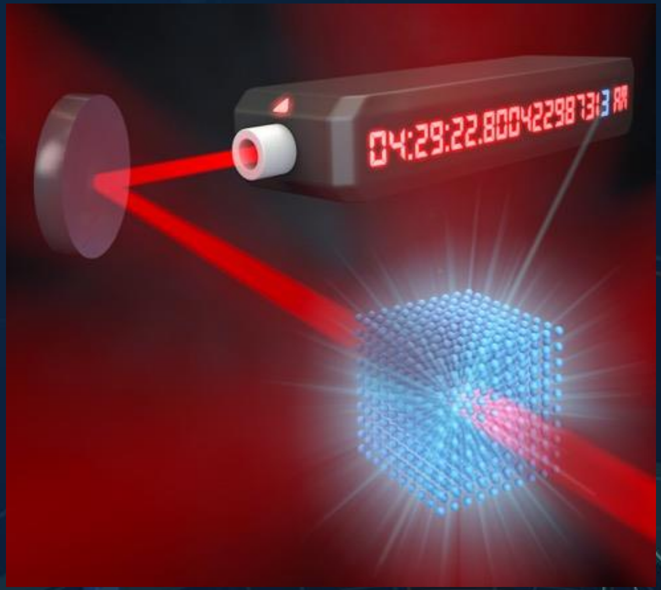
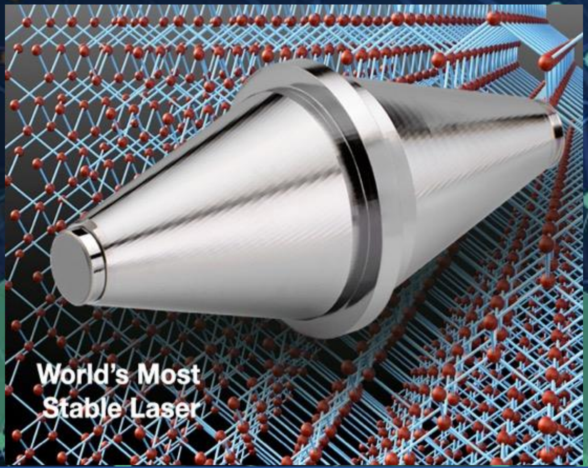
Optical Atomic Clocks – Opening New Perspectives on the Quantum World



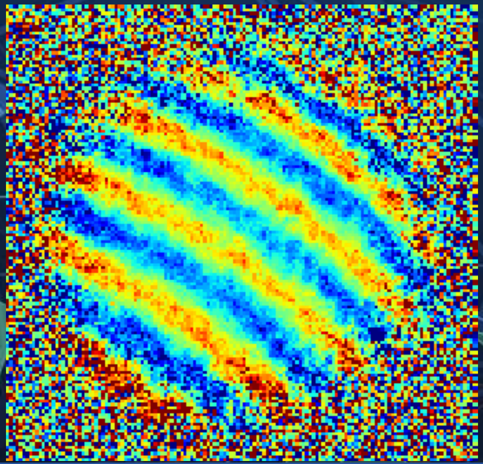
Jun Ye, JILA, NIST & University of Colorado

26th CGPM Open Session, November 16 2018

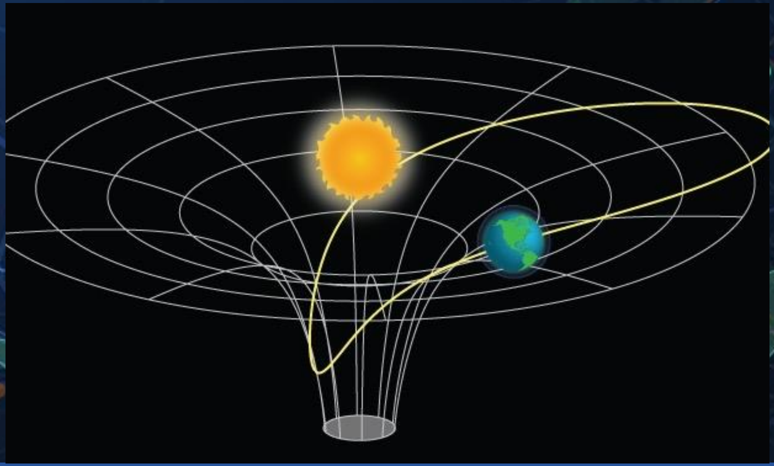
Ultra-coherence



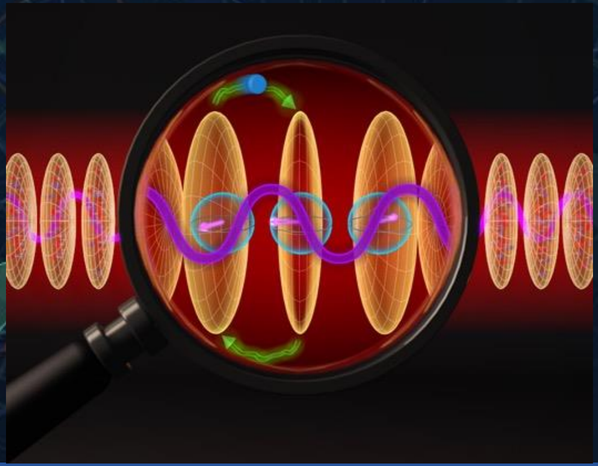
Quantum sensing



New physics on table top



Many-body dynamics

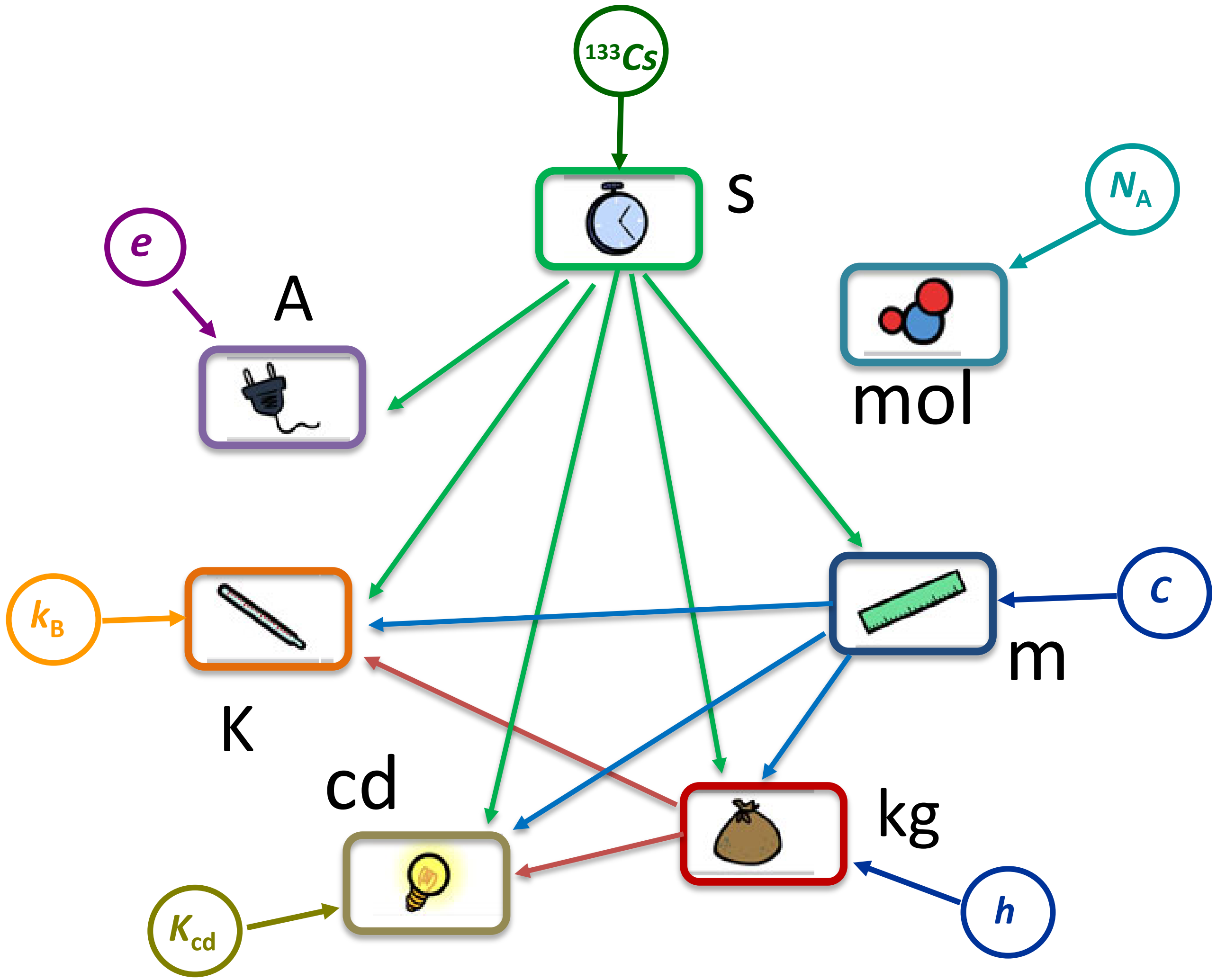


Credit: NIST

National Institute of Standards and Technology
U.S. Department of Commerce

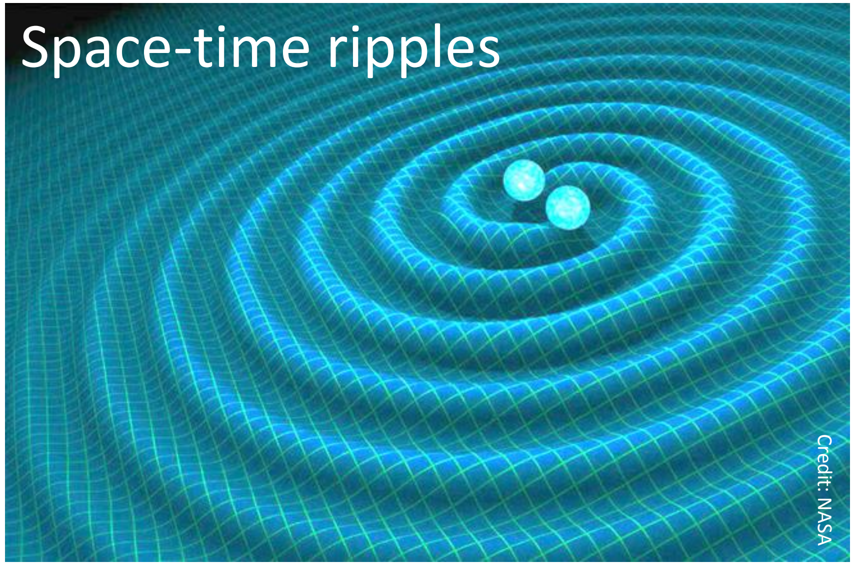
7 SI Base Units

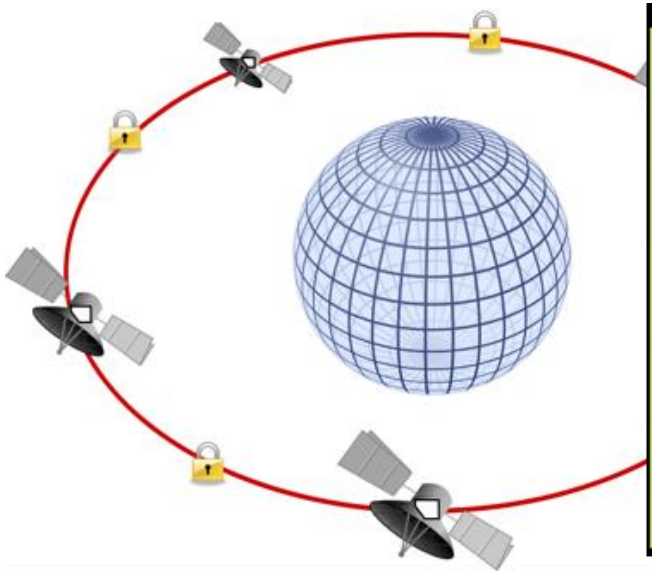
Almost all units, base or derived, can be traced to time

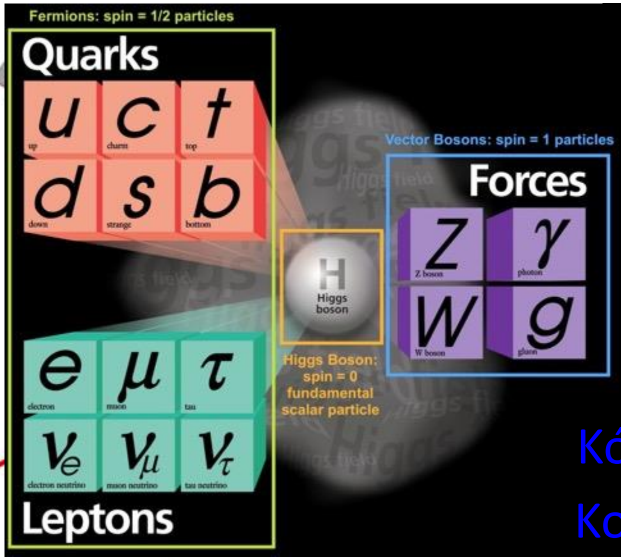


- Fundamental laws & constants *are* our units
- "For all ***times***, **For all people."**

Probes for Fundamental Physics







Standard Model ←→ SI units

of clocks (10^{-21}):

eline interferometry

But, it is INCOMPLETE :

- Dark matter & energy
- Matter-antimatter asymmetry

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

Time Scales

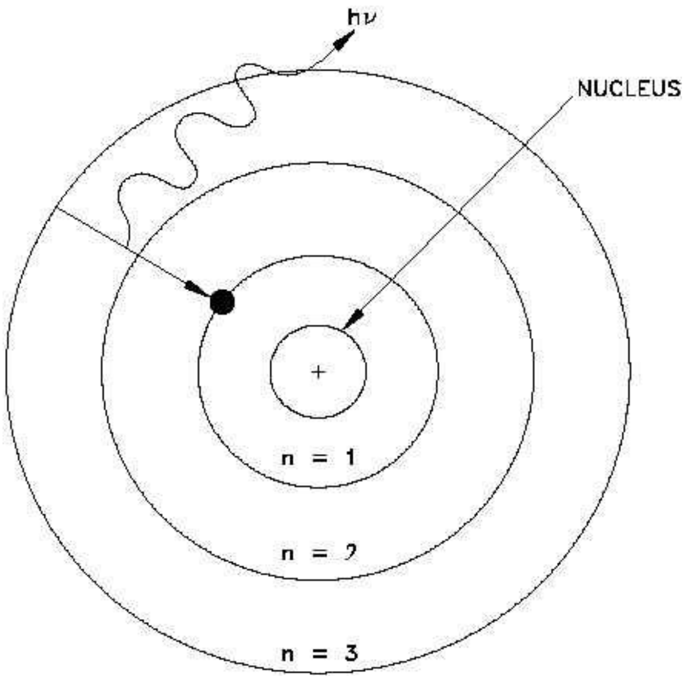
JILA
CU Boulder and NIST

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

The geometric mean ~30 s

Sr atoms:

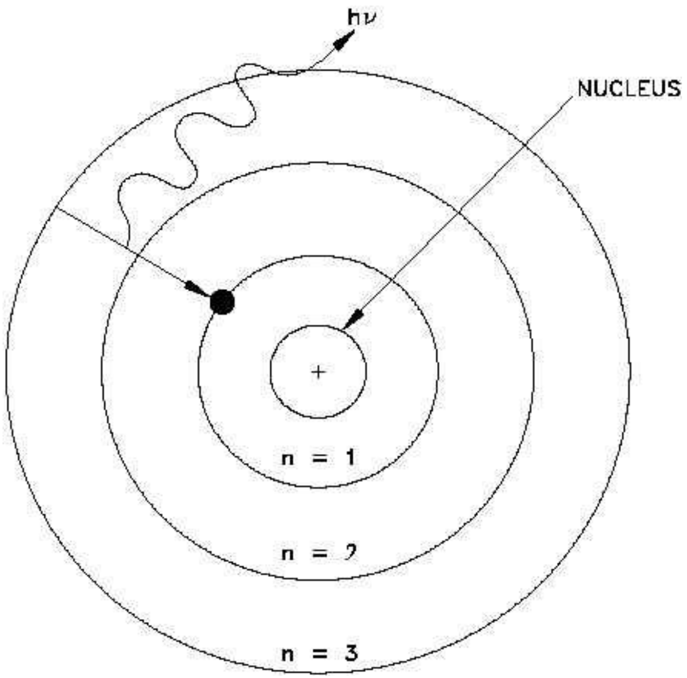
- $^1S_0 \leftrightarrow {}^3P_0$ (160 s)
- $Q \sim 10^{17}$



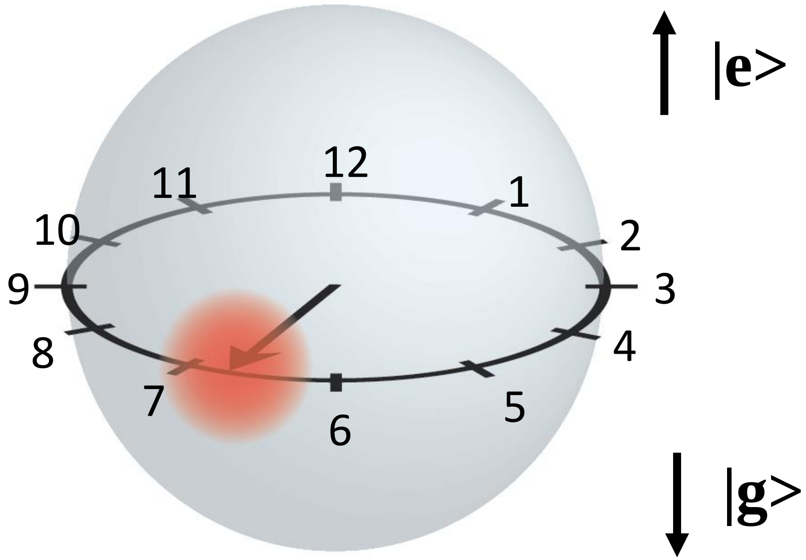
Credit: NASA

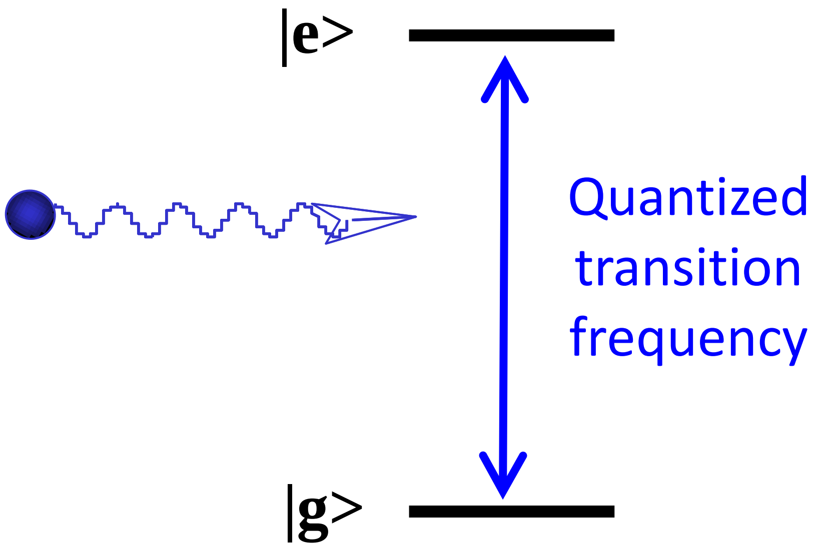
Life of the Universe: 15 billion years (10^{18} s)
1,000,000,000,000,000,000 seconds

Quantum Certainty and Uncertainty



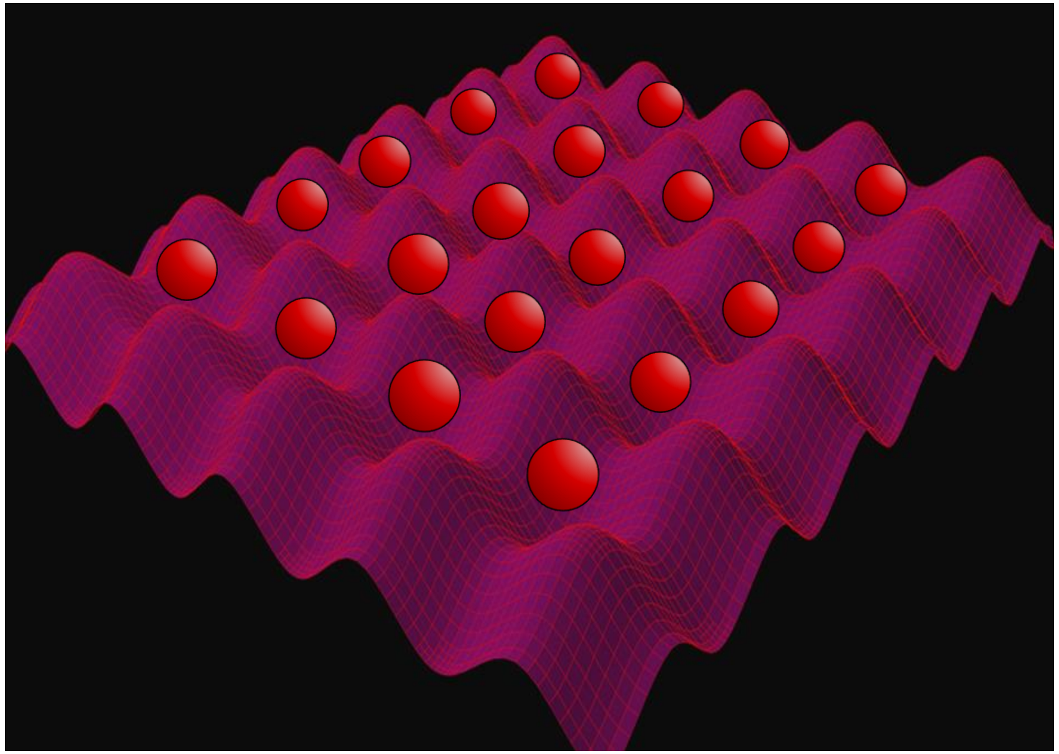
$$\frac{1}{\sqrt{2}}\left(e^{i\phi}|e\rangle + |g\rangle\right)$$





The Strength of MANY – when you are certain

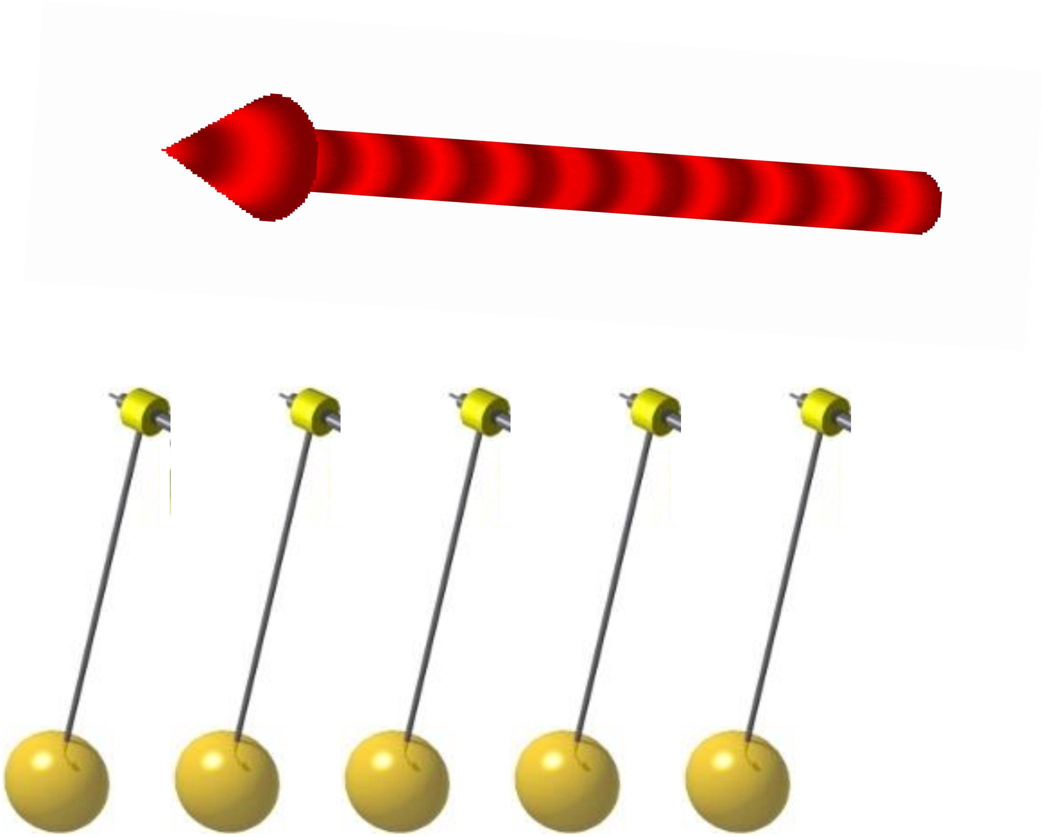
Quantum Phase Noise of Atoms



Quantization of Motion & Interaction
(Quantum Certainty)

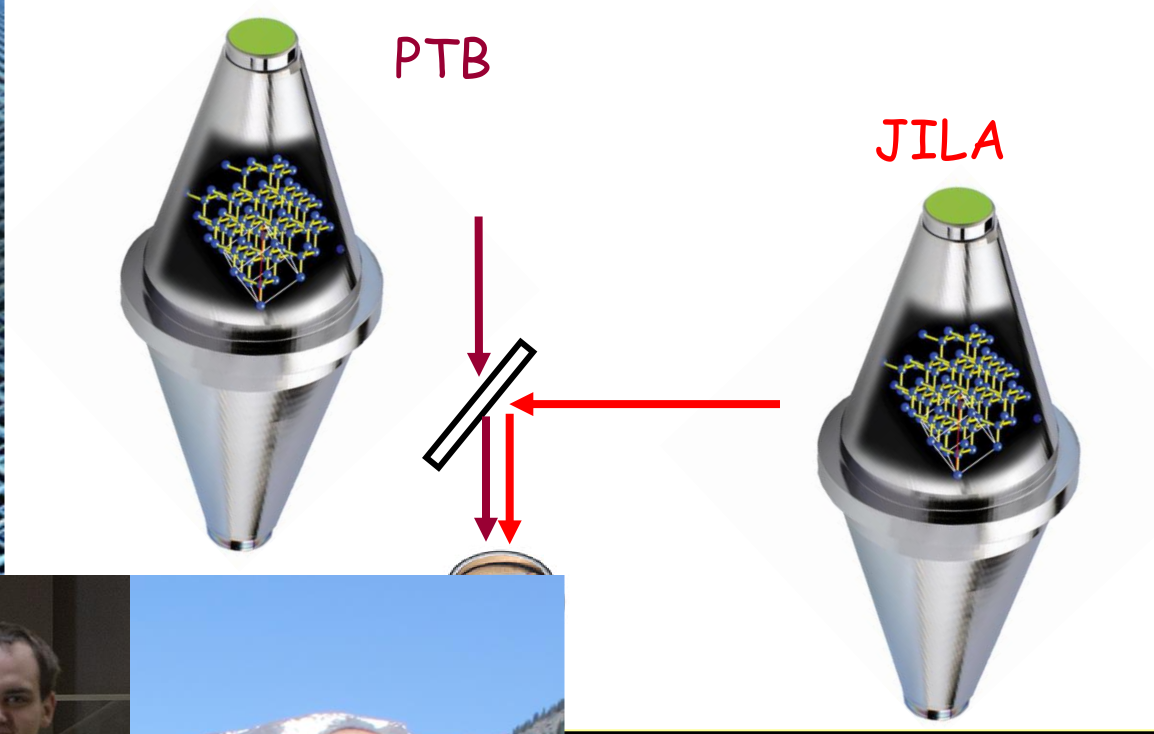
$$Df_{SQL} = \frac{1}{\sqrt{N}}\,\text{rad}$$

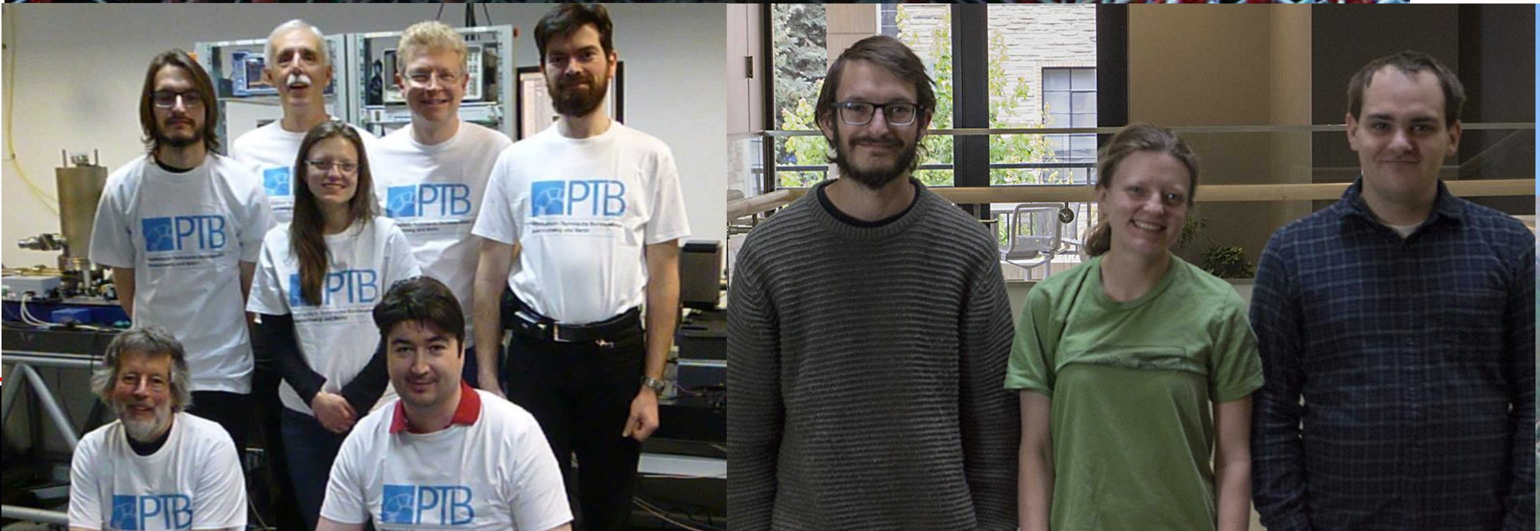
Classical Phase Noise of Probe Laser

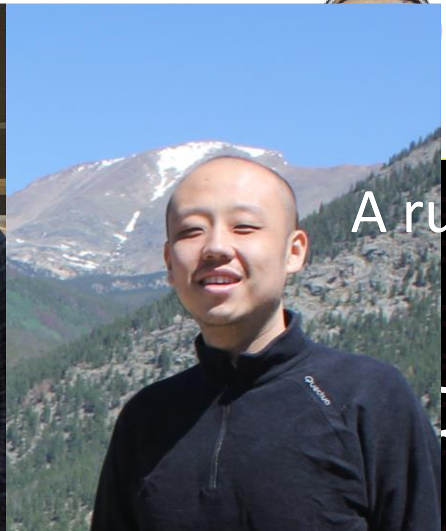


Laser is *the* Central Ruler of Time & Space

ptical Coherence time ~ 1 minute

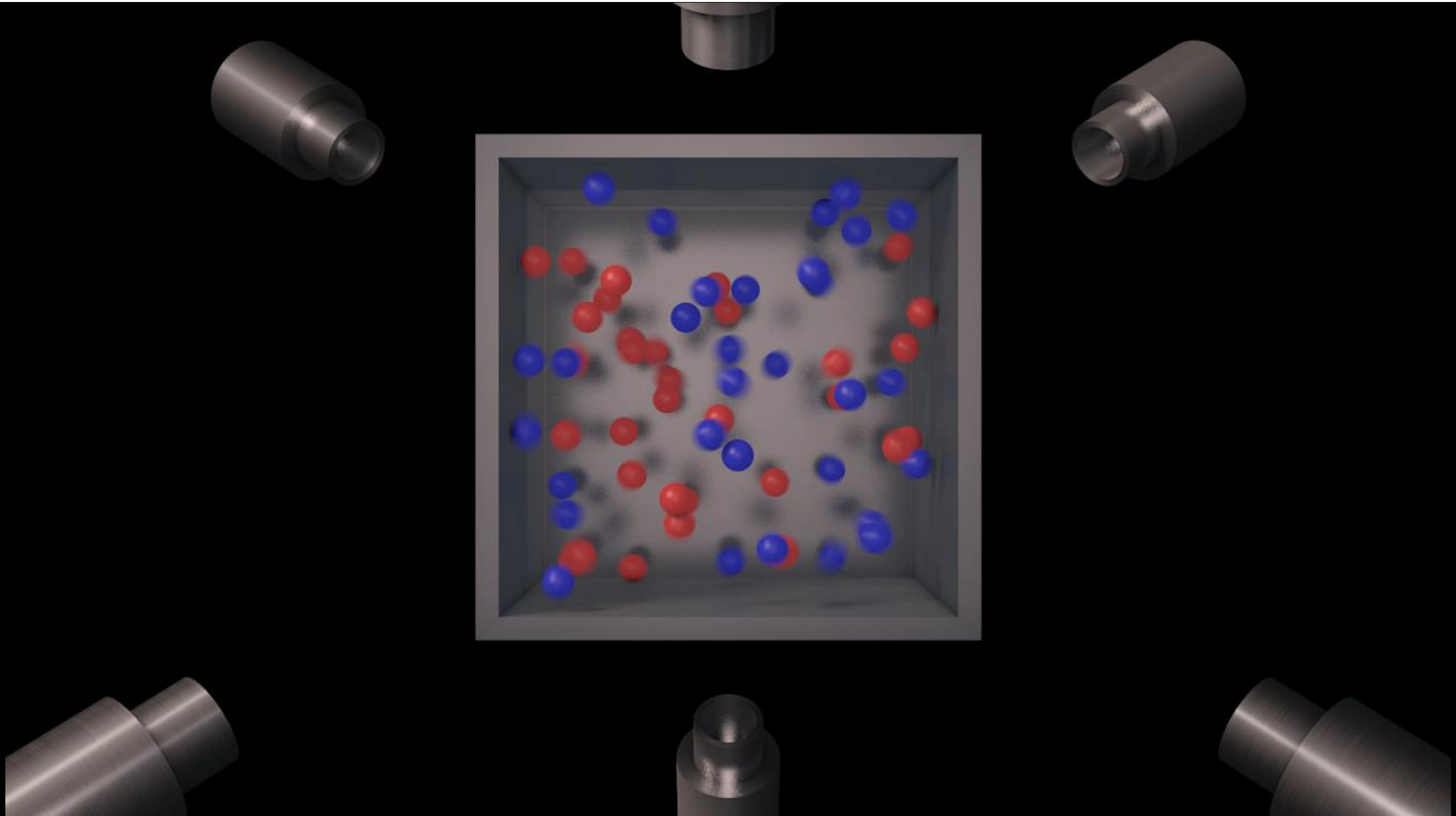






Cooling Atoms with Light

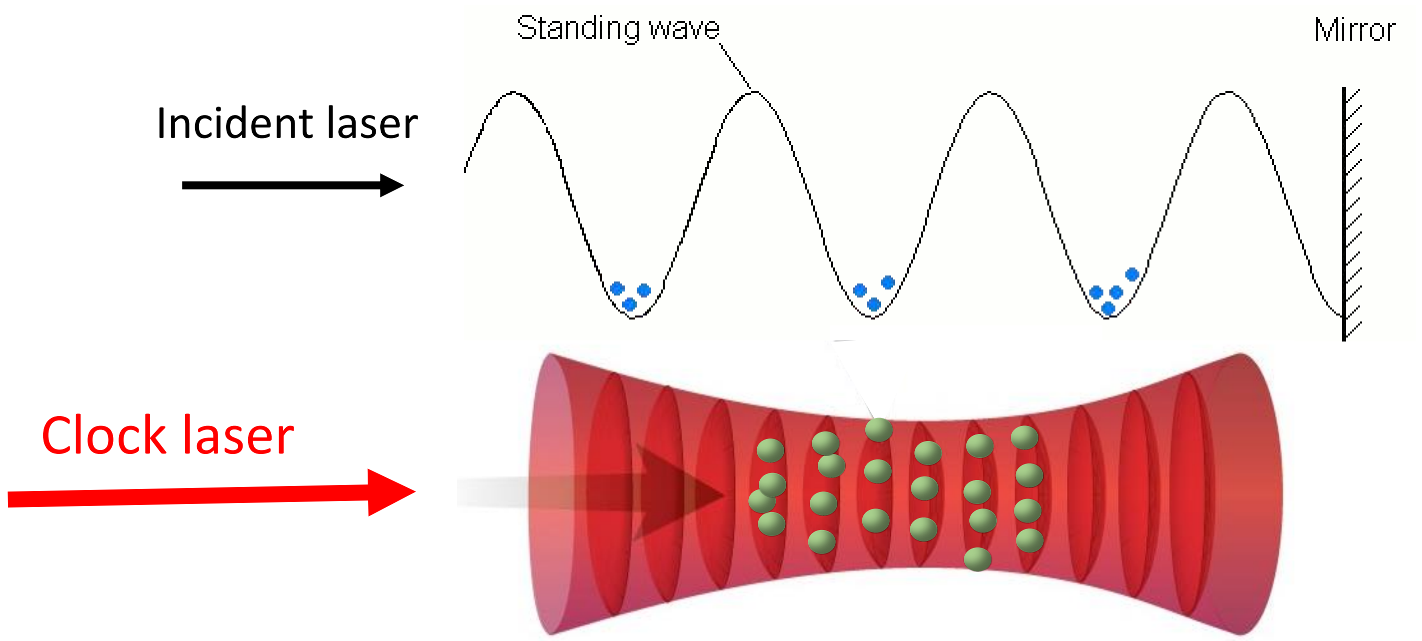
Chu, Cohen-Tannoudji, Phillips

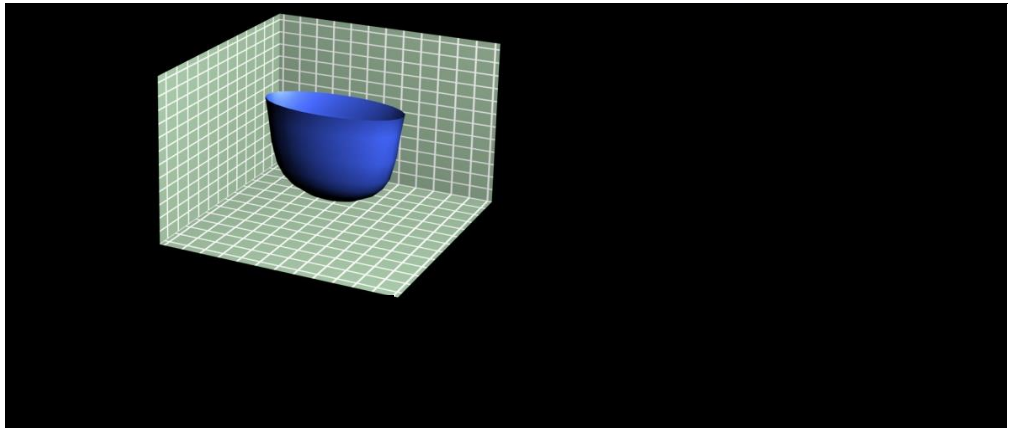


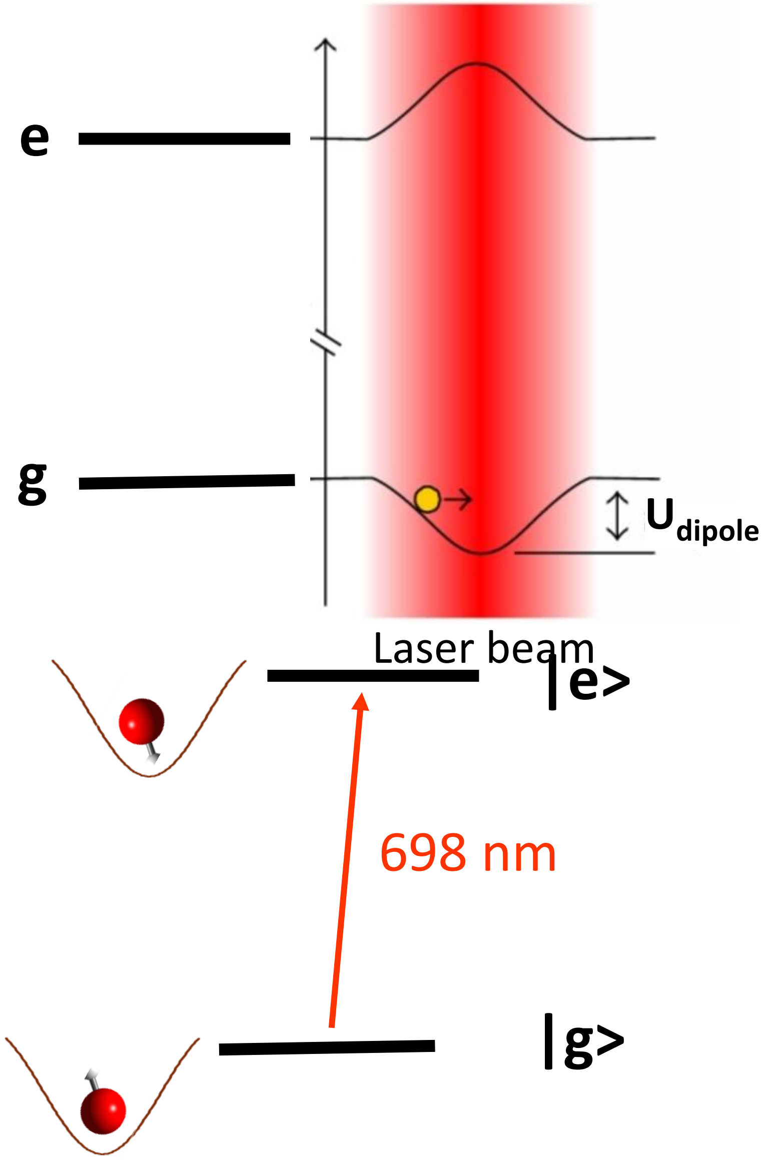
Holding Atoms in a Magic Light Bowl

Ashkin, …

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



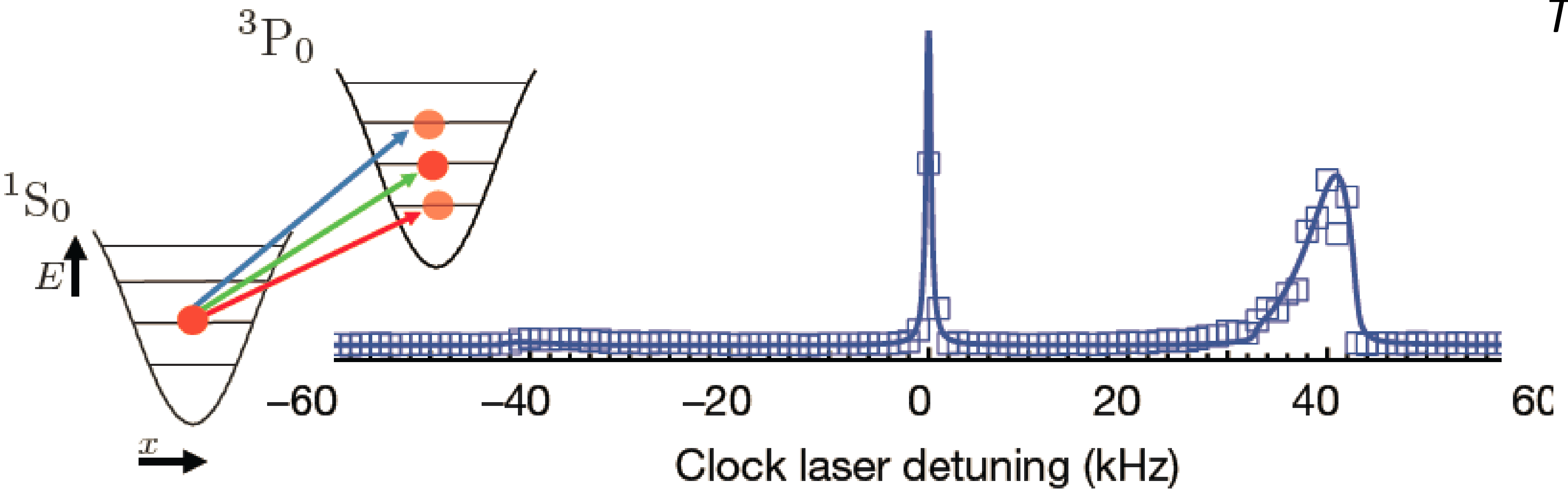


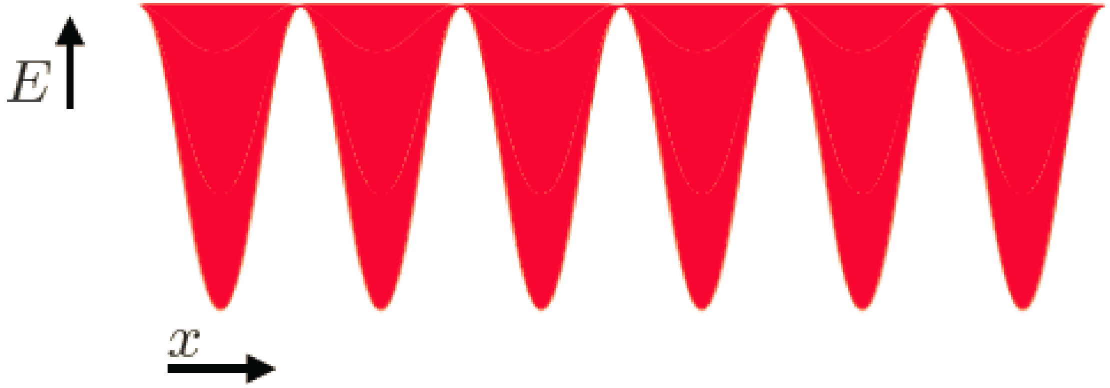


Quantizing the Doppler Effect

Kolkowitz *et al*., Nature **542**, 66 (2017).

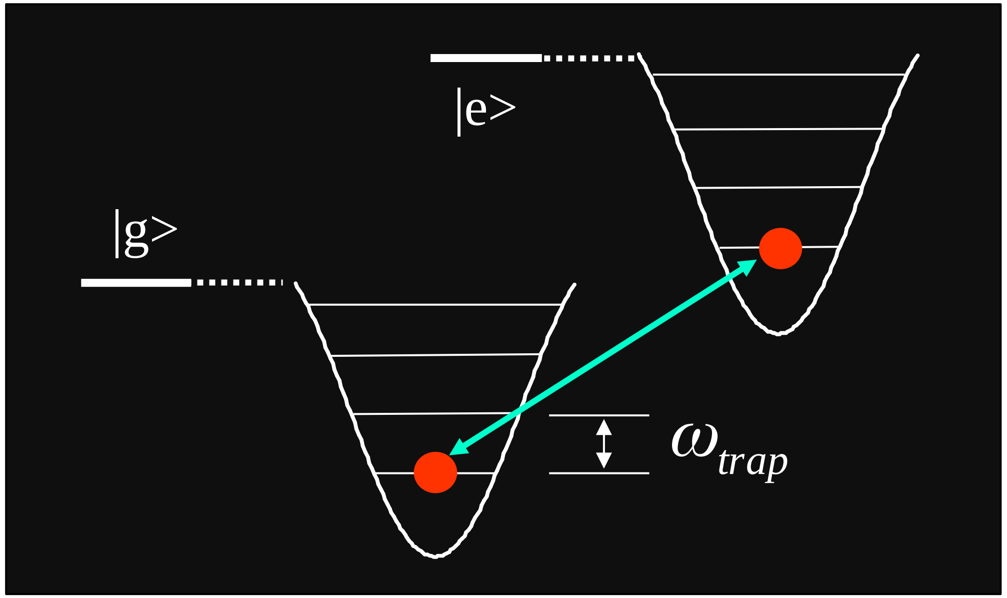
T = 1 μK



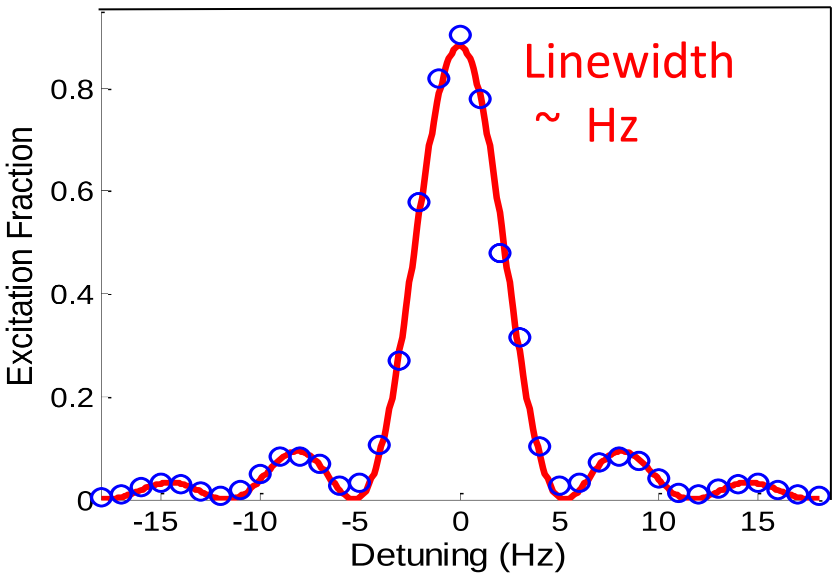


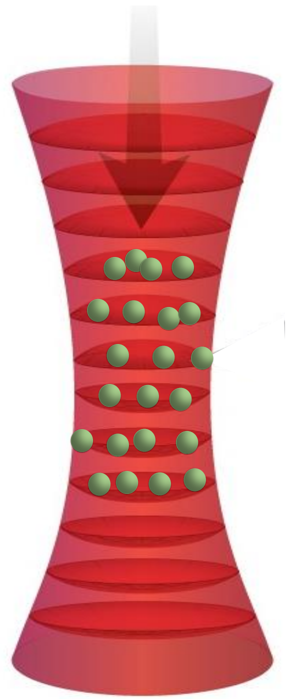
Quantum State Control

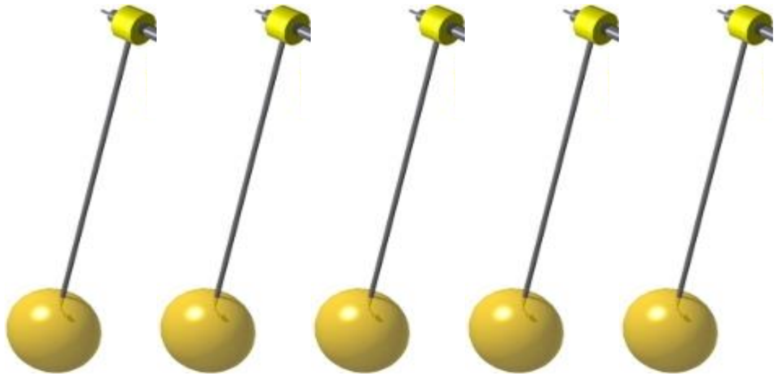
Haroche, Wineland



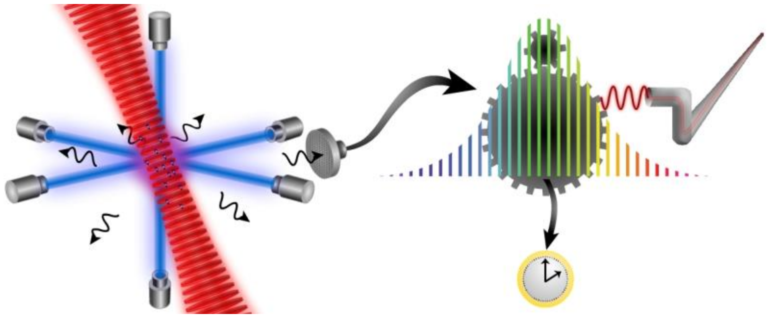
Ludlow *et al.*, Rev. Mod. Phys. **87**, 647 (2015).





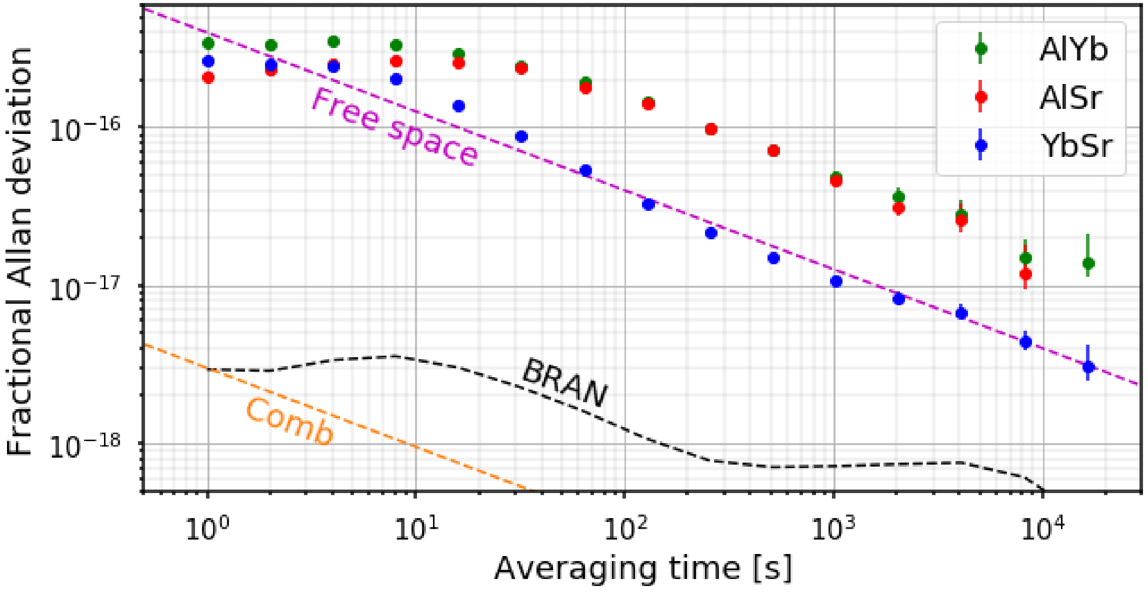


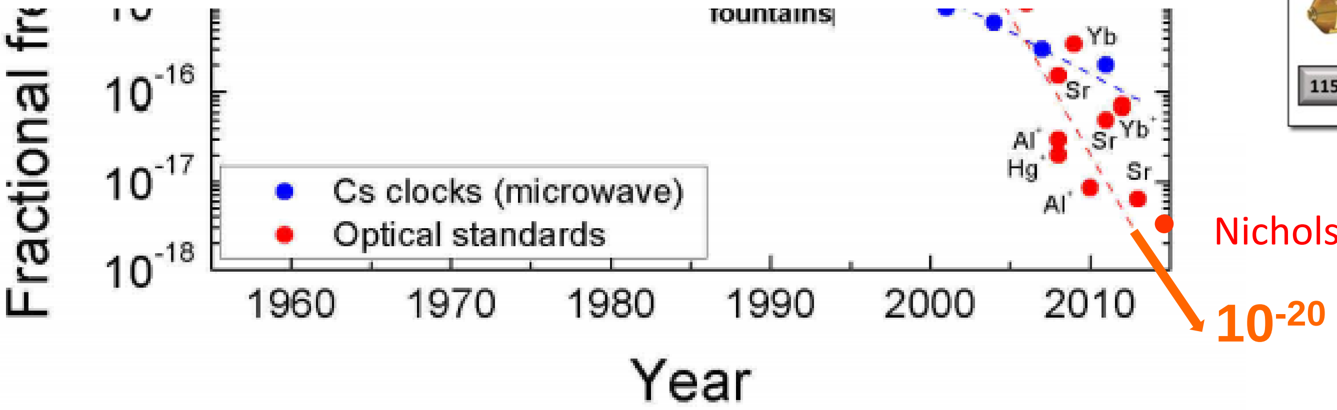
- Doppler shift = 0 (motion quantized)
- Precision improvement by $N^{1/2}$



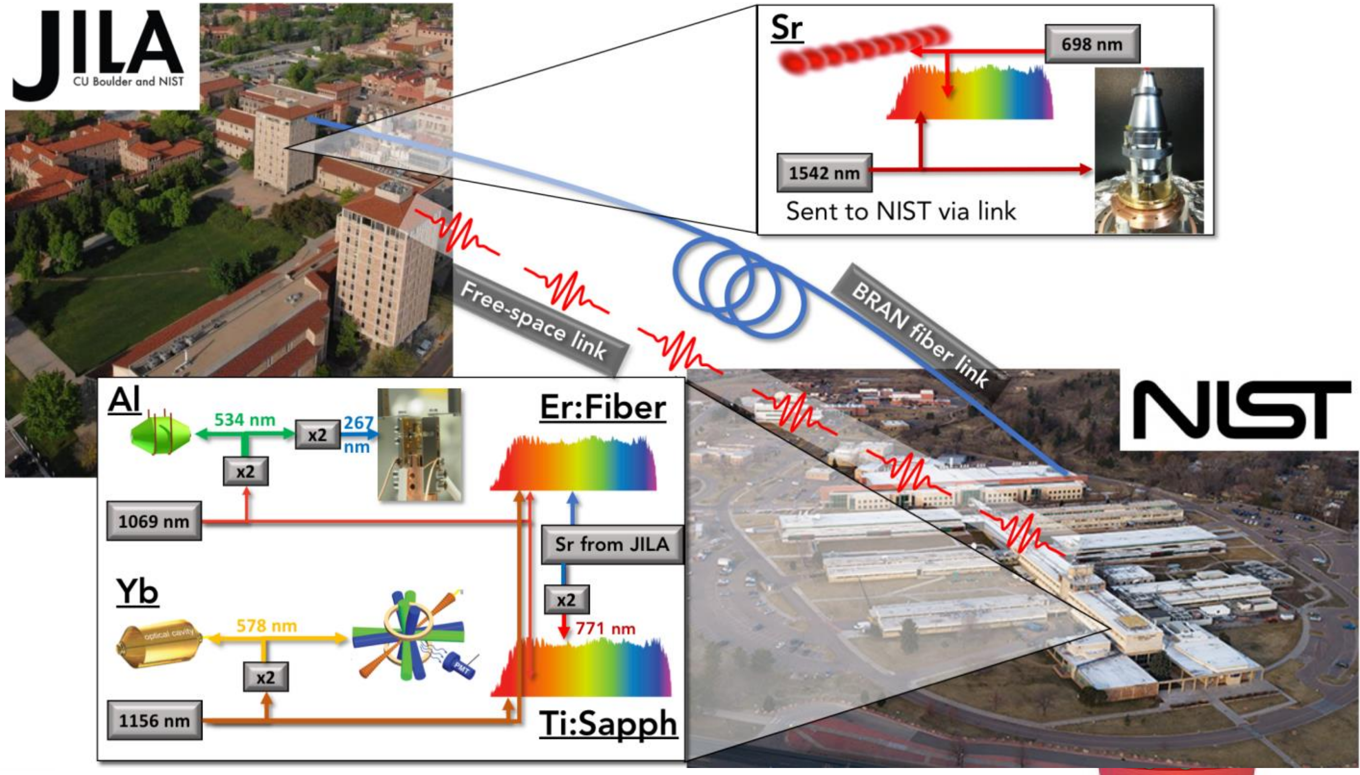
JILA Sr Clock II : 2.1×10^{-18}
Nicholson *et al.*, Nature Comm. **6** (2015).

Atomic Clock: Sensors of Space-time

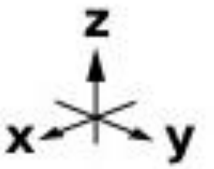


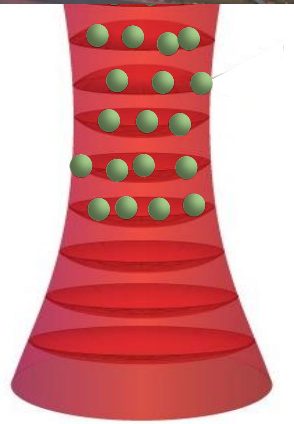


Poli *et al.* La rivista del Nuovo Cimento, **36**, 555 (2013).



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





Quantization along x & y

3D Fermi Gas Clock

Quantum gases: Cornell, Ketterle, Wieman; Jin

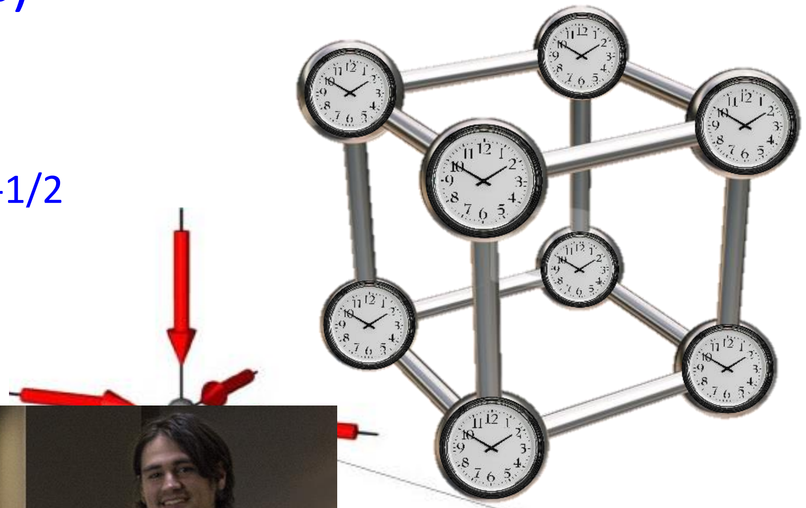
JILA CU Boulder and NIST

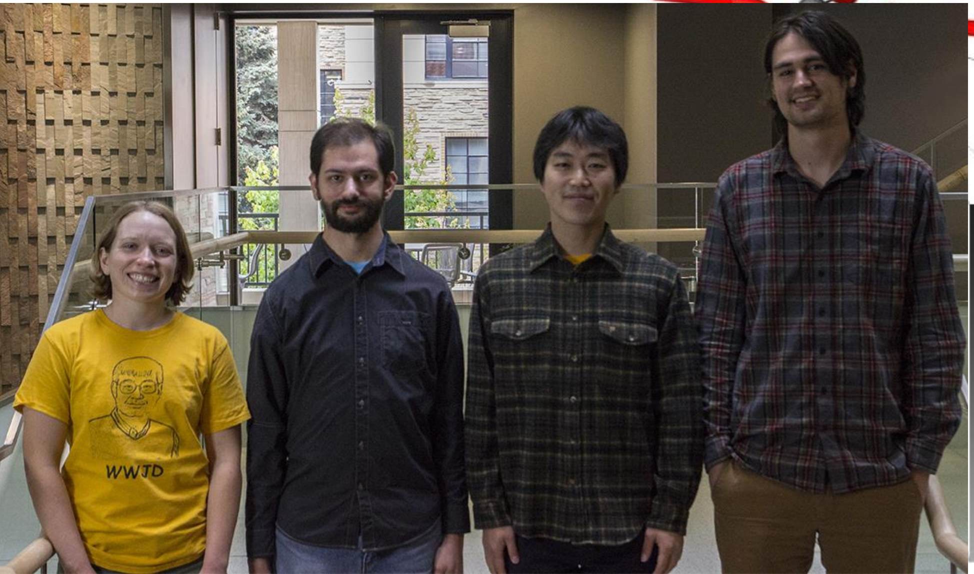
Scaling up the Sr quantum clock:

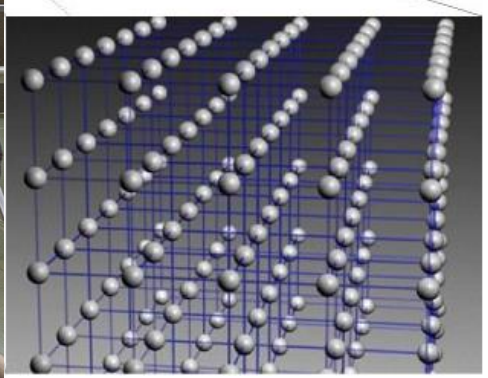
1 million atoms
(100 x 100 x 100 cells)

Coherence 160 s

Precision 3 x 10^{-20} $Hz^{-1/2}$

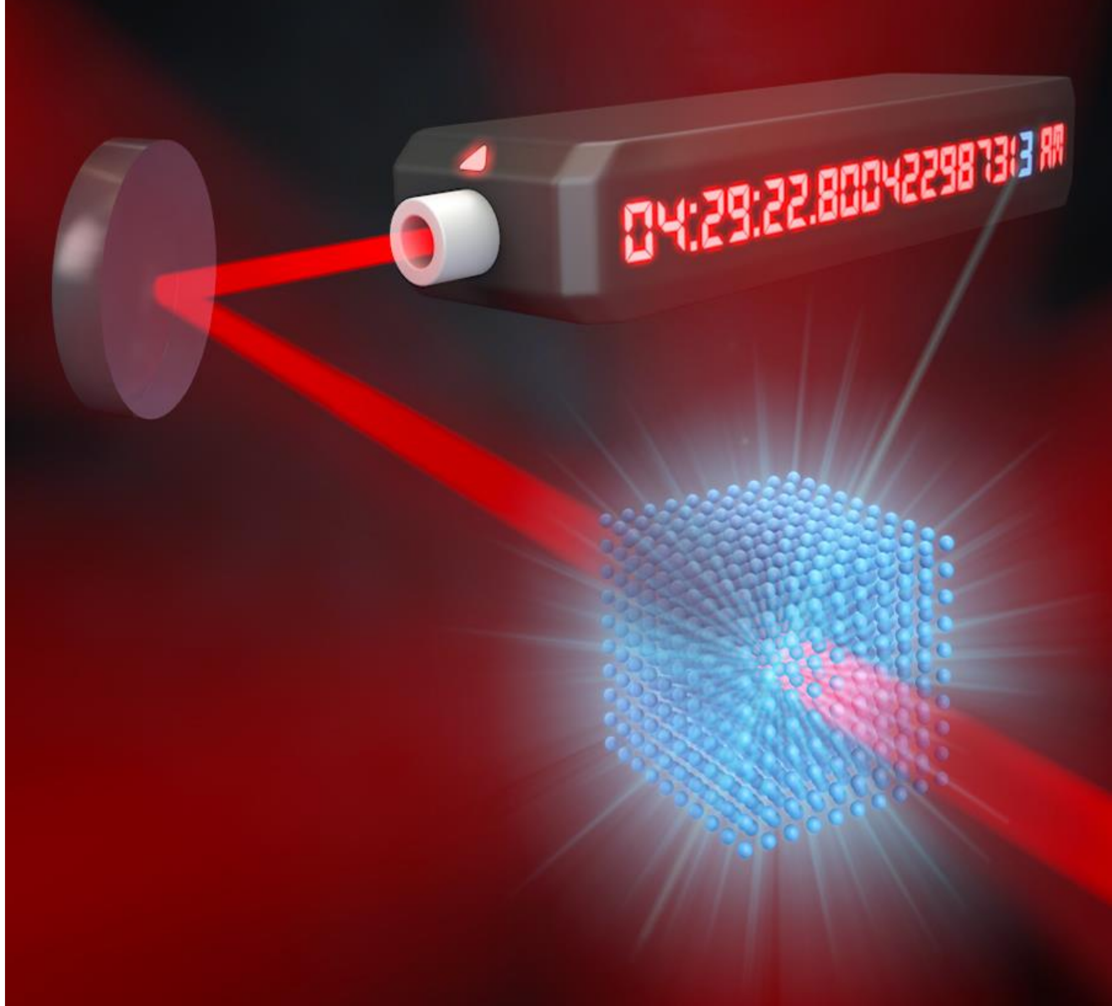






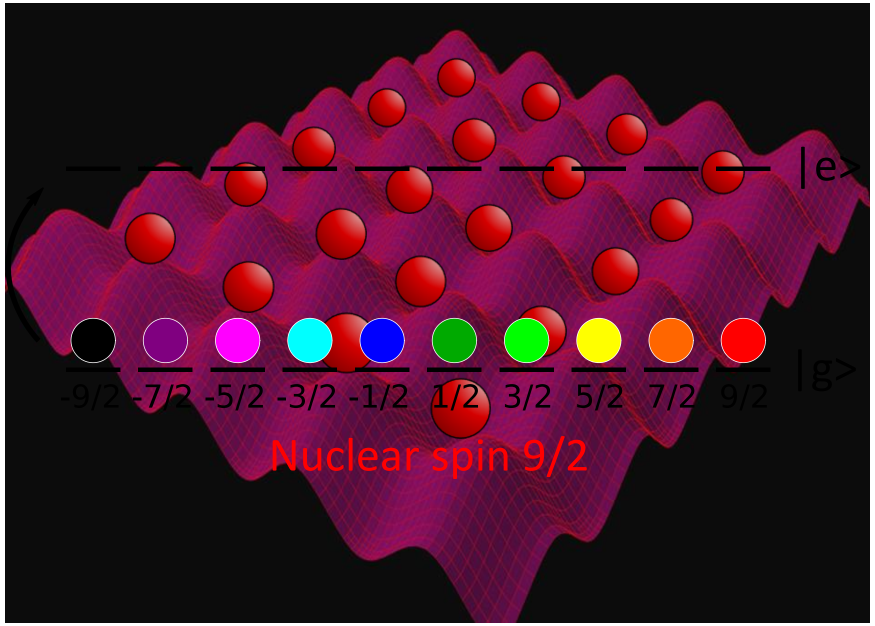
Pauli Exclusion Principle

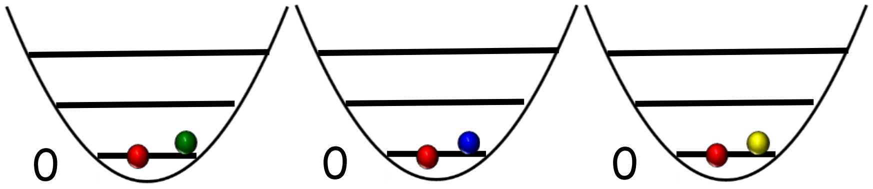
→ 1 atom (clock) per site

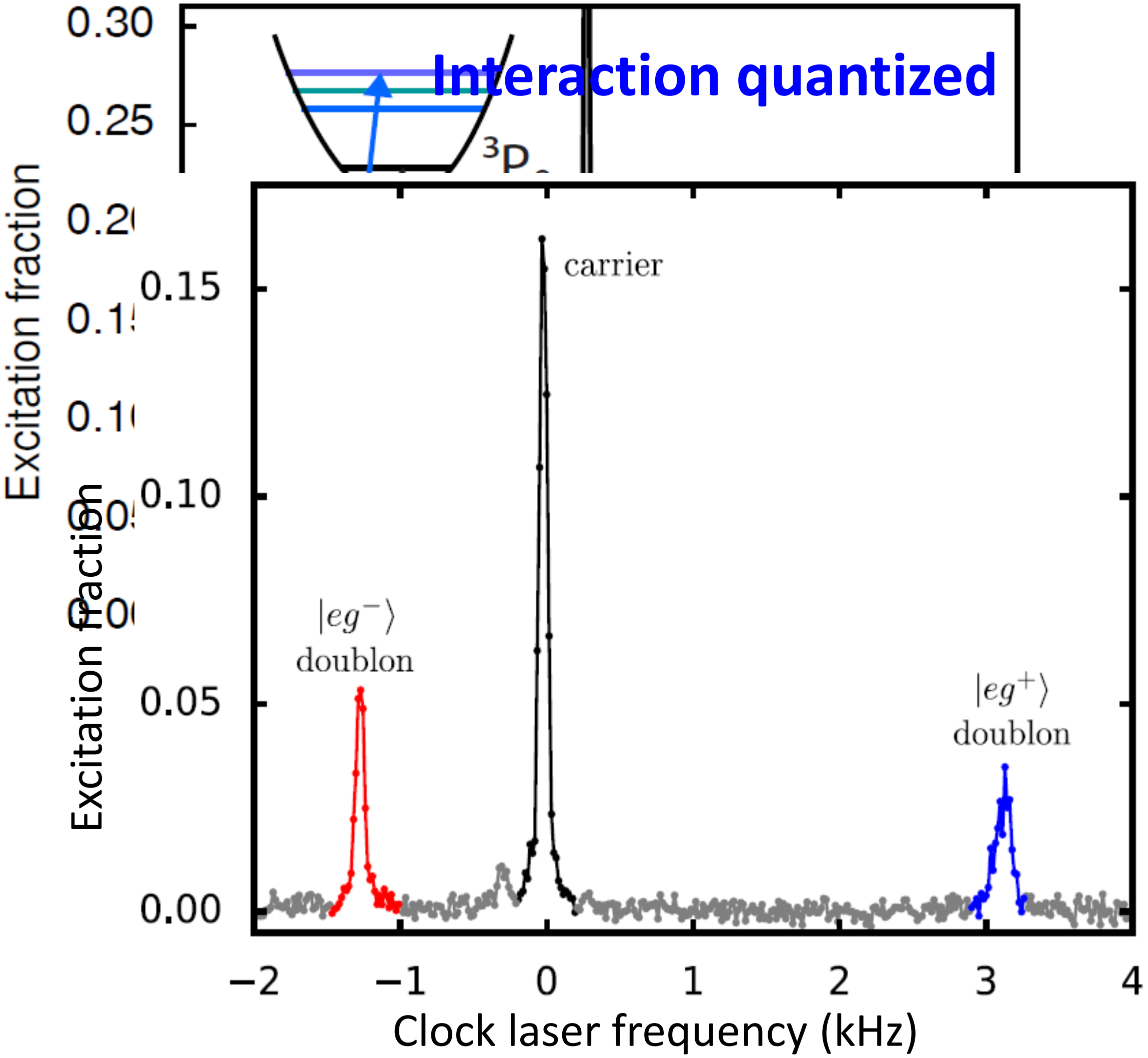


A Fermi Gas Mott Insulator Clock

Goban *et al.*, Nature **563**, 369 – 373 (2018).

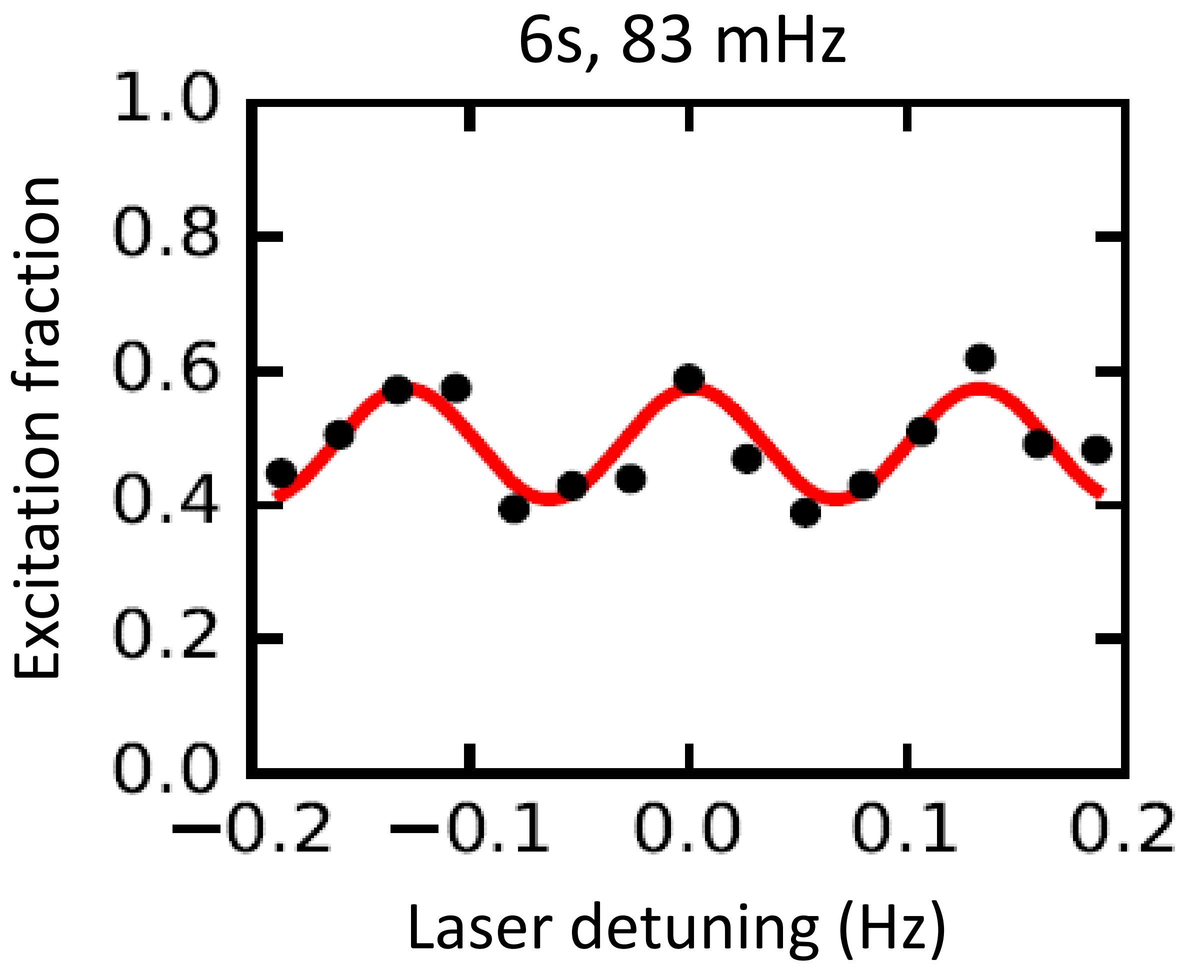






Long Atom-Light Coherence

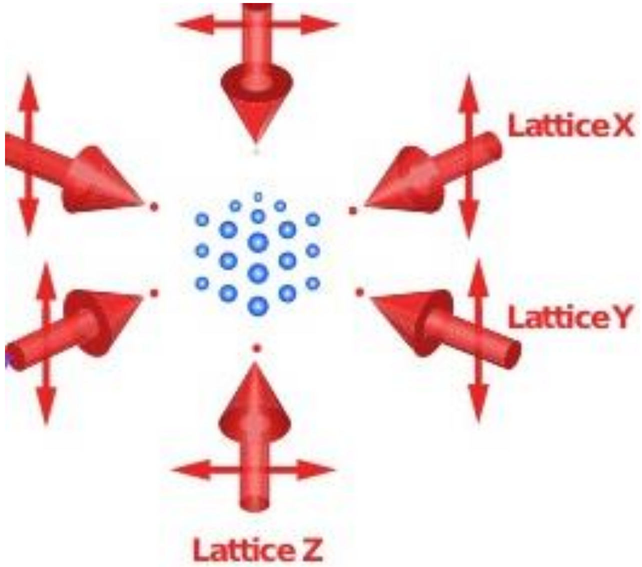
S. Campbell *et al.*, Science **358**, 90 (2017).



Atom-Light coherence: 10 s

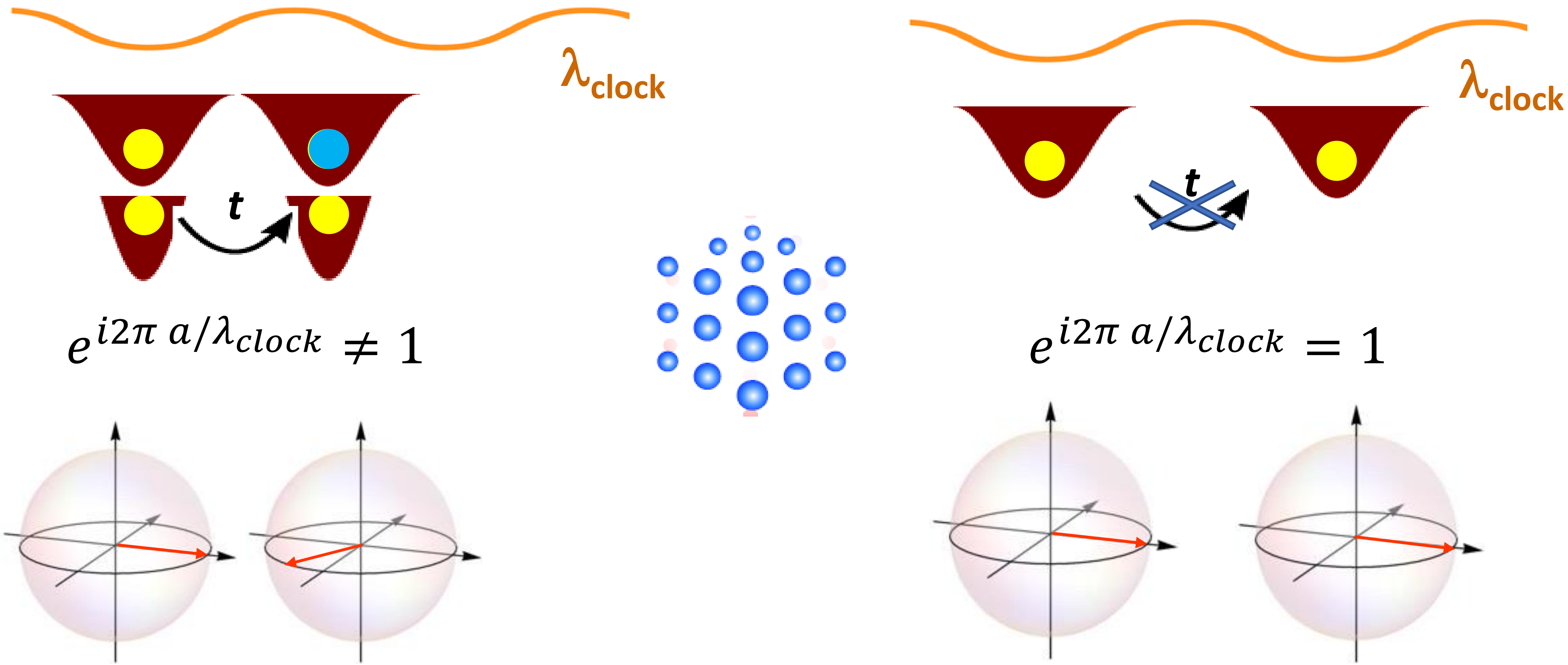
Quality factor: 8 x 10^{15}

Limit: photon scattering ; need shallow lattices



A Fermi Band/Mott Insulator Clock

JILA CU Boulder and NIST

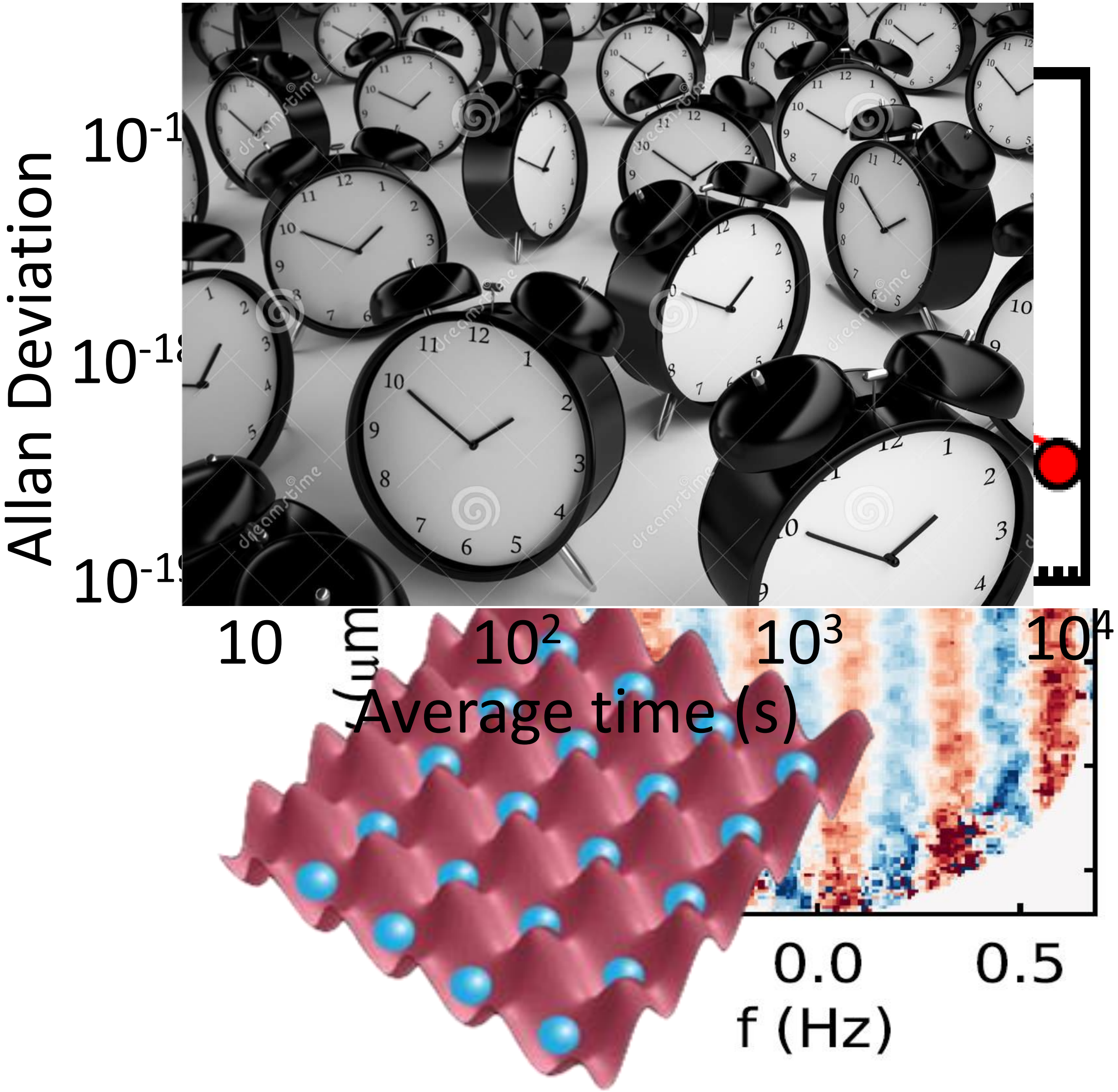


Kolkowitz *et al.*, Nature **542**, 66 (2017); Bromley *et al.*, Nature Phys. **14**, 399 (2018).

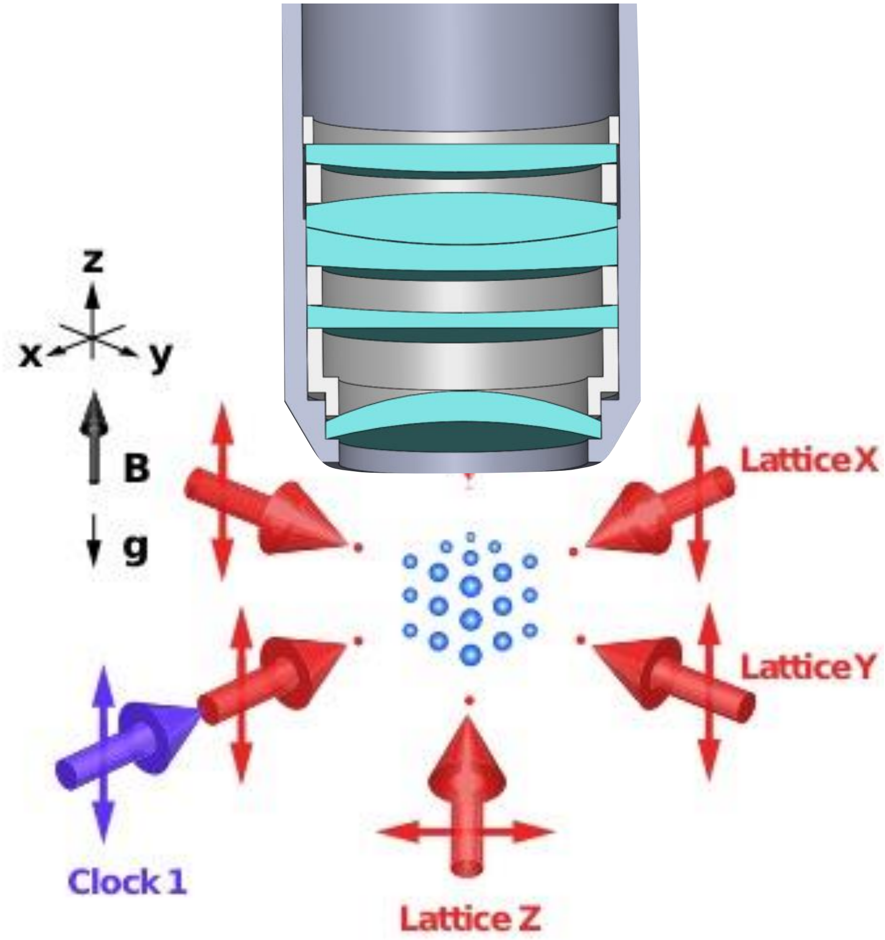
Clock under a Microscope

JILA
CU Boulder and NIST

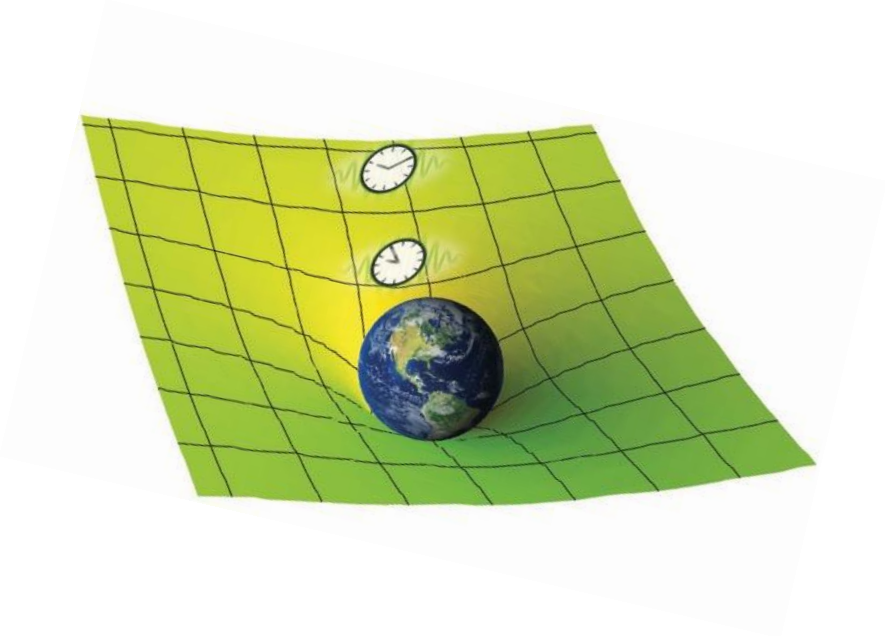
Marti *et al.*, Phys Rev Lett **120**, 103201 (2018).



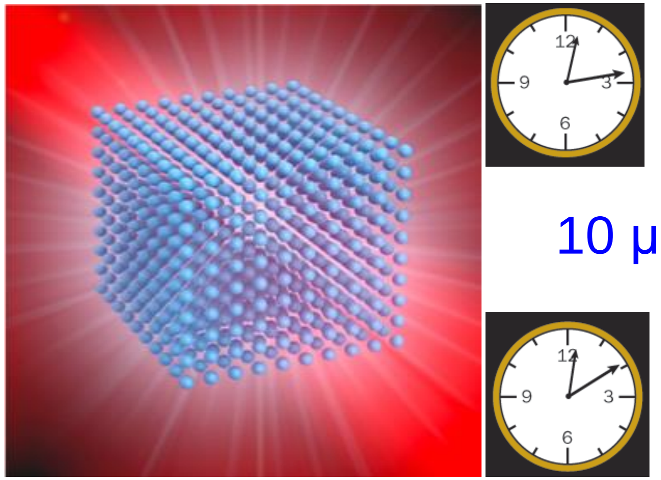
∇B_x



Gravitational Potential & Atomic Coherence



Extreme spatial resolution & precision



10 μm height: 10^{-21} effect

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JILA
CU Boulder and NIST

Sr optical clock – a big playground

E. Marti (Stanford U)
S. Bromley (U. Durham)
W. Zhang (NIST)
S. Campbell (UC Berkeley)
S. Kolkowitz (U. Wisconsin)
X. Zhang (Peking U.)
T. Nicholson (NUS)
M. Bishof (Argonne)
B. Bloom (Atom Compute)
M. Martin (Los Alamos)
J. Williams (JPL/Caltech)
M. Swallows (Honeywell)
S. Blatt (MPQ, Garching)

A. Ludlow (NIST)
G. Campbell (JQI, NIST)
T. Zelevinsky (Columbia U.)
Y. Lin (NIM)
M. Boyd (AO Sense)
J. Thomsen (U. Copenhagen)
T. Zanon (Univ. Paris 6)
S. Foreman (U. San Fran)
X. Huang (WIPM)
T. Ido (NICT Tokyo)
X. Xu (ECNU)
T. Loftus (Honeywell)

Current Sr Group

T. Bothwell
D. Kedar
C. Kennedy

W. Milner
E. Oelker
J. Robinson

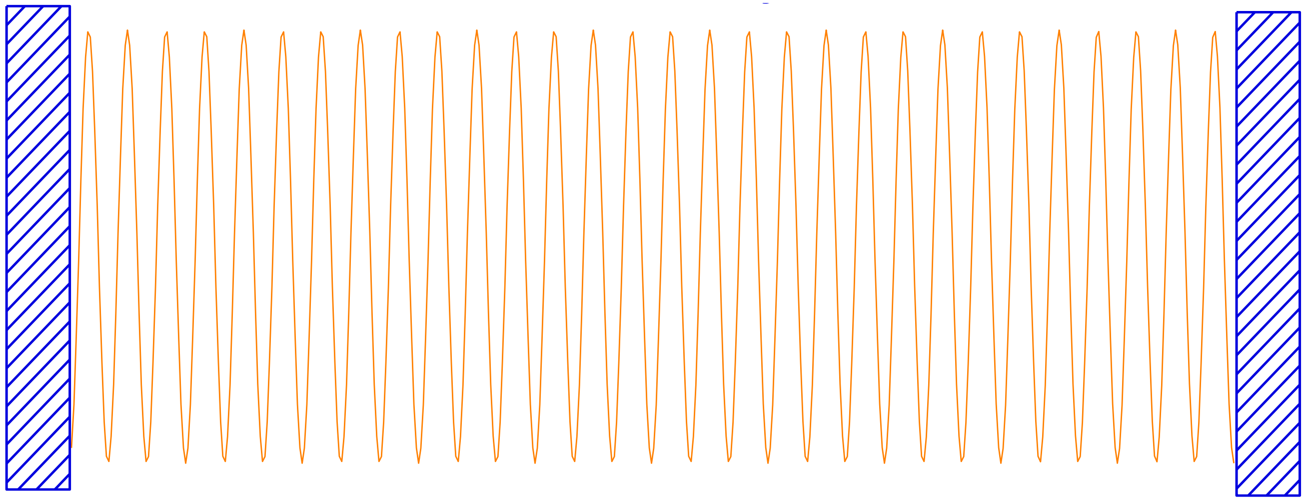
A. Goban
R. Hutson
C. Sanner
L. Sonderhouse

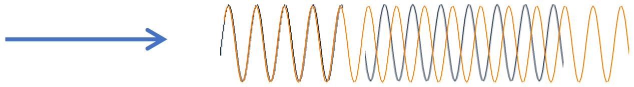
Collaboration: NIST Time & Frequency,
PTB (Riehle, Sterr, Legero)

Theory: A. M. Rey, M. Safronova, P. Julienne, M. Lukin, P. Zoller, …

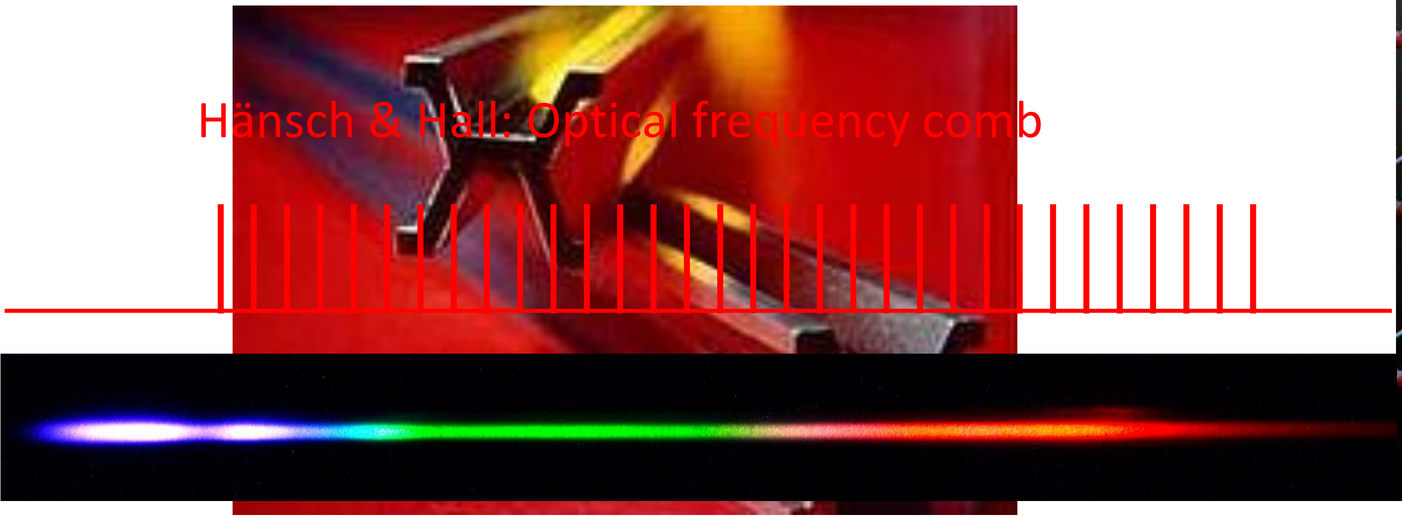
Laser is *the* Central Ruler of Time & Space

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



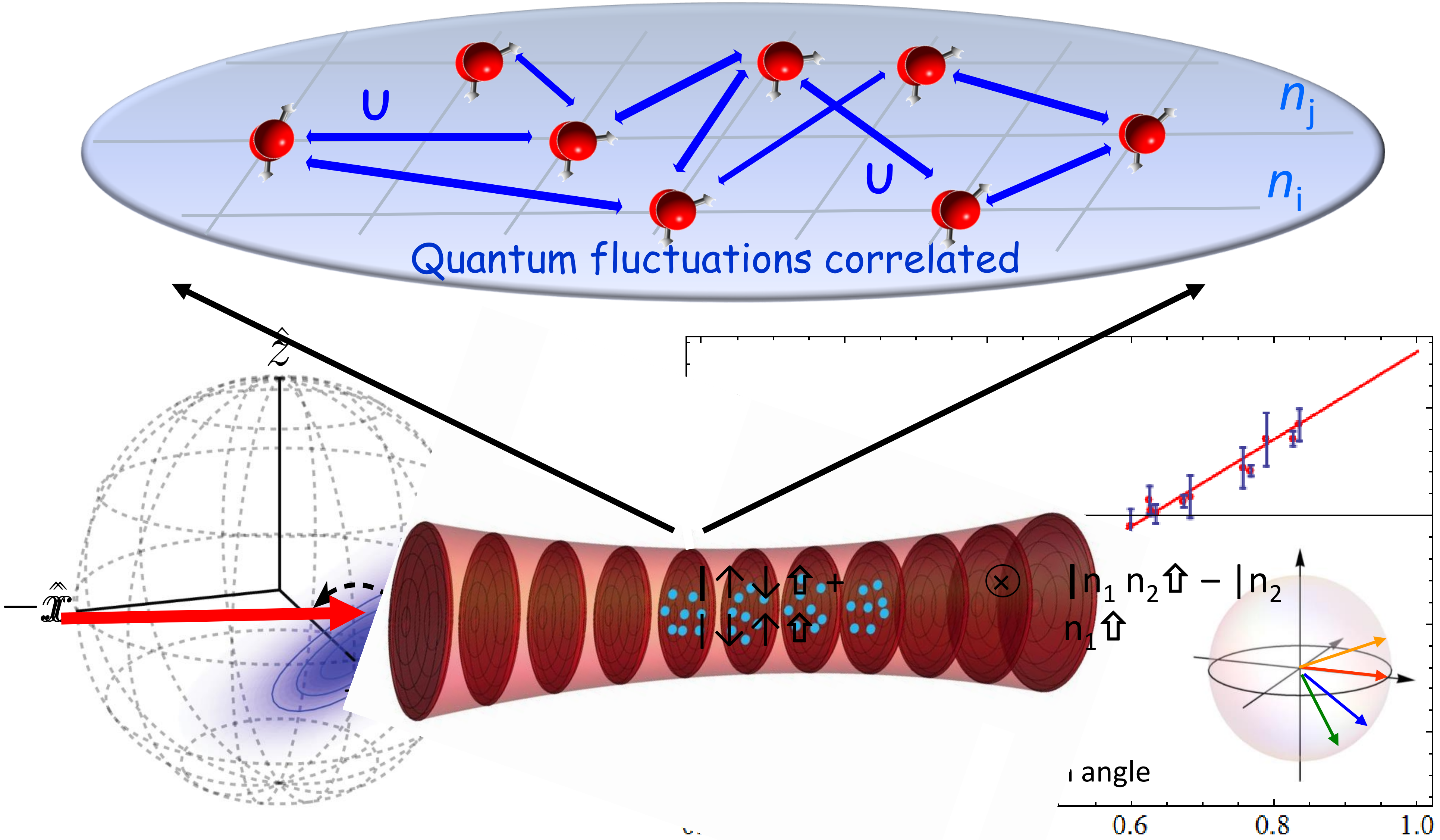


Length is linked to Time via *c*



Clock Meets Atomic Interactions

Martin *et al.*, Science **341**, 632 (2013). Zhang *et al.*, Science **345**, 1467 (2014).



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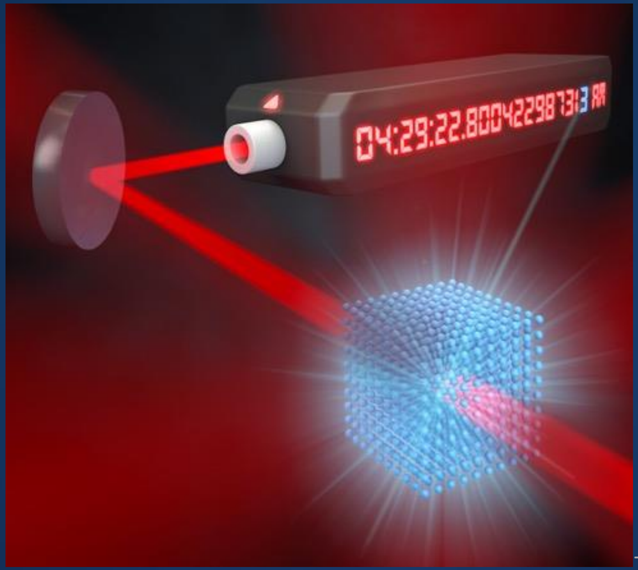
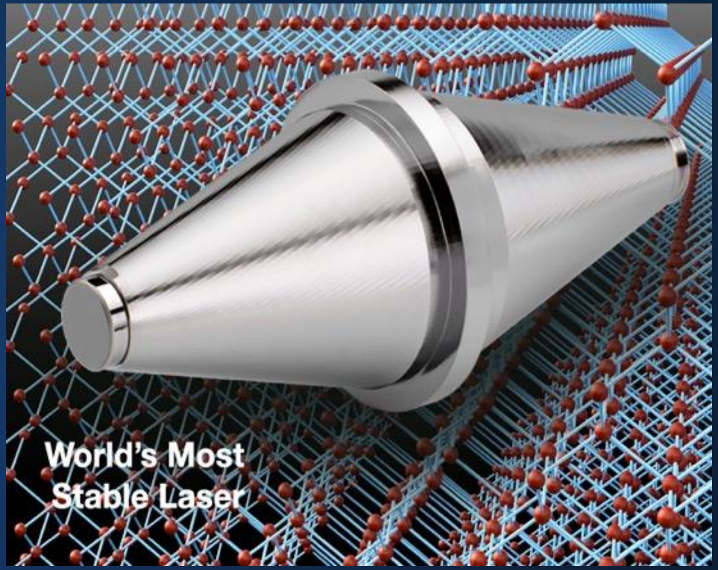


Credit: Ye Group



Credit: NIST

Quantum sensing

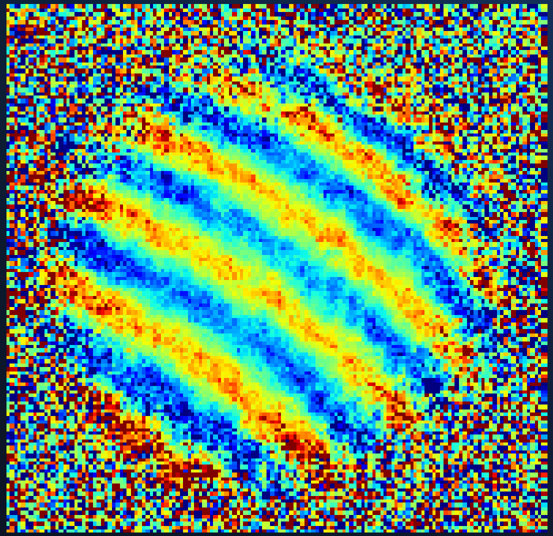
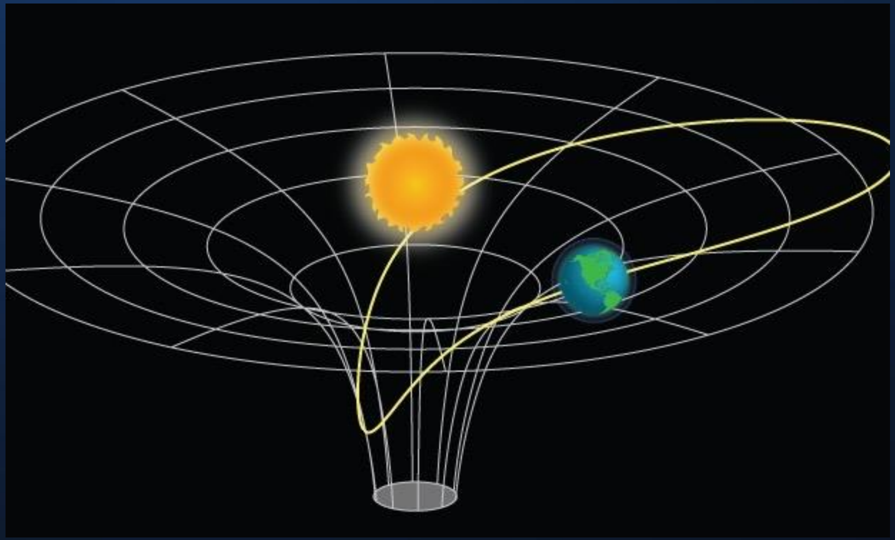
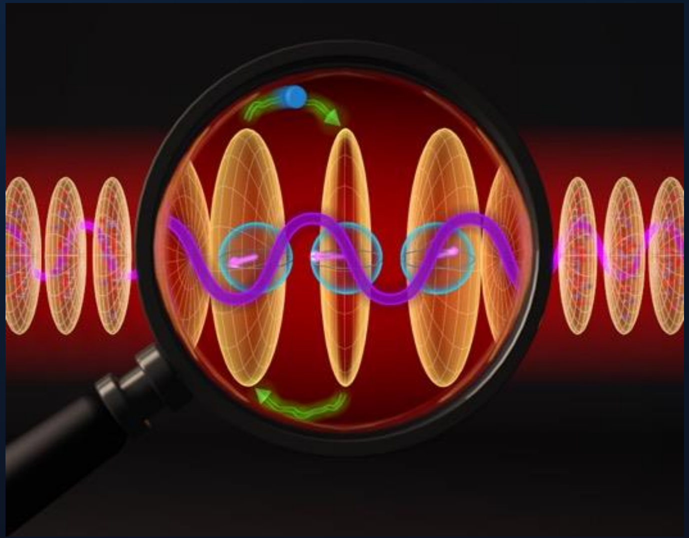


Table-top search for new physics



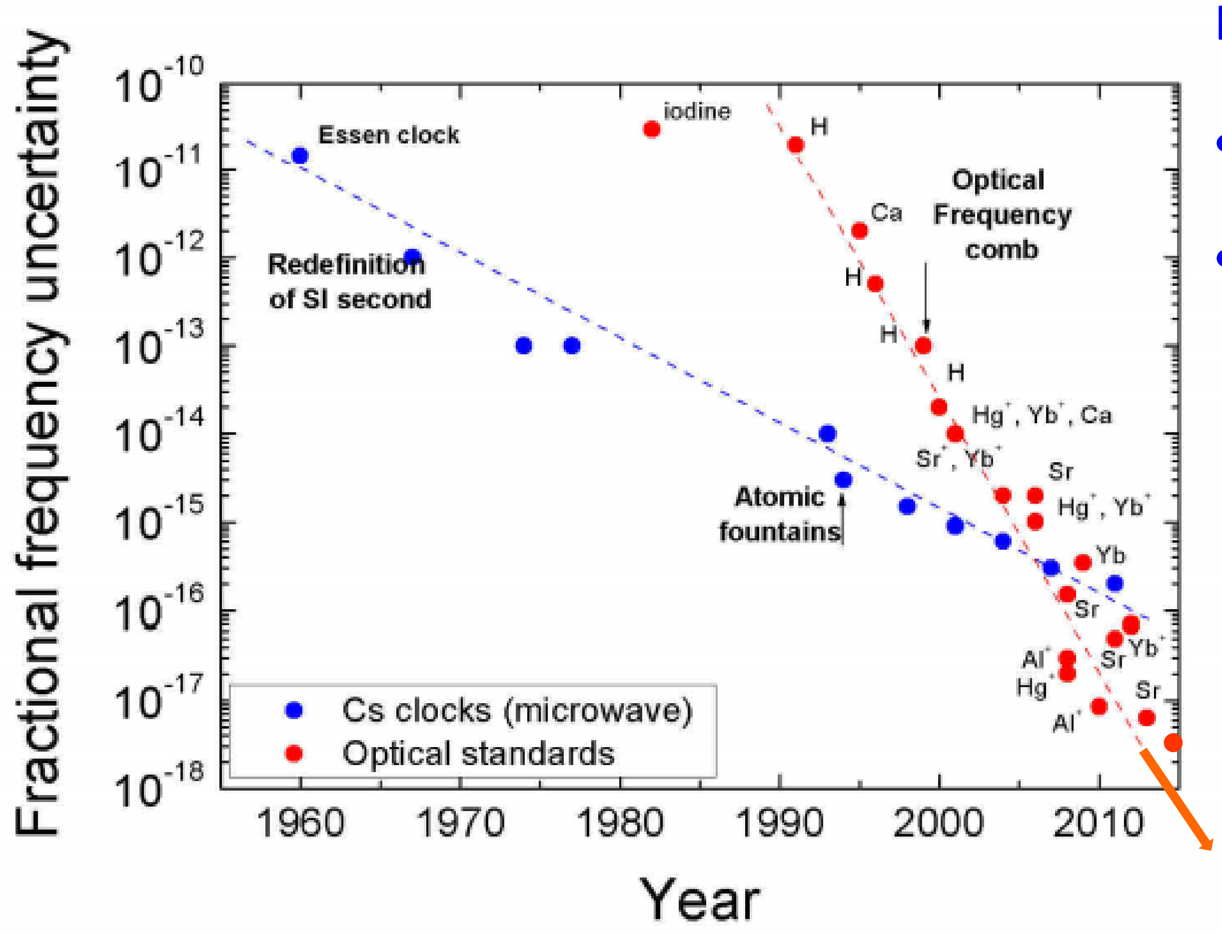
Many-body dynamics



Credit: Ye Group

Atomic Clock: Sensors of Space-time

JILA CU Boulder and NIST



10^{-20}

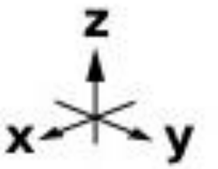
Poli *et al.* La rivista del Nuovo Cimento, **36**, 555 (2013).

Important innovations:

- Higher Q **optical** transitions
- New laser phase control: optical coherence > 1 s
- Trapped atoms/ions: high *N*, long coherence
- Optical frequency comb

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

- Current accuracy ~10^{-18} : gravitational redshift 1 cm
- Quantum many-body and coherence



Quantization along x & y