Control of light for precision measurement

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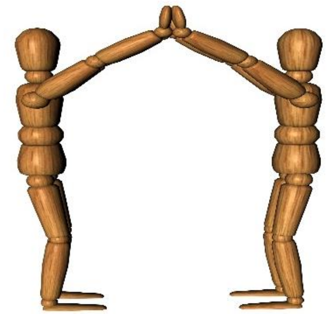
JILA, NIST & University of Colorado

Fermi School Course 191 - Quantum Matter at Ultralow Temperatures,
July 7, 2014

Quantum matter & metrology

Martin *et al.*, Science **341**, 632 (2013); Zhang *et al.*, Science, in press (2014).

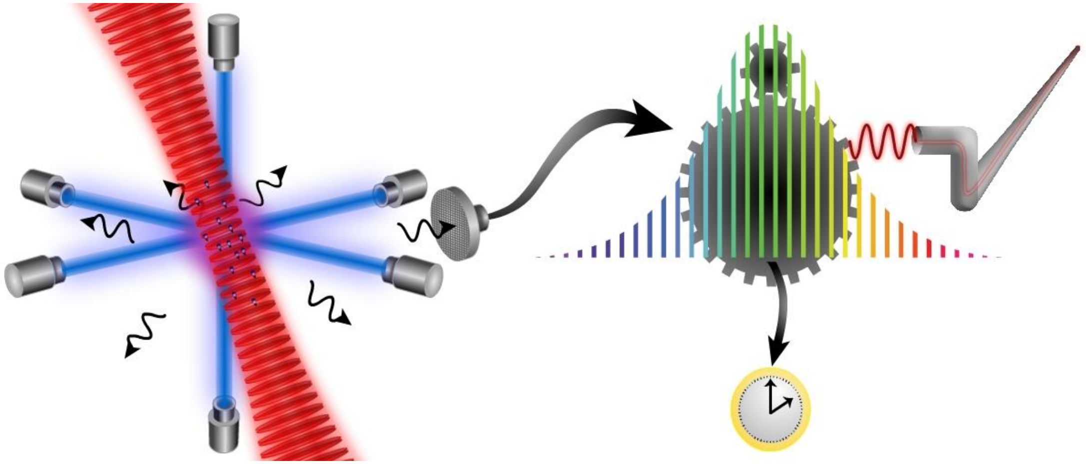
Precision Measurement

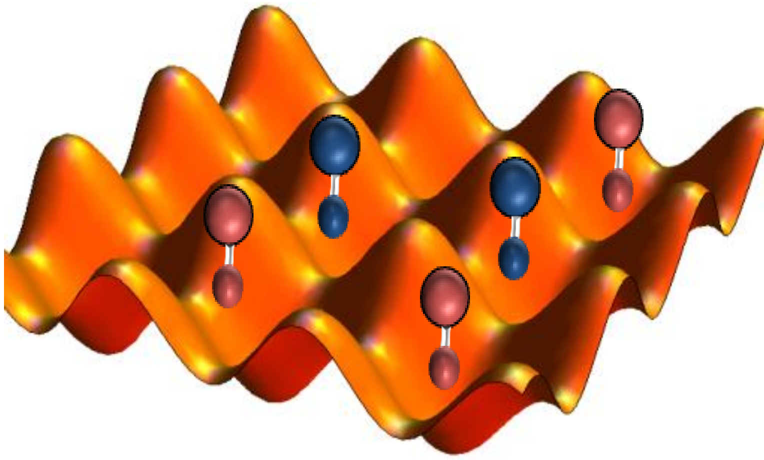


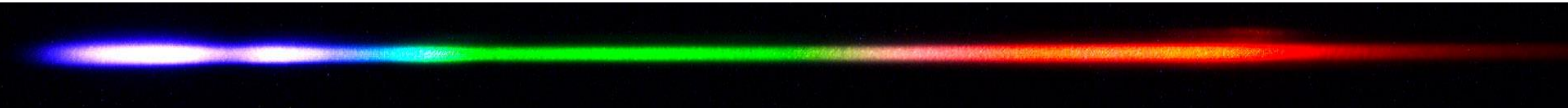
Many-particle Quantum systems

Many-body quantum systems advance the fundamental limit for measurement

Precision measurement determines microscopic properties & dynamics







Lecture I: Light control for precision measurement

Lecture II: Clock and quantum matter

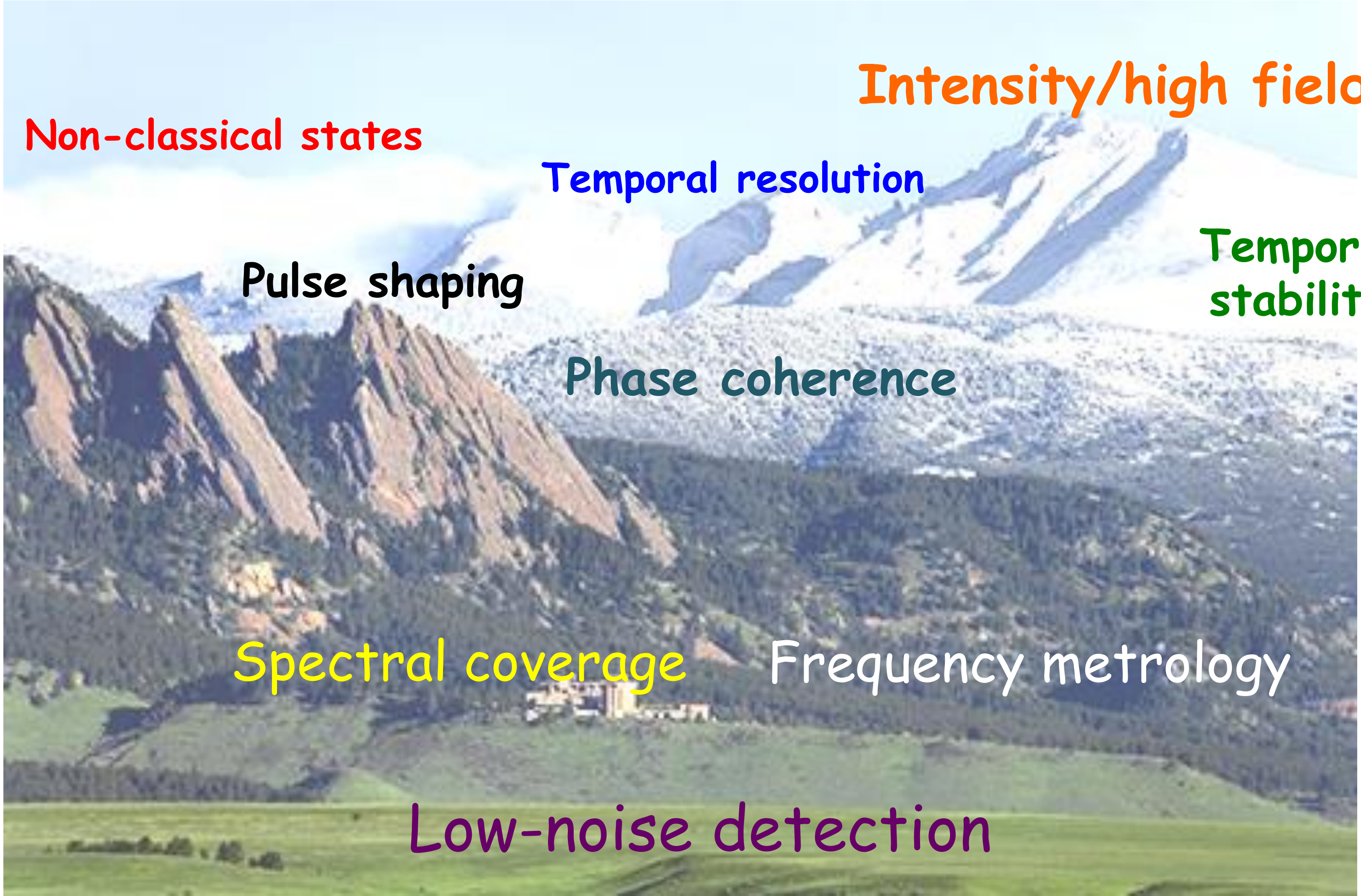
Lecture III: Molecular quantum gas – a new frontier

– A remarkable convergence of
Ultracold,
Ultrafast,
Ultrastable,
Ultraprecise

Light in modern science

What makes a versatile photon laboratory?

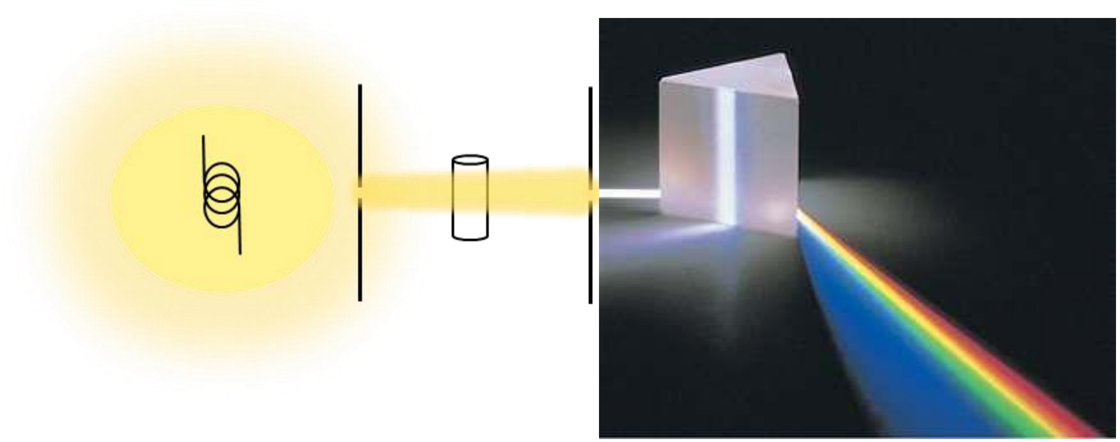
Scientifically useful photons span many dimensions



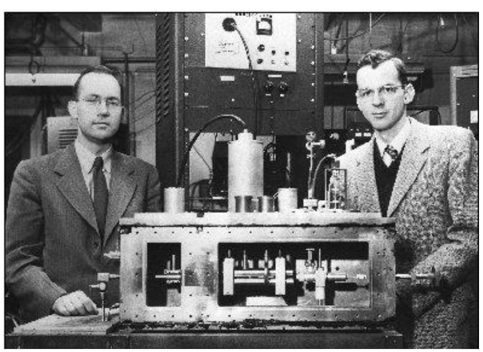
Spectral resolution – Nature's finger prints

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

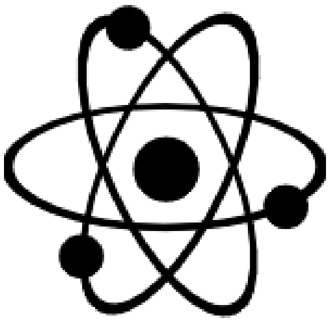
ca. 1660
I. Newton

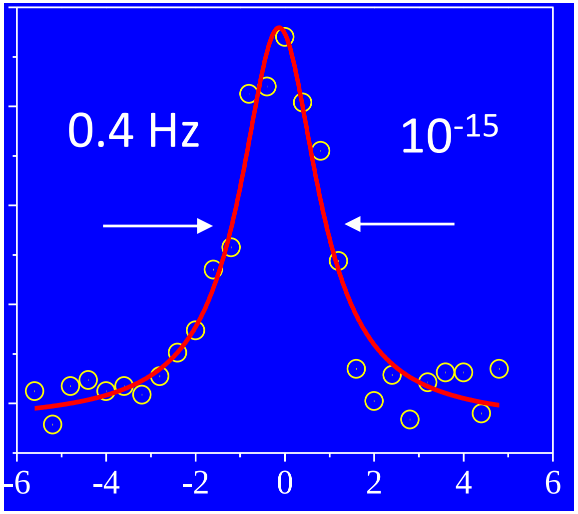


Laser spectroscopy
- Measure frequency
- Resolution 10^{-15}



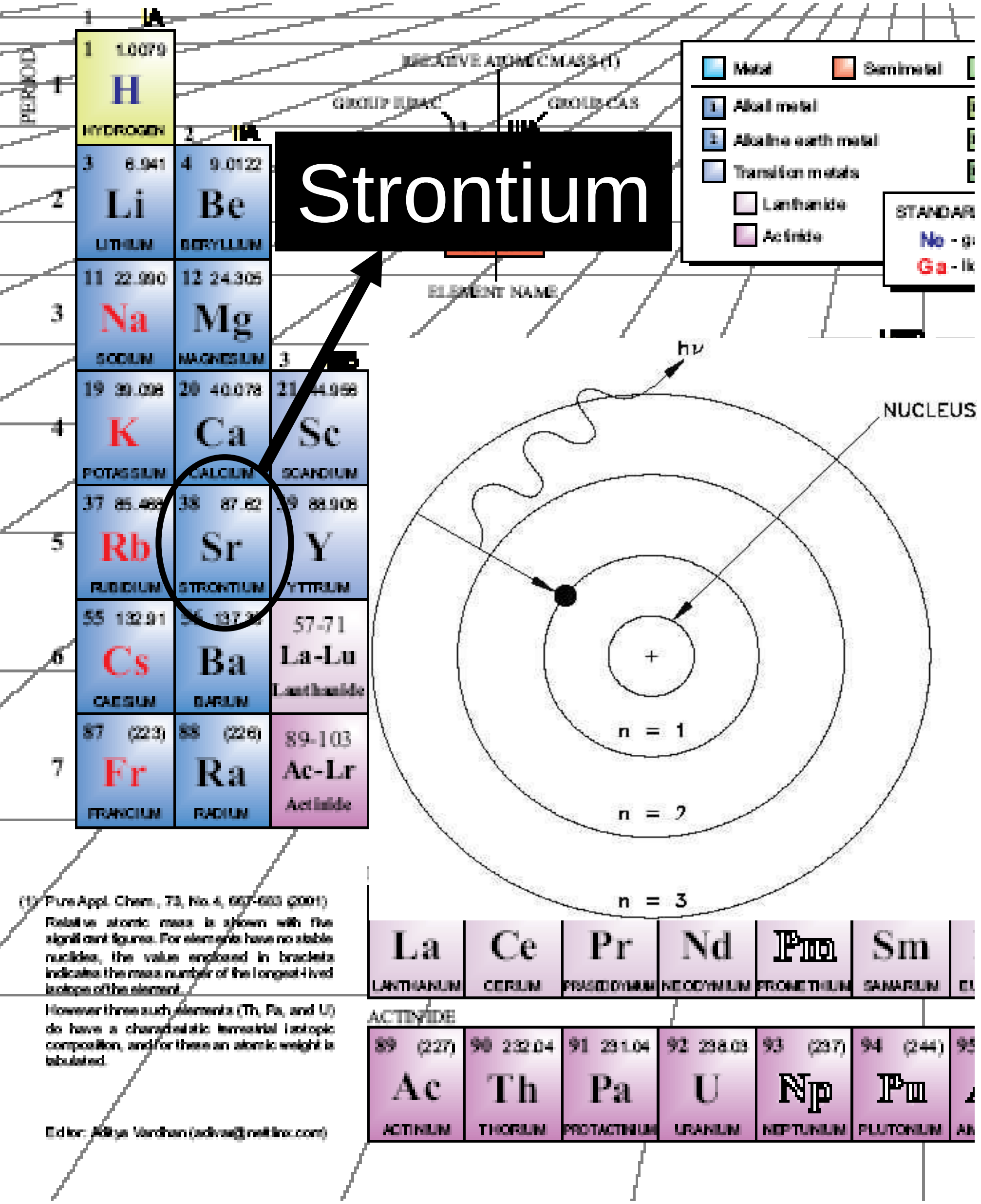
ca. 1960
C. Townes





Nature's high Q oscillators

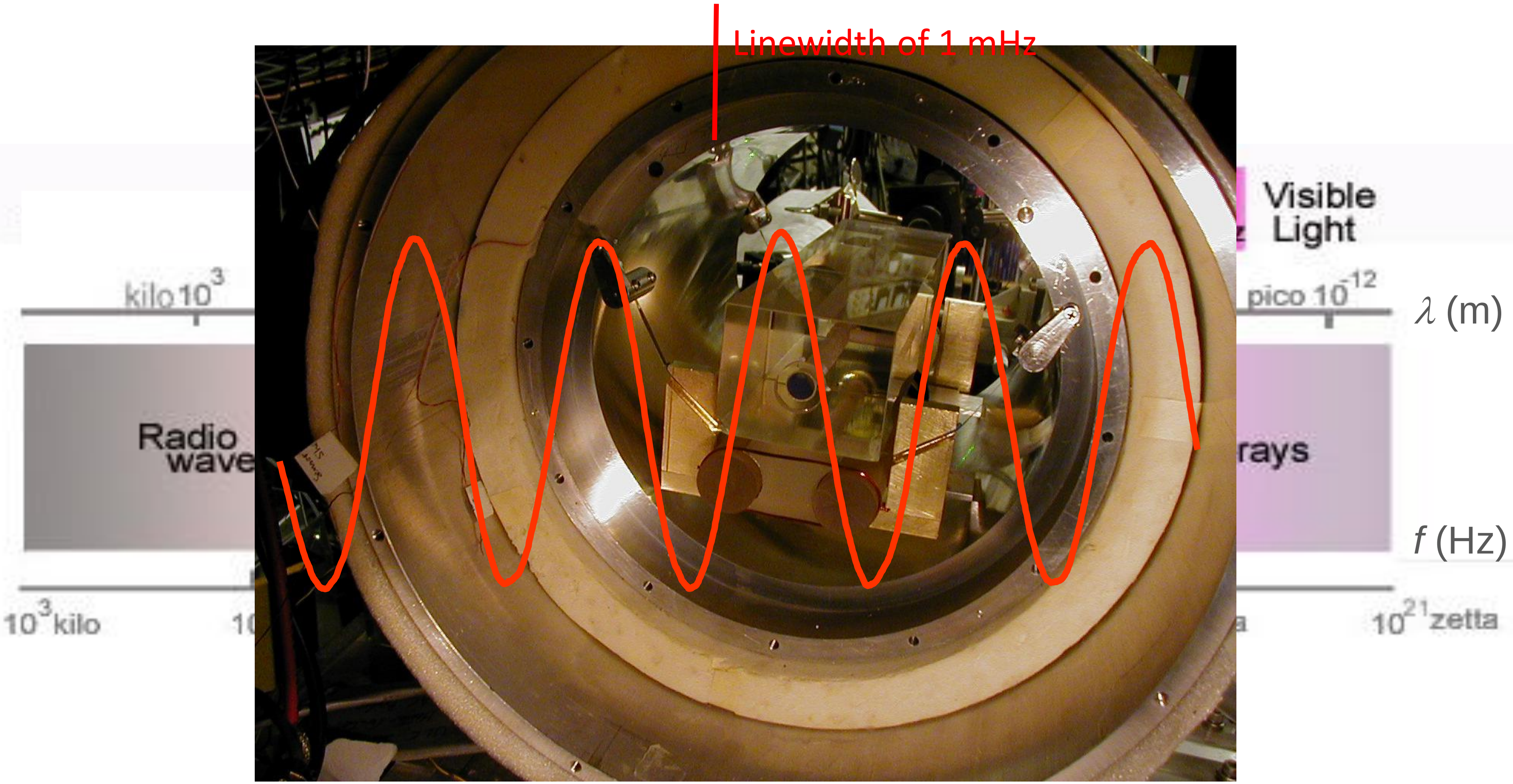
Boyd *et al.*,
Science **314**, 1430 (2006).



Quality factor
> 10^{17}

Once set, it swings during
the entire age of the universe

The landscape of the electromagnetic spectrum

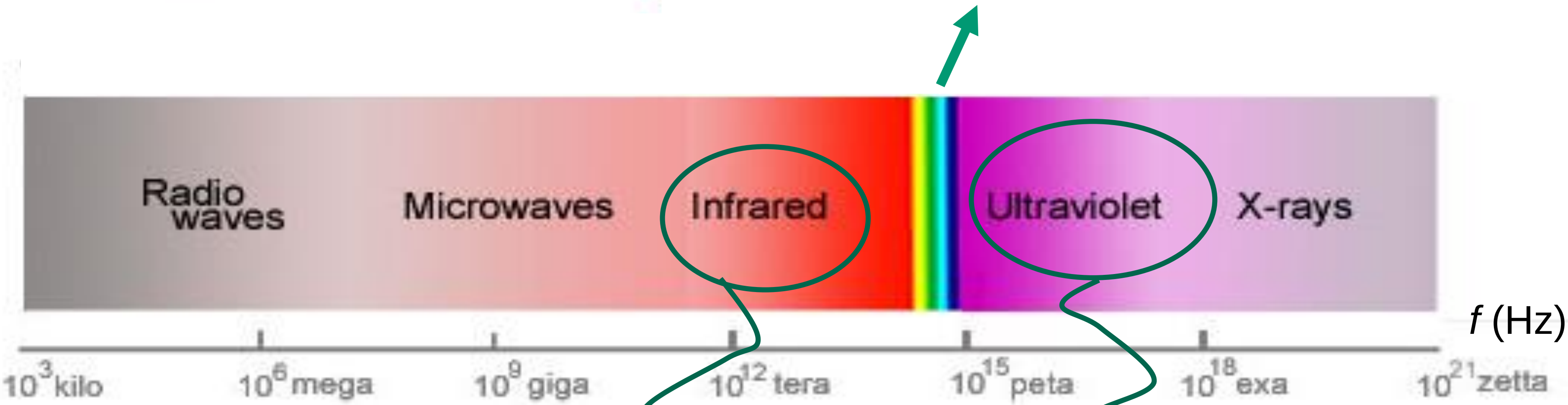


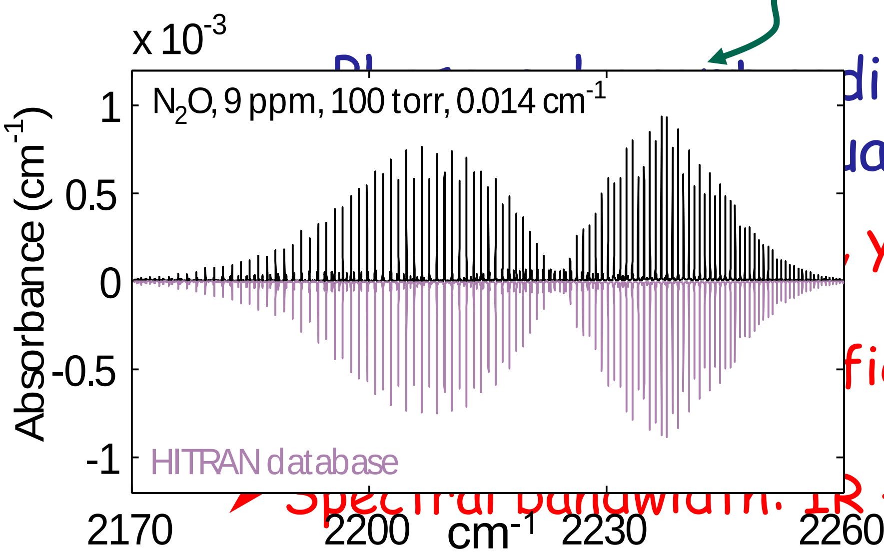
Zoom in 1 million times

Zoom in another 1 million times

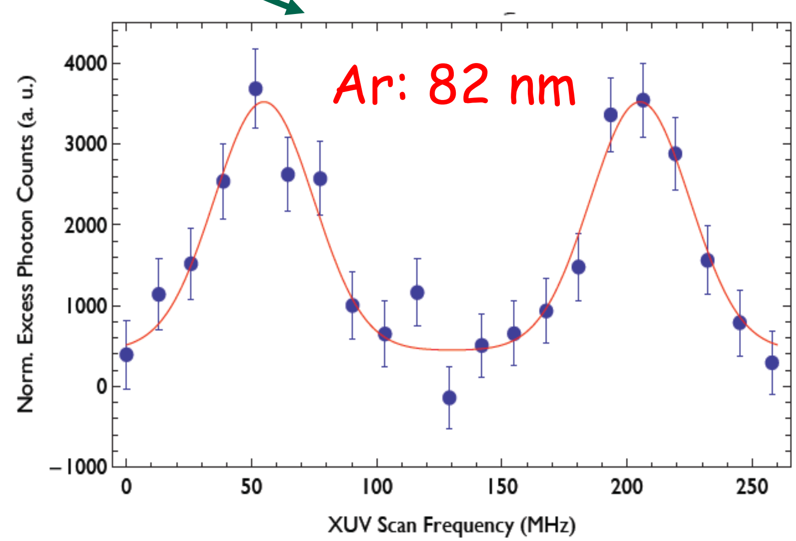
Phase control of light

Phase-coherent synthesis of the electromagnetic spectrum

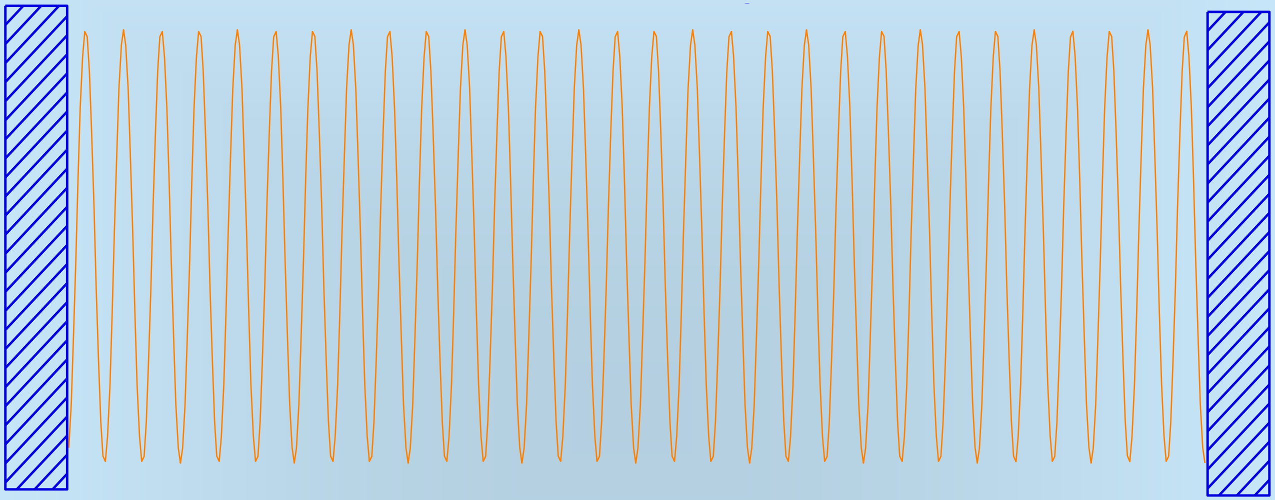




diations –
uantum C
, yet main
fields, but
Spectral bandwidth: IR – XUV; S

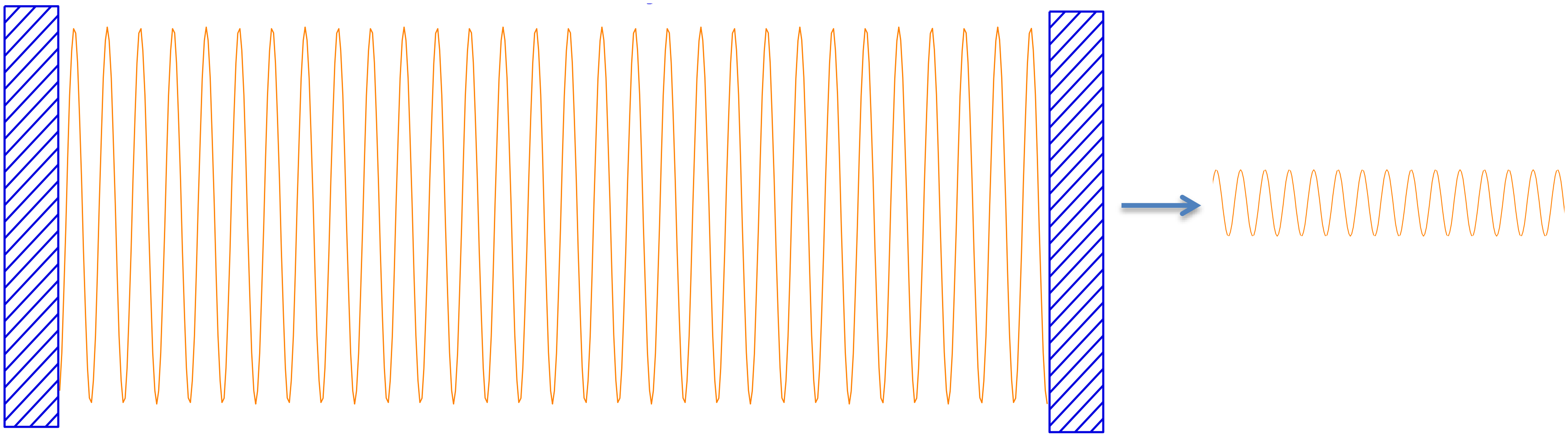


First, make the field steady -
Stable optical cavity

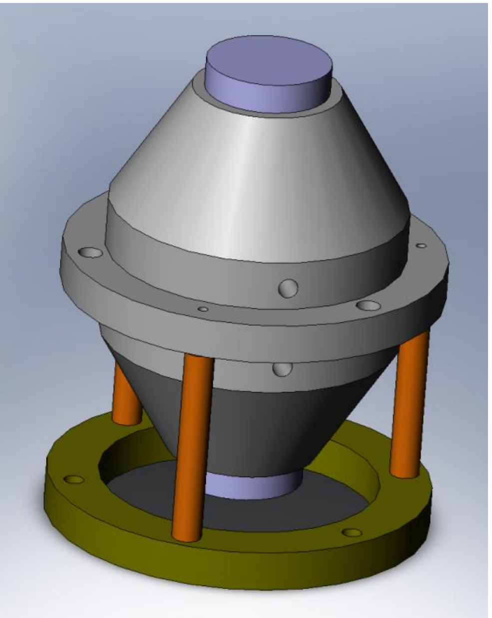


Cavity length 1 m	:	fits 10^6 optical waves	(10^{-6})
Finesse 10^5	:	error amplified by 10^5	(10^{-11})
Division of a cycle	:	10^5	(10^{-16})

Laser is the Central Ruler of Time & Space



Cavity length L ~ 1 m → ΔL ~ 10^{-16} m (size of a nucleus: 10^{-14} m)



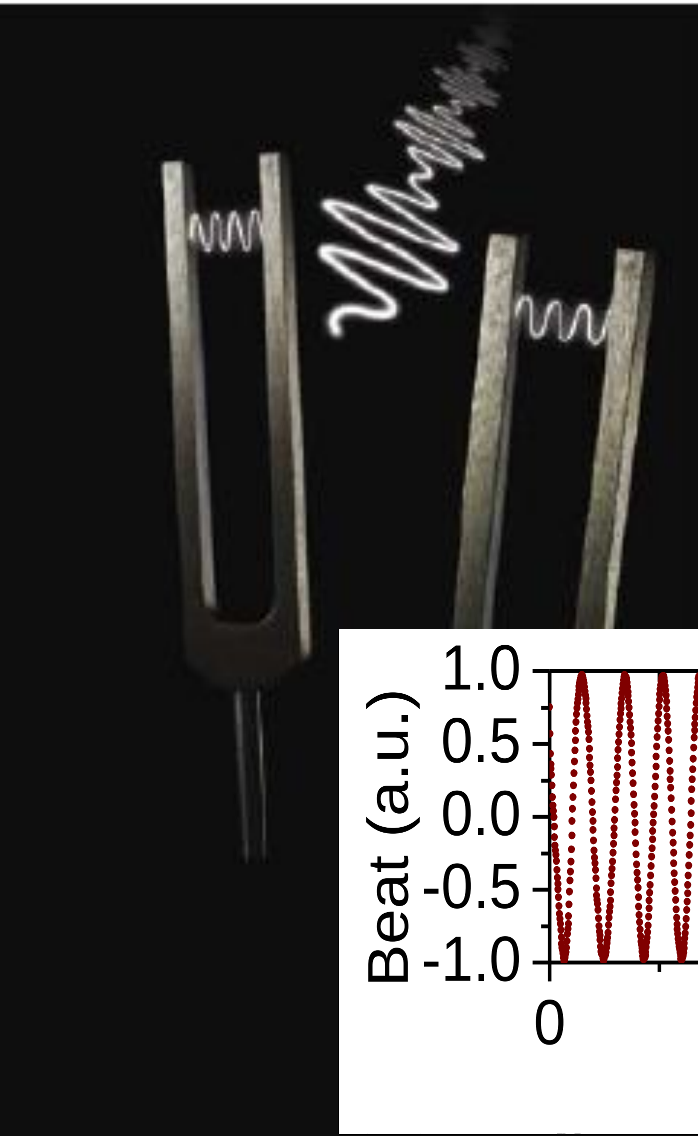
Connected by the speed of light, Length joins Time/Frequency as the most accurately measureable quantity.

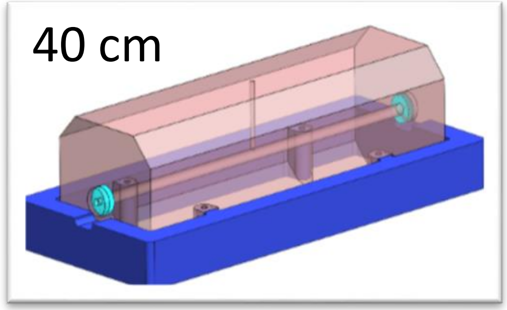
Ludlow *et al.*,
Opt. Lett. **32**, 641 (2007).

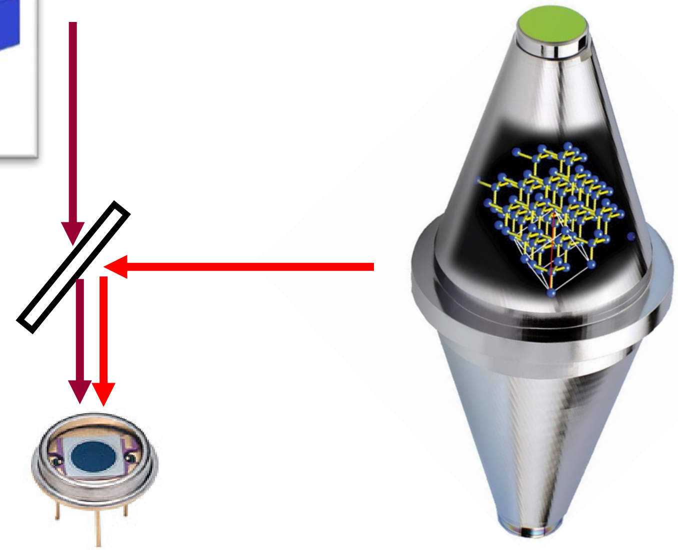
Coherence – how long a wave lasts

~10 s

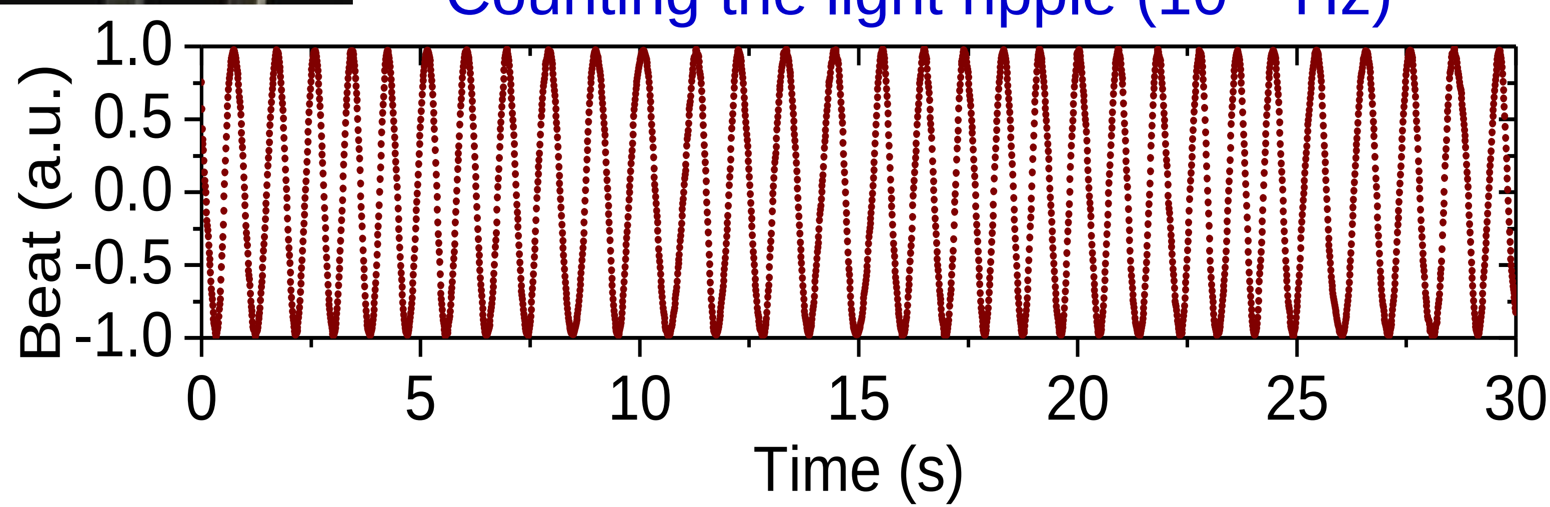
Beating of two sound waves (10^3 Hz)



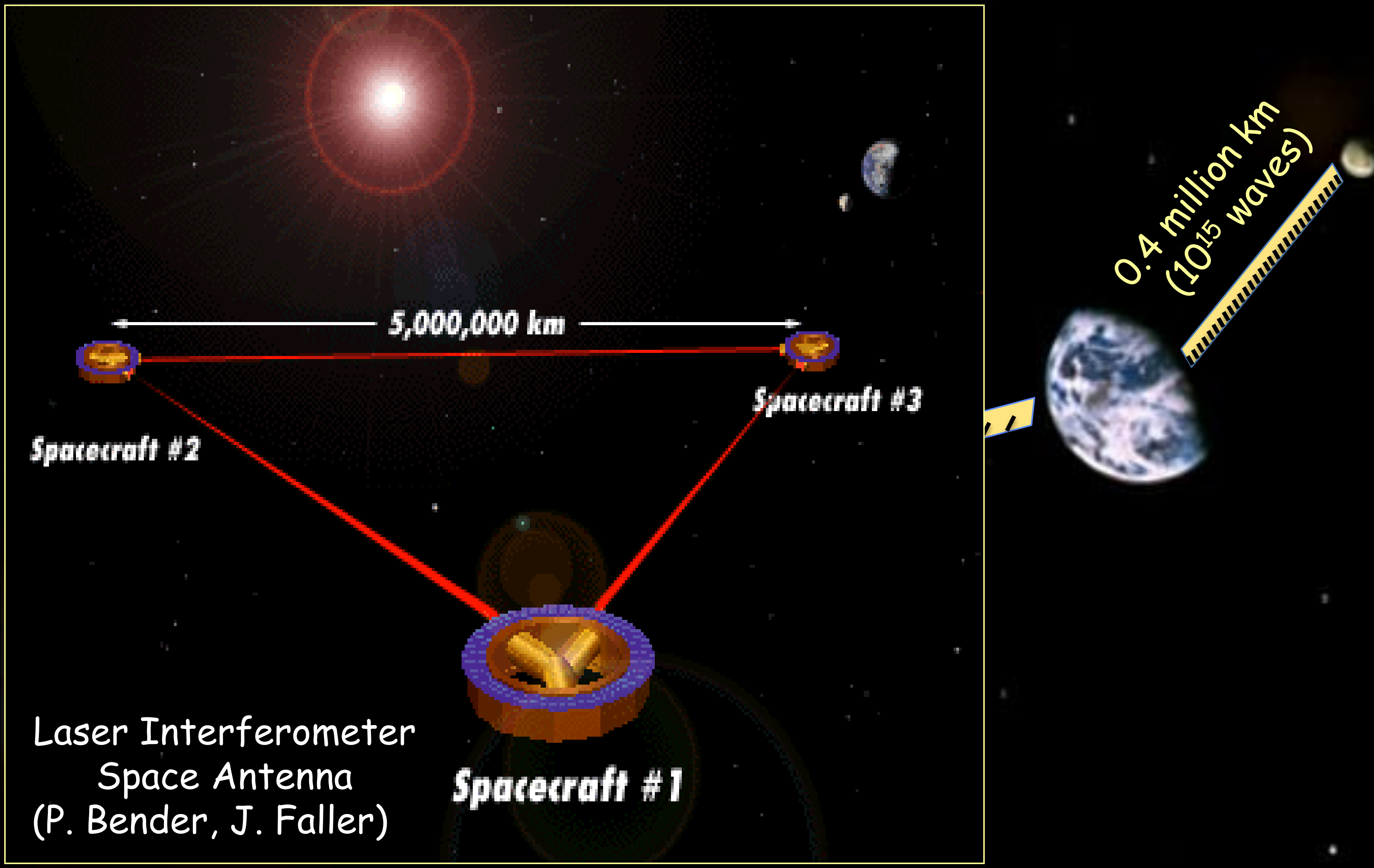




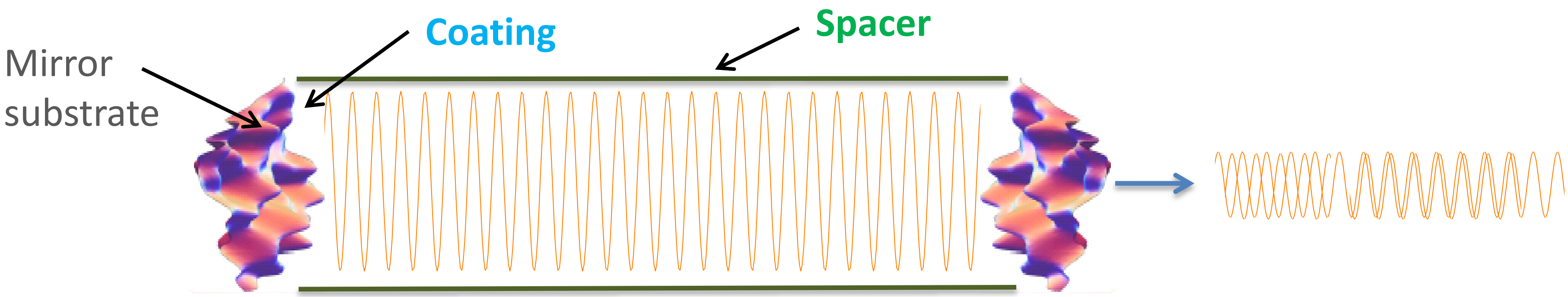
Counting the light ripple (10^{15} Hz)



A Ruler for the Universe

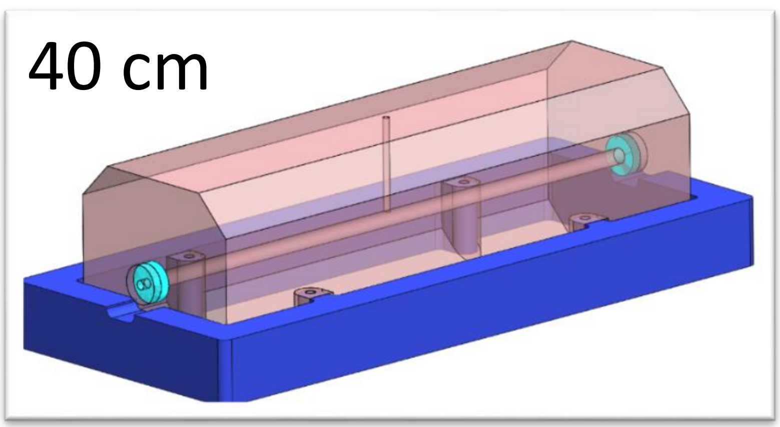


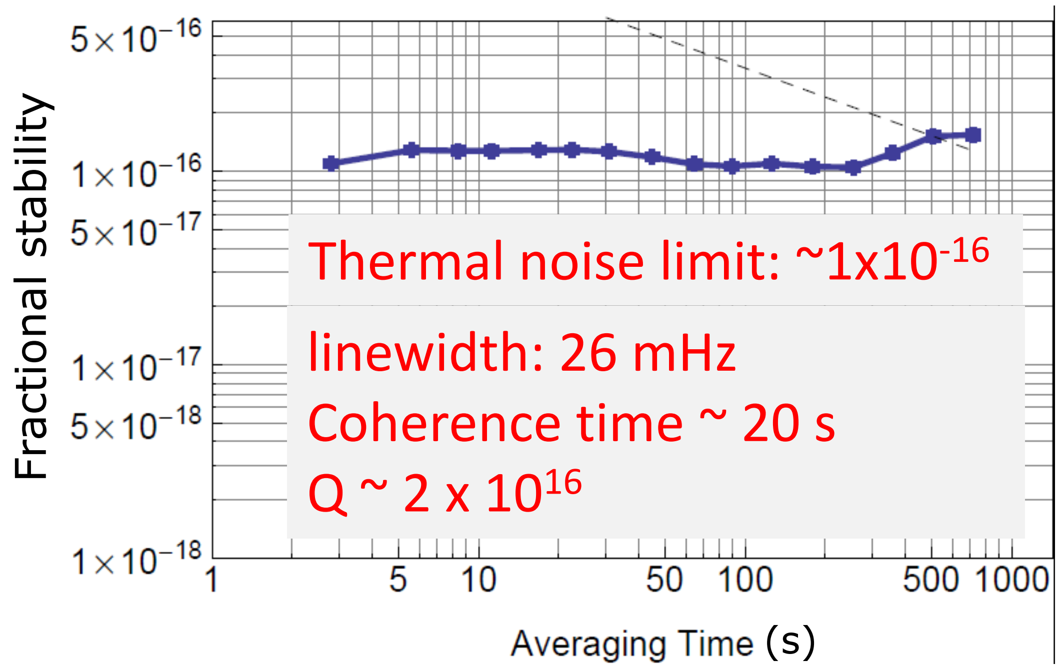
Optical coherence & spectral resolution



Cavity length L ~ 1 m → ΔL ~ 10^{-16} m

Mirror Thermal Noise: a fundamental process





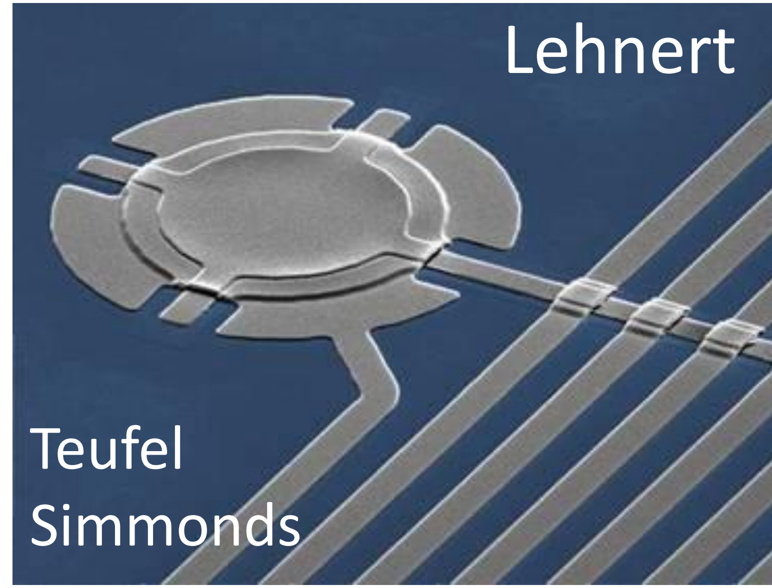
JILA Sr large ULE cavity:

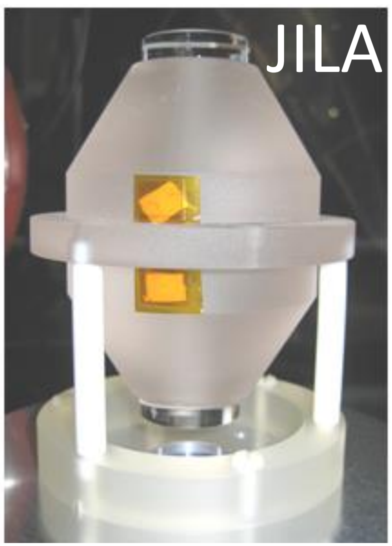
Bishof *et al.*, PRL **111**, 093604 (2013).

Thermal noise: a challenge for all !

- The best interferometers (at all scales) are thermal noise limited
- Many scientific communities attempting to make similar advances

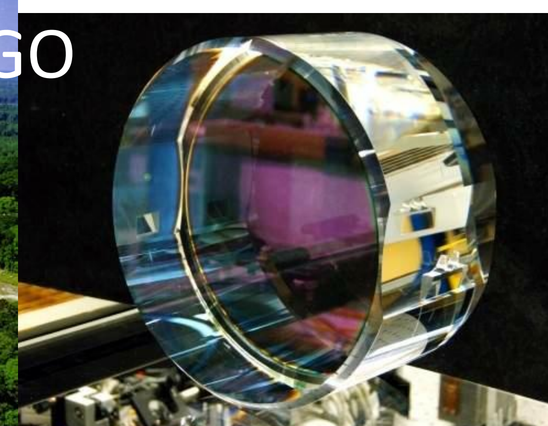
15 μm



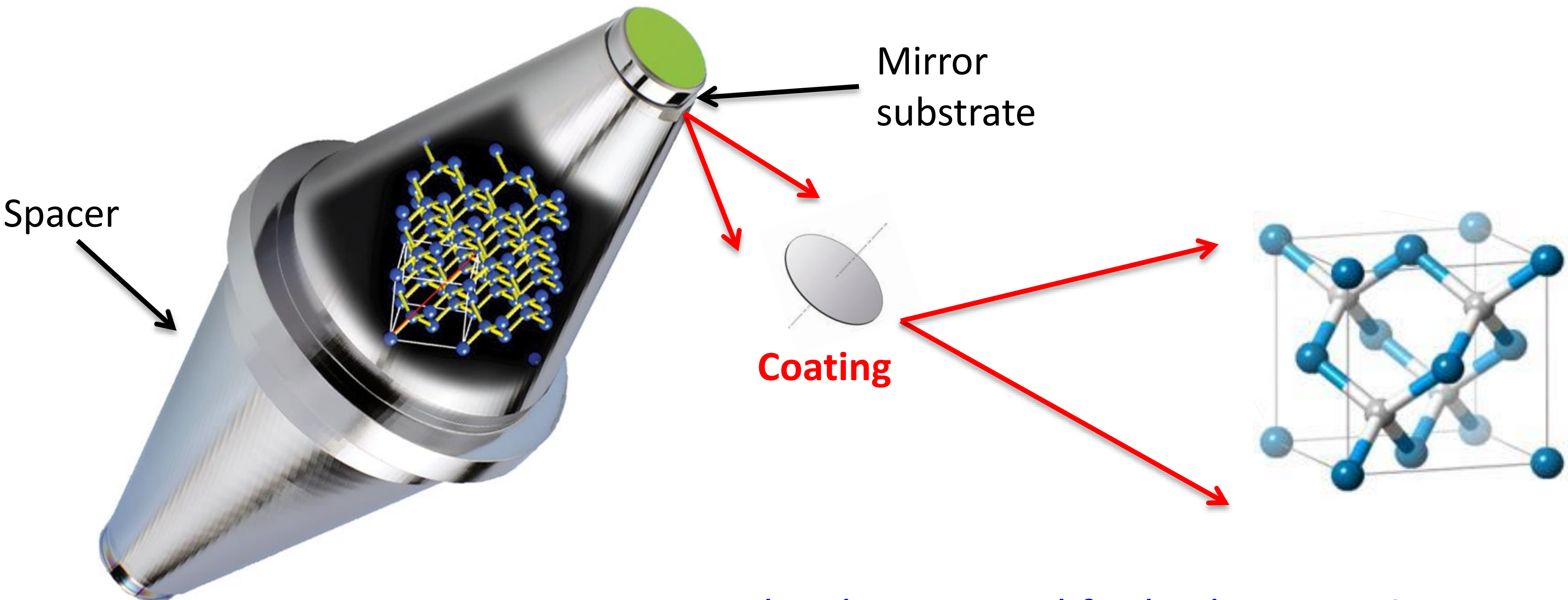


10 cm

1 km



Single-crystal optical cavity



- A single Silicon crystal for both spacer & mirrors
- Mechanically stiff – and low loss (large E_0 & Q)
- Thermal expansion coefficient = 0 at T = 124 K

- Crystalline optical coating (AlGaAs)

$$\text{Thermal noise} \sim \sqrt{\frac{T}{E_0 Q}}$$

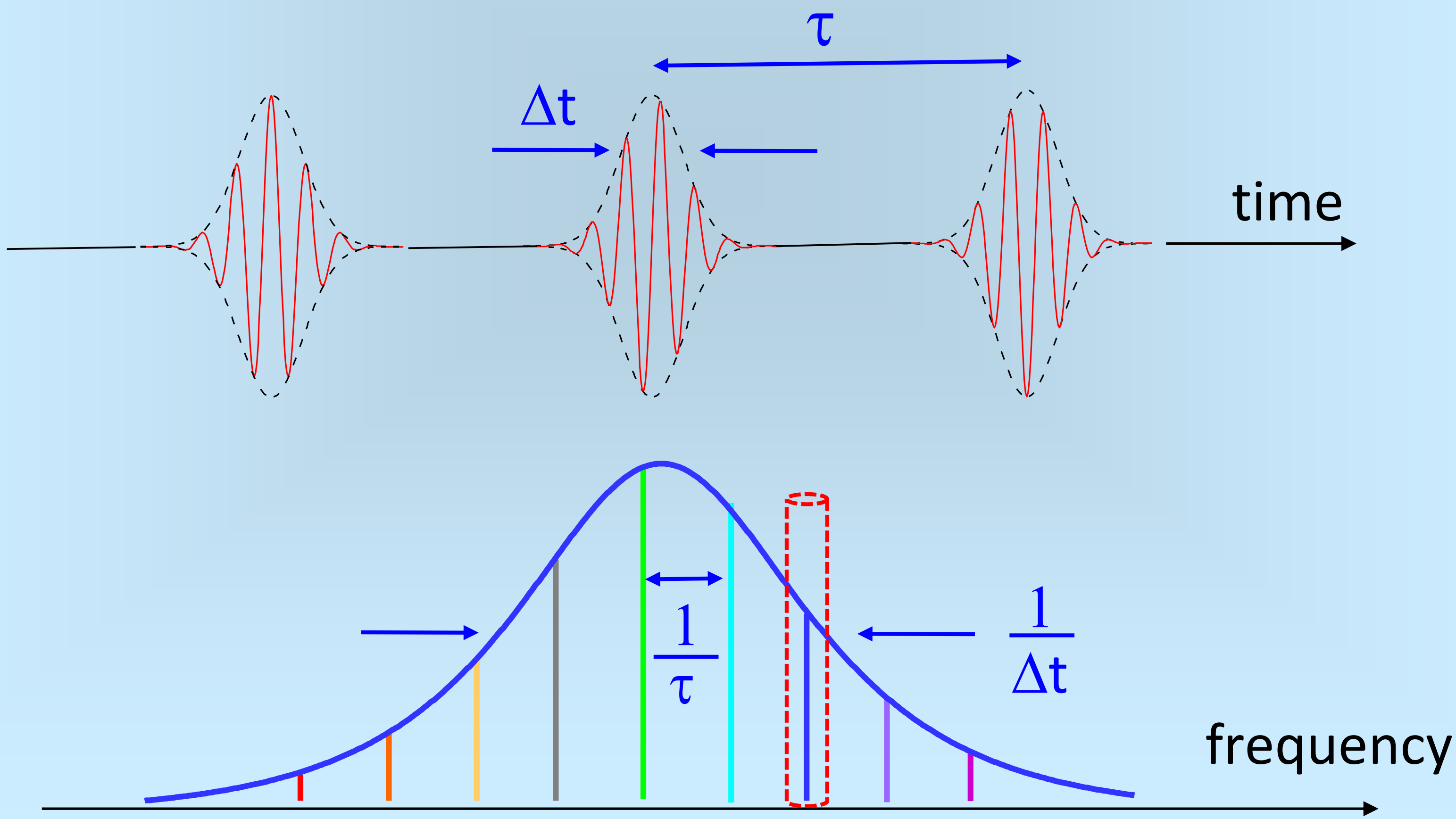
PTB – JILA: Silicon crystal cavity
Nature Photon. **6**, 687 (2012).

Vienna – JILA: 10^{-17} feasible
Nature Photon. **7**, 644 (2013).

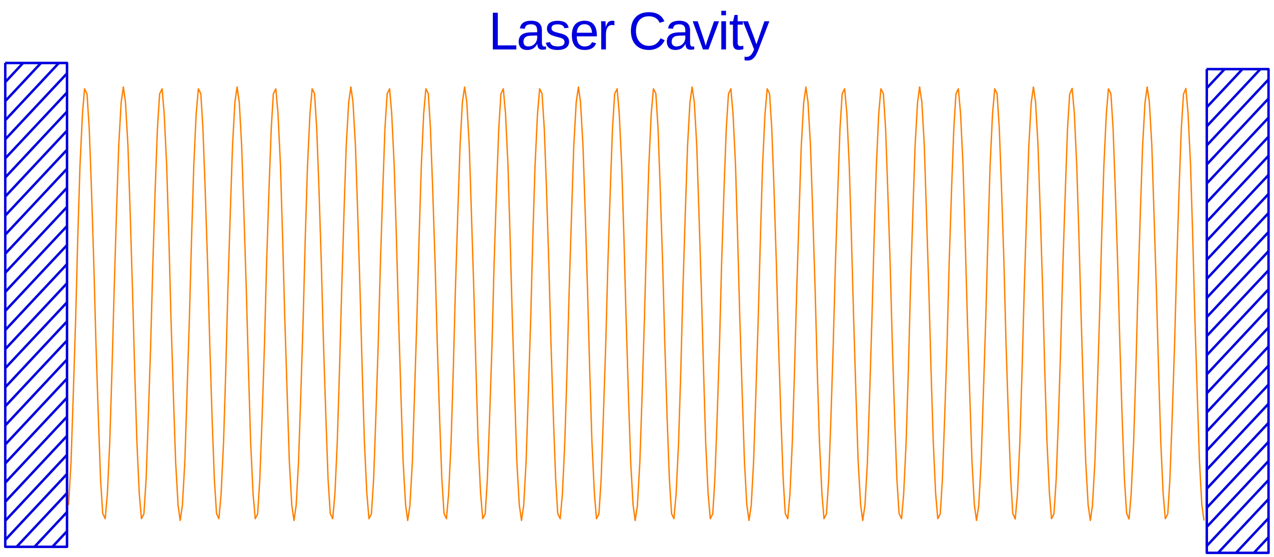
Time - frequency correspondence

(from one optical frequency to many)

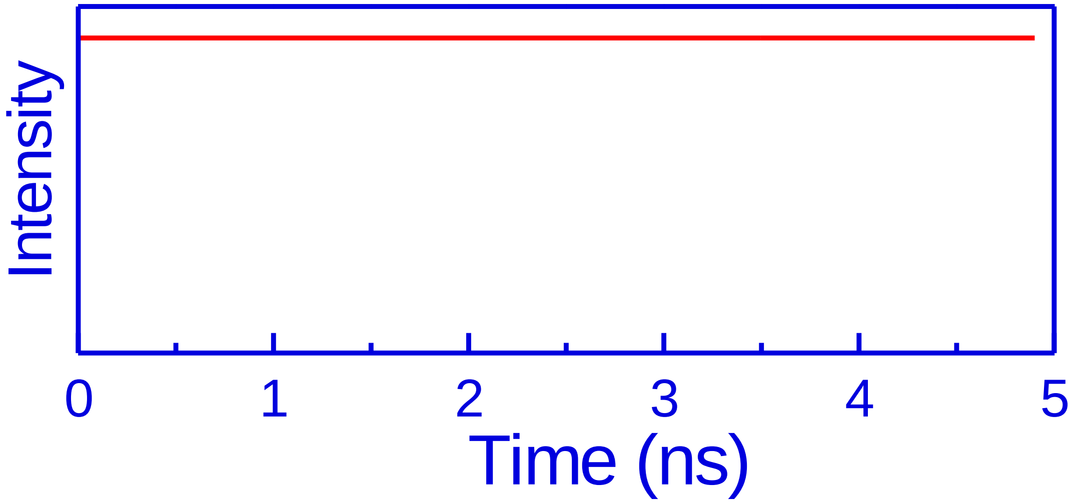
- Temporal pulse width ⟷ Spectrum bandwidth
- Train of pulses ⟷ comb of frequencies



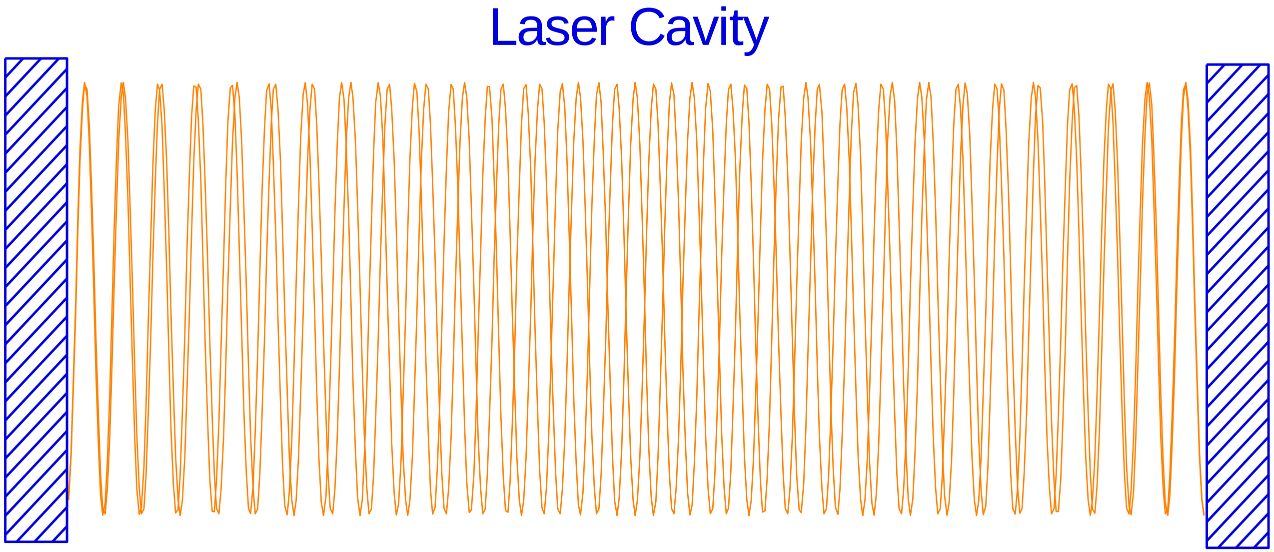
Modelocking



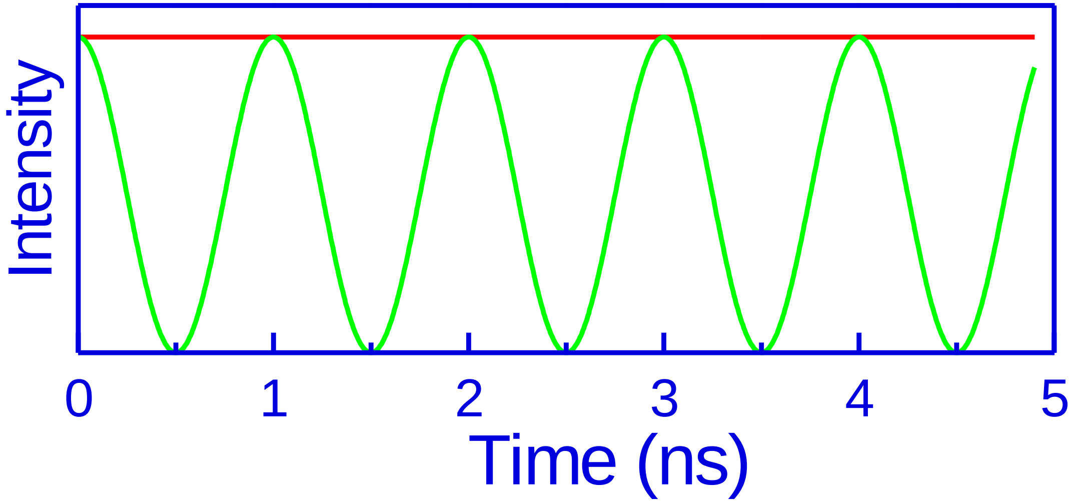
Single mode
cw laser



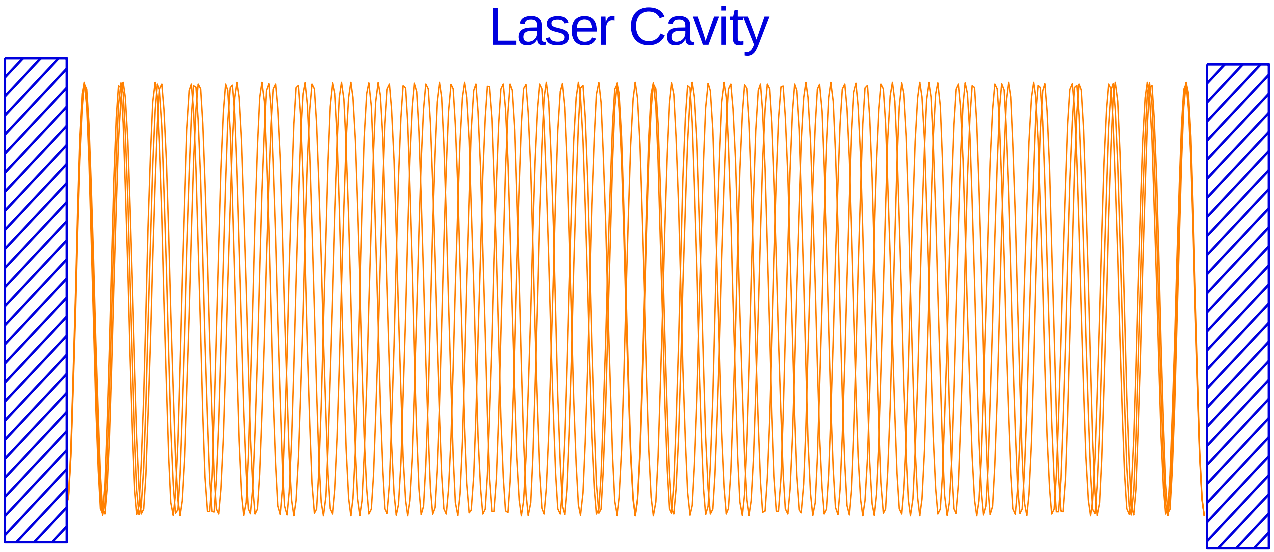
Modelocking



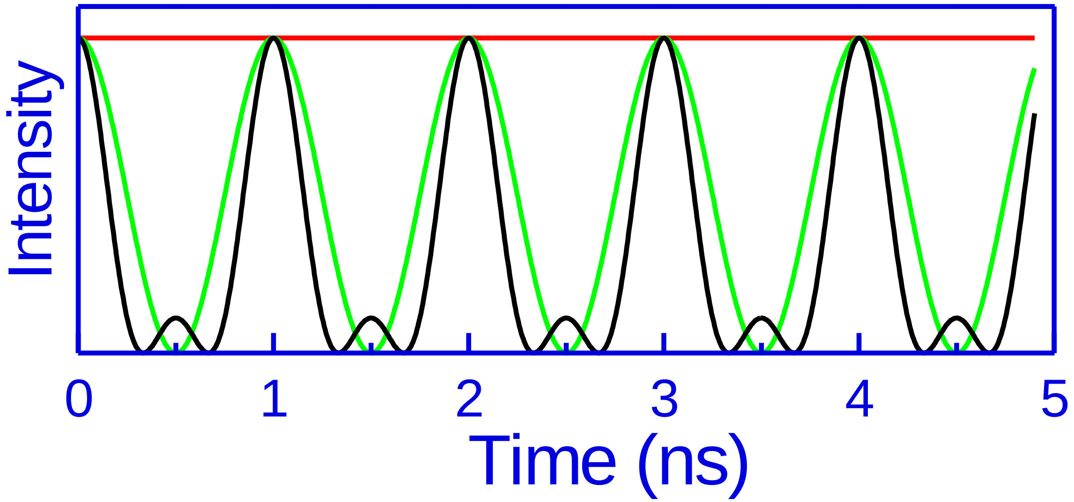
2 modes



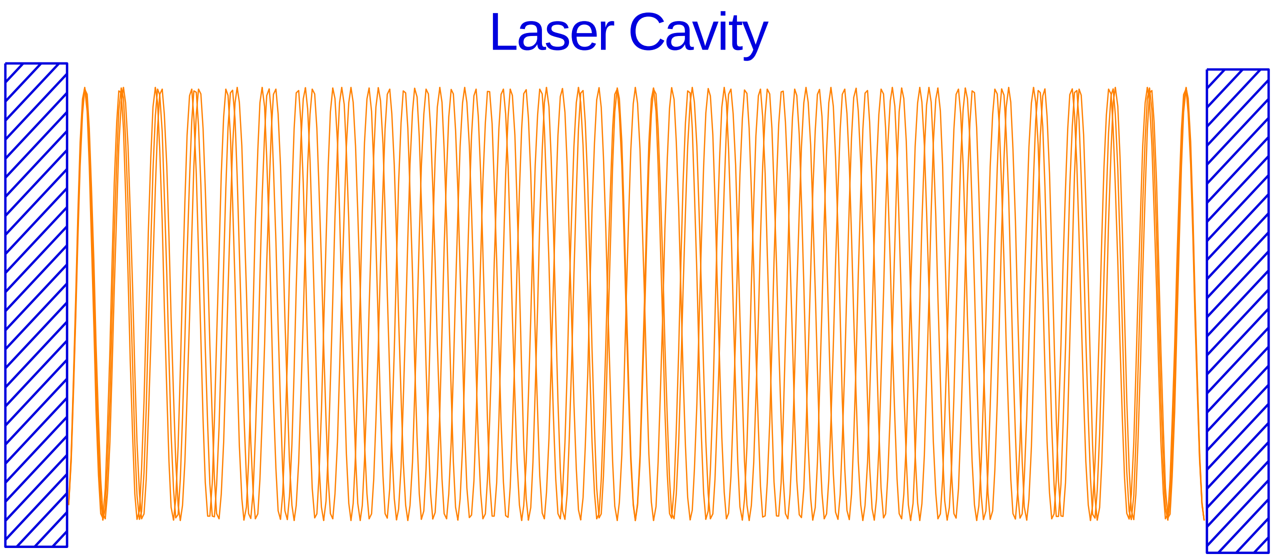
Modelocking



3 modes

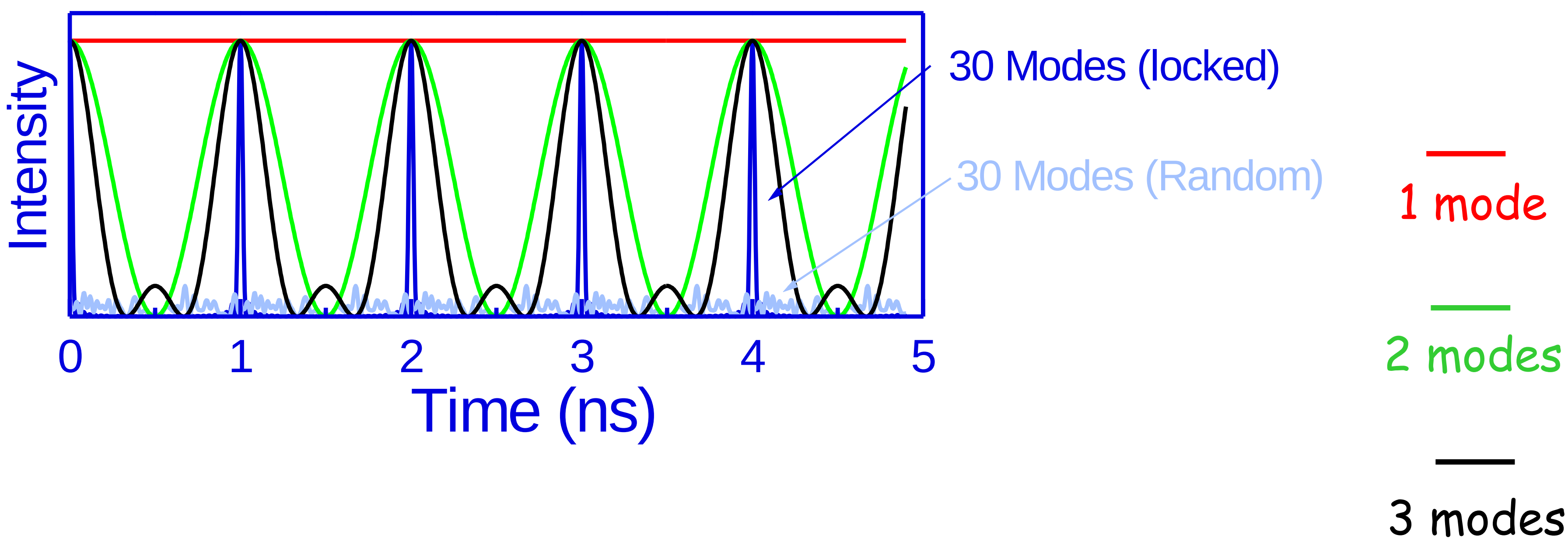


Modelocking

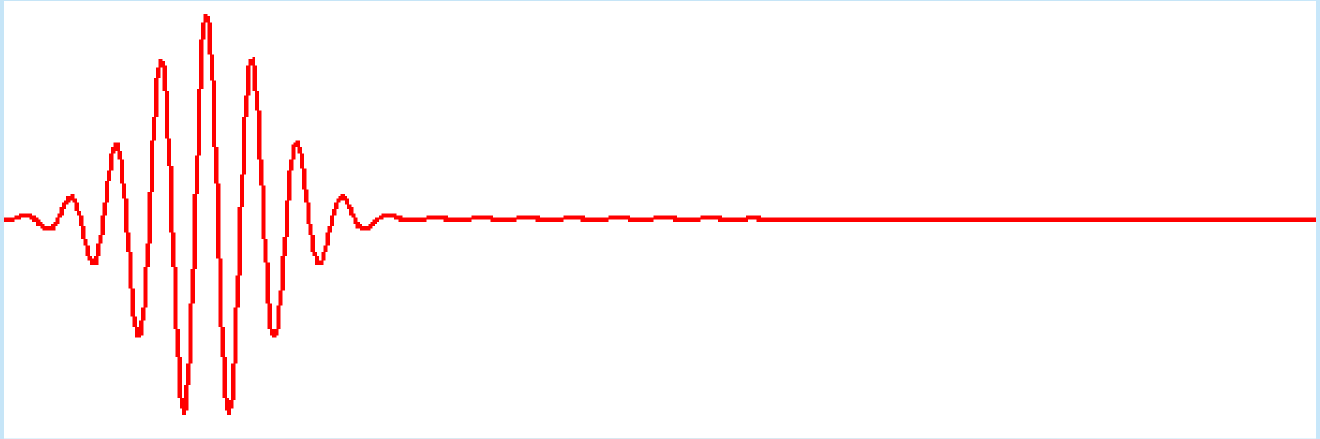


2 degrees of freedom:
- single-mode phase
- dispersion

Constructive interference among phase-locked cavity modes



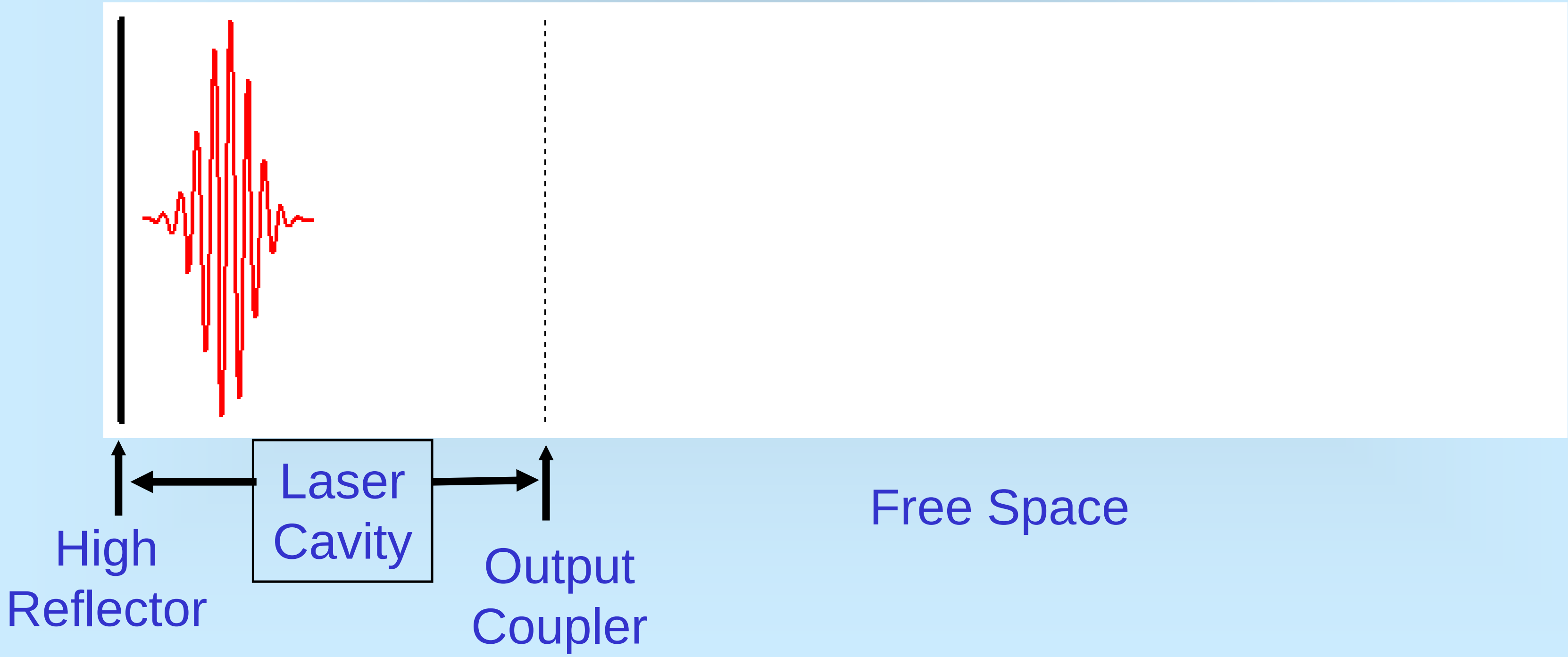
Group vs. Phase Velocity



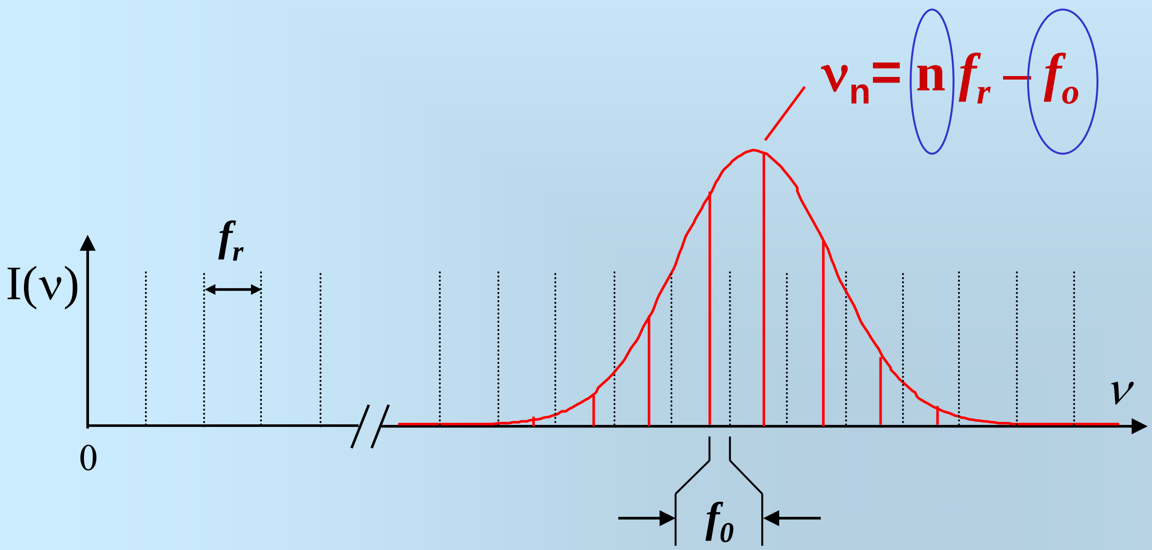
- In any material, the group and phase velocities differ
- Carrier phase slowly drifts through the envelope as a pulse propagates

Group vs. Phase in Modelocked Lasers

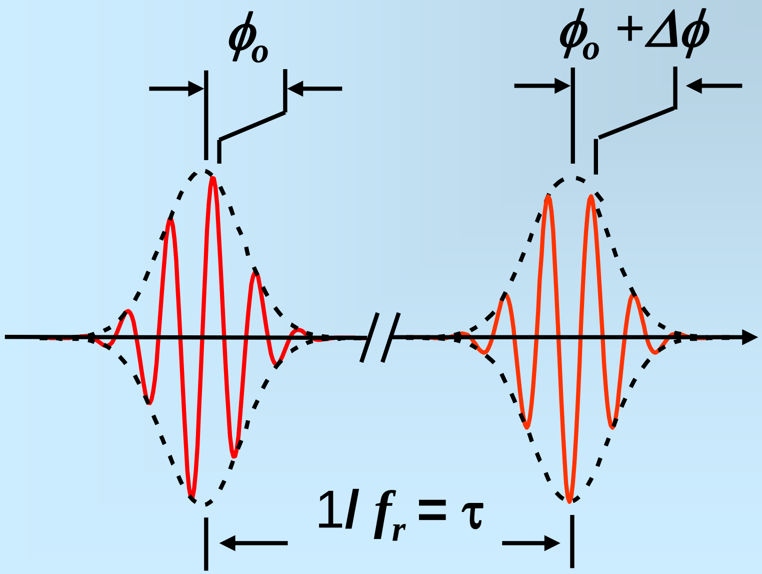
Each emitted pulse has a distinct envelope-carrier phase
– due to group-phase velocity difference inside cavity



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

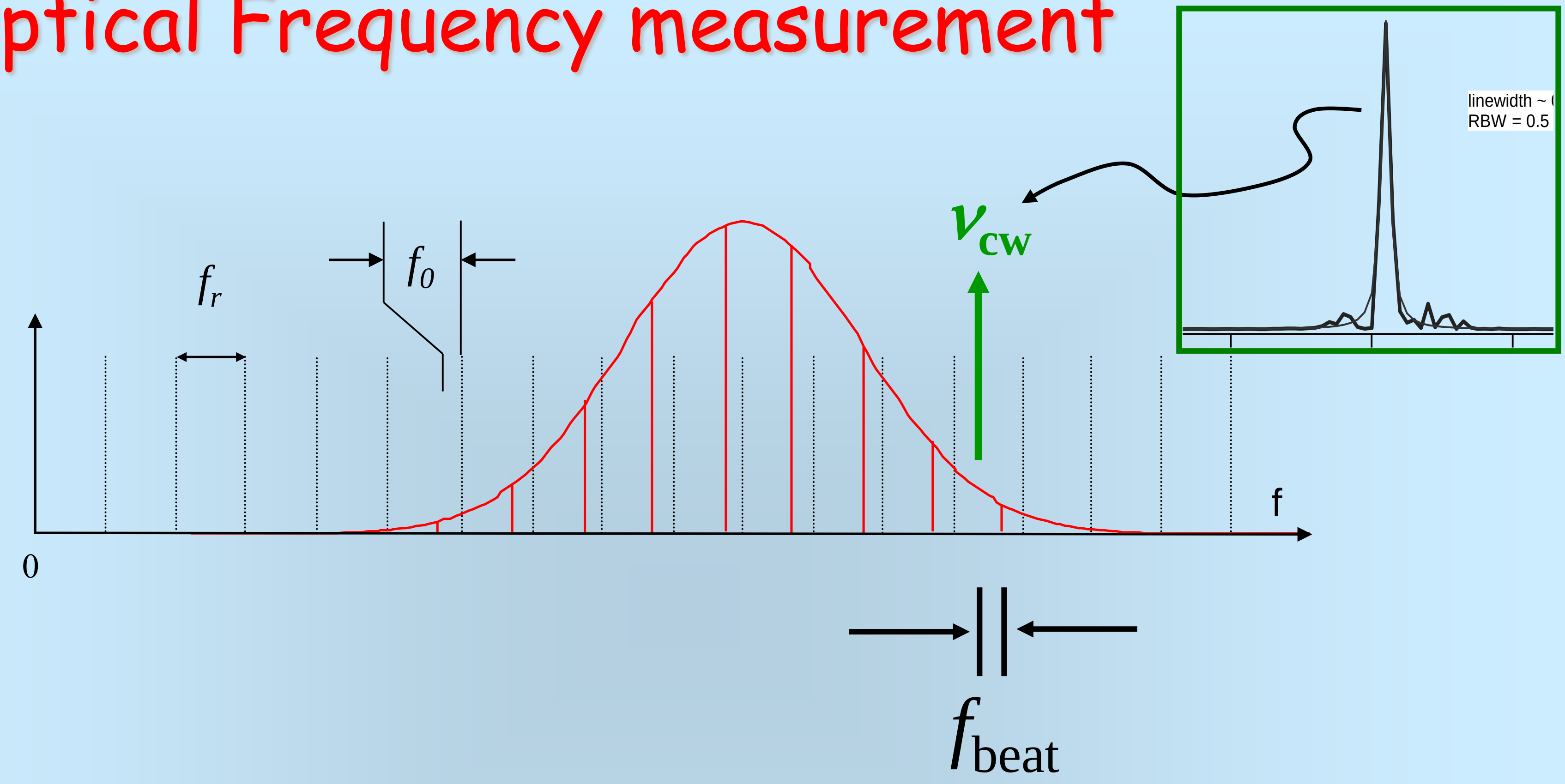


$$2\pi\nu_n \cdot \tau + \Delta\phi = 2n\pi \rightarrow$$

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

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



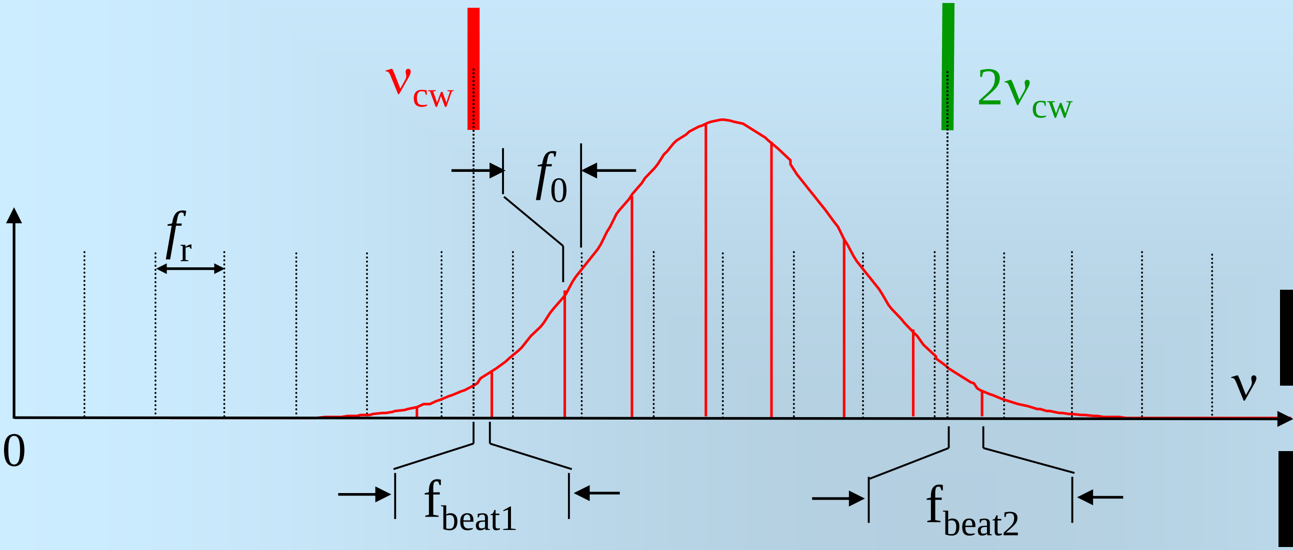
$$f_{beat} = n f_r + f_0 - \nu_{cw}$$

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

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

Optical octave bandwidth

- a quick way to measure and control f_0



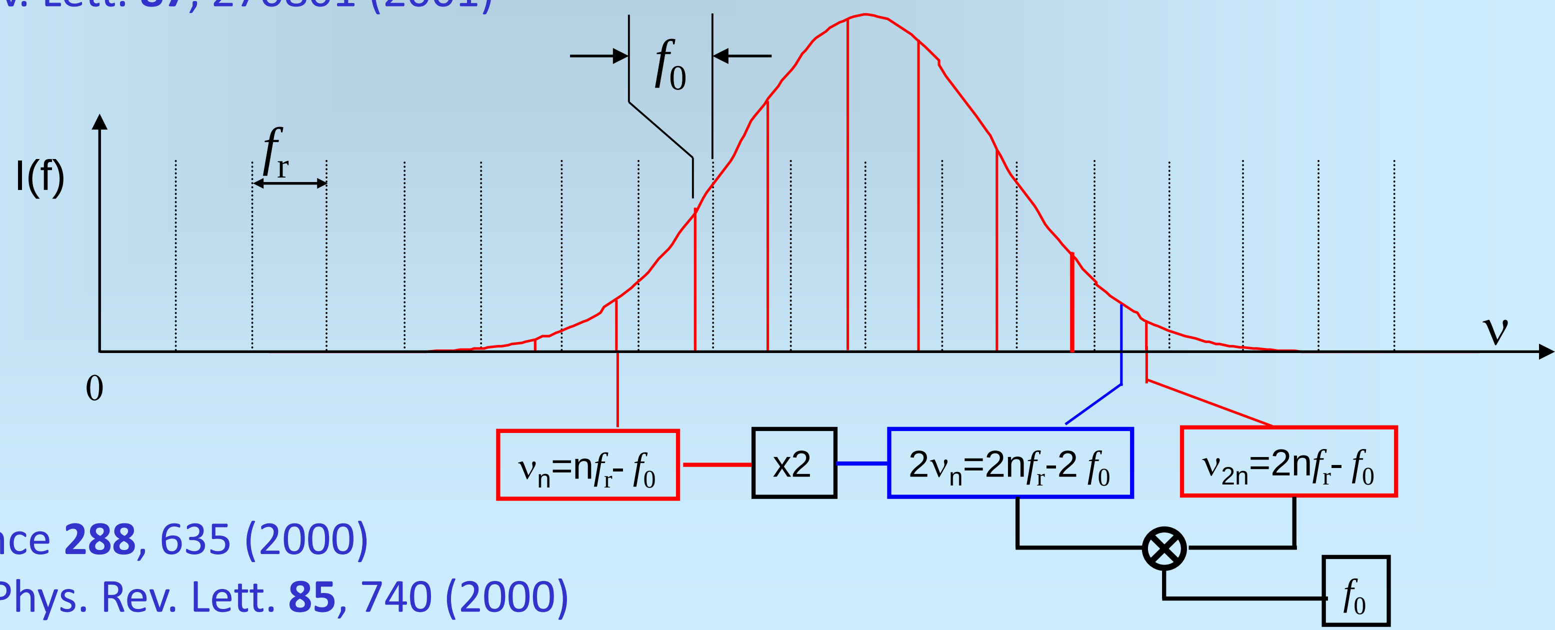
$$f_{beat1} = n f_r + f_0 - \nu_{cw}$$

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

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

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

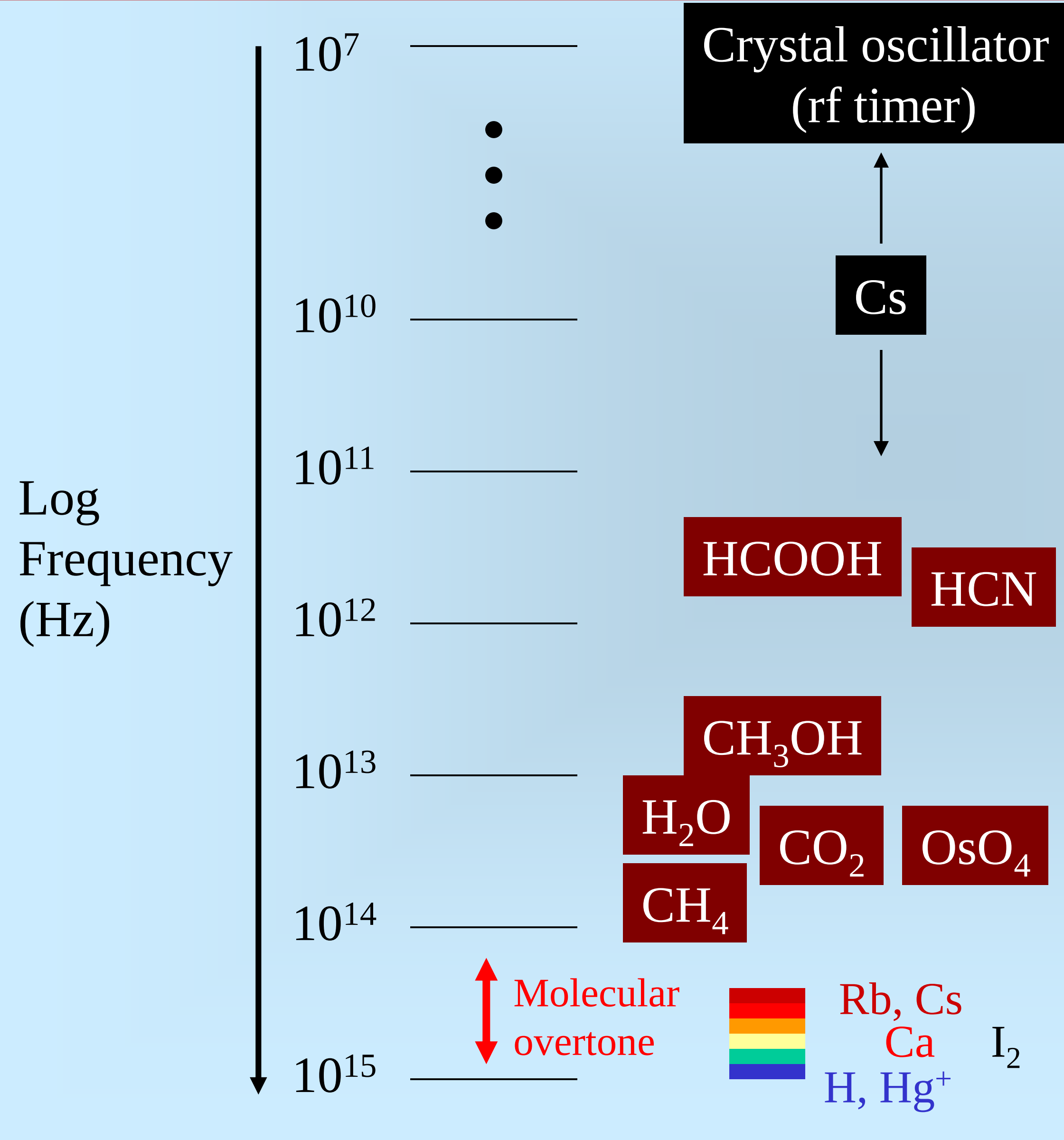
Ye *et al.*, Phys. Rev. Lett. **87**, 270801 (2001)

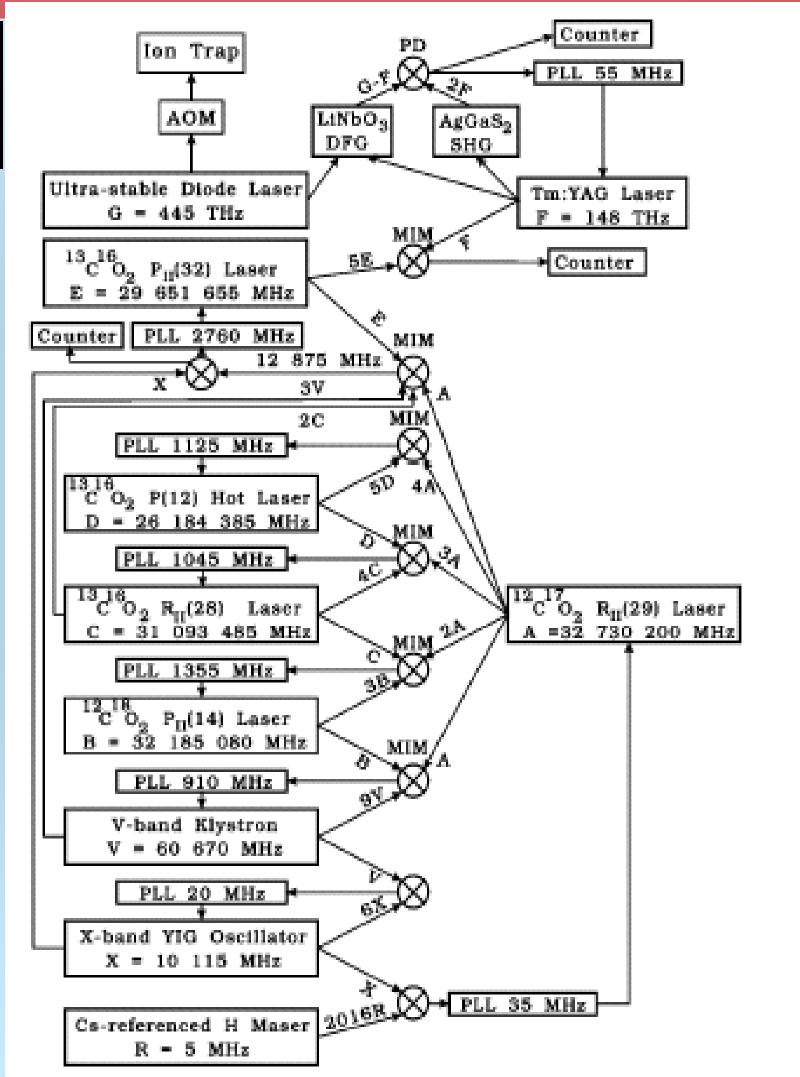


Jones *et al.*, Science **288**, 635 (2000)

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

Frequency spectrum in optical frequency synthesis

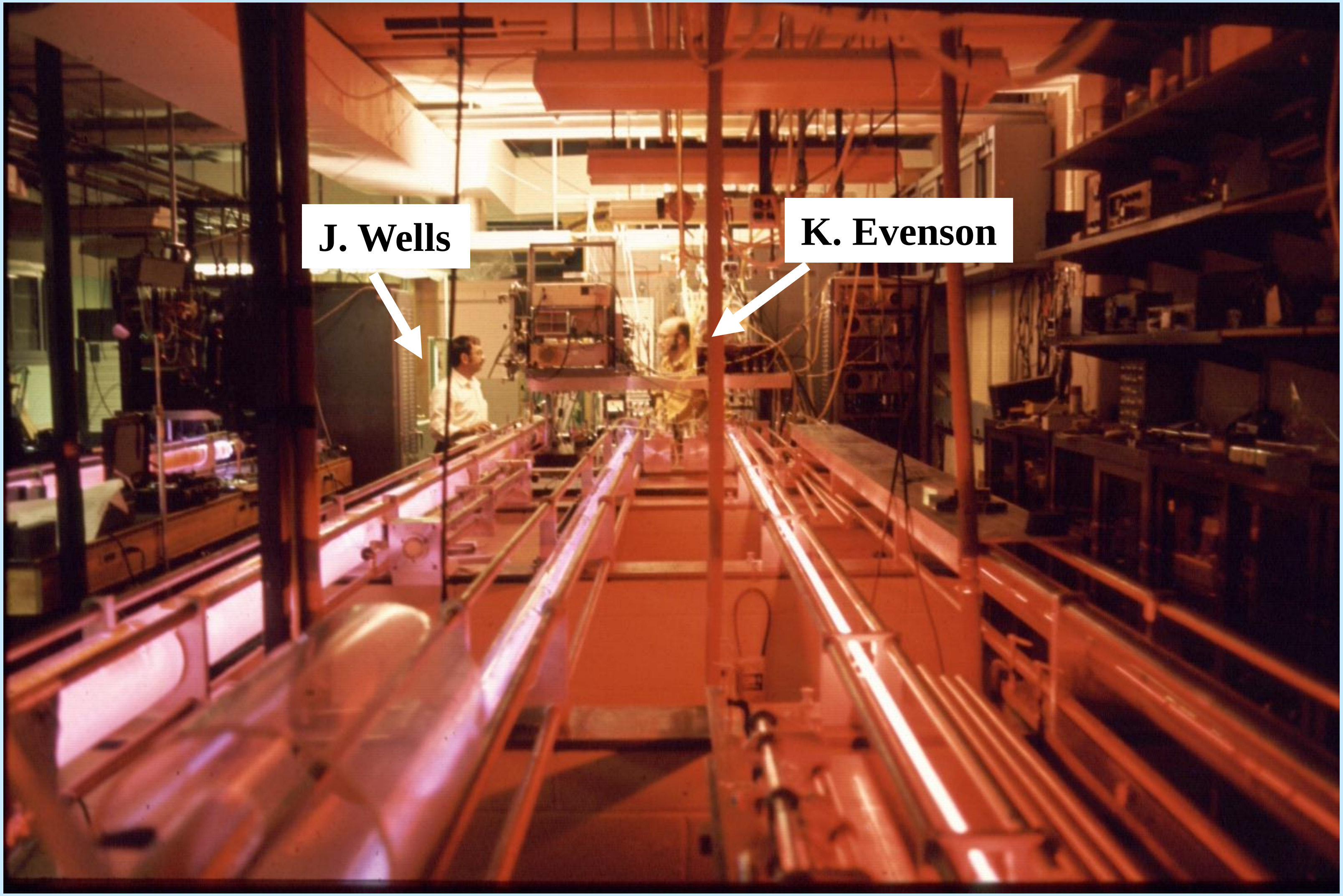




Harmonic frequency chains, PTB, NRC, …
H. Schnatz *et al*., PRL **76**, 18 (1996).

The First Optical Frequency Chain

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

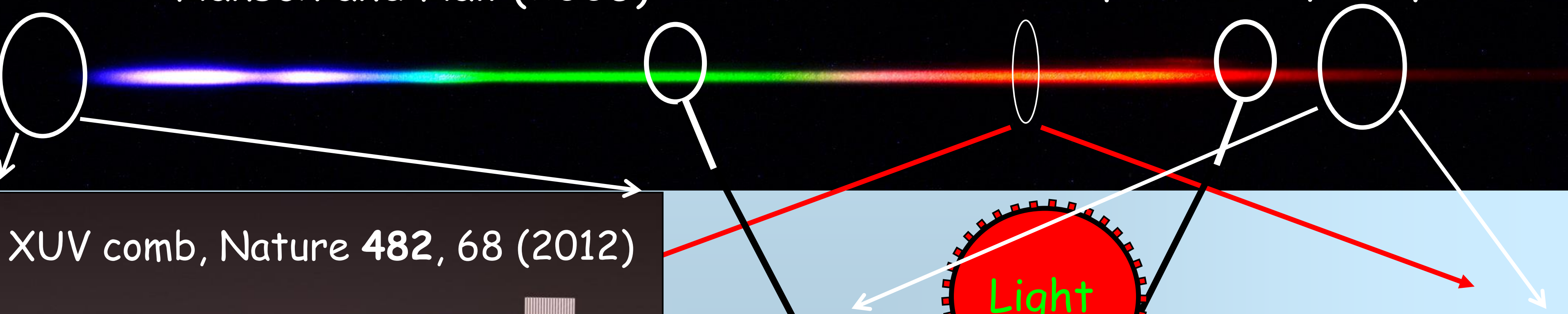


J. L. Hall & J. Ye, "NIST 100th birthday", Optics & Photonics News **12**, 44, Feb. 2001

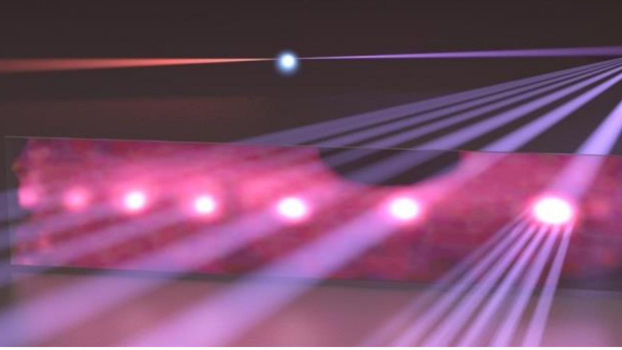
Ultrafast meets ultraprecision
- A million lasers with 10^{-16} precision

Hänsch and Hall (2005)

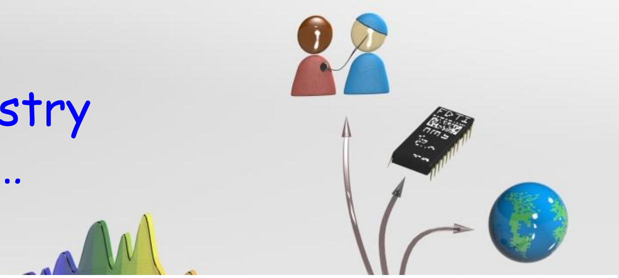
Optical frequency comb

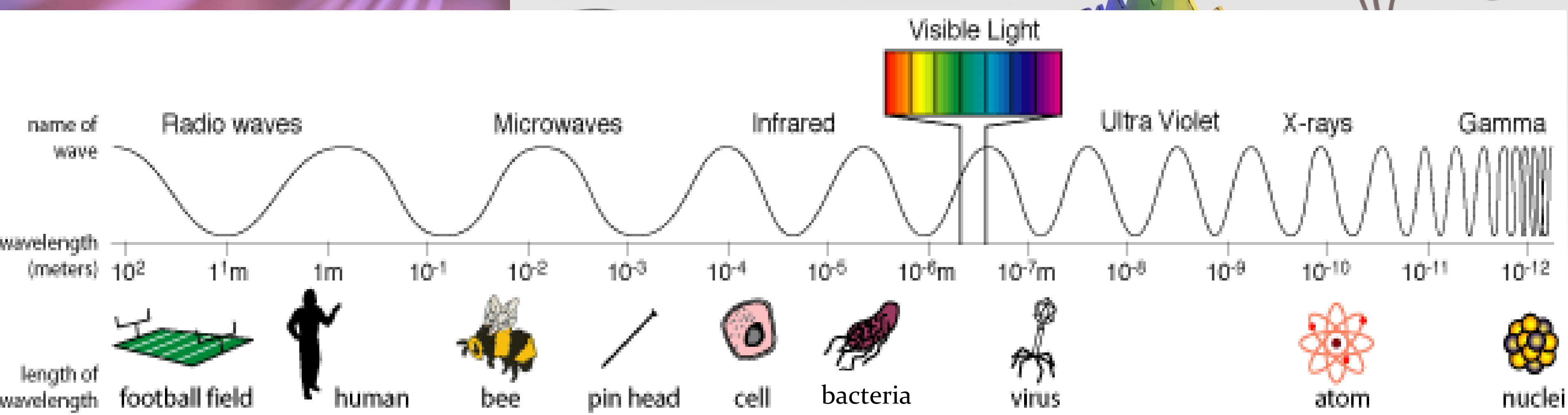


XUV comb, Nature **482**, 68 (2012)

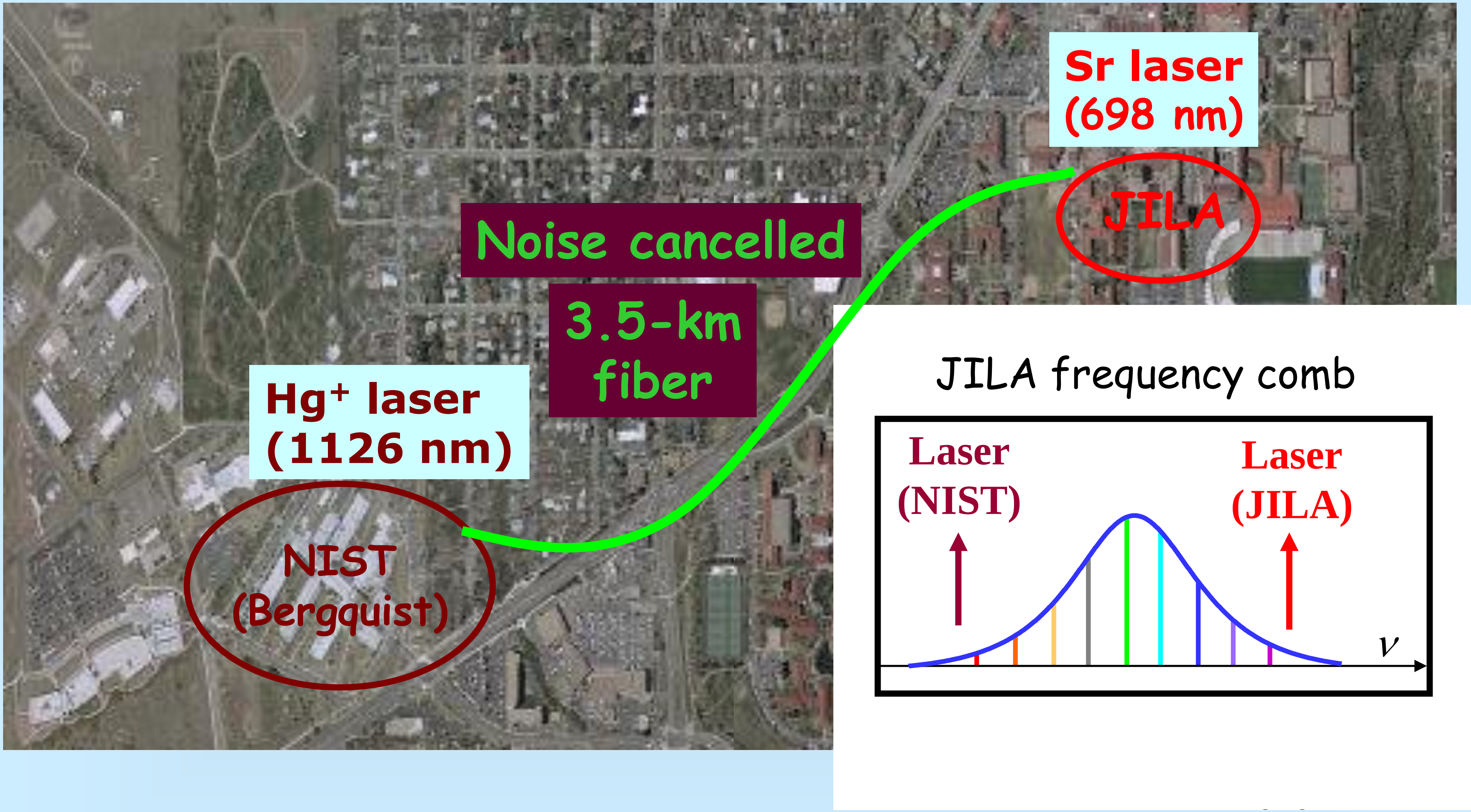


Optical nose for:
medicine, environment, industry
Science **311**, 1595 (2006), …





Optical phase comparison
- two spatially & spectrally separated lasers

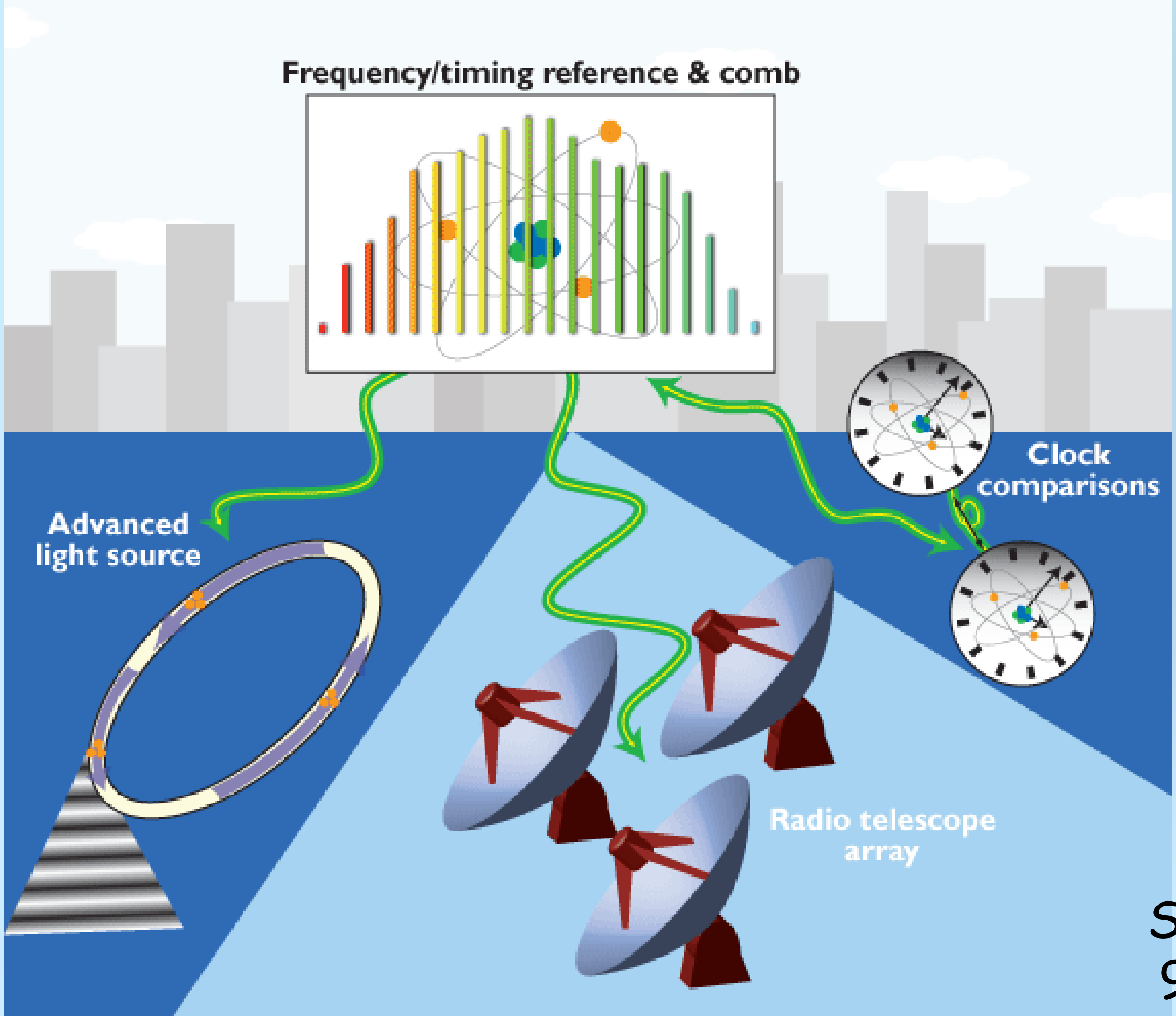


Foreman et al., Phys. Rev. Lett. **99**, 153601 (2007).

Precise distribution of ultra-stable signals

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

SYRTE, PTB, NIST, INRIM, …



100 km fiber:

1×10^{-17} @ 1 s;

1 Hz optical linewidth;

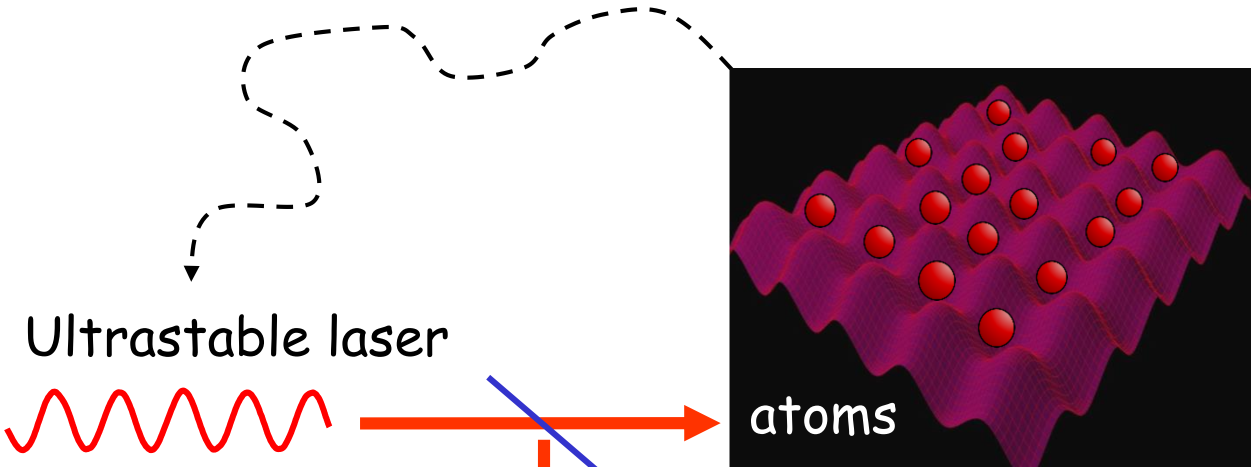
0.1 fs jitter (20 MHz BW)

Predehl et al.,
Science **336**, 441 (2012).
900 km link in Germany

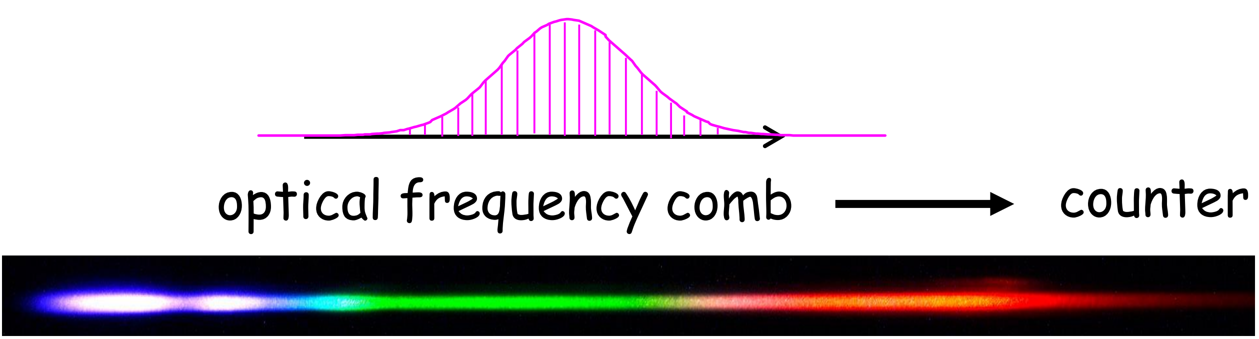
Optical Atomic Clock

Bloom *et al.*, Nature **506**, 71 (2014).

Boyd *et al.*,
Science **314**, 1430 (2006).



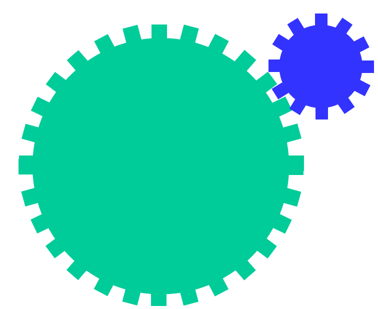
Linewidth: 0.03 Hz
Bishof *et al.*, PRL **111**,
093604 (2013).



Oscillator

Quality factor
>10^{17}

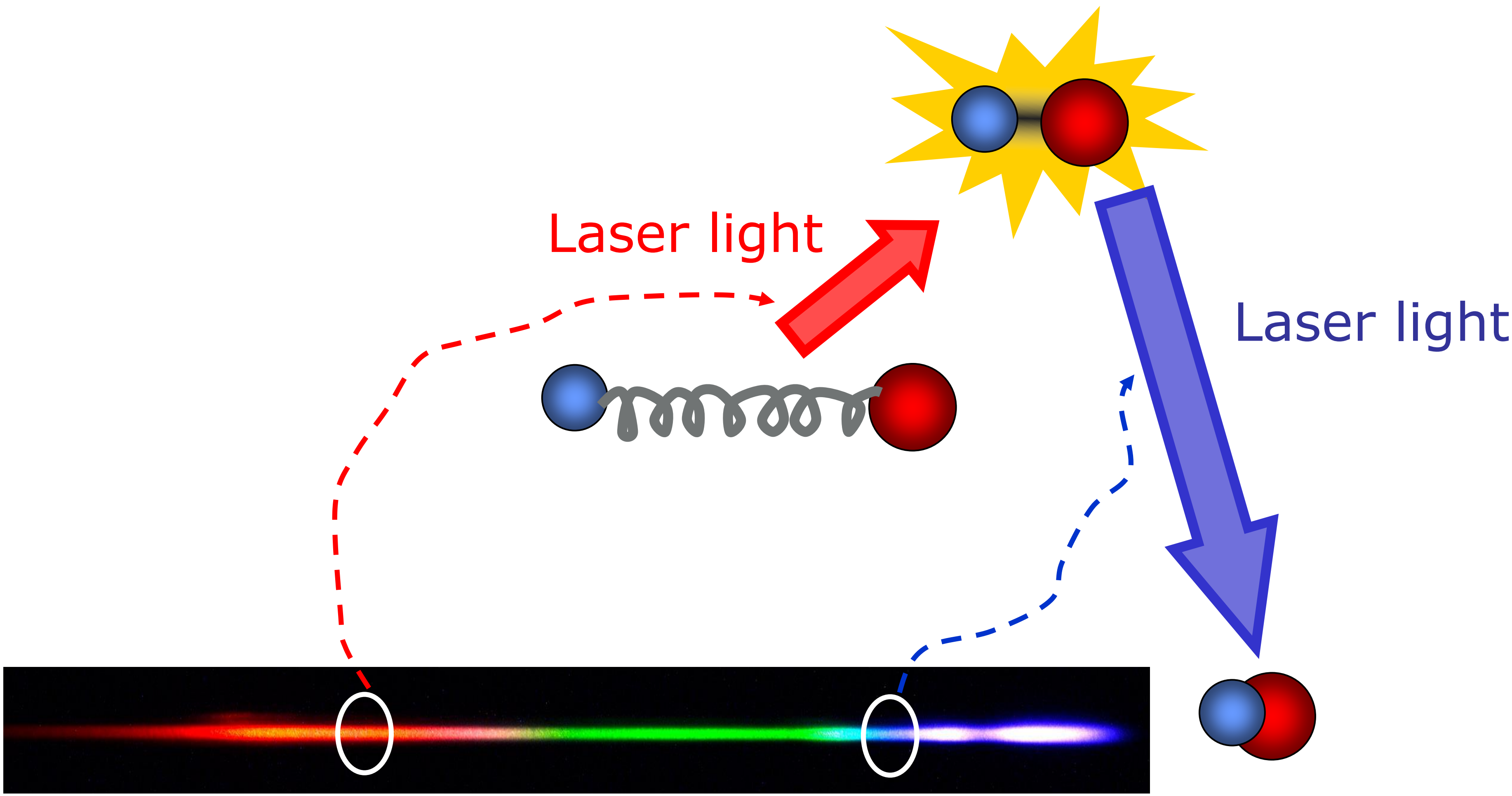
Counter



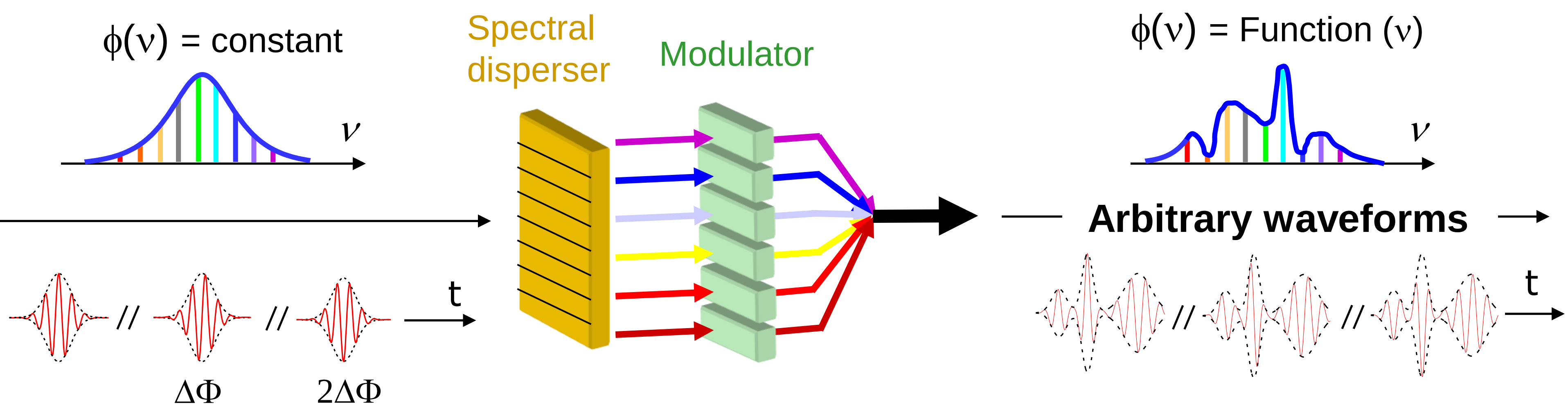
Teach atoms to form molecules
- chemistry near absolute zero

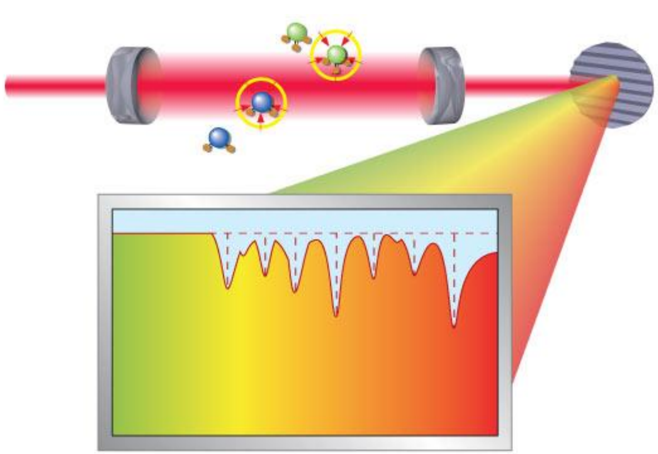
Science **322**, 231 (2008)

Photons carry away the energy!



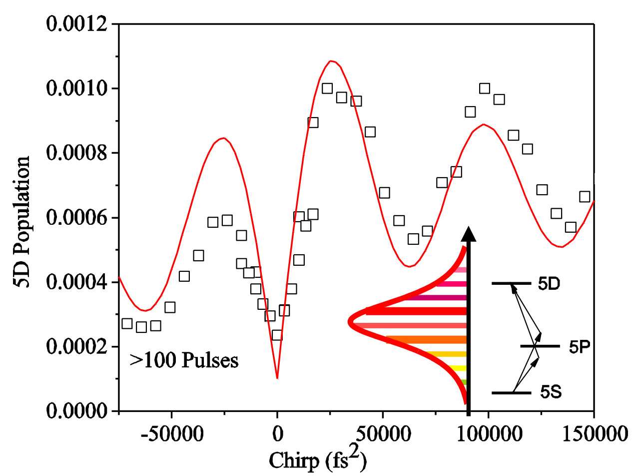
Optical Arbitrary Waveform Generation





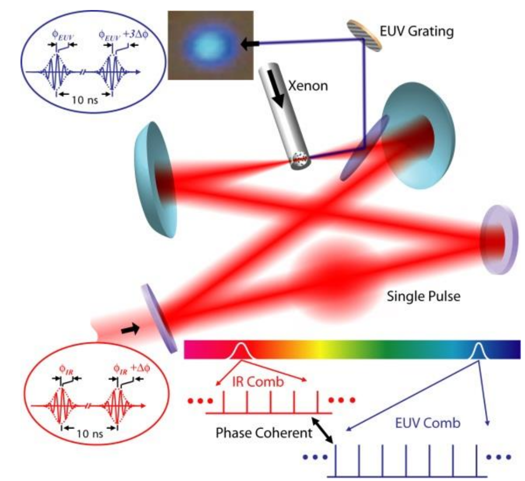
Molecular spectroscopy (cold molecules)

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



Quantum control

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



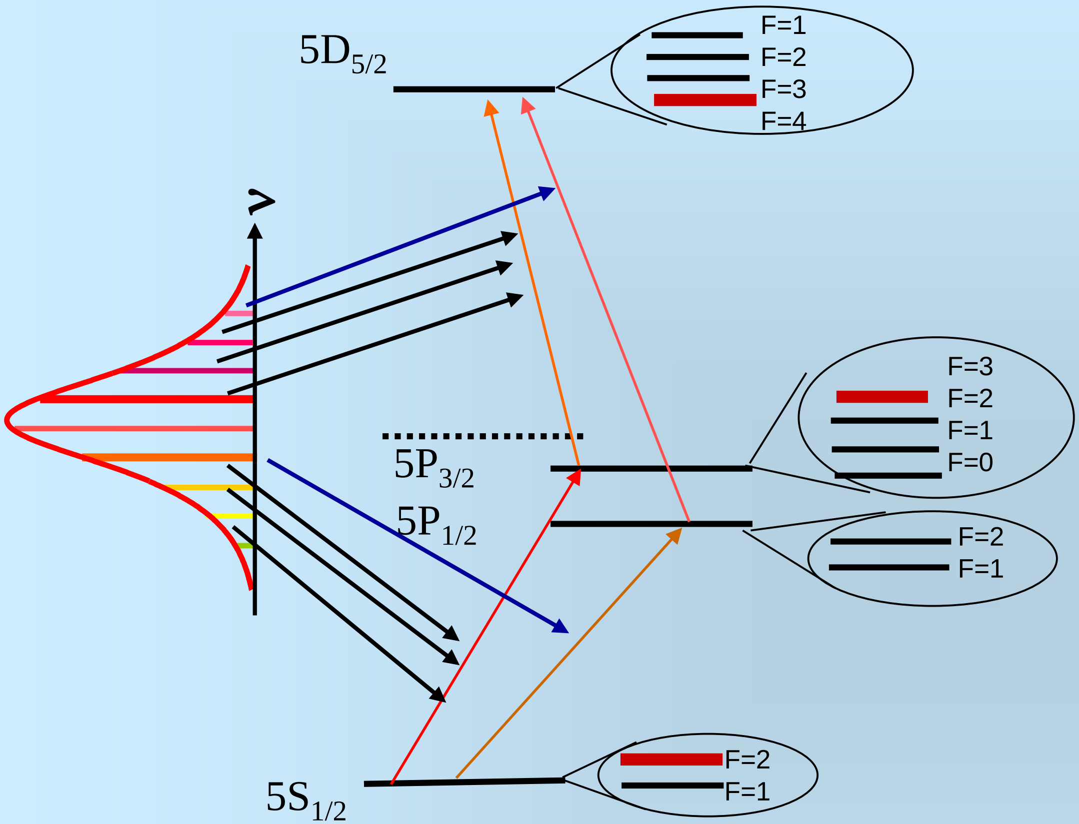
XUV comb

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

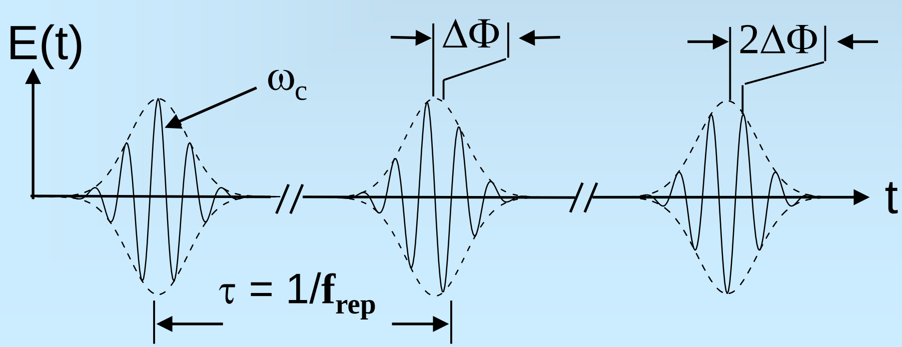
Direct Frequency Comb Spectroscopy

Marian *et al.*,
Science **306**, 2063 (2004).

Stowe *et al.*,
Phys. Rev. Lett. **96**, 153001 (2006).
Phys. Rev. Lett. **100**, 203001 (2008).



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



Quantum & optical coherence

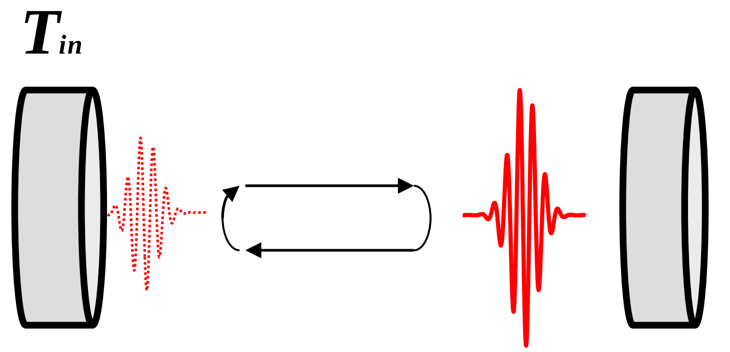
High resolution quantum control

Precision spectroscopy: global atomic structure

Coupling a comb into a cavity

Time Domain

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



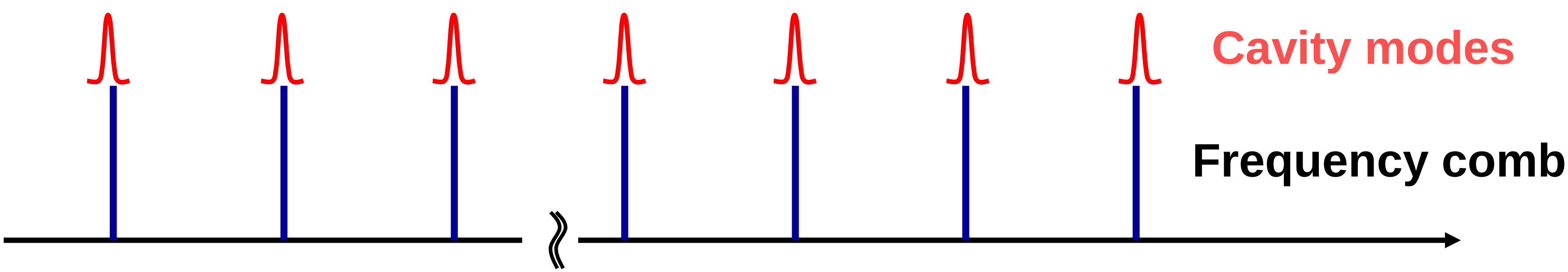
- Linear response
- Preserves coherence
- **Power & Length enhancement**

Cavity enhancement:

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

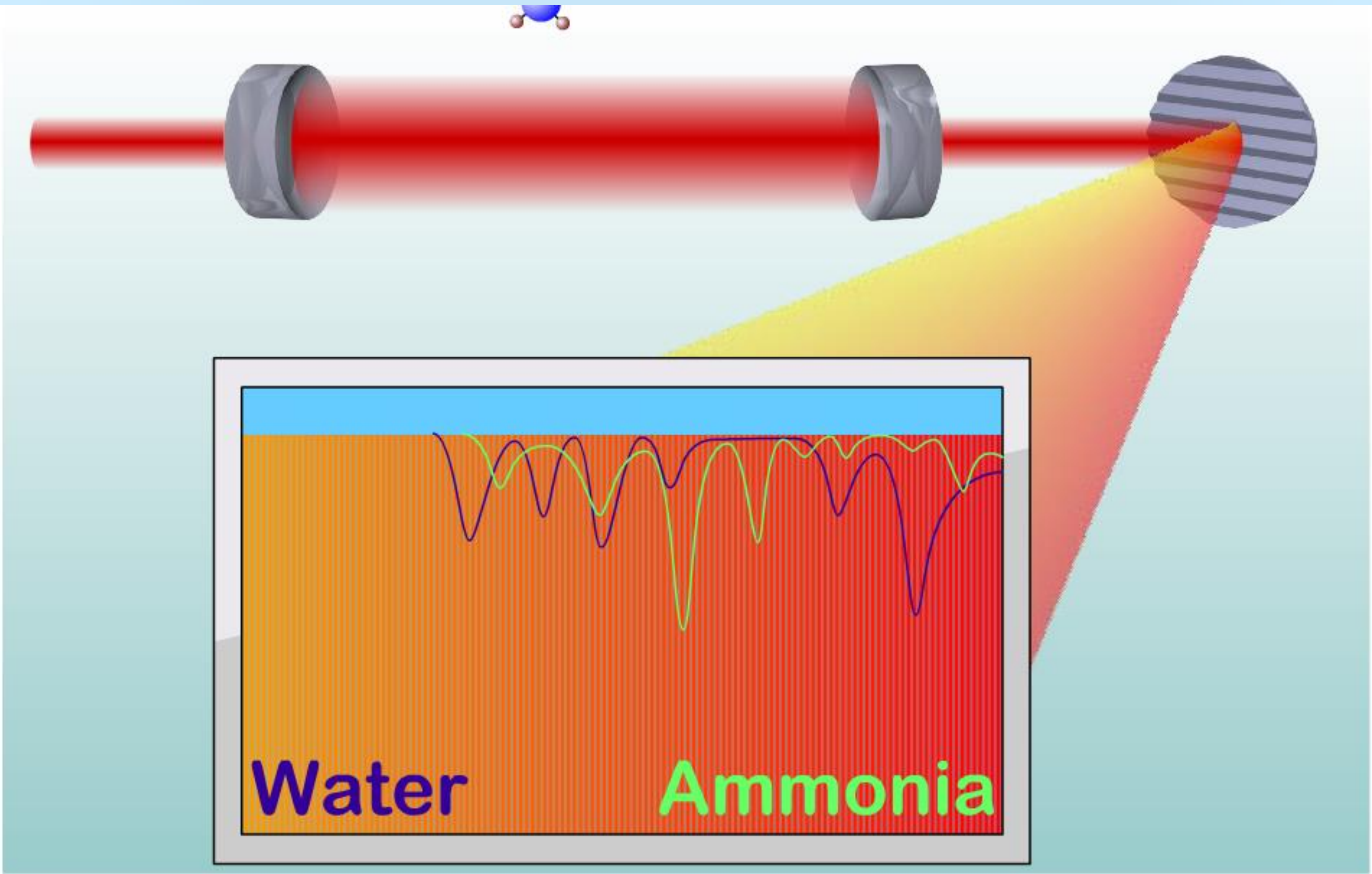
Frequency Domain

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



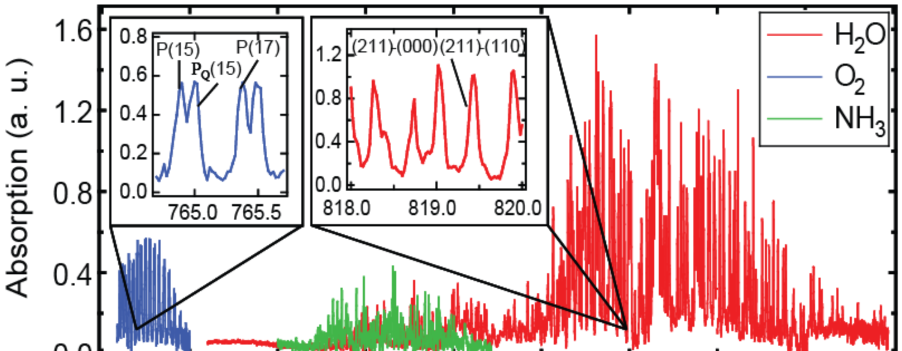
Massively parallel detections of molecules

Thorpe et al., Science **311**, 1595 (2006). Chem. Rev. 2010; Phys. Rev. Lett. 2011.

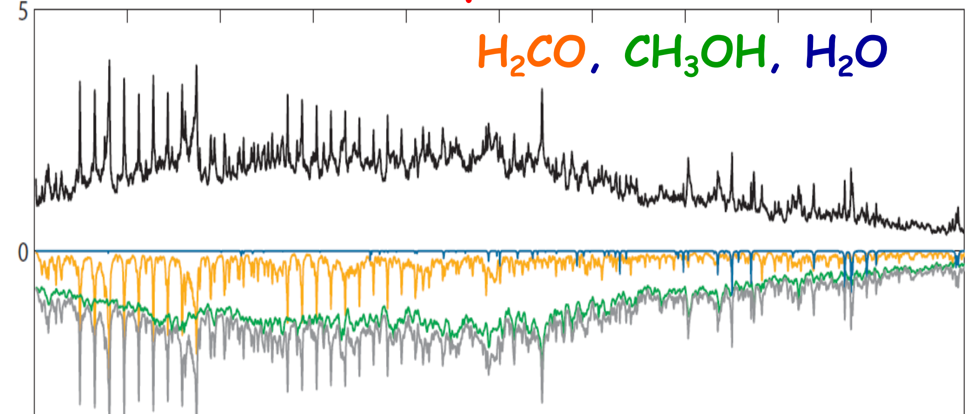


Wide spectral coverage

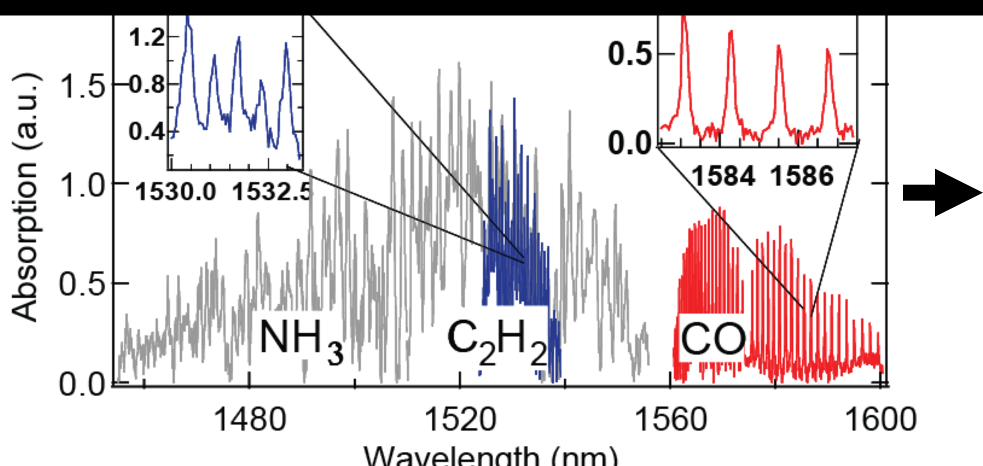
800 nm comb

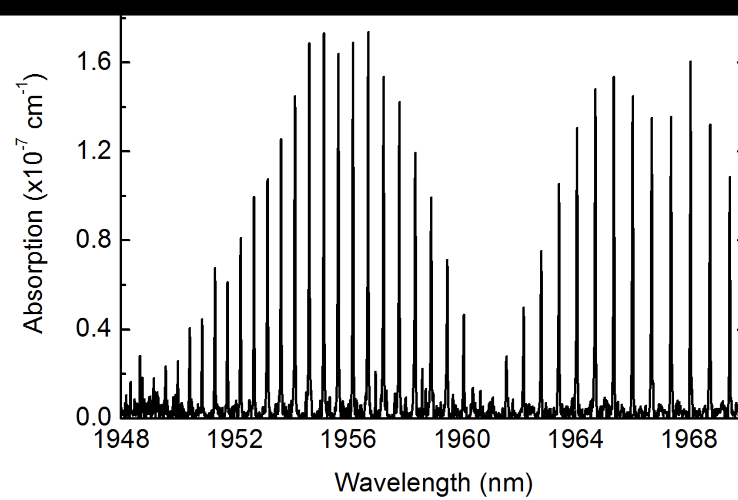


3 – 5 µm comb



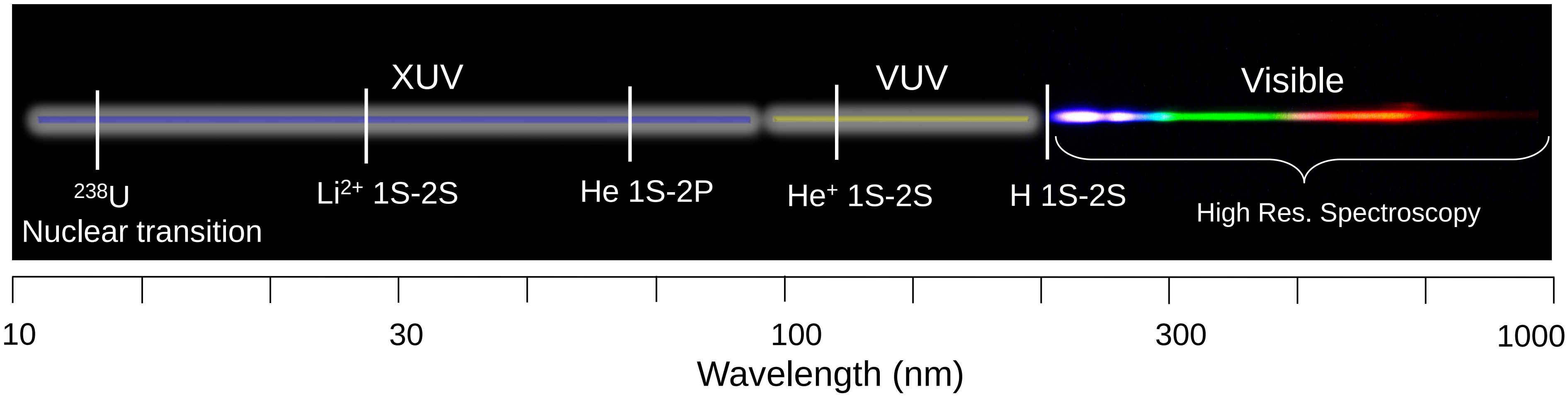
- **Broad spectral coverage**
- **High sensitivity** (1 x 10^{-10} $cm^{-1}Hz^{-1/2}$; parts per 10^9)
- **High resolution**
- **Real time acquisition**





Charting the extreme ultraviolet landscape

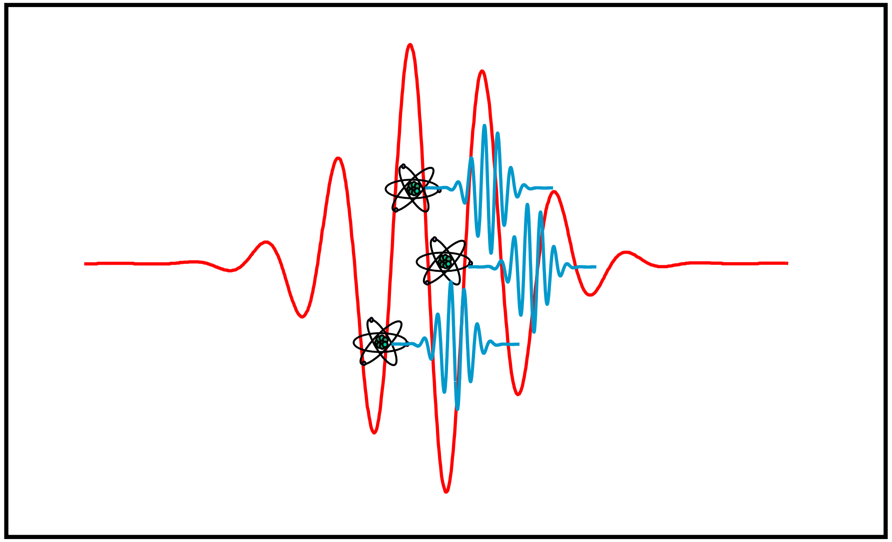
(Ultrahigh-resolution XUV spectroscopy)



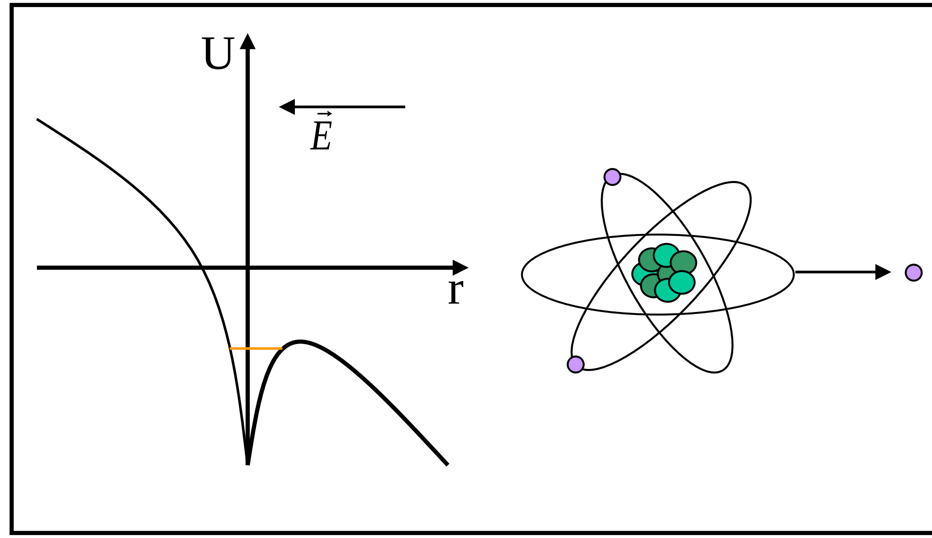
- Precision tests of fundamental physics
- Simple 3-body systems (i.e. helium), but also complex molecules
- Nuclear transitions
- Highly charged ions and precision test of QED
    - Ground state Lamb shift scales as Z^4
    - Higher-order corrections scale as Z^6

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

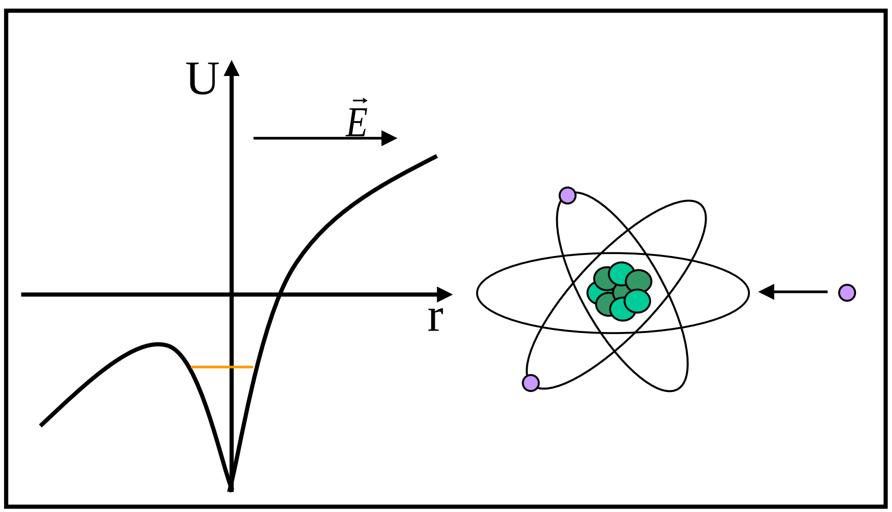
Three step model



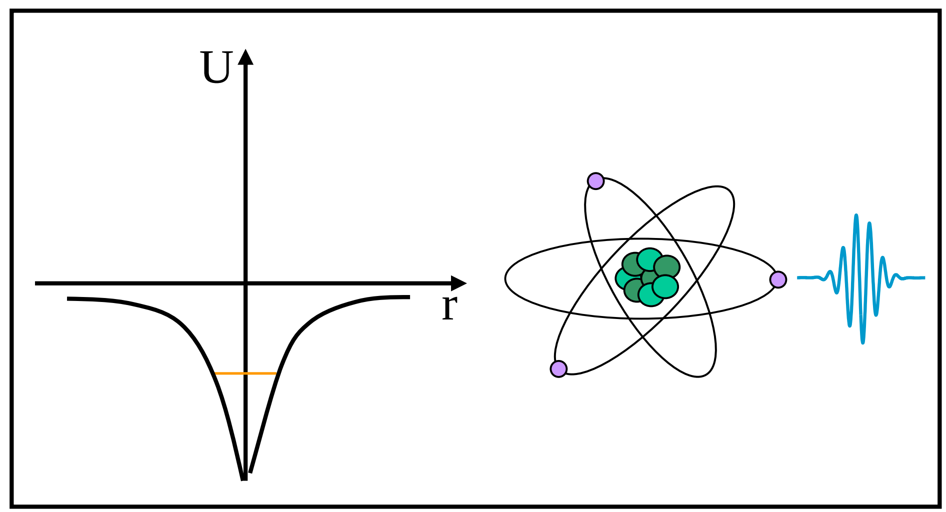
Step 1: Ionization



Step 2: Field Reversal



Step 3: Recombination



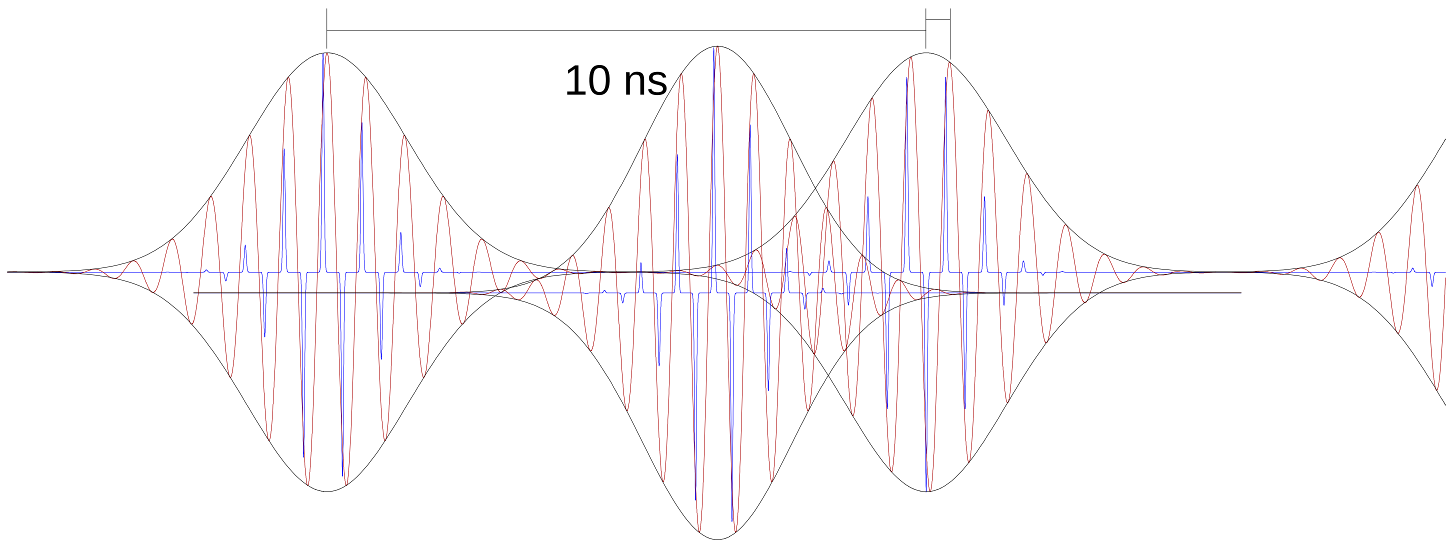
Corkum, Phys Rev Lett 71, 1994

Coherent VUV and XUV radiation

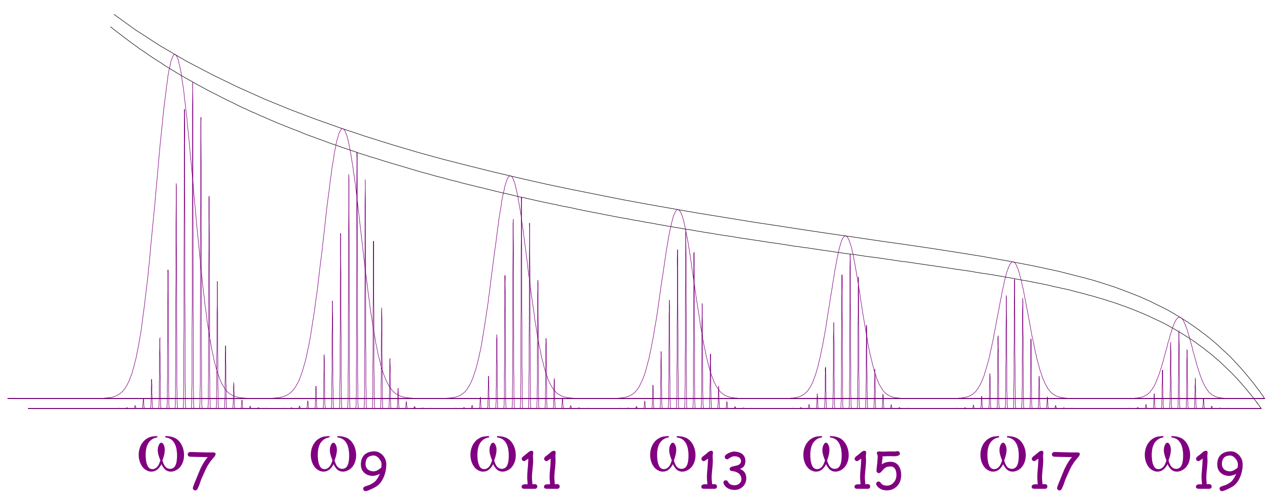
Harmonic Generation with a train of IR pulses-
The XUV frequency comb is born

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

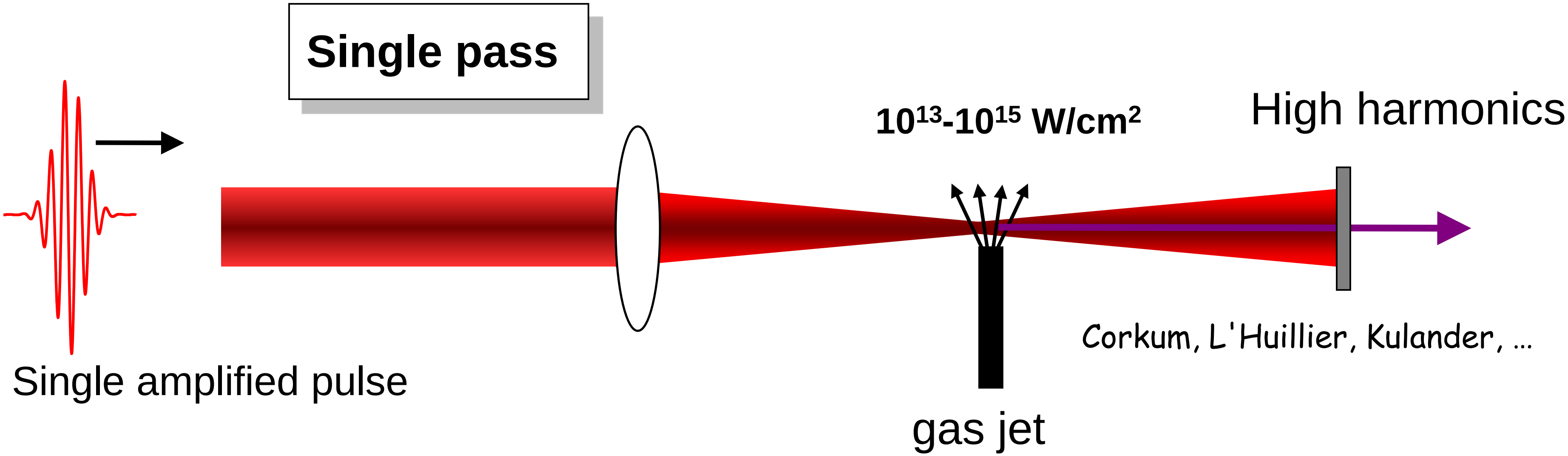
Time domain



Frequency domain



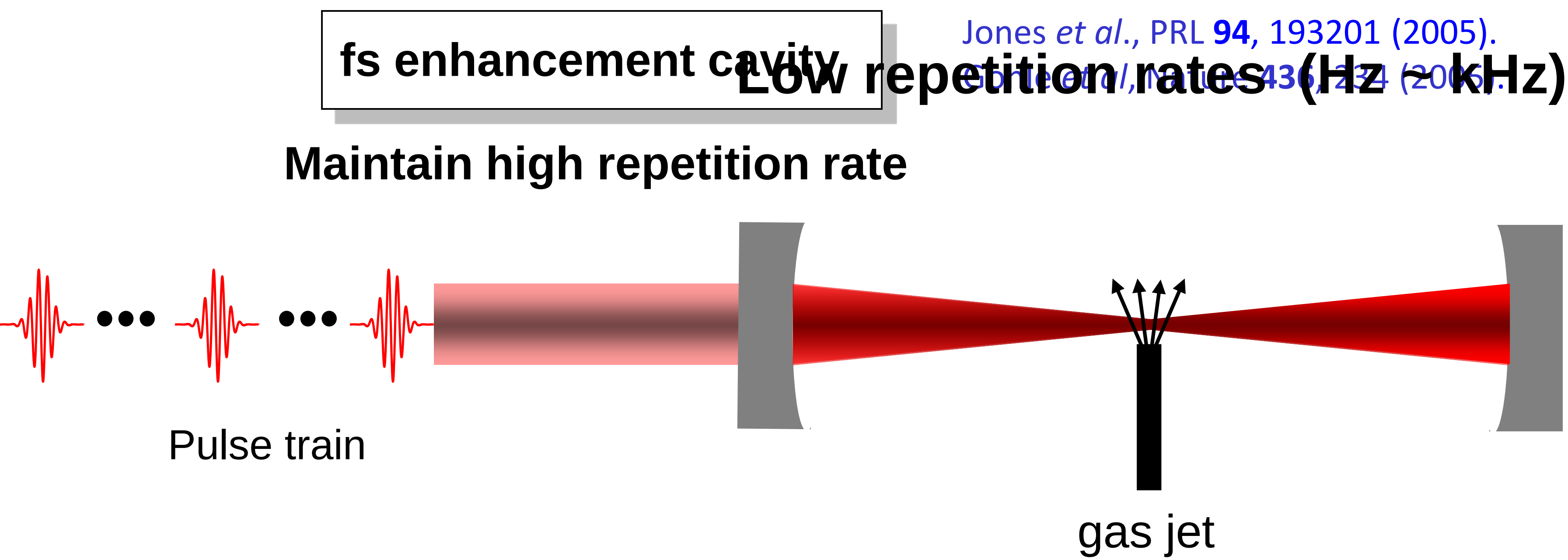
High-harmonic generation



Jones *et al.*, PRL **94**, 193201 (2005).

Gohle *et al.*, Nature **436**, 234 (2005).

Low repetition rates (Hz ~ kHz)



Intra-cavity HHG at high rep rate

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

JILA:

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

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

Benko *et al*., Nature Photon. **8**, 530 (2014).

MPQ:

Pupeza *et al.* Nat. Photon. **7**, 608 (2013)

Pupeza *et al.* PRL **112**, 103902 (2014)

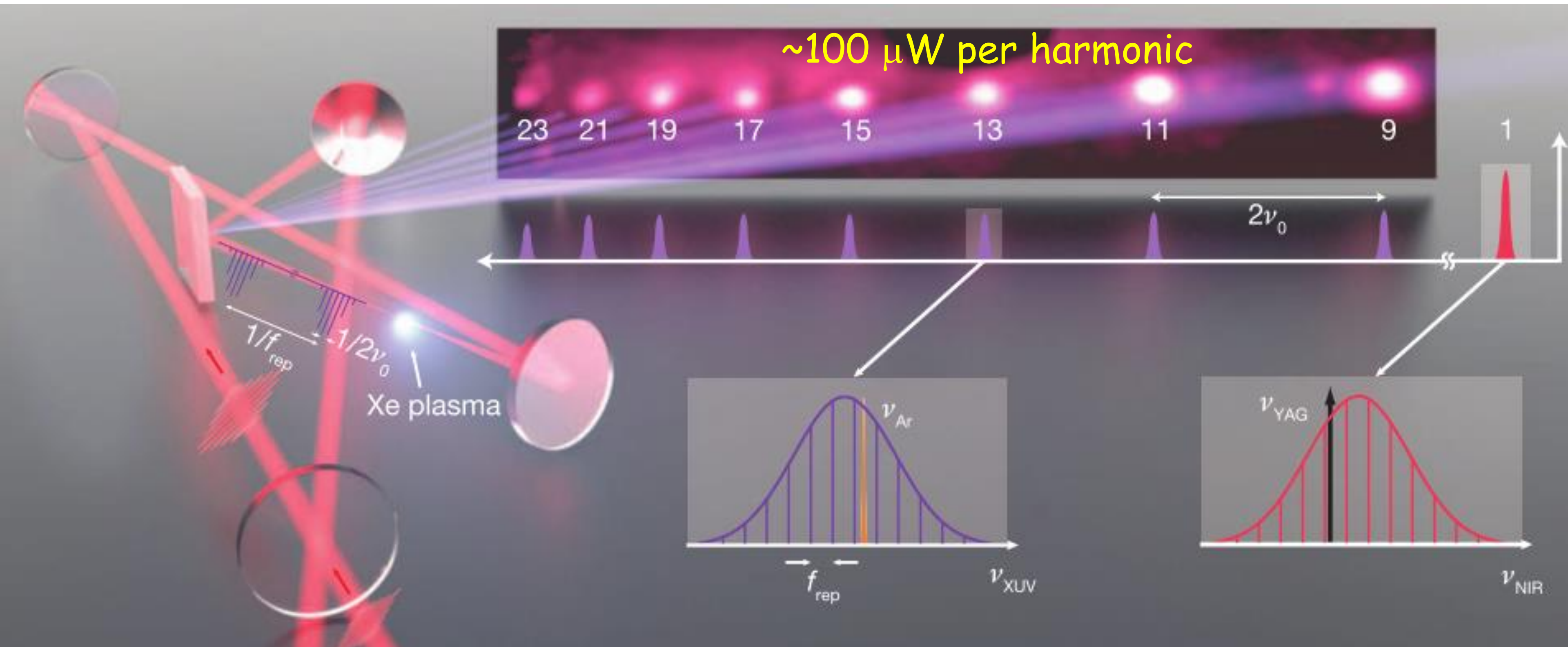
U. Arizona:

Carlson *et al.* Opt. Lett. **36**, 2991 (2011)

Lee *et al.* Opt. Exp. **19**, 23315 (2011)

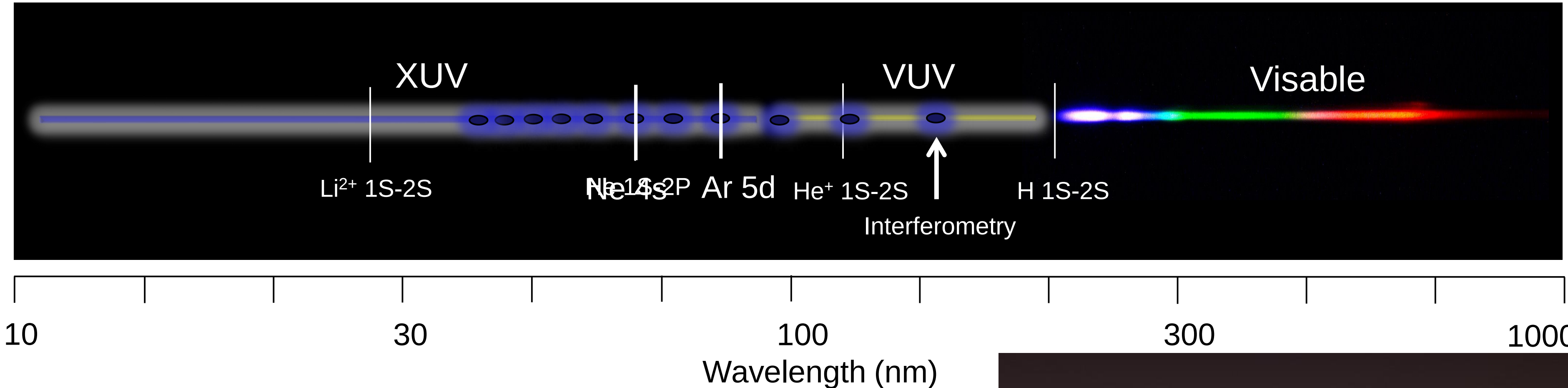
UBC:

Mills *et al.* J. Phys. B. **45,** 14201 (2012).

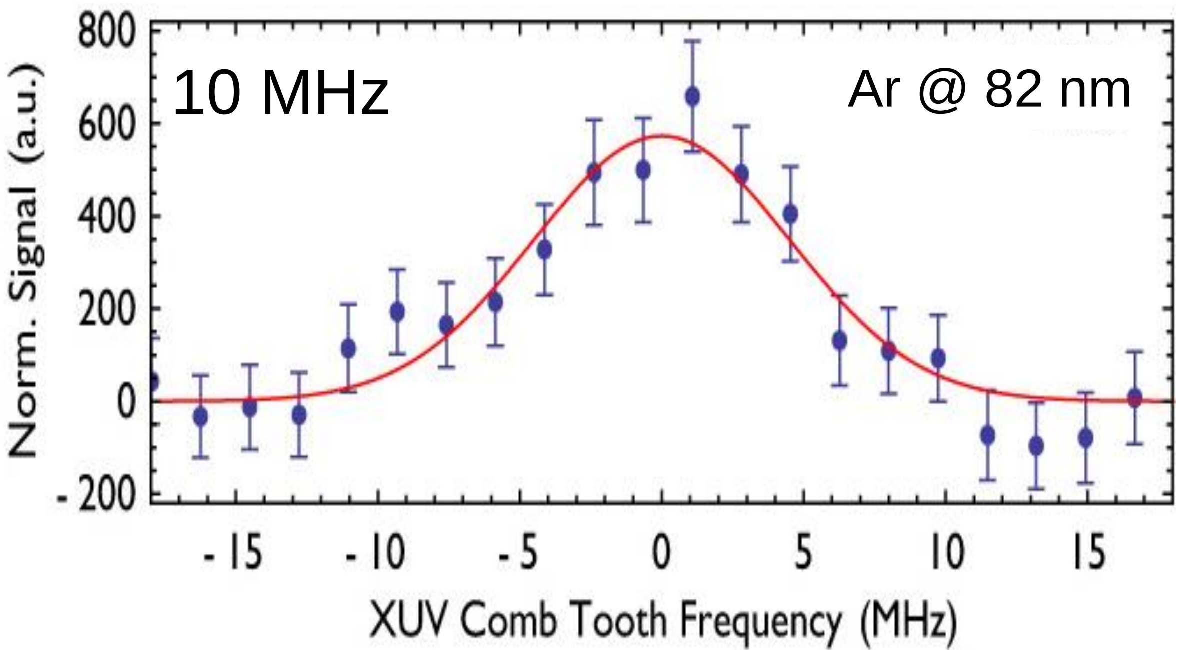


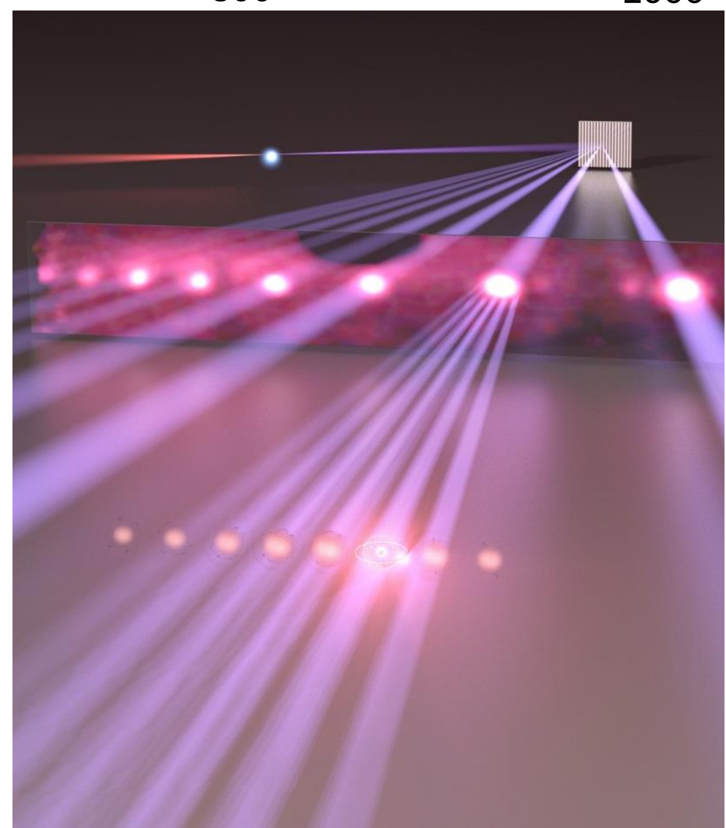
High resolution XUV Spectroscopy

Cingöz et al., Nature 482, 68 (2012).



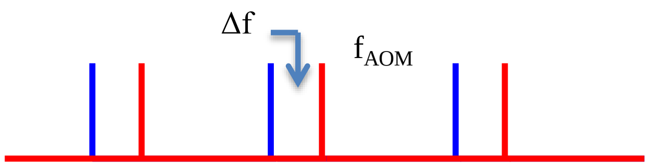
- Natural linewidth ~10 MHz
- Absolute frequency determination 100 kHz

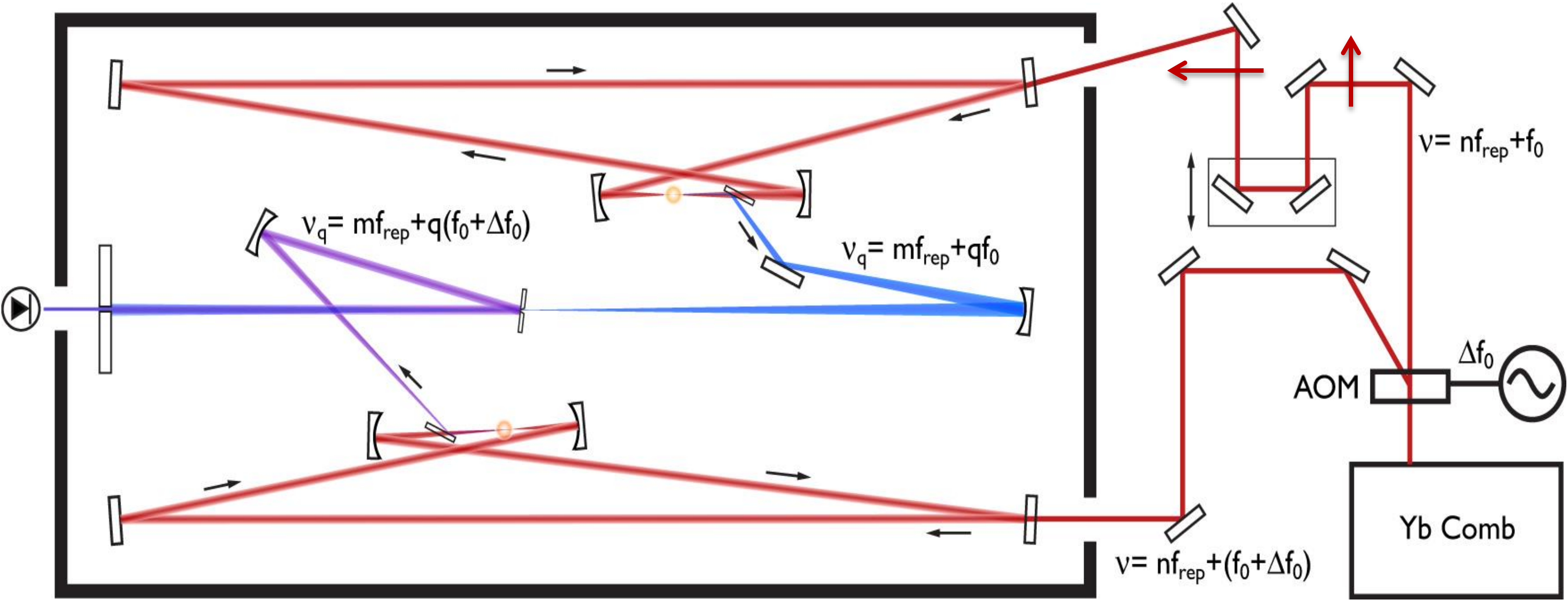




Direct heterodyne beat of two XUV combs

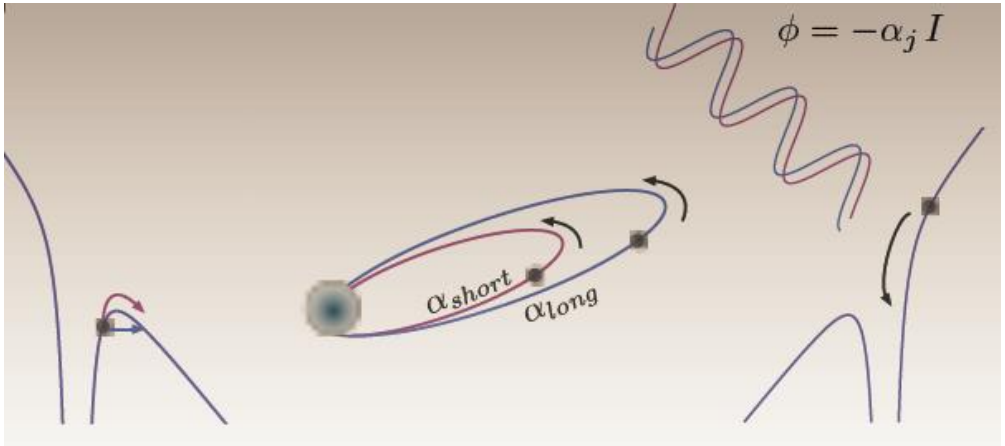
- Direct measurement of phase of HHG (XUV comb)
- Phase probe of attosecond processes

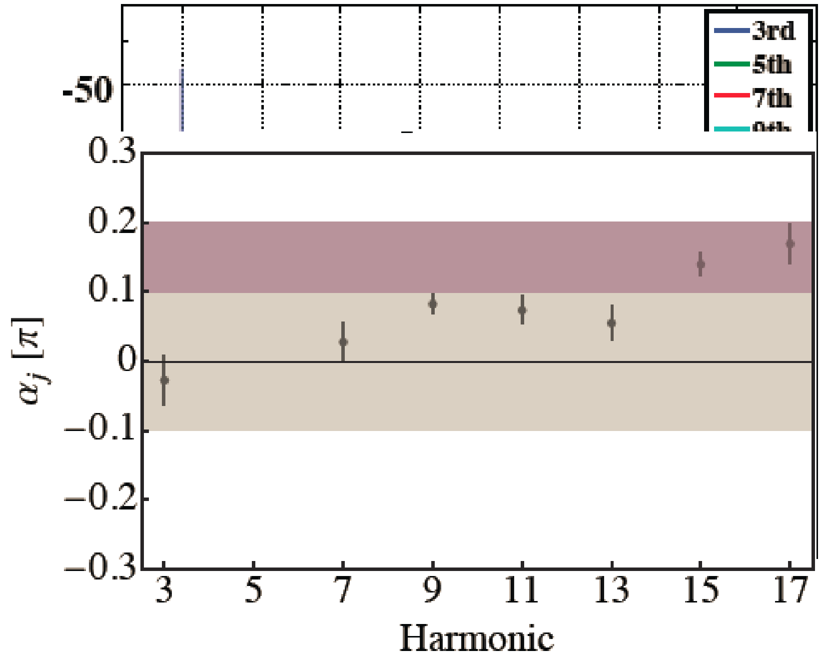


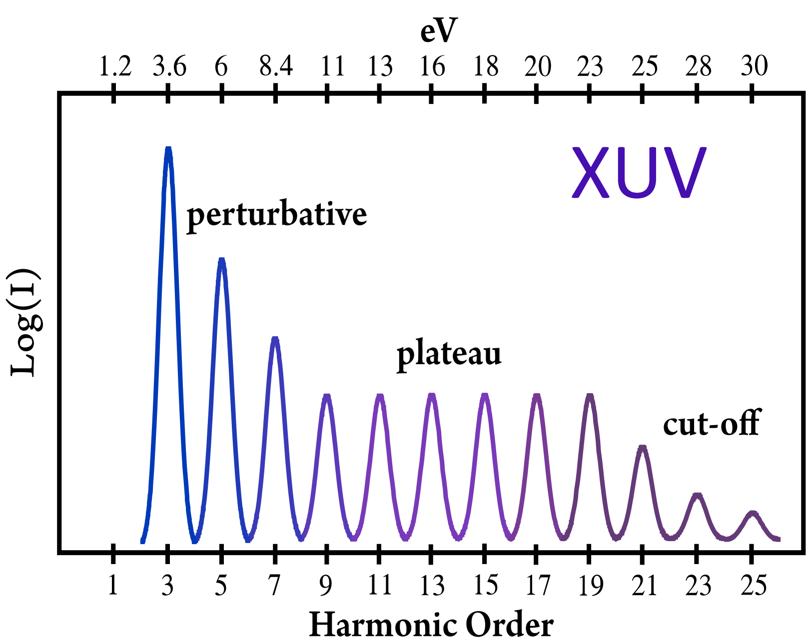


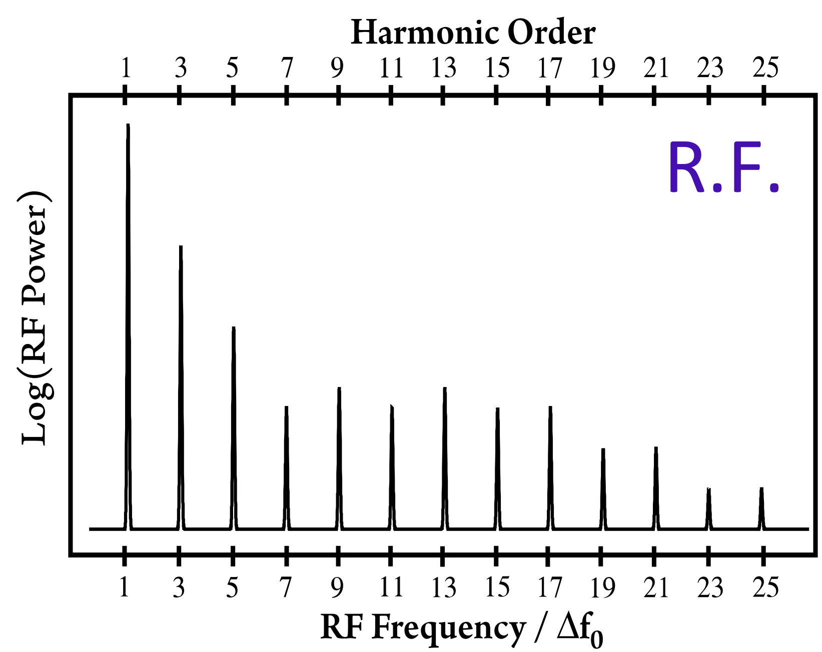
Direct phase measurement of attosecond phys.

Benko *et al.*, Nature Photonics **8**, 530 (2014).







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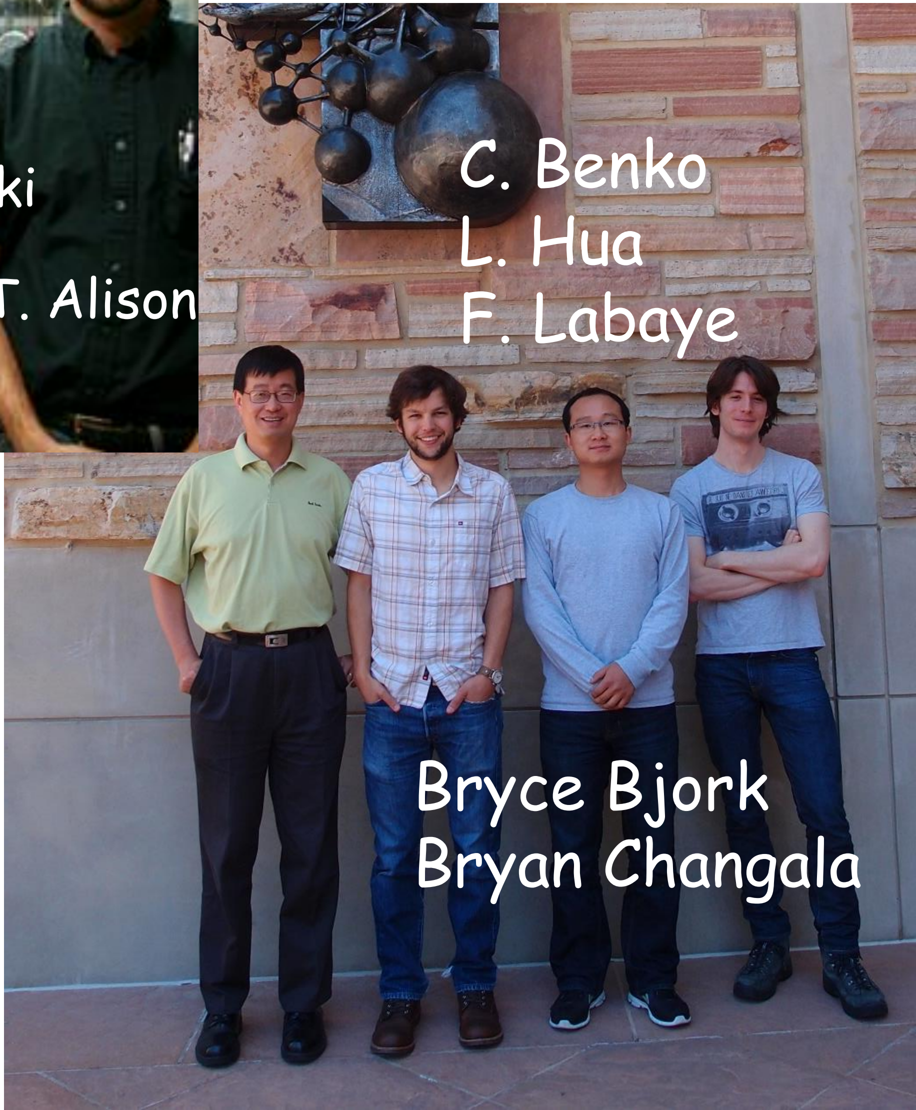
T. Alison
A. Foltynowicz


C. Benko
L. Hua
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Over the years …

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