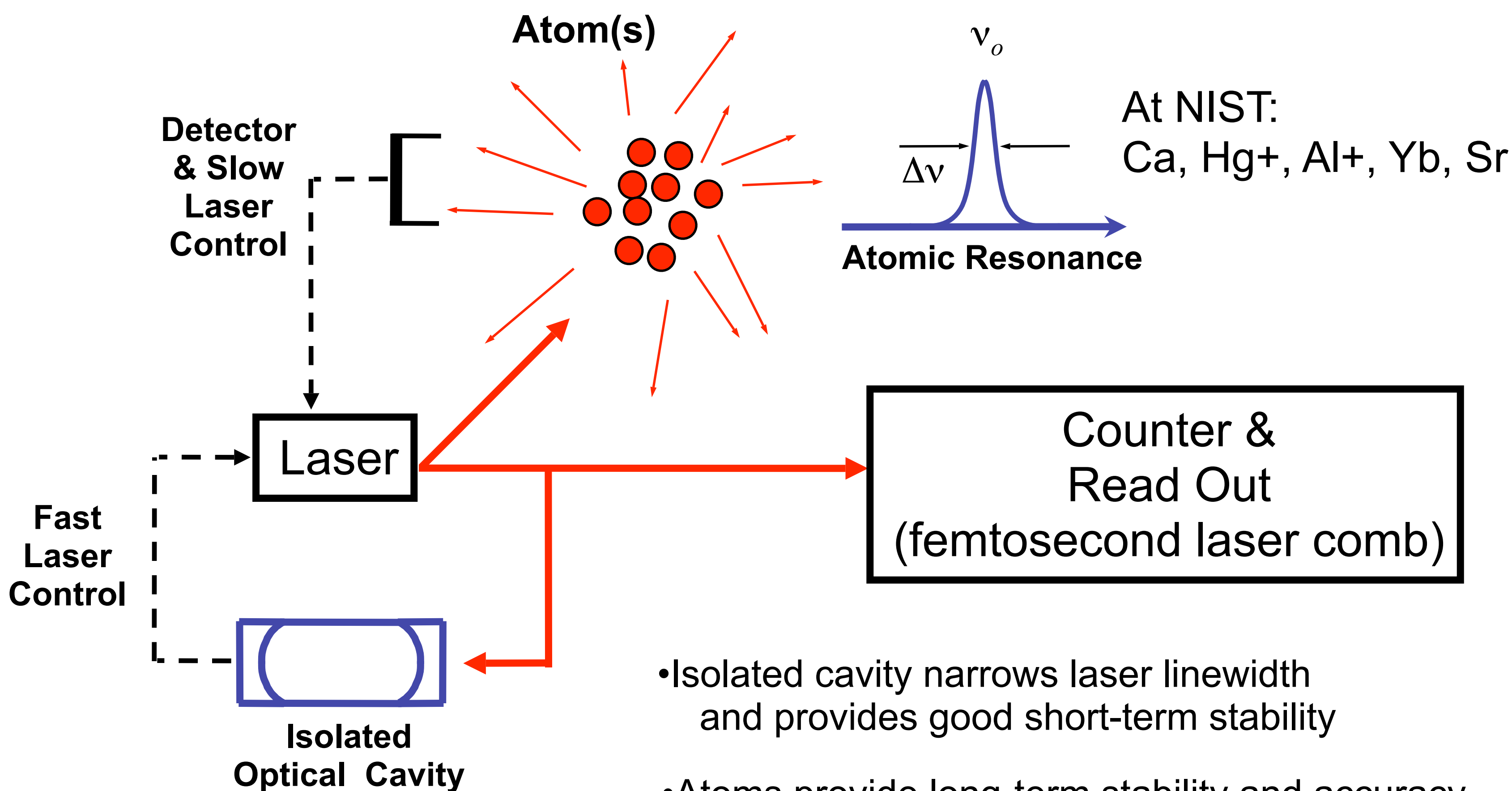
$$Q \equiv \frac{\text{clock frequency}}{\text{linewidth}}$$

$$= 1.6 \times 10^{14}$$

Time & Frequency Division

NIST

Components of an Optical Clock



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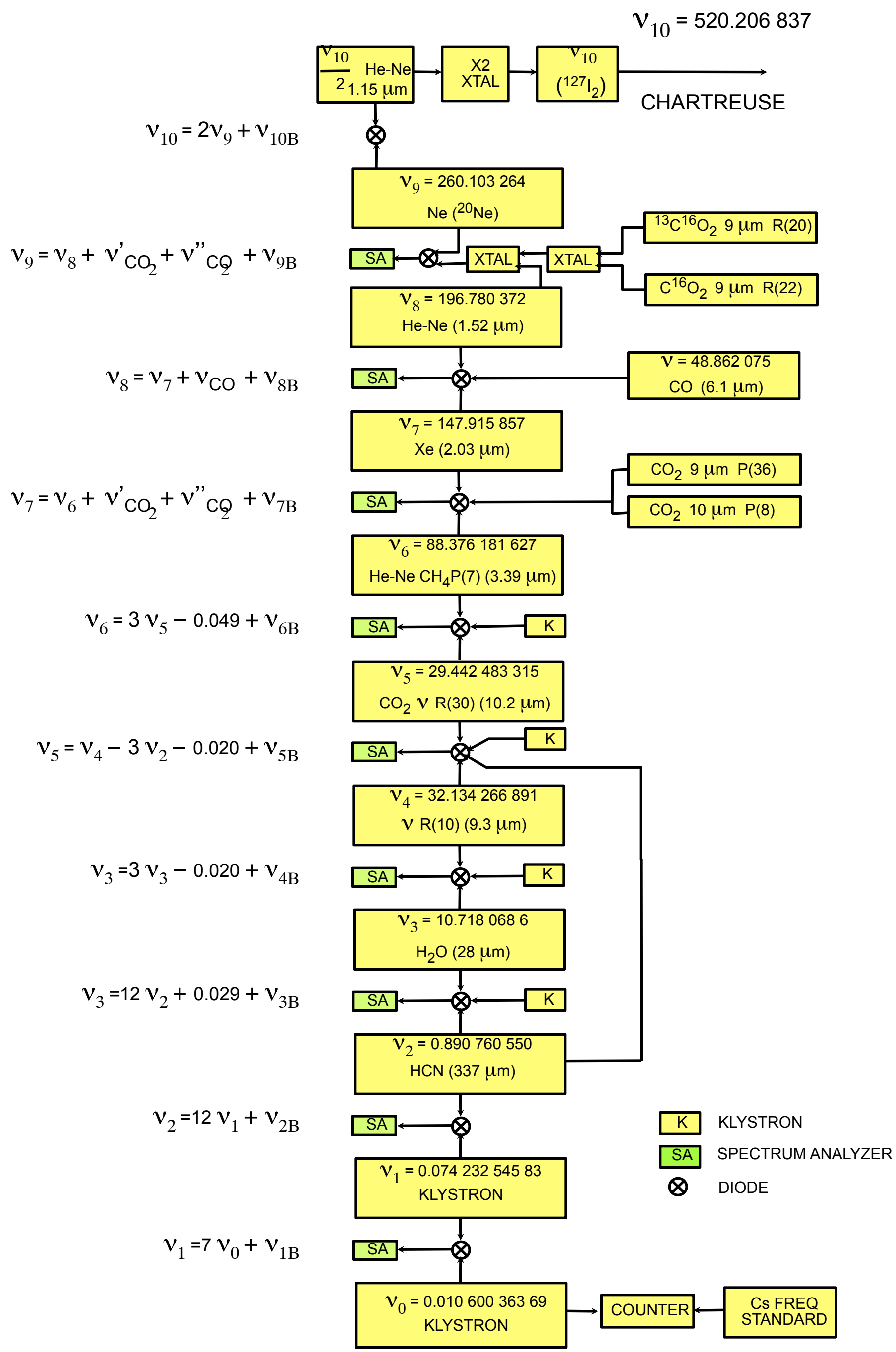


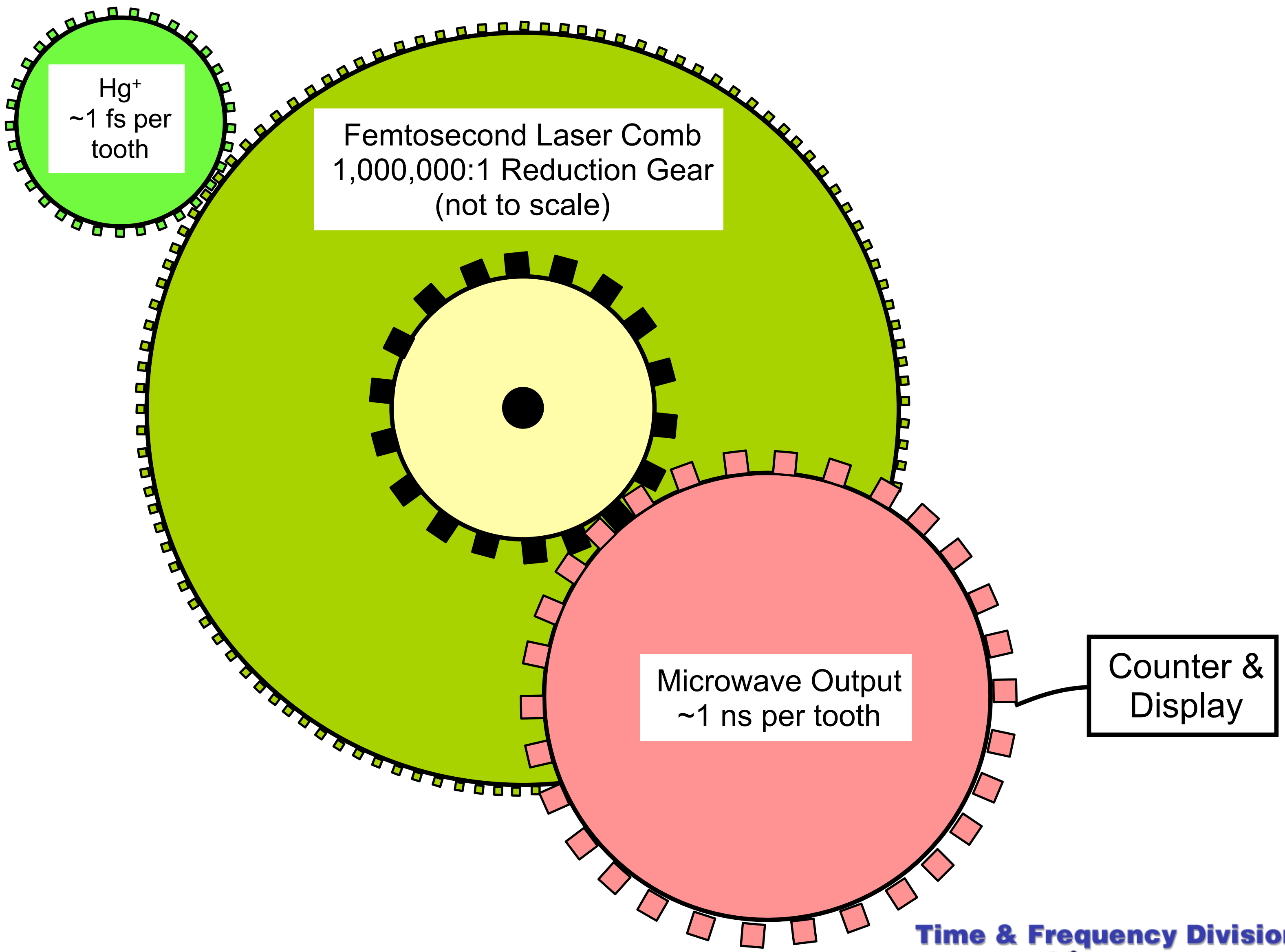
all frequencies in THz

NBS Laser Frequency Synthesis Chain (1979)

K. M. Evenson
D. A. Jennings
J. S. Wells
C. R. Pollock
F. R. Petersen
R. E. Drullinger
E. C. Beaty
J. L. Hall
H. P. Layer
B. L. Danielson
G. W. Day
R. L. Barger

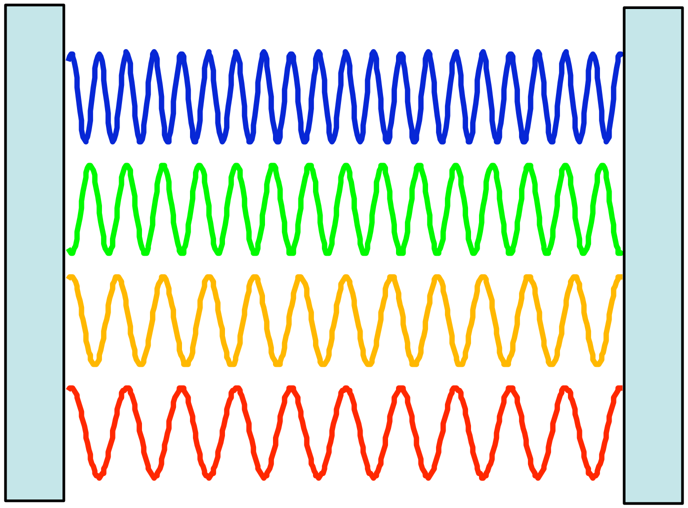
Time & Frequency Division

Mechanical Analogy of the Optical Clock



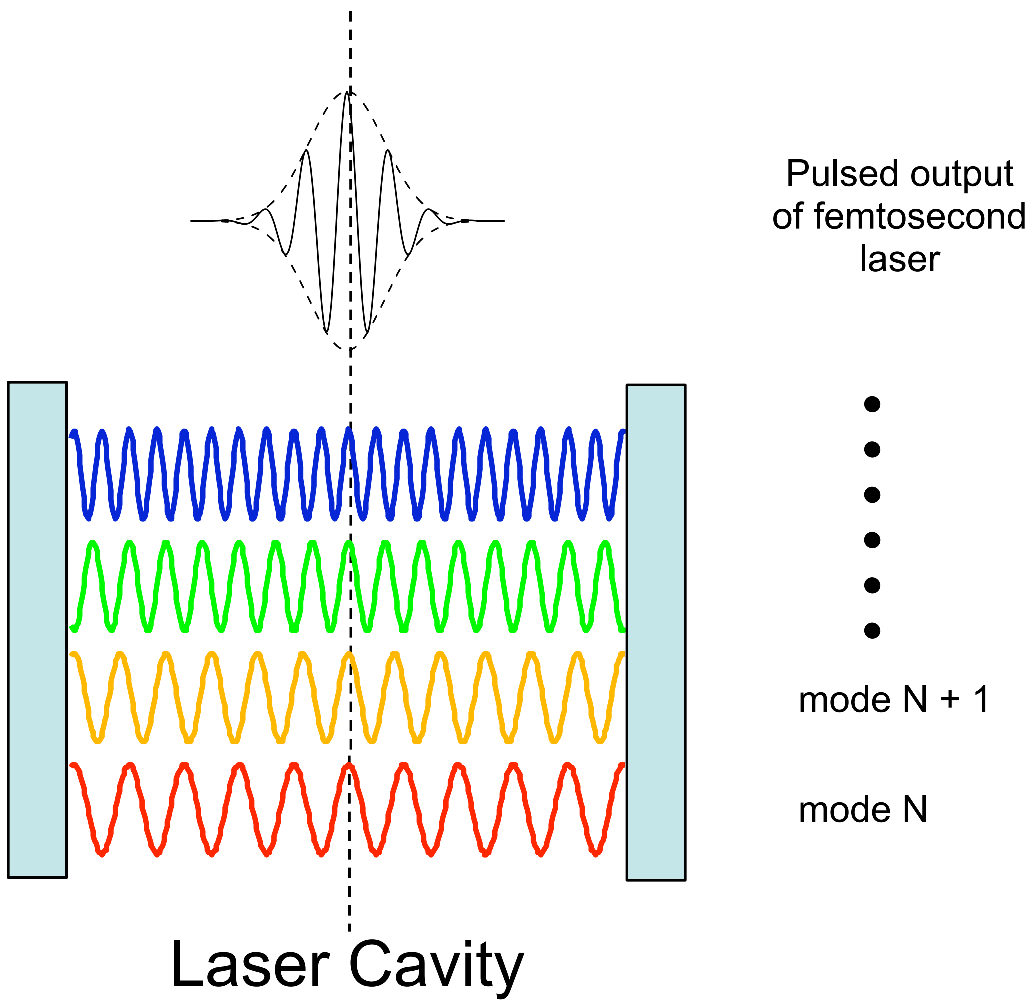
Time & Frequency Division
NIST

The femtosecond mode-locked laser comb



Laser Cavity

The femtosecond mode-locked laser comb



Time & Frequency Division
NIST

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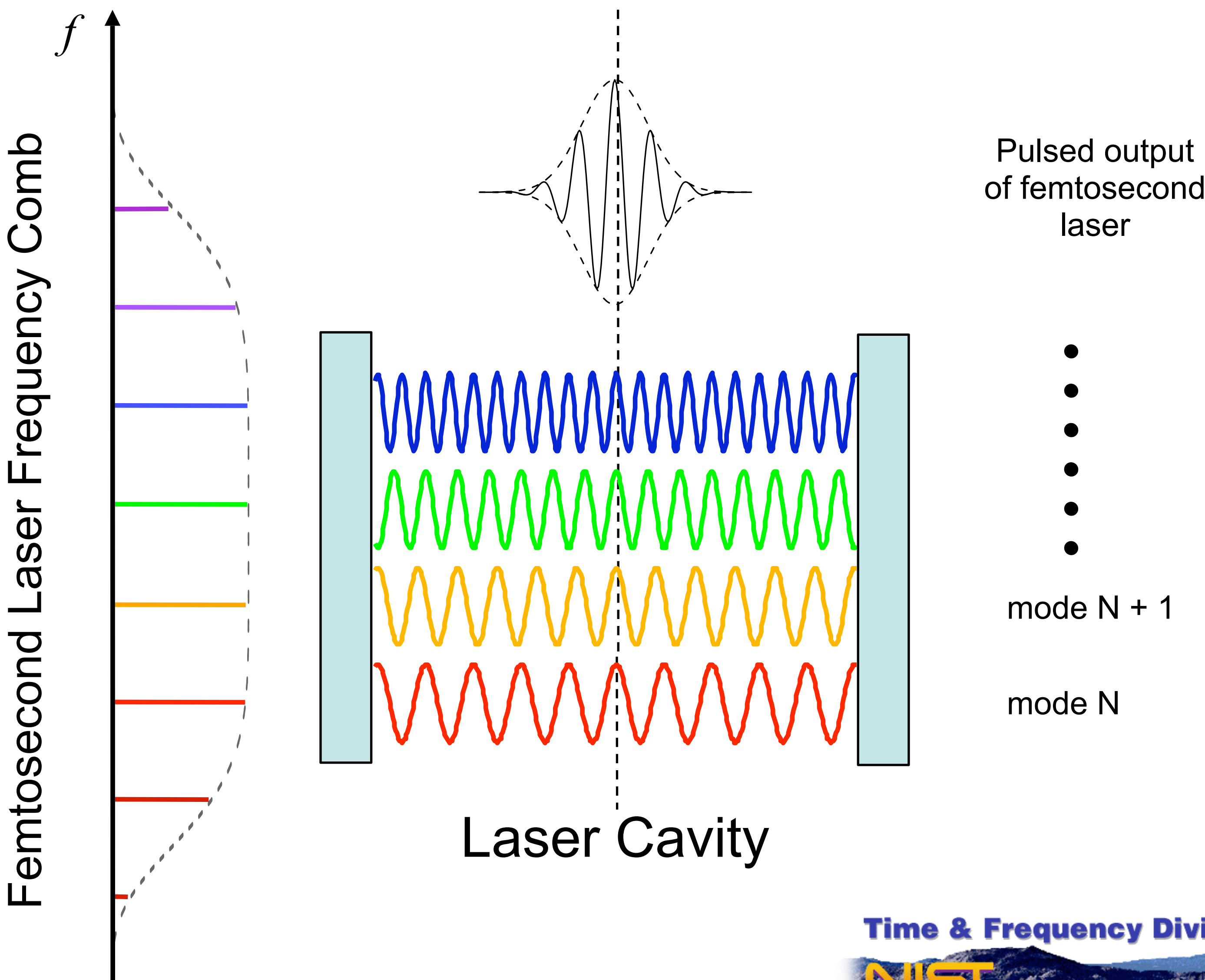
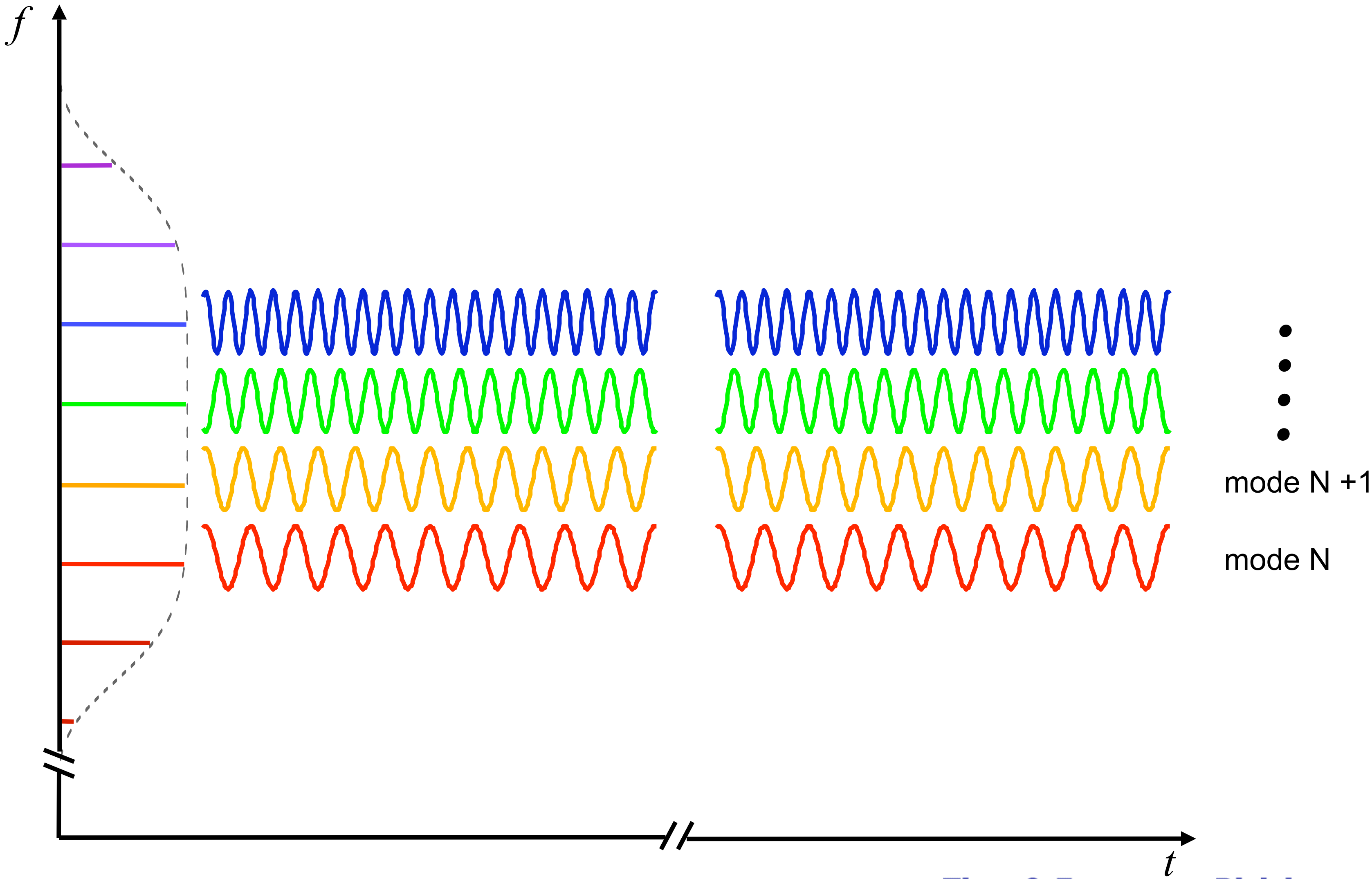


Time & Frequency Division NIST

Controlling the Femtosecond Laser Comb



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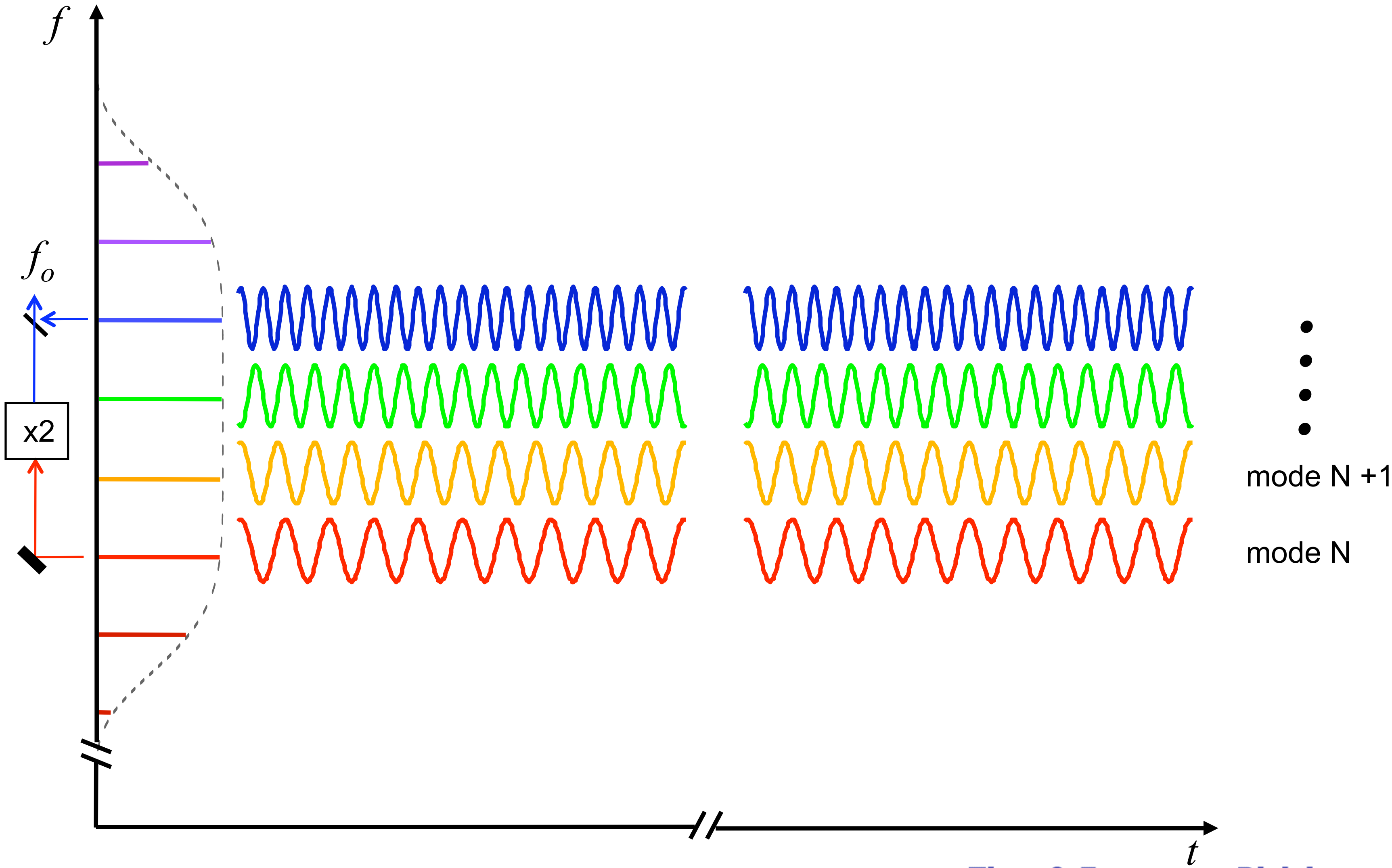

Time & Frequency Division

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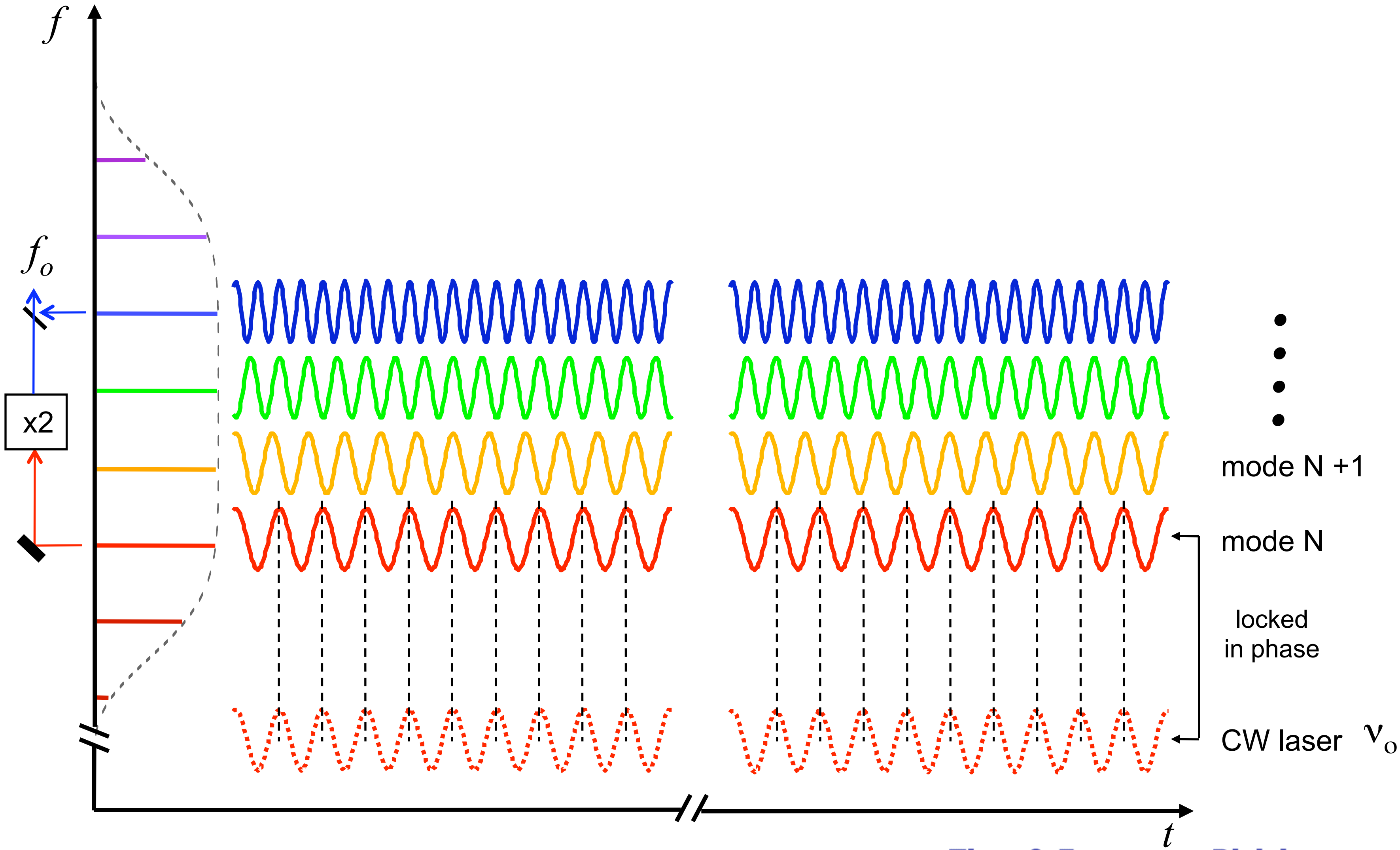

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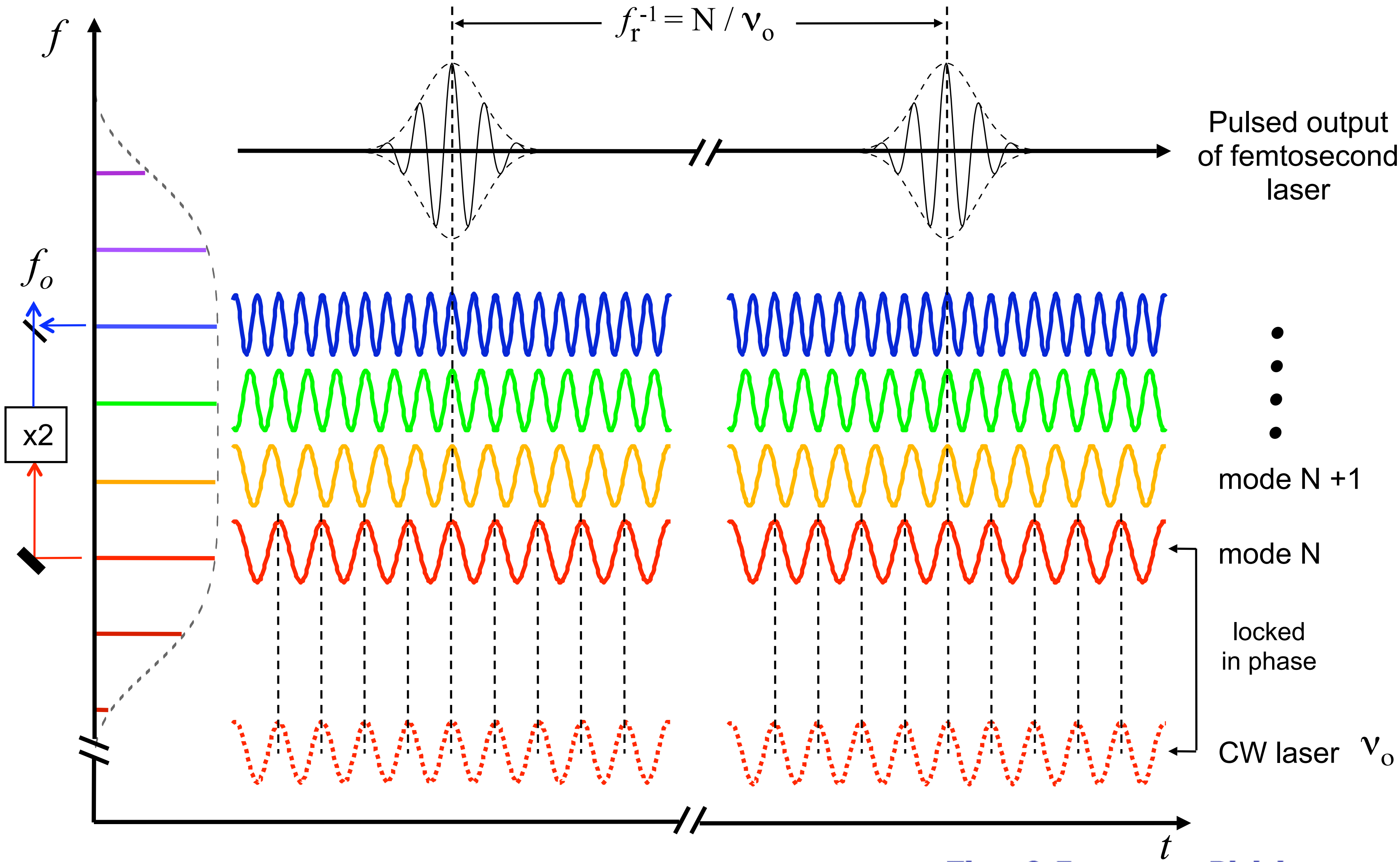
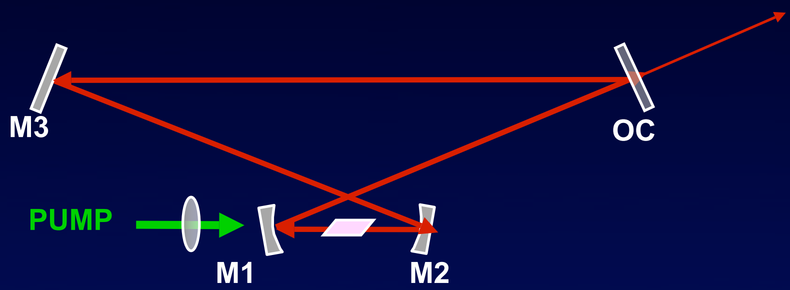


Time & Frequency Division

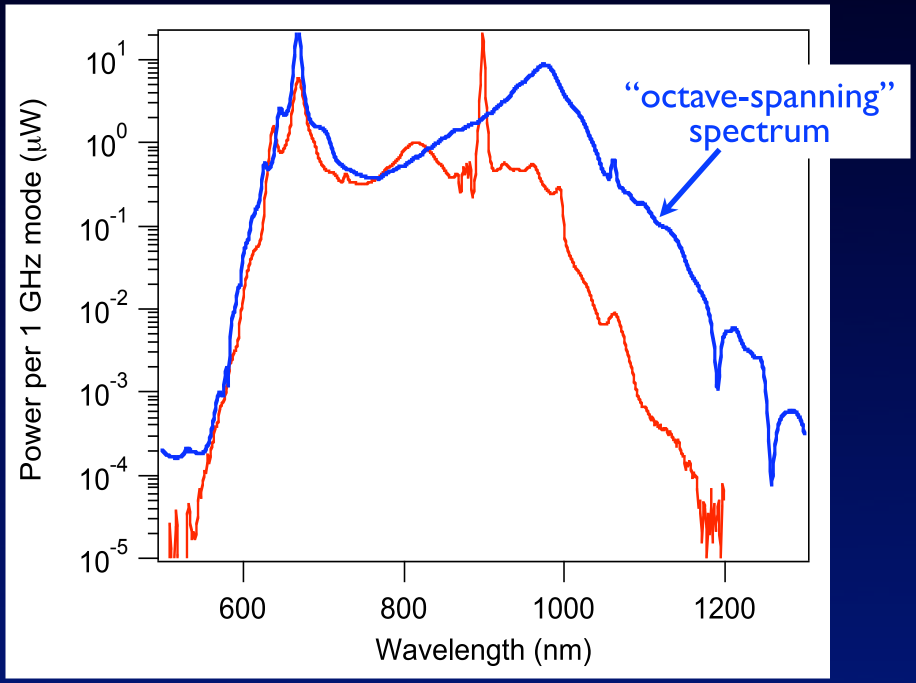
GHz Repetition Rate Frequency Combs

A. Bartels, T. Fortier



$$\nu_n = f_0 + n f_{rep}$$

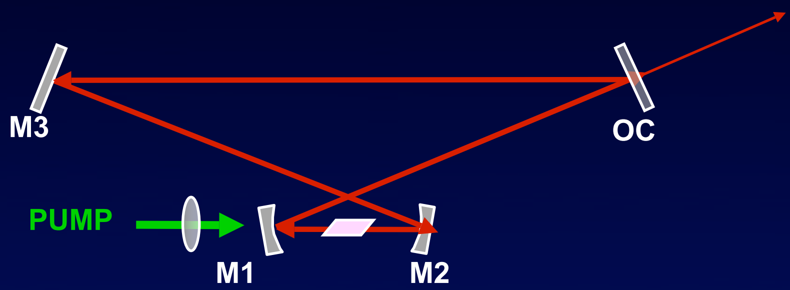
- Control f_0 with pump power
- Control f_{rep} with PZT (cavity length)



A. Bartels, H Kurz, *Opt. Lett.* 27, 1839 (2002)
T. Fortier, A. Bartels, S. Diddams, *Opt. Lett.* 31, 1011 (2006)

GHz Repetition Rate Frequency Combs

A. Bartels, T. Fortier



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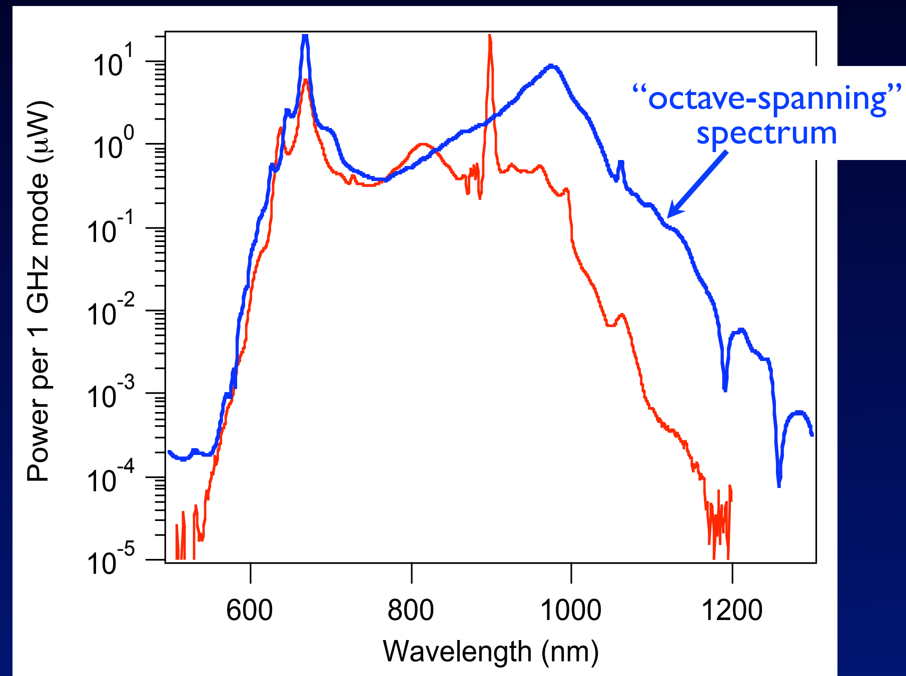

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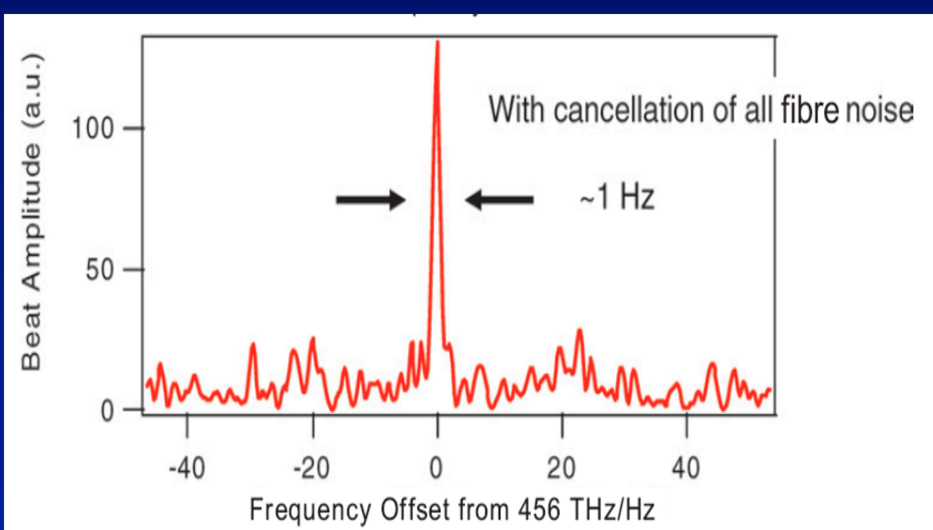
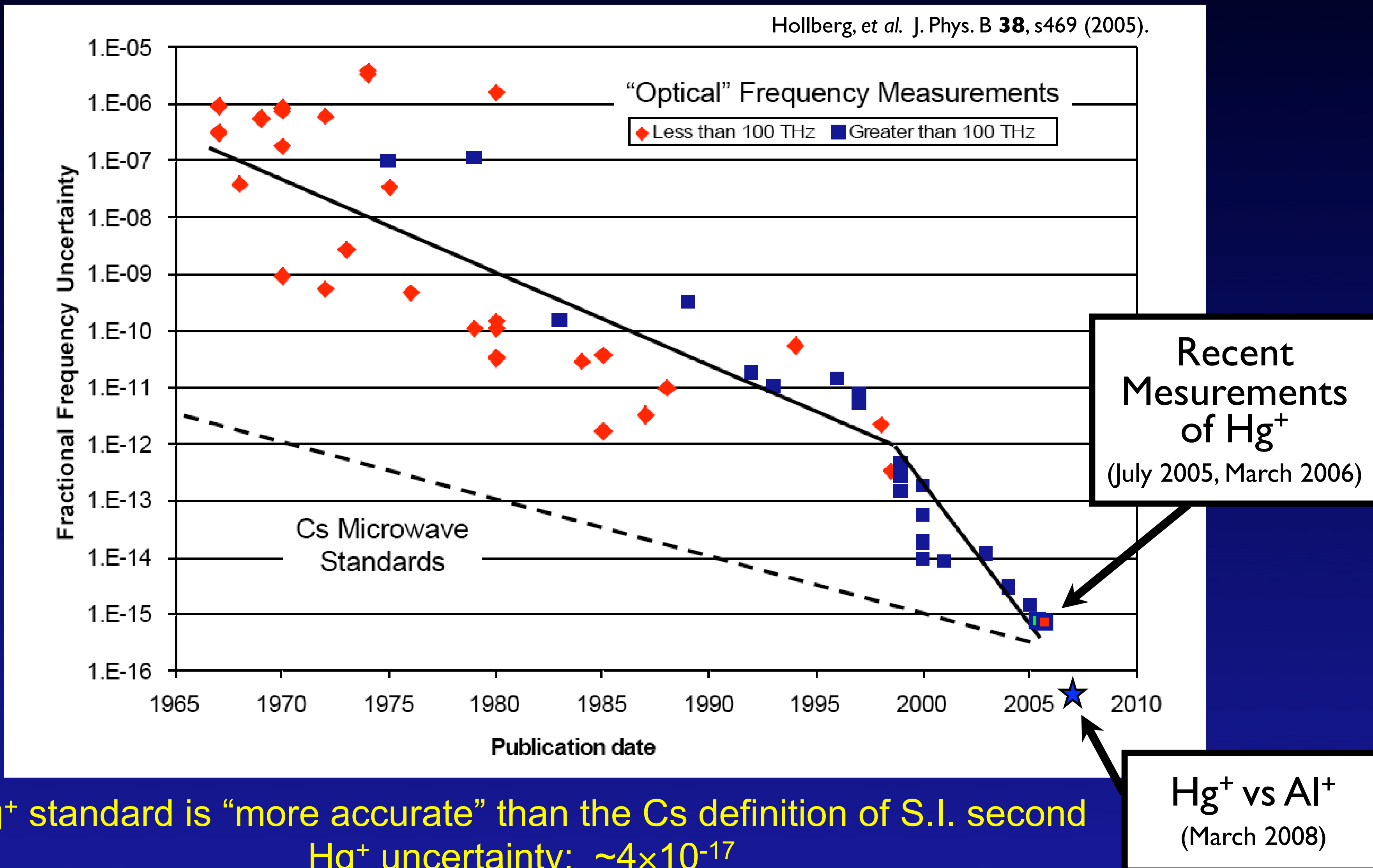


A. Bartels, C.W. Oates, L. Hollberg, S. Diddams, *Opt. Lett.* 29, 1081 (2004).

Stabilized Comb = 10^6 Modes
⇒ with Hz-level linewidths
⇒ residual frequency noise at 1×10^{-19} level

2006: Optical Standards Surpass Cesium



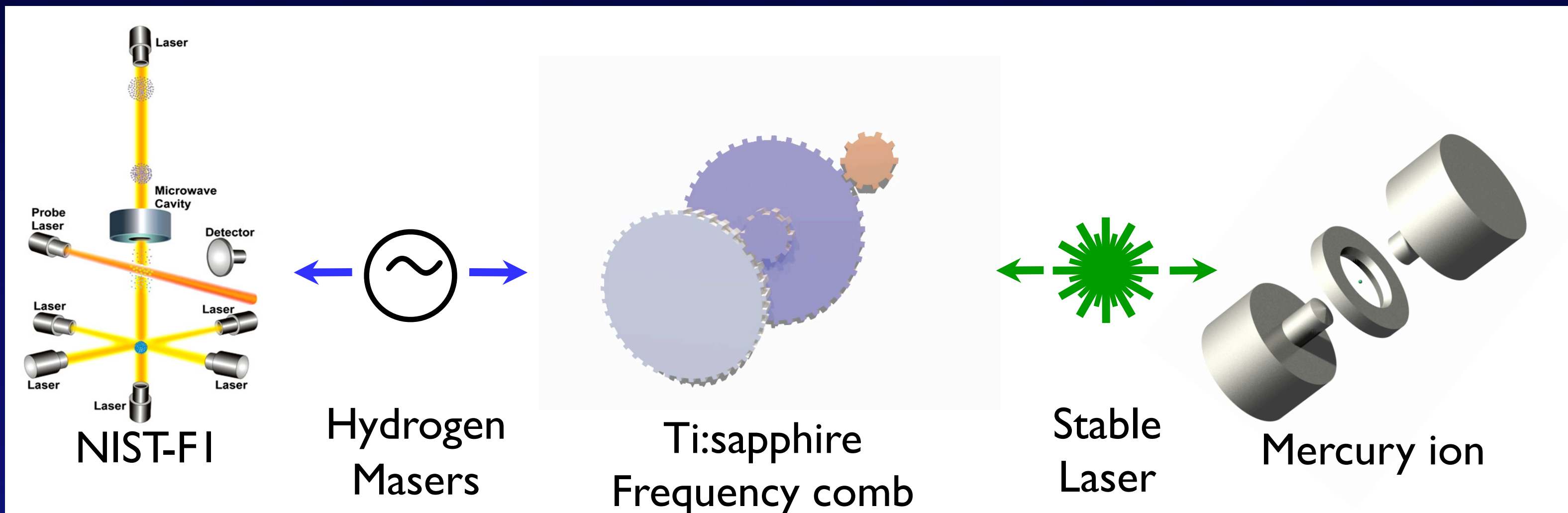
Hg^+ standard is "more accurate" than the Cs definition of S.I. second

Hg^+ uncertainty: $\sim 4\times10^{-17}$

Cs uncertainty: $\sim 4\times10^{-16}$

W. H. Oskay, et al. *Phys. Rev. Lett.* **97**, 020801 (2006)

Hg^+ ion (1 064 000 GHz) versus Cs fountain (9. 192 620 770 GHz)

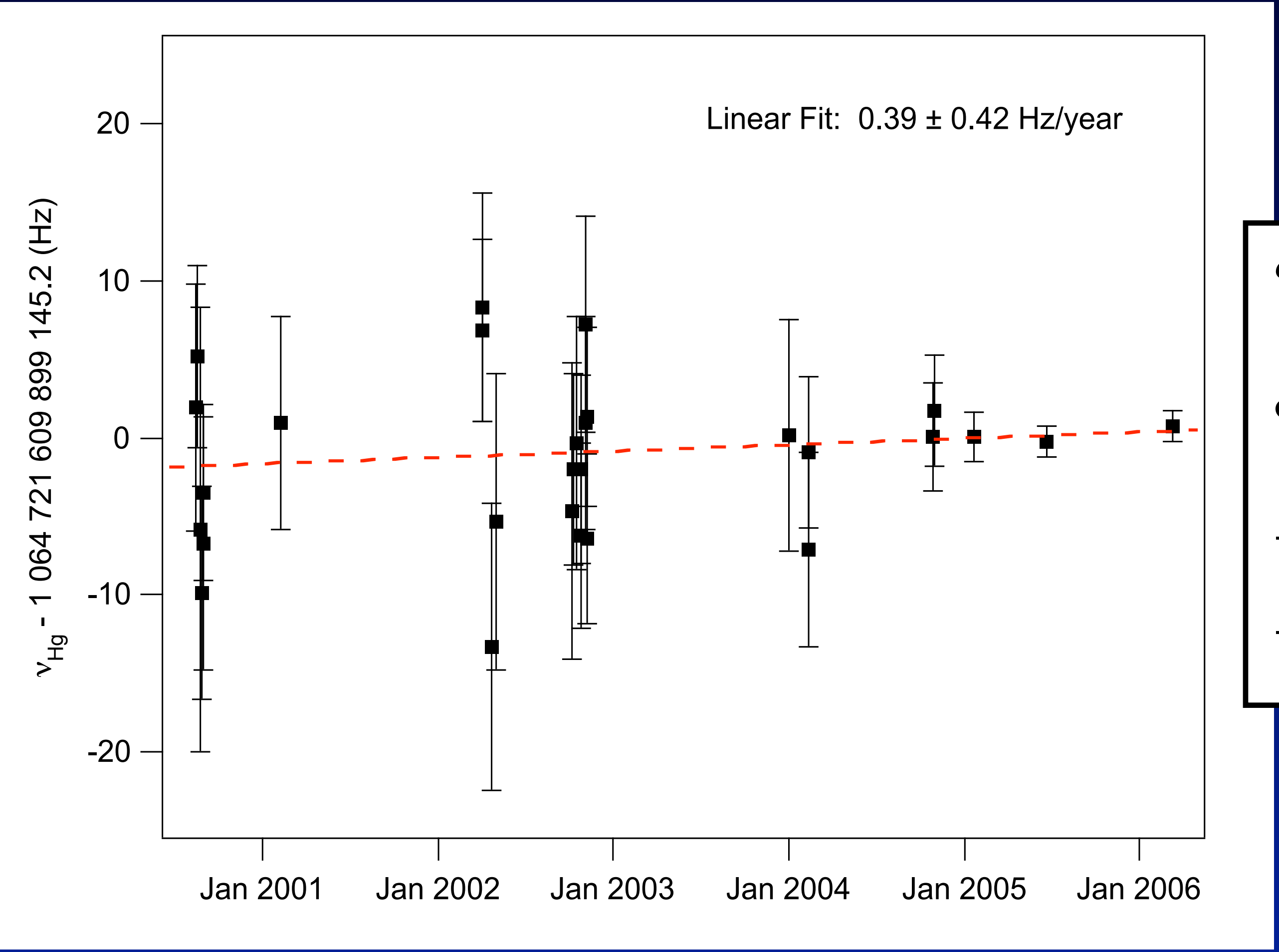


Cs Fountain	Femtosecond Comb	Hg^+ Ion
E. A. Donley	S. A. Diddams	J. C. Bergquist
T. P. Heavner	T. Fortier	W. M. Itano
S. R. Jefferts	L. Hollberg	M. Jensen
F. Levi	K. Kim	L. Lorini
T. E. Parker	J. Stalnaker	W. Oskay

Hg-Cs Comparison & Searches for "New Physics"

- Does the frequency ratio change in time? (time variation of α)
- Does the frequency ratio change in space? (Local Position Invariance)

Answer: Not within our measurement resolution



$$\dot{\alpha}/\alpha = (6.2 \pm 6.5) \times 10^{-17}\ \text{yr}^{-1}$$

or a coupled constraint of :

$$-1.5 \times 10^{-15} < \dot{\alpha}/\alpha < 0.4 \times 10^{-15}$$

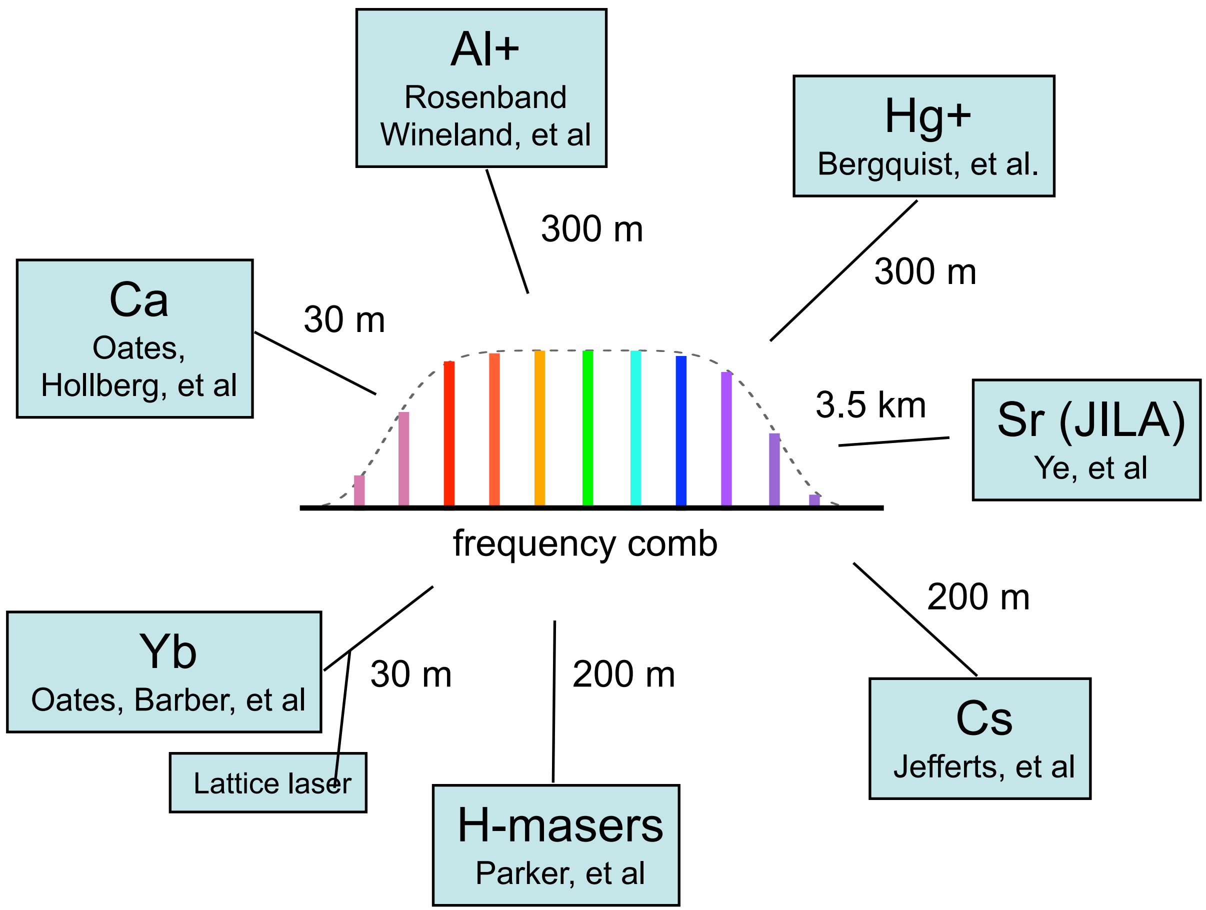
$$-2.7 \times 10^{-15} < \frac{d}{dt} \ln \frac{\mu_{Cs}}{\mu_B} < 8.6 \times 10^{-15}$$

Th. Udem, et al. Phys. Rev. Lett. **86**, 4996 (2000)
S. Bize, et al. Phys. Rev. Lett. **90** 150802 (2003)
W. Oskay et al. *Phys. Rev. Lett*. **97**, 020801 (2006)

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

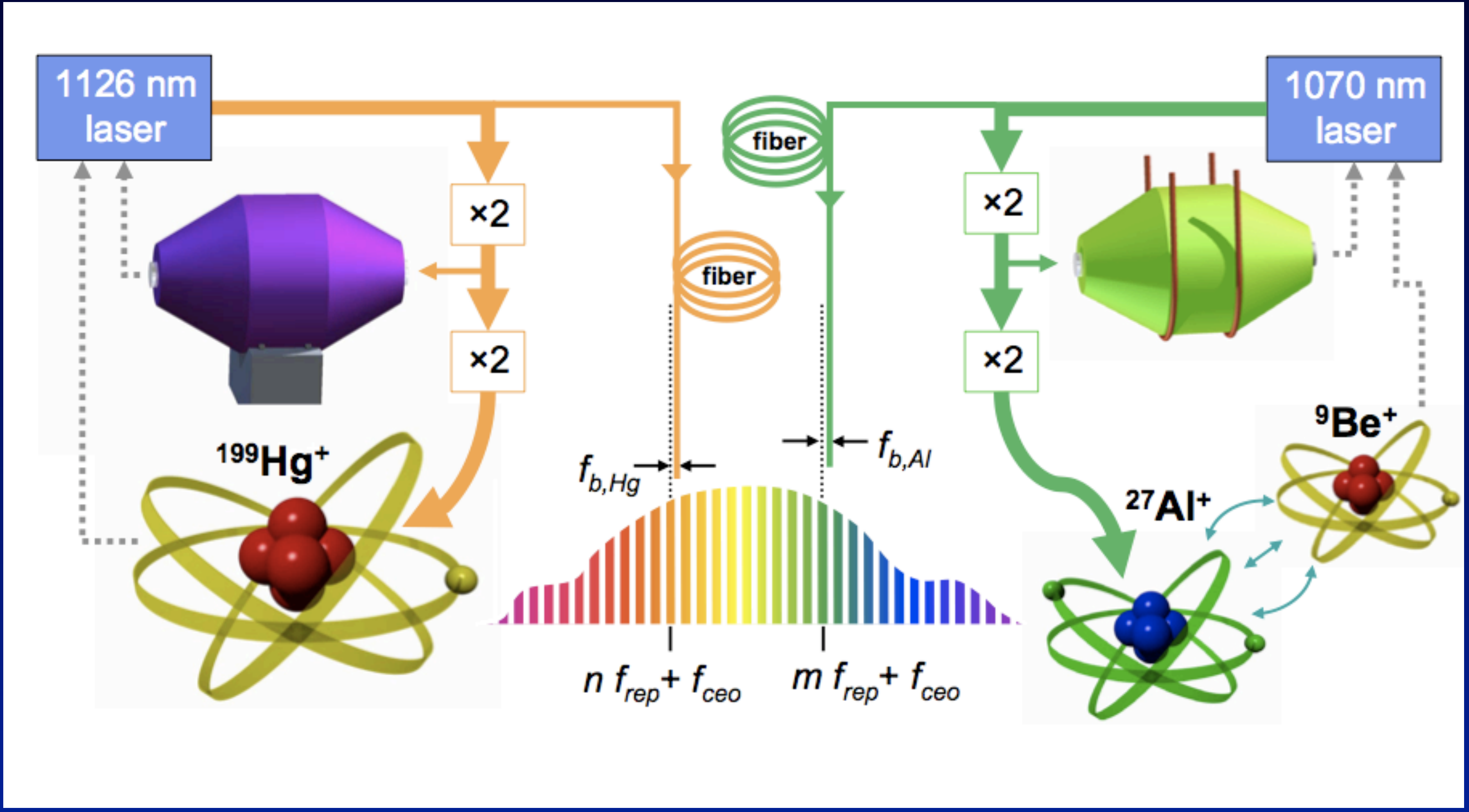
Atomic Standards in Boulder

- 5 optical standards, 2 microwave standards within ~3 km
- All connected by optical fibers or co-axial cable to the frequency comb
- Uncertainties $<1\times10^{-15}$ now routine and $\sim3\times10^{-17}$ achieved with ions



$Al^+ : Hg^+$

Single Hg-ion compared to the Al-ion quantum logic clock



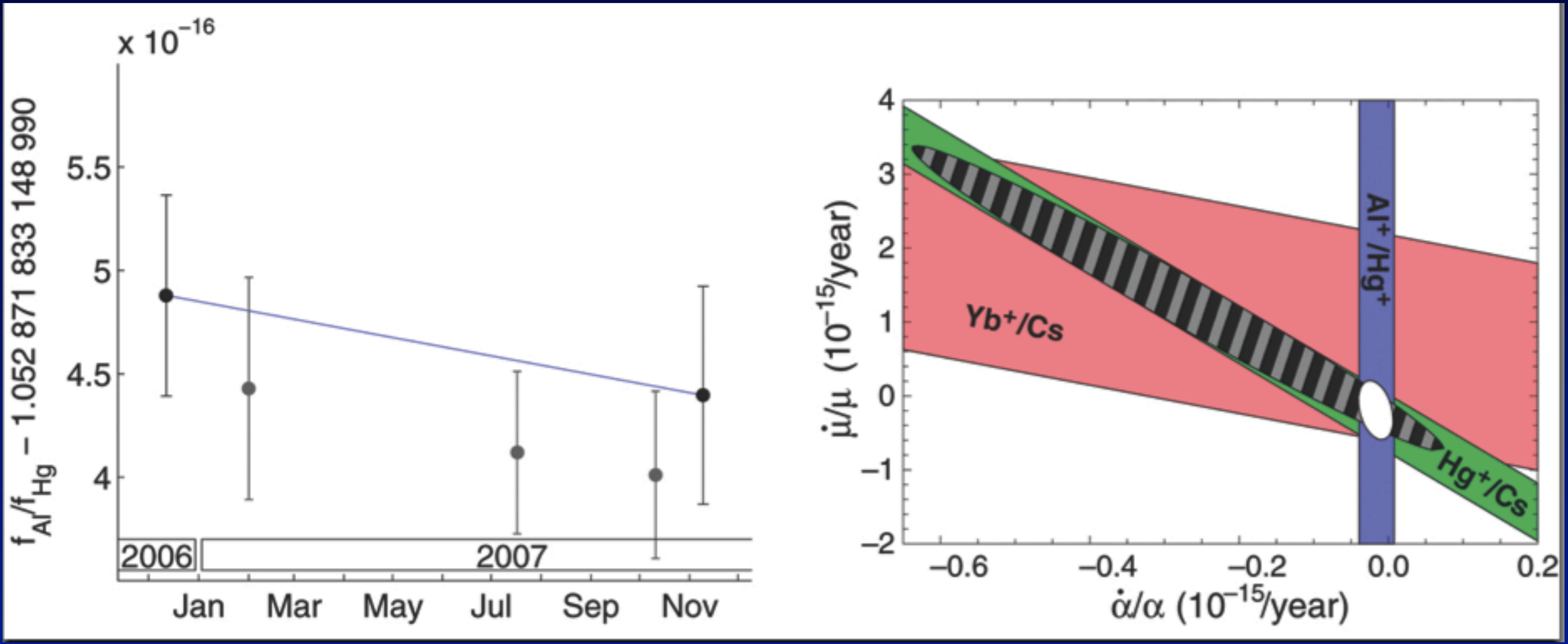
Sciencexpress / www.sciencexpress.org / 6 March 2008 / Page 3 / 10.1126/science.1154622

Ratio of Al$^+$ and Hg$^+$ frequencies

$$\nu_{Al^+}/\nu_{Hg^+} \text{ is } 1.052871833148990438(55)$$

Uncertainty of ~5x10^{-17}

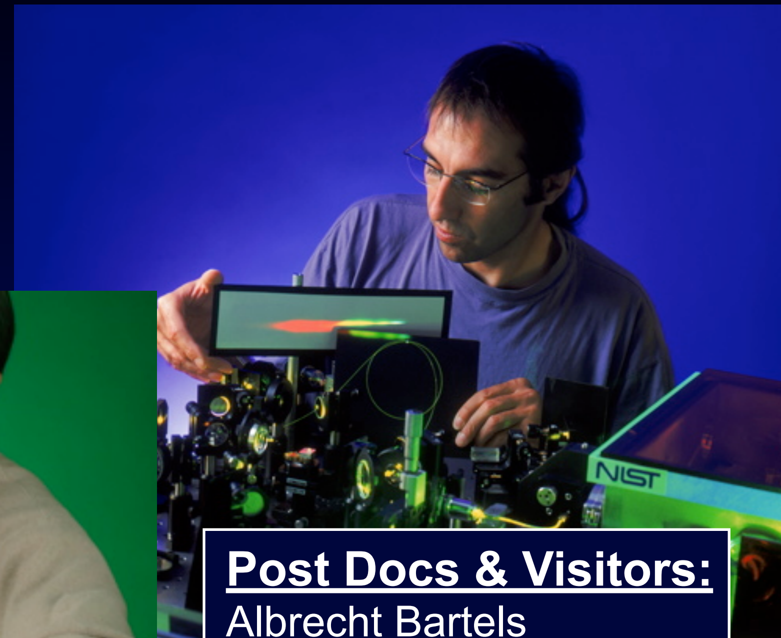
Till Rosenband et al, Science, March 2008



$$\dot{\alpha}/\alpha = (-1.6 \pm 2.3) \times 10^{-17} \text{ / year}$$

Time & Frequency Division NIST

Many thanks to…



NIST Staff:
Jim Bergquist
Steve Cundiff
Bob Drullinger
John Hall
Tom Heavner
Leo Hollberg
Wayne Itano
Steve Jefferts
Nate Newbury
Chris Oates
Tom Parker
Till Rosenband
Dave Wineland
Jun Ye

Students:
Zeb Barber
Dave Hume
Stephanie Meyer
Matt Kirchner
Nathan Lemke
Qudsia Quraishi

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Nicola Poli
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Shijun Xiao

$$ NIST, DARPA, ONR-CU-MURI, NASA, LANL

Time & Frequency Division