The art of light control & precision measurement

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ICAP Summer School, Paris, July 19, 2012

NIST, NSF,
DARPA, AFOSR

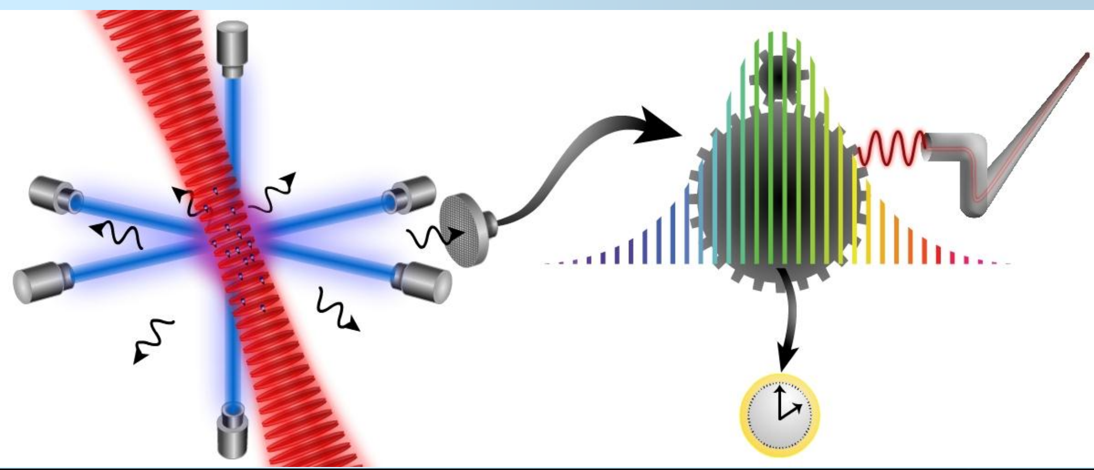
A modern epoch in quantum metrology

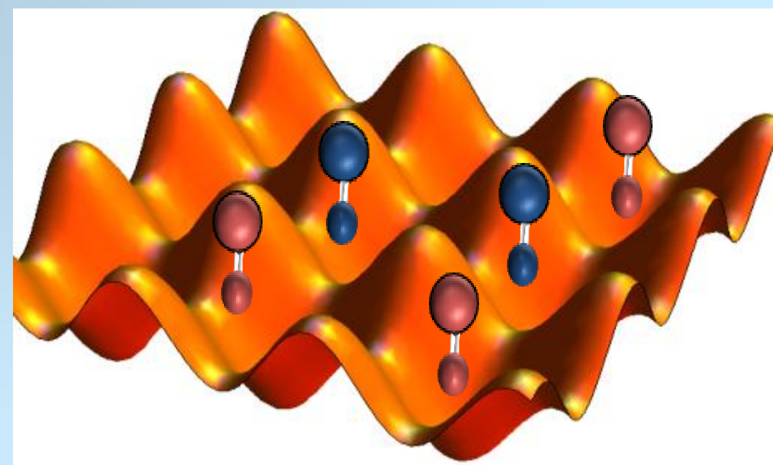
Precision Measurement

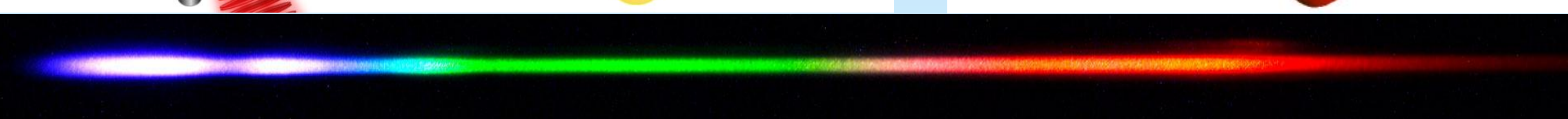
Many-particle Quantum systems

Many-body physics & novel quantum states push the fundamental limit of measurement

Precision measurement & clocks determine microscopic parameters and system properties







Lecture I: Art of light control

Lecture II: Precision quantum metrology

Lecture III: Ultracold molecules – a new frontier

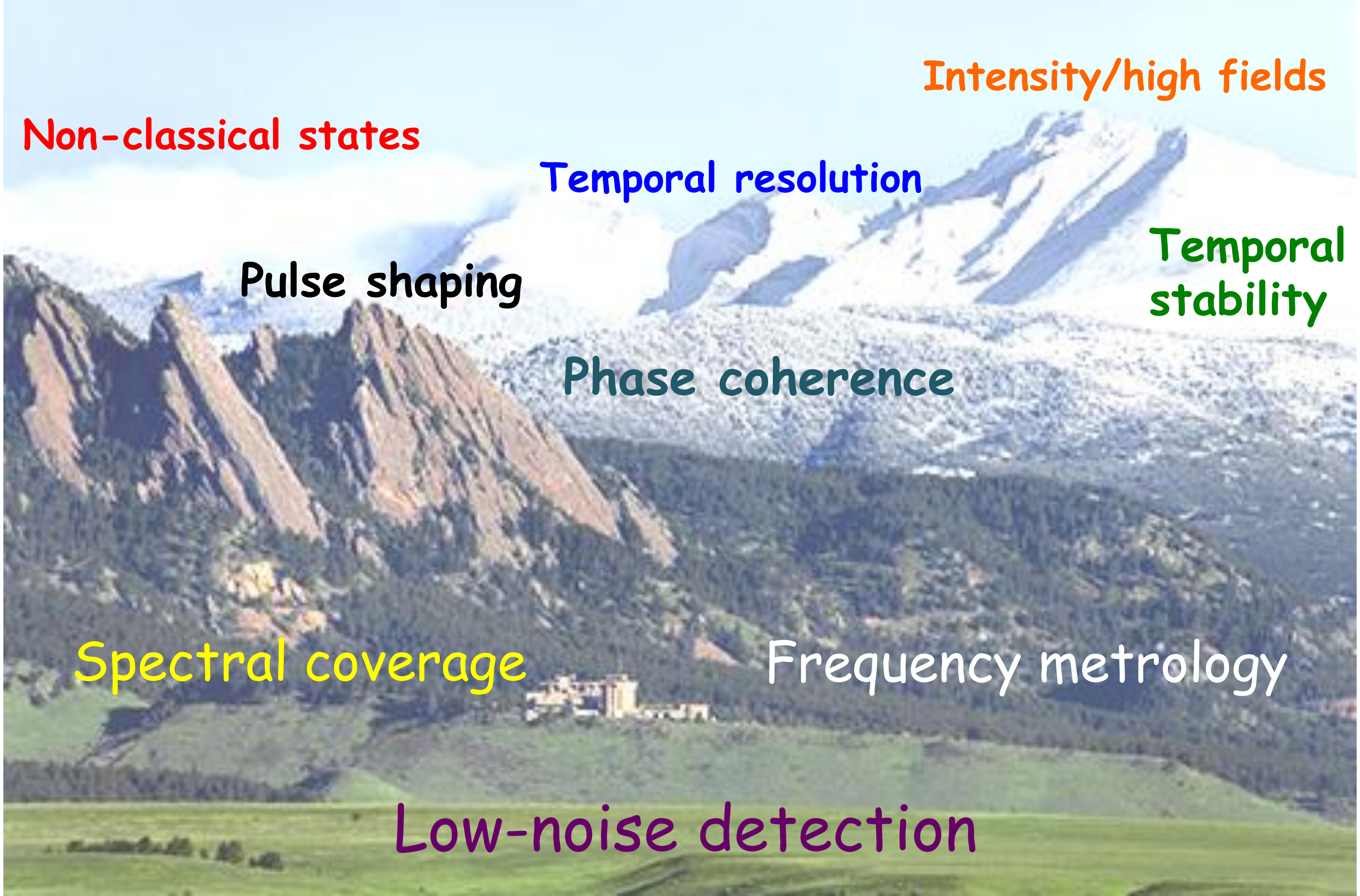
– A remarkable convergence of

Ultracold,
Ultrafast,
Ultrastable,
Ultraprecise

Light at JILA

What makes a versatile photon laboratory?

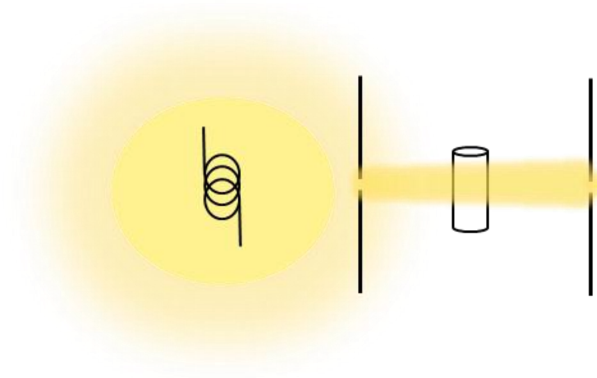
Scientifically useful photons span a space of many dimensions

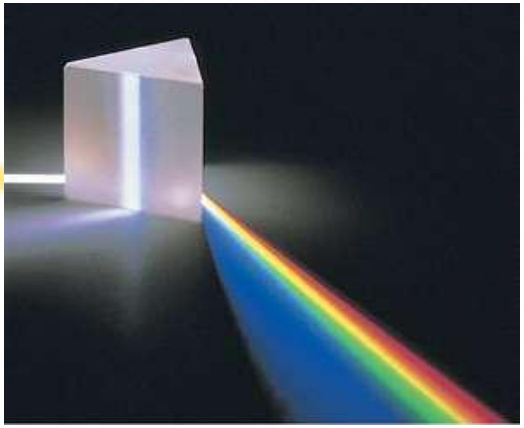


Spectral resolution - Nature's finger prints

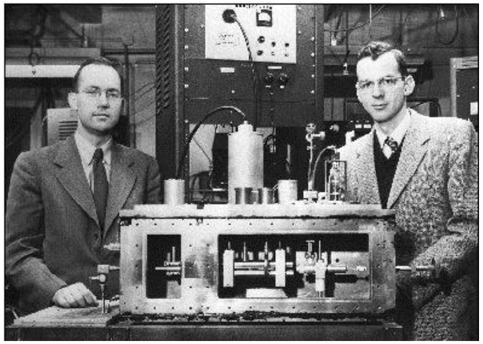
Dispersive Spectrometer
- Measure wavelength
- Resolution 10^{-6}

ca. 1660
I. Newton

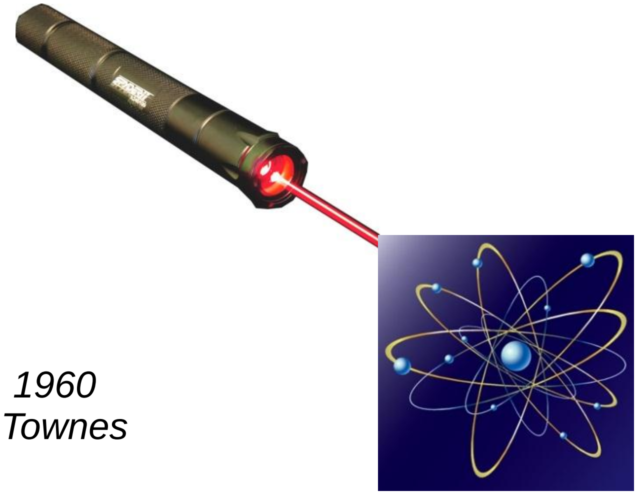


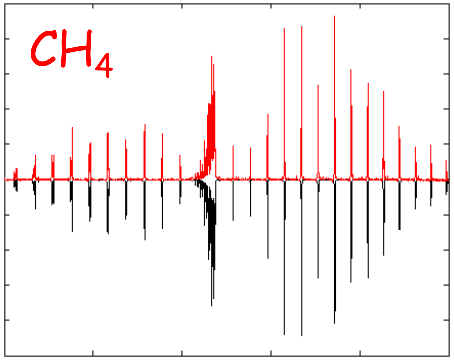


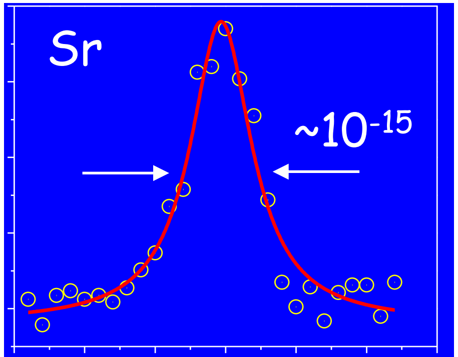
Laser spectroscopy
- Measure frequency
- Resolution 10^{-15}



ca. 1960
C. Townes

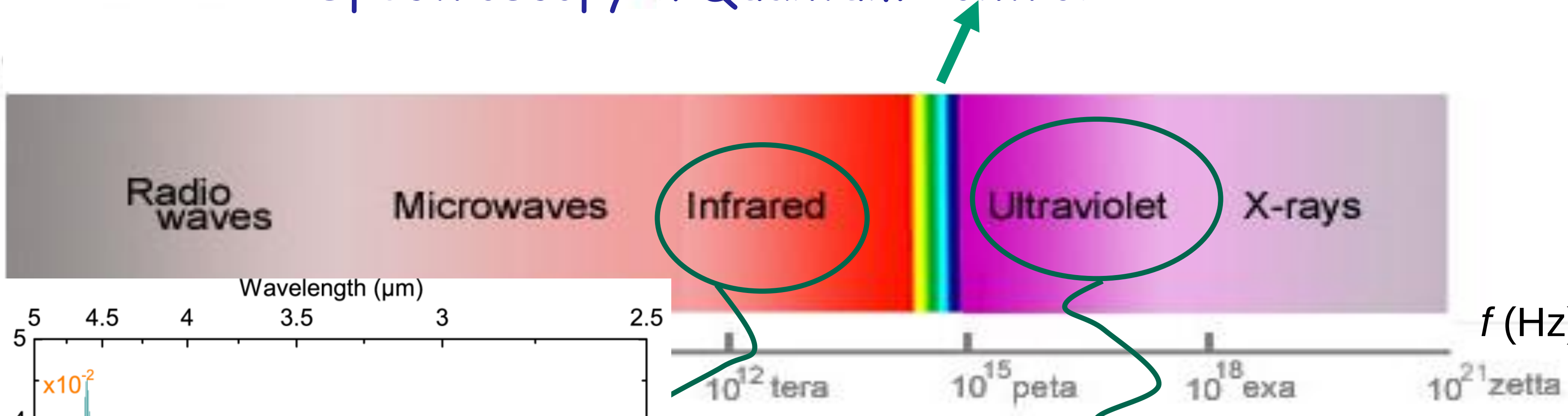


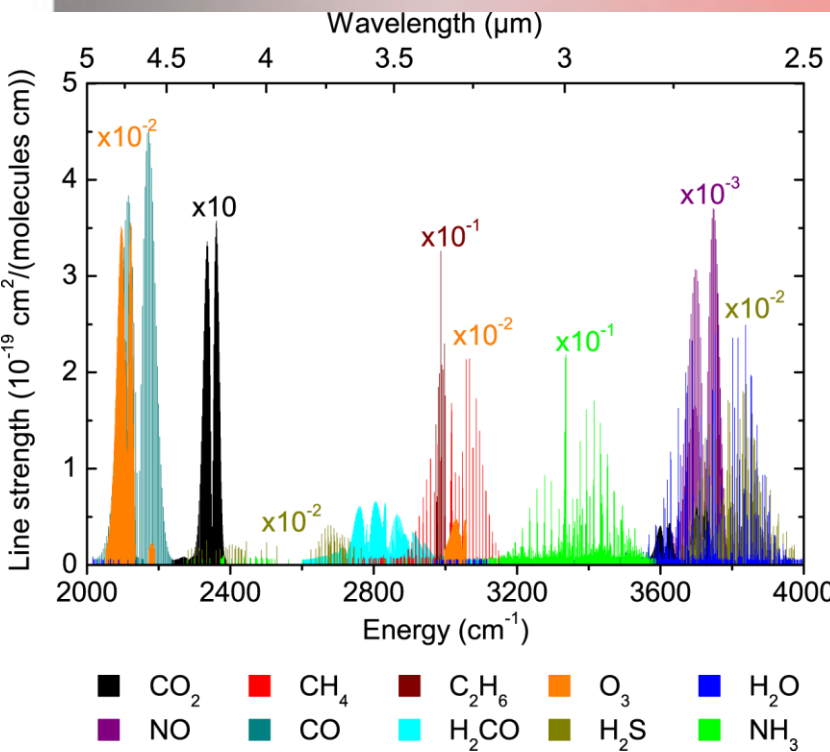


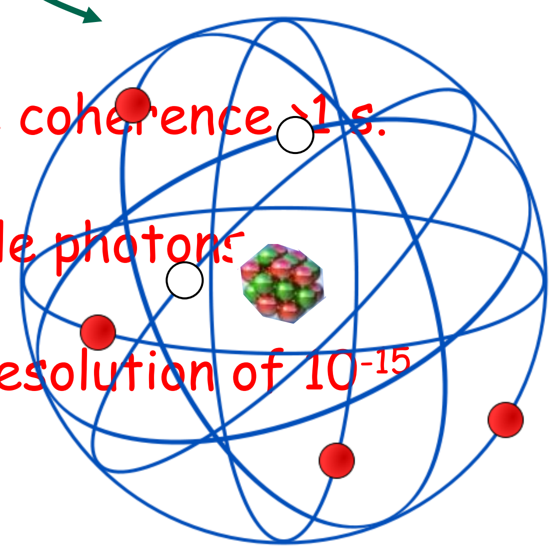


Coherent synthesis of Electromagnetic spectrum

- Phase-coherent radiations – IR to XUV
- Spectroscopy & Quantum Control





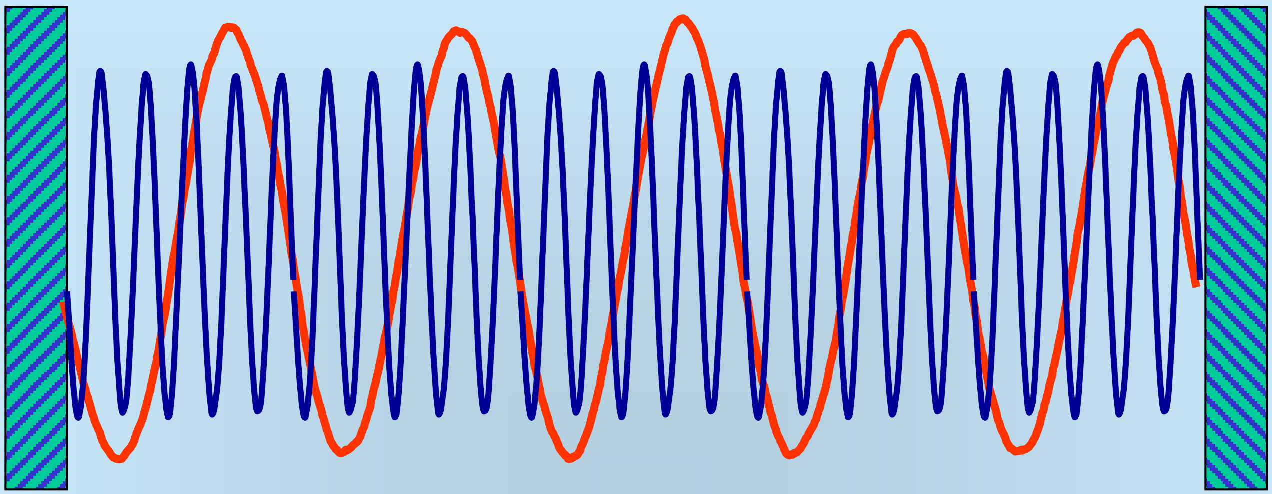


yet maintain phase coherence >1 s.

ields, but also single photons

– XUV; Spectral resolution of 10^{-15}

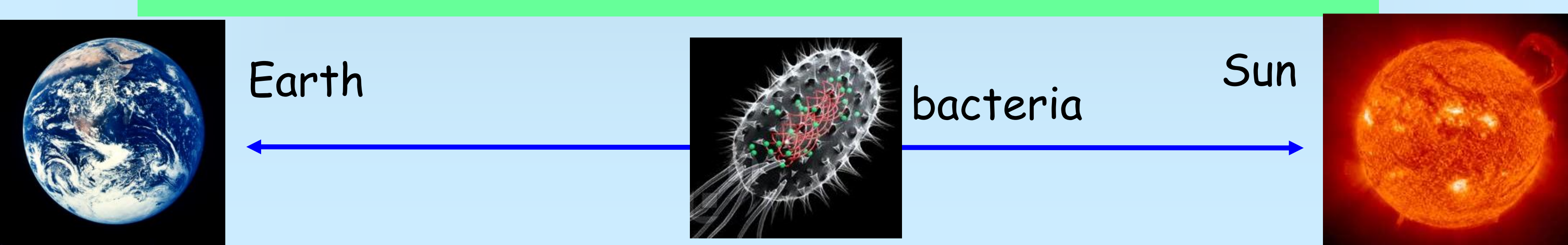
Why light ? - Chasing the SPEED!



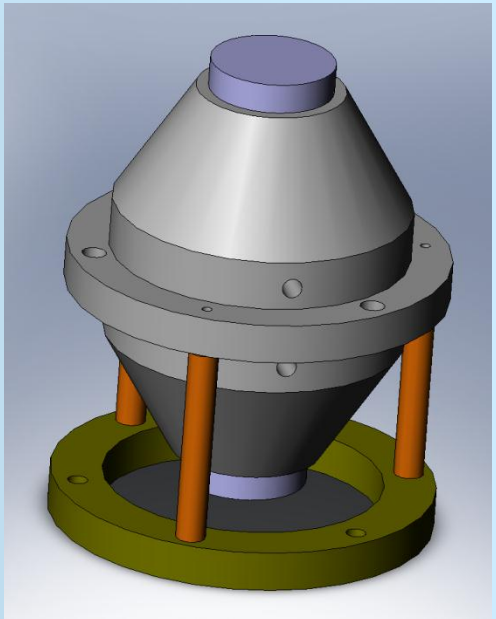
Faster oscillations → More cycles → Smaller errors

Light ripples: 10^{15} cycles per second, & we count every one

Precision: 1 000 000 000 000 000 ± 1

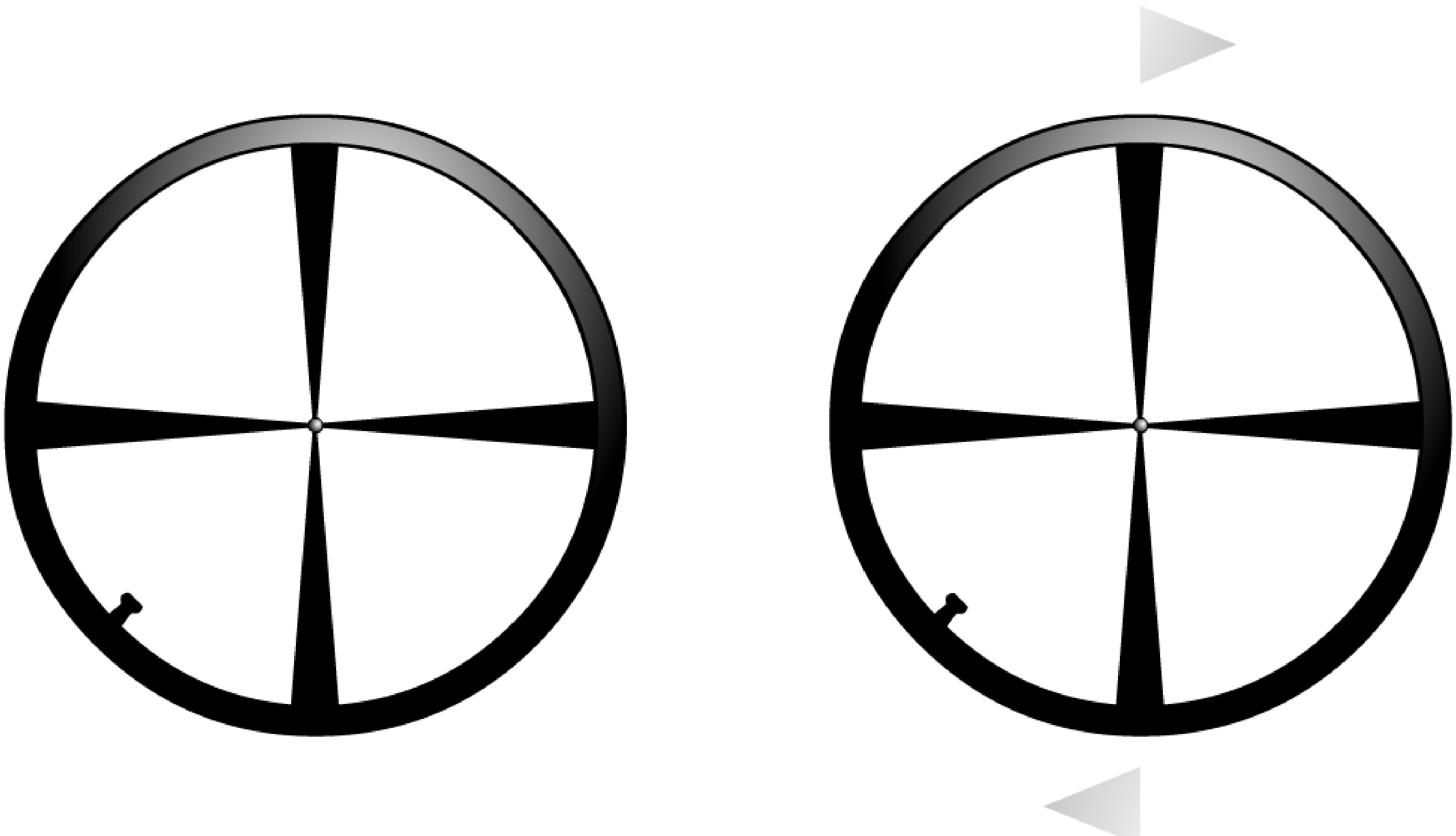


First, make the field steady - Stable optical cavity

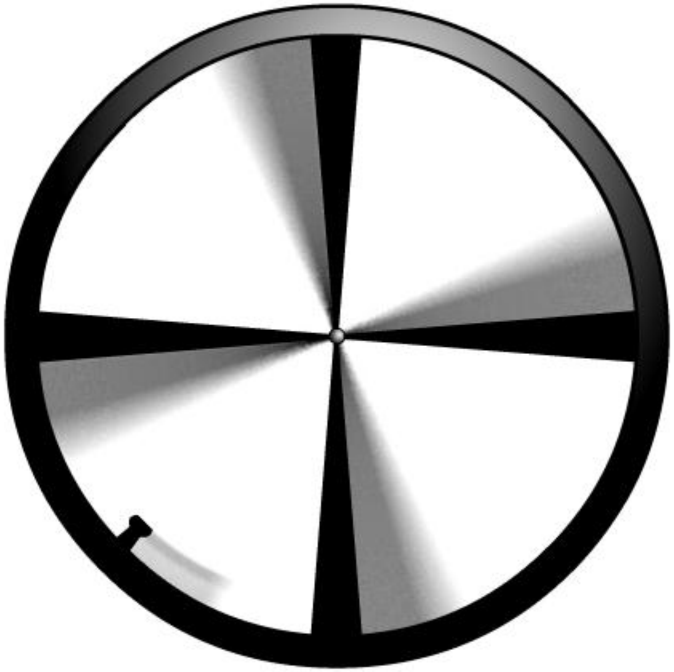


Cavity length 1 m	:	fits 10^6 optical waves	(10^{-6})
Finesse 10^5	:	error amplified by 10^5	(10^{-11})
Division of a cycle	:	10^5	(10^{-16})

But wait, how do you count so fast?

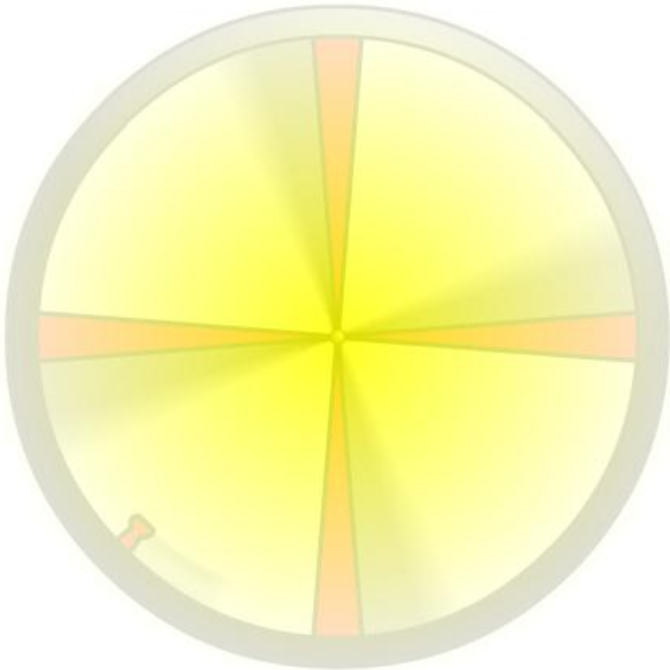


But wait, how do you count so fast?



But wait, how do you count so fast?

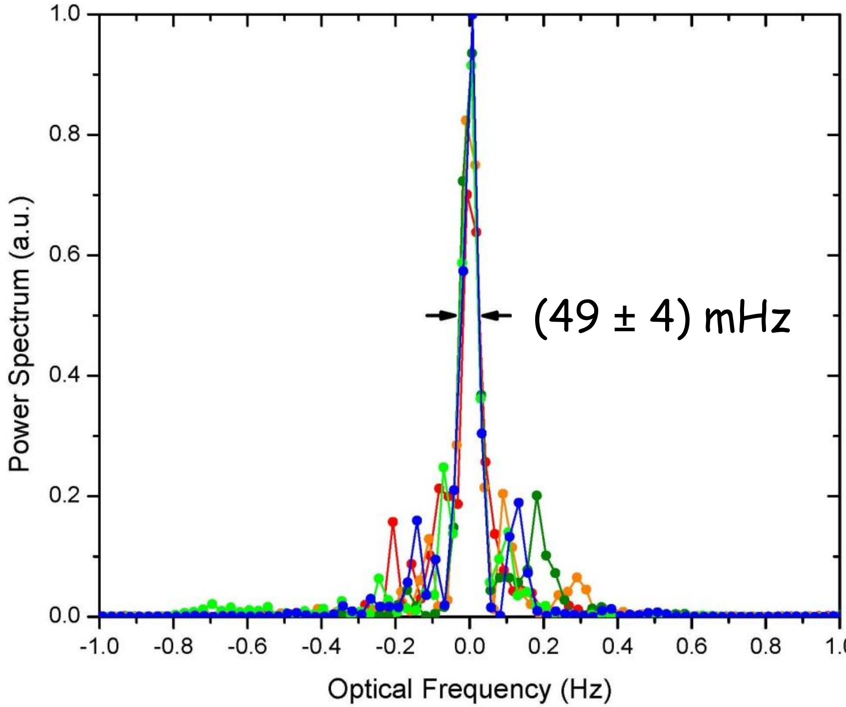
Something runs equally as fast, and very stable!

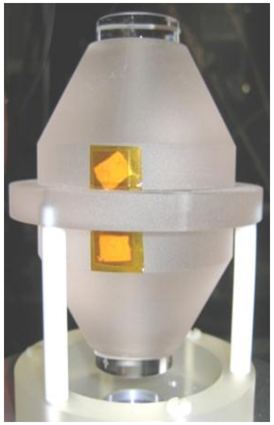


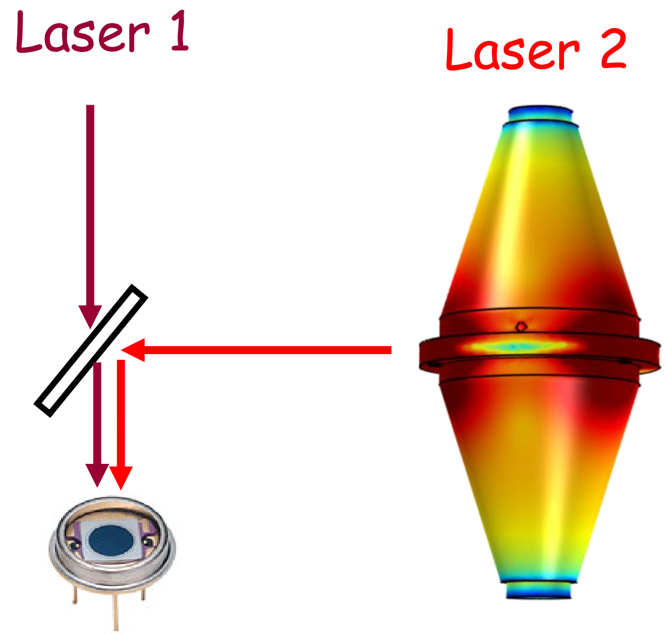
Coherence – how long a wave lasts

~10 s

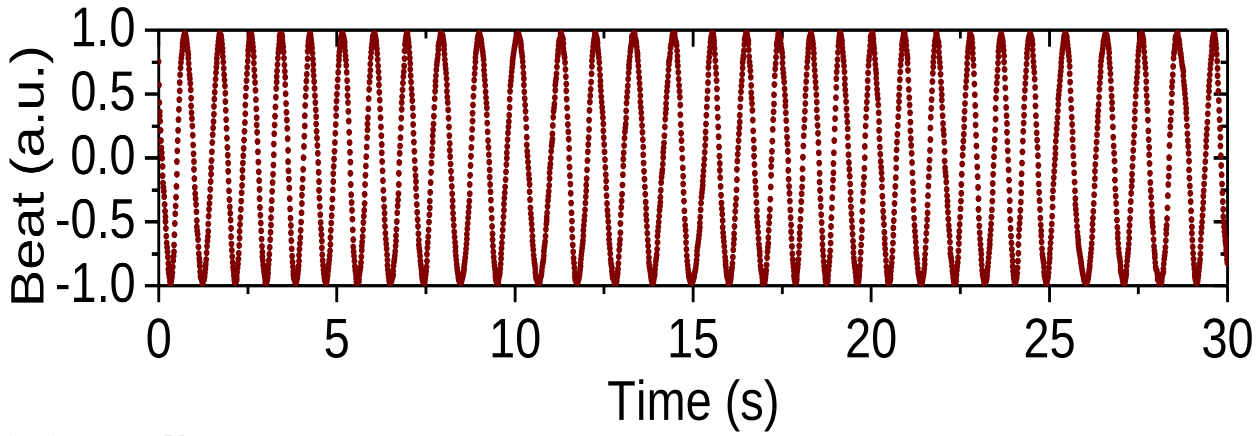
Beating of two optical waves (10^{15} Hz)





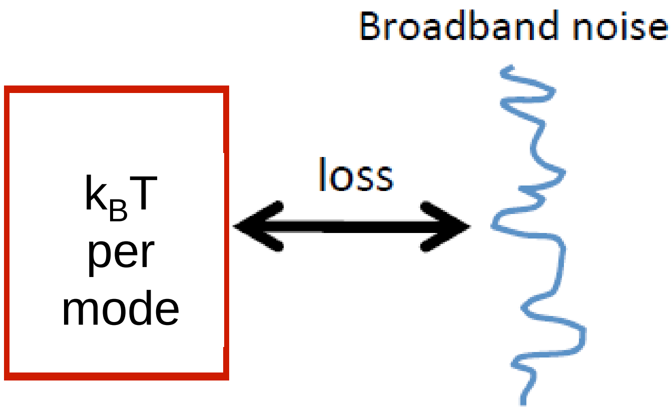


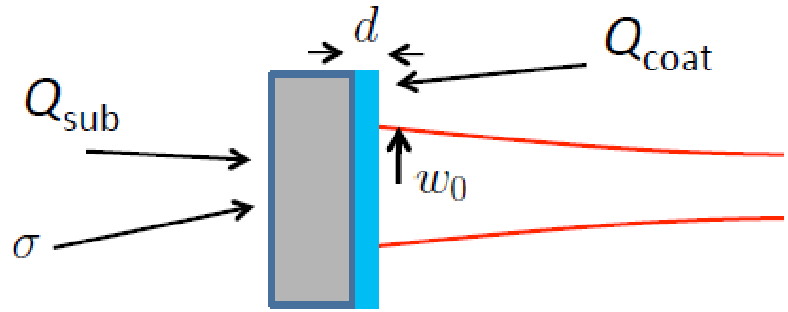
Counting the light ripple (10^{15} Hz)



Mirror thermal noise

Complex (lossy) Young's modulus: $E(\omega) = E_0 [1 + i\phi(\omega)]$



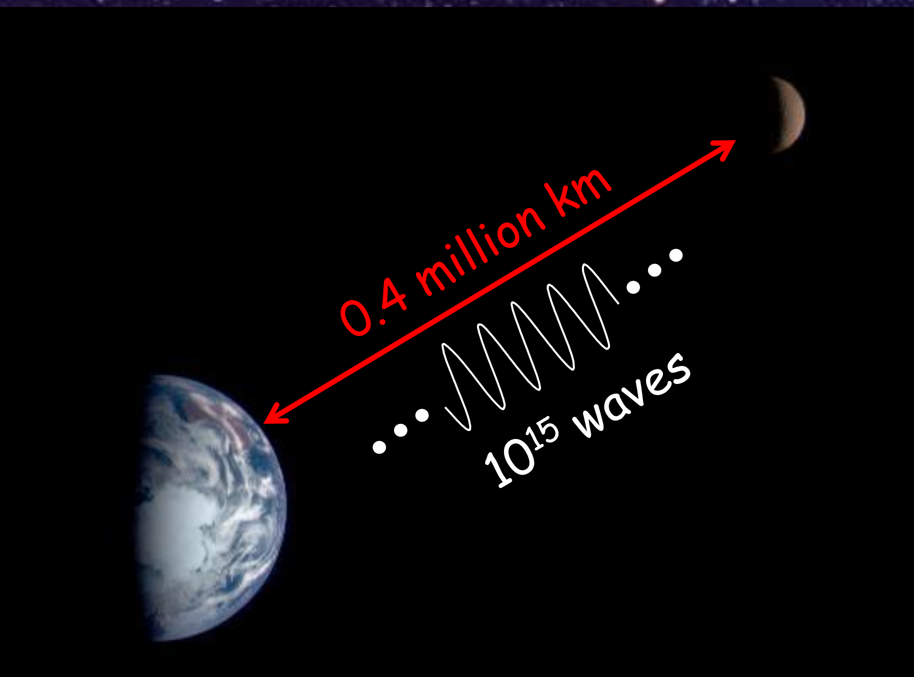


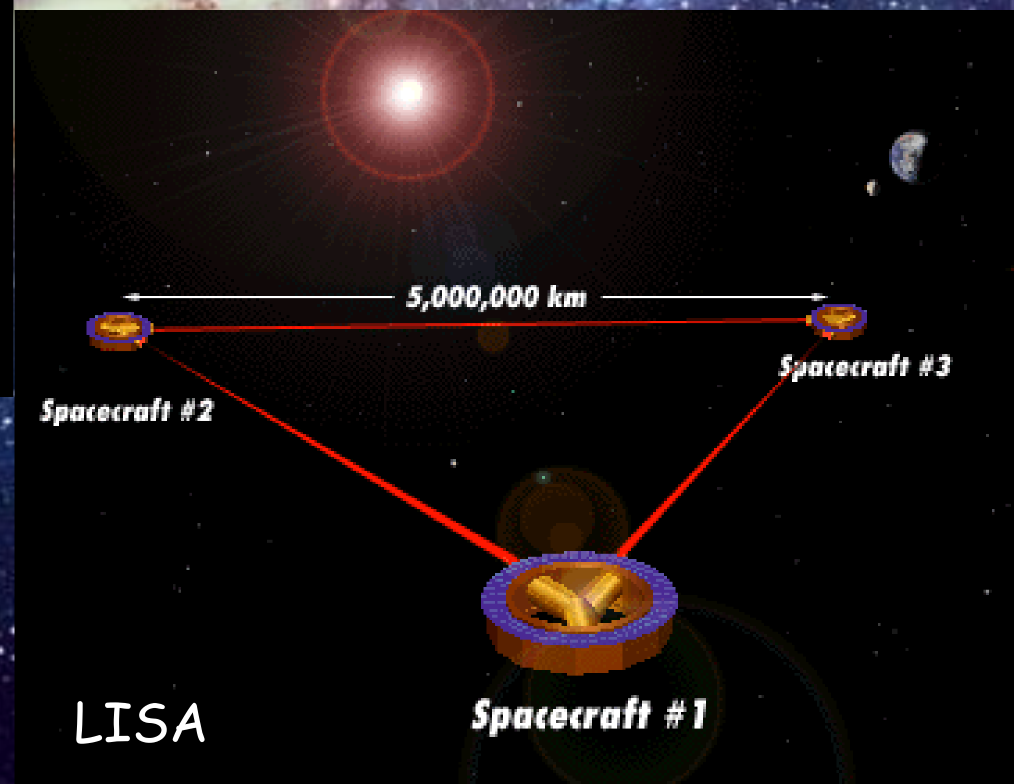
$$S_{x,\,mirror} \simeq \frac{4k_B T}{\omega} \frac{1-\sigma^2}{\sqrt{\pi} E w_0} \phi_{sub} \left(1 + \frac{2}{\sqrt{\pi}} \frac{1-2\sigma}{1-\sigma} \frac{\phi_{coat}}{\phi_{sub}} \frac{d}{w_0}\right)$$

Y. Levin. ***PRD*** 57, 659 (1997).
K. Numata et. al. ***PRL*** 93, (2004).
G. M. Harry et. al. ***Class. Quant. Grav***. 19, (2002).

Rulers for the Universe

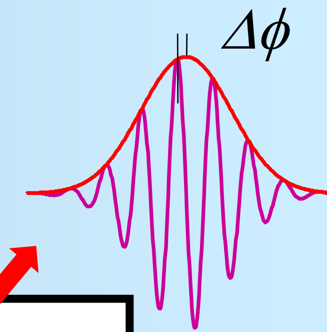
Testing the fundamental laws of Nature

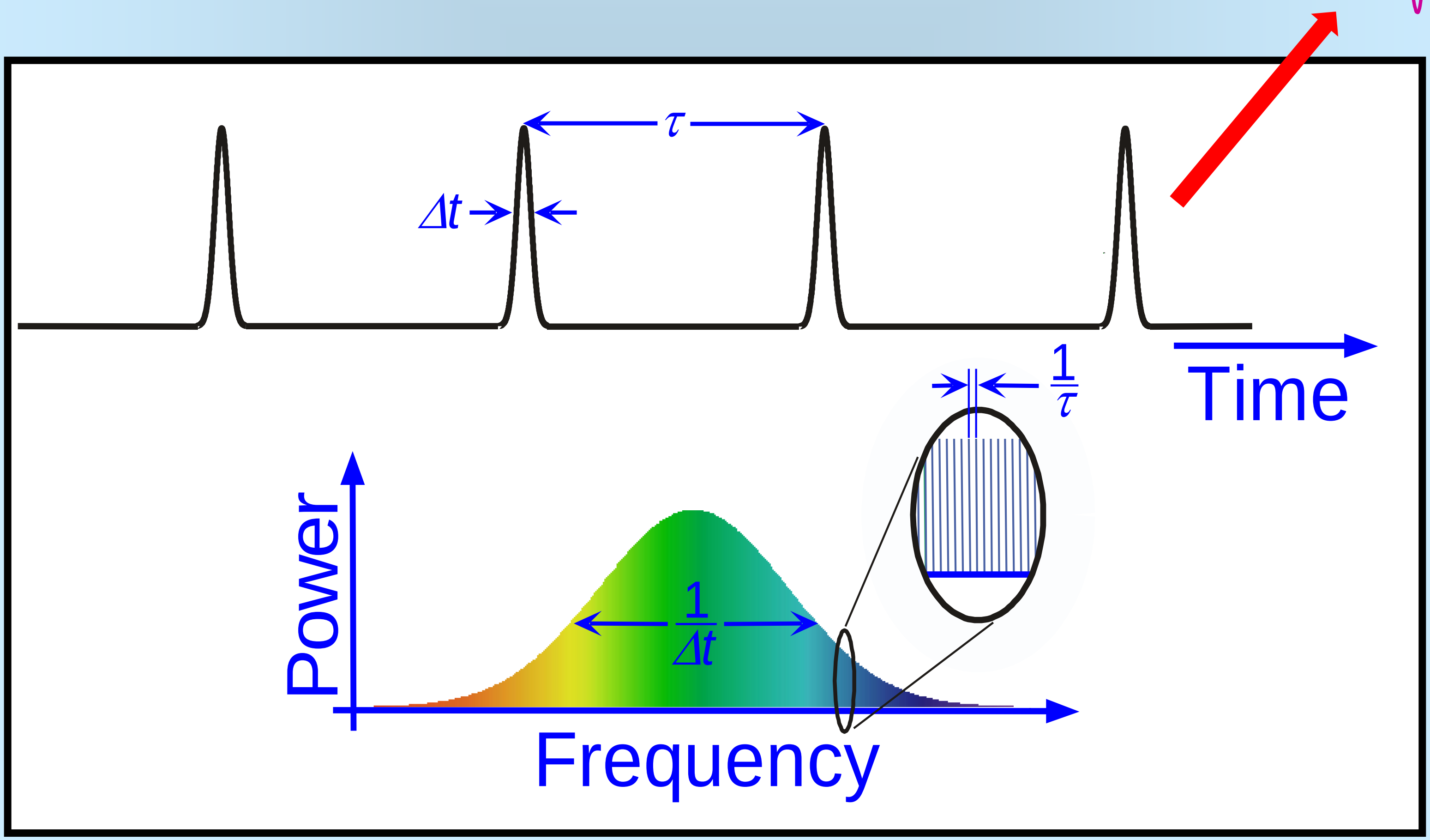




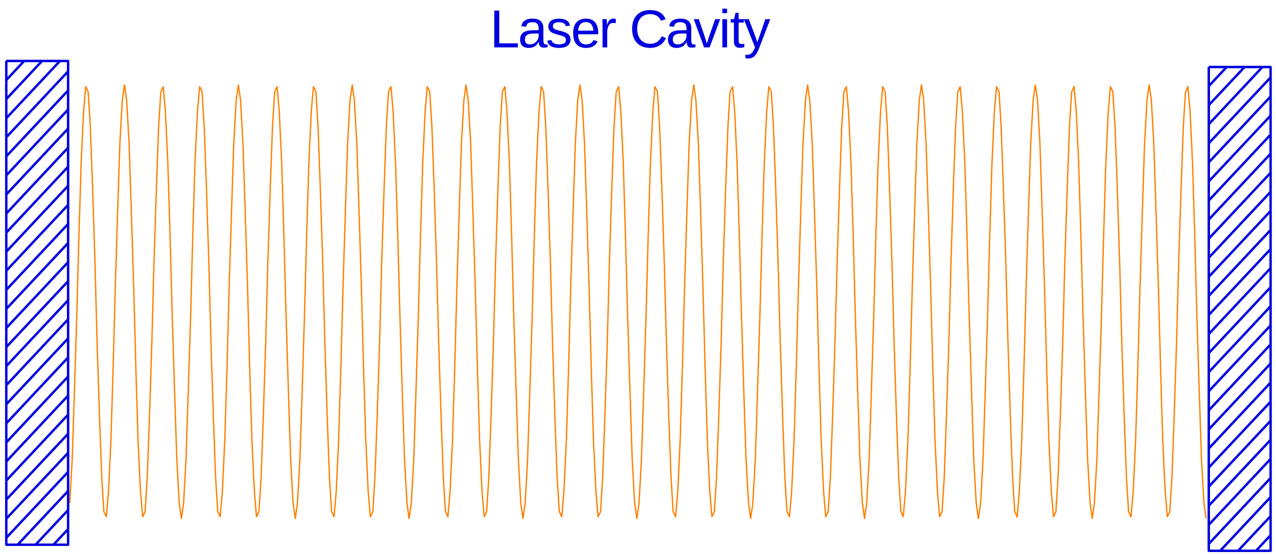
Time - frequency correspondence

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

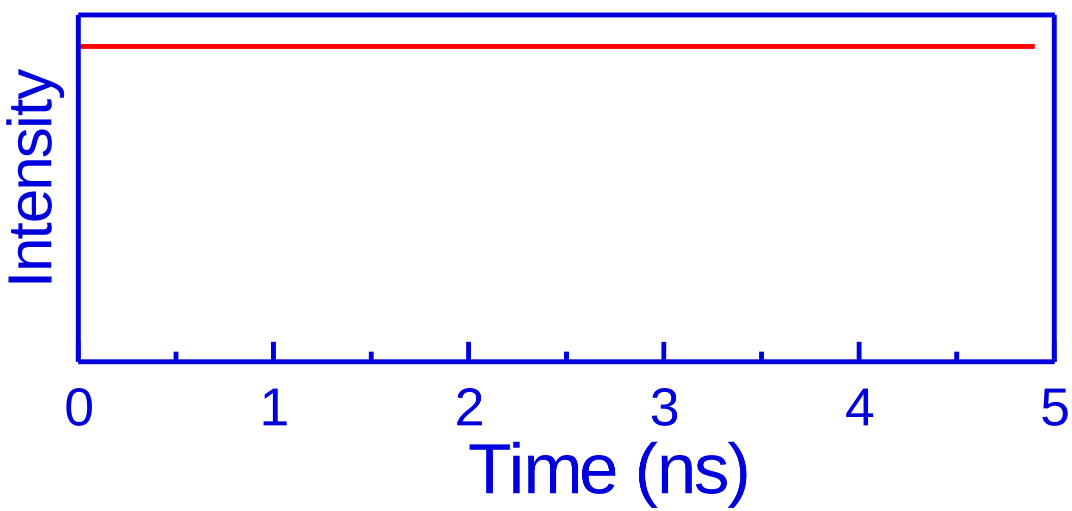




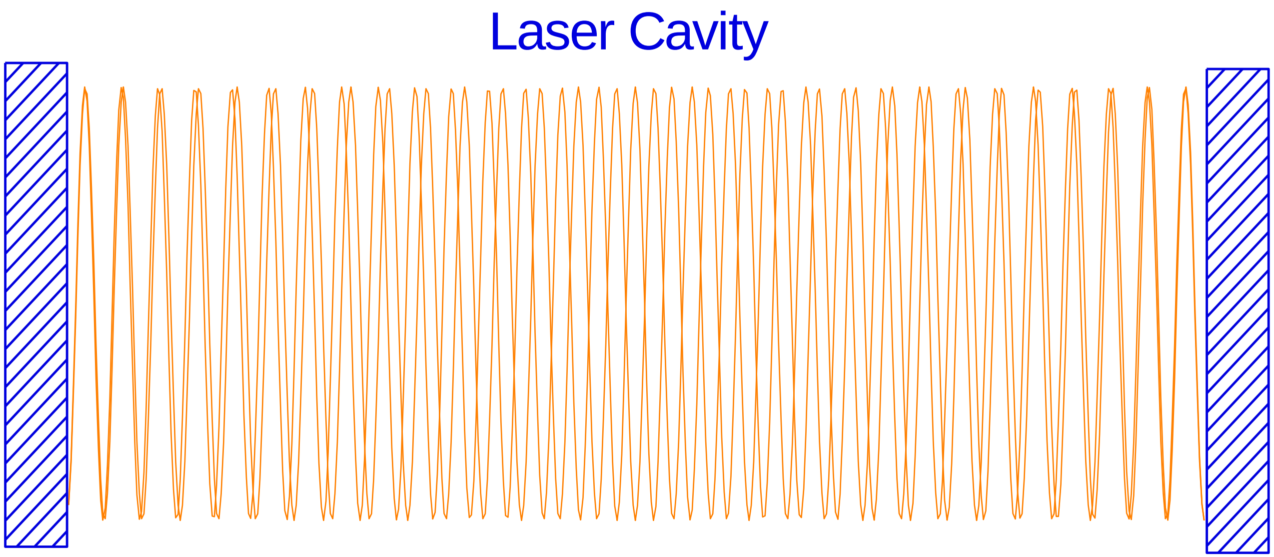
Modelocking



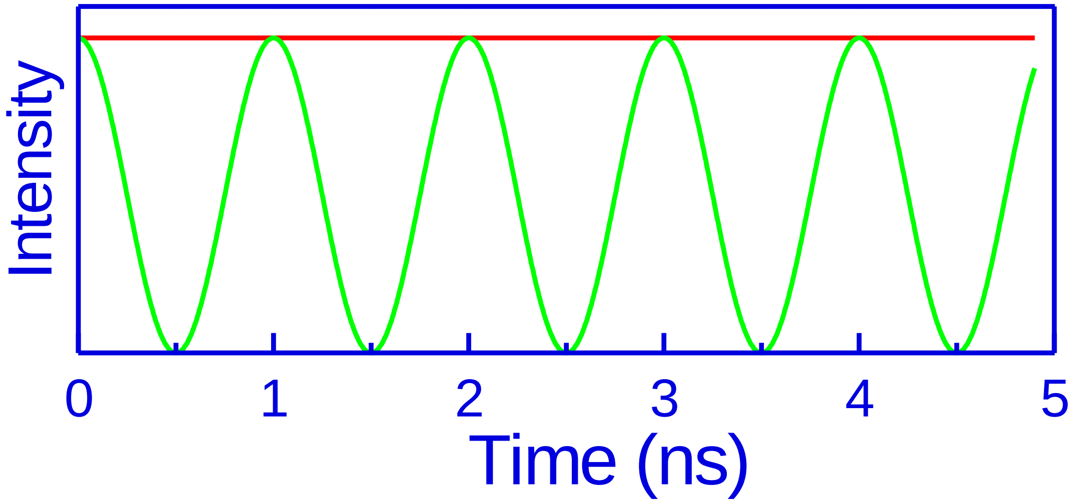
Single mode
cw laser



Modelocking

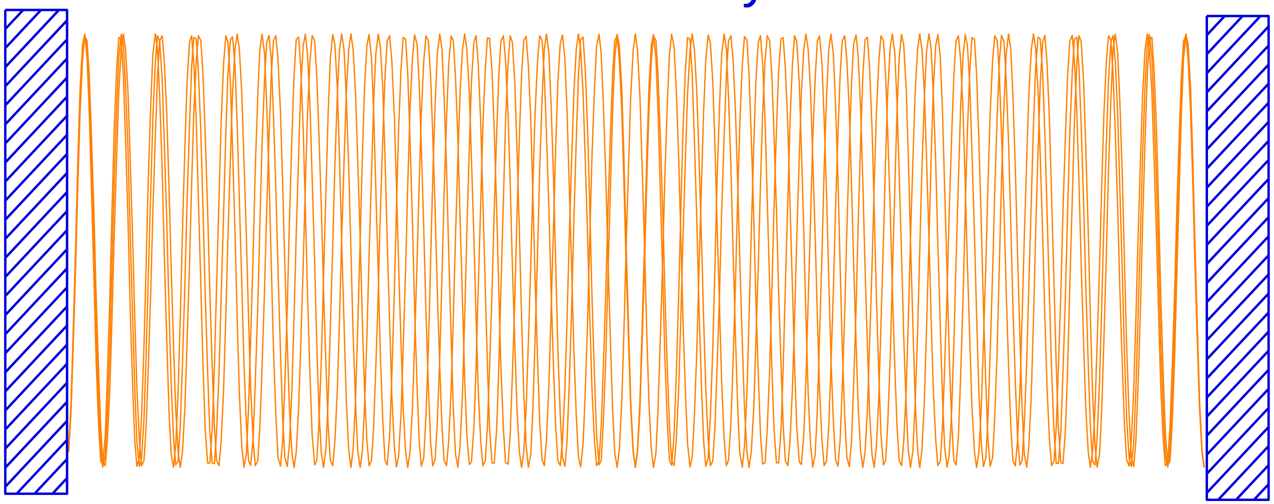


2 modes

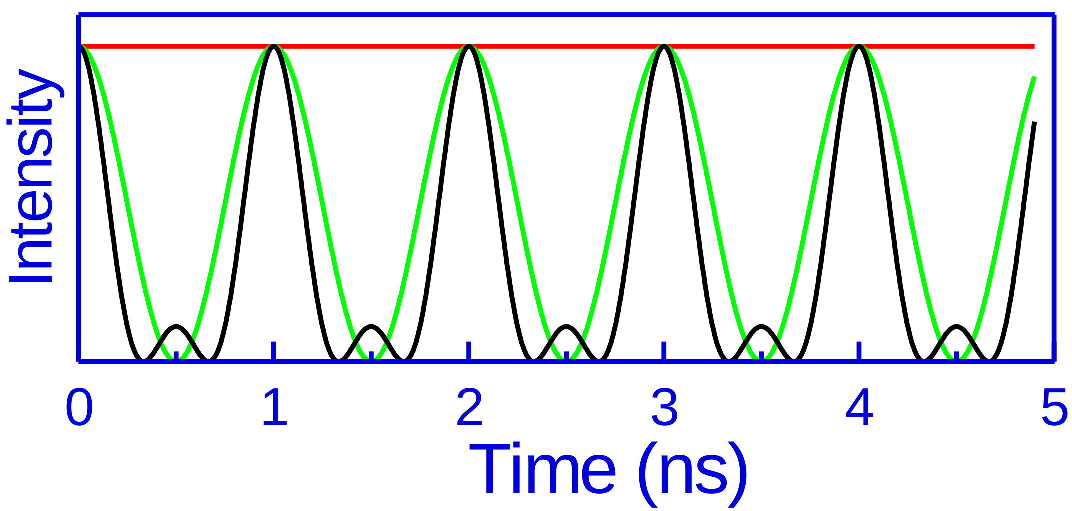


Modelocking

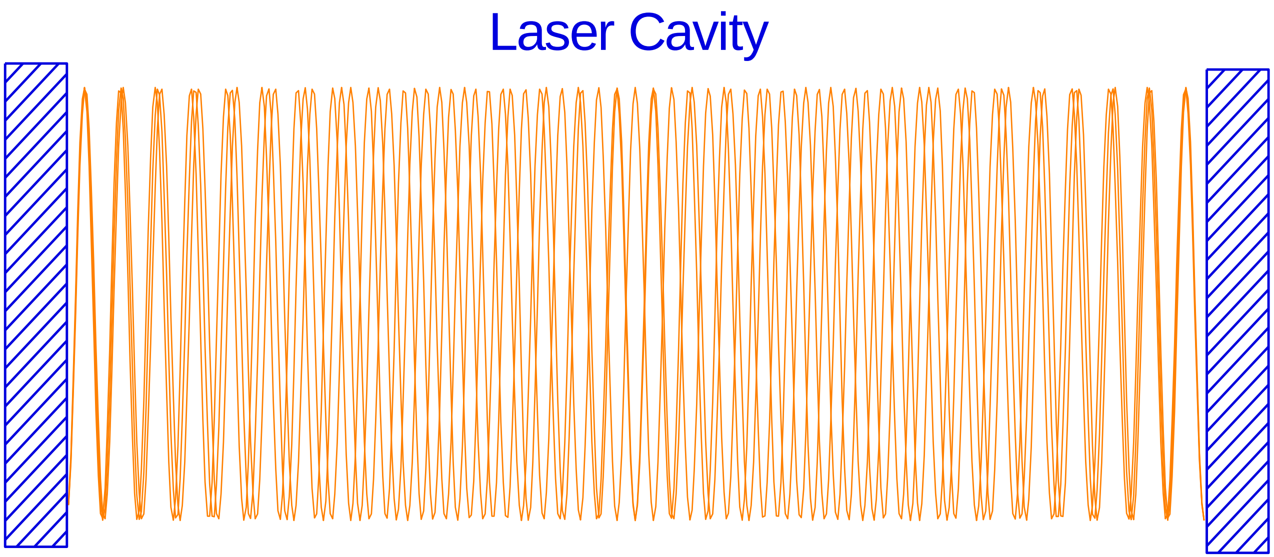
Laser Cavity



3 modes

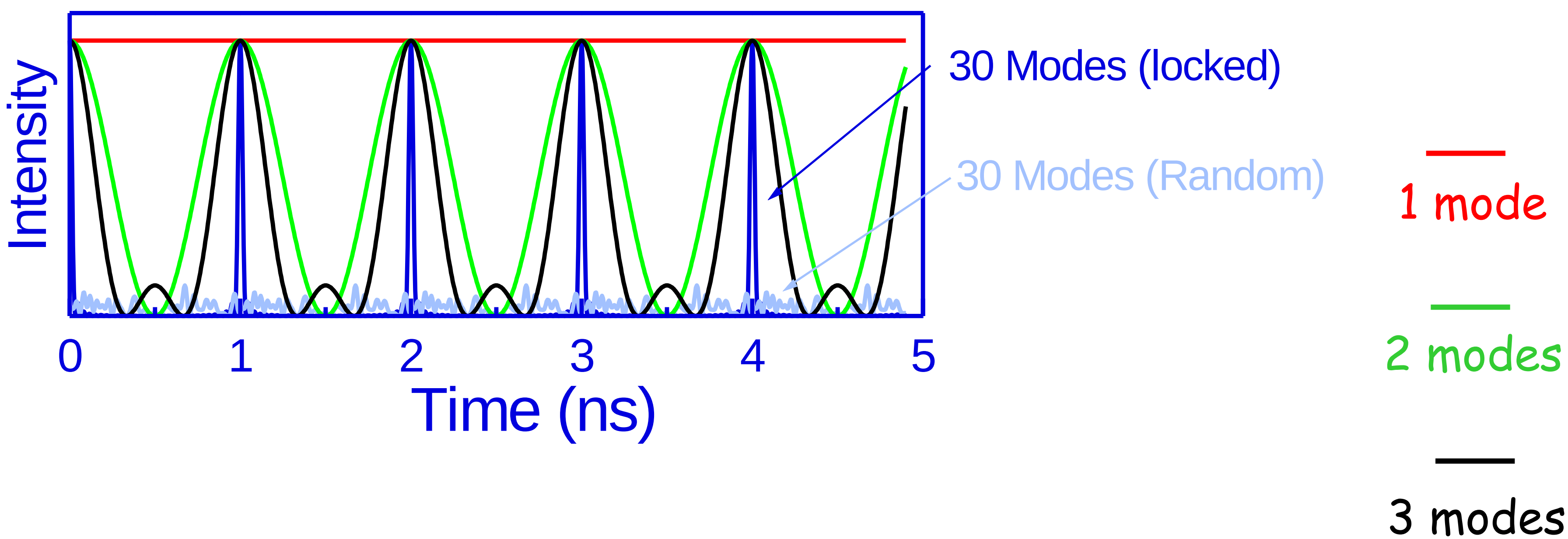


Modelocking

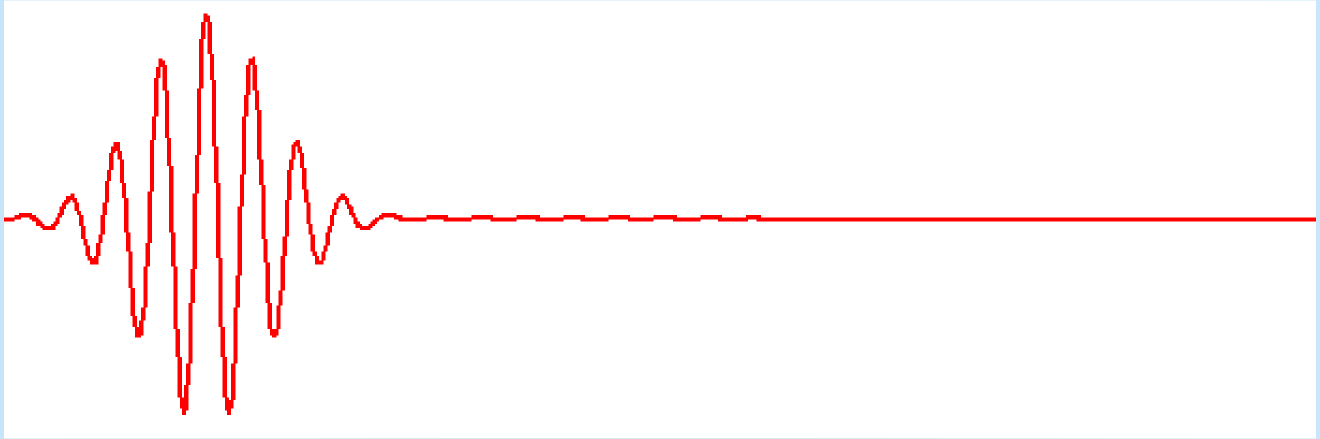


2 degrees of freedom:
- single-mode phase
- dispersion

Constructive interference among phase-locked cavity modes



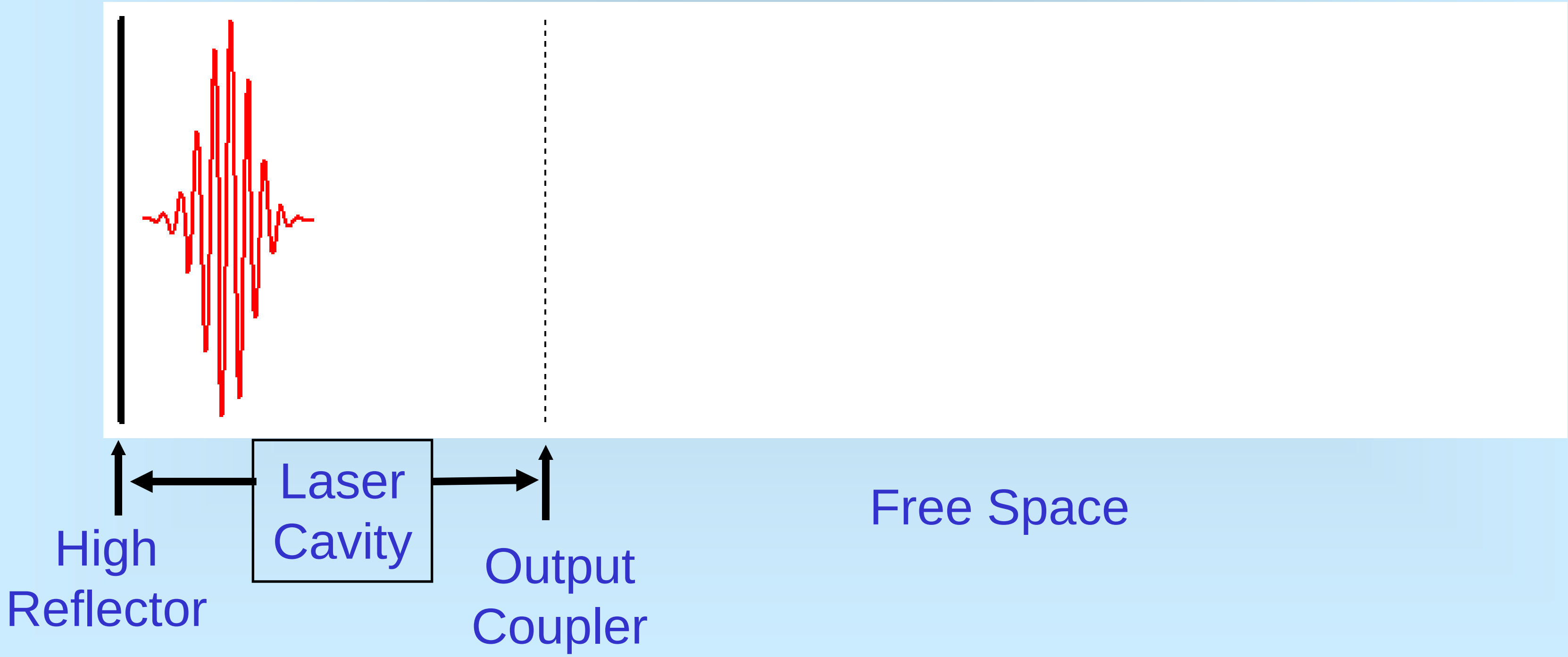
Group vs. Phase Velocity



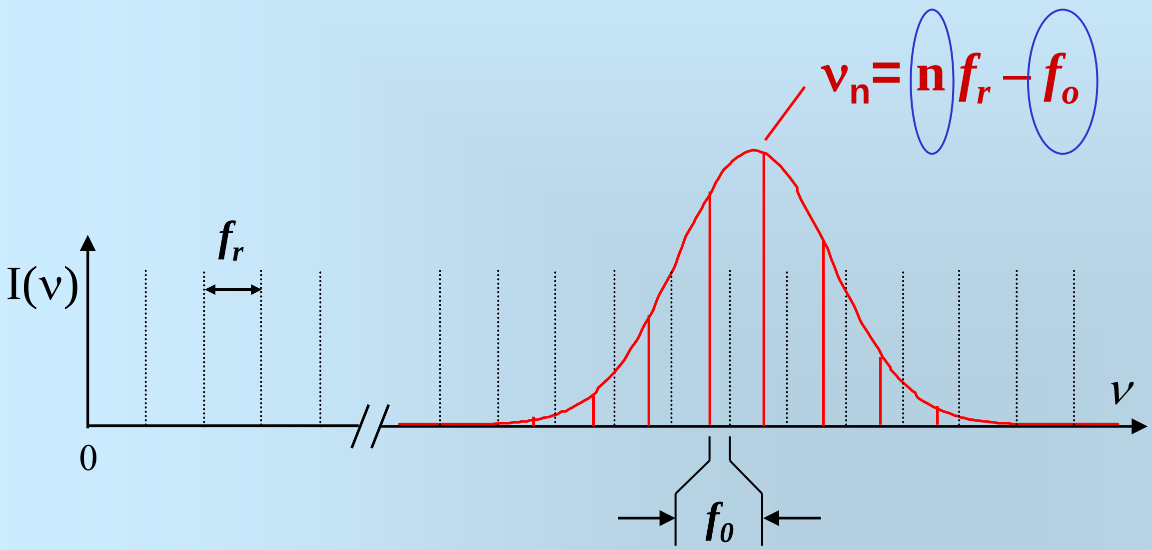
- In any material, the group and phase velocities differ
- Carrier phase slowly drifts through the envelope as a pulse propagates

Group vs. Phase in Modelocked Lasers

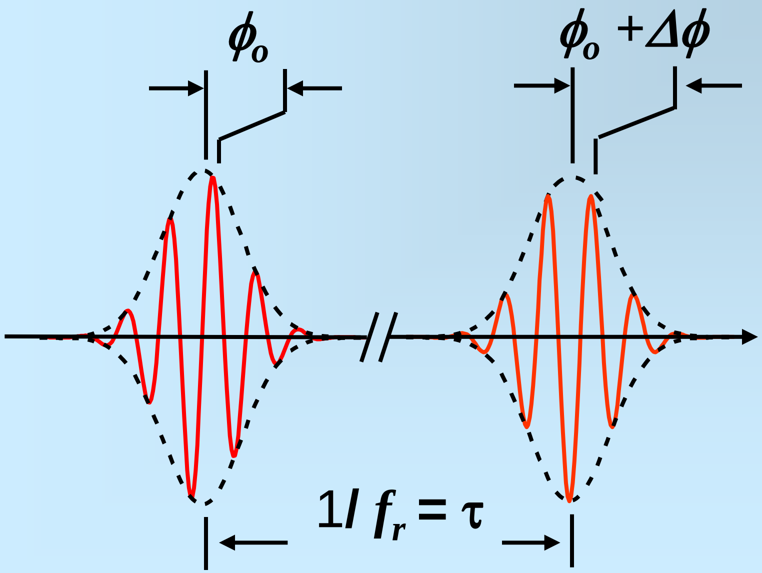
Each emitted pulse has a distinct envelope-carrier phase – due to group-phase velocity difference inside cavity



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

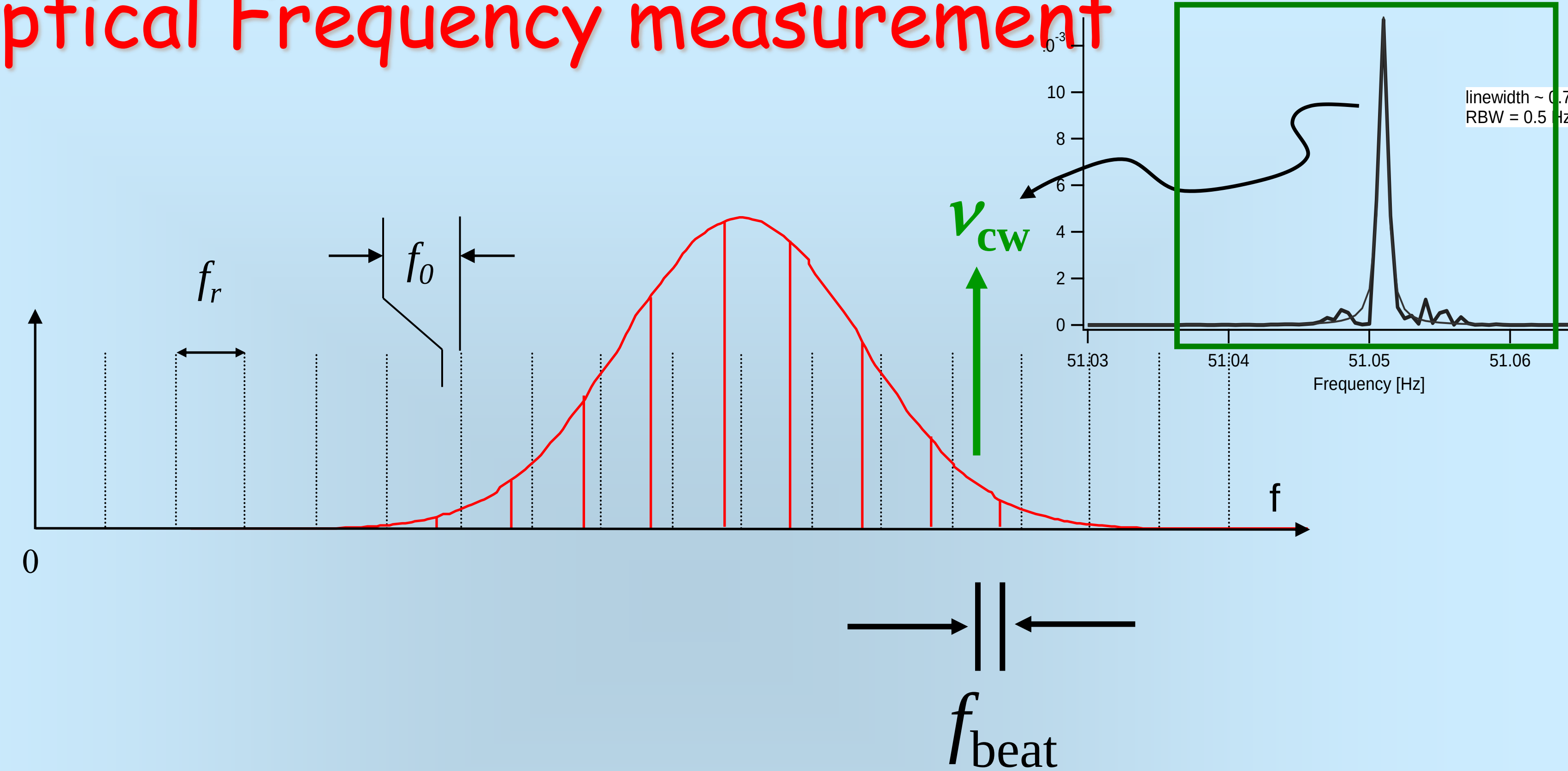


$$2\pi\nu_n \cdot \tau + \Delta\phi = 2n\pi \rightarrow$$

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

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



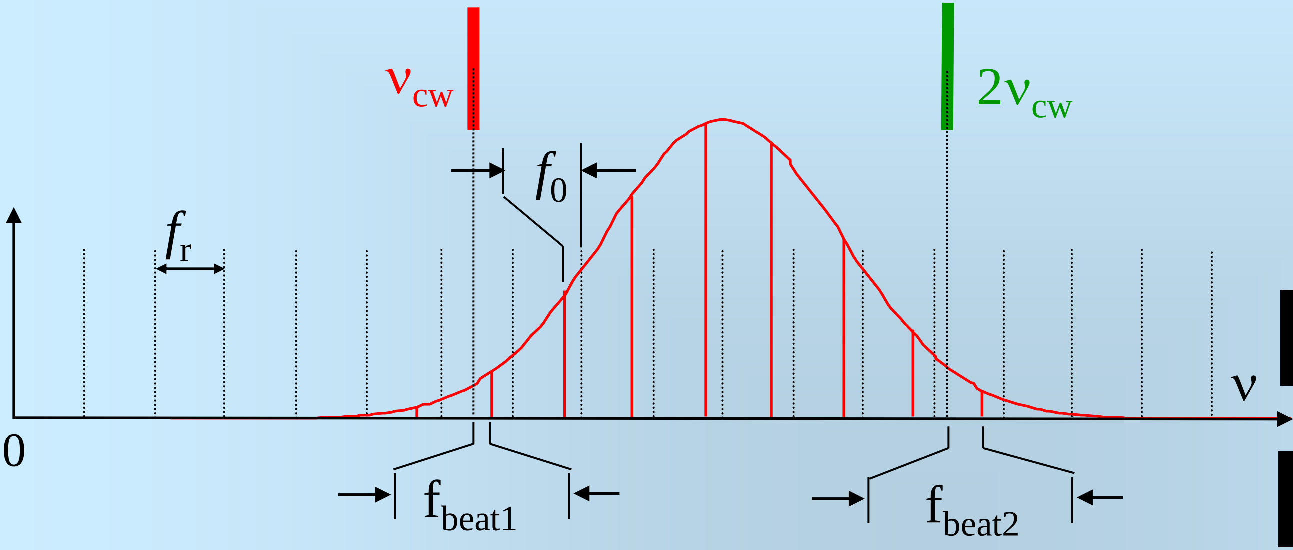
$$f_{\text{beat}} = n f_r + f_0 - \nu_{cw}$$

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

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

Optical octave bandwidth

- a quick way to measure and control f_0



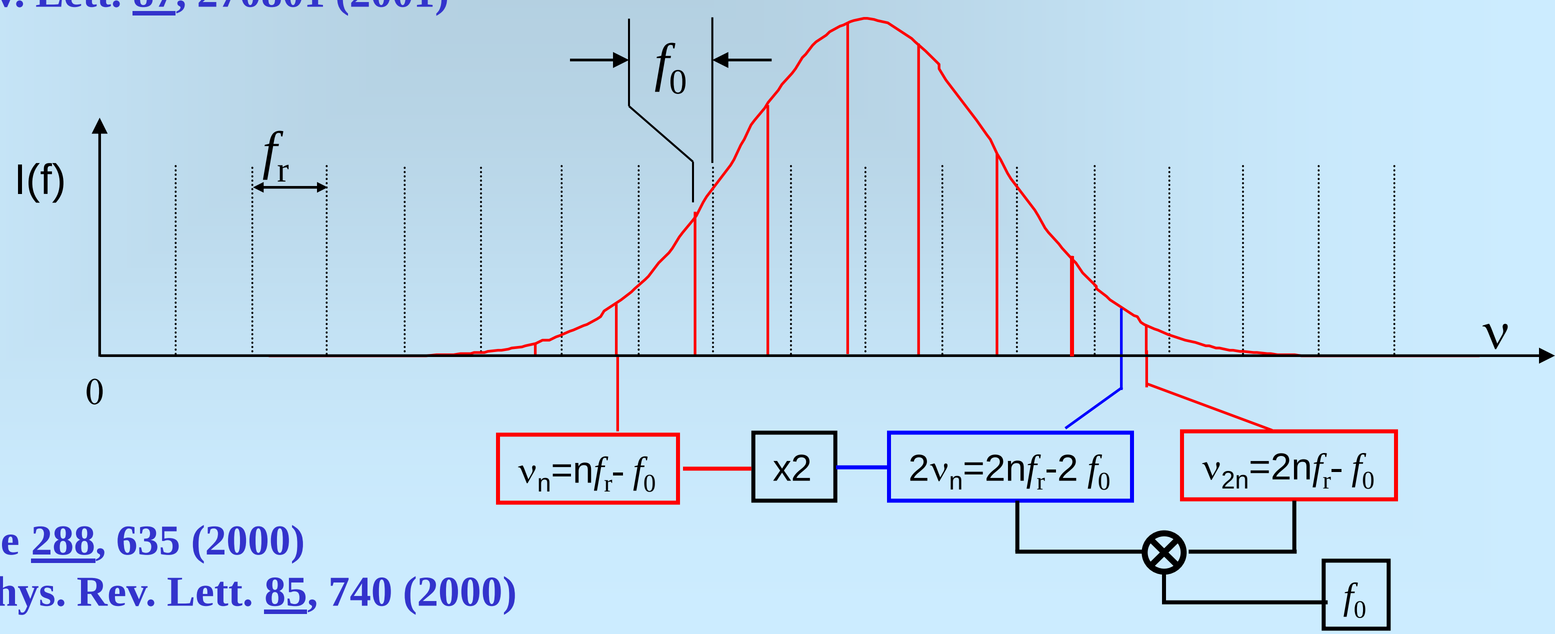
$$f_{beat1} = n f_r + f_0 - \nu_{cw}$$

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

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

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

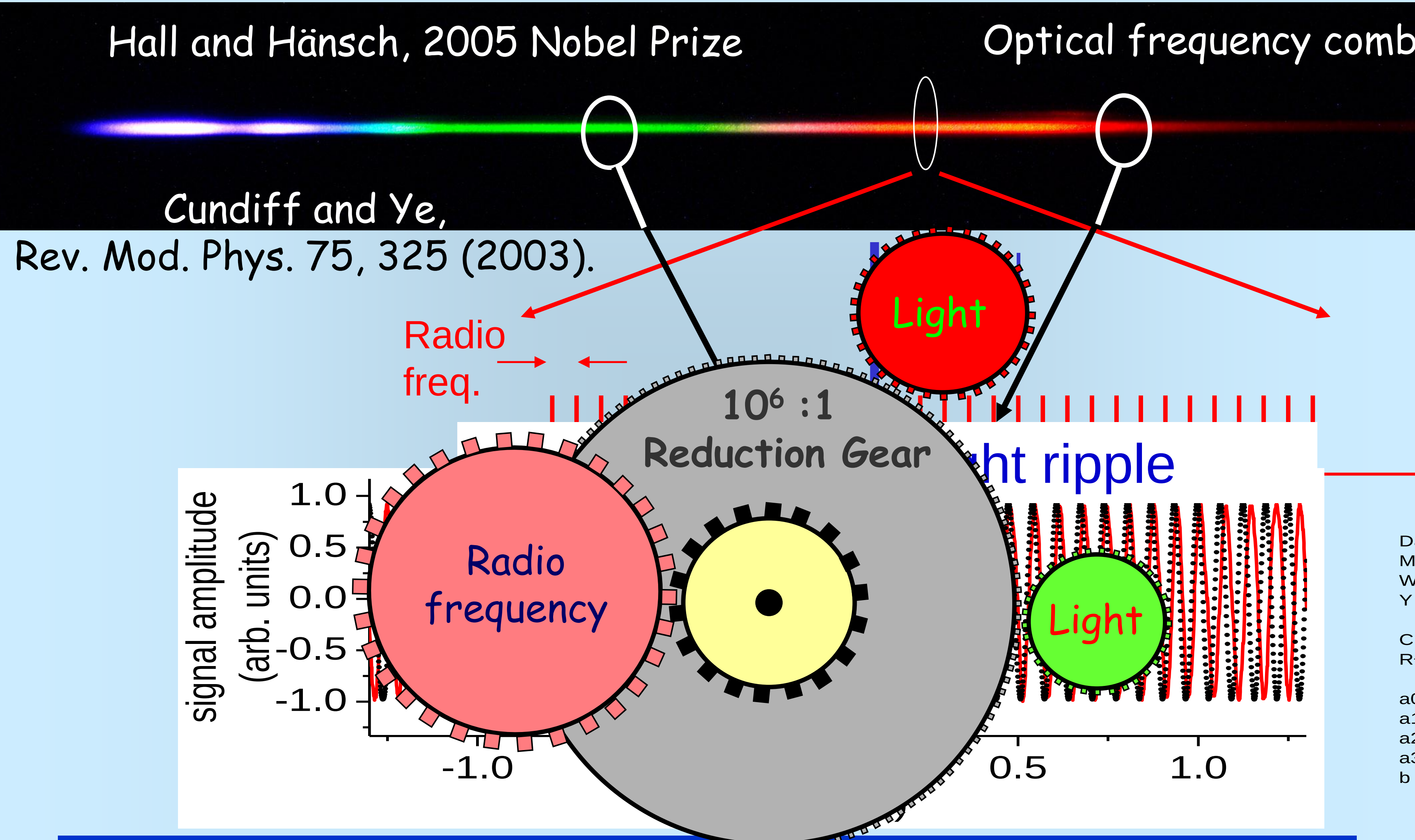
Ye *et al.*, Phys. Rev. Lett. 87, 270801 (2001)



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

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

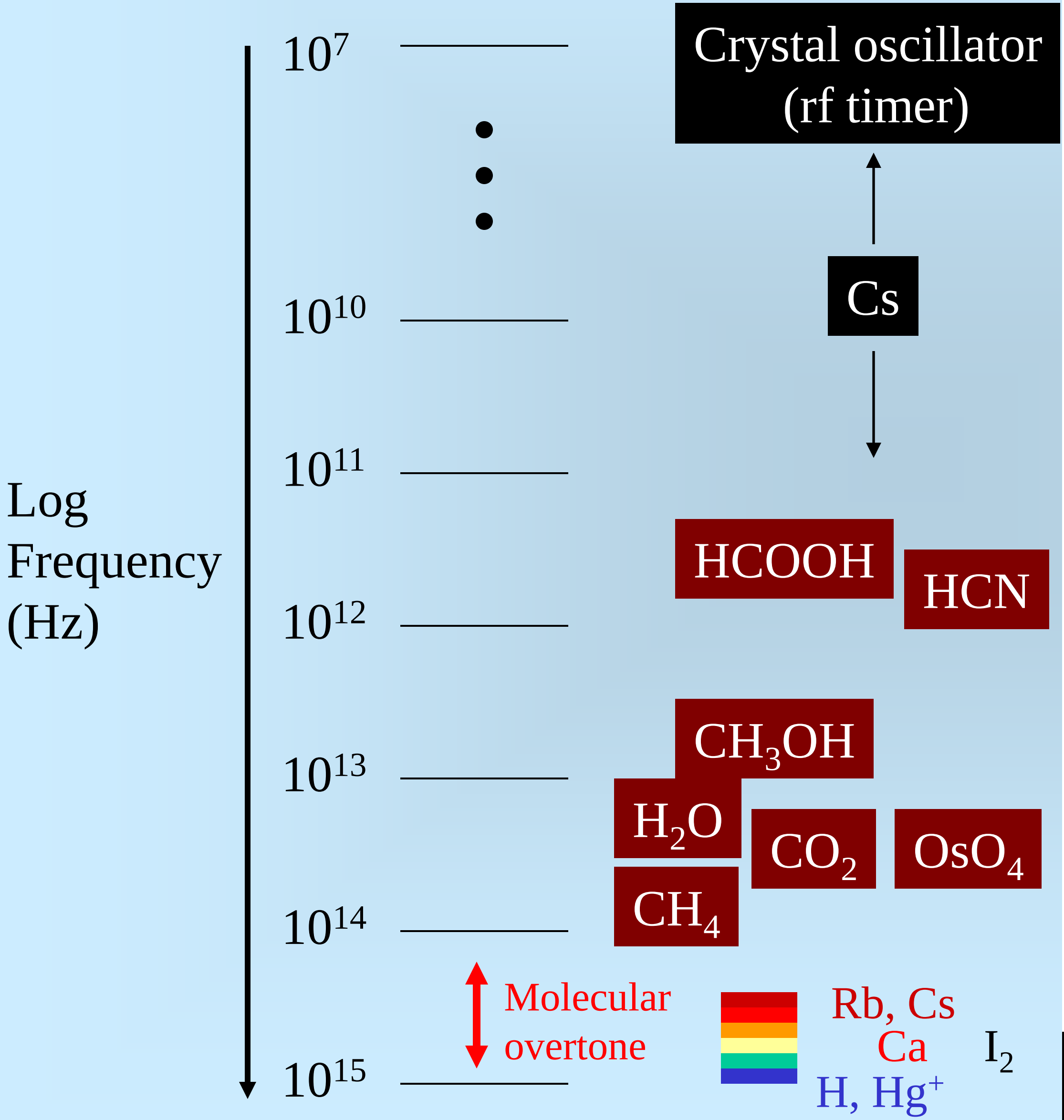
A rainbow spectrum with 10^{-19} precision

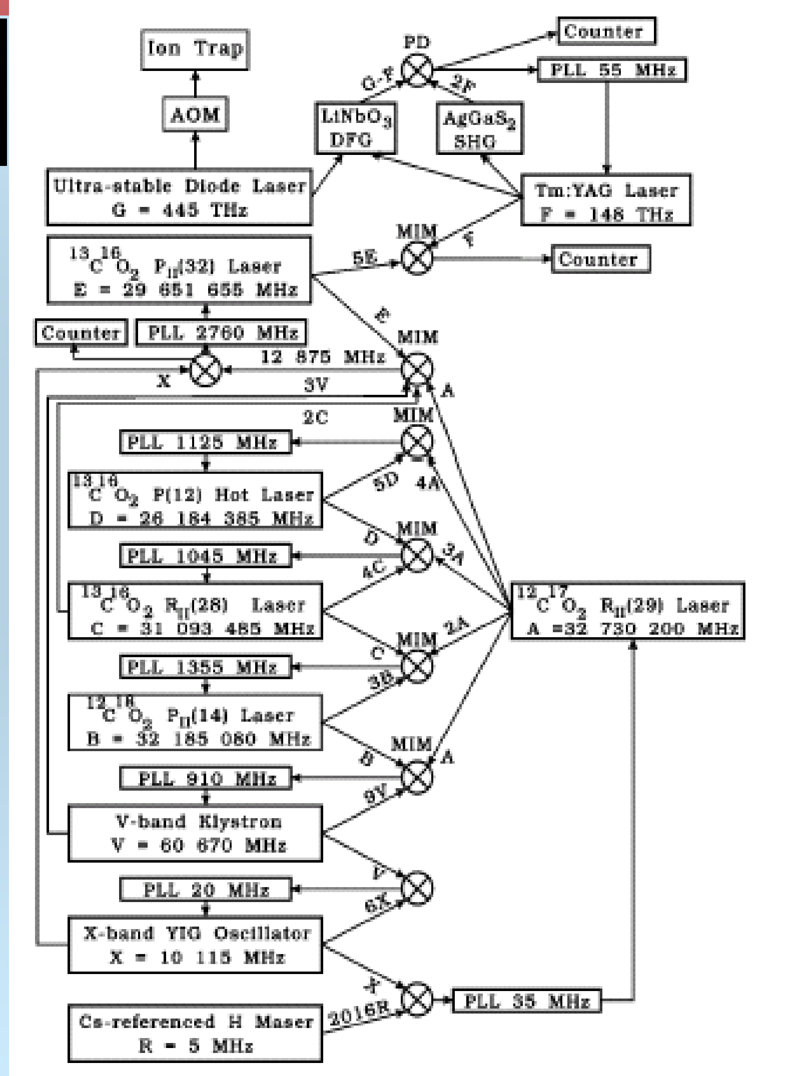


Optical coherence time > 1 s (<10^{-15}), anywhere in the visible

Schibli *et al.*, Nature Photonics 2, 355 (2008).

Frequency spectrum in optical frequency synthesis

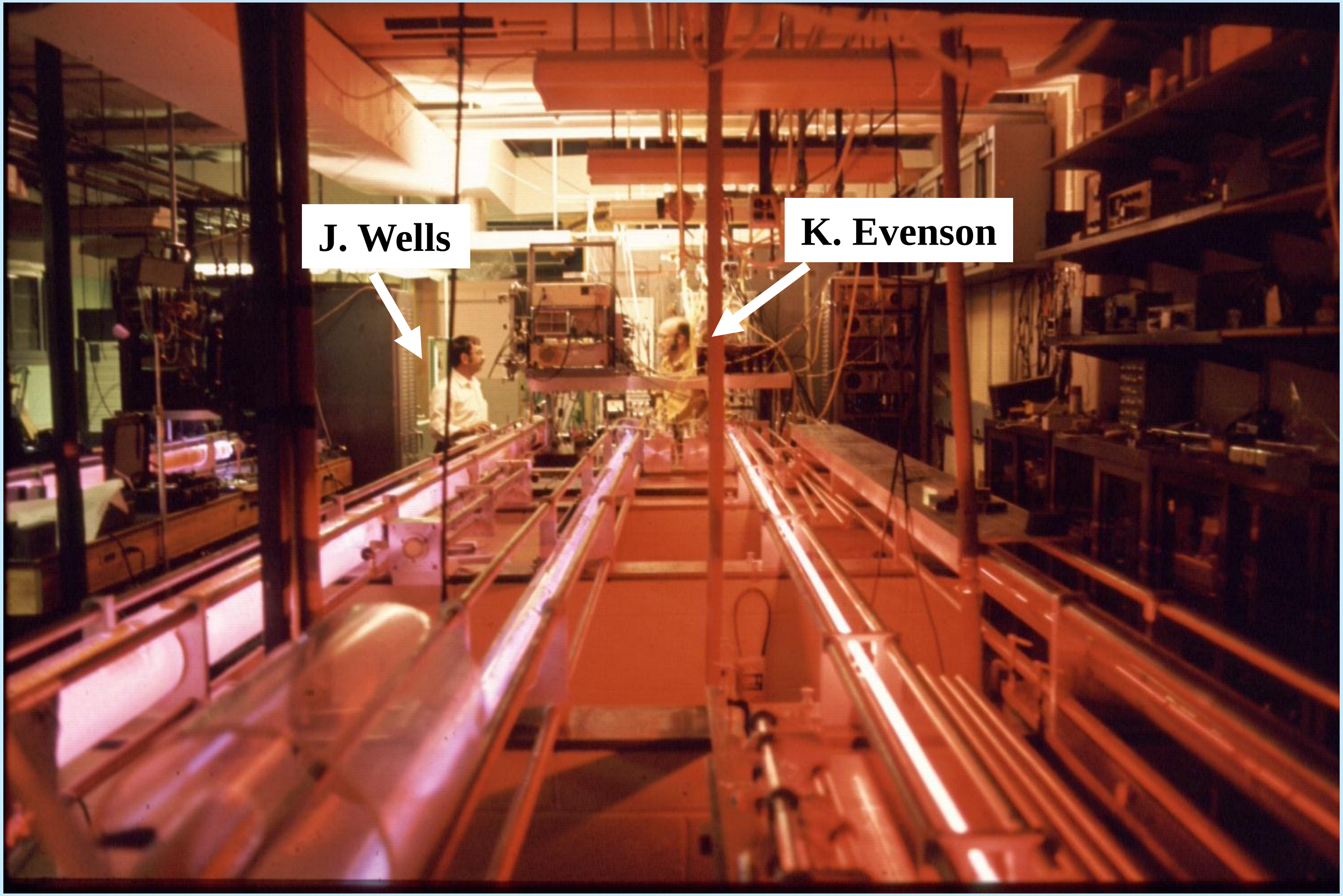




Harmonic frequency chains, PTB, NRC, …
H. Schnatz *et al*., PRL **76**, 18 (1996).

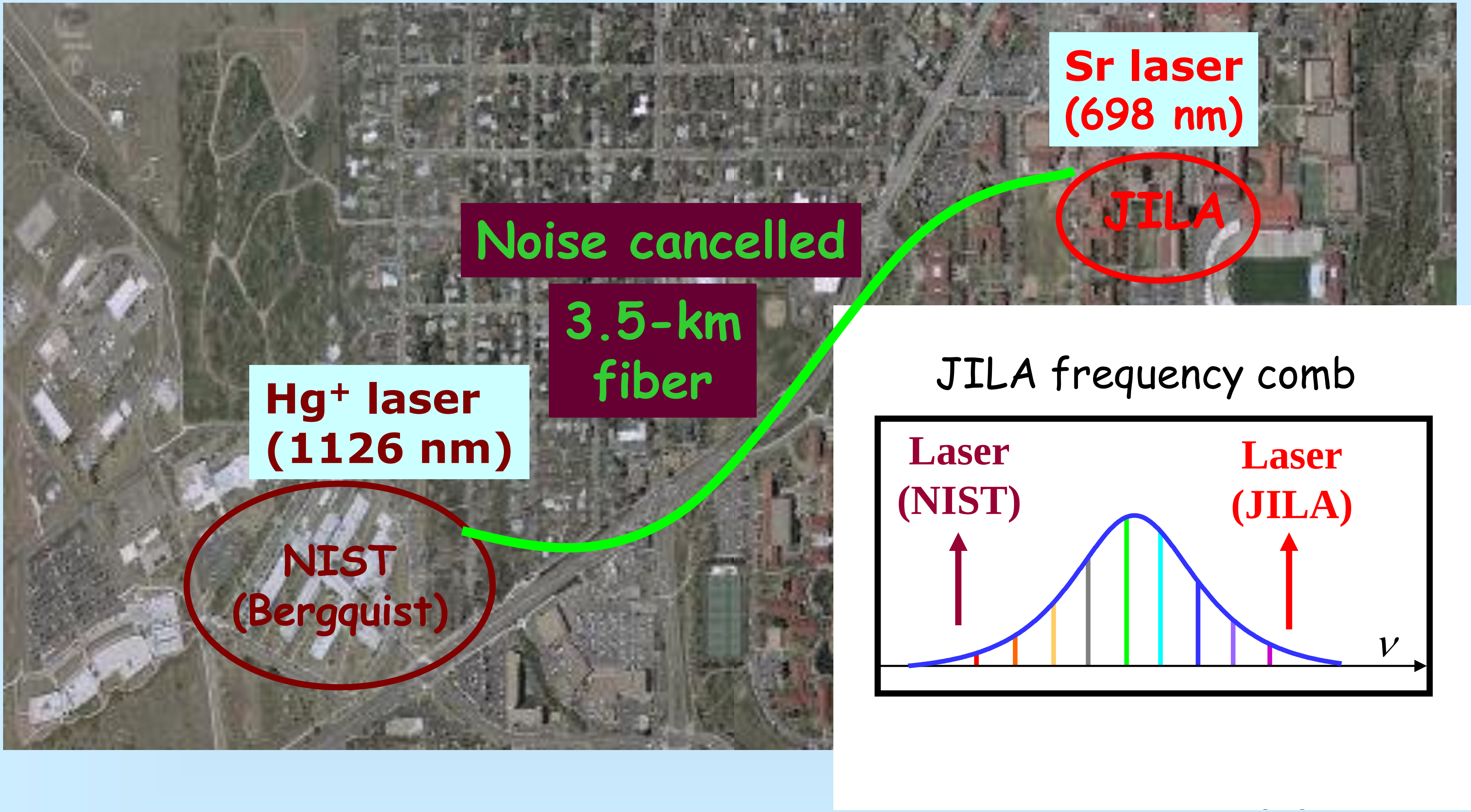
The First Optical Frequency Chain

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



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

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

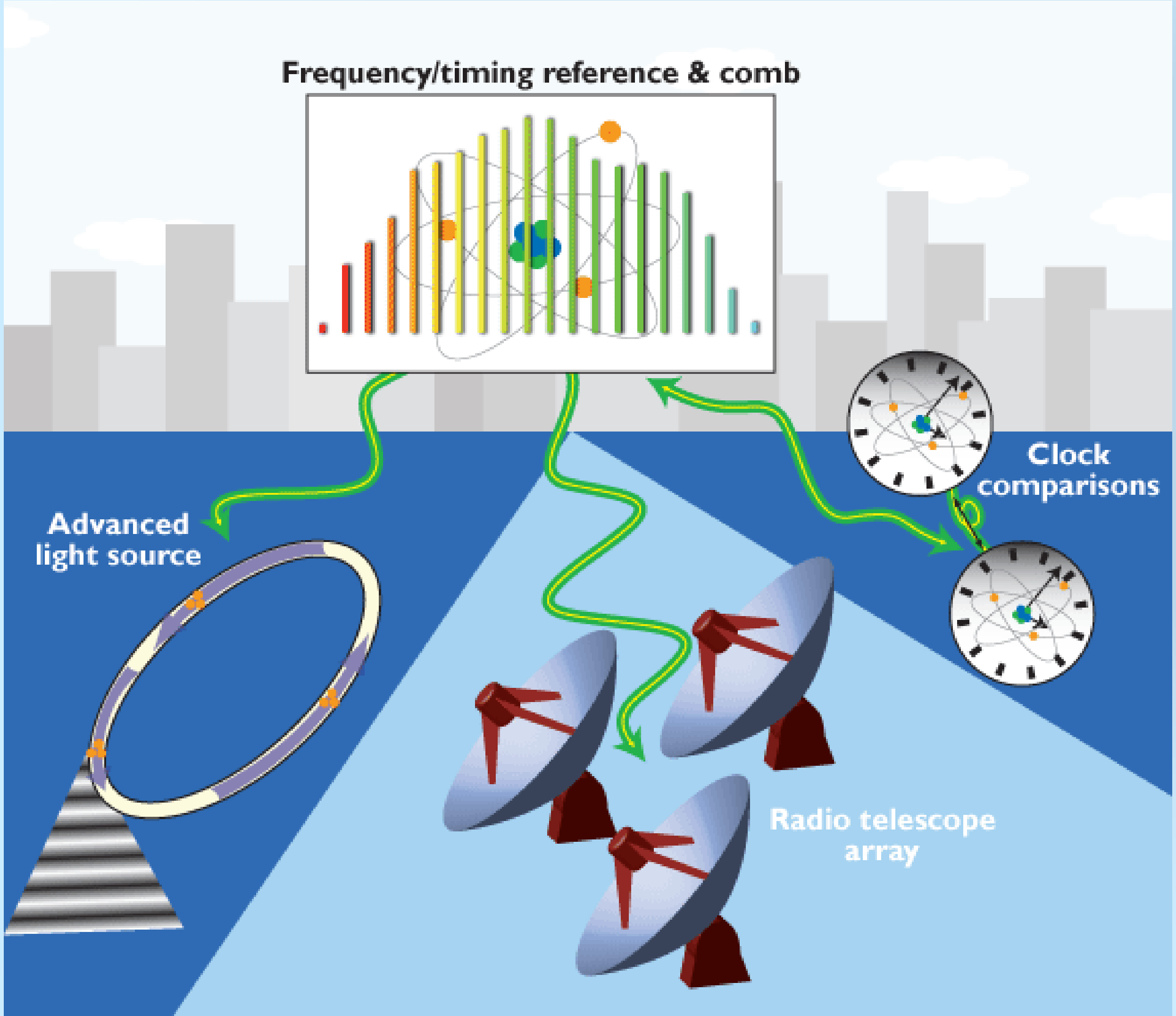


Foreman et al., Phys. Rev. Lett. 99, 153601 (2007).

Precise distribution of ultra-stable signals

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

SYRTE, NIST, ...



100 km fiber:

1×10^{-17} @ 1 s;

1 Hz optical linewidth;

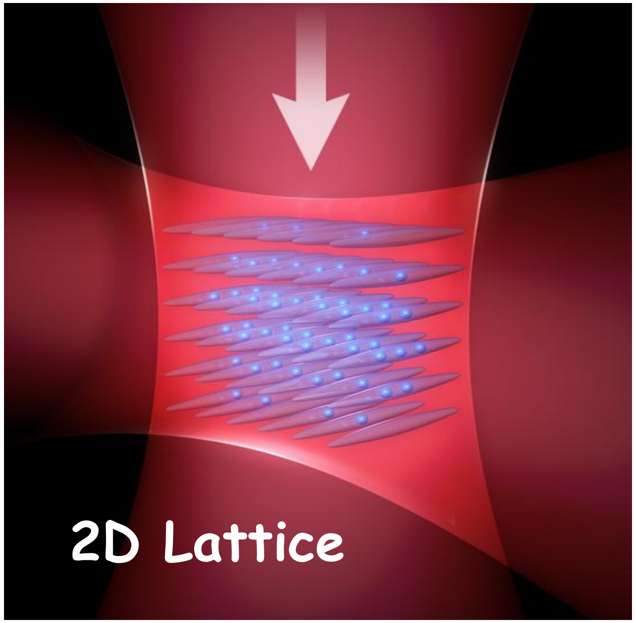
0.1 fs jitter (20 MHz BW)

Optical lattice - a many-body quantum system

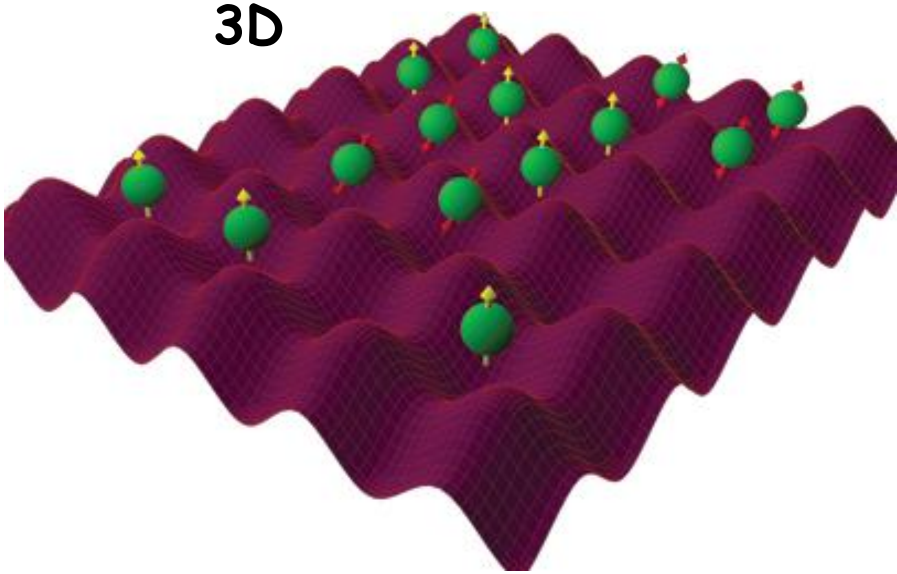
Science **331**, 1043 (2011)

- ✓ Engineered quantum states → eliminating motional effects
- ✓ Separation of internal and external degrees of freedom
- ✓ Isolation from environment
- ✓ Long coherence times
- ✓ Large atom numbers to increase signal and accuracy

1D Lattice



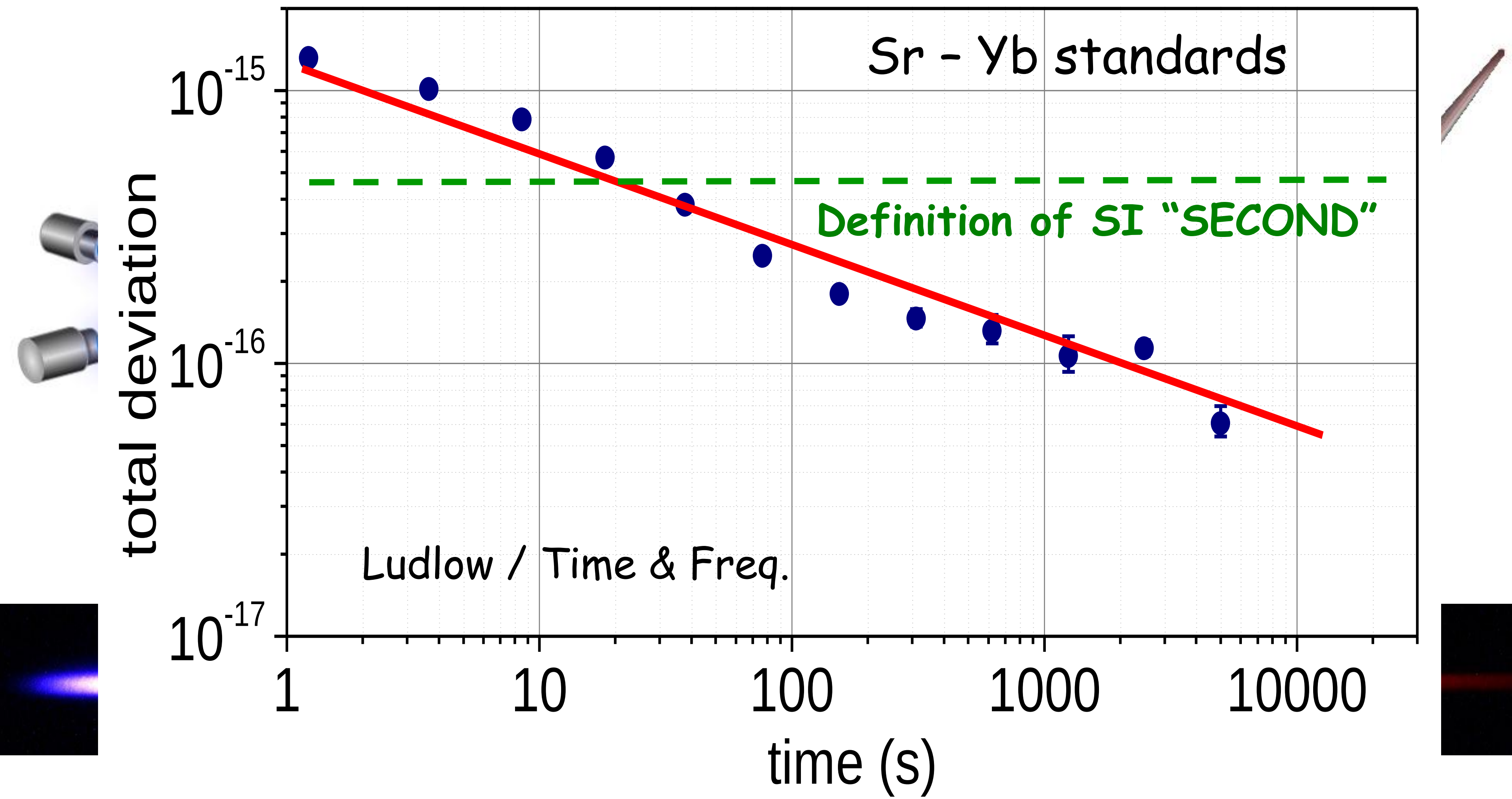
3D



JILA Sr atomic clock

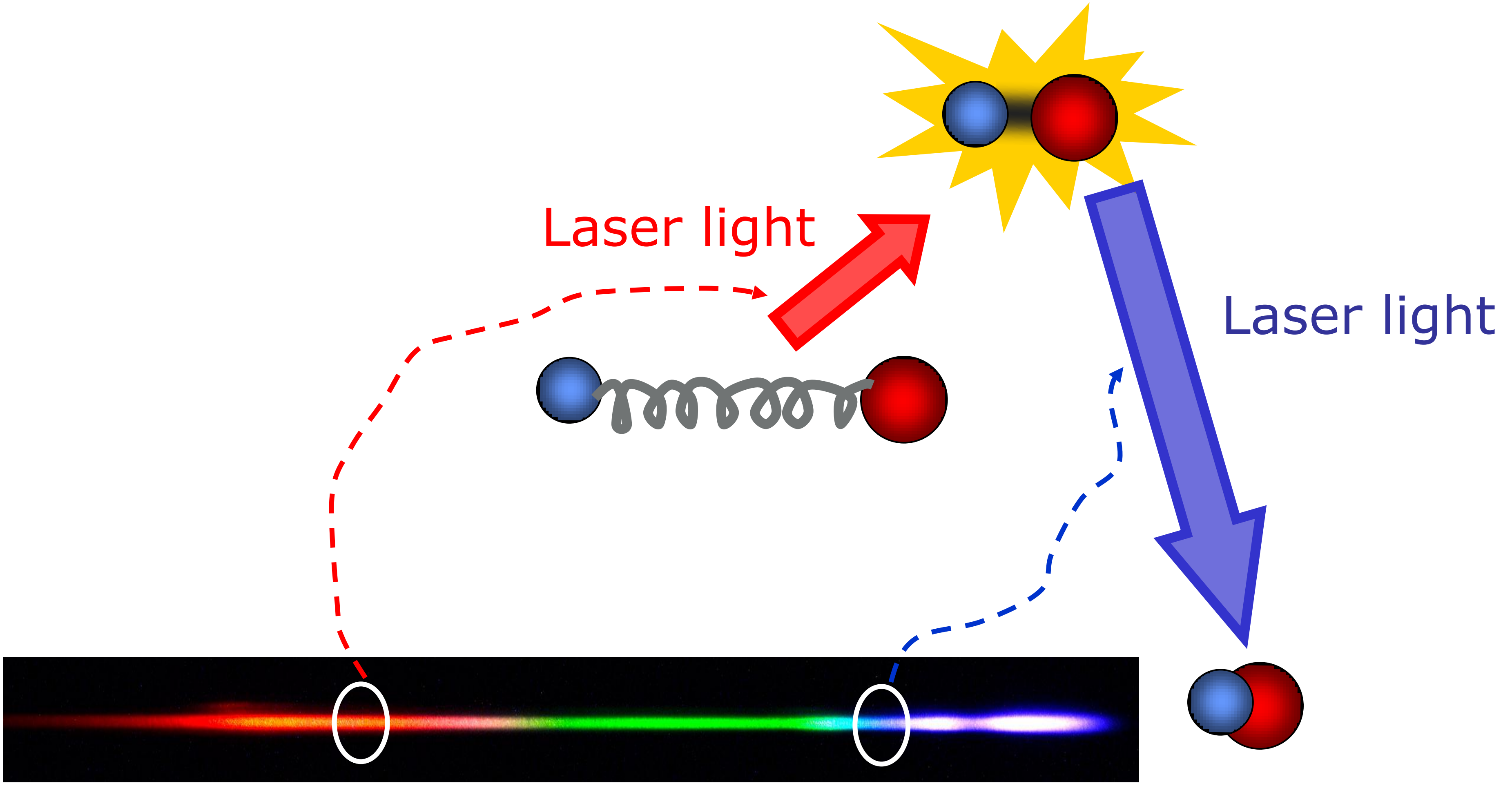
Science **314**, 1430 (2006); Science **319**, 1805 (2008); Science **320**, 1734 (2008); Science **324**, 360 (2009); Science **331**, 1043 (2011).

10, 000, 000, 000, 000, 000 ± 1 (10^{-16})



Teach atoms to make molecules
- chemistry near absolute zero

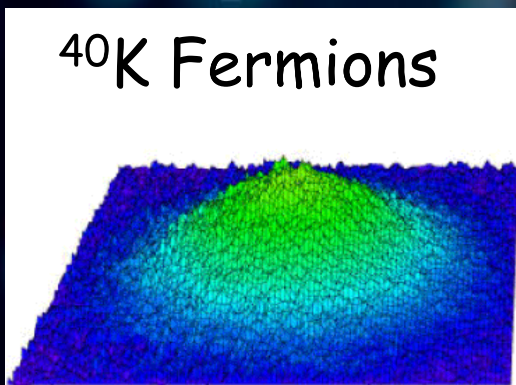
Photons carry away the energy!

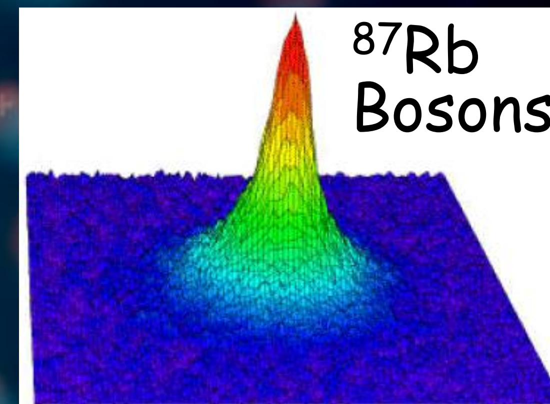


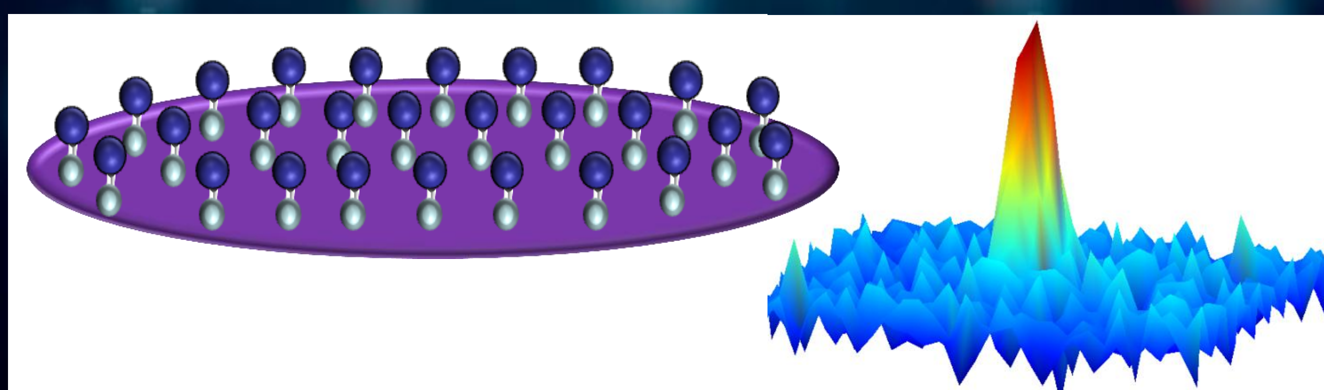
Polar molecules in the quantum regime

D. Jin
J. Ye

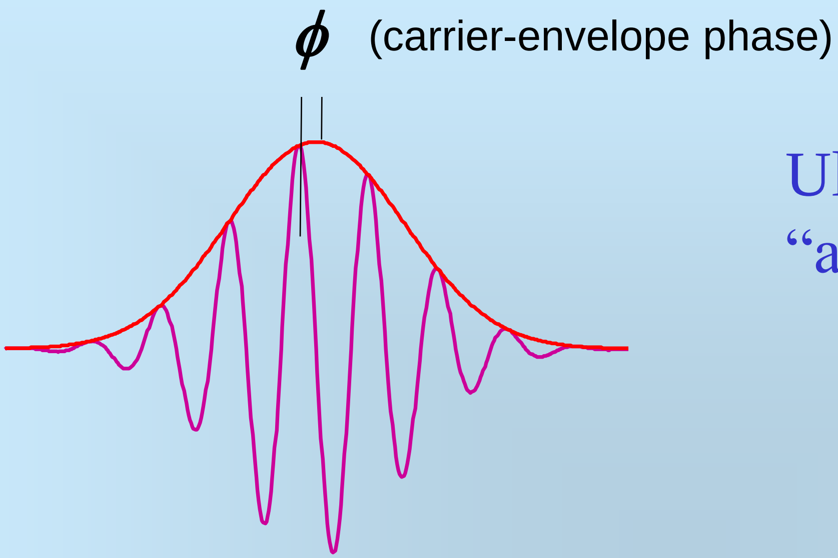
Science 322, 231 (2008)
Science 327, 853 (2010)
Nature 464, 1324 (2010)







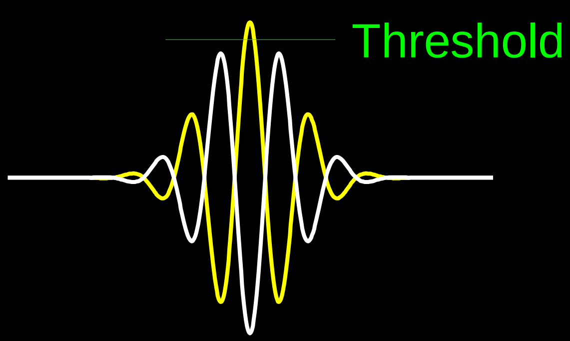
Phase-sensitive ultrafast science

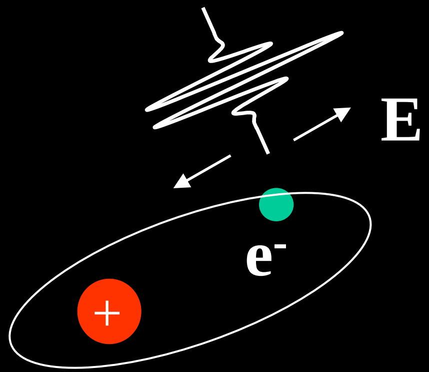


Ultra-short pulse provides "absolute" phase reference

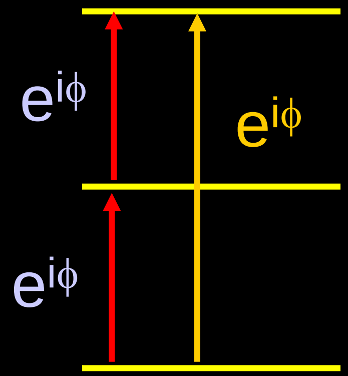
Processes sensitive to E-field ("extreme nonlinear optics")

- Ionization & x-ray generation
- Tunneling from metal surface

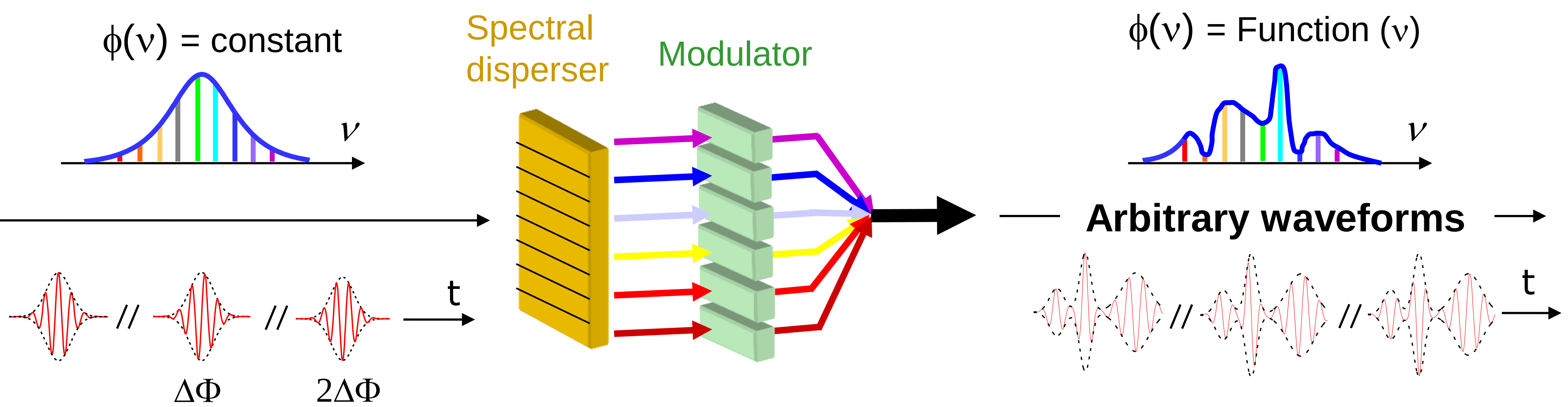


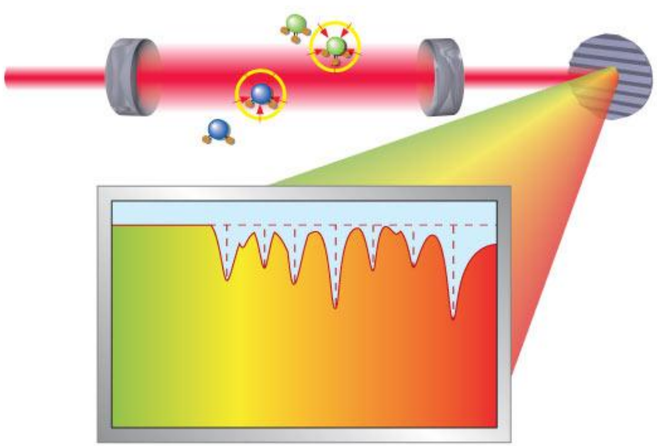


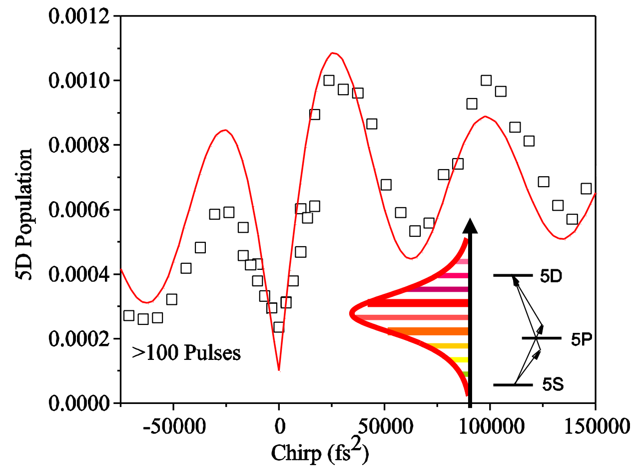
Quantum interference between perturbation orders

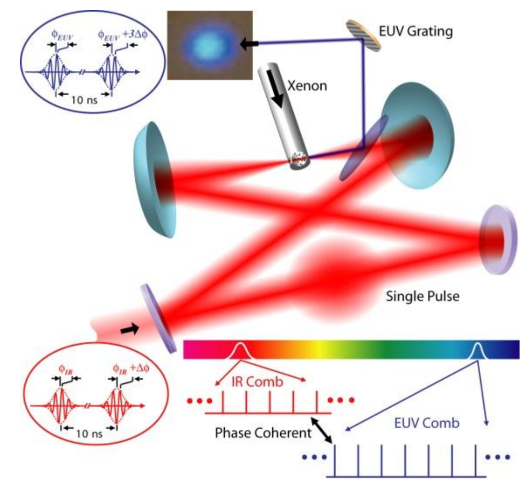


Optical Arbitrary Waveform Generation









J. Ye, Nature Photonics 1, 447 (2007).

Molecular spectroscopy (cold molecules)

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

Quantum control

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

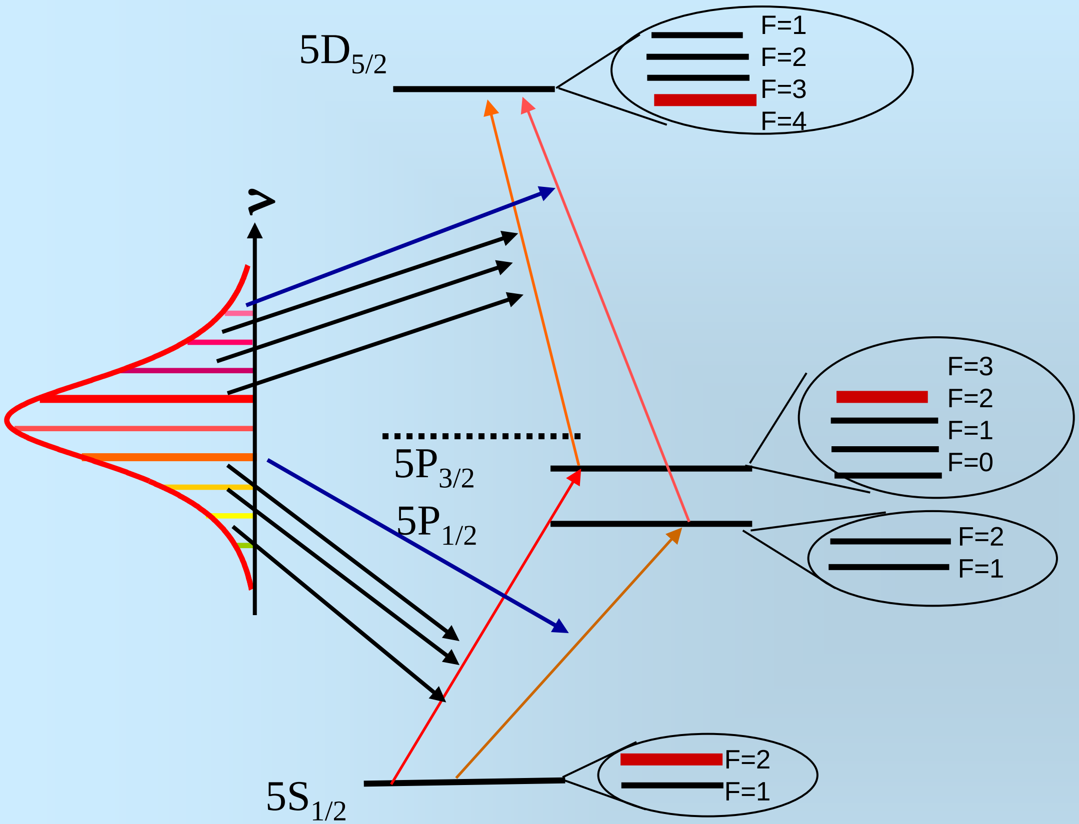
XUV comb

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

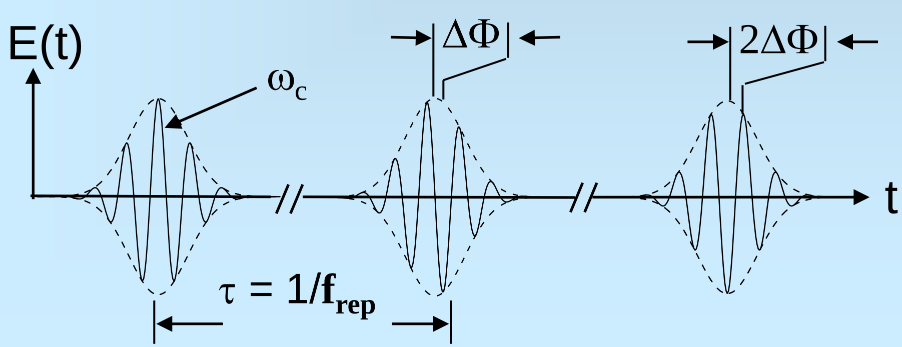
Direct Frequency Comb Spectroscopy

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

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



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



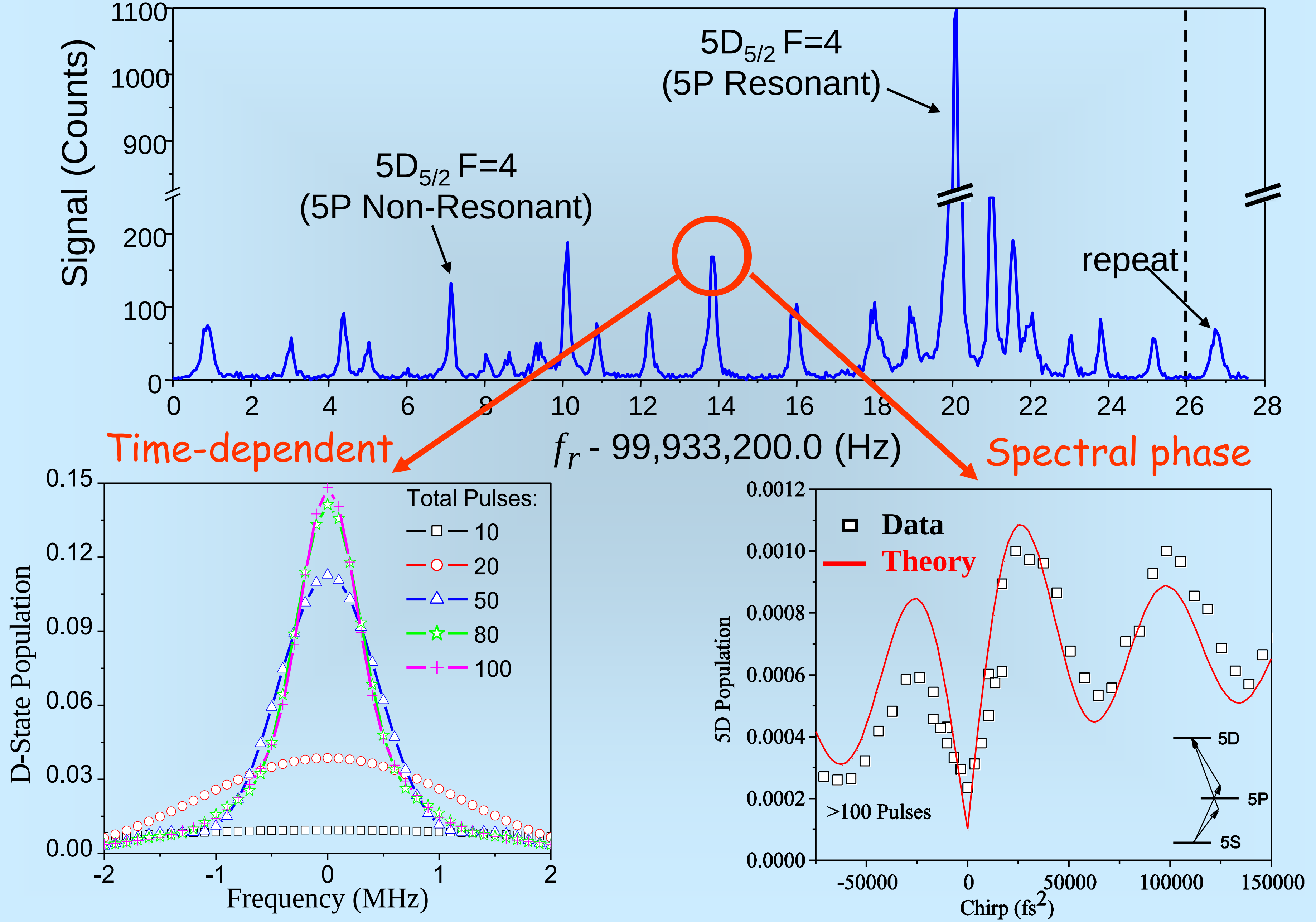
Quantum & optical coherence

High resolution quantum control

Precision spectroscopy: global atomic structure

Ultracold Rb

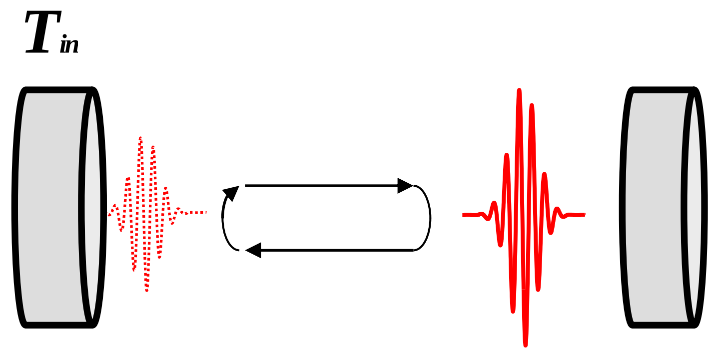
Global atomic structure & Control



Cavity - comb coherent coupling

Time Domain

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



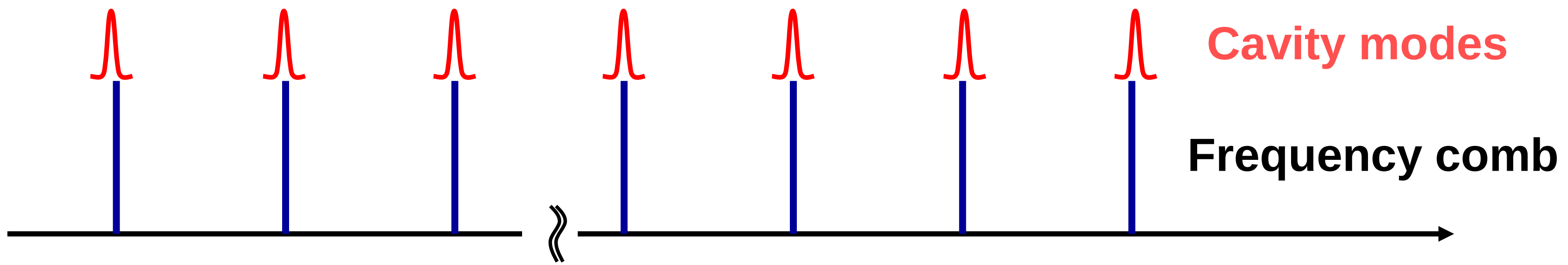
- Linear response
- Preserves coherence
- **Power & Length enhancement**

Cavity enhancement:

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

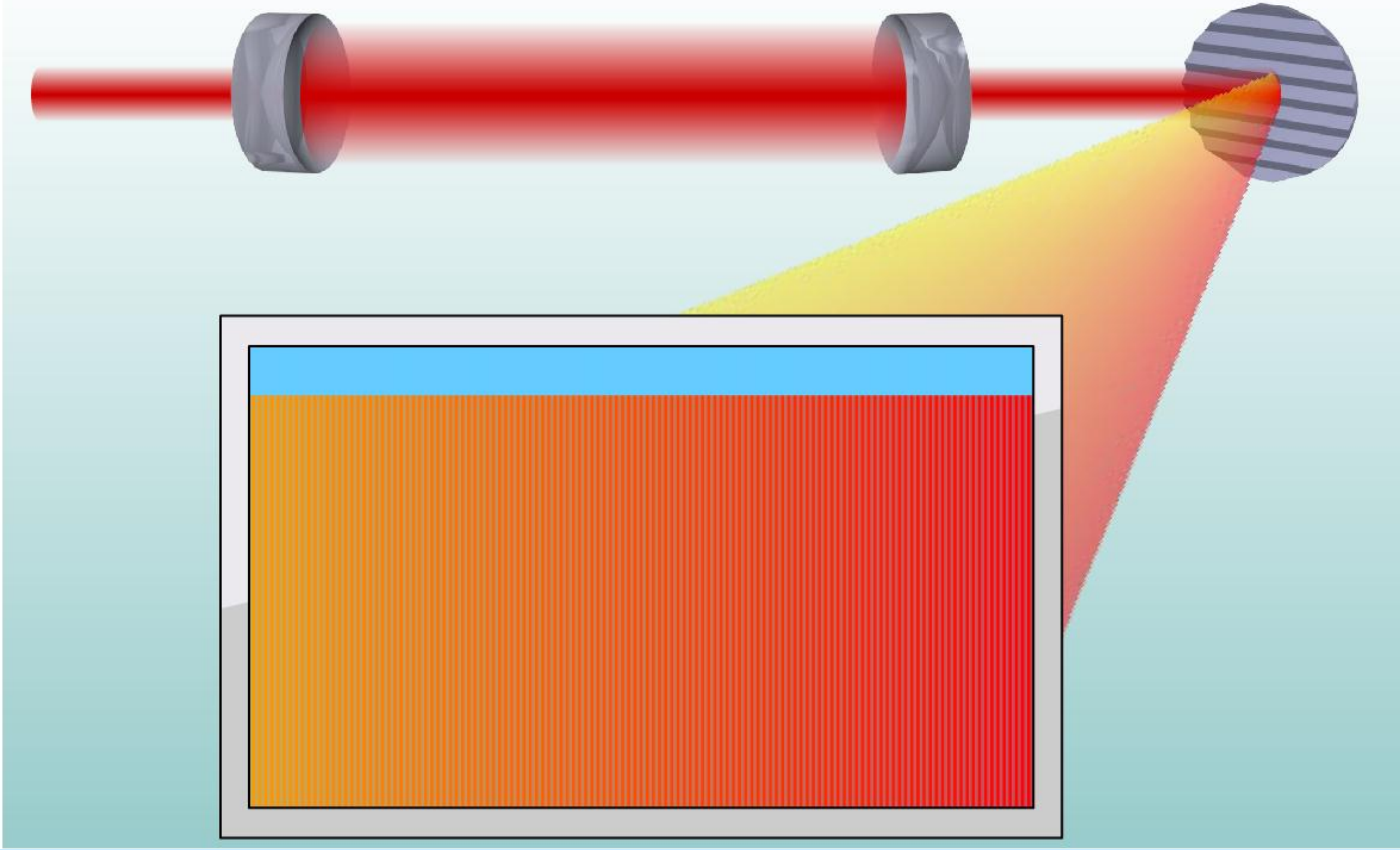
Frequency Domain

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



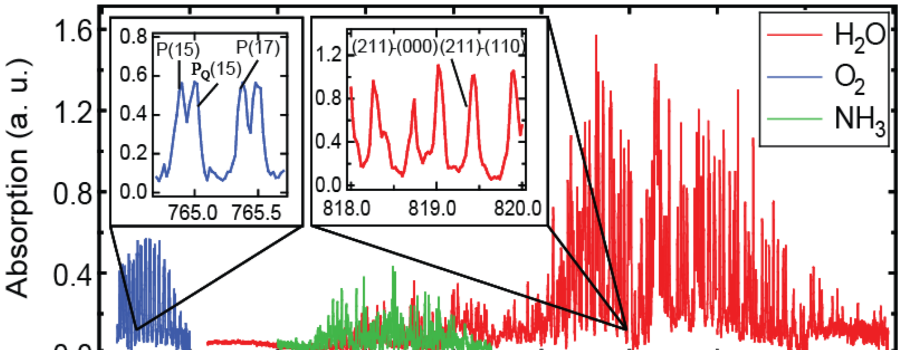
Cavity-enhanced Direct Frequency Comb Spectroscopy

Thorpe et al., Science **311**, 1595 (2006).
Foltynowicz et al., PRL **107**, 233002 (2011).

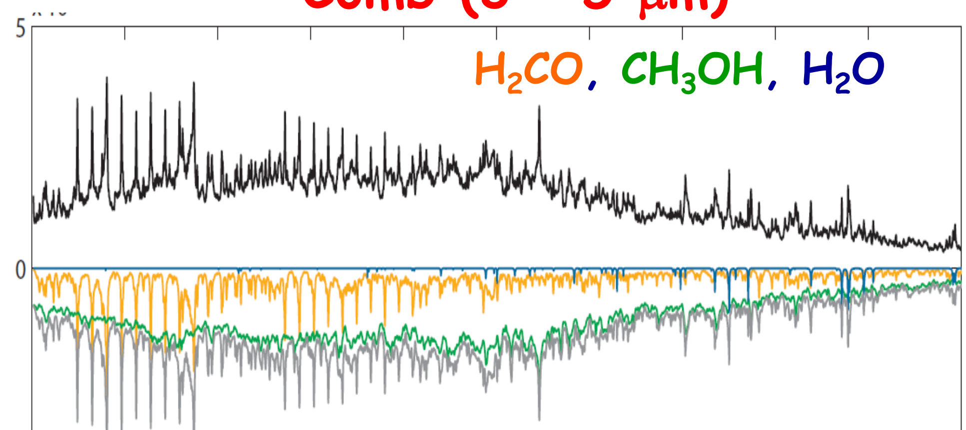


Wide spectral coverage

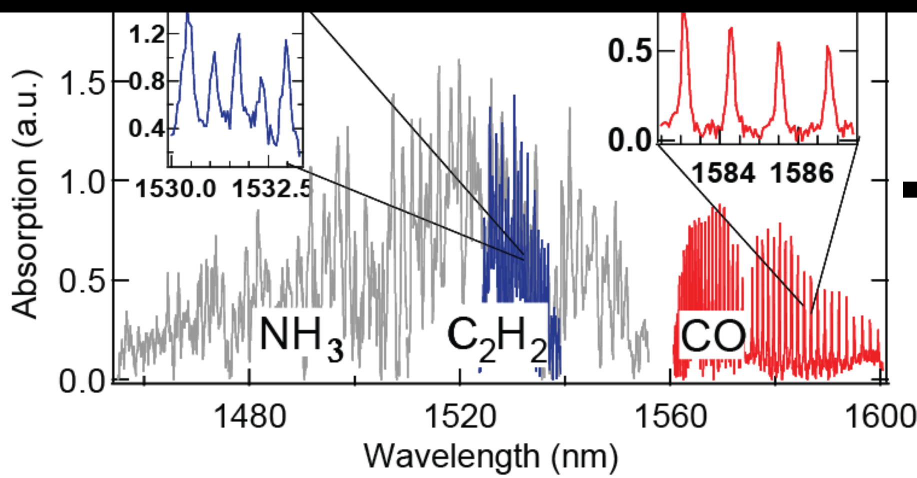
800 nm comb

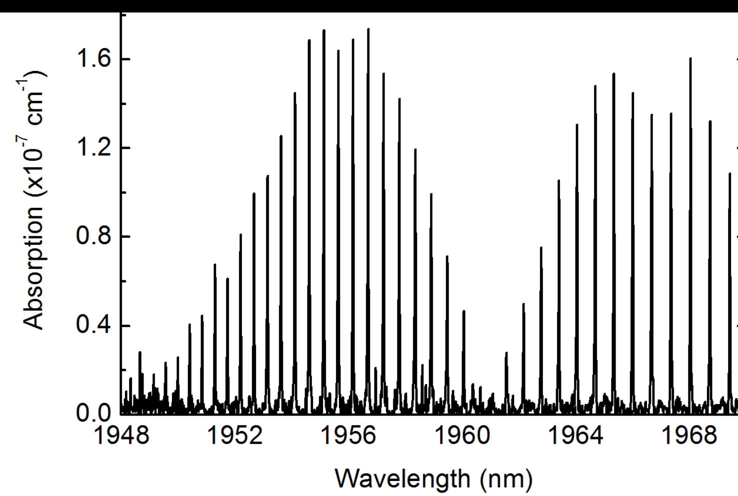


Comb (3 – 5 μm)



- **Broad spectral coverage**
- **High sensitivity** (1 x 10^{-10} $cm^{-1}Hz^{-1/2}$; parts per 10^9)
- **High resolution**
- **Real time acquisition**



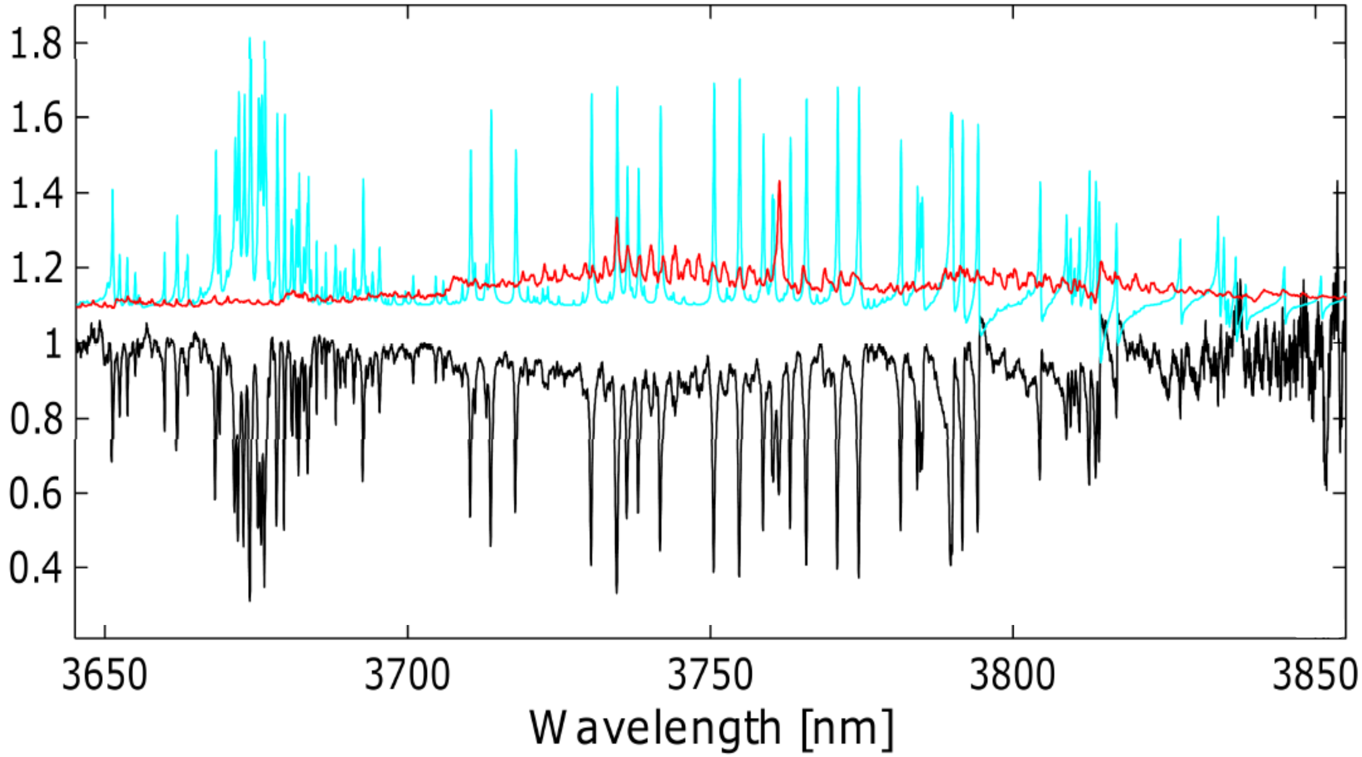


Application case: Breath analysis

H_2O_2: Marker of Acute Respiratory Distress Syndrome
Mortality: 30-40%

Elevated level of H_2O_2 in breath of ARDS cases: ~10 ppm
Dr. John Repine, Univ. Colo. Medical School, J. Pulmonar Respirat Med 2012.

Comb detection limit: 0.1 ppm

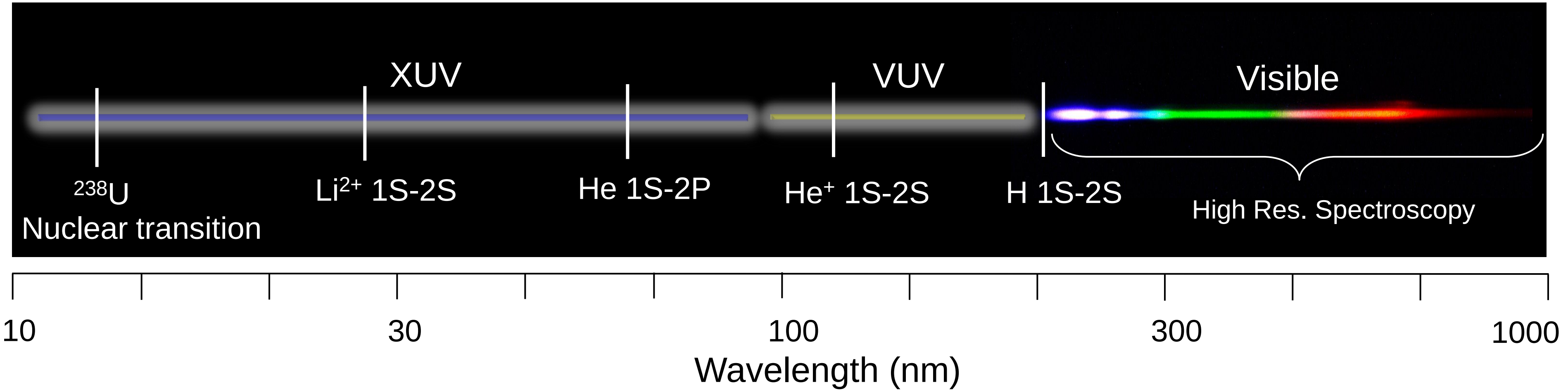


1.2% H_2O
5 ppm H_2O_2

Foltynowicz et al., Appl. Phys. B, DOI 10.1007/s00340-012-5024-7 (2012).

Charting the extreme ultraviolet landscape

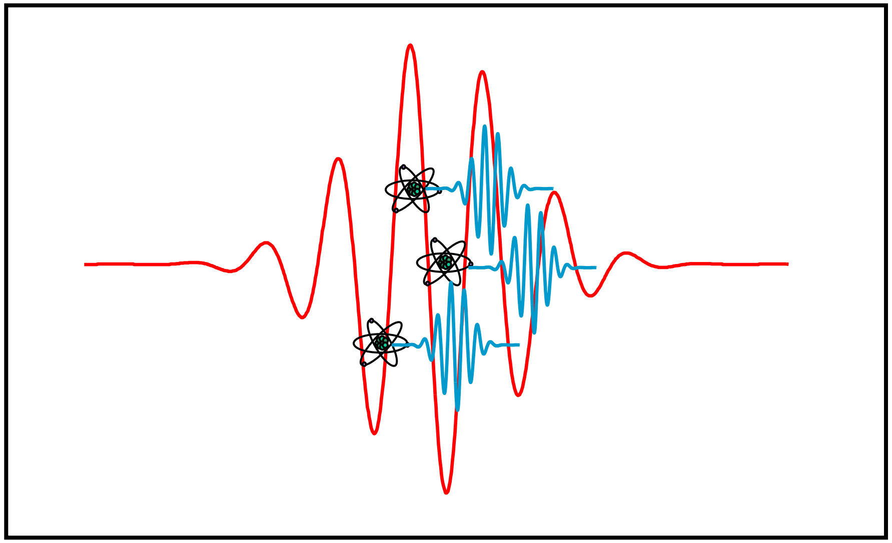
(Ultrahigh-resolution XUV spectroscopy)



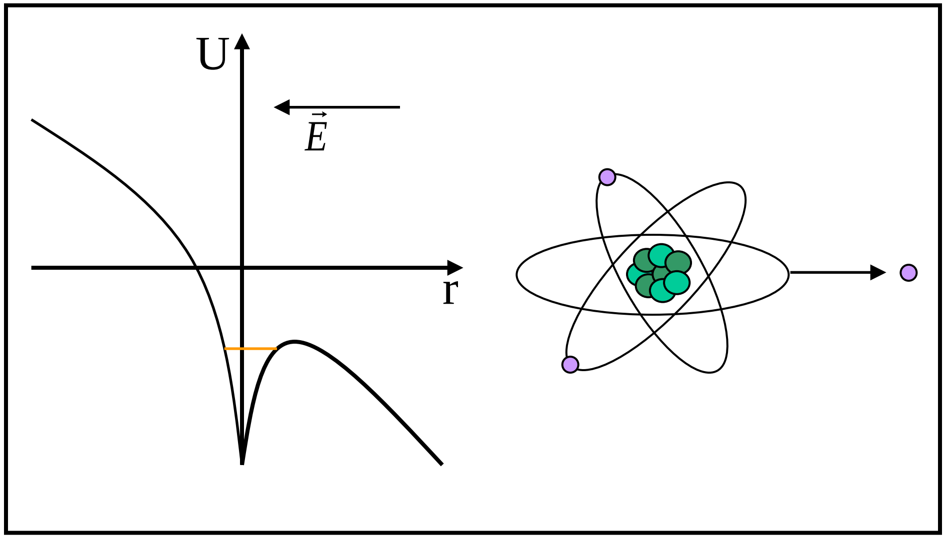
- Precision tests of fundamental physics
- Simple 3-body systems (i.e. helium), but also complex molecules
- Nuclear transitions
- High-precision test of QED
    - Ground state Lamb shift scales as Z^4
    - Higher-order corrections scale as Z^6

High-harmonic generation —— VUV, EUV, soft X-ray

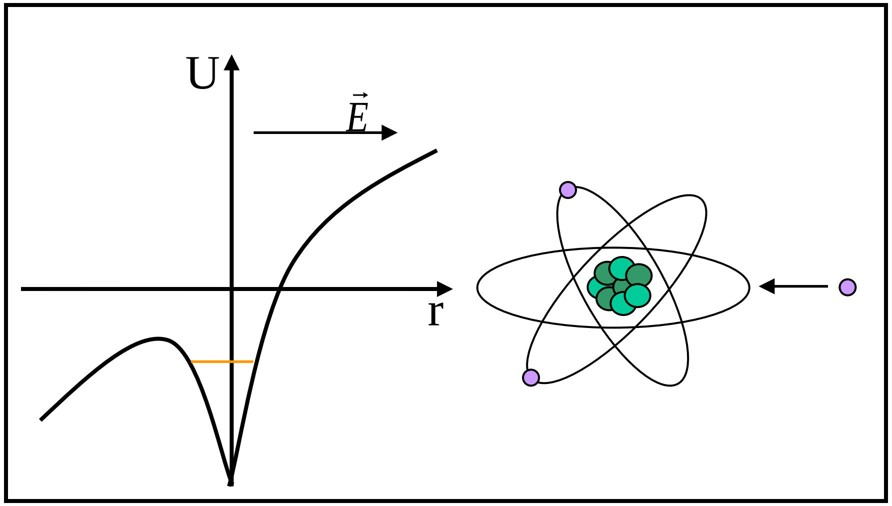
Three step model



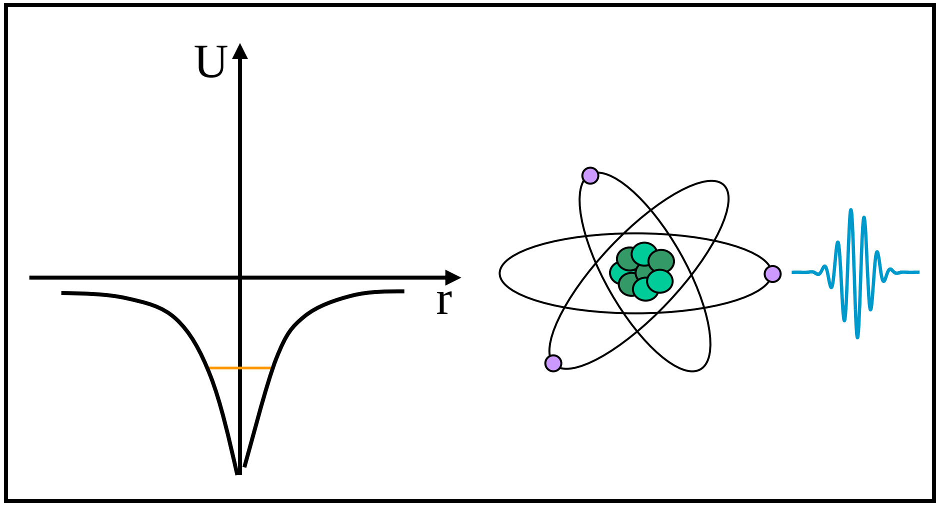
Step 1: Ionization



Step 2: Field Reversal



Step 3: Recombination



Corkum, Phys Rev Lett 71, 1994

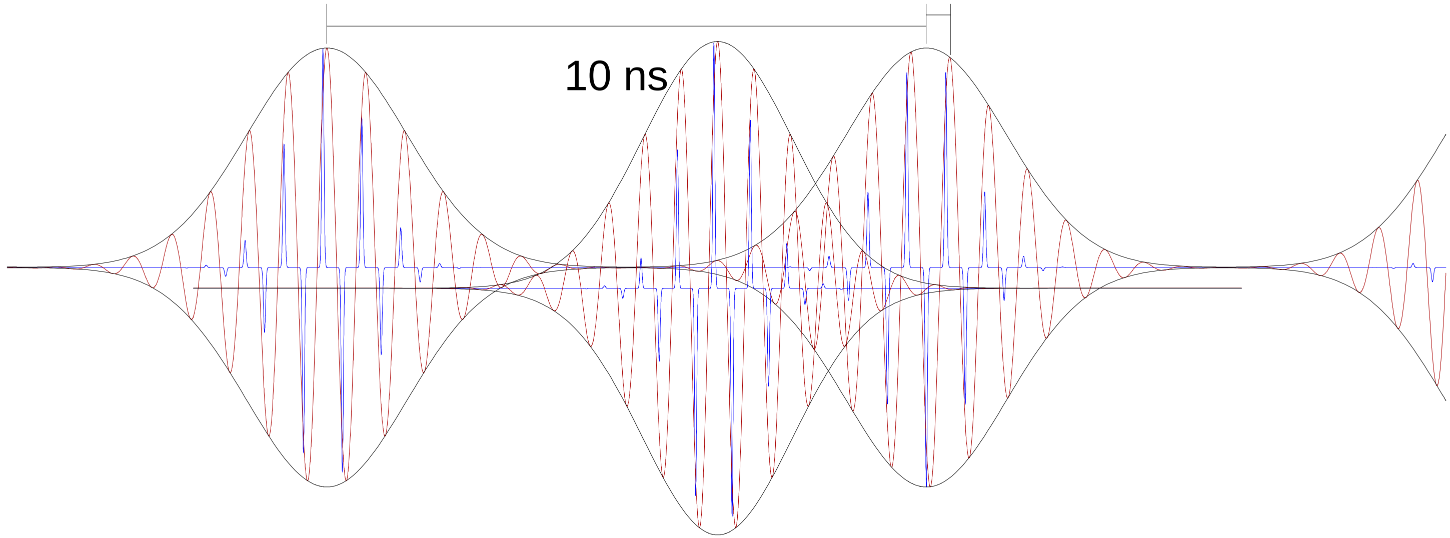
Coherent VUV and XUV radiation

Harmonic Generation with a train of IR pulses-

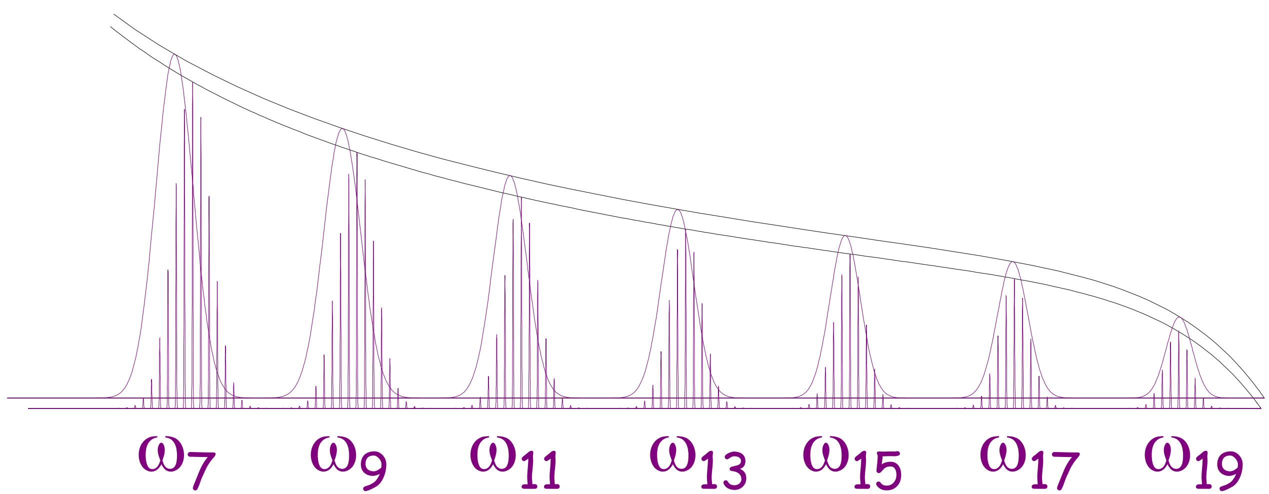
The XUV frequency comb is born

Harmonic Generation with a single IR pulse - *a train of attosecond pulses*

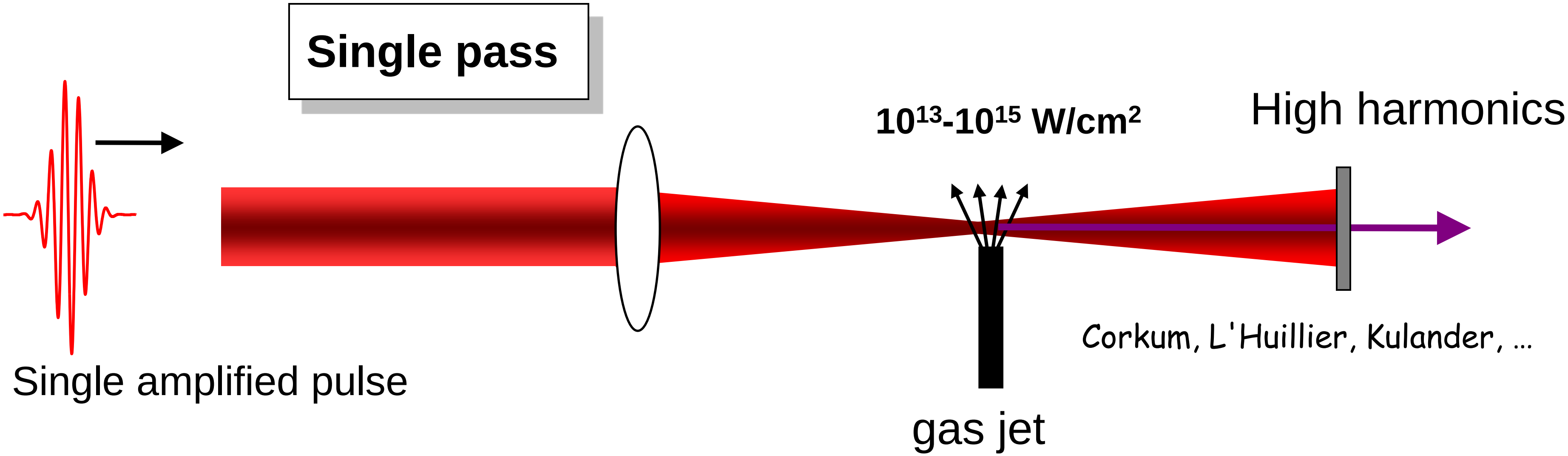
Time domain



Frequency domain



High-harmonic generation



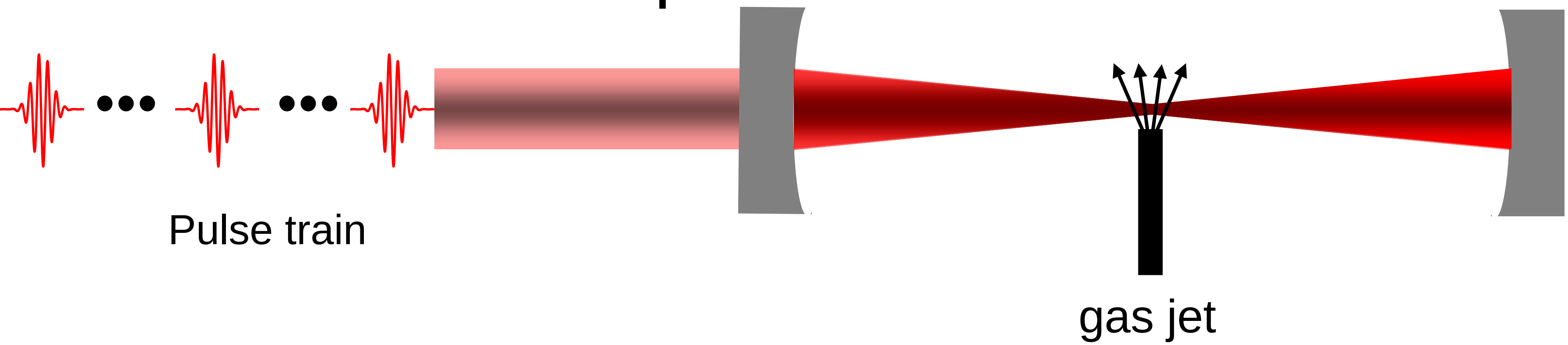
Low repetition rates (Hz ~ kHz)

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

fs enhancement cavity

Jones & Ye, Opt. Lett. 27, 1848 (2002)
Gohle *et al*, Nature 436, 234 (2005)
Jones *et al*., PRL 94, 193201 (2005).

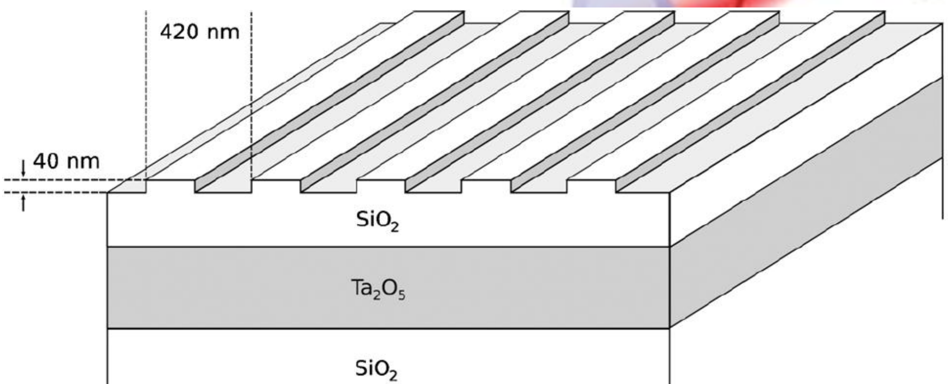
→ **Recycle unconverted light**
→ **Maintain full repetition rate**

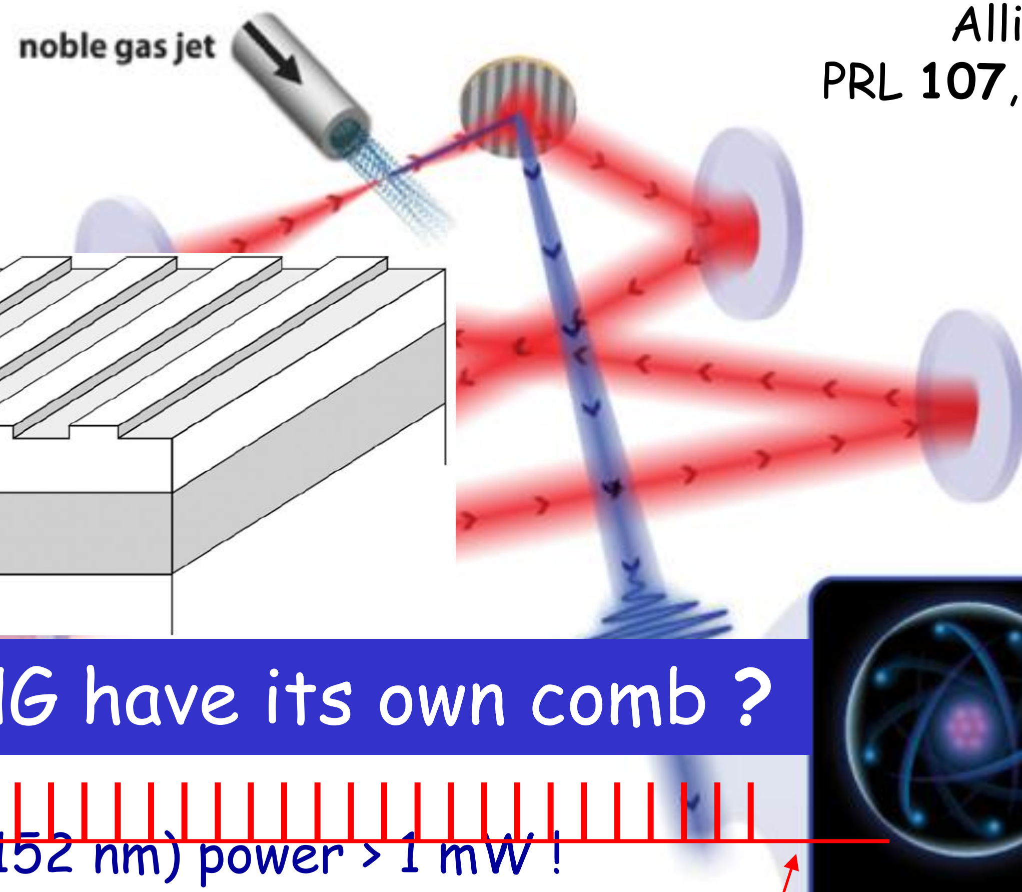


Power scaling - XUV frequency Comb

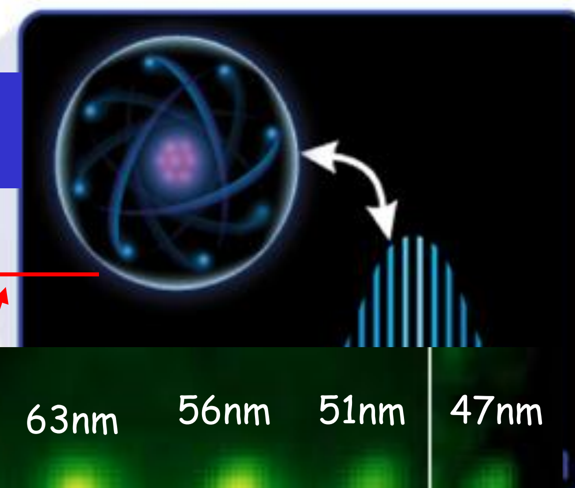
Allison et al.,
PRL **107**, 183903 (2011).

Yost *et al.*, Opt. Lett.
33, 1099 (2008)

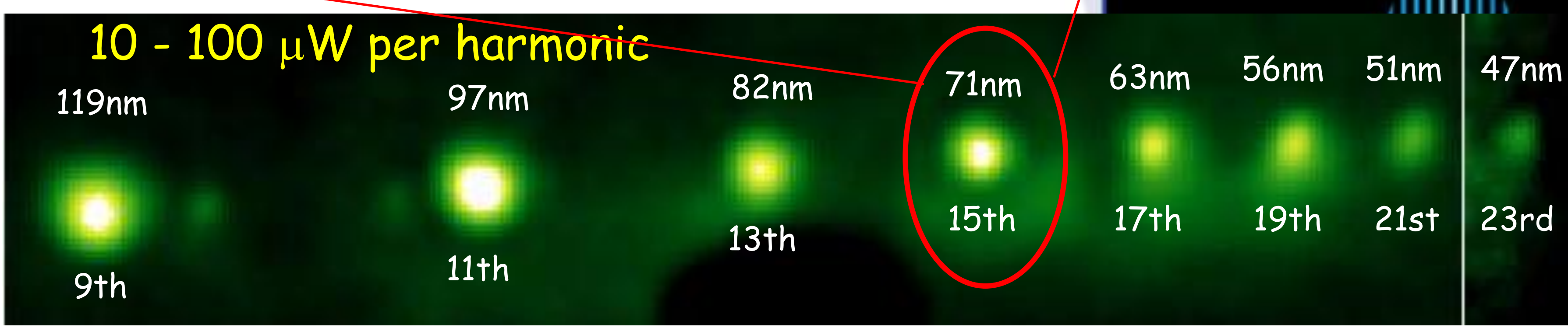




Does each HHG have its own comb ?



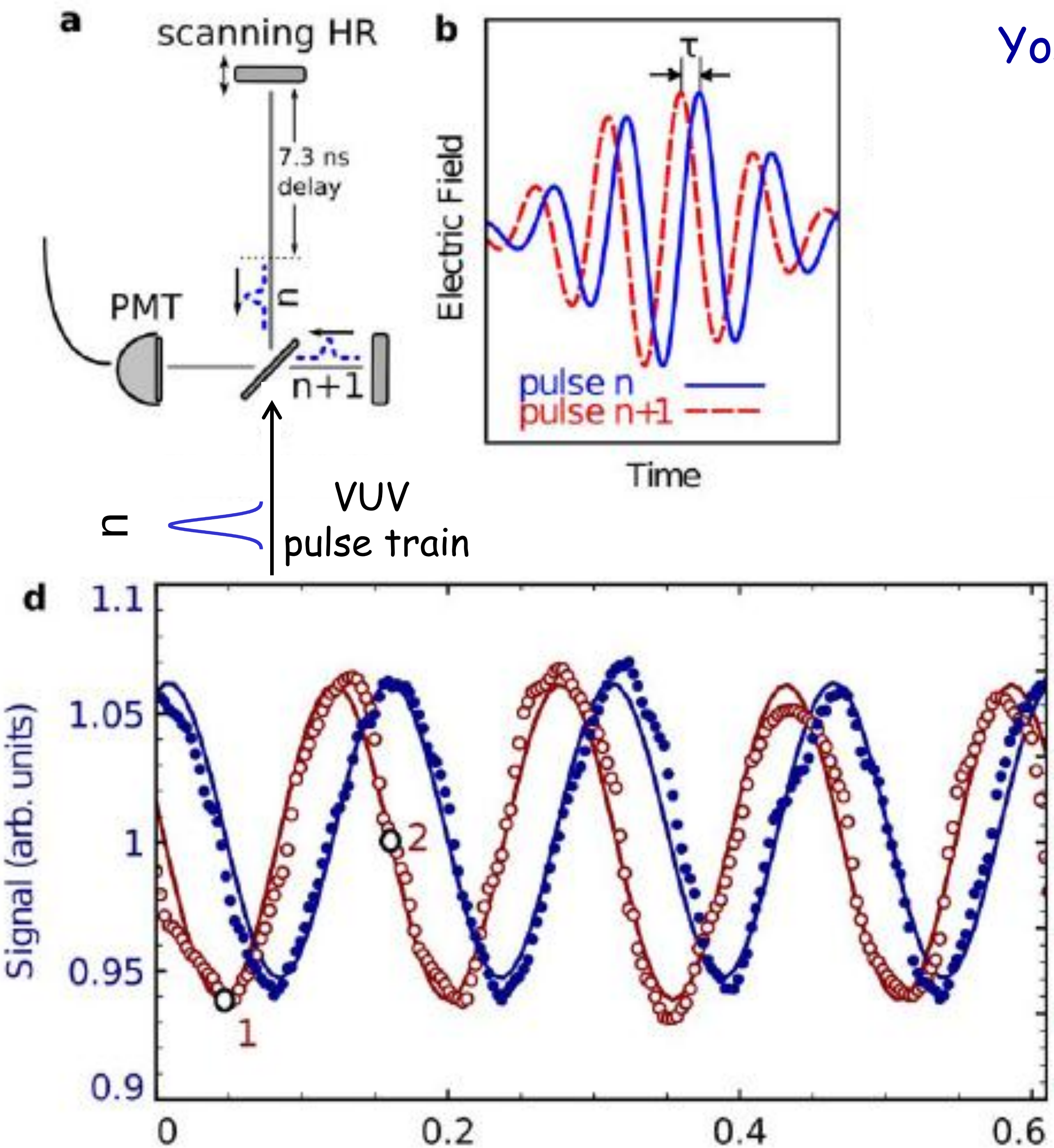
7^{th} harmonic (152 nm) power > 1 mW !

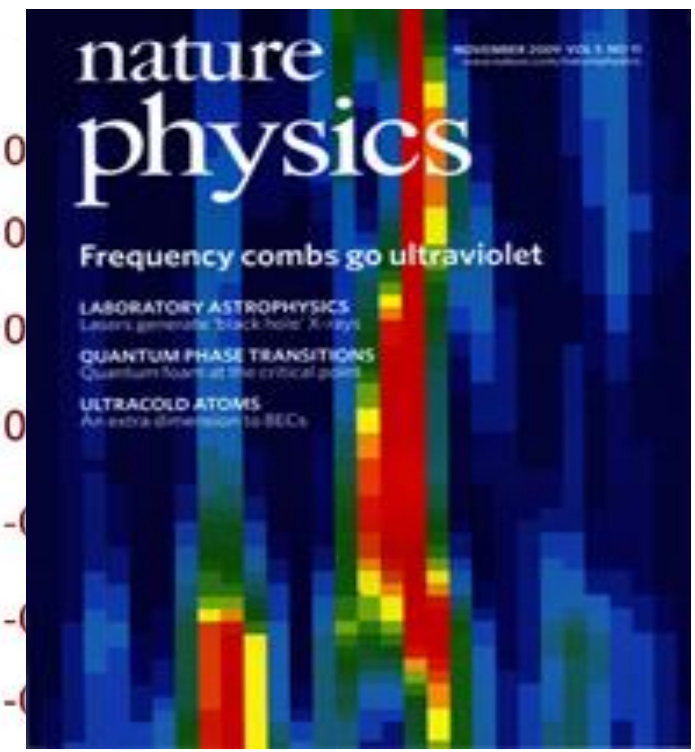


Confirmation of VUV comb

Yost et al., Nature Physics **5**, 815 (2009).

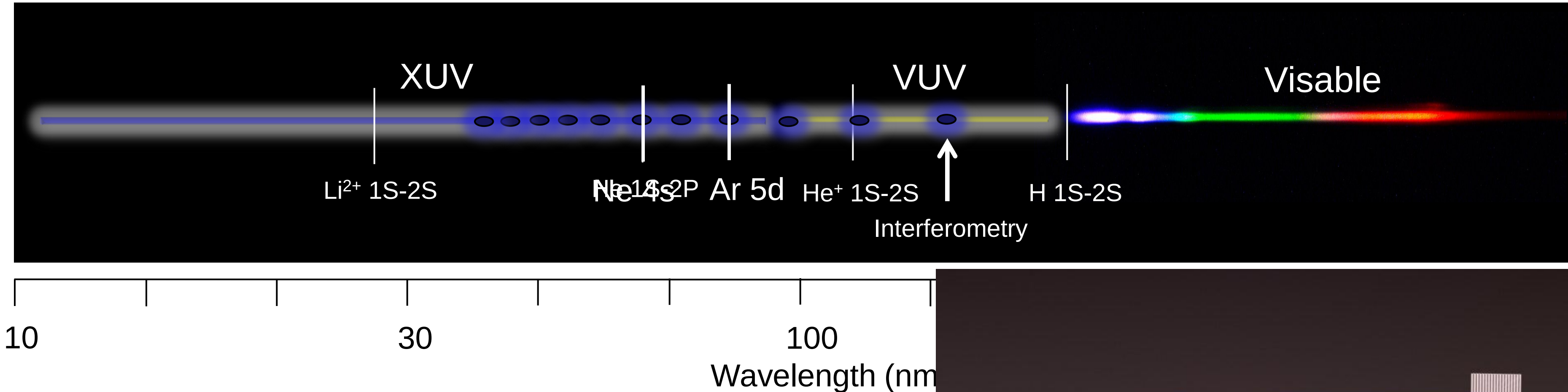
VUV (7th harmonic) comb linewidth $\lesssim$ 20 MHz

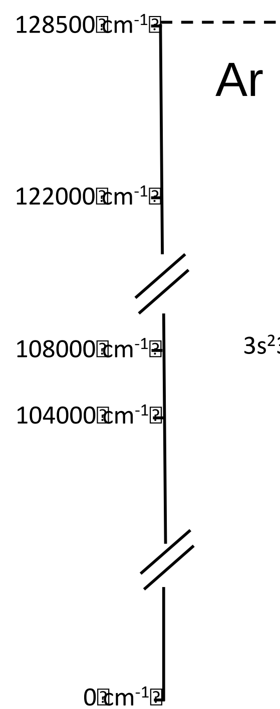


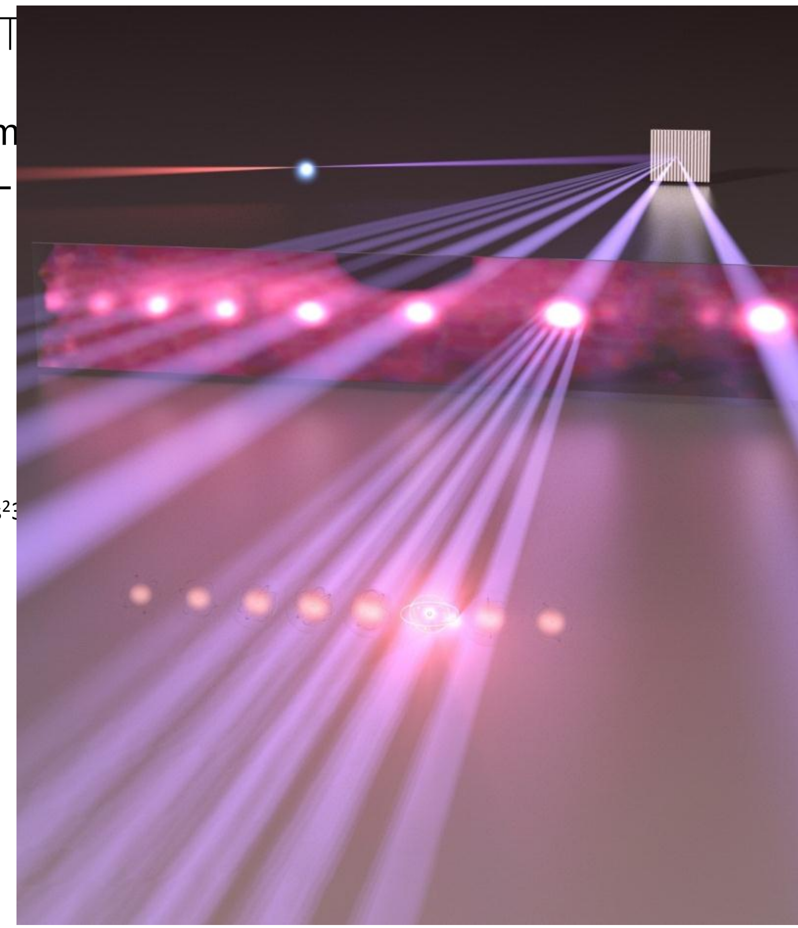


Spectroscopy – the ultimate test

Cingöz et al., Nature 482, 68 (2012).



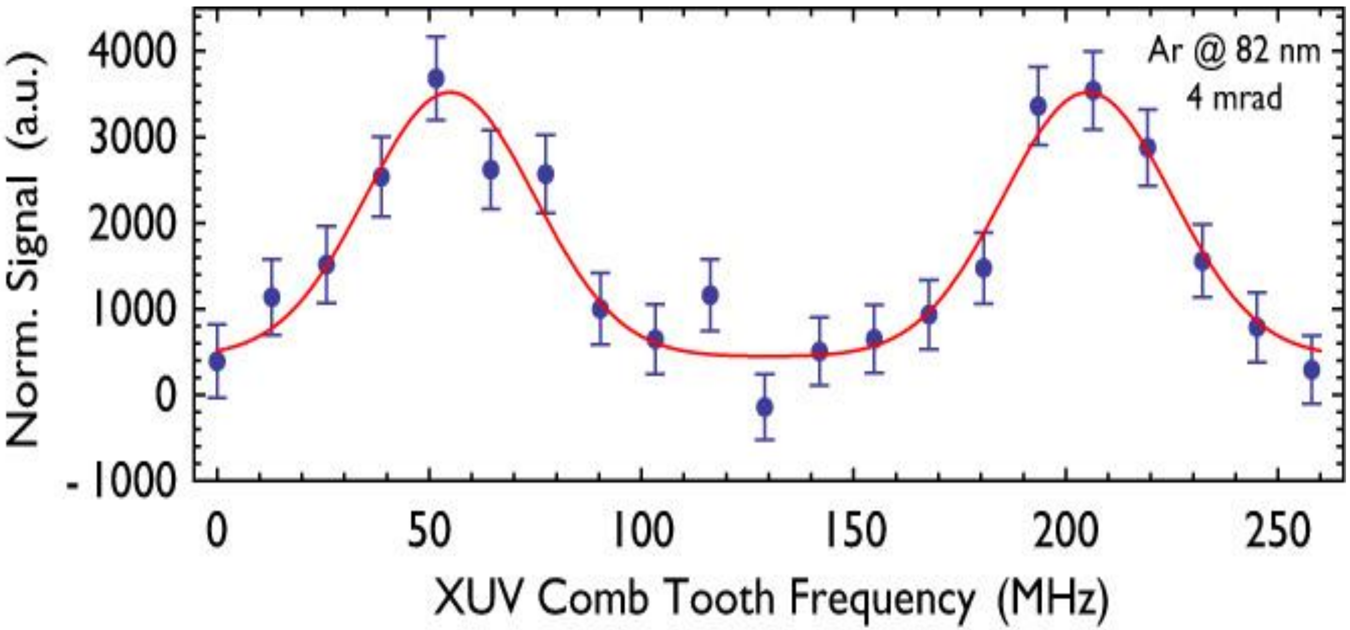




- (CW) spectroscopy with 10 pW
- Direct fluorescence detection (95%)
- Natural linewidth ~10 MHz
- Absolute frequency determination 100 kHz

Comb-Resolved Spectroscopy

Cingoz *et al.*, Nature 482, 68 (2012).



Scan a single comb across resonance

Reduce the Doppler broadening

Also,
Ne transition;
17^{th} harmonic
(62 nm)

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A. Cingöz
T. Alison
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A. Marian (MPG, Berlin)