Spin Squeezed ^{171}Yb Atomic Clock beyond the Standard Quantum Limit

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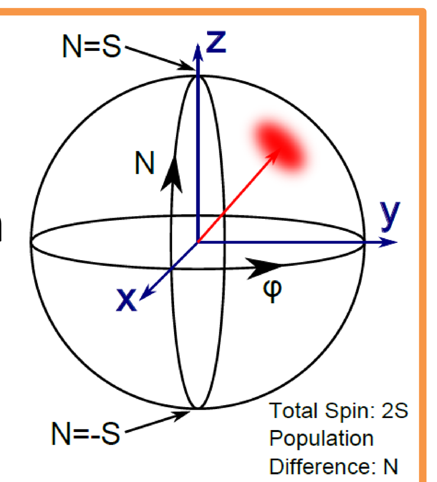
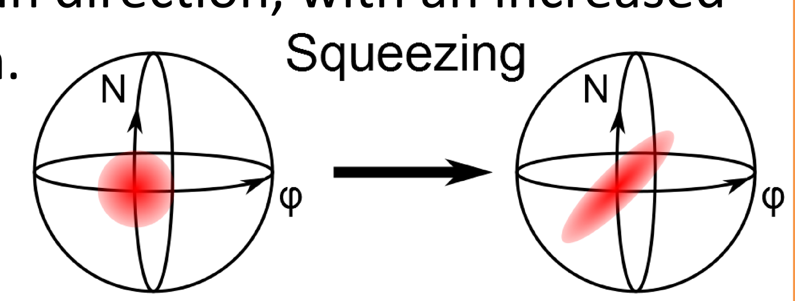
Introduction

State of the art optical lattice clocks have the relative uncertainty of 10^{-18} [1], and are rapidly approaching the standard quantum limit (SQL) of the quantum projection noise[2]. This limit has been overcome with a spin squeezed atomic clock on a microwave transition[3]. We apply this technique to optical transition and try to exceed the SQL in an optical lattice clock of visible light transition to expand the boundaries of precision time metrology.

Spin Squeezing



An ordinary coherent ensemble of independent two level systems has an uncertainty distribution symmetric between the population difference and phase directions. With spin squeezing, which is essentially a correlated behavior of many entangled spins, we can distort the error distribution and get smaller uncertainty in a certain direction, with an increased uncertainty in the other direction.

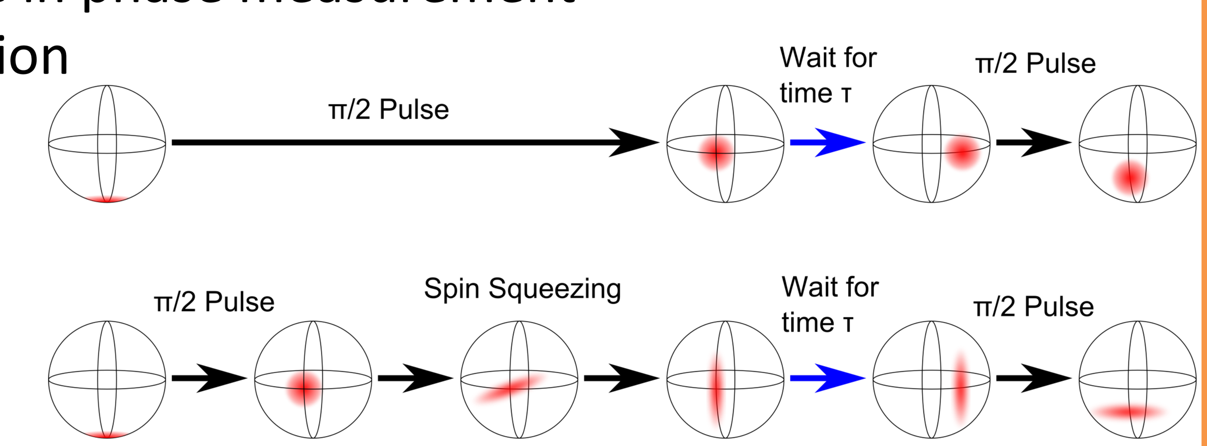


Spin Squeezed clock

Time measurement by an atomic clock is the fine tuning of a local oscillator (i.e. a laser) to a very narrow transition called a clock transition. This is performed by a measurement of phase difference between the local oscillator and the atoms. This is most easily accomplished using a Ramsey sequence where the atoms are placed in an equal superposition of the ground and excited states. With spin squeezing, we can reduce the phase uncertainty.

$\Rightarrow$ smaller noise in phase measurement

$\Rightarrow$ better precision



Yb Atomic Clock Transitions

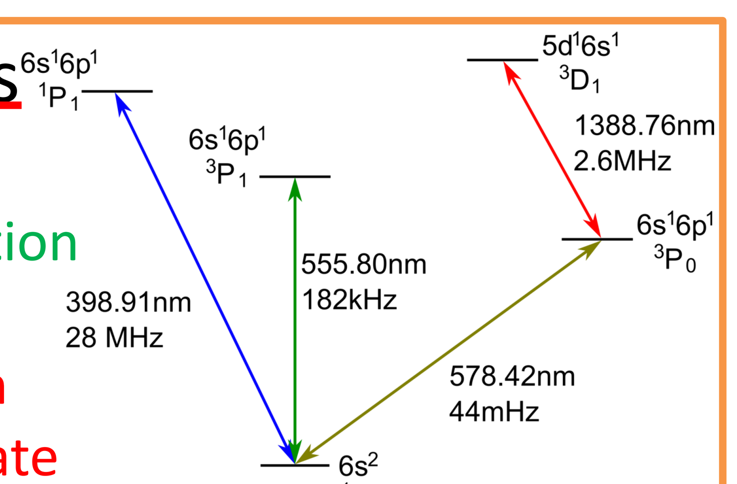
398.91 nm: slowing/molasses

555.80 nm: MOT, squeezing, detection

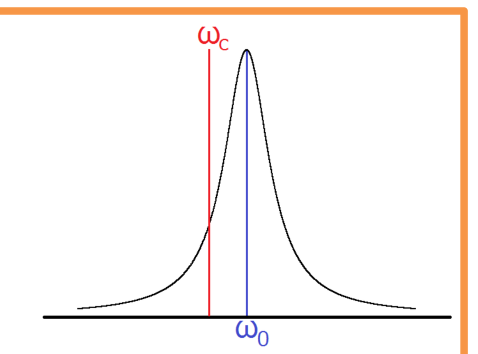
578.42 nm: clock transition

759.35 nm: lattice laser wavelength

1388.76nm repump laser for $^3P_0$ state



Cavity Feedback Squeezing



Relevant Hamiltonian:

$$H = \hbar \chi S_z^{\,2}$$

We get this term using a high finesse cavity probed with light of large detuning.

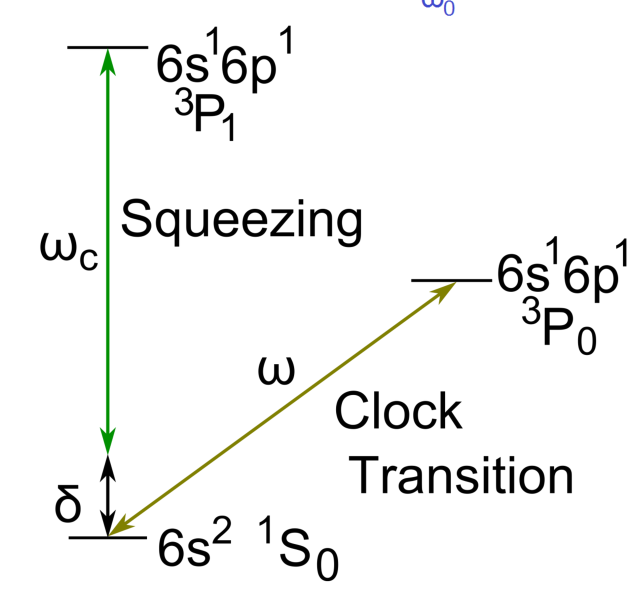
Cavity around atoms

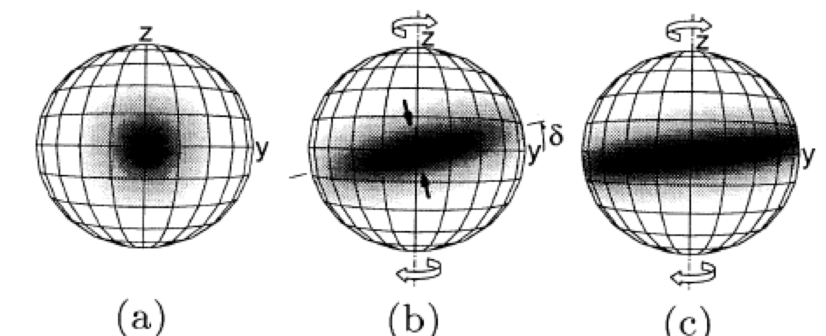
+ light detuned from a transition

→ AC Stark shift per atom ∝ photon number in cavity ∝ atom number

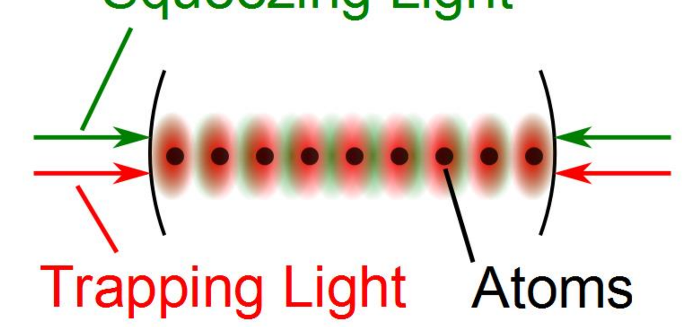
→ $H \propto S_z^{\,2}$

→ On Bloch sphere, rotation in phase direction is proportional to S_z.





Effect of $S_z^{\,2}$ Hamiltonian on a coherent spin state[4]



Cavity Design

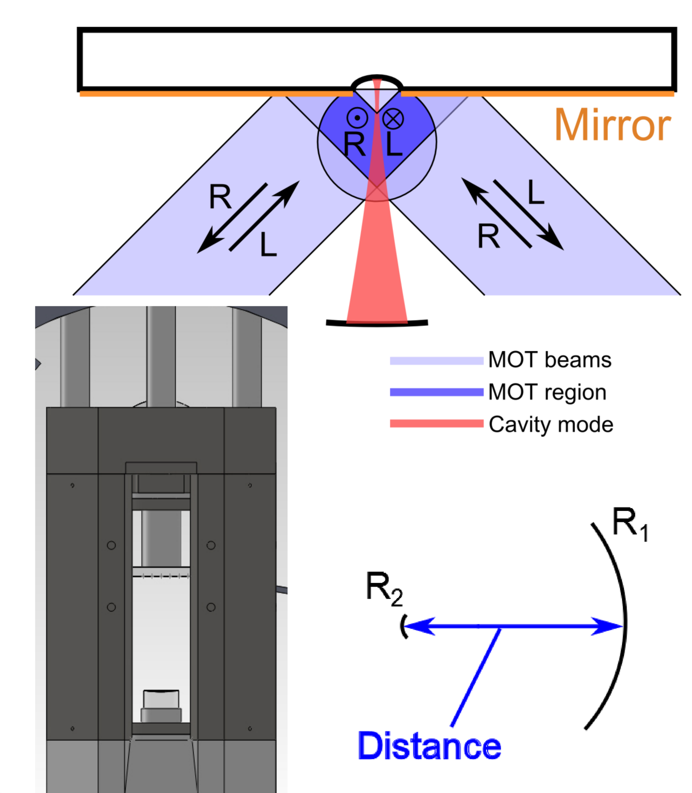
Asymmetric cavity with micro mirror

Measured Finesse of the Cavity

$\mathcal{F} \approx 25{,}000$ for squeezing laser

$\mathcal{F} \approx 3{,}200$ for trapping laser

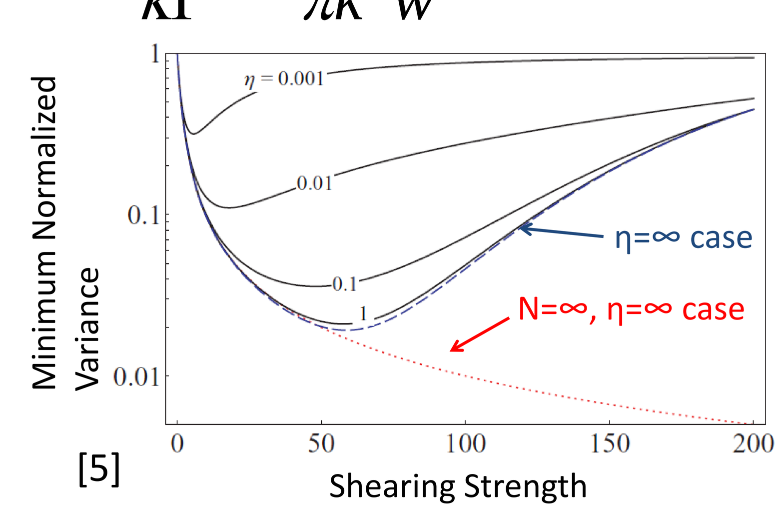
Expected Atom number ~10^4

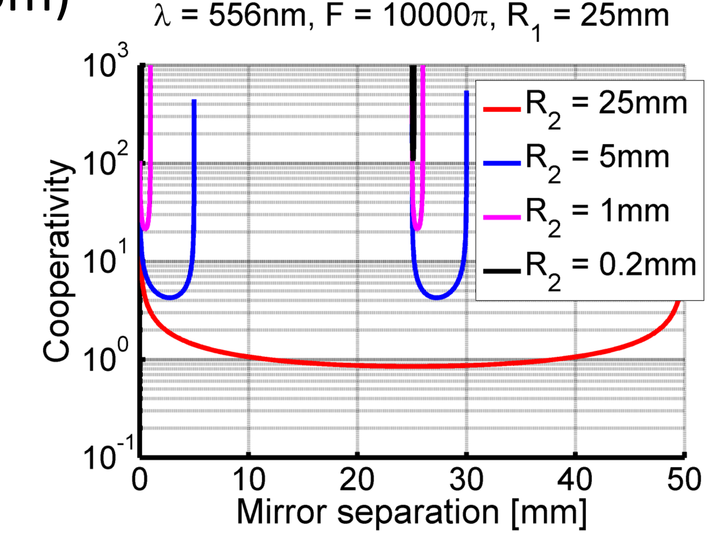


Why asymmetric cavity?

Important factor: Cooperativity

$$\eta = \frac{4g^2}{\kappa\Gamma} = \frac{24\mathcal{F}}{\pi k^2 w^2} \quad \text{(for single atom)}$$



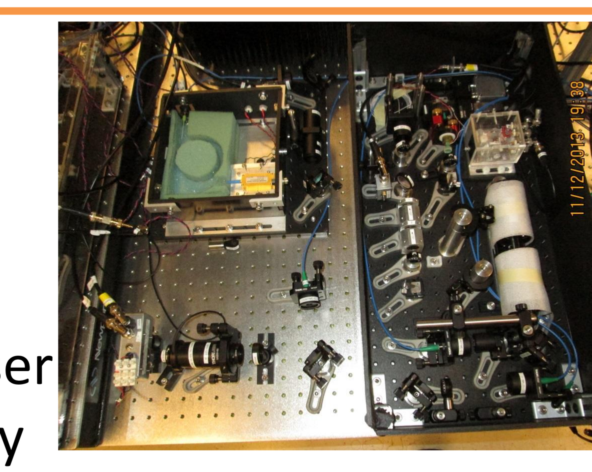


High cooperativity (especially $\eta \gg 1$, strongly coupled limit)

$\Rightarrow$ interesting states even beyond squeezed state

Asymmetric Cavity: High cooperativity + sufficient space for laser and atomic beam access

Lasers



399 nm: ECDL with DAVLL lock

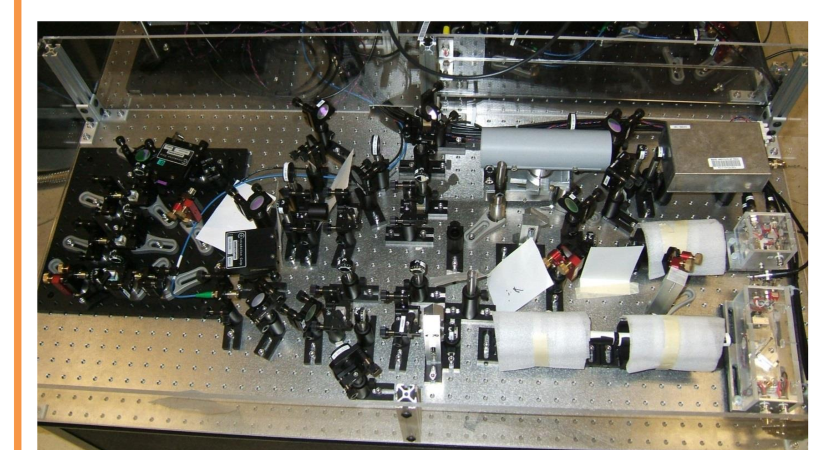
556 nm: fiber laser + SHG

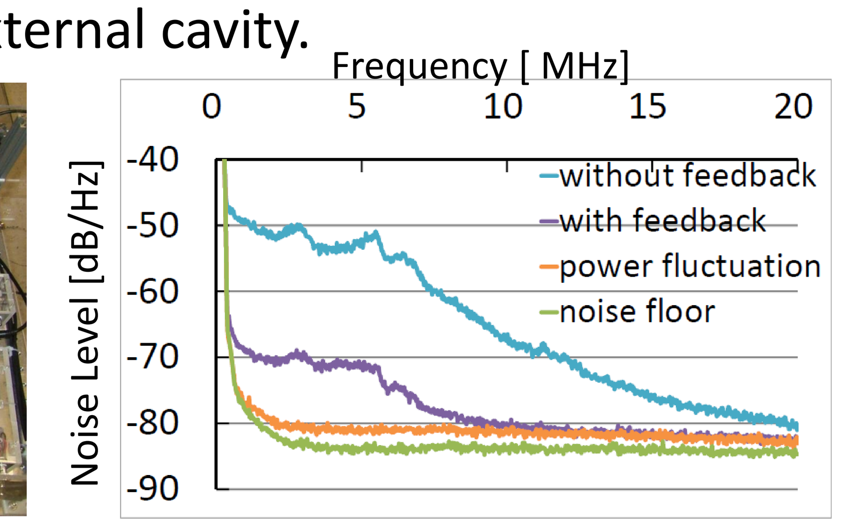
578 nm: IR laser (DFB+LD) + SHG

759 nm: DBR laser 1389 nm: DFB laser

556, 578 nm: locked to ultrastable cavity

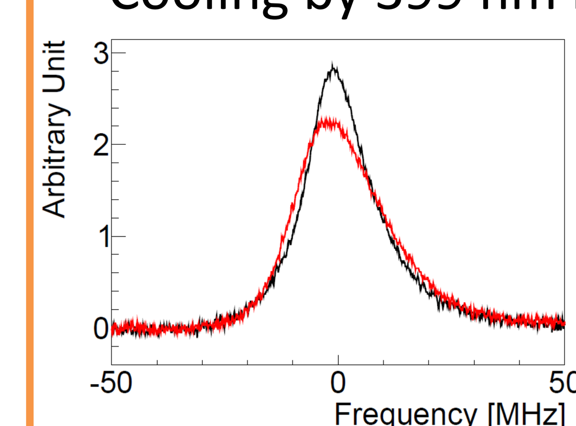
IR laser for 578nm and 759nm laser have narrowing system with optical feedback from a long external cavity.

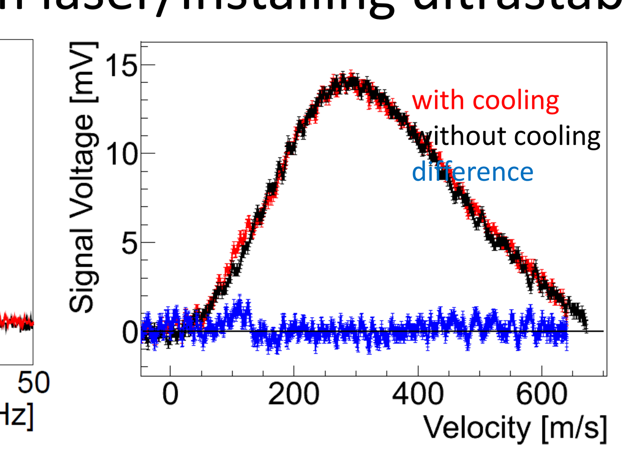




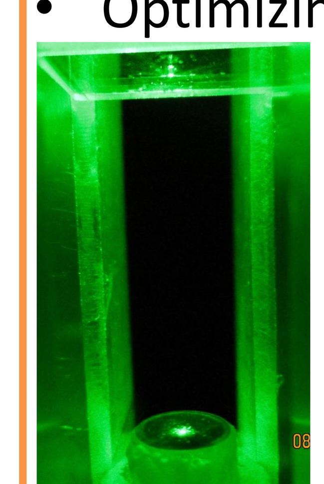
Other Recent Progress

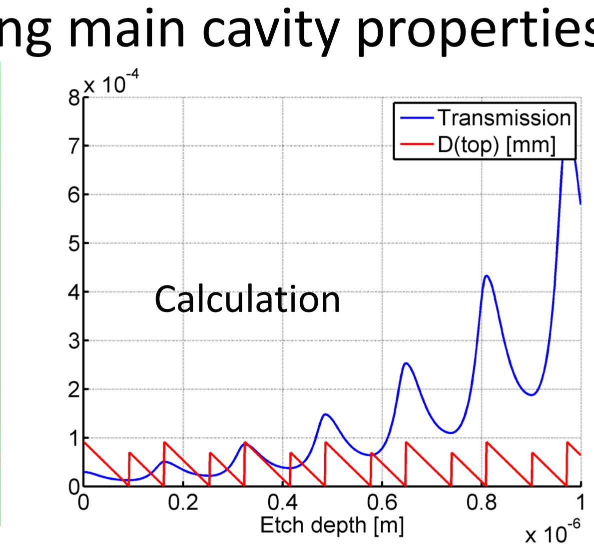
- Cooling by 399 nm laser/Installing ultrastable cavity

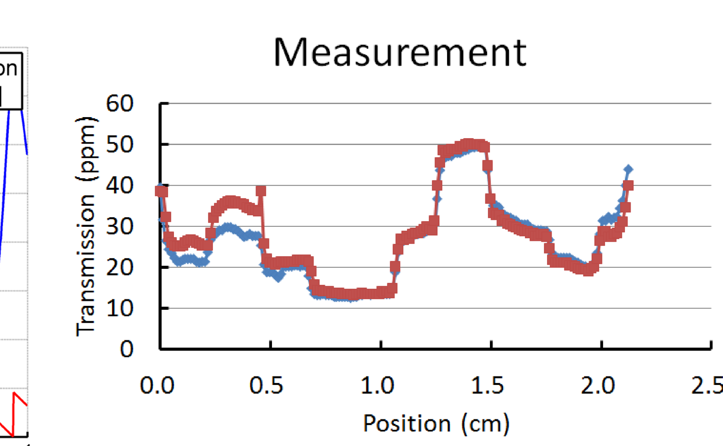




- Optimizing main cavity properties







Current status and Outlook

- Oven and heated window have been improved.
- Trying to get trapped atoms.
- Establishing the controlling system.
- Once we have atoms trapped and install the cavity, we can start the experiment.

Reference

[1] Hinkley *et al.*, Science **341**, 1215 (2013) [4] Kitagawa *et al.*, PRA **47**, 5138 (1993)

[2] Nicholson *et al.*, PRL **109**, 230801 (2012) [5] Schleier-Smith *et al.*, PRA **81**, 021804 (2010)

[3] Leroux *et al.*, PRL **104**, 250804 (2010)