Science and Technology Facilities Council

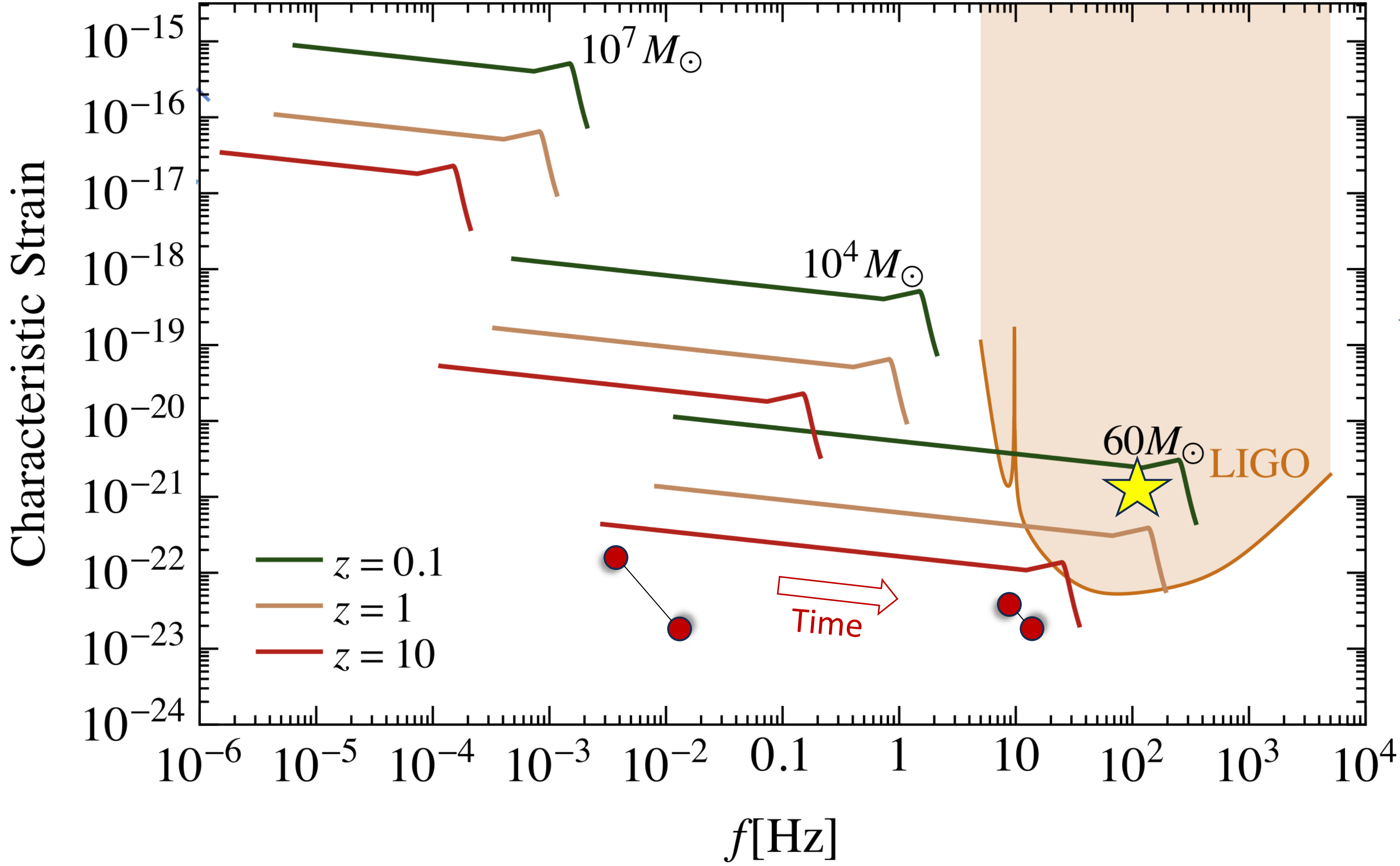
Imperial College London

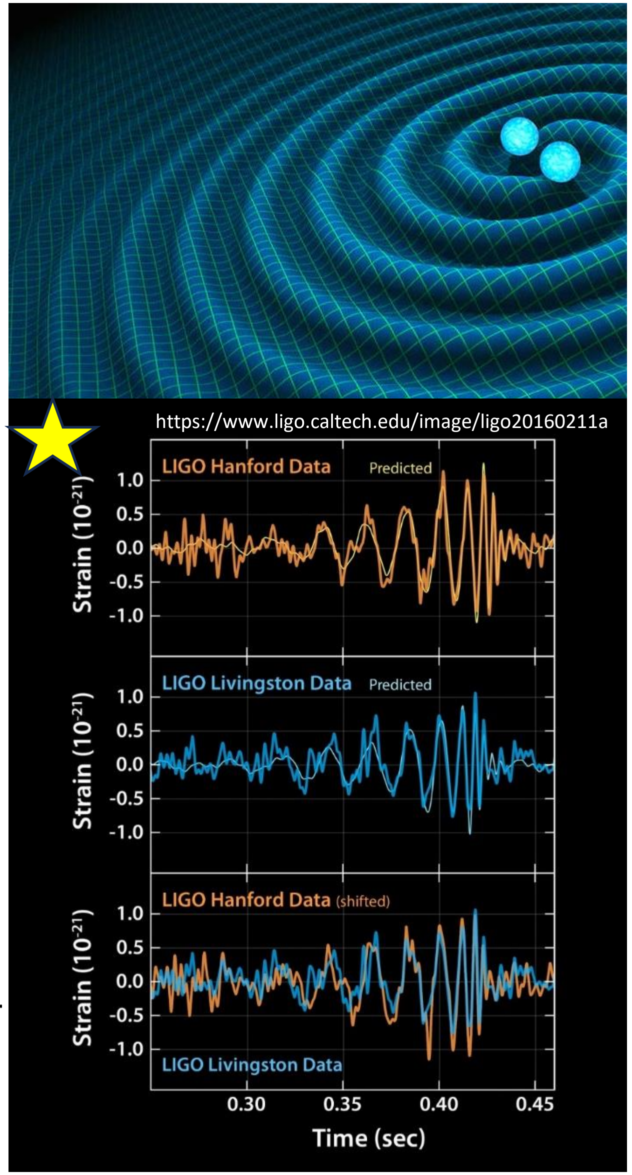
AION

Prospects for squeezed clock interferometry

Richard Hobson, Imperial College London, AION collaboration

Motivation: Gravitational waves





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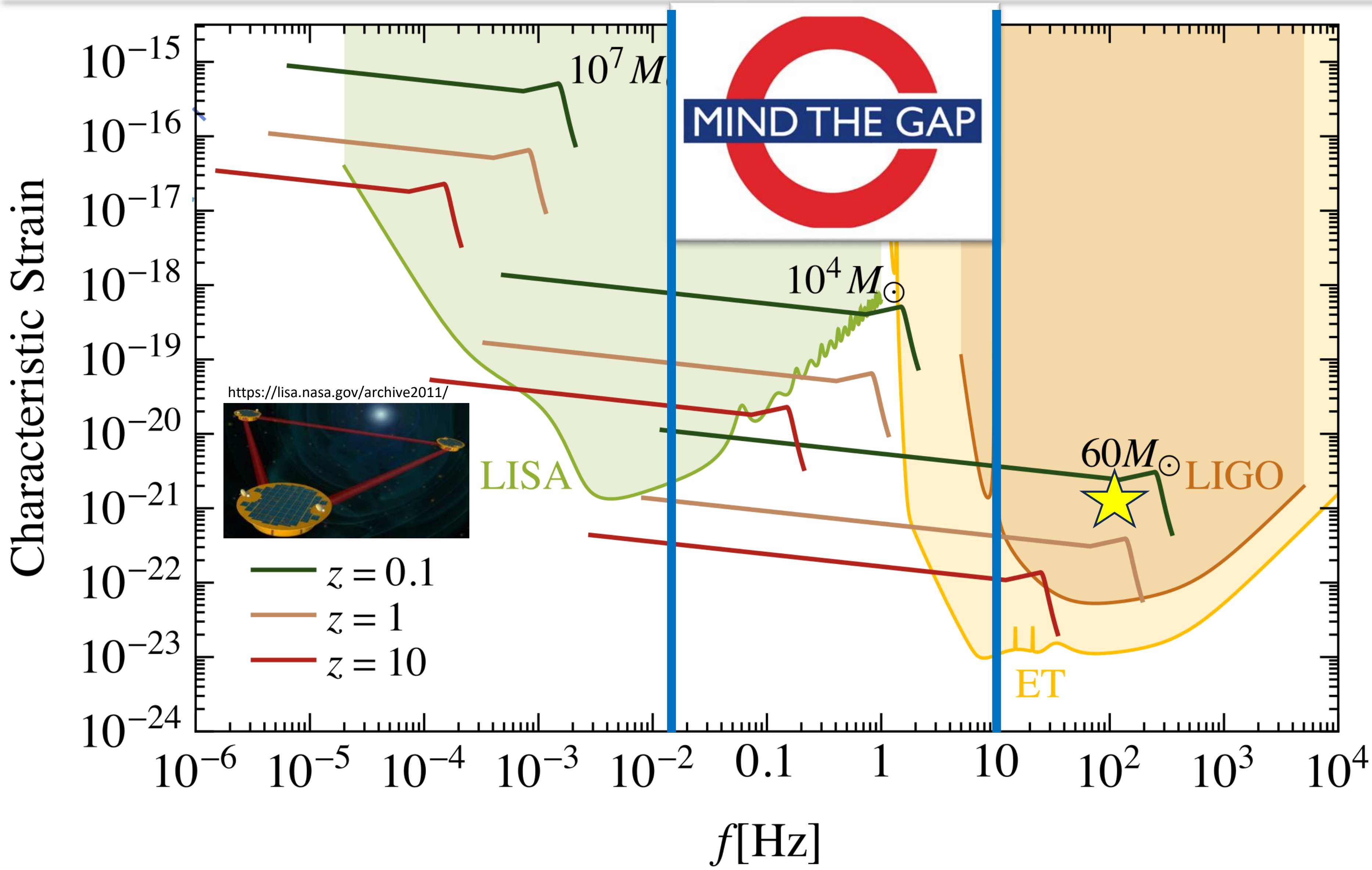

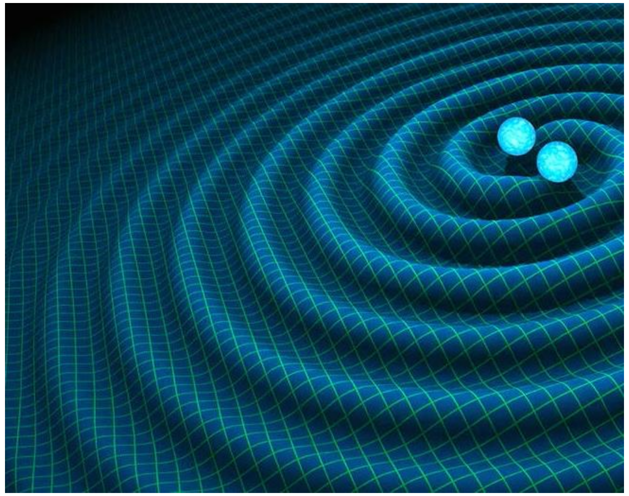

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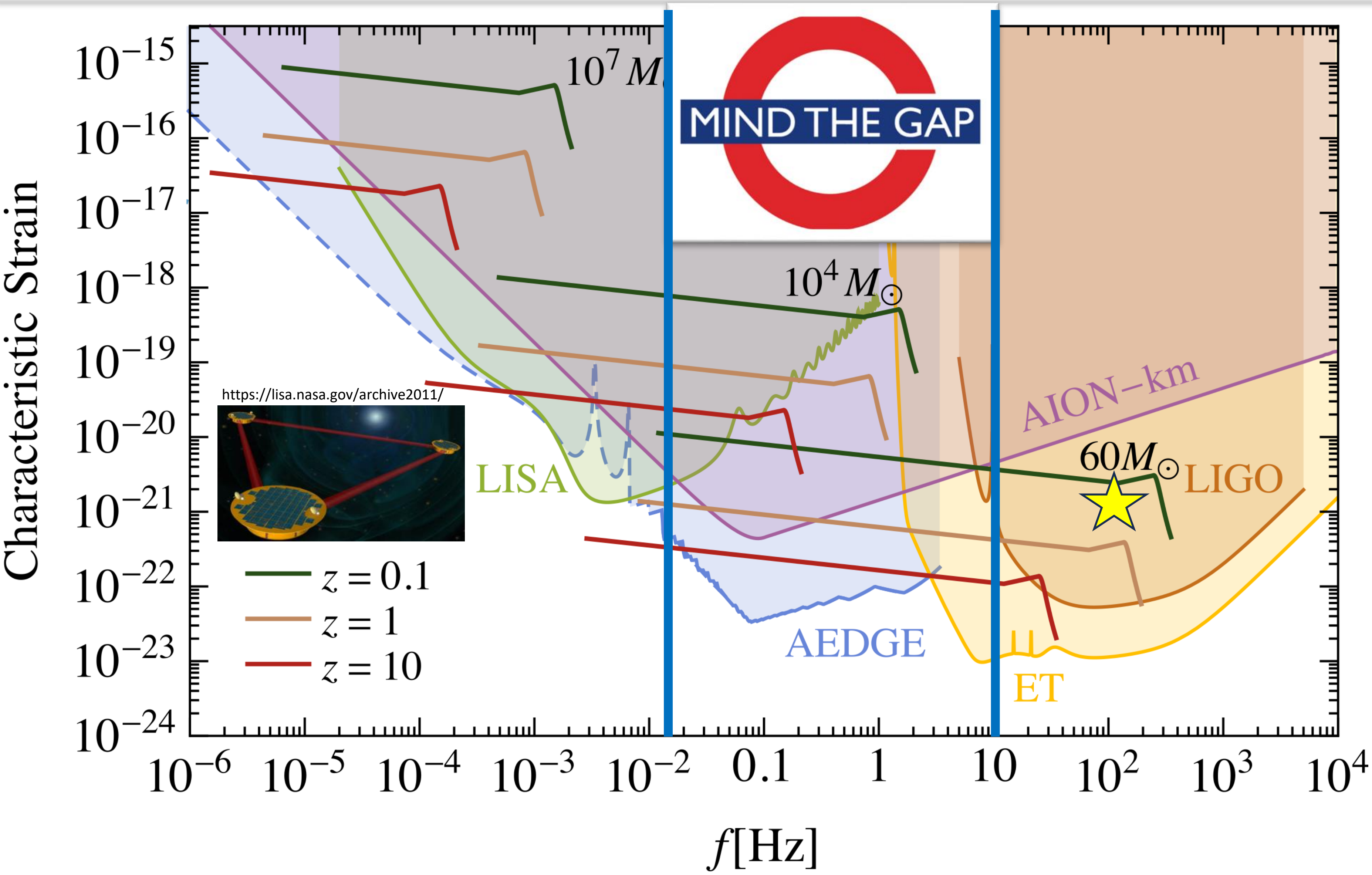

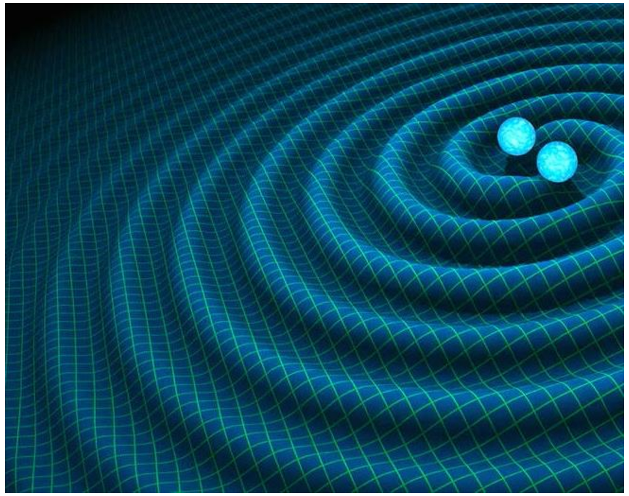

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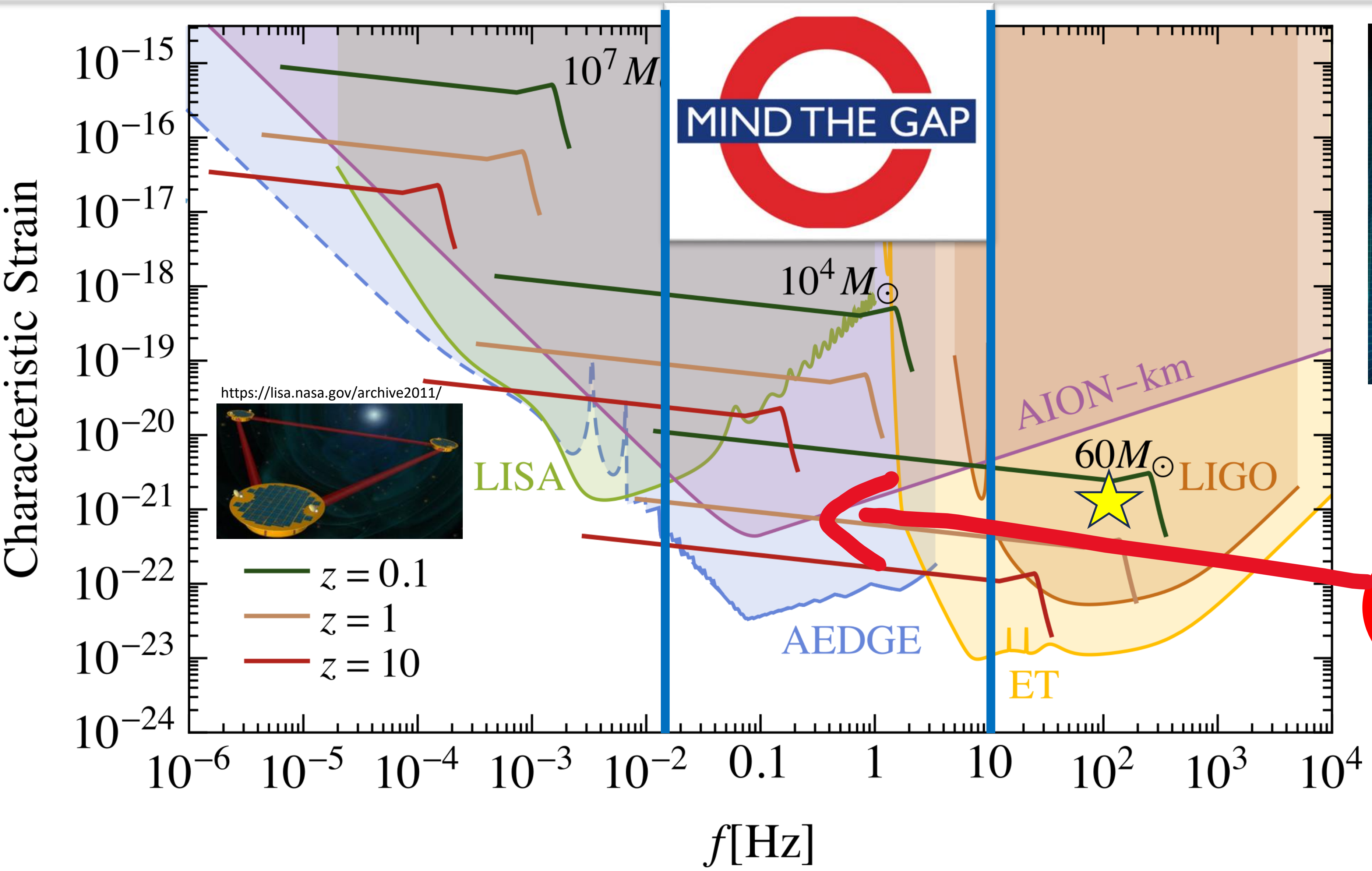
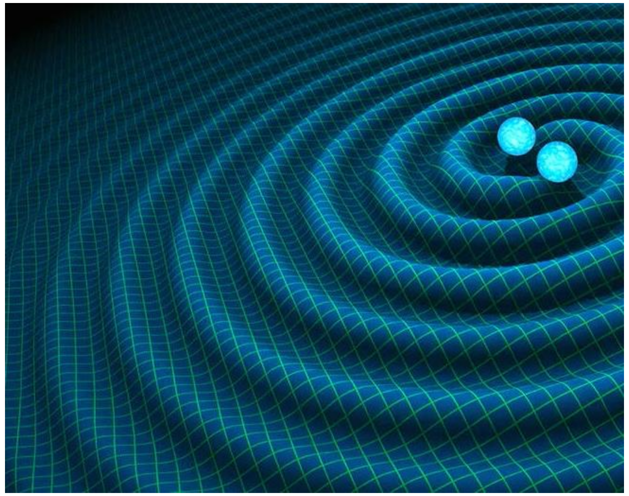




$\delta\phi \sim 10^{-5}/\sqrt{\text{Hz}}$

Roadmap to low phase noise

$\delta\phi \sim 10^{-2}/\sqrt{\mathrm{Hz}}$ → ? → $\delta\phi \sim 10^{-5}/\sqrt{\mathrm{Hz}}$

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

Quantum squeezing

$(\xi < 1)$

More atoms…

But can we reach $10^{10}/\mathrm{s}$?

Why squeezed states?

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

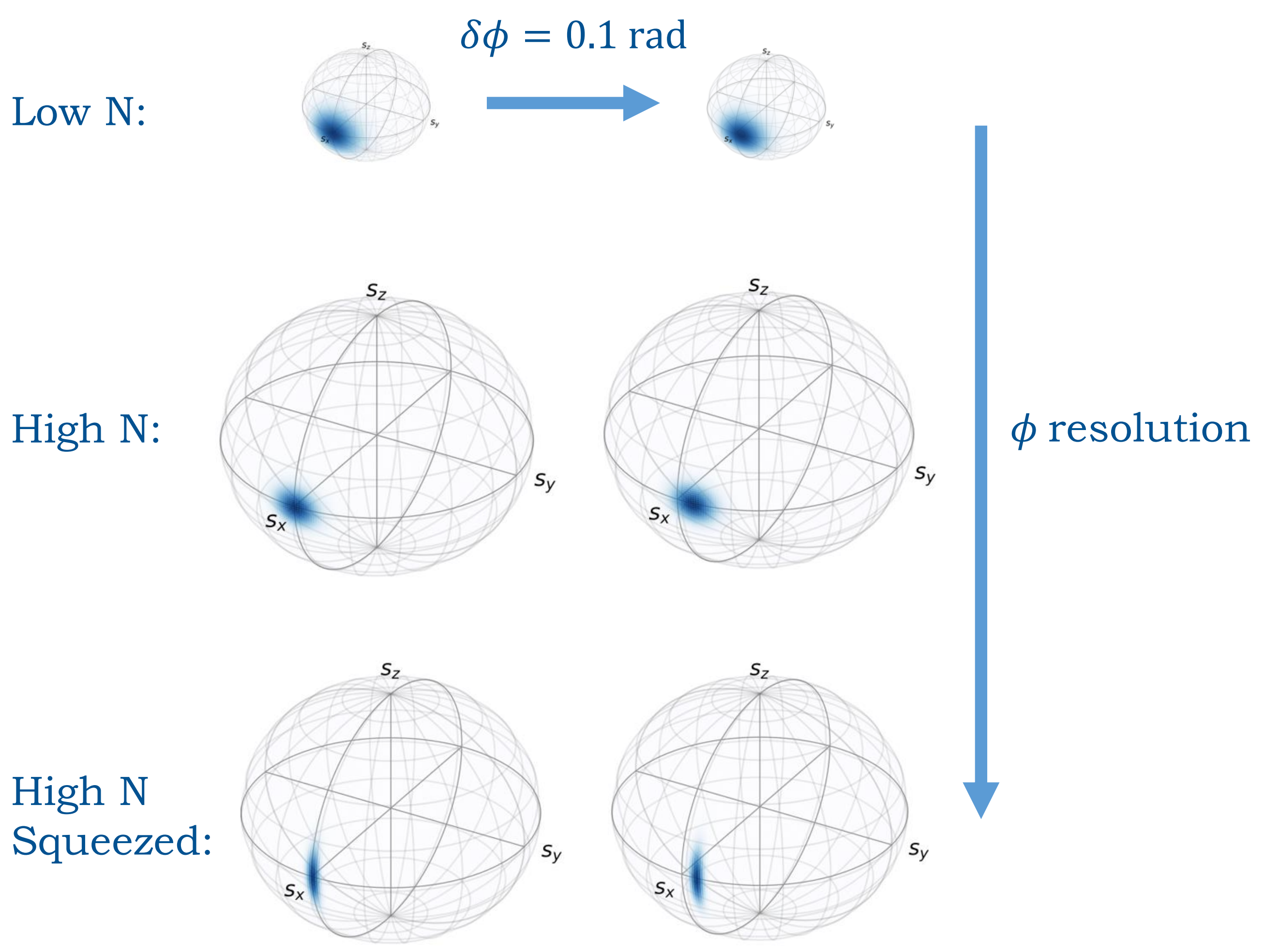
Atom shot noise limit:

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

Quantum squeezing

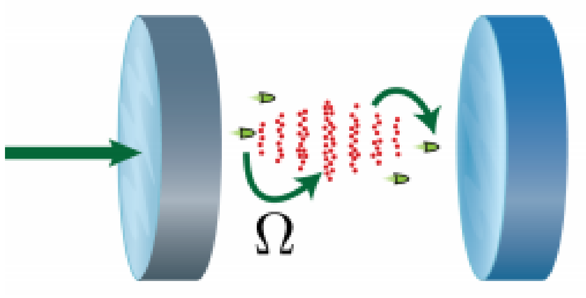
$(\xi < 1)$

More atoms

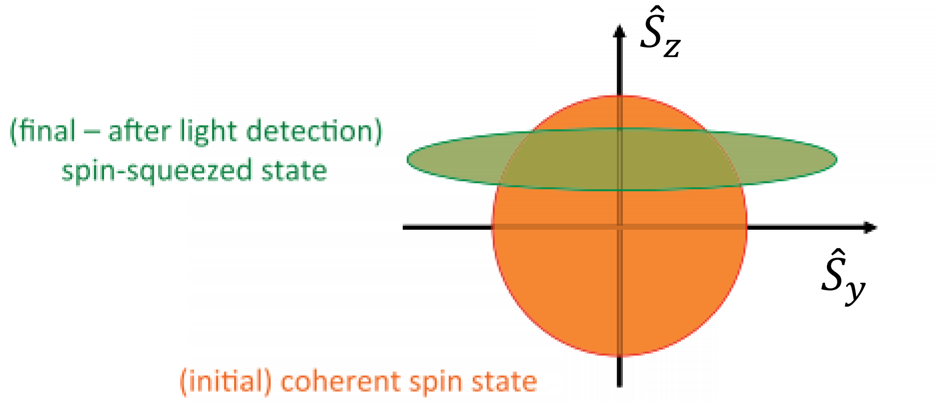


Cavity squeezing – Intro

Method: Place atoms inside a cavity

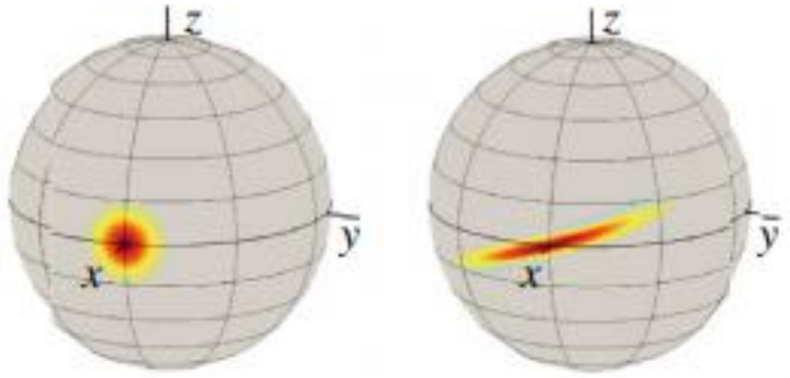


1. Quantum nondemolition (QND) measurement of $\hat{S}_z$



2. Nonlinear “twisting” Hamiltonian

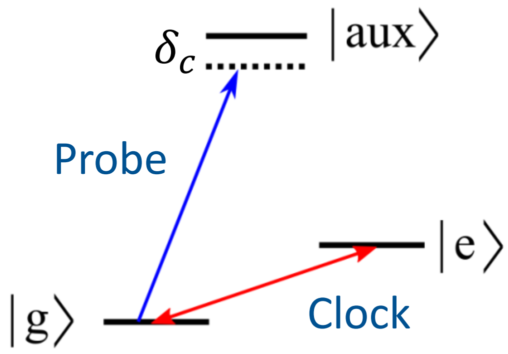
$\mathrm{H} \propto \hat{S}_z^2$



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

Cavity squeezing – Intro

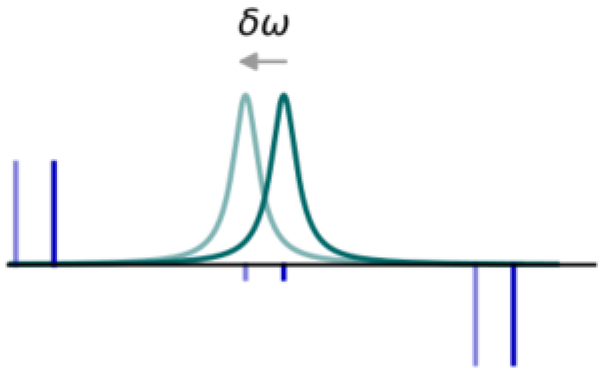
In the off-resonant, $|g\rangle$-coupled scheme (right), we see a cavity mode shift



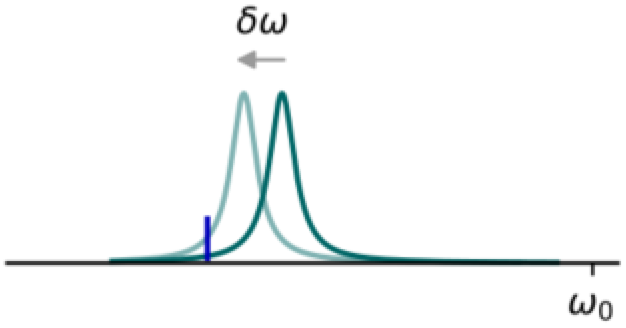
$$\delta\omega \propto N_g$$

→ Squeezing methods:

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



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



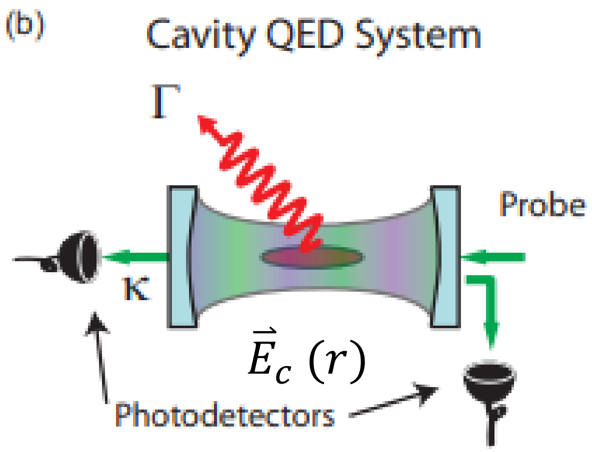
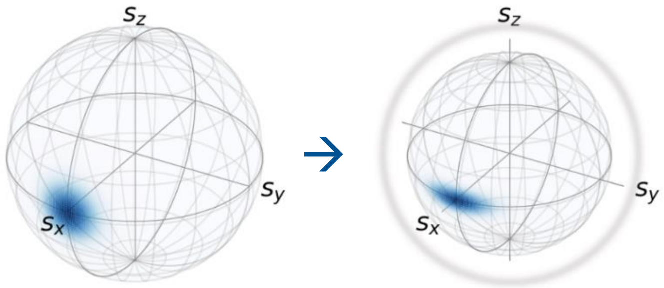
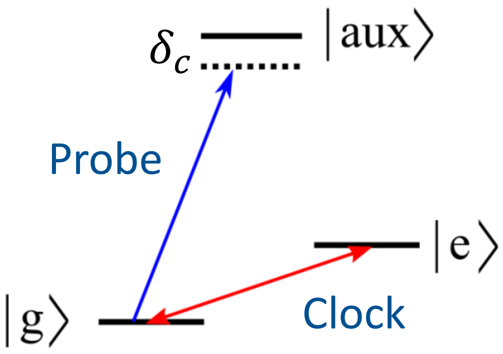


Figure from Zilong Chen et al:
https://link.aps.org/doi/10.1103/PhysRevA.89.043837

Cavity squeezing – limits

As you squeeze, some atoms scatter photons → effectively smaller atom number N





Squeezing per scattered photon is limited by the "collective cooperativity":

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

→ 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)]

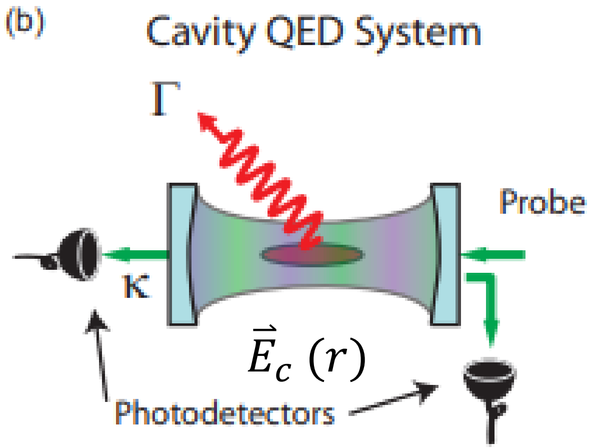


Figure from Chen paper: https://link.aps.org/doi/10.1103/PhysRevA.89.043837

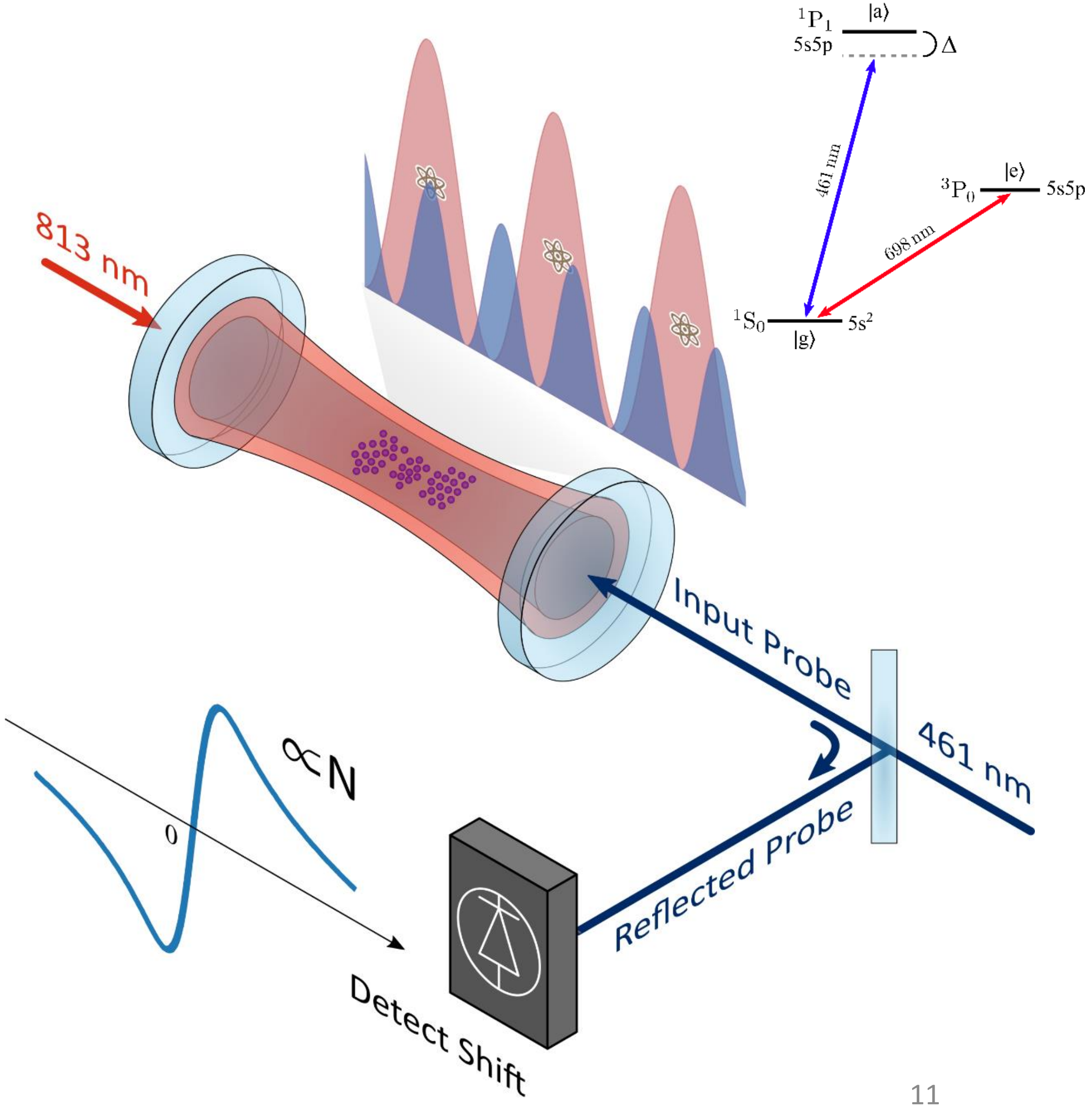
Cavity squeezing – NPL Sr clock

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



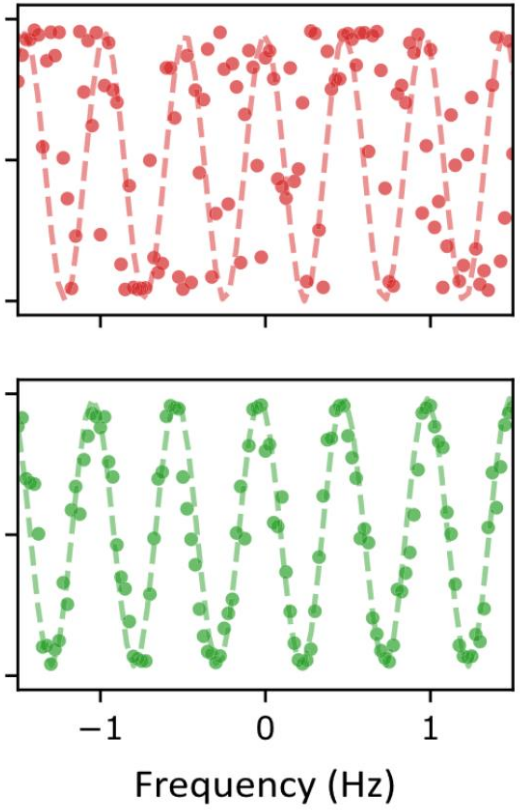
Cavity squeezing – NPL Sr clock

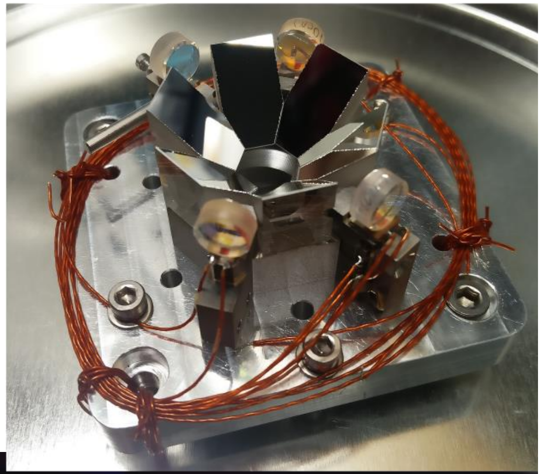
We achieved quantum non-demolition measurement, and could improve the clock

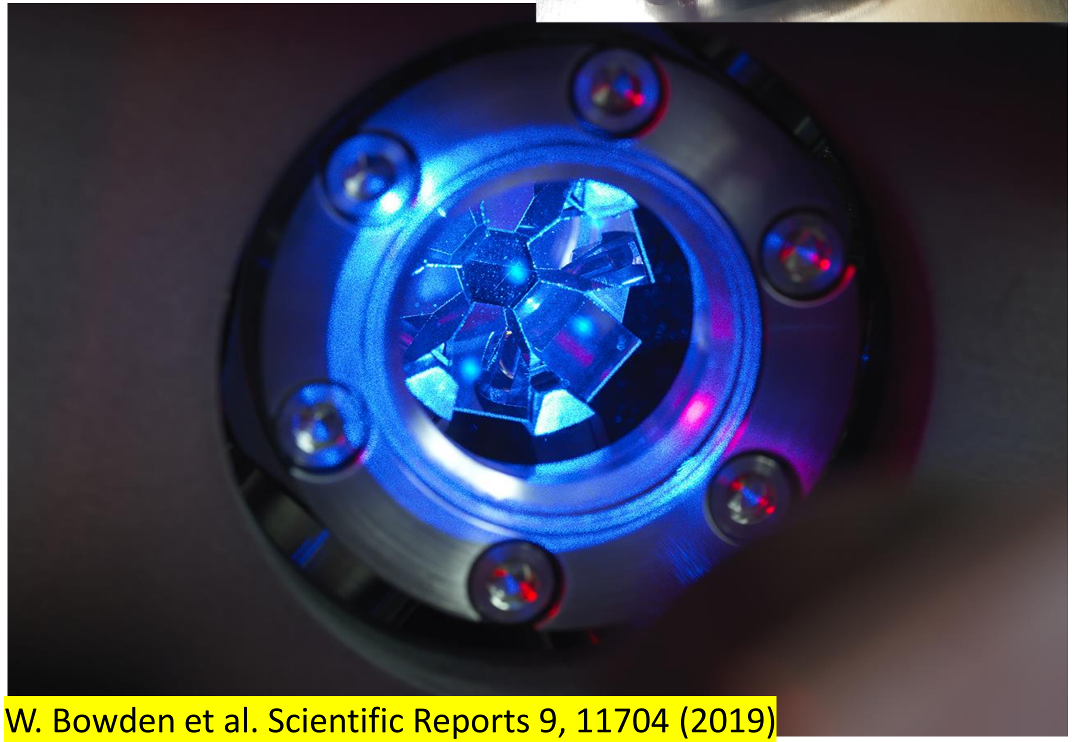
E.g. 2-second Ramsey clock (in clock 2) using an atom phase lock (to clock 1)

No atom phase lock:

With atom phase lock:





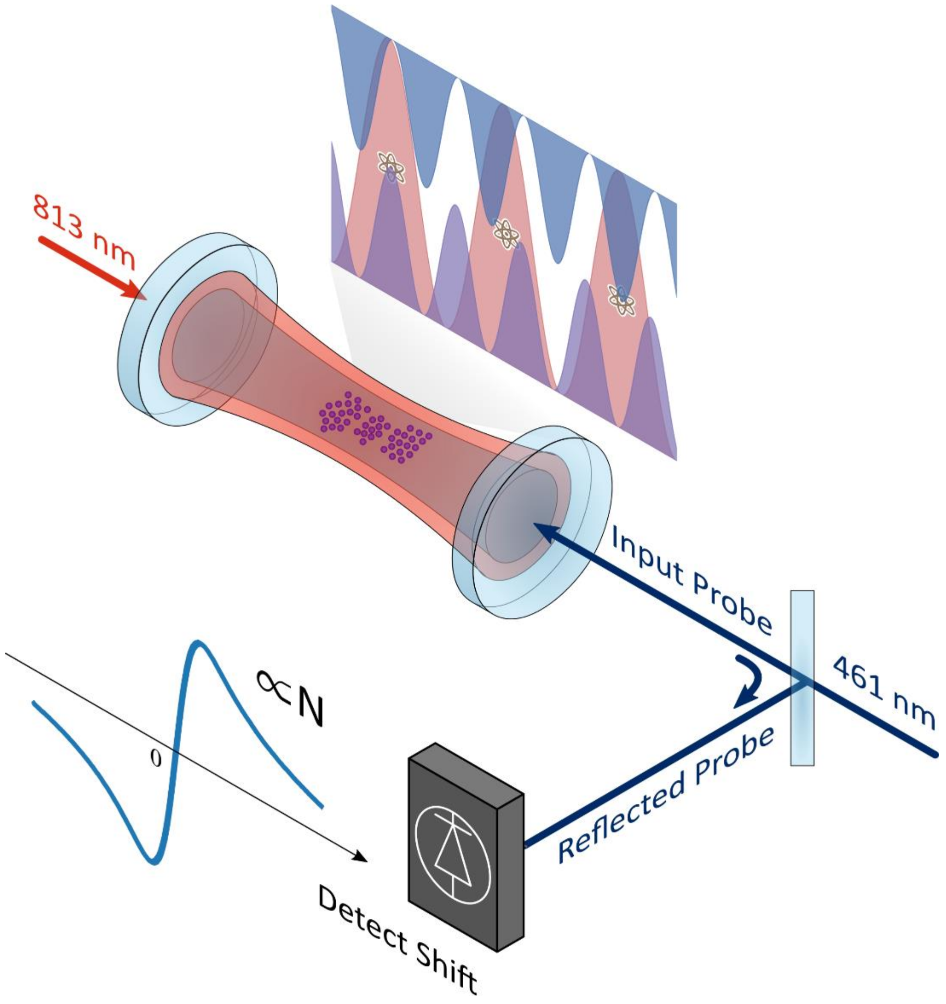


R Hobson et al. Optics Express 27, 26, 37099-37110 (2019)
W. Bowden et al. PRX 10, 4, 041052 (2020)

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

Cavity squeezing – NPL Sr clock

But… No squeezing



Many technical problems

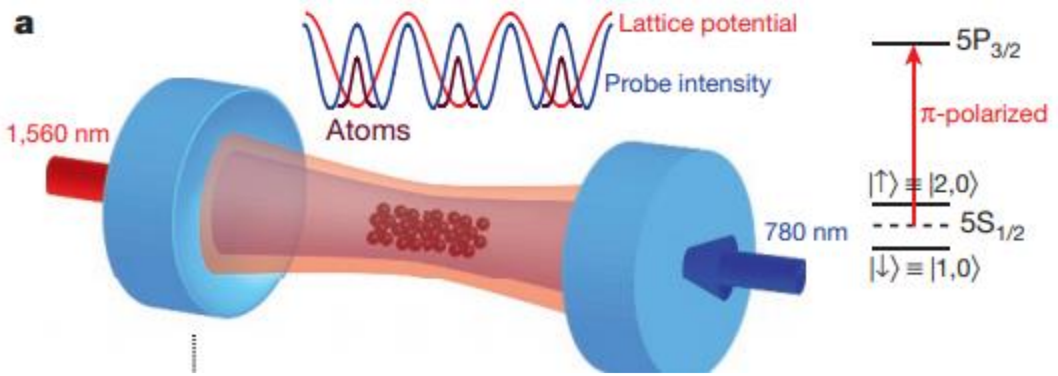
- Cavity length noise ~ 100 kHz pk-pk → complex locking scheme needed, residual technical detection noise at acoustic frequencies
- Inhomogenous atom-cavity coupling (+ve and –ve modes)
  - → Not all atoms participate equally, and large range of Stark shifts
- Large detuning → large Stark shift per scattered 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

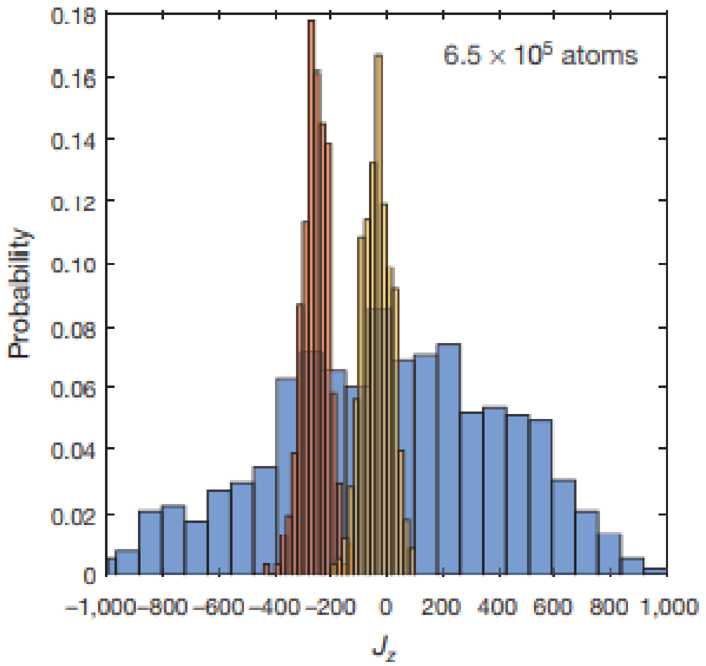
Cavity squeezing – Imperial AION plan

Neat trick from Onur Hosten/Mark Kasevich group:

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

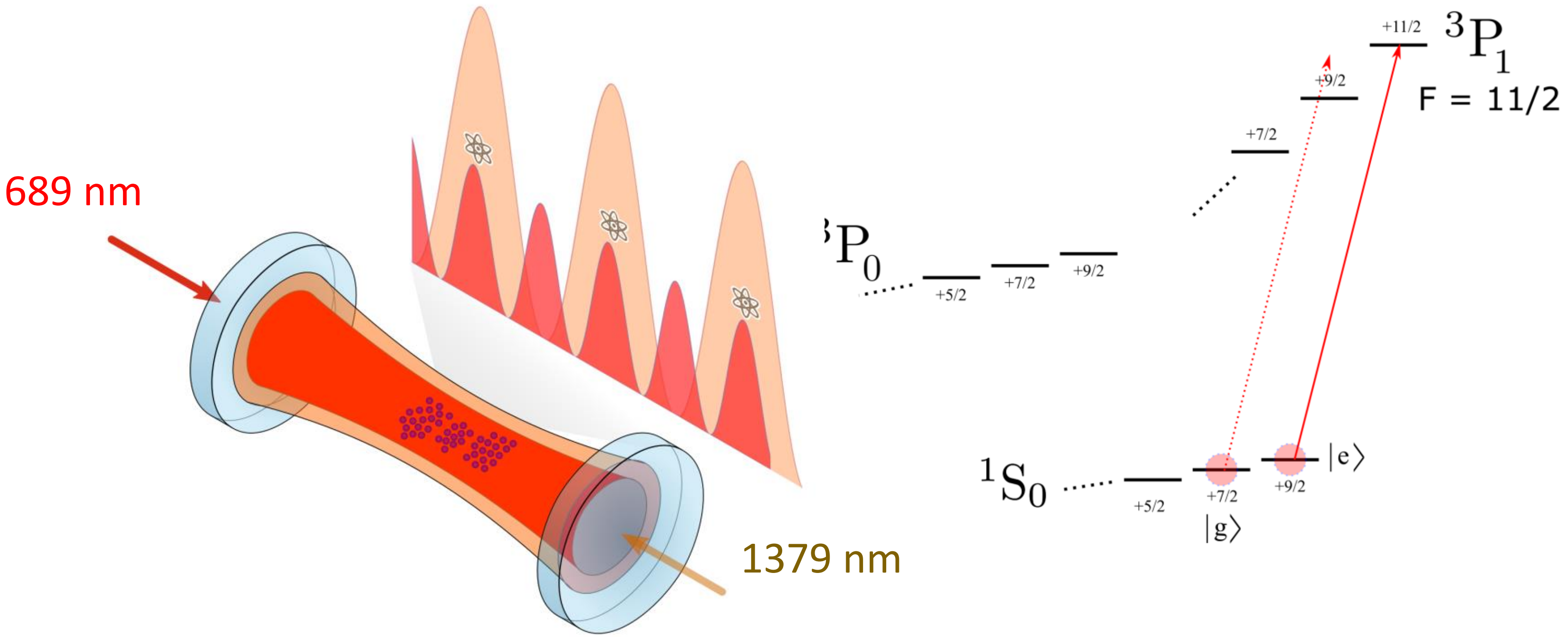
→ World record squeezing factor: **100**





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

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



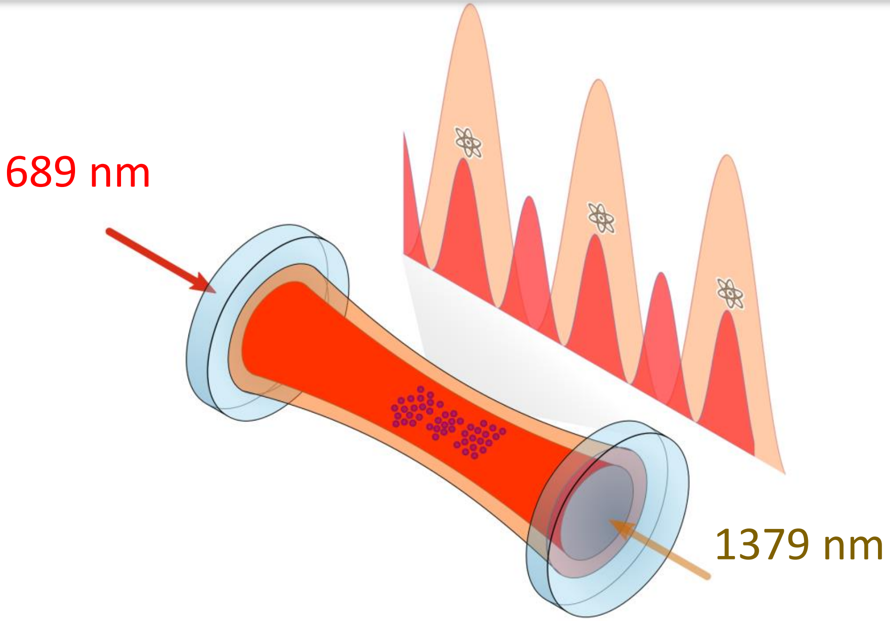
Cavity squeezing – Imperial AION plan

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

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

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

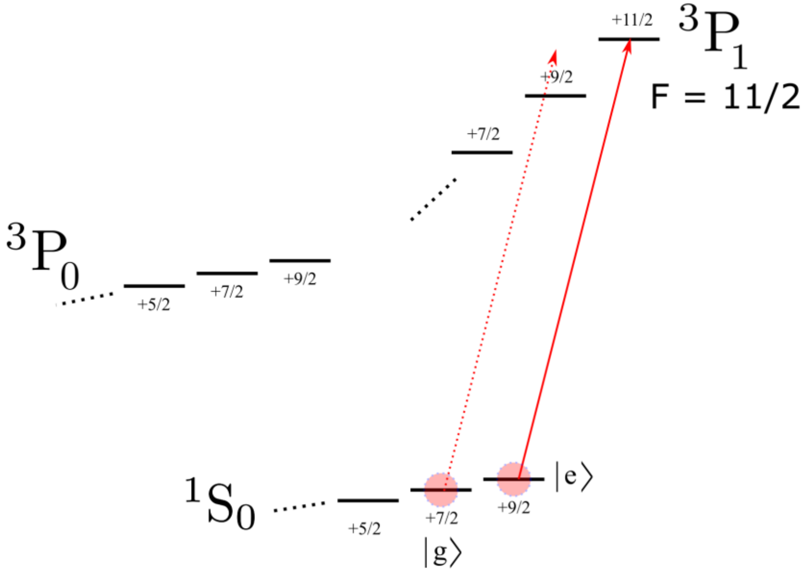
→ Squeezing beyond 20 dB seems possible!



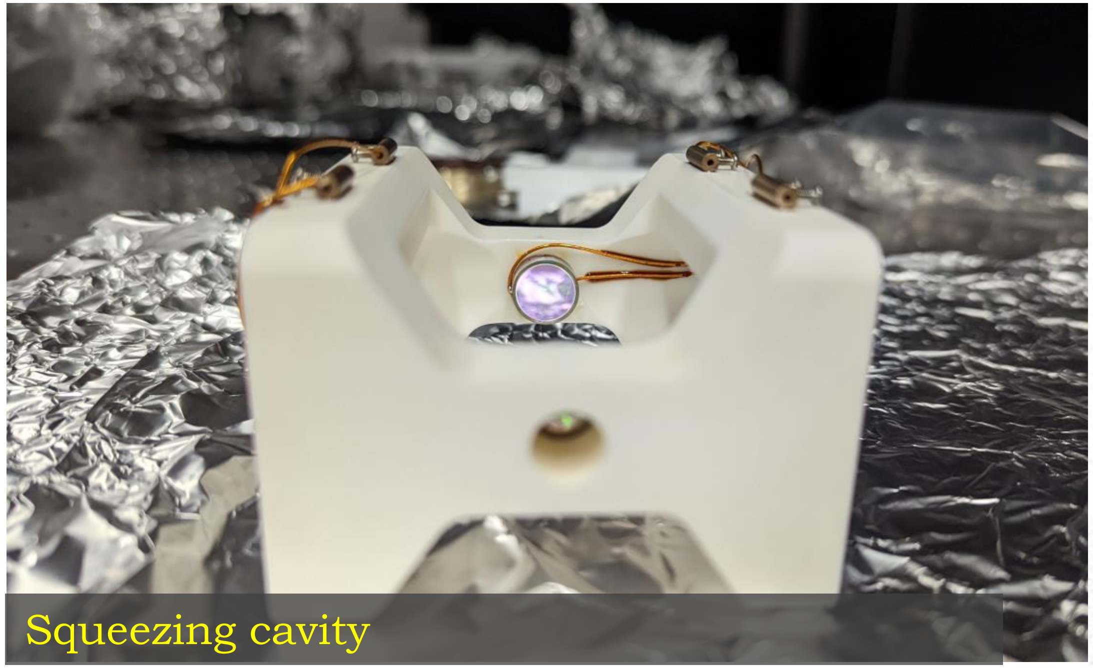
An open question: how close can we get to fundamental limits?

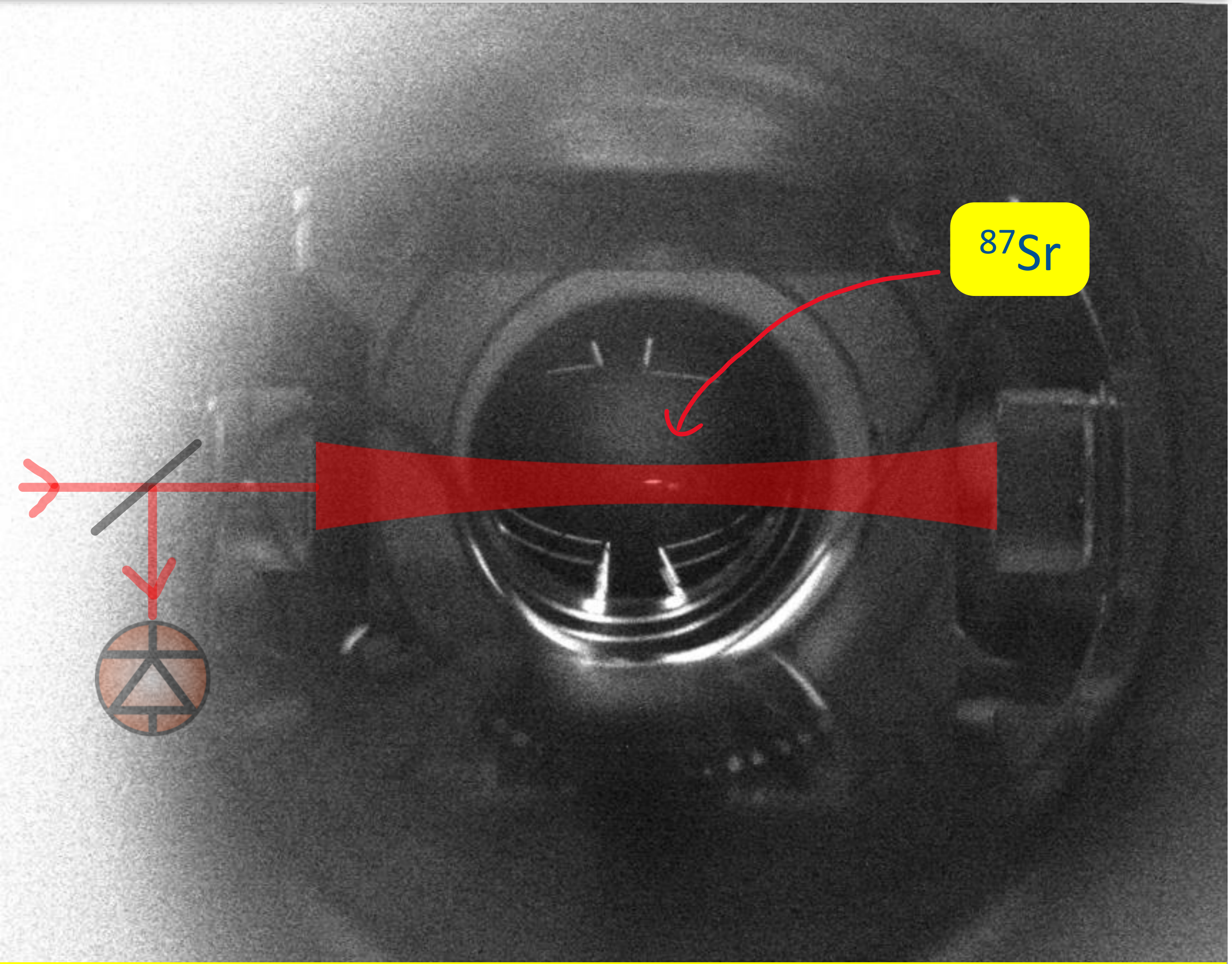
It’s a game of controlling the (many) technical noise sources…

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 – ^{87}Sr clock interferometer





For more, see "*Differential, single-photon interferometry with the ^{87}Sr clock transition for AION*" - Charles Baynham

The ultracold Sr group

Leonie, Ludo, Charles, Richard, David, Elizabeth, Alice, Tom, Dillen, and Oliver