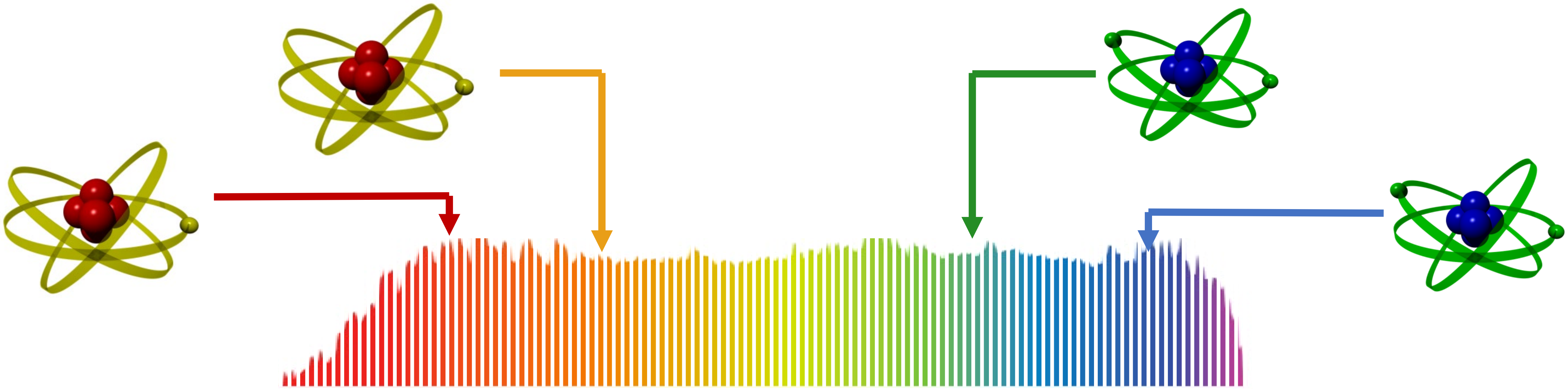
Quantum Metrology and Tests of Fundamental Physics with Trapped Ions

David Hume, NIST *Ion Storage Group*

KITP Workshop

May 3, 2021



Outline

I. Precision measurements with trapped ions
II. Tests of fundamental physics
III. Extending the reach of trapped-ion measurements
    A. Quantum logic spectroscopy
    B. Improving measurement stability

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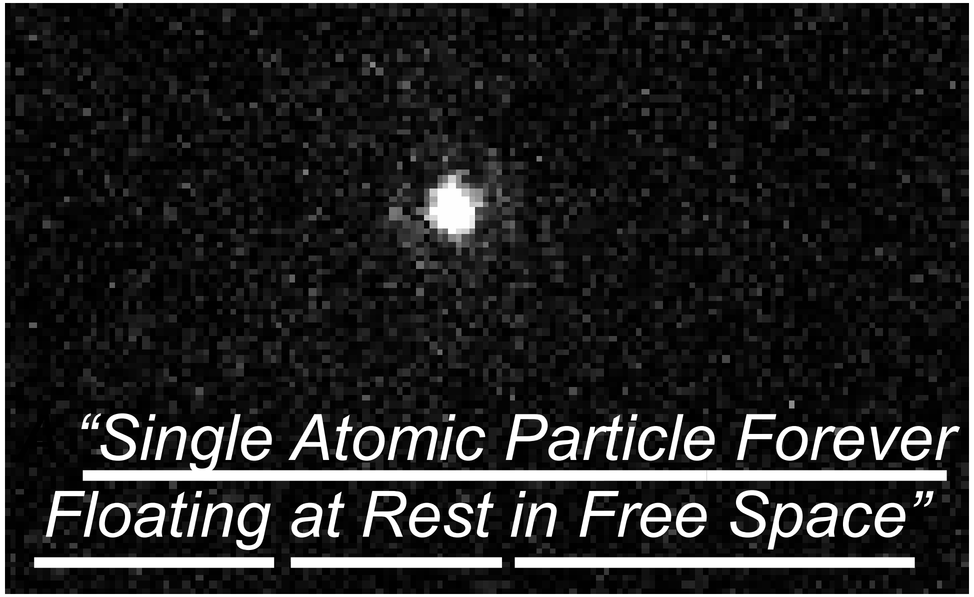
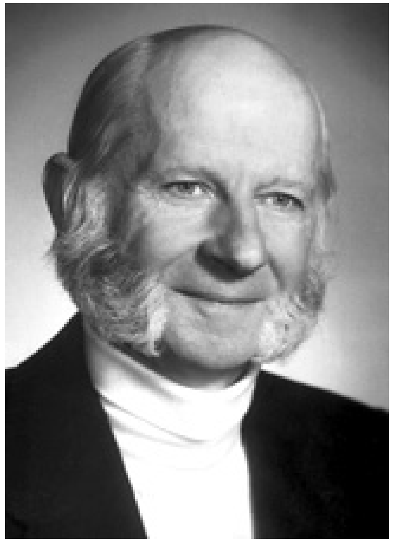
Trapped Atomic Ions



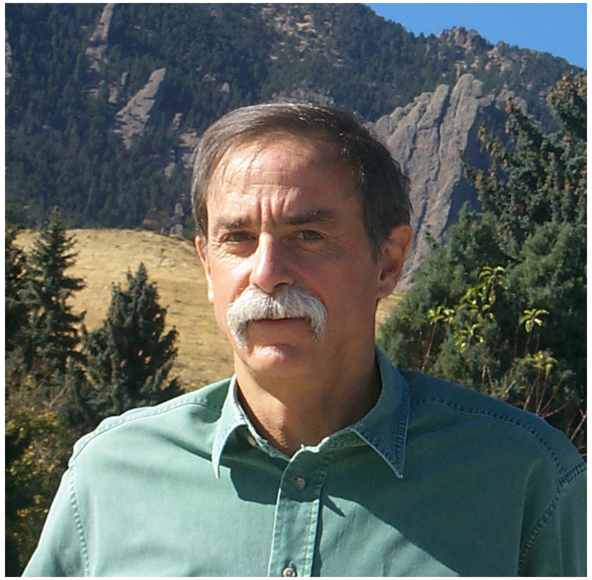
- Quantum-limited experiments
- Long interaction times
- Small relativistic shifts
- Small perturbation from EM fields

Predicted resolution of $1\text{x}10^{-18}$



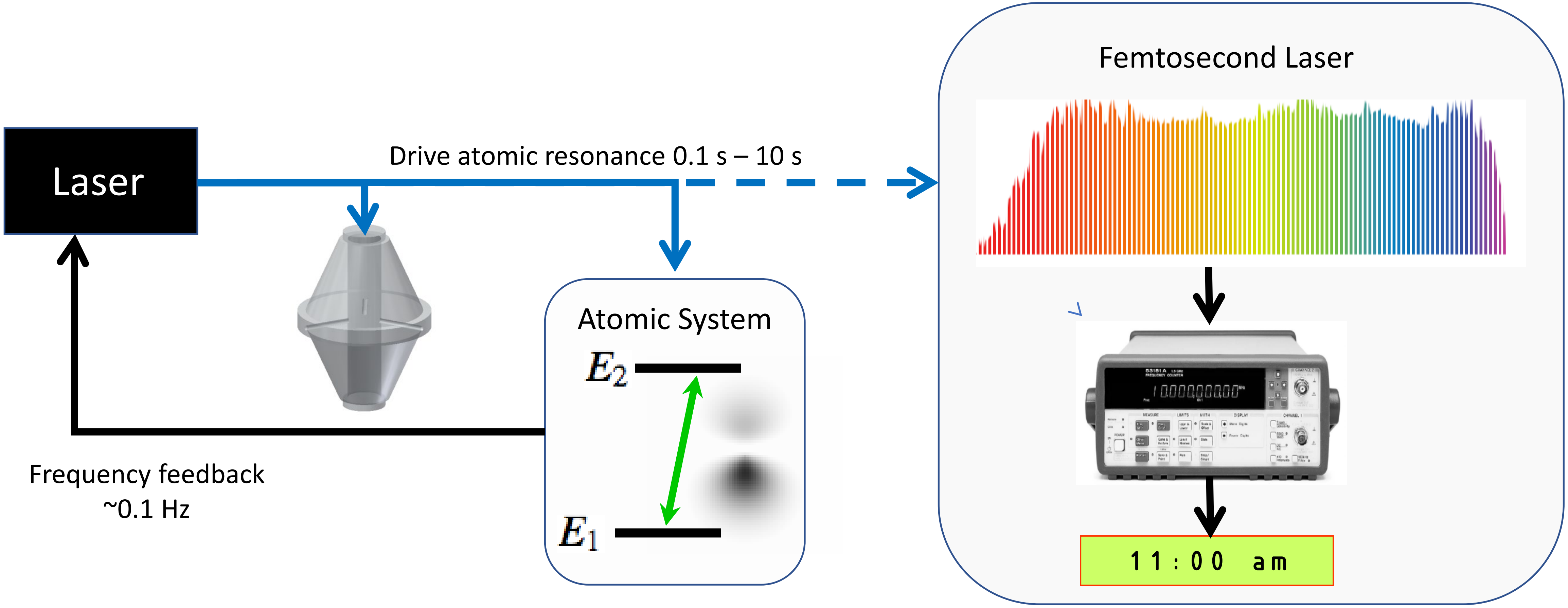
Hans Dehmelt

Hans Dehmelt 1988 *Phys. Scr.* **1988** 102



+ Strong, controllable interactions between ions

Principle of Optical Clocks



Clock frequency: $f_0 = \dfrac{E_2 - E_1}{h}$ ≈10^{15} Hz

Atomic Clock Performance

$$f(t)/f_0 = 1 + \epsilon + y(t)$$

Accuracy

- Systematic uncertainty in clock frequency.
- Two types of shifts
  1. **Field shifts** e.g. Zeeman shift and black body shift
  2. **Motional shifts** e.g. Relativistic Doppler

$$\frac{\Delta f}{f} = \frac{\langle \vec{v} \cdot \hat{k} \rangle}{c} - \frac{\langle v^2 \rangle}{2c^2} - \frac{\langle \vec{v} \cdot \hat{k} \rangle^2}{2c^2} + \cdots$$

Stability

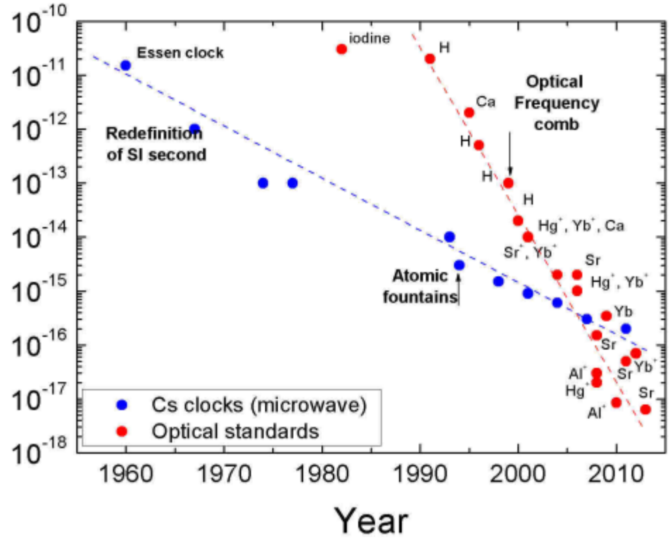
- Average fractional frequency variations
- Typically characterized by the *Allan deviation:*

$$\sigma_y(\tau) \cong \frac{1}{Q} \frac{1}{SNR} \sqrt{\frac{T_C}{\tau}}$$

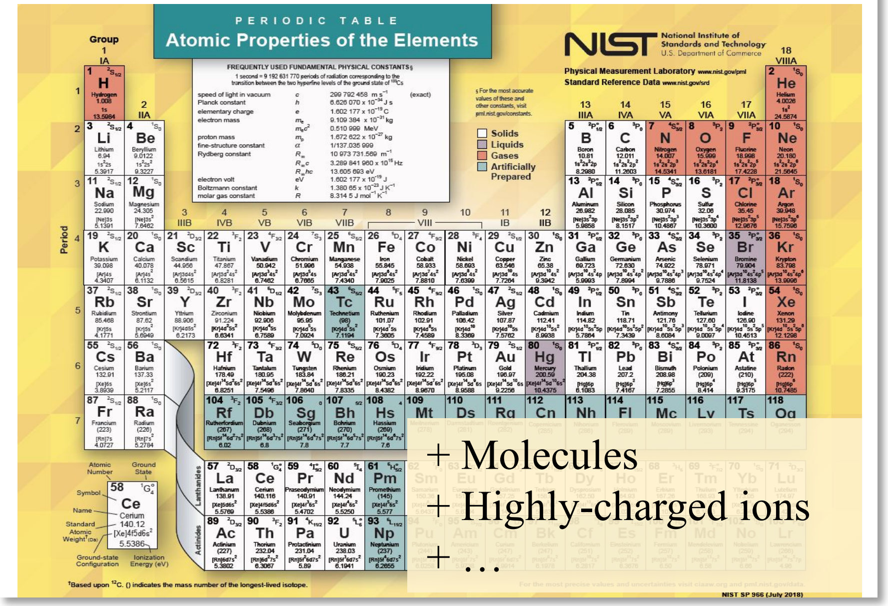
Trends in Precision Frequency Metrology

In recent years, optical frequency measurements have. . .

…improved more than 100x in accuracy



…been applied to a vast array of atomic species



…extended across continental distances

…approached quantum limits in precision

…found numerous applications in fundamental and applied physics

Search for new physics with atoms and molecules

REVIEWS OF MODERN PHYSICS, VOLUME 90, APRIL–JUNE 2018

M. S. Safronova, D. Budker, D. J. Kimball, D. Demille, A. Derevianko, C. W. Clark

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I. Precision measurements with trapped ions
II. <u>Tests of fundamental physics</u>
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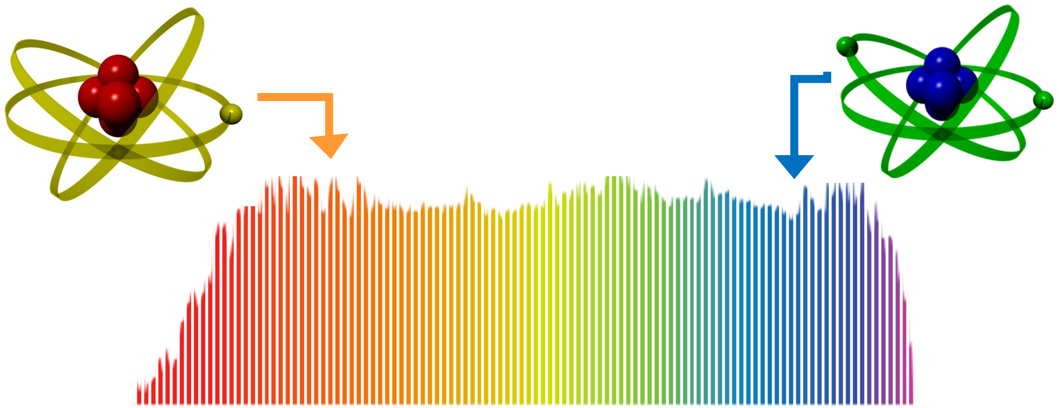
Searching for Spacetime-Variation in Clock Frequencies

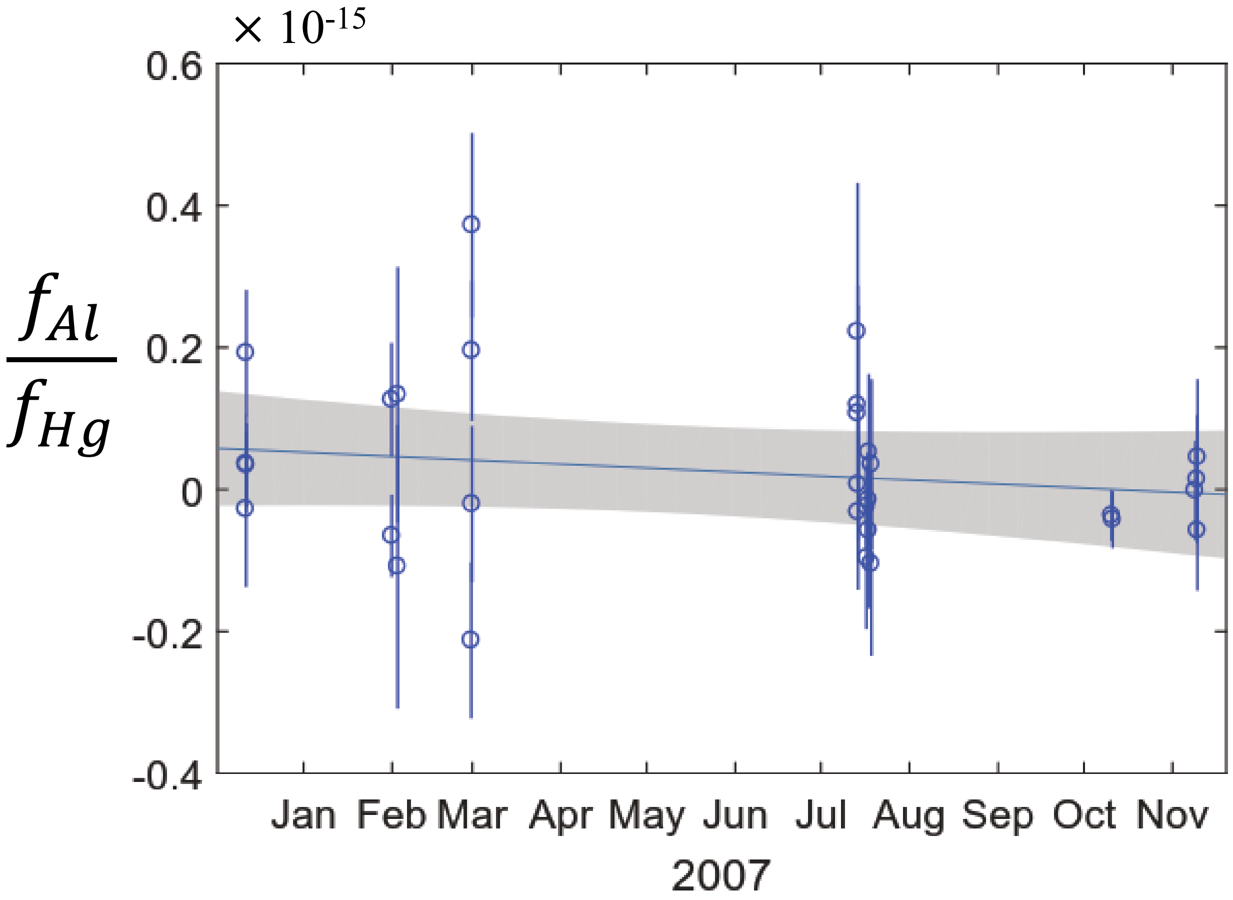


$$R(t) = \frac{\omega_1(t)}{\omega_2(t)}$$

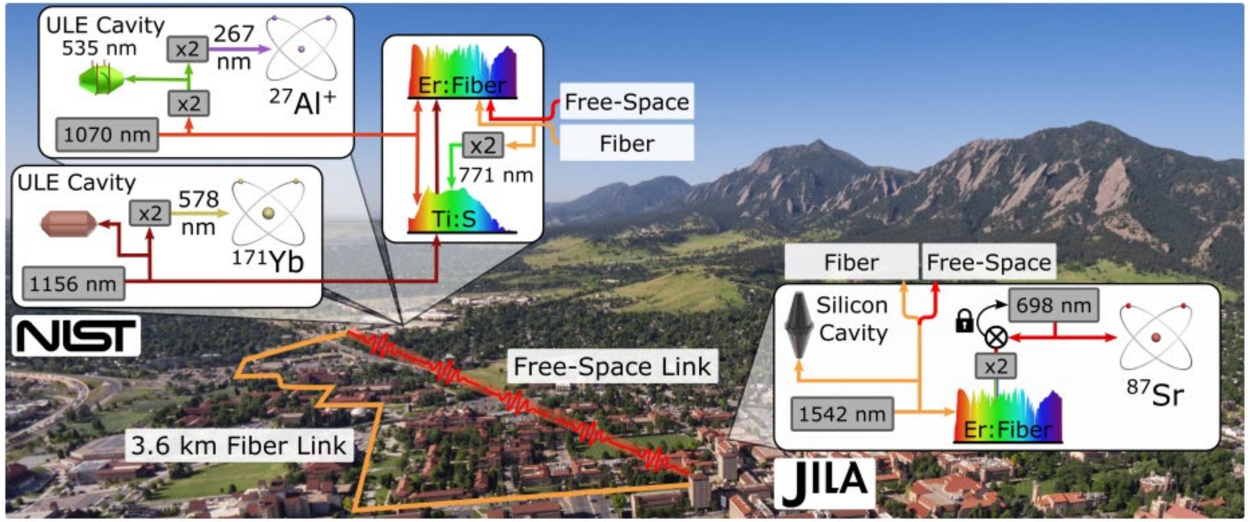
What might cause clock frequencies to vary?

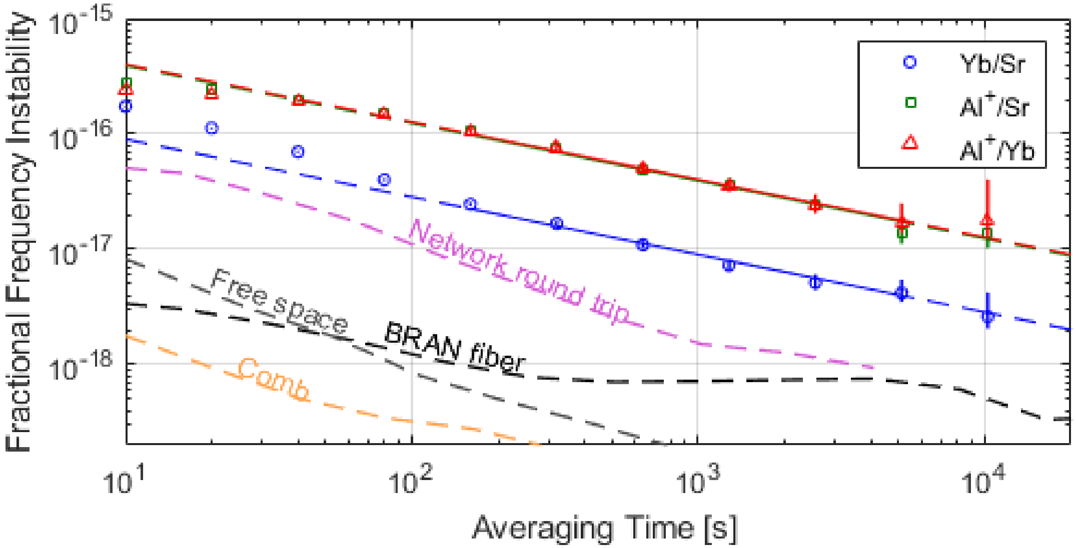
- Drifts in the fundamental constants
- Violations of relativity theory
  - Local position invariance
  - Lorentz invariance
- Coupling to exotic particles or fields
  - Ultralight dark matter (mass ~ 10^{-22} – 10^{-15} eV)

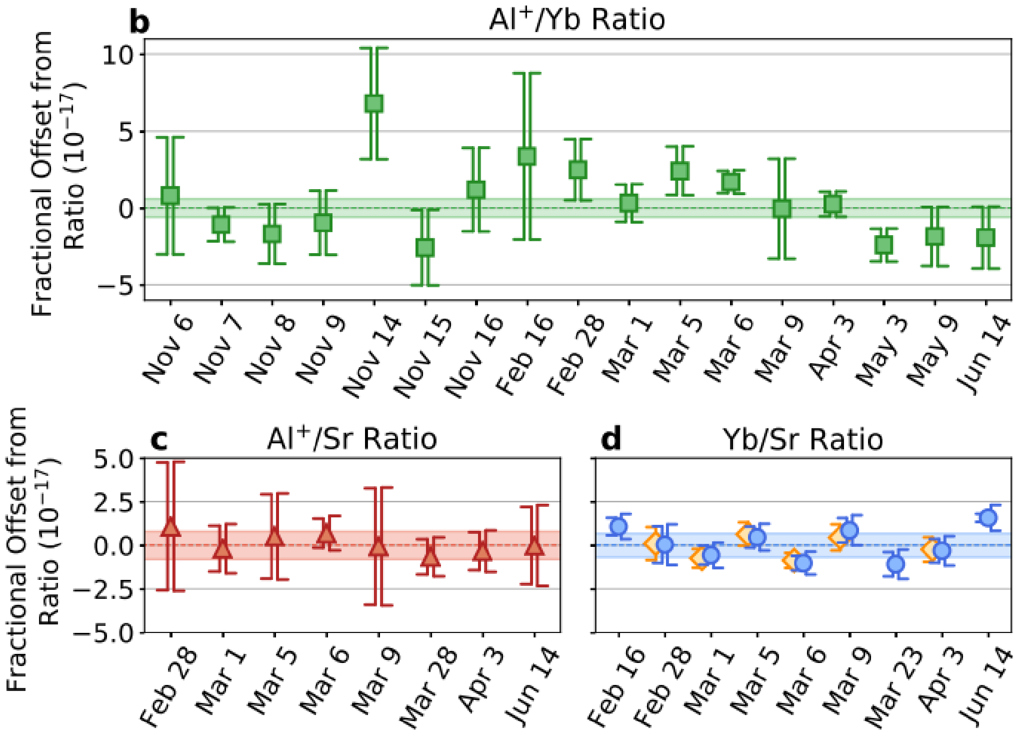
$$\frac{\dot{\alpha}}{\alpha} = (-1.6 \pm 2.3) \times 10^{-17}/\text{year}$$



Boulder Atomic Clock Optical Network







ν_{Al+}/ν_{Yb} = 2.162 887 127 516 663 703(13)

ν_{Al+}/ν_{Sr} = 2.611 701 431 781 463 025(21)

ν_{Yb}/ν_{Sr} = 1.207 507 039 343 337 848 2(82)

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

New Bounds on Ultralight Dark Matter

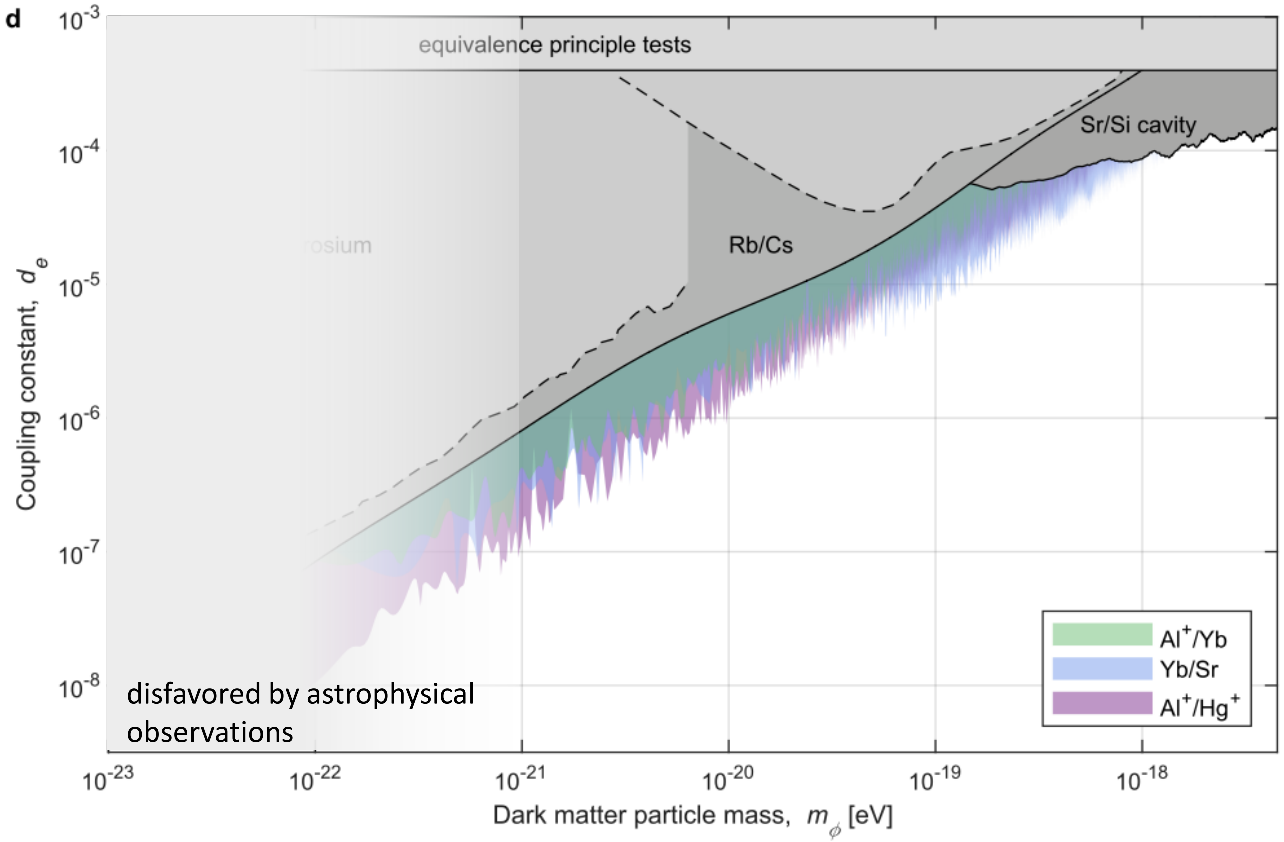
Search for oscillations in the frequency ratio

$$R = R_0 + dR\sin(\omega_{DM}t + \phi_{DM})$$

Compton Frequency: $\omega_{DM} = \frac{m_\phi c^2}{\hbar}$

Atom, transition	A
^{199}Hg+, $^2S_{1/2} \rightarrow {}^2D_{5/2}$	- 3.0
^{27}Al+, $^1S_0 \rightarrow {}^3P_0$	+ 0.0079
^{171}Yb, $^1S_0 \rightarrow {}^3P_0$	+ 0.31
^{87}Sr, $^1S_0 \rightarrow {}^3P_0$	+0.06

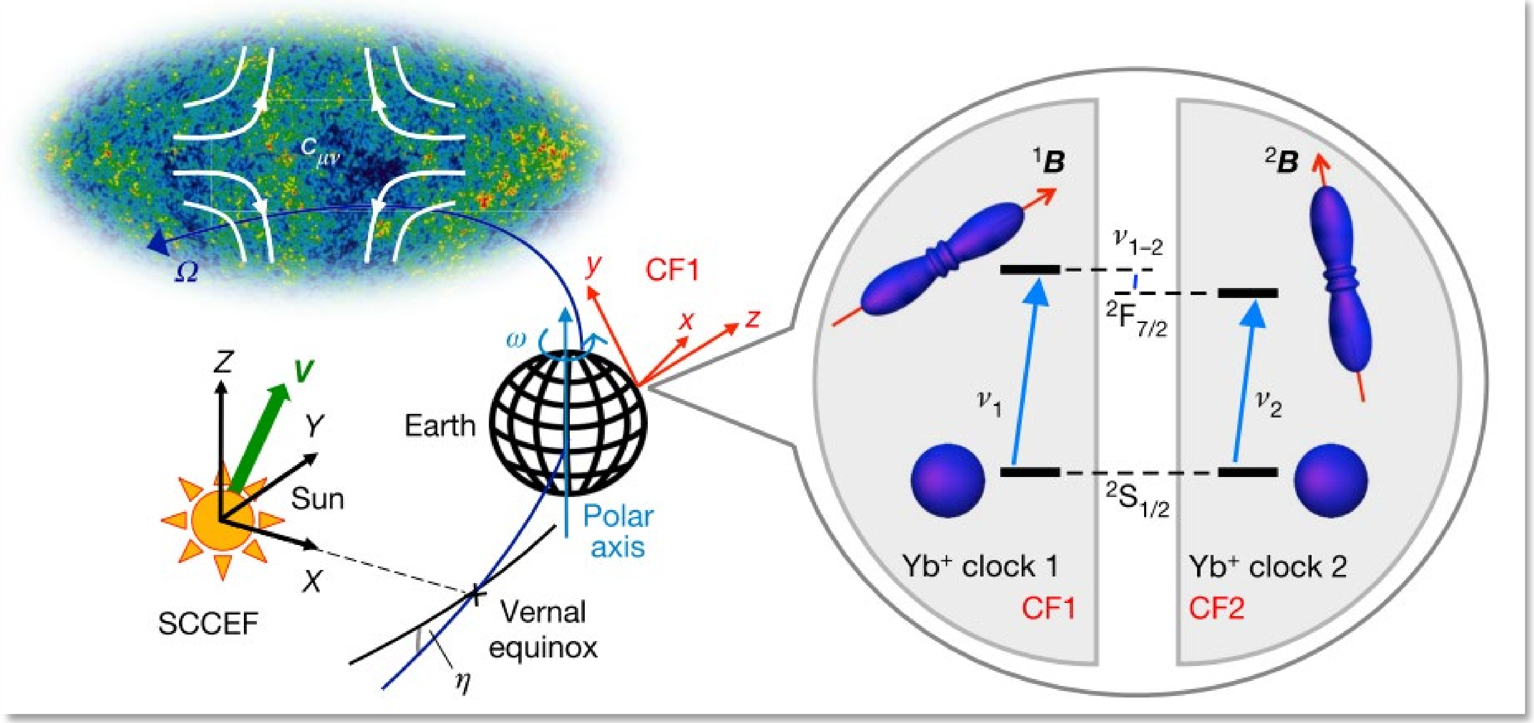
Depends on dark matter density (0.4 GeV/cm^3), coupling constant (d_e) and atom-dependent sensitivity

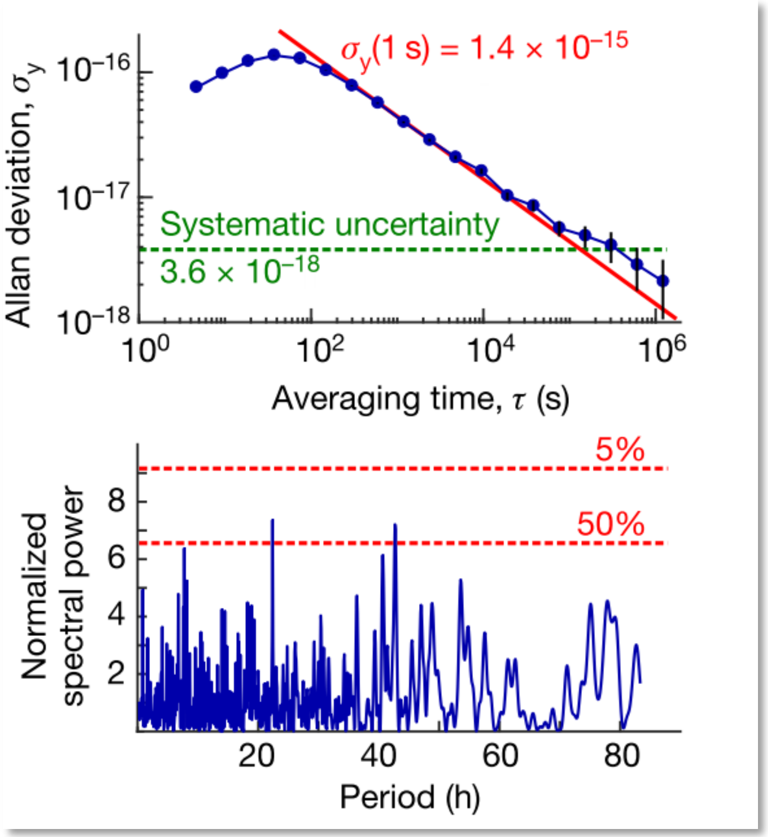


~ 10X improvement over several orders of magnitude in mass

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

Testing Lorentz Symmetry





Sanner *et al.*, Nature 567, 204 (2019)

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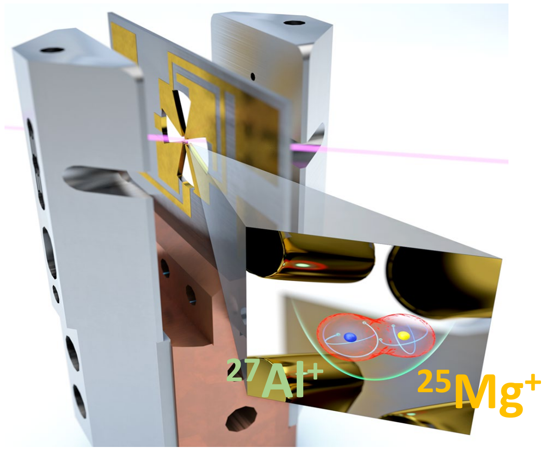
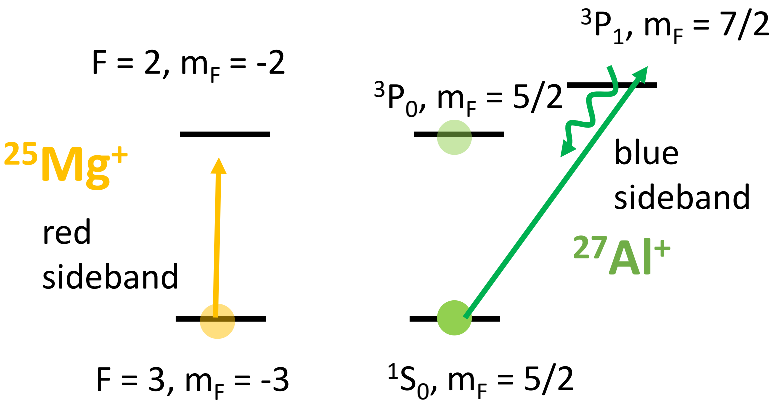
Quantum logic spectroscopy (QLS)

Sympathetic cooling + state detection using a quantum gate

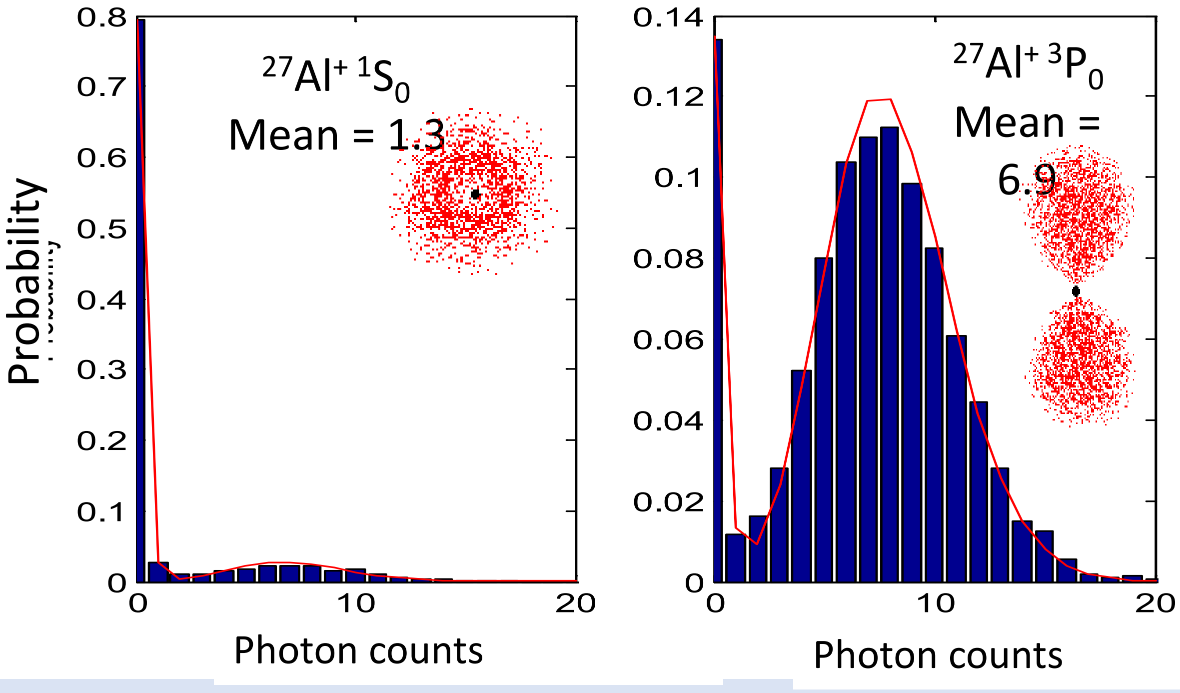


Brewer et al., PRL 123, 033201 (2018)



1. Cool to motional ground-state with qubit
2. Sideband pulse on Al^{+} (excites state-dependent motion)
3. Detect vibrational quantum with qubit

QND measurement can also serve as state preparation



D. J. Wineland, *et al.* *Proc. 6th Symp. Freq. Stds. and Metr. (2001)*

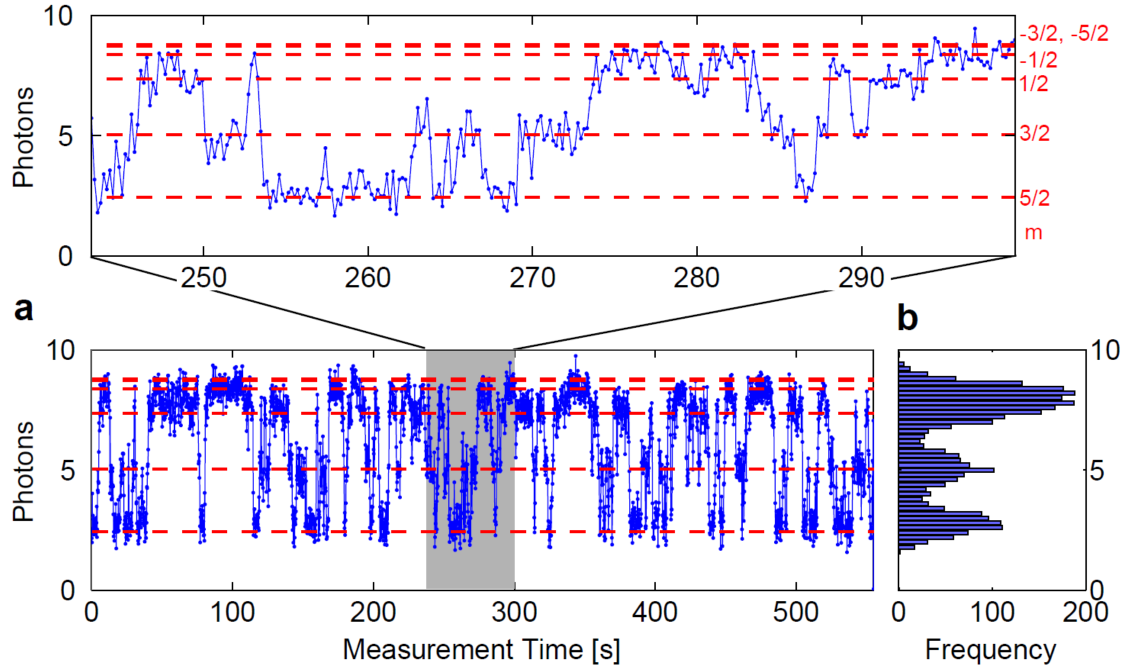
P.O. Schmidt, *et al.* *Science* **309**, 749 (2005)

T. Rosenband, *et al.* PRL **98**, 220801 (2007)

D. B. Hume, *et al.* PRL **99**, 120502 (2007)

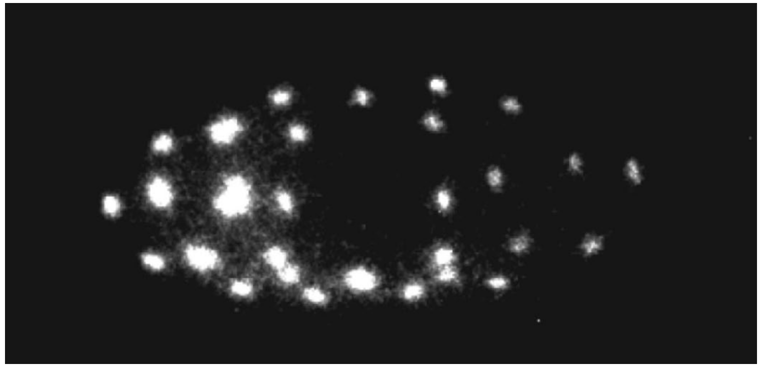
Quantum logic spectroscopy in new systems

Zeeman sublevels in the ground state of Al^+



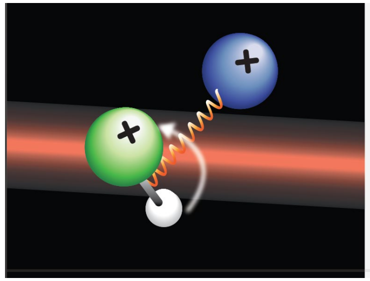
Hume et al., PRL 107 24392 (2011)

Highly-charged ions (here Ar^{13+})



Micke et al., Nature 578, 60 (2020)

Molecular ions (CaH^+, MgH^+)

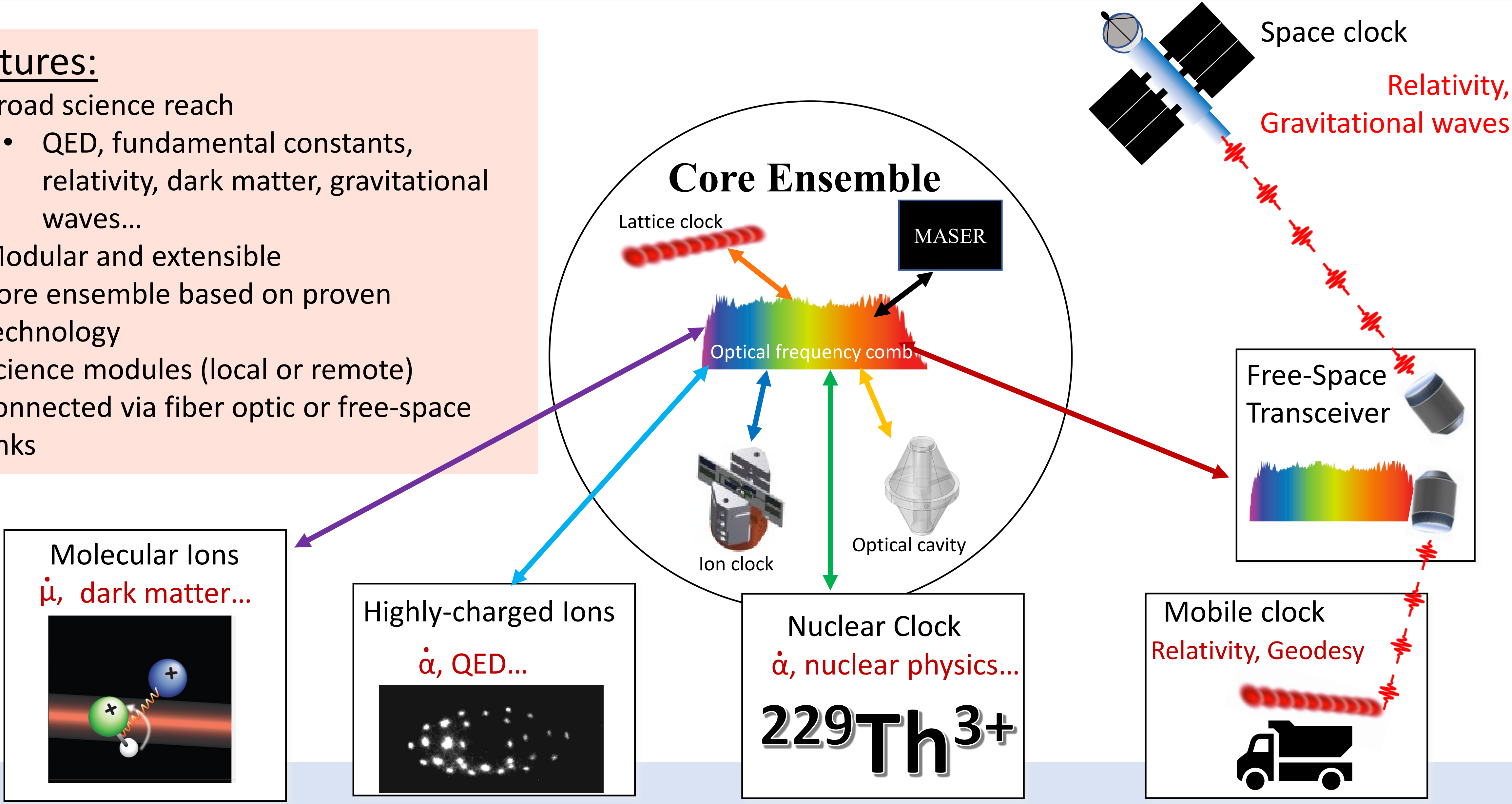


Chou et al., Science 367, 6485 (2020)
Wolf et al., Nature 530, 7591 (2016)

An Atomic Observatory for Fundamental Physics

Features:

- Broad science reach
  - QED, fundamental constants, relativity, dark matter, gravitational waves…
- Modular and extensible
- Core ensemble based on proven technology
- Science modules (local or remote) connected via fiber optic or free-space links



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Improving measurement stability

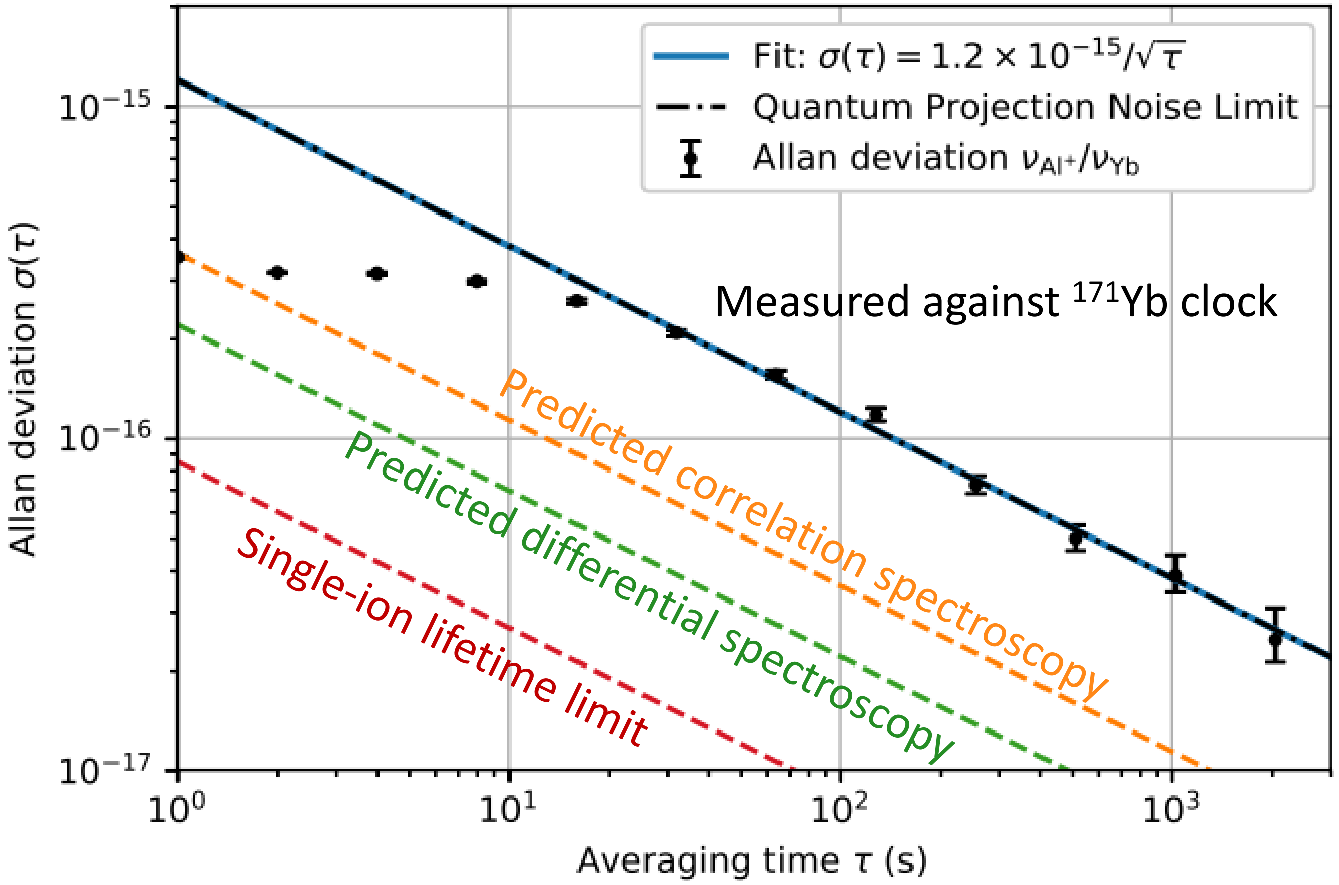
$$\sigma_y(\tau) = \frac{\Delta\nu}{2\pi\nu_0}\frac{1}{\sqrt{N_{atom}}}\sqrt{\frac{T_C}{\tau}}$$

Assuming:

- No technical noise
- Uncorrelated atomic states
- Global addressing

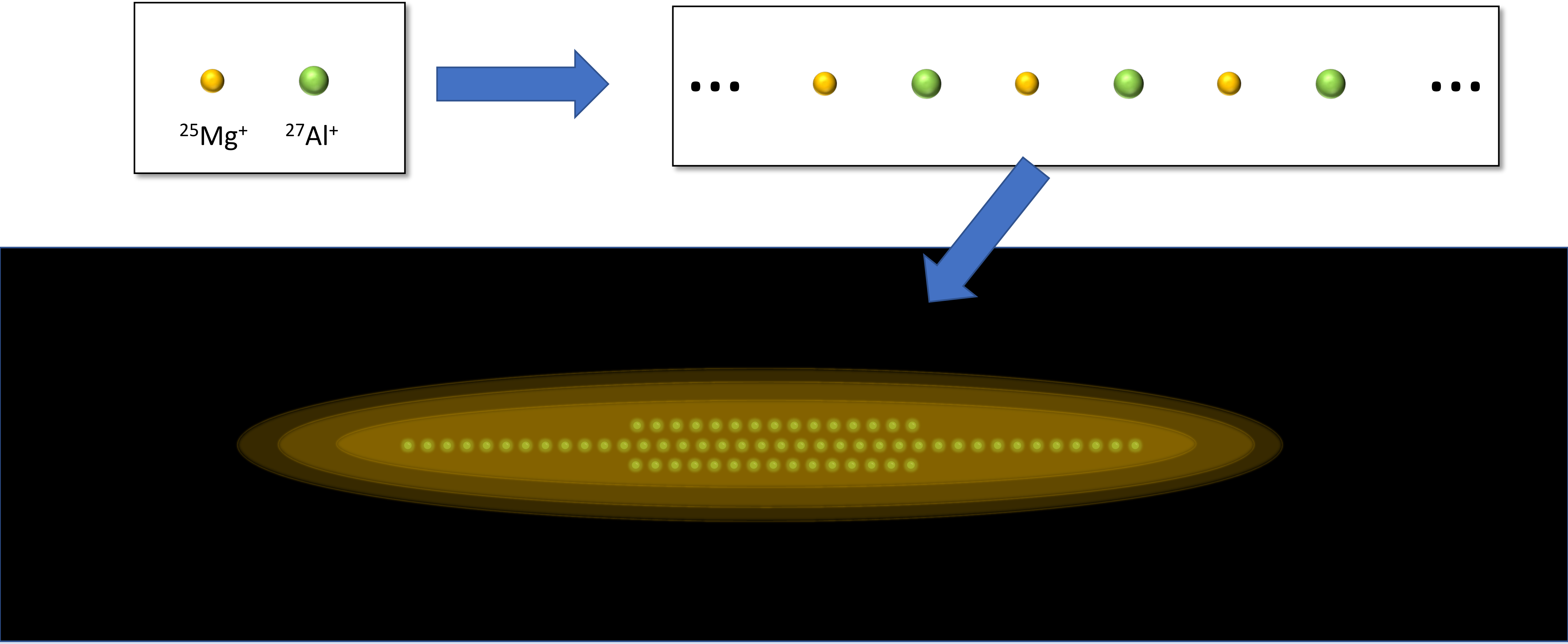
➢ Higher-stability laser
➢ Larger atom number
➢ Longer measurement (more robust operation)

Example of the Al+ optical clock



Brewer et al., PRL 123, 033201 (2018)

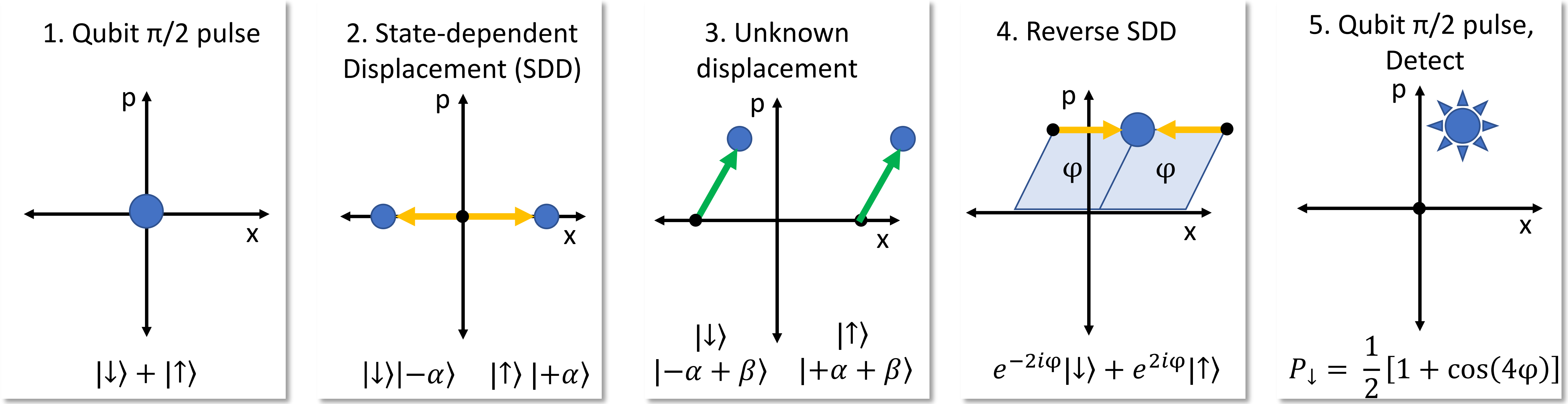
Scaling up Quantum Logic Spectroscopy?



A Schrödinger Cat Interferometer

Sensitive detection of ion motional displacement

Motional phase-space picture



Unknown displacement affects qubit populations via a geometrical phase

Demonstrations/Applications of Cat States

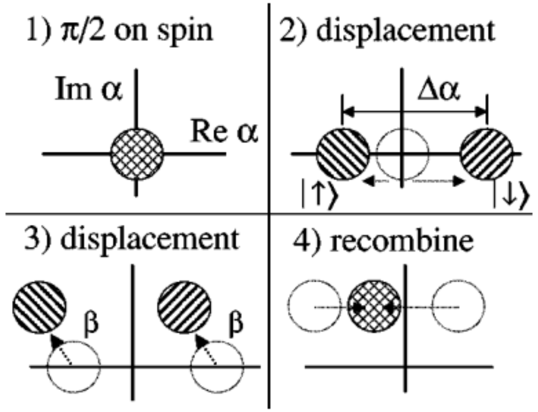
A "Schrödinger Cat" Superposition State of an Atom

C. Monroe,* D. M. Meekhof, B. E. King, D. J. Wineland

$$\psi = \frac{|☺\rangle|\uparrow\rangle + |☹\rangle|\downarrow\rangle}{\sqrt{2}}$$

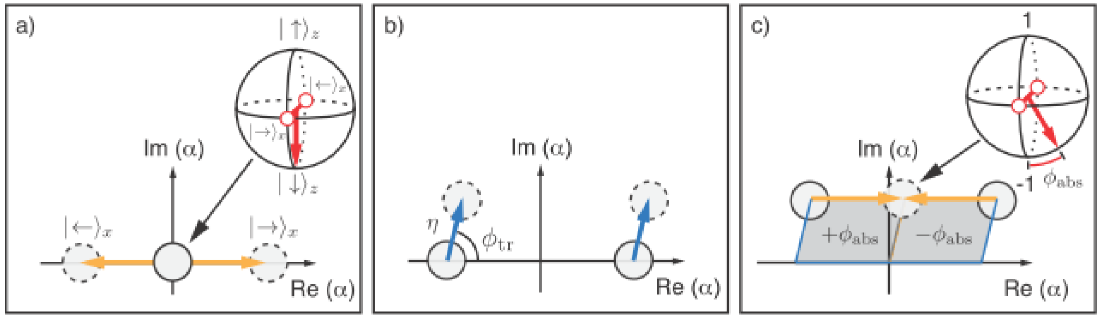
Monroe et al., Science 272, 1131 (1996)

Studying motional decoherence



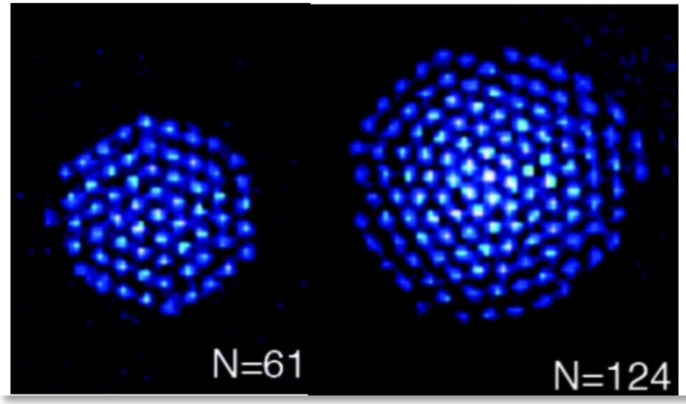
Turchette et al., PRA 62, 053807 (2000)

Detecting single-photon recoils



Benhelm et al., Nat. Phot. 7, 630 (2013)

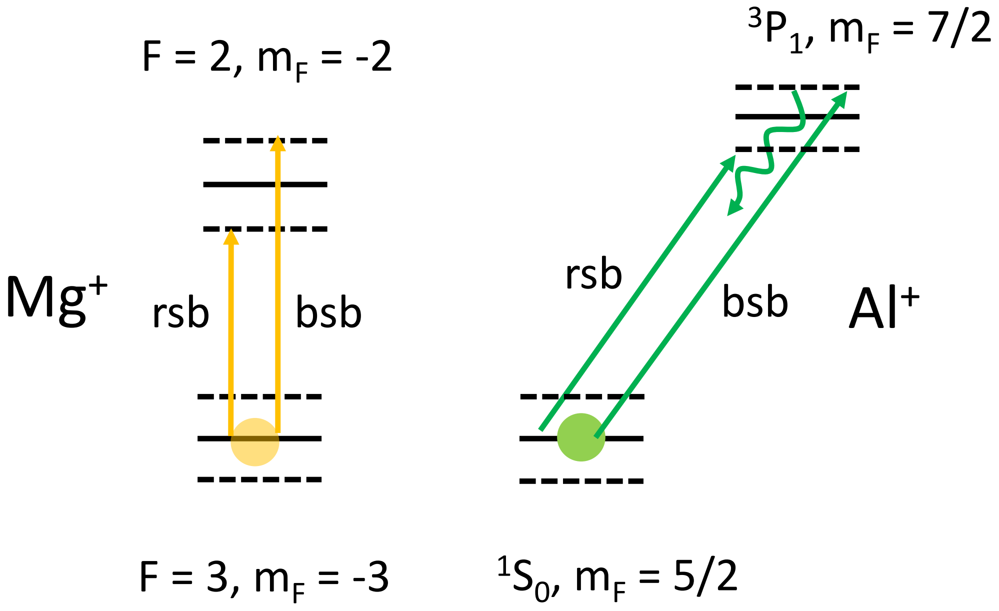
Sensitive force detection

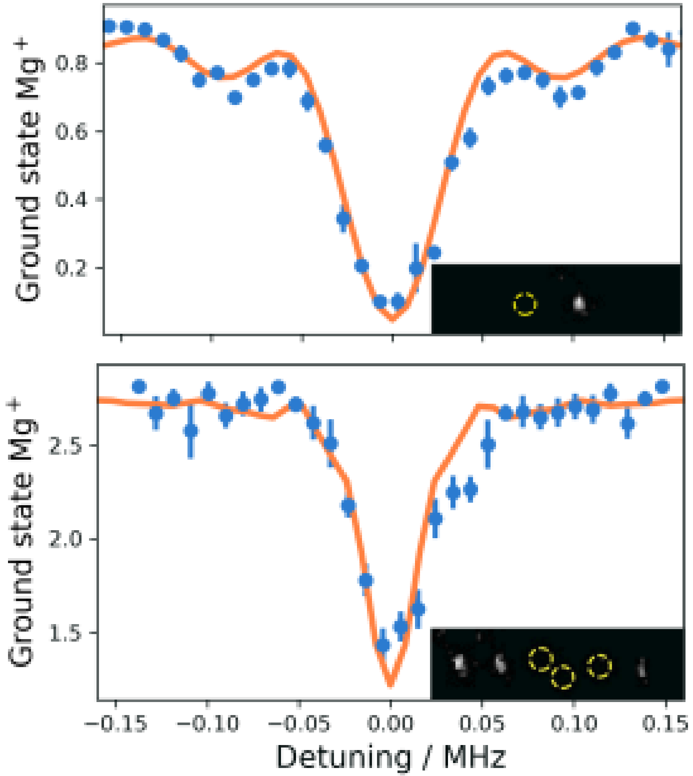


Gilmore et al., PRL **118**, 263602 (2017)

Cat state spectroscopy

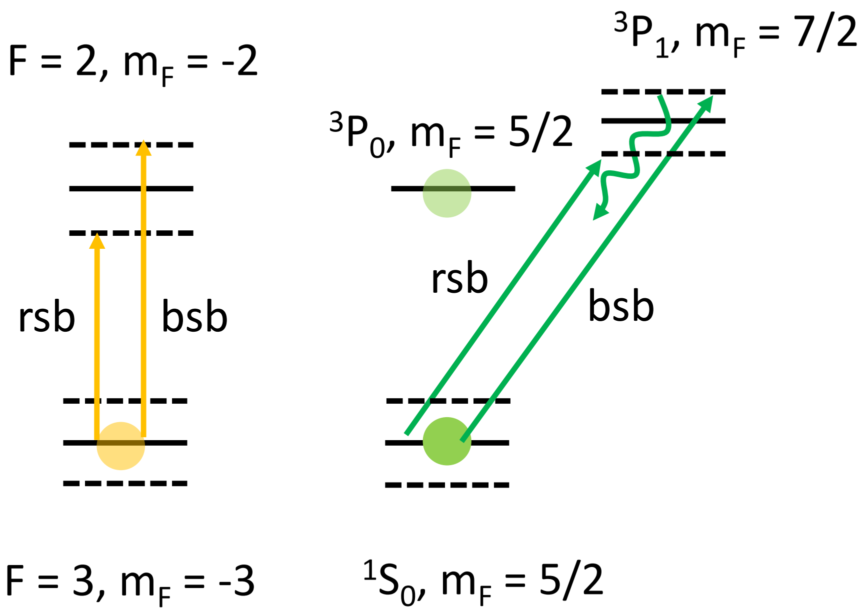
Mg⁺ Cooling	Mg⁺ MS 1 $\varphi_m = 0$	Al⁺ carr. $\frac{\pi}{2}$	Al⁺ MS $\varphi_m = \frac{\pi}{2}$	Mg⁺ MS 2 $\varphi_m = \pi$	Mg⁺ Detection
~ 1 ms	~ 20 us	~ 3 us	~ 20 us	~ 20 us	~ 100 us



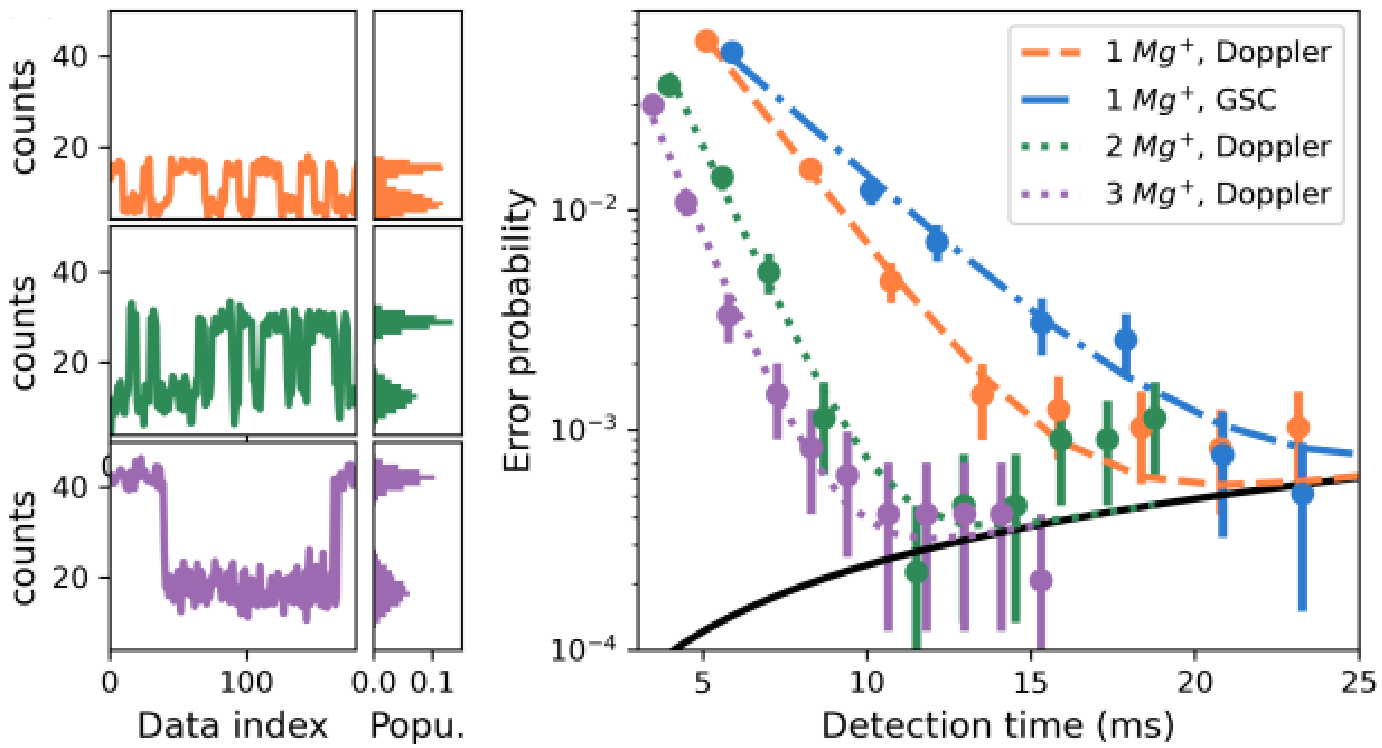


Detection Efficiency

Each qubit ion acts as an independent detector of the clock ion state



State detection is more efficient at the Doppler limit

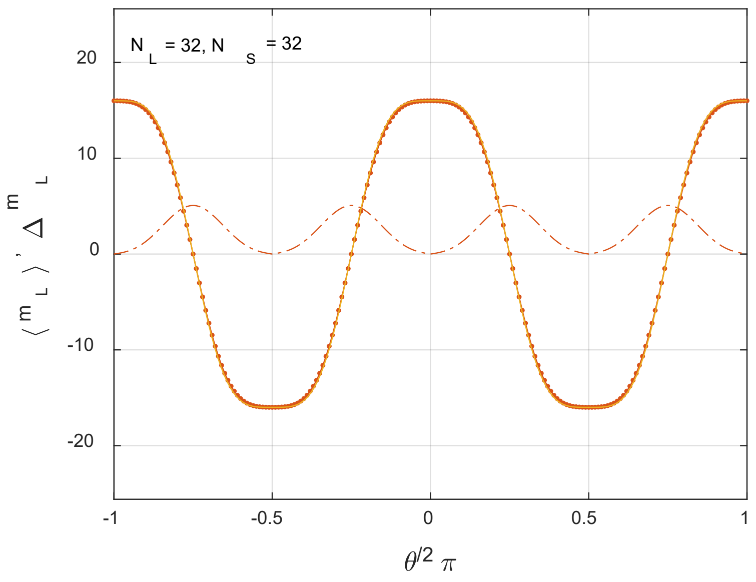


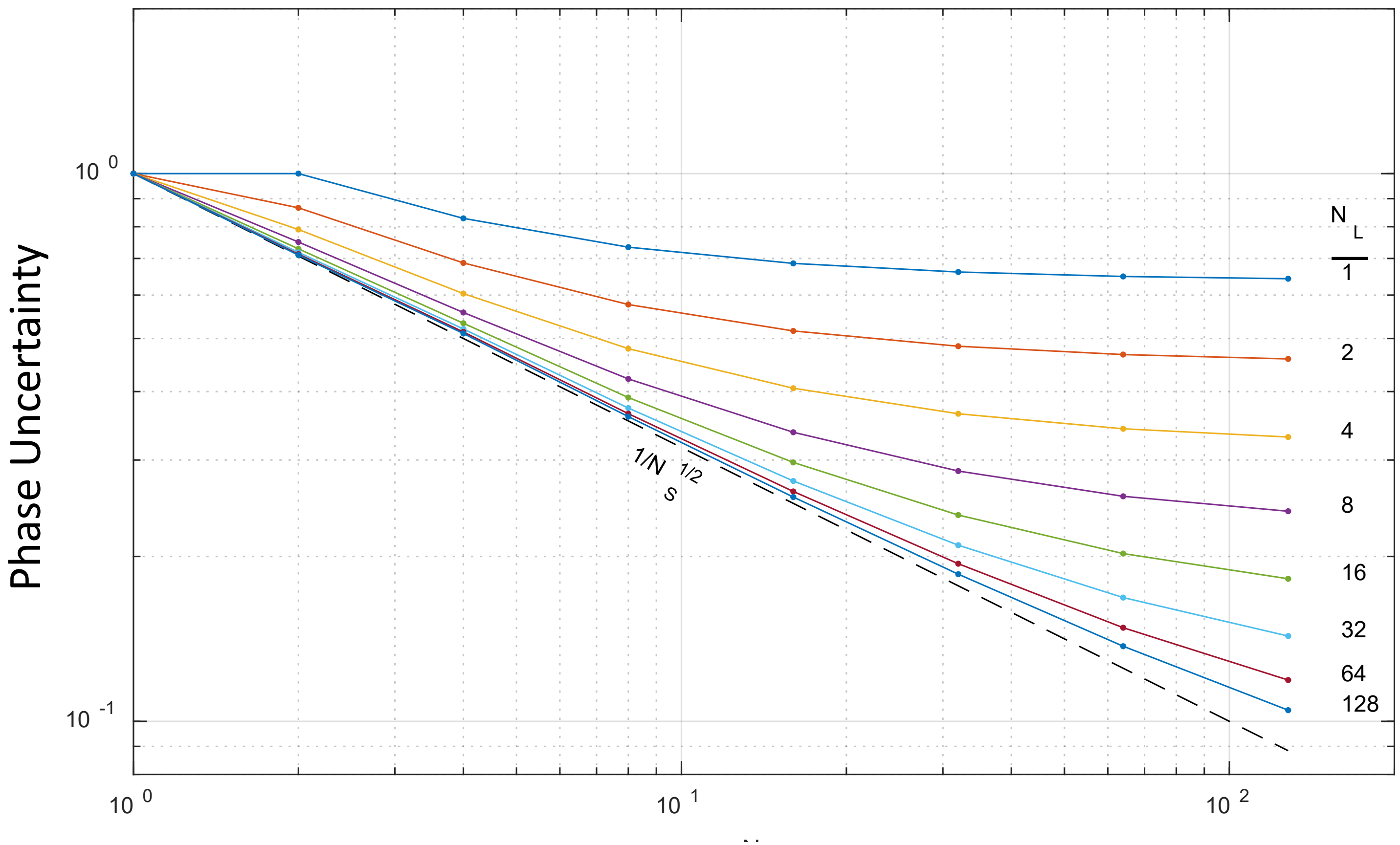
Reaching the Projection Noise Limit

Both the spectroscopy ions and the logic ions will contribute to the projection noise

N_L: number of "logic ions"
N_S: number of "spectroscopy ions"

32 ion Ramsey experiment





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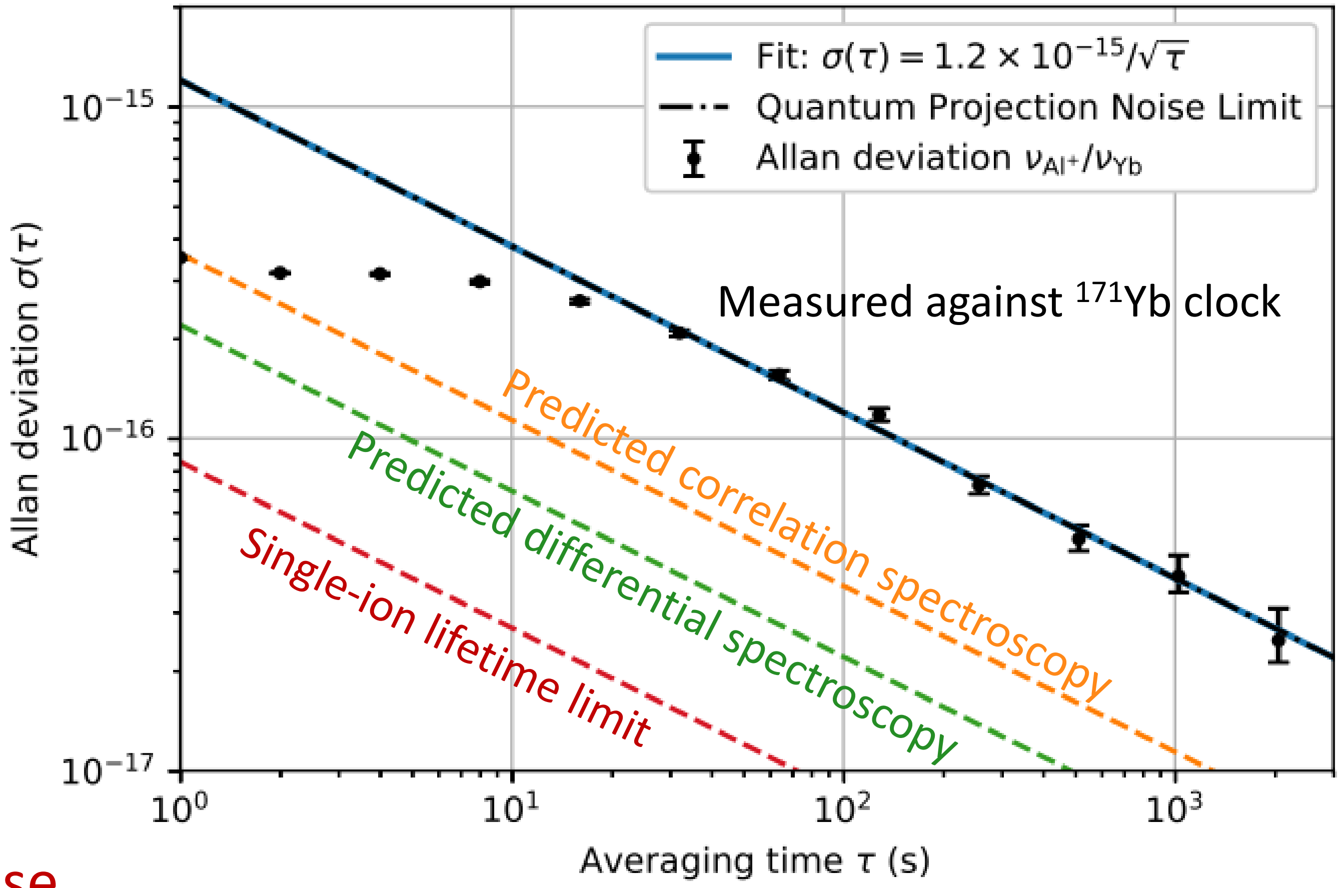
Assuming:

- No technical noise
- Uncorrelated atomic states
- Global addressing

- ➢ Higher-stability laser
- ➢ Larger atom number
- ➢ Longer measurement (more robust operation)
- ➢ New techniques to mitigate laser noise

Example of the Al+ optical clock

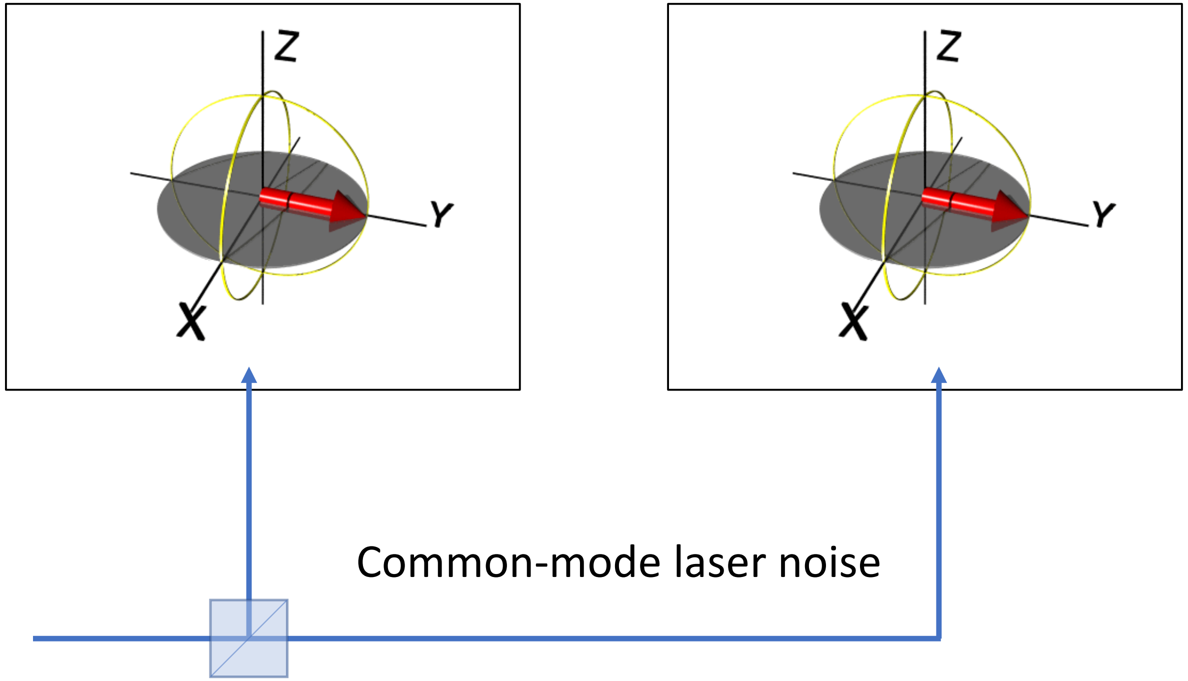


Brewer et al., PRL 123, 033201 (2018)

Probing Beyond the Laser Coherence Time I

Synchronized laser pulses

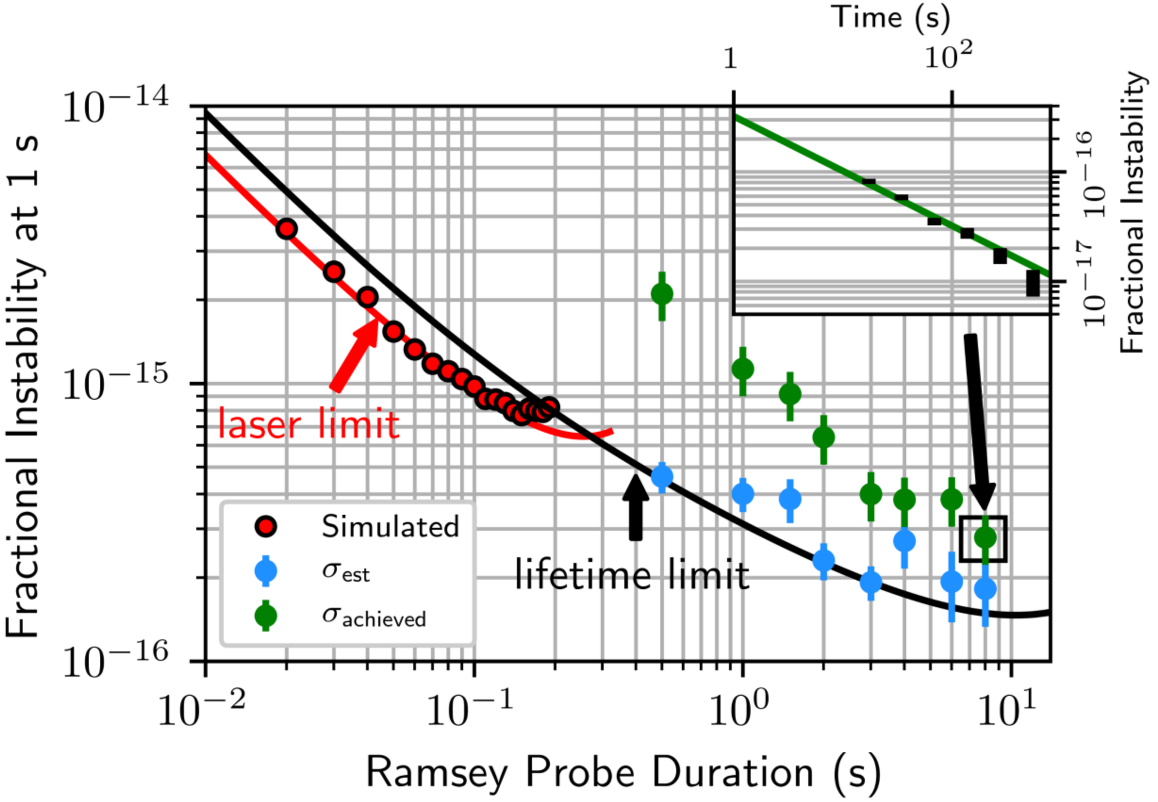
Clock A:	$\pi/2$	Free evolution T	$\pi/2$	Detect
Clock B:	$\pi/2$	Free evolution T	$\frac{\pi}{2}+\phi$	Detect



Clements *et al.* PRL 125, 243602 (2020)

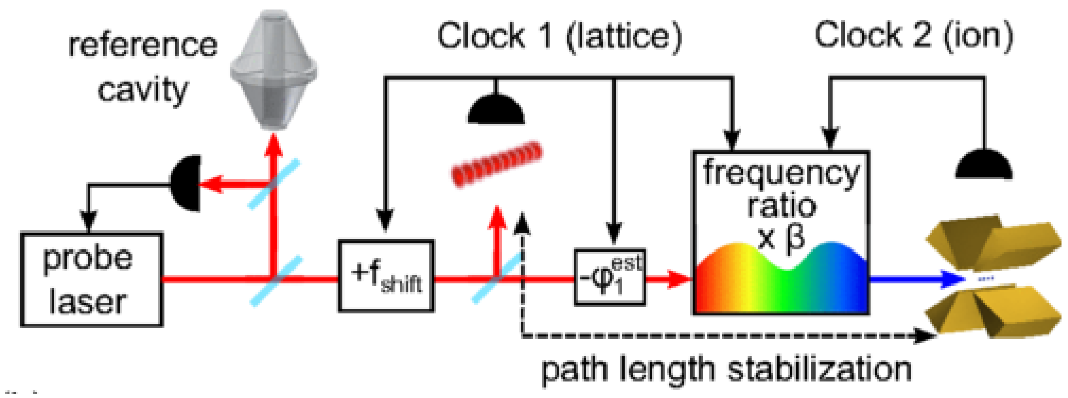
$$\frac{1}{2}\left(\cancel{|\downarrow\downarrow\rangle + |\uparrow\uparrow\rangle} + \overbrace{|\downarrow\uparrow\rangle + |\uparrow\downarrow\rangle}^{\text{Decoherence free subspace}}\right)$$

Measure 2-atom parity after second $\pi/2$ pulse

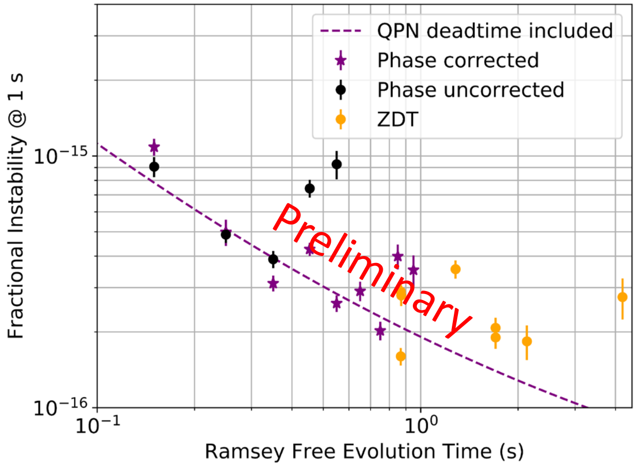


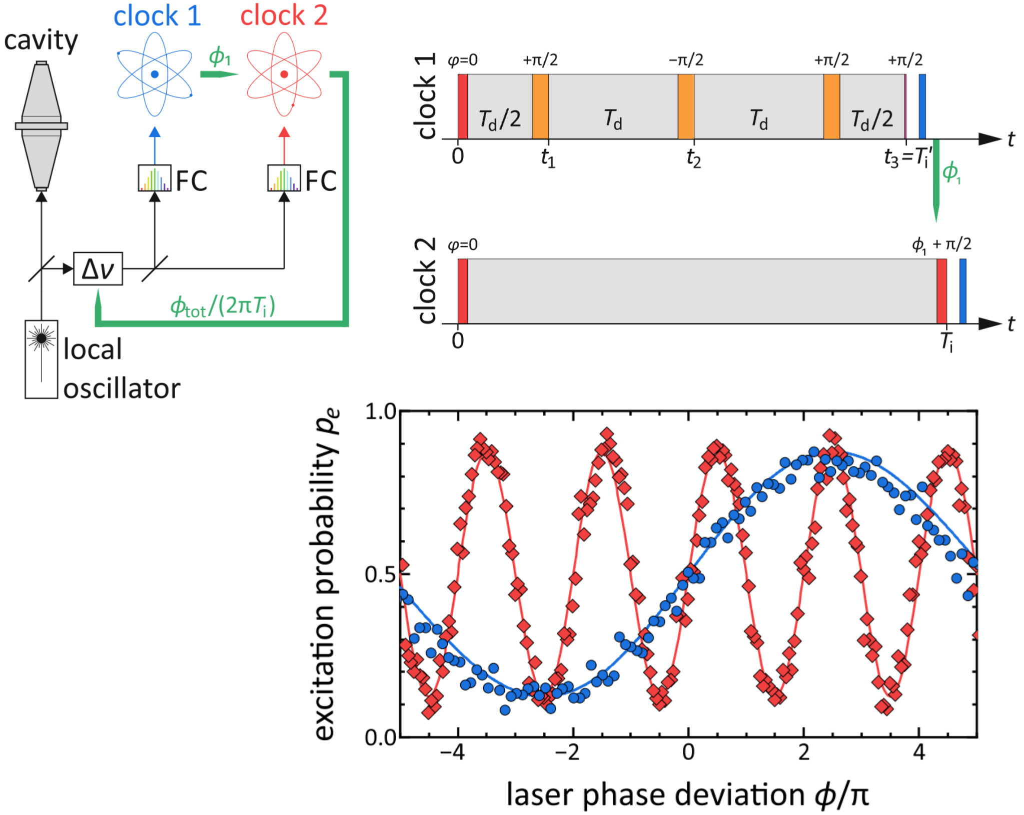
Probing Beyond the Laser Coherence Time IV

Comparisons between different clock species?



Hume PRA 93, 032138 (2016)





Doerscher Comm. Phys. 3, 185 (2020)

Thanks!

University of Colorado
Boulder