

Femtosecond lasers: the gears of optical atomic clocks

*Scott A. Diddams
Time & Frequency Division
National Institute of Standards and Technology
Boulder, Colorado 80305*

Time & Frequency Division

NIST

The NIST logo is positioned over a background image of a mountain range. The logo consists of the letters 'NIST' in a stylized, bold font. The 'N' and 'I' are orange, while the 'S' and 'T' are blue. The background image shows a range of mountains with a blue sky and a white foreground, possibly representing a valley or a specific location.

NIST, Time & Frequency Division:

• Optical Frequency Measurements

Leo Hollberg

Anne Curtis (grad student)

Chris Oates

Tanya Ramond (post-doc)

Isabell Thomann (grad student)

Kristan Corwin (post-doc)

Nate Newbury

• Ion Storage

Jim Bergquist

Sebastian Bize (post-doc)

Bob Drullinger

Wayne Itano

Windell Oskay (post-doc)

Dave Wineland

• Atomic Standards

Steve Jefferts

Tom Heavner

Tom Parker

Guest Researchers:

Albrecht Bartels (U. Aachen)

Eugene Ivanov (U. West. Aust.)

Long-Sheng Ma (U. Colorado & BIPM)

Lennart Robertsson (BIPM)

Utako Tanaka (CRL, Japan)

Carol Tanner (Notre Dame U.)

Thomas Udem (MPQ)

Karl Weber (U. Melbourne)

Tim Birks (U. of Bath)

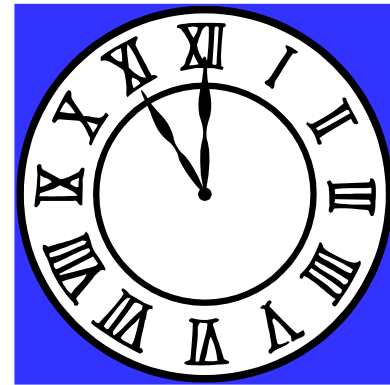
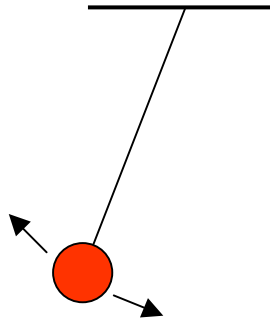
Robert Windeler (OFS)

What Makes a Clock?

Oscillator

+

Counting Mechanism



Earth Rotation
Pendulum
Quartz Crystal

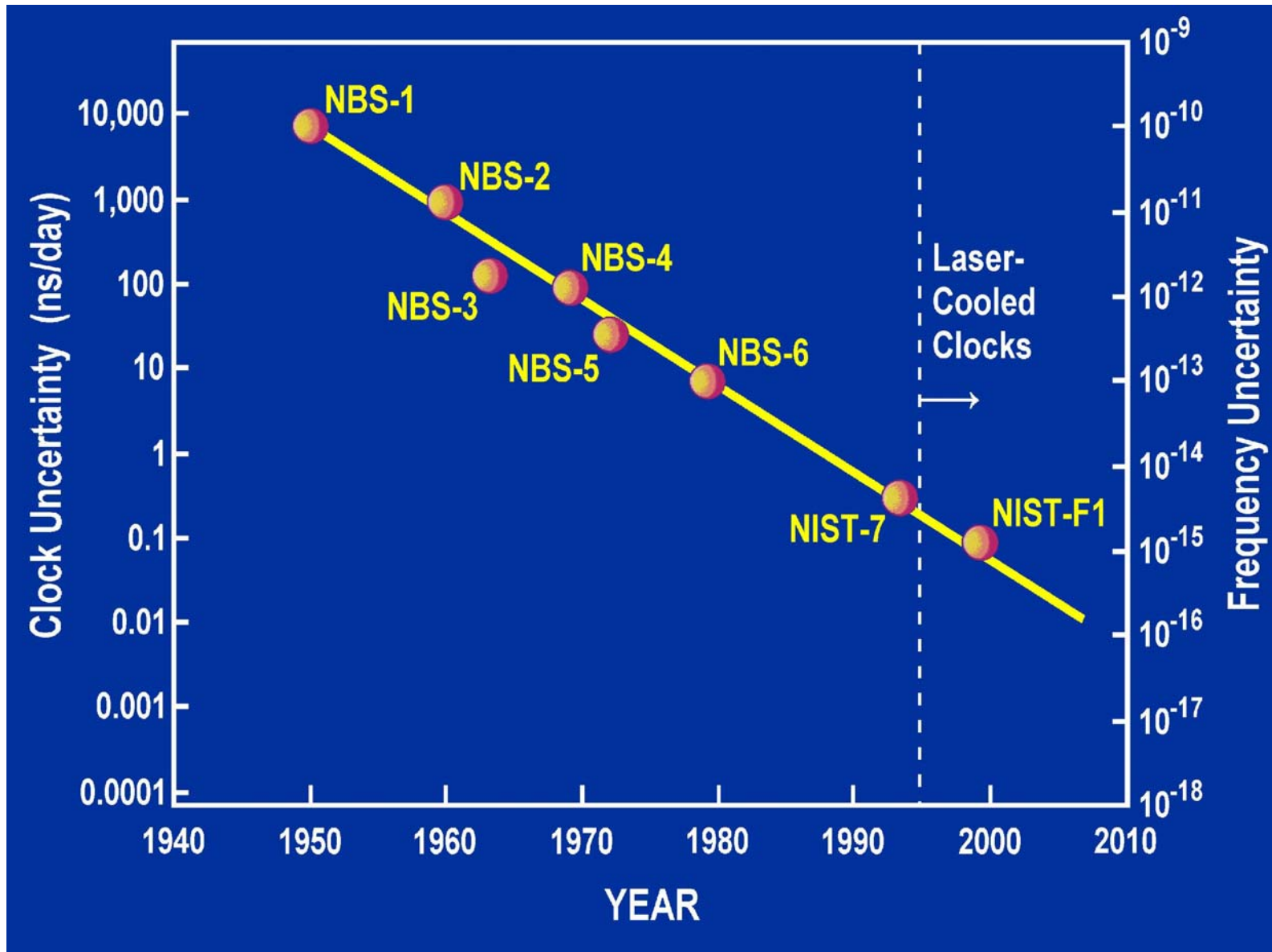
Sundial
Clock Gears/Hands
Electronic Counter

ATOMIC CLOCKS

Microwave Transition + Oscillator
Optical Transition + Laser

Electronic Counter
Frequency Chain

Improvement of Cs microwave standards over 50 years



Optical Clocks

Why are they interesting?

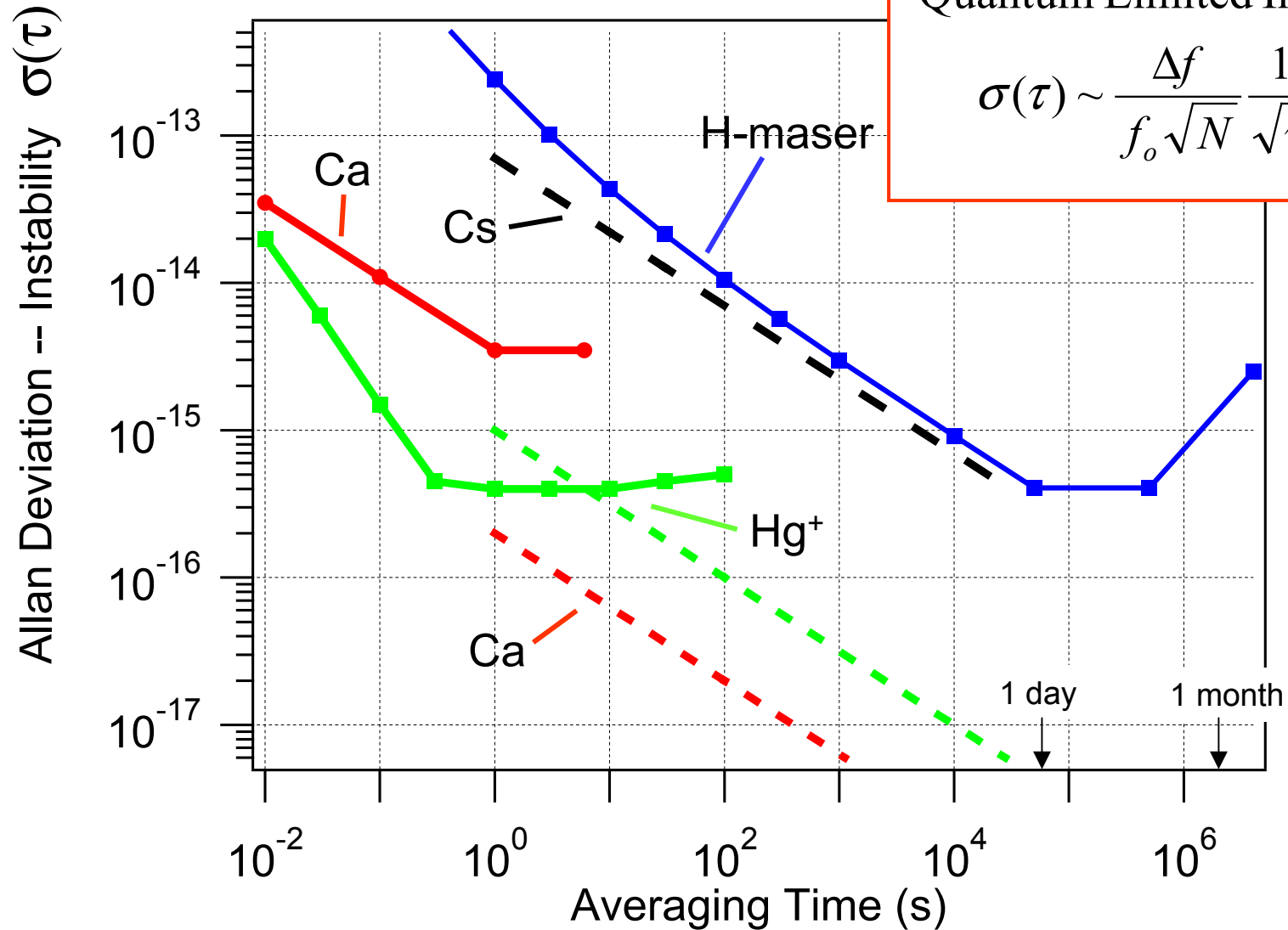
- Optical standards have superior stability:

$$\sigma(\tau) \sim \frac{\Delta f}{f_0 \sqrt{N}} \frac{1}{\sqrt{\tau}}$$

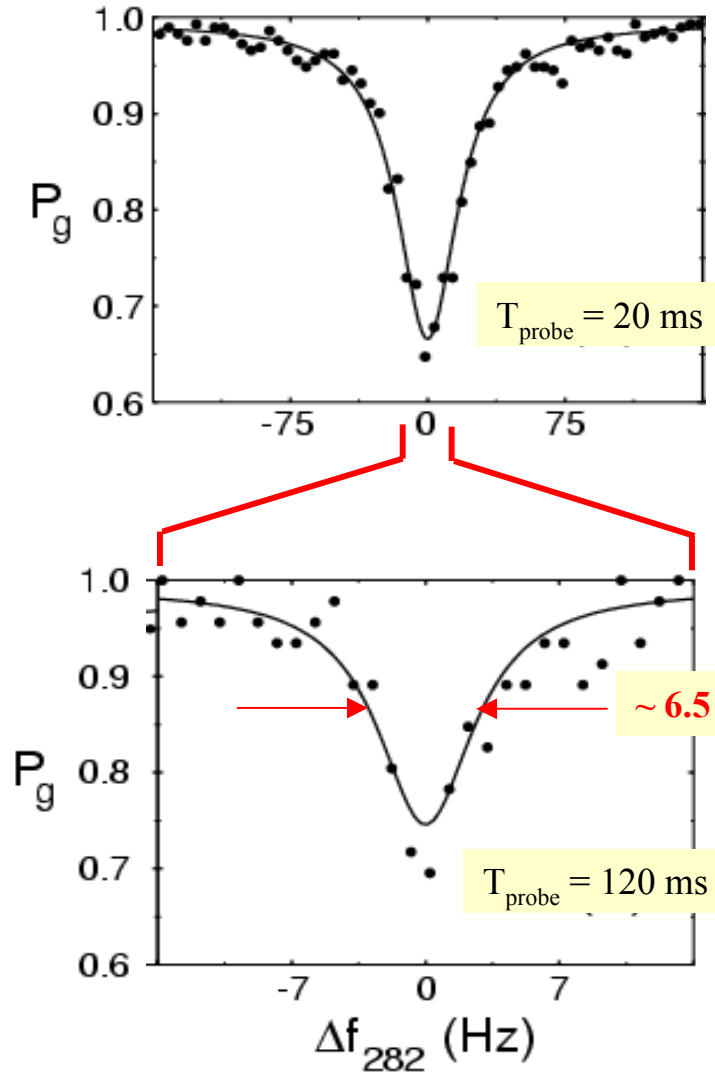
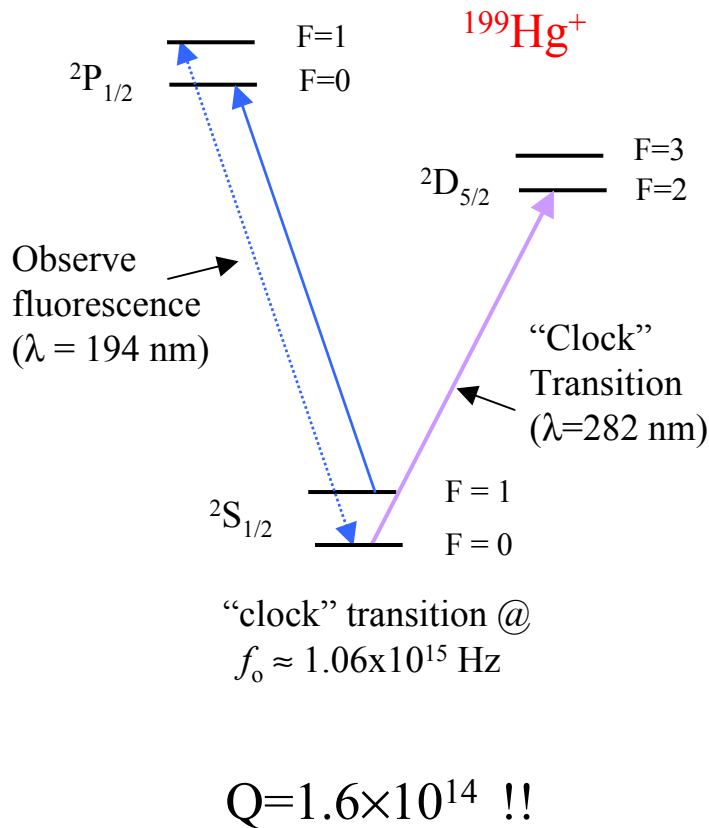
e.g. Ca optical standard
<2x10⁻¹⁶ at 1 s

- Optical standards have the potential for greatly improved accuracy: e.g. approaching 1x10⁻¹⁸ for single trapped ions

Oscillator Stability



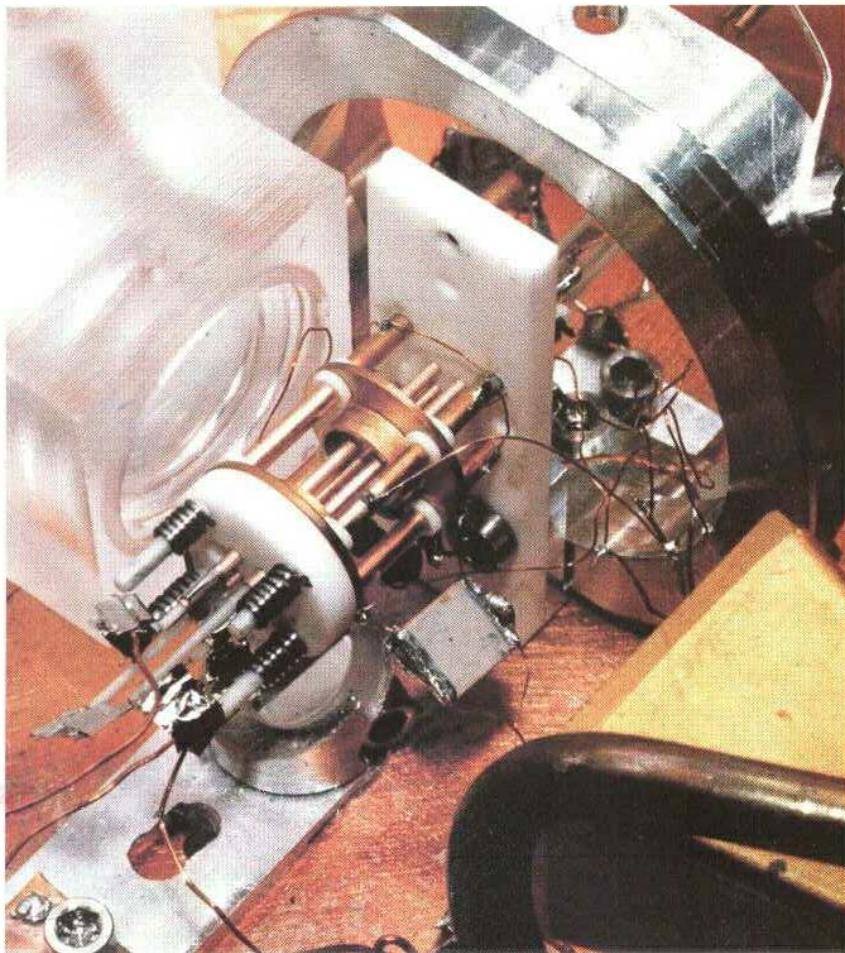
Single Hg⁺ Ion Optical Standard



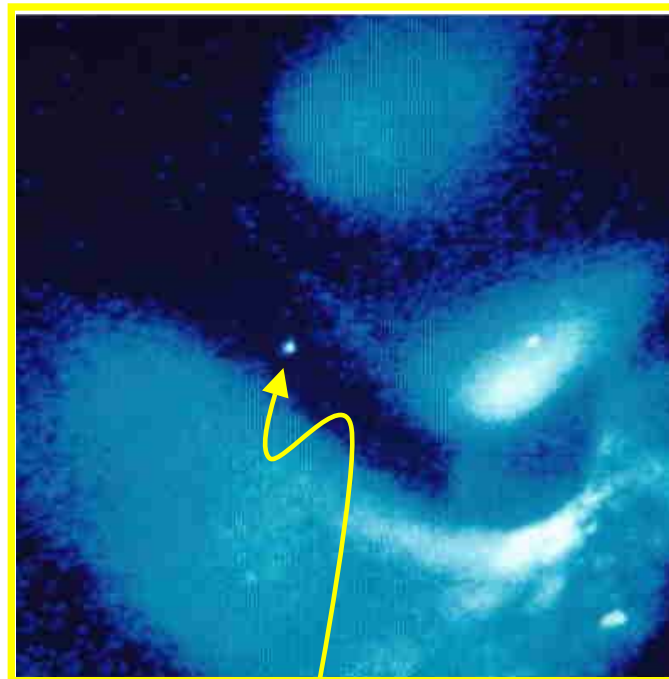
J. Bergquist, et al. (NIST)

PHYSICS TODAY

MARCH 2001



SPECIAL FOCUS: CELEBRATING NIST'S CENTENNIAL



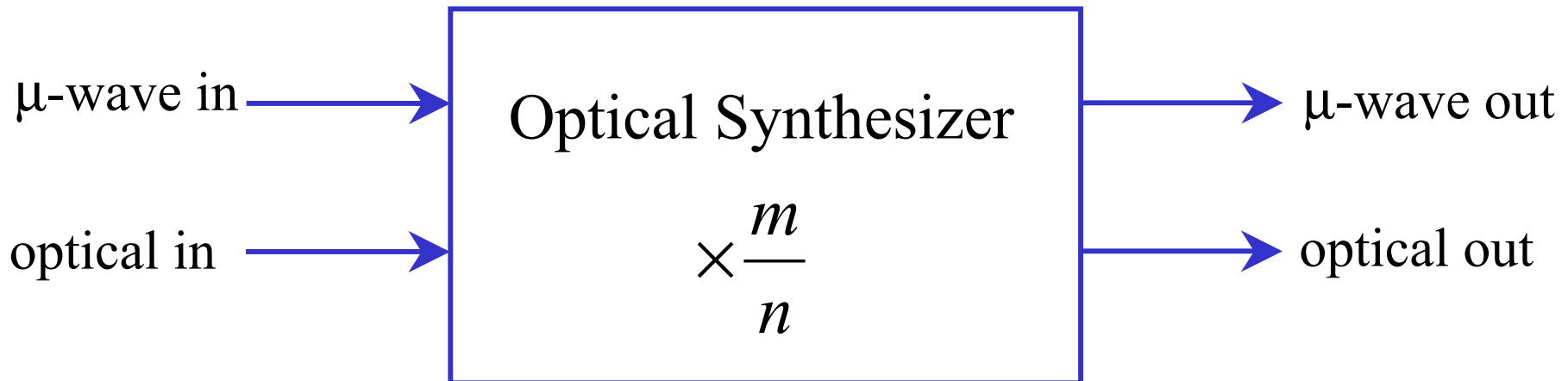
Single Hg⁺ ion

NIST

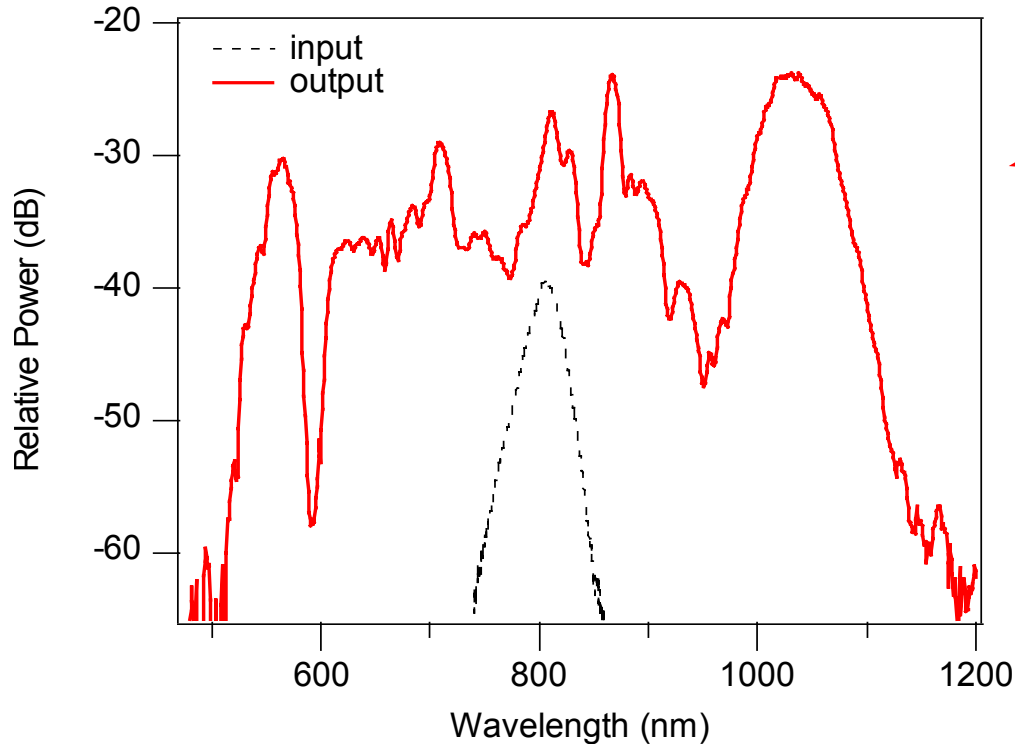
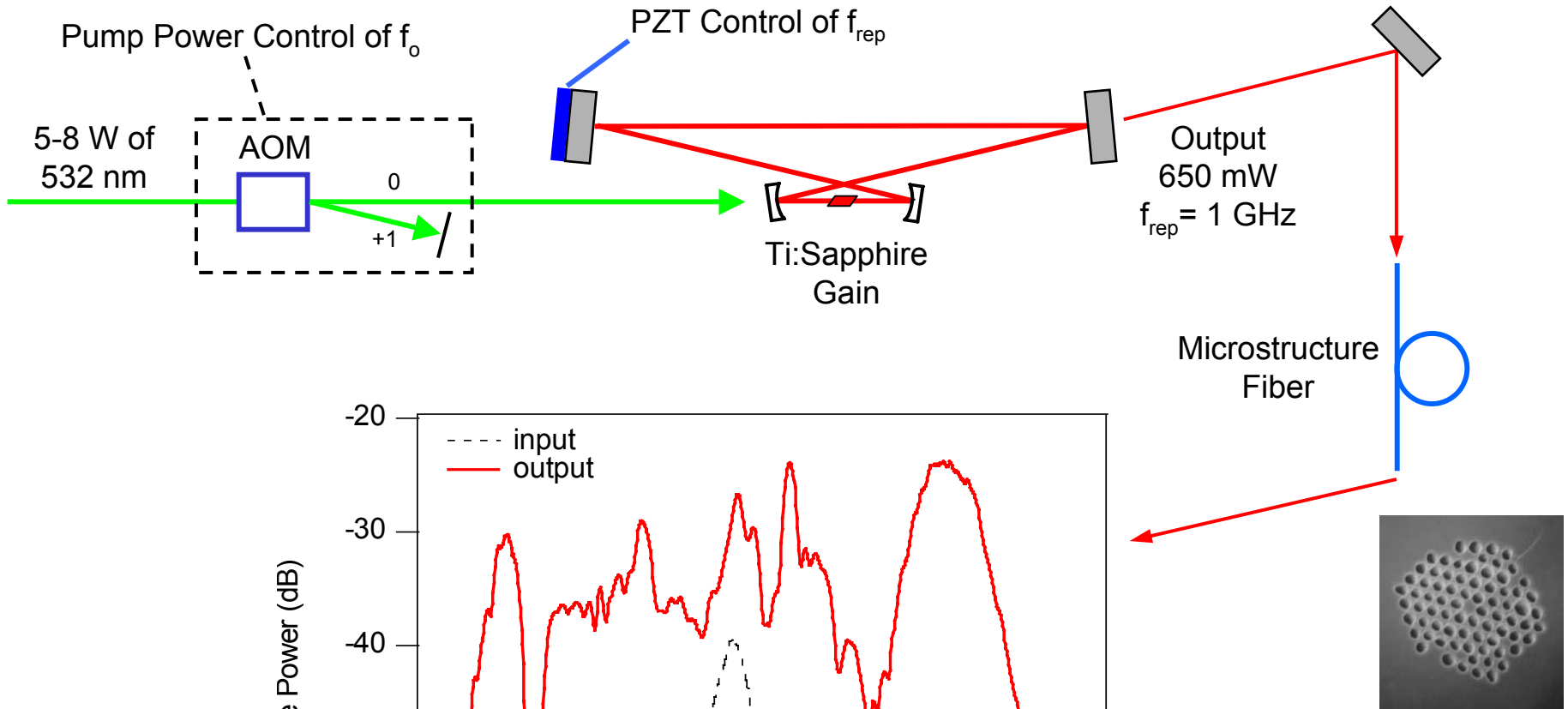
National Institute of Standards and Technology

Femtosecond-Laser-Based Optical Synthesizer

- **What is it?** A device that phase-coherently connects optical and RF/microwave domains.



Femtosecond-Laser-Based Synthesizer



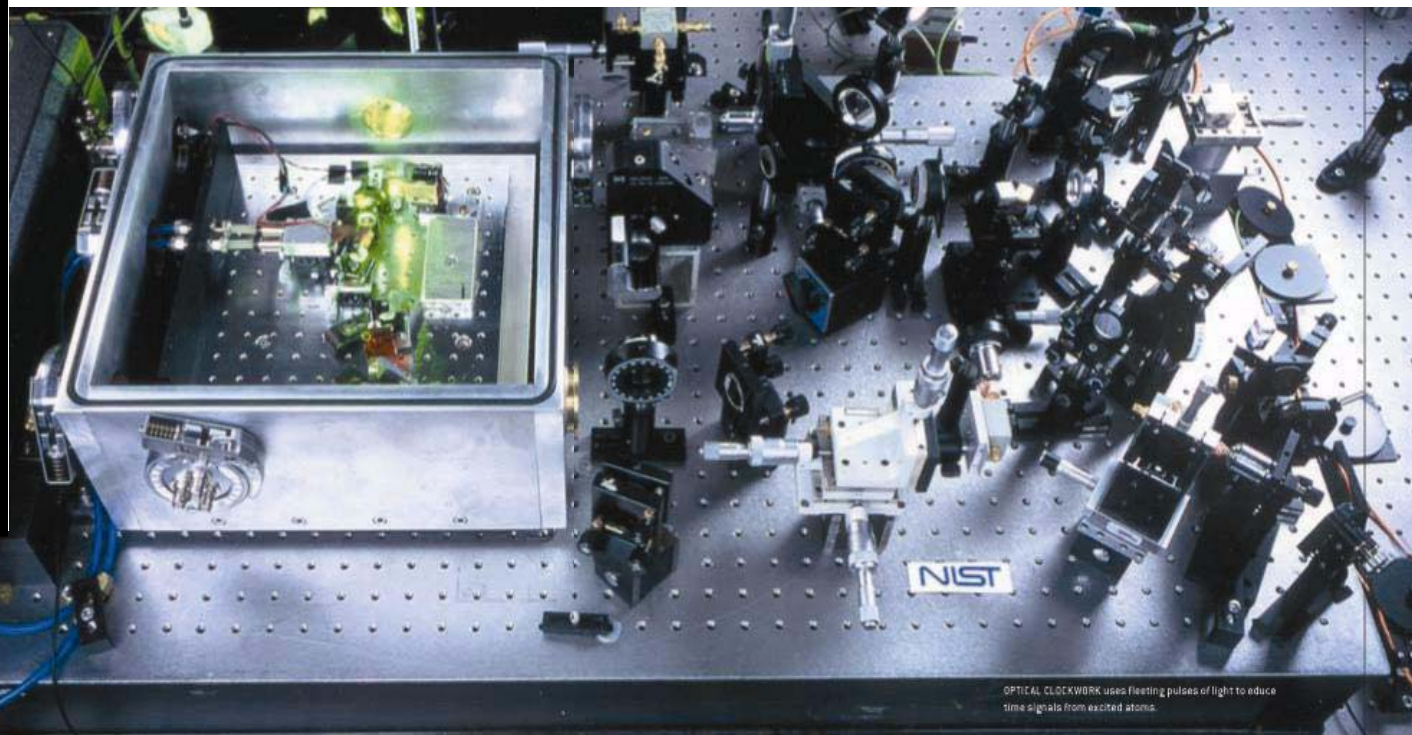
S.A. Diddams, *et al.*
Proc. SPIE vol. 4269 (200)

A MATTER OF TIME

Time's Mysterious Physics
Building Time Machines
The Mind and Time
Ultimate Clocks

The Philosophy of Time
The Body's Clocks
Time and Culture
And more...

COURTESY OF SCIENTIFIC AMERICAN



OPTICAL CLOCKWORK uses fleeting pulses of light to induce time signals from excited atoms.

OVERVIEW

- A renaissance under way in atomic clock building is expected to improve the precision of timekeeping by 1,000-fold.
- In theory, one can measure time with infinite accuracy. But gravity and motion distort time, imposing a practical limit to clocks' precision.
- Atomic clocks are short-lived. Engineers are also designing a mechanical clock that could operate through the year 12,000.

ULTIMATE CLOCKS

Atomic clocks are shrinking to microchip size, heading for space—and approaching the limits of useful precision **By W. Wayt Gibbs**

Dozens of the top clock makers in the world convened in New Orleans one muggy week

this past May to present their latest inventions. There was not a mechanic among them; these were scientists, and their conversations buzzed with talk of spectrums and quantum levels, not gears and escapements. Today those who would build a more accurate clock must advance into the frontiers of physics and engineering in several directions at once. They are cobbling lasers that spit out pulses a quadrillionth of a second long together with chambers that chill atoms to a few millionths of a degree above absolute zero. They are snaring individual ions in tar pits of light and magnetism and manipulating the spin of electrons in their orbits.

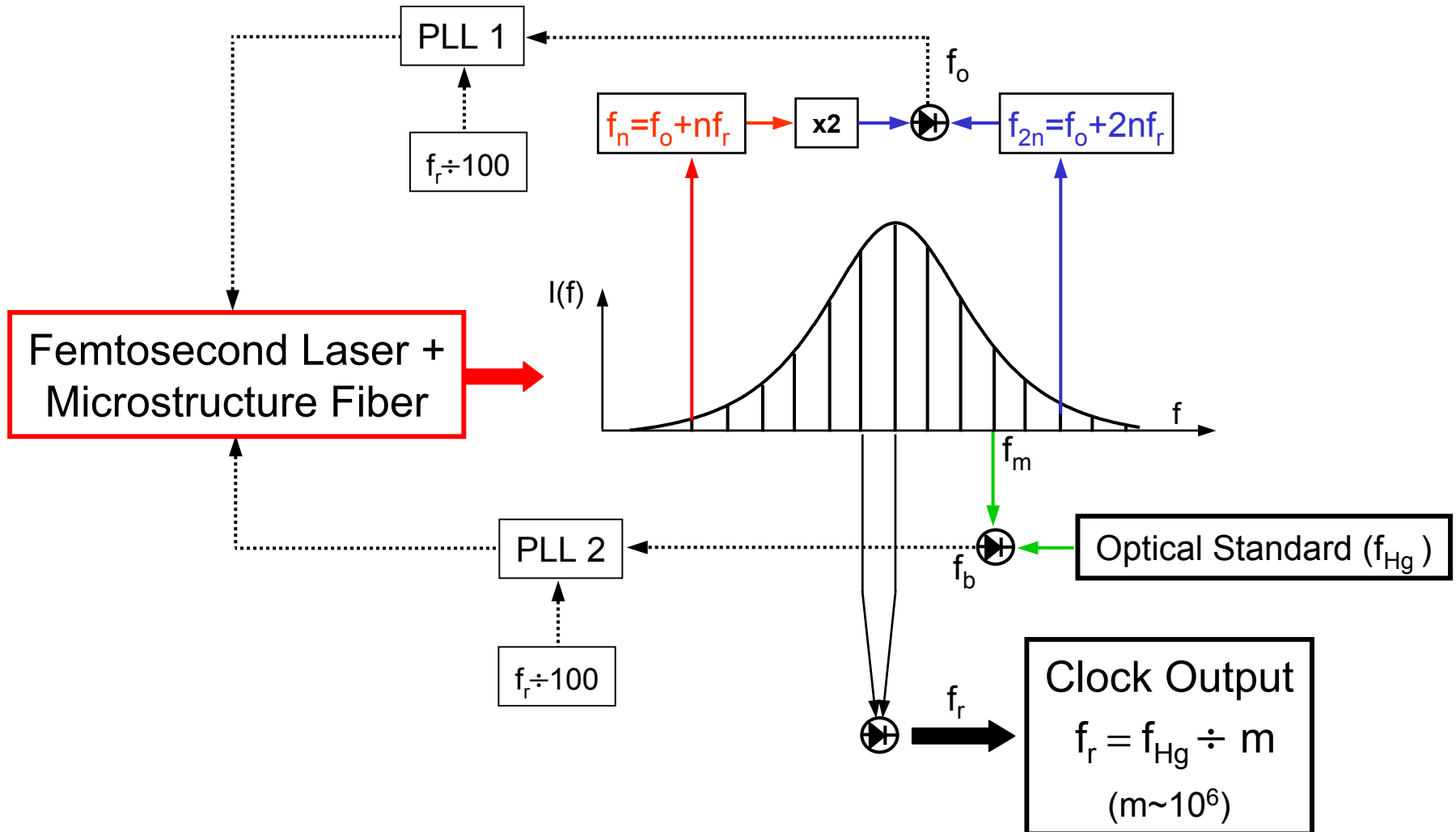
And thanks to major technical advances, the art of ultraprecise timekeeping is progressing with a speed not seen for 30 years or more. These days a good cesium beam clock, of the kind Agilent sells for \$63,000, will tick off seconds true to about a microsecond a month, its frequency accurate to five parts in 10^{13} . The primary time standard for the U.S., a cesium fountain clock installed in 1999 by

the National Institute of Standards and Technology (NIST) at its Boulder, Colo., laboratory, is good to one part in 10^{15} (usually written simply as 10^{-15}). That is 500 times the accuracy of NIST's best clock in 1975. But space-based clocks set to fly on the International Space Station by 2005 are expected to tick with uncertainties better than 10^{-16} . And successful prototypes of new clock designs—devices that extract time from calcium atoms or mercury ions instead of cesium—lead physicists to expect that within three years, accuracy will reach the 10^{-18} range, a 1,000-fold improvement in less than a decade.

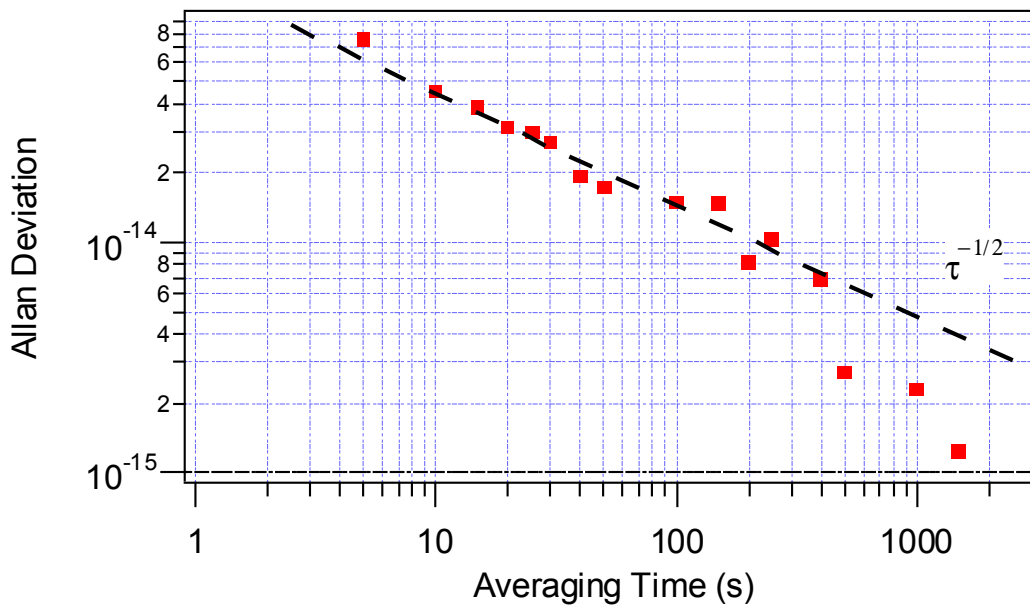
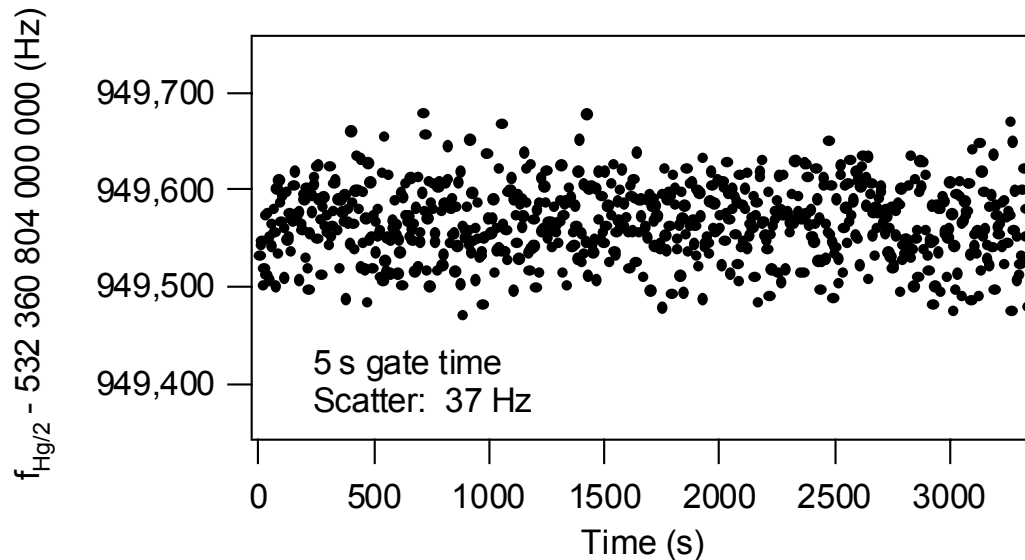
Accuracy may not be quite the right word. The second was defined in 1967 by international fiat to be "the duration of 9,192,631,770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the cesium 133 atom." Leave aside for the moment what that means: the point is that to measure a second, you have to look at cesium. Very soon now the best clocks

NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY

Optical Clock with a Femtosecond Synthesizer



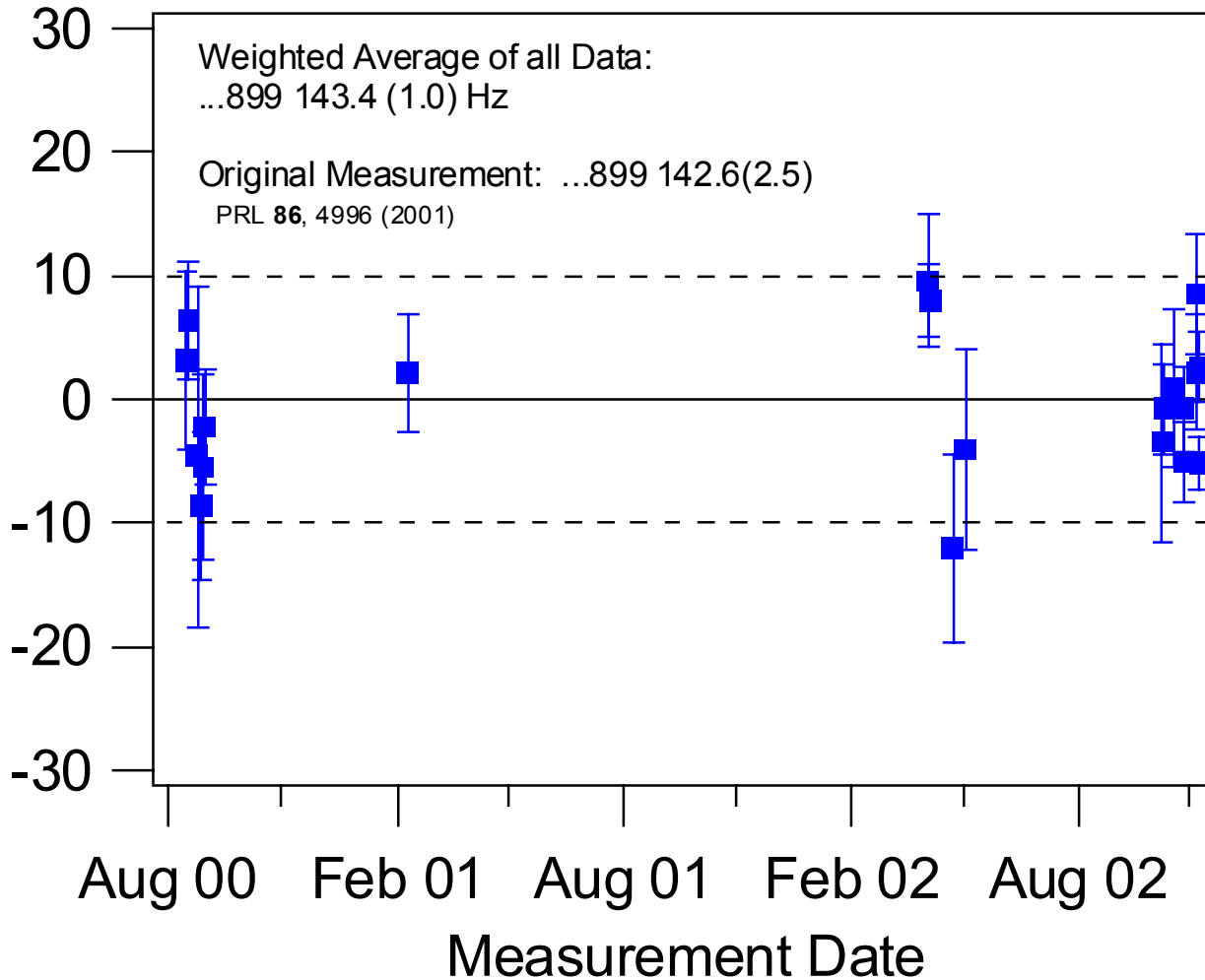
Comparison of Hg⁺ Optical Clock to a H-maser



Instability limited
by H-maser

Comparison of Hg⁺ (optical) to Cs (microwave)

$f_{\text{Hg}} - 1\,064\,721\,609\,899\,143.4$ (Hz)



Hg⁺ -- Cs comparison limits

possible variation of α

$$\frac{V_{Cs}}{V_{Hg}} \propto g_{Cs} \left(\frac{m_e}{m_p} \right) \alpha^{6.03}$$

Dzuba, Flambaum, Webb
PRA **59**, 230 (1999)

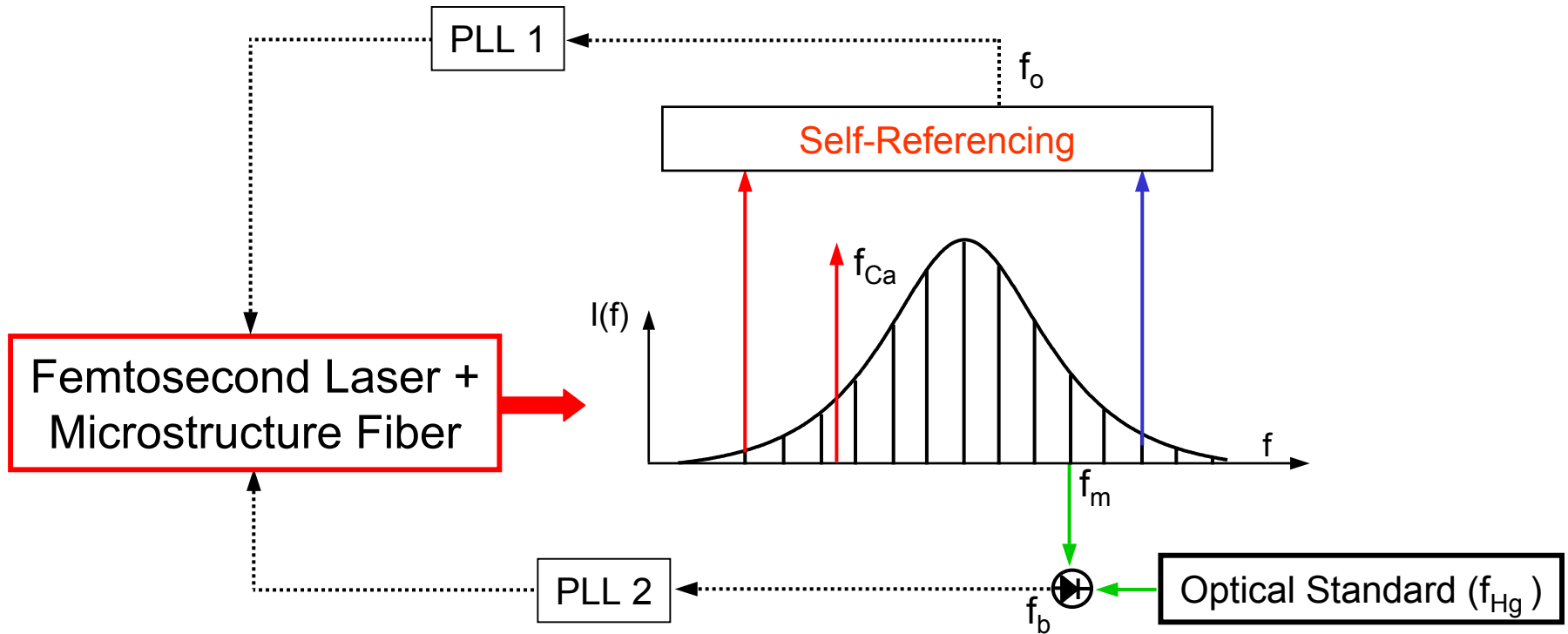
Present data constrains possible variations of

$$\left(\frac{V_{Cs}}{V_{Hg}} \right) \text{ to } \leq 7 \times 10^{-15} \text{ yr}^{-1}$$

or

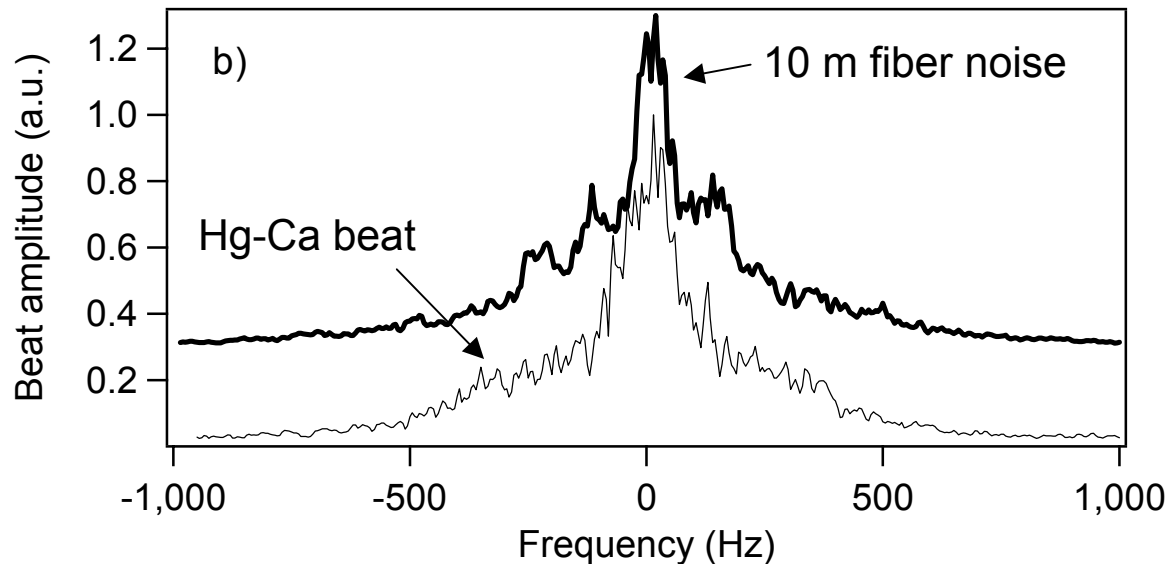
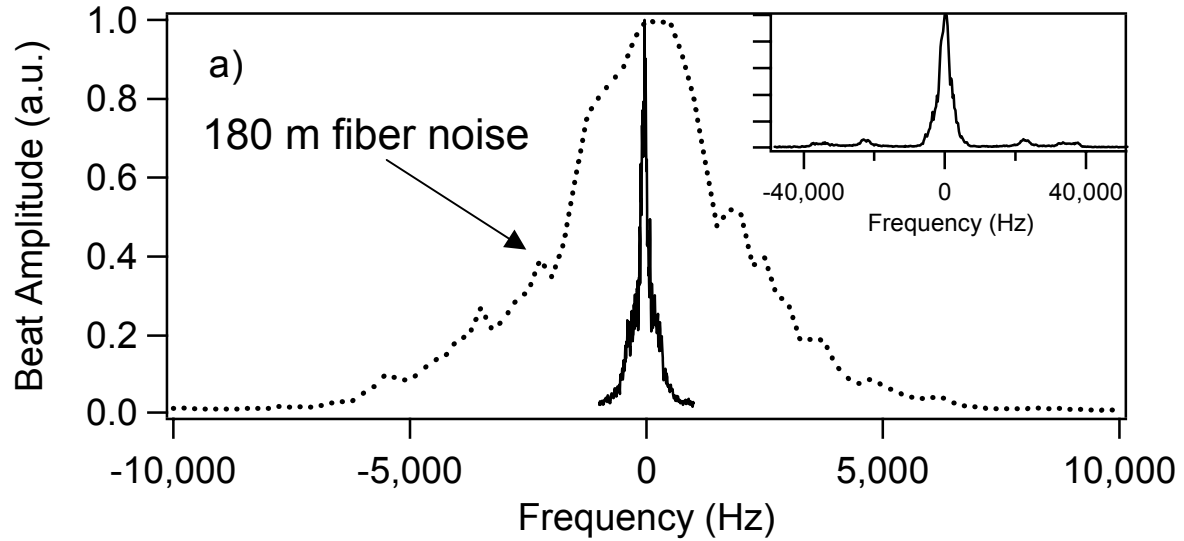
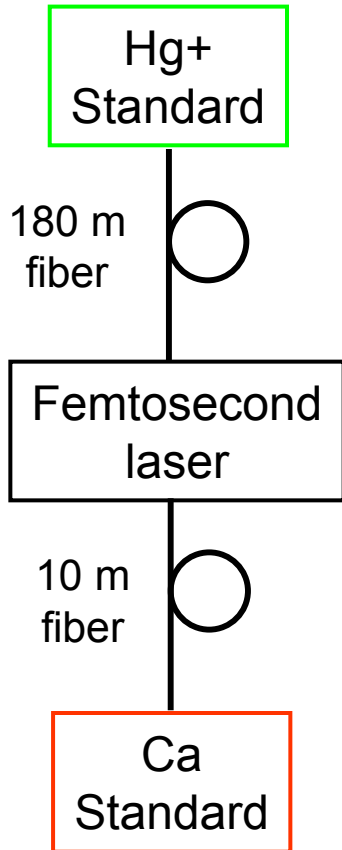
$$\frac{\dot{\alpha}}{\alpha} \leq 1.1 \times 10^{-15} \text{ yr}^{-1} \quad \text{if } g_{Cs} \text{ and } \left(\frac{m_e}{m_p} \right) \text{ are assumed constant}$$

Hg-Ca Optical Comparison

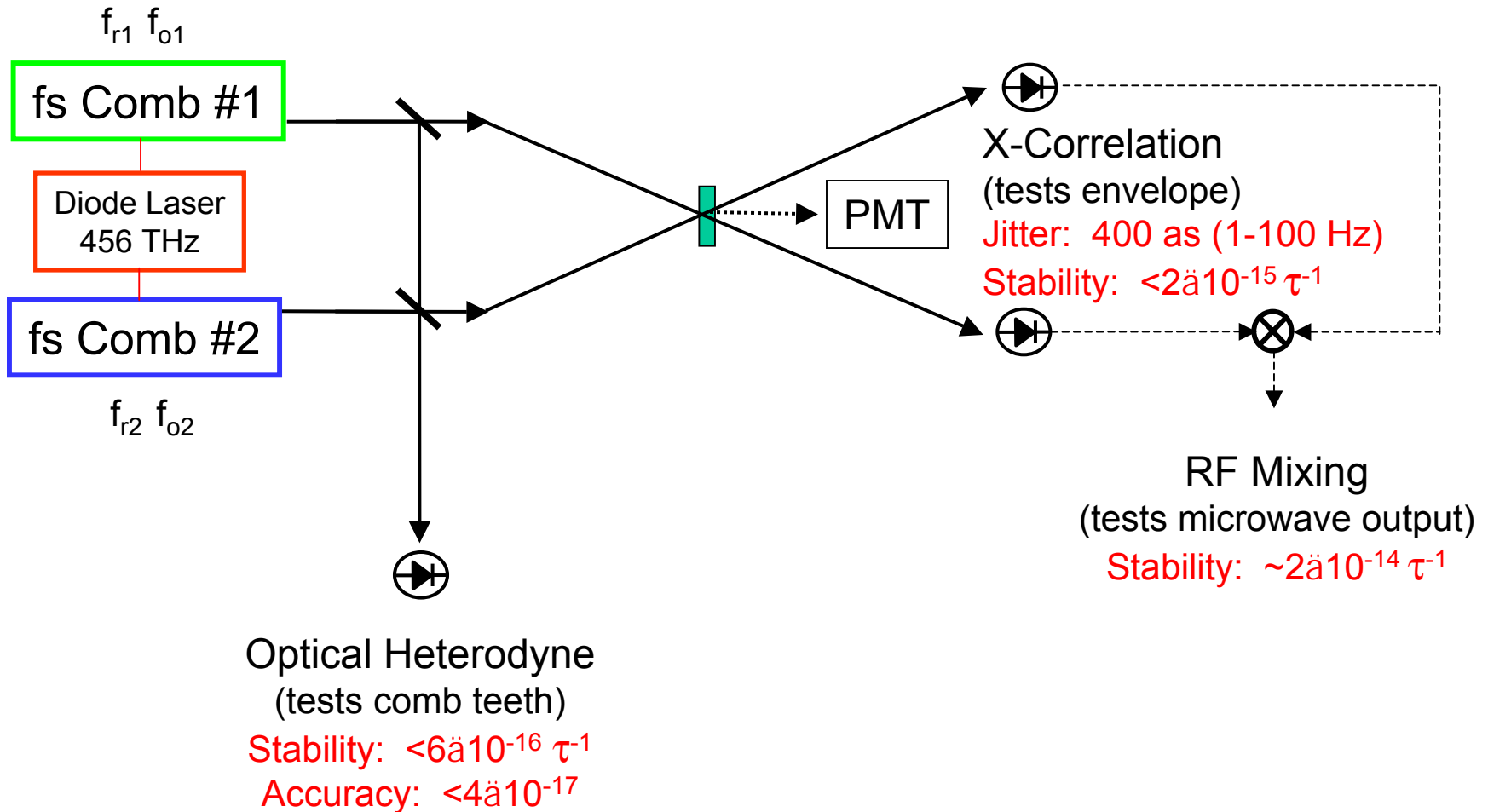


“Beat” between Hg⁺ and Ca across 76 THz

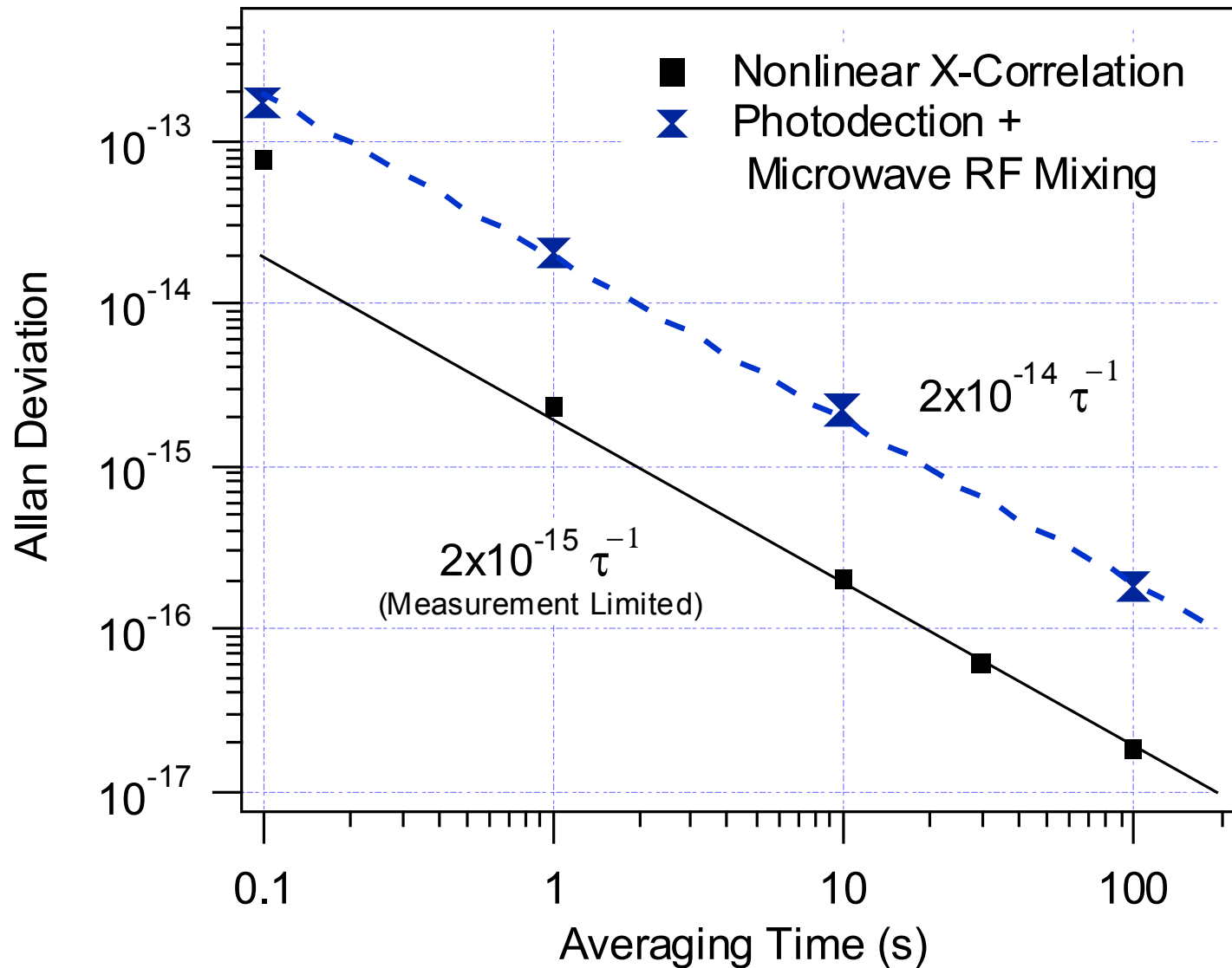
Millions of Narrow Linewidth Oscillators



Testing the Femtosecond Synthesizer

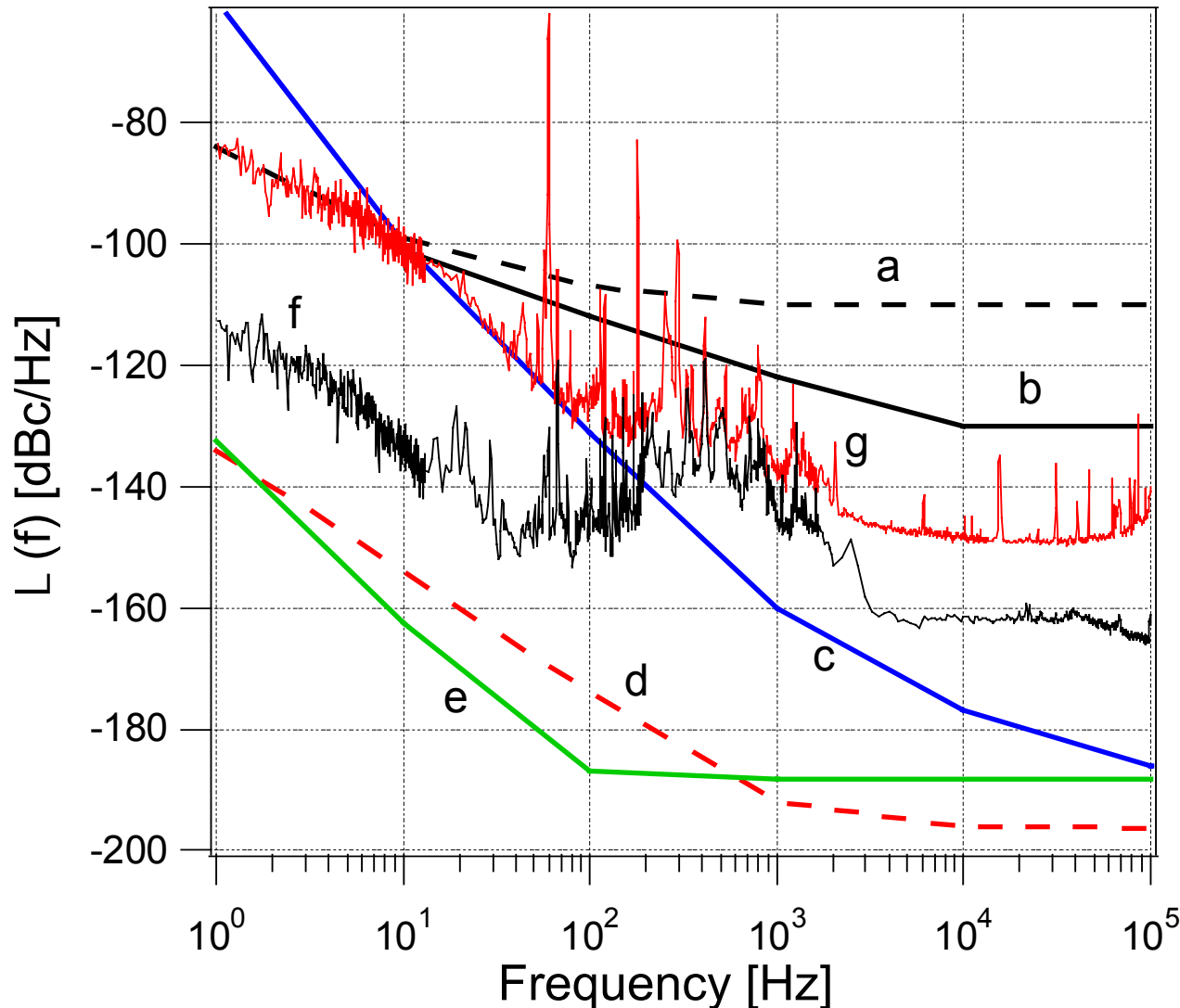


Stability of Microwave and Optical Signals



Comparison of Various Oscillators/Synthesizers

Phase noise for 1 GHz carrier



- a. Premium quartz oscillator
- b. Low noise synthesizer
- c. Sapphire oscillator
- d. Ca optical (projected)
- e. Hg⁺ optical cavity
- f. fs synthesizer: optical pulse train
- g. fs synthesizer: microwave output

Potential Limitations to RF Stability

• **Shot Noise:**
$$\sigma_y^{shot}(\tau) = \frac{1}{2\pi n f_r \tau} \sqrt{\frac{6eiR\Delta f}{P_{rf}}}$$

$$\sigma_y^{shot}(\tau) = 1 \times 10^{-15} \tau^{-1} \text{ for } i = 4 \text{ mA, } P_{rf} = -10 \text{ dBm, } \Delta f = 150 \text{ kHz}$$

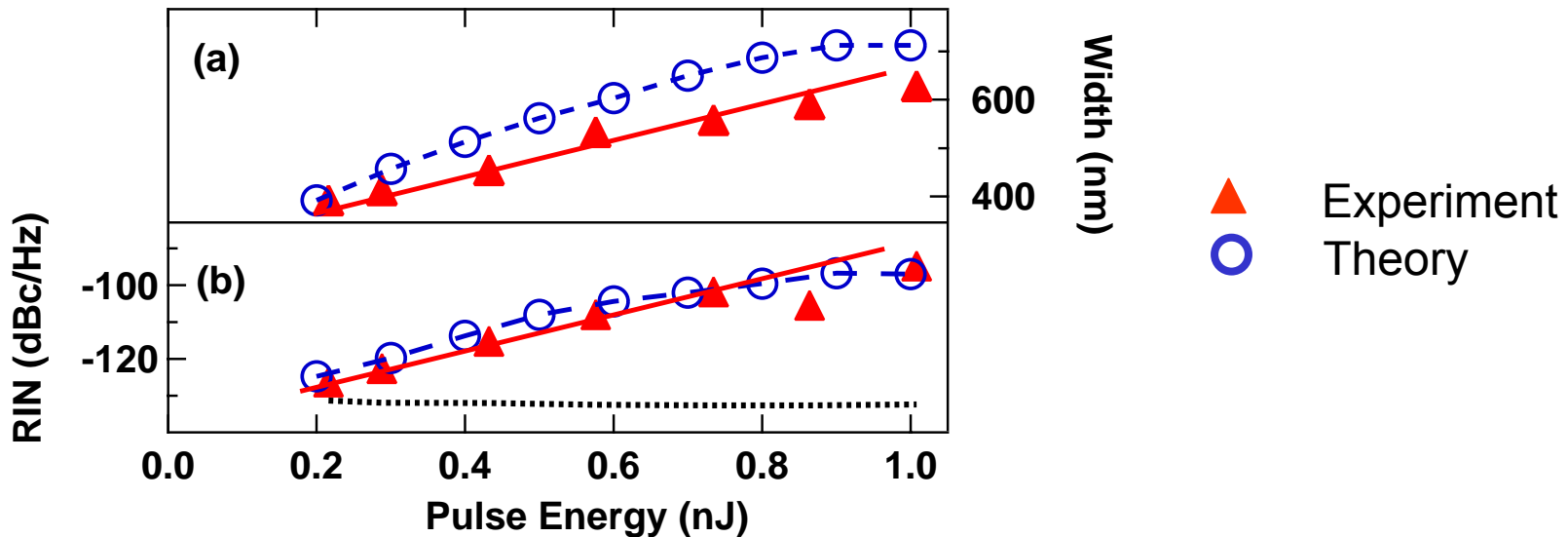
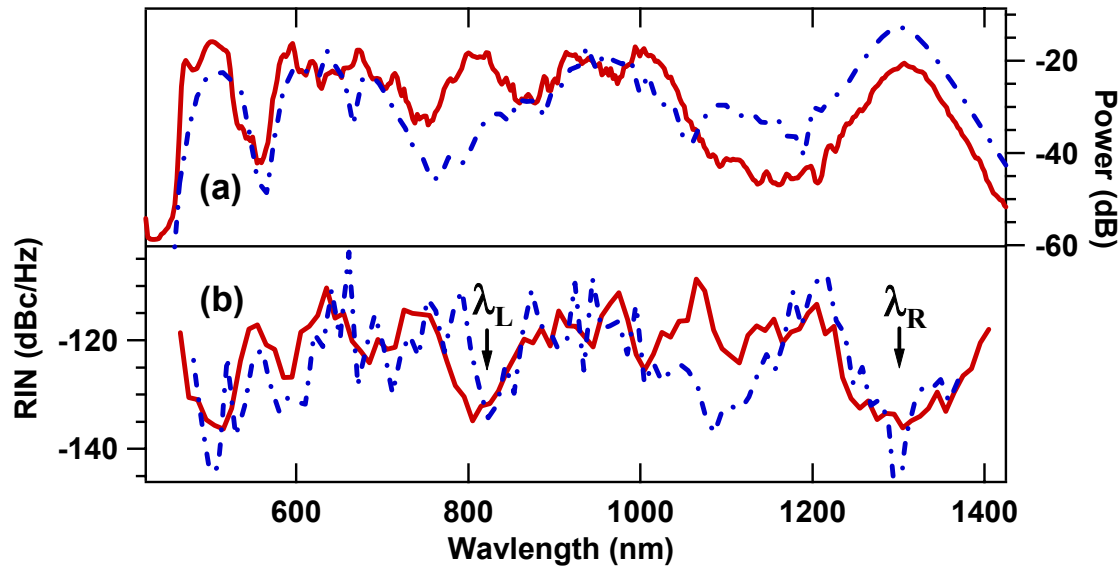
• **Excess Phase Noise in Photodetection**

- AM-PM conversion exists. For example, timing jitter of 1-10 ps/mW in various photodetectors.
- Saturation with high peak power??

• **Excess noise from Laser or Microstructure Fiber**

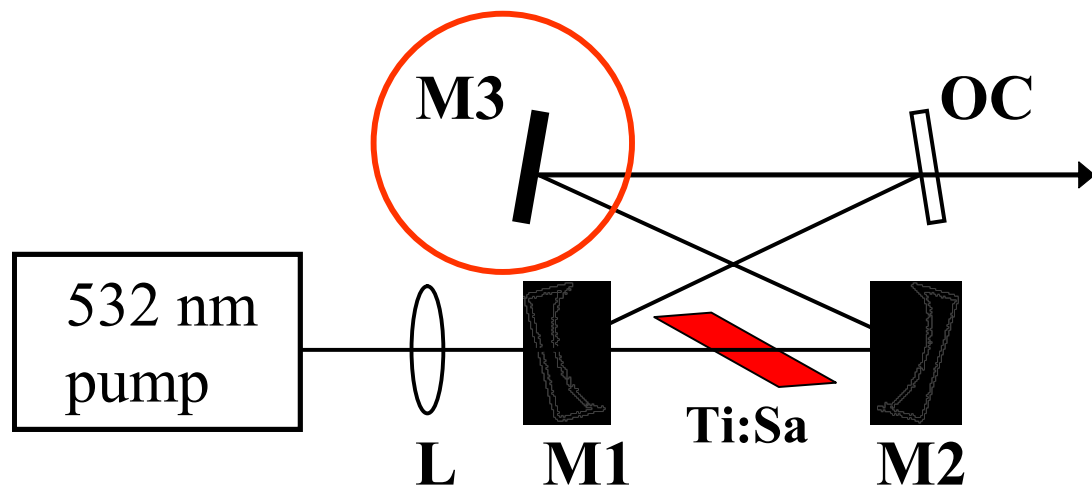
Amplification of Fundamental Noise in Microstructured Fibers

K. Corwin, N. Newbury, J. Dudley, S. Coen, K. Weber, S. Diddams, R. Windeler (to appear in PRL)



A New, Simpler Tool: 1 GHz Ti:sapphire Octave-Spanning Oscillator

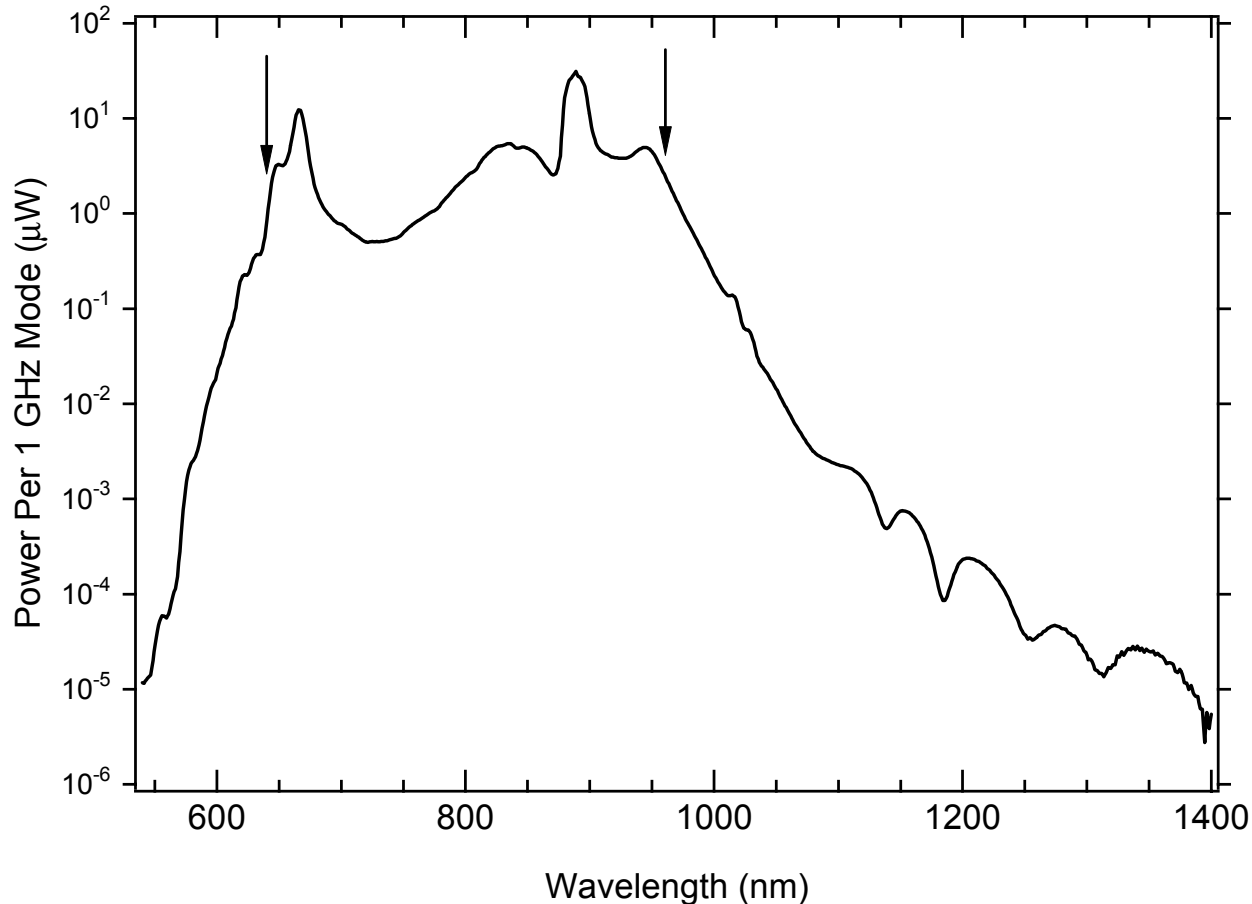
A. Bartels and H. Kurz, Opt. Lett. 27, 1839 (2002)



- High repetition rate—800 mW total power
- Compact, 5-element ring design

KEY ELEMENT: 1000mm ROC convex mirror (M3)
increased self-amplitude modulation → shorter pulses → enhanced self-phase modulation

Output spectrum of laser

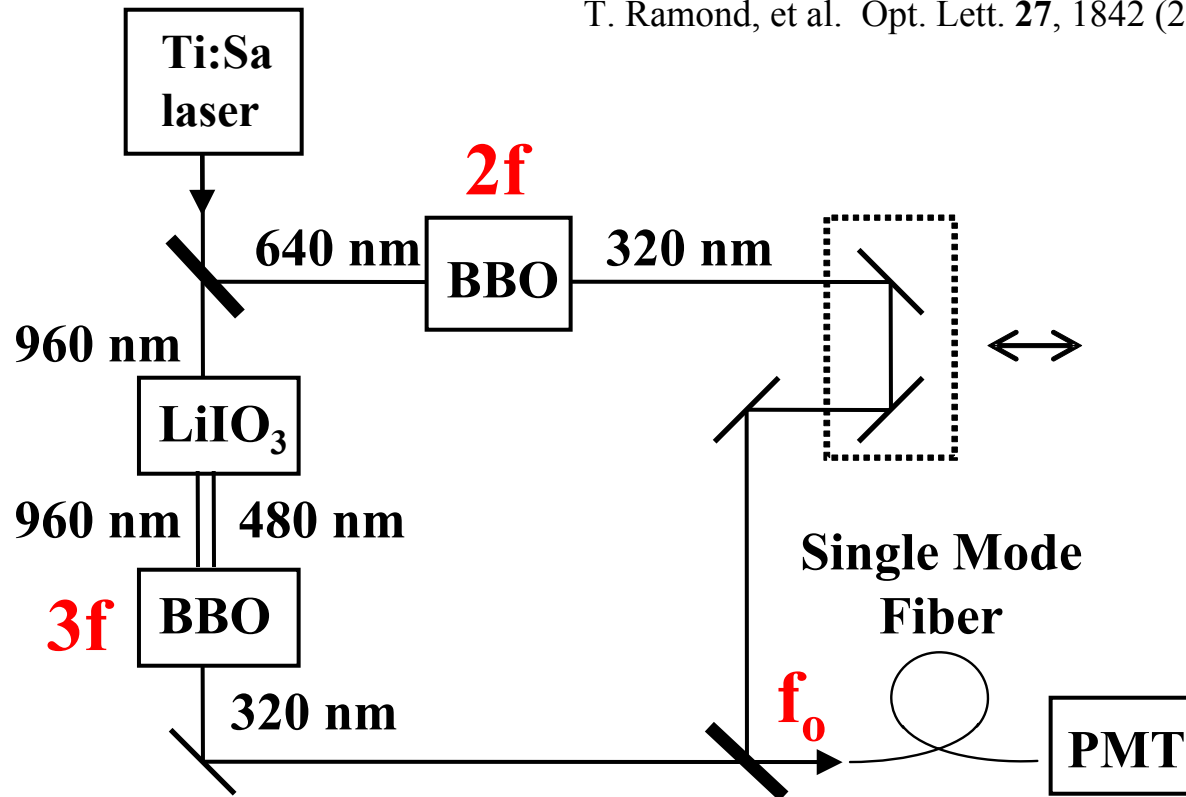


**Frequency triple 960nm and double 640nm to obtain
320nm heterodyne (f_o)**

$$3f_n - 2f_m = 3(nf_r + f_o) - 2(mf_r + f_o) = f_o$$

Detection of f_0 without microstructure fiber

U. Morgner, et al. Phys. Rev. Lett. **86**, 5462 (2001).
T. Ramond, et al. Opt. Lett. **27**, 1842 (2002).

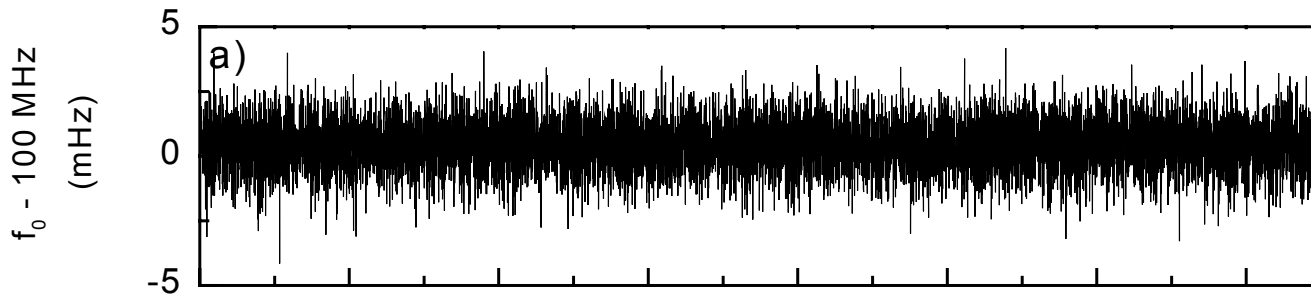


**No critical alignment of nonlinear elements
Can be phase-locked nearly indefinitely....**

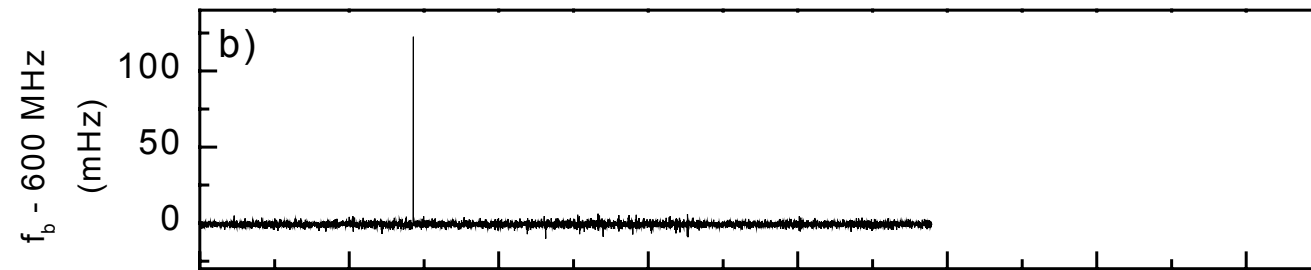
Long-term Phase Locking of Broadband Laser

Control of femtosecond laser: $< 6 \times 10^{-18}$ @ 10 s

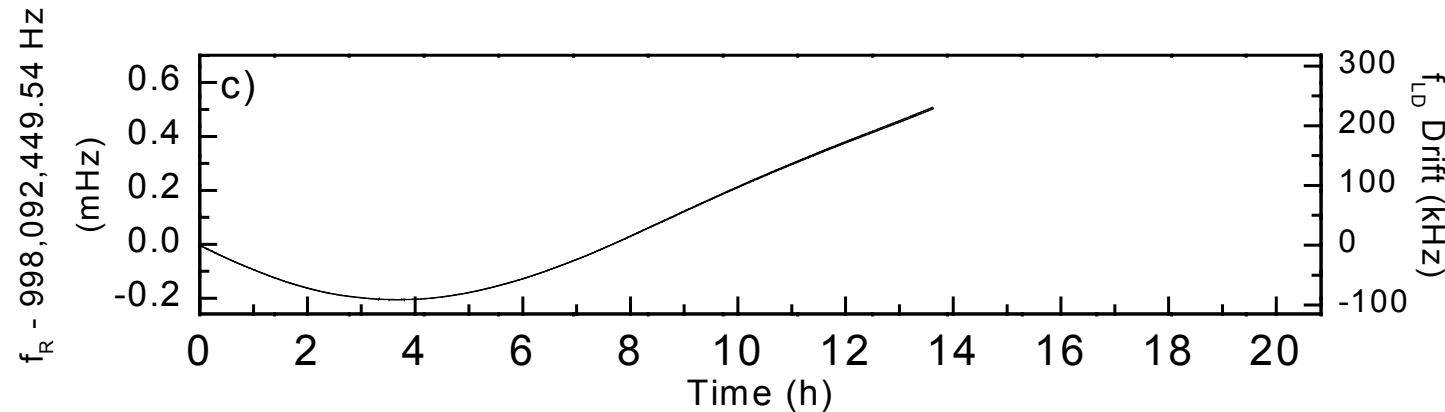
i can count $> 10^{19}$ optical cycles without missing a single one!



Offset Frequency



Beat with Stabilized
Laser Diode



Repetition
Rate

Summary + Outlook

- Femtosecond lasers combined with cold atom standards will be the basis of future atomic clocks
(stability $\sim 1\mu 10^{-16}$ @1s, accuracy $< 1\mu 10^{-17}$)
- Emerging applications and uses:
 - secure communications
 - ultra low noise microwaves (RADAR)
 - length metrology
 - time/frequency transfer over fiber networks
 - remote sensing
 - extreme nonlinear optics
- Smaller, more compact, more robust
 - novel solid state femtosecond lasers
 - broader spectra, different wavelength regimes