Optical Atomic Clocks

Defining and *measuring (Optical) Frequencies*
then, now and next

John L. Hall → **Jun Ye**

JILA, National Institute of Standards and Technology and
Department of Physics, University of Colorado at Boulder

http://Jilawww.Colorado.edu

http://HallStableLasers.com

NI$T
N$F
NA$A
ONR

NIST-CU

Hall_Labs 2000

Today's Symposium: - Fundamental Physics – looking inside

Kaon Lifetimes Dark Matter	Local Lorentz Invariance? Dark Energy?	Are the Numbers of Physics time-dependent?

How to make progress?

a. Visit the Tools store (specializing in laser and electro-optics for all your needs)
b. Be sure you can get more resolution with whatever tools you buy! $\sim N^{3/2}$

New Comb Tools

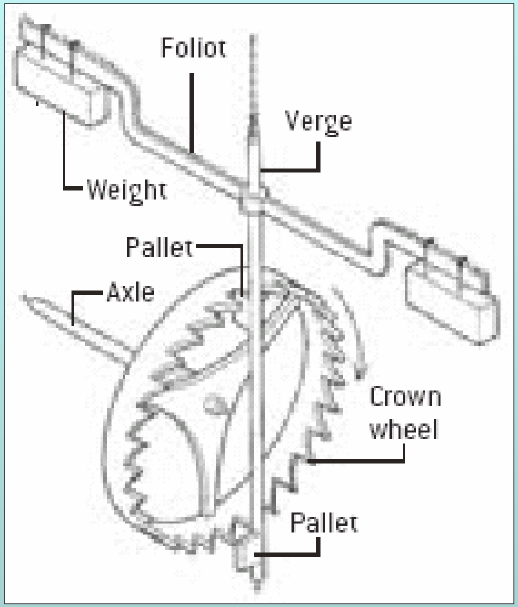
for Speedy & Accurate Frequency/Phase Measurement

A Great Highway!

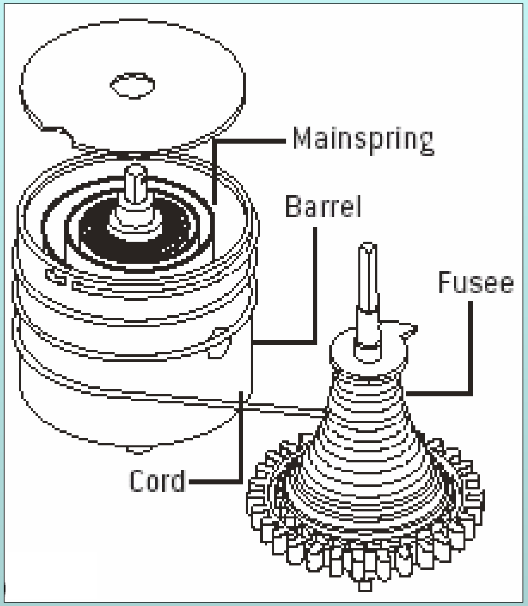
With 15^{+} digits, you *might* find something interesting …

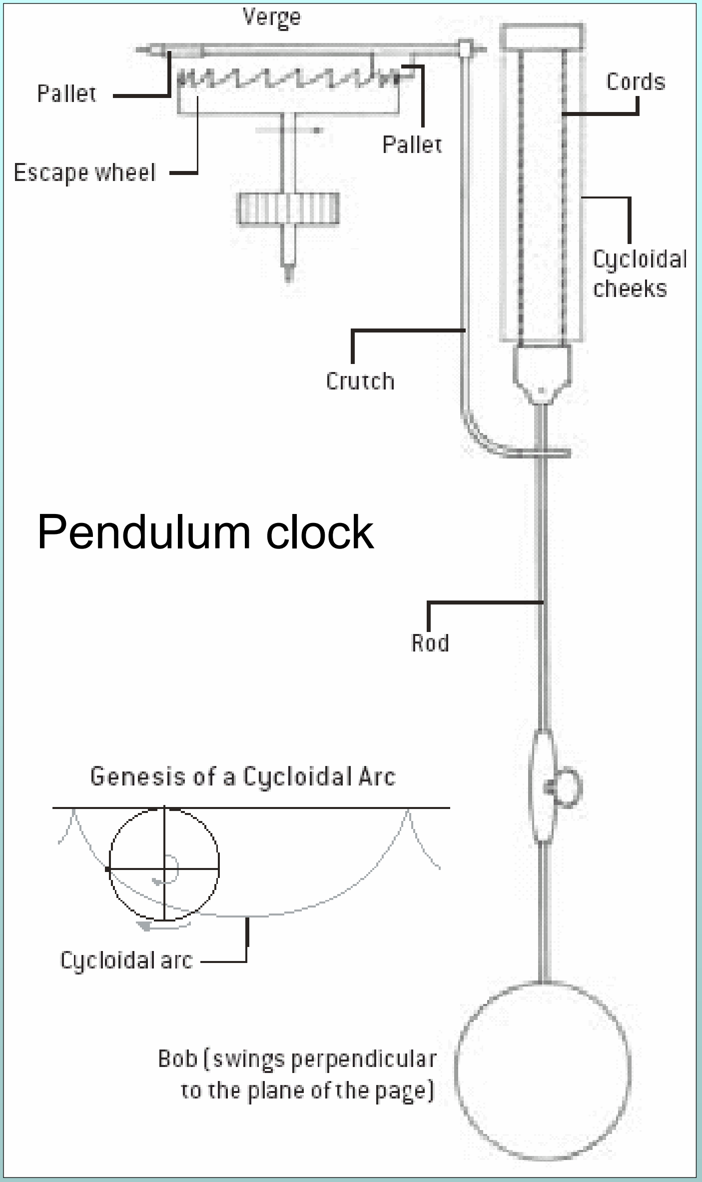
Mechanical clockworks

Verge and Foliot escapement



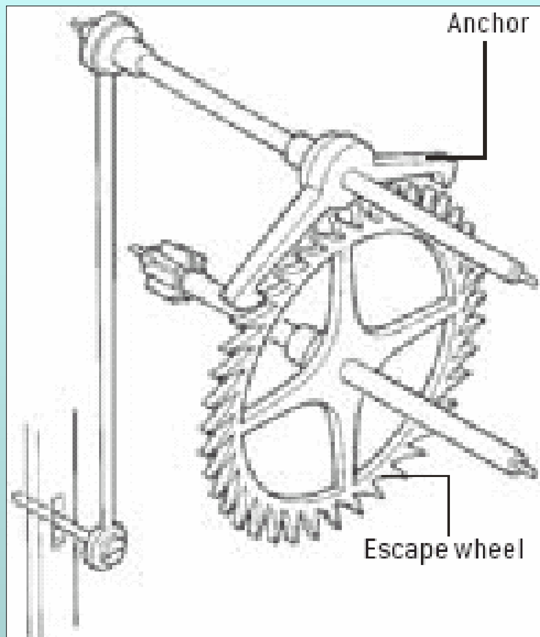
Fusee





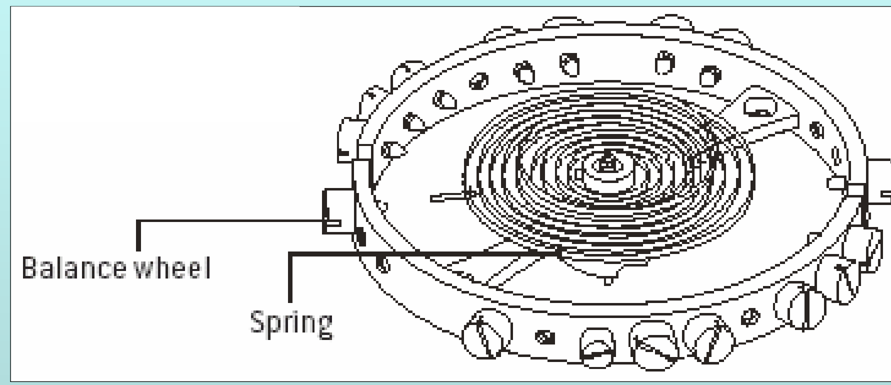
Mechanical clockworks

Anchor escapement



~1670, in England

Spiral balance spring



1675, Huygens, Netherlands

1772, John Harrison, clock H-5
1 s per 3 days (~4 x 10^{-6})

Sundial, 1st or 2nd century A.D.

Water clock & Sandglass.

Mechanical clock, 1657.

Watch, 2002.

Quartz clock

Atomic hydrogen maser clock, early 1960s.

Atomic micro clock

Grandfather clock

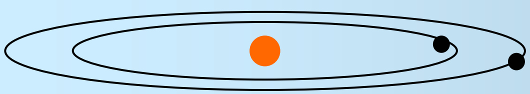
Atomic Time from NIST, by radio

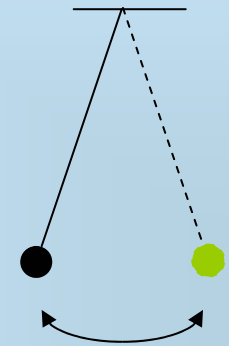
WWVB
60 kHz
Ft. Collins
Colorado

"Sweet Spot"
Better than needed
Just-right Tech
Cost Effective

What is a clock?

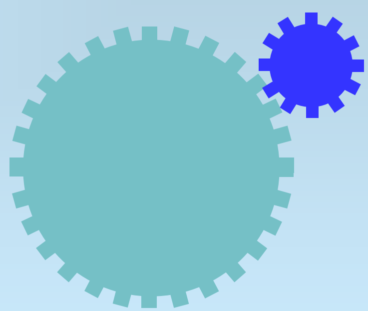
Stable Oscillator

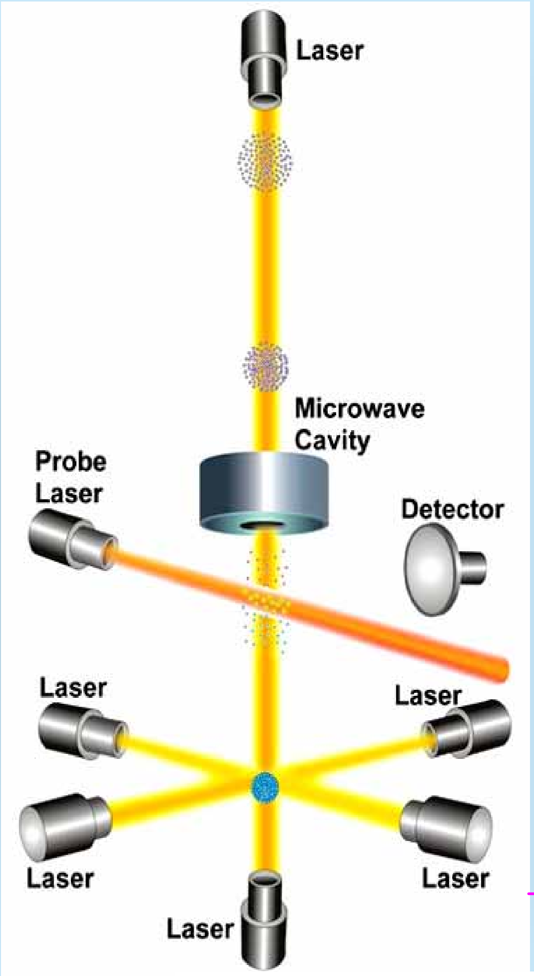




Counter

Caveman's
Marks on the
cave walls

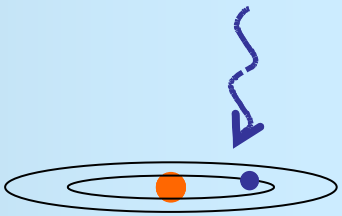


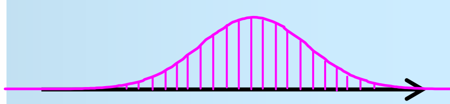


NIST-F1
BNM - SYRTE

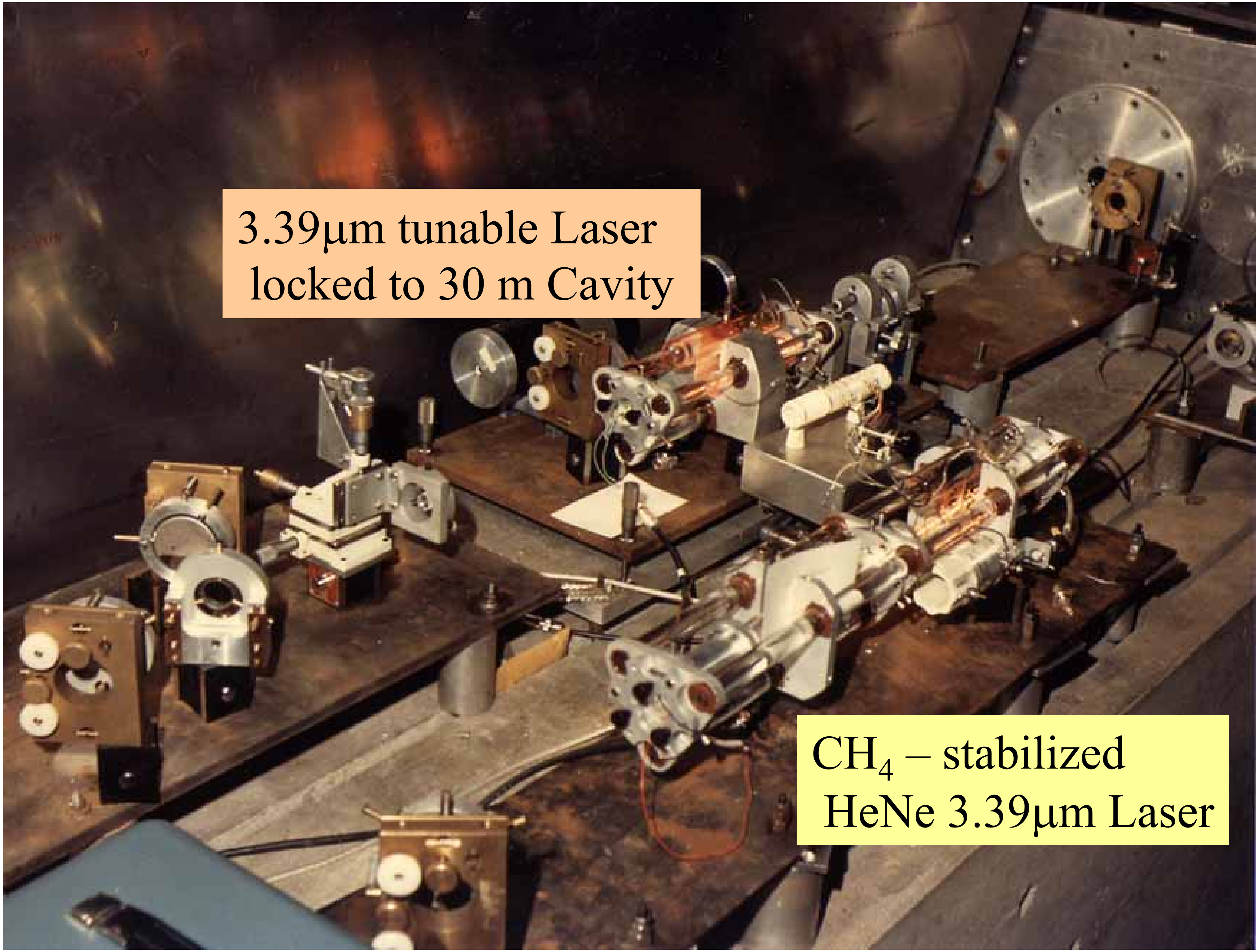
Counter

laser

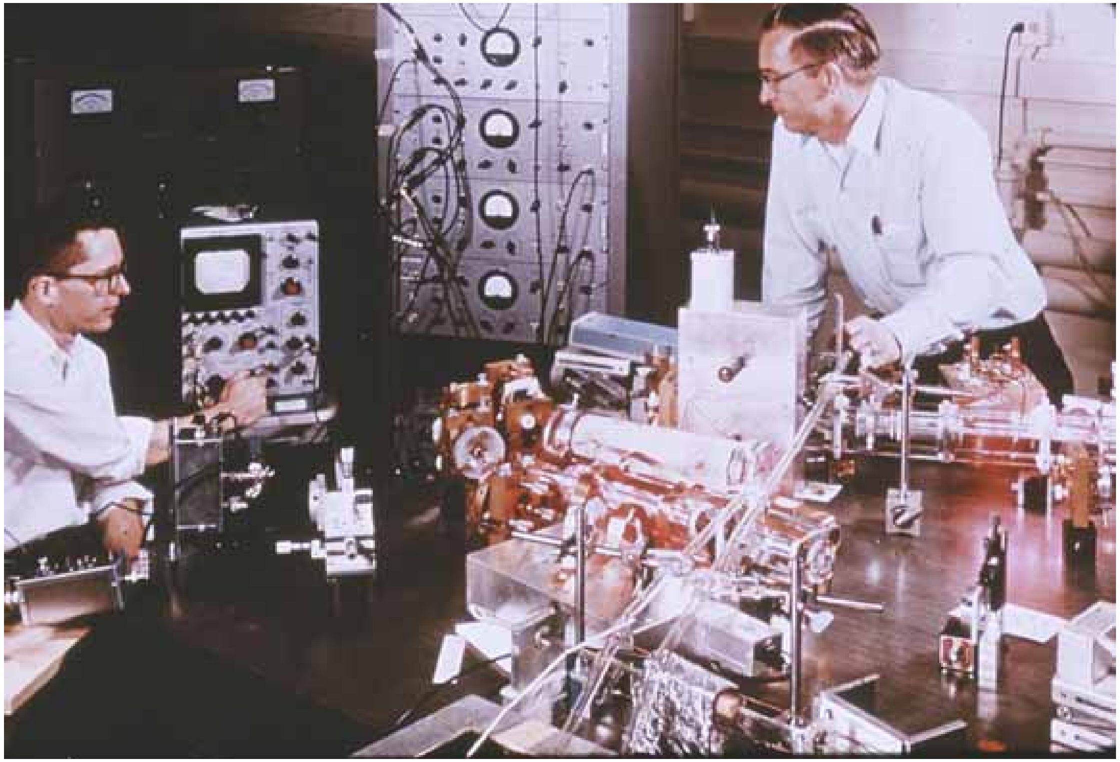




fs comb


3.39μm tunable Laser locked to 30 m Cavity
CH_4 – stabilized HeNe 3.39μm Laser

Saturated Absorption in Methane Gas

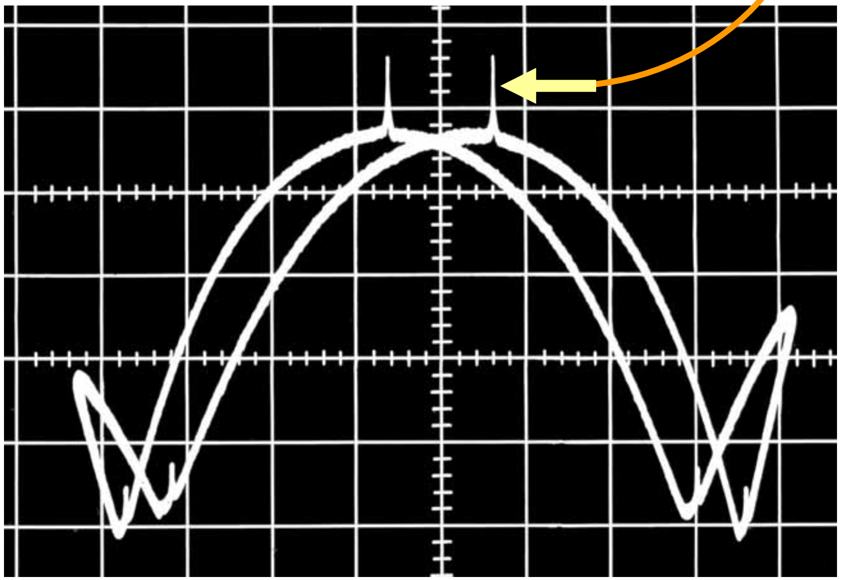


Line “Q” ~10^9

Reproducibility ~10^{-11}

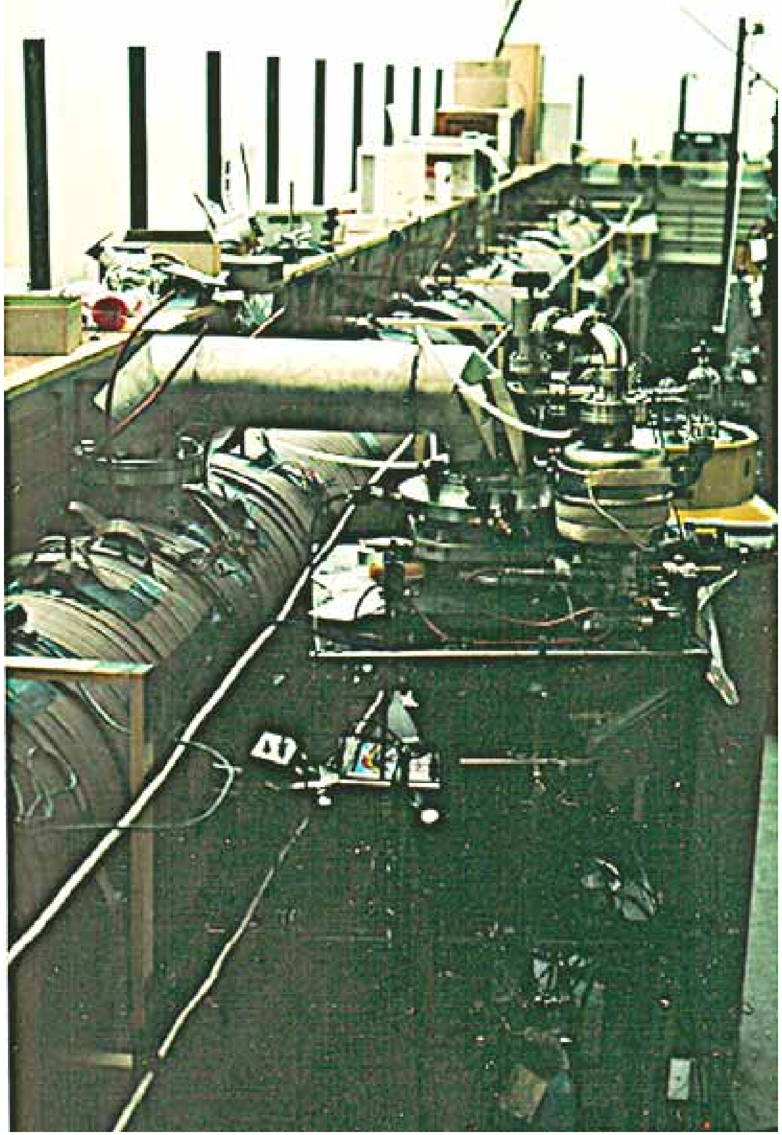
Instability < 10^{-13}

prl 1969



“Working with the Methane-stabilized HeNe Laser at 3392 nm (3.39 μm)”

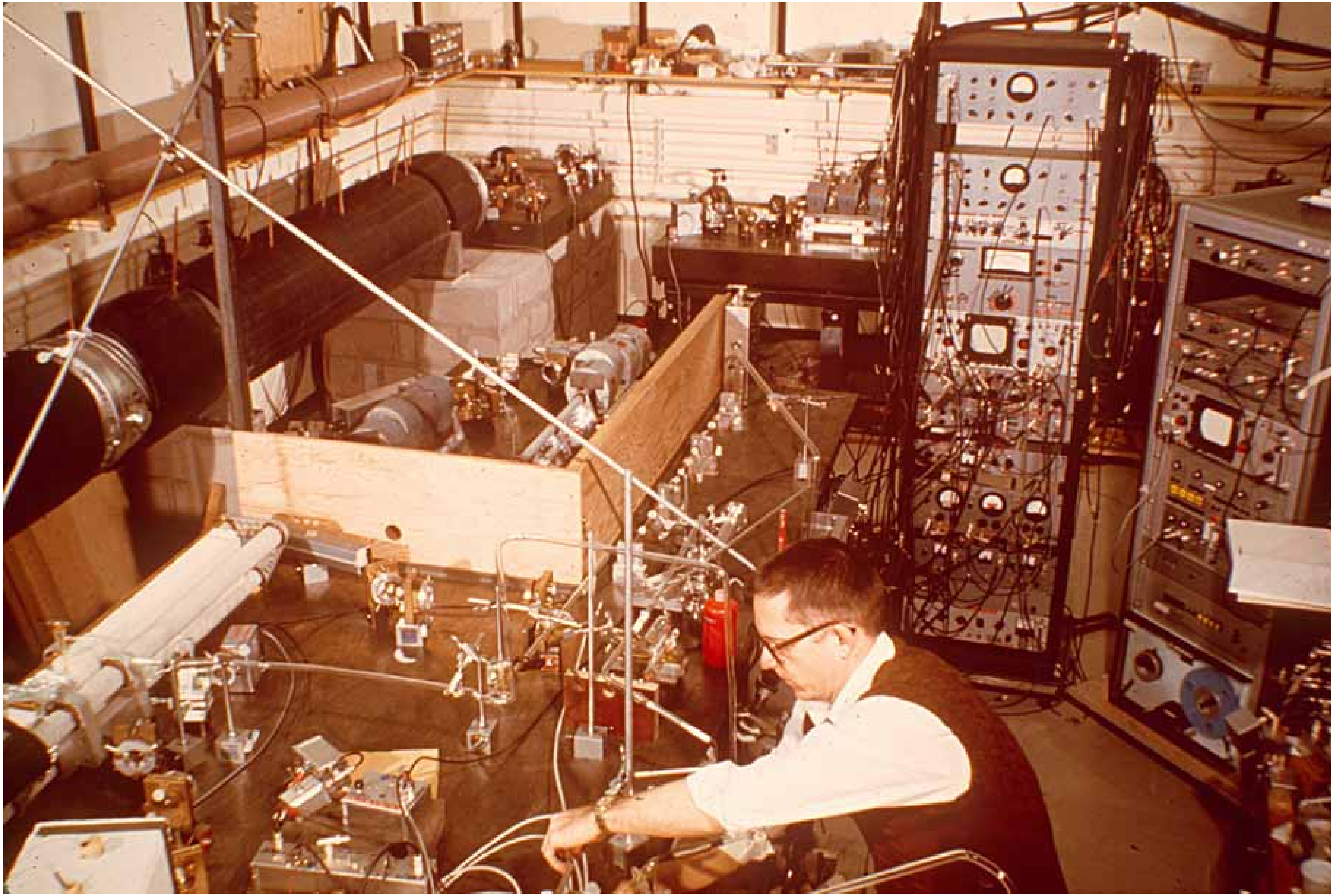
Jan Hall and Dick Barger ~ 1972



$$\tau_{tr} = w_0 / v$$

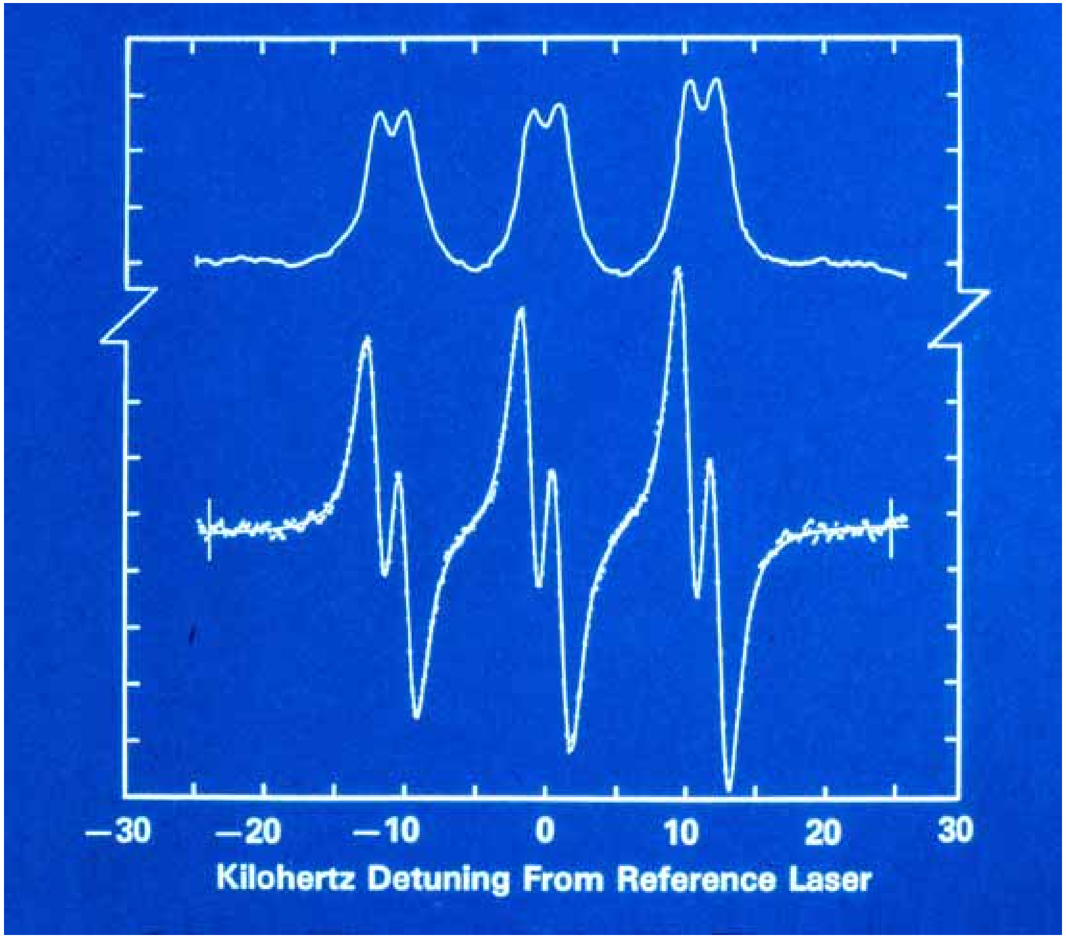
$$\Delta\nu \cong 88 \text{ kHz} \cdot \text{mm} / w_0$$

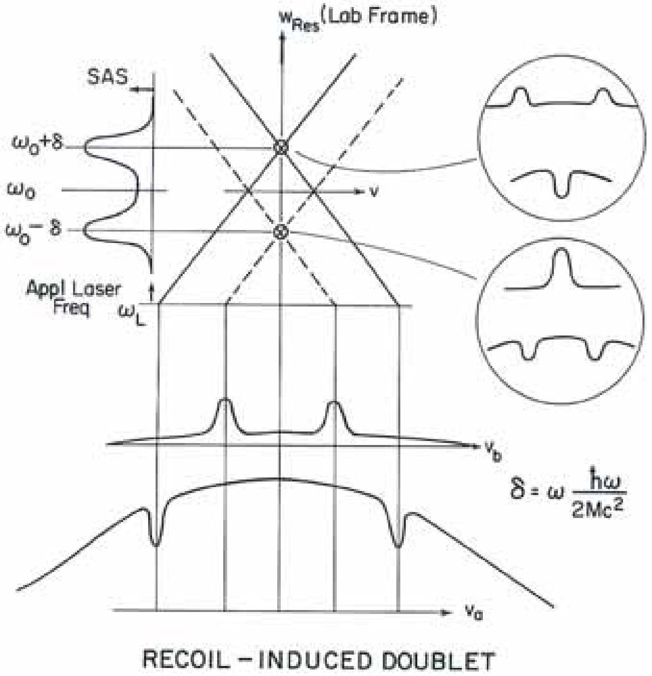
Transit-time Increase, with Big Beams



Pushing up the Resolution ~ 1973

1 kHz HWHM ~ 10^{-5} *Doppler Width

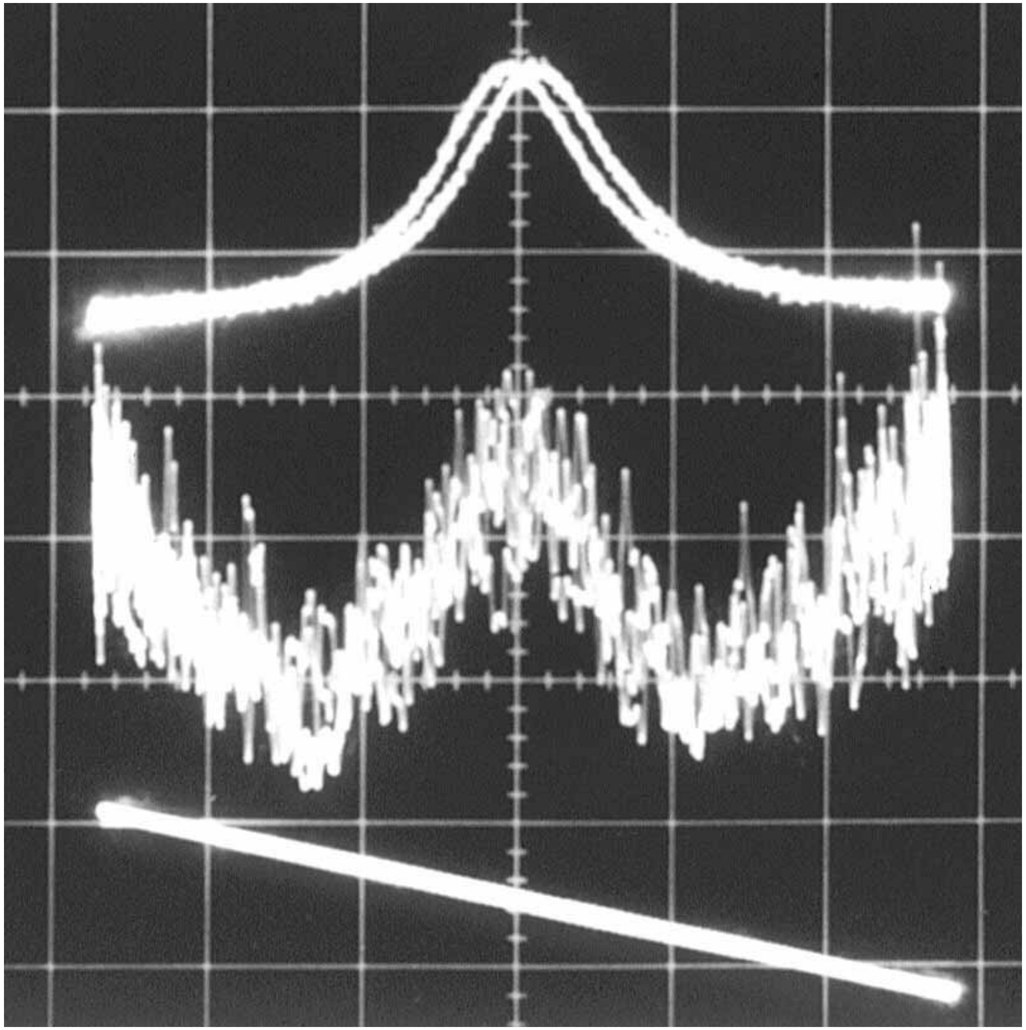




Hall, Bordé, Uehara
prl **37** 1339 (1976)

Recoil-induced splitting of hfs Lines (CH_4)

A New Wavelength Standard? !!!



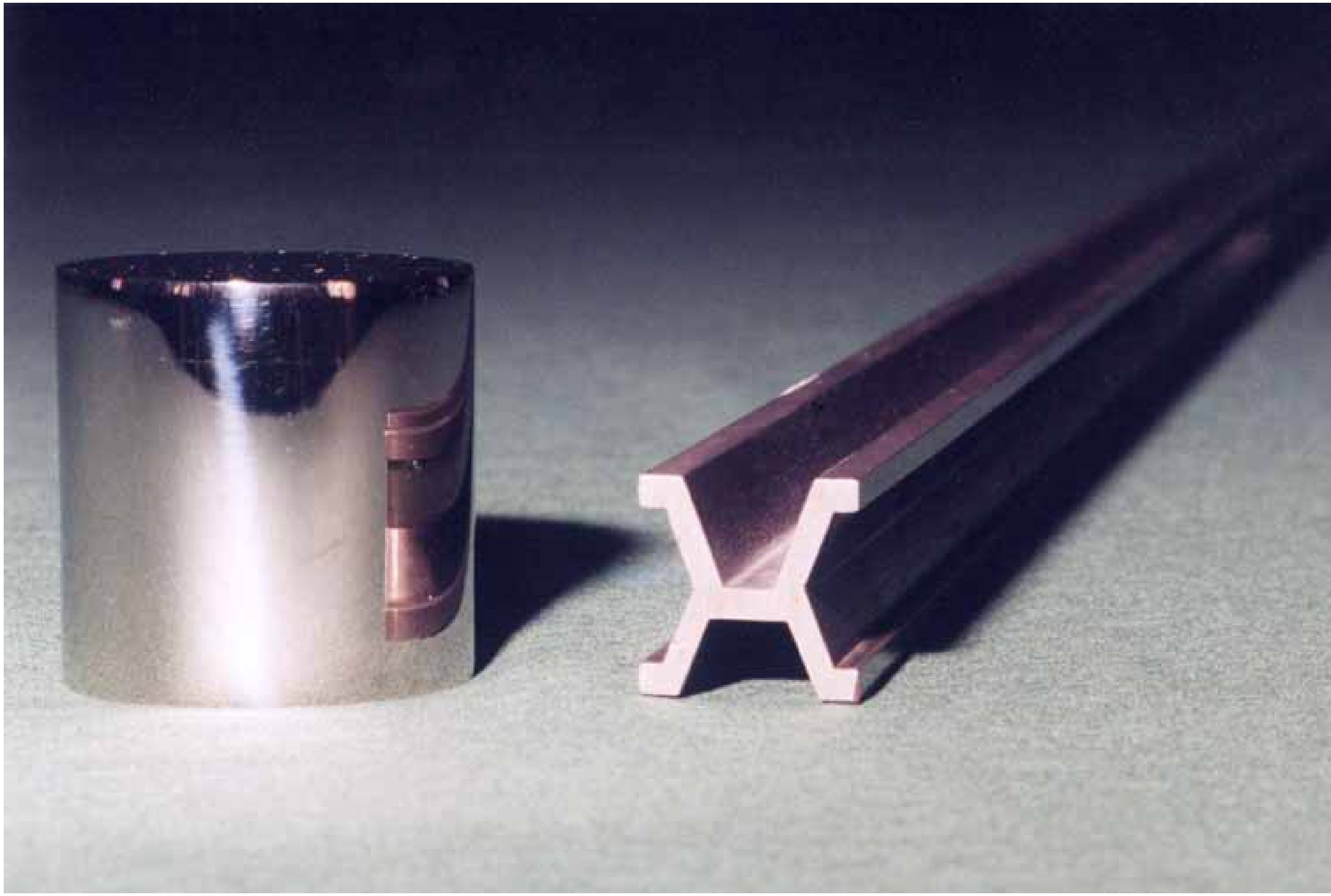
HeNe fringes
At 3.39 μm

Krypton fringes
At 605.7 nm   (1960)

4 x10^{-9} in 300 s !

Frequency Scan

R. L. Barger and JLH
'71 ; APL **22**, 196 (1973)



BIPM's Kg and Metre ProtoTypes

Metre bar replaced in 1960 by light-wave definition – Krypton 605.7 nm line (Isotope 86)

First optical fringe measurement by A. A. Michelson 1887 → Nobel Prize 1907

Metrology, the Mother of Science

Today's Symposium features **Length** and **Time/Frequency**

Ell, Braunschweig		~1600
Metre Bar, Paris		~1875
Cadmium Lamp A.A.Michelson		1887
Nobel Prize A.A.M.	$\pm 4 \times 10^{-7}$	1907
Krypton Lamp	$\pm 4 \times 10^{-9}$	1960 ←
Methane-Stab. Laser	$\pm 1 \times 10^{-11}$	1972
c adopted constant	0	1983 →

Length – Depends on:
Inter-atomic distances,
E & M/ Quantum Mechanics

Day		
Mean Solar Day		1875
Tropical Astronomical Year		1960
Cesium Second		1967
Cs Fountain Clock	$\pm 1 \times 10^{-15}$	~2000
Hg+ -stabilized Laser	±1 x10-15	2004

Frequency – Depends on:

Internal electronic energy differences
E & M/ Quantum Mechanics
Fine-Structure Constant

Measuring Optical Frequencies

Frequency Starting Point: 9, 192, 631, 770 cycles per second

Target Frequency of Mercury Ion: 1 064 721 609 899 143 cps

Frequency Ratio Needed: 115 823.372 081 …

A ratio of 115 Thousand !

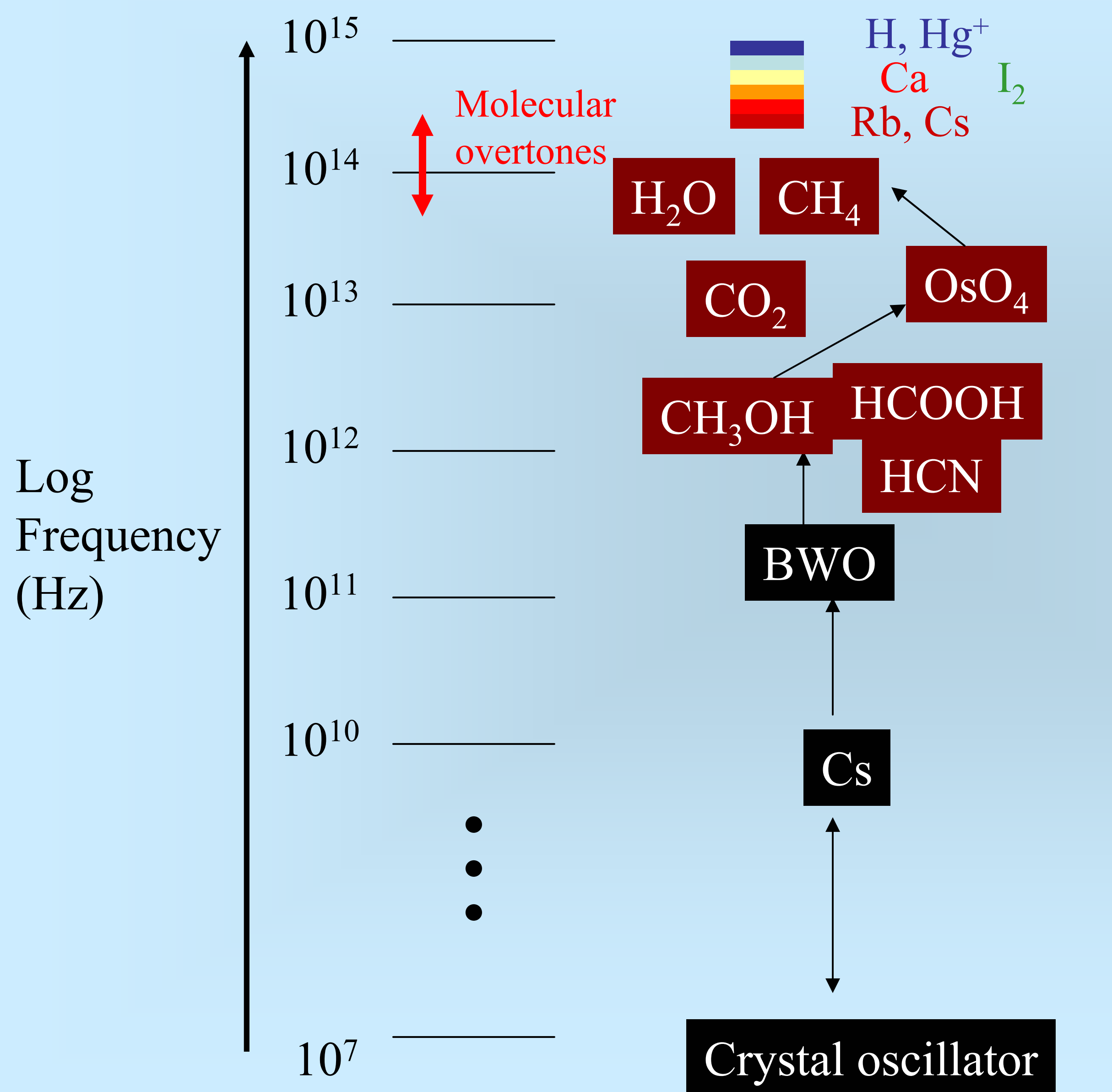
How can we **ever** do this?

Here's the first Government PLAN

x7   x2 x2 x2 x2 x2 x2 x2 x2 x2 x2 x2 x2 x2 x2

1 electronic + 14 Laser stages

Frequency spectrum in optical frequency synthesis



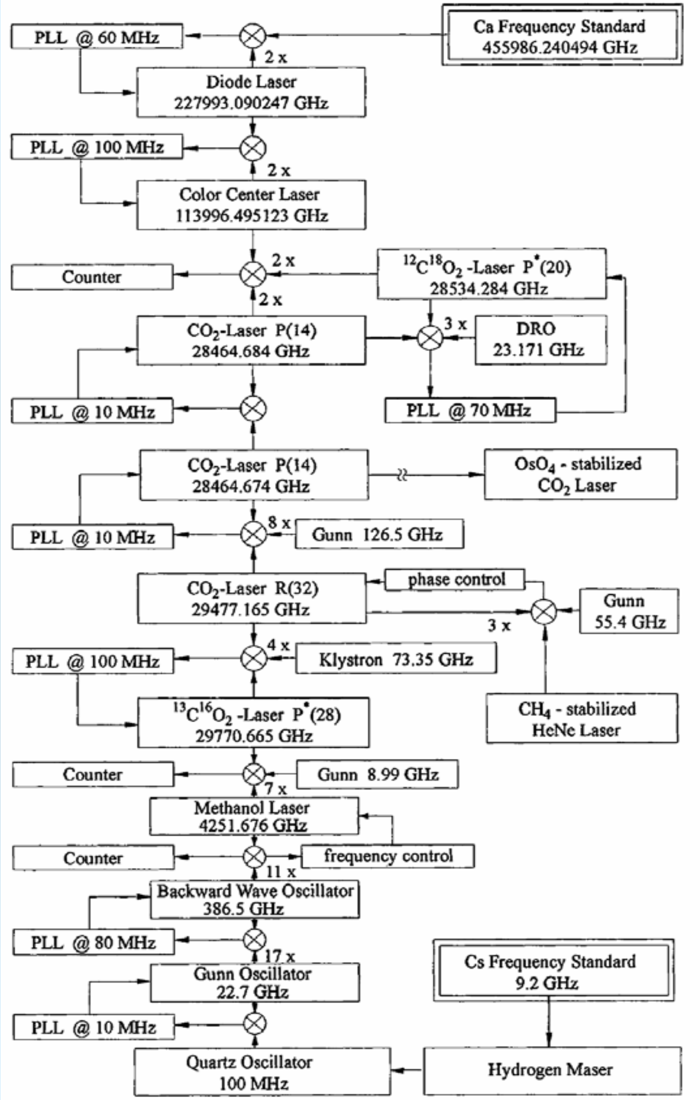
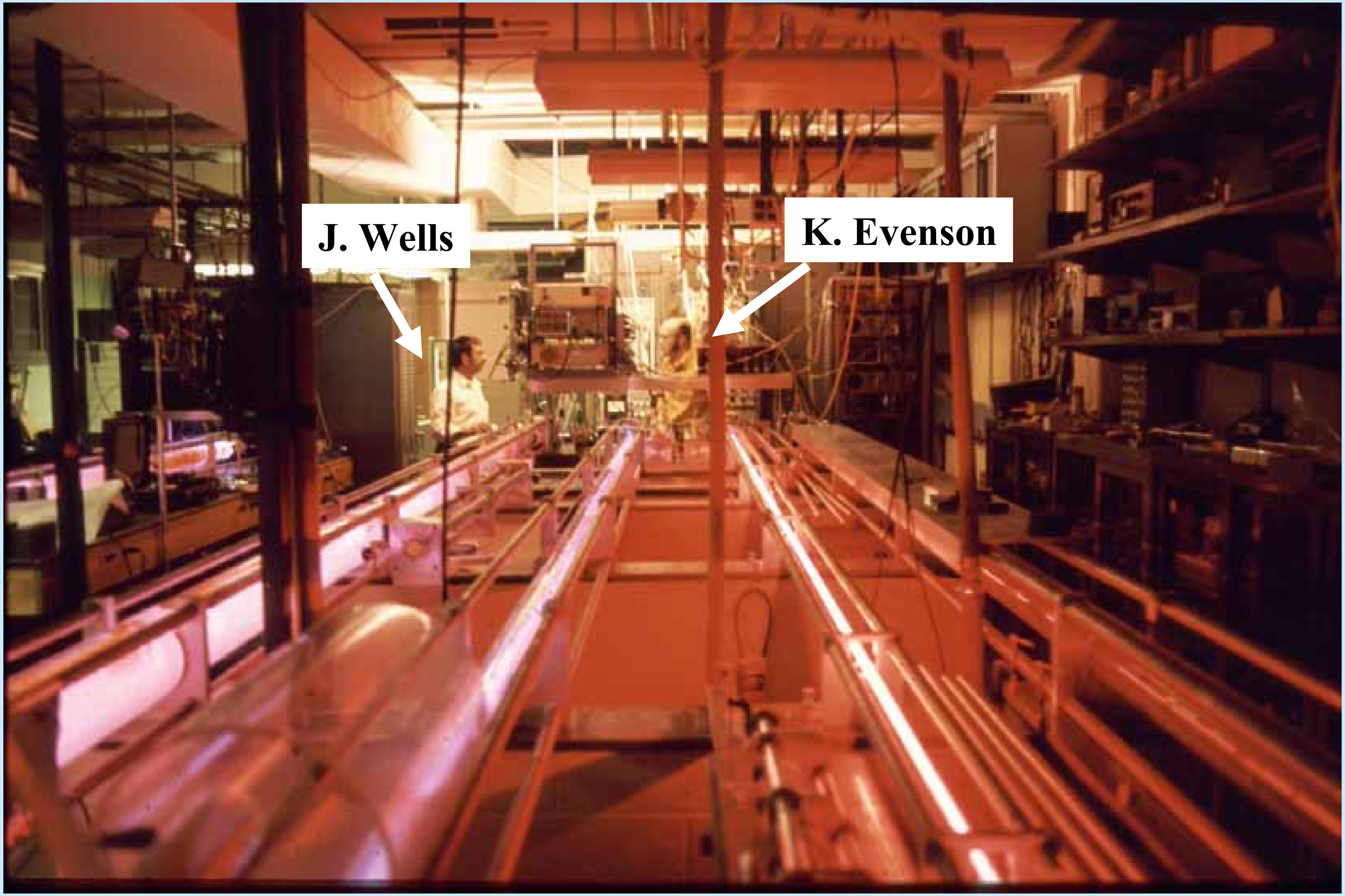


FIG. 1. PTB's frequency chain to the Ca intercombination line (PLL = phase locked loop, details are given in the text).

The First NBS Optical Frequency Chain

NBS (NIST): measurement of speed of light, 1972



J. L. Hall & J. Ye, "NIST 100th birthday", Optics & Photonics News 12, 44, Feb. 2001

The NBS Speed of Light Program: $c = \nu \lambda$

ν =88 376 181 627. kHz
± 50.

Evenson's ν Team

K.M.E., J.S. Wells, F.R. Petersen
B.L.Danielson, & G.W. Day
And D. A. Jennings

λ =3 392.231 390 nm
± .000 01

JILA λ Team

R. L.Barger & J. L. Hall

c = 299, 792, 457.4 m/s **Our Finest Product !**

PRL **29** 1346 (1972)

Richard L. Barger | Kenneth M Evenson | John L. Hall | Bruce L. Danielson | F. Russell Petersen | Gordon W. Day | Joseph S. Wells

1974 Department of Commerce Gold Medal Team

"for the *last* measurement of the speed of light"

"The Metre is the length of the path travelled by light (in vacuum) in 1/299 792 458 of a second"

ie., c = 299 792 458 m/s, exactly

CGPM 1983

1983 Metre Re-Definition & Demotion

Meanwhile, on Hwy 50, W of Port Allen, Kauai
(Hawaii)

Molecular Frequency Standards ~1997

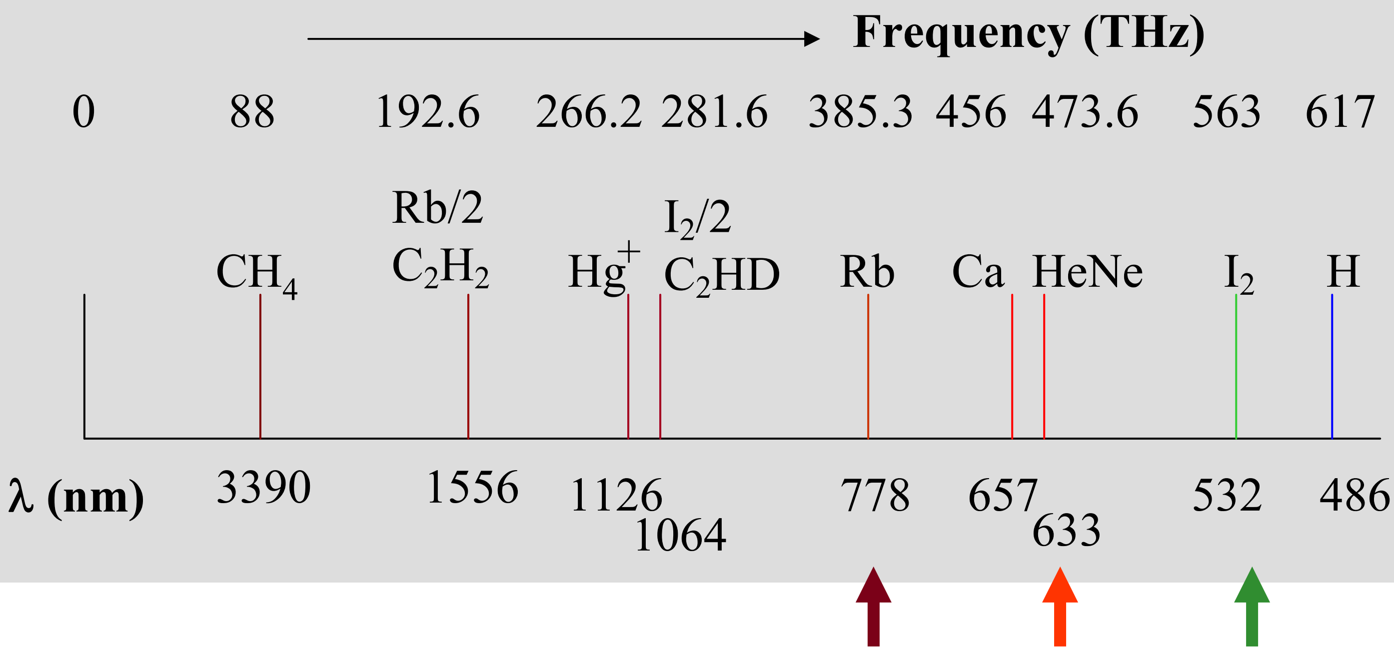
- HeNe Laser w CH_4 Absorber — 3.39 μm
- HeNe vis Laser w I_2 Absorber — ~5 vis λ's
- CO_2 Laser w CO_2 Absorber — 10.6 μm
- CO_2 Laser w OsO_4 Absorber — 10.6 μm
- Ar^+ Laser w I_2 Absorber — 514 nm
- Nd:YAG Laser w I_2 Absorber — 1064 nm
- Nd:YAG Laser w C_2HD Abs. — 1064 nm
- Yb:YAG Laser w C_2H_2 Abs. — 1030 nm
- Diode Lasers w C_2H_2 Abs. — 1550 nm

Venya Chebotayev &
Ken Evenson

"How *are* we going
to measure those
optical frequencies?"

Lindy, Vera, Ken, & Venya

Celebrating the new Hall_Labs,
April 1988



$$f_{(\lambda=778\ nm)} + f_{(\lambda=532\ nm)} = 2 \times f_{(\lambda=632\ nm)}$$

$$f_{(\lambda=632\ nm)} = f_{(\lambda=633\ nm)} + \underline{660\ GHz}$$

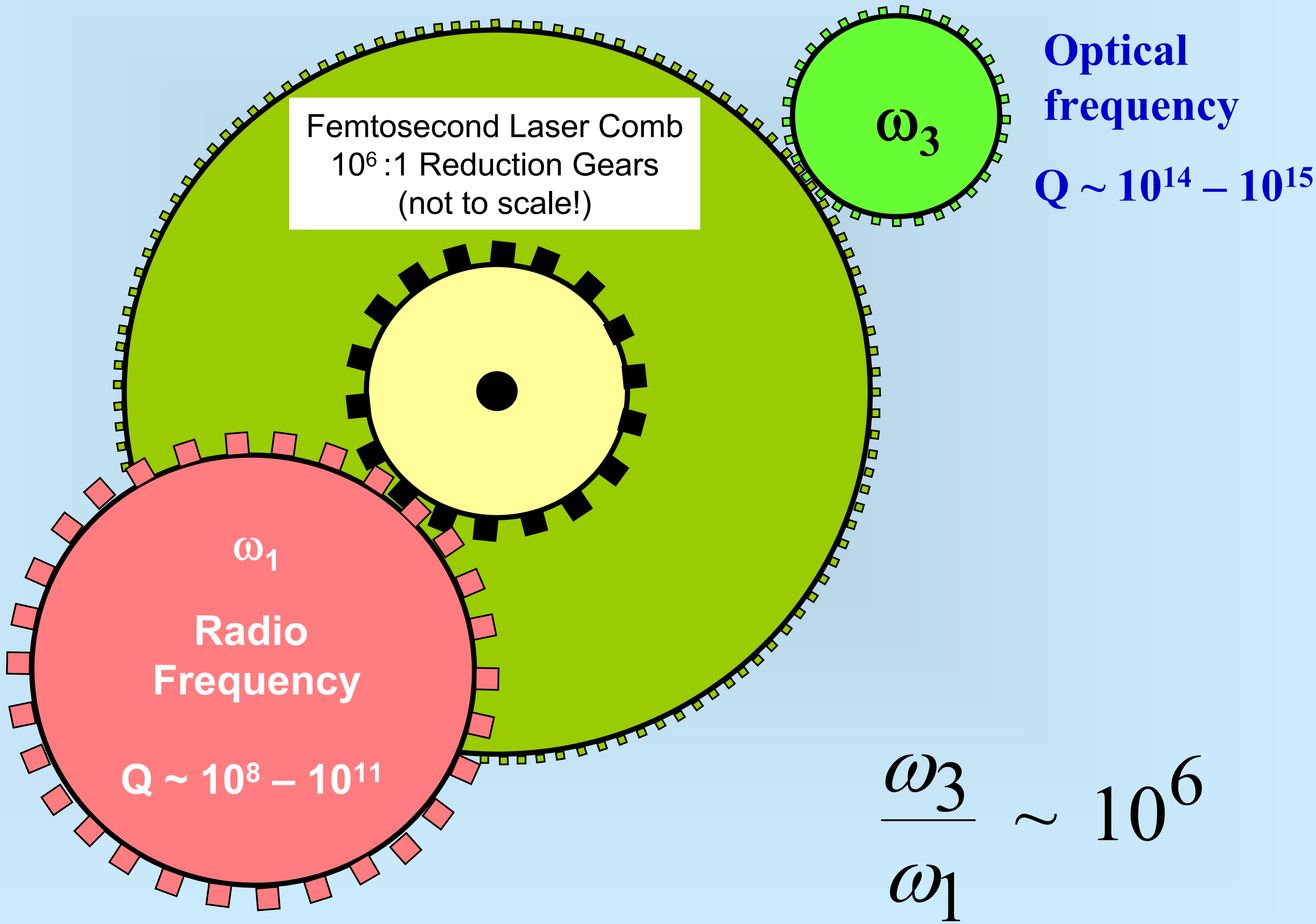
Kourogi's 1994 Comb!

= 66 x 10 GHz (μ-wave/optical comb)

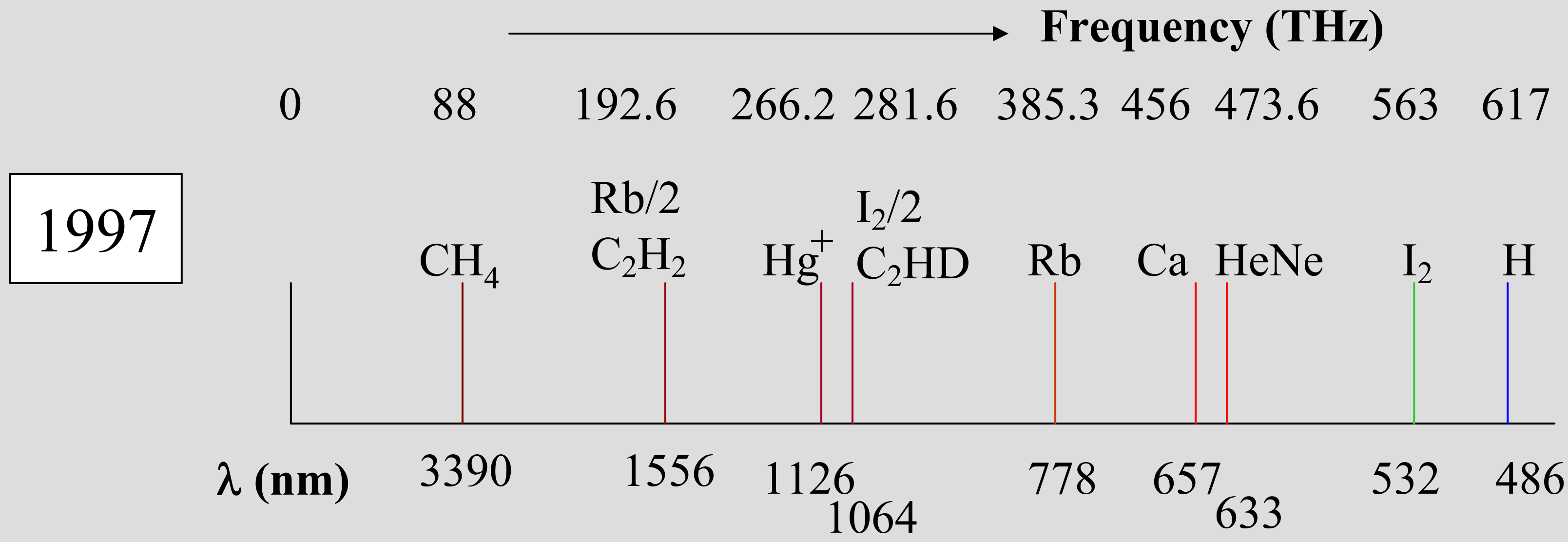
The JILA $f_{(\lambda=532\ nm)}$ frequency measurement scheme

IEEE Trans. Instrum & Meas. **48** 583 (1999)

Phase coherent distribution

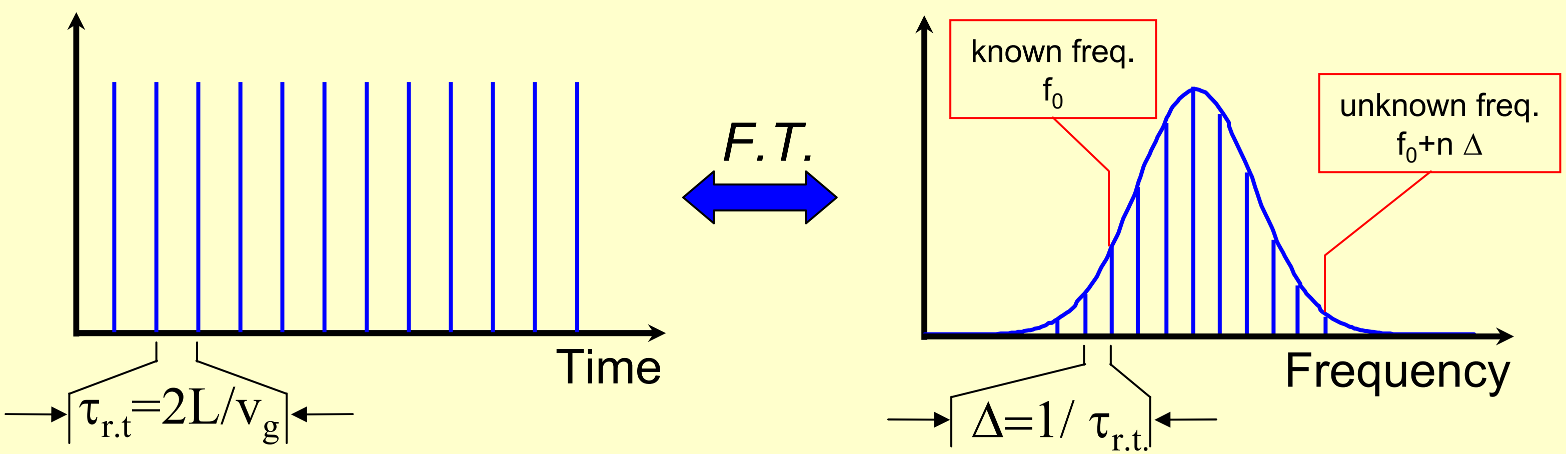


$$\frac{\omega_3}{\omega_1} \sim 10^6$$

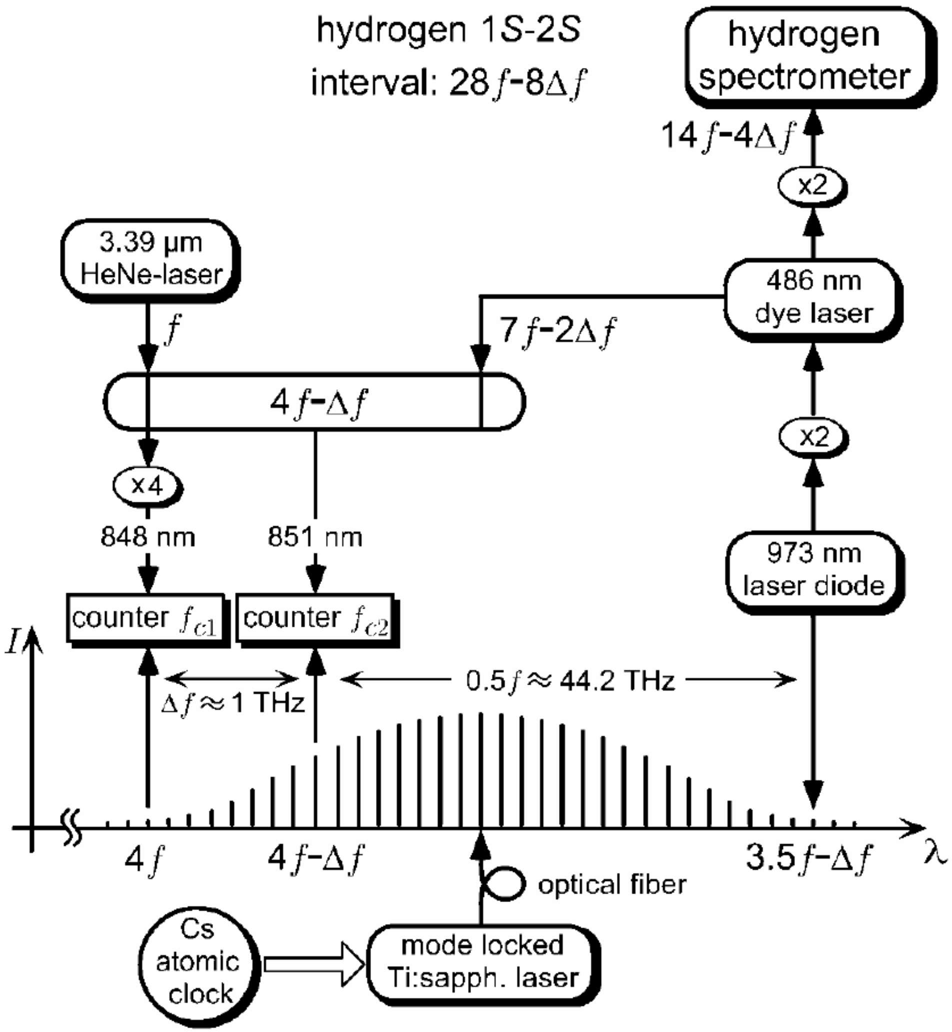


Measuring Spectral δ-functions with Temporal δ-functions?!

- Periodicity in Time = Periodicity in Frequency



T. Hänsch (1978), V. P. Chebotayev (1977); Th. Udem,et al. PRL **82**, 3568 (1999).



The First Comb RF-Optical Link

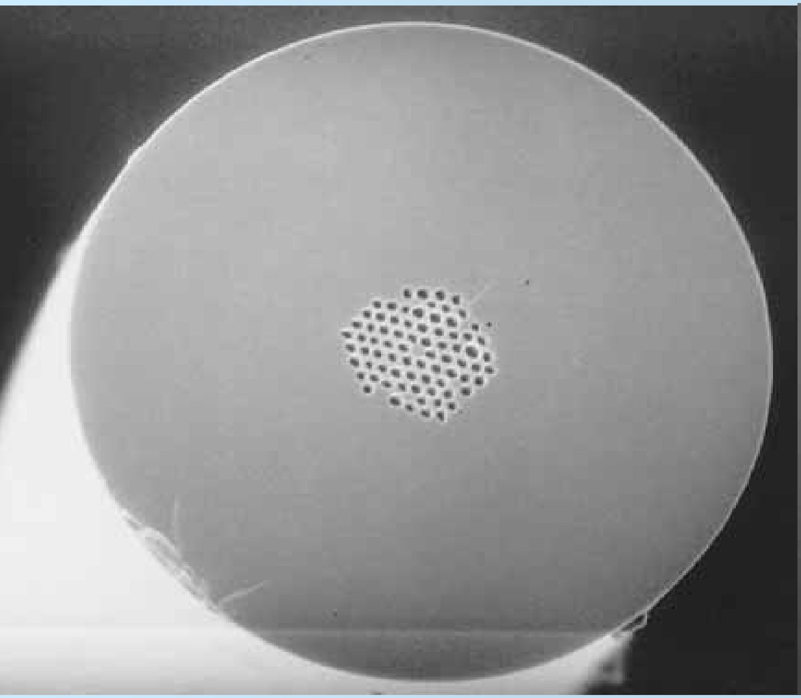
$4f - 3.5\,f = n\,f_{rep}$

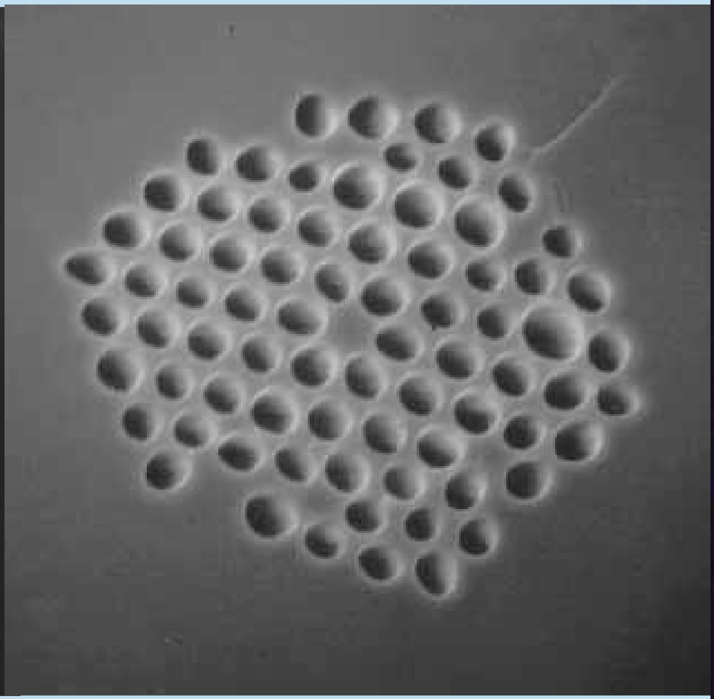
So: $f = 2\,n\,f_{rep}$

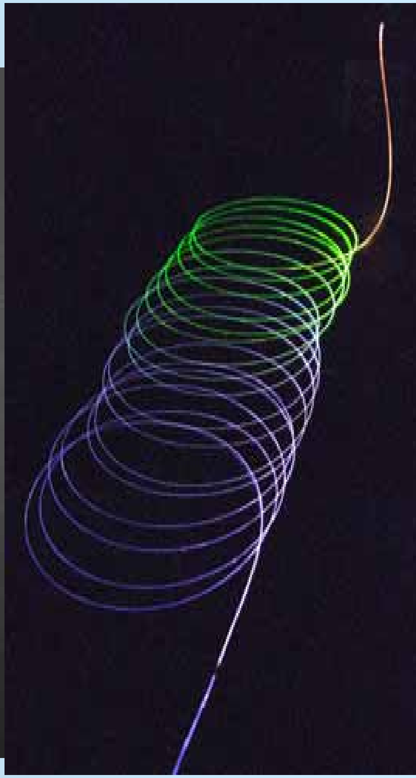
"Phase Coherent Vacuum-Ultraviolet to Radio Frequency Comparison with a Mode-Locked Laser," PRL 84 3232 (2000) 10 April 2000
J. Reichert, M. Niering, R. Holzwarth, M. Weitz, Th. Udem, and T. W. Hänsch

Honeycomb Microstructure Optical Fiber

CLEO,May, 1999





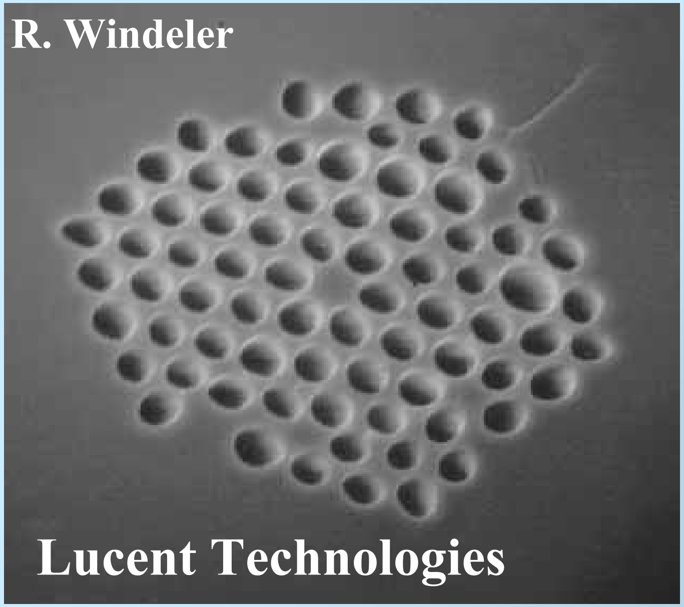


Dawn of a new Epoch !

courtesy of Jinendra Ranka

Lucent Technologies
Bell Labs Innovations

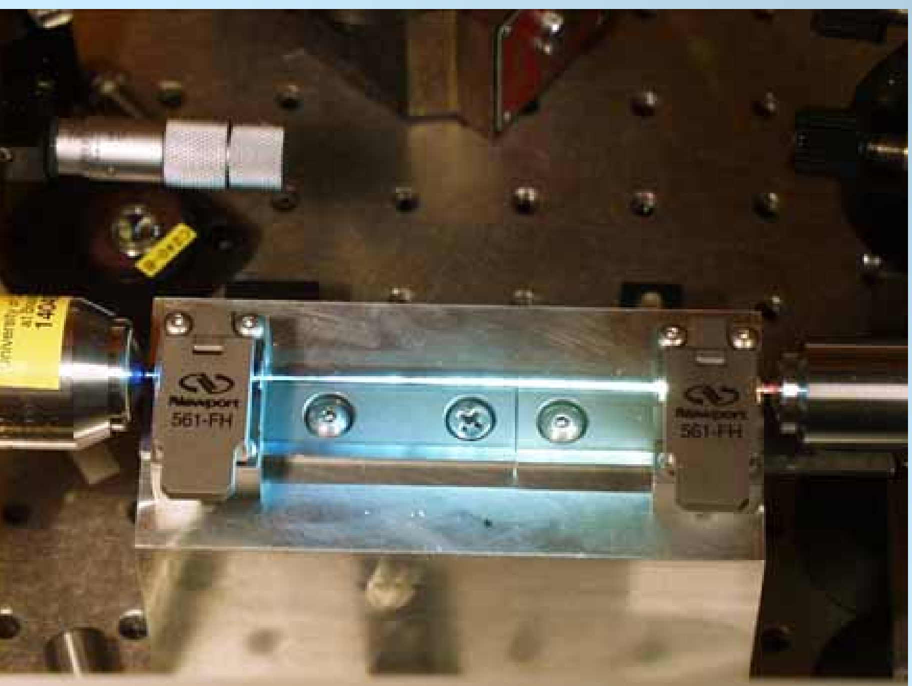
Seriously- nonlinear optics (O(20))

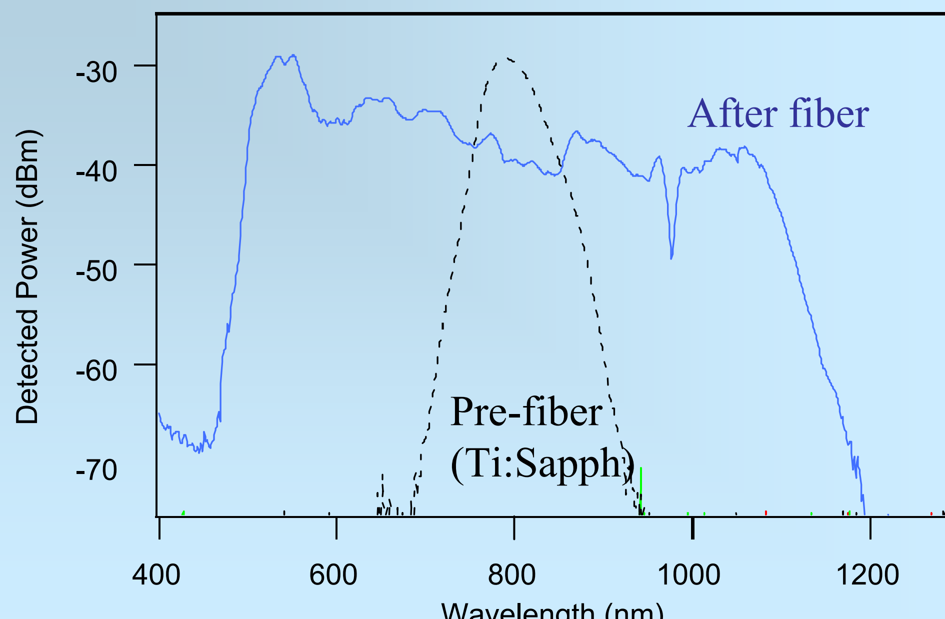


J.K Ranka, R. S. Windeler, A. Stenz, Opt. Lett. ***25****, 25 (Jan. 2000)*

Microstructured fiber

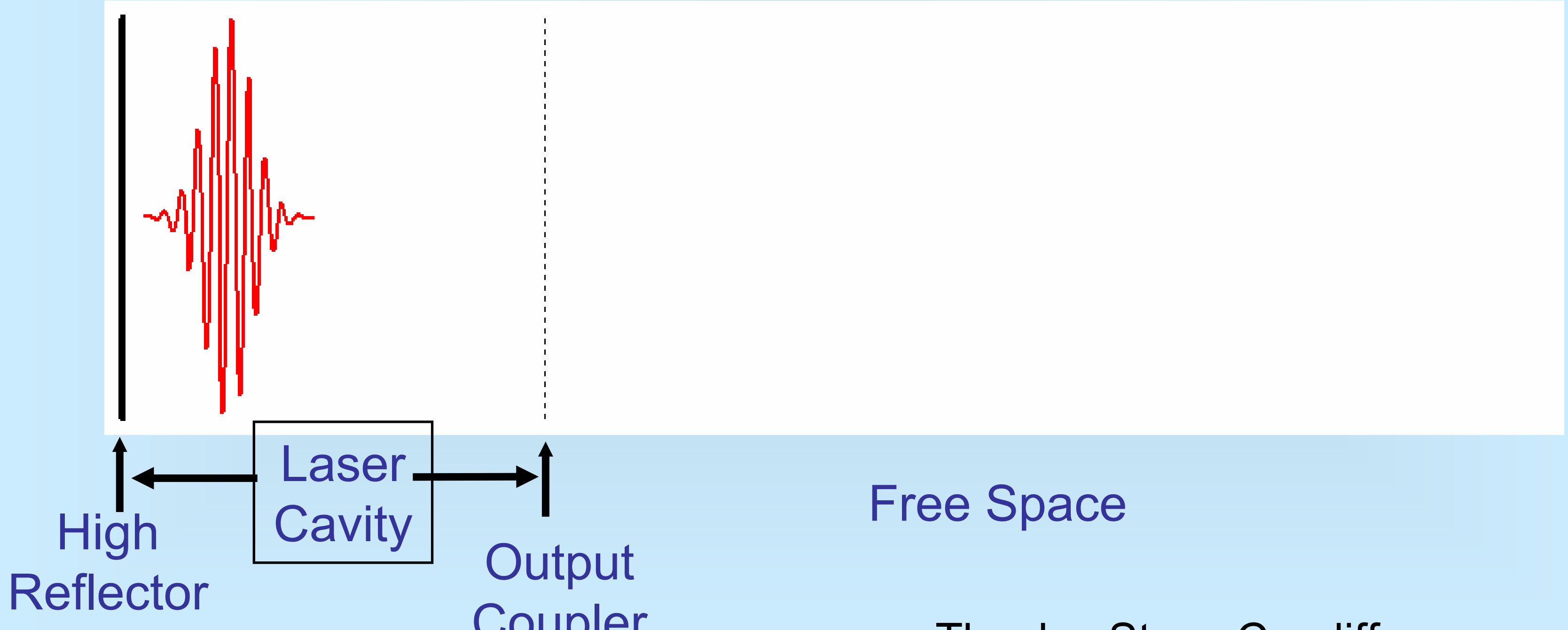
- **dispersion zero at ~800 nm**
- **pulses do not spread**
- **continuum generation via self-phase modulation**





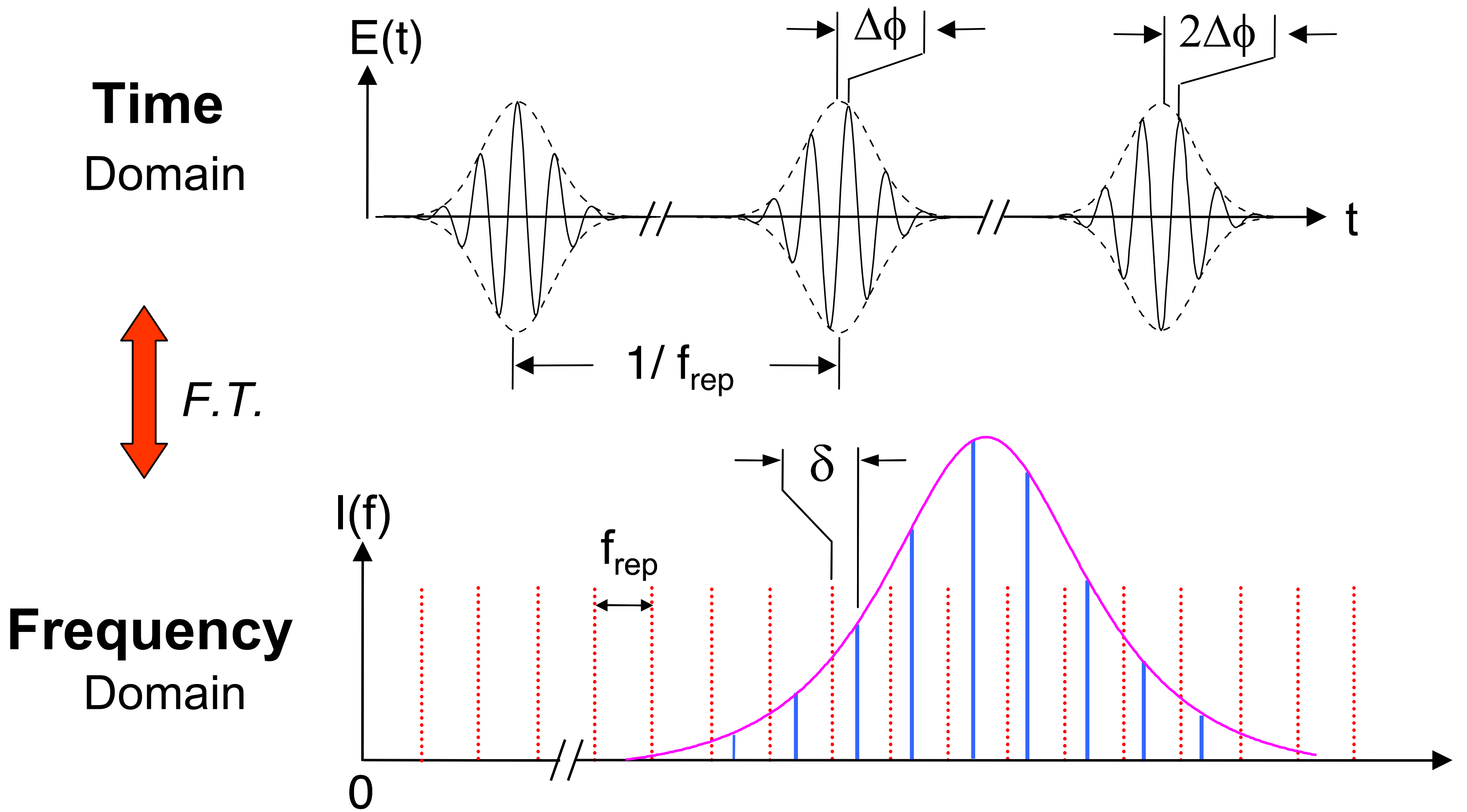
Group vs. Phase in Modelocked Lasers

- Each pulse emitted by a modelocked laser has a distinct envelope-carrier phase
  - due to group-phase velocity differential inside cavity



Thanks: Steve Cundiff

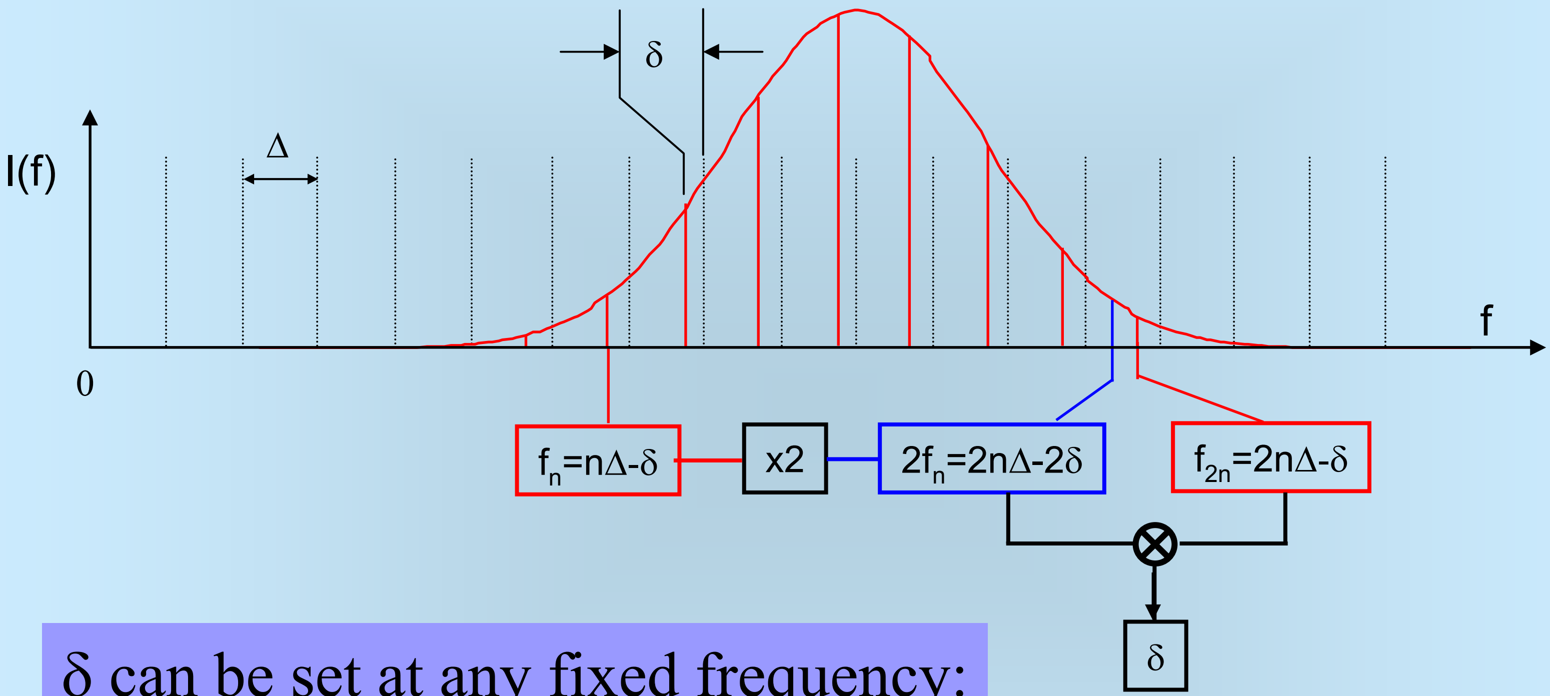
Time Domain ⟷ Frequency Domain



•Frequency modes of the fs pulse are offset from $f_{n=0}=0$ by δ

$$2\pi\delta = \Delta\phi \; f_{rep}$$

Self-referenced Optical Frequency Synthesizer



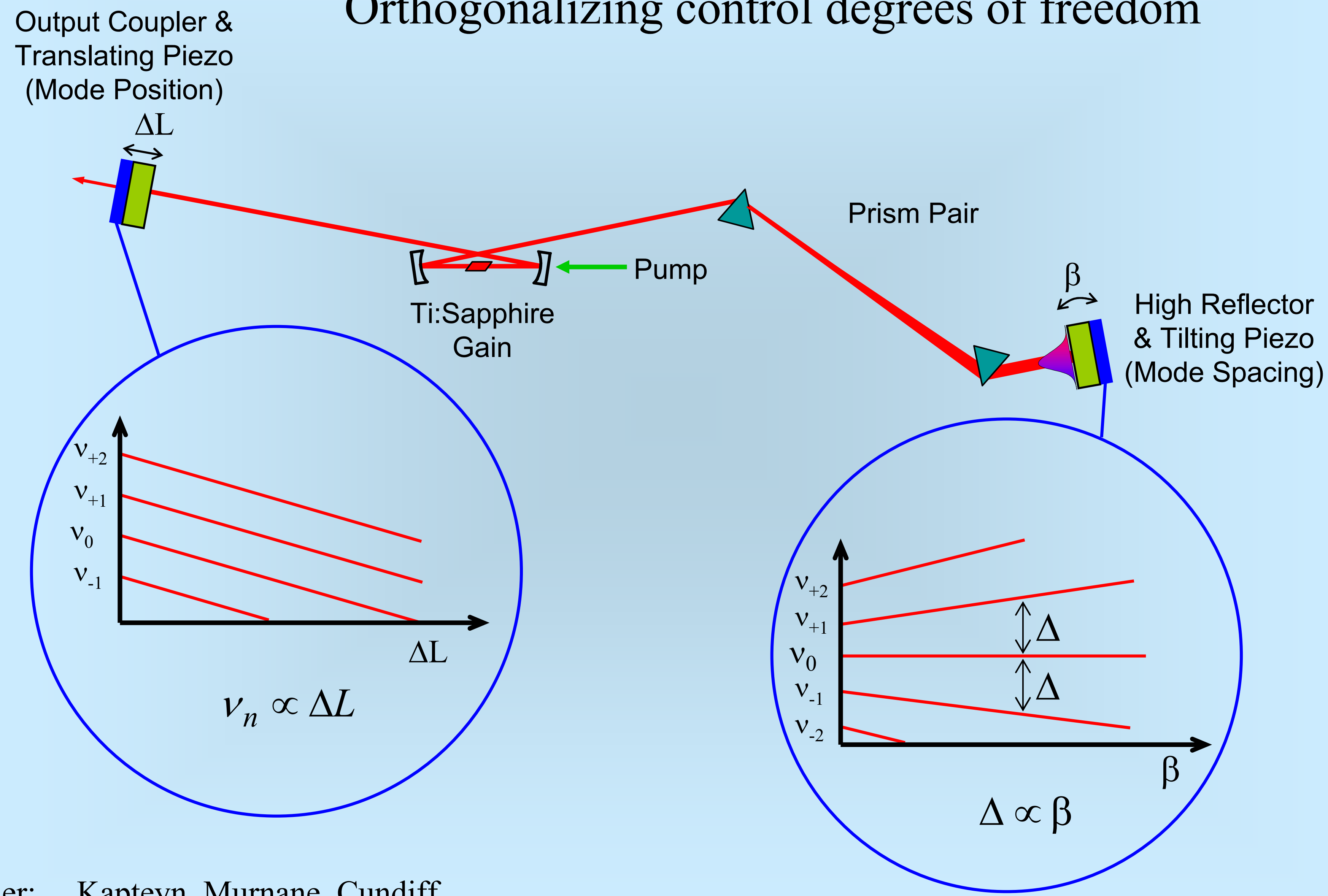
δ can be set at any fixed frequency:
For example, $\delta = 0$: $f_n = n\,\Delta$

Telle, Appl Phys B '99
Jones, Science '00

Absolute control of carrier-pulse phase: extreme nonlinear optics, precision optical waveforms

Phase-Controlled 10 fs Laser

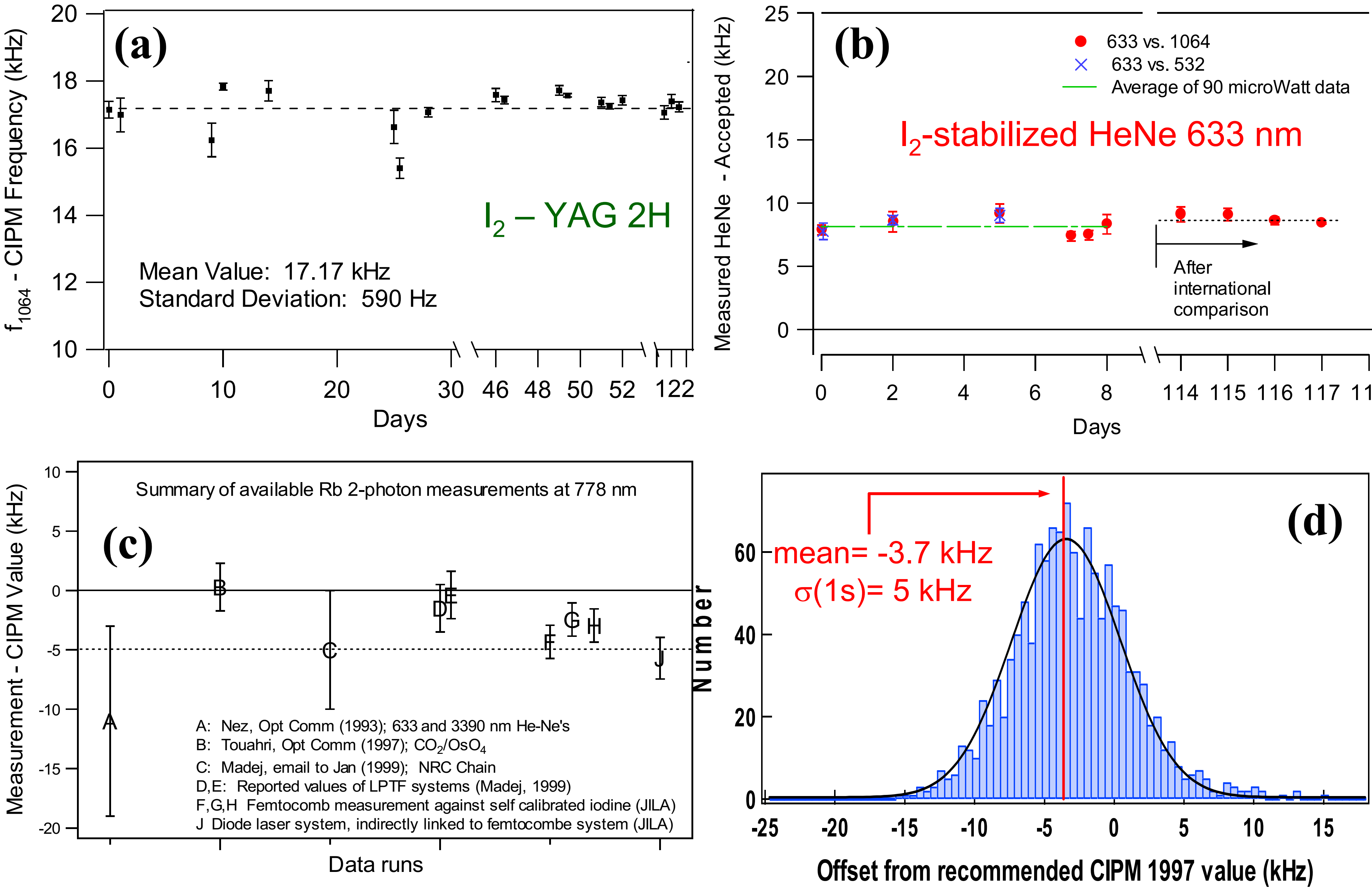
Orthogonalizing control degrees of freedom



Laser: Kapteyn, Murnane, Cundiff

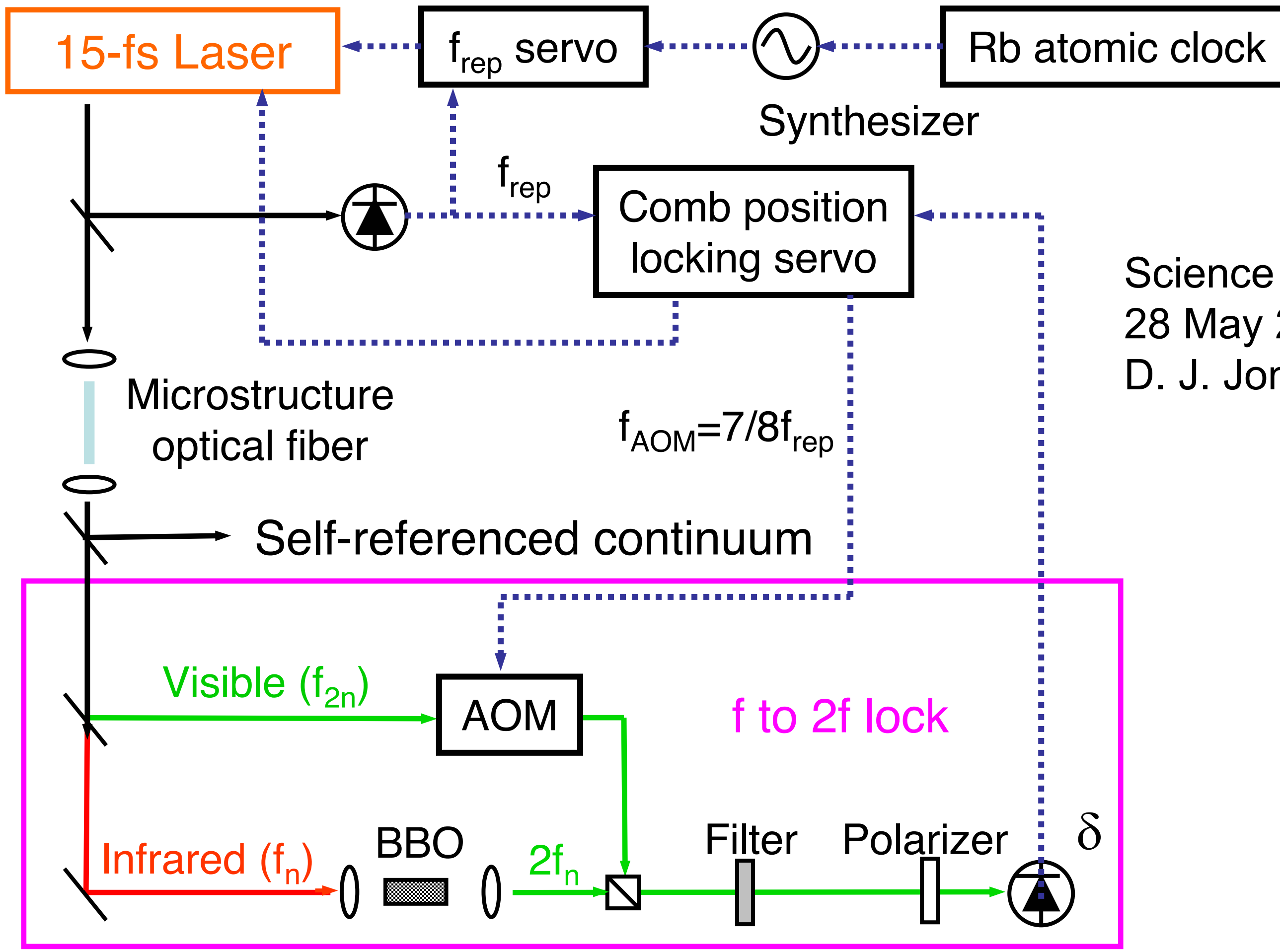
Control Ideas: Udem et. al., Hall, Ye

Th. Udem, et al, PRL **82**, 3568 (1999).



Three Absolute Frequency Measurements using the Self-Referencing Comb Method

Self-Reference: JILA Experimental Setup

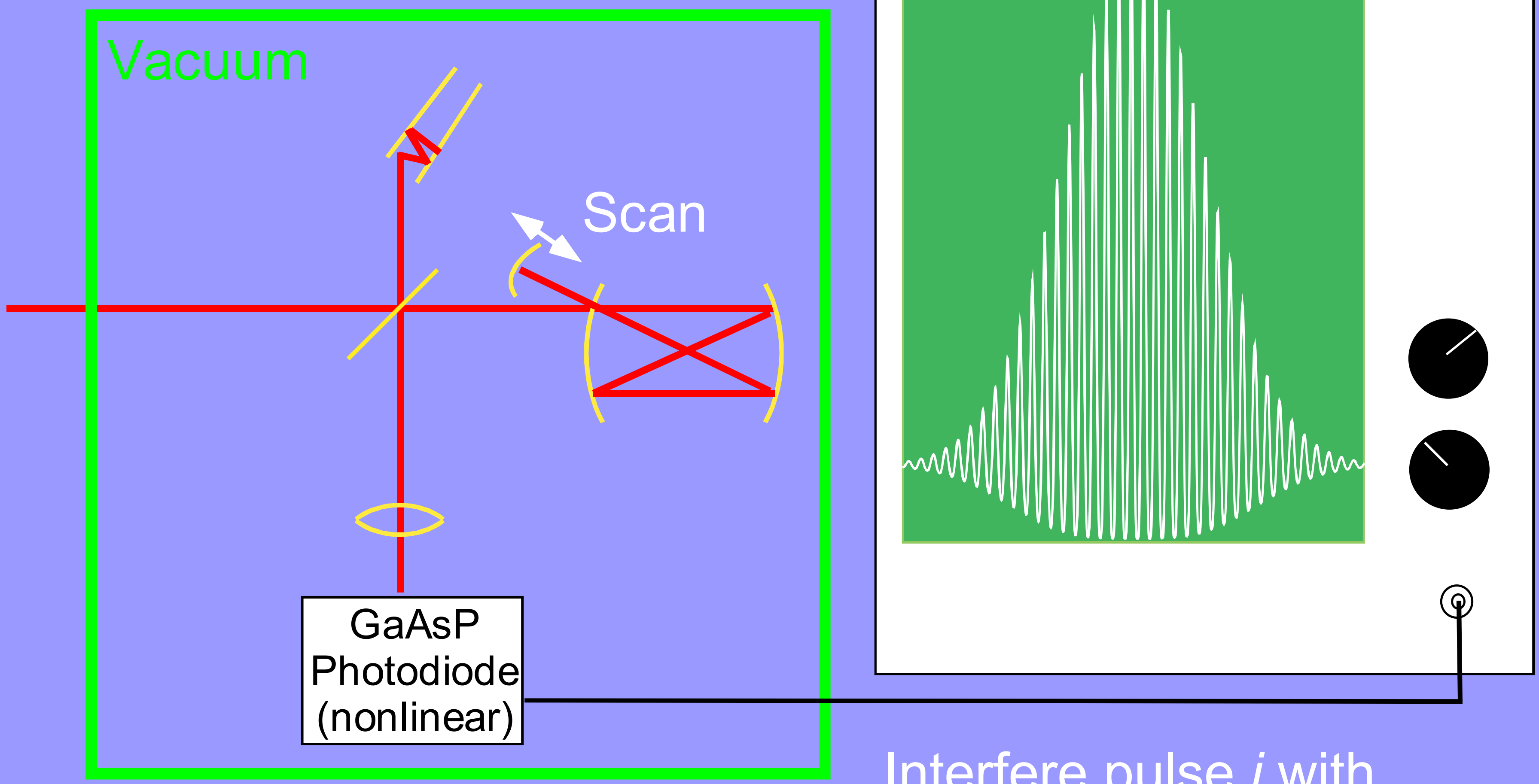


Science **288**, 635
28 May 2000
D. J. Jones et al.

- Relative carrier-envelope phase: $\Delta\phi = 2\pi \frac{\delta}{f_{rep}} = 2\pi \frac{m}{16}$

Time Domain Cross-Correlator

Matched mirror bounces

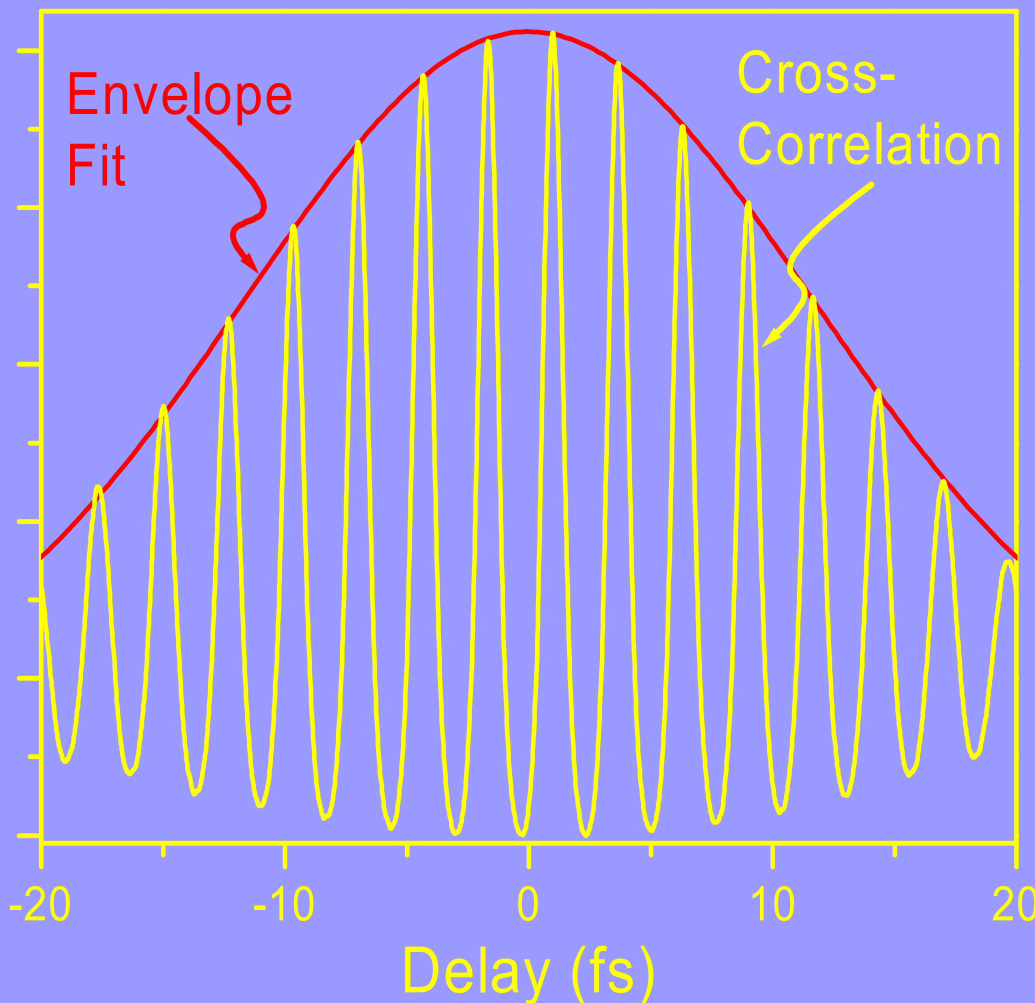


L. Xu, et al., Opt. Lett. 21, 2008 (1996)

Interfere pulse *i* with pulse *i* + 2.

Cross-Correlation

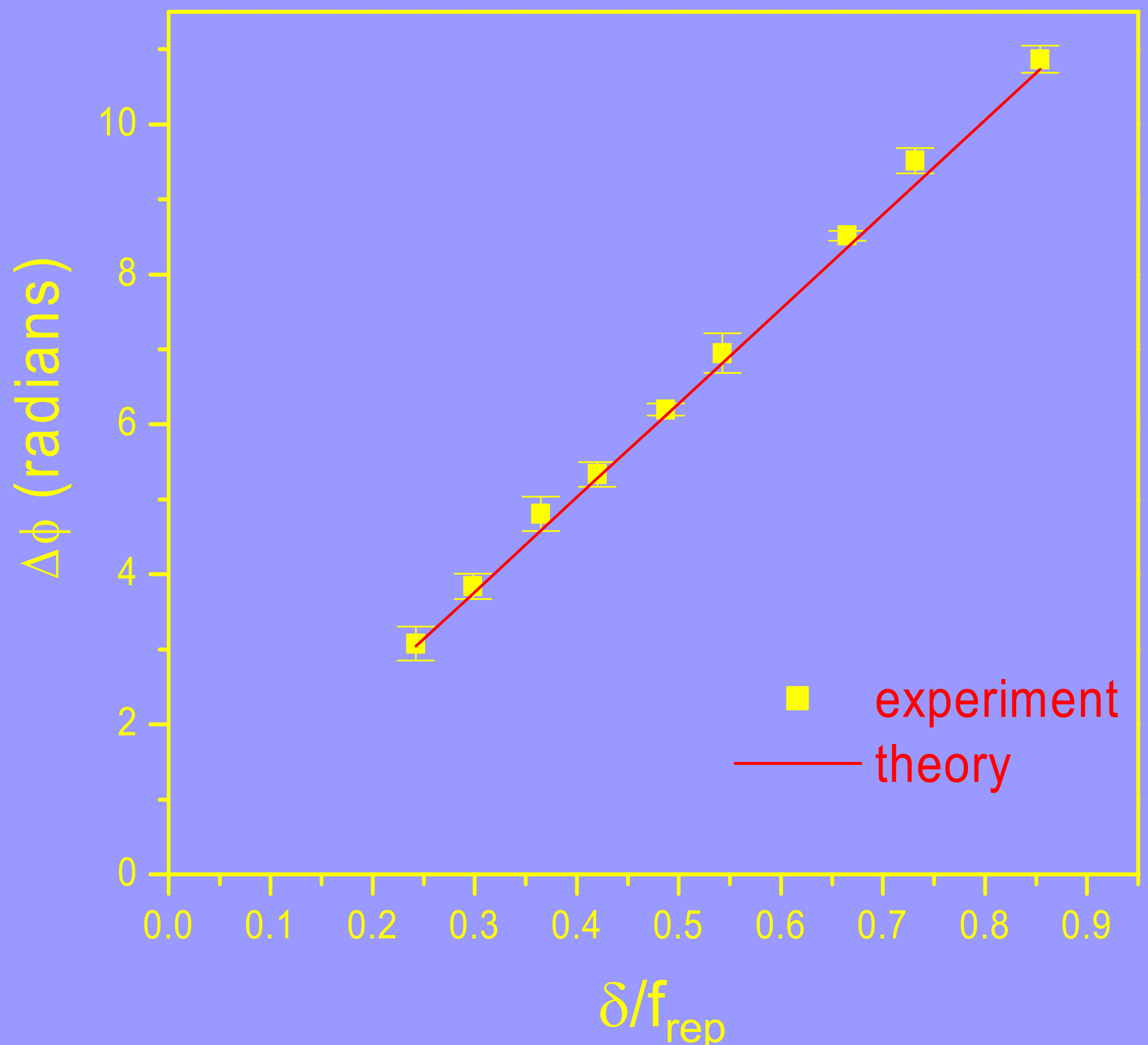
- Auto-correlation is always symmetric
- Cross-correlation fringes shift: pulse to pulse phase
- Fit to obtain envelope peak
- Extract carrier phase shift relative to envelope



S. Cundiff & D. J. Jones /JILA

Systematic Phase Control

D. J. Jones, et al.
Science **288** 635 ’00



“Dial-in” pulse-to pulse phase

T. M. Fortier *et al.*, SPIE 4271, p.183 (2001).

Fiber phase noise issues, T. Fortier, PhD thesis ‘03

Friendly - but **Hot** - Competition!

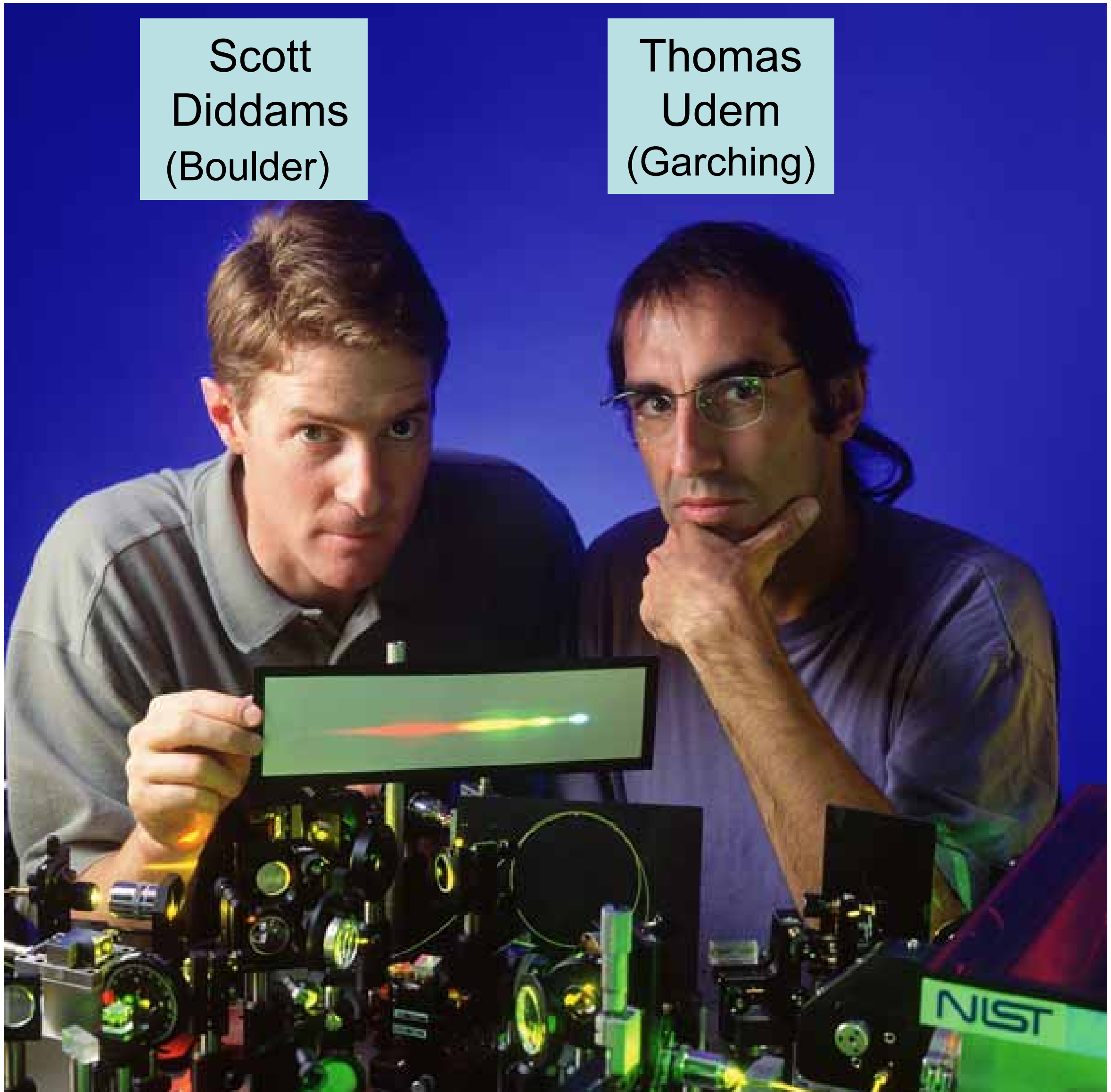
- **“Phase Coherent Vacuum-Ultraviolet to Radio Frequency Comparison with a Mode-Locked Laser,”** J. Reichert, M. Niering, R. Holzwarth, M. Weitz, Th. Udem, and T. W. Hänsch, ***PRL*** **84** 3232 10 April 2000

- **"Carrier-envelope phase control of femtosecond mode-locked lasers and direct optical frequency synthesis,"** D. J. Jones, S. A. Diddams, J. K. Ranka, A. Stentz, R. S. Windeler, J. L. Hall, and S. T. Cundiff, ***Science***, vol. **288**, pp. 635-639, 28 April 2000.

- **“Direct Link between Microwave and Optical Frequencies,”** Diddams et al., JILA; Ranka et al., Lucent; & Holzwarth et al. MPQ

  PRL **84** 5102 29 May 2000

Positive Interference



It makes:

Coherent Comb Lines

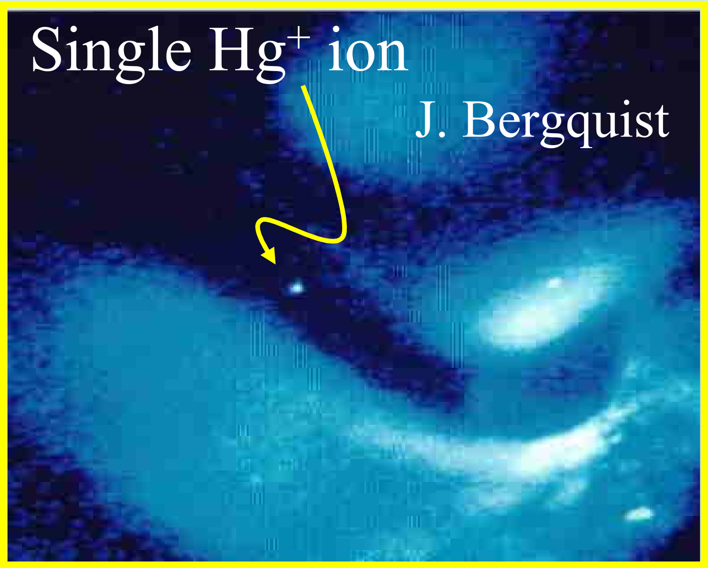
Great Fun & Progress

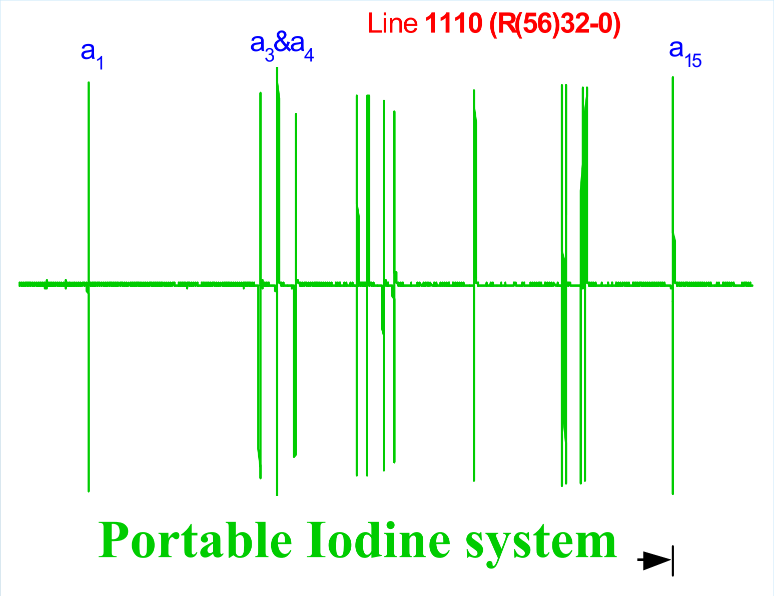
fs Comb-Measured Optical Frequencies

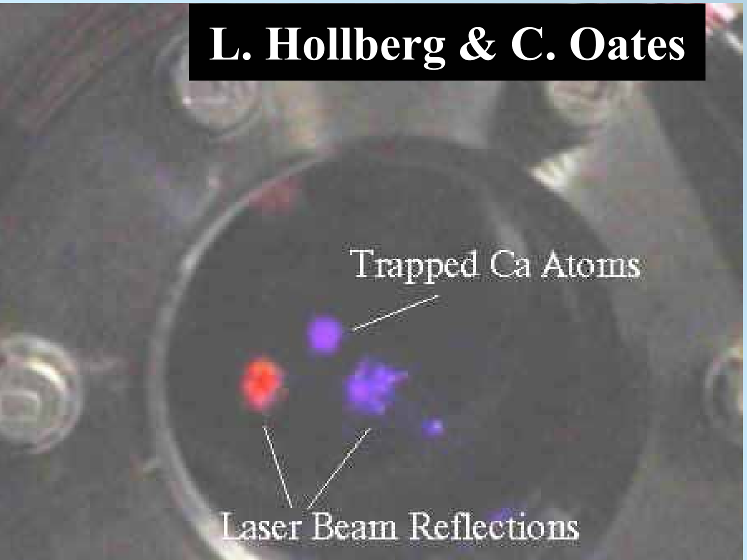
• Ca	657 nm	Schnatz – PTB	PRL 1 Jan '96
• C_2H_2	1.5 μm	Nakagawa - NRLM	JOSA-B Dec '96
• Sr^+	674 nm	Bernard – NRC	PRL 19 Apr '99
• In^+	236 nm	v. Zanthier - MPQ	Opt.Comm. Aug'99
• H	243 nm	Reichert - MPQ	PRL 10 Apr '00
• Rb	778 nm	D. Jones - JILA	Science 28 Apr 00
• I_2	532 nm	Diddams - JILA	PRL 29 May '00
• H	243 nm	Niering - MPQ	PRL 12 June '00
• Yb^+	467 nm	Roberts - NPL	PRA 7 July '00
• In^+	236 nm	v. Zanthier – MPQ	Opt. Lett. 1 Dec.'00
• Ca	657 nm	Stenger – PTB	PRA 17 Jan '01
• Hg^+	282 nm	Udem – NIST	PRL 28 May '01
• Ca	657 nm	Udem – NIST	PRL 28 May '01
• Yb^+	435 nm	Stenger – PTB	Opt. Lett. 15 Oct '01

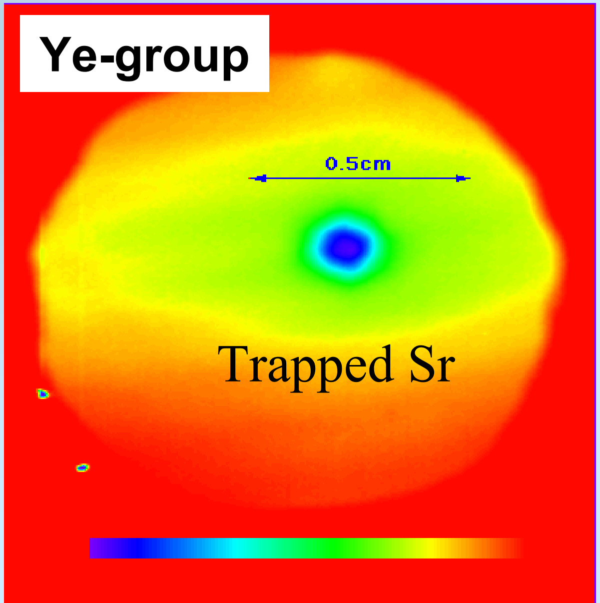
Advanced optical frequency standards

- Bergquist, Hall, Hollberg, Ye

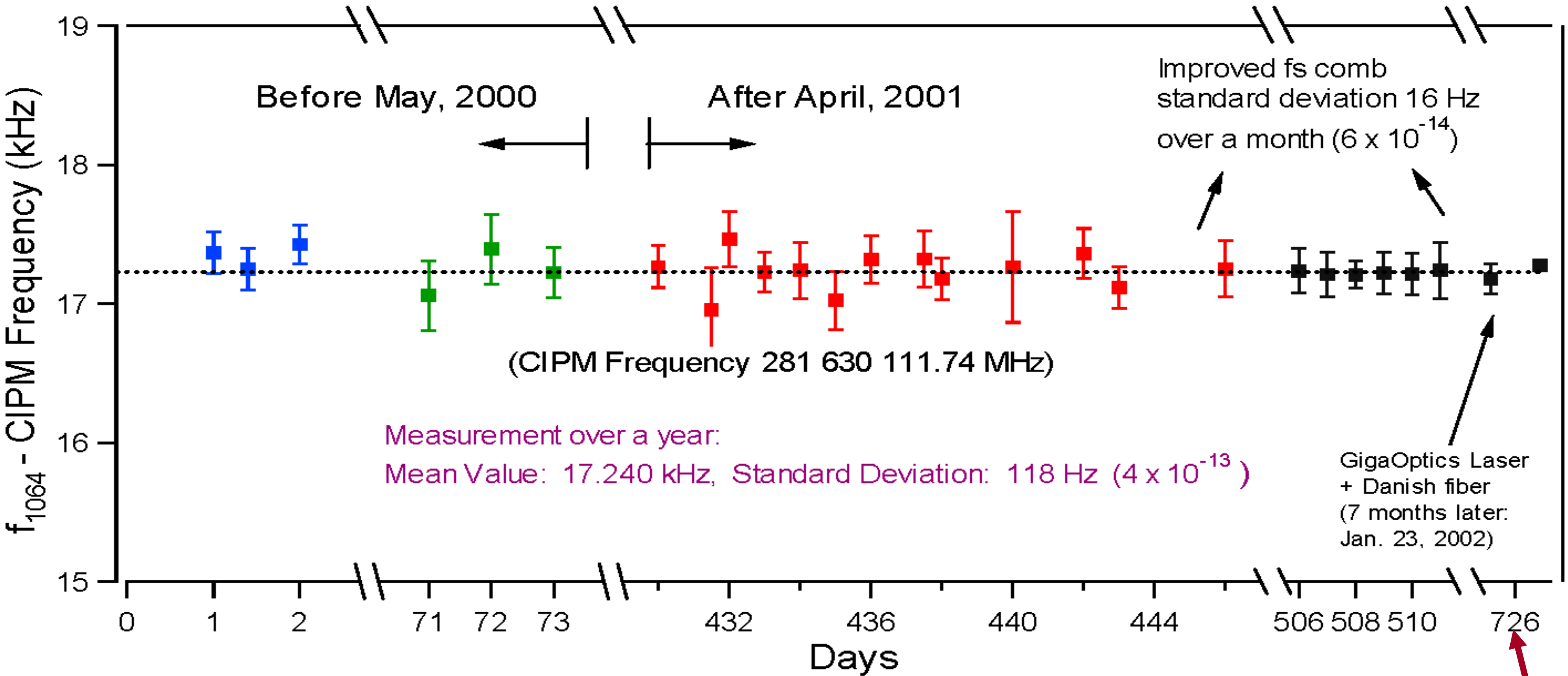








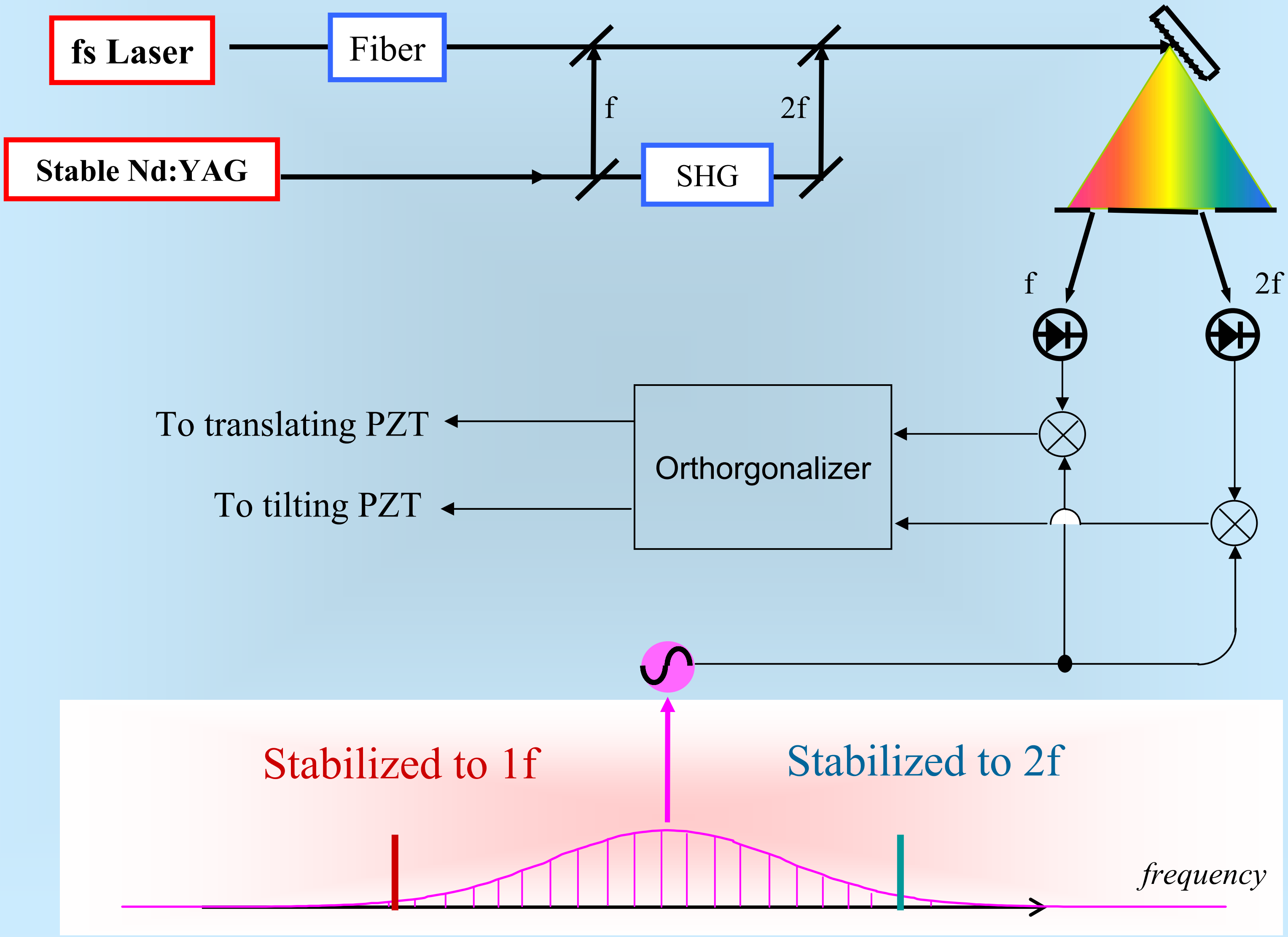
Nd:YAG/I_2 Long term reproducibility



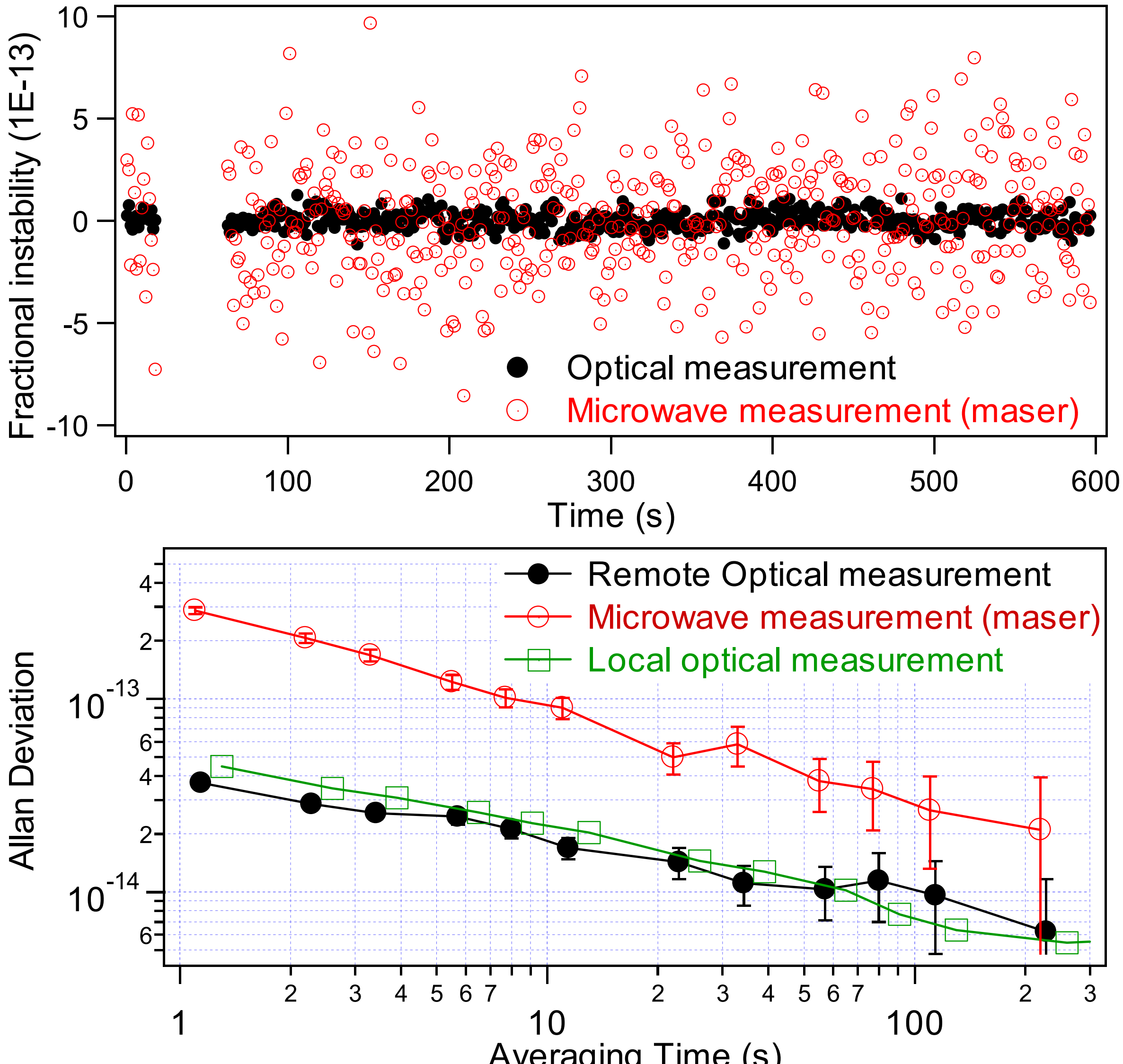
Measured frequency is confirmed by 375 MHz system/new fiber

Prototype of an optical clock –

fs Laser Stabilization by Phase Lock to Reference

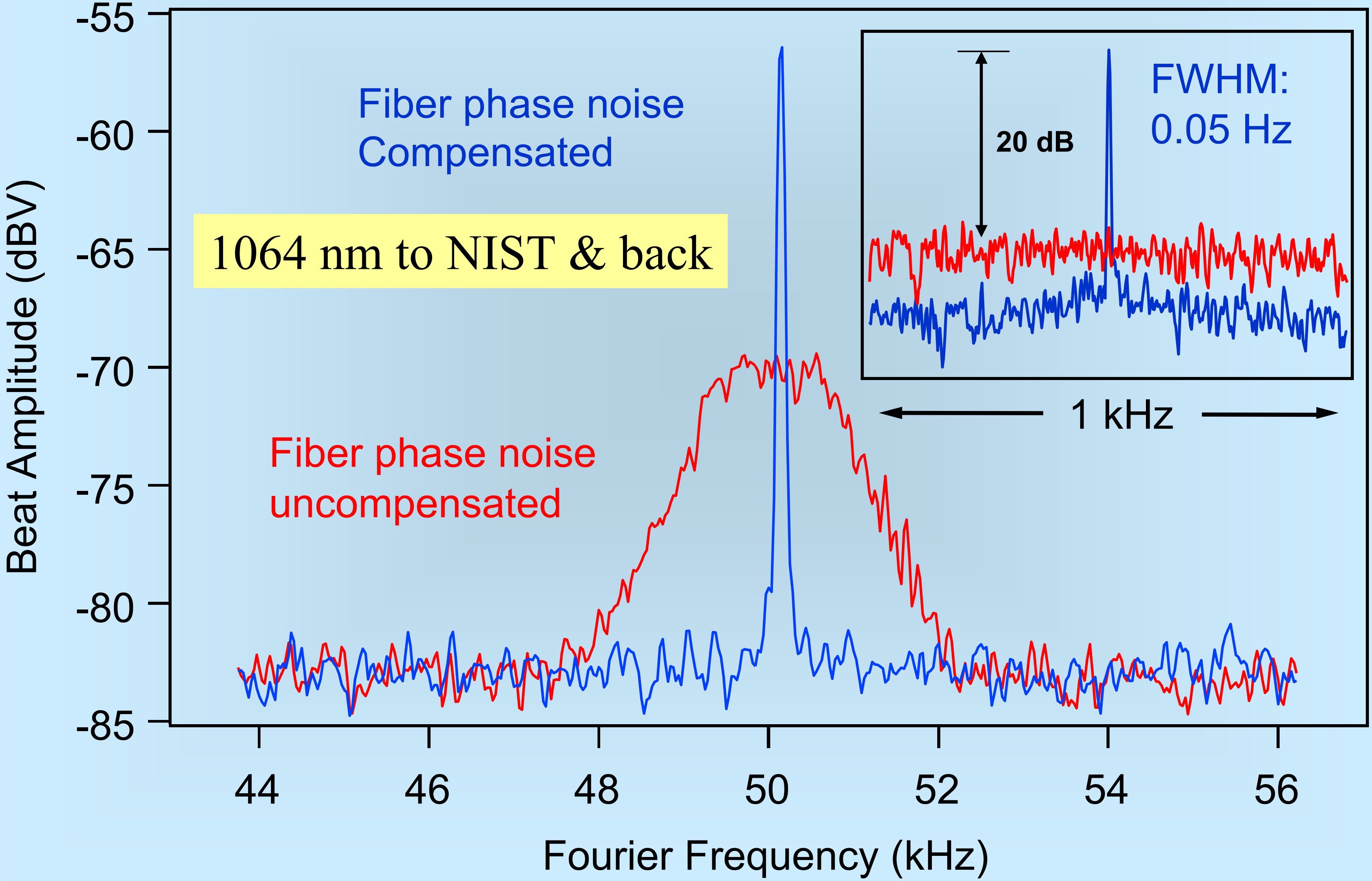


JILA I_2 Optical Standard vs NIST Hg^+ Reference

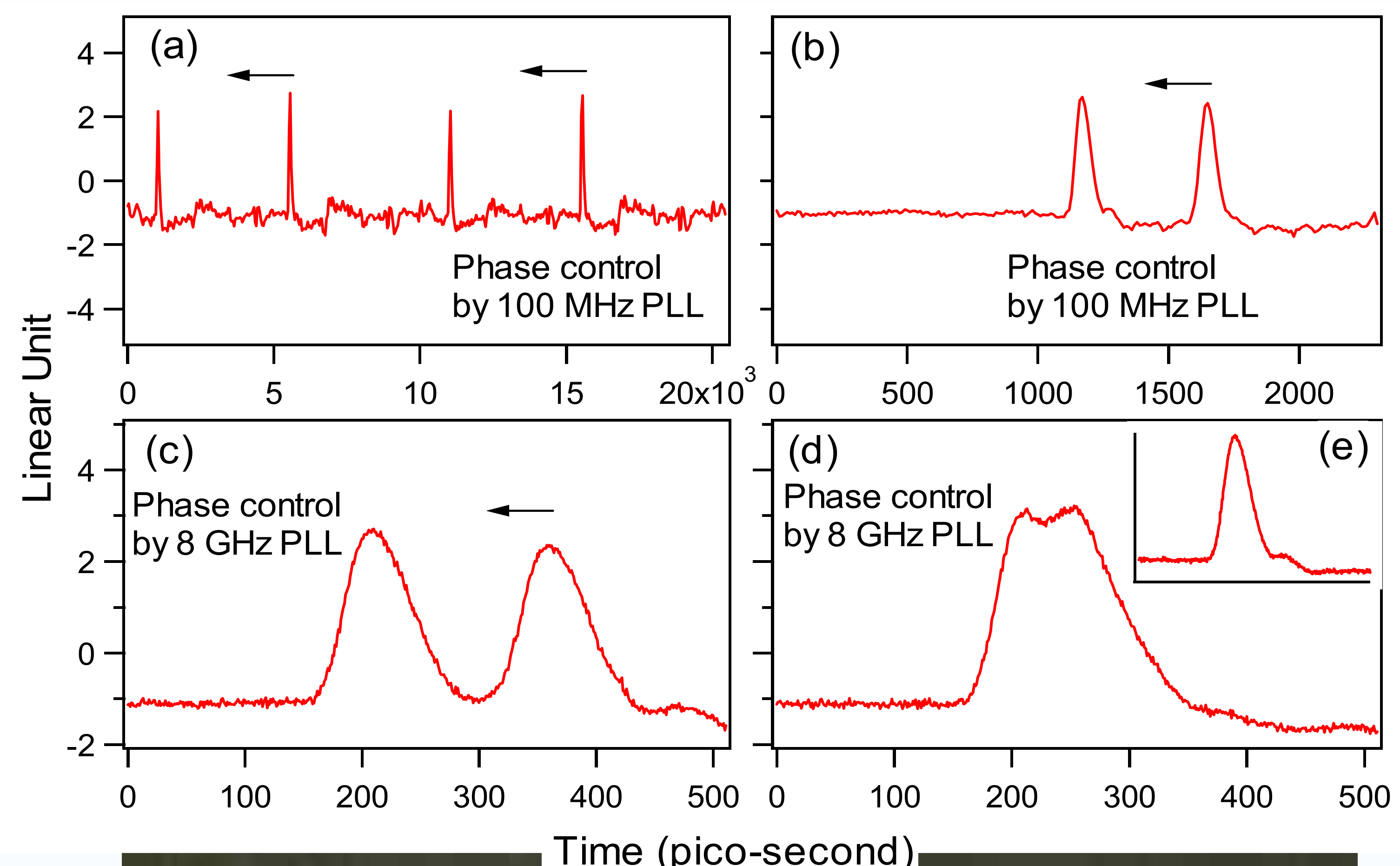


Fiber Phase Noise Compensation

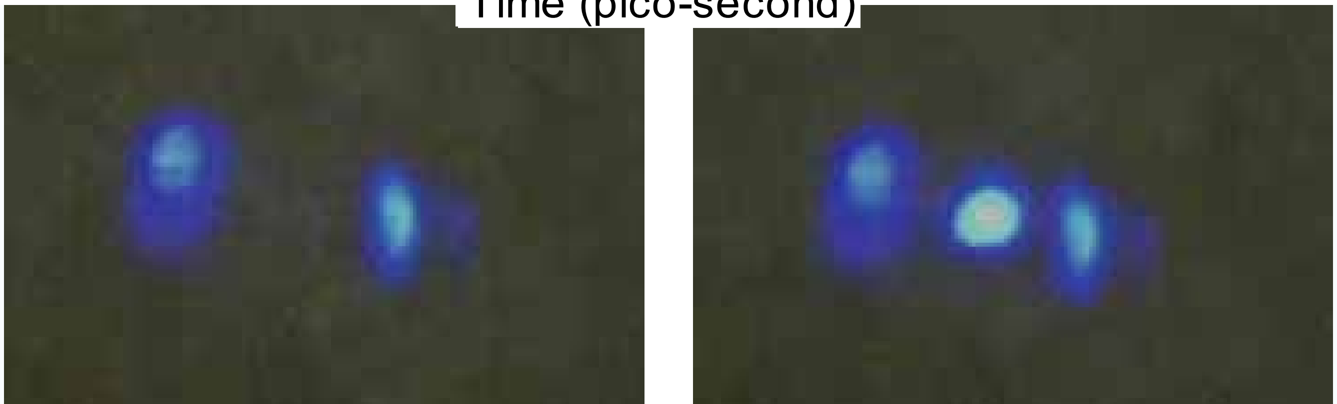
(Boulder Regional Area Network fiber, 3.4 km)



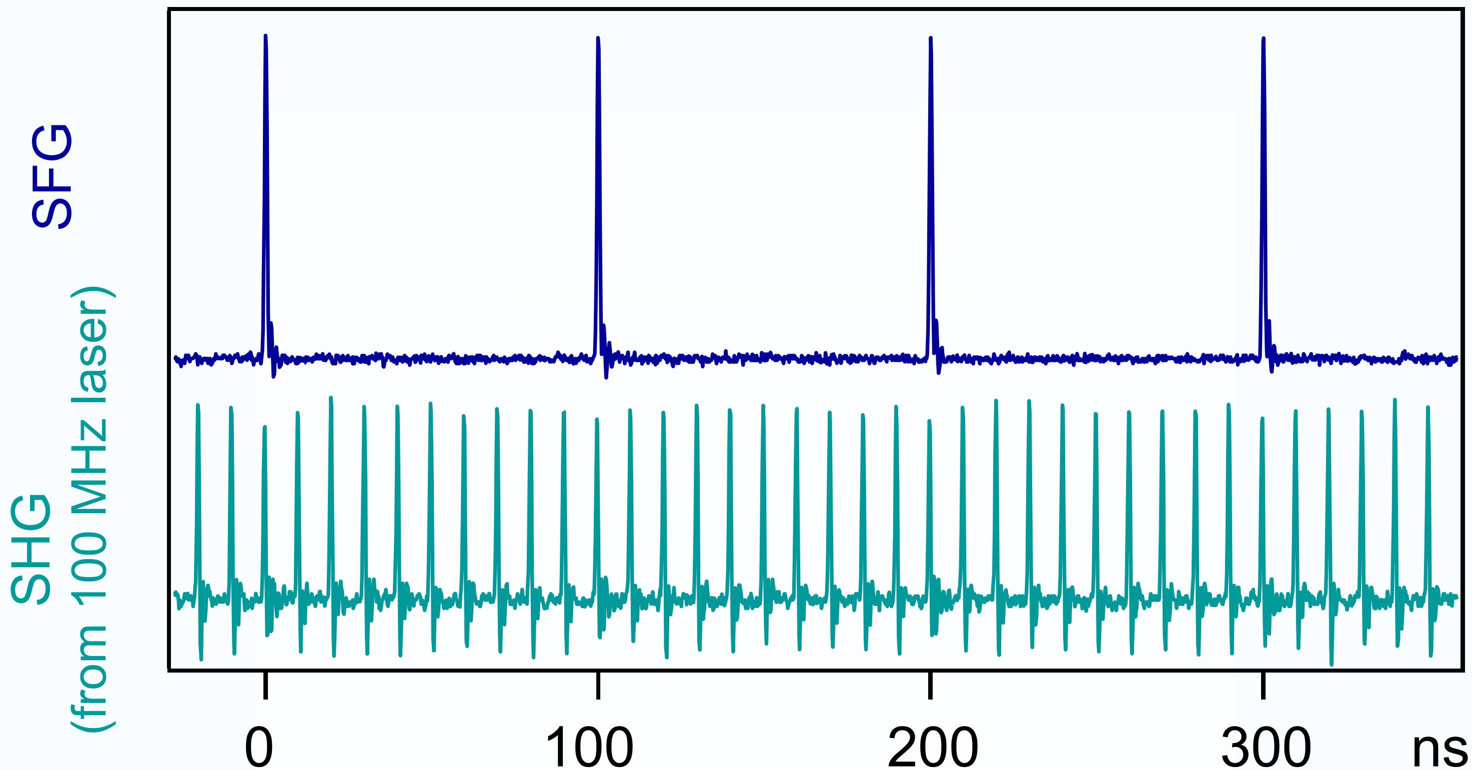
Synchronization between 2 fs lasers



Ye,
Shelton

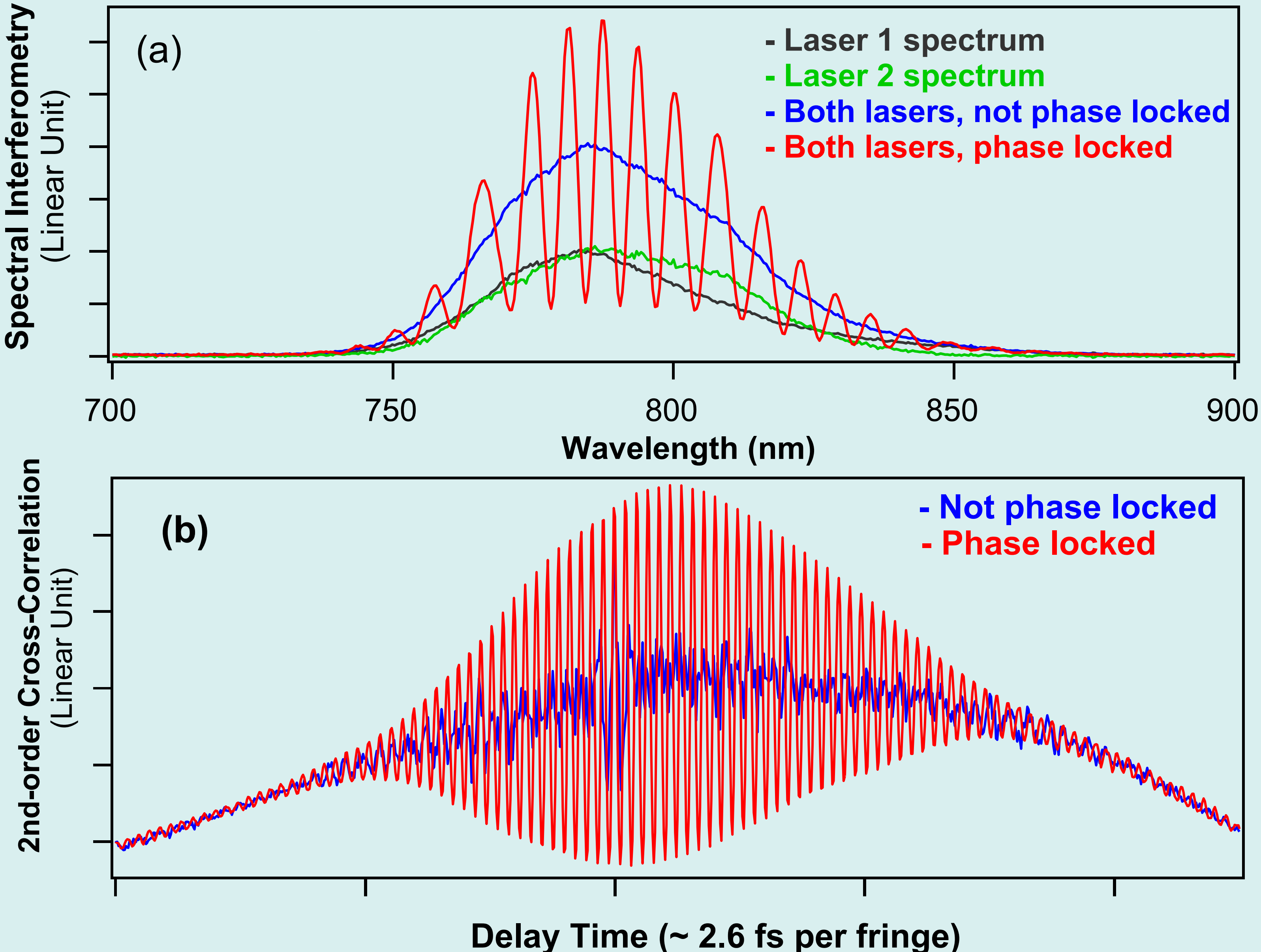


Arbitrary Repetition Rates

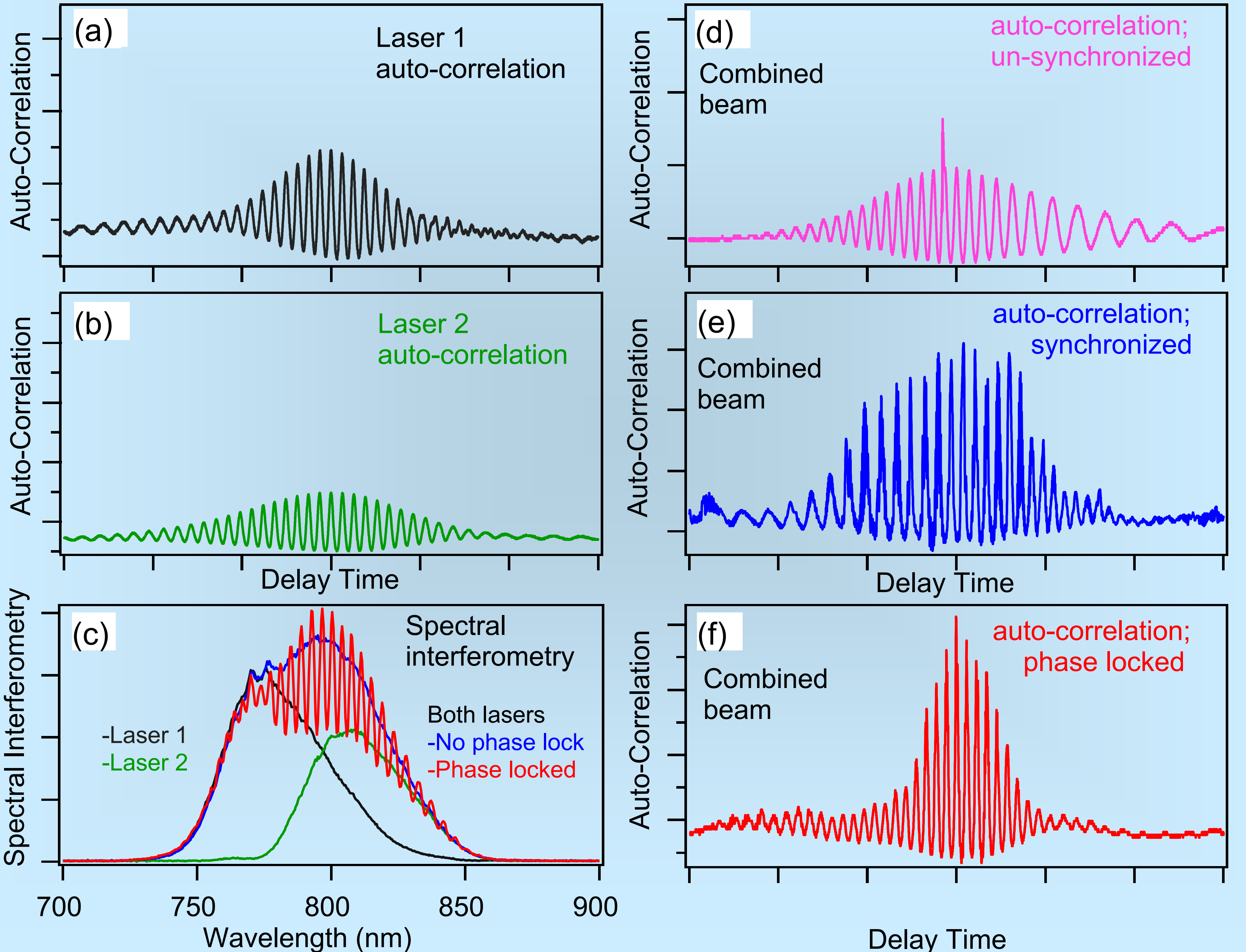


One laser running at 100 MHz, the other at 90 MHz
The resultant sum frequency repetition rate is 10 MHz

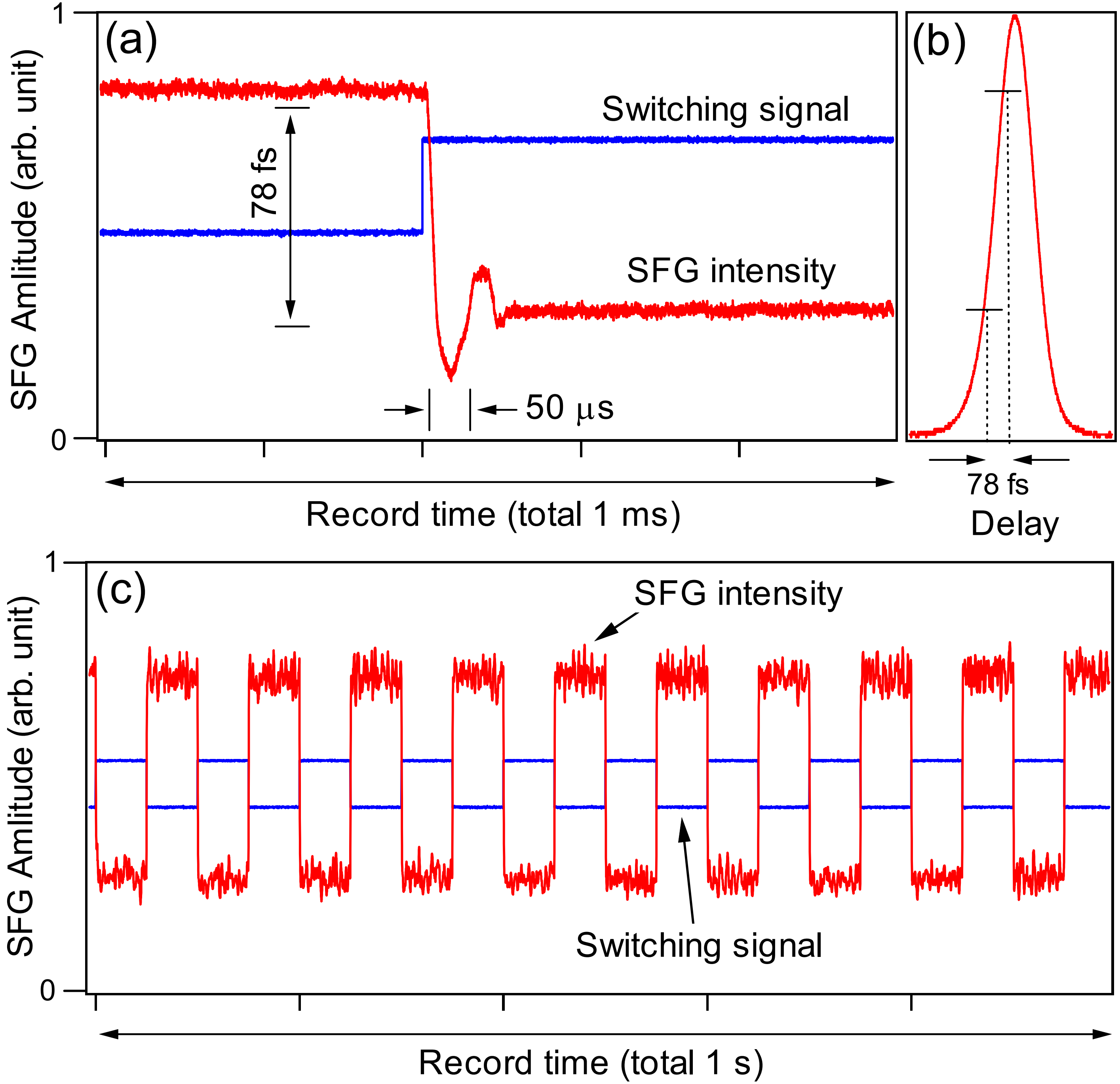
Interference fringes between two femtosecond lasers

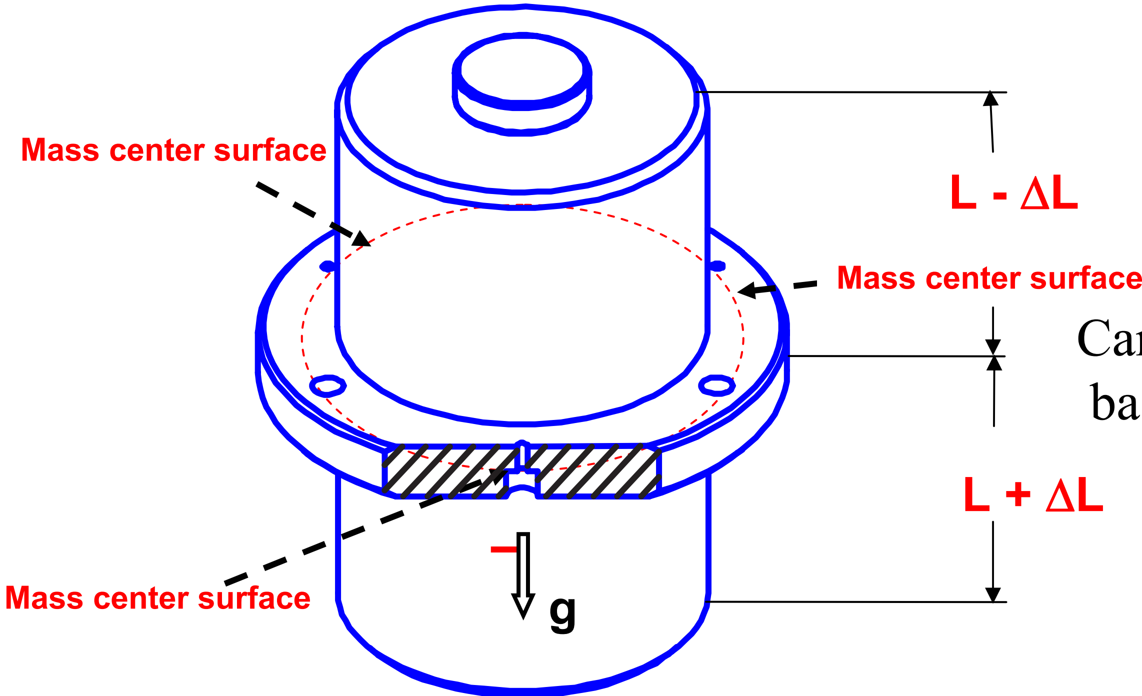


"Synthesized" Pulse



Shelton, Ye, et al
Opt. Lett. **27**, 312
1 Mar 2002

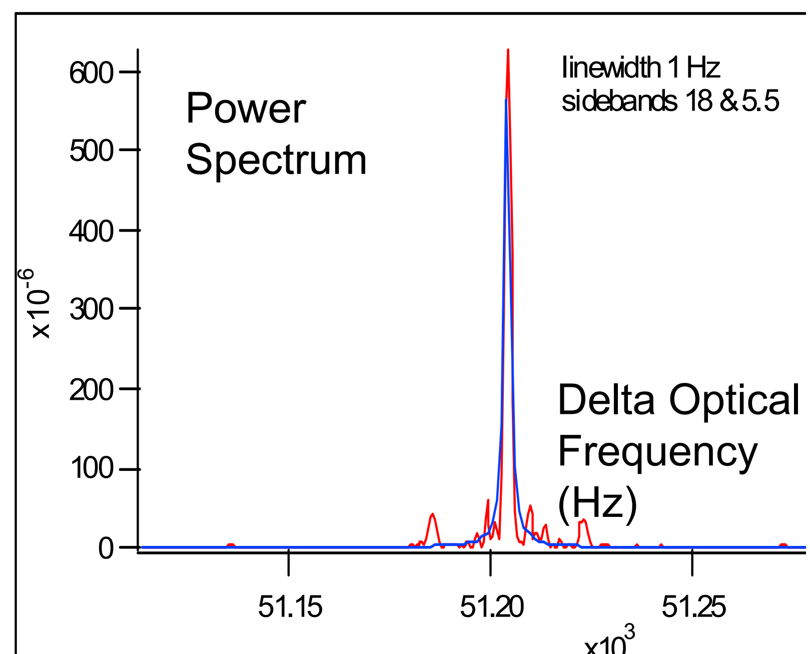




Cancellation of Length Change, based on Symmetry!

Vibration-Insensitive Reference Cavity

Sub-Hertz Laser Linewidth -- on a Table Top !



JILA/HallGroup_05

Future Plans & Opportunities

Improved Local Oscillators:

Stable Optical Reference + fs Laser Comb - "Gearbox" - better, & best

Already-demonstrated stability (1 s) 4 $\times 10^{-14}$

vs H Maser (present LO for DSN) 3 $\times 10^{-13}$

New Paradigm Frequency Counters simpler & better

fs laser gearbox + quartz + GPS 1 $\times 10^{-14}$ at 1 day

Improved Physical Tests/Measurements

Gravity Gradient and Climate Explorer –II please use optical reference

LISA Gravitational Astronomy - heterodyne interferometry

Astrometric Interferometric Mission – curvature of local space, planet-finding

Local Lorentz Invariance – Special Relativity tests in zero –g

Clock Tests - "Alpha-dot," Strong Force/Elect. & Mag., CPT: H vs anti-H

Tutorial-type Background Refs

- “An introduction to phase-stable optical sources,” in International School of Physics 'Enrico Fermi', Course CXVIII, Laser Manipulation of Atoms and Ions (E. Arimondo, W. D. Phillips, and F. Strumia, Eds., North Holland, 1992), pp. 671-702.

- “Frequency stabilization of tunable lasers,” in Atomic, Molecular and Optical Physics: Electromagnetic Radiation (F. B. Dunning and R. G. Hulet, Eds., Experimental Methods in the Physical Sciences series, Vol. 29C, Academic, San Diego, 1997),103-36 with M. Zhu.

- “External Laser Stabilization,” John L. Hall, in *Laser Physics at the Limit*, a T. W. Haensch FestShrift, H. Figger, D. Meschede and C. Zimmermann, Eds., (Springer-Verlag, Berlin, 2002) pp. 51-59.

- "Optical Frequency Synthesis Based on Modelocked Lasers," S.T. Cundiff, J. Ye and J.L. Hall, Rev. Sci. Inst., 72, 3749-3771 (2001). (review paper).

- “Laser Stabilization,” J. L. Hall, M. Taubman and J. Ye,
  in OSA Handbook IV, Chapter 27 (2002).

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