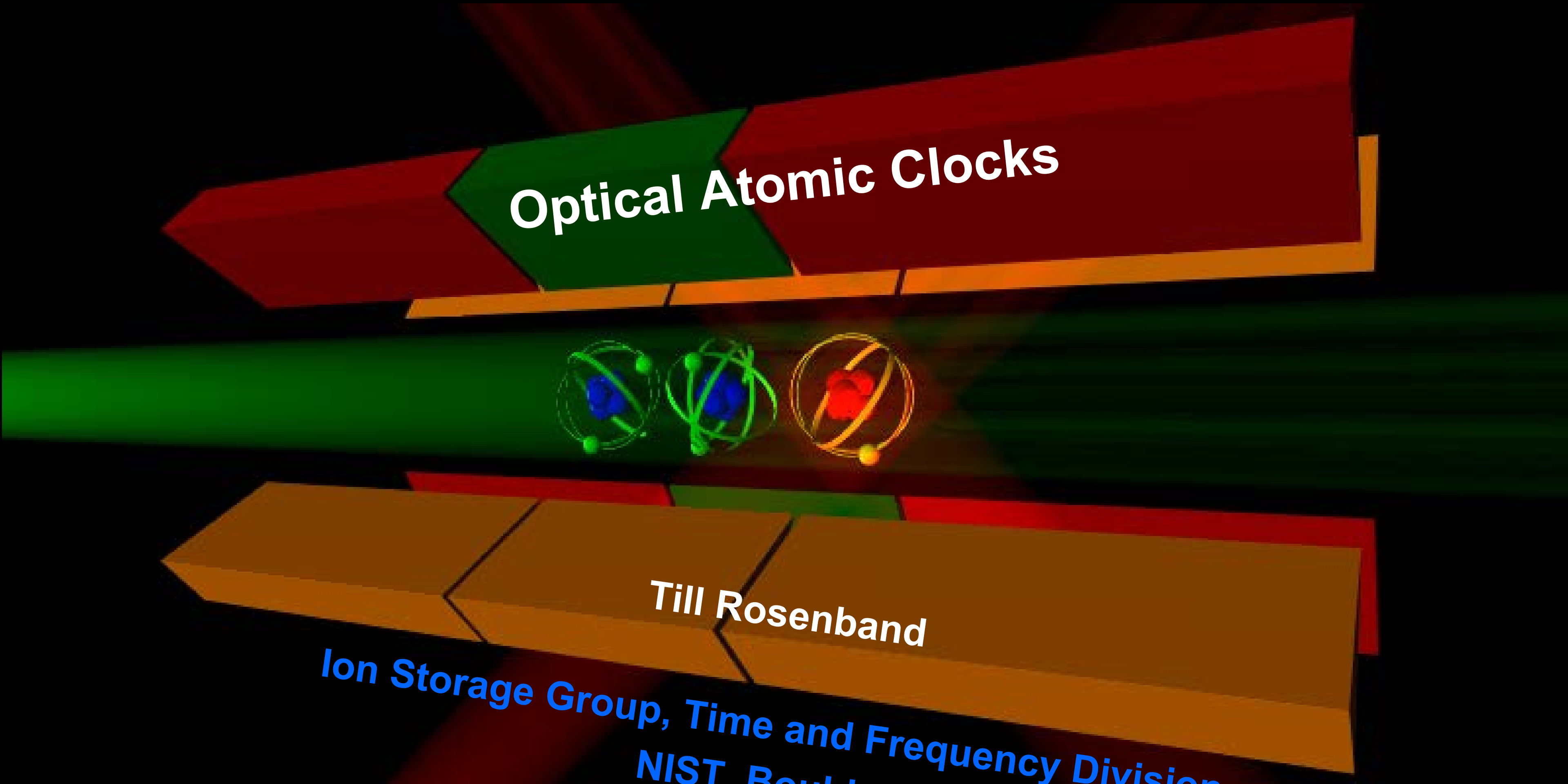
Optical Atomic Clocks



Till Rosenband

Ion Storage Group, Time and Frequency Division
NIST, Boulder

The only reason for time is so that everything doesn't happen at once.

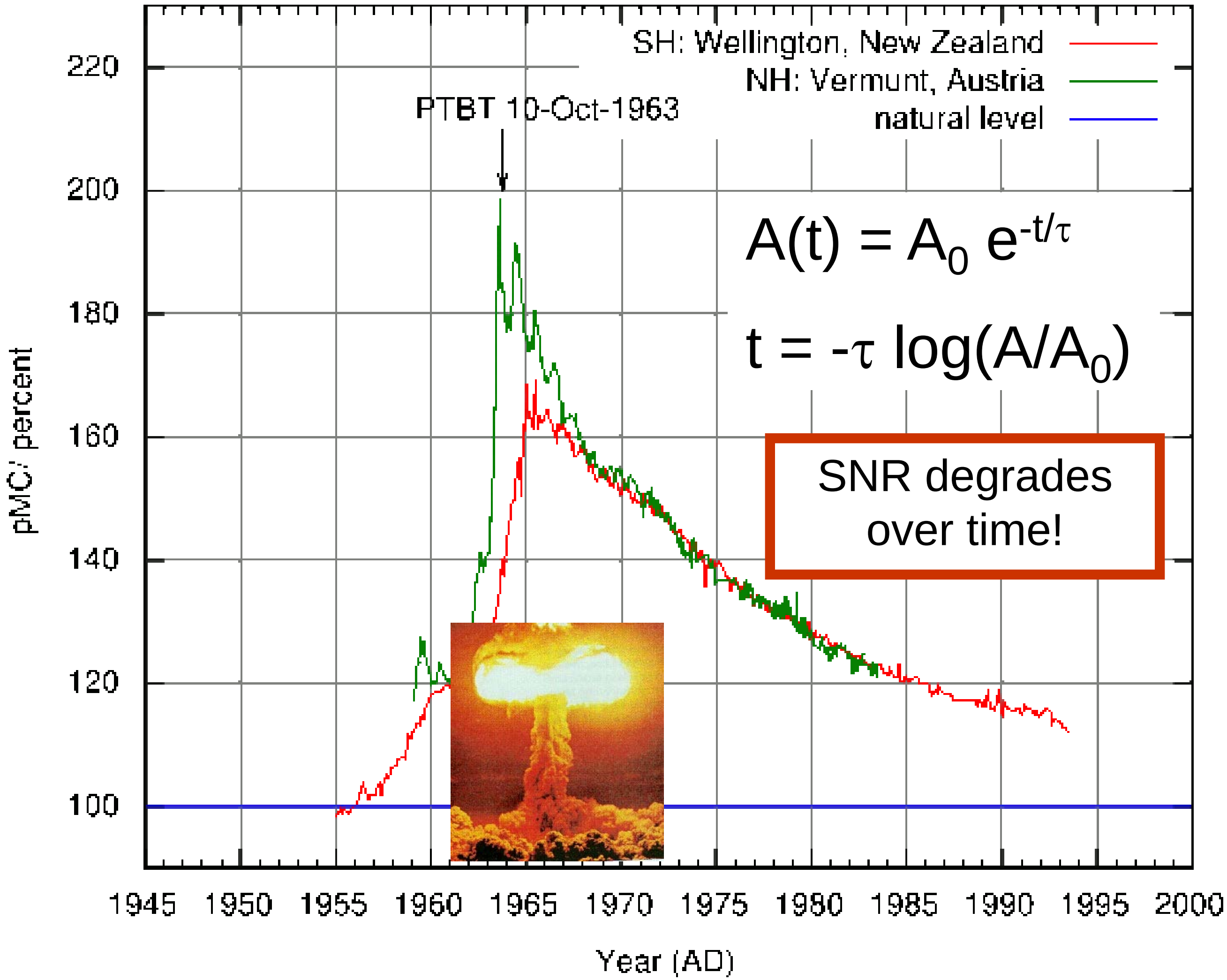
- Albert Einstein

What is a clock?

Salvador Dali: *The Persistence of Memory* (1931)

Any time-dependent physical process that can be inverted mathematically

Radiocarbon clock

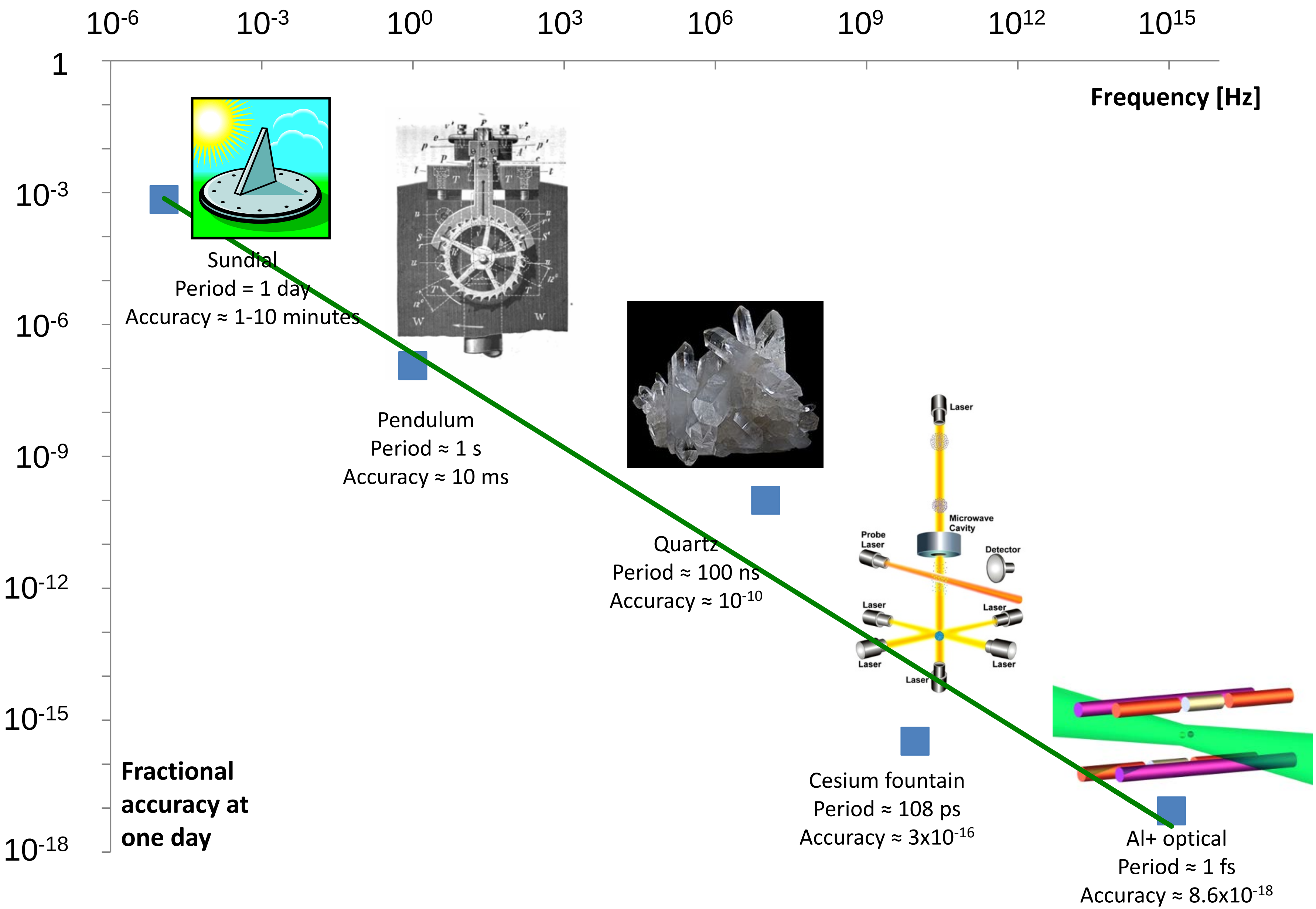


$$A(t) = A_0\, e^{-t/\tau}$$

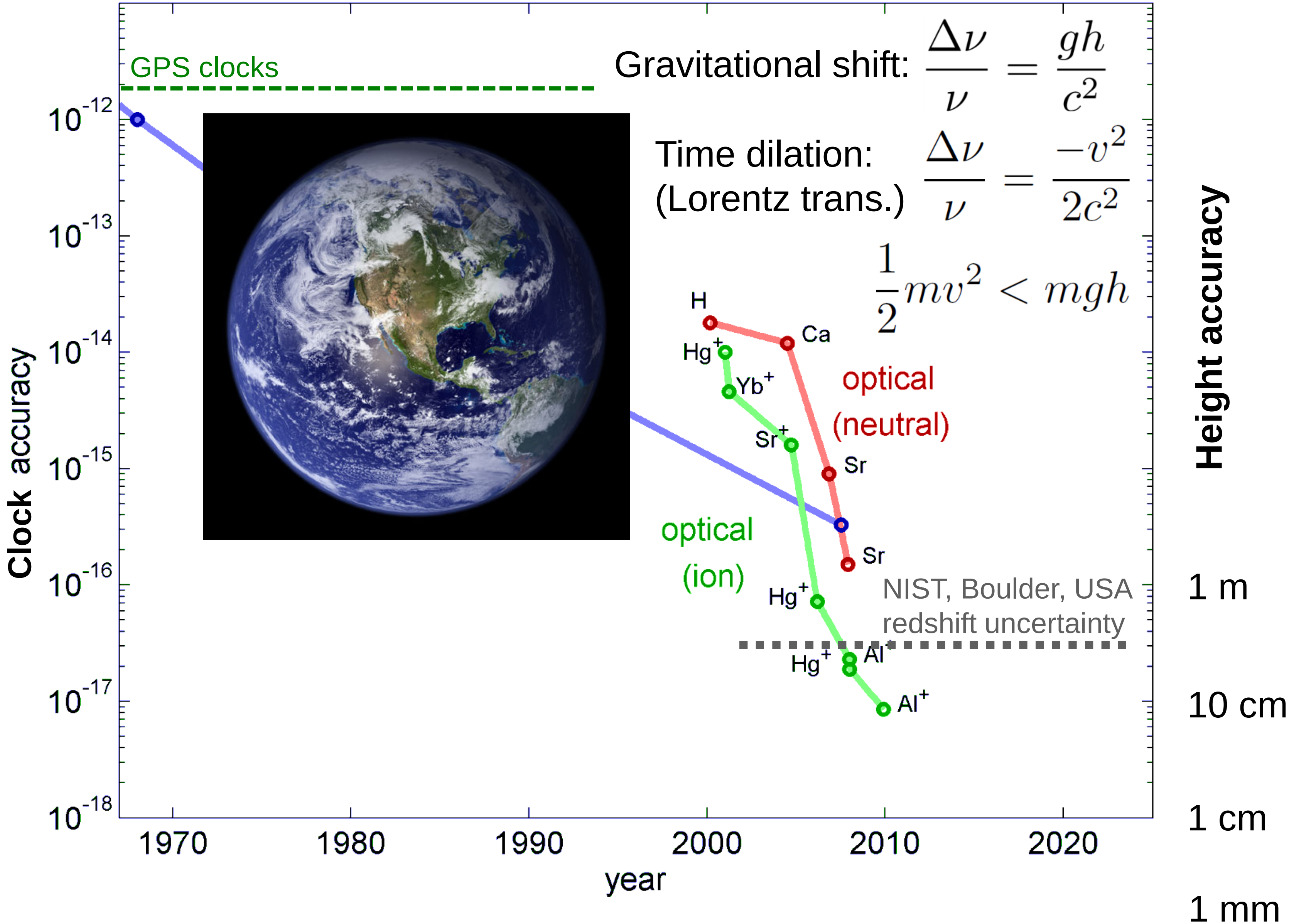
$$t = -\tau \log(A/A_0)$$

SNR degrades over time!

Clock speed vs. accuracy



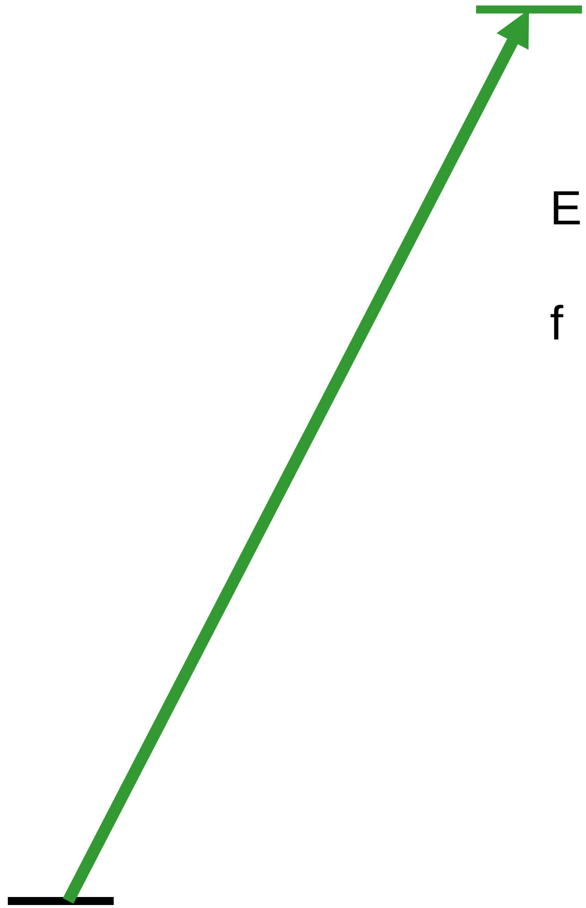
Recent atomic clock accuracy



$^{27}Al^+$

$I = 5/2$

$2p^63s3p$ $\quad$ $^3P_0$ λ=267.43 nm, τ=21 s



E = 4.636 146 95 (10) eV

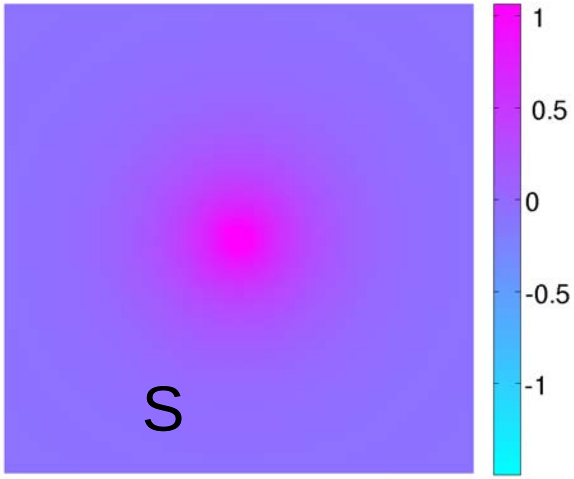
f = 1 121 015 393 207 857.4(7) Hz

- Insensitive to external fields
- Smallest known temperature sensitivity (5×10^{-20} / Kelvin)
- Two-ion quantum logic techniques for cooling, state preparation & clock readout [1]

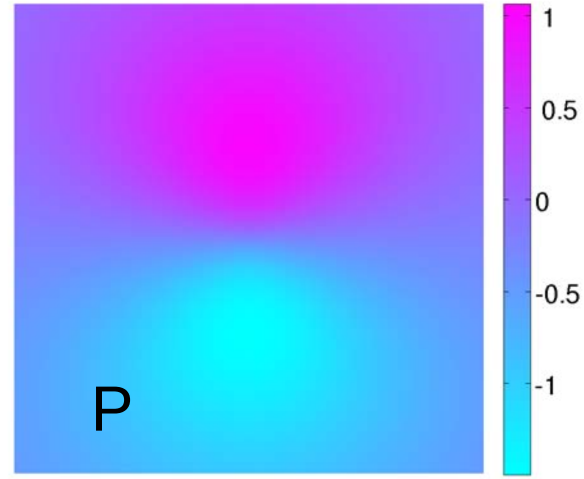
$2p^63s^2$ $\quad$ $^1S_0$

[1] D.J. Wineland *et al.*,
Proc. 6th Symp. Freq. Stds. and Metrology, 2001, pp. 361-368

“Ticking” of Al^+ clock

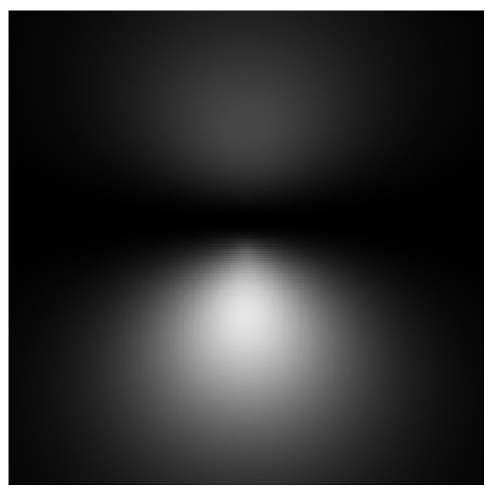


$+ \quad e^{-i\omega t}$



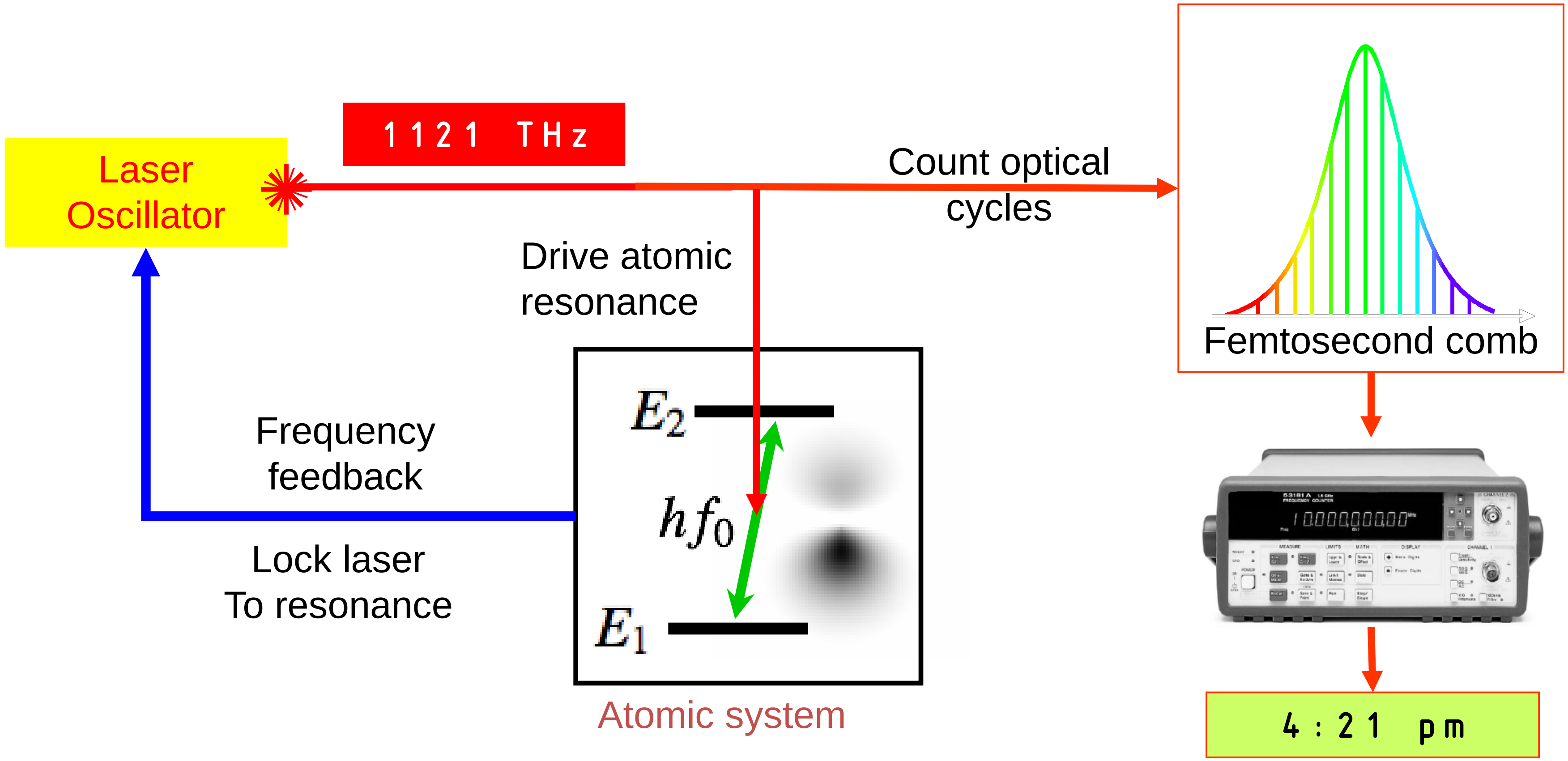
^{2}

=



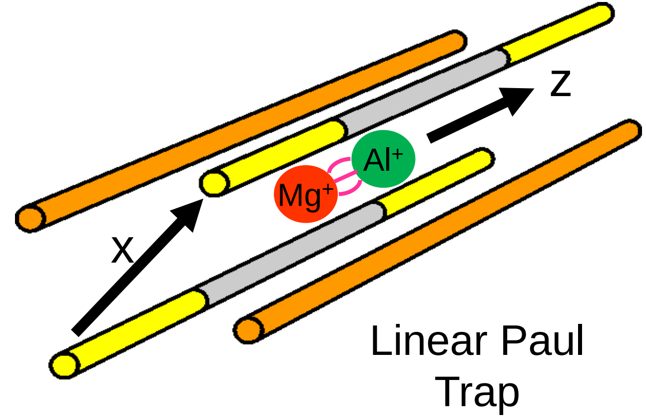
$\omega = 2\pi \times 10^{15}$ Hz

Optical Atomic Clock



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

Coupled motion (normal modes)

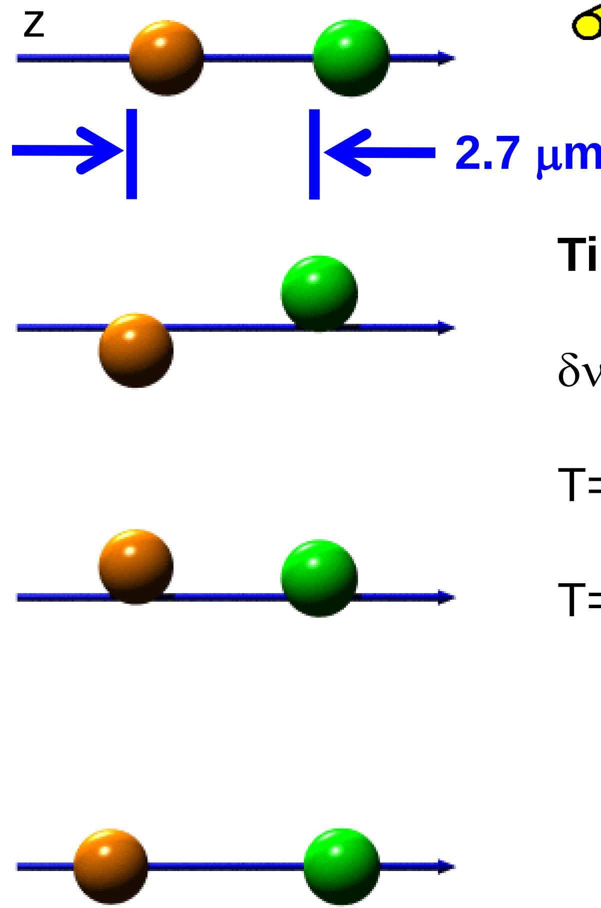


z in-phase 2.9 MHz

x out-of-phase 3.4 MHz

x in-phase 4.6 MHz

z out-of-phase 5.1 MHz



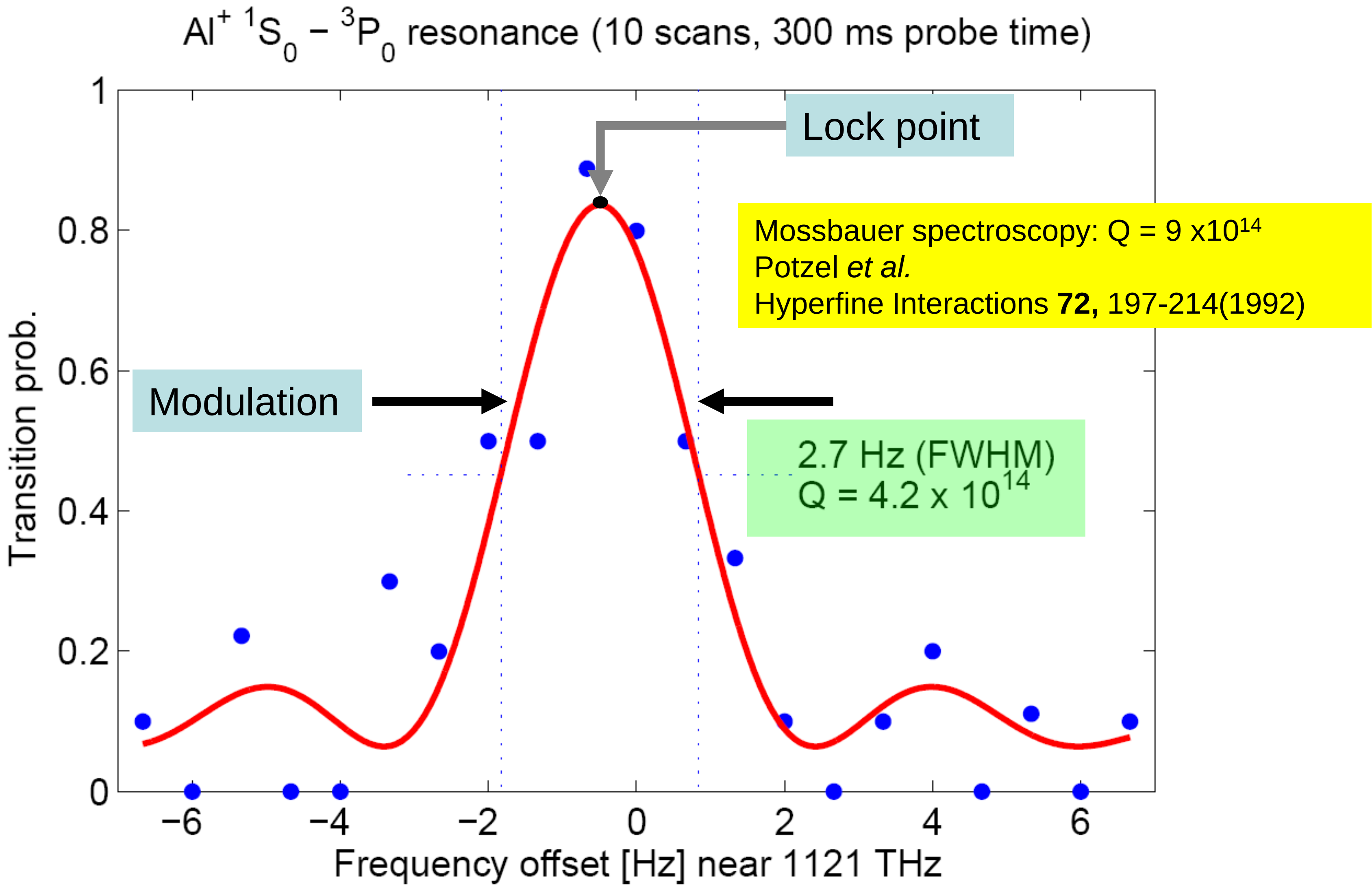
Time dilation:

$\delta\nu/\nu = v^2/(2c^2)$ $mv^2 = kT$

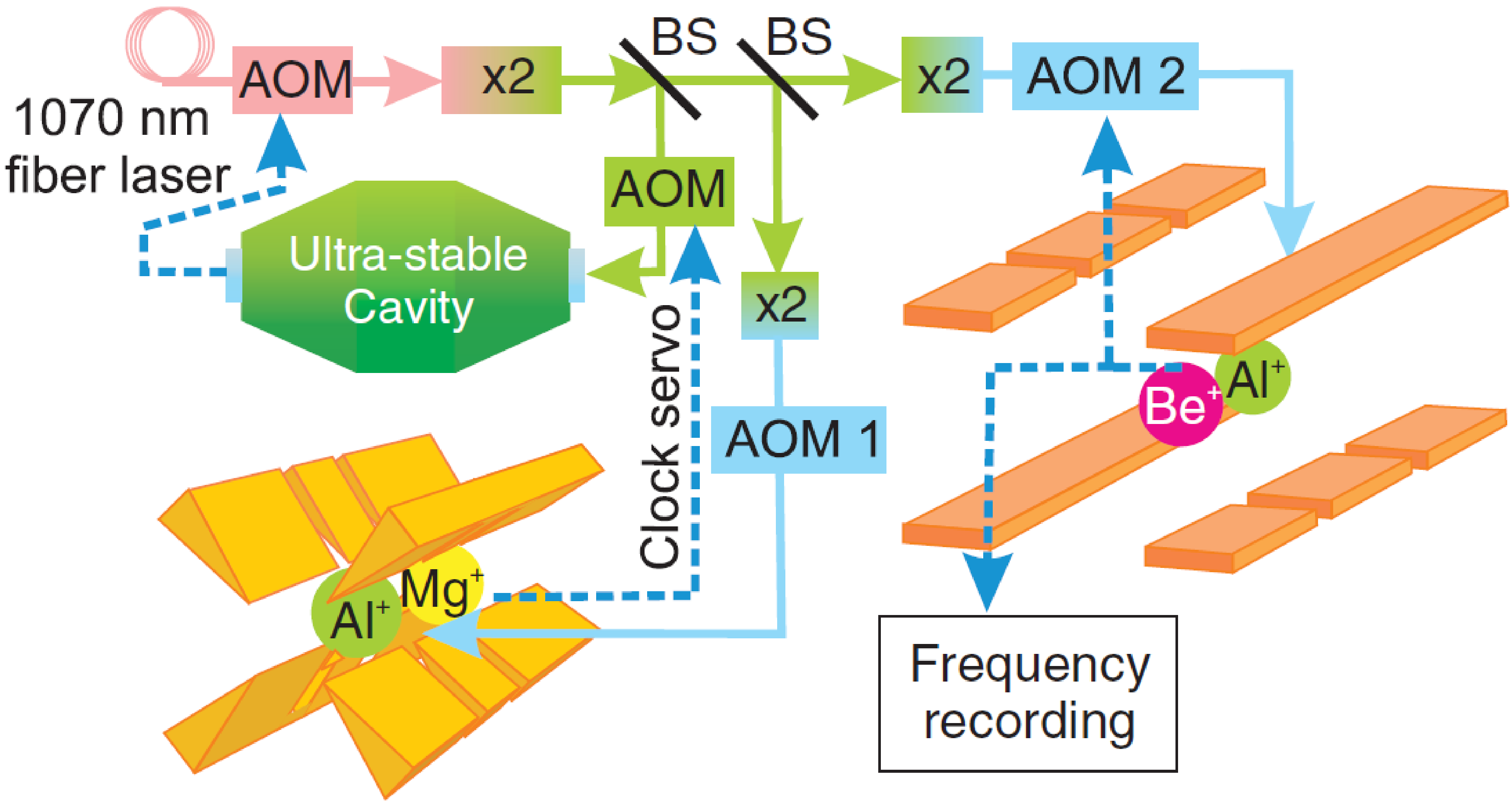
$T=300K \rightarrow \delta\nu/\nu = 5\times10^{-11}$

$T=0.0001K \rightarrow \delta\nu/\nu = 10^{-18}$

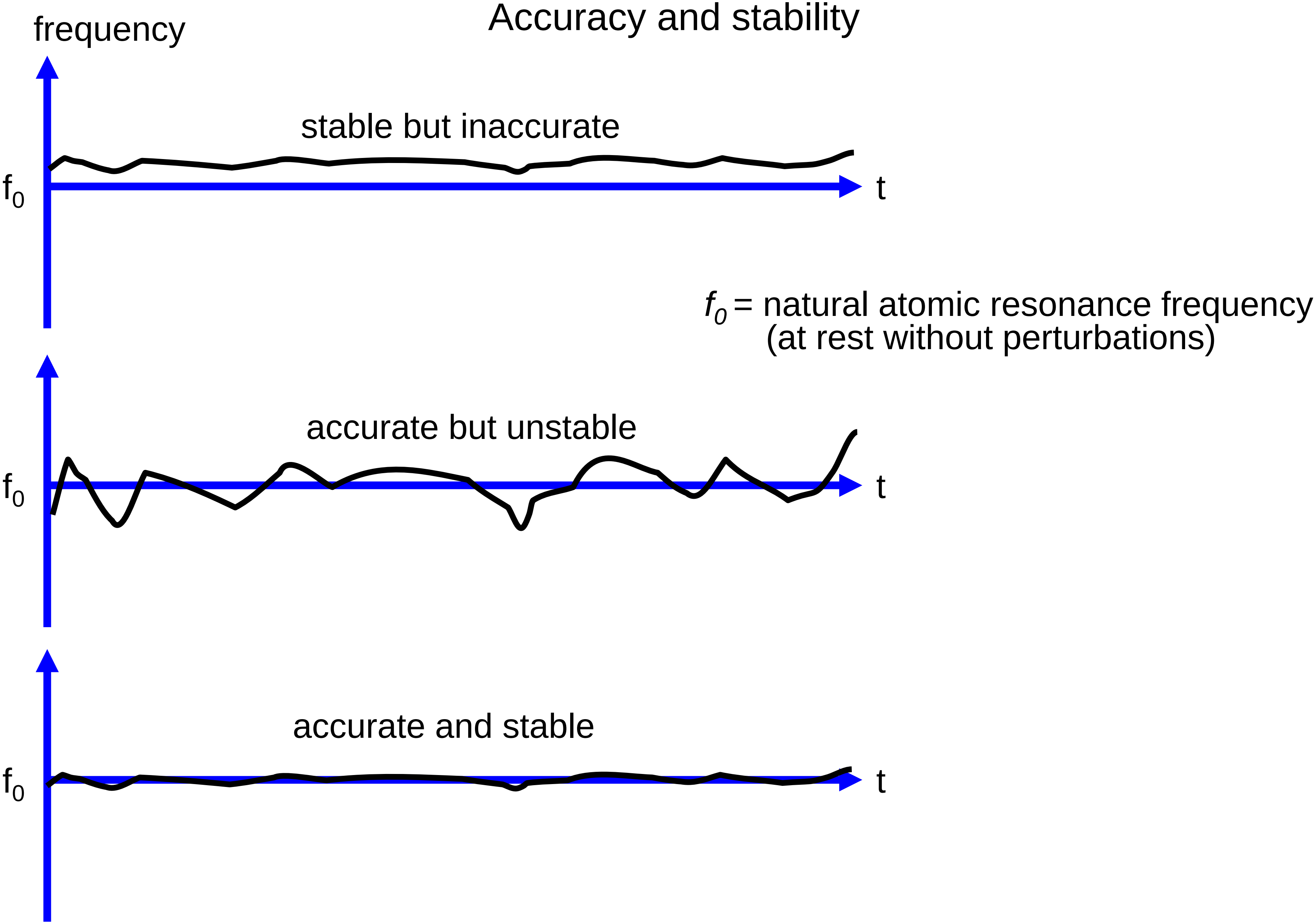
Al^+ Spectroscopy



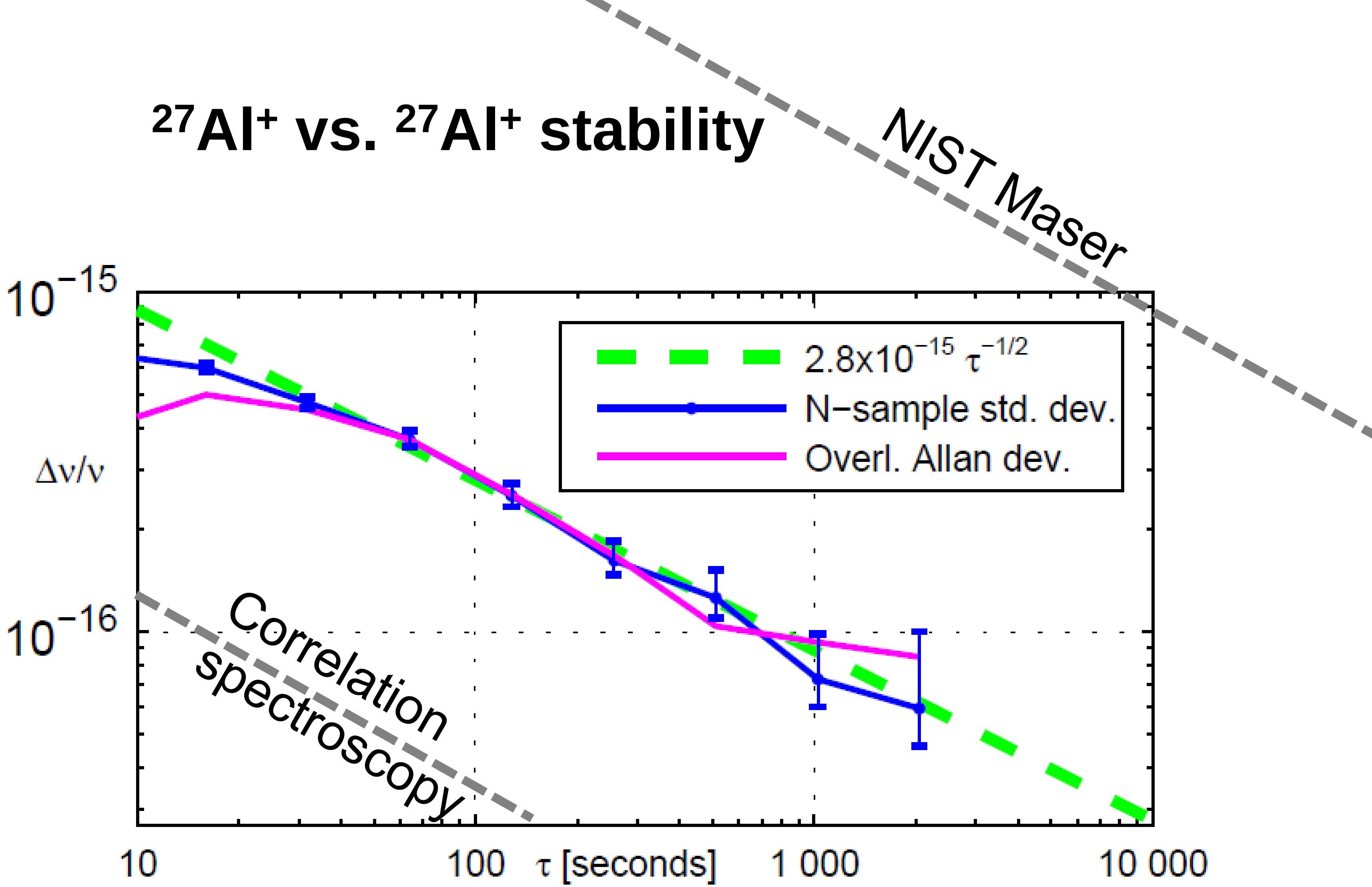
$^{27}Al^{+}$ vs. $^{27}Al^{+}$


1070 nm
fiber laser
AOM
x2
BS
BS
x2
AOM 2
AOM
Ultra-stable
Cavity
x2
Clock servo
AOM 1
Mg+
Al+
Be+
Al+
Frequency
recording

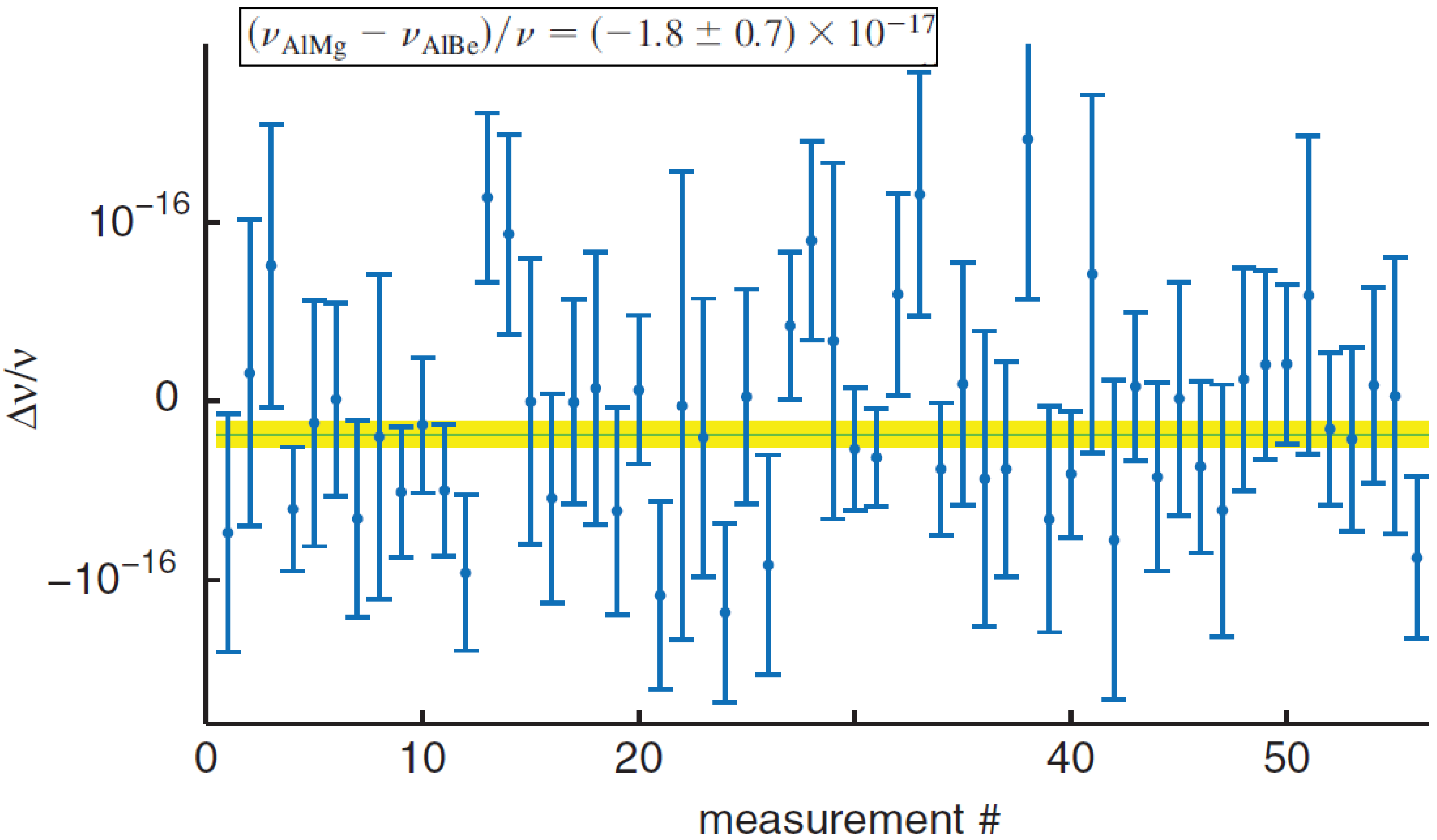
Accuracy and stability



$^{27}Al^+$ vs. $^{27}Al^+$ stability



$^{27}Al^+$ vs. $^{27}Al^+$



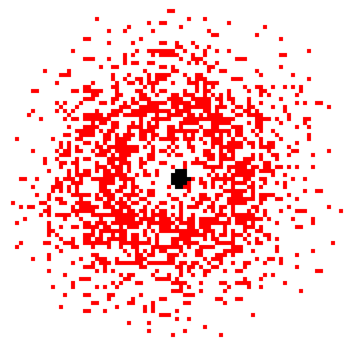
$(\nu_{AlMg} - \nu_{AlBe})/\nu = (-1.8 \pm 0.7) \times 10^{-17}$
10^{-16}
0
-10^{-16}
Δν/ν
0
10
20
40
50
measurement #

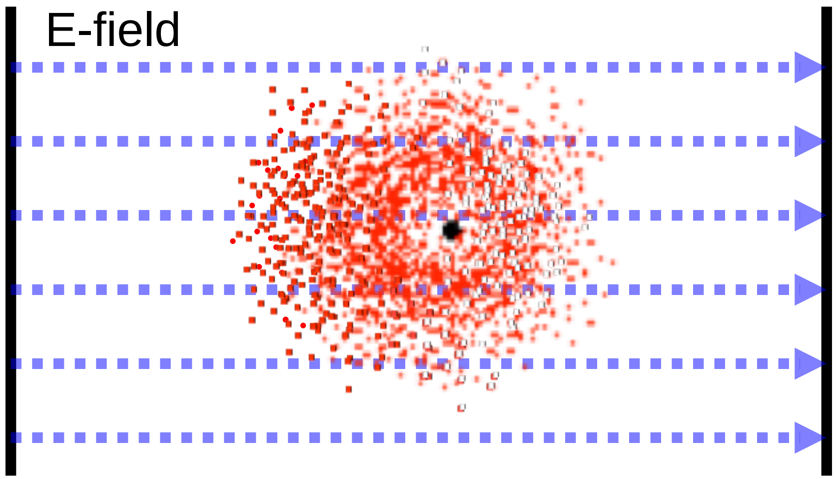
$^{27}Al^+$ error budgets

Reduced in 3rd gen. trap ?

Effect	Parameter	Al^+/Be^+ **1st gen. uncertainty** ***[x 10 $^{-17}$]***	Al^+/Mg^+ **2nd gen. uncertainty** ***[x 10 $^{-17}$]***
Blackbody radiation shift	Operating temperature/ Polarizability	0.5	0.3
Micromotion time dilation	Axial RF fields (trap imperfections)	0.3	0.6
Micromotion time dilation	Radial static field (stray charges)	2	
Secular motion time dilation	Radial temperature (measurement uncertainty)	0.8	0.5
2nd order Zeeman	RMS magnetic field	0.1	0.07
Cooling laser Stark shift	I / Isat and Polarizability	0.2	0.15
1st-order Doppler from correlated ion movement		0.1	.03
Total (quadrature sum)		**2.3**	**0.86**

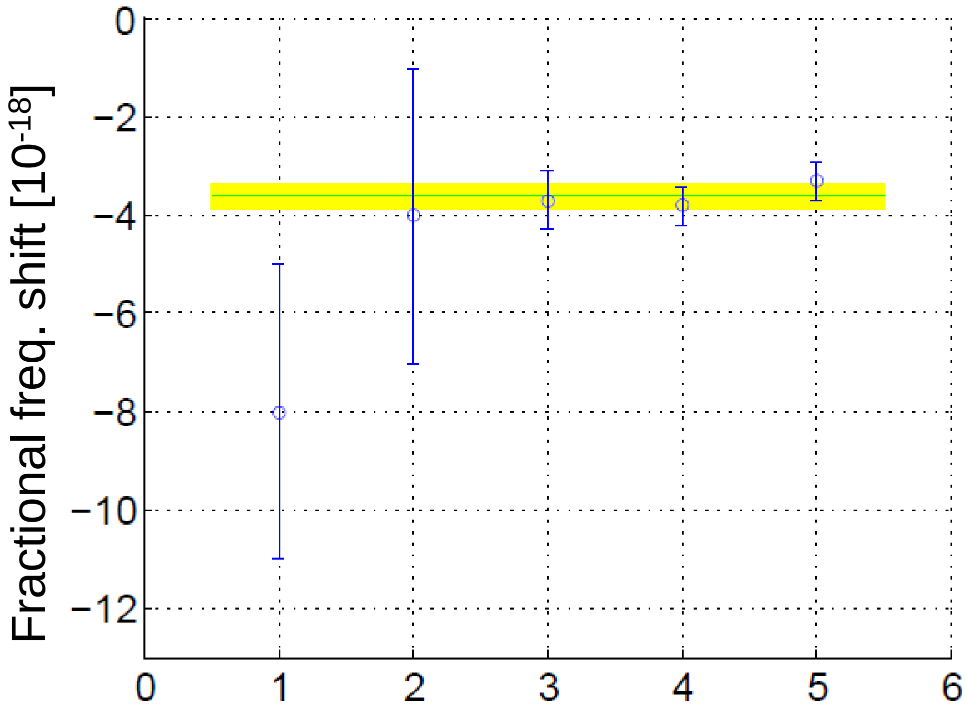
Room Temperature Blackbody shift





Quadratic Stark shift

Room Temperature Blackbody shift



[1] Rosenband et al. 2006 -8 +/- 3 x 10^{-18}

[2] Mitroy et al. 2008 -4 +/- 3 x 10^{-18}

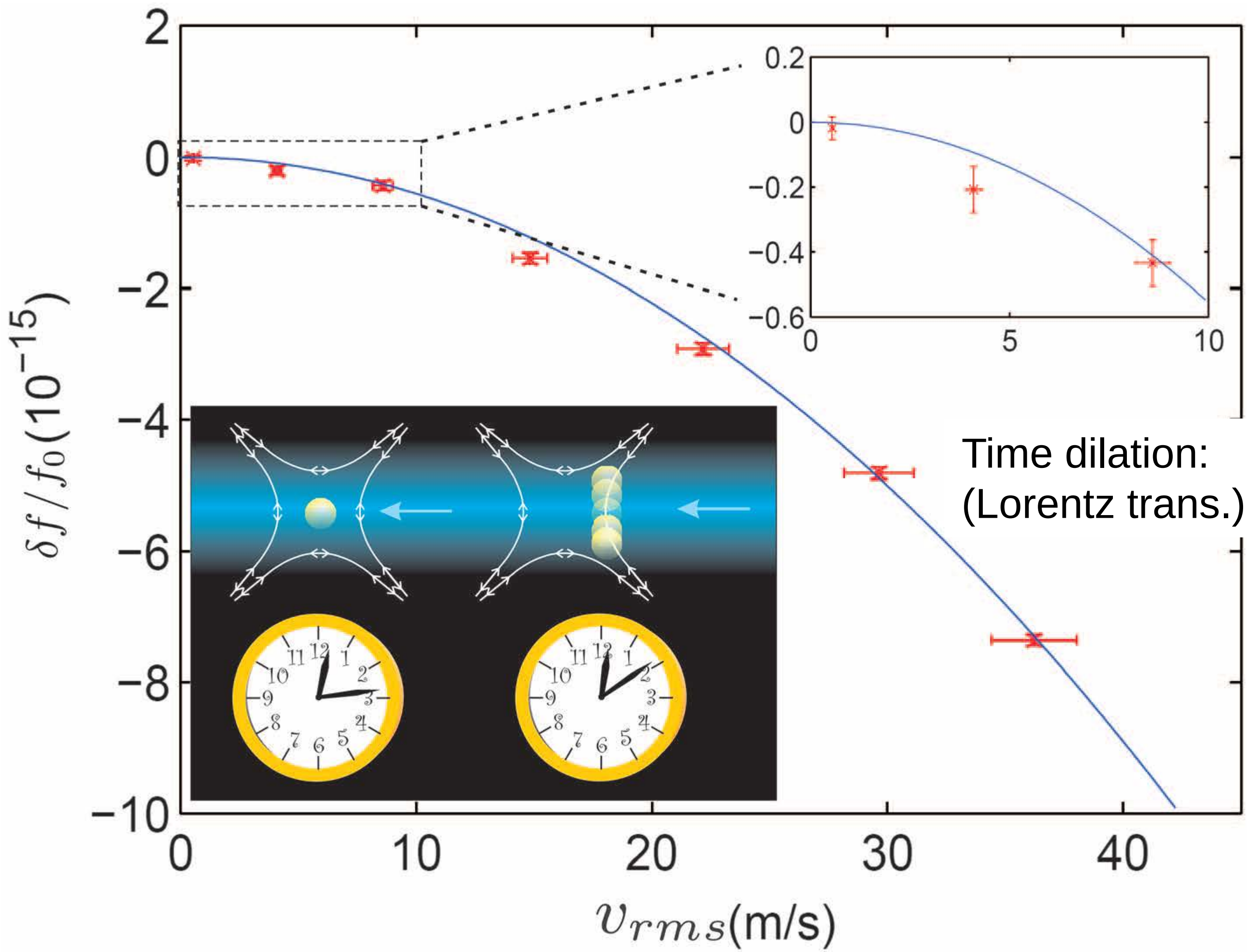
[3] Kallay et al. 2011 -3.7 +/- 0.6 x 10^{-18}

[4] Safronova et al. 2011 -3.8 +/- 0.4 x 10^{-18}

[5] In preparation -3.3 +/- 0.4 x 10^{-18}

Species	fractional shift *[x 10^{-18}]*
Al^+	3.7 +/- 0.4
In^+	< 70
Yb^+	580
Sr^+	670
Ca	2200
Yb	2400
Sr	5100
Cs	21000

Twin paradox (motional time-dilation)

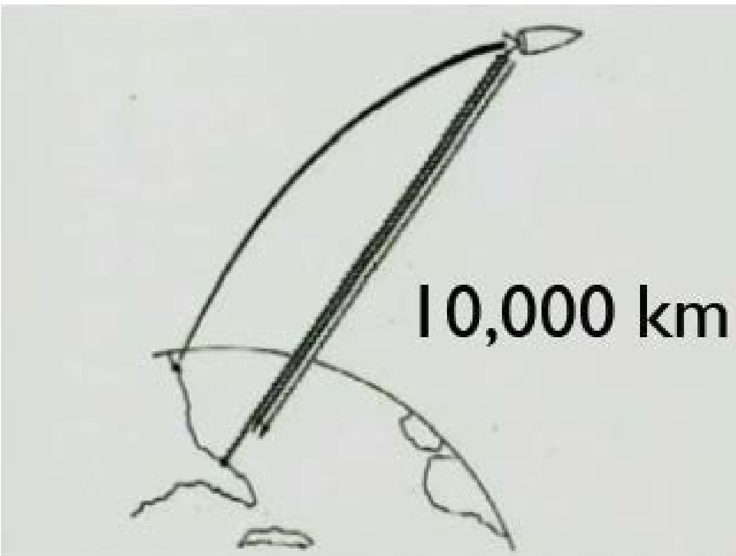


Time dilation:
(Lorentz trans.)

$$\frac{\Delta\nu}{\nu} = \frac{-v^2}{2c^2}$$

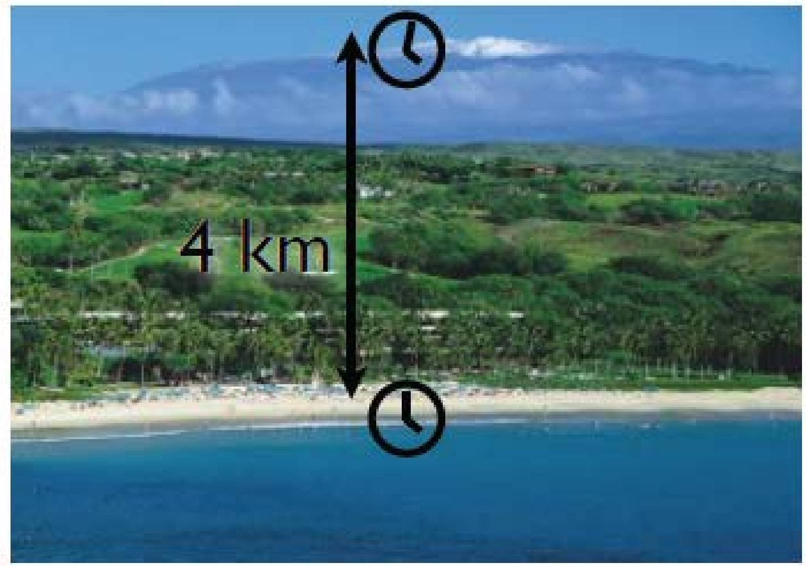
Gravitational redshift measurements

$$\frac{\Delta\nu}{\nu} = \frac{gh}{c^2}$$



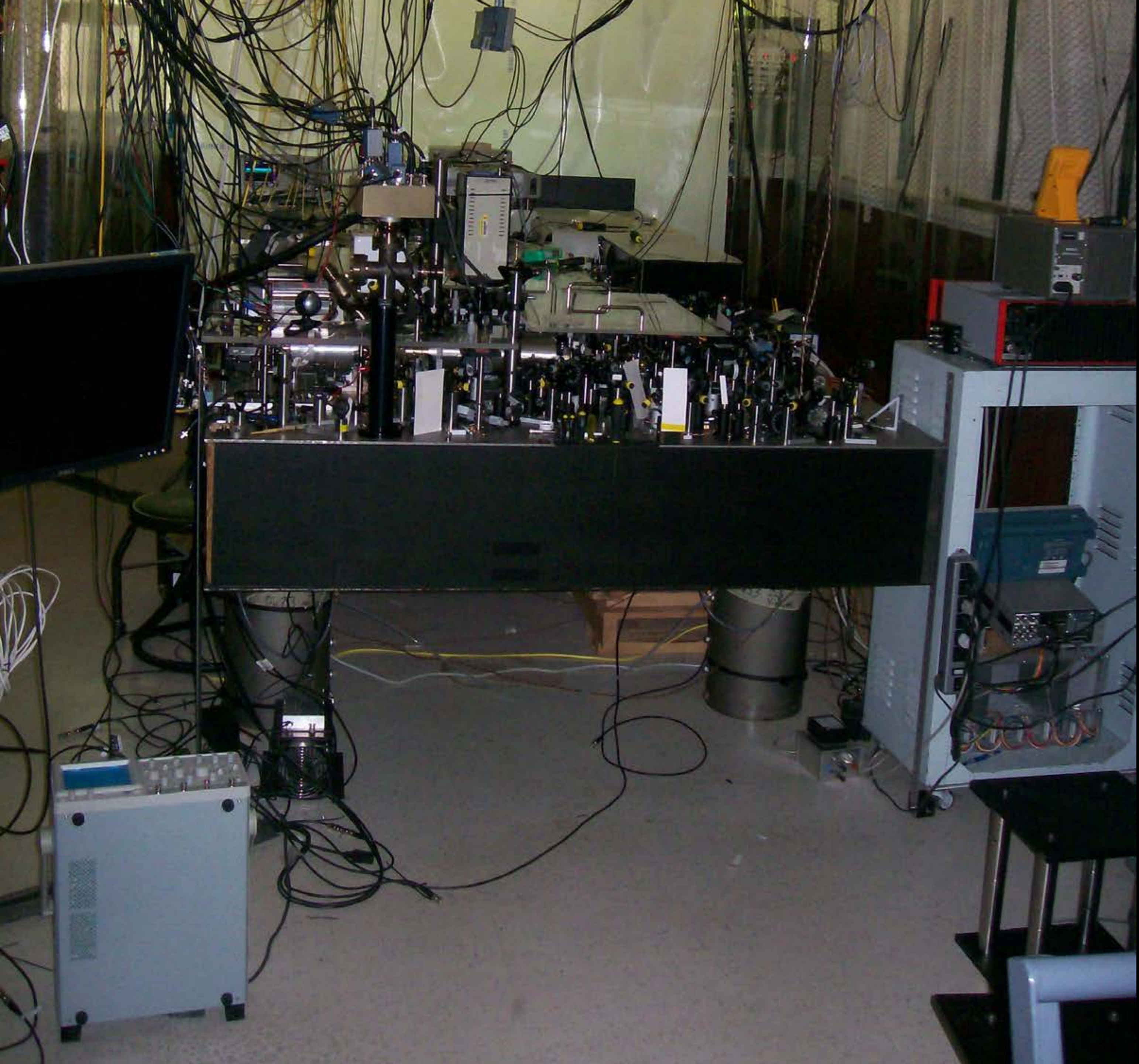
1976

Vessot et al., maser on rocket
Test of redshift with uncertainty 10^{-4}

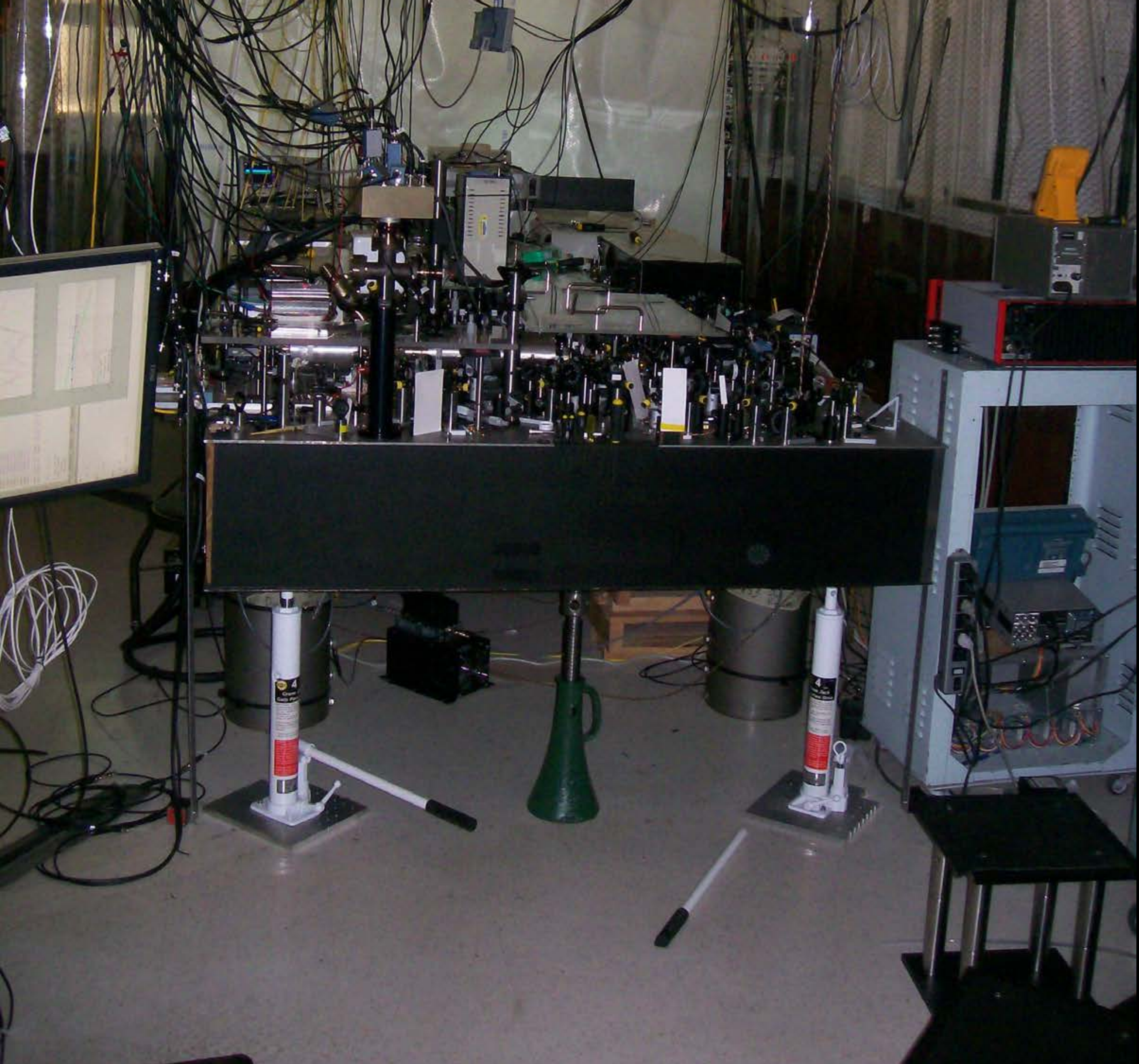


2017?

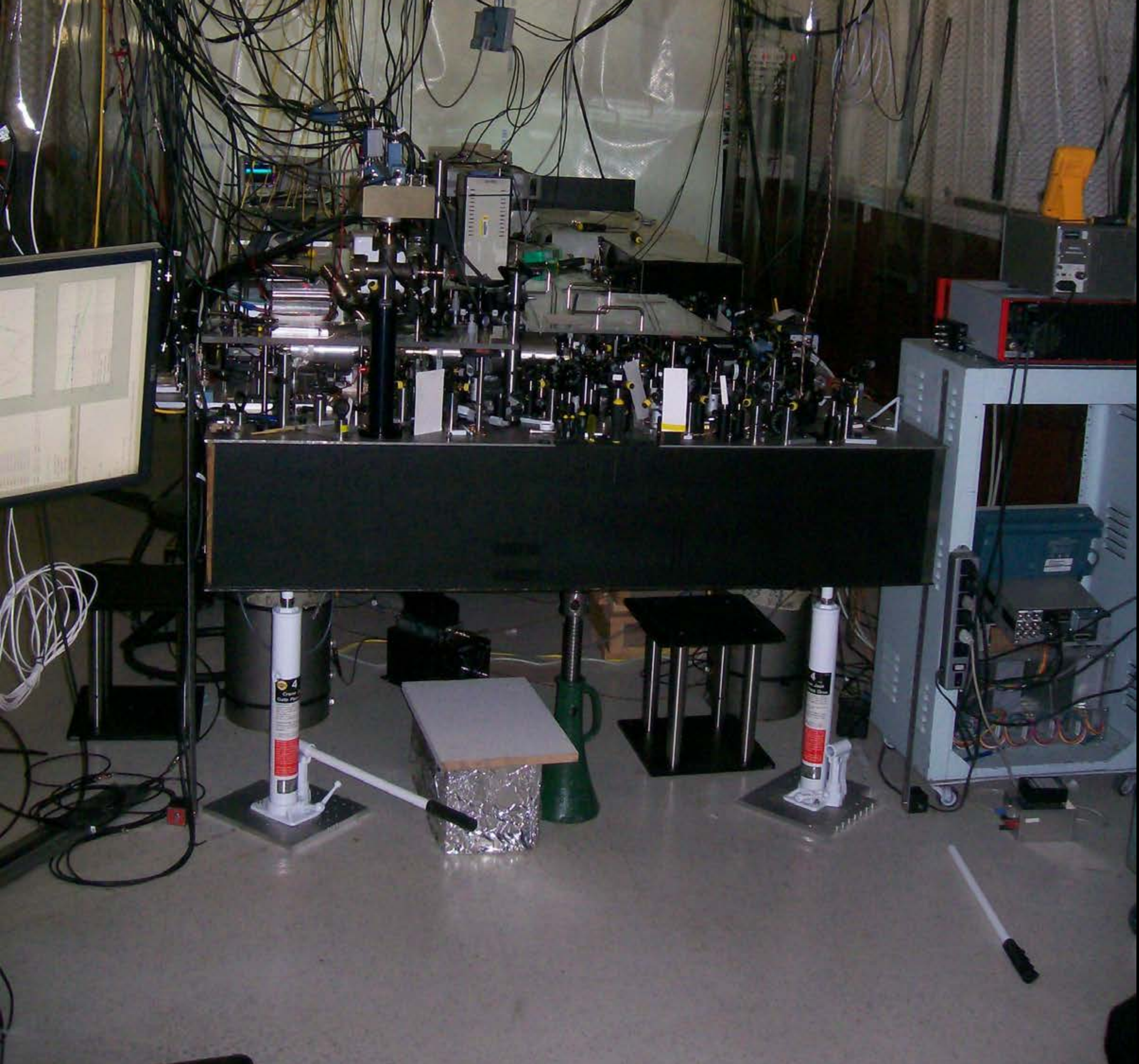
Comparison of Al+ clocks
Redshift uncertainty $< 3 \times 10^{-5}$



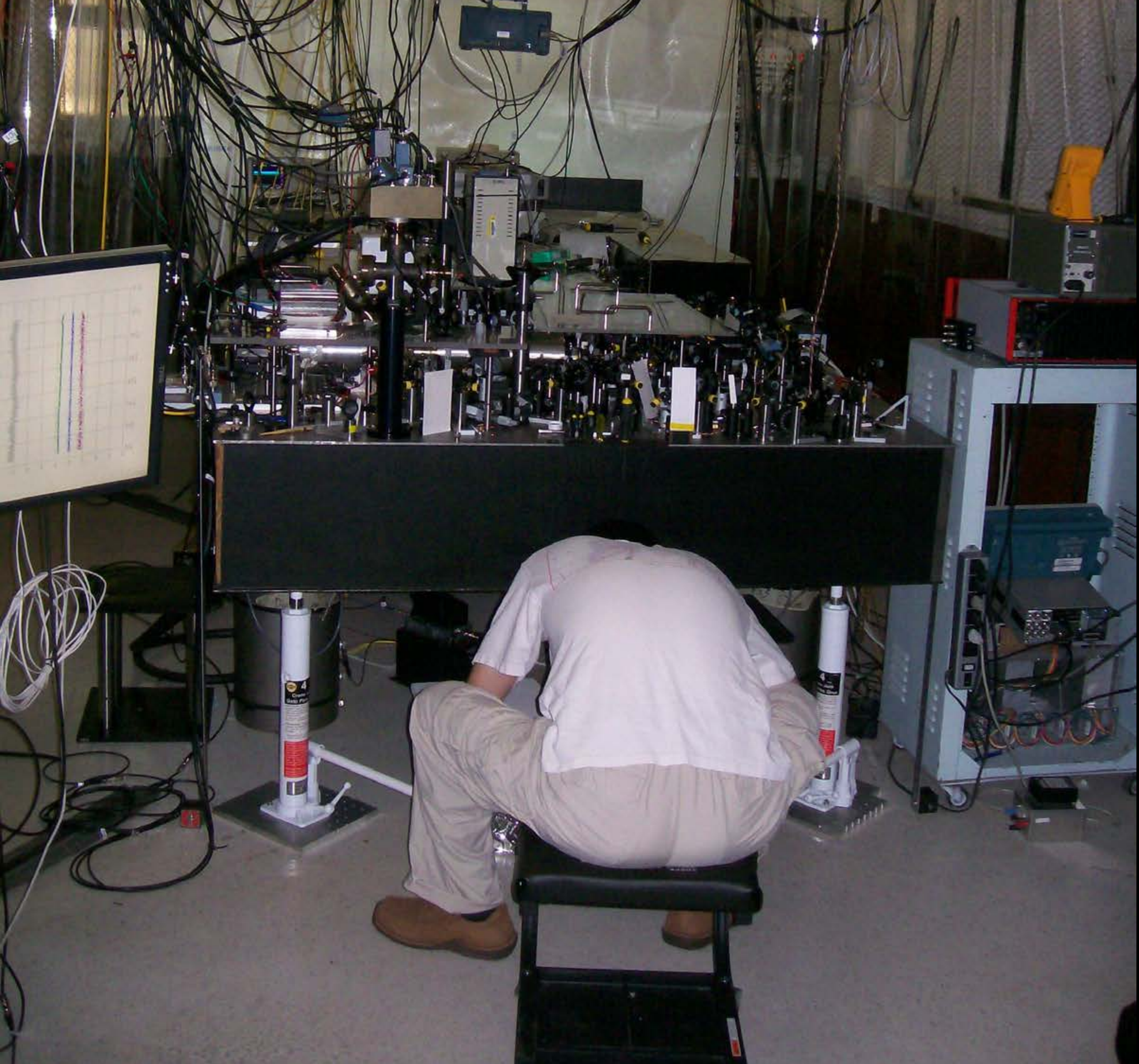
0×10^{-18}



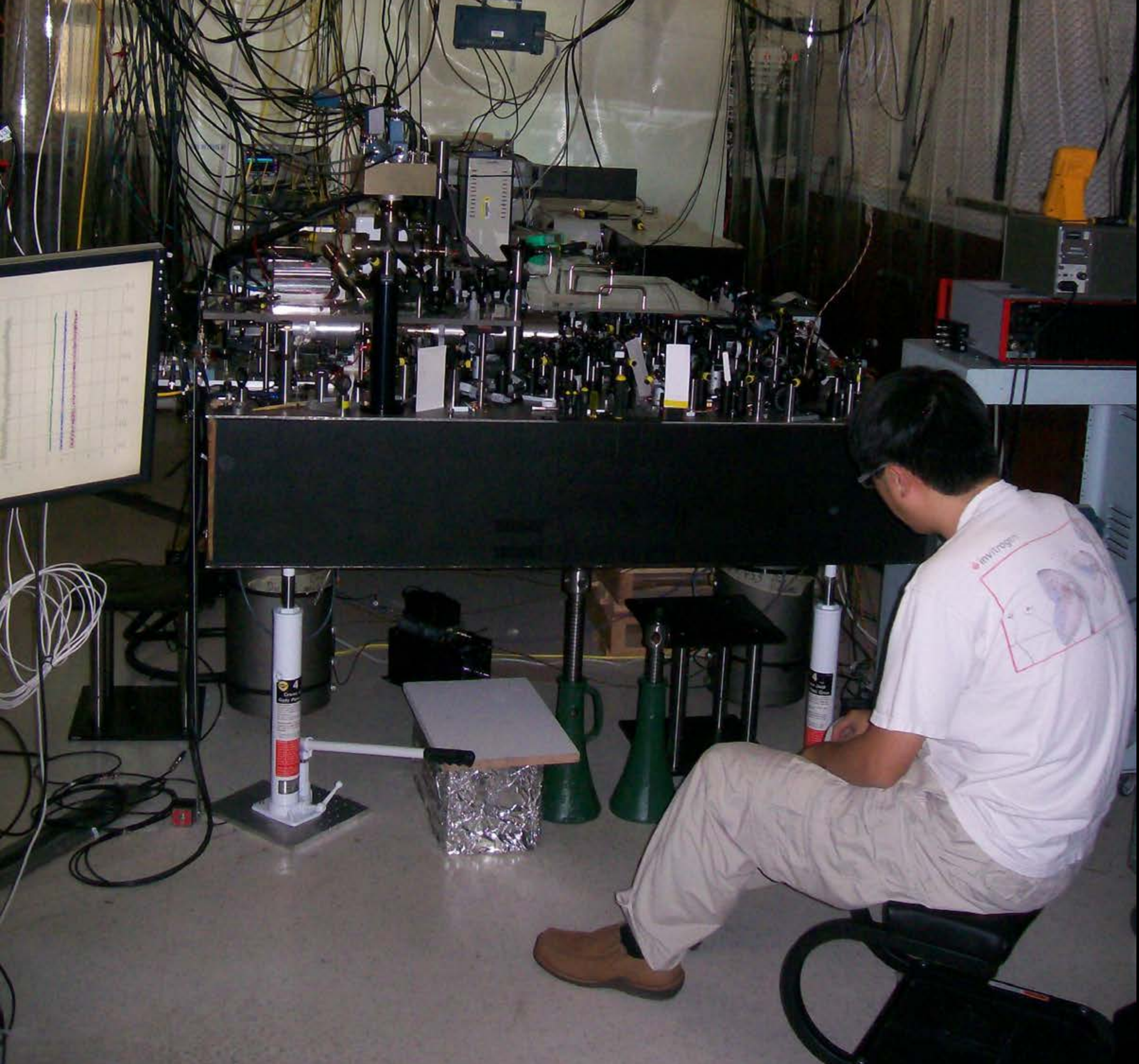
0×10^{-18}



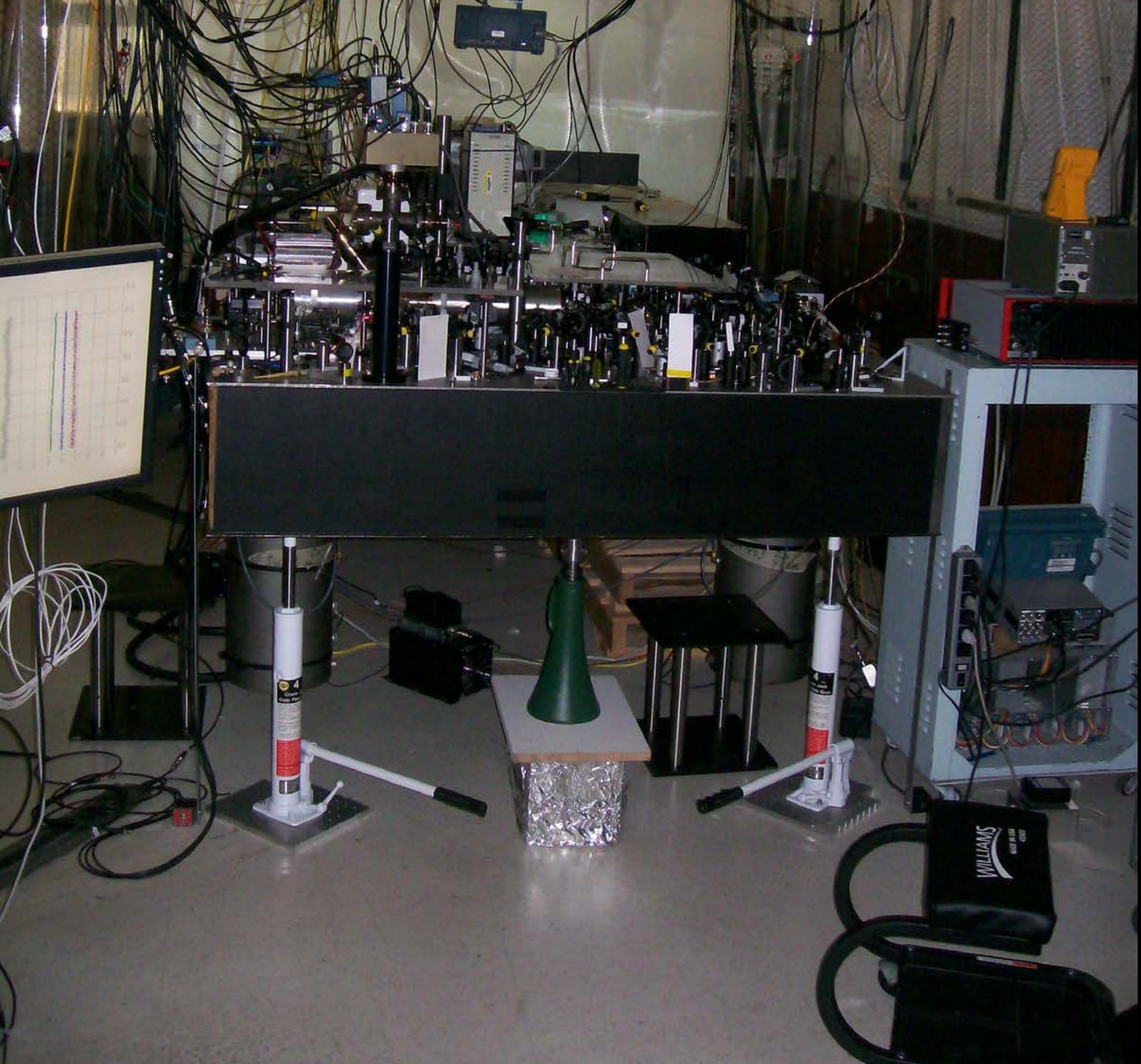
3×10^{-18}



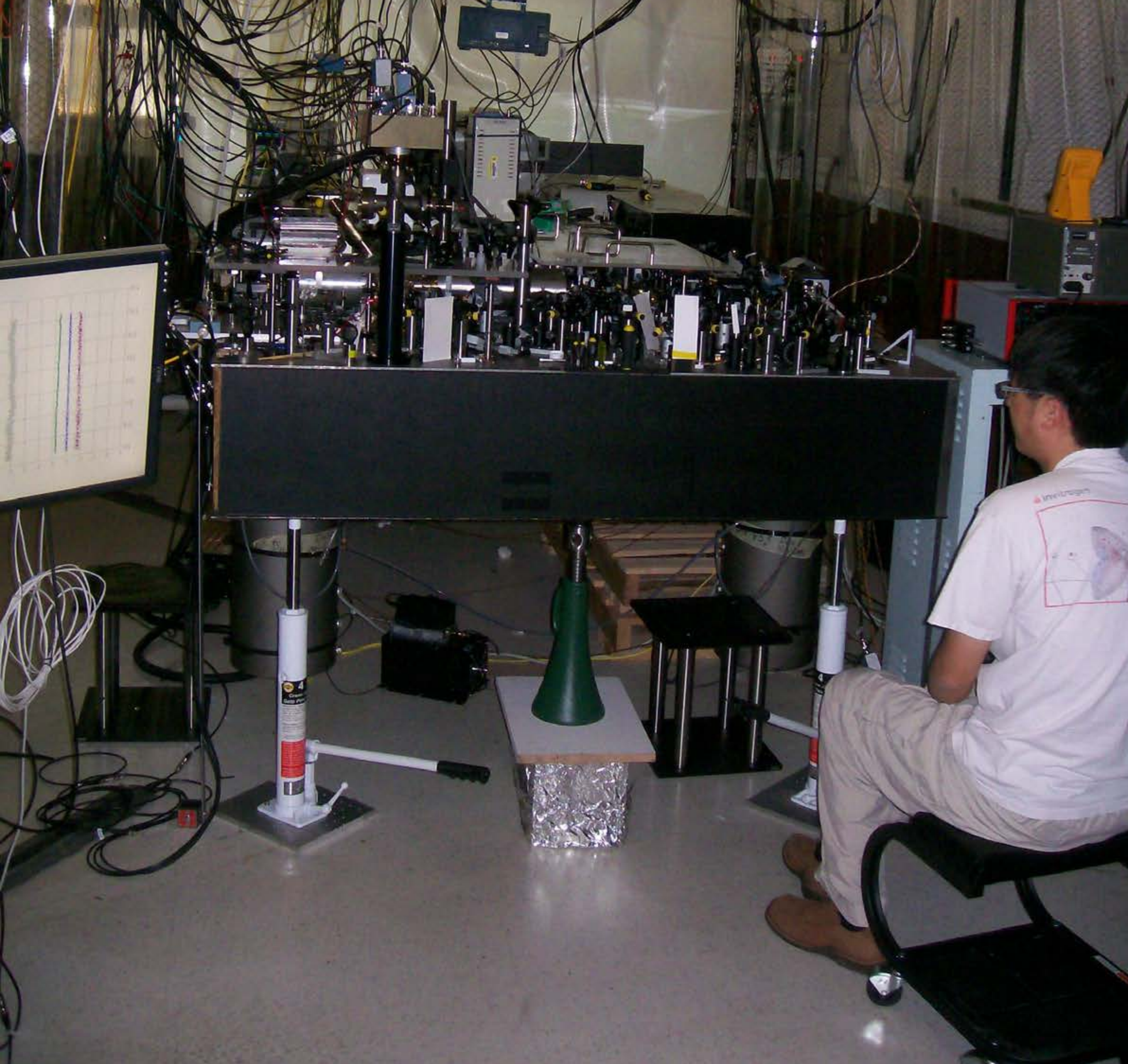
7×10^{-18}



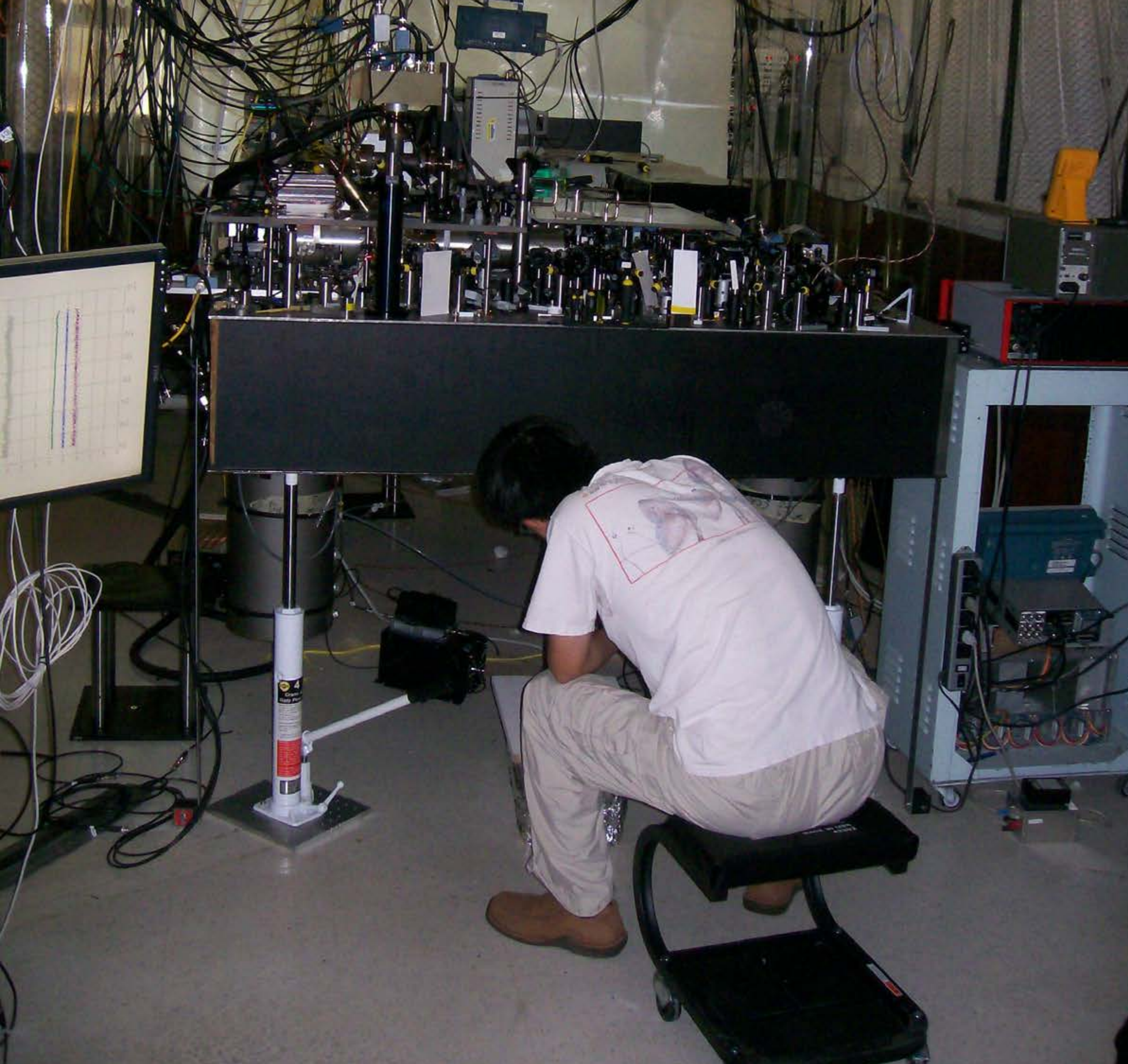
10×10^{-18}



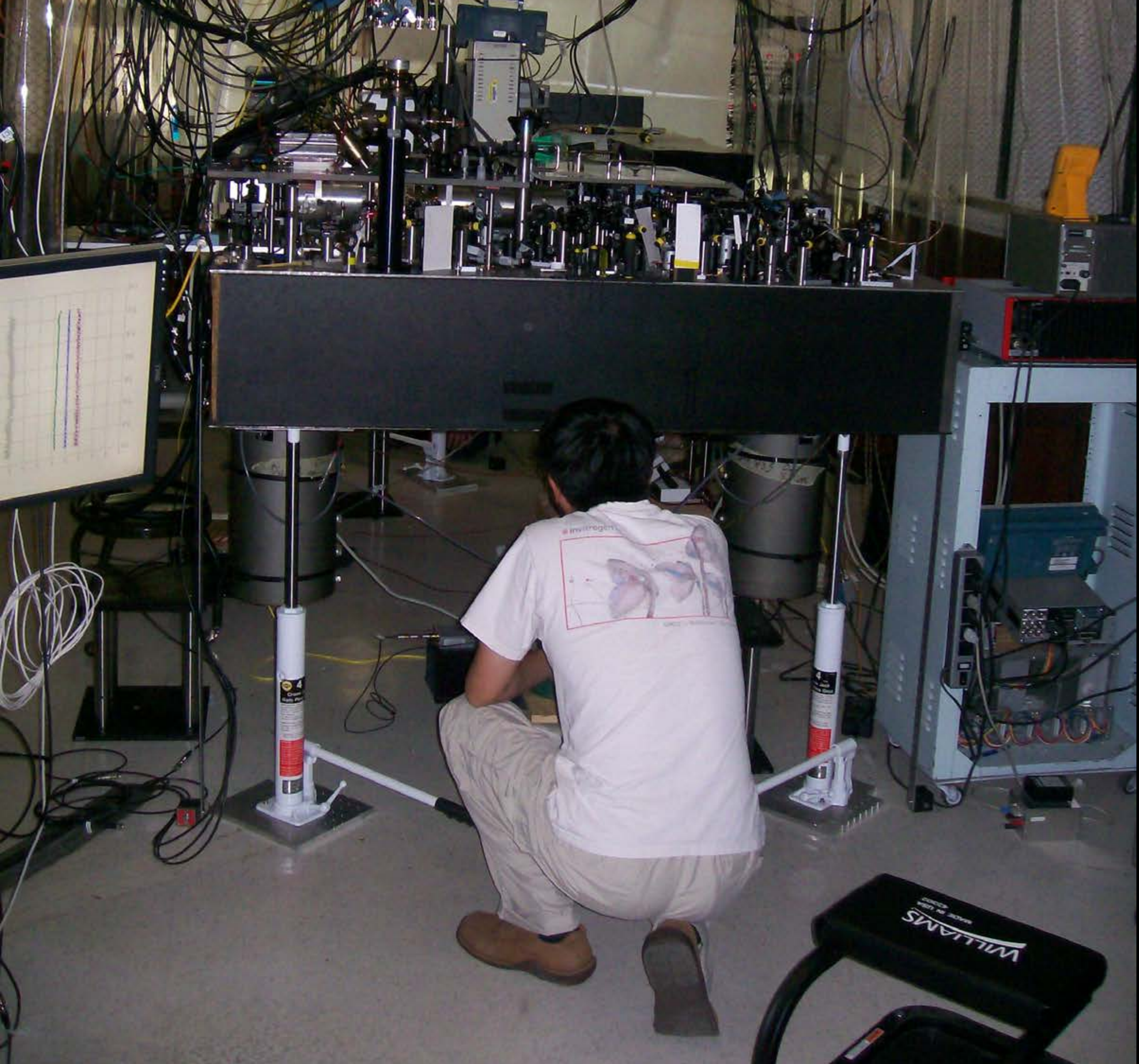
16×10^{-18}



20×10^{-18}



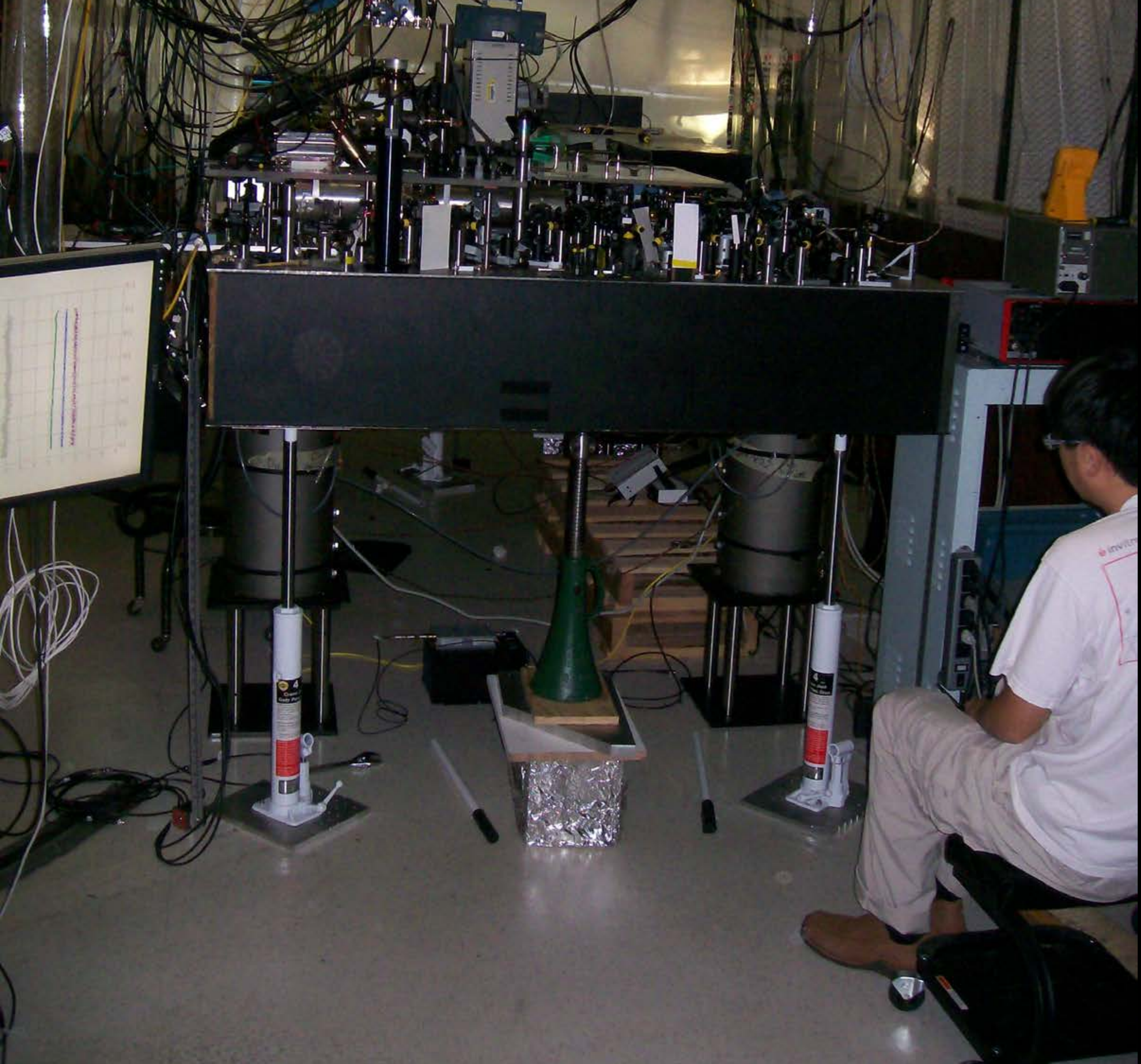
27×10^{-18}



33×10^{-18}

38×10^{-18}

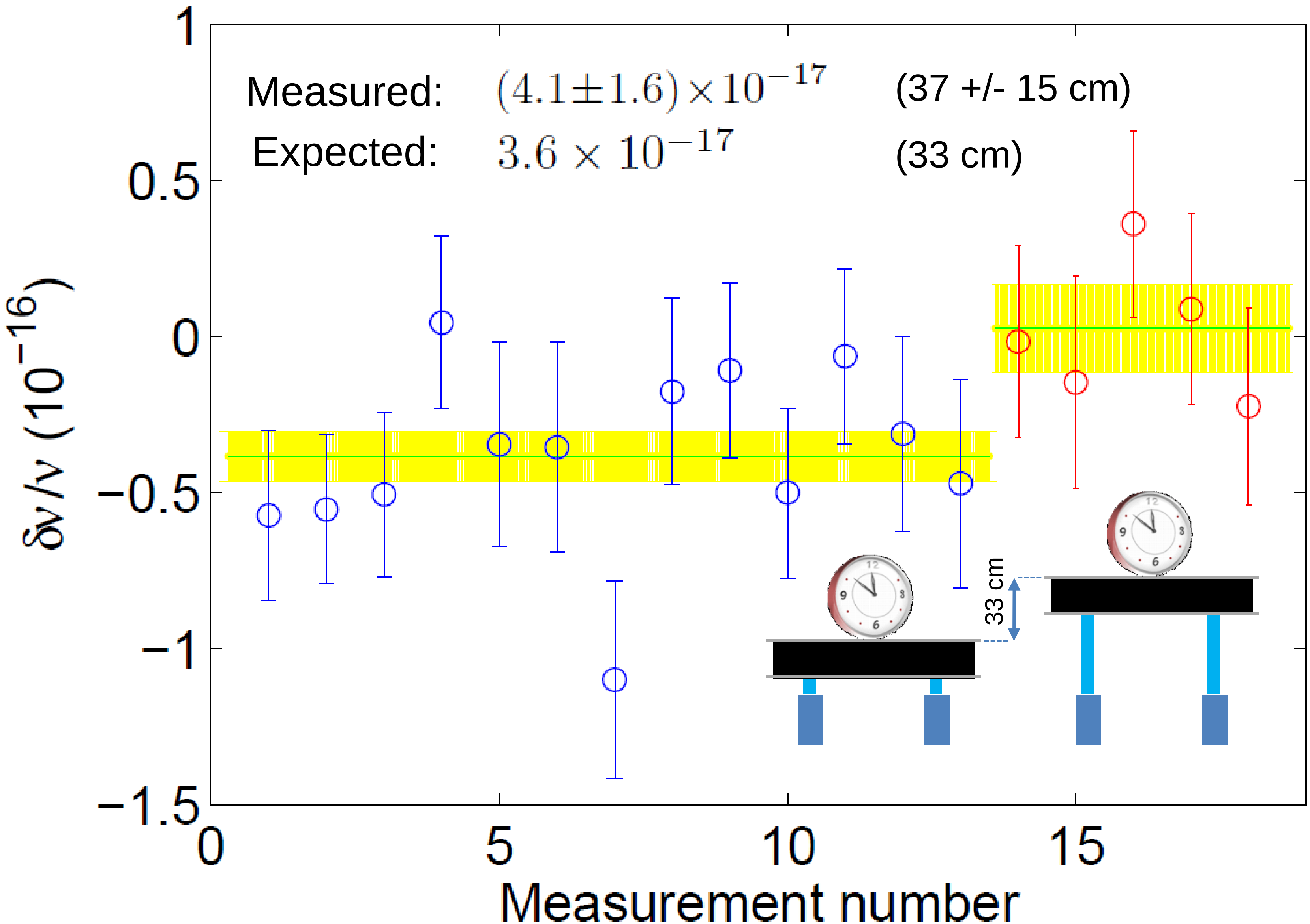
38×10^{-18}



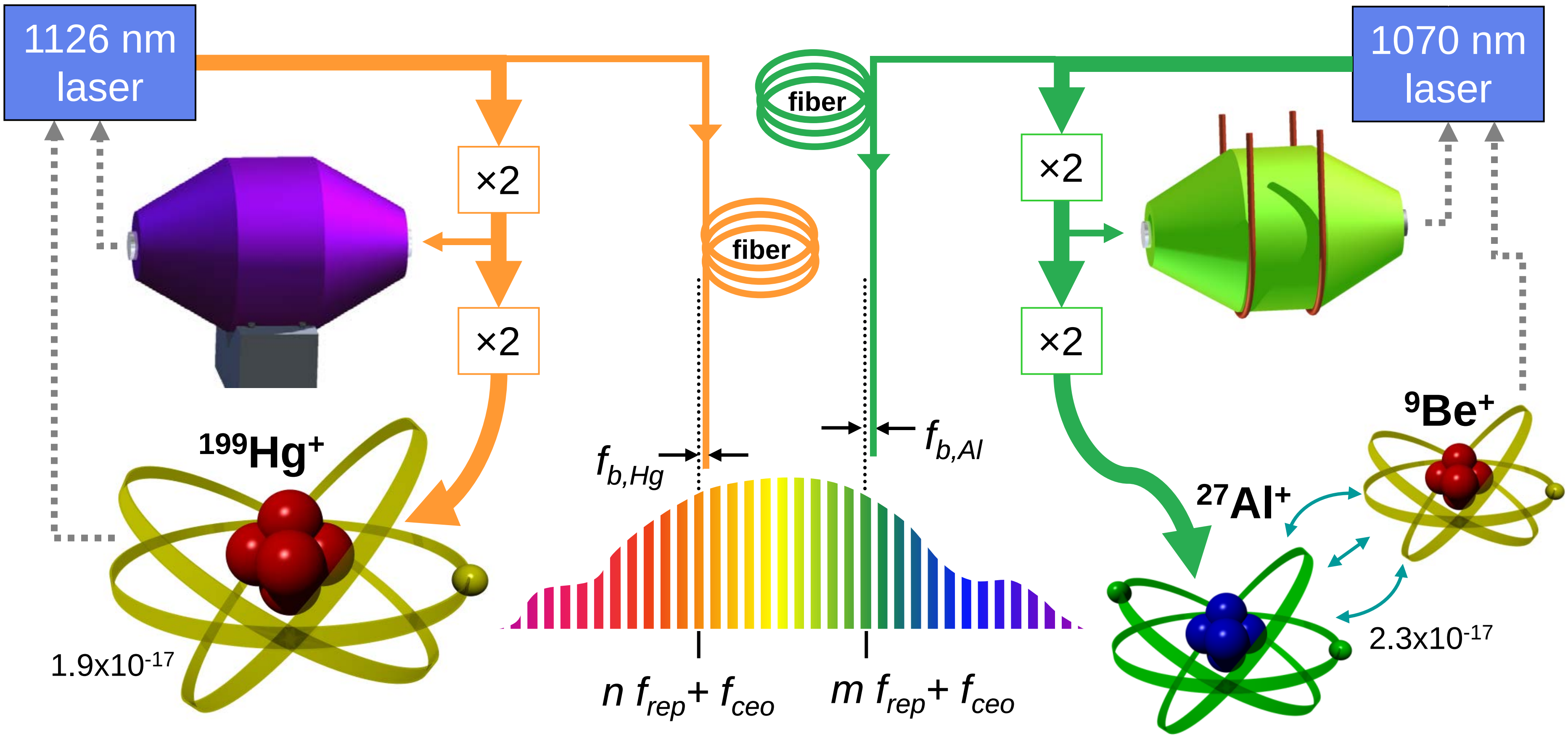
36×10^{-18}

Chou (front),
Hidden: Hume,
Rosenband

First sub-1 m height measurement with clocks



Al^+/Hg^+ Comparison



$$\frac{\nu_{Al+}}{\nu_{Hg+}} = 1.052\ 871\ 833\ 148\ 990\ 438 \pm 5.5 \times 10^{-17}$$

Variation of fundamental constants

Physical laws

Unit-less constants

1.052 871 833 148 990 438 ± 5.5 x 10^{-17} = $r = \frac{\nu_{Al^+}}{\nu_{Hg^+}} = f(\alpha, \frac{m_p}{m_e}, g_p, g_n, \ldots)$

$$\alpha = \frac{e^2}{\hbar c} \approx \frac{1}{137.036}$$

Is α really constant?

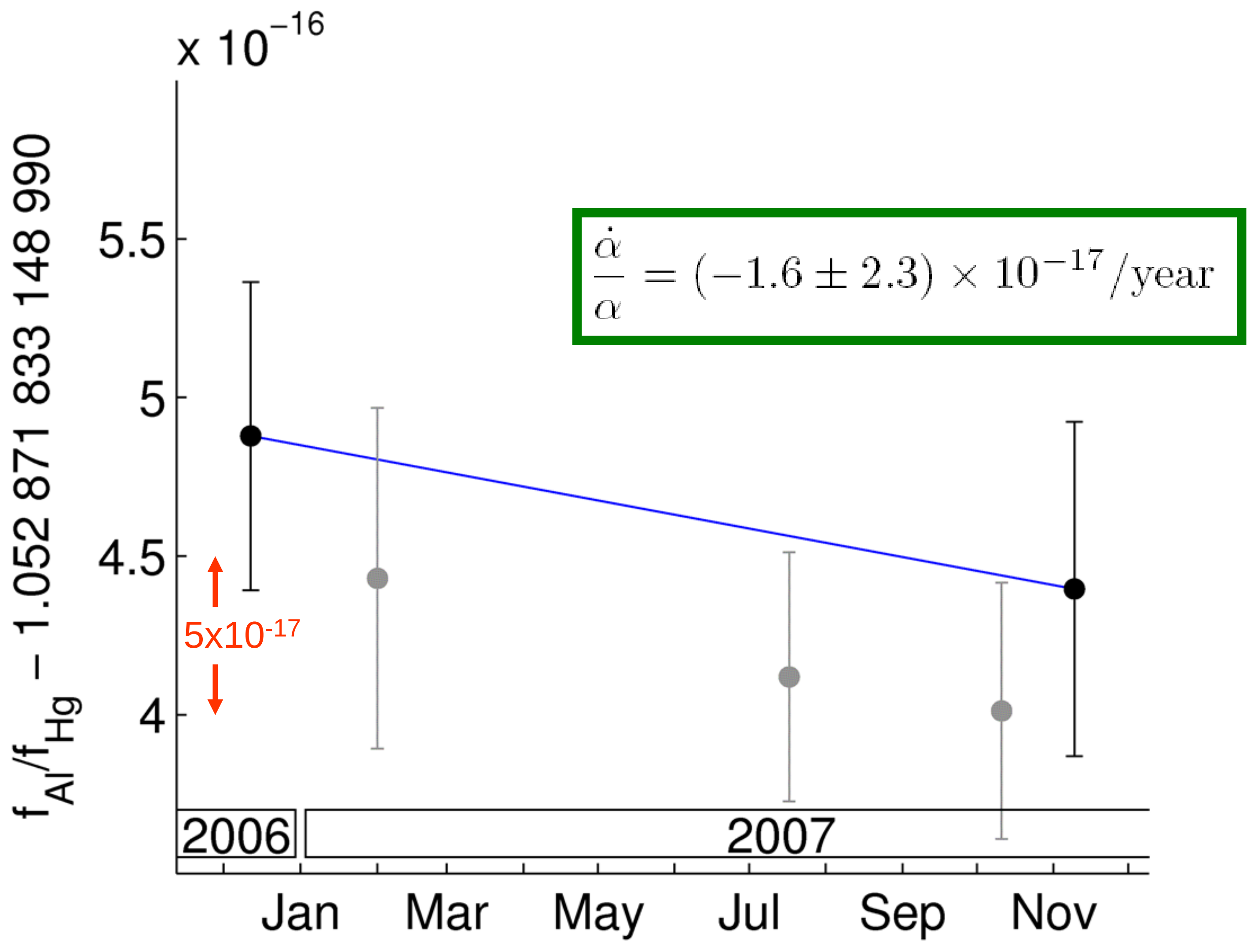
Atomic structure calculations: $\frac{\Delta\alpha}{\alpha} \approx 0.34 \frac{\Delta r}{r}$

V.A. Dzuba, V.V. Flambaum, J.K. Webb
Phys. Rev. A **49**, 230 (1999)

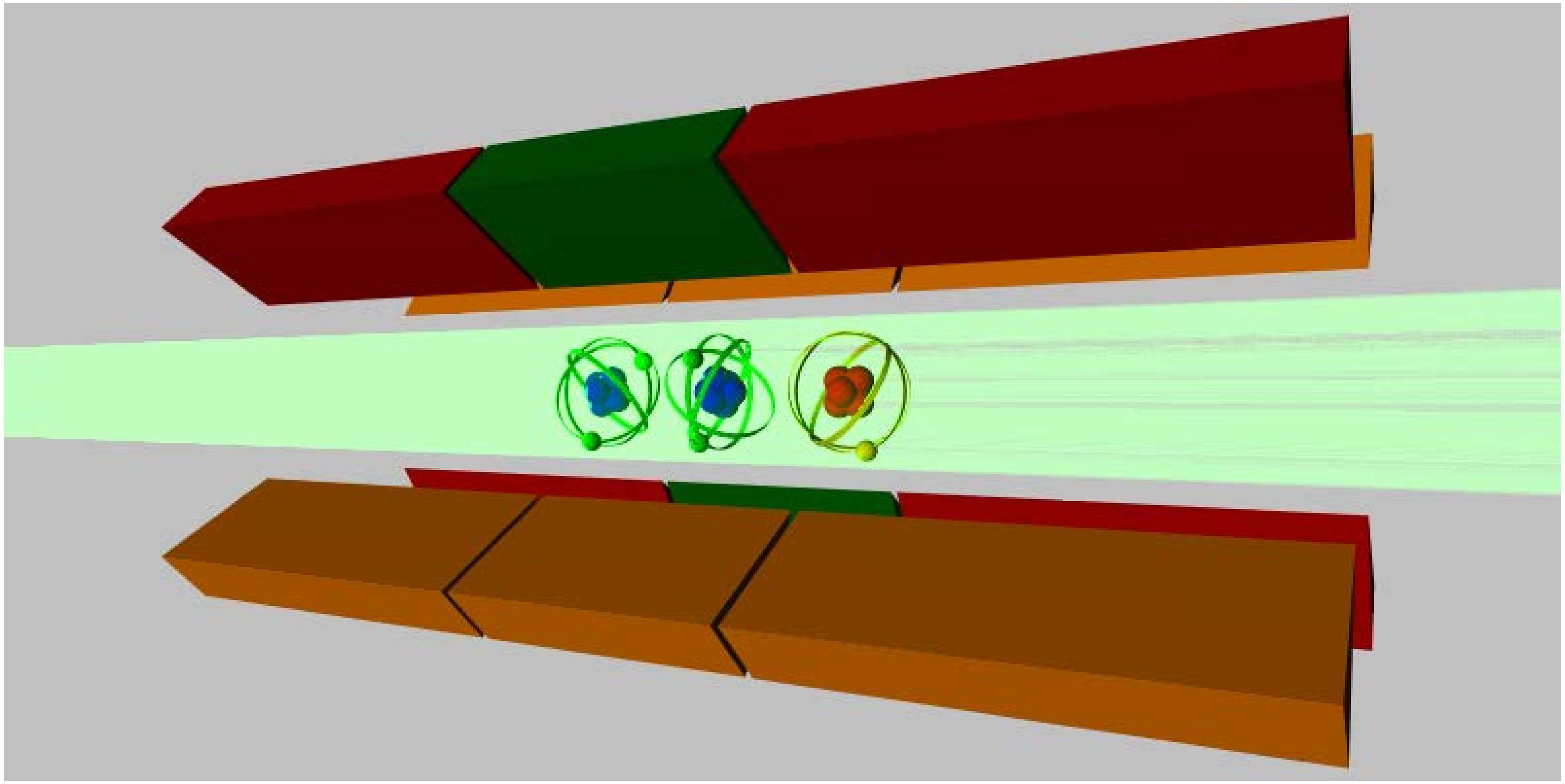
V.A. Dzuba, V.V. Flambaum
arXiv:0712.3621v1 (2008)

If α changes, then the frequency ratios *r* of different clocks will also change.

Al^+/Hg^+ Comparison
(search for variation of α)

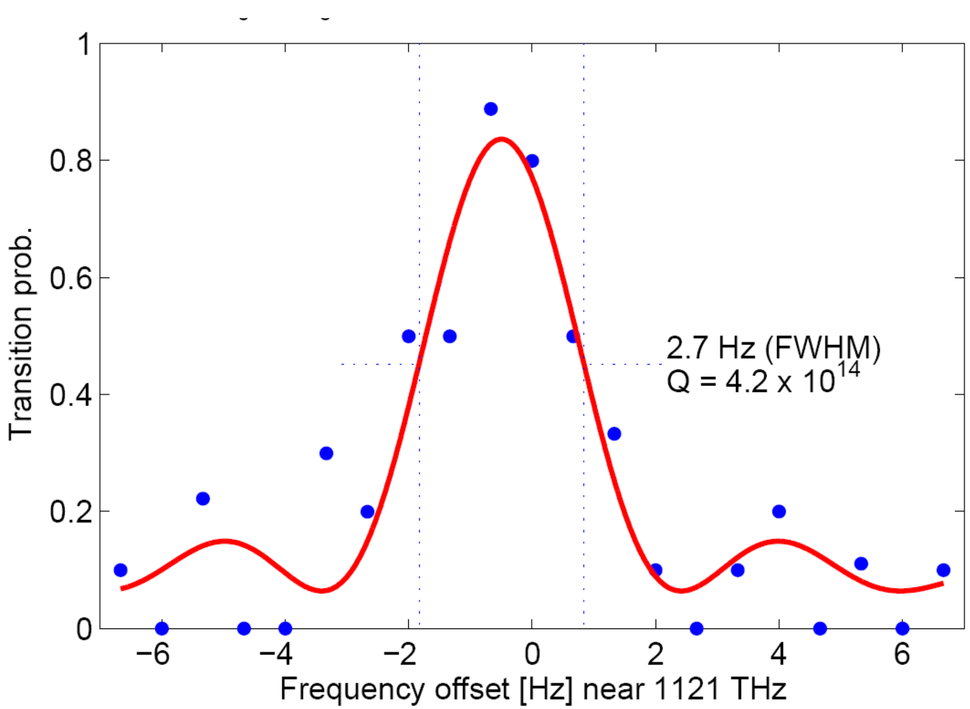


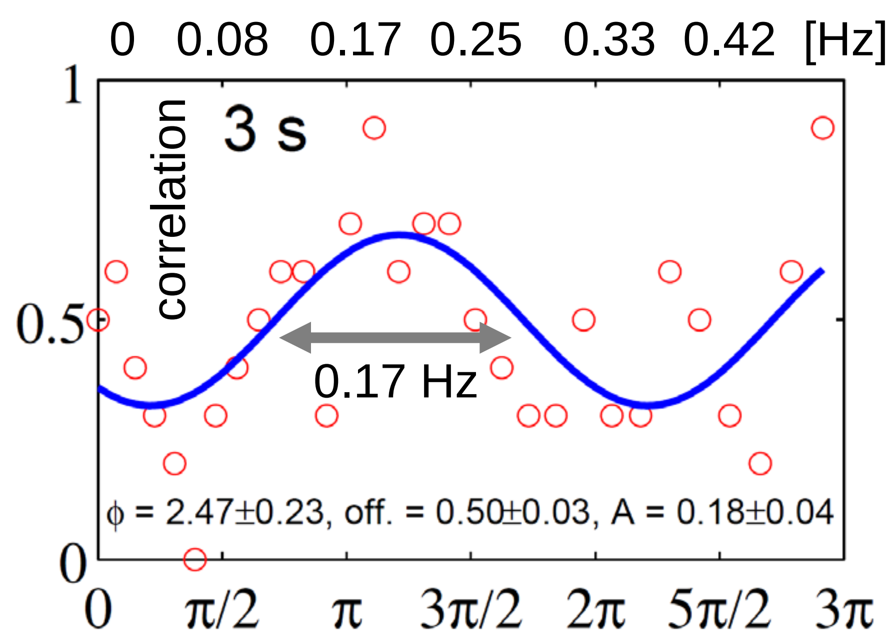
Quantum-correlation spectroscopy



Factor 50-100 measurement speedup

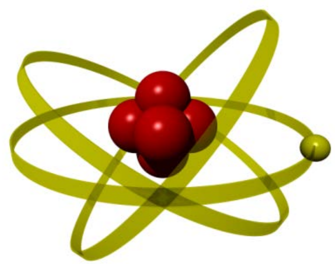
- $Q = \frac{1.121 \times 10^{15}}{0.17} = 6.7 \times 10^{15}$ (observed)

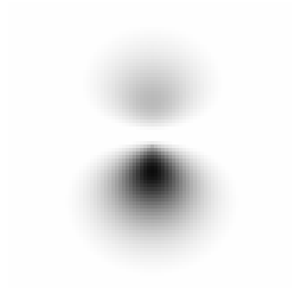




Quantum metrology in atomic clocks

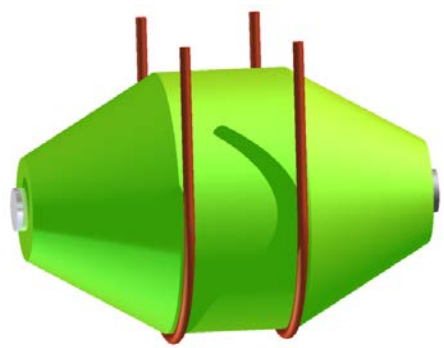
Atoms





Very coherent.
Observation leads to quantum projection noise.

Classical oscillator



Less coherent.
Impervious to observation.

How should we put these parts together for best performance?

arXiv: 1303.6357 [quant-ph]

Digitization of phase-difference can yield exponential performance gain compared to simple averaging.

Summary

- Al^+ / Mg^+ clock has 8.6×10^{-18} accuracy

$$\approx \frac{\textit{1/100}^{th}\textit{ human hair diameter}}{\textit{Earth-sun distance}}$$

- Measured 37 +/- 15 cm height-difference via relativistic geodesy
- Constrained drift of fine-structure constant to $(-1.6 \pm 2.3) \times 10^{-17}$/year
- Quantum-correlation spectroscopy with Al^+ yields $Q > 6 \times 10^{15}$, Measurement speed-up of 50 – 100 x

Acknowledgements

Al$^+$

Jwo-Sy Chen

Sam Brewer

Chin-Wen Chou

David B. Hume

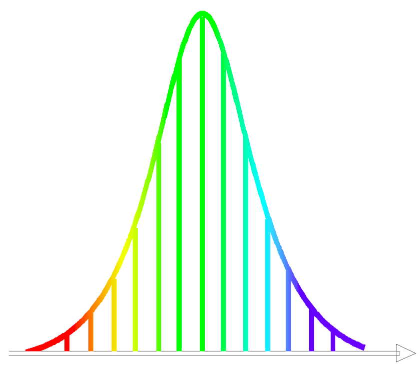
David J. Wineland

Hg$^+$

David Leibrandt

David J. Wineland

James C. Bergquist



fs-comb (Ti:Sapphire)

Tara M. Fortier

Scott A. Diddams