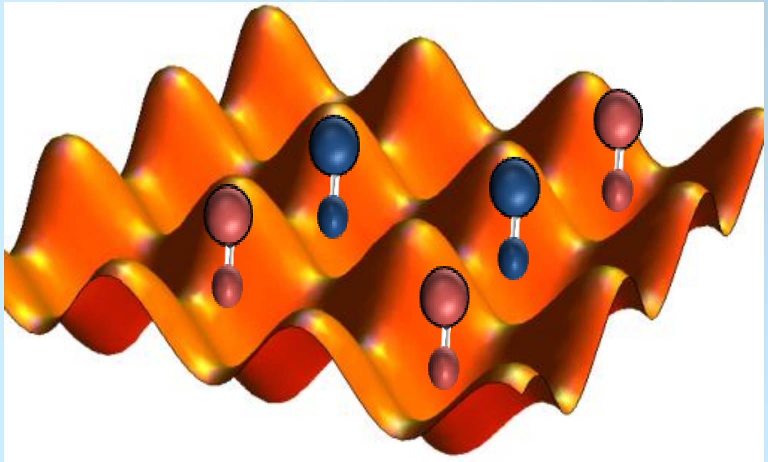
Optical Atomic Clock & Absolute-Zero Chemistry – Probing Quantum Matter with Precision Light

Jun Ye

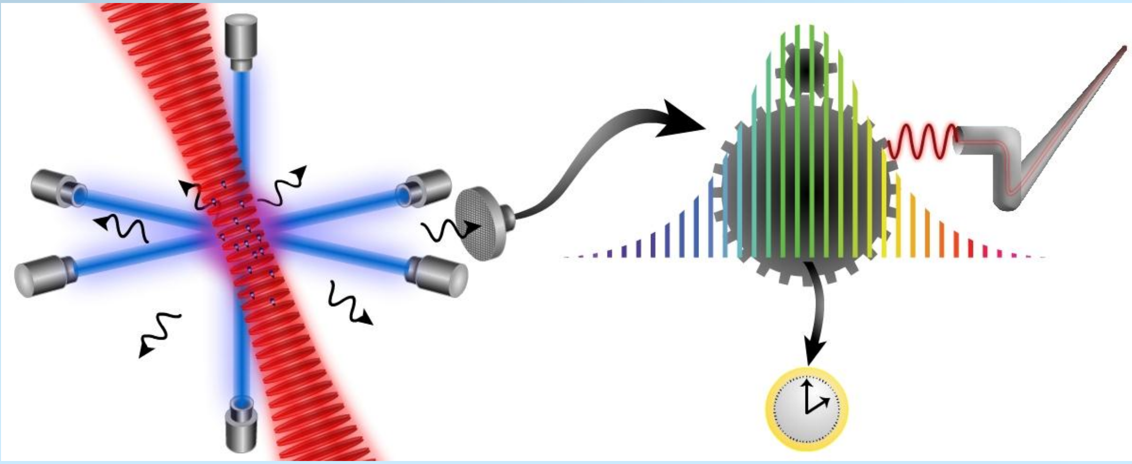
JILA, NIST & University of Colorado

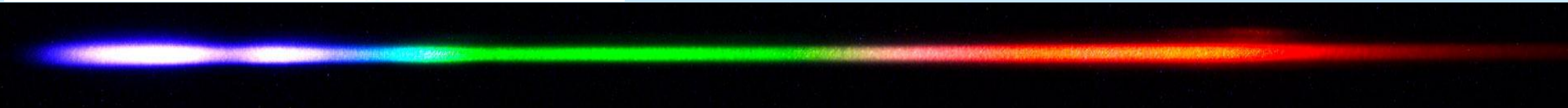
MURI 25th Birthday, Washington DC, Nov. 9, 2011

Many-body quantum systems



Optical atomic clocks





Optical Clocks: ***Fundamental aspects, practical issues and enabling technology***

Bergquist, Cundiff, Delfyett, Diels, Gibble, Hall, Hollberg, Jones,
Kapteyn, Kimble, Ye (PI)

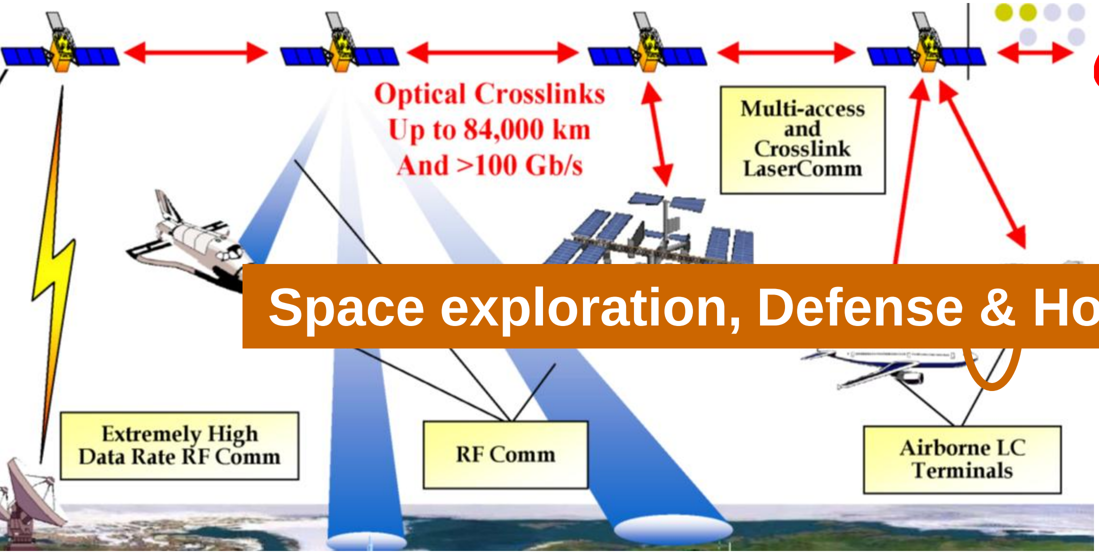
JILA/Colorado, Caltech, Central Florida, New Mexico, NIST, Penn State

(Peter Reynolds) ONR/MURI, 2001

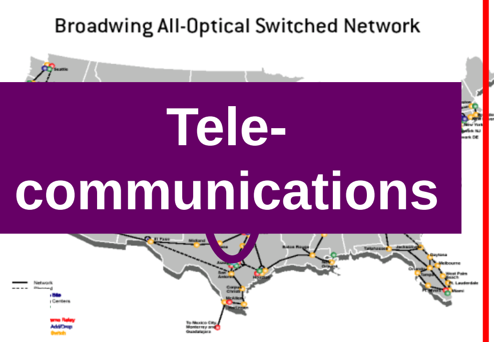
Outside Collaborations

MIT (the other MURI team)

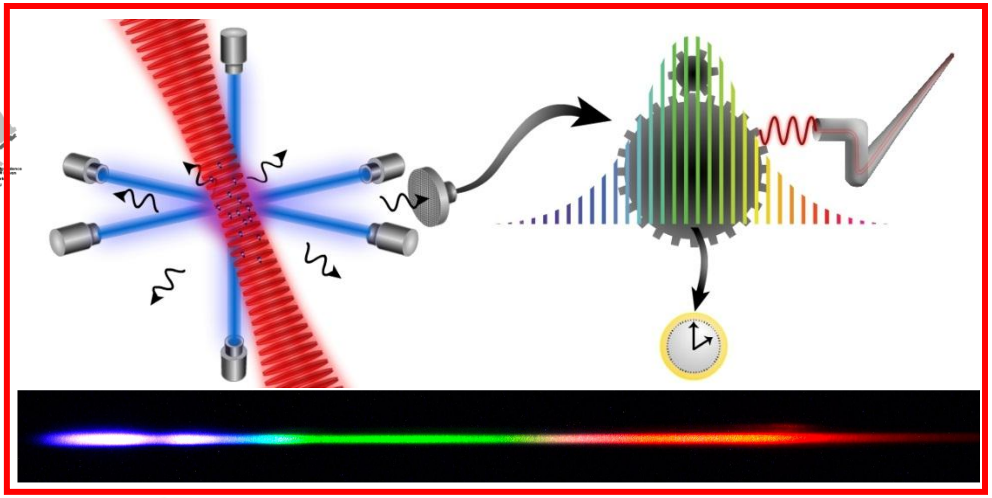
Clocks are everywhere



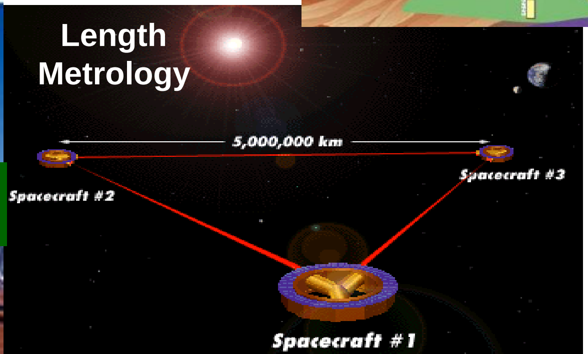
Space exploration, Defense & Homeland security



Tele-communications

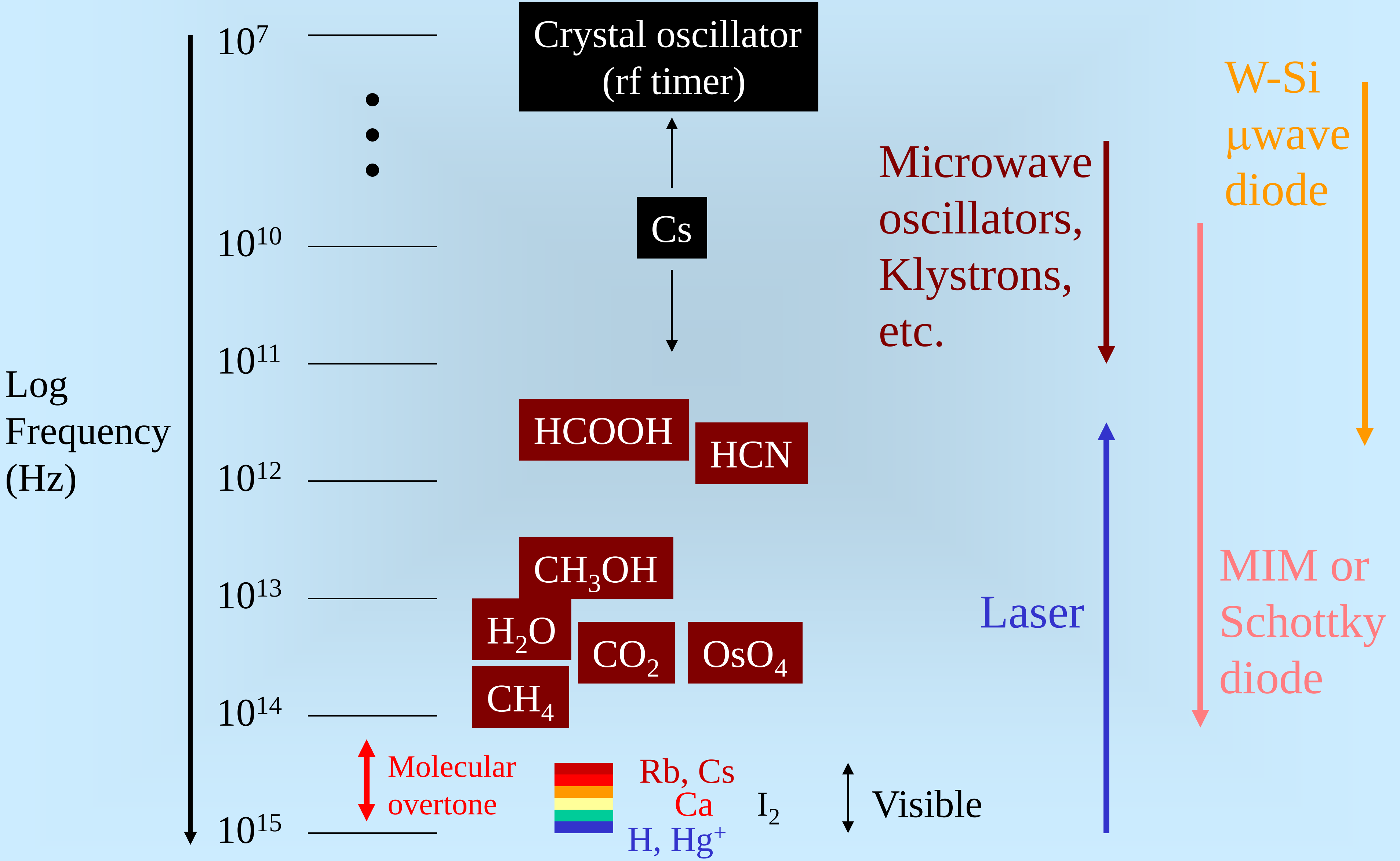


Standards for Industry

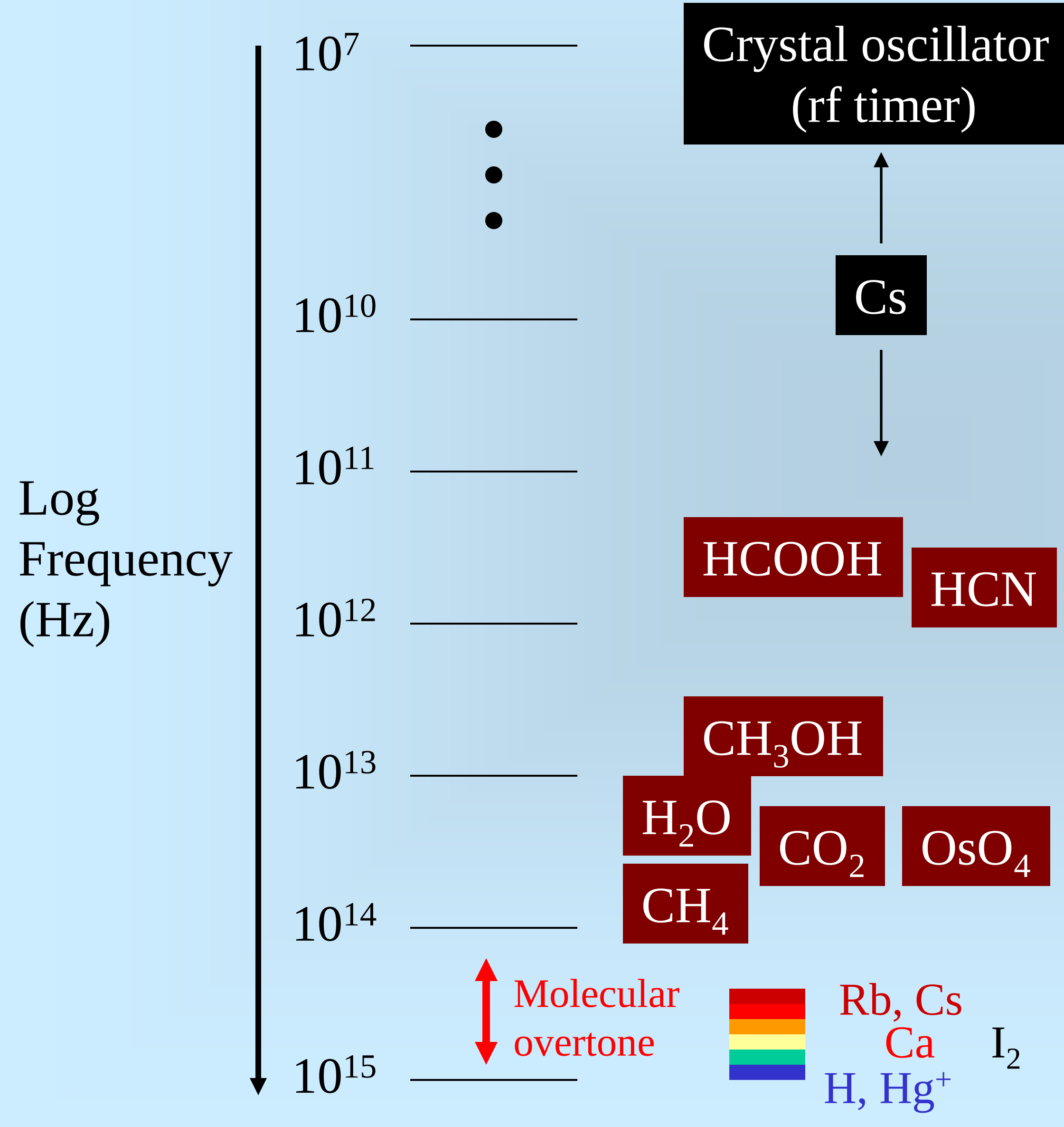


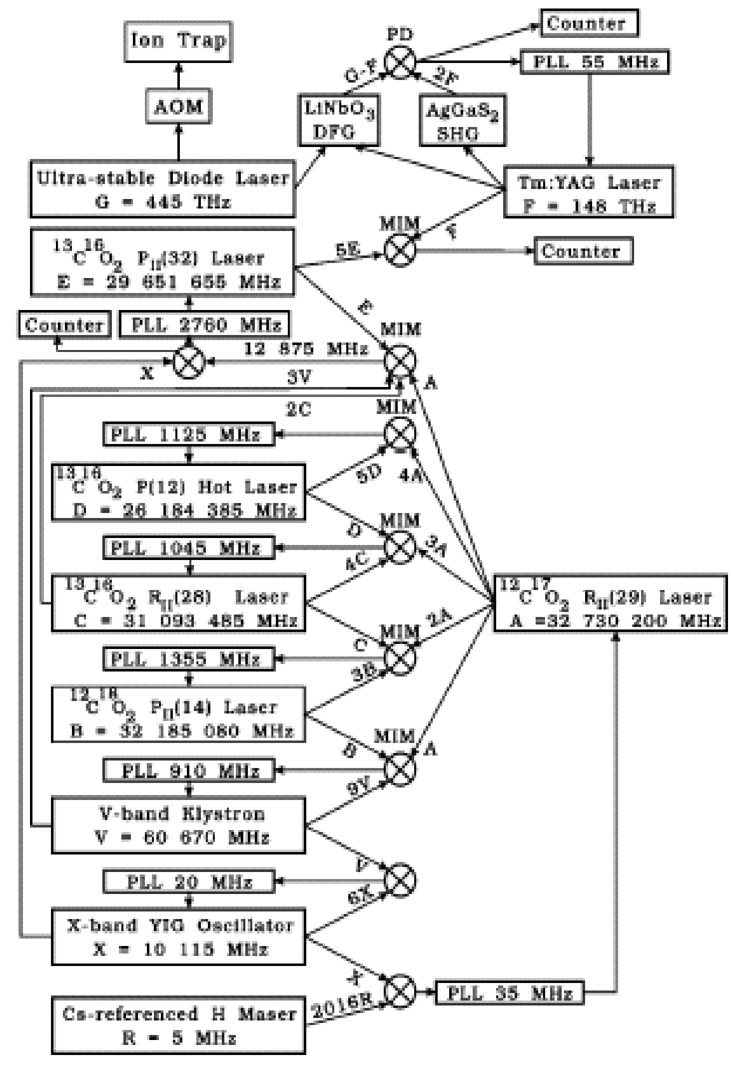
Fundamental and Applied Science

Spectrum in optical frequency synthesis



Spectrum in optical frequency synthesis

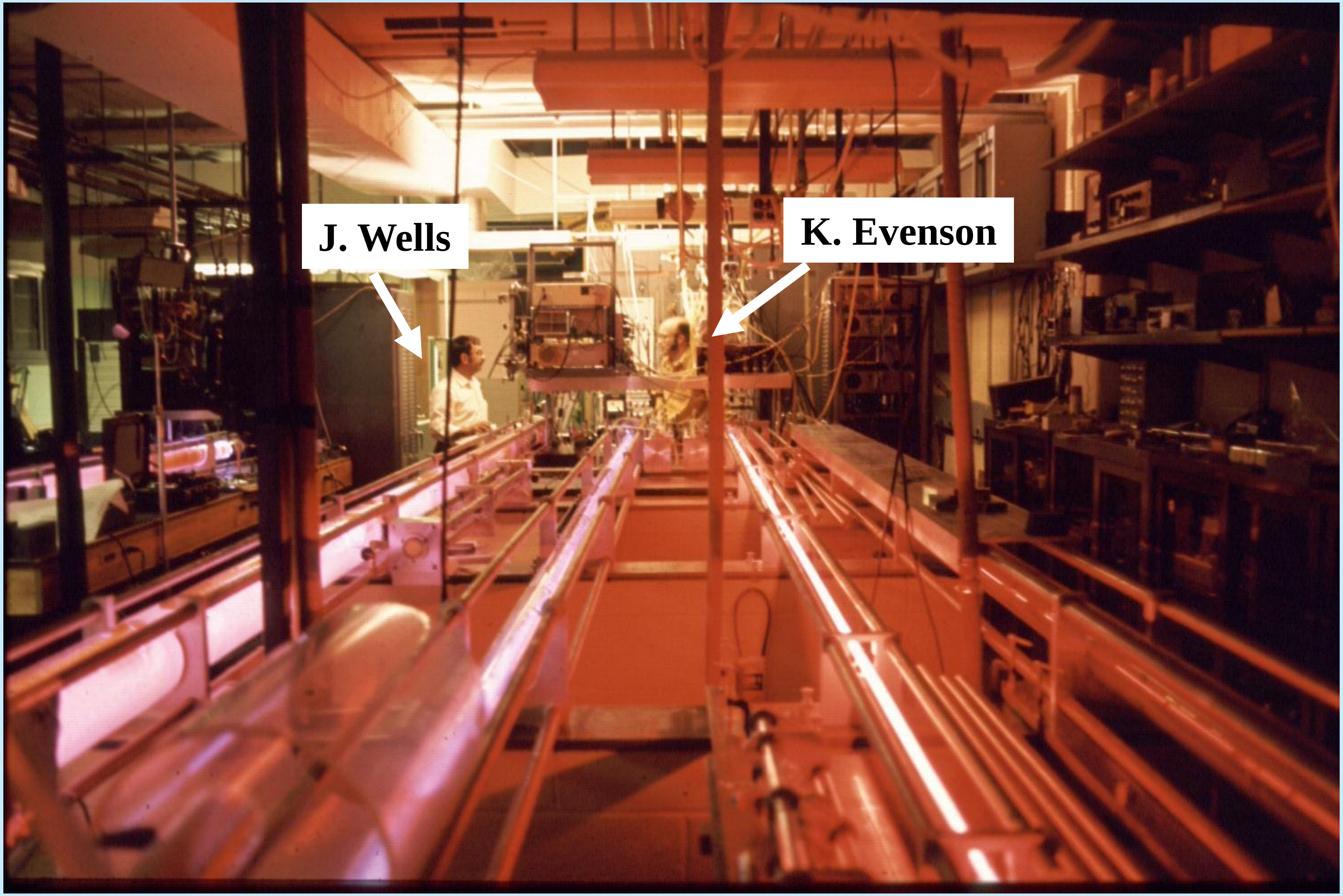




Harmonic frequency chains – NRC; PTB; …

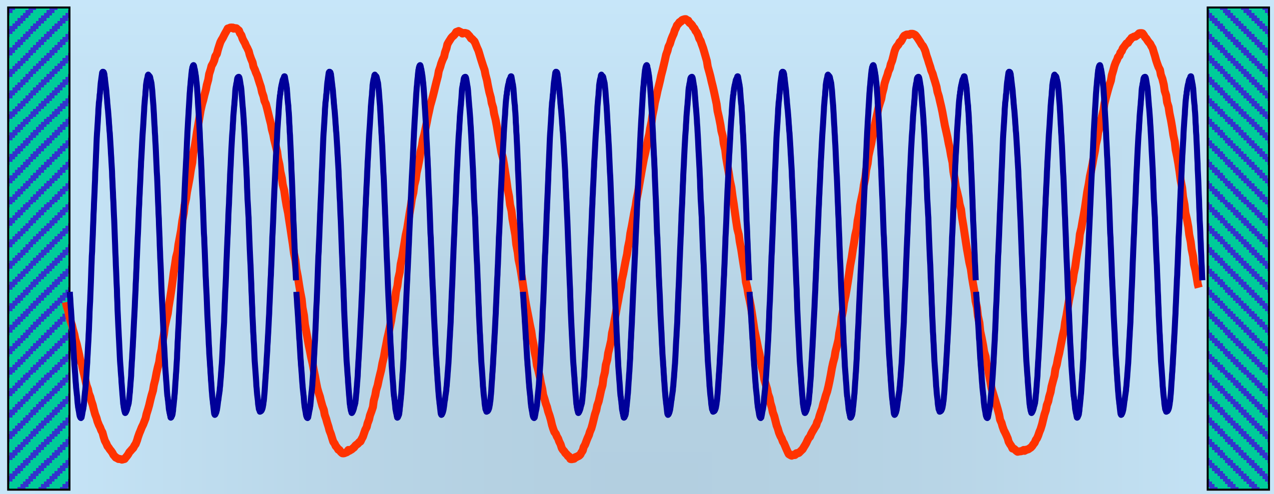
An Optical Frequency Chain

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



Hall & Ye, "NIST 100th birthday", Optics & Photonics News 12, 44 (2001).

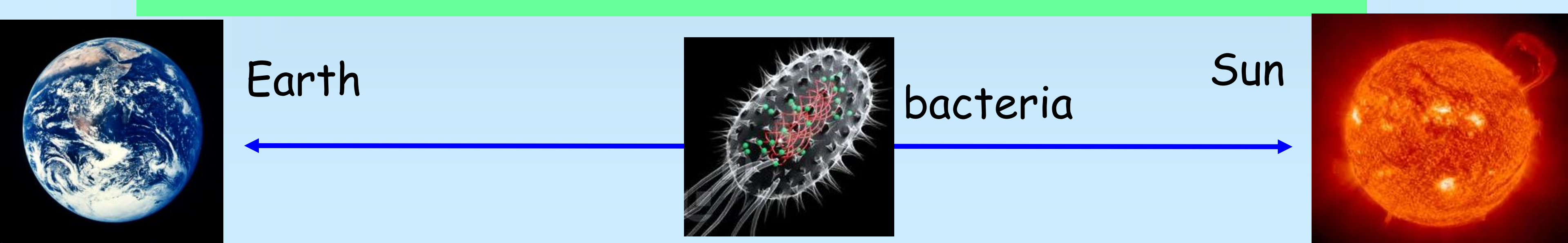
The age of atomic clocks - Chasing the SPEED!



Faster oscillations → More cycles → Smaller errors

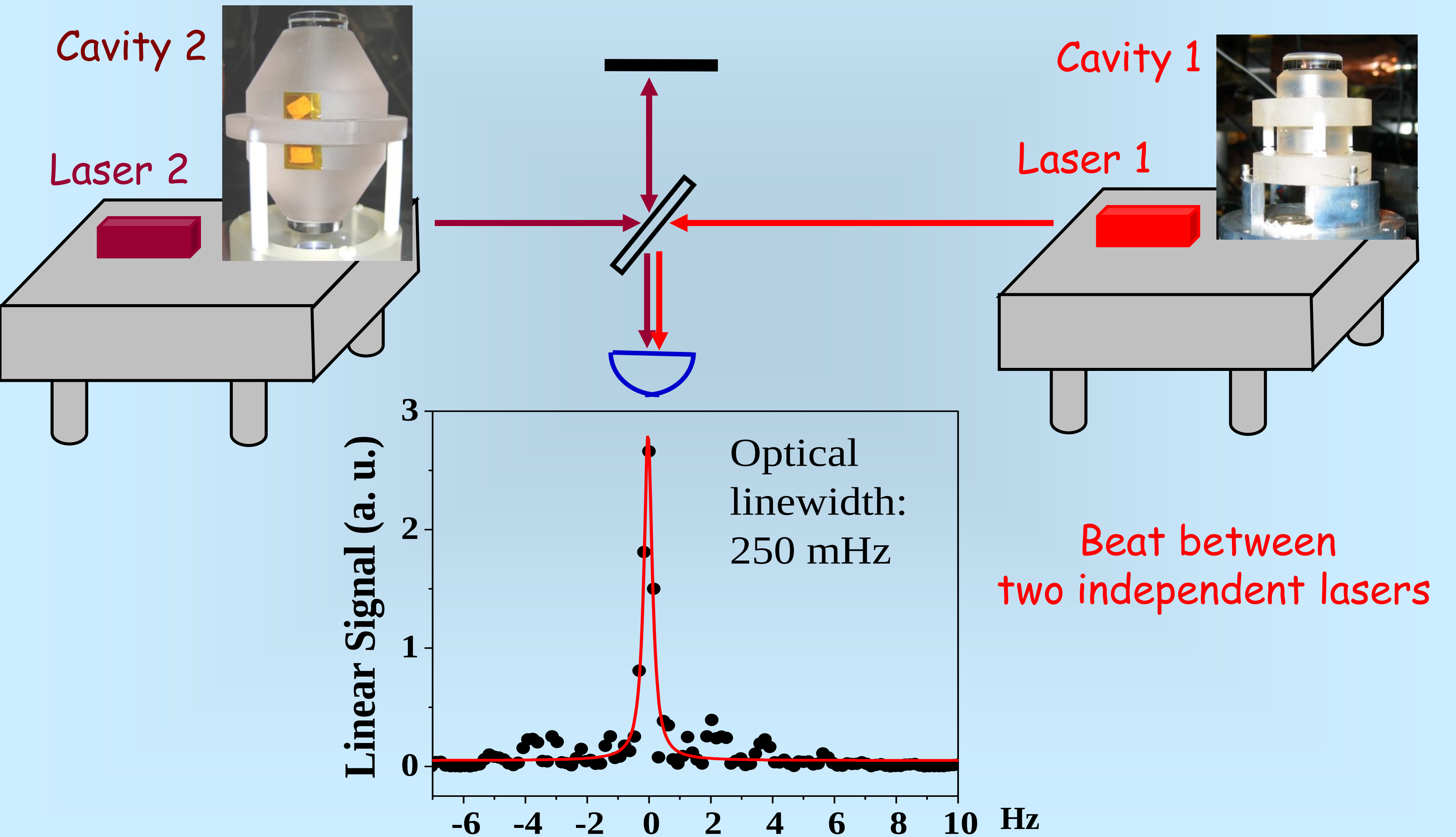
Light ripples: 10^{15} cycles per second, & we count every one

Precision: 1 000 000 000 000 000 ± 1

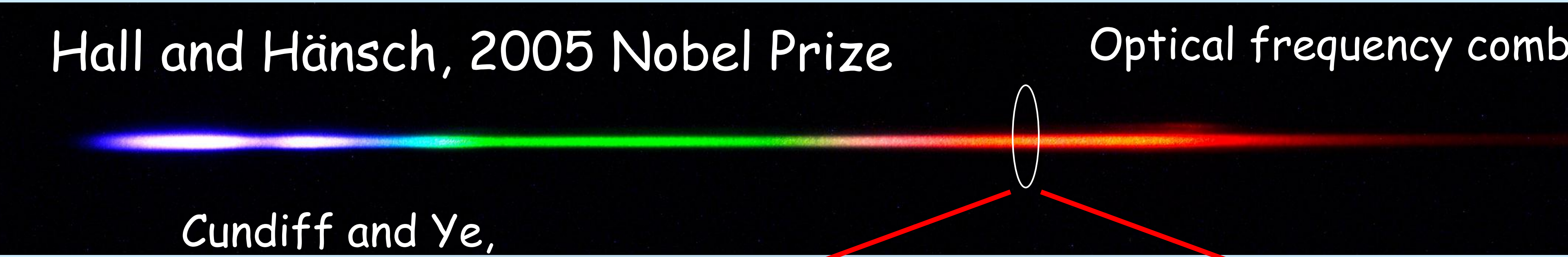


Long-term optical coherence (~~1 s~~) 10 s

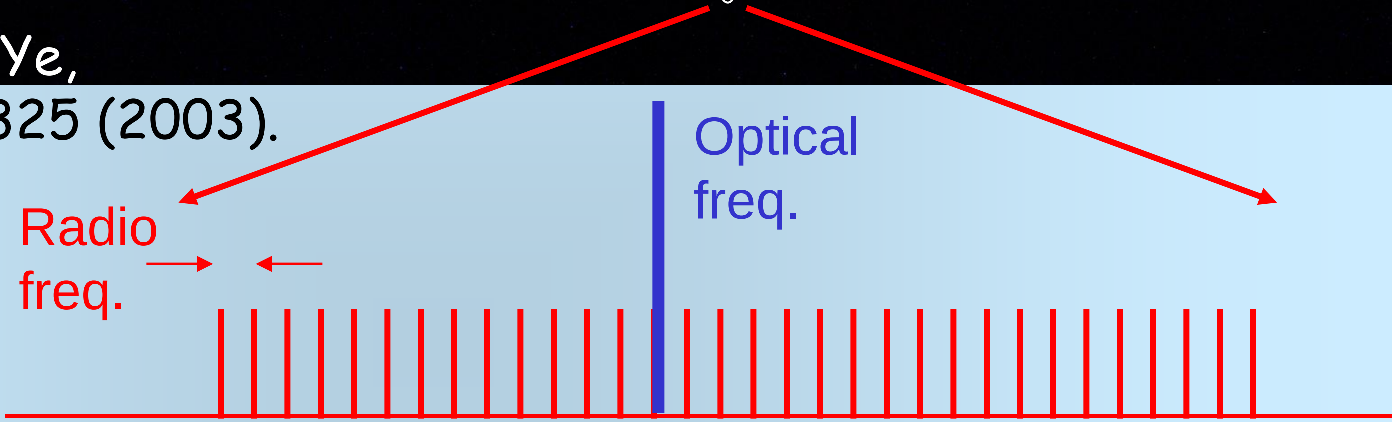
Ludlow *et al.*, Opt. Lett. 32, 641 (2007).



A rainbow spectrum with 10^{-19} precision



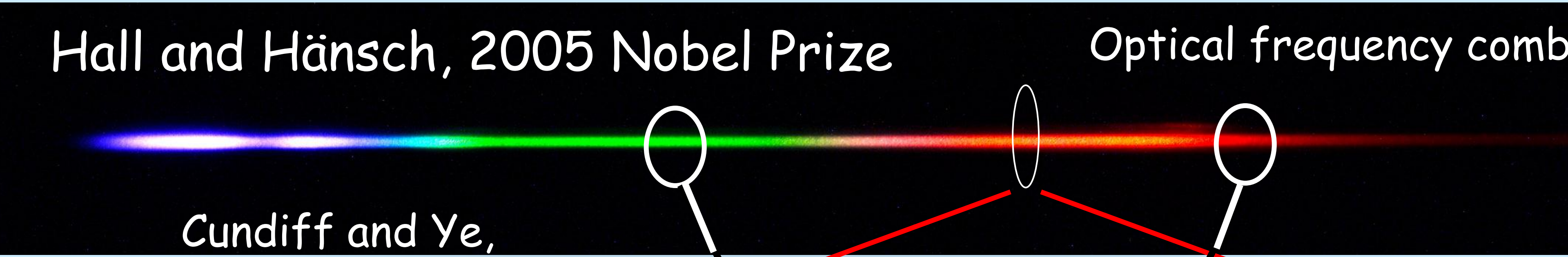
Rev. Mod. Phys. 75, 325 (2003).



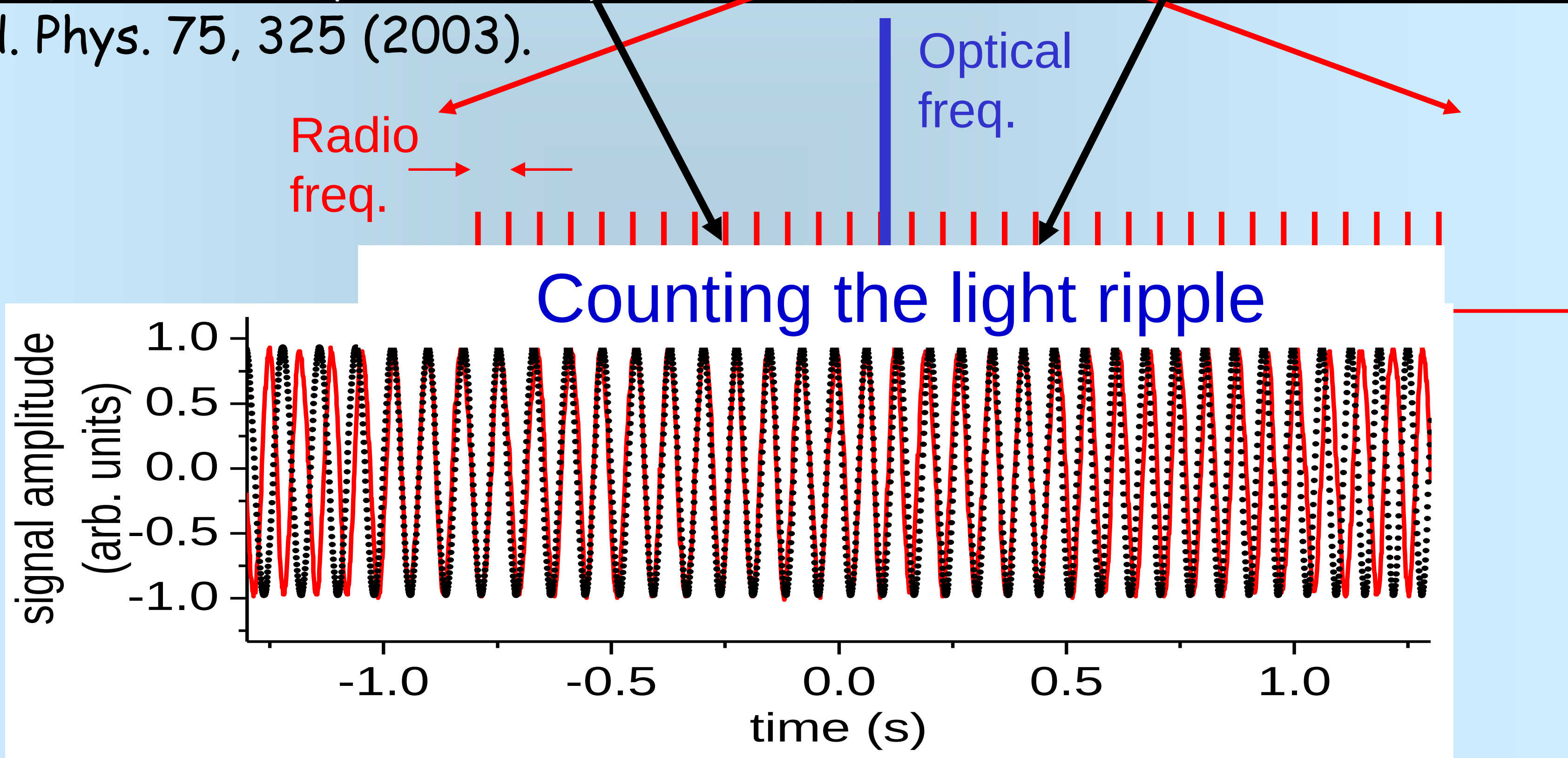
Optical coherence time > 1 s ($<10^{-15}$), anywhere in the visible

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

A rainbow spectrum with 10^{-19} precision



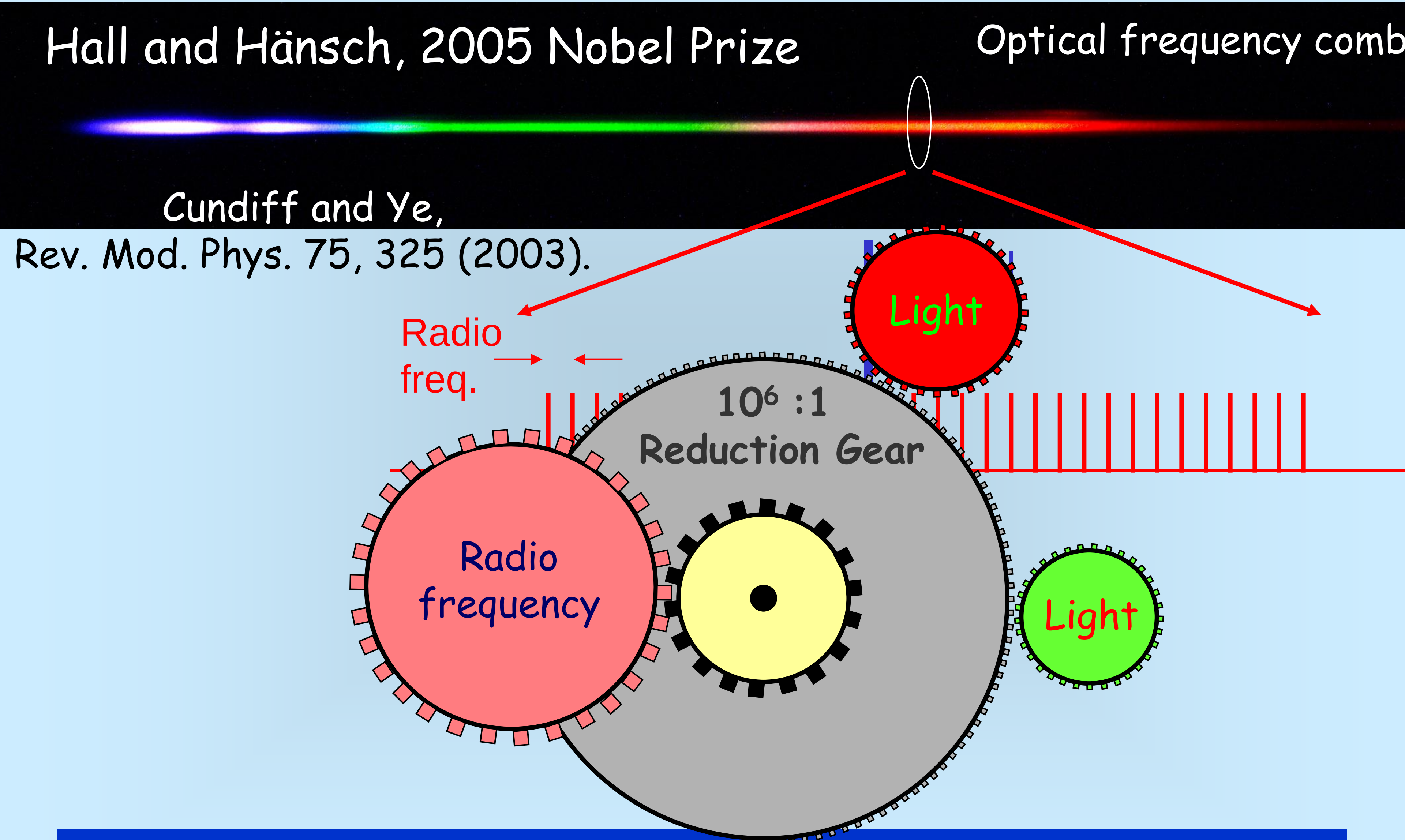
Rev. Mod. Phys. 75, 325 (2003).



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

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

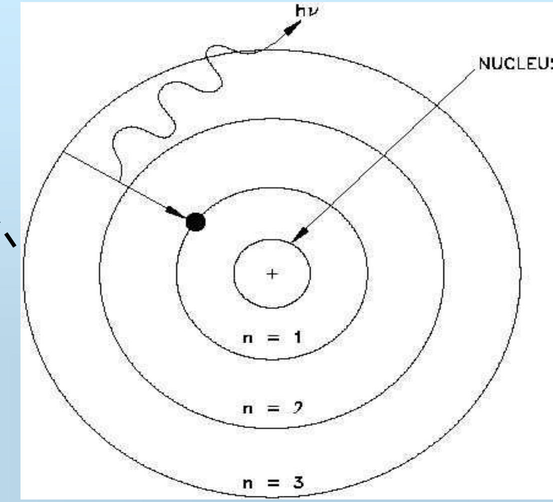
A rainbow spectrum with 10^{-19} precision

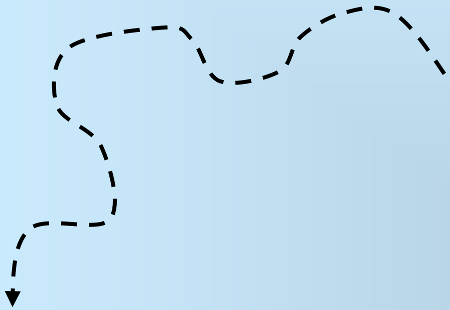


Optical coherence time > 1 s (<10^{-15}), anywhere in the visible

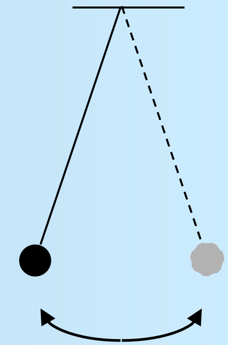
Schibli et al., Nature Photonics 2, 355 (2008).

Optical atomic clocks

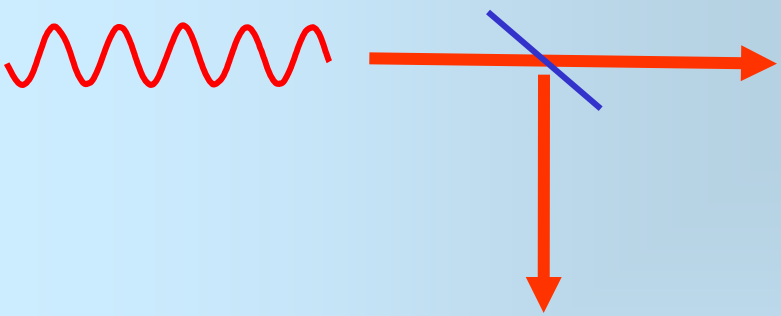


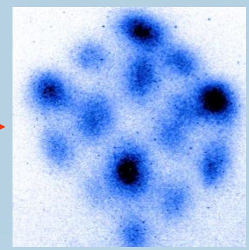


Oscillator



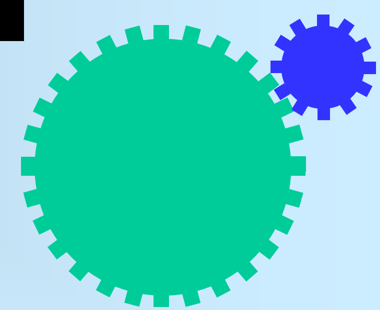
Ultrastable laser

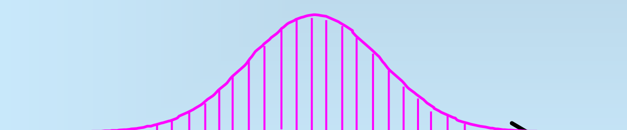




Sr atoms

Counter





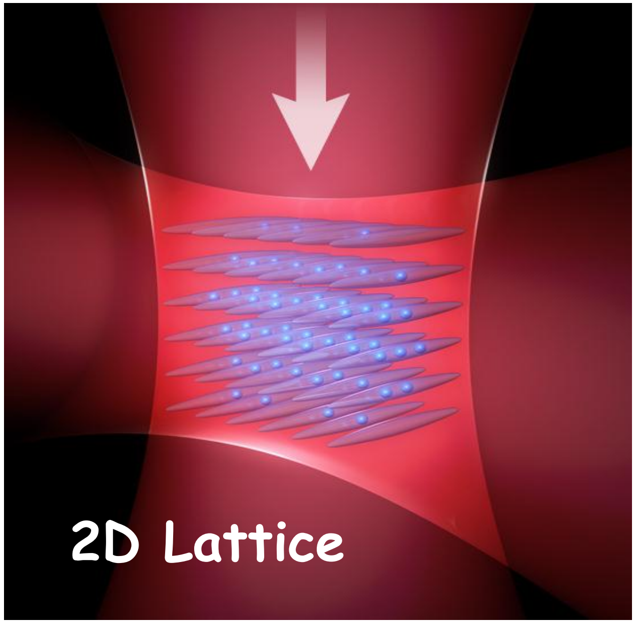
optical comb → optical frequency counter

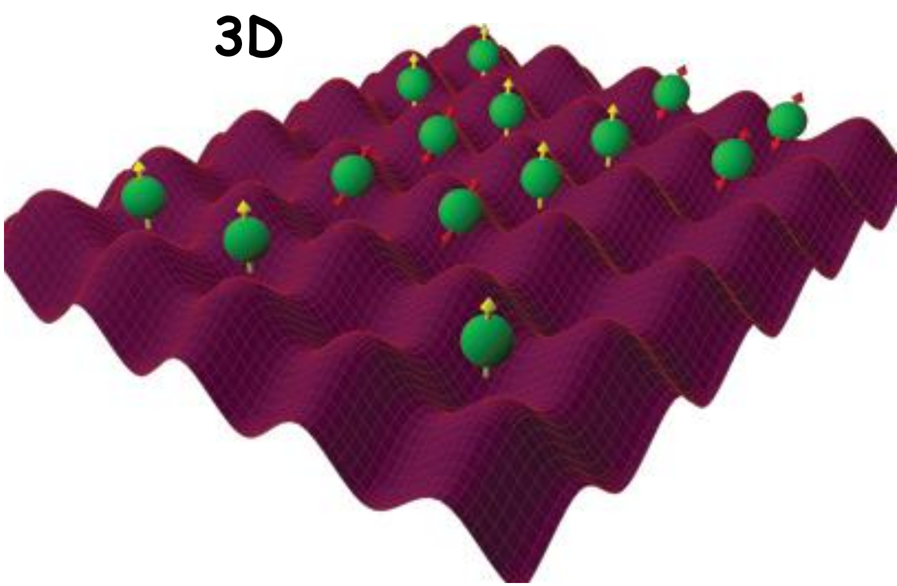
Optical lattice – a many-body quantum system

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

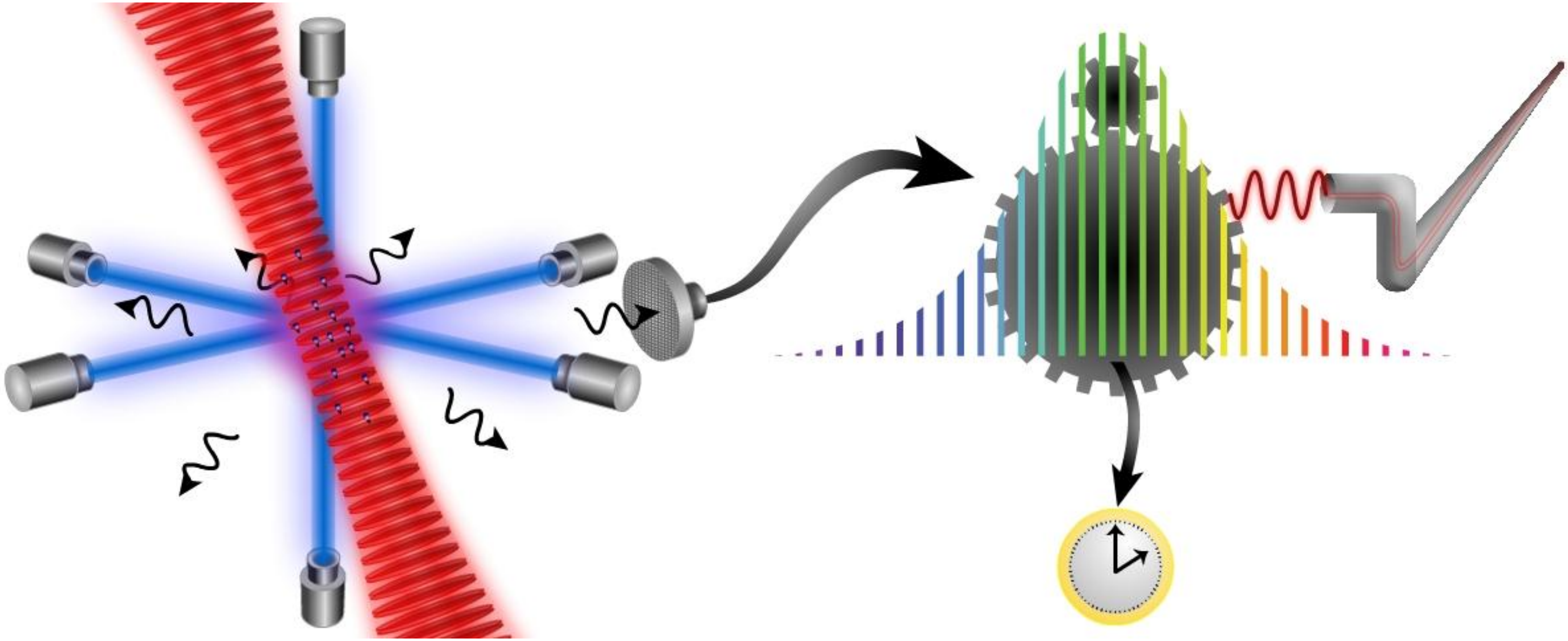


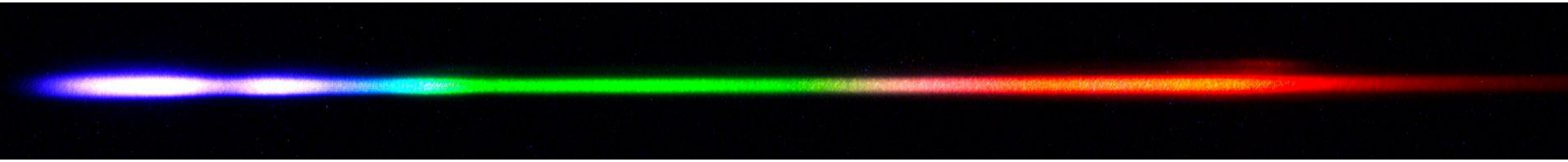


JILA Sr atomic clock

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})

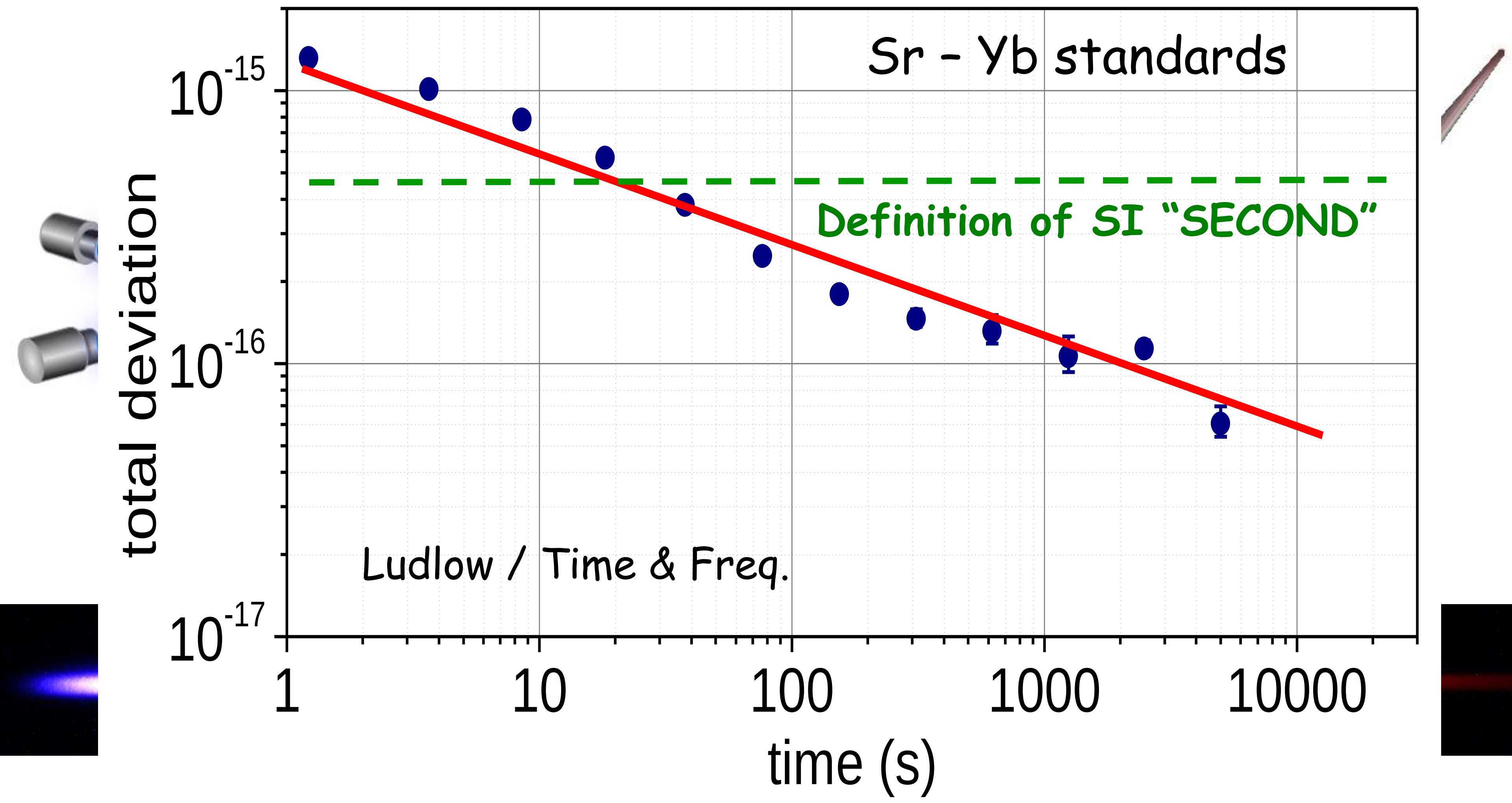




JILA Sr atomic clock

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

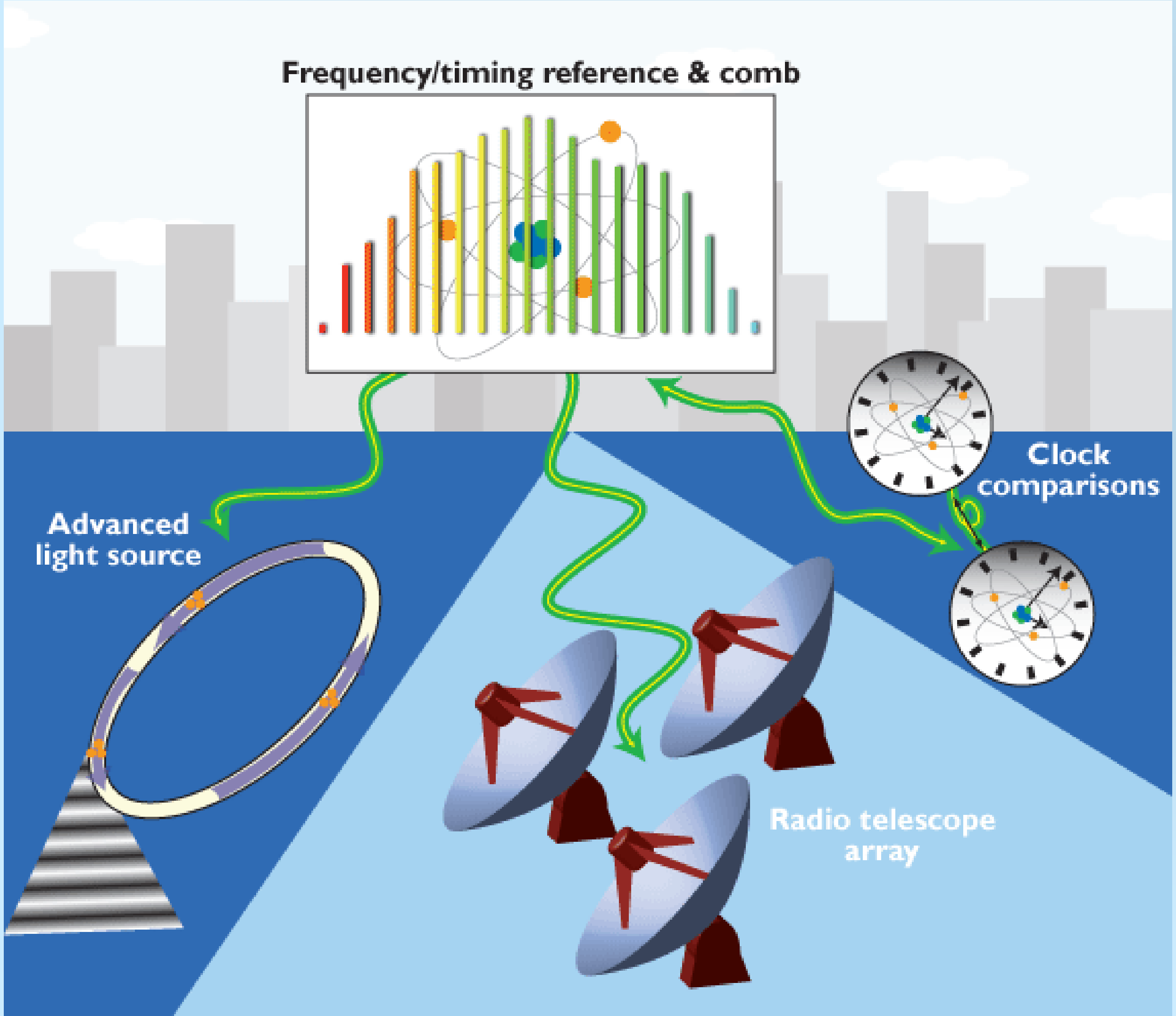
10, 000, 000, 000, 000, 000 ± 1 (10^{-16})



Precise distribution of ultra-stable signals

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

SYRTE, NIST, ...



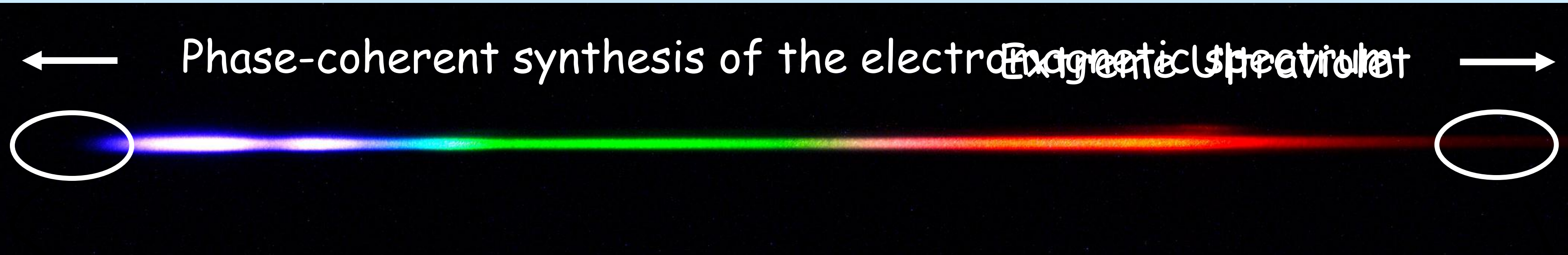
100 km fiber:

1×10^{-17} @ 1 s;

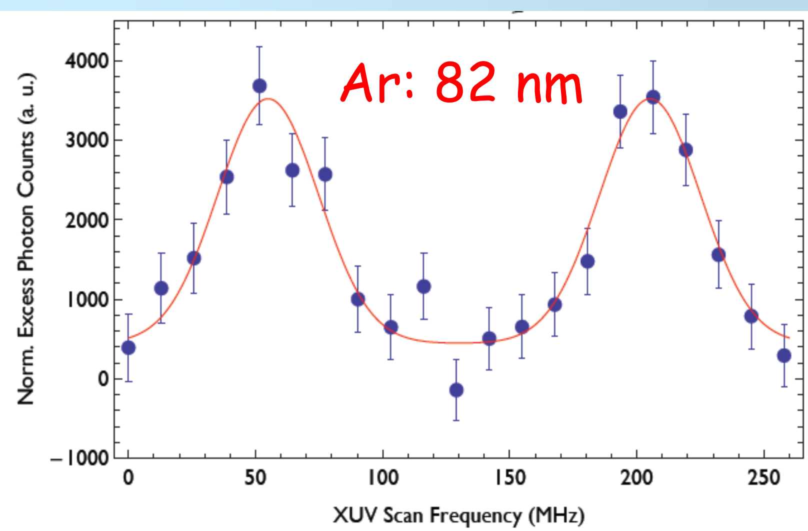
1 Hz optical linewidth;

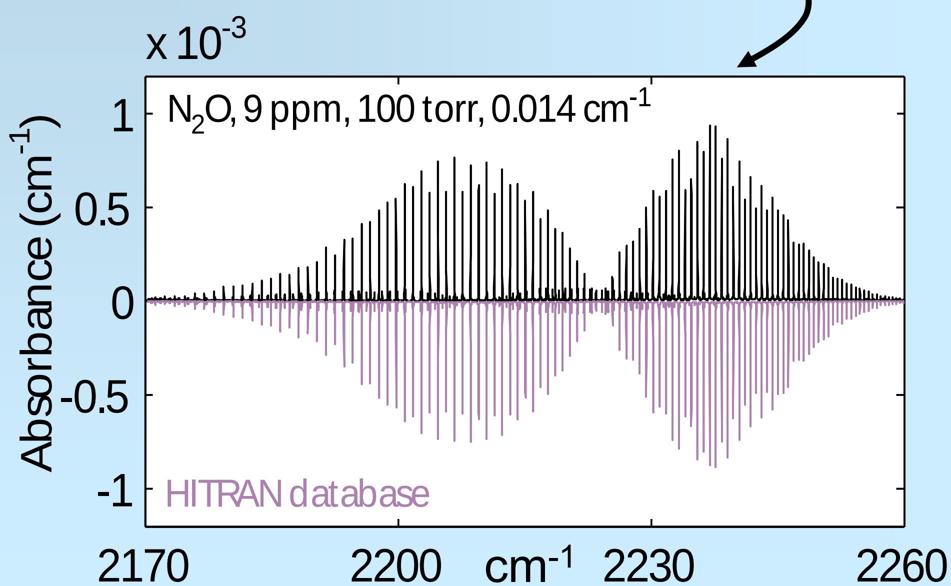
0.1 fs jitter (20 MHz BW)

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

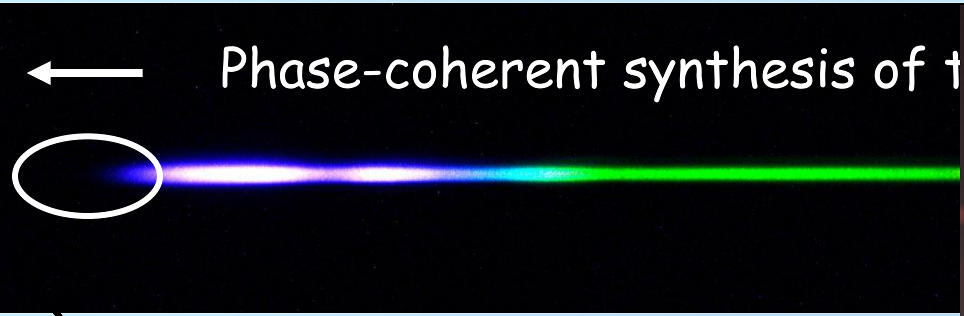


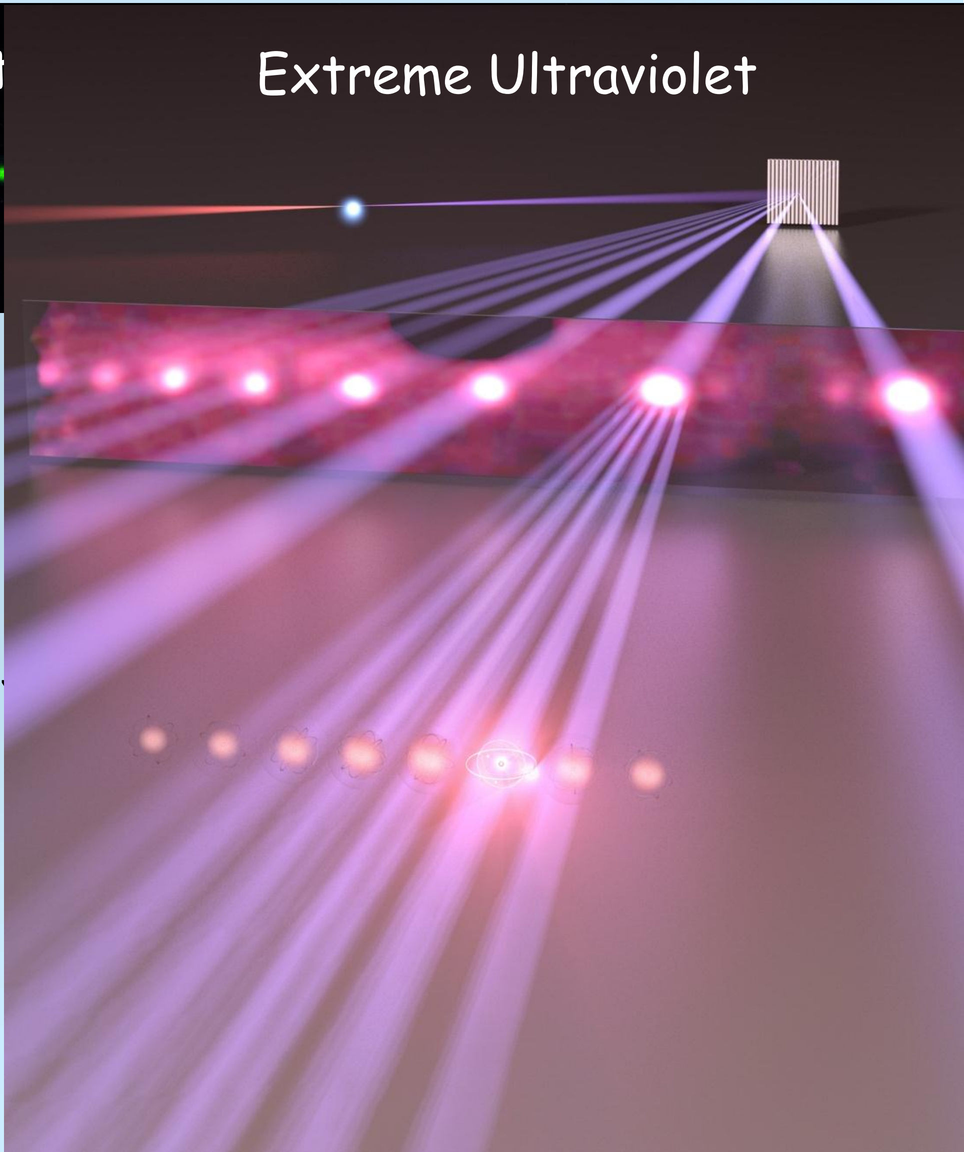
Nature, in press (2011).



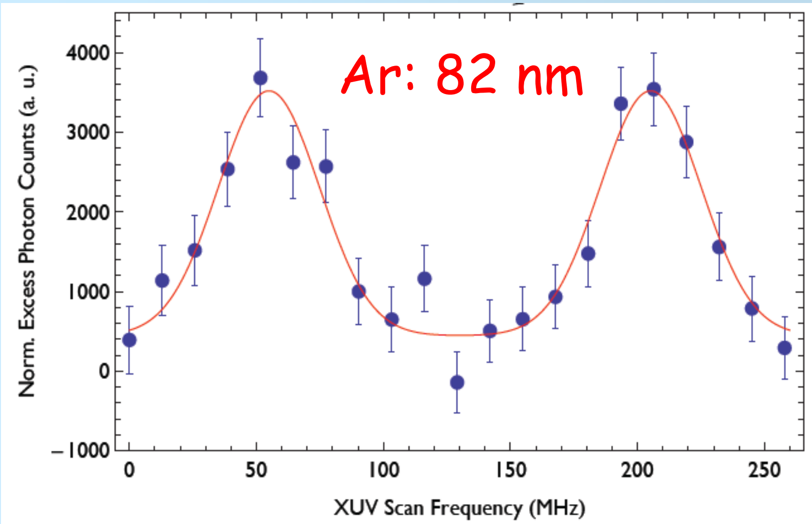


Phase-coherent radiations - IR to XUV - Spectroscopy & Quantum Control



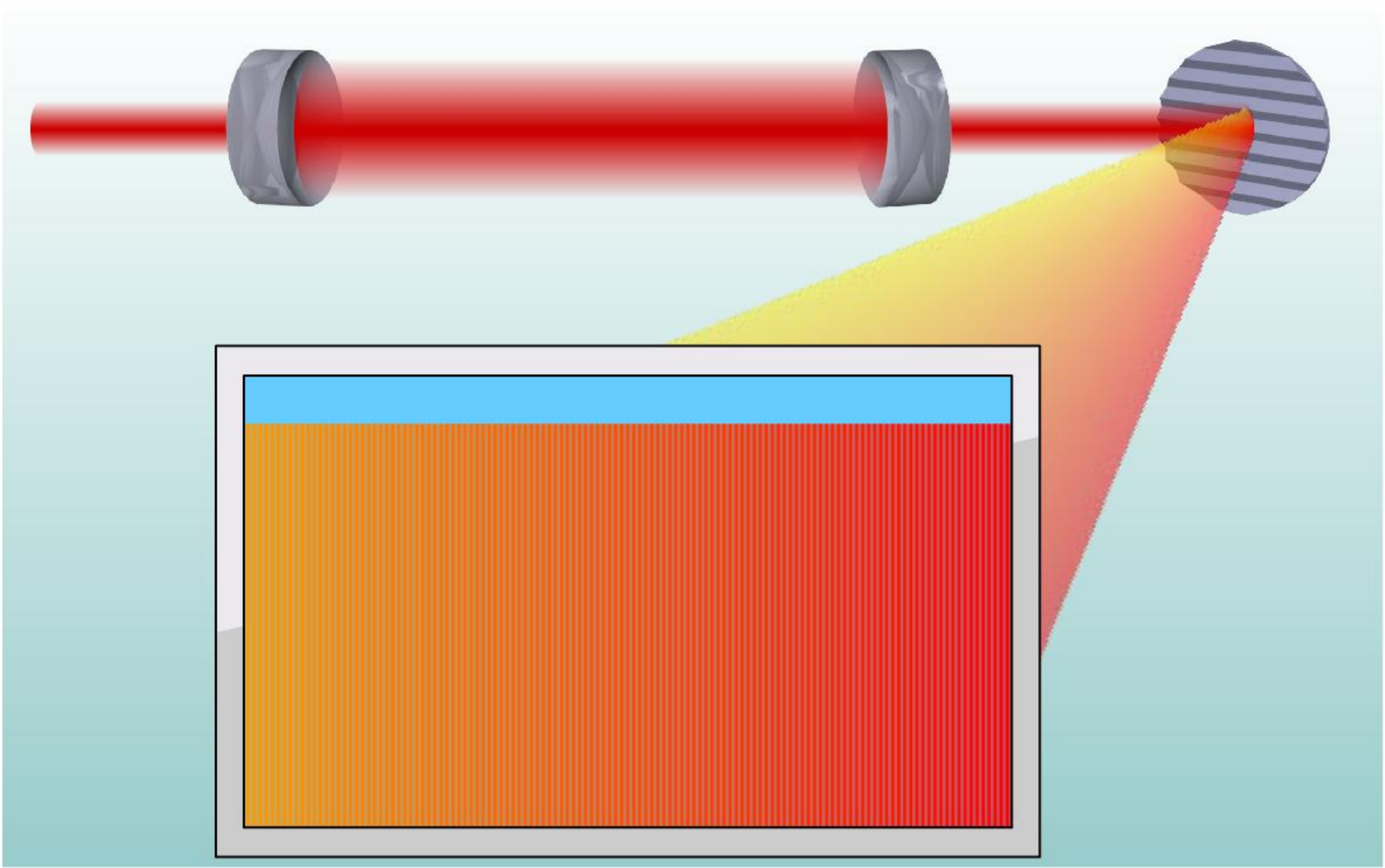


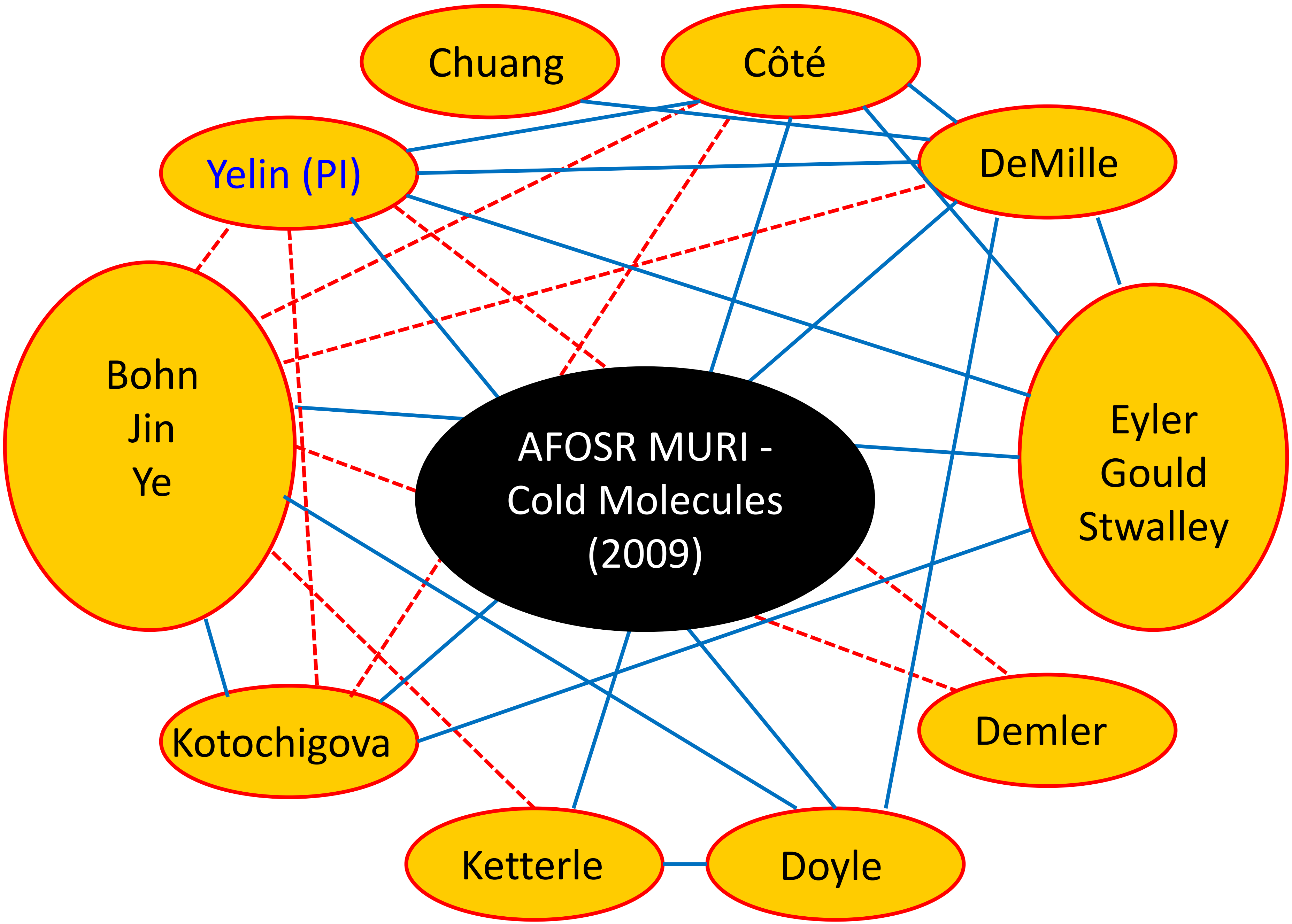
Nature, in press (2011).



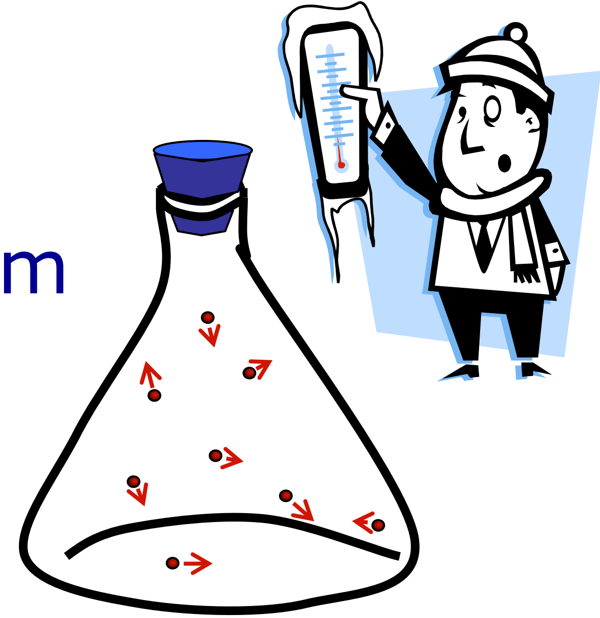
Direct Frequency Comb Spectroscopy

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




Chuang
Côté
Yelin (PI)
DeMille
Bohn
Jin
Ye
AFOSR MURI -
Cold Molecules
(2009)
Eyler
Gould
Stwalley
Kotochigova
Demler
Ketterle
Doyle

Ultracold gases



Precise control of a quantum system

applications:

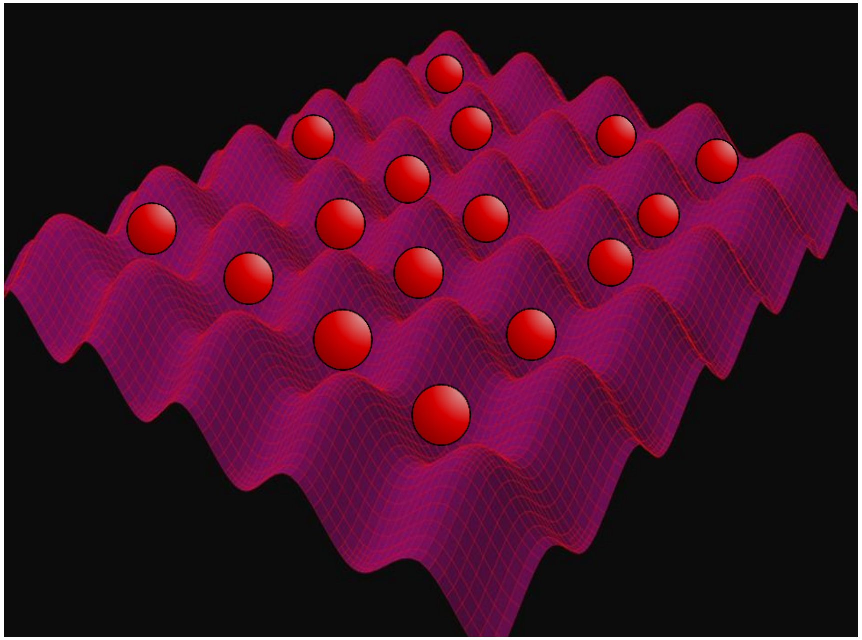
quantum computing
atomic clocks
precision measurements
cold-atom-based sensors

Control: A tool for understanding complexity.

Build up strongly correlated many-body quantum systems

- Fermi superfluidity

- fermions or bosons in an optical lattice



Why polar molecules?

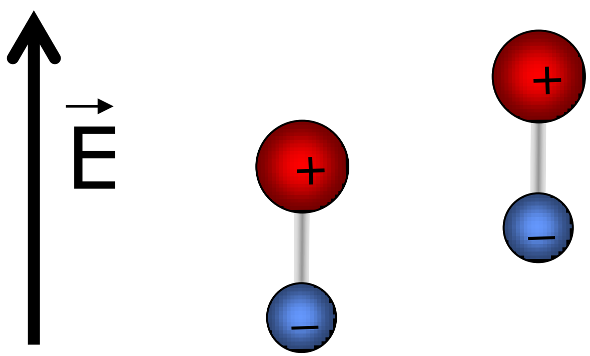
Extend our capability to control quantum systems

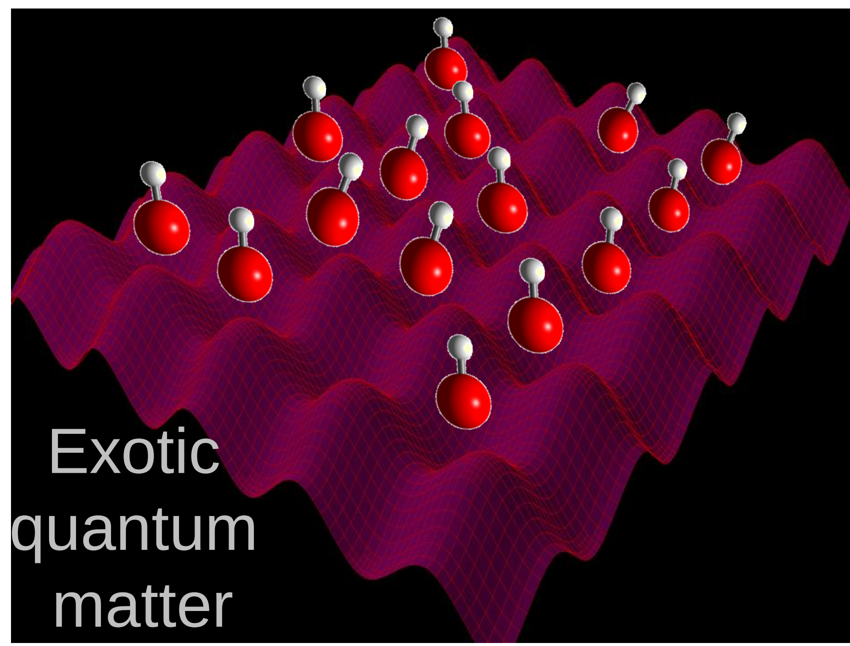
What's new (compared to ultracold atoms)?

- New internal degrees of freedom

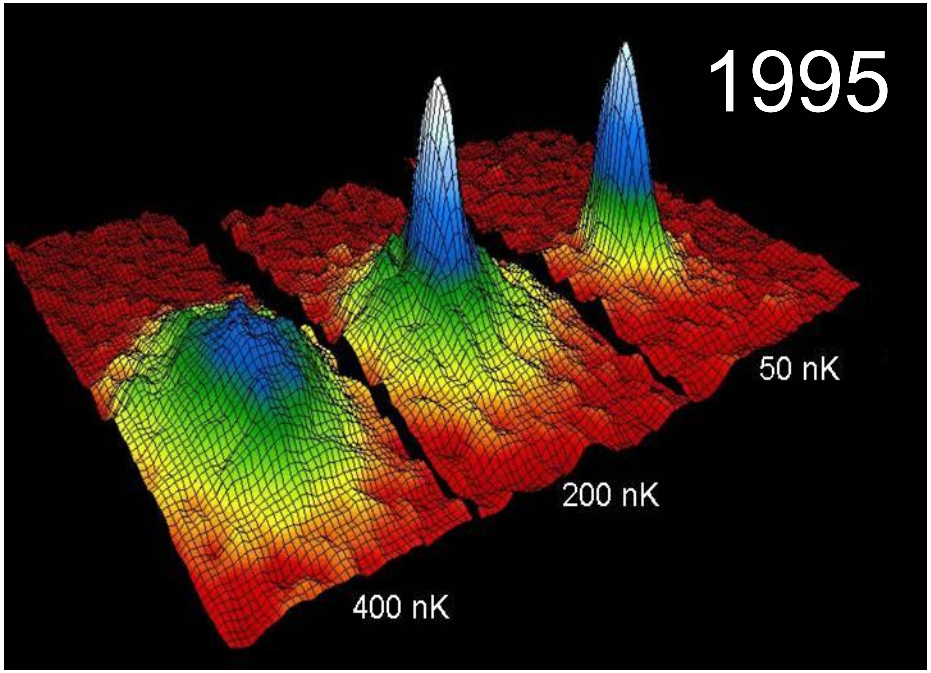
  vibration, rotation

- Chemistry
- Long-range interactions





Atom vs. molecule



Bose-Einstein Condensation

$T = 100$ nK

$N = 10^6$ atoms

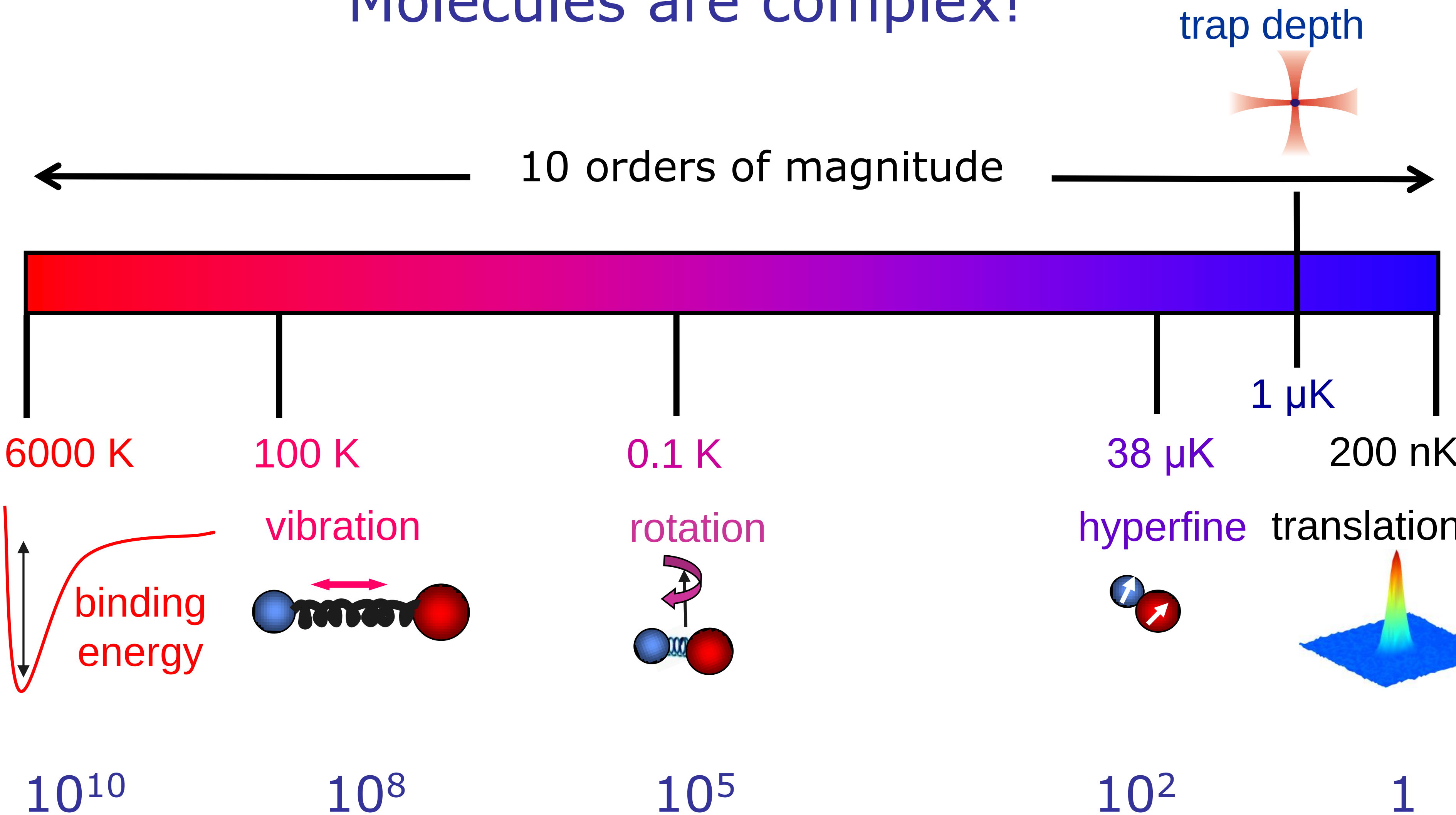
$n = 10^{13}$ cm^{-3}

Molecules:

$T = 100$ mK, $n = 10^6$ cm^{-3}

Ultracold molecules: The challenge

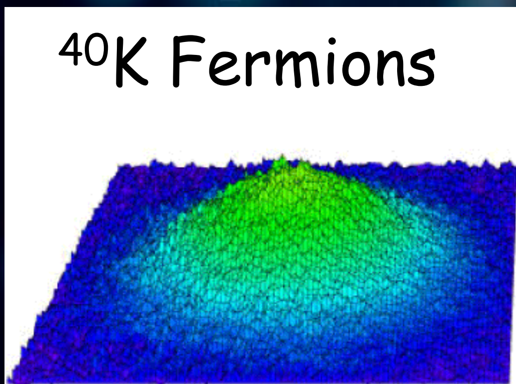
Molecules are complex!

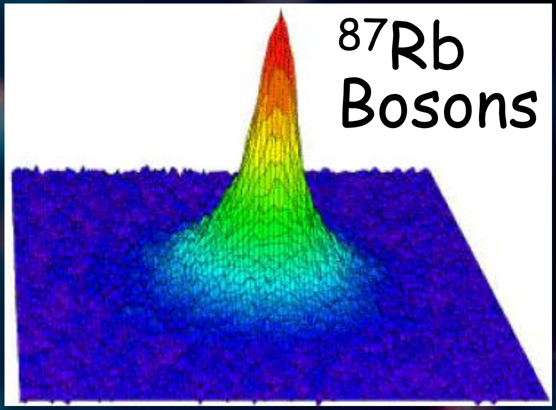


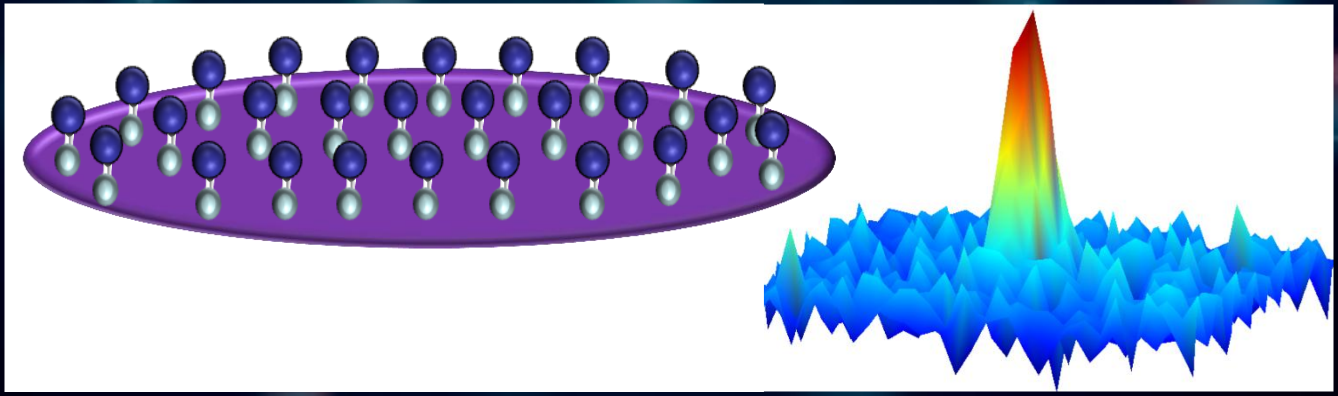
Quantum gas of polar molecules

Debbie Jin
J. Ye

Science <u>322</u>, 231 (2008)
Science <u>327</u>, 853 (2010)
Nature <u>464</u>, 1324 (2010)

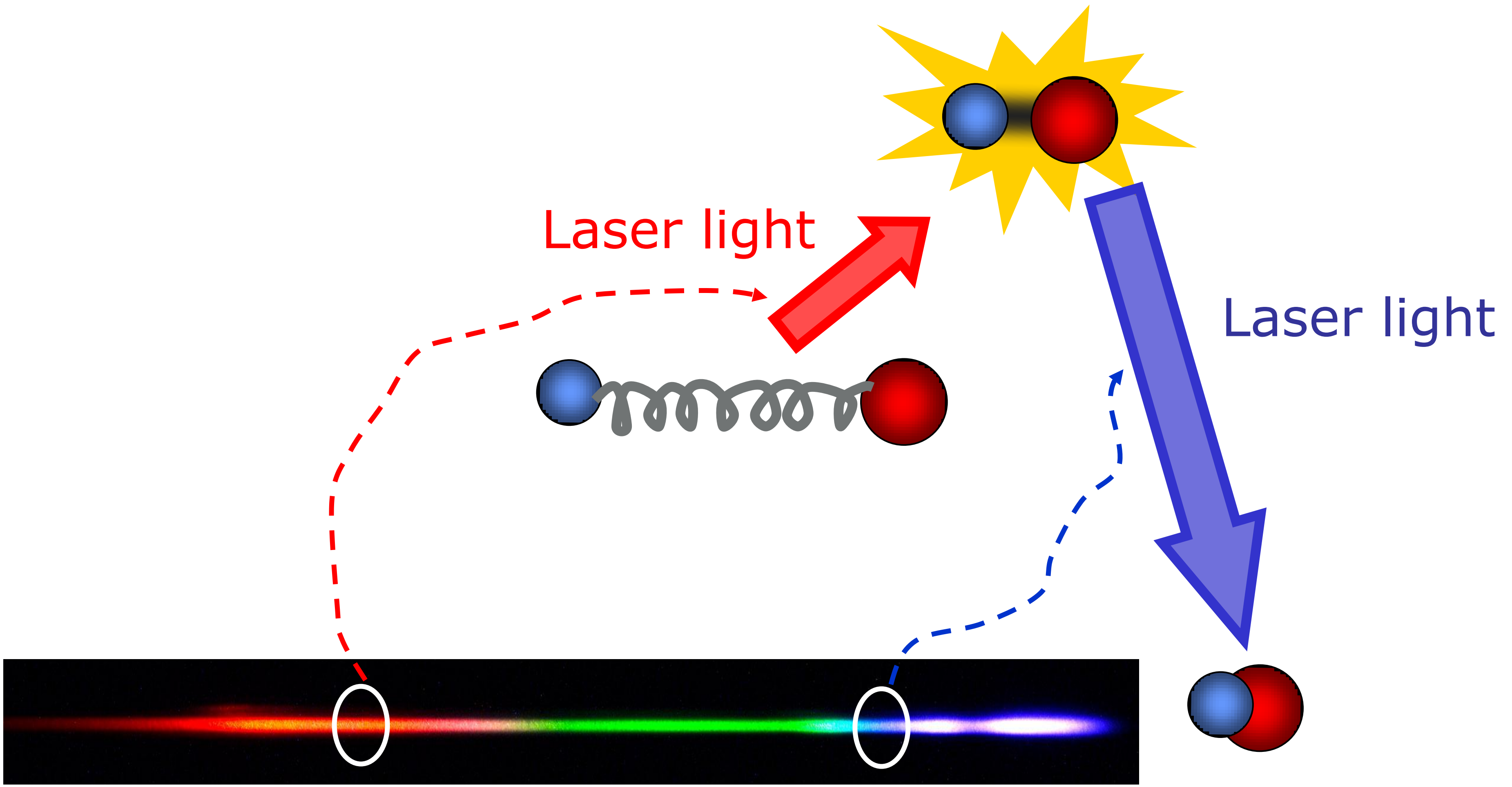






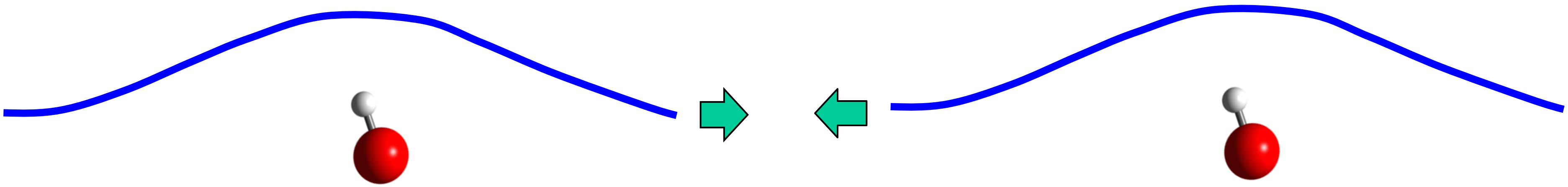
Light provides the answer

Photons carry away the energy!

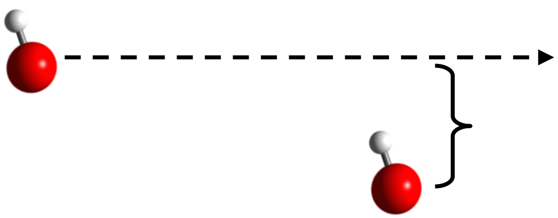


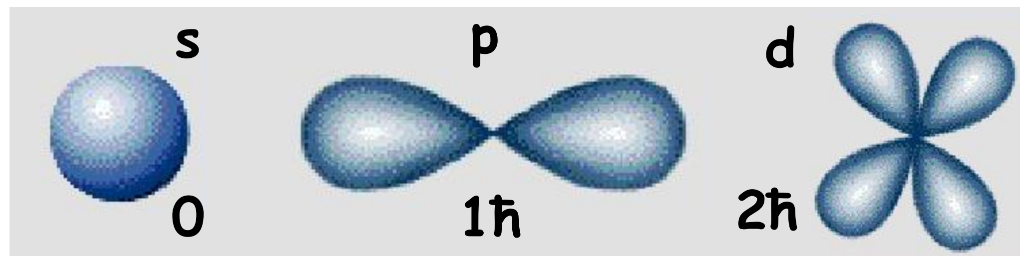
Chemistry near absolute zero

(1) Molecules behave like waves

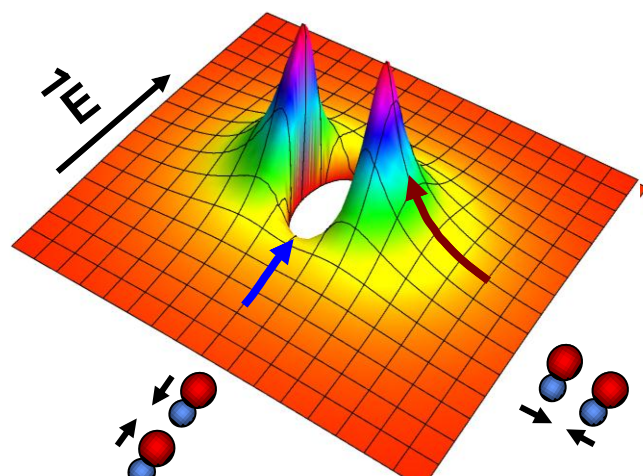


(2) Angular momentum is quantized



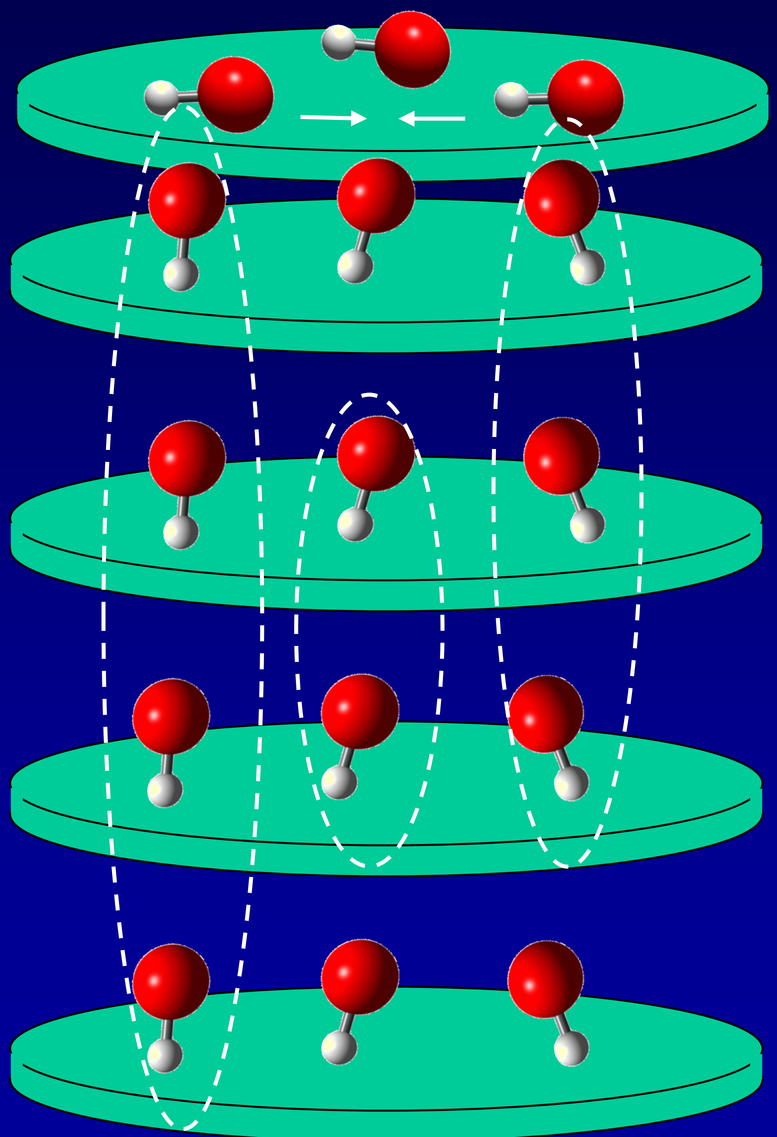


(3) Quantum statistics matter



Fermions ⇨
L = 1, *p*-wave collisions

New quantum phases and dynamics



Revolution Ongoing !

E

- Correlated Fermi pairs
- Bi-layer Bose condensation?
- Super solids?
- … …

Zoller, Demler, Santos, … …

Over the years …

http://JILA.Colorado.edu/YeLabs

F. Adler (NIST)
S. Blatt (Harvard)
J. Bochinski (Faculty, NC State)
M. Boyd (AO Sense, industry)
G. Campbell (Faculty, U. Maryland)
L. Chen (Faculty, WIPM)
S. Foreman (Stanford U.)
K. Holman (Staff, Lincoln Lab)
E. Hudson (Faculty, UCLA)
T. Ido (Senior staff, Tokyo NICT)
D. Jones (Faculty, UBC)
J. Jones (Faculty, U. Arizona)
Y. Lin (Staff, Nat. Inst. Metrology)
T. Loftus (AO Sense, industry)
H. Lewandowski (Faculty, U. Colorado)
A. Ludlow (Scientist, NIST)
K. Moll (Precision Photon., industry)
M. Notcutt (ATF, industry)
B. Lev (Faculty, Stanford U.)
S. Ospelkaus (Faculty, U. Hannover)
A. Pe'er (Faculty, Bar-Ilan U.)
B. Sawyer (NIST)
T. Schibli (Faculty, U. Colorado)
M. Stowe (Staff, Lincoln Lab)
M. Thorpe (NIST)
D. Wang (Faculty, U. Hong Kong)
X. Xu (Faculty, ECNU)
T. Yoon (Faculty, Korea Nat. U.)
T. Zanon (Faculty, Univ. Paris)
T. Zelevinsky (Faculty, Columbia U.)

& current group members … …