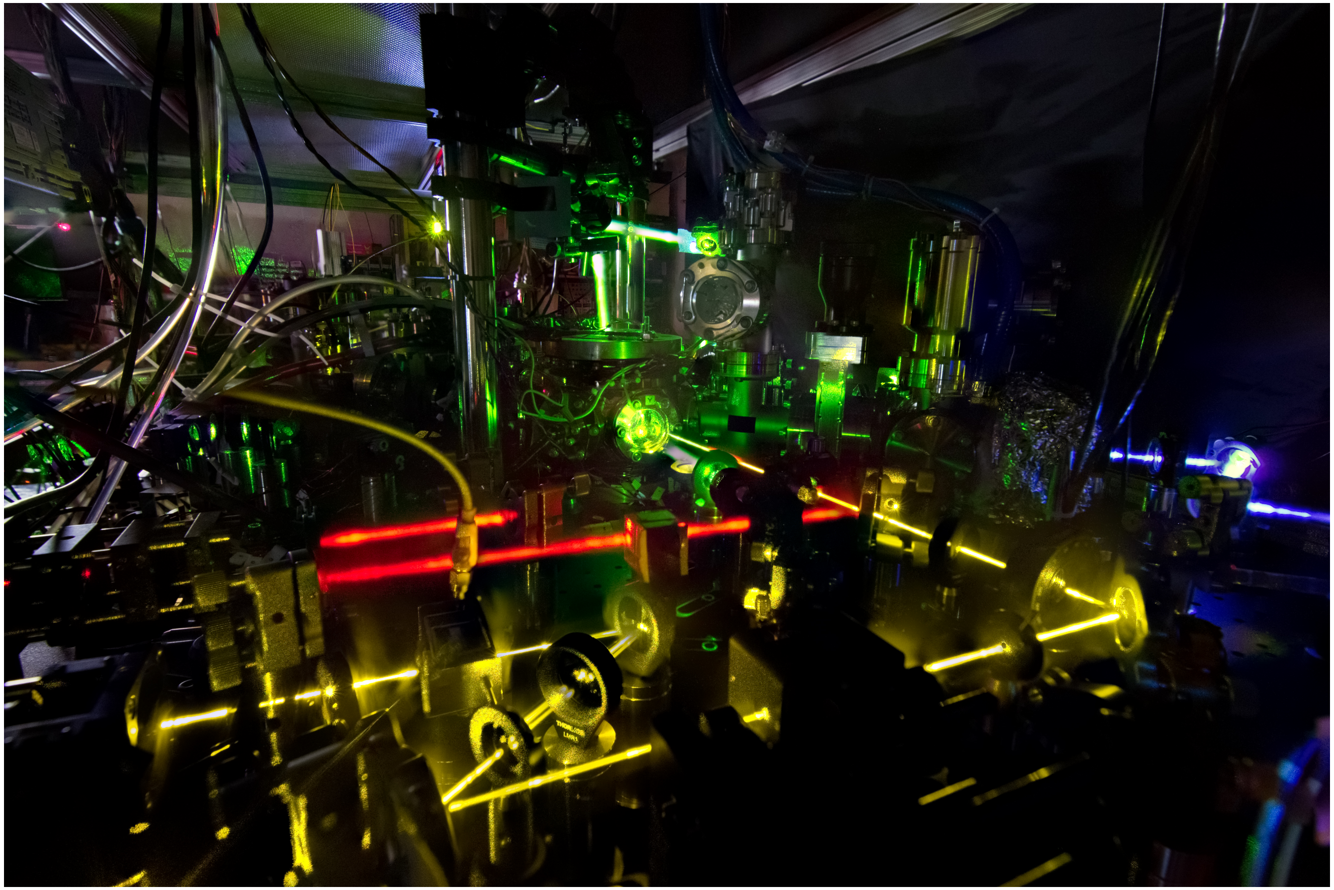
Yb Optical Lattice Clocks



Optical Frequency Measurements Group - Chris Oates

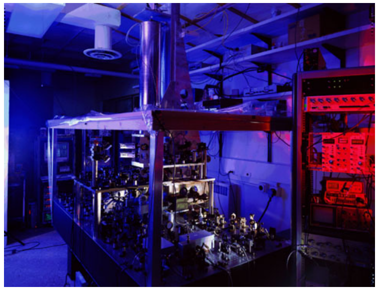
National Institute of Standards and Technology, Boulder, CO   USA

OFM Group – overview and motivations

Optical Frequency Measurements Group

~ 30 scientists (5 postdocs, 11 grad students, 3 visiting scientists)

Focuses on neutral atom optical frequency standards (Andrew Ludlow) + fs-laser frequency combs (NIST Fellow Scott Diddams)

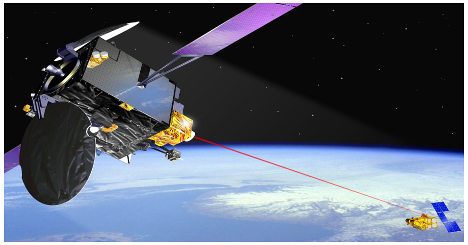


Core NIST metrology role

Time by far the most accurately realized SI unit ($<1 \times 10^{-15}$)

Other units depend on time (length, ampere, candela)

+ more?

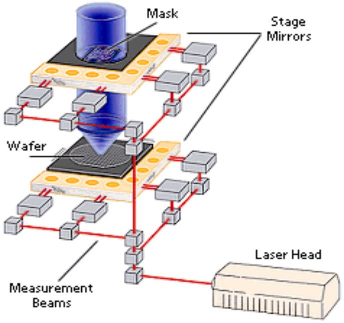


Precision metrology and fundamental science

Tests of fundamental physics

Improved timing for high energy physics and astronomy

Search for new physics



Support for U.S. industry

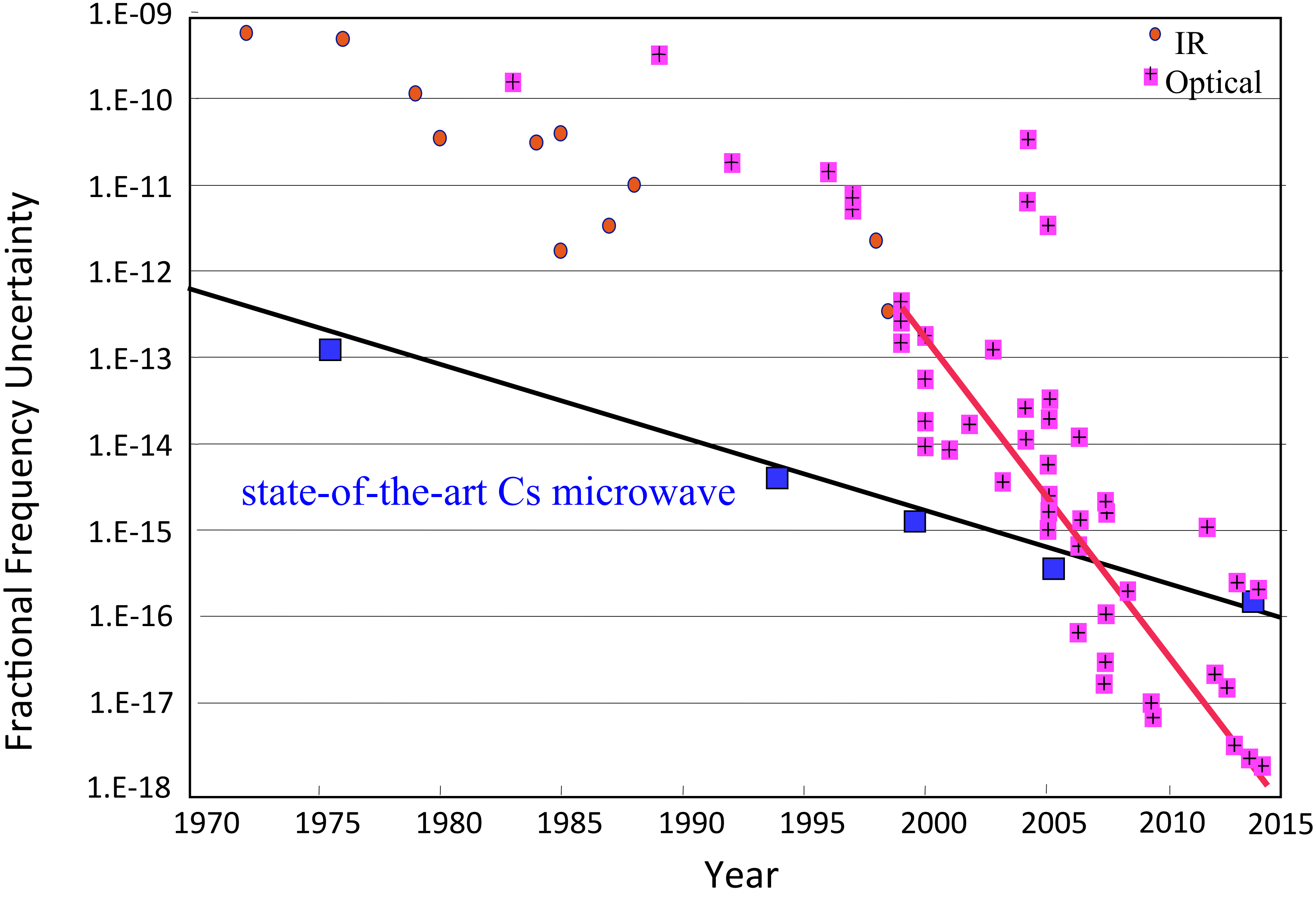
Enhanced timing capabilities: femtoseconds vs. picoseconds

Optical communications systems

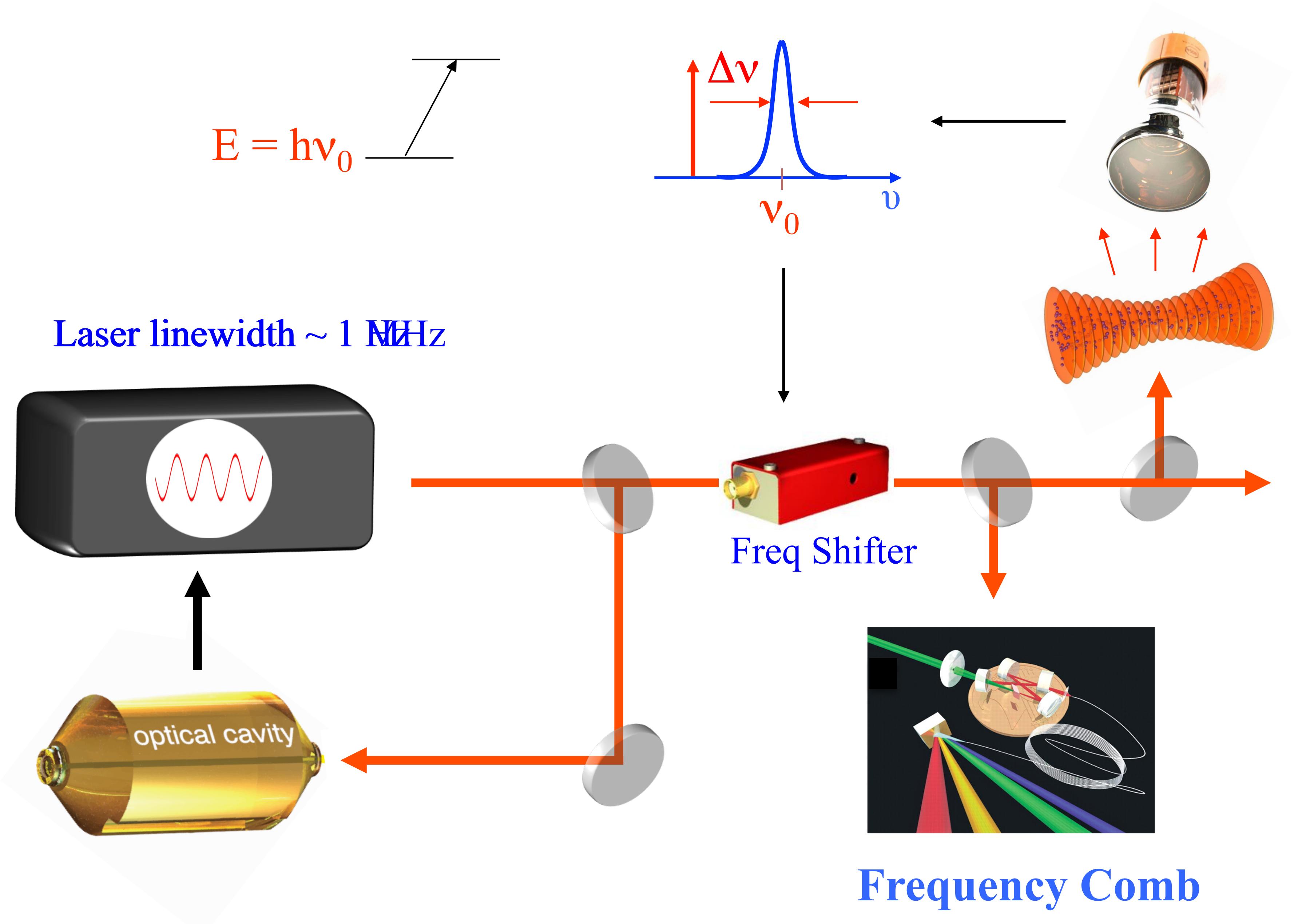
New methods for distribution of length standards

High sensitivity transducers for other quantities (e.g., geodesy)

Optical clock uncertainty through the years



Building blocks of an optical atomic clock



$E = h\nu_0$

$\Delta\nu$

ν_0

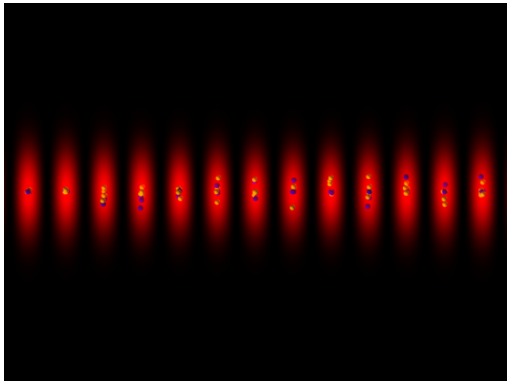
υ

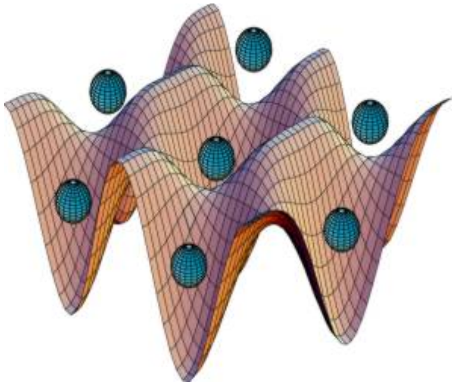
Laser linewidth ~ 1 MHz

Freq Shifter

Frequency Comb

Why use an optical lattice?





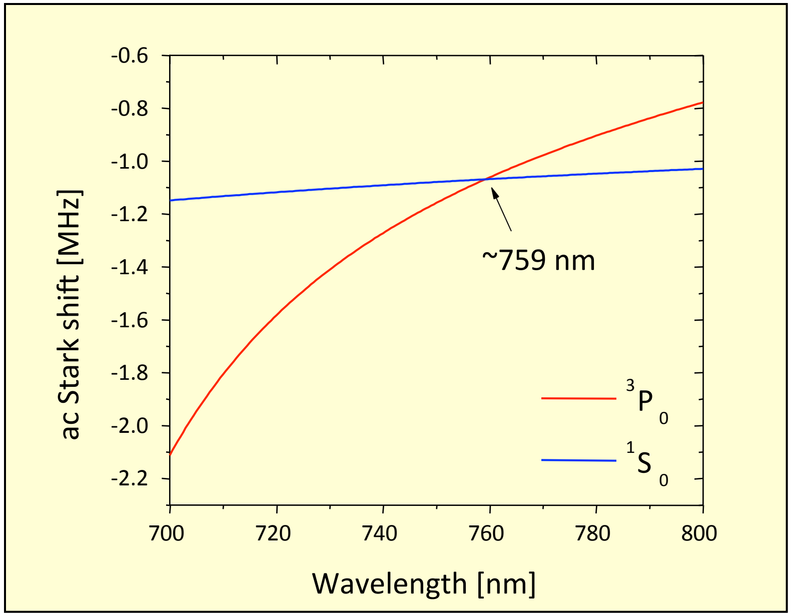
Confine atoms tightly in a 1-D or 3-D standing light wave

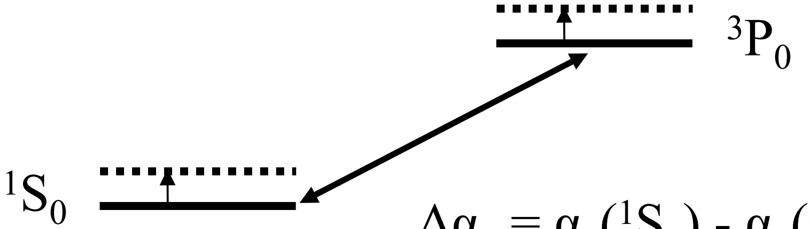
- Tight confinement Doppler & recoil-free
- Long interaction time high Q
- Large numbers ($\sim 10^4$) high S/N

$$\sigma_y(\tau) = \frac{\Delta\nu}{\nu_0}\sqrt{\frac{T}{N\,\tau}}$$

Lattice clocks based on Sr (~18), Yb (~9), and Hg (~3), and Mg

Controlling the lattice-induced shifts





$$\Delta\alpha_1 = \alpha_1(^1S_0) - \alpha_1(^3P_0)$$

$$\Delta\nu = \Delta\alpha_1(\nu_{lat}, \hat{e}_{lat})\, I + \Delta\alpha_2\, I^2 \ldots$$

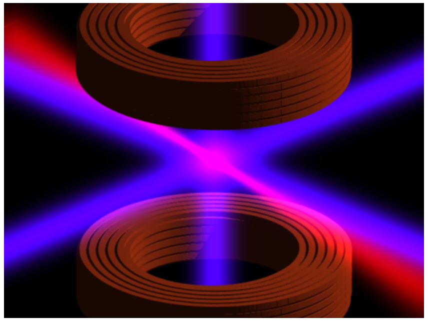
(1) Choose a $J = 0 \rightarrow J = 0$ transition to remove ê dependence (Katori 2001)

(2) Tune $\lambda_{lattice}$ to λ_{magic} $\rightarrow \alpha_1 = 0$ $(\Delta\nu_{clock} / \Delta\nu_{lat} \sim 10^{-8})$

(3) Investigate higher order shifts (e.g., $\Delta\alpha_2$), M1, E2 effects residual ê dependence

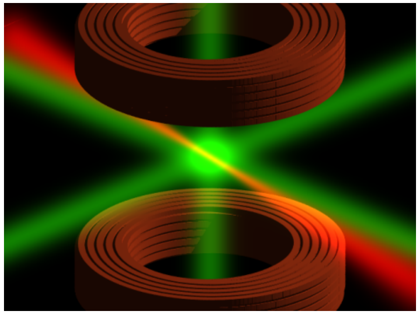
Lattice clock measurement sequence

399 nm
MOT
50 ms



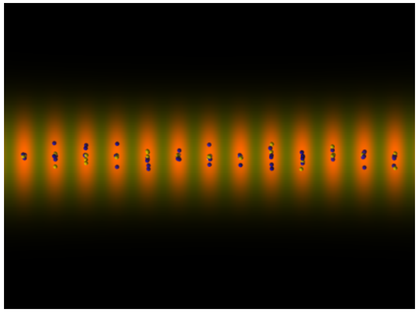
$N \sim 10^6$
$T \sim 5$ mK

556 nm
MOT
50 ms



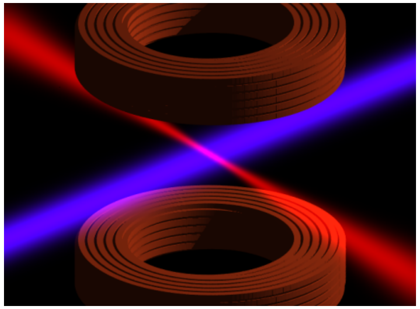
$N \sim 10^6$
$T \sim 50\ \mu K$

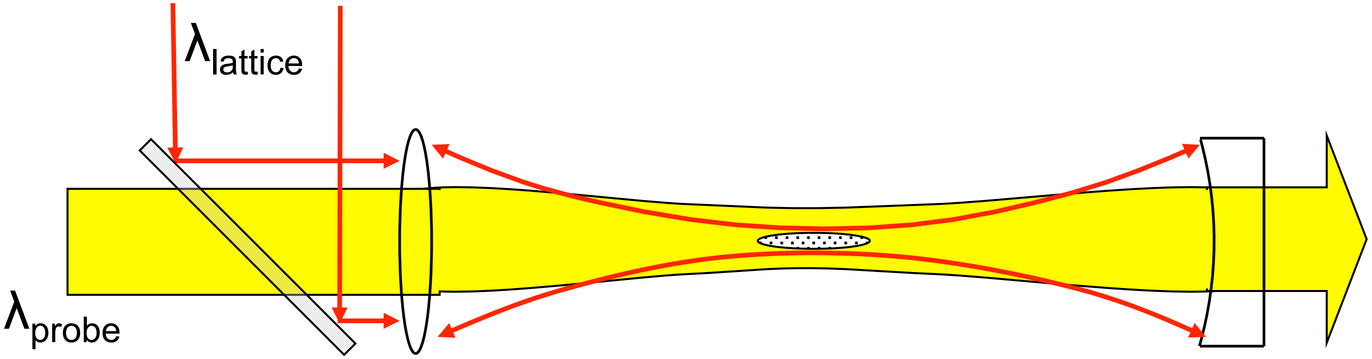
Probe atoms
in lattice
~ 360 ms



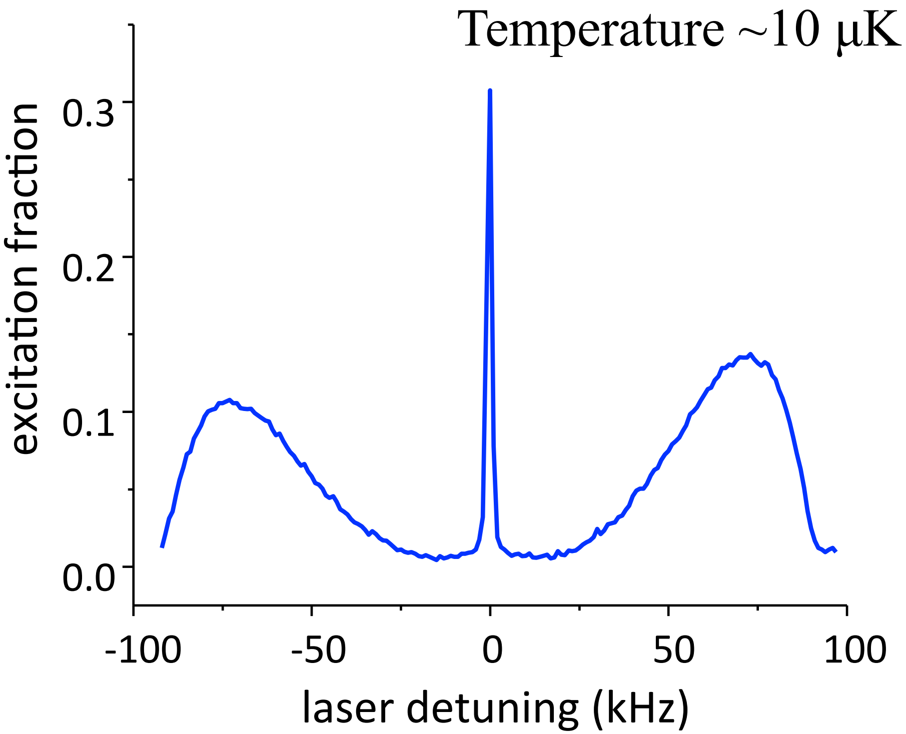
$N \sim 10^4$
$T \sim 2\text{-}15\ \mu K$

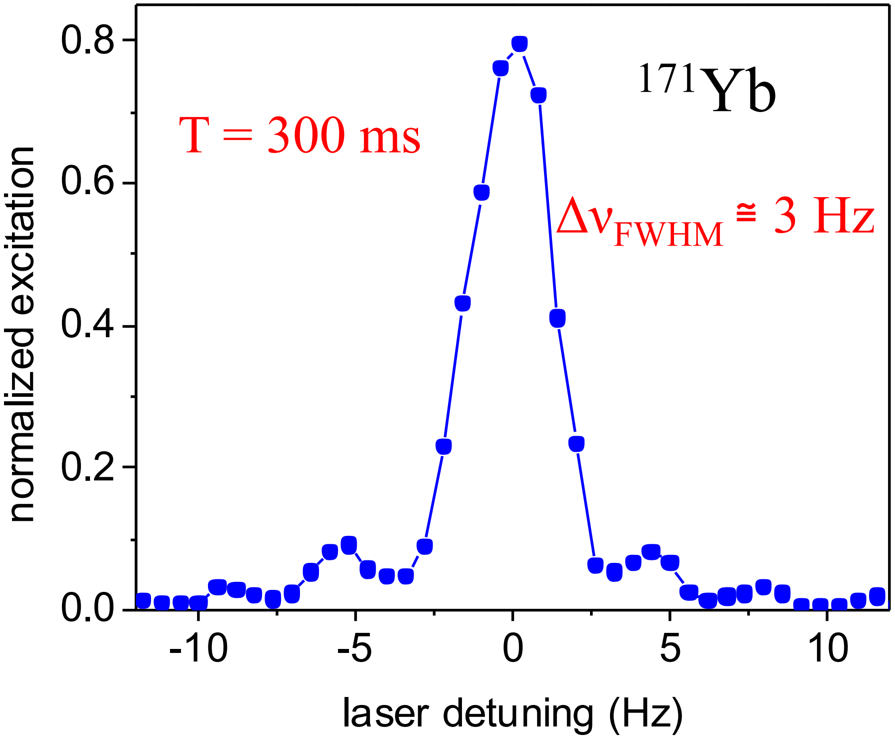
Normalized
shelving
detection



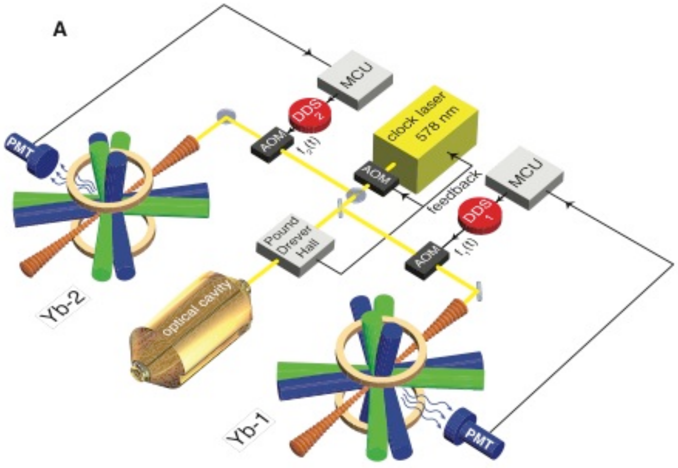


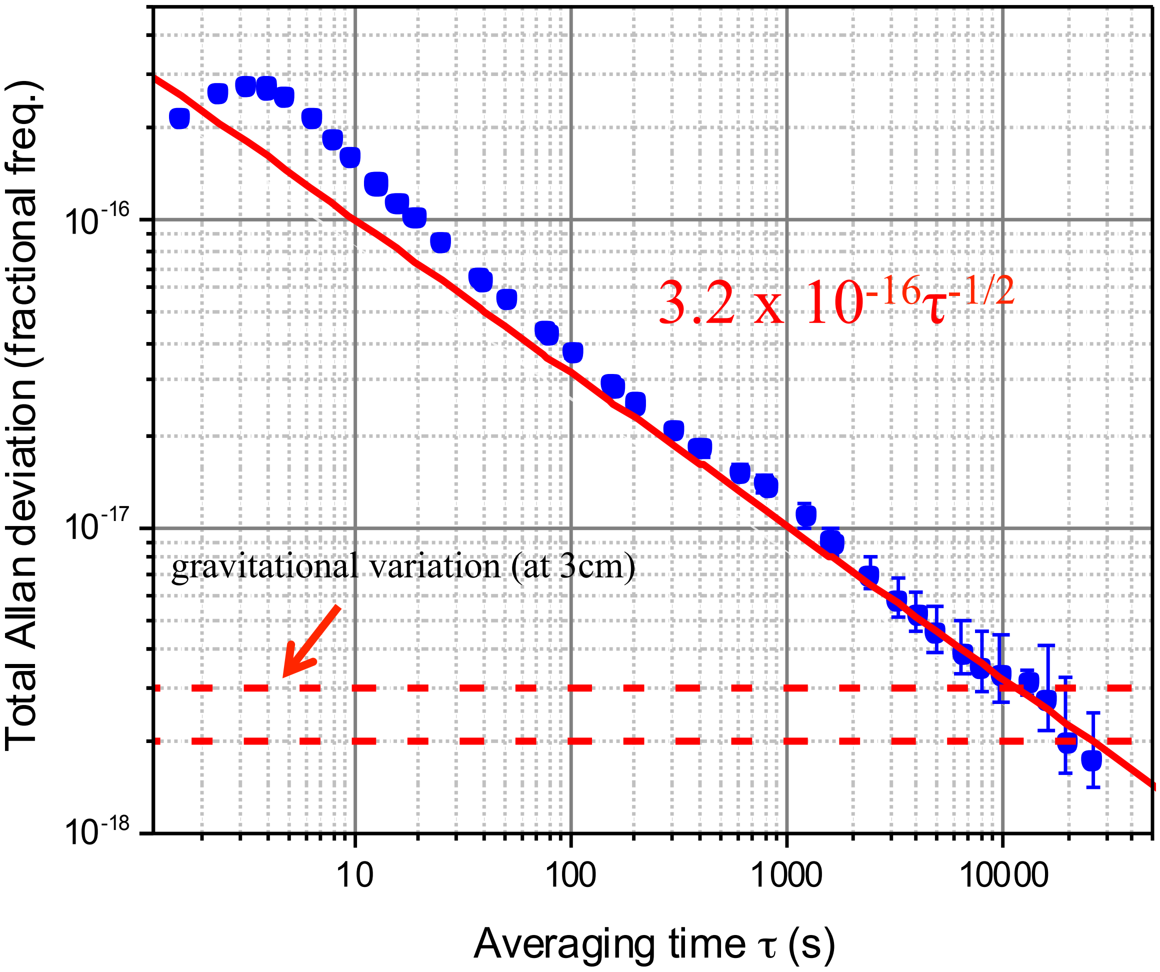
Spectroscopy in an optical lattice





An optical clock with 10^{-18} instability

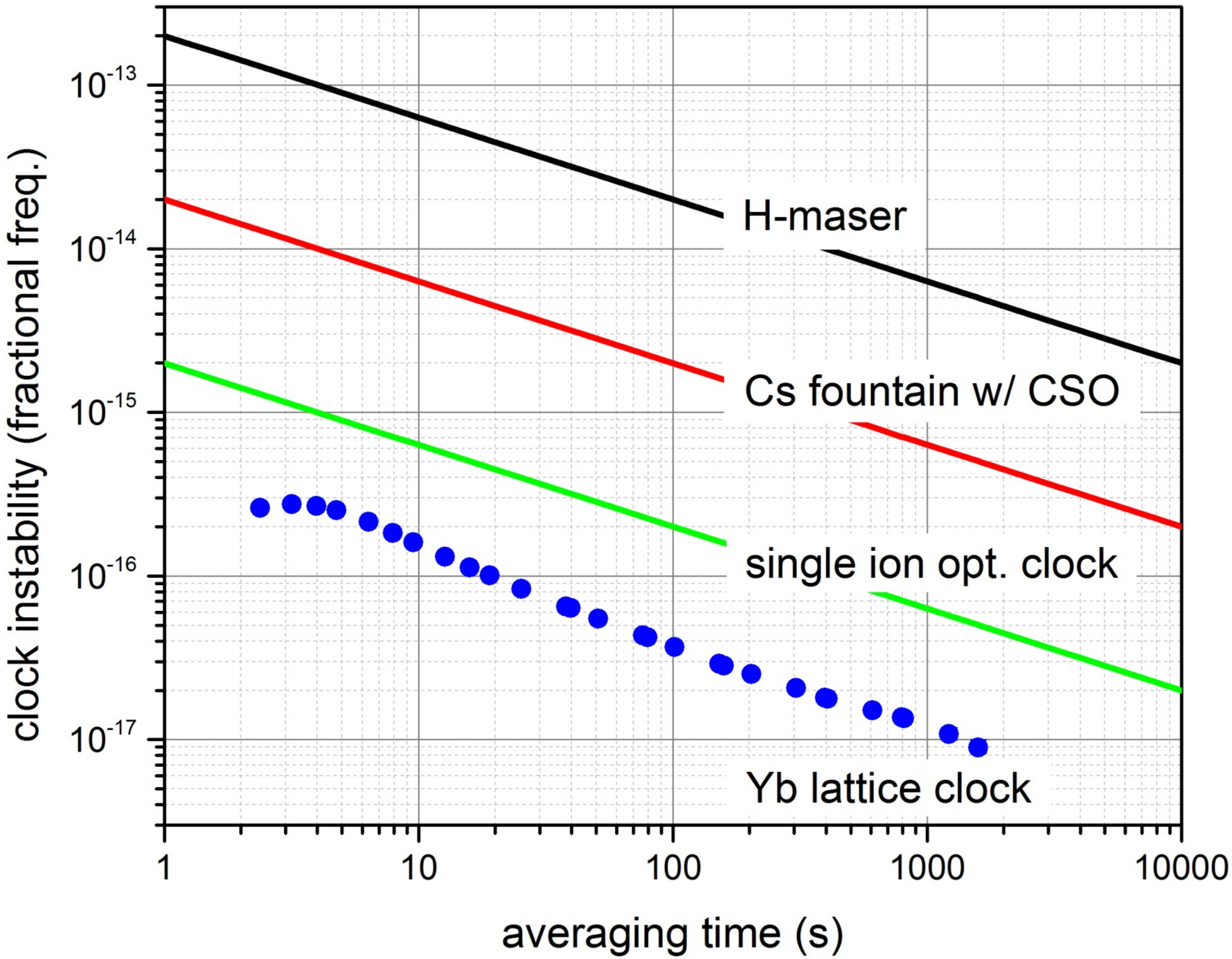




First demonstration of atomic clocks averaging into 10^{-18} s

Hinkley et al., Science **341**, 1215 (2013)

Instability for different clock systems



Still above the instability formula limits

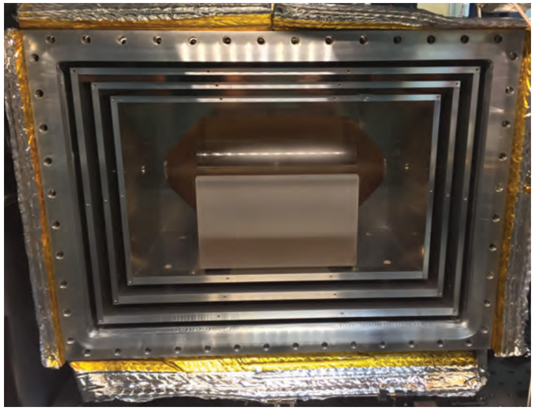
fountain: J. Guena et al., TUFFC 59 391 (2012), single ion: Chou et al., PRL 104, 070802 (2010)

Cavities – present and future

Low atom projection noise limit for optical lattice clocks means clock laser frequency noise (i. e., clock pre-stabilization) often limits lattice clock stability

Continual improvement of optical reference cavities and locking techniques are a critical part of our program

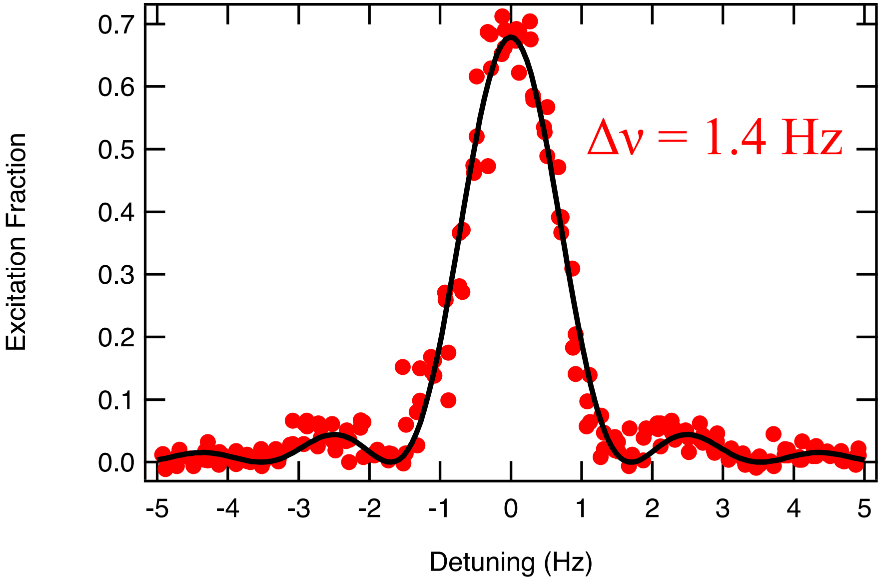
- Newly installed cavity has a Finesse of 700,000 and a linewidth of 590 Hz.
- Multi-layer shield yields residual drift = 35 mHz/s, compensated to 0.2 mHz/s.

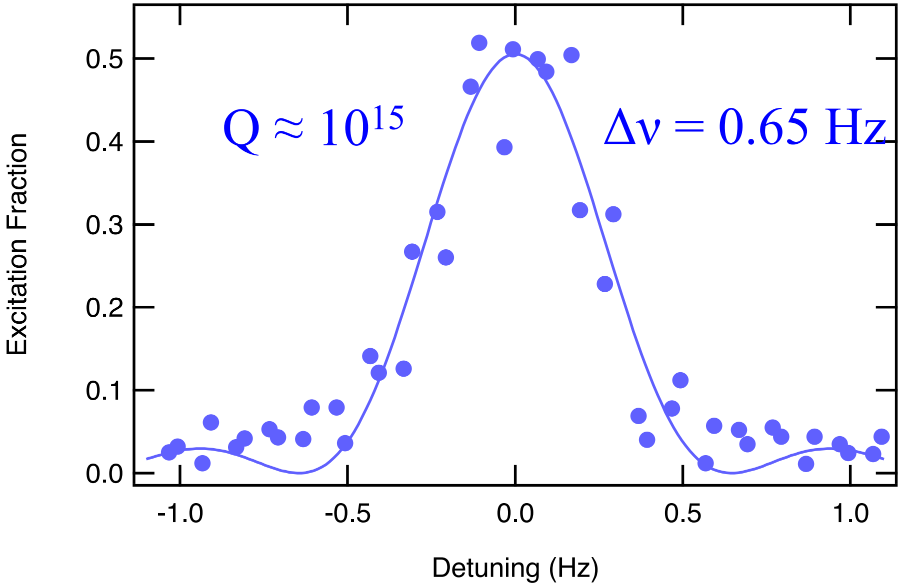


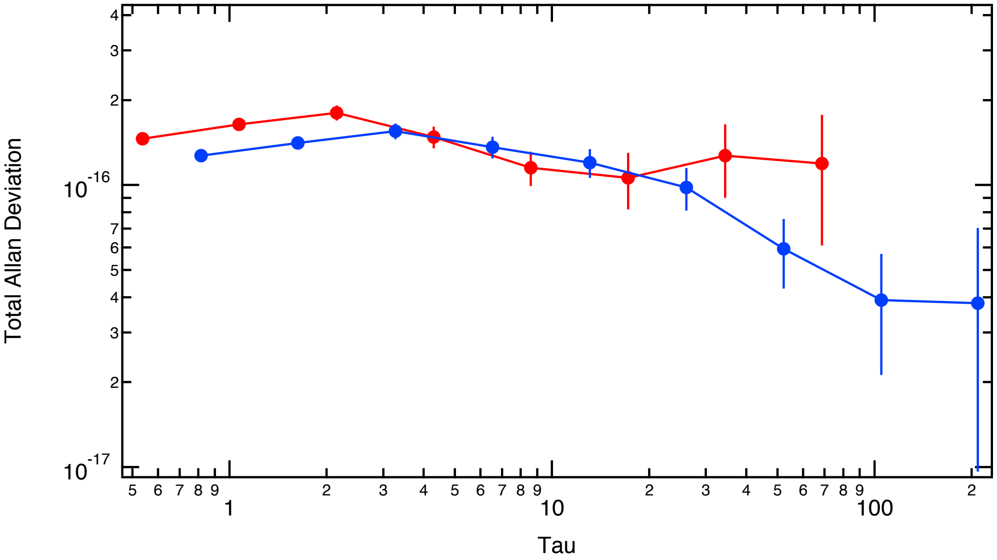
Future plans include building cavities with lower fundamental thermal noise limits, even at cryogenic temperatures

5 K

Recent spectroscopic results







Upper limit of 1-2 x 10^{-16} @ 1 s for clock laser and atom signal

Preliminary results indicate lowest clock stability to date worldwide

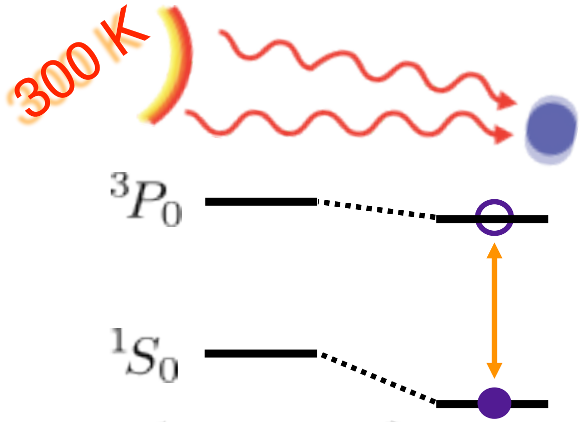
Frequency uncertainty for NIST Yb clock

Effect	Shift (10^{-17})	Uncertainty (10^{-17})
Blackbody	-250	25
Lattice polarizability	37	21
Cold Collisions	-161	8
First-order Zeeman	4	4
Second-order Zeeman	-17	1
Probe light	0.5	2
AOM phase chirp	0	1
Others	0	1
Total	-38.7	3.4

Systematic Total: 3.4×10^{-16}

Lemke et al, PRL *103*, 063001 (2009)

Reducing the blackbody uncertainty



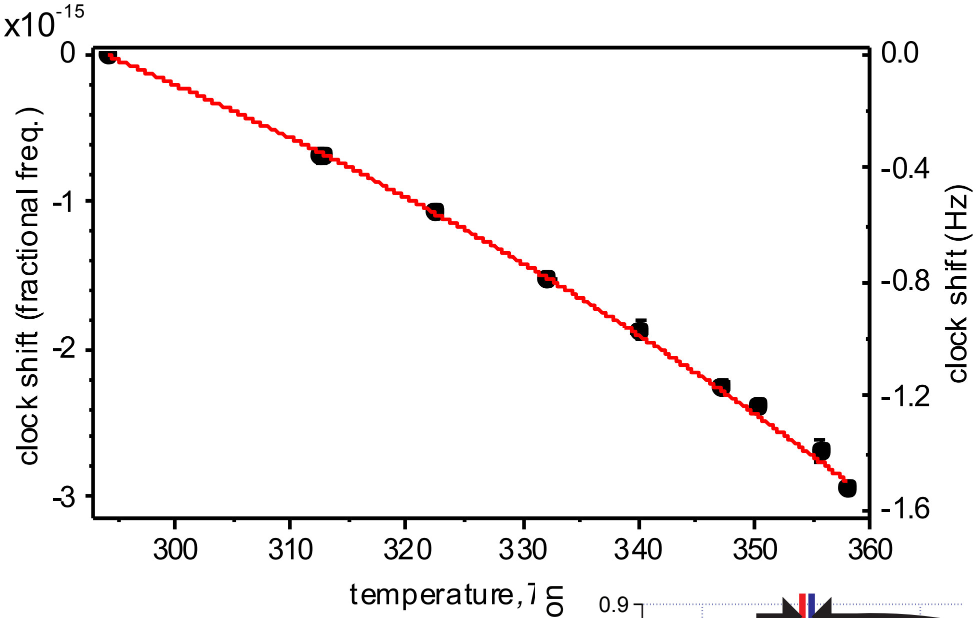
$$\Delta\nu_{\mathrm{BBR}} = \underbrace{-\tfrac{1}{2}\alpha_{\mathrm{clock}}}_{2 \times 10^{-5}\ \text{uncertainty}} \langle E^2\rangle_T \underbrace{[1+\eta_{\mathrm{clock}}]}_{<1 \times 10^{-3}\ \text{uncertainty}}$$

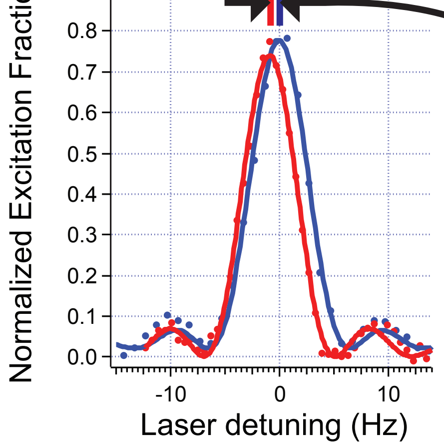
$$\langle E^2\rangle_T \approx (8.319\ \mathrm{V/cm})^2 \left(\frac{T}{300\ \mathrm{K}}\right)^4$$

~ 0.03 K effective temperature uncertainty

↓

1 x 10^{-18} BBR clock uncertainty

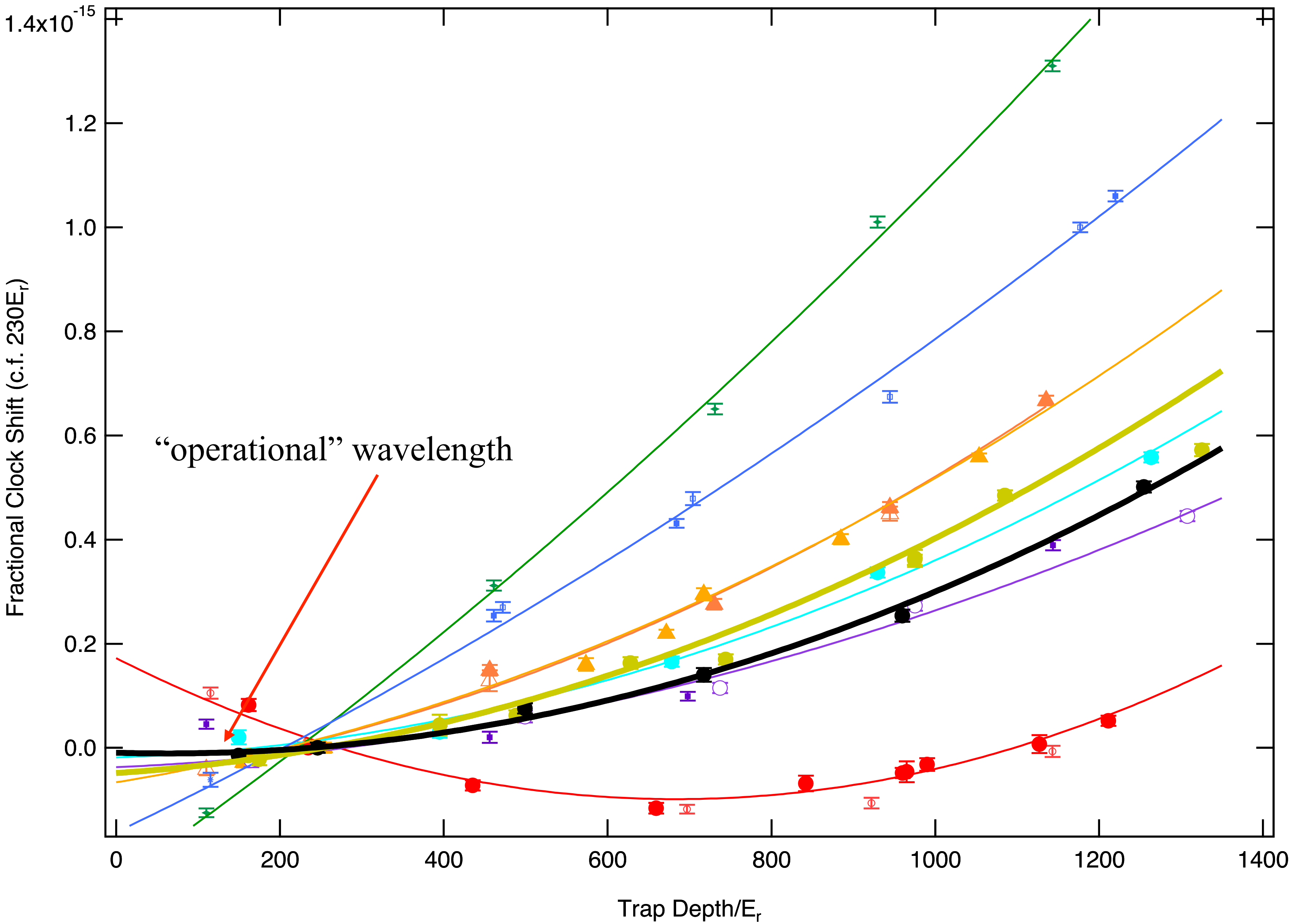




Scans of the $^1S_0$-$^3P_0$ clock transition:
clock at T=300 K
clock at T=380 K

Beloy et al. PRL **113**, 260801 (2014).

Zeroing in on the magic wavelength



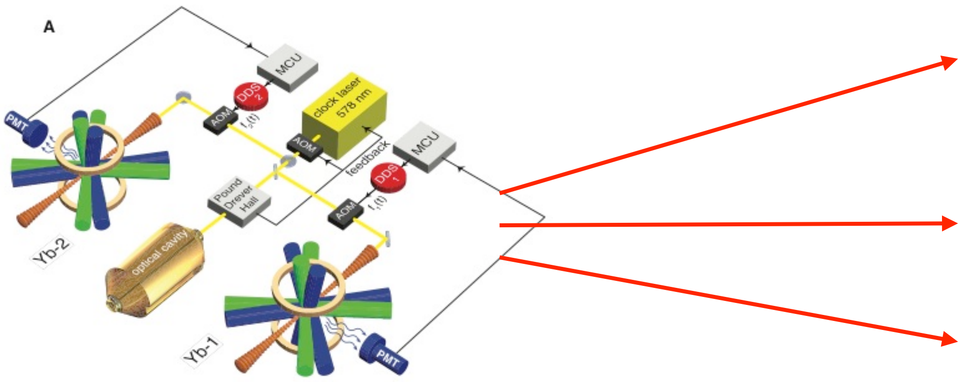
Yb clock: Present status/upcoming measurements

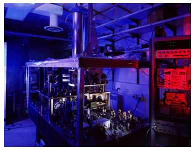
- Finish evaluation of systematic effects at the 10^{-18} level

Doppler shifts, blackbody shifts, density effects

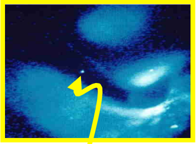
Blackbody	-250	25
Lattice polarizability	37	21
Cold Collisions	-161	8
First-order Zeeman	4	4
Second-order Zeeman	-17	1
Probe light	0.5	2
AOM phase chirp	0	1
Others	0	1
Total	-38.7	3.4

- Frequency comparisons with other clock systems

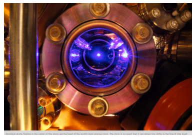




NIST Cs fountains

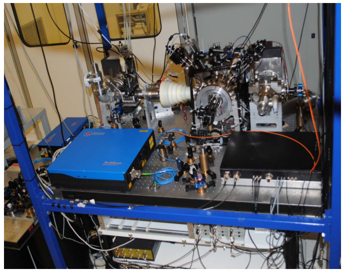


NIST Al^+, Hg^+ ion clocks



JILA Sr lattice clock

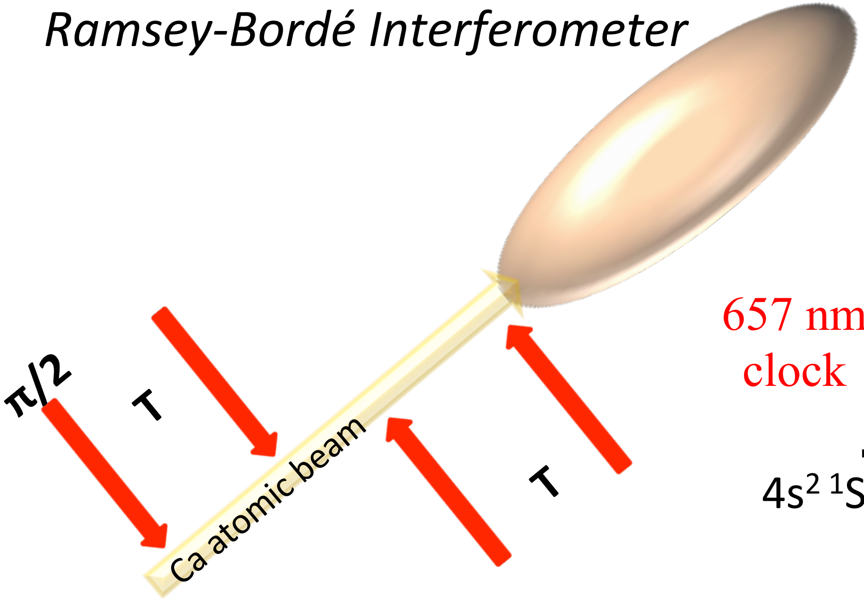
- Construction of a third, transportable system
  - overcome time transfer limitations
  - prototype for new, optically-based NIST Timescale

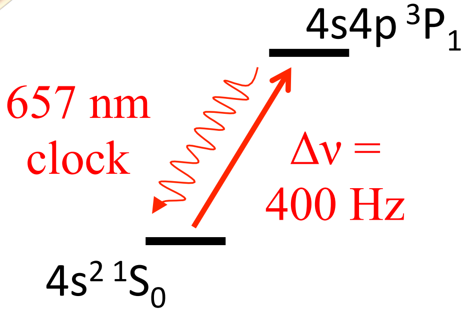


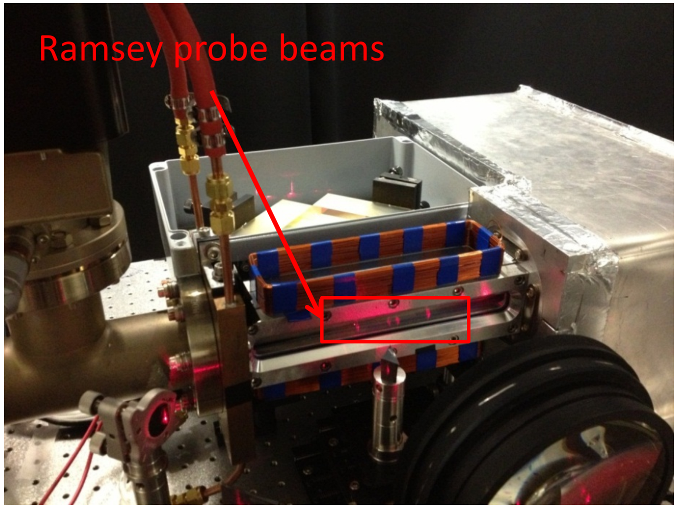
- Continued development of a compact, commercialized optical clock based on Ca

Ca thermal beam clock

Ramsey-Bordé Interferometer







- Based on research first performed at NIST in 1979 by Barger, Bergquist, et al.

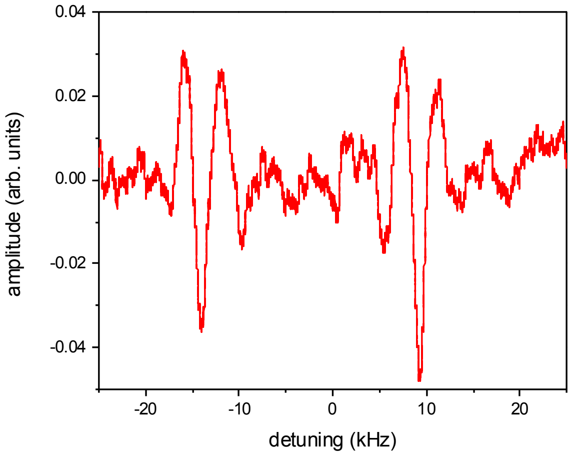
- Clock built for low instability, **not** small uncertainty – consistent with requirements of many applications

- Possible applications include low noise microwave generation, compact optical reference, ultra-stable reference oscillator for accurate clocks

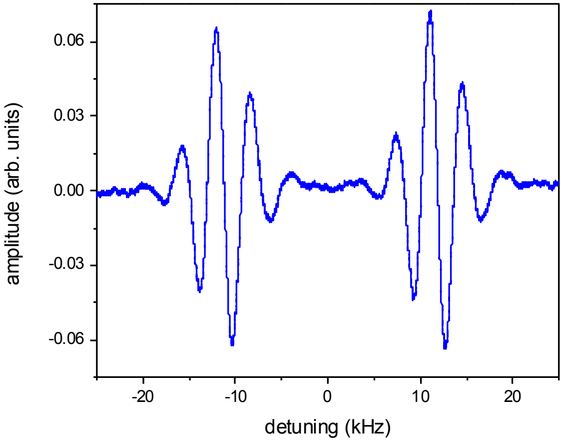
- Working with two US companies to construct field-able prototypes

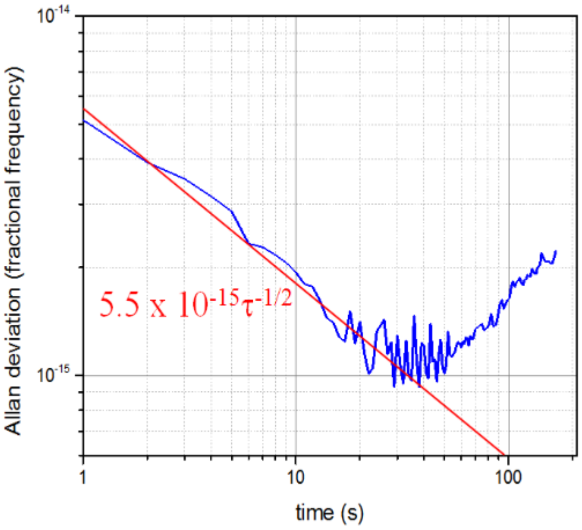
Compact Ca thermal beam clock - results

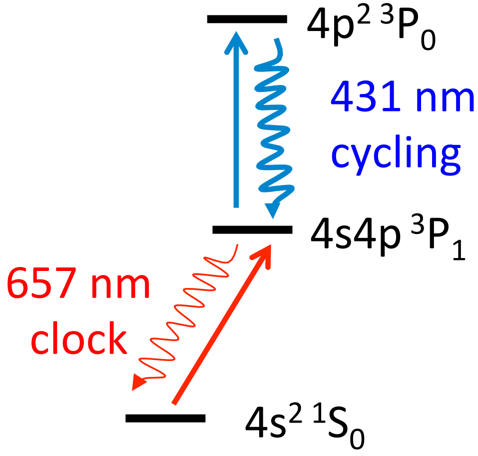
red detection



blue detection







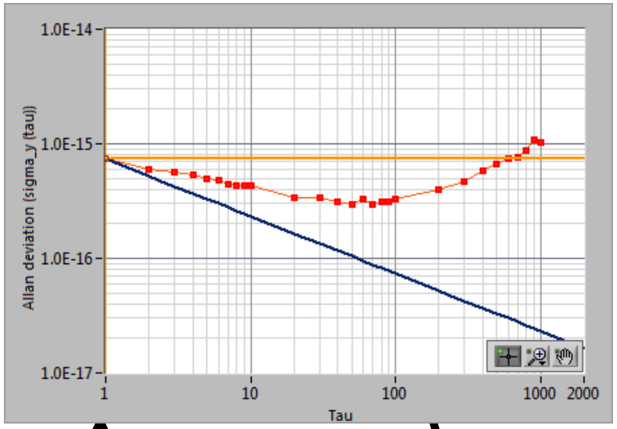
$4p^2\ {}^3P_0$

431 nm cycling

$4s4p\ {}^3P_1$

657 nm clock

$4s^2\ {}^1S_0$



7. 4 x 10^{-16} @ 1s

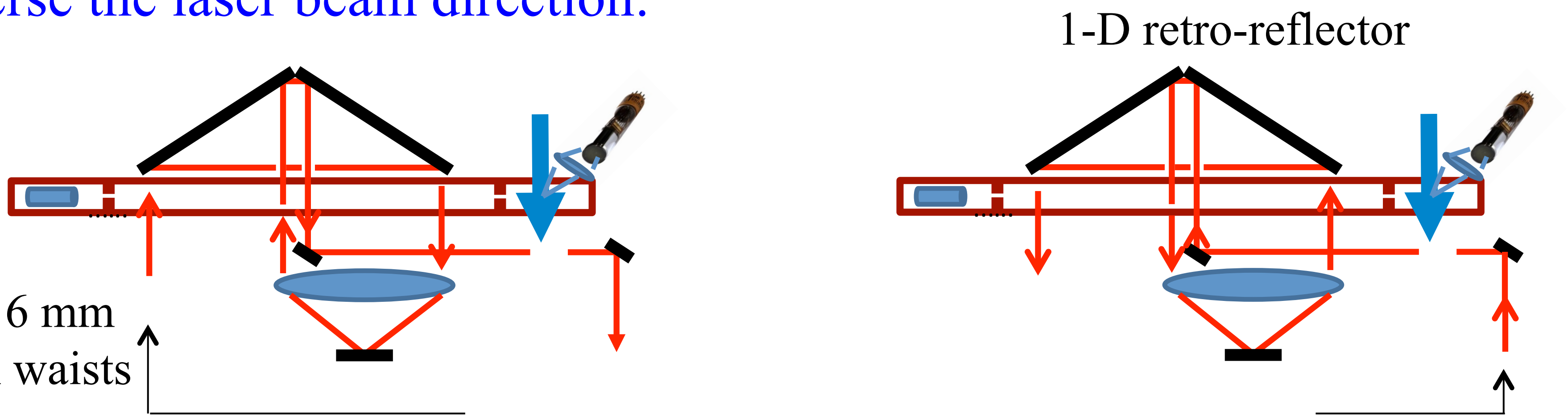
3 x 10^{-16} @ 50s

~ 100x lower instability than any other thermal-atom based system

Competitive with more complicated systems (and cavities?) on short time scales?

Beam reversal to cancel 1st order Doppler

Reverse the laser beam direction:



Or reverse the atoms!