The art of light-based precision measurement

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**NIST, NSF,
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NASA, DOE
DARPA**

Lecture I: Art of light control

Lecture II: Ultracold Sr optical lattice

Lecture III: Cold & Ultracold molecules

Exciting time for light control

Continuous wave laser: < 1 Hz stability and accuracy

Ultrafast pulse: < 1 fs generation and control

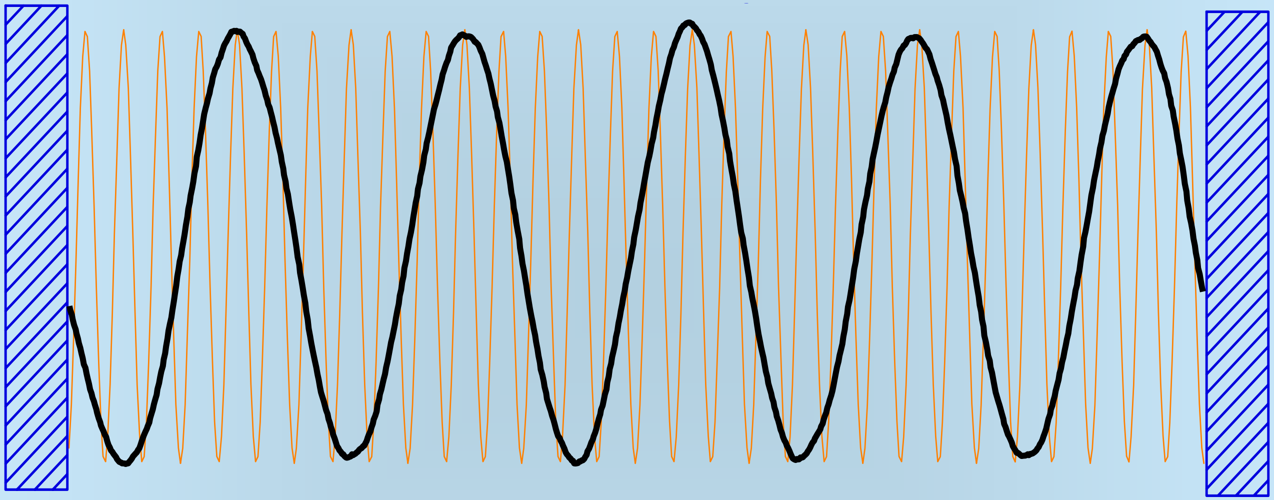
Figure of merit: $<10^{-15}$

Phase coherence after $>10^{15}$ optical cycles

Frequency comb: Precision measurement & control at highest resolution over widest bandwidth

Spectral - time - spatial domains

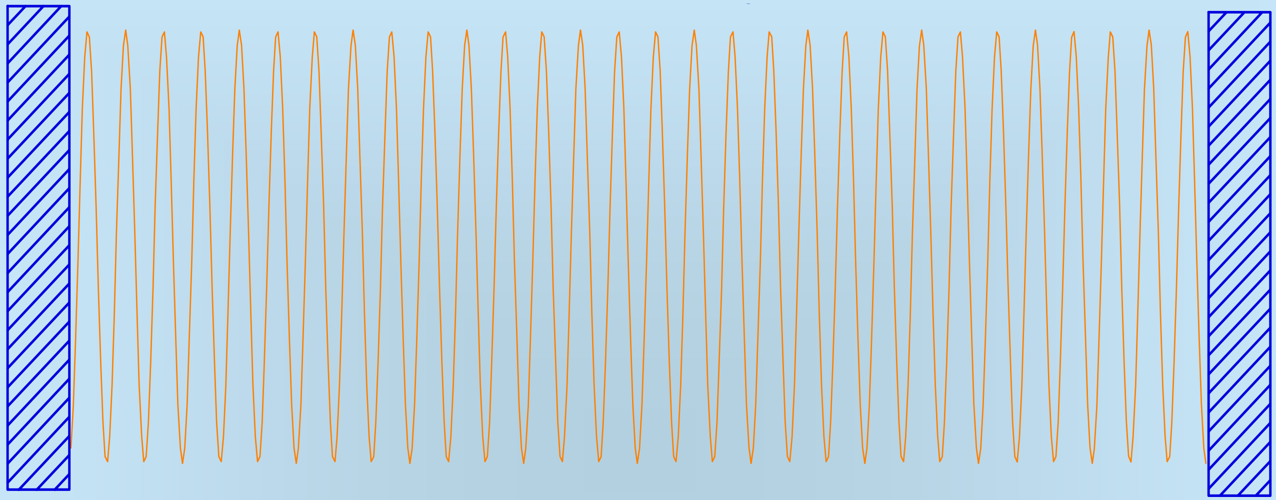
Why light?



5 times faster oscillations,
5 times more accurate measurement
of the length, or time, or other physical quantities

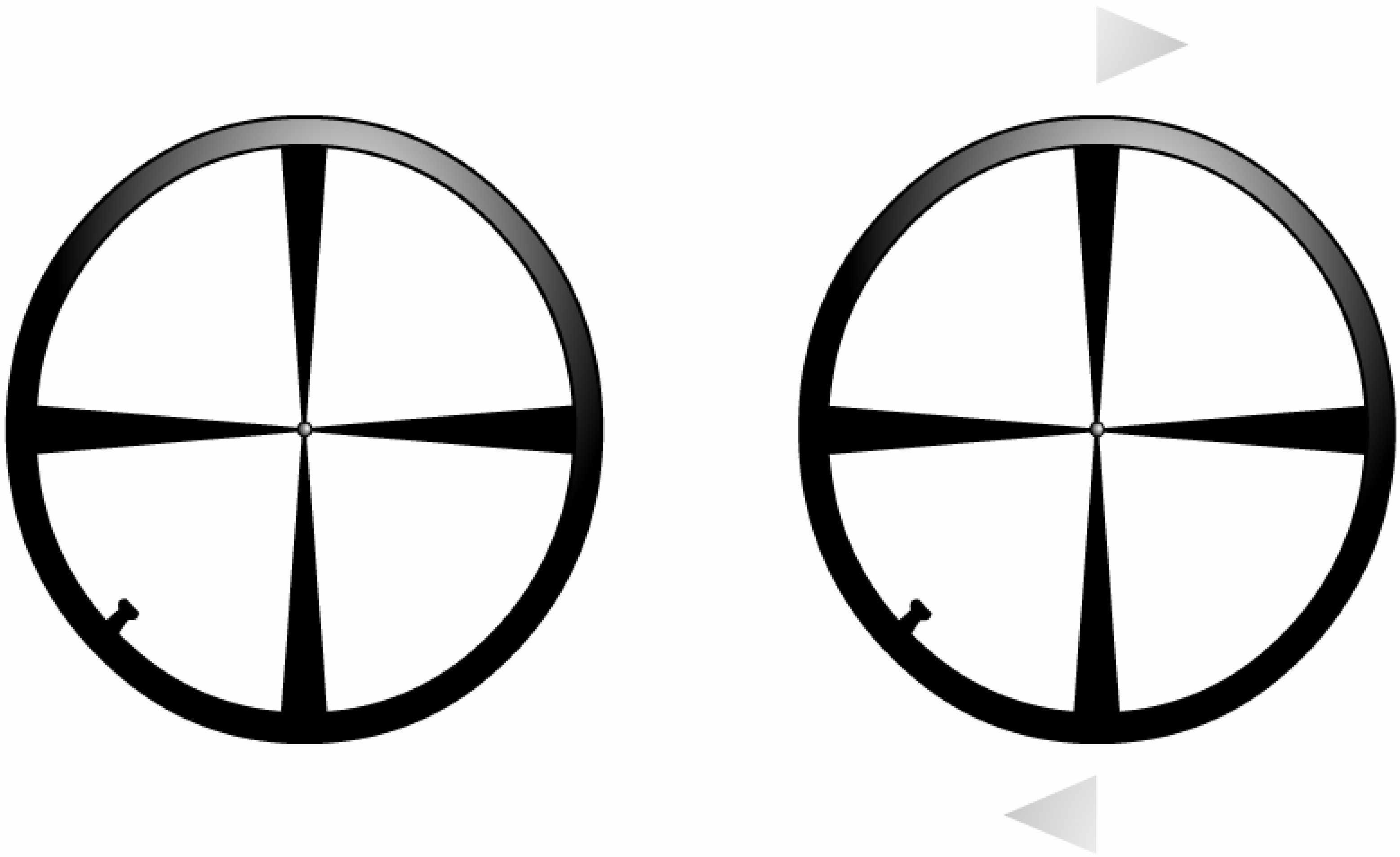
Ratio between light and radio frequency: 10^6

Stable optical cavity

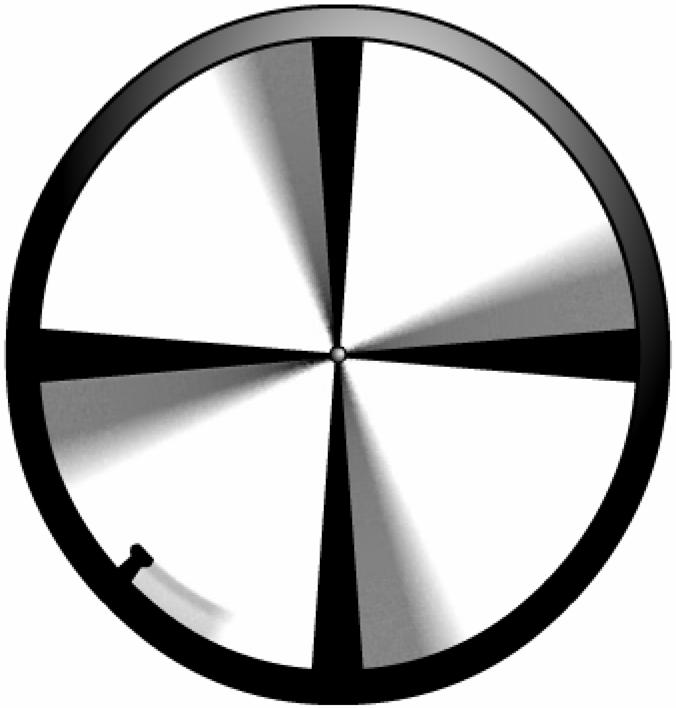


Cavity length 1 m	:	fits 10^6 optical waves	(10^{-6})
Finesse 10^5	:	error amplified by 10^5	(10^{-11})
Division of a cycle	:	10^4	(10^{-15})

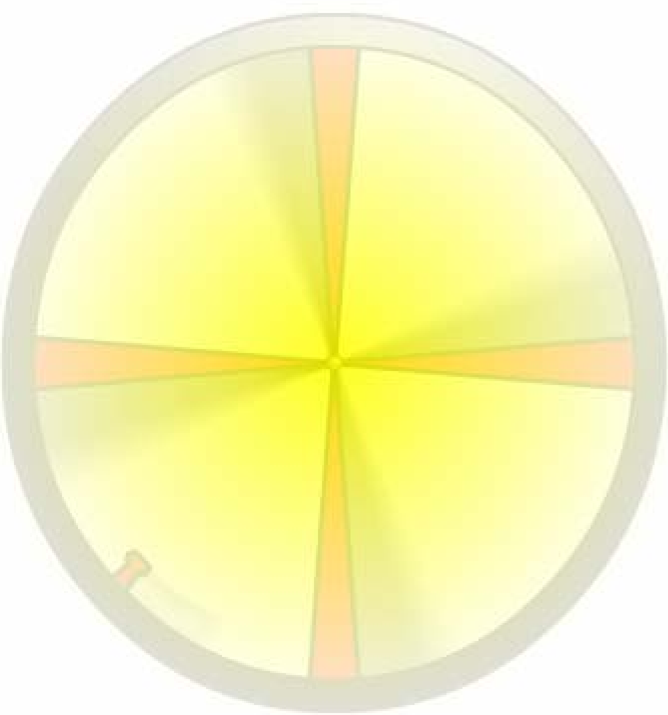
How to measure such high frequencies? - Heterodyne beat



How to measure such high frequencies? – Heterodyne beat

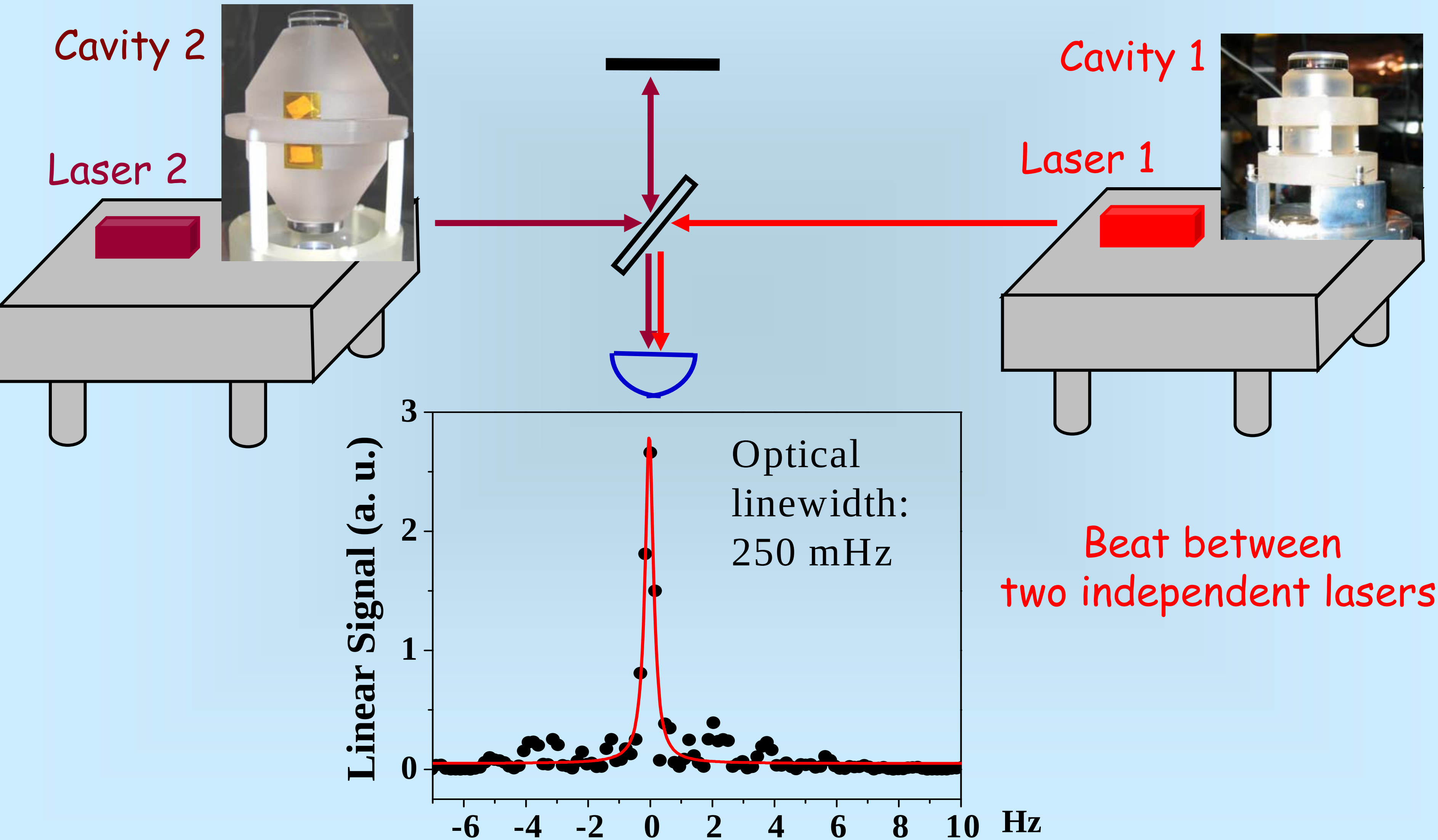


How to measure such high frequencies?
– Heterodyne beat



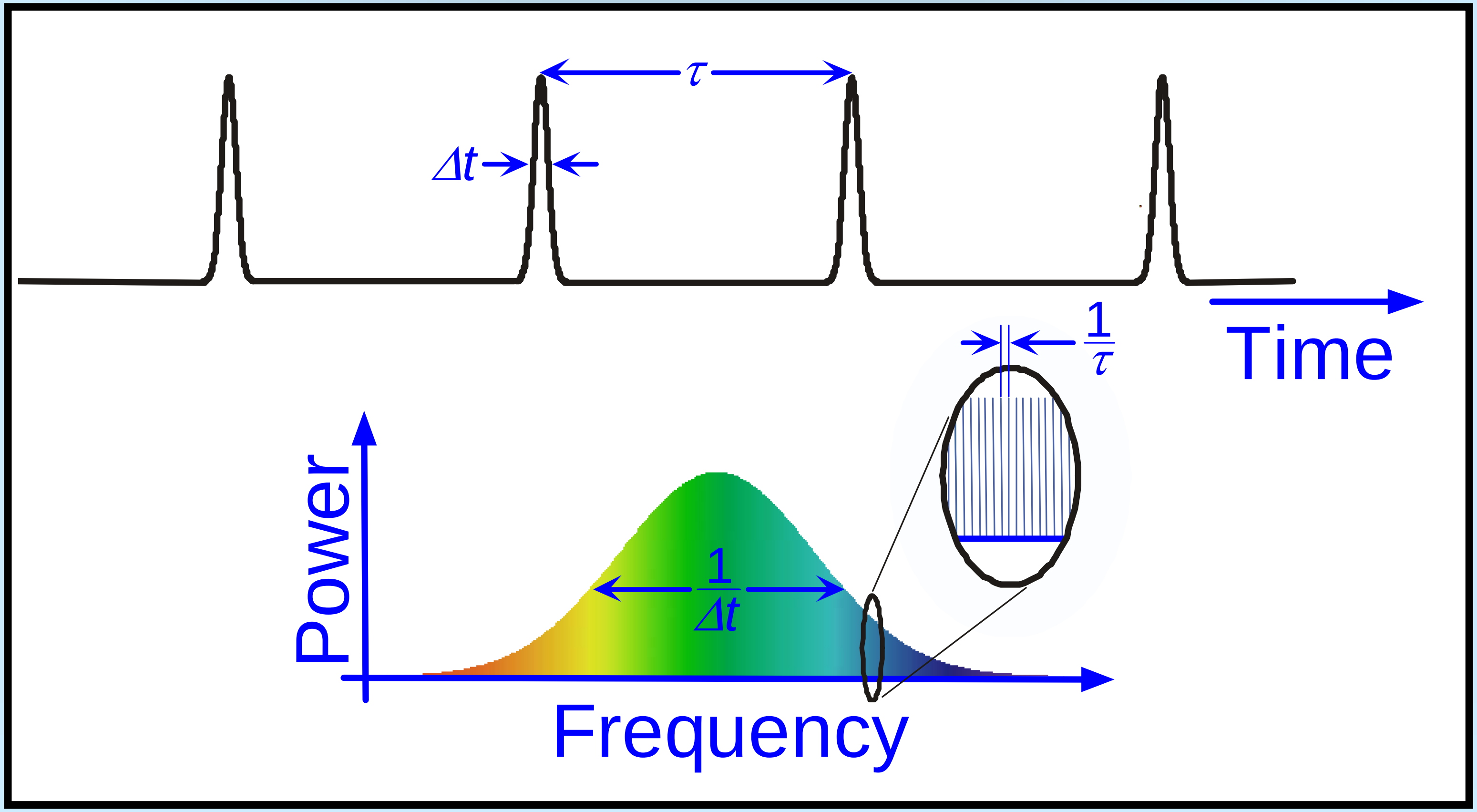
Long-term optical coherence (>1 s) – across the visible spectrum

Ludlow *et al.*, Phys. Rev. Lett. 96, 033003 (2006); Opt. Lett. 32, 641 (2007).

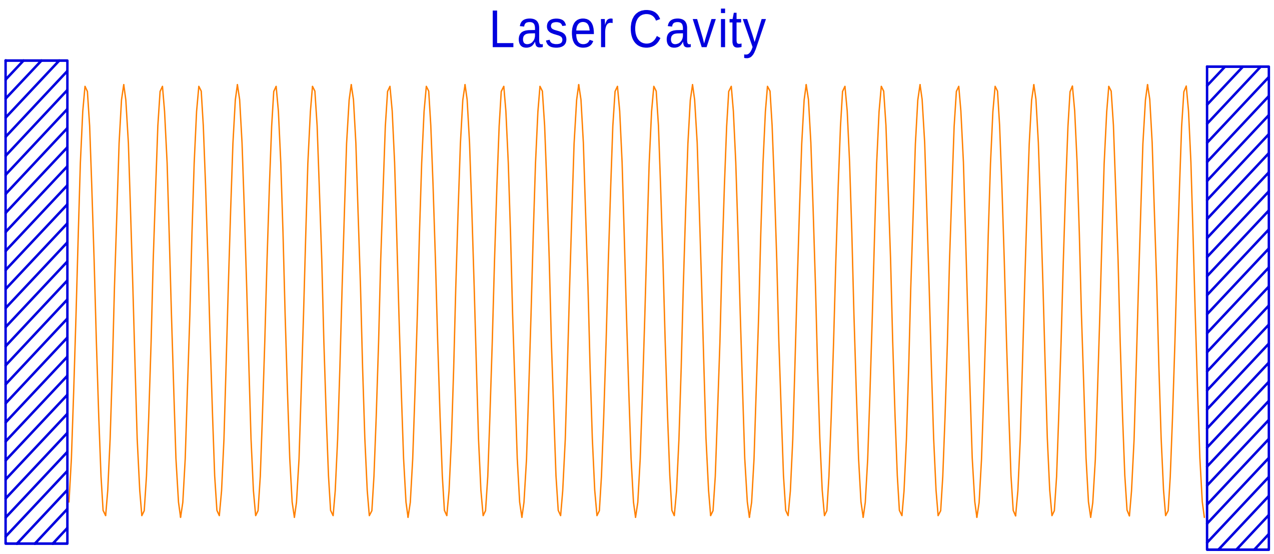


Frequency Spectrum of Mode-Locked Laser

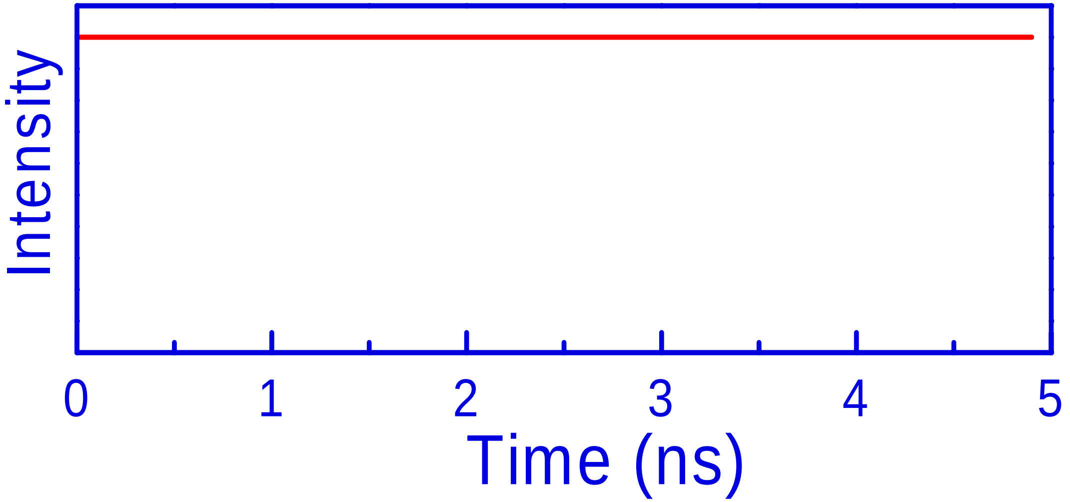
- Temporal pulse width ⟷ Spectral bandwidth
- Train of pulses ⟷ comb of frequencies



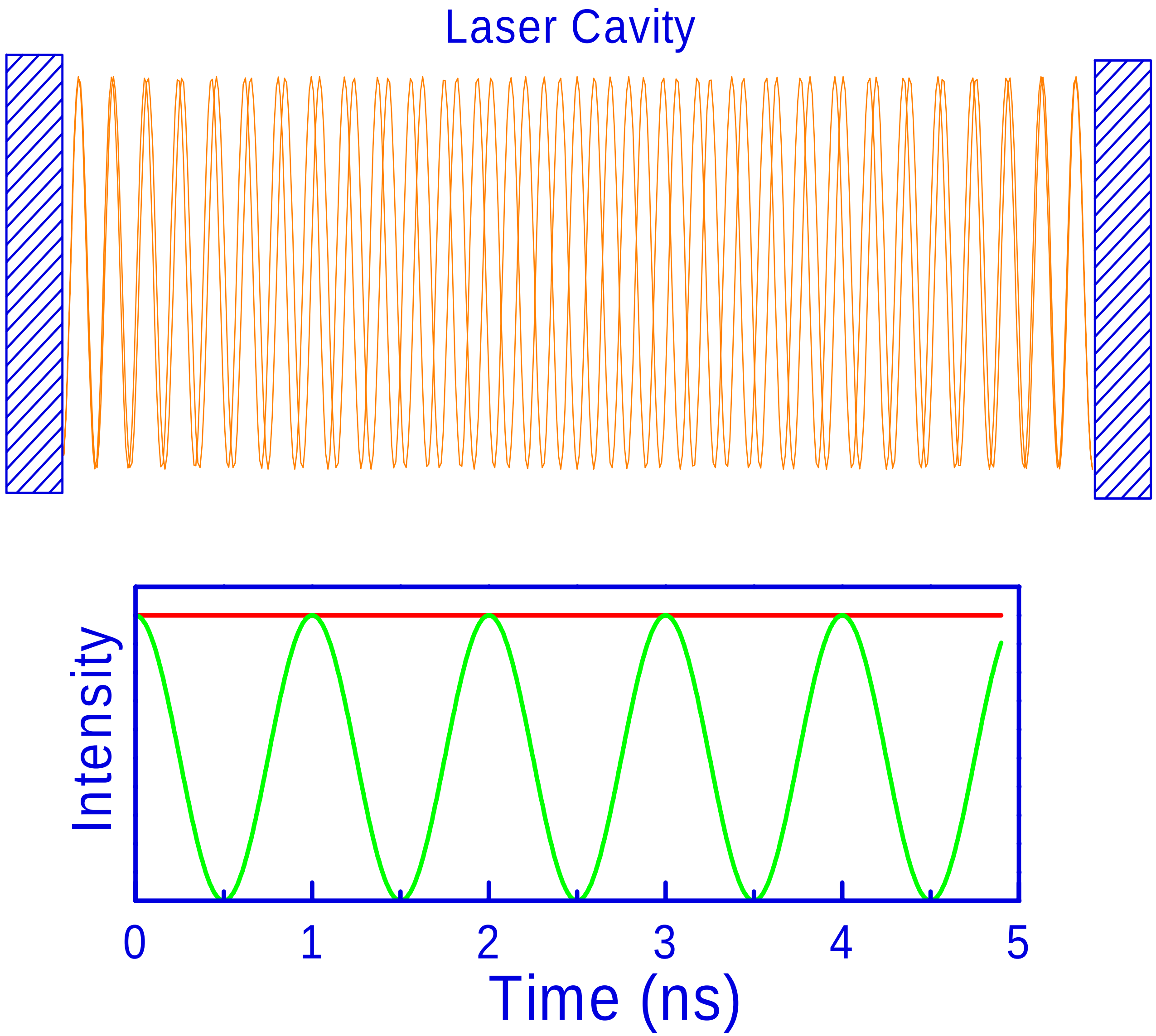
Modelocking



Single mode
cw laser

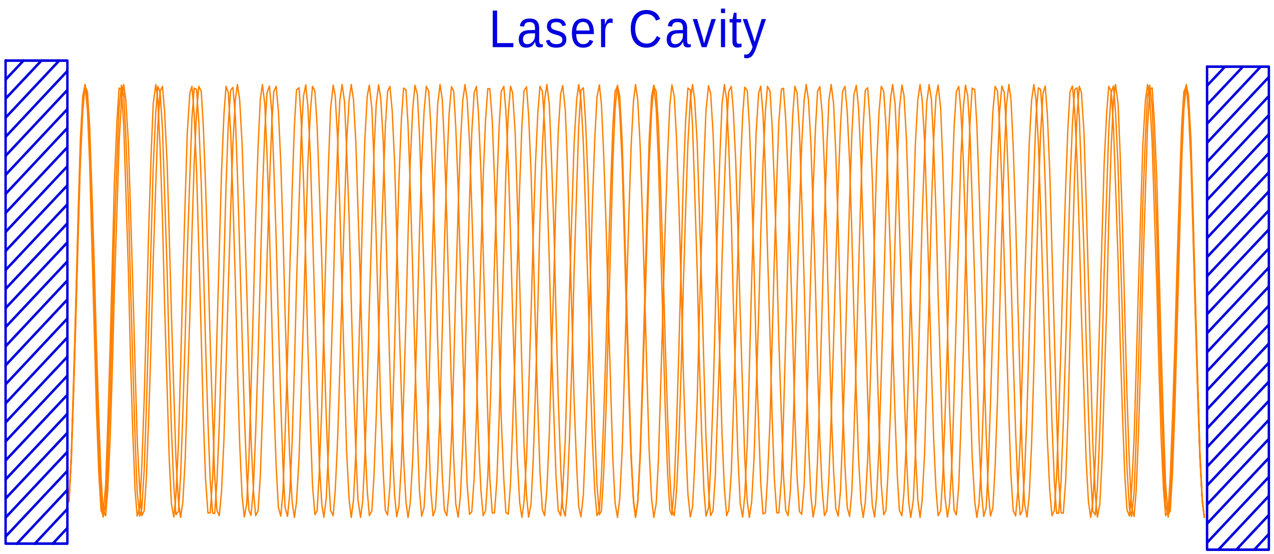


Modelocking

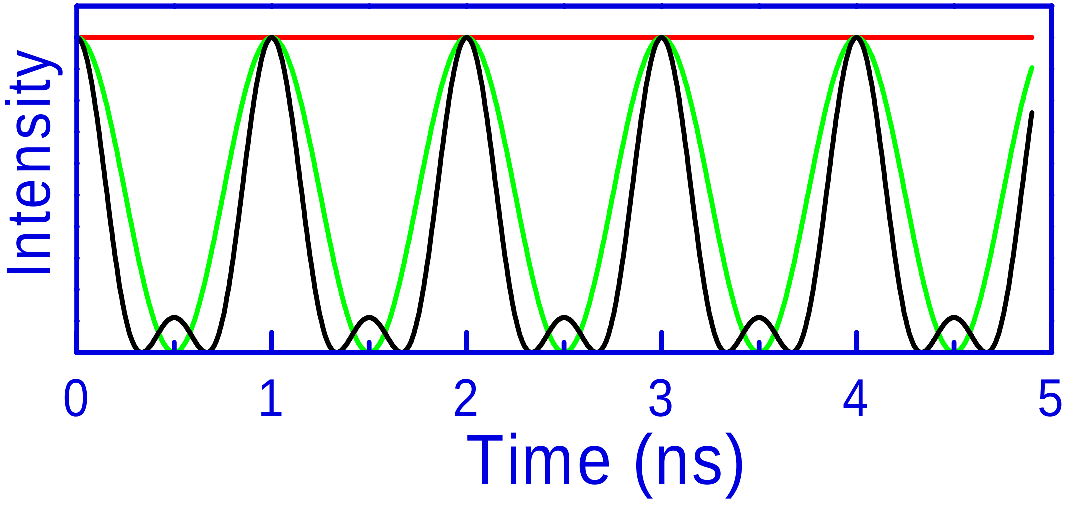


2 modes

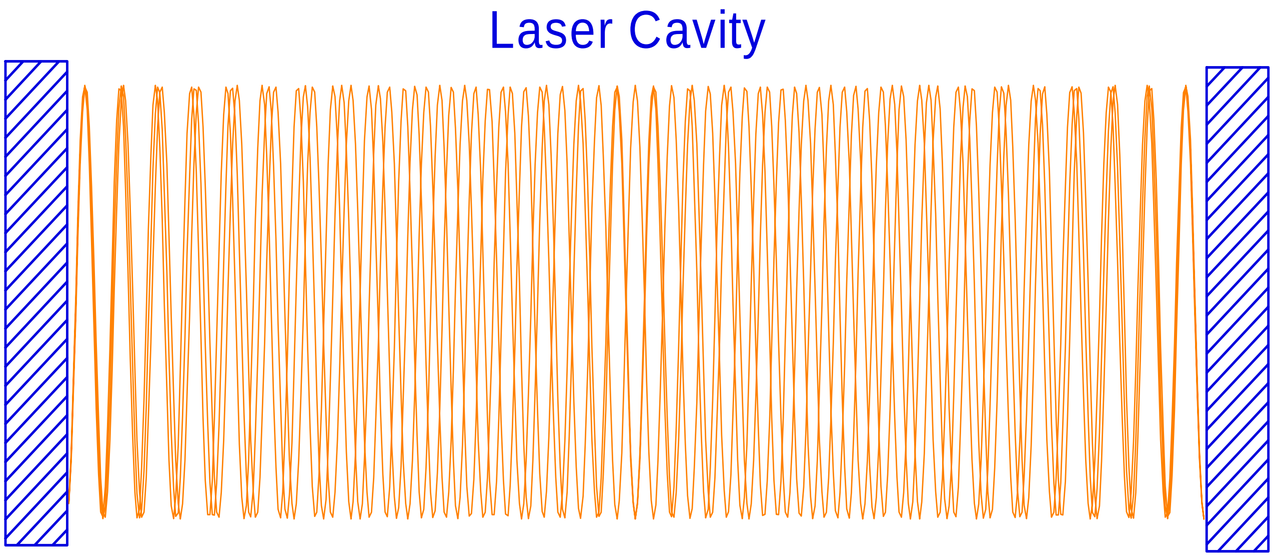
Modelocking



3 modes

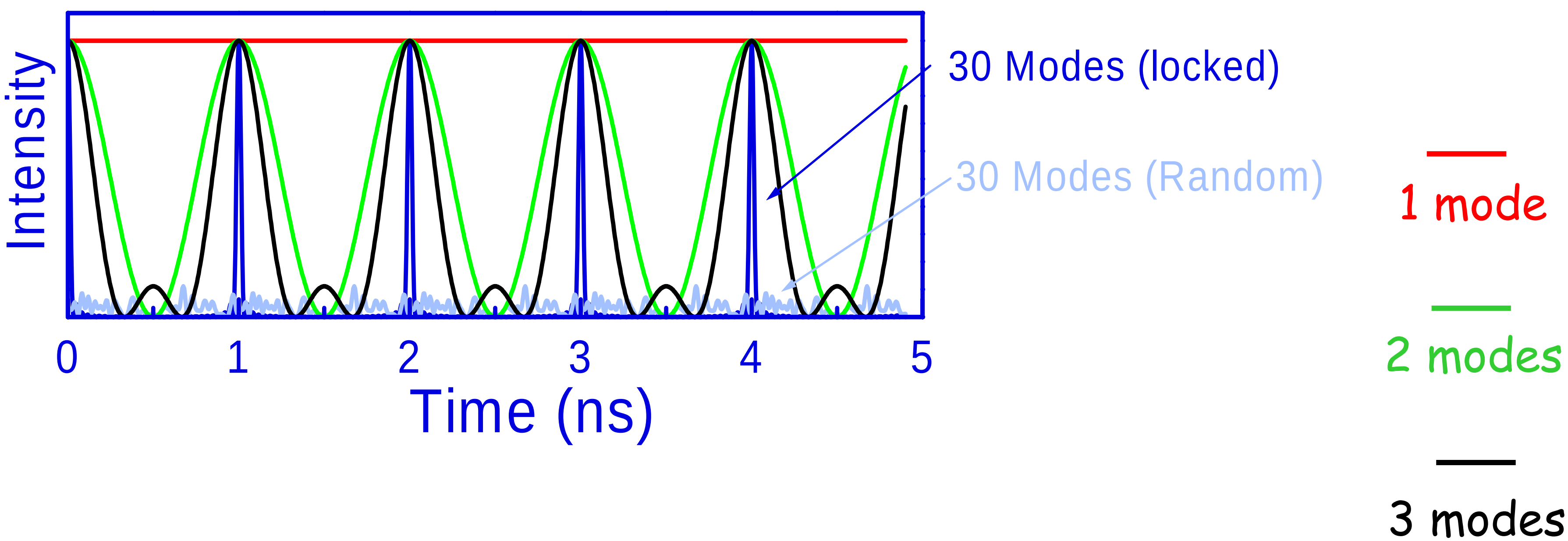


Modelocking



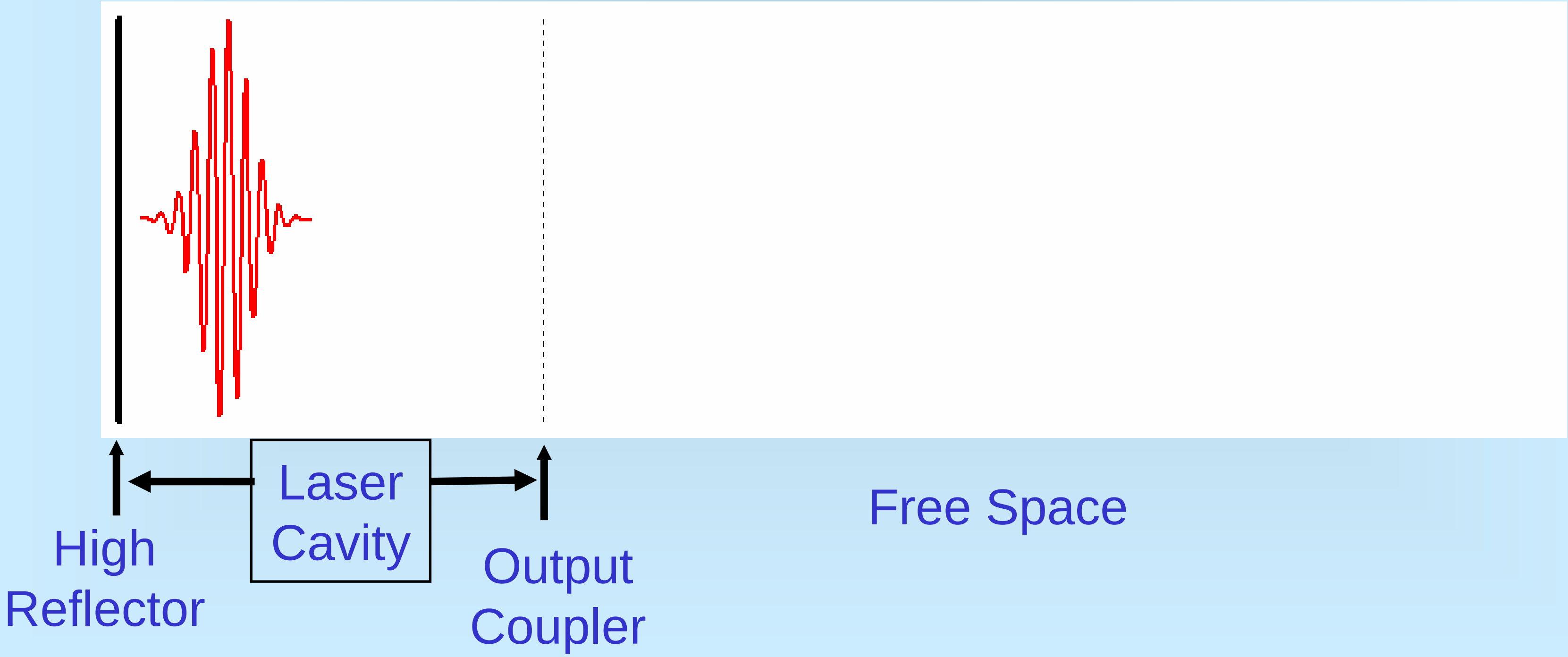
2 degrees of freedom:
- single-mode phase
- dispersion

Constructive interference among phase-locked cavity modes

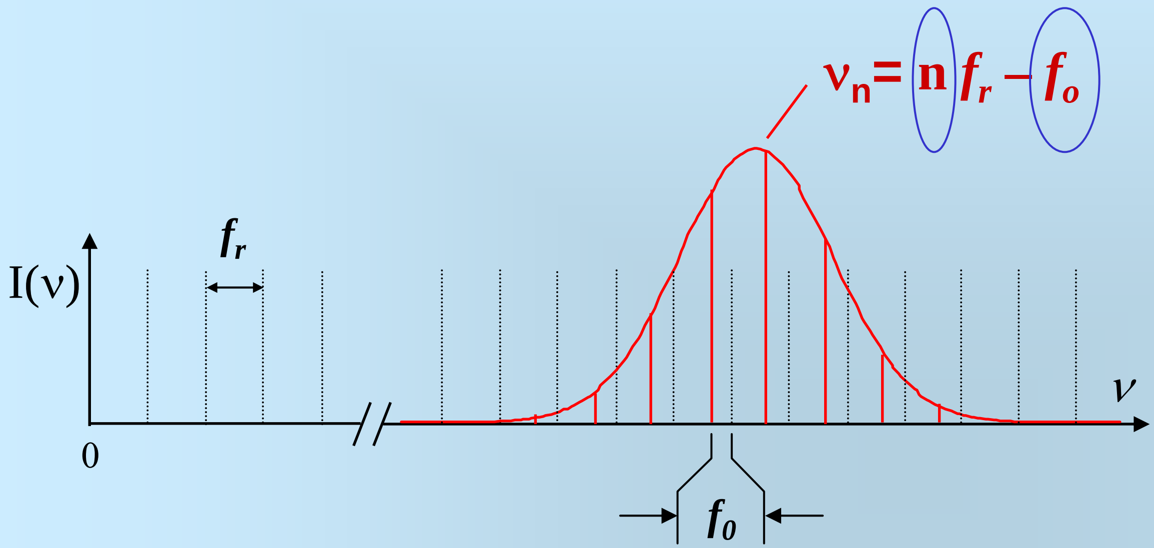


Group vs. Phase in Modelocked Lasers

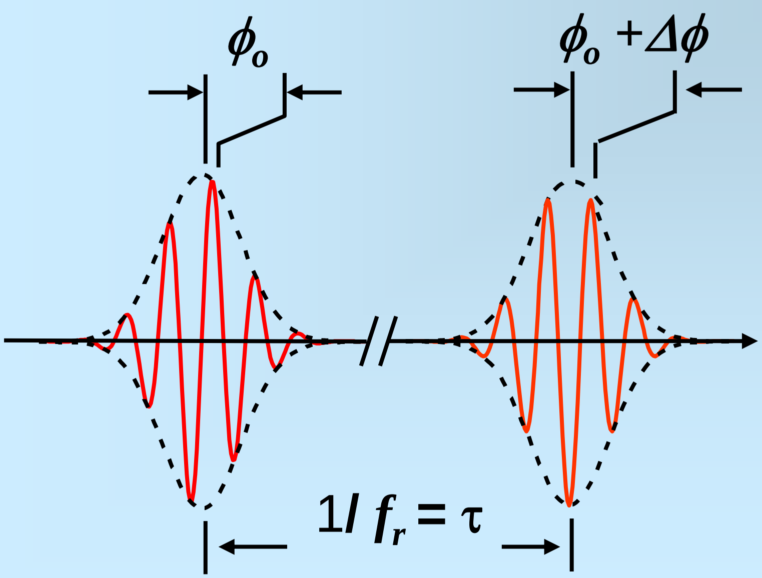
Each emitted pulse has a distinct envelope-carrier phase – due to group-phase velocity difference inside cavity



Time- and frequency-domain connections



f_r = Comb spacing
f_o = Comb offset from harmonics of f_r
$\Delta\phi$ = Phase slip b/t carrier & envelope each round trip

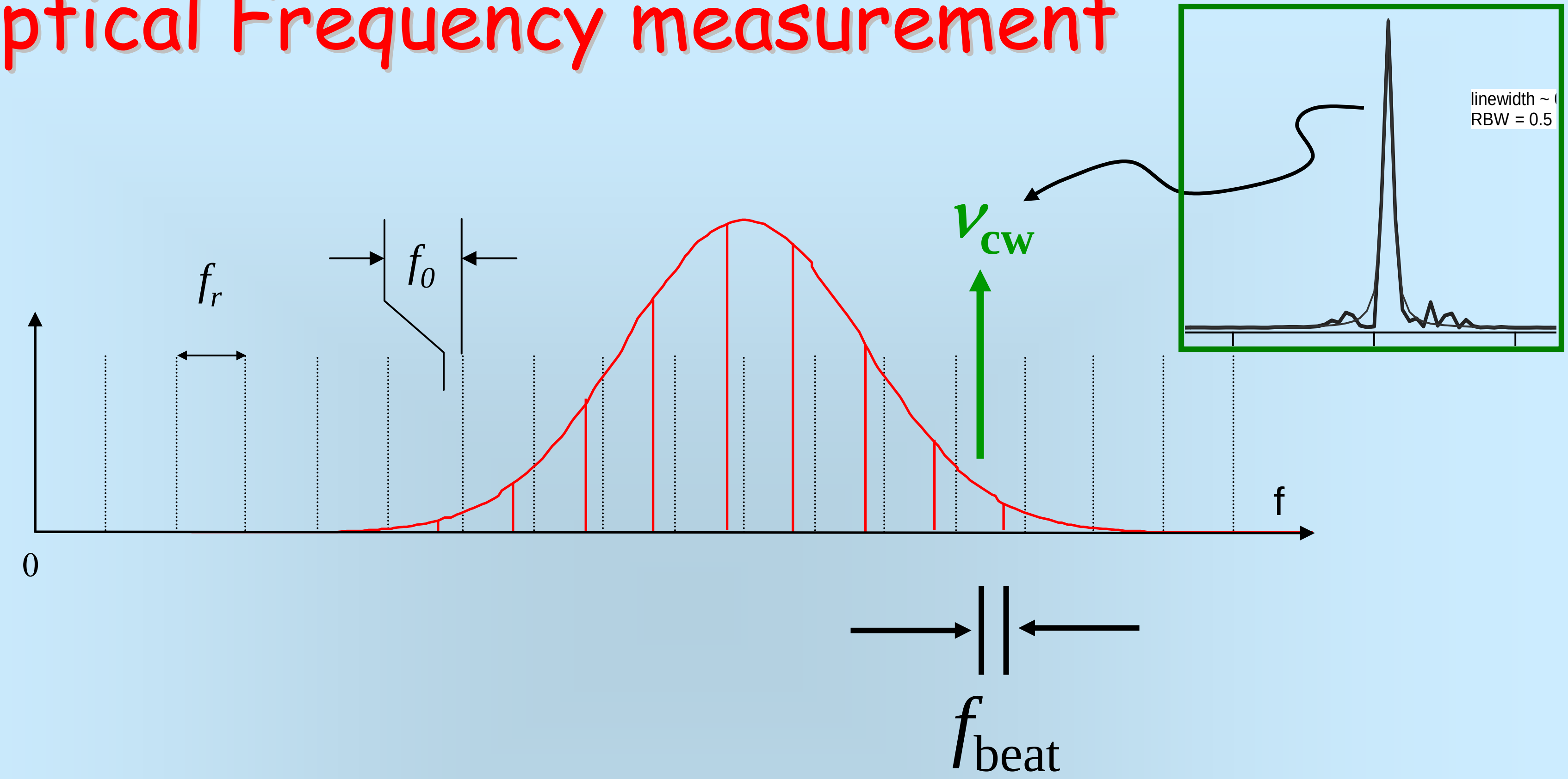


$$2\pi\nu_n \cdot \tau_{r.t} + \Delta\phi = 2n\pi \rightarrow$$

$$\nu_n = nf_r - \underbrace{\Delta\phi\, f_r / 2\pi}_{f_o}$$

Hänsch, 1978, Garching and Boulder 1999 – 2000
Udem *et al*., Phys. Rev. Lett. 82, 3568 (1999).
Diddams *et al*., Phys. Rev. Lett. 84, 5102 (2000).

Optical Frequency measurement



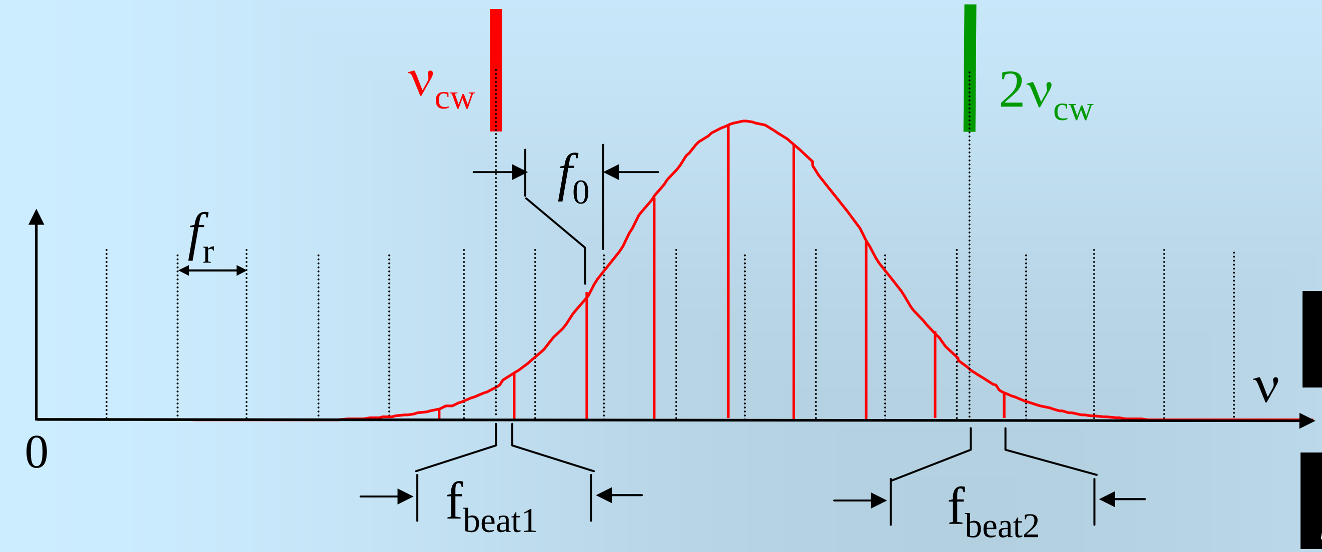
$$f_{beat} = n f_r + f_0 - \nu_{cw}$$

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

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

Optical octave bandwidth

- a quick way to measure and control f_0



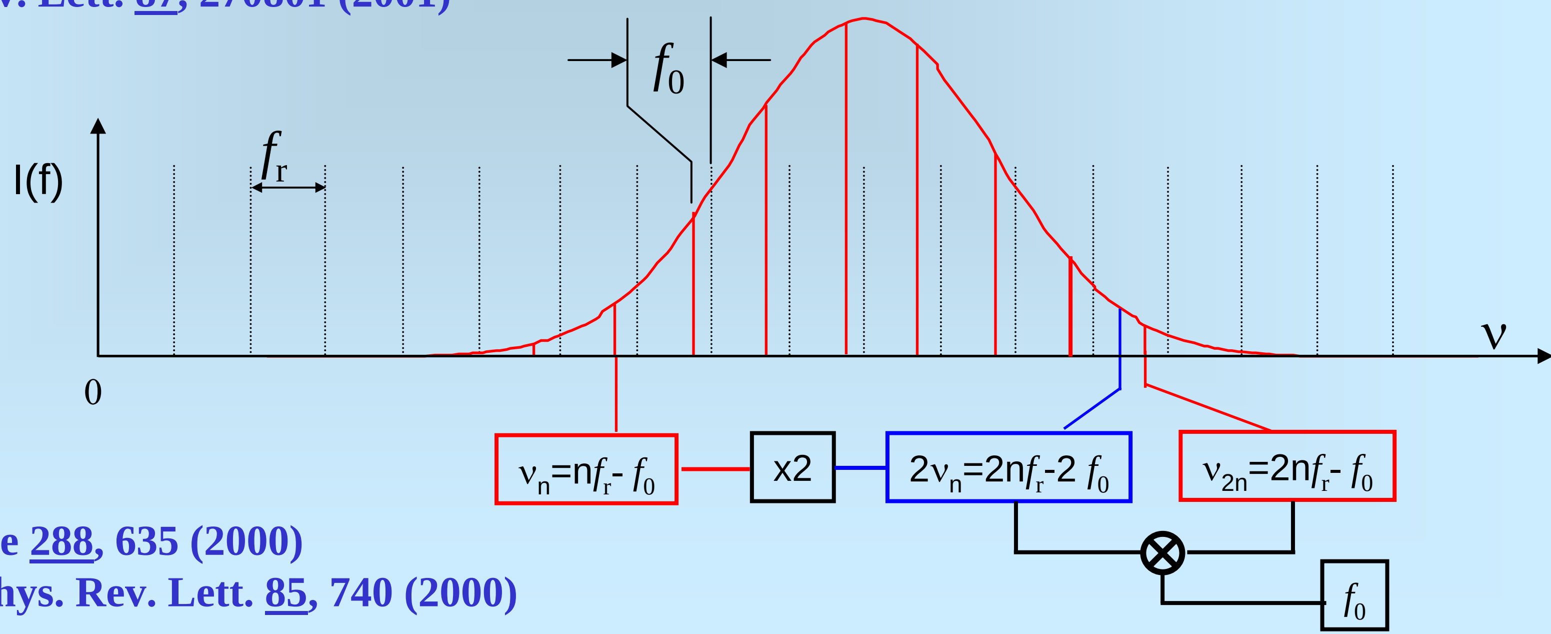
$$f_{beat1} = n f_r + f_0 - \nu_{cw}$$

$$f_{beat2} = 2n f_r + f_0 - 2\nu_{cw}$$

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

$$f_r = (\nu_{cw} - f_{beat1} - f_0)/n$$

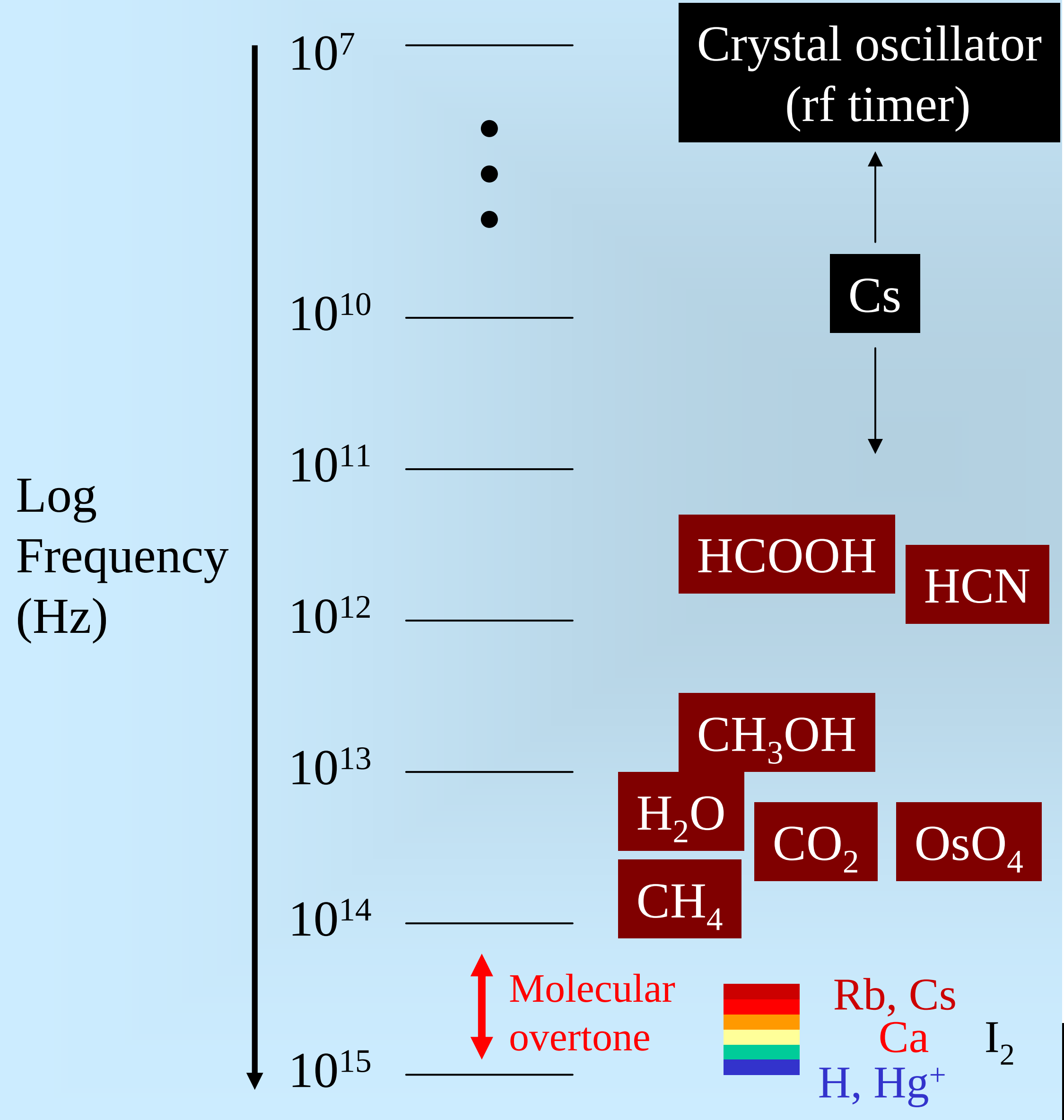
Ye *et al.*, Phys. Rev. Lett. 87, 270801 (2001)

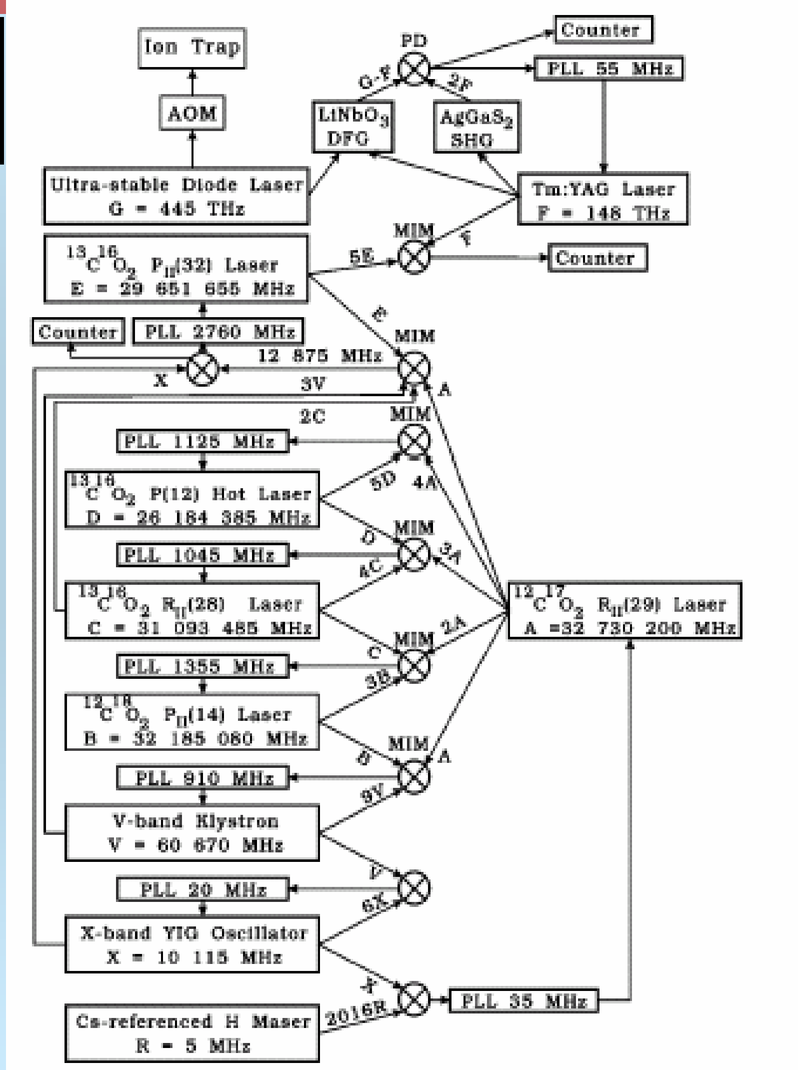


Jones *et al.*, Science 288, 635 (2000)

Apolonski *et al.*, Phys. Rev. Lett. 85, 740 (2000)

Frequency spectrum in optical frequency synthesis

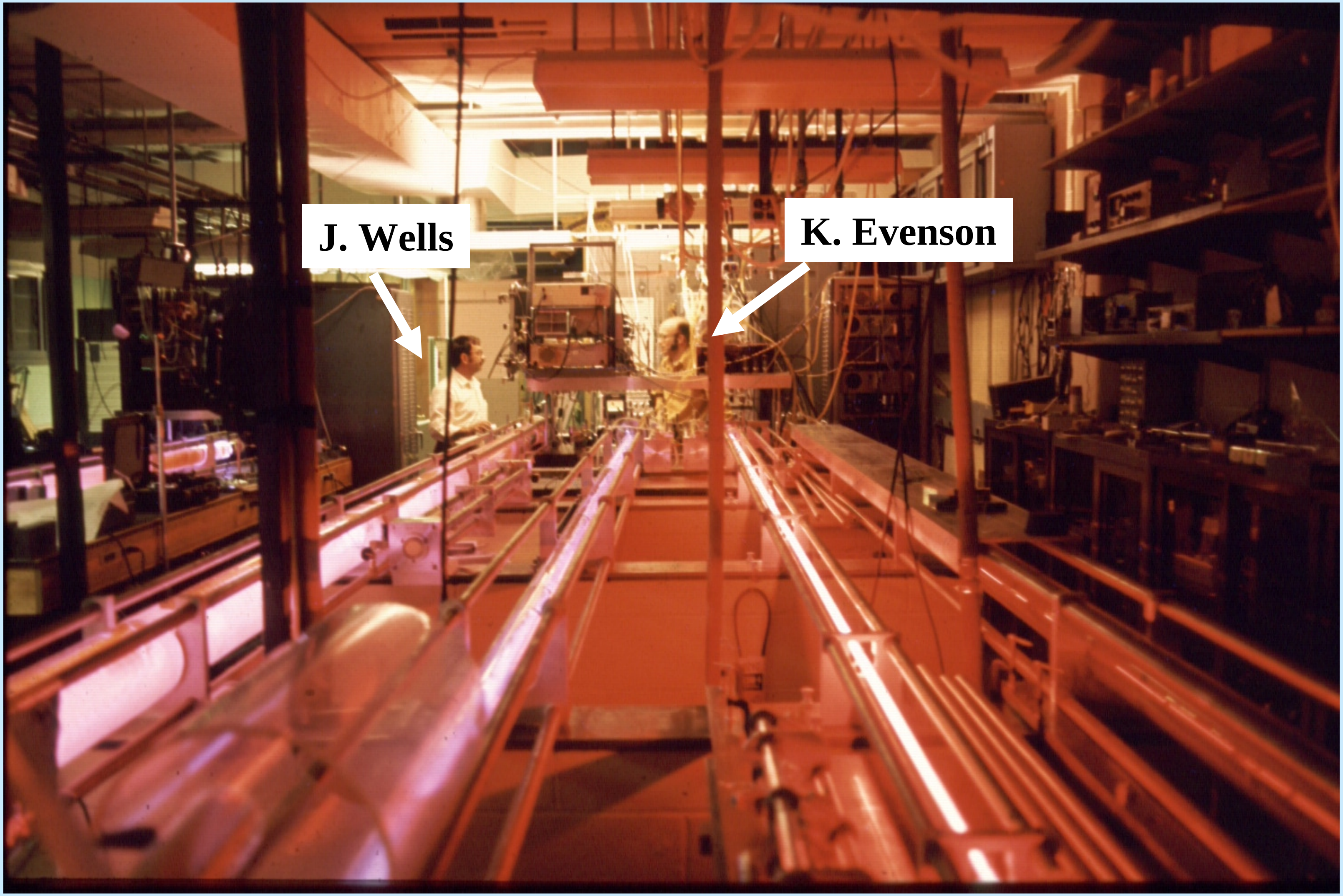




Harmonic frequency chains, PTB, NRC, …
H. Schnatz *et al.*, PRL **76**, 18 (1996).

The First Optical Frequency Chain

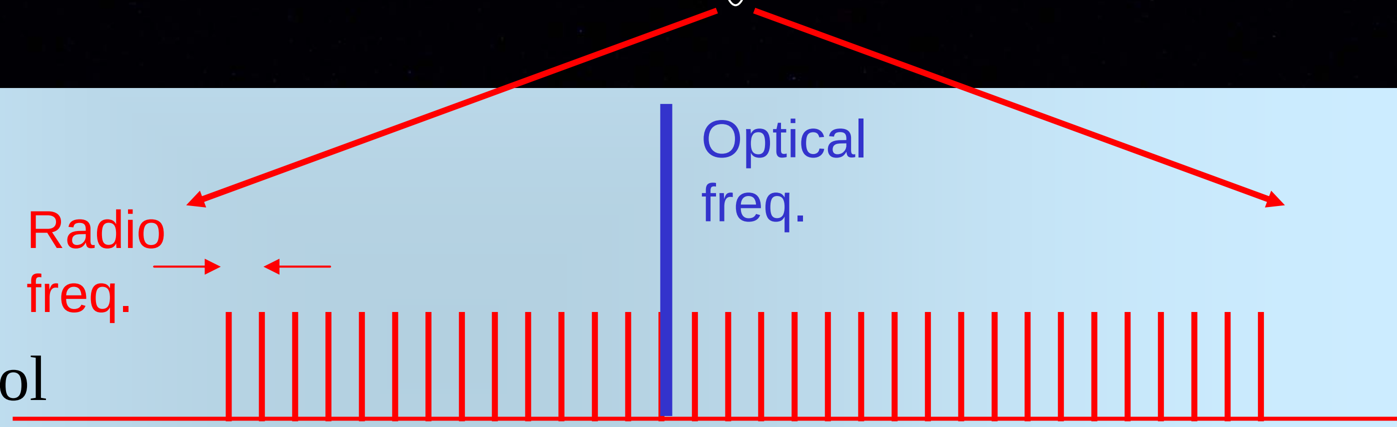
NBS (NIST): measurement of speed of light, 1972



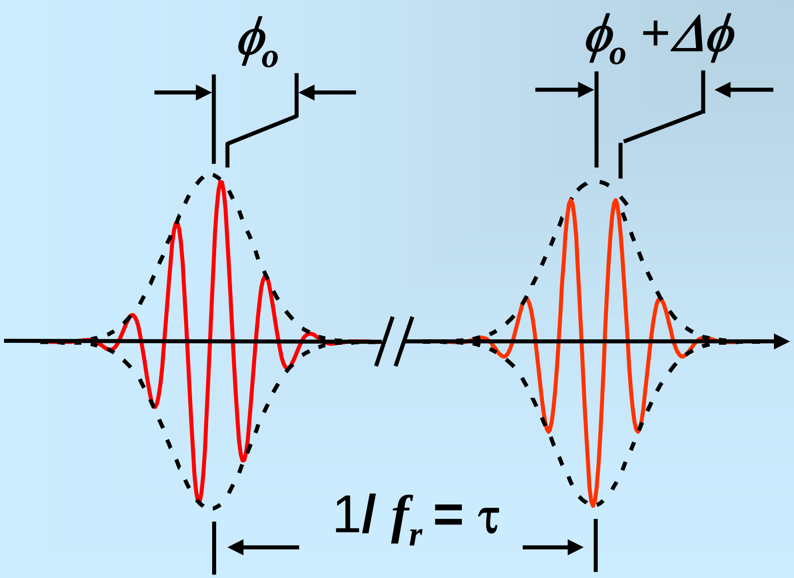
J. L. Hall & J. Ye, "NIST 100th birthday", Optics & Photonics News 12, 44, Feb. 2001

Millions of stable lasers at once!

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

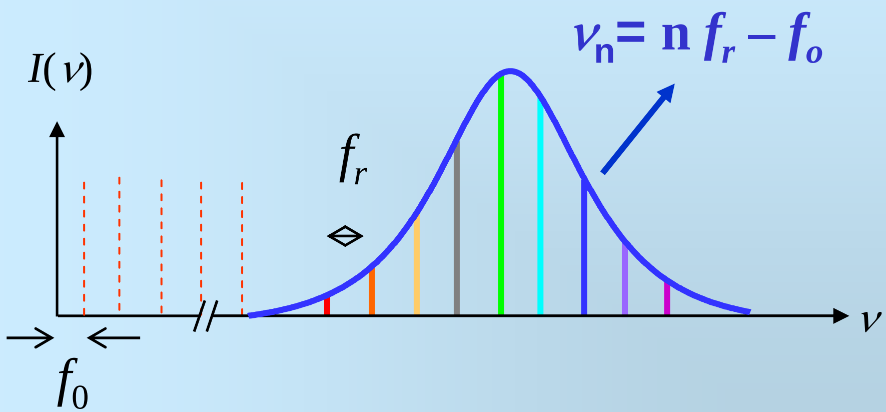


- Waveform control



- **Inaccuracy ~ 10^{-19}**
- **Short term instabilities ~ 10^{-16} @ 1s**
- **Linewidth ~ 0.3 Hz**
- **$\Delta\phi < 10^{-2}$ rad, timing jitter < 1 fs**

Frequency comb: state-of-the-art

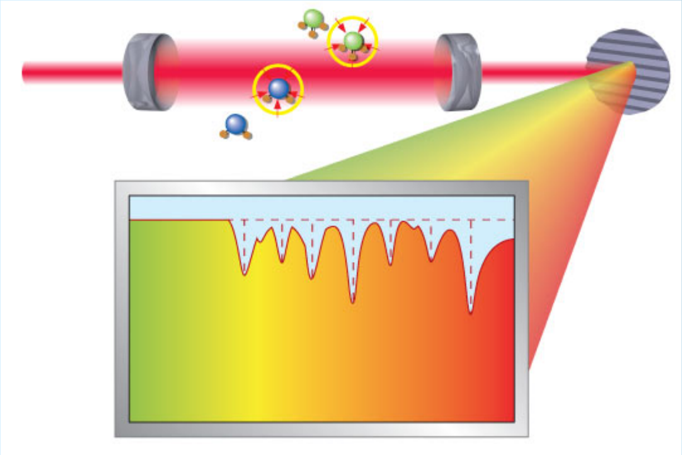


Optical Synthesizer & clock

Ludlow *et al.*, Science **319**, 1805 (2008).

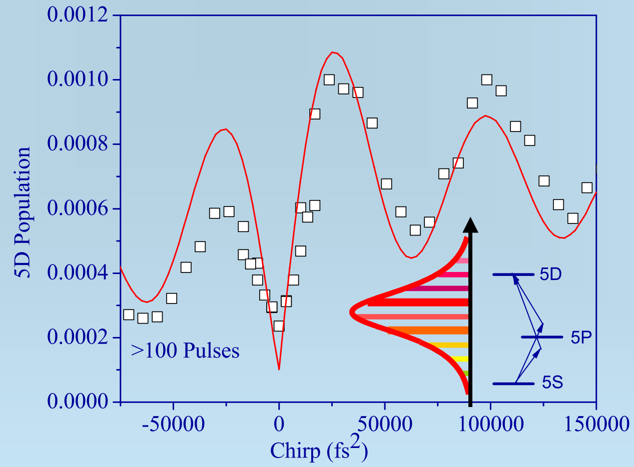
Lecture II: Optical lattice clocks

Lecture III: Ultracold molecules!



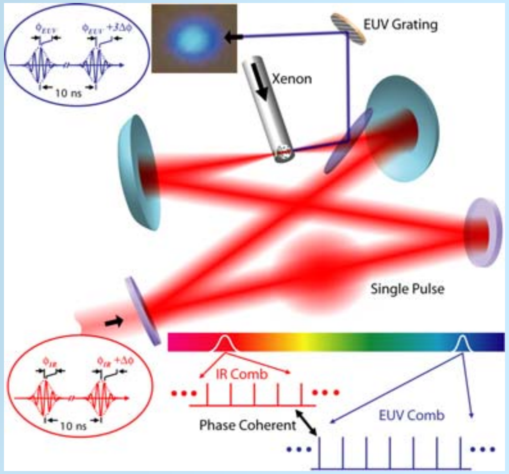
Molecular spectroscopy

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



Quantum control

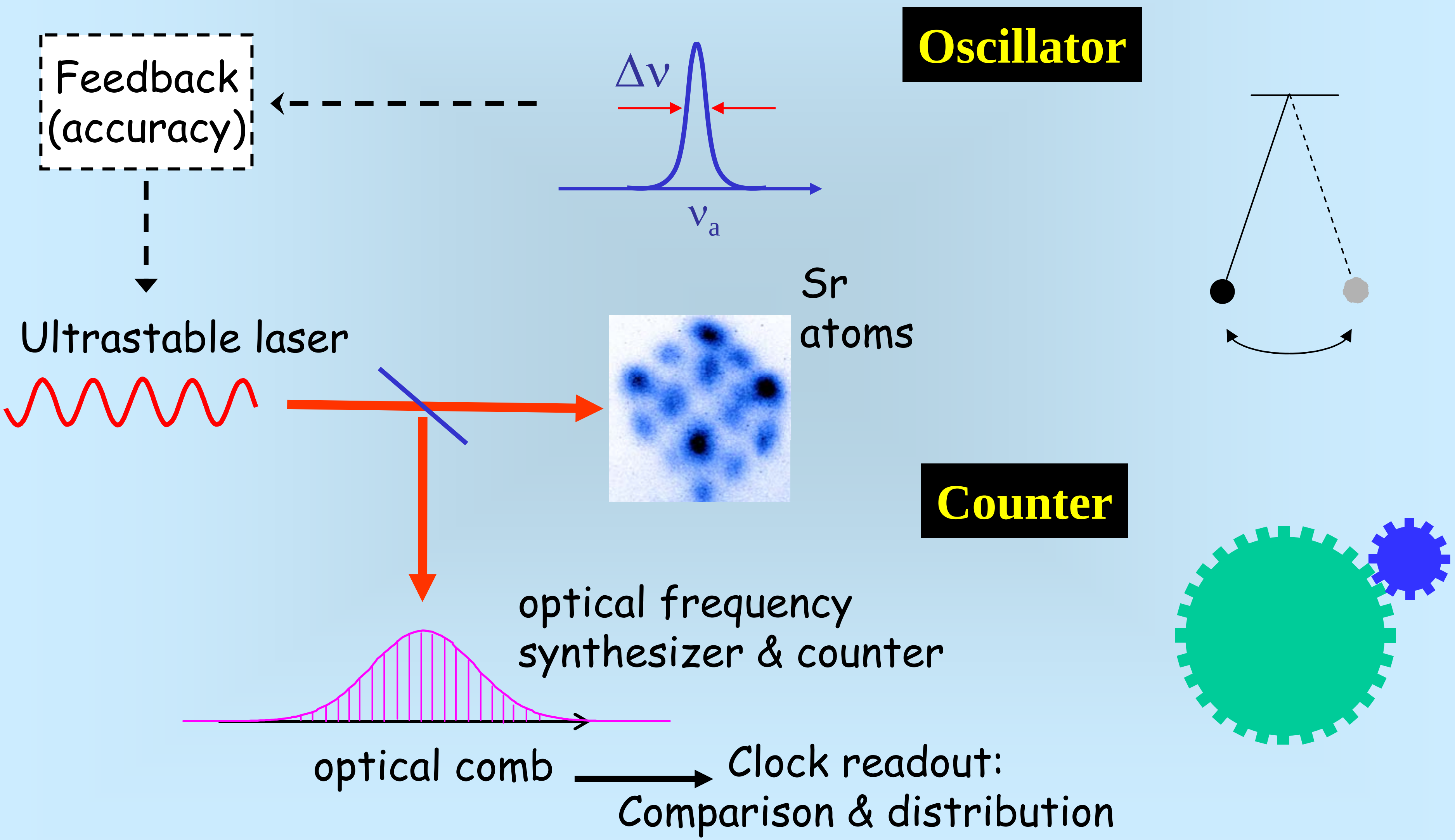
Stowe *et al.*,
PRL **96**, 153001(2006).
PRL **100**, 203001 (2008)



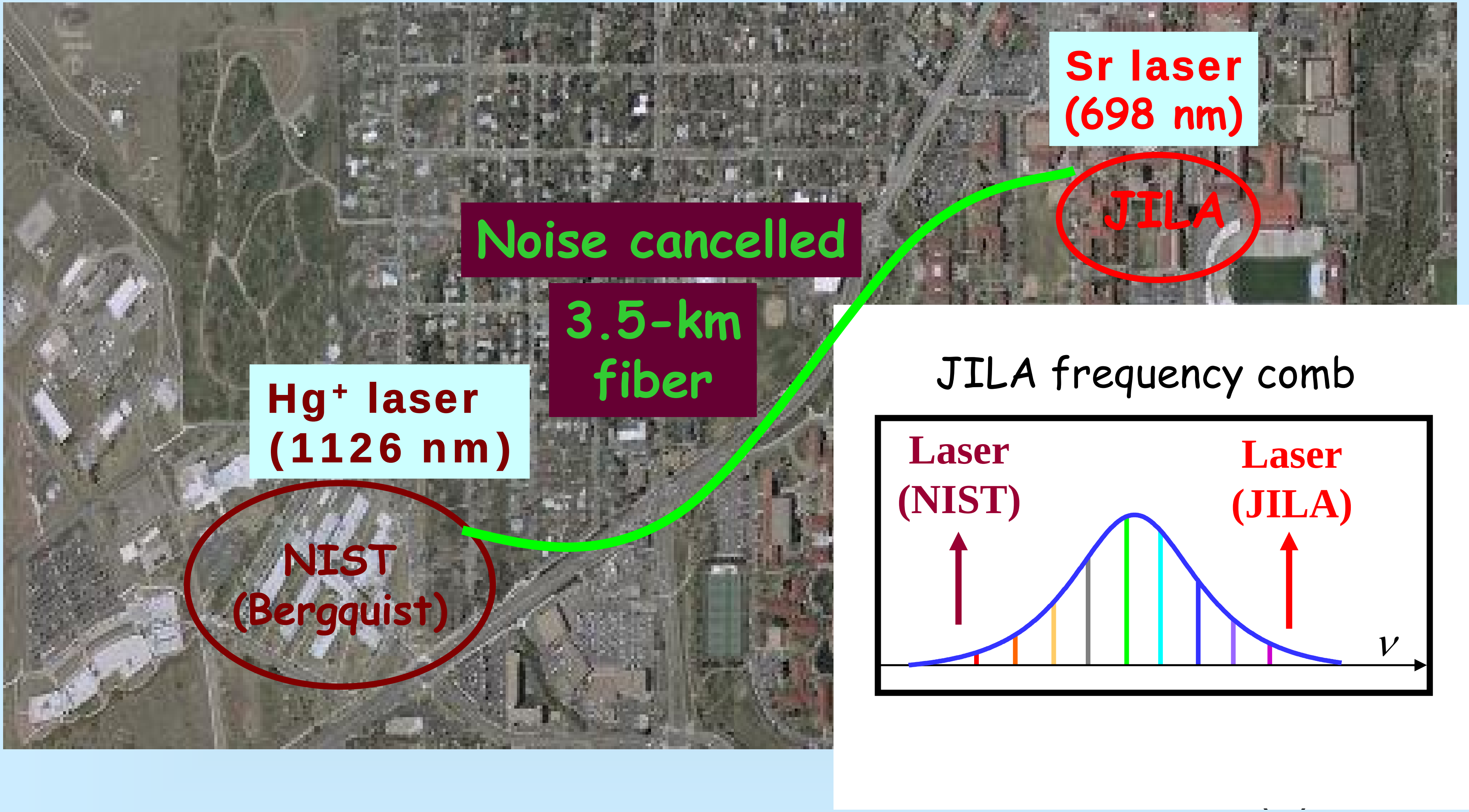
XUV comb

Jones *et al.*
PRL **94**, 193201 (2005).
C. Gohle *et al.*,
Nature 436, 234 (2005).

Optical atomic clocks



Optical comparison at 1-Hz - two spatially & spectrally separated lasers

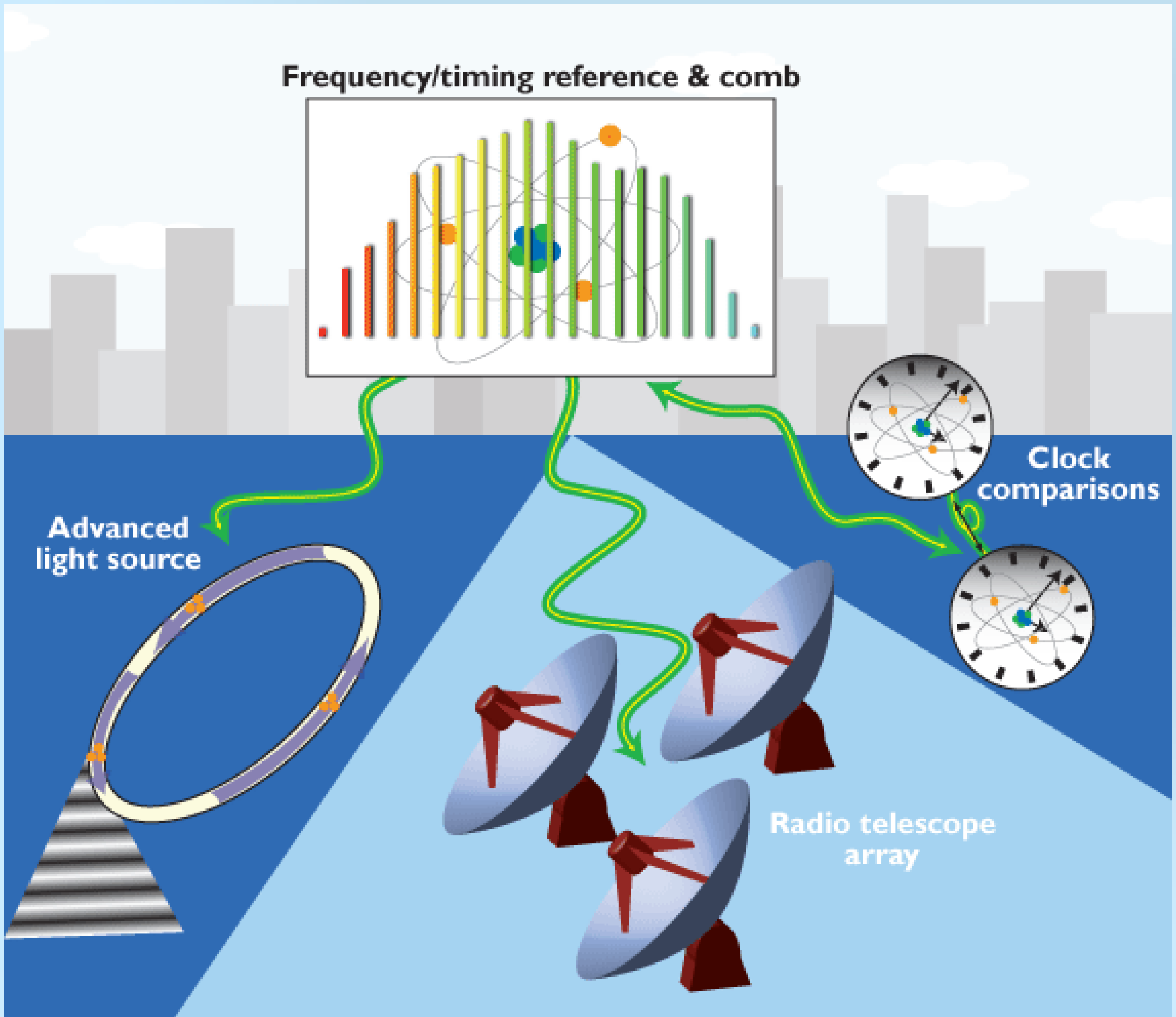


Foreman et al., Phys. Rev. Lett. 99, 153601 (2007).

Precise distribution of ultra-stable signals

Foreman, Holman, Hudson, Jones, and Ye,
Rev. Sci. Instrum. 78, 021101 (2007).

SYRTE, NIST, ...



> 30 km fiber:

1×10^{-17} @ 1 s;

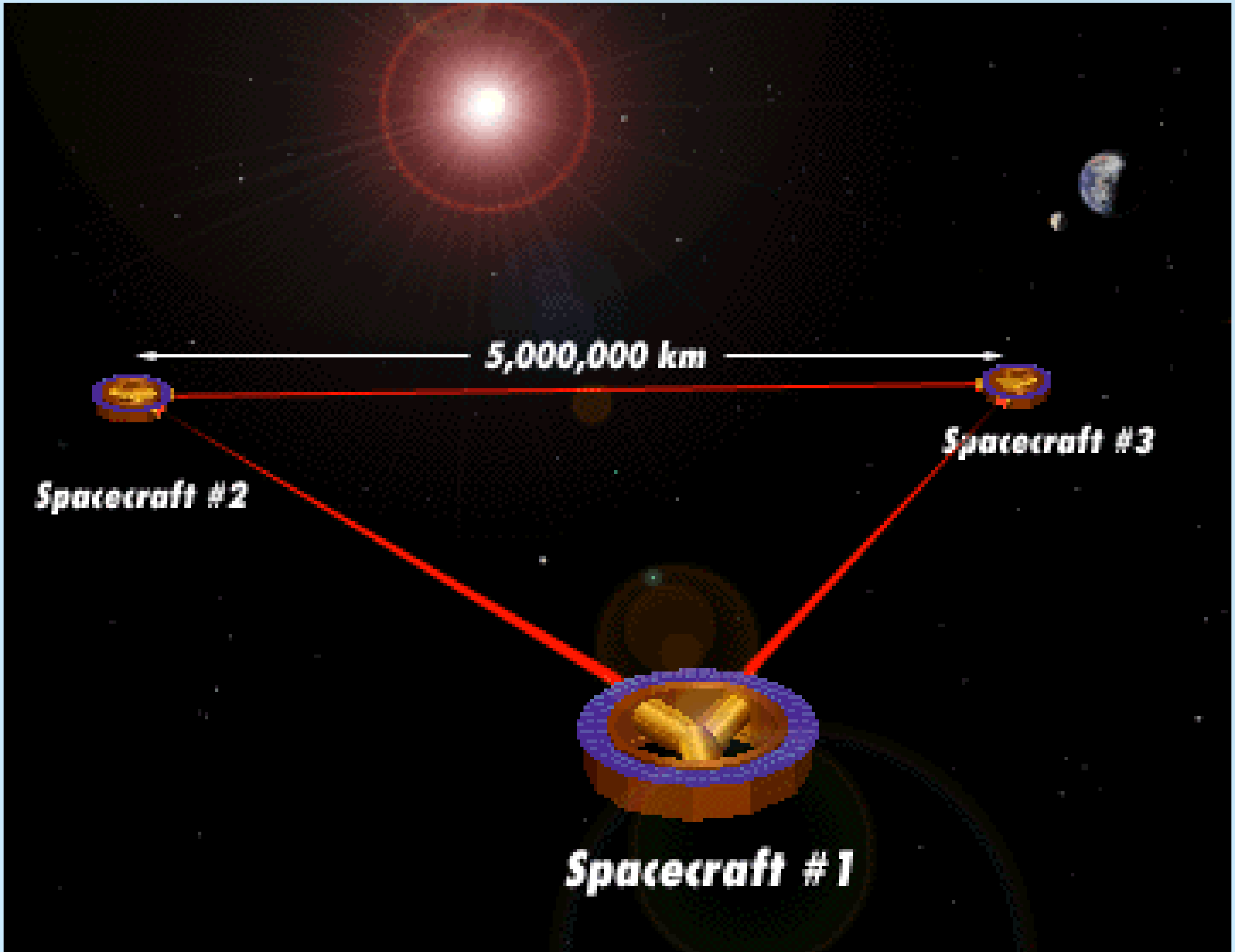
1 Hz optical linewidth;

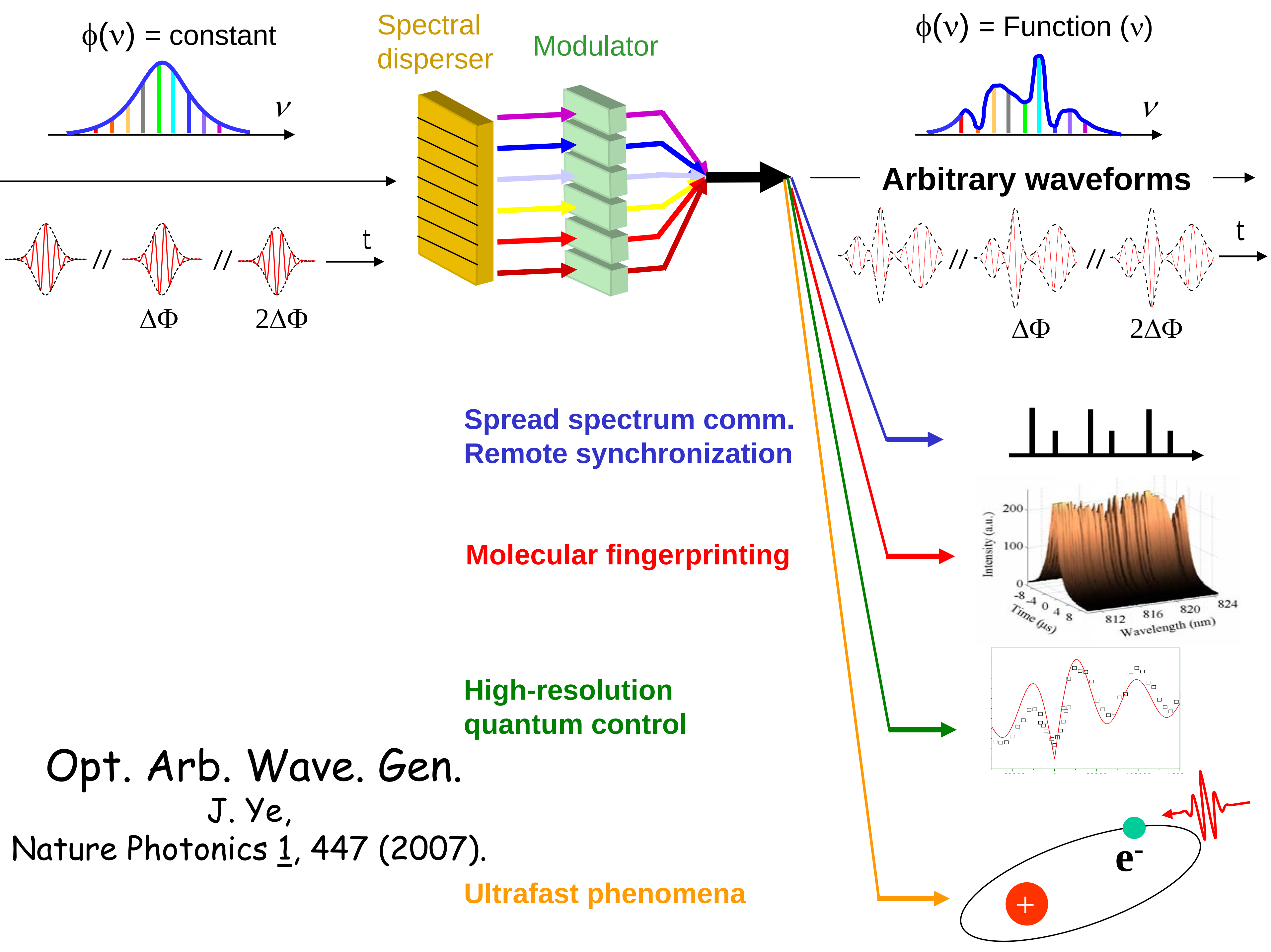
0.1 fs jitter (20 MHz BW)

All in one - Space Clock and Laser Ranging

Time meets length Ye, Opt. Lett. 29, 1153 (2004).

Space based interferometer Courtesy of P. Bender





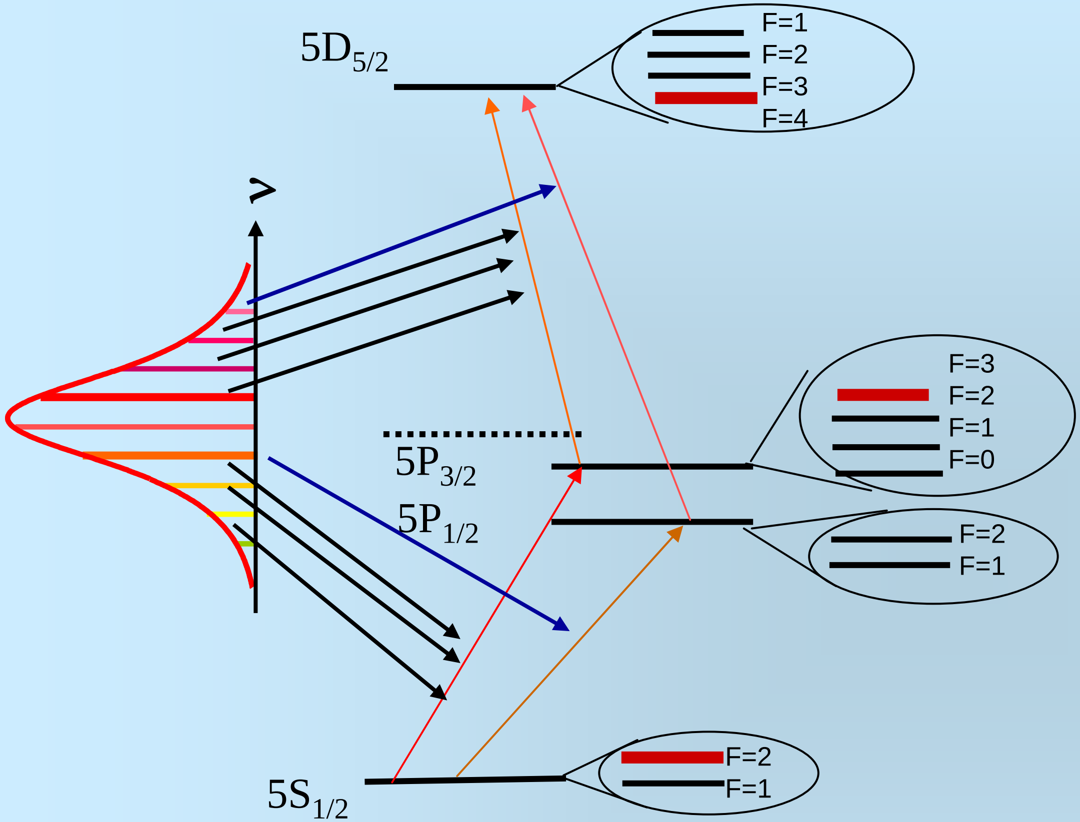
φ(ν) = constant
ν
ΔΦ
2ΔΦ
t
Spectral disperser
Modulator
φ(ν) = Function (ν)
ν
Arbitrary waveforms
t
ΔΦ
2ΔΦ
Spread spectrum comm.
Remote synchronization
Molecular fingerprinting
Intensity (a.u.)
200
100
0
-8 -4 0 4 8
Time (μs)
812 816 820 824
Wavelength (nm)
High-resolution quantum control
Ultrafast phenomena
e⁻
+
Opt. Arb. Wave. Gen.
J. Ye,
Nature Photonics 1, 447 (2007).

Direct Frequency Comb Spectroscopy

Marian, Stowe, Lawall, Felinto, & Ye
Science 306, 2063 (2004).

Stowe, Cruz, Marian, & Ye,
Phys. Rev. Lett. 96, 153001 (2006).

Stowe, Pe'er & Ye,
Phys. Rev. Lett. 100, 203001 (2008).

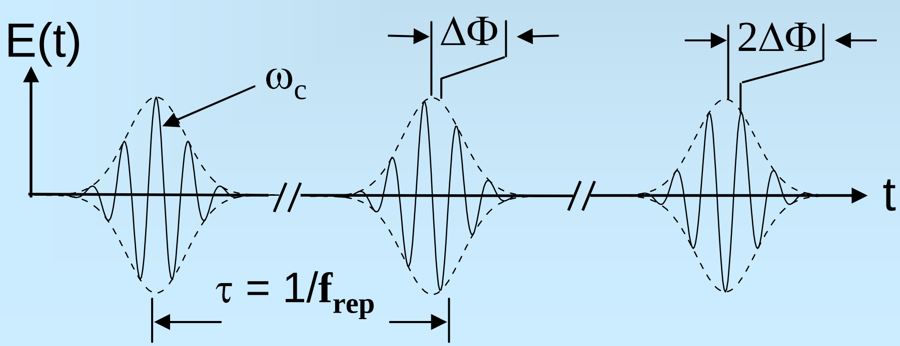


Quantum & optical coherence

High resolution quantum control

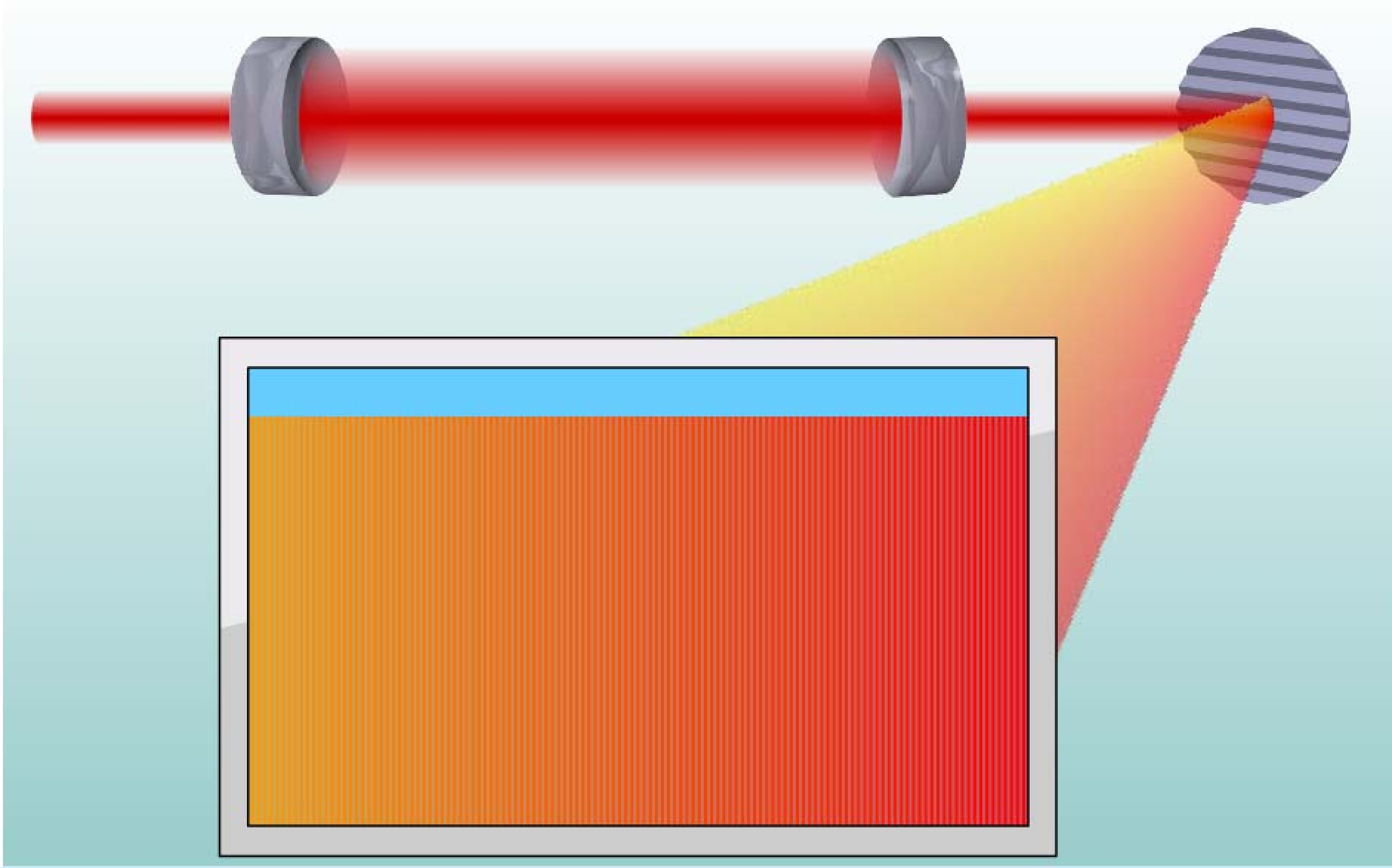
Precision spectroscopy: global atomic structure

$$\Delta\Phi = 2\pi\,(f_0/f_{rep})$$



Wide bandwidth, high resolution, real time molecular detection

Thorpe, Moll, Jones, Safdi, Ye, Science 311, 1595 (2006).

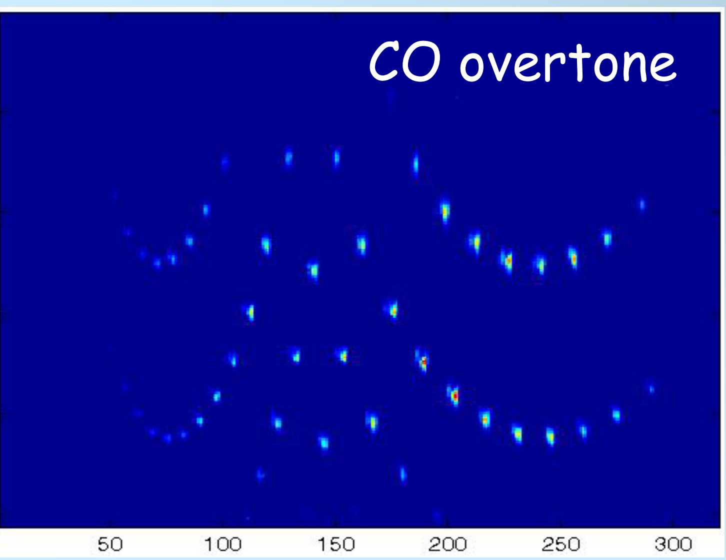


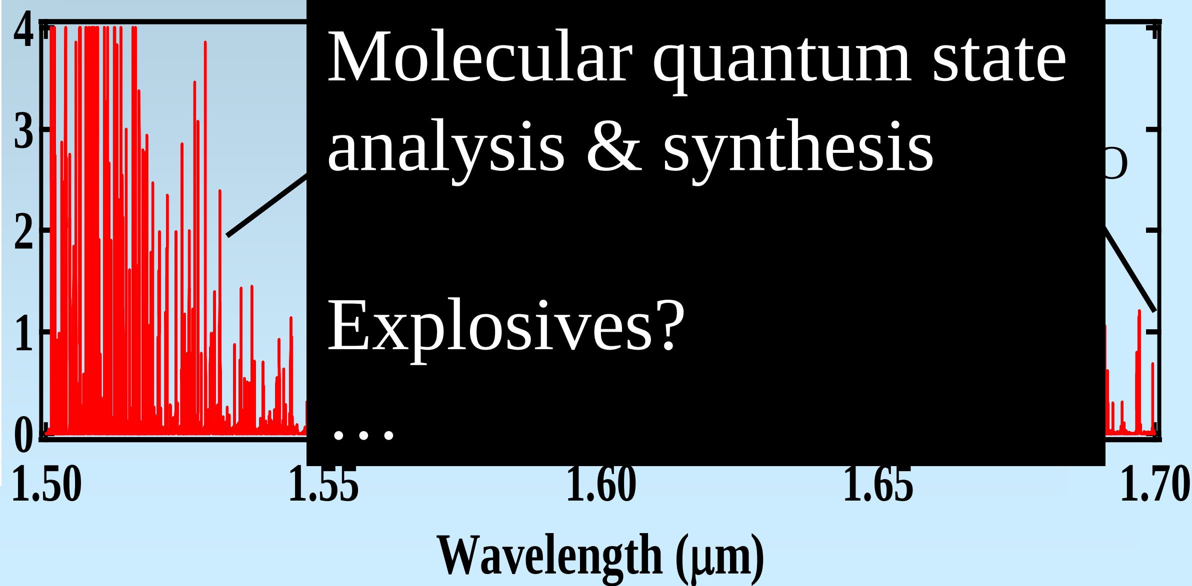
Cavity-enhanced frequency comb spectroscopy

Thorpe et al., Opt. Lett. 32, 307 (2007); Opt. Exp. 16, 2387 (2008).

- **Broad spectral coverage (> 100nm)**
- **High sensitivity (1 part per billion volume @ 1 s)**
- **High resolution (< 1 MHz)**
- **Real time acquisition (~ 10 μs)**

Molecular pattern recognition





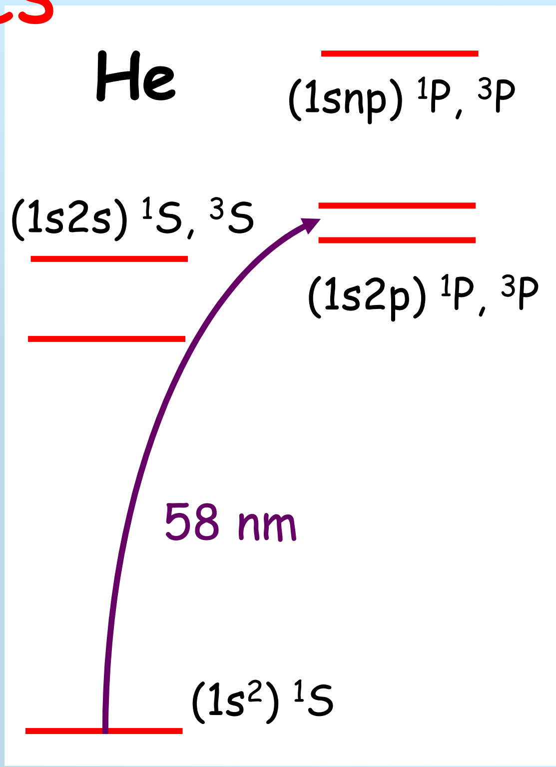
Breath analysis;

Molecular quantum state analysis & synthesis

Explosives?

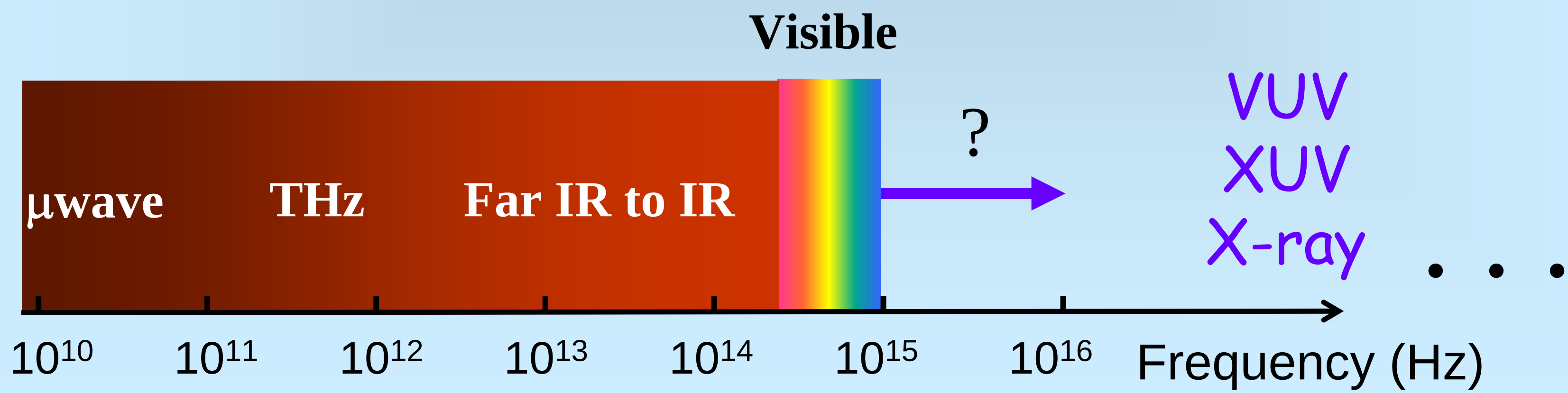
…

EUV metrology & quantum optics



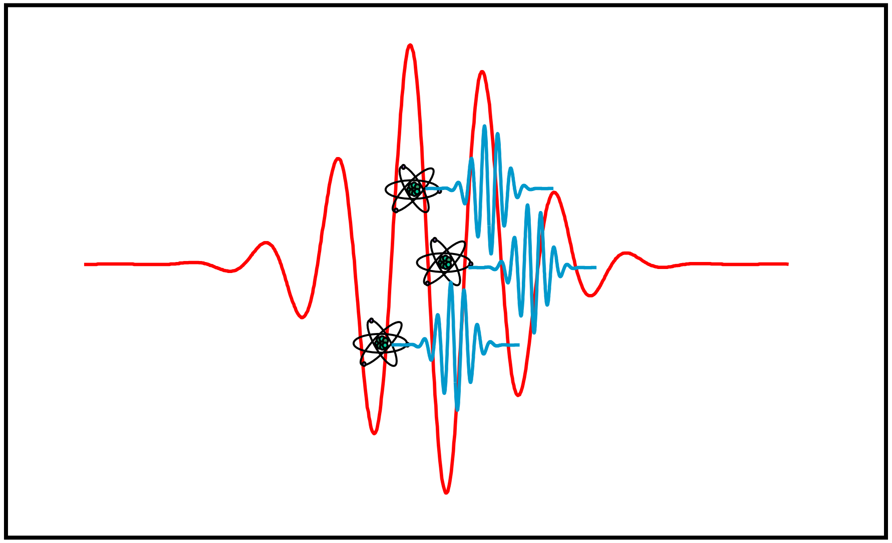
- Precision test of fundamental physics
- High-resolution spectroscopy & state control (many-electron atoms and molecules)
- EUV atomic clocks, nuclear transitions?

High energy photons with Hz-resolution?

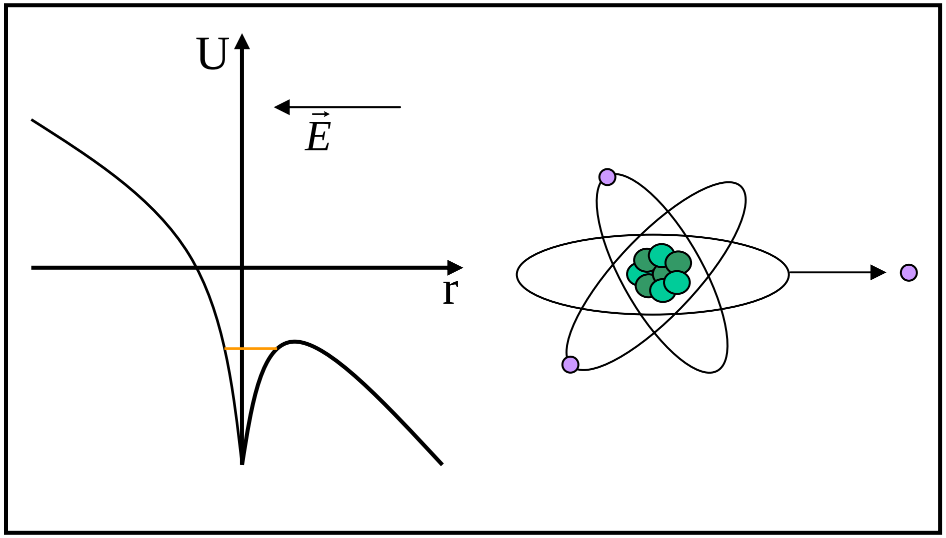


High-harmonic generation

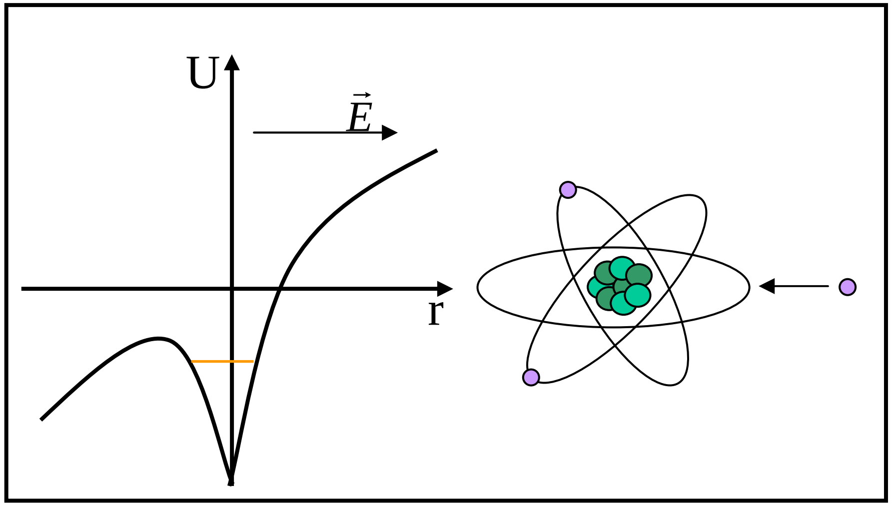
Three step model



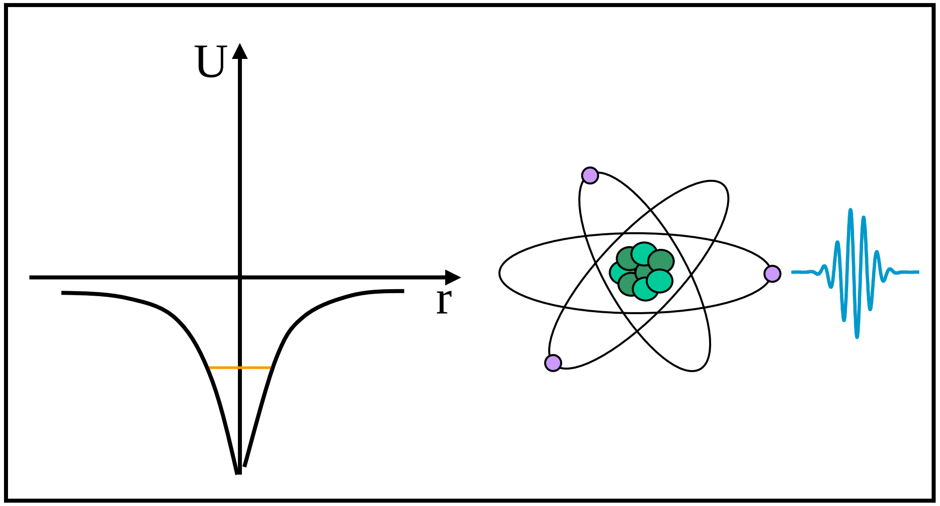
Step 1: Ionization



Step 2: Field Reversal



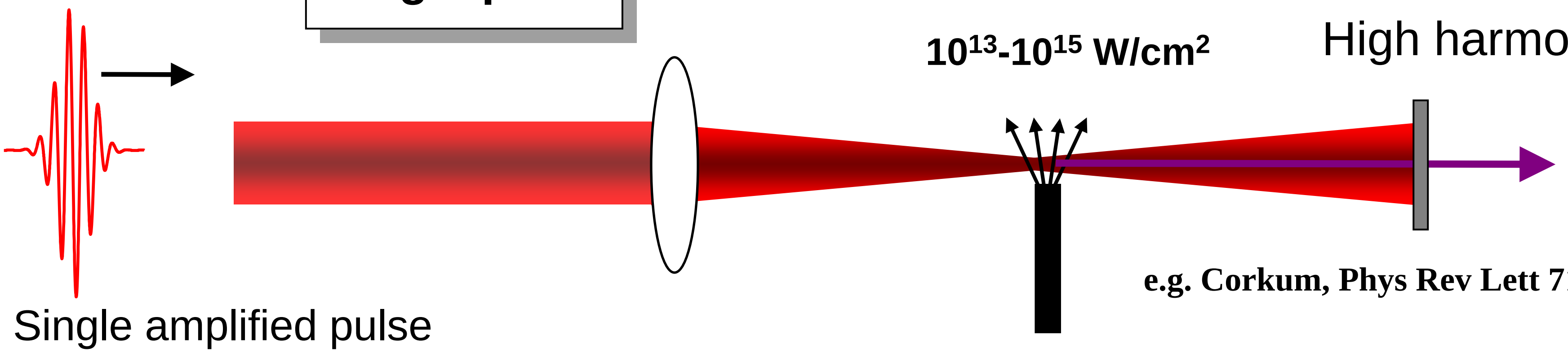
Step 3: Recombination



Corkum, Phys Rev Lett 71, 1994

High-harmonic generation

Single pass



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

Low repetition rates (Hz ~ kHz)

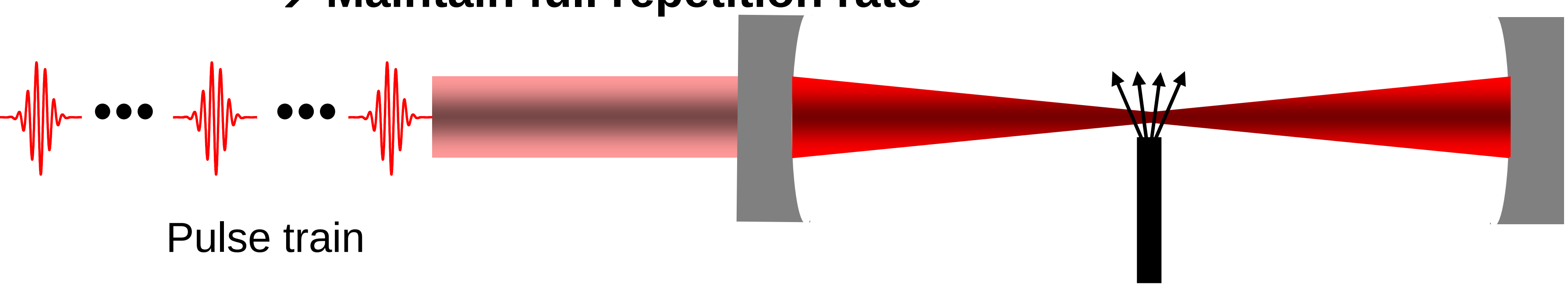
Conversion efficiency 10^{-5} ~ 10^{-8}

fs enhancement cavity

→ Recycle unconverted light

→ Maintain full repetition rate

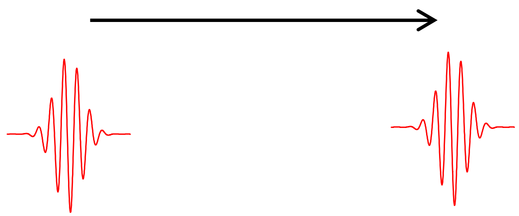
Jones & Ye, Opt. Lett. 27, 1848 (2002)
Jones & Ye, Opt. Lett. 29, 2812 (2004)
Thorpe *et al.*, Opt. Express 13, 882 (2005)
Moll *et al.*, Opt. Express 13, 1672 (2005)
C. Gohle *et al*, Nature 436, 234-237 (2005)

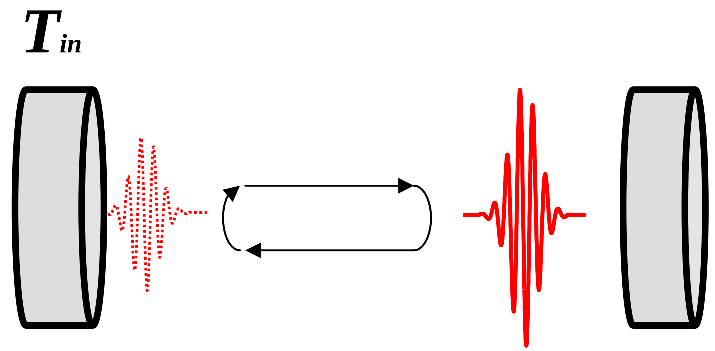


Cavity-based coherent pulse buildup

Time Domain

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





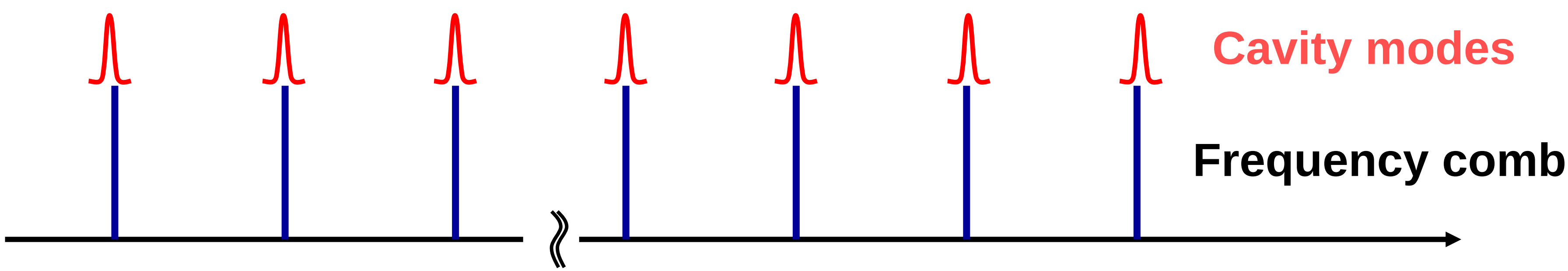
- **Linear response**
- **Preserves coherence**
- **Power enhancement**

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)



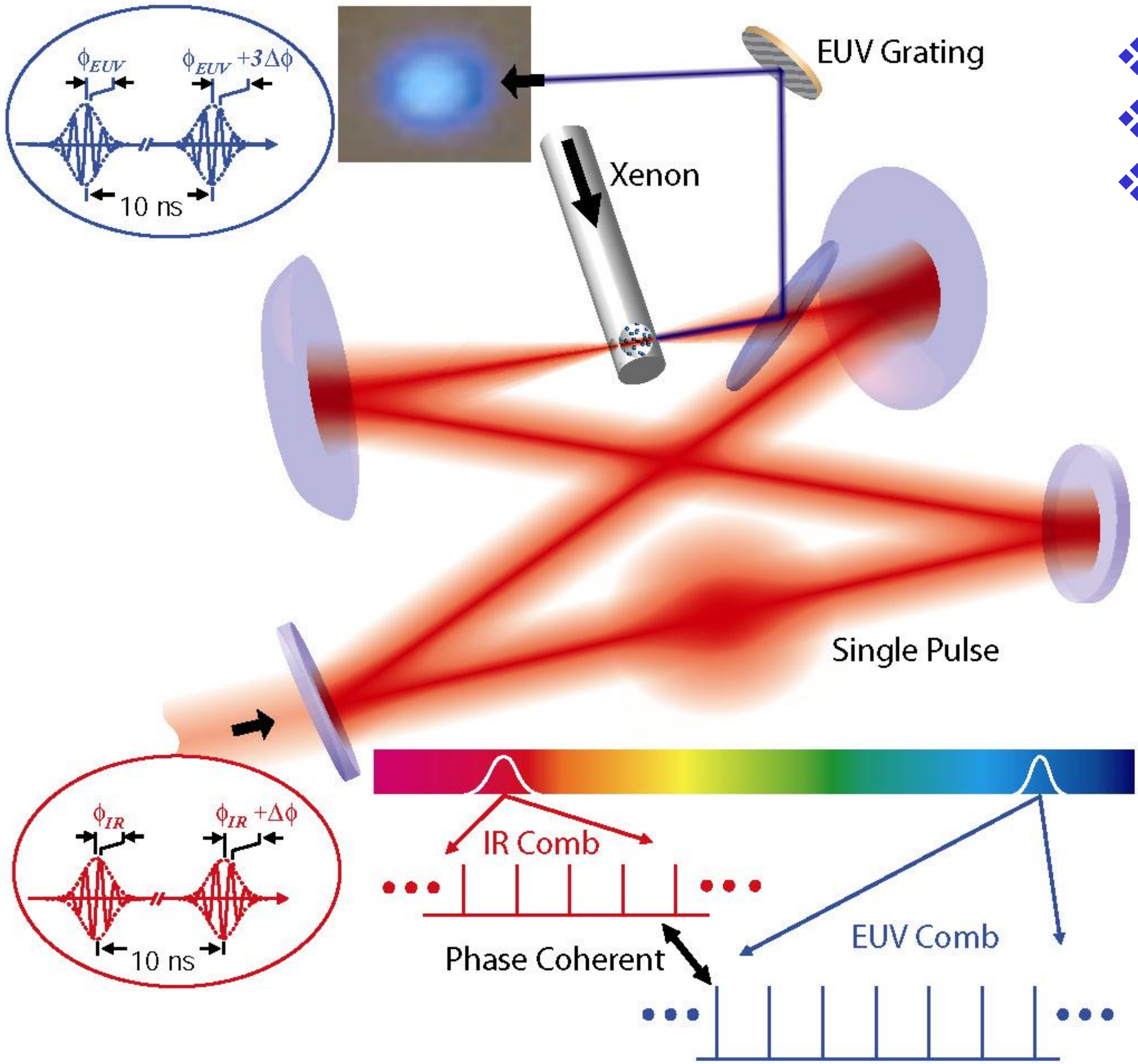
Intra-cavity HHG at 100 MHz

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



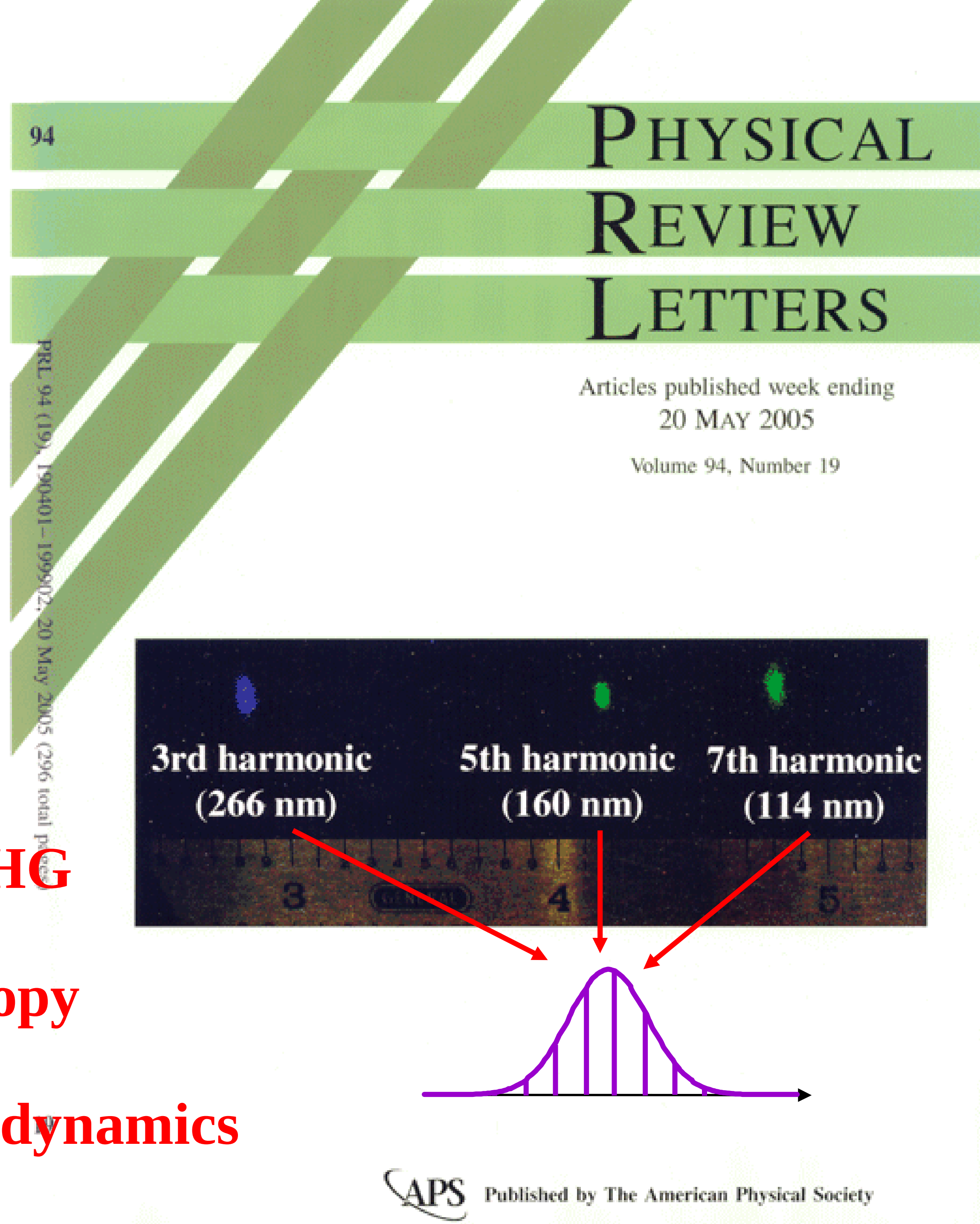
- **8 nJ ⟶ ~ 4 μJ per pulse!**
- **> 10^{13} W/cm^2 peak intensity**
- **100 MHz repetition rate**

Ionization of Xe at intracavity focus

HHG spectrum

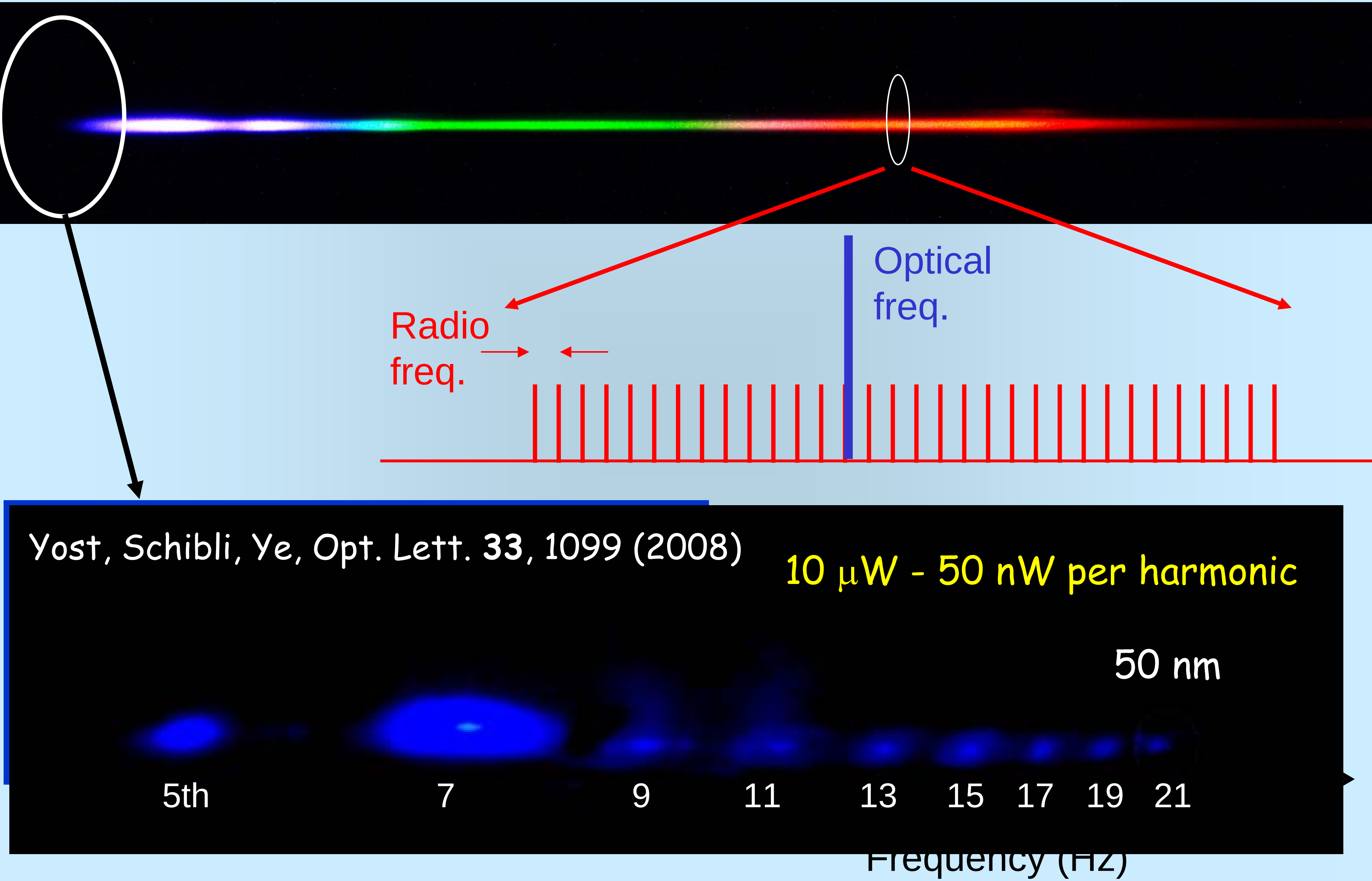
> 5 μW average power for the 3rd harmonic

3rd, 5th, 7th, 9th



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

March to the EUV goes on!



Special thanks

Femtosecond comb
& Quantum control

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T. Schibli

S. Foreman (Stanford)
R. J. Jones (Arizona)
Marian (MPG, Berlin)