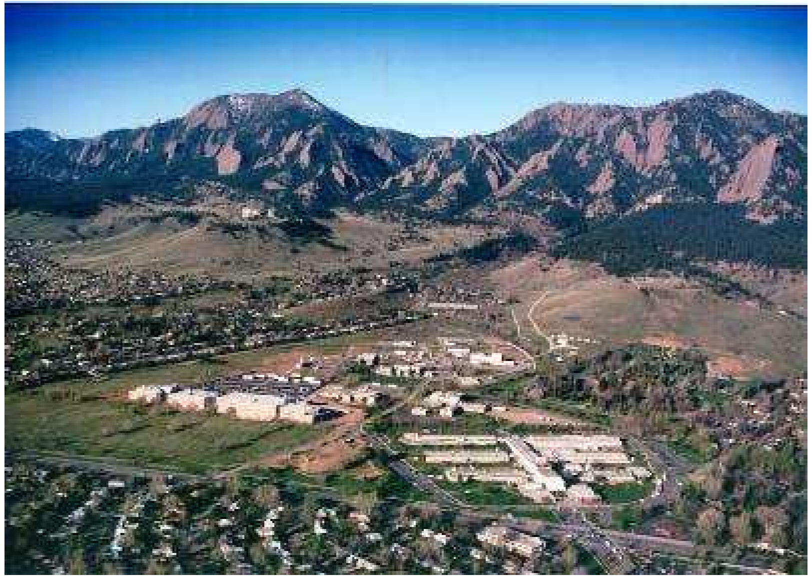
Optical Clock Network at NIST-Boulder



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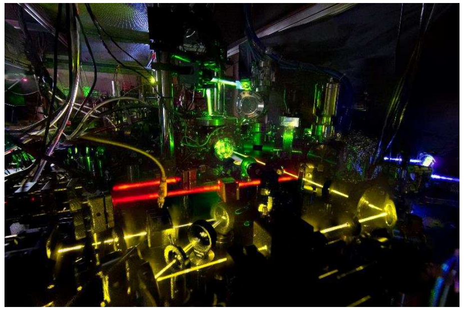
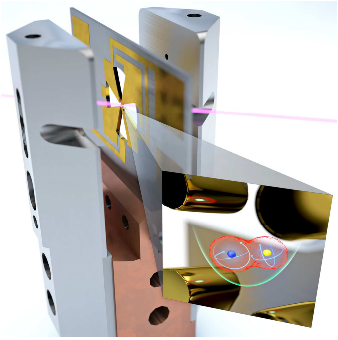
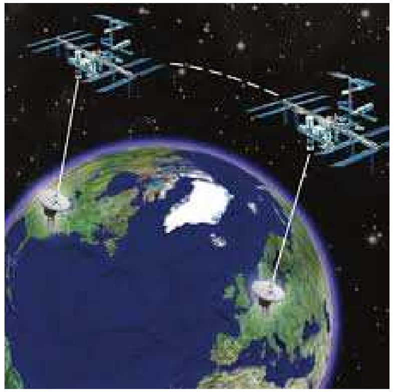
NIST's role in the ACES Mission

1) Microwave Link Ground Terminal (MWL GT)

2) Clock ensemble for international clock comparisons via the microwave link







Microwave Link Ground Terminal

1) Installed MWL GT hardware on the roof of the Gebbie Labs

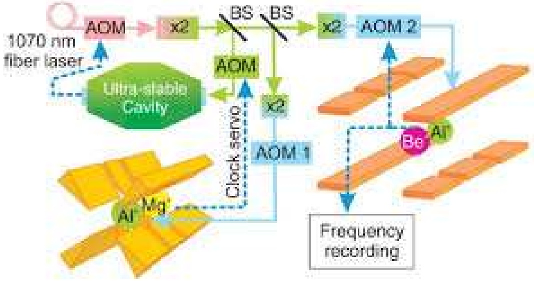
2) Moving ground plane of NIST time scale near the link

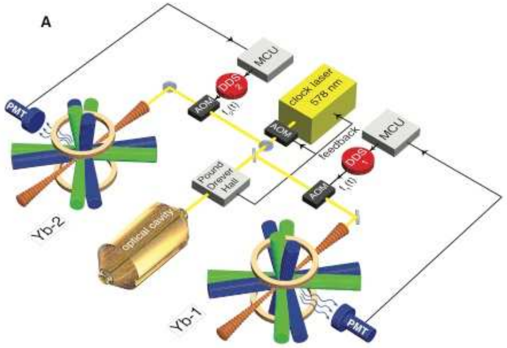
3) Preparing data analysis with simulated ACES clock signals

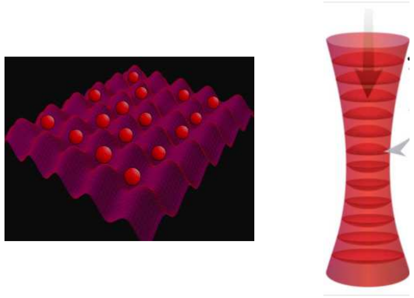
Atomic clocks at NIST

1) NIST Timescale based on an ensemble of microwave clocks

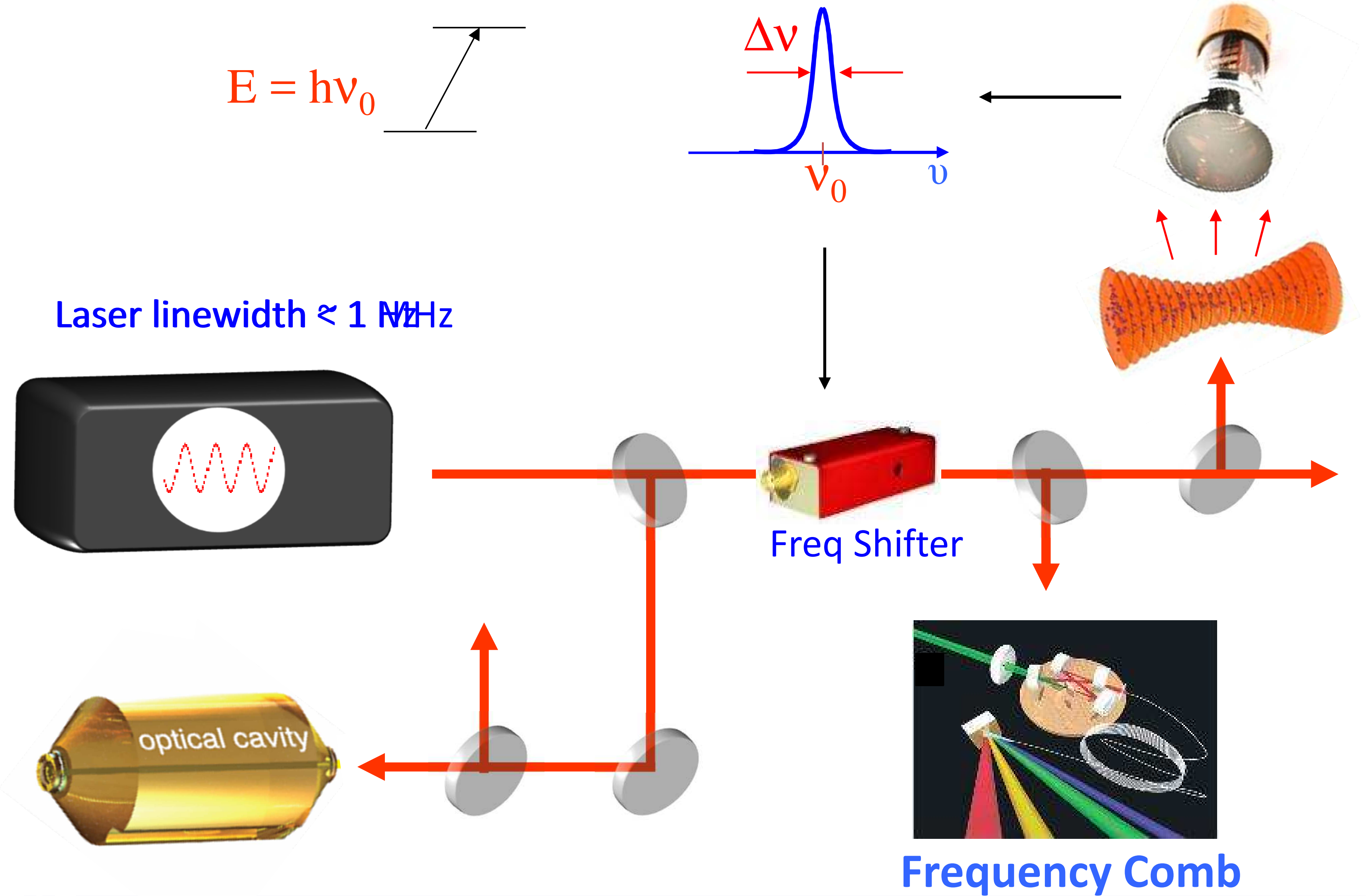
2) Collection of optical clocks based on charged and neutral atoms







Building blocks of an optical atomic clock



$E = h\nu_0$

$\Delta\nu$

ν_0

υ

Laser linewidth ≲ 1 MHz

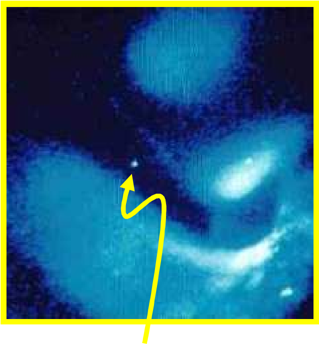
Freq Shifter

Frequency Comb

Two types of trapped atom optical clocks

Harmonic traps suppress motional effects, enable long interaction times

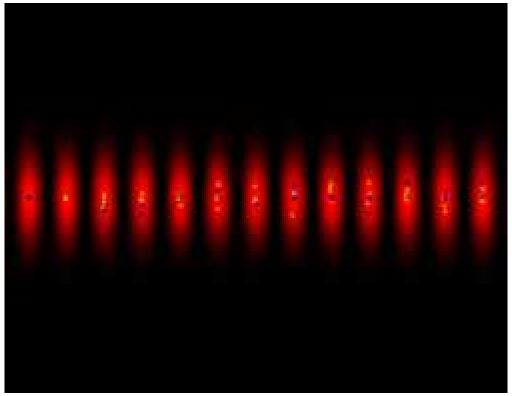
Trapped ions: Al^+, Hg^+, Yb^+, Sr^+, Ca^+



Exc. immunity to environmental effects

Limited S/N ratio – typically one clock ion

Neutral atoms: Sr, Yb, Hg, Ca



Need to use tailored optical lattices in 1, 2, or 3D

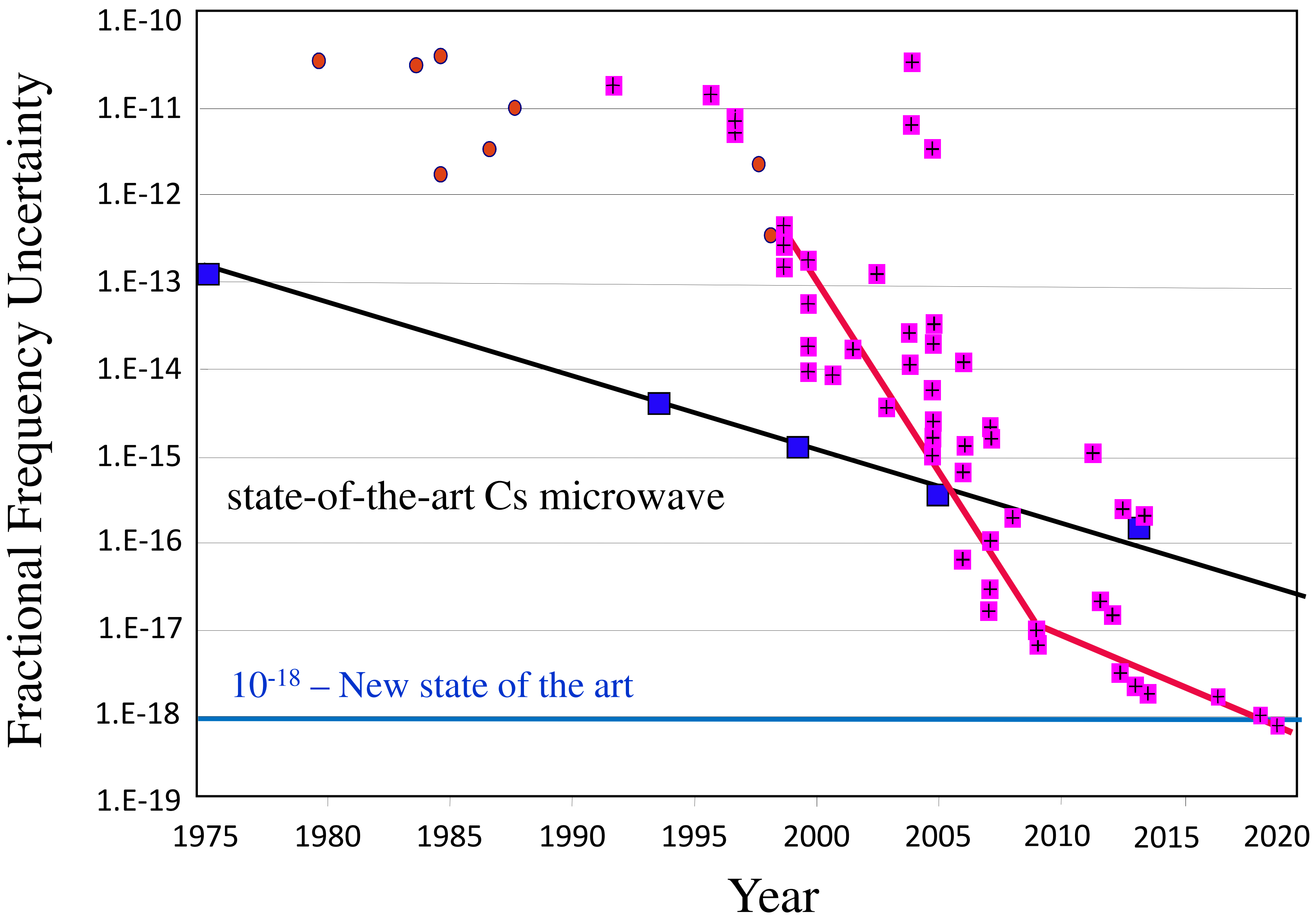
(Prof. H. Katori, U of Tokyo)

Good immunity to environmental effects

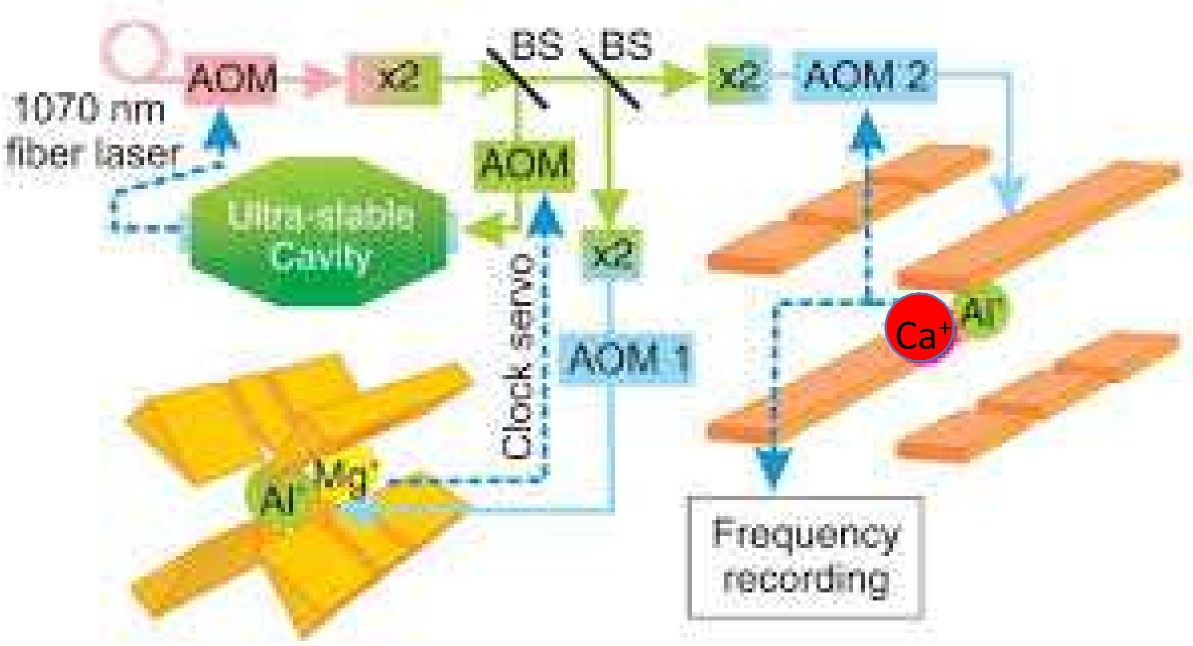
Potential for very high S/N (N > 10,000)

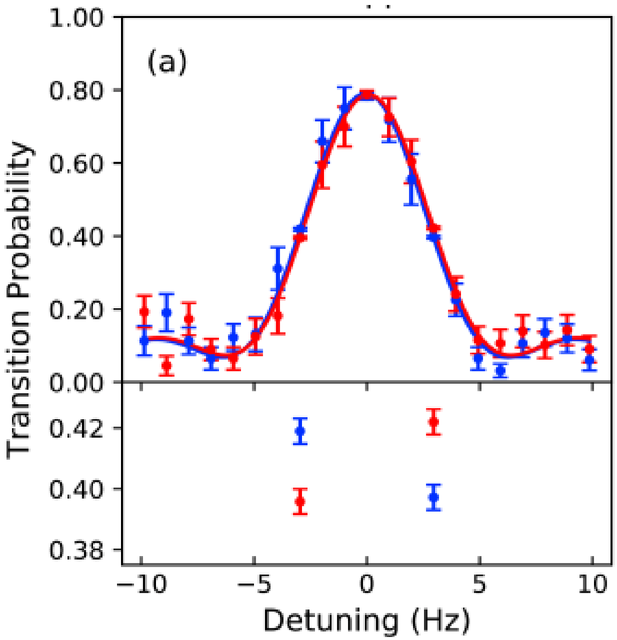
Dozens of trapped-atom optical clocks worldwide

Uncertainty of atomic clocks through the years



Recent progress in optical clocks at NIST – Al⁺ clock





- Two systems: Al⁺-Mg⁺ , Al⁺-Ca⁺

- Reduced secular motion heating – operation near 3-D ground state

Brewer et al., PRL 123, 033201 (2019)

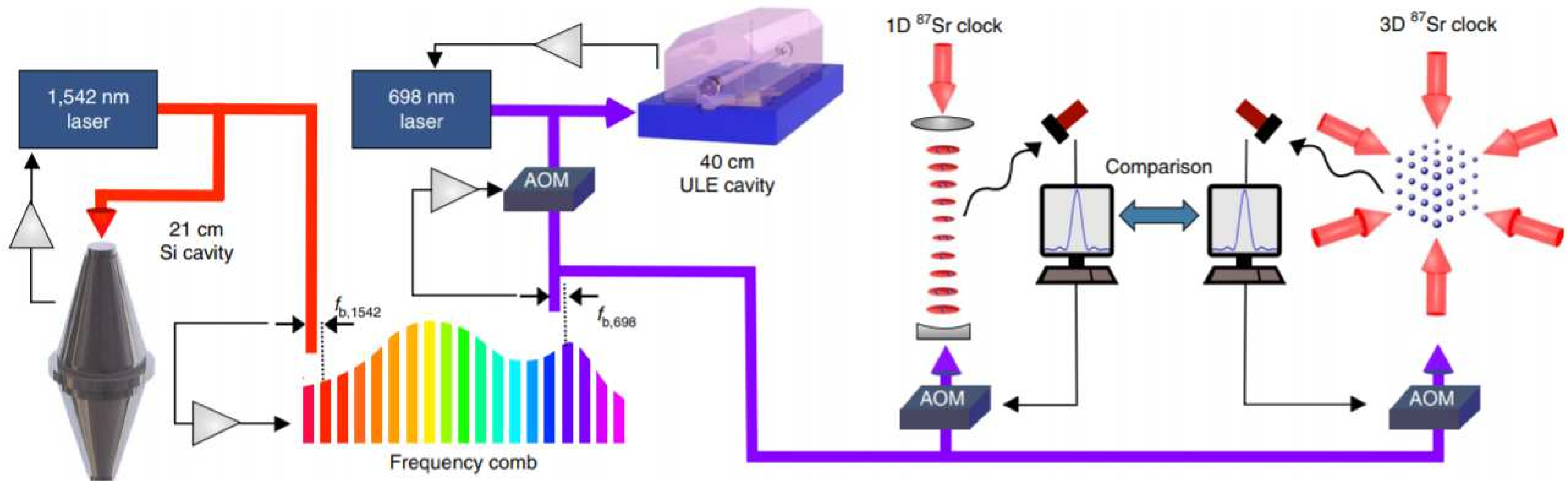
Frequency uncertainty for the Al⁺ clock

Effect	Shift (10^{-19})	Uncertainty (10^{-19})
Excess micromotion	-45.7	5.9
Blackbody radiation	-30.5	4.3
Quadratic Zeeman	-9241.6	3.7
Secular motion	-17.3	2.9
Background gas collisions	-0.6	2.4
Firs		
Clock laser Stark	0	2.0
Others	0	<1
Total	-9335.7	9.5 x 10^{-19}

First atomic clock uncertainty in the 10^{-19}'s

Brewer et al., PRL 123, 033201 (2019)

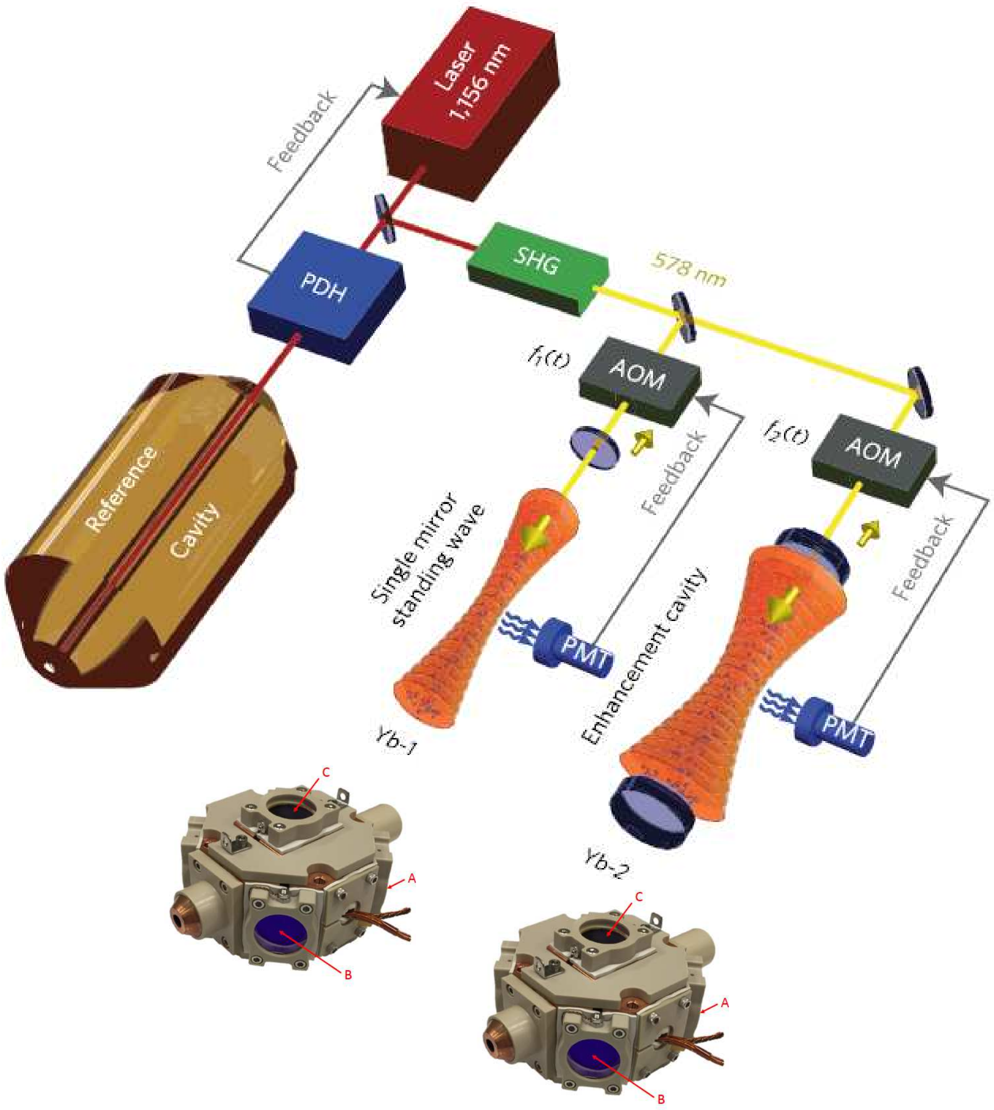
Recent progress – JILA Sr lattice clocks

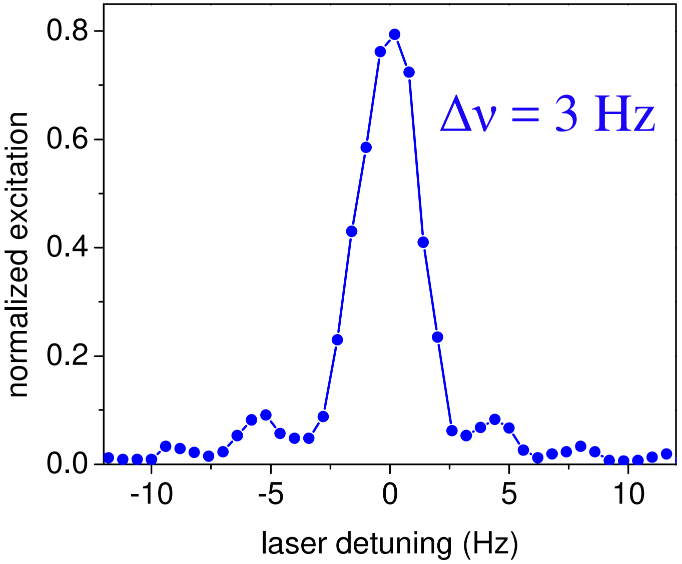


- Two operational Sr lattice clocks with different dimensionality
- Demonstrated record clock fractional instability ~ 5 x 10^{-17} @ 1 s
- Sr clock fractional uncertainty 2.0 x 10^{-18}
- Dramatic cavity progress (with PTB) ~ thermal noise floor of 6.5 x 10^{-17}

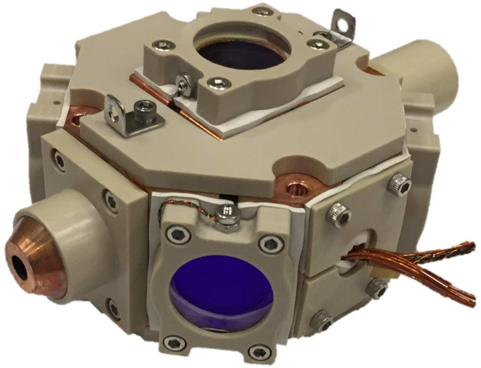
Bothwell et al., arXiv:1906.06004 (2019) Oelker et al., Nat. Phot. 13, 714 (2019)

Recent Progress - NIST Yb lattice clocks





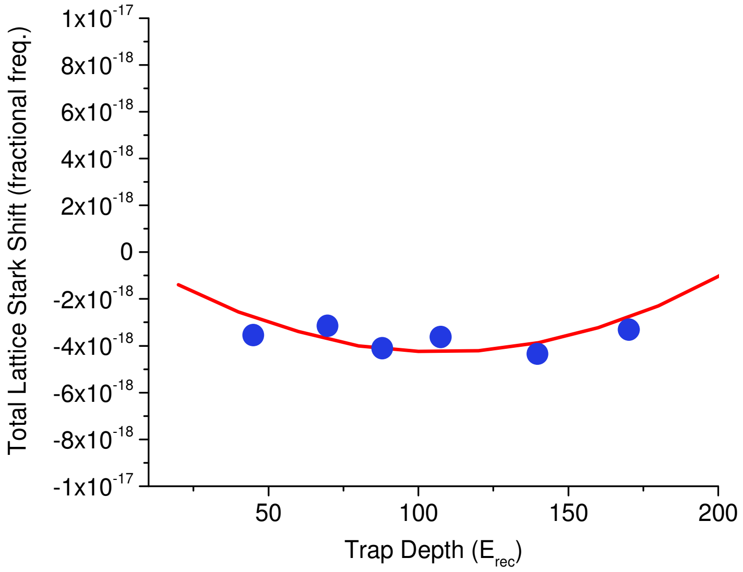
Reducing Yb lattice clock systematic effects

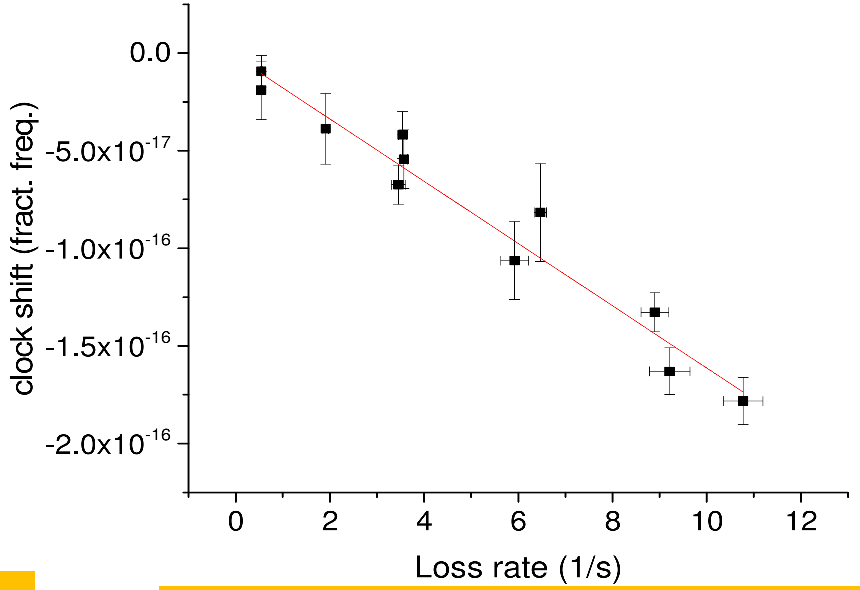


DC Stark uncertainty < 4 x 10^{-20}

Room temperature BBR uncertainty to < 5 x 10^{-19}

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





Lattice Stark shift uncertainty to < 8 x 10^{-19}

Collisional effects ~ 4 x 10^{-19}

Katori et al., PRA **113** 260801 (2014)

Gibble PRL **110**, 180802 (2013)

Yb lattice clock uncertainty budget

	Yb-1 ($\times 10^{-18}$)		Yb-2 ($\times 10^{-18}$)	
Systematic effects	**Shift**	**Uncertainty**	**Shift**	**Uncertainty**
BBR Stark	-2361.2	0.9	-2371.7	1.0
Lattice statistical	-1.5	0.8	-1.5	0.8
Lattice model	0	0.3	0	0.3
Lattice traveling wave	0	<0.1	0	0
Second-order Zeeman	-118.1	0.2	-117.9	0.1
Cold collision	-0.21	0.07	-0.04	0.02
Background gas collision	-5.5	0.5	-3.6	0.3
DC Stark				0.07
Probe AC Sta				0.01
First-order Doppler	0	0.02	0	0.01
Second-order Do				.1
Tunnelling				.01
Servo error				.1
Line Pulling	0	<0.1	0	<0.1
AO Phase Chirp (OFS)	0	0.1	0	0.1
Total	**-2486.5**	**1.4**	**-2494.7**	**1.4**

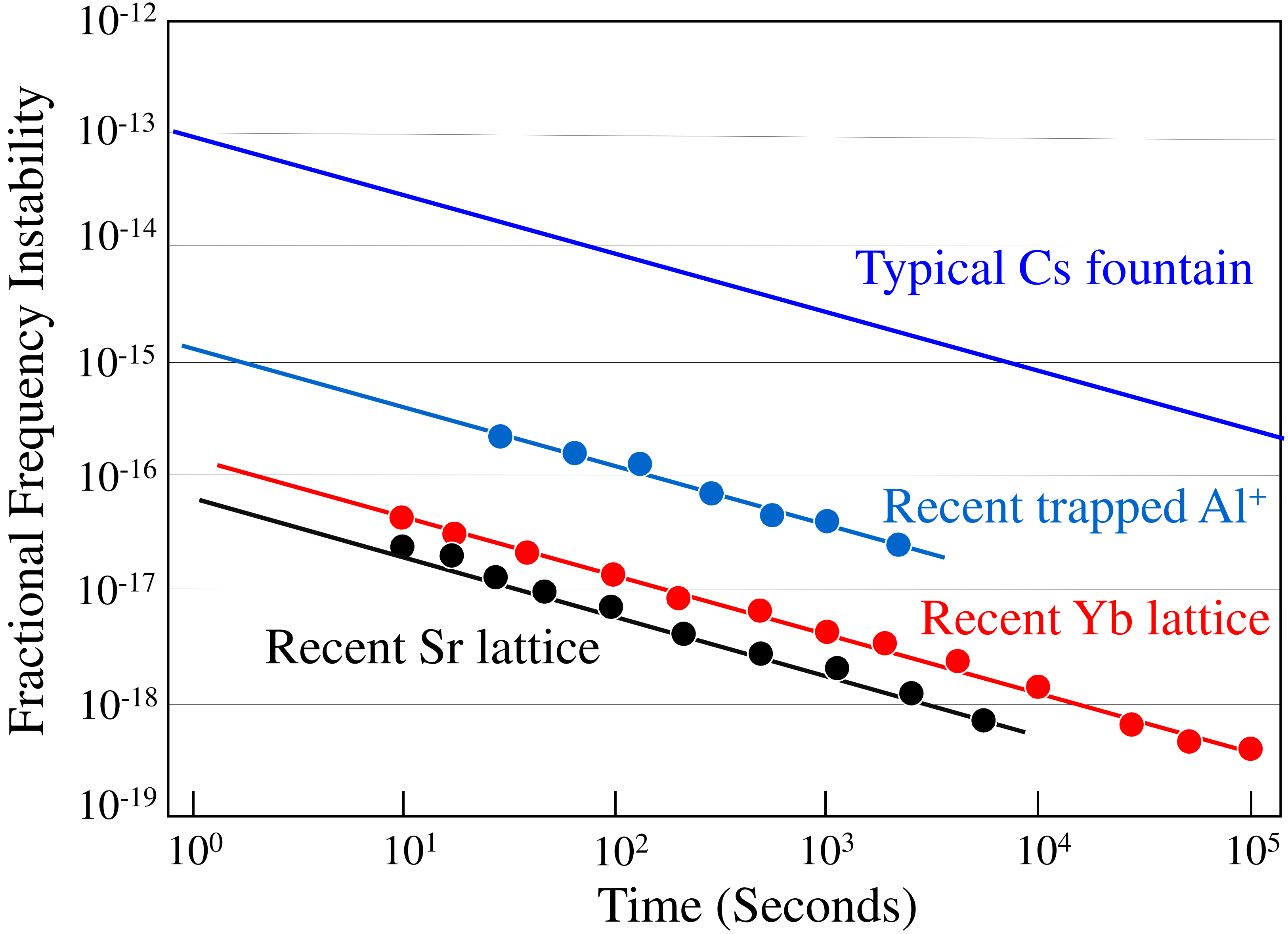
Clock uncertainty below geodetic uncertainty (6×10^{-18})

Two Yb clocks agree at 7×10^{-19}

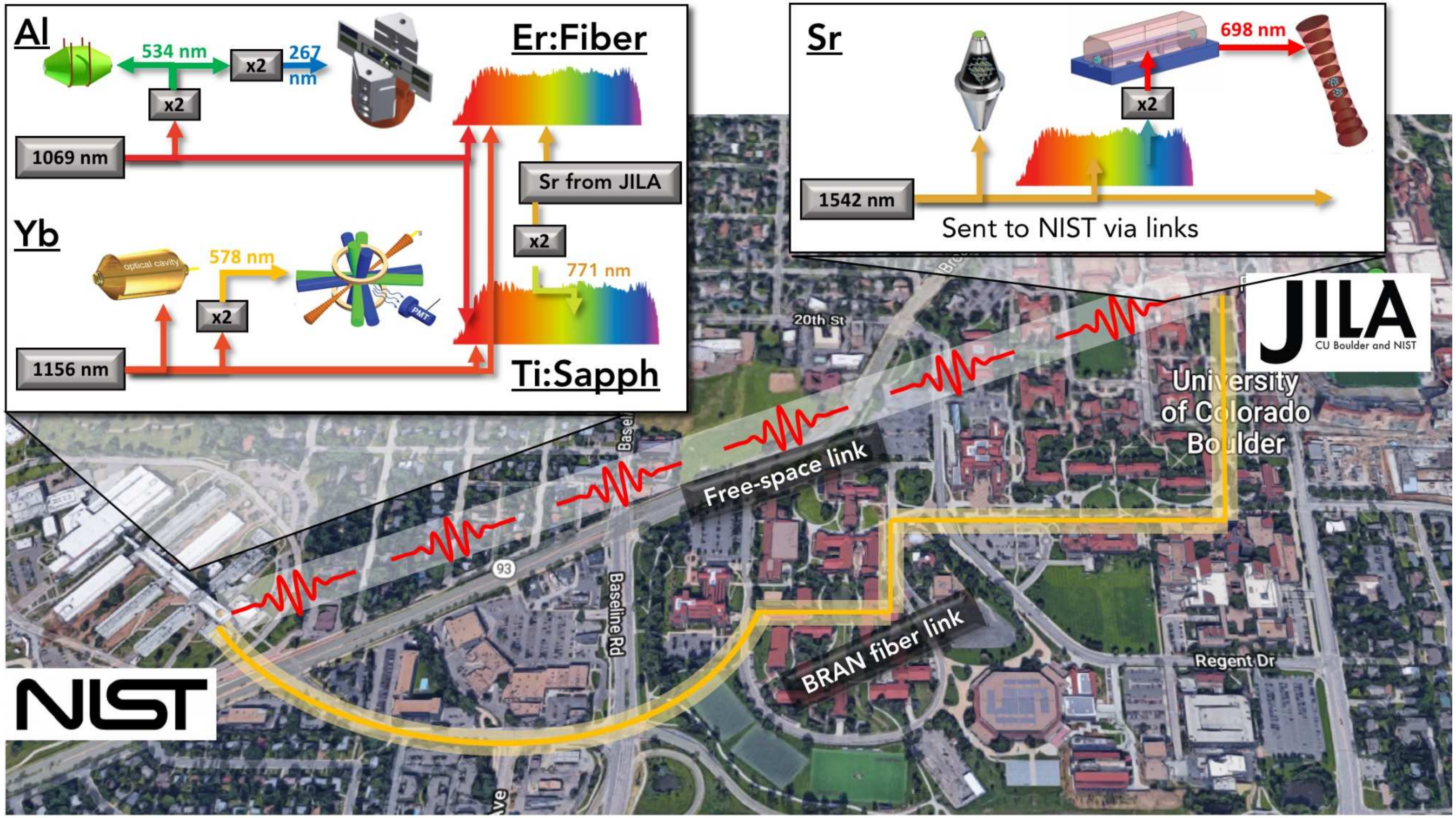
NIST clocks linked to Timescale –
Yb absolute frequency 2.1×10^{-16}

Brown et al., PRL **119**, 253001 (2017); McGrew et al., Nature **564** 87 (2018)

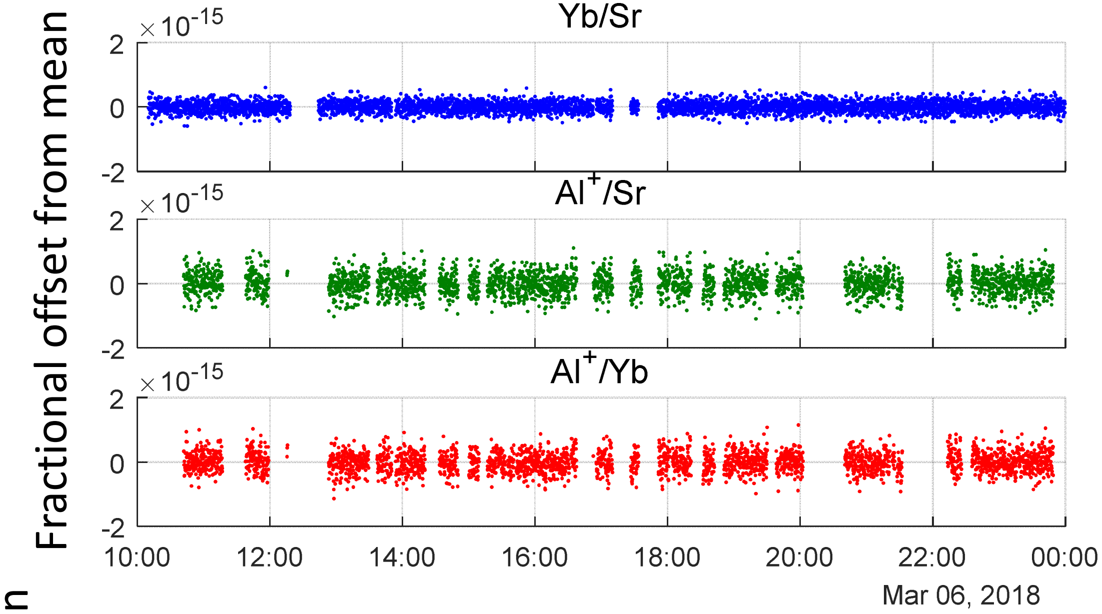
Atomic Clocks – optical clock stability



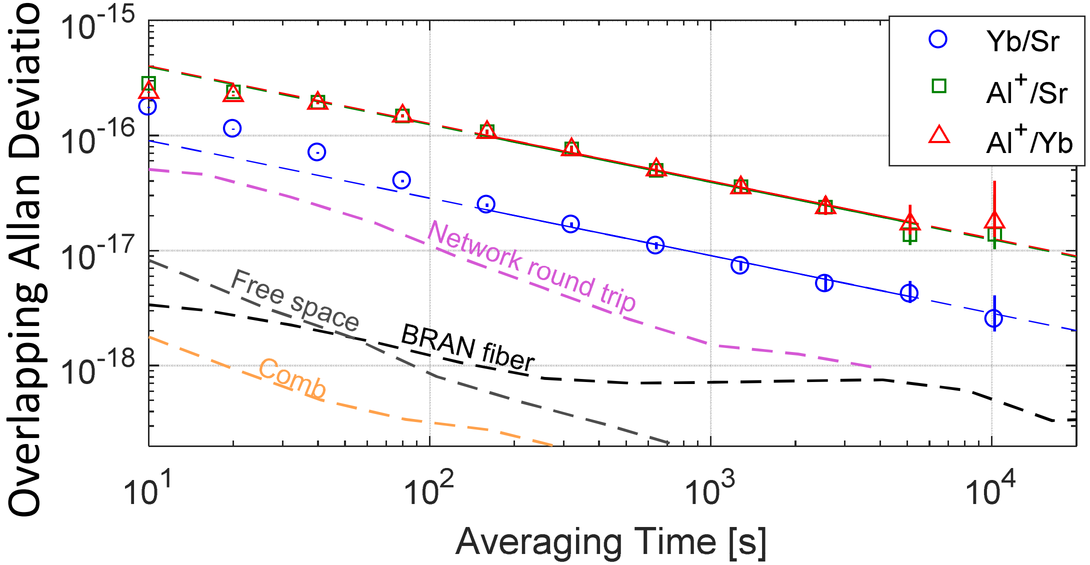
NIST/JILA optical clock comparisons



Frequency ratios between Al⁺, Sr, and Yb



- 10 s per point
- Clock uptimes 70% – 90%
- 30,000 – 40,000 seconds of data total
- Al^+ uptime limited by AlH^+ formation



- Network instabilities below the level of any of the clocks
- Extrapolate to the full dataset to estimate statistical uncertainty

Al^+ clock stability: 1.3×10^{-15} @ 1s

Yb/Sr stability: 3.1×10^{-16} @ 1s

NIST Clock Network Summary

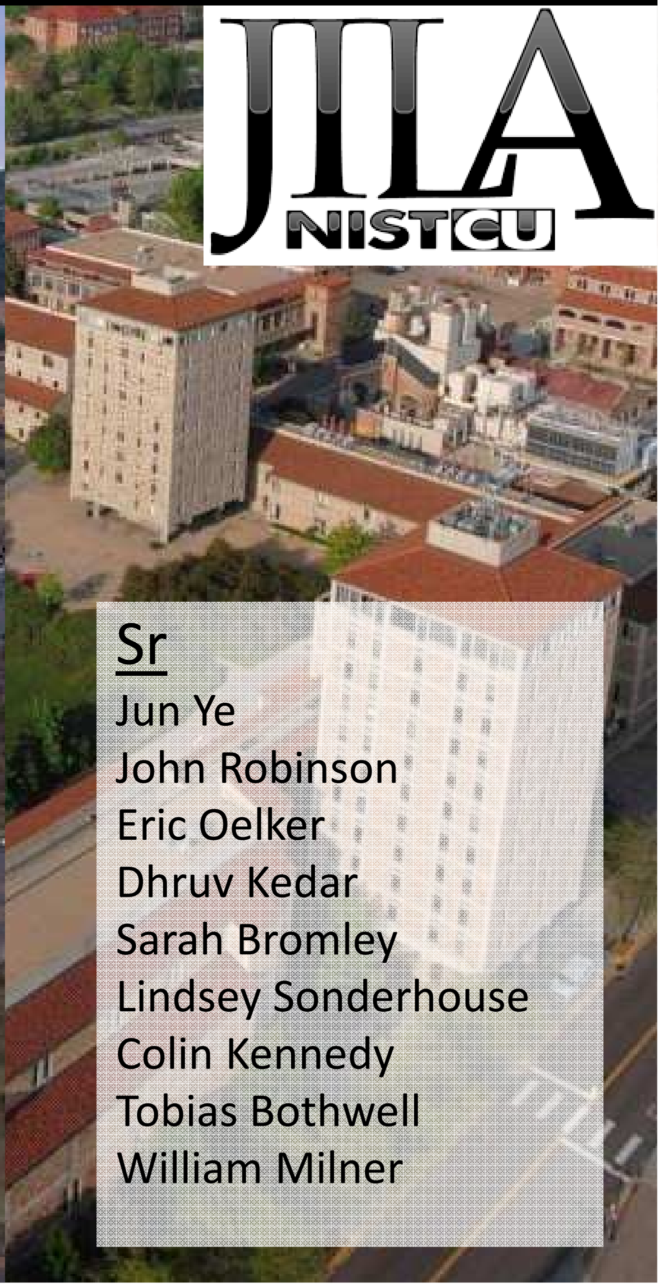
Enormous progress worldwide in optical clocks – 18+ digits

Redefinition for the SI second in the coming decade?

- The clocks in the NIST network are involved in a variety of experiments
  - Frequency ratios between optical clocks (search for ultralight scalar dark matter)
  - Long term comparisons (explore gravitational coupling to the fundamental constants and LPI violations)
  - Global observatory of optical clocks for constraining coupling to topological dark matter

- NIST's highest performance clocks are now linked to each other and to the NIST timescale – ready for international clock comparisons via ACES

The Teams



Al
David Leibrandt
David Wineland
David Hume
Samuel Brewer
Jwo-Sy Chen

Yb
Andrew Ludlow
Kyle Beloy
William McGrew
Xiaogang Zhang
Robbie Fasano
Daniele Nicolodi

Free Space
Nathan Newbury
Laura Sinclair
J-D Deschenes
Isaac Khader
Martha Bodine
Bill Swann

Combs
Scott Diddams
Tara Fortier
Holly Leopardi

Timescale
Jeff Sherman
Tom Parker
Jian Yao

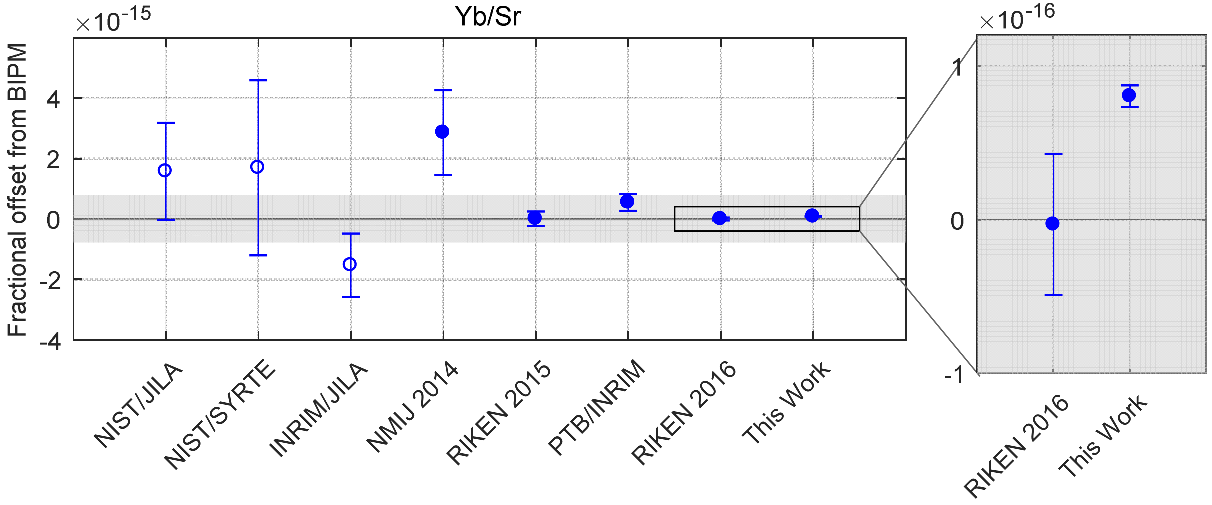
Sr
Jun Ye
John Robinson
Eric Oelker
Dhruv Kedar
Sarah Bromley
Lindsey Sonderhouse
Colin Kennedy
Tobias Bothwell
William Milner

Uncertainties in the ratio measurements

Total uncertainty for all frequency ratios (**units 10^{-18}**)

	Al^+/Yb	Al^+/Sr	Yb/Sr
$^{27}Al^+$	1.6	1.5	--
^{171}Yb	1.4	--	1.4
^{87}Sr	--	6.7	6.8
Network	< 0.4	< 0.1	< 0.1
Geopotential	0.2	0.4	0.4
Statistical	5.4	5.7	4.2
Total	**8.1**	**8.9**	**8.1**

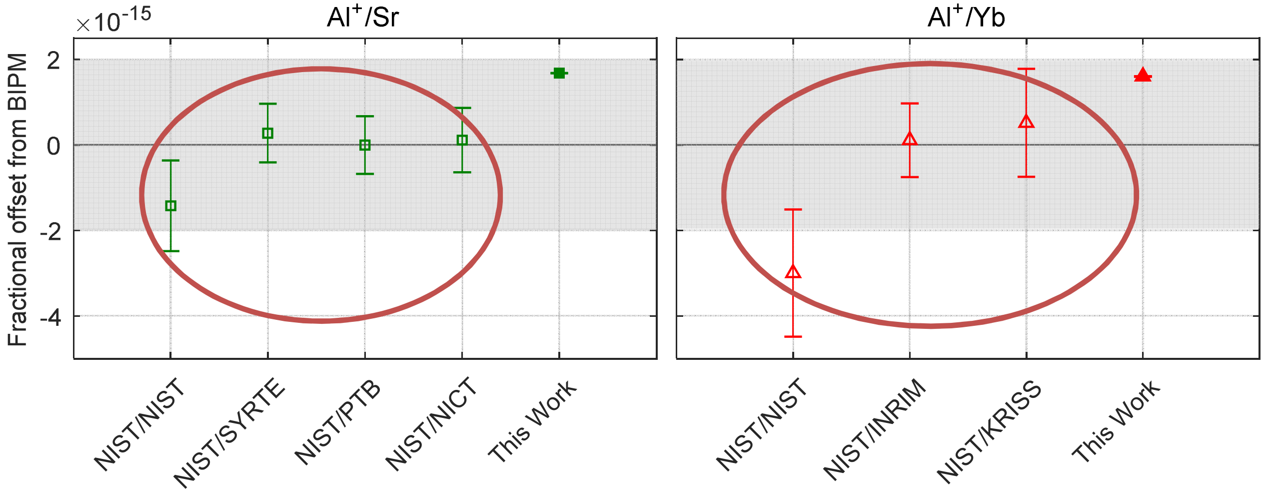
Comparison with ratio values worldwide



▨ BIPM uncertainty

Open symbols: Absolute frequency measurements

Closed symbols: Direct comparisons



Based on Al^+/Hg^+ ratio measurement combined with Hg^+ absolute frequency measurement

Fundamental physics with time/frequency metrology

Our existing theories (QFT(SM), GR, ΛCDM) are not complete

Timing tests:

Compare clocks at different speeds, locations, gravitational fields

Improve the tests (tighter constraints):

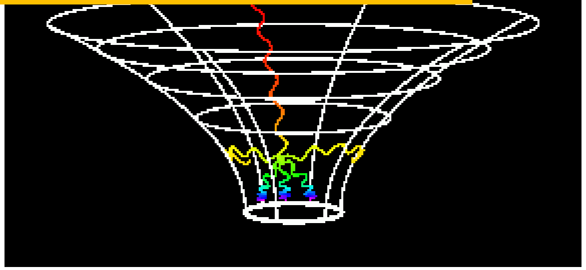
1) Enhance sensitivities => Go to space
2) Improve clock performance

Freq

(i) U

(ii) Local Lorentz Invariance (isotropy of speed of light, Atomic energy levels, Lorentz symmetries)

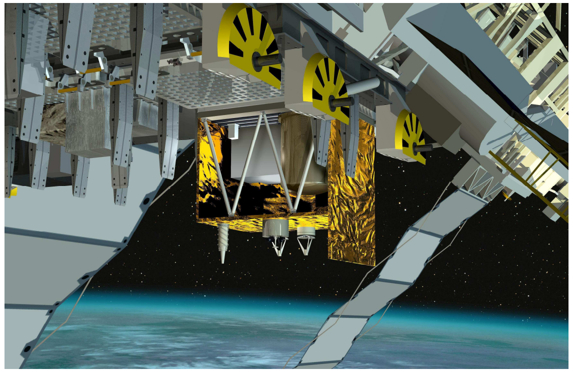
(iii) Local Position Invariance (drifts of fundamental constants, gravitation redshift)



Jila.edu

Delva, Hees, and Wolf, Space Science Reviews **212**, 1385 (2017).

Cs microwave clock in space – ESA ACES program



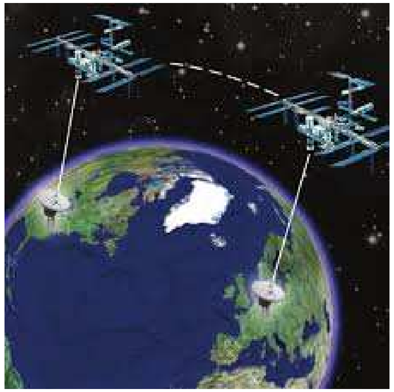
Slow Cs beam clock – 10 s interaction

~10^{-16} uncertainty

~$10^{-13}\ \tau^{-1/2}$ instability

Mission clock objectives:

high performance atomic clocks in space environment
high stability space-to-ground t/f transfer,
synchronize ground clocks, improve international time



Physics tests:

accurate measurement of gravitational redshift (35x)
search for drifts of fundamental constants ($< 10^{-17}$/year)
test standard model extension ($\delta c/c < 10^{-10}$)

Deep Space Atomic Clock – microwave ion clock for deep space navigation