Clock, quantum matter, & fundamental physics

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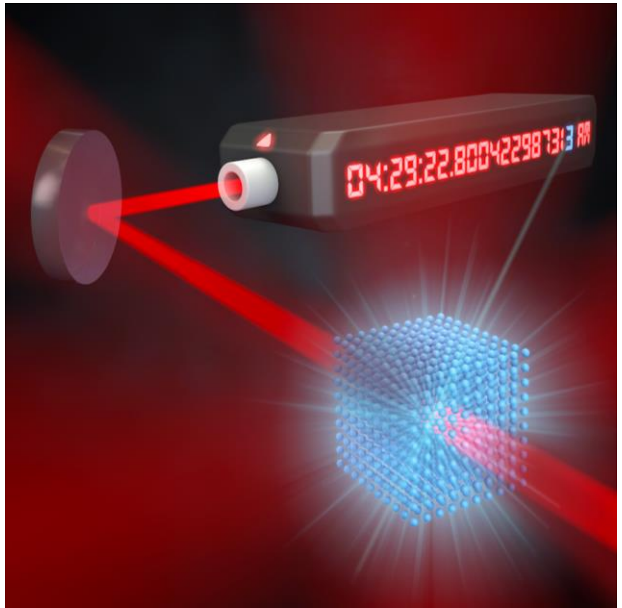
2021 Boulder Summer School for Condensed Matter and Materials Physics
July 12, 2021

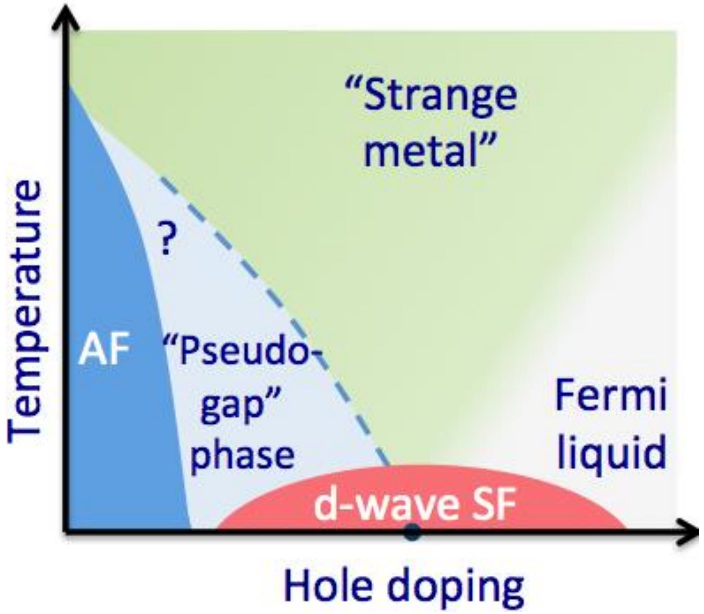
control

Quantum sensing



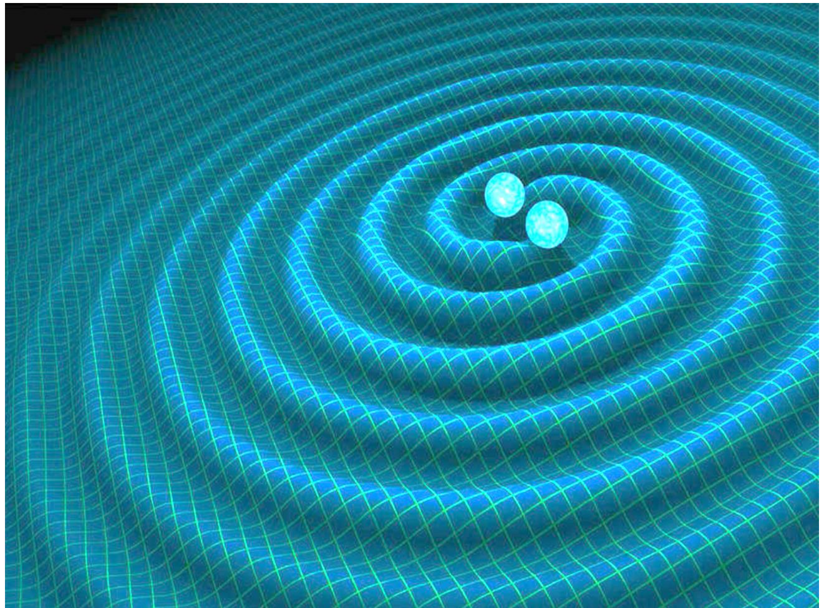
understand

Quantum simulation



apply

Fundamental physics



Coherence, precision, entangled states

Precise state preparation

Quantum coherence

Optimal measurement

Quantum Science

Precision frontier

Entanglement resources

System Engineering

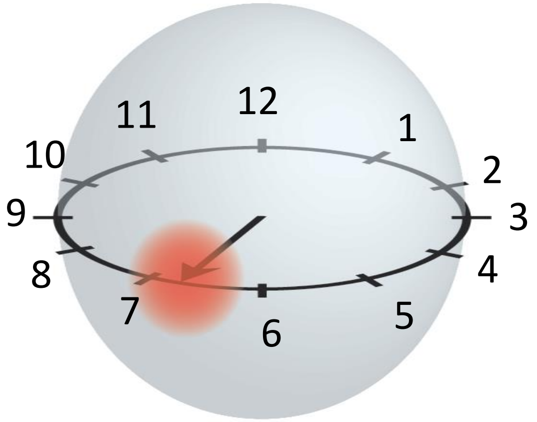
Application

Long coherence time

$Q \sim 10^{17}$

Quantum system design

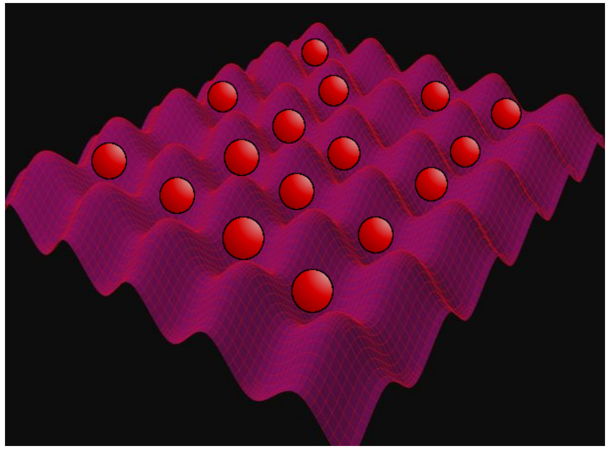
Large count rate



Std quantum limit: $N^{1/2}$

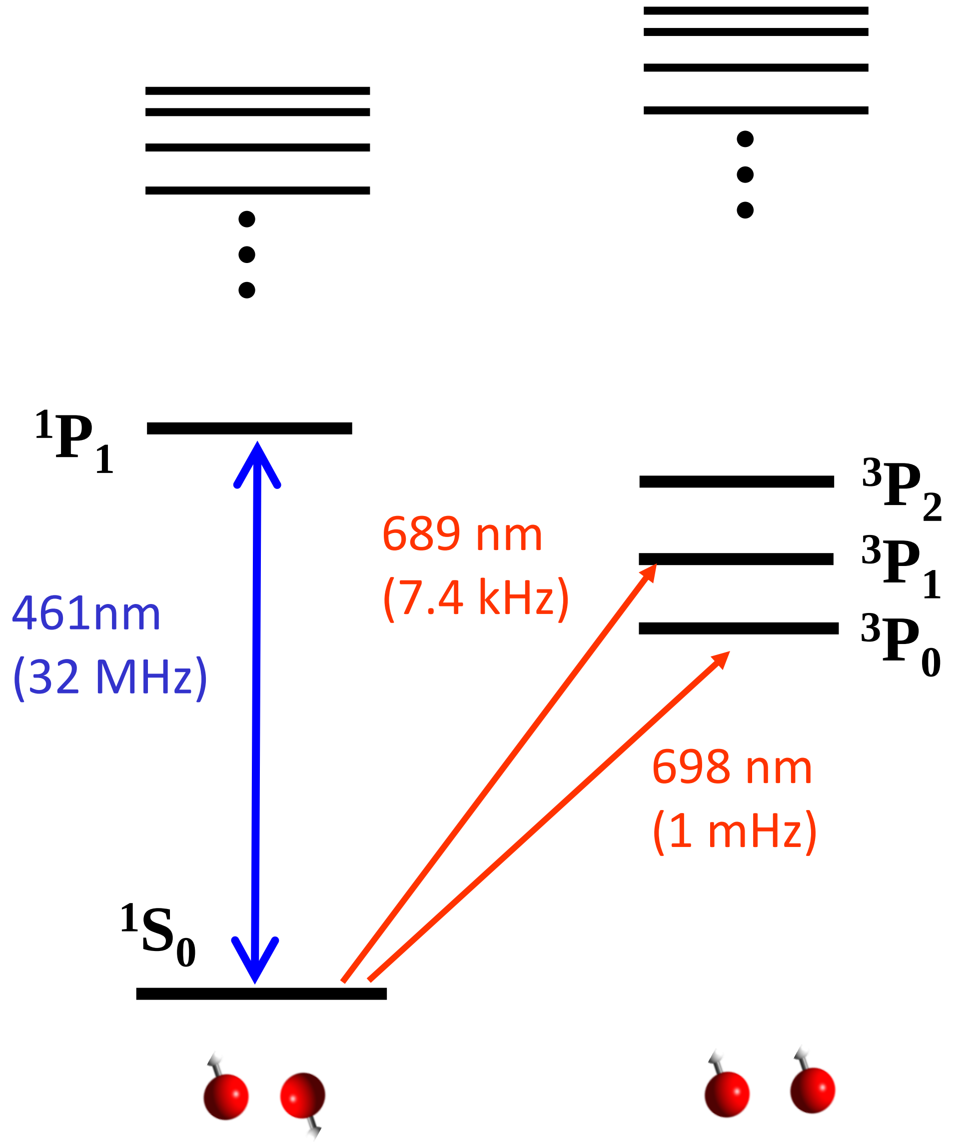
Heisenberg limit: N

Many-body state



Quantum protection & enhancement

Sr atoms - A tale of twin electrons



$Q \sim 10^{17}$

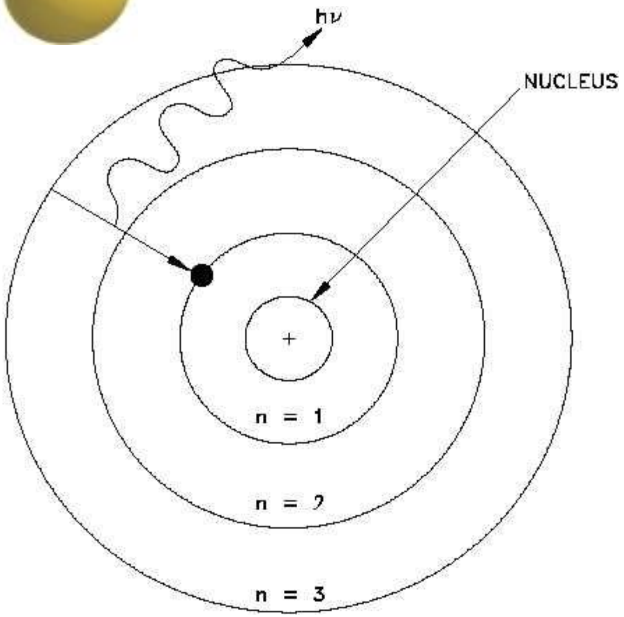
- $^3P_0$ long life (160 s)
- Clock states J = 0
- Field insensitive
- Scalar atom-light coupling

Time scales

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

Sr atoms:

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



The geometric mean ~30 s

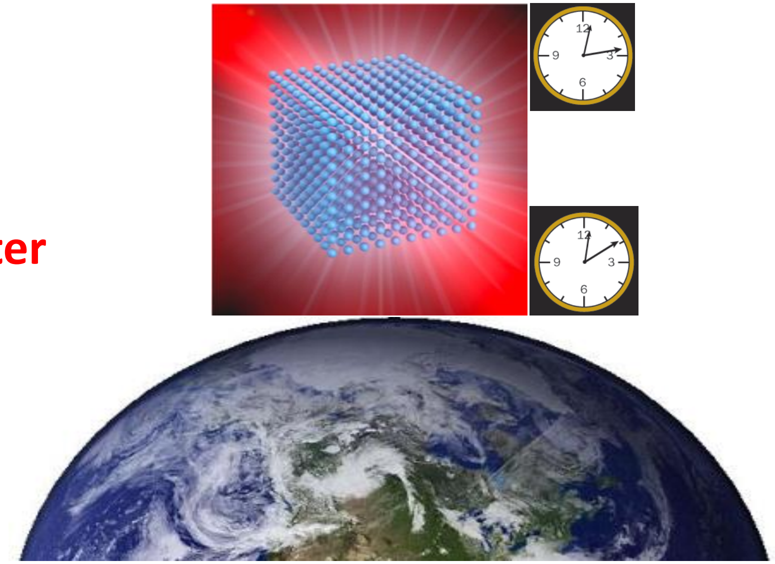
Life of the Universe: 15 billion years (10^{18} s)
1000,000,000,000,000,000 seconds

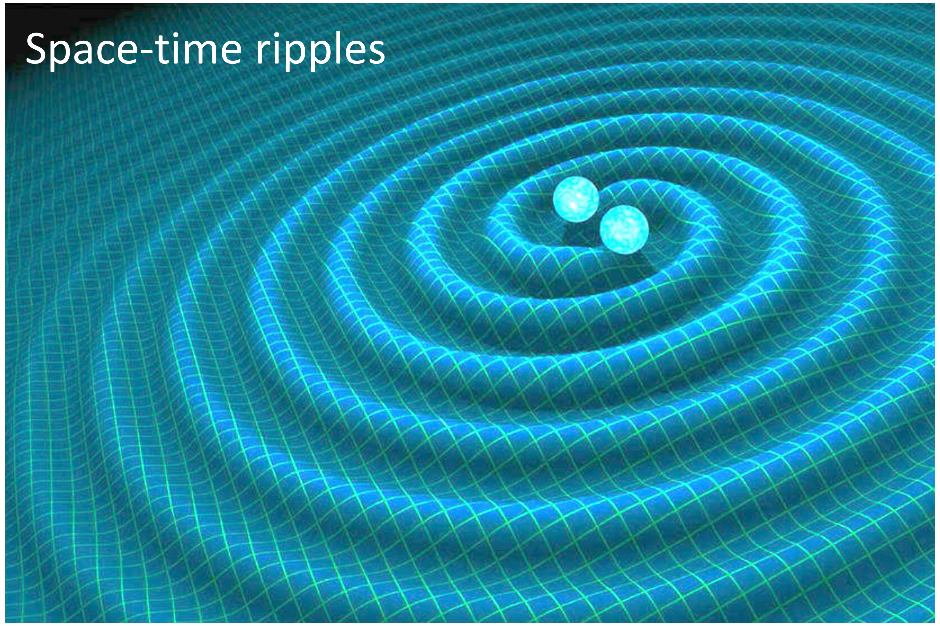
Probes for fundamental physics

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

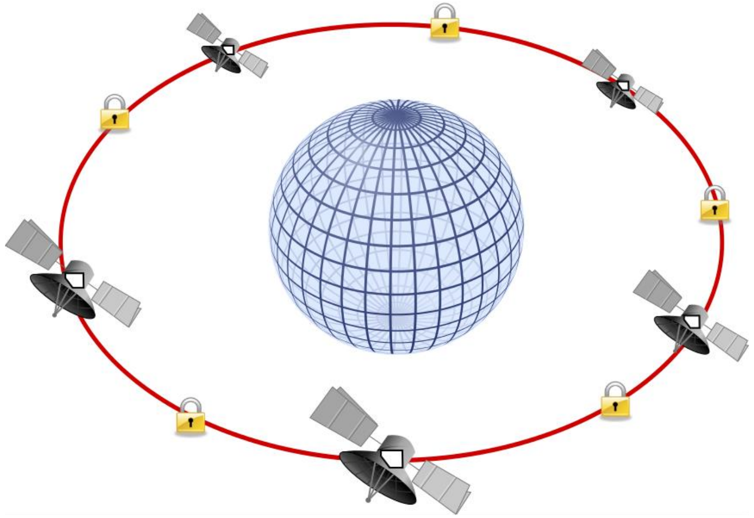
- **A giant telescope:**
  Gravitational waves, Dark Matter

- **A high-resolution microscope:**
  geophysics on Earth

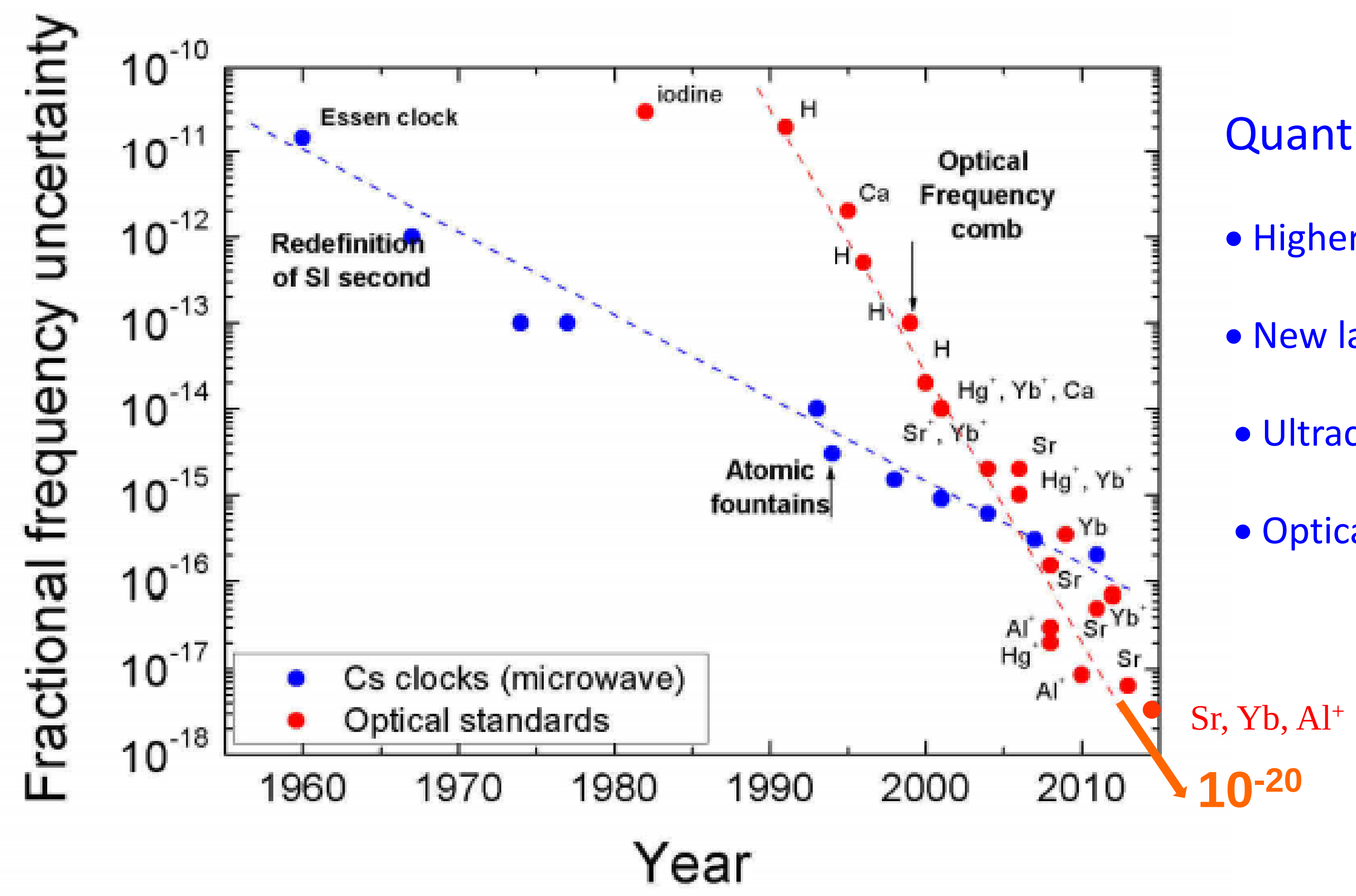




Network of clocks ($\mathbf{10^{-21}}$):
long baseline interferometry



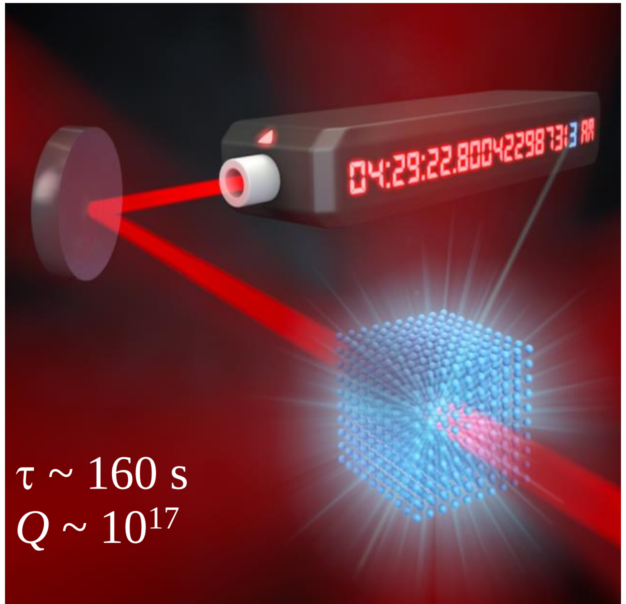
Atomic clock: sensors of Time & Space



Poli *et al.*, *La rivista del Nuovo Cimento*, **36** 555 (2013); Ludlow *et al*, RMP **87**, 637 (2015).

Quantum Technologies:

- Higher Q **optical** transitions: ions & neutral atoms
- New laser stabilization: optical coherence ~ 1 minute
- Ultracold atoms in optical lattice: engineered many-body states
- Optical frequency comb

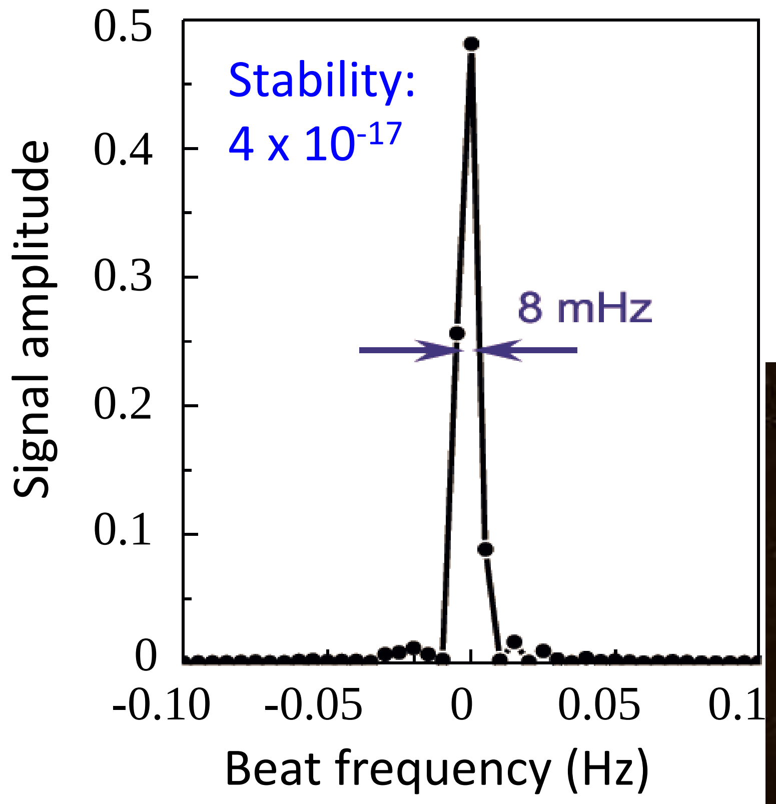


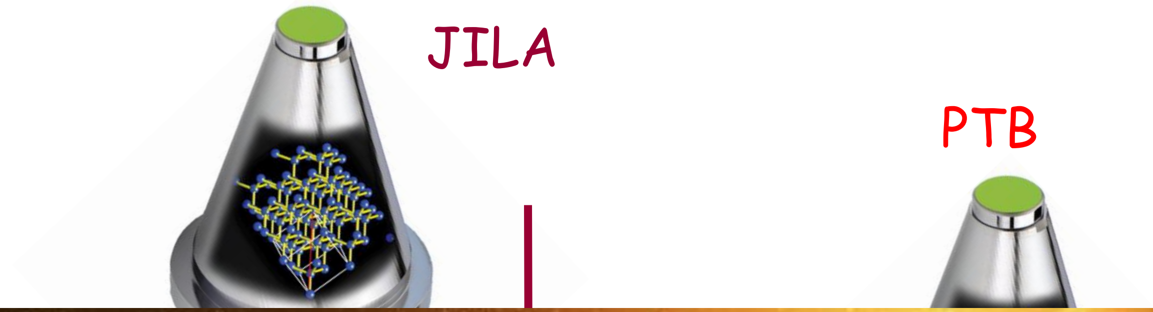
- Current accuracy ~10^{-18} = grav. redshift @ 1 cm
- Precision ~ 1 x 10^{-19} (today)
- Many-body, entanglement, & coherence

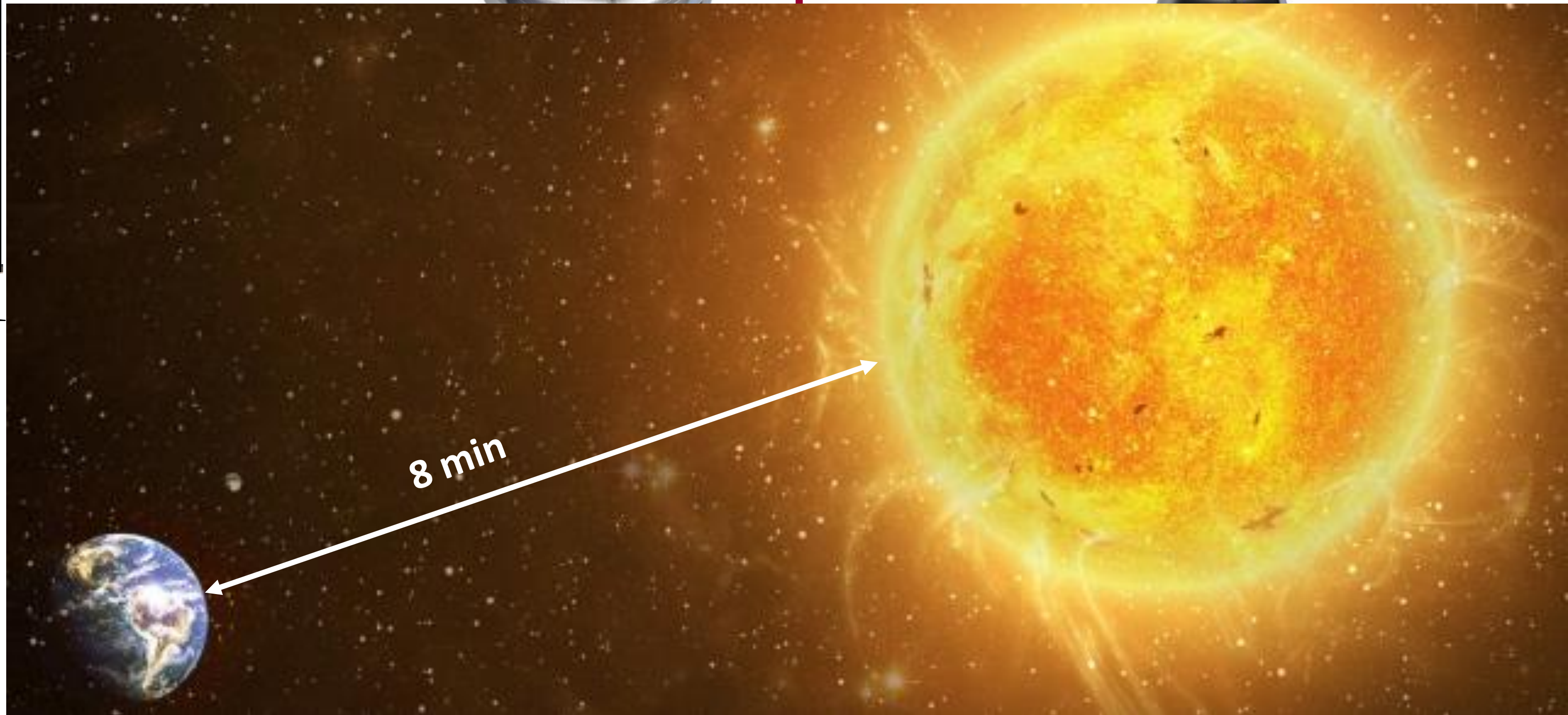
A new generation of stable lasers

Optical coherence time at tens of seconds

Matei *et al*., PRL **118**, 263202 (2017); Zhang *et al*., PRL **119**, 243601 (2017).

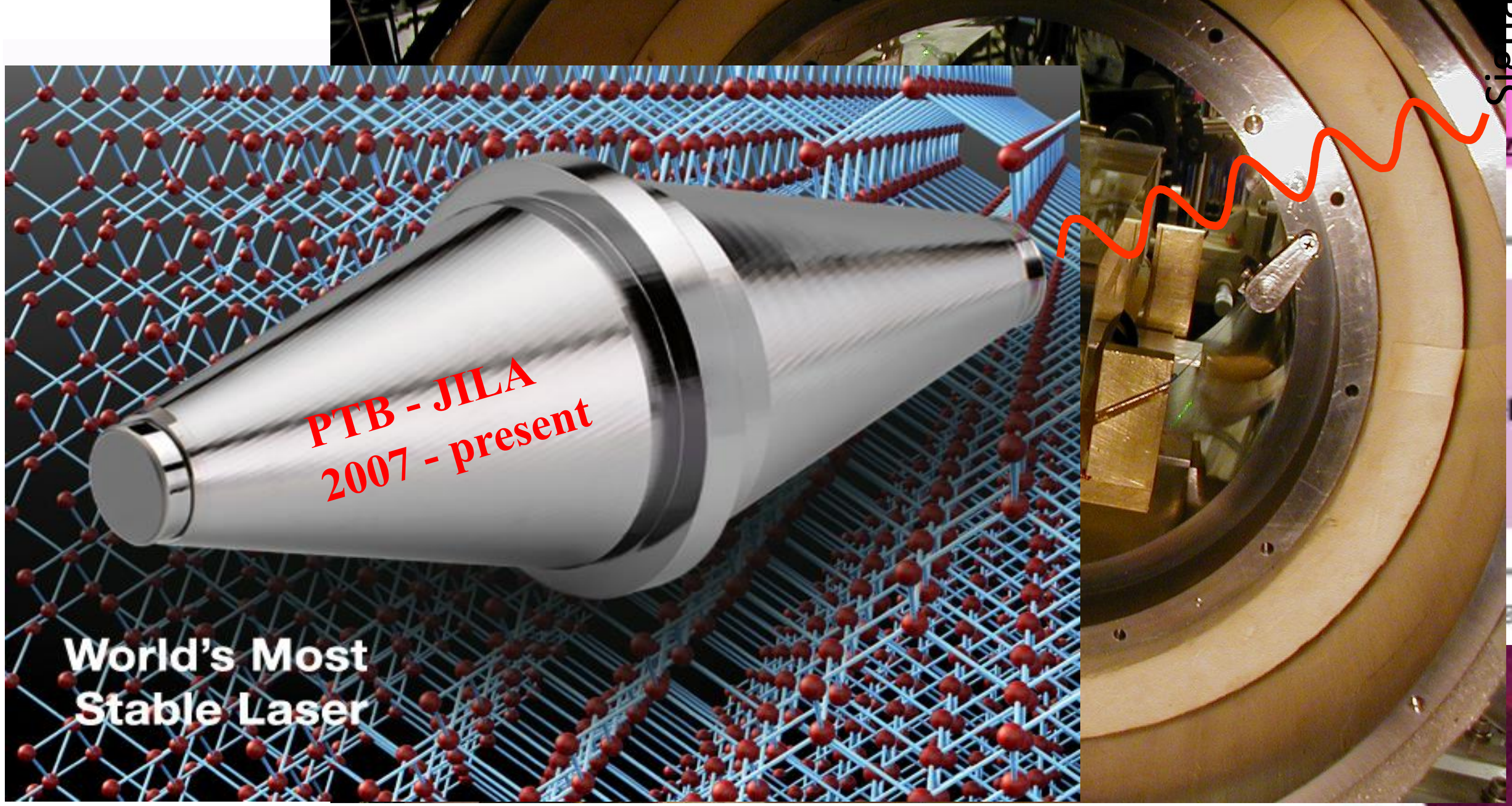


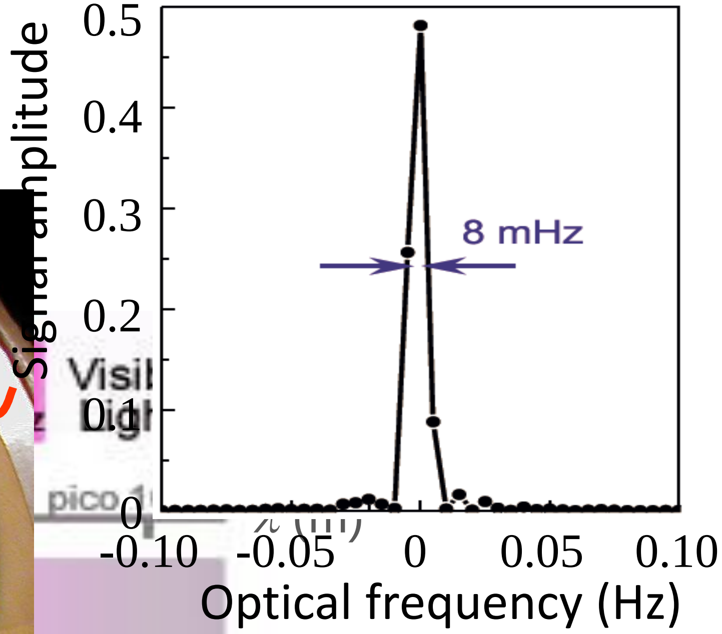


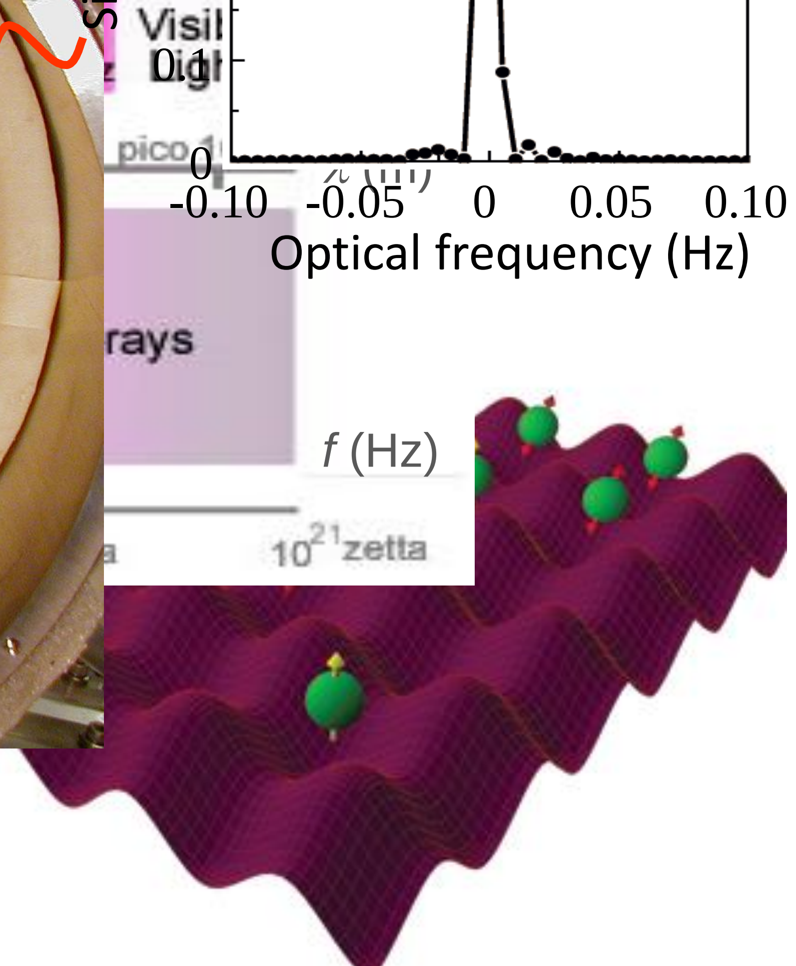


Control of light –
the electromagnetic spectrum

Silicon crystal cavity
PRL **118**, 263202 (2017); PRL **119**, 243601 (2017).







Zoom in 1 million times

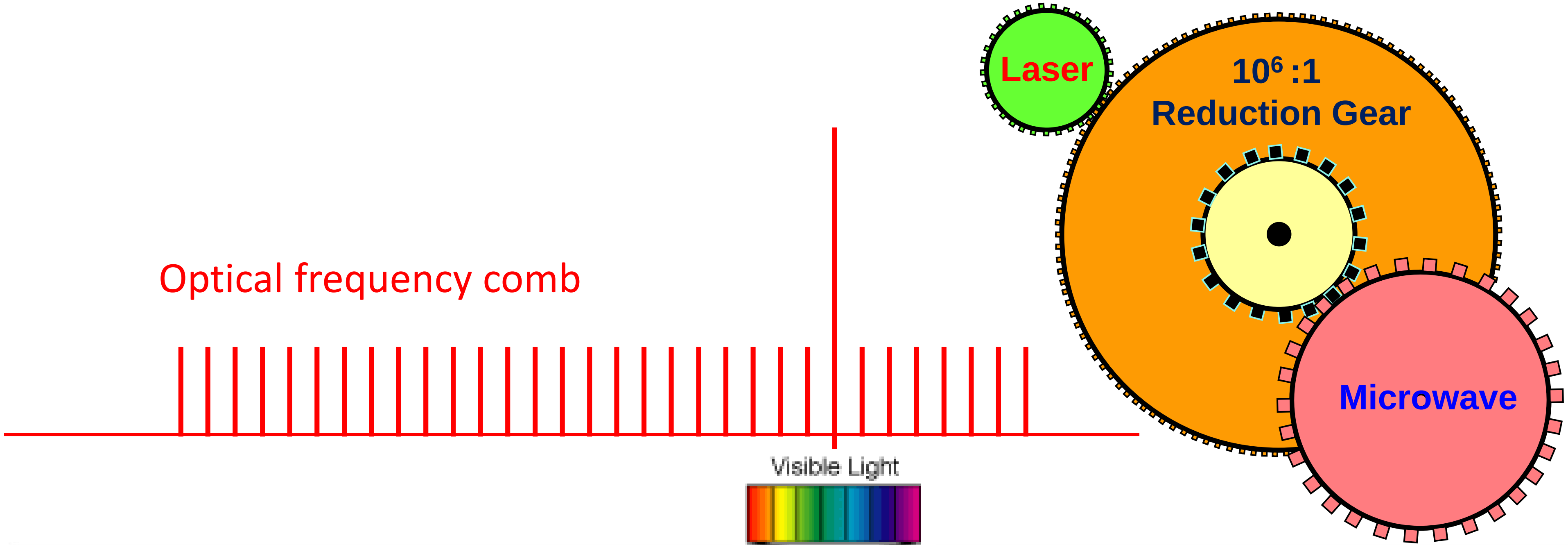
Zoom in another 1 million times

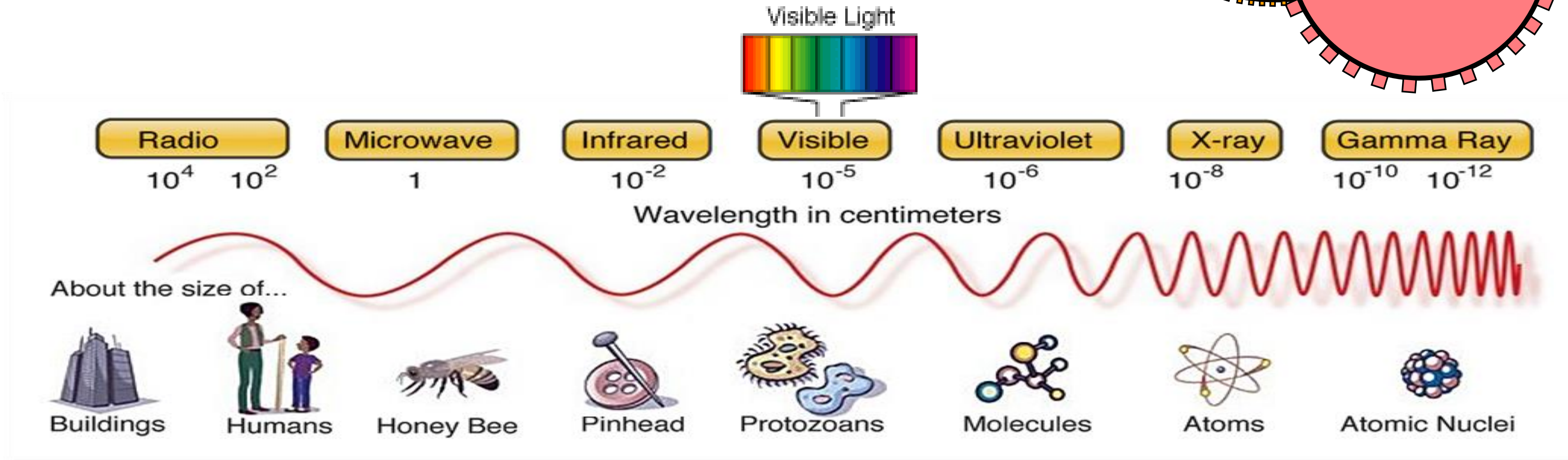
Control of light –

DIGITAL synthesis of electromagnetic spectrum

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

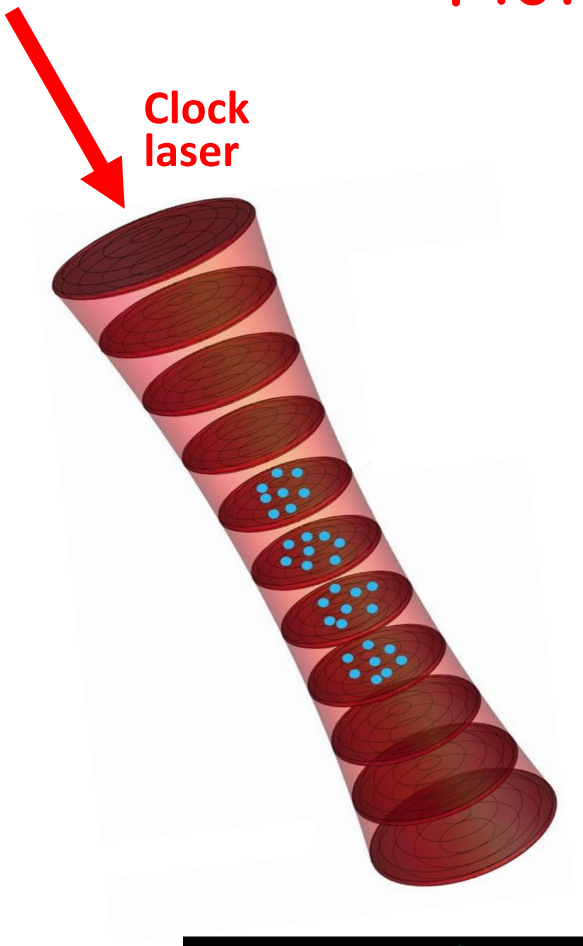
Nature **482**, 68 (2012).

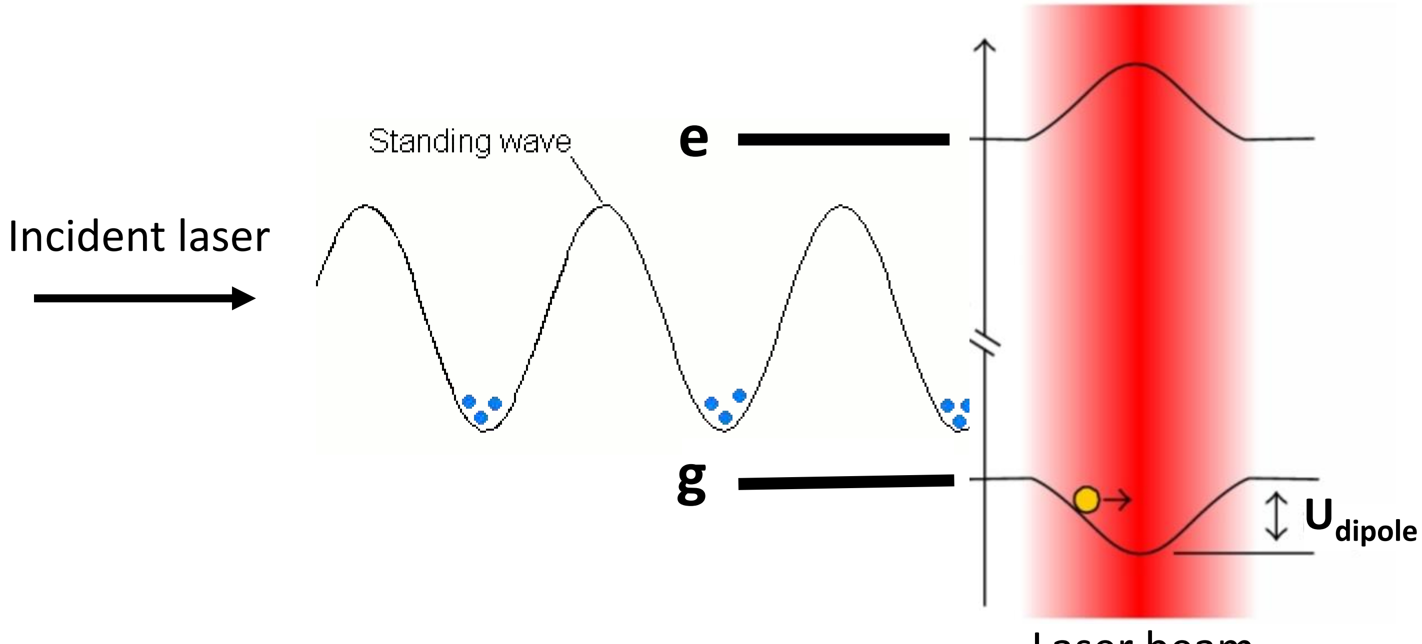


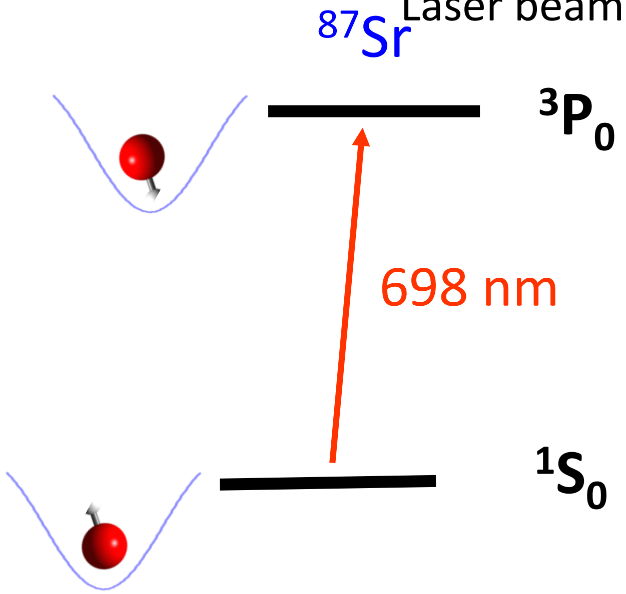


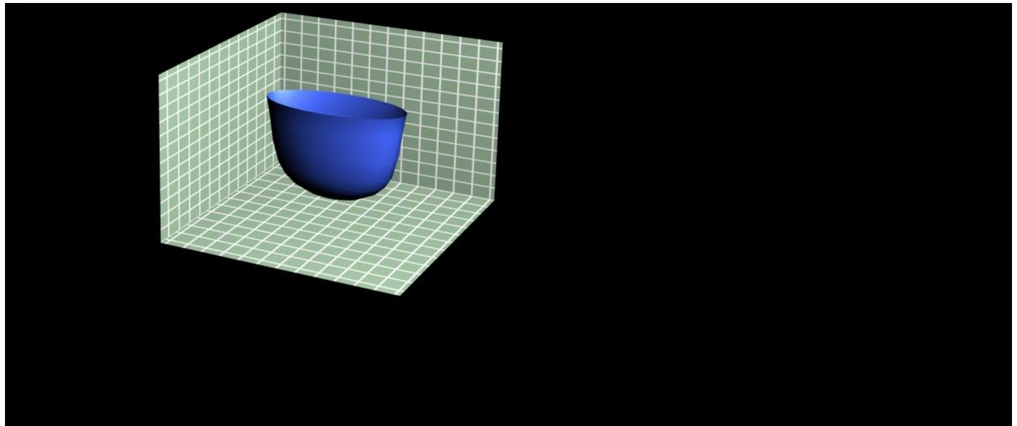
Holding atoms in a magic light bowl

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





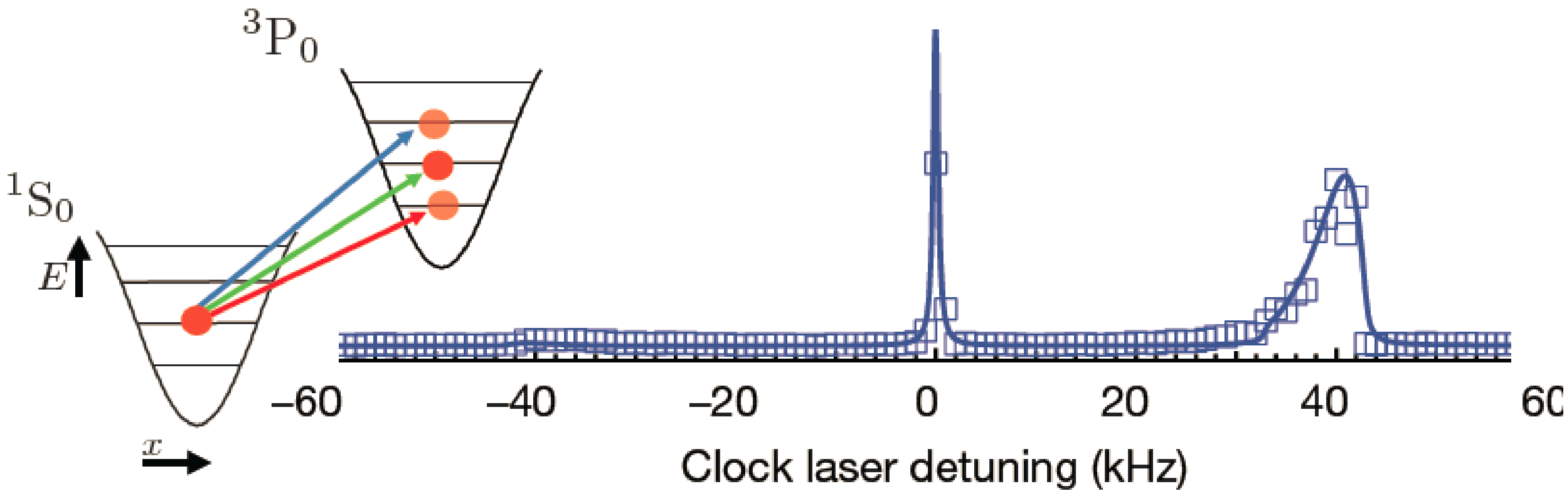


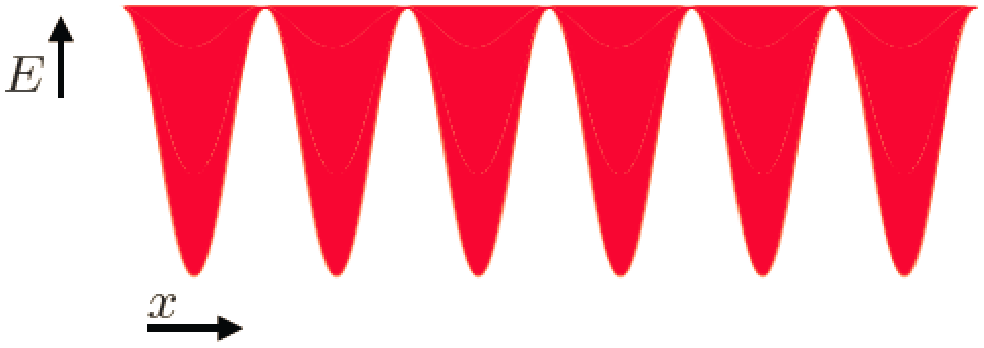


Quantizing the Doppler effect

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

$T < 5\ \mu K$

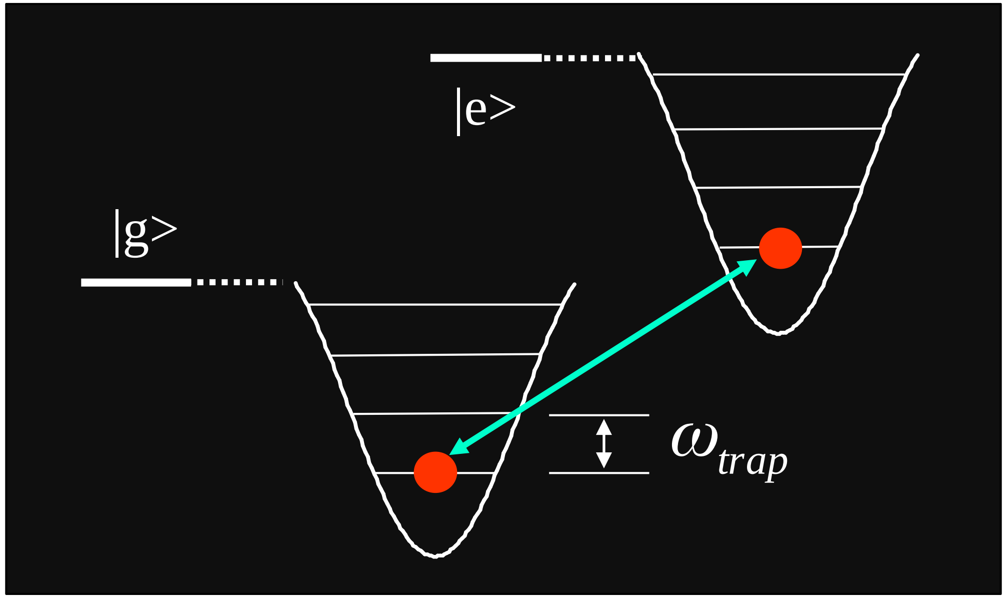


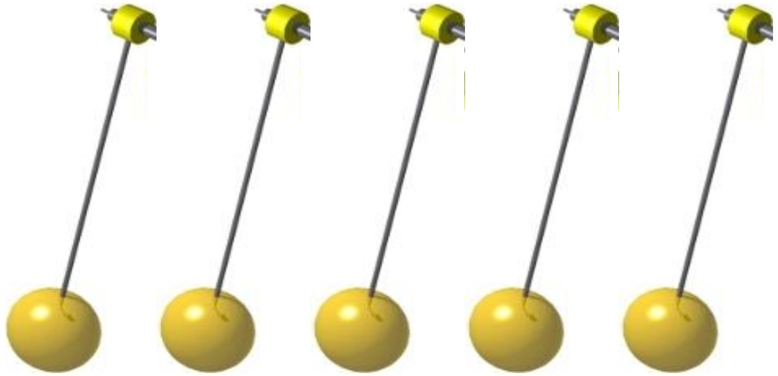


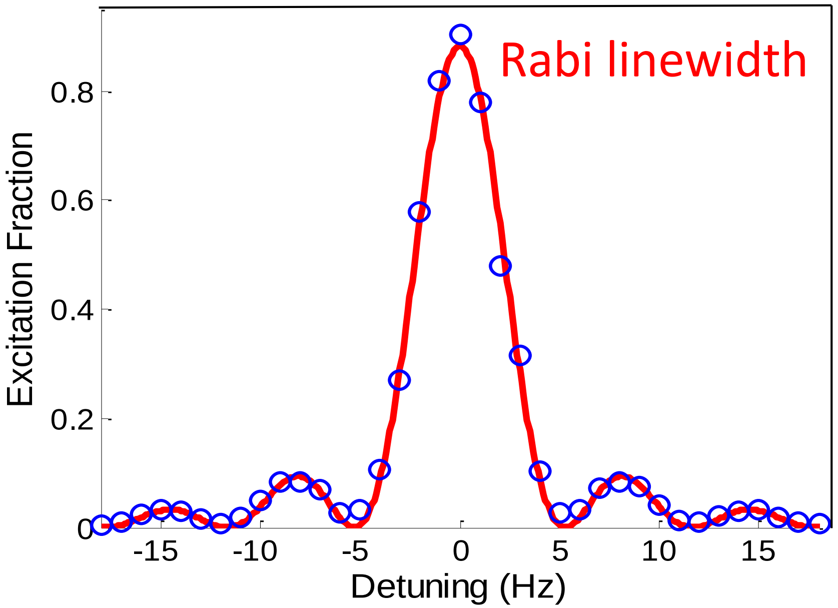
Quantum state control

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

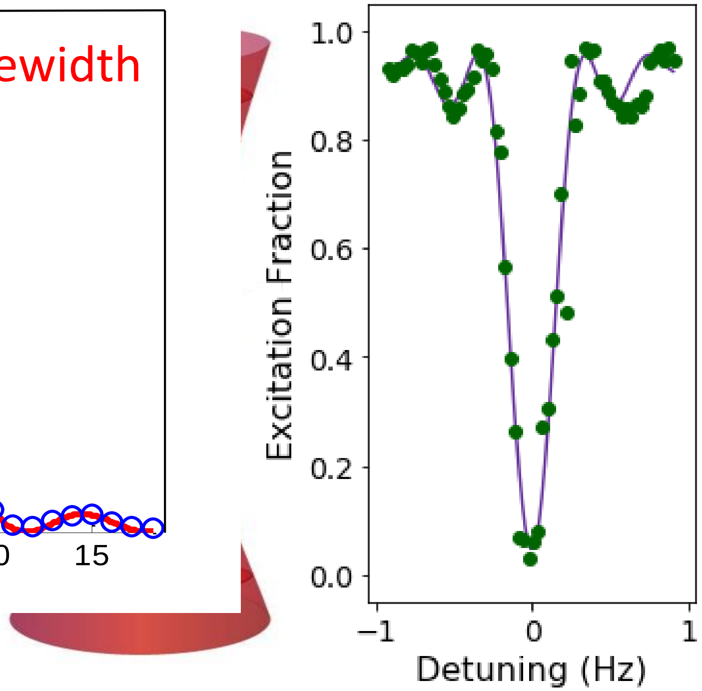
Haroche, Wineland







(2021)
0.3 Hz

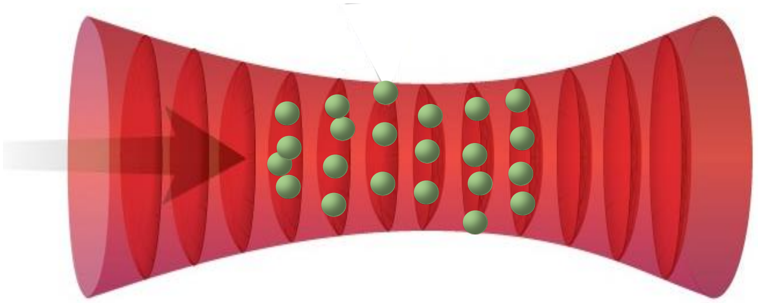


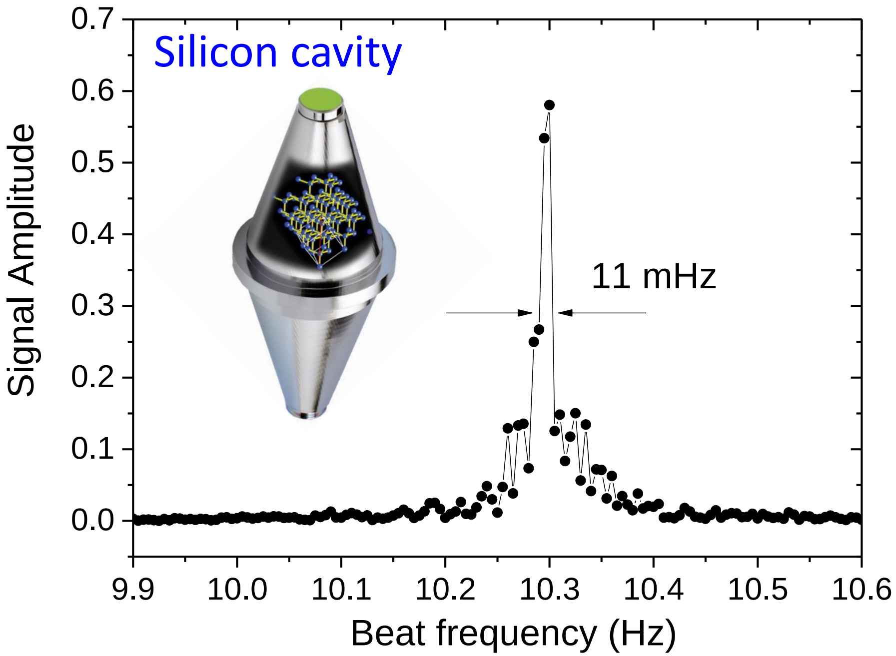
- Doppler, recoil, trap shifts ≈ 0
- Precision improvement by $N^{1/2}$

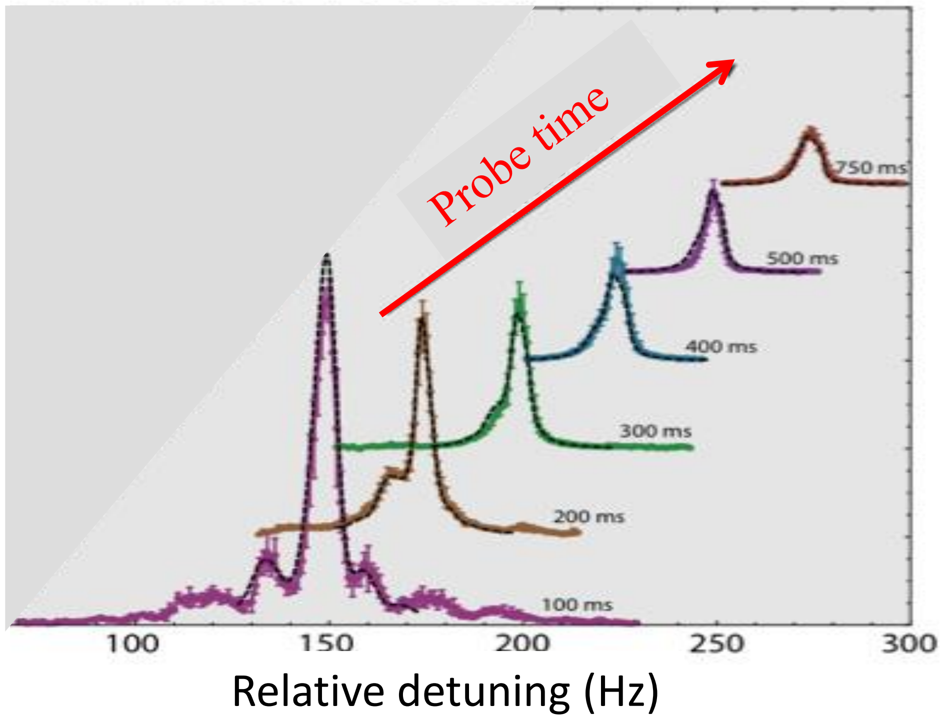
Precision metrology meets many-body physics

Martin *et al.*, Science **341**, 632 (2013).

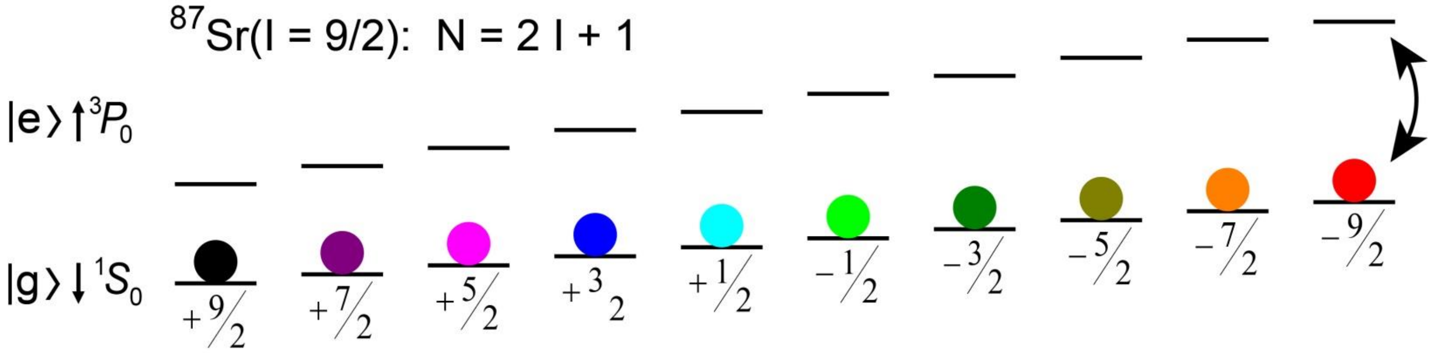
A new generation of stable lasers



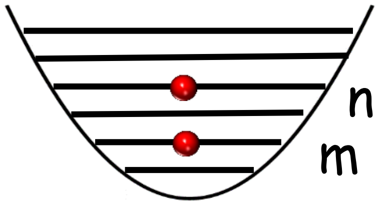




3 degrees of freedom: electronic, nuclear, spatial

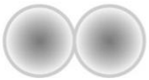


hyperfine coupling
$I \cdot J = 0.$



|n m>+|m n>

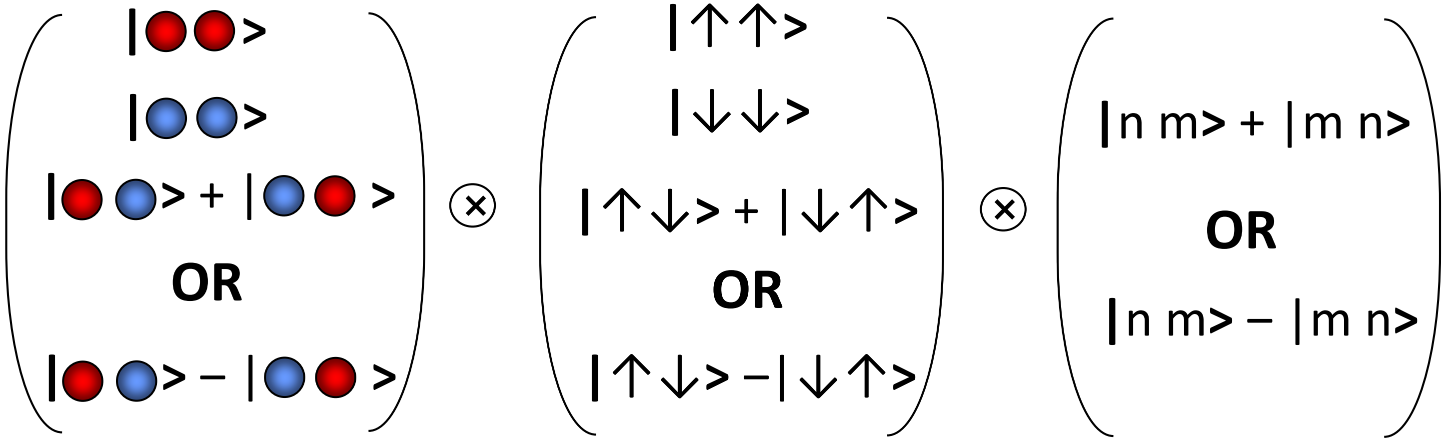
Spatially Symmetric



|n m>-|m n>

Spatially Anti-Symmetric

nuclear ⊗ electronic ⊗ motional



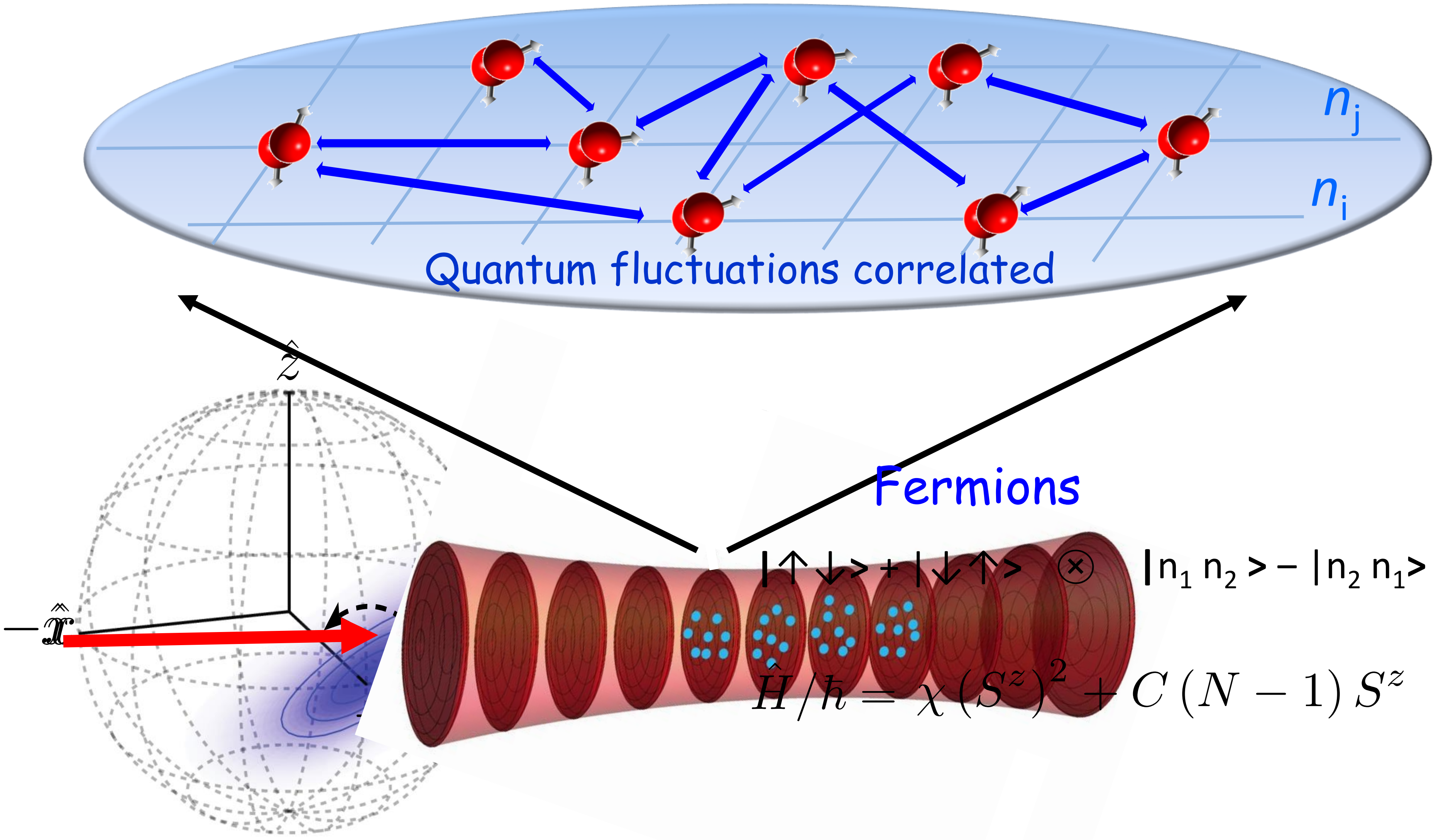
= “ – ”

Gorshkov *et al*., Nature Phys. **6**, 289 (2010).

Interacting fermions in 2D

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

A.M. Rey *et al.*, Annals Phys. **340**, 311 (2014).



3D Fermi insulator clock

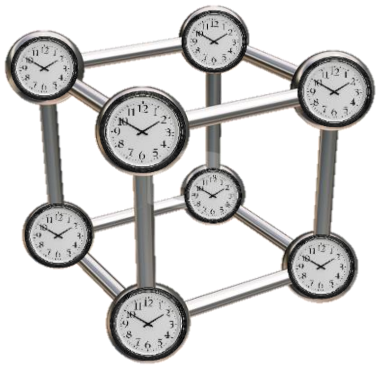
Scaling up the Sr quantum clock:

1 million atoms
(100 x 100 x 100 cells)

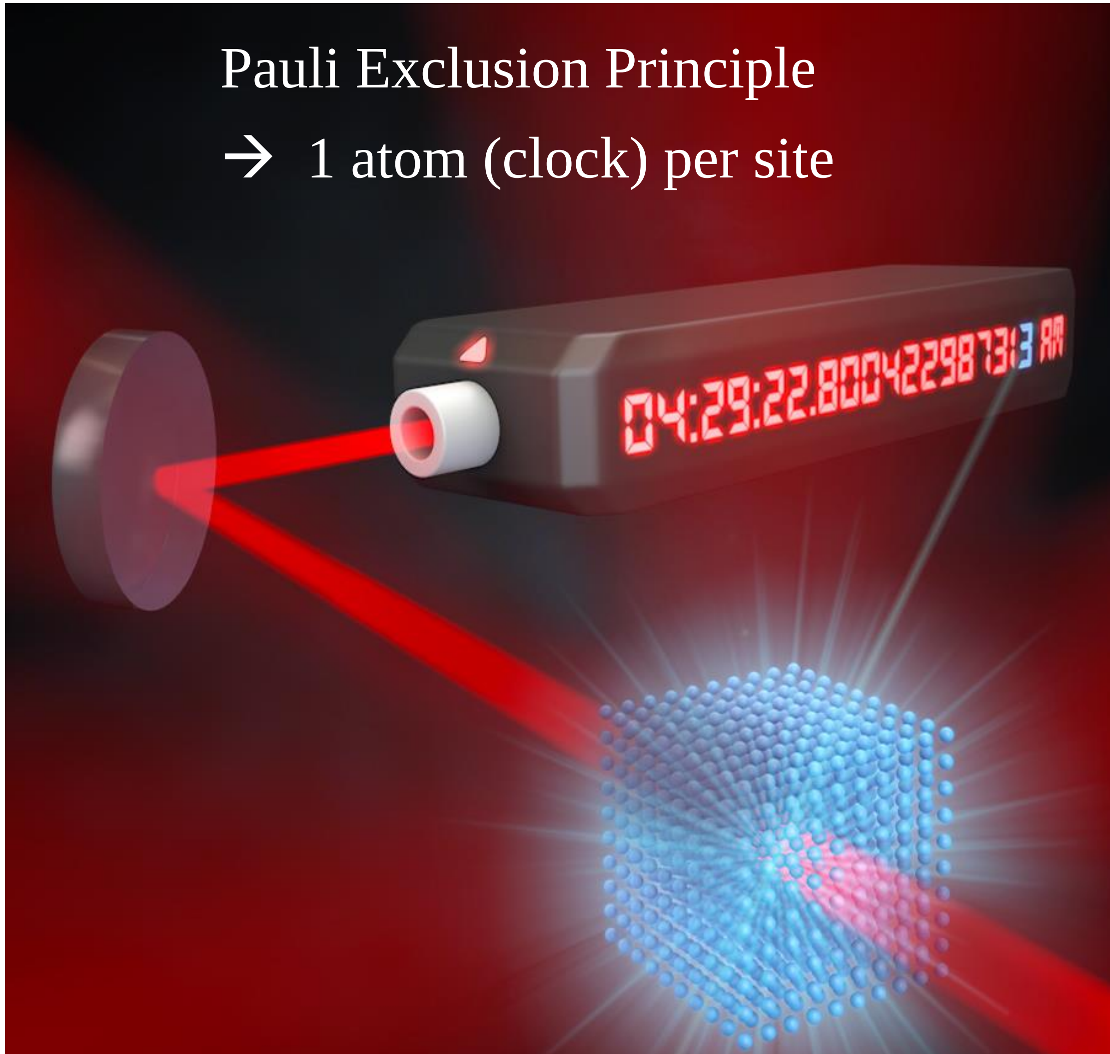
Coherence 160 s

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

Current record: 3 x 10^{-17} at 1 s

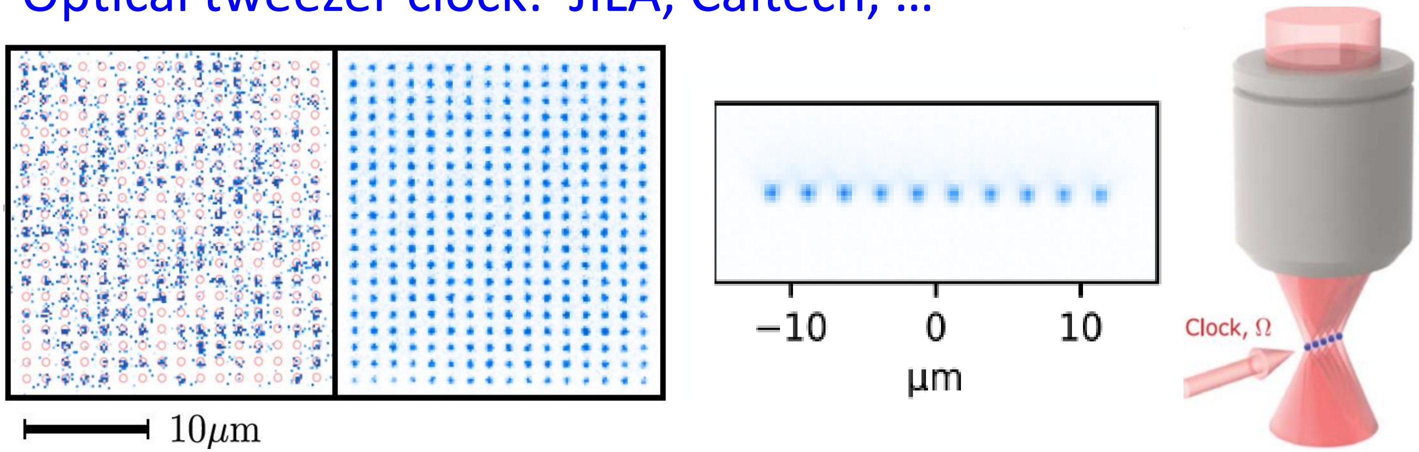


Quantum simulator & sensor (Fermi Hubbard model)



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

Optical tweezer clock: JILA, Caltech, …

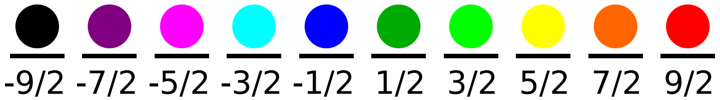


Young, …, Ye, Kaufman *et al.*, Nature **588**, 408 (2020).

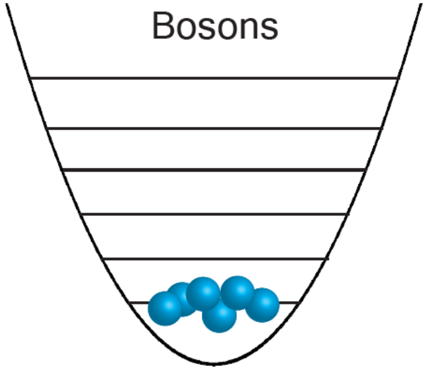
Fermions under SU(N)

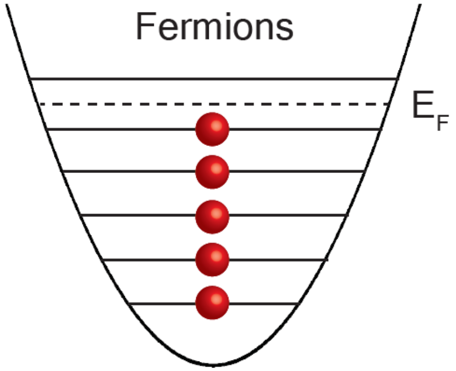
Sonderhouse *et al.*, Nature Phys. **16**, 1216 (2020).

$I \cdot J = 0$ → different spin states interact in the same way



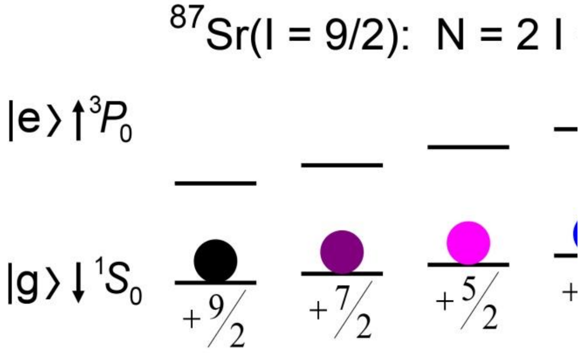
^{87}Sr, $^{1}S_0$, $I = 9/2$

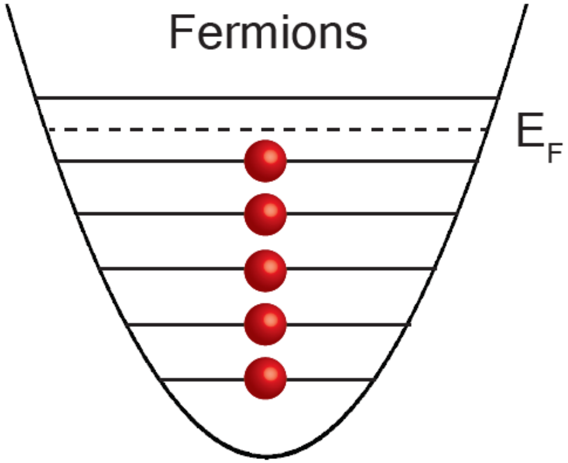


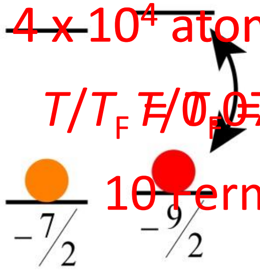


ly degenerate Fermi gas

s (optical "Stern-Gerlach







4 x 10^4 atoms per spin

$T/T_F = 0.07$

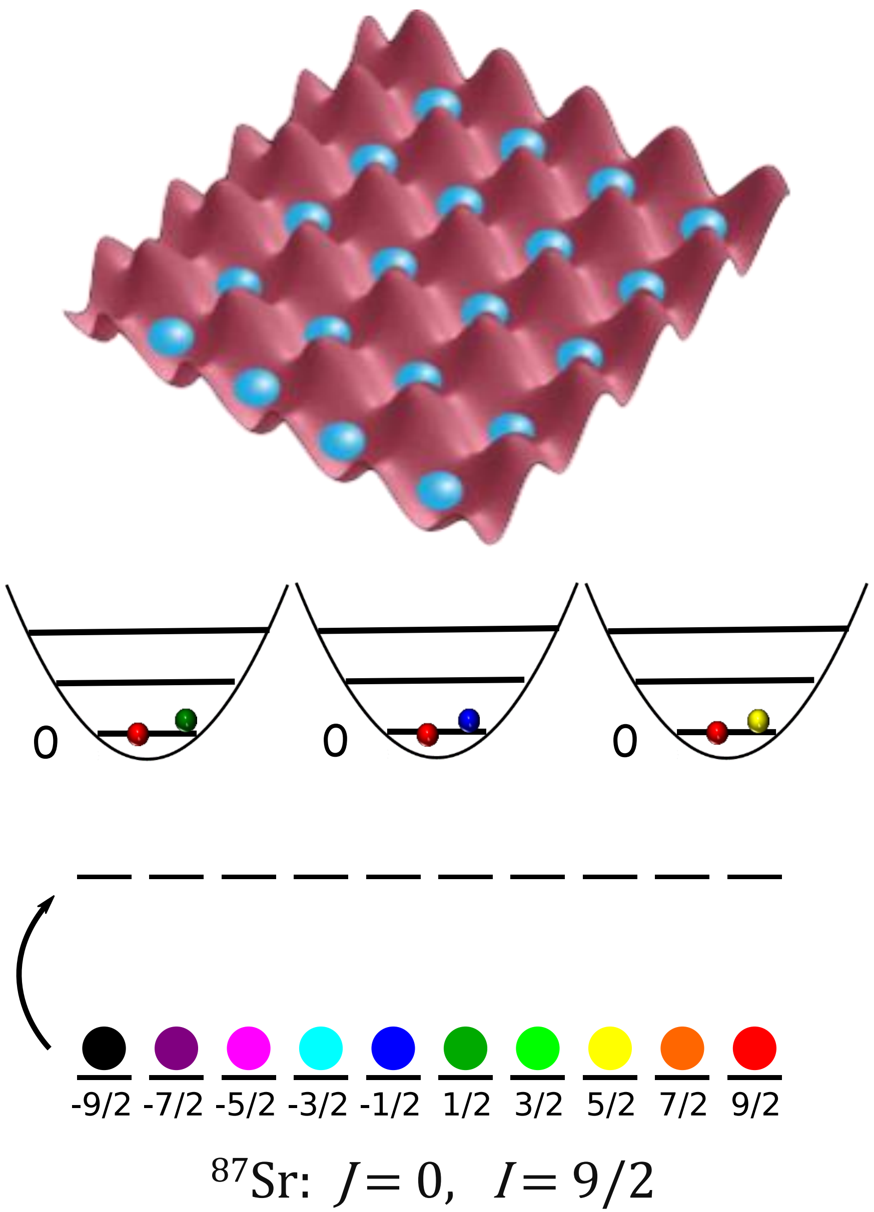
10 Fermi seas

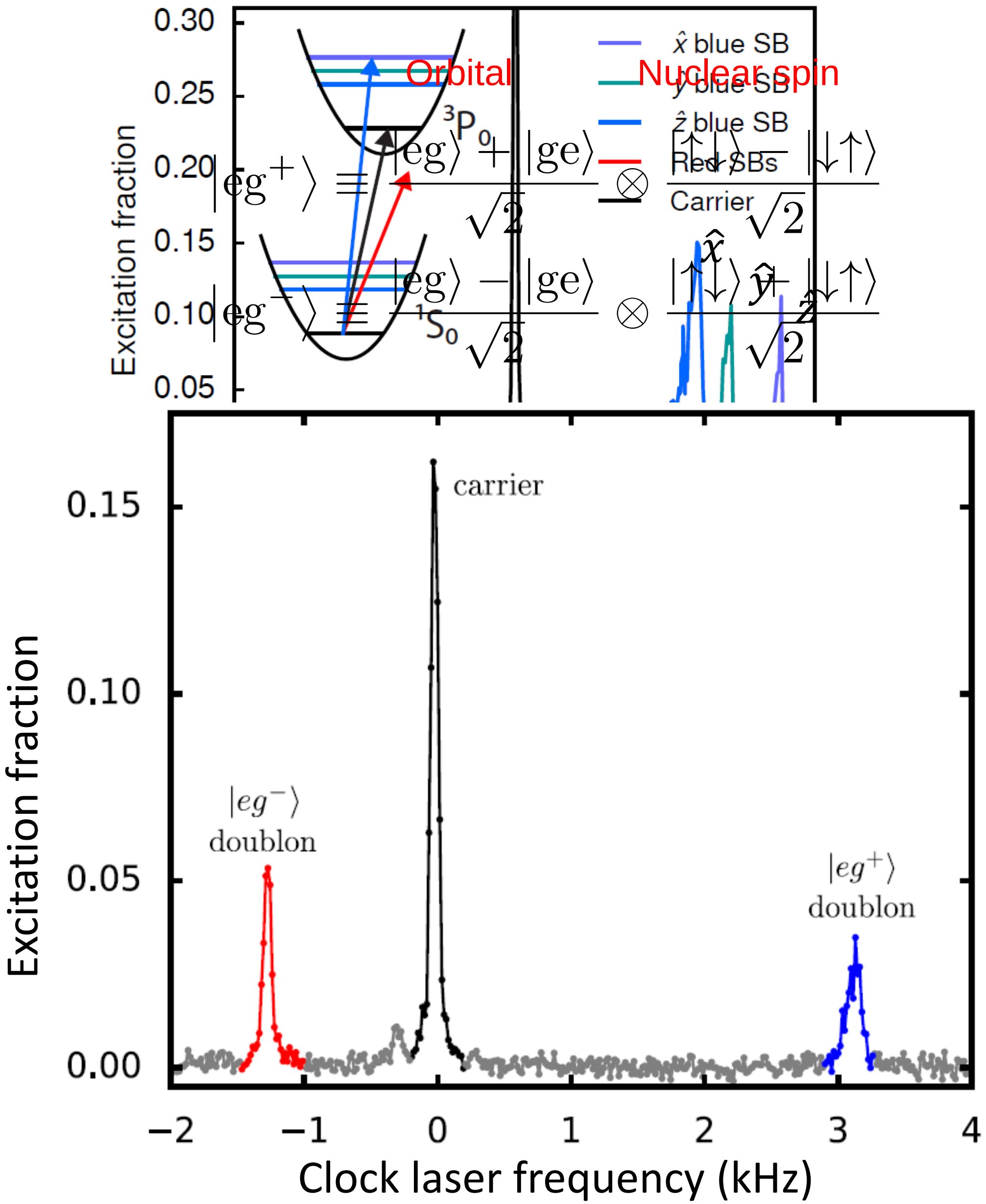
hyperfine coupling

$I \cdot J = 0$.

Quantized Interactions

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

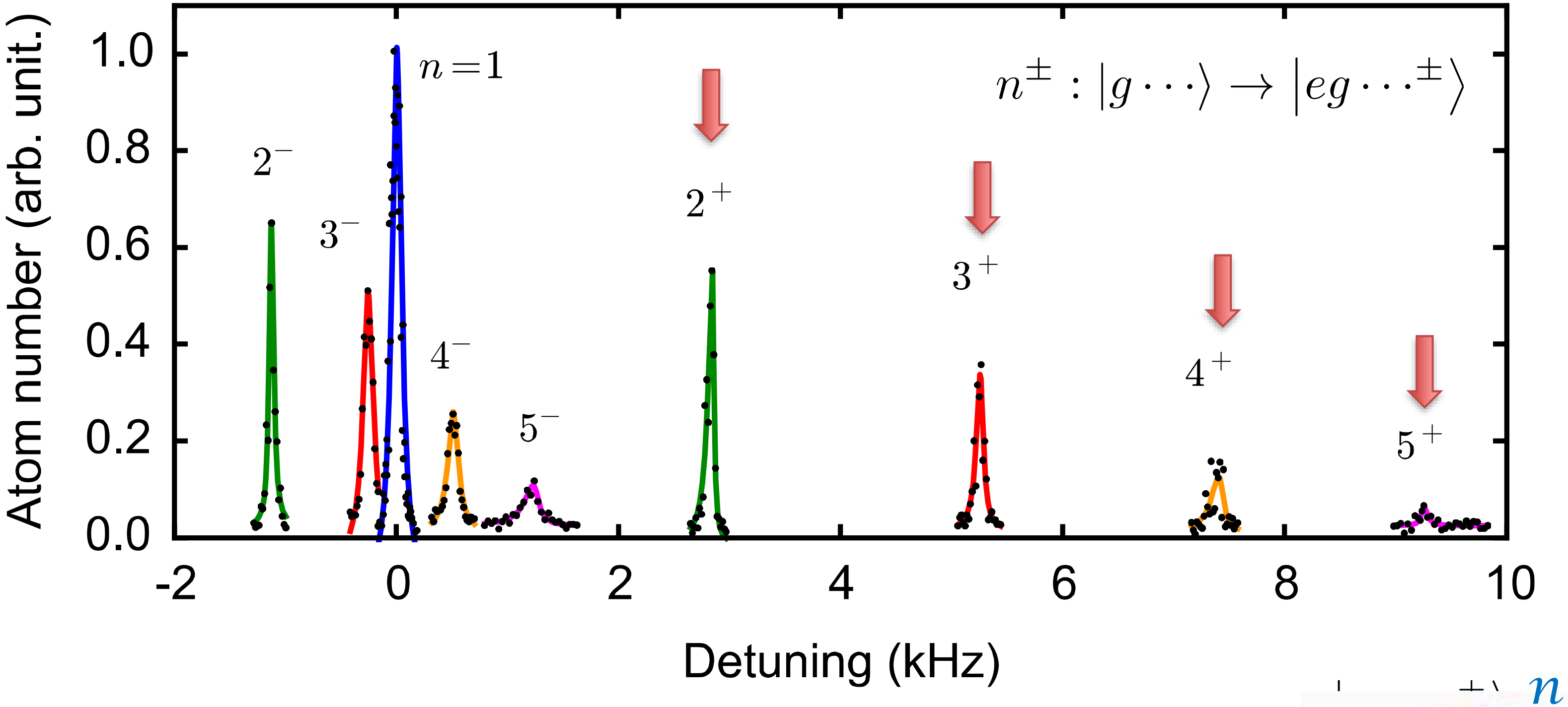


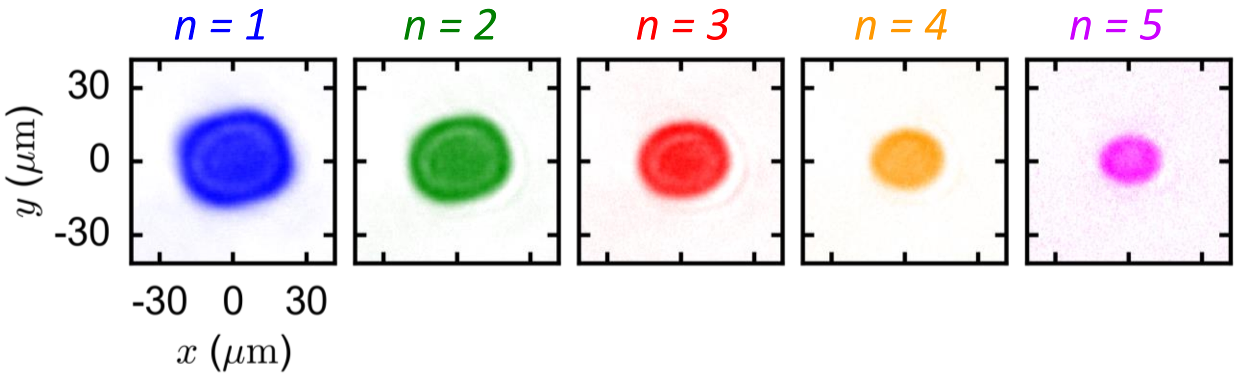


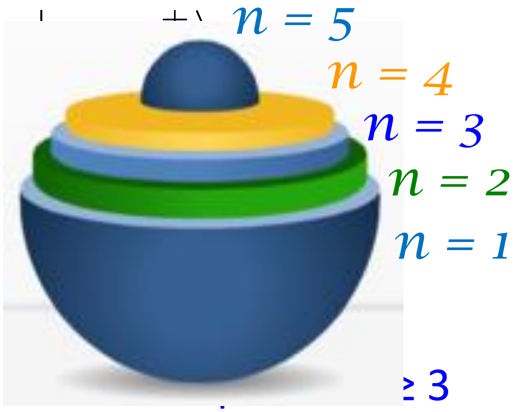
Imaging entangled atoms under SU(*N*)

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

With SU(*N*) symmetry ($I \cdot J = 0$), only two peaks for each *n*-occupied site



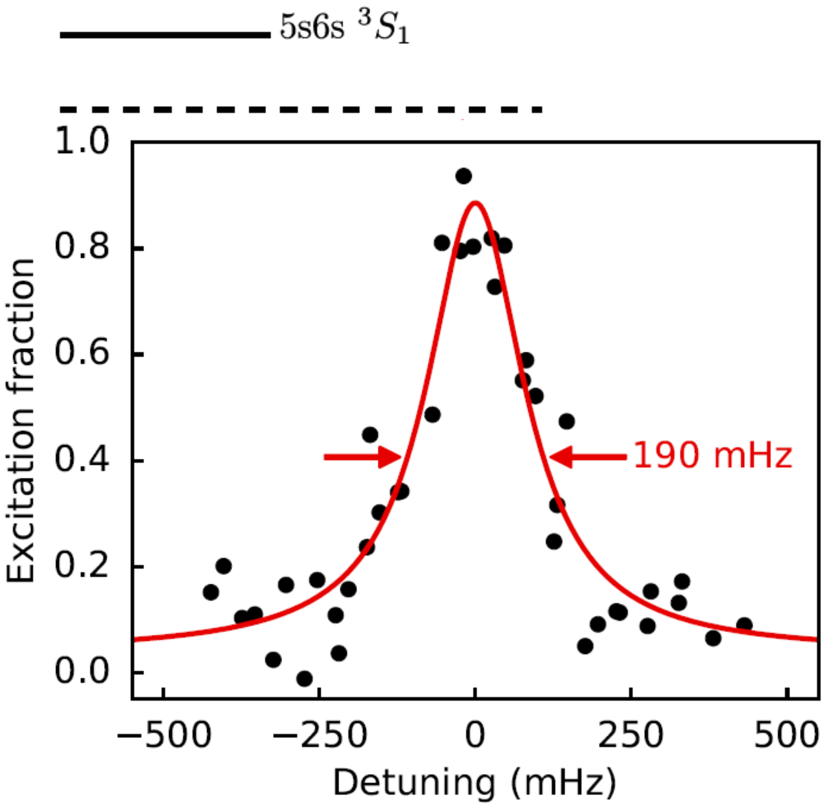


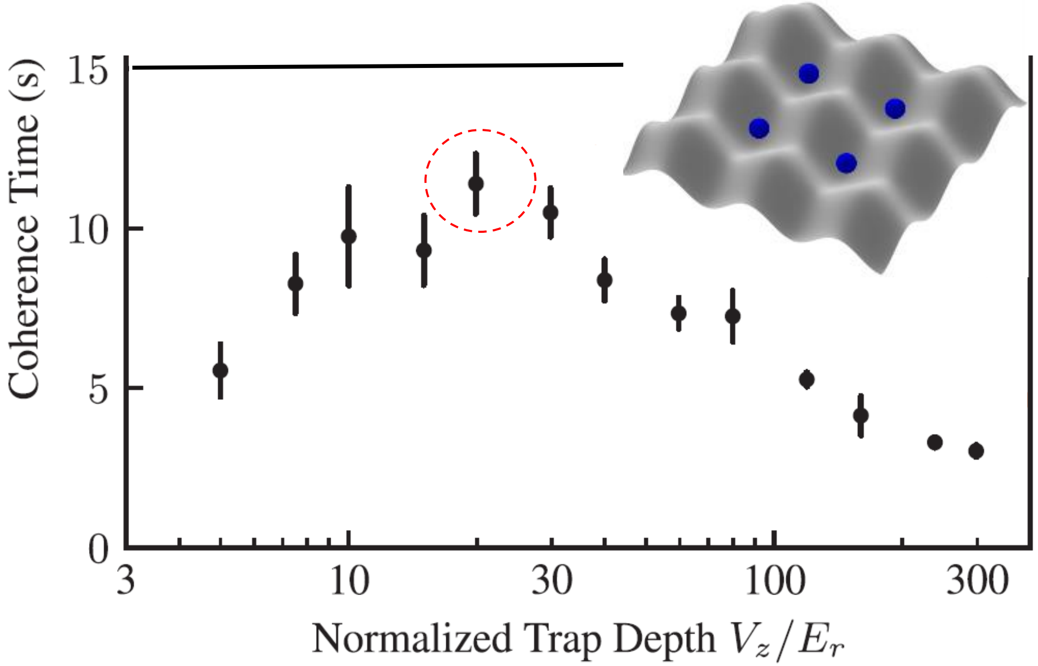


Chasing the best atom-light coherence

Coherence time of 12 s (Q = 1 x 10^{16})

Hutson *et al*., Phys. Rev. Lett. **123**, 123401 (2019).

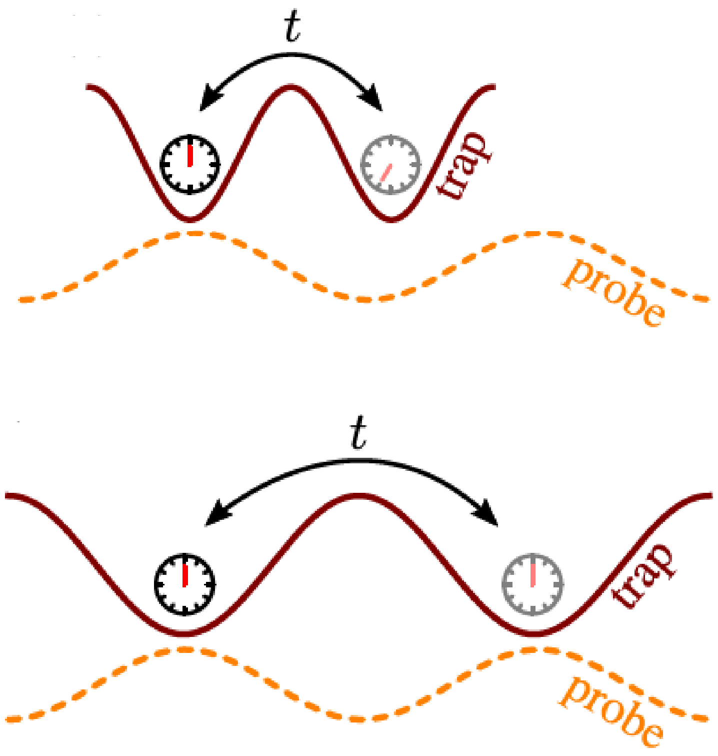


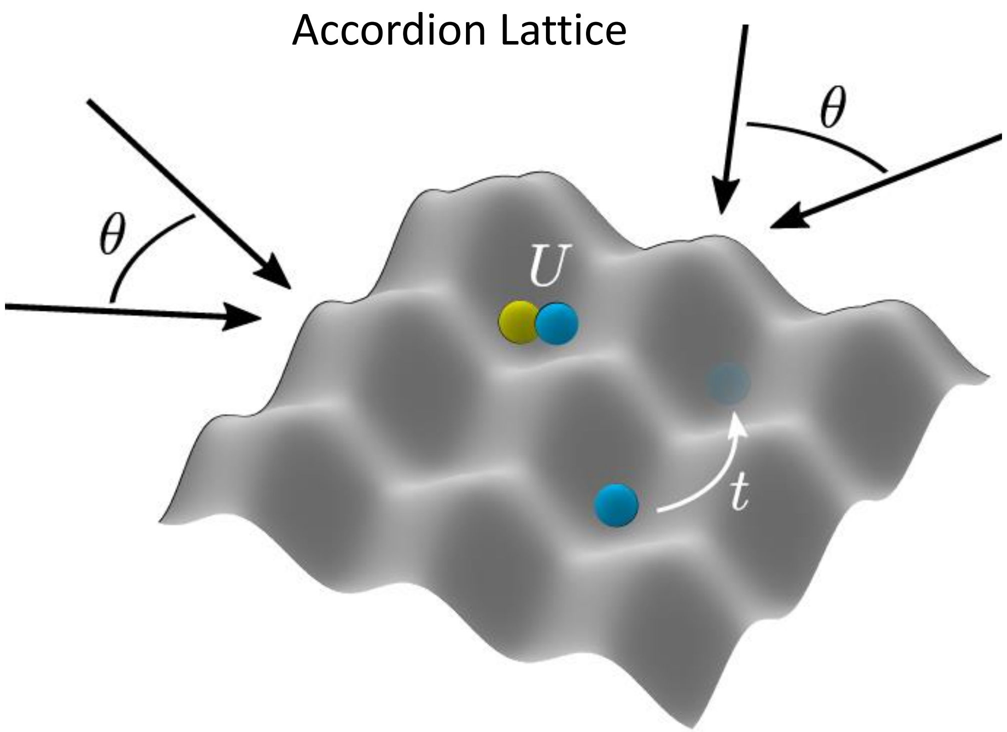


Use a shallow lattice
(tune the lattice constant)

A band/Mott insulator clock

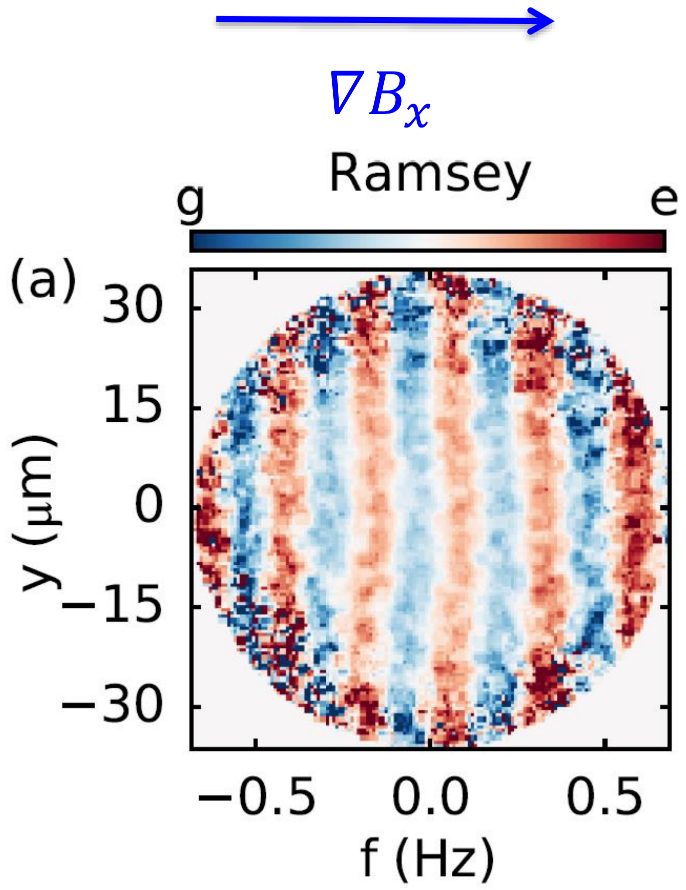
Kolkowitz *et al*., Nature **542**, 66 (2017); Hutson *et al*., Phys. Rev. Lett. **123**, 123401 (2019).

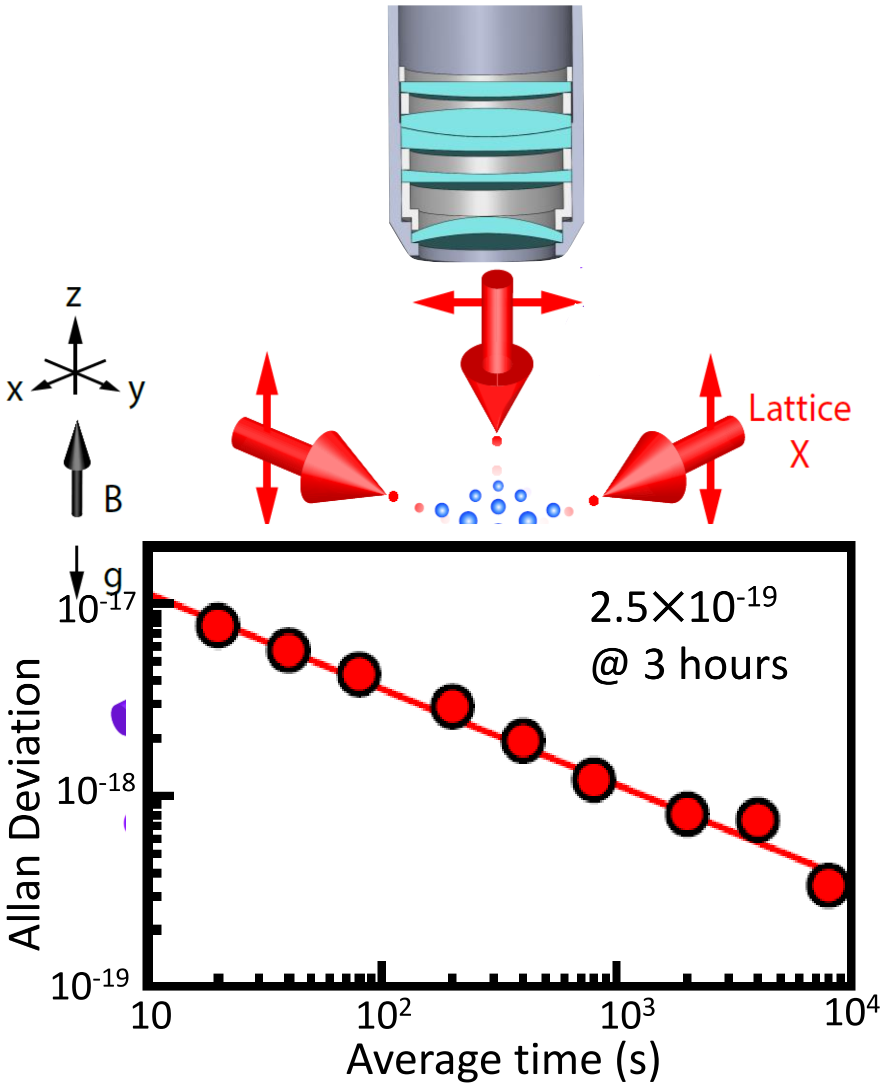




Imaging field gradients via optical phase

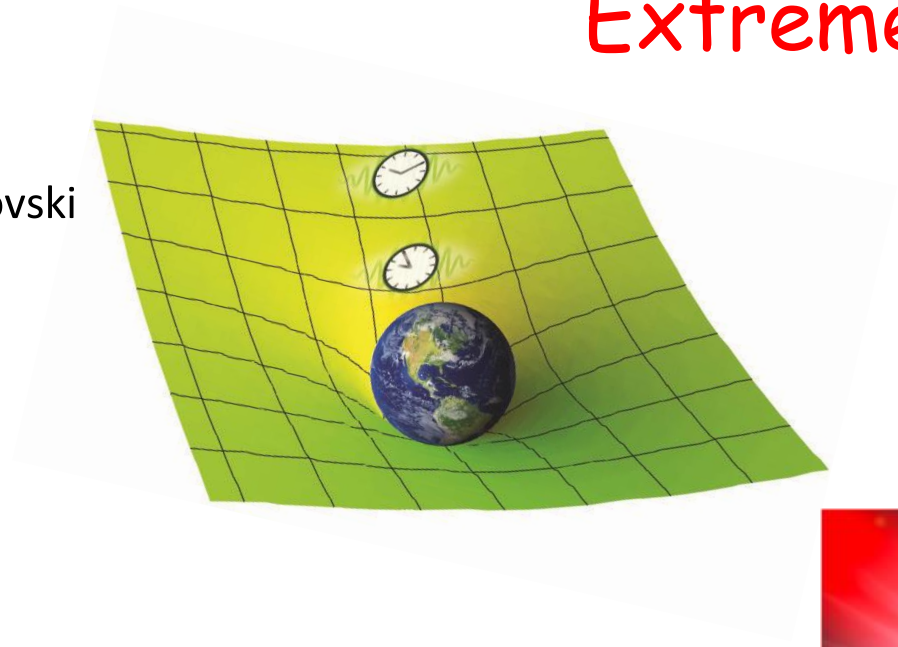
Marti *et al.*, Phys Rev Lett **120**, 103201 (2018).





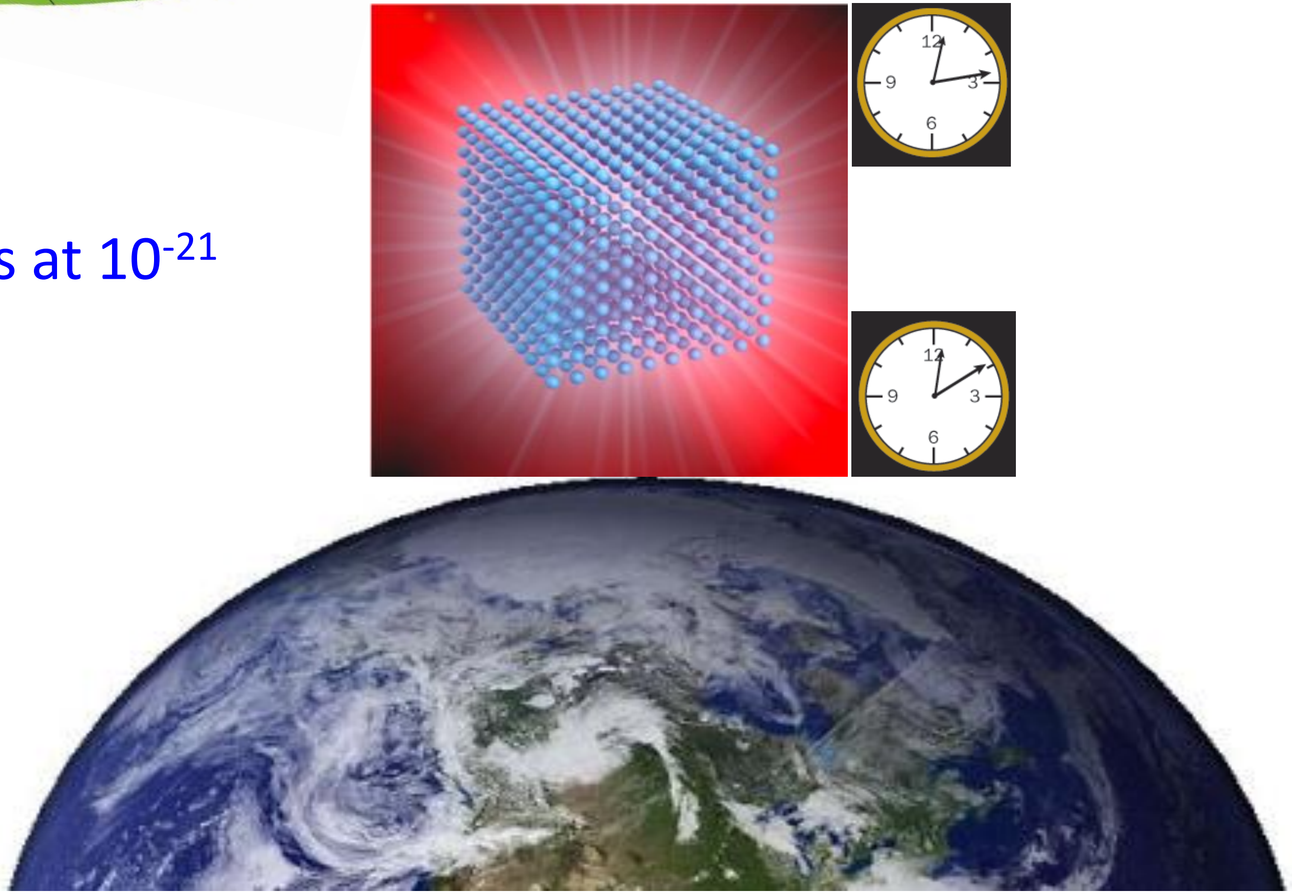
Extreme Space-Time Resolution

Igor Pikovski



Many-body states & entanglement under curved space time

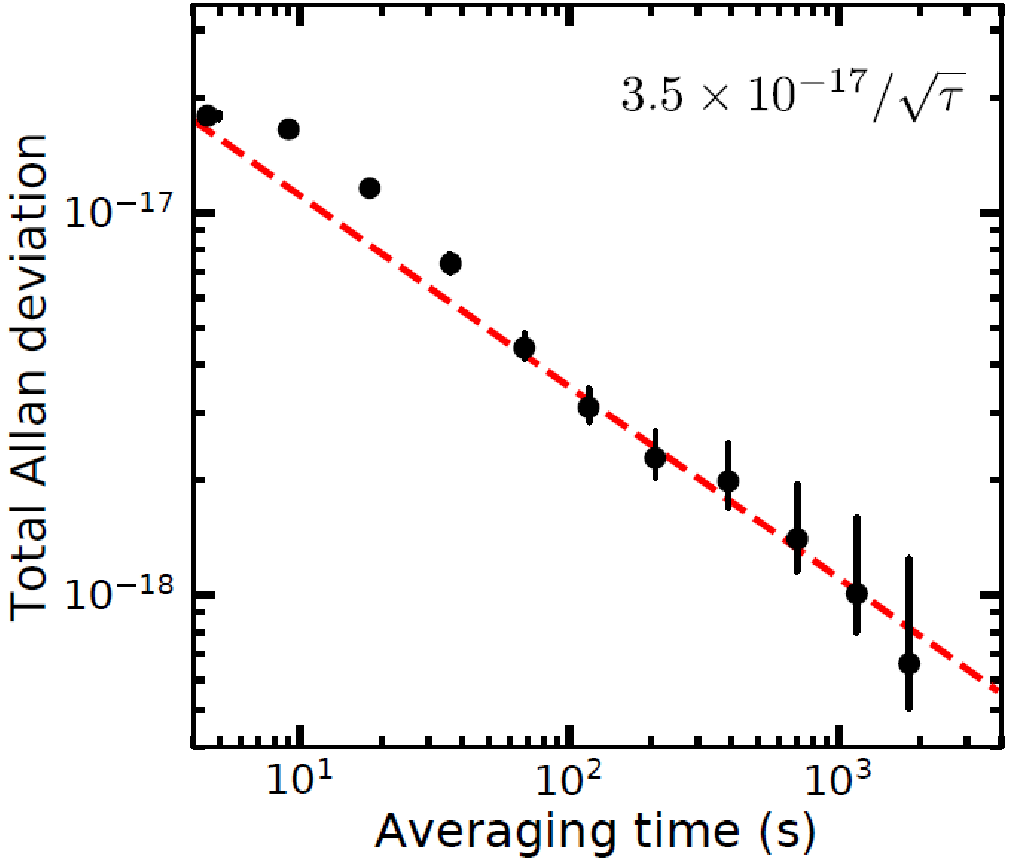
Need clocks at 10^{-21}

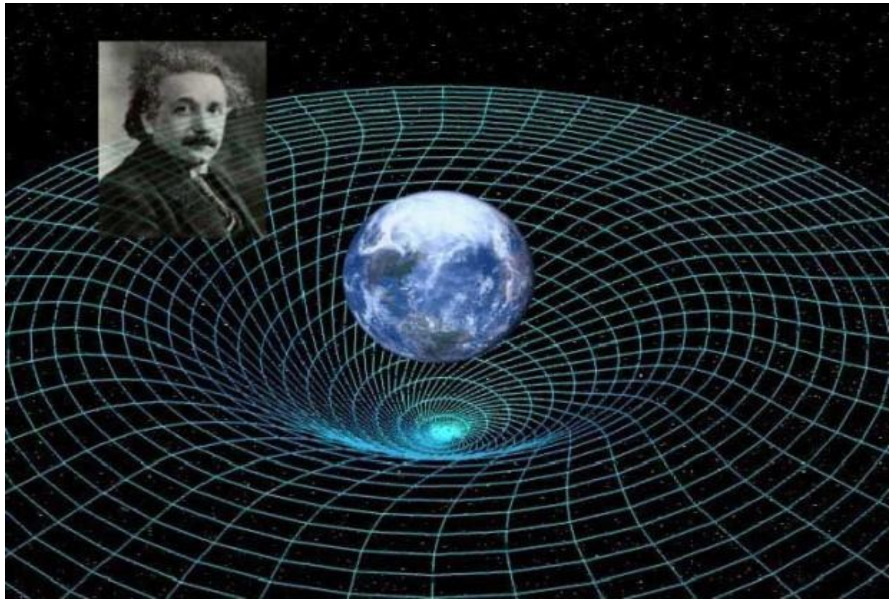


Record stability for optical clocks

Oelker *et al.*, Nature Photon. **13**, 714 (2019).

6 x 10^{-19} in one hour



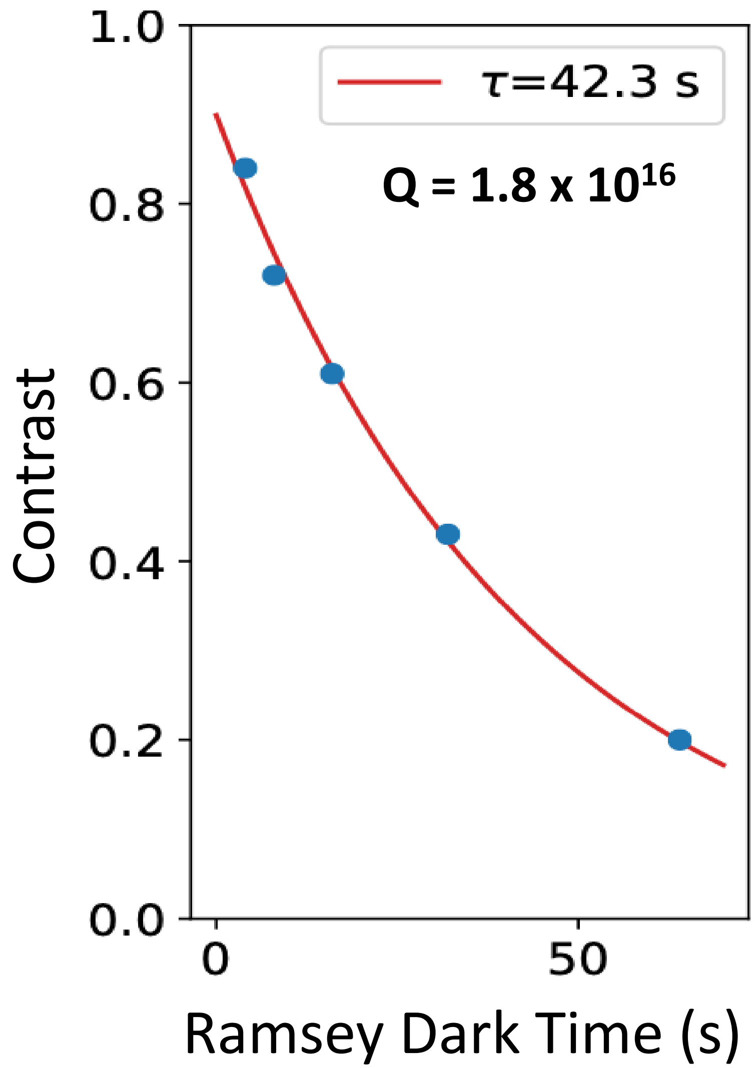


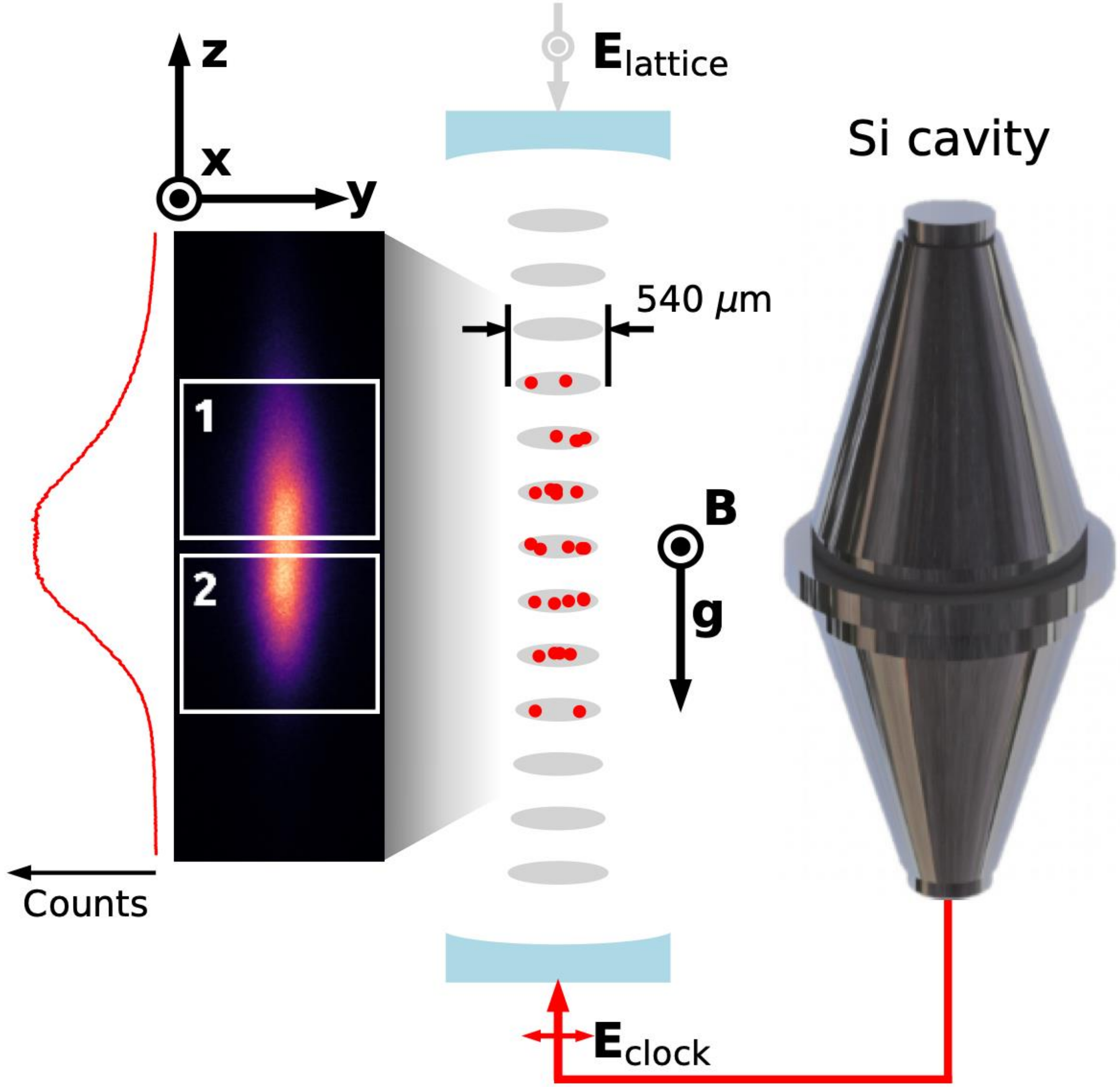
Gravitational potential difference of 1 cm in 20 minutes

Local Position Invariance
Relativistic Geodesy

"New" JILA Sr-1 system: really large "pancakes"

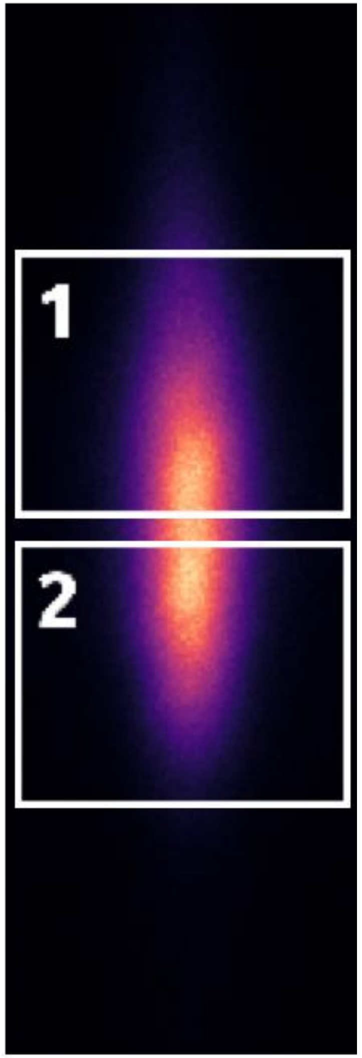
Tobias Bothwell *et al.*, in preparation (2021).

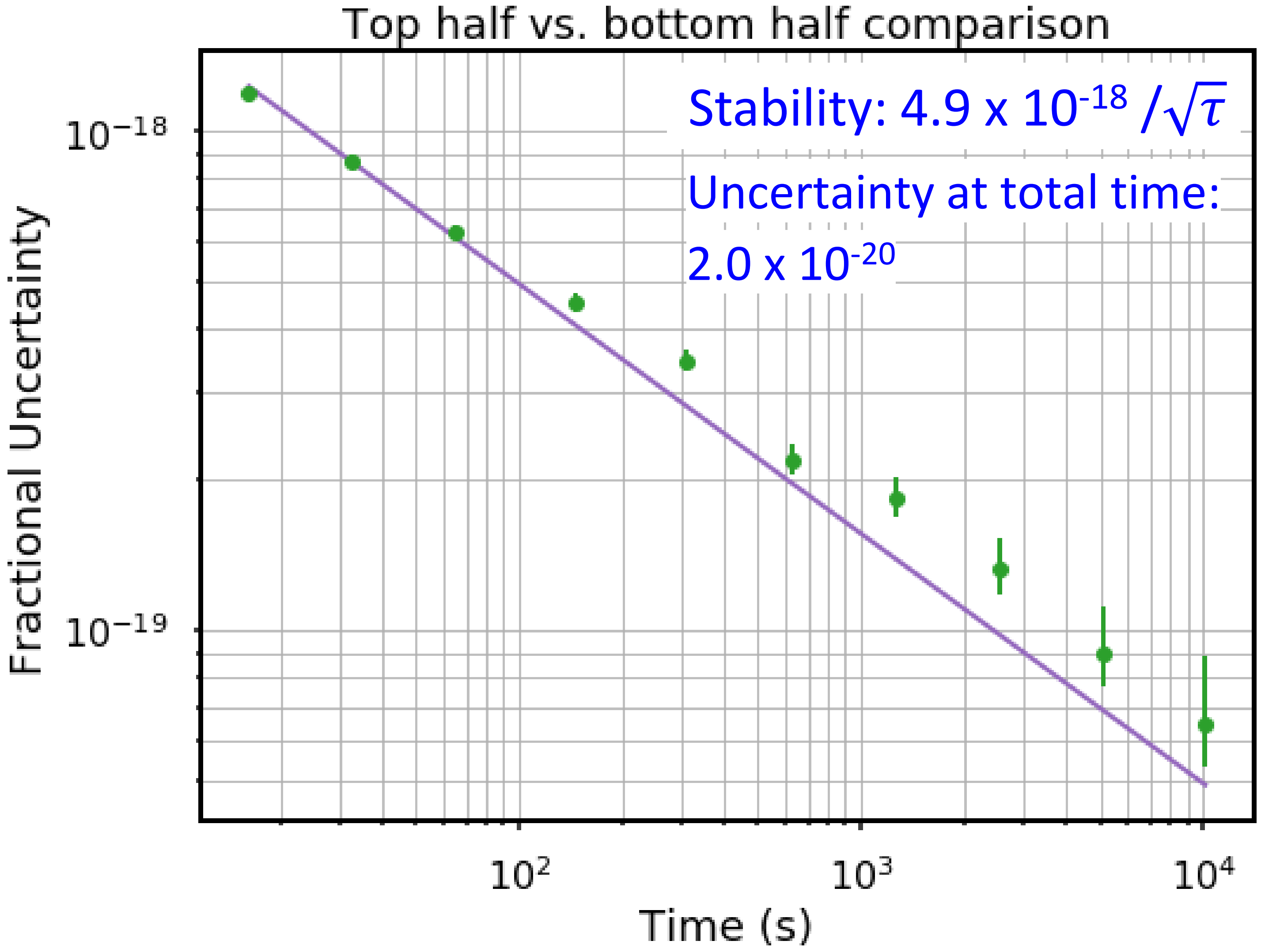




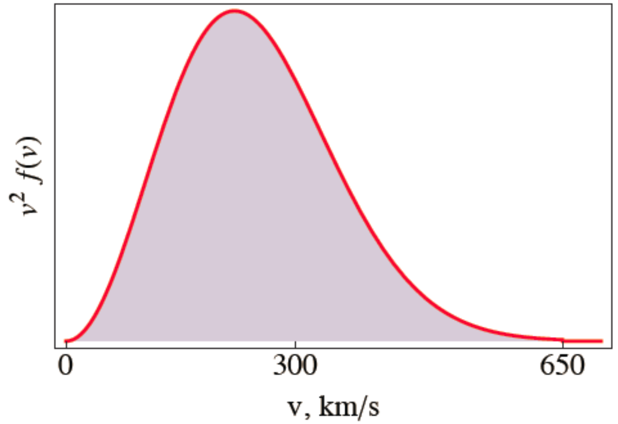
Intrinsic clock precision enters the 20th digit

Synchronous comparison, single clock precision: $2.5 \times 10^{-18} / \sqrt{\tau}$





The Dark Matter puzzle: particle vs field



Galactic orbital motion
v_G ~ 300 km/s

Energy density
$\rho_{DM} \sim 0.3\ \mathrm{GeV/cm^3}$

$$\frac{\mathrm{Number_{DM}}}{\mathrm{mode}} \sim \left(\frac{\rho_{\mathrm{DM}}}{m_{\mathrm{DM}}c^2}\right) \times \left(\lambda_{\text{de Broglie}}\right)^3$$

"Classical fields" | "Particles"

10^{-20} | 10^{-10} | 10^{0} | 10^{+10} | 10^{+20} | m_{DM}, eV

Ultralight DM

WIMPs

Coherent on detector scale

Particle-like energy deposition

DM field oscillates at Compton frequency: $\omega_{DM} = \frac{m_{\mathrm{DM}}c^2}{\hbar}$ ~ 30 kHz * [$m_{\mathrm{DM}}/10^{-10}$ eV]

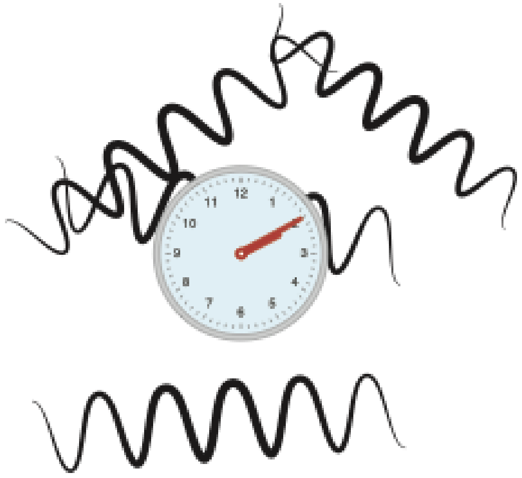
DM field virialized $\Rightarrow$ coherence $Q = \omega_{\mathrm{DM}} / \Delta\omega_{\mathrm{DM}} \approx \frac{c^2}{\Delta v^2} \approx 10^6$

Ultralight scalar DM field & fundamental constant α

- Dilaton (spin 0, even parity) – A scalar field to modify fundamental constants: Example, fine structure constant α
- Ratio of frequencies from different clocks → sensitive to variations of fundamental constants

A relativistic effect $$\frac{\Delta\omega}{\omega} = K\frac{\Delta\alpha}{\alpha}$$

Clock transition	Enhancement factor K
Sr	0.06
Yb	0.37
Hg	0.8
Yb^+ (E2)	1.0
Yb^+ (E3)	-6.0
Al^+	0.008
Hg^+	-2.9
Eu^{14+}	218



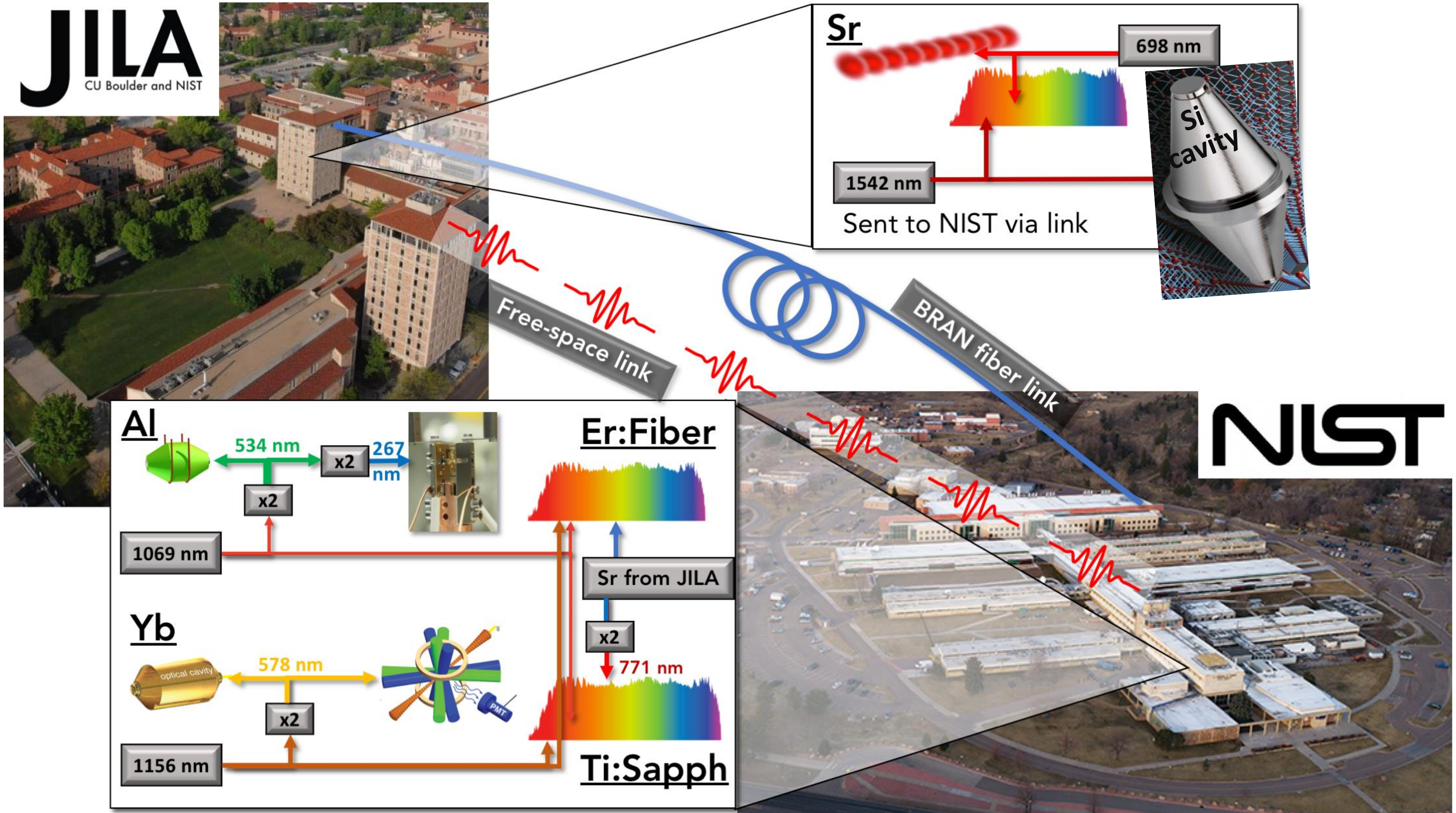
Oscillating variations of α

Safronova *et al.*, RMP **90**, 025008 (2018)
Arvanitaki *et al.*, PR D **91**, 015015 (2015)
Van Tilburg *et al.*, PRL **115**, 011802 (2015)

Boulder Area Optical Clock Network

Beloy *et al.*, Nature **591**, 564 (2021).

Three ratios consistent at ~ 7 x 10^{-18}



Sr optical clock: many-body meets precision

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