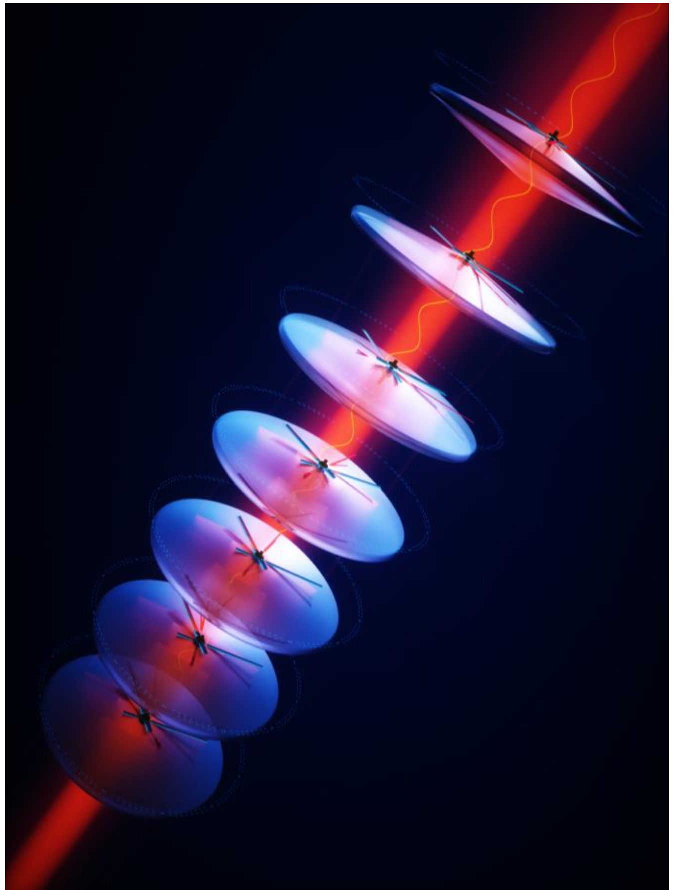
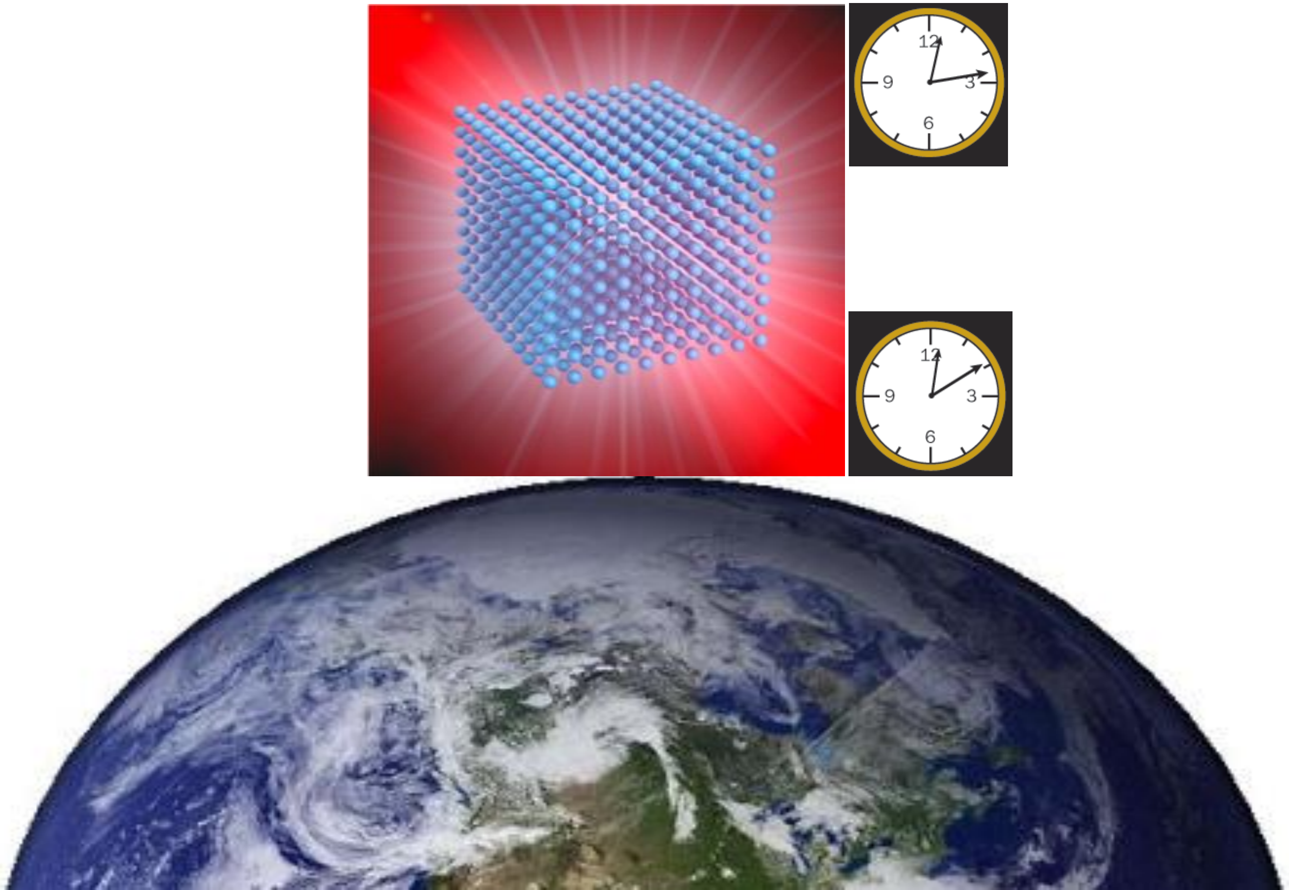
Precision Measurements and Atomic Clocks

Jun Ye

JILA, NIST & Univ. Colorado

NAS Board on Physics & Astronomy, April 30, 2025

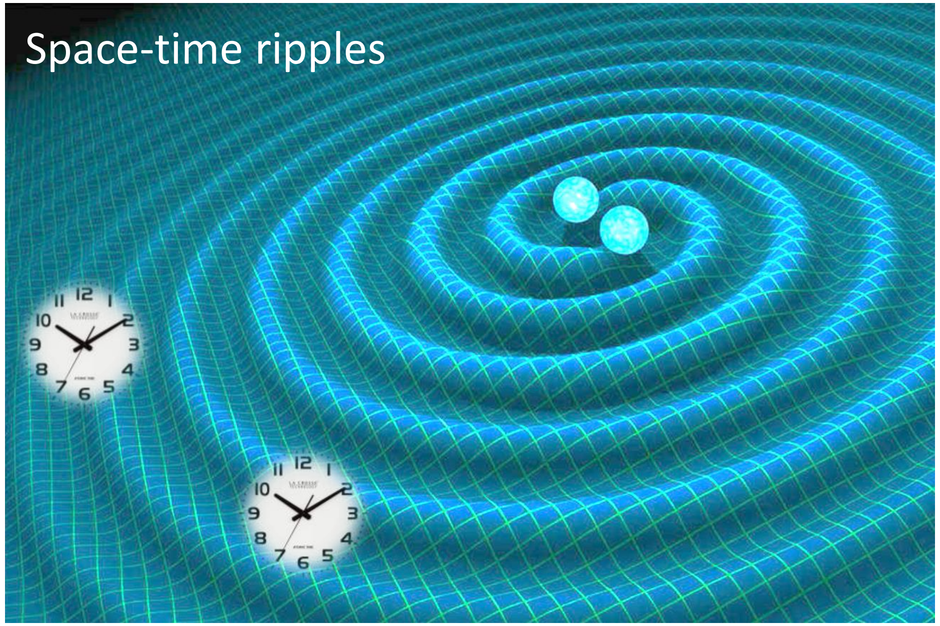




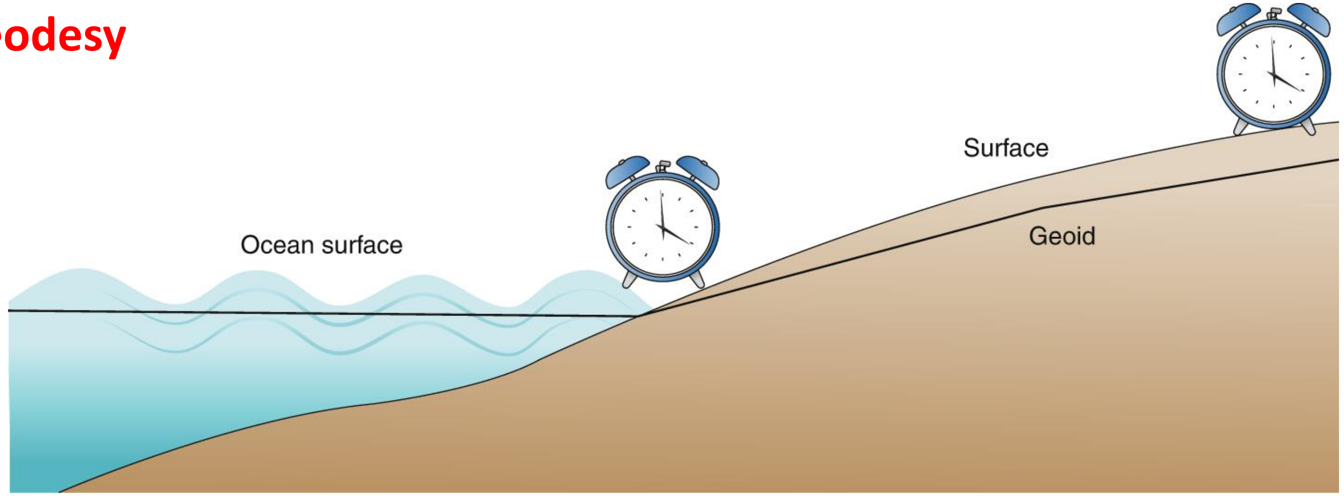
Clock is our "telescope" and "microscope"

Kolkowitz *et al.*, Phys. Rev. D **94**, 124043 (2016) C. Kennedy *et al.*, Phys. Rev. Lett. **125**, 201302 (2020).

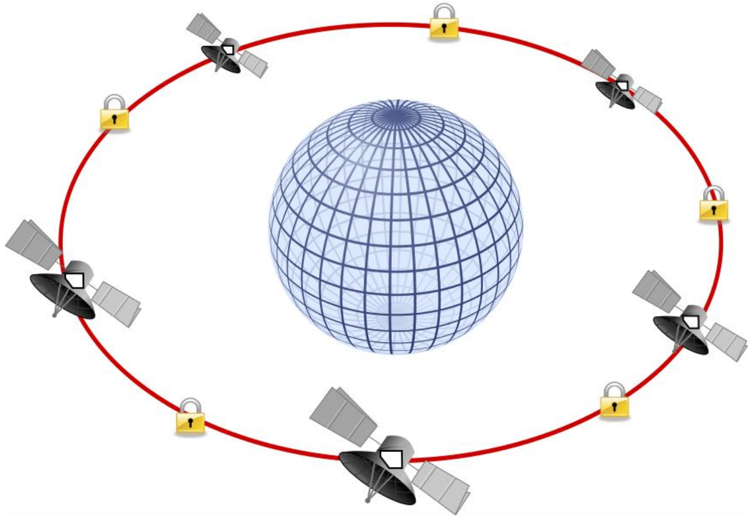
Telescope:
- **Gravitational waves**
- **Dark Matter**



Microscope:
- **Earth geodesy**



Clock network: long baseline interferometer

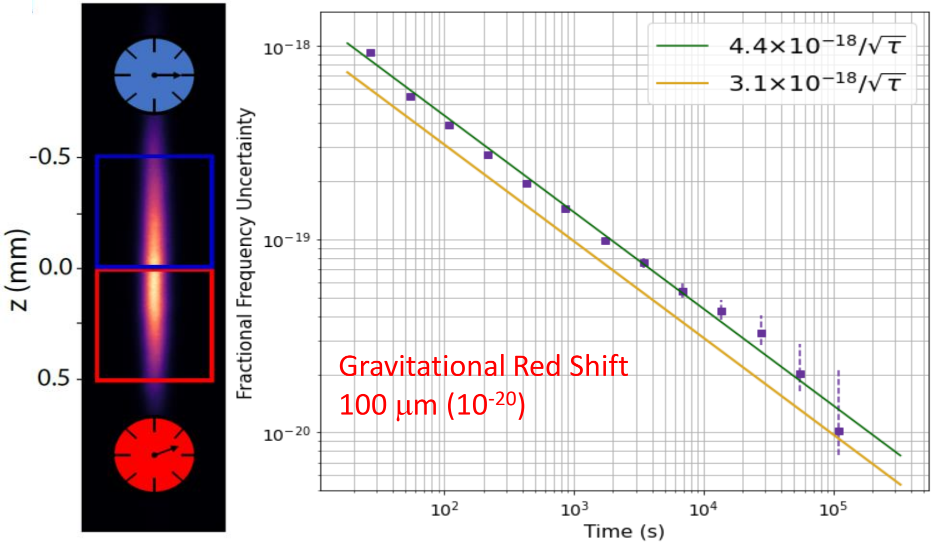


State-of-the-art clock performances

Precision

Bothwell…Ye, Nature (2022)

Zheng… Kolkowiz, Nature (2022).



Accuracy

Brewer…Wineland, Hume, Leibrandt, PRL (2019)

Aeppli…Ye, Phys. Rev. Lett. (2024)

PHYSICAL REVIEW LETTERS **133,** 023401 (2024)

Editors' Suggestion | Featured in Physics

Clock with 8×10^{-19} Systematic Uncertainty

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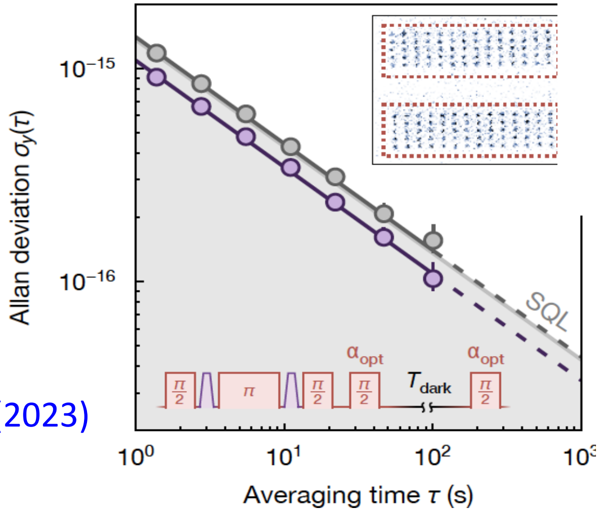
PHYSICAL REVIEW LETTERS **123,** 033201 (2019)

Editors' Suggestion | Featured in Physics

$^{27}Al^+$ Quantum-Logic Clock with a Systematic Uncertainty below 10^{-18}

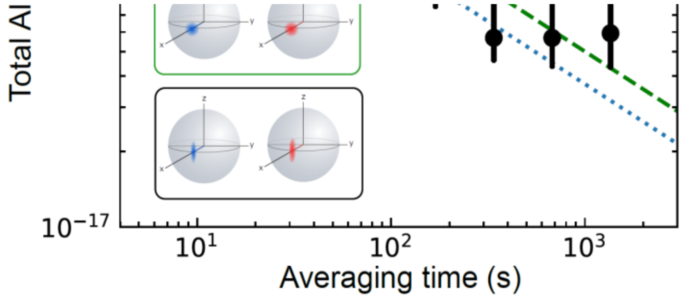
S. M. Brewer,[1,2,*] J.-S. Chen,[1,2,†] A. M. Hankin,[1,2,‡] E. R. Clements,[1,2] C. W. Chou,[1] D. J. Wineland,[1,2,3] D. B. Hume,[1] and D. R. Leibrandt[1,2,§]

[1] *Time and Frequency Division, National Institute of Standards and Technology, Boulder, Colorado 80305, USA*
[2] *Department of Physics, University of Colorado, Boulder, Colorado 80309, USA*
[3] *Department of Physics, University of Oregon, Eugene, Oregon 97403, USA*



Rydberg-squeezed clocks

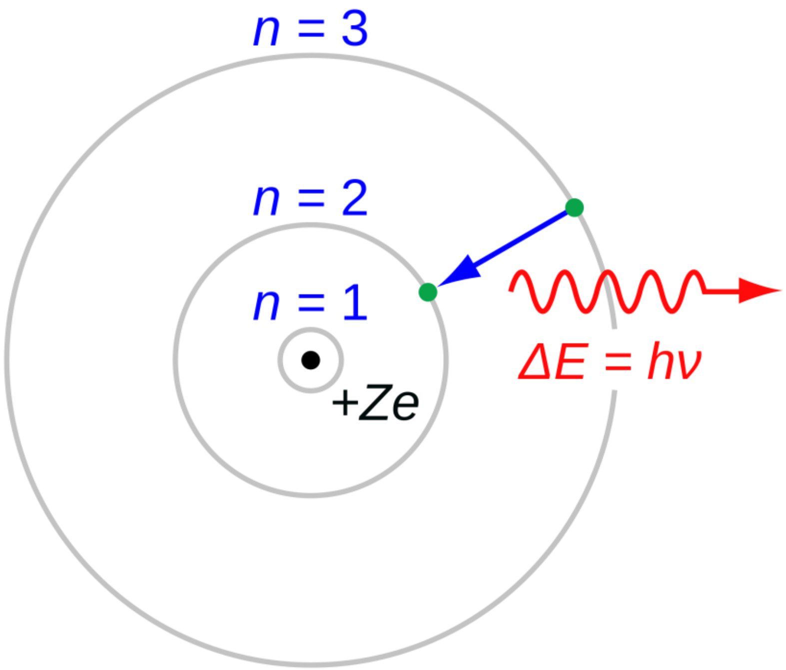
Eckner…Ye, Kaufman, Nature (2023)

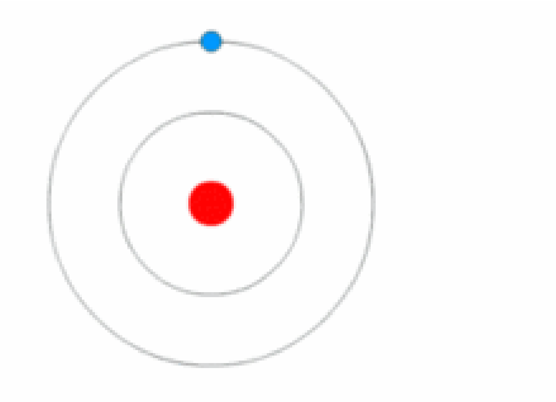


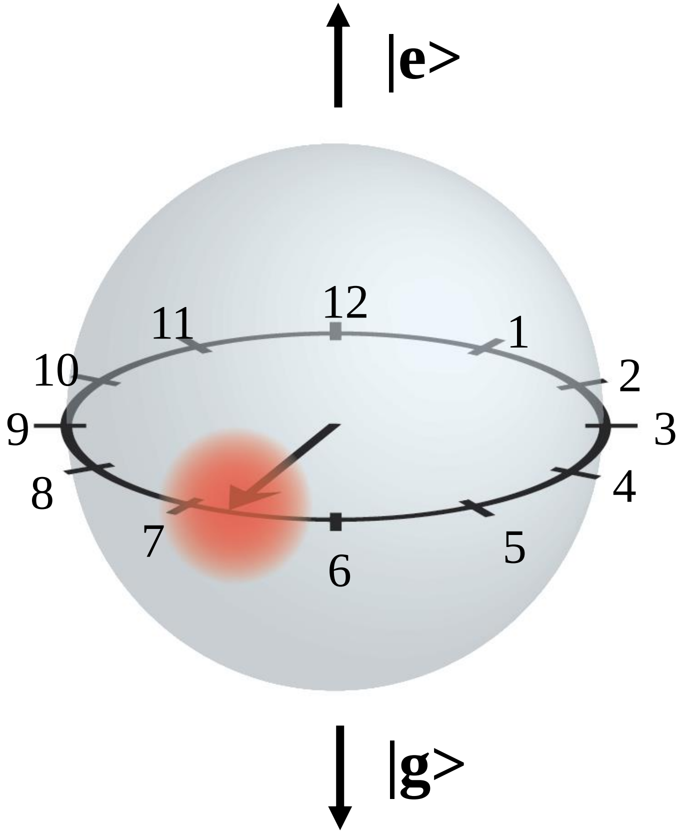
Entangled clock comparison

Robinson…Thompson, Ye, Nature Phys. (2024)

Bohr's Certainty & Heisenberg's Uncertainty

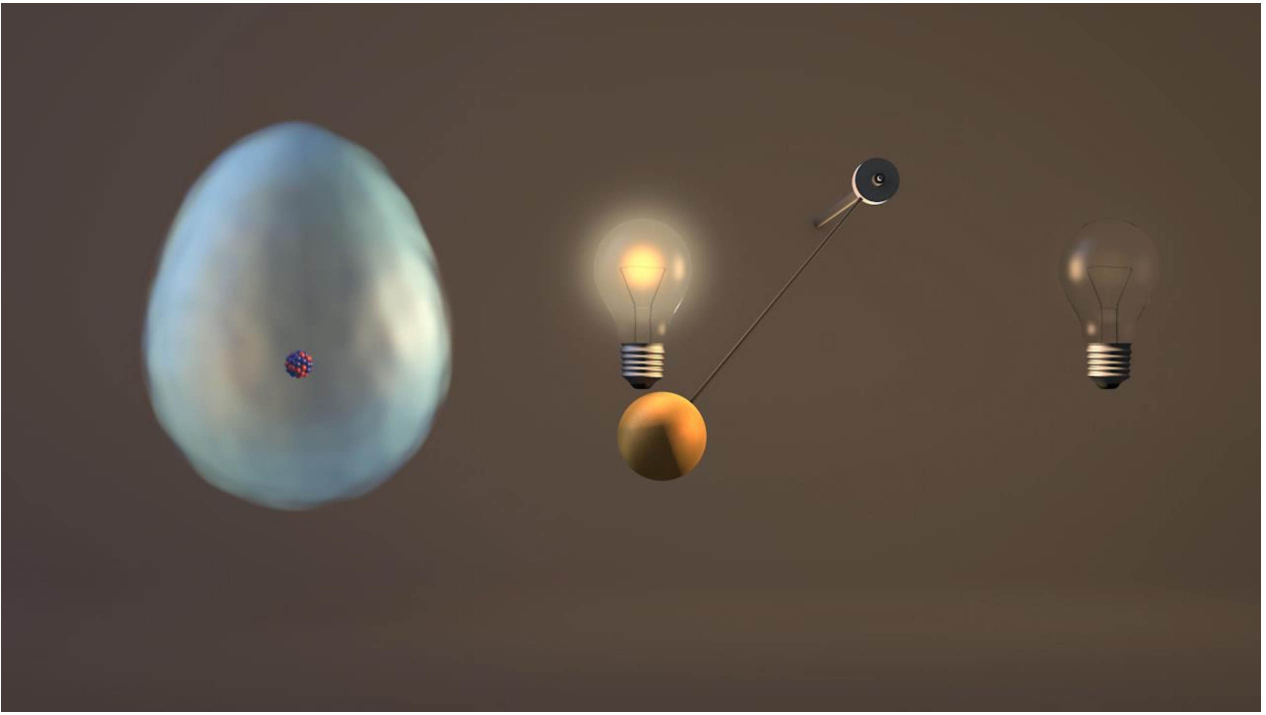






$$\frac{1}{\sqrt{2}}\left(e^{-iEt}|e\rangle + |g\rangle\right)$$

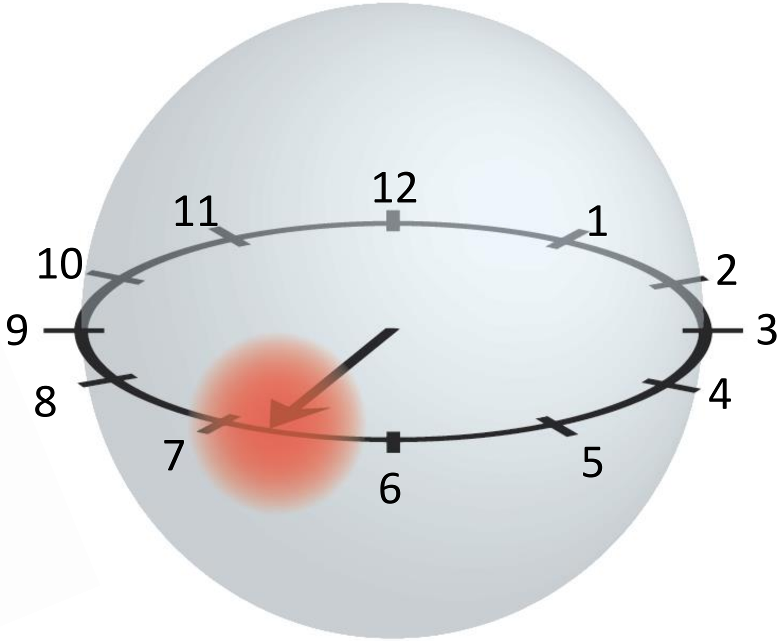
Atomic evolution probed by laser



Sr coherence: 1 minute

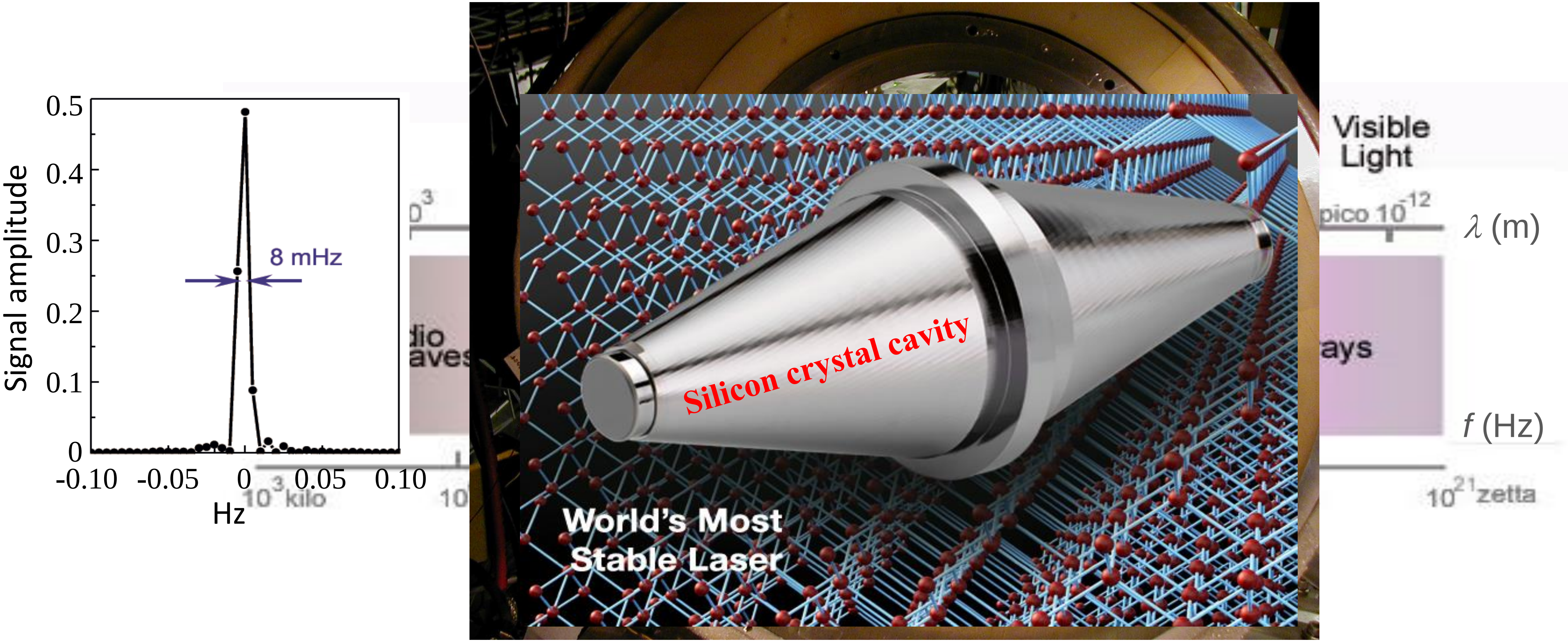
Quantum Phase Noise of Atoms

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



Control of light –

the electromagnetic spectrum



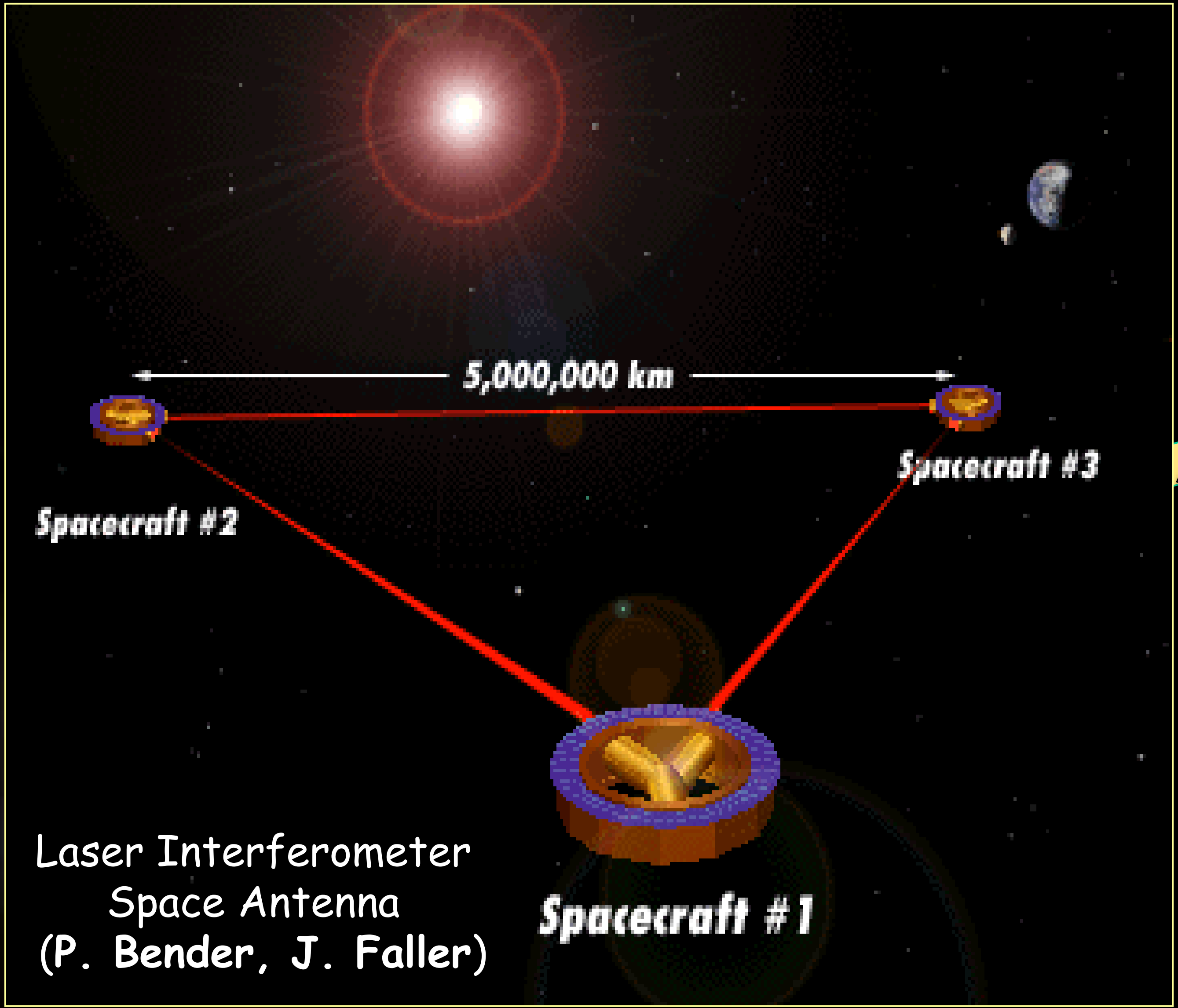
Zoom in 1 million times

Zoom in another 1 million times

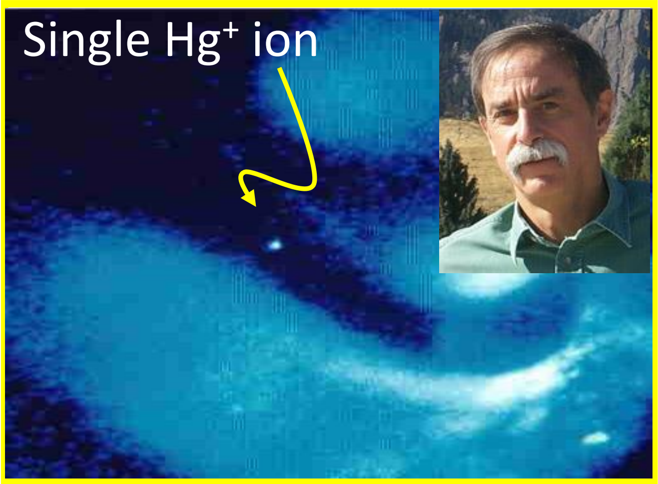
Zoom in 1 million times for the 3rd time

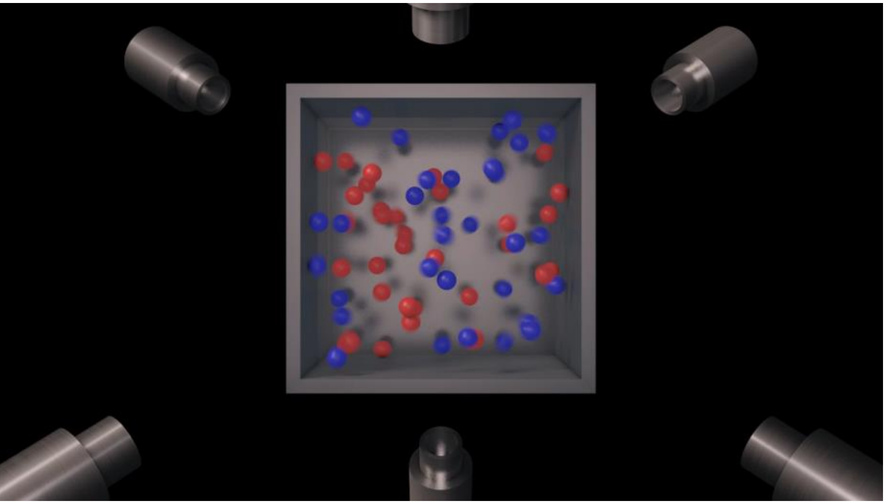
A new generation of stable lasers

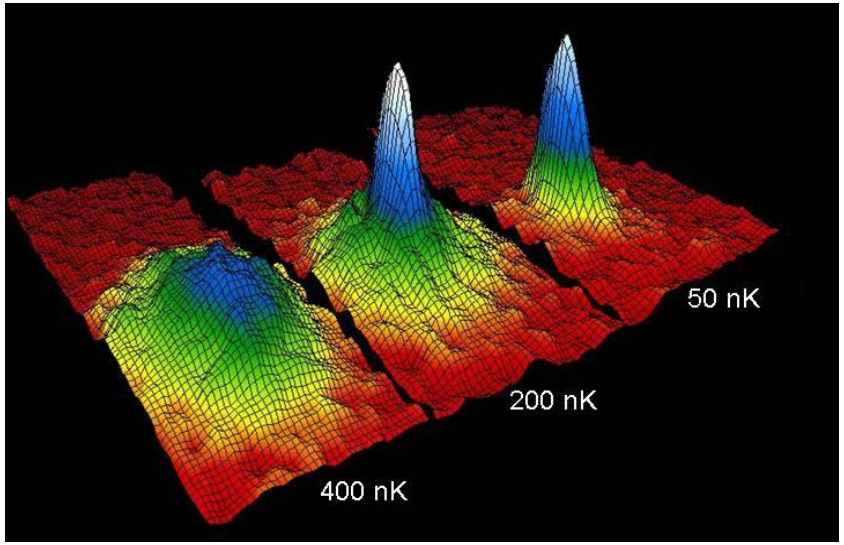
Optical coherence time approaching 1 minute

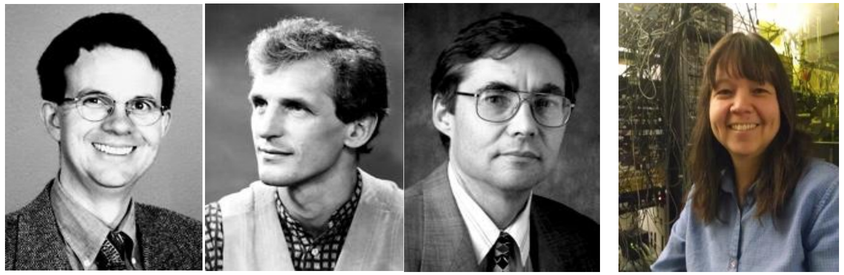


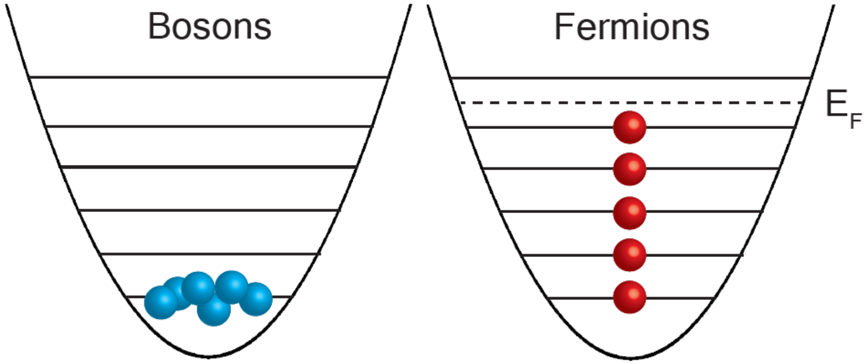
Scaling up the quantum clock: from one to many

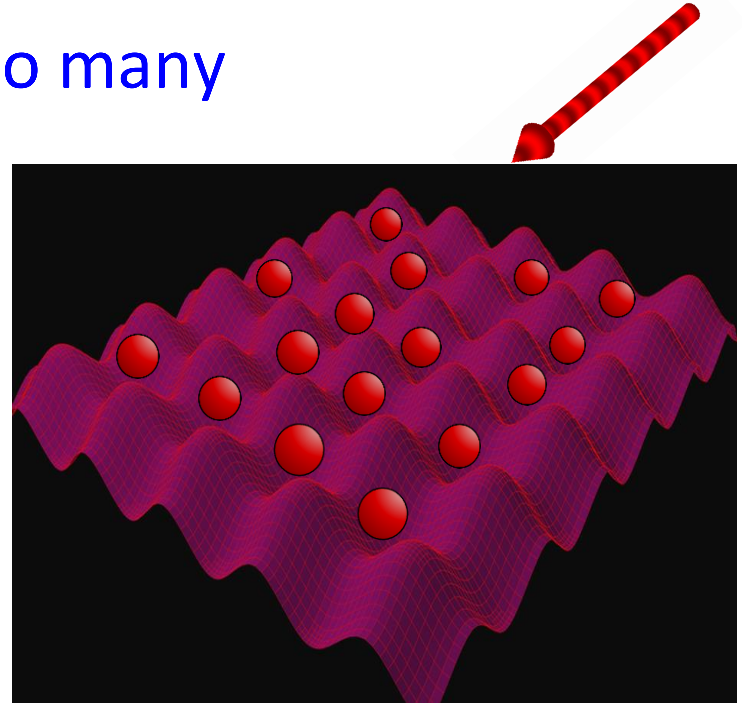


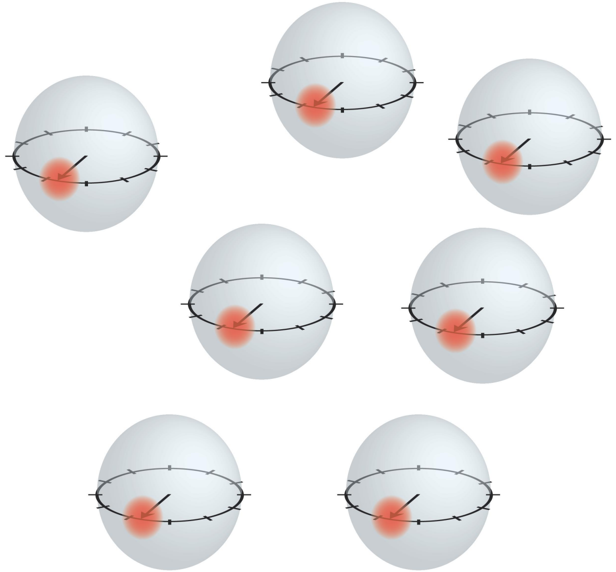






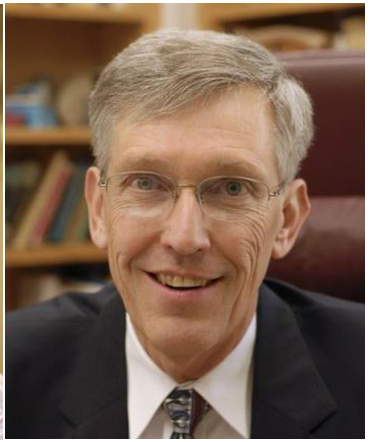


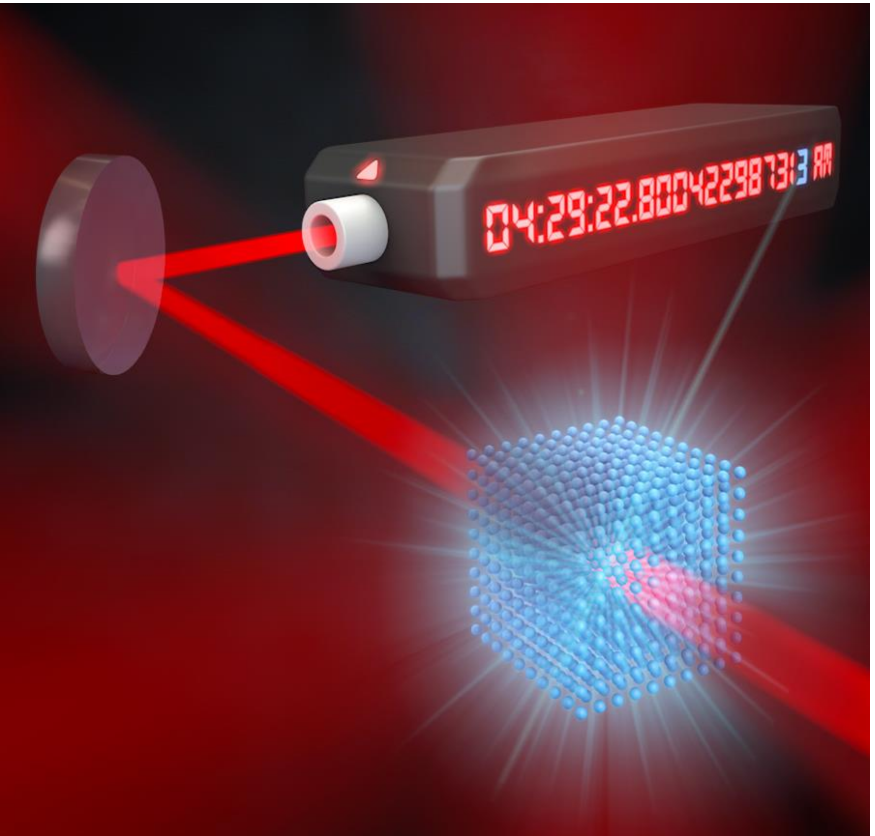


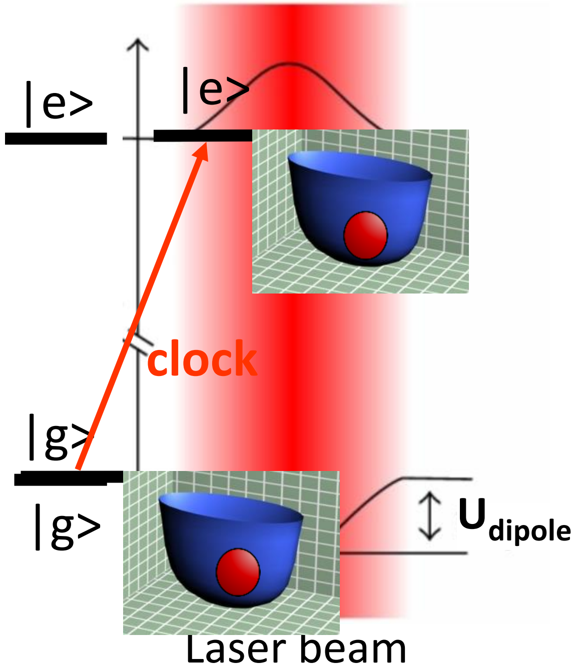


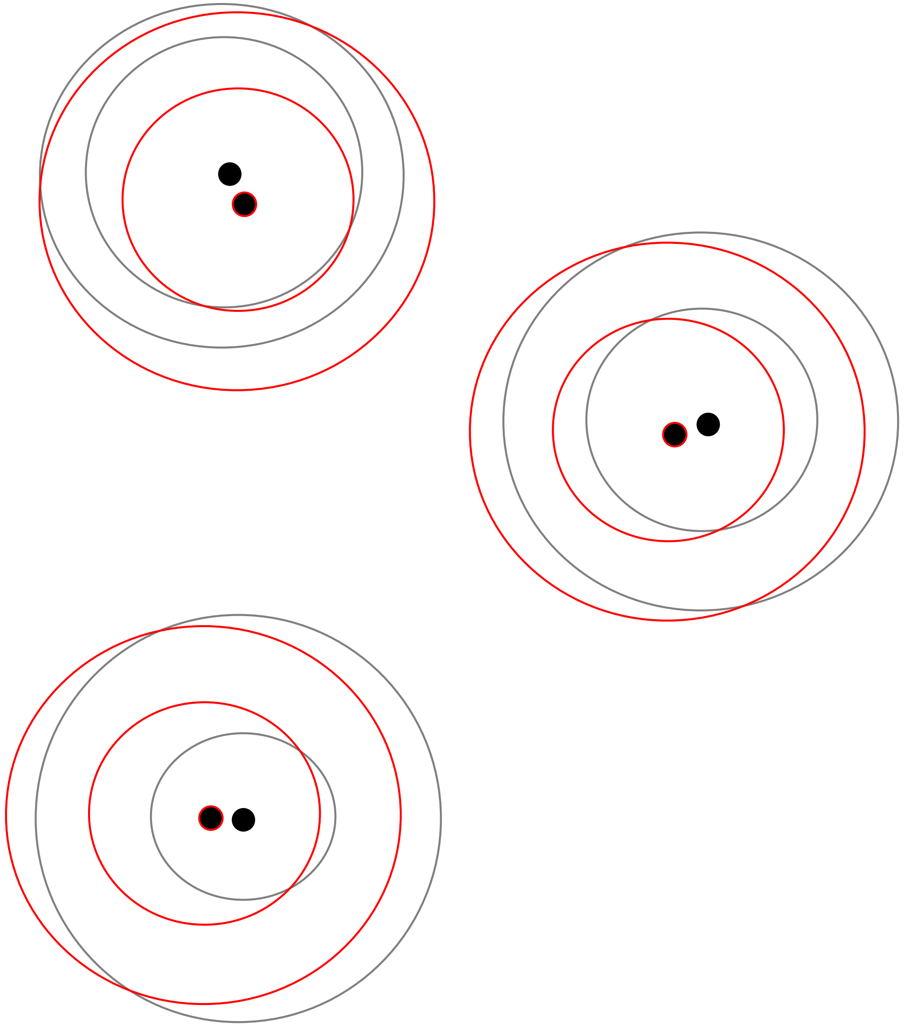
Hold atoms in magic light bowls

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



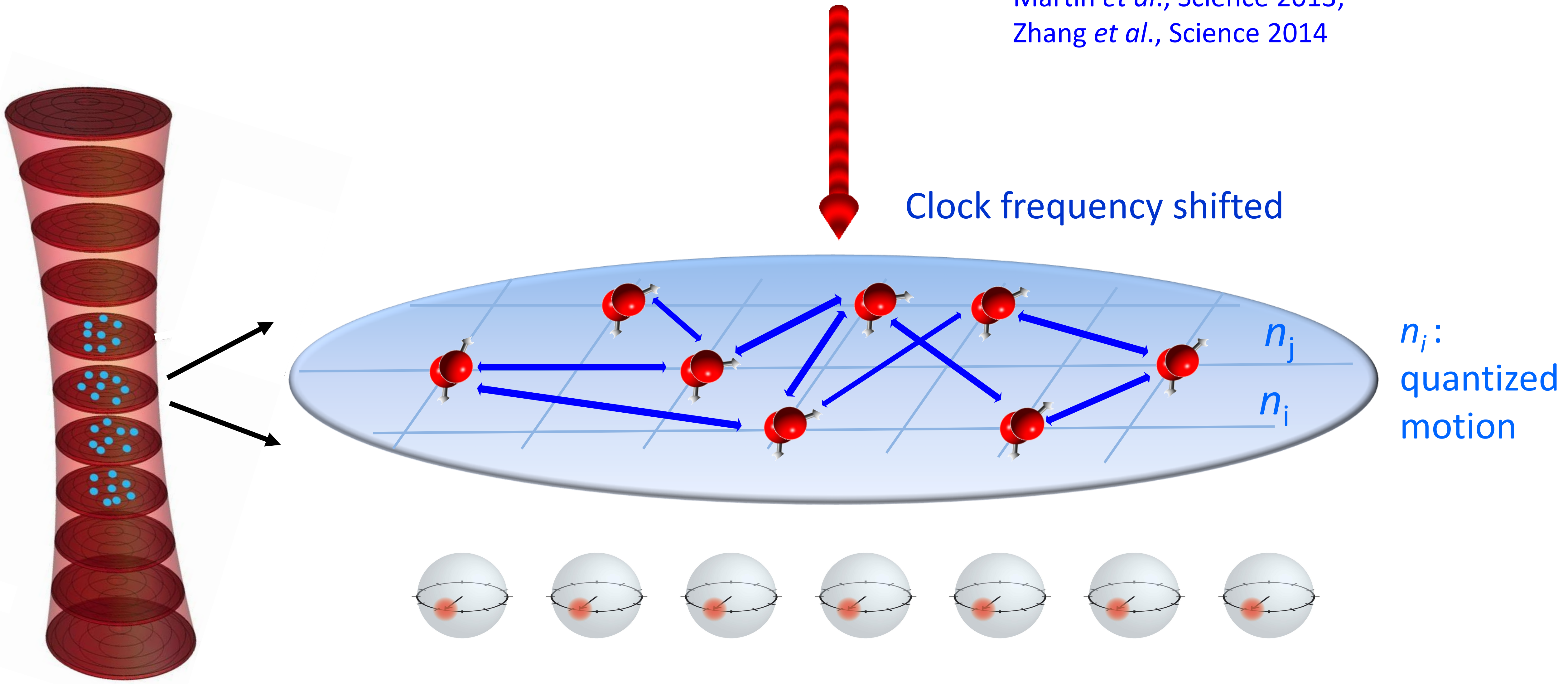






Clock with many identical atoms

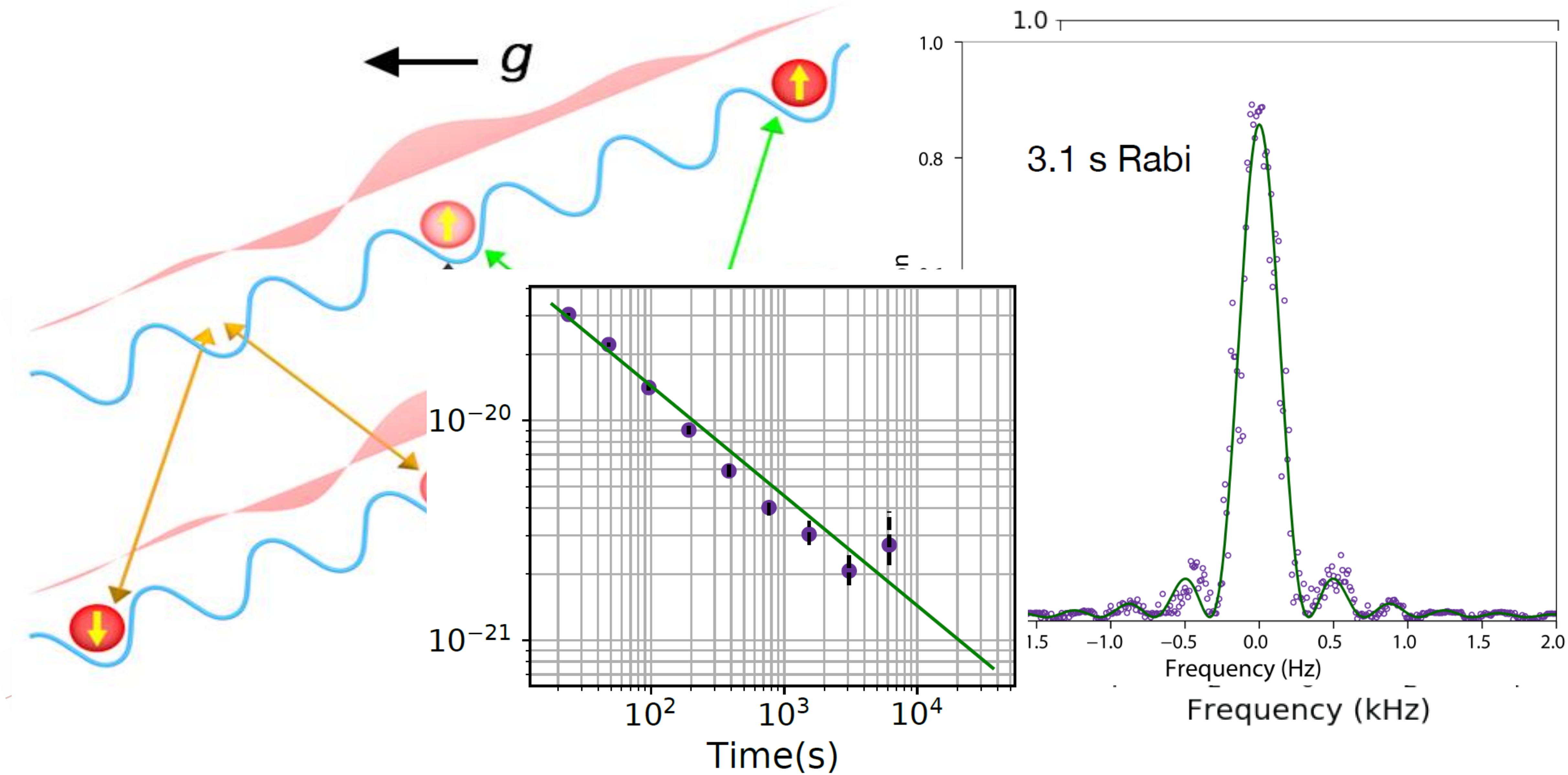
Martin *et al.*, Science 2013;
Zhang *et al.*, Science 2014



$|ge\rangle + |eg\rangle \otimes |n_1\, n_2\rangle - |n_2\, n_1\rangle$ Fermions

A Wannier-Stark lattice clock

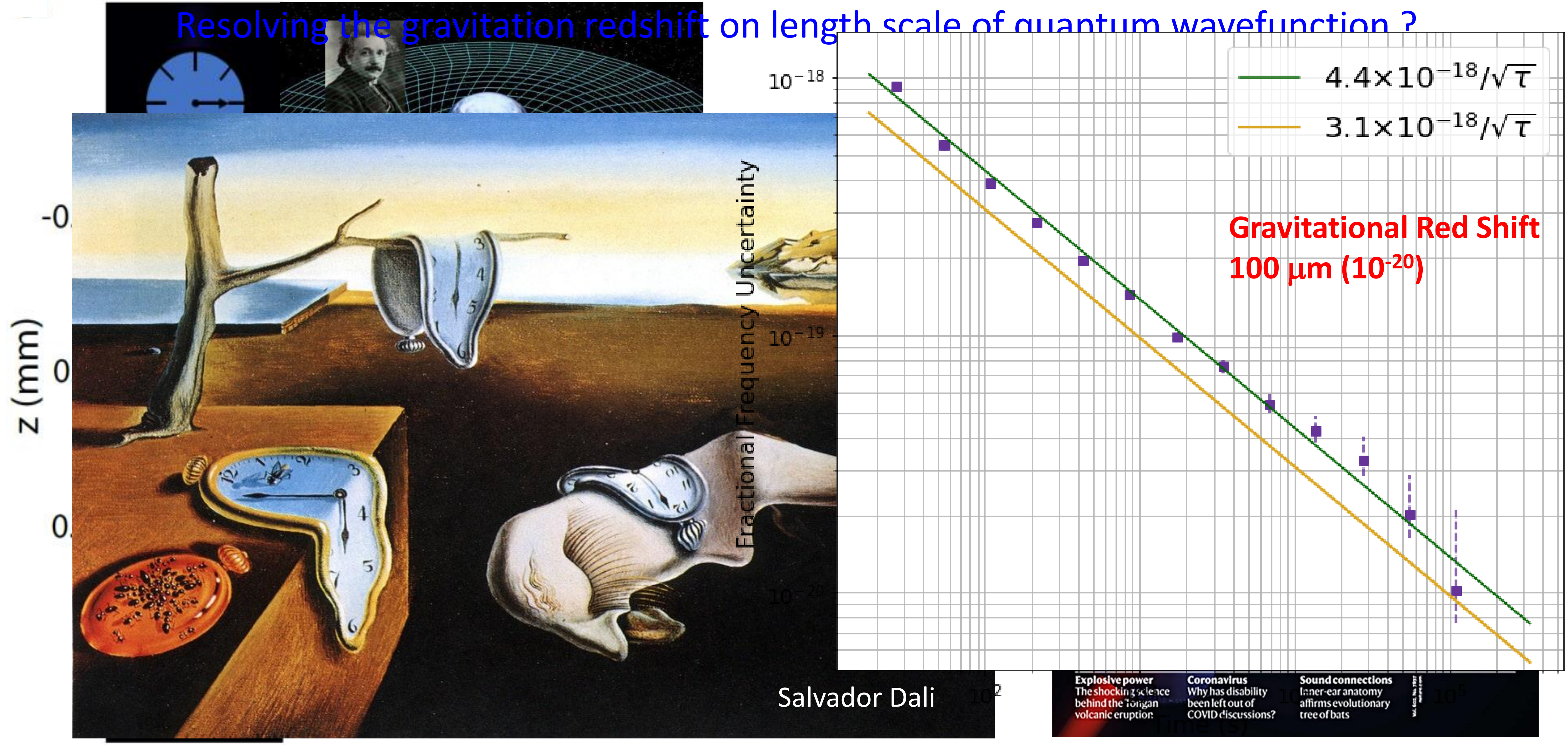
Bothwell *et al*., Nature **602**, 420 (2022).   Aeppli *et al*., Science Adv. **8**, eadc9242 (2022).



Clock precision reaches 6 x 10^{-21}

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

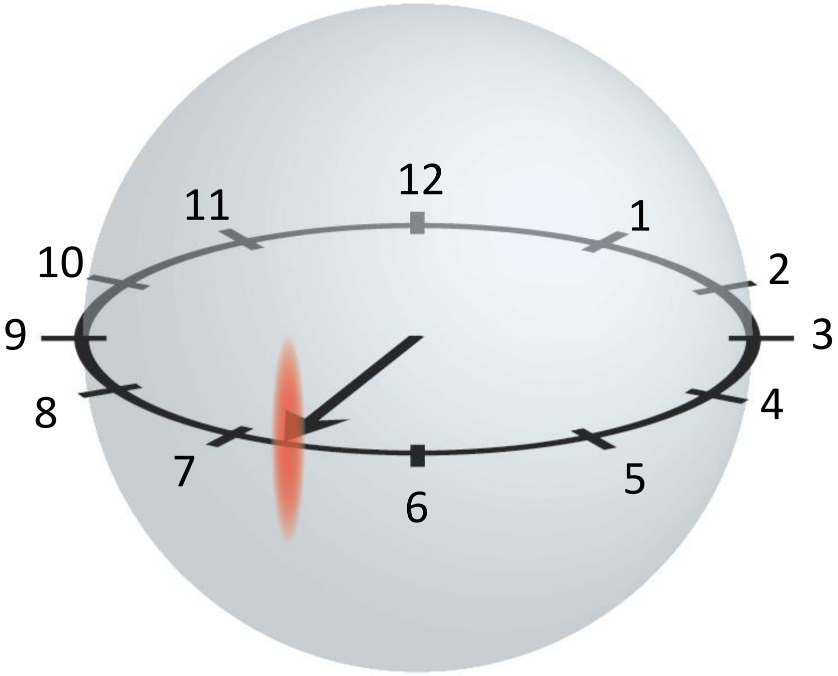
Resolving the gravitation redshift on length scale of quantum wavefunction ?



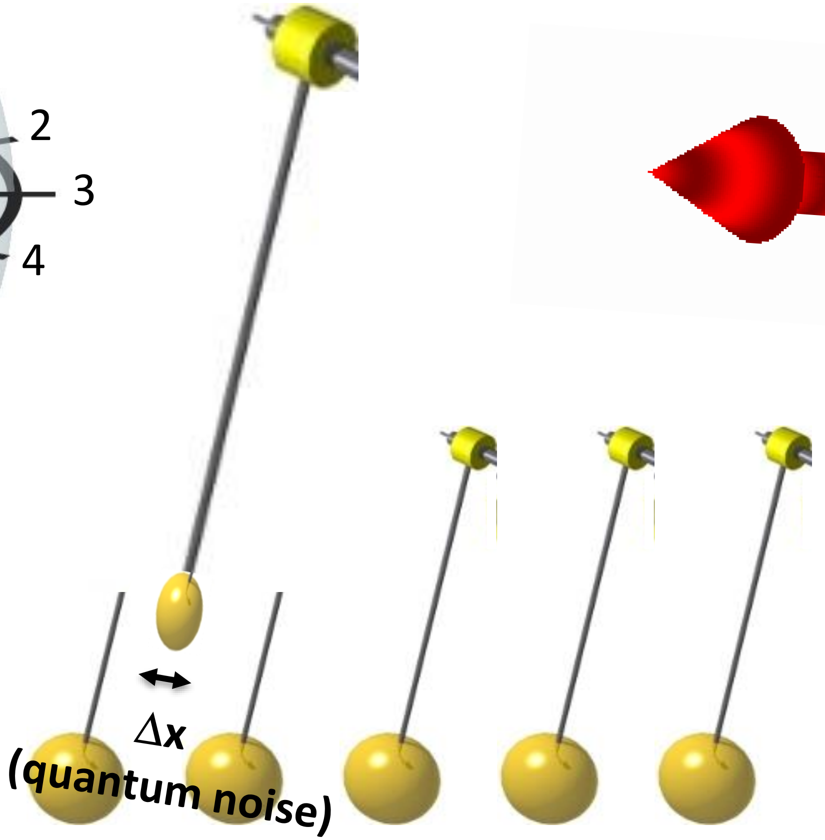
Quantum noise

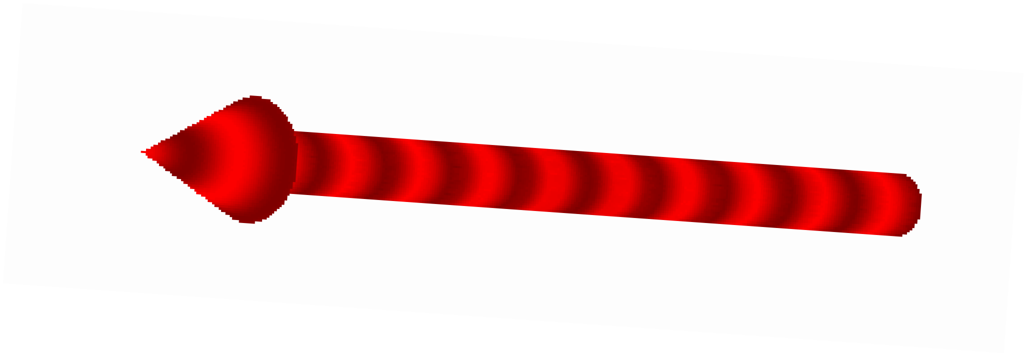
Quantum Phase Noise of Atoms

Phase of Coherent Laser



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

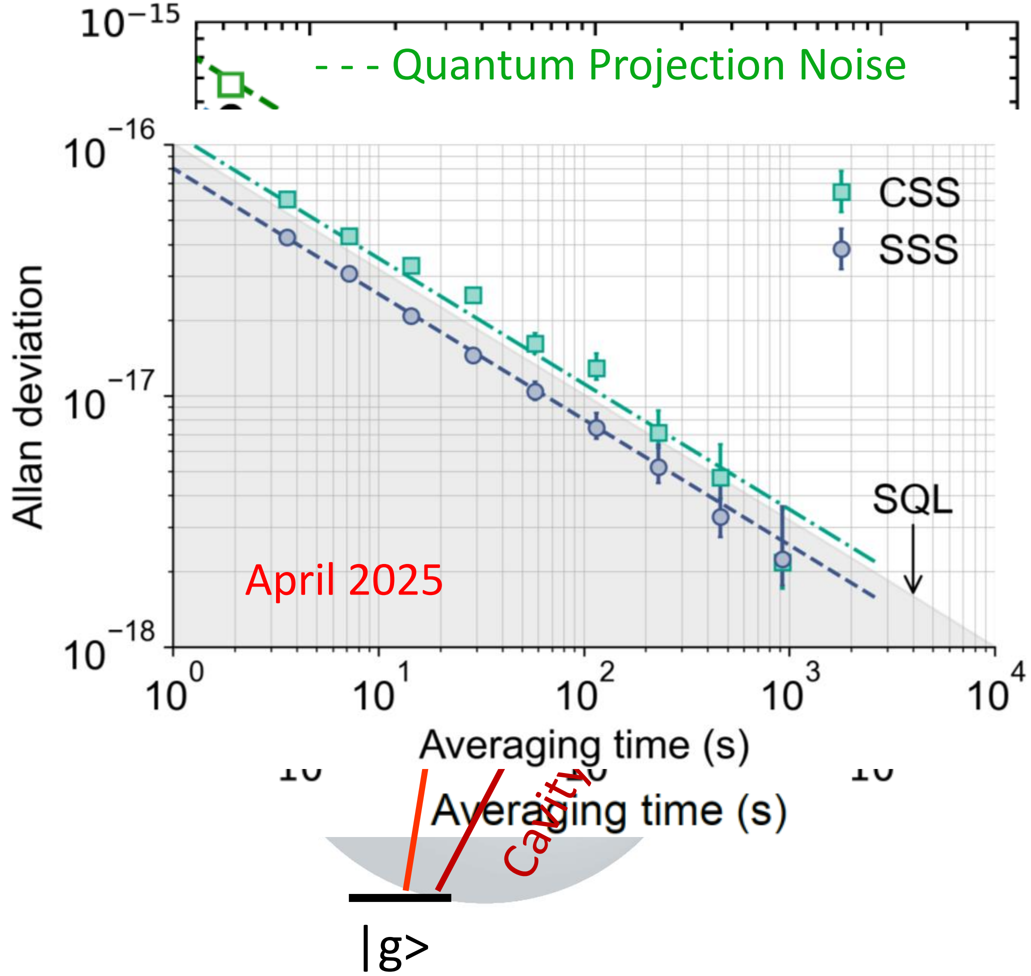


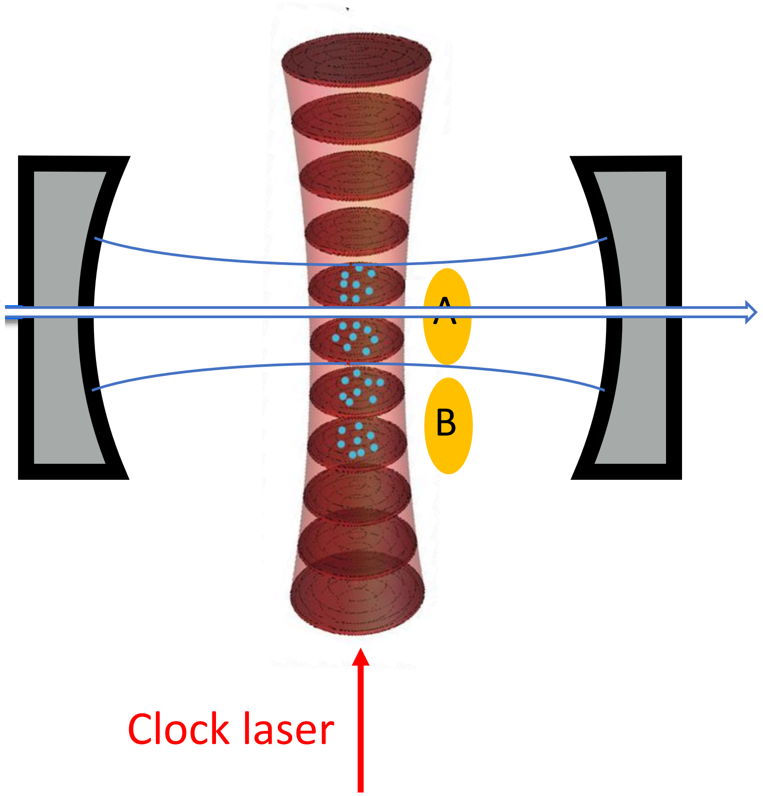


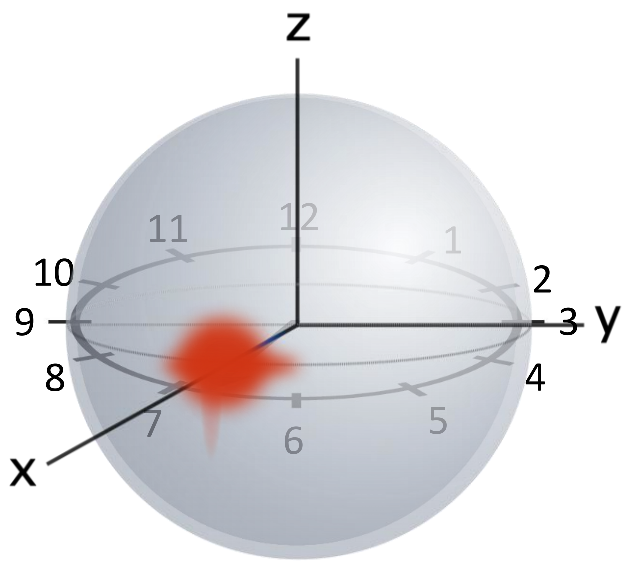
$$\mathrm{D}f_{SQL} = \frac{1}{N}$$

Spin entanglement in state-of-the-art clock

- Spin Squeezing at 10^{-17}
- Direct clock comparison
- Robinson *et al.*, Nature Phys. **20**, 208 (2024).







Scaling up atom number

Quantum simulator & sensor (Fermi Hubbard model)

Degenerate Fermi gas of Sr atoms:

1 million atoms

$$\hat{H} = -t\sum_{j,\sigma}\left(\hat{c}^{\dagger}_{j,\sigma}\hat{c}_{j+1,\sigma} + h.c.\right) + U\sum_{j}\hat{n}_{j,\uparrow}\hat{n}_{j,\downarrow} + \frac{\Omega}{2}\sum_{j}\left(e^{ij\phi}\hat{c}^{\dagger}_{j,\uparrow}\hat{c}_{j,\downarrow} + h.c.\right)$$

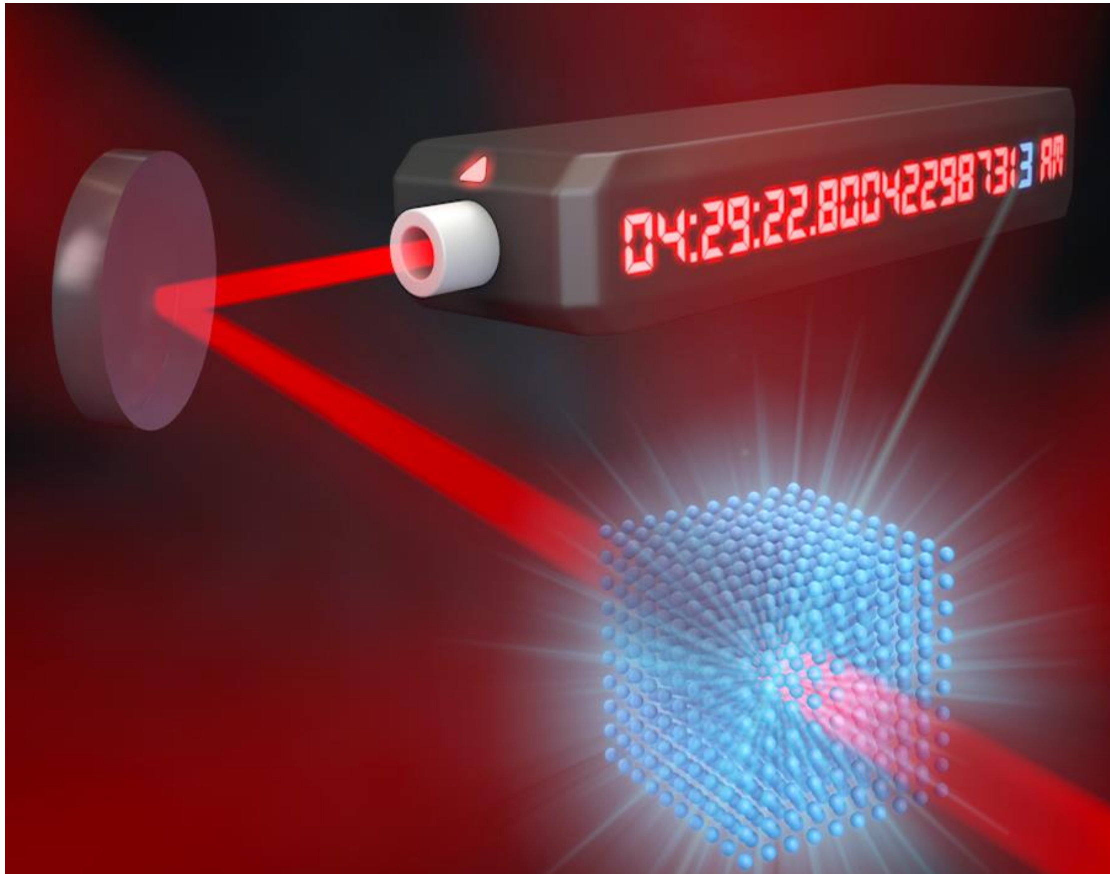
Coherence 120 s

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

Densely packed atoms impact light-atom interactions

→ limit for measurement precision ?

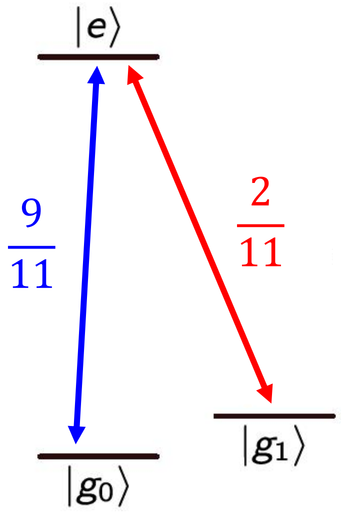
- Spin SU(*N*) symmetry Nature **563**, 369 (2018)
- Spin-orbit dynamics & spin exchange Science (May 1, 2025)
- Collective dipolar coupling Science **383**, 384 (2024)



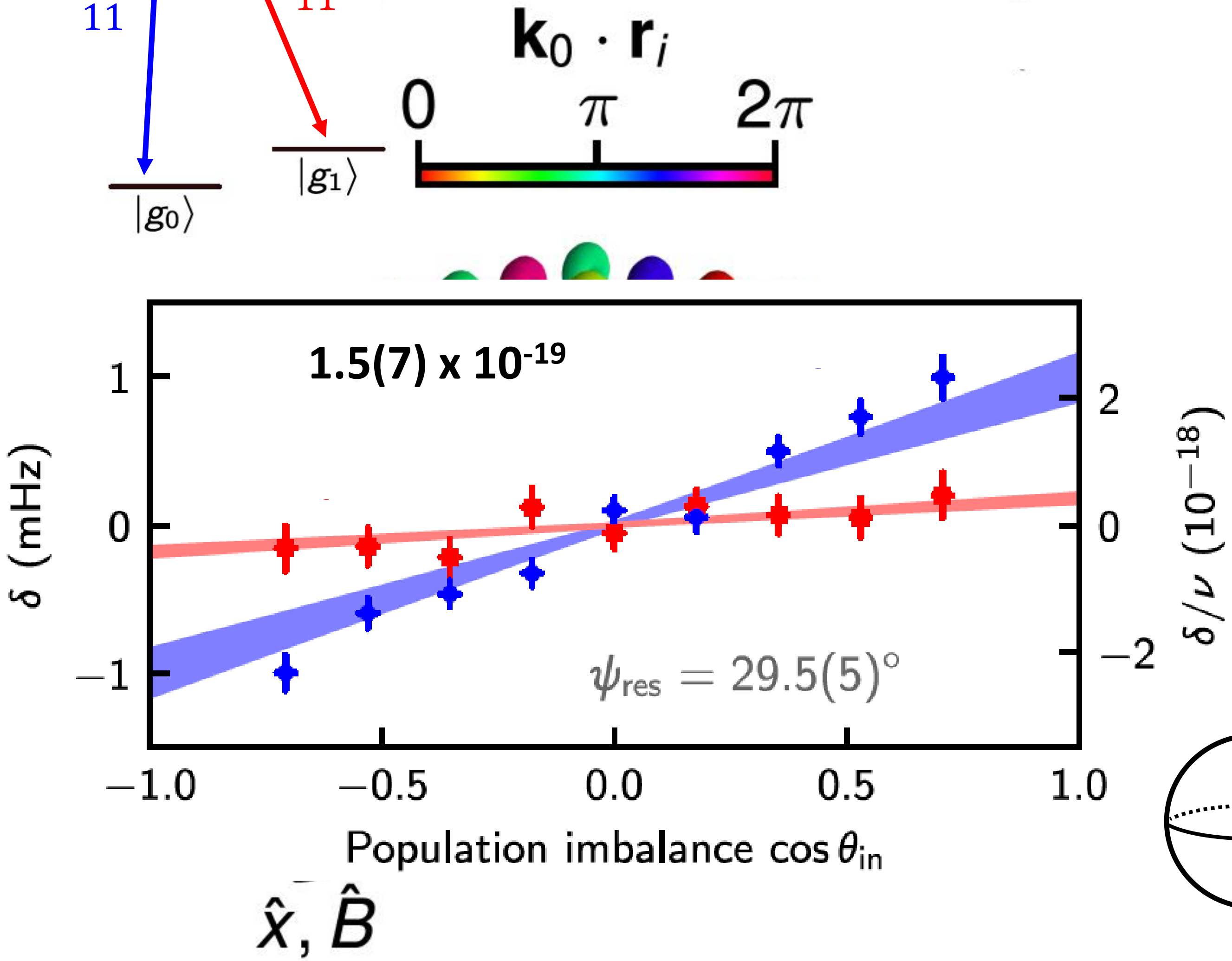
S. Campbell *et al.*,
Science **358**, 90 (2017).

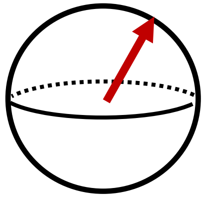
Collective coupling of radiative dipoles

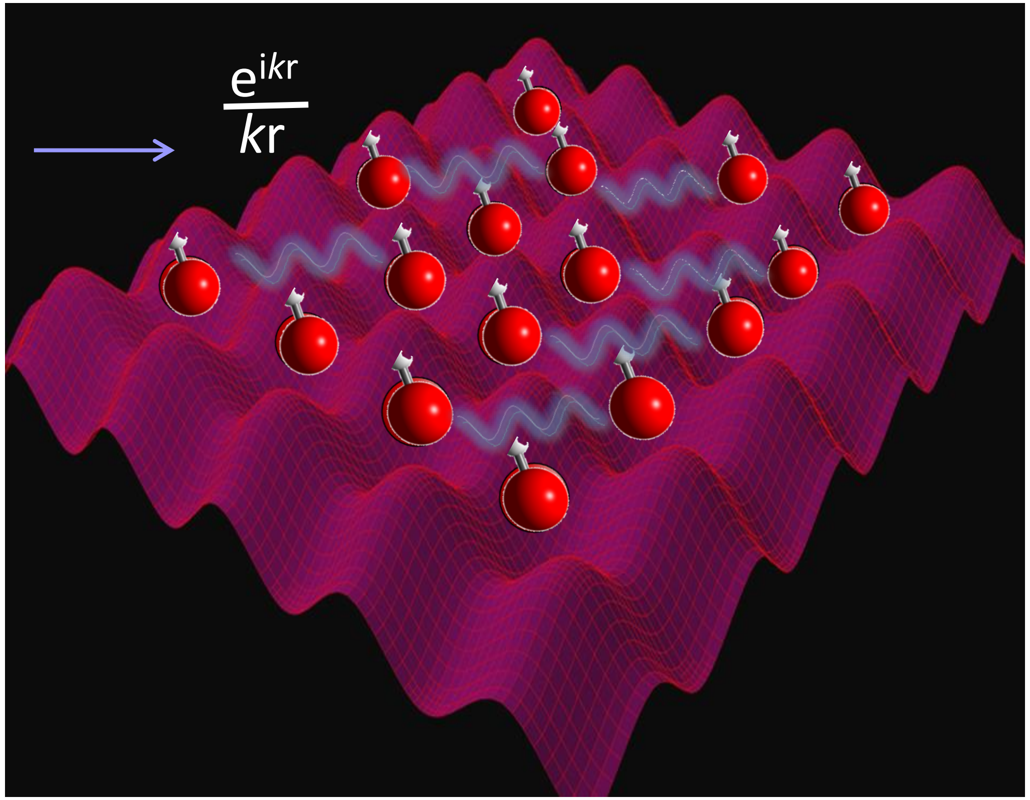
Chang, Ye, Lukin, Phys. Rev. A **69**, 023810 (2004); Hutson *et al.*, Science **383**, 384 (2024).



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



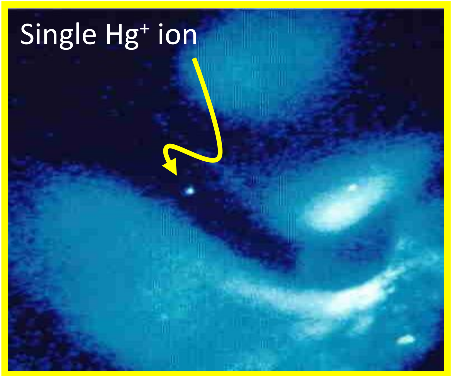


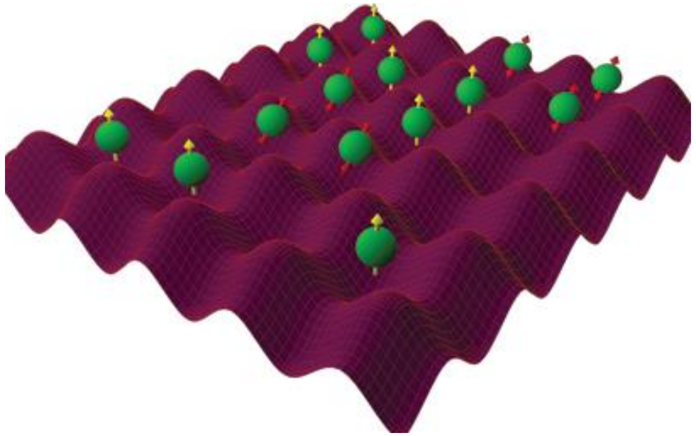


Historical lesson & Number scaling

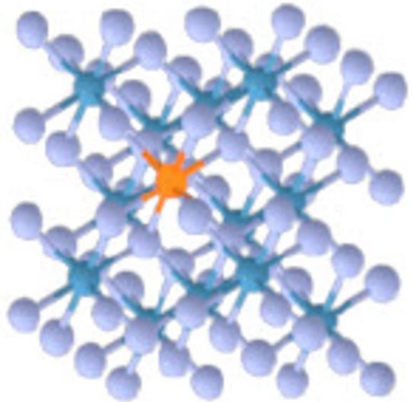
Doppler-free transition through motional state control

Atomic clocks
(coherent)



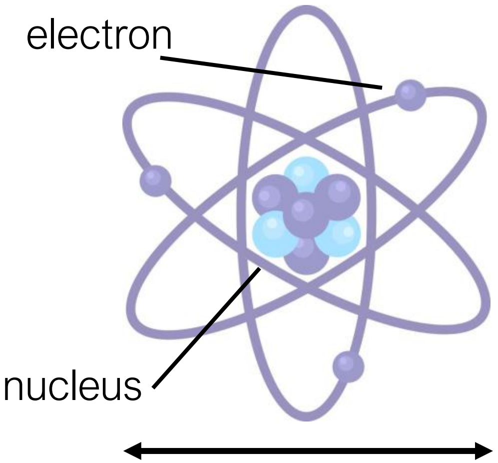


Mössbauer spectroscopy
(incoherent → coherent)

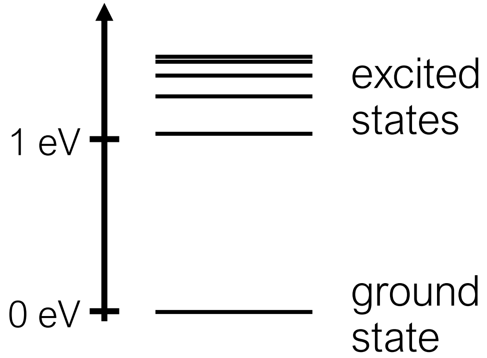


Nuclear energy levels vs. atomic energy levels

Electronic transitions

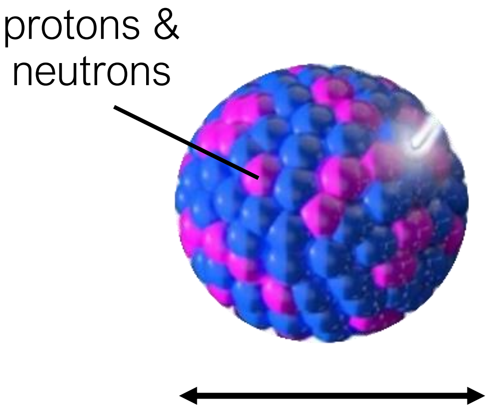


10^{-10} m

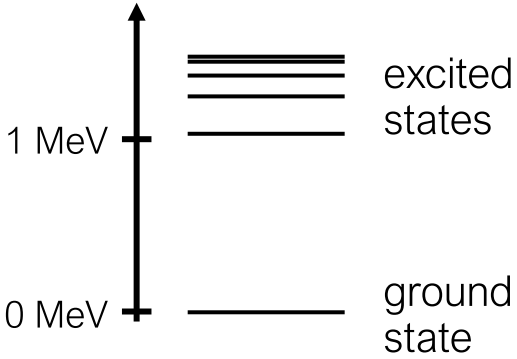


E ~ 1 eV ⇔ λ ~ 10^3 nm

Nuclear transitions



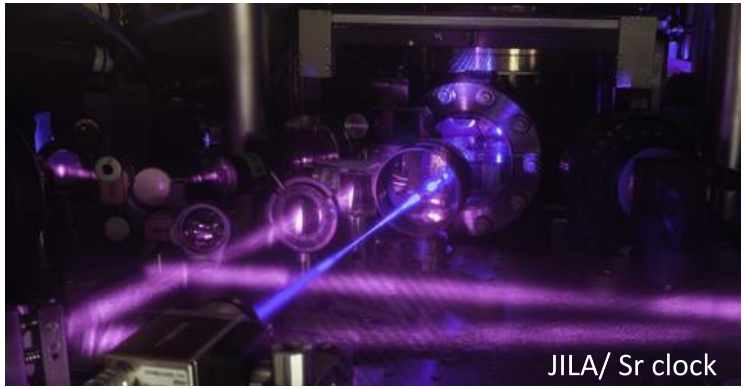
10^{-14} m



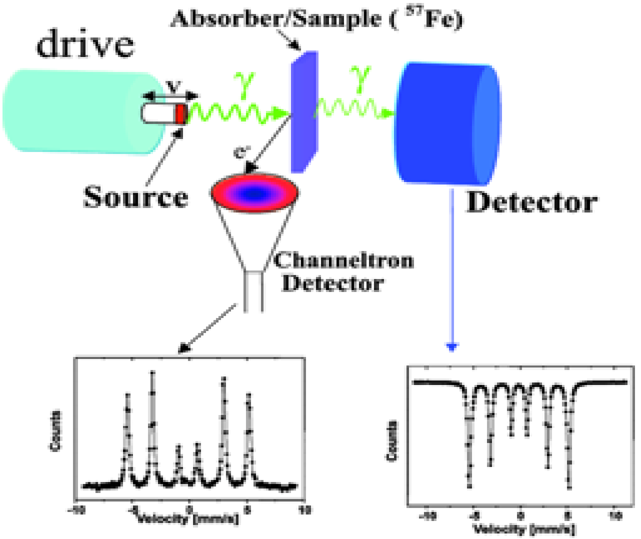
E ~ 1 MeV ⇔ λ ~ 0.001 nm

Light Source:

Coherent visible/infrared lasers



X-rays/Gamma rays



Coherent Mössbauer spectroscopy for nuclear clock

Peik & Tamm, Europhys. Lett. **61,** 181 (2003); Tiedau ... Peik, PRL **132**,182501 (2024). Elwell ... Hudson, PRL **133**, 013201 (2024).

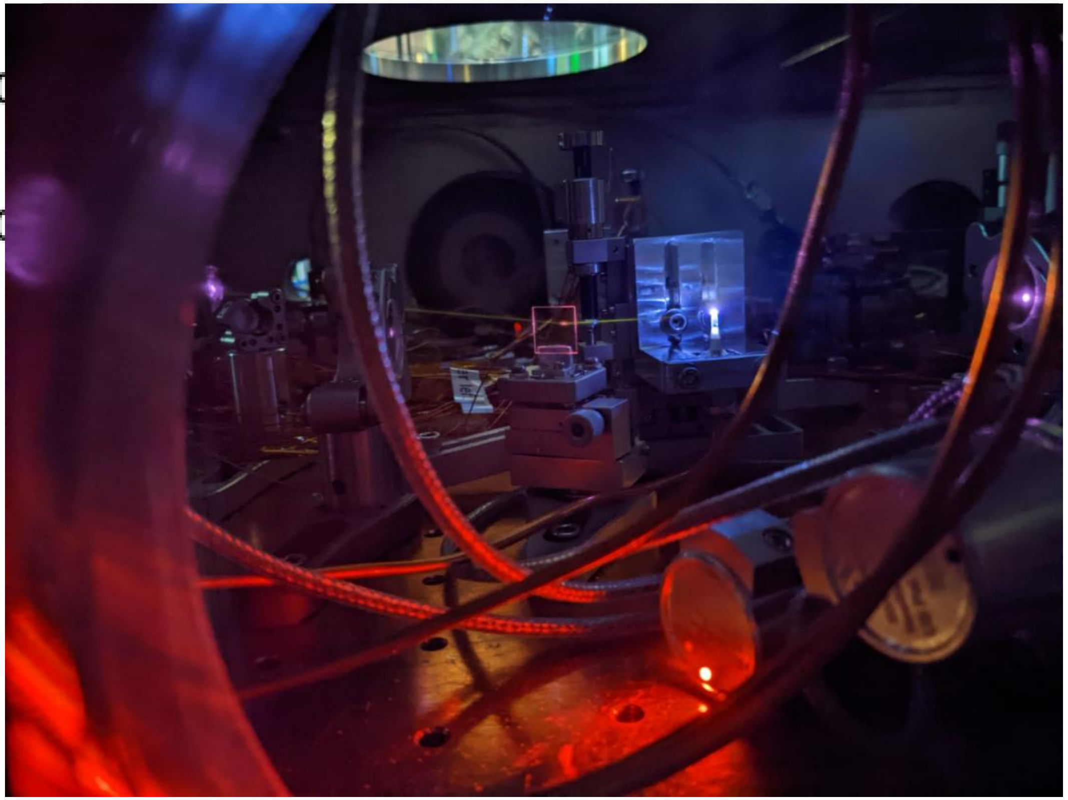
Phase-coherent vacuum-ultraviolet frequency comb

Wavelength [nm]

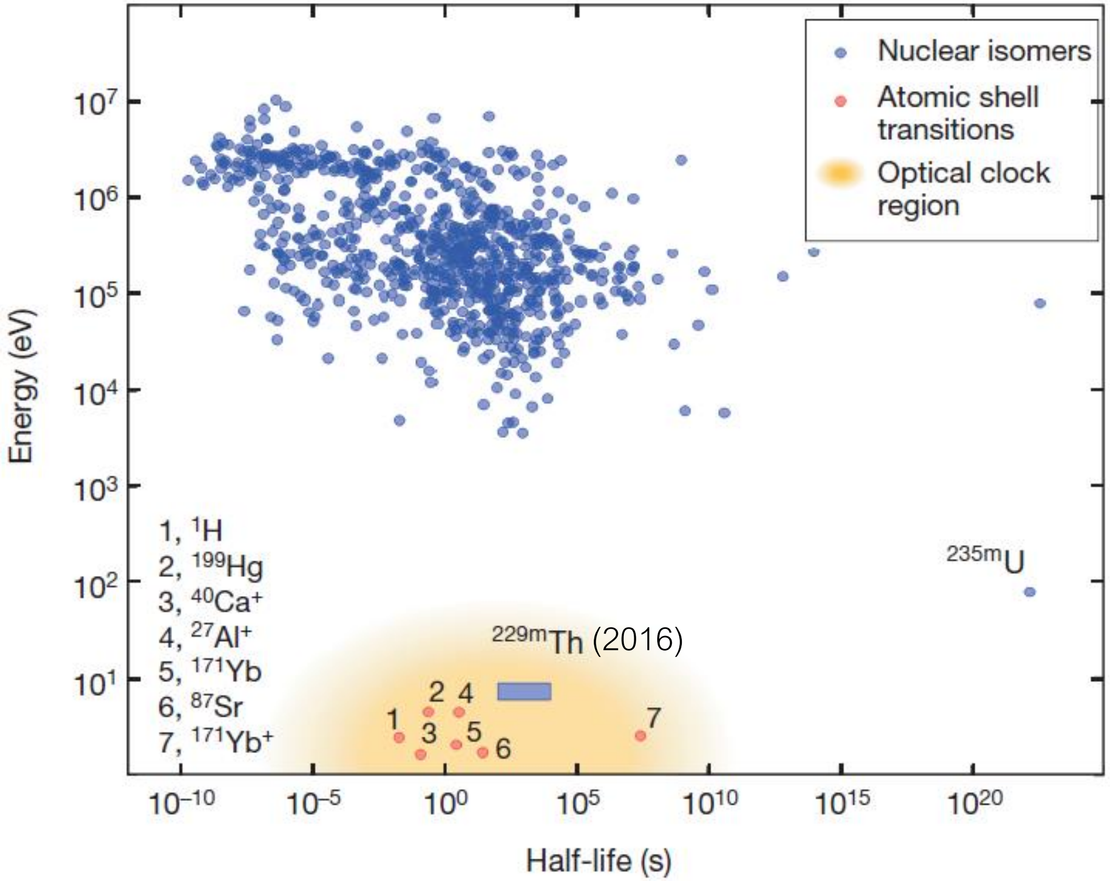
148.387 148.382 148.377

100

50



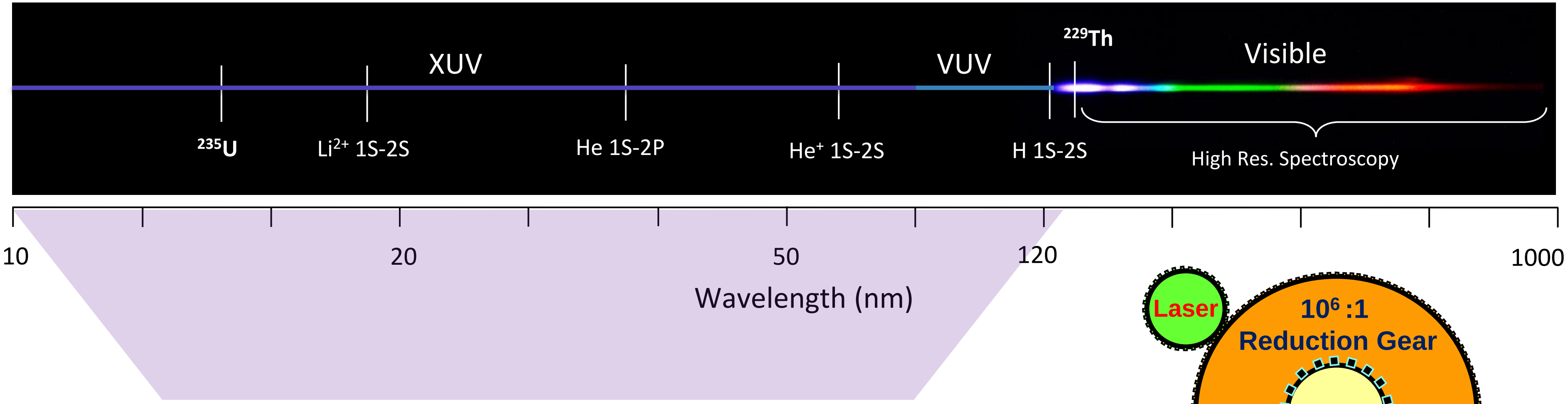
Uniquely low energy transition in ^{229}Th

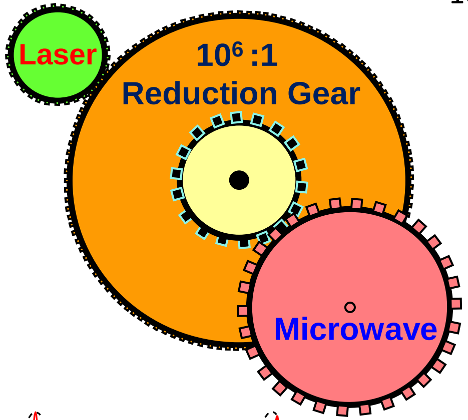


R. J. Jones *et al.*, Phys. Rev. Lett. **94**, 193201 (2005)
C. Gohle *et al.*, Nature **436**, 234 (2005)

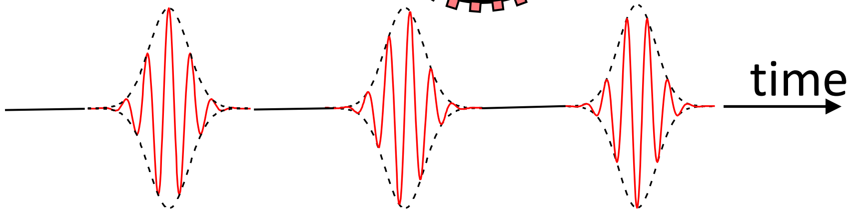
L. v.d.Wense *et al.*, Nature **533**, 47 (2016)

Need: coherent extreme/vacuum ultraviolet light





- Free electron lasers, synchrotron radiations broadband
- High resolution spectroscopy for atoms, ions, & nuclei



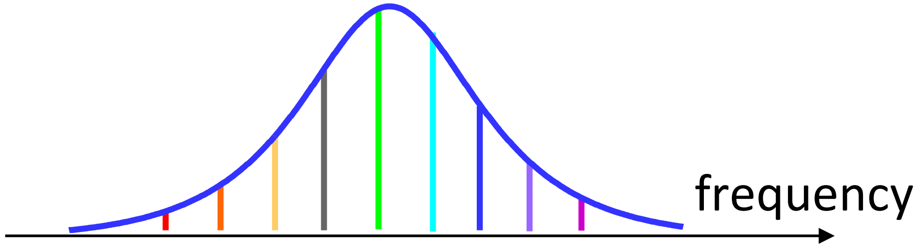


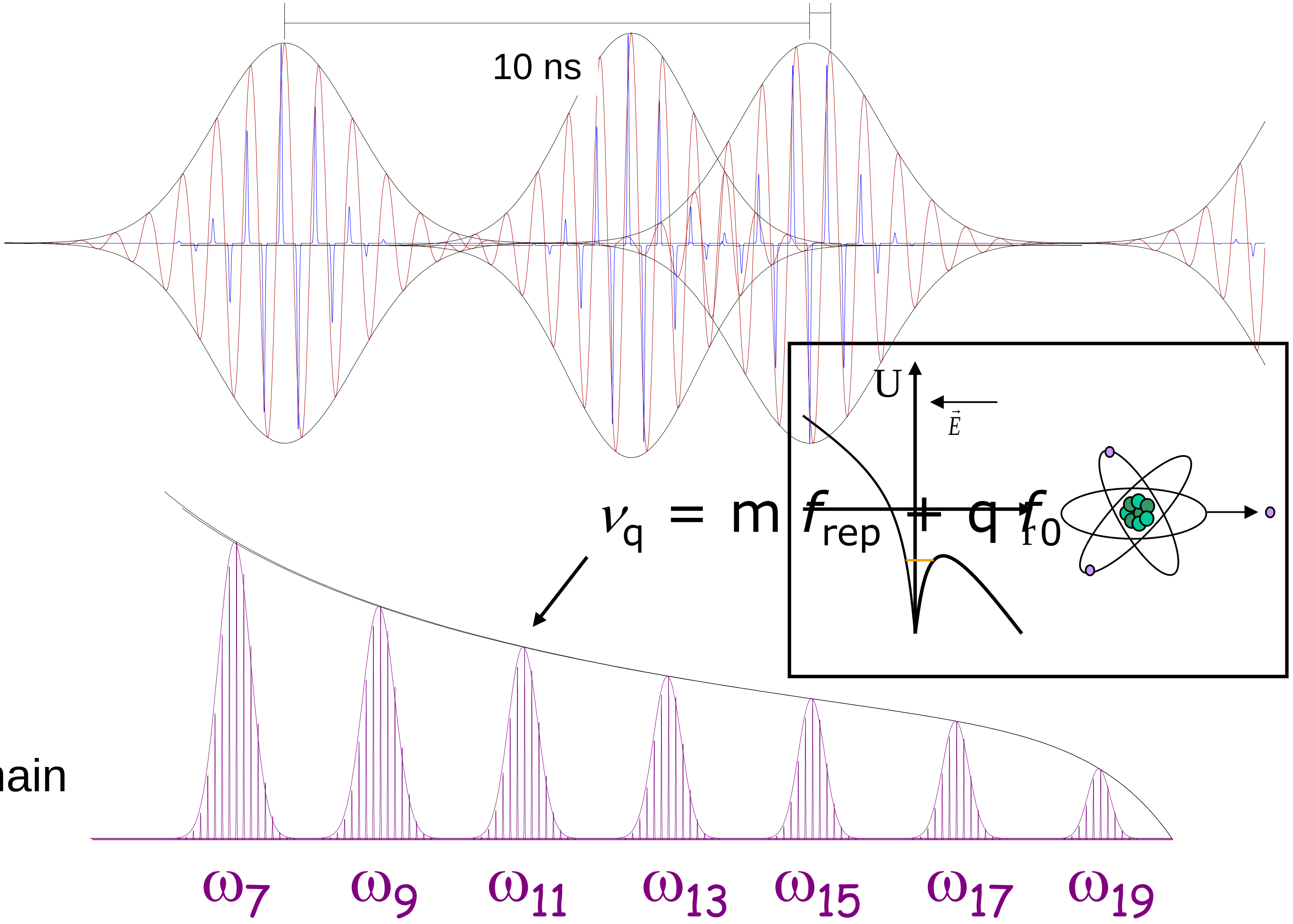
Table-top coherent VUV and XUV radiation

Harmonic Generation with a single IR pulse → *XUV attosecond pulse*

Harmonic Generation with a train of IR pulses → *train of XUV frequency combs*

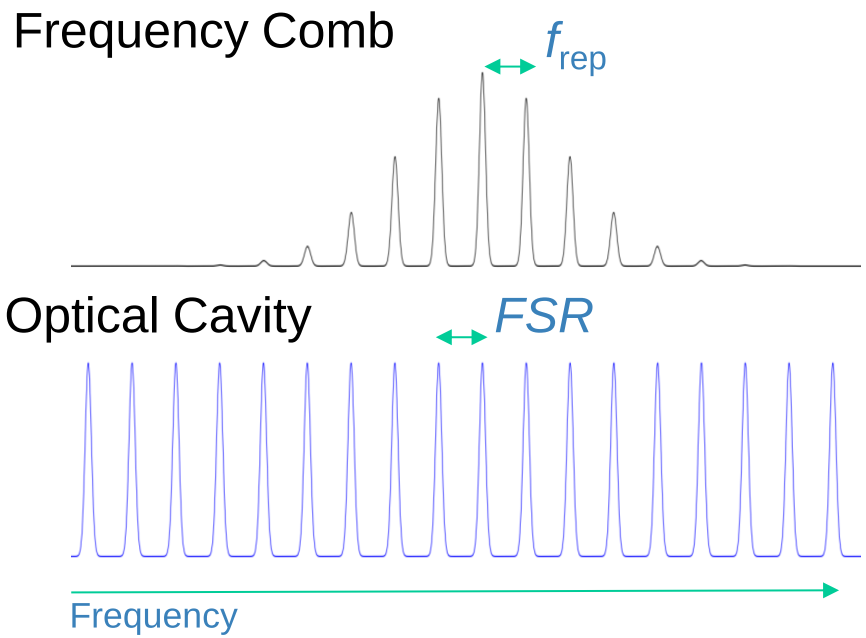
Time domain

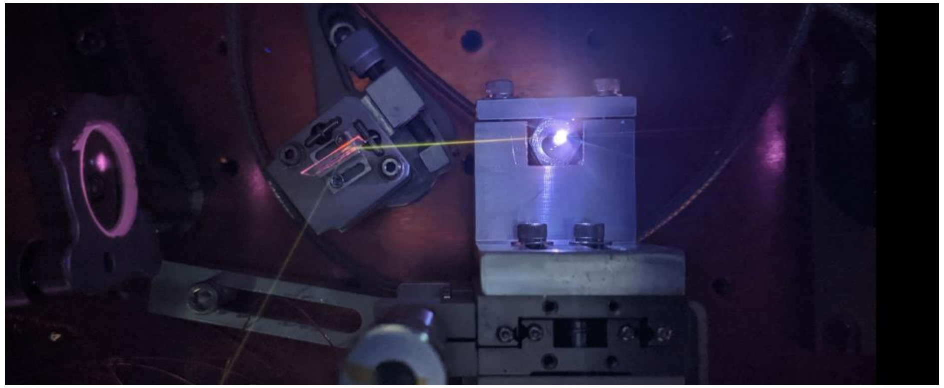
Frequency domain

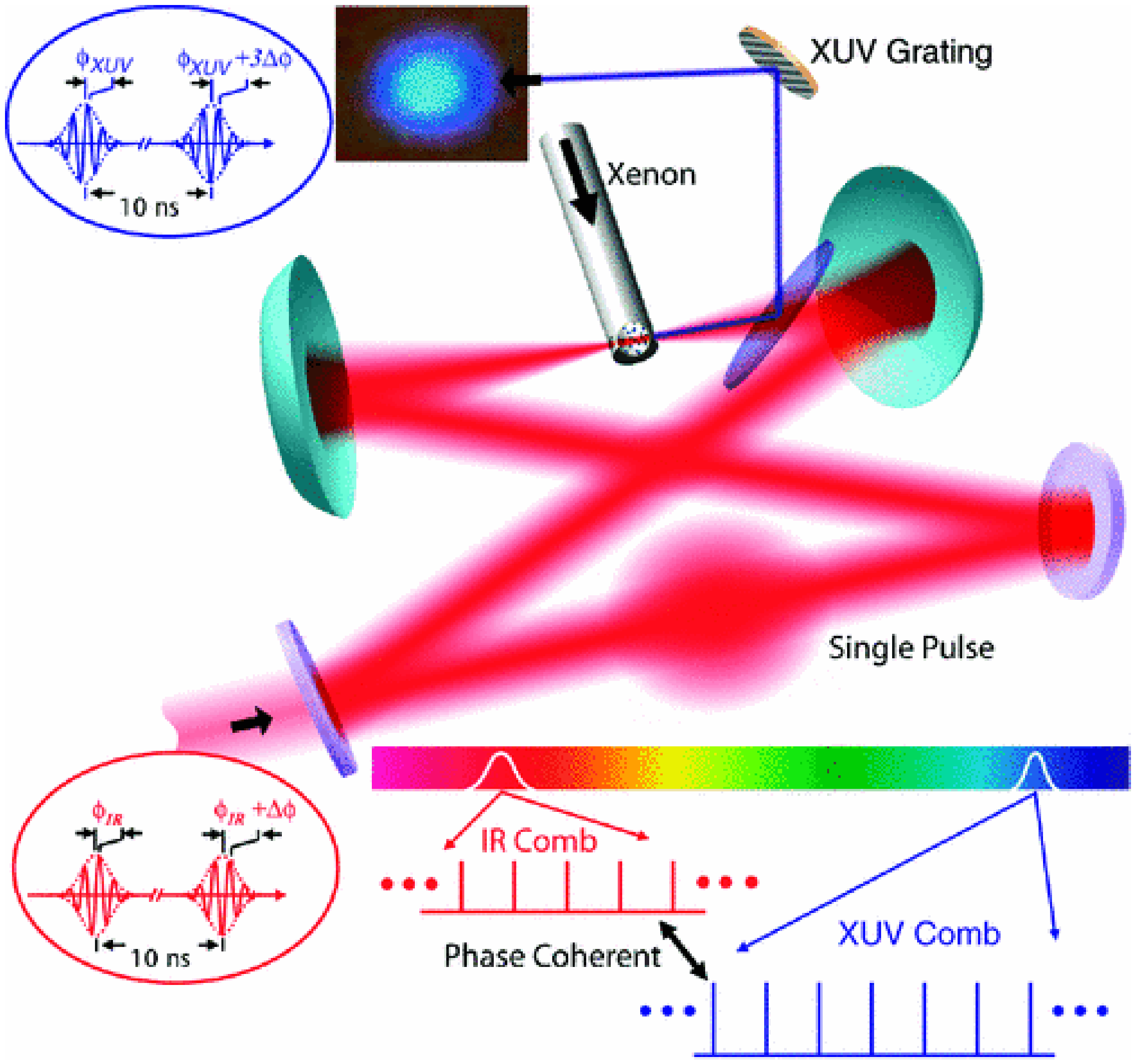


Making a VUV frequency comb

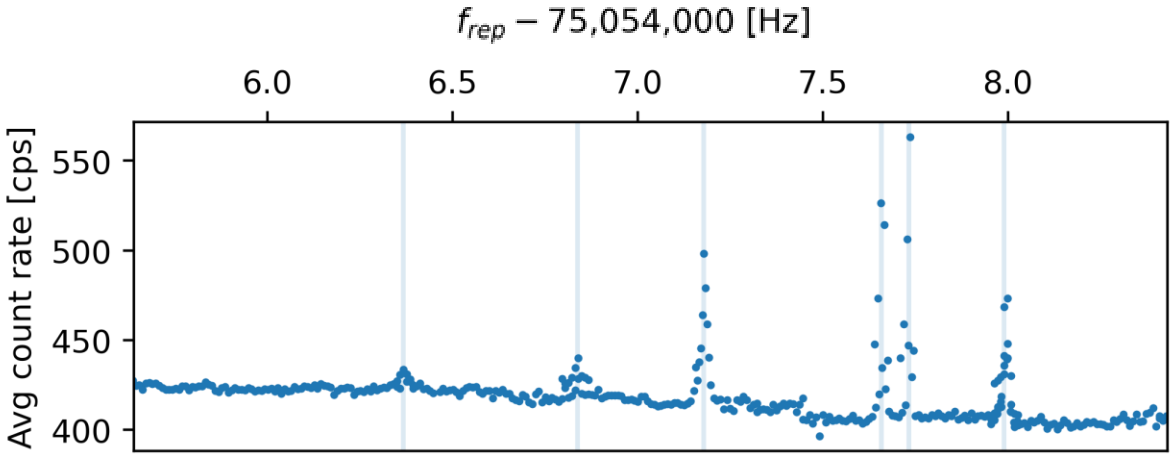
R. J. Jones & J. Ye, Opt. Lett. **27,** 1848 (2002)
R. J. Jones *et al*., Phys. Rev. Lett. **94**, 193201 (2005)
C. Gohle *et al*., Nature **436**, 234 (2005)



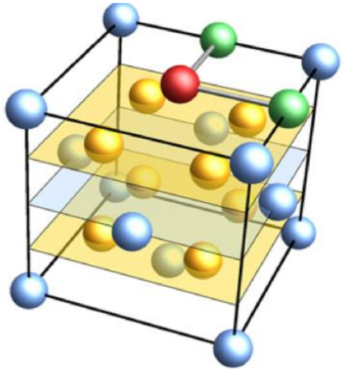




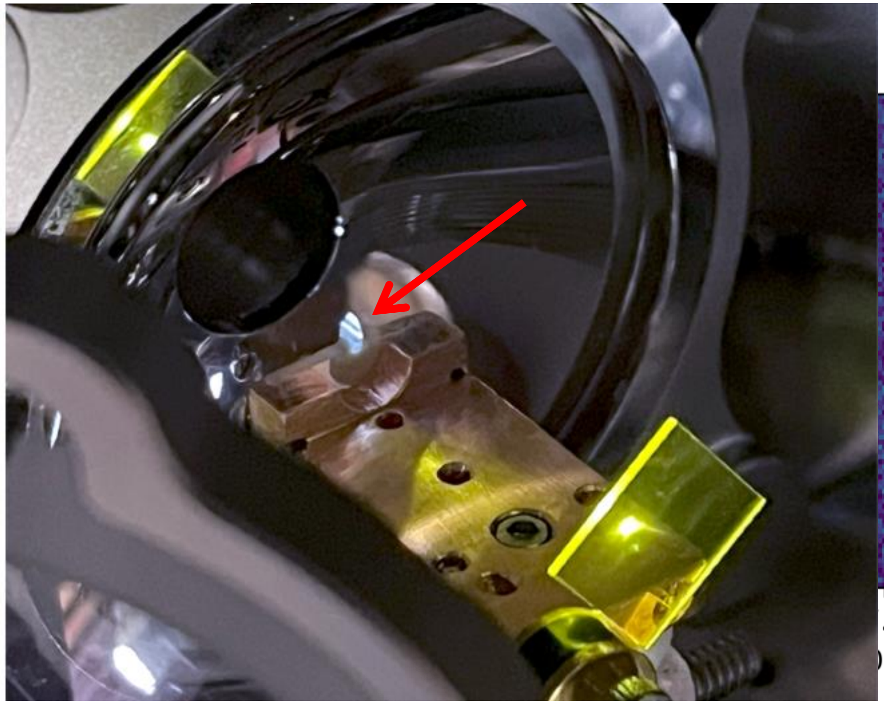
Parallel scan of comb lines on ^{229}Th – doped CaF_2 crystal

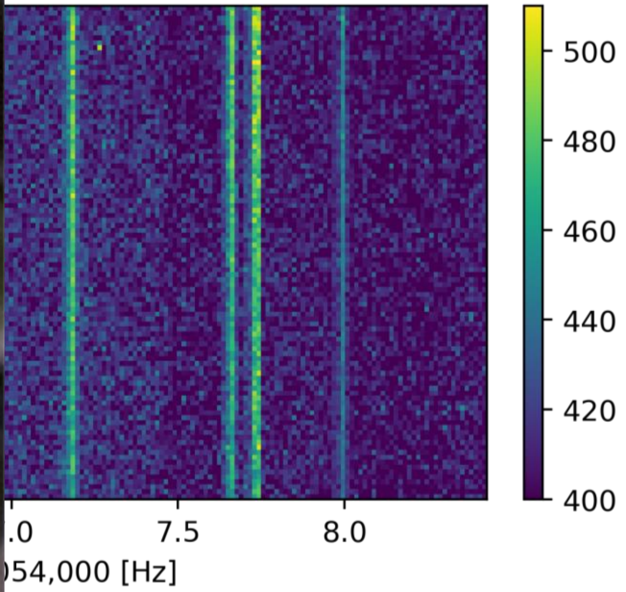


^{229}Th concentration:
4×10^{18} cm^{-3}

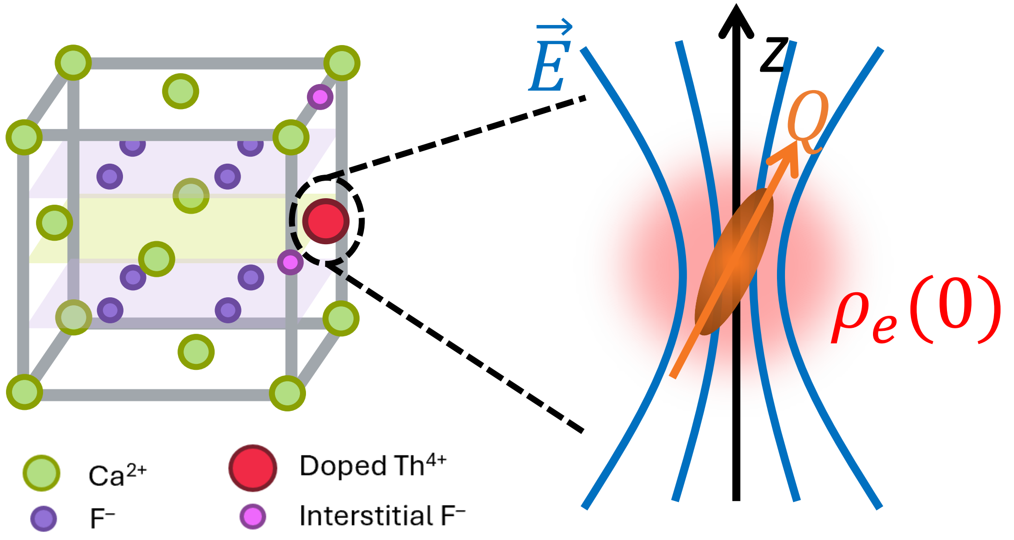


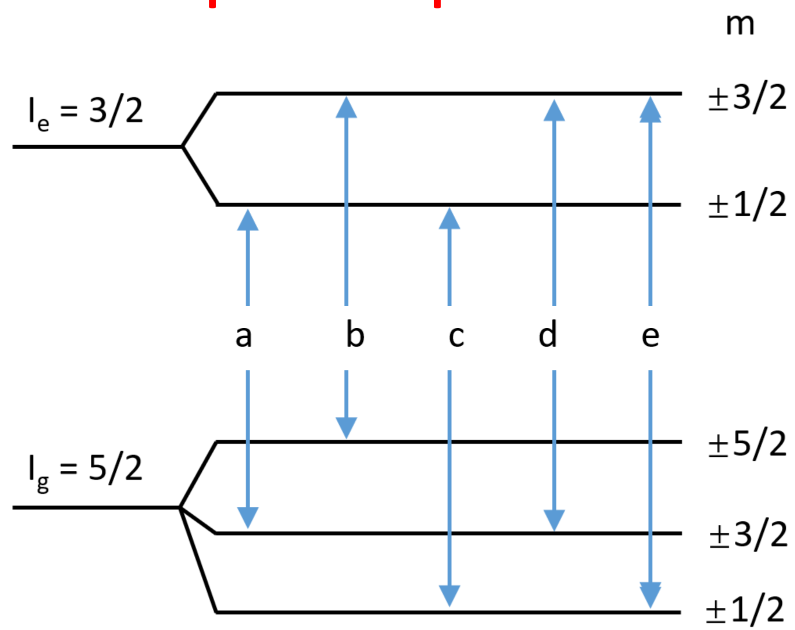
Thorsten
Schumm



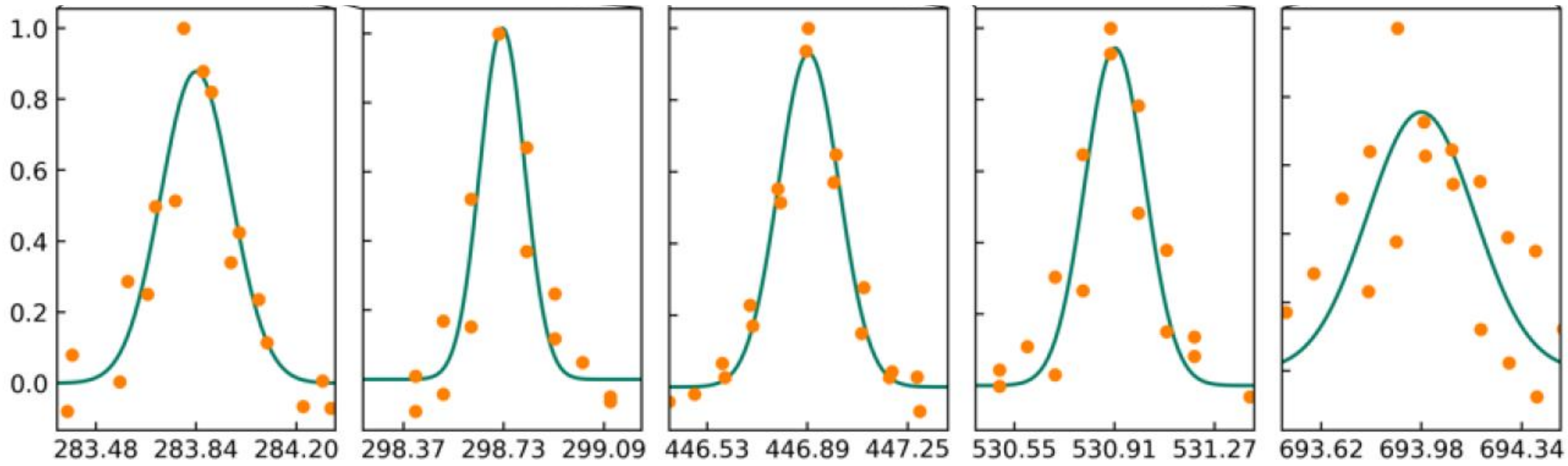


Quantum-state resolved nuclear electric quadrupoles

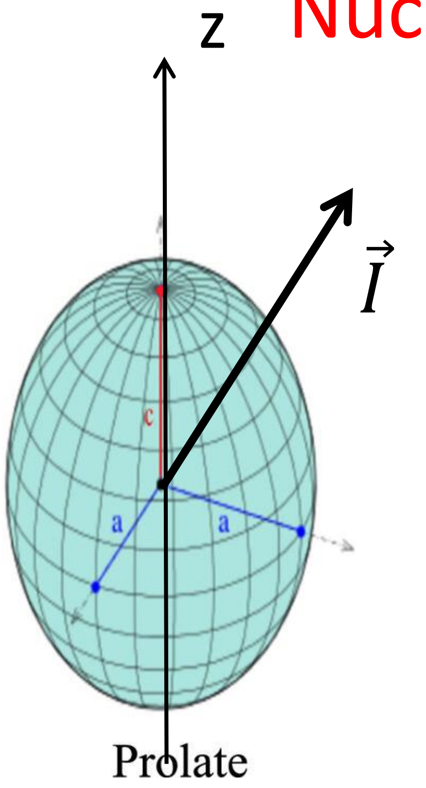




Linewidth ~200 kHz



Nuclear structure & new physics beyond standard model



Beeks … Schumm, Ye, Safronova, arXiv:2407.17300 (2024).

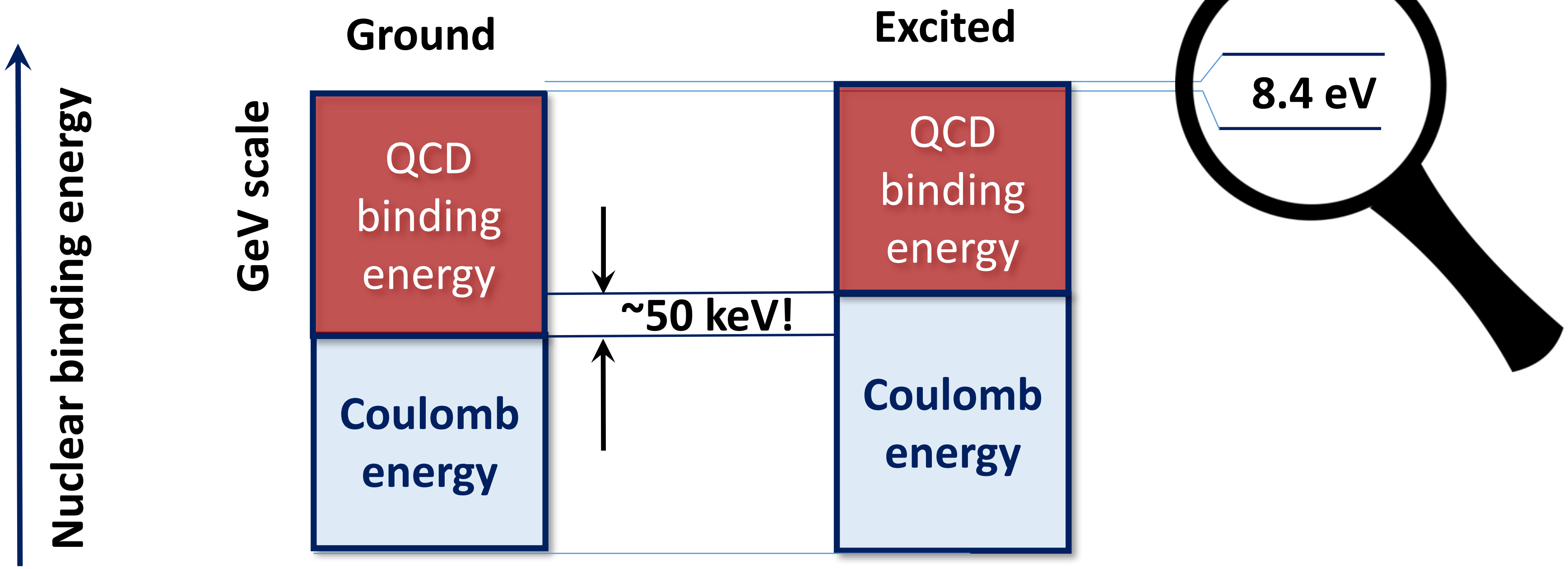
Quadrupole moment ratio

$$\frac{Q_{\mathrm{is}}}{Q_{\mathrm{g}}} = 1.01791(2)$$

$\Rightarrow$

Nuclear volume:

$$\frac{V_{\mathrm{is}}}{V_{\mathrm{g}}} = 1.00055$$



Coulomb interaction $\sim \alpha$

Strong force

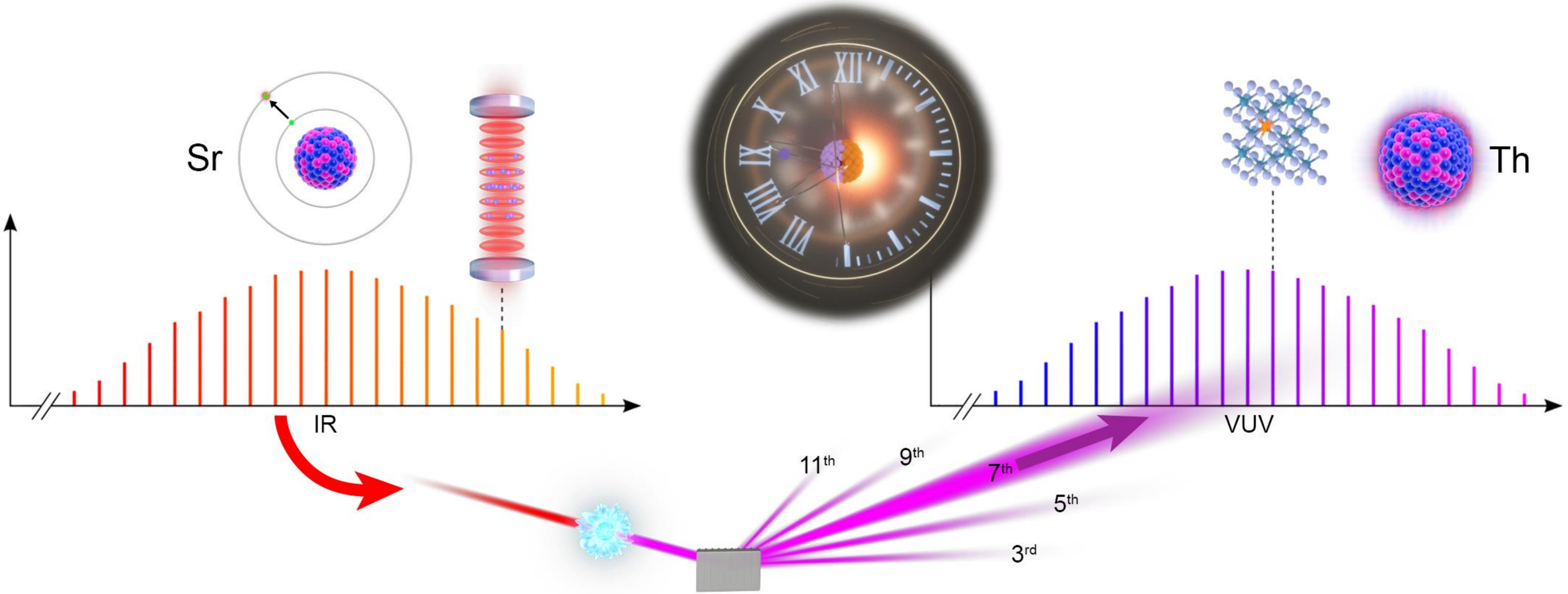
Sensitivity to variation of α

$$\boxed{\frac{49(19)\ \mathrm{keV}}{8.4\ \mathrm{eV}} \sim 5900(2300)}$$

Connecting ^{229m}Th isomeric frequency to ^{87}Sr atomic clock

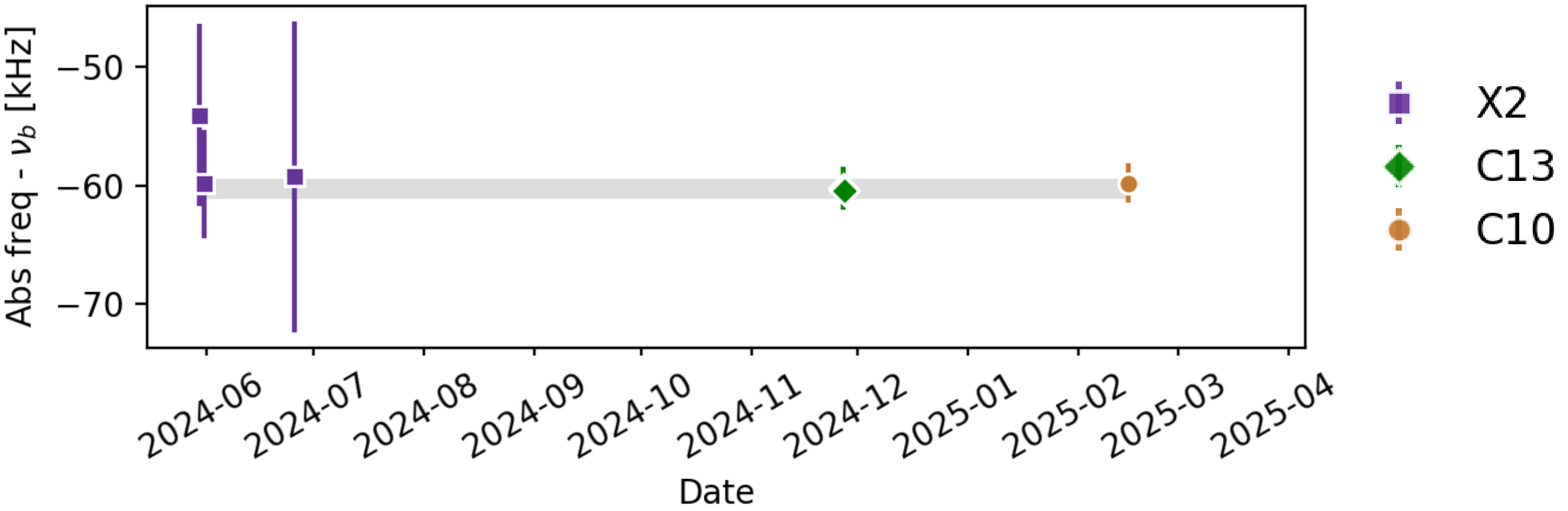
Zhang … Thirolf, Schumm, Ye, Nature **633**, 63 (Sept. 5, 2024).

$$\frac{\nu_{^{229}\mathrm{Th}}}{\nu_{^{87}\mathrm{Sr}}} = 4.707\,072\,615\,078(5)$$

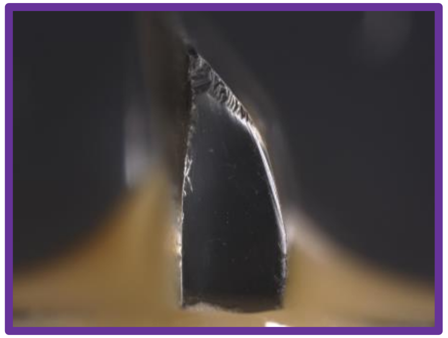


$^{229}Th:CaF_2$: Frequency reproducibility

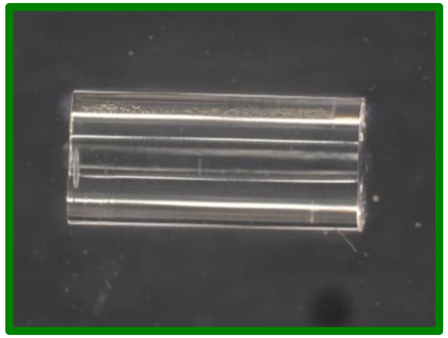
Higgins … Schumm, Ye, Phys. Rev. Lett. **134**, 113801 (2025).



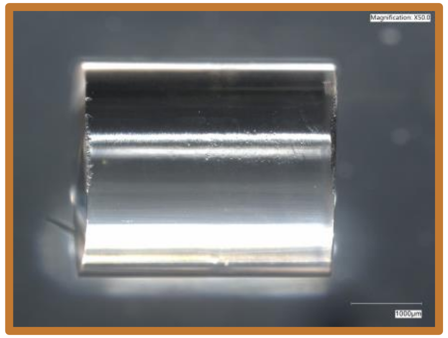
X2: 4×10^{18} cm^{-3}
19 May 2021



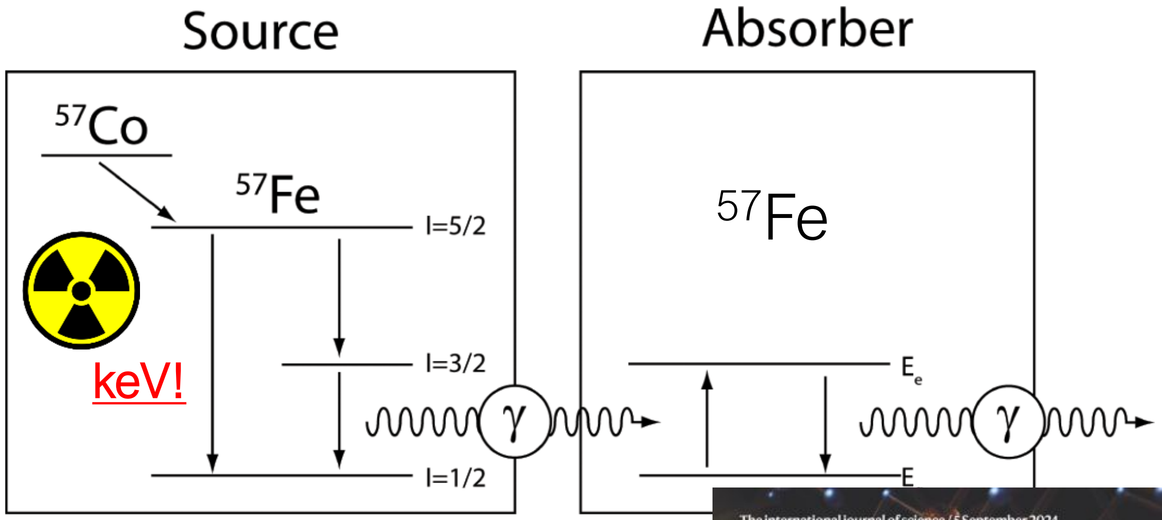
C13: 0.8×10^{18} cm^{-3}
7 Dec 2020



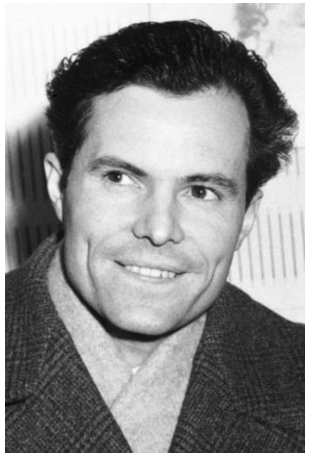
C10: 0.3×10^{18} cm^{-3}
23 Nov 2020



Precision sensing for fundamental physics



Mössbauer spectroscopy
nuclear transitions



Gravitational red shift measured with

PHYSICAL REVIEW LETTERS

VOLUME 4 APRIL 1, 1960

APPARENT WEIGHT OF PHOTONS*

R. V. Pound and G. A. Rebka, Jr.
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachu
(Received March 9, 1960)

Bothwell *et al*., Nature **602** 420 (2022)
Zhang *et al*., Nature **633**, 63 (2024)

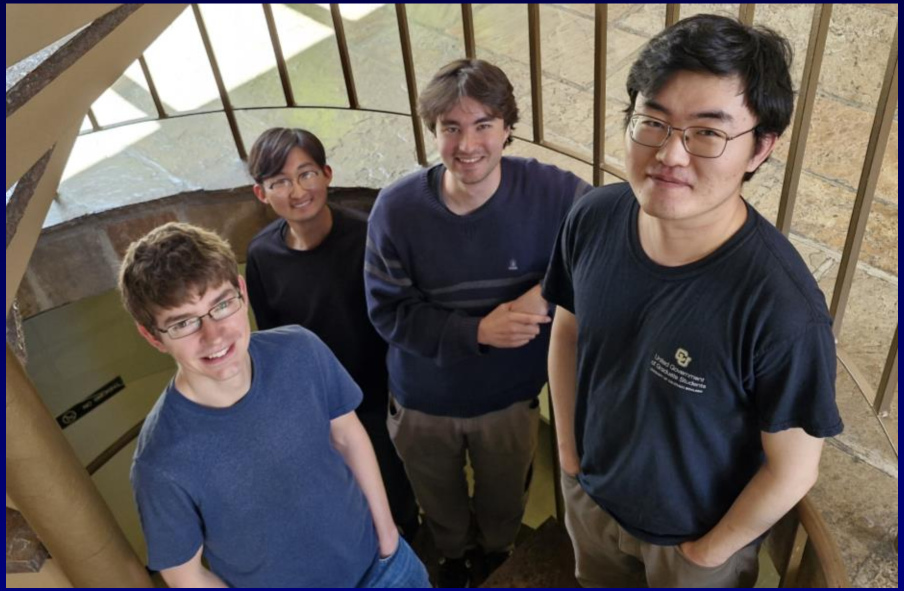
A nuclear-atomic connection

Sr optical clock: quantum meets precision

K. Kim
A. Aeppli
W. Warfield

Z. Hu
D. Lee
B. Lewis

L. Yan
S. Lannig
M. Frankel
Y. Lee



Y. Yang
Y. M. Tso
J. Hur
M. Miklos
S. Kraus
Y. Yang

Collaboration: A. M. Rey, J. Thompson, A. Kaufman, M. Safronova, M. Lukin, P. Zoller, … …

PTB, NIST T&F

^{229}Th nuclear clock

Many JILA scientists and staff members

Tian Ooi Jake Higgins **Chuankun Zhang** John Doyle

JILA

NIST