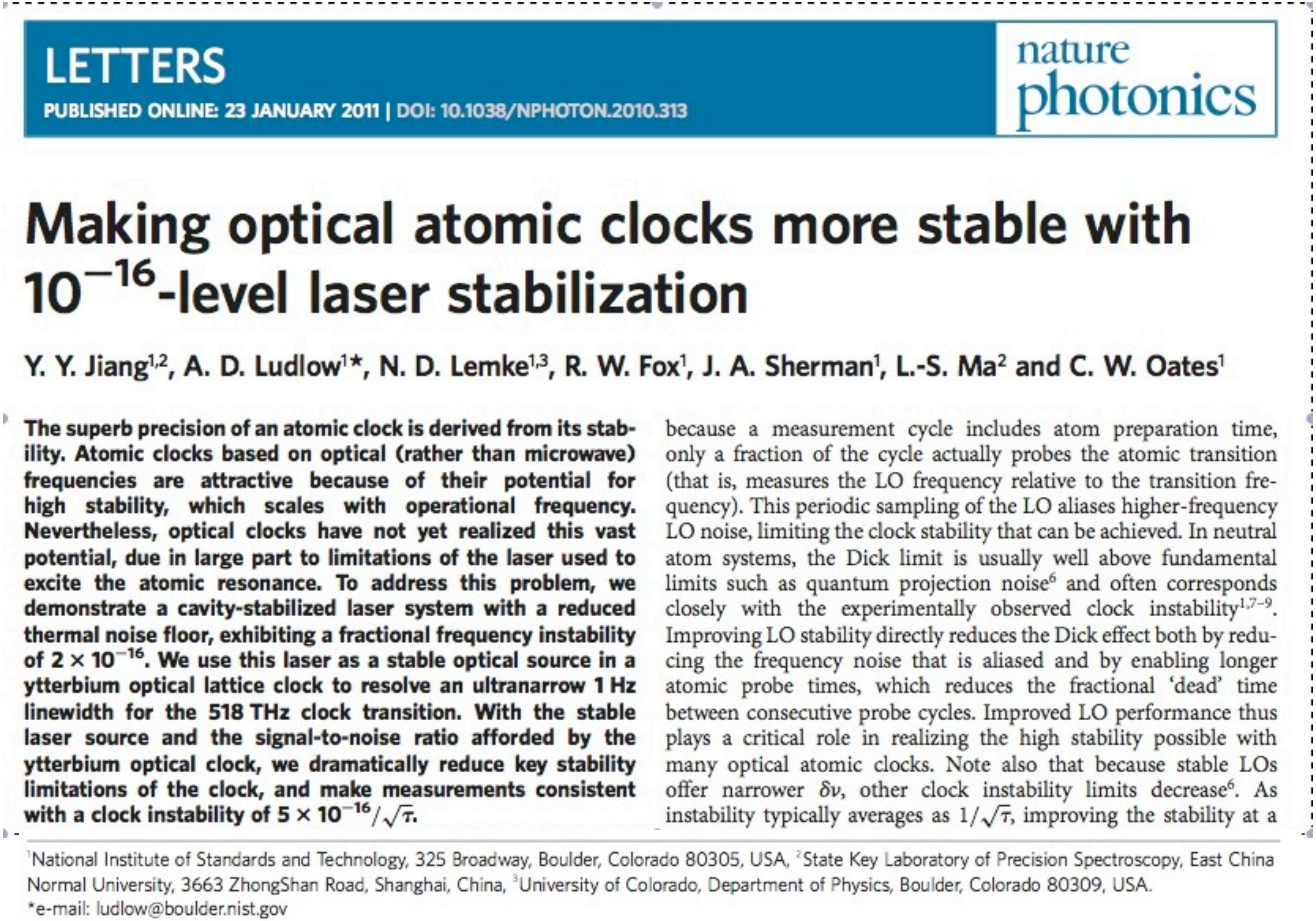
Making optical atomic clocks more stable with 10^{-16}-level laser stabilization

Matin Hallaji
Group Meeting
March 9th 2011

The Paper



LETTERS

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Making optical atomic clocks more stable with 10^{-16}-level laser stabilization

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The superb precision of an atomic clock is derived from its stability. Atomic clocks based on optical (rather than microwave) frequencies are attractive because of their potential for high stability, which scales with operational frequency. Nevertheless, optical clocks have not yet realized this vast potential, due in large part to limitations of the laser used to excite the atomic resonance. To address this problem, we demonstrate a cavity-stabilized laser system with a reduced thermal noise floor, exhibiting a fractional frequency instability of 2×10^{-16}. We use this laser as a stable optical source in a ytterbium optical lattice clock to resolve an ultranarrow 1 Hz linewidth for the 518 THz clock transition. With the stable laser source and the signal-to-noise ratio afforded by the ytterbium optical clock, we dramatically reduce key stability limitations of the clock, and make measurements consistent with a clock instability of $5 \times 10^{-16}/\sqrt{\tau}$.

because a measurement cycle includes atom preparation time, only a fraction of the cycle actually probes the atomic transition (that is, measures the LO frequency relative to the transition frequency). This periodic sampling of the LO aliases higher-frequency LO noise, limiting the clock stability that can be achieved. In neutral atom systems, the Dick limit is usually well above fundamental limits such as quantum projection noise[6] and often corresponds closely with the experimentally observed clock instability[1,7–9]. Improving LO stability directly reduces the Dick effect both by reducing the frequency noise that is aliased and by enabling longer atomic probe times, which reduces the fractional 'dead' time between consecutive probe cycles. Improved LO performance thus plays a critical role in realizing the high stability possible with many optical atomic clocks. Note also that because stable LOs offer narrower $\delta\nu$, other clock instability limits decrease[6]. As instability typically averages as $1/\sqrt{\tau}$, improving the stability at a

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Clocks , and definition of a Second

- NIST: The second is 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 Cesium 133 atom.
- can we measure it in a more precise way?
- Answer: Yes!

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ROLEX
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MASTER
HRONOMETER
TIFIED

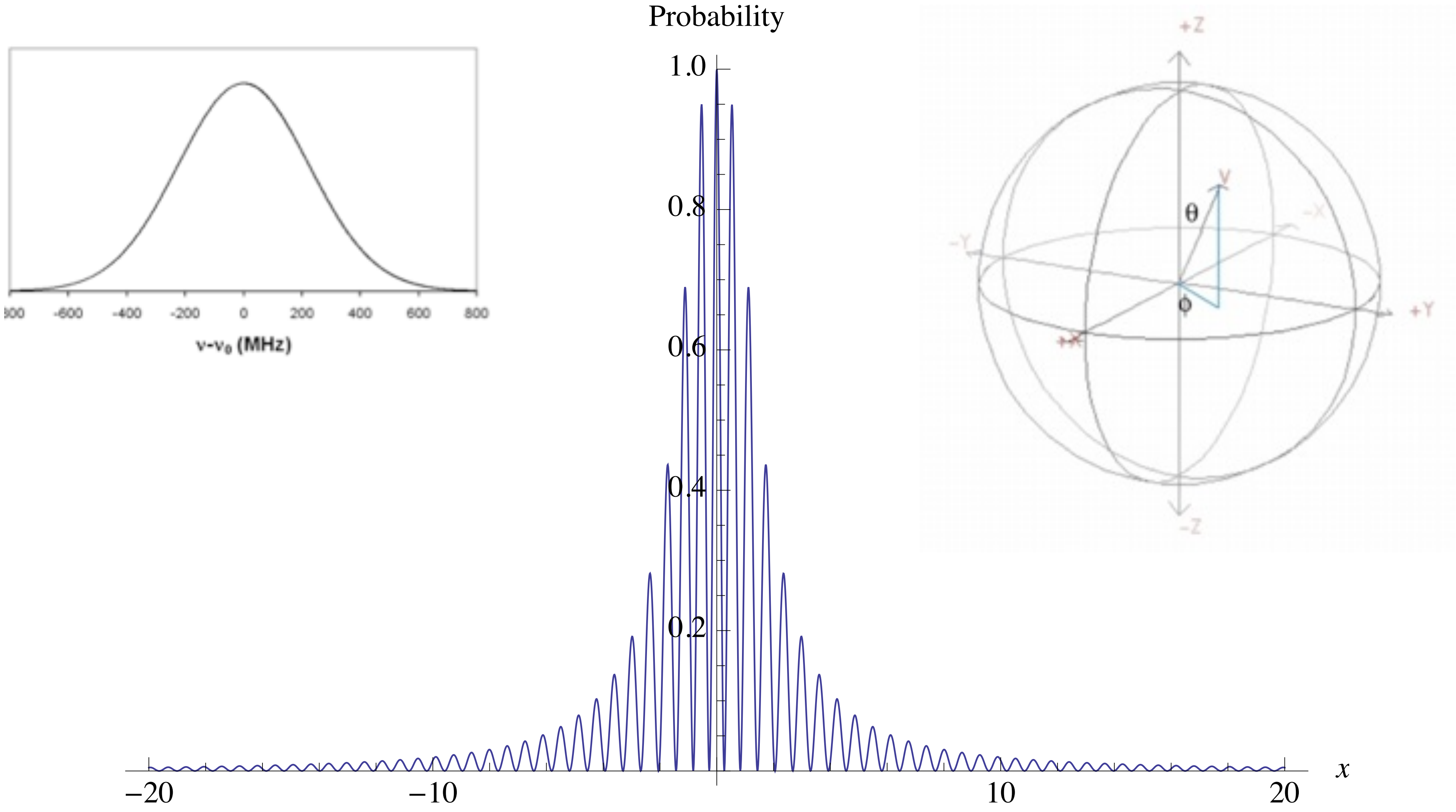
Atomic Clocks in Microwave region

- 9,192,631,770 Hz
- δυ/υ
- To increase the ratio optical atomic clocks are used!

Spectroscopy

- Doppler Broadening
- ...
- Saturated Spectroscopy
- ...
- Ramsey Fringes

Ramsey Fringes



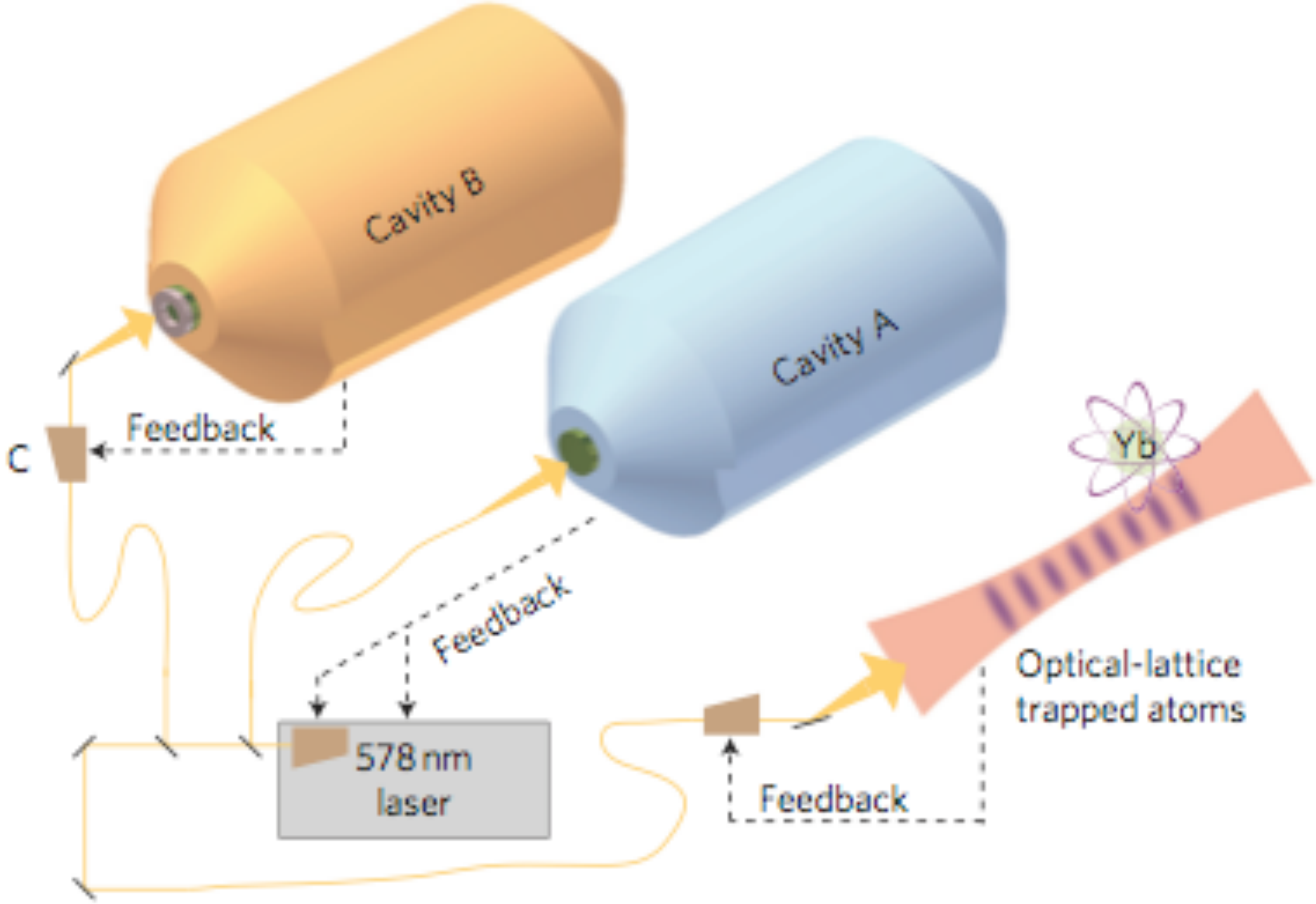
Having a very narrow Laser, why not just scan the transition with this narrow Laser!

Limits:
Laser Line-width
Laser Stability
Dick Effect

What these guys did

- Cavity stabilized laser
- reduced thermal noise floor
- fractional instability of $2*10^{-16}$
- resolved 1 Hz linewidth of ytterbium 518 THz clock transition
- Clock instability of $5*10^{-16}/\tau^{0.5}$

Apparatus


Cavity B
Cavity A
C
Feedback
Feedback
Yb
Optical-lattice trapped atoms
578 nm laser
Feedback

Cavities:

- Fabry-Perot very high reflectivity mirrors, in vacuum chamber, temperature controlled (mK fluctuation in 24h!), the ability to measure 10^{-11} m/s^2 acceleration!
- Length stability is so important!
- fundamental limit: Brownian thermal mechanical fluctuations, the fractional frequency instability limit from thermal noise: (dominated by the two cavity mirrors)

$$\sigma_{\mathrm{therm}} = \sqrt{\ln 2 \frac{8 k_{\mathrm{B}} T}{\pi^{3/2}} \frac{1-\sigma^2}{E w_0 L^2} \left(\phi_{\mathrm{sub}} + \phi_{\mathrm{coat}} \frac{2}{\sqrt{\pi}} \frac{1-2\sigma}{1-\sigma} \frac{d}{w_0} \right)}$$

Lowering this limit:

- lowest thermal noise instability: $3*10^{-16}$ to 10^{-15}
- in order to reduce: choice of substrate and length, beam size and temperature!
- by choosing ultra low expansion glass as substrate they reduced thermal noise by 1.8!
- they final instability: $1.4*10^{-16}$

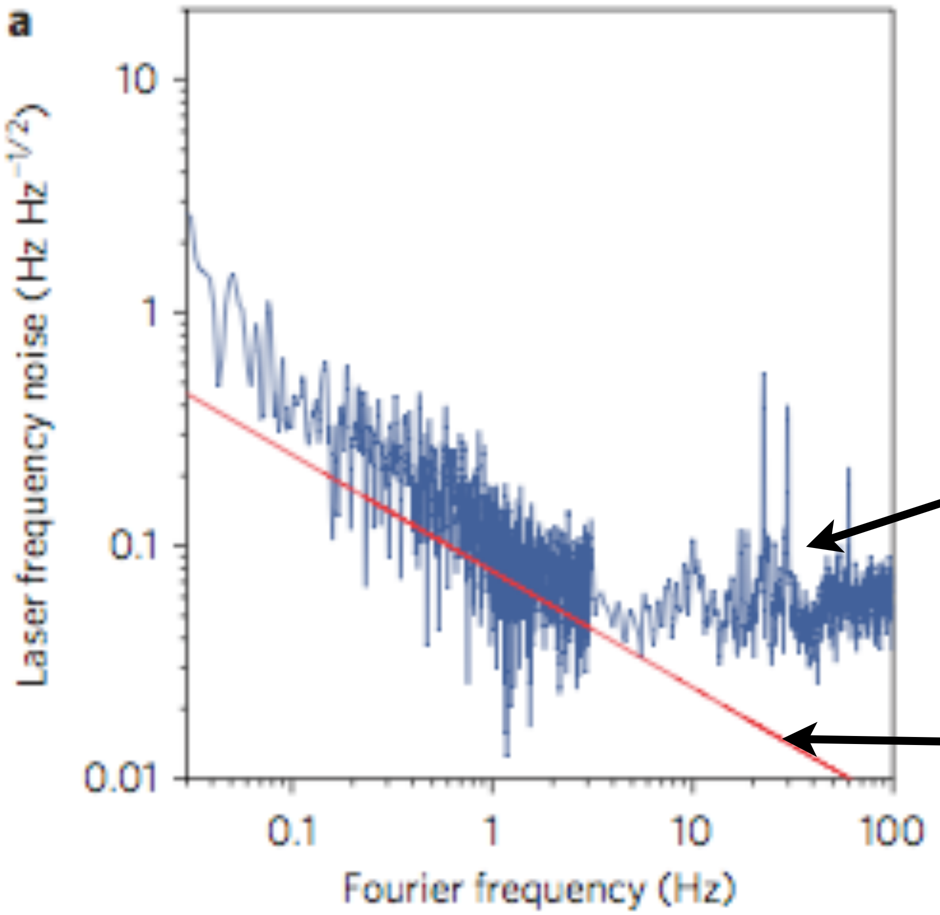
Laser Coherence Measurement

- Free running 578 nm laser was locked to cavity A using Pound-Drever-Hall, fast electronics feedbacks to AOM and slow electronics feedback to piezo.
- to measure the laser noise spectrum they used cavity B, using PDH signal of cavity B to serve as a frequency discriminator

Lattice

- 10000 Yb 171 atoms cooled down to 10 micro kelvin trapped in 1D
- the lattice facilitated long interrogation of ultracold Yb atoms while eliminating most doppler and recoil rffects
- The excitations of clock transition was detected by monitoring the ground and excited state population after spectroscopic probing.

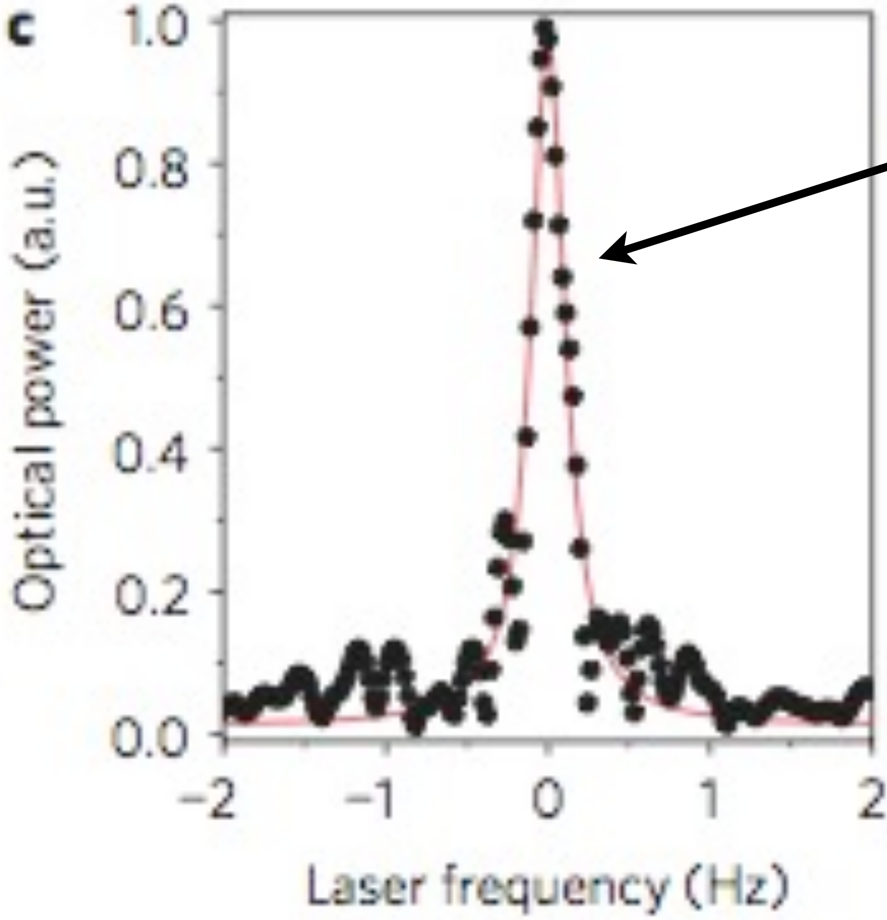
they used the second cavity to measure the laser coherence properties:

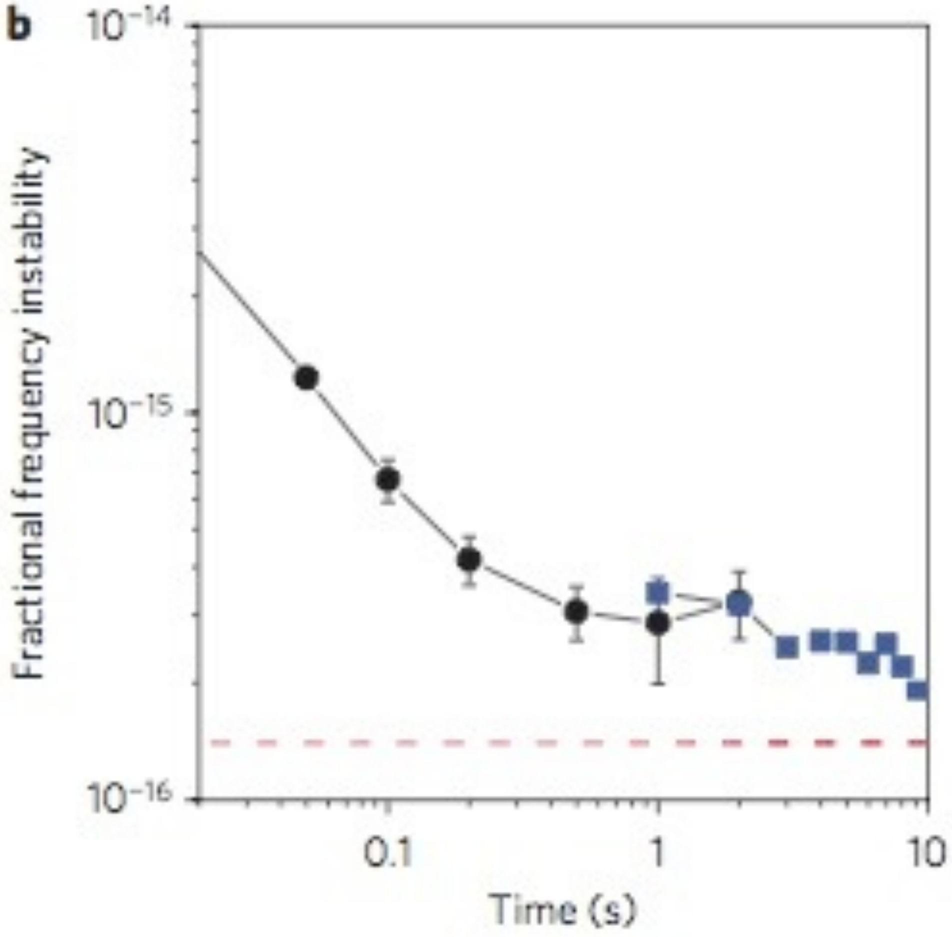


White noise spikes due to seismic noise

thermal noise

Power spectrum
250 mHz !!

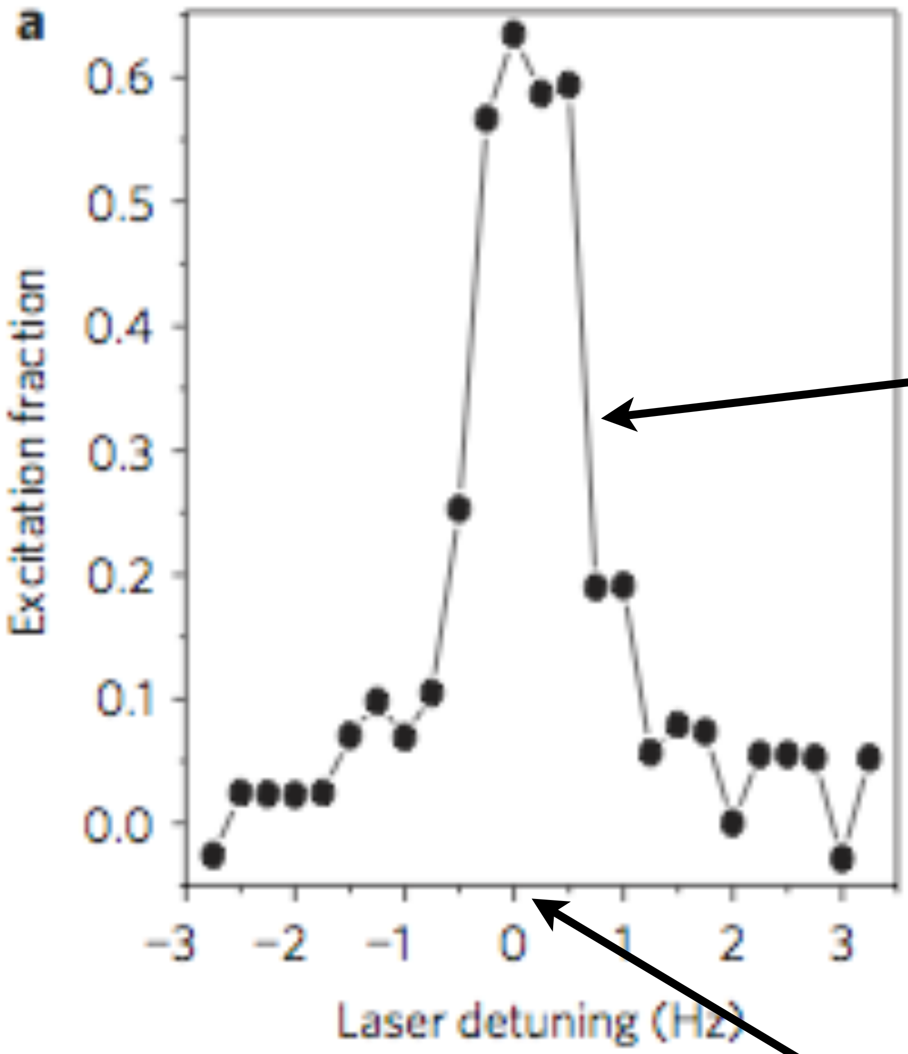




averaging below 10s: $2*10^{-16}$

Having the probe ready...

- $^1S_0$ to $^3P_0$ transition of Yb 171 in an optical lattice
- With low noise probe they could coherently excite the transition for long times
- stepping the LO frequency by 0.25 Hz on each cycle the probed the 1Hz transition linewidth

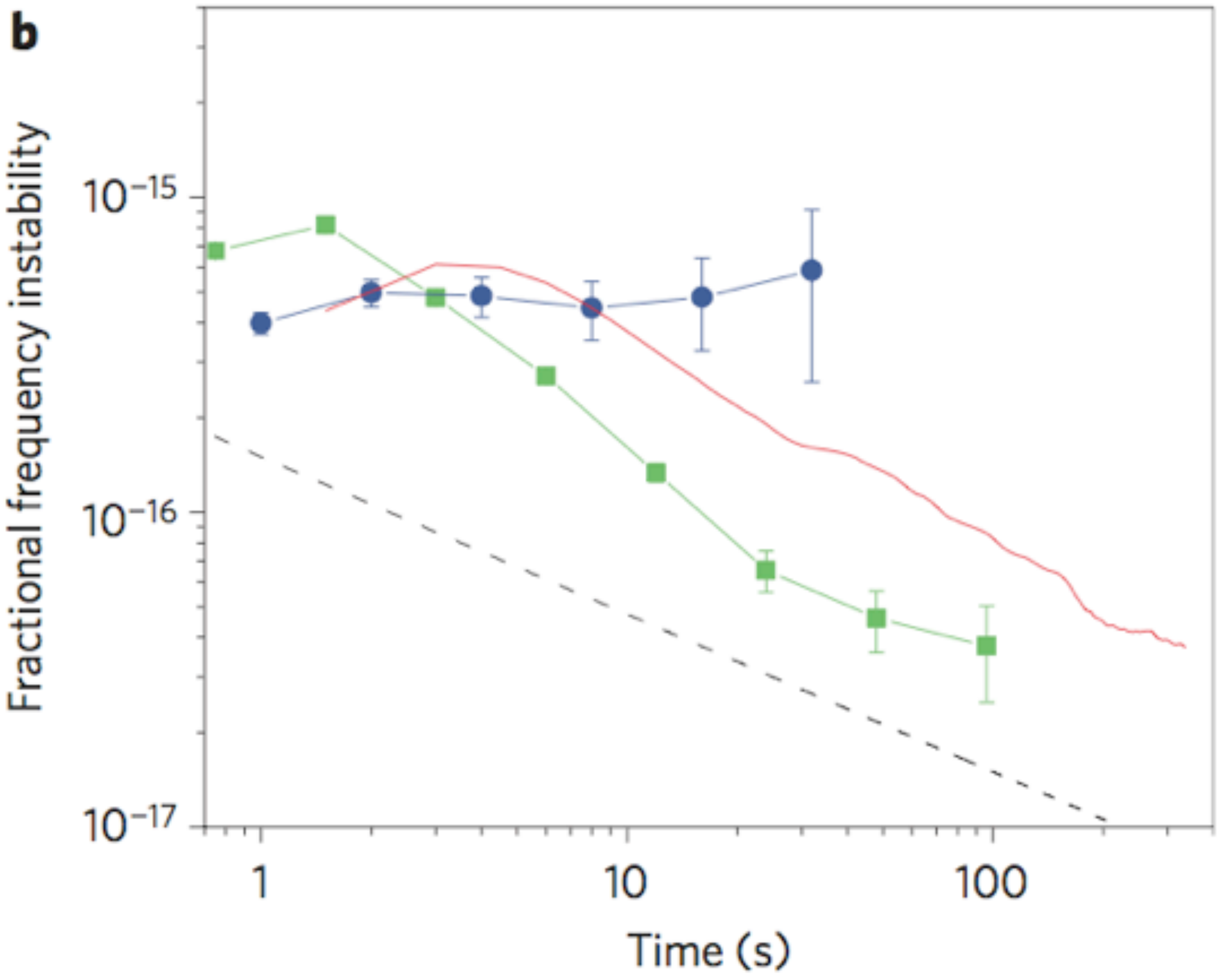


1 Hz FWHM

$\nu_0/\delta\nu > 5 \times 10^{14}$

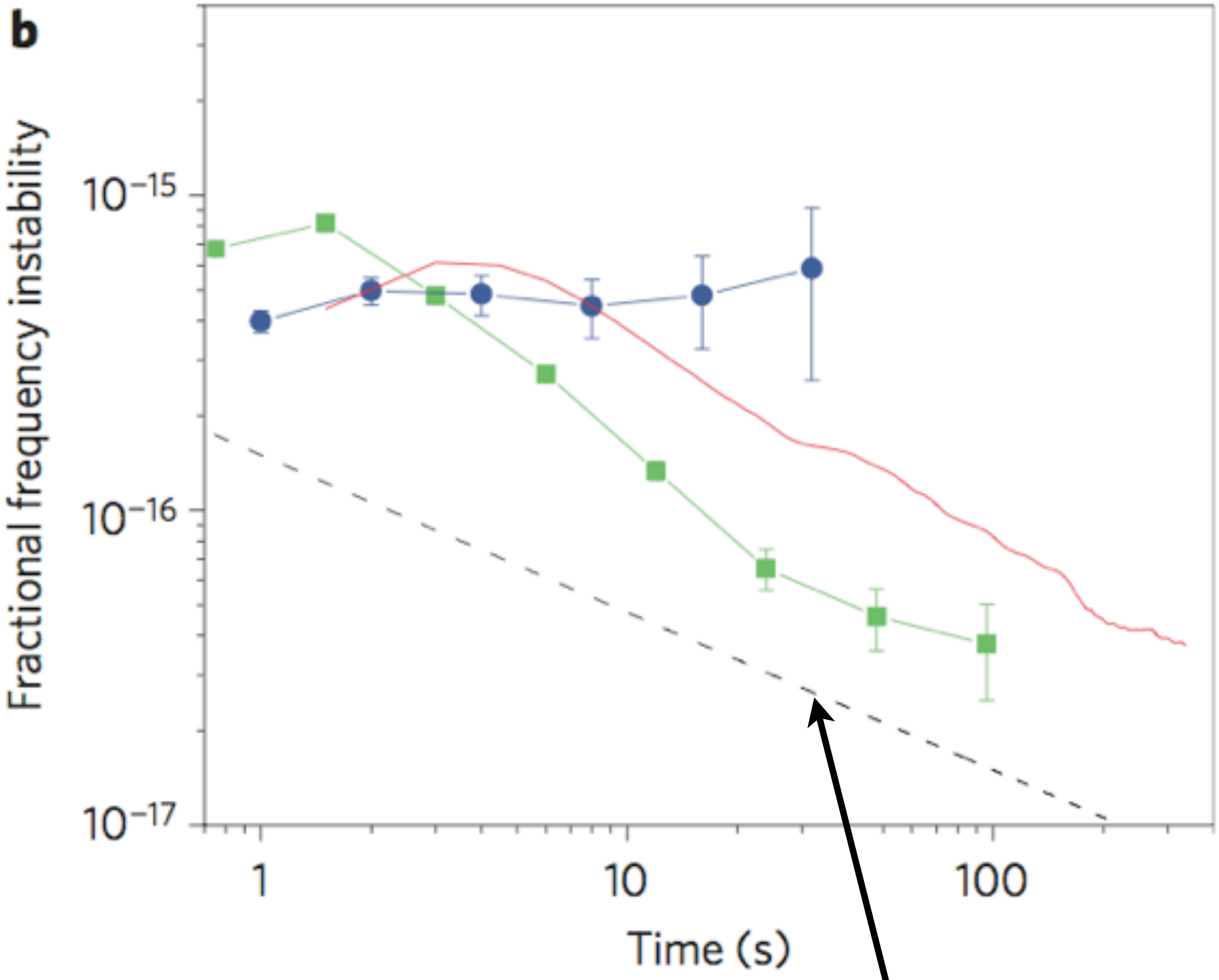
518 THz

To rigorously assess clock instability, it must be compared to another standard with even lower instability!



Although the 0.9 s probe time enables narrow atomic spectra, still the transition lock is sensitive to short-time laser frequency excursions which exceeds 1 Hz!

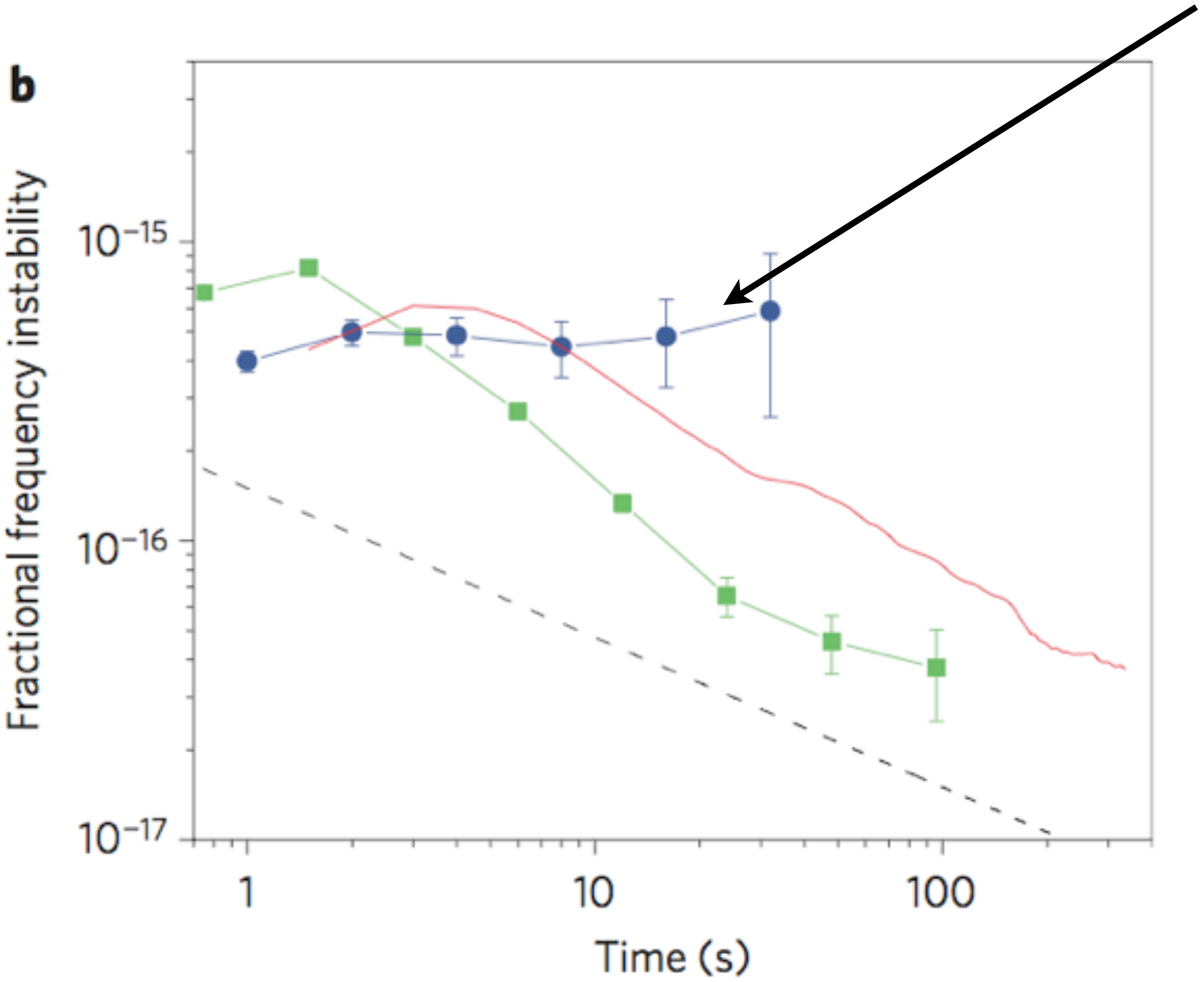
“the measurement done by from excitation of the Pi-transition of the mf=1/2 state ”



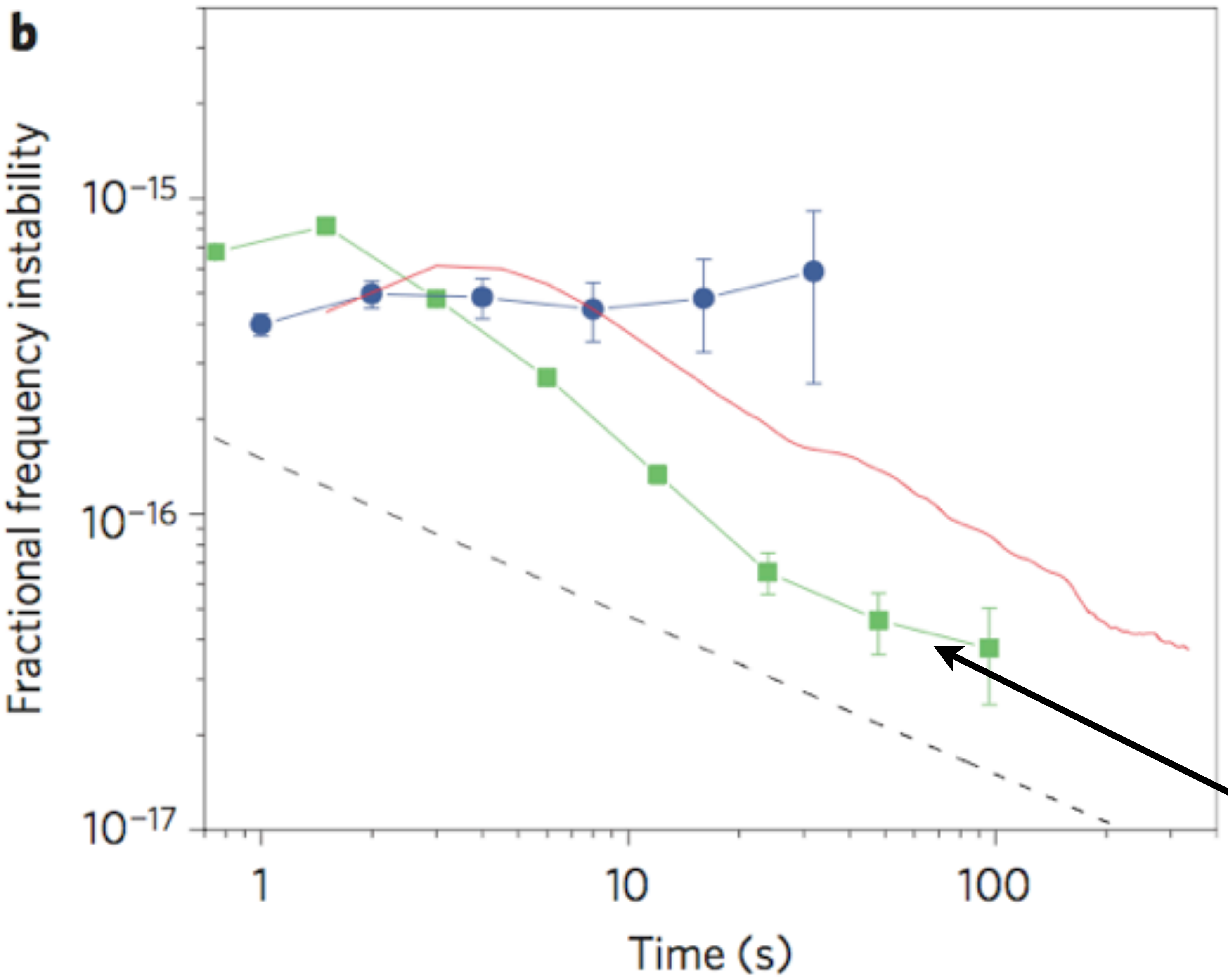
$1.5 \times 10^{-16}/\sqrt{\tau}$

Break down the cycle to 0.3 s Probe time($\delta\upsilon$=3 Hz) out of 0.75 total cycle. under these condition the Dick limit is the dashed line!

$\lesssim 5 \times 10^{-16}$



Tuning the LO frequency on resonance and measured the number of excitations. This out of loop measurement sensitive to both LO instability but also all the other optical instabilities



When closing the loop to lock the atomic transition, instability starts decreasing

$(5 \times 10^{-16})/\sqrt{\tau}$

Thank you!