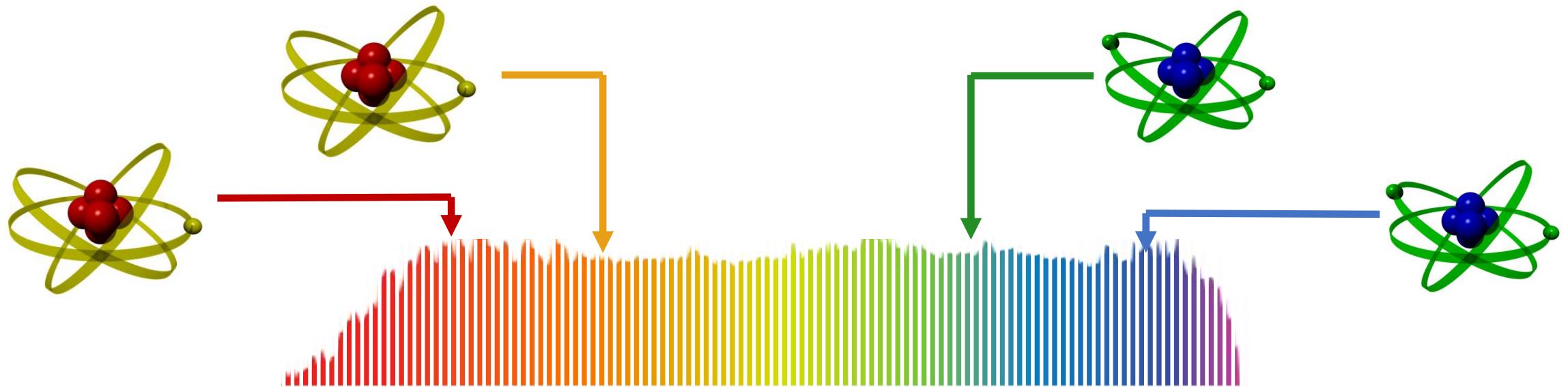


Quantum-Limited Measurements with Optical Clocks

David Hume, **NIST** *Ion Storage Group*

ECFA Detector R&D Roadmap Symposium

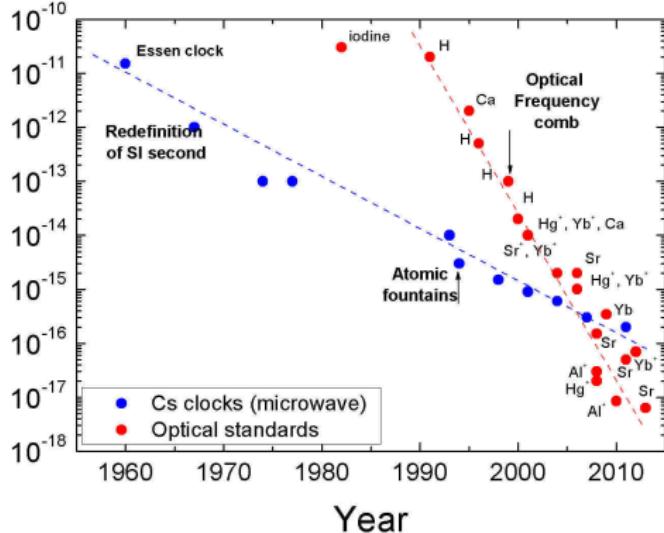
April 12, 2021



Background: Precision Frequency Metrology

In recent years, optical frequency measurements have . . .

...improved more than 100x in accuracy



...approached quantum limits in precision



...been applied to a vast array of atomic species

+ Molecules
+ Highly-charged ions
+ ...

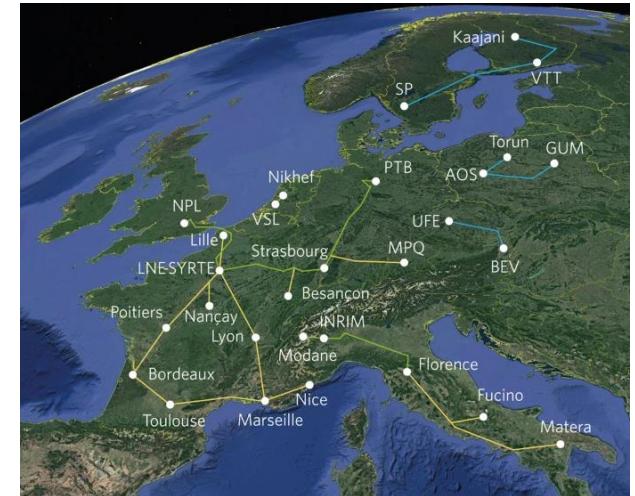
...found numerous applications in fundamental and applied physics

Search for new physics with atoms and molecules

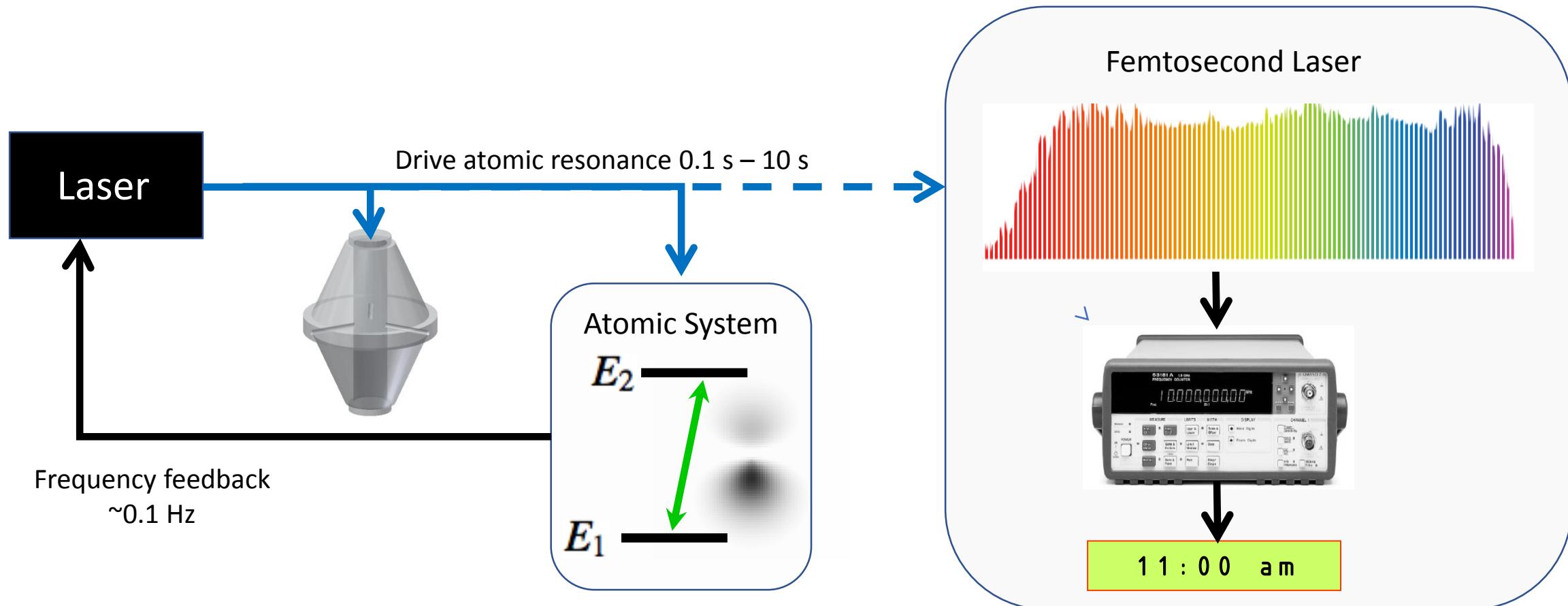
REVIEWS OF MODERN PHYSICS, VOLUME 90, APRIL–JUNE 2018

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

...extended across continental distances



Principle of Optical Clocks



$$\text{Clock frequency: } f_0 = \frac{E_2 - E_1}{\hbar} \approx 10^{15} \text{ Hz}$$

Scope of Optical Clock Efforts Worldwide



- Numerous clocks with performance beyond Cesium standards (many candidate atoms)
- Regional networks of ultrastable optical links (optical fiber + free-space)
- Transportable standards, space-based clocks
- More exotic systems (Highly-charged ions, thorium nuclear transition, molecules...)
- New control and measurement techniques (quantum logic spectroscopy, spin-squeezing...)
- Applications: Relativistic geodesy, tests of fundamental physics

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

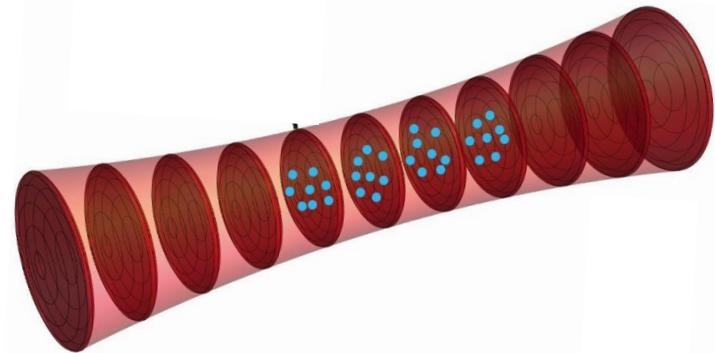
Stability

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

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

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

Optical Lattice Clocks and Trapped Ion Clocks



- Magic wavelength optical lattice
- Typically, 1000s of atoms
- Laser cooled to uK temperatures
- Dominant systematics:
blackbody radiation, lattice light shifts

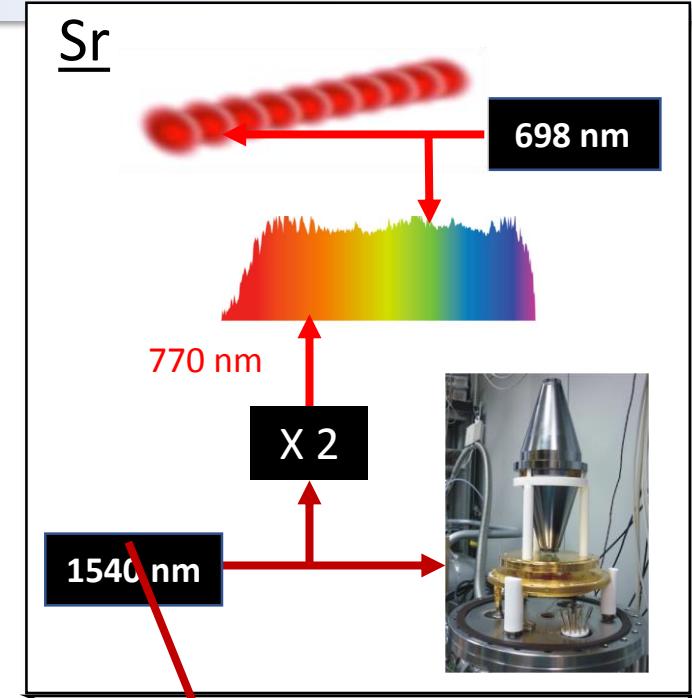
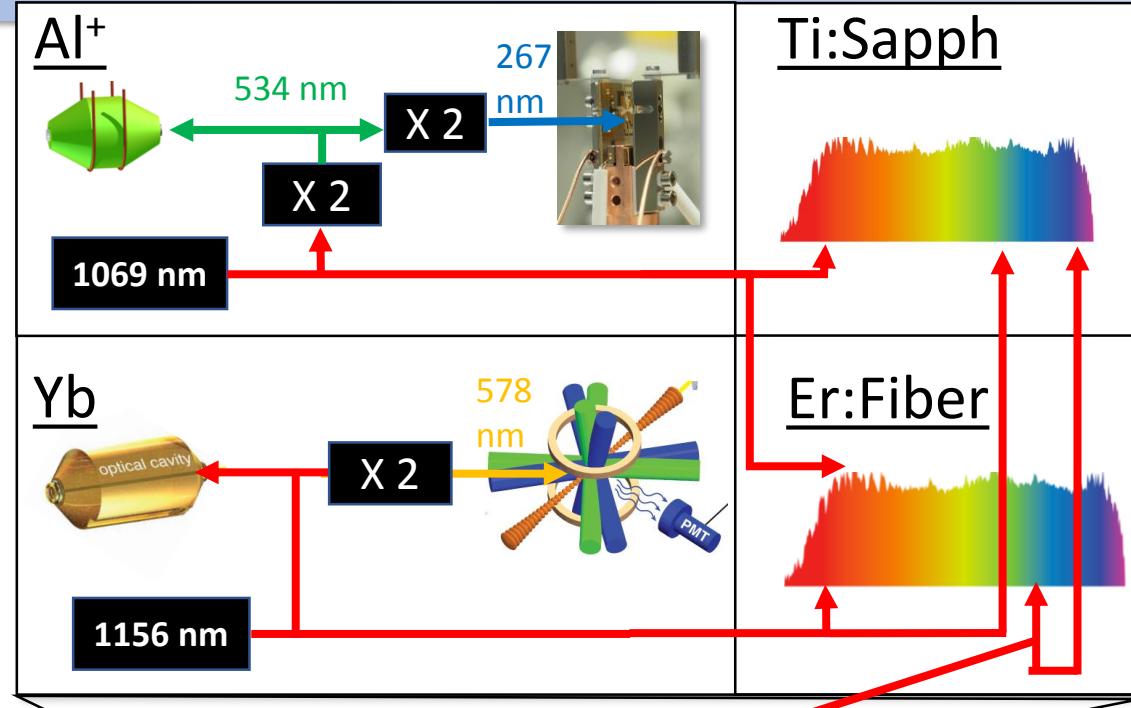
More atoms = higher stability



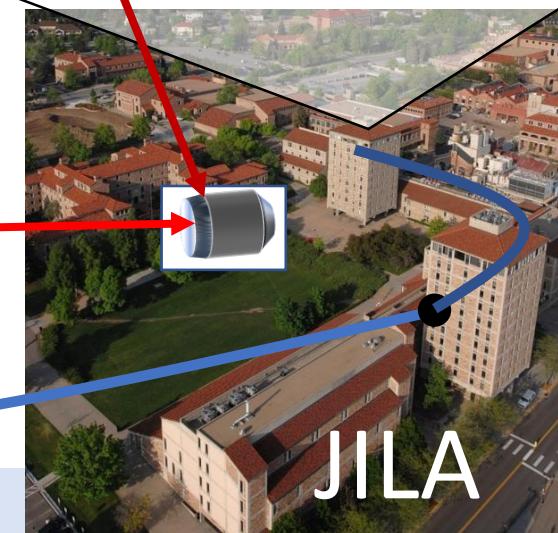
- RF Paul trap
- Typically, single ions
- Can be cooled to ground state
- Dominant systematics: 2nd-order Doppler, blackbody radiation

Applicable to any ionic species

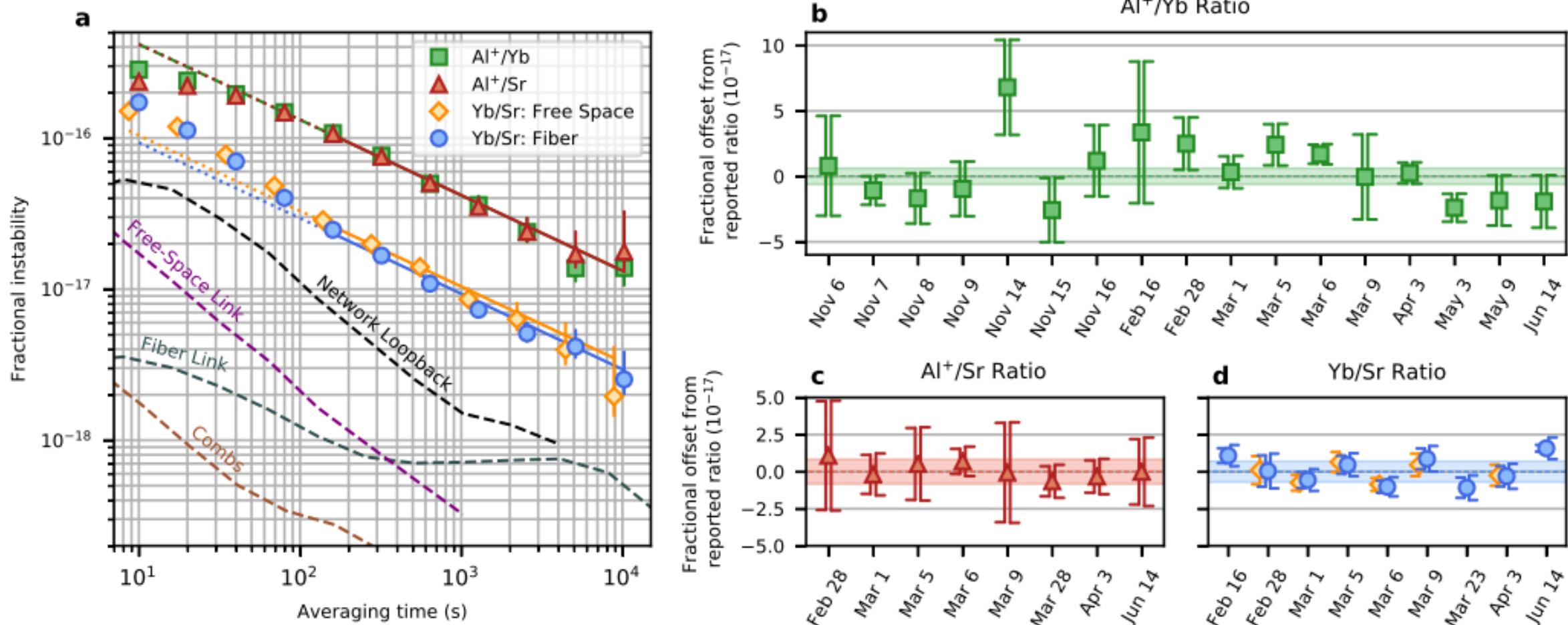
Boulder Atomic Clock and Optical Network



1.5 km
Fiber Frequency Transfer



BACON Measurement Campaign



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

BACON results

$$\frac{\nu_{Al^+}}{\nu_{Yb}} = 2.162\ 887\ 127\ 516\ 663\ 703(13)$$

$$\frac{\nu_{Al^+}}{\nu_{Sr}} = 2.611\ 701\ 431\ 781\ 463\ 025(21)$$

$$\frac{\nu_{Yb}}{\nu_{Sr}} = 1.207\ 507\ 039\ 343\ 337\ 848\ 2(82)$$

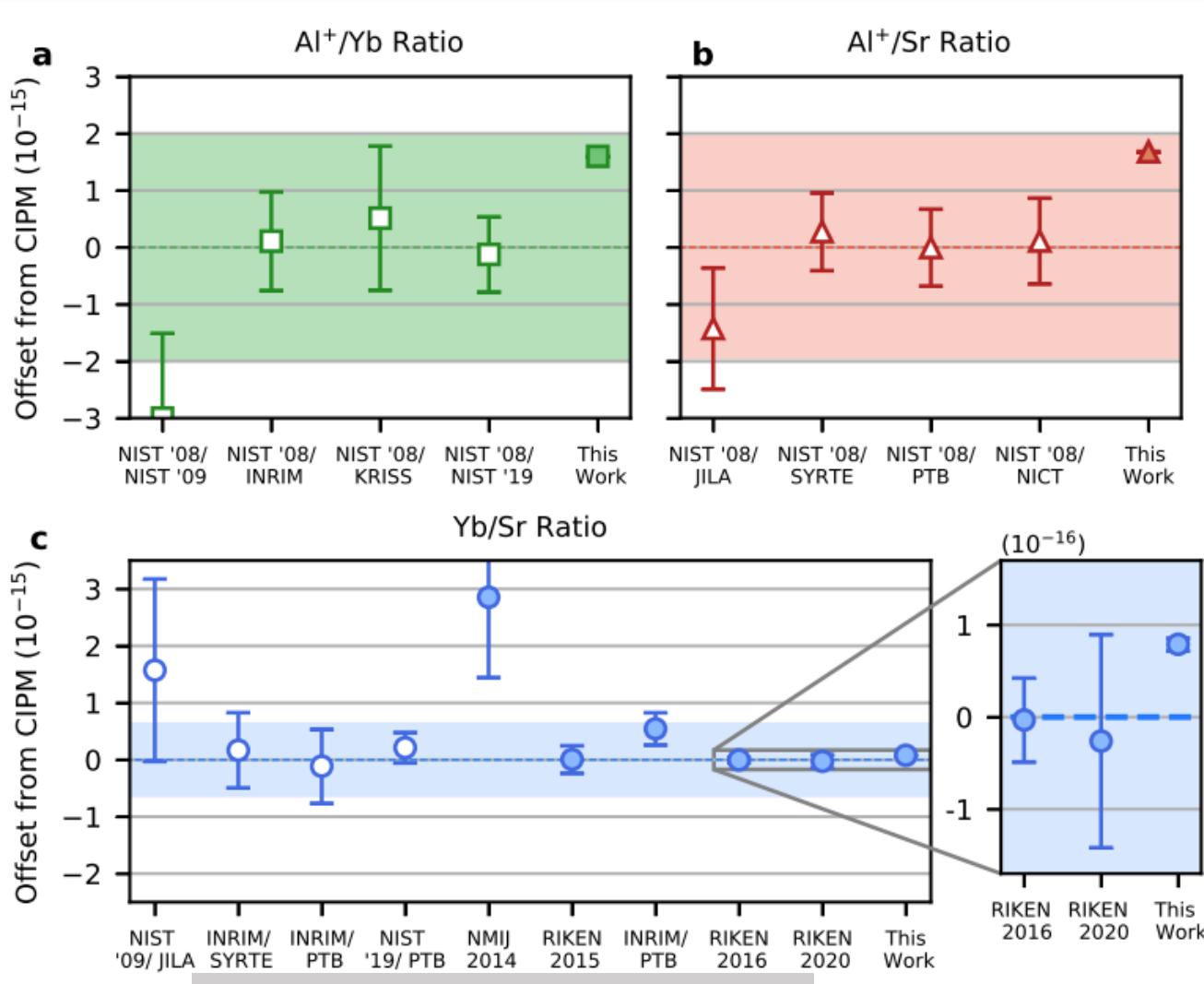
$$\frac{\Delta R_{Al^+/Yb}}{R_{Al^+/Yb}} = 5.9 \times 10^{-18}$$

$$\frac{\Delta R_{Al^+/Sr}}{R_{Al^+/Sr}} = 8.0 \times 10^{-18}$$

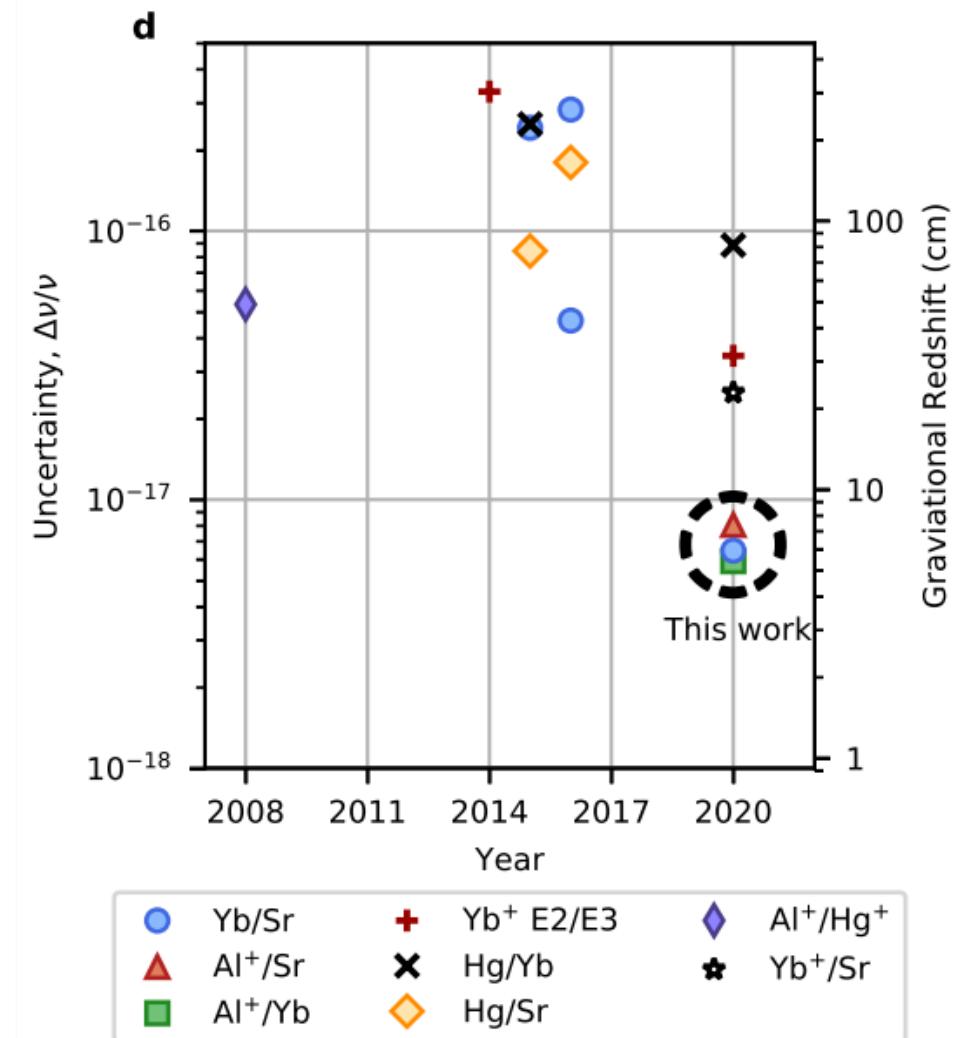
$$\frac{\Delta R_{Yb/Sr}}{R_{Yb/Sr}} = 6.8 \times 10^{-18}$$

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

Comparison with World Data



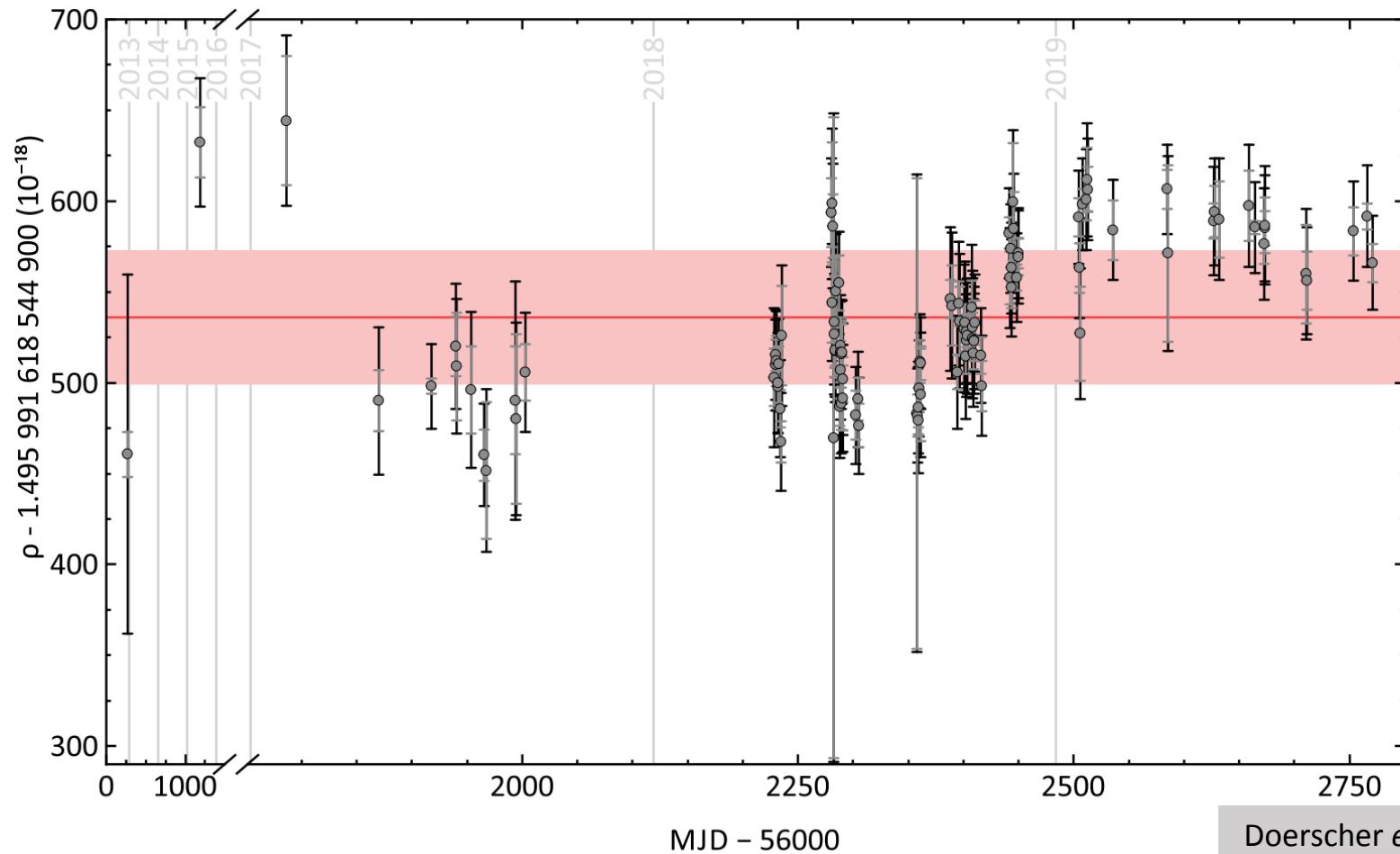
Belyov *et al.*, Nature 591, 564 (2021)



Yb^+/Sr comparison at PTB

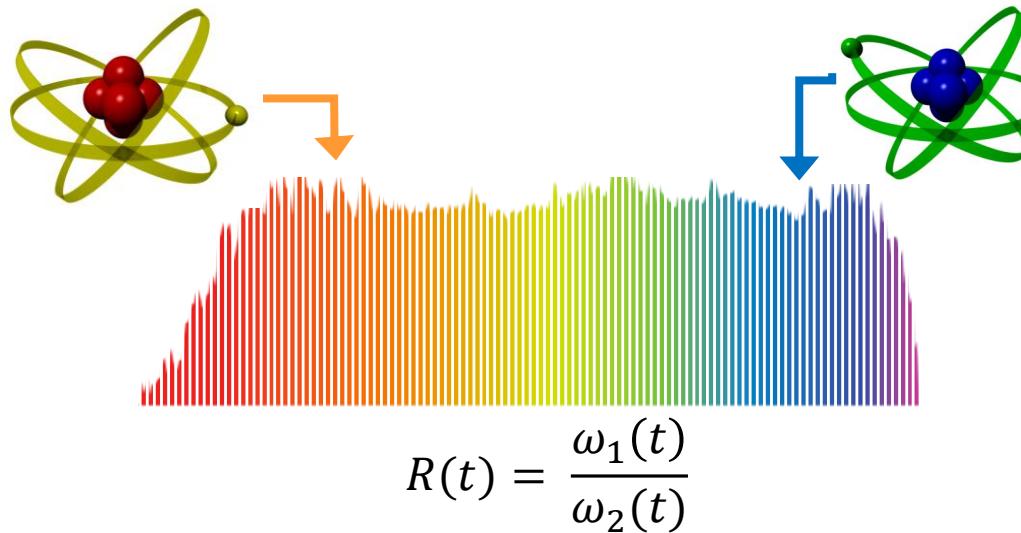
$$\frac{\nu_{\text{Yb}^+}}{\nu_{\text{Sr}}} = 1.495\ 991\ 618\ 544\ 900\ 537(38)$$

$$\frac{\Delta R_{\text{Yb}^+/\text{Sr}}}{R_{\text{Yb}^+/\text{Sr}}} = 2.5 \times 10^{-17}$$



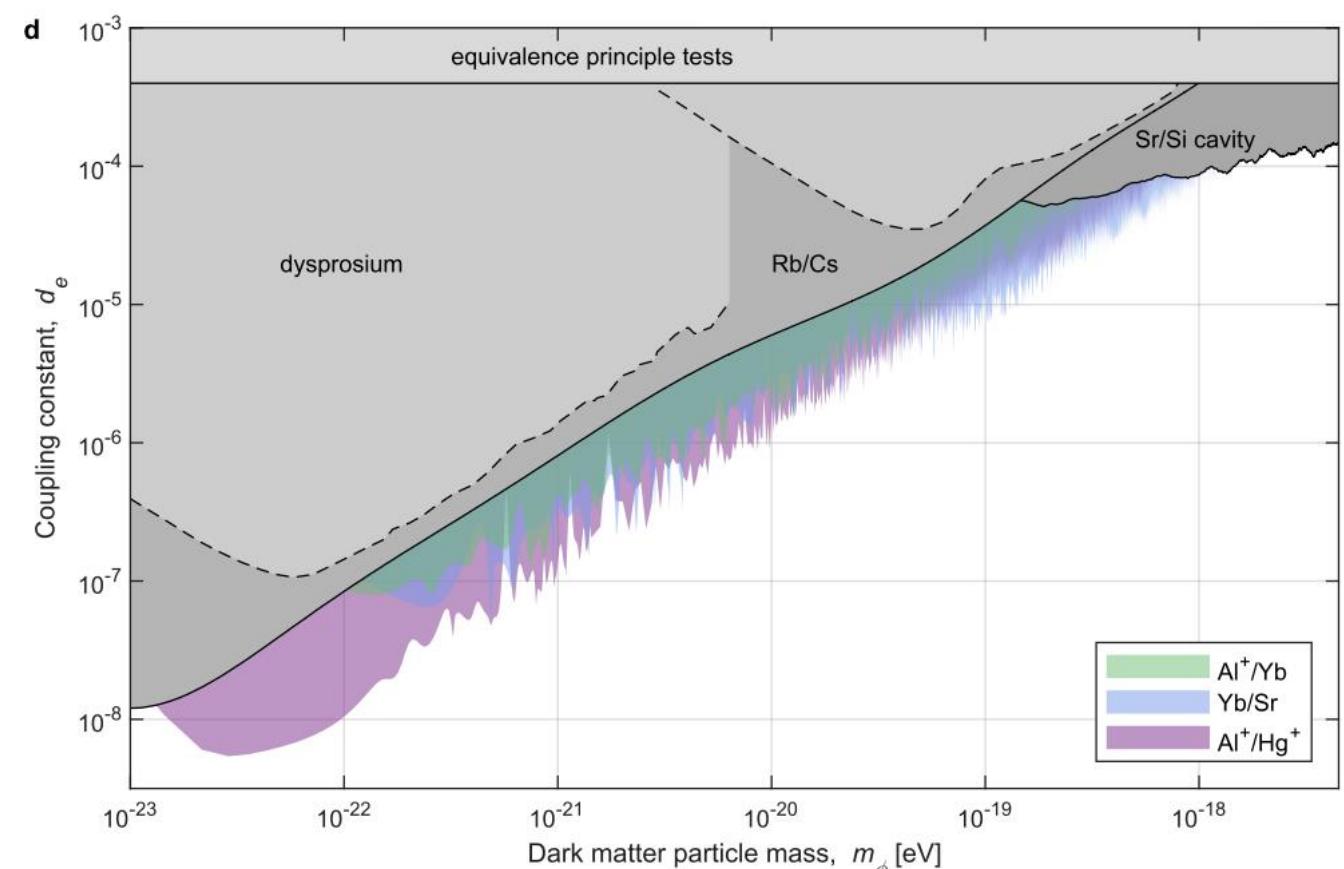
Doerscher *et al.*, Metrologia 58, 015005 (2021)

Searching for Spacetime-Variation in Clock Frequencies



What might cause clock frequencies to vary?

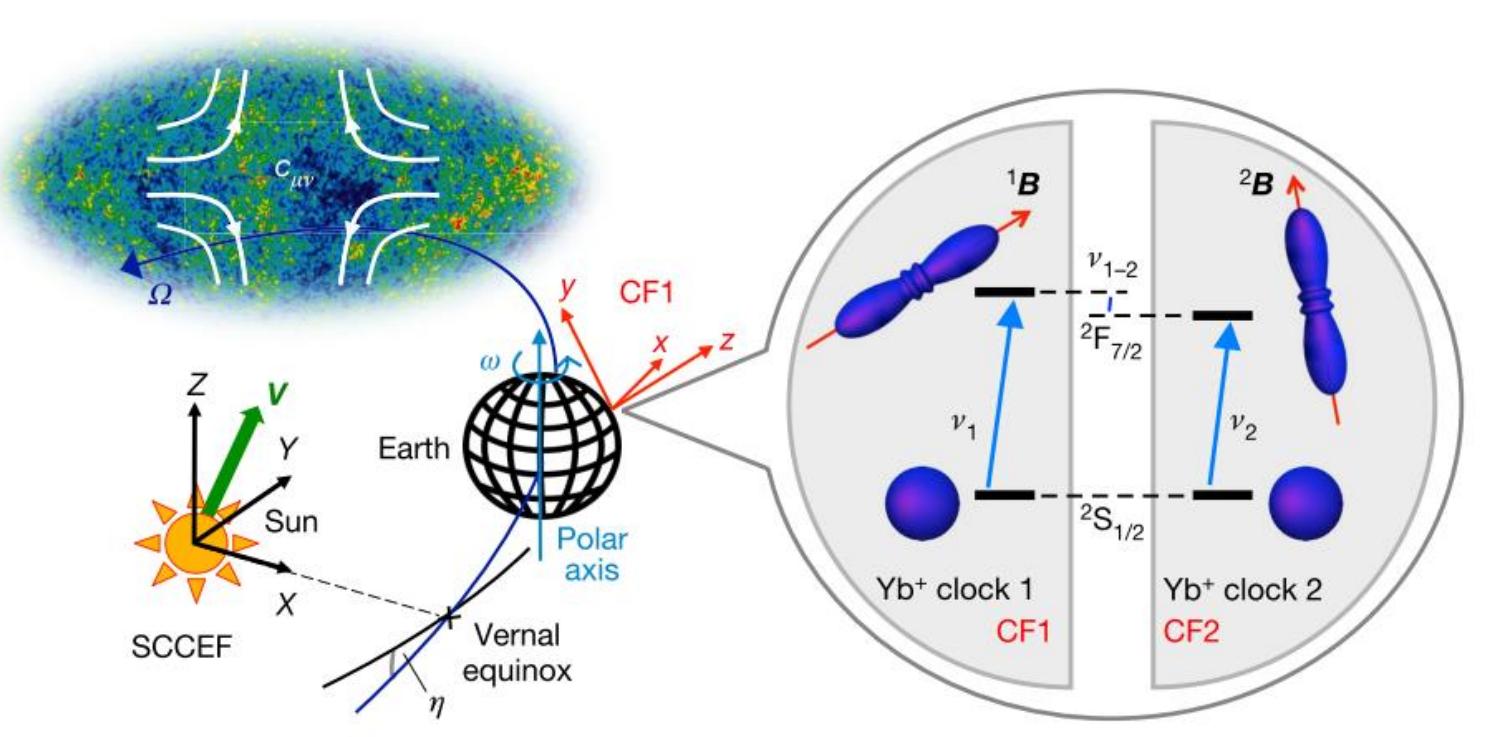
- Drifts in the fundamental constants
- Violations of relativity theory
 - Local position invariance
 - Lorentz invariance
- Coupling to exotic particles or fields
 - Ultralight dark matter (mass $\sim 10^{-22} - 10^{-15}$ eV)
- Nothing? (Tests all the above at an unprecedented level)



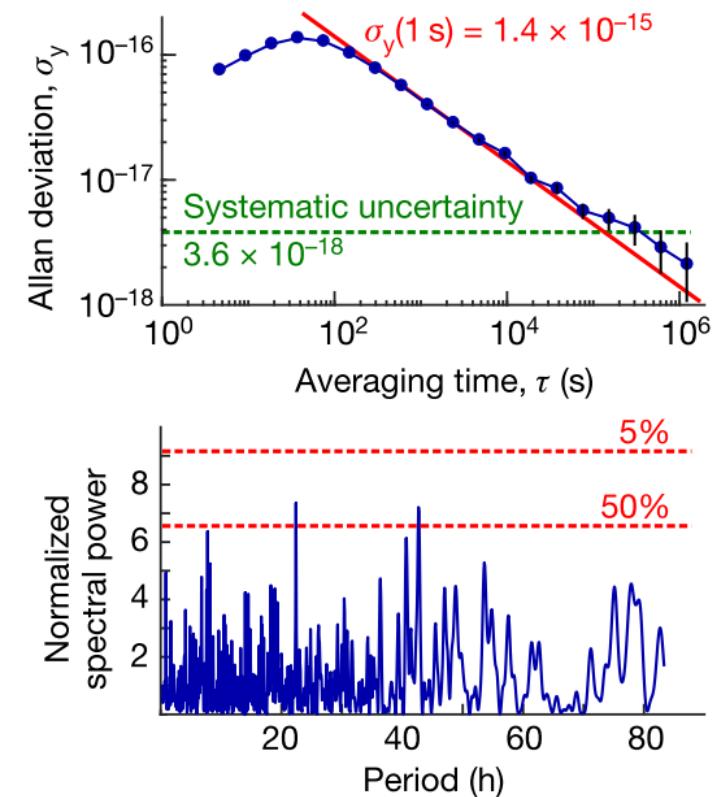
~ 10X improvement over 5 orders of magnitude in particle mass

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

Testing Lorentz Symmetry



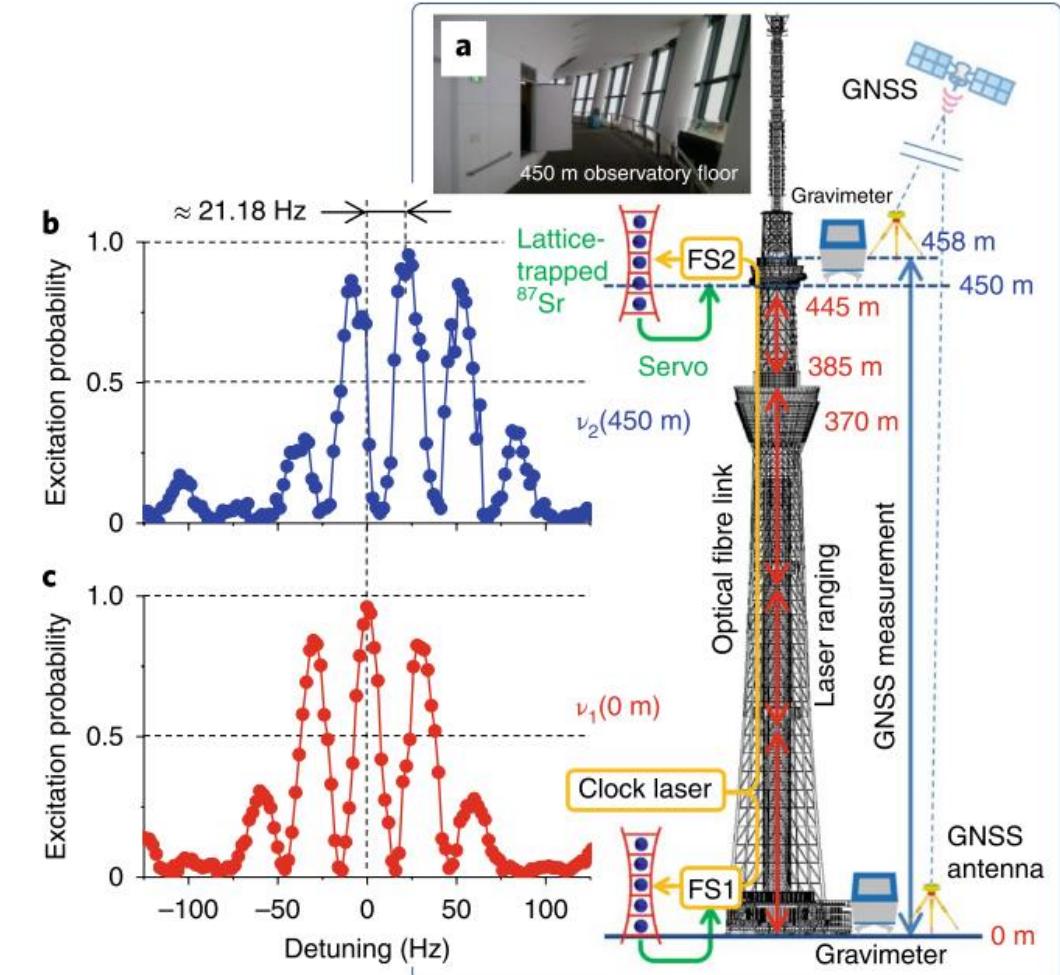
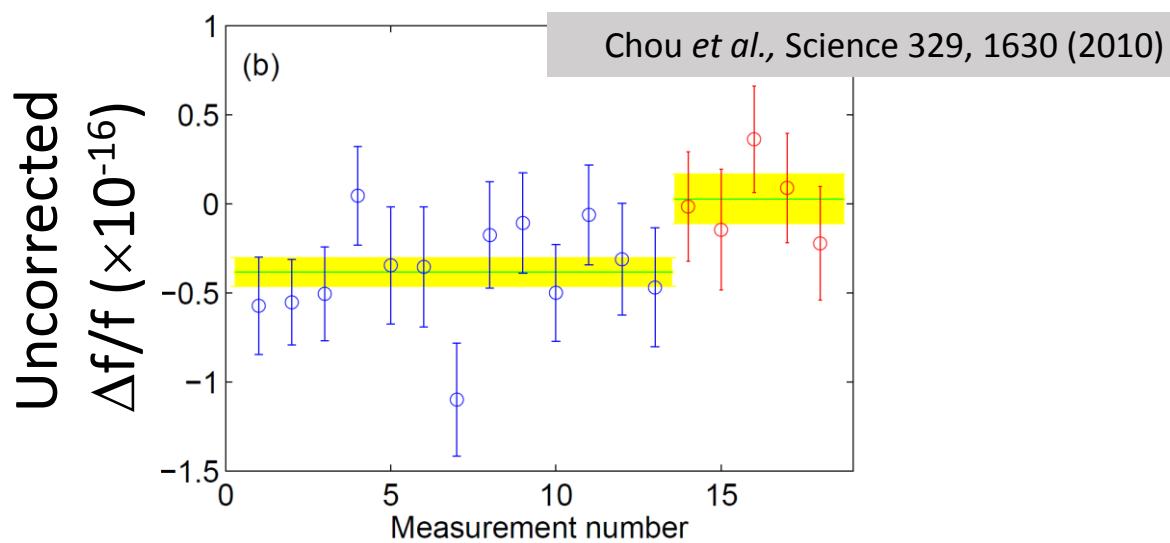
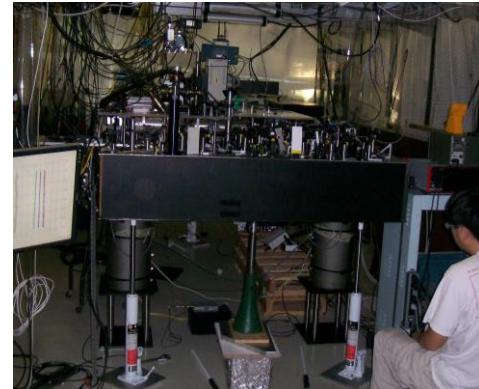
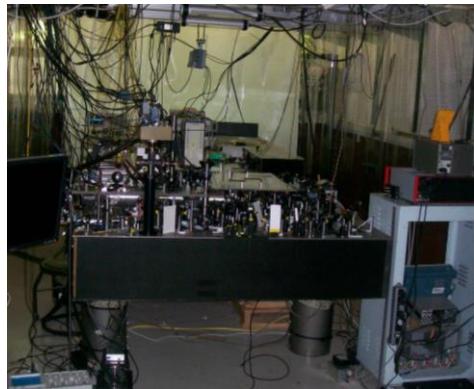
Sanner *et al.*, Nature 567, 204 (2019)



Measuring the Gravitational Redshift

$$\Delta f/f = g\Delta h/c^2$$

$$g/c^2 \sim 1.1 \times 10^{-18}/\text{cm}$$

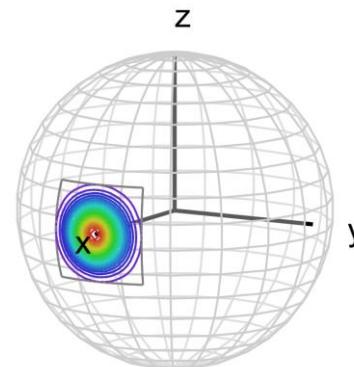


Quantum-Enhanced Metrology with Atoms

Entangled states of atoms with reduced projection-noise

Standard quantum limit

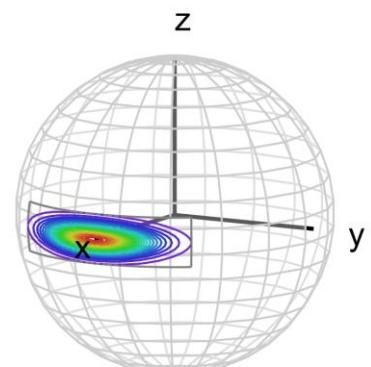
$$\frac{1}{\sqrt{N_{Atom}}}$$



Independent spins

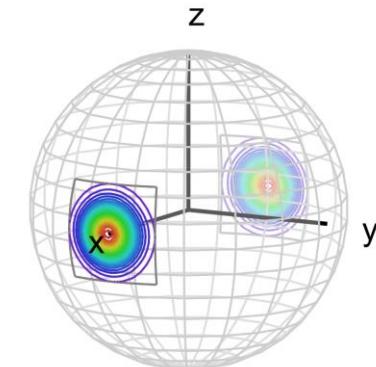
Heisenberg limit

$$\frac{1}{N_{Atom}}$$



Spin-squeezed states

cf, Kitagawa & Ueda, PRA 47, 5138 (1993)
Pedrozo-Peñaflor et al., Nature 588, 414 (2020)



Maximally-entangled “GHZ” states

cf, Bollinger et al., PRA 54, 4649 (1996)
Monz et al, PRL 106, 130506 (2011)

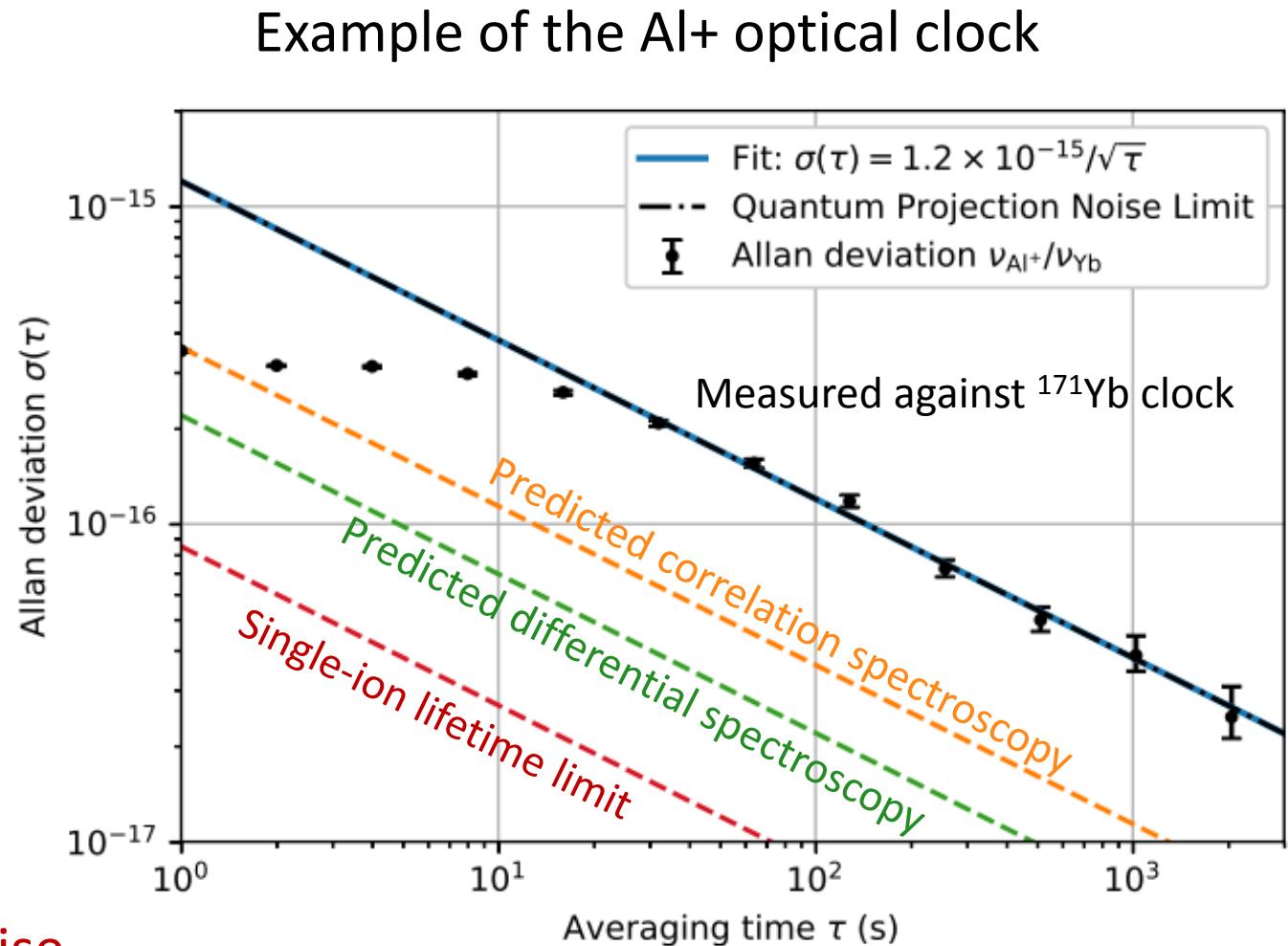
At present, no high-performance atomic clock operates using entangled quantum states

Improving Clock Stability

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

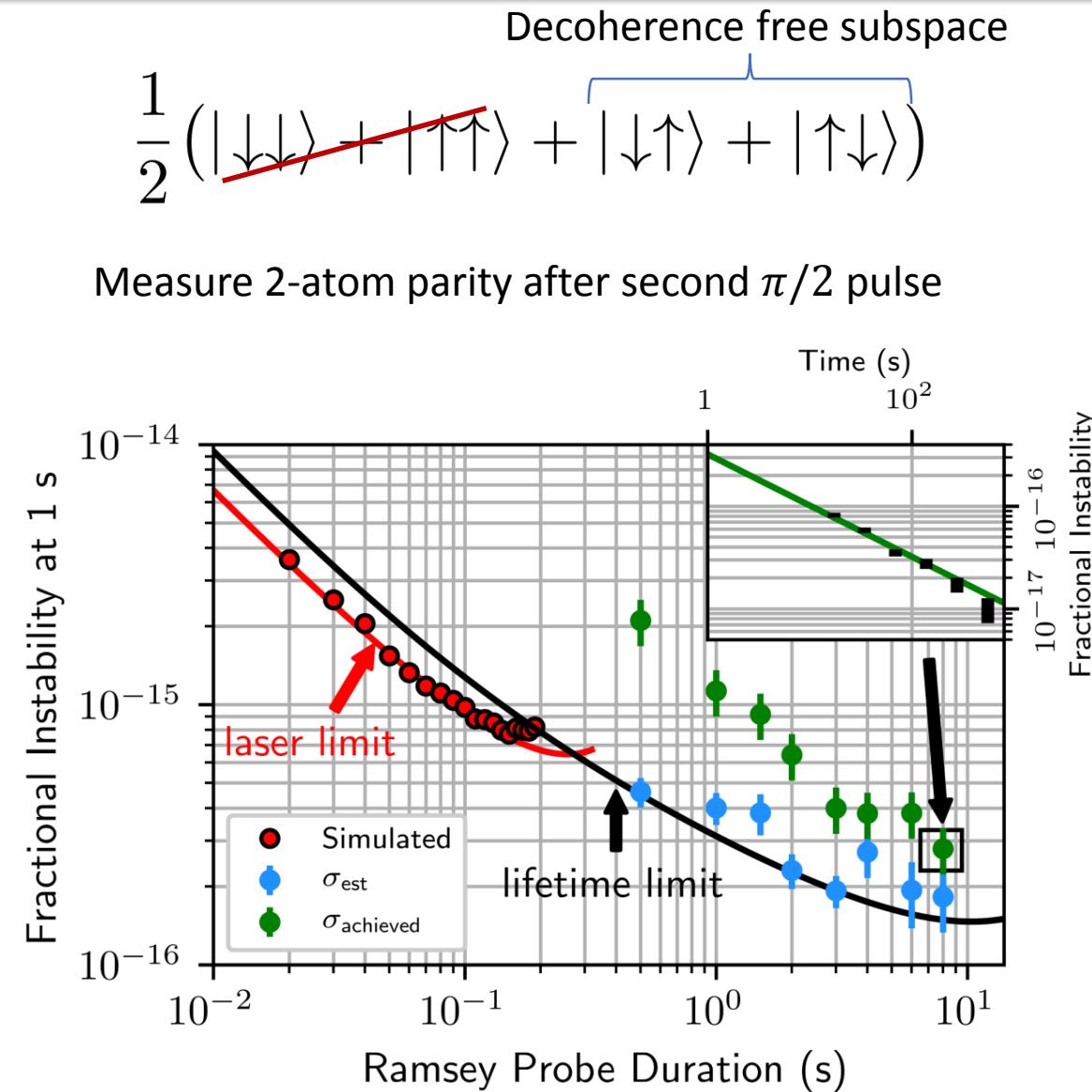
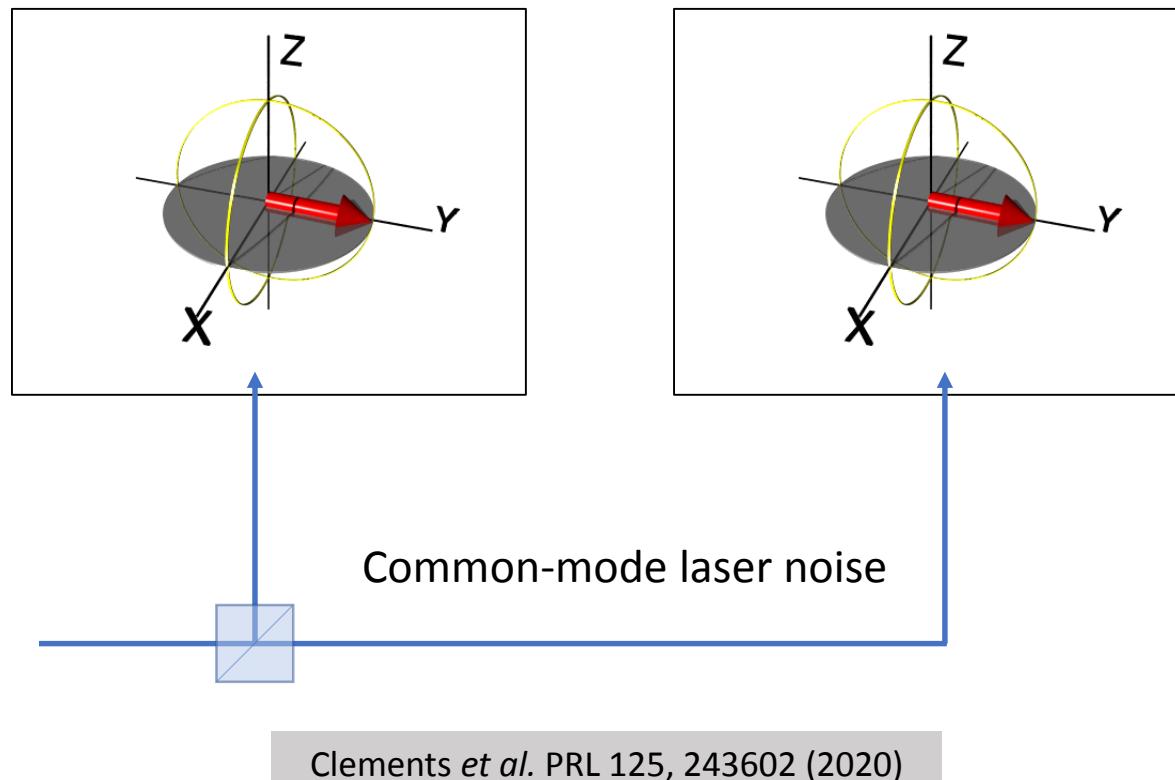
Assuming:

- No technical noise
 - Uncorrelated atomic states
 - Global addressing
- Higher-stability laser
- Larger atom number
- Longer measurement
(more robust operation)
- New techniques to mitigate laser noise

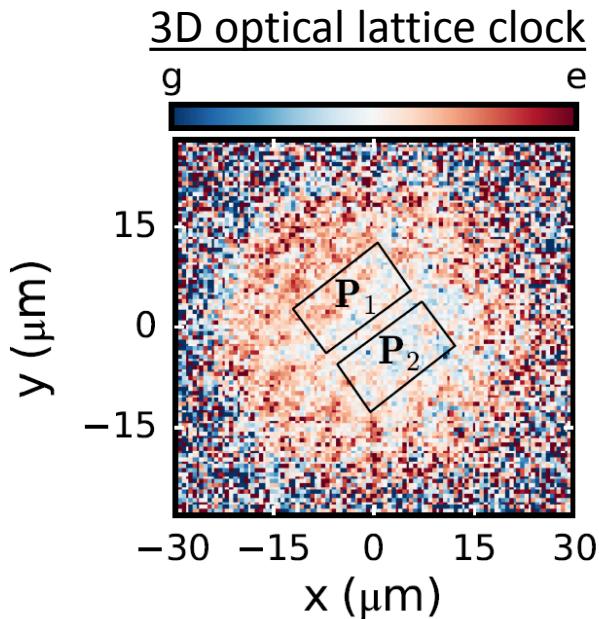


Brewer et al., PRL 123, 033201 (2018)

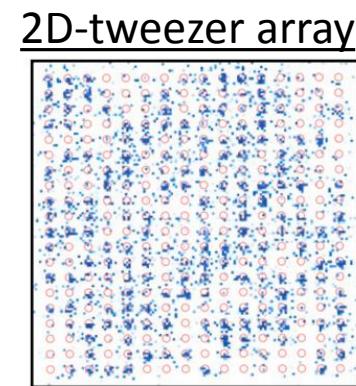
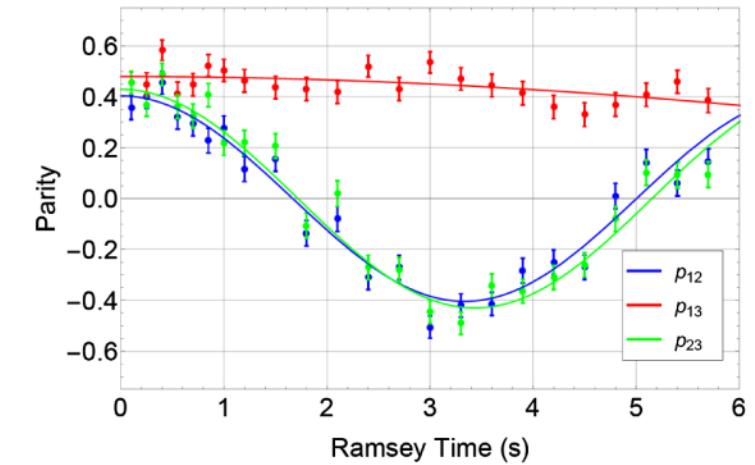
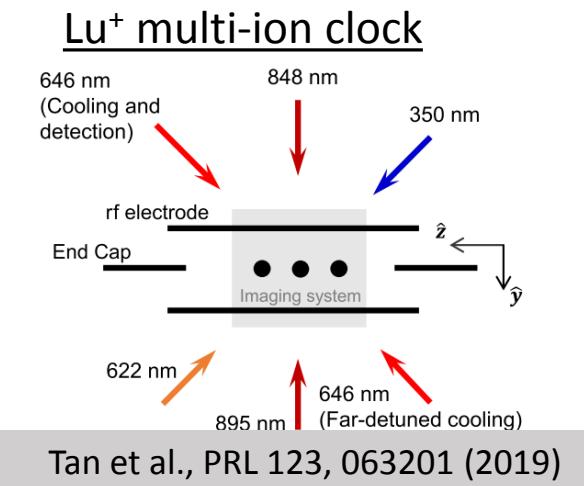
Probing Beyond the Laser Coherence Time I



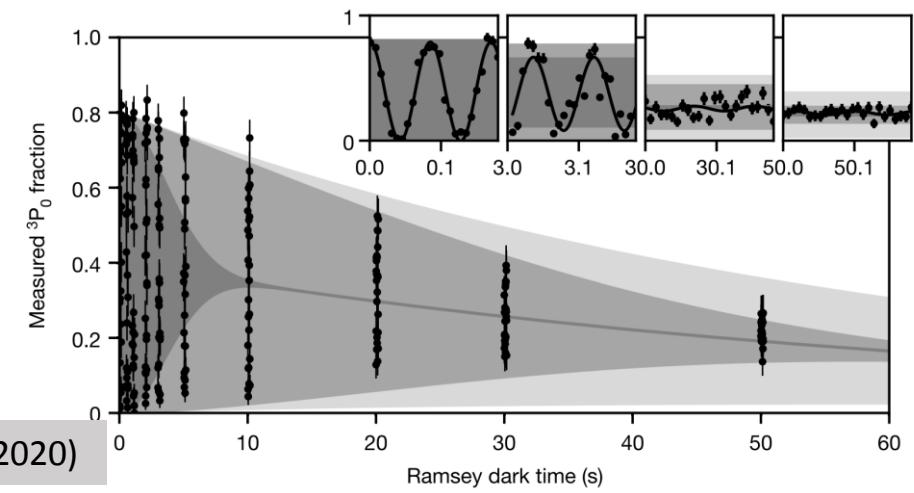
Probing Beyond the Laser Coherence Time II



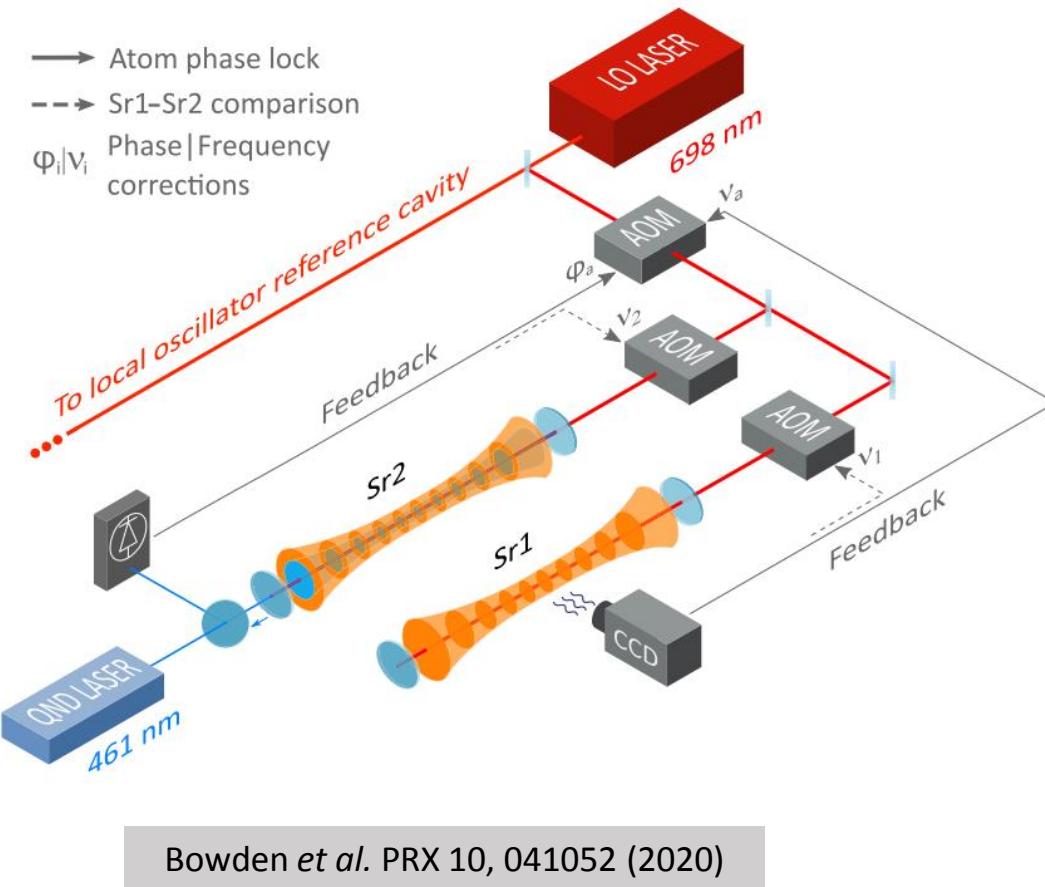
Marti, et al. Phys. Rev. Lett. 120, 103201 (2018)



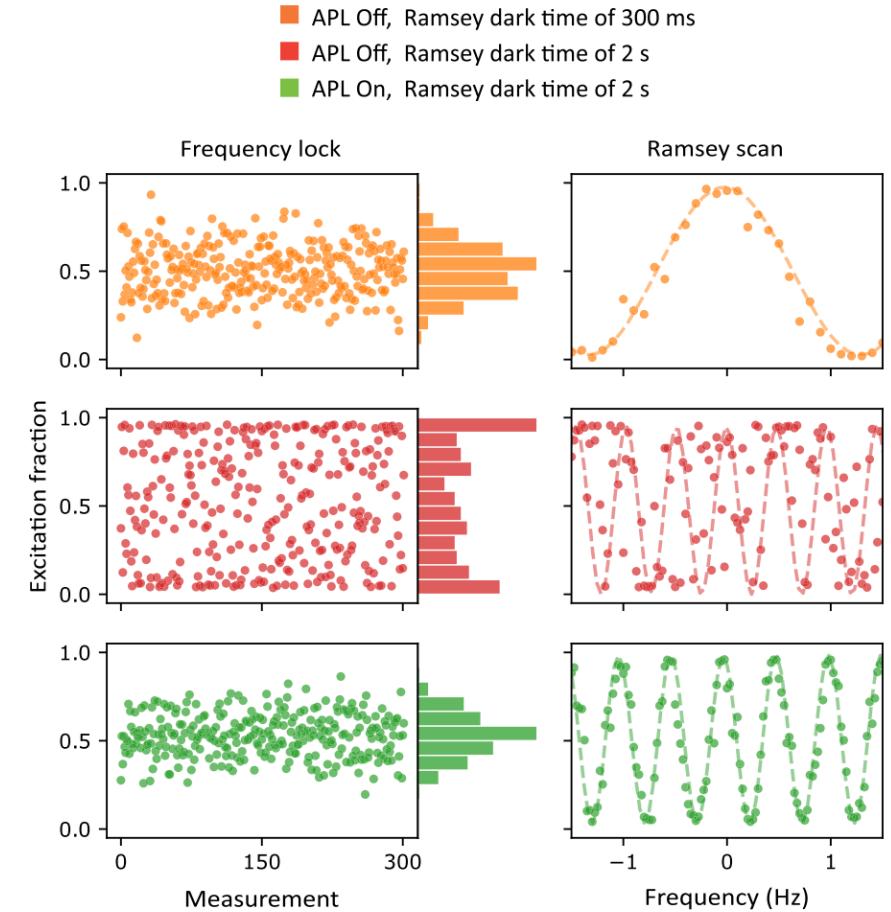
Young et al., Nature 588, 409 (2020)



Probing Beyond the Laser Coherence Time III

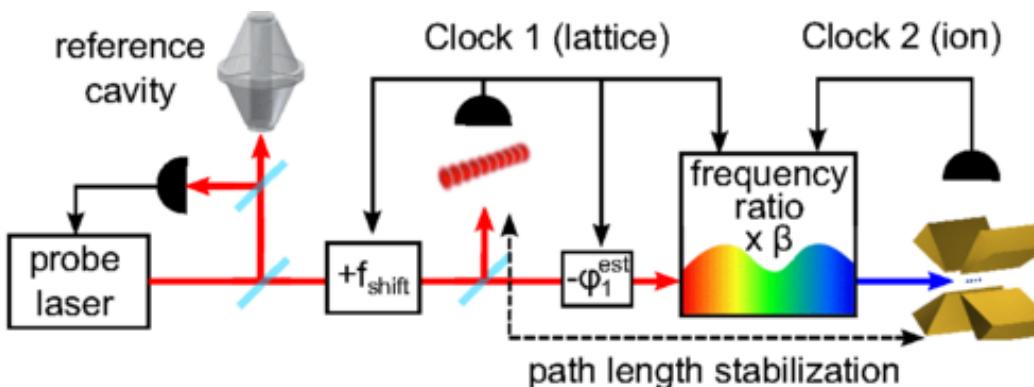


Bowden *et al.* PRX 10, 041052 (2020)

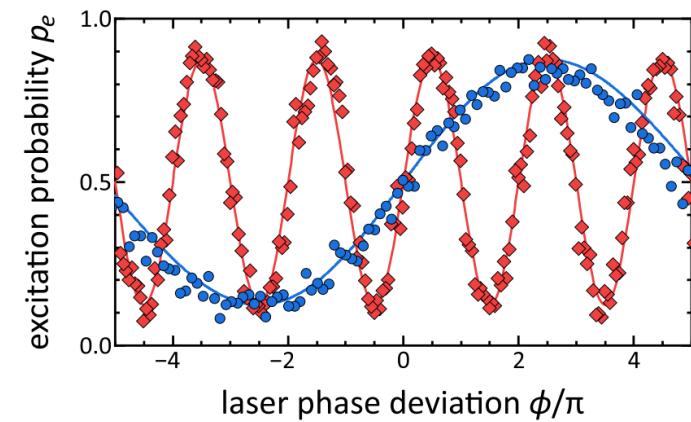
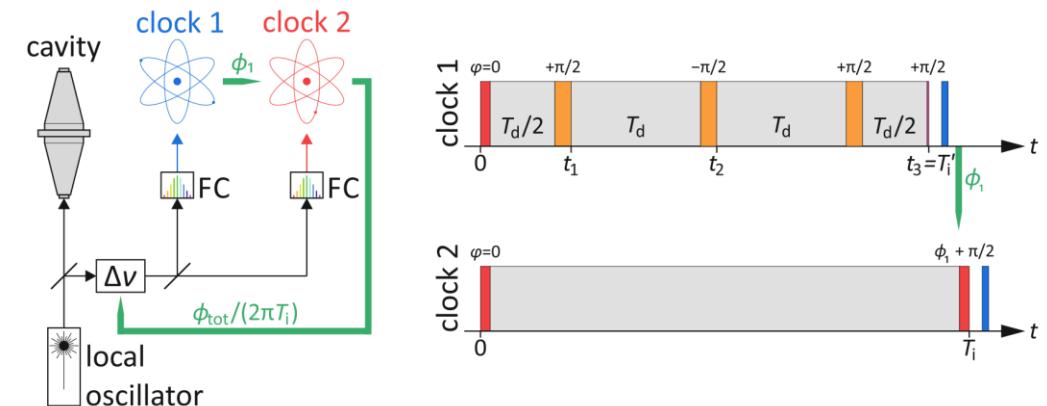
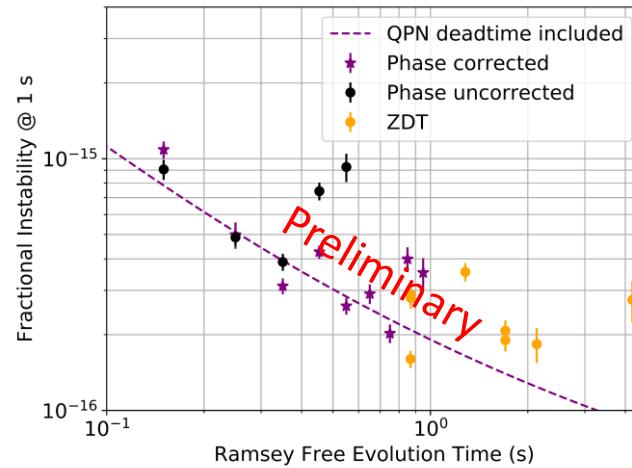


Probing Beyond the Laser Coherence Time IV

Comparisons between different clock species?



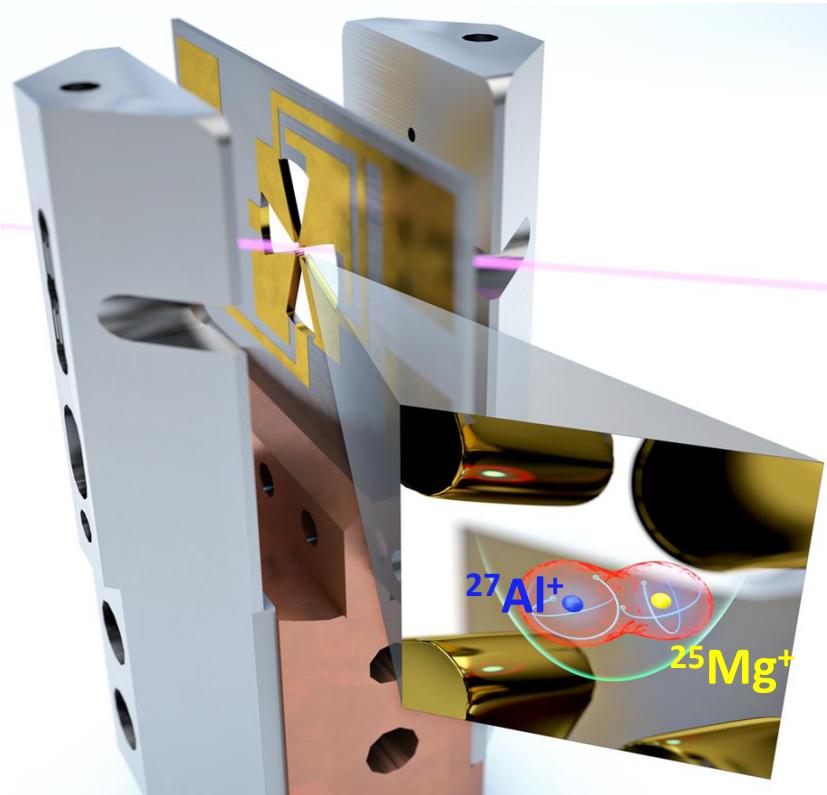
Hume PRA 93,
032138 (2016)



Doerscher Comm. Phys. 3, 185 (2020)

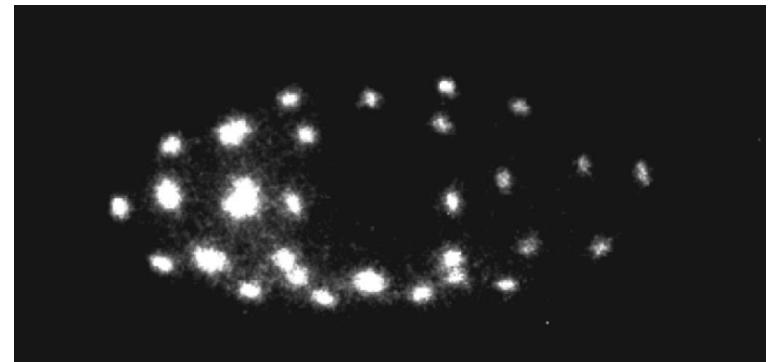
Quantum logic spectroscopy

Sympathetic cooling + state detection using a quantum gate



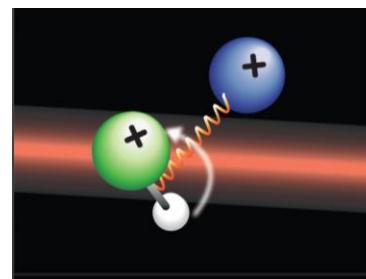
Brewer et al., PRL 123, 033201 (2018)

Highly-charged ions (here Ar¹³⁺)



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

Molecular ions (CaH⁺, MgH⁺)

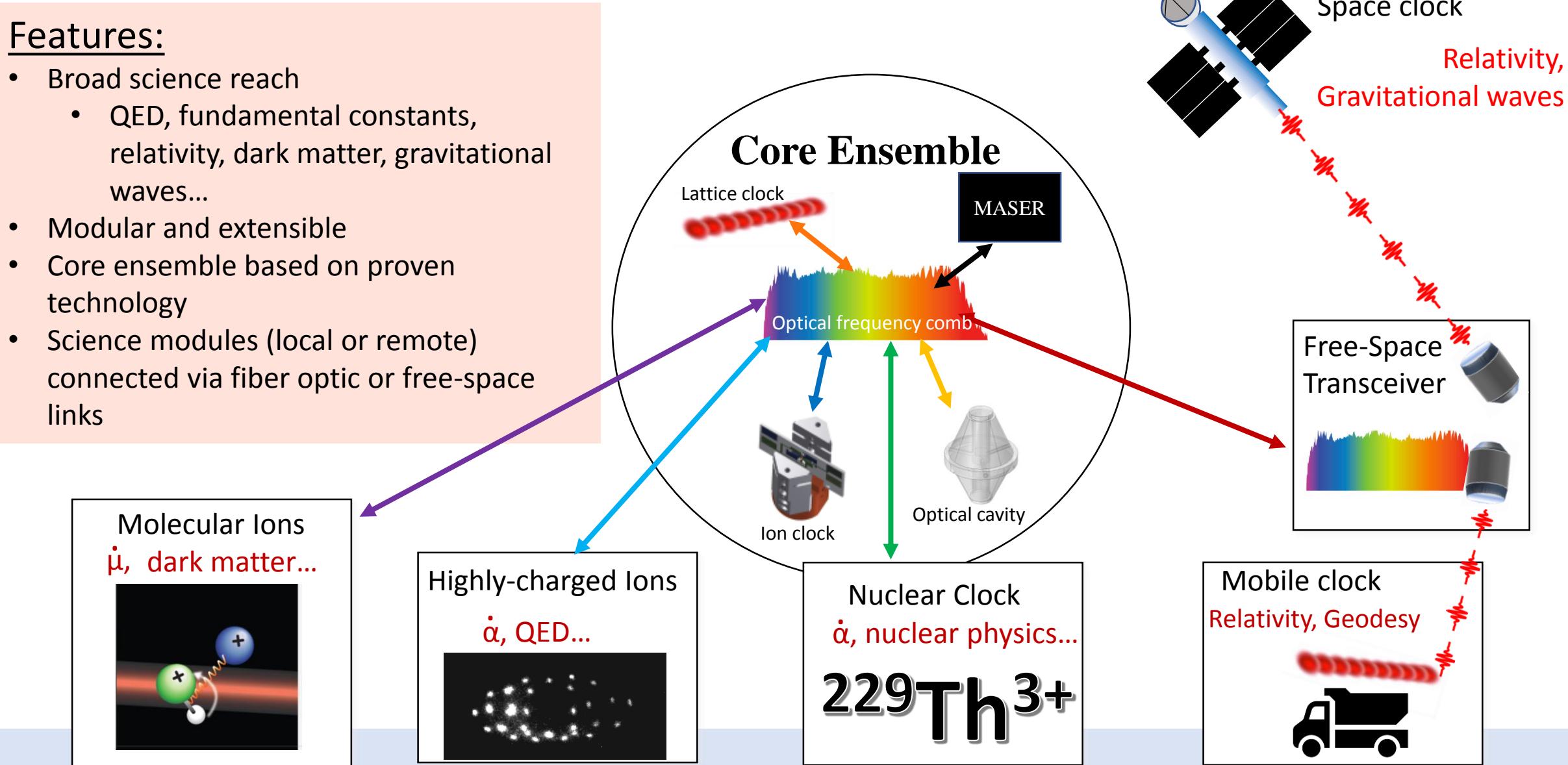


Chou et al., Science 367, 6485 (2020)
Wolf et al., Nature 530, 7591 (2016)

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



Musing about future clock stability and accuracy

- **Clock stability (more foreseeable?)**
 - Sr lattice clock with 10,000 atoms, 10 s probe time
 1×10^{-19} in a few minutes
 - $^{27}\text{Al}^+$ clock with 10 atoms, 10 s probe time
 1×10^{-19} in a few hours
- **Clock systematic uncertainty (difficult to measure and predict)**
 - Cesium clock accuracy improved by a factor of 10X/decade for many decades.
 - There has been a jump with optical clocks by about a factor of 100, but... will it continue?
 - In the case of Al+, I know the details of the systematic uncertainty budget enough to anticipate an improvement to 1×10^{-19}