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**Introduction to Optofluidics**

***1 - 5 June 2009***

# Application of SLMs and high-speed imaging in optical tweezers for microfluidics

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# Application of SLMs and high-speed imaging in optical tweezers for microfluidics

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**Department of Physics and Astronomy**

University of Glasgow

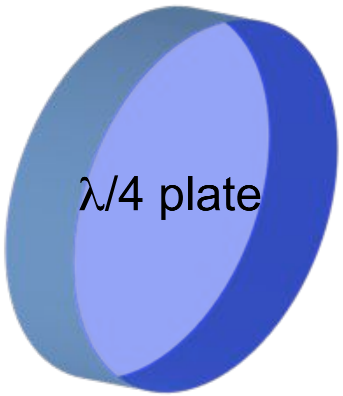
## Part 3

- Applications of SLMs and High-speed Imaging
  - Optical pumps
  - Hydrodynamic coupling
  - Trap dynamics

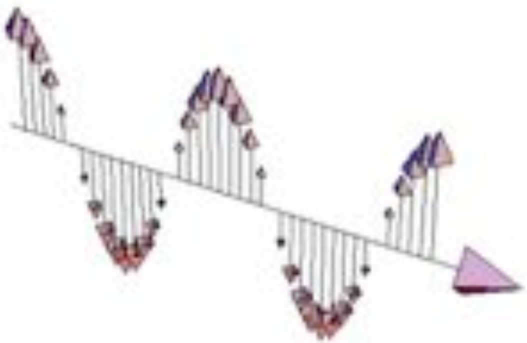
# Transfer of spin AM

Circular polarisation

Spin AM $\hbar$/photon




Linear Polarisation



No AM

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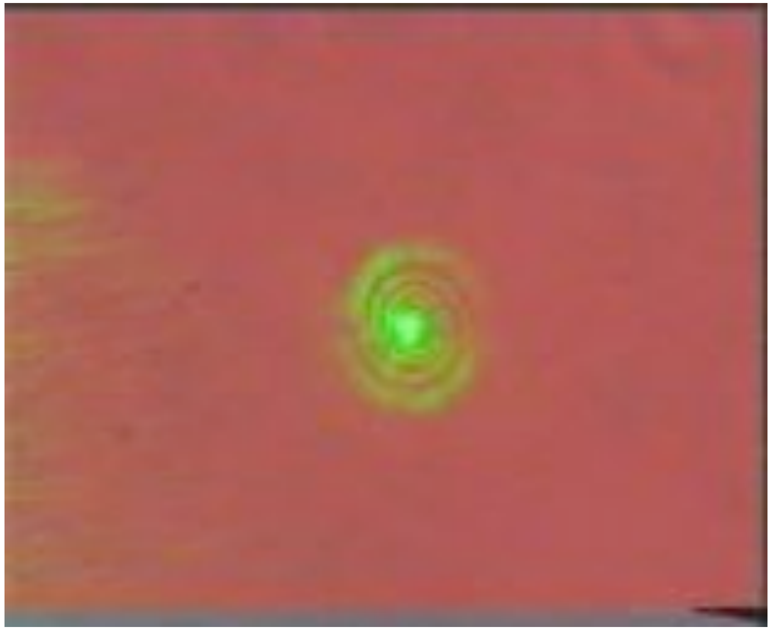
## Transfer of spin AM in tweezers

- Within optical tweezers
  - Circularly polarised trapping beam
  - 2μm dia. Calcite ≈ $\lambda/4$
  - For r < $\lambda/4$ plate
    - torque $\alpha$ r
  - Viscous drag scales with $r^3$
    - Small particles rotate faster

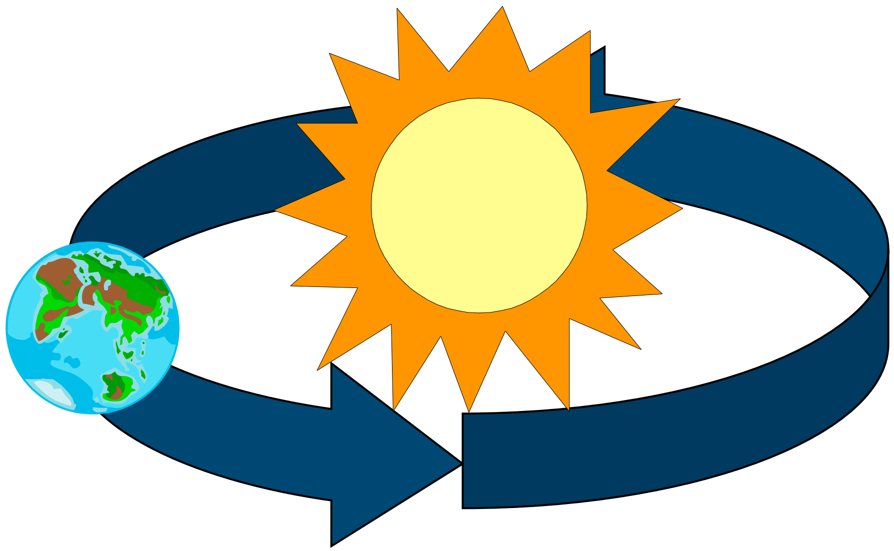


**Friese, Nature 394, 348, 1998**

# Angular momentum

Spin angular momentum
(SAM)

Orbital angular momentum
(OAM)



## Optical vortex =Helical phasefronts

- Description of light
  - Intensity (θ,r), $I \geq 0$
  - Phase (θ,r), $2\pi \geq \phi \geq 0$

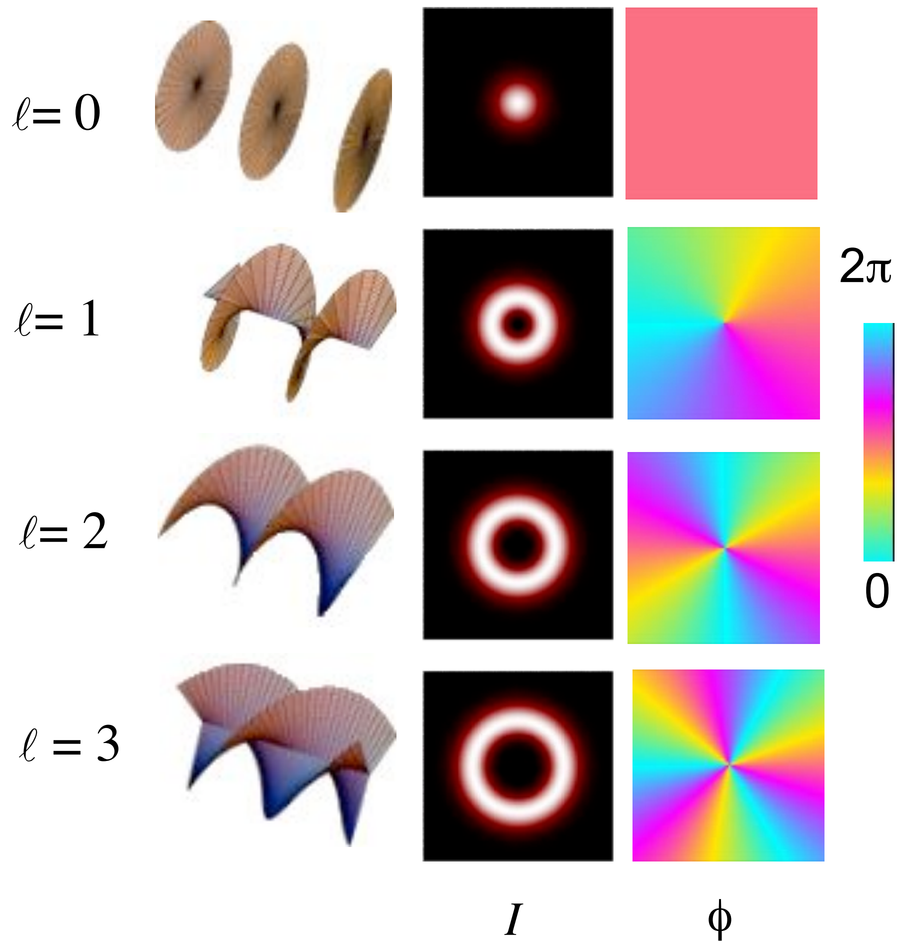
    $\phi(\theta,r) = \omega t + kz + \ell\theta$

    $\ell$ = 0, plane wave

    $\ell$ = 1, helical wave

    $\ell$ = 2, (double) helical

    etc.




$\ell$= vortex charge

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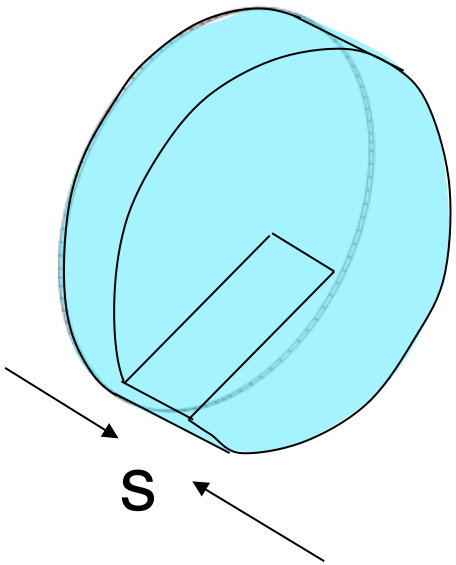
## A vortex of what?

- Momentum flow perpendicular to phase-fronts
- Helical phasefronts
  - ▹ azimuthal momentum
    - ➢ orbital angular momentum
    - ➢ $\ell\hbar$ per photon (Allen *et al.*)
- A vortex of optical energy and momentum

**Padgett *et al.* Phys Today 57, 35, 2004**

# Designing helical phase hologram

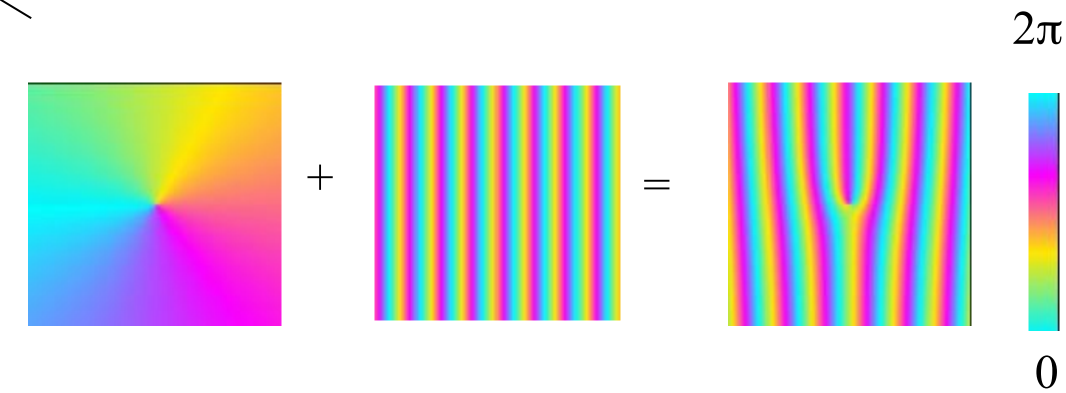



- Spiral Phase-plate

  $s = \ell\lambda/(n-1)$

- Holographically

  e.g. $\ell = 1$ ▹



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## Software for driving SLMs


- Software for hologram design and drive of SLMs
  - http://www.physics.gla.ac.uk/Optics/projects/tweezers/slmcontrol/

**Click Here!**

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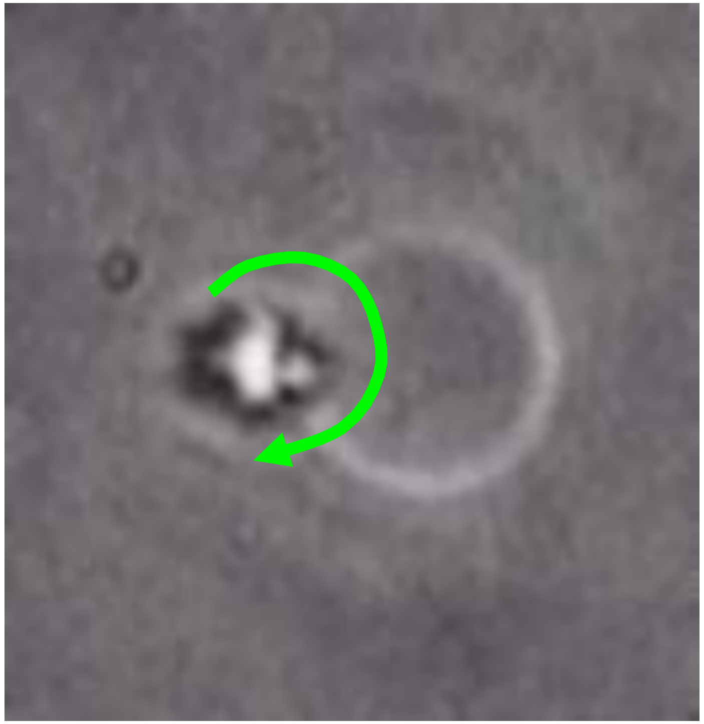
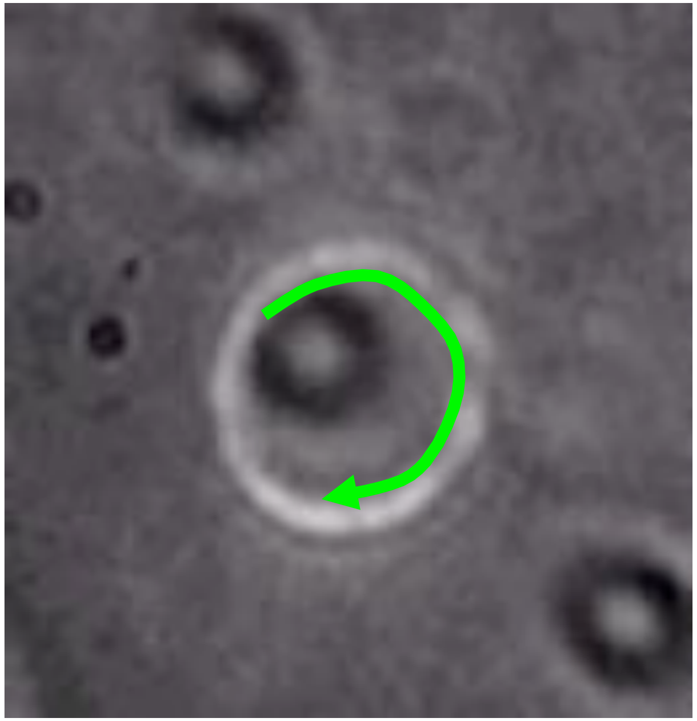
## SAM/OAM transfer to particle held in optical tweezers



SAM
Particle spins on its own axis

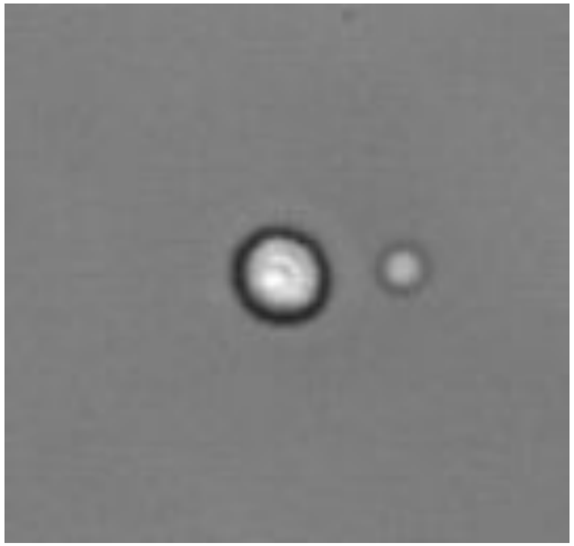


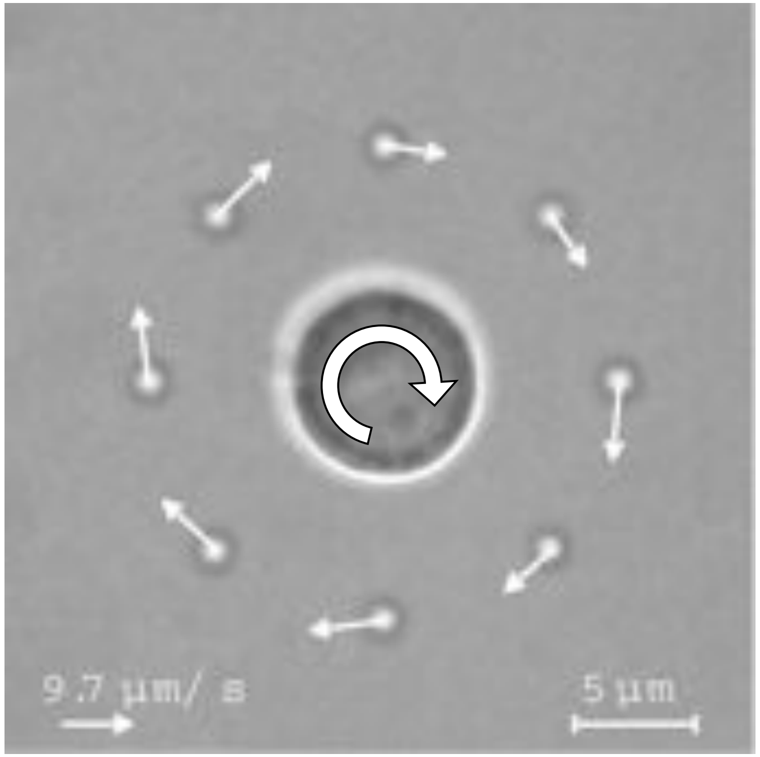
OAM
Particle orbits the beam axis

**O'Neil *et al.* PRL 88, 053601, 2002**

## Measurement of fluid flow

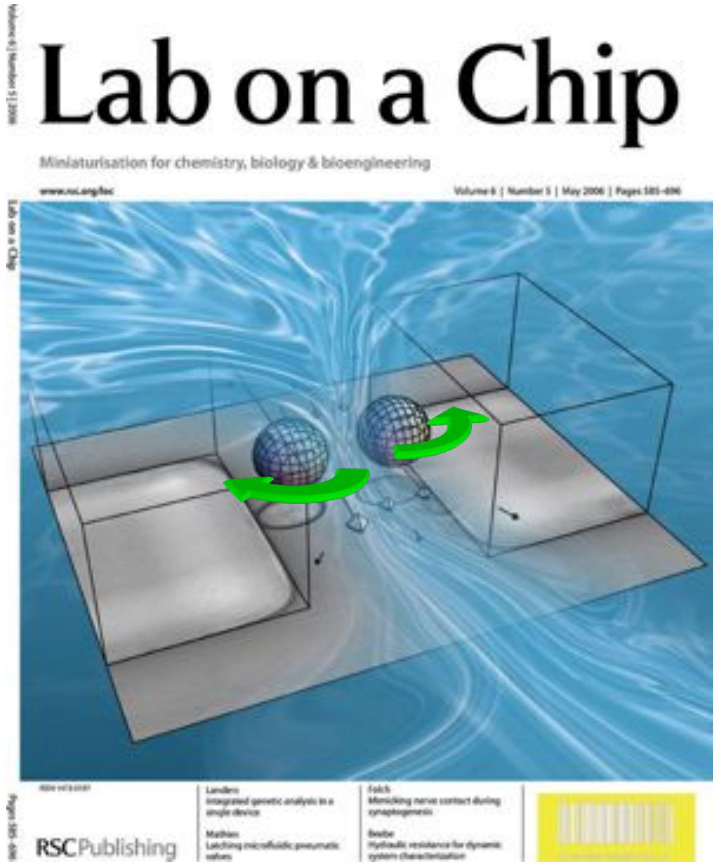
- Use holographic tweezers to trap and position probe particle in flow
  - High speed video sync. to ≈40Hz modulation of trap





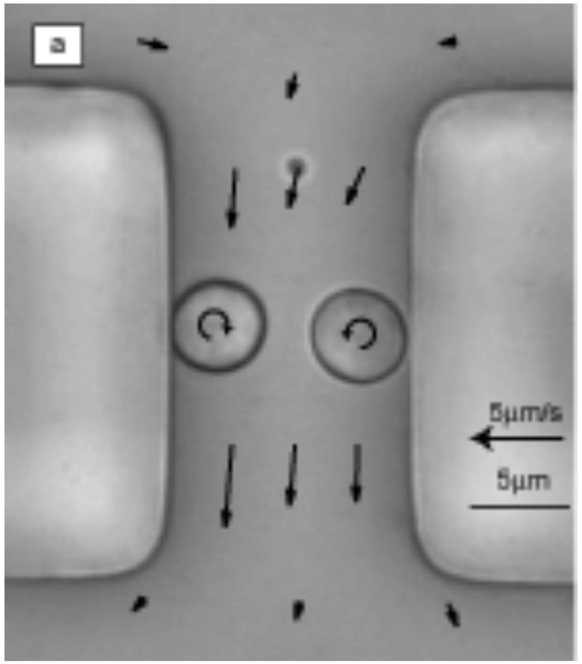
## Generating flow in micro-fluidic channel

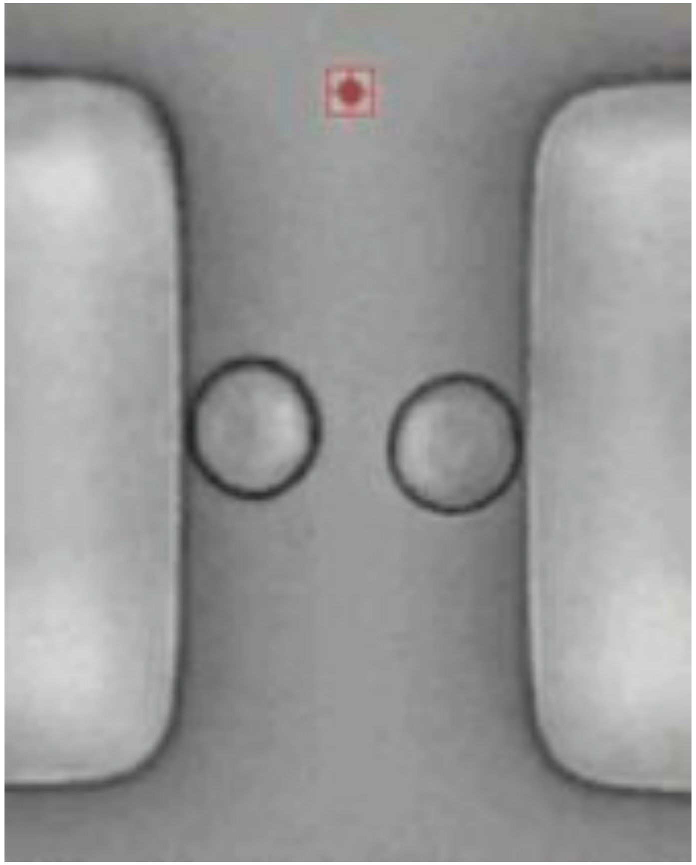
- Use scanning beam to move beads (Marr et al.)
- Use OAM to circulate beams (Grier et al.)
- Counter-rotating 5µm dia. vaterite beads driven by light's spin angular momentum
  - 15µm wide channel in PDMS
  - Flow µm/s ≈ plittre/sec



## Optically driven pump

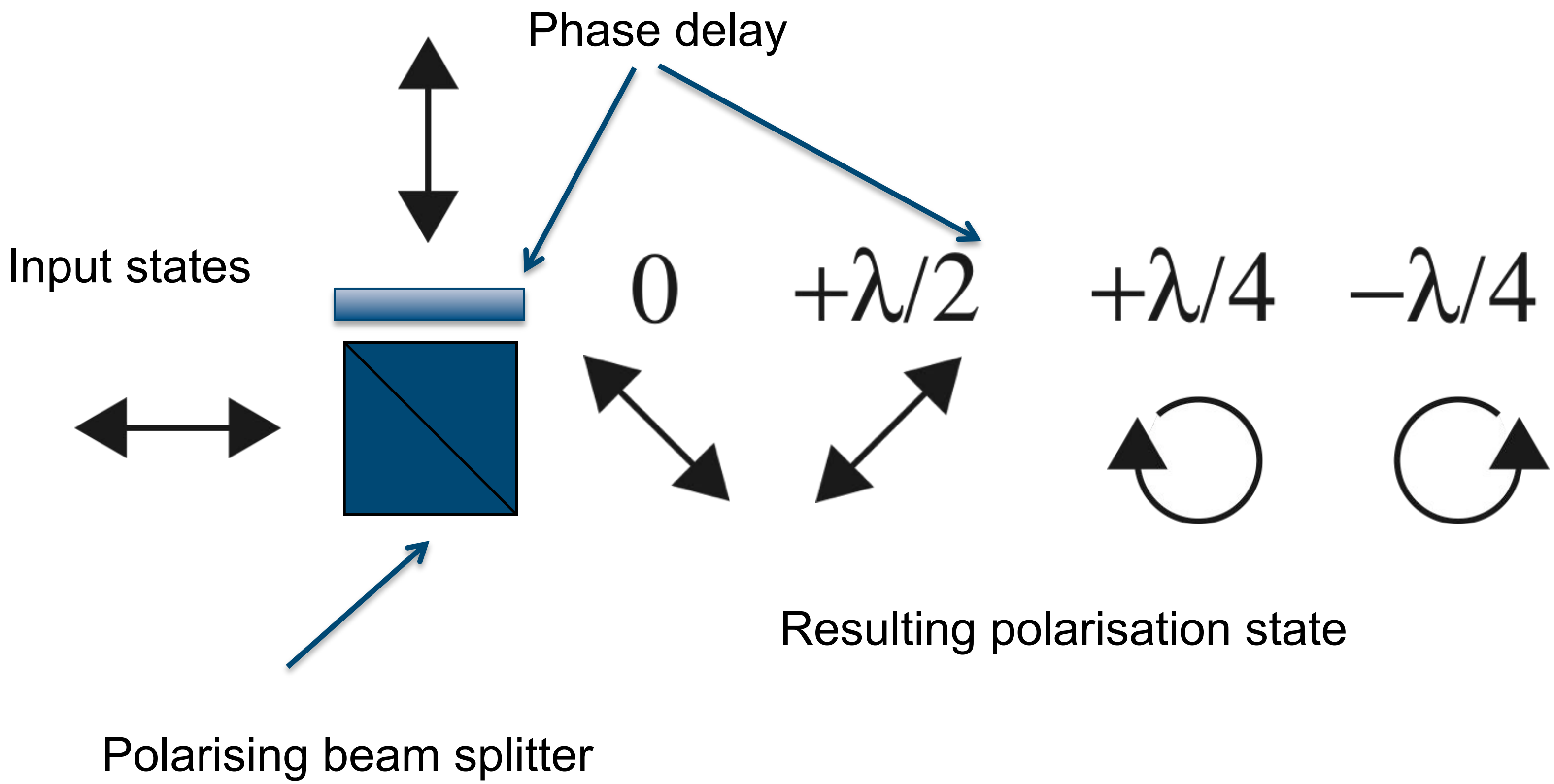
- Flow ≈ 200μm³/s (plittre/sec)



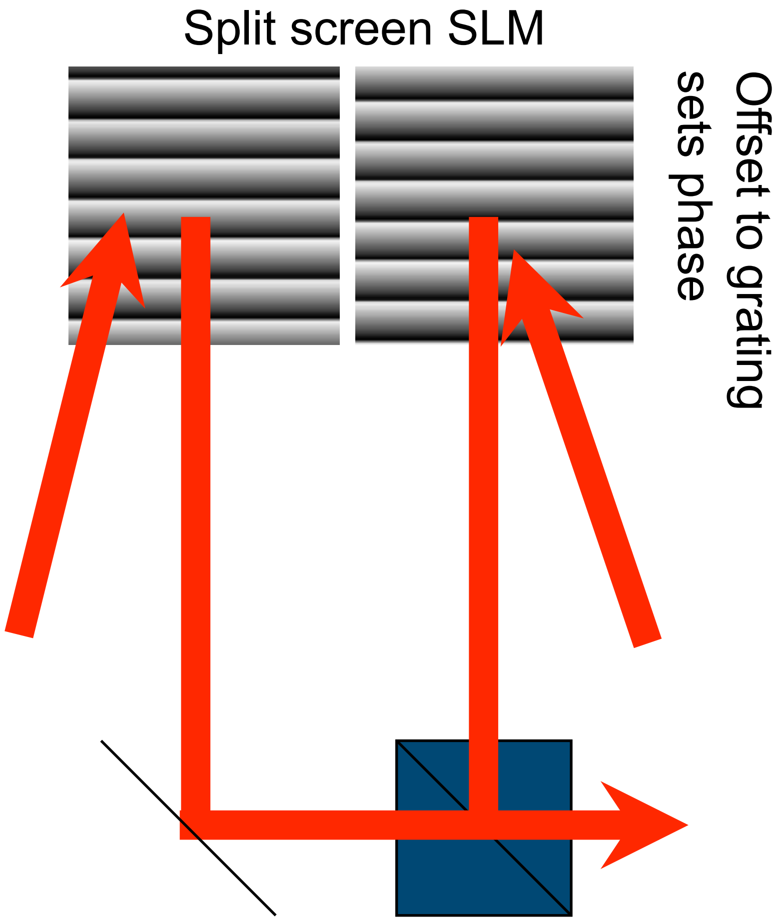



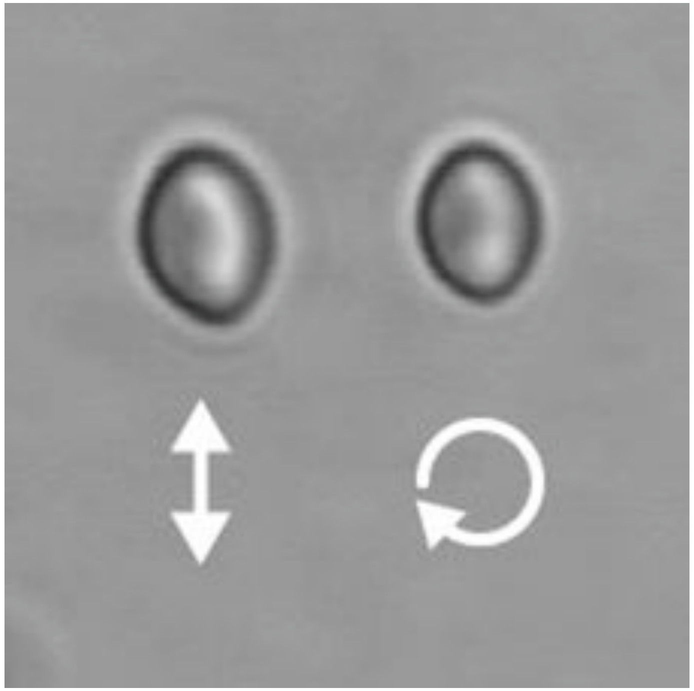
Leach *et al.* Lab Chip 6, 735, 2006

## Control of optical SAM



## Control of optical SAM

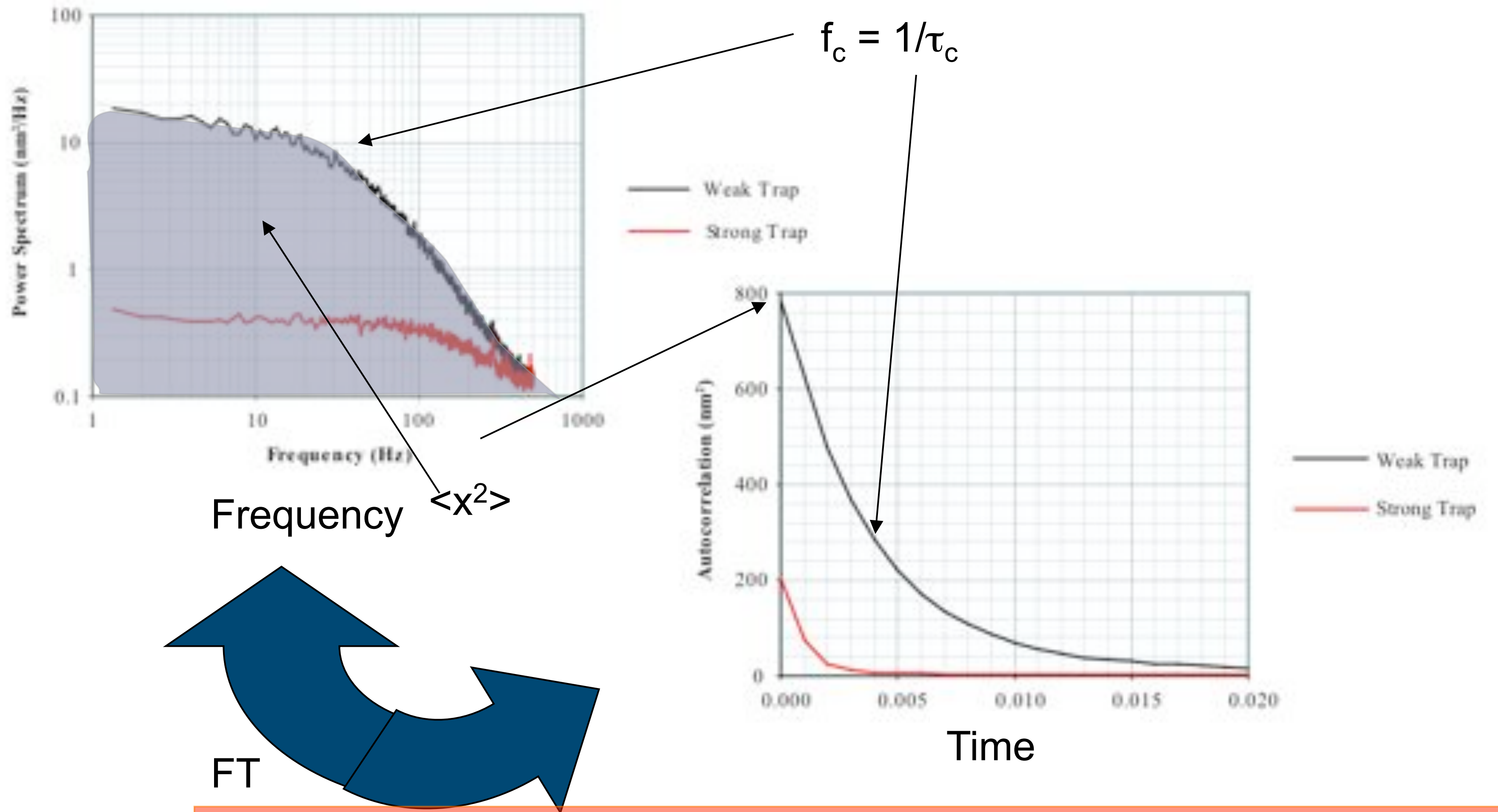


We can turn the angular momentum in the beam "on and off"

Preece *et al.* Opt. Express, 16, 15897, 2006

## Power Spectra and Auto correlations




**Berg-Sorensen *et al*. Rev. Sci. Instrum E, 75, 594, 2004**

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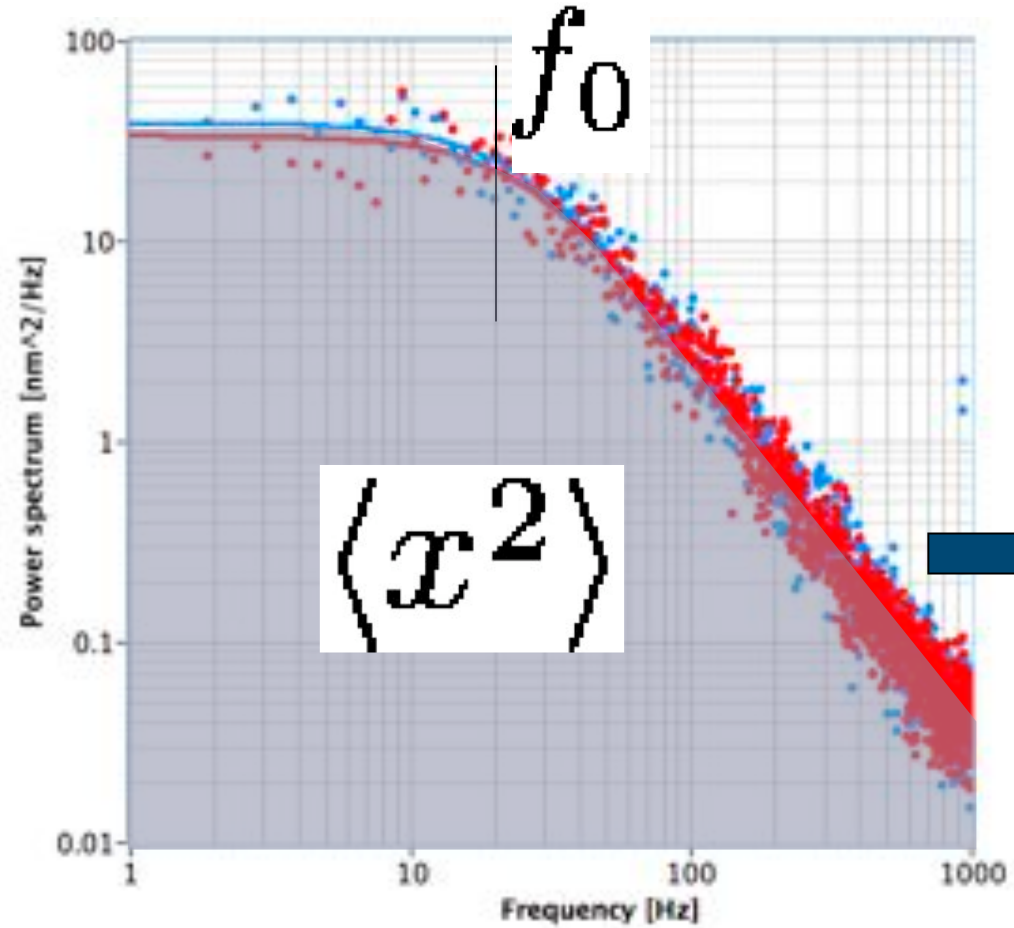
## Fitting the power spectrum



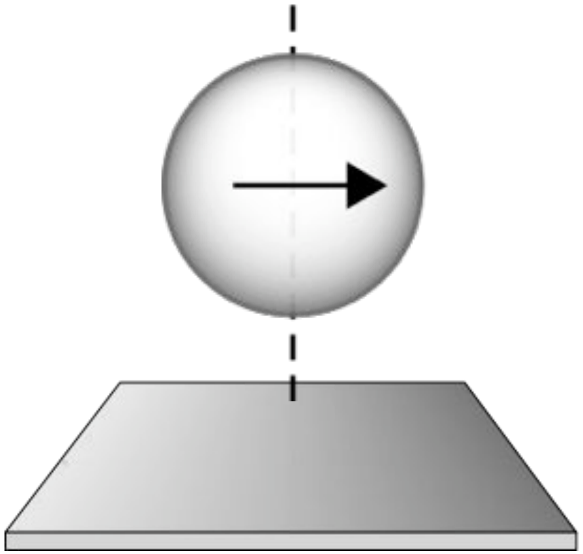

$$f_0 = \frac{k_B T}{12\pi^2 \eta a \langle x^2 \rangle}$$

$$1/2\, k \langle x^2 \rangle = 1/2\, k_B T$$

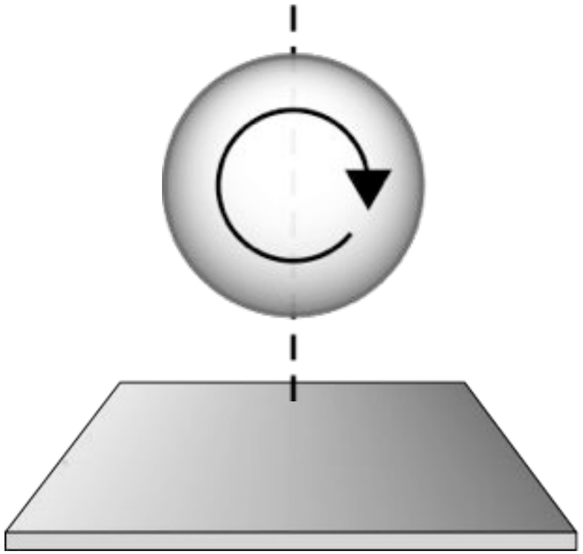
$$\eta = \frac{k_B T}{12\pi^2 a f_0 \langle x^2 \rangle}$$

## Forces and Torques

Force on a translating sphere



Torque on a rotating sphere



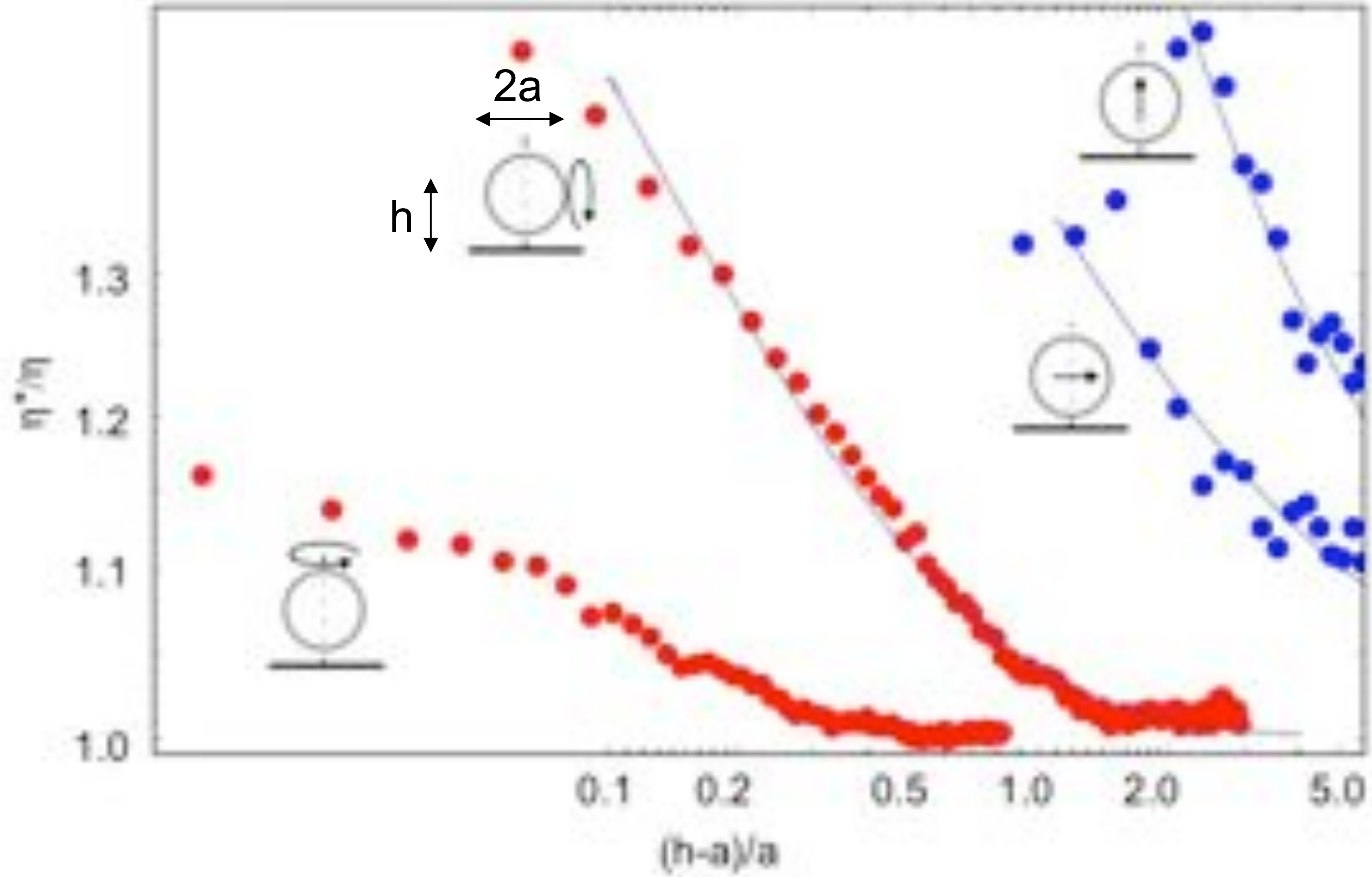
*For unbounded Newtonian fluids at low Reynolds numbers

$$\gamma = 6\pi\eta a$$

$$\beta = 8\pi\eta a^3$$

**Bishop *et al.* Phys Rev. Lett. 92, 198104, 2004**

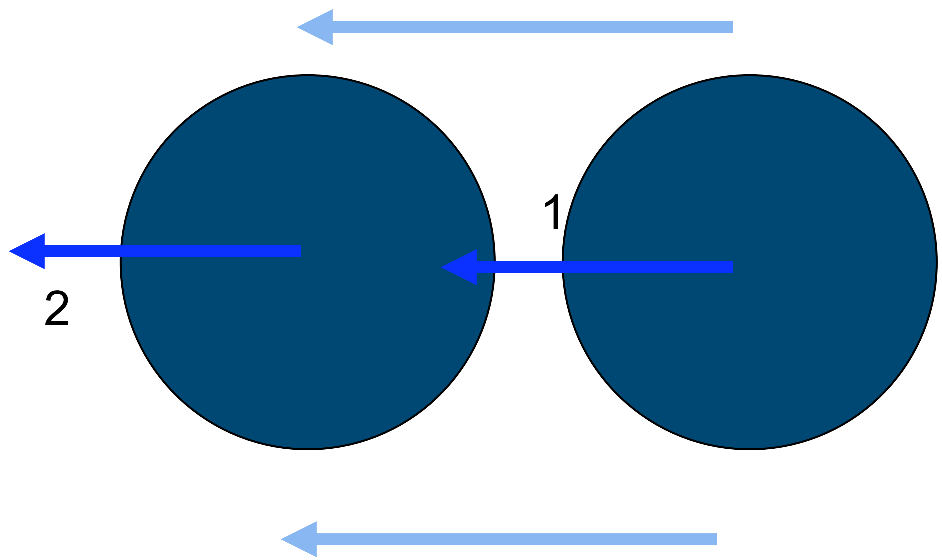
## Faxen's correction for translational & rotational motion




**Leach *et al*. Phys. Rev. E 79, 026301,2009**

## Observing the (hydrodynamic) coupling

- Motion of one bead creates fluid flow which then exerts Stokes drag force on neighbouring beads
  - $F_2 \alpha V_1$




**Meiners and Quake Phys Rev. Lett. 82, 2211, 1999**

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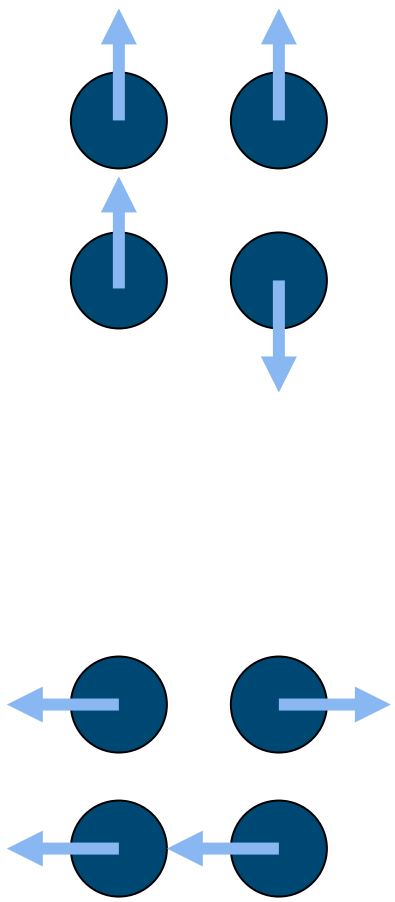
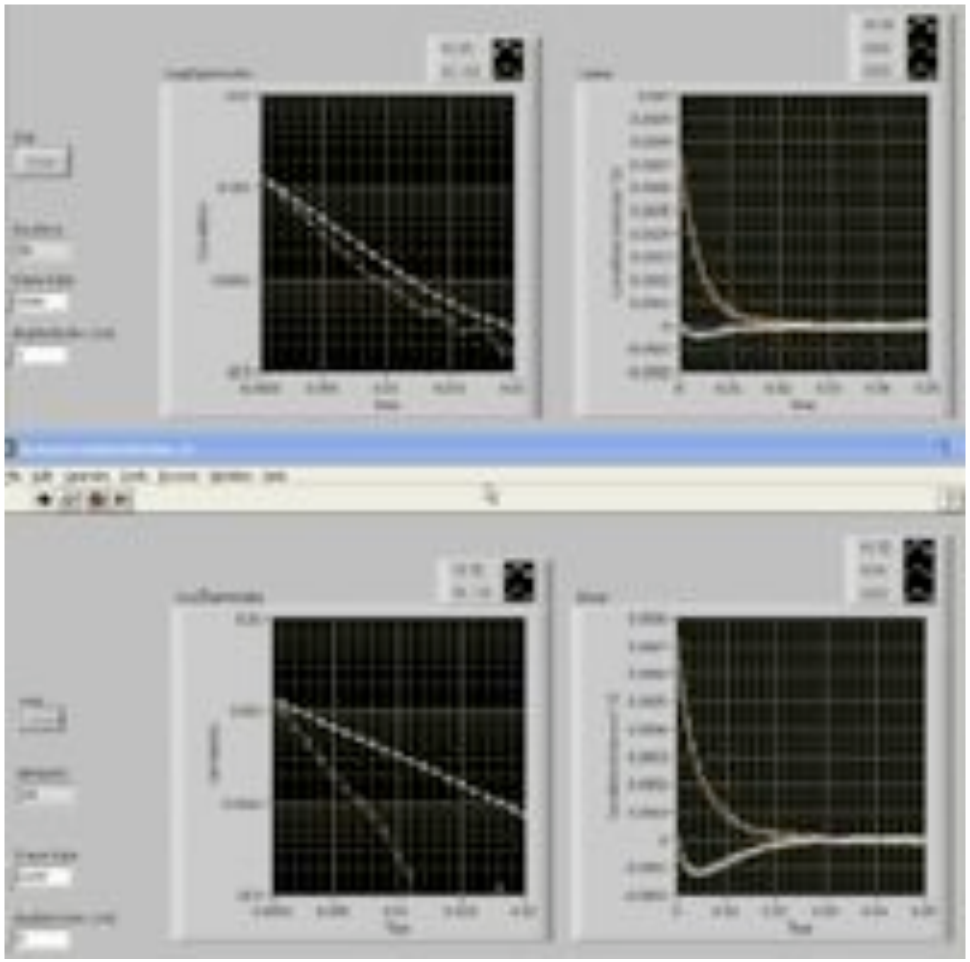
## Observing the (hydrodynamic) coupling

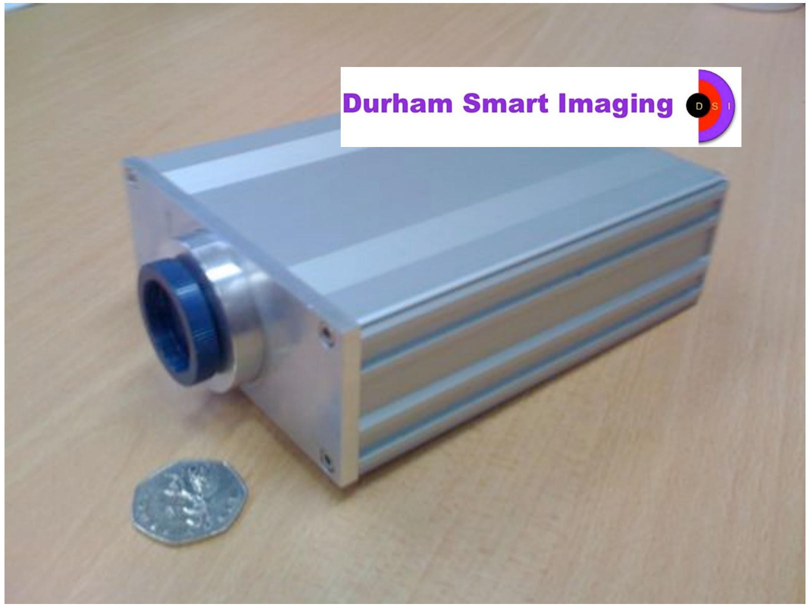


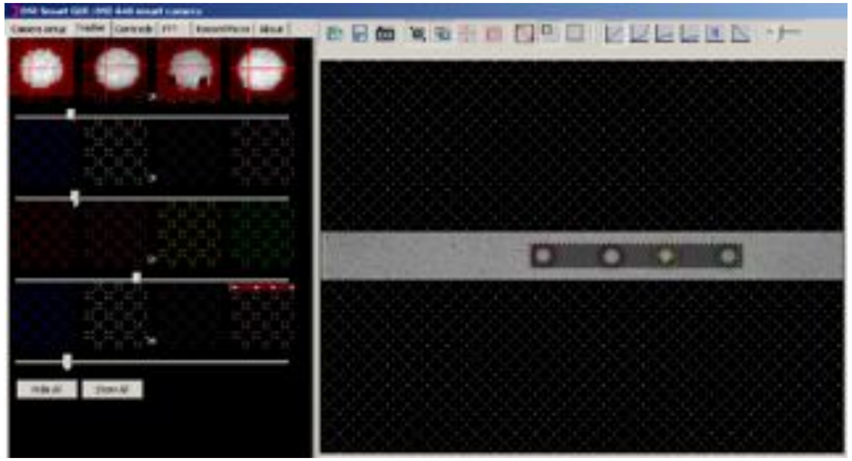


**Meiners and Quake Phys Rev. Lett. 82, 2211, 1999**

## Program. CMOS (collab. Love and Saunter, Durham)

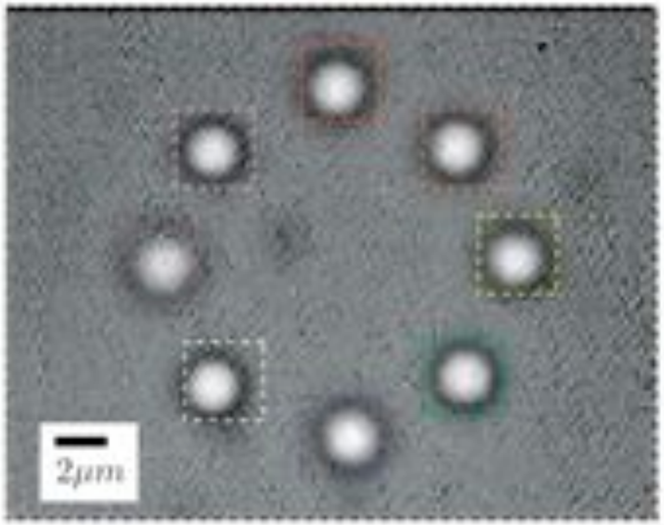
- CMOS (480x640)
- 8-bit digitisation
- Frame-rate Typ. 2000Hz
- Multi point (16), real time tracking
- Particle Co-ordinates passed to logging computer (Firewire)

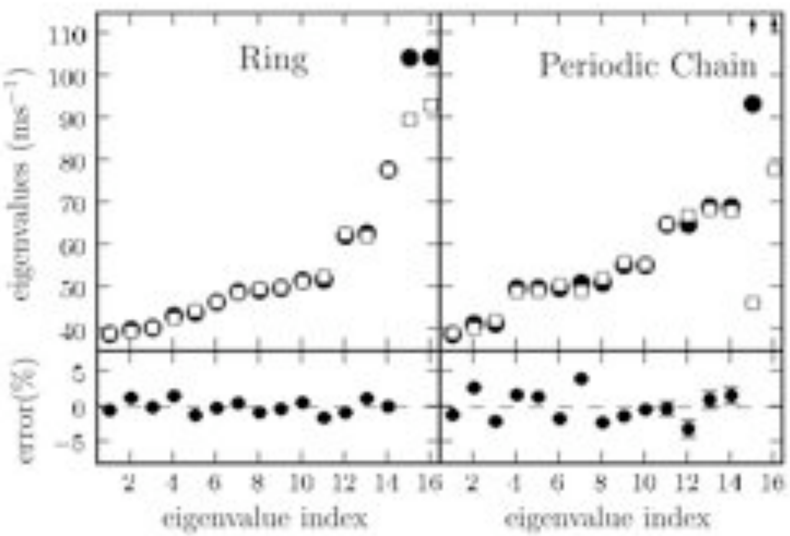


## Mutli-Particle Correlation (collab. DiLeonardo, Rome)

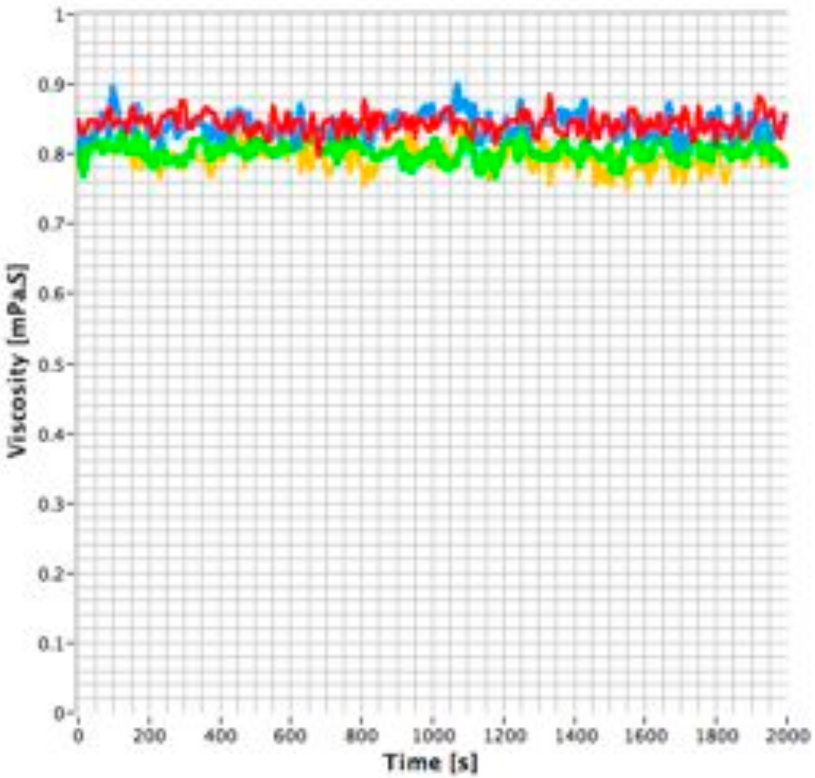
- Eigenmode analysis of hydrodynamically coupled 8 particle ring

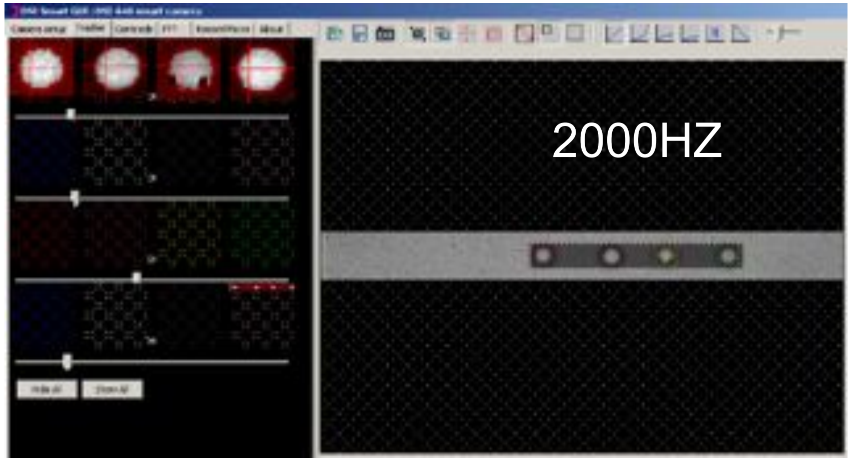



**Di Leonardo *et al*. Phys. Rev. E, 76, 061402, 2007**

# Multipoint viscosity measurement



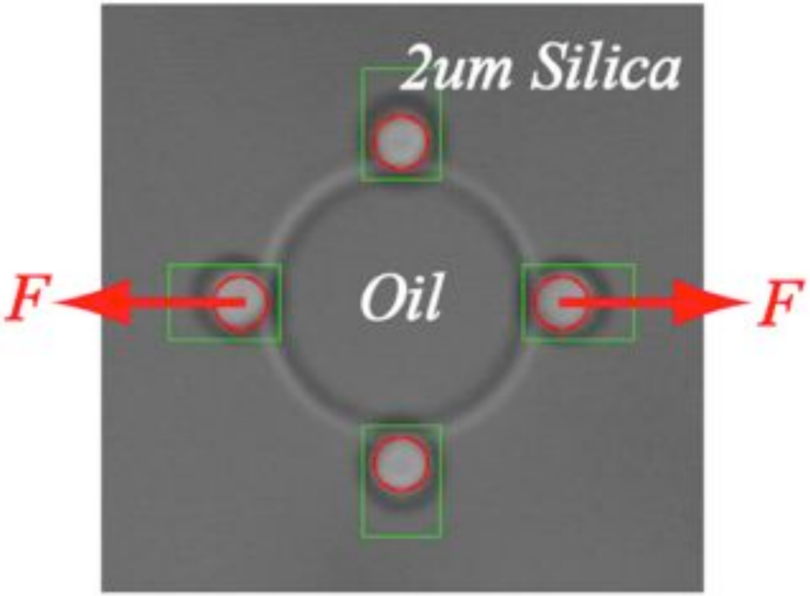



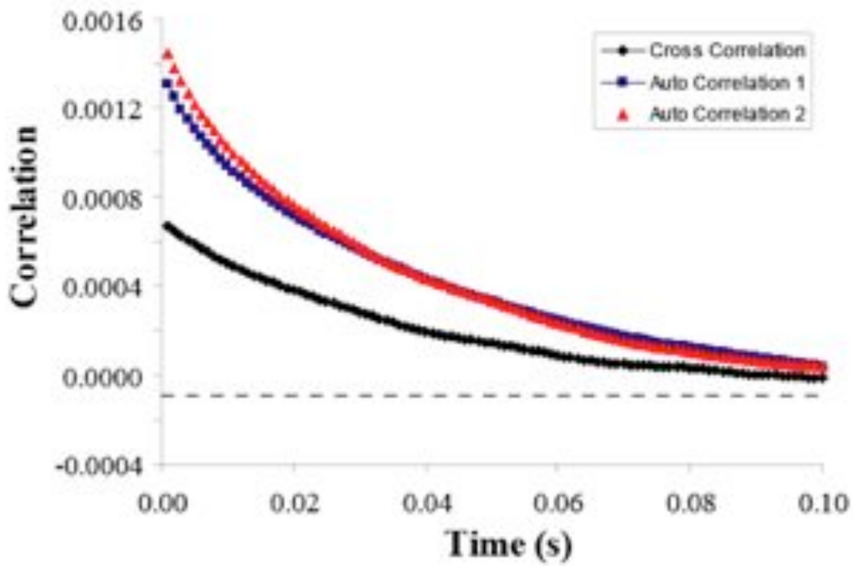

$$\eta = \frac{k_B T}{12\pi^2 a f_0 \langle x^2 \rangle}$$

viscosity of water at 25C = 0.89 mPa.S

# How squishy is that droplet ?

- Measuring compliance at DC AND AC



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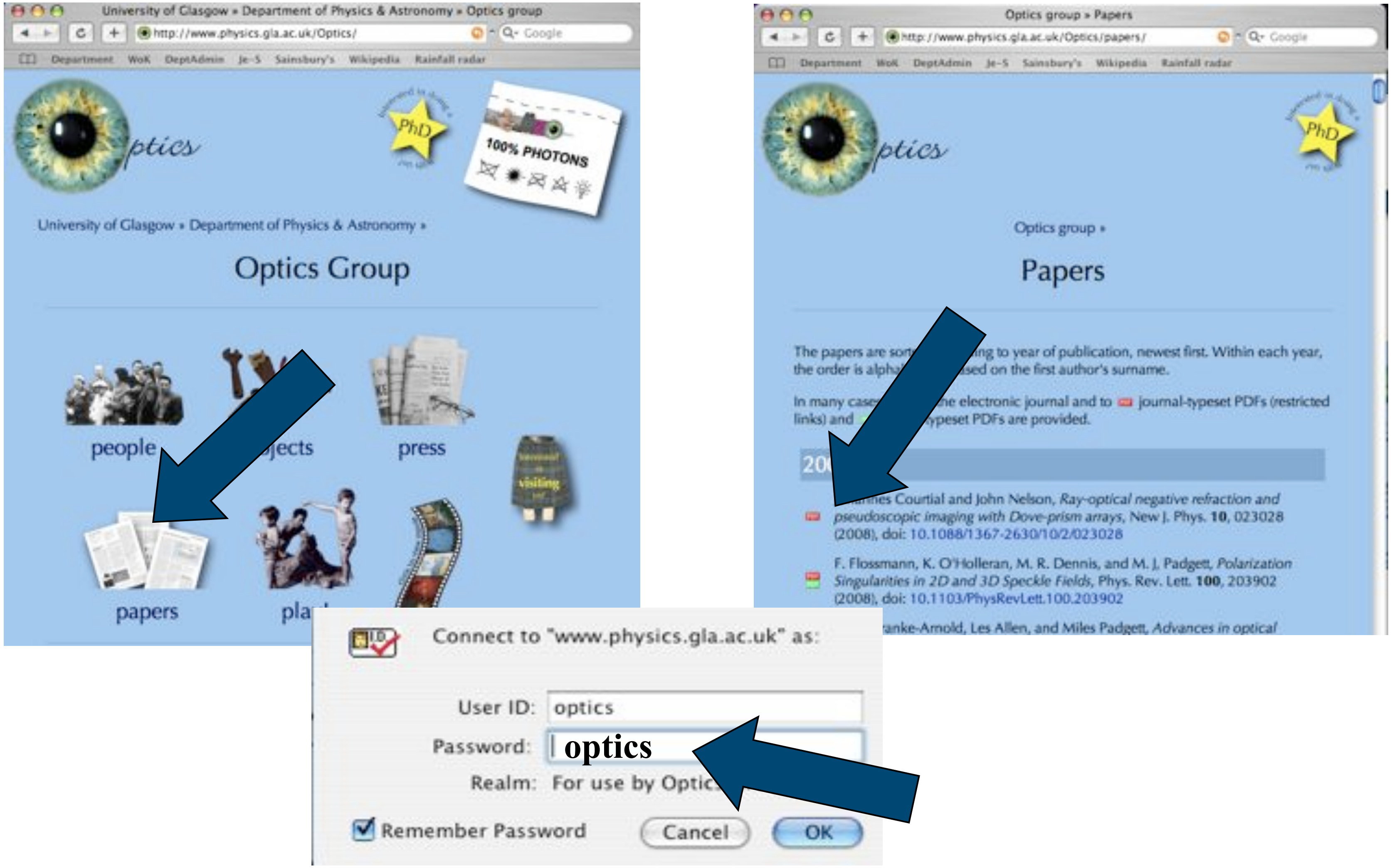
## www.physics.gla.ac.uk/Optics



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# Some of my collaborators

## Internal

Jonathan Leach
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Richard Bowman
Glasgow

Graham Gibson
Glasgow

Daryl Preece
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## External

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Rome

Gordon Love
Durham

Mervyn Miles
Bristol

Jon Cooper
Glasgow EE

## Many Thanks

Come and visit us!

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