Science and
Technology
Facilities Council

Imperial College
London

AION

Progress towards a squeezed-state atom interferometer in a linear cavity

Richard Hobson, Imperial College London, AION collaboration

Why squeezed states?

$$\delta\phi \sim 10^{-2} \xrightarrow{?} \delta\phi \sim 10^{-5}$$

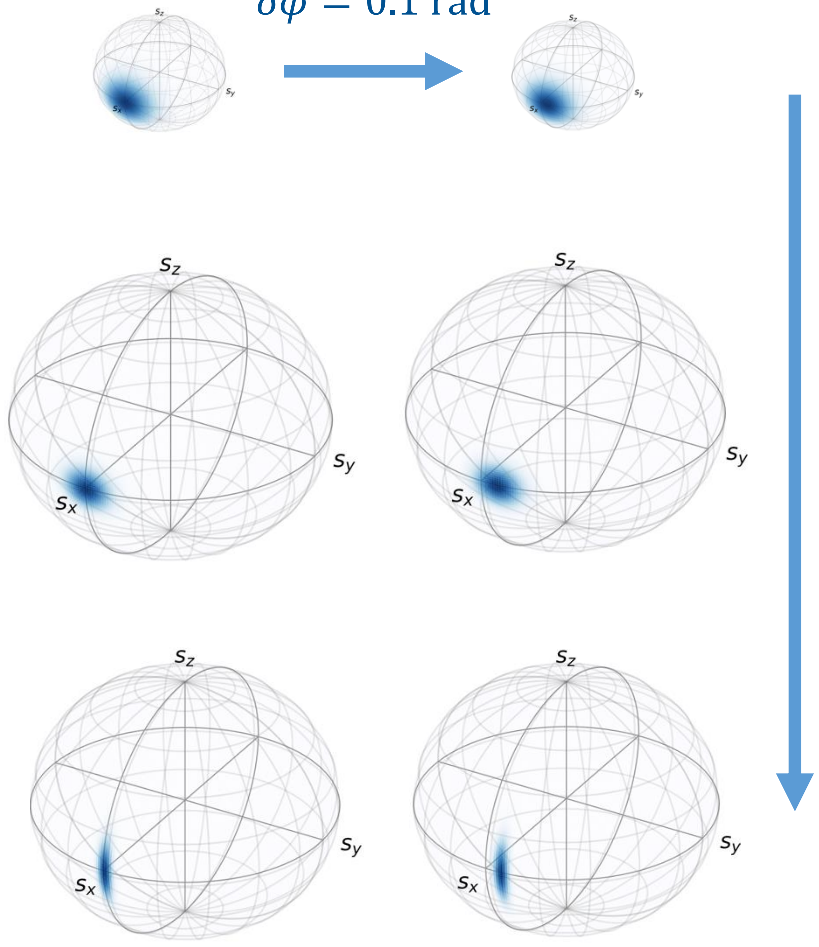
Atom shot noise limit:

$$\delta\phi = \xi \times \frac{1}{\sqrt{N_{atoms}}}$$

Quantum squeezing

$(\xi < 1)$

More atoms



Low N:

$\delta\phi = 0.1$ rad

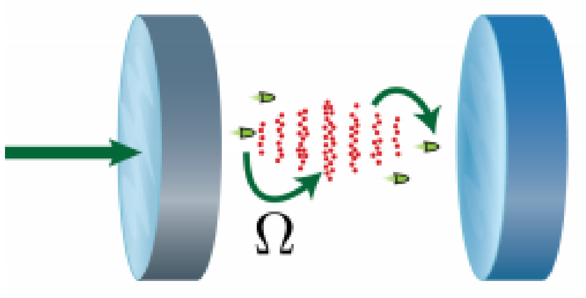
High N:

High N
Squeezed:

ϕ resolution

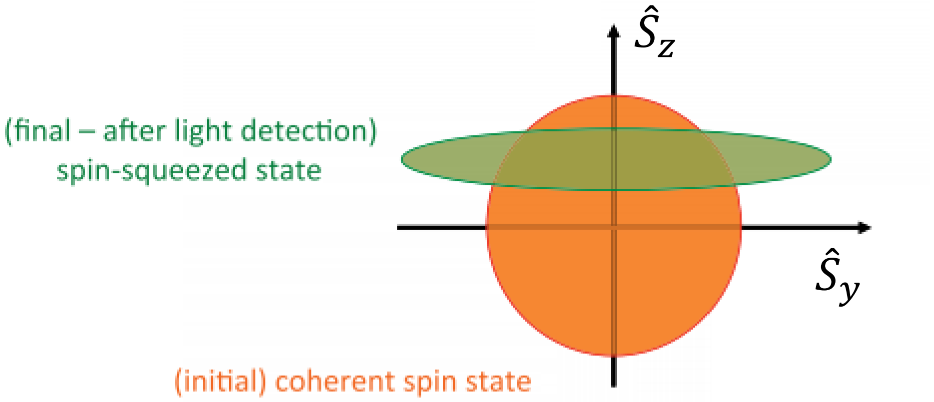
Cavity squeezing – Intro

Method: Place atoms inside a cavity

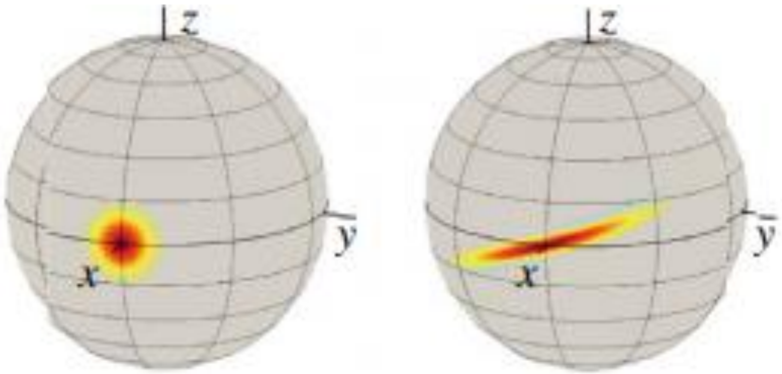


1. Quantum nondemolition (QND) measurement of $\hat{S}_z$

2. Nonlinear “twisting” Hamiltonian

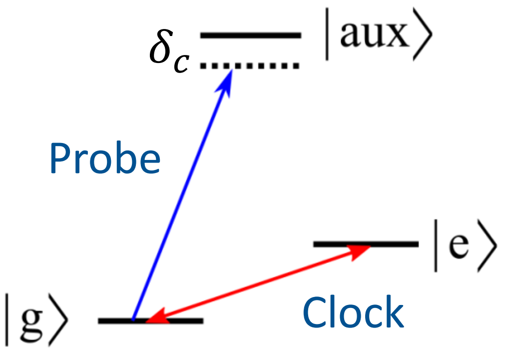


$H \propto \hat{S}_z^2$



Figures from Luca Pezze: https://link.aps.org/doi/10.1103/RevModPhys.90.035005

Cavity squeezing – Intro

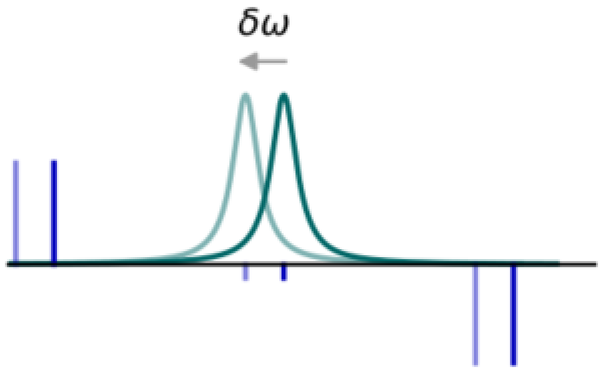


Cavity electric field interacts with atomic dipole with strength $g(r) \propto \vec{d}.\vec{E}_c\,(r)$

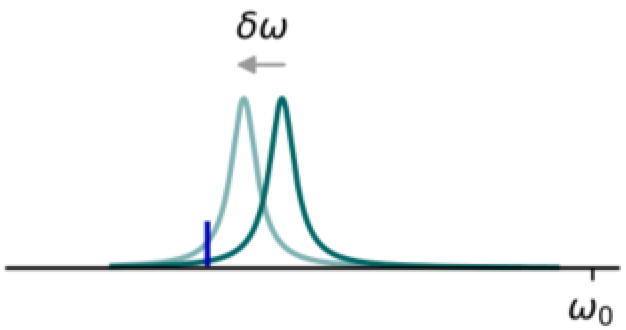
In the $|g\rangle$-coupled scheme (right), cavity modes are shifted by the number of atoms N_g

→ Squeezing methods:

1) QND measurement
$\hat{S}_z = (N_e - N_g)/2$



Or 2) Twisting: $\mathrm{H} \propto \hat{S}_z^2$



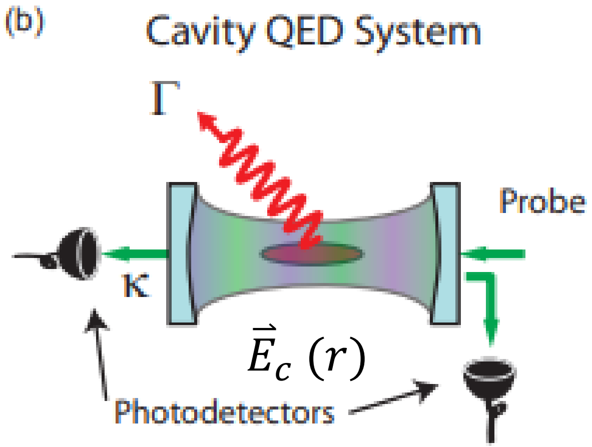
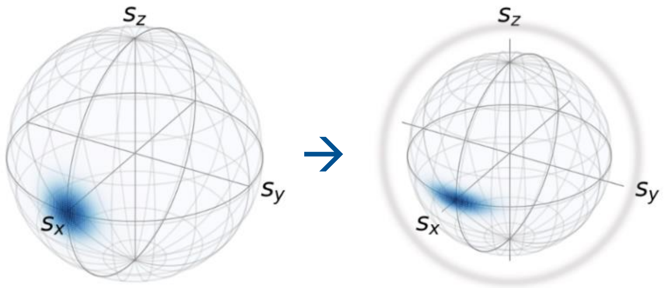


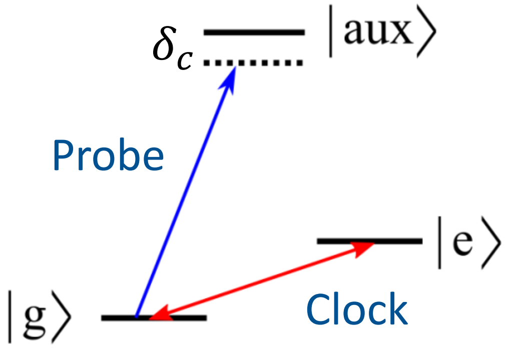
Figure from Zilong Chen et al:
https://link.aps.org/doi/10.1103/PhysRevA.89.043837

Cavity squeezing – limits

As you squeeze, you get decoherence from scattered photons → effectively smaller N



$$\xi_W = \frac{\Delta S / N^{\frac{1}{2}}}{\langle S \rangle / N}$$



Maximum squeezing per scattered photon is determined by the "collective cooperativity":

$$\text{NC} = \frac{4Ng^2}{\kappa\Gamma}$$

→ For best squeezing, we want

- Large atom number N
- High vacuum Rabi frequency g (i.e. small cavity mode waist)
- Low cavity decay rate κ (i.e. high cavity finesse)
- [Low atom decay rate (but Γ depends as d^2, so cancels with g)]

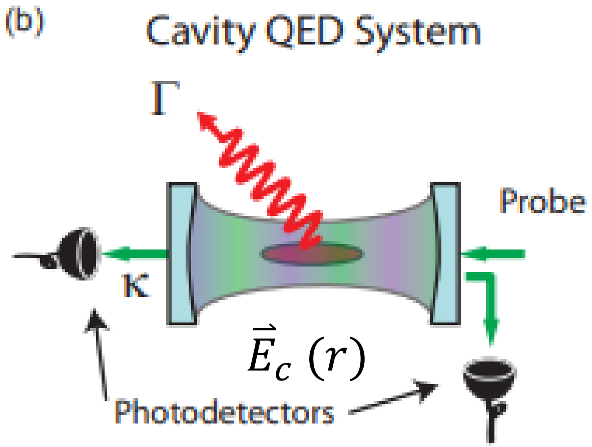


Figure from Chen paper:
https://link.aps.org/doi/10.1103/PhysRevA.89.043837

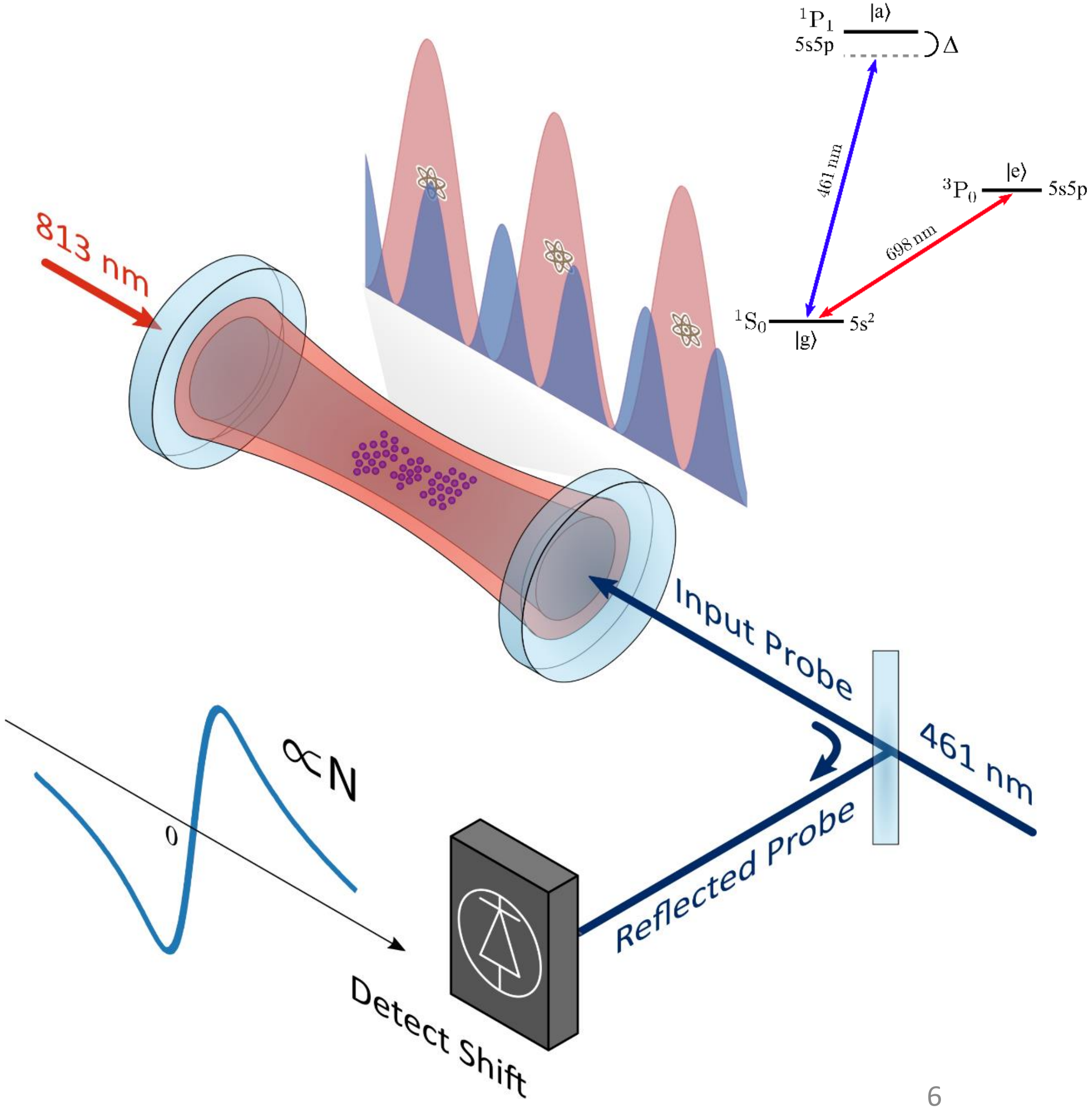
Cavity squeezing – NPL Sr clock

Far-detuned cavity mode → Atoms act as a dispersive medium depending internal atomic state $(|g\rangle, |e\rangle)$

For **weak probe** and for **large cavity detuning** $\Delta_n \gg g\sqrt{N}$ each cavity mode is shifted in frequency by

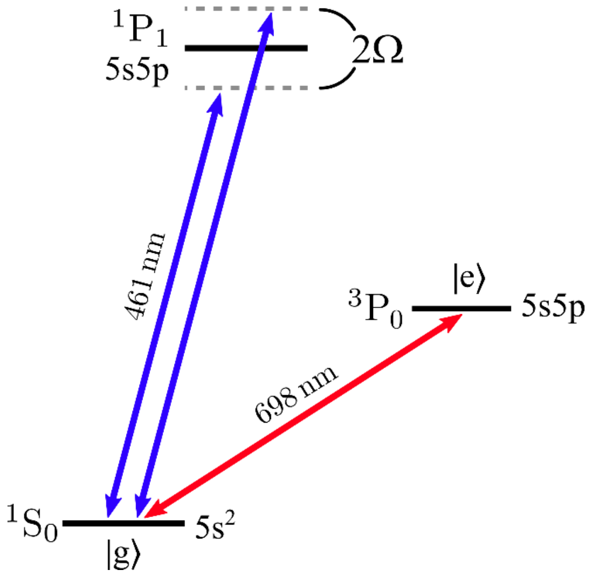
$$\Delta\omega_n = \frac{\langle g_n^2 \rangle}{\Delta_n} N_g$$

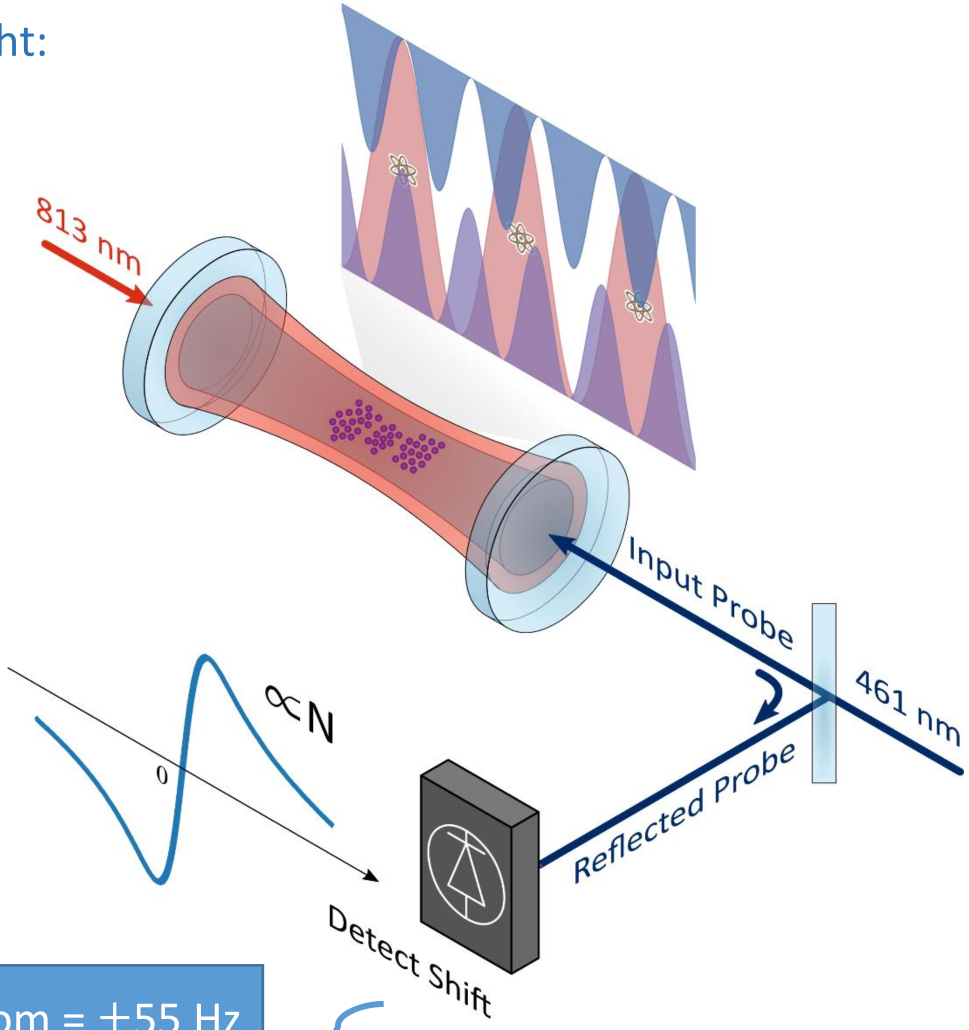
1 atom = 55 Hz shift



Cavity squeezing – NPL Sr clock

In detail: Two cavity modes probed with red- and blue-detuned QND light:





1 atom = ±55 Hz shift

Blue/red cavity modes are shifted in frequency by **opposite sign**

→ We probe the **frequency difference** to measure N_g

$$\Delta\omega_n = \frac{\langle g_n^2 \rangle}{\Delta_n} N_g$$

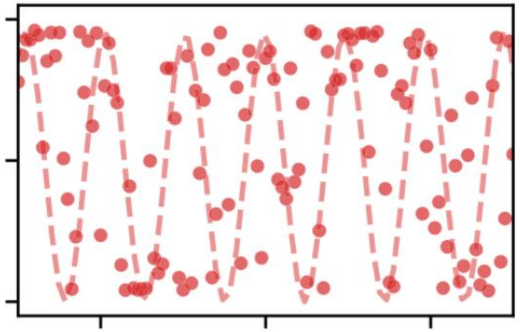
R Hobson et al. Optics Express 27, 26, 37099-37110 (2019)

Cavity squeezing – NPL Sr clock

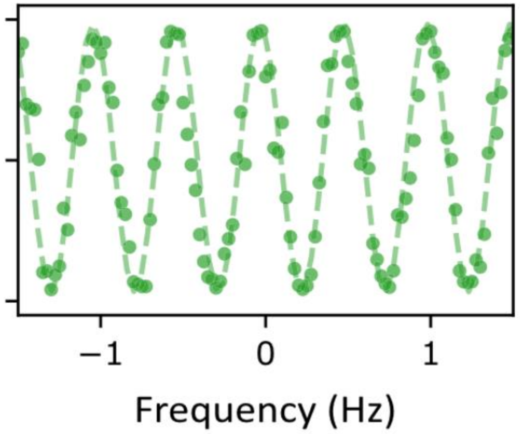
The NPL QND method worked well!

E.g. 2-second Ramsey clock (in clock 2) using an atom phase lock (to clock 1)

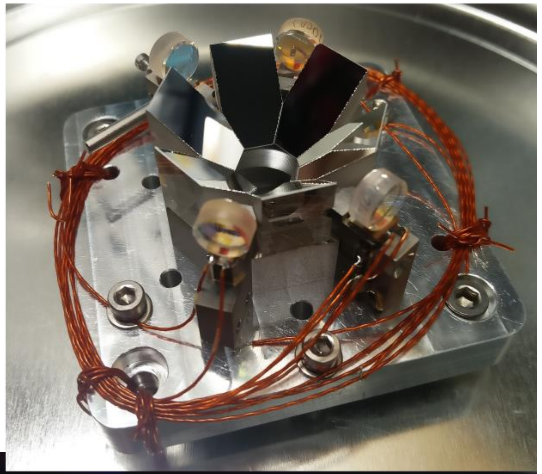
No atom phase lock:

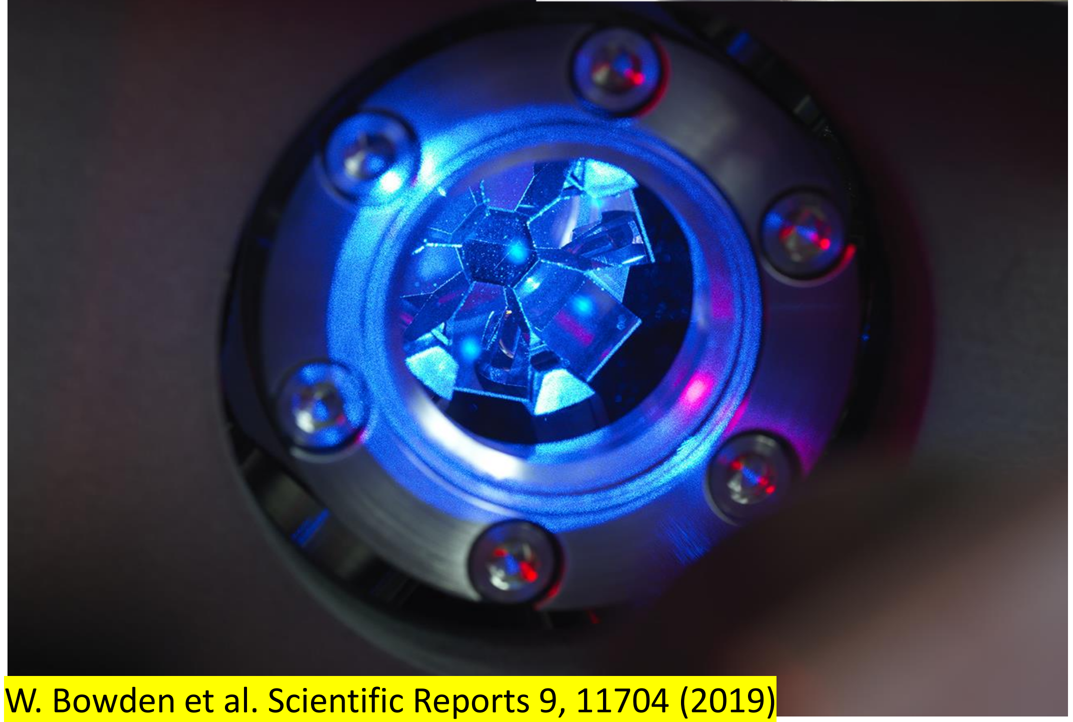


With atom phase lock:



W. Bowden et al. PRX 10, 4, 041052 (2020)





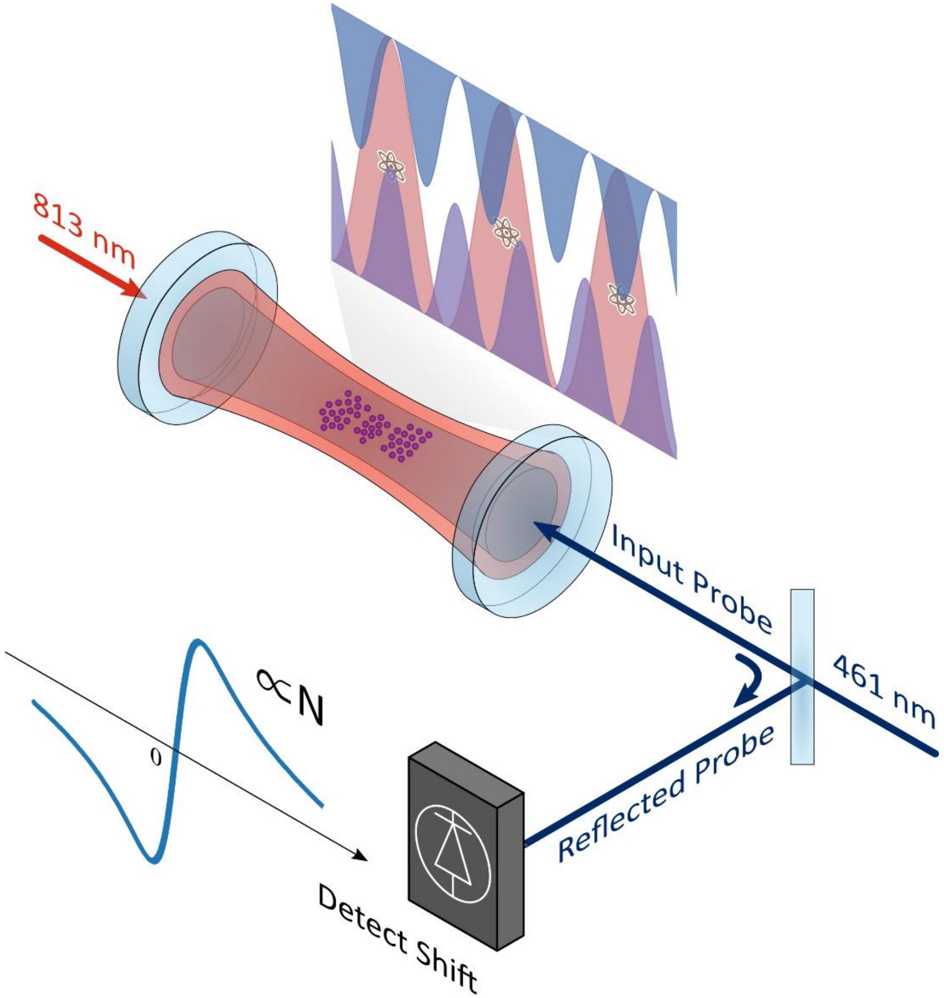
W. Bowden et al. Scientific Reports 9, 11704 (2019)

Cavity squeezing – NPL Sr clock

But… No squeezing

Many technical problems

- Cavity length noise ~ 100 kHz pk-pk → complex locking scheme needed, residual technical detection noise at acoustic frequencies
- Inhomogenous atom-cavity coupling (+ve and –ve modes)
    - → Not all atoms participate equally, and large range of Stark shifts
- Large detuning → large Stark shift per scattered photon
    - → Enhanced dependence on local probe power; probe-induced dipole potential causes atomic heating
- Excitation phase $|g\rangle + e^{ik_{698}z}|e\rangle$ depends on lattice site
    - → If atoms released for atom interferometry, phase would be random
- Need magic wavelength lattice → constraint on cavity mode positions

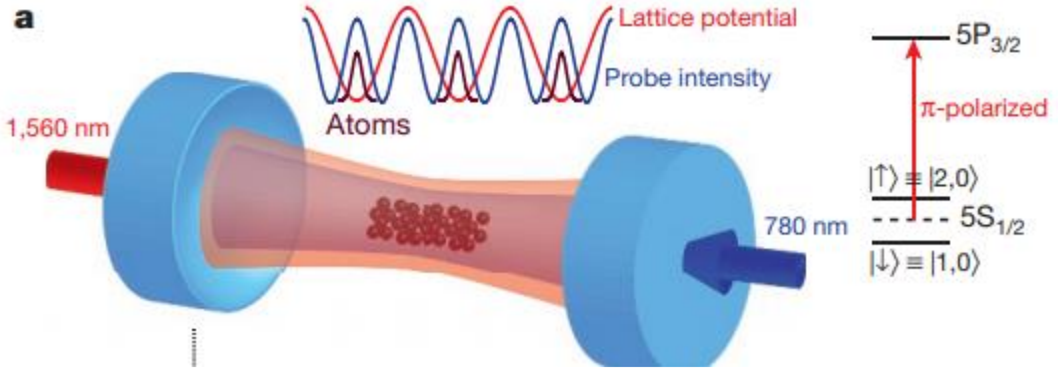


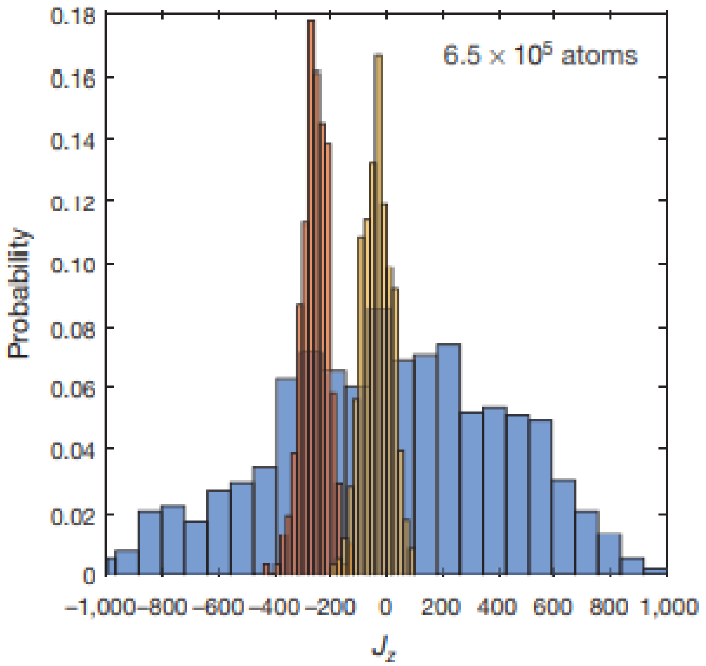
Cavity squeezing – Imperial AION plan

Neat trick from Onur Hosten/Mark Kasevich group:

Overlap lattice/probe modes line up → uniform, high coupling

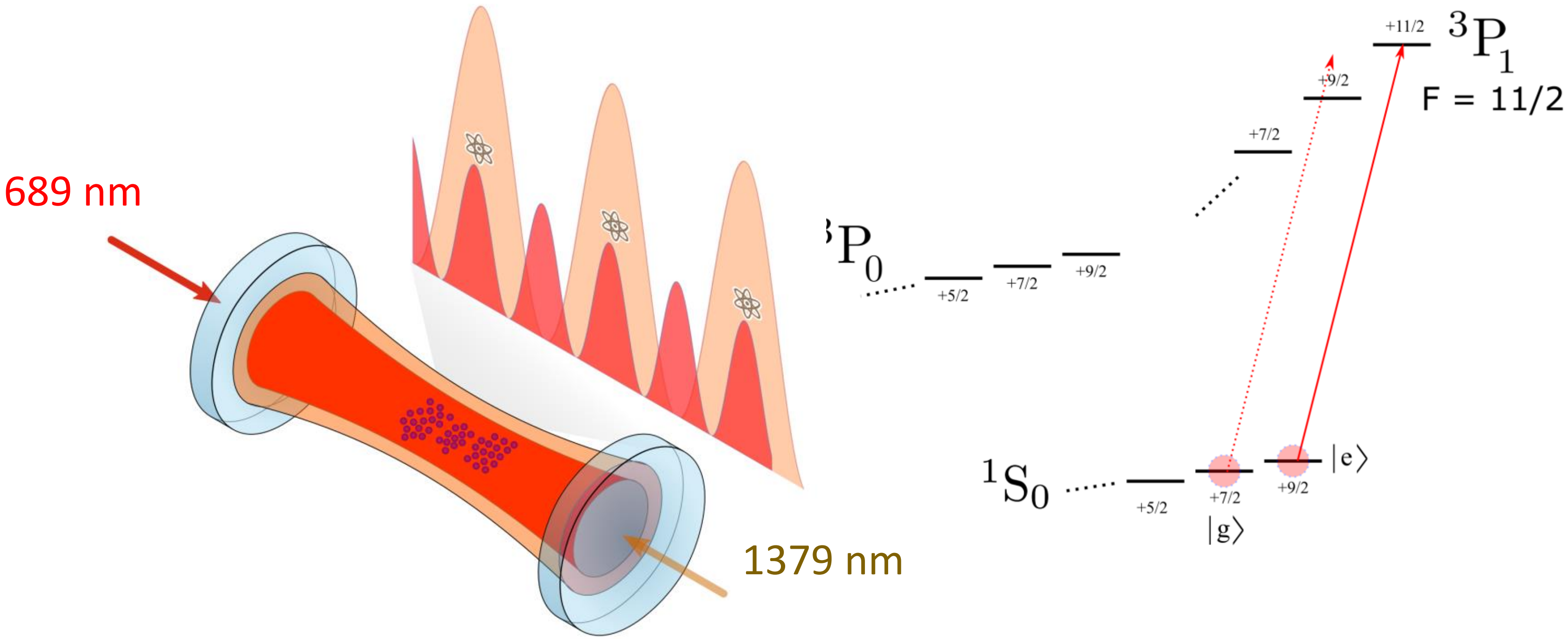
→ World record squeezing factor: **100**





Figures from Hosten/Kasevich (Stanford): https://www.nature.com/articles/nature16176

Imperial plan for Sr – squeeze internal states, then map to momentum



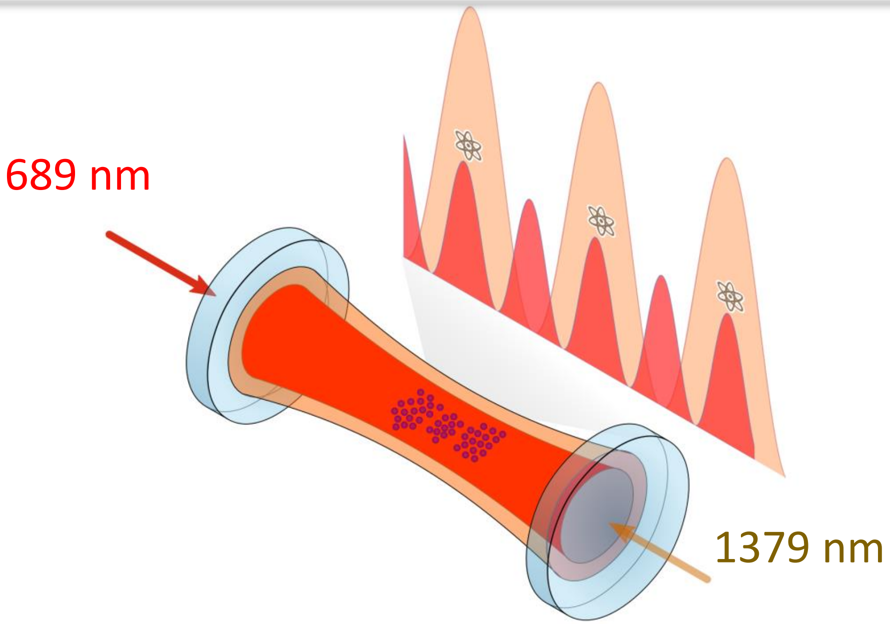
Cavity squeezing – Imperial AION plan

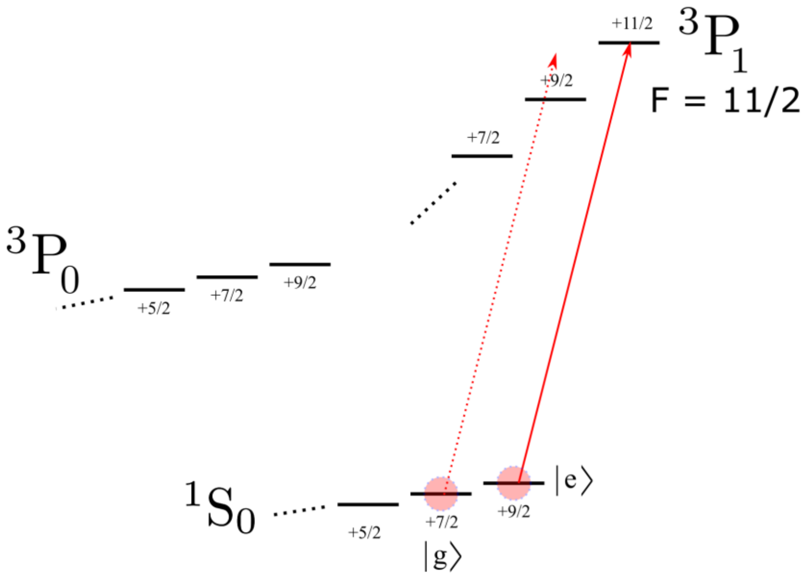
The fundamental squeezing limit (for a given cavity) is given by the collective cooperativity

$$NC = \frac{4g^2}{\kappa\Gamma} = \frac{6\lambda^2 F}{\pi^3 w_0^2}$$

$$= \left(\frac{\lambda}{689\ nm}\right)^2 \times \left(\frac{100\mu m}{w_0}\right)^2 \times \frac{F}{10^5} \times \frac{N}{10^5} \times 9.2 \times 10^4$$

→ Squeezing beyond 20 dB seems possible!





An open question: how close can we get to fundamental limits?

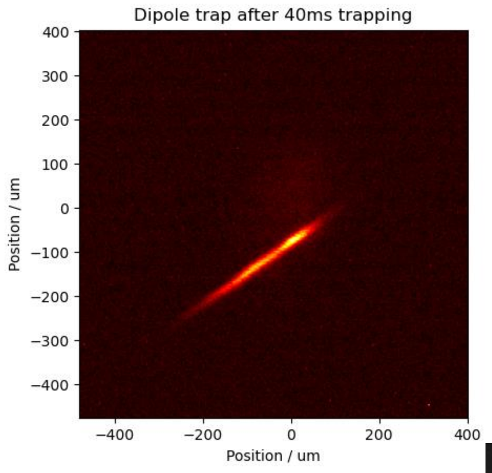
It’s a game of controlling the (many) technical noise sources…

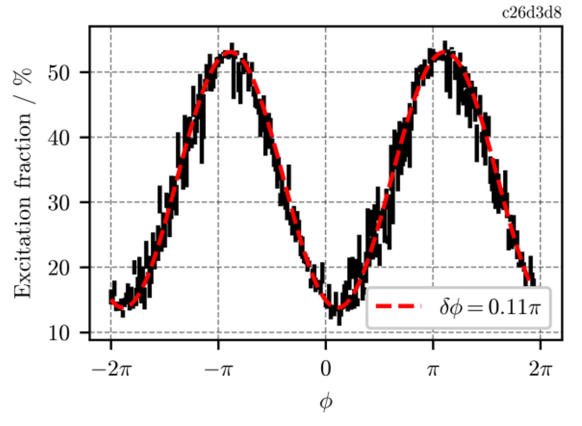
Detection noise, cavity length noise, probe spectral impurity, atom motion, atom position spread, RF pulse fidelity (amplitude and frequency noise), magnetic field noise, probe-cavity coupling efficiency, atom-atom interactions (collisions), spin-flips or leakage to other internal states (Raman scatter, off-resonant excitation)

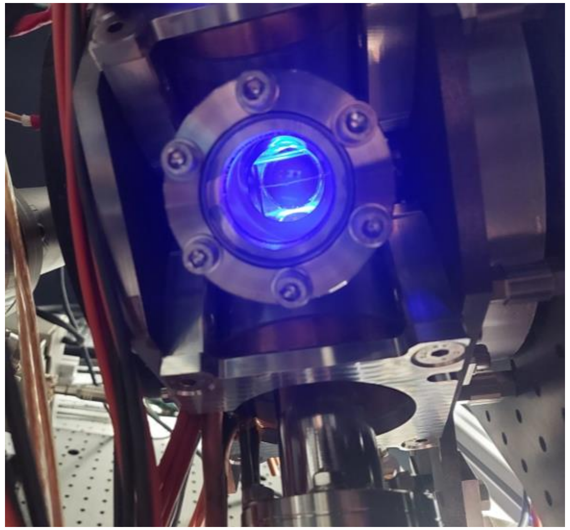
Experimental progress

We first moved into the lab in Feb 2022:

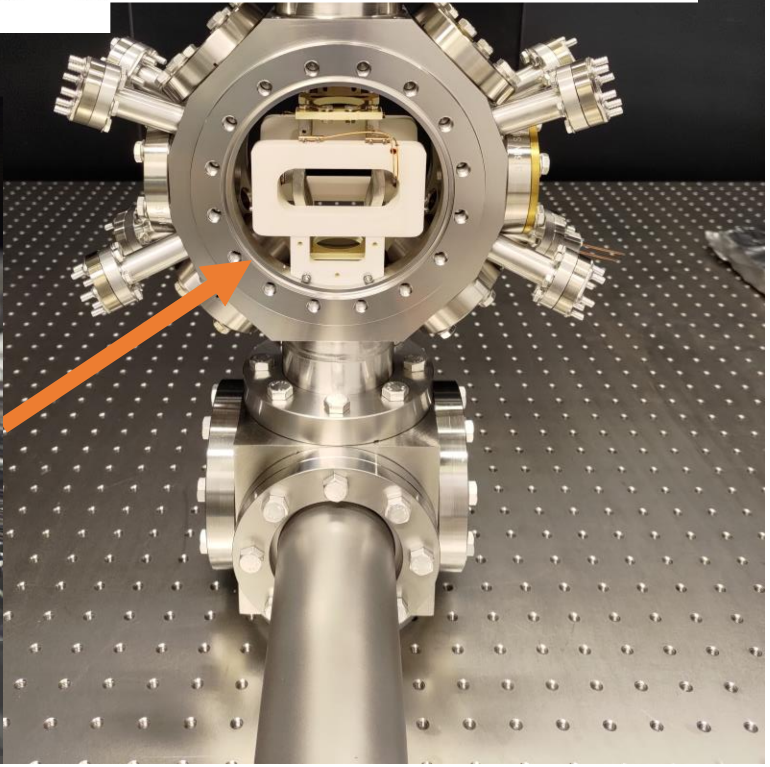
- Squeezing cavity installed, with 200k finesse
- Blue MOT, red MOT, dipole trap, 689 nm interferometry, and intracavity lattice-trapped atoms






2D MOT source

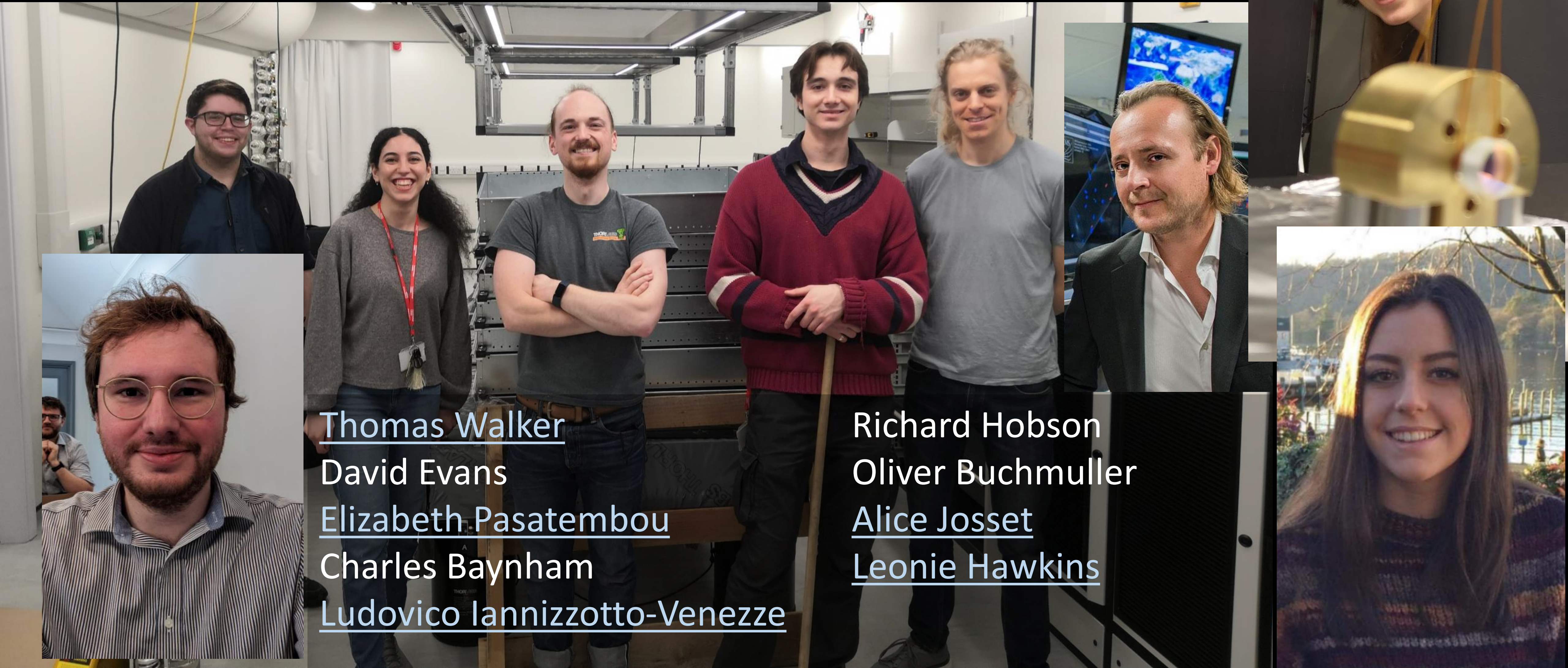

Squeezing cavity



AION Imperial team

Look out for our posters this afternoon (underlined)

And come find us for a lab tour



Thomas Walker
David Evans
Elizabeth Pasatembou
Charles Baynham
Ludovico Iannizzotto-Venezze

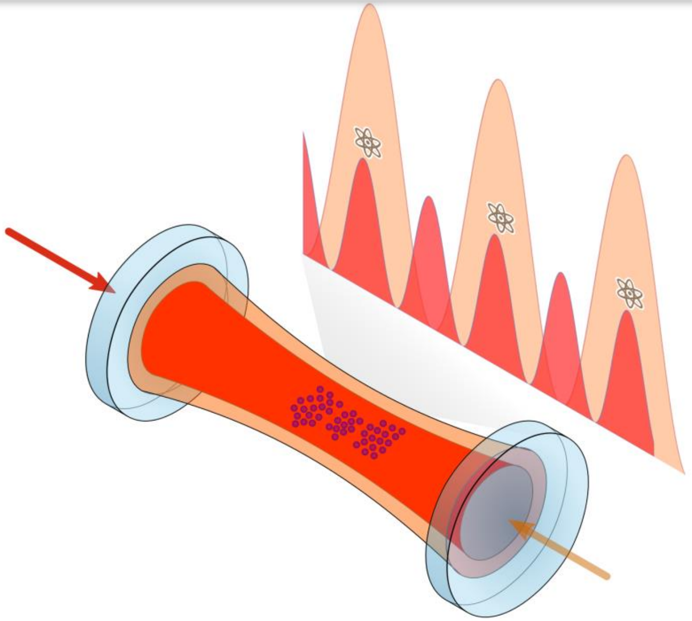
Richard Hobson
Oliver Buchmuller
Alice Josset
Leonie Hawkins

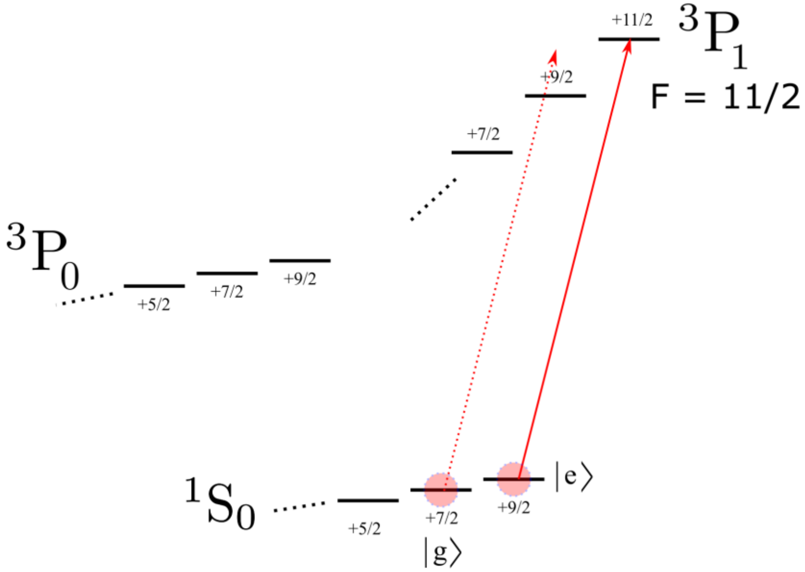
Squeezing backup slides

Cavity QED – Imperial proposal

Borrow ideas from previous squeezing experiments:

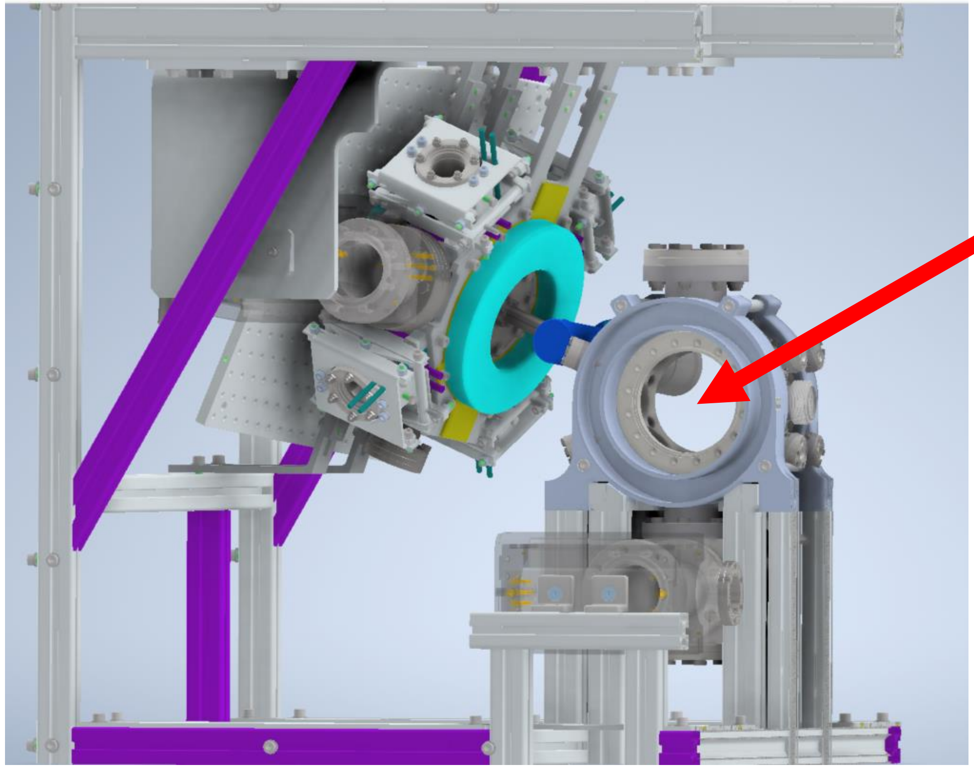
- Narrow line transition and $\delta_c = 0$
  - → Small Stark shifts
- Commensurate lattice/probe
  - → Homogenous atom/cavity coupling
- Squeeze between magnetic sublevels of ground state
  - → No constraint on trap wavelength (hyperfine tensor shift only)
  - → All atoms have same excitation phase → coherent after release from trap for atom interferometry
  - → Allows trapping at convenient wavelengths (1064 nm, 1379 nm)
- Challenges
  - Coherent transfer between magnetic sublevels while maintaining closed two-level system (avoid leakage to M < 7/2 using 689 nm plug beam?)
  - Many other challenges to be discovered along the way

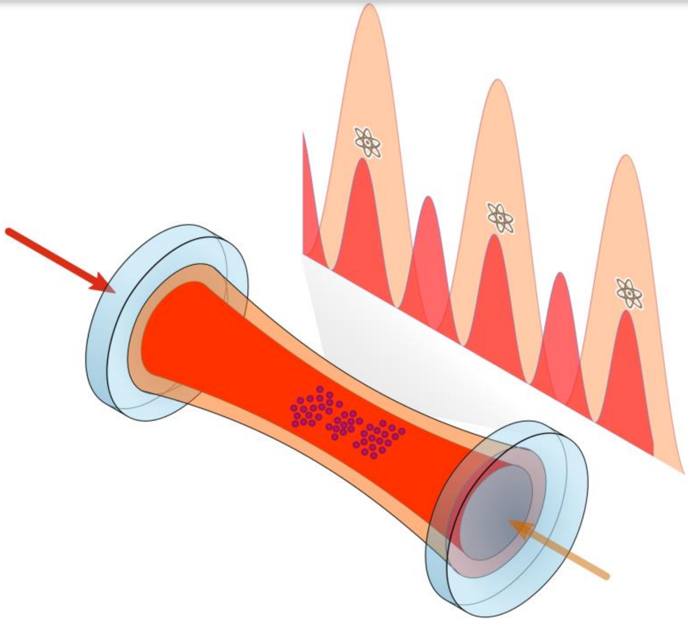




Proposed squeezing R&D plan

1. First 3 years: Squeezing in chamber 2 (see pictures)
2. Evaluate best route to long-term goals (see table)

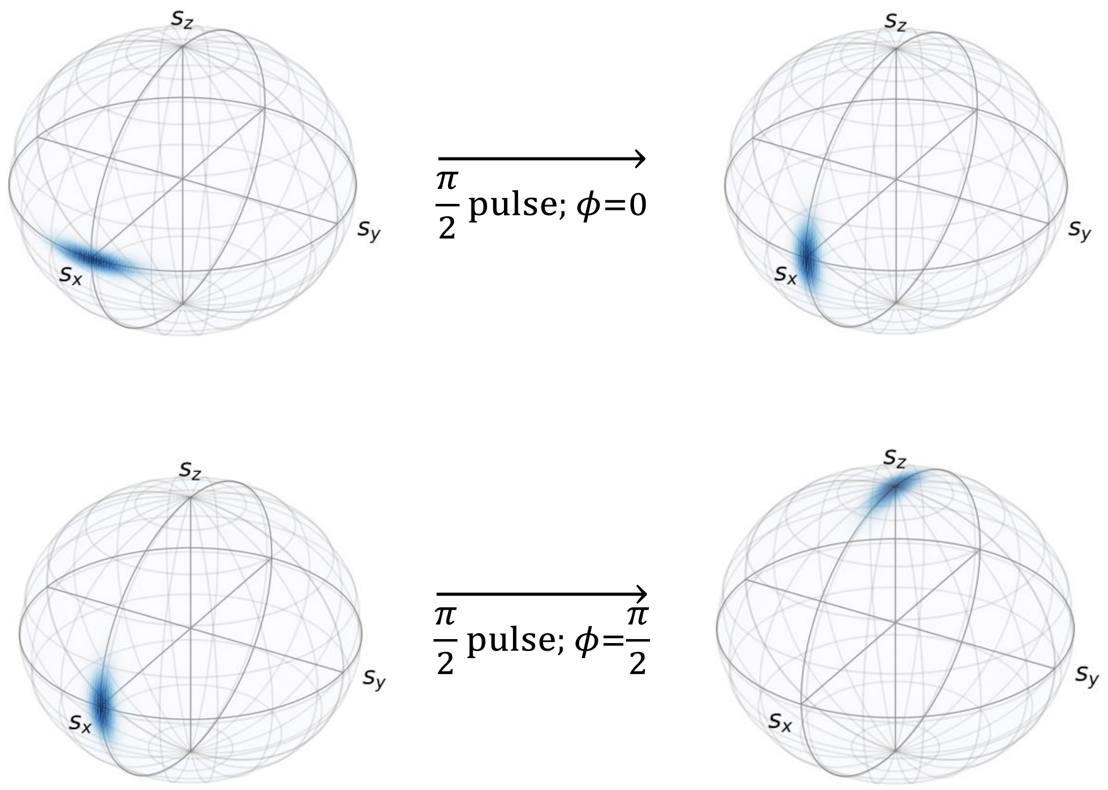




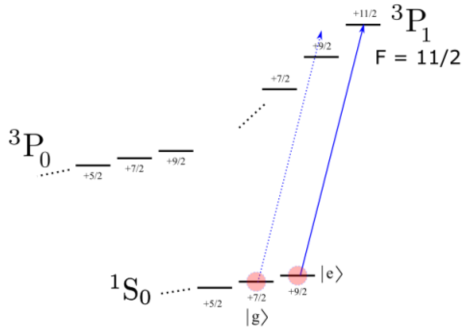
Detector Stage	Target $\delta\varphi_{noise}$ $[1/\sqrt{Hz}]$	Atoms/sec without squeezing	Atoms/sec with 20dB squeezing
AION-10 (initial)	10^{-3}	10^{6}	10^{4}
AION-10 (goal) & AION-100 (initial)	10^{-4}	10^{8}	10^{6}
AION-100 (goal) & AEDGE (space)	10^{-5}	10^{10}	10^{8}
AION-km	0.3×10^{-5}	10^{11}	10^{9}

Tools – state rotations

1. Rotations around the Bloch sphere



2. Swapping to a different Bloch sphere basis of states



$|e = 1S_0, M_F = 1/2\rangle \xrightarrow[\pi\text{ pulse}]{} |e = 3P_0, M_F = 3/2\rangle$

$|g = 1S_0, M_F = 5/2\rangle$ $|g = 1S_0, M_F = 5/2\rangle$

Can we pick a state orientation & basis of states g,e which are robust during transport, then rotate into a phase-sensitive squeezed state in the AI tube?

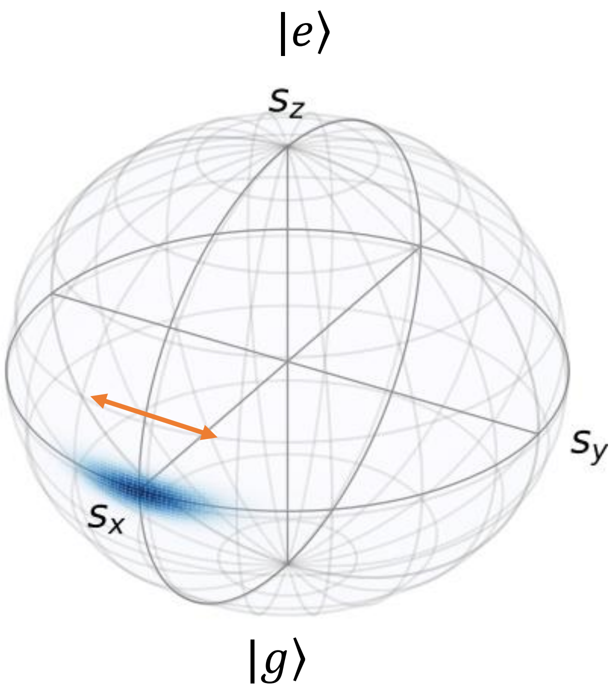
The problem with transporting squeezed states

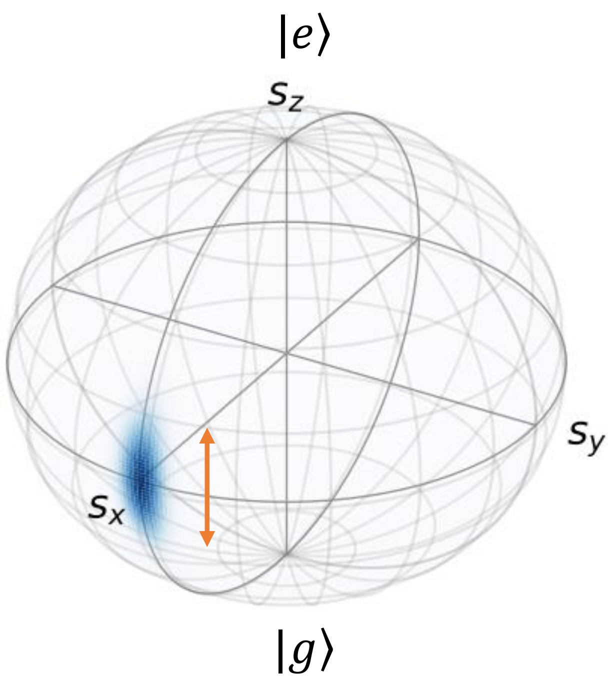
Diffusion along S_y

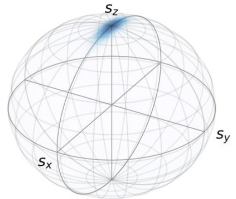
- Zeeman & ac Stark shifts
- Elastic collisions
- LO frequency noise (mismatch of LO vs $E_e - E_g$)

Diffusion along S_z

- Raman “spin flip” scatter
- Inelastic collisions





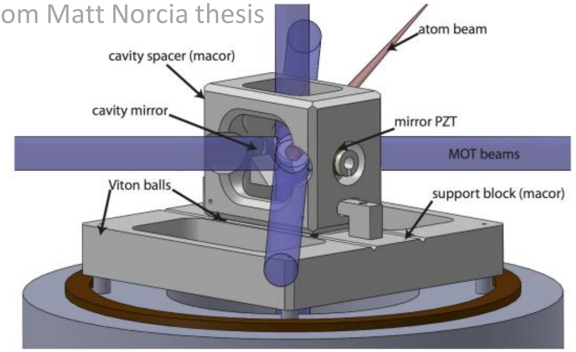


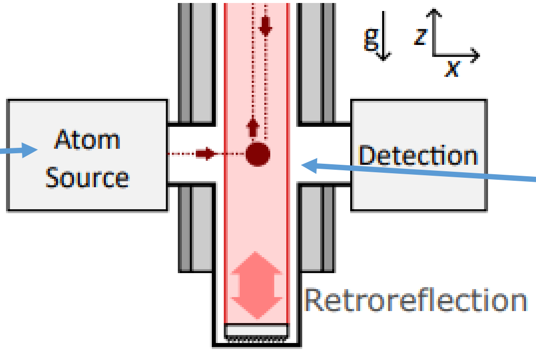
Preliminary thoughts:

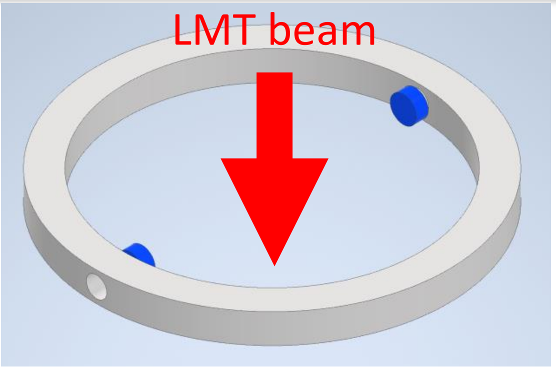
Population squeezed states are probably more robust (Sx diffusion mechanisms are faster than Sz);
Using a {g,e} basis within the 1S0 manifold is probably better (inelastic collisions are much lower)

Trade-offs: Sidearm vs AI tube squeezing

From Matt Norcia thesis



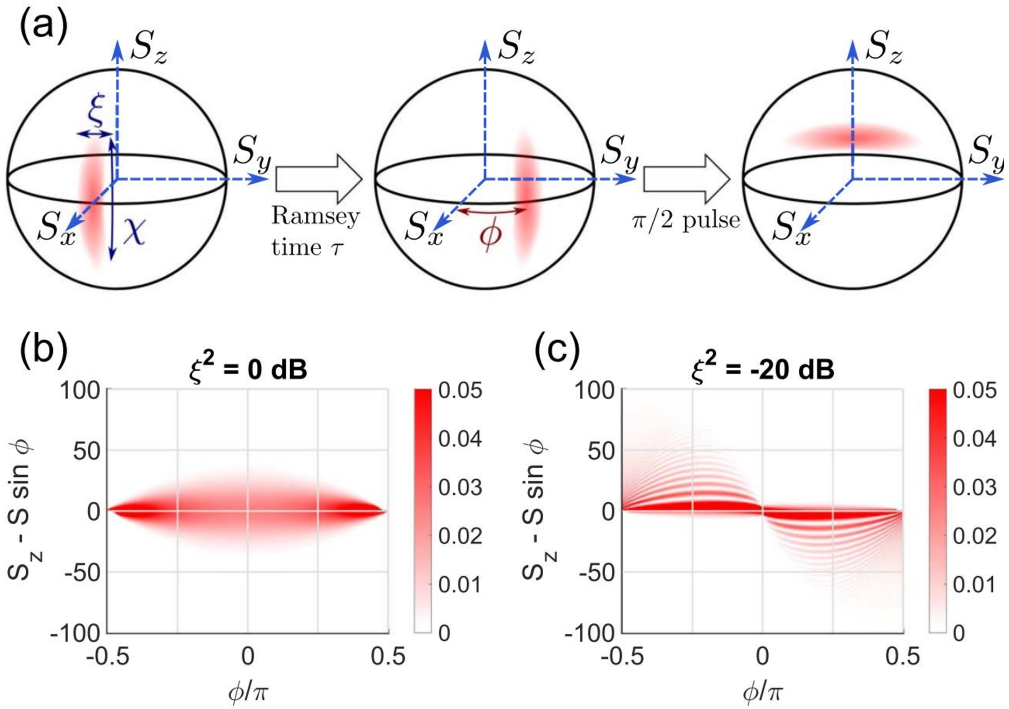


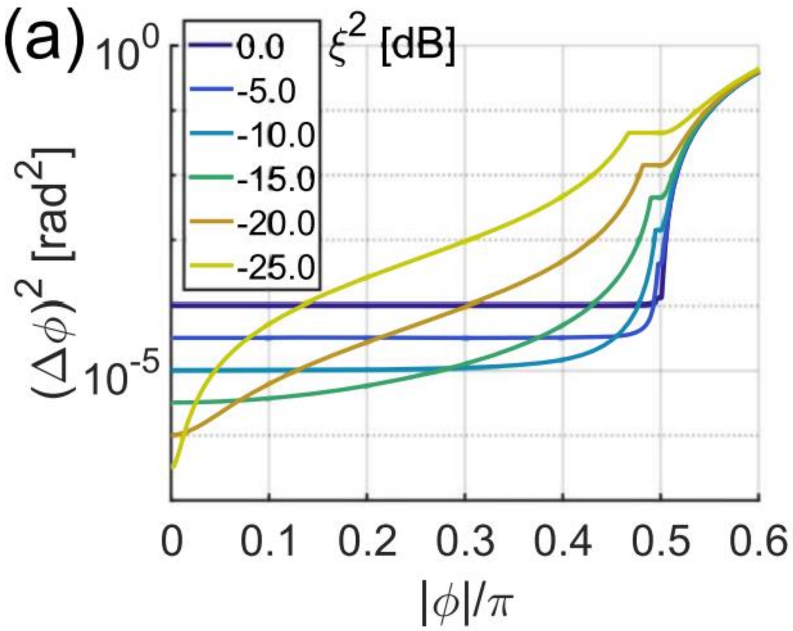


Advantage\Location of squeezing	Sidearm	AI tube	Mitigation
Magnetic field coils can fit around/inside sidearm (helpful for some squeezing protocols)	✓	✗	Use squeezing schemes which don't need strong, or oscillating, magnetic fields
Short cavity → less sensitive to mechanical noise	✓	✗	Carefully engineer a stiff, vibration-insensitive cavity to fit into the AI tube
Short cavity → large cavity linewidth → $\kappa > \Gamma$ compatible with F > 100k → high cooperativity	✓	✗	Accept lower finesse, or squeezed in far-detuned regime $\delta_c \gg g\sqrt{N}$ and carefully control probe ac Stark shifts
Short cavity → small mode waist → high cooperativity	✓	✗	Accept lower cooperativity, or use near-concentric cavity with tighter waist (at the expense of near-instability)
No transport stage needed → avoids decoherence	✗	✓	Rotate into "robust" squeezed state? Fast transport?
Can use (clean) LMT beam for state rotations	✗	✓	Find ways to cleanly rotate the state in chamber 2 (clean 698 nm beams and/or RF drive between magnetic sublevels)
No compromise to sidearm optical access	✗	✓	Design gaps in the cavity spacer for cooling & transport beams

Is squeezing useful?

1. For squeezing in general, antisqueezing kills you if the mean phase is wrong!





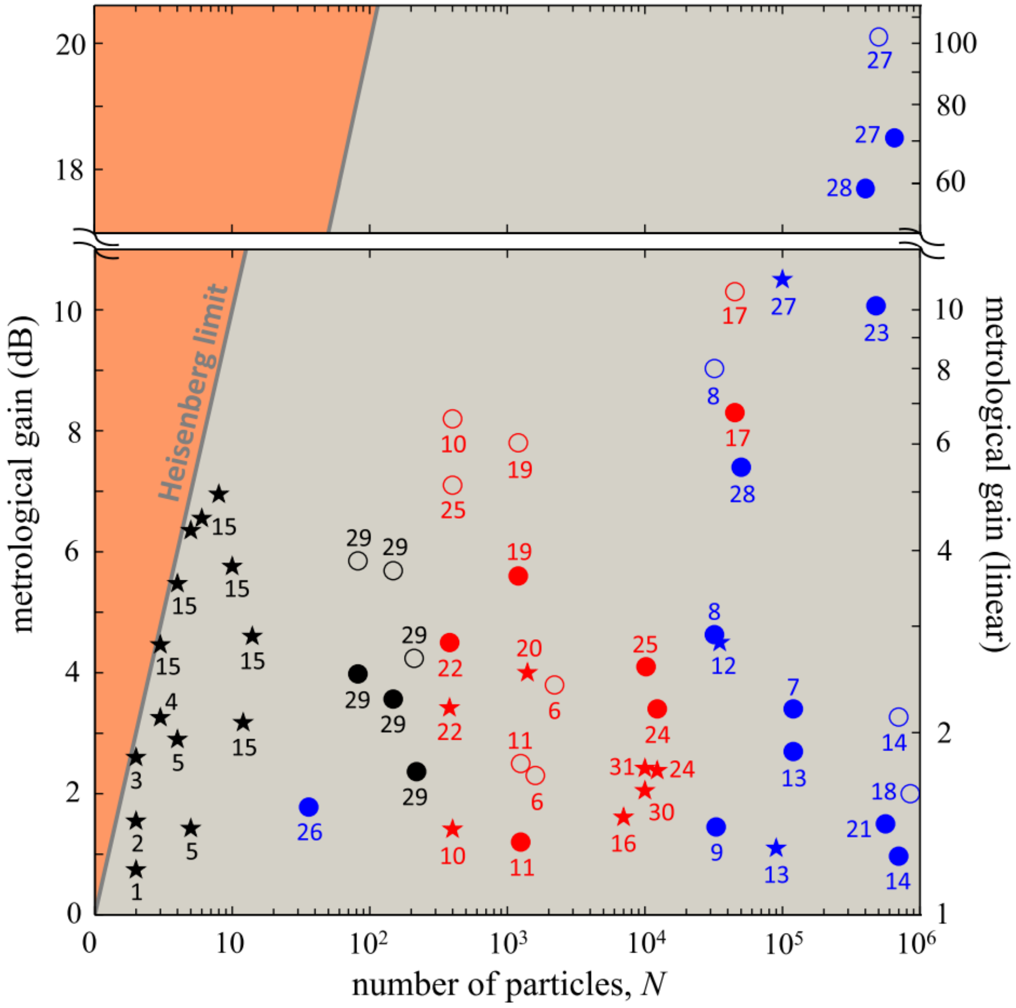
Braverman (2018) http://stacks.iop.org/1367-2630/20/i=10/a=103019

2. Extra squeezing problems specific to interferometry:

a) We have to squeeze in the baseline tube (difficult while leaving clearance for LMT beam), or preserve squeezing during transport

b) The interferometer phase isn't uniform (there are fringes) so the phase is necessarily wrong in much of the cloud

Squeezing history



TRAPPED IONS

[1] Sackett *et al.*, 2000
[2] Meyer *et al.*, 2001
[3] Leibfried *et al.*, 2003
[4] Leibfried *et al.*, 2004
[5] Leibfried *et al.*, 2005
[15] Monz *et al.*, 2011
[29] Bohnet *et al.*, 2016

BOSE-EINSTEIN CONDENSATES

[6] Estève *et al.*, 2008
[10] Gross *et al.*, 2010
[11] Riedel *et al.*, 2010
[16] Lücke *et al.*, 2011
[17] Hamley *et al.*, 2012
[19] Berrada *et al.*, 2013
[20] Ockeloen *et al.*, 2013
[22] Strobel *et al.*, 2014
[24] Muessel *et al.*, 2014
[25] Muessel *et al.*, 2015
[30] Kruse *et al.*, 2016
[31] Zou *et al.*, 2018

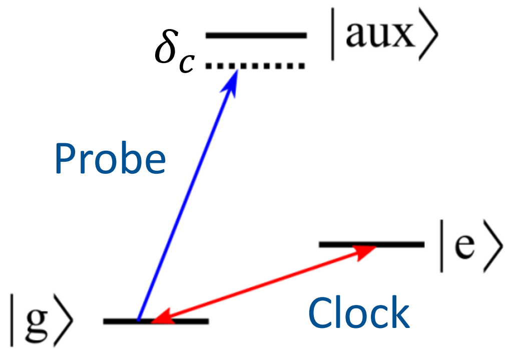
COLD THERMAL ATOMS

[7] Appel *et al.*, 2009
[8] Leroux *et al.*, 2010a
[9] Schleier-Smith *et al.*, 2010b
[12] Leroux *et al.*, 2010b
[13] Louchet-Chauvet *et al.*, 2010
[14] Chen *et al.*, 2011
[18] Sewell *et al.*, 2012
[21] Sewell *et al.*, 2014
[23] Bohnet *et al.*, 2014
[26] Barontini *et al.*, 2015
[27] Hosten, Engelsen *et al.*, 2016
[28] Cox *et al.*, 2016

Pezze et al. (2018) 10.1103/RevModPhys.90.035005

Cavity QED – regimes for squeezing

Two different regimes we could consider depending on atom-cavity detuning δ_c



1. $\delta_c = 0$

→ Cavity mode splits into two, at $\pm g\sqrt{N}$

→ Cavity mode linewidth $\kappa' = \frac{1}{2}(\kappa + \Gamma)$

→ Con: Only efficient if $\kappa \geq \Gamma$

→ Pro: Stark shift/photon is small

2. $\delta_c \gg \kappa, \Gamma$

→ Cavity mode shifts by $\mathrm{N}\frac{g^2}{\delta_c}$

→ Cavity mode linewidth $\kappa' = \kappa(1 + N\frac{g^2}{\delta_c^2}\frac{\Gamma}{\kappa})$

→ Pro: Compatible with high finesse $\kappa < \Gamma$

→ Con: Stark shift/photon is big

Other technical considerations

- Cavity length noise → always want to take frequency difference between cavity modes
- Atomic structure is important – no atom is a two level system!
- E-field is not homogenous in cavity; clock pulses are not perfect; probe light has intensity and frequency noise; photodetectors are noisy; the atoms move; many more things…

Cavity QED – Vuletic approach (Yb)

Regime: $\delta_c = 0$ for atoms in $|\uparrow\rangle$

- OK because they're using narrow-line transition, so $\kappa \geq \Gamma$

Two modes probed off-resonance → twisting Hamiltonian

Weird cavity geometry (micromirror, ~ 5 um mode waist) → very high cooperativity (but low-ish atom number)

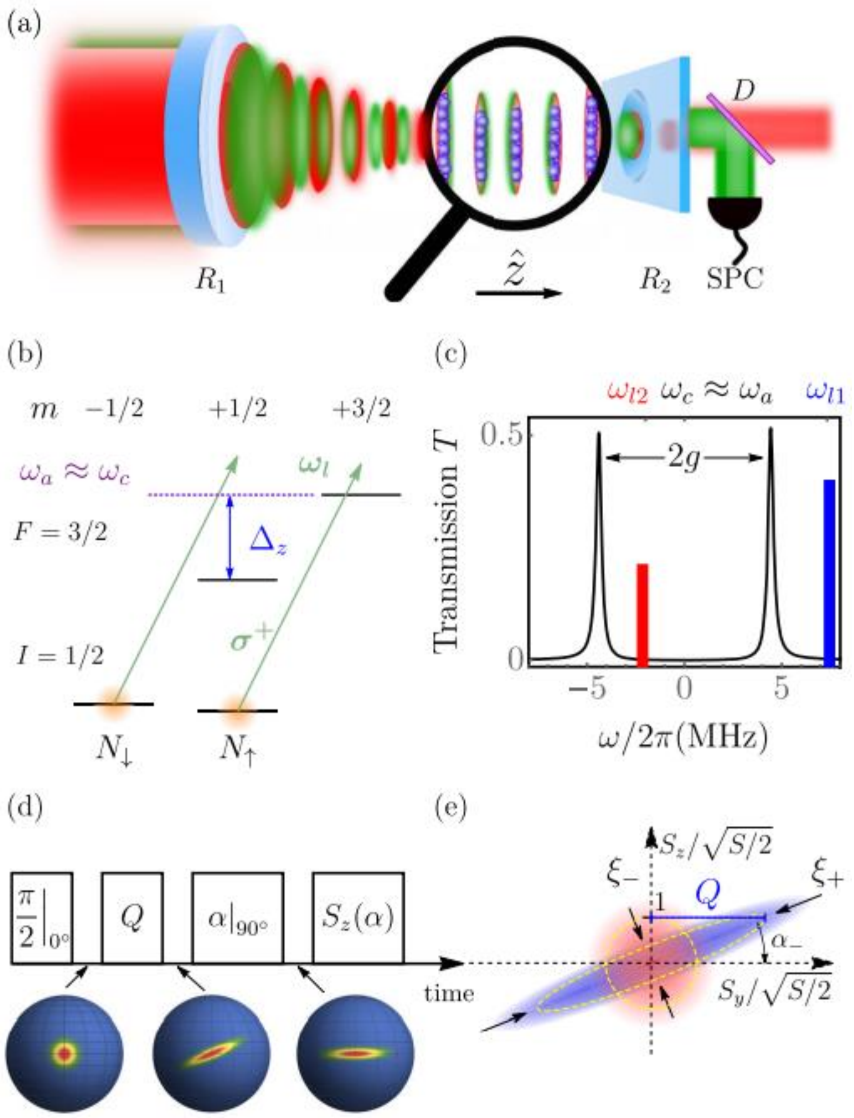


Figure from Braverman/Vuletic paper (MIT): https://link.aps.org/doi/10.1103/PhysRevLett.122.223203

Recently (2020) they mapped this squeezing to the optical clock transition: https://www.nature.com/articles/s41586-020-3006-1