# $^{87}$Sr Optical Lattice Clock

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Workshop on an Optical Clock Mission
in ESA's Cosmic Vision Program

March 8th, 2007

NIST-CU

# Today's Talk

$^{87}Sr$

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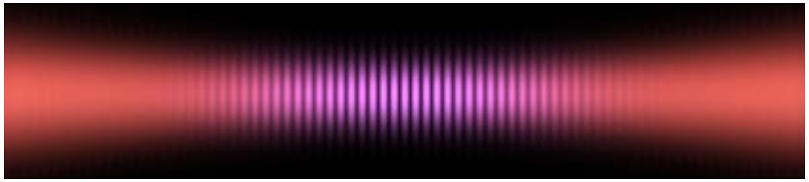
## Spectroscopy & Atomic Physics



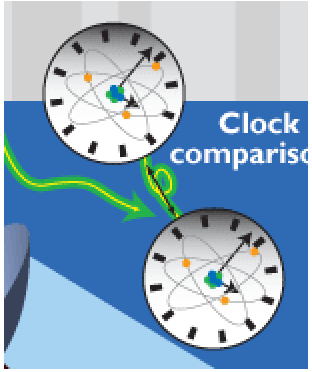
2

## Clock Systematics & Stability

$$\sigma_y(\tau) \propto \frac{1}{Q} \cdot \frac{1}{S/N} \cdot \frac{1}{\sqrt{\tau}}$$

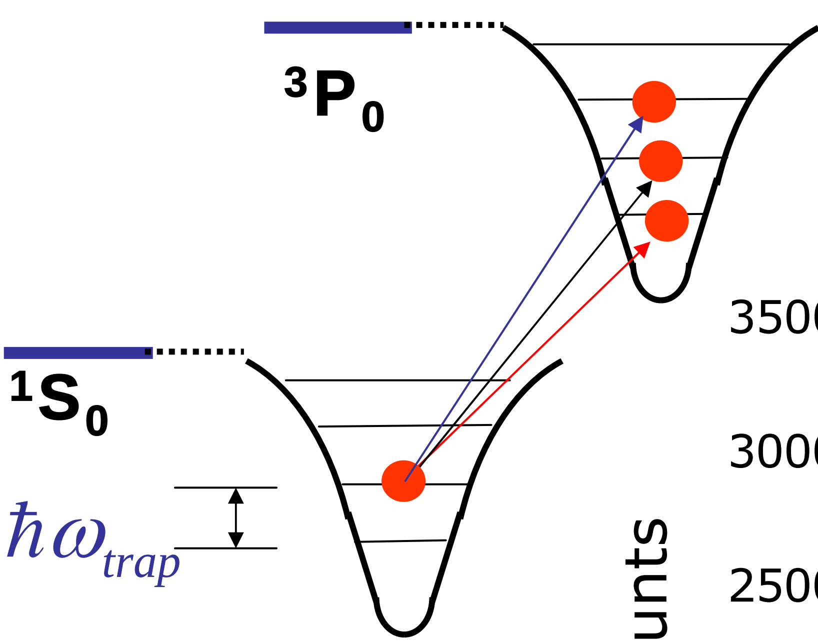
3

## Clock Comparisons



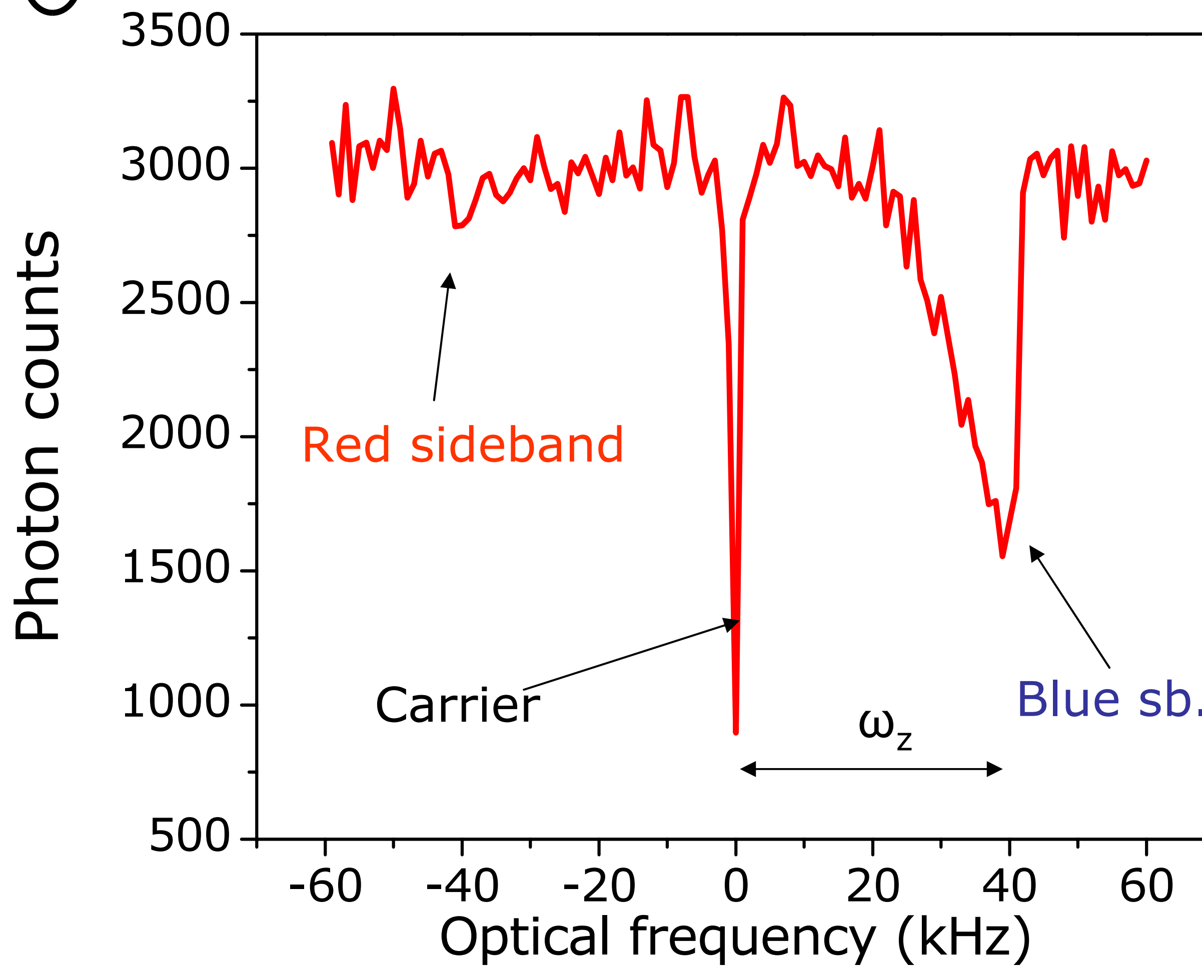
# Spectroscopy at the Magic Wavelength

Ludlow *et al.*, PRL **96**, 033003 (2006)




## 1-D Lamb-Dicke Regime

$$\eta = kx_0 = \sqrt{\omega_{recoil} / \omega_z} \sim 0.3$$

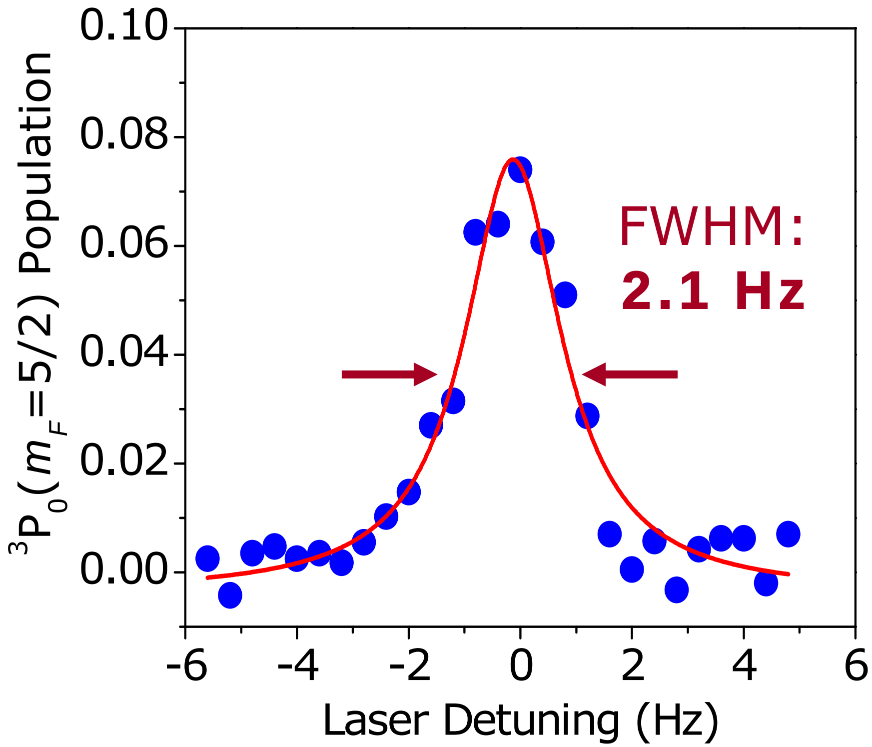


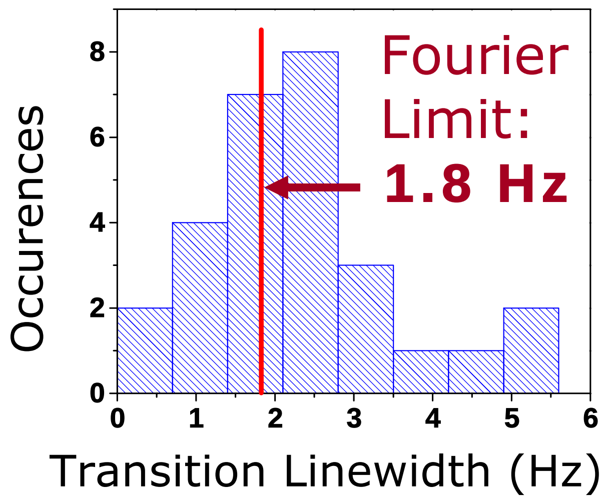

$$\omega_{recoil} << \omega_{trap}$$

$$\Gamma_{clock} << \omega_{trap}$$

# Q ~ 2.5 x $10^{14}$

Boyd *et al.*, Science **314**, 1430 (2006)
Ludlow *et al.*, Opt. Lett. **32**, 641 (2007)




- Single trace without averaging
- Estimated instability

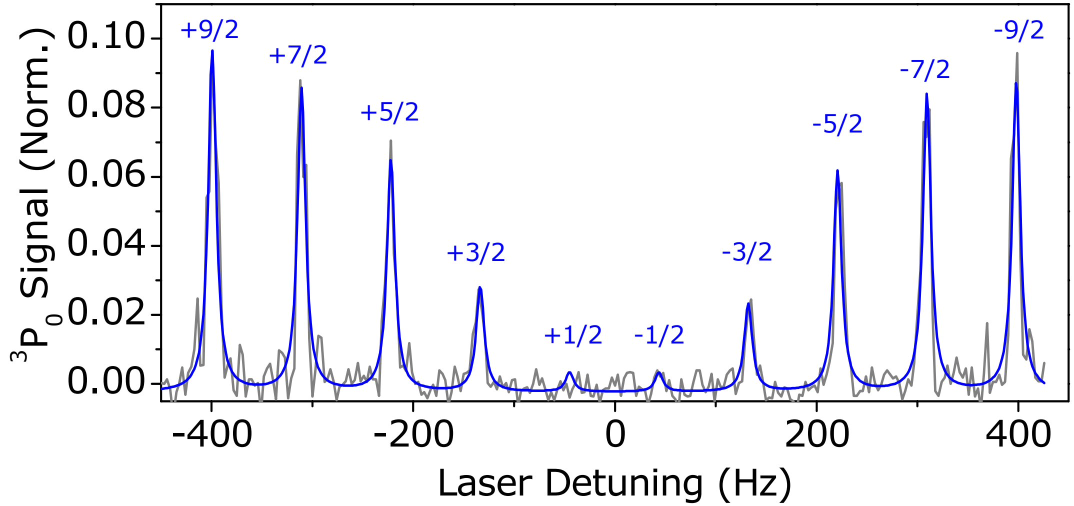
$$\sigma(\tau) \sim 2\times10^{-15}/\sqrt{\tau}$$

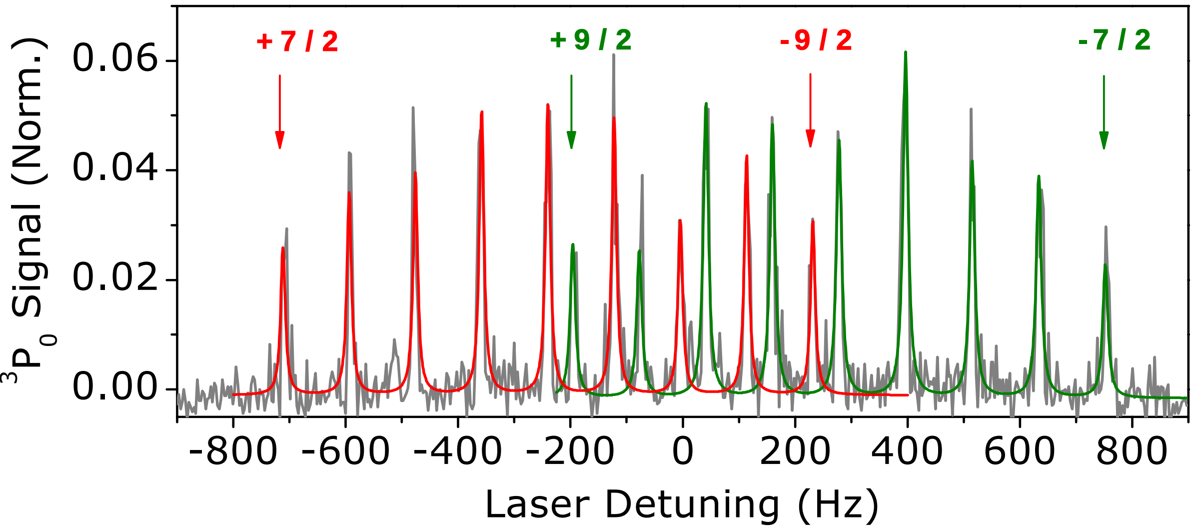
- Probe-time limited (~500ms)
- Loading-time limited

→ Probe-time limited regime

# Optical NMR Experiment

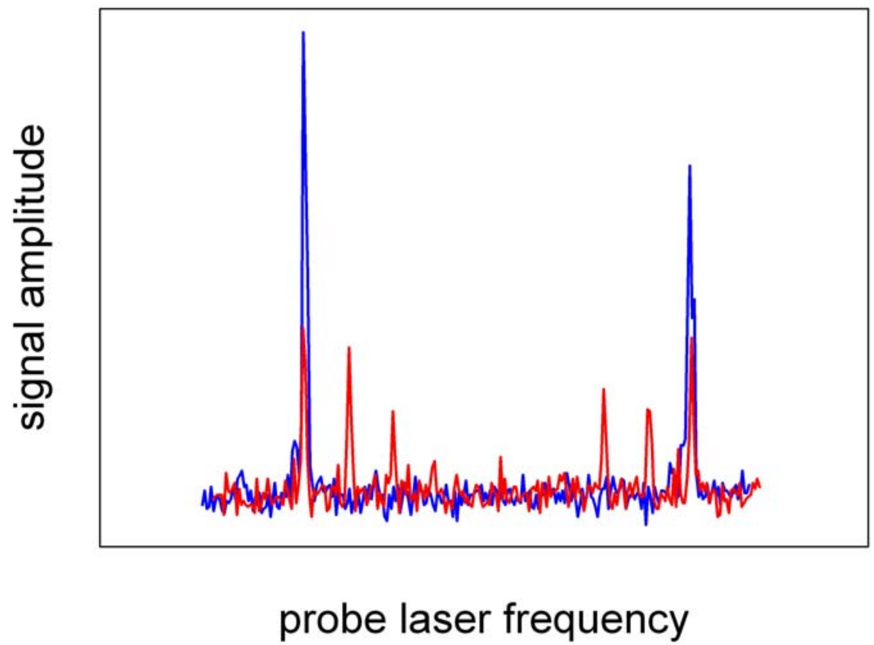
- HFI (I=9/2)
  → differential g-factor




- $\Delta g$ = -108.5(4) Hz/Gauss per $m_F$
- $^3P_0$ Lifetime 140(40) s

# State Preparation




- Resolve magnetic sublevels
- Spin-polarize using $\pi$ transitions
- Average frequency independent of $m_F$-antisymmetric shifts!
- Starting point for quantum optics techniques
  → spin-squeezing to improve S/N

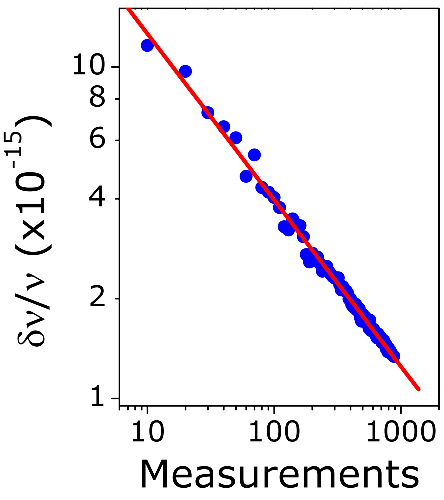
# Atomic Systematics Boyd *et al.*, PRL **98**, 083002 (2007)

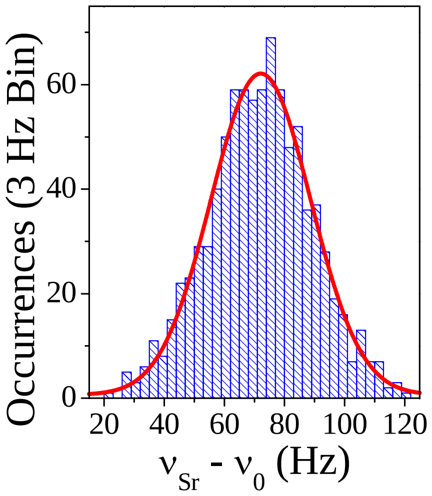
**Carrier: 429 228 004 229 874 Hz**

| Contributor | Uncertainty | |
|---|---|---|
| Zeeman shift | 5.3 E-16 | Linear part gone. Spin-polarize. |
| Lattice AC Stark | 6.0 E-16 | Locked to fs-comb. |
| Probe AC Stark | 1.2 E-16 | Needs larger intensity range. |
| Blackbody | 1.6 E-16 | Needs **direct** measurement. |
| Atom density shift | 3.3 E-16 | Still consistent with zero effect. ($10^6$ x smaller than for Cs) |
| **Systematics Total** | **8.8 E-16** | |

# Comparison vs Cs-fountain / H-maser

- 24h data run to eliminate time-of-day bias
- Gaussian statistics, averages as $N^{-1/2}$




| Contributor | Uncertainty |
|---|---|
| Sr Systematics (prev slide) | 0.88 E-15 |
| Fiber transfer | 0.1 E-15 |
| NIST Maser calibration | 1.7 E-15 |
| Synthesizer temp. drift | 0.7 E-15 |
| Gravitational shift | 0.02 E-15 |
| Counting Statistics | 1.4 E-15 |
| **Total** | **2.5 E-15** |

Get better frequency reference!

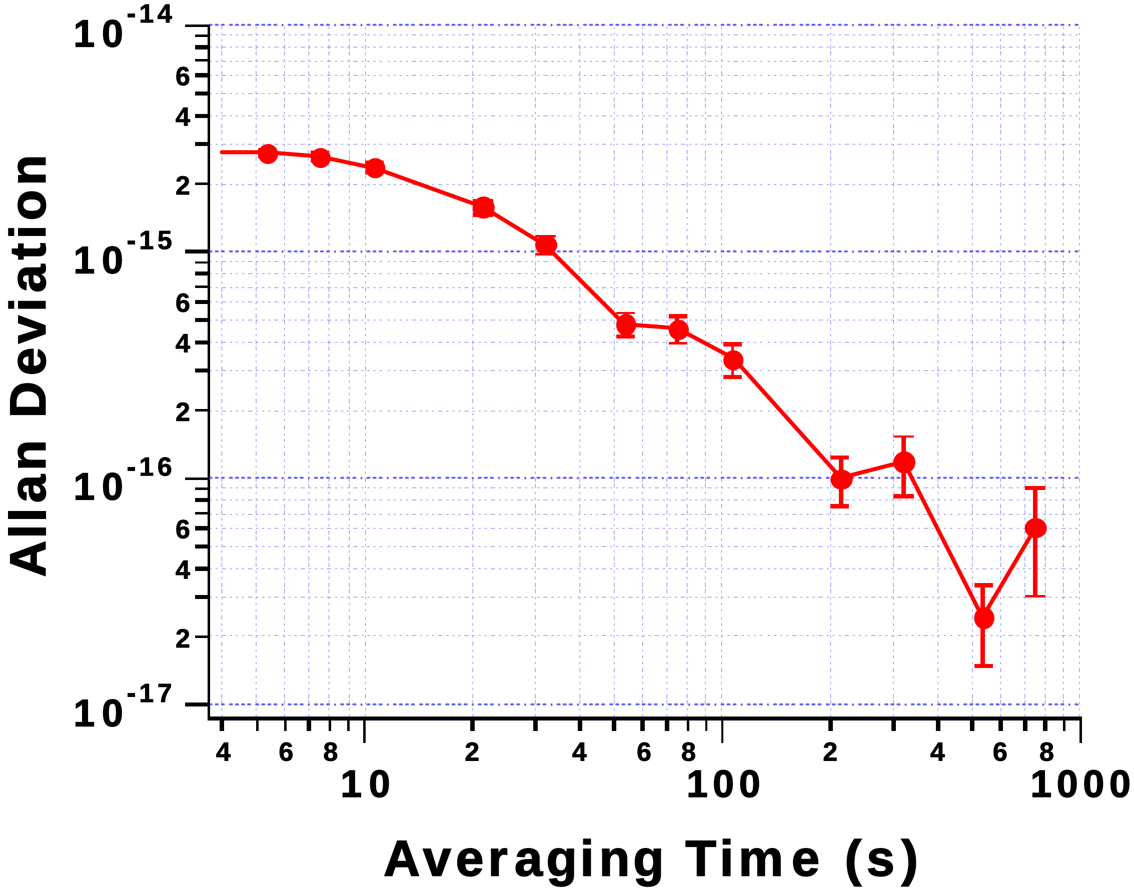
# Lock to Sr line: In-Loop estimates

Boyd *et al.*, PRL **98**, 083002 (2007) vs H-maser

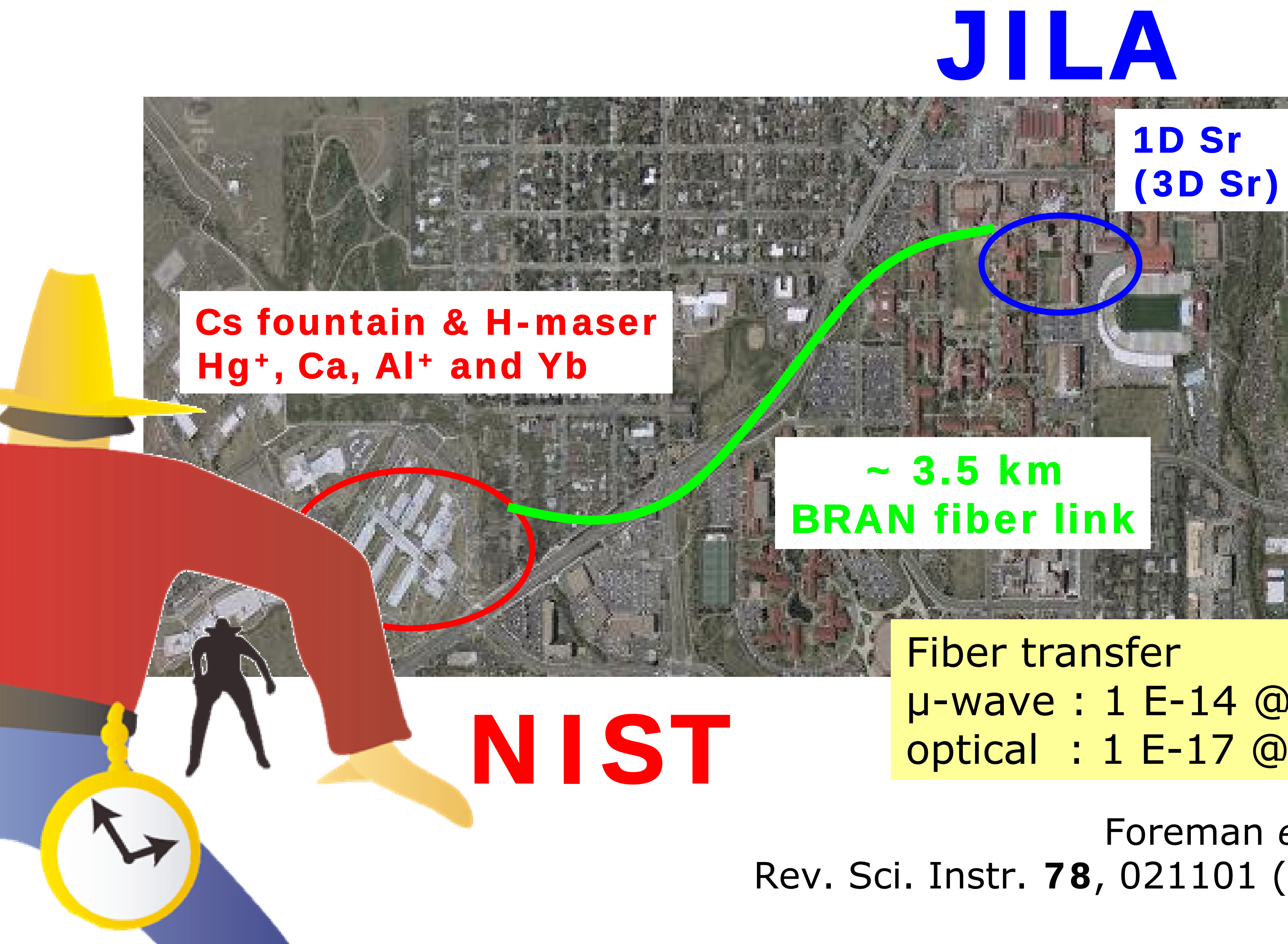
Counting Statistics (24 h) = 1.4 E-15

In-loop estimate with lock to clock transition

Counting Statistics (200 s) ~ 1 E-16



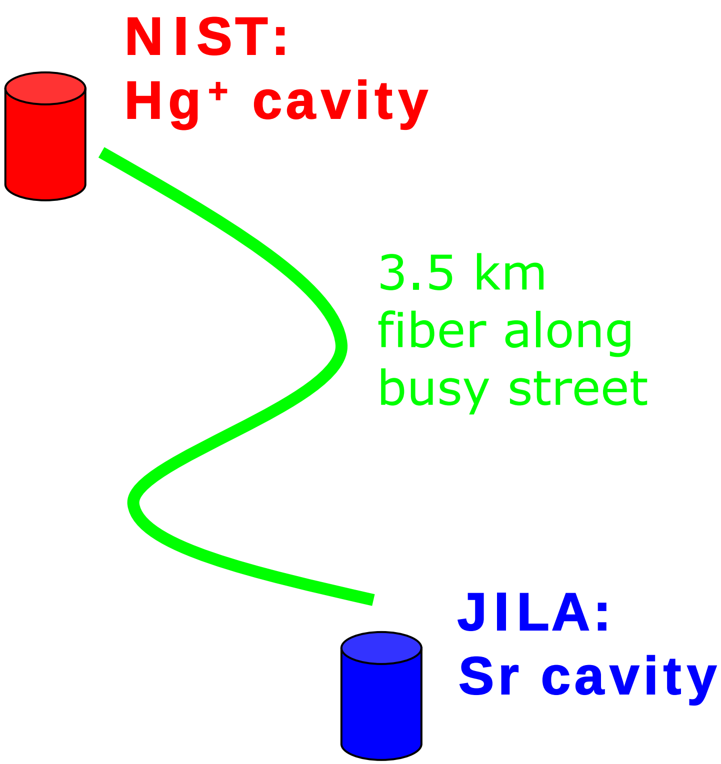
# Optical Clock Comparisons

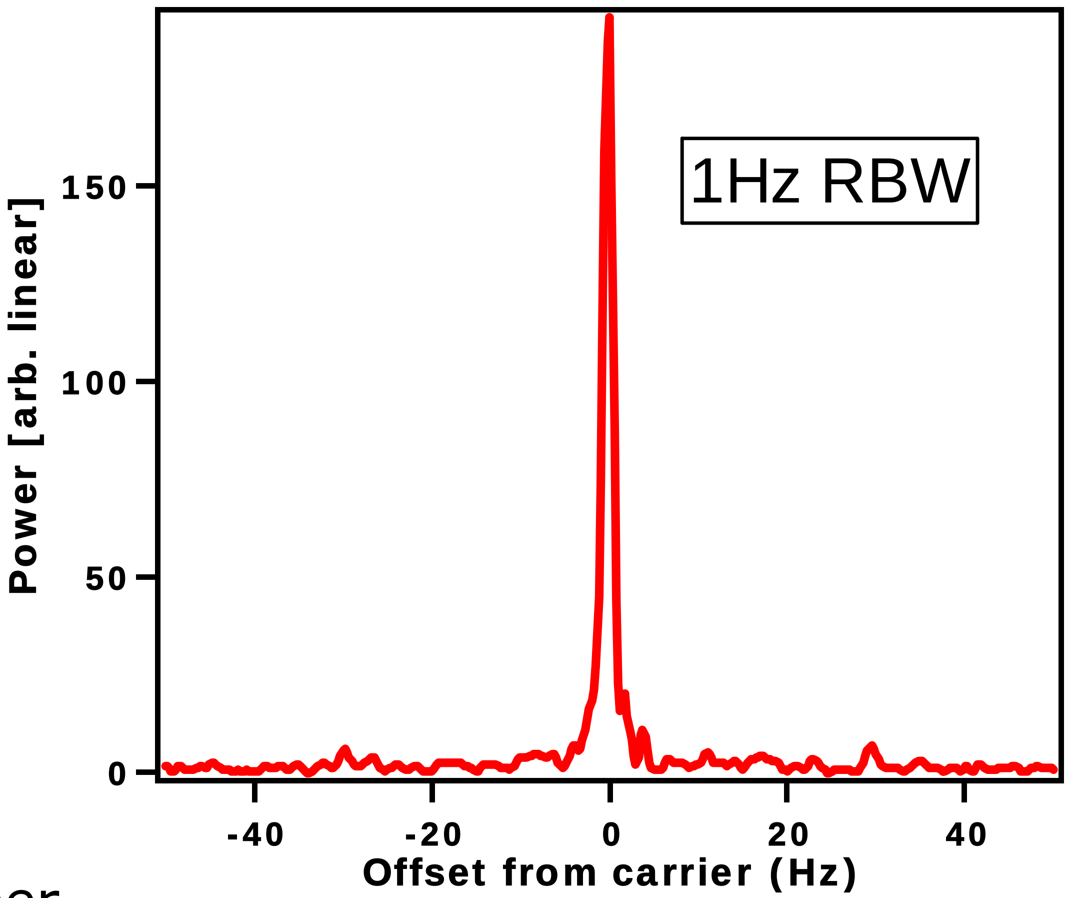



Fiber transfer
μ-wave : 1 E-14 @ 1 s
optical : 1 E-17 @ 1 s

Foreman *et al.*,
Rev. Sci. Instr. **78**, 021101 (2007)

# Direct Optical Transfer: Remote Cavity




Sr vs $Hg^{+}$ remote cavity comparison over 3.5 km fiber

Beat between spectroscopy lasers stabilized to reference cavities only, no atomic signal.

# Conclusion: $10^{-17}$ in reach

**now**

- Spin-polarizing / state preparation
- magic wavelength
  → magic frequency

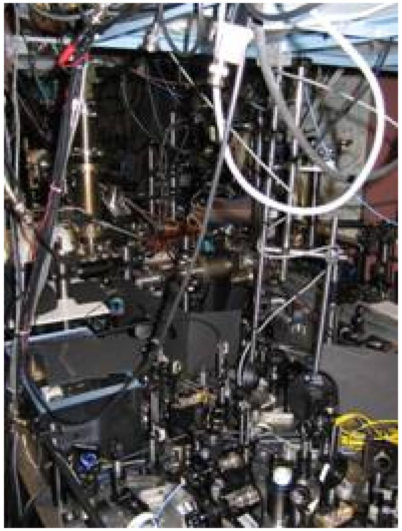
**soon**

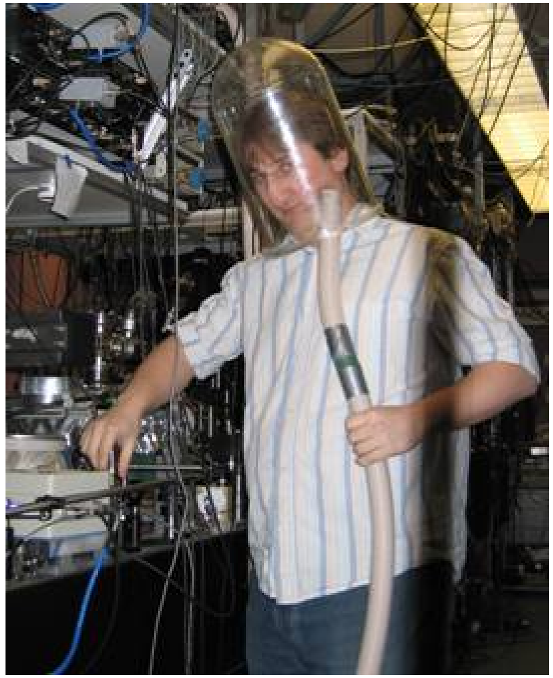
- direct optical clock comparison
- 3D lattice for purer environment

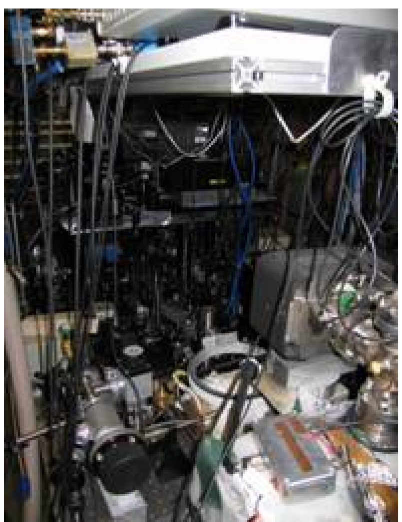
**O(1 yr)**

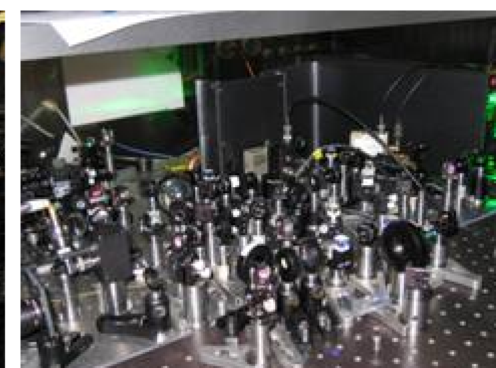
- Spin-squeezing
  → better S/N
- measure blackbody shift directly
- EIT scheme for spinless isotope

# Once we have that…









Launch 5 optical tables, 4 grad students
and 3 post-docs into space

## Sr Gang

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## Frequency Transfer

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S. Diddams
J. Stalnaker

J. Bergquist

$$$ ONR NSF NASA NIST $$$