Measurement at the Quantum Frontier

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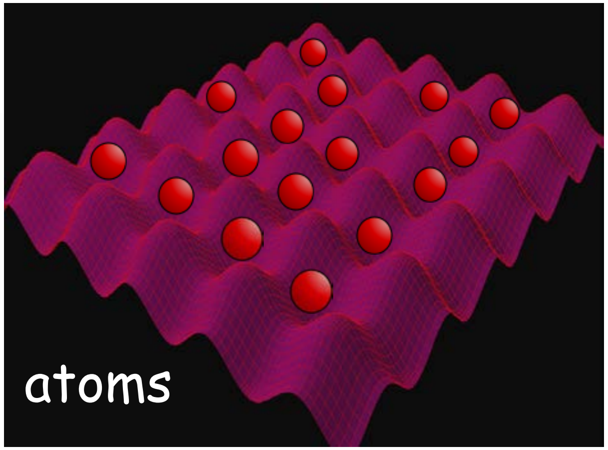
JILA, NIST & Univ. of Colorado

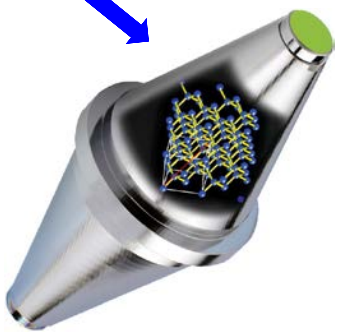
Boulder Summer School,
July 23, 2018

Opportunities for AMO/quantum physics

Probe fundamental physics & emerging phenomena
with "clock" precision and control

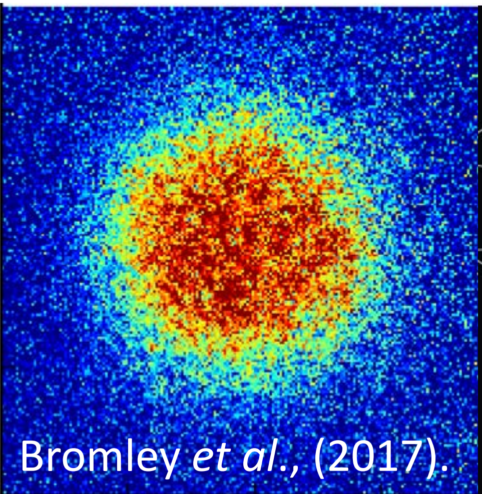


Search for
dark matter

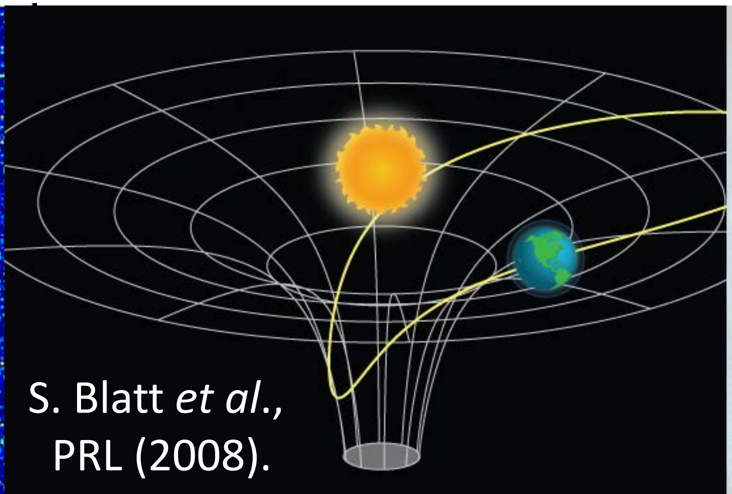


Spin manybody

Table-top search for new physics



Bromley *et al.*, (2017).



S. Blatt *et al.*,
PRL (2008).

Kolkowitz *et al.*, PRD (2016).

Lecture outlines

Lecture I

- Simple atomic physics
- Basic quantum physics
- Basic laser science

→ The ingredients for control & measurement of quantum coherence

Lecture II

- Atomic interactions
- Spin Hamiltonians
- Emergence of complexity from simple ingredients

→ A new frontier: quantum metrology & many-body physics

Lecture outlines

Lecture III

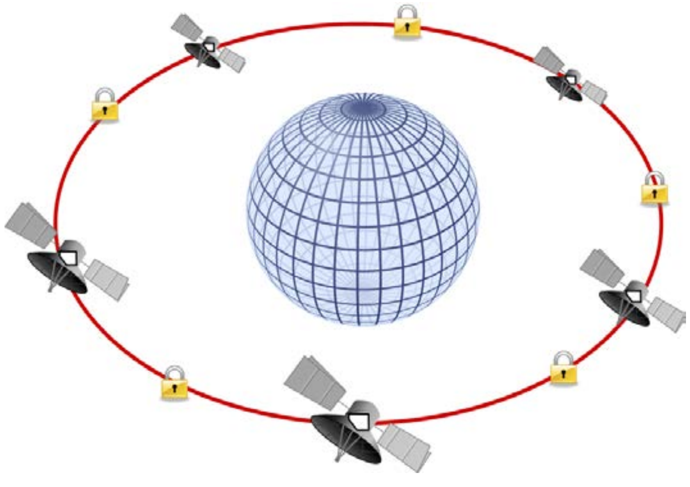
- Broad scientific motivations for cold molecules
- Technology developments
- Quantum degenerate gas of polar molecules

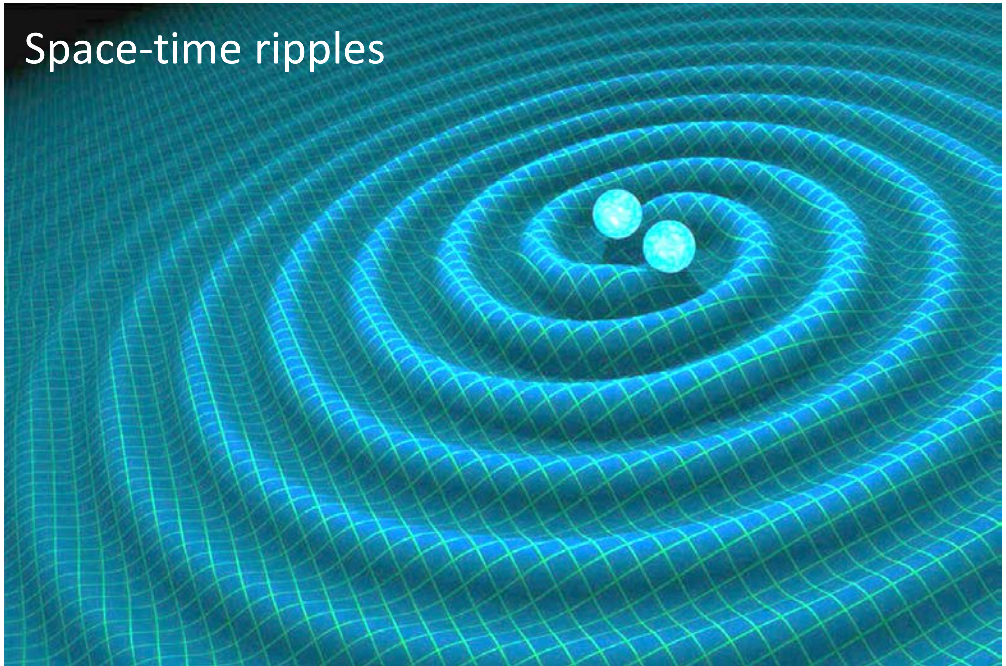
→ A new playground for quantum physics and chemistry

Probes for fundamental physics

Kómár *et al.*, Nat. Phys. **10**, 582 (2014); Kolkowitz *et al.*, Phys. Rev. D **94**, 124043 (2016).

Network of clocks (**10^{-21}**):
long baseline interferometry

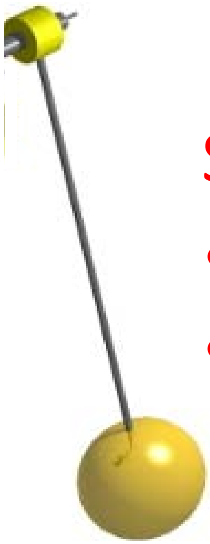




Time Scales

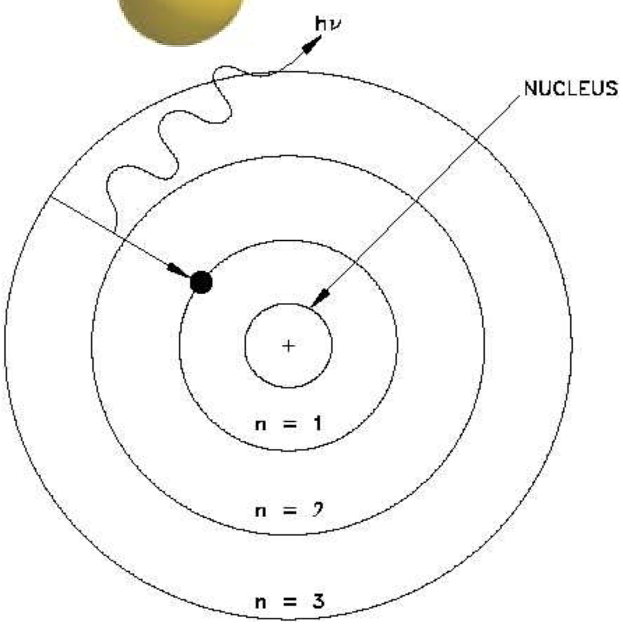
Quantum pendulum period: 10^{-15} s
0.000,000,000,000,001 seconds

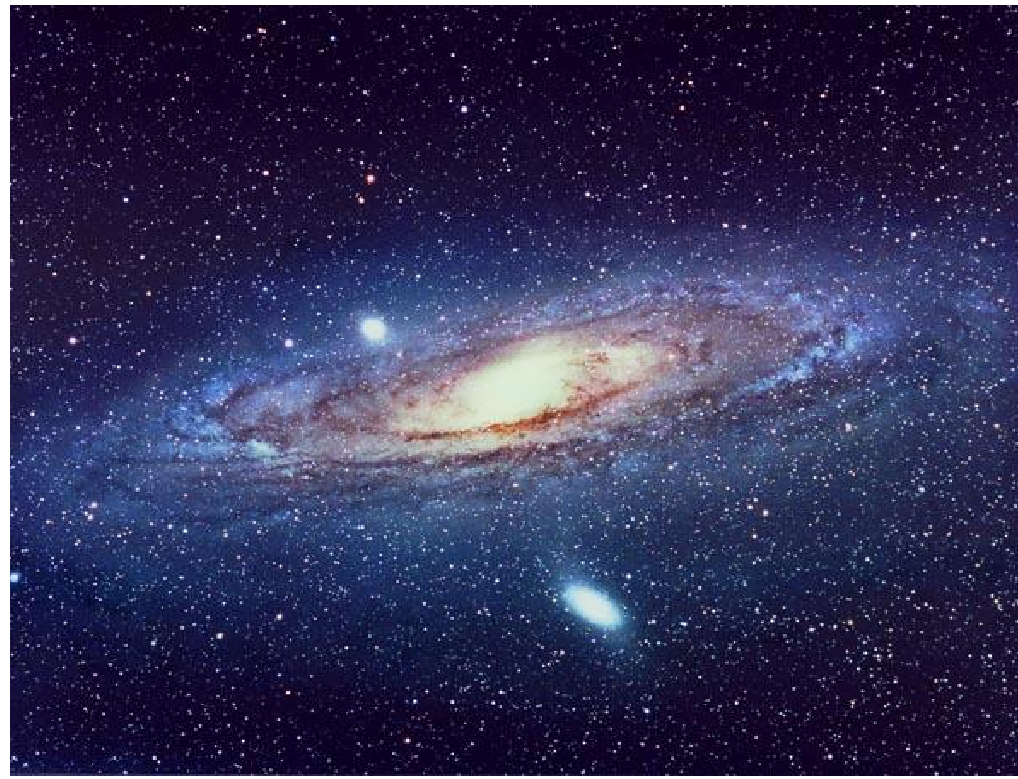
The geometric mean
~30 s



Sr atoms:

- $^1S_0 \leftrightarrow {}^3P_0$ (160 s)
- $Q \sim 10^{17}$

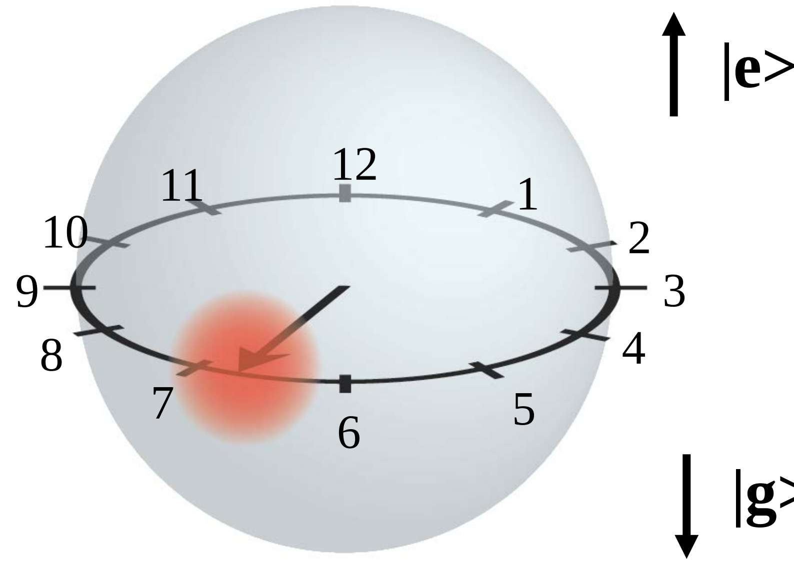


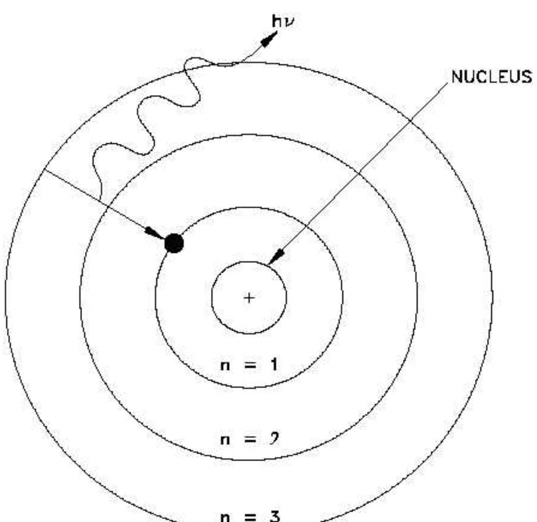


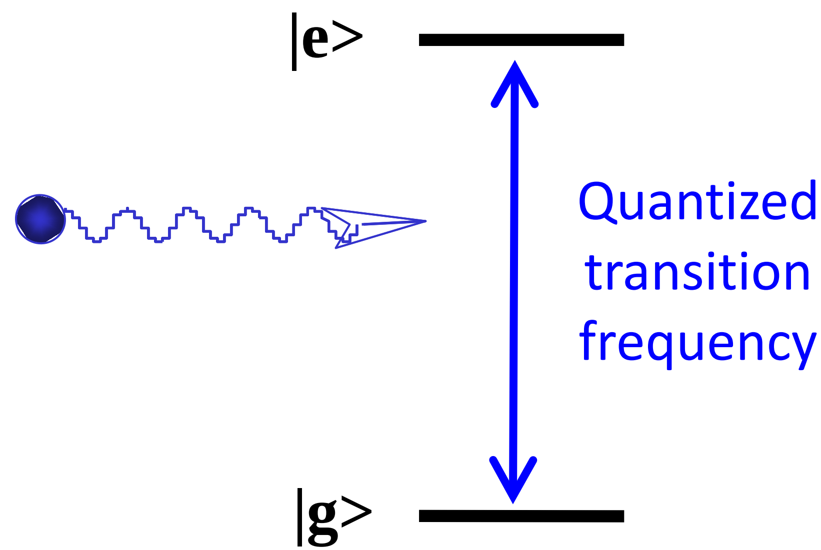
Life of the Universe: 15 billion years (10^{18} s)
1000,000,000,000,000,000 seconds

Quantum Certainty & Uncertainty

$$\frac{1}{\sqrt{2}}(|e\rangle + |g\rangle)$$

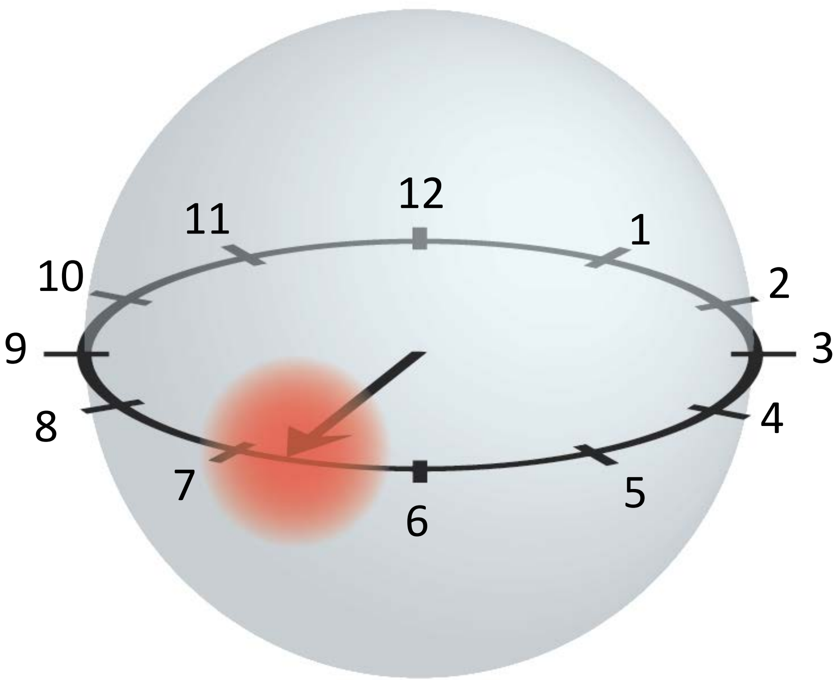




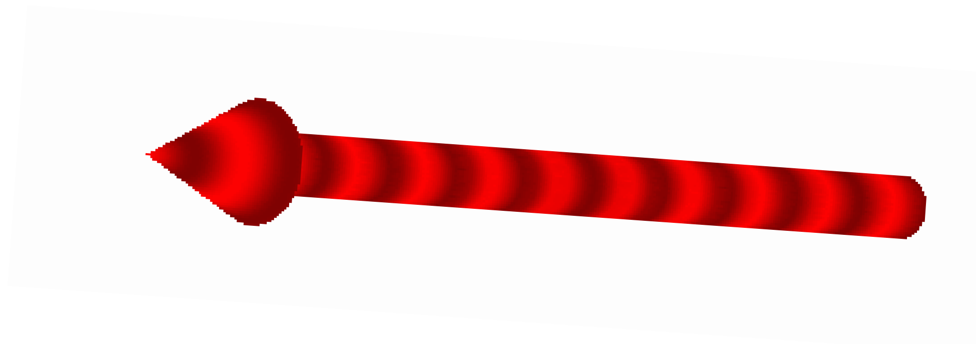


Standard quantum limit

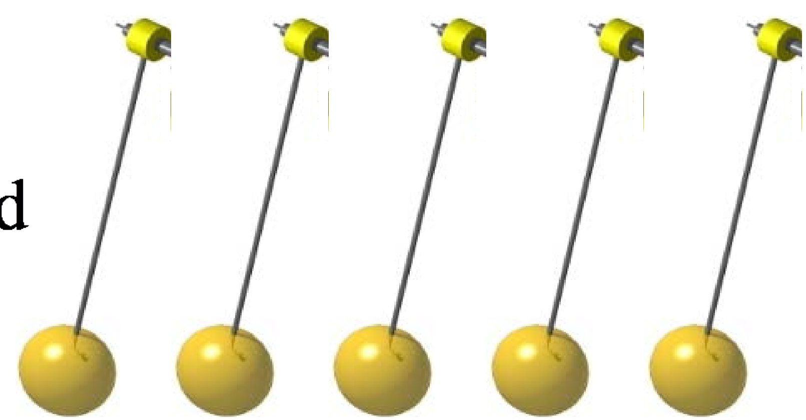
Quantum Phase Noise
of Atoms



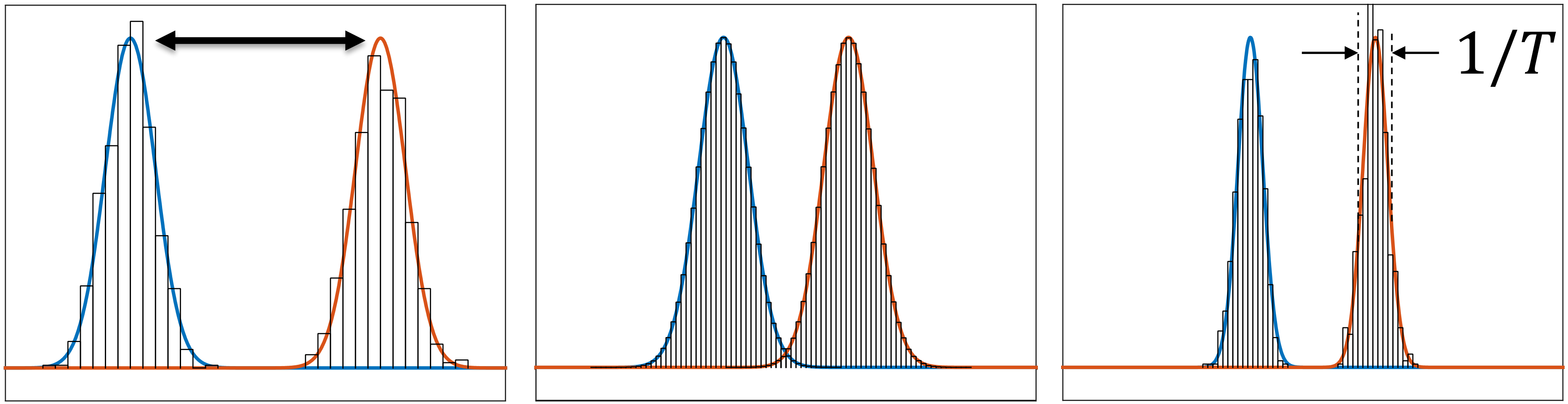
Classical Phase Noise
of Probe Laser



$$\Delta\phi_{SQL} = \frac{1}{\sqrt{N}}\,\mathrm{rad}$$



Recipe for a good spectroscopy signal



Large desired effect

Large count rate
(split resonance by $\sqrt{N}$)

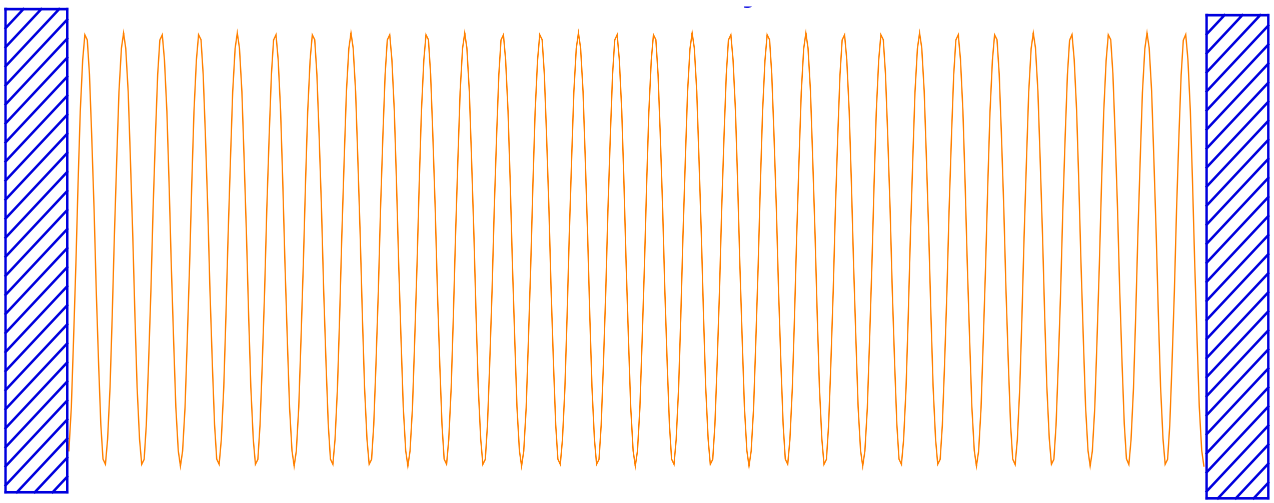
Long coherence time
(narrow resonance)

$$\sigma_{\mathrm{QPN}}(\tau) = \frac{1}{\omega T\sqrt{N}} \sqrt{\frac{T + T_{\mathrm{d}}}{\tau}}$$

Sync the laser to the atom

Laser is *the* Central Ruler of Time & Space

"The METER is the length of the path travelled by light in vacuum during a time interval of 1/299792458 seconds ."

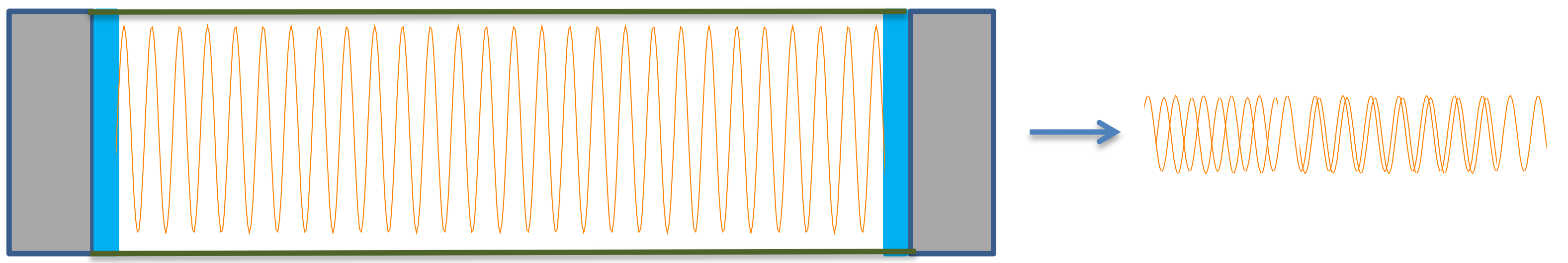


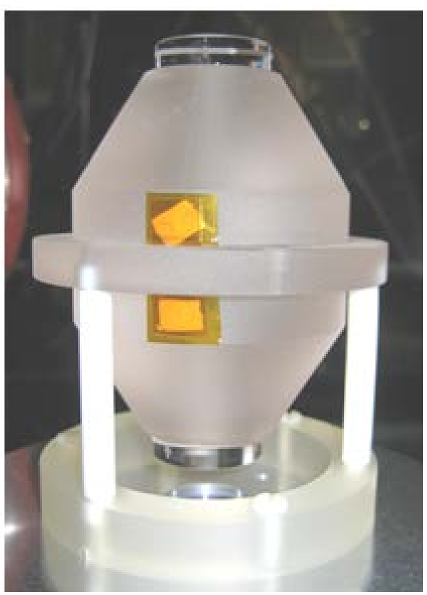
Time/Frequency is the most accurately measureable quantity.

Length is linked to Time via *c*.

Optical cavity length

Cavity length $L \sim 1$ m $\rightarrow$ $\Delta L \sim 10^{-16}$ m (size of a nucleus: 10^{-14} m)





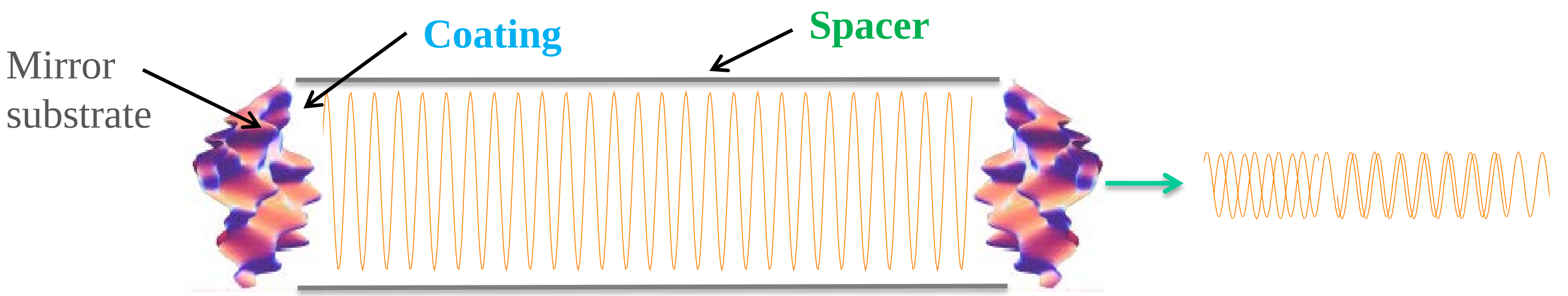
Vibration noise: symmetric mounting

Pressure noise $\Delta n/n$: vacuum ~10^{-7} torr

Spurious optical interference, etc

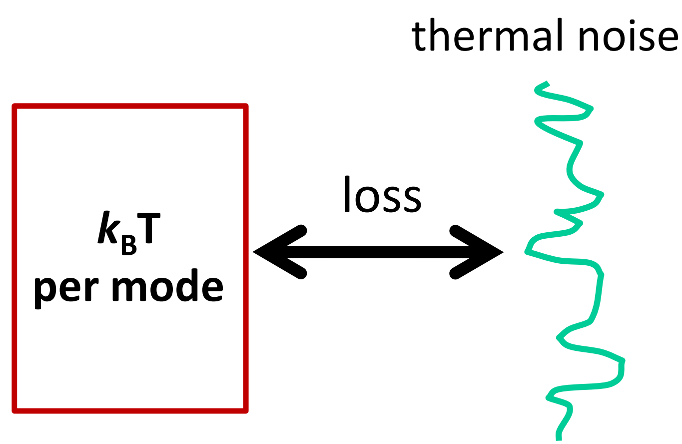
Laser is the Central Ruler of Time & Space

Cavity length $L \sim 1$ m → $\Delta L \sim 10^{-16}$ m (size of a nucleus: 10^{-14} m)



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

$$\frac{\Delta L}{L} \sim \sqrt{\frac{k_B T}{E_0 Q}}$$

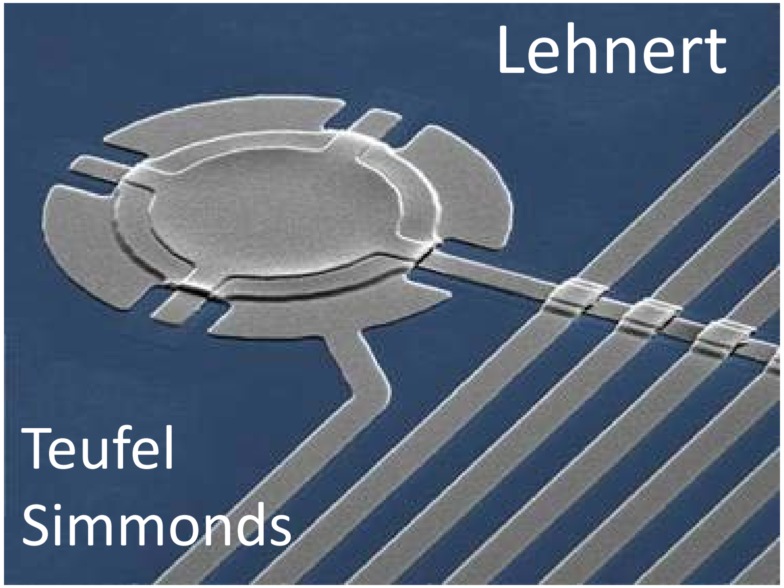


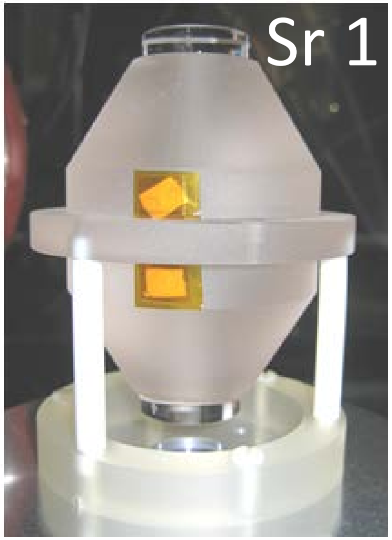
Bishof *et al.*, PRL **111**, 093604 (2013).

Thermal Noise: a challenge for all !

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

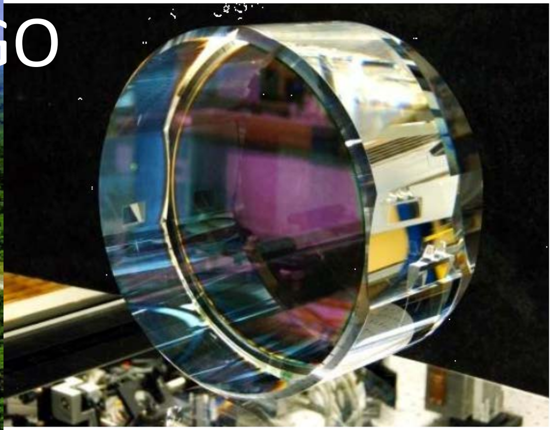
15 μm



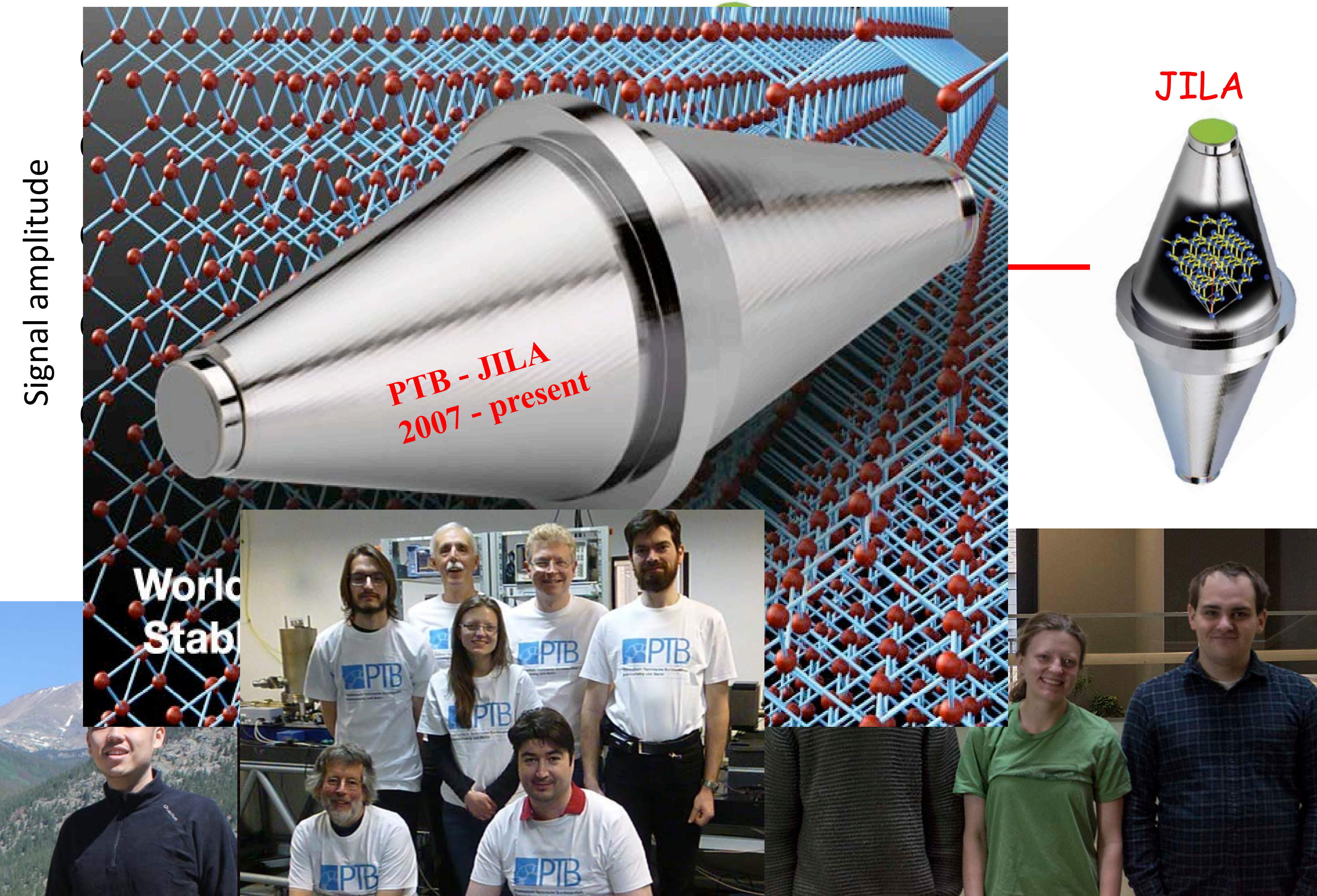


10 cm

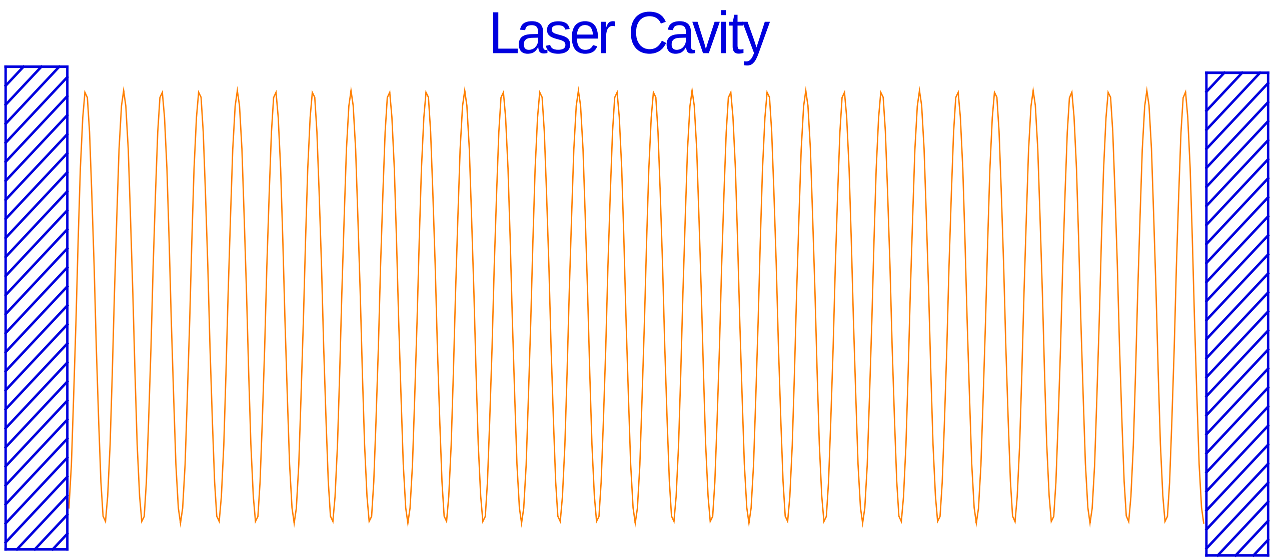
1 km



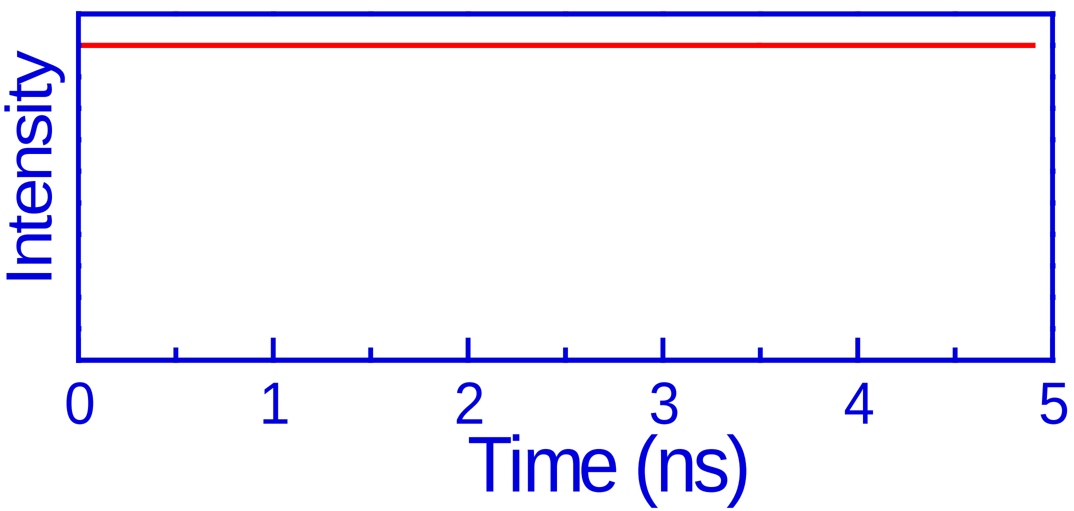
Pushing optical coherence to ~ 1 minute



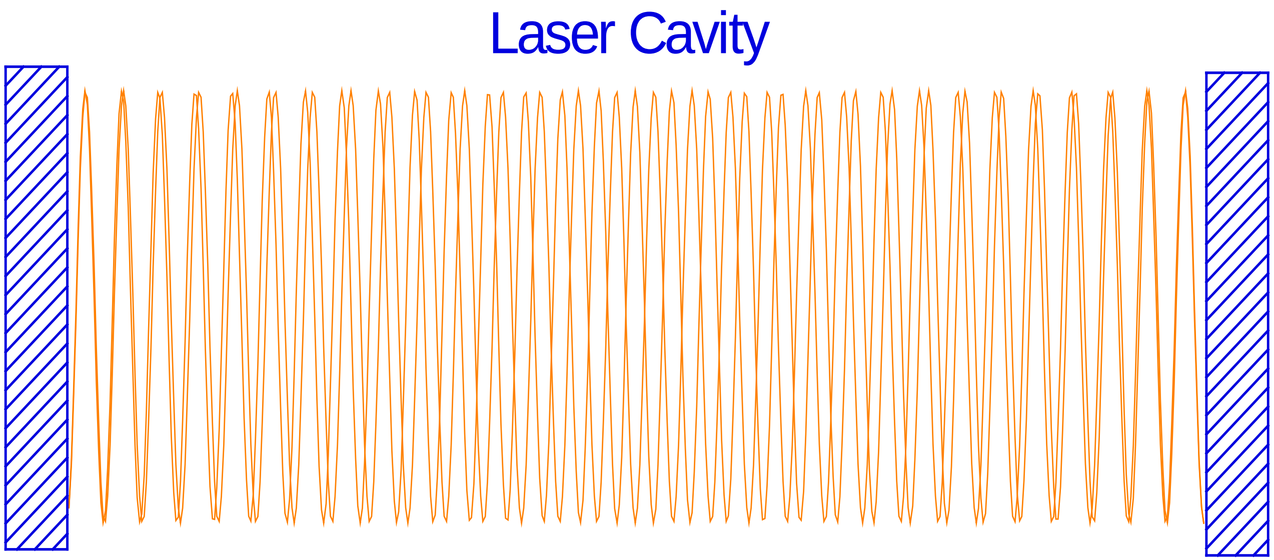
From one optical frequency to many



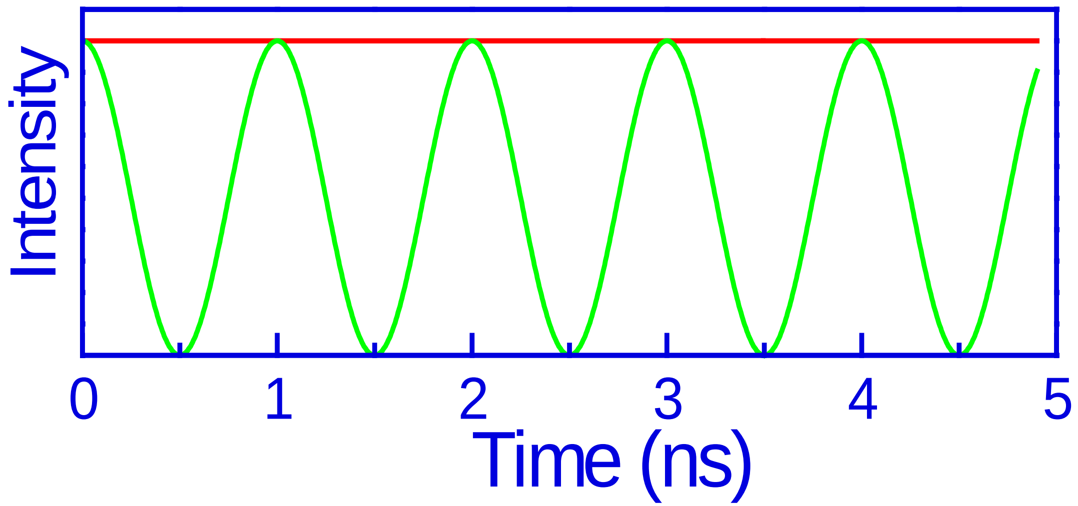
Single mode
cw laser



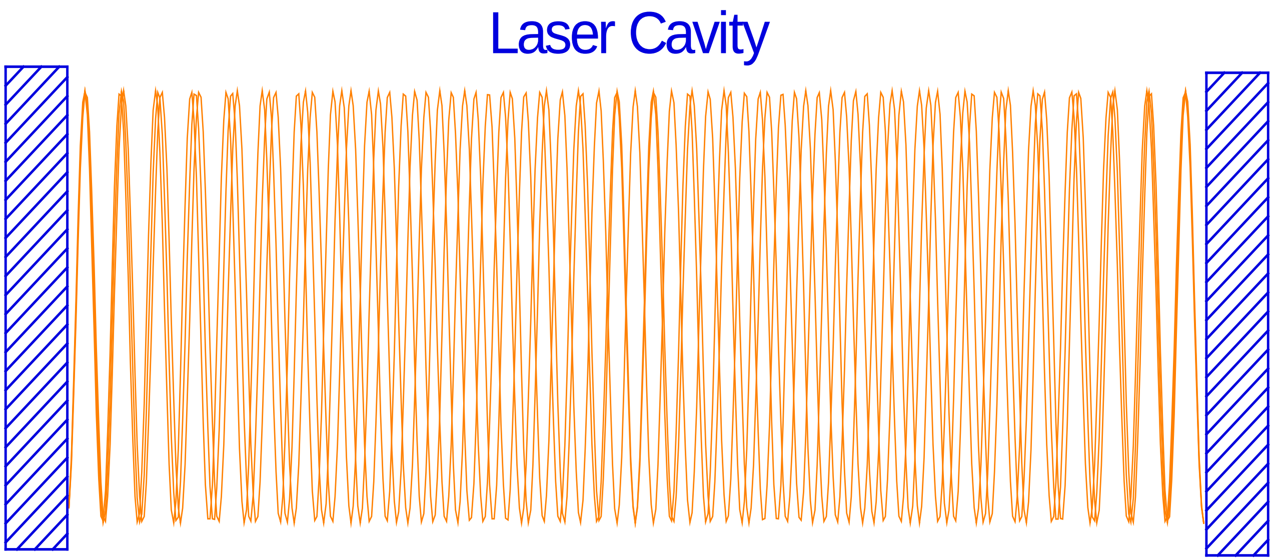
From one optical frequency to many



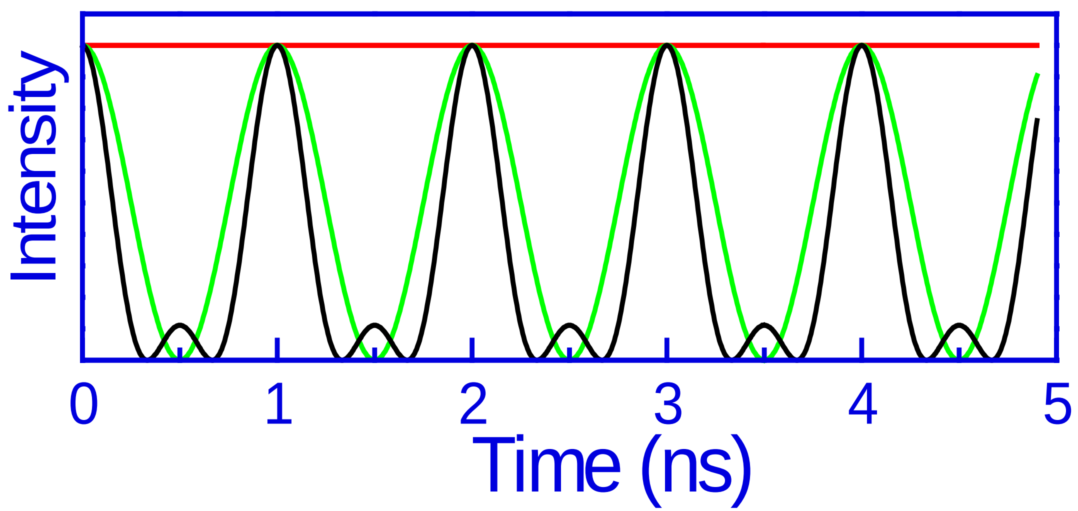
2 modes



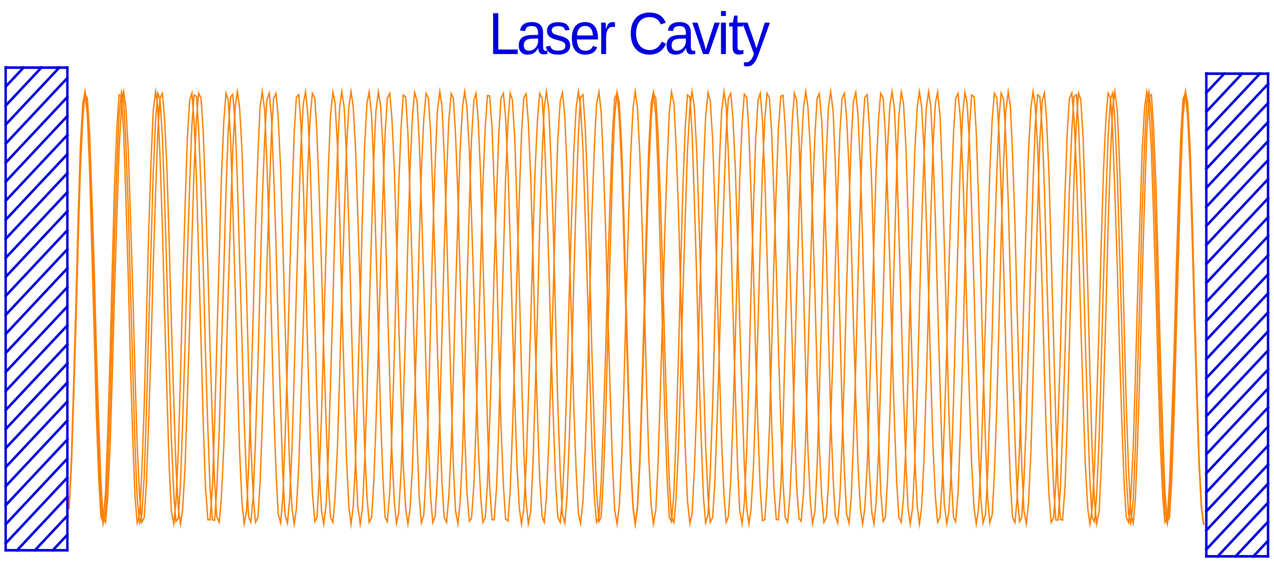
From one optical frequency to many



3 modes

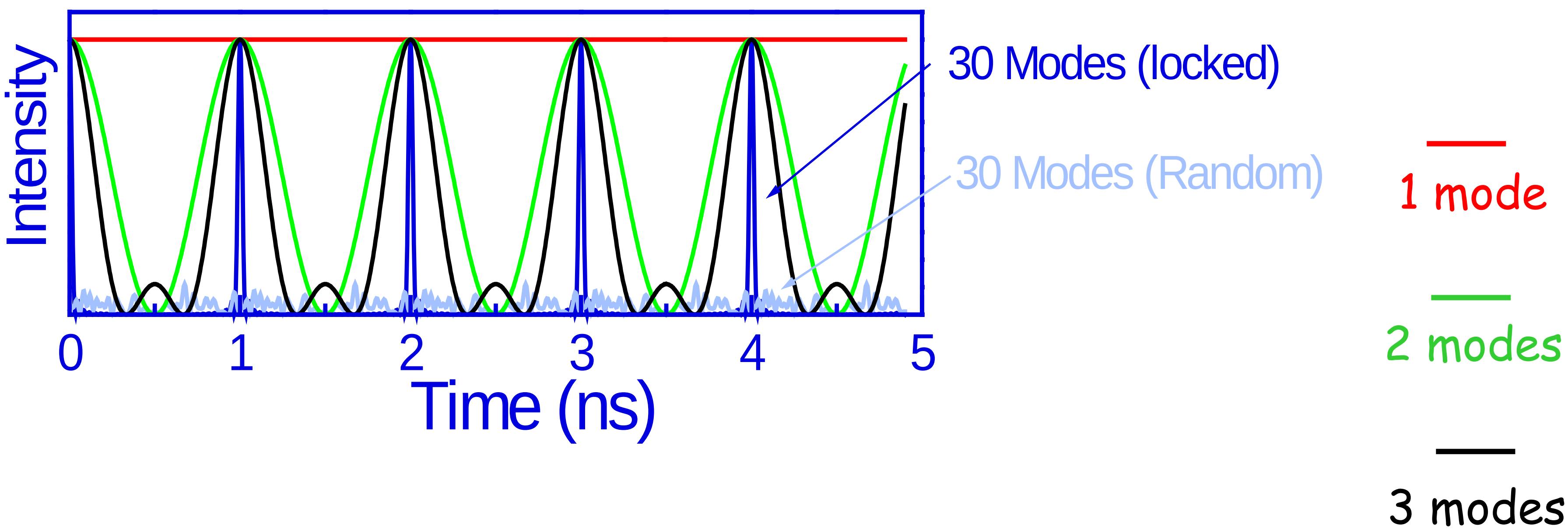


From one optical frequency to many



Interference among many cavity modes

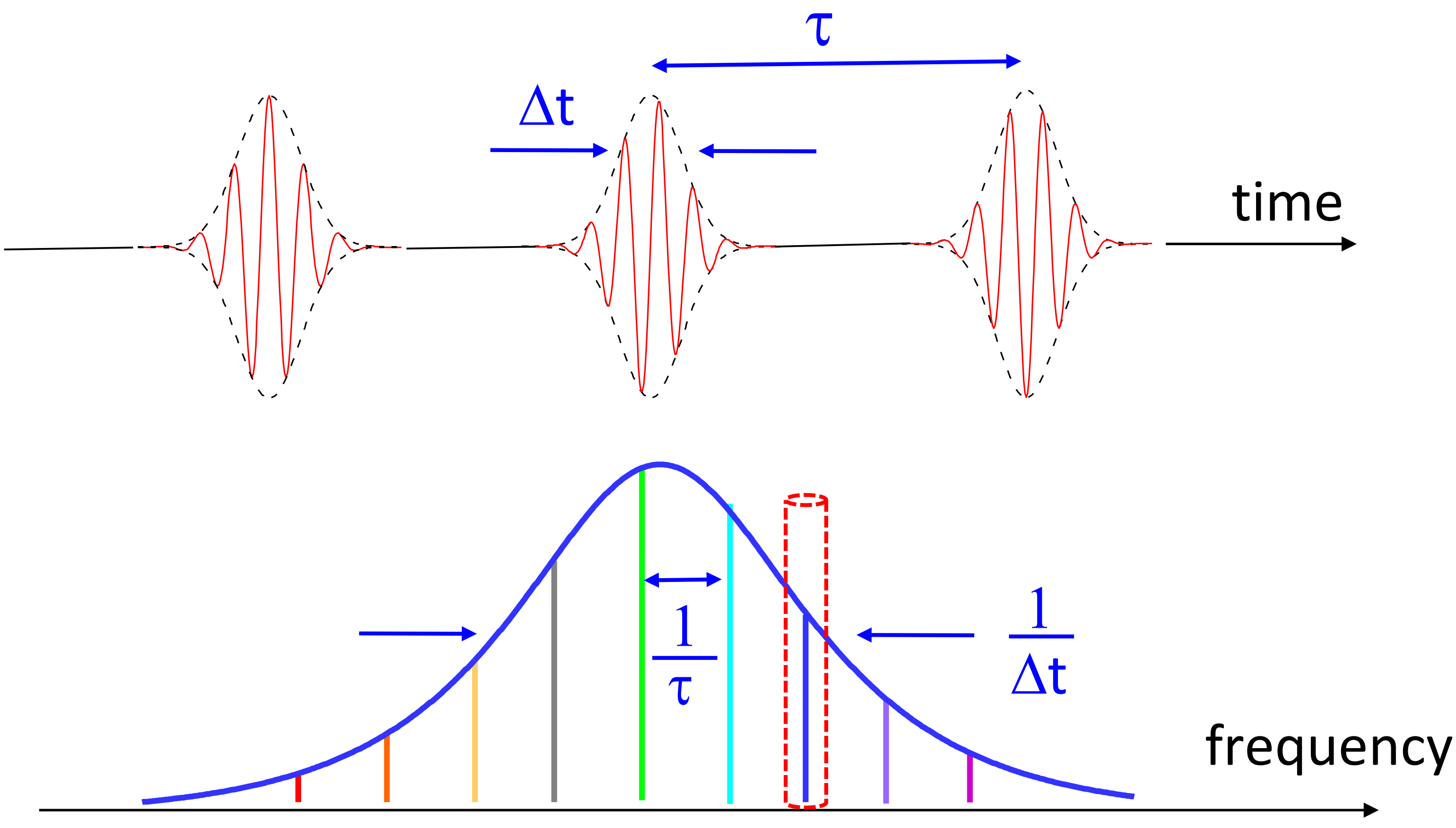
Phase locked



Time - frequency correspondence

(from one optical frequency to many)

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



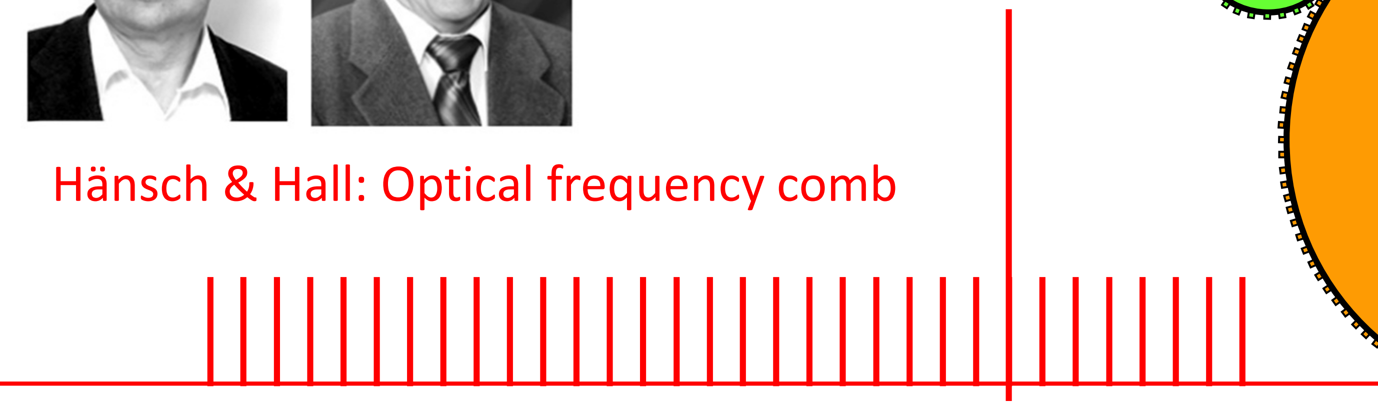
Control of light –

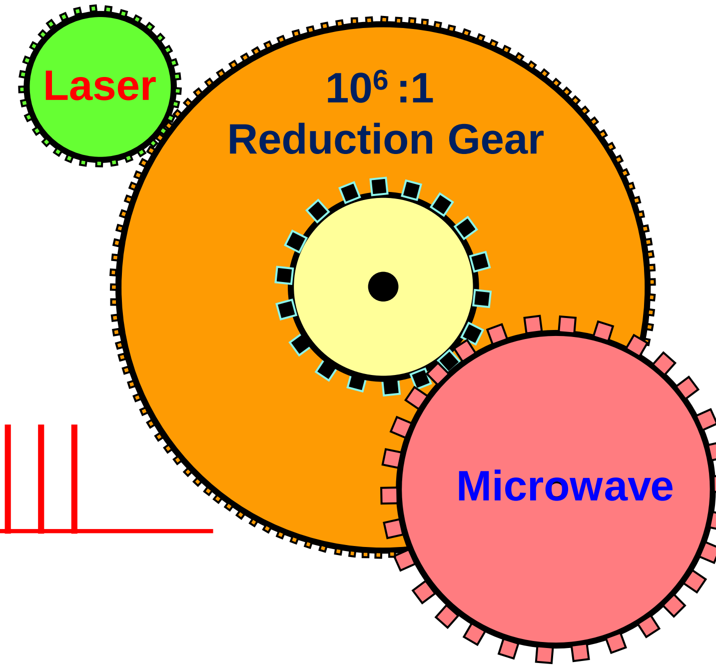
DIGITAL synthesis of electromagnetic spectrum

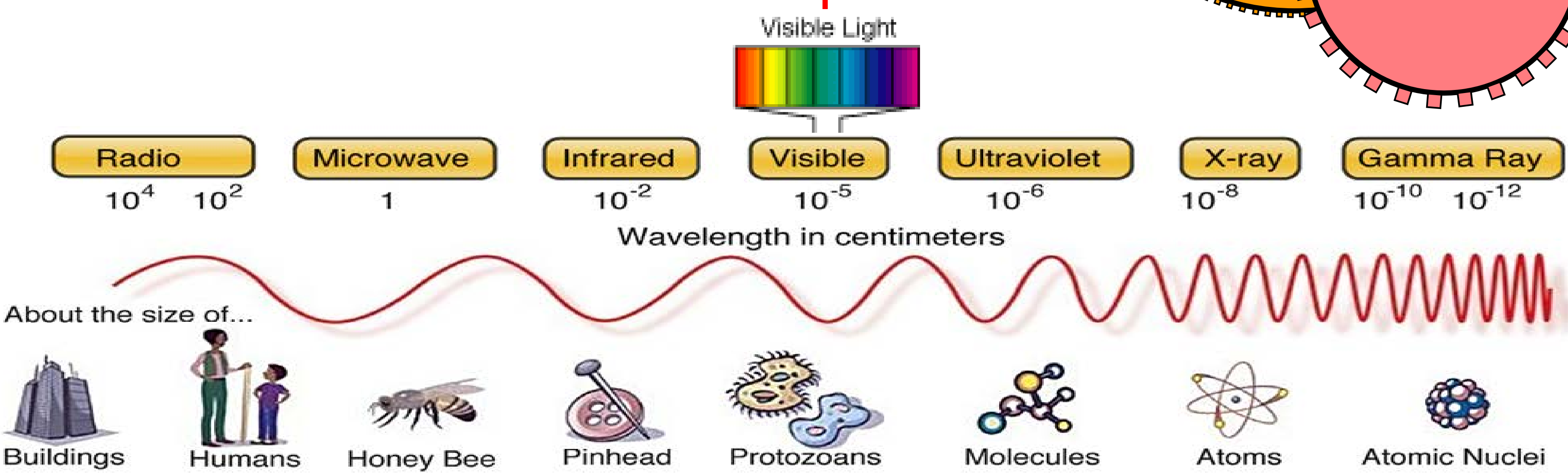
A stable laser delivers phase coherence anywhere from IR to UV.

Nature **482**, 68 (2012).

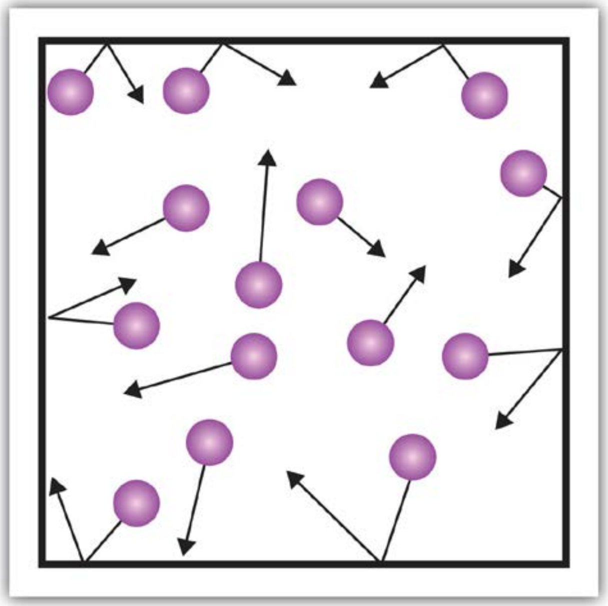
Hänsch & Hall: Optical frequency comb

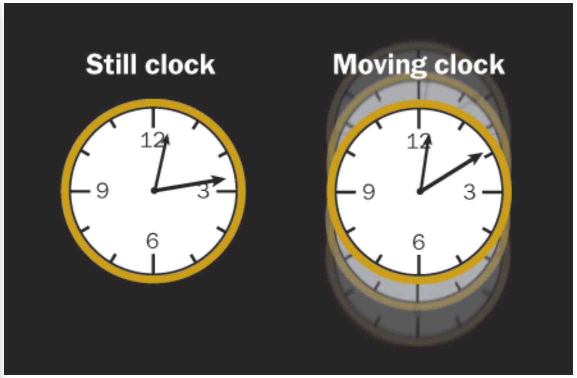


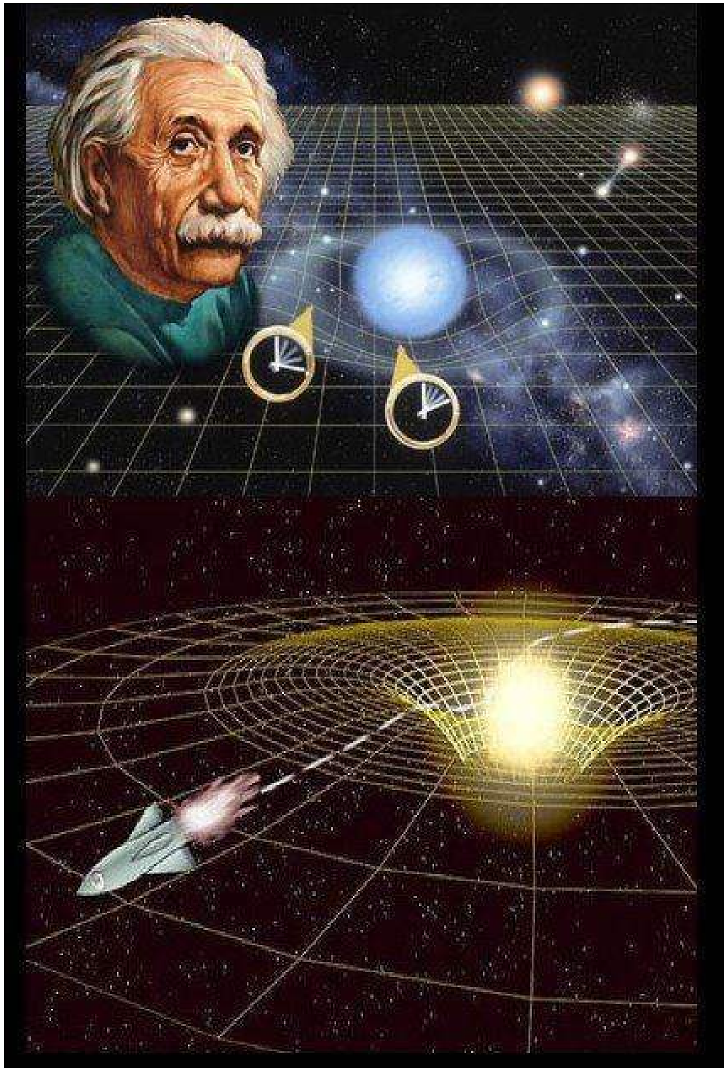




Time is relative - Motion is "bad"





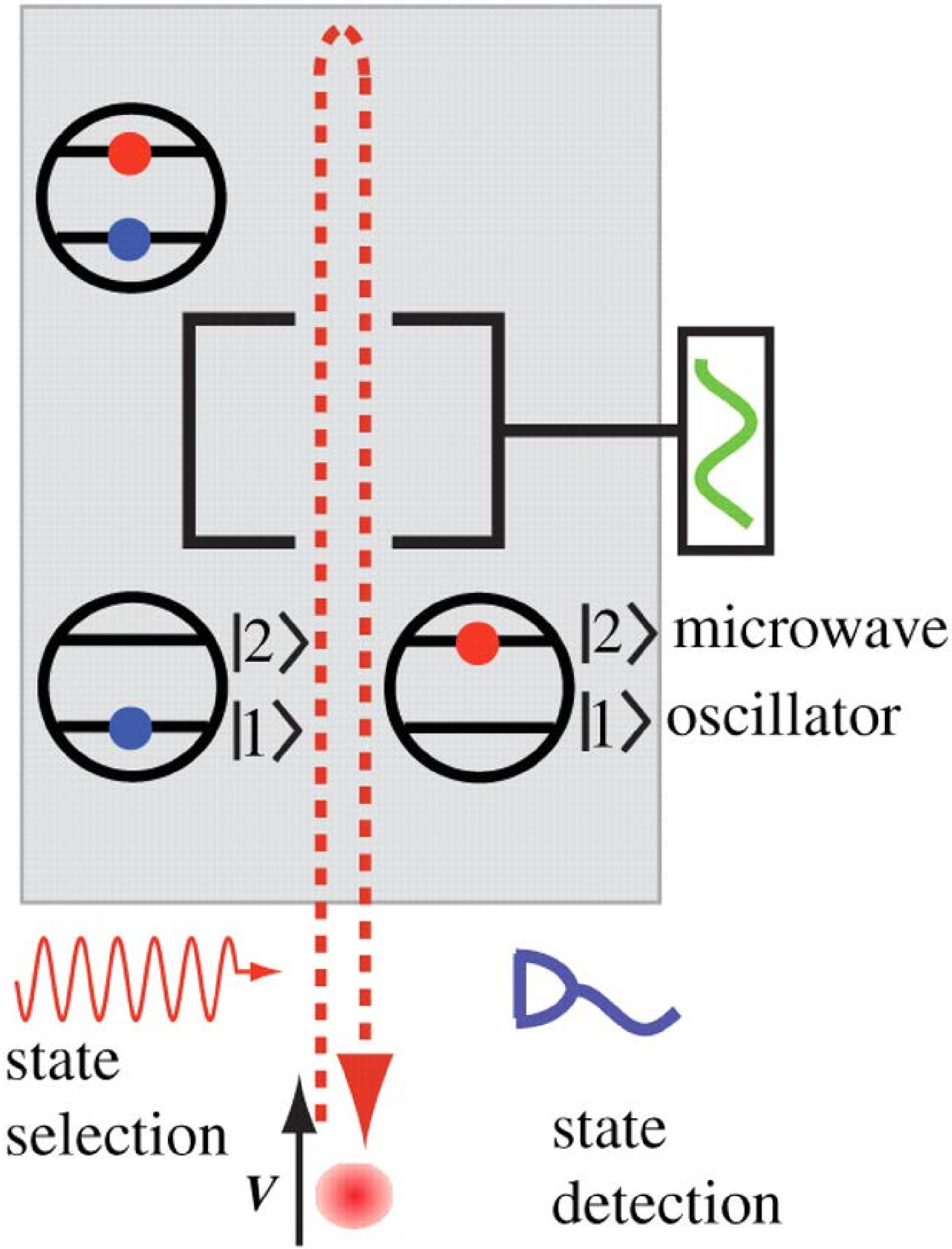


$$\frac{\Delta\omega}{\omega} = -\frac{1}{2}\frac{v^2}{c^2}$$

Cooling atoms with light

Chu, Cohen-Tannoudji, Phillips

Atomic Fountain Clock



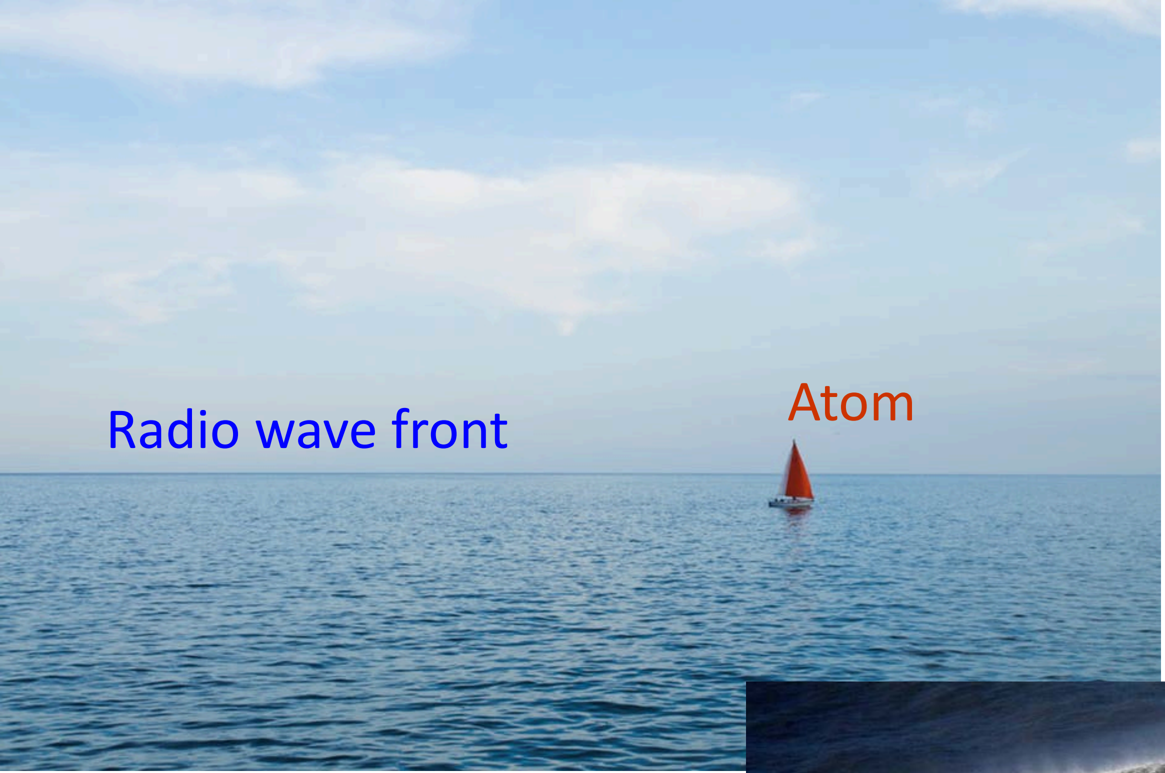
First realization
(Stanford 1989):

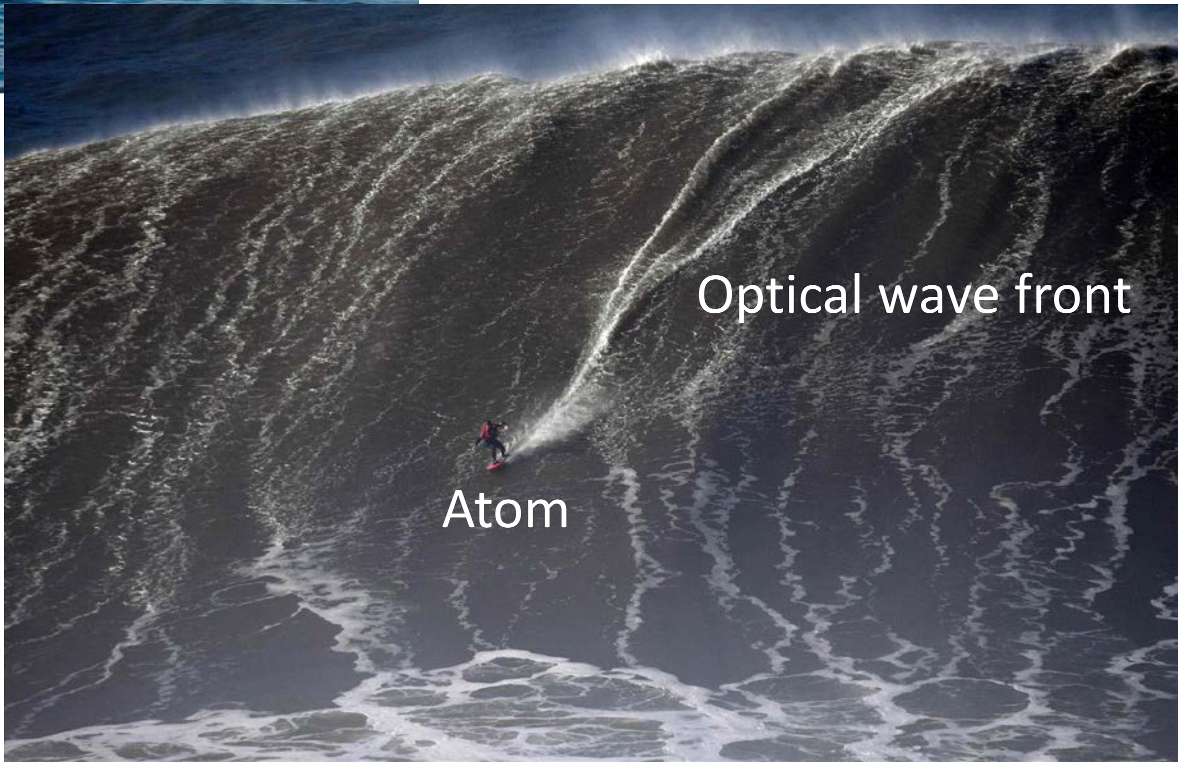
Coherence time: 0.25 s
Accuracy: 10^{-9}
Big improvements ahead

Surfing the waves

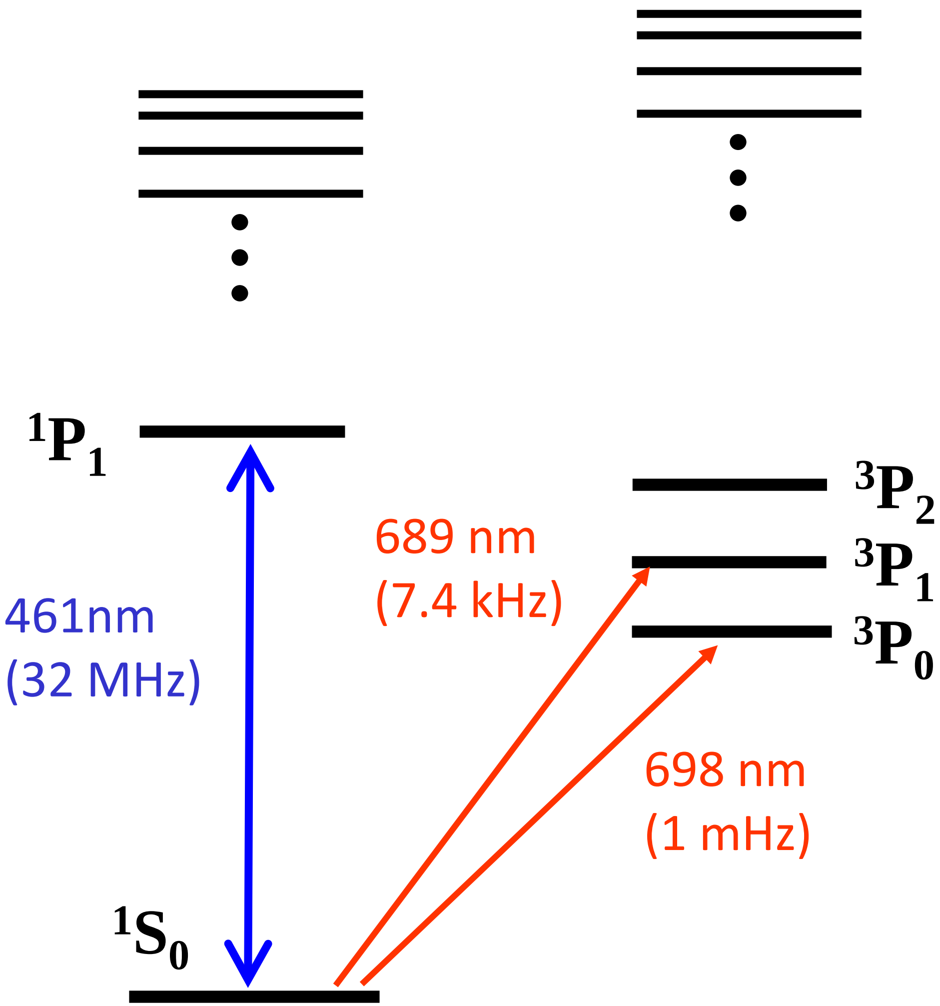
microwave wavelength

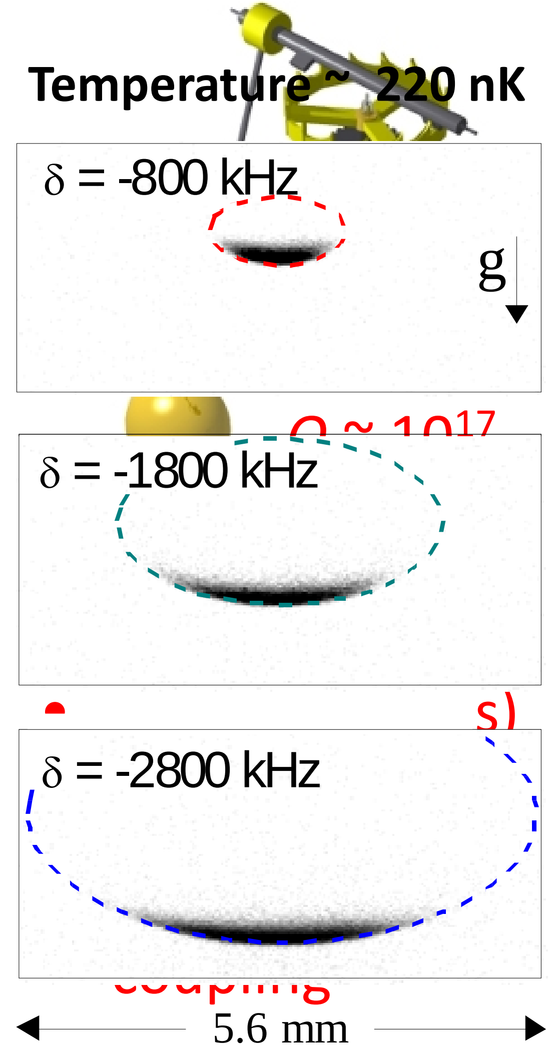
= 10^5 x optical wavelength





Sr atoms - A tale of twin electrons

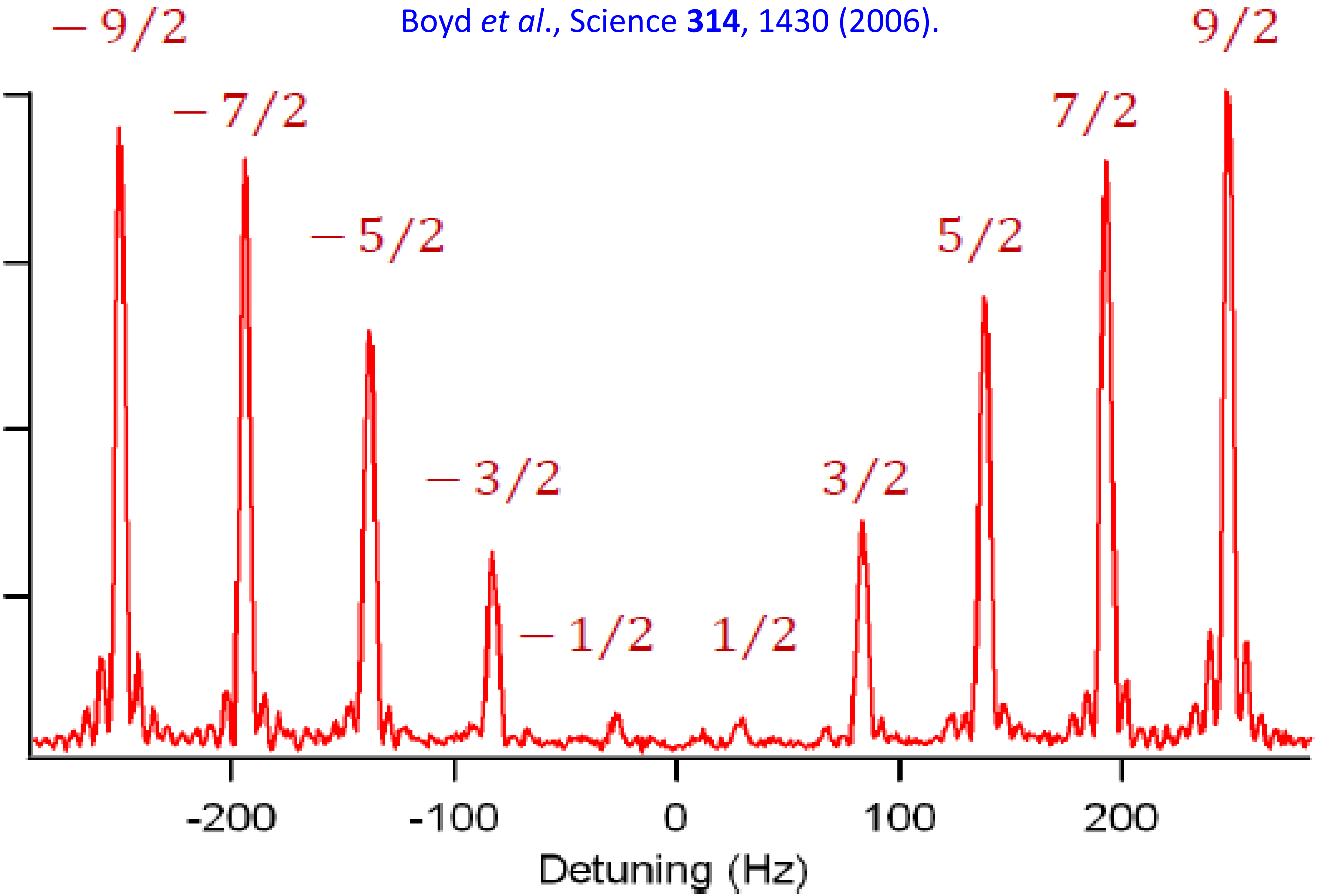




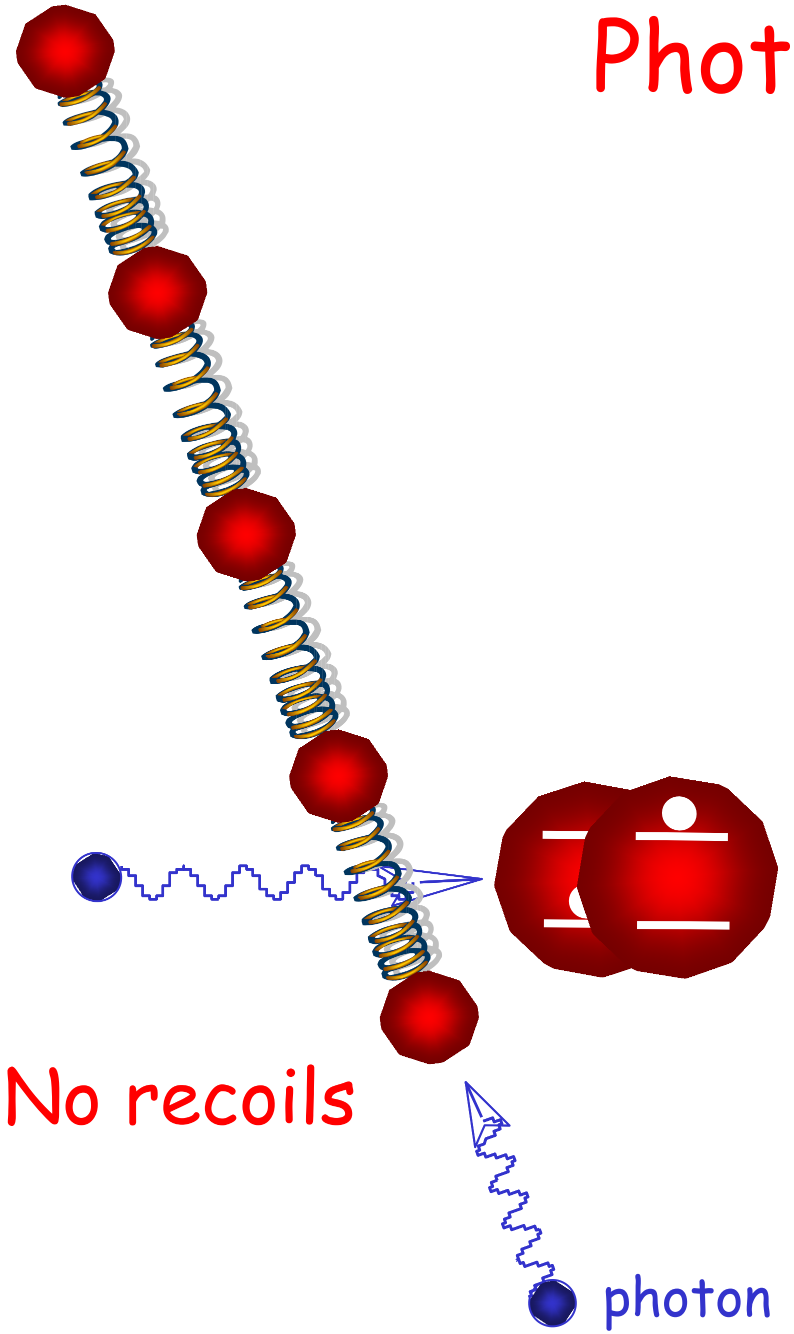
Loftus *et al.*,
PRL **93**, 073003 (2004).

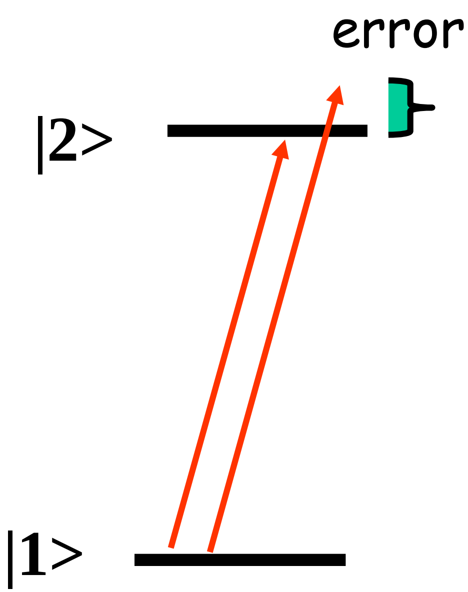
[illegible]

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

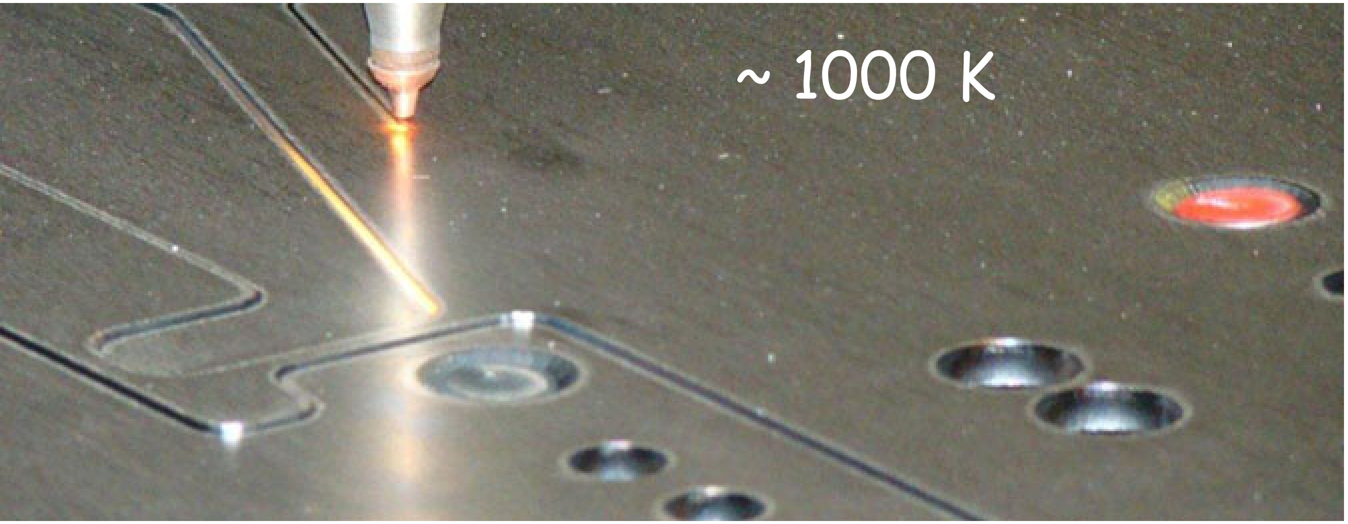


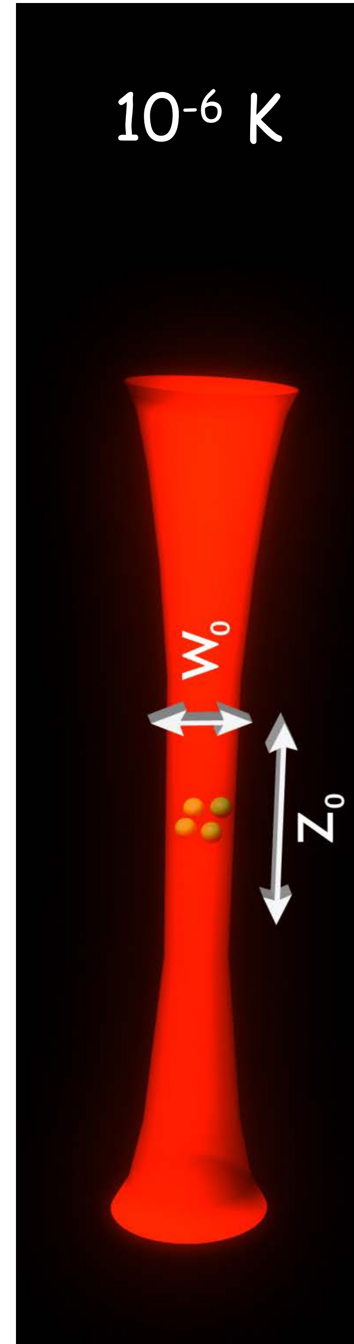
Photon recoil

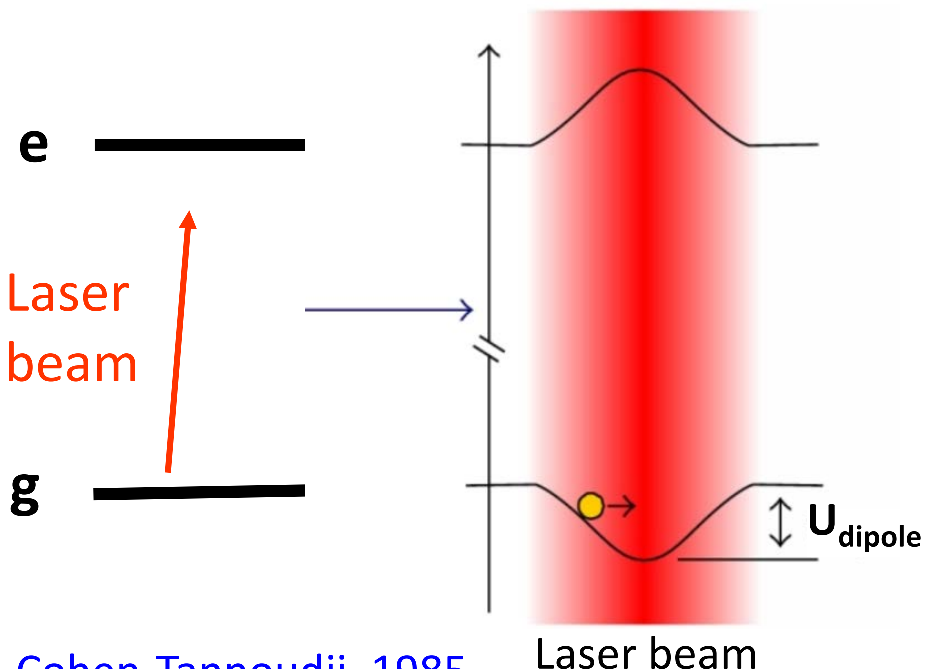




Holding atoms with light



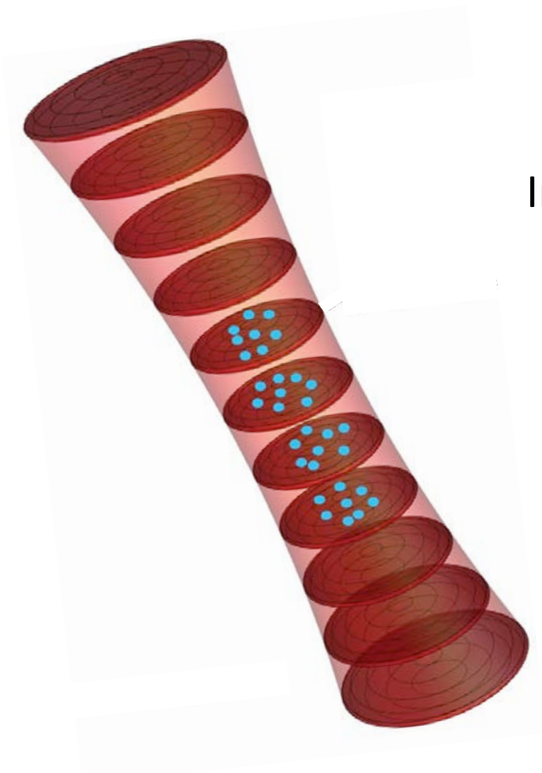


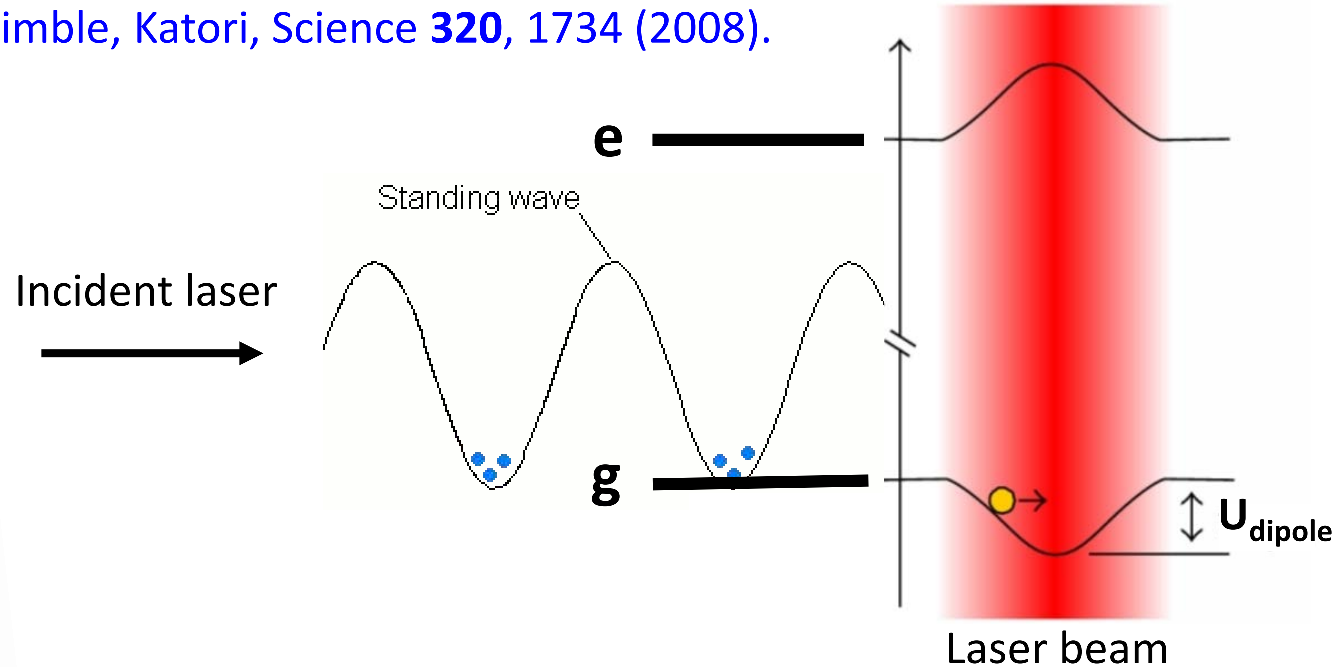


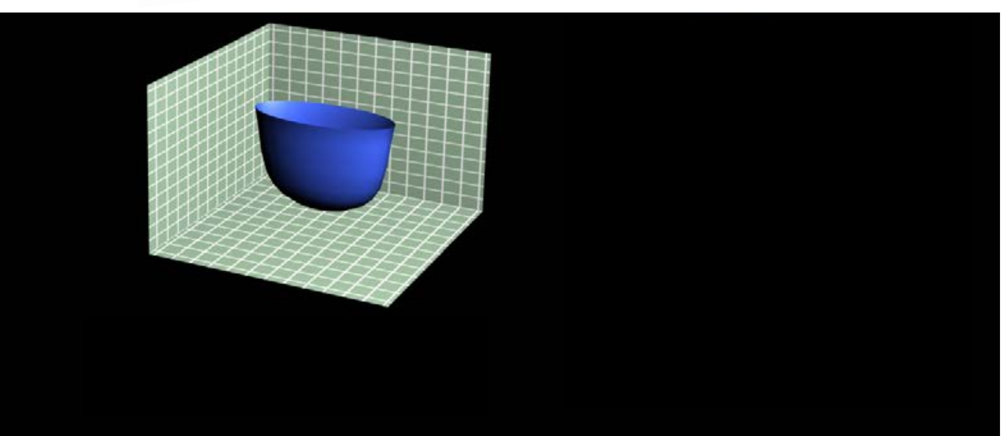
See, Dalibard & Cohen-Tannoudji, 1985

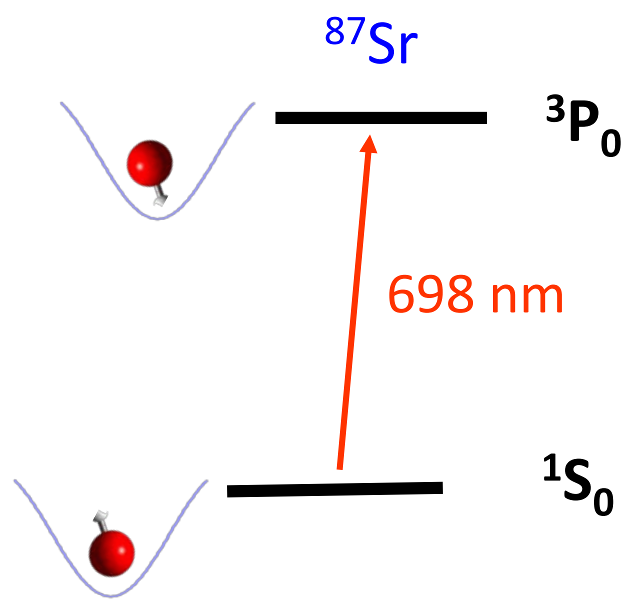
Holding atoms in a magic light bowl

Ye, Kimble, Katori, Science **320**, 1734 (2008).

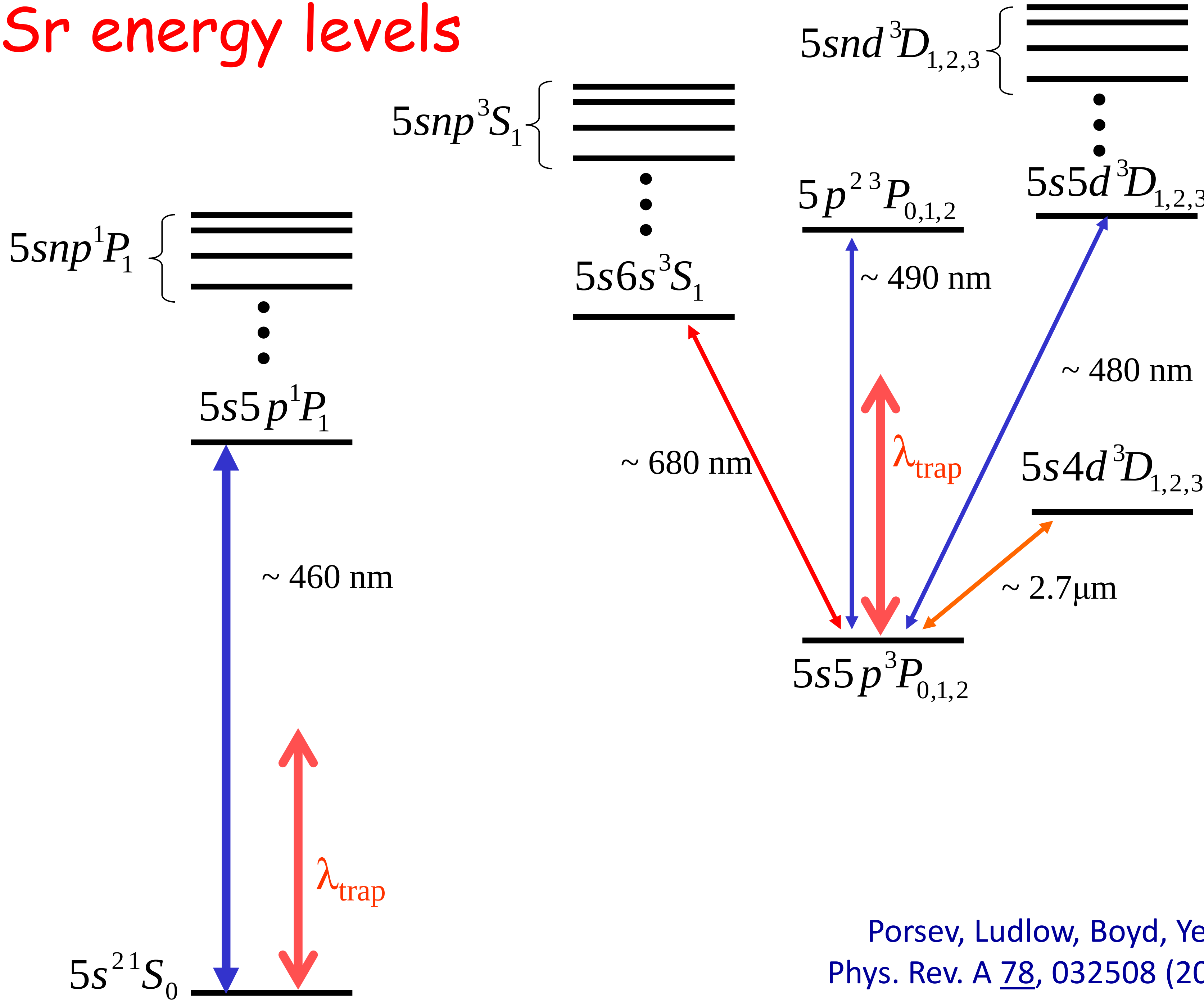






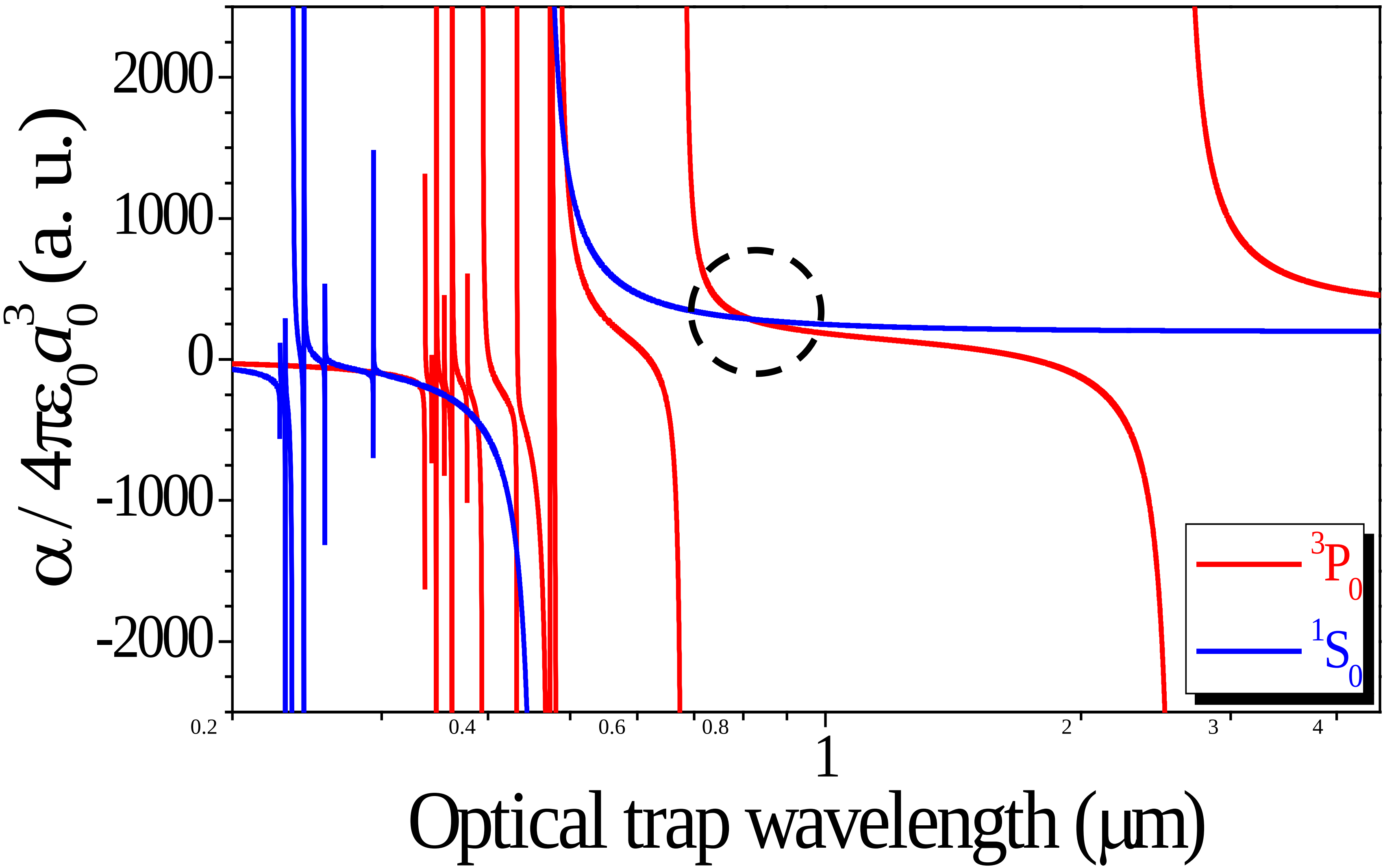


Sr energy levels



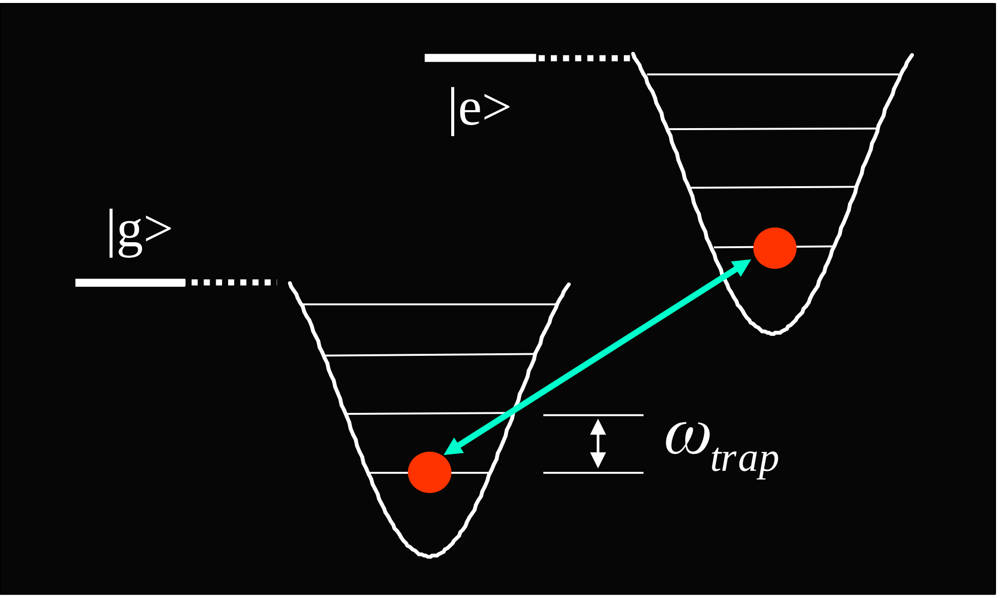
Porsev, Ludlow, Boyd, Ye,
Phys. Rev. A 78, 032508 (2008).

Crossing of polarizabilities

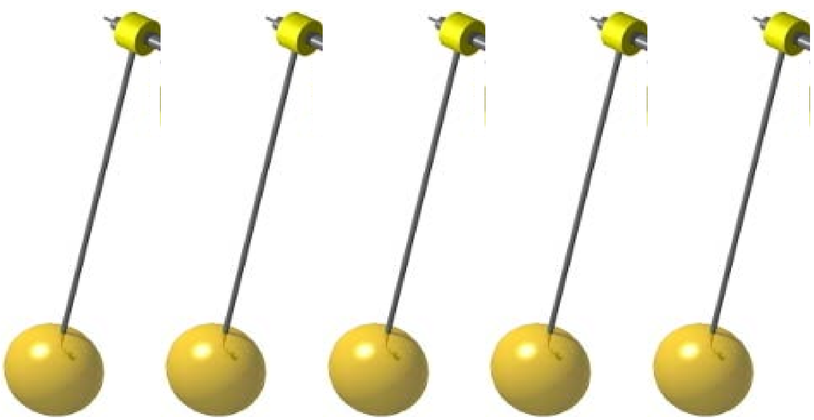


Quantum state control

Ye, Kimble, Katori, Science **320**, 1734 (2008).



Haroche, Wineland, 2012
~ 10^{-17}

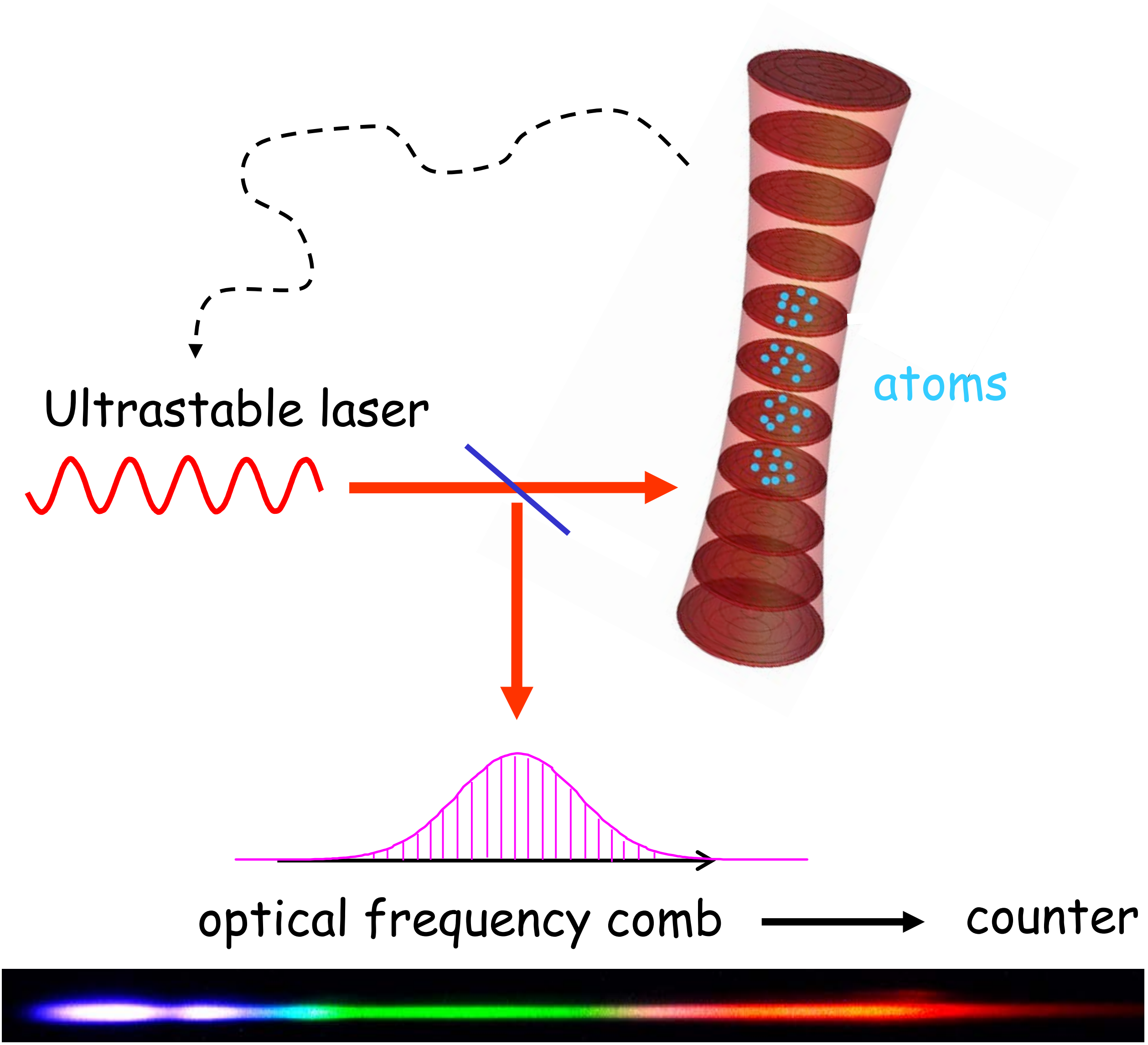


- Doppler, recoil, trap shifts = 0
- Precision improvement by $N^{1/2}$

❖ At 10^{-18} accuracy, atomic interactions can be controlled

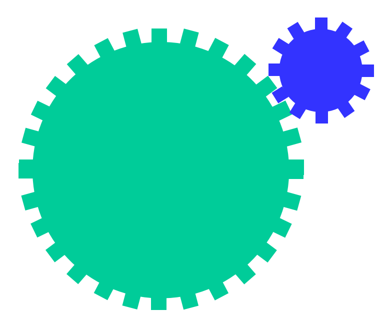
❖ Opportunity to harness quantum many-body science for precision gains

Putting all ingredients together



Oscillator

Counter



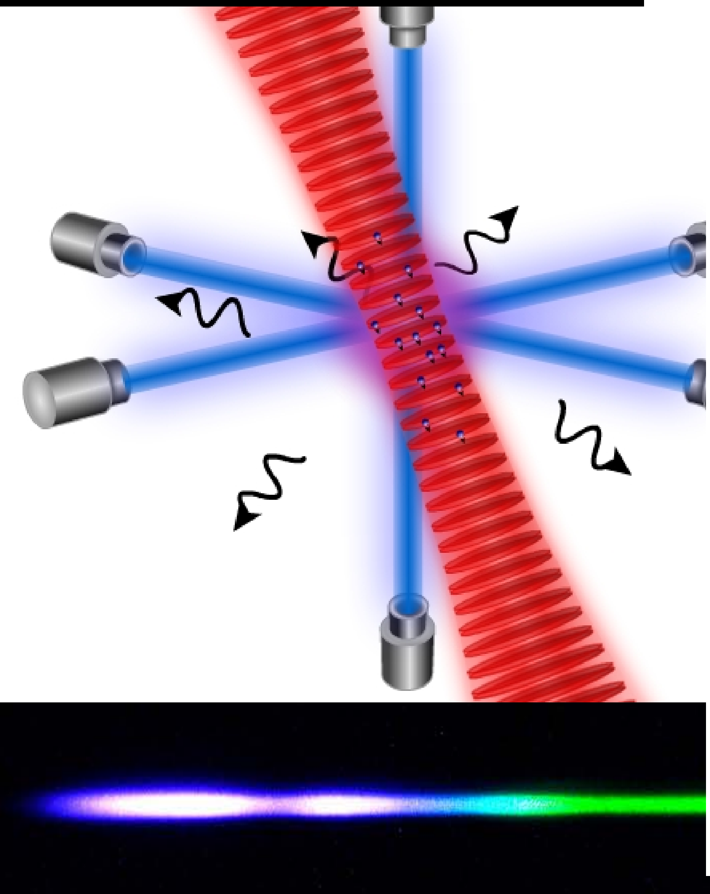
Reaching the Cs primary standard

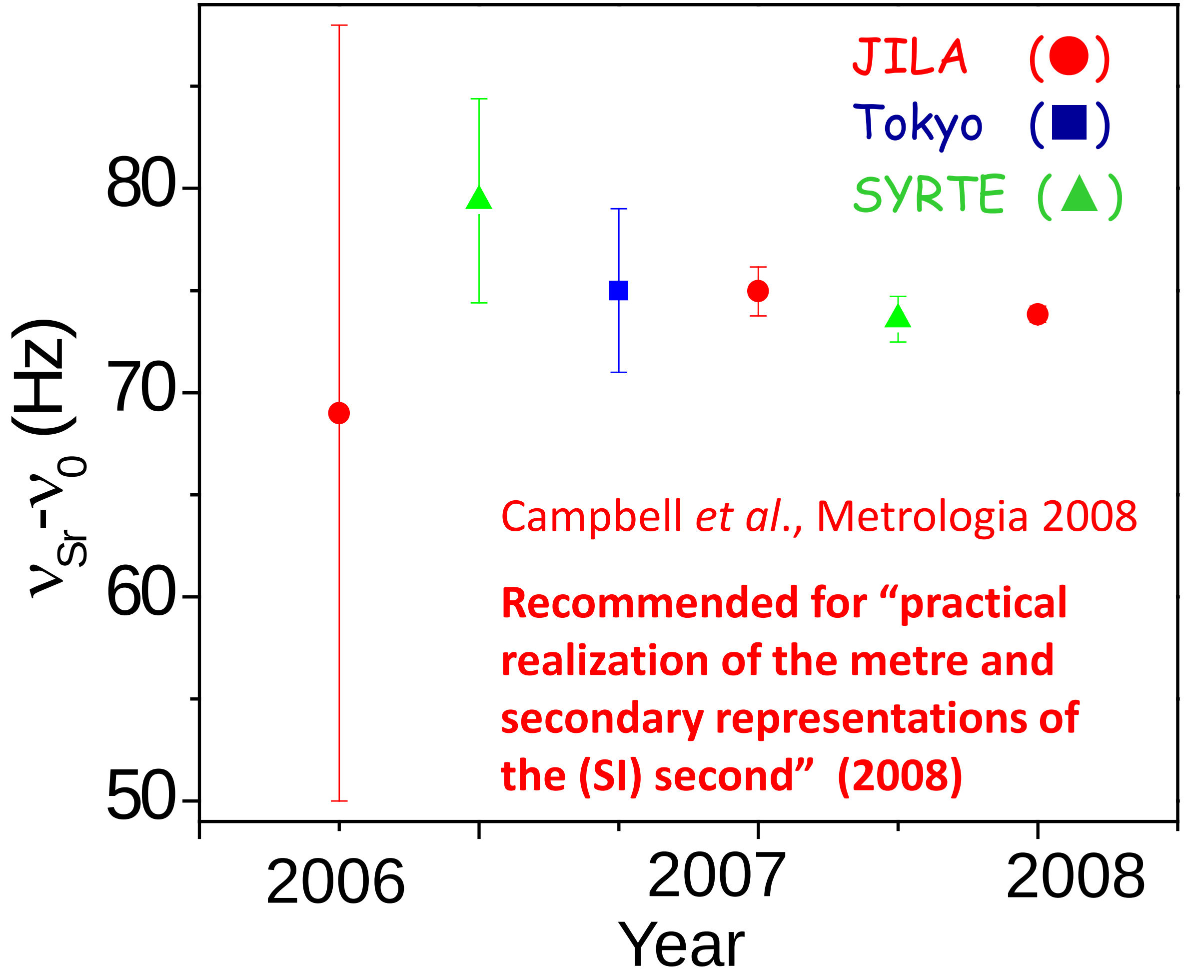
Ludlow *et al.*, Science **319**, 1805 (2008). (10^{-16})

JILA, Tokyo, SYRTE, PTB, Firenze, INRIM, NICT, NIM, NPL, NRC

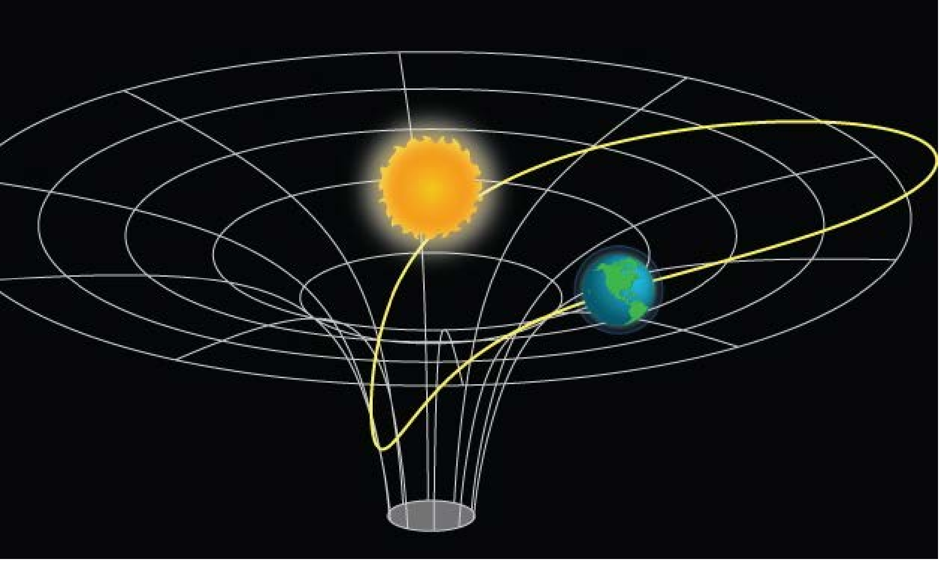
Le Targat *et al.*, Nat. Comm. **4**, 2109 (2013); Falke *et al.*, New J. Phys. **16**, 073023 (2014).

Optical "Second"



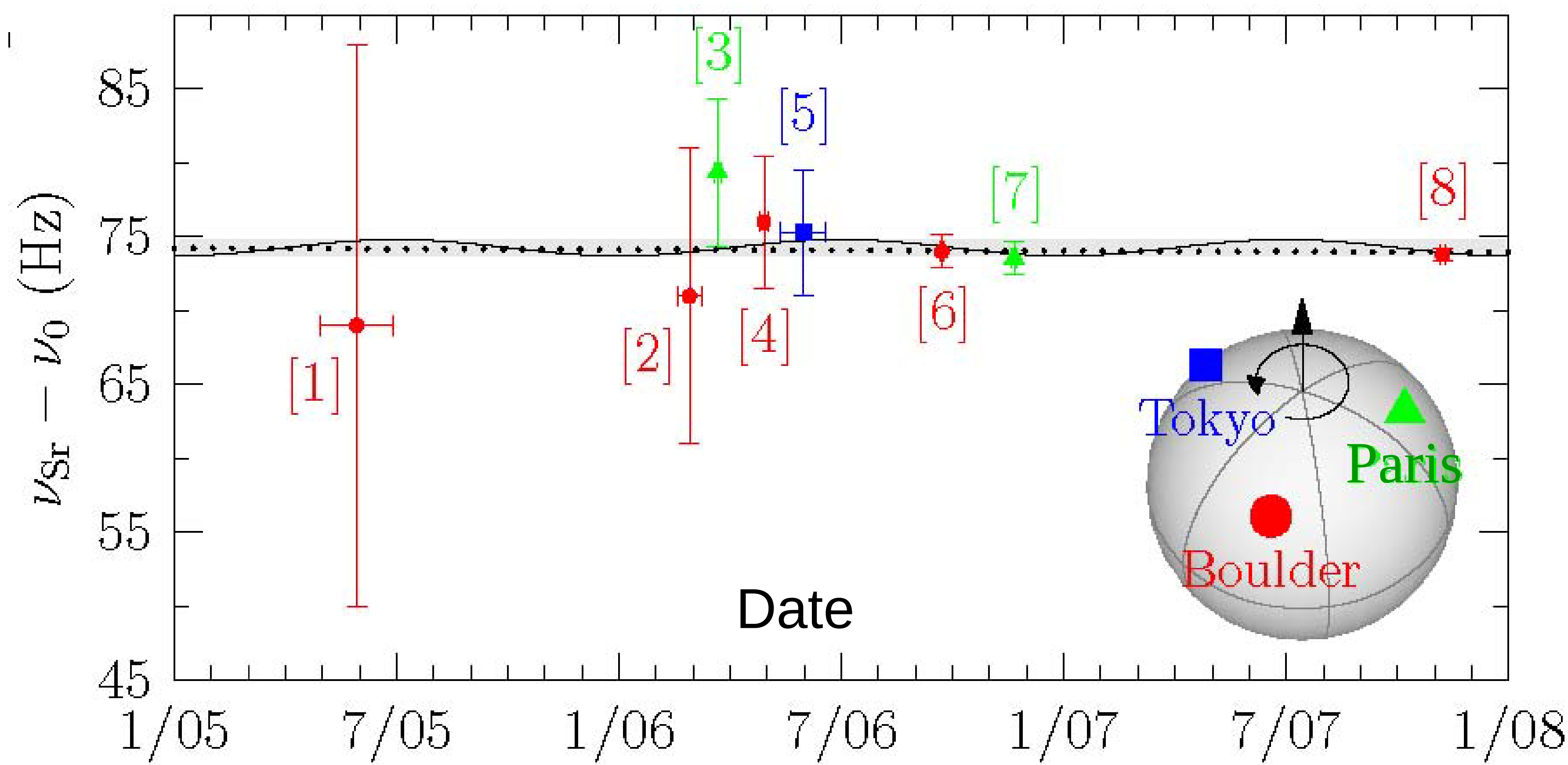


Local Lorentz Invariance

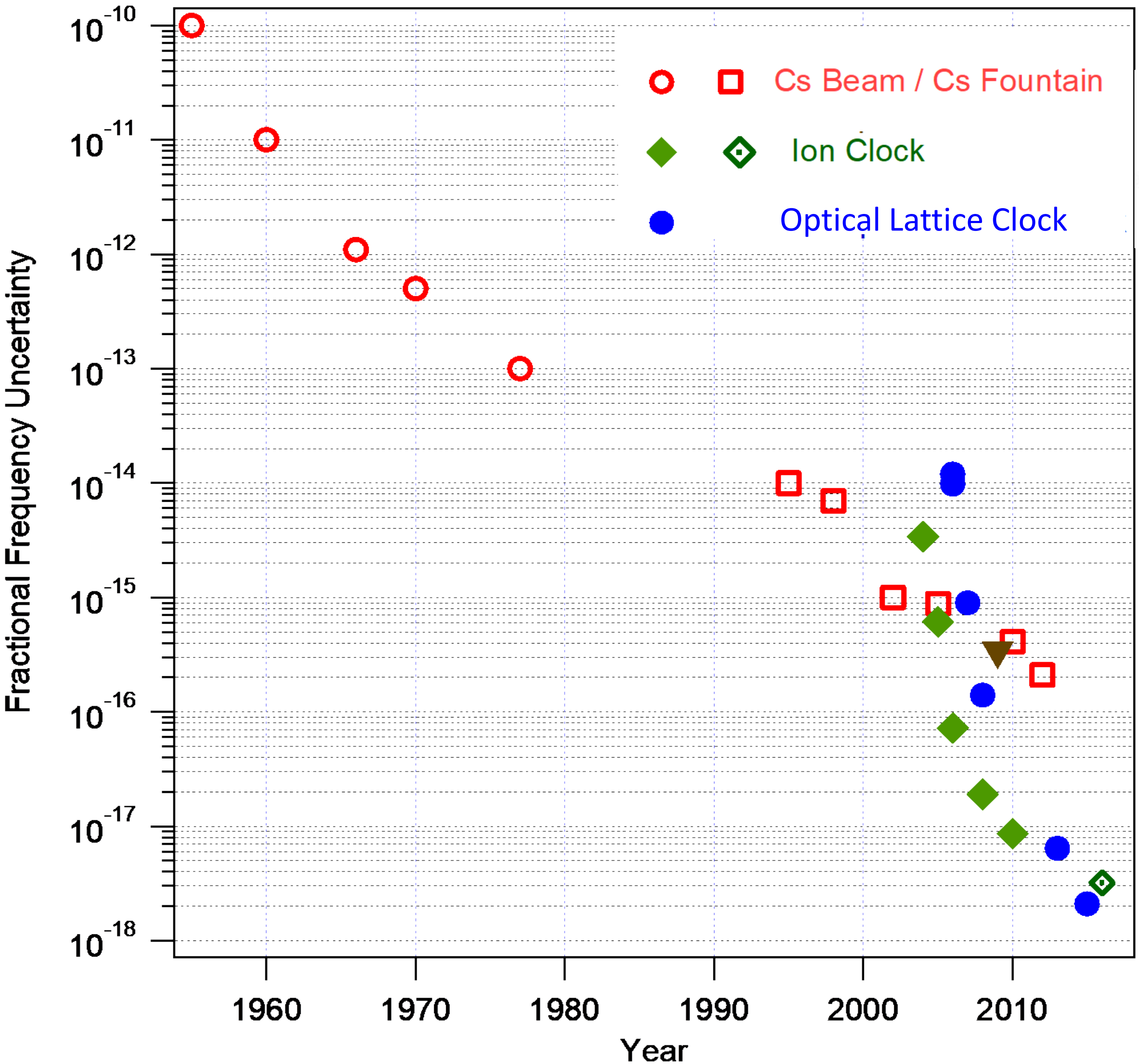


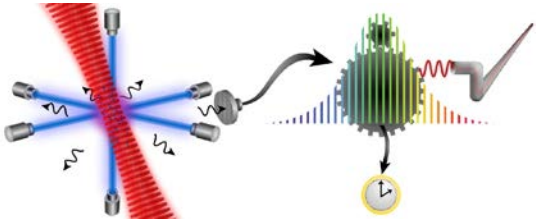
Fundamental constants & gravitational potential

S. Blatt *et al.*,
Phys. Rev. Lett. **100**, 140801 (2008).



A new frontier for clock stability & accuracy





JILA Sr Clock II :

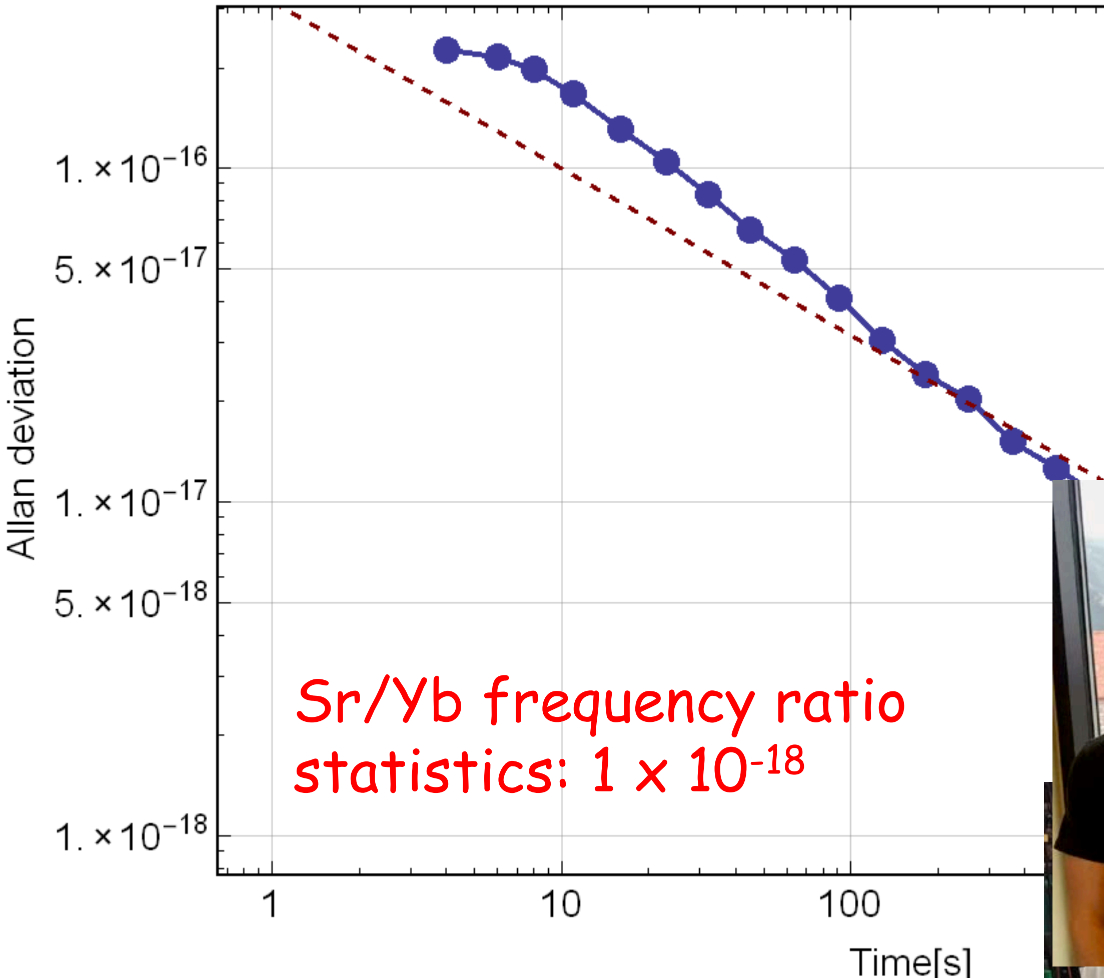
2.1×10^{-18}

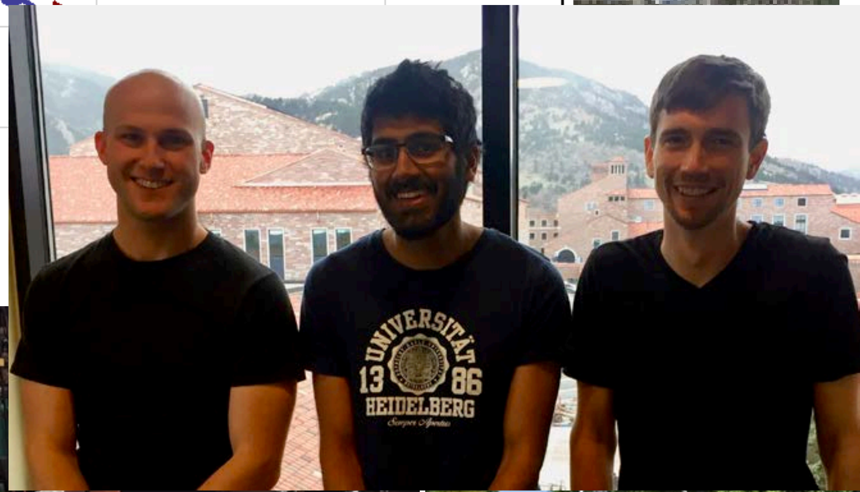
Bloom *et al.*,
Nature **506**, 71 (2014).

Huntemann *et al.*,
PRL **116**, 063001 (2016).

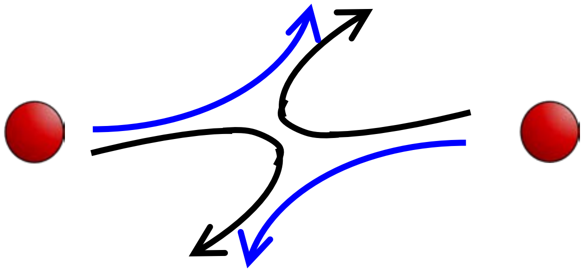
Nicholson *et al.*,
Nature Comm. **6** (2015).

State-of-the-art clock comparison



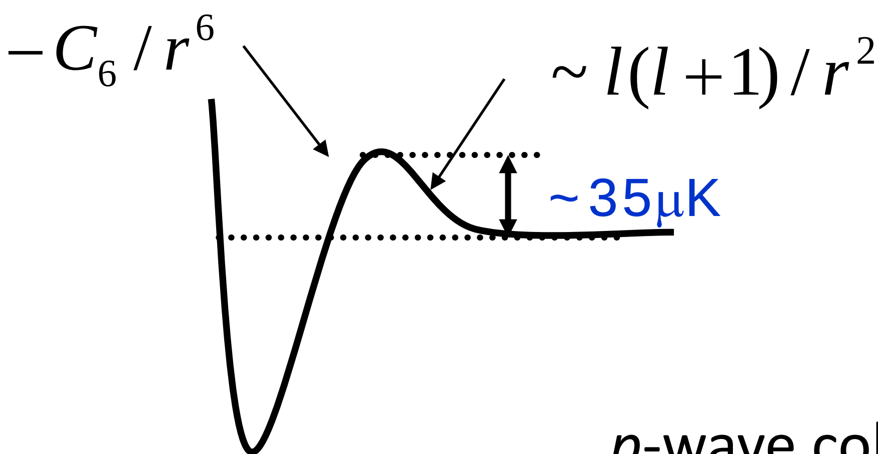


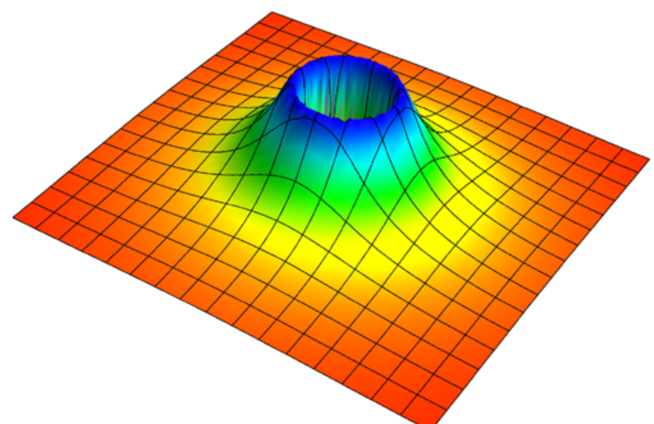
Collision between identical Fermions



$$|\psi_0\rangle|\psi_1\rangle - |\psi_1\rangle|\psi_0\rangle$$

- Ultracold → lowest possible angular momentum collision channel
- Fermions → $l = 1\hbar$, *p*-wave collisions





p-wave collisions
(suppressed as E^2, as $E \rightarrow 0$)

Dalibard Fermi School 1998

Precision metrology meets many-body physics