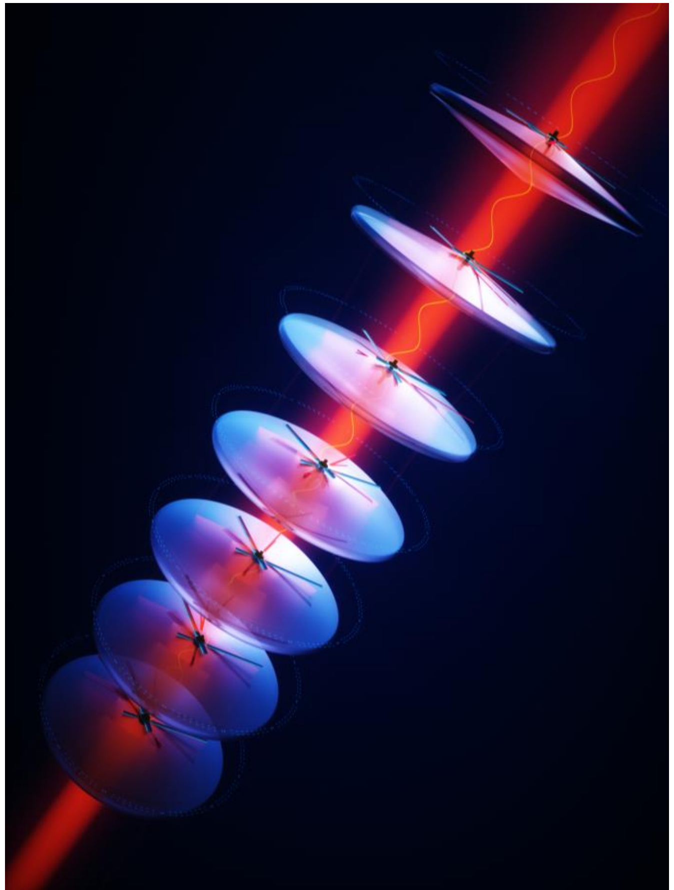
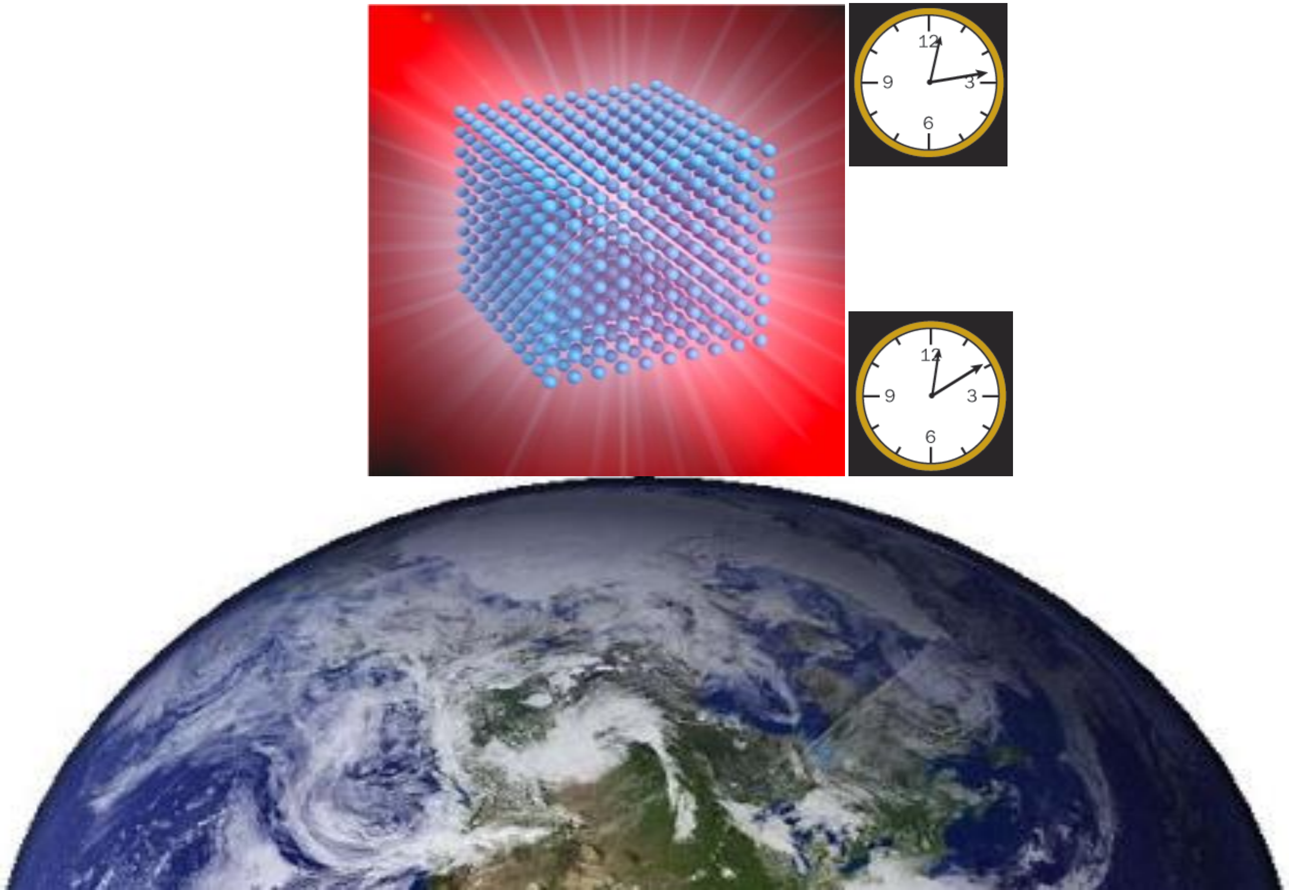
Quantum matter and clocks
from emergent phenomena to fundamental physics

Jun Ye

JILA, NIST & Univ. Colorado

CERN Colloquium, July 27, 2023

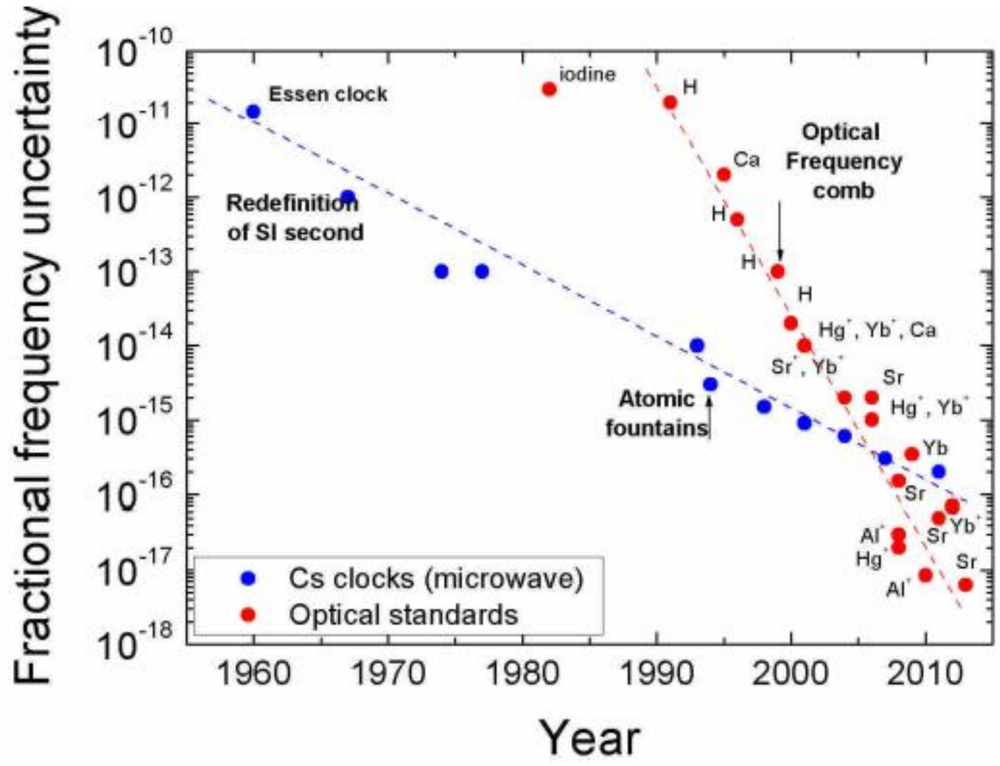




Quantum metrology

Precision frontier meets Quantum frontier

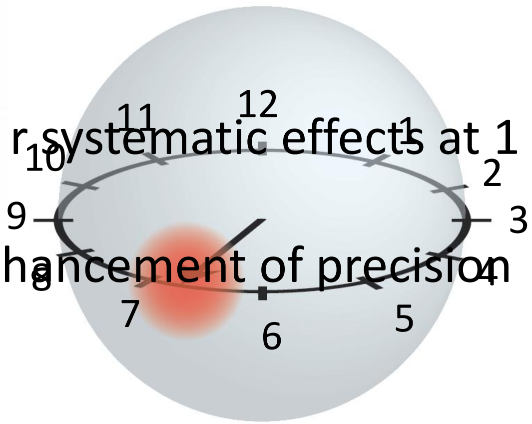
Poli *et al.*, *Nuovo Cimento*, **36** 555 (2013)
Ludlow *et al.*, RMP **87**, 637 (2015).



?

- Quantum control: *High Q optical transitions*
- Laser technology: *Optical coherence ~ 1 minute*
- Frequency comb: *Synthesis of EM fields*
- Quantum gas: *Many-body states*

Large count rate

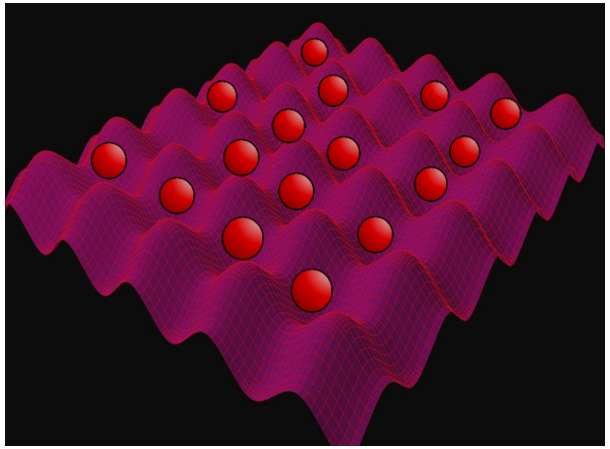


r systematic effects at 1 x 10^{-19}

n for enhancement of precision

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

Many-body states

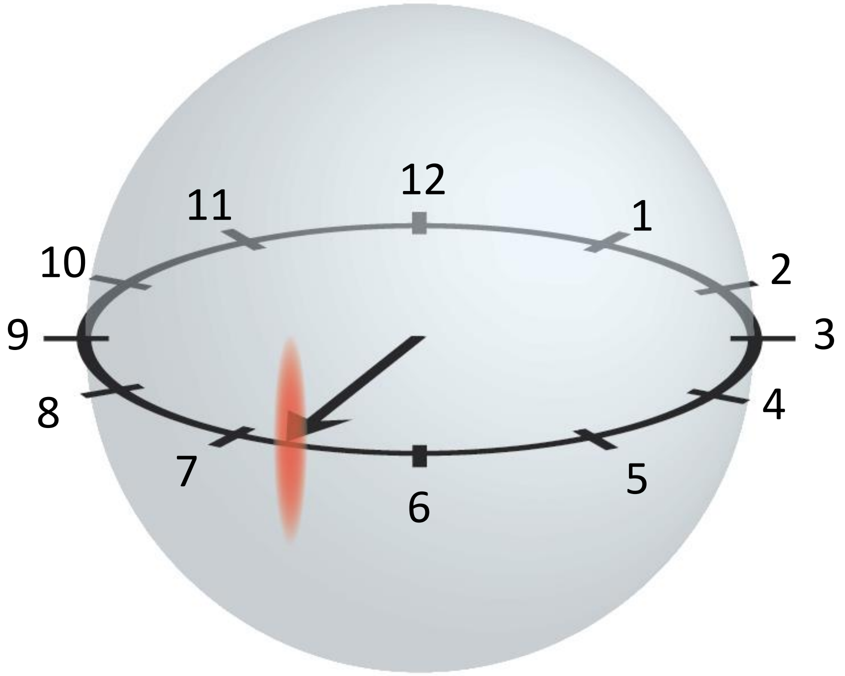


Quantum optimization & enhancement

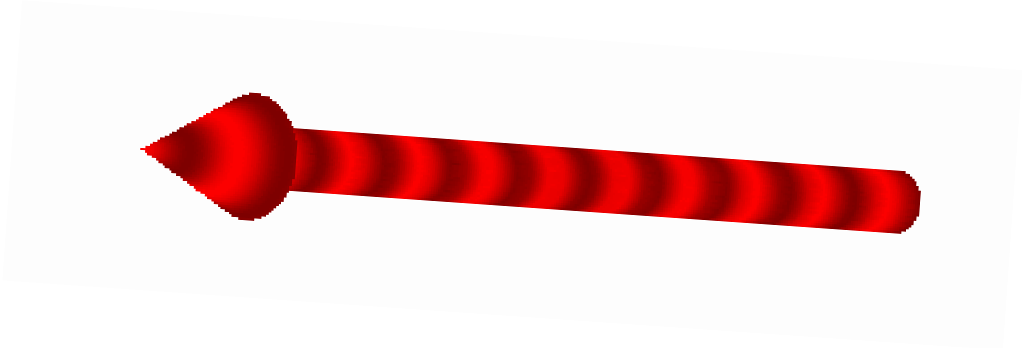
Quantum noise

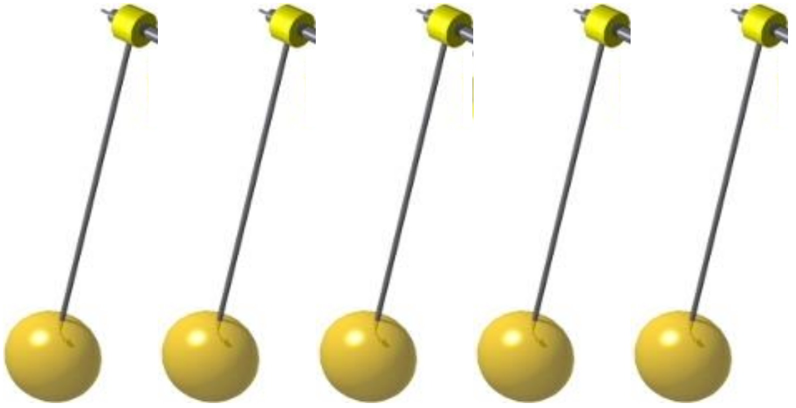
Quantum Phase Noise of Atoms

Phase of Coherent Laser



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



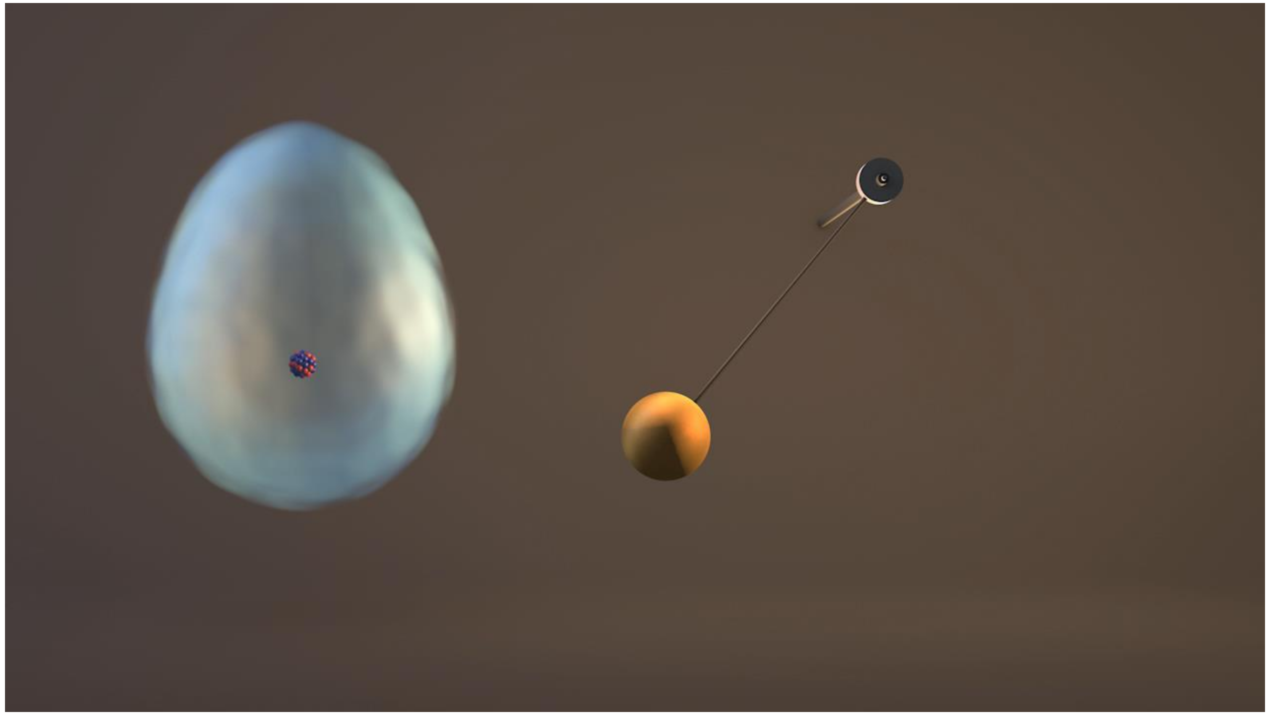


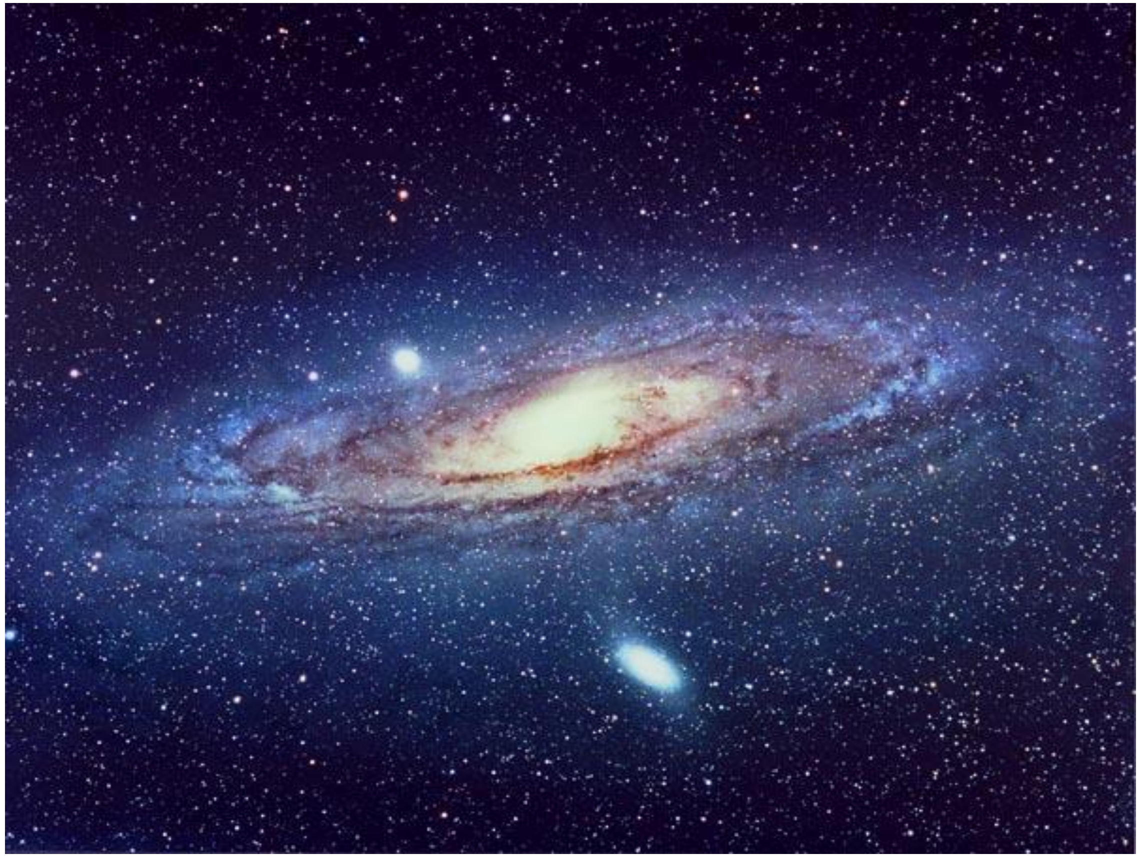
$$\Delta\phi_{SQL} = \frac{1}{N}\,\text{rad}$$

Time scales

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

The geometric mean ~ 1 minute
(Our quantum technology now provides this “mid point”)



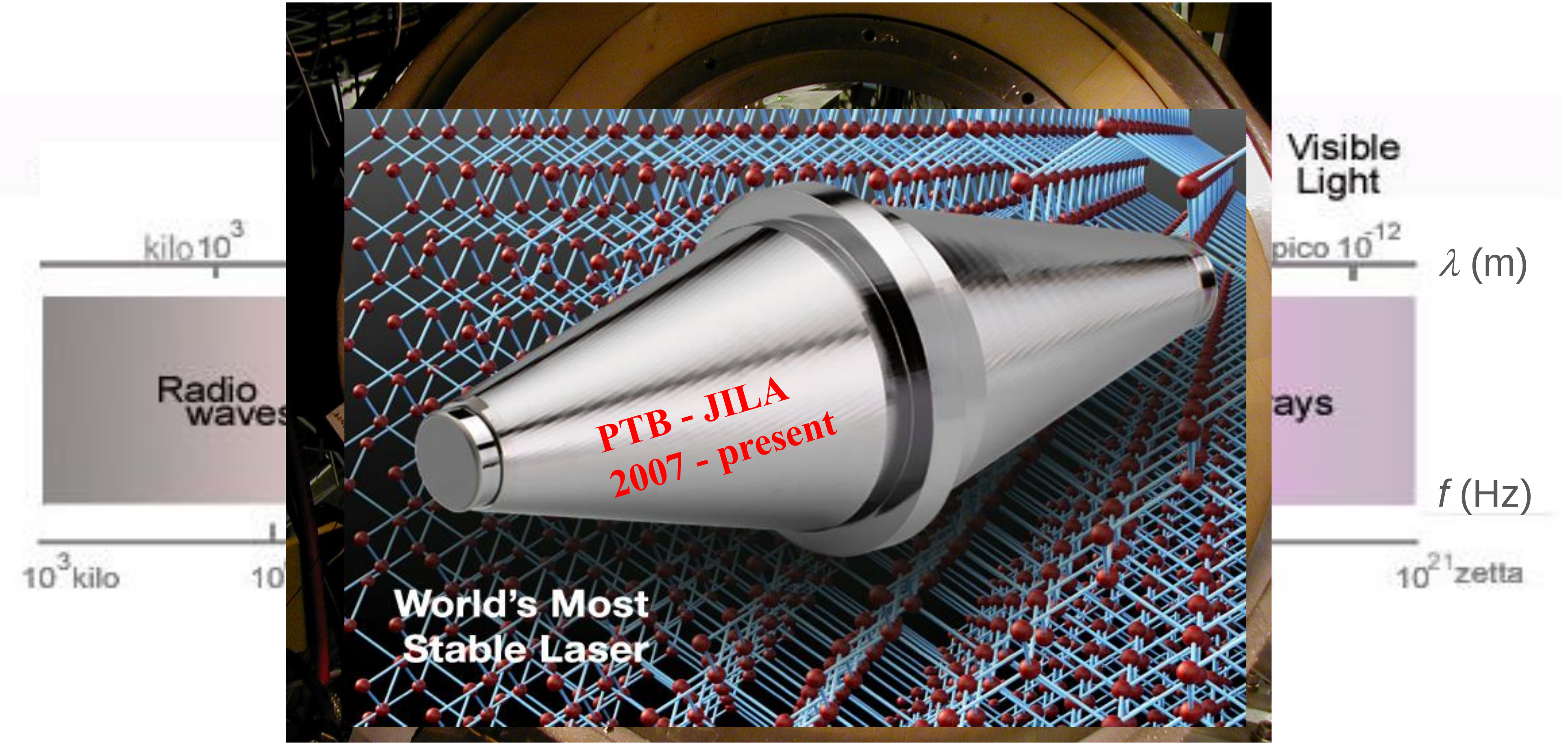


Sr atoms:

Quantum superposition lifetime: 120 s

Life of the Universe: 14 billion years (10^{18} s)
1000,000,000,000,000,000 seconds

Control of light –
the electromagnetic spectrum

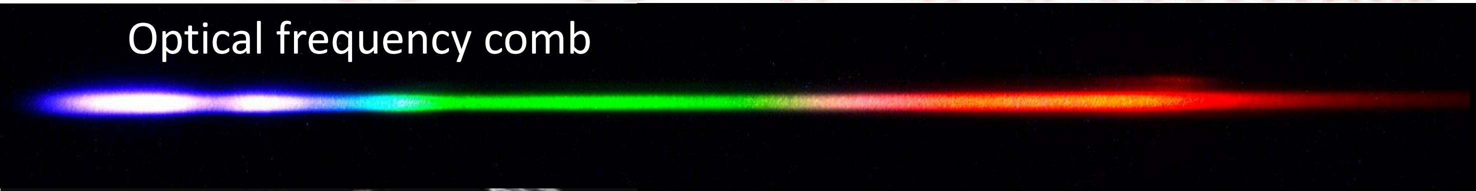


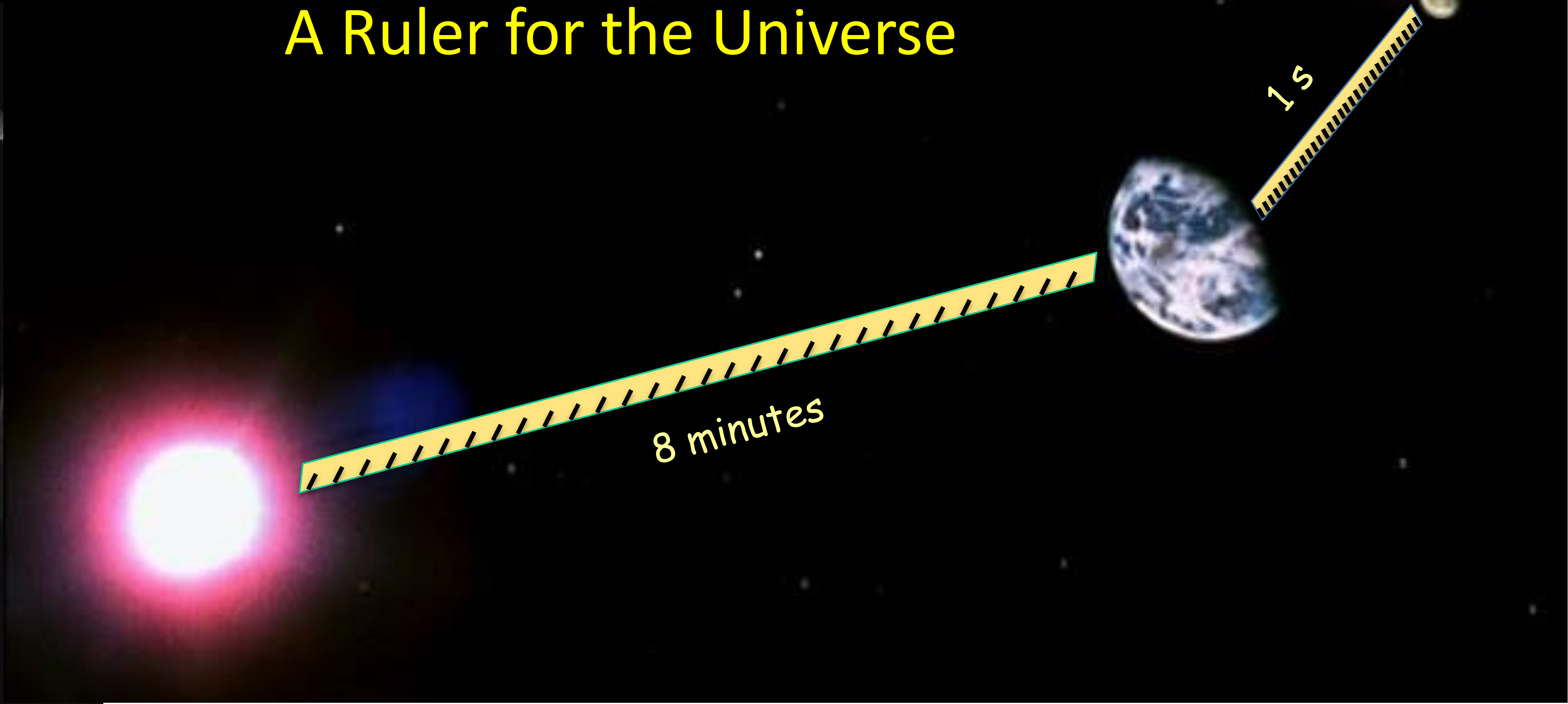
Zoom in 1 million times
Zoom in another 1 million times
Zoom in 1 million times for the 3rd time

A new generation of stable lasers

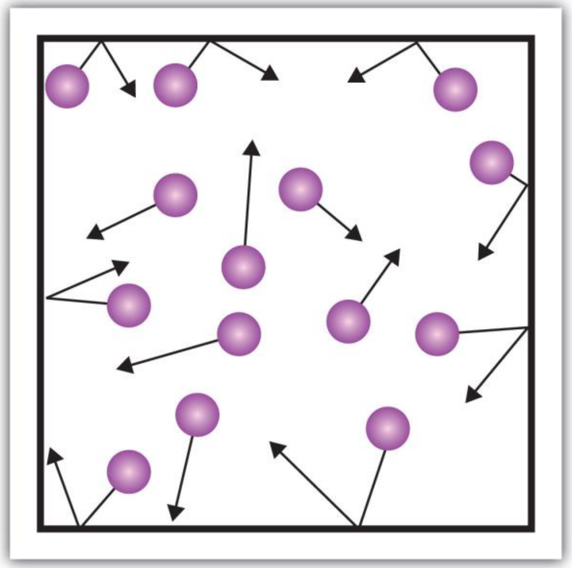
Optical coherence time approaching 1 minute

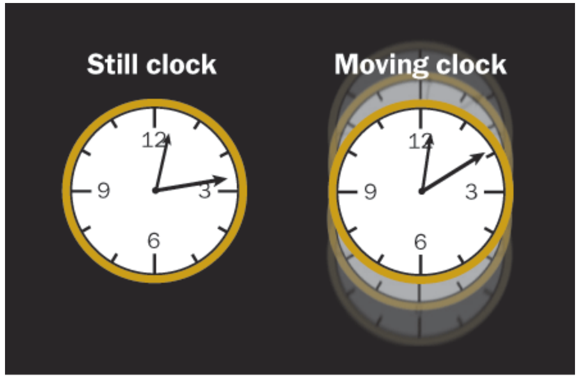
Matei *et al.*, PRL **118**, 263202 (2017); Oelker *et al.*, Nature Photon. **13**, 714 (2019).





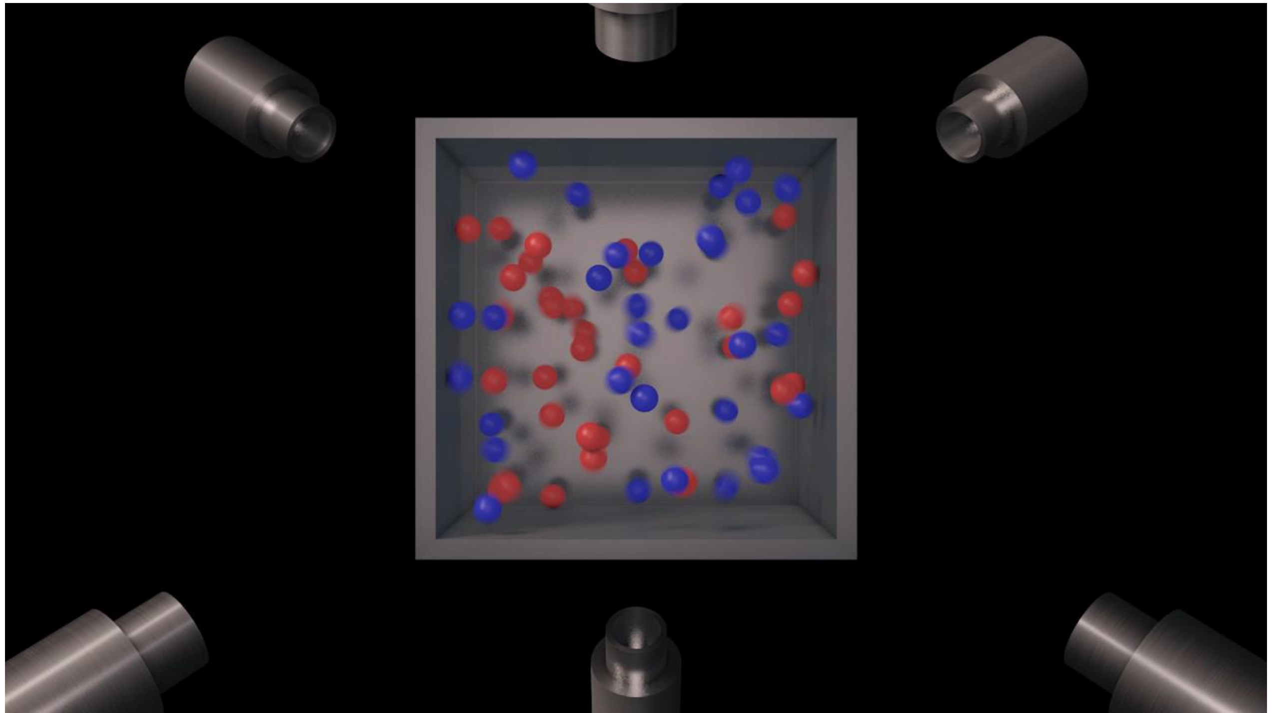
Taming atoms: time is all relative

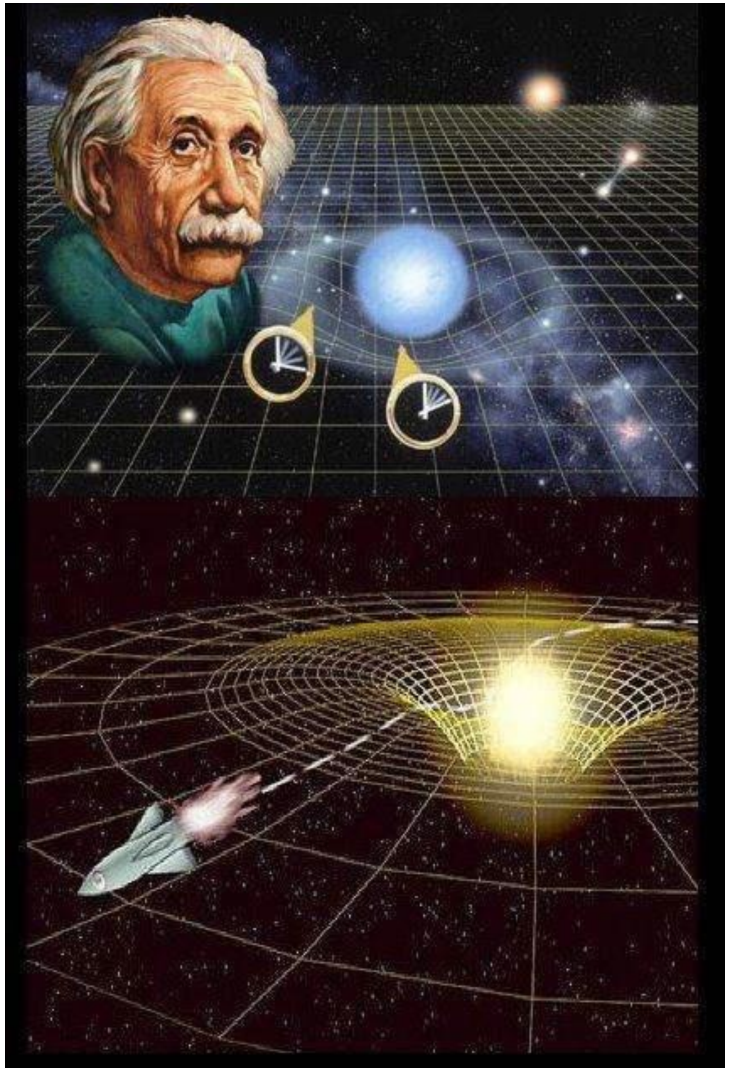




$$\frac{\Delta\omega}{\omega} = -\frac{1}{2}\frac{v^2}{c^2}$$

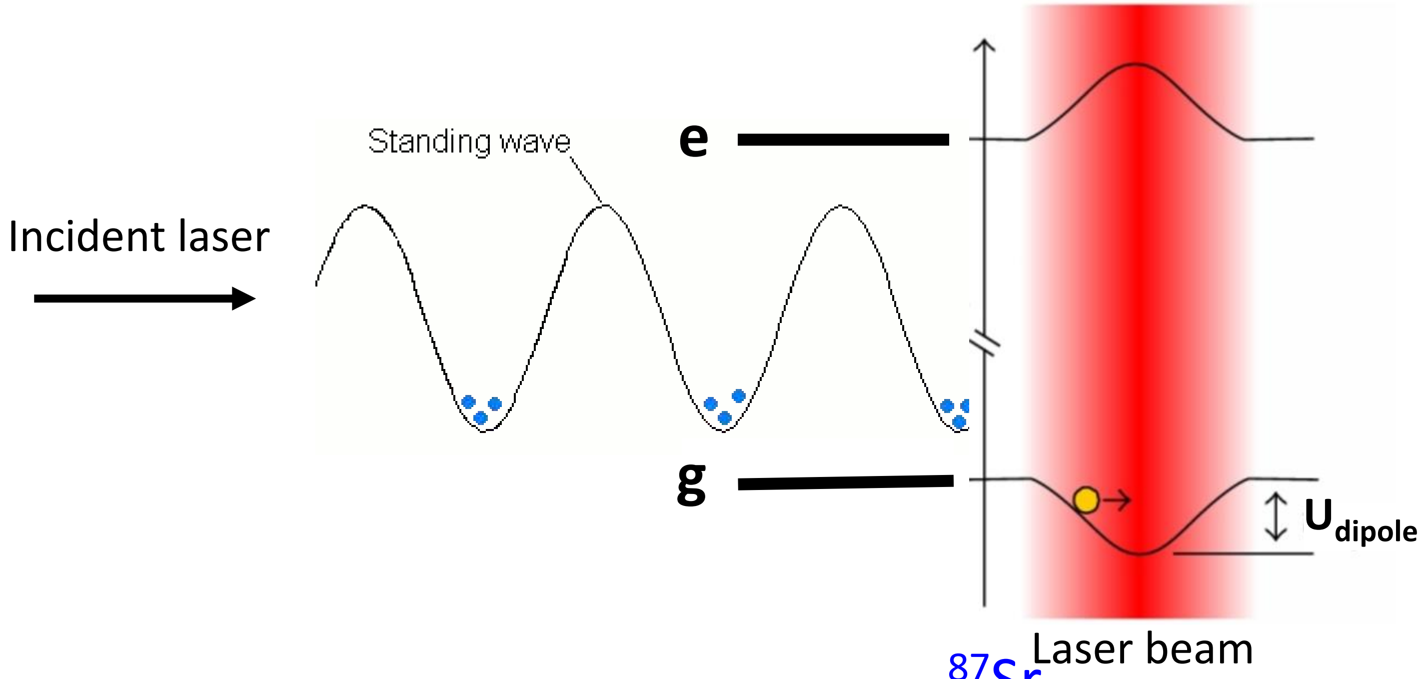
$$\frac{\Delta\omega}{\omega} = \frac{gh}{c^2}$$

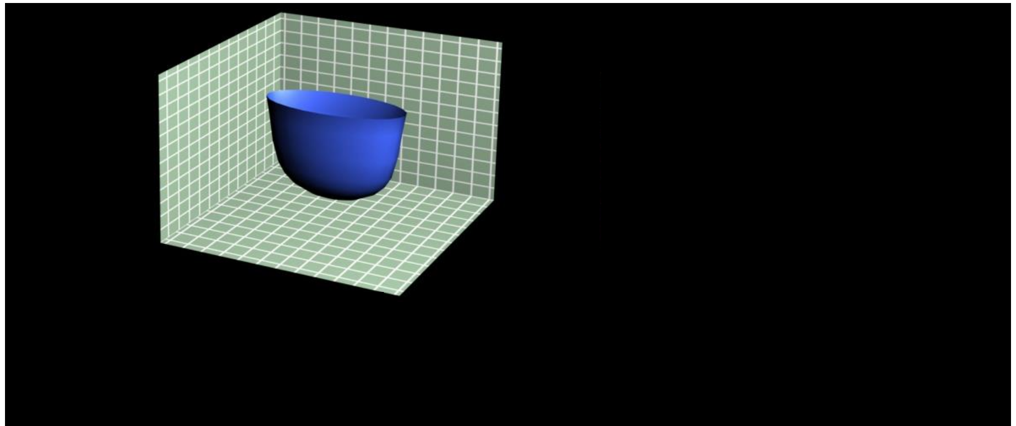


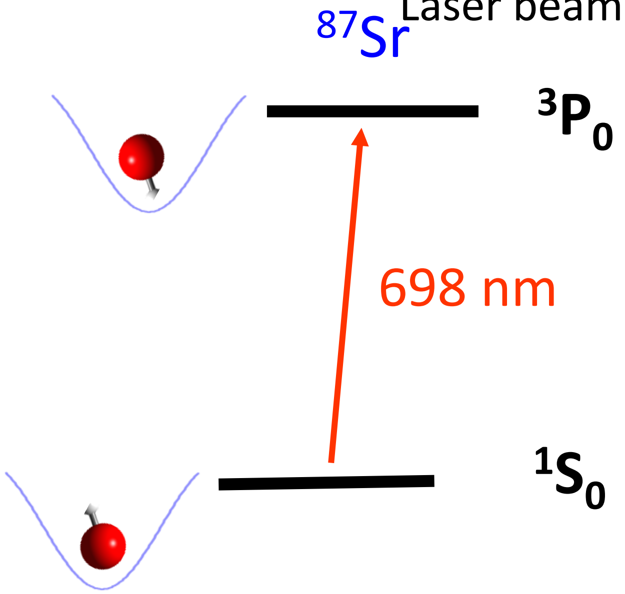


Holding atoms in a magic light bowl

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

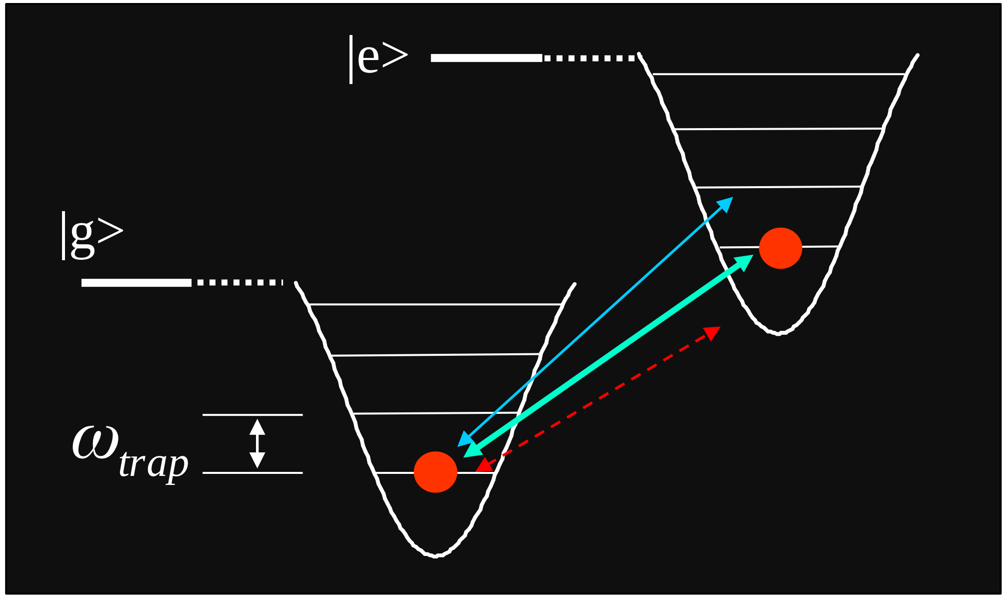


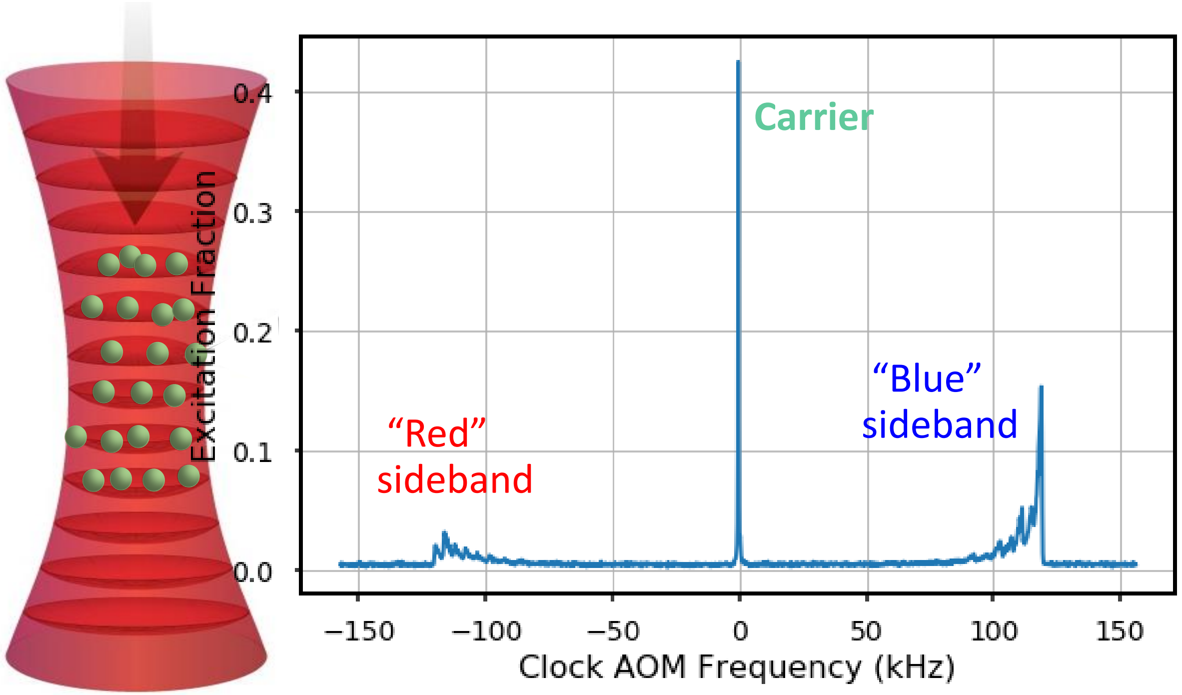


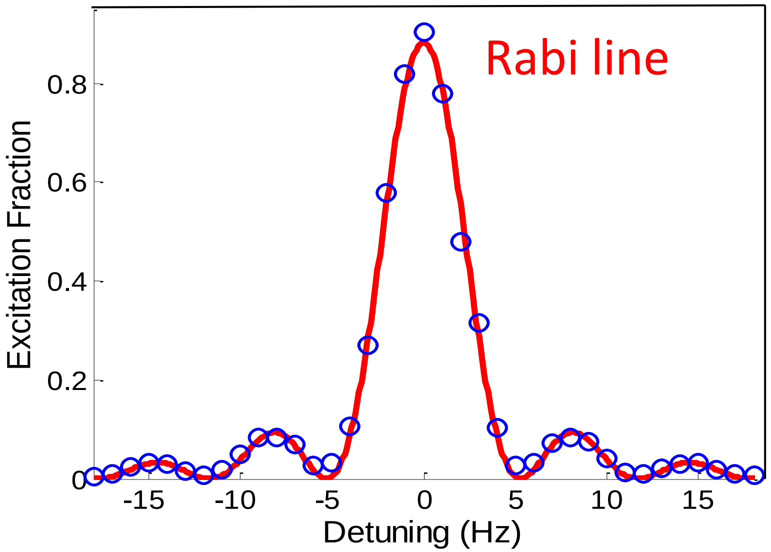


Decoupling spin & motion

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







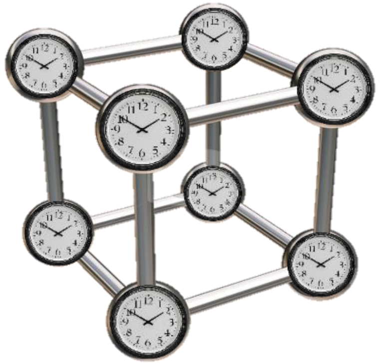
Overall AC Stark shift uncertainty: 3.5×10^{-19}

Phys. Rev. Lett. **130**, 113203 (2023).

3D Fermi insulator clock

Scaling up the Sr quantum clock:

1 million atoms
(100 x 100 x 100 cells)

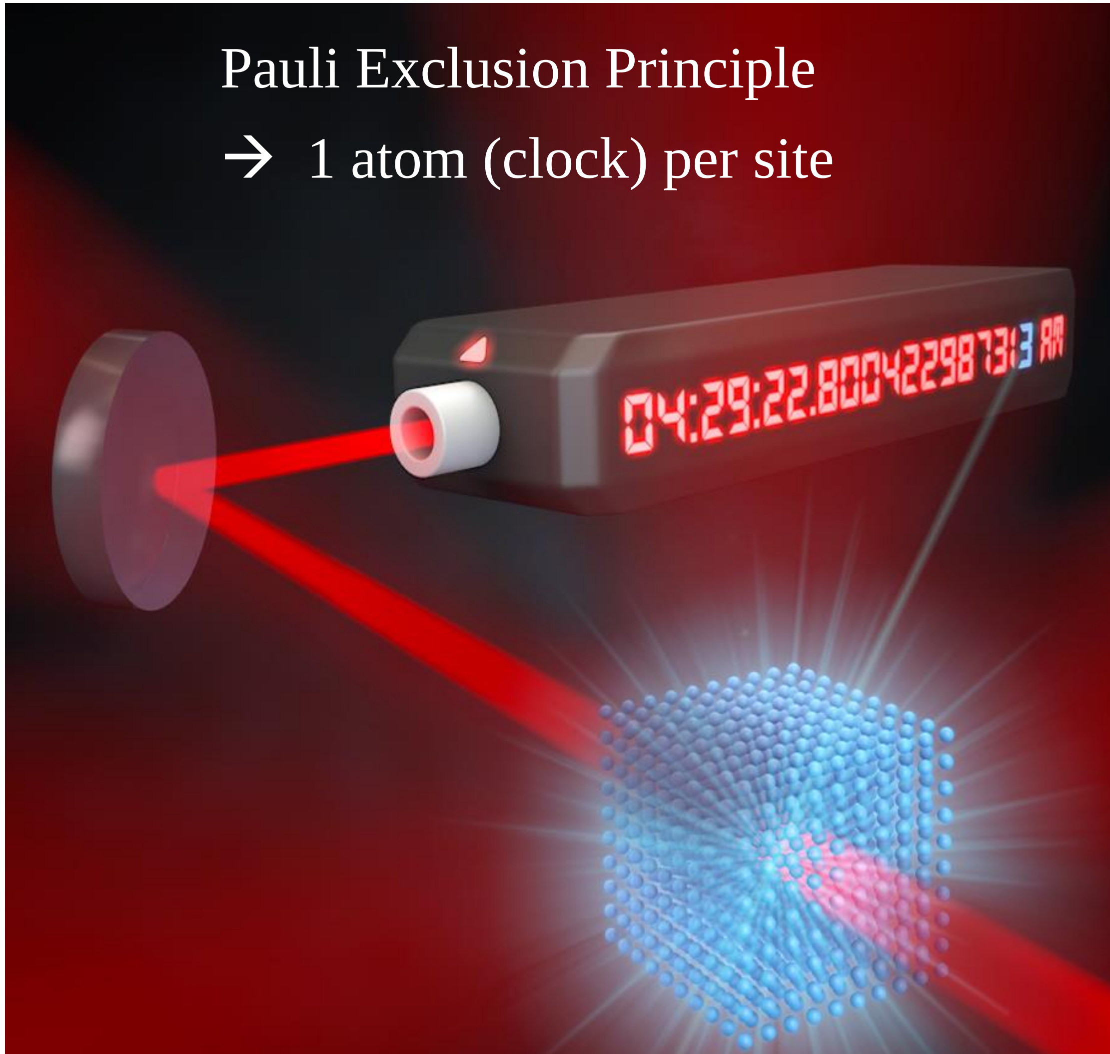


Coherence 120 s

Precision 4 x 10^{-20} at 1 s

Current Record: 3 x 10^{-18} at 1 s

Quantum simulator & sensor (Fermi Hubbard)

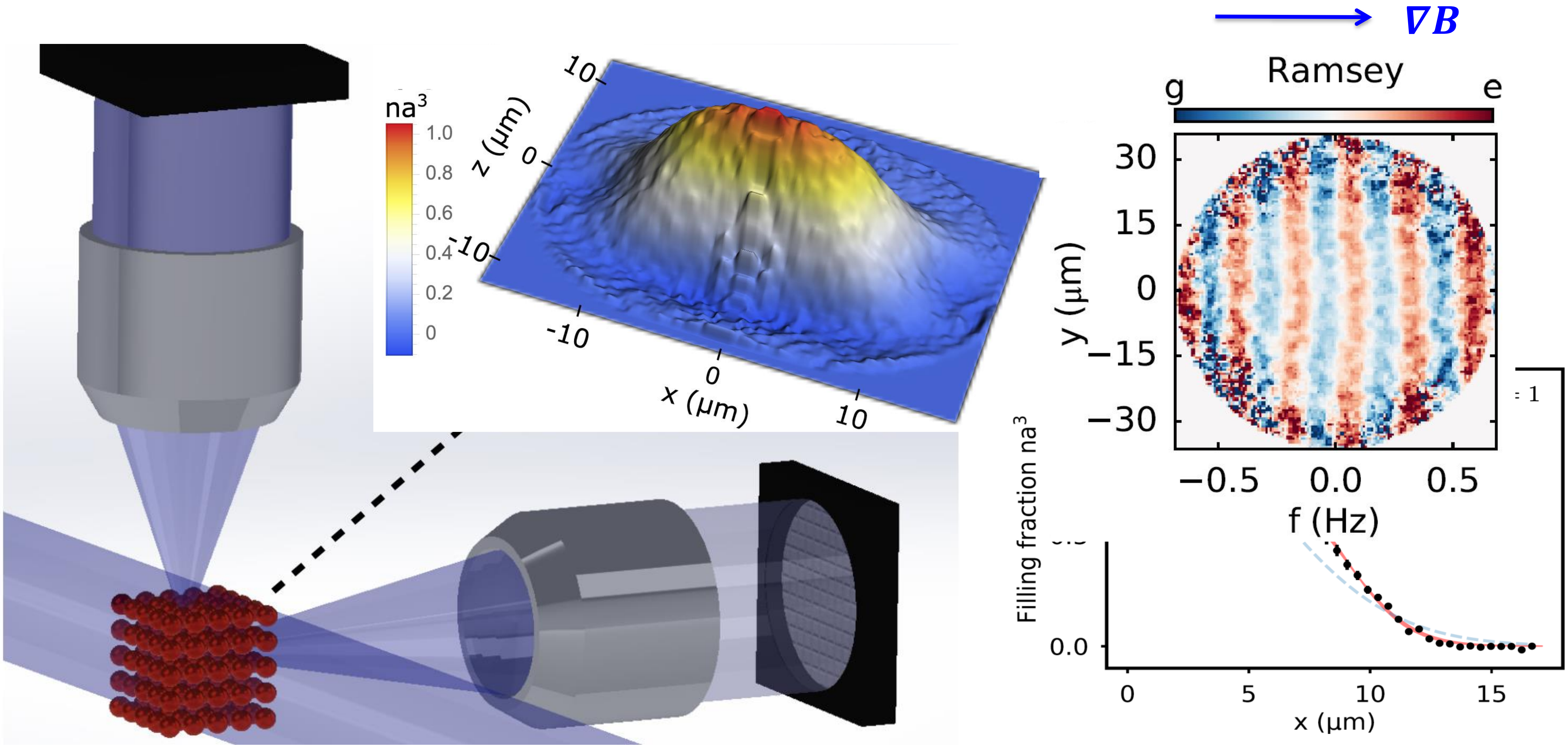


S. Campbell *et al.*,
Science **358**, 90 (2017).

Densely packed atoms impact light-atom interactions
→ Important systematic effects for clock

Spatial + Spectral Imaging

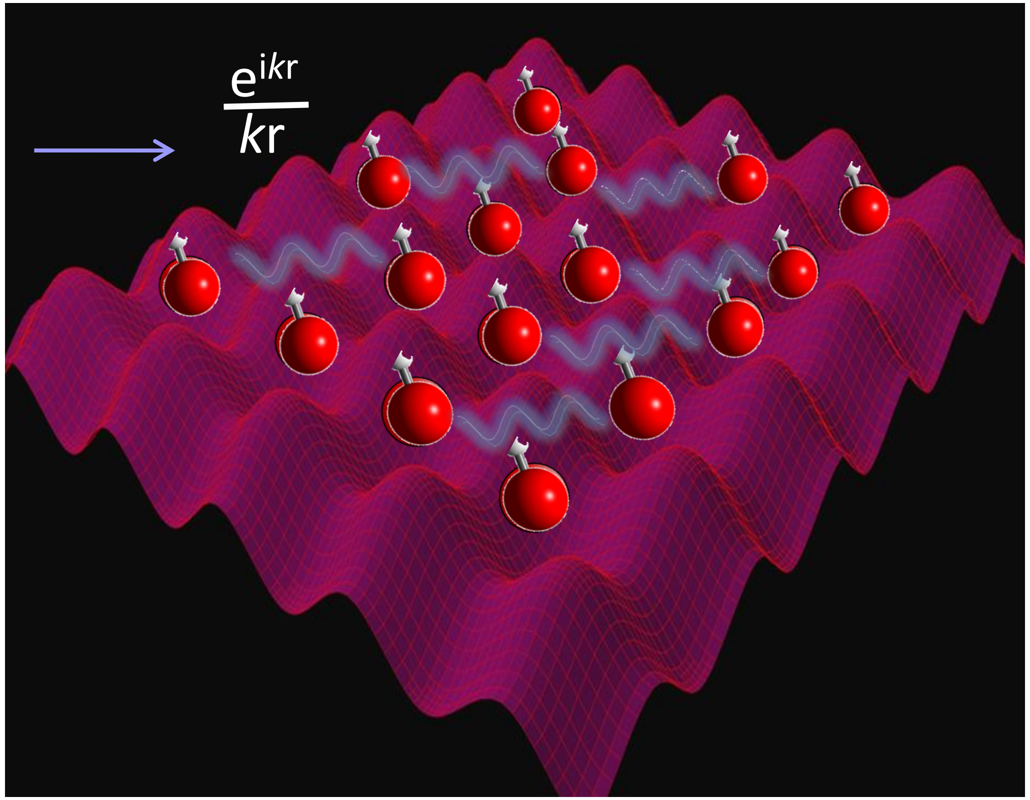
Marti *et al.*, PRL 2018; Sonderhouse *et al.*, Nature Phys 2020; Milner *et al.*, PRA 2023.

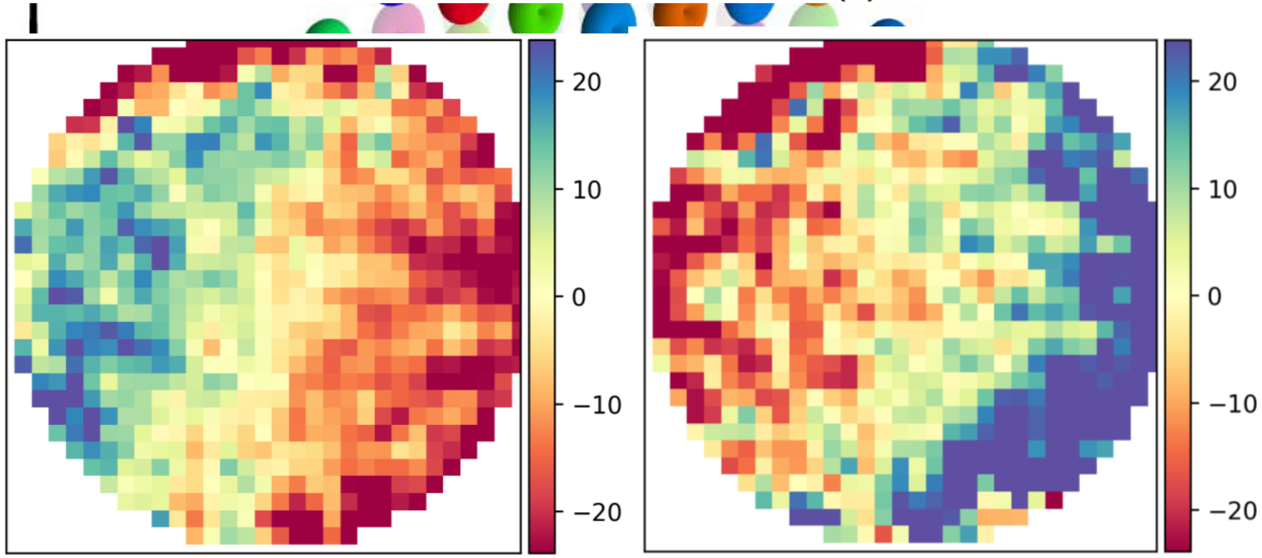


A radiative dipolar spin lattice

Hutson *et al.*, Science (in press 2023.)

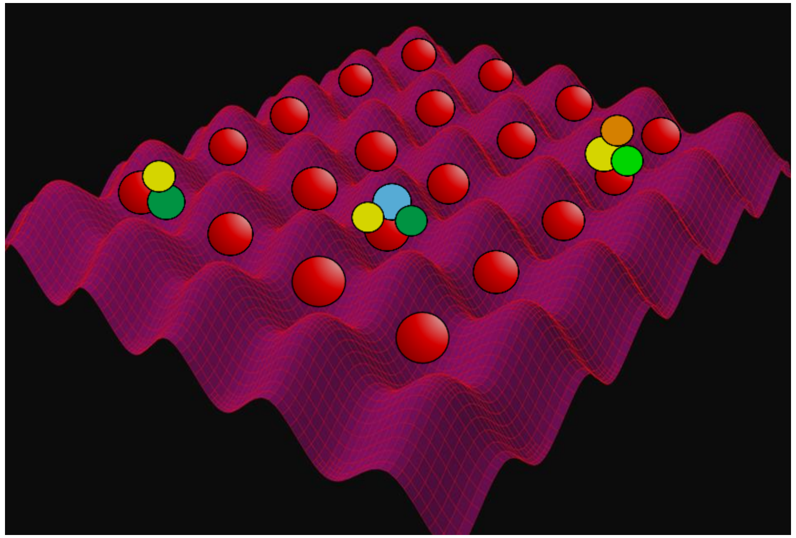
- Transition dipole ~ 10^{-6} Debye
- Cooperative Lamb shift (10^{-19})
- Many-excitation limit
- Engineerable photon dispersion

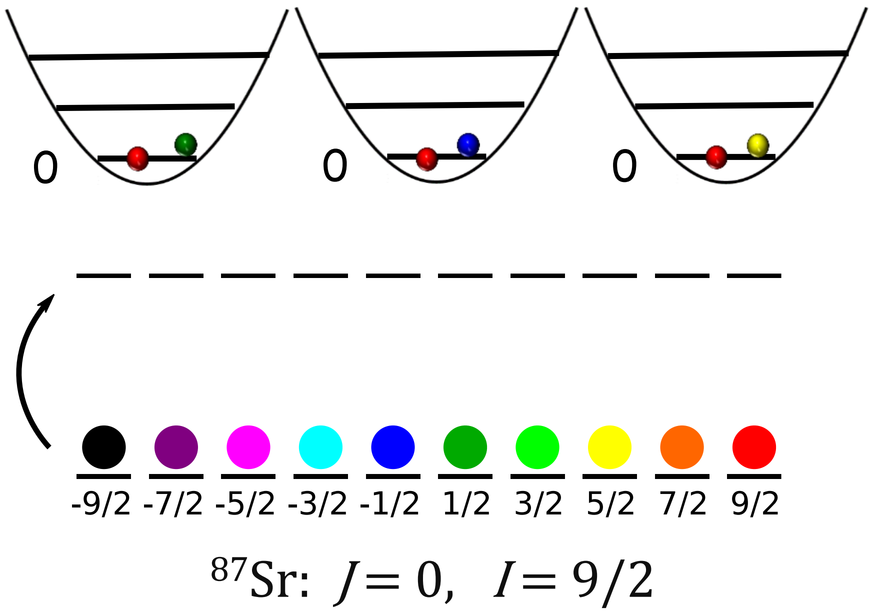


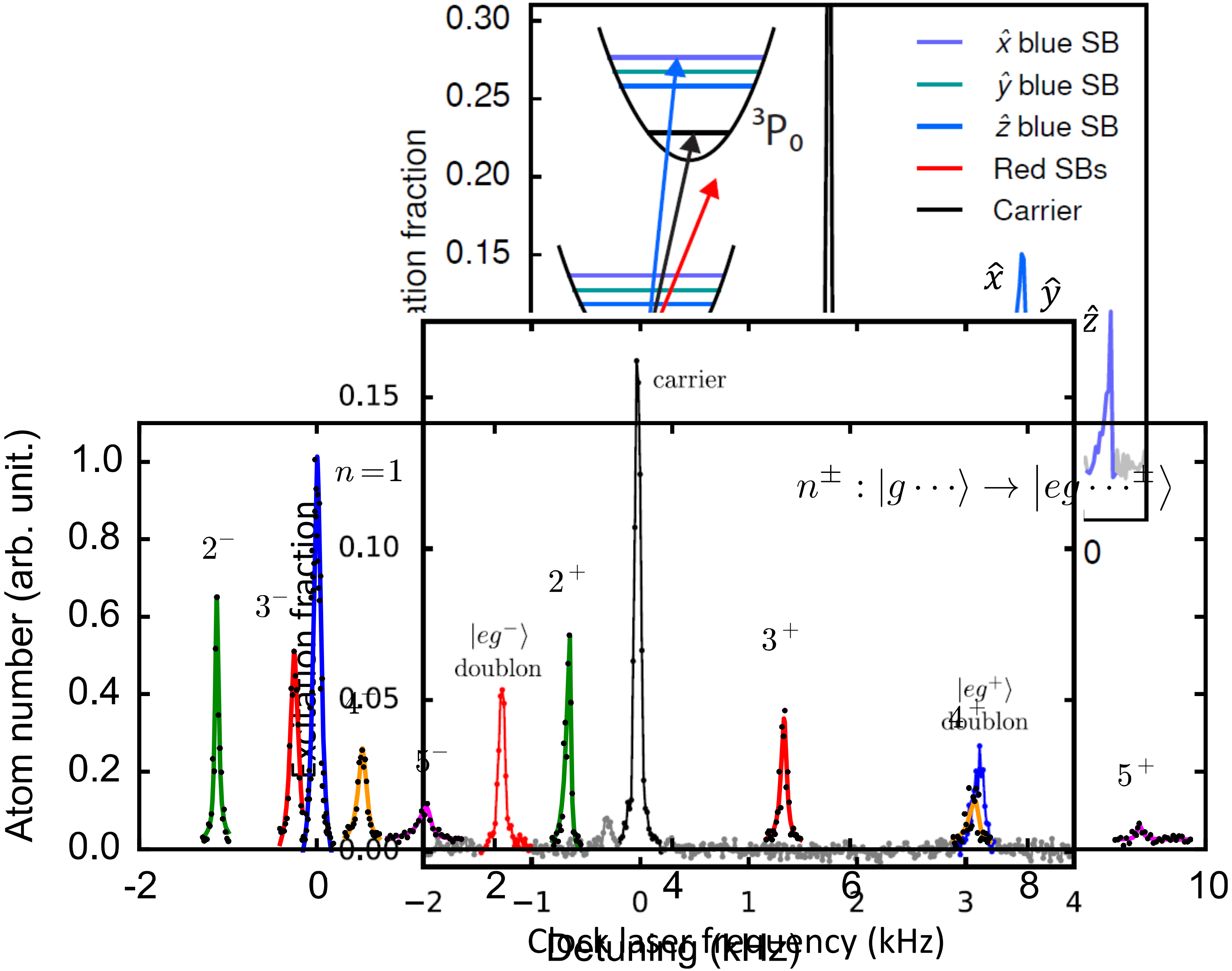


Quantized interaction

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



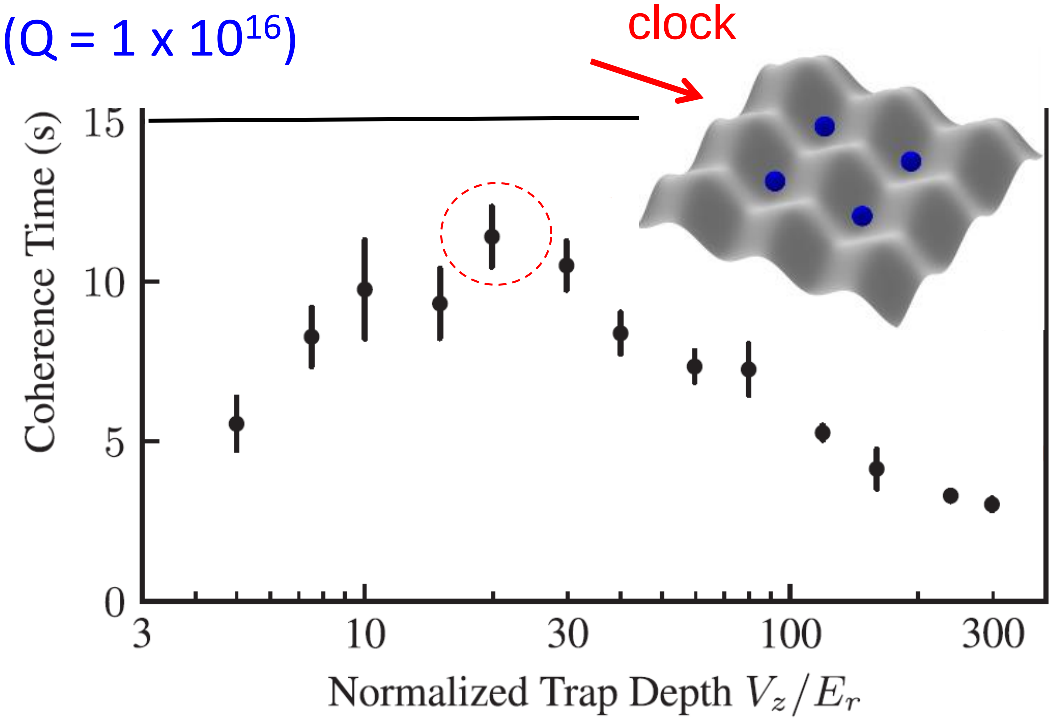


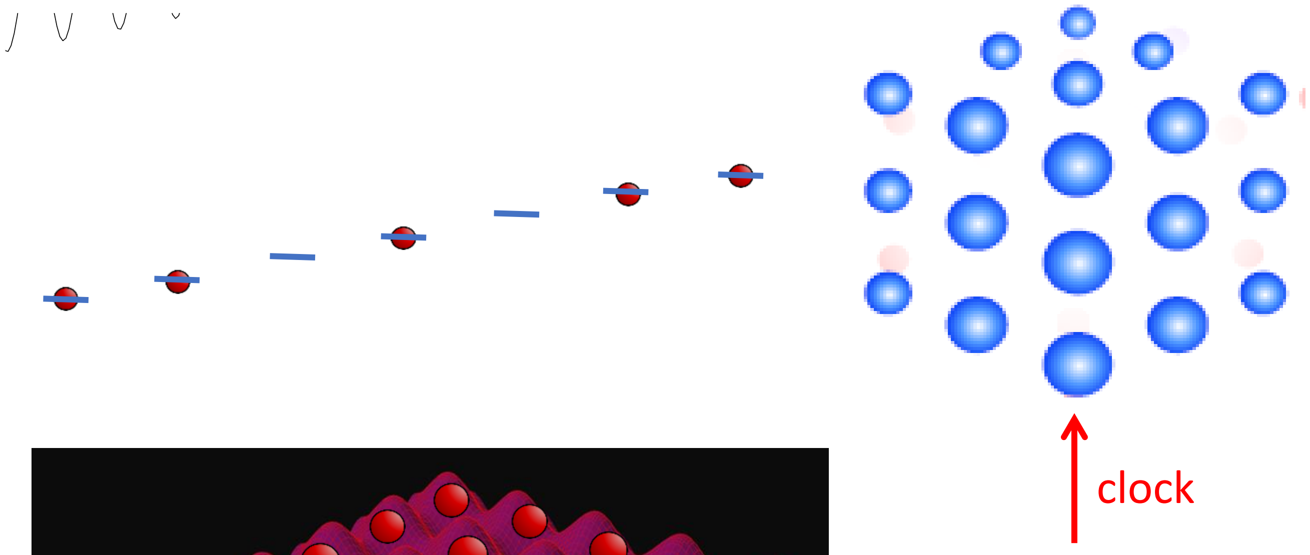


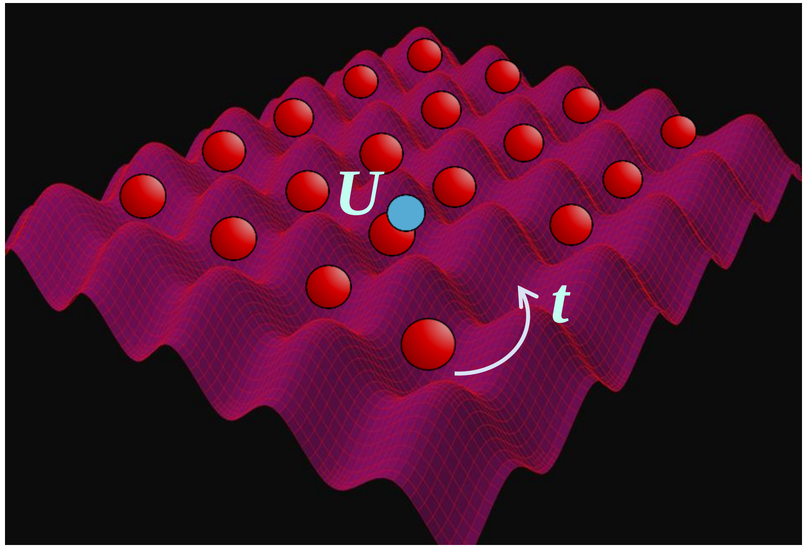
Atom-light coherence

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

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



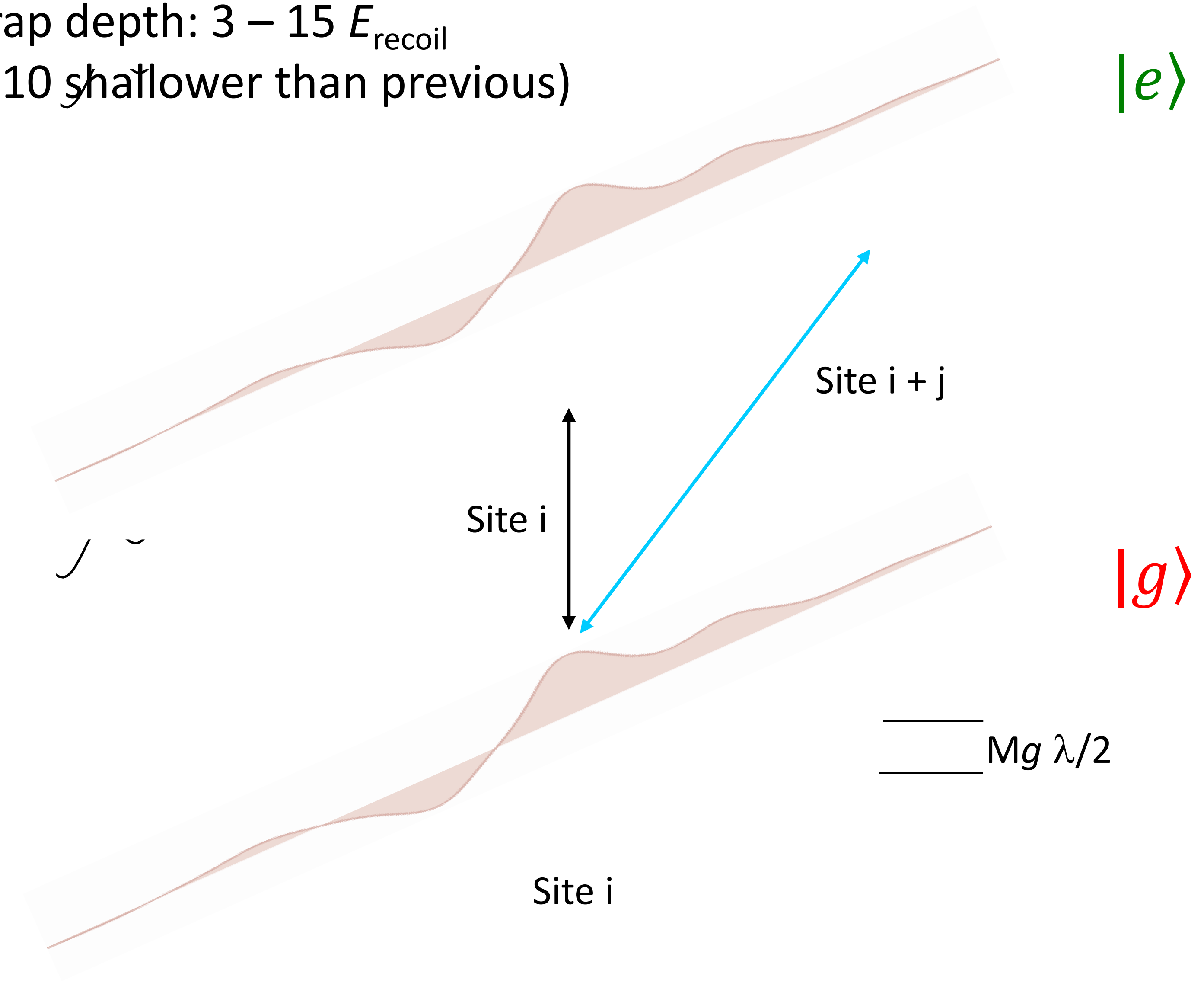


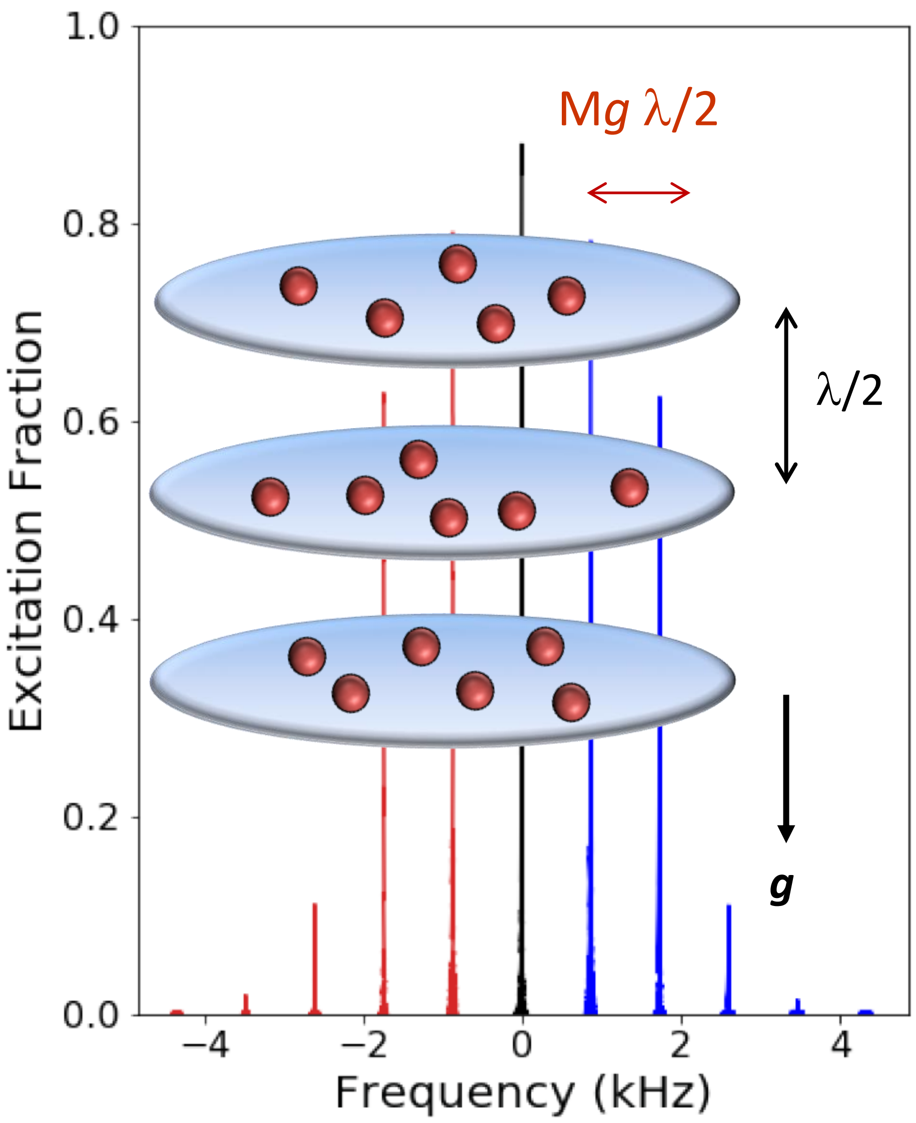


A Wannier-Stark lattice clock

Bothwell *et al.*, Nature **602**, 420 (2022).

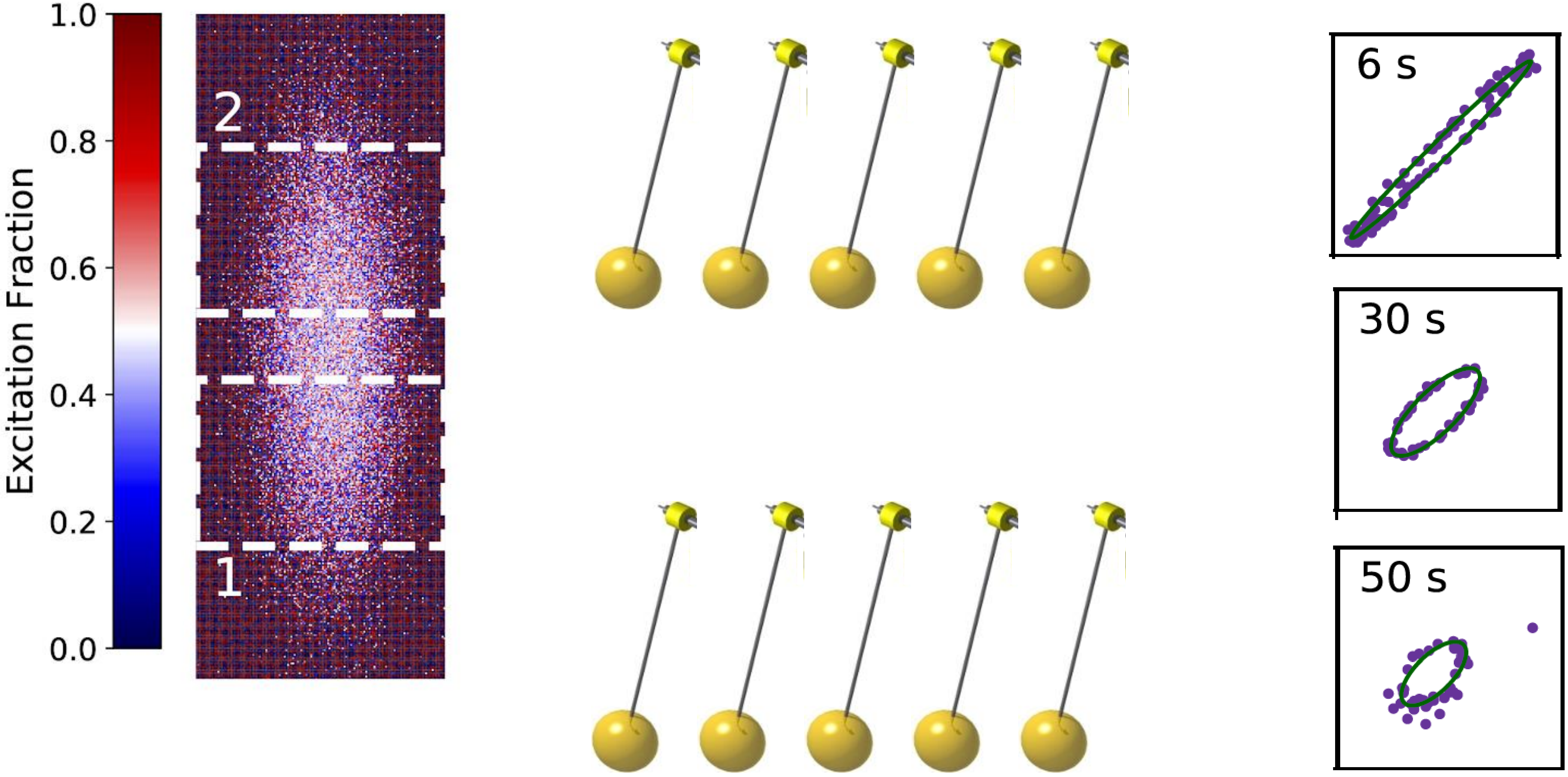
Trap depth: 3 – 15 E_{recoil}
(x10 shallower than previous)





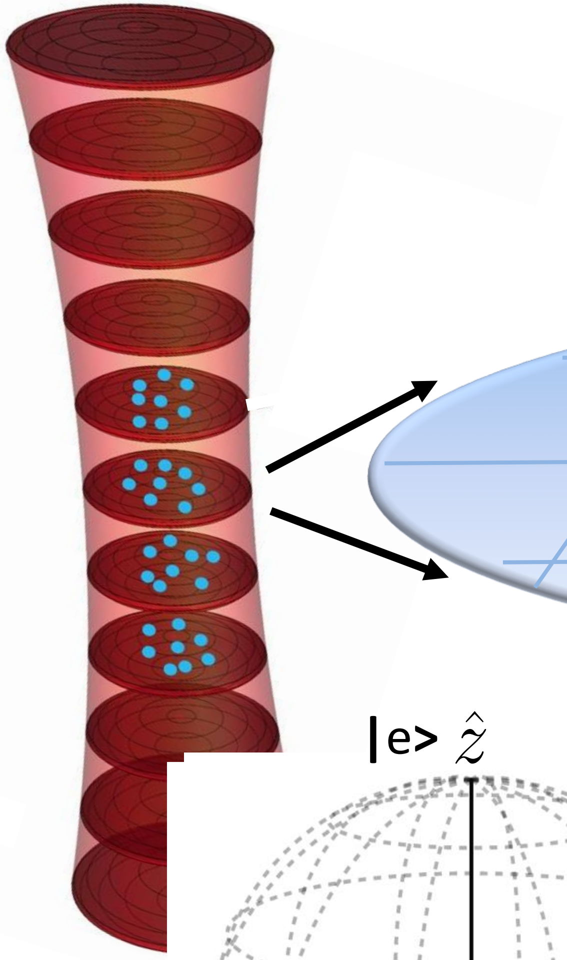
A Wannier-Stark lattice clock

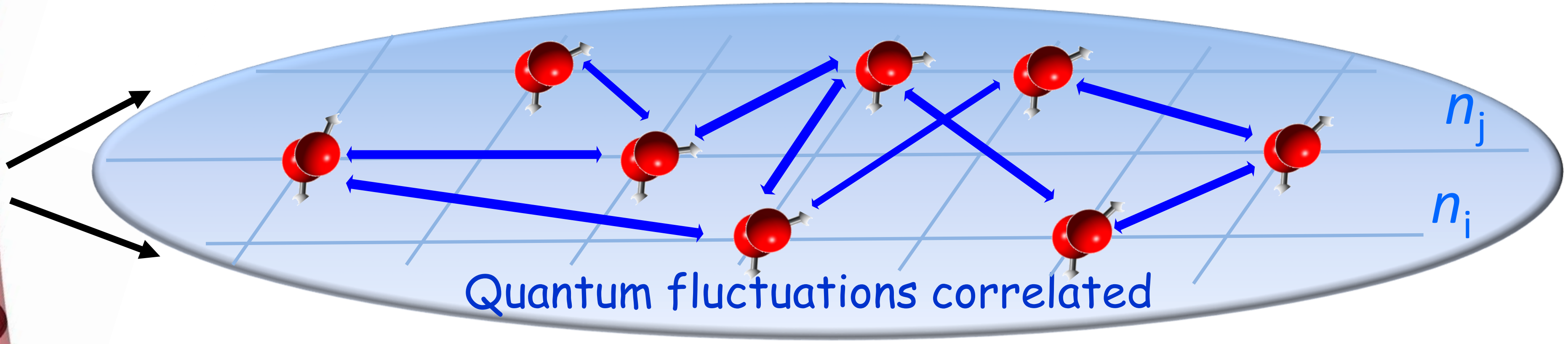
100,000 atoms



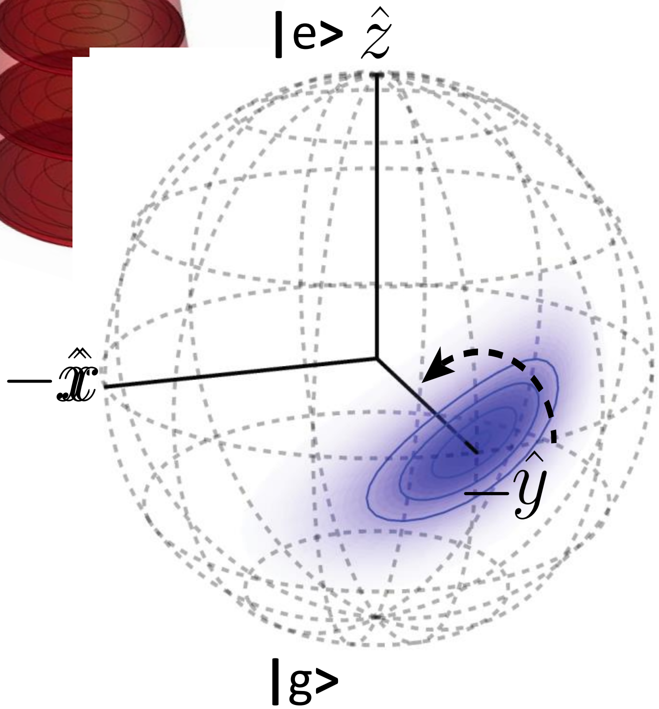
Many interacting spins

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





n_i : motional quanta



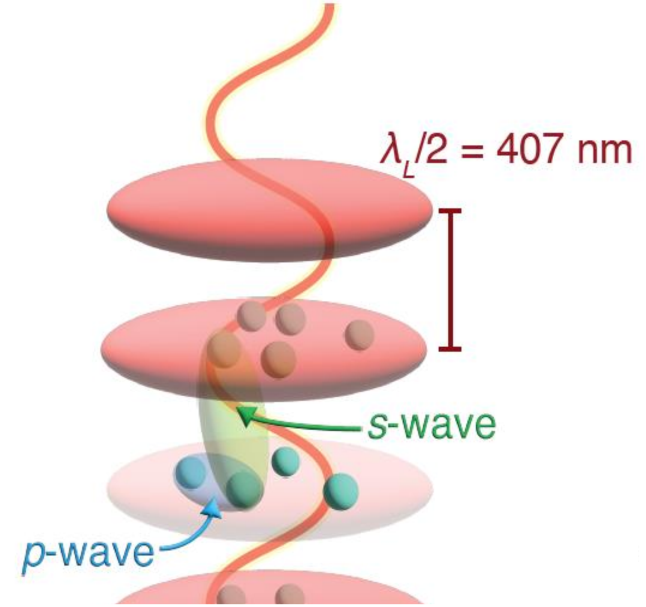
|ge> + |eg> ⊗ |n_1 n_2 > – |n_2 n_1> Fermions

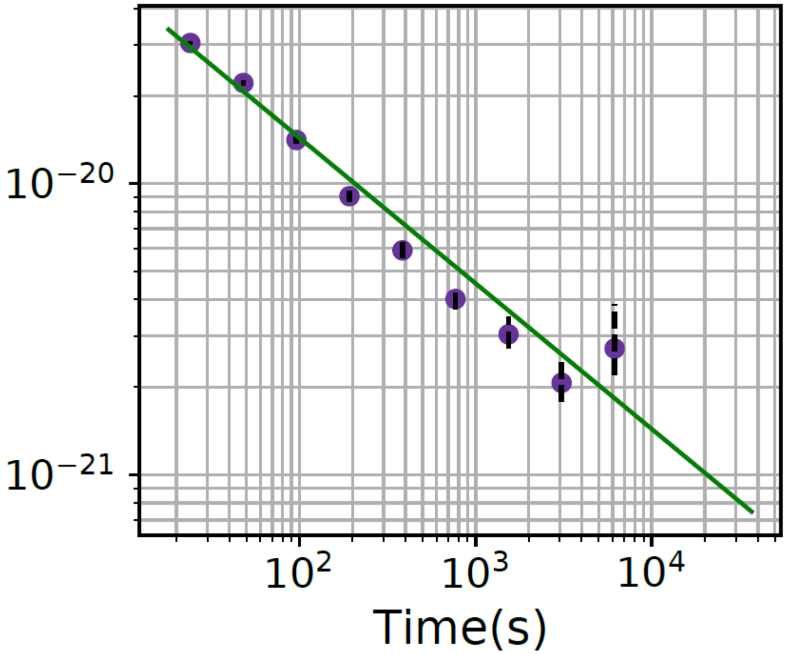
Collective spin: $S = N/2$

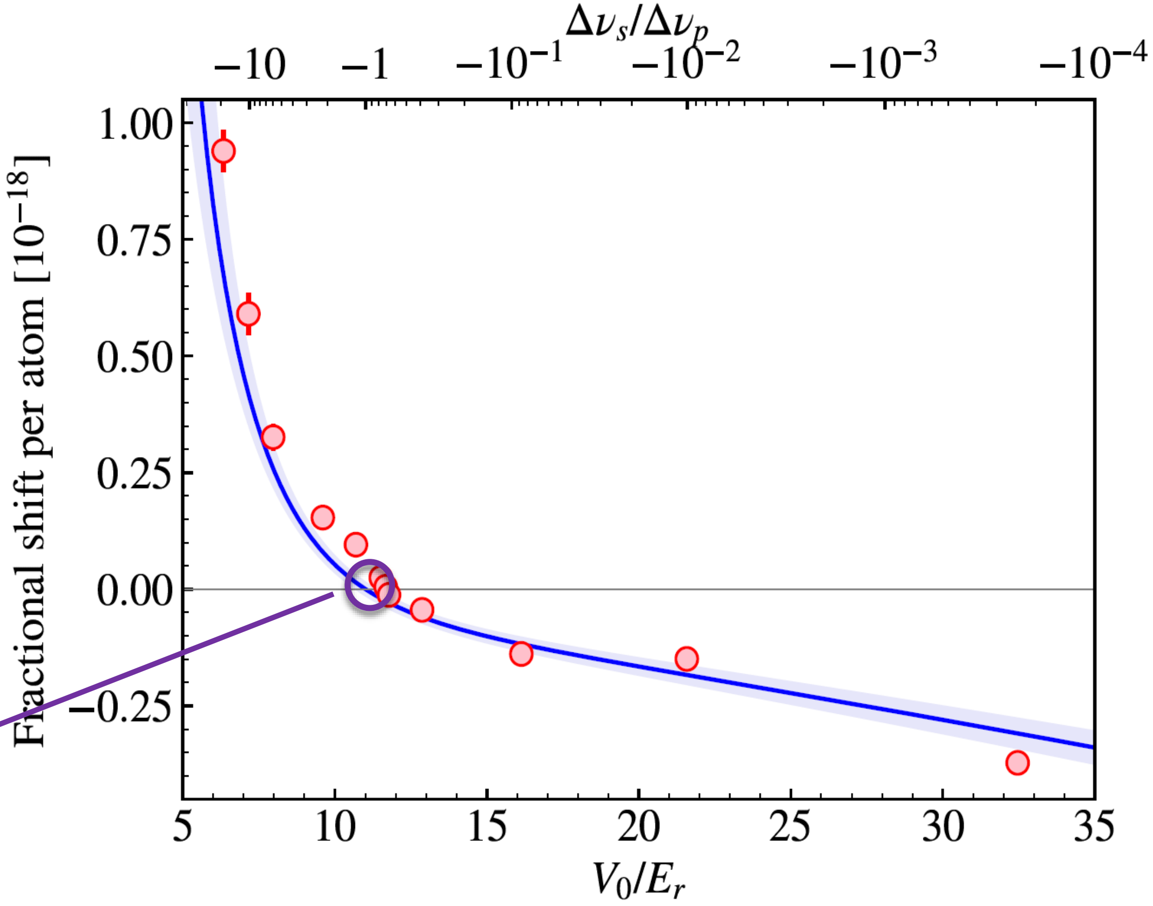
$$\hat{H}/\hbar = \chi\,(S^z)^2 + C\,(N-1)\,S^z$$

Tuning Fermionic interactions to zero

Aeppli *et al.*, Science Adv. **8**, eadc9242 (2022).

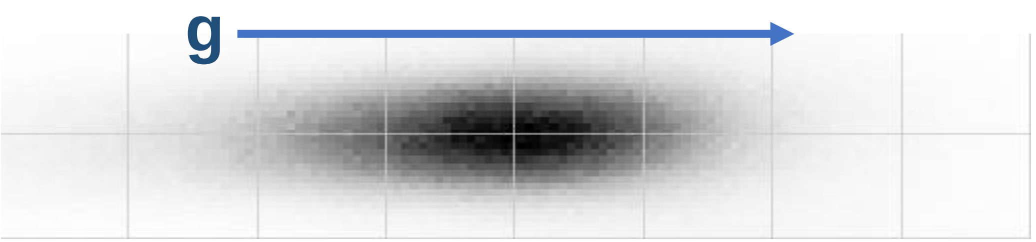




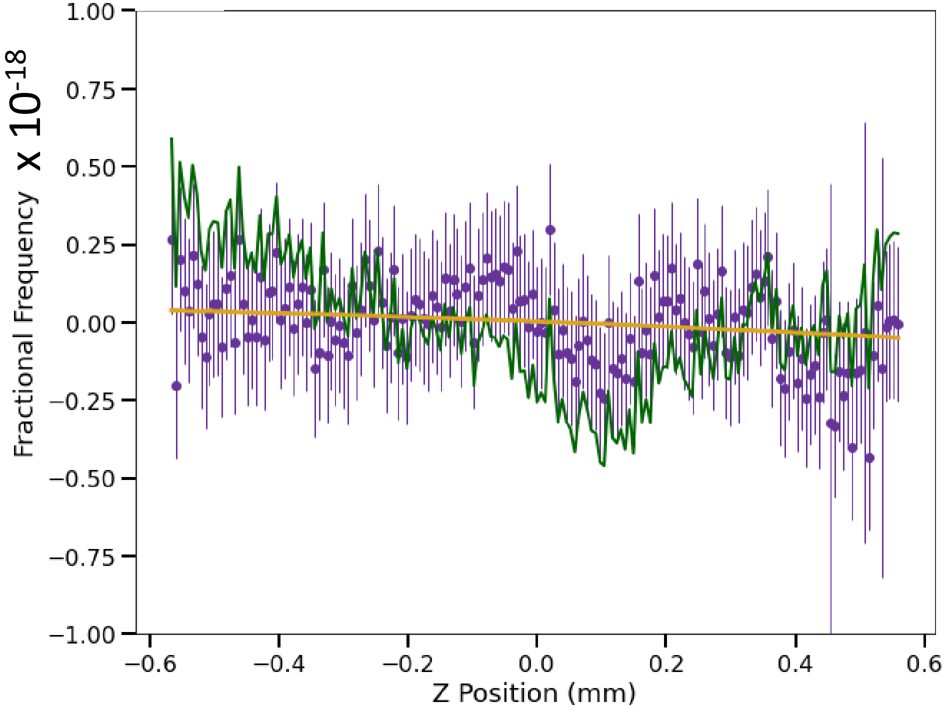


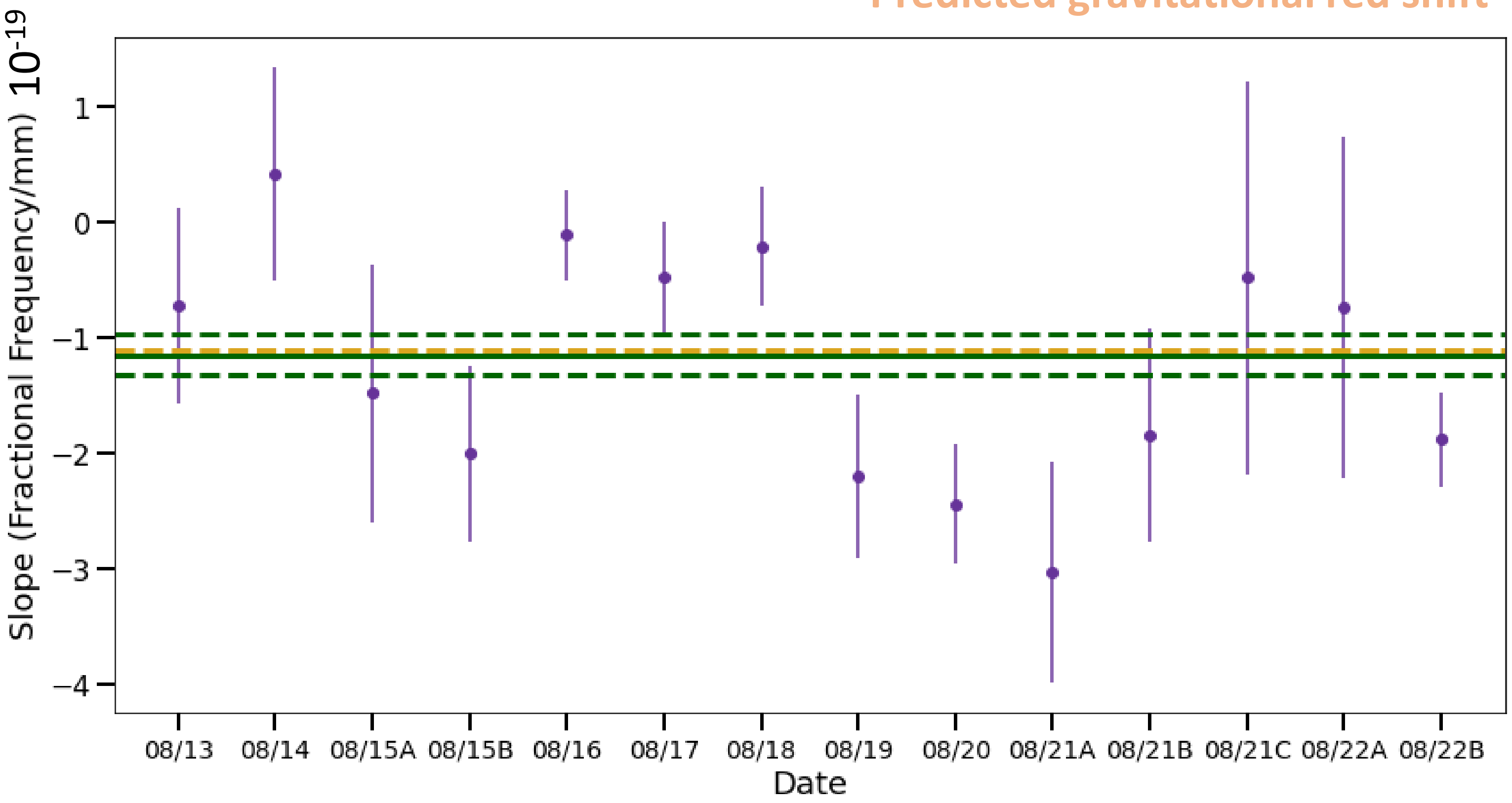
Optical Lattice Clock Imaging Spectroscopy

In-situ detection + correction for systematic frequency shifts

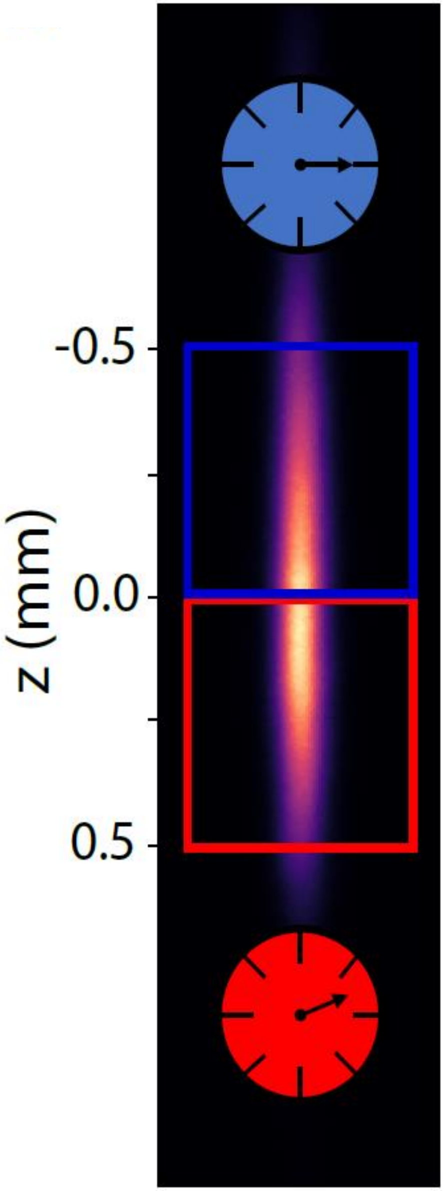


Yellow dashed line:
Predicted gravitational red shift

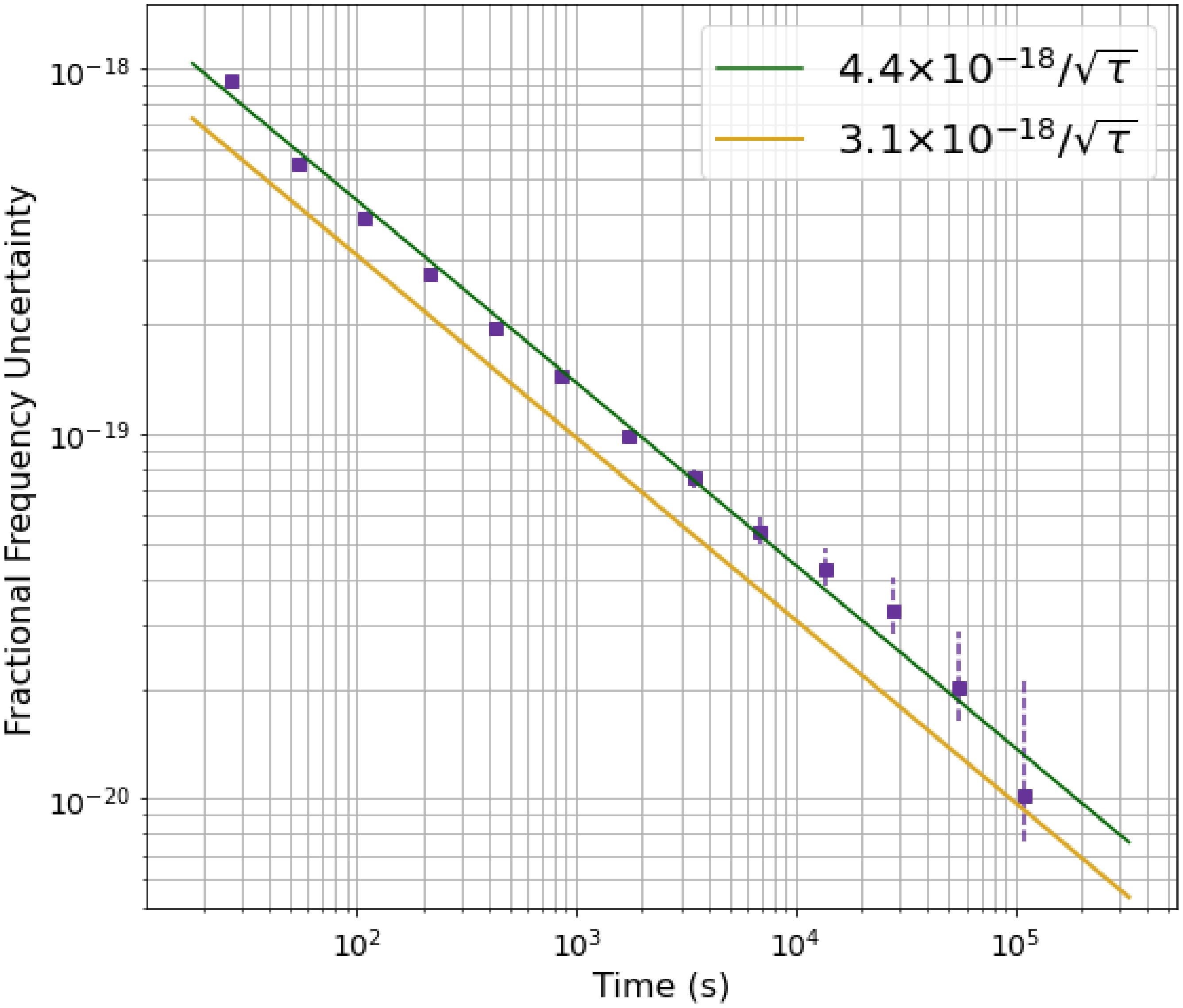


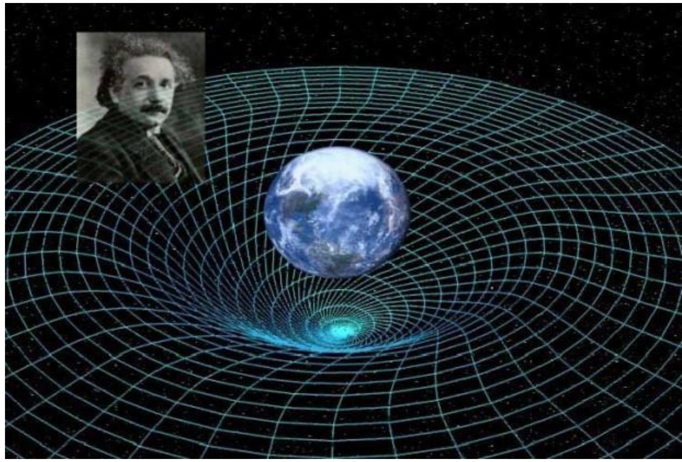


Clock precision enters 21st digit



Reach 1×10^{-20} in 10^5 seconds





Gravitational Red Shift
100 μm (10^{-20})

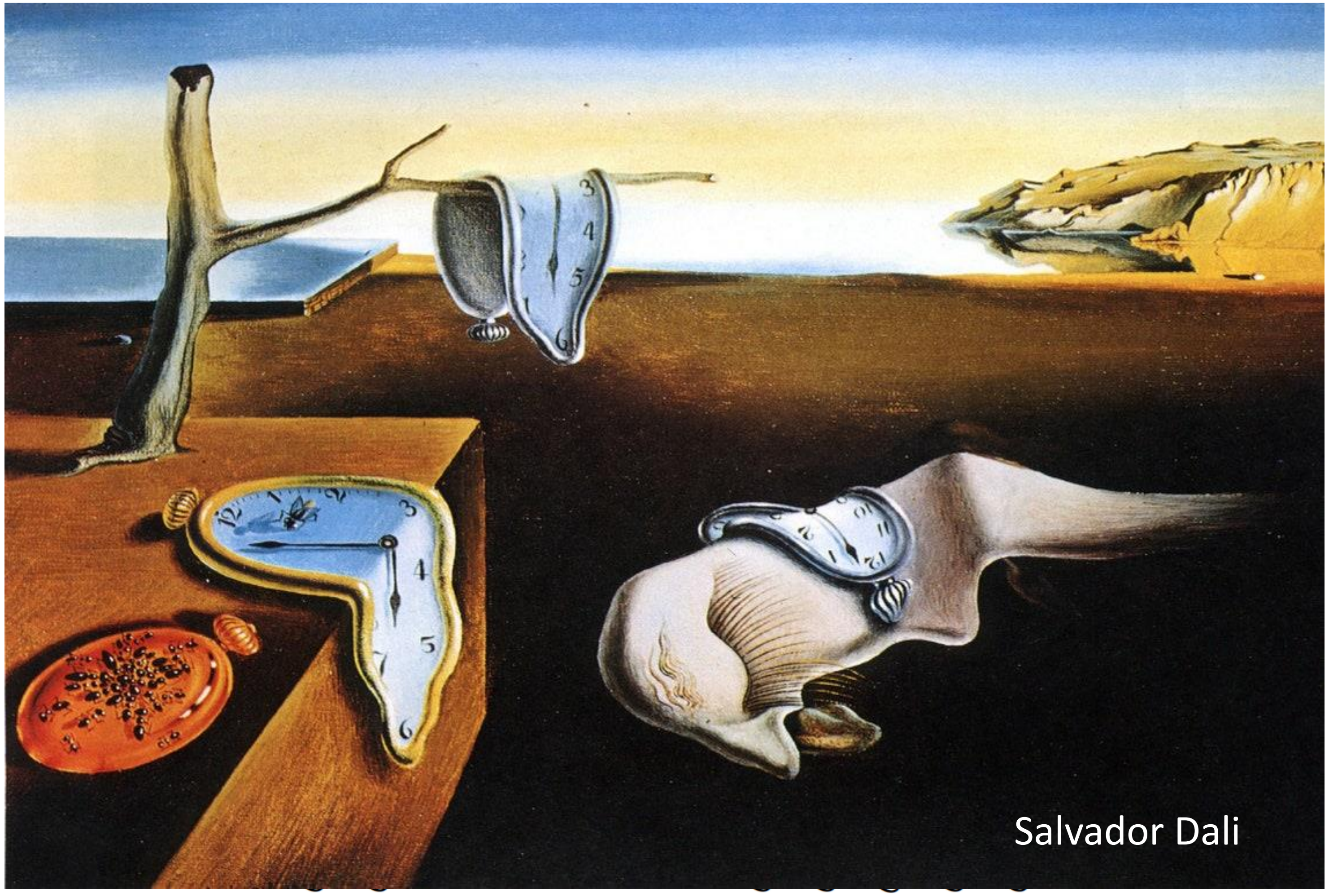
6×10^{-21}
for each clock

Gravitational red shift in a single atomic ensemble

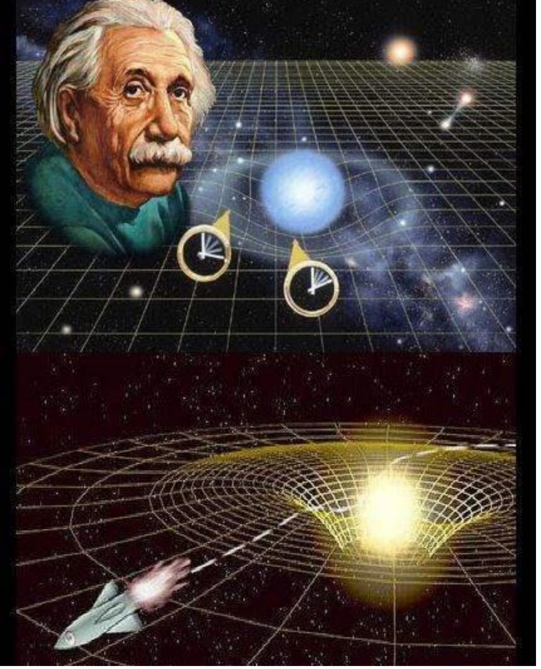
Resolving the gravitational redshift on length scale of quantum wave function?

Bothwell et al., Nature 602, 420 (2022) Zheng et al., Nature 602, 425 (2022).

Measured: $-1.06(21) \times 10^{-19}$ for 1 mm

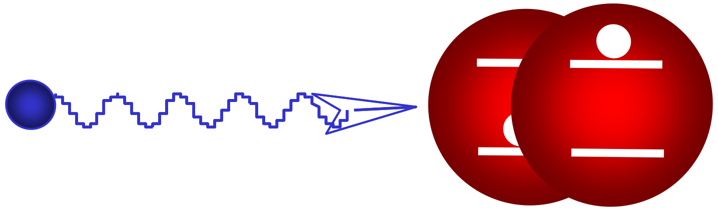


Measurement Date



$$E = M c^2$$

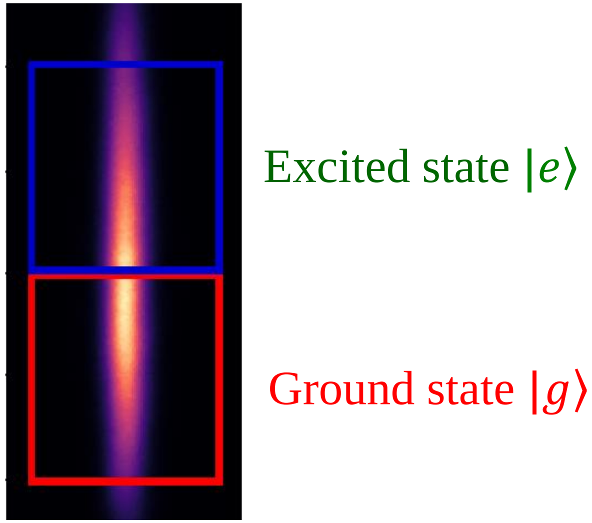
$|2\rangle$ —— $M_{Sr} + h\nu/c^2$

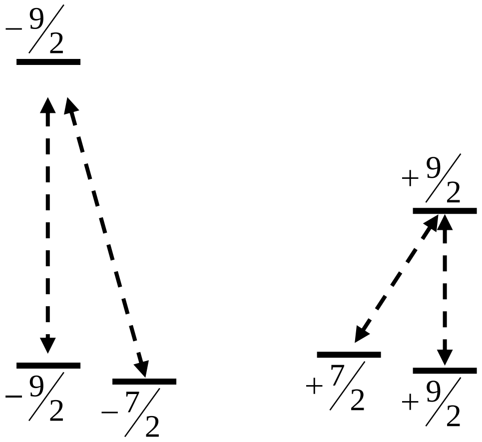


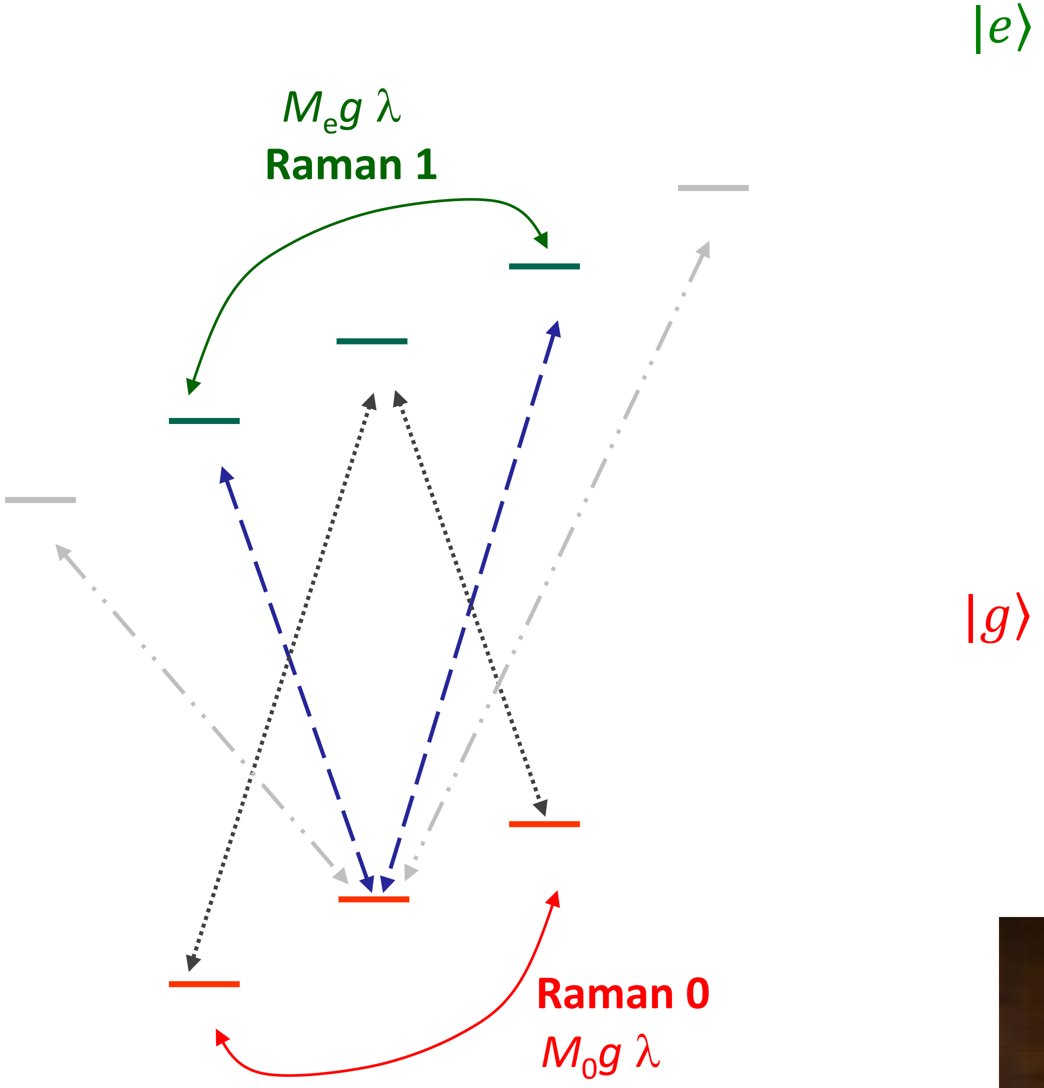
$|1\rangle$ —— M_{Sr}

V. J. Martínez-Lahuerta *et al.*, arXiv: 2202.10854 (2022).

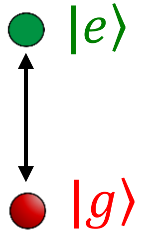
Measuring a single photon mass







Leading order general relativity effects



Weak gravity: mass defect on single-particle: $M_e c^2 = M_g c^2 + \hbar\omega_0$

$\sim 10^{-11}$

$$H_0 = \sum_{\alpha=\{g,e\}} \int \mathrm{d}^3\mathbf{R}\, \psi_\alpha^\dagger(\mathbf{R}) \left[-\frac{\hbar^2}{2M_\alpha}\nabla^2 + V_{\mathrm{lattice}}(\mathbf{R}) + M_\alpha g Z \right] \psi_\alpha(\mathbf{R}) + \hbar\omega_0 \int \mathrm{d}^3\mathbf{R}\, \psi_e^\dagger(\mathbf{R})\psi_e(\mathbf{R})$$

Motional redshift $(v^2/c^2) \sim 4 \times 10^{-22}$

$$H_0 = \sum_{\alpha=\{g,e\}} \int \mathrm{d}^3\mathbf{R}\, \psi_\alpha^\dagger(\mathbf{R}) \left[-\frac{\hbar^2}{2M_g}\nabla^2 + V_{\mathrm{lattice}}(\mathbf{R}) + M_g g Z \right] \psi_\alpha(\mathbf{R}) + \hbar\omega_0 \int \mathrm{d}^3\mathbf{R}\, \psi_e^\dagger(\mathbf{R}) \left[1 + \frac{\hbar^2}{2M_g^2 c^2}\nabla^2 + \frac{gZ}{c^2} \right] \psi_e(\mathbf{R})$$

Gravitational Redshift

$\sim 4.4 \times 10^{-23}$ per site

V. J. Martínez-Lahuerta *et al.*, arXiv: 2202.10854 (2022).
A. Chu /A. Rey, K. Hammerer, P. Zoller ,…

Gravity & quantum many body

$$H = H_{\mathrm{on-site}} + H_{\mathrm{off-site}} + H_{\mathrm{laser}}$$

$$H_{\mathrm{on-site}}/\hbar = \sum_n \chi_0 S_n^z S_n^z$$

Commute with H_{GR}

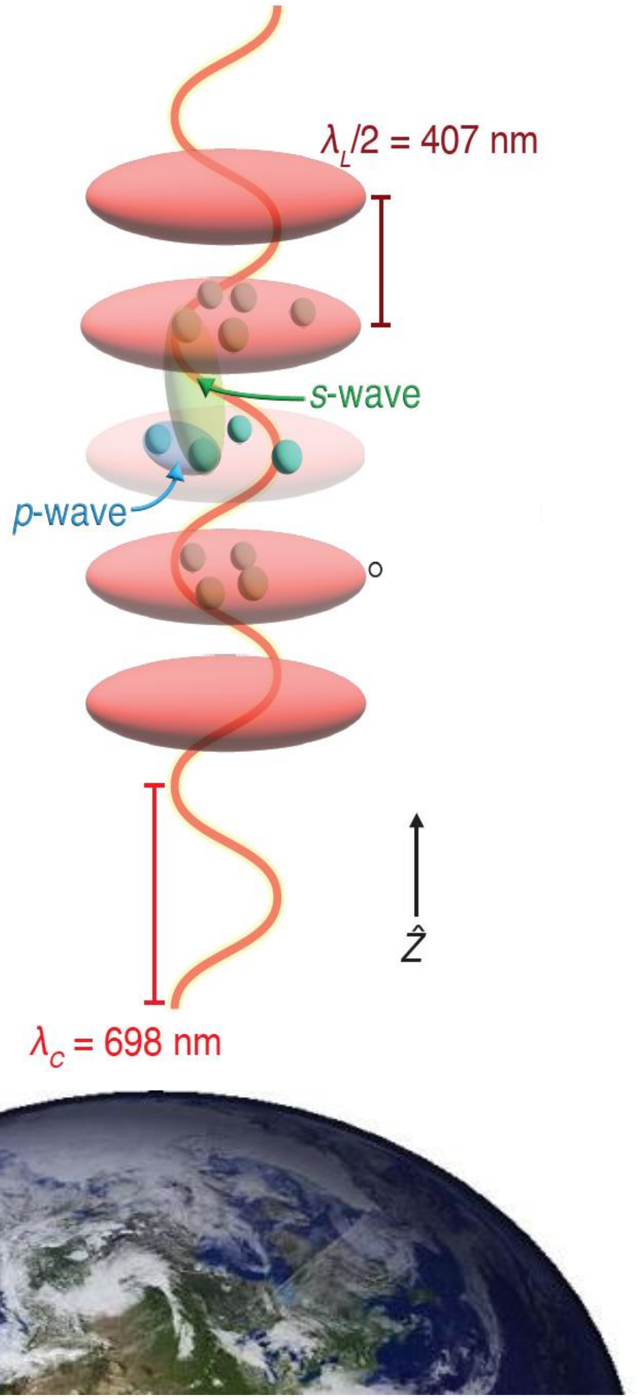
$$H_{\mathrm{off-site}}/\hbar = \sum_n \chi_1 S_n^z S_{n+1}^z$$

Not commute with H_{GR}

Shift ~ 10^{-23} - 10^{-24}

$$H_{\mathrm{laser}}/\hbar = \sum_n \left[-\delta S_n^z + \Omega_0 S_n^x \right]$$

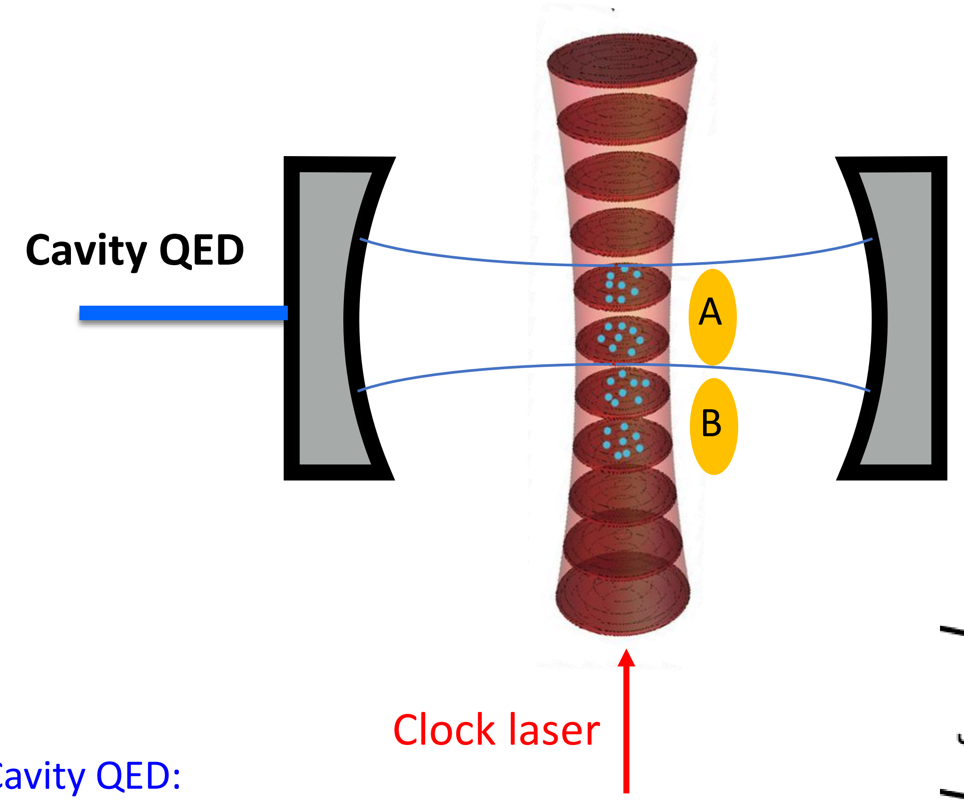
$$H_{\mathrm{GR}} = \hbar\omega_0 \sum_n \frac{g a_L n}{c^2} S_n^z$$

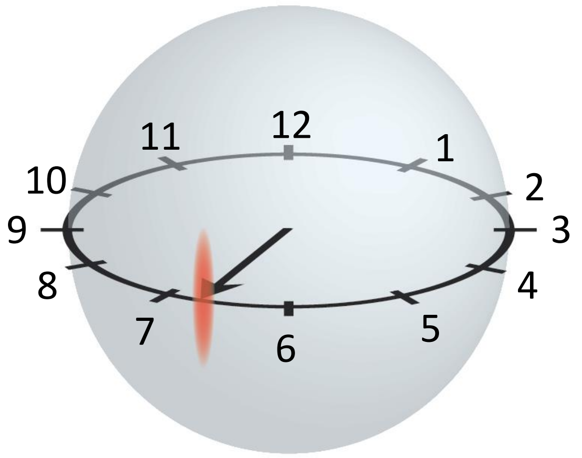


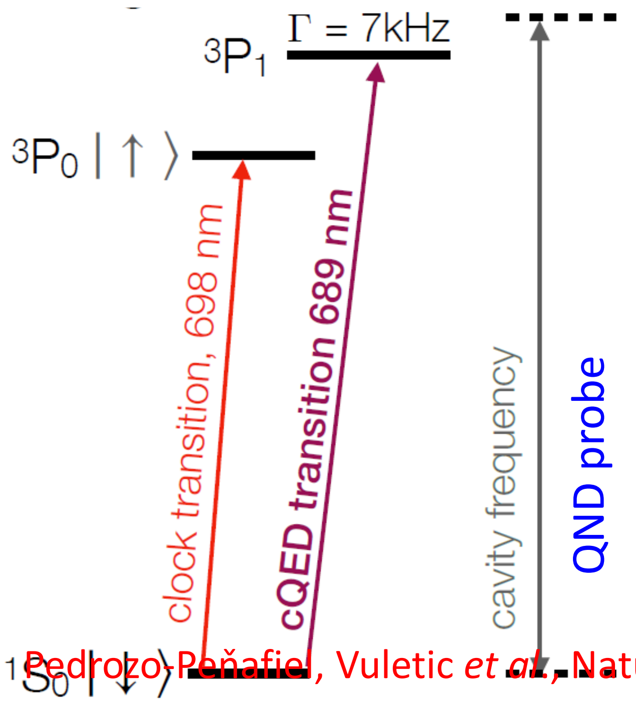
Spin squeezing

Kasevich, Polzik, Schleier-Smith, Thompson, Vuletic

- Spin Squeezing at 10^{-17}
- Direct clock comparison with quantum advantage

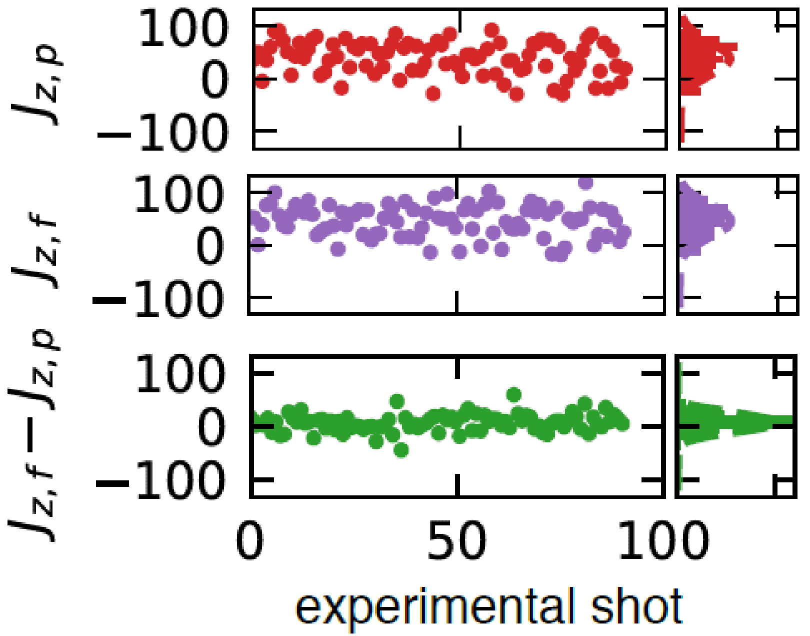






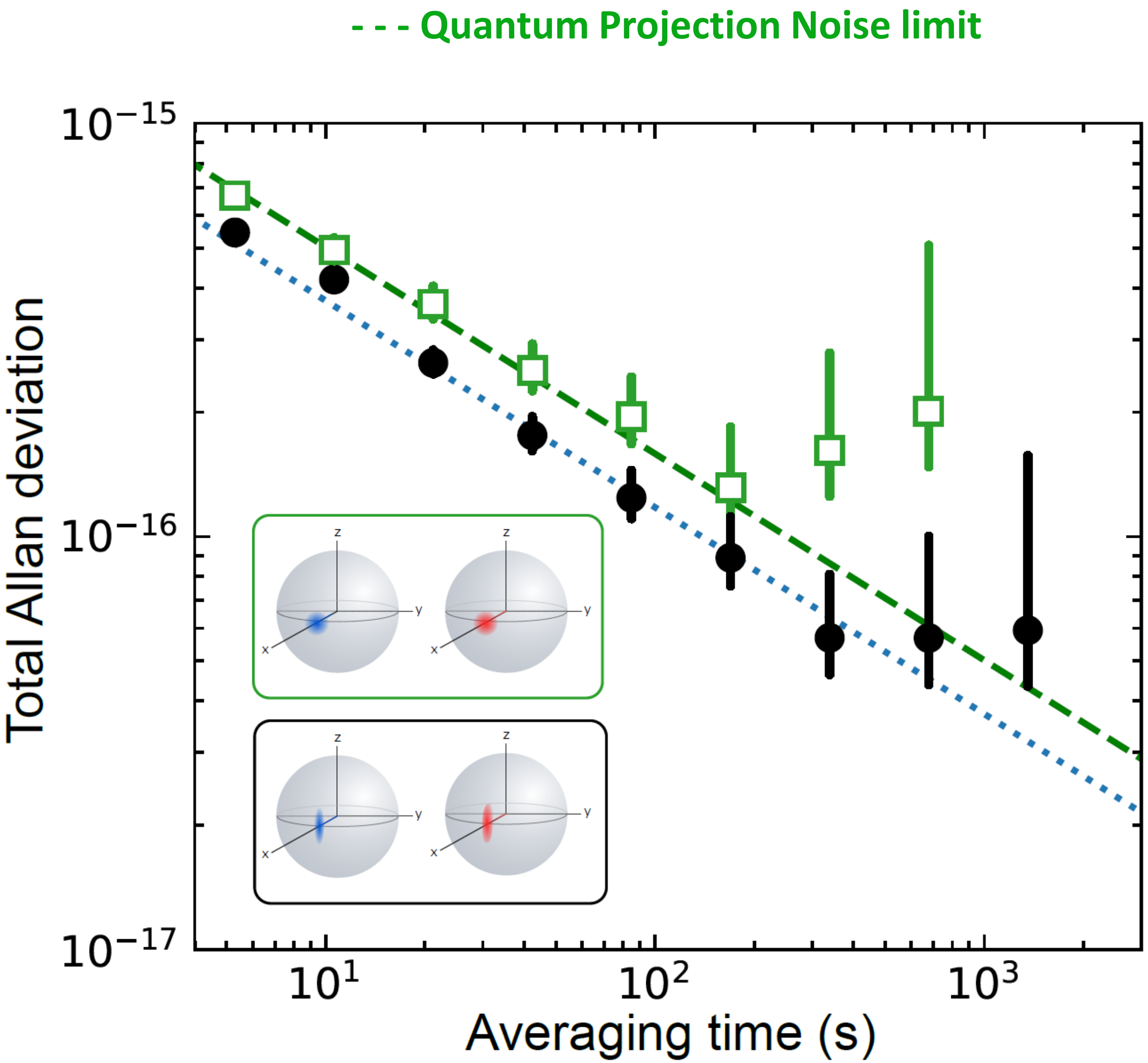
Cavity QED:

$\kappa/2\pi$ = 157 kHz
$\Gamma/2\pi$ = 7.5 kHz
C_{eff} = 0.03
N_{eff} = 10^4
$N_{eff}C_{eff} >> 1$



Pedrozo-Peñafiel, Vuletic *et al.*, Nature **588**, 414 (2020).

Direct verification of squeezing-enhanced stability

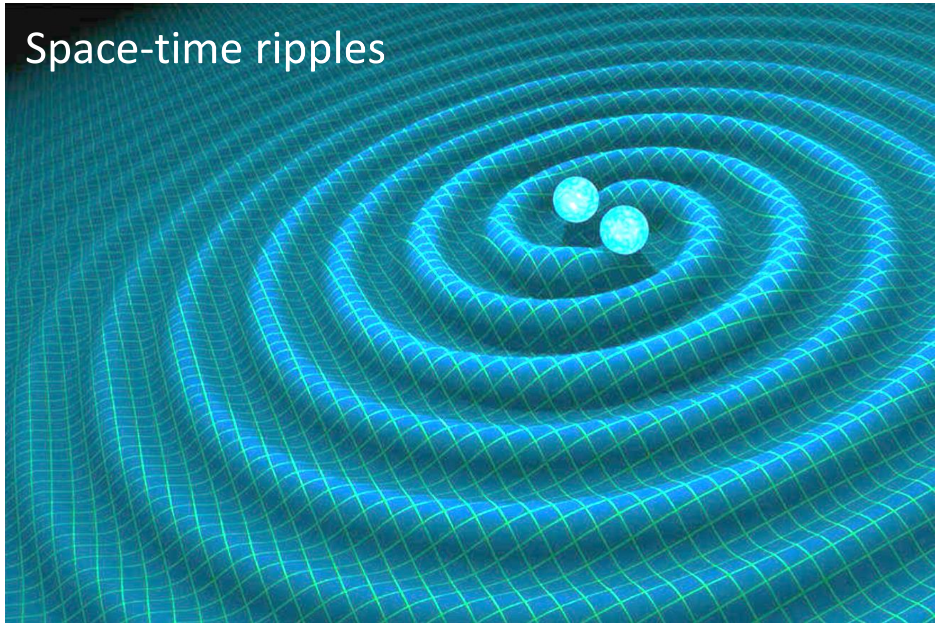


Clock comparison
between two squeezed samples

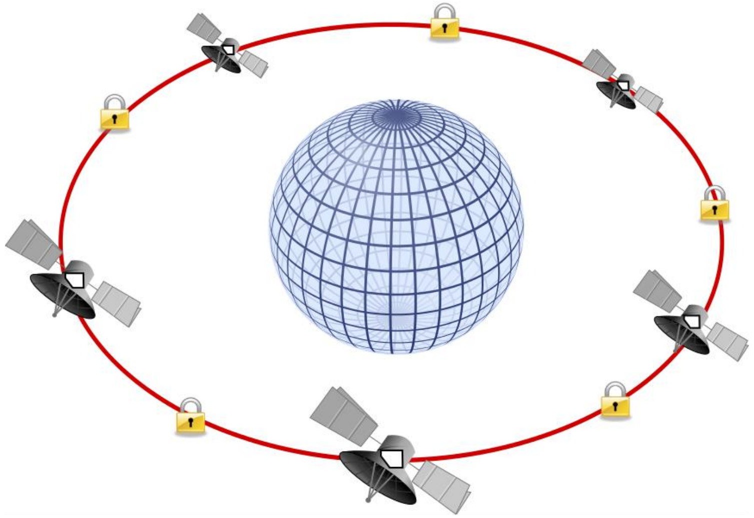
Probes for the Universe & our Earth

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

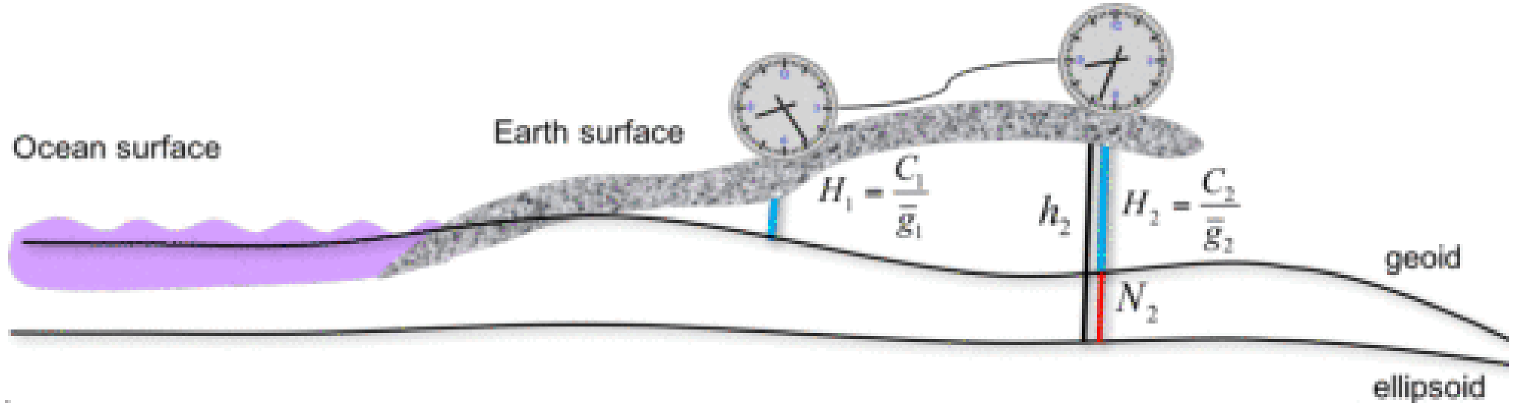
Telescope:
- **Gravitational waves**
- **Dark Matter**



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



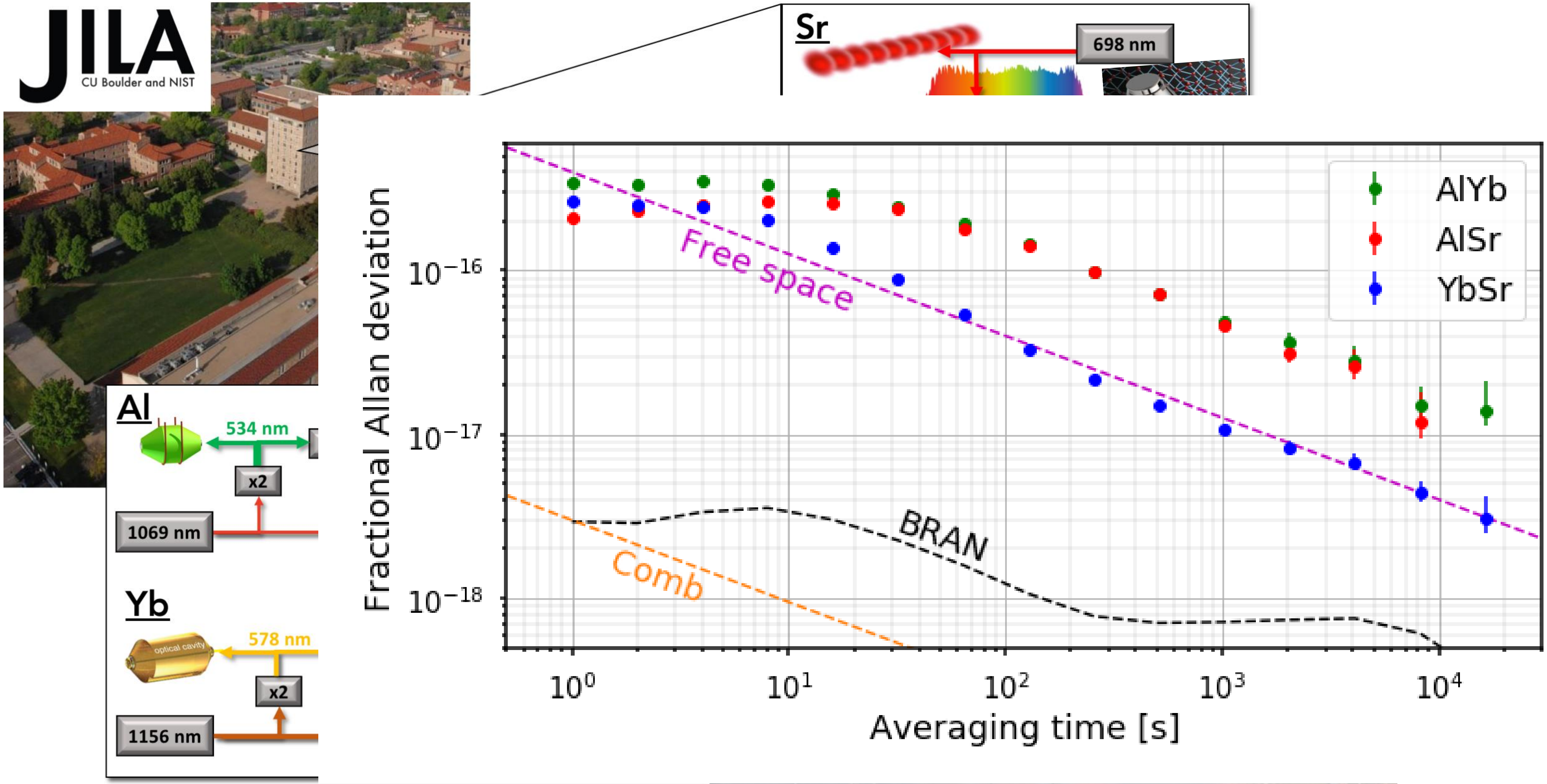
Microscope:
- **Earth geodesy**



Boulder Area Optical Clock Network

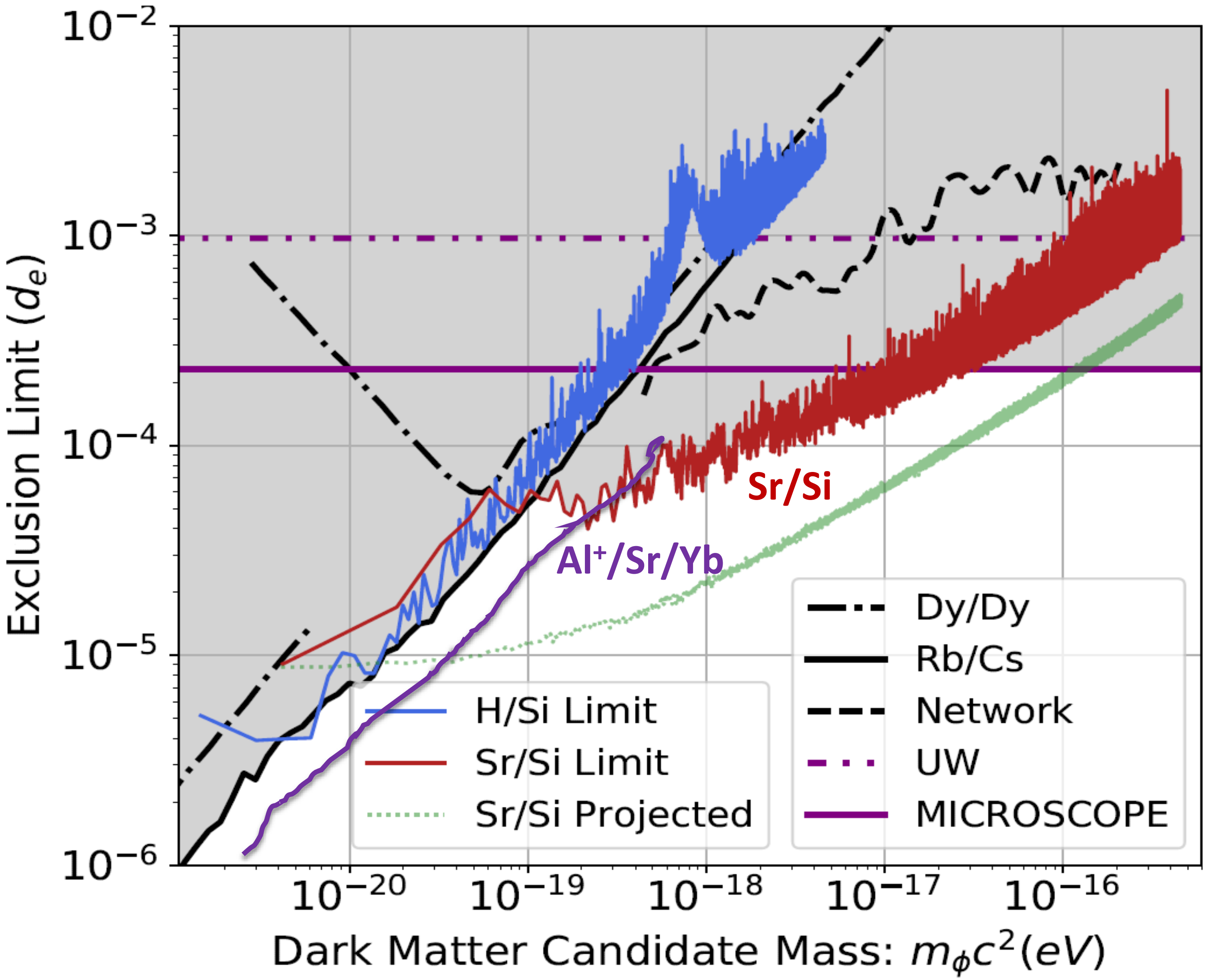
Beloy *et al.*, Nature **591**, 564 (2021).

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



Search for ultralight dark matter

C. Kennedy *et al.*, Phys. Rev. Lett. **125**, 201302 (2020). Beloy *et al.*, Nature **591**, 564 (2021).



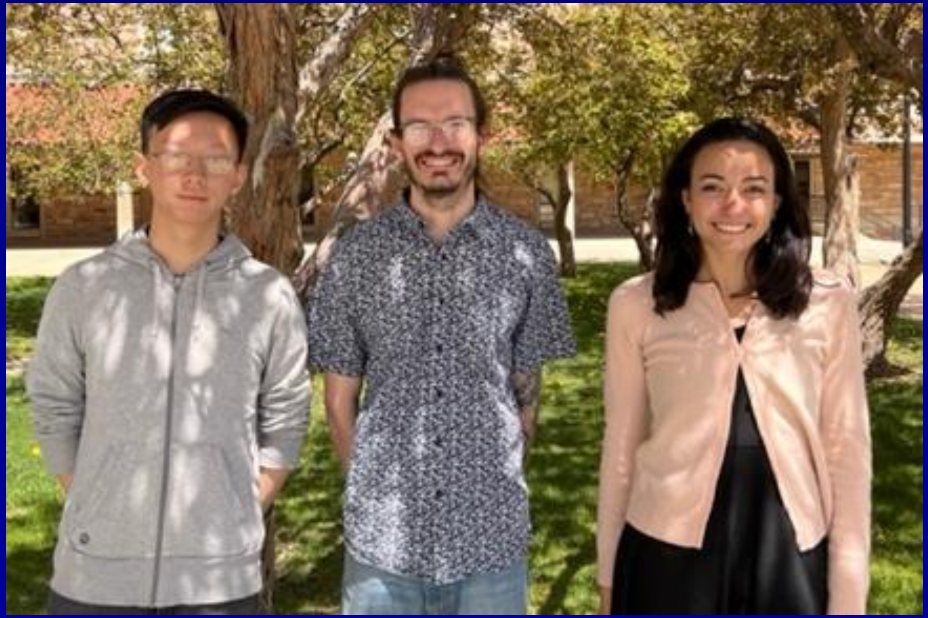
Sr optical clock: quantum meets precision

K. Kim
A. Aeppli
W. Warfield

D. Kedar
B. Lewis
Z. Yao

C. Sanner
L. Sonderhouse
R. Hutson
W. Milner
L. Yan

M. Miklos
J. Robinson
Y. M. Tso



Theory:
A. M. Rey

Collaboration: J. Thompson, A. Kaufman, M. Holland, M. Safronova, M. Lukin, P. Zoller, … , NIST T&F, PTB