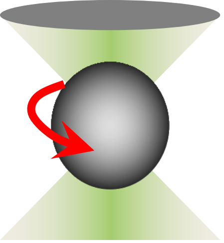
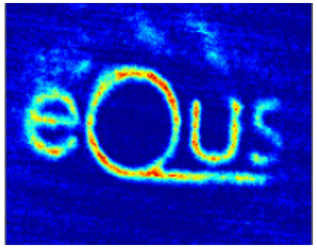
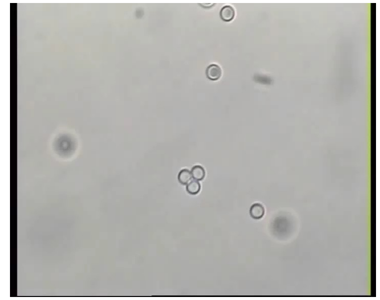
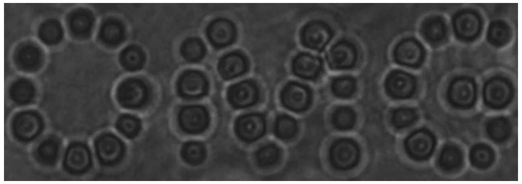


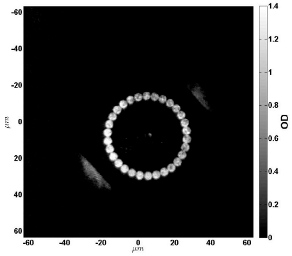


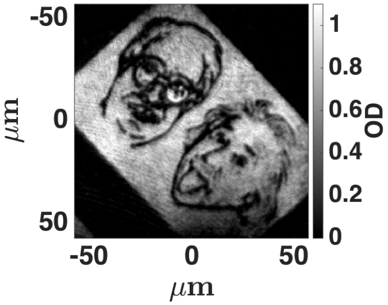




Sculpted Light and Applications

Halina Rubinsztein-Dunlop
T. Neely, G. Gauthier, S. Simianovski, Z. Kerr, M. Davis, I. Favre-Bulle, D. Armstrong, M. Watson, T Nieminen, A. Stilgoe
ARC Centre of Excellence for Engineered Quantum Systems and Optical Micromanipulation Group, School of Mathematics and Physics, The University of Queensland, Brisbane, Queensland 4072, Australia.





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AUSTRALIAN INSTITUTE OF PHYSICS CONGRESS
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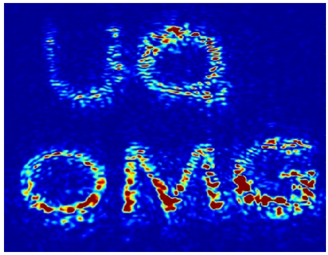
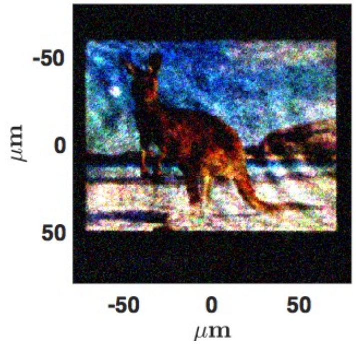
7th INTERNATIONAL WORKSHOP OF SPECIALTY OPTICAL FIBRES AND THEIR APPLICATIONS
COMMAD
CONFERENCE ON OPTOELECTRONIC AND MICROELECTRONIC MATERIALS AND DEVICES

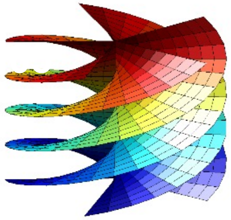
EQUS

OUTLINE

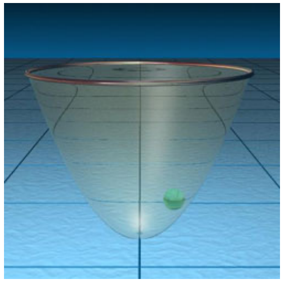


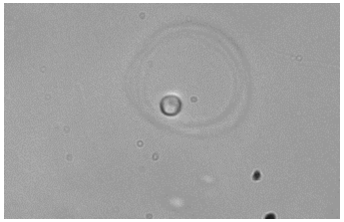
- *Why use sculpted light*
- *How to create sculpted light*
  - *How to create best image – corrections, feedback*
- *BECs in configurable, dynamic optical dipole traps*
  - *Putting the Bose and Einstein back in BEC*
  - *Atomtronics*





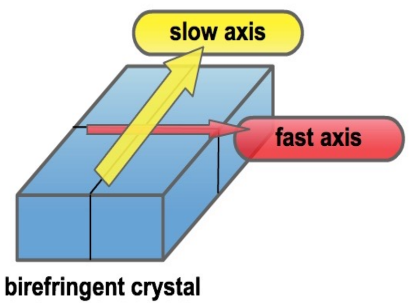
- Optical Micromanipulation
  - *Transfer of Linear Momentum of light*
  - *Transfer of Angular Momentum of Light*
  - *Applications*
    - *Measurements of Complex Biological Systems*
    - *Light Shaping for Optically-driven Micromachines*
    - *Light shaping for active matter*

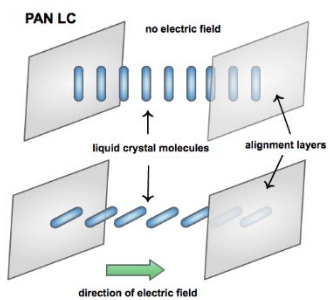




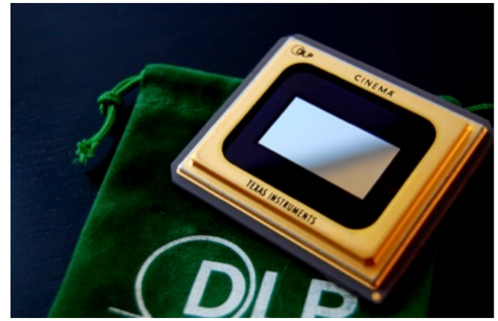
Which SLM to use?

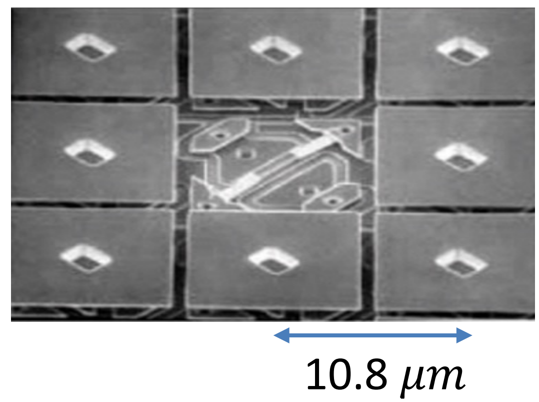
Liquid Crystal (LC) SLM

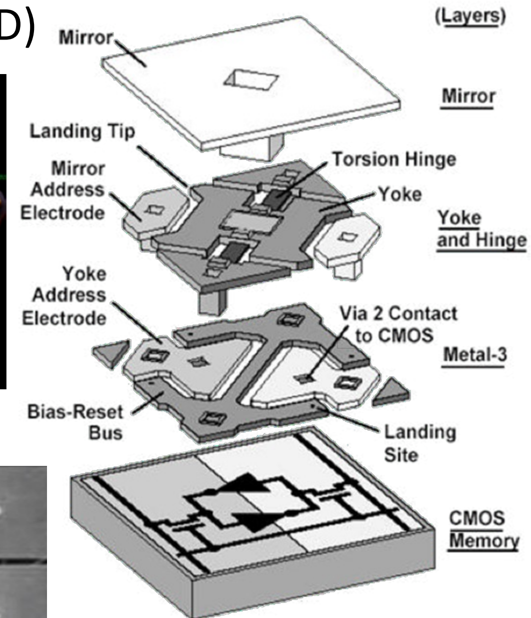




Digital Micromirror Device (DMD)



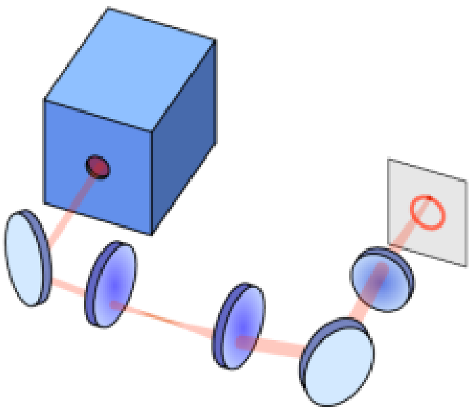




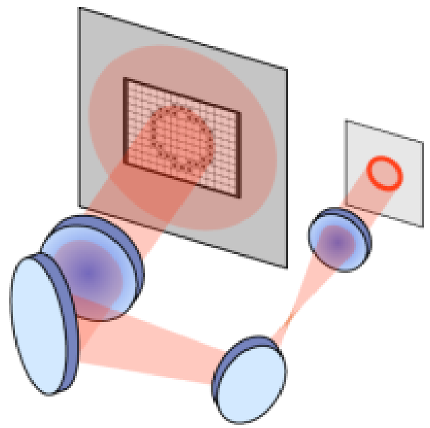
Type	Speed	Resolution	Diffraction Eff.	Cost
DMD	20 - 30 kHz	1920 × 1200	~40 – 50%	10k – 30k
LC SLM	< 300 Hz	1920 x 1080	~65 – 80%	10k – 30k
DM	20 kHz	64 x 64	~60 – 80%	> 100k
AOD	2 MHz	1 x 1	> 90%	3k – 15k

Optical trapping technologies

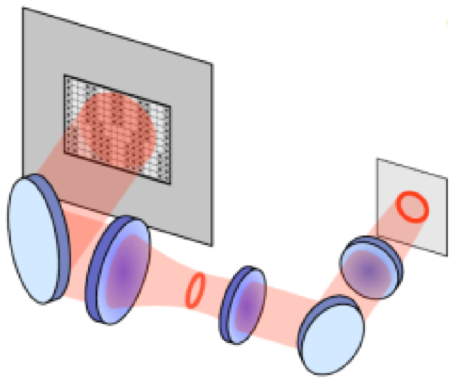
example - a ring shape potential



A bidirectional beam deflector (AOD or EOD) - rapid scanning of the focused beam 'paints' the time-averaged potential.

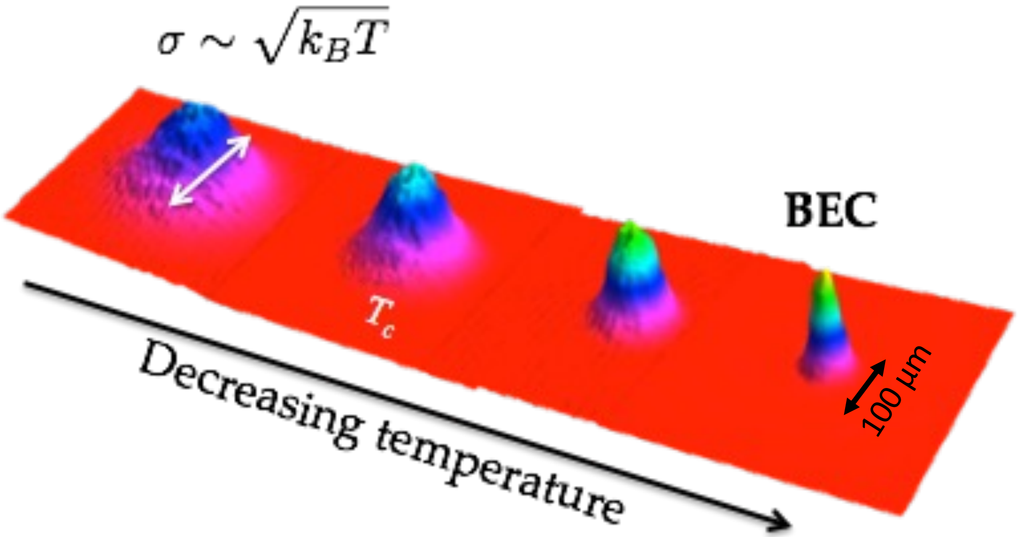


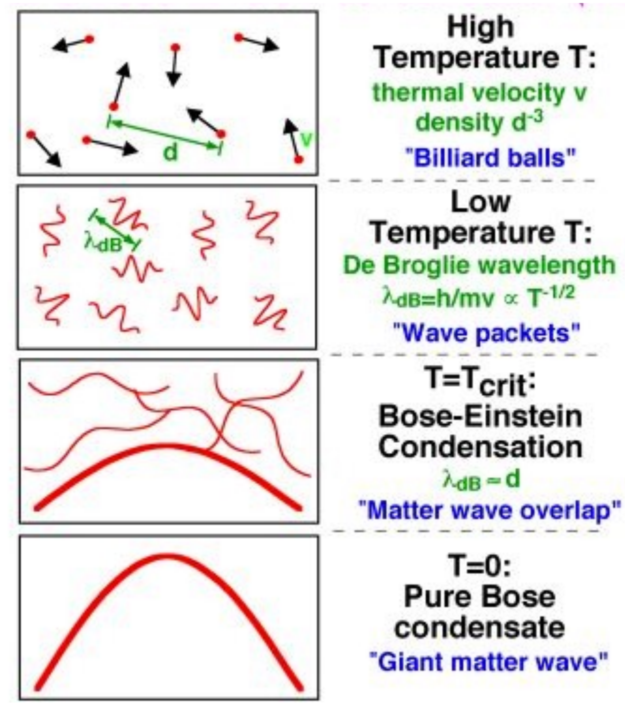
Direct imaging of a digital micromirror device (DMD-SLM)- the mirrors configured to produce a ring-shaped mask that is directly imaged to focal region



A liquid-crystal spatial light modulator (LCD-SLM) produces a ring trap - changing the spatial properties of light in the Fourier plane →projected by the optical system into a field in the image plane.

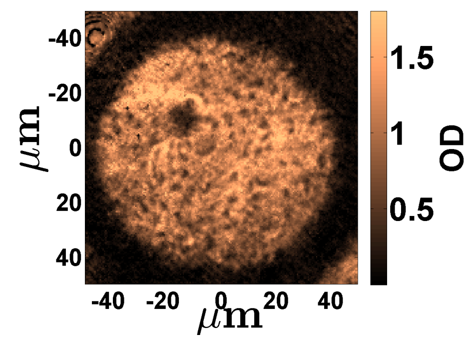
Bose-Einstein condensation in dilute gases





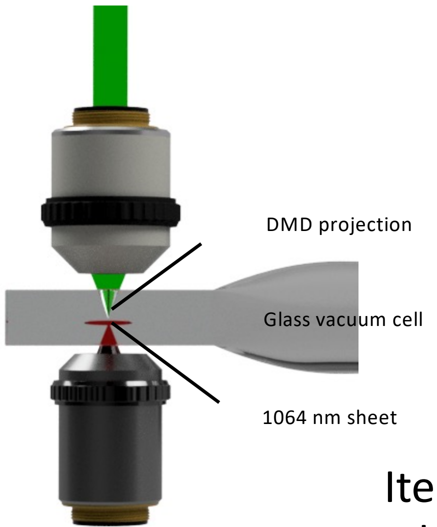
Superfluid - frictionless fluid flow (zero viscosity), quantised vortices

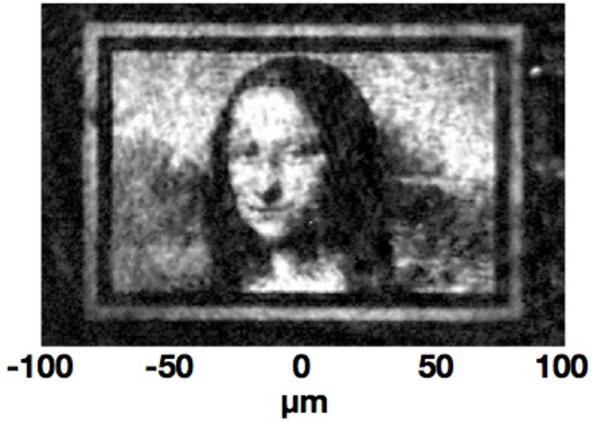
Frictionless flow in superfluid helium

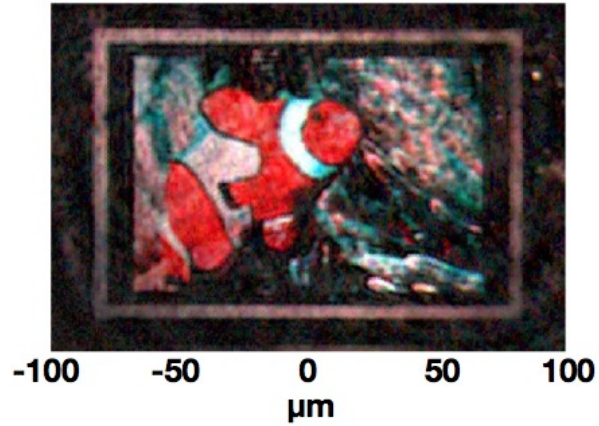


Quantised vortices (small density dips in an atomic BEC)

The UQ superfluid art gallery (optimised halftoning)

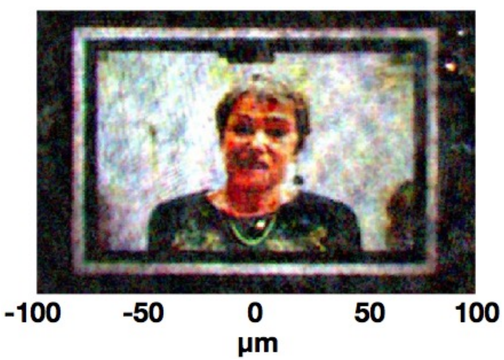




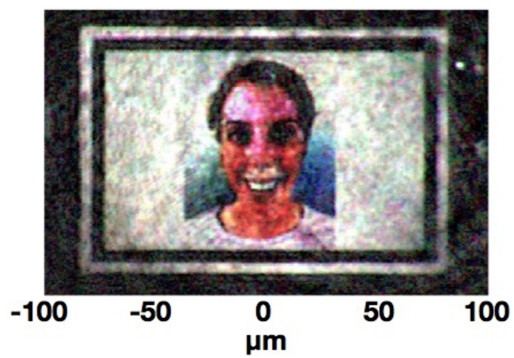


Iterative feedforward of the DMD pattern based on binary half toning, where multiple mirrors contribute to each point in the projected potential

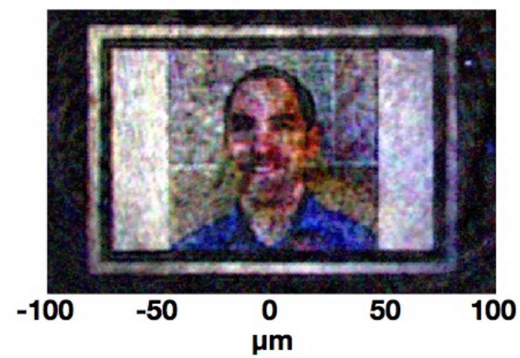
Liang, Jinyang, et al. "1.5% root-mean-square flat-intensity laser beam formed using a binary-amplitude spatial light modulator." Applied Optics ***48*** *(2009): 1955-1962.*



Halina Rubinsztein-Dunlop



Lauren McQueen

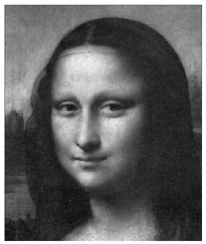


Tyler Neely

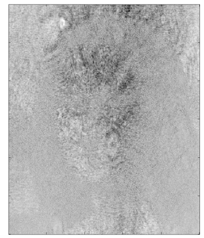
Feedforwards Algorithm

No Feed back

Target Image

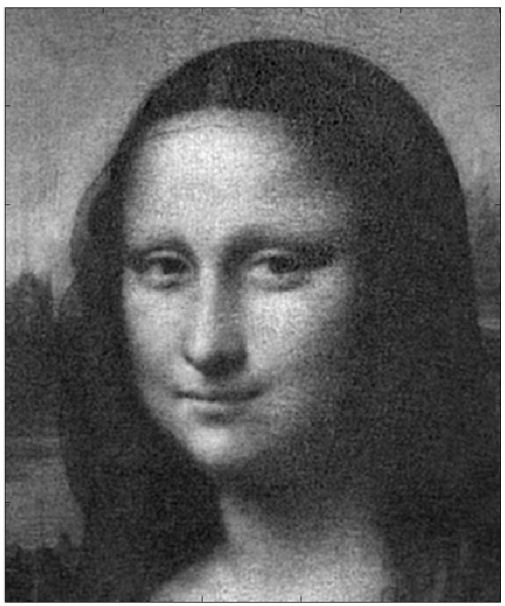


Correction Map

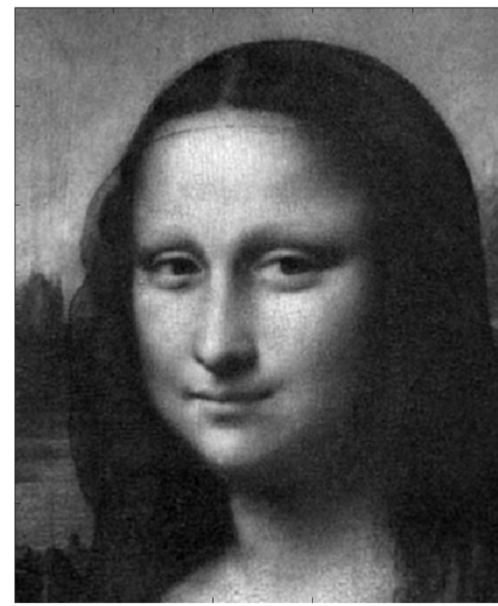


```
While Feedback
   Projected_Light = FloydDithering(Corrected_Target)
   Capture Image
   Correction_Map = Image - Target_Image
   Corrected_Target = Corrected_Target - factor * Correction_Map
```

1 Tone Floyd Dithered Feed forwards

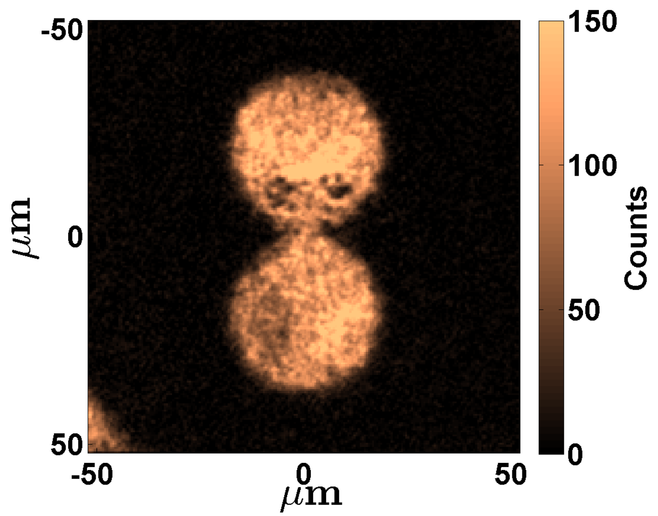


4 Tone Floyd Dithered Feed forwards



Superfluid atomtronic circuits

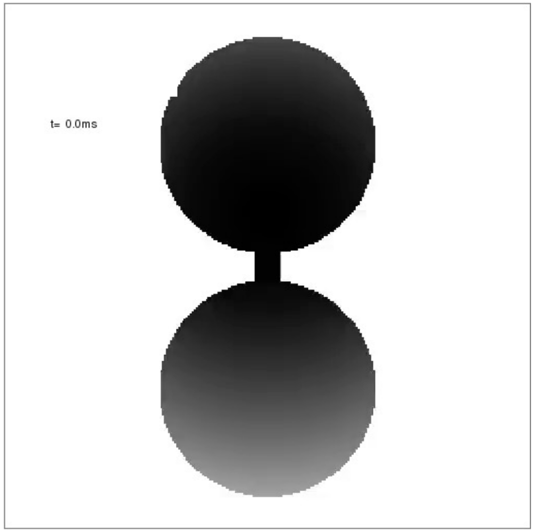
Highly-tunable superfluid oscillator circuit in a quantum gas



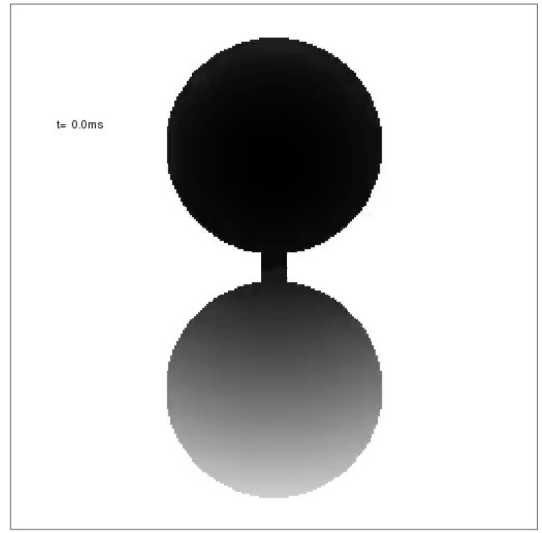
A simple atomtronic circuit – superfluid oscillates between two reservoirs under an initial chemical potential bias. Large biases lead to resistive shedding of quantised vortices.

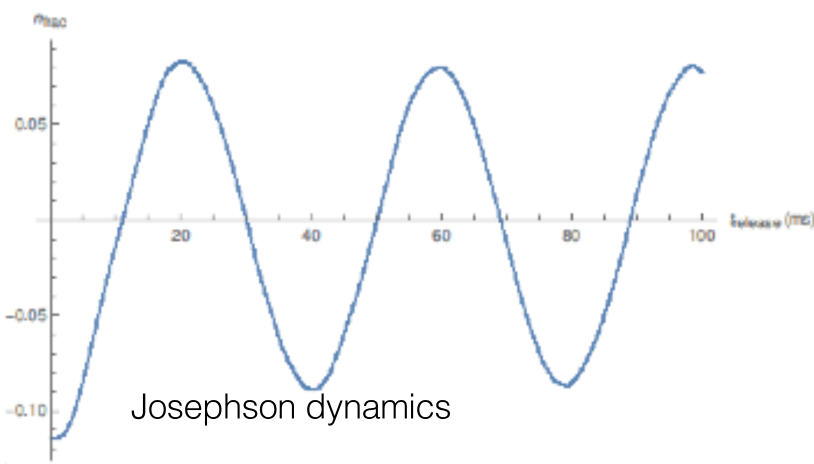
Atomtronic Oscillator
Small bias case (UQ simulations) — 7 μm channel

11% initial bias (UQ)

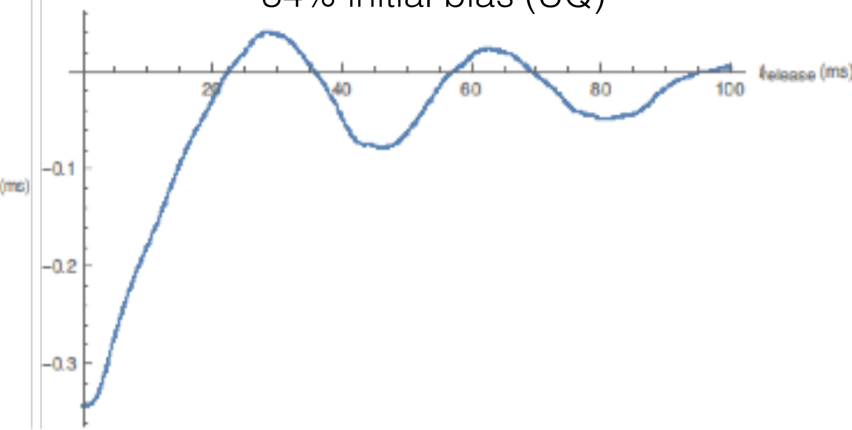


22% initial bias (UQ)





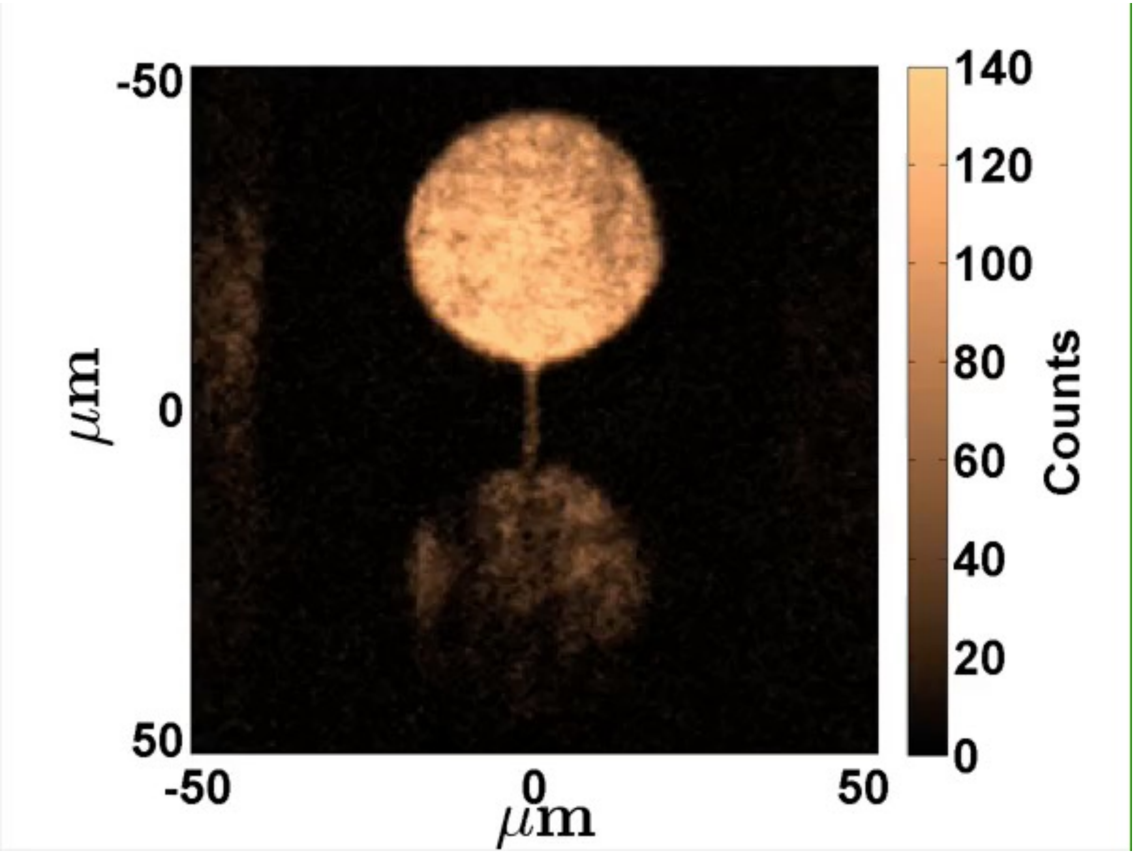
34% initial bias (UQ)



$$f_N = \frac{(N_L - N_R)}{N_L + N_R} \qquad \dot{\theta} = -\frac{\Delta\mu}{\hbar}$$

$$\dot{f}_N = \frac{2\kappa}{\hbar}\sin(\theta) \qquad \kappa = \text{tunnel coupling}$$

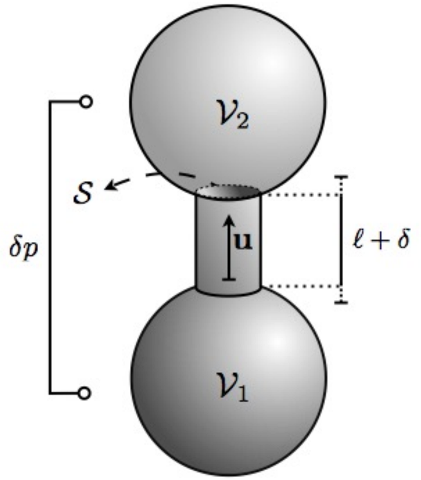
Coupled reservoir dynamics

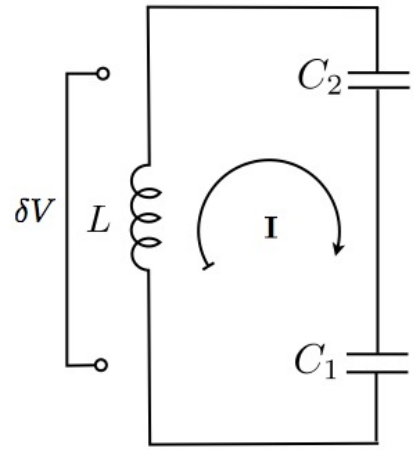


- Continuing previous sequence, with 25 ms steps between frames
- Atom transport apparent
- Excitations visible on some frames

Acoustic model for an atomtronic oscillator

Acoustic Helmholtz Oscillator





LC circuit

Acoustical

$$E = \frac{1}{2}\int d^3x\,(\rho_0|\mathbf{u}|^2 + \kappa\,\delta p^2)$$

$$\omega = c\left[\frac{\mathcal{S}}{(\ell+\delta)}\left(\frac{1}{\mathcal{V}_1}+\frac{1}{\mathcal{V}_2}\right)\right]^{1/2}$$

$\delta p \leftrightarrow \delta V$

$\Longleftrightarrow$

$\mathcal{S}\mathbf{u} \leftrightarrow \mathbf{I}$

Electrical

$$E = \frac{1}{2}(LI^2 + C\,\delta V^2)$$

$$\omega = \left[\frac{1}{L}\left(\frac{1}{C_1}+\frac{1}{C_2}\right)\right]^{1/2}$$

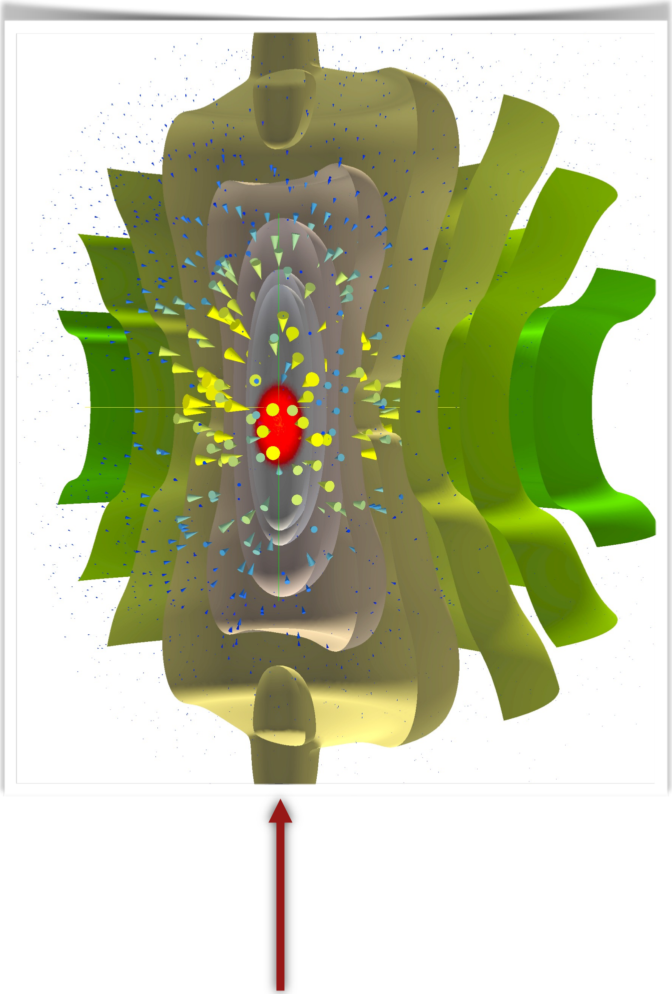
Equivalence for acoustical and 'lumped' circuit model — can this be applied to the atomtronic circuit?

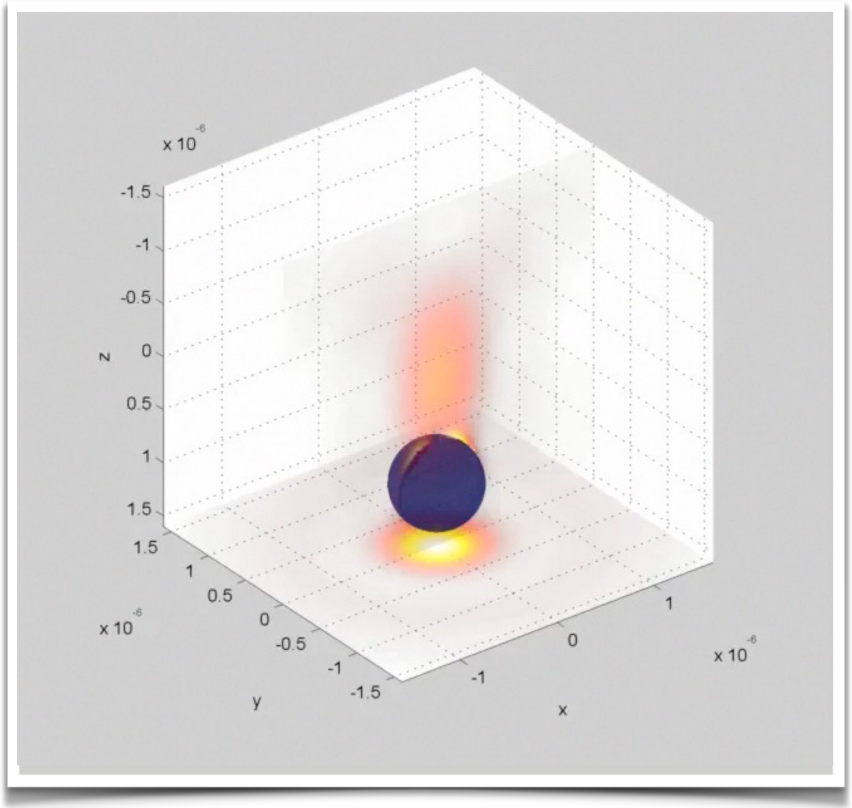
Resulting frequency (proportional to speed of sound *c*):

$$\omega = c\left[\frac{\mathcal{S}}{(\ell+\delta)}\left(\frac{1}{\mathcal{V}_1}+\frac{1}{\mathcal{V}_2}\right)\right]^{1/2}$$

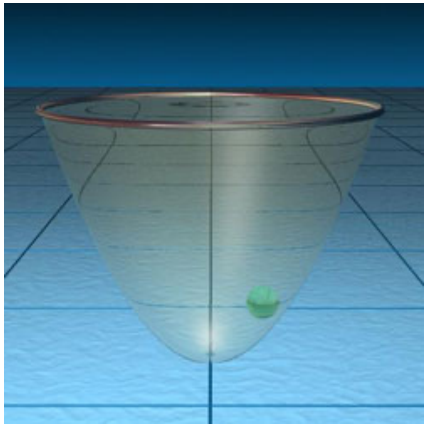
Guillaume Gauthier et al, PHYSICAL REVIEW LETTERS 123, 260402 (2019)

Optical tweezers



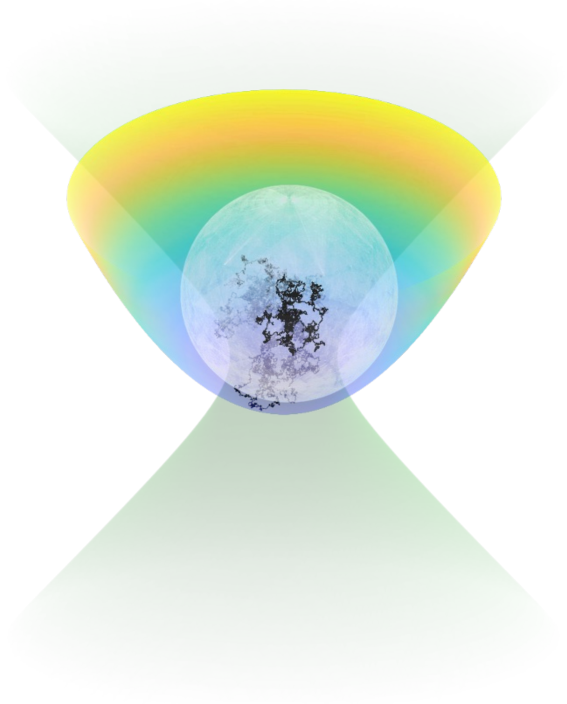


Why Optical Tweezers

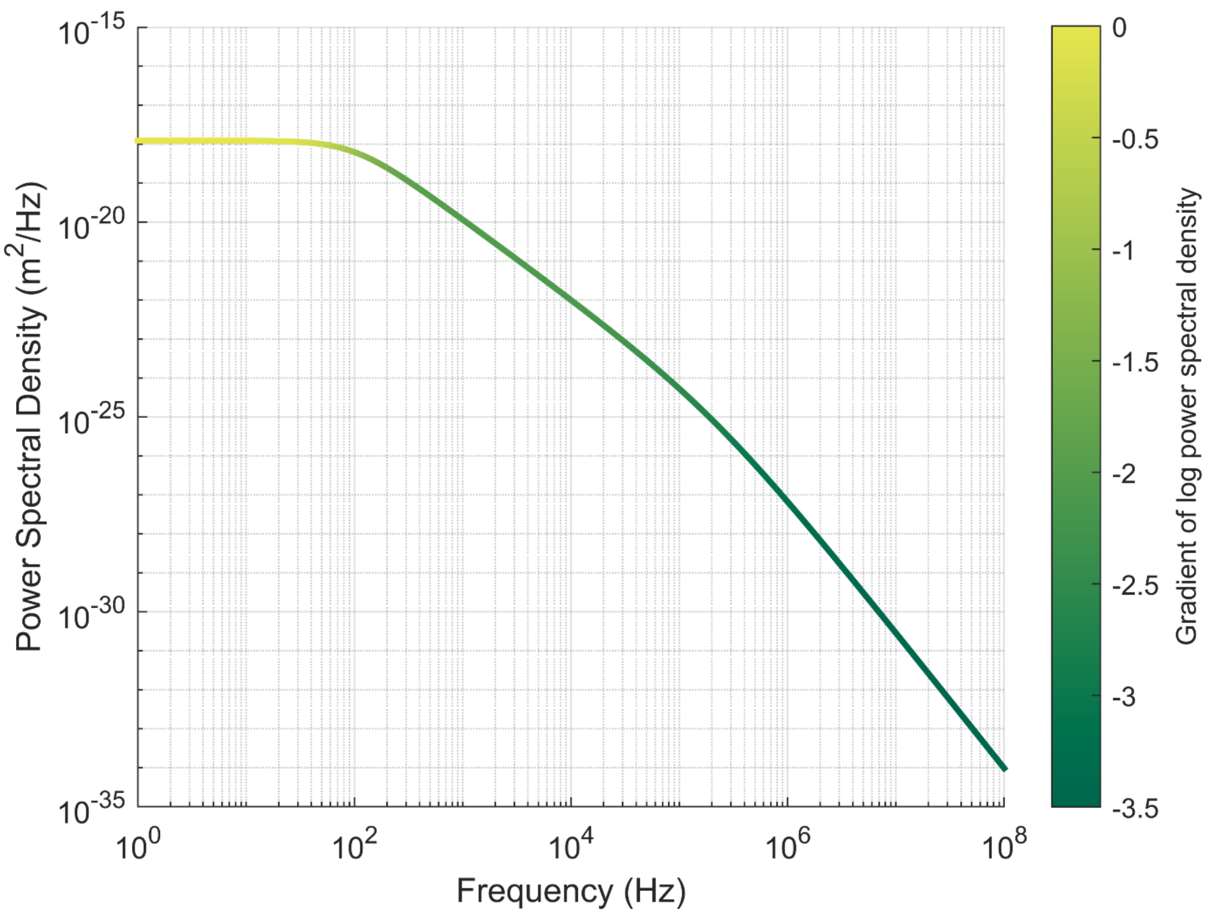


- Exploring classical-quantum interface
  - Cooling to the ground state
  - Quantum friction
- Diagnosis of medical conditions
  - Limited sample volume available
- Characterisation of inhomogeneous fluids
  - Micron sized structures can be explored
  - Possible deduce properties of polymer structures
- Measurements in tight geometries
  - Rheology inside and around cells
- Broad frequency measurements
  - Large scale rheometry is limited by inertial effects

Dynamics in the trap



$$\tfrac{1}{2}k_B T = \tfrac{1}{2}\alpha\left\langle x^2 \right\rangle$$

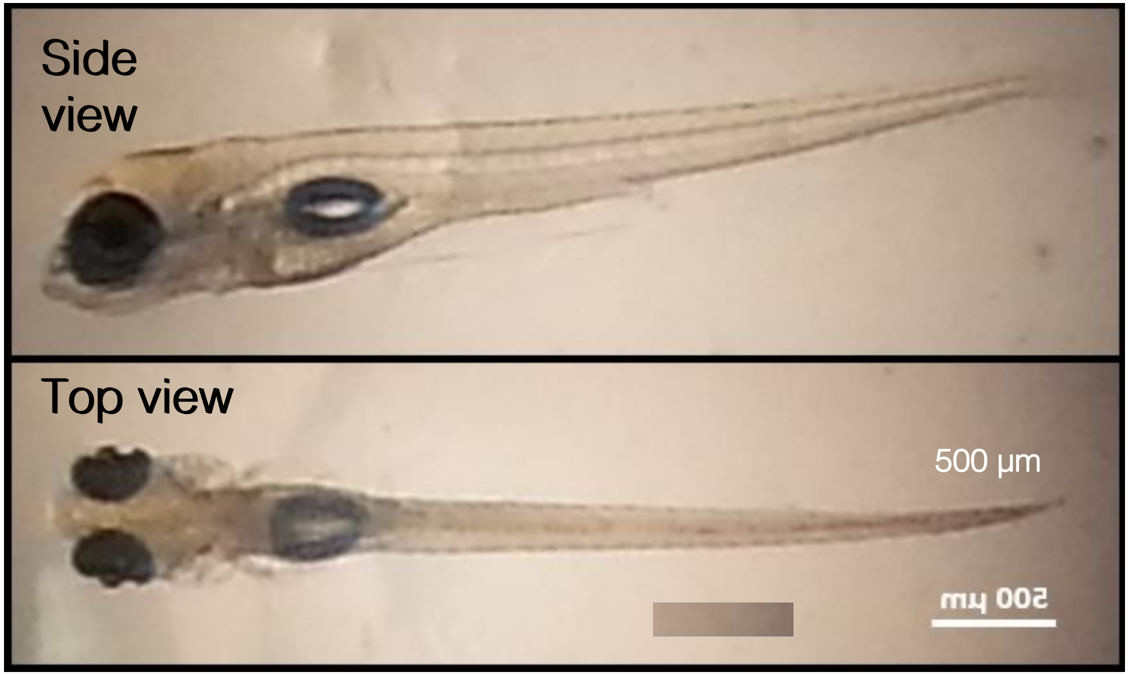


- roll off frequency f_0
- trap stiffness

$$\alpha = 2\pi\, f_0 \cdot 6\pi\, a\eta$$

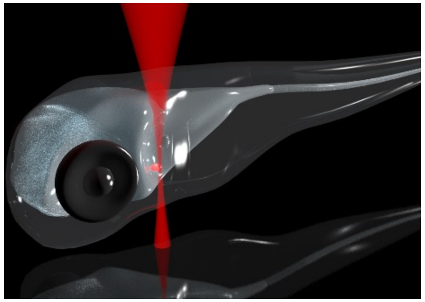
Light shaping for Optogenetics in zebrafish

Optical Trapping for in-vivo manipulations

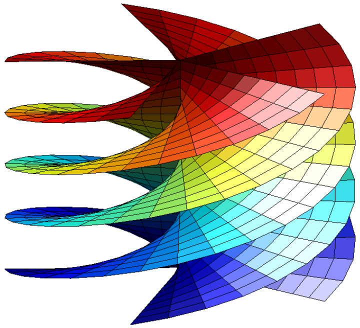


I. Favre-Bulle, Unpublished data

Zebrafish: Model for brain processes



Optical Tweezers

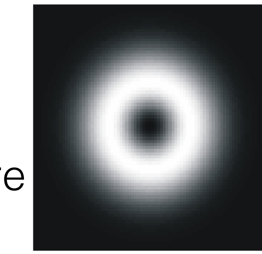


- Can also transfer angular momentum
- Phase-front curvature allows orbital angula. momentum transfer

$$\pm l\hbar/photon$$

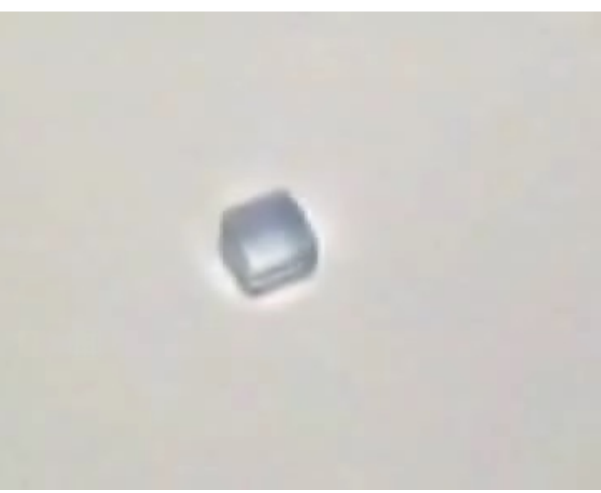
of orbital angular momentum

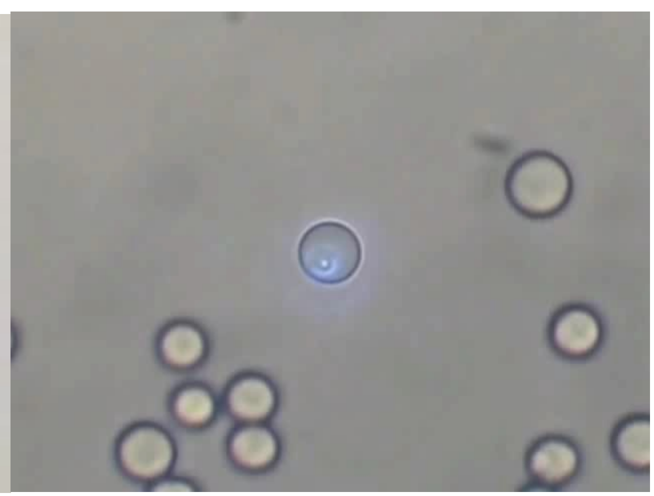
- optical vortex’
- ‘singular beam’
- ‘Gauss-Laguerre
- GL$_{pl}$

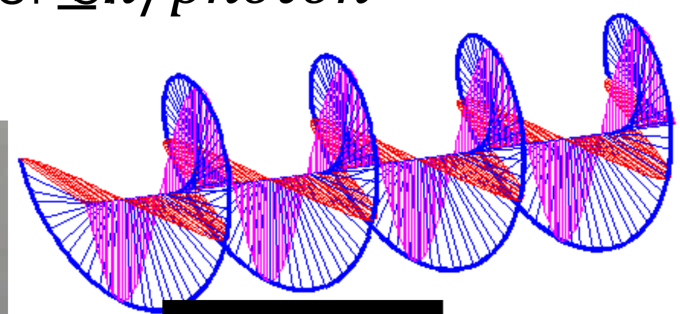


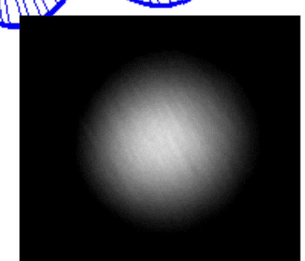
- Polarisation change allows spin transfer of $\pm\hbar/photon$

e.g. birefringence









Gaussian beam

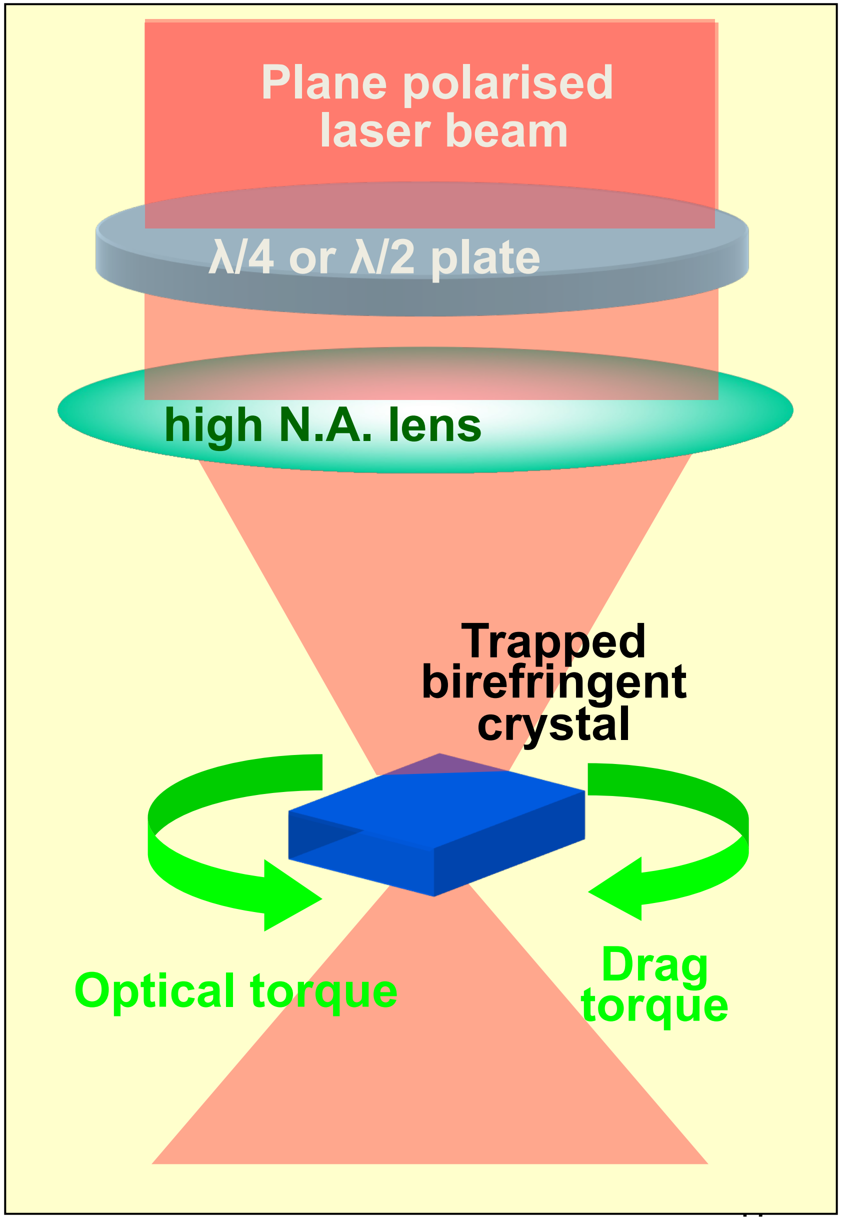
Transfer of AM to a waveplate

- $CaCO_3$ particles in H_2O are 3-D trapped in polarised light

- They either rotate continuously or align to a particular orientation

- In linear light, their orientation is controllable

- In elliptical light, their rotation frequency is controllable.



Friese *et al.*, *Nature 1998*

Transfer of angular momentum of light

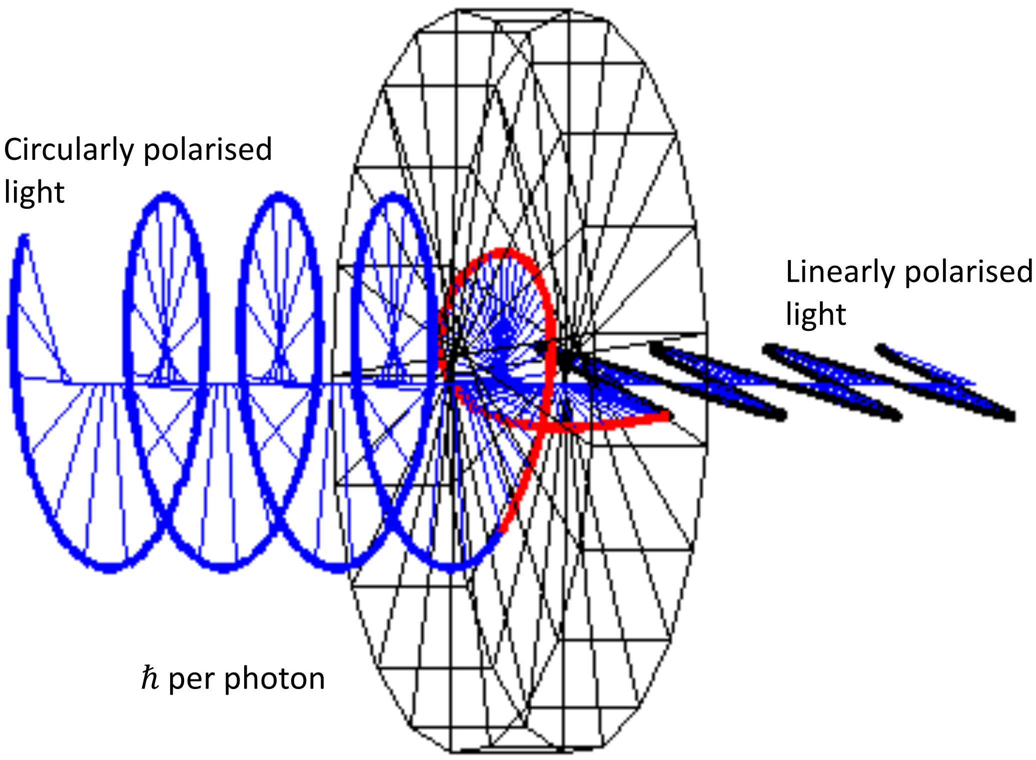
alignment

rotation

Optical axis of crystal aligns to electric field vector

Friese et al 1998, Nature, **10.1038/28566**

Angular Momentum Transfer - birefringence



particle rotates to reduce the change in angular momentum.

- optically applied torque

$$\tau_R = \frac{\Delta\sigma P}{\omega}$$

- viscous drag torque

$$\tau_D = 8\pi\mu a^3\Omega$$

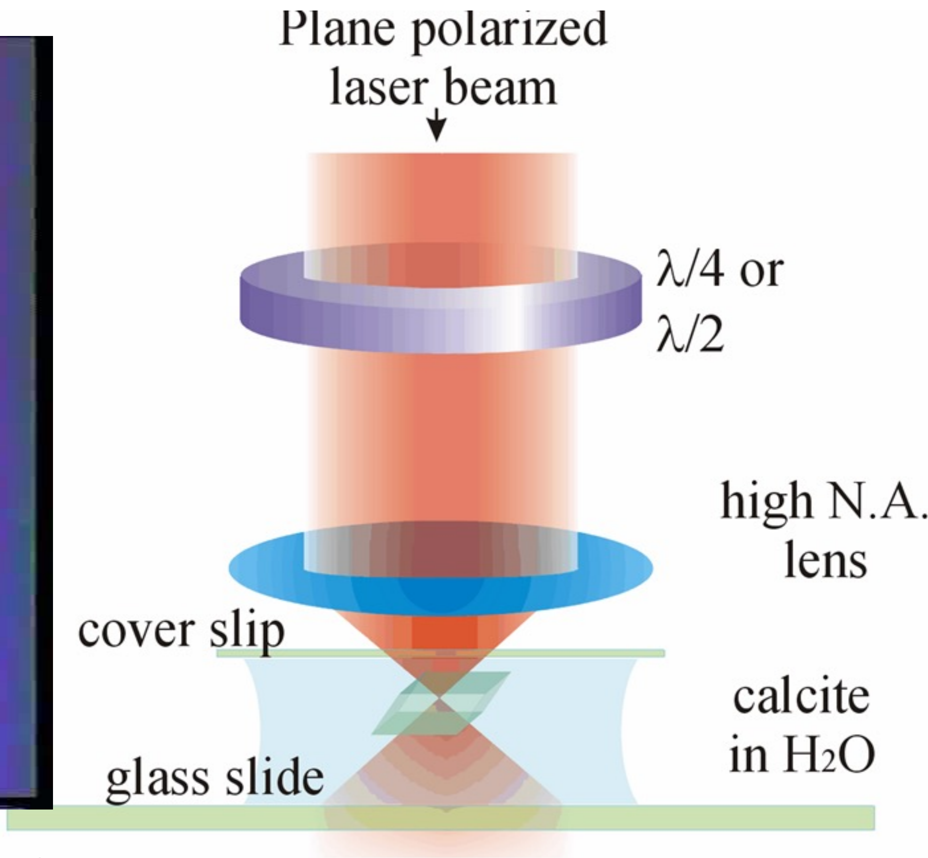
$\Delta\sigma$ = change in polarisation
P = laser power
ω = optical frequency

μ = viscosity of surrounding liquid
a = sphere's radius
Ω = frequency of rotation

$$\mu = \frac{\Delta\sigma P}{8\pi a^3\Omega\omega}$$

Transfer of angular momentum of light

rotation



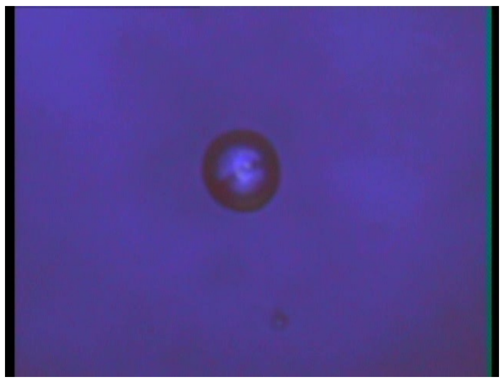
Calcite crystal rotates in circularly polarised light

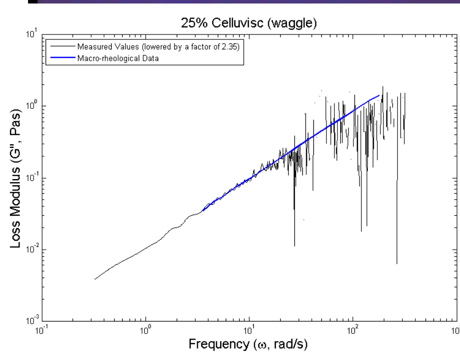
Experimental and handbook values for viscosity agree within 3%

Microviscosity

•We can three-dimensionally trap and rotate vaterite microspheres.

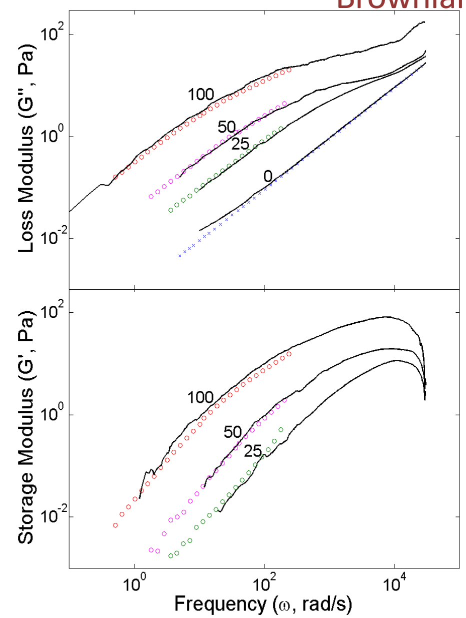
•Use 45° flipping for maximum torque.





Active measurement

Brownian Motion

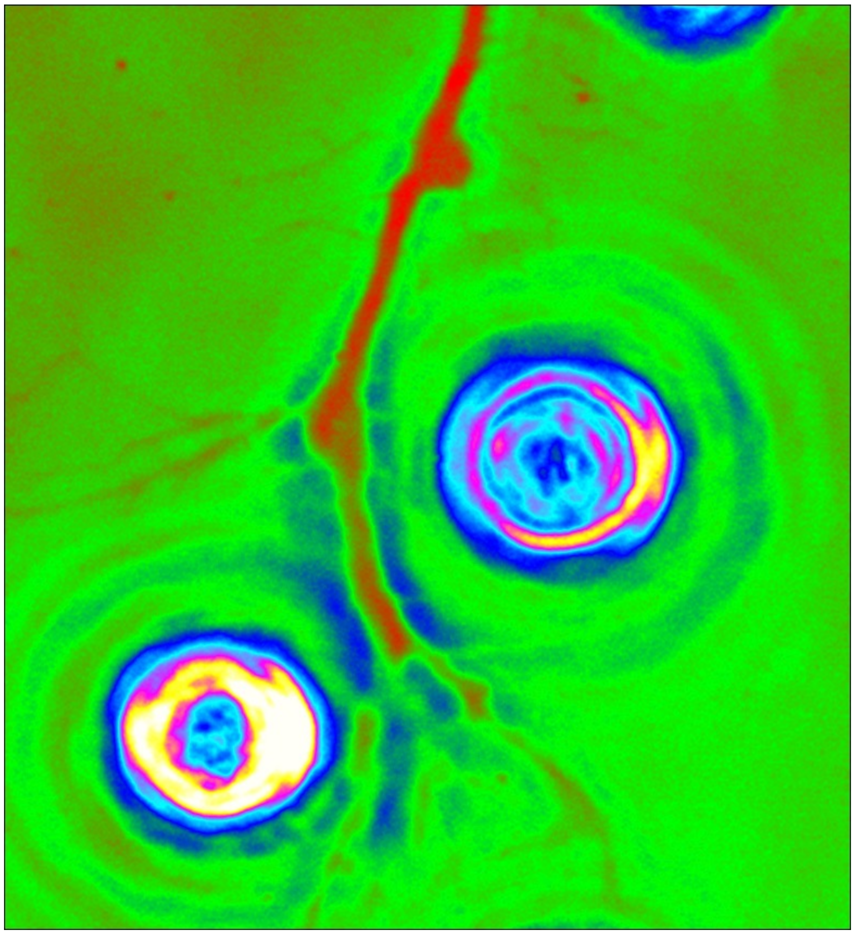


Brownian Motion Measurements (lines) in Water, 25%, 50% and 100% Celluvisc eye drops agree with macro-rheological data (circles) and theory (crosses).

James Bennett et al. Scientific Reports, 2013

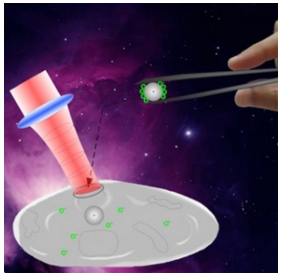
Photon-driven micromotor

Directional nerve fibre growth

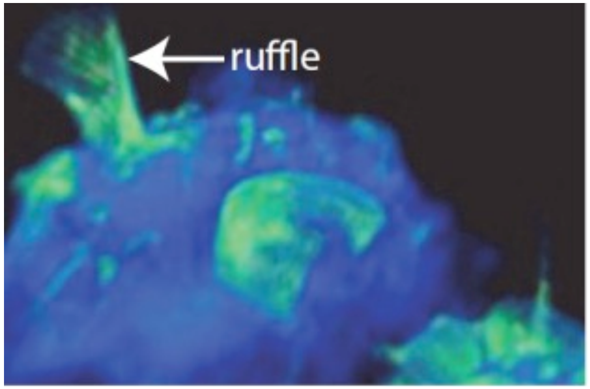

Goldfish retinal ganglion cell axons

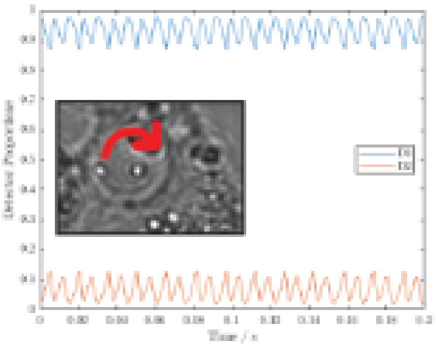
A localized microfluidic flow generating an estimated 0.17 pN shear force against the growth cone that turns in response to the shear.

Tao Wu et al, Nature Photonics, vol 6 , January 2012

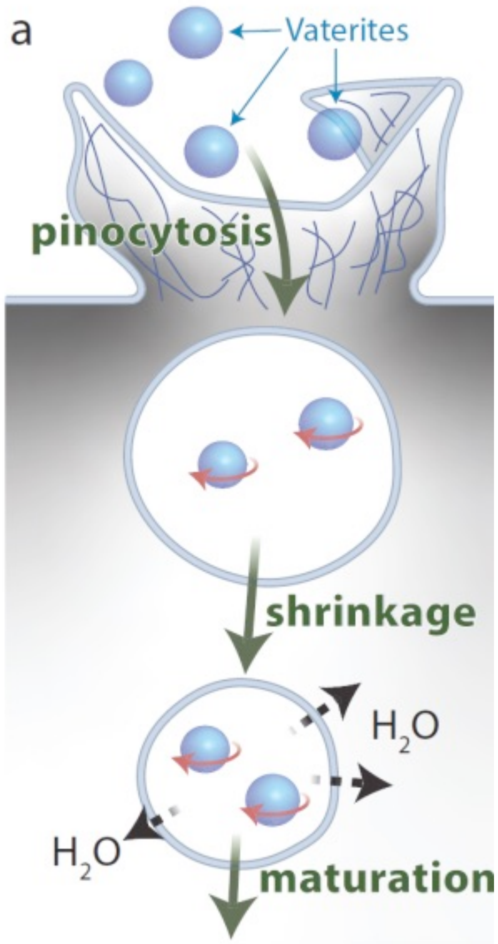


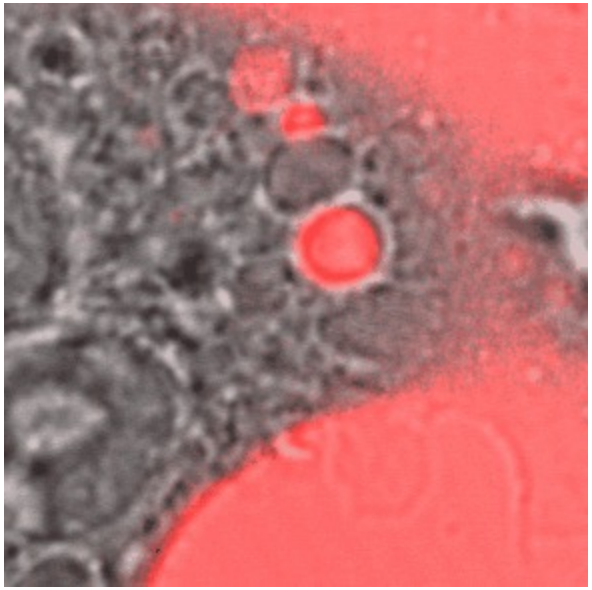
Macropinocytosis

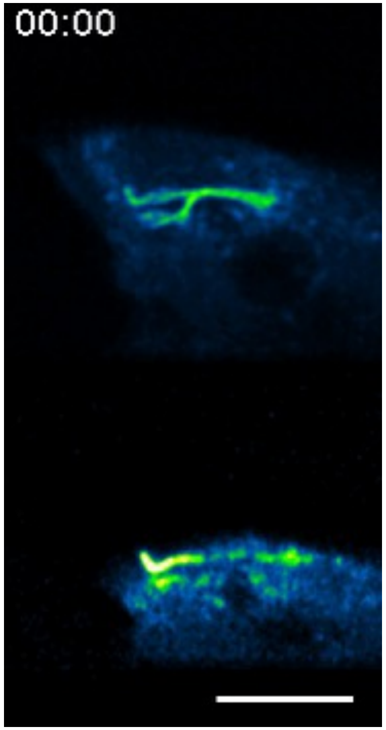




Lattice Light Sheet Microscopy image of a ruffle



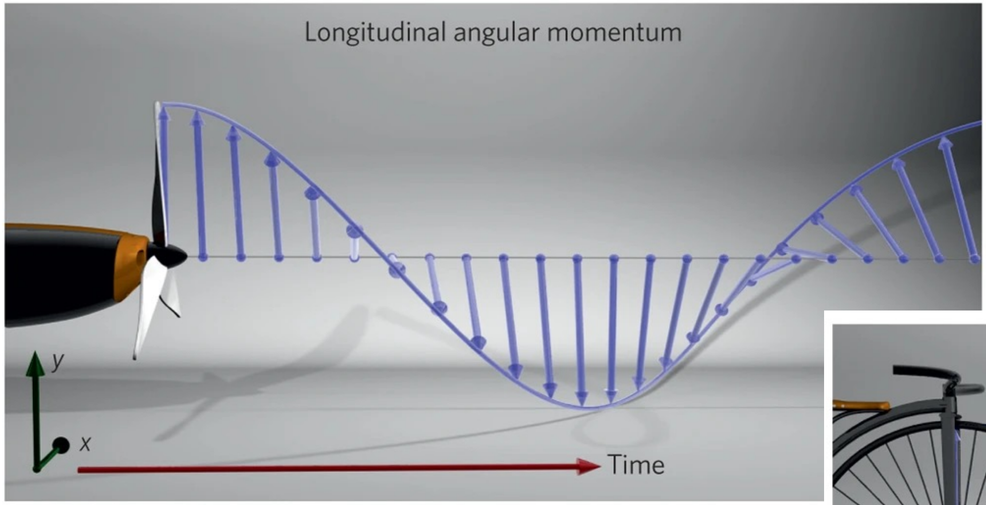




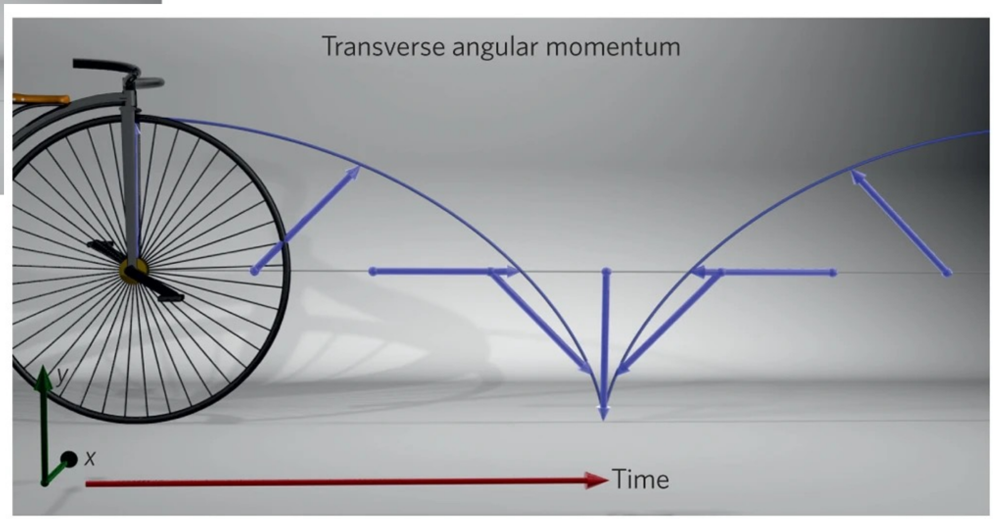
Calibration Methods for in vivo Microrheology with Rotational Optical Tweezers ***Mark Watson, Monday Biophotonics***

Mark Watson et al, Optica 1066 Vol. 9, No. 9 / September 2022

Axial and transverse momentum flux

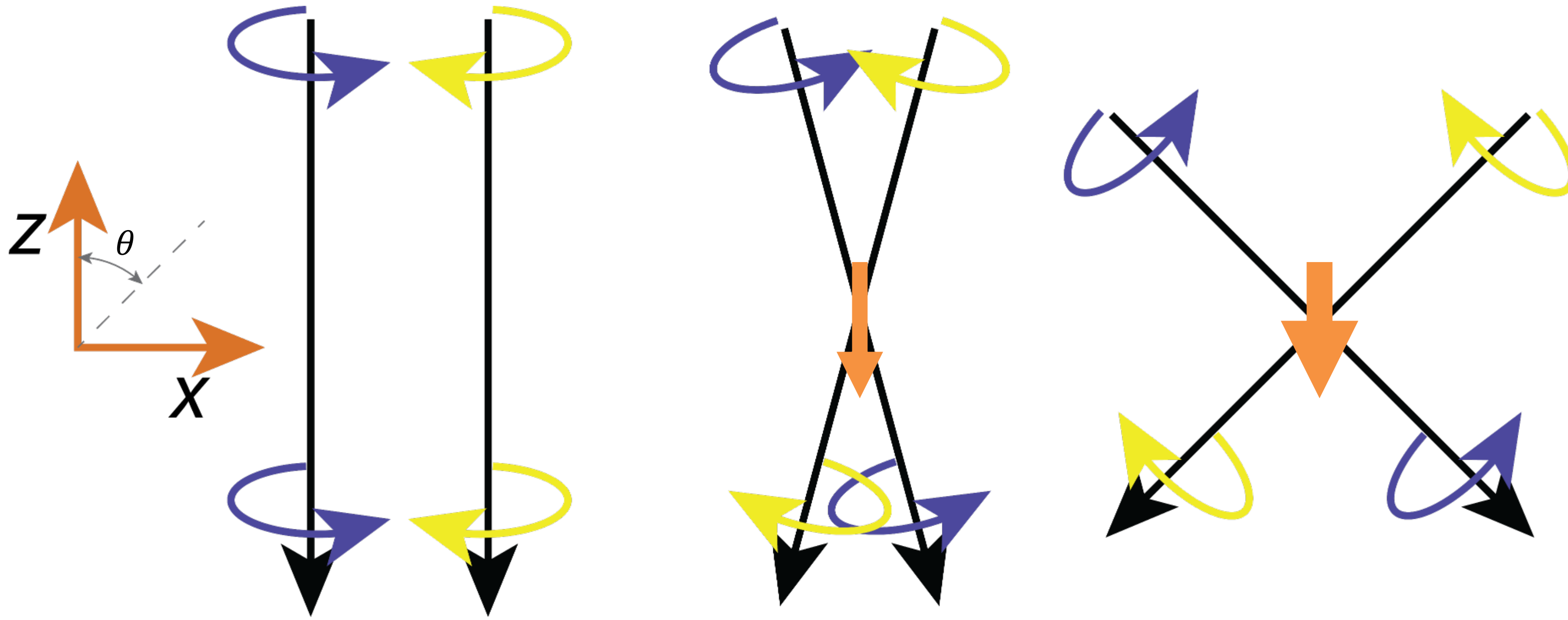


- Transfer of spin angular momentum to absorbing nano-particles.



Aiello et al 2015, 10.1038/nphoton.2015.203
Banzer et al 2013, 10.2971/jeos.2013.13032

Geometrical construction of TAM beam



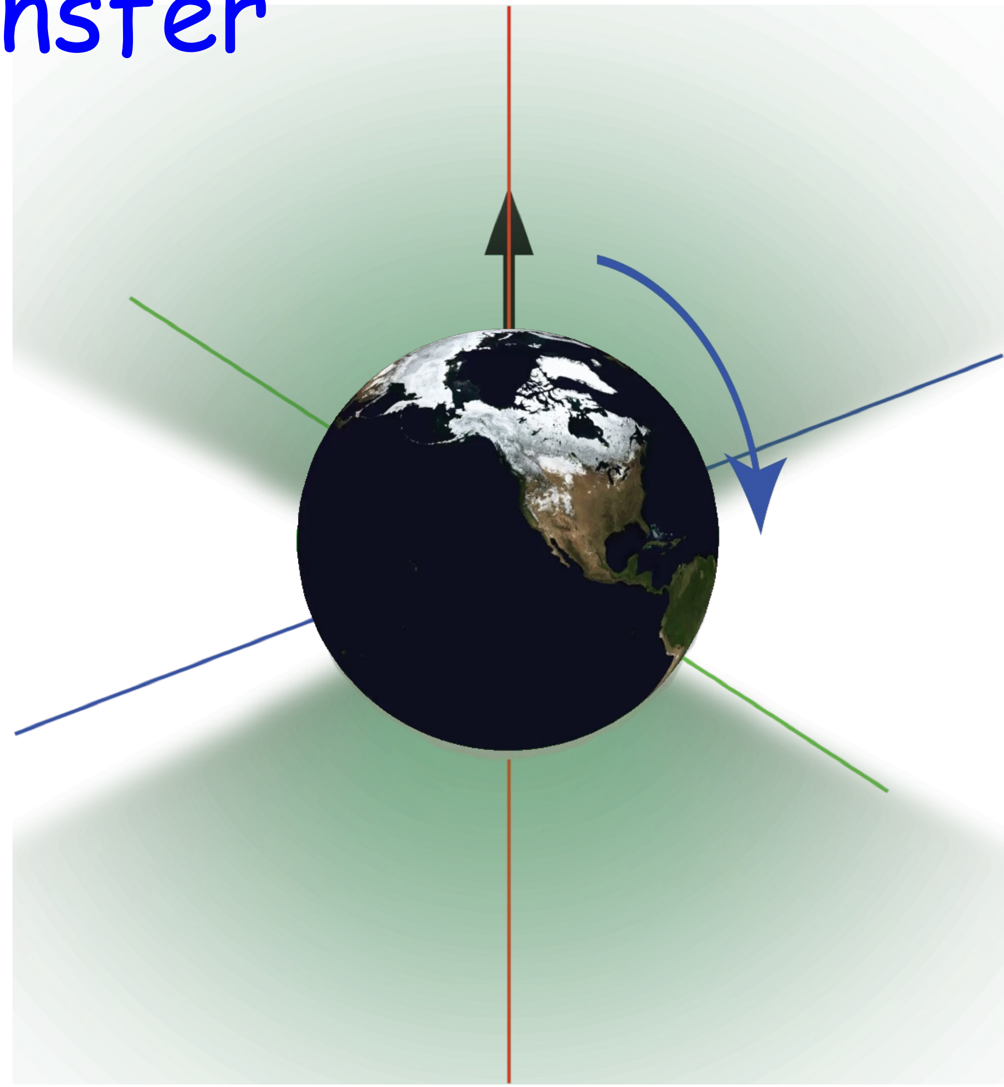
Transverse $\boldsymbol{x}: \sigma_+ \sin\theta_+ + \sigma_- \sin\theta_-$

Axial $\boldsymbol{z}: \sigma_+ \cos\theta_+ + \sigma_- \cos\theta_-$

Stilgoe et al, Nature Photonics ***16****, 346–351 (2022)*

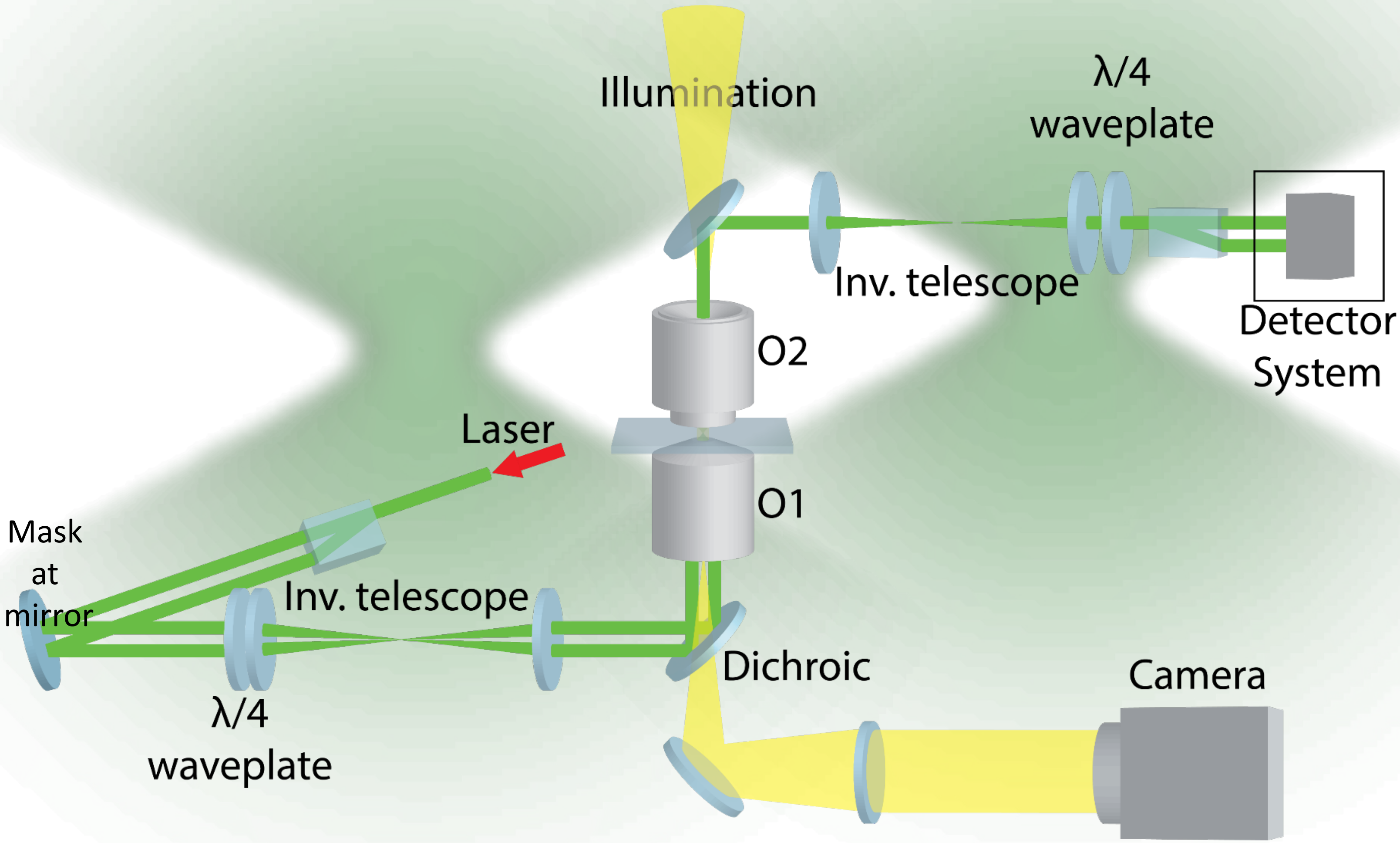
Transverse angular momentum transfer

- Our functional definition: *"Angular momentum transfer with components orthogonal to mean beam propagation direction"*
- Displacement from beam causes this but that is unstable
- In the focus, rotation can be stable



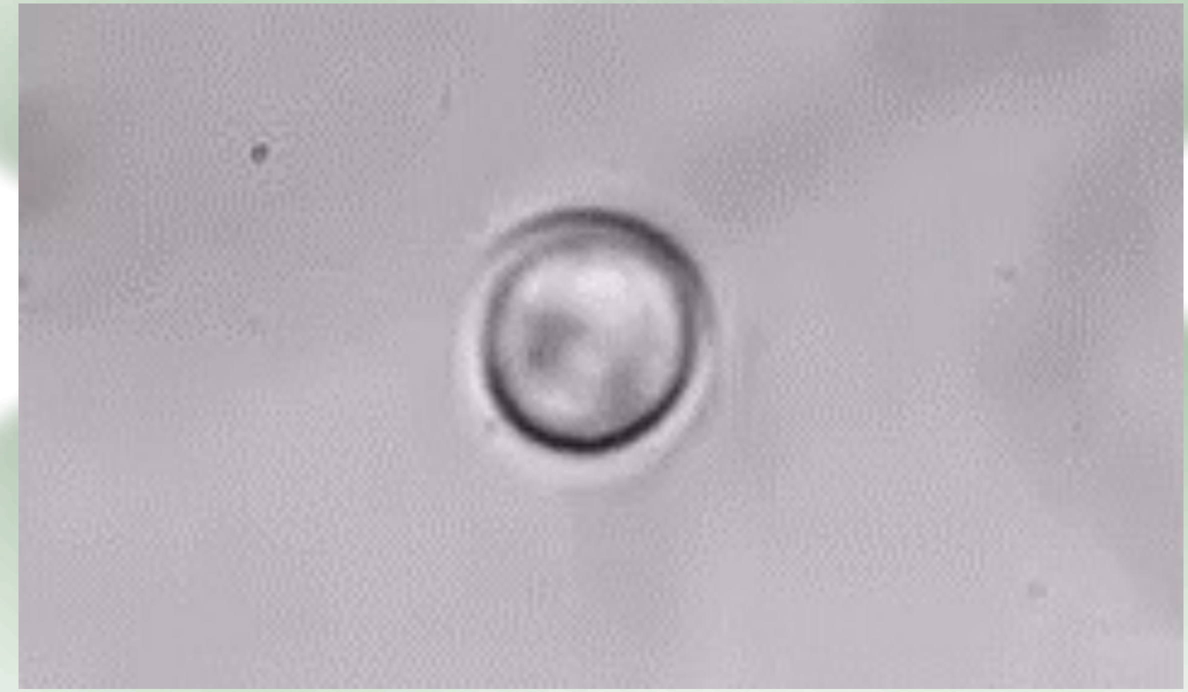
A. Stilgoe et al, Nature Photonics ***16****, 346–351 (2022)*

Apparatus

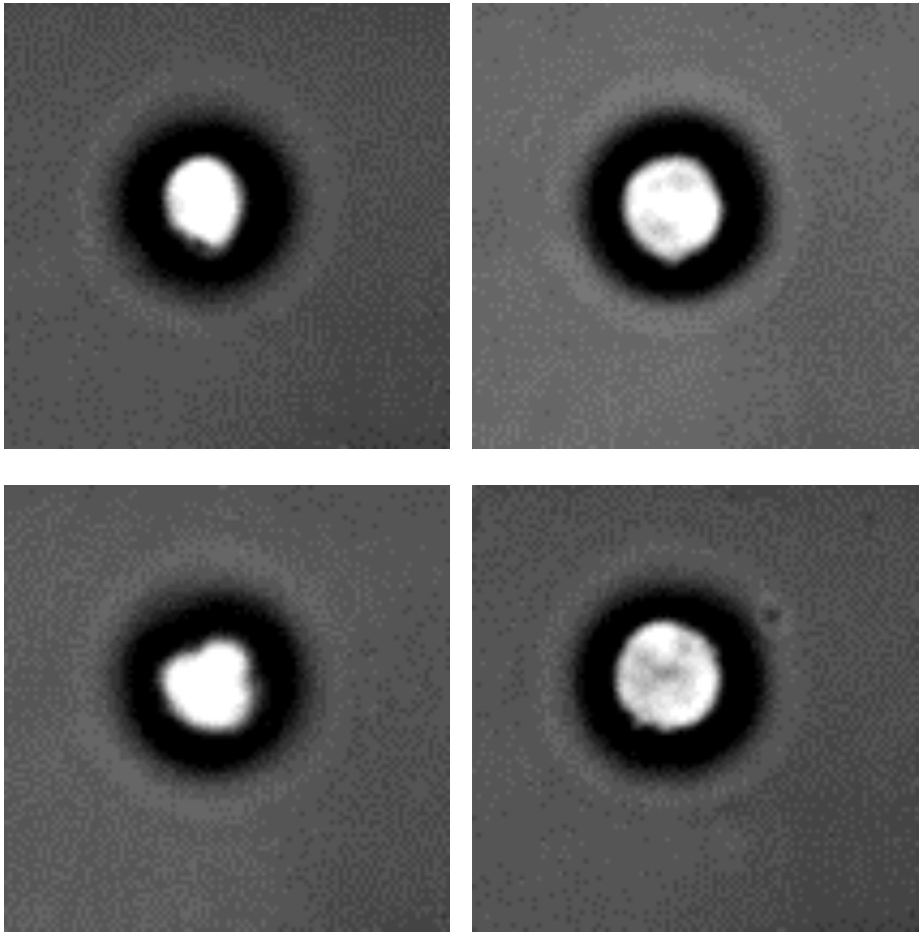


A. Stilgoe et al, Nature Photonics ***16****, 346–351 (2022)*

A deformed candidate:



A. Stilgoe et al, Nature Photonics ***16****, 346–351 (2022)*



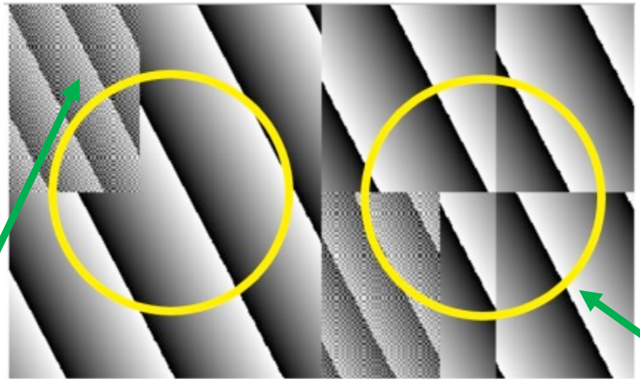
A. Stilgoe et al, Nature Photonics ***16****, 346–351 (2022)*

Rotation about an arbitrary axis

Rotation around any axis → a system that creates dynamically changing polarisation states

Change polarisation states of a beam → rotation speed and direction could be altered.

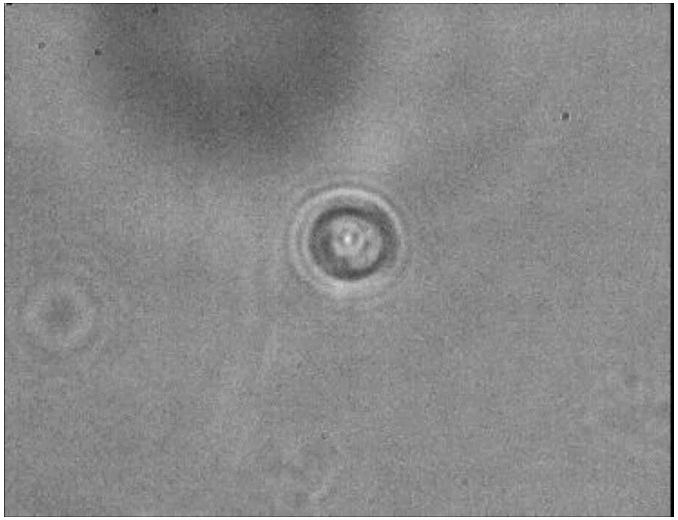
Sections of the SLM to project 6 polarisations states

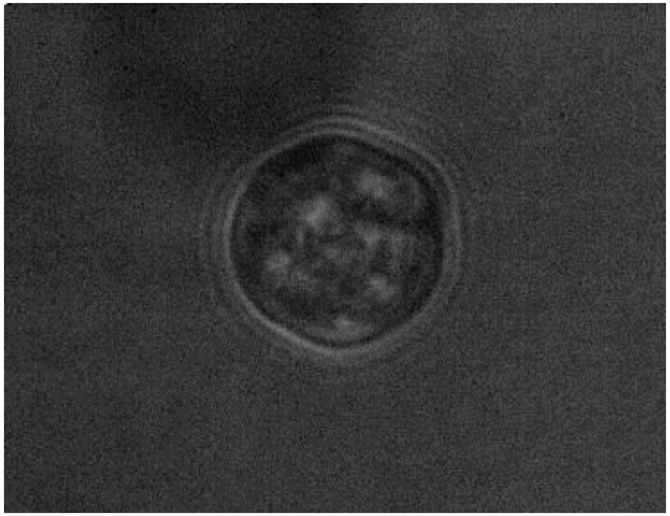


removes the horizontal beam using a masking pattern

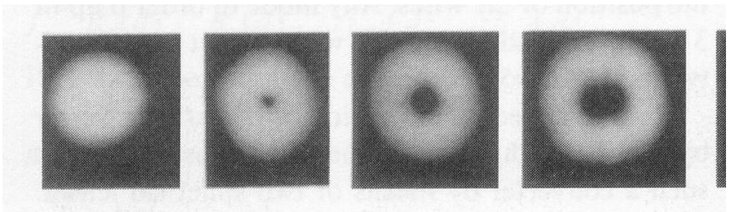
removes the vertical beam

Rotation about an arbitrary axis



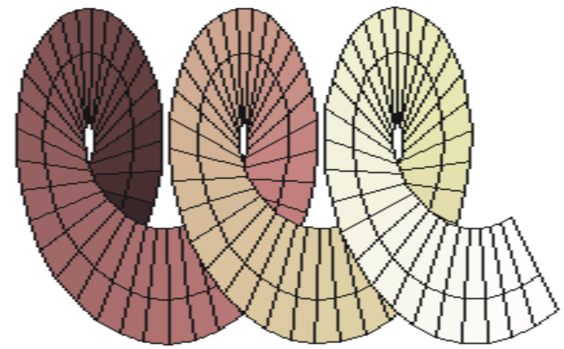


Orbital angular Momentum - Laguerre Gauss beams LG_{pl}



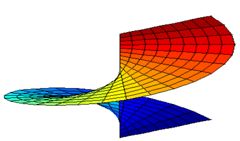
0,0 0,1 0,2 0,3

p =0 “doughnut beams”

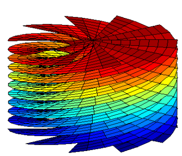


$l = 1$

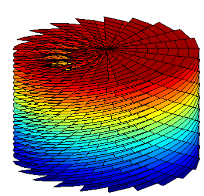
- $l \neq 0$ Helical wave fronts
- Angular momentum eigenmodes, $l\hbar$ per photon
- Phase singularity on axis, dark spot
- Generated by laser, or phase plate or hologram



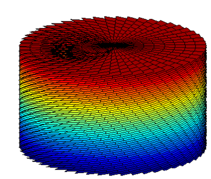
LG_{01}



LG_{010}

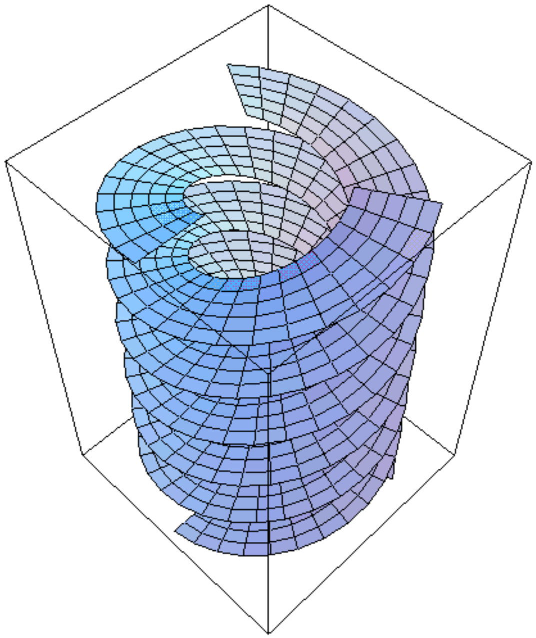


LG_{020}



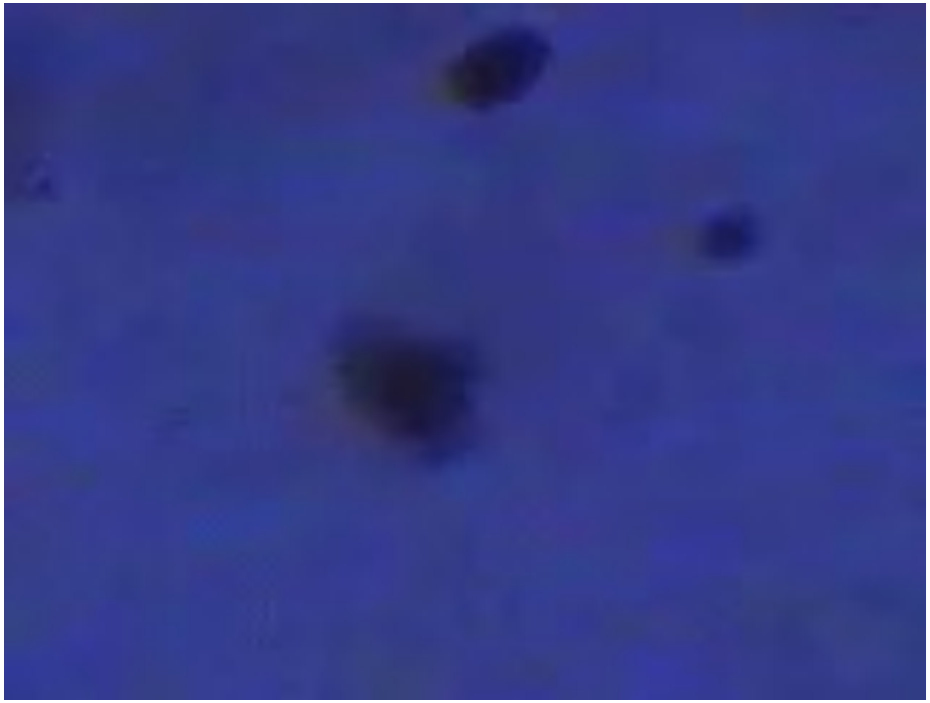
LG_{050}

Laser beam with orbital a.m. and absorbing particles



Helical wavefronts

$l = 3$



Absorbing particle

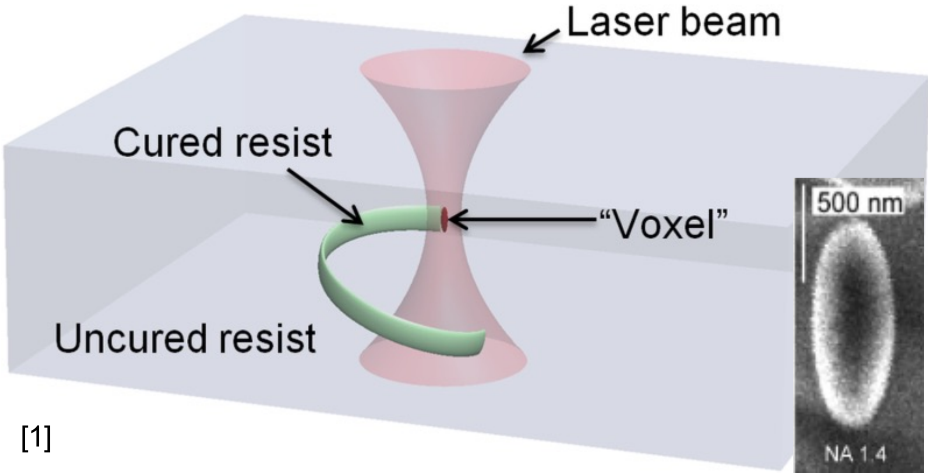
He et al., PRL (1995)

Based on absorption -> heating

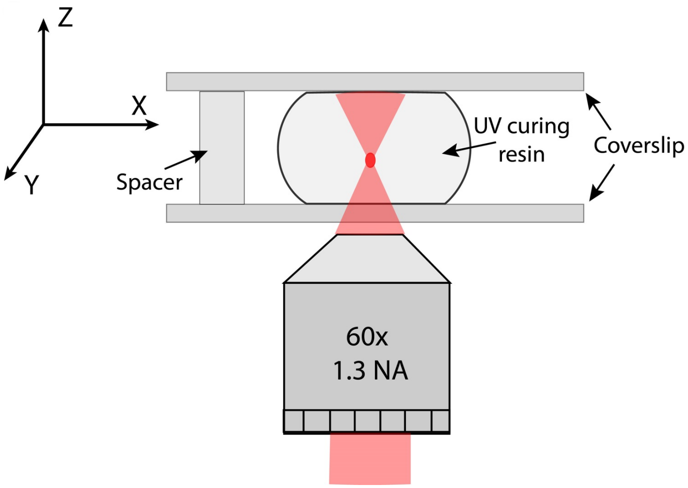
Orbital angular momentum

Optical vortices

2PHOTON PHOTOPOLYMERIZATION IMPLEMENTATION



[1]

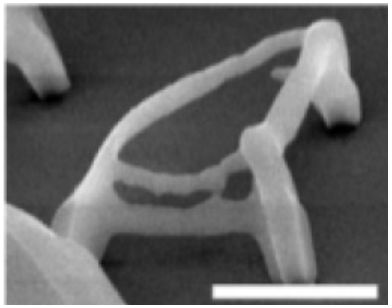


[1] Saha, Sourabh K., et al. "Effect of proximity of features on the damage threshold during submicron additive manufacturing via two-photon polymerization." *Journal of Micro and Nano-Manufacturing* 5.3 (2017).

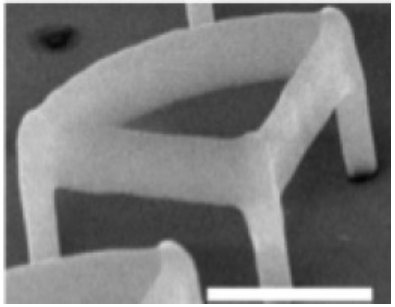
Aberration Correction

Is beam aberration correction required?

- Reduce size of focus
- Increasingly important for small structures
- Required for hollow or thin objects



Without SLM correction



[1]

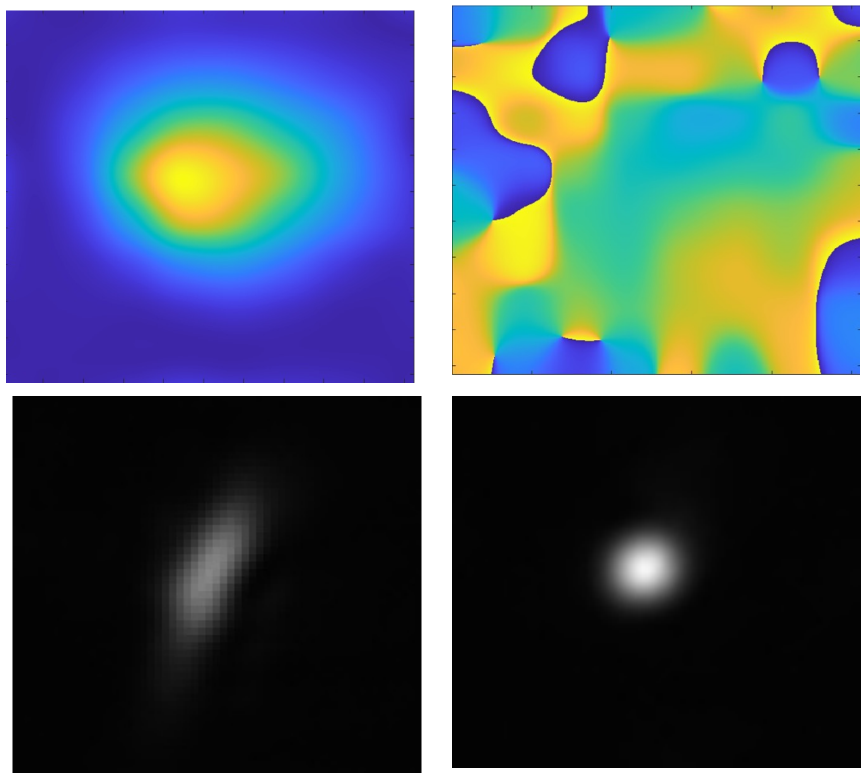
With SLM correction

[1] **Kelemen, Lóránd, Pál Ormos, and Gaszton Vizsnyiczai. "Two-photon polymerization with optimized spatial light modulator."** ***Journal of the European Optical Society-Rapid publications*** **6 (2011).**

Beam Aberrations

Beam amplitude at SLM

Found phase correction



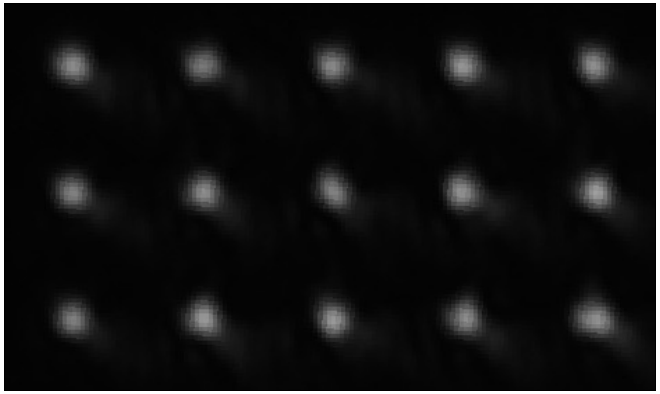
Focused uncorrected beam

Focused corrected beam

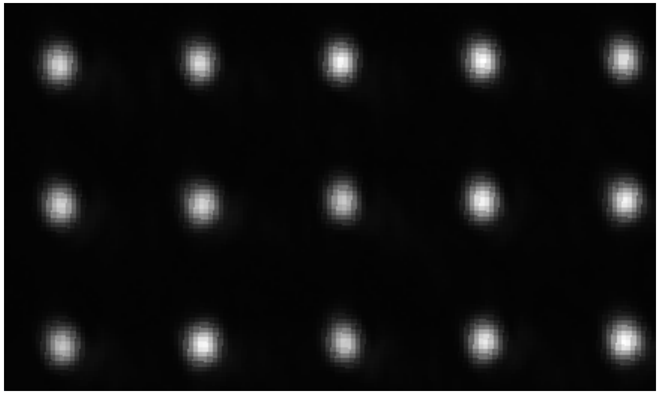
Declan Armstrong et al., Frontiers in Nanotechnology, DOI 10.3389/fnano.2022.998656, 2022

Beam Aberrations

In addition to improvements in confinement, there is substantial improvements in diffracted intensity, leading to more uniform and efficient polymerisation when using multiple spots.



No correction applied

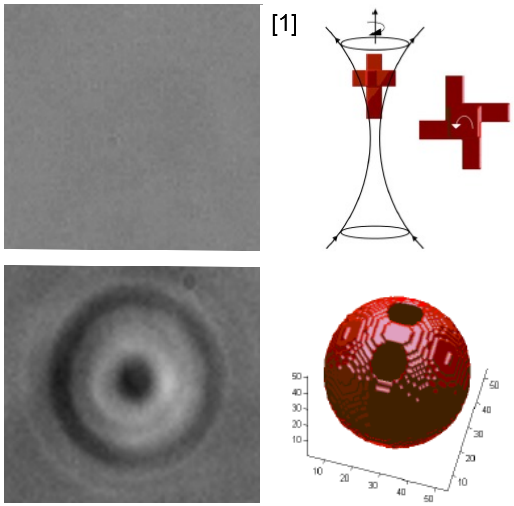


With correction applied

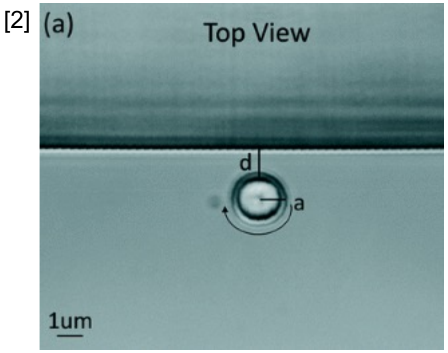
Declan Armstrong et al., Frontiers in Nanotechnology, DOI 10.3389/fnano.2022.998656, 2022

IN-HOUSE MICROFABRICATION

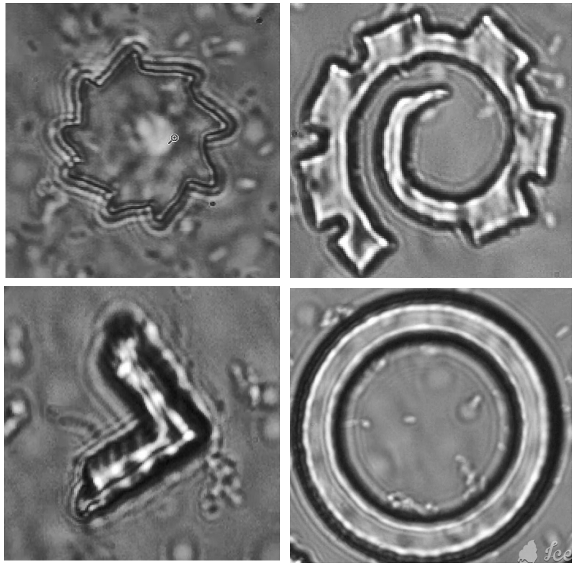
OT Devices



Hydrodynamics



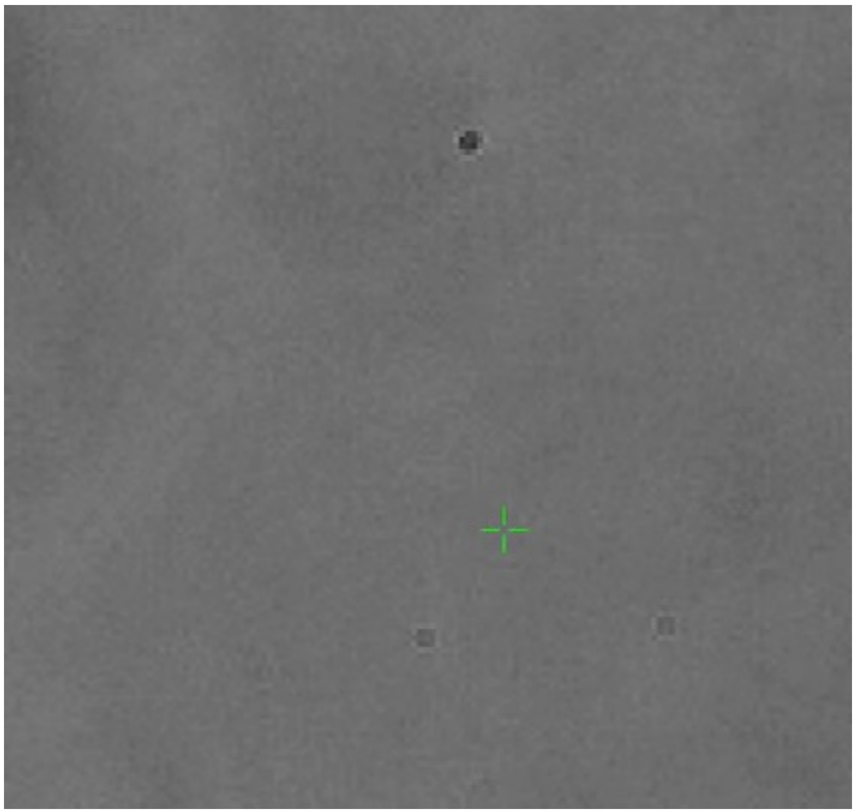
Cell Studies

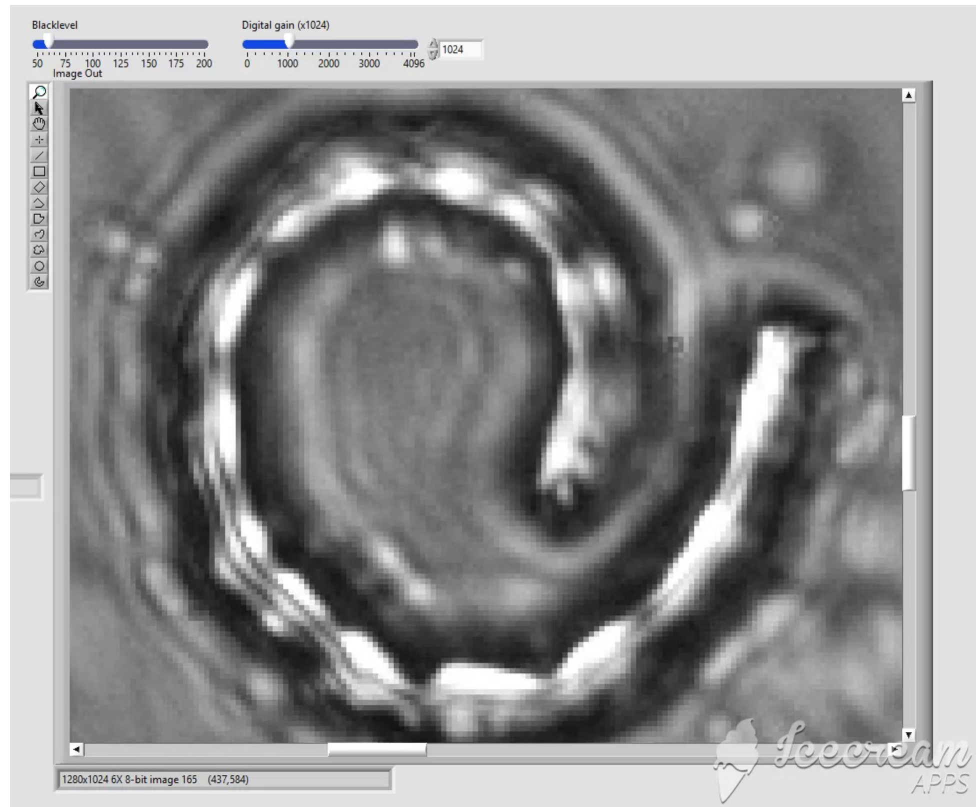


[1] ASAVEI, THEODOR. "OPTICALLY FABRICATED AND DRIVEN MICROMACHINES." (2010).

[2] ZHANG, SHU, ET AL. "IMPACT OF COMPLEX SURFACES ON BIOMICRORHEOLOGICAL MEASUREMENTS USING OPTICAL TWEEZERS." *LAB ON A CHIP* 18.2 (2018): 315-322.

Production of aberration free structures





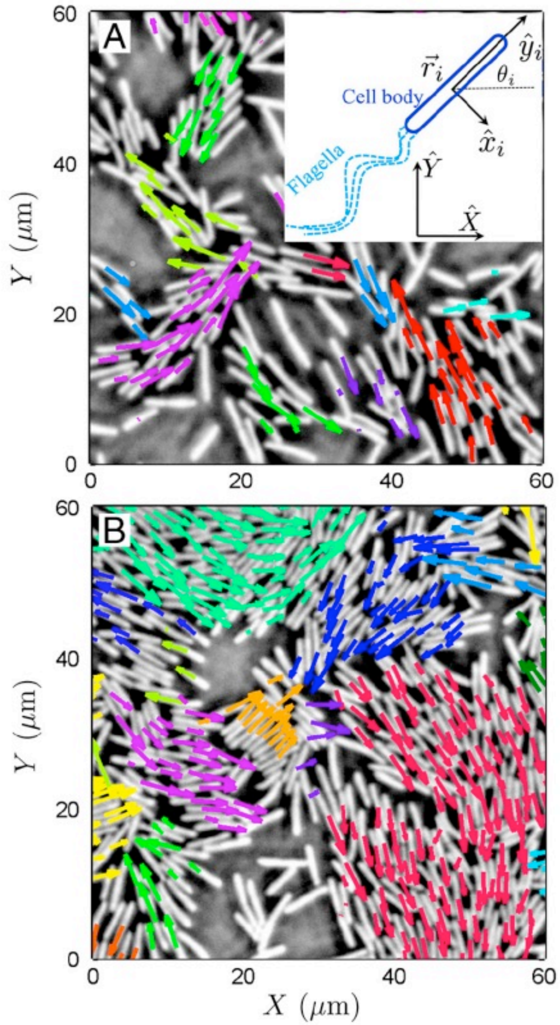
Studies of active media

Declan Armstrong Structured light in optical tweezers for functional microstructures. 58

Declan Armstrong, 2022

Collective Motion

wild-type Bacillus subtilis bacteria in a colony



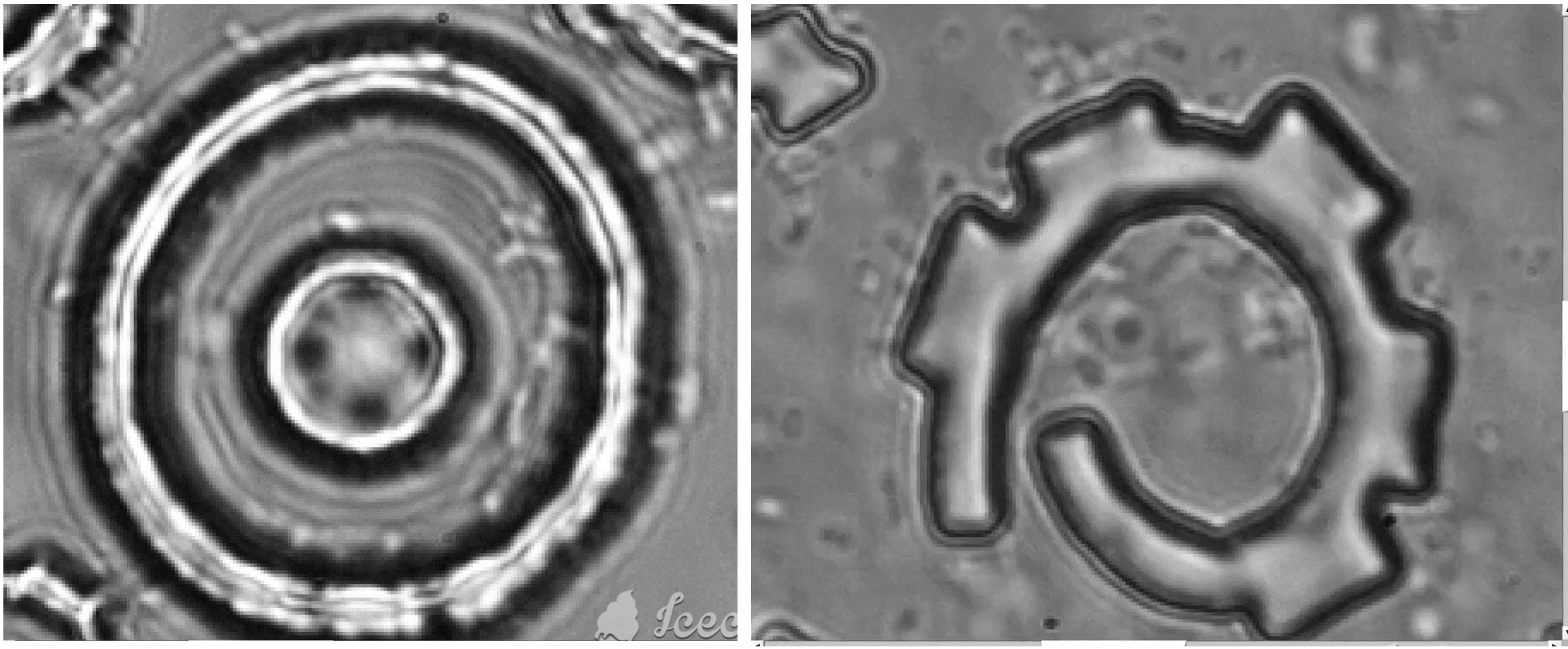
Instantaneous configurations at two densities with the average total number of bacteria in the imaging window N_{total} = 343 (A) and N_{total} = 718 (B)

Velocity vectors are overlayed on the raw images of bacteria. The length of the arrows corresponds to bacterial speed, and nearby bacteria with arrows of the same colour belong to the same dynamic cluster.

“giant number fluctuations”

Collective motion and density fluctuations in bacterial colonies. H. P. Zhang, Avraham Be’er, E.-L. Florin, and Harry L. Swinney, PNAS 13626–13630 / PNAS / August 3, 2010 / vol. 107 / no. 31

Production of aberration free structures



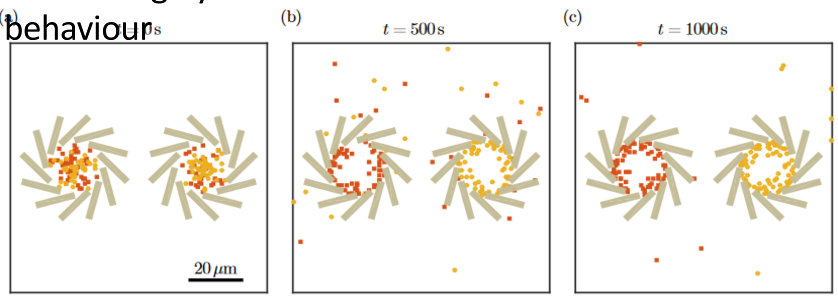
Studies of active media in different geometries

Declan Armstrong, 2022

2pp structures for cell studies

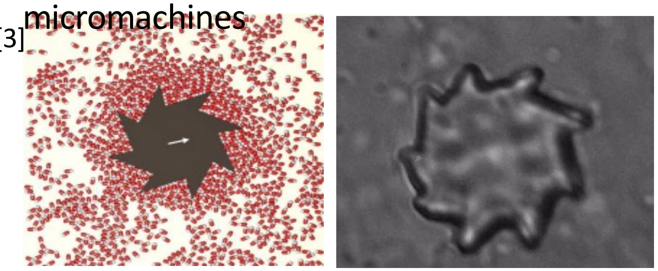
Cell sorting by size or behaviour

[1]



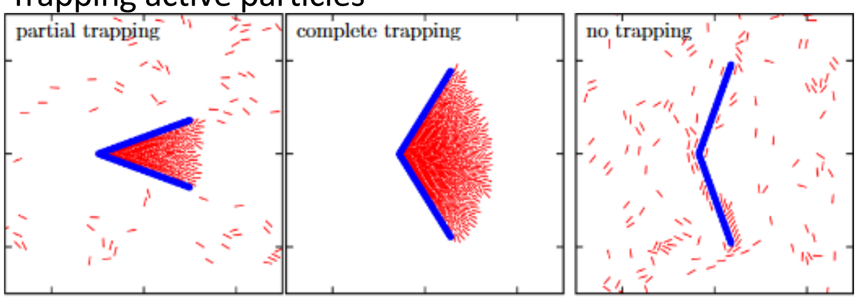
Bacteria driven micromachines

[3]



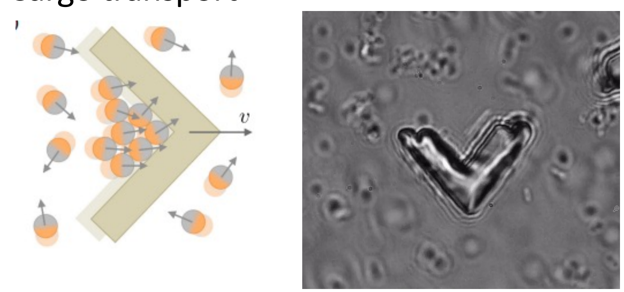
Trapping active particles

[2]



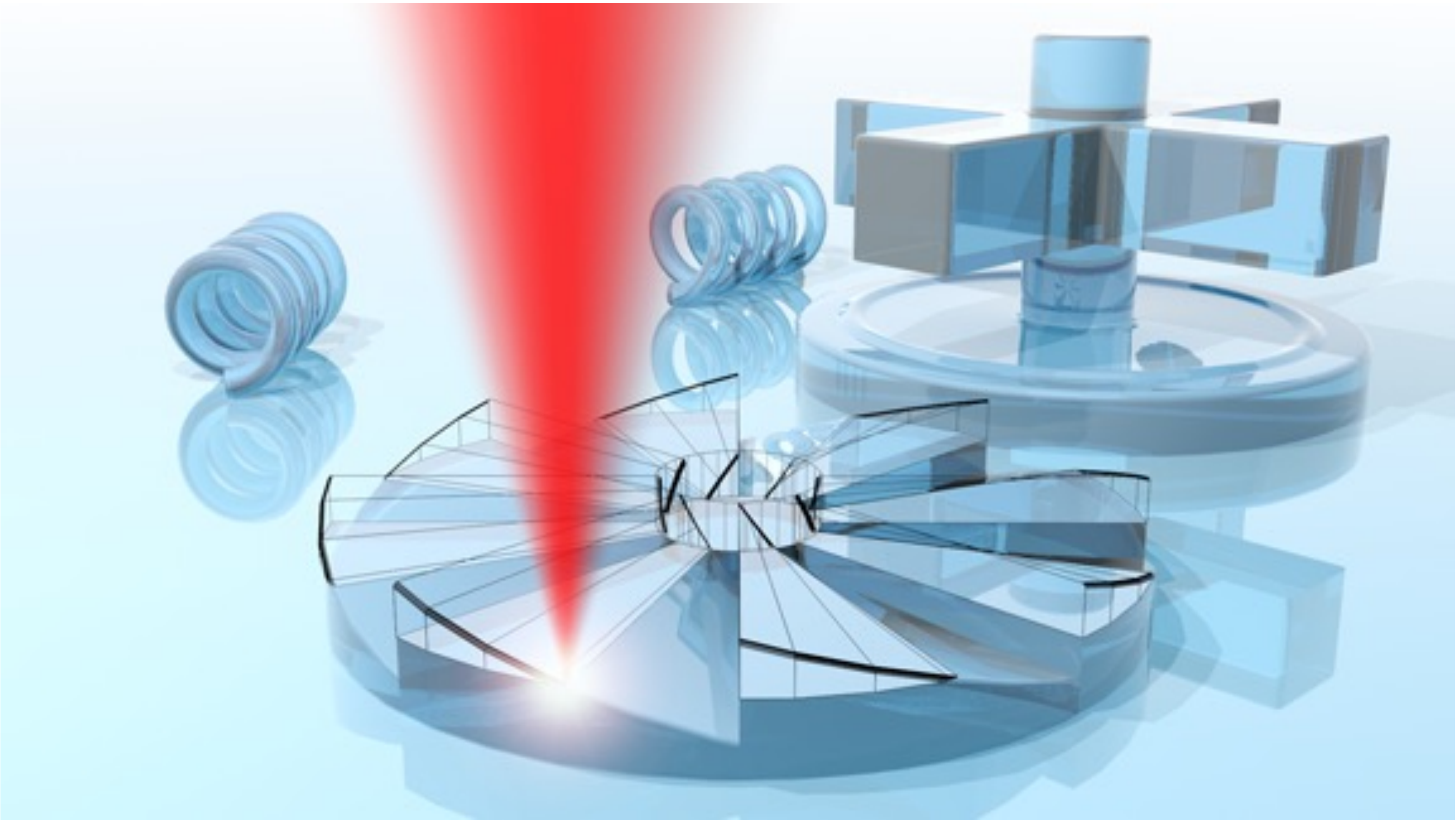
Cargo transport

[4]



[1] Mijalkov, Mite, and Giovanni Volpe. "Sorting of chiral microswimmers." *Soft Matter* 9.28 (2013): 6376-6381.
[2] Kaiser, A., H. H. Wensink, and H. Löwen. "How to capture active particles." *Physical review letters* 108.26 (2012): 268307
[3] Di Leonardo, Roberto, et al. "Bacterial ratchet motors." *Proceedings of the National Academy of Sciences* 107.21 (2010): 9541-9545.
[4] Kaiser, Andreas, et al. "Transport powered by bacterial turbulence." *Physical review letters* 112.15 (2014): 158101.

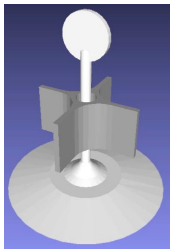
Nano and micromachines and micro-optical elements



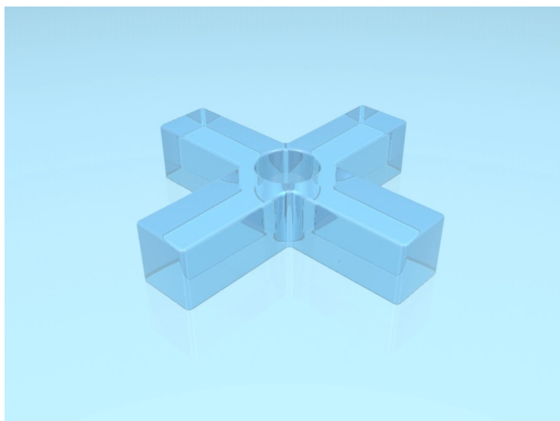
Rotors
Diffractive optical elements
Helices

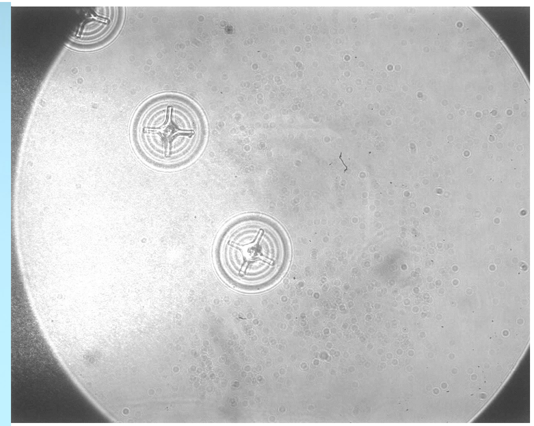
+ sculptured light

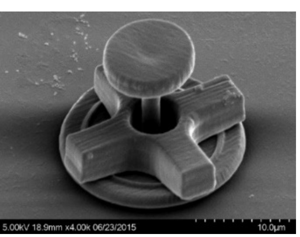
Bioanalogs and rotors



Production of rotors by two photon photopolymerisation



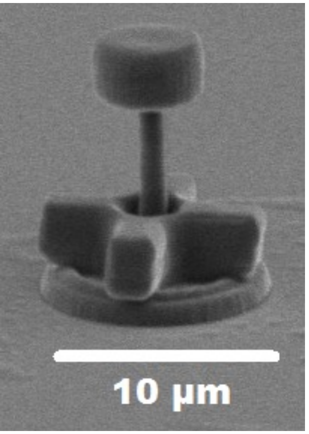


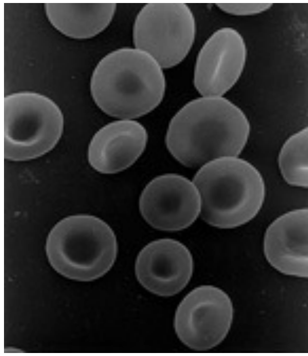


Rotor moved using Laguerre-Gauss beam LG_{20}

Scanning Electron Microscope

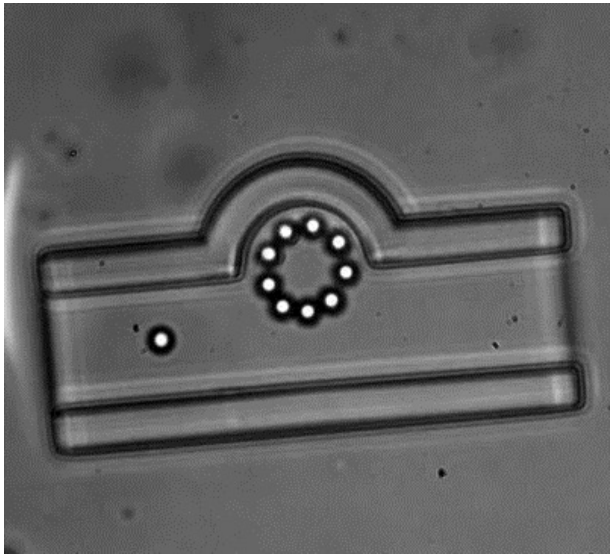
Optical Tweezers in Action





Rotor spun using orbital angular momentum

Jannis Köehler's optical tweesers powered pump



Red blood cell stretched using optical tweezers

Acknowledgements QAO Team

Dr Guillaume Gauthier

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Zac Kerr

Arghavan Safavi-Naini

Dr Tyler Neely

Maarten Christenhusz

Dr Charles Woffinden

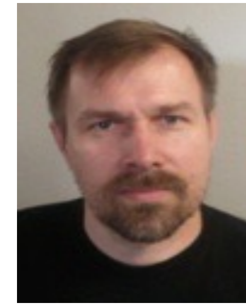
Prof. Matthew Davis

Prof. Halina Rubinsztein- Dunlop

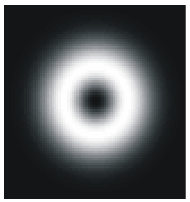
Acknowledgments - the Team

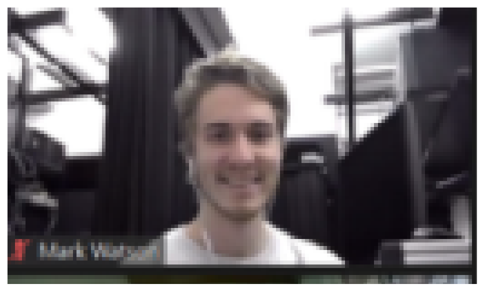
Alex Stilgoe

Itia Favre-Bulle



Timo Nieminen





Mark Watson

Declan Armstrong

Halina Rubinsztein-Dunlop

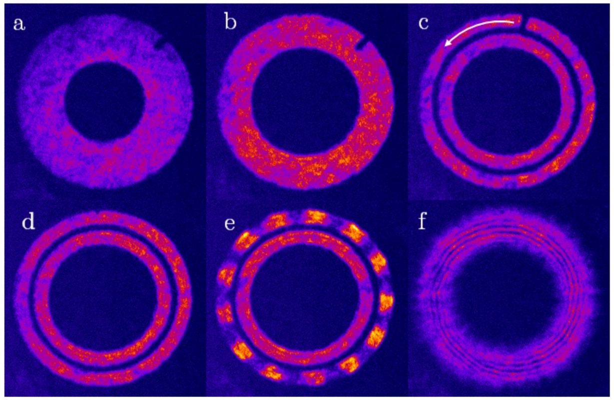
Jessicah Ferguson-Jones

Join the group

DST-funded PhD scholarship on trapped atom rotation sensing!

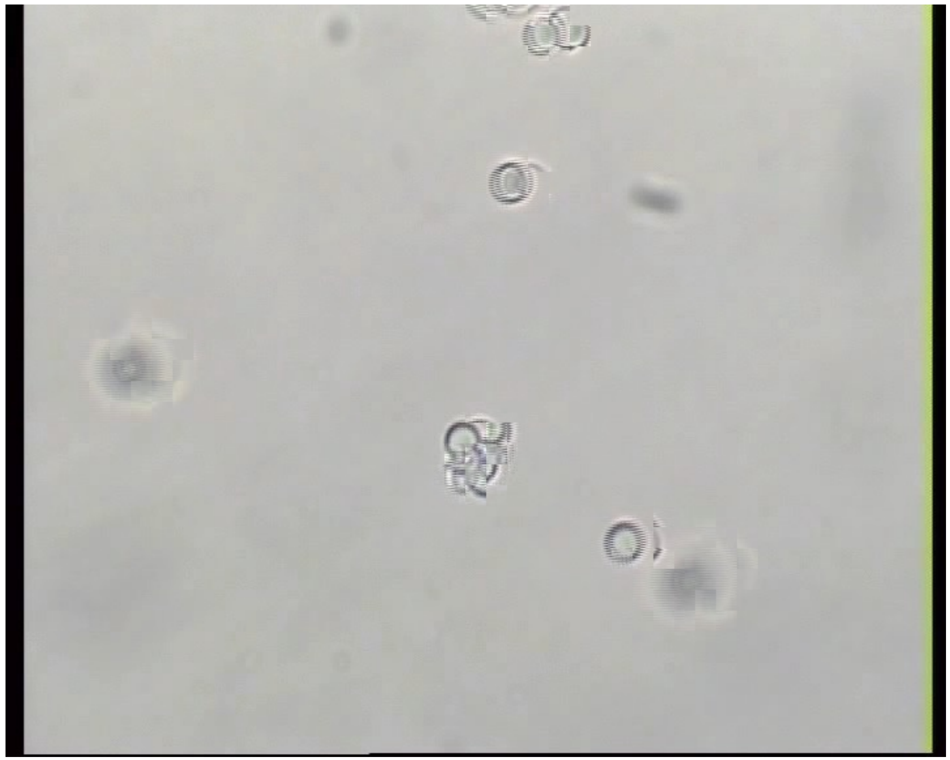
-- RTF equivalent or $10k/year top-up on receipt of an RTF and travel $

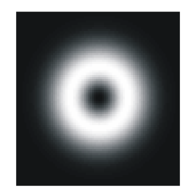
-- Commencing Q2 or Q3 2023



Contact: Tyler Neely (t.neely@uq.edu.au), Halina Rubinsztein-Dunlop (halina@physics.uq.edu.au)

Thank you





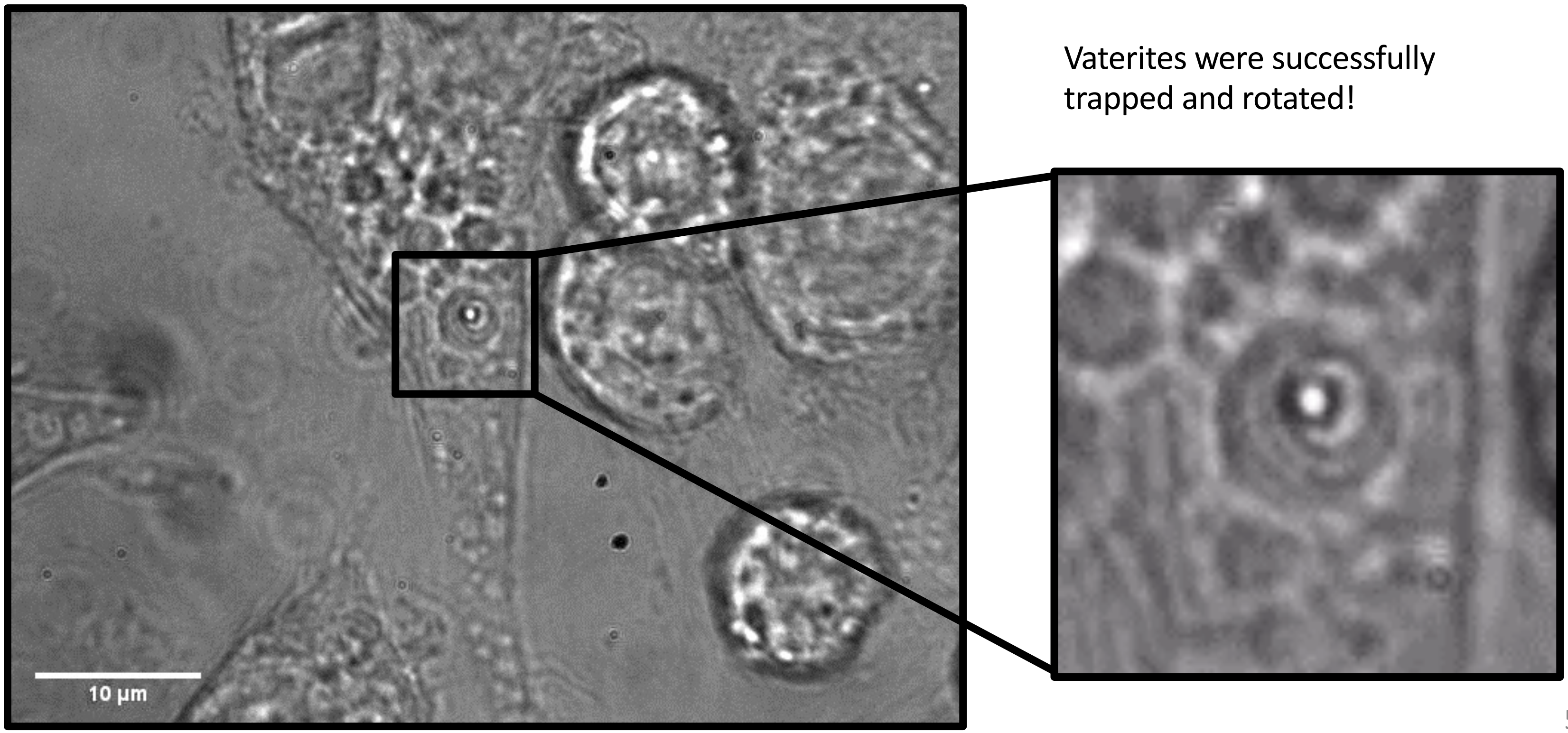
Optical vortices

Orbital Angular Momentum

Macropinosoms

Successful Trapping and Rotating

The small vaterites were internalised into macrophages treated with YM201636 for optical trapping and rotation



Vaterites were successfully trapped and rotated!

Mark Watson

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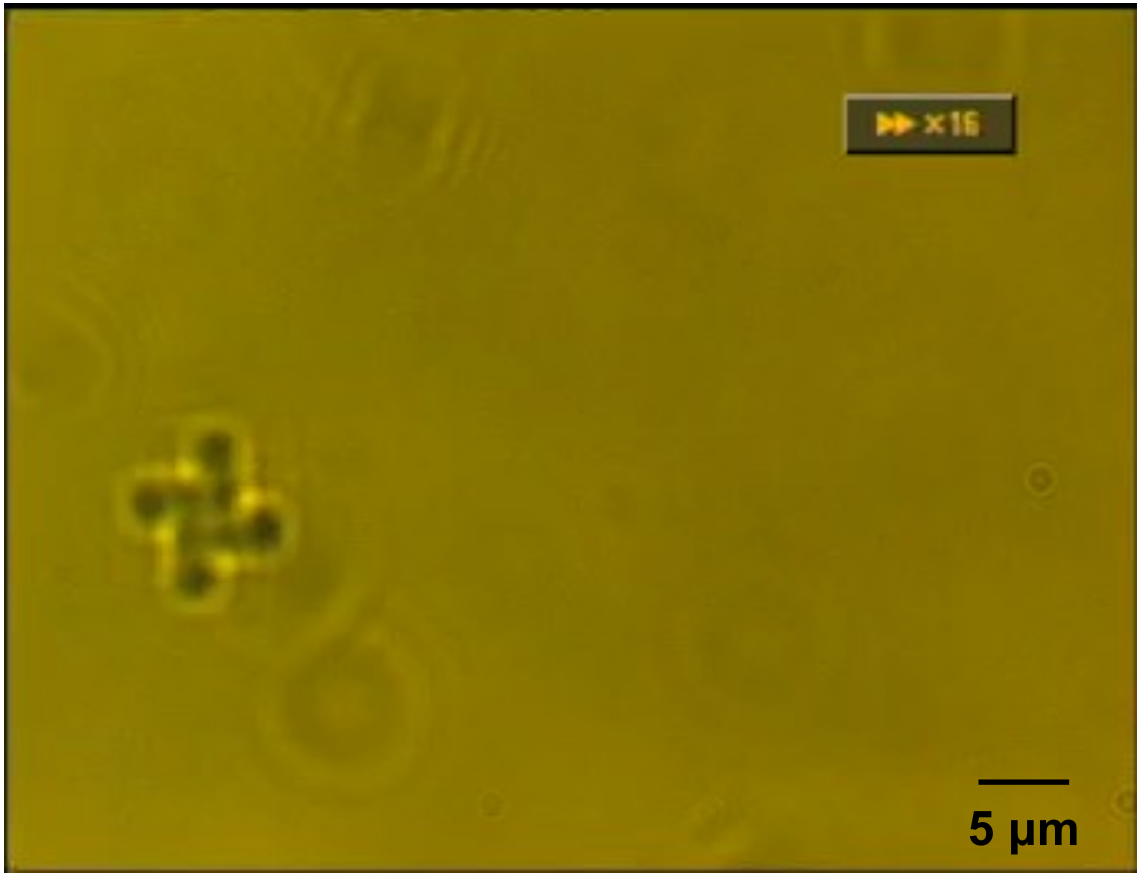
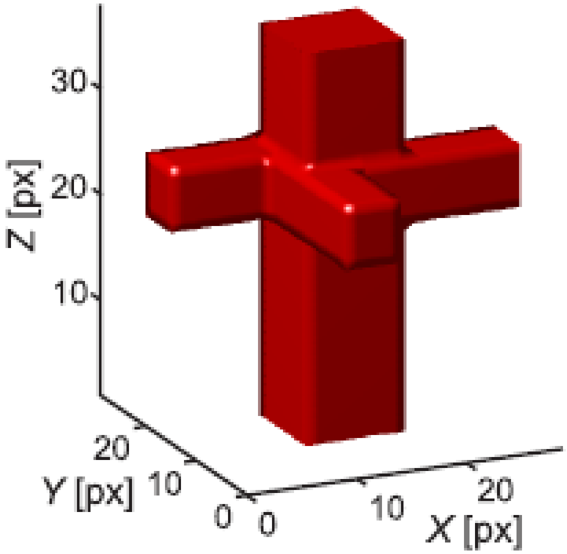
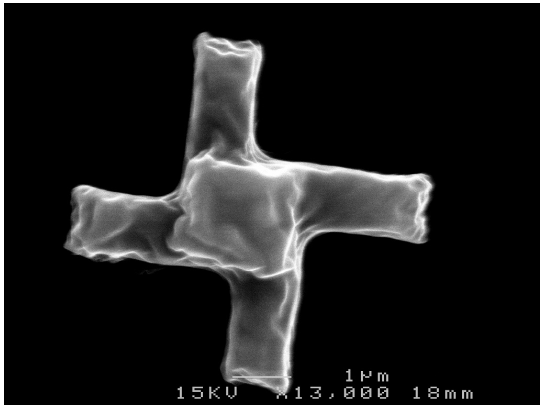
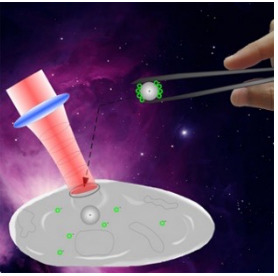
Fabrication process







- each structure is fabricated in ~ 15 min
- raster scanning, now using vector scanning



Macropinocytosis

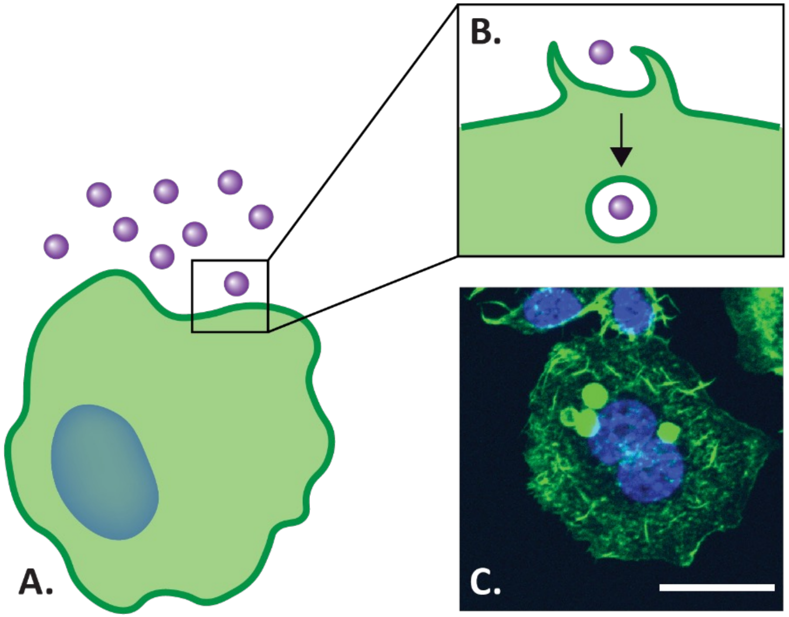
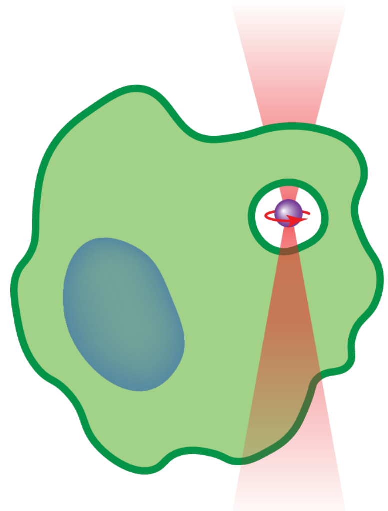
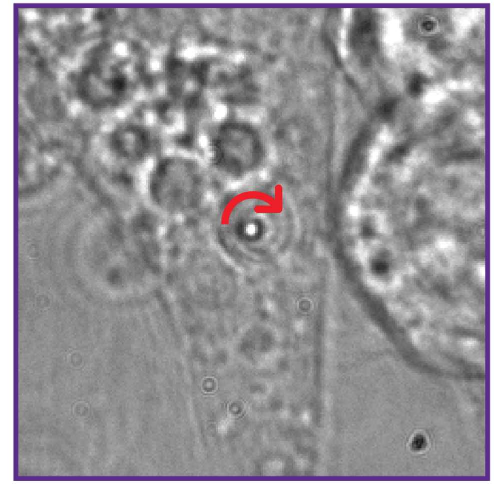
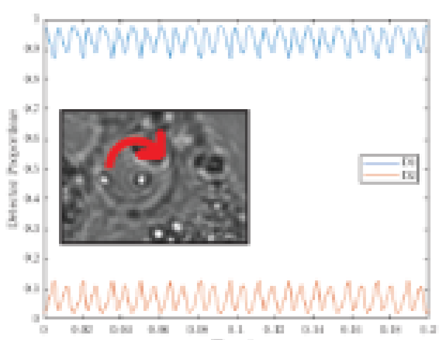
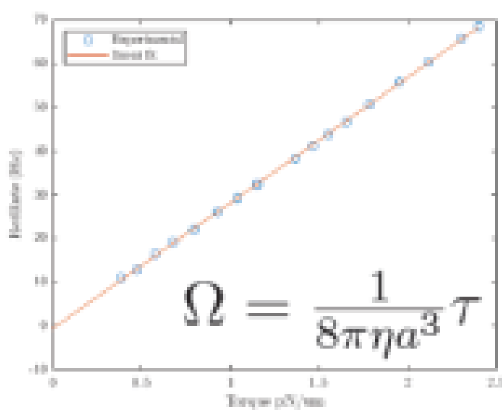


Figure 1. A) Vaterites being added to the macrophage cell surroundings. **B)** Illustration of vaterite internalisation via macropinocytosis. **C)** An IF image of internalised vaterite microspheres with Phalloiding fluorescing F-actin filaments (green) and DAP fluorescing DNA (blue). Scale bar is 15um.









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