# The Yb lattice clock (and others!) at NIST for space-based applications

Andrew Ludlow, Jeff Sherman, Nathan Hinkley, Nate Phillips, Kyle Beloy, Nathan Lemke, and Chris Oates

*National Institute of Standards and Technology, Boulder, CO USA*

Special thanks to:

NIST Fs-laser team: Scott Diddams, Tara Fortier, Frank Quinlan et al.

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JILA folks: Ana Maria Rey, Jun Ye, and colleagues

Significant past contributors: Leo Hollberg, Nicola Poli, Marco Pizzocaro, Valera Yudin, Alexei Taichenachev, Zeb Barber, Chad Hoyt, Yanyi Jiang, L-S Ma

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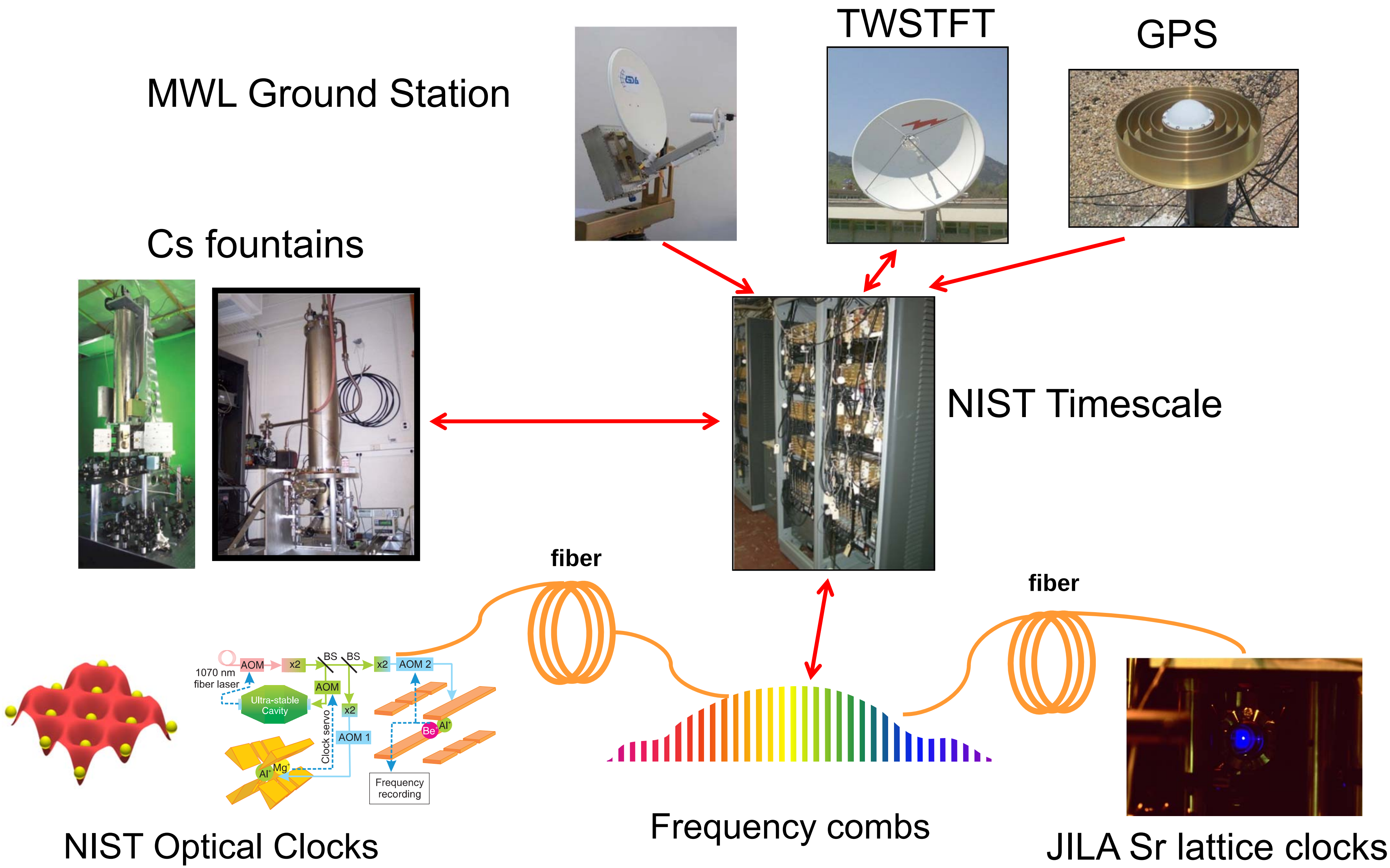
# NIST Space Clock Support Capabilities



# NIST Timescale and UTC(NIST)

**4 Cesium Beam standards**
**8 more by 2014**

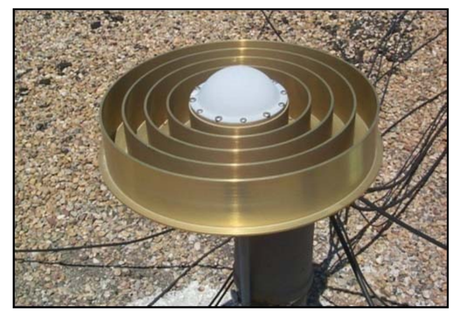

**6 Hydrogen Masers**
**8 more by 2014**

**UTC(NIST)**

**Measurement System**
**New digital system under development**

**MWL**

**Two-way satellite time & frequency transfer**

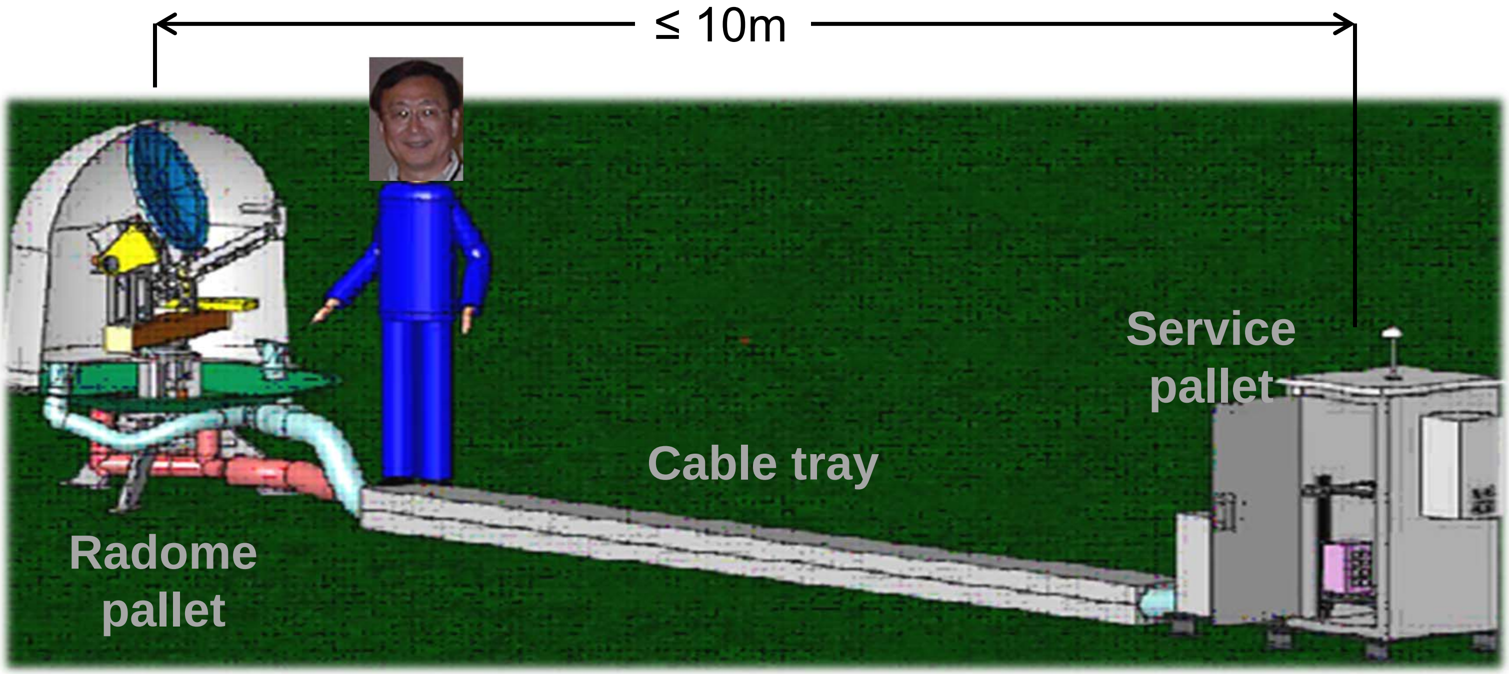


**GPS**

Calibrated by NIST-F1 primary frequency standard

International coordination of time and frequency: UTC, TAI, etc.

# NIST MWL Ground Station - Status




**Radome pallet**

- dimension: 1.6m(L)x1.6m(W)x1.9m(H)
- weight: < 240kg
- Mounted on flat surface (3 bolts)

**Power requirement (for both pallets):**

- 110VAC or 220VAC
- on emergency power
- ≤ 11kW

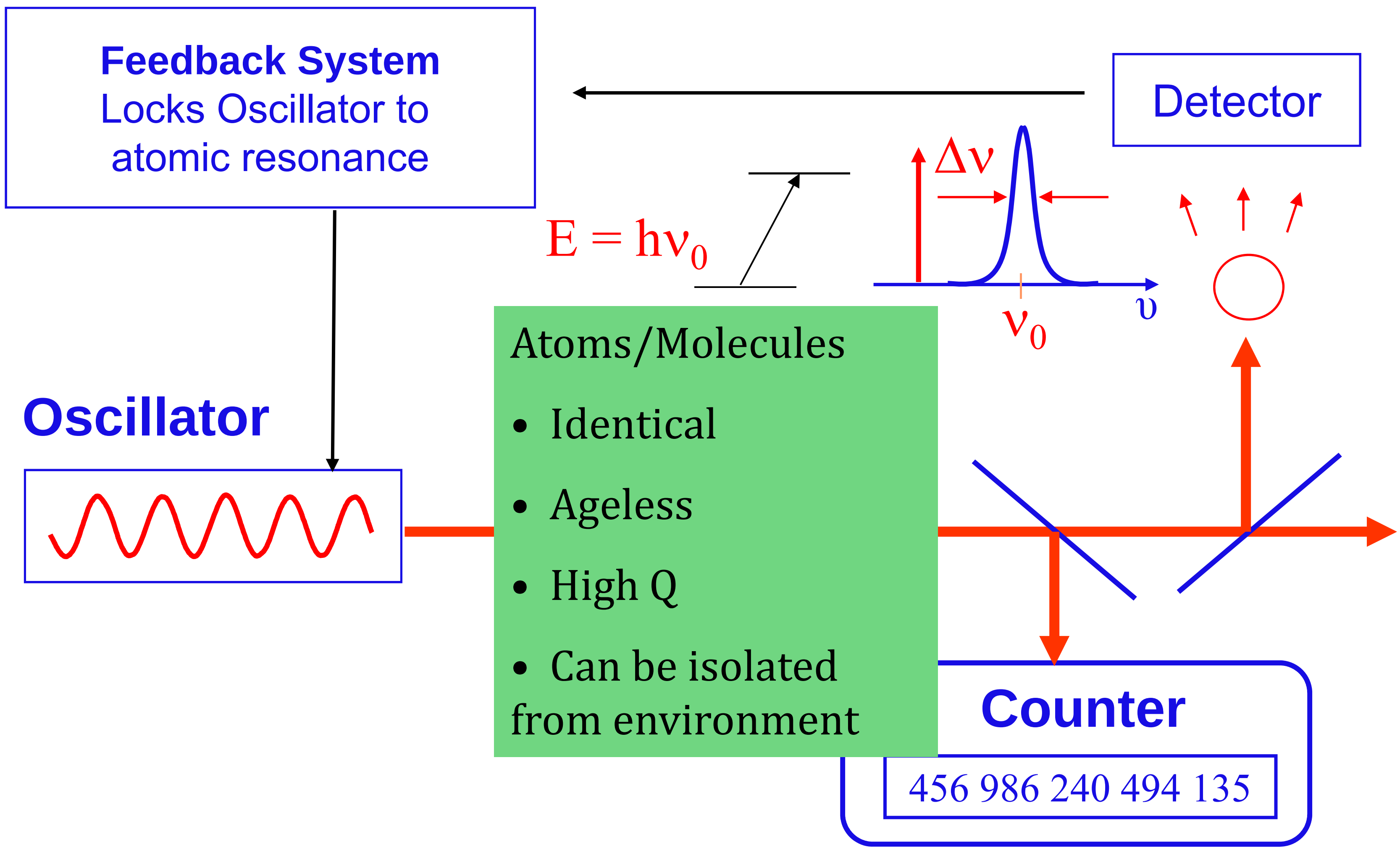
**Service pallet**

- dimension: 1.7m(L)x1m(W)x1.7m(H)
- weight: < 650kg
- Mounted on flat surface (8 bolts)

**Update**

- Location selected
- Delivery of MWL hardware expected in 2014

# Building blocks of an atomic clock



# Characterization of clock signals - definitions

Stability – how much the frequency changes over a specified time interval

$$\sigma_y = \frac{\Delta \nu}{\nu_0} \frac{\sqrt{\mathrm{T}_C}}{\sqrt{N}\sqrt{\tau}}$$

Optical clocks have much higher $\nu_0$!

Accuracy – two meanings:

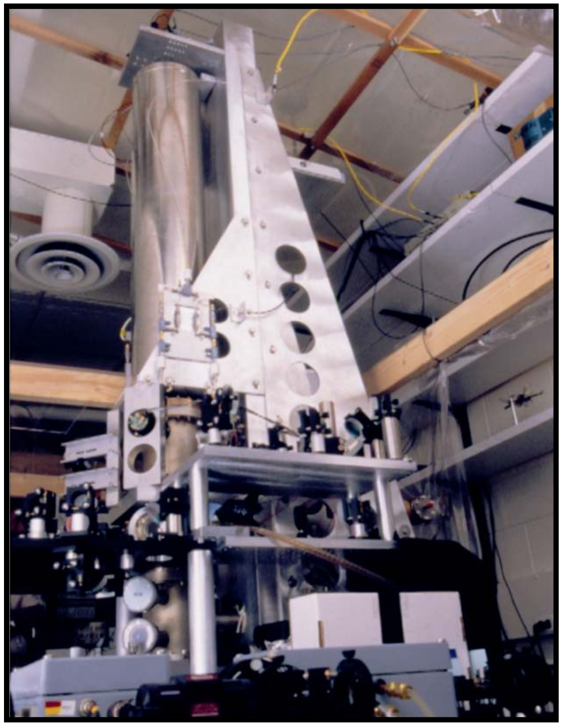
(1) How well the signal produces an exact frequency in terms of the SI second

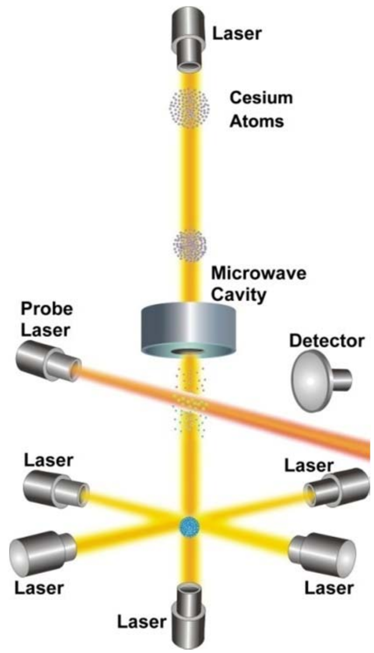
(2) How well the standard represents the natural frequency of the atomic transition - **Uncertainty**

Both important – relative importance depends on the application!

# NIST-F1 Cs Fountain Microwave Clock

## Primary Frequency Standard for the United States






1 second is defined as the duration of 9,192,631,770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the $^{133}$Cs atom.

*NIST-F1 laser-cooled cesium primary frequency standard*

Current "in house" frequency uncertainty $\Delta f/f \sim 3 \times 10^{-16}$.

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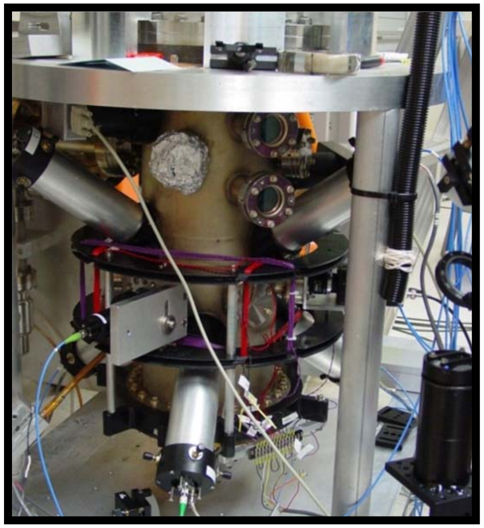
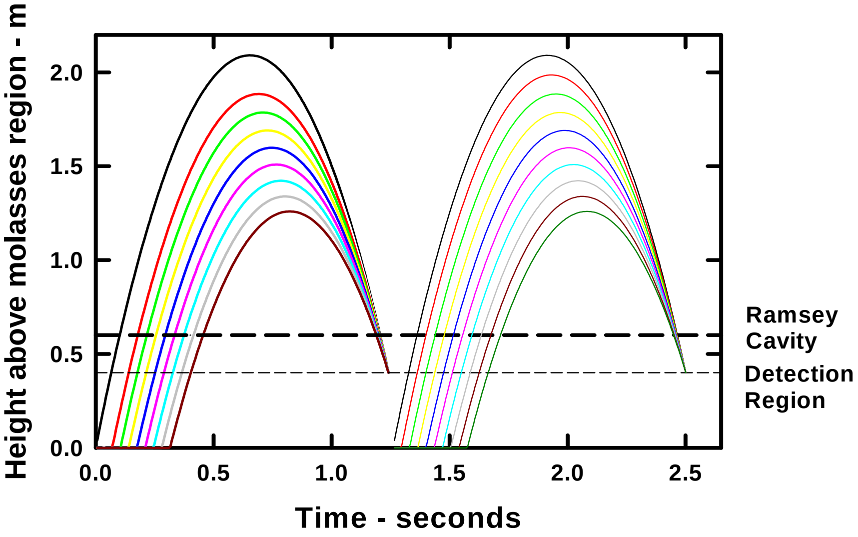
# NIST-F2 Cs Fountain Microwave Clock

## Next Generation Microwave Primary Frequency Standard

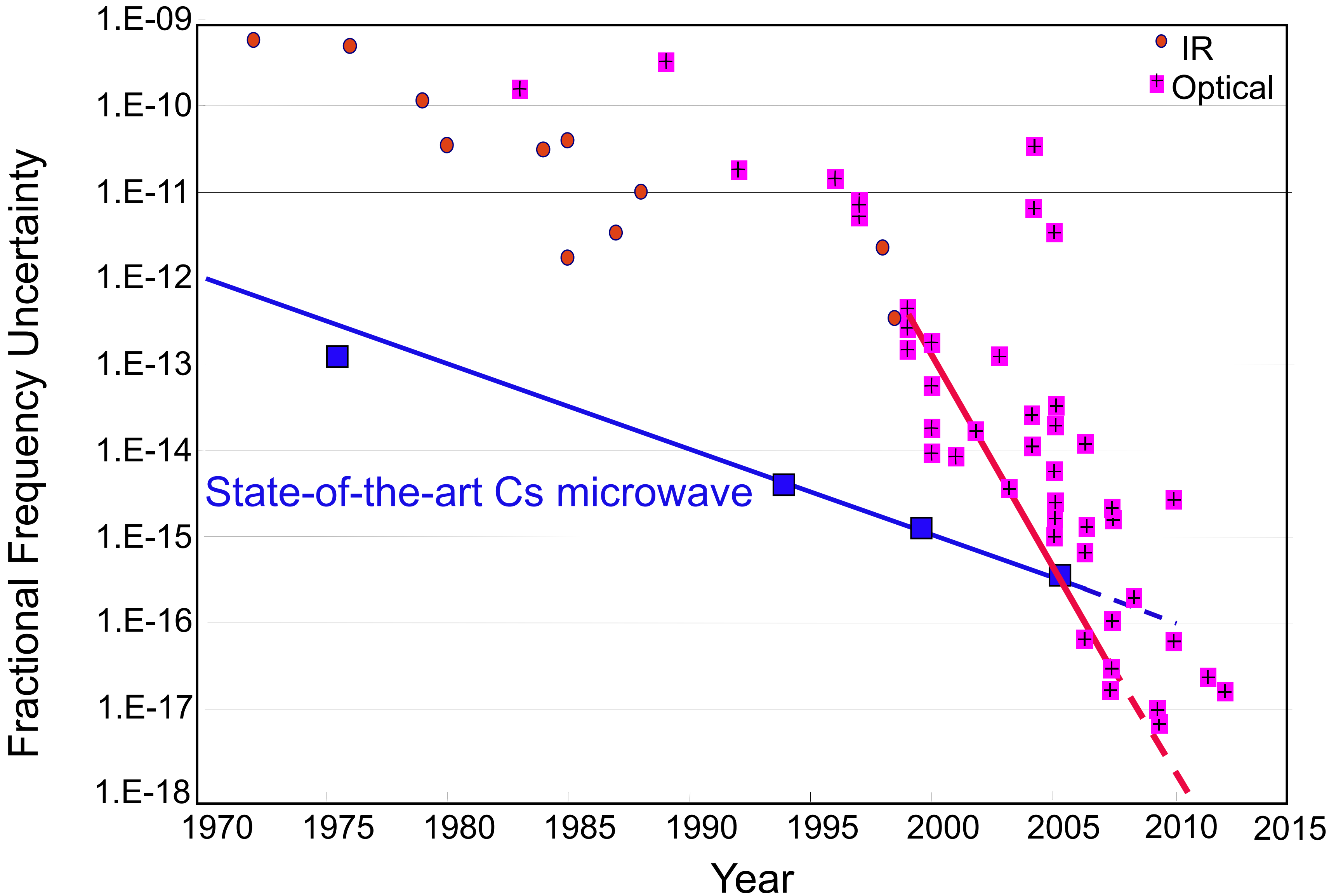


- Cryogenic drift tube to reduce blackbody shift.
- “Multitoss” atom ball launch to reduce collisional shifts.

Expected uncertainty
$\Delta f/f \sim 1 \times 10^{-16}$ or better.



# Optical atomic clock performance - uncertainty

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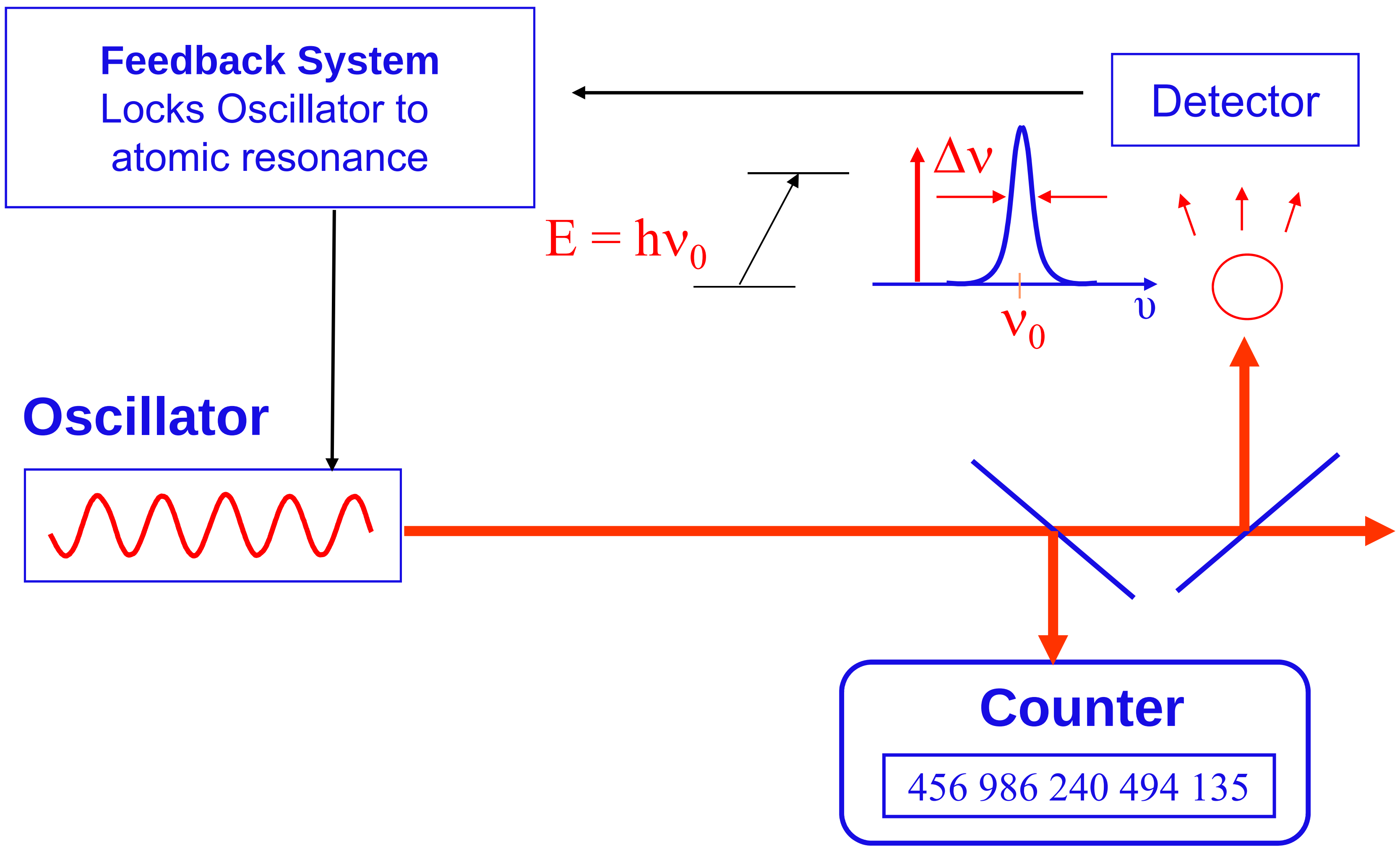
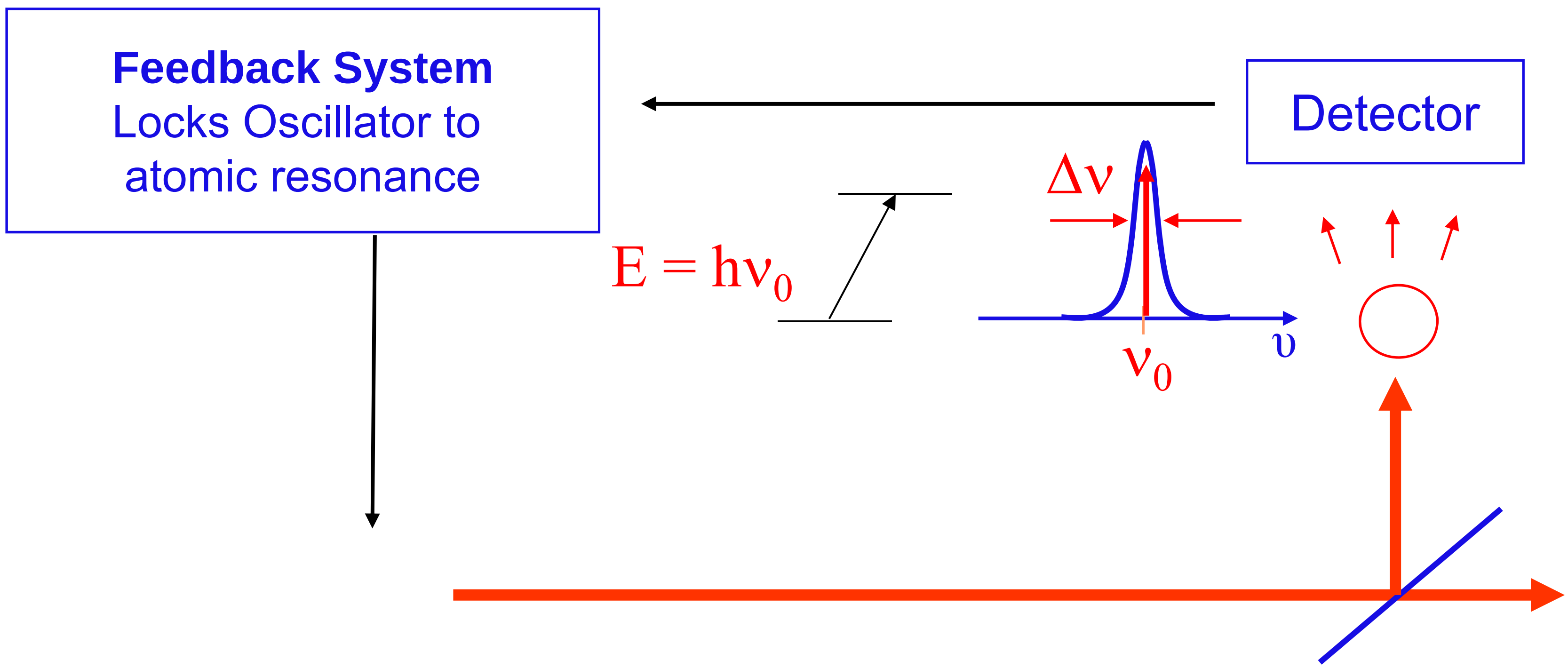
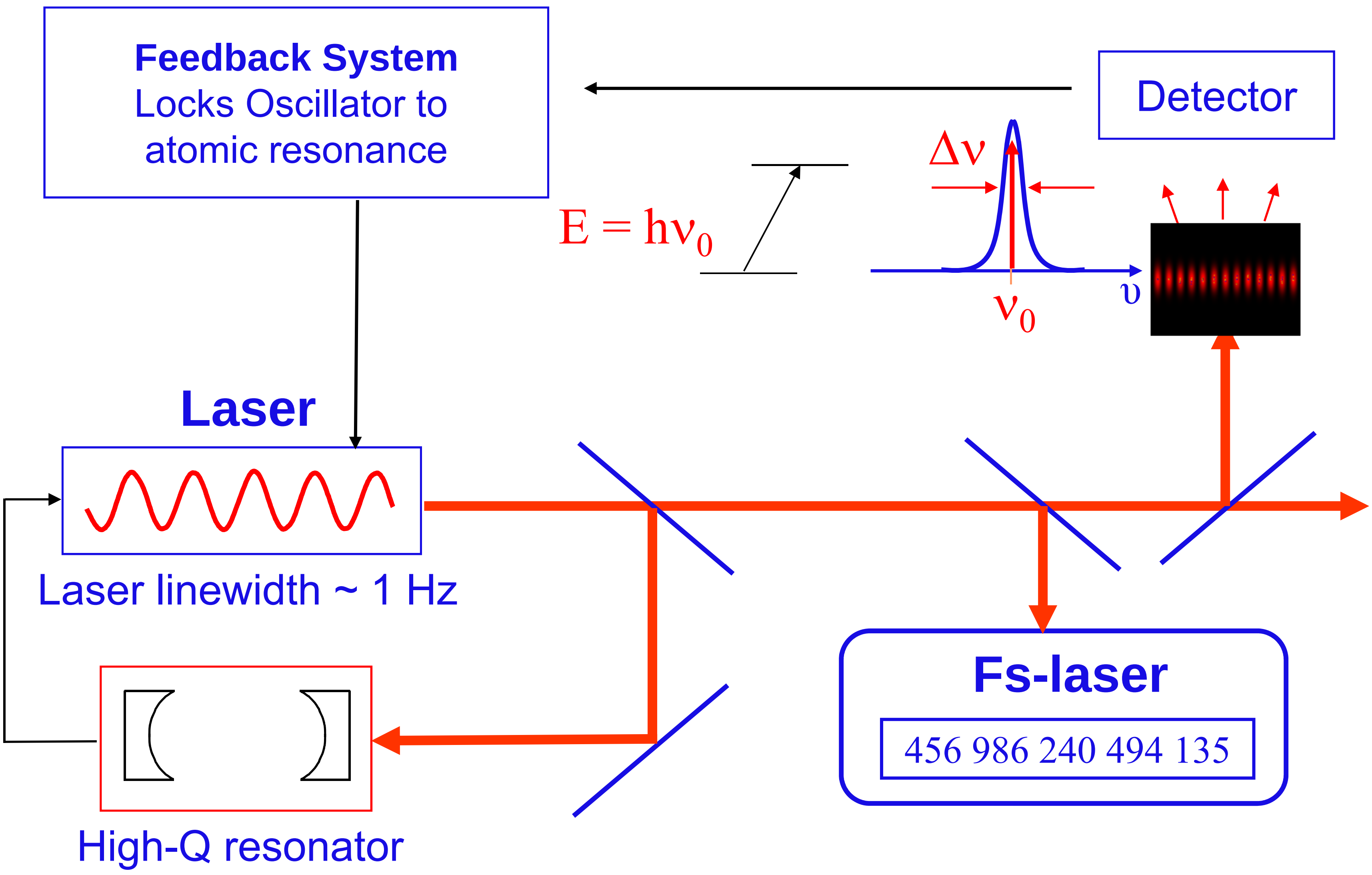
# Building blocks of an atomic clock



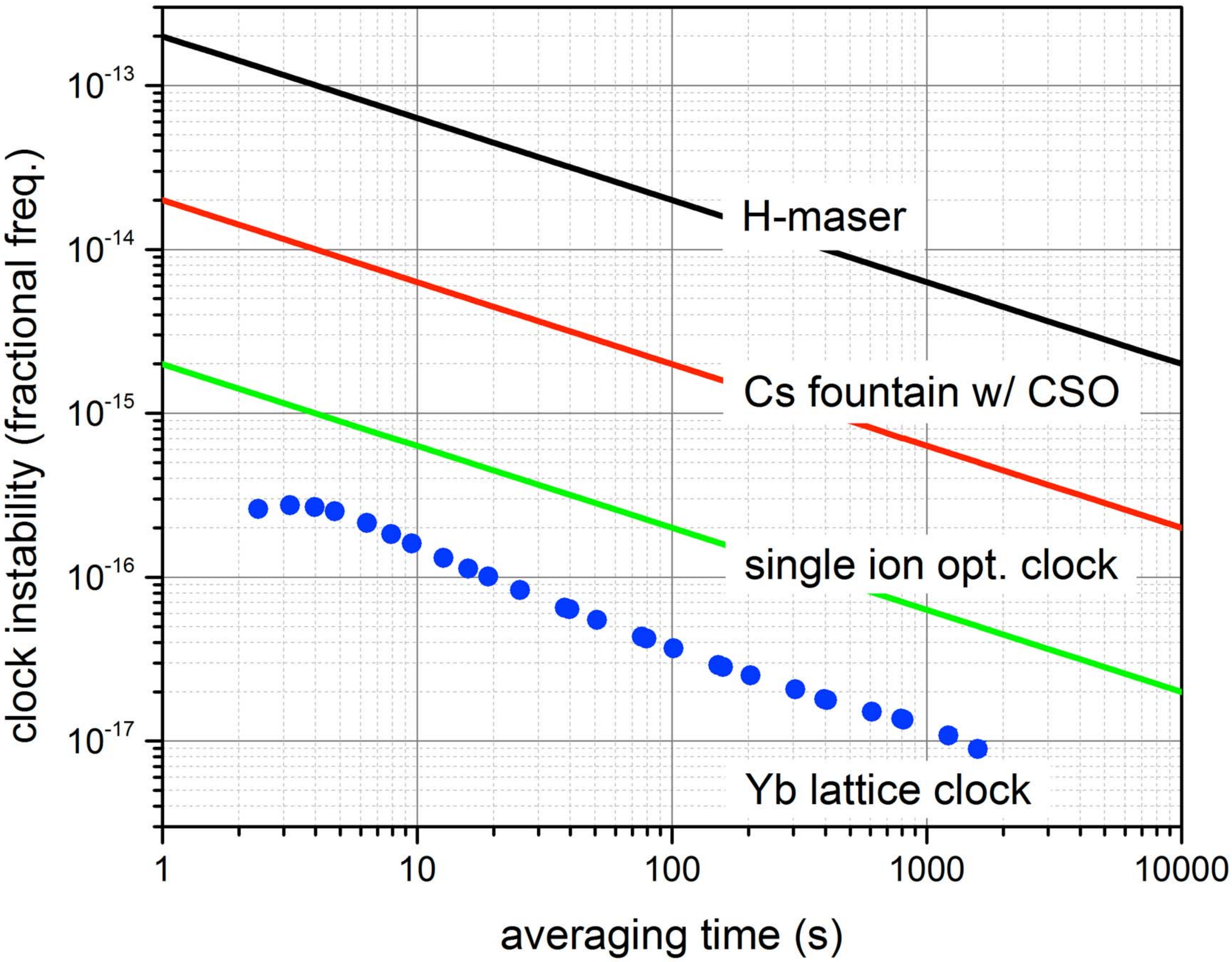
# Building blocks of an atomic clock



# Building blocks of an optical atomic clock

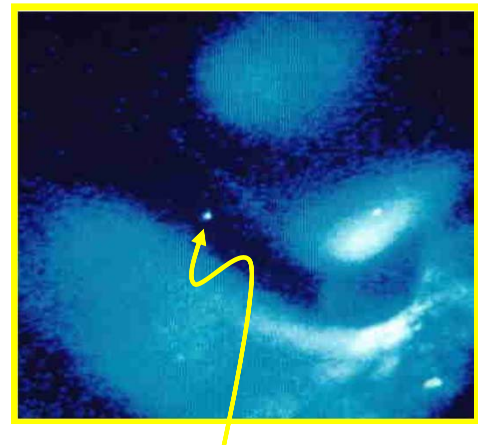


# High stability of optical clocks



# Two types of optical atomic clocks

## Trapped ions:  Al+, Hg+, Yb+, Sr+

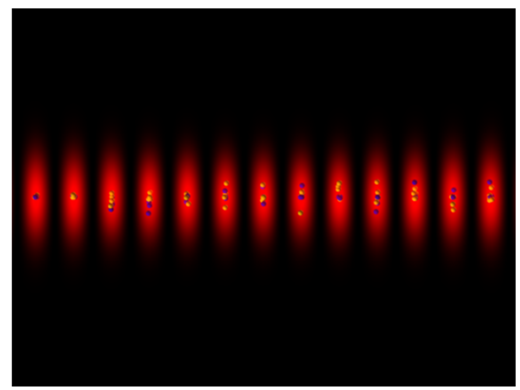


Ion traps suppress motional effects

Exc. immunity to environmental effects ($\Delta\nu/\nu_0 < 10^{-17}$ !)

Limited S/N ratio – typically one clock ion

## Neutral atoms:  Sr, Yb, Hg

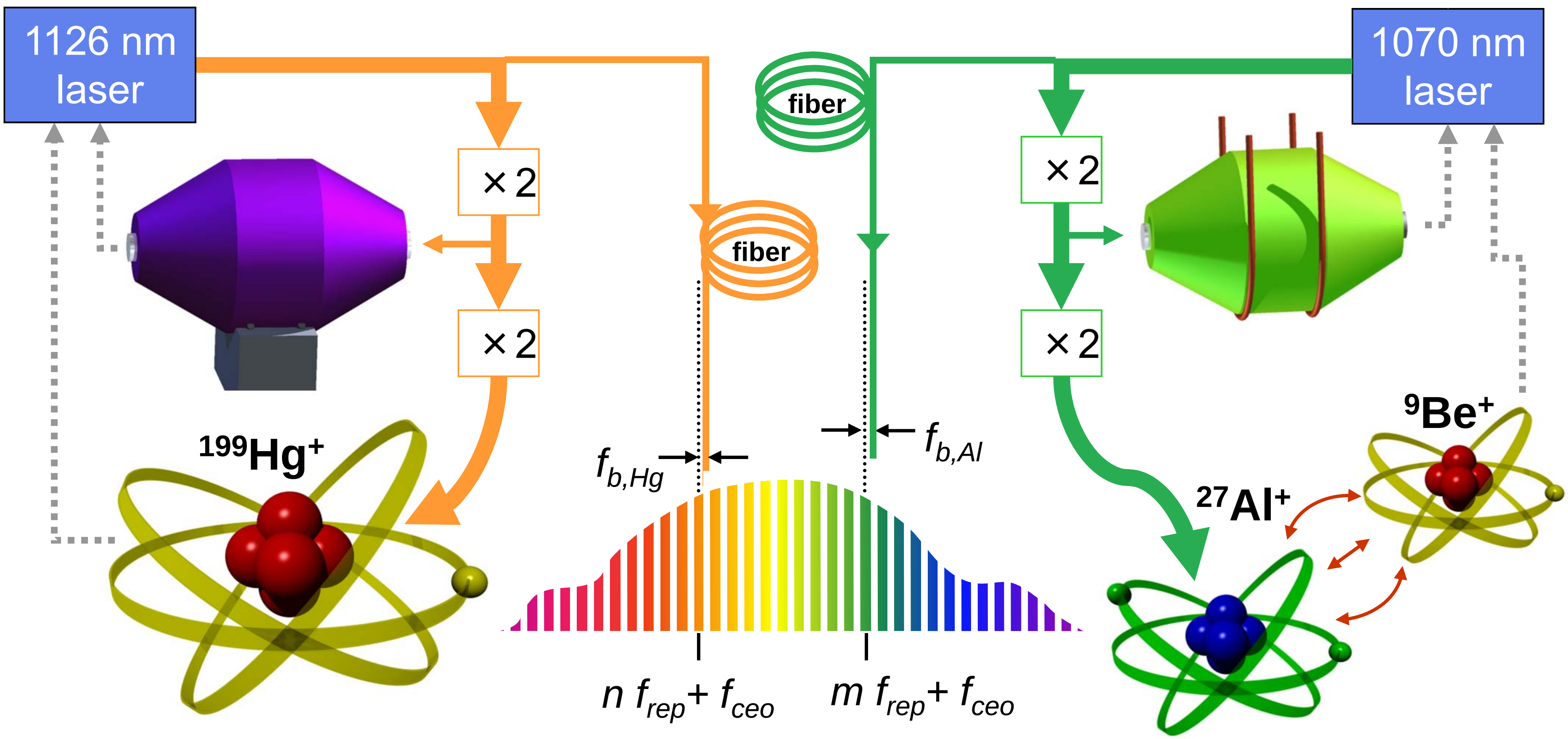


Need to use laser traps for tight confinement

Good immunity to environmental effects

Potential for very high stability

# Comparison of Hg⁺ and Al⁺ Clocks at NIST




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

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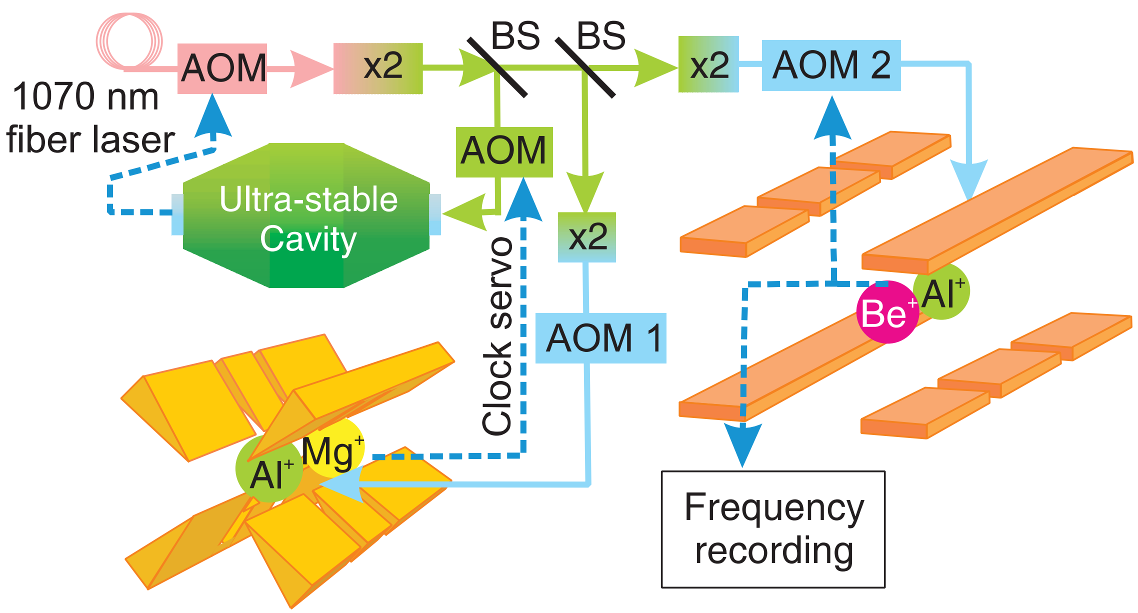
# $Al^+$ quantum logic clock – most accurate in the world

PRL **104,** 070802 (2010) PHYSICAL REVIEW LETTERS week ending 19 FEBRUARY 2010

## Frequency Comparison of Two High-Accuracy $Al^+$ Optical Clocks

C. W. Chou,* D. B. Hume, J. C. J. Koelemeij,† D. J. Wineland, and T. Rosenband
*Time and Frequency Division, National Institute of Standards and Technology, Boulder, Colorado 80305, USA*
(Received 23 November 2009; published 17 February 2010)



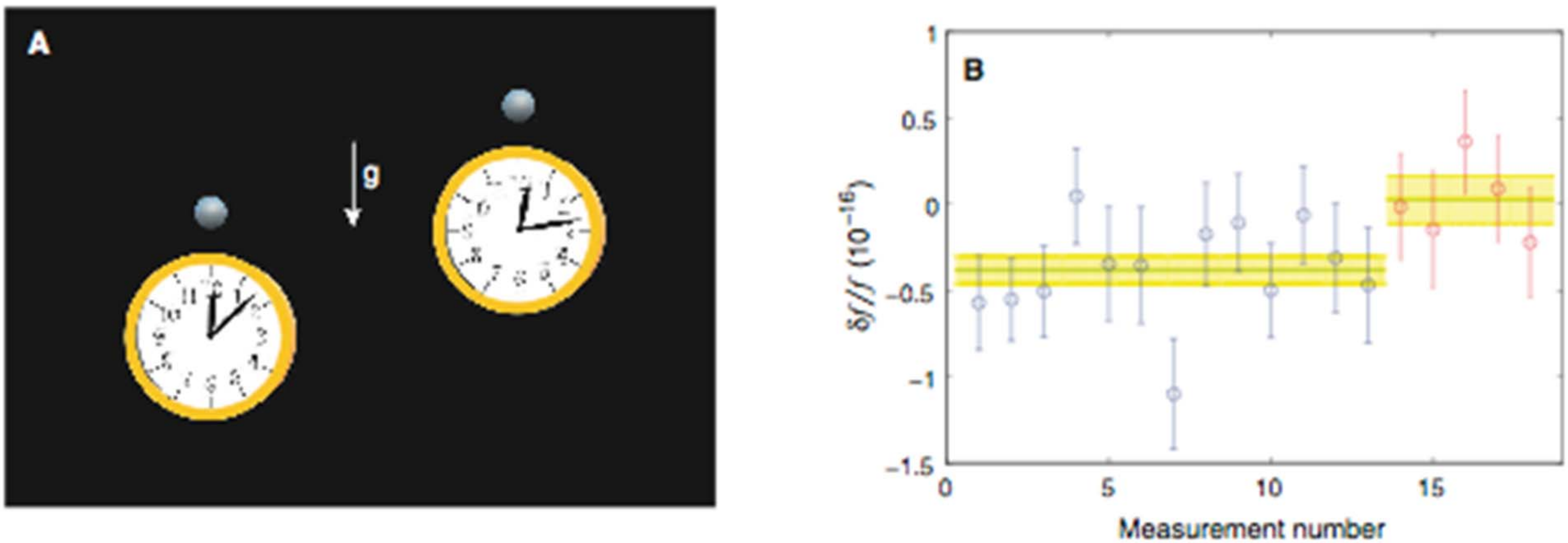

$$\Delta\nu/\nu_0 = 8.6 \times 10^{-18}$$

# Relativistic geodesy

## Optical Clocks and Relativity

C. W. Chou,* D. B. Hume, T. Rosenband, D. J. Wineland

24 SEPTEMBER 2010 VOL 329 SCIENCE



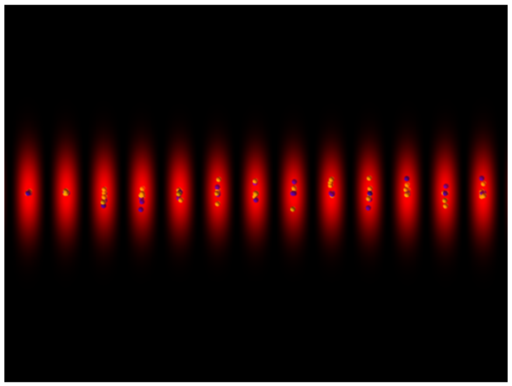

1 part in $10^{18}$ corresponds to 1 cm displacement

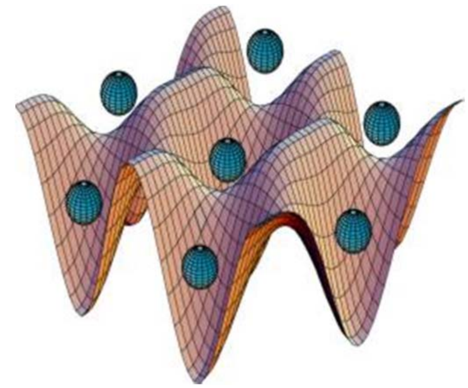
Use 1 fixed clock and 1 clock in the field to map out g

What about gravitational fluctuations (Kleppner)? 10-20 cm/day

# Advantages of an optical lattice

Confine neutral atoms in ion-like environment



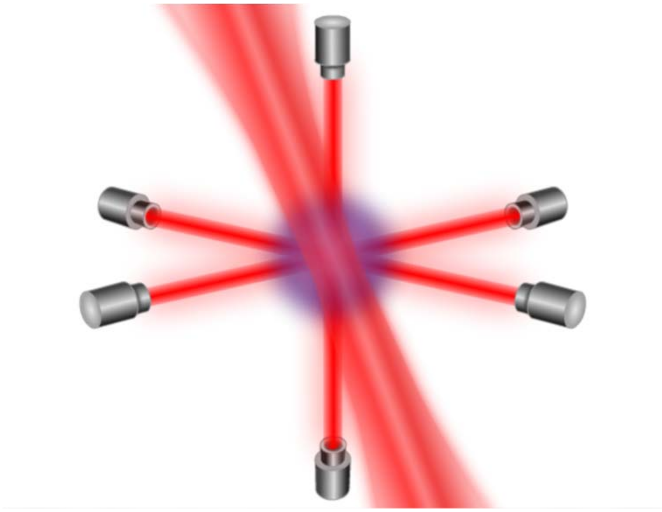


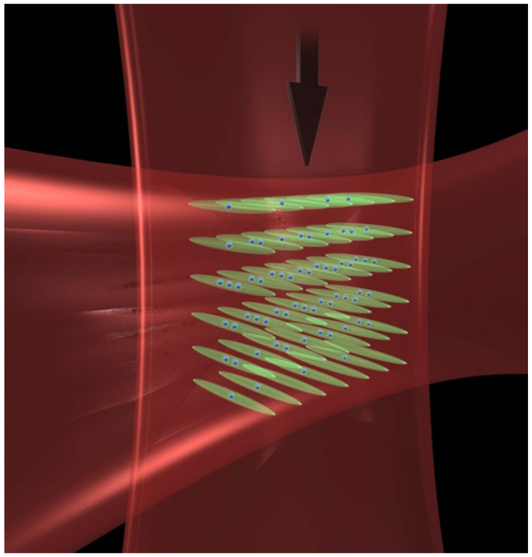
- Tight confinement — Doppler & recoil-free
- Long interaction time — high Q
- Large numbers ($\sim 10^4$) — high S/N

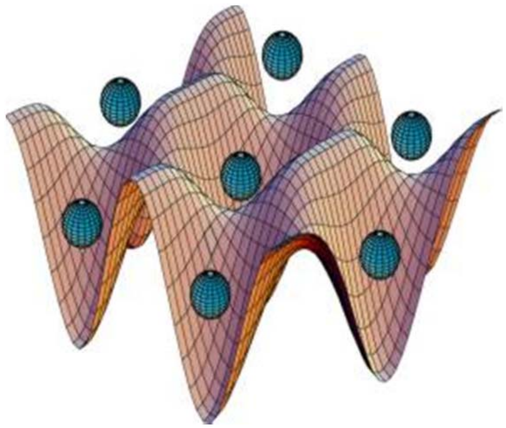
~ 20 lattice clocks around the world (Sr, Yb, and Hg)!

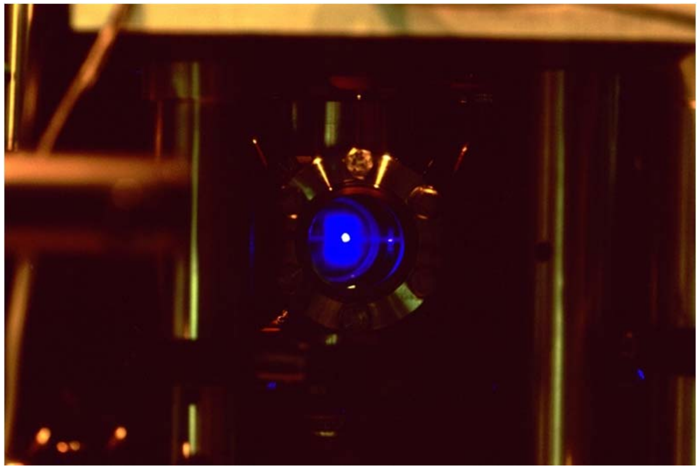
H. Katori, M. Takamoto, M., V. G. Pal'chikov, et al., *PRL* **91**, 173005 (2003)

# NIST Optical Frequency Standards





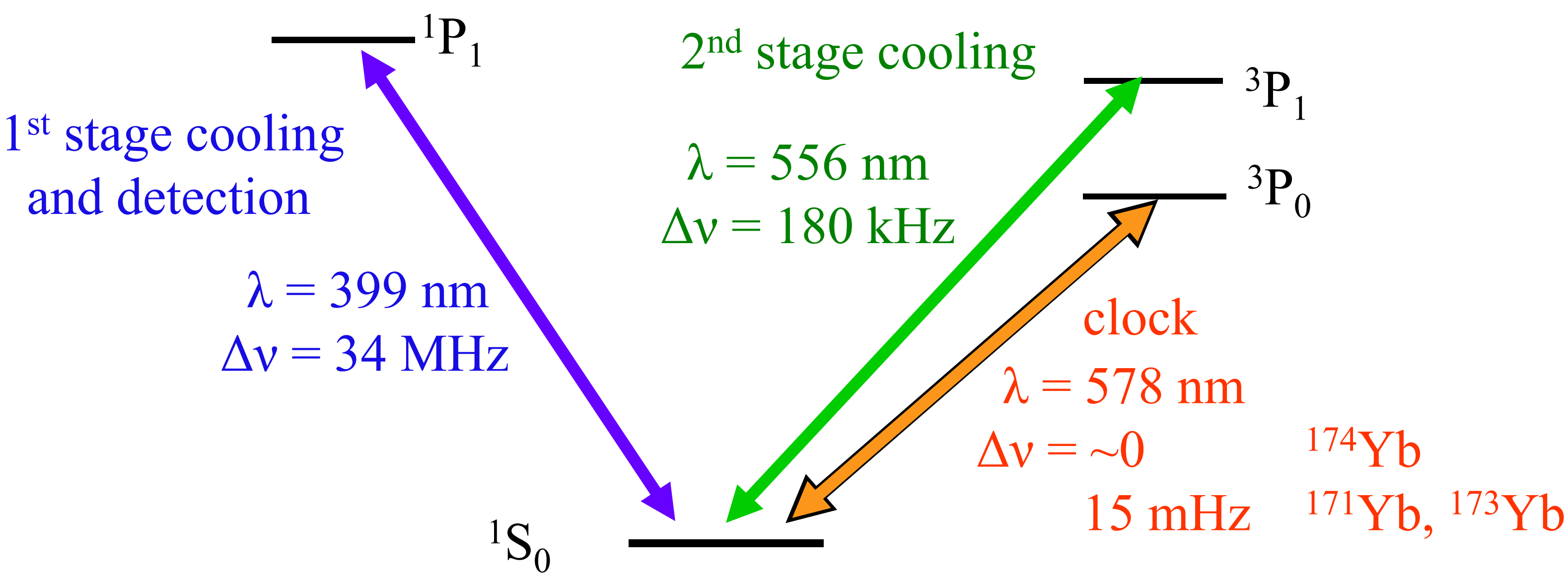




Optical Lattice Clocks

- Ytterbium (NIST)
- Strontium (JILA)
- ~ $10^{-16}$, rapidly improving

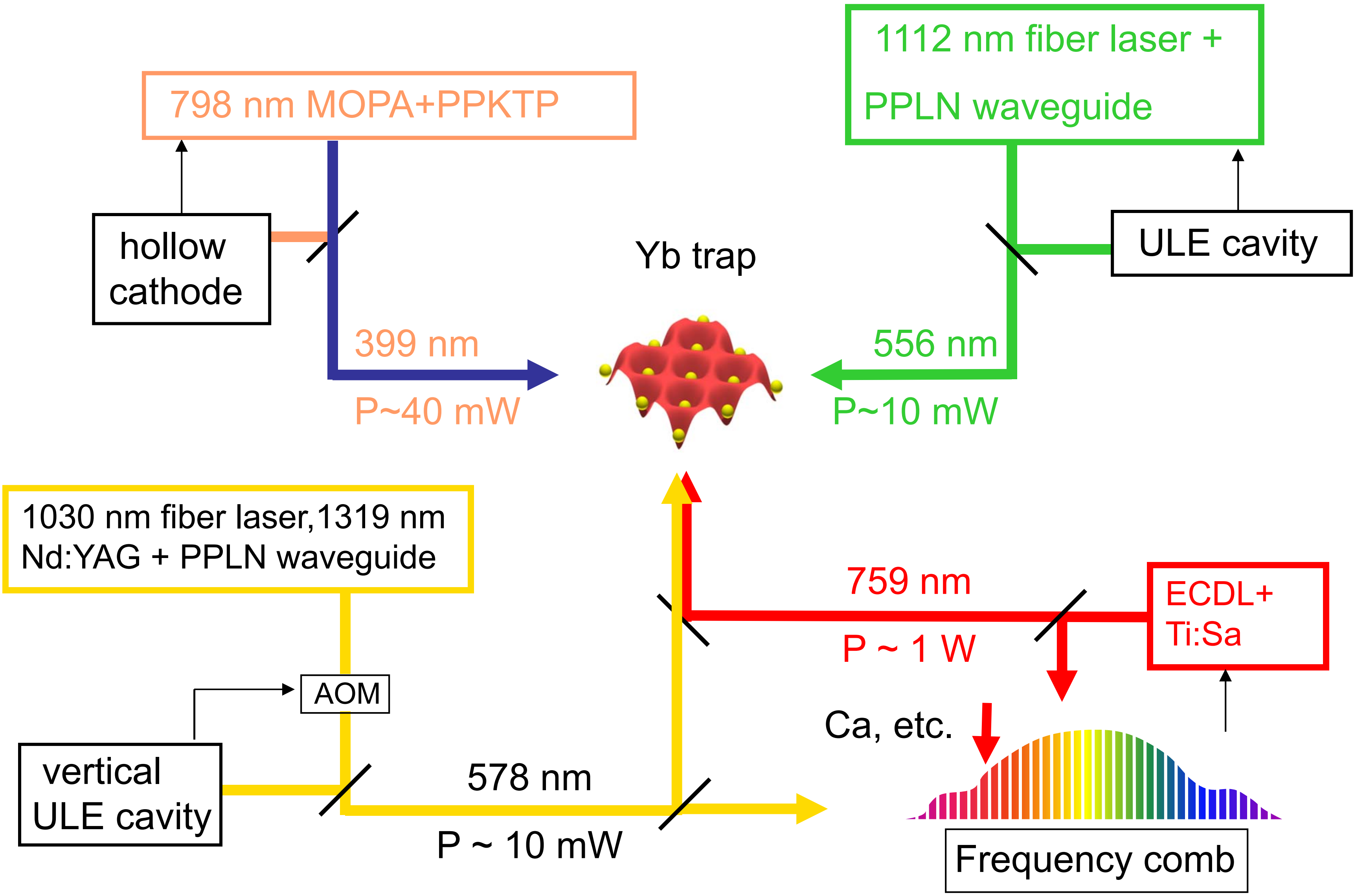
# Lattice clocks based on neutral ytterbium



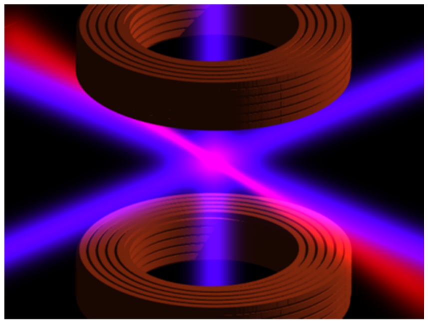
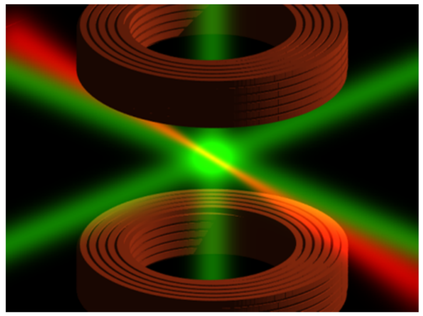
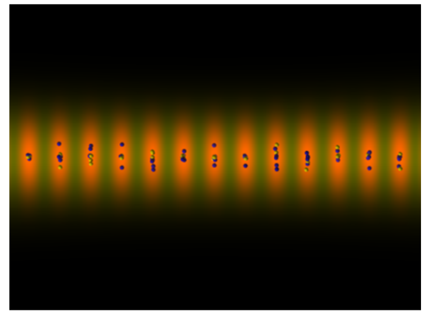
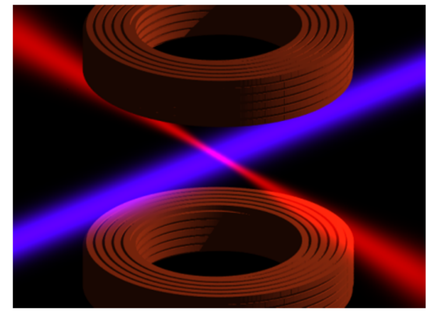

- Many abundant isotopes, different spins (I = 0, 1/2, 5/2)

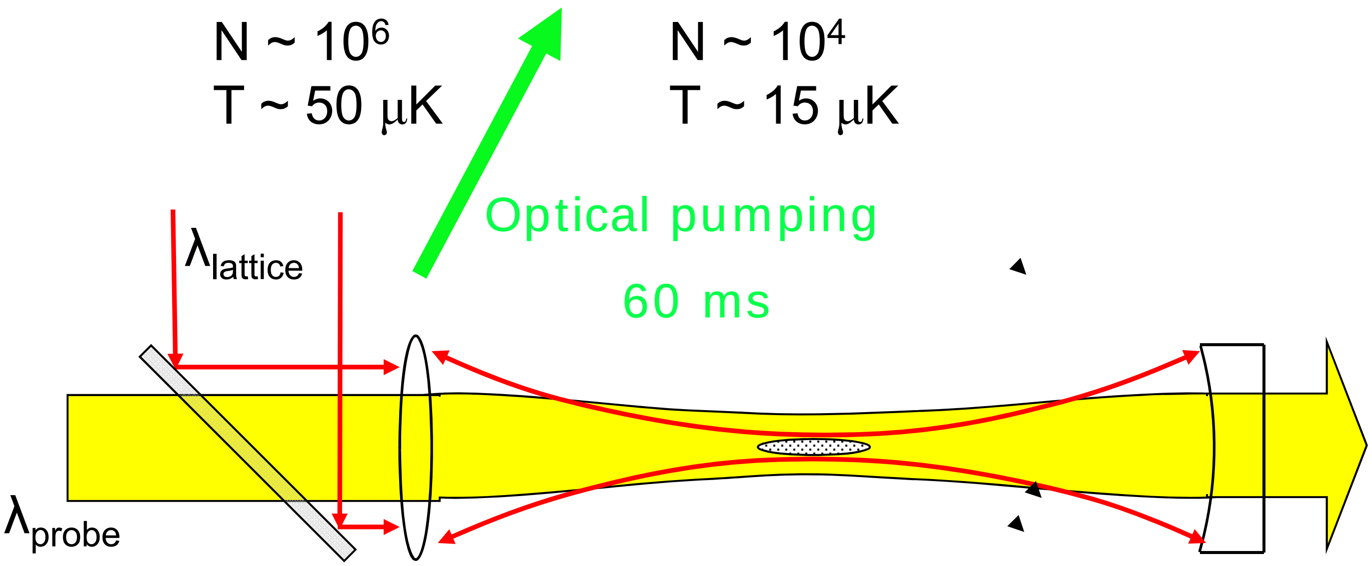
- Today we focus on NIST-based experiments on $^{171}$Yb (I = 1/2)

# Lasers for the Yb lattice clock



# Lattice clock measurement sequence

| 399 nm MOT 60 ms | 556 nm MOT 80 ms | Probe atoms in lattice ~ 80 ms | Norm. shelving detection 40 ms |
|---|---|---|---|
|  |  |  |  |
| N ~ $10^6$<br>T ~ 5 mK | N ~ $10^6$<br>T ~ 50 $\mu$K | N ~ $10^4$<br>T ~ 15 $\mu$K | |

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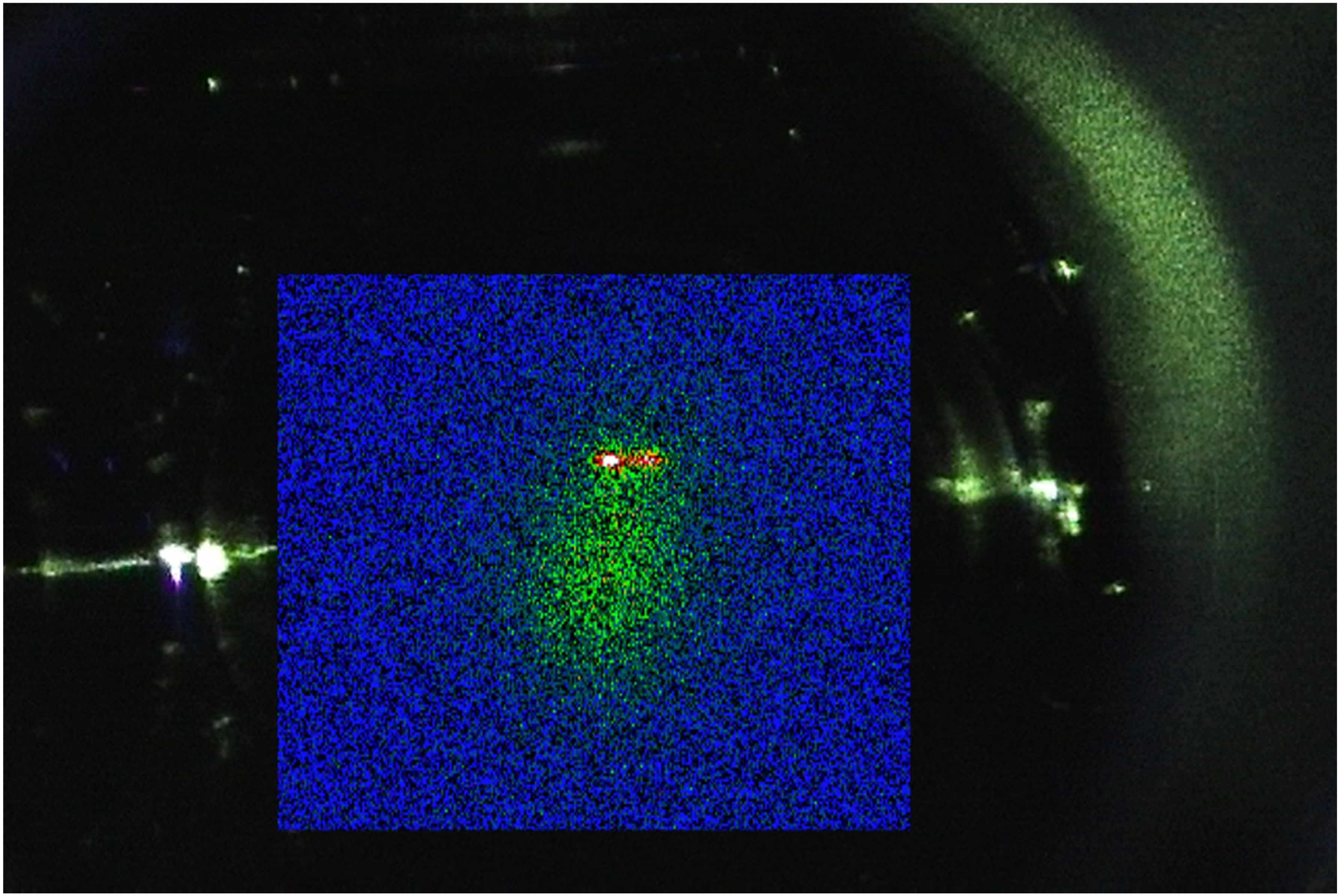
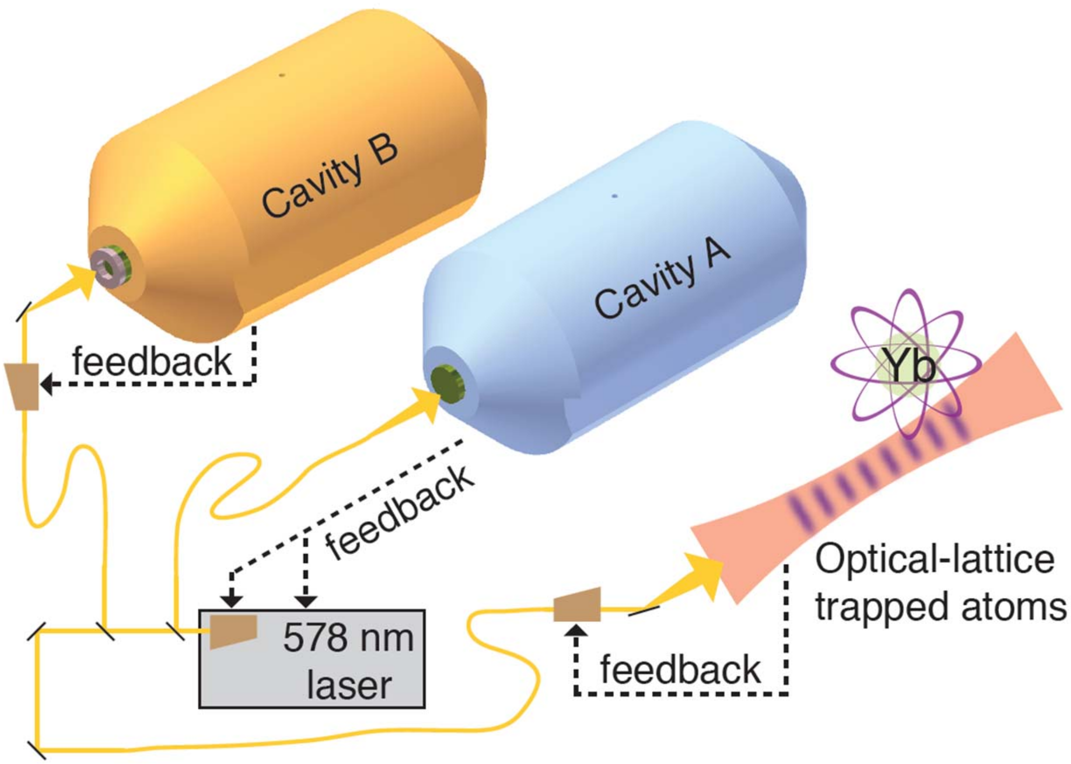
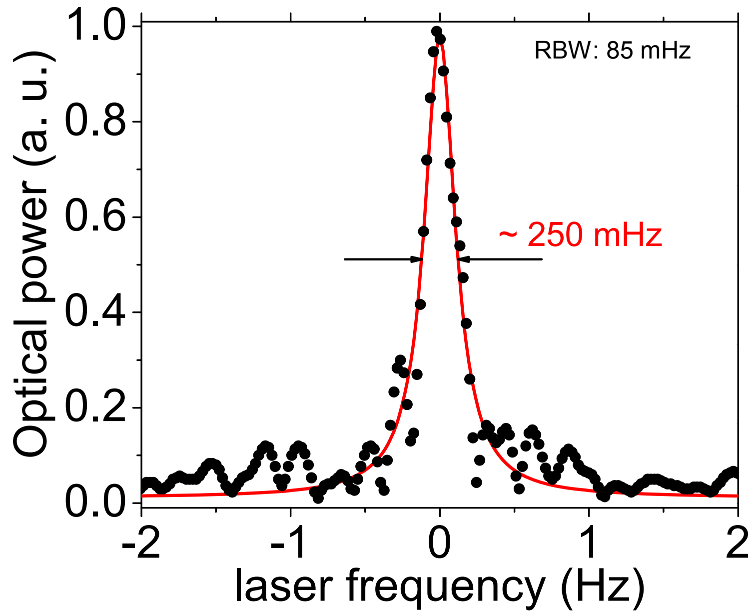
# Trapped Yb atoms



# Laser stabilization: sub-Hz linewidth lasers

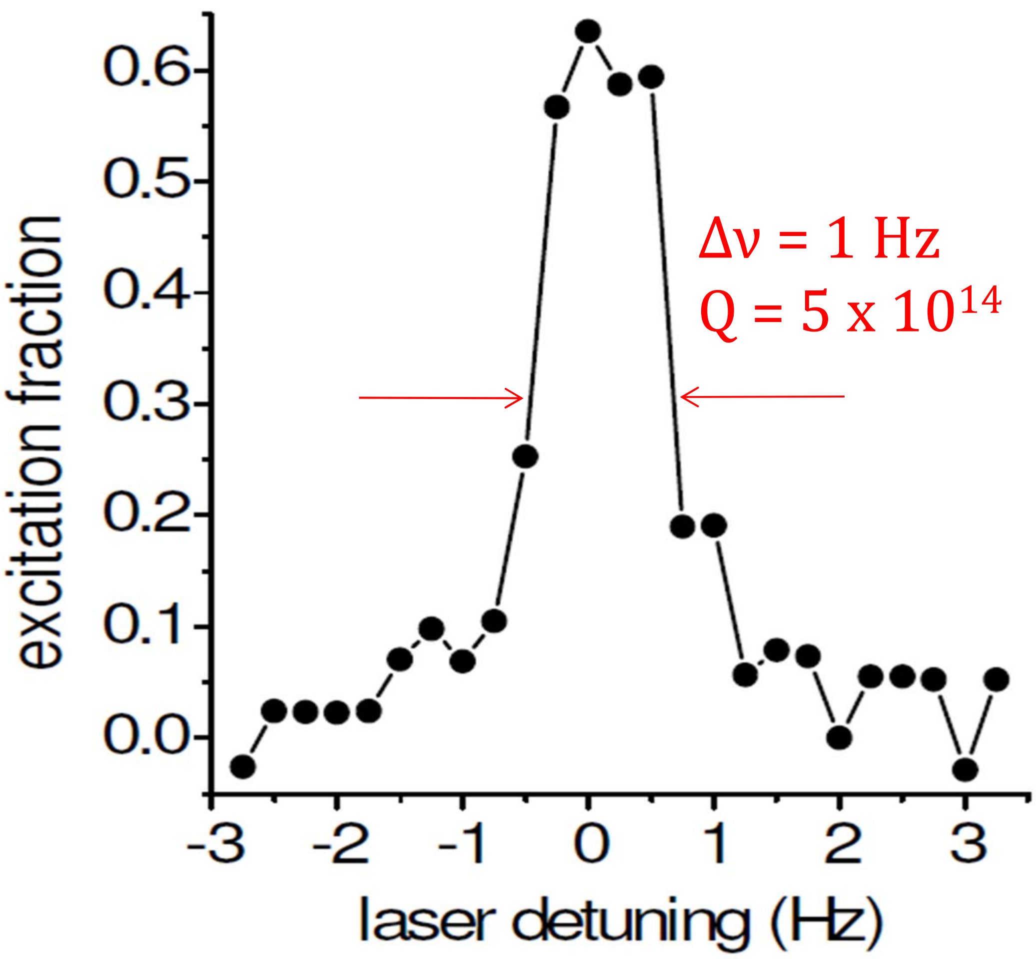



Jiang et al, Nature Photonics **5** 160 (2011)

# Sub-Hz optical spectroscopy

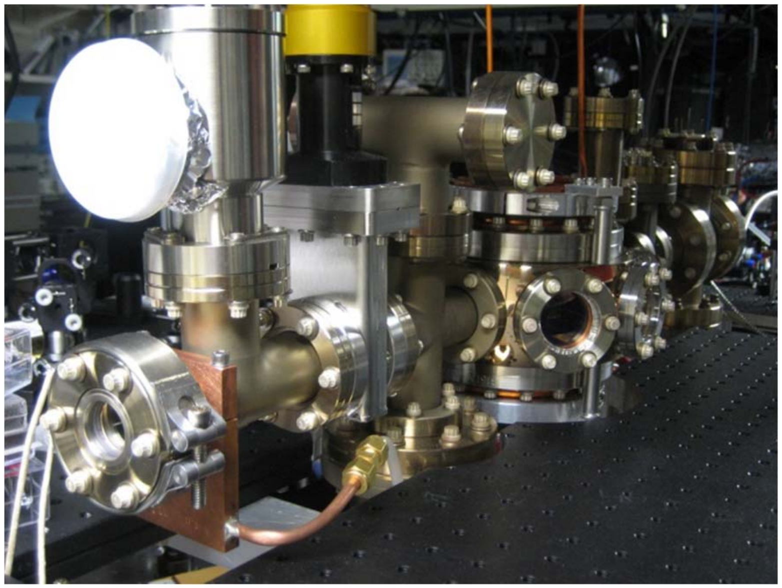
900 ms probe time



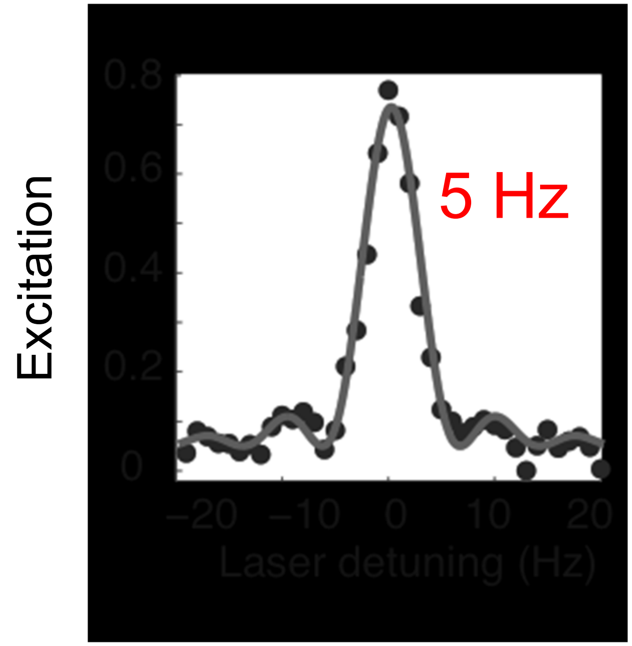

Jiang et al, Nature Photonics **5** 160 (2011)

# Two Yb lattice clocks - comparisons

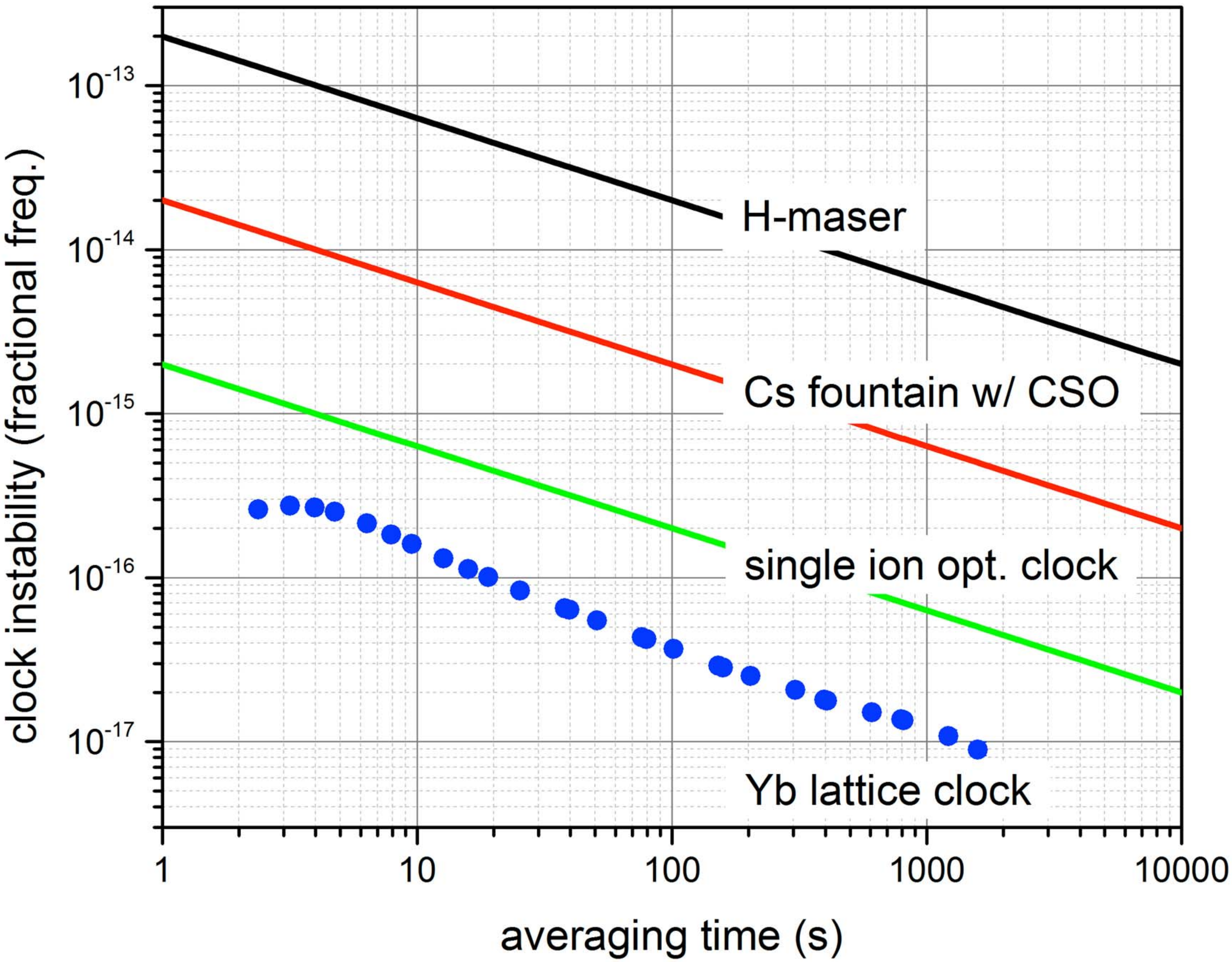
A second Yb lattice clock system



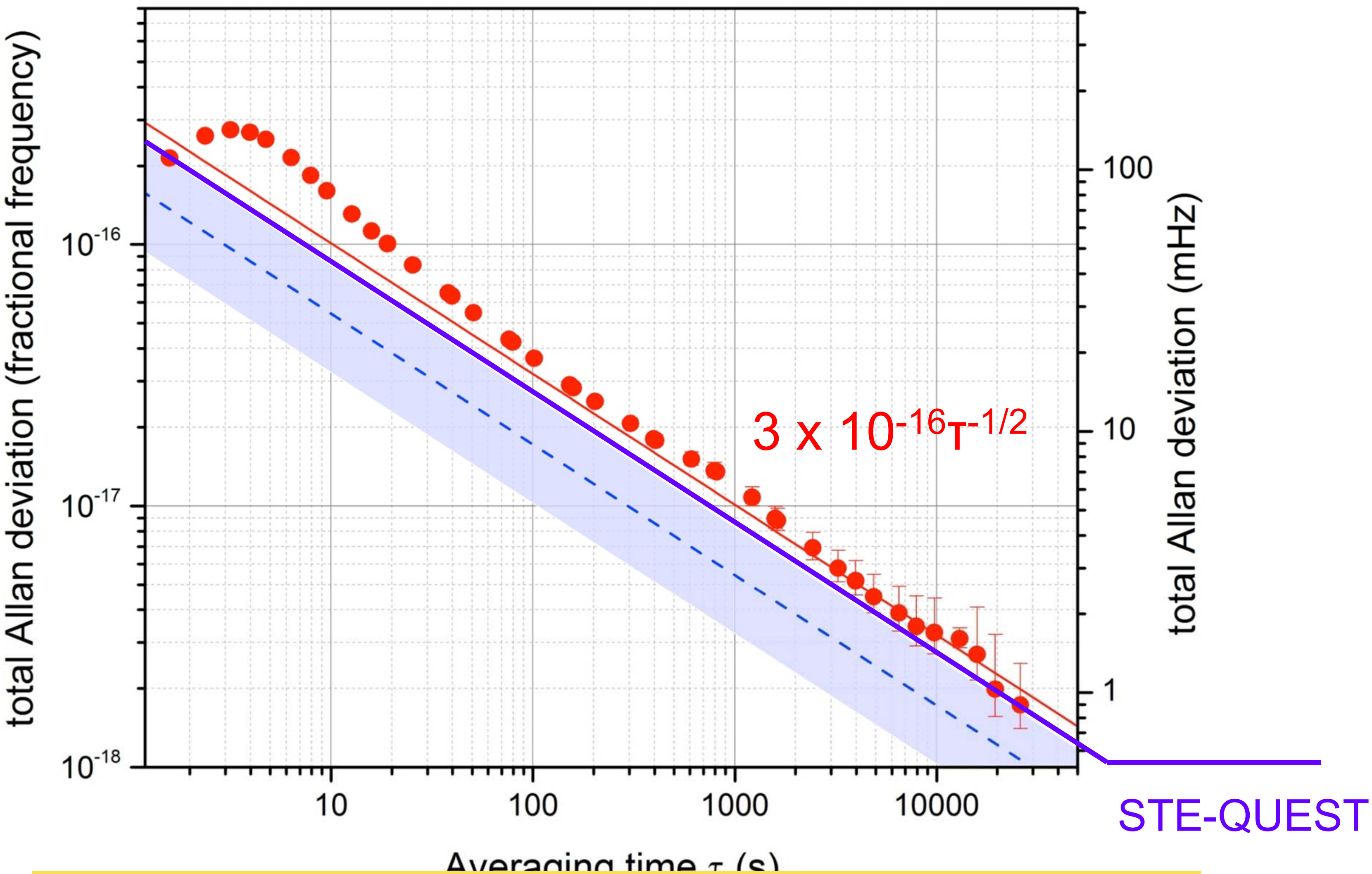
Clock spectroscopy



# High stability of optical clocks



# 1.8 x $10^{-18}$ instability for the Yb lattice clock




Necessary to control collision effects and have clean lattice spectra!

# Frequency uncertainty for NIST Yb clock

| Effect | Shift ($10^{-16}$) | Uncertainty ($10^{-16}$) |
|---|---|---|
| Blackbody | -25.0 | 2.5 |
| Lattice polarizability | 3.7 | 2.1 |
| Cold Collisions | -16.1 | 0.8 |
| First-order Zeeman | 0.4 | 0.4 |
| Second-order Zeeman | -1.7 | 0.1 |
| Probe light | 0.05 | 0.2 |
| AOM phase chirp | 0 | 0.1 |
| Others | 0 | 0.1 |
| Total | -38.7 | 3.4 |

Systematic Total: $3.4 \times 10^{-16}$

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

# Transition frequency uncertainty

| Effect | Shift ($10^{-16}$) | Uncertainty ($10^{-16}$) |
|---|---|---|
| Blackbody | -25.0 | 0.3 |
| Lattice polarizability | 3.7 | 2.1 |
| Cold Collisions | 0 | 0.005 |
| First-order Zeeman | 0.4 | 0.4 |
| Second-order Zeeman | -1.7 | 0.1 |
| Probe light | 0.05 | 0.2 |
| AOM phase chirp | 0 | 0.1 |
| Others | 0 | 0.1 |
| Total | -38.7 | 3.4 |

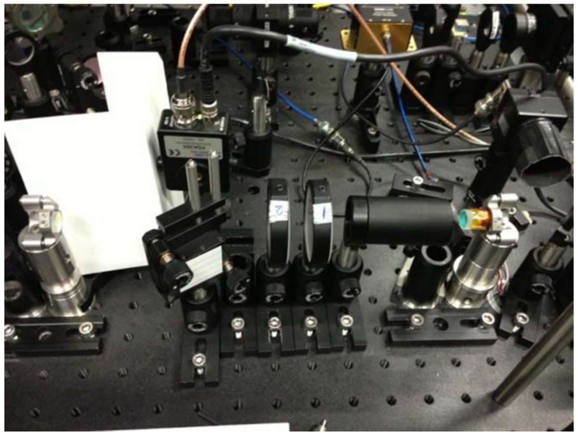
Good prospects for a Yb lattice clock at ~ $10^{-17}$

NIST

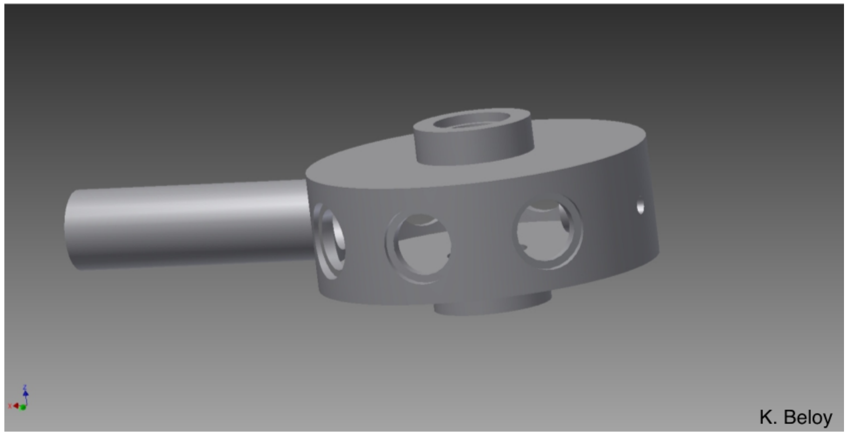
# Reducing the uncertainty further

What's next…….

A build-up cavity to enhance (temporarily!) lattice-based shifts and reduce density



A temperature-controlled chamber to minimize BBR uncertainties



# Conclusions and future prospects

NIST is preparing for the ACES mission (STE QUEST)?

Stability of optical clocks far surpasses all others, and optical lattice clocks are designed for high stability – $1.8 \times 10^{-18}$ in 20,000 s

In the near future – there will be many different clocks at $10^{-17}$ level, many of which will be striving for the $10^{-18}$'s

Key issues: BBR shift, lattice light shifts

Key questions:

How do we handle gravity at the $10^{-18}$ level? (QUEST?)

How do compare remote clocks < $10^{-16}$ level? (ACES, QUEST?)

How best to space qualify optical clocks (SOC)?

NIST

# Acknowledments


**Yb Clock**

**Present:** Andrew Ludlow, Nathan Lemke, Jeff Sherman, Rich Fox, Nathan Hinkley, Kyle Beloy , Nate Phillips

**Past:** Zeb Barber, Yanyi Jiang, Marco Pizzocaro, Nicola Poli, Jason Stalnaker, Chad Hoyt, Leo Hollberg

**Frequency Comb**

Tara Fortier, Matt Kirchner, Scott Diddams, *et al*

**$Al^+$, $Hg^+$ Clocks**

Jim Bergquist, Till Rosenband, James Chou, *et al*

**Sr Lattice Clock**

Jun Ye, Matt Swallows, Mike Martin, Mike Bishof, *et al*

**Cs Fountain & Timescale**

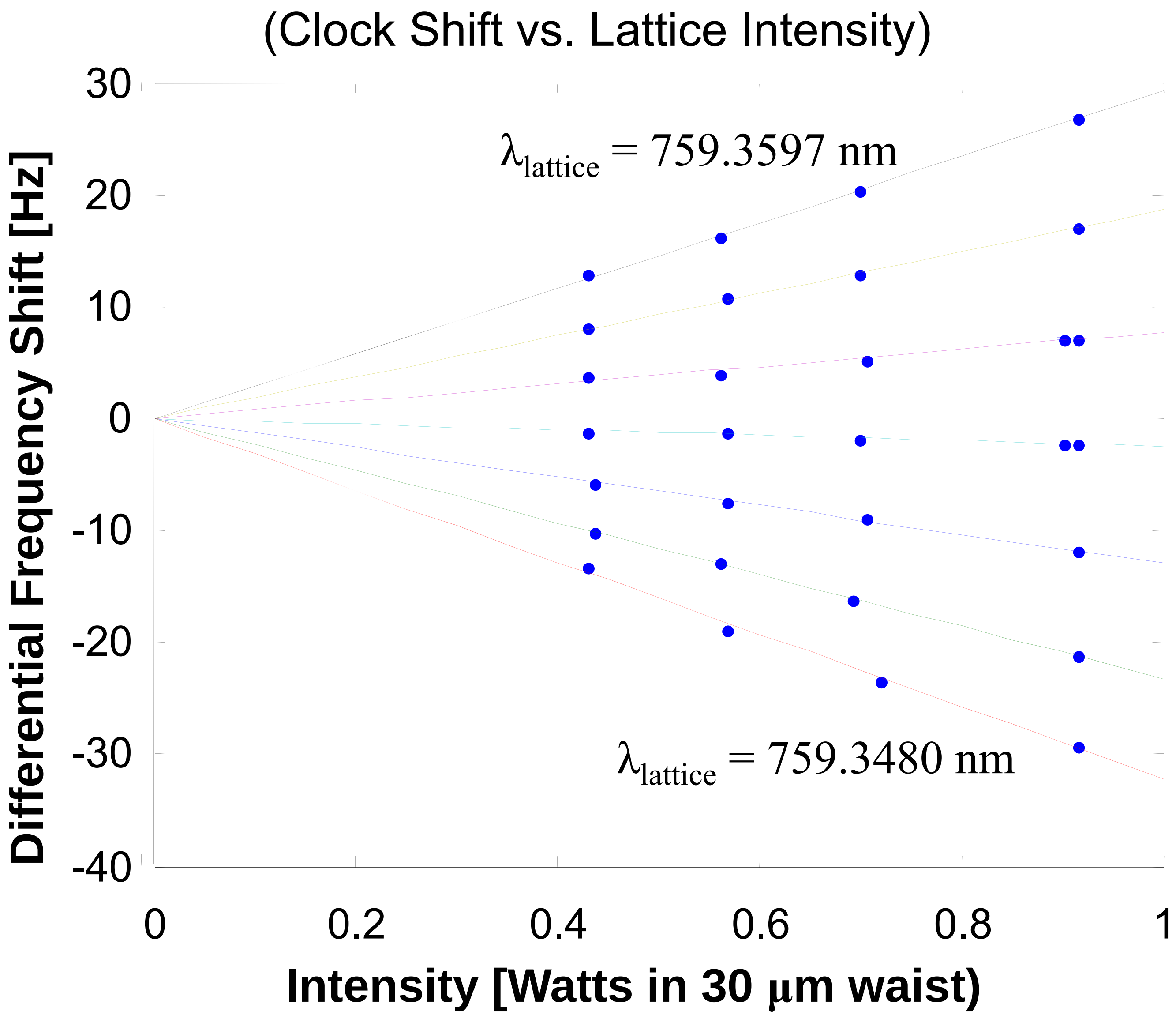
Steve Jefferts, Tom Heavner, Tom Parker, Stefania Romisch

Funding: NASA (Fundamental Physics)

DARPA QuASAR NIST

Thanks to Tom O’Brian and Andrew Ludlow for help with the slides!

# Finding the magic wavelength

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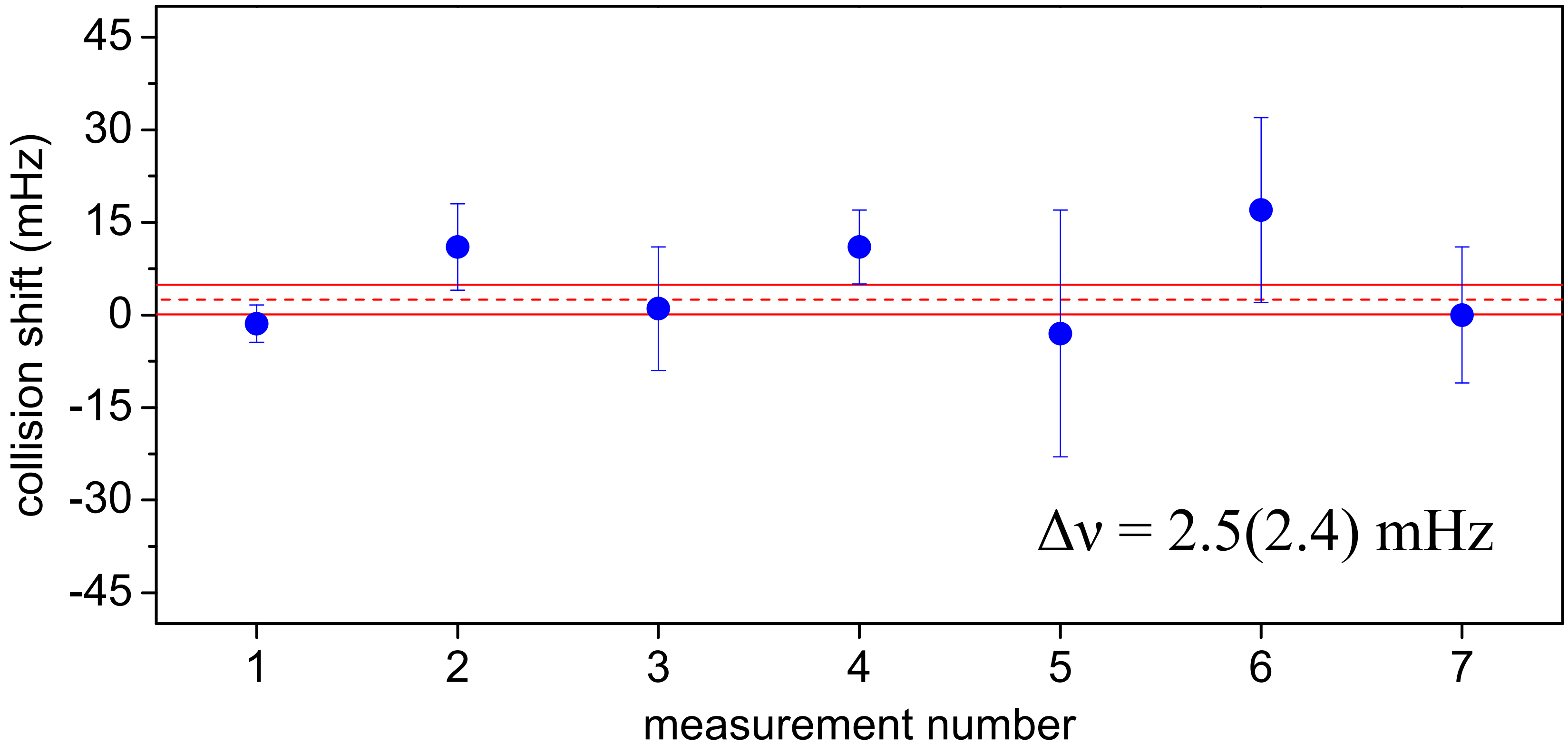
# Reducing the Cold Collision Shift



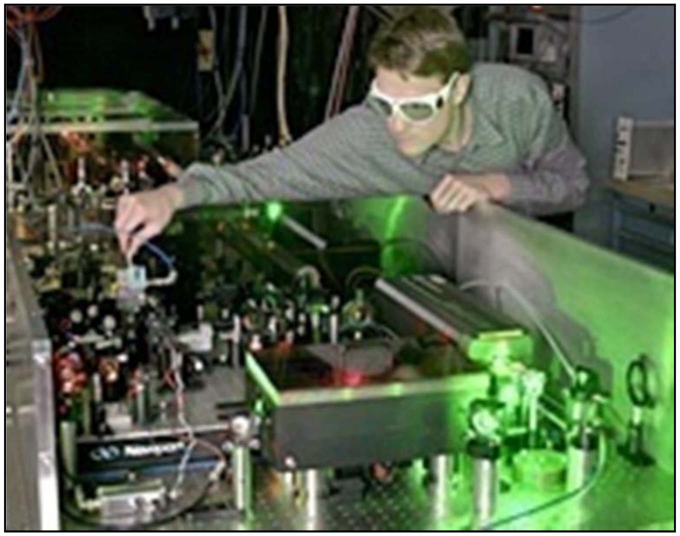

In a 1-D lattice ➔ collision shift < $5 \times 10^{-18}$

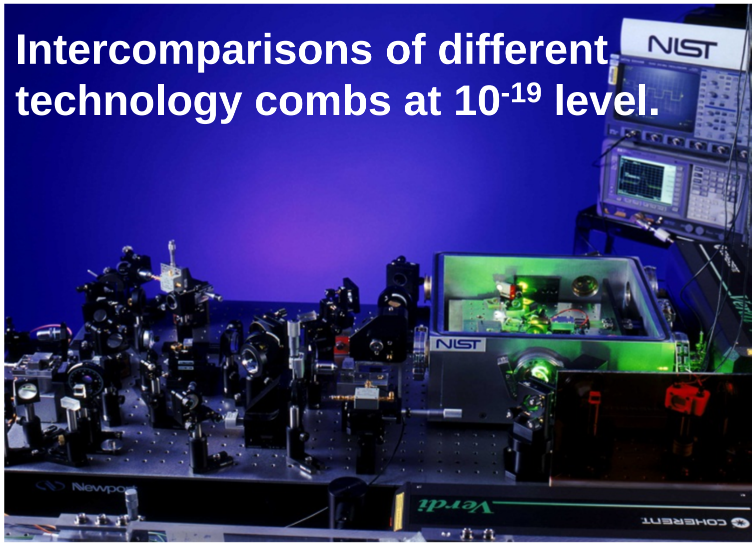
Can operate with larger lattice volume ➔ low density

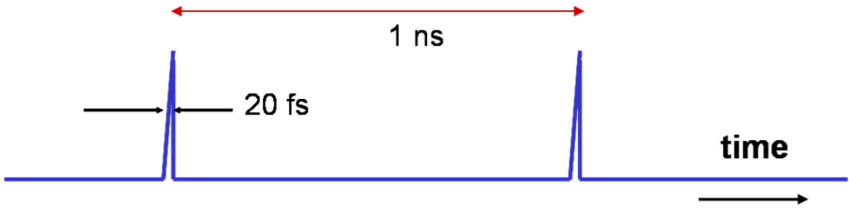
A. D. Ludlow et al., Phys. Rev. A **84**, 052724 (2011)

# High stability of optical clocks

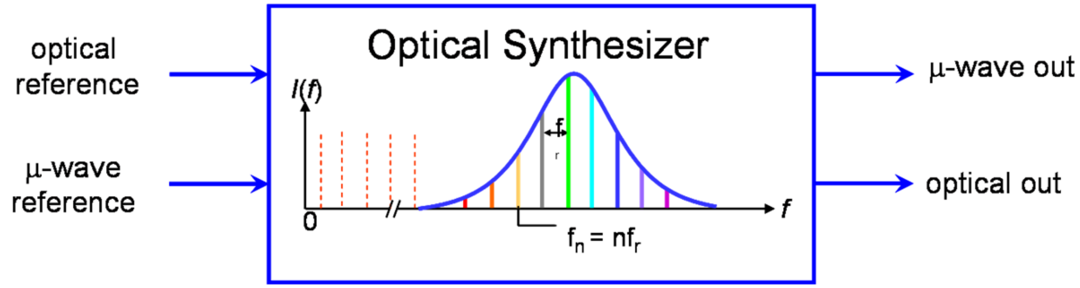
- Microwave standards at ~$10^{10}$ Hz.
  - Direct cycle counting.
  - Convenient broadcast frequencies.
- Optical standards at ~$10^{15}$ Hz.
  - Femtosecond laser frequency combs permit first direct measurements of optical frequencies.
  - Disseminate optical time and frequency information at convenient carrier wavelengths.



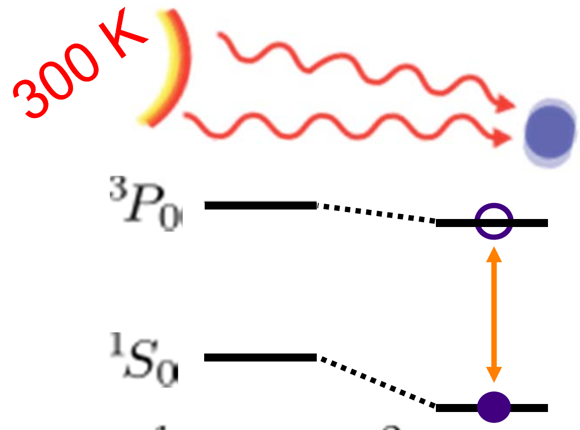



**Repetitive pulse train ◊ Frequency Comb ◊ "ruler for frequency/time"**



# Blackbody situation – what's left?




$$\Delta\nu_{\mathrm{BBR}} = -\frac{1}{2}\alpha_{\mathrm{clock}}\langle E^2\rangle_T\,[1+\eta_{\mathrm{clock}}]$$

2 x $10^{-5}$ uncertainty

<1 x $10^{-3}$ uncertainty

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

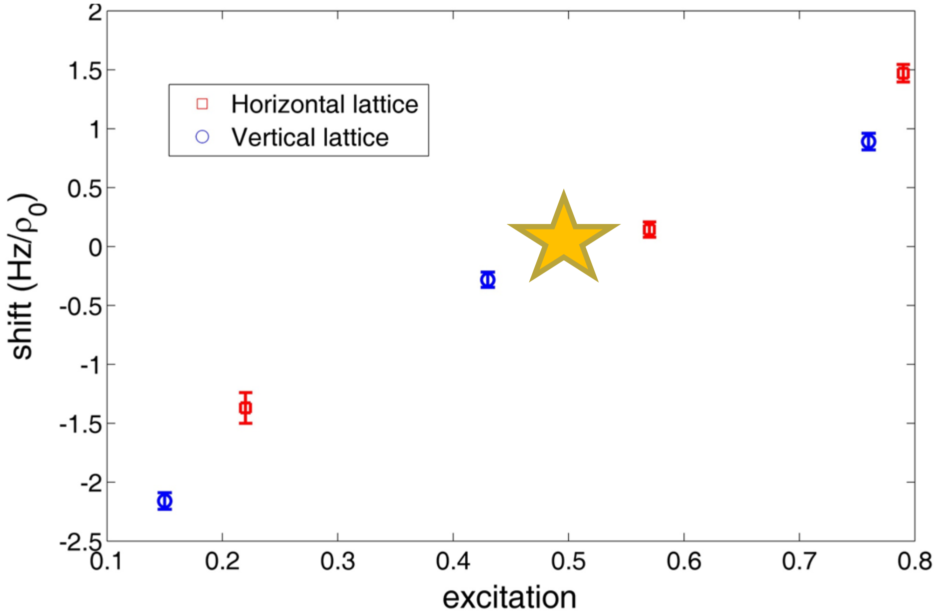
~1 K effective temperature uncertainty

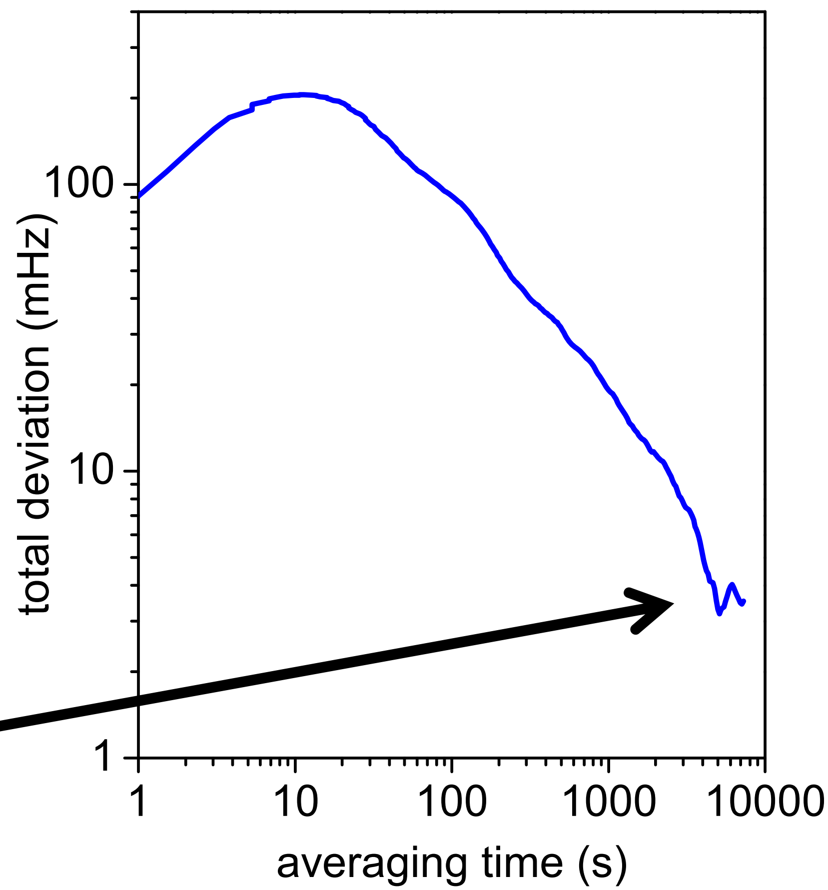
1.3% shift uncertainty

3 x $10^{-17}$ clock uncertainty

Is this a blackbody?

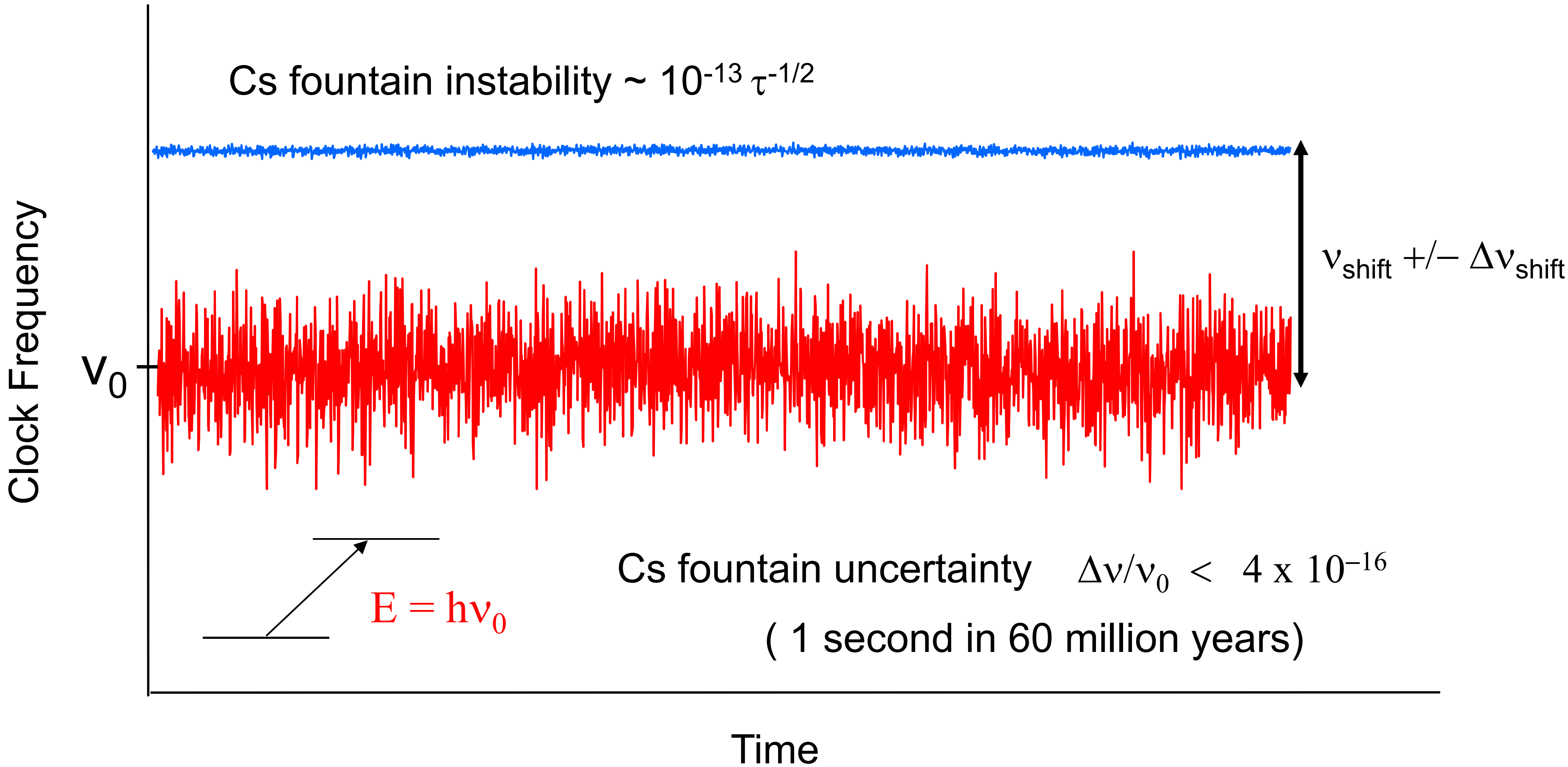
# Reducing the Cold Collision Shift



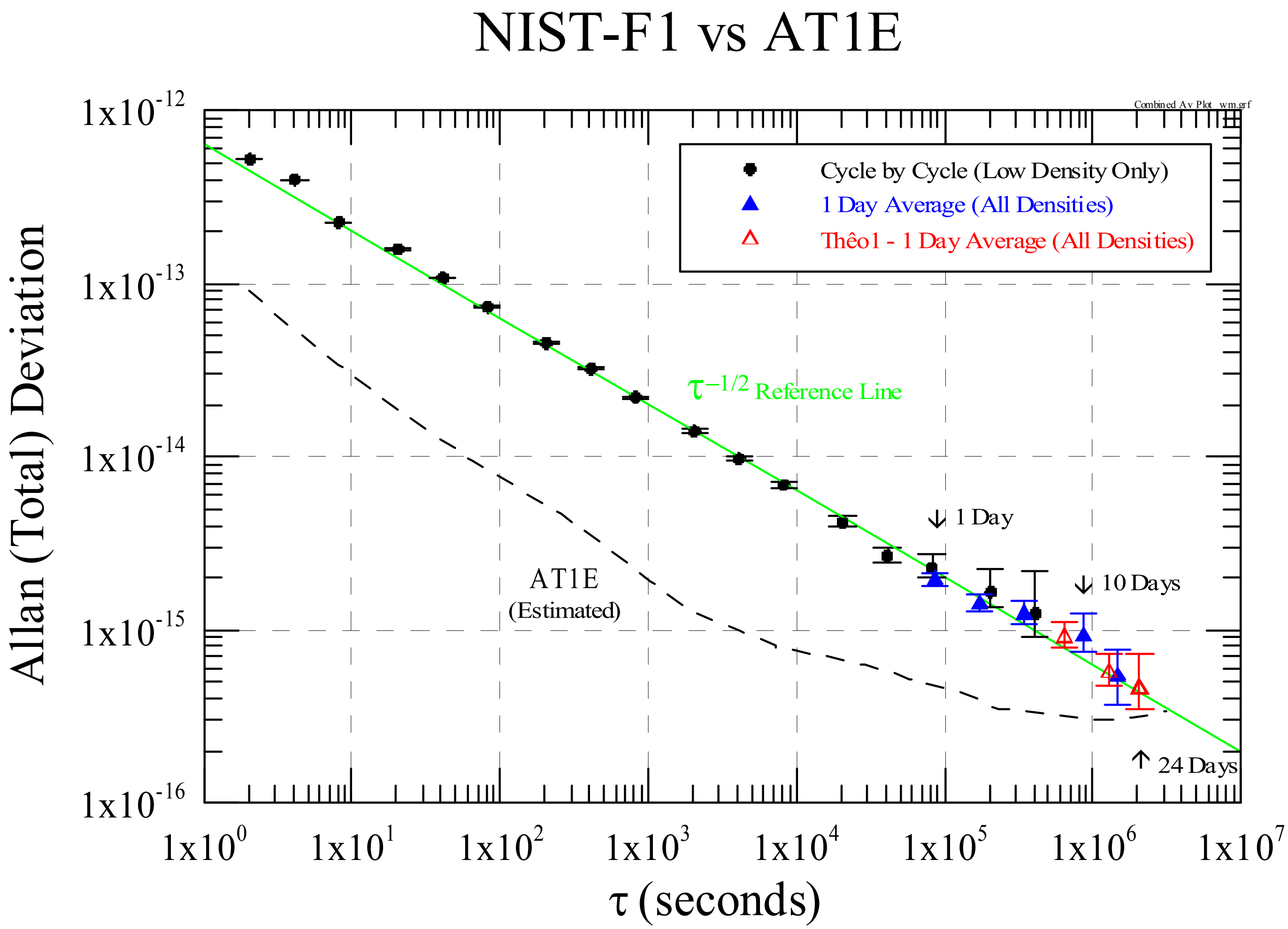




-1.4(3) mHz, 14500 s,
extrapolate white freq noise 1s:
5 x $10^{-16}$ at 1s

# What is a good clock? Uncertainty / stability



# Maybe some UTC transfer stuff?




6 hydrogen masers + 4 cesium beam standards.
Time scale performance among best in the world.