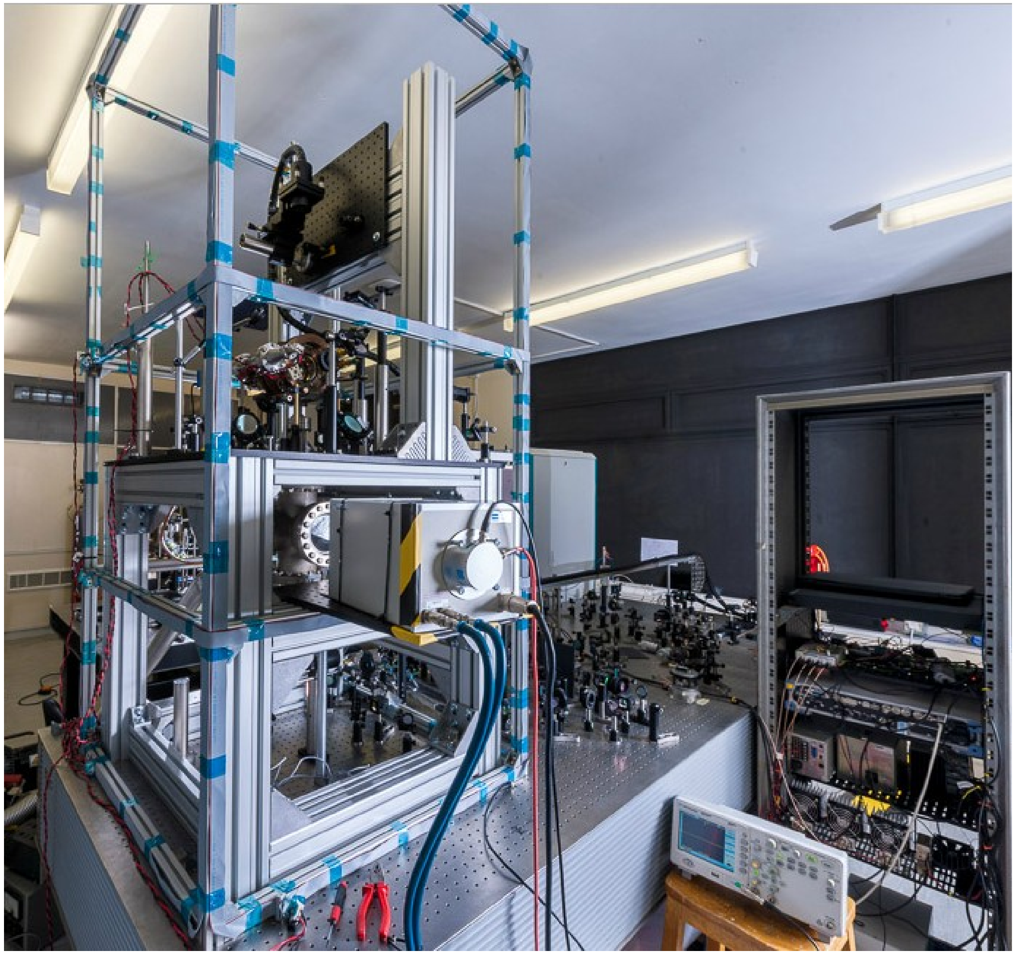
A Prototype Atomic Interferometer for Fundamental Physics

David Morris
Liverpool Particle Physics
Atom Interferometry Experiment

On behalf of the collaboration

University of Sussex IOP

March 2016



Science & Technology Facilities Council

UNIVERSITY OF LIVERPOOL

The Cockcroft Institute of Accelerator Science and Technology

Outline

- Atom interferometry concepts
- Motivation for building this detector

  - Developing the next generation of gravity sensors and gyroscopes for use in fundamental physics searches

  - Can dark energy be detection on the laboratory scale? [1]

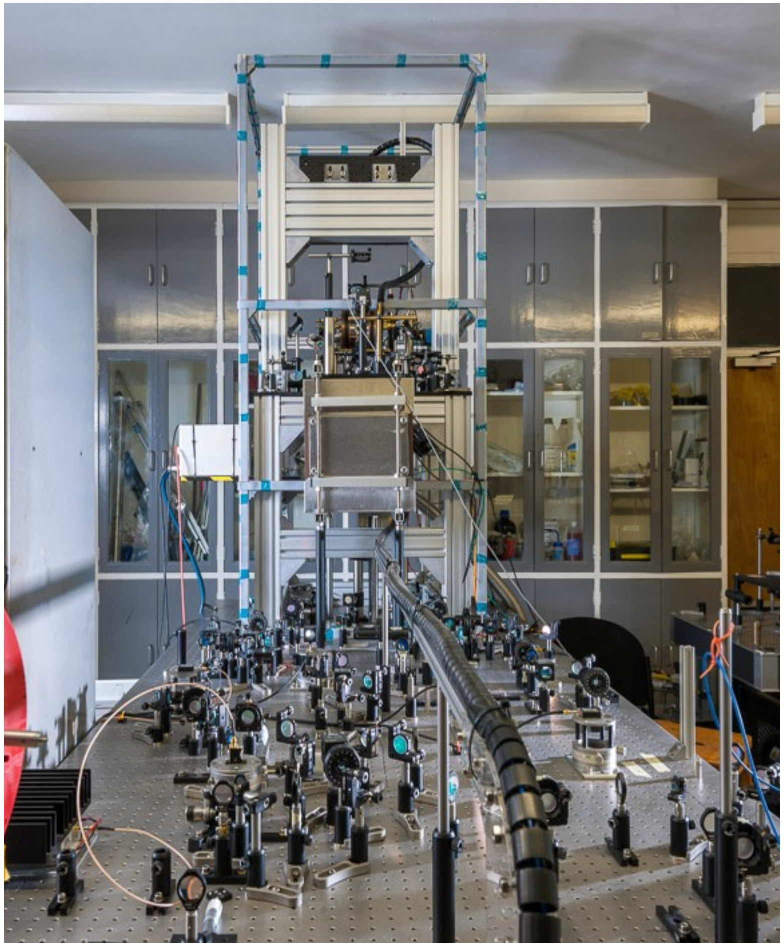
- Status of the prototype

  - First step is to build a prototype atomic interferometer and use this to measure local gravity

  - Experiment upgrades

- Future development

  - Experiment goals



Experimental set-up of an Atomic interferometer

[Reference 1]

A terrestrial search for dark contents of the vacuum, such as dark energy, using atom interferometry
Martin L. Perl arXiv:1101.5626

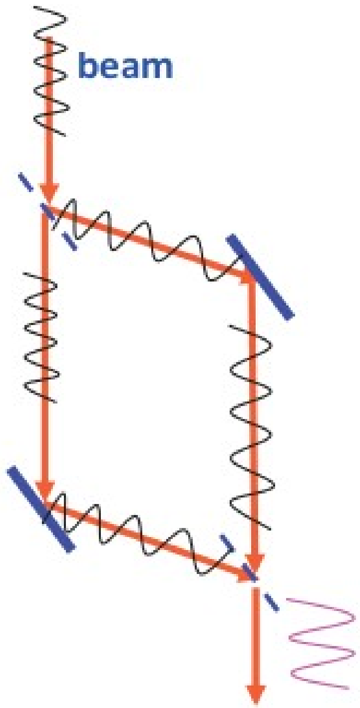
Atom Interferometry

• Atomic interferometry - powerful tool for extremely precise measurements of fields.

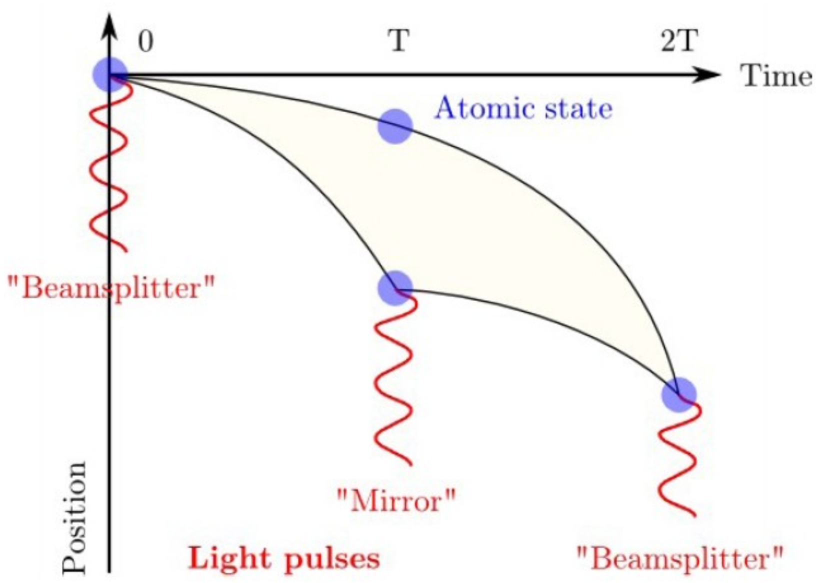
• Laser Cooled atoms to nK temperatures

• Wave-like nature of atoms used to form a superposition which results in interference analogous to a laser interferometer

Interferometry

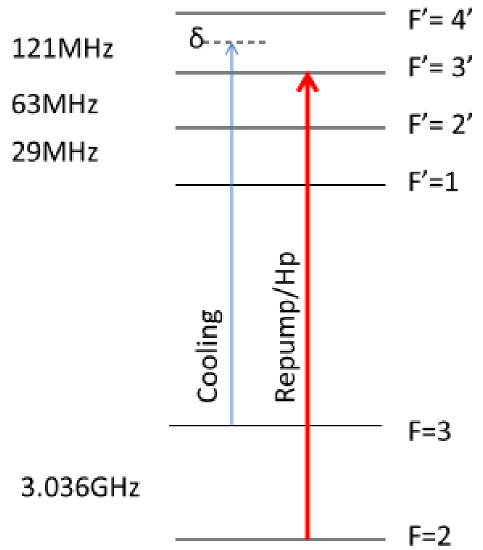


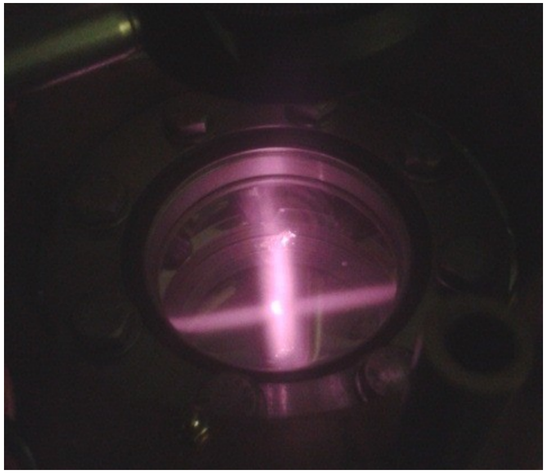
The classical trajectory of a falling atom that is "split" and "recombined" by light pulses.
[M. Perl *et al*, "Terrestrial search for DCV," 2011]

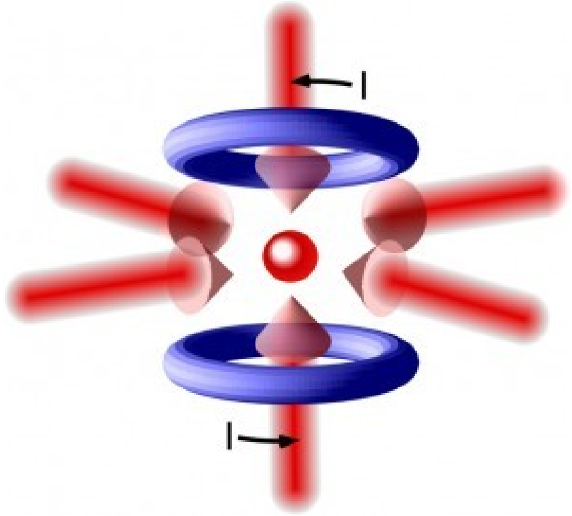


Magneto-Optical Trapping

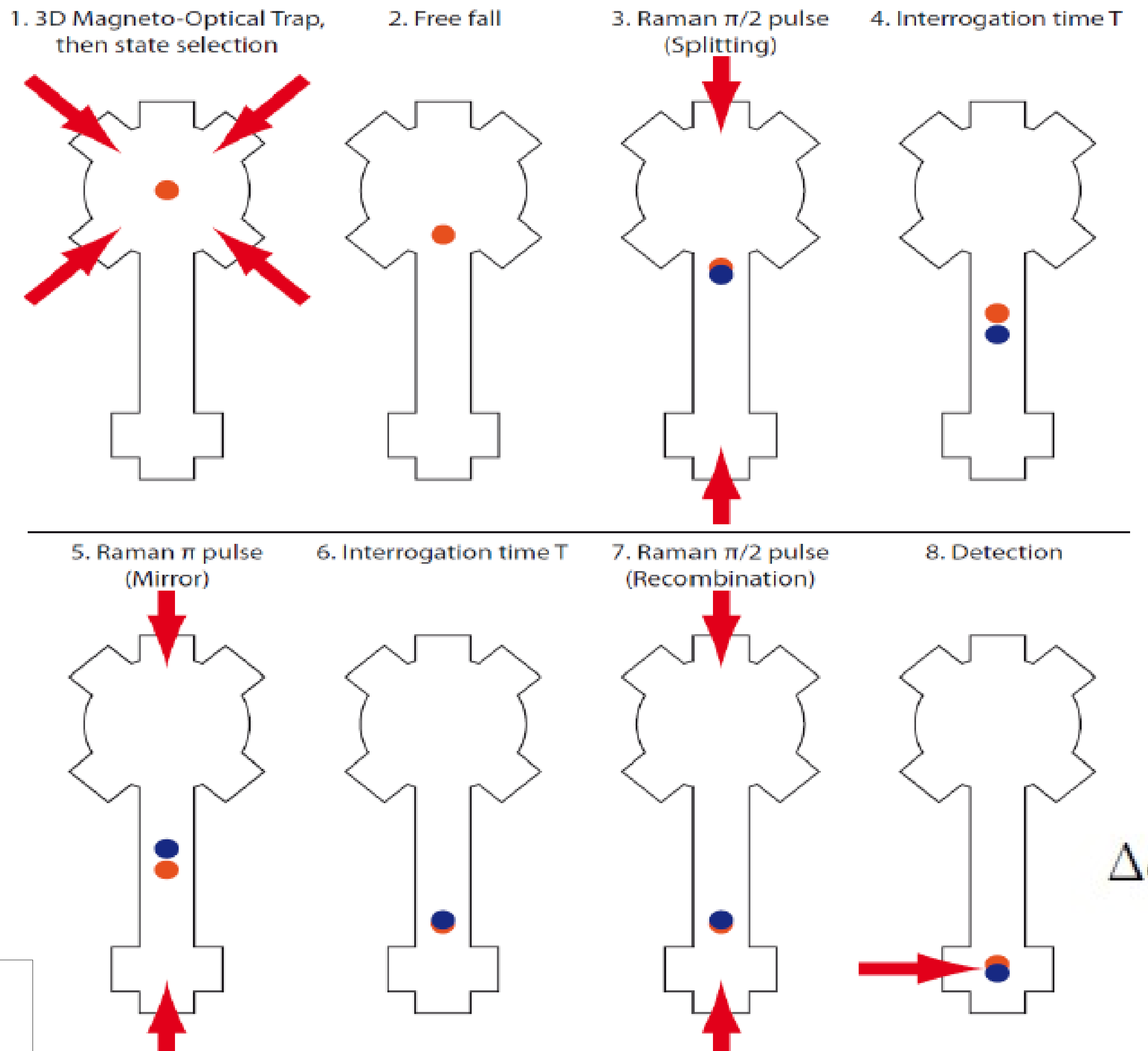
- Doppler cooling using 3 orthogonal pairs of counter propagating laser beams
- Magnetic field creates a position dependent trapping force
- Pumping laser keeps atoms in resonance with the cooling laser
- The atom trap is filled with ^{85}Rb from an atomic oven







Atom Interferometry



$$\Delta\phi = k_{eff} g T^2$$

Ph.D. Thesis 2011
M. Schmidt
Humboldt University

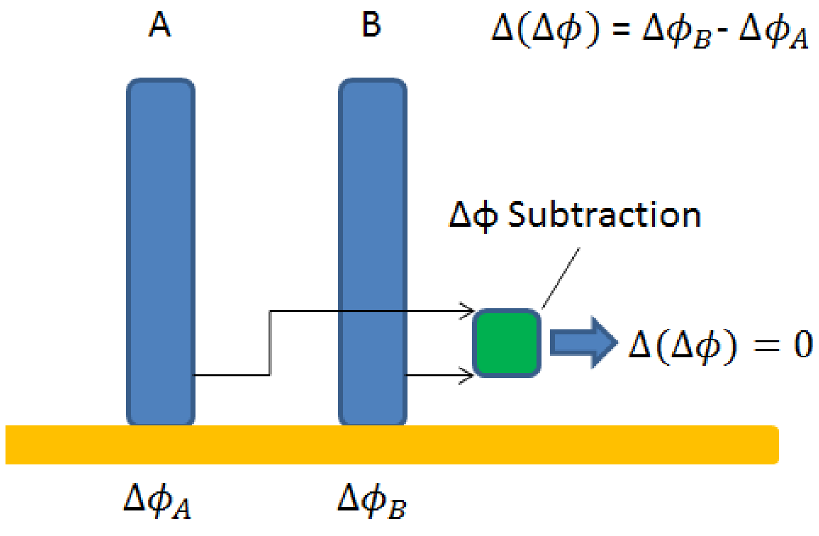
Experiment Aims

- Investigate the contents of the vacuum on the laboratory scale
- Two interferometers are set up side by side
- Measure a variation between the phase differences of the interferometers due to an external potential.

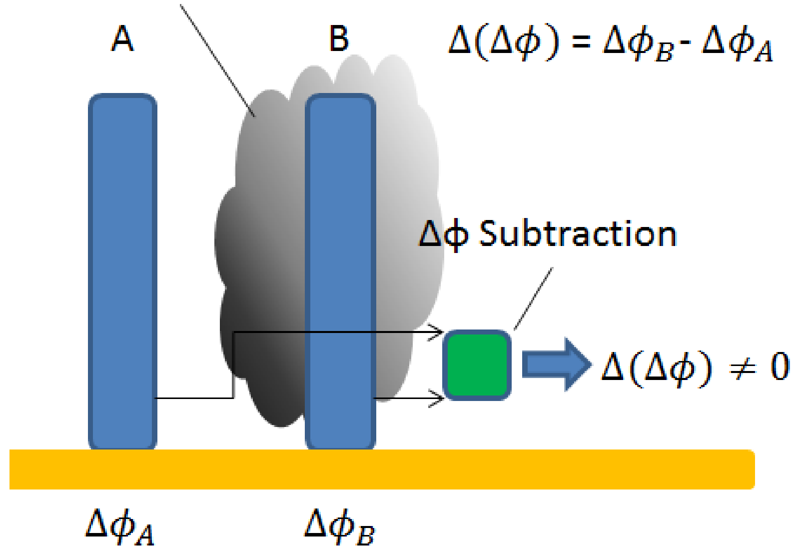
Assumptions for detection

- External potential has inhomogeneous spatial distribution.
- Exert a force on matter which is non-gravitational.

No vacuum fluctuations



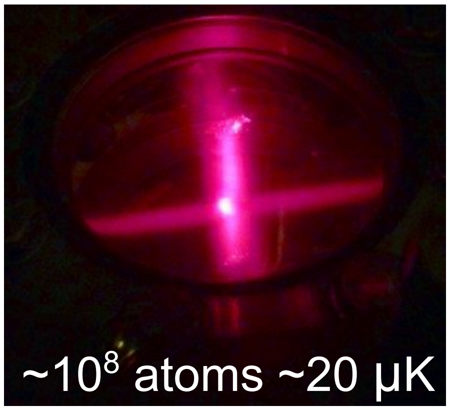
Phase difference from external potential



Prototype Interferometer

Preparation

• 10^8 ultracold atoms in free-fall under gravity



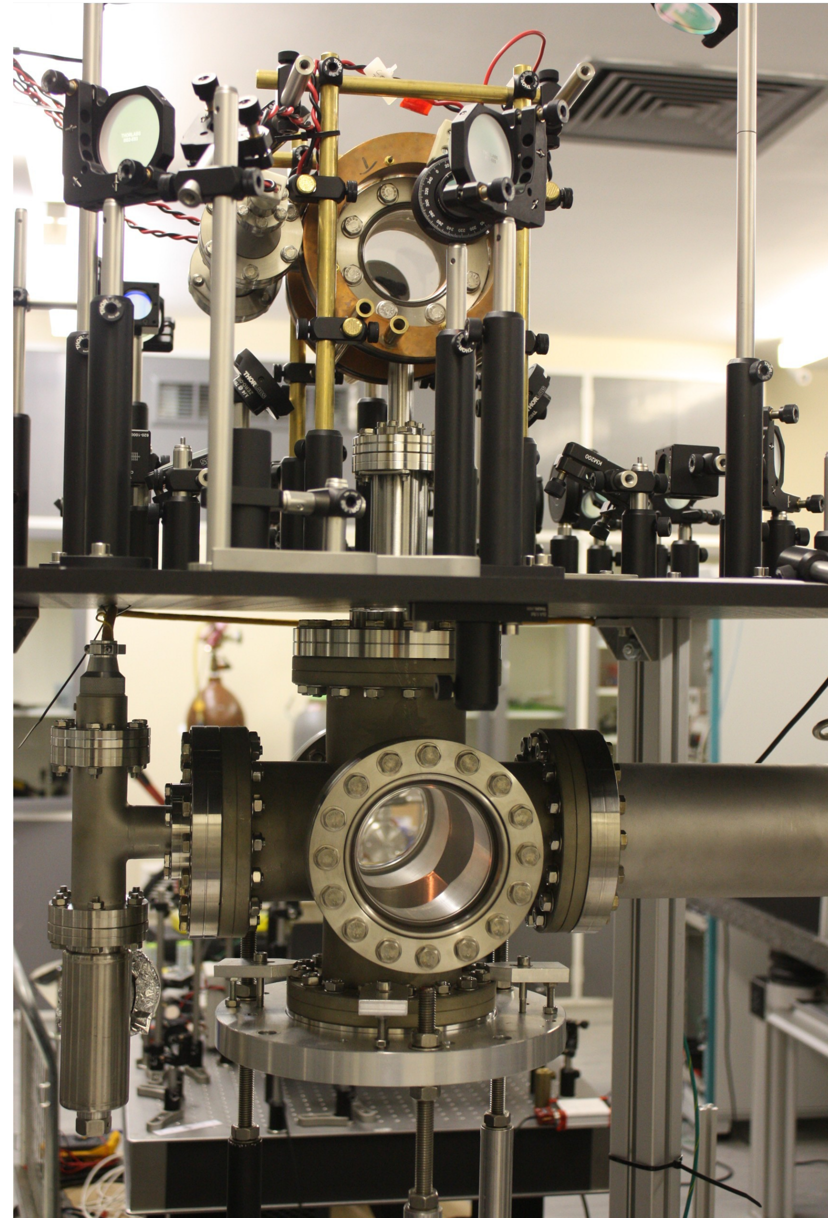
Interferometry Region

• Light-pulse interferometry sequence with Raman beams

Detection Region

• Interference fringes

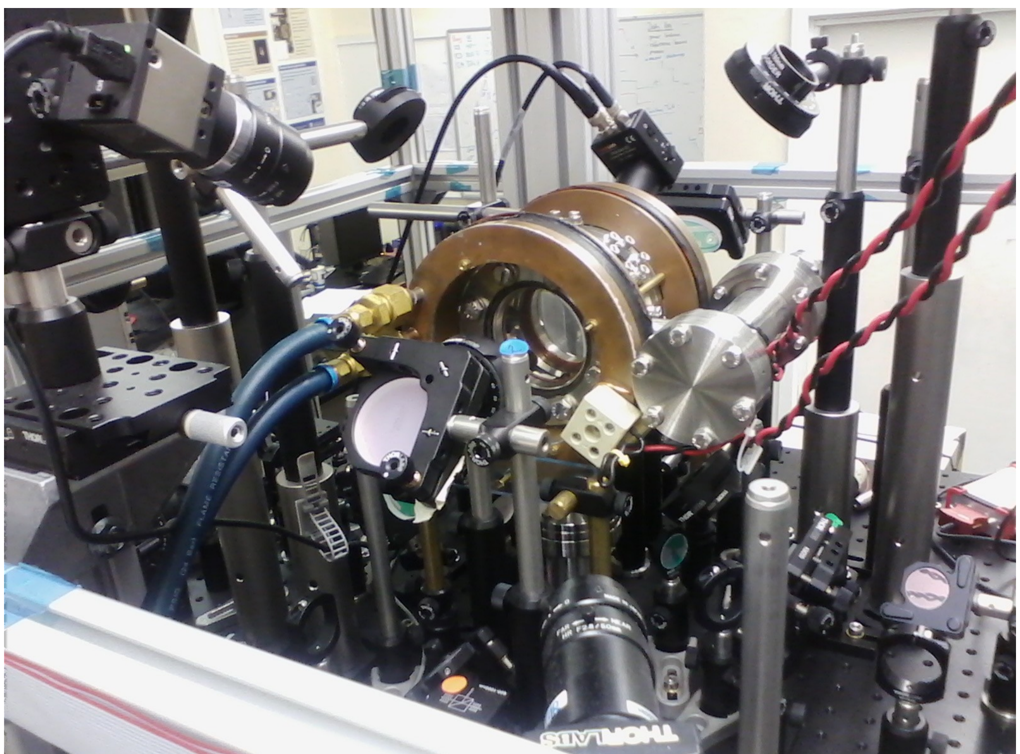
• Atom population ratio measurement are sensitive to phase difference

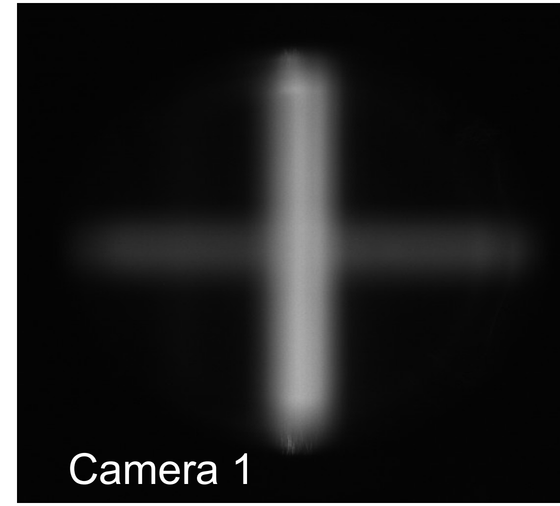


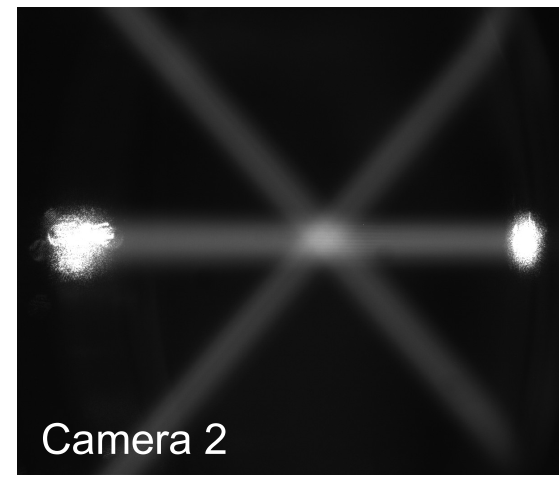
Beam Alignment

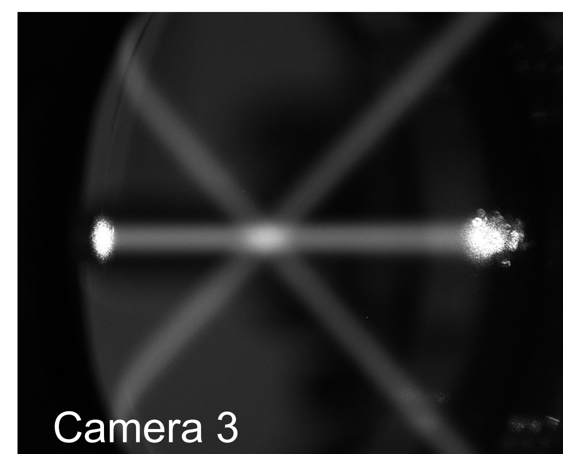
- 3 quasi-orthogonal cameras used to align the MOT cooling beams

- Enables beams crossing to be placed within a pixel and set beams to be orthogonal.





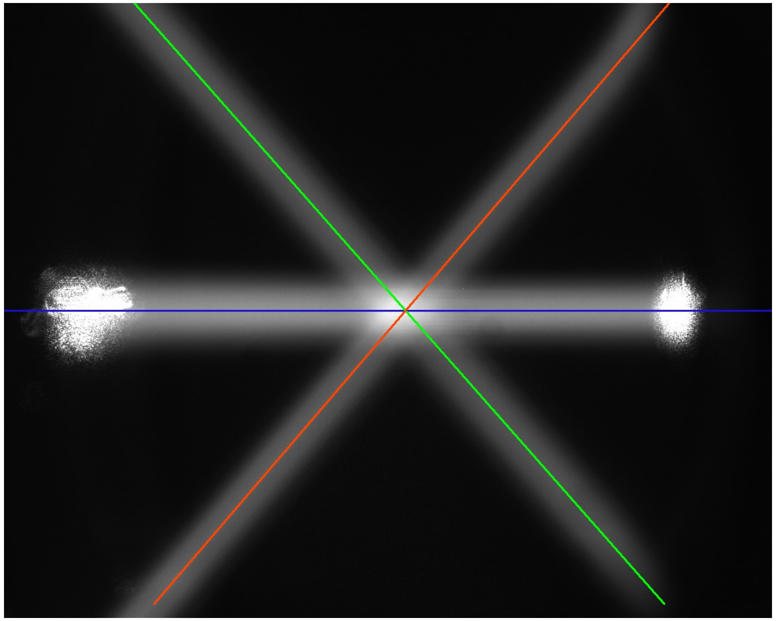


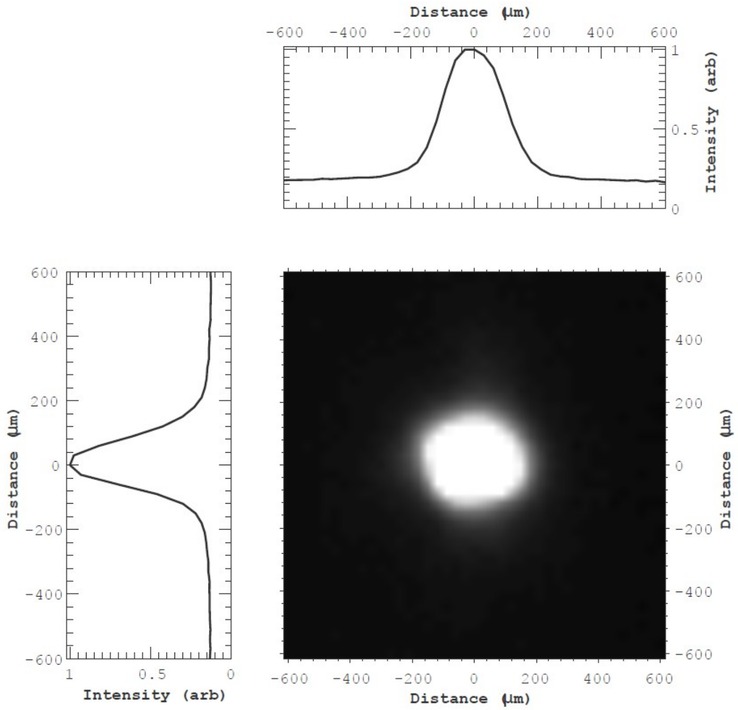


Beam Alignment

• MOT cooling beams are set to all cross within 1 pixel on each camera and have a gradient of less then 1 pixel over 1000 pixels

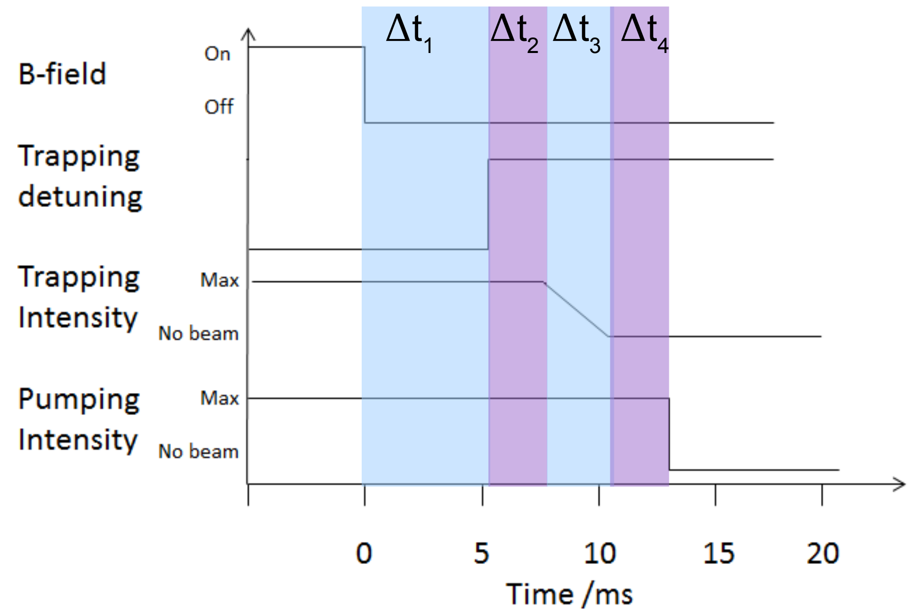
• After precision alignment a uniform MOT can be produced. With equal forces being applied by each of the 6 beams





Molasses Sequence

- Doppler limit is ~ 200 µk
- Additional cooling by using polarisation gradient cooling ~2 µK
- FGPA timing sequences varies magnetic field, laser power and detuning



- Parameters to vary

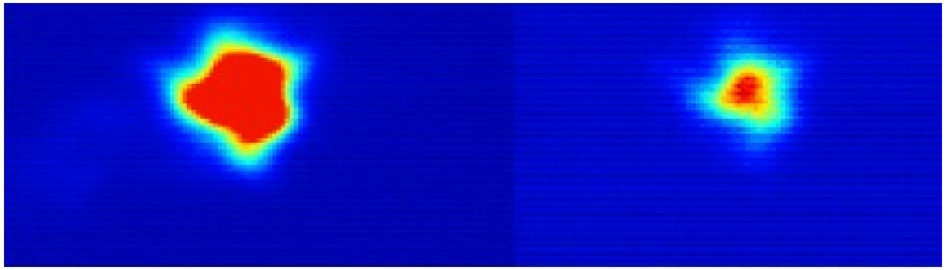
Δt_1 – eddies currents

Δt_2 – cooling

Δt_3 – ramping

Δt_4 - pump beam

a) Loading Trap b) Molasses



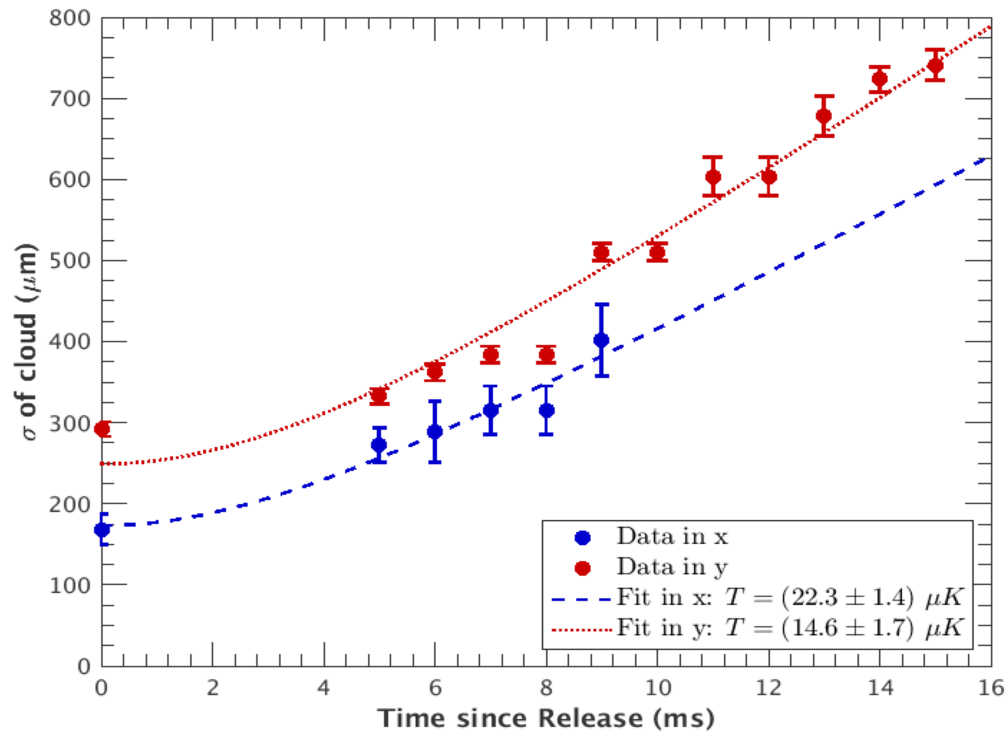
4 s $\Delta t_m \sim$ 5 ms

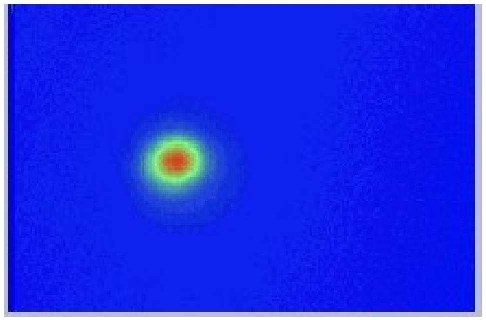
Temperature Measurement

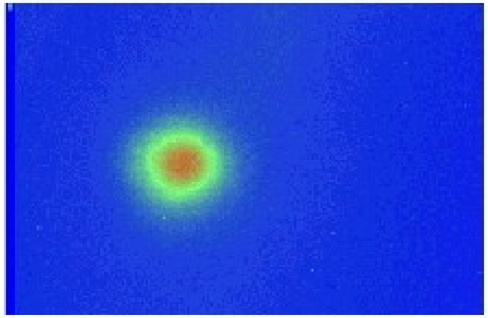
- Imaging expanding atomic cloud at varying times after release from molasses

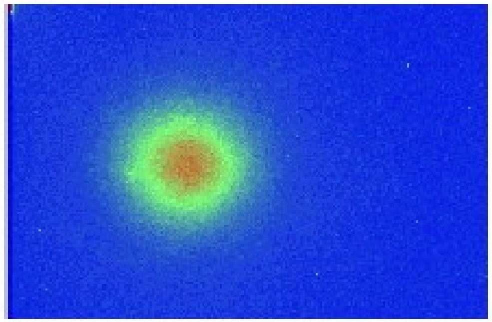
- Radius of cloud is related to velocity and therefore temperature

$$\sigma_x(t) = \sqrt{\sigma_x^2(0) + \frac{k_B T_x}{m} t^2}.$$



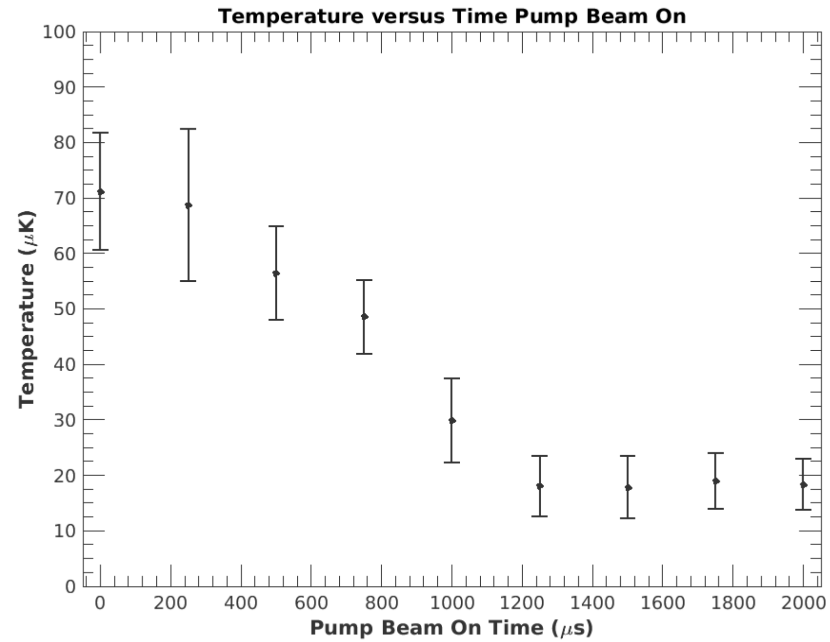

5 ms

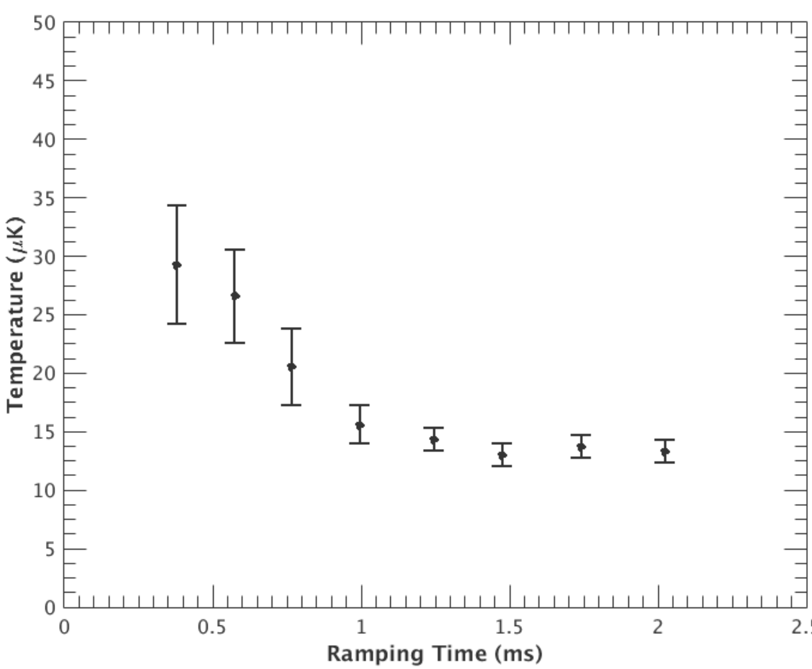

6 ms

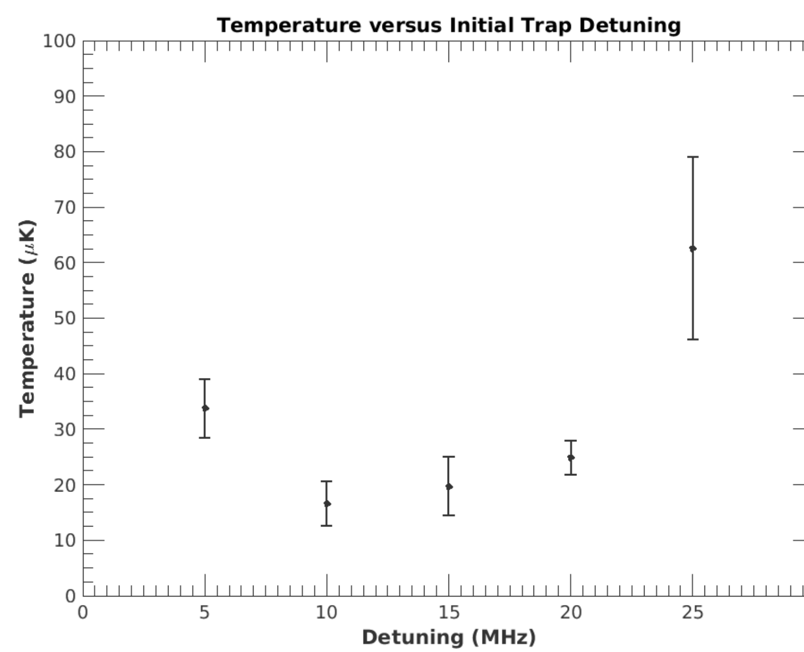

7 ms

Temperature Optimisation

- Example of some of the parameters which are varied to optimise the molasses temperature

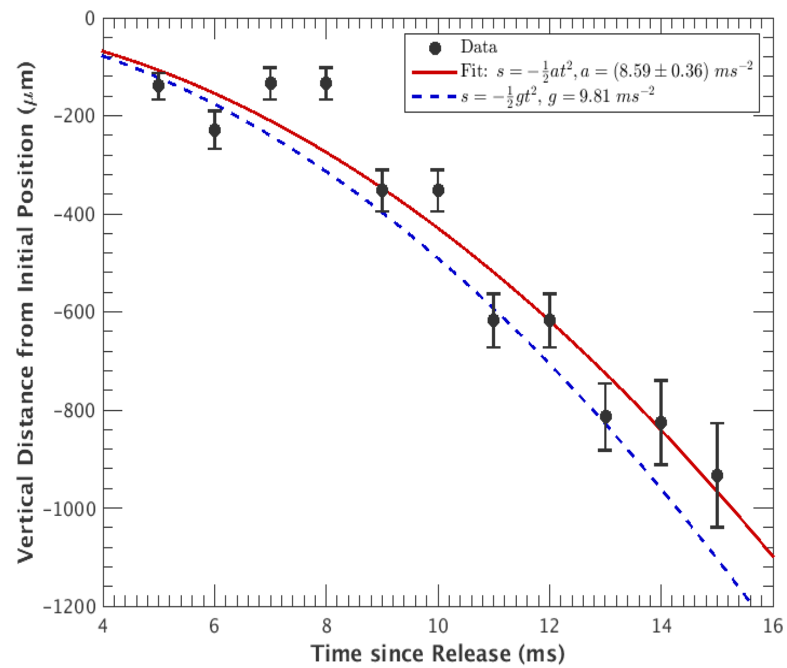


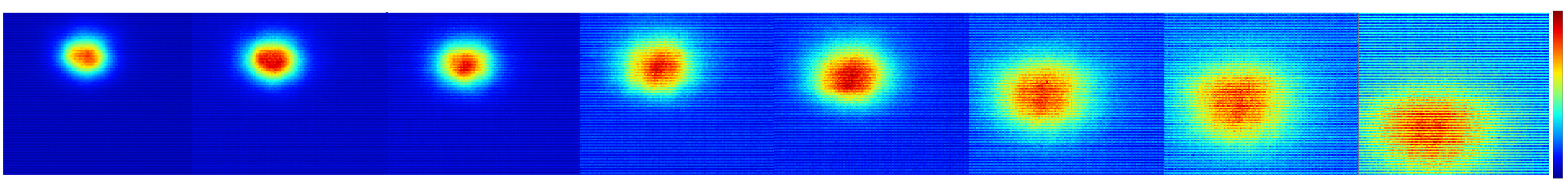




Atom Drop

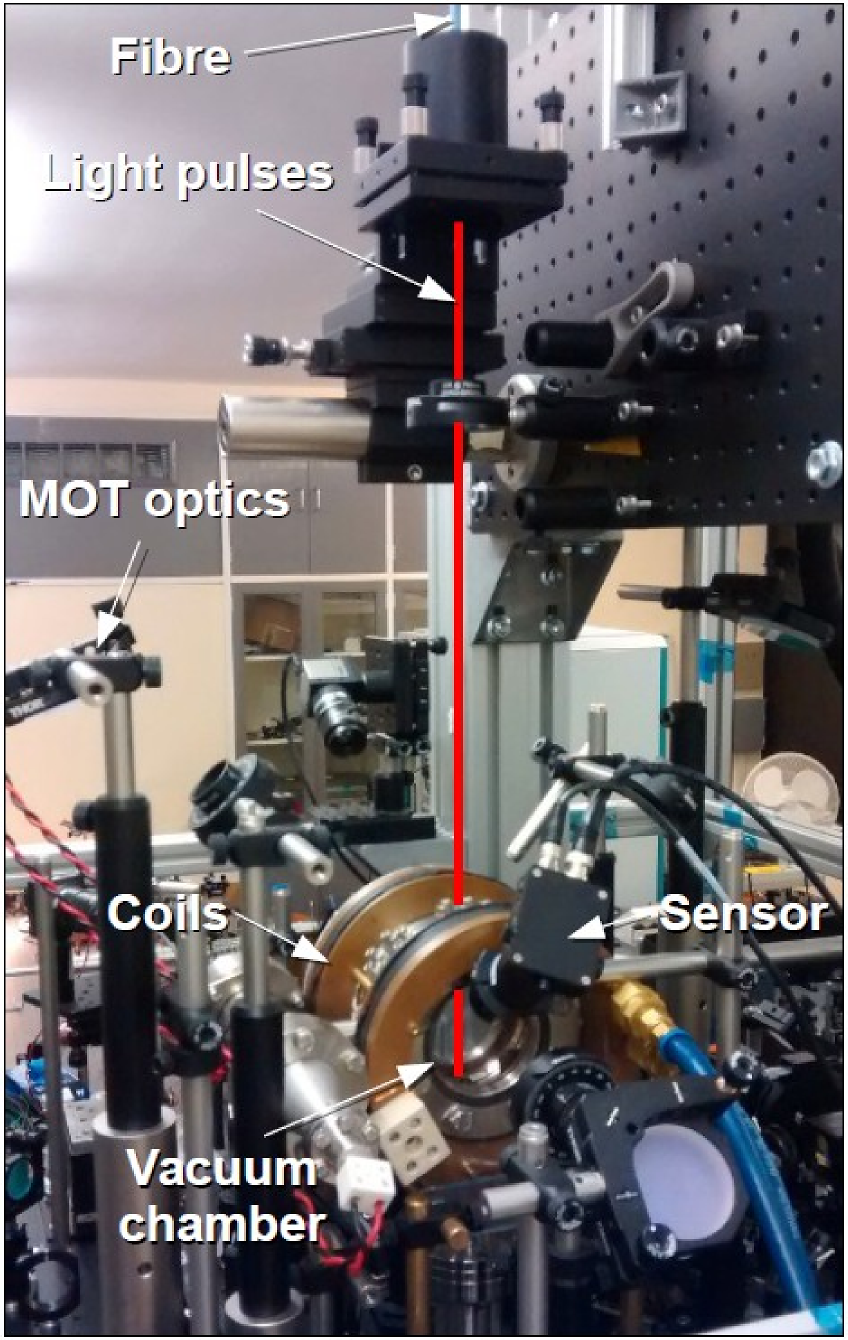
- Sufficient thermal energy removed from atoms
- See the atom cloud influenced by the Earth's gravitational field
- Another step closer to being able to do atomic interferometry



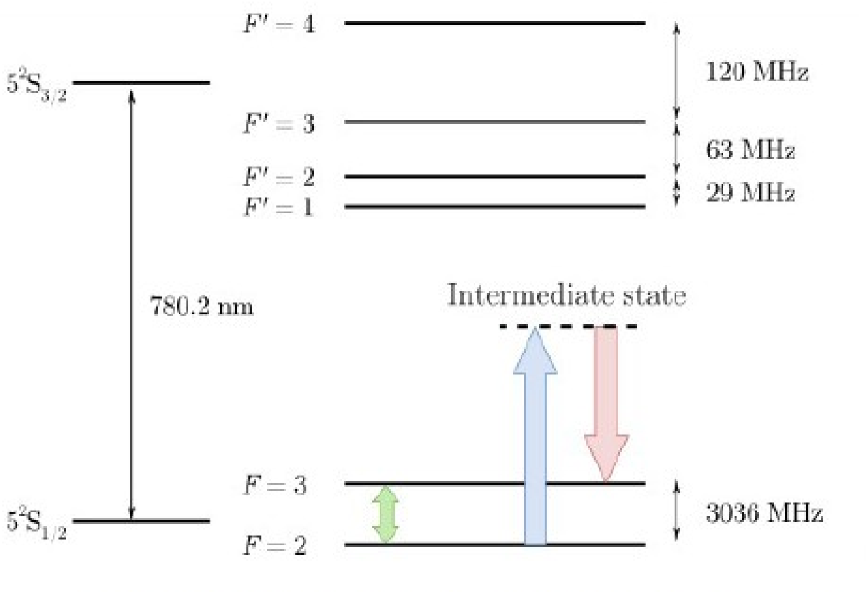


5 ms 7 ms 9 ms 11 ms 13 ms 15 ms 17 ms 19 ms

Raman Beams



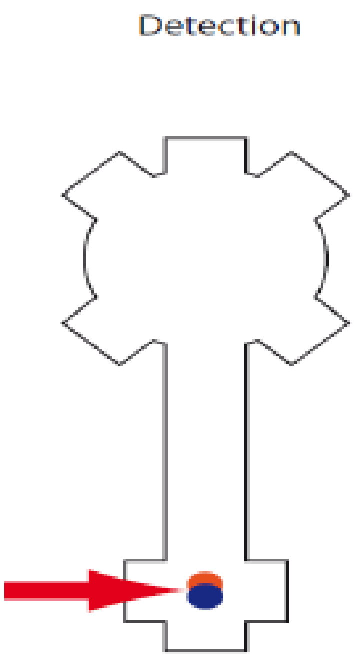
- Delivered by a fibre
- Two photon Raman transition, separated by 3 GHz
- “π-pulse” = “mirror” pulse
- “π/2-pulse” = “beamsplitter” pulses (half duration)

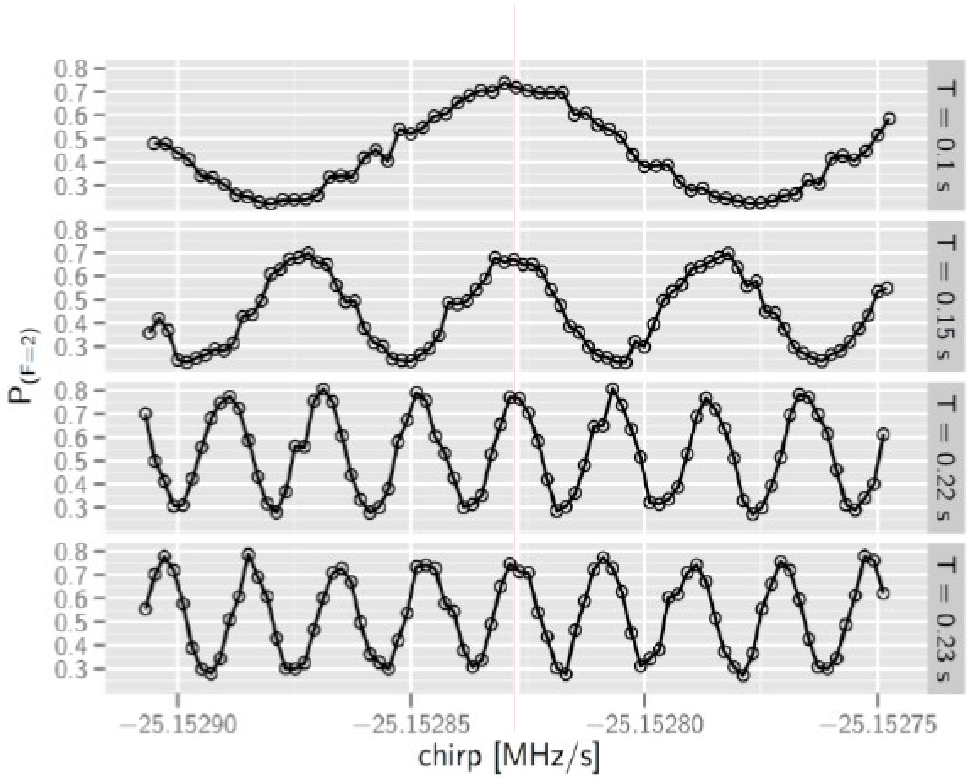


Rubidium-85 atomic energy level fine structure

Measurement of Gravity

- Varying the chirp rate of the Raman beams traces out the interferometer fringes
- Changing the time T between Raman pluses traces out different fringe patterns
- Where the fringes meet corresponds to the chirp rate required to cancel out the Doppler shift due to gravity





A Mobile Atom Interferometer for
High-Precision Measurements of Local Gravity, Alexander Senger

Future Plans

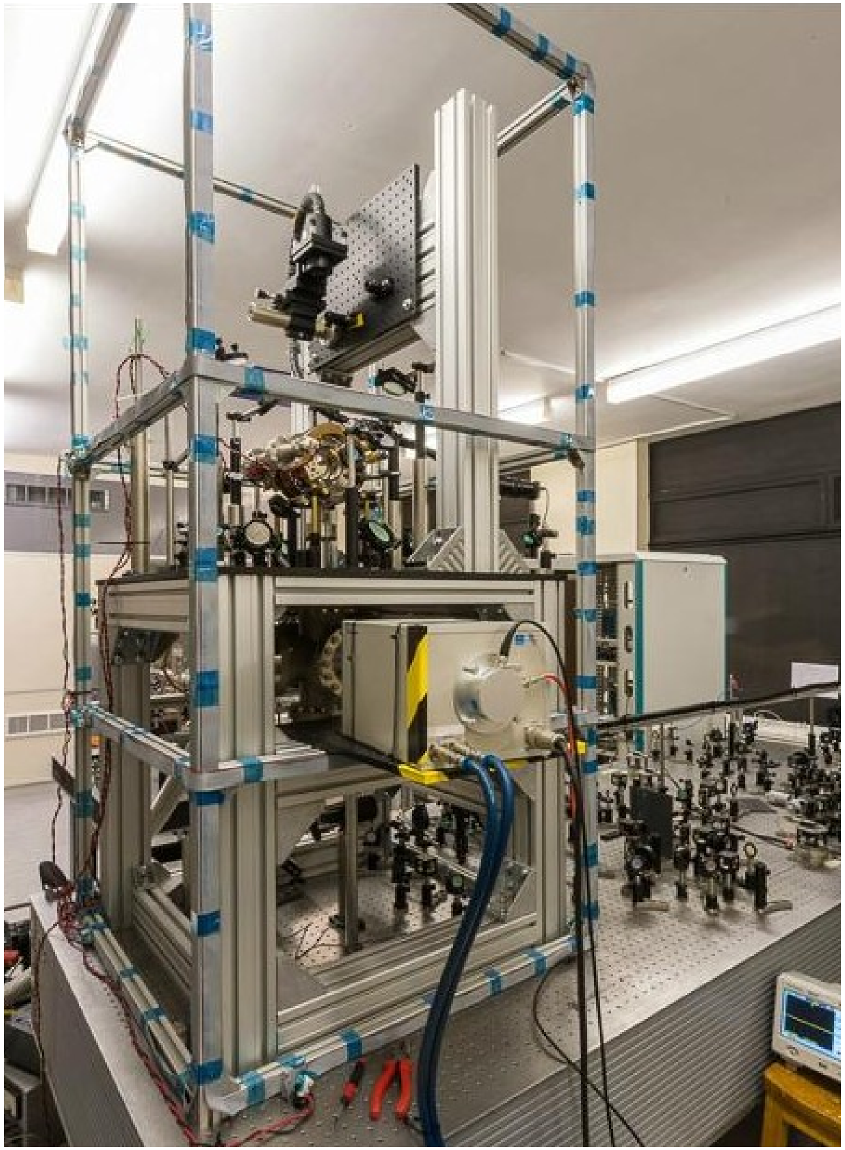
- Finishing commissioning in the coming months

  - increase the power in the raman beams

- Measurement of local gravity as a benchmark

- Optimisation of device

- Implement double interferometer



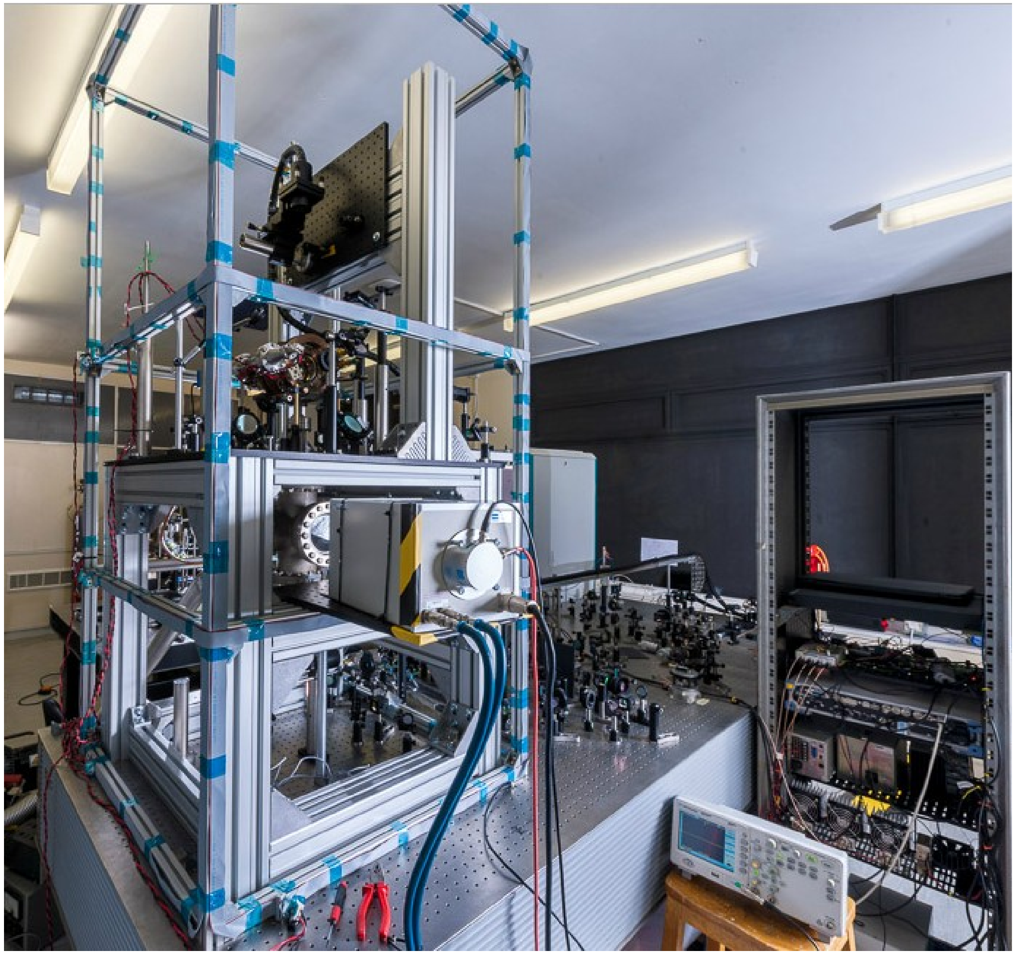
A Prototype Atomic Interferometer for Fundamental Physics

David Morris
Liverpool Particle Physics
Atom Interferometry Experiment

On behalf of the collaboration

University of Sussex IOP

March 2016



Science & Technology Facilities Council

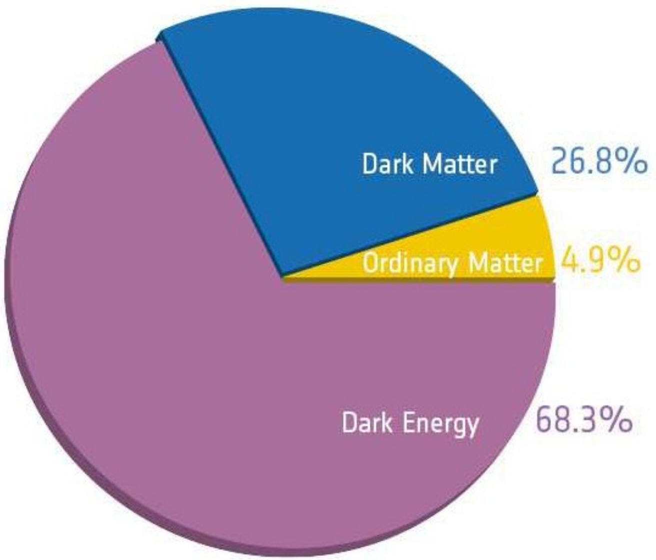
UNIVERSITY OF LIVERPOOL

The Cockcroft Institute of Accelerator Science and Technology

Additional Slides

Nature of Dark Energy

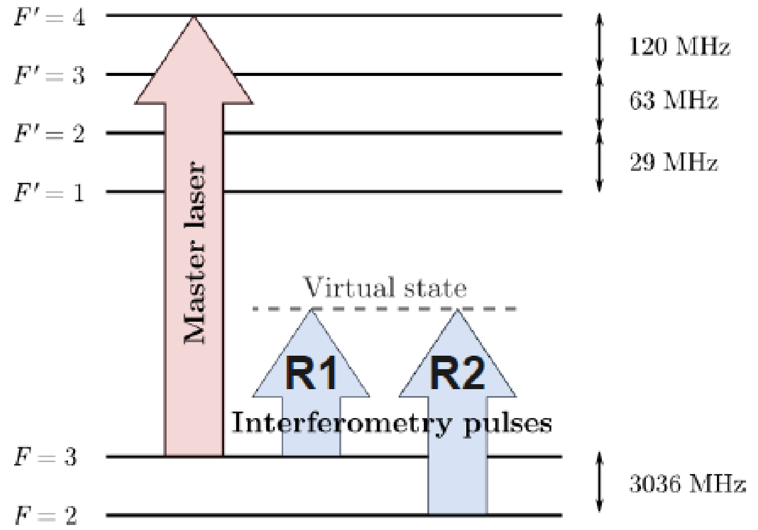
- Cosmological observations indicate 68% of the universe is dark energy.
- Present theory offers no fundamental understanding of the nature of dark energy
- Dark energy has a small but non-zero density 1.67×10^{-27} kg m^{-3}. Is this measurable on a terrestrial scale?



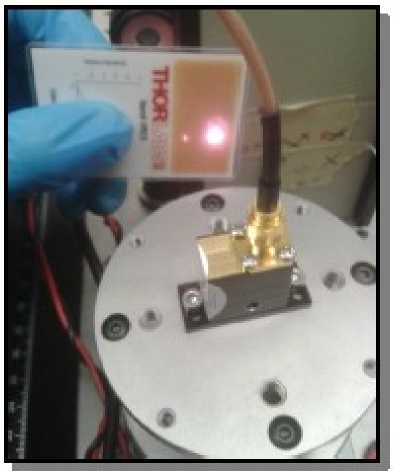
Planck Results arXiv:1303.5062

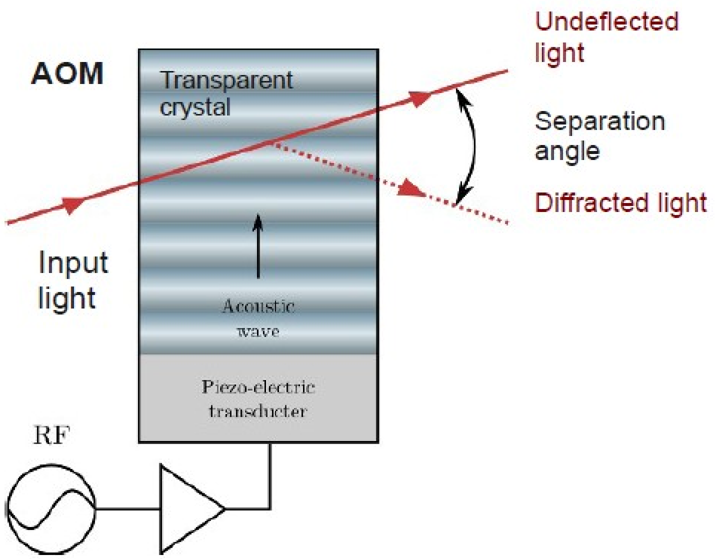
Frequency Control System

- Many frequencies required for the atom interferometer – from only two lasers
- Optical circuit generates all required frequencies from and acousto-optical modulators (AOM)
- Interferometry requires a two-photon transition
- AOM's allow the lasers to be vary in frequency and intensity



Rubidium-85 hyperfine structure



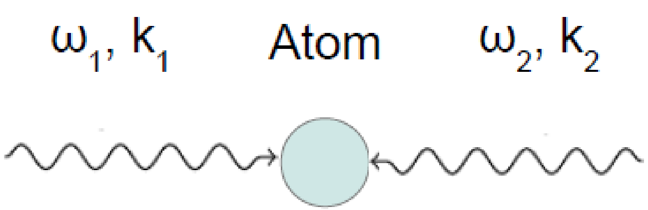


Raman Transitions

$$P_e(\tau) = \frac{\Omega_{\text{eff}}^2}{\Omega_{\text{eff}}^2 + (\delta_{12} - \delta^{AC})^2} \sin^2\left(\sqrt{\Omega_{\text{eff}}^2 + (\delta_{12} - \delta^{AC})^2} \cdot \frac{\tau}{2}\right)$$

Excited-state population P_e as a function of Rabi frequency Ω and detuning δ. [Schmidt thesis, Eq. 2.55]

"For a resonant Raman process the frequency detuning $\delta \approx 0$ and the detuning Δ from the intermediate state remains large, so that excitation by the single-photon absorption is negligible in comparison to the coherent transfer from |g> to |e>" [C. J. Foot *Atomic Physics* p209]



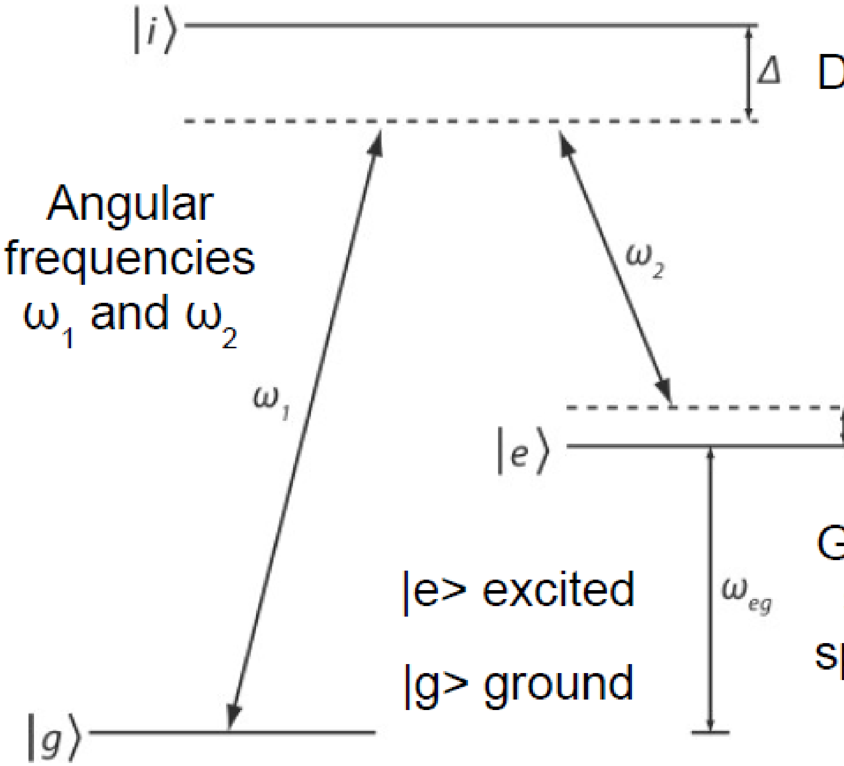
Recoil velocity = $2hk_{eff}/M$

where $k_{eff} = k_1 - k_2$

|i> intermediate state

Detuning

Angular frequencies ω_1 and ω_2



|e> excited

|g> ground

Ground state splitting ω_{eg}

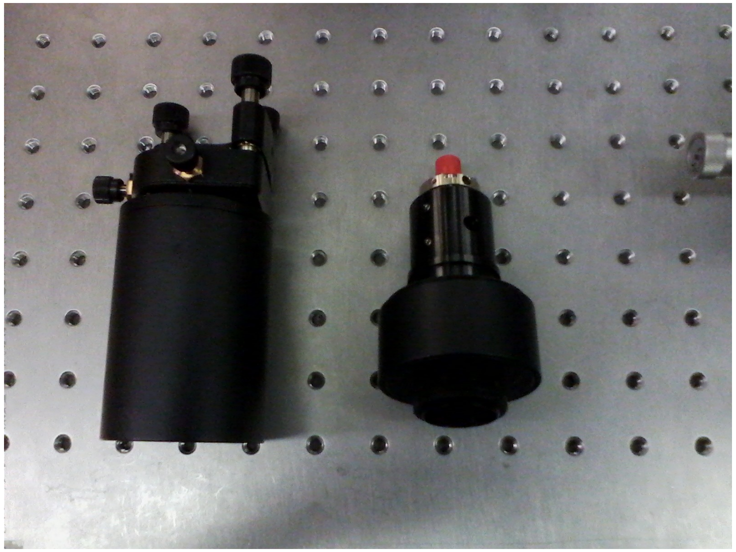
Level scheme of three-level Raman transitions, simplified to exclude AC Stark shifts

$\omega_{eff} = \omega_1 - \omega_2 \approx \omega_{eg}$

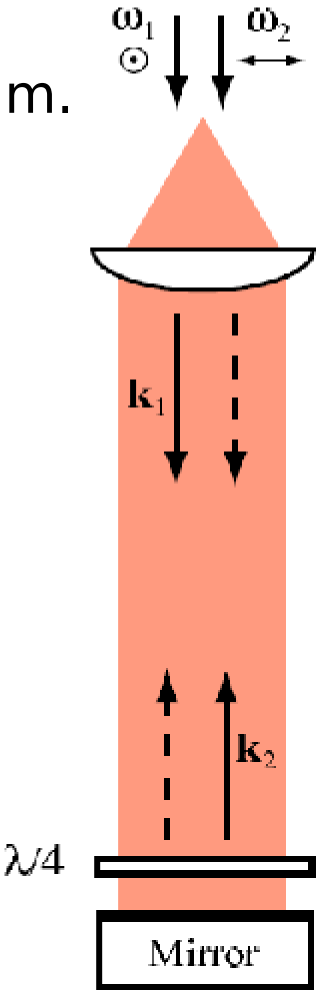
[Schmidt thesis, Fig. 2.1]

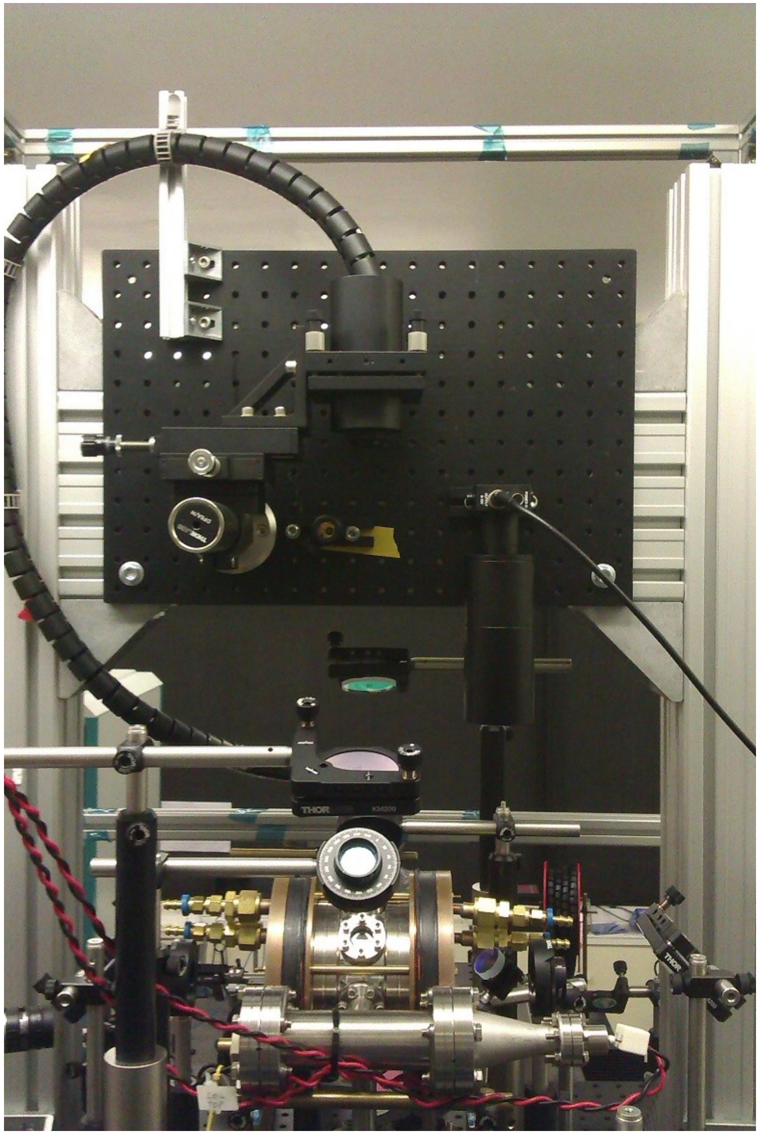
Raman Beam Delivery

- Fibre delivers the Raman beams
- 10 m fibre cleans up modes of beam.
- Collimated into 10.8 mm beam.

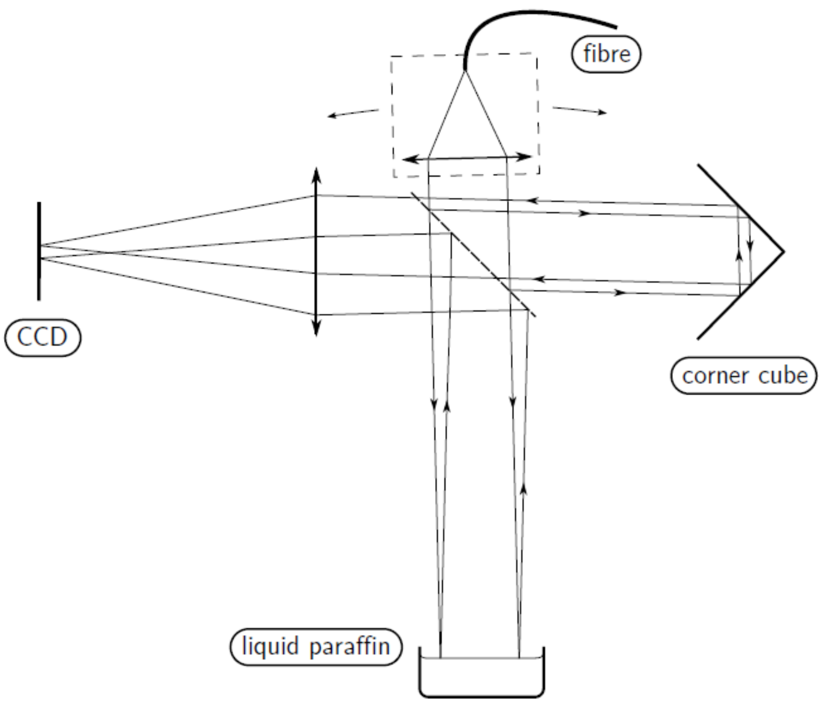


Collimator mount





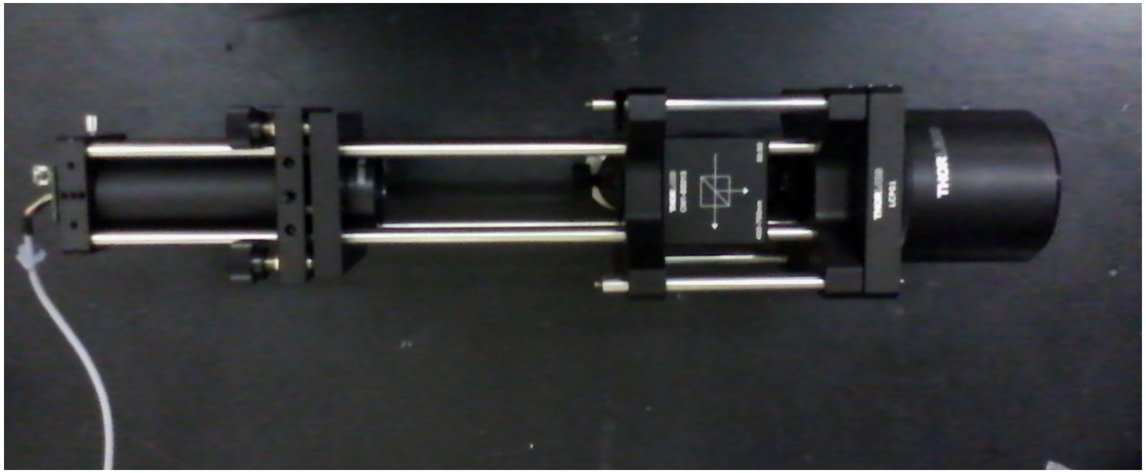
Precision Alignment

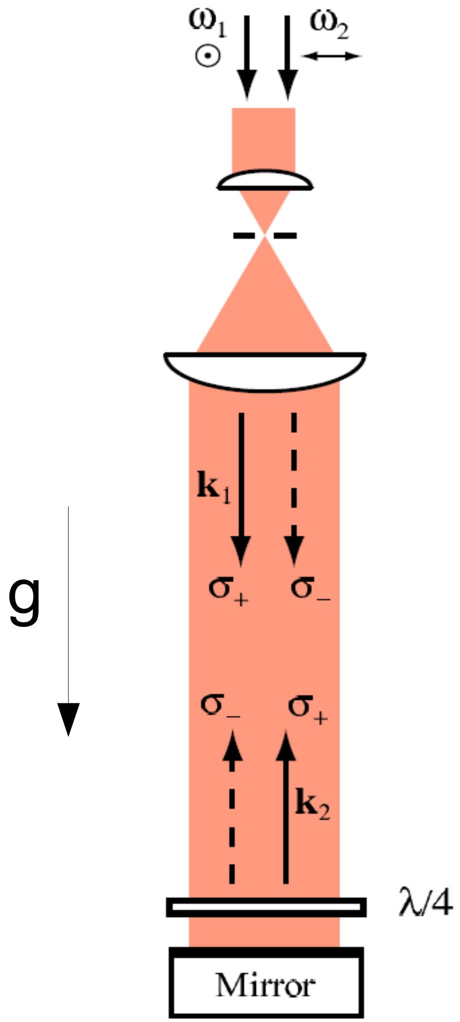


Using precision optics with

- Extremely flat surfaces, λ/20

- Small beam deviations, 10 urads

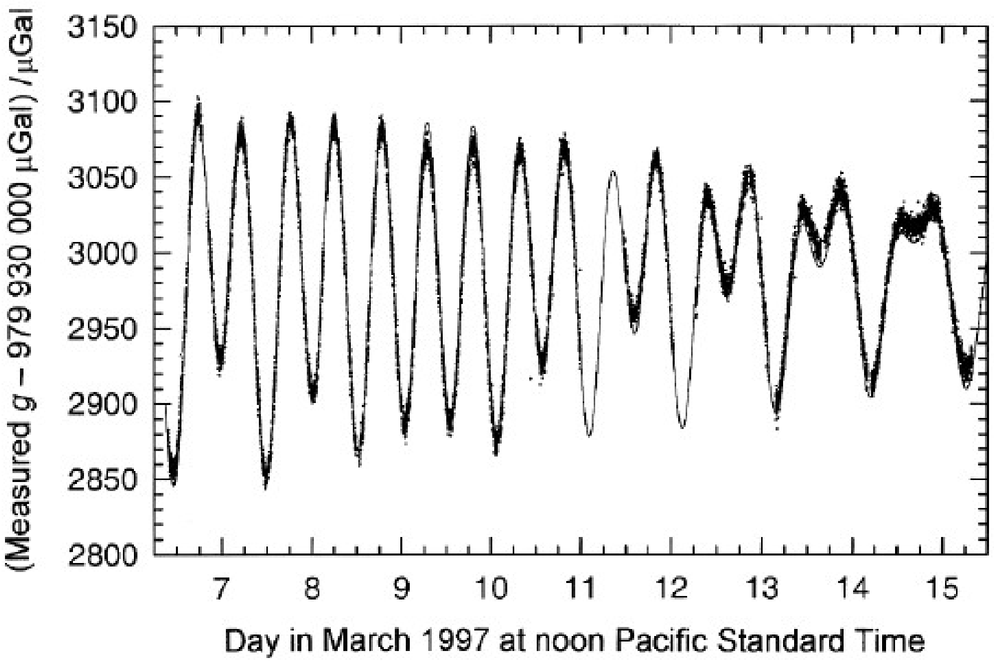




Improving Sensitivity

Using atom interferometers to measure tidal effects:
σ_g need to be 10^7 $\Delta\phi = k_{eff} g T^2 =$

If long data taking takes several days to reach 10^7 than daily tidal variations would not be observable.



1 µGal = 10-8ms-2

- Require having large phase shift ΔΦ:
- T is time of flight for the atom cloud
- Prototype under construction height ~ 1 m
- T^2 is proportional to h,
- h = 10 m, approx 10 x improvement in ΔΦ,

Increased atom number gives increased statistical power

Increased drop length gives greater sensitivity of each measurement

Polarisation Gradient Cooling

[Himsworth thesis, "Coherent Manipulation..." 2009]

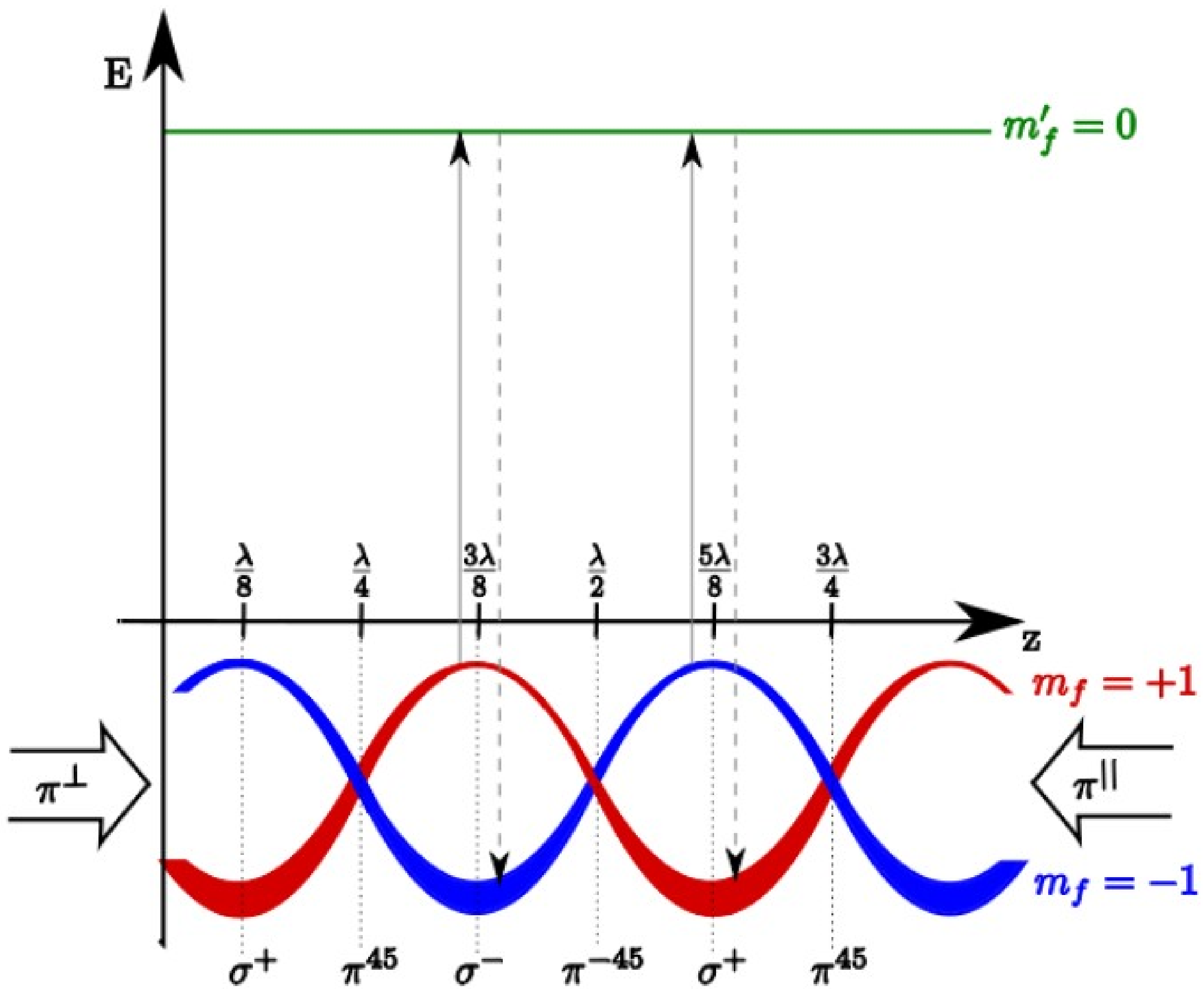
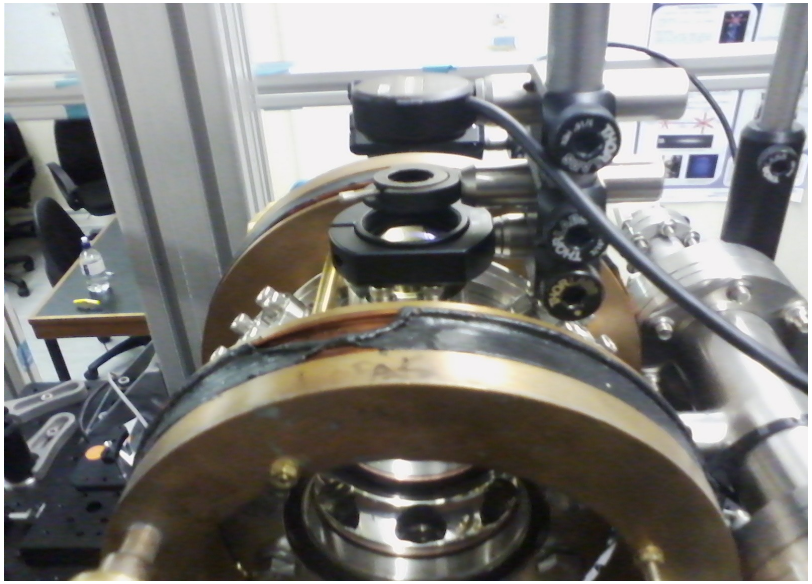


FIGURE 5.4: *The Sysiphus effect of Sub-Doppler cooling. See text for details. The width of the lower m_F states (red and blue) representative of the state populations.*

Atom Number



Power: Atom No. Solid angle ,Scatting rate Photon energy

Calculation

•Measure flux for some small area

•Extrapolate 4π flux

•Subtract laser fluorescence background

•Take ratio: divide by single atom flux (scattering rate * photon energy)

- i.e. N = total flux / single atom flux

Time of flight measurement

$$\sigma_x(t) = \sqrt{\sigma_x^2(0) + \frac{k_B T_x}{m} t^2}.$$

Thesis Kevin J. Weatherill Durham Atomic physics

A CO2 Laser Lattice Experiment for Cold Atoms

2007