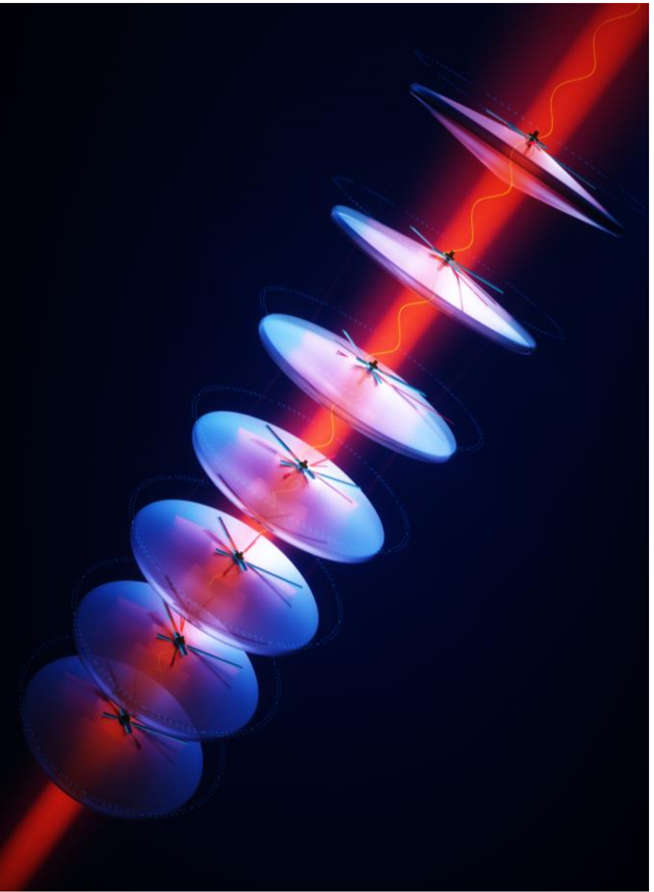
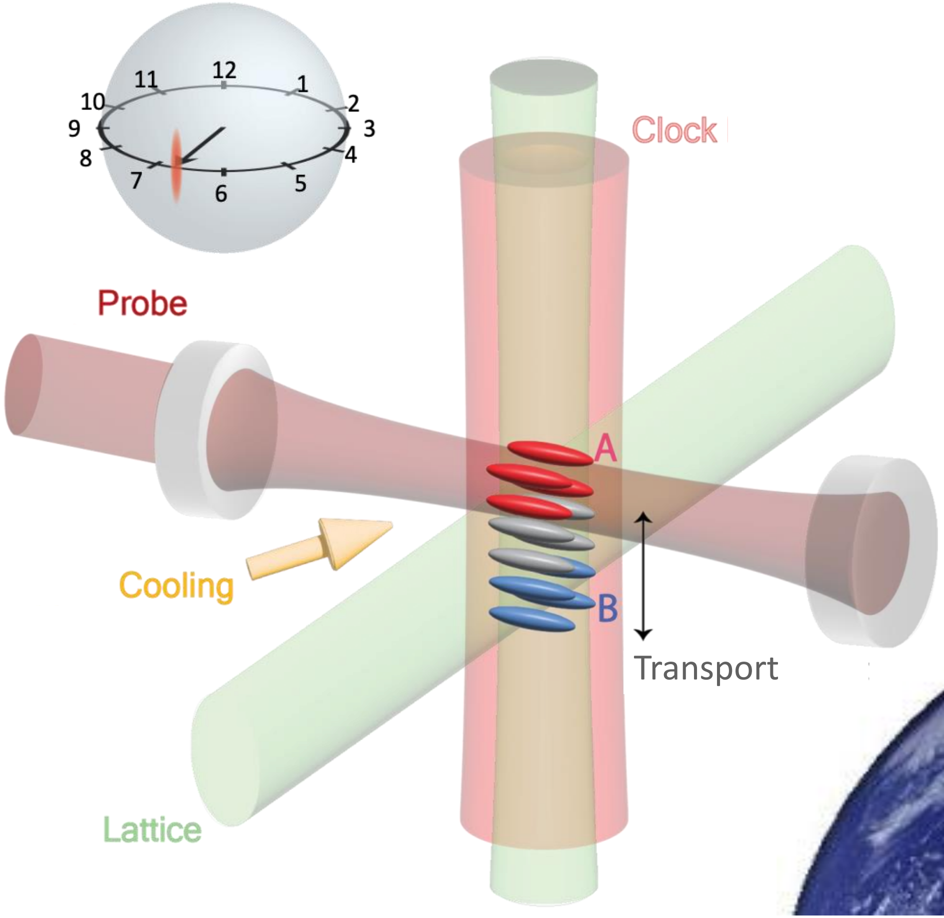
Engineering a Quantum Frontier for Clocks & Fundamental Physics

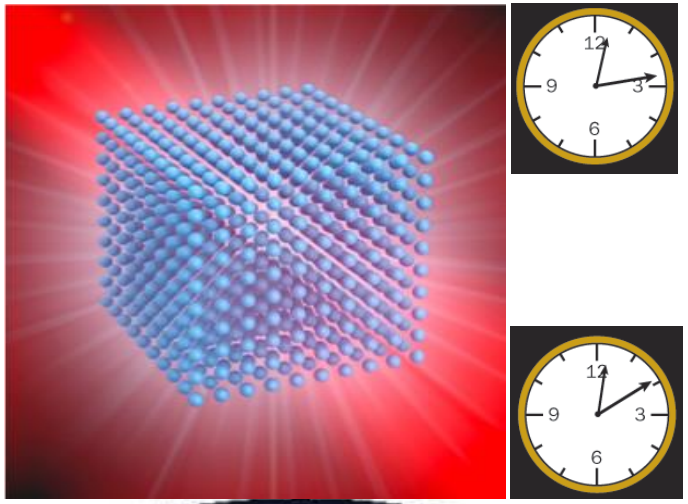
Jun Ye

JILA, NIST & Univ. Colorado

841. Heraeus Seminar on Quantum technologies, Steinbach, September 1 – 4, 2025



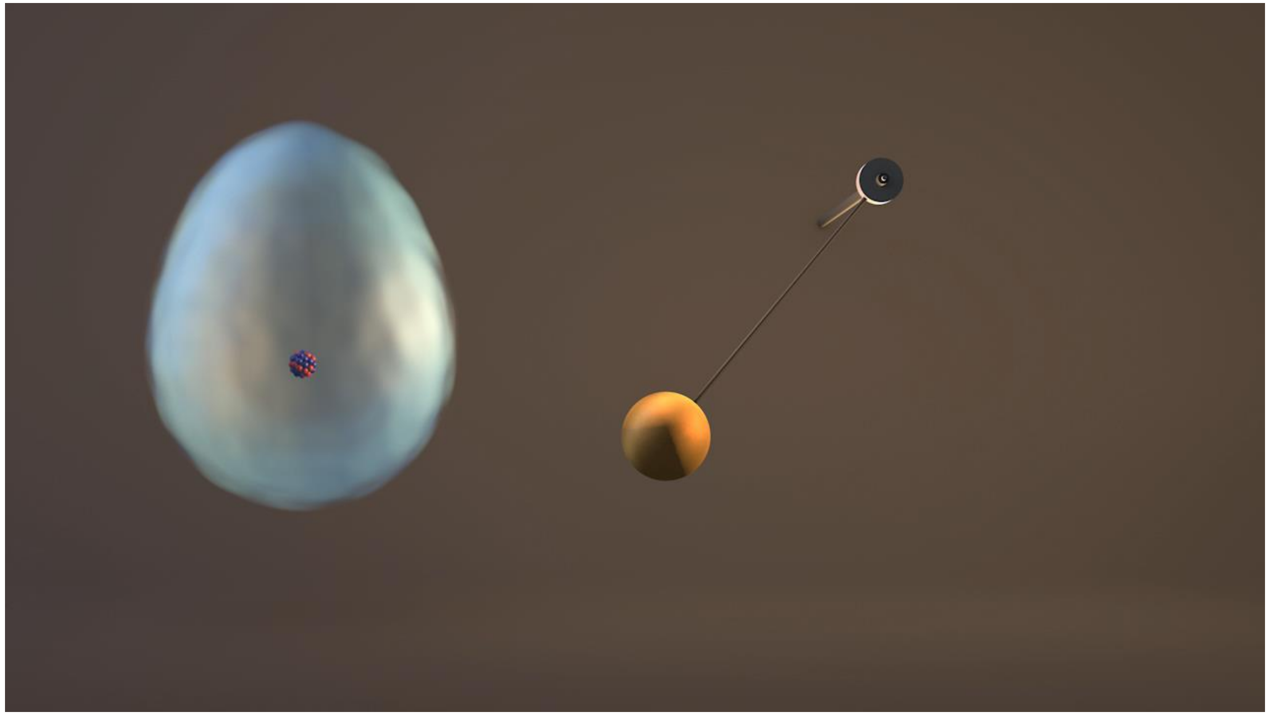


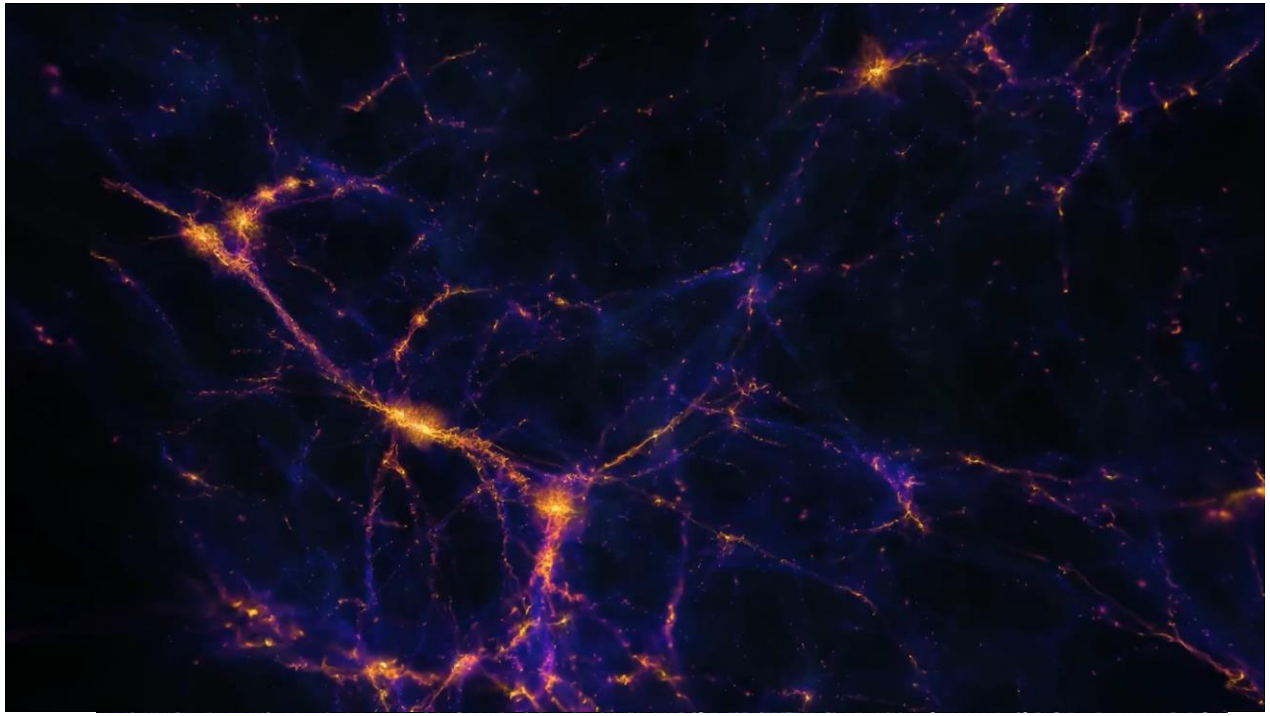


Time scales

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

The mid point (geometric mean) ~ 1 minute





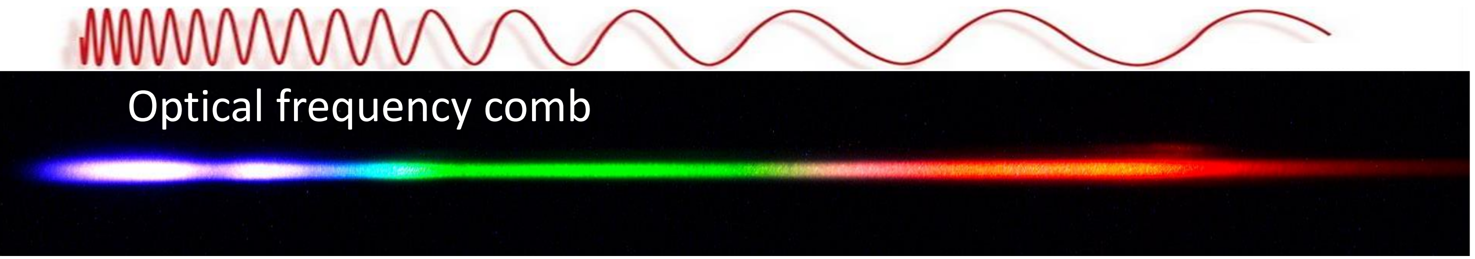
Quantum superposition / coherence

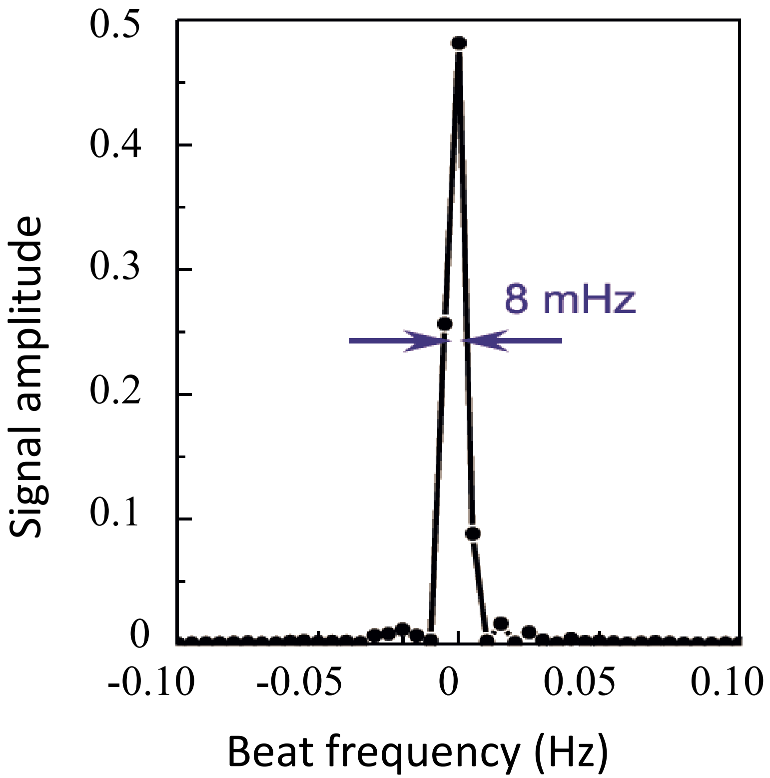
Lifetime of the Universe: 14 billion years (10^{18} s)
1000,000,000,000,000,000 seconds

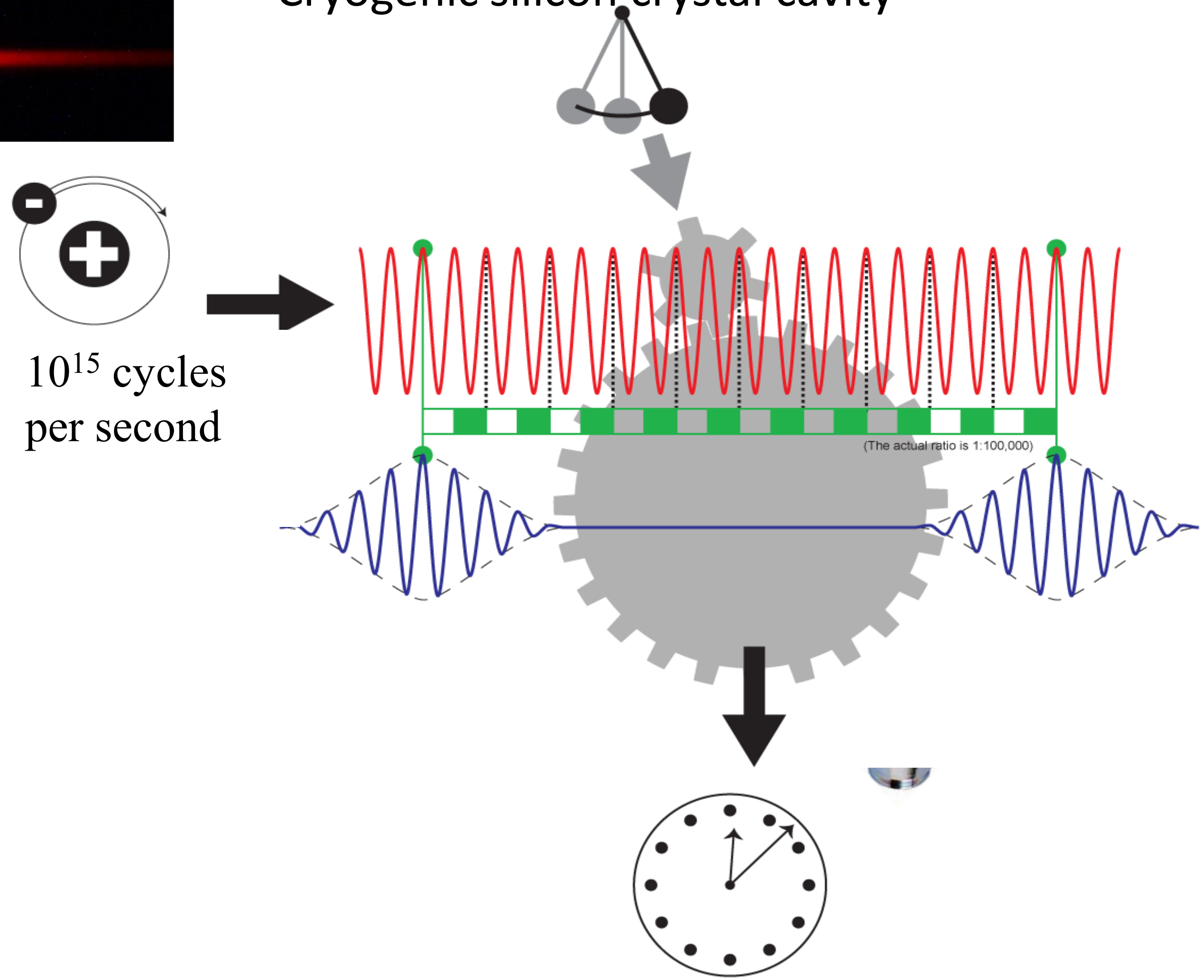
A new generation of stable lasers

Optical coherence > 10 s

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







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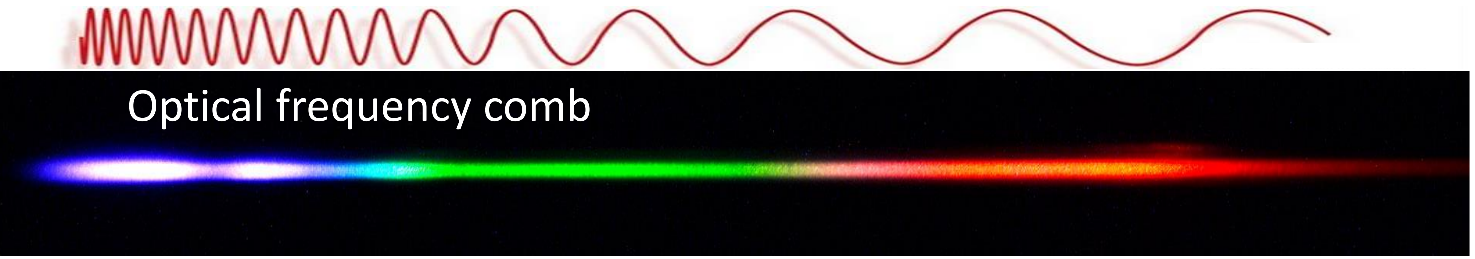

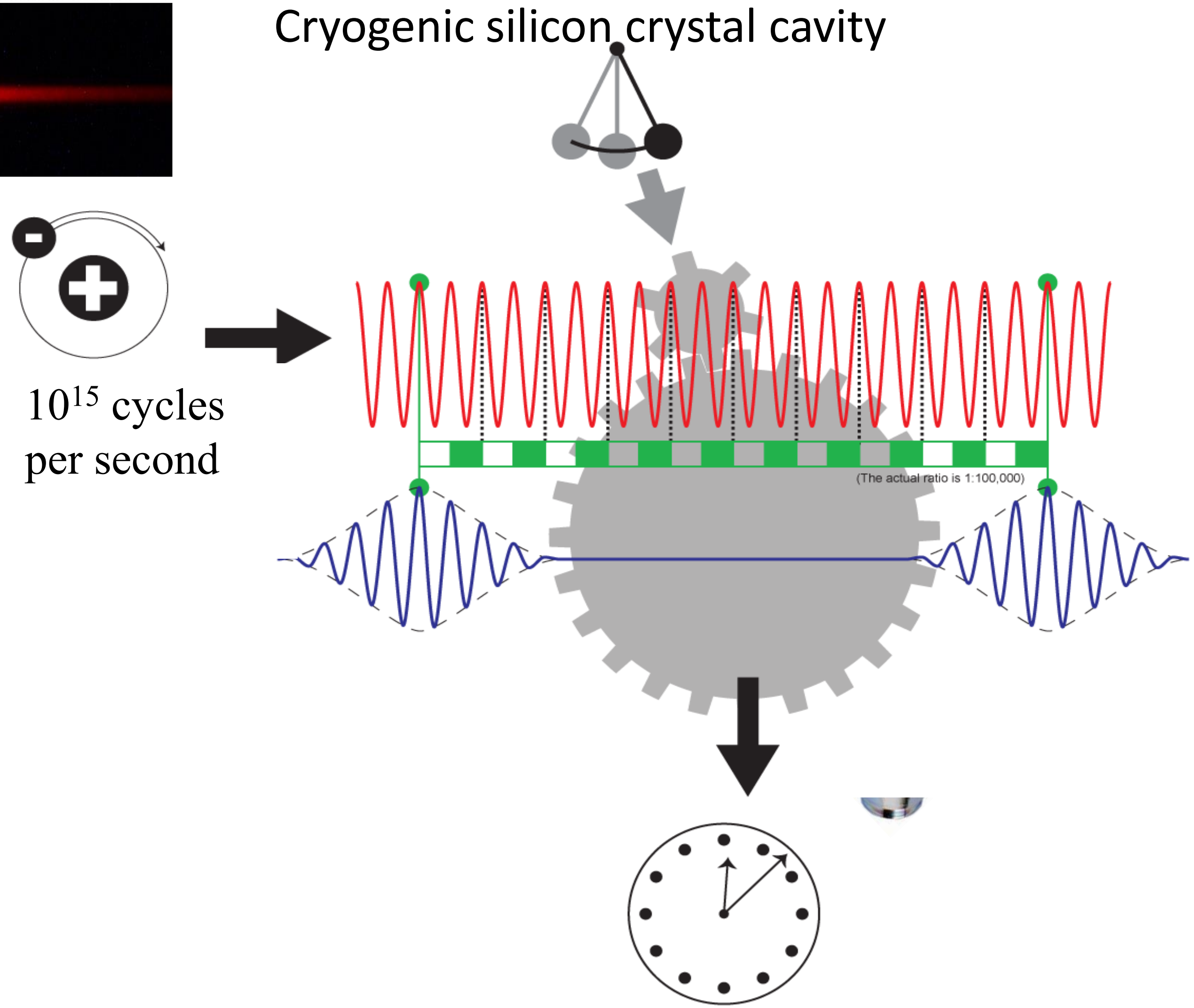

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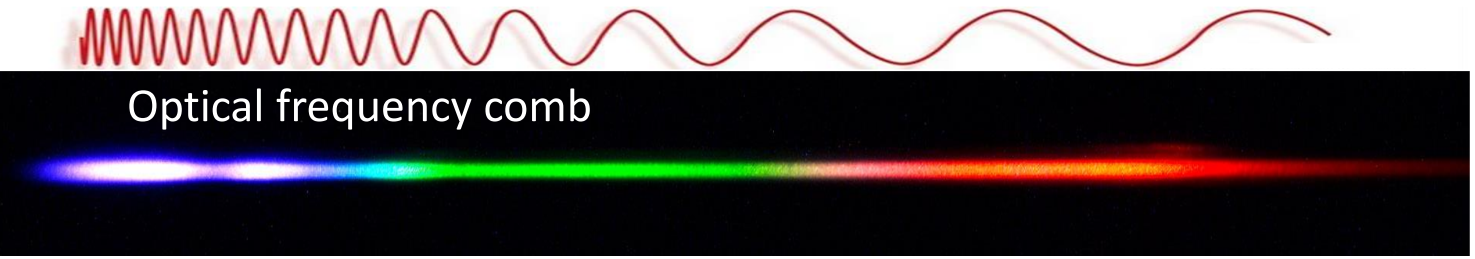
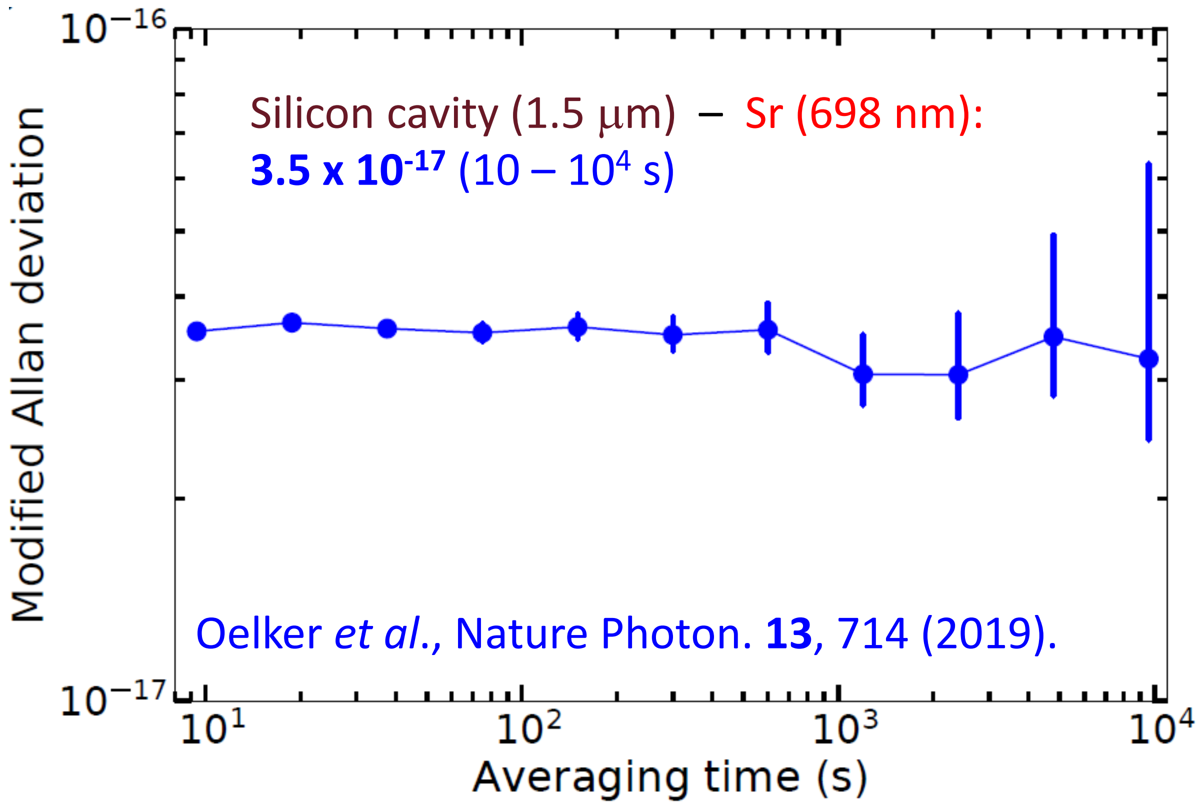
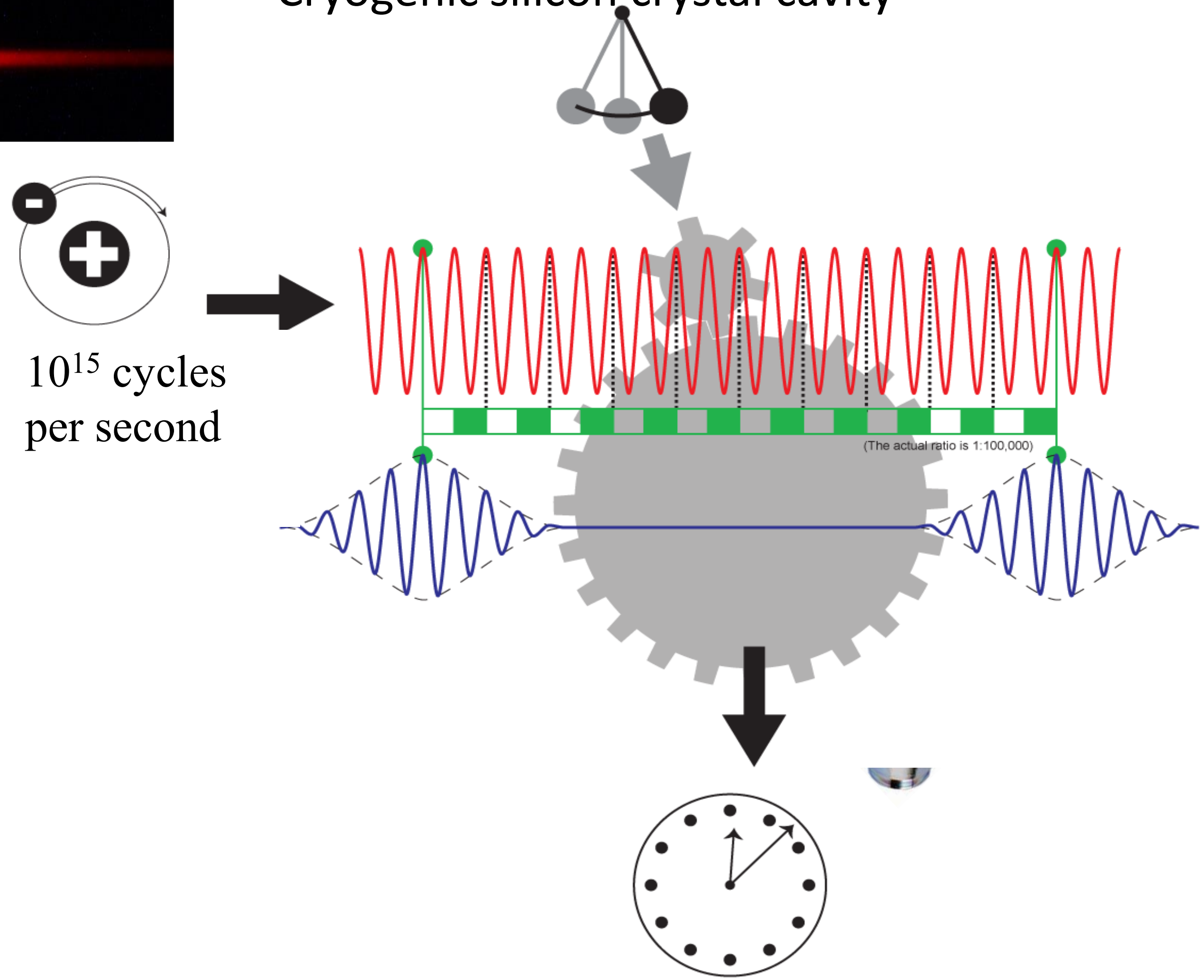
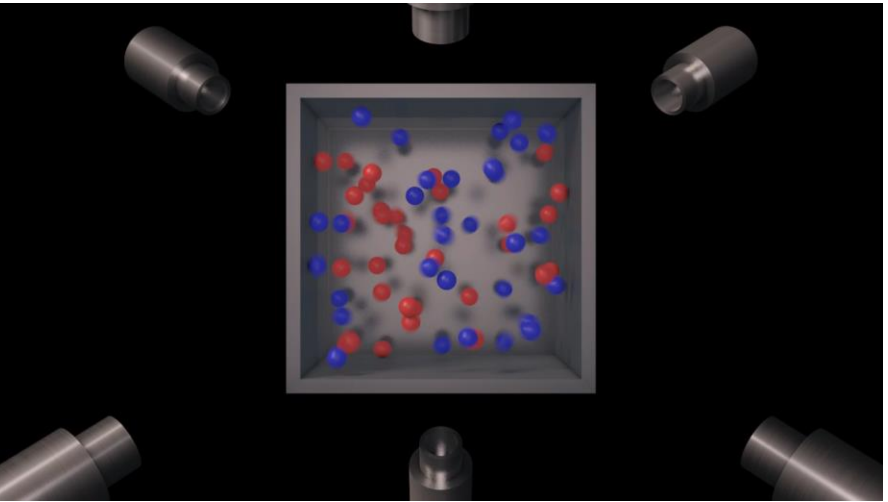
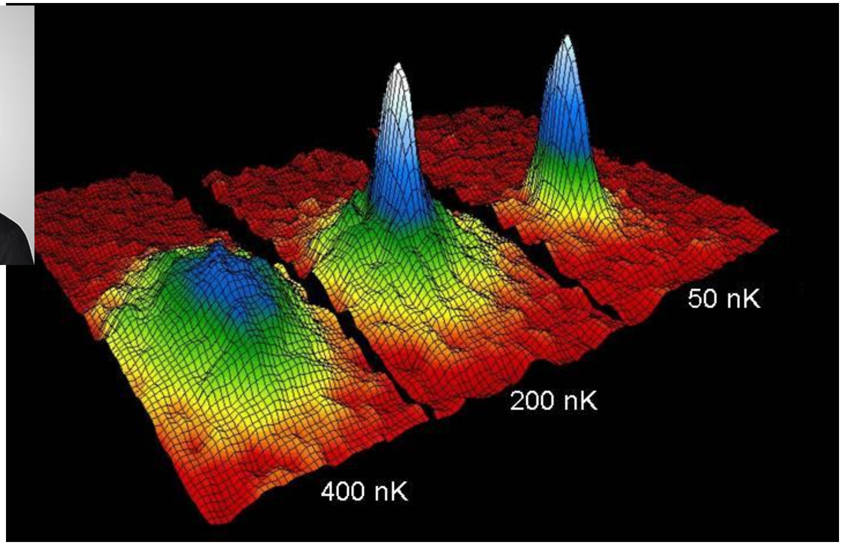


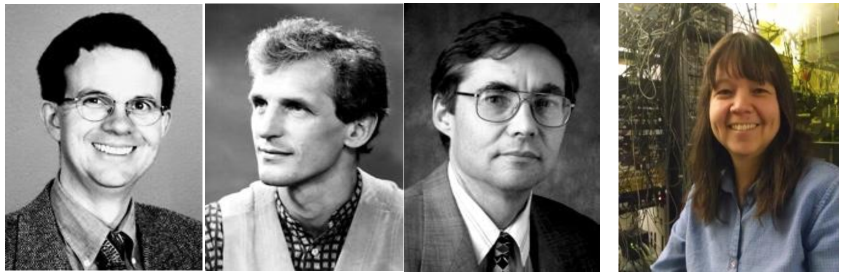


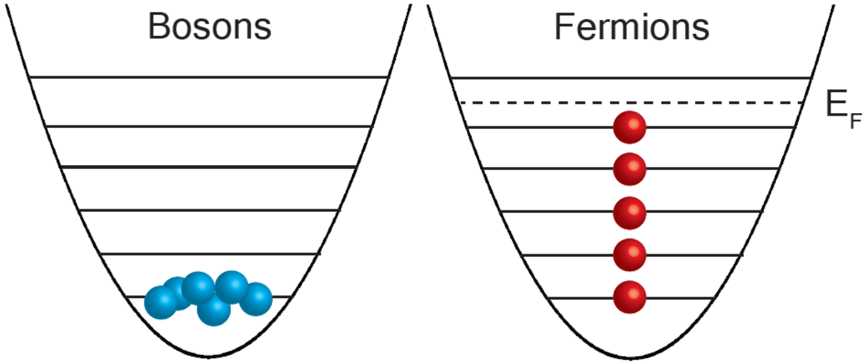


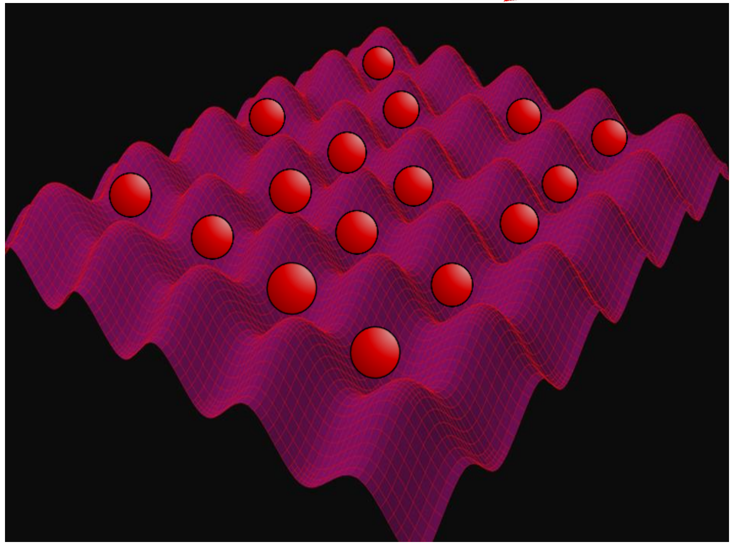
Scaling up atomic clocks: from one to many

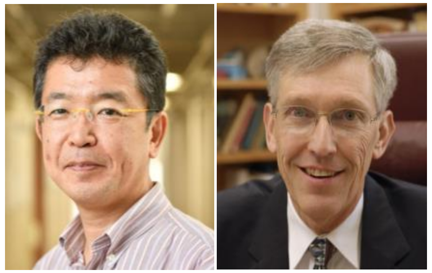




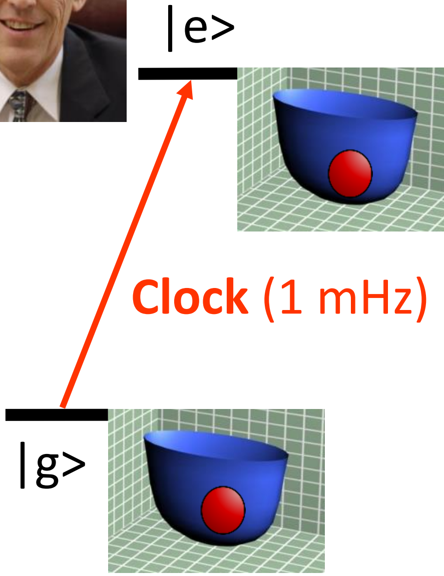






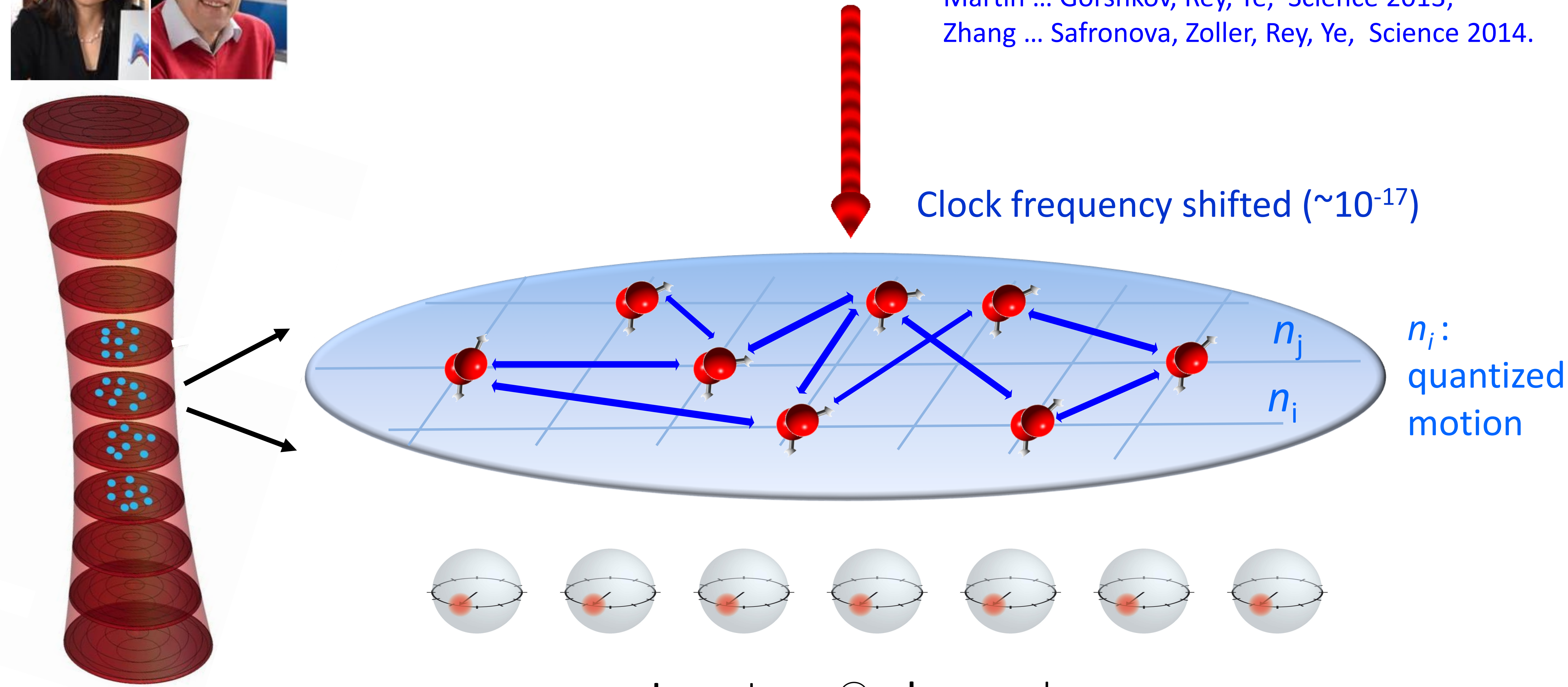


Ye, Kimble, Katori Science (2008).



Clock with many identical fermions

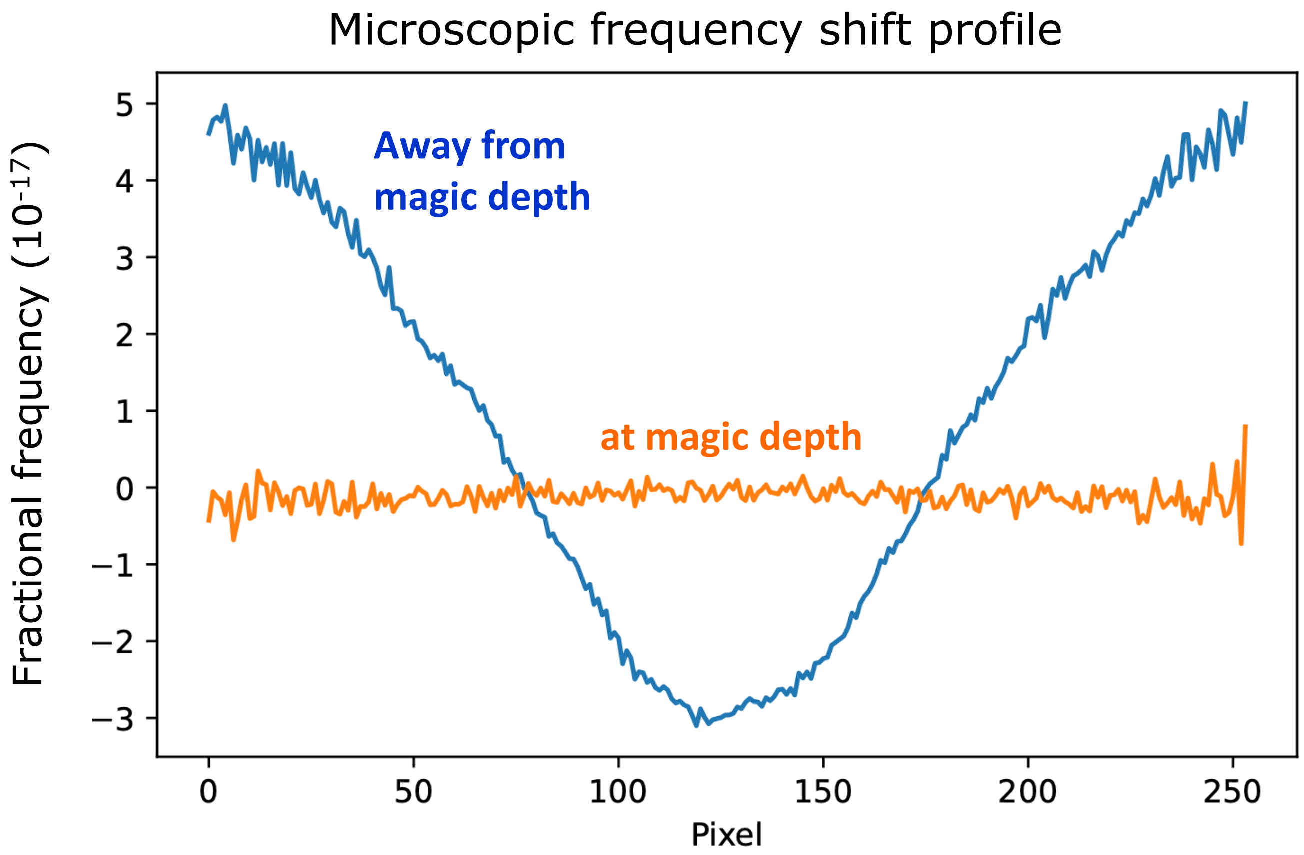
Martin ... Gorshkov, Rey, Ye, Science 2013;
Zhang ... Safronova, Zoller, Rey, Ye, Science 2014.

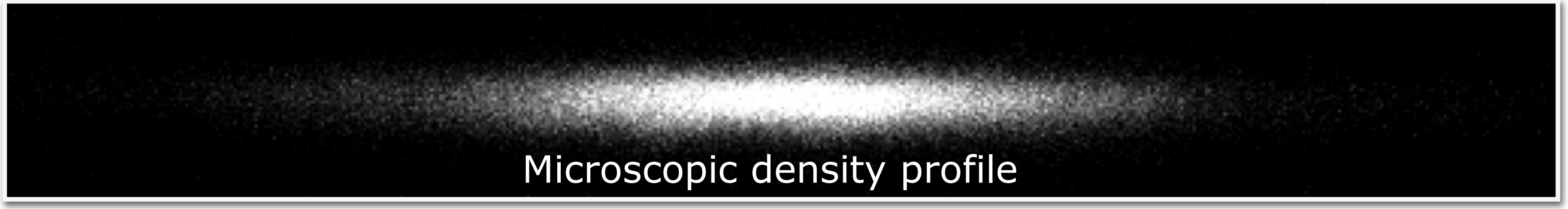


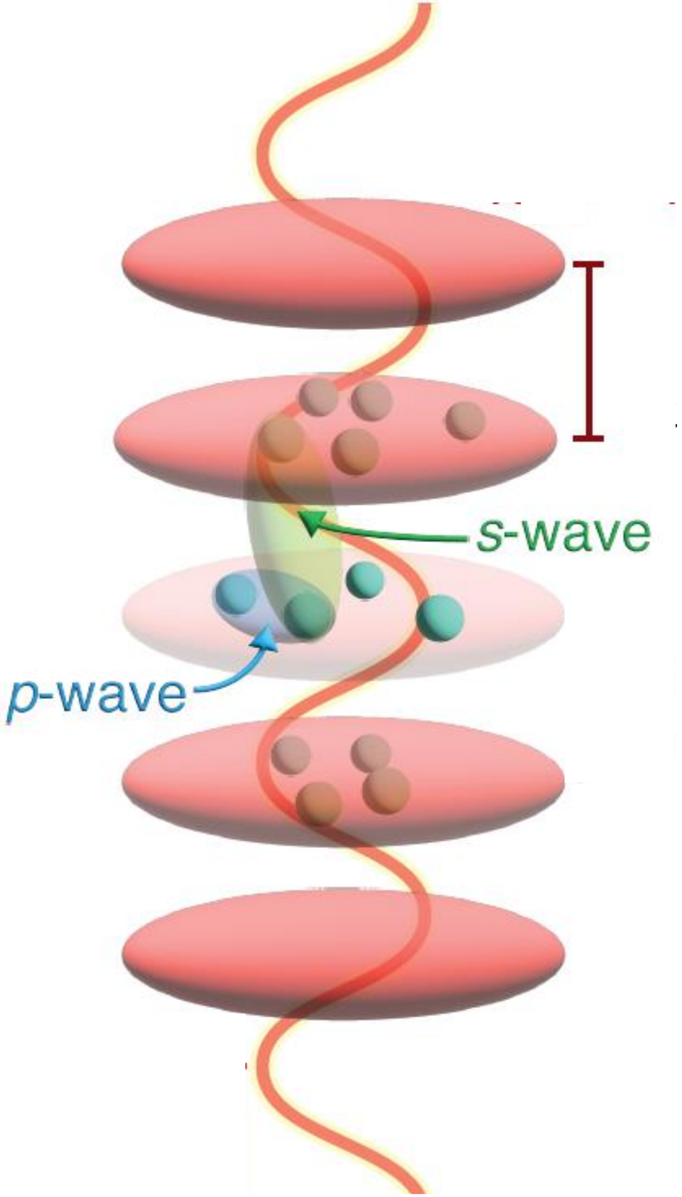
$|ge\rangle + |eg\rangle \otimes |n_1 n_2\rangle - |n_2 n_1\rangle$

A Wannier-Stark lattice clock

Bothwell … Ye, Nature **602**, 420 (2022). Aeppli … Rey, Ye, Science Adv. **8**, eadc9242 (2022).

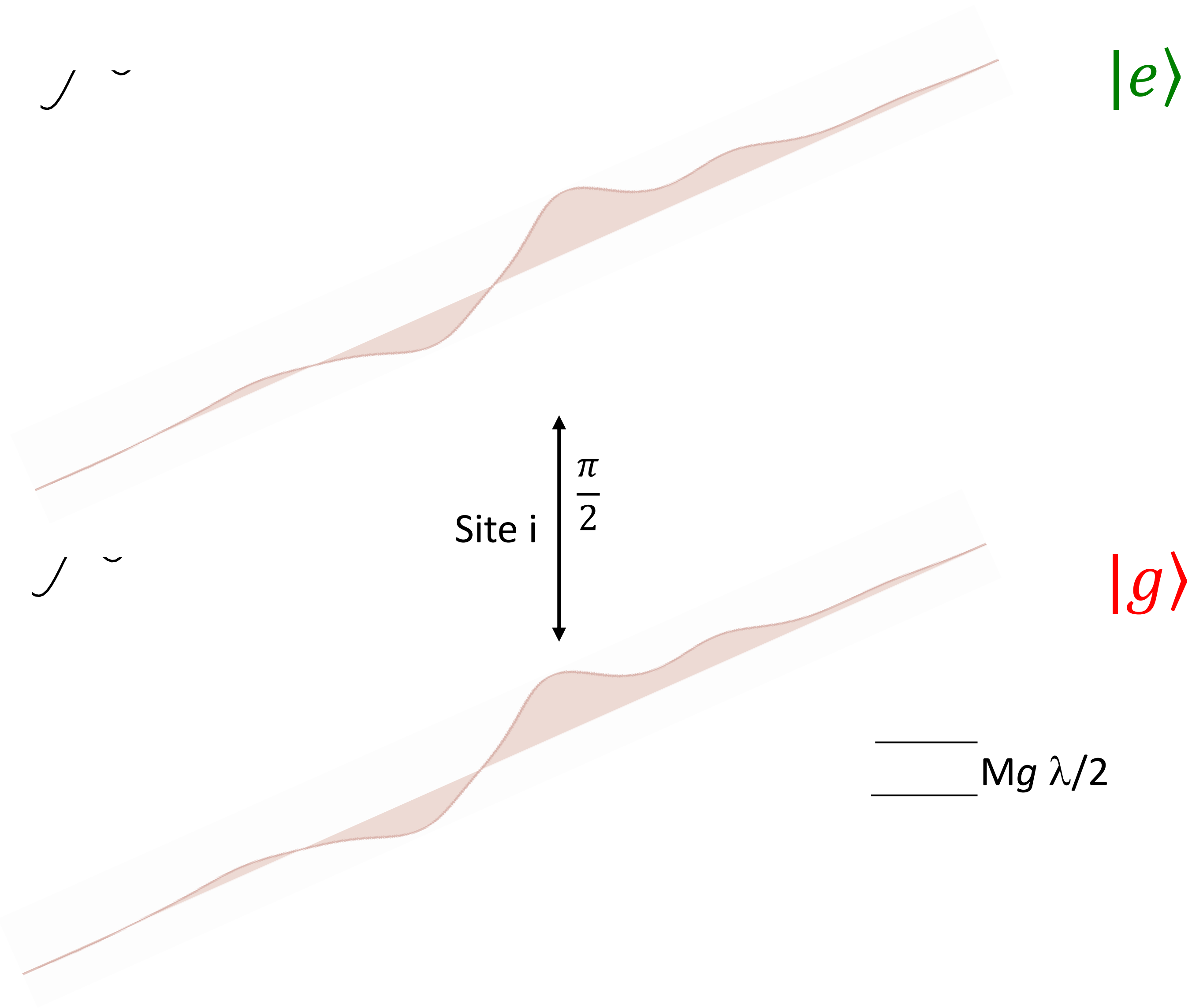




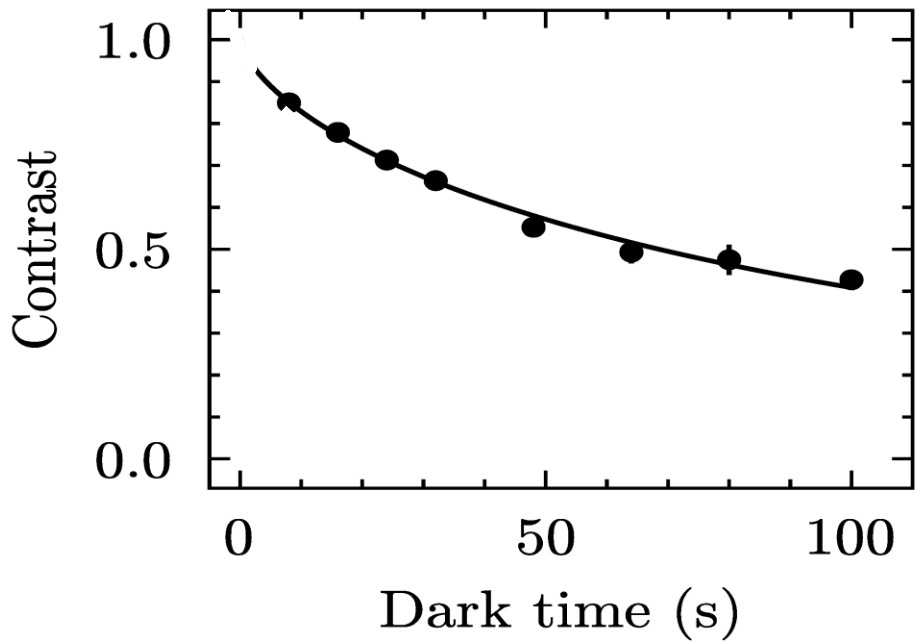


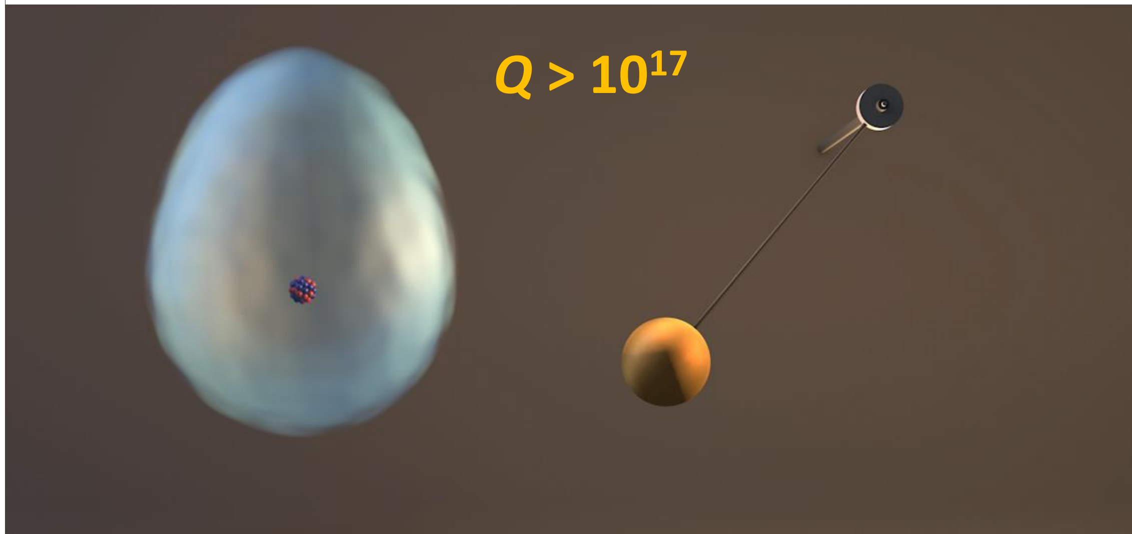
Optical atomic coherence of 2 minutes

Kim … Rey, Ye, Phys. Rev. Lett. (in press, 2025).



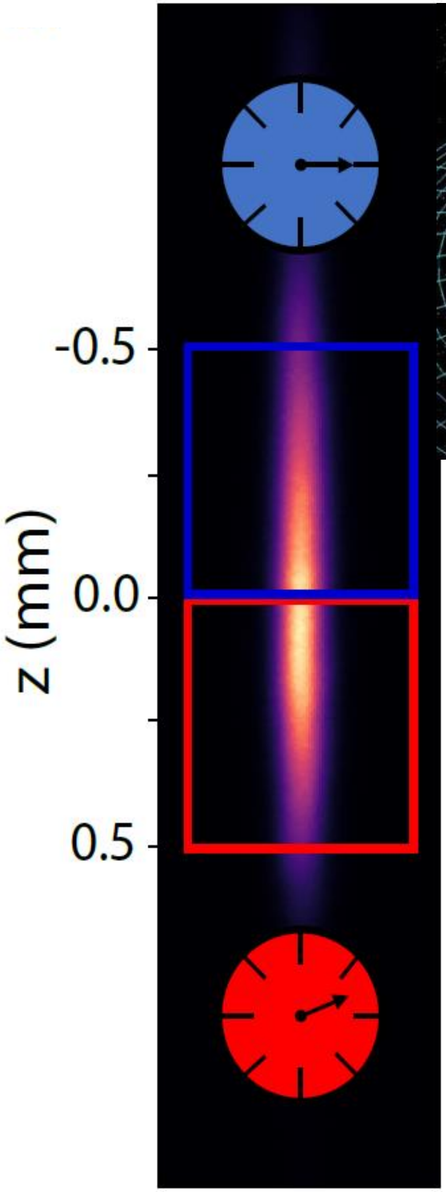
Coherence 118 (9) s

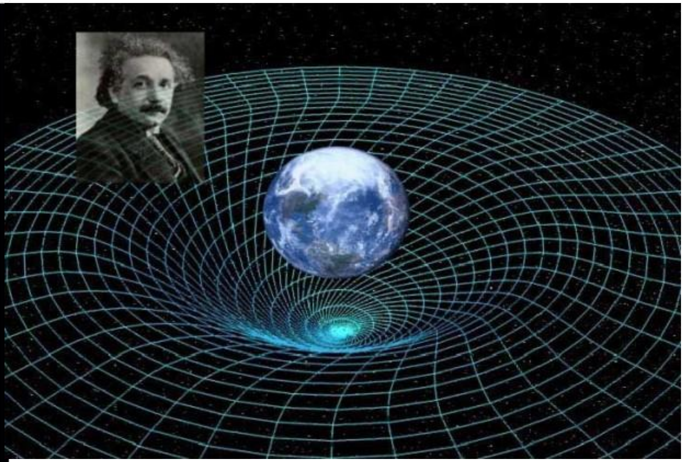


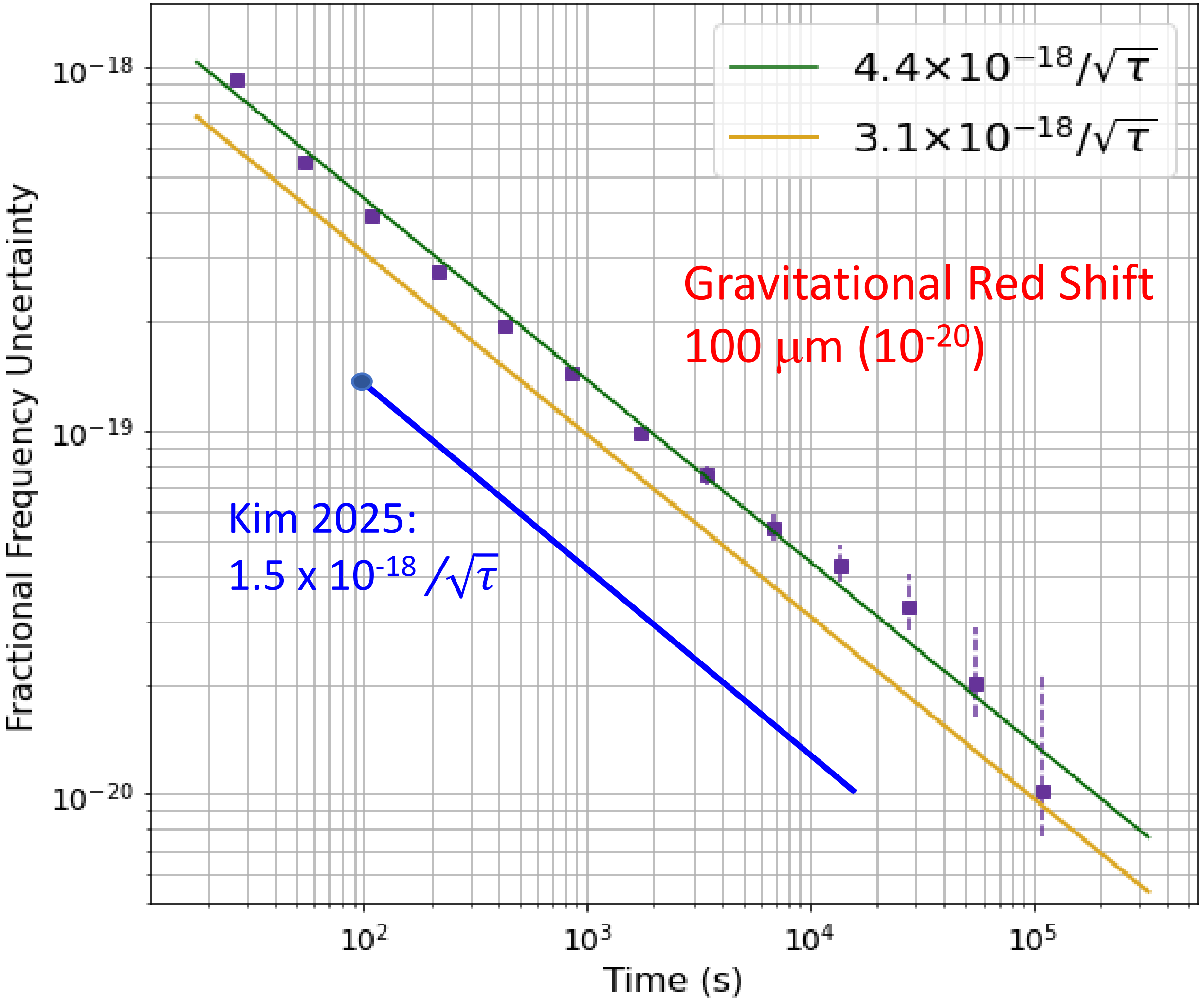


Clock precision reaches <10^{-20}

Bothwell … Ye, Nature **602**, 420 (2022). Kim … Rey, Ye, Phys. Rev. Lett. (in press, 2025).







Clock precision reaches <10^{-20}

Bothwell … Ye, Nature **602**, 420 (2022). Kim … Rey, Ye, Phys. Rev. Lett. (in press, 2025).

Resolving the gravitation redshift on length scale of quantum wavefunction ?

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

Commute with H_{GR}

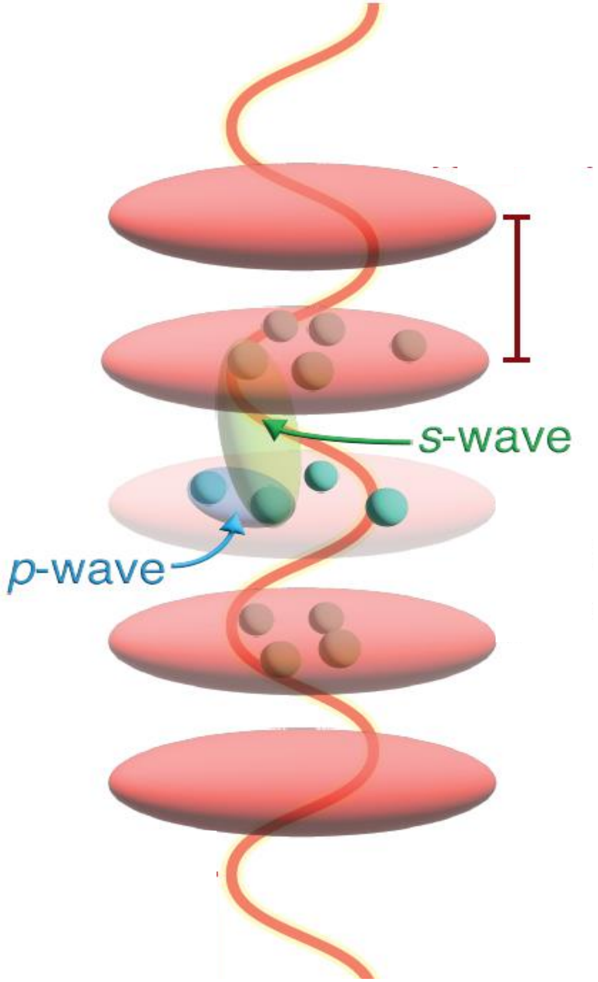
$$H_{\mathrm{off-site}}/\hbar = \sum_n \chi_1 S_n^z S_{n+1}^z$$

Not commute with H_{GR}

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

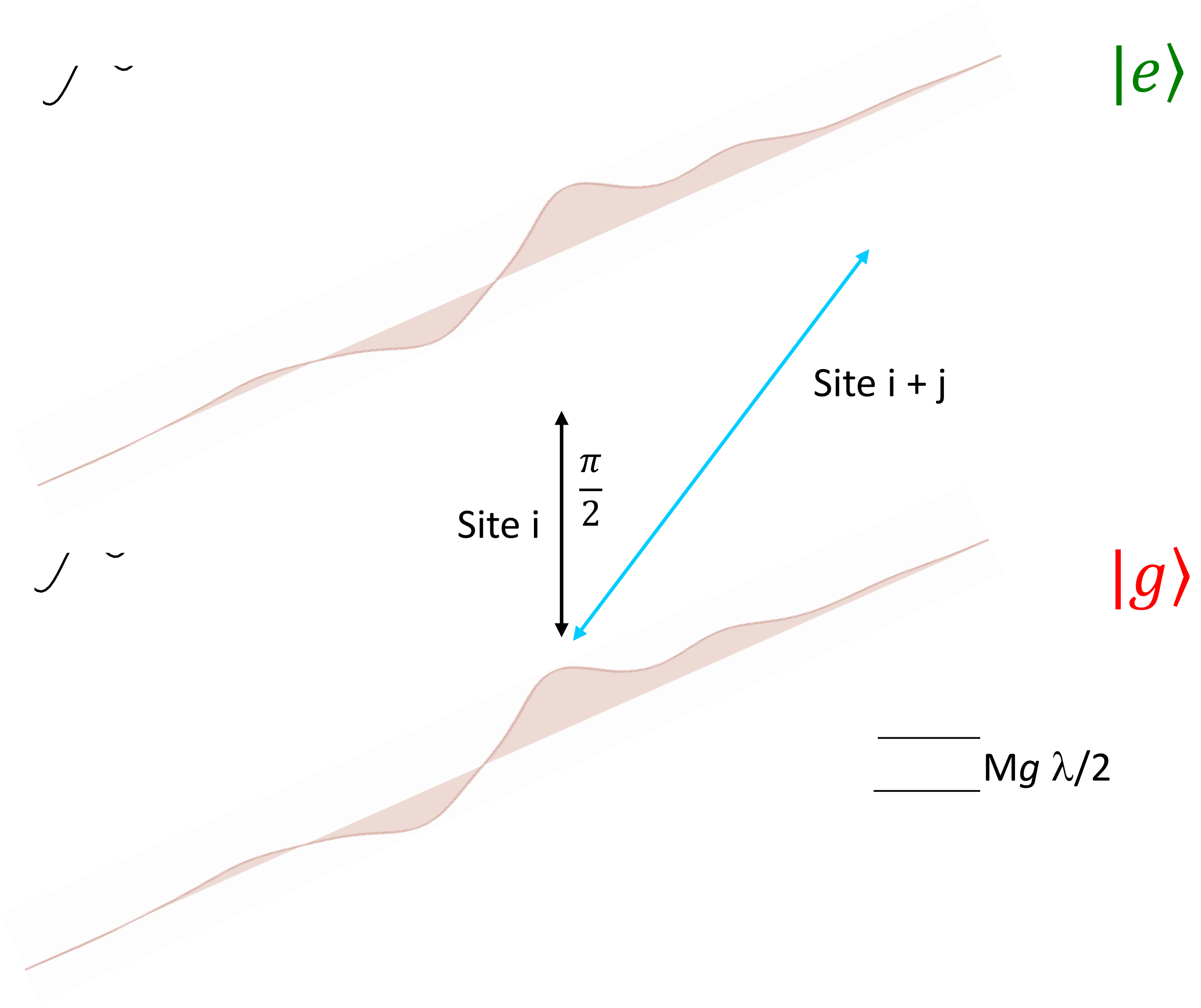
$$H_{\mathrm{laser}}/\hbar = \sum_n \left[-\delta S_n^z + \Omega_0 S_n^x \right]$$

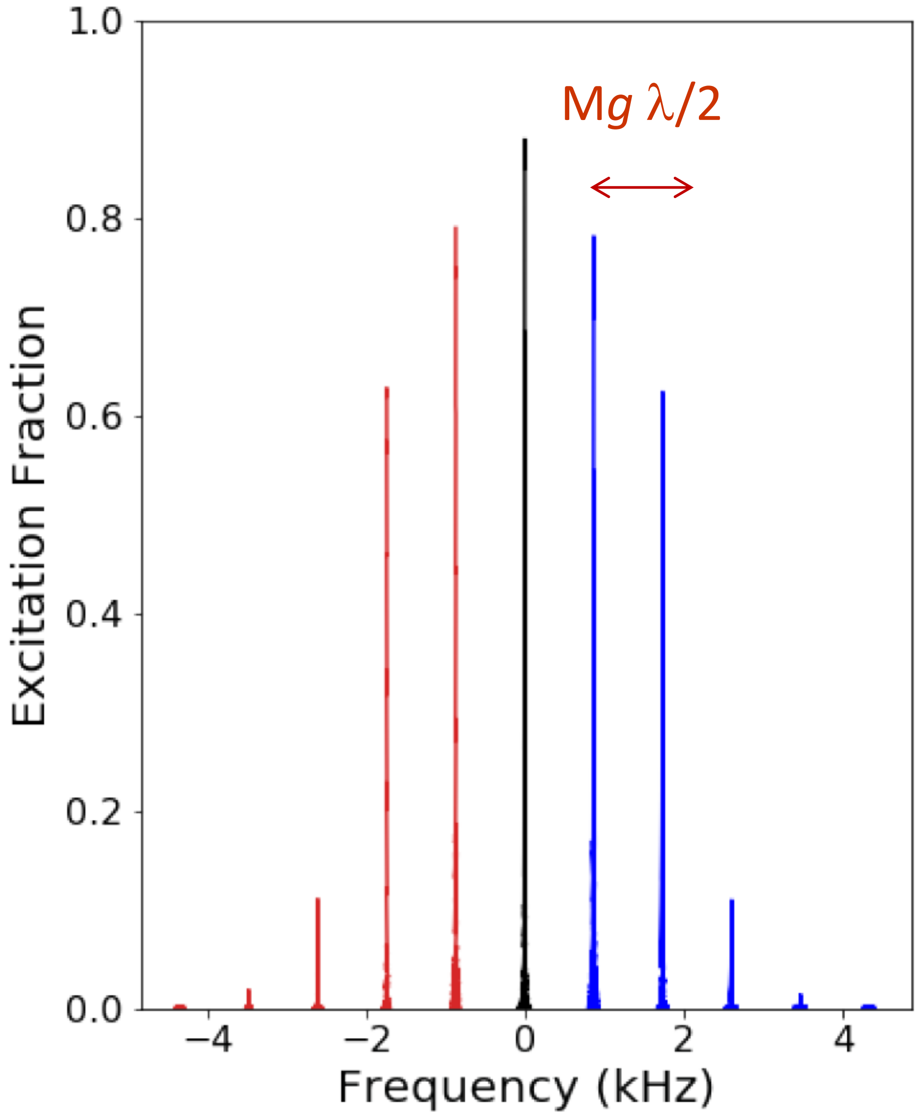
$$H_{\mathrm{GR}} = \hbar\omega_0 \sum_n \frac{g a_L n}{c^2} S_n^z$$



Chu… Zoller, Hammerer, Ye, Rey, Phys. Rev. Lett. **134**, 093201 (2025).

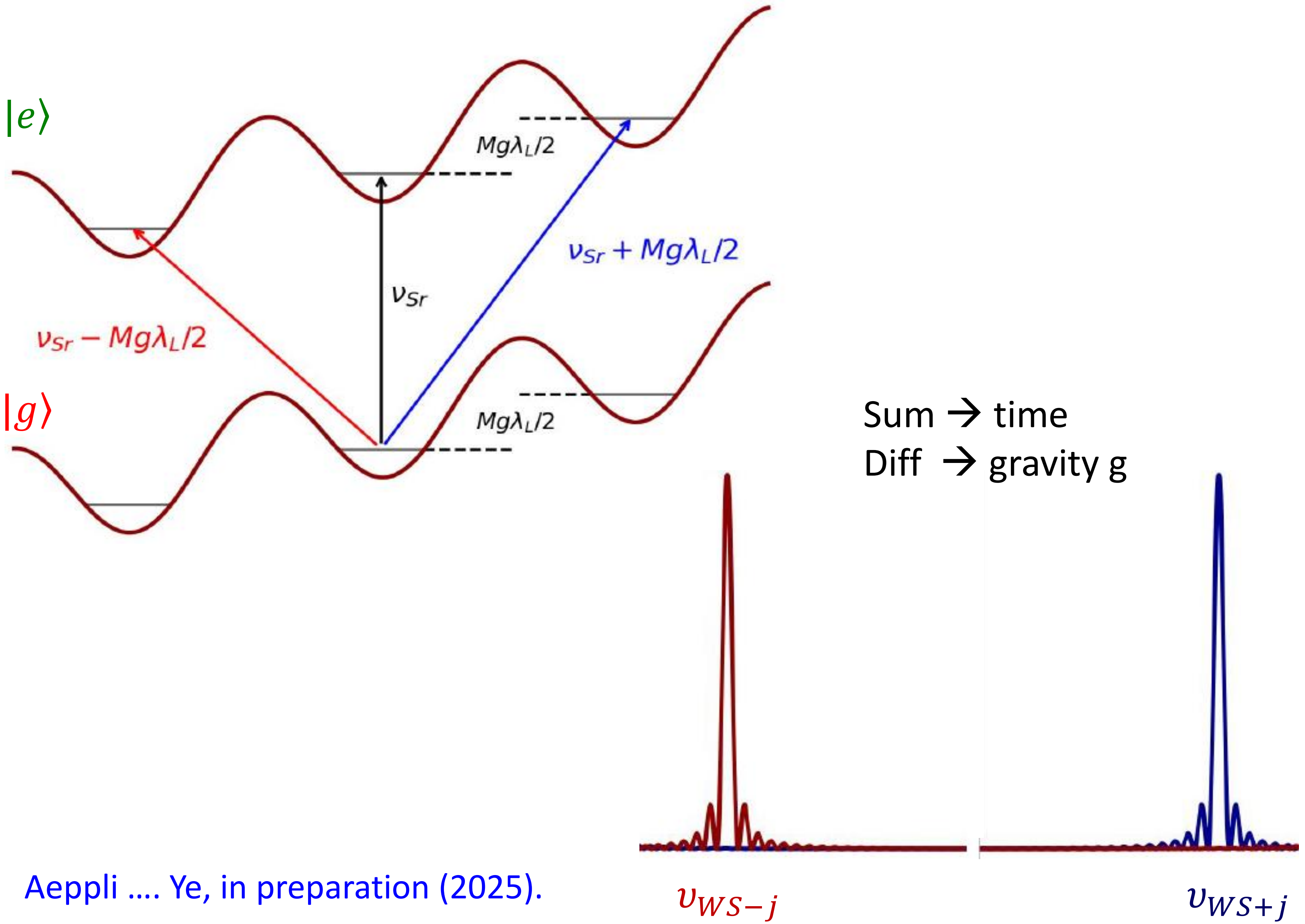
Wannier-Stark offsite resonances





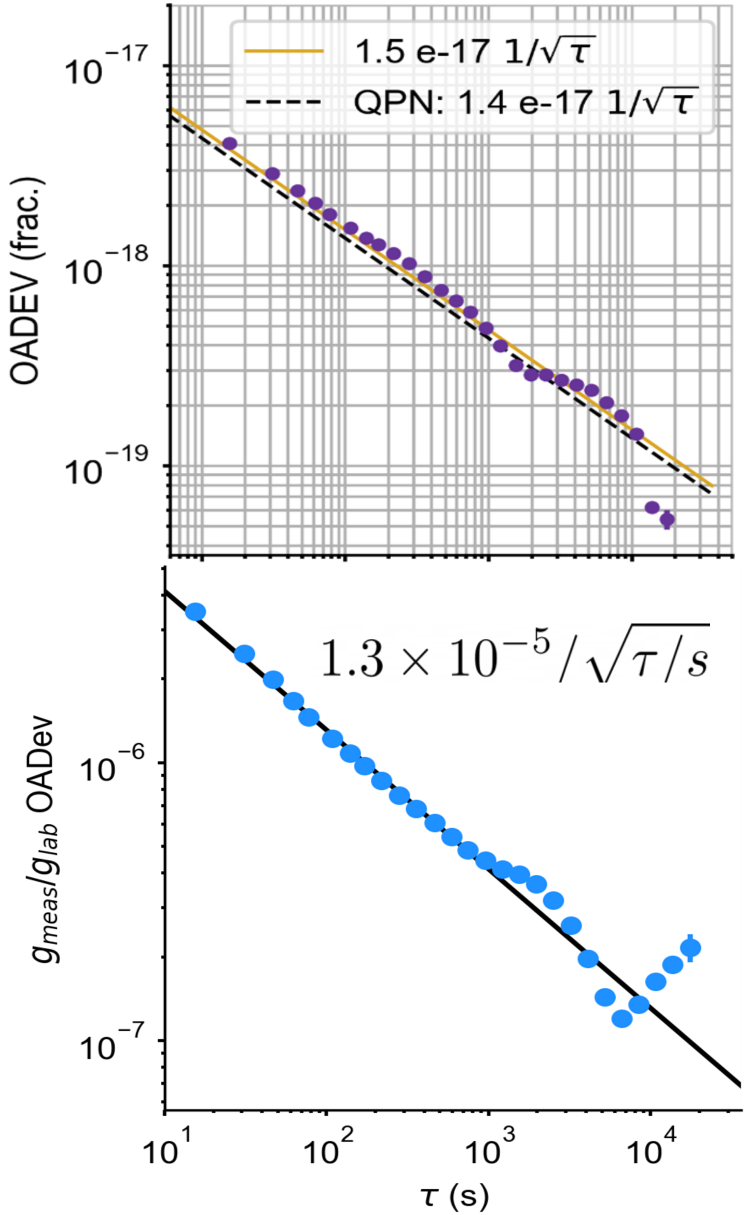
Atomic clock & atom interferometer: all in one

Simultaneous measurement of gravity (g) & gravitational potential (time)



Sum → time

Diff → gravity g

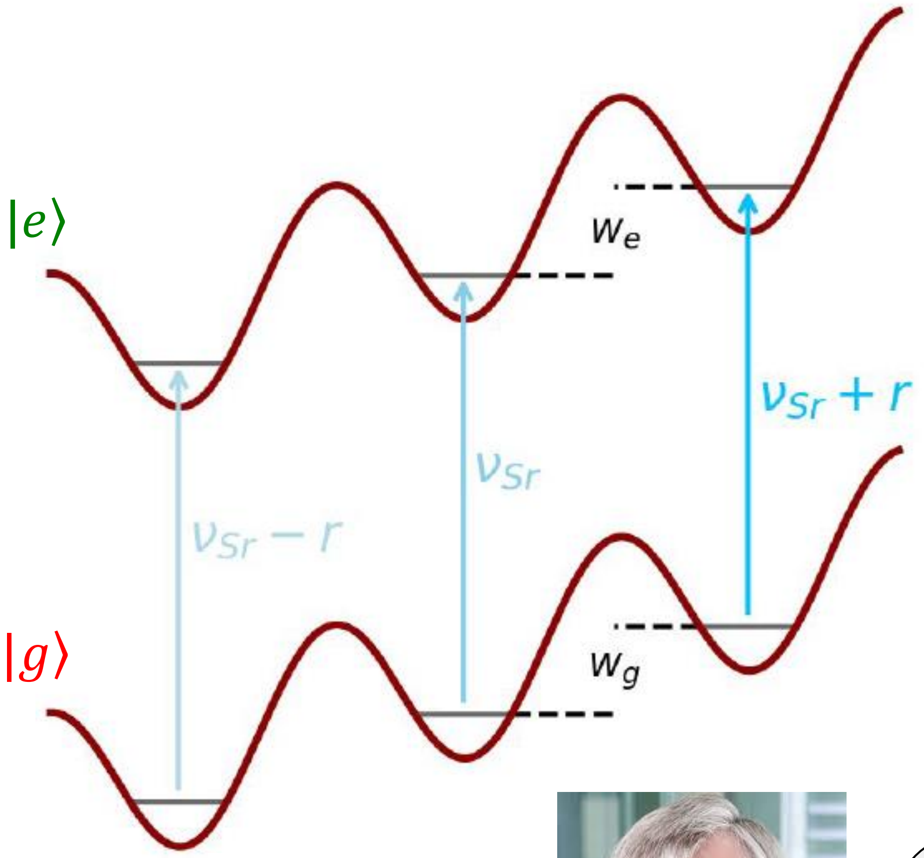


Aeppli …. Ye, in preparation (2025).

Single photon mass: equivalence to gravitational time dilation

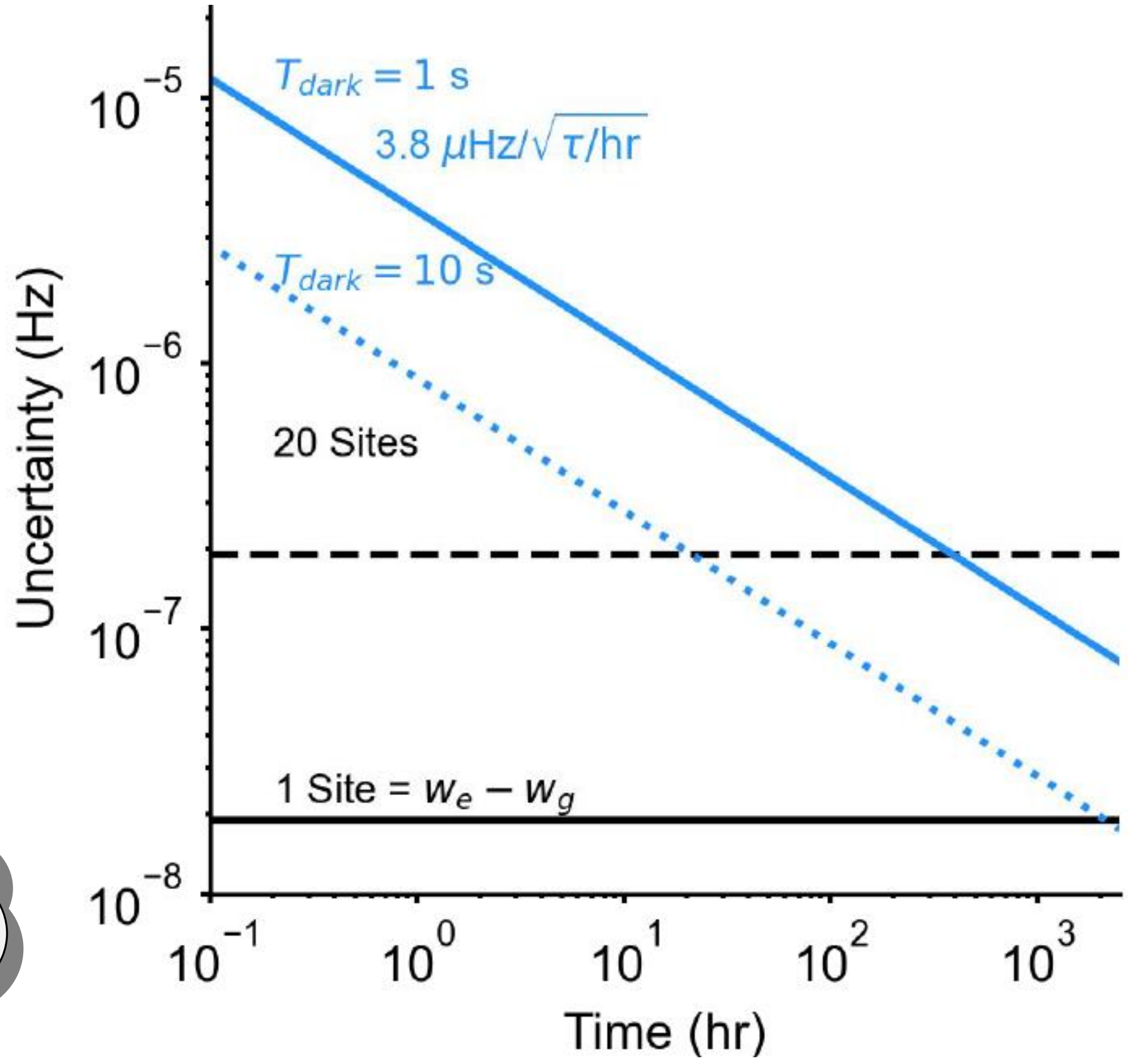
Aeppli *et al.*, in preparation (2025).

$$M_e = M + \frac{h\nu}{c^2}$$



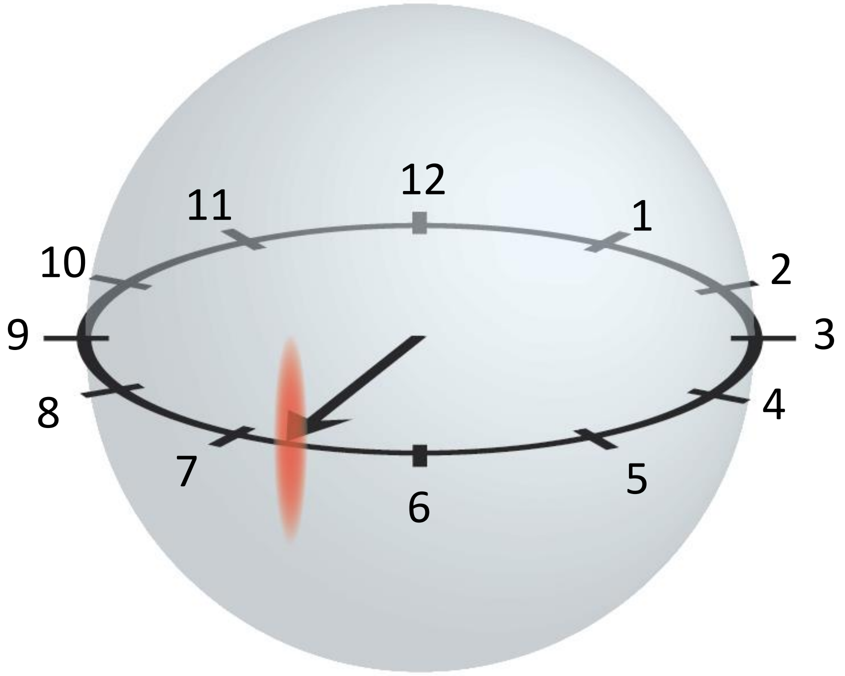
M

… Weigh photon rest mass with a cavity

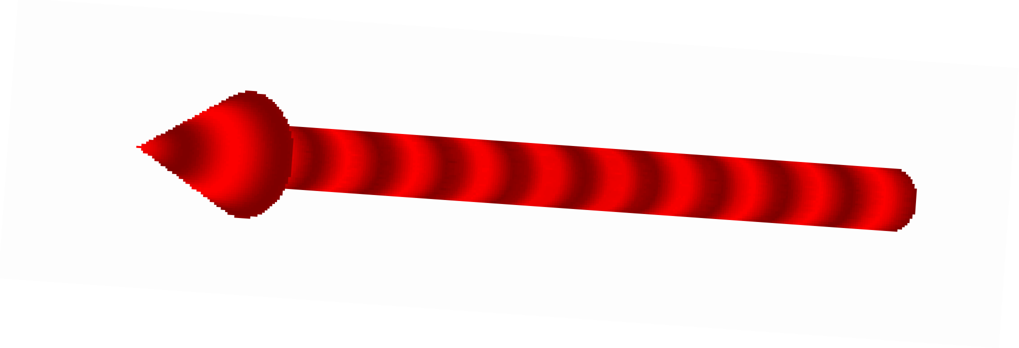


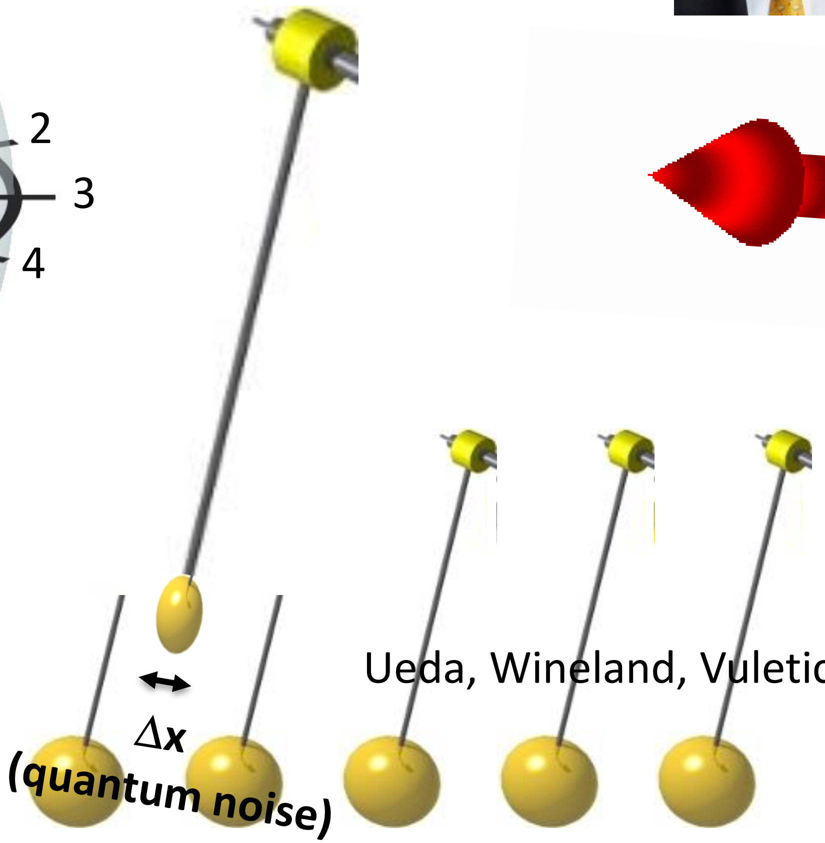
Quantum noise

Quantum Phase Noise of Atoms



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



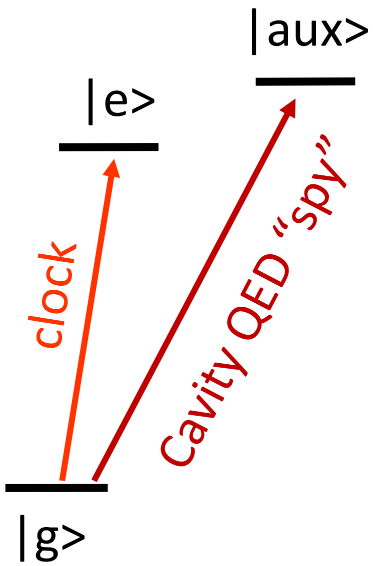


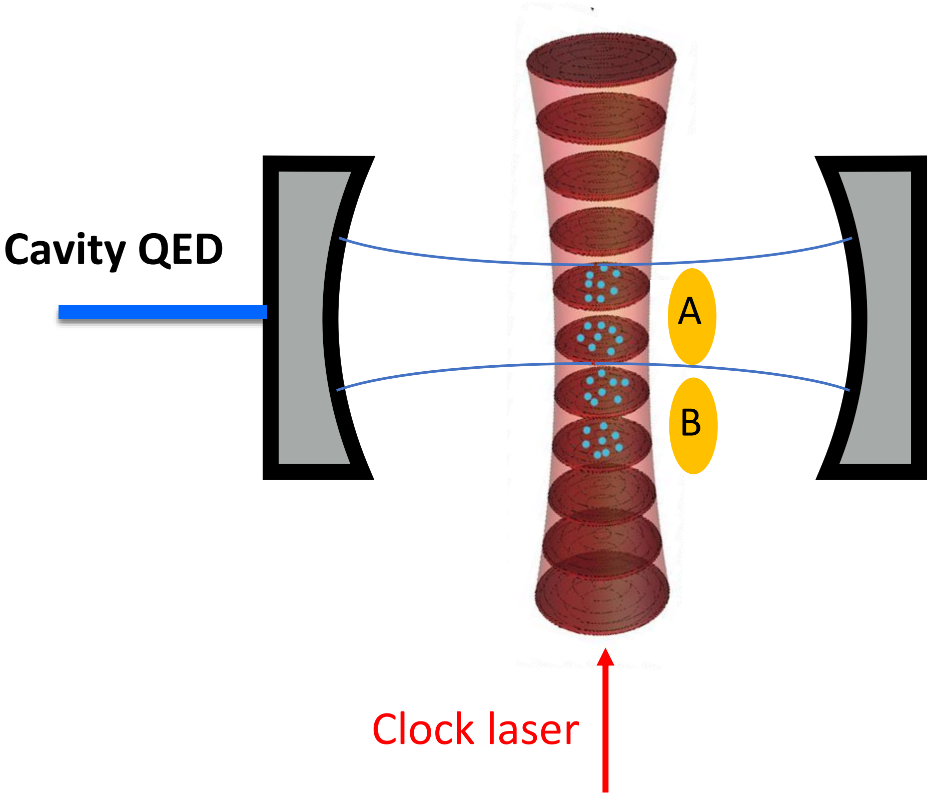
$$\Delta\phi_{SQL} = \frac{1}{N}$$

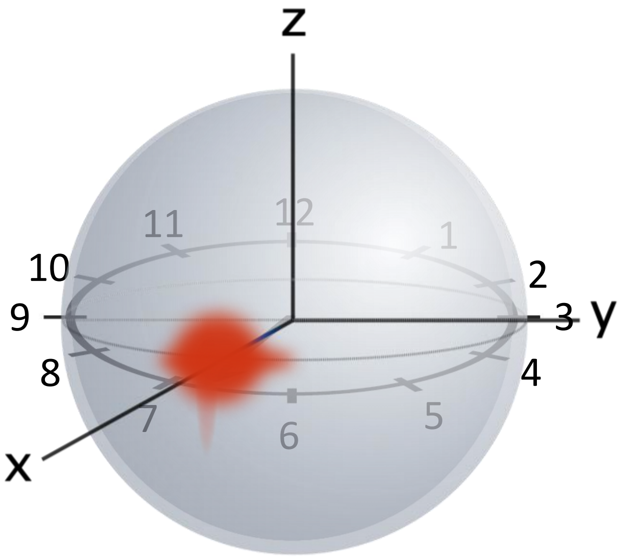
Ueda, Wineland, Vuletic, Polzik, Kasevich, Thompson …

Spin squeezed clock

- Spin Squeezing at 6 x 10^{-17}
- Robinson … Thompson, Ye, Nature Phys. **20**, 208 (2024).

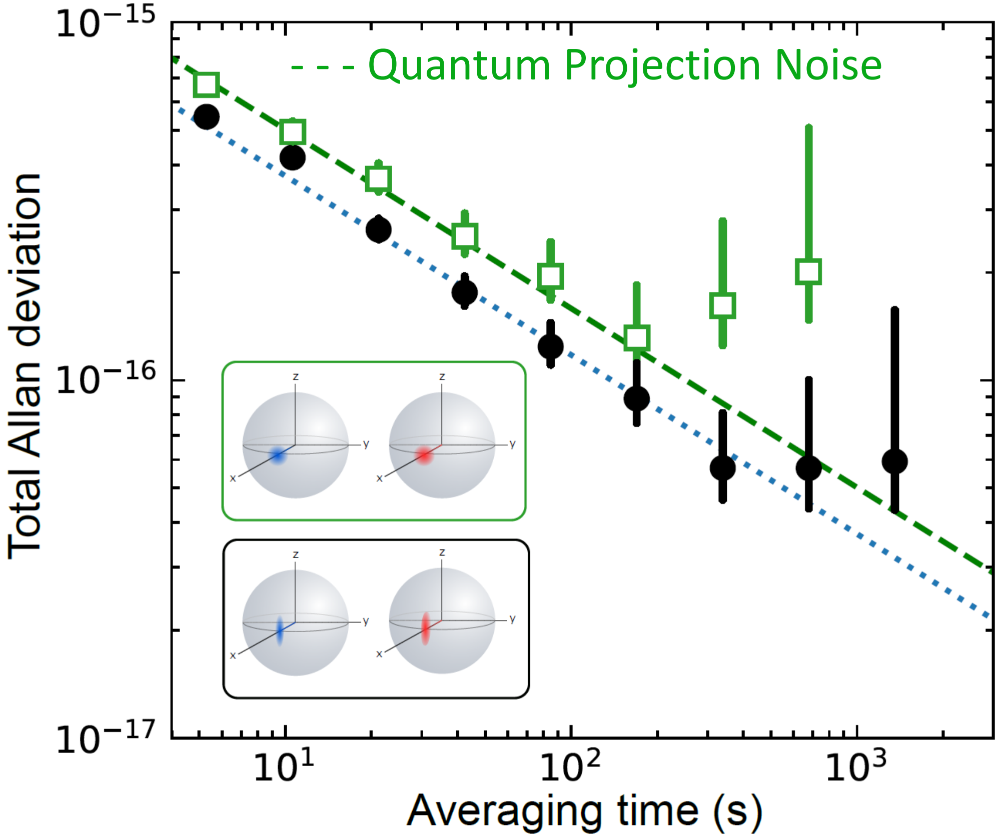






Pedrozo-Peňafiel … Vuletic, Nature **588**, 414 (2020).

Spin squeezed clock



- Spin Squeezing at 6 x 10^{-17}
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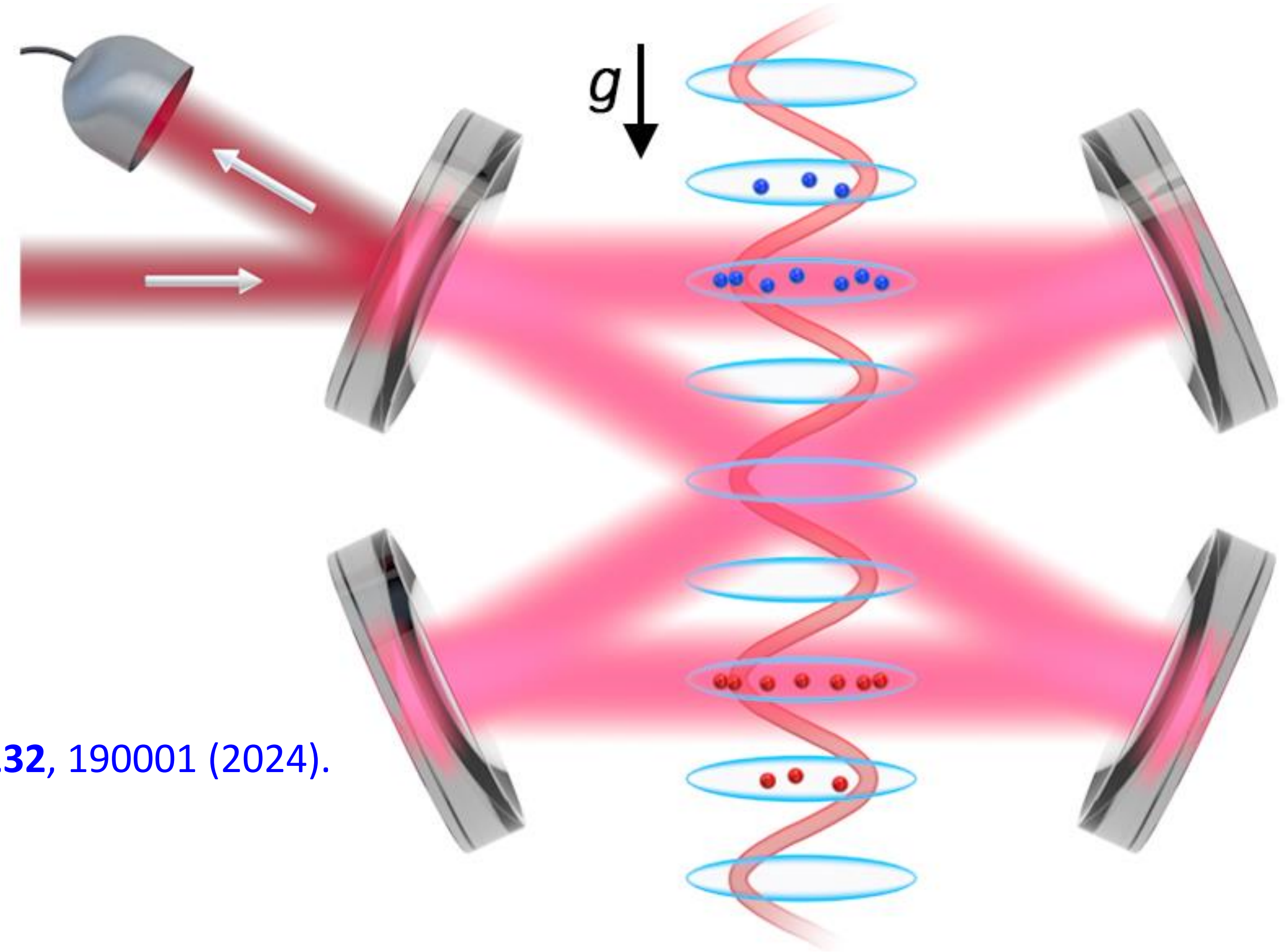


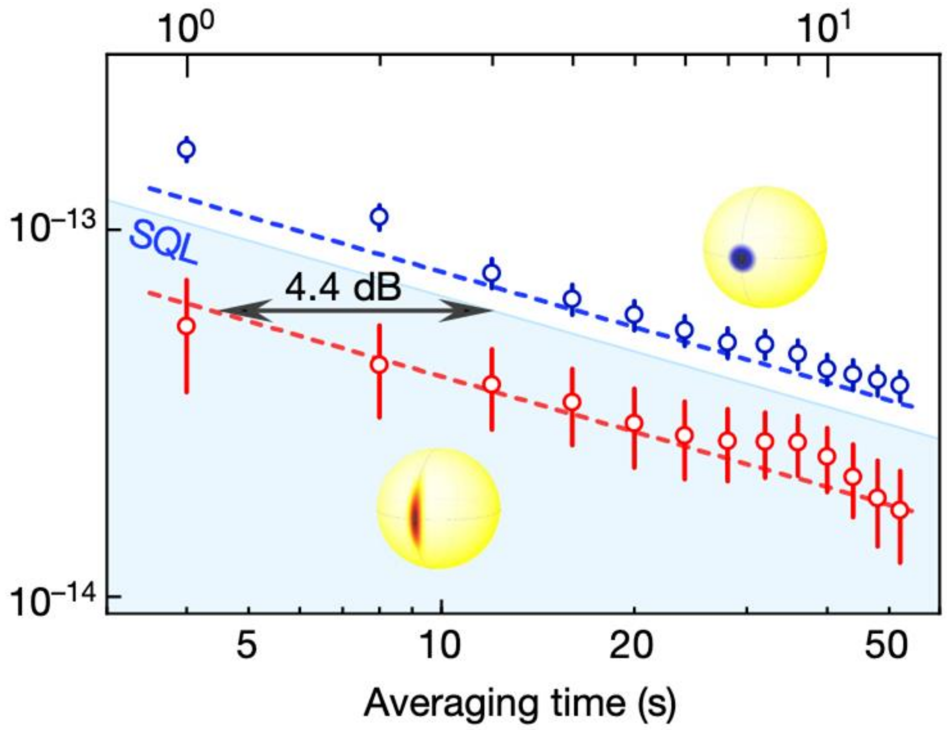
Ye & Zoller, Phys. Rev. Lett. **132**, 190001 (2024).

Challenges: chasing the absolute state of the art

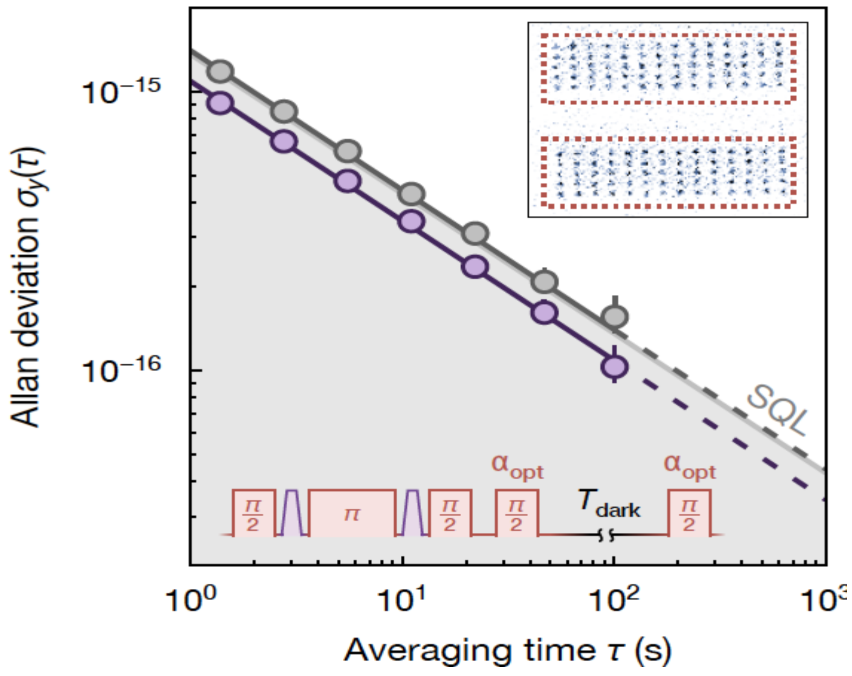
Single clock instability: squeezed $\sim 1 \times 10^{-15}/\sqrt{\tau}$ vs. (JILA Sr1) $1.5 \times 10^{-18}/\sqrt{\tau}$

Need:

- Generation of squeezed state of large *N*
- Long-lived quantum entanglement
- High fidelity spin preparation & readout



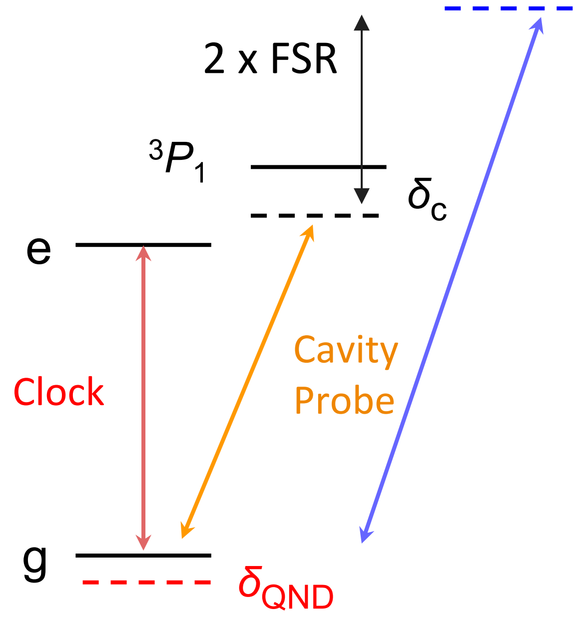
Pedrozo-Peñafiel … Vuletic, Nature **588**, 414 (2020).

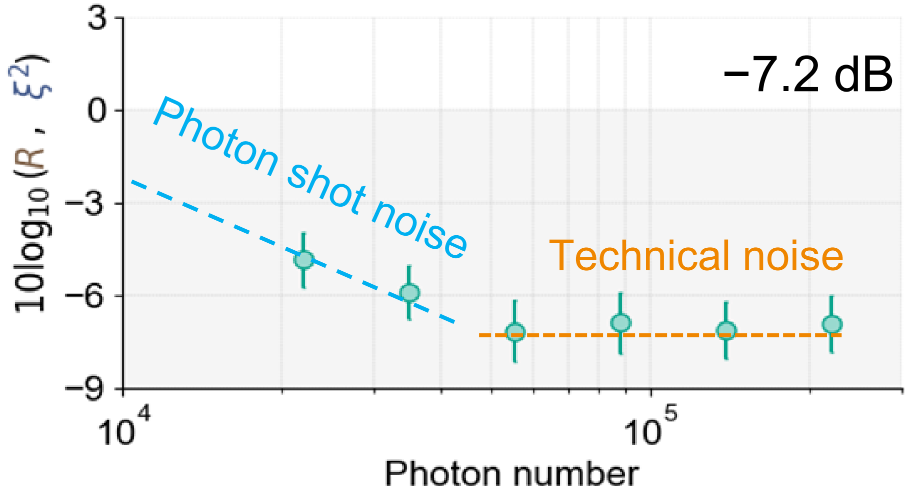


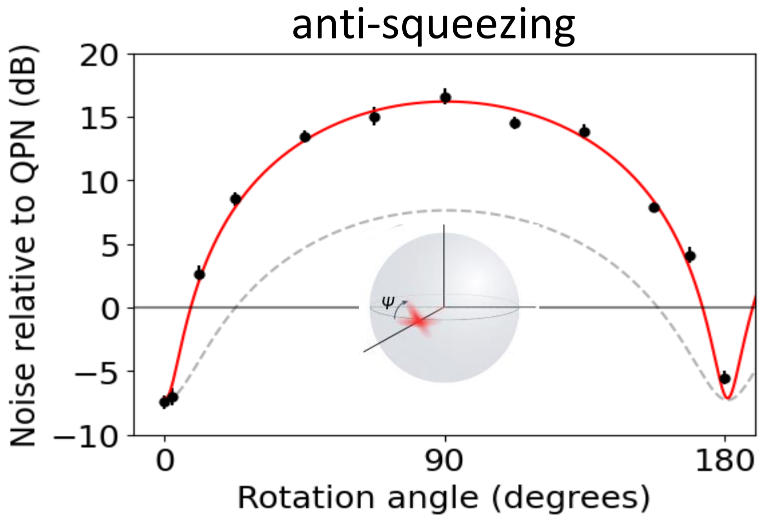
Rydberg-squeezed clock

Eckner…Ye, Kaufman, Nature (2023).

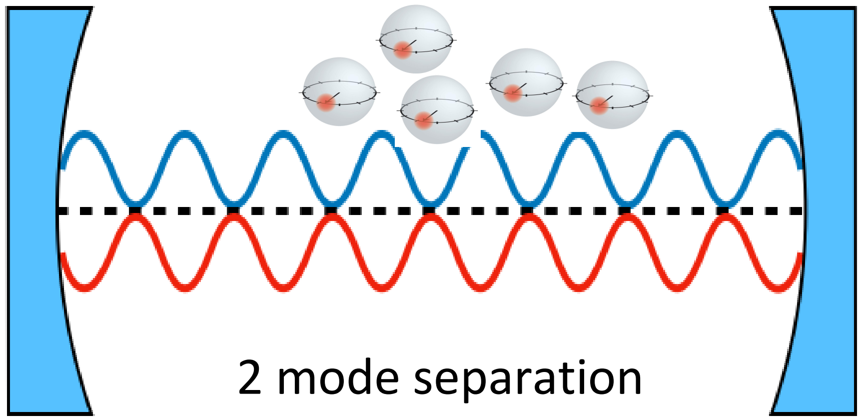
Making QND truly non-demolition (coherence)

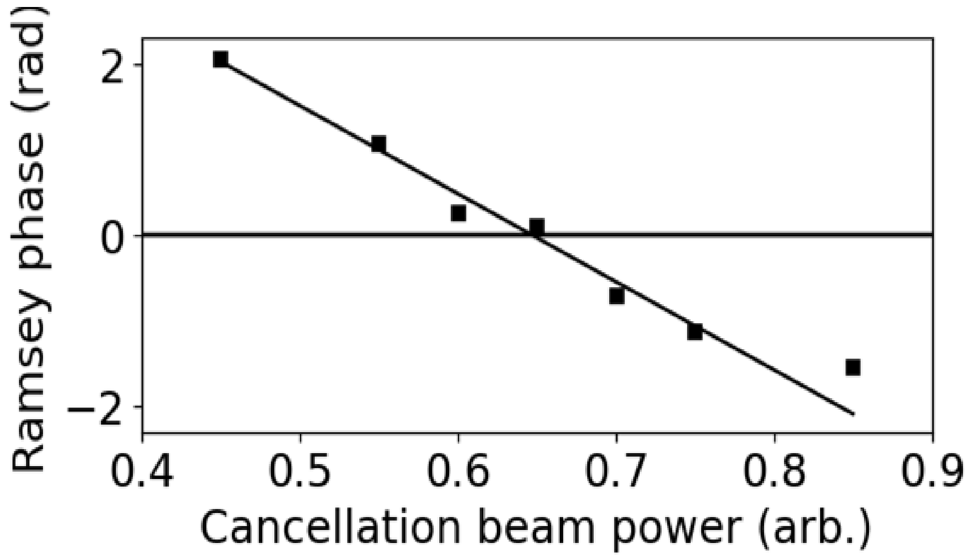






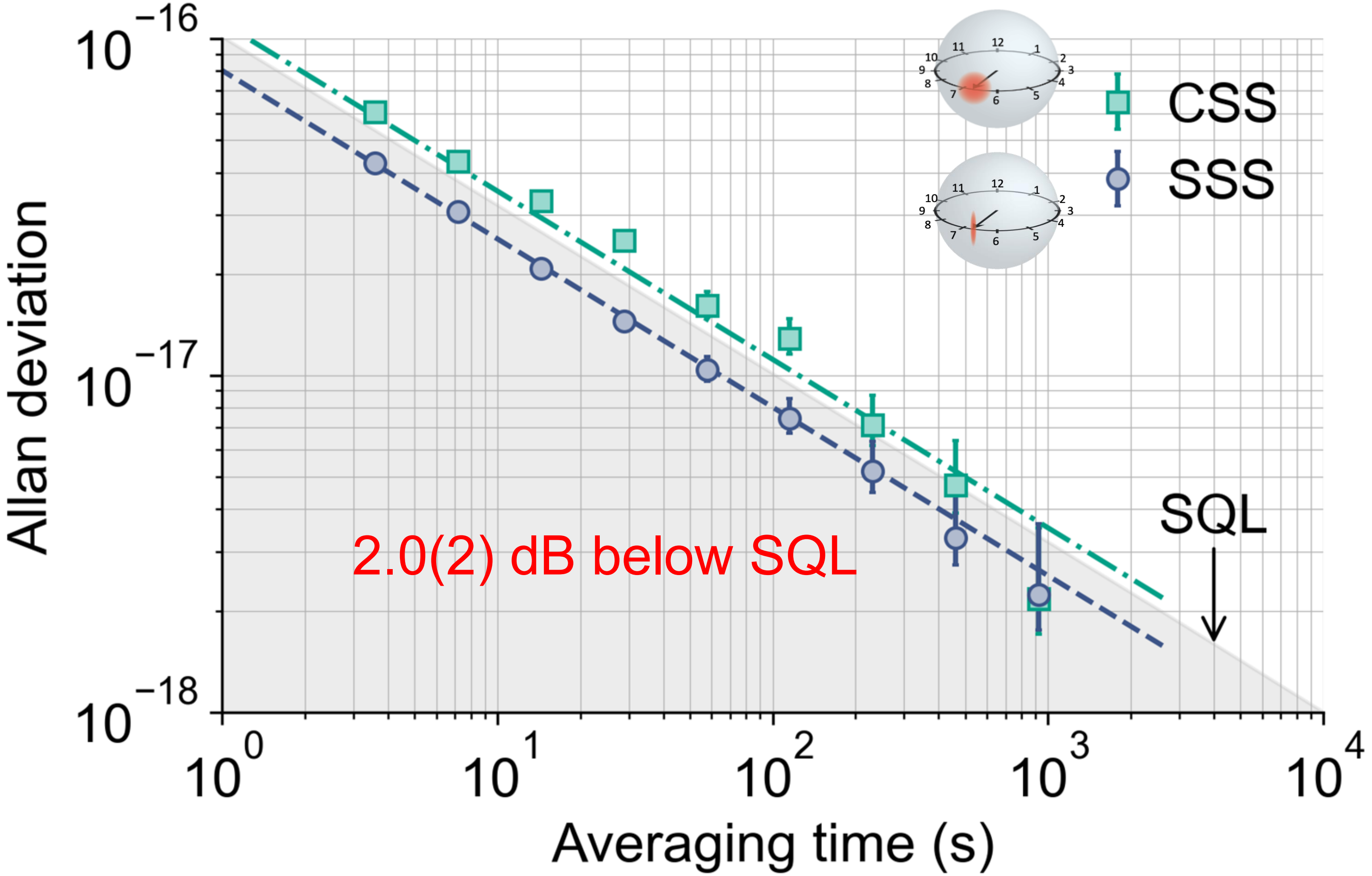
Cancelling QND probe Stark shift





Chasing the absolute state of the art

- Spin-squeezed clock: 5.7×10^{-17} (1 s), 1×10^{-18} (3000 s)
- x20 improvement
- Yang … Ye, arXiv:2505.04538 (2025).



JILA Sr1: unentangled atoms
$N = 10^5$
7 s interrogation
$$1.5 \times 10^{-18}/\sqrt{\tau}$$

JILA Sr3: entangled atoms
$N = 3 \times 10^4$
0.06 s interrogation
$$5.7 \times 10^{-17}/\sqrt{\tau}$$

JILA Sr3: Projected
$N = 5 \times 10^4$
5 s interrogation
$$\xi^2 \sim -3\ \mathrm{dB}$$
$$1.2 \times 10^{-18}/\sqrt{\tau}$$

Scaling up atom number

Degenerate Fermi gas of Sr atoms:

1 million atoms

Coherence 120 s

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

Quantum simulator & sensor (Fermi Hubbard model)

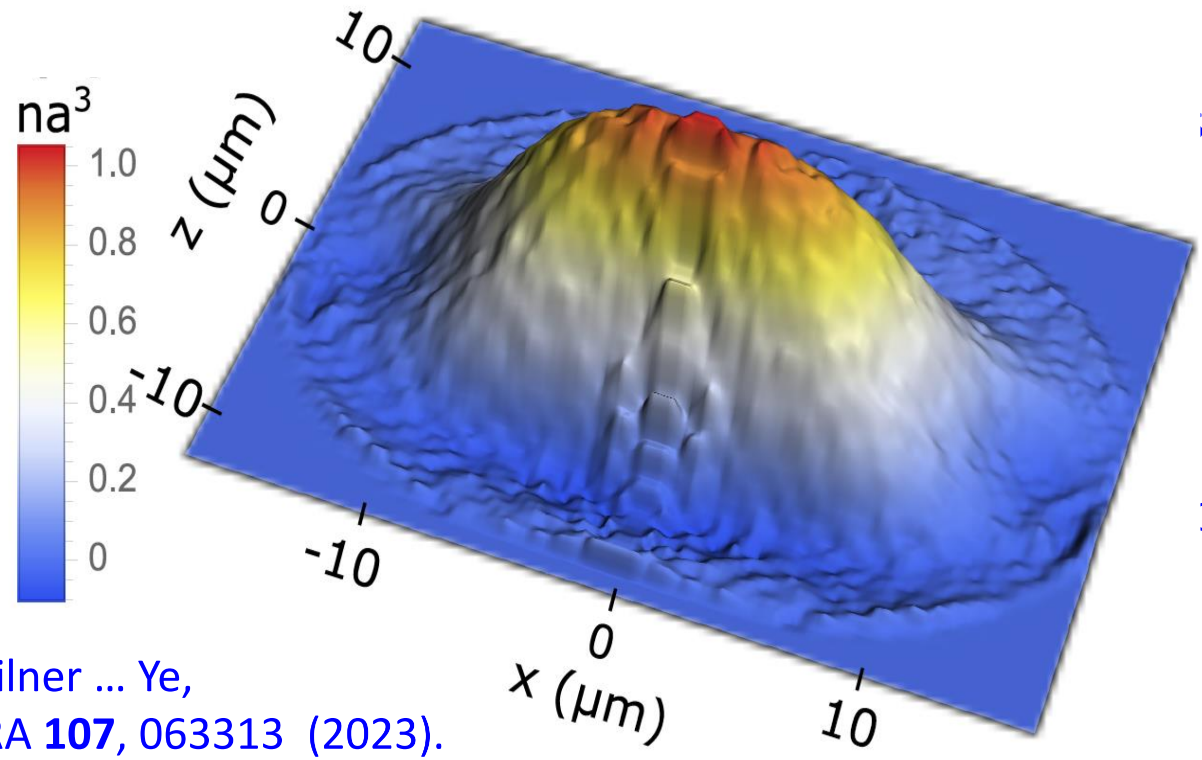
$$\hat{H} = -t\sum_{j,\sigma}\left(\hat{c}^{\dagger}_{j,\sigma}\hat{c}_{j+1,\sigma} + h.c.\right) + U\sum_{j}\hat{n}_{j,\uparrow}\hat{n}_{j,\downarrow} + \frac{\Omega}{2}\sum_{j}\left(e^{ij\phi}\hat{c}^{\dagger}_{j,\uparrow}\hat{c}_{j,\downarrow} + h.c.\right)$$

De

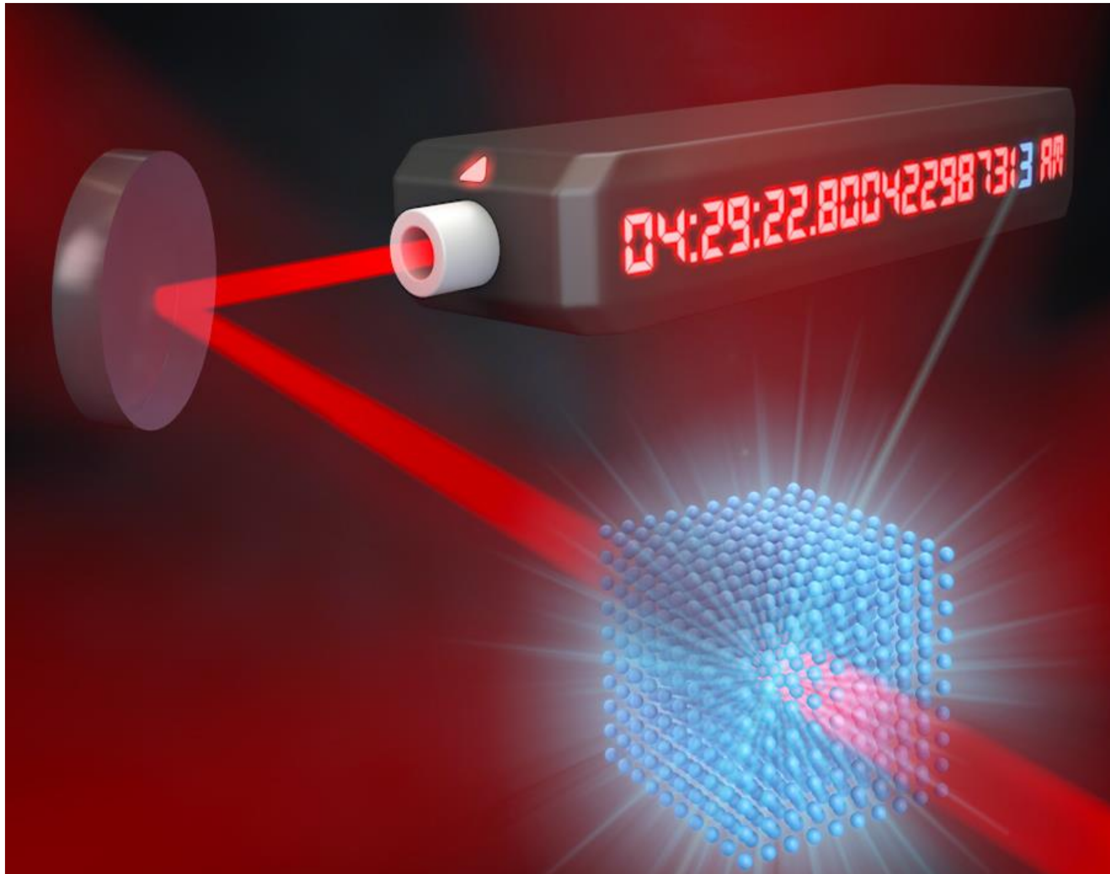
→

- S
- S
- C

025)



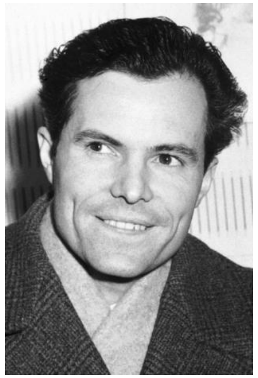
Milner … Ye,
PRA **107**, 063313 (2023).



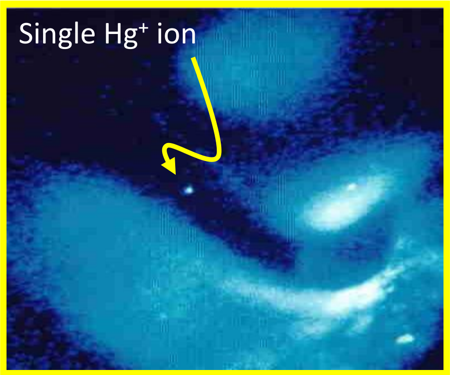
S. Campbell … Ye,
Science **358**, 90 (2017).

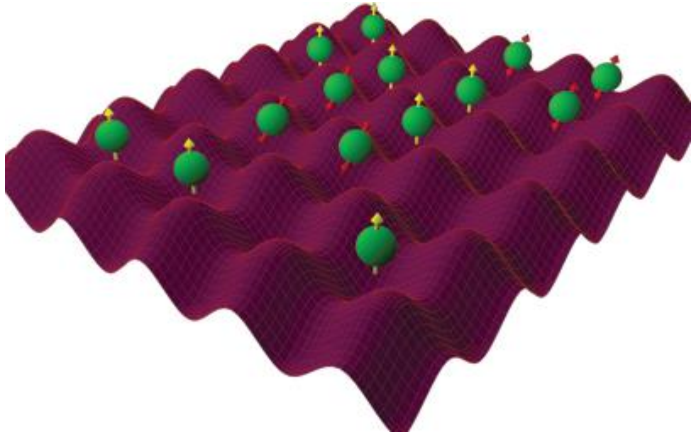
Historical lesson & Number scaling

Can we have an Avogadro's number of quantum absorbers?

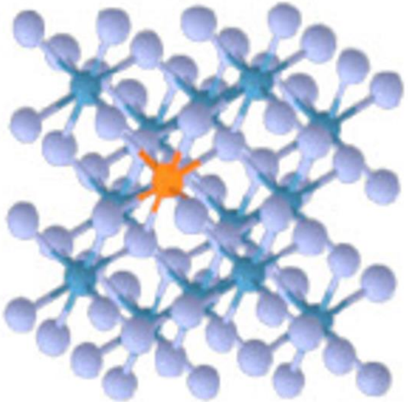


Atomic clocks
(coherent)



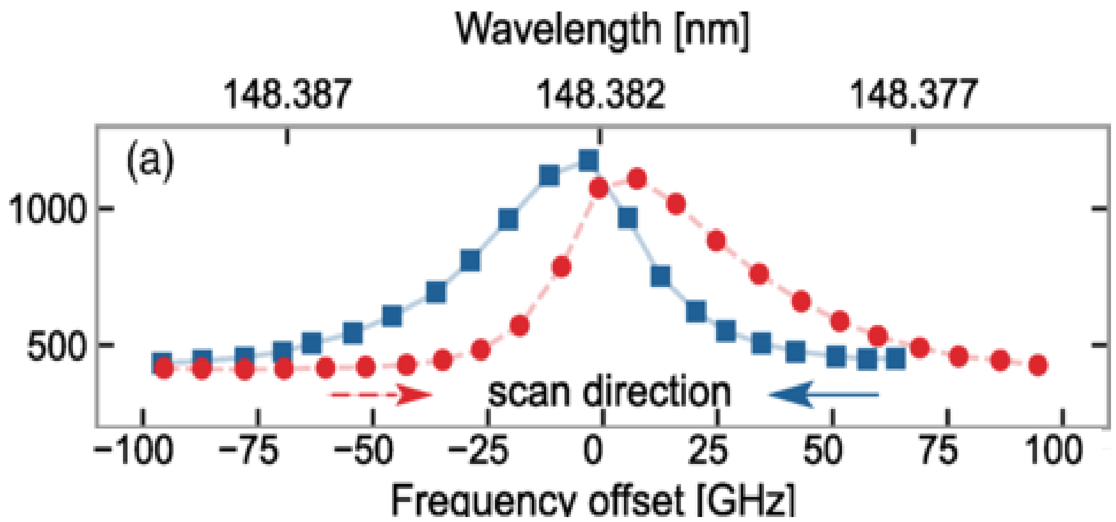


Mössbauer spectroscopy
(incoherent → coherent)



Coherent Mössbauer spectroscopy for nuclear clock

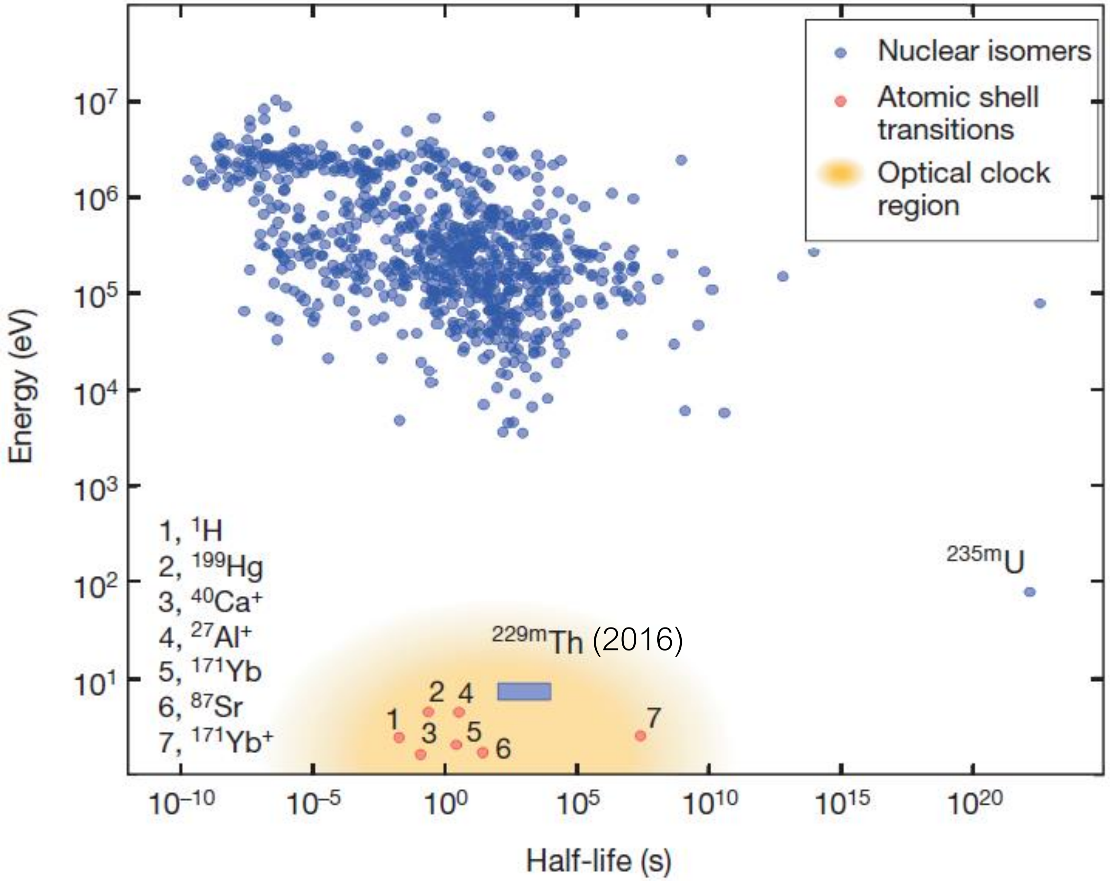
Tiedau ... Peik, PRL **132**,182501 (2024).   Elwell ... Hudson, PRL **133**, 013201 (2024).



Urgent:

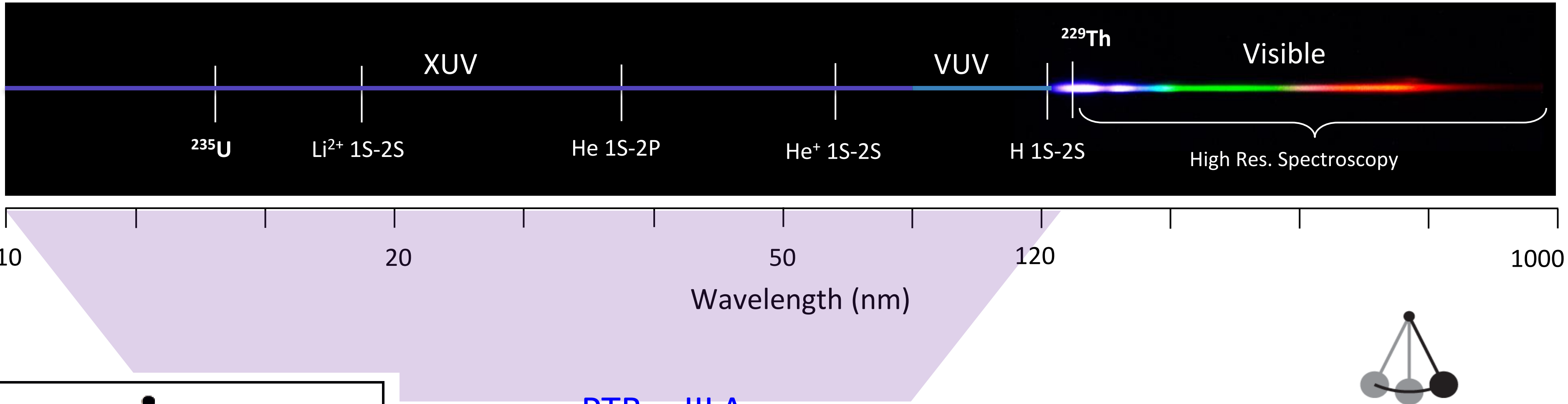
- **High pow** **ewidth VUV laser**

Uniquely low energy transition in ^{229}Th



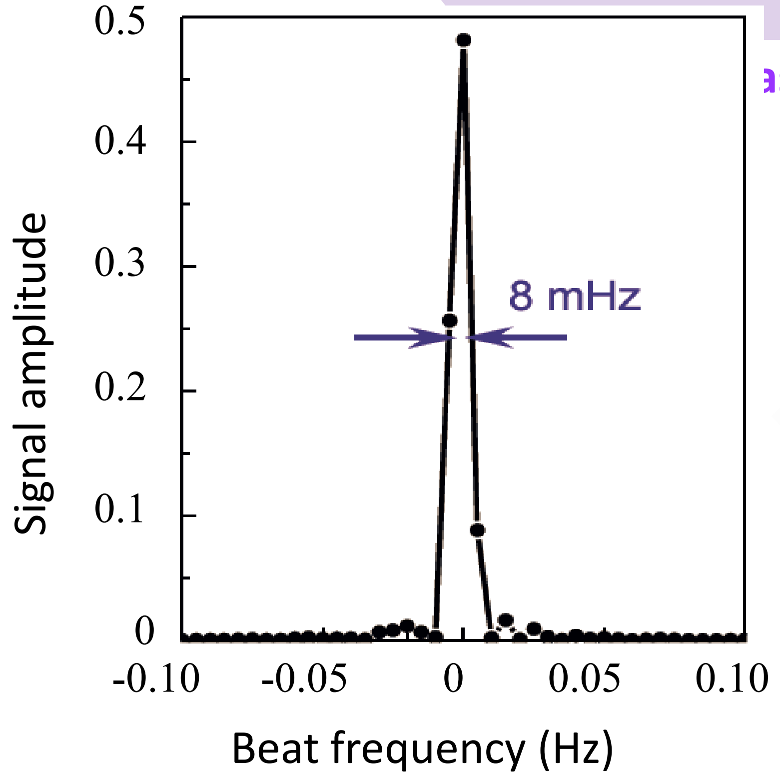
Peik & Tamm, Europhys. Lett. **61,** 181 (2003).
L. v.d.Wense ... Thirolf, Nature **533,** 47 (2016)

High resolution extreme/vacuum ultraviolet light



asers, synchrotron radiations

PTB – JILA
(2007 – present)



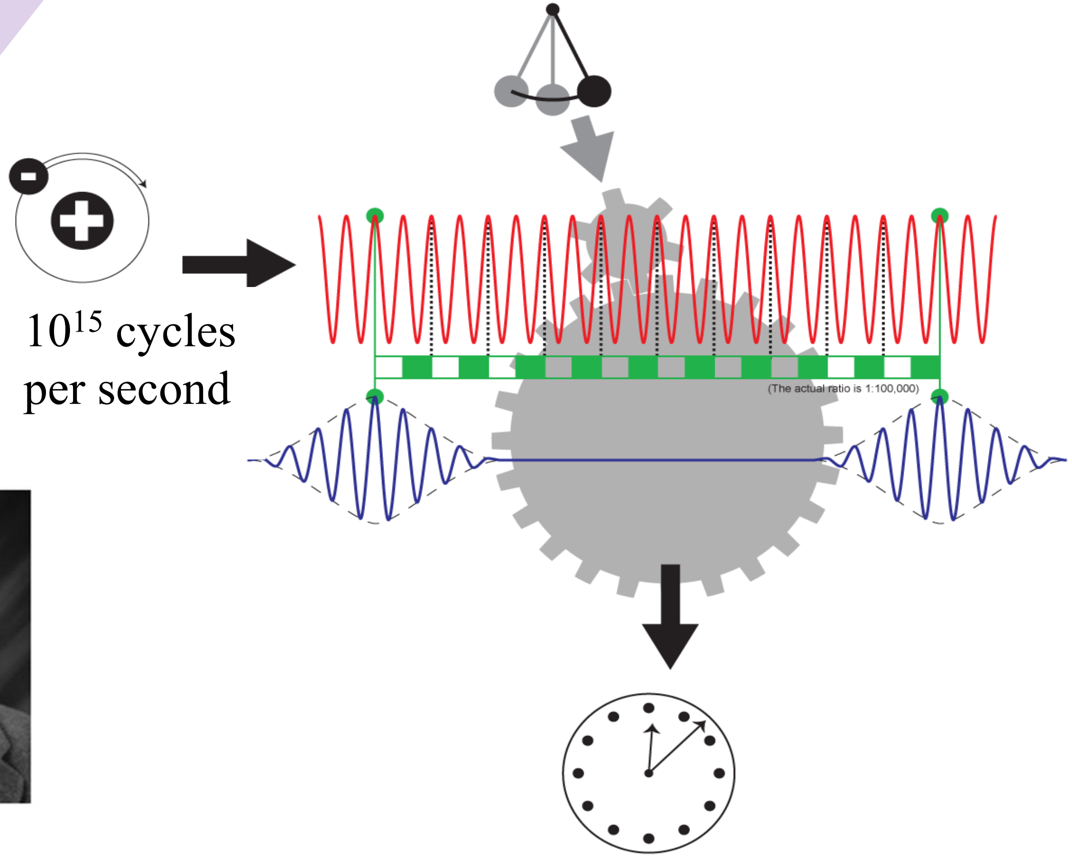
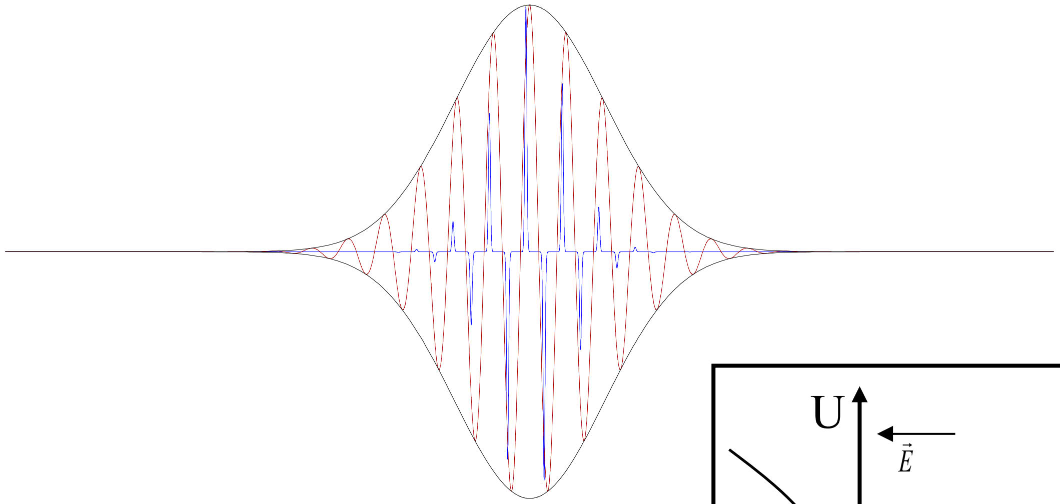


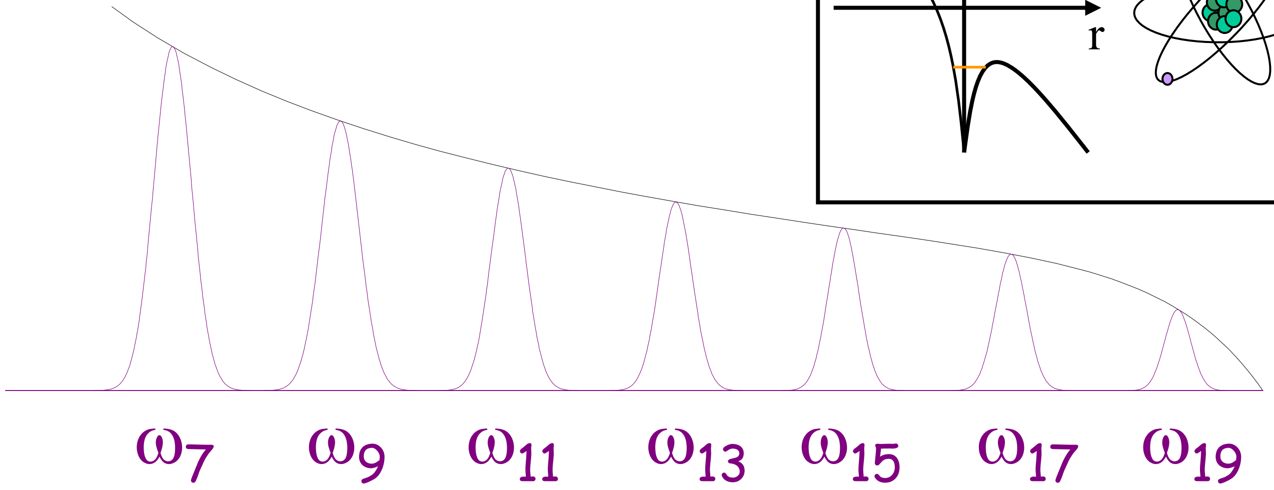
Table-top coherent VUV and XUV radiation

Harmonic Generation with a single IR pulse - *a train of attosecond pulses*

Time domain



Frequency domain



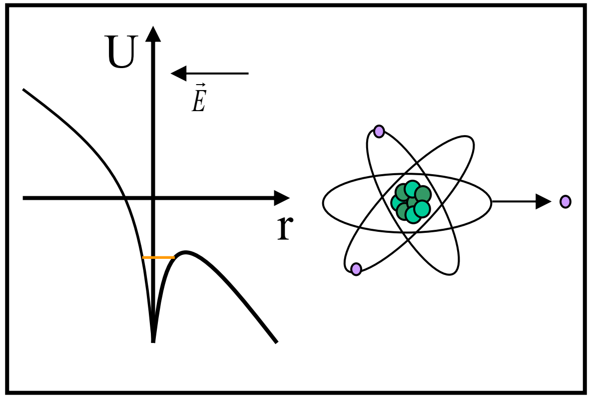
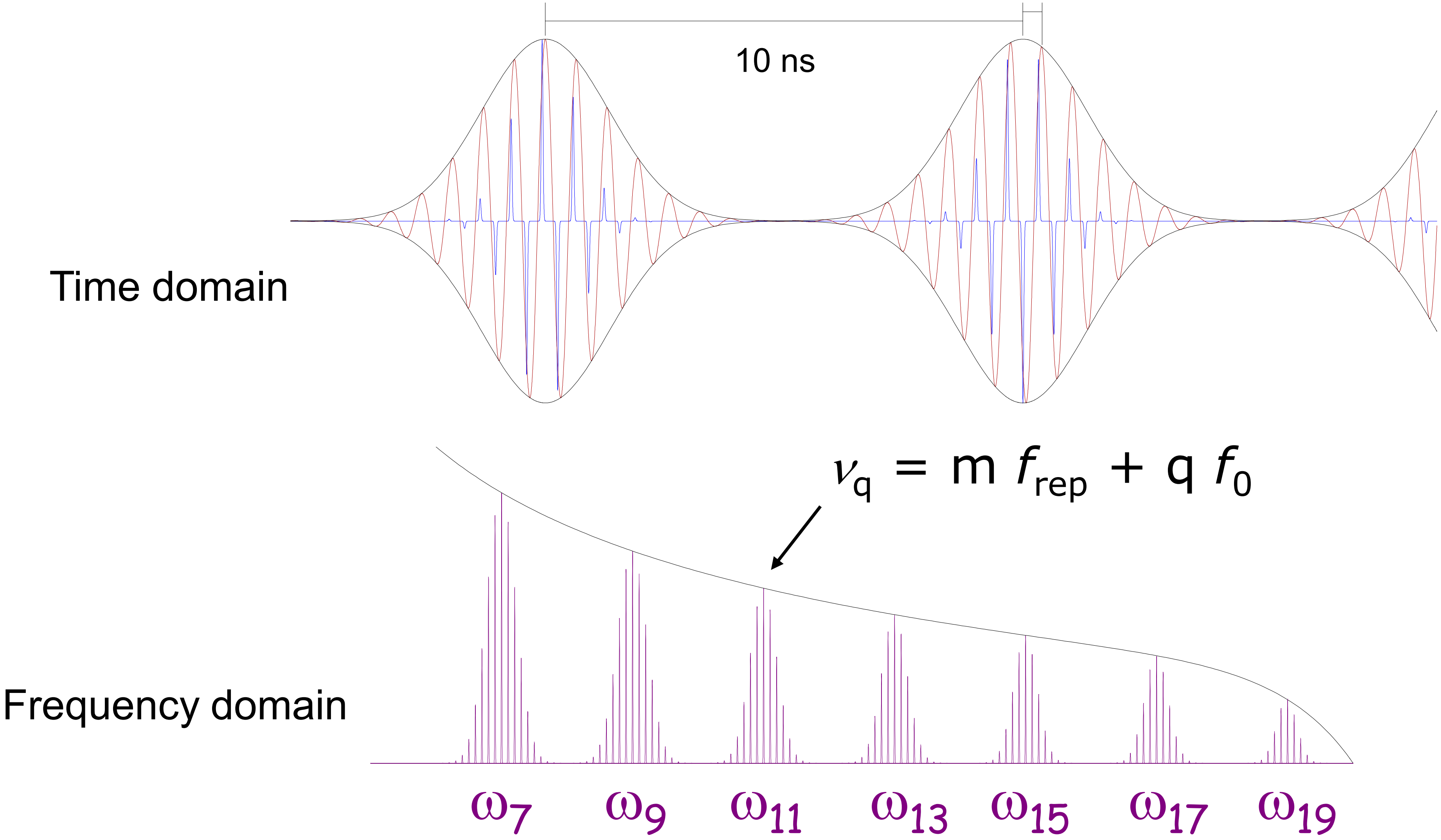


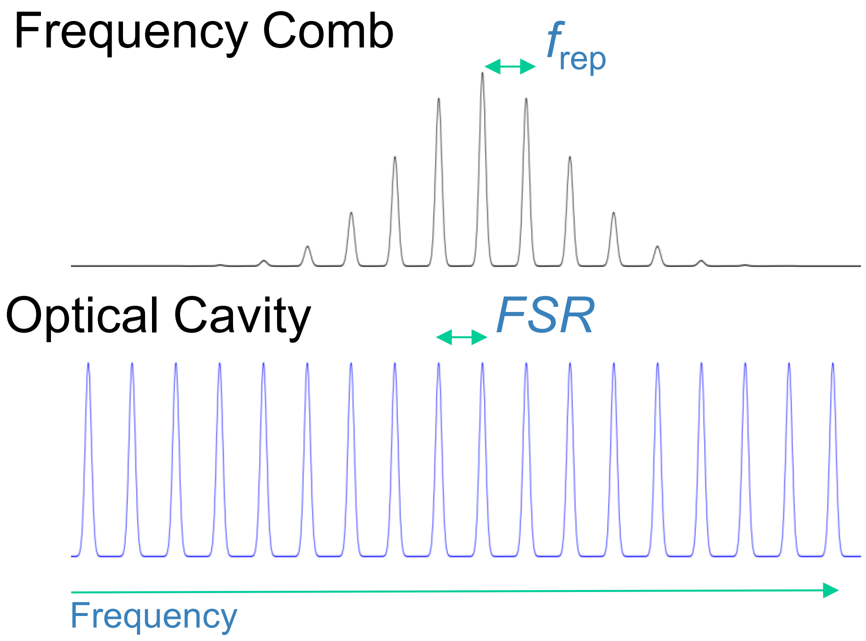
Table-top coherent VUV and XUV radiation

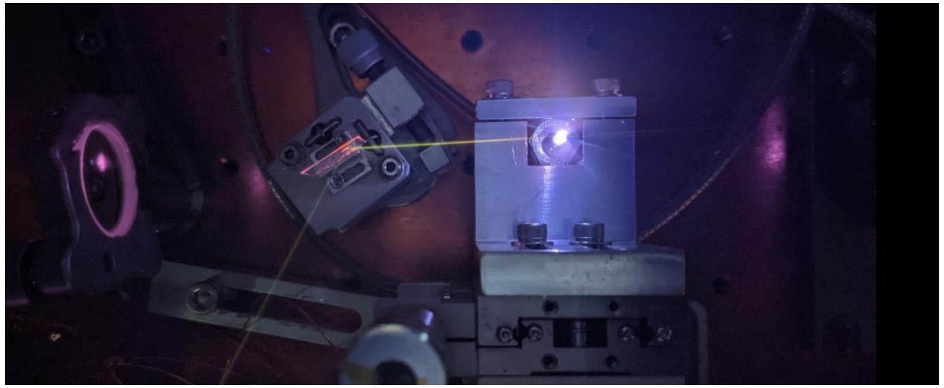
Harmonic Generation with a train of IR pulses → *XUV frequency comb*

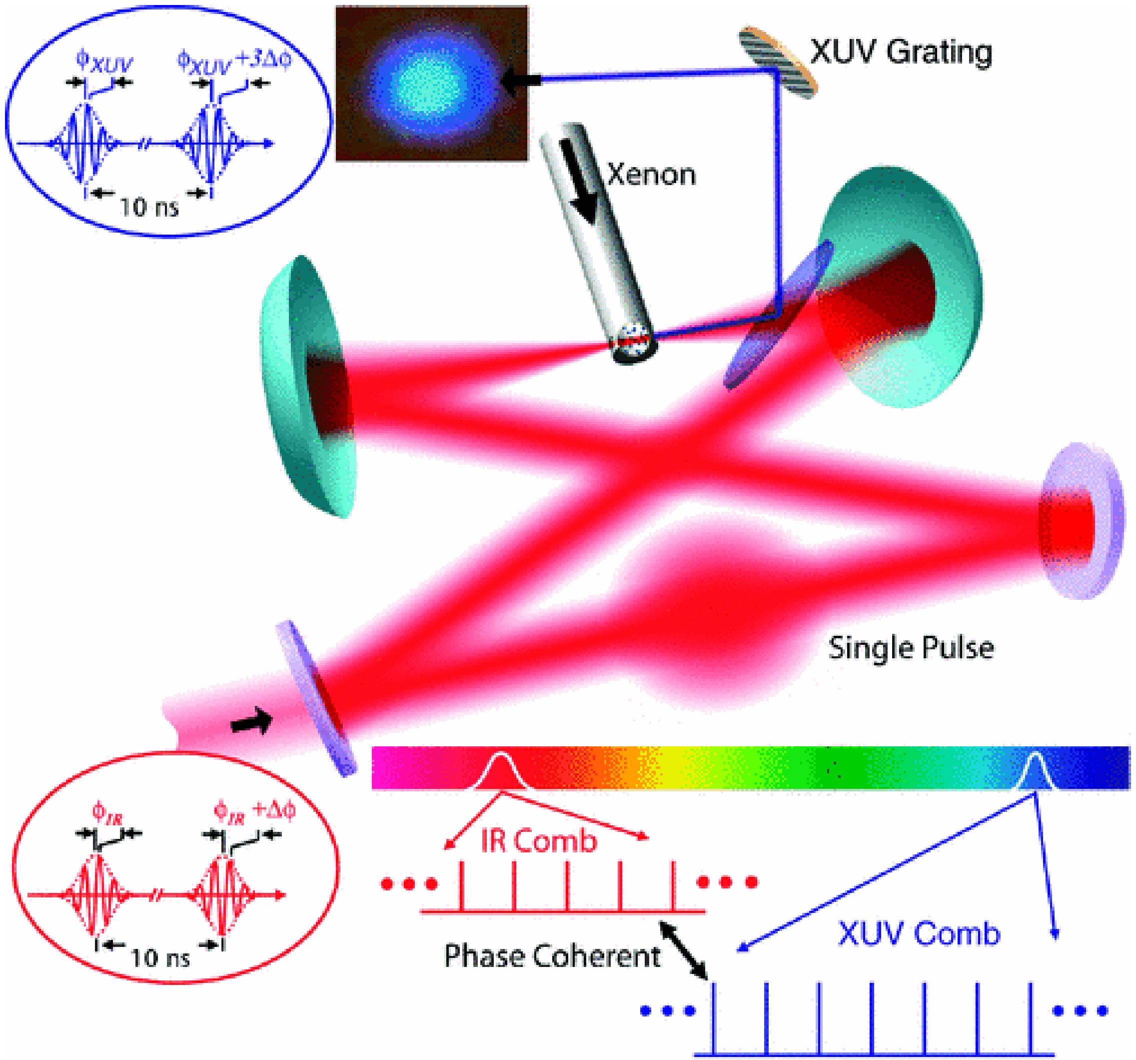


Making a VUV frequency comb

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



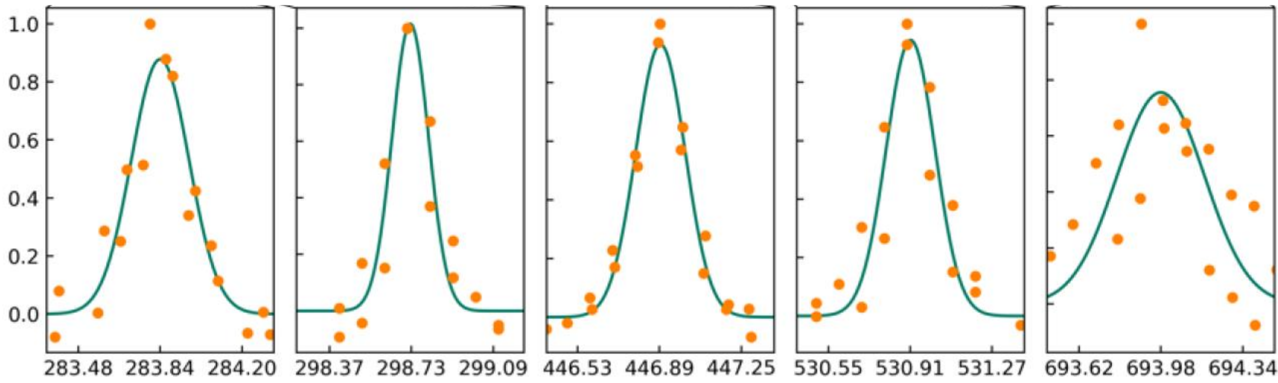


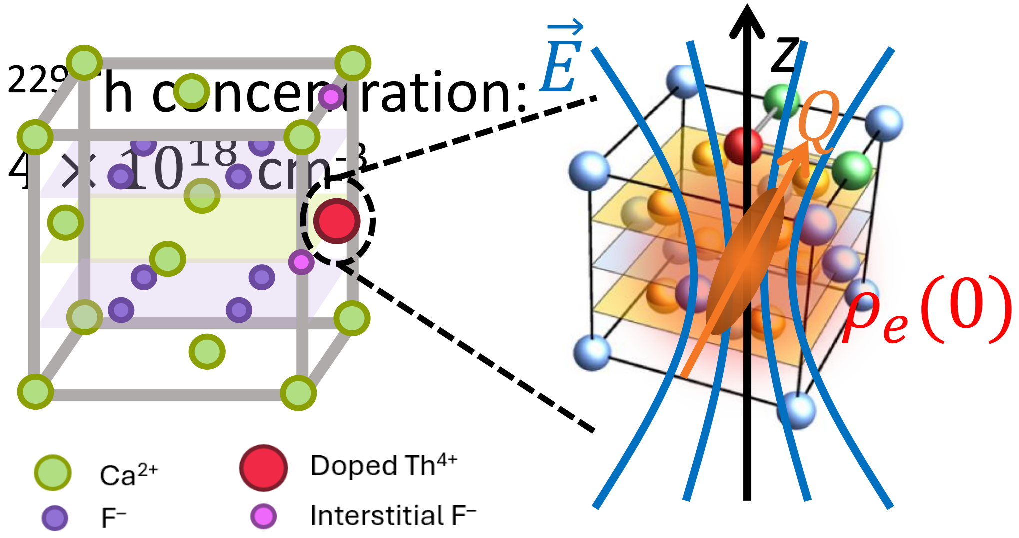


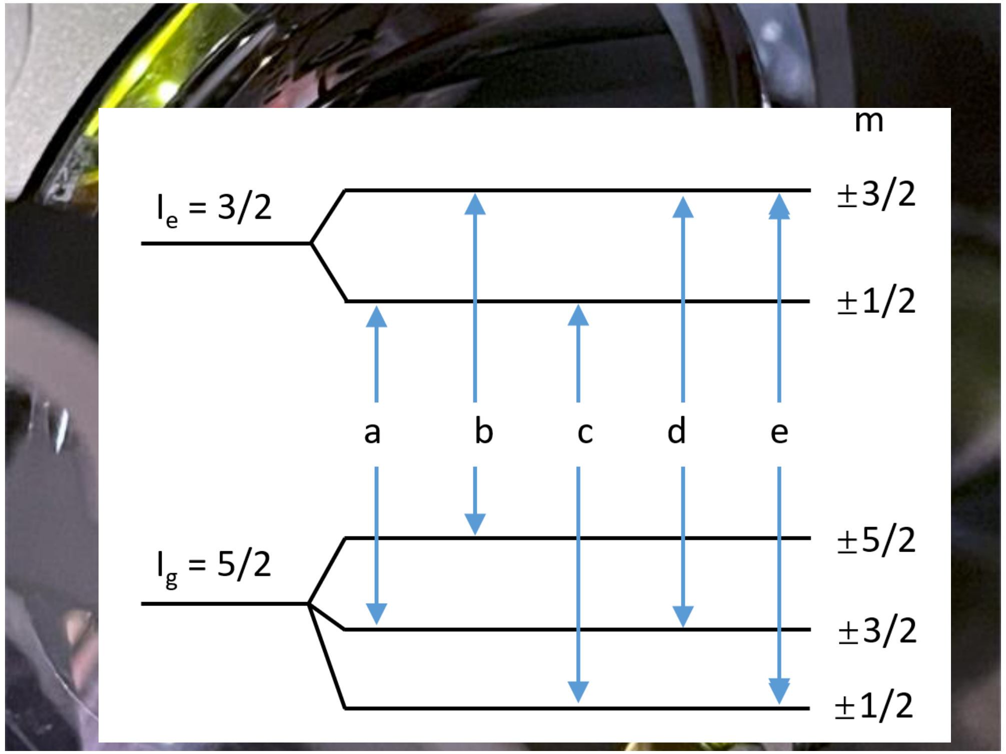
Comb parallelism – high resolution, broad bandwidth

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

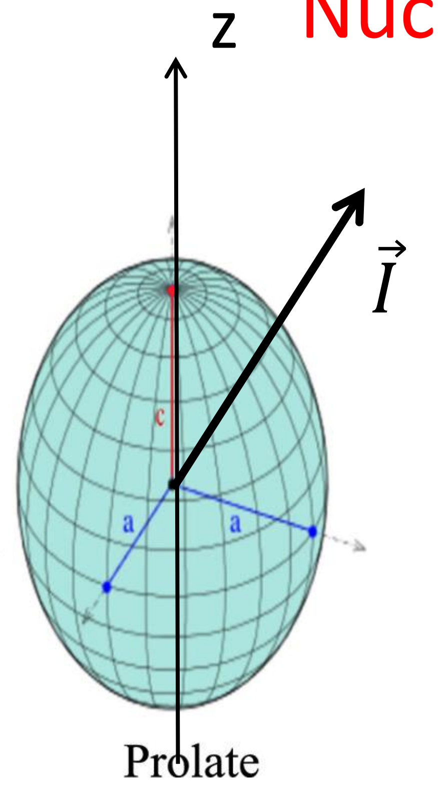
Thorsten Schumm







Nuclear structure & new physics beyond standard model



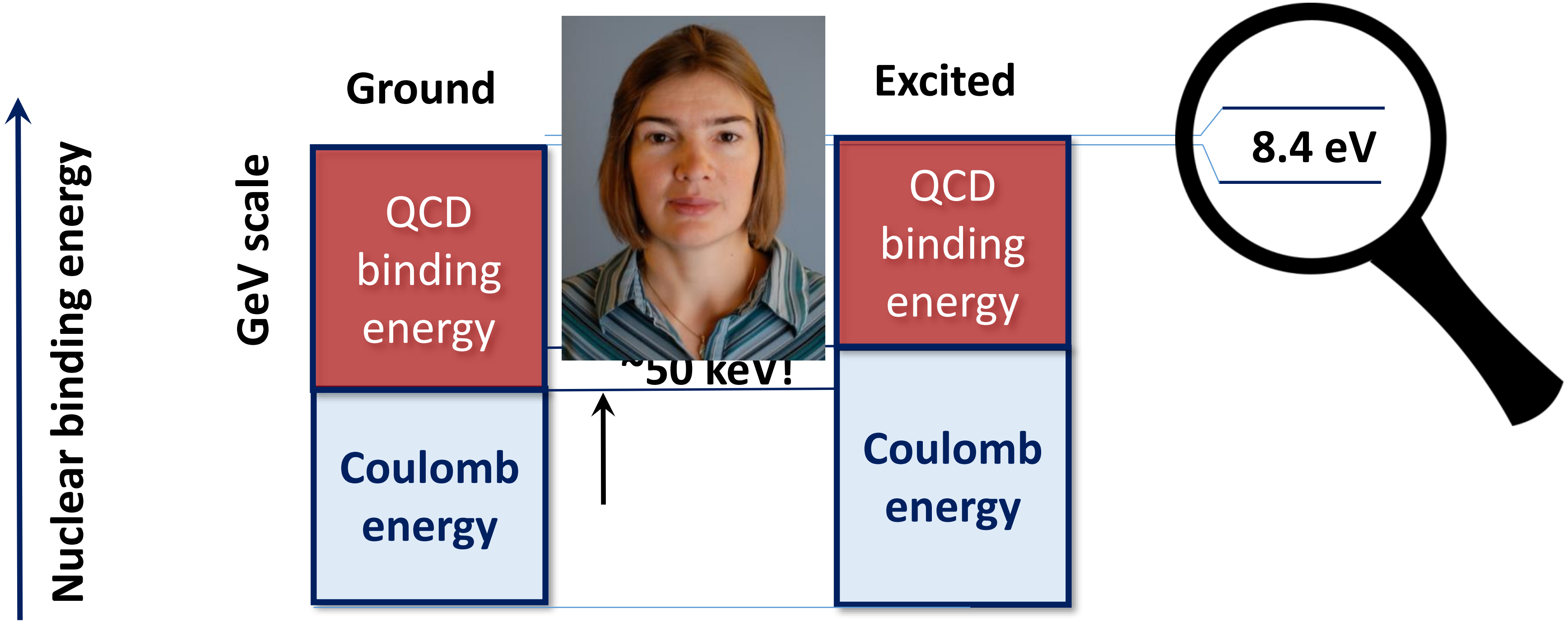
Beeks … Schumm, Ye, Safronova, arXiv:2407.17300 (2024).

Quadrupole moment ratio

$$\frac{Q_{\text{is}}}{Q_{\text{g}}} = 1.01791(2) \quad \Rightarrow$$

Nuclear volume:

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



Coulomb interaction ~ α

Strong force

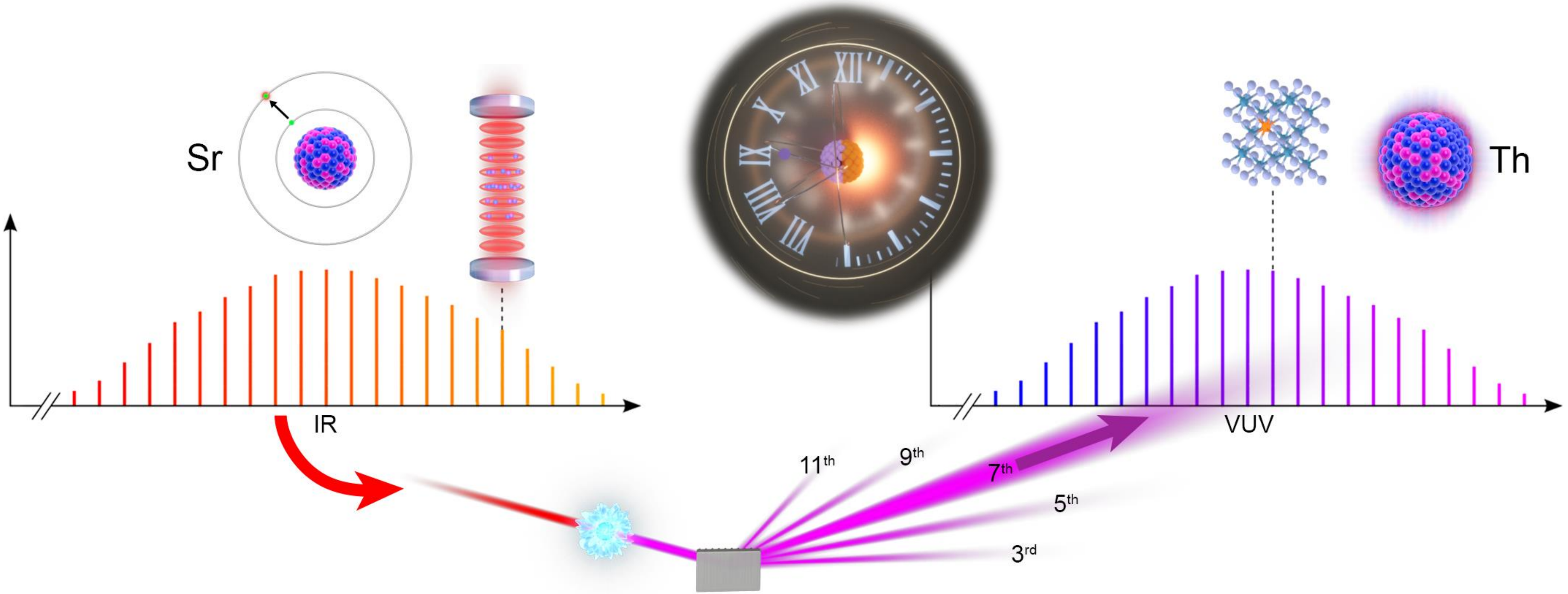
Sensitivity to variation of α

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

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

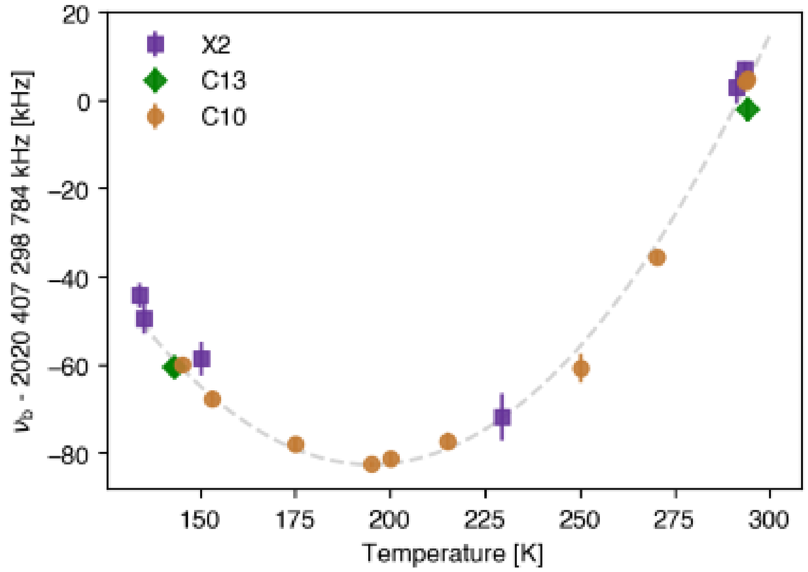
Zhang … Thirolf, Schumm, Ye, Nature **633**, 63 (Sept. 5, 2024).

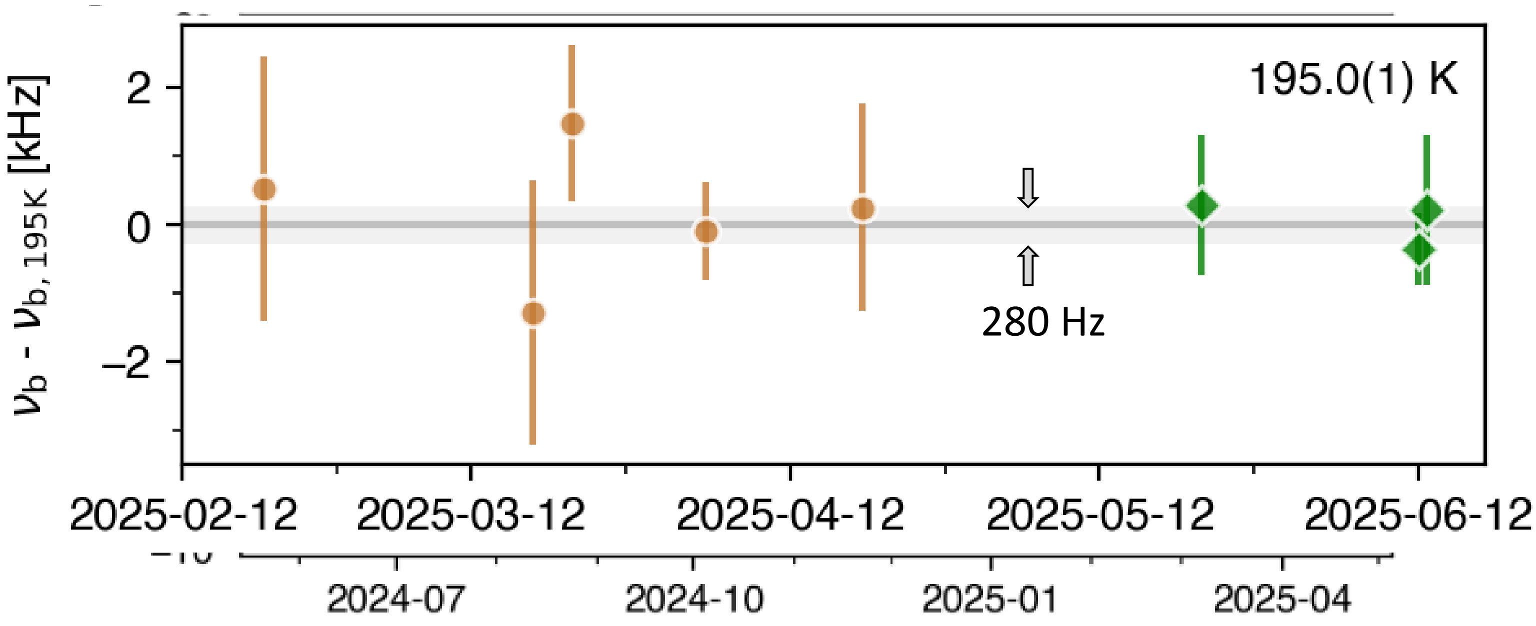
$$\frac{\nu_{^{229}\mathrm{Th}}}{\nu_{^{87}\mathrm{Sr}}} = 4.707\,072\,615\,078(5)$$



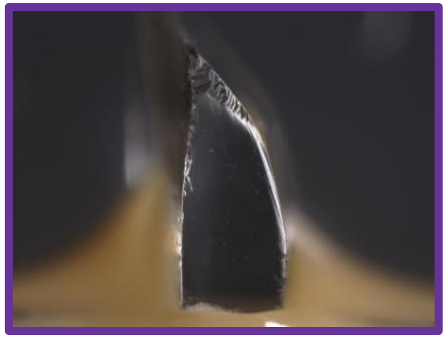
$^{229}Th:CaF_2$: Frequency reproducibility

Higgins … Schumm, Ye, Phys. Rev. Lett. **134**, 113801 (2025); Ooi … Schumm, Ye, arXiv:2507.01180 (2025).

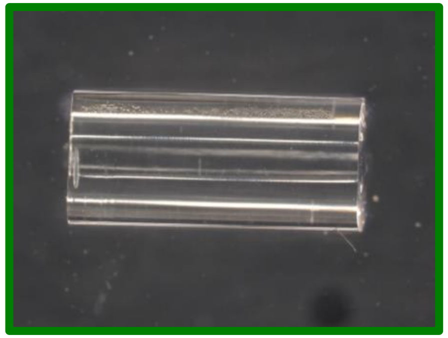




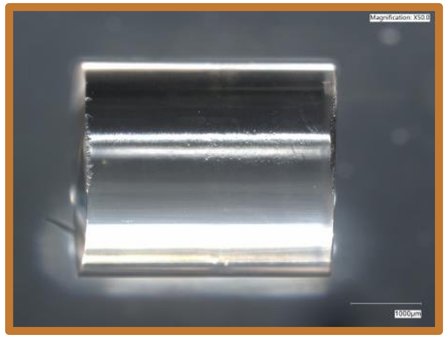
X2: 4×10^{18} cm^{-3}
19 May 2021



C13: 0.8×10^{18} cm^{-3}
7 Dec 2020



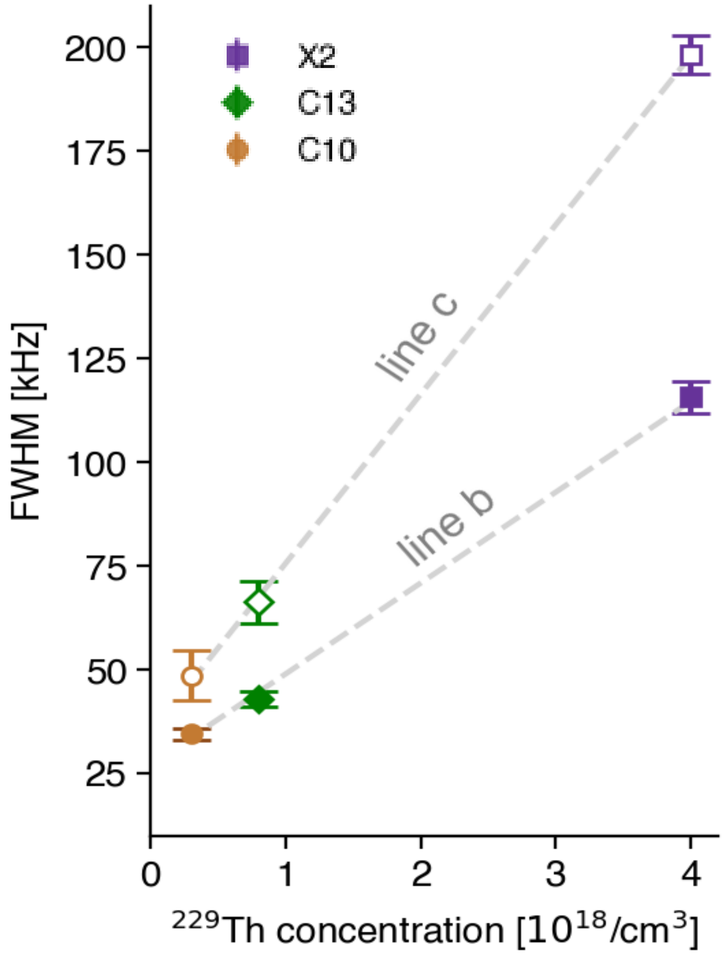
C10: 0.3×10^{18} cm^{-3}
23 Nov 2020

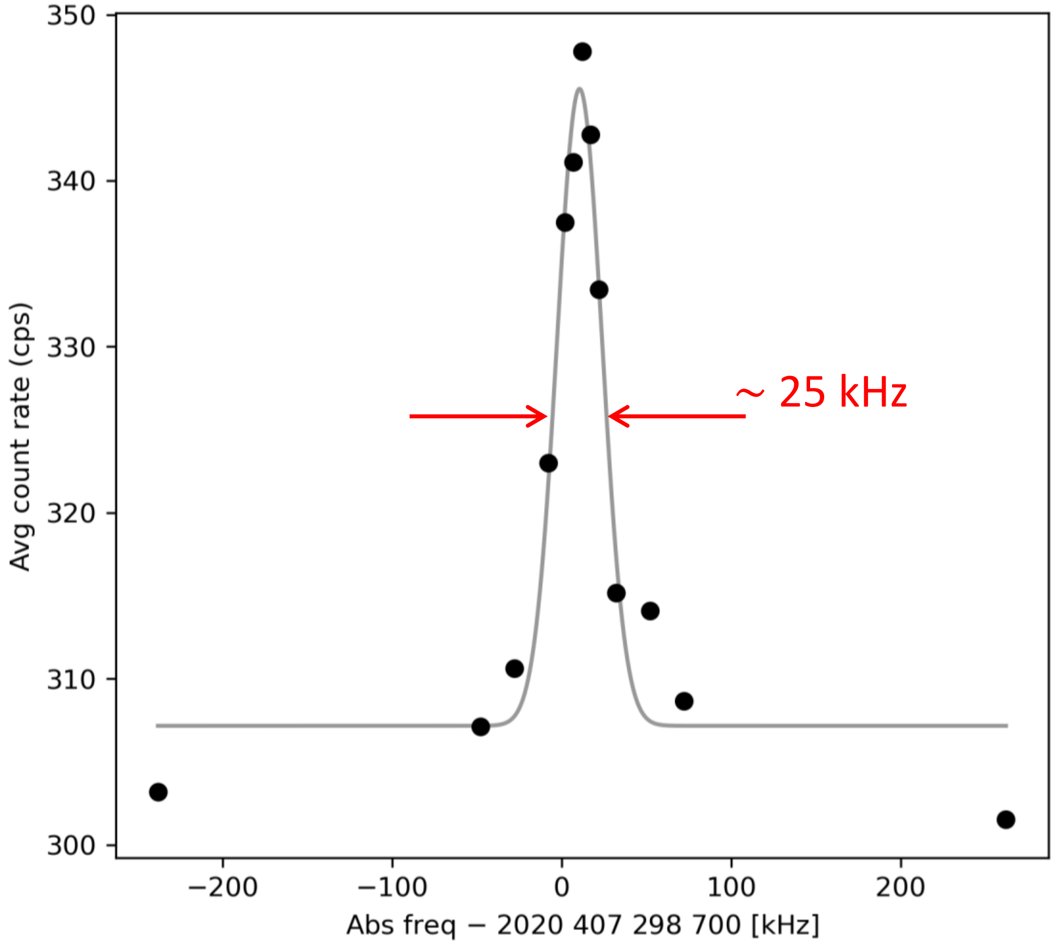


$^{229}Th:CaF_2$: linewidth vs. doping concentration

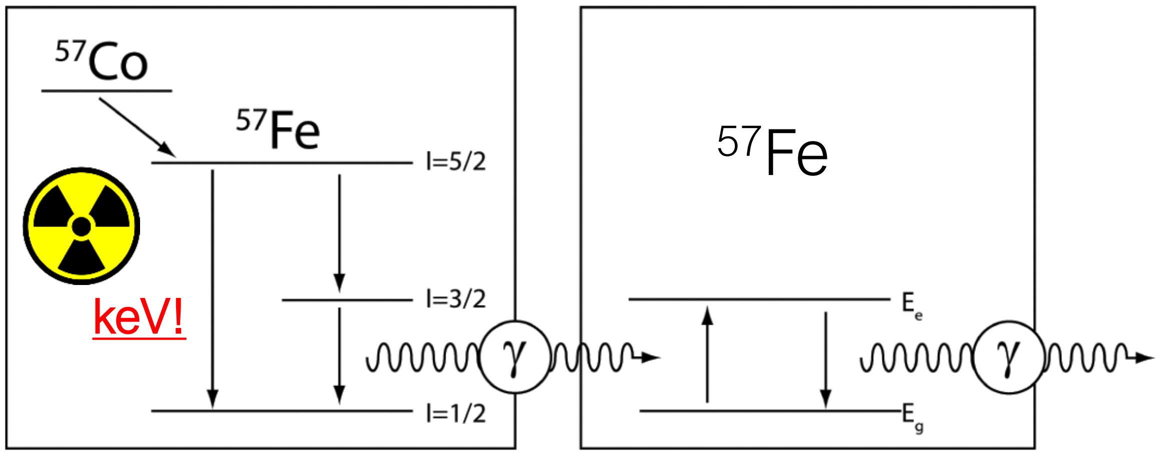
X2: $4 \times 10^{18}/cm^3$
C13: $0.8 \times 10^{18}/cm^3$
C10: $0.3 \times 10^{18}/cm^3$

Temperature-independent linewidth

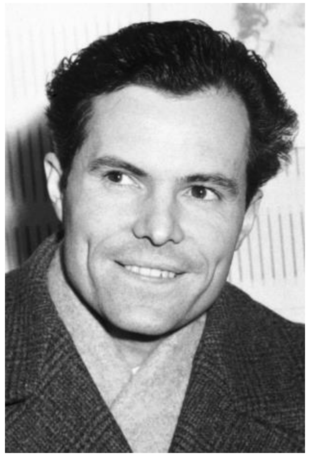




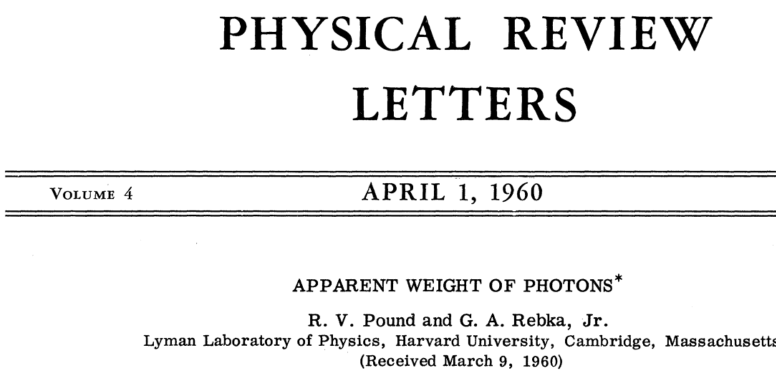
Precision sensing for fundamental physics



Mössbauer spectroscopy
nuclear transitions



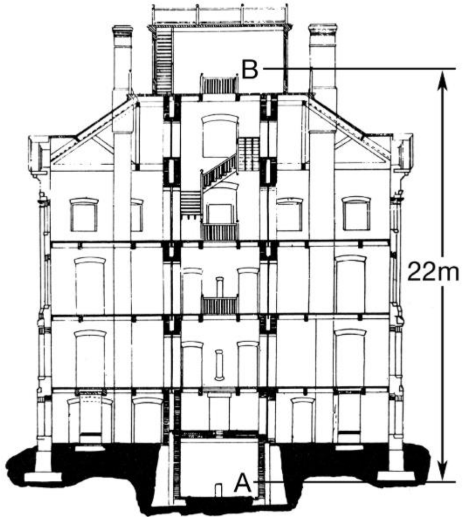
Gravitational red shift measured with nuclear transition


PHYSICAL REVIEW LETTERS

VOLUME 4 APRIL 1, 1960

APPARENT WEIGHT OF PHOTONS*

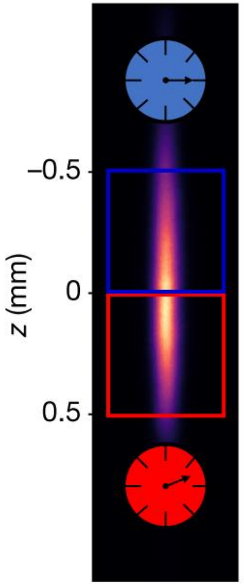
R. V. Pound and G. A. Rebka, Jr.
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts
(Received March 9, 1960)



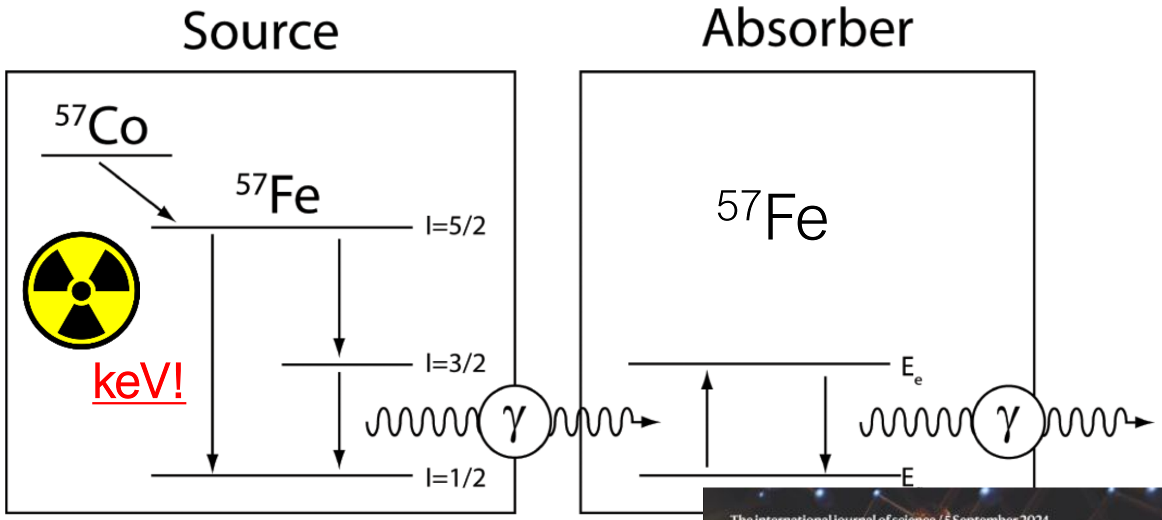
$$\frac{\Delta\nu}{\nu} = 10^{-15}$$

$$\frac{\Delta\nu}{\nu} = 10^{-20}$$

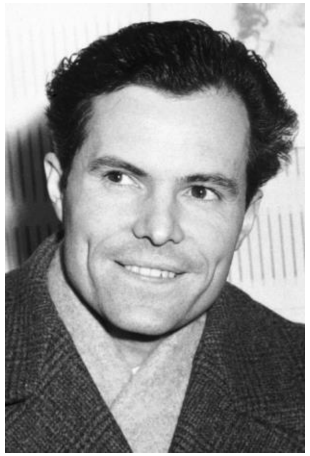
A nuclear-atomic connection



Precision sensing for fundamental physics



Mössbauer spectroscopy
nuclear transitions



Gravitational red shift measured with

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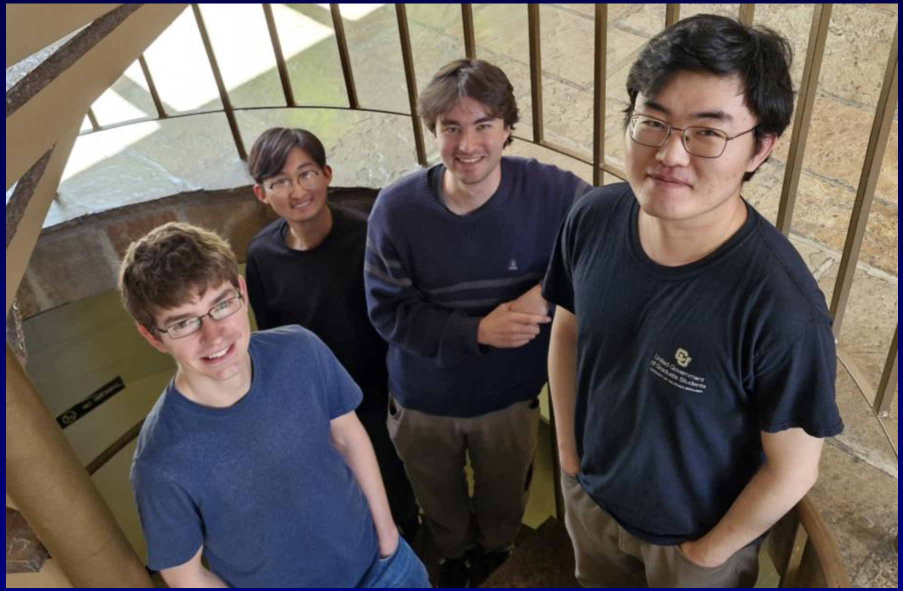
Bothwell *et al.*, Nature **602** 420 (2022)
Zhang *et al.*, Nature **633**, 63 (2024)

A nuclear-atomic connection

Sr optical clock: quantum meets precision

K. Kim
A. Aeppli
W. Warfield

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



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

Z. Hu
D. Lee
B. Lewis

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

^{229}Th nuclear clock

Many JILA scientists and staff members
T. Schumm (TU Wien)

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

JILA

NIST