Ultra-precise optical phase control:

Optical frequency measurement & synthesis

Seth Foreman

on behalf of

Jun Ye

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

foreman@colorado.edu

IFCS, Frequency Control Tutorial, Miami, June 4, 2006

$ Funding $

ONR, NASA, NSF, NIST, AFOSR

Exciting time for light control

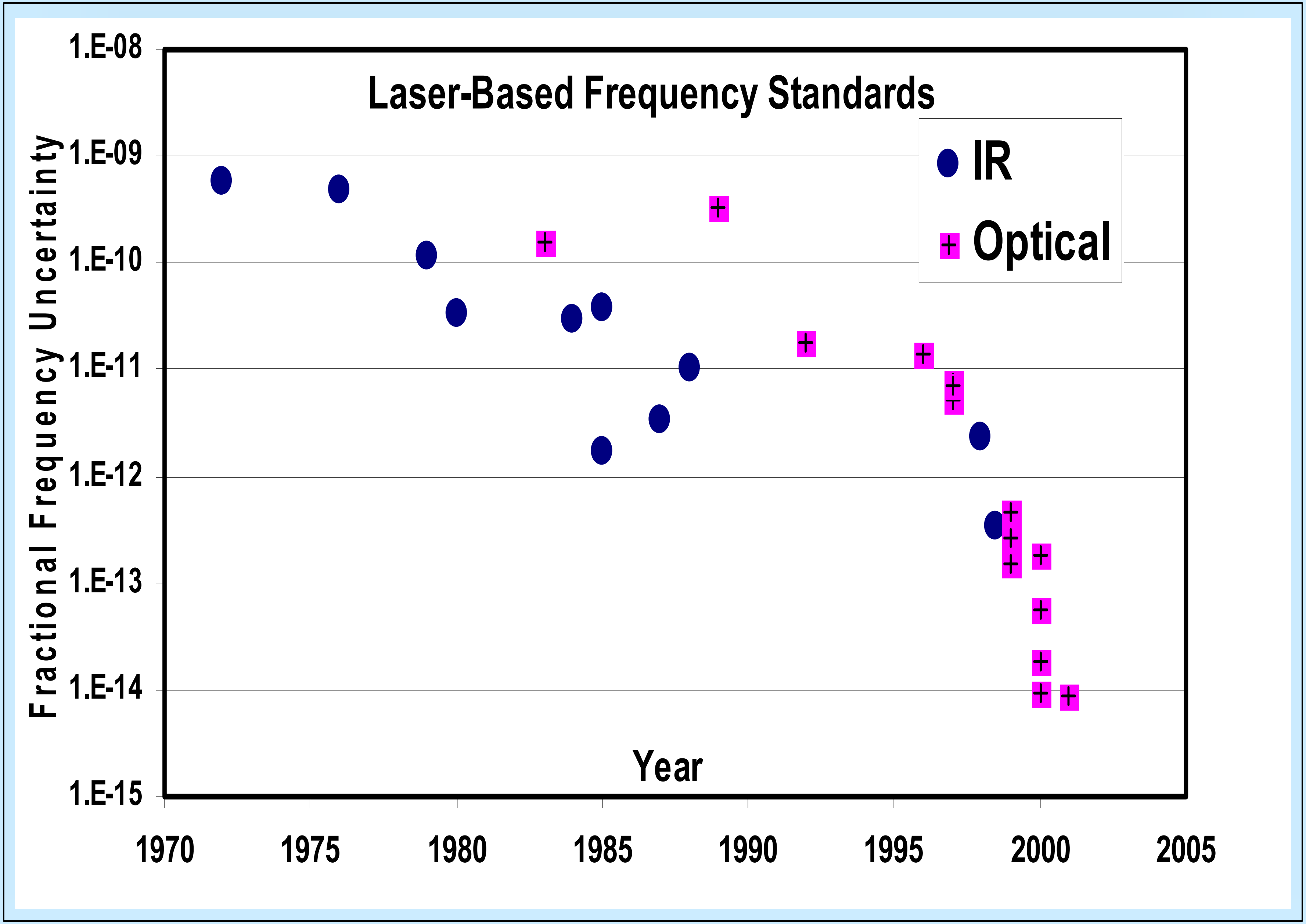
Continuous wave laser: **< 1 Hz stability and accuracy**

Ultrafast pulse: **< 1 fs generation and control**

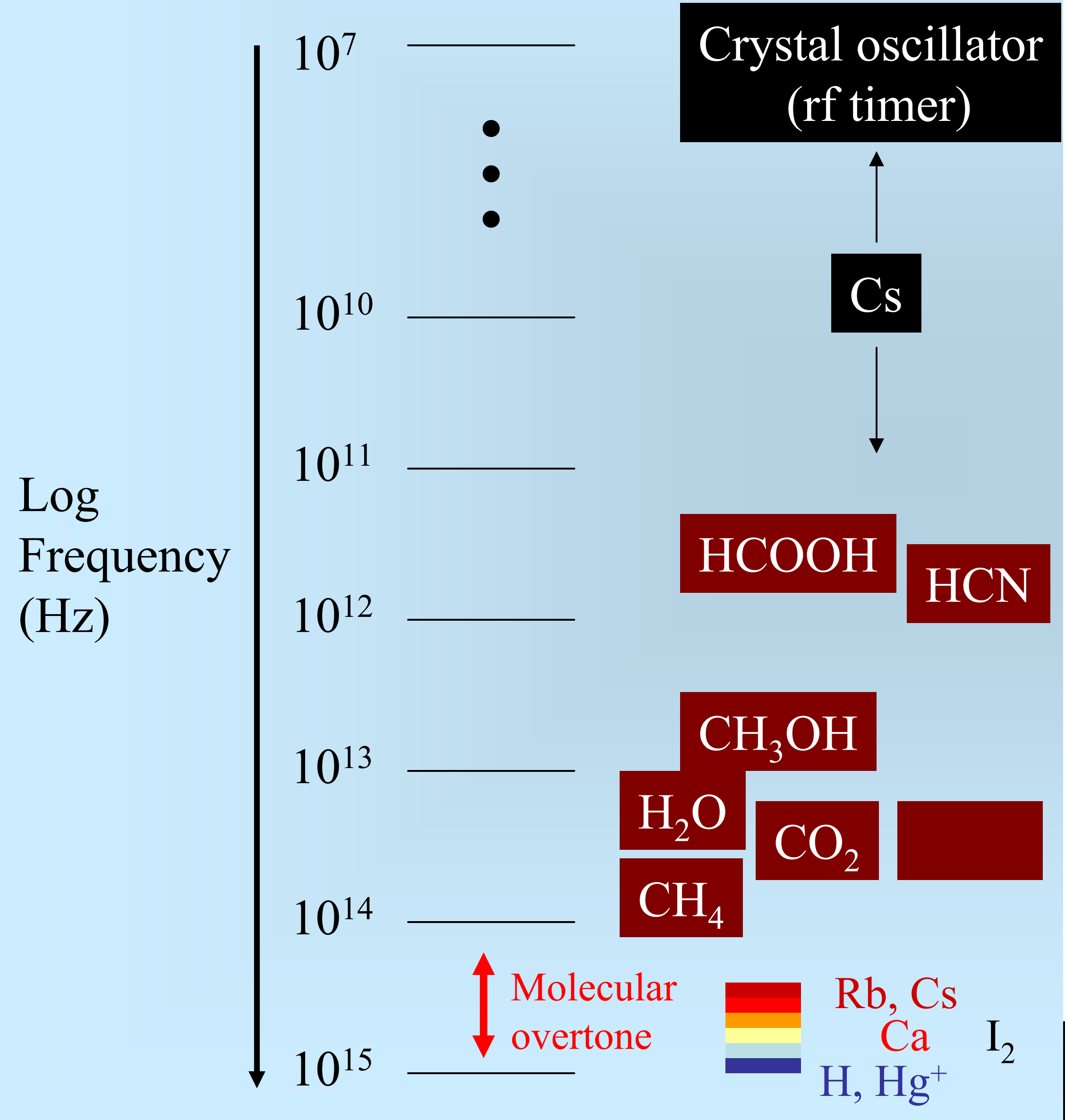
Figure of merit: 10^{-15}

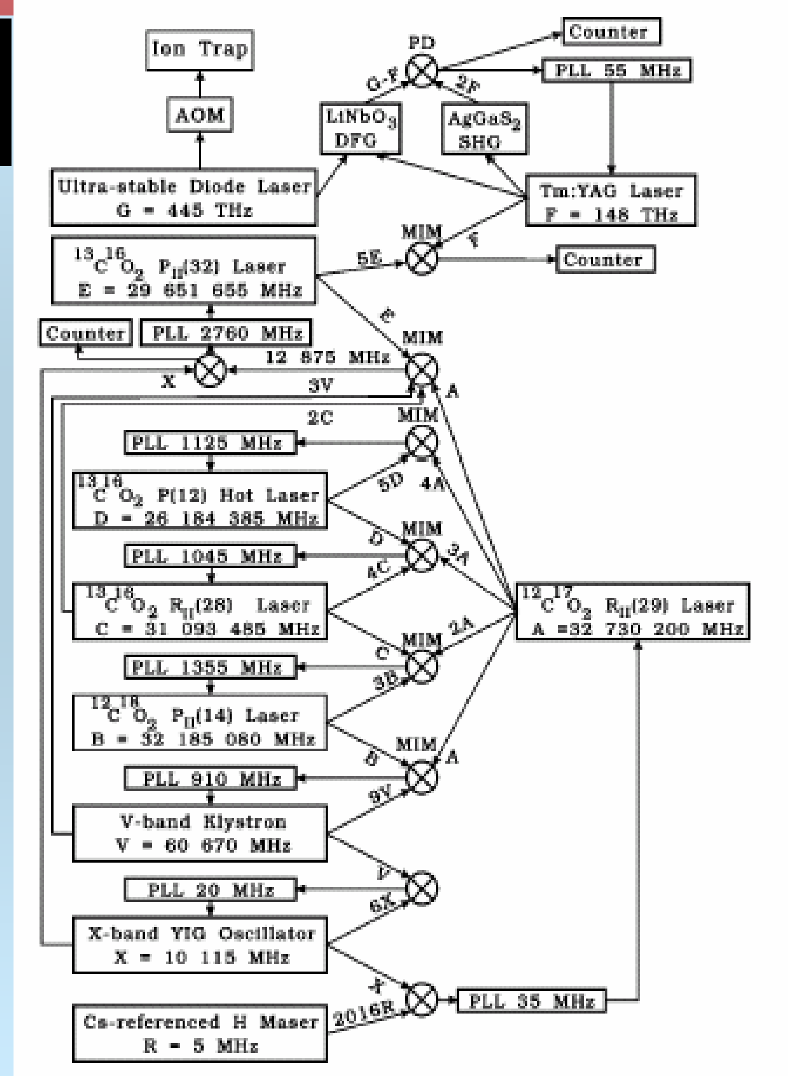
Phase coherence after 10^{15} optical cycles

Progress in optical frequency measurement



Frequency spectrum in optical frequency synthesis





Harmonic frequency chains, PTB, NRC, …
H. Schnatz *et al*., PRL **76**, 18 (1996).

The First Optical Frequency Chain

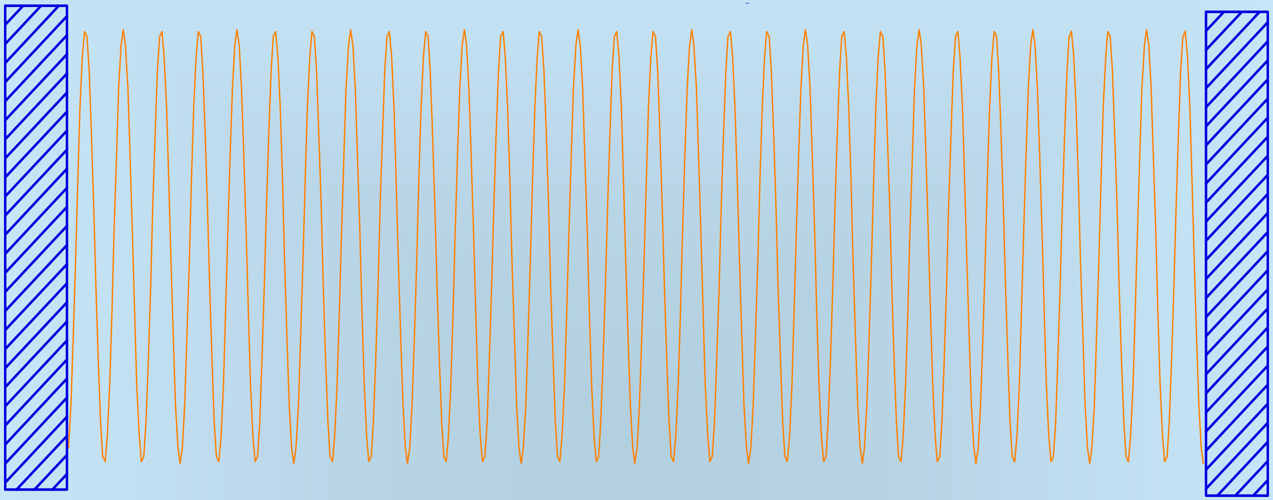
NBS (NIST): measurement of speed of light, 1972

J. Wells

K. Evenson

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

Stable optical cavity



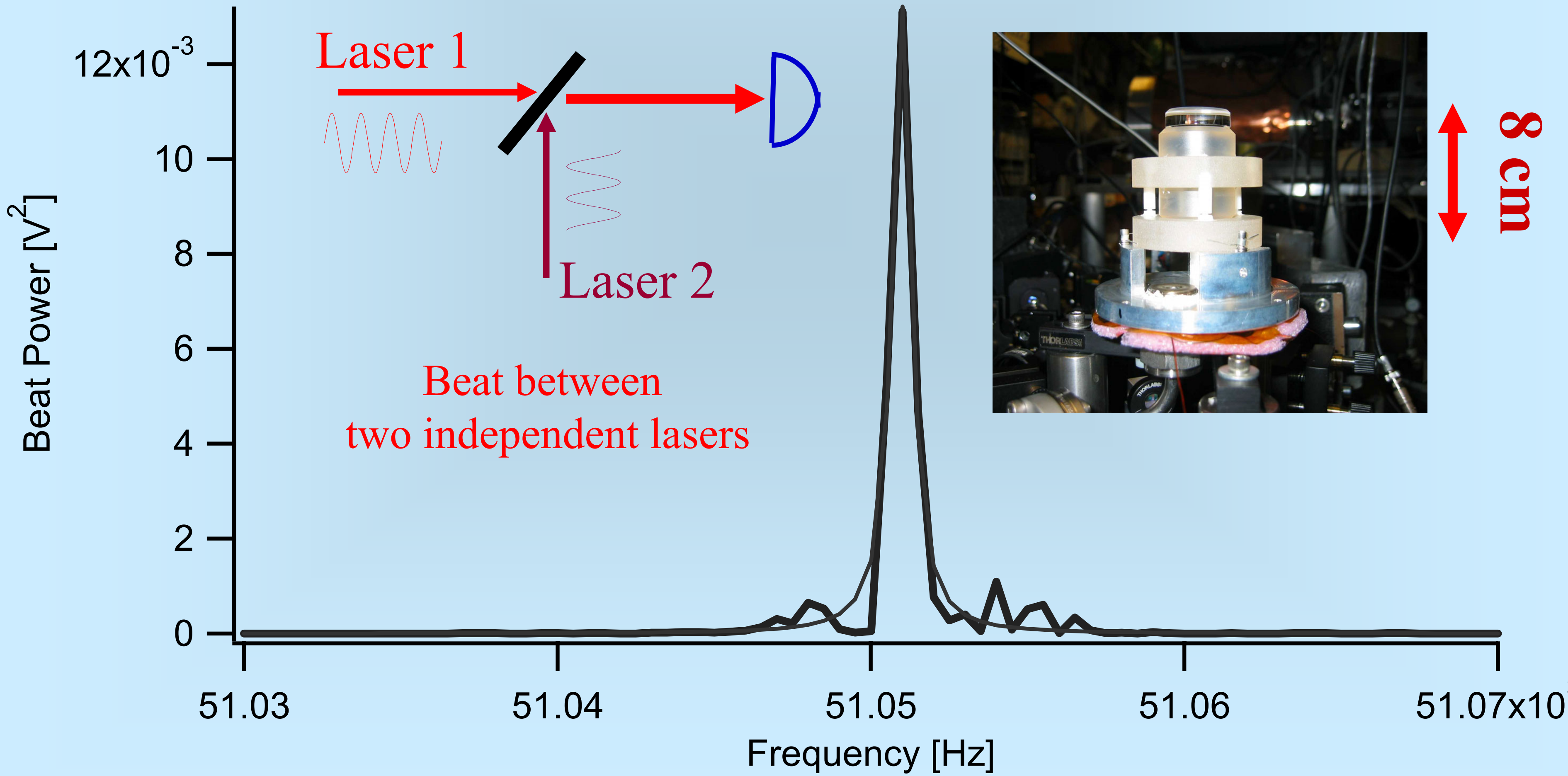
Cavity length 1 m	:	fits 10^6 optical waves	**(10^{-6})**
Finesse 10^5	:	error amplified by 10^5	**(10^{-11})**
Division of a cycle	:	10^4	**(10^{-15})**

Optical phase remains coherent within 1 radian after 10^{15} optical cycles

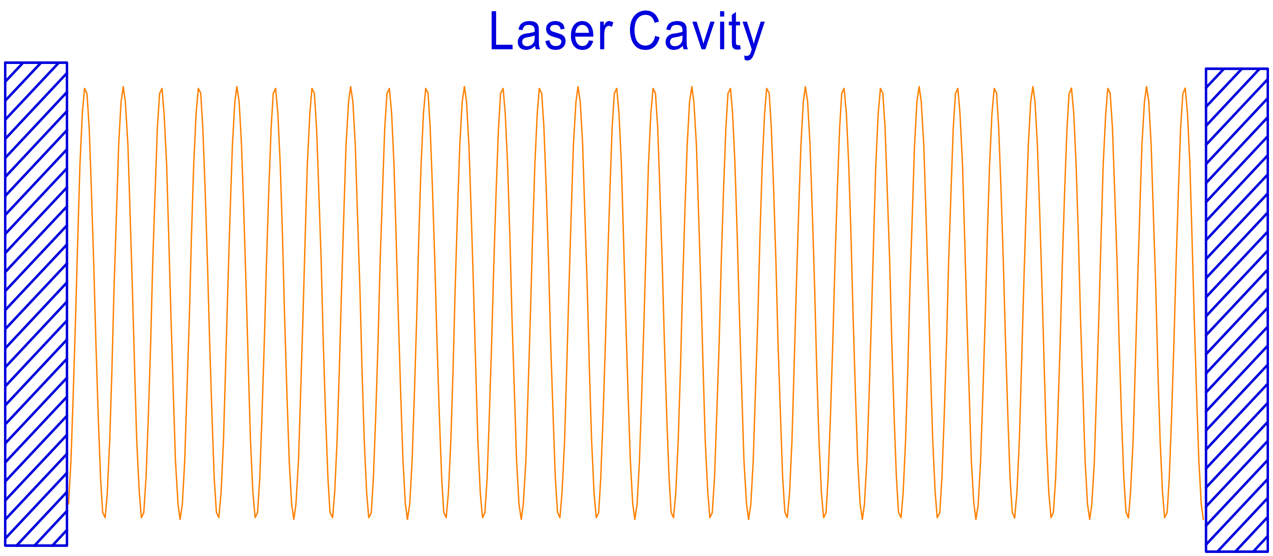
M. Notcutt *et al.*, Opt. Lett. 30, 1815 (2005).

Stability ~ 1 x10^{-15} at 1 s

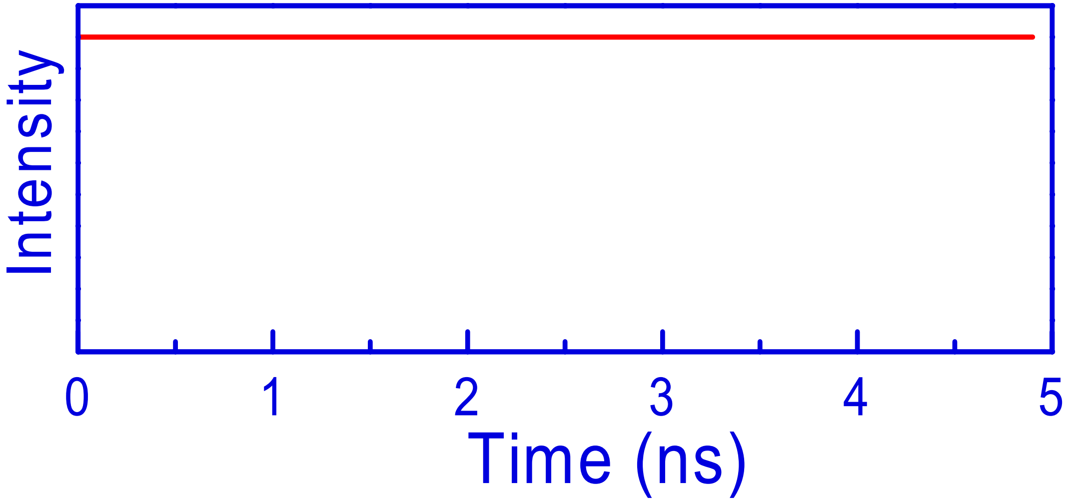
Laser linewidth ~ 0.5 Hz



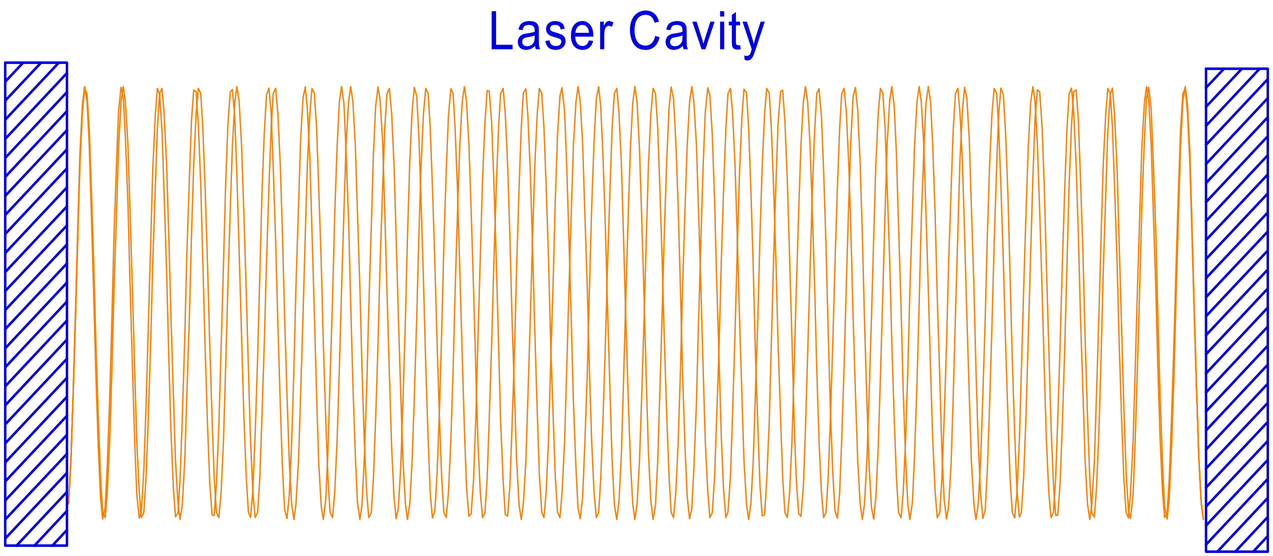
Modelocking



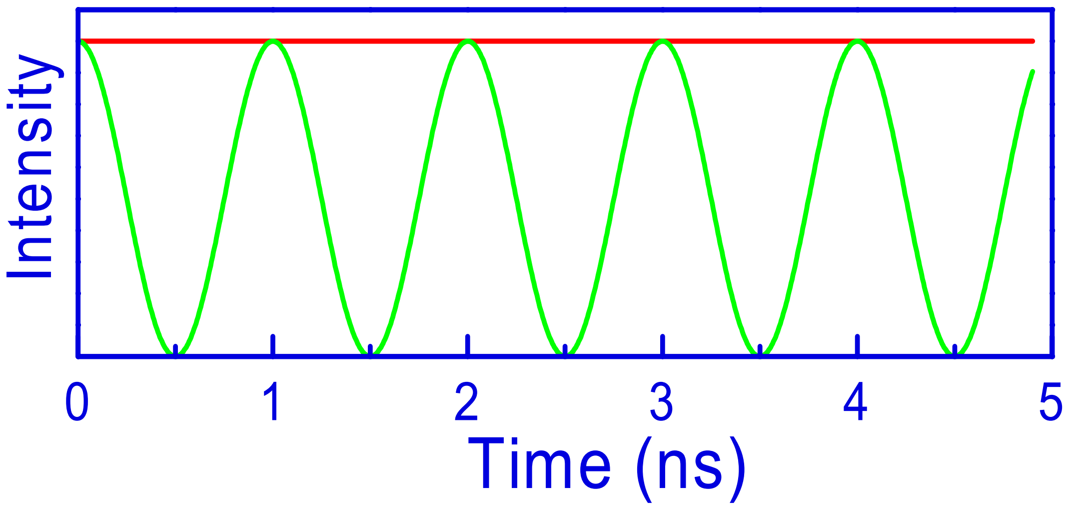
Single mode
cw laser



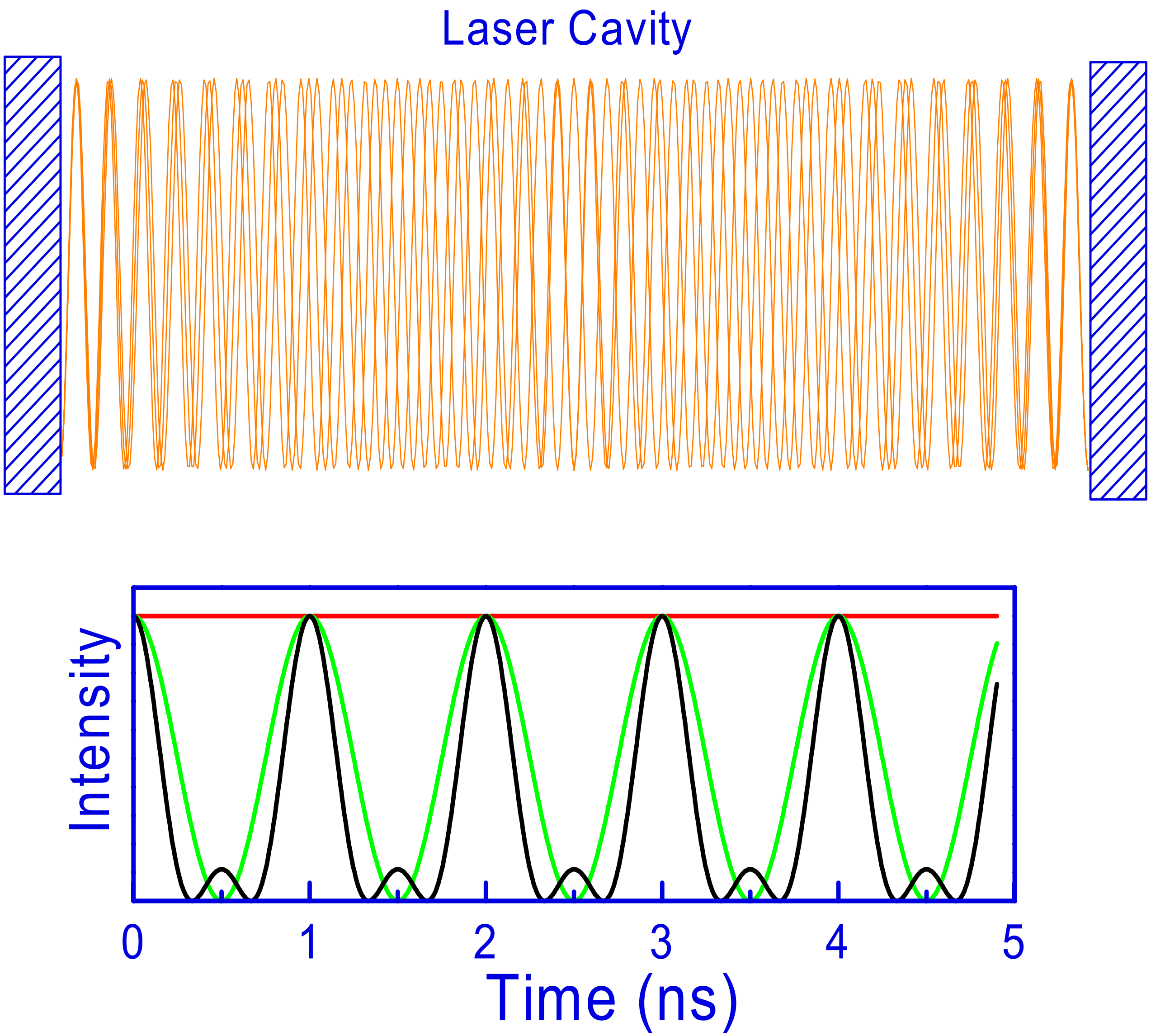
Modelocking



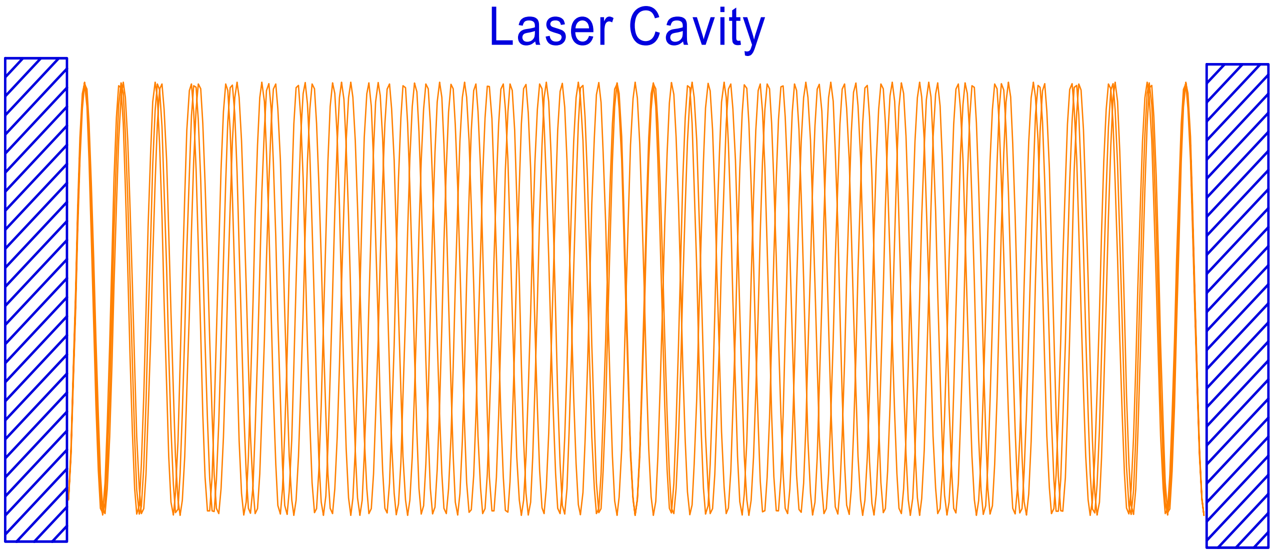
2 modes



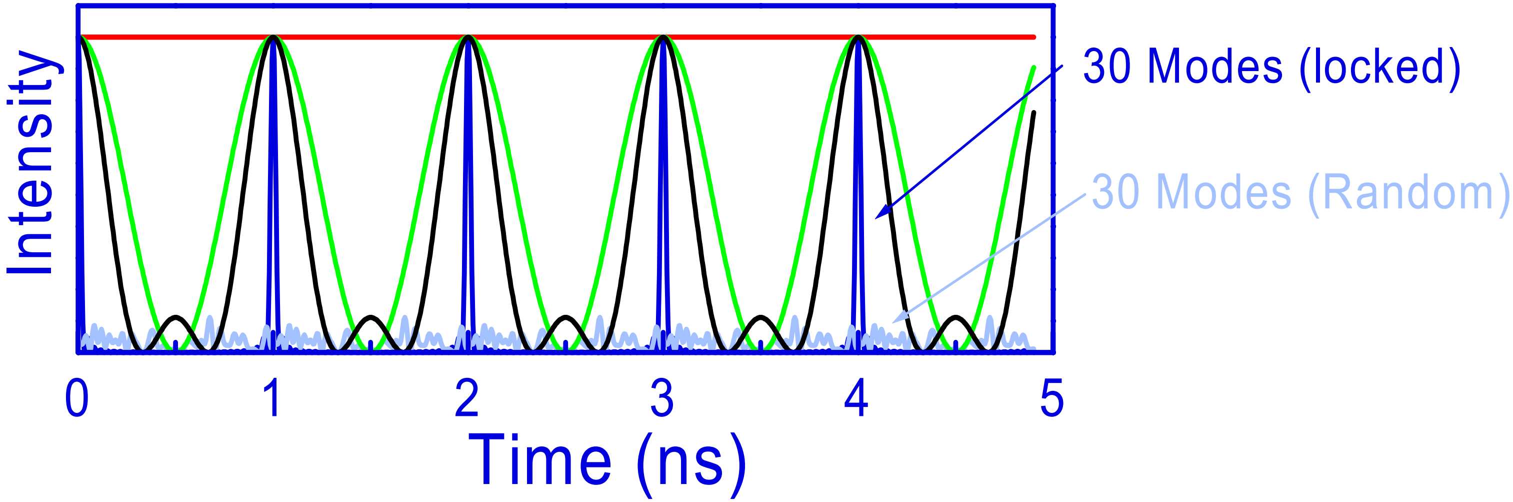
Modelocking



Modelocking

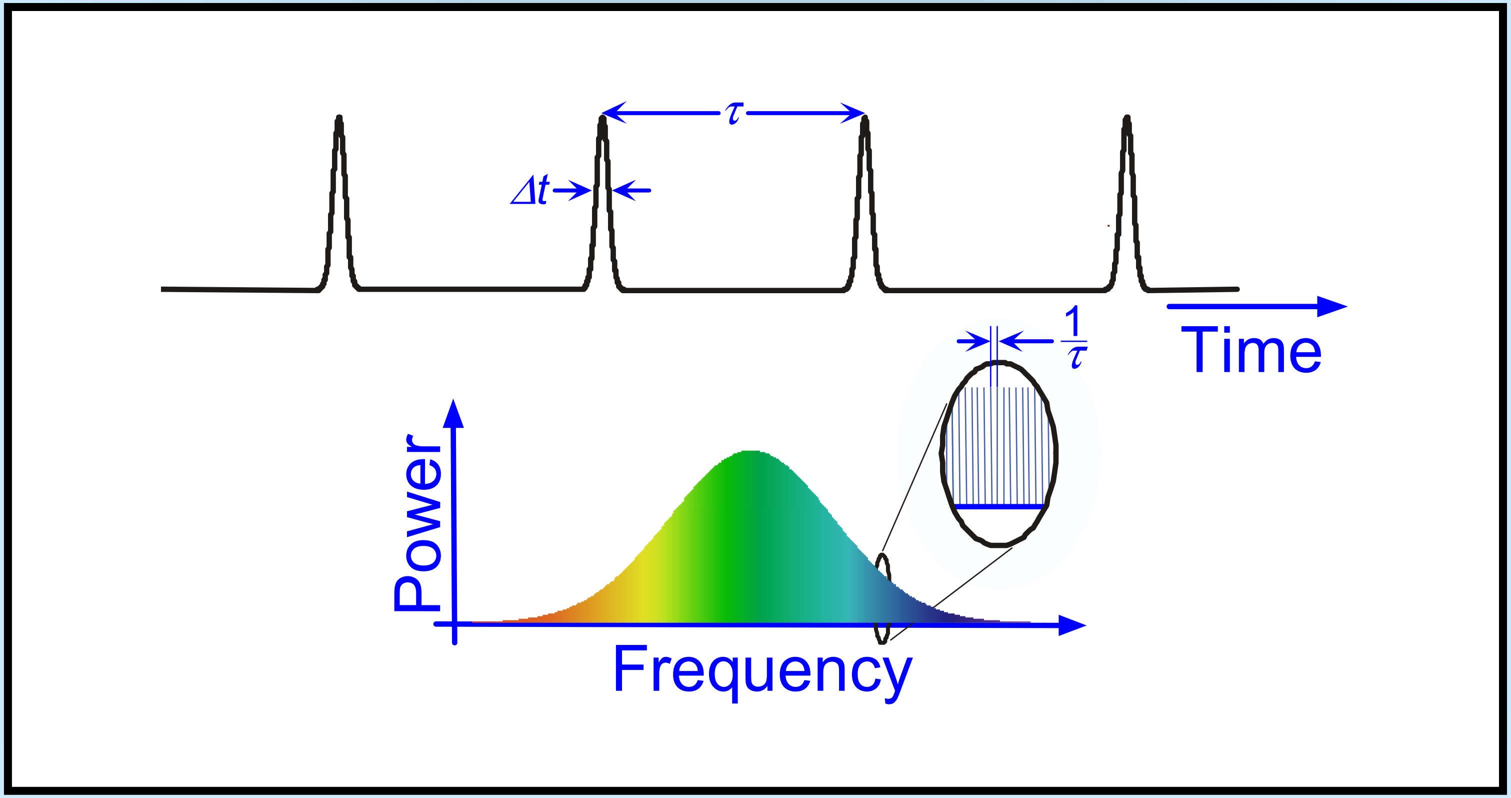


- Constructive interference between phase locked cavity modes

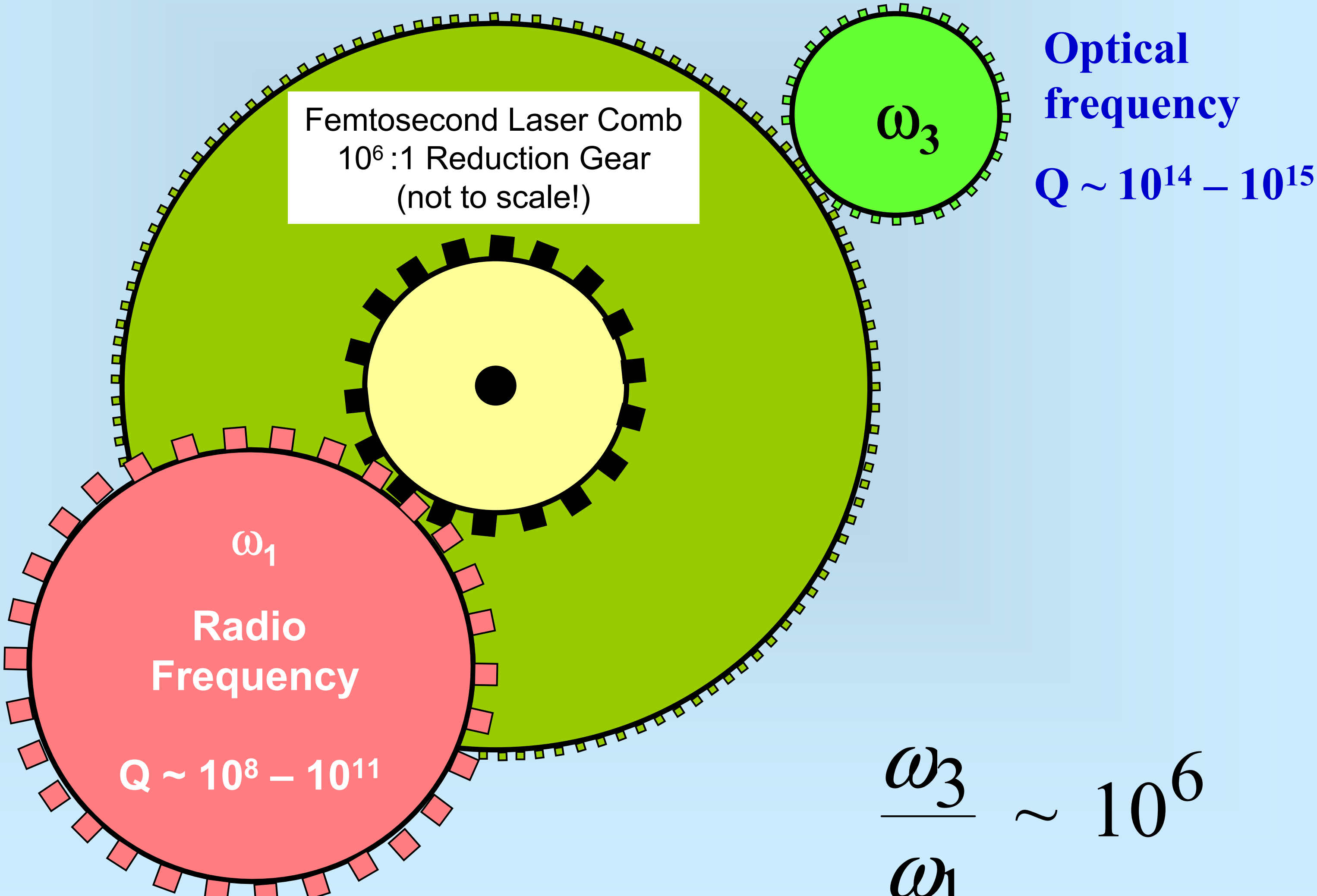


Frequency Spectrum of Mode-Locked Laser

- Temporal pulse width ⟷ Spectrum bandwidth
- Train of pulses ⟷ comb of frequencies



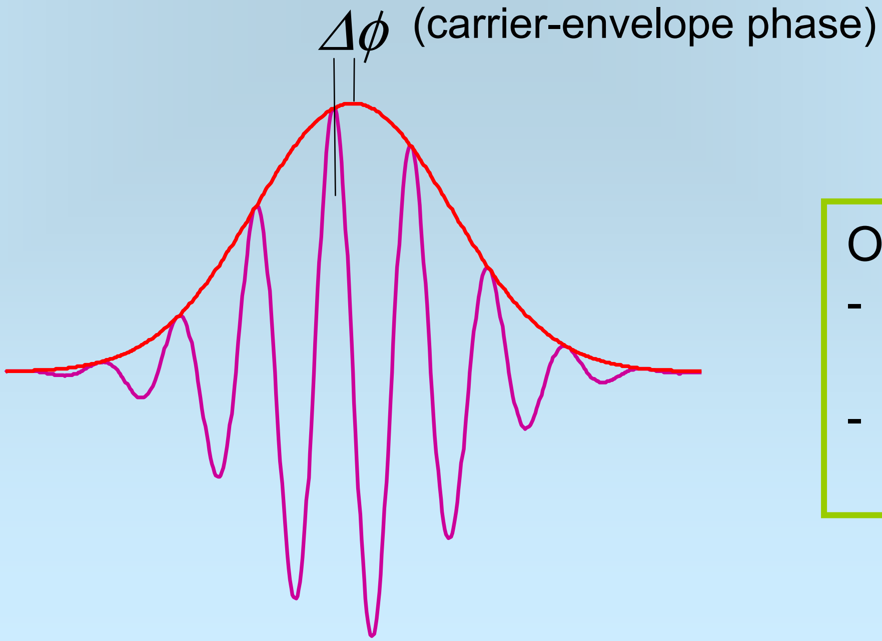
Clockwork for optical frequency standards
– Optical frequency synthesizer



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

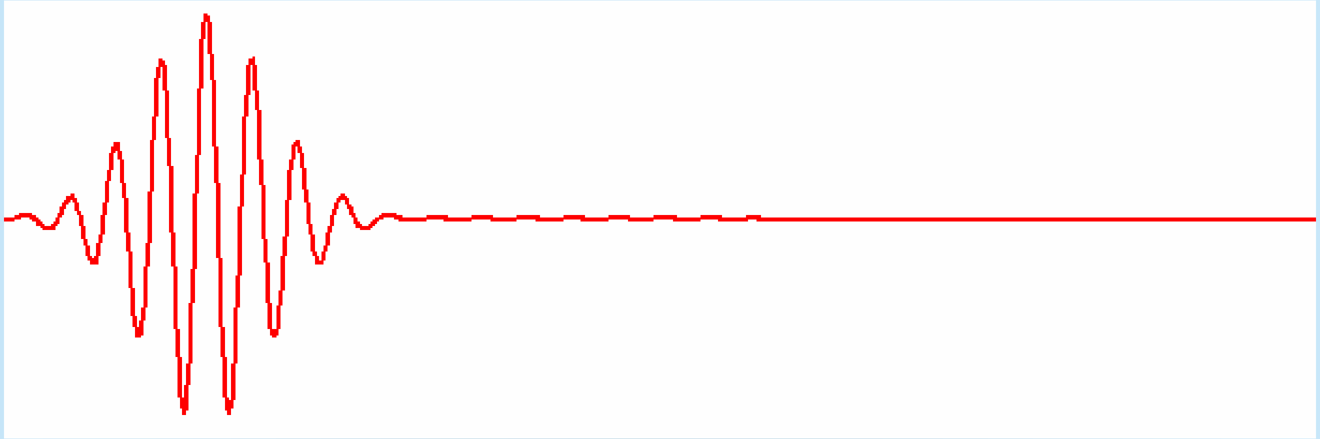
Absolute Pulse Phase

- Generally in optics:
  - absolute phase never matters
  - only relative phases
- Ultrashort pulse (~10 fs or less)
  - envelope provides "absolute" phase reference



Of course:
- arbitrary envelope "absolute" phase
- but comparable to clock

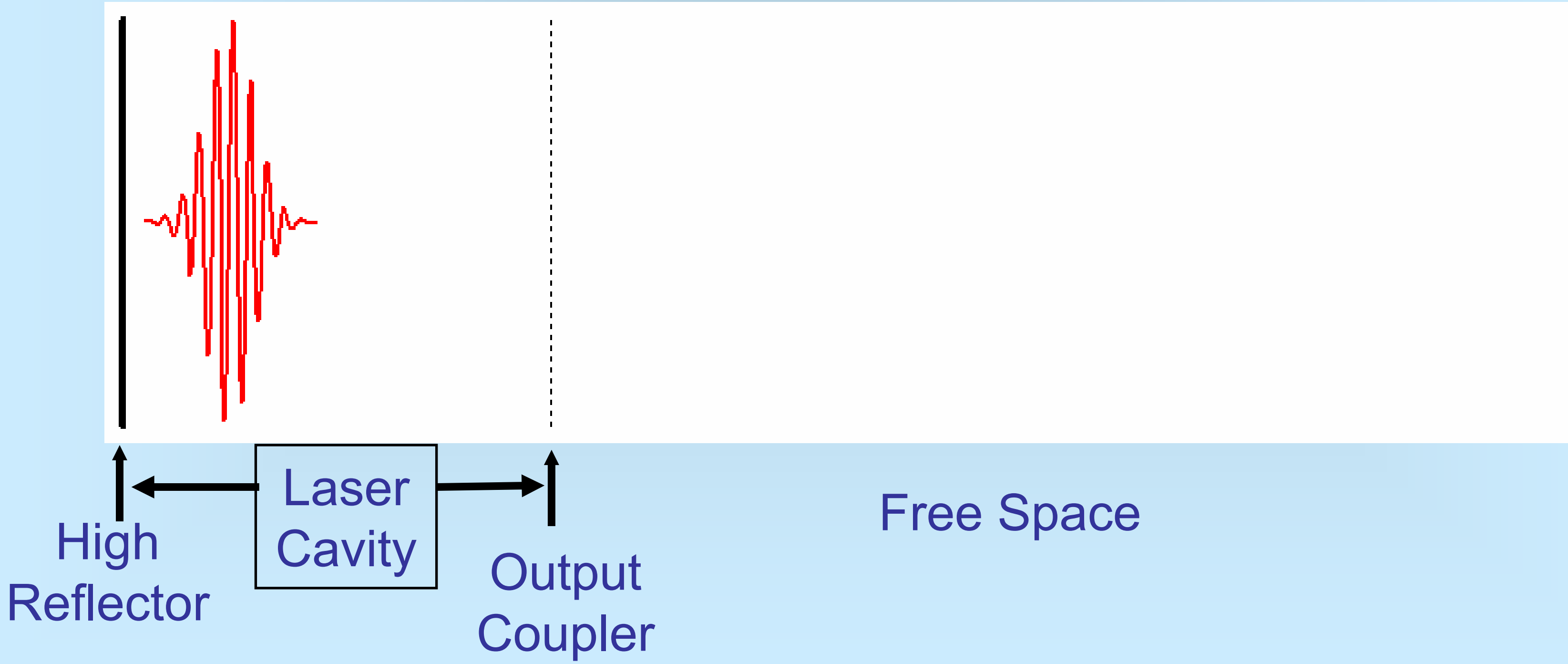
Group vs. Phase Velocity



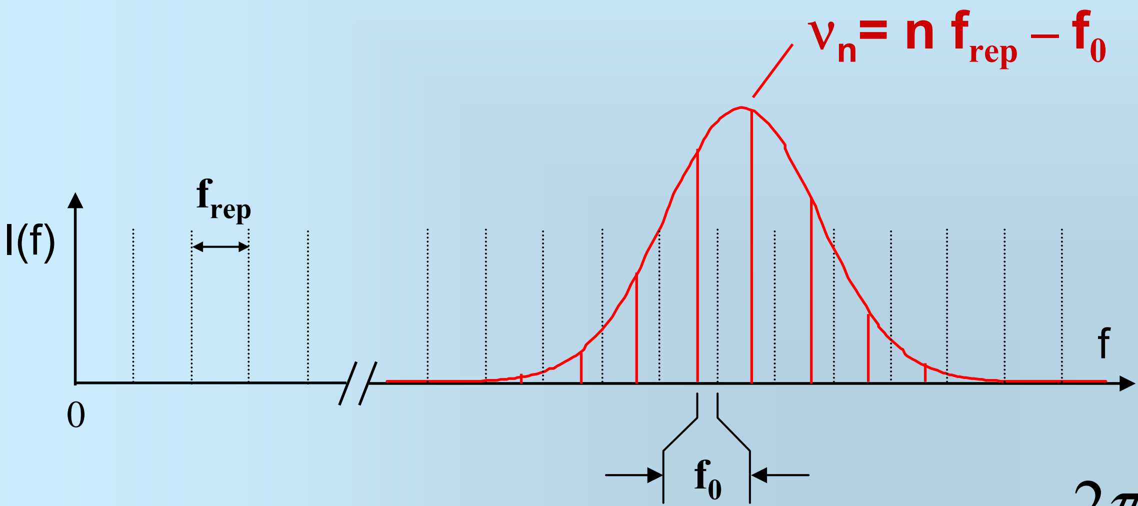
- In any material, the group and phase velocities differ
- Therefore carrier phase slowly drifts through the envelope as a pulse propagates

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



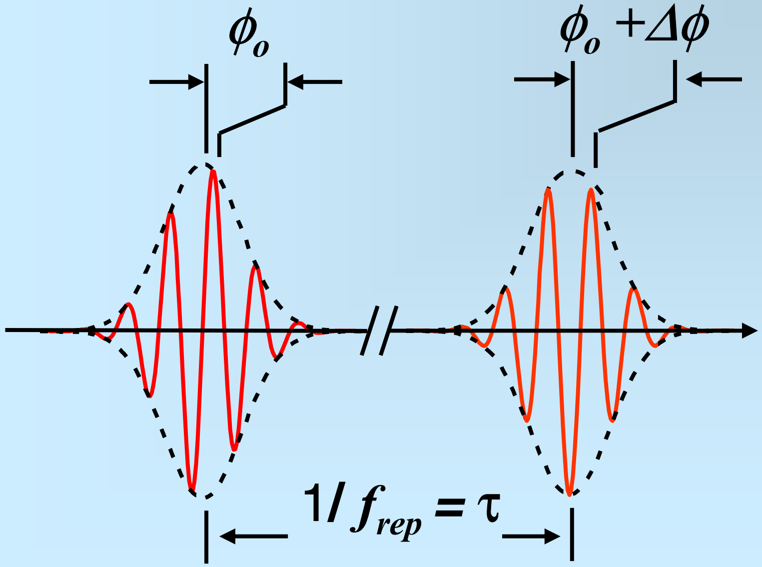
Time-Domain Consequences of Frequency-Domain Control



f_{rep} = Comb spacing
f_0 = Comb offset from harmonics of f_{rep}
$\Delta\phi$ = Phase slip b/t carrier & envelope each round trip

$$2\pi\nu \cdot \tau_{r.t} + \Delta\phi = 2n\pi \rightarrow$$

$$\nu = nf_{rep} - \underbrace{\Delta\phi\, f_{rep}/2\pi}_{f_0}$$

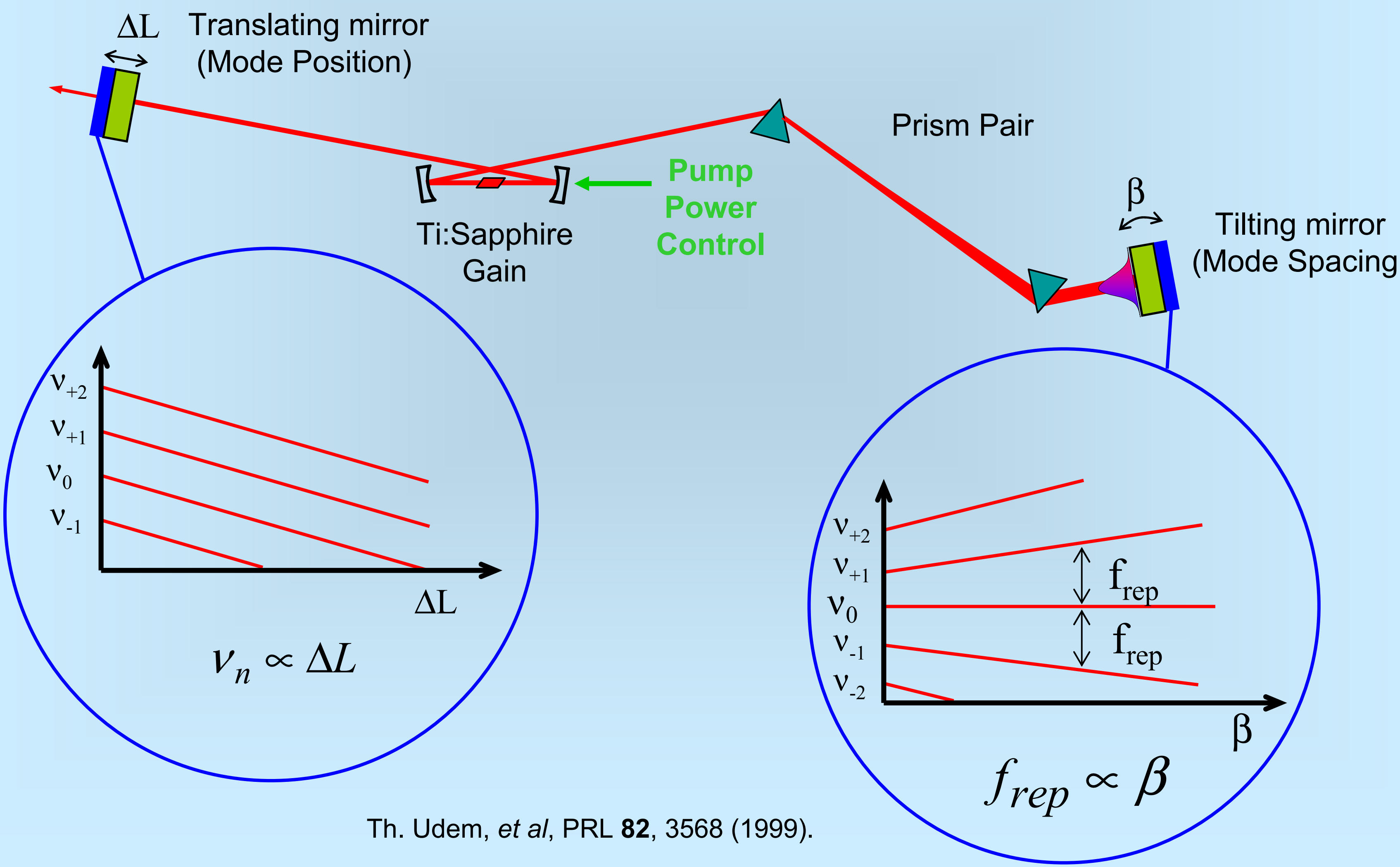


Hänsch, 1978.
Xu, Krausz *et al*., Opt. Lett. **21**, 2008 (1996).
Hänsch, Udem, Holzwarth *et al*., 1999.
Udem *et al*., Opt. Lett. **24**, 881; PRL **82**, 3568 (1999).

Phase-Controlled 10 fs Laser

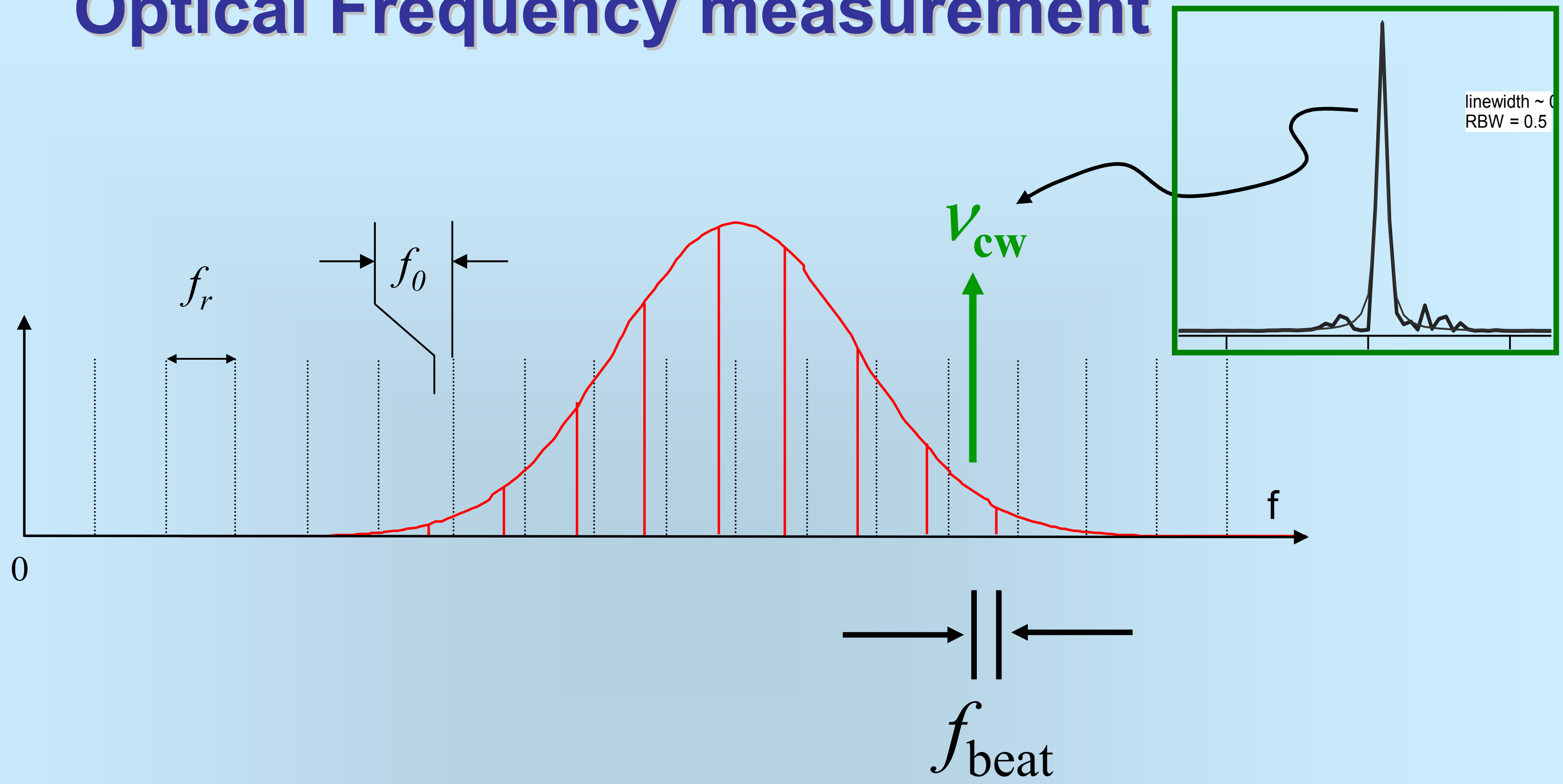
Kerr-Lens Modelocked Ti:Sapphire: large bandwidth, shortest pulse, (amazingly) simple

Orthogonal control of two degrees of freedom



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

Optical Frequency measurement

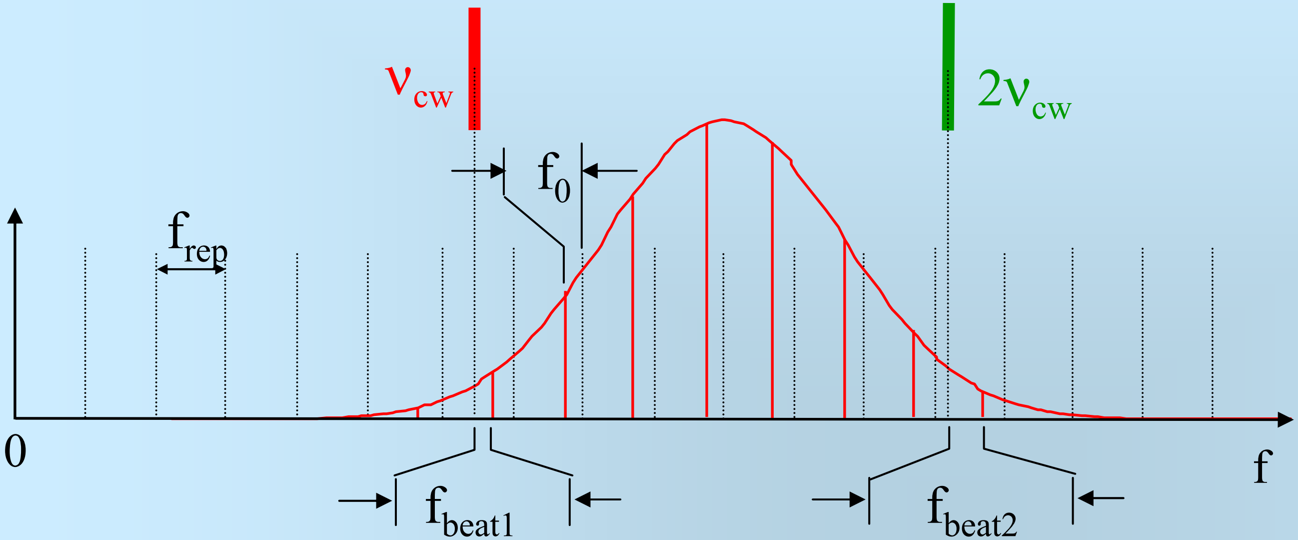


$$f_{beat} = n f_r + f_0 - \nu_{cw}$$

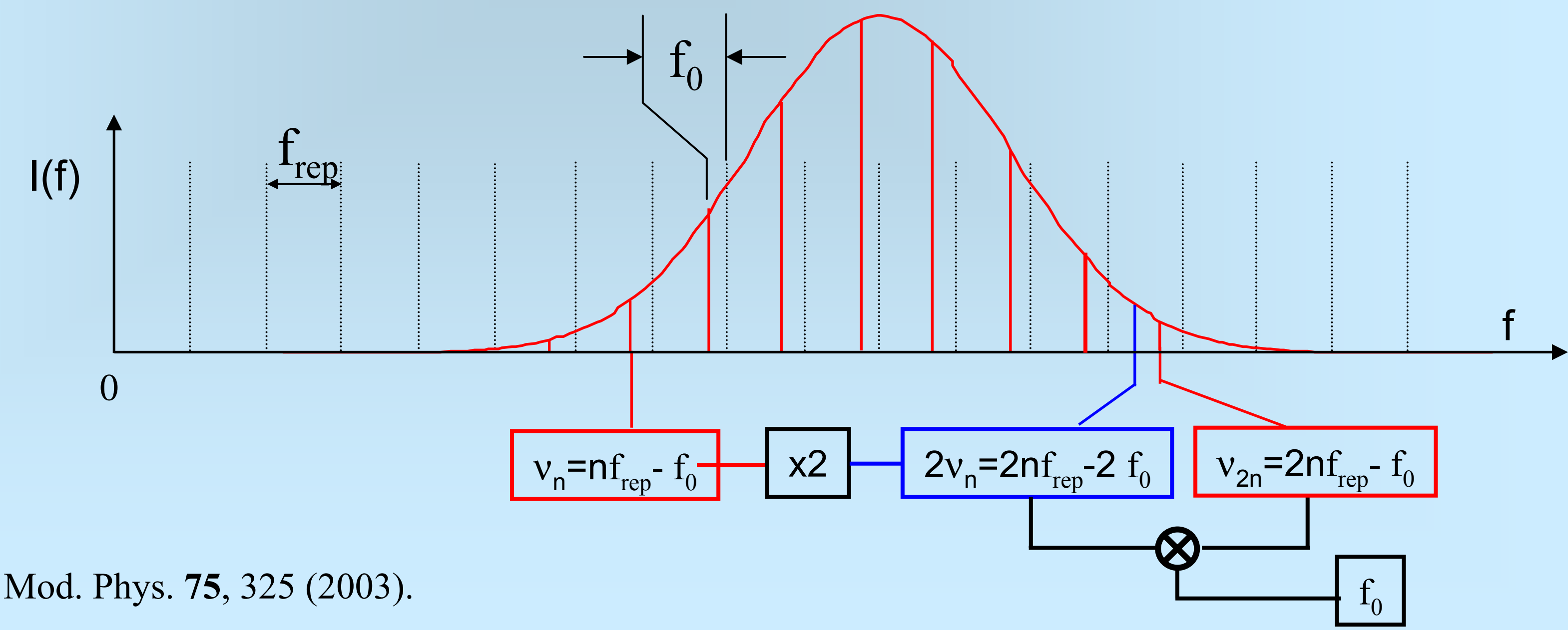
$$f_{beat} + \Delta f_{beat} = n(f_r + \Delta f_r) + f_0 - \nu_{cw}$$

$$n = \Delta f_{beat} / \Delta f_r$$

Optical octave bandwidth
- a quick way to measure f_0

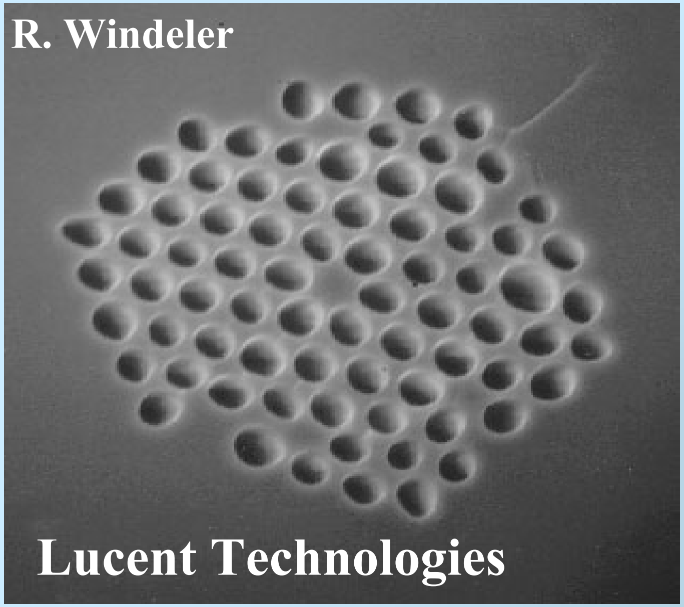


$$f_0 = 2f_{beat1} - f_{beat2}$$



Cundiff & Ye, Rev. Mod. Phys. **75**, 325 (2003).

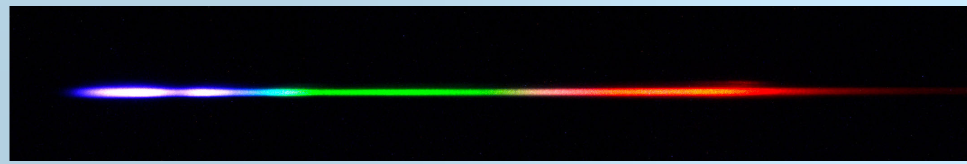
Serious nonlinear optics

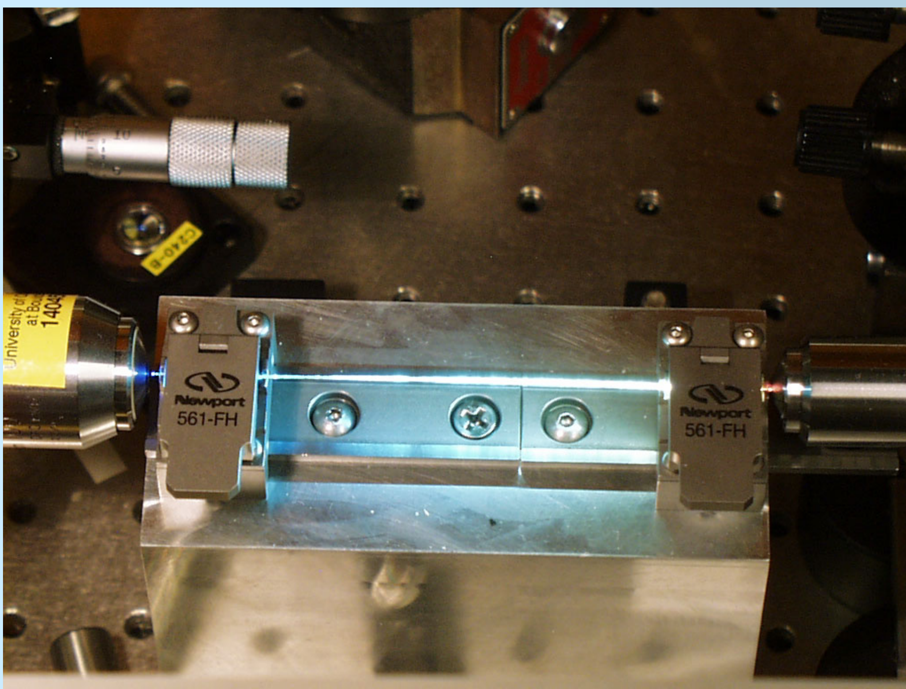


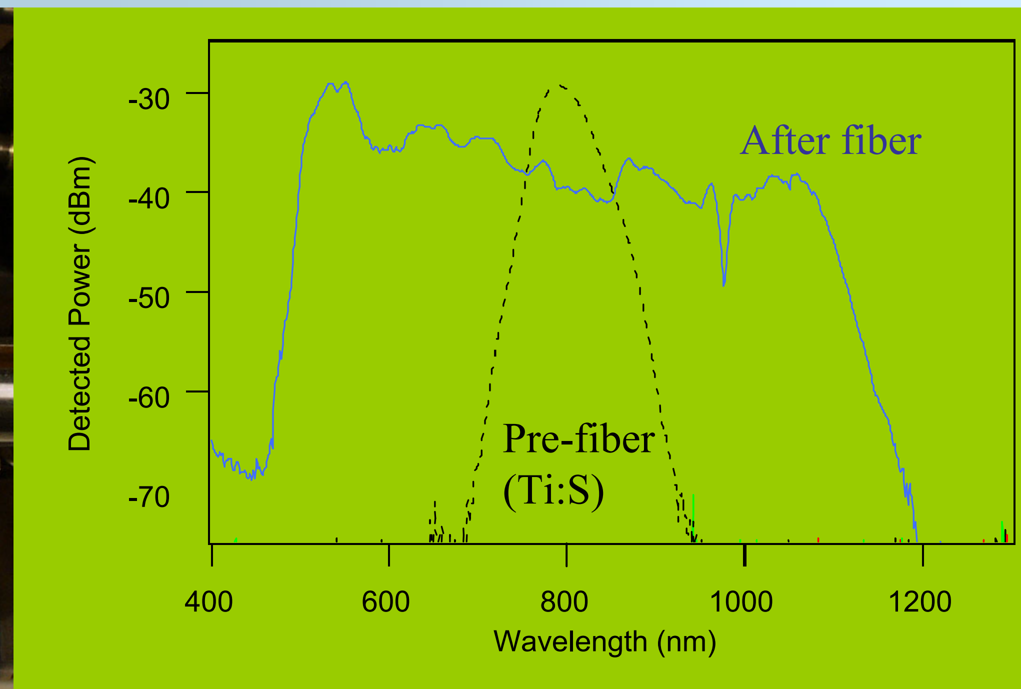
J.K Ranka, et al, Opt. Lett. ***25****, 25 (Jan. 2000)*

Microstructured fiber

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

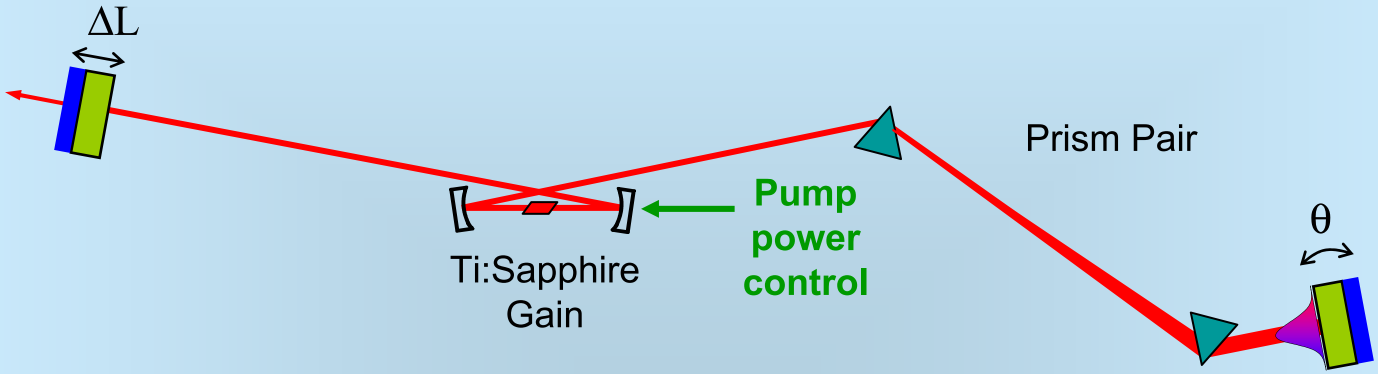




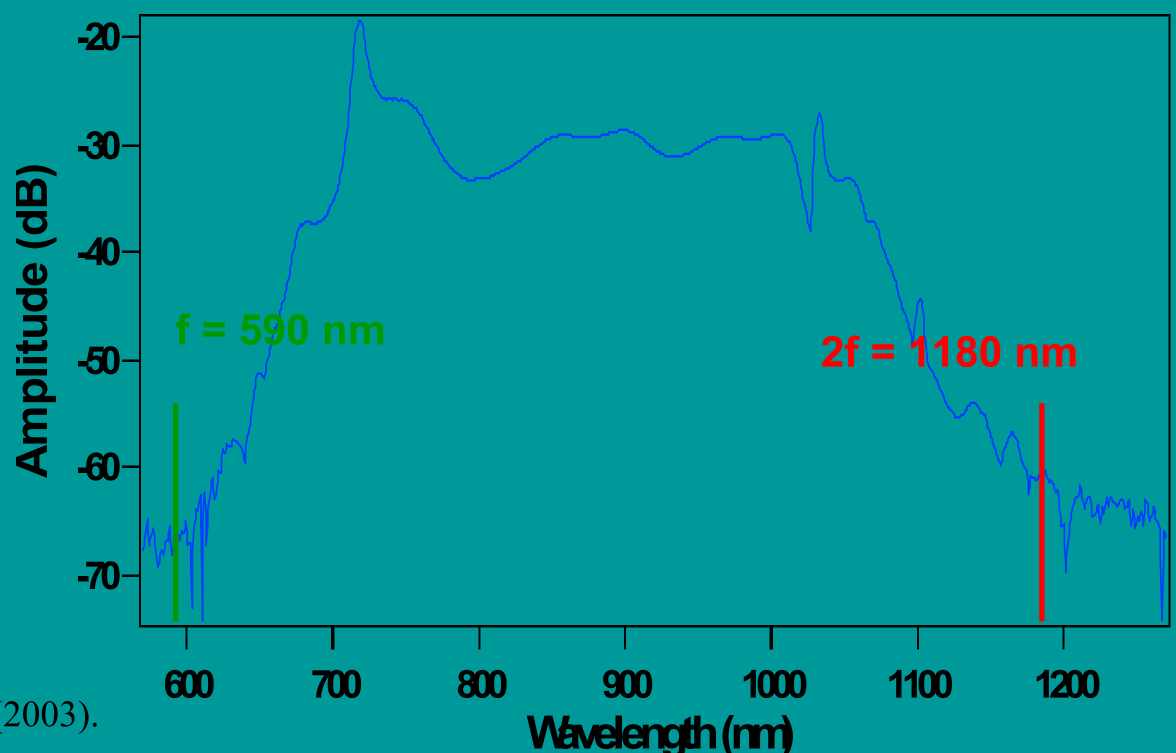


One laser alone can do the trick!

Kerr-Lens Mode-locked Ti:Sapphire: large bandwidth, short pulse, (amazingly) simple



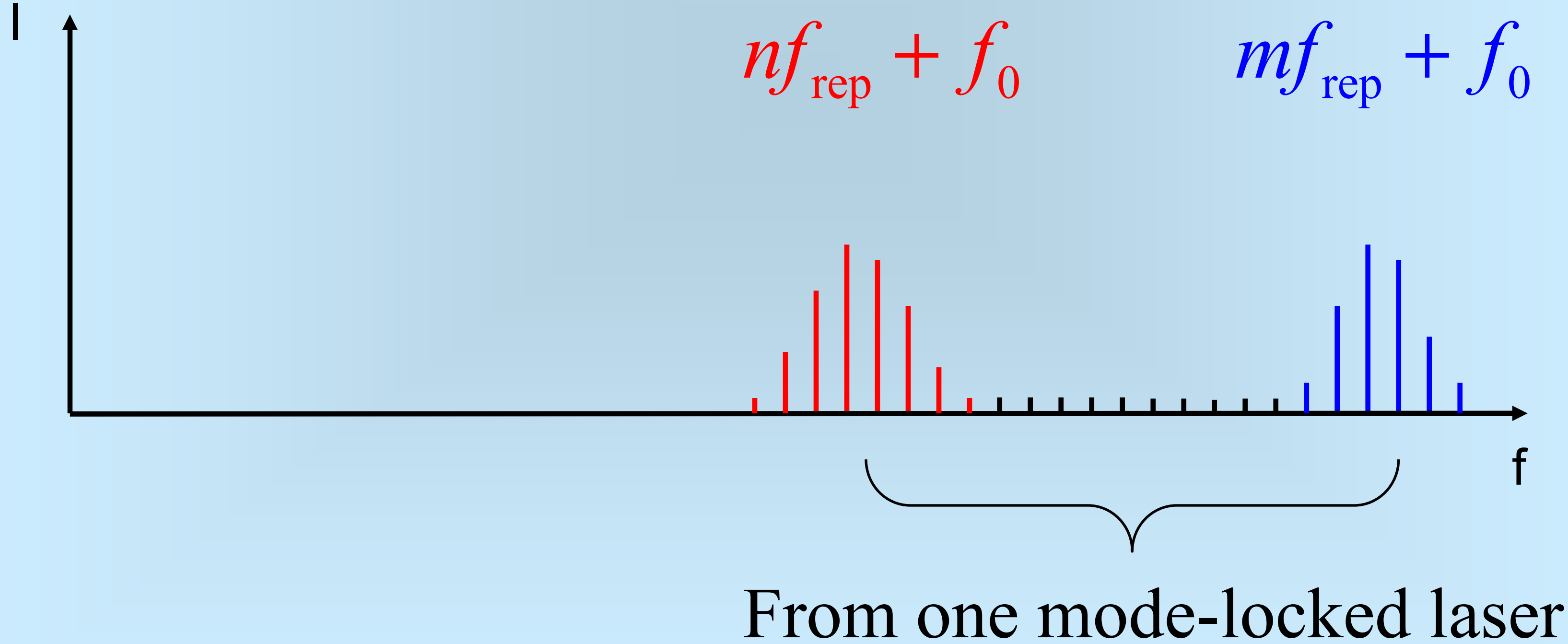
Directly from the mode-locked laser



Fortier et al., Opt. Lett. **28**, 2198 (2003).

Carrier-envelope frequency independent optical clockwork

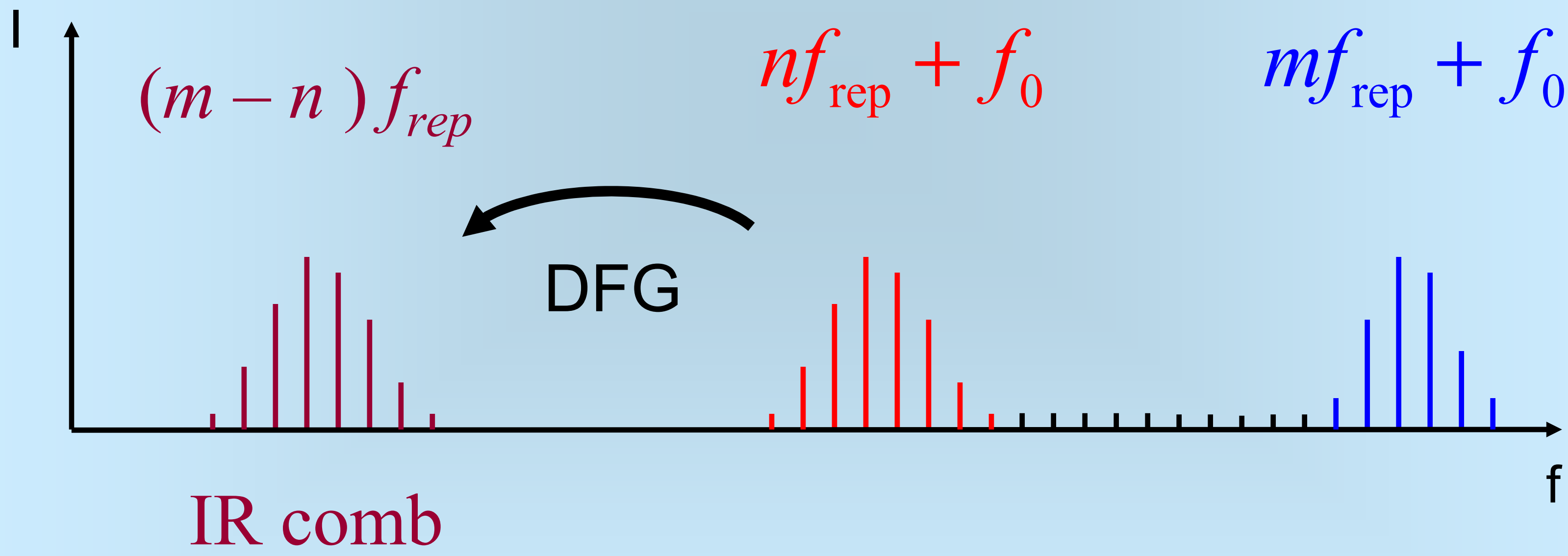
Carrier-envelope frequency independent DFG comb



O. Mücke et al., Opt. Lett., in press (2004).

Carrier-envelope frequency independent optical clockwork

Carrier-envelope frequency independent DFG comb



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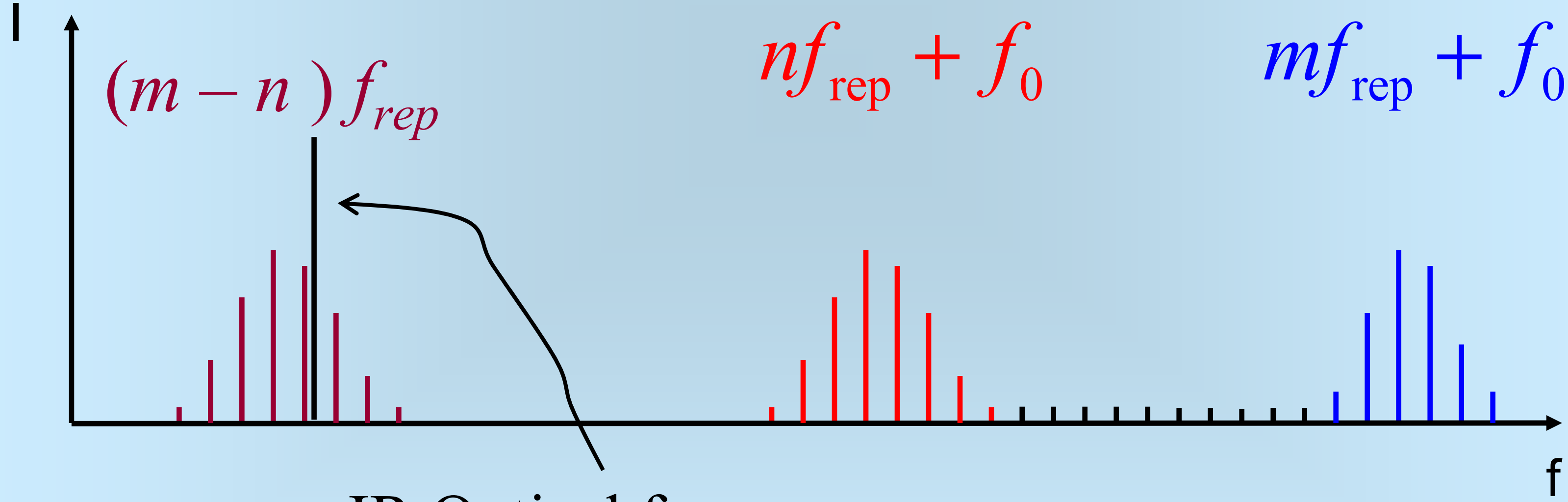
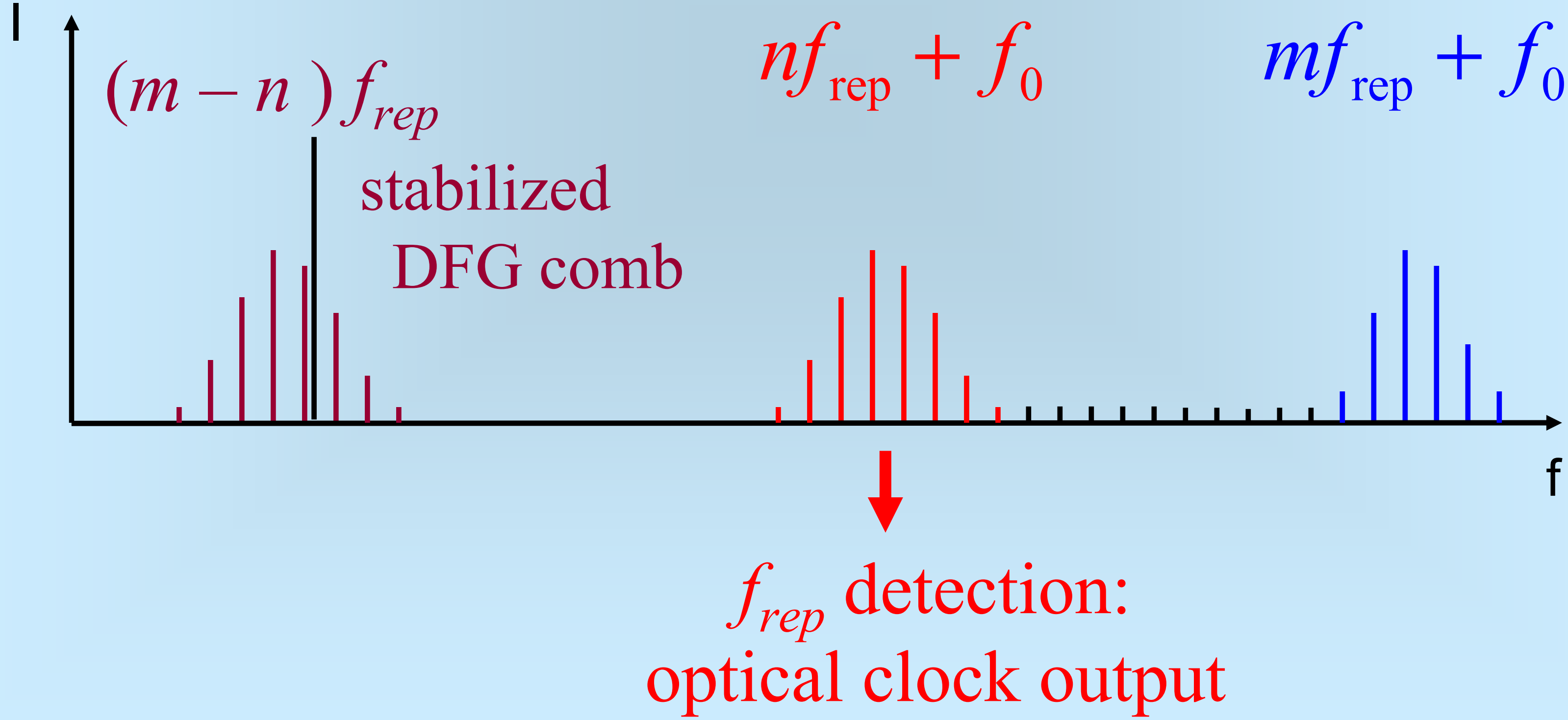


IR Optical frequency standard:
HeNe laser stabilized on CH_4 at 3.4 μm

Carrier-envelope frequency independent optical clockwork

Carrier-envelope frequency independent DFG comb



Frequency domain applications:

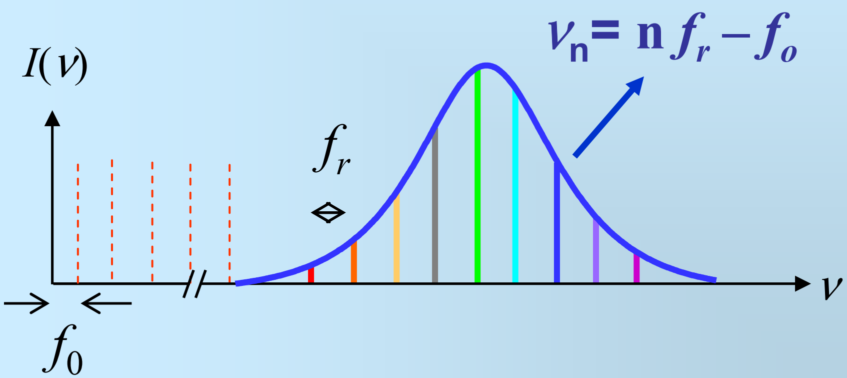
- Optical frequency synthesizer
- Optical atomic clock
- Timing signal transfer
- Time-frequency combined spectroscopy

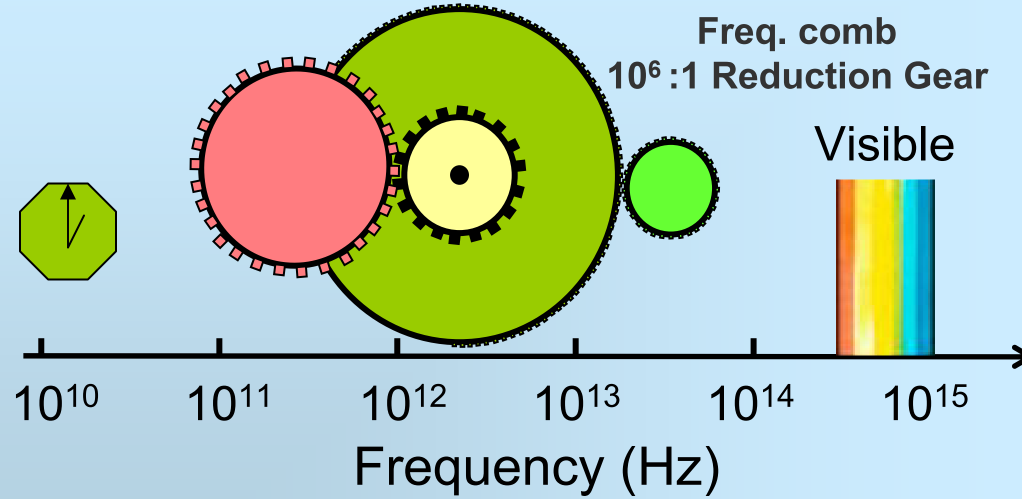
Time domain applications:

- Carrier-envelope phase control
- Coherent pulse synthesis
- Nonlinear Microscopy
- Gainless amplifier

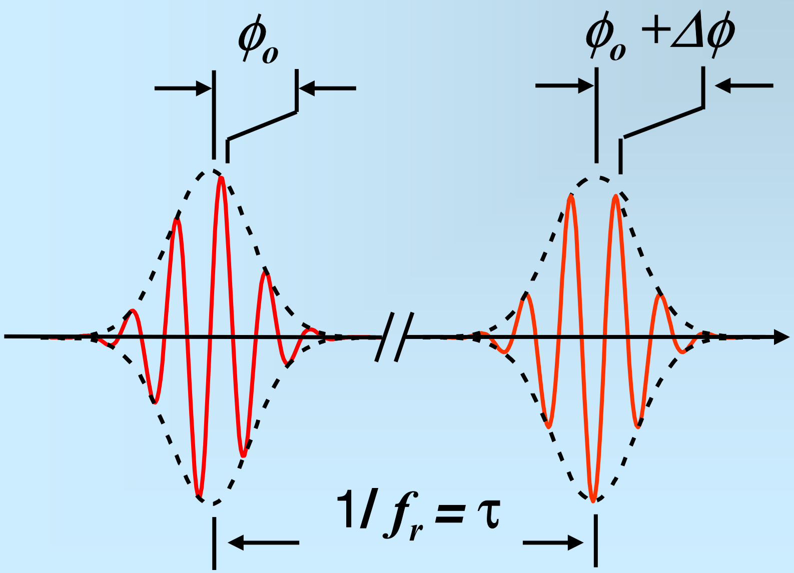
Frequency comb: state-of-the-art

- Optical Synthesizer





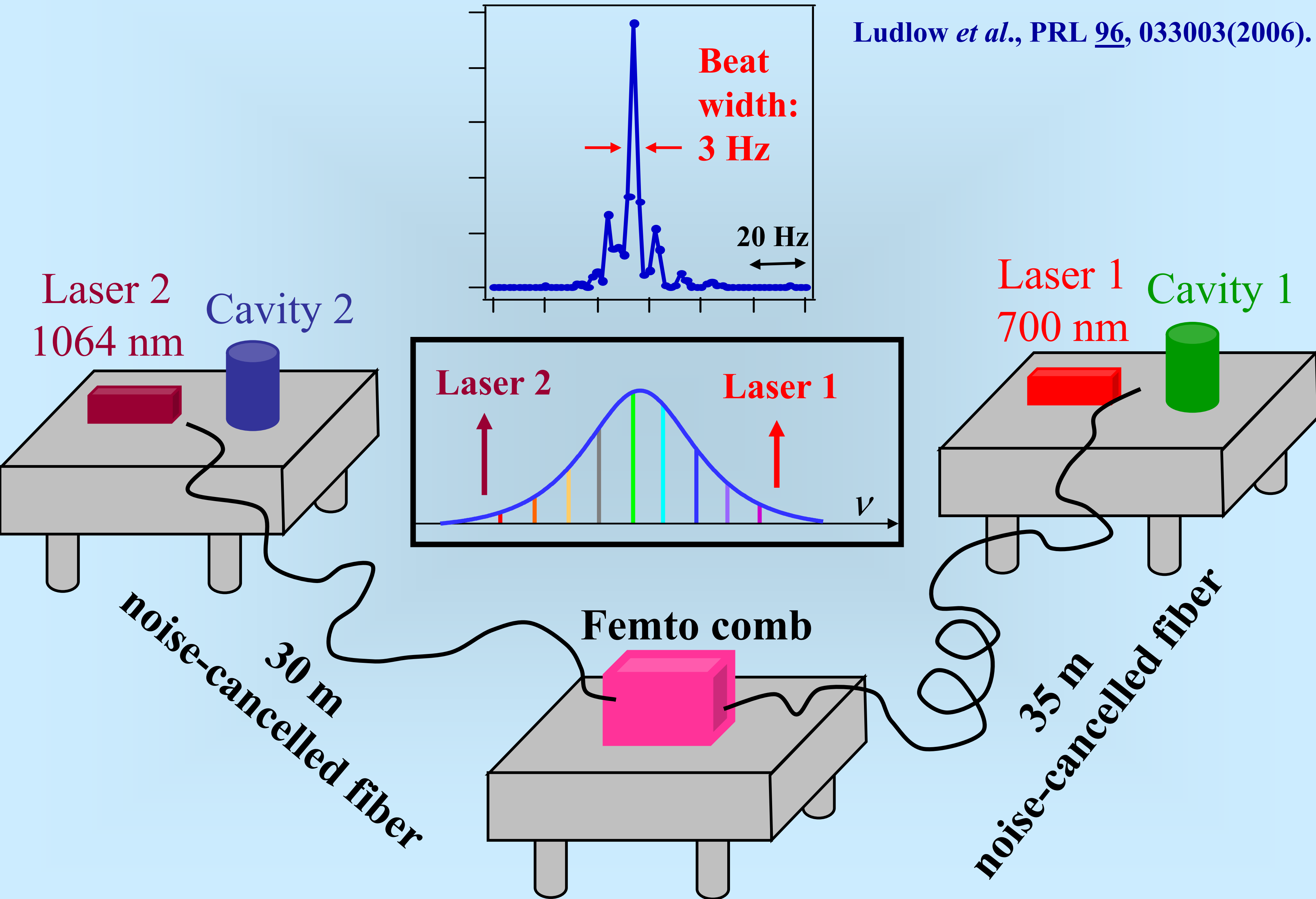
- Waveform control



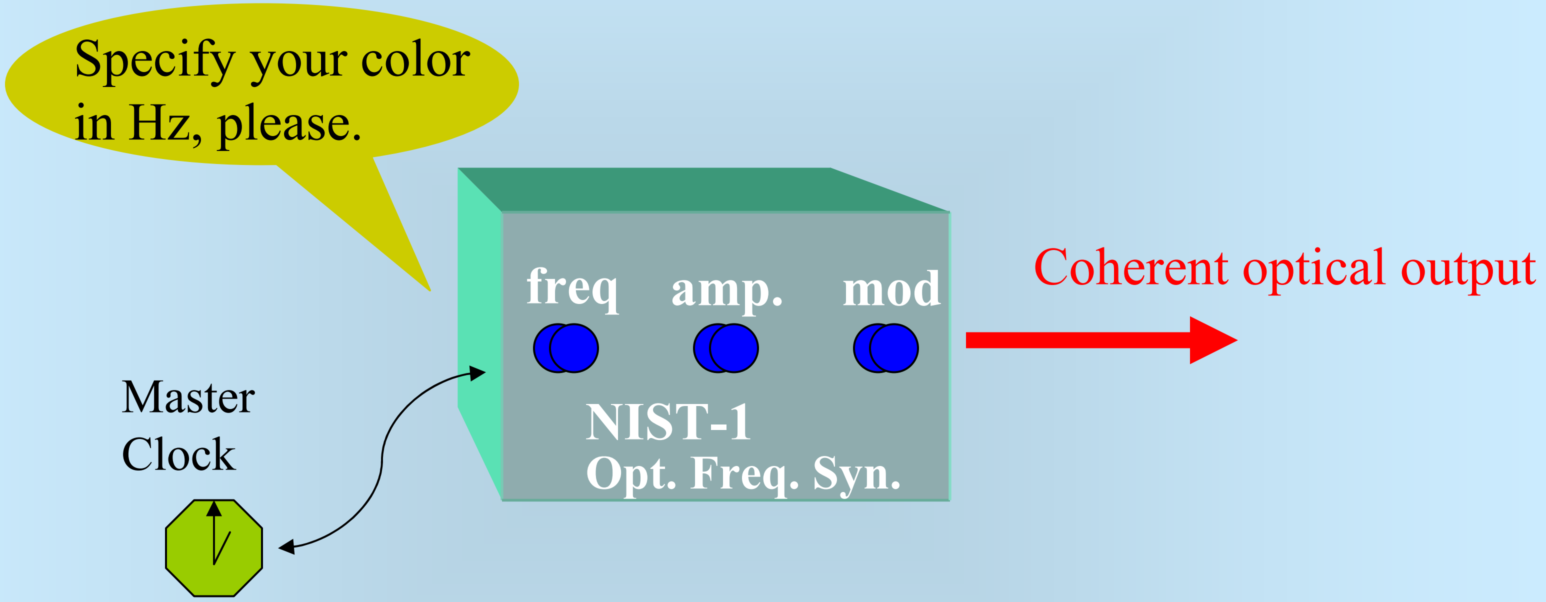
- f_r uniformity < 10^{-18}
- Absolute inaccuracy < 10^{-15}
- Short term instabilities ~ 10^{-15} @ 1s
- Comb linewidth ~ 0.3 Hz
- $\Delta\phi < 10^{-2}$ rad, timing jitter < 1 fs

Ye & Cundiff, Eds., “Comb” book, Springer (2005).
Udem, Holzworth, & Hänsch, Nature 416, 233 (2002).

Comparison of Hz-linewidth lasers across the visible spectrum



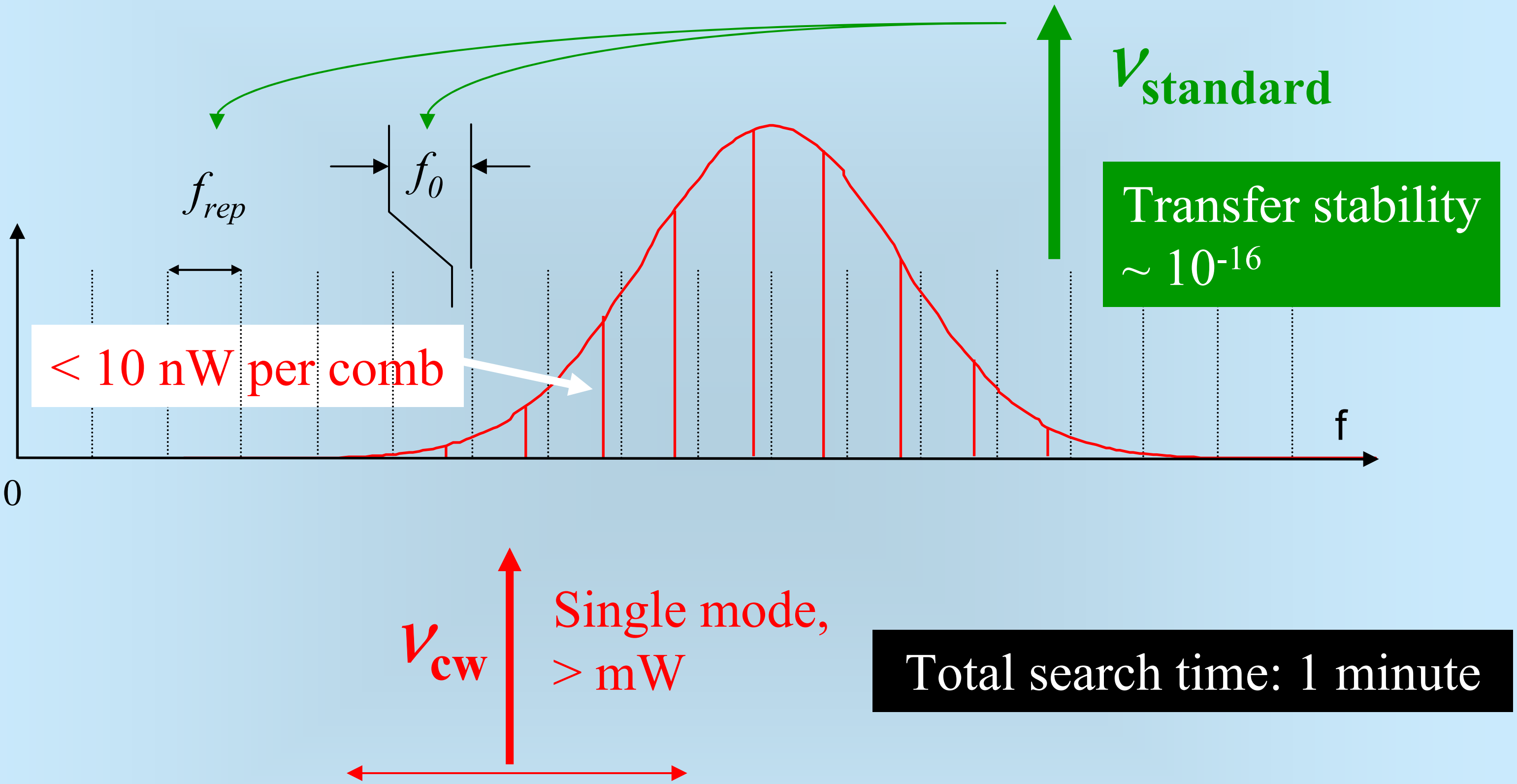
Optical Frequency Synthesizer



Deliver Hz-linewidth anywhere in the optical spectrum!

Simultaneous RF and optical readout

Optical Frequency Synthesizer



Total search time: 1 minute

Jost *et al*., Opt. Express **10**, 515 (2002)

Frequency domain applications:

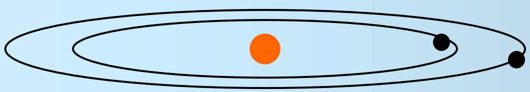
- Optical frequency synthesizer
- Optical atomic clock
- Timing signal transfer
- Time-frequency combined spectroscopy

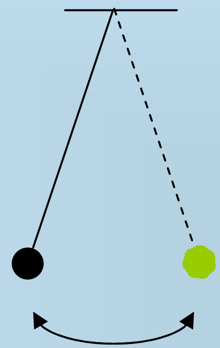
Time domain applications:

- Carrier-envelope phase control
- Coherent pulse synthesis
- Nonlinear Microscopy
- Gainless amplifier

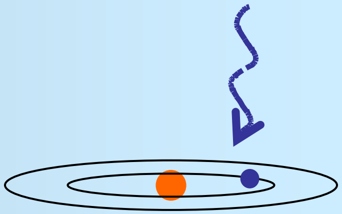
What is a clock?

Oscillator



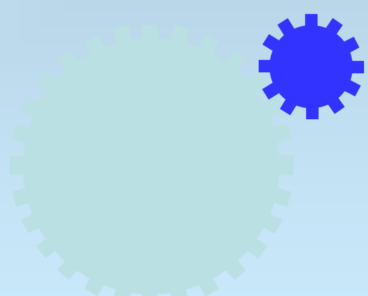


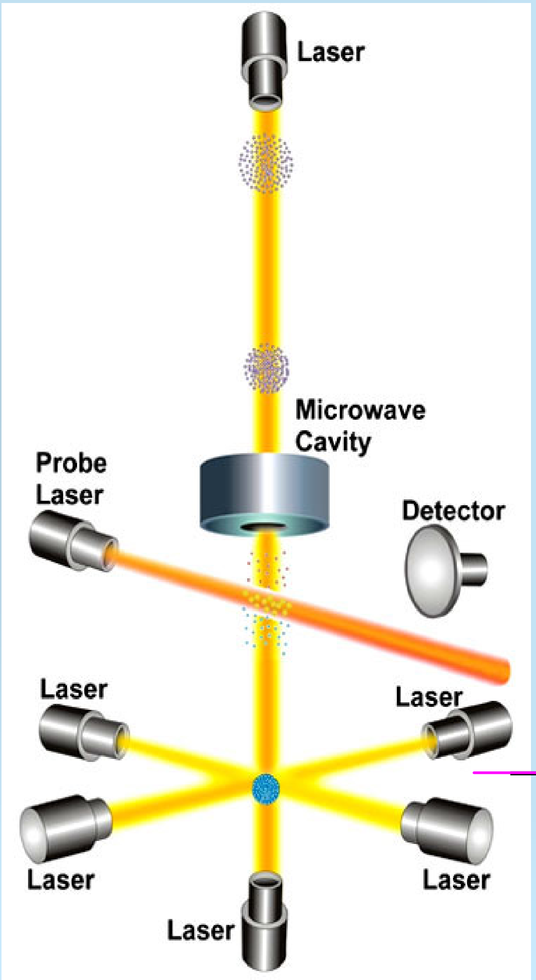
laser



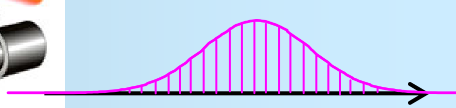
Counter

Caveman's marks



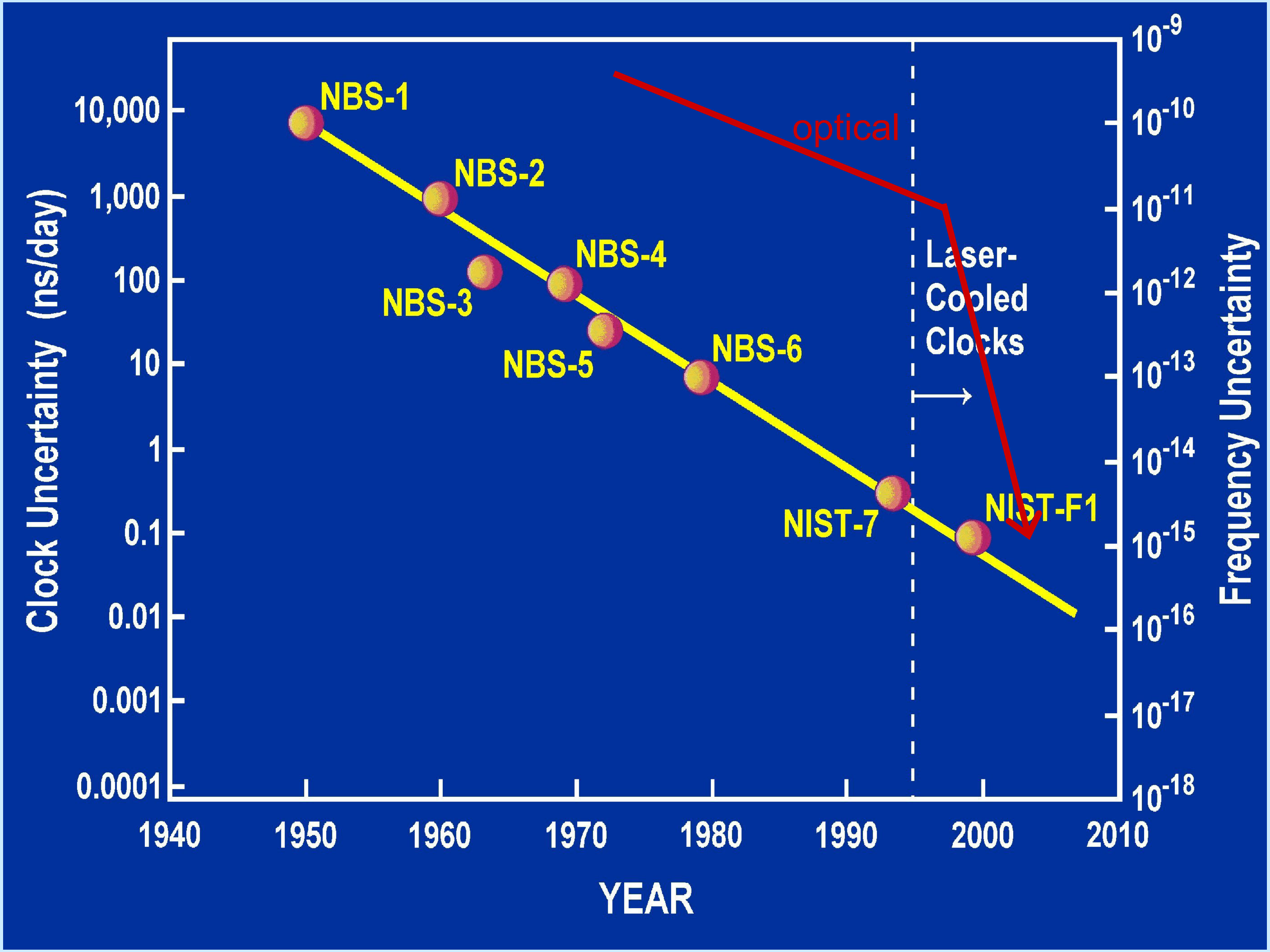


NIST-F1

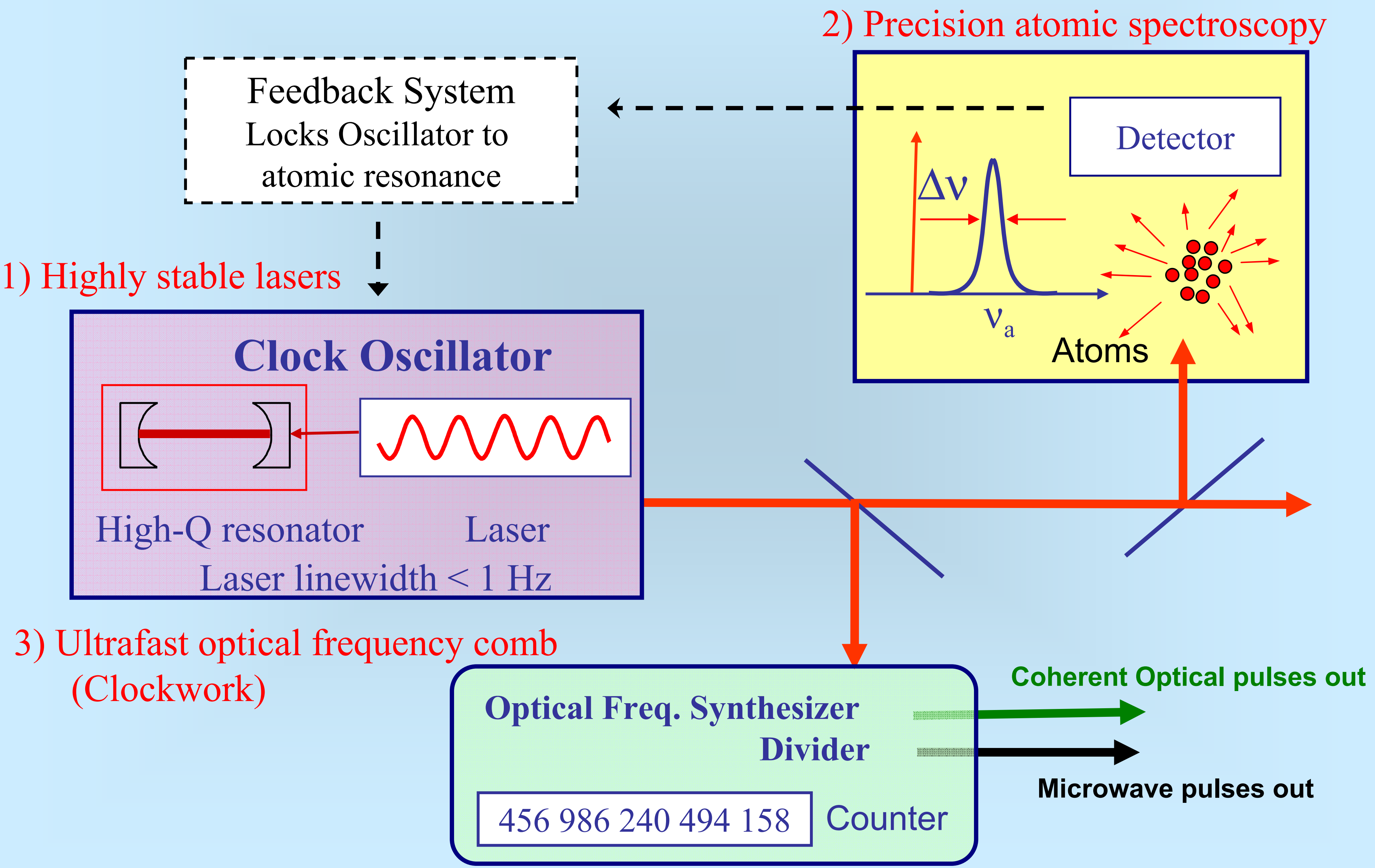


fs comb

Improvement of Cs microwave standards over 50 years

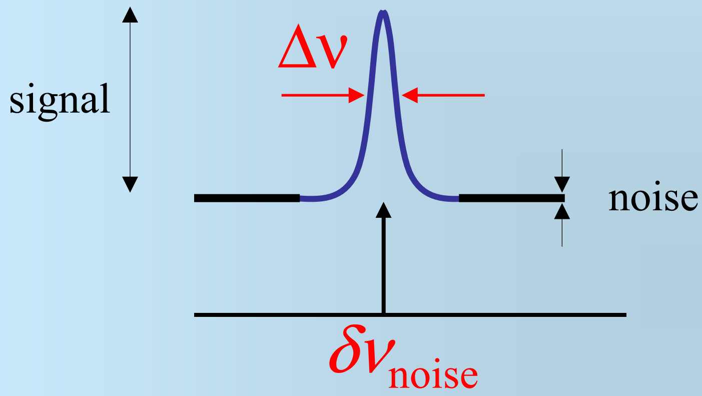


New era for optical frequency standards & optical atomic clocks



Optical Frequency Standards
sensitivity and resolution

High line Q & good signal-to-noise ratio (stability)

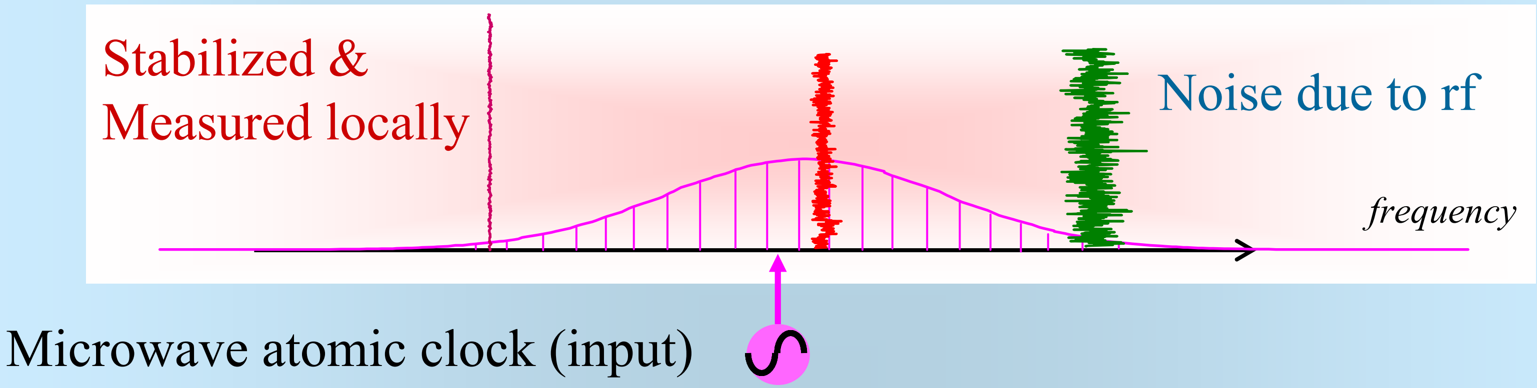


$$\delta\nu_{noise} \approx \frac{\Delta\nu\ (FWHM)}{(S/N)|_{\tau}} \longrightarrow \frac{\delta\nu_{noise}}{\nu_0} \approx \frac{1}{Q}\cdot\frac{1}{S/N}\cdot\frac{1}{\sqrt{\tau}}, \qquad Q \approx \nu_0 / \Delta\nu$$

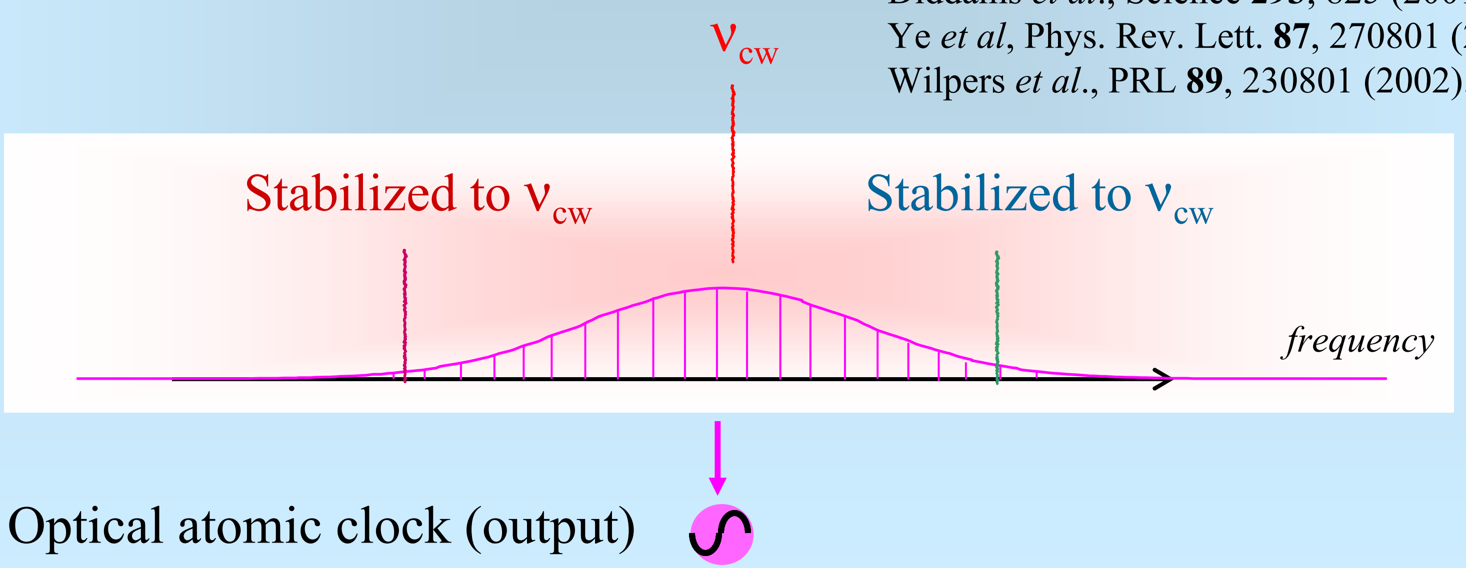
$$\frac{\nu_0 \text{ optical}}{\nu_0 \text{ microwave}} \approx \frac{10^{15}}{10^{10}} \approx 10^5$$

Microwave vs.Optical Clocks
- friendly competition and corporation

Niering *et al.*, PRL **84**, 5496 (2000); Ye *et al.*, Opt. Lett. **25**, 1675 (2000)

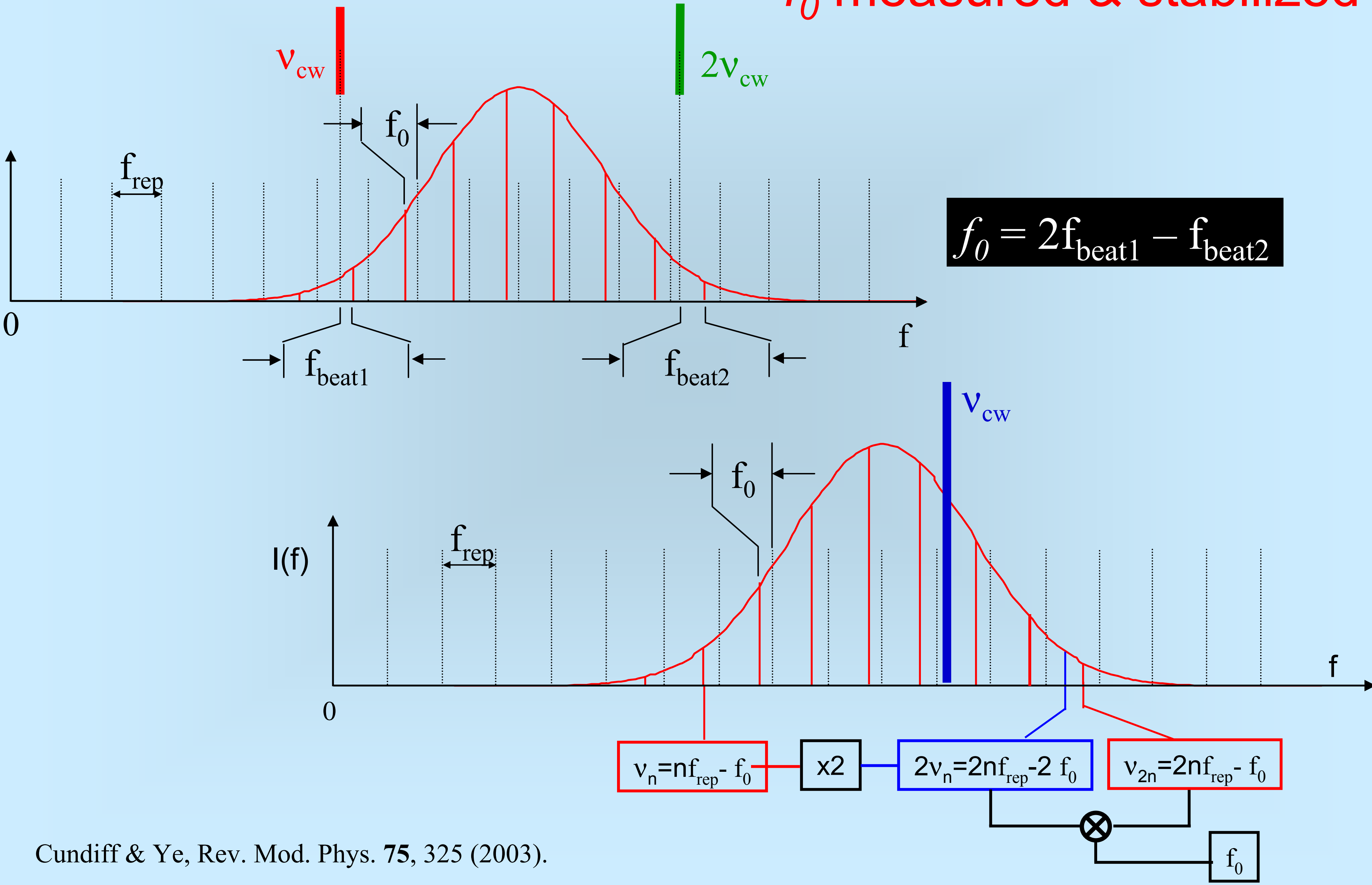


Diddams *et al.*, Science **293**, 825 (2001).
Ye *et al*, Phys. Rev. Lett. **87**, 270801 (2001).
Wilpers *et al.*, PRL **89**, 230801 (2002).



Derive f_{rep} from optical frequency ν

f_0 measured & stabilized

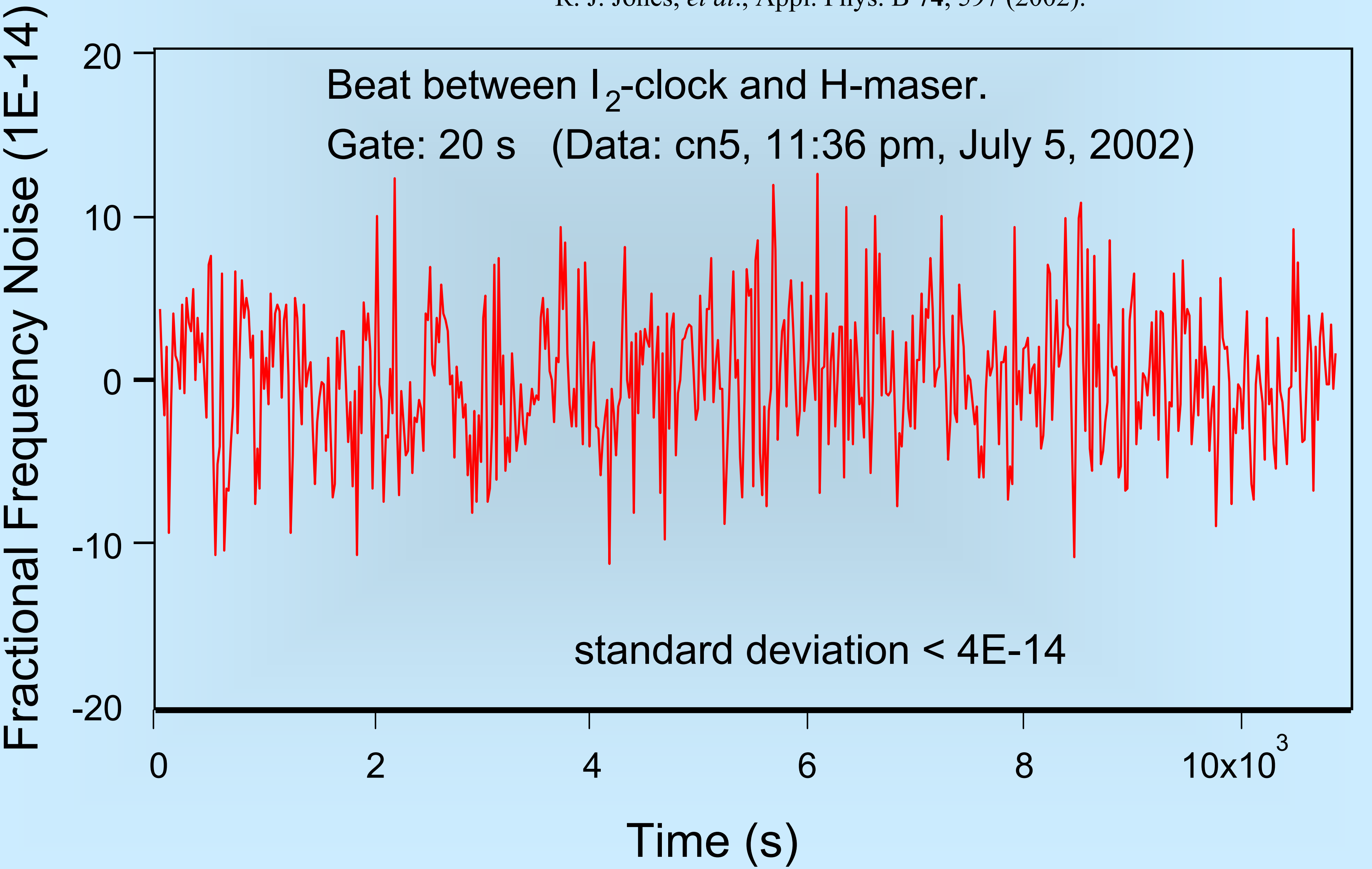


$$f_0 = 2f_{beat1} - f_{beat2}$$

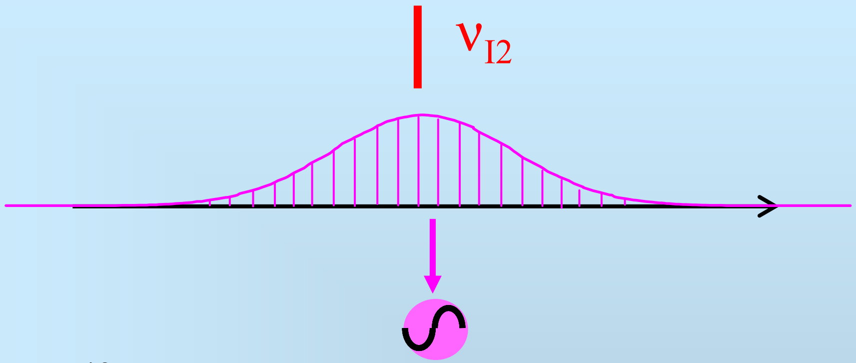
Cundiff & Ye, Rev. Mod. Phys. **75**, 325 (2003).

Continuously running optical clock

R. J. Jones, *et al.*, Appl. Phys. B **74**, 597 (2002).

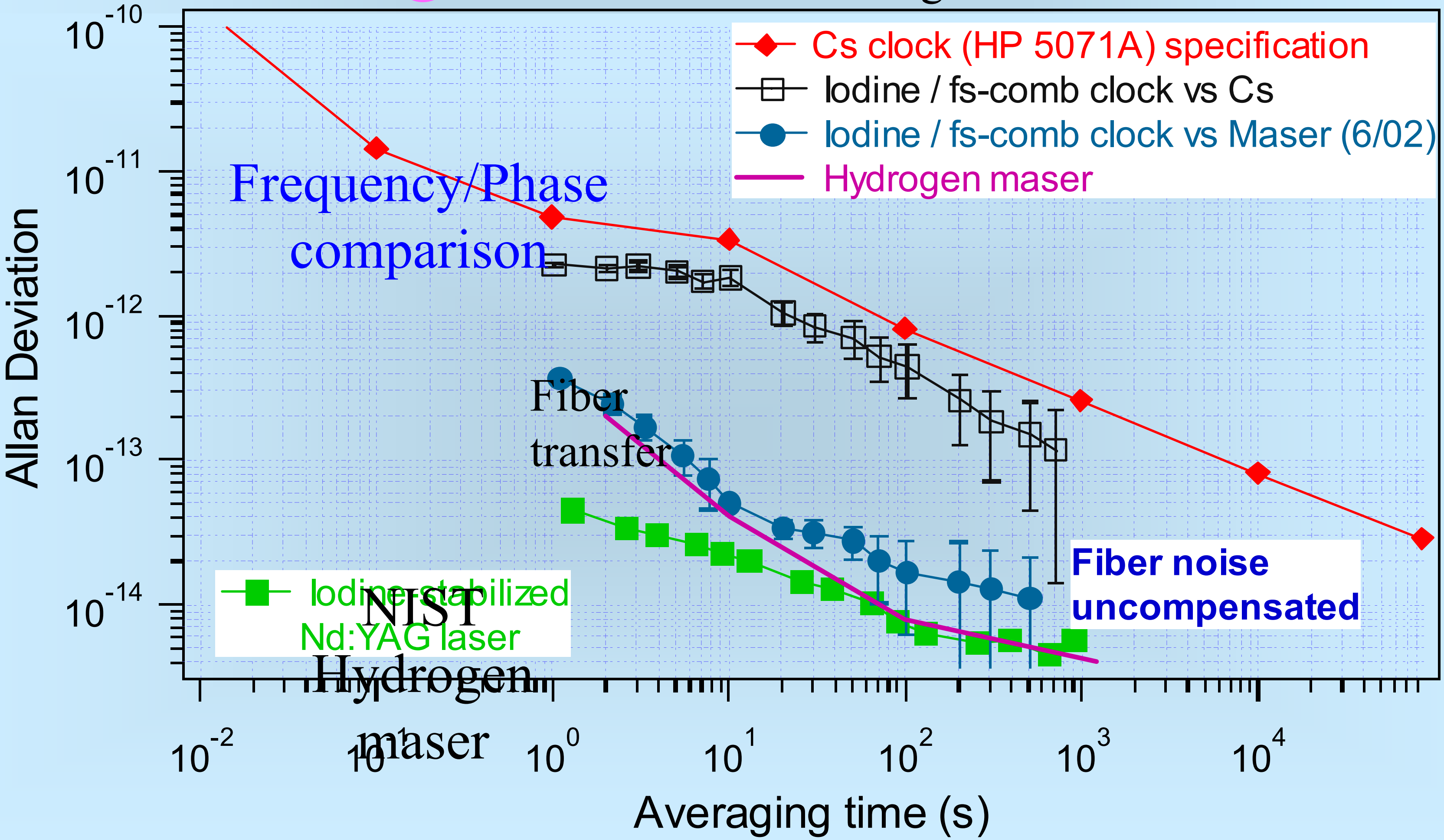


Molecular Clock of Iodine



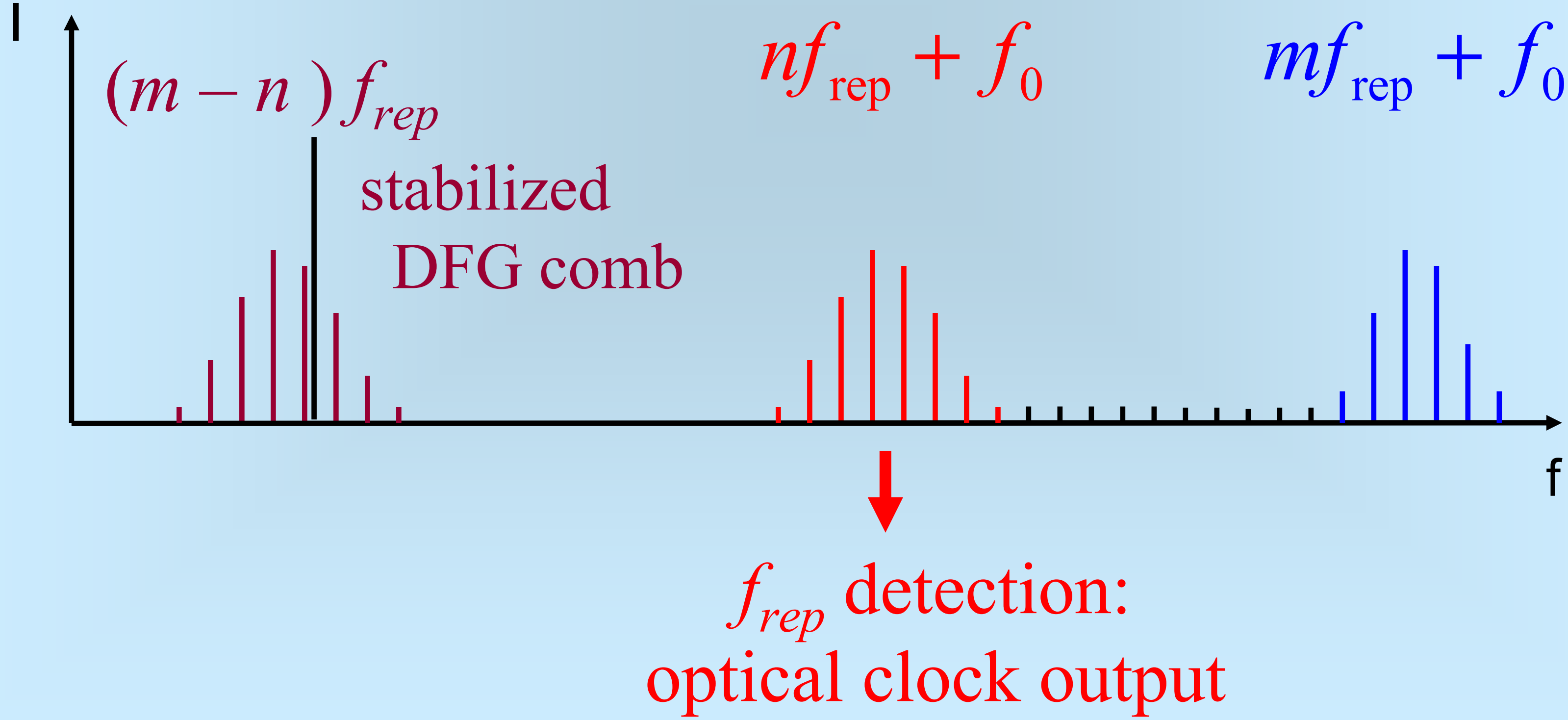
Ye *et al*, PRL **87**, 270801 (2001).
Ye *et al*., J. Opt. Soc. B **20**, 1459 (2003).

Comparing optical clock against other RF clocks



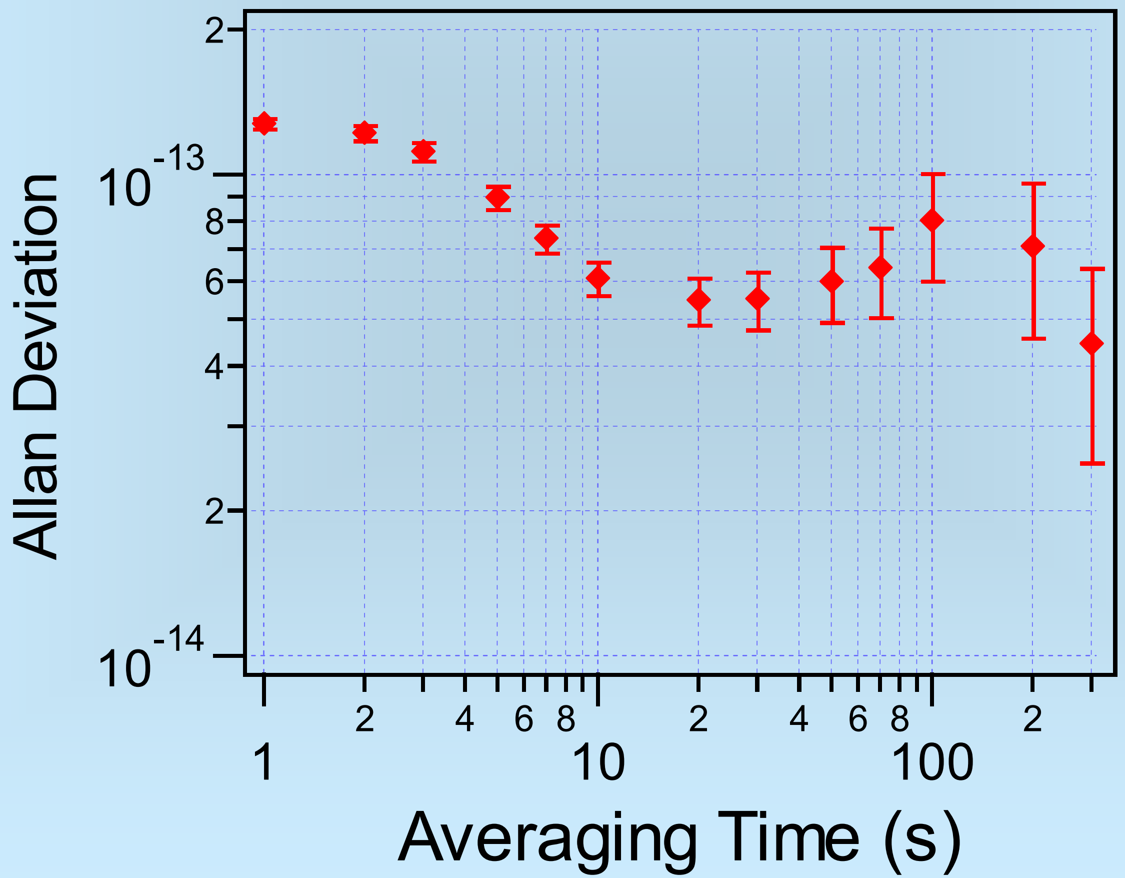
Carrier-envelope frequency independent optical clockwork

Carrier-envelope frequency independent DFG comb

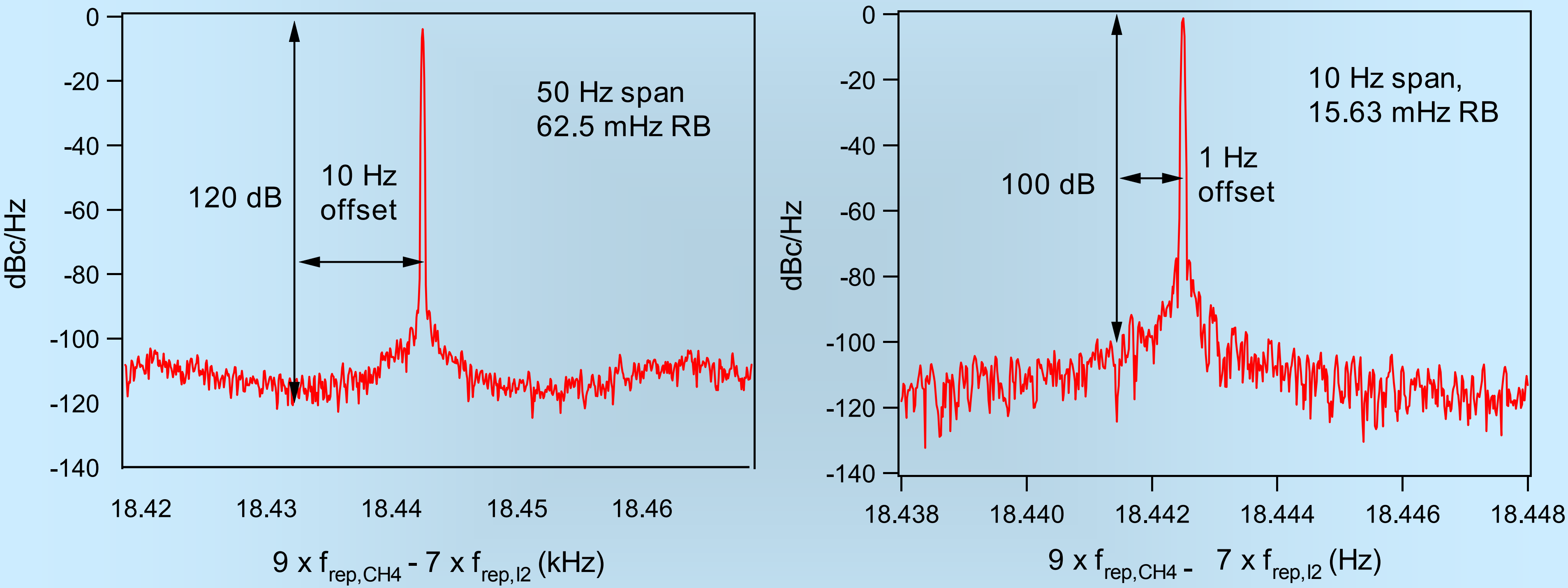


Comparison of two optical molecular clocks

- electronic transition in I_2 ,
- vibrational transition in CH_4



Low phase noise microwave beat



Cold atom based optical frequency standards – the ultimate performance

Lifetime τ_0; $\tau/(2\tau_0)$ interactions over averaging time τ.
For a single measurement, $SNR \sim \sqrt{N_{at}}$.

$$SNR \sim \sqrt{N_{at}} \times \sqrt{\tau/2\tau_0}$$

$$\sigma_y(\tau) = \frac{\delta\nu}{\nu_0} = \frac{1}{\nu_0}\frac{\Delta\nu}{SNR} = \frac{\Delta\nu}{\nu_0}\frac{1}{\sqrt{N_{at}}} \cdot \sqrt{\frac{2\tau_0}{\tau}}$$

$$= \frac{1}{2\pi\nu_0}\frac{1}{\sqrt{N_{at}}}\frac{1}{\sqrt{\tau_0\tau}}$$

$$= \frac{1}{2\pi\nu_0}\frac{1}{\sqrt{N_{at}T_R\tau}}$$

(Interrogation time $T_R < \tau_0$)

^{88}Sr: $^1S_0 - {}^3P_1$, $\tau_0 \sim 22$ μs lifetime, $\nu_0 = 435$ THz; $N_{at} = 10^6$; $\sigma_y(\tau) = 7 \times 10^{-16}$ at 1-s

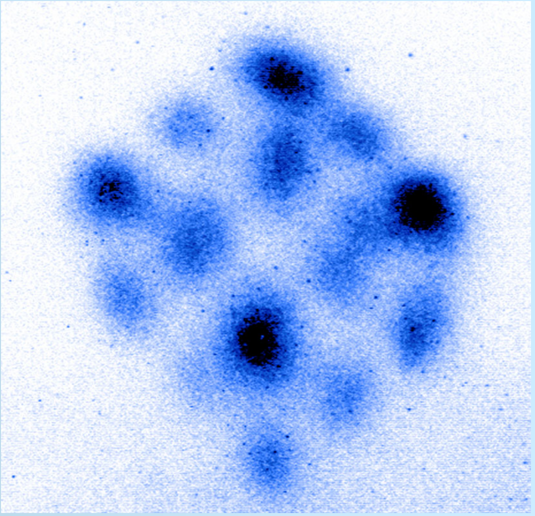
^{87}Sr: $^1S_0 - {}^3P_0$, $\tau_0 > 1$ s, $\sigma_y(\tau) < 5 \times 10^{-18}$ at 1 s

Ye *et al*., IEEE J. Select. Topics. Quantum Elect. **9**, 1041 (2003).

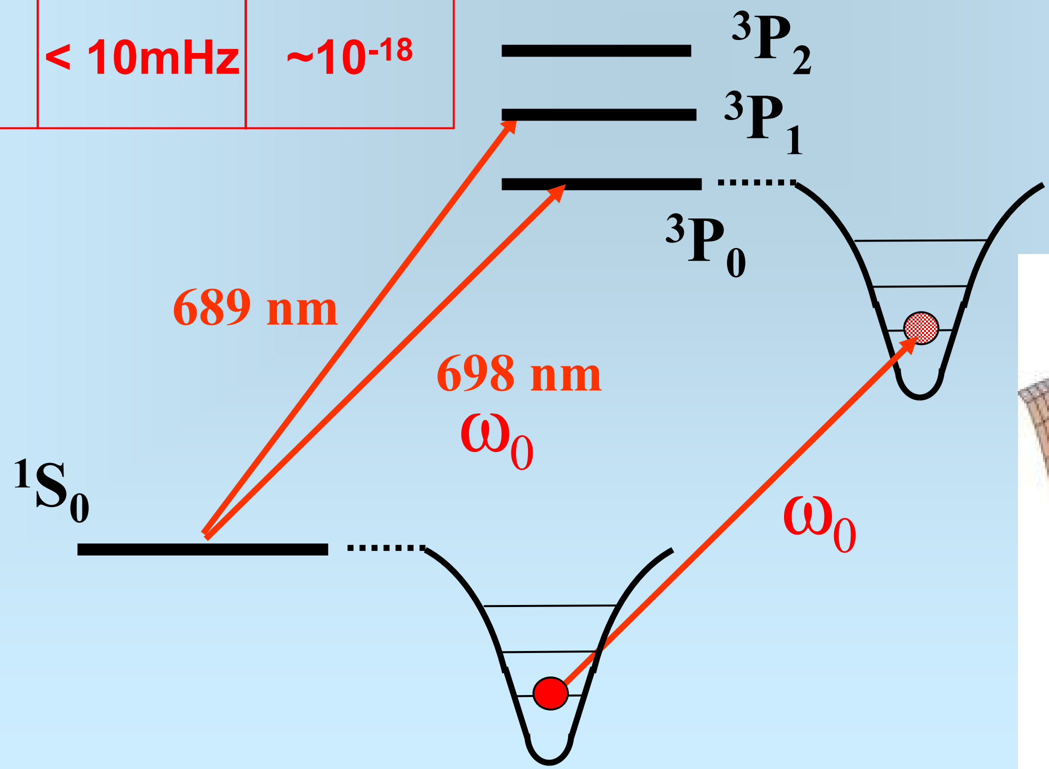
Cool Alkaline Earth – Strontium

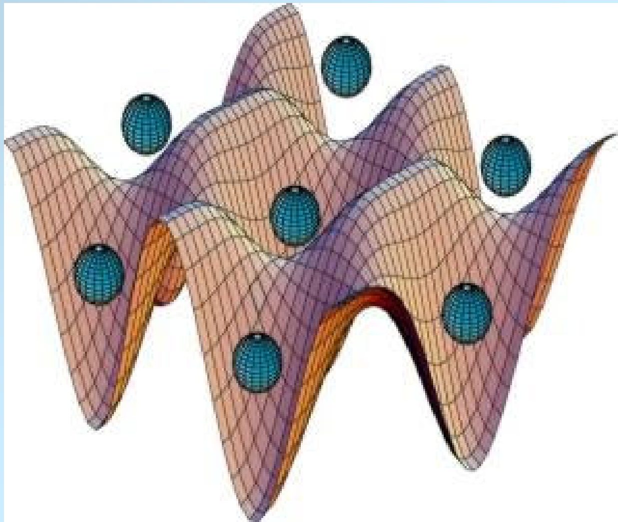
Xu *et al.*, Phys. Rev. Lett. 90, 193002 (2003).
Loftus *et al.*, Phys. Rev. Lett. 93, 073003 (2004).
Ido *et al.*, Phys. Rev. Lett. 94, 153001 (2005).
Santra *et al.*, Phys. Rev. Lett. 94, 173002 (2005).
Ludlow *et al.*, Phys. Rev. Lett. 96, 033003 (2006).

T ~ 0.5 photon recoil
~ 220 nK



	$\Gamma/2\pi$	$\delta\nu/\nu$ at 1s
$^{88}Sr\ ^1S_0$-$^3P_1$	7.6 kHz	7×10^{-16}
$^{87}Sr\ ^1S_0$-$^3P_0$	< 10mHz	$\sim10^{-18}$





Sr Narrow Line Transitions

Katori, 6th Symp. Freq. Standards & Metrology (2002)

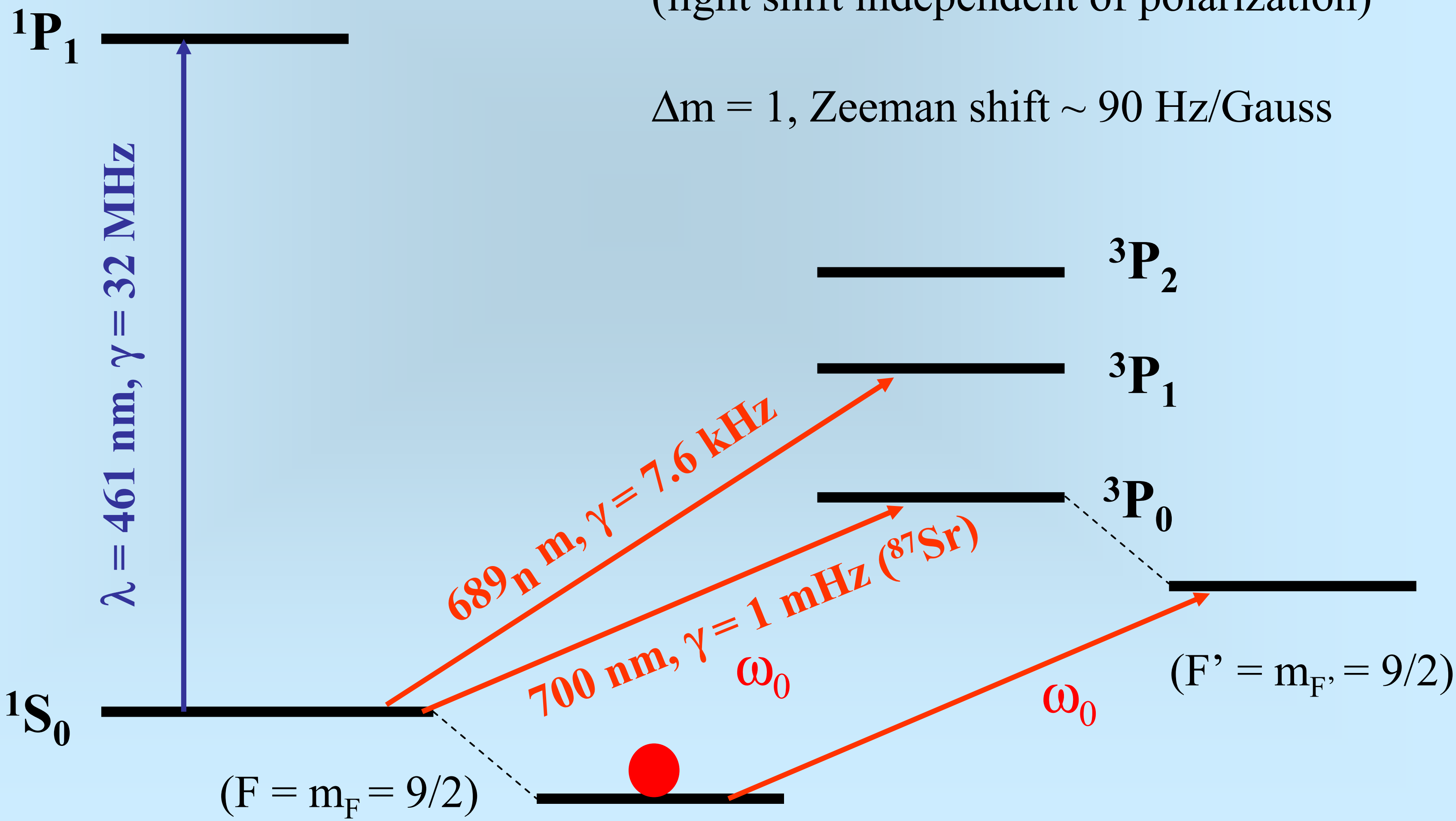
Xu *et al*., Phys. Rev. Lett. **90**, 193002 (2003).

Xu *et al*., JOSA B **20**, 968 (2003).

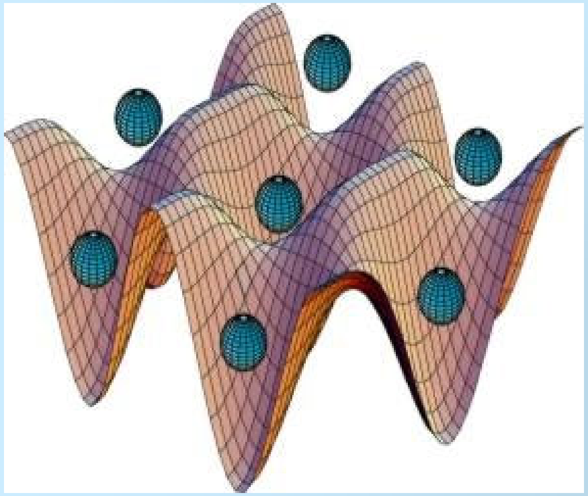
Doubly forbidden; but made possible due to Hyperfine mixing (F = 9/2, ^{87}Sr)

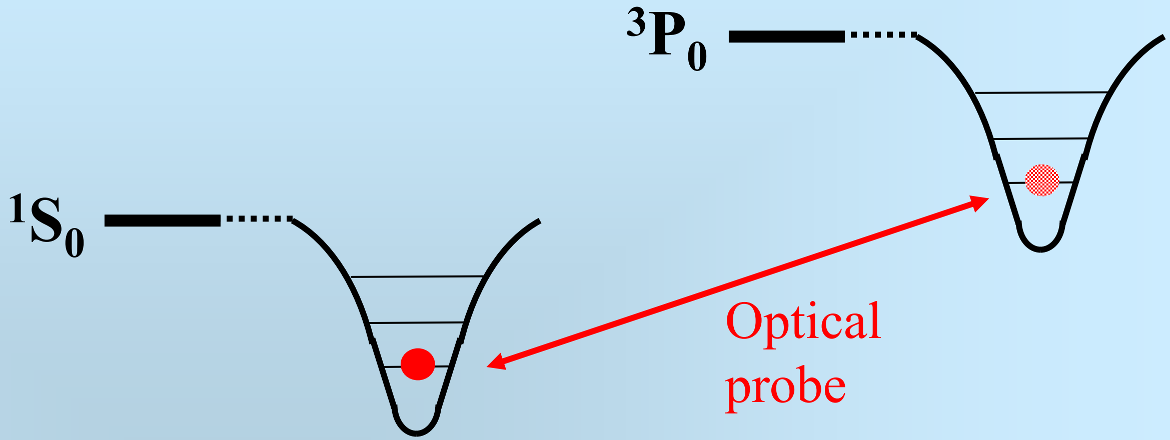
Scalar polarizability
(light shift independent of polarization)

Δm = 1, Zeeman shift ~ 90 Hz/Gauss



Lattice based optical frequency standard



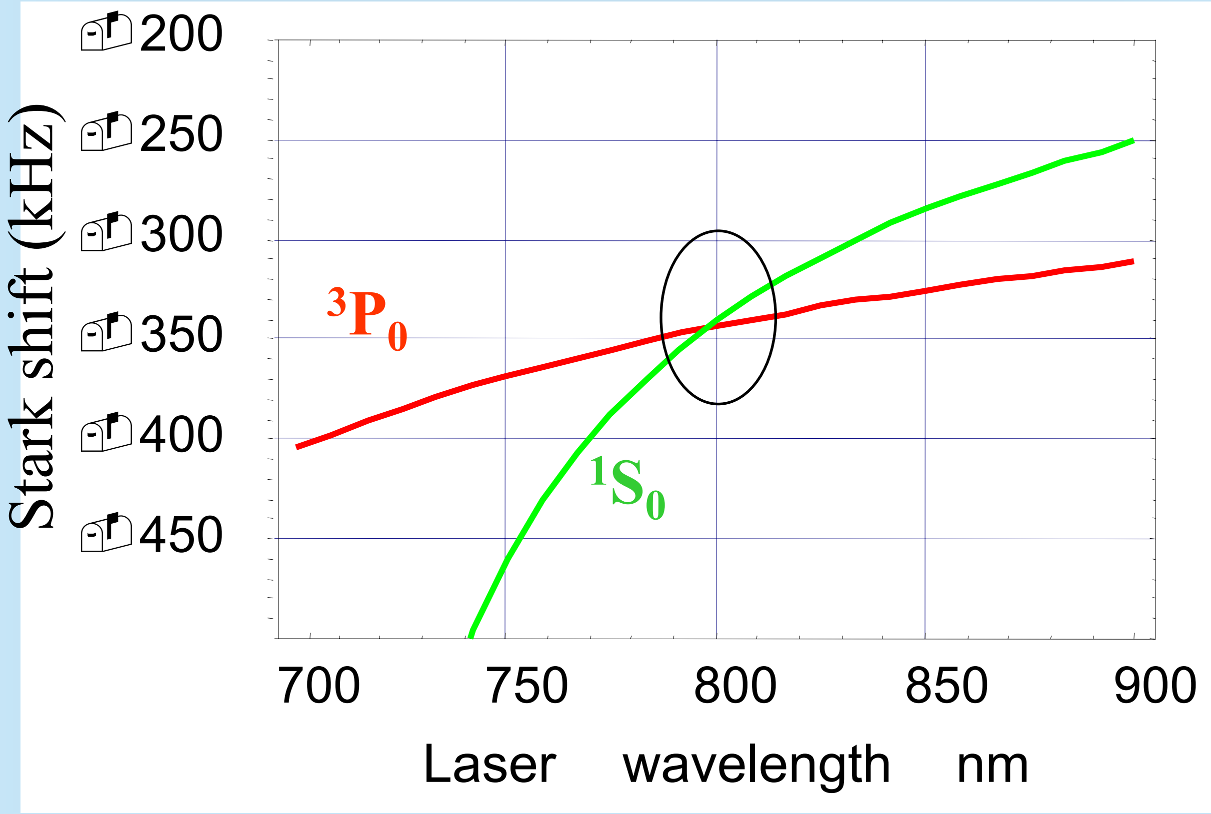


- **Atoms confined in Lamb-Dicke regime**
- **FORT potential identical for $^1S_0$ and $^3P_0$**

Katori et al., Sixth Symposium Freq. Standards & Metrology (2002)

- N quantum absorbers can potentially improve stability by $N^{1/2}$
- Collision shift minimized
- Long observation time; Zero Doppler shift

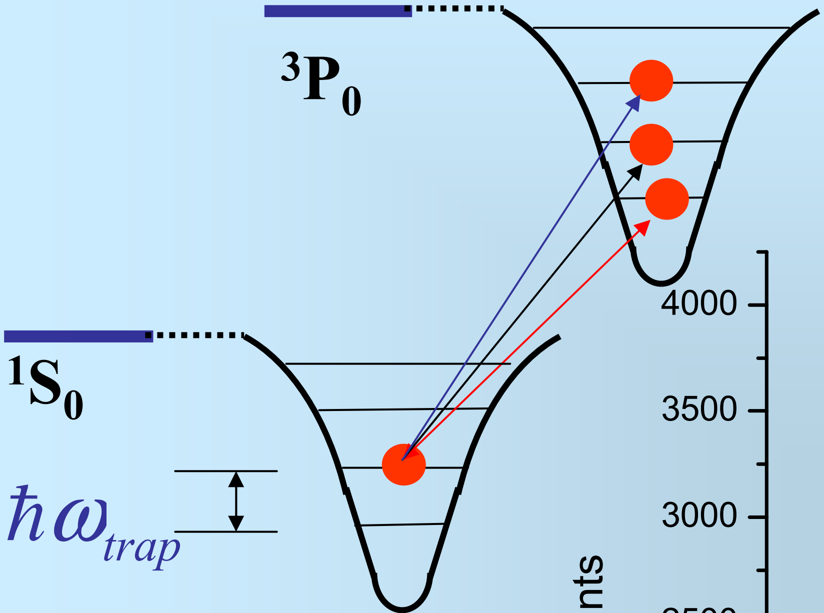
Matching the polarizabilities

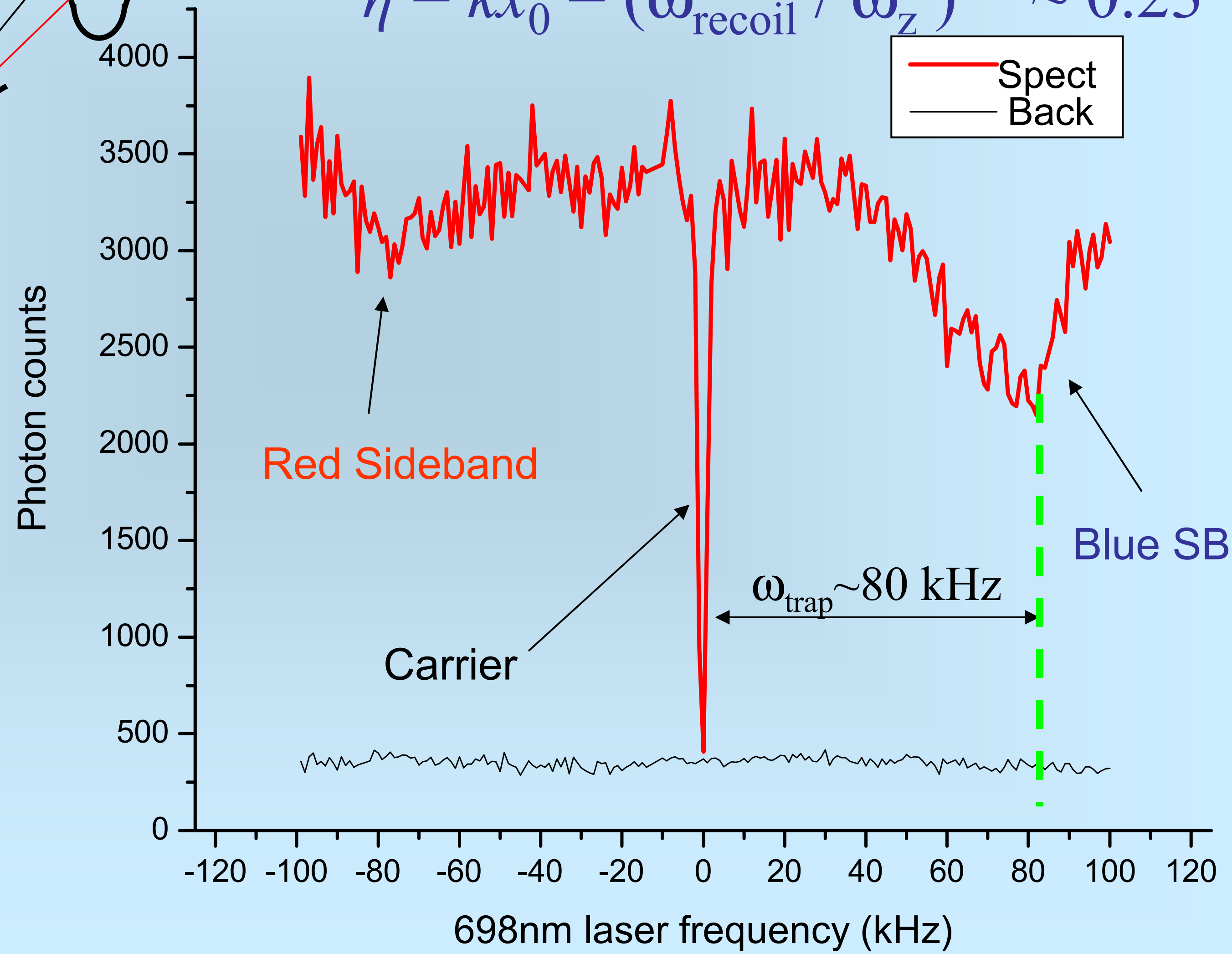


Spectroscopy at the magic wavelength

1-D Lamb-Dicke Regime

$$\eta = kx_0 = (\omega_{recoil} / \omega_z)^{0.5} \sim 0.23$$

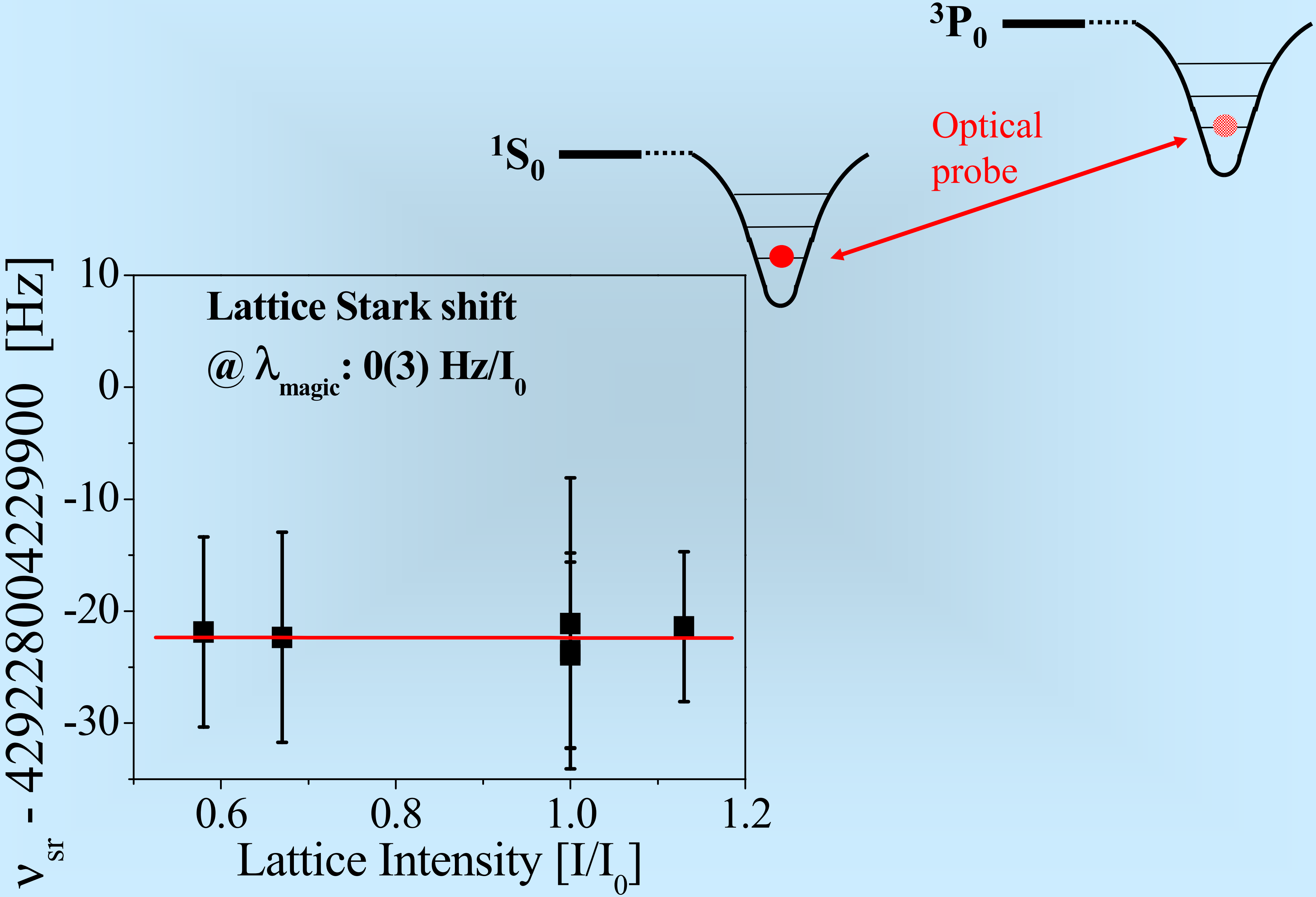




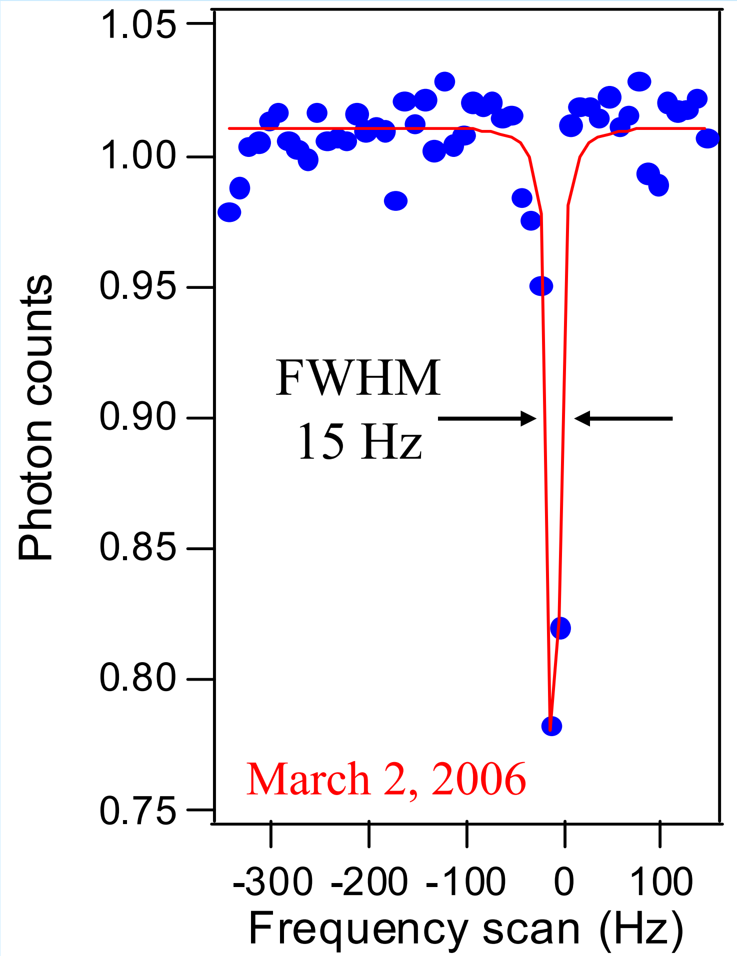
$$\omega_{recoil} << \omega_{trap}$$

$$\Gamma_{clock} << \omega_{trap}$$

AC Stark shift of the lattice potential at λ_{magic}



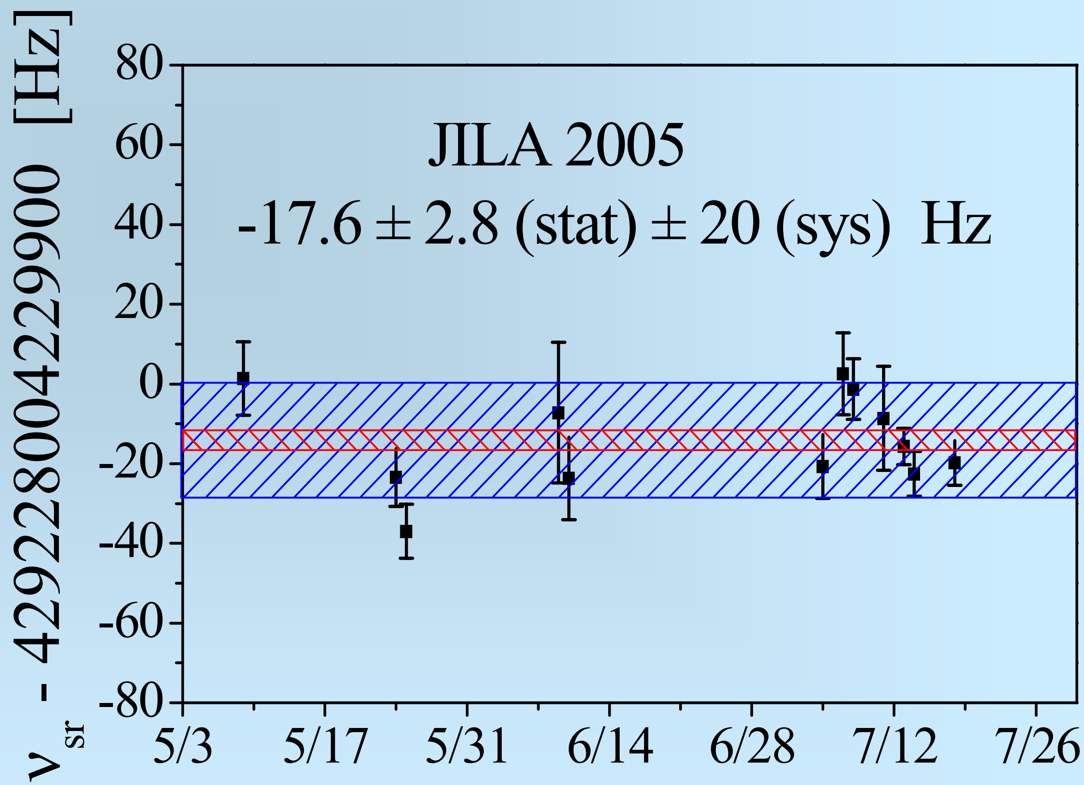
Absolute Frequency of ^{87}Sr $^1S_0 - {}^3P_0$



Ludlow *et al.*, Phys. Rev. Lett. 96, 033003 (2006).

- against NIST Cs fountain clock

6.5×10^{-15}



JILA ^{87}Sr Absolute Frequency Record (2005)

Optical local oscillators

State-of-the-art performance

Hall, Bergquist, …

Relative stabilization to < 10 mHz (< 5E-17)

Absolute laser linewidth ~ 0.2 Hz (~ 2E-16)

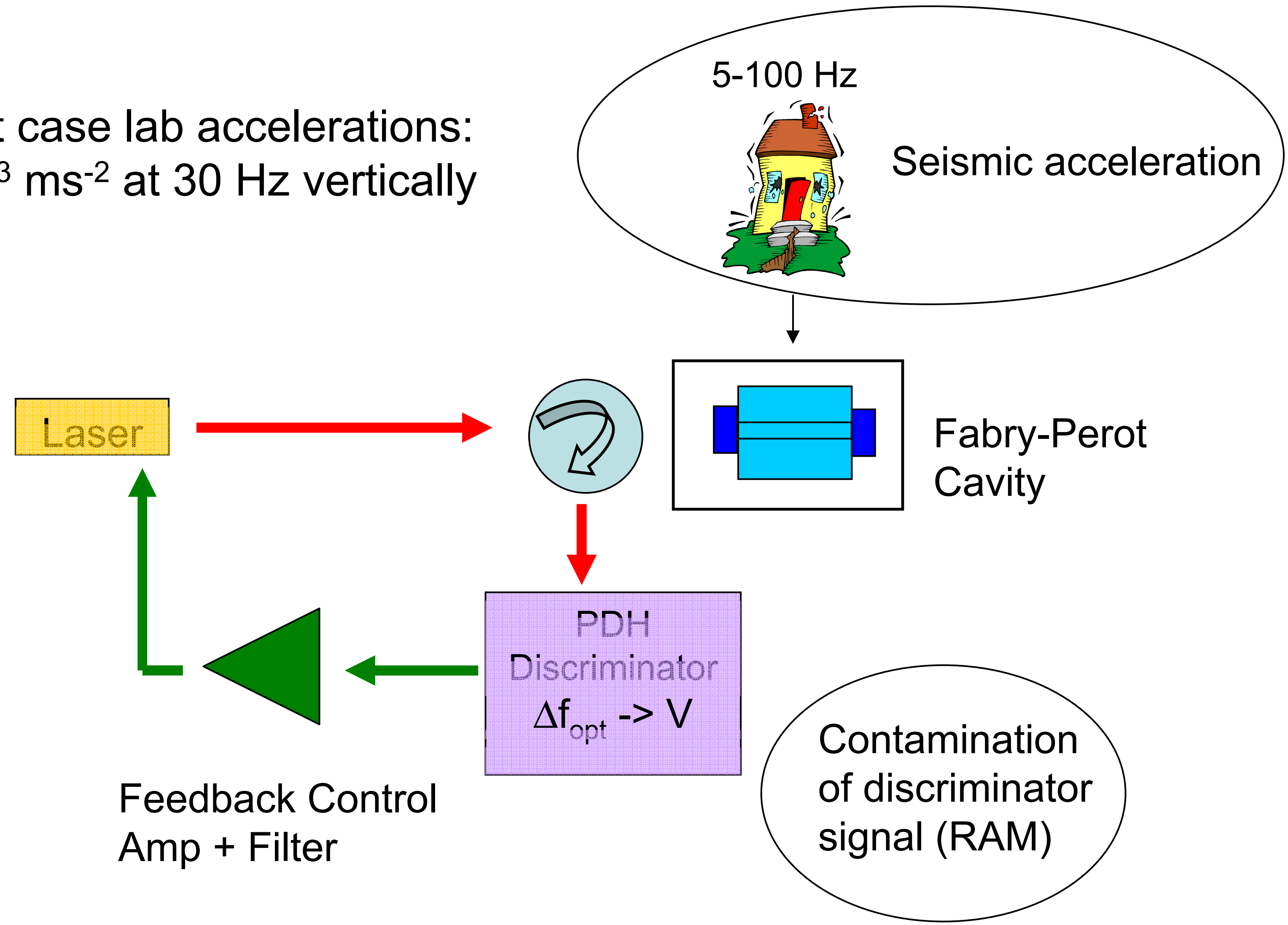
Frequency drift < 0.1 Hz/s

Modern laser stabilization ↔ isolation of passive optical cavity

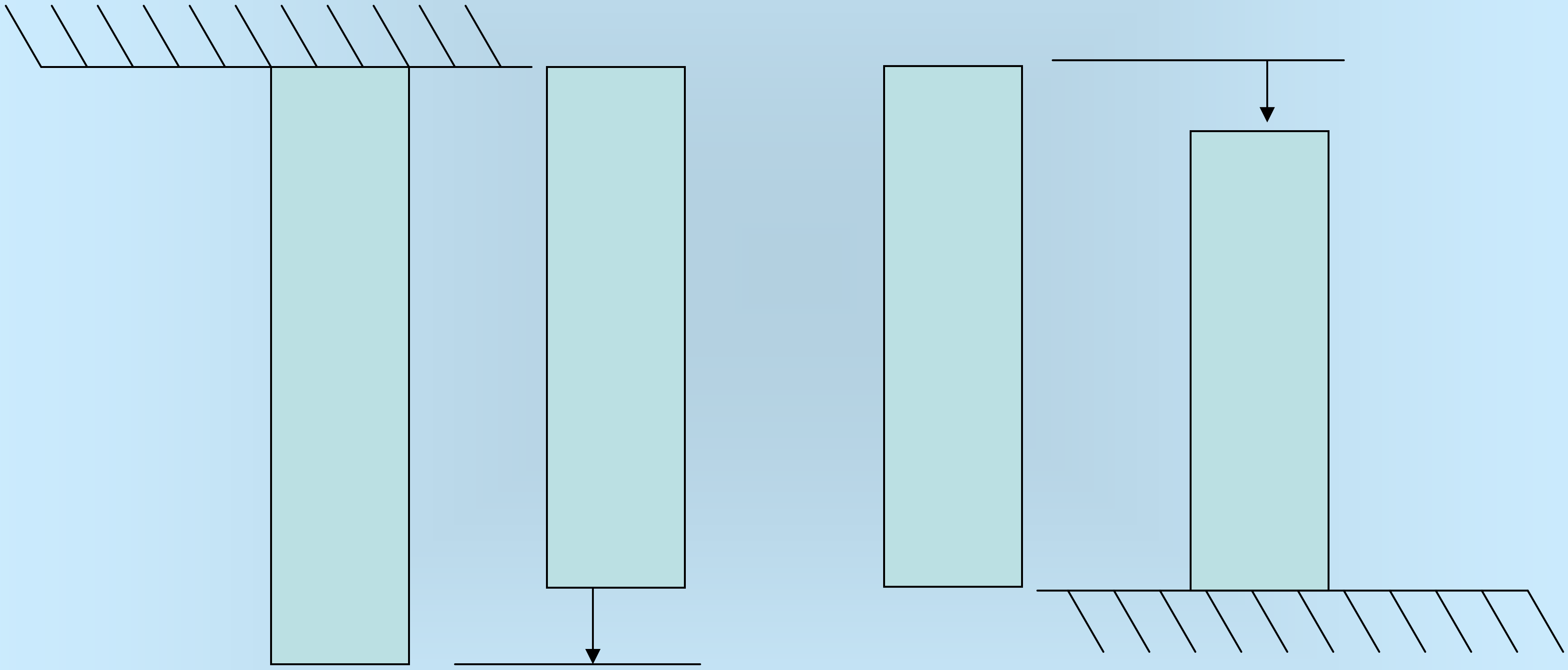
- Vibration noise cancelled cavity geometry
- Novel mounting configuration
- Improved vibration isolation & thermal control
- Compact system design

Introduction – noise sources

worst case lab accelerations:
~ 10^{-3} ms^{-2} at 30 Hz vertically

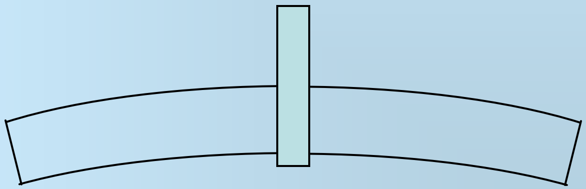


- Gravity is a BIG deal –
- ~ 24 MHz for 30 cm cavity

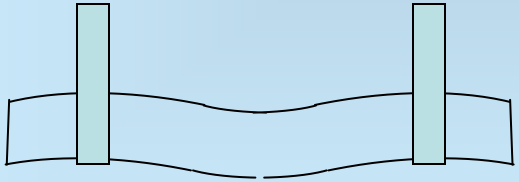


$\delta\nu \sim 4.3\ 10^{-8}$ per g for ULE; $\delta\nu$ scales α L :

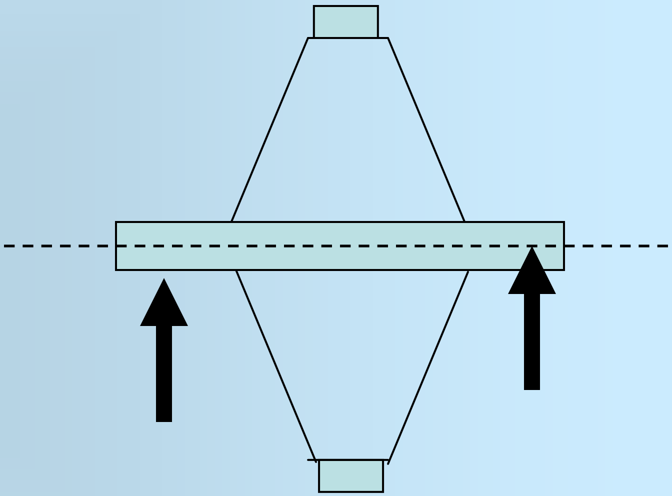
There may be a better support idea?



Horizontal → expect a reduction
but …
Observed Sensitivity ~ 1 x
(Tilt effect linear in angle)

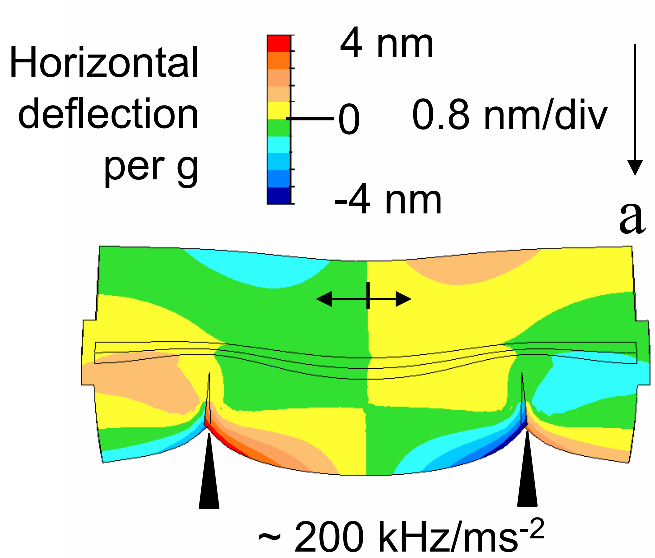


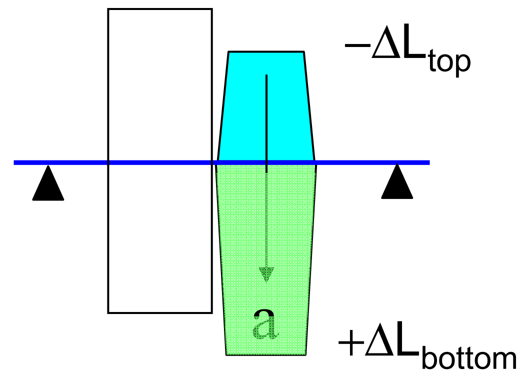
Better? Airy Points ?



Vertical → Max Sensitivity
but …
Symmetry reduction ~200 x
(Tilt effects only quadratic)

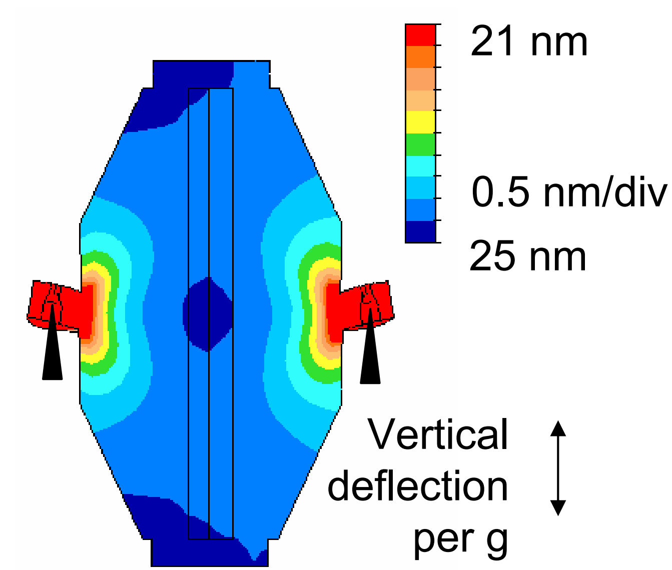
Deflection of cavities with acceleration





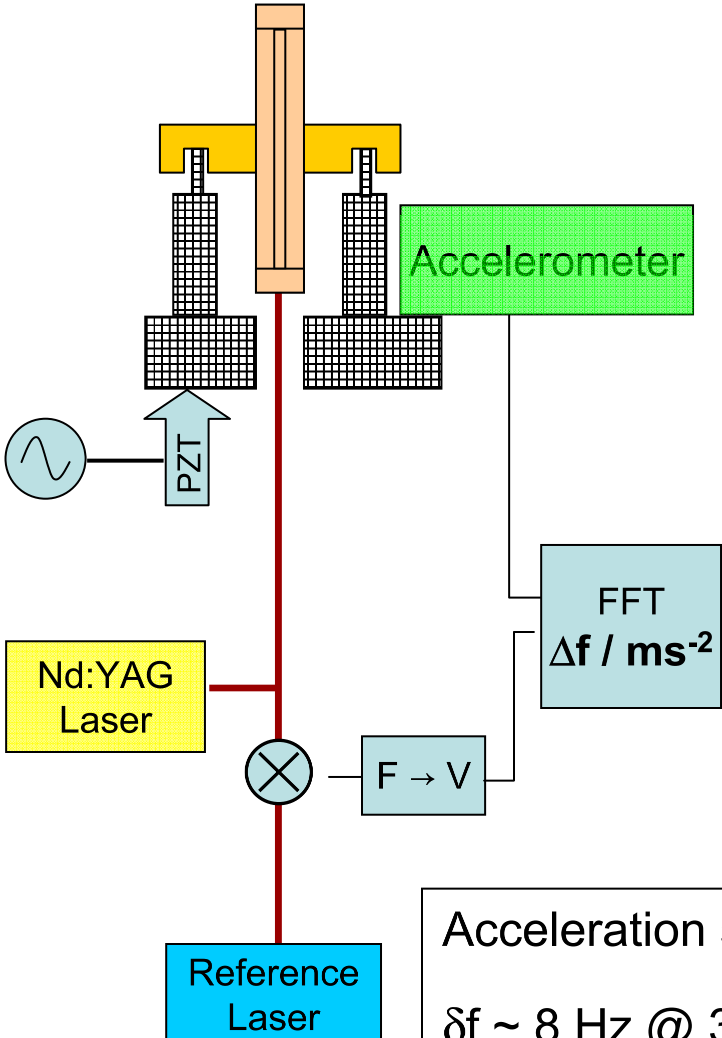
$\Delta L/L = ½ \rho a L/E$

- Short cavity
- Support near geometrical center for CMRR
- Vertical orientation for symmetry
- ΔL_{cavity} ~50 pm



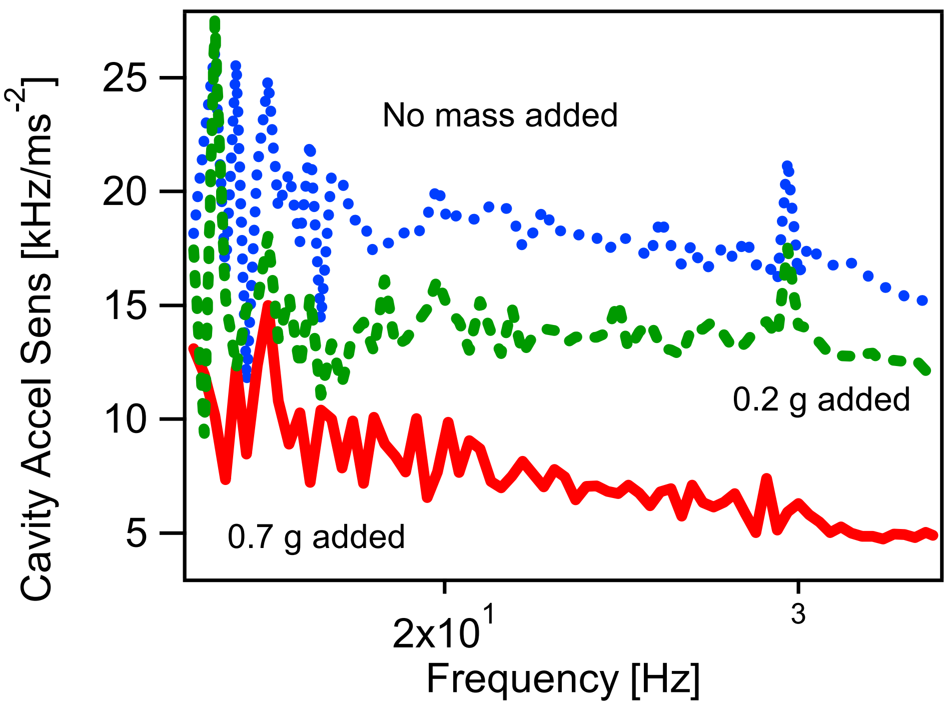
Mark Notcutt

Measuring cavity's acceleration sensitivity



Shake cavity & measure beat Δf / ms^{-2}

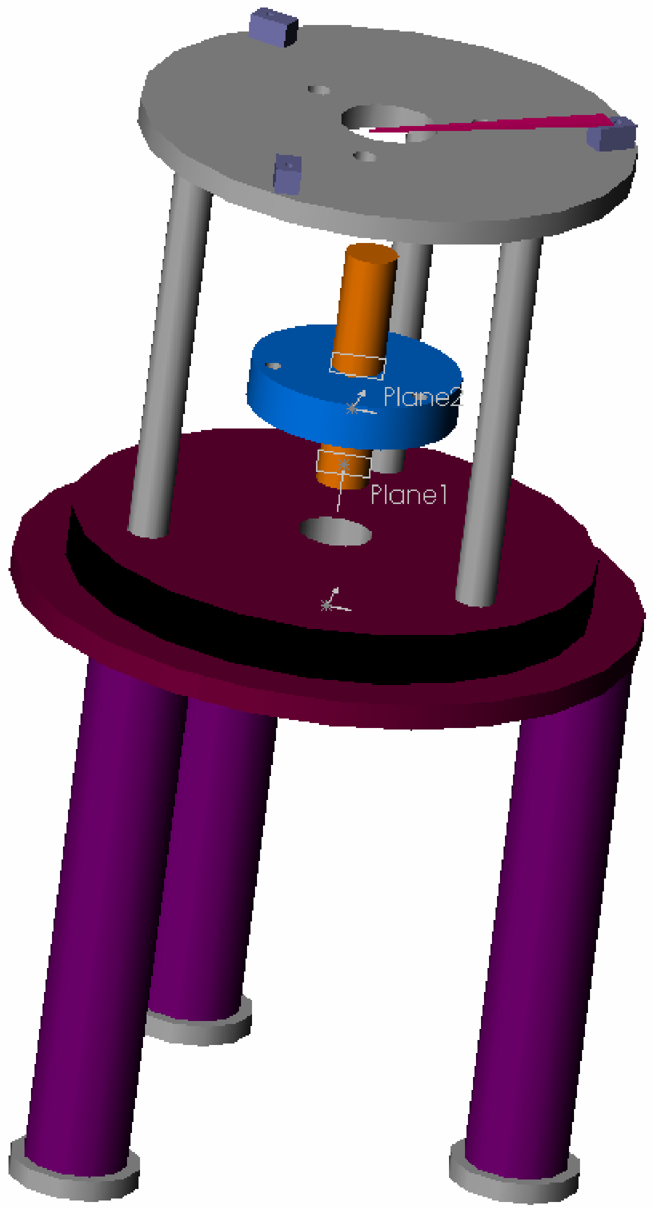
Add mass to end of cavity to move center of mass about support plane



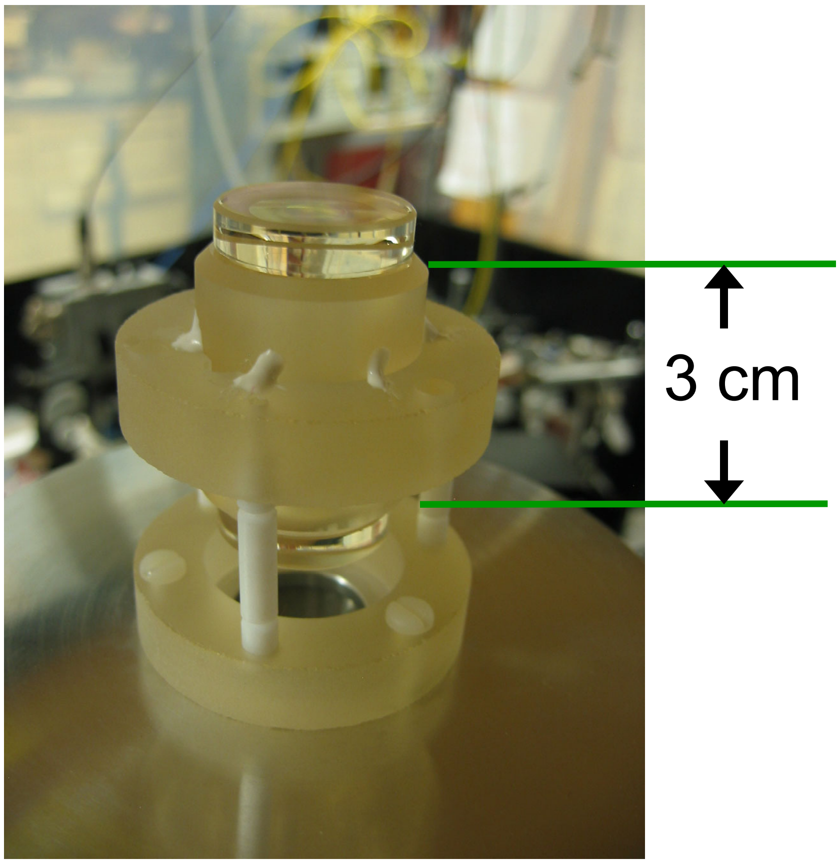
Acceleration sensitivity ~ 8 kHz/ms^{-2}

δf ~ 8 Hz @ 30 Hz

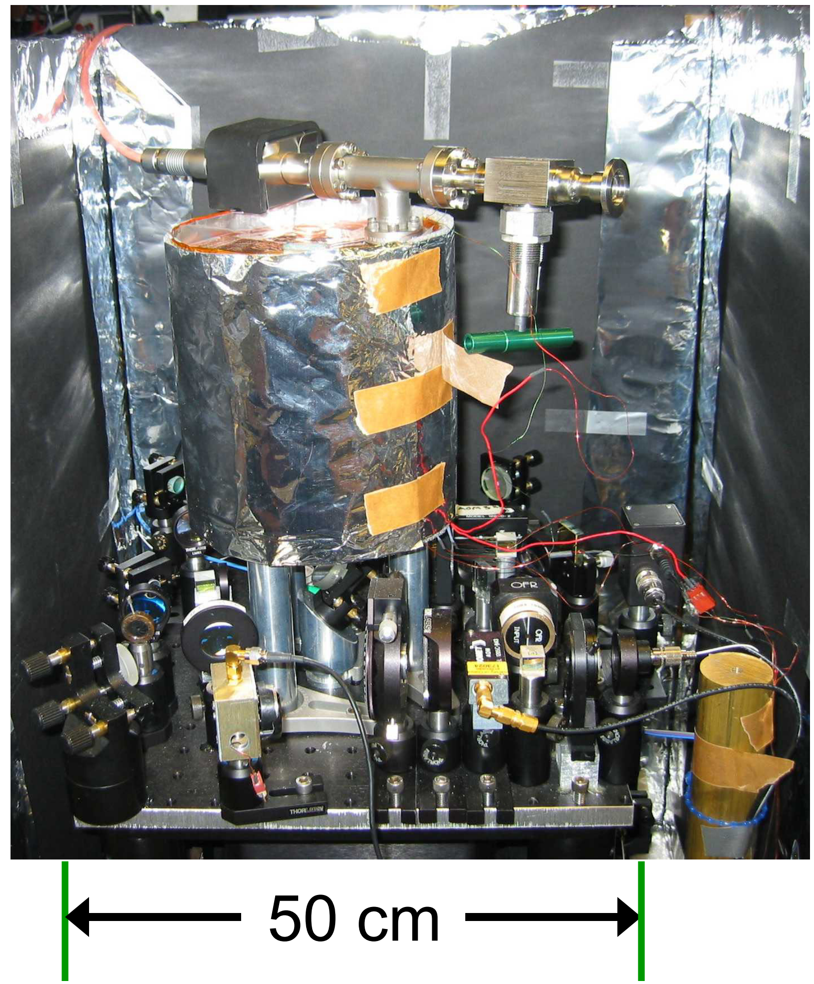
Reduces vibration isolation needed


Plane2
Plane1

698 nm probe laser



Finesse ~400,000

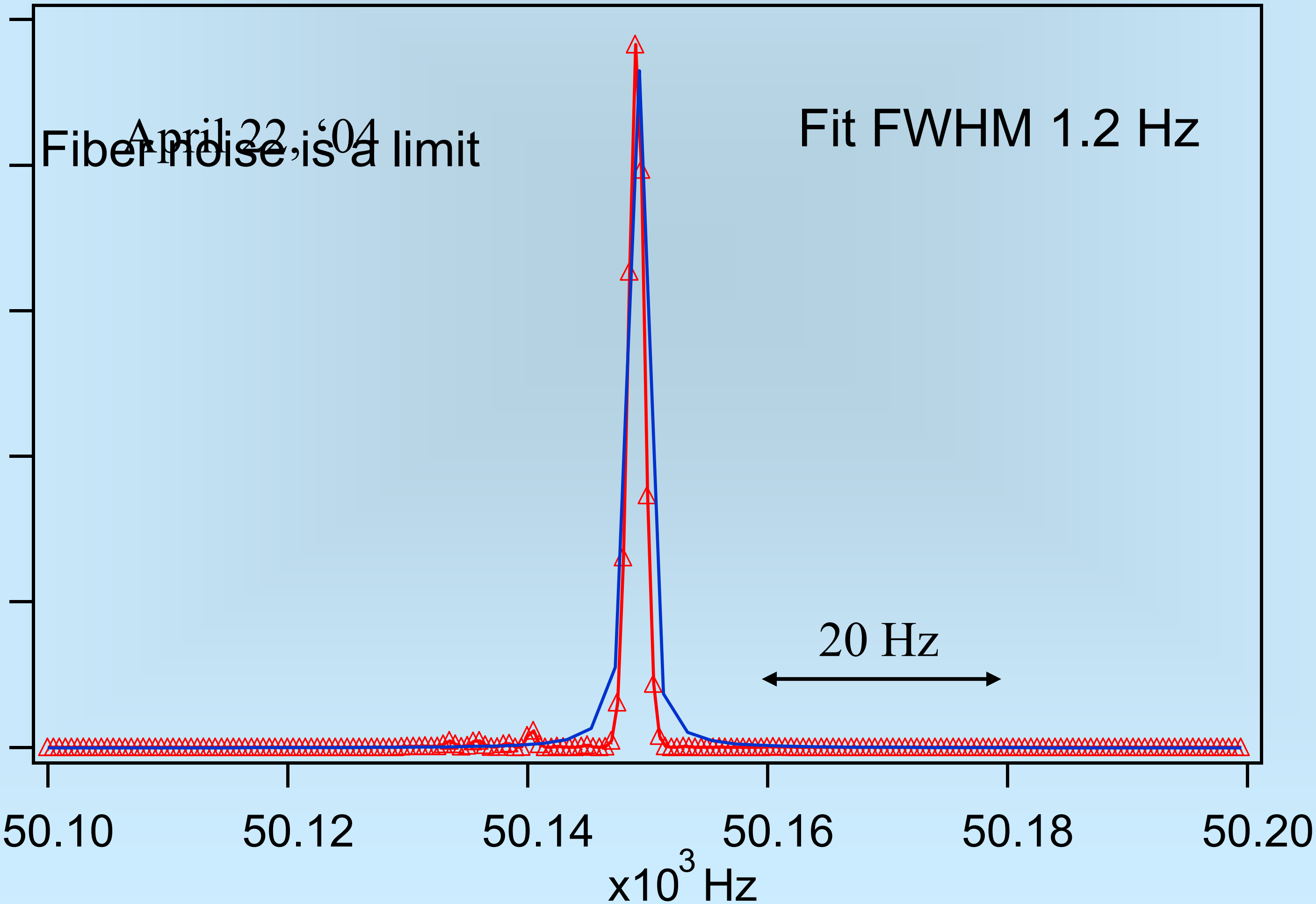


Andrew Ludlow

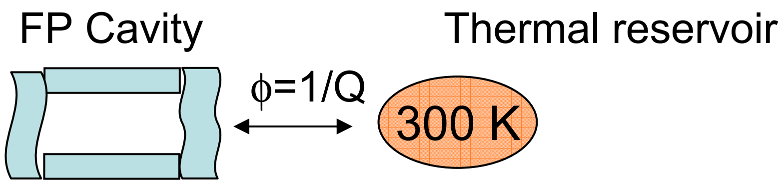
Linewidth ~ 1 Hz

Beat between two independent lasers at 1.064 μm

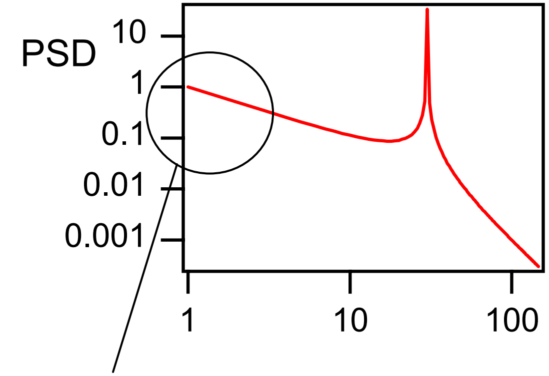
M. Notcutt, J. Hall, et al. …



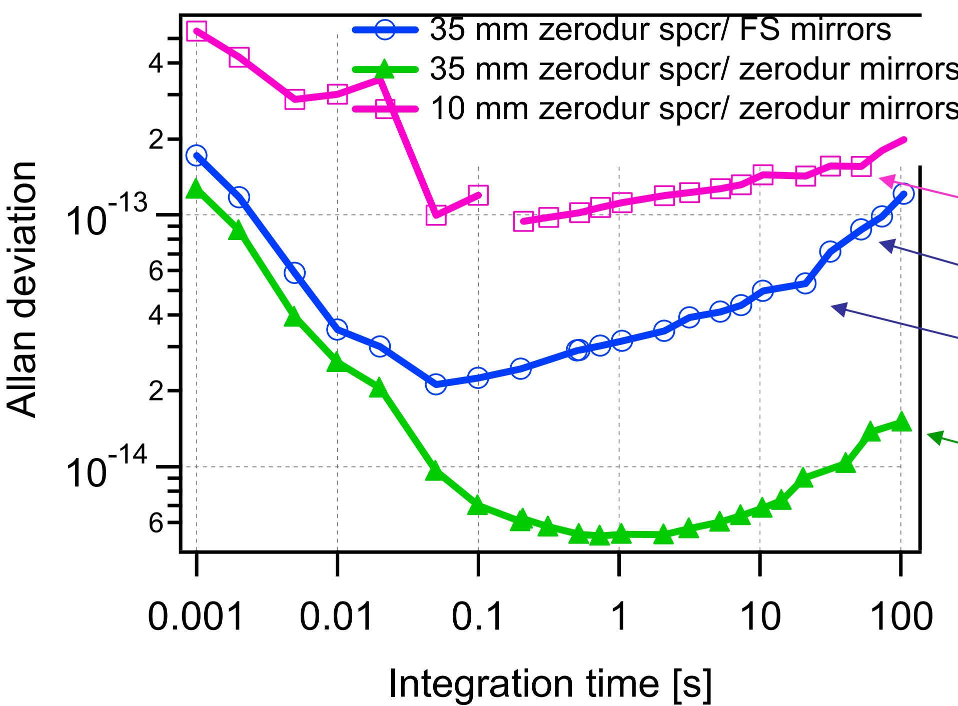
Thermal noise in Fabry-Perot Cavities



	Loss angle ϕ
Zerodur	3e-4
Fused Silica	1e-6
Coating	4e-4



- Frequency region of interest
- Mirror substrates & coating dominate displacement fluctuations
- Lock laser to cavity, measure Δf using a reference laser



35mm -> 10mm long spacer

FS mirrors -> Zerodur mirrors

Measured/calculated ~ 1.8-2.6

K Numata, PRL **93,** 250602 (2004)

Frequency domain applications:

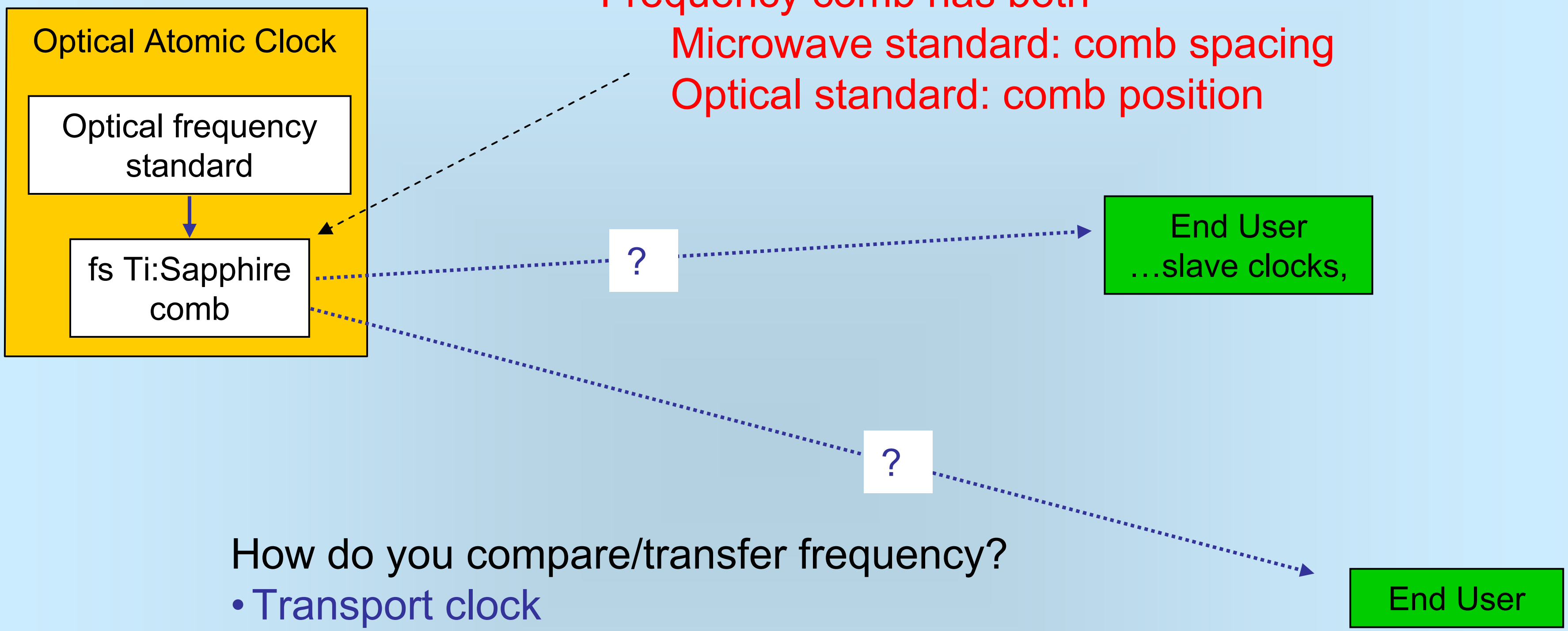
- Optical frequency synthesizer
- Optical atomic clock
- Timing signal transfer
- Time-frequency combined spectroscopy

Time domain applications:

- Carrier-envelope phase control
- Coherent pulse synthesis
- Nonlinear Microscopy
- Gainless amplifier

Distribution of Frequency Standards

Frequency comb has both
Microwave standard: comb spacing
Optical standard: comb position



How do you compare/transfer frequency?

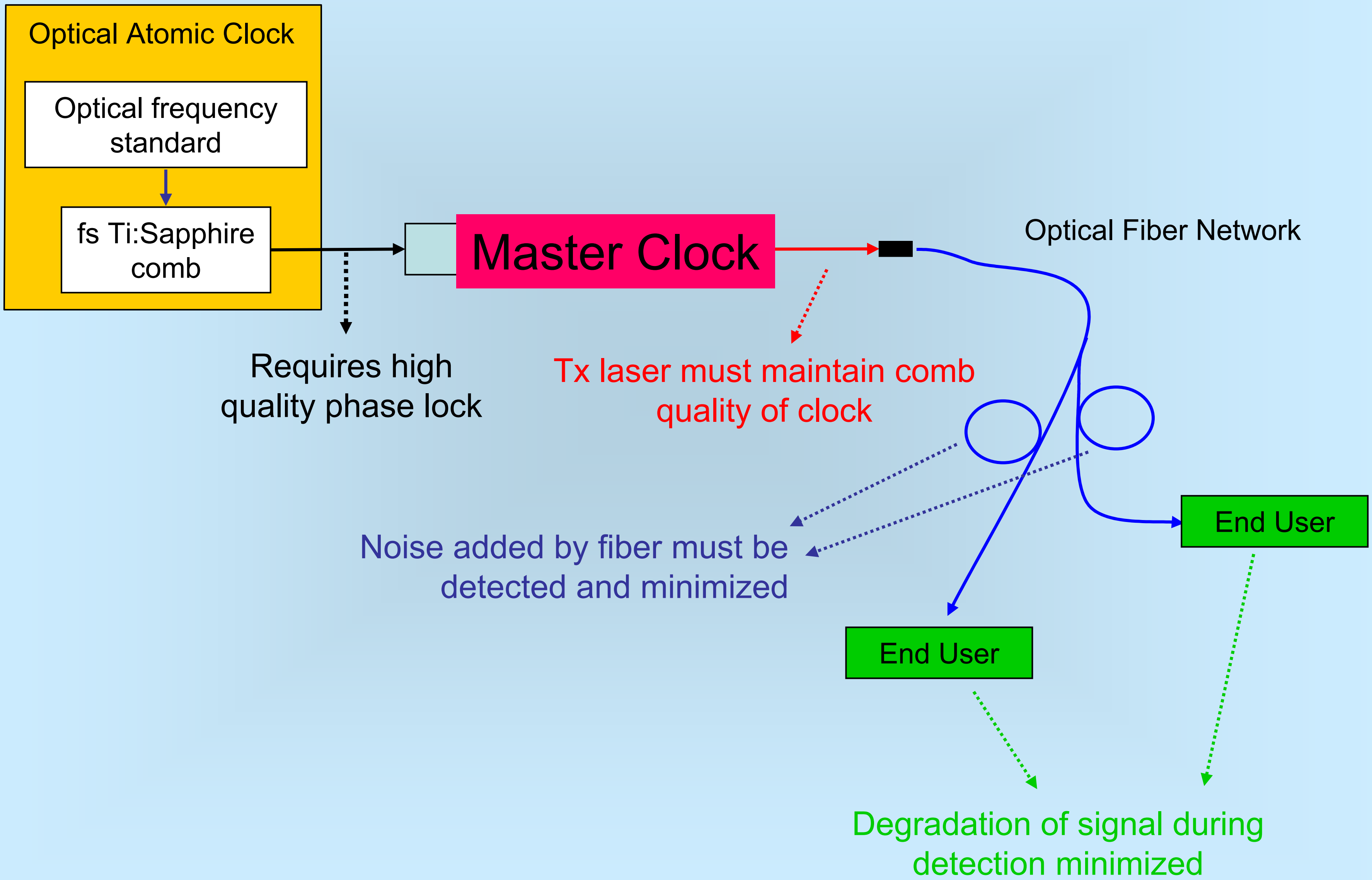
- Transport clock
- via GPS/ two way satellite transfer
- optical fiber link

Increase in stability ↑

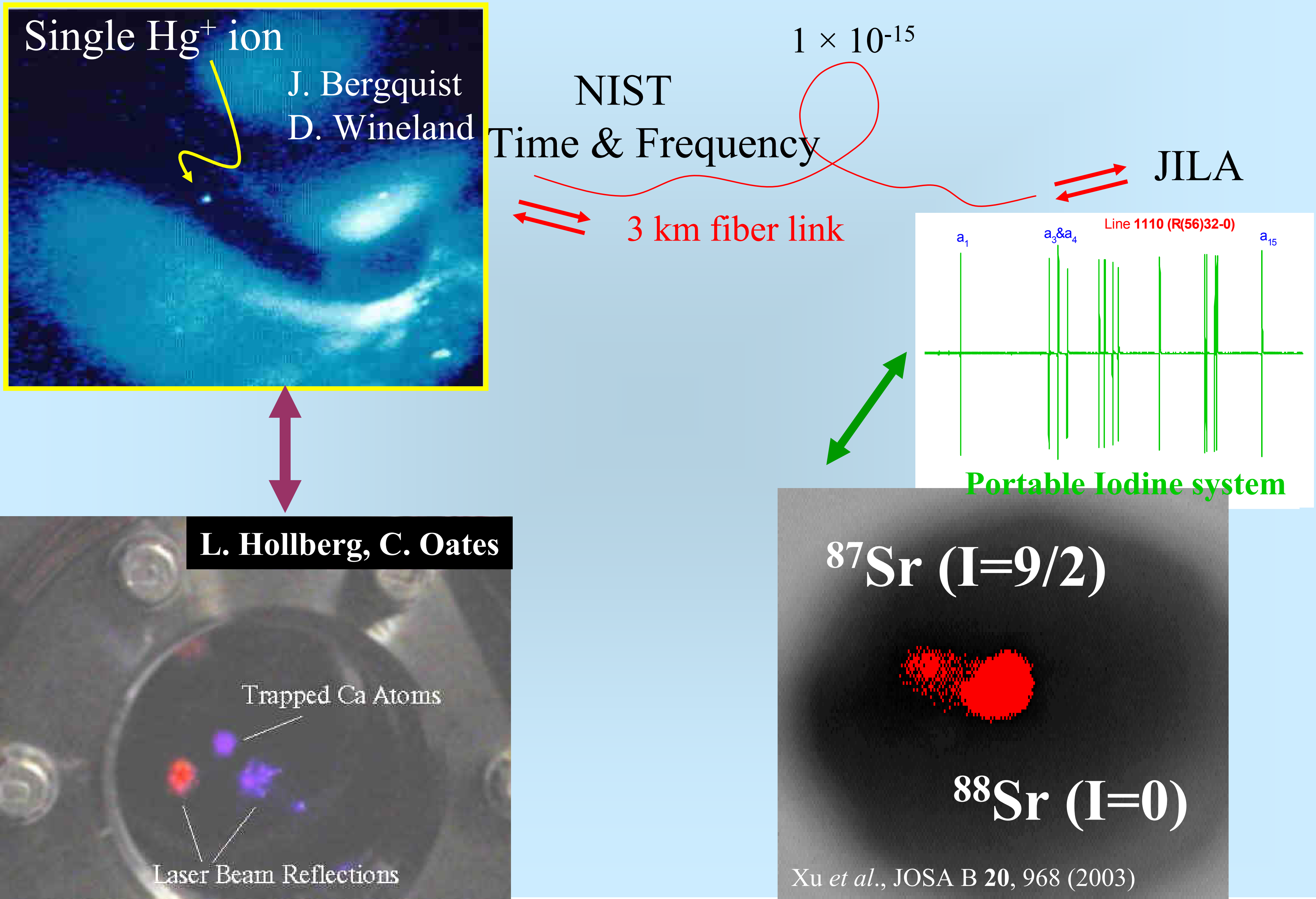
Motivation for high stability transfer of frequency standards

- Comparison of optical standards for fundamental physics,…
- Remote pulse synchronization: Laser and Linac
- Surveillance
- Telecom network synchronization

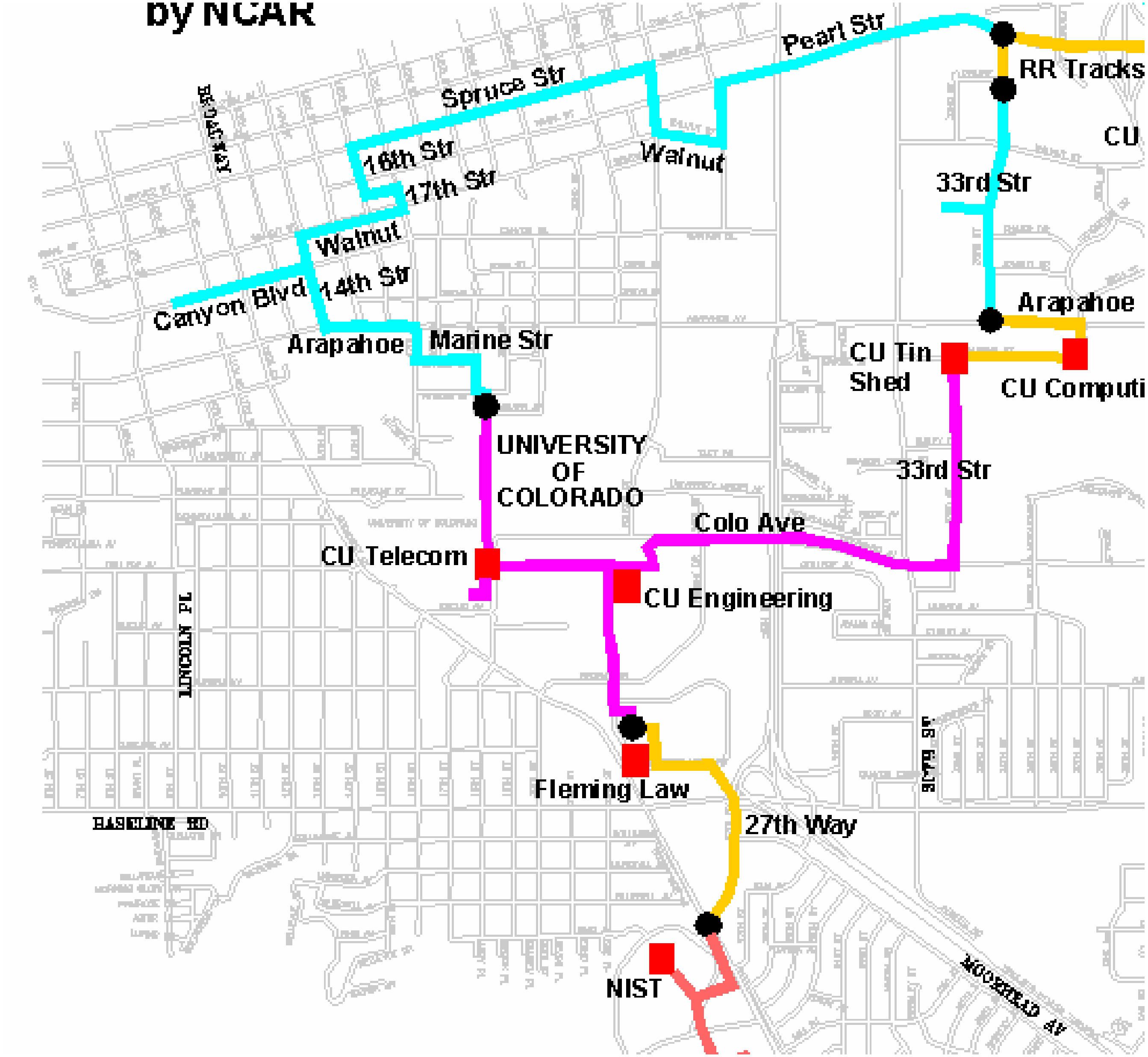
Distribution over Fiber Networks



Optical Clock transfer and comparison

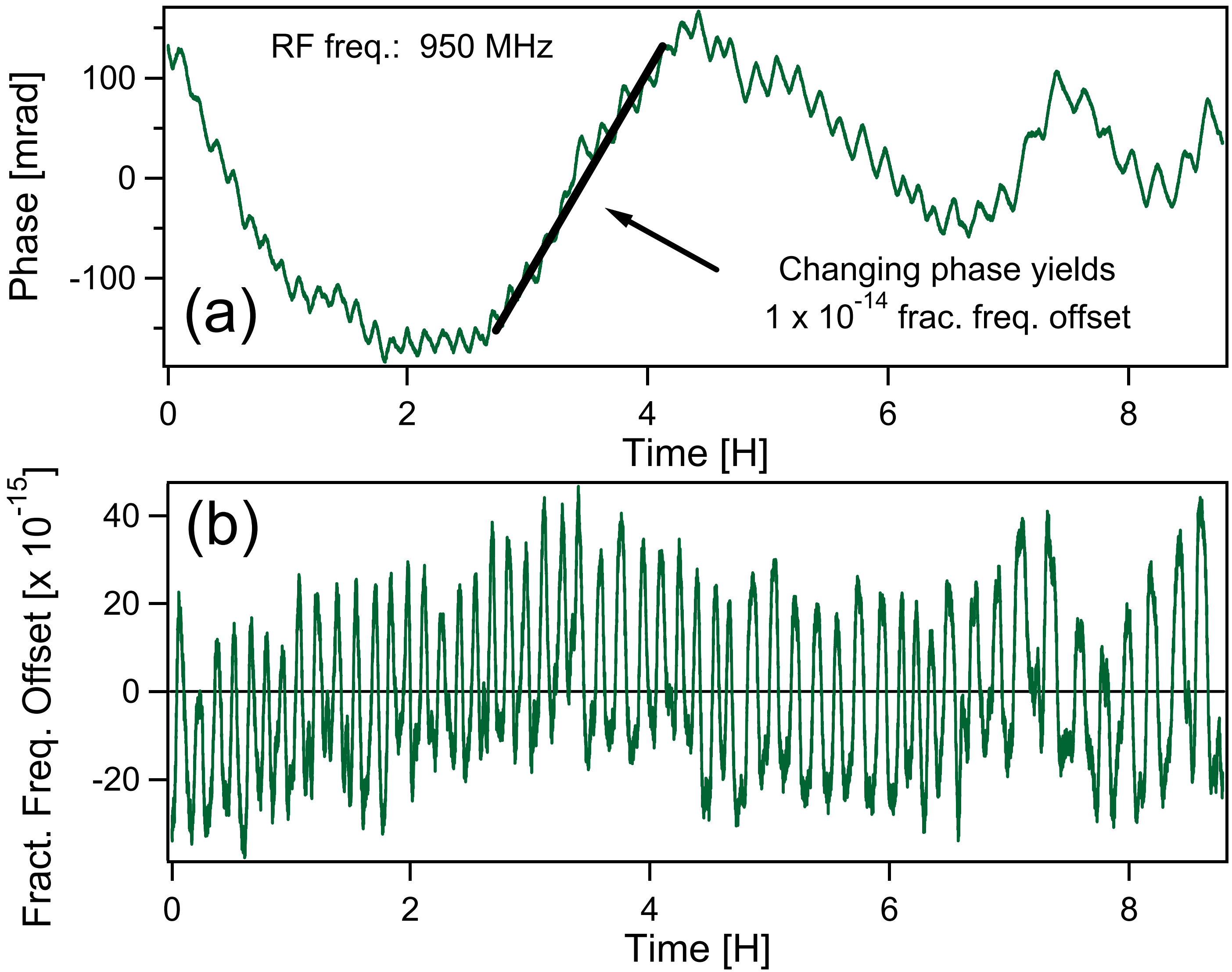


by NCAR

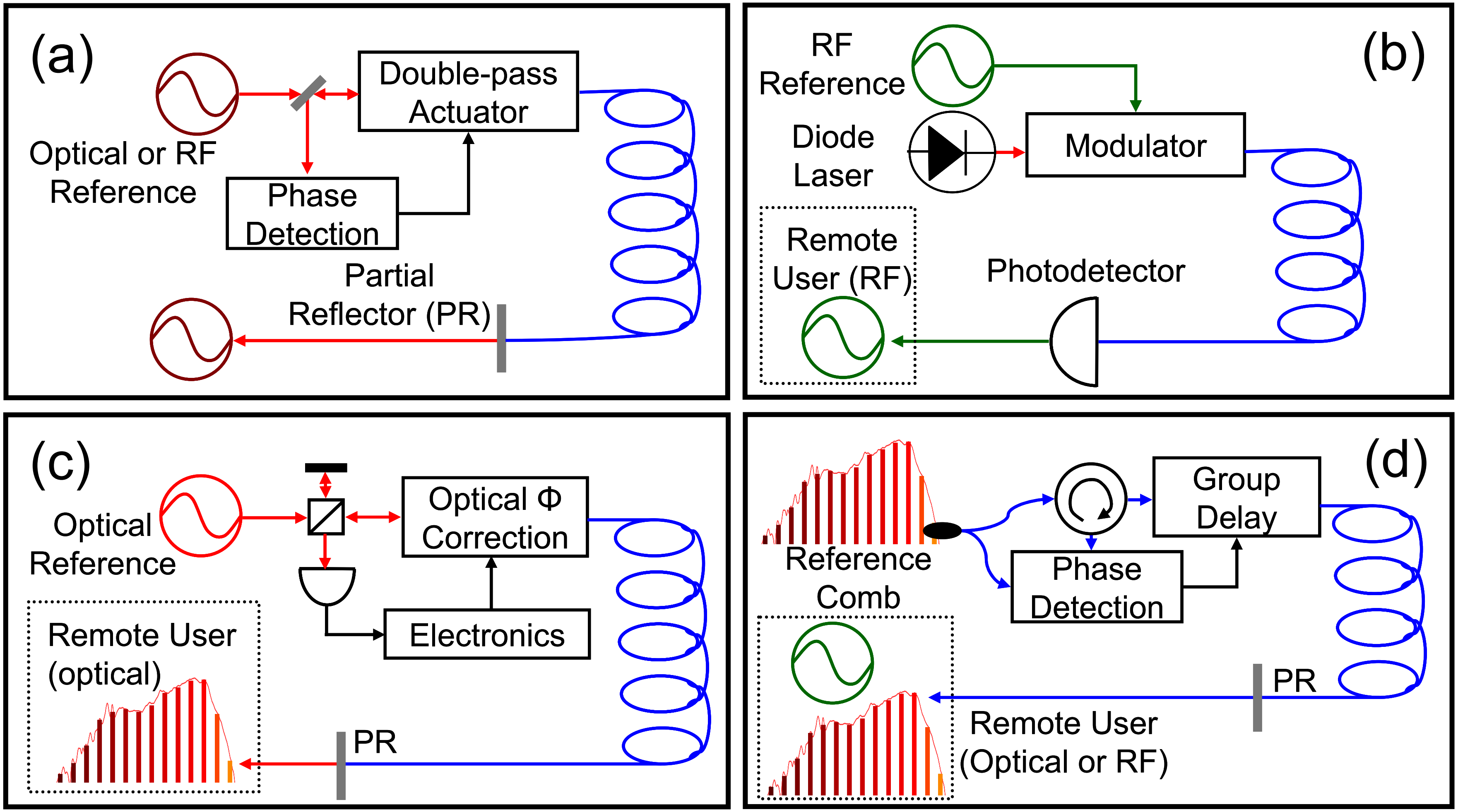


Pearl Str
RR Tracks
Spruce Str
CU
16th Str
Walnut
17th Str
33rd Str
Walnut
14th Str
Canyon Blvd
Arapahoe
Arapahoe
Marine Str
CU Tin Shed
CU Computi
UNIVERSITY OF COLORADO
33rd Str
Colo Ave
CU Telecom
CU Engineering
Fleming Law
27th Way
NIST
BROADWAY
LINCOLN PL
BASELINE RD
MOORHEAD AV

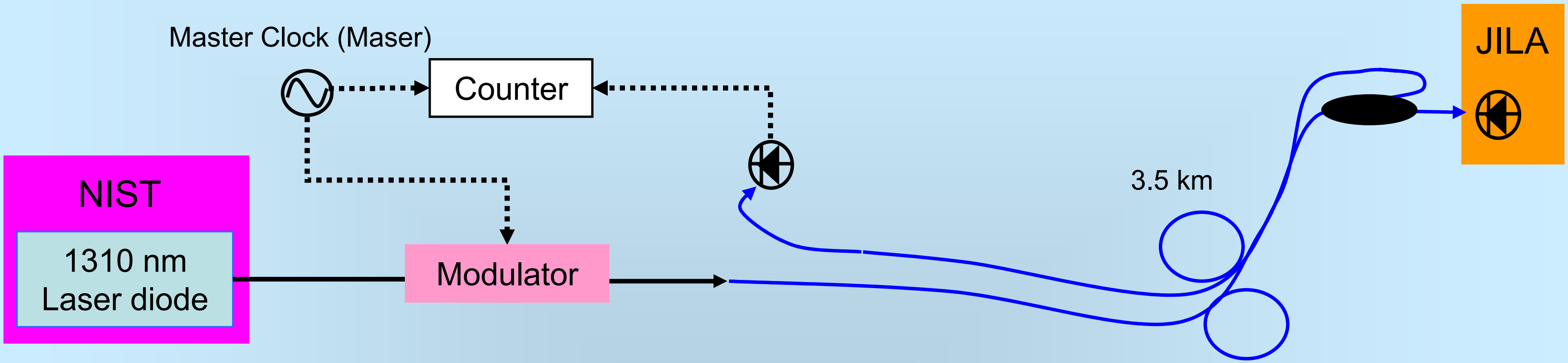
Fiber transfer phase/frequency fluctuations

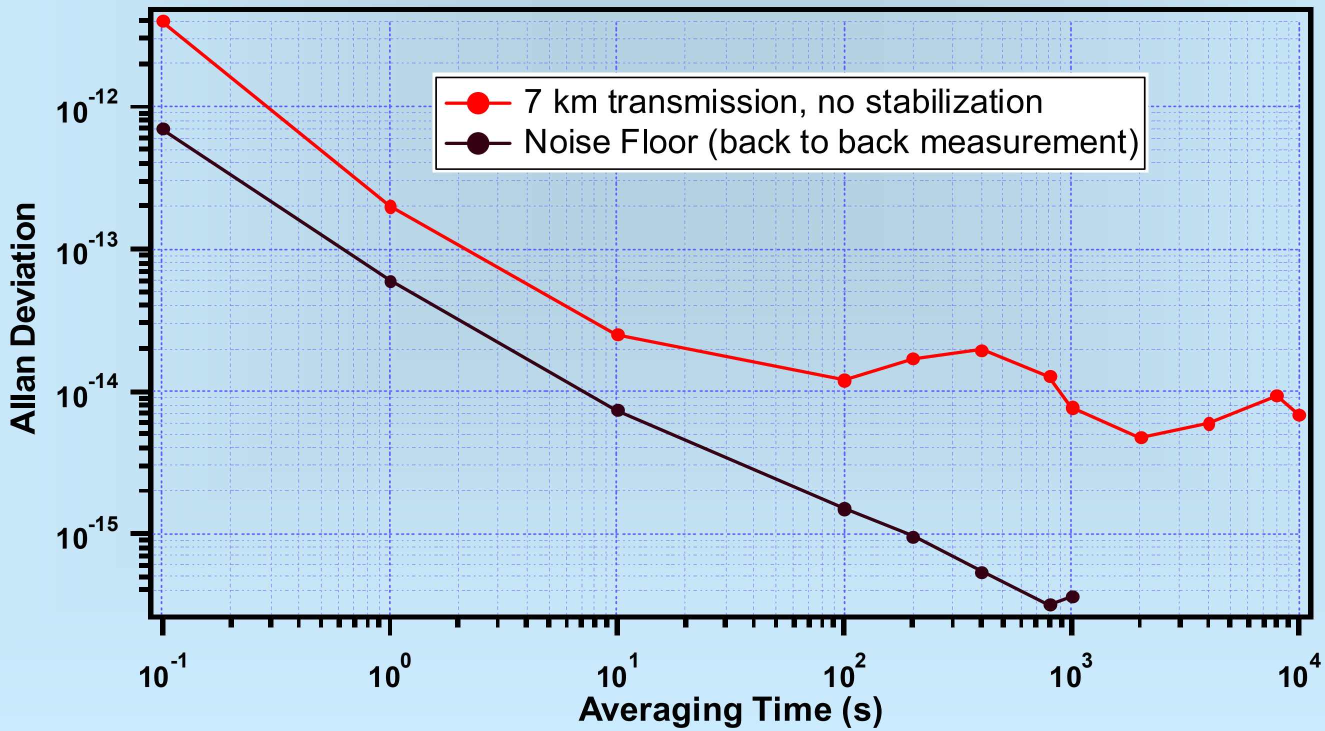


Methods for Stable Frequency Transfer



Transmission of Maser from NIST to JILA (7 km)

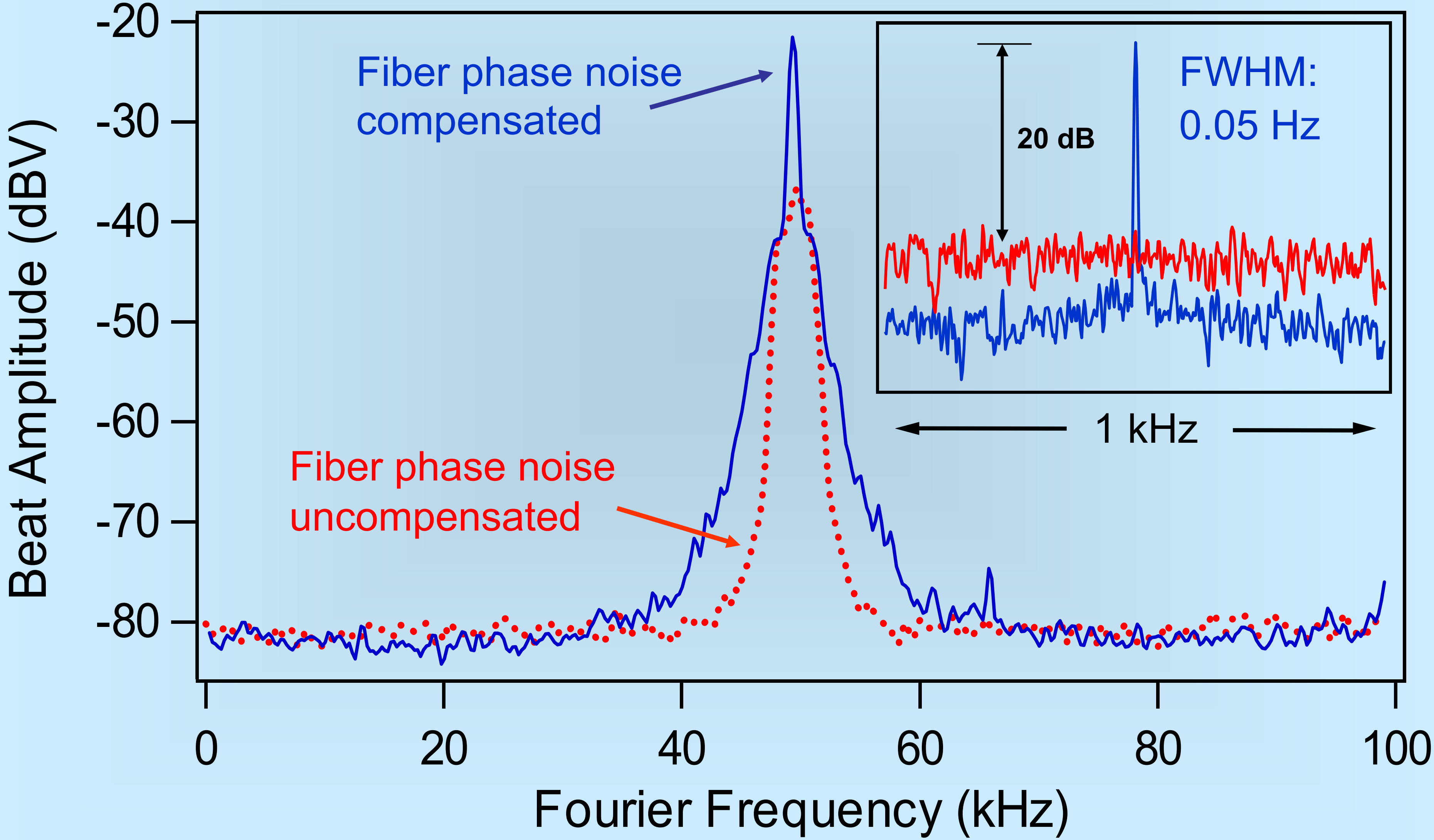




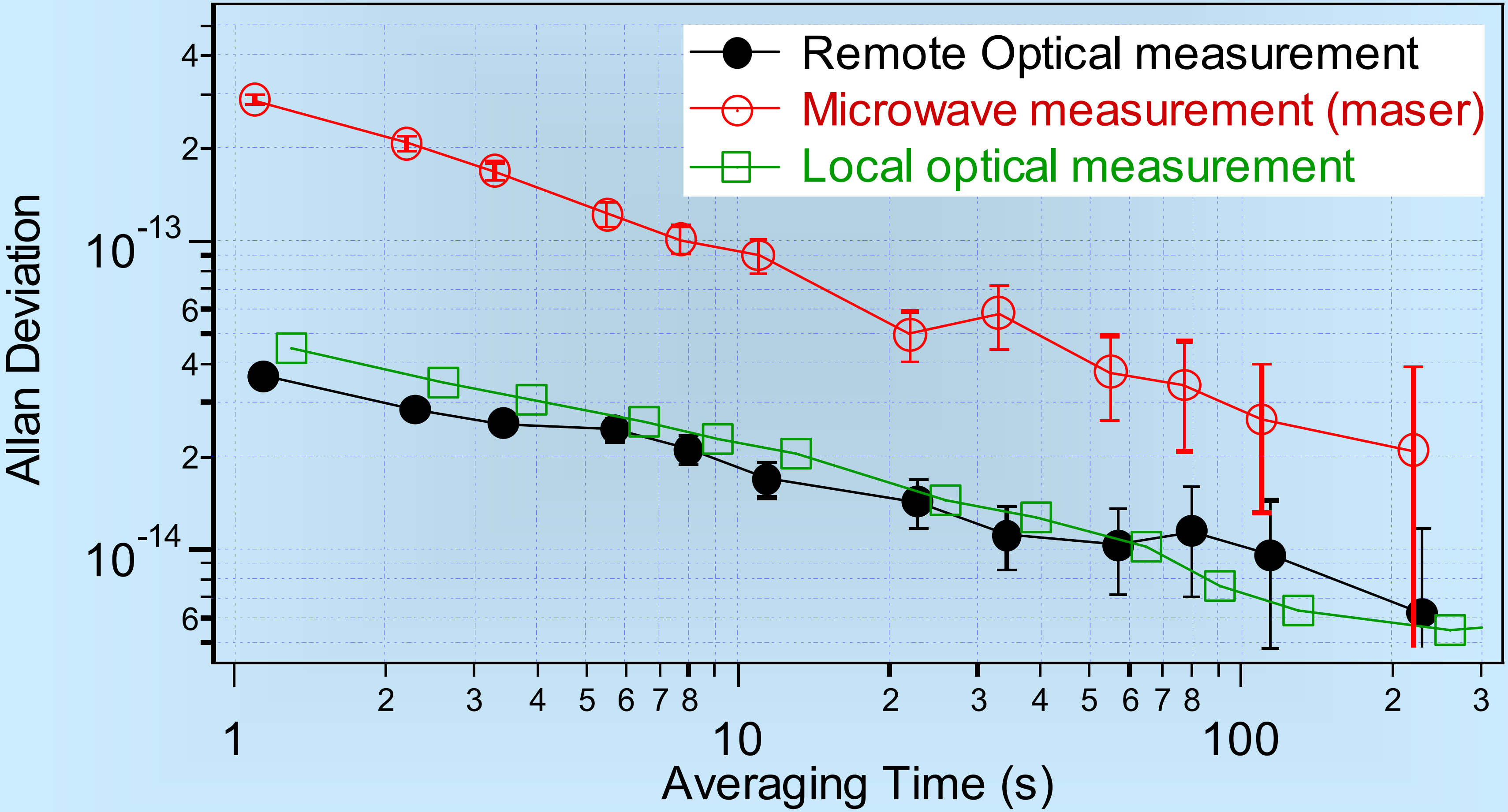
• similar performance in NASA/JPL work on frequency distribution system for radio telescopes

Active Fiber Phase Noise Compensation

Ye *et al.*, J. Opt. Soc. B **20**, 1459 (2003).



A new type of optical communication - Direct transfer of optical frequency



Mode-locked Lasers for Transmission

- easier to transfer optical stability to transmitting laser (all optical)

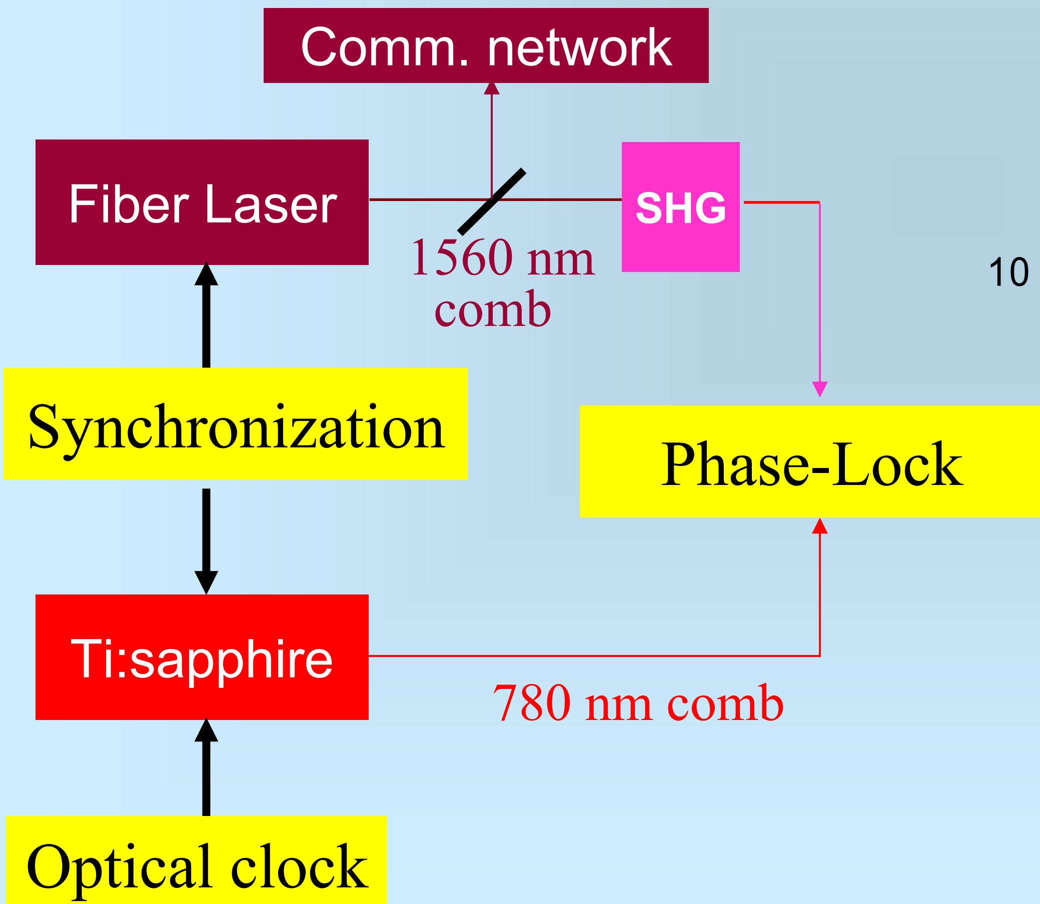
- more sensitive manner to derive noise error signal (optical pulse cross-correlation)

- transmission is time gated (less effect of noise)

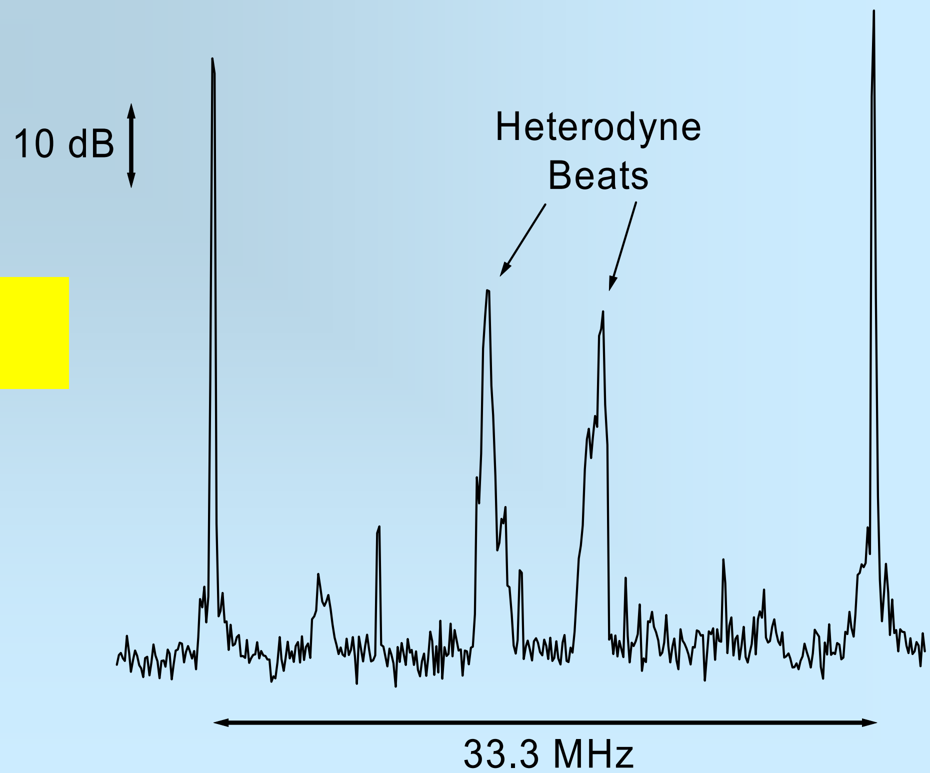
- benefits at photo-detection points

Compact Comb Source: Fiber Laser, Mode-locked diode laser, …

- Synchronization of commensurable rep rates
- Phase link from 780 nm to 1560 nm with spectral overlap by SHG

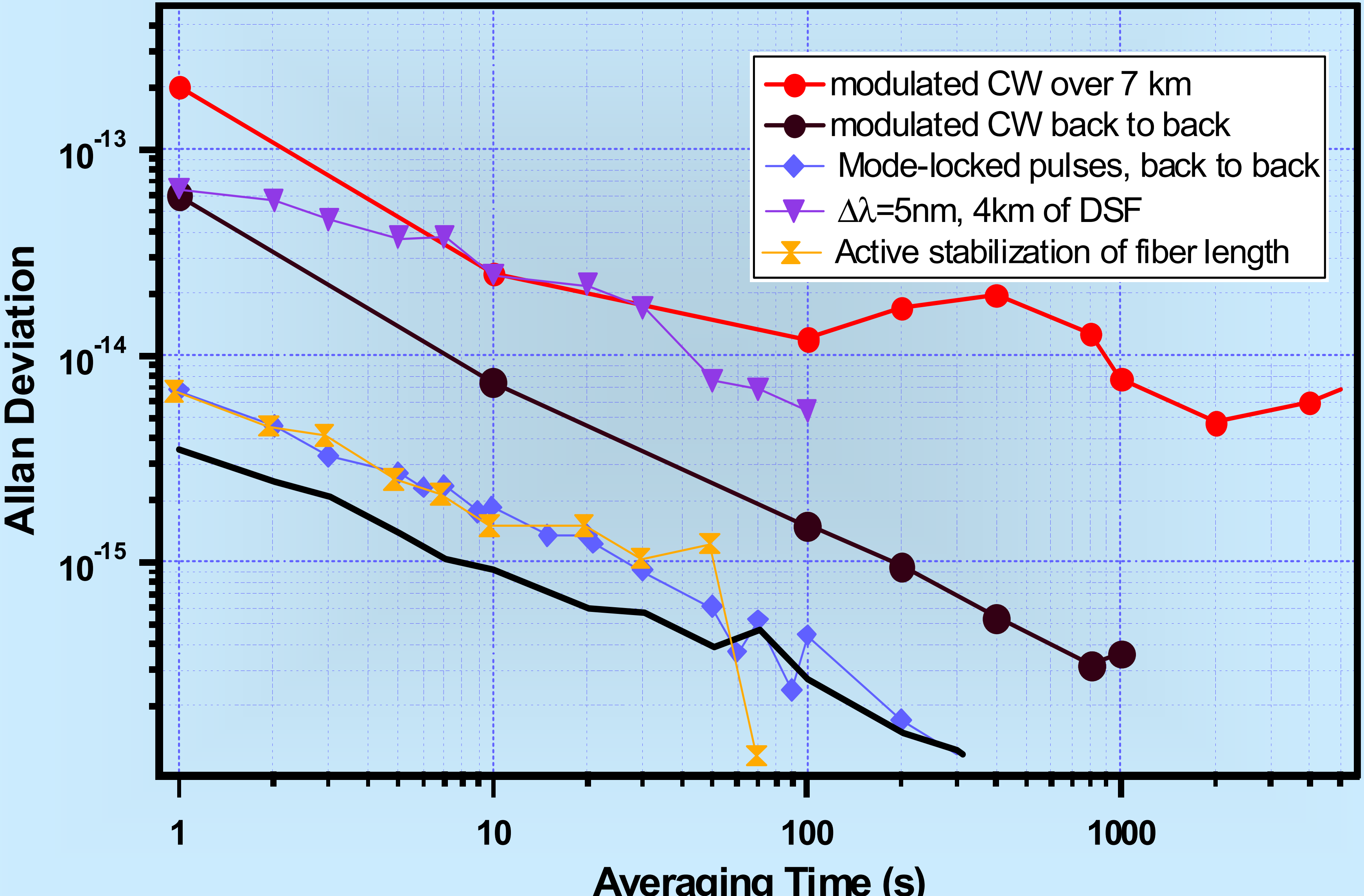


Rauschenberger, Opt. Express **10**, 1404 (2002).
Holman *et al*., Opt. Lett. **28**, 2405 (2003).
Holman *et al*., Opt. Lett. **29**, 1554 (2004).



Dispersion Shifted Fiber & active fiber noise cancellation

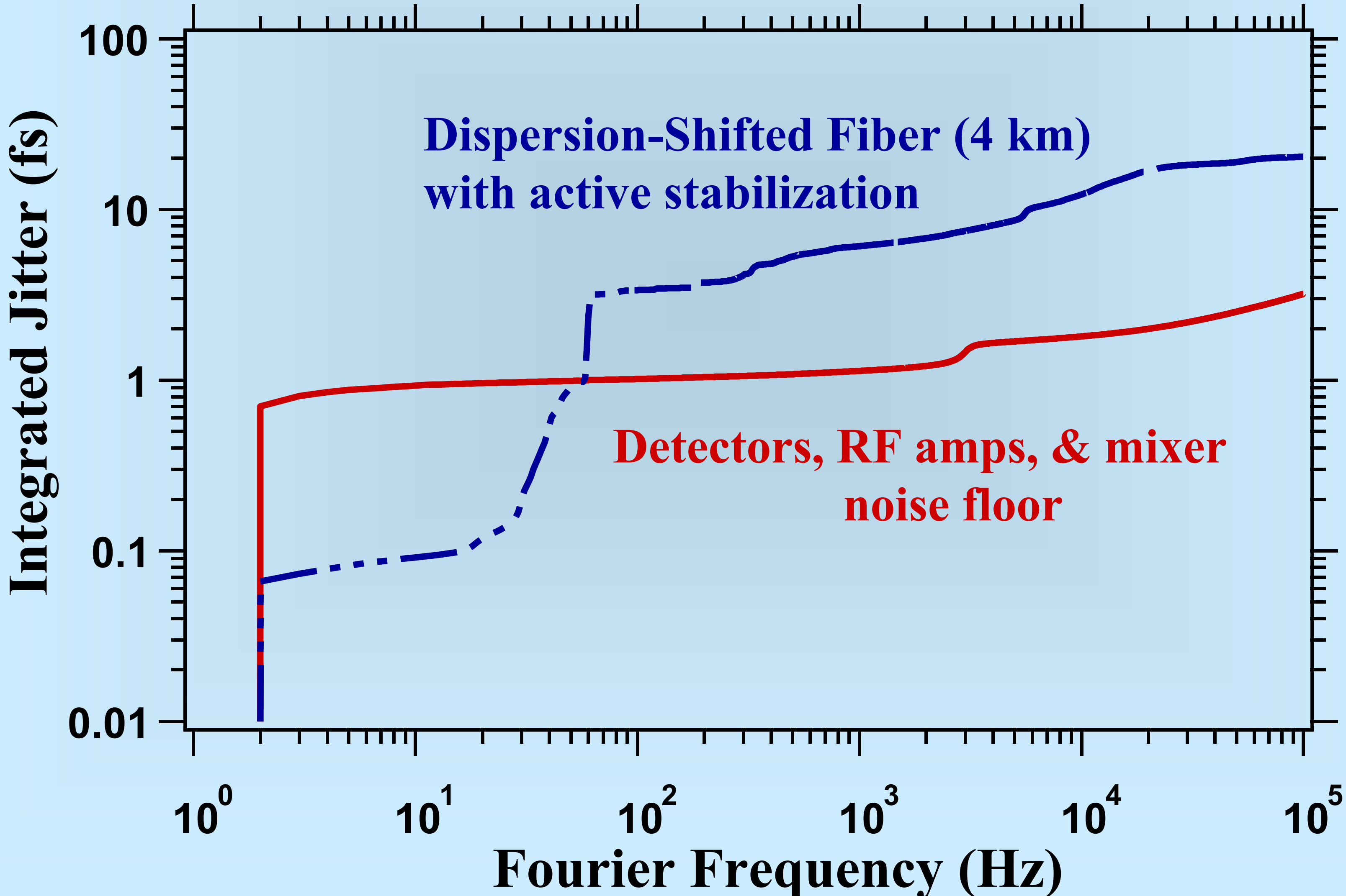
Holman *et al.*, Opt. Lett. **29**, 1554 (2004).



Dispersion Shifted Fiber & active fiber noise cancellation

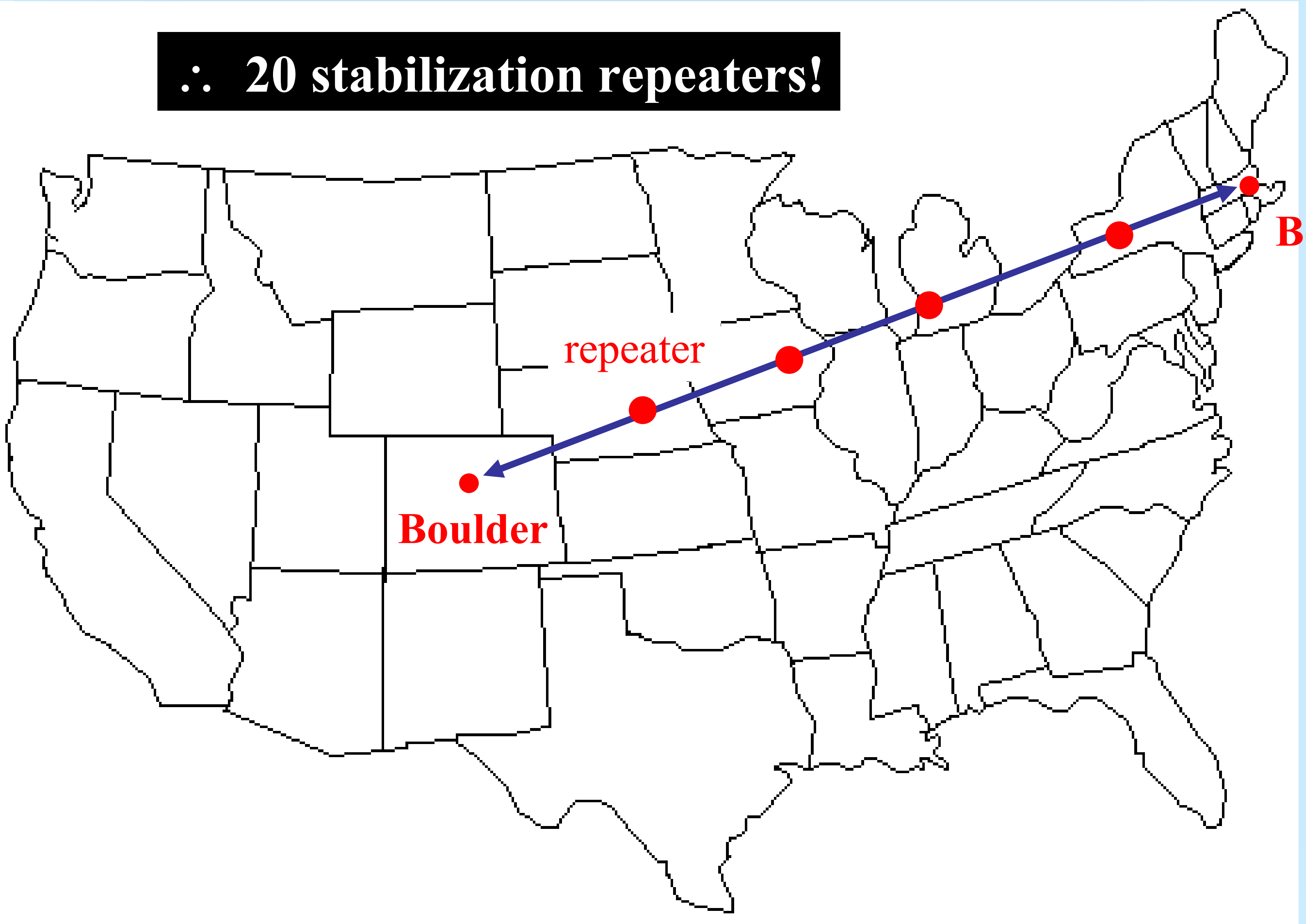
Total rms timing jitter (10 MHz BW) ~ 20 fs for 4 km fiber system

Holman, 11:30 am, Thur. 8/26, FC1E-4/PS1-42



Transcontinental optical clock signal

100 Hz servo BW → Delay (max) ~ 1/(2π 100) s → Distance (max) ≥ 150 km



Time domain applications:

- Coherent pulse synthesis
- Nonlinear Microscopy
- Gainless amplifier

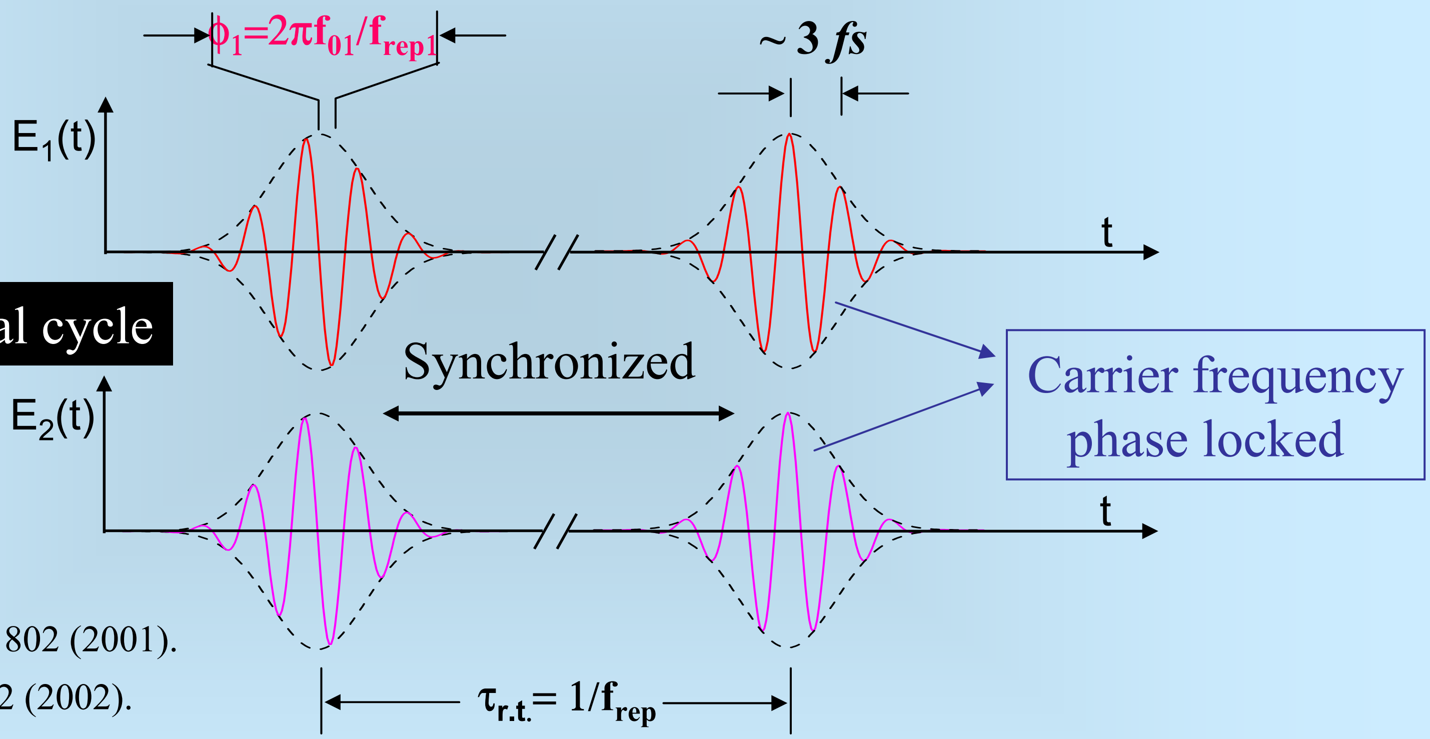
Frequency domain applications:

- Optical atomic clock
- Optical frequency synthesizer
- Quantum Interference
- Precision spectroscopy

Phase coherence of separate femtosecond lasers

— Step (1) Control of Pulse timing jitter

(a) Time domain

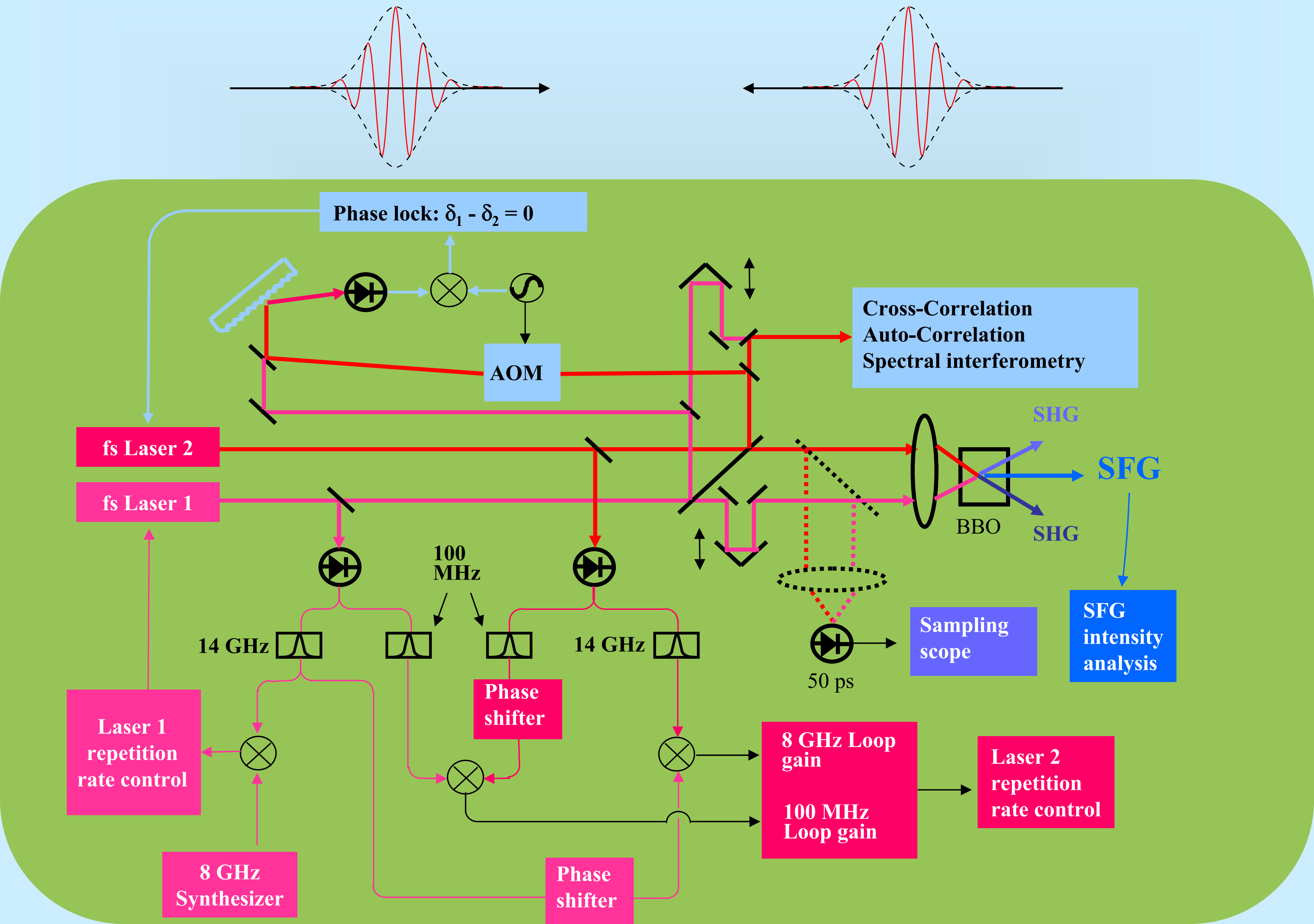


Pulse jitter < 1/2 optical cycle

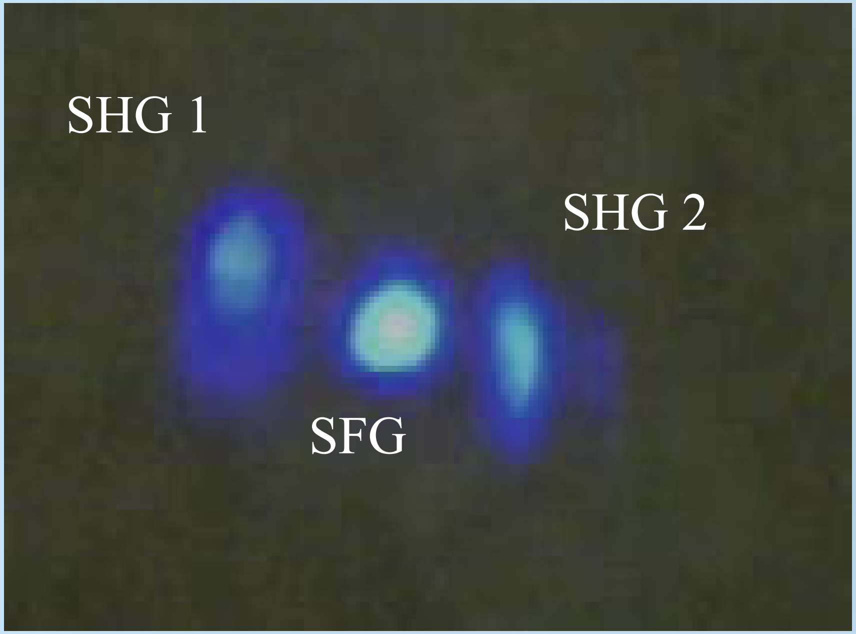
Ma *et al*., Phys. Rev. A **64**, 021802 (2001).

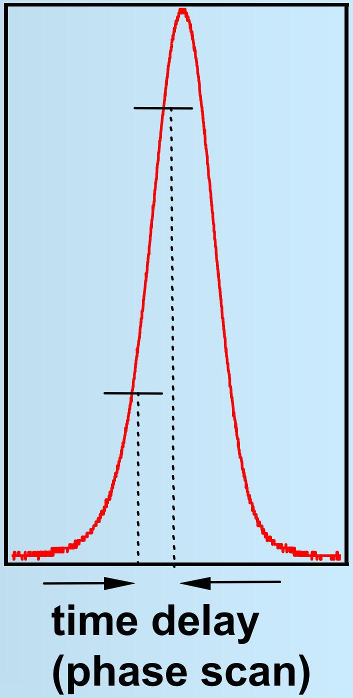
Shelton *et al*., Opt. Lett. **27**, 312 (2002).

Synchronization between fs lasers



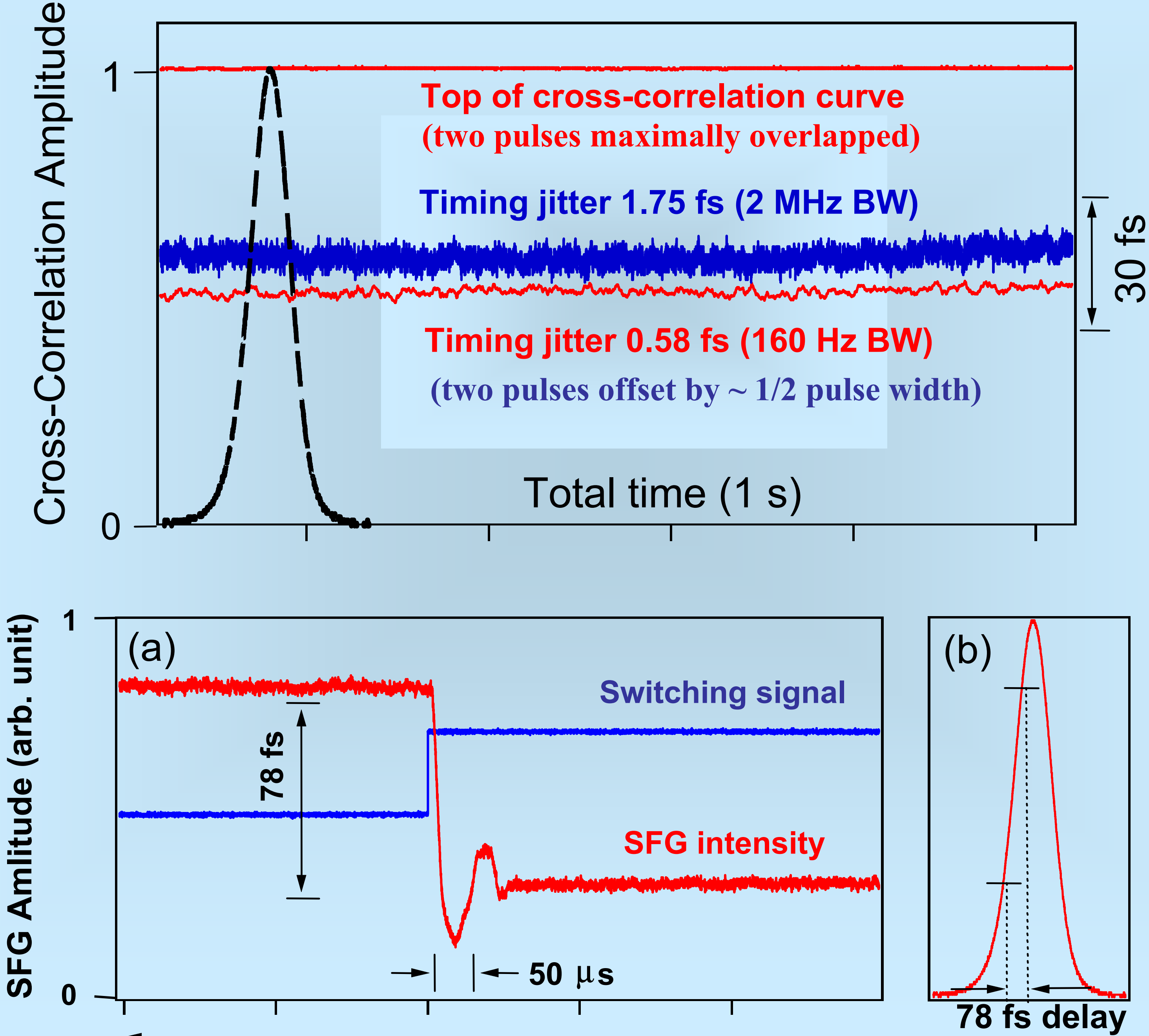
Cross-Correlation measurement by electronic phase scan





Superior reliability, repeatability, and speed for setting delay time without hysteresis.

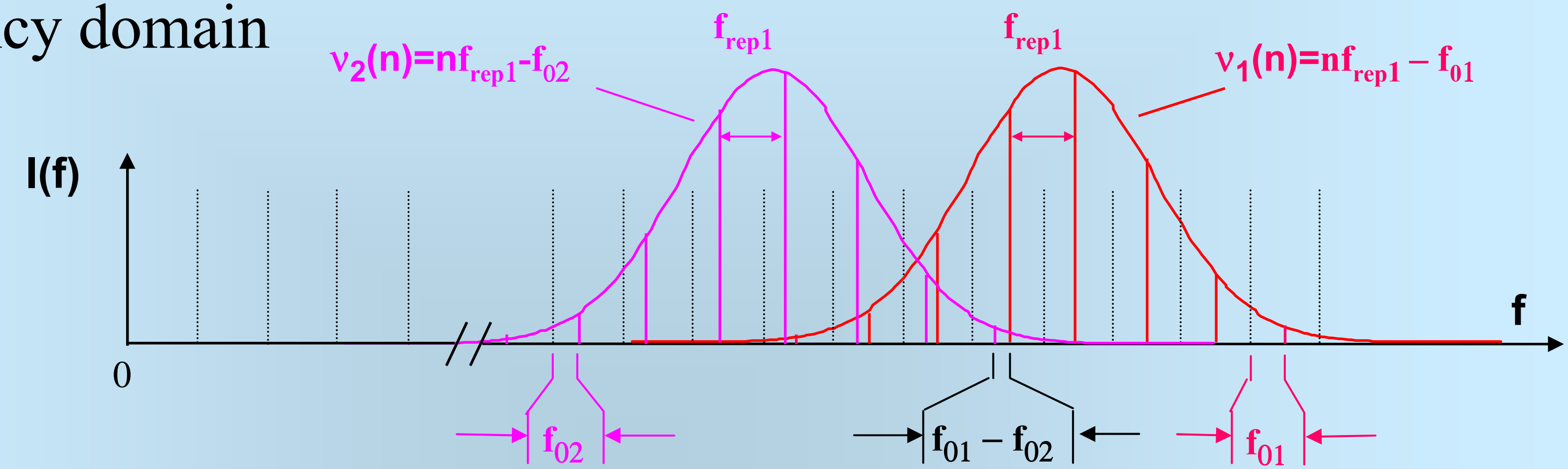
Stability of the synchronization

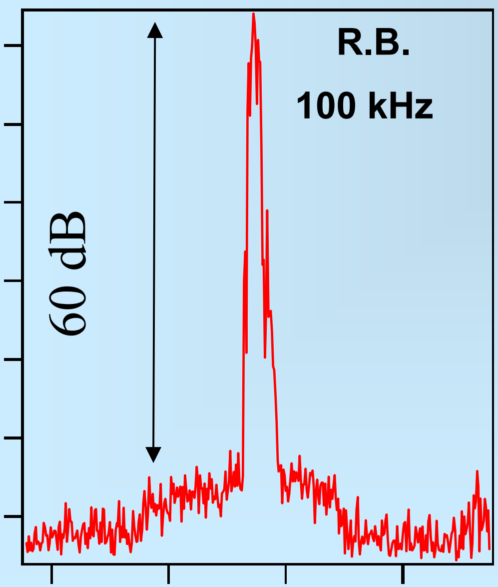


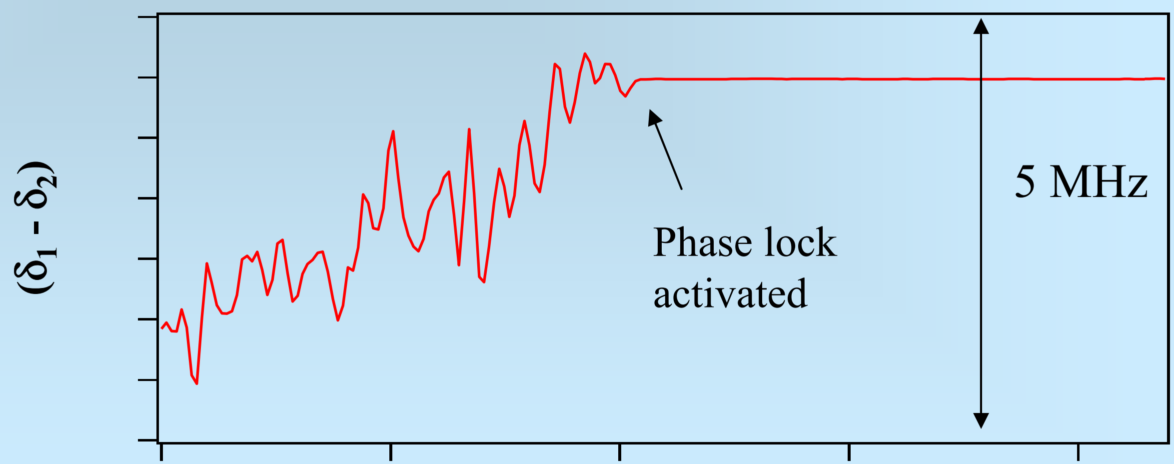
Phase coherence of two femtosecond lasers

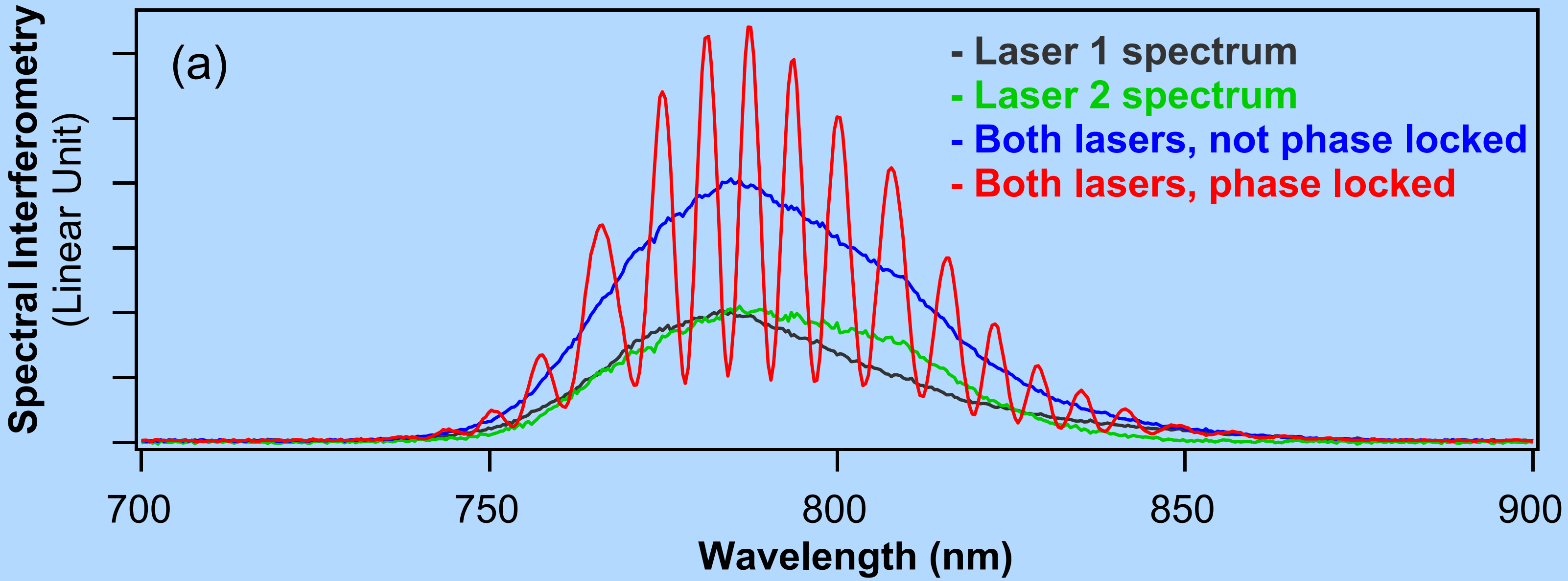
— Step (2) Carrier phase locking

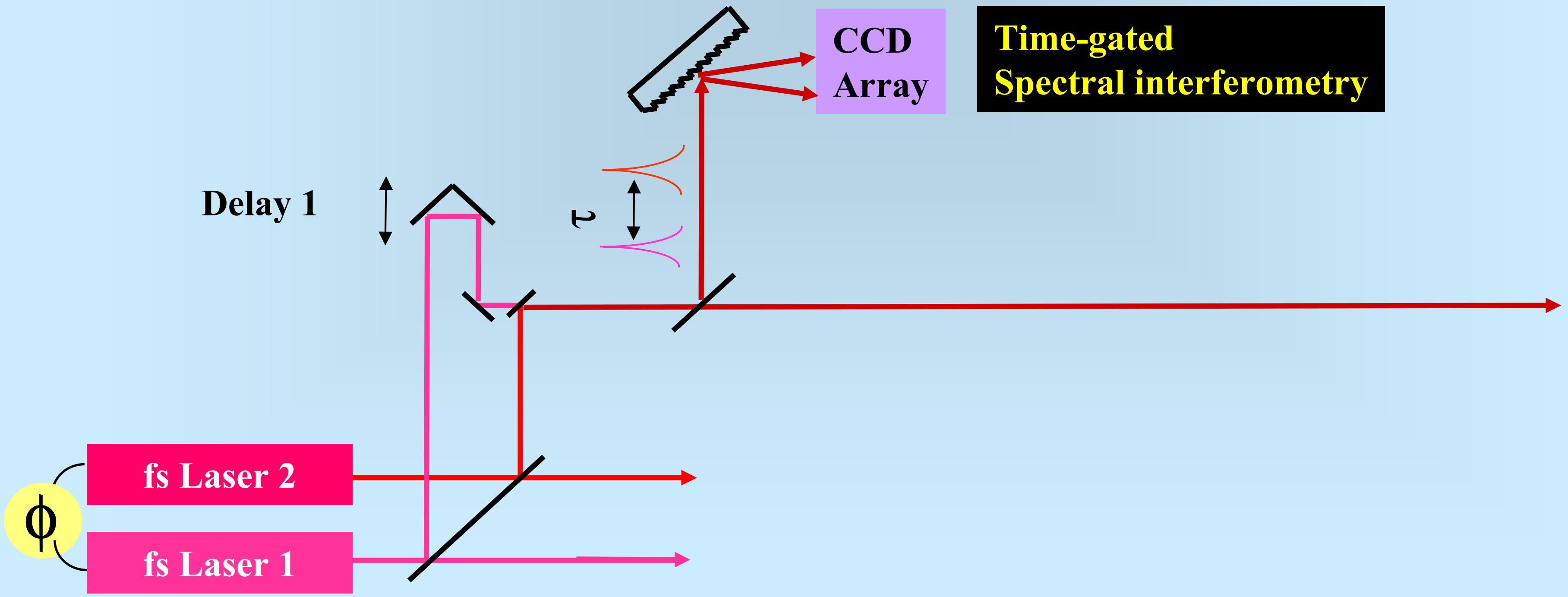
(b) Frequency domain



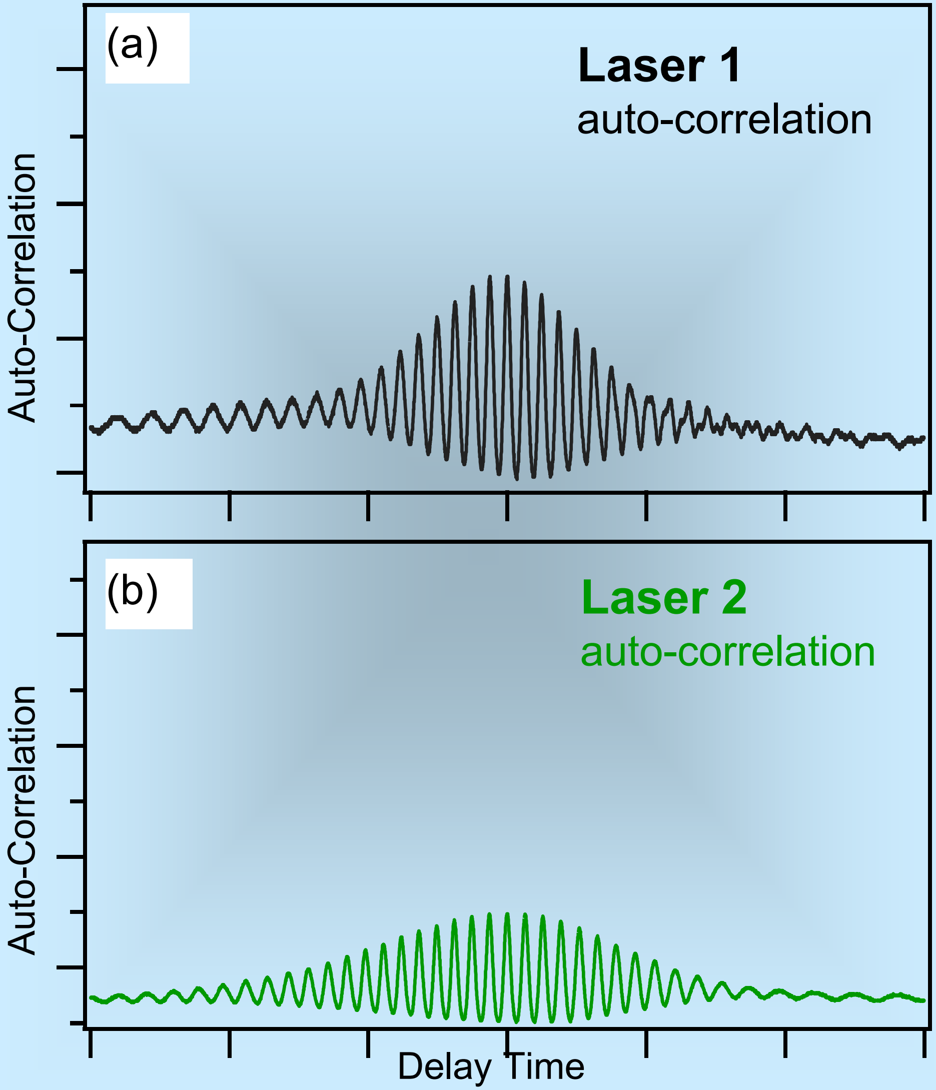




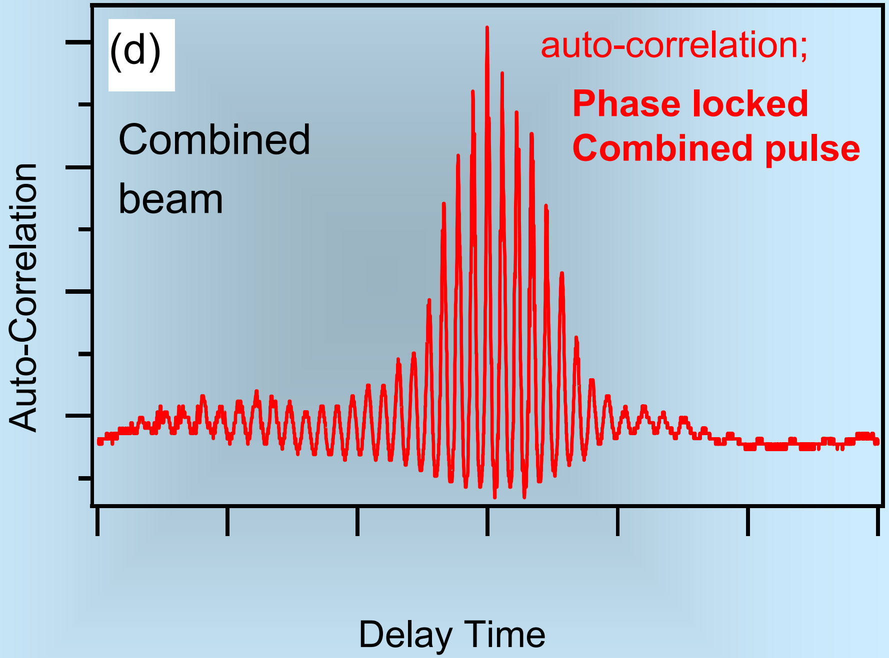

Spectral Interferometry
(Linear Unit)
(a)
- Laser 1 spectrum
- Laser 2 spectrum
- Both lasers, not phase locked
- Both lasers, phase locked
700
750
800
850
900
Wavelength (nm)


CCD
Array
Time-gated
Spectral interferometry
Delay 1
τ
fs Laser 2
fs Laser 1
ϕ

Time domain coherence between two femtosecond lasers



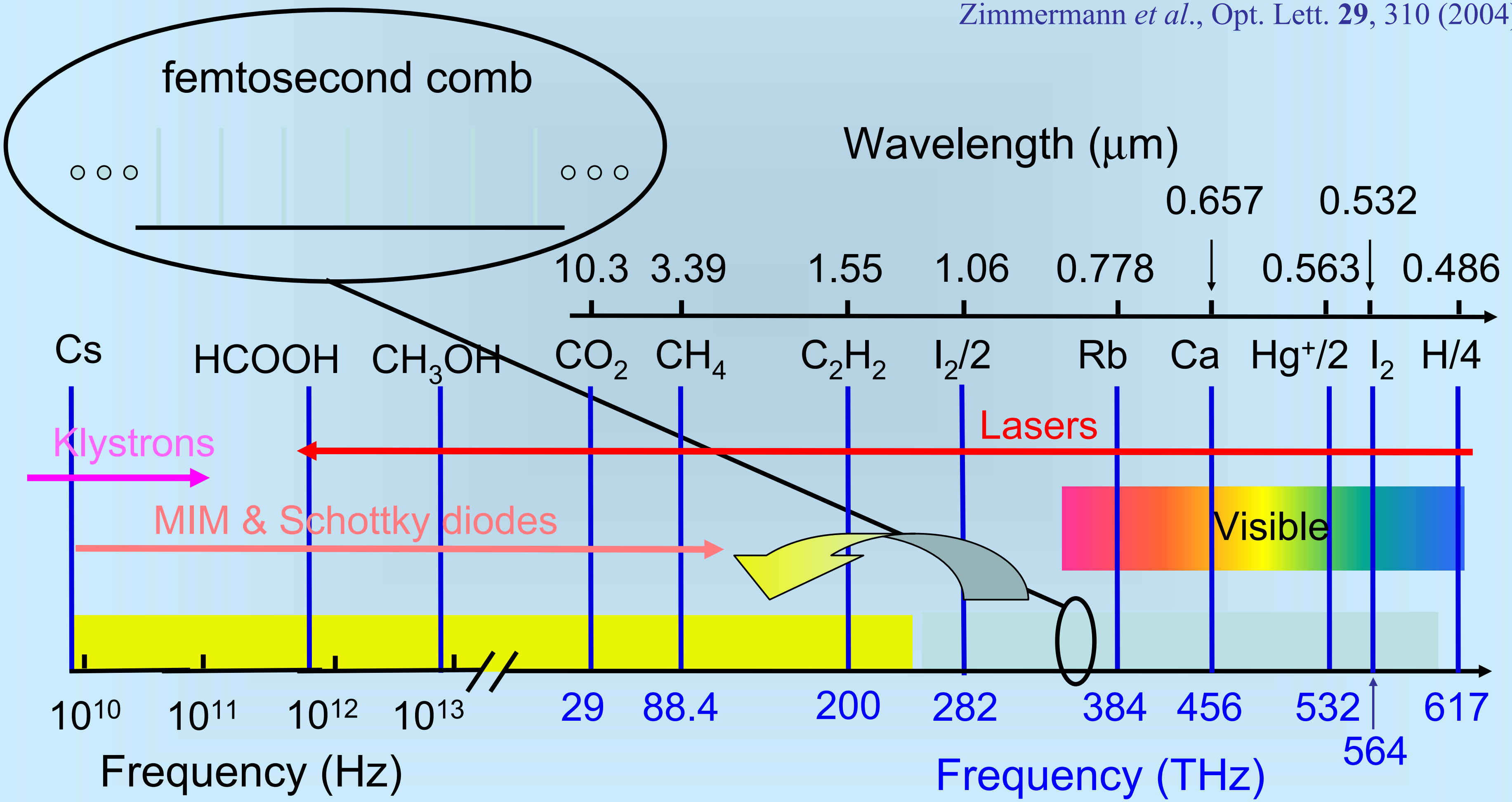
"Synthesized" Pulse



Shelton *et al*, ***Science*** **293** 1286 (2001).

Synthesis of EM Spectrum

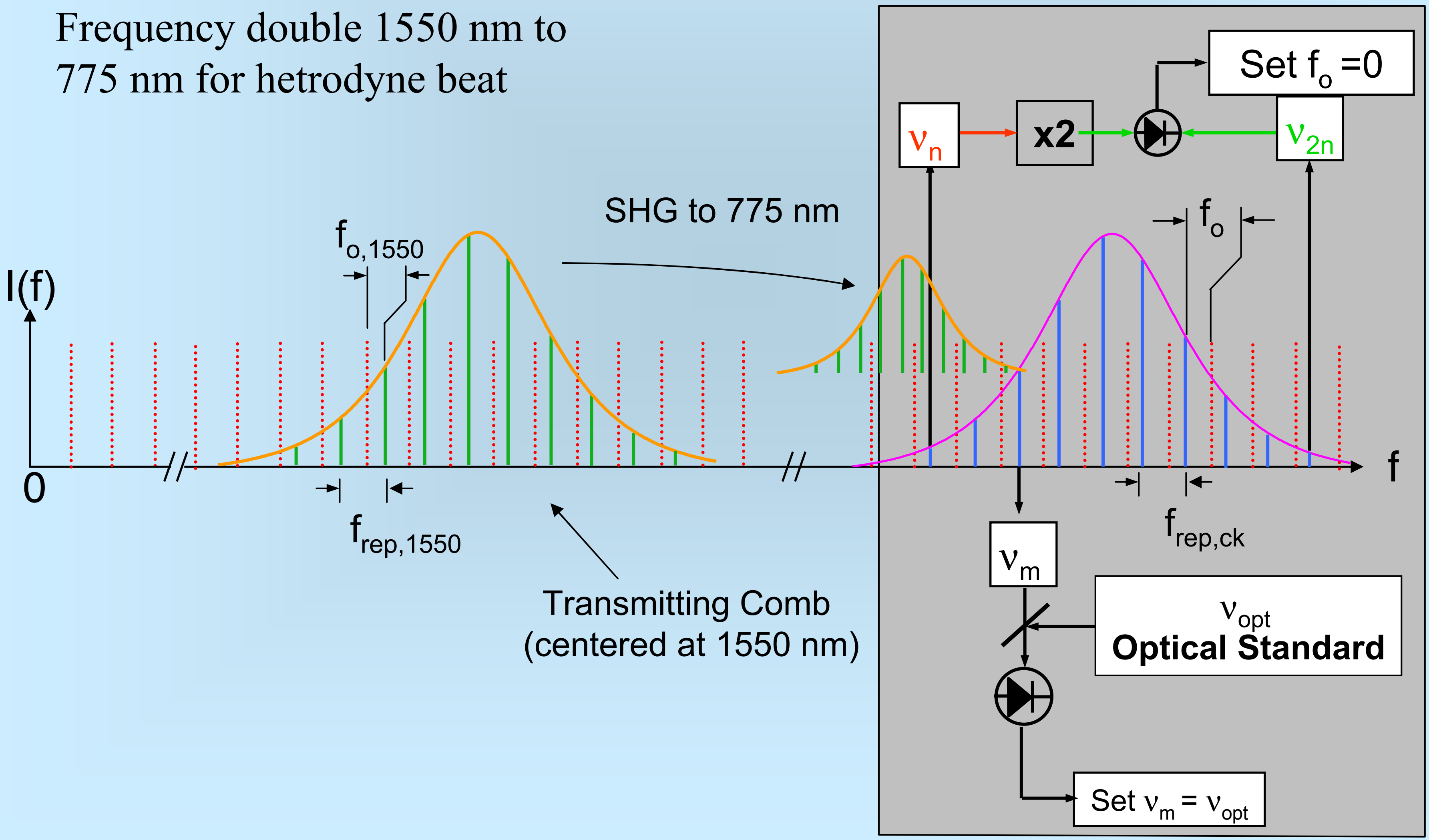
Shelton *et al*, Science **293**, 1286 (2001).
Foreman *et al*., Opt. Lett. **28**, 370 (2003).
Holman *et al*., Opt. Lett. **28**, 2405 (2003).
Zimmermann *et al*., Opt. Lett. **29**, 310 (2004).



Coherent link between 800 nm and 1550 nm optical comb

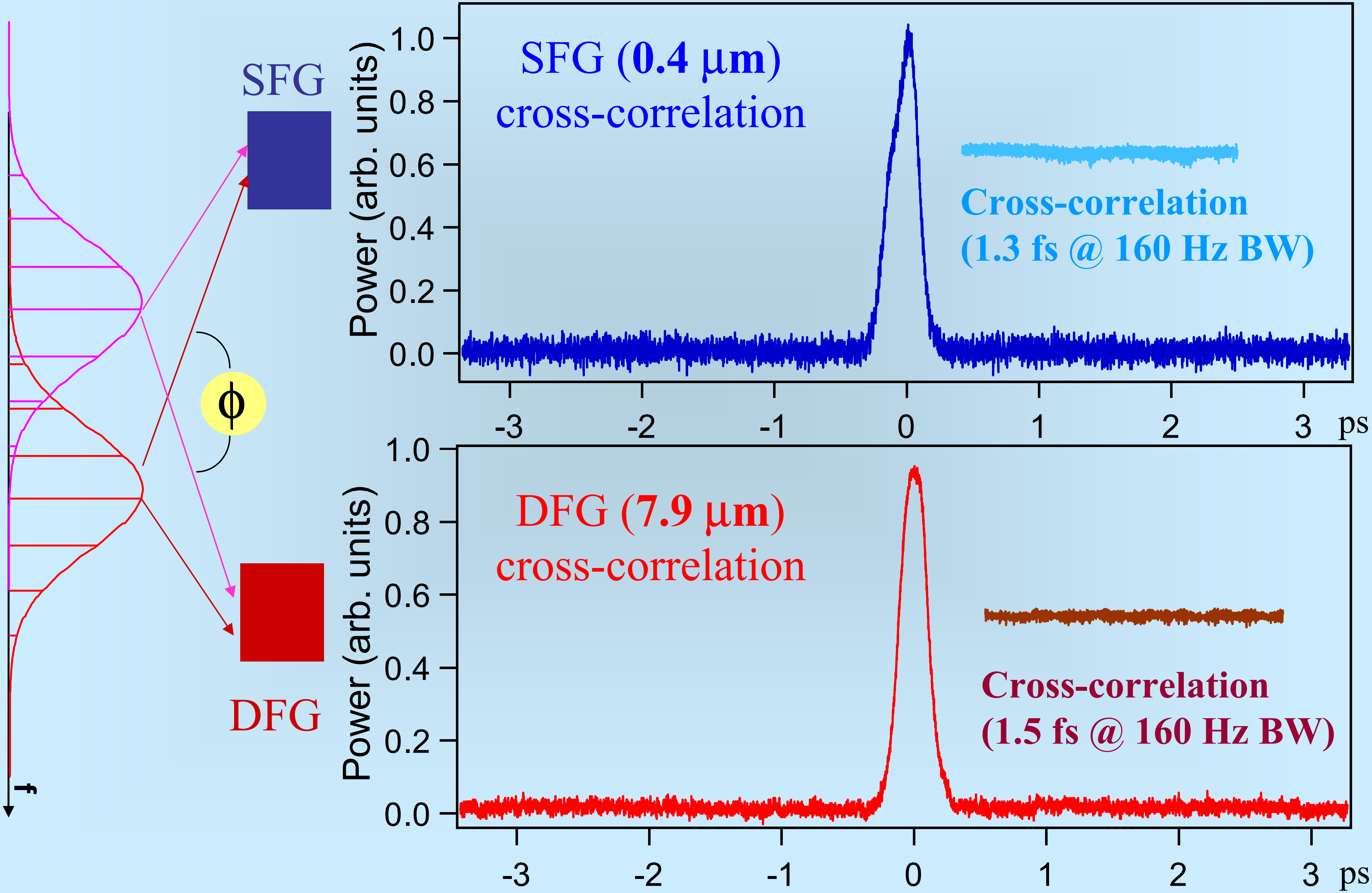
- Synchronization of MLLD is step towards coherent locking
- Phase locking is obtained with spectral overlap

  Frequency double 1550 nm to 775 nm for hetrodyne beat

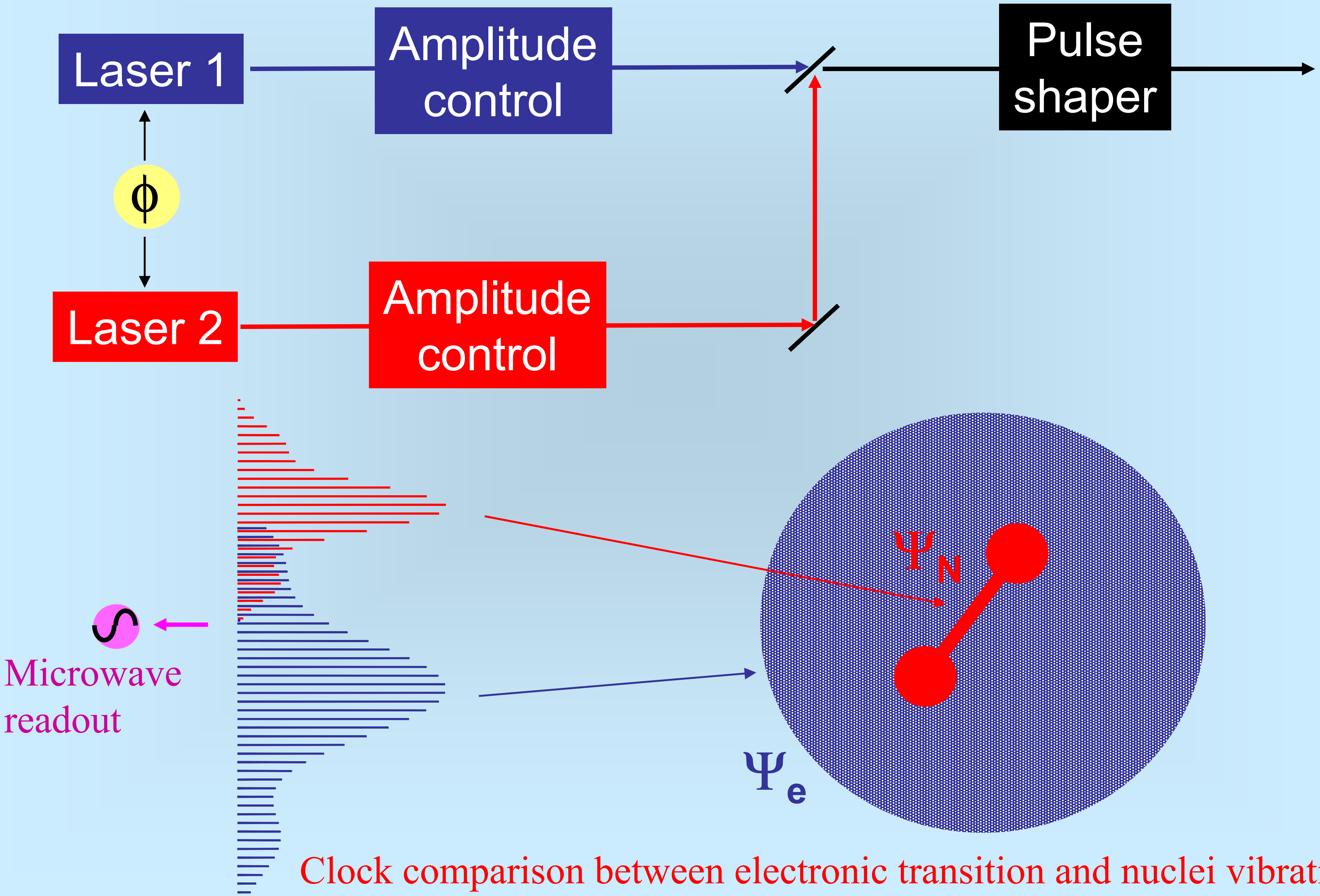


Nonlinear frequency conversion

Foreman, Jones, & Ye, Opt. Lett. **28**, 370 (2003).



High Resolution Spectroscopy and Quantum Coherent Control



Clock comparison between electronic transition and nuclei vibration

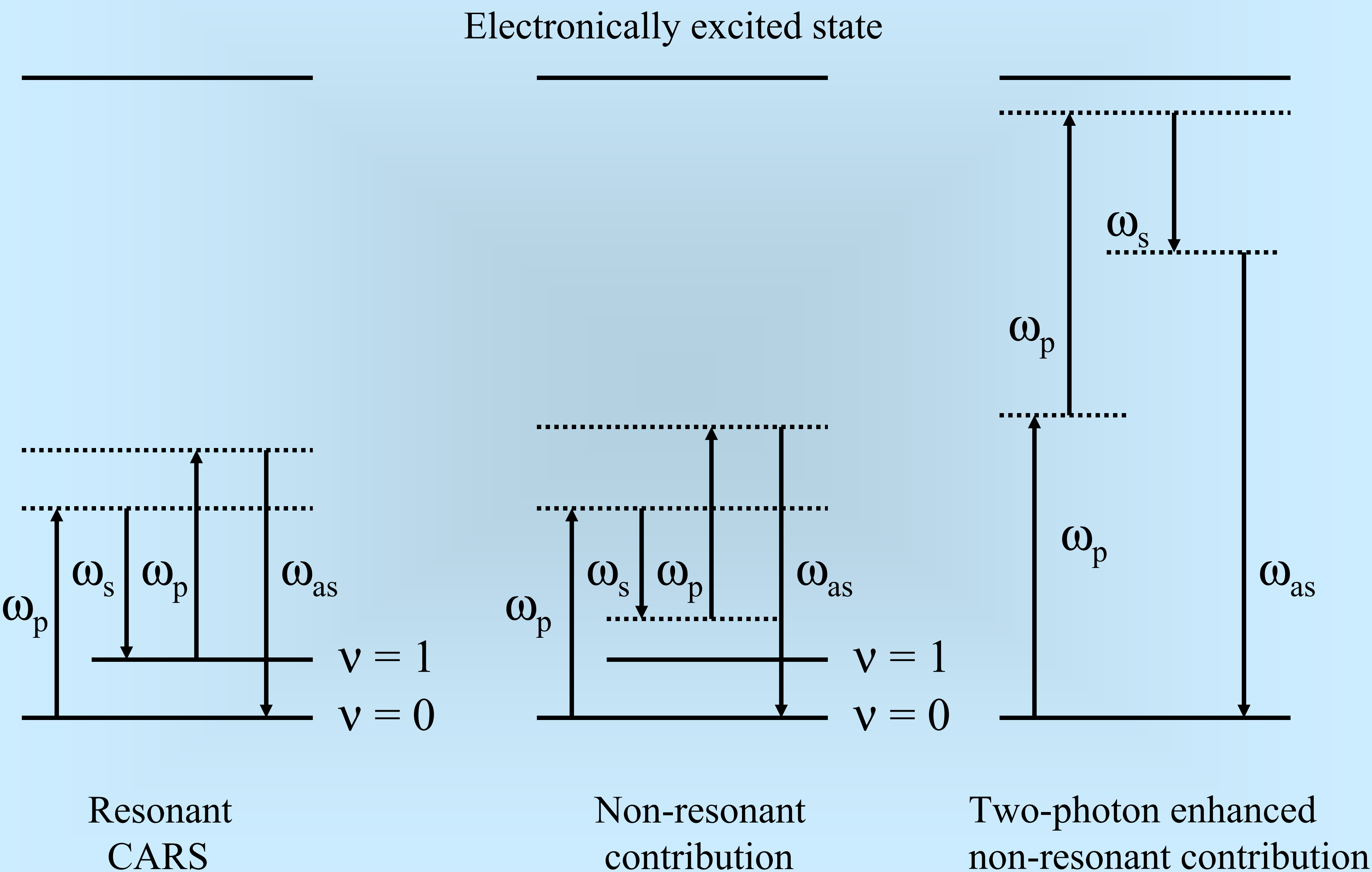
Time domain applications:

- Carrier-envelope phase control
- Coherent pulse synthesis
- Nonlinear Microscopy
- Gainless amplifier

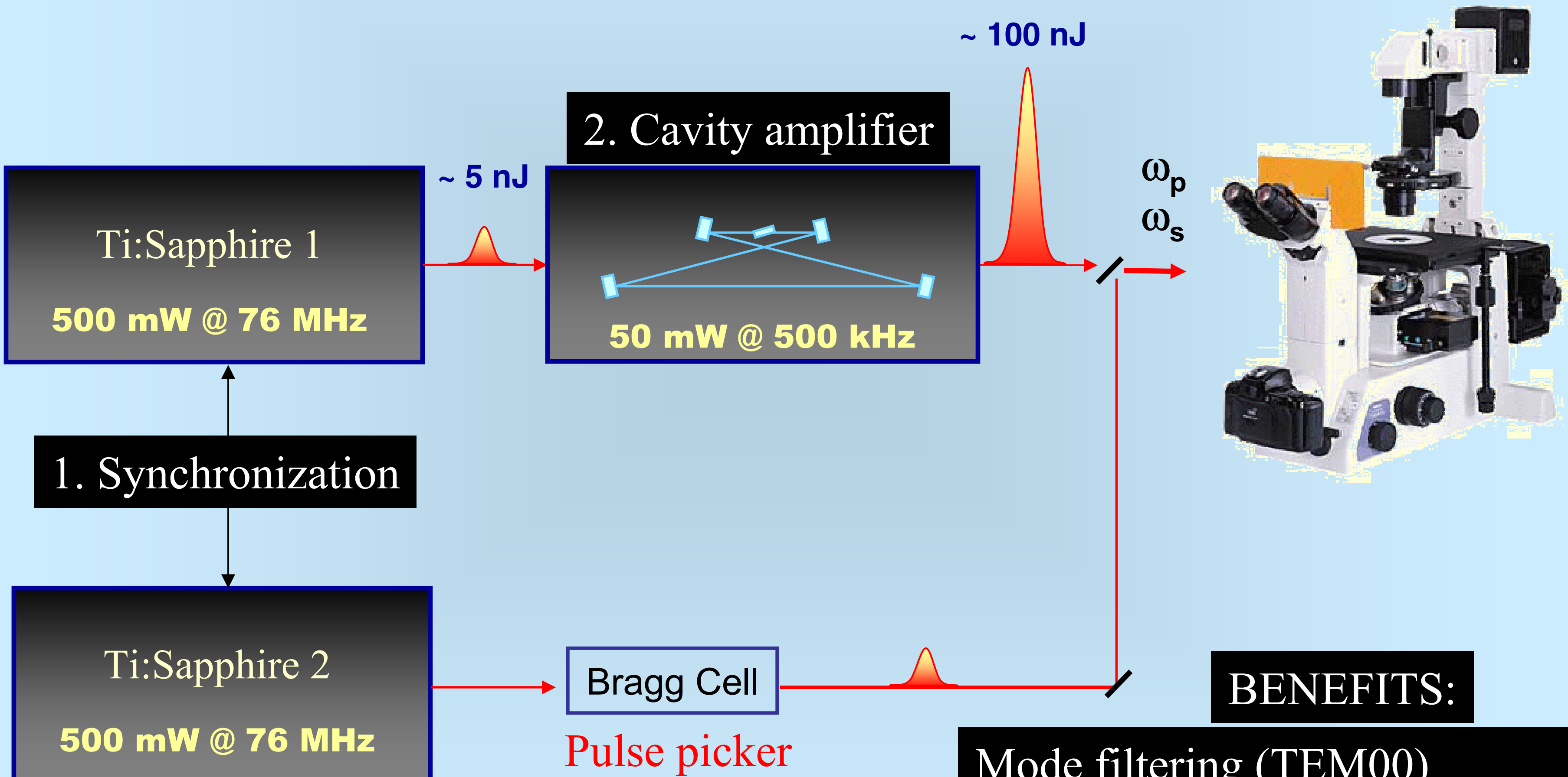
Frequency domain applications:

- Optical atomic clock
- Optical frequency synthesizer
- Quantum Interference
- Precision spectroscopy

Coherent Anti-stokes Raman Spectroscopy



CARS
Spectroscopy (molecule) + Microscopy (spatial)

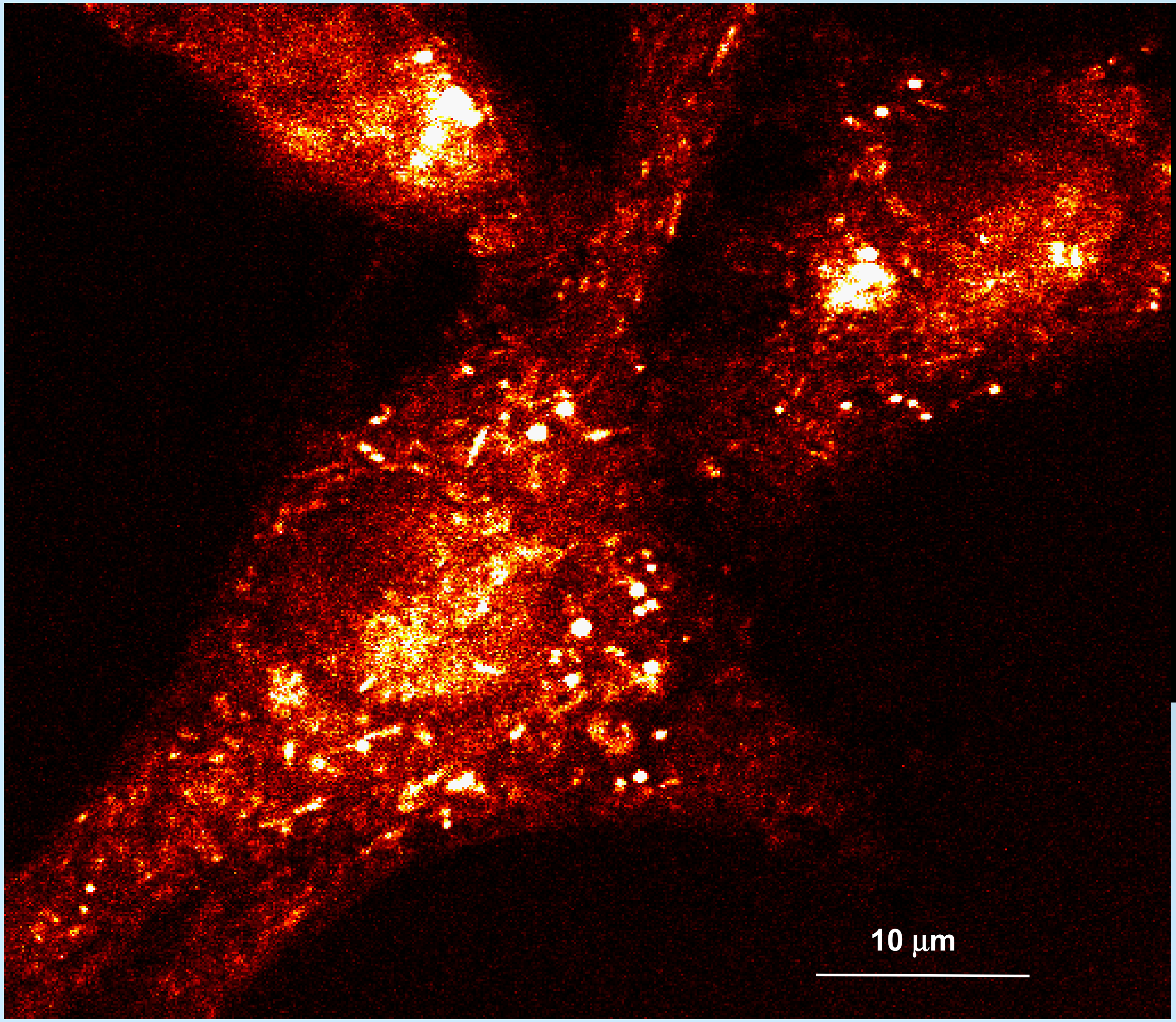


BENEFITS:

- Mode filtering (TEM00)
- Signal enhancement ~ energy^2
- Reduced scanning time
- Pulse shaping by cavity detuning

Live unstained fibroblast cells

C-H stretching vibration contrast: distribution of lipids



Coherent
Anti-stokes
Raman
Spectroscopy

$f_{laser1} - f_{laser2}$

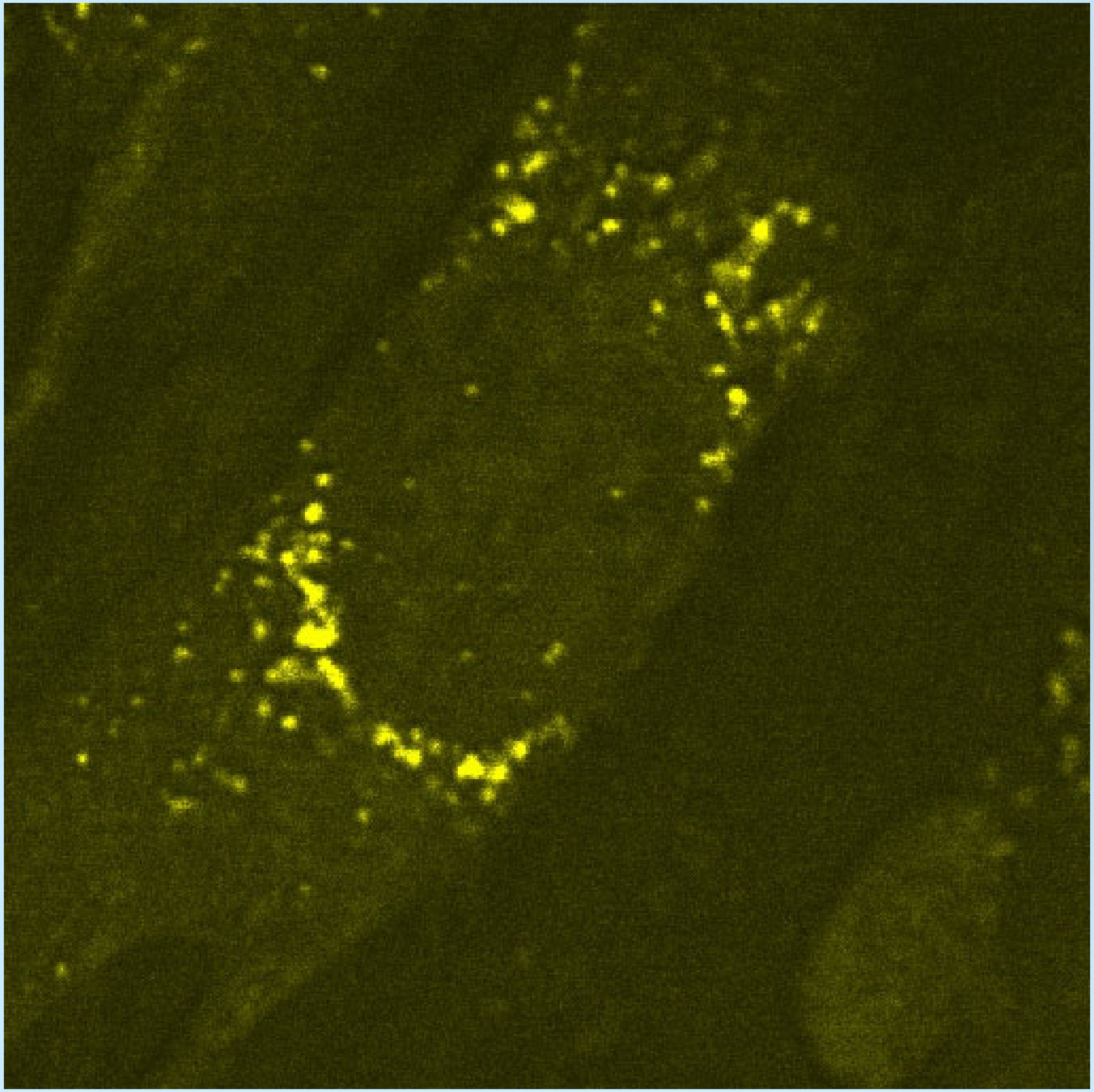
= vibration band

Image acquisition time limited by available S/N (pulse energy).

Potma *et al*. Opt Lett. **27**, 1168 (2002).

Live unstained fibroblast cells

C-H stretching vibration contrast: distribution of lipids



Coherent
Anti-stokes
Raman
Spectroscopy

$f_{laser1} - f_{laser2}$

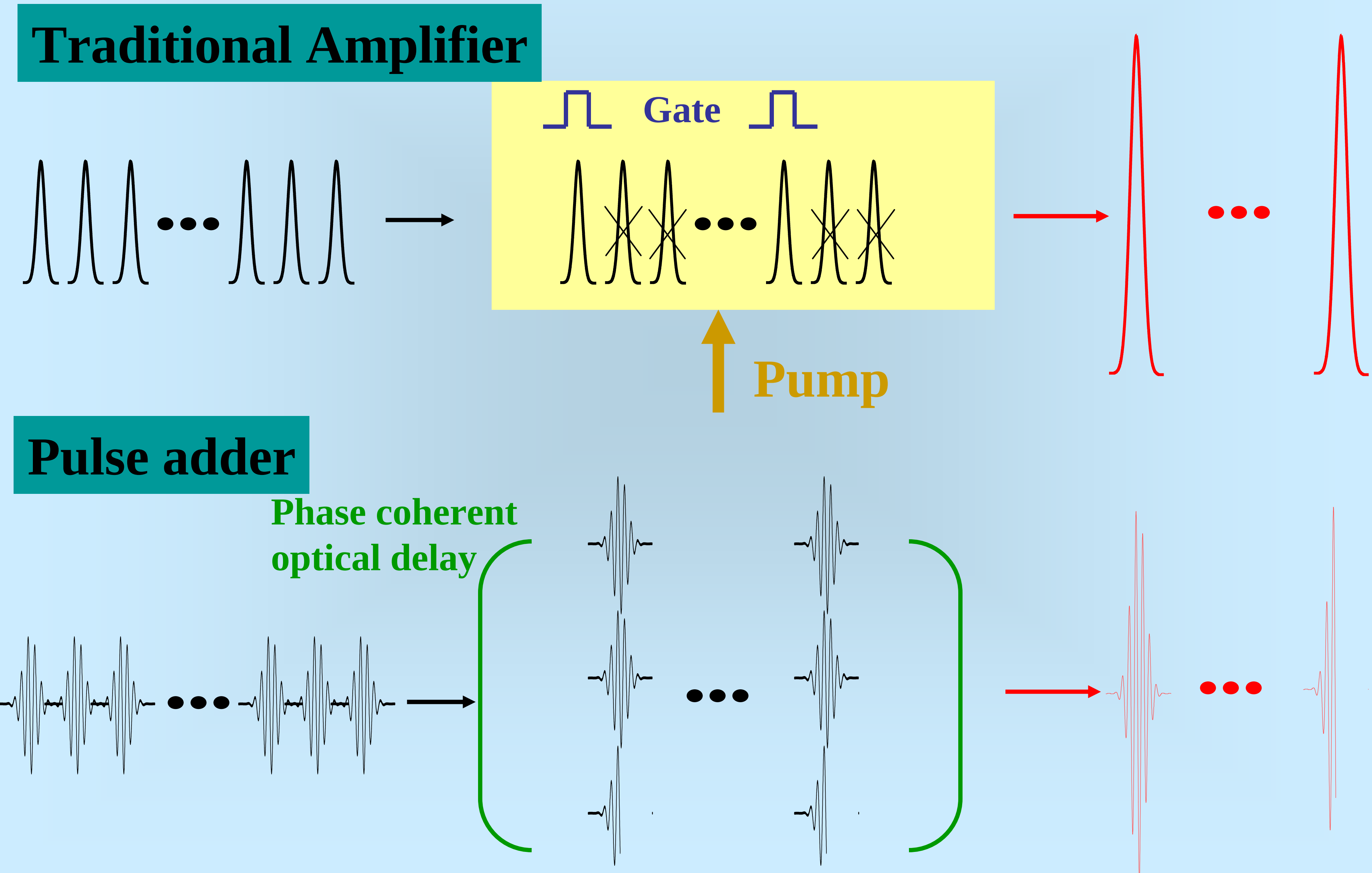
= vibration band

1 s/frame for 5 min, showing active transport of liposomes.

Image taken by Potma

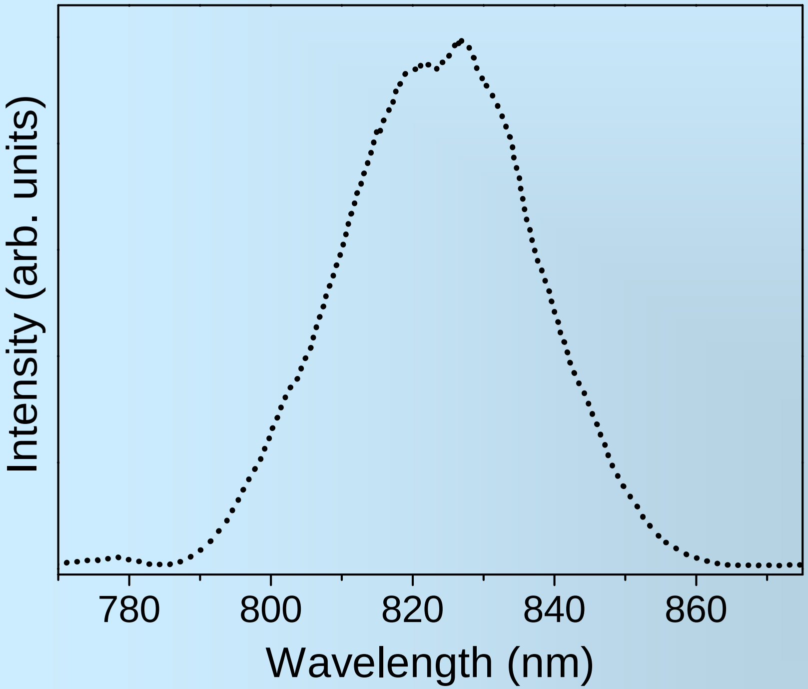
Gainless amplifier - Coherent pulse adder

Jones & Ye, Opt. Lett. **27**, 1848 (2002).



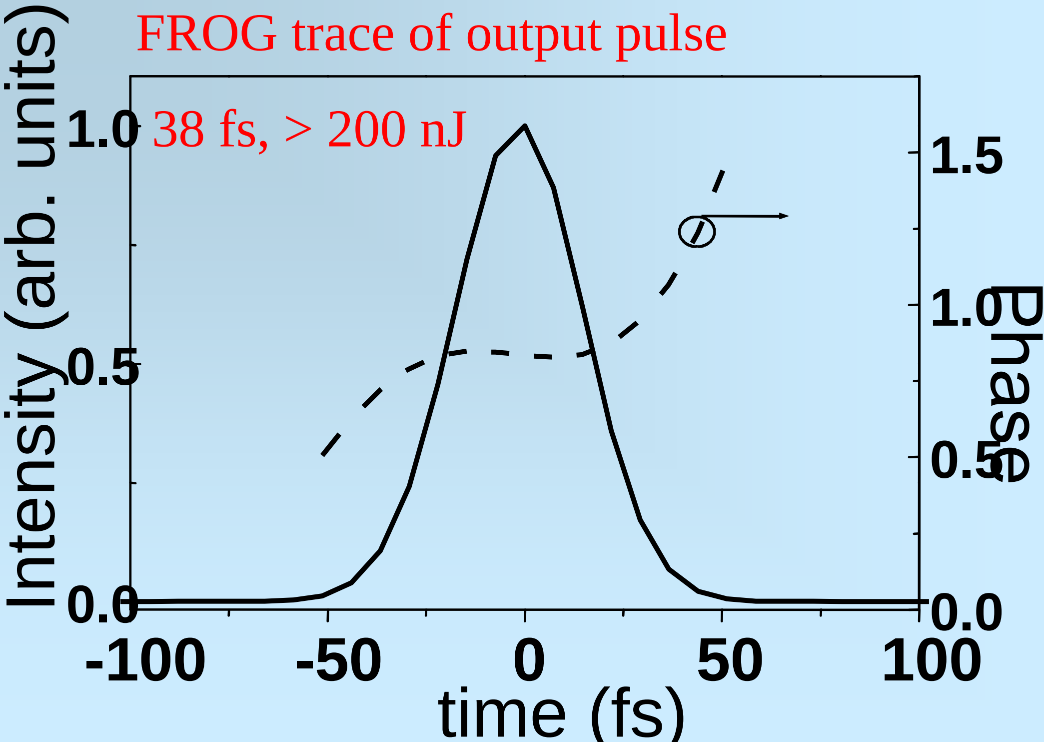
Coherent accumulation of pulses < 40-fs

Jones & Ye, Opt. Lett., in press (2004).

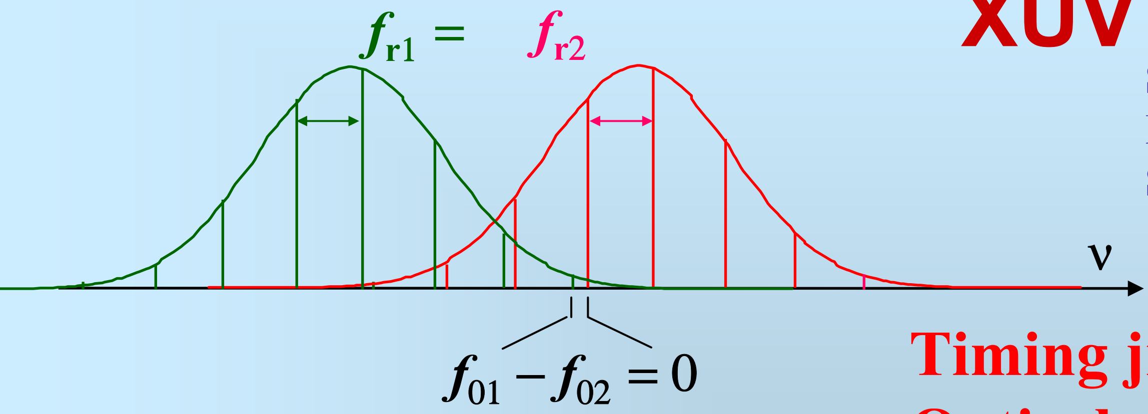


> 170 intracavity buildup
> 45 "amplification"
for < 40 fs pulses

FROG trace of output pulse

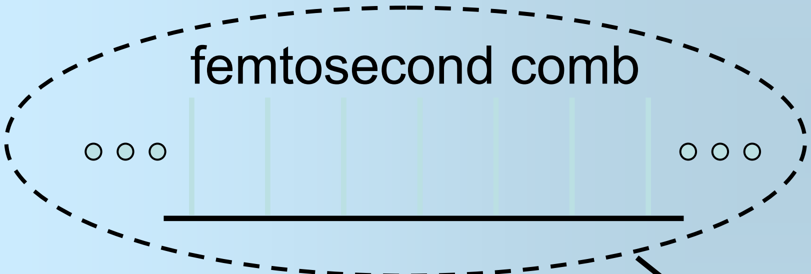


Synthesis of EM spectrum – Advance to XUV



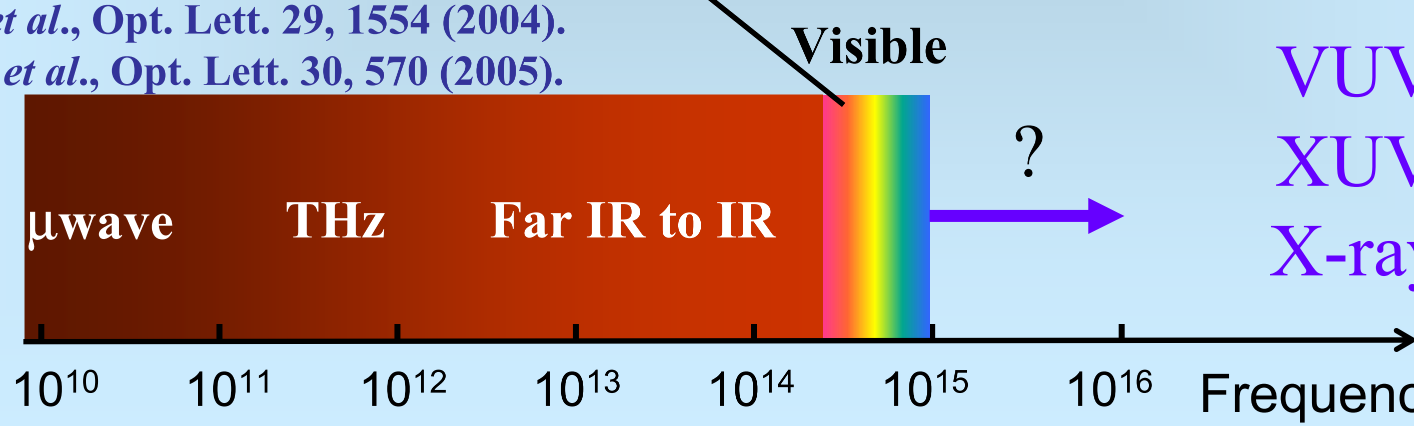
Shelton *et al*, Science 293, 1286 (2001).
Ma *et al*., Phys. Rev. A 64, 021802 (2001).
Shelton *et al*., Opt. Lett. 27, 312 (2002).

Timing jitter control < 1 fs
Optical phase lock to stitch spectra



Foreman *et al*., Opt. Lett. 28, 370 (2003).
Holman *et al*., Opt. Lett. 28, 2405 (2003).
Holman *et al*., Opt. Lett. 29, 1554 (2004).
Foreman *et al*., Opt. Lett. 30, 570 (2005).

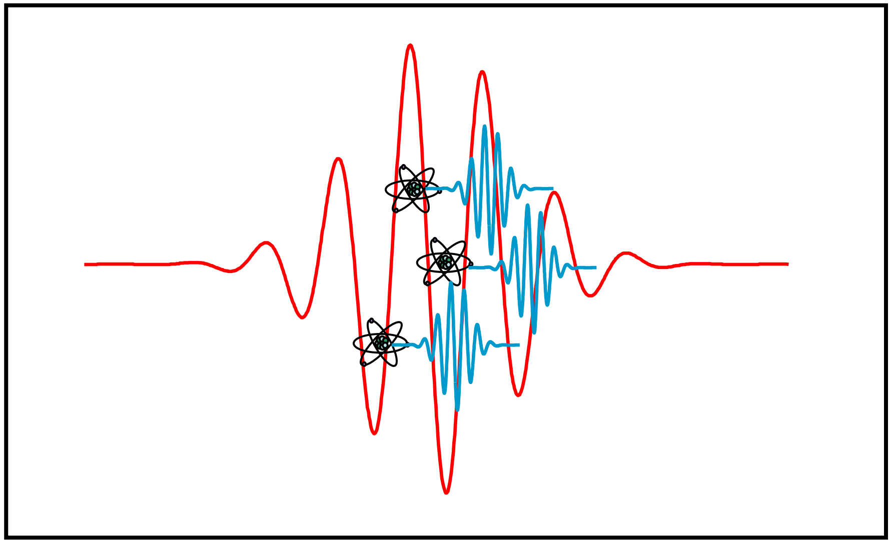
10 eV photons
with Hz-resolution?



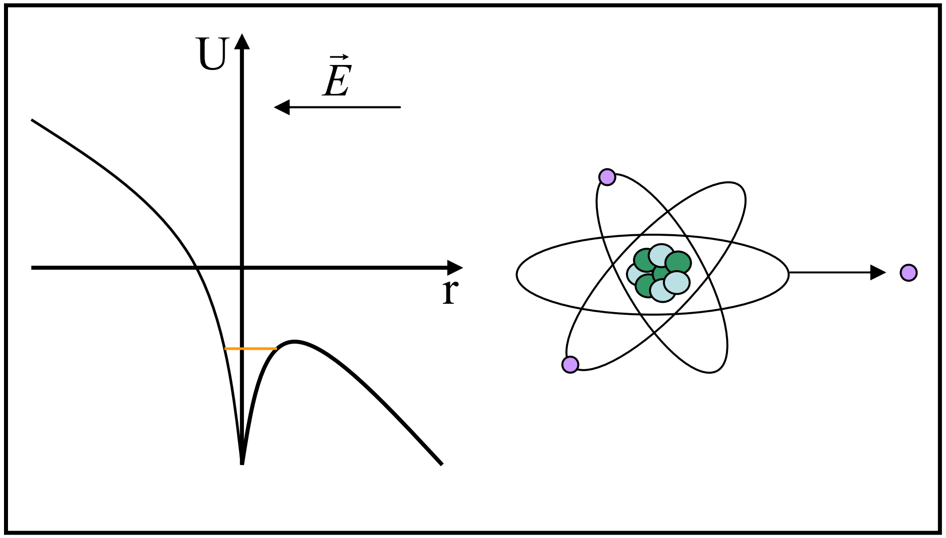
VUV
XUV
X-ray . . .

High-harmonic generation

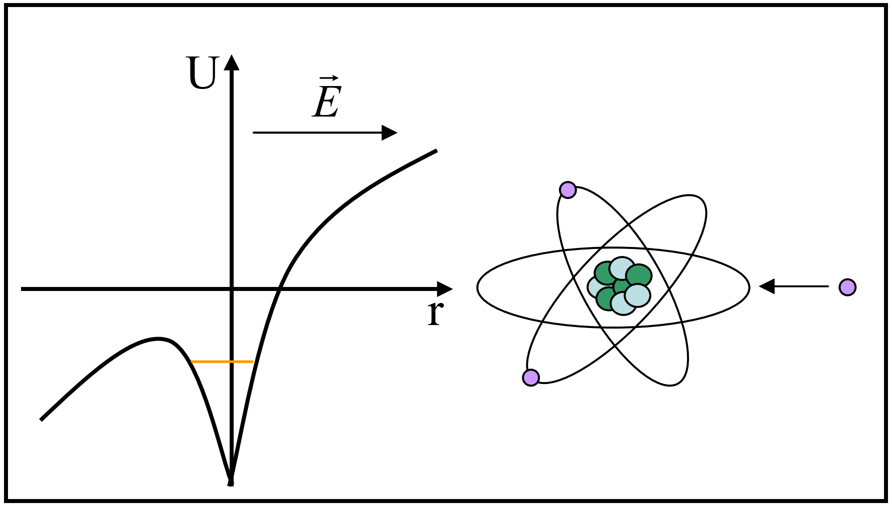
Three step model



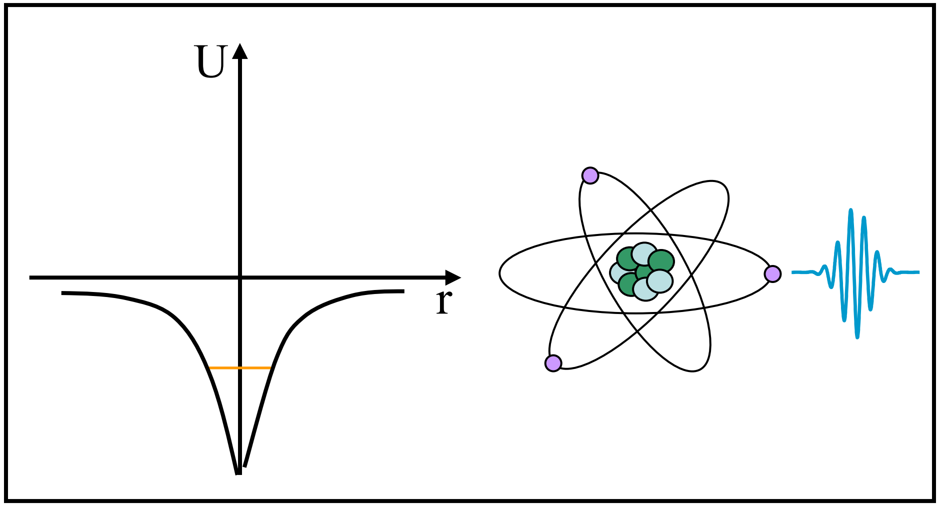
Step 1: Ionization



Step 2: Field Reversal



Step 3: Recombination

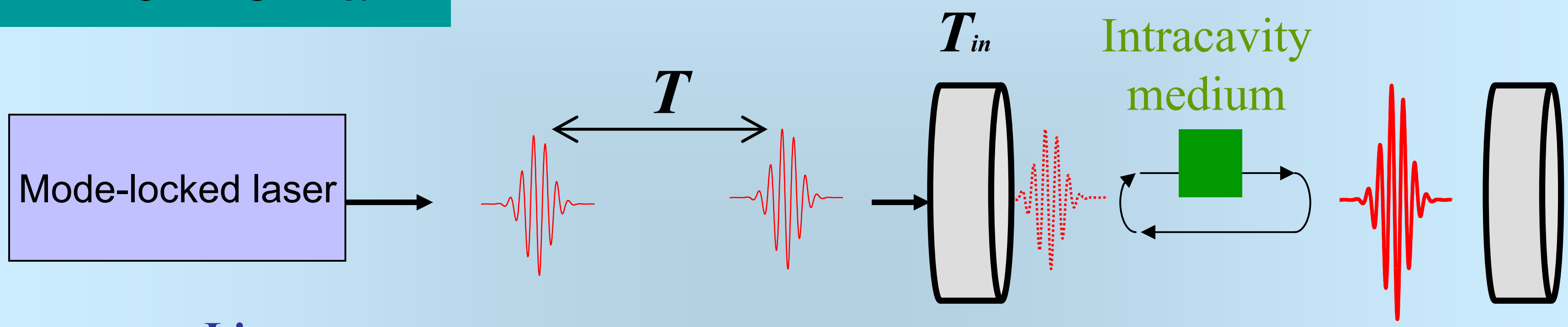


Corkum, Phys Rev Lett 71, 1994

Cavity-assisted coherent pulse buildup

Time Domain

Jones & Ye, Opt. Lett. 27, 1848 (2002).



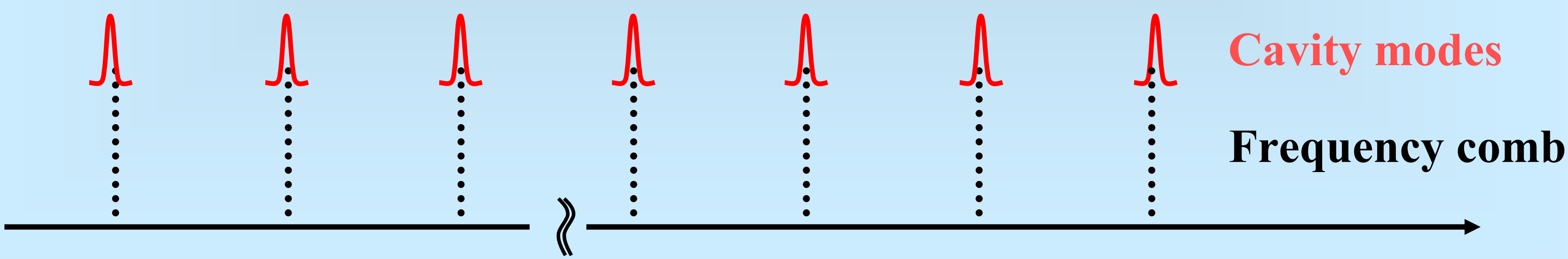
- Linear response
- Coherence preserved
- Provides effective enhancement in any wavelength range

Cavity enhancement:

$$N = \frac{4T_{in}}{L^2} = 4T_{in}\left(\frac{F}{2\pi}\right)^2$$

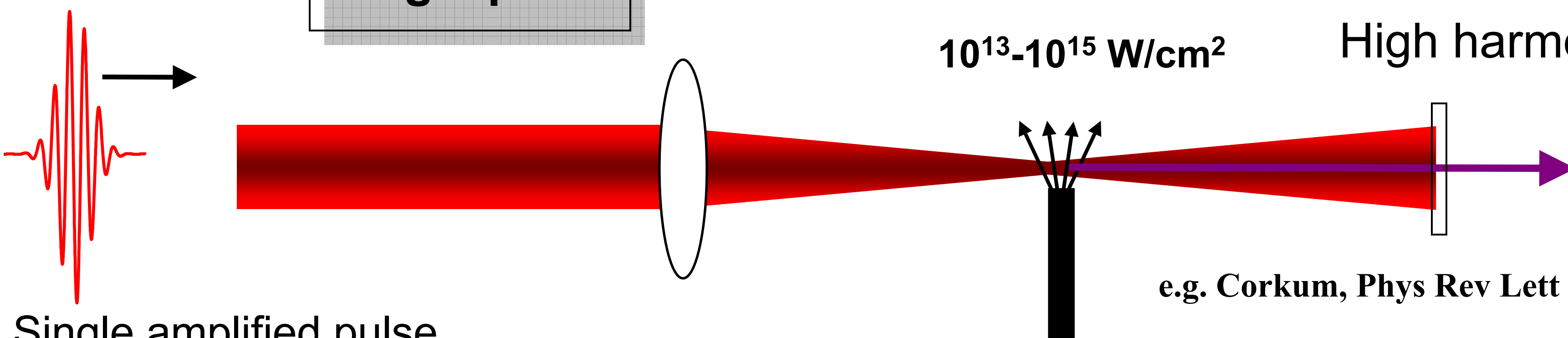
Frequency Domain

Jones *et al*., Phys. Rev. A 69, 051803 (R) (2004).



High-harmonic generation

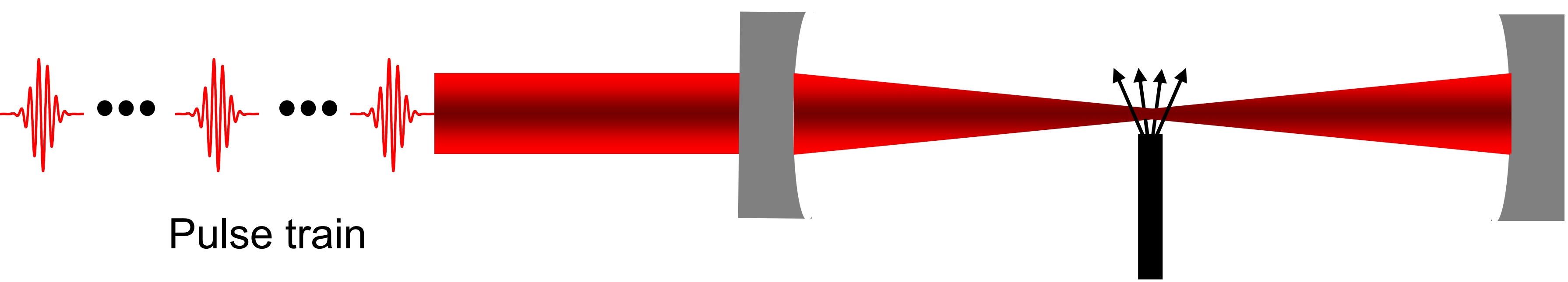
Single pass



e.g. Corkum, Phys Rev Lett 71, 1994

fs enhancement cavity

Jones & Ye, Opt. Lett. 27, 1848 (2002).
Jones & Ye, Opt. Lett. 29, 2812 (2004).
Thorpe *et al*., Opt. Express 13, 882 (2005).
Moll *et al*., Opt. Express 13, 1672 (2005).



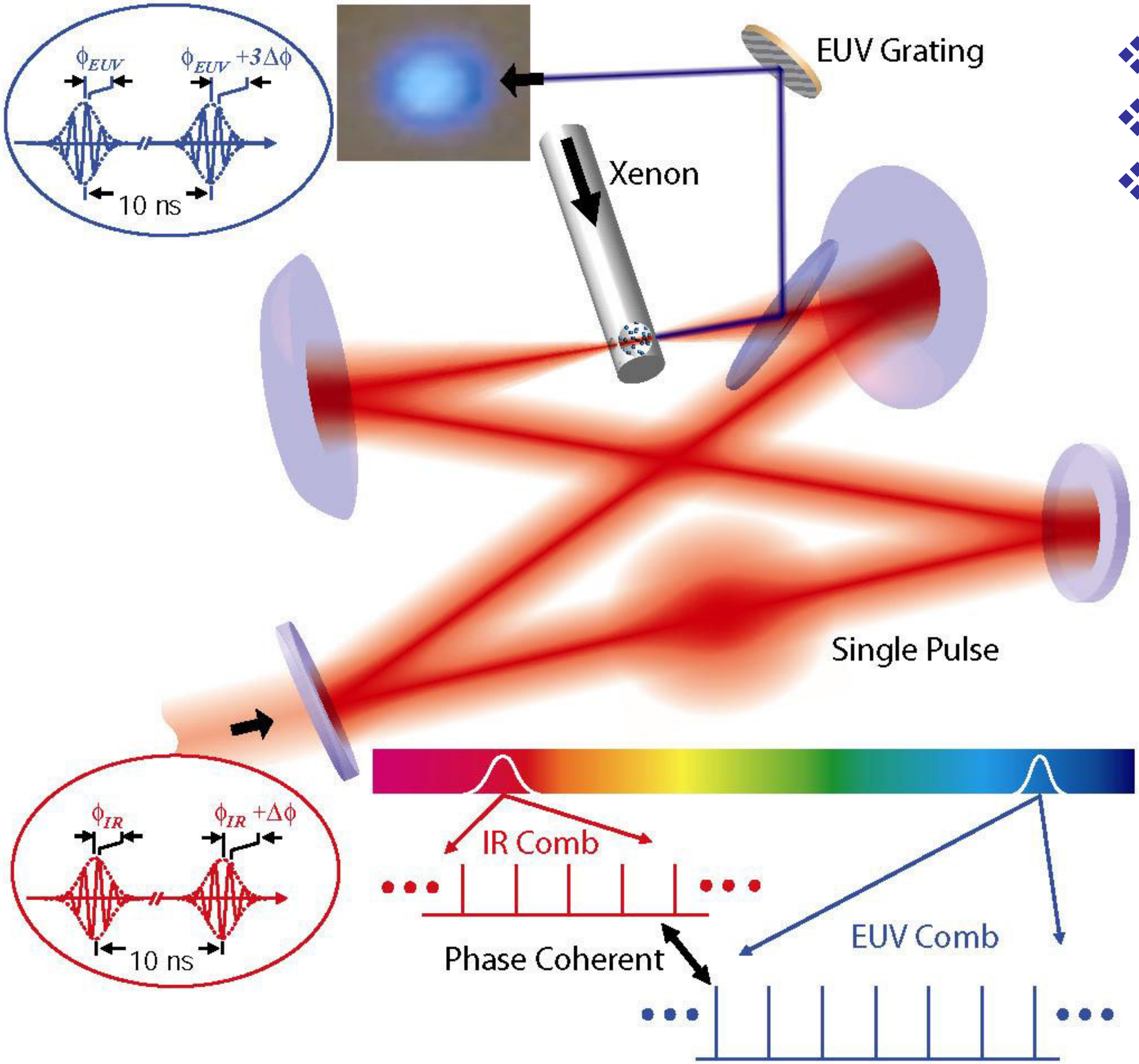
Intra-cavity HHG at 100 MHz

A fs comb in the EUV

R. J. Jones et. al., Phys. Rev. Lett. 94, 193201 (2005).

C. Gohle, T. Udem, T.W. Hänsch, et. al., Nature 436, 234 (2005).

Actual HHG beam

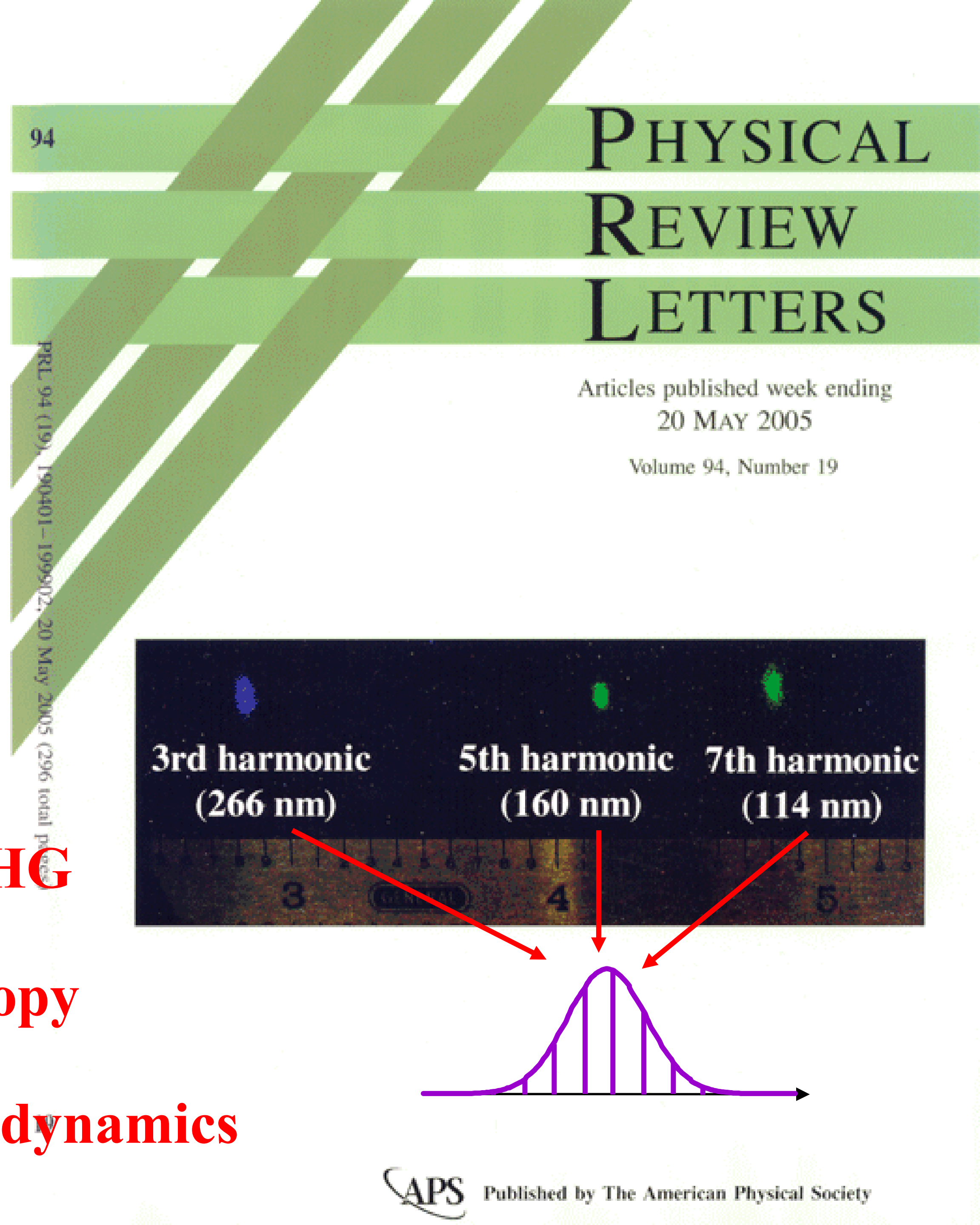


- 8 nJ ⟶ ~ 4 μJ per pulse!
- > 10^{13} W/cm^2 peak intensity
- 100 MHz repetition rate

Ionization of Xe at intracavity focus

HHG spectrum

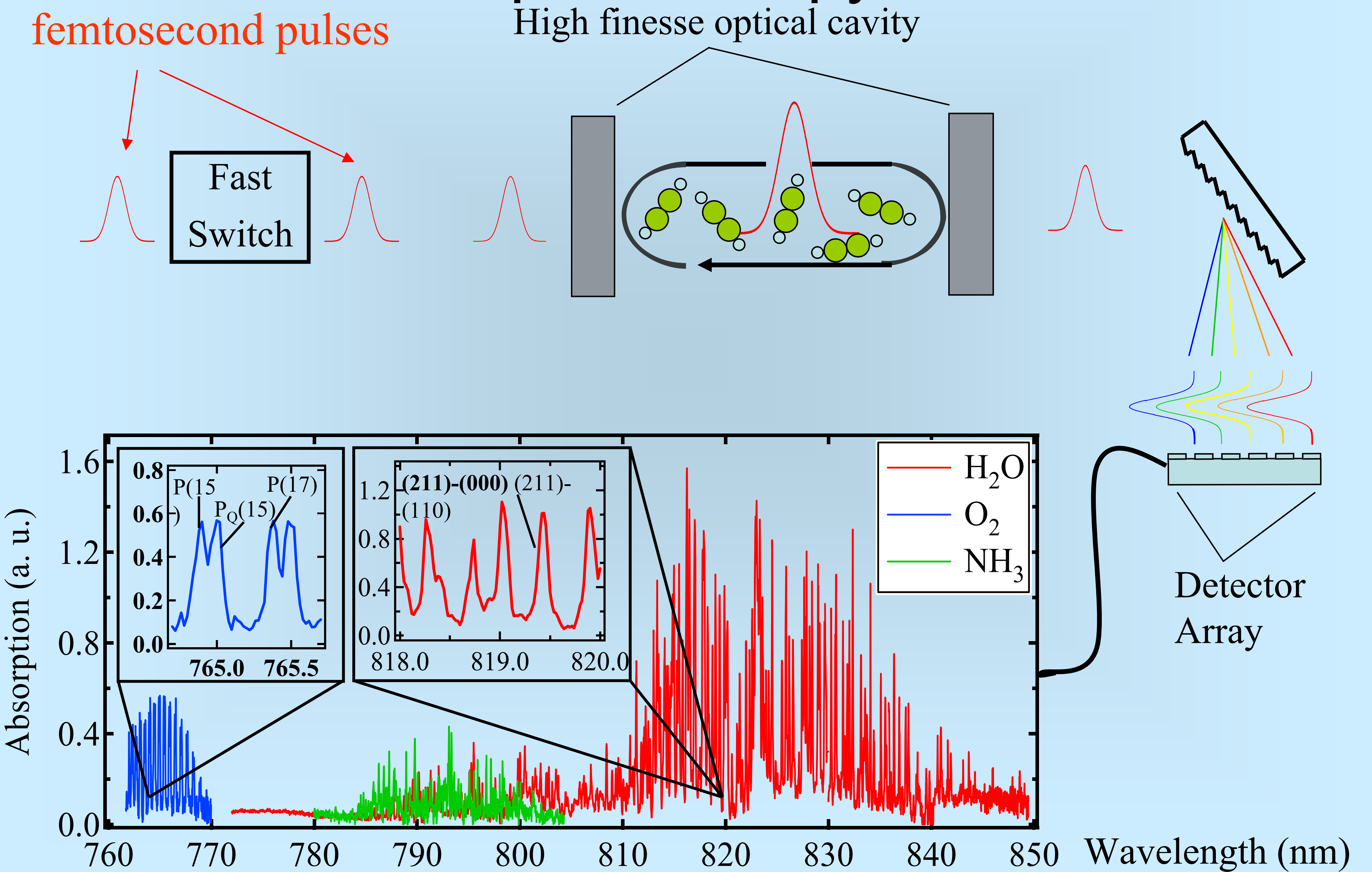
> 5 μW average power for the 3rd harmonic



- **High repetition rate HHG**
- **Precise XUV spectroscopy**
- **Coherent time domain dynamics**

Broadband cavity ringdown spectroscopy

Thorpe *et al.*, Science **311**, 1595 (2006).



Molecular lines on CCD

Thorpe *et al.*, Science **311**, 1595 (2006).

- **> 100nm of real time spectral information**
- **0.01 cm^{-1} resolution**
- **Integrated absorption sensitivity < 10^{-8} @ 1 s**