Quantum Clock & Fundamental Physics

Search for ultra-light FIPs with clocks & cavities

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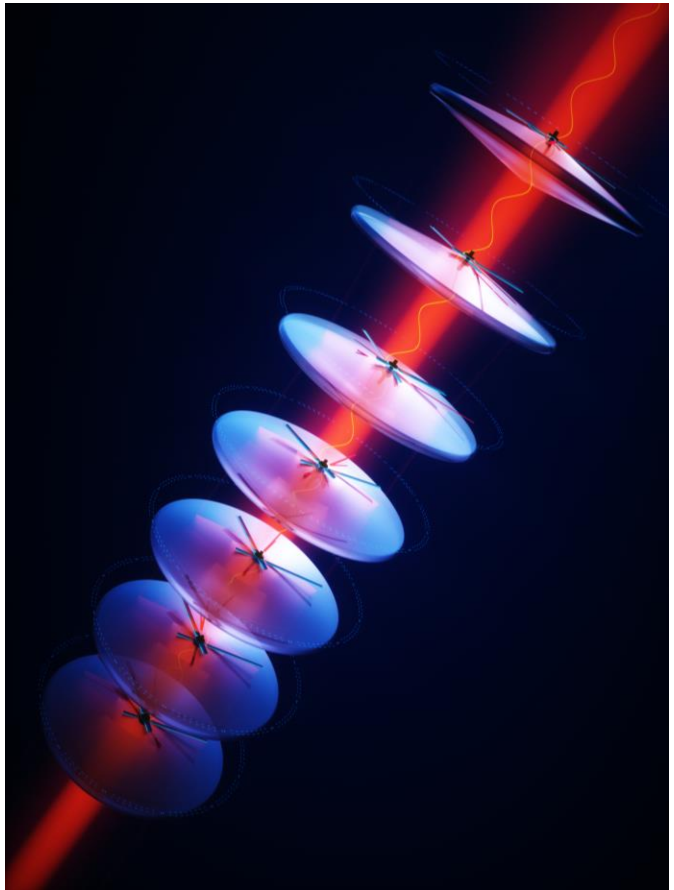
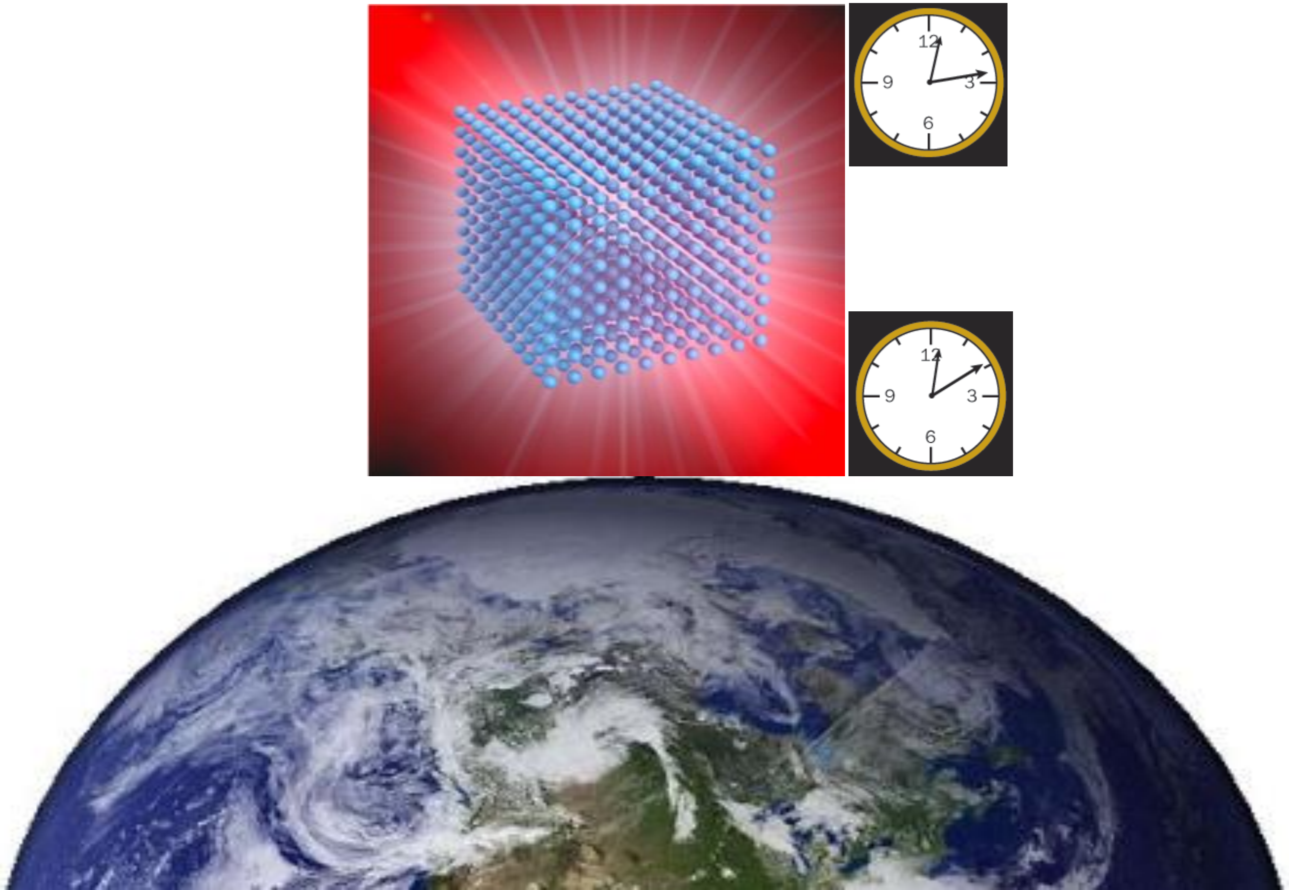
JILA, NIST & Univ. Colorado

FIPs 2022 Workshop, CERN, October 17 – 21, 2022





Coherence, precision, entangled states

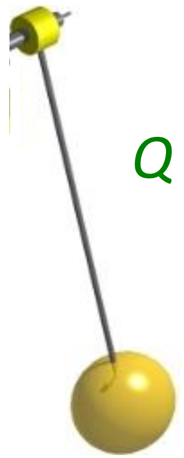
Precision frontier meets Quantum frontier

Optical atomic clocks:

- Current accuracy ~10^{-18} → < 1×10^{-18} ?
- Precision 3×10^{-19} → 6×10^{-21}

- Quantum control: *High Q optical transitions*
- New laser technology: *Optical coherence*
- Optical frequency comb: *Phase distribution*
- Quantum gas & optical trapping: *Many-body states*

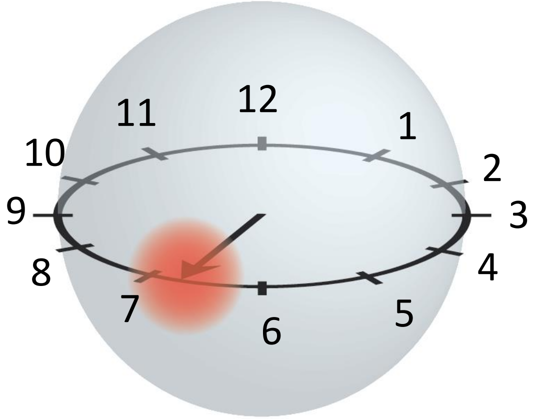
Long coherence time



$Q \sim 10^{17}$

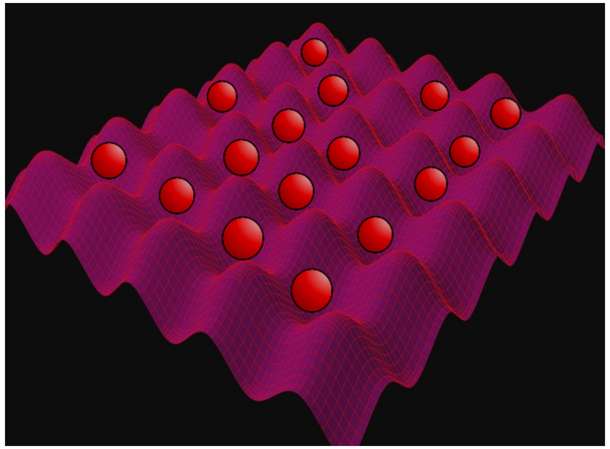
Quantum system design

Large count rate



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

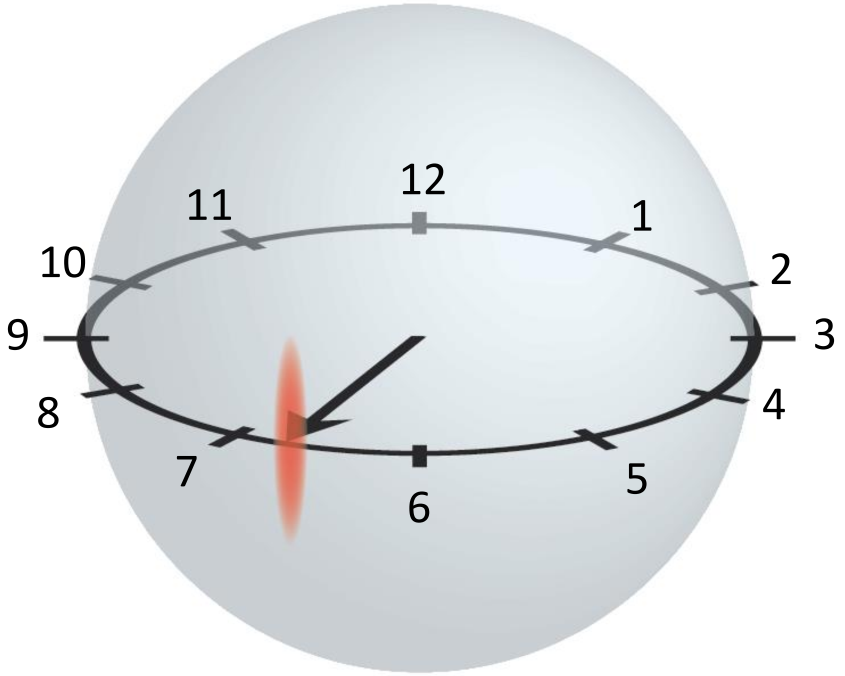
Many-body states



Quantum optimization & enhancement

Quantum noise

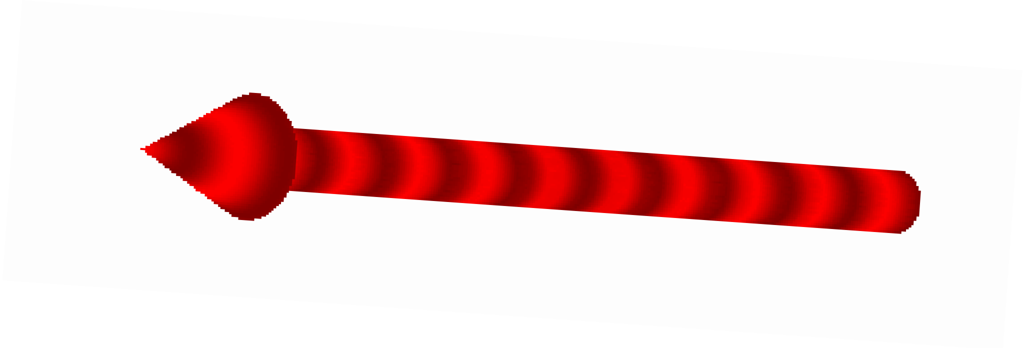
Quantum Phase Noise of Atoms

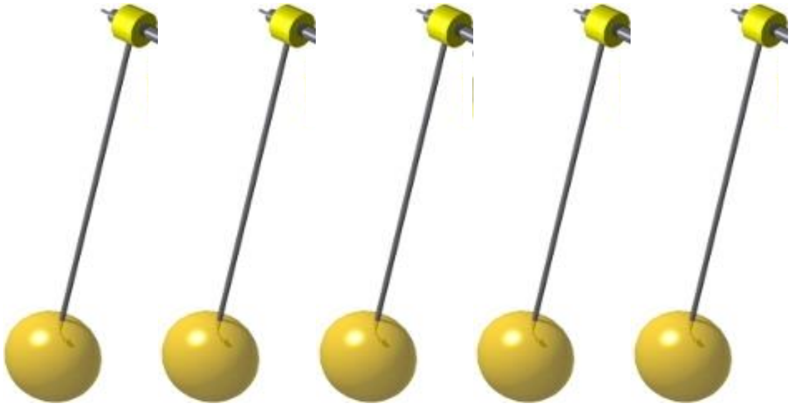


$$\frac{1}{\sqrt{2}}\left(e^{-iEt}|e\rangle + |g\rangle\right)$$

Sr coherence: 120 s

Phase of Coherent Laser





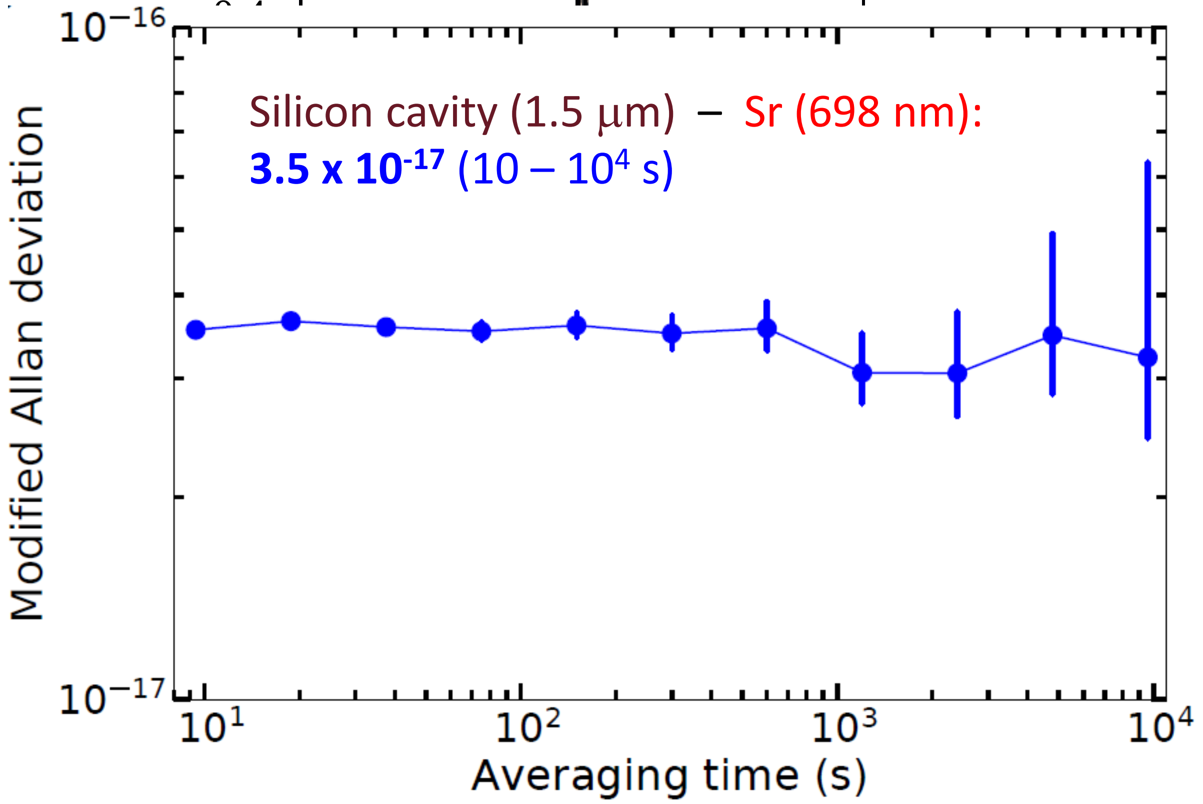
$$\Delta\phi_{SQL} = \frac{1}{N}\,\text{rad}$$

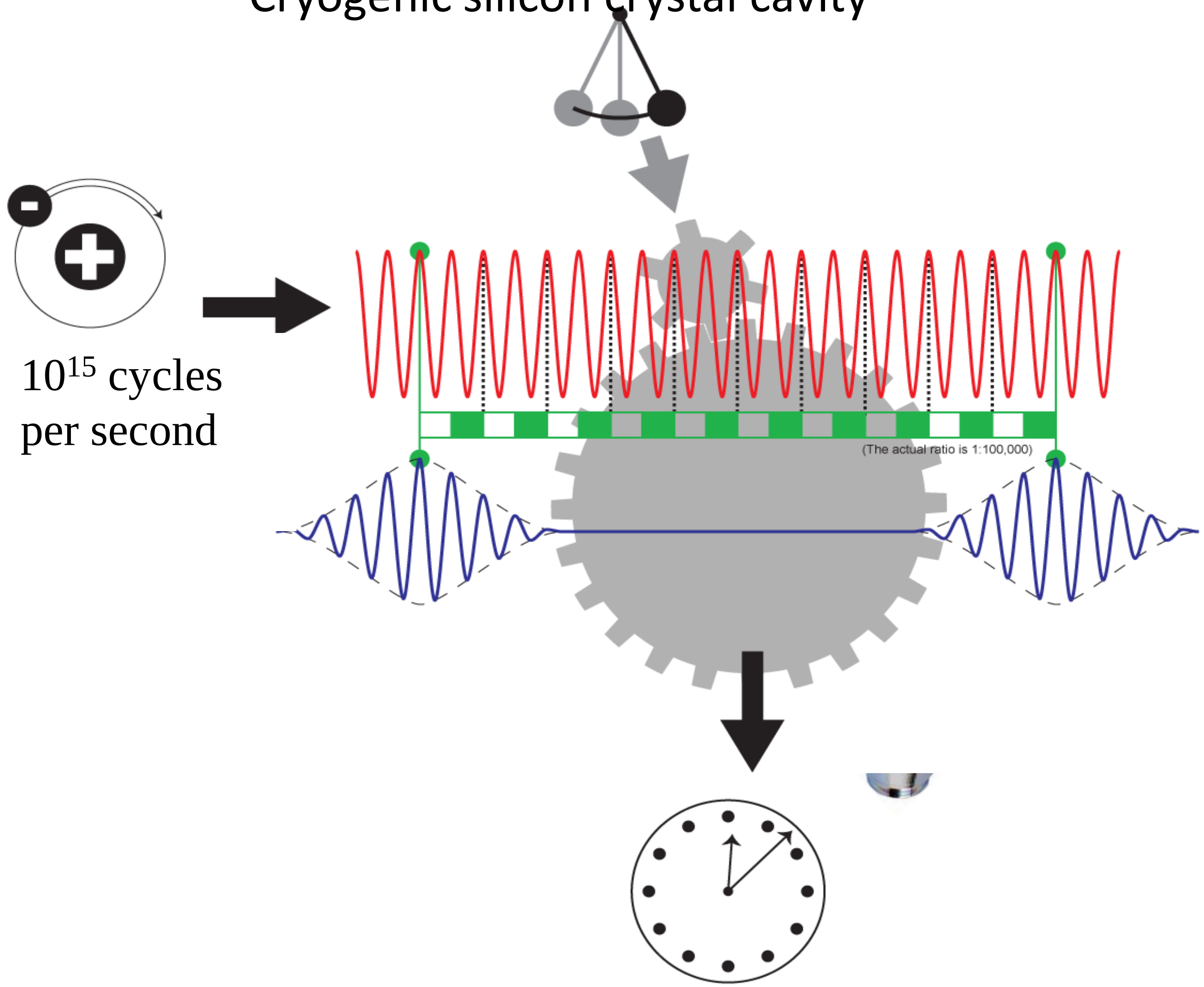
A new generation of stable lasers

Optical coherence approaching 1 minute

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

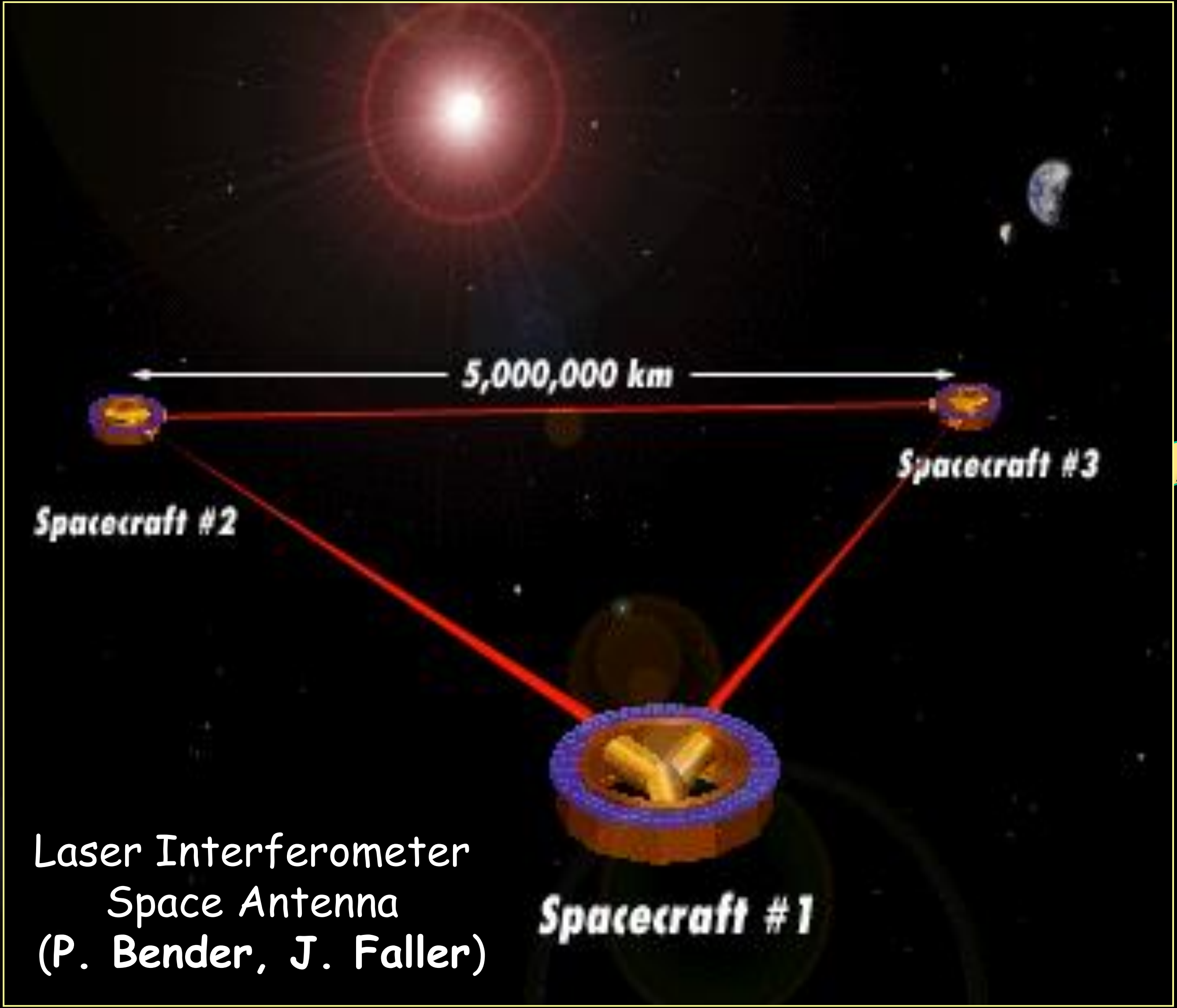
Oelker *et al.*, Nature Photon. **13**, 714 (2019).



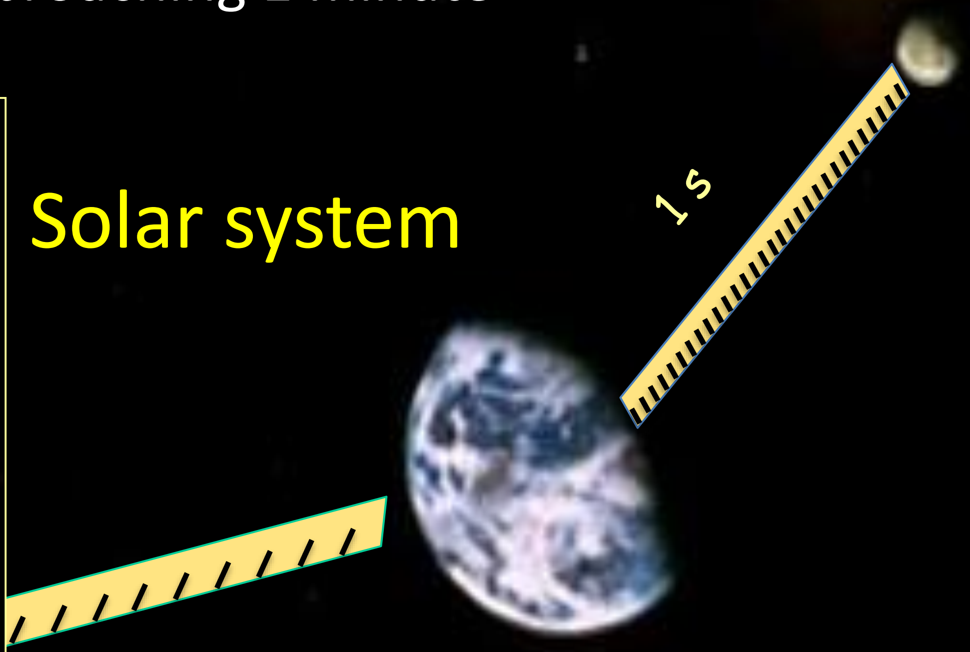


A new generation of stable lasers

Optical coherence time approaching 1 minute

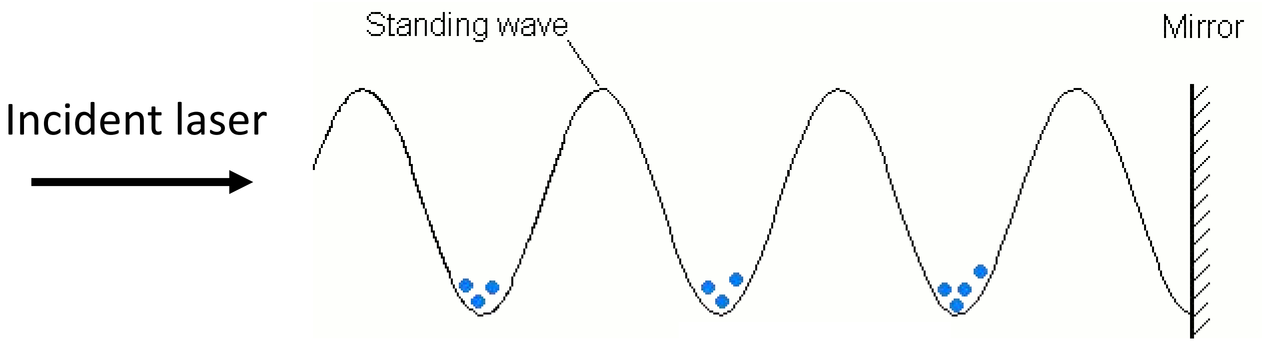


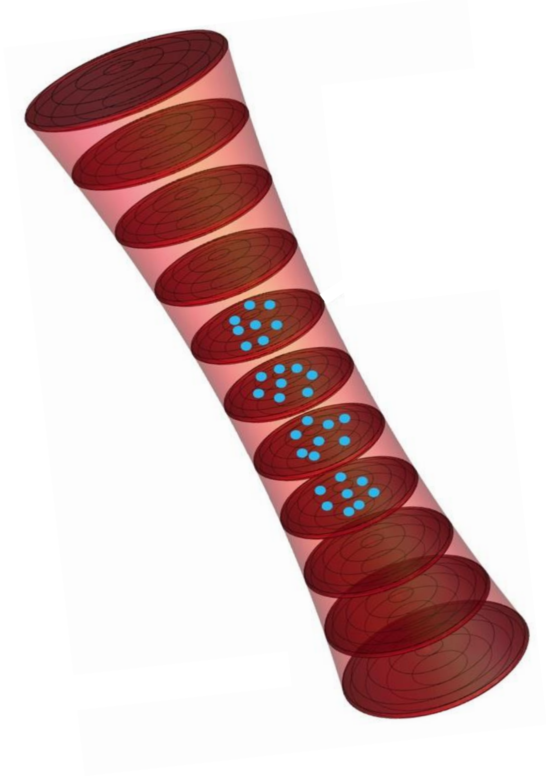
Solar system

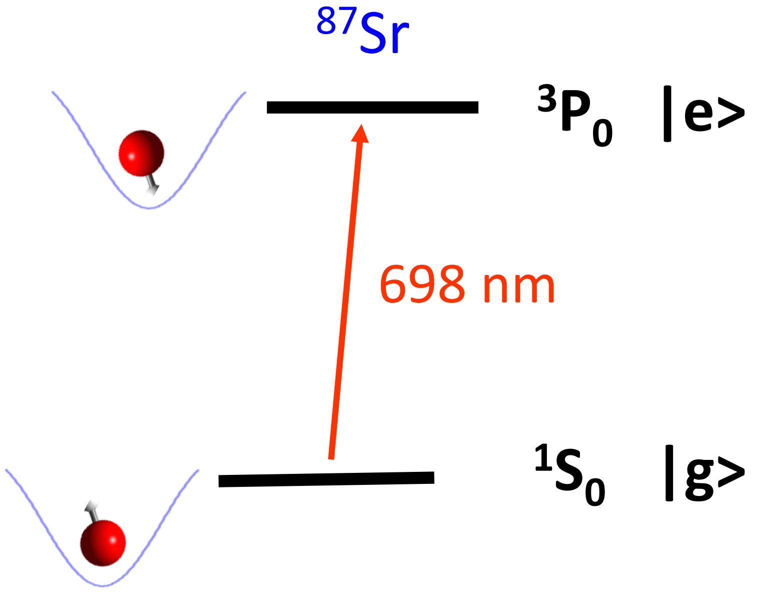


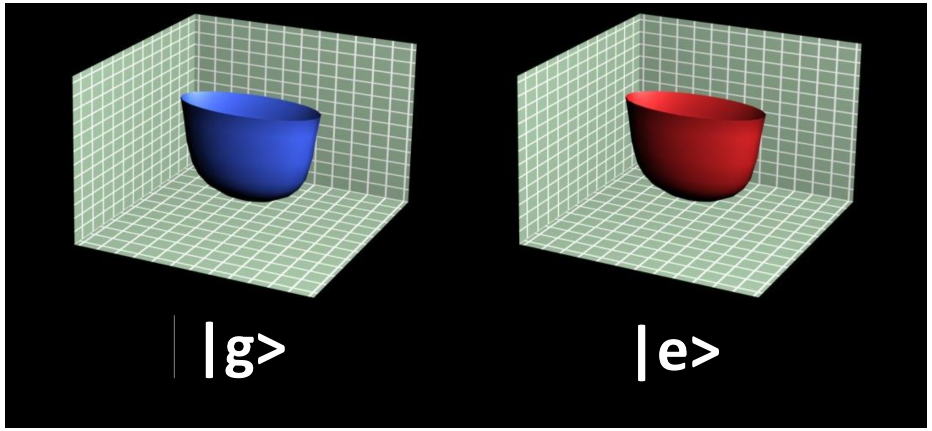
Holding atoms in a magic light bowl

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



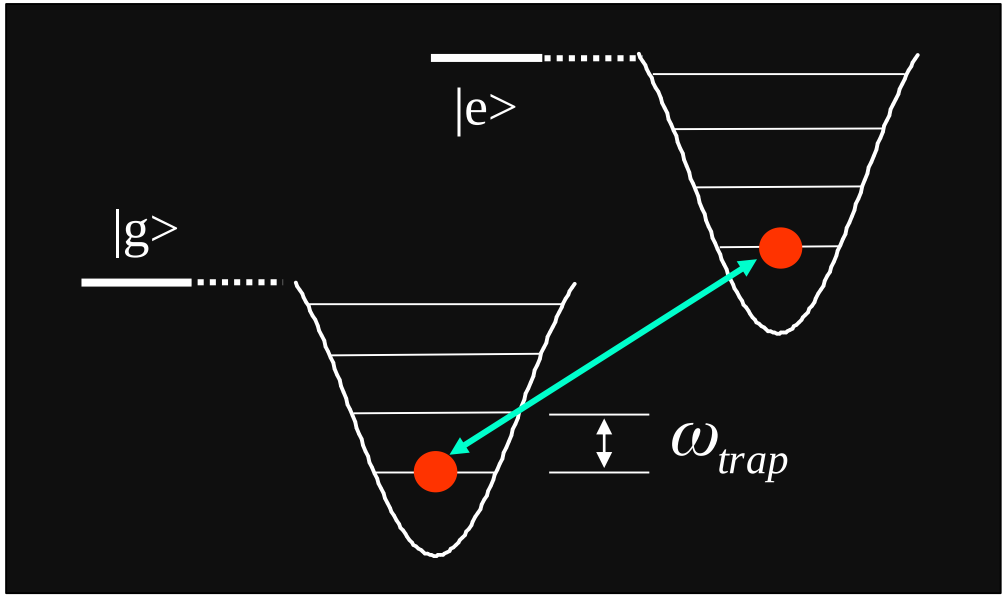


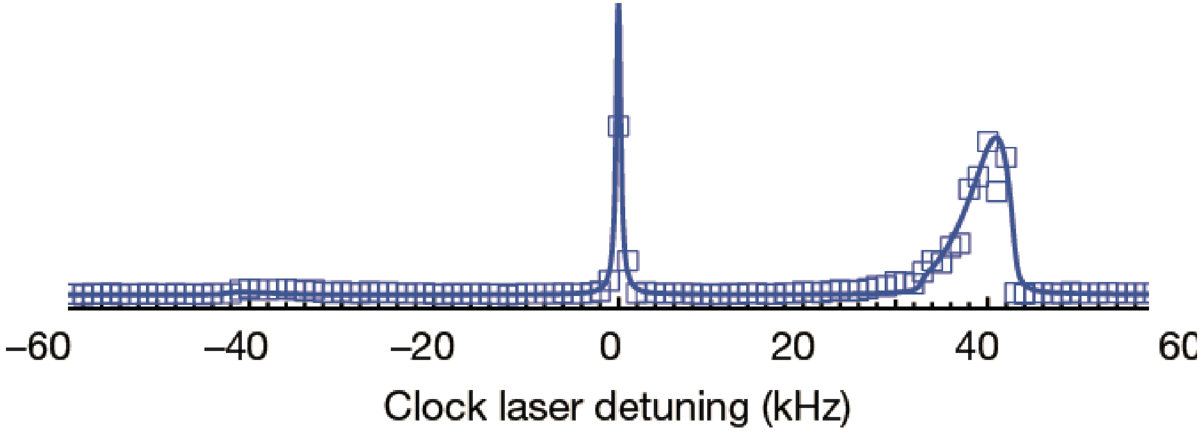


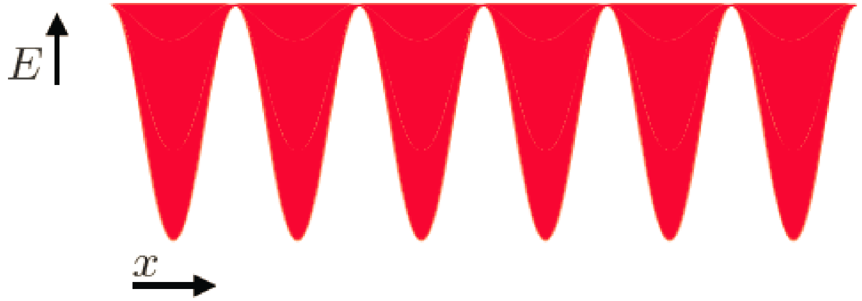


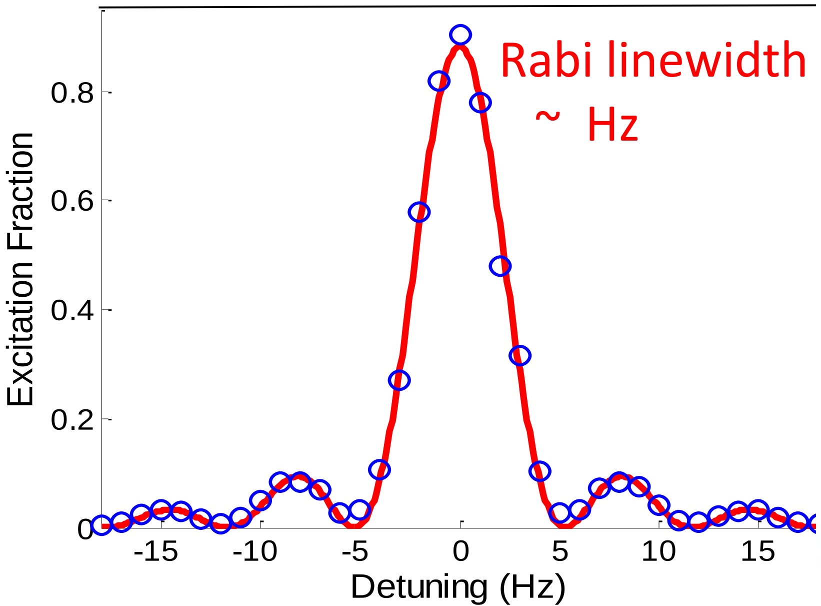
Quantized motion

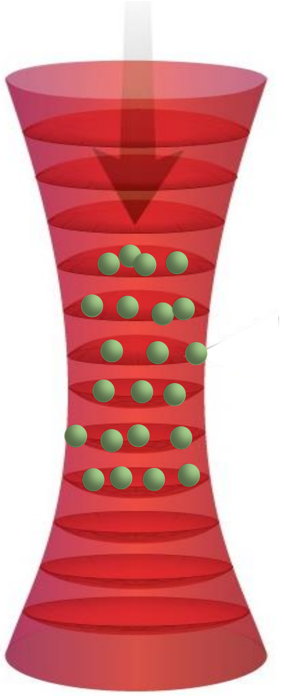
Ye, Kimble, Katori, Science **320**, 1734 (2008).









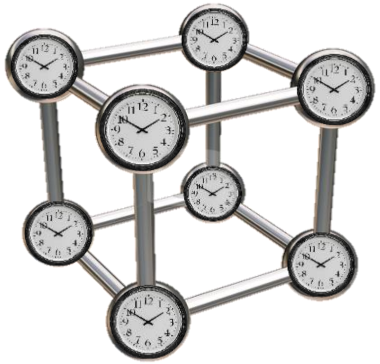


- Doppler, recoil, trap shifts = 0
- Precision improvement by $N^{1/2}$

3D Fermi insulator clock

Scaling up the Sr quantum clock:

1 million atoms
(100 x 100 x 100 cells)

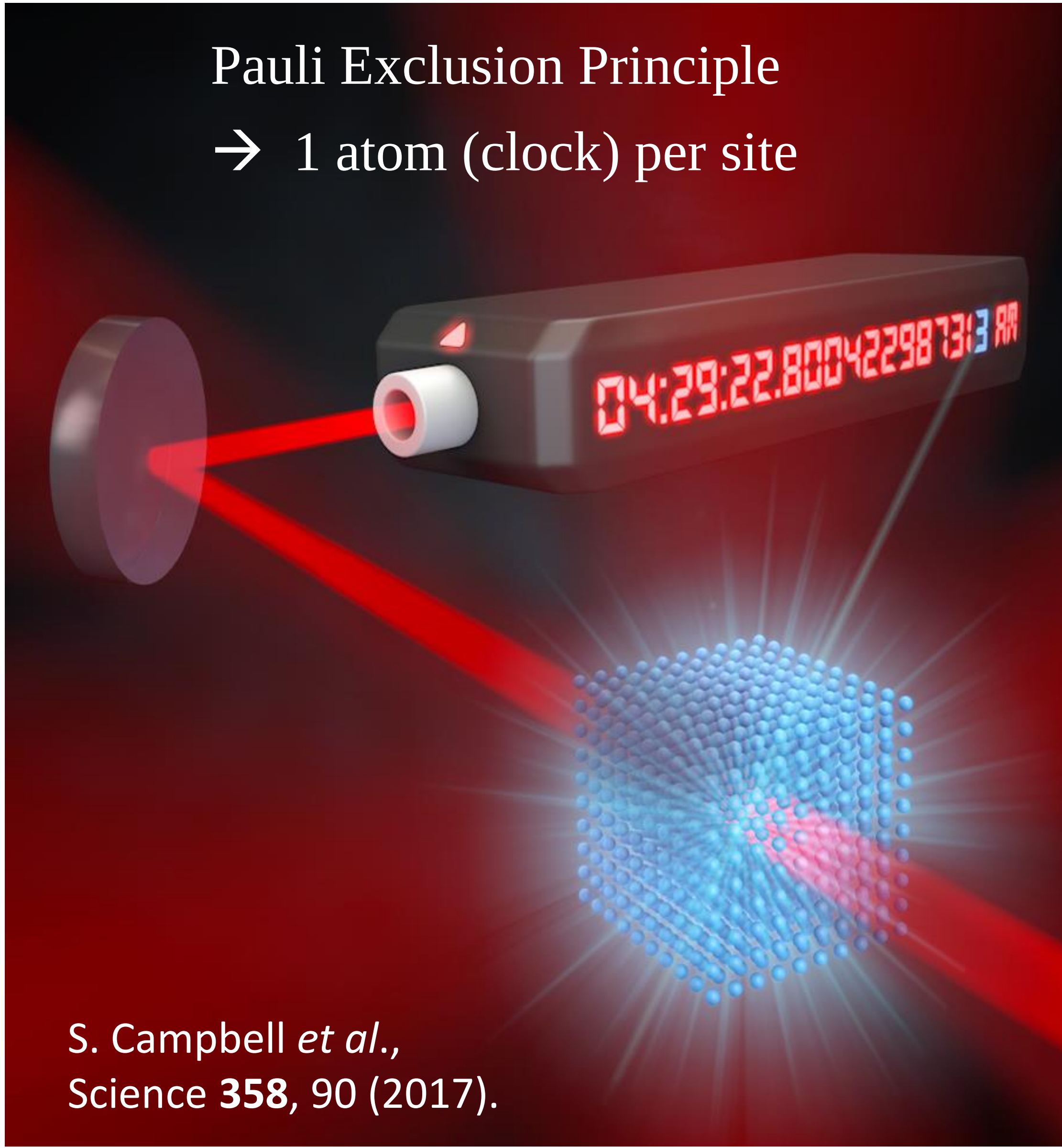


Coherence 120 s

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

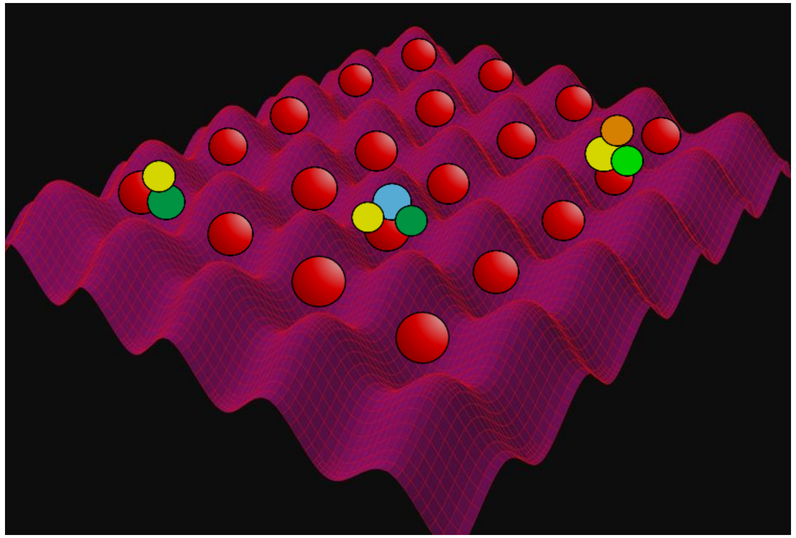
2022 Record: 3 x 10^{-18} at 1 s

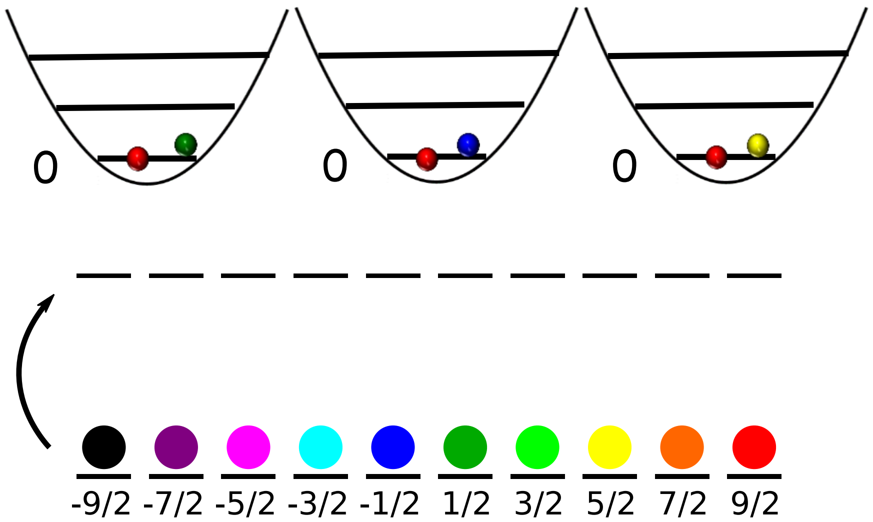
Quantum simulator & sensor (Fermi Hubbard)



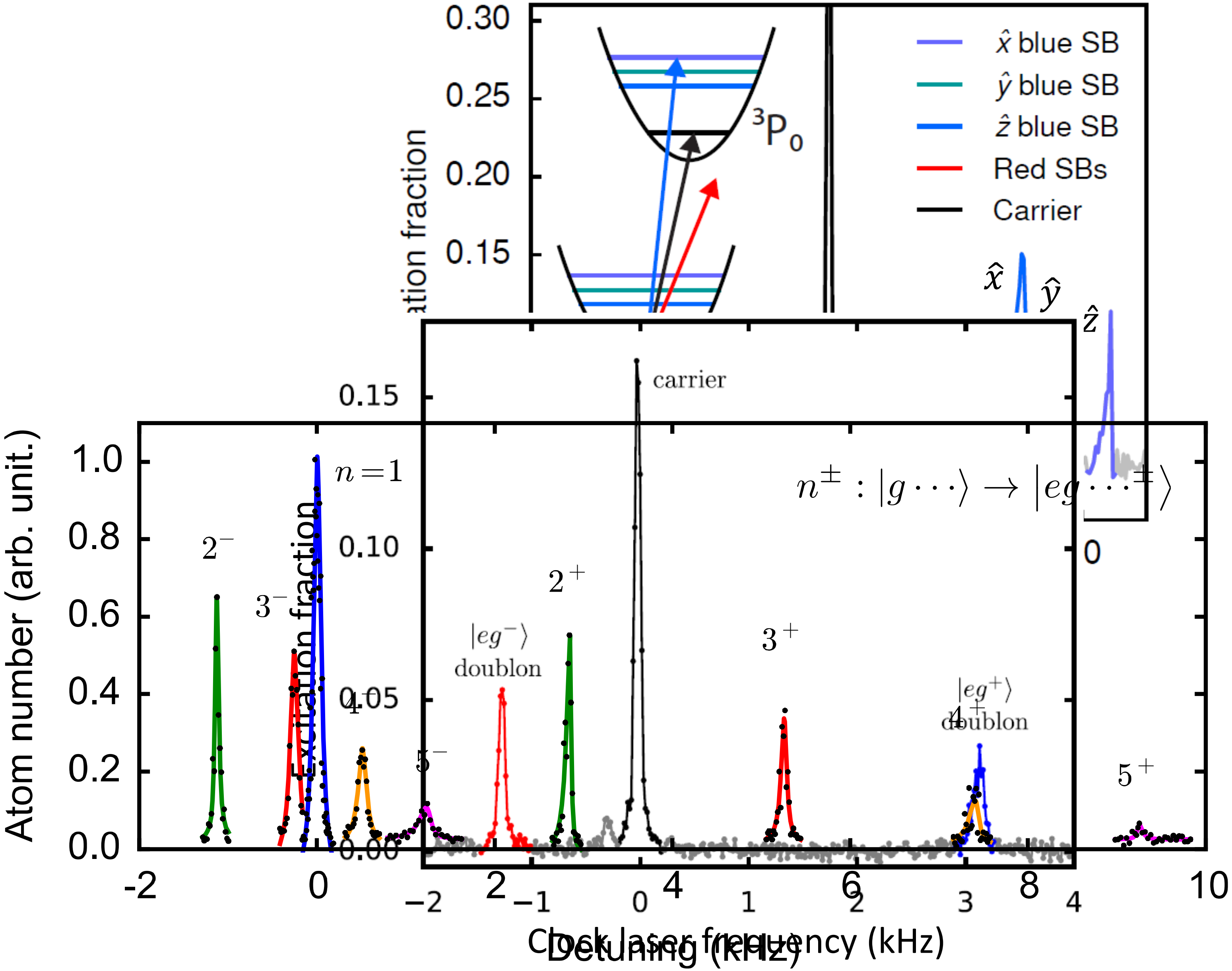
Quantized interaction

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





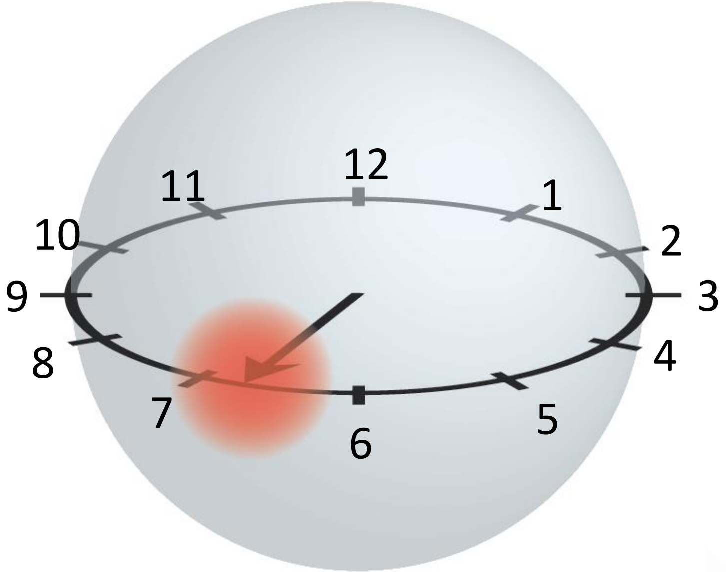
^{87}Sr: $J = 0, \quad I = 9/2$

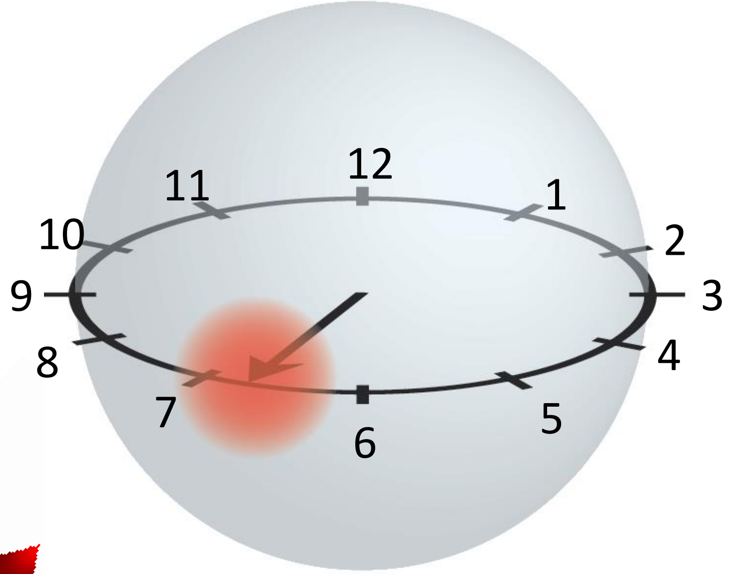


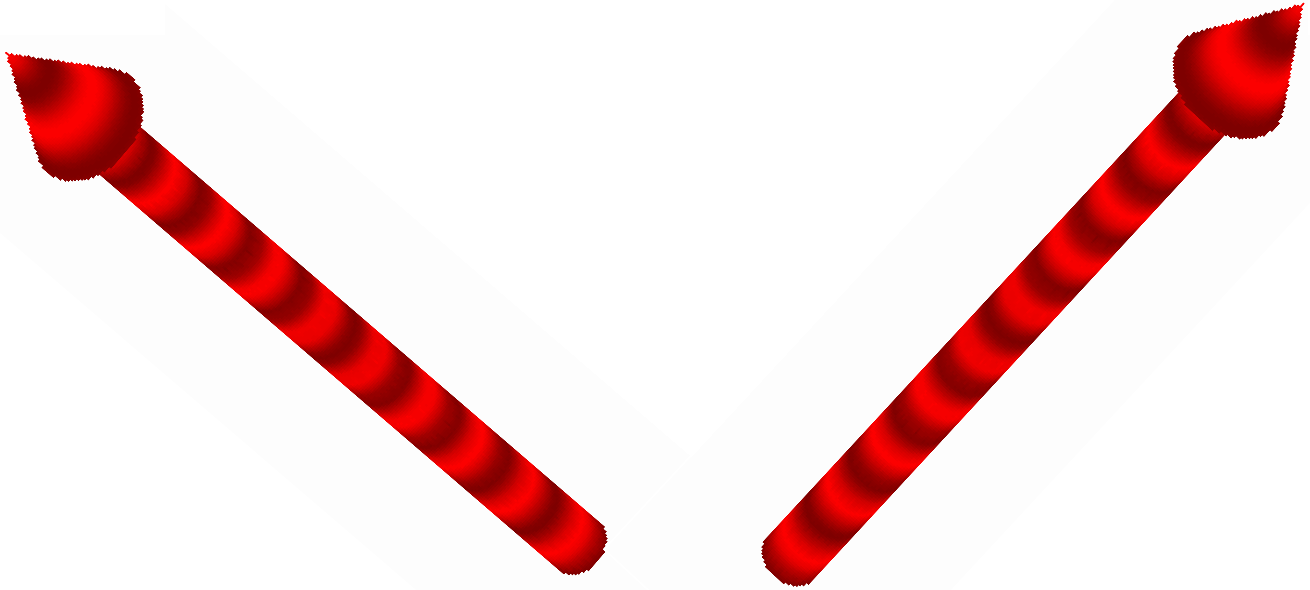
Clock comparison

1. Common local oscillator: atom vs. atom

2. Separate local oscillators: frequency ratio

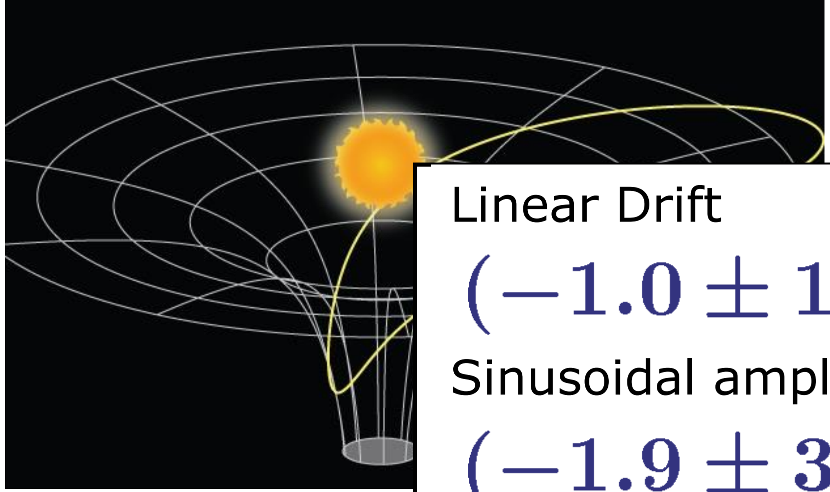






Local Lorentz Invariance

Fundamental constants vs gravitational potential



Linear Drift

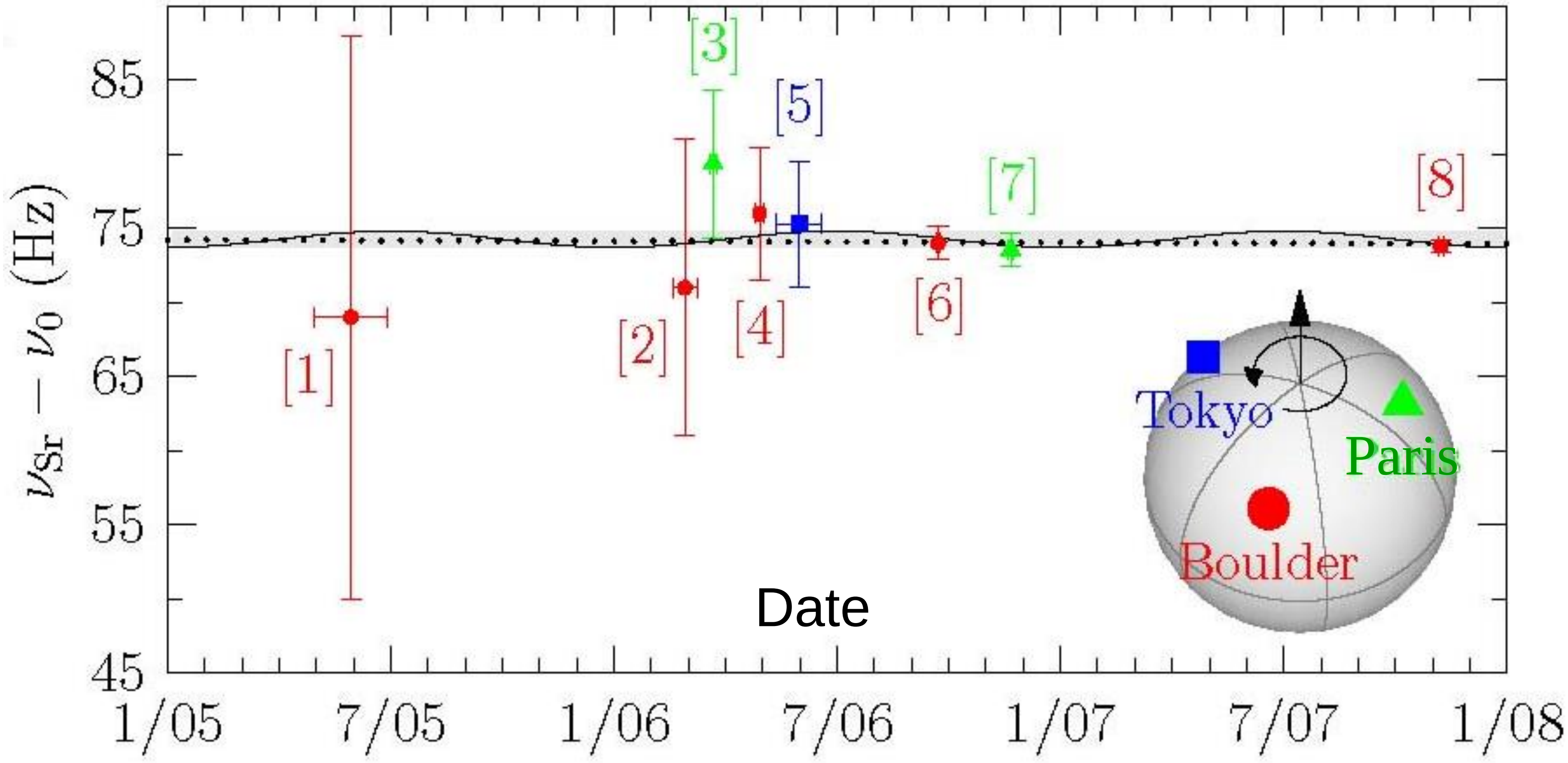
$$(-1.0 \pm 1.8) \times 10^{-15}$$

← constrains linear drift of fundamental constants

Sinusoidal amplitude

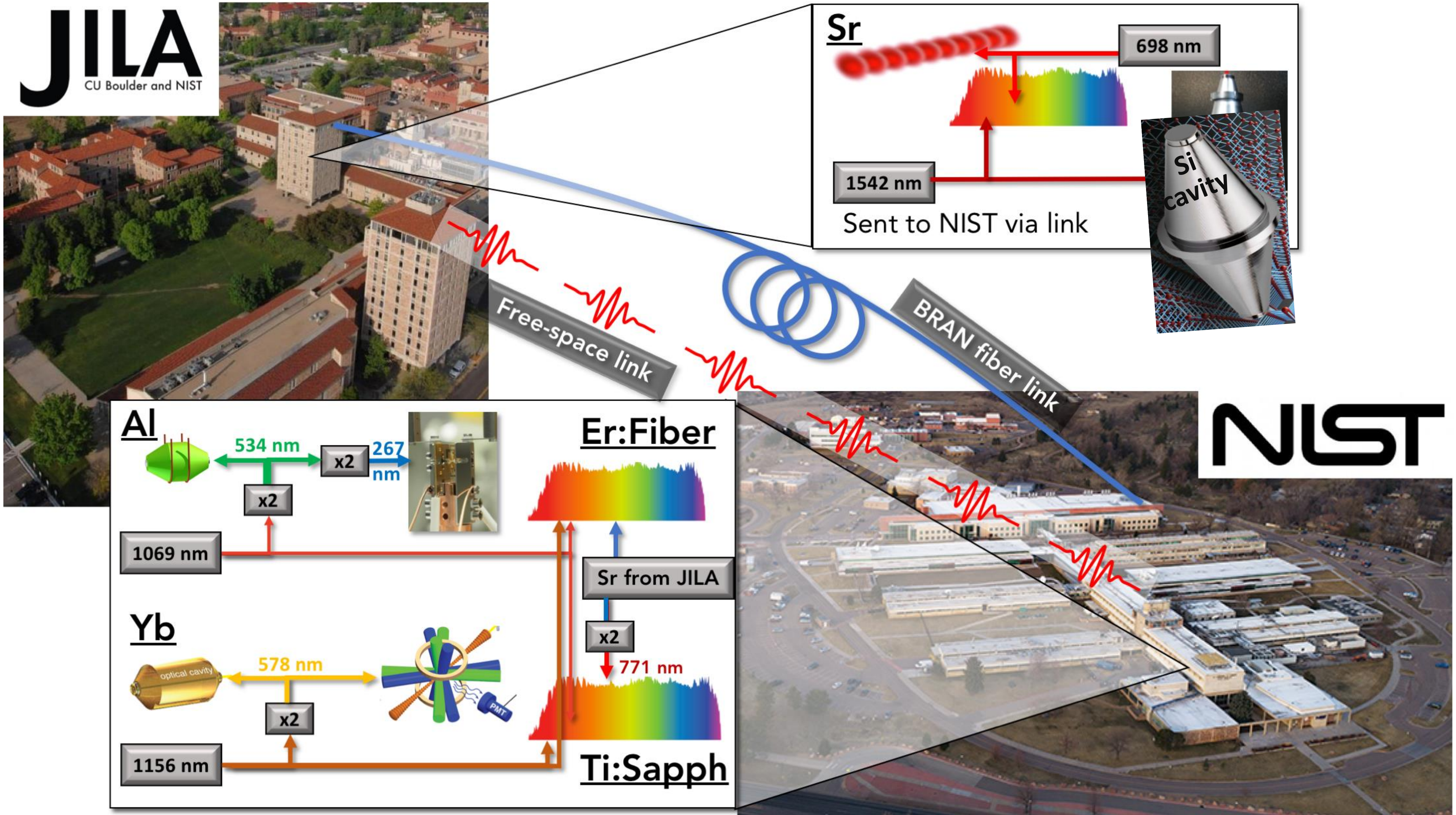
$$(-1.9 \pm 3.0) \times 10^{-15}$$

← constrains coupling coefficients to gravitational potential



Optical Clock Network

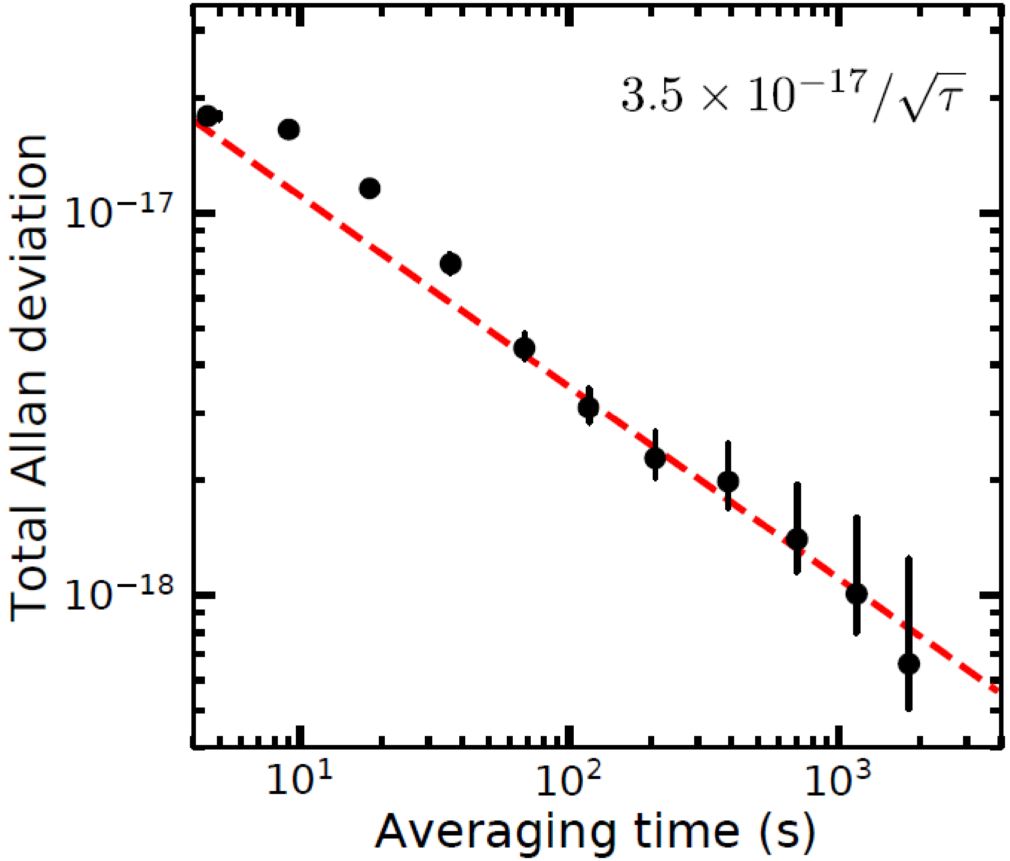
Beloy *et al.*, Nature **591**, 564 (2021): Three ratios measured at ~ 7 x 10^{-18}

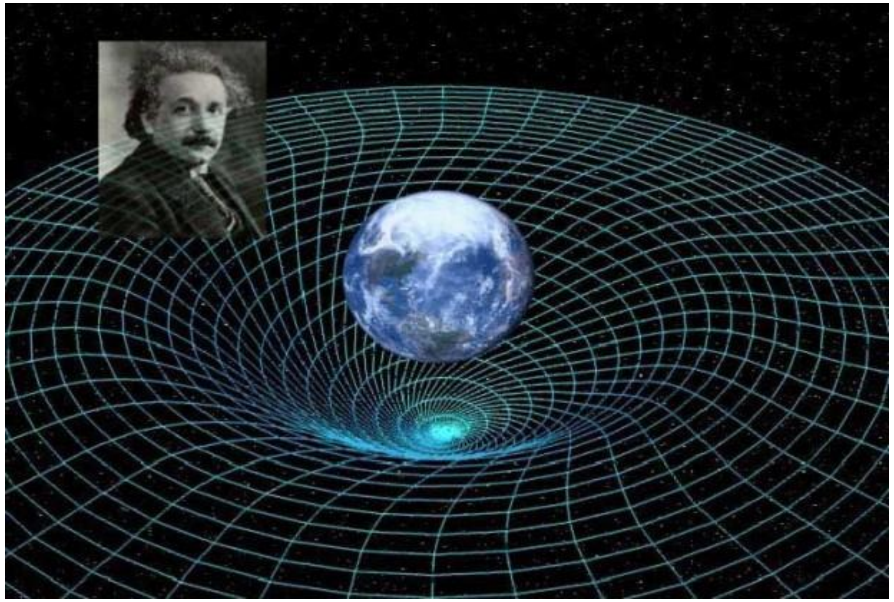


New stability for optical clocks

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

1 x 10^{-18} in 20 minutes (x 10 faster than any clocks prior to 2019)

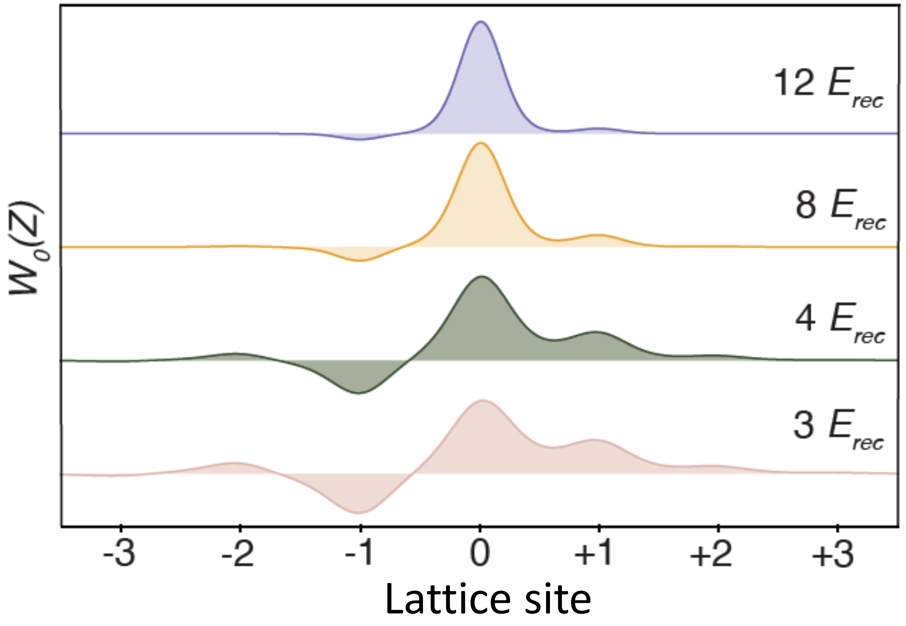




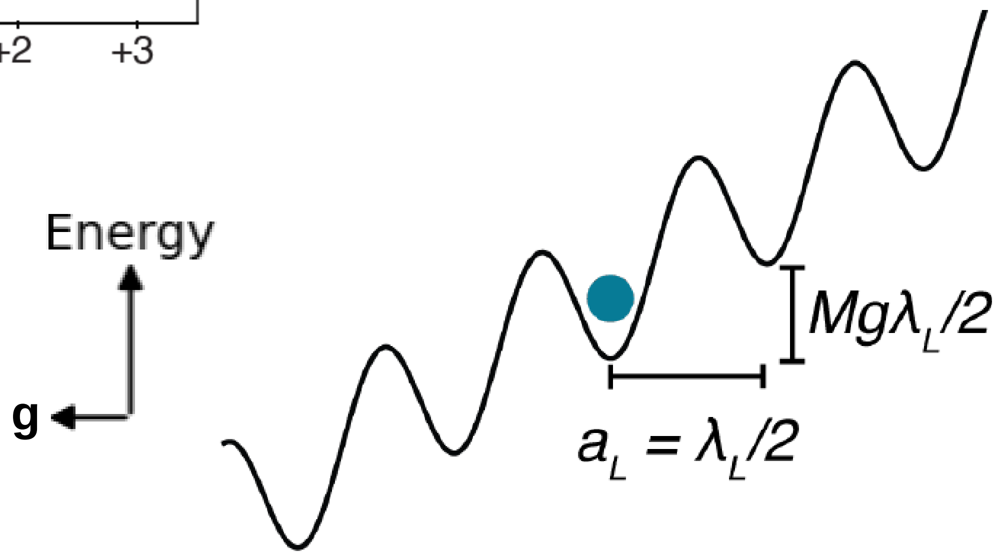
Gravitational potential difference of 1 cm in 20 minutes

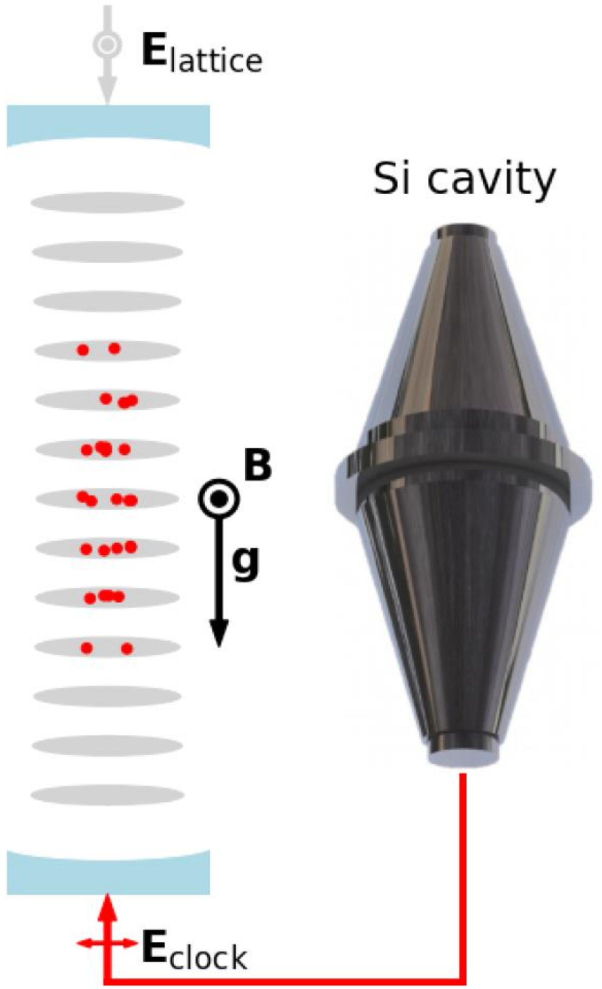
A new approach: Wannier-Stark lattice

Trap depth: U = 3 to 15 E_{recoil} (x10 shallower than traditional)



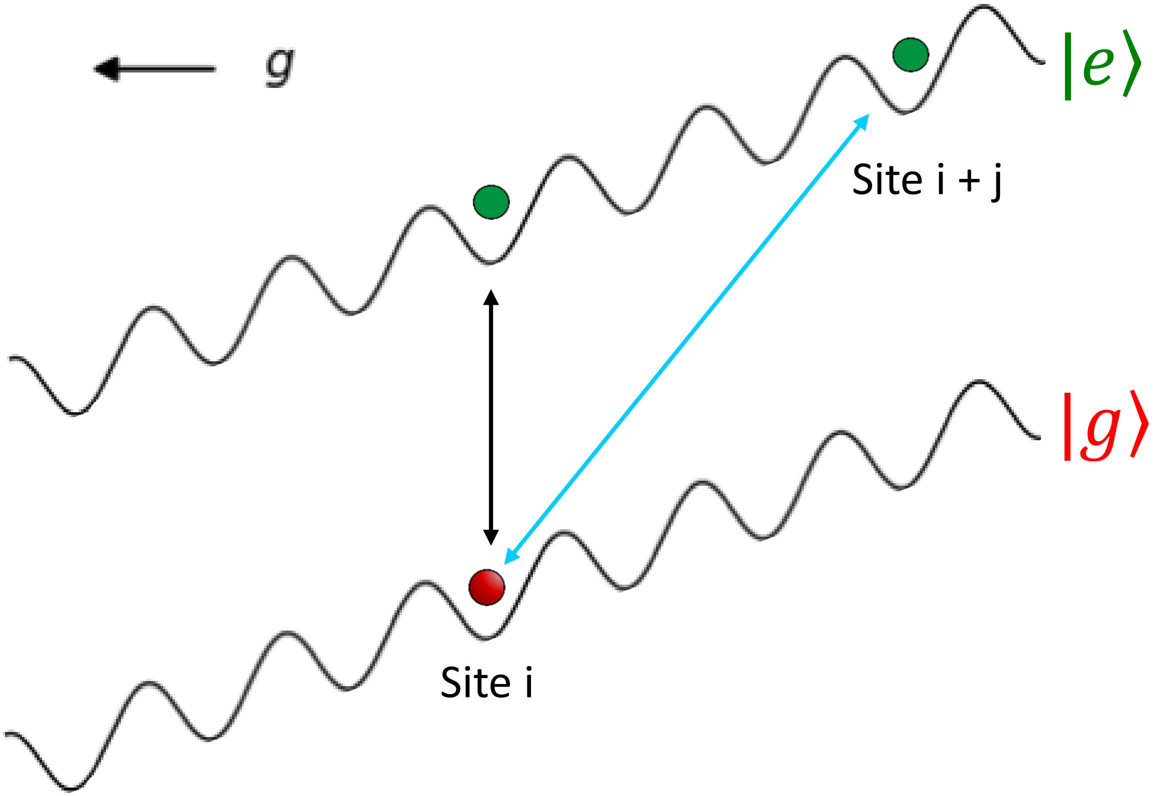
Wannier-Stark states:
Eigenstates of lattice plus gravity

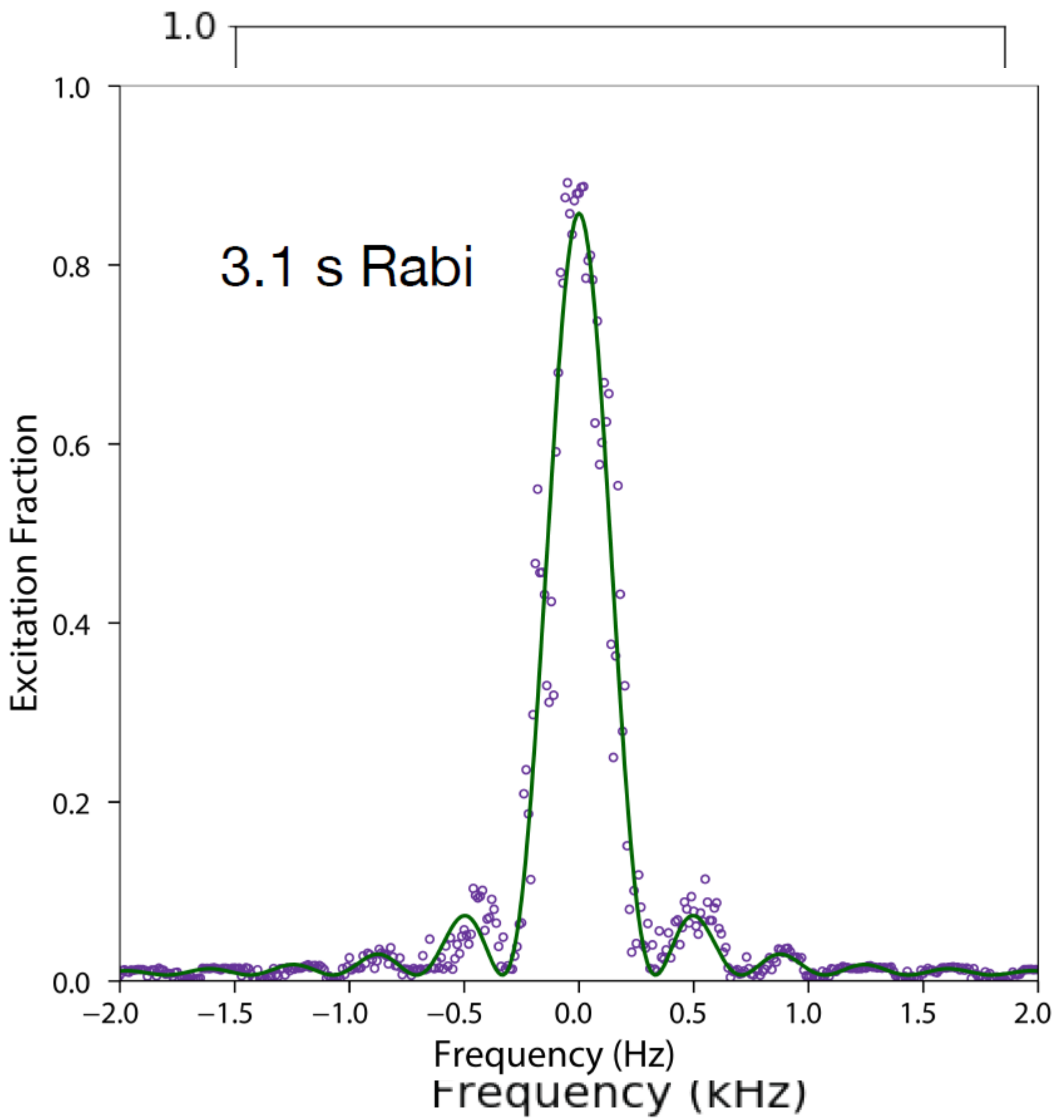




Record long atomic coherence

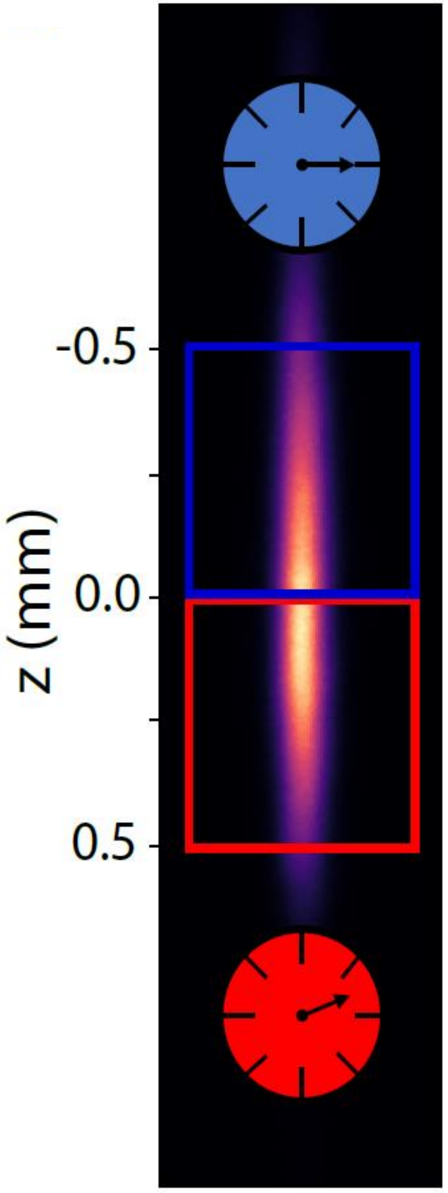
Bothwell *et al.*, Nature **602**, 420 (2022).

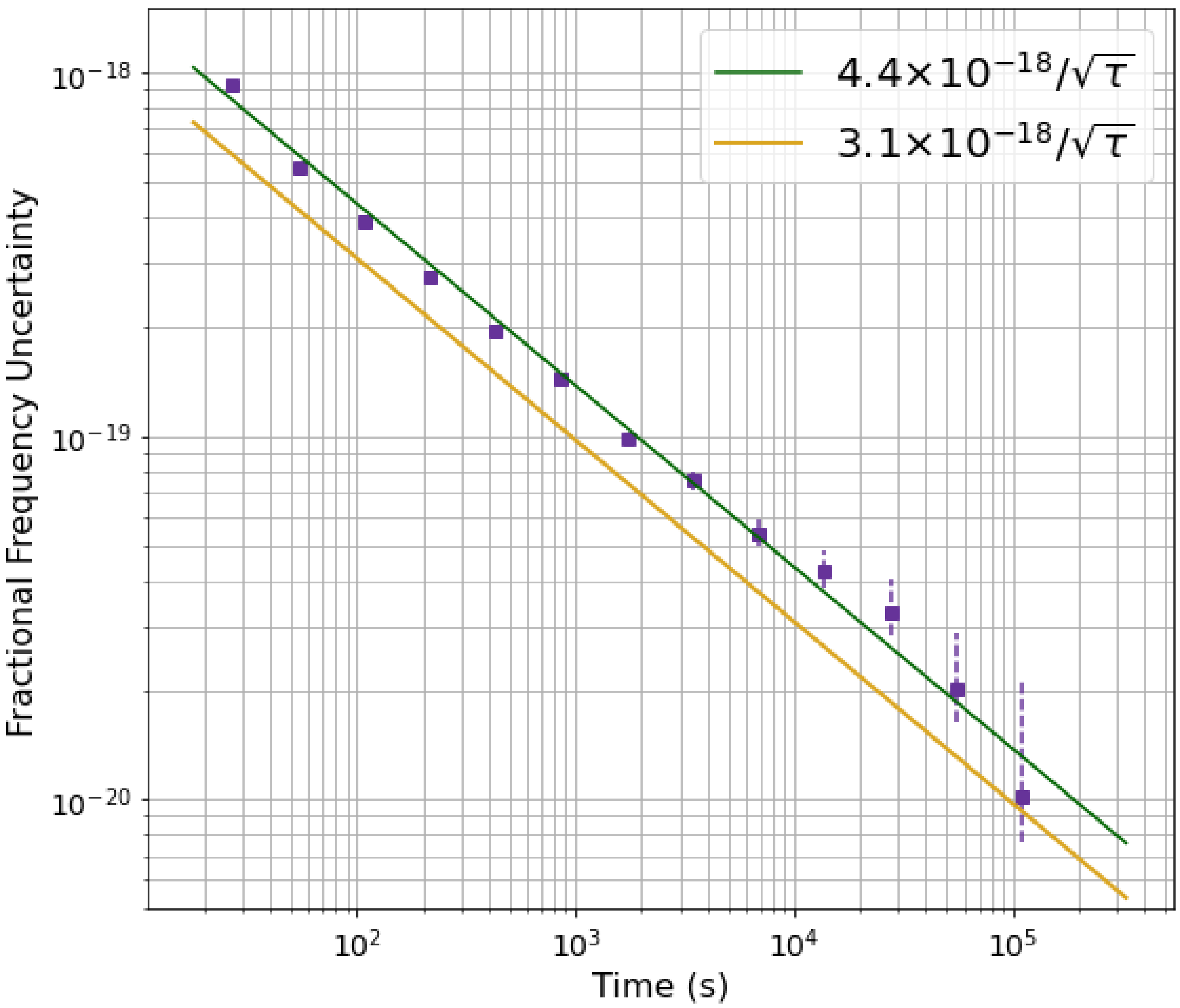




Clock precision enters 21st digit

Reach 1 x 10^{-20} in 10^5 seconds



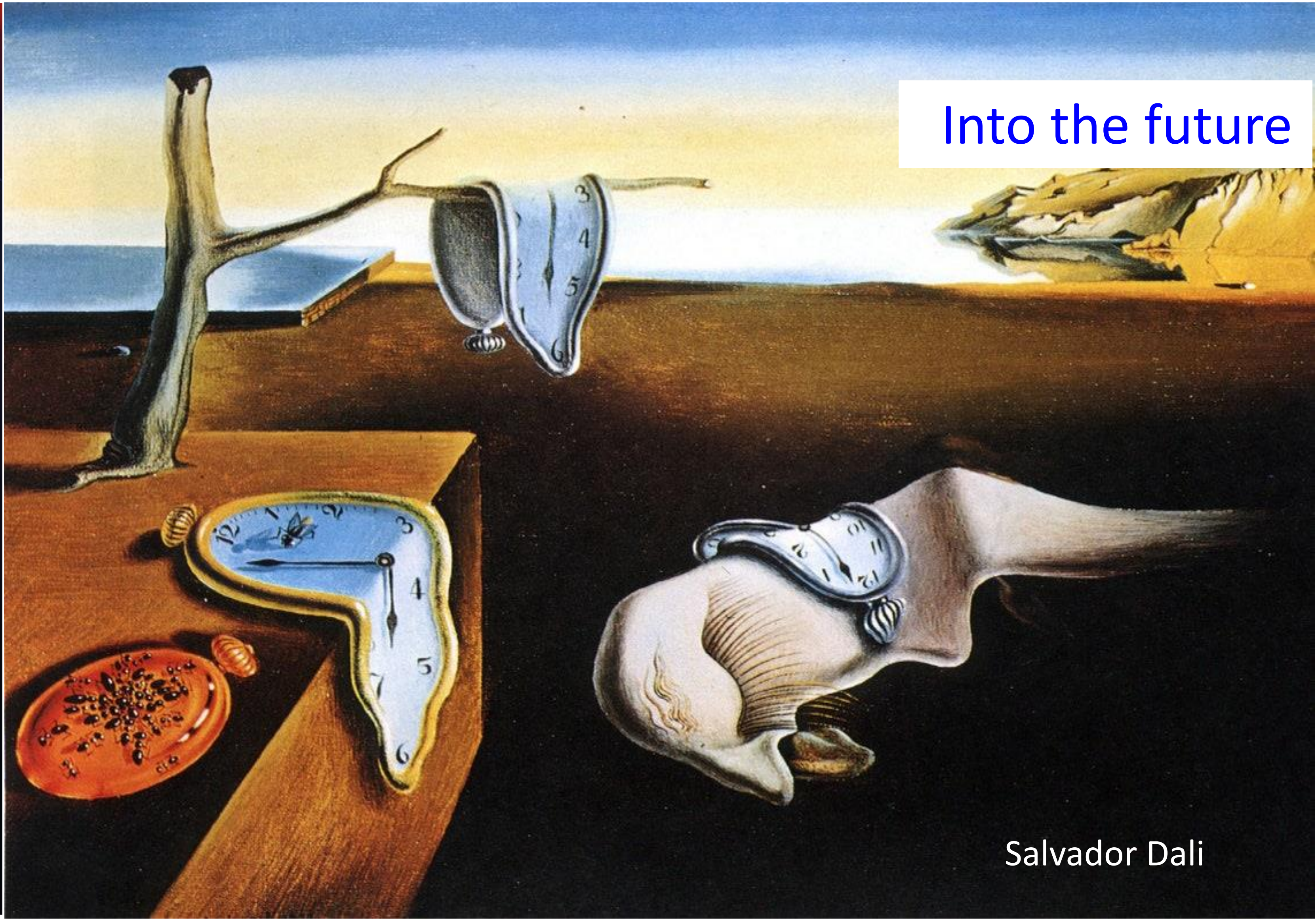


Gravitational Red Shift
100 μm (10^{-20})

6 x 10^{-21}
for each clock

Extreme Space-Time Resolution

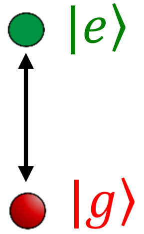
Resolving the gravitation redshift on length scale of quantum wavefunction ?



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 ,...

Leading order general relativity effects

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

$$H_{\text{on-site}}/\hbar = \sum_n \left[J_0^{\perp} \mathbf{S}_n \cdot \mathbf{S}_n + \chi_0 S_n^z S_n^z + C_0 N_n S_n^z \right]$$

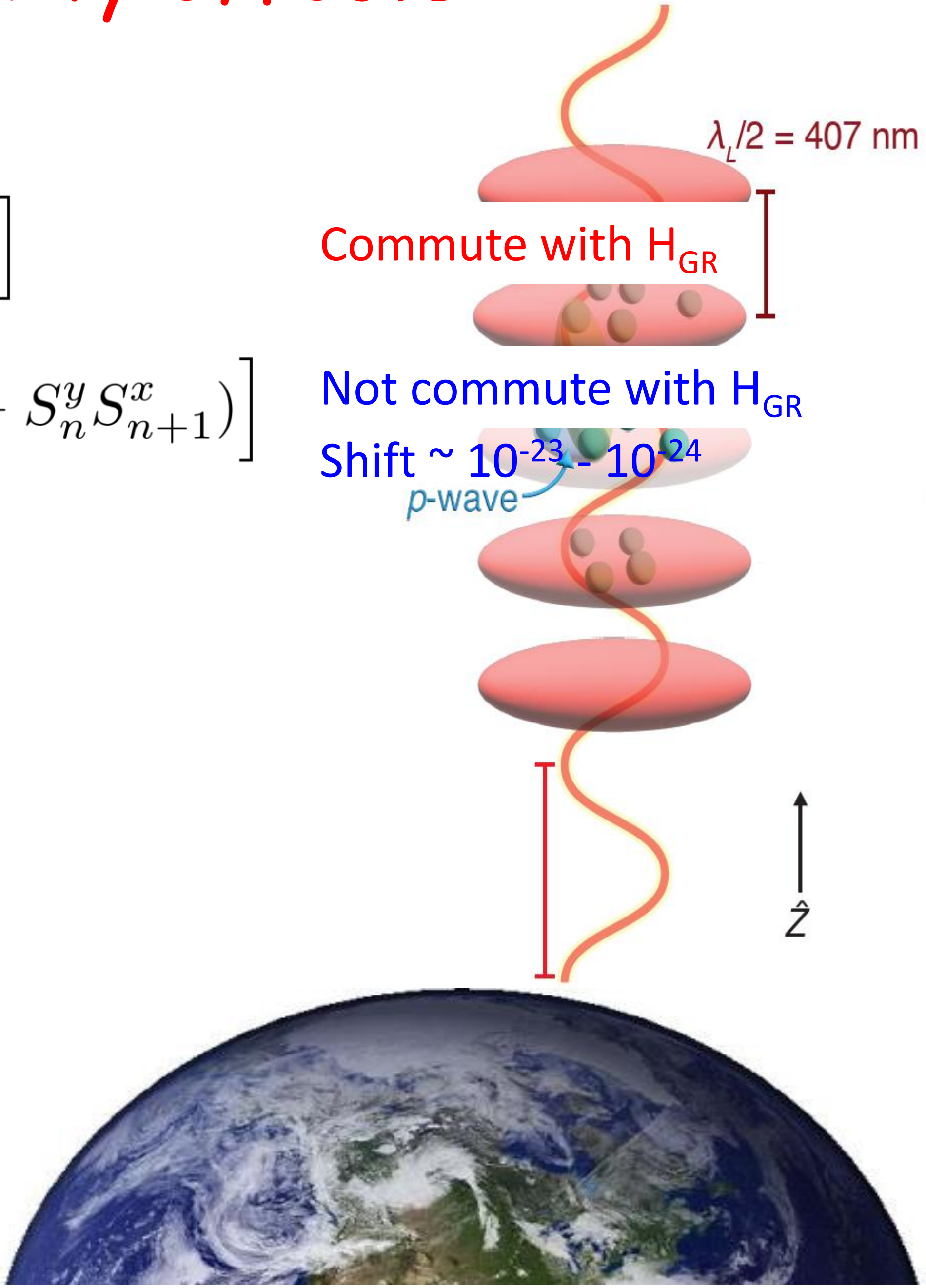
$$H_{\text{off-site}}/\hbar = \sum_n \left[J_1^{\perp} \mathbf{S}_n \cdot \mathbf{S}_{n+1} + \chi_1 S_n^z S_{n+1}^z + D_1 (S_n^x S_{n+1}^y - S_n^y S_{n+1}^x) \right]$$

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

Commute with H_{GR}

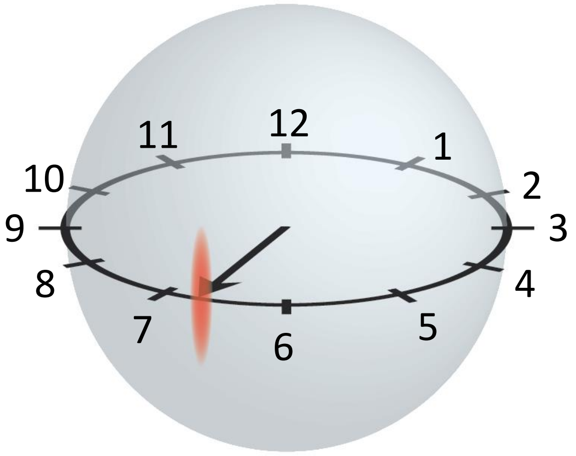
Not commute with H_{GR}

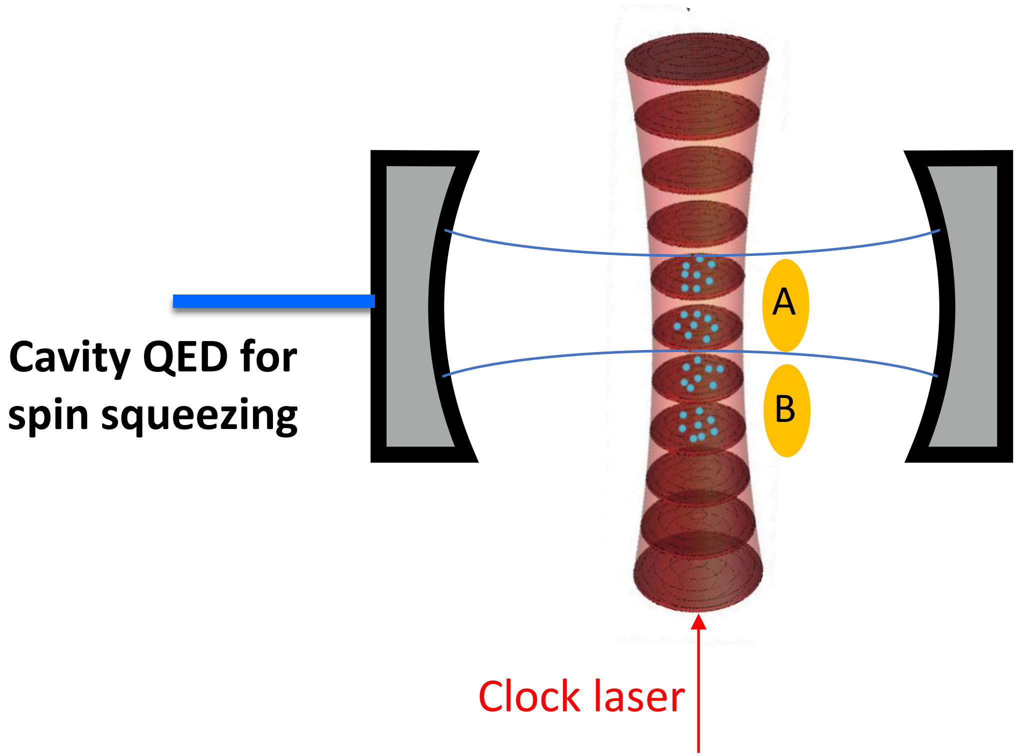
Shift ~ 10^{-23} - 10^{-24}



Spin entanglement in state-of-the-art clock

Polzik, Vuletic, Kasevich, Thompson, …

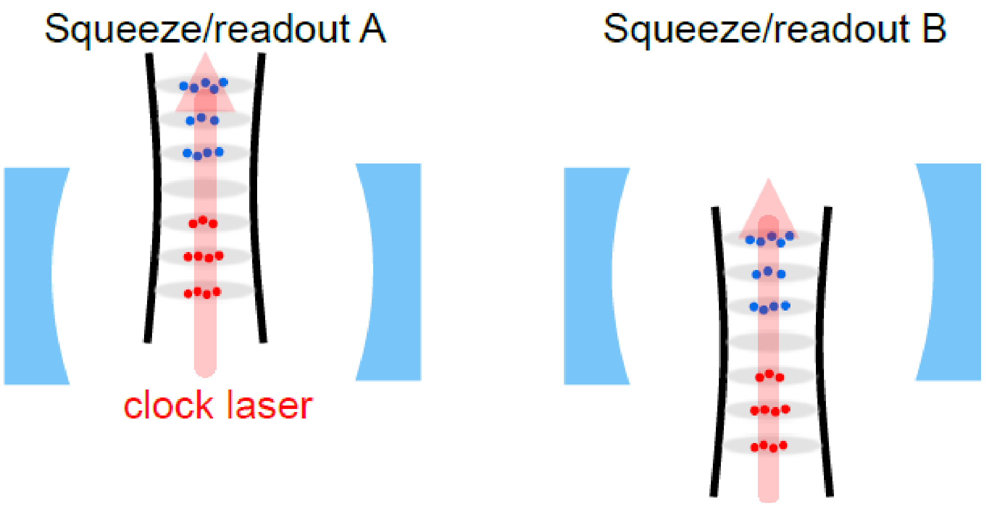


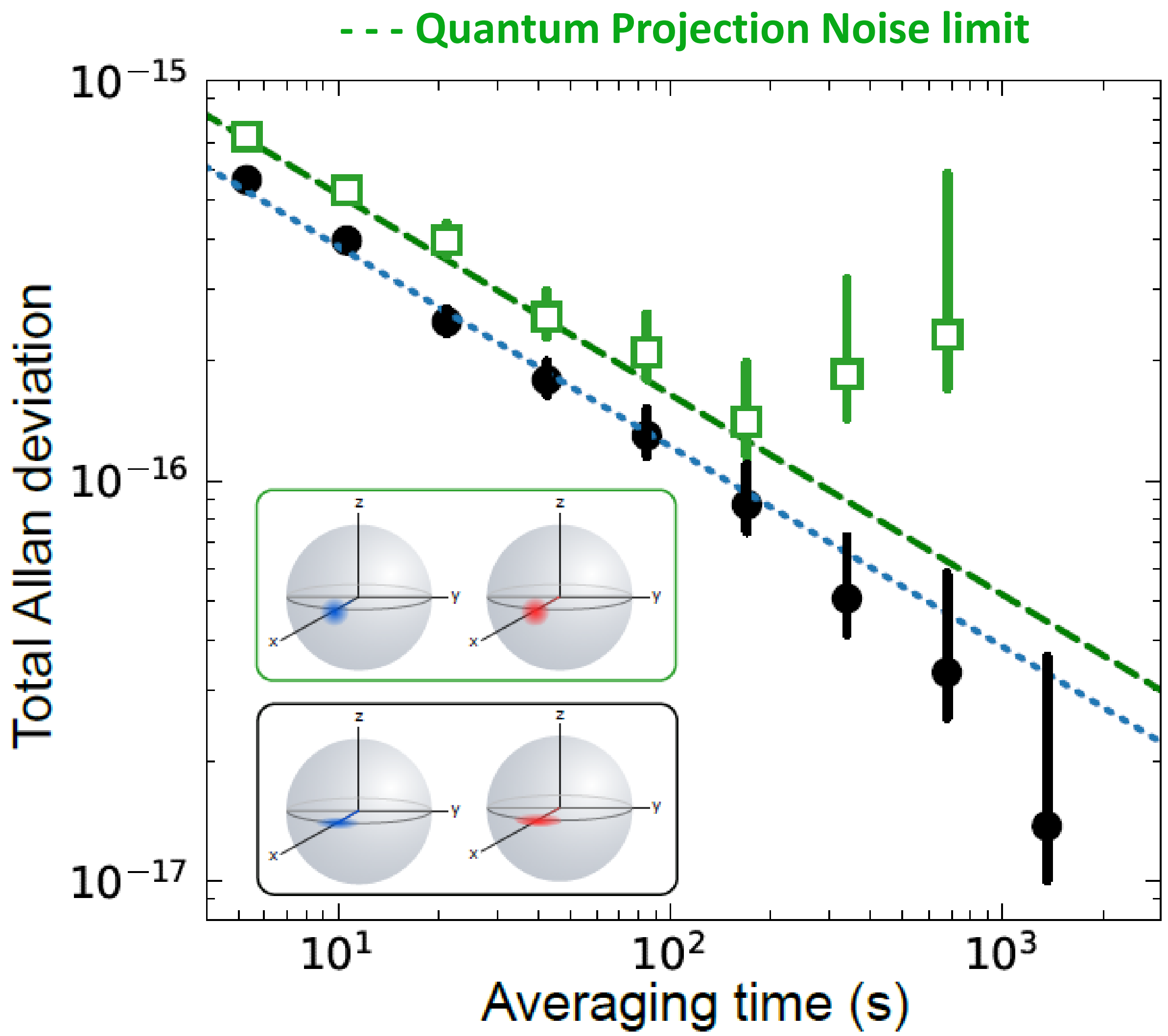


- Spin Squeezing at 10^{-17}
- Metrological gain
- Clock comparison/ Direct verification
- No post data processing/ No noise subtraction

Direct verification of squeezing-enhanced stability

Clock comparison
between two squeezed samples

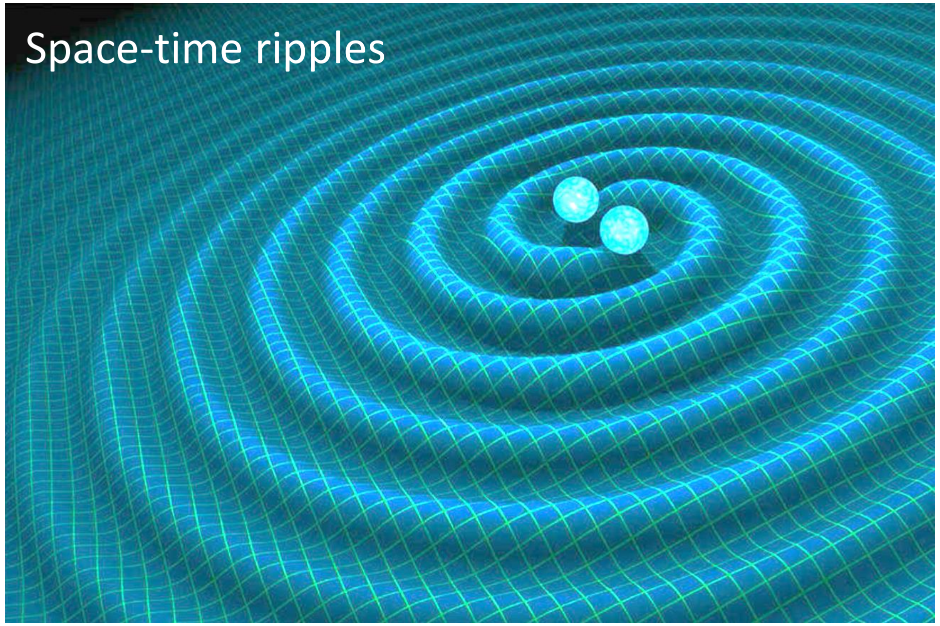




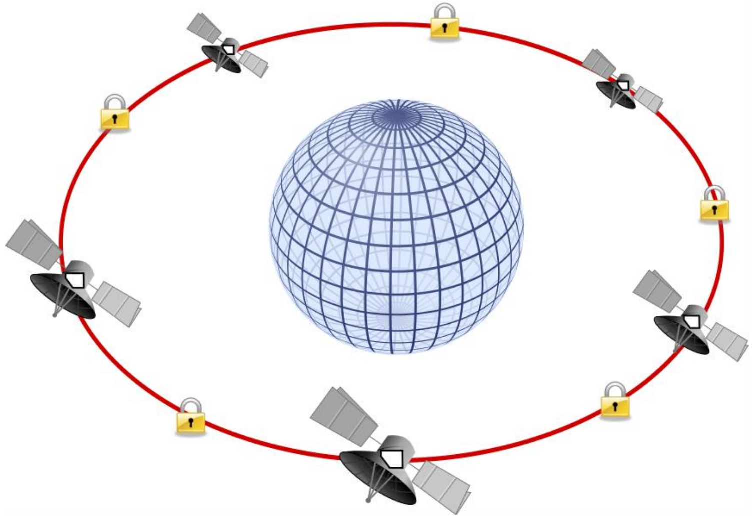
Probes for the Universe & our Earth

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

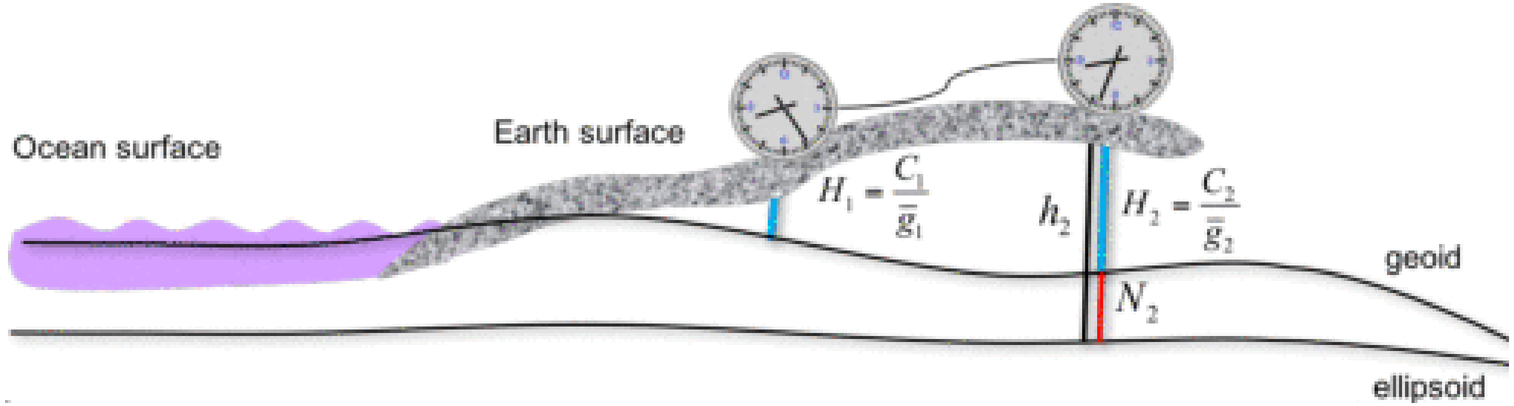
Telescope:
Gravitational waves
Dark Matter



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



Microscope:
Earth geodesy



A new strategy for particle physics ?

- **Longstanding expectations:** new physics at electroweak (TeV) scale

-- Likely solution to many known problems (WIMP, Higgs mass, CP violation)

-- **BUT:** no new discoveries so far, no detection of WIMP dark matter, no SUSY, no EDMs

-- Prospects to directly probe higher scales seem very distant

-- *Alternatively*: **Probe** new physics in weakly coupled, lower-mass particles

- **Many motivated examples known for some time:**

-- "axions" (spin 0, odd parity) to explain mysterious absence of CP violation in strong force/QCD

-- "dilatons" (spin 0, even parity) from string theory, grand unified theories, extra dimensions

-- "dark photon" (spin 1, odd parity) a force carrier for DM (electrically polarize, magnetic spin precession)

-- All are viable dark matter candidates

Challenge: particle mass or coupling scales basically unknown !

⇒ Need broad search strategies

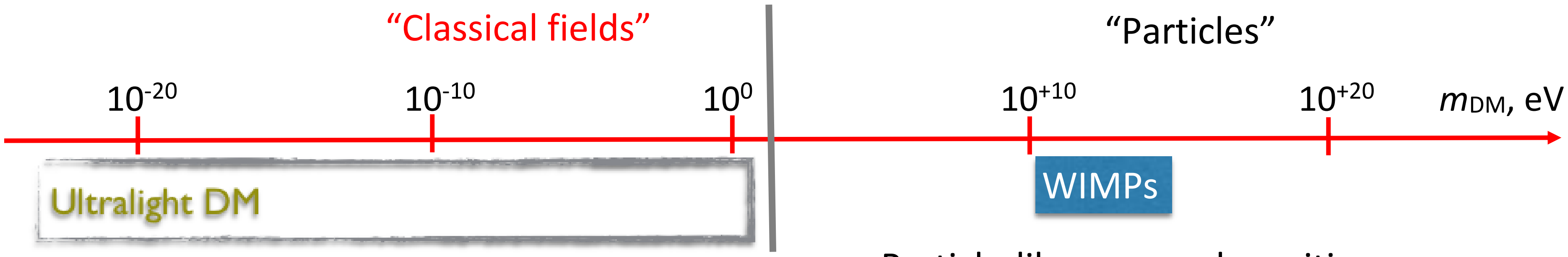
Dark matter: particles vs. fields

Compton wavelength: $\lambda_C = \dfrac{\hbar}{m_{DM}\, c}$

Galactic size (~10 kpc) > λ_C > Schwarzschild radius

$\Rightarrow 10^{-22}$ eV << m_{DM} << 10^{+28} eV

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



Coherent on detector scale

Particle-like energy deposition

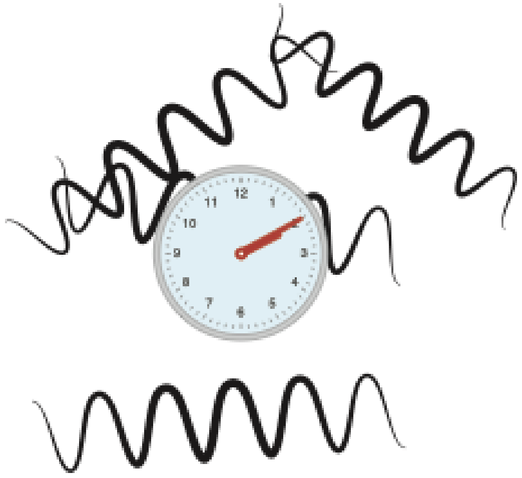
DM field oscillates at Compton frequency: $\omega_{DM} = \dfrac{m_{DM}c^2}{\hbar}$ ~ 30 kHz * [$m_{DM}/10^{-10}$ eV]

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

Ultralight scalar Dark Matter

Dilaton (spin 0, even parity) – A scalar field to modify fundamental constants: fine structure constant α, particle masses, etc.

Transition type	Scaling dependence on constants
Atomic s-p	$Ry * (1 + Z^2\alpha^2)$
Atomic p-d	$Ry * (1 - Z^2\alpha^2)$
Atomic hyperfine	$Ry * \alpha^2 * (m_e/m_p) * g_N$
Molecular rotation	$Ry * (m_e/m_p)$
Molecular vibration	$Ry * (m_e/m_p)^{1/2}$
Nuclear	$\Lambda_{QCD} * (m_q/m_p)$
Cavity	$\alpha\ m_e c^2$



Oscillating variations of α

Relativistic effect: $\frac{\Delta\omega}{\omega} = K\,\frac{\Delta\alpha}{\alpha}$

Ratio of frequencies from different clocks ➔ sensitive to variations of α

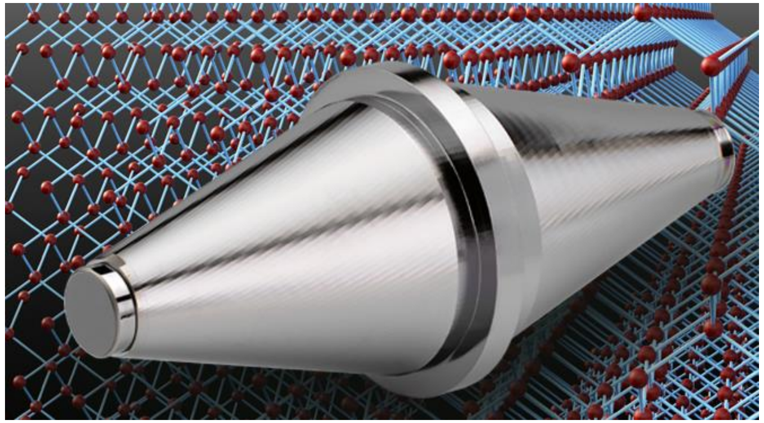
Arvanitaki *et al.*, PR D **91**, 015015 (2015); Van Tilburg *et al.*, PRL **115**, 011802 (2015).

Multi-party Search for ultralight dark matter

C. Kennedy *et al.*, Phys. Rev. Lett. **125**, 201302 (2020).

Stadnik & Flambaum, PRA 93, 063630 (2016).

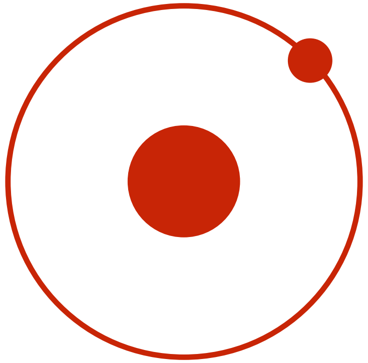
Silicon



$\omega \sim \alpha\, m_e c^2$

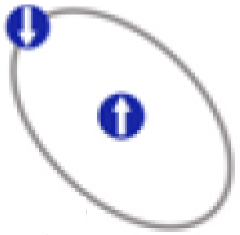
$\omega \sim \alpha^{2.06}\, m_e c^2$

$\omega \sim \alpha^4\, m_e^2 c^2$



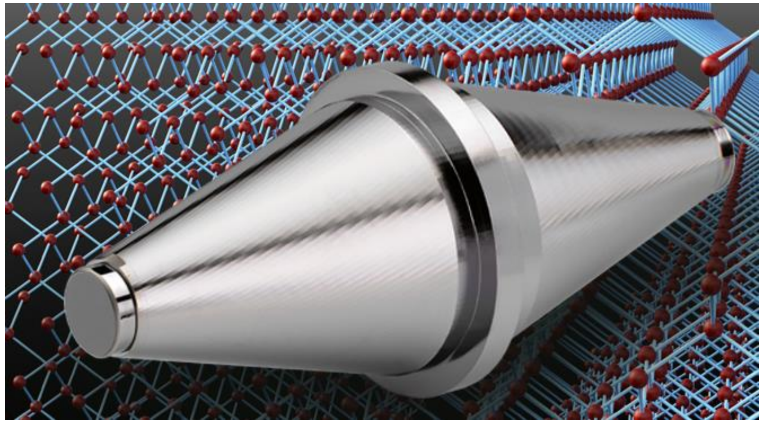
Sr

H



Multi-party Search for ultralight dark matter

Silicon

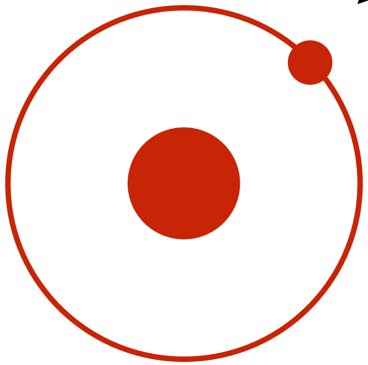


$$\frac{\Delta\omega}{\omega} = \frac{\Delta\alpha}{\alpha}$$

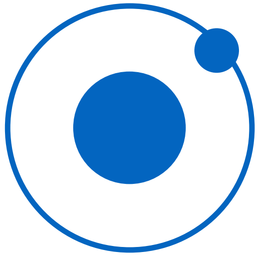
$$\frac{\Delta\omega}{\omega} = 0.06\,\frac{\Delta\alpha}{\alpha}$$

$$\frac{\Delta\omega}{\omega} = 0.37\,\frac{\Delta\alpha}{\alpha}$$

Sr



Does the 19th digit change?



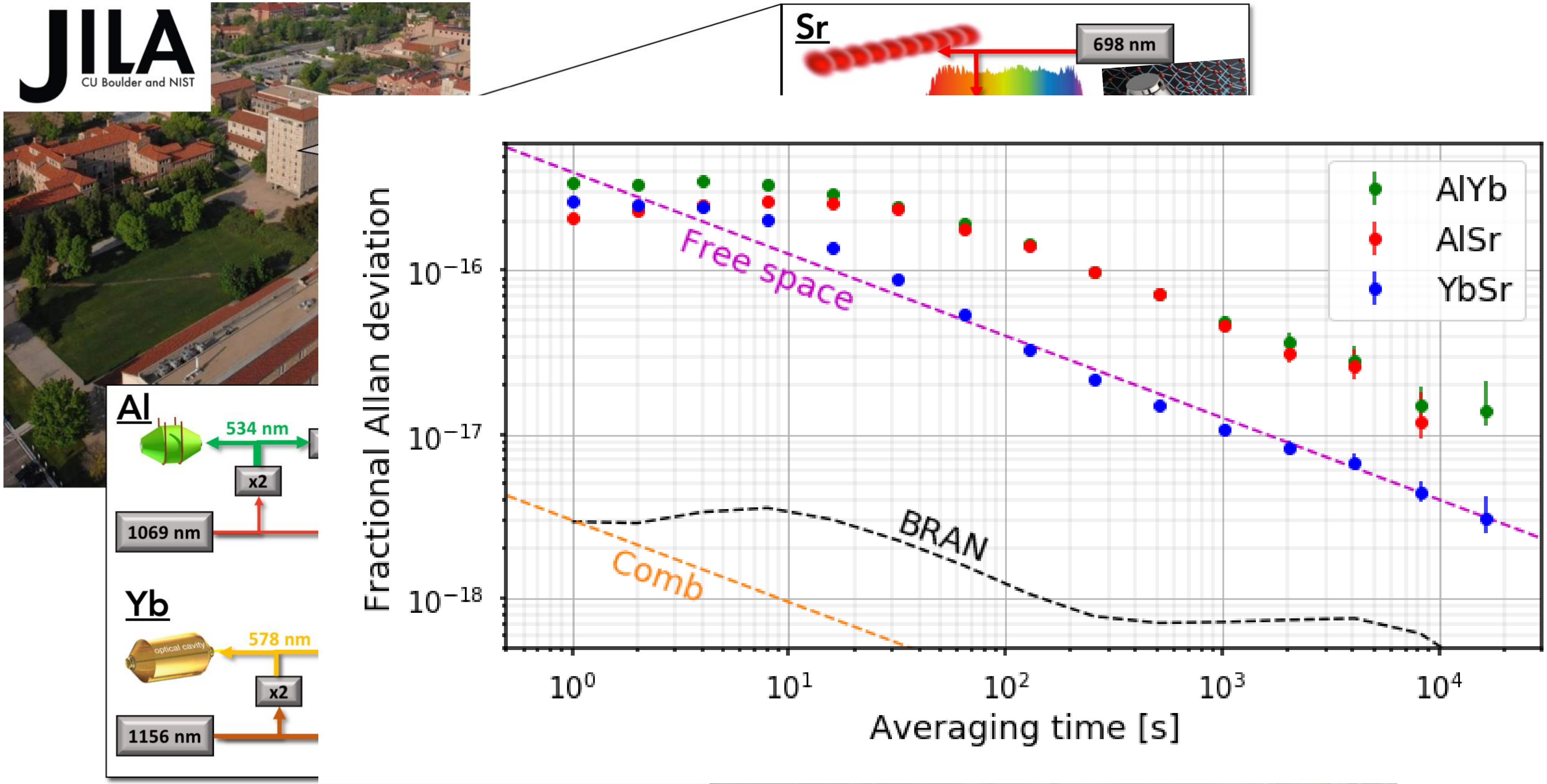
Yb

Godun, *et al.*, PRL **113**, 210801 (2014)
Huntemann, *et al.*, PRL **113**, 210802 (2014)

Boulder Area Optical Clock Network

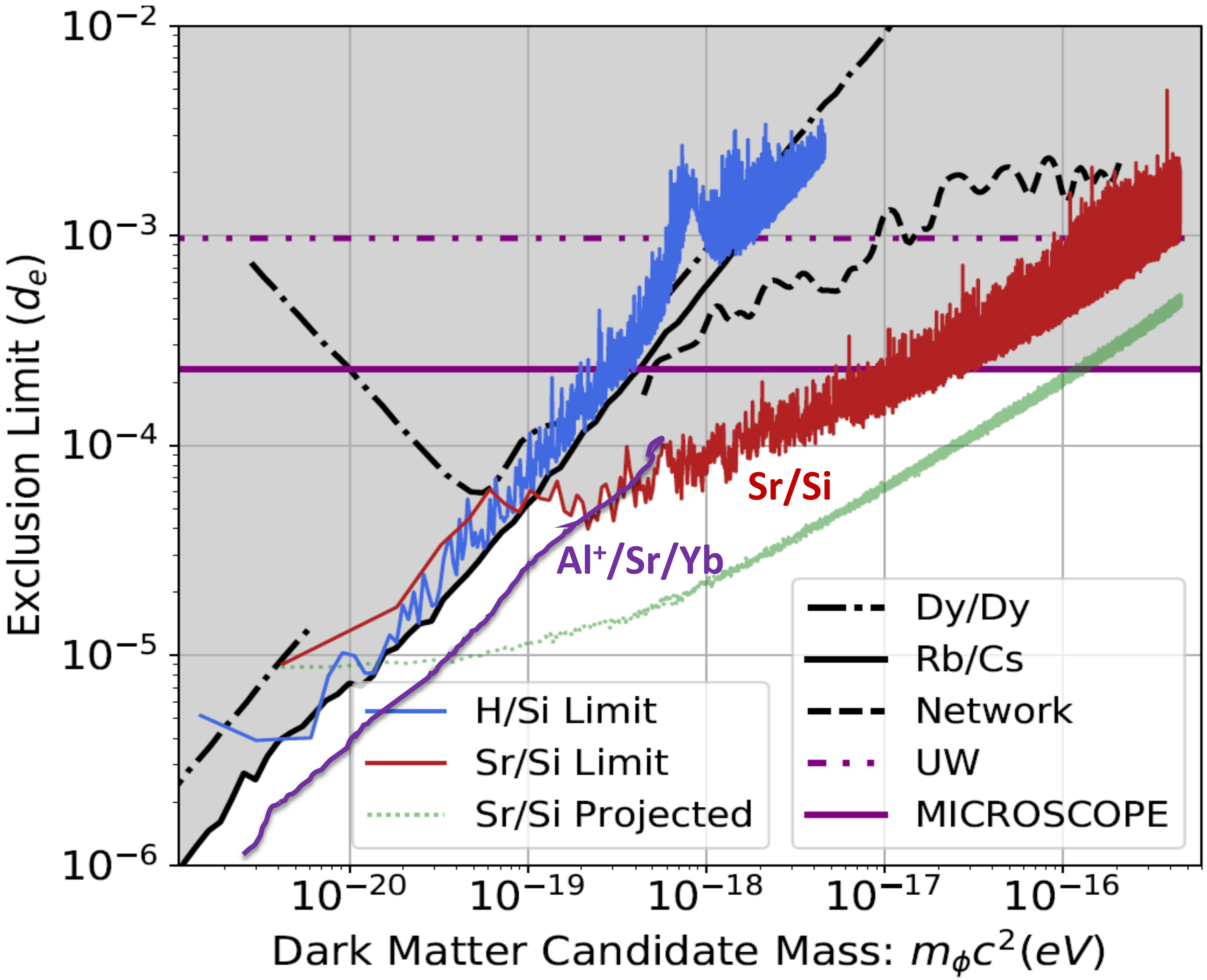
Beloy *et al.*, Nature **591**, 564 (2021).

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

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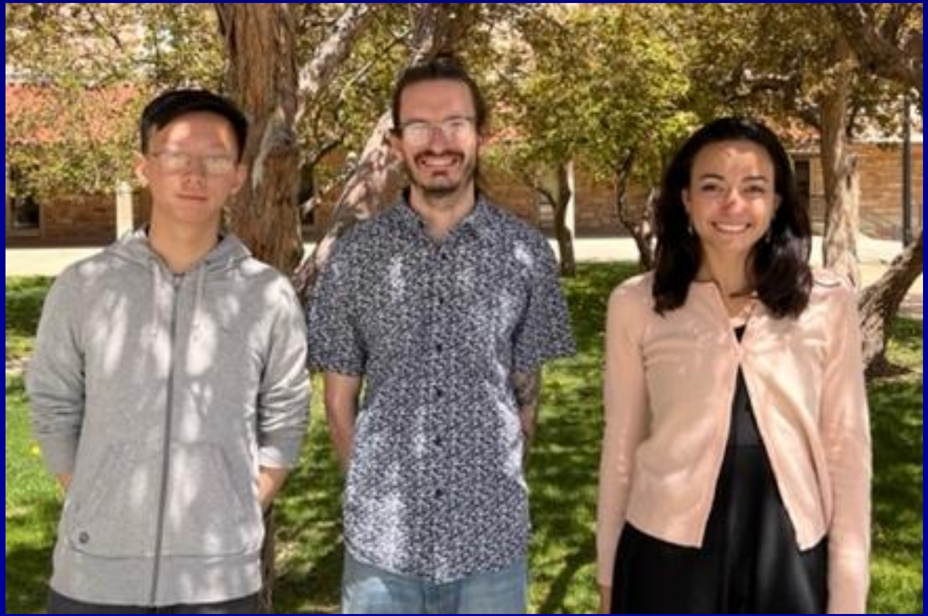

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