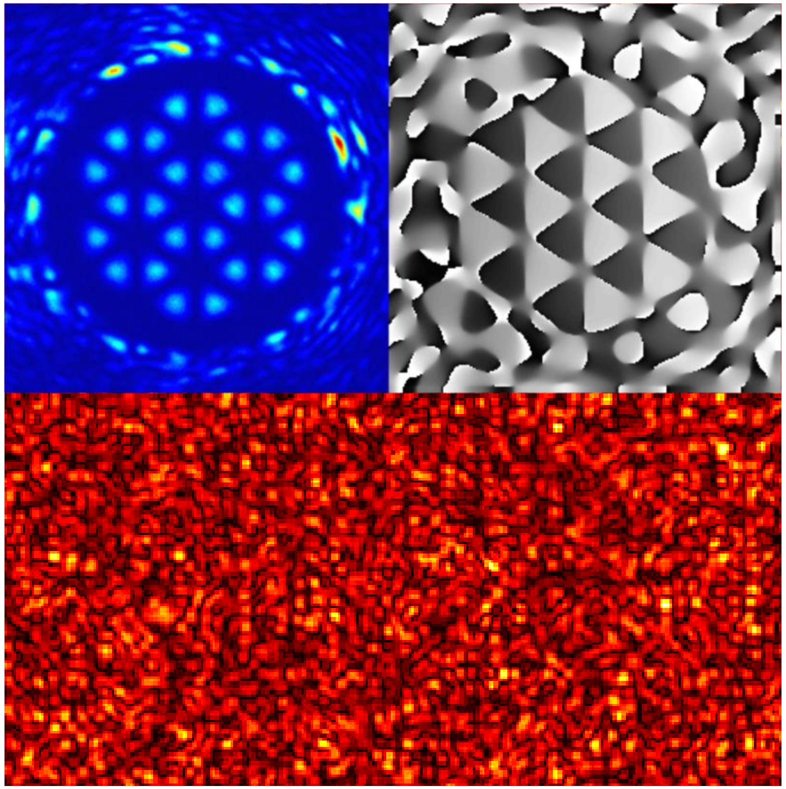
Making the most of interference:

the application of laser speckle and computer-generated holography to cold atoms, optical trapping and precision metrology



Graham D. Bruce

University of St Andrews

@grahamdbruce

ColOpt Winter School on collective effects, structured light and quantum matter

7th March 2018

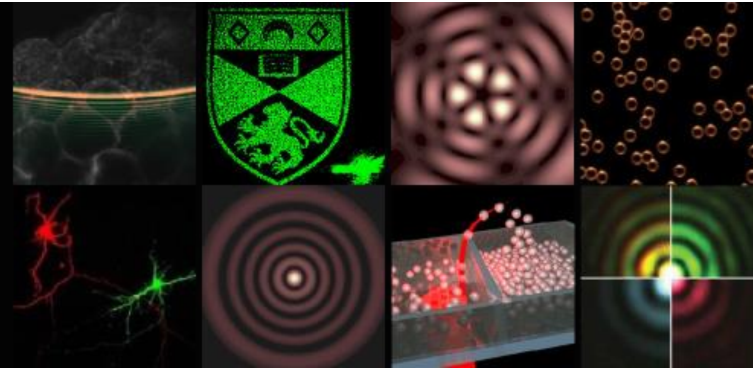
University of St Andrews | 600 YEARS 1413 – 2013

8000 students at University
47% from outside UK
Physics: 40 academic staff; 60 research staff; 80 PhD students
http://www.st-andrews.ac.uk/physics/index.php

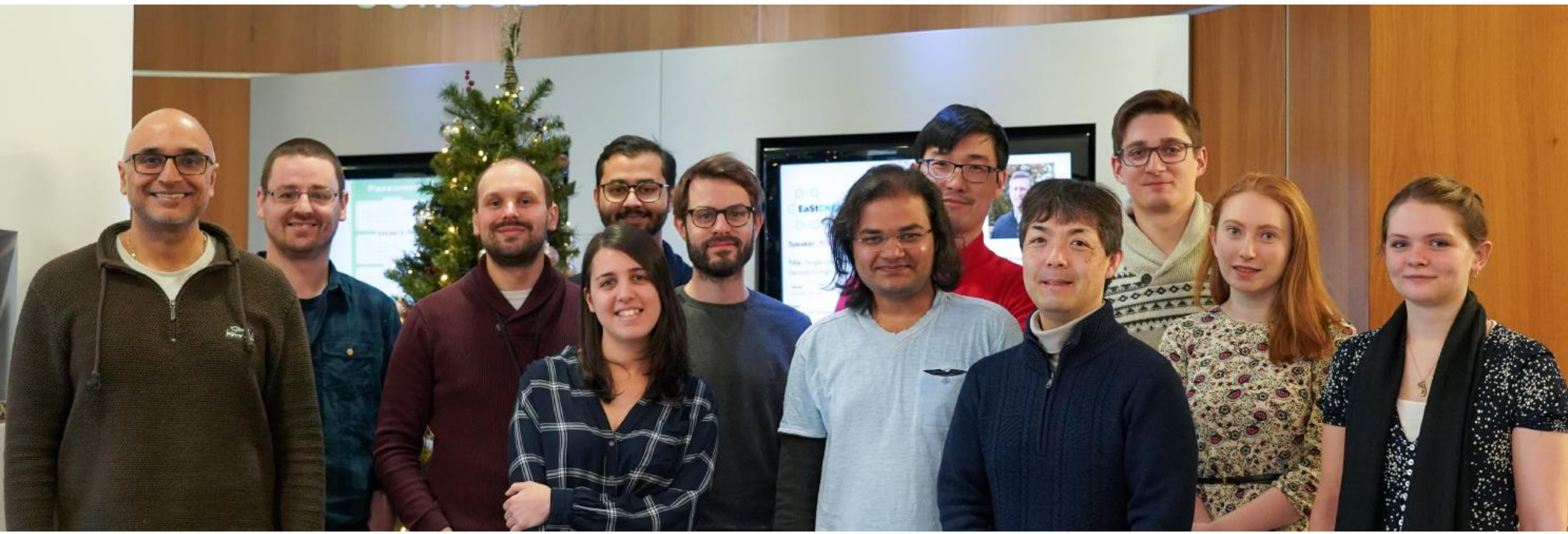

University of Glasgow
University of Strathclyde Glasgow
University of the West of Scotland
UWS
University of Aberdeen
University of Dundee
University of St Andrews
The University of Edinburgh
Heriot Watt University


SUPA

optical manipulation
ST ANDREWS



University of St Andrews



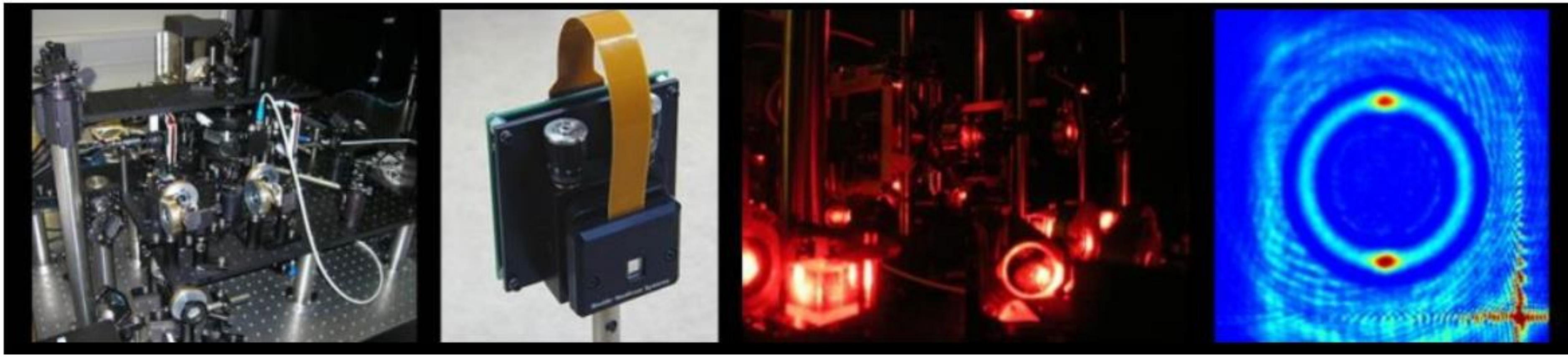
M SQUARED

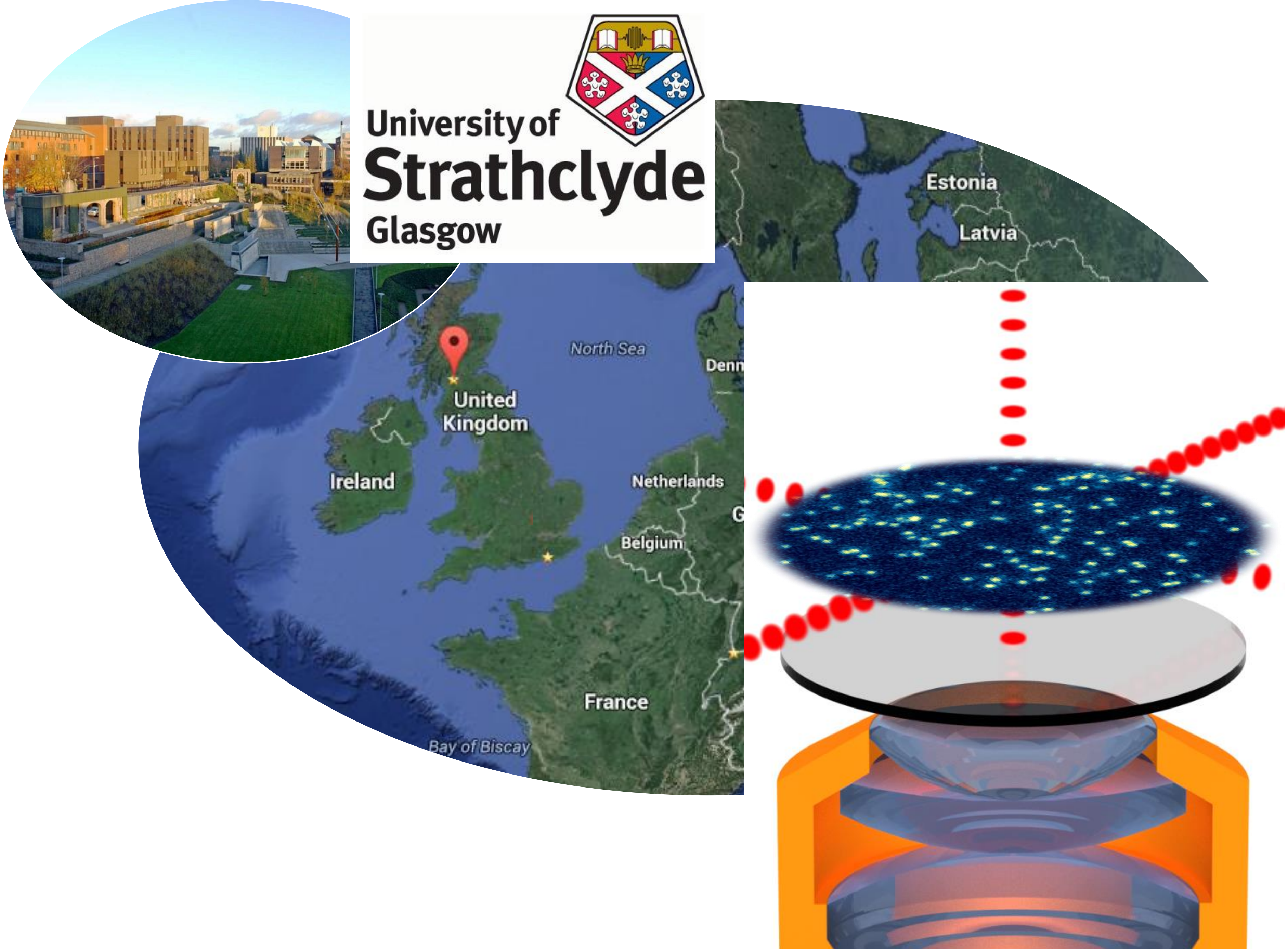
EPSRC
Engineering and Physical Sciences Research Council

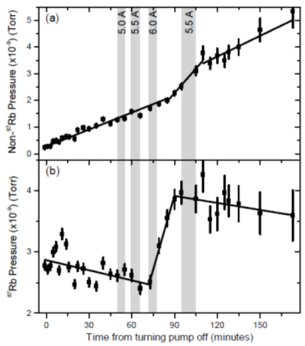
LEVERHULME TRUST

University of St Andrews

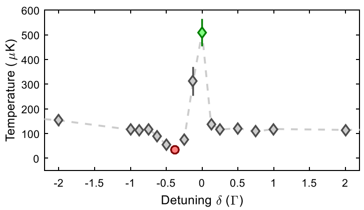
Cold Atoms Group



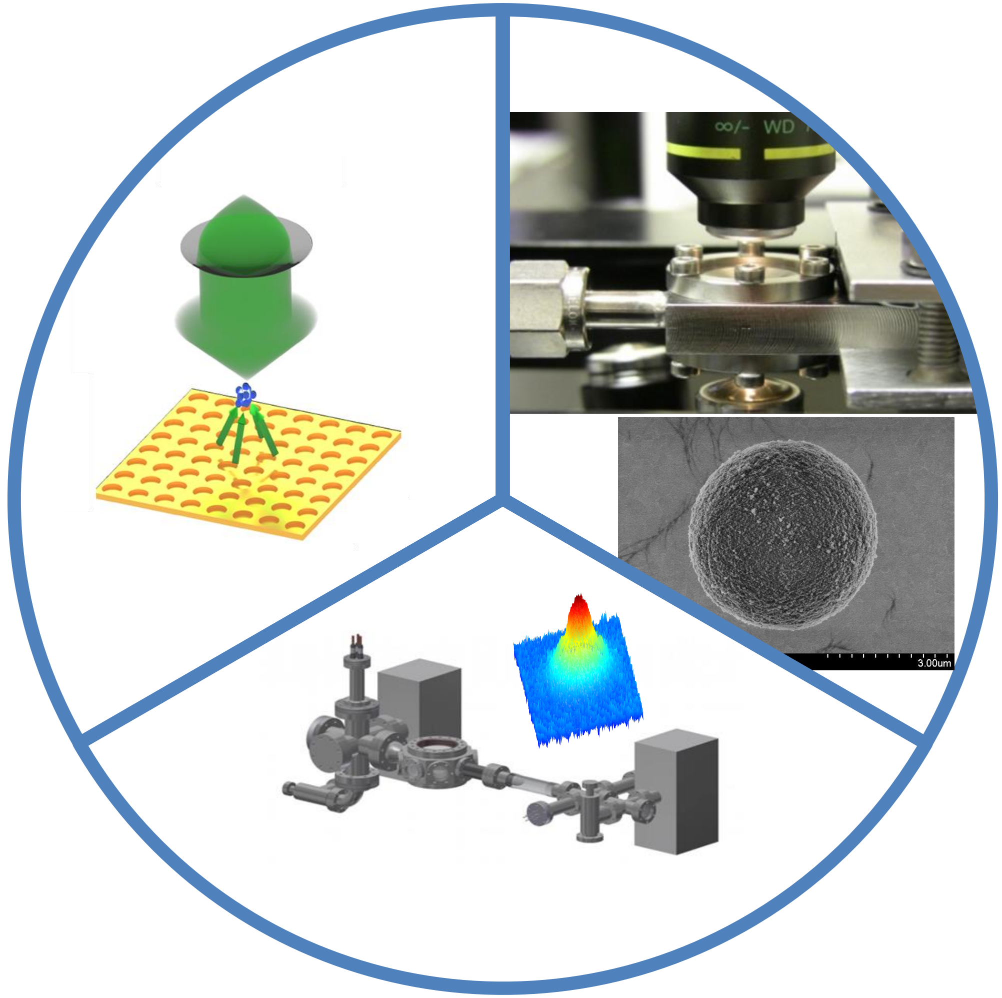

University of
Strathclyde
Glasgow
Estonia
Latvia
North Sea
Denn
United
Kingdom
Ireland
Netherlands
Belgium
France
Bay of Biscay

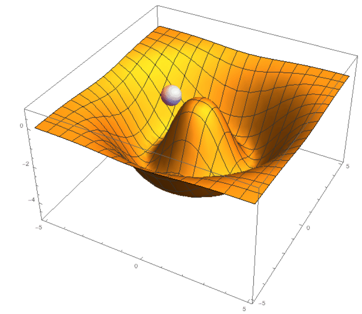


Sci Rep **5,** *14729 (2015)*
Rev Sci Inst **86,** *093108 (2015)*



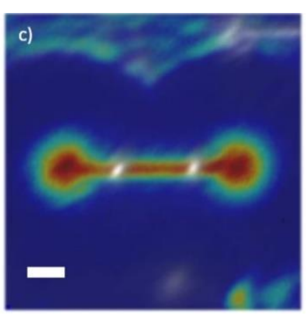
J Phys B **50,** *095002 (2017)*



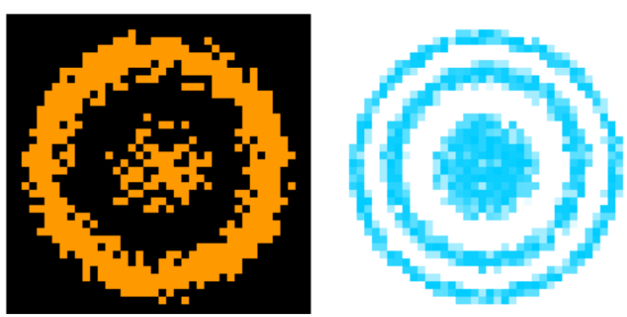


JOSA B **34**, *C14 (2017)*
Phys Rev A **94**, *053821 (2016)*

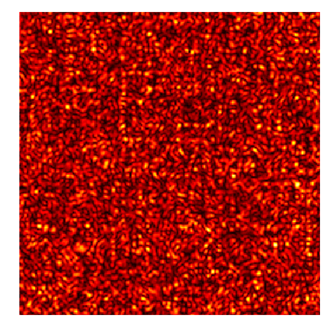
Nature Comm **4**, *2374 (2013)*



Opt Express **25,** *11692 (2017)*
Opt Express **23,** *8365 (2015)*
Opt Express **22,** *26548 (2014)*



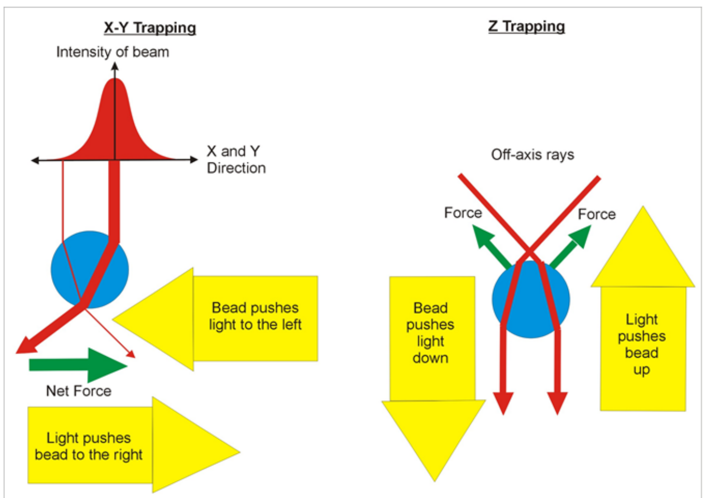
New J Phys **18** *075012 (2016)*
Phys Rev A **94** *051601 (2016)*



Opt Lett **44** *1367 (2019)*
Nature Comm **8**, *15610 (2017)*
Opt Lett **39** *96 (2014)*

Optical Gradient Force

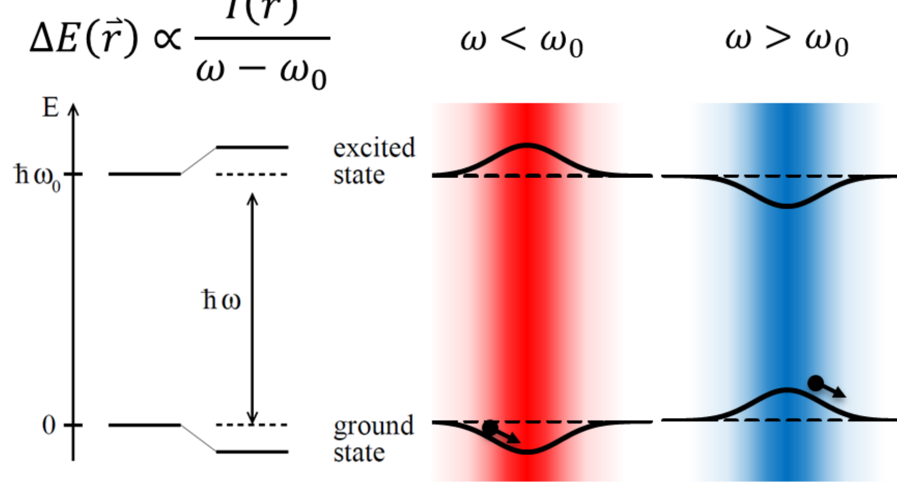
Microparticles



Optical Dipole Force

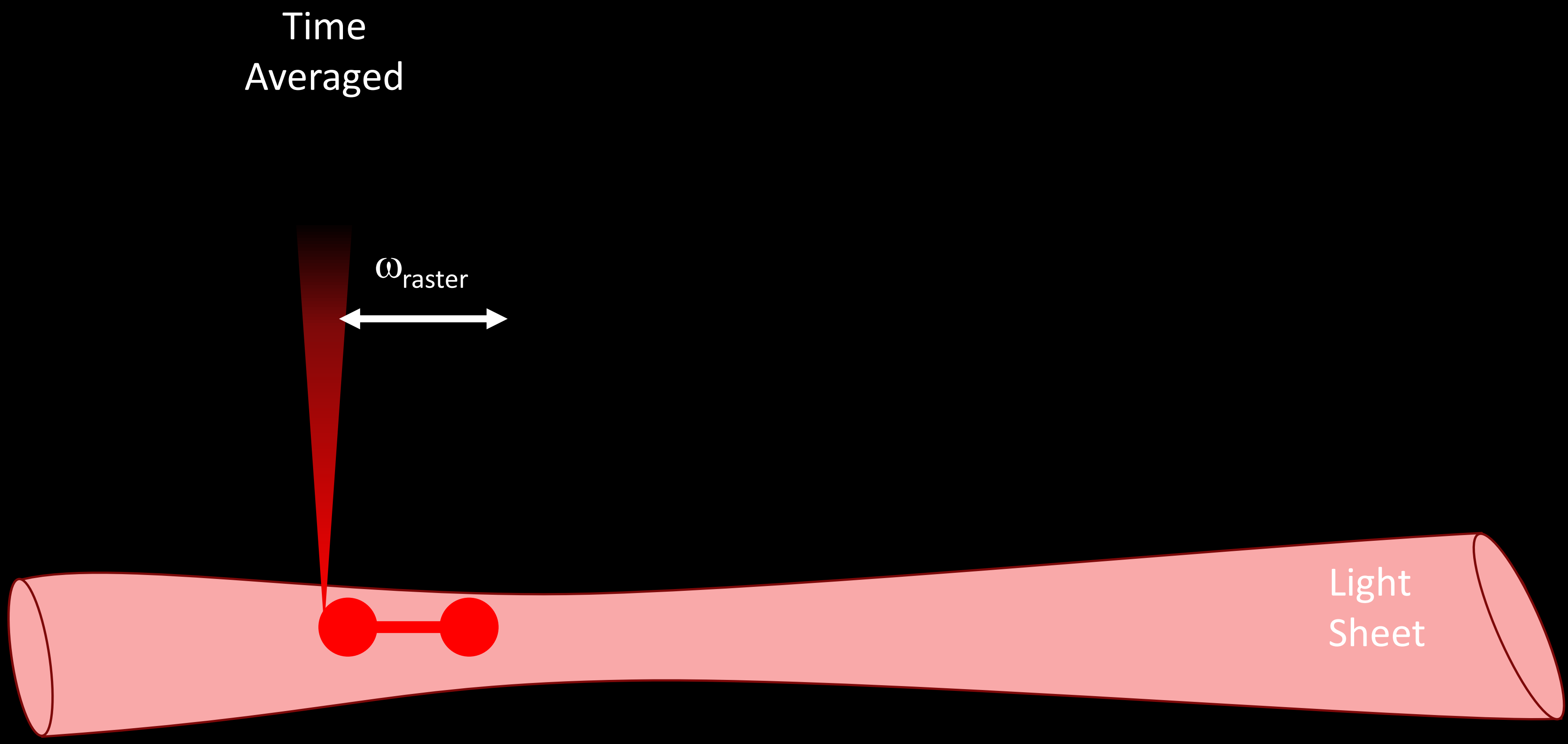
Atoms

$$\Delta E(\vec{r}) \propto \frac{I(\vec{r})}{\omega - \omega_0}$$

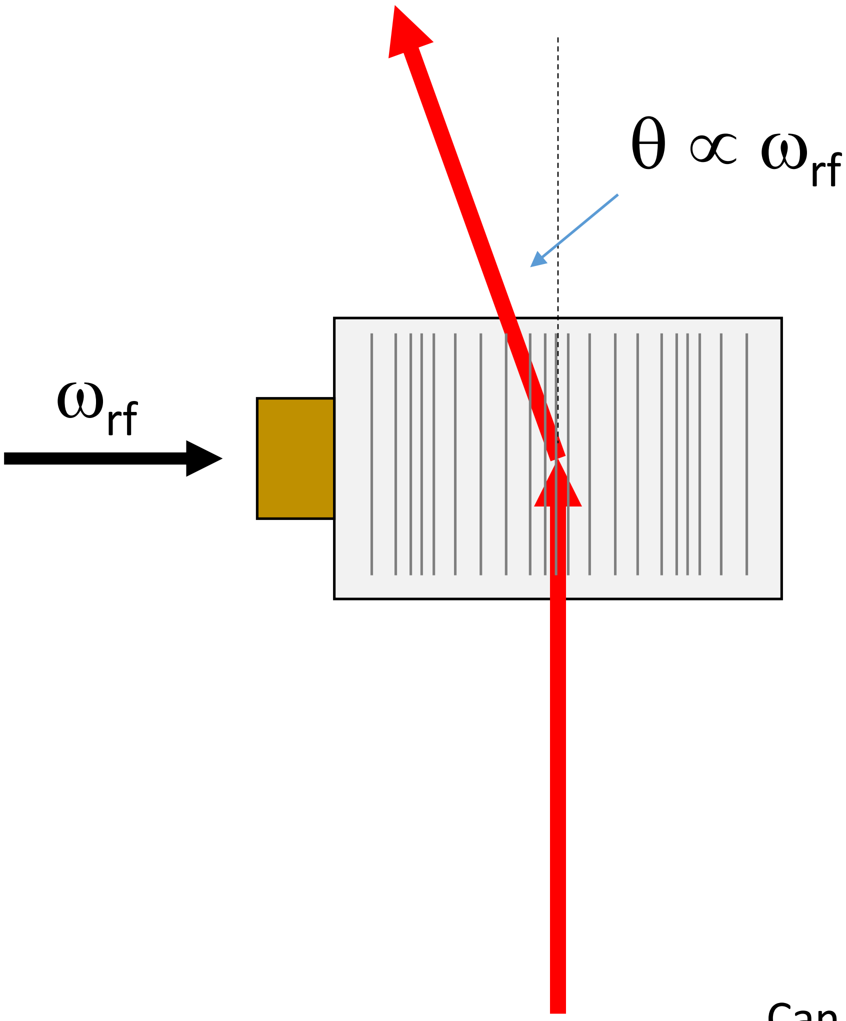


R Grimm et al, Adv. At. Mol. Opt. Phys. ***42****, 95-170 (2000)*

How much control do we have over optical trapping geometry?

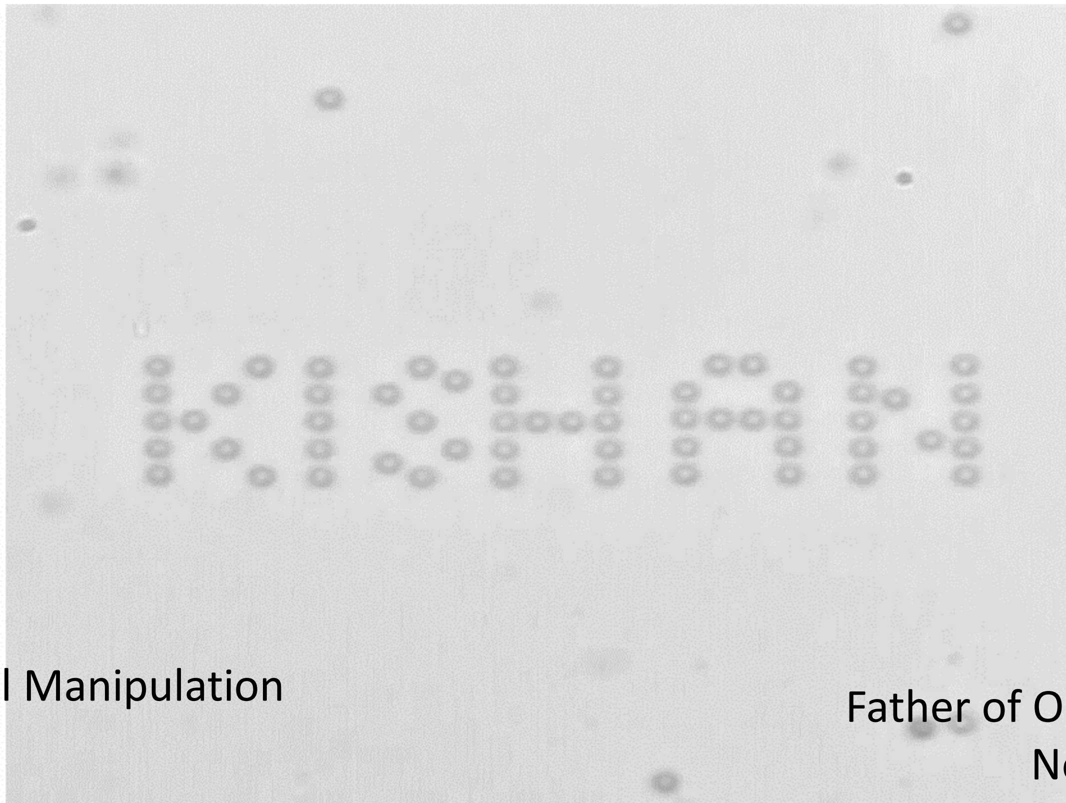


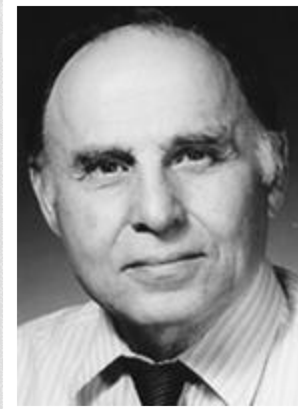
(not necessary for microparticles)



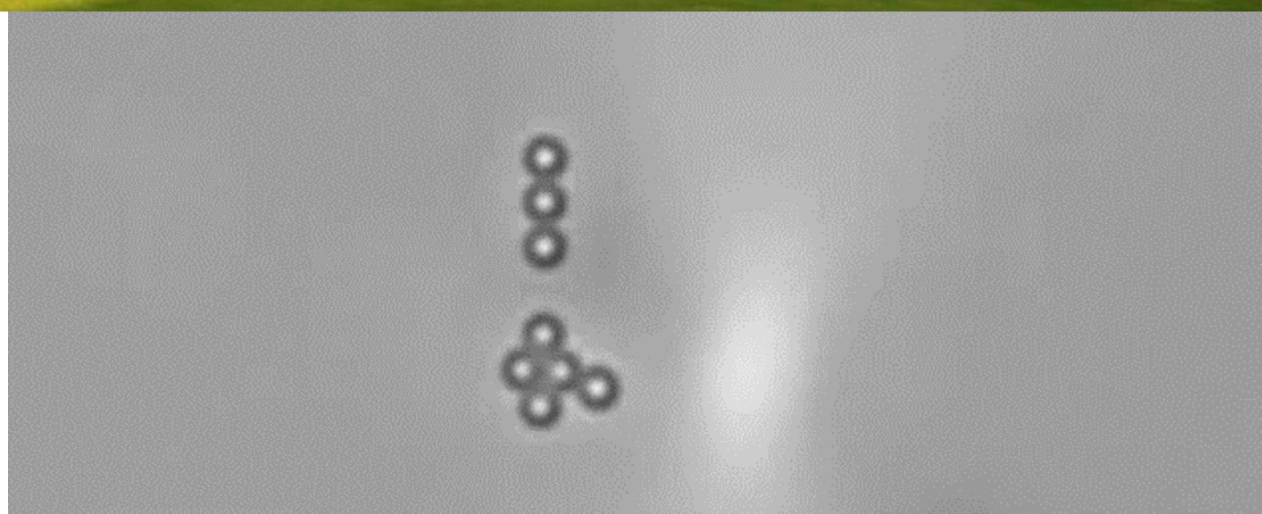
Can be modulated at MHz rates

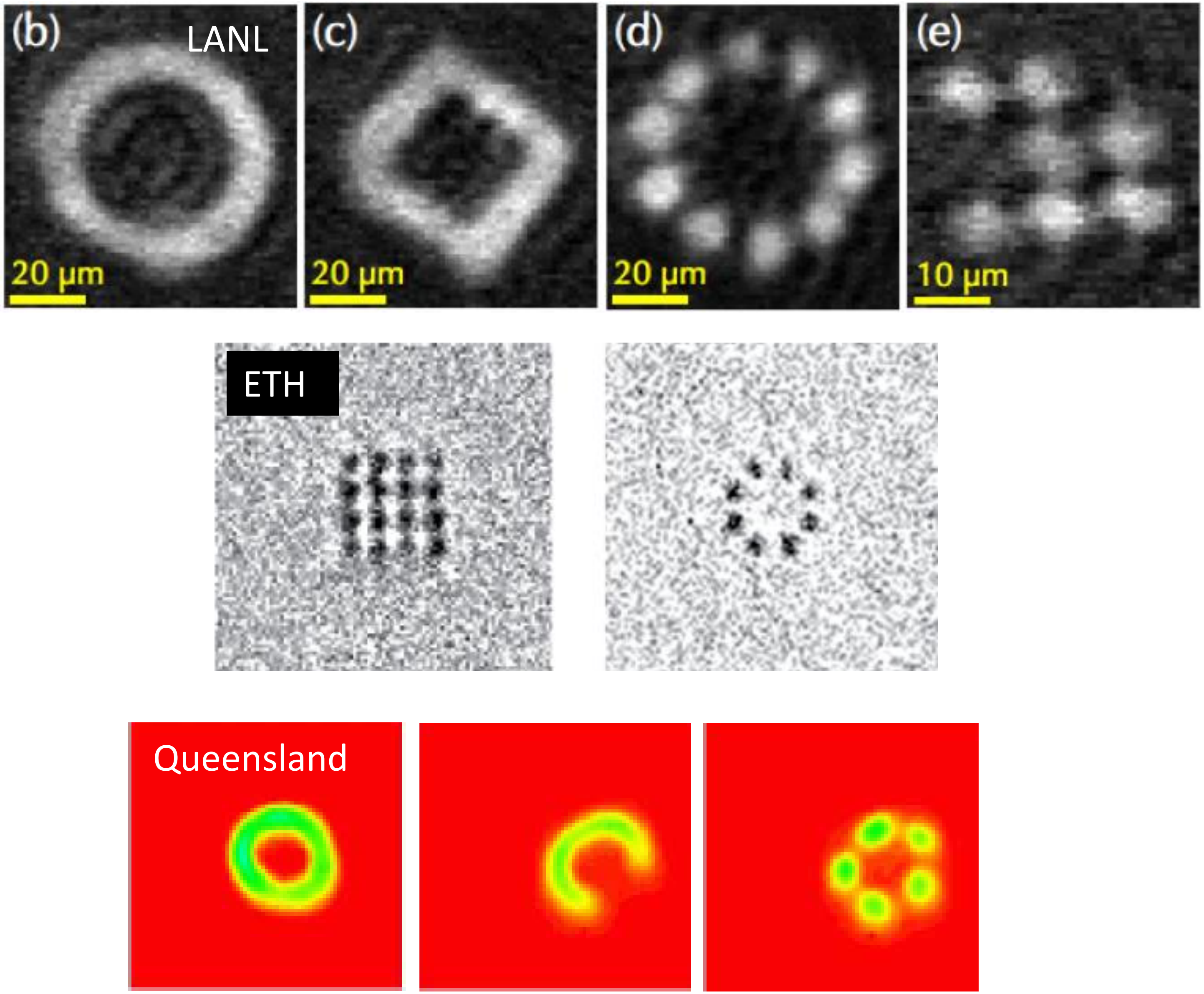
Kishan Dholakia
Professor of Optical Manipulation
St Andrews

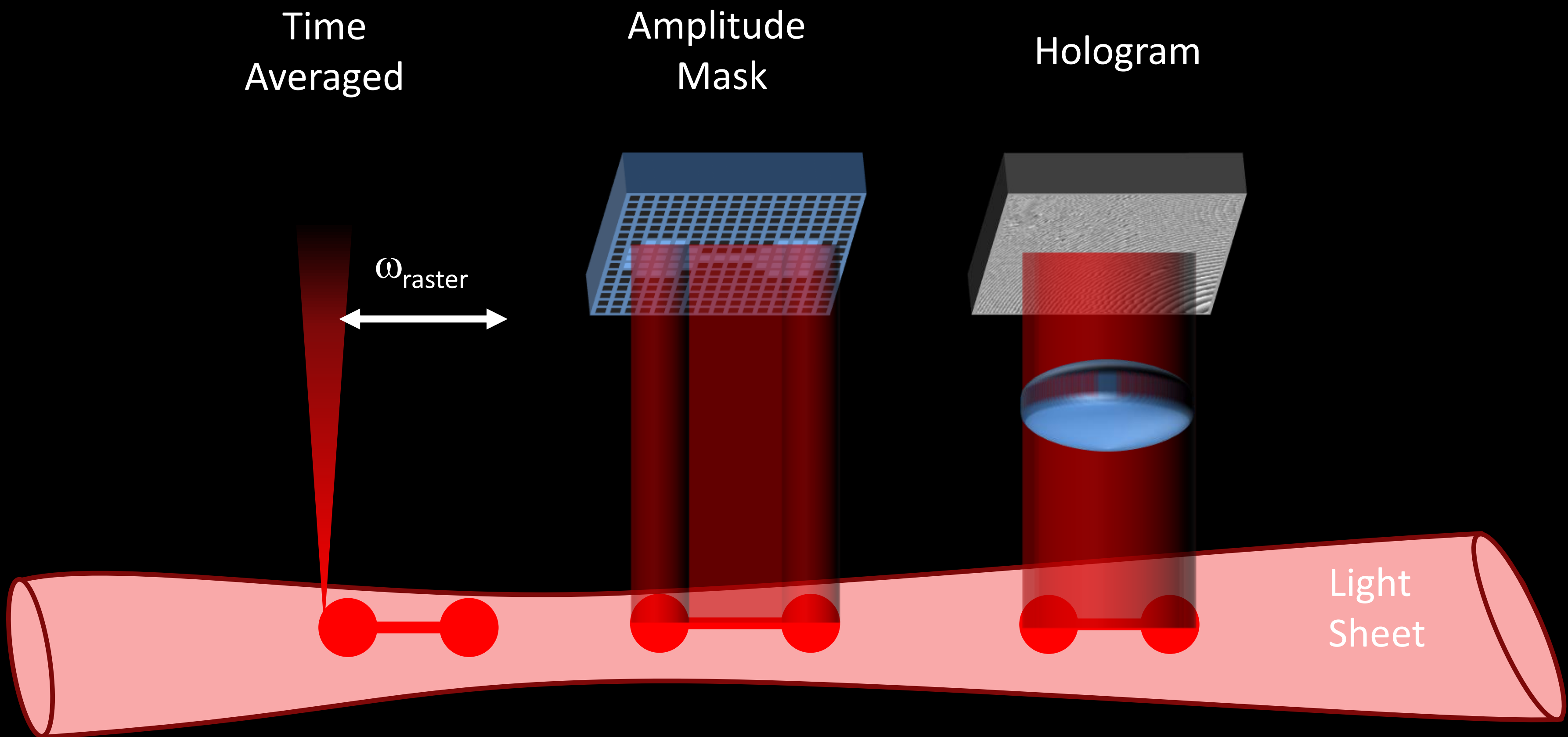




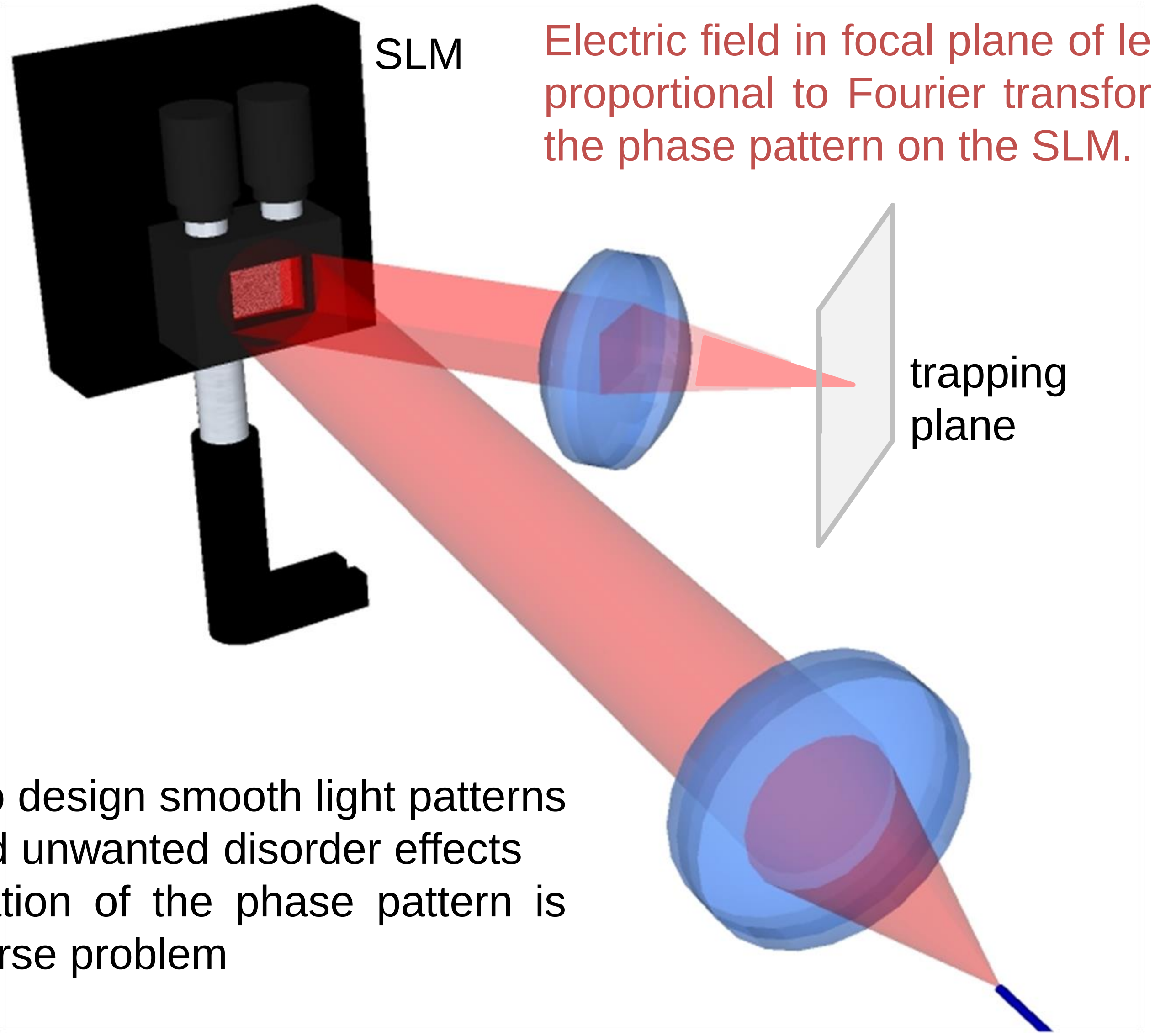
Arthur Ashkin
Father of Optical Tweezers
Nobel Prize 2018




(b)
LANL
20 μm
(c)
20 μm
(d)
20 μm
(e)
10 μm
ETH
Queensland

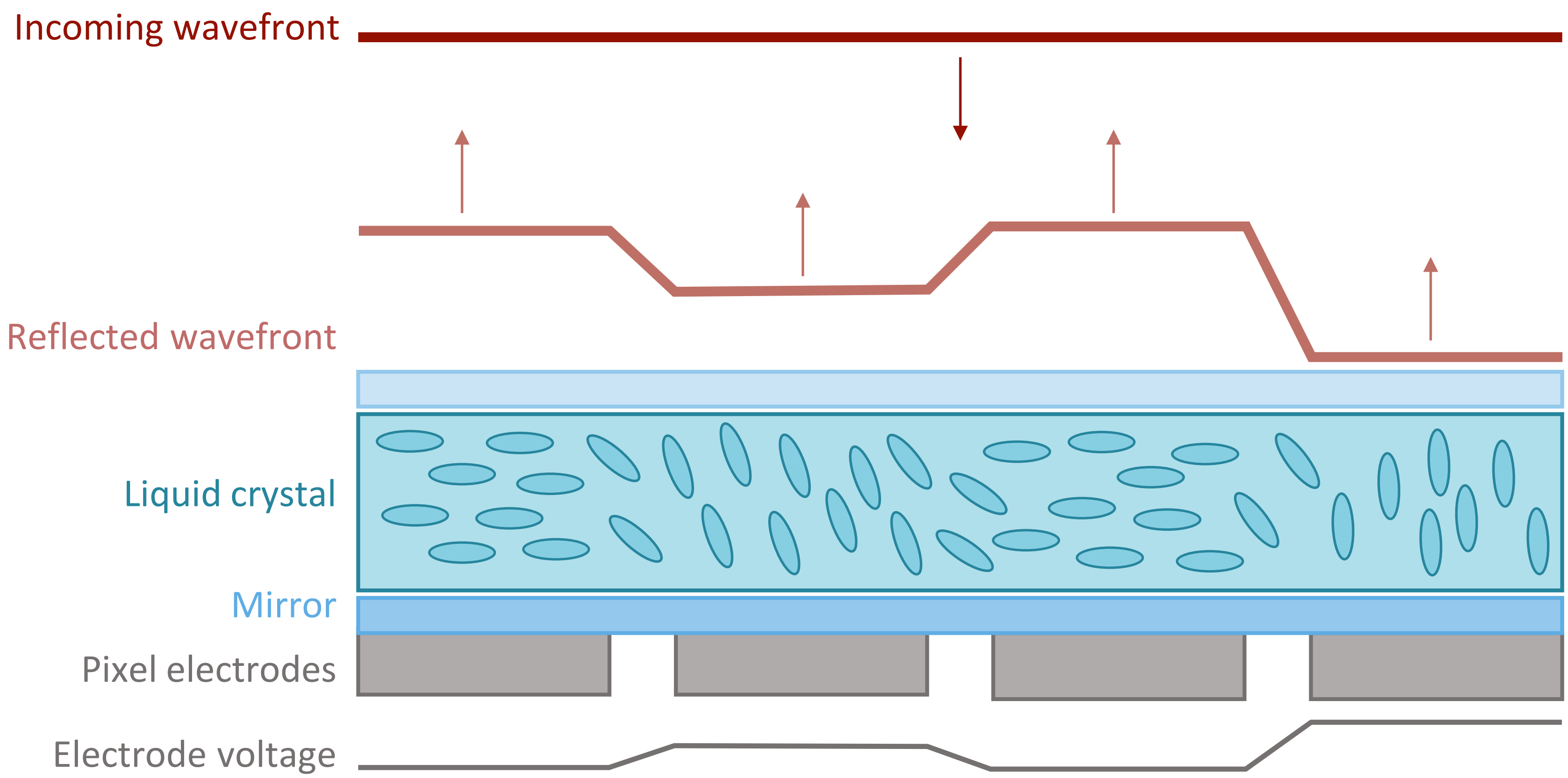

Time
Averaged
Amplitude
Mask
Hologram
ω_{raster}
Light
Sheet

Computer Generated Holography

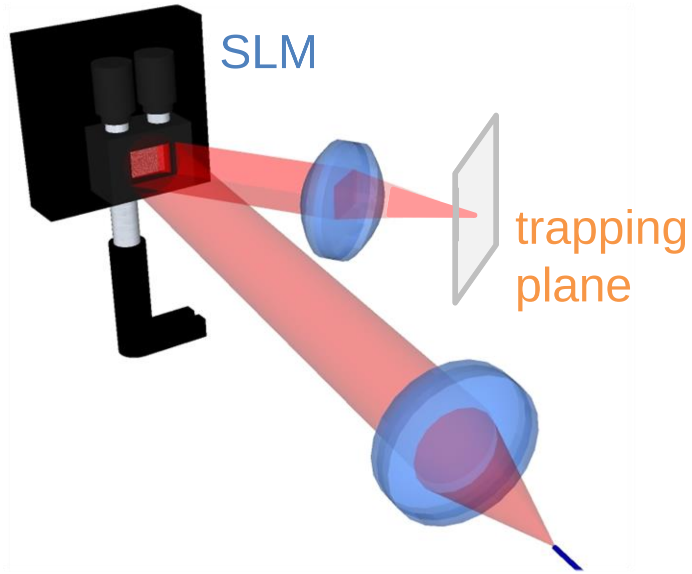


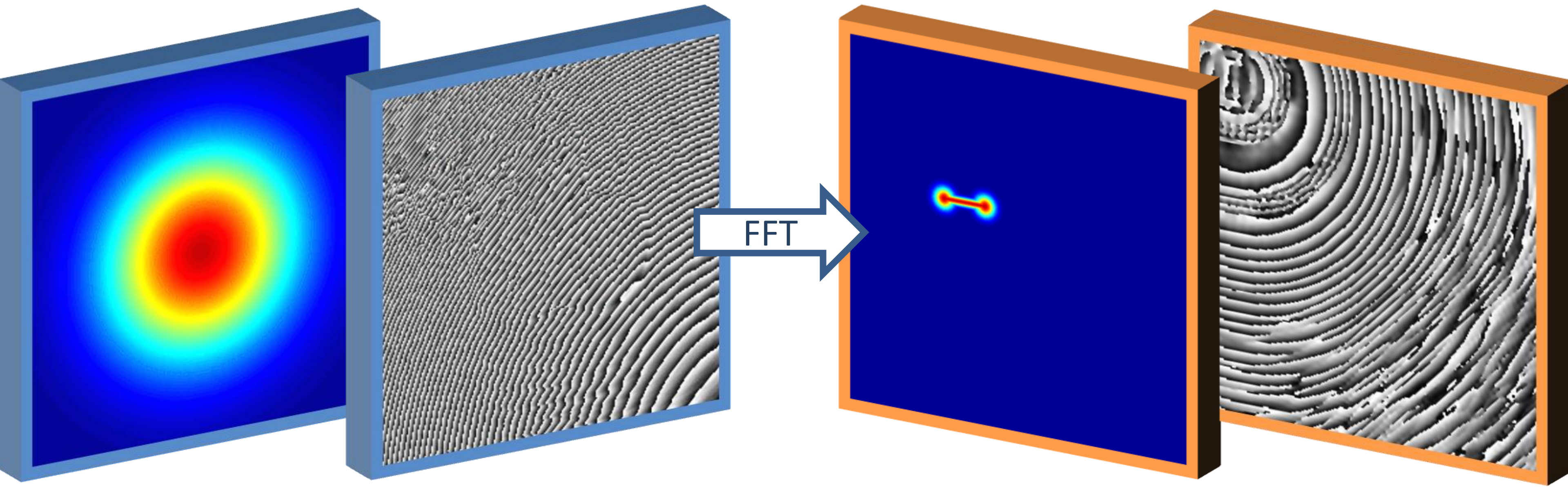
- Want to design smooth light patterns to avoid unwanted disorder effects
- Calculation of the phase pattern is an inverse problem

Computer Generated Holography

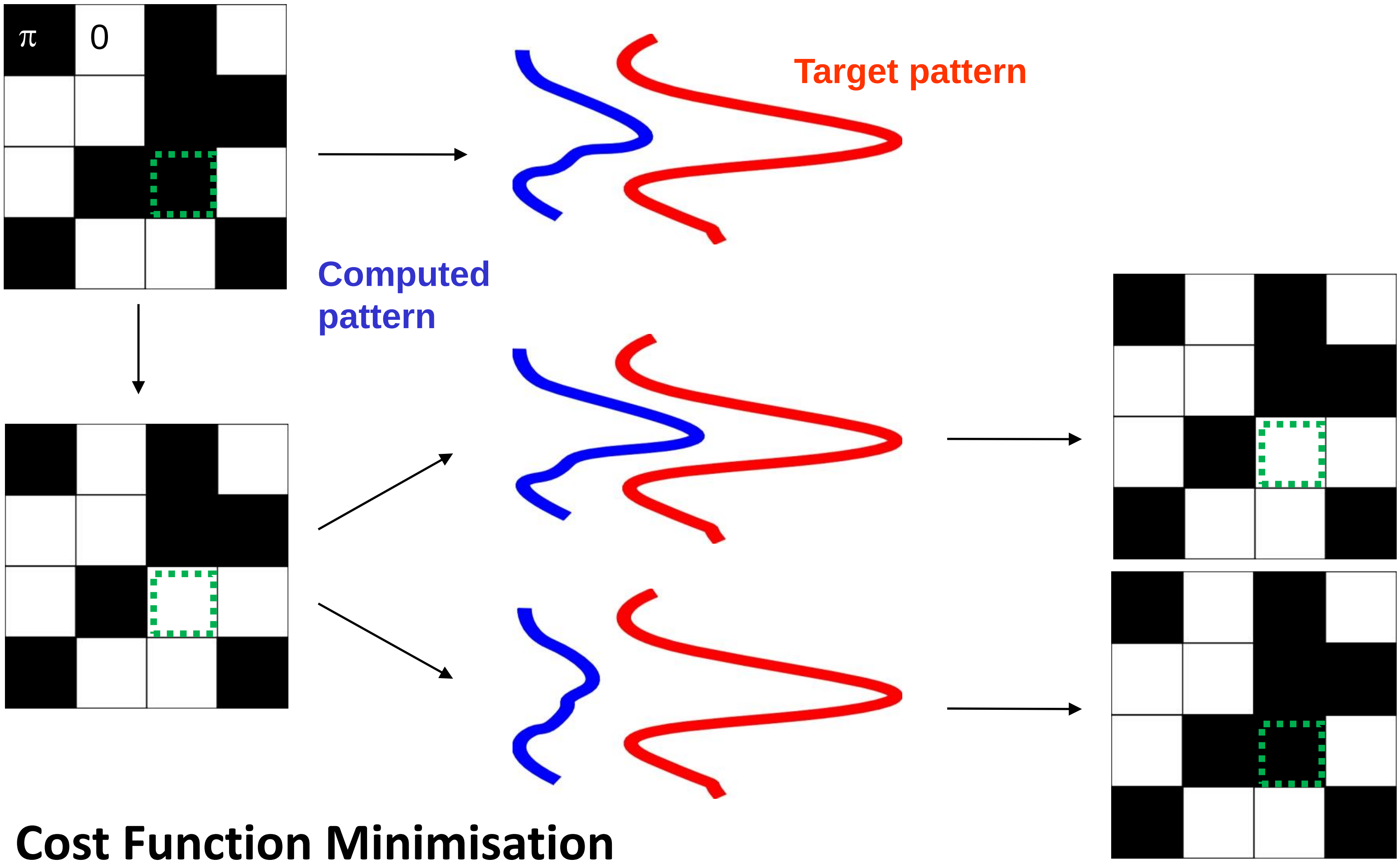


Calculating Holograms





Direct Binary Search Algorithm

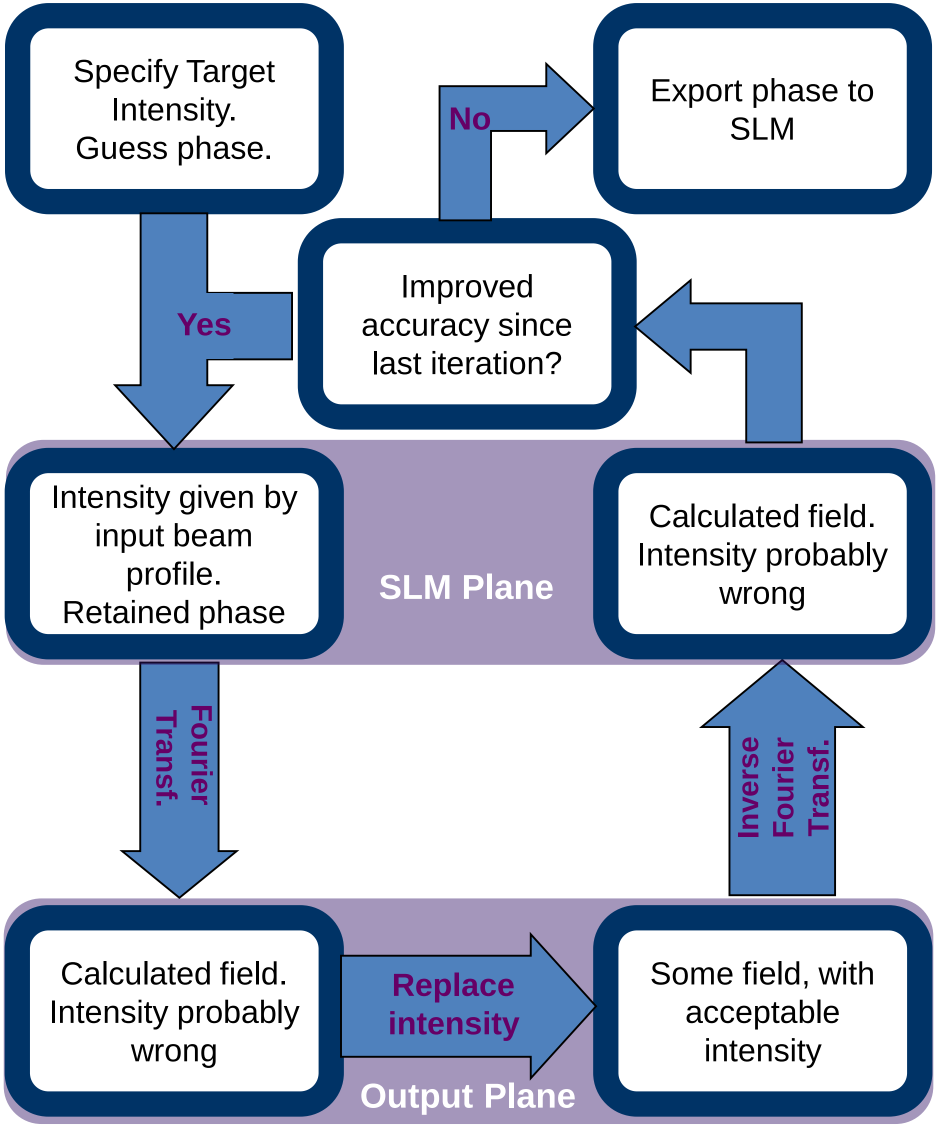


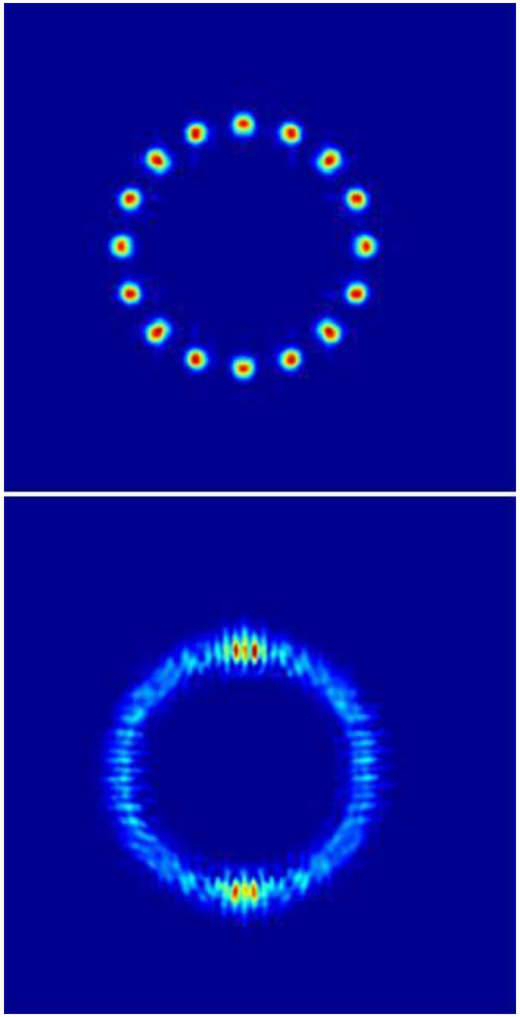
Cost Function Minimisation

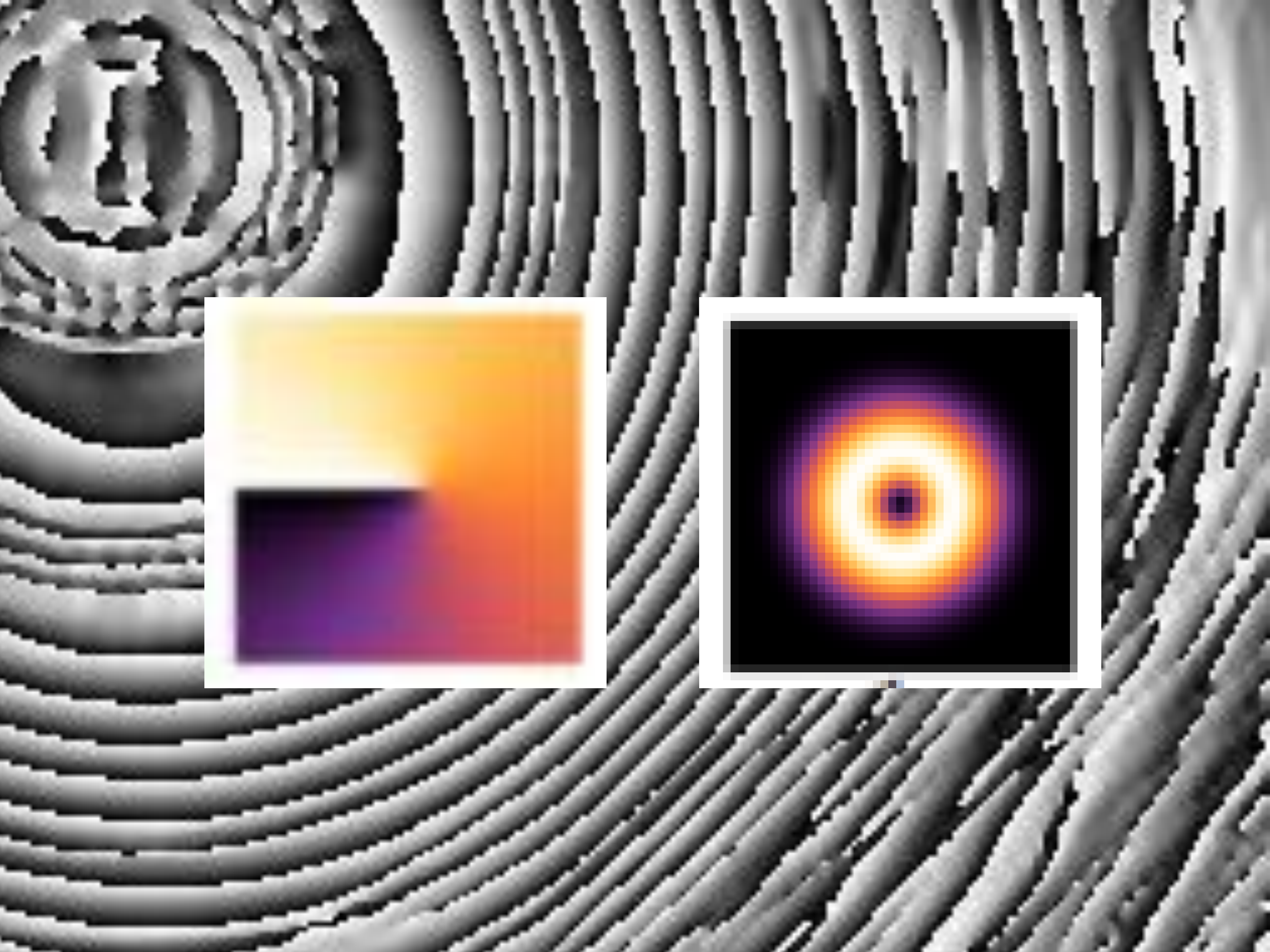
Example cost function: $C = T - |E_{out}|^2$

Iterative, unguided optimisation

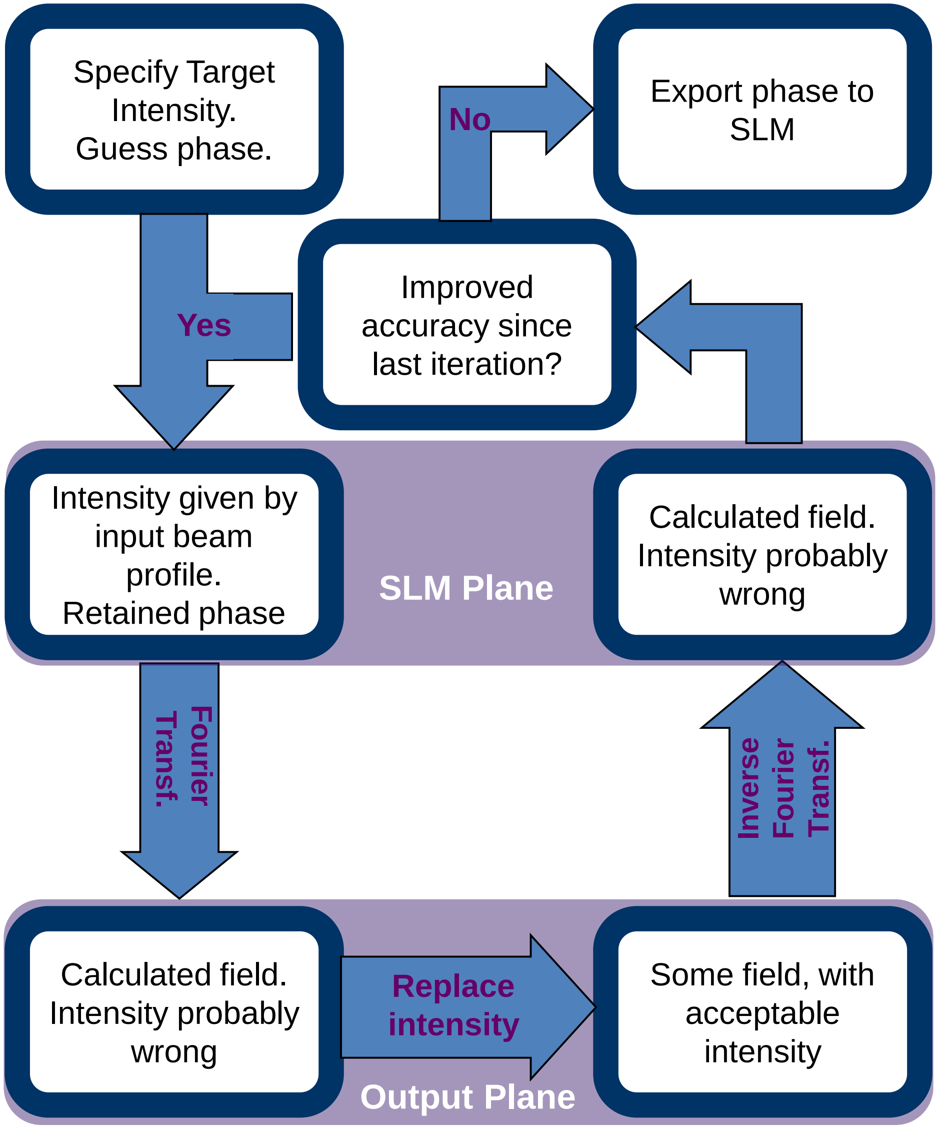
Iterative Fourier Transform Algorithm

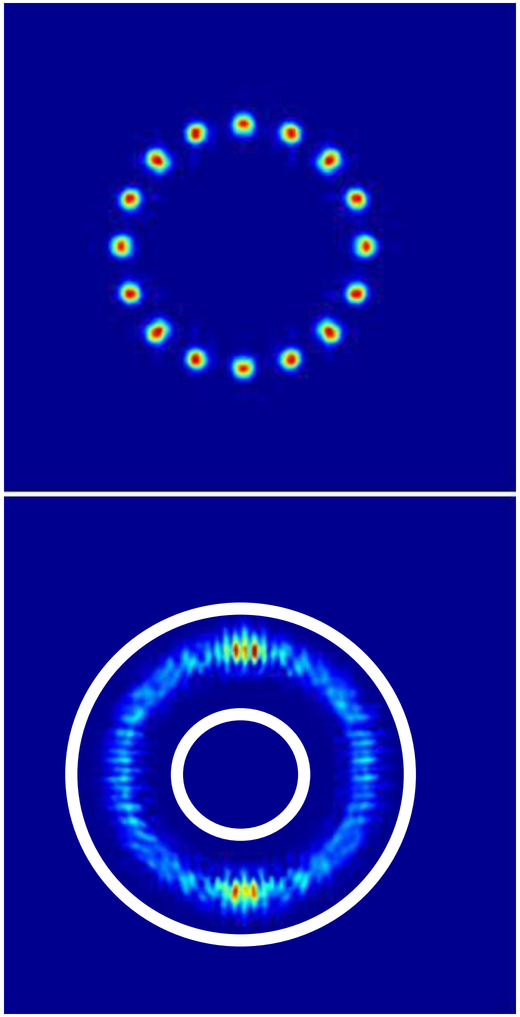




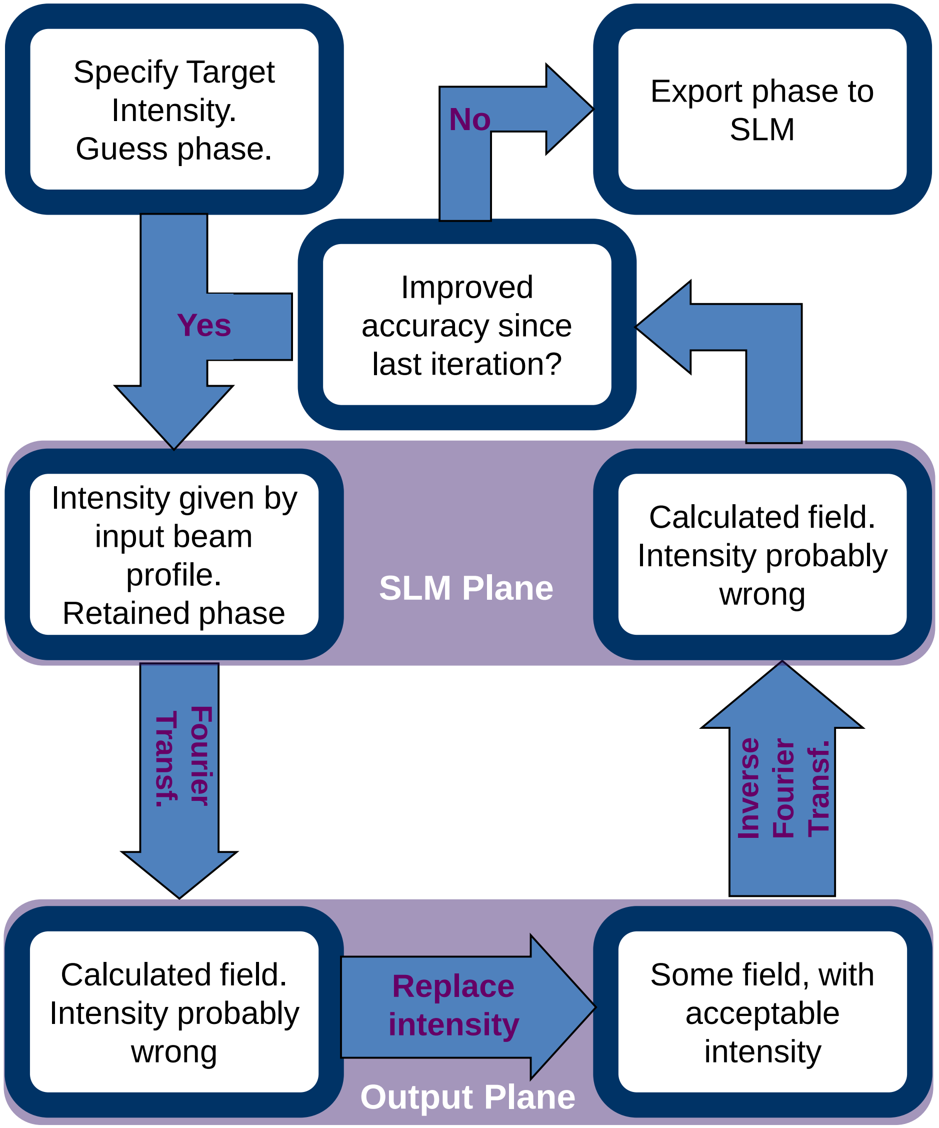


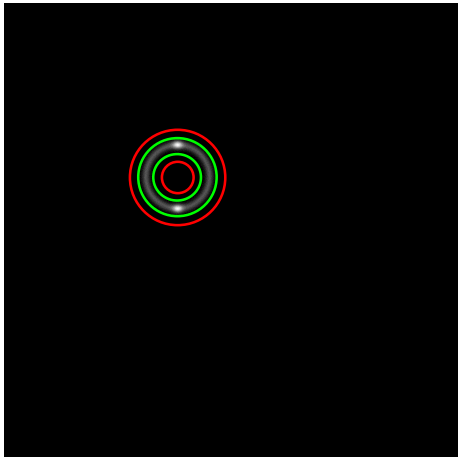
Iterative Fourier Transform Algorithm

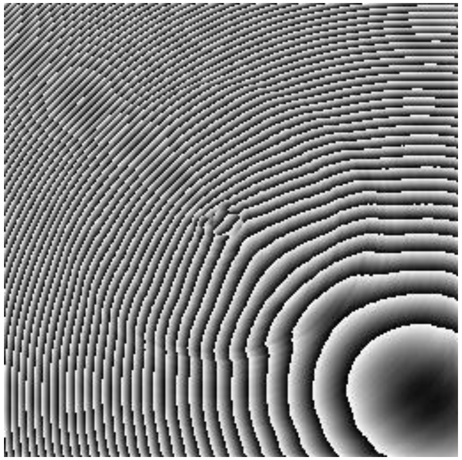




Iterative Fourier Transform Algorithm





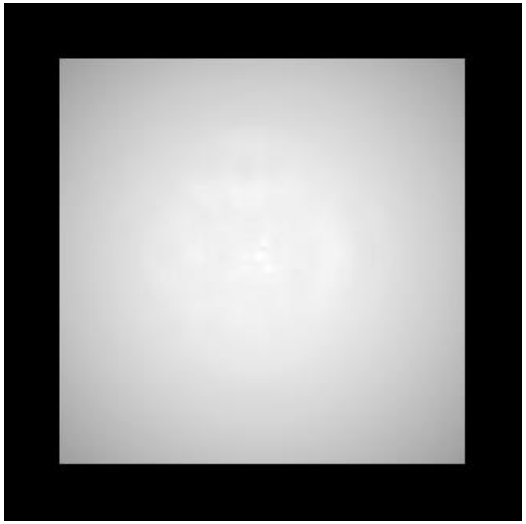


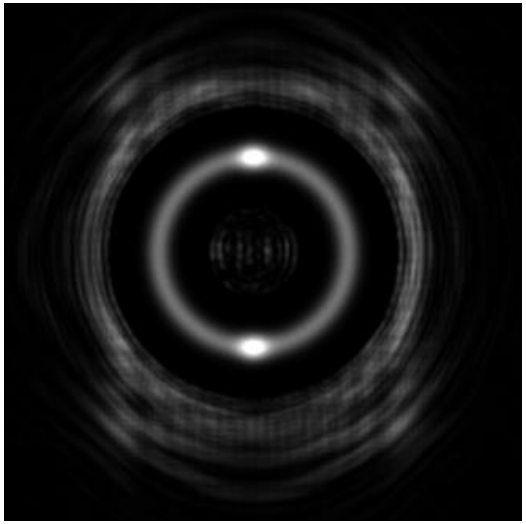
Pasienski and DeMarco, Opt Expr ***16****, 2176 (2008).*

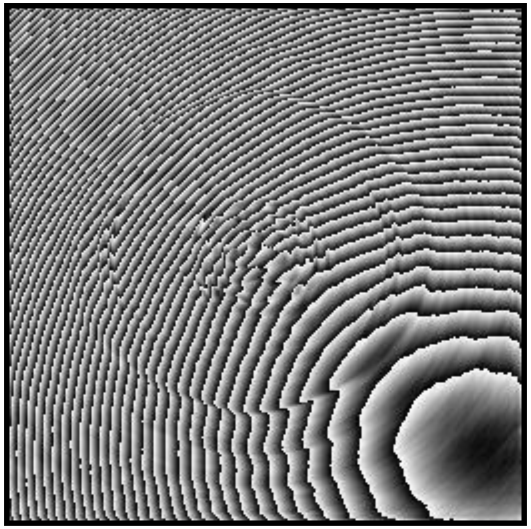
MRAF Algorithm

SLM plane

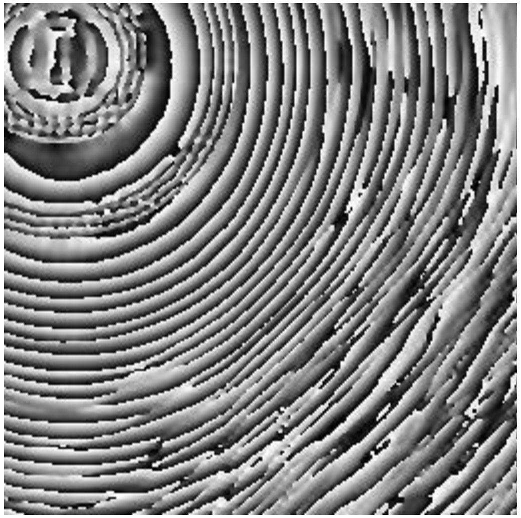
Fourier plane



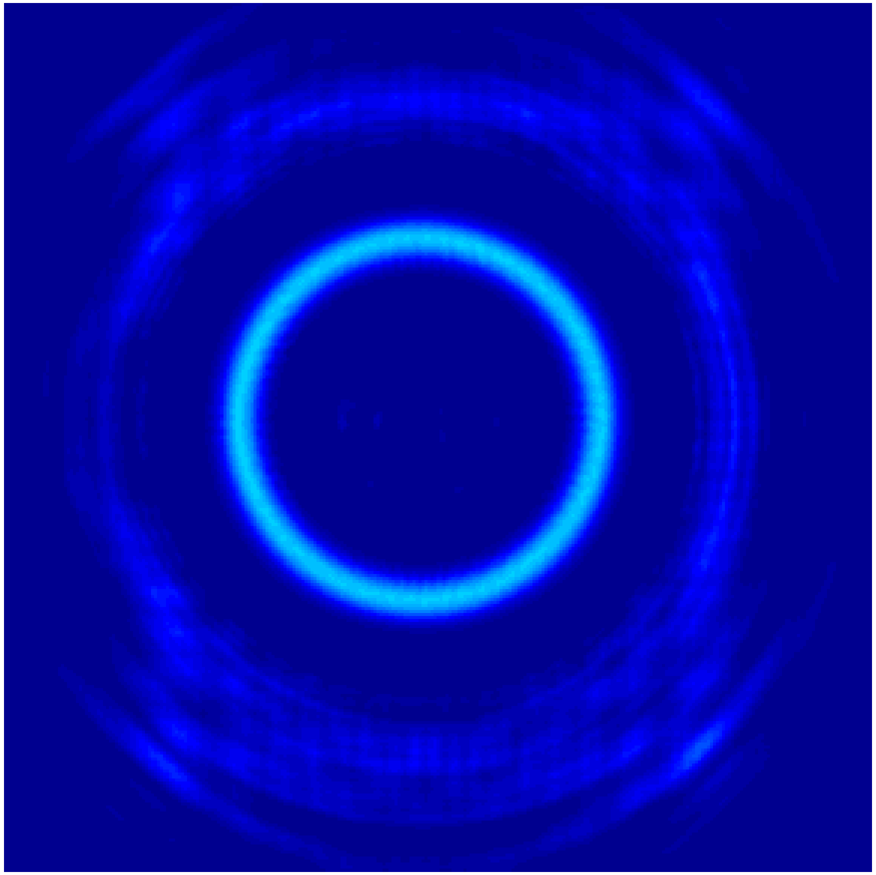




i = 116

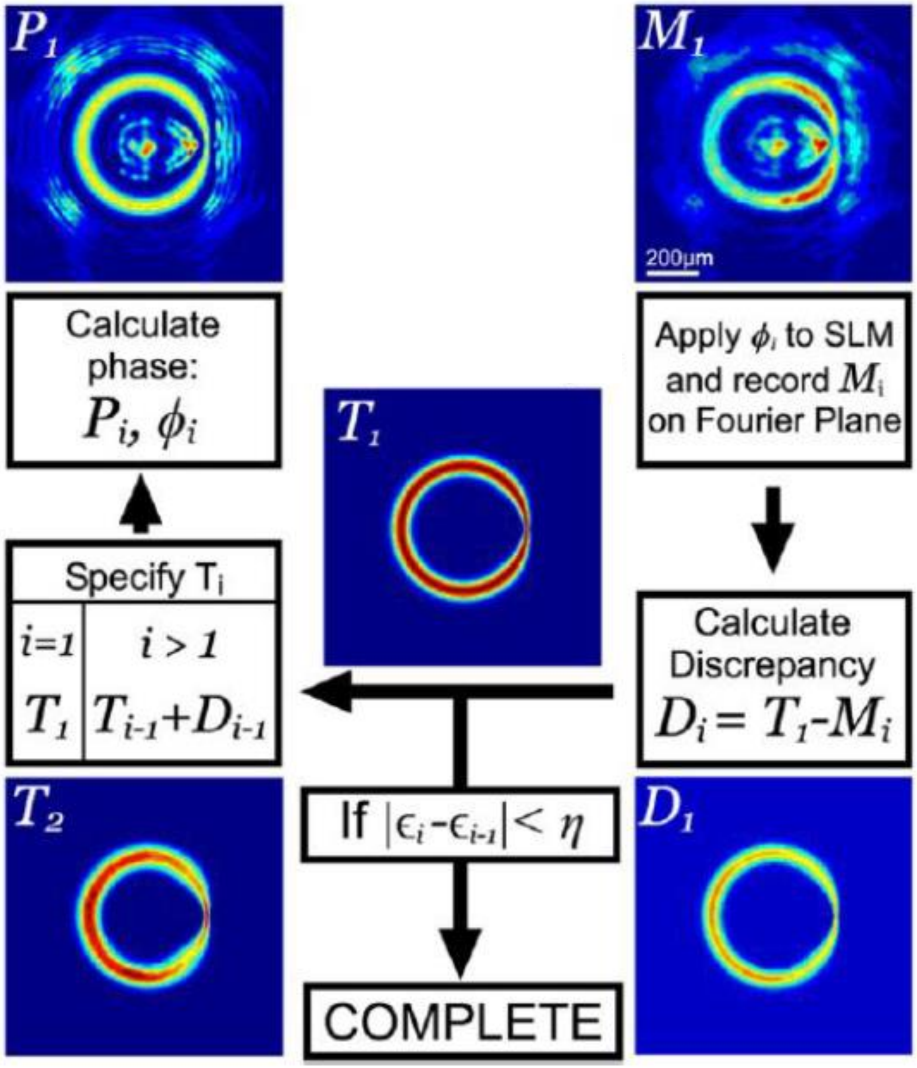


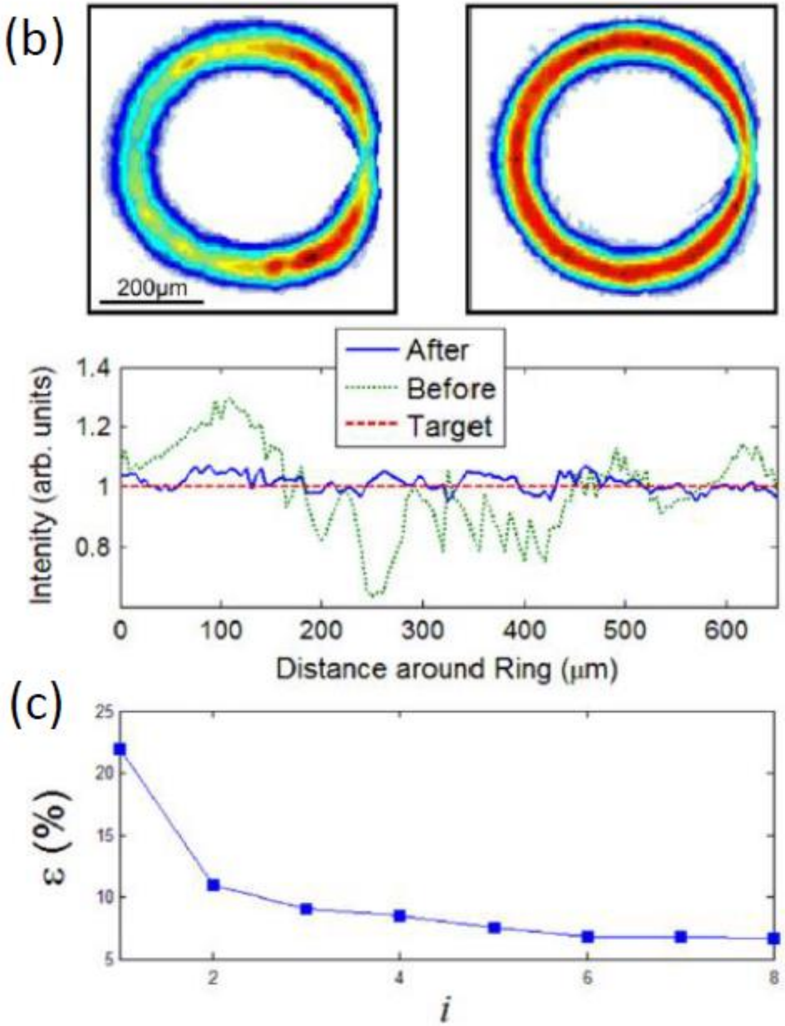
Inducing Superflow



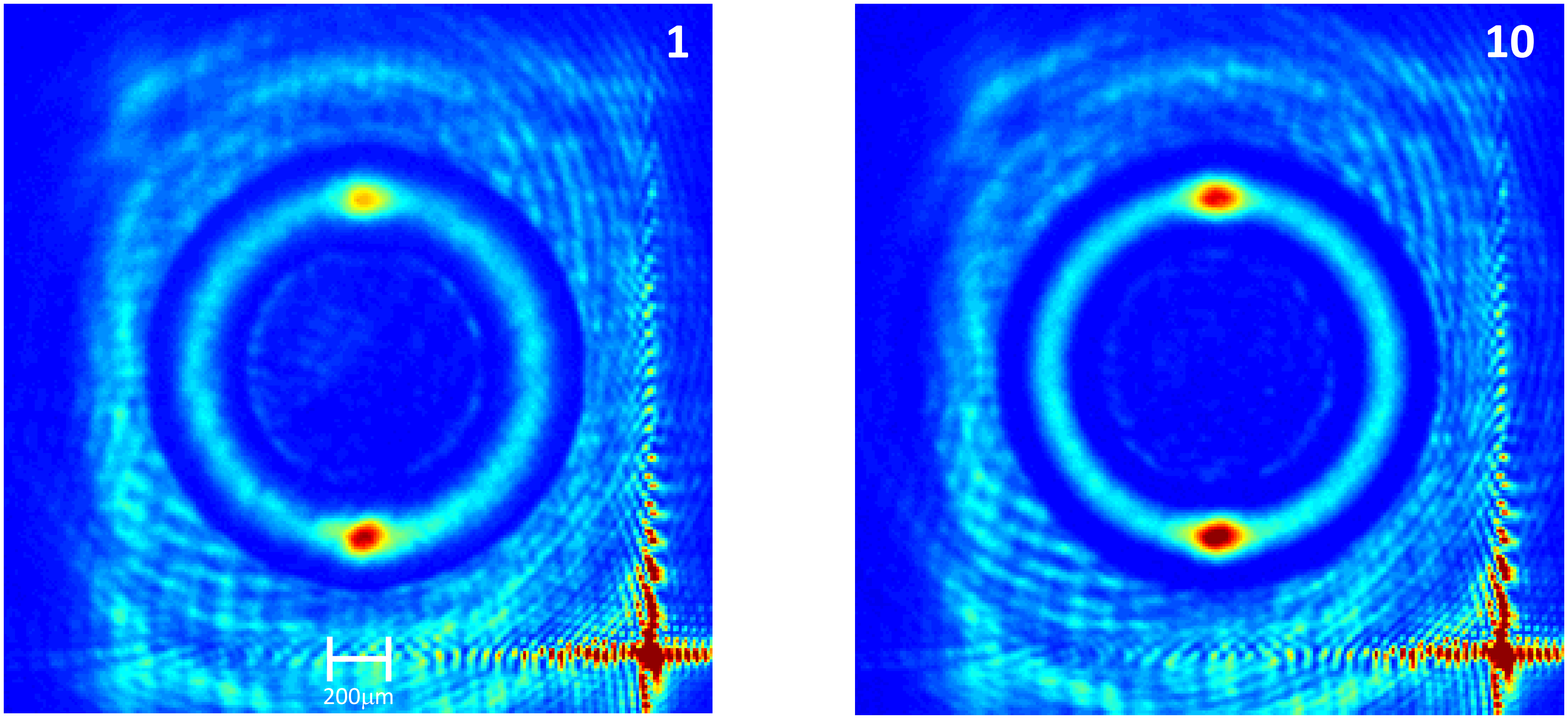
GB et al, Physica Scripta T143, 014008 (2011)

Experimental implementation



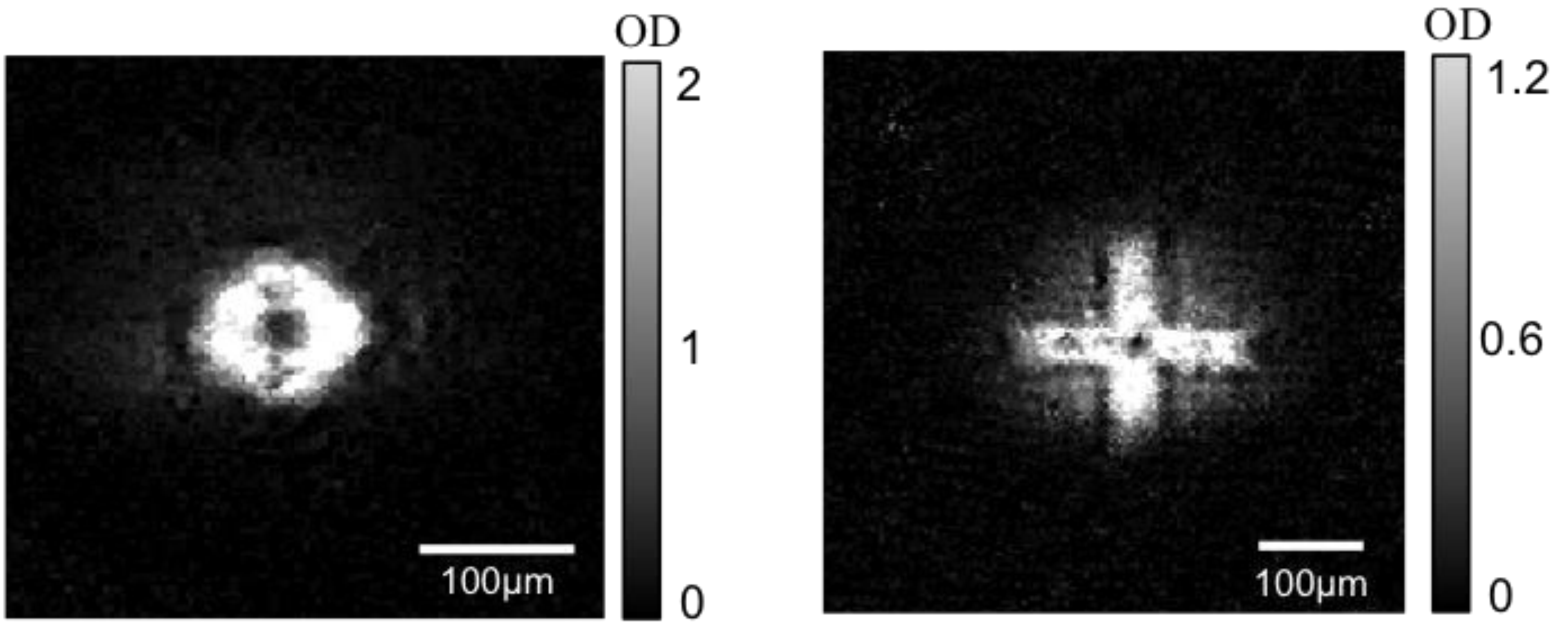


GB et al, J Phys B 48, 115303 (2015)



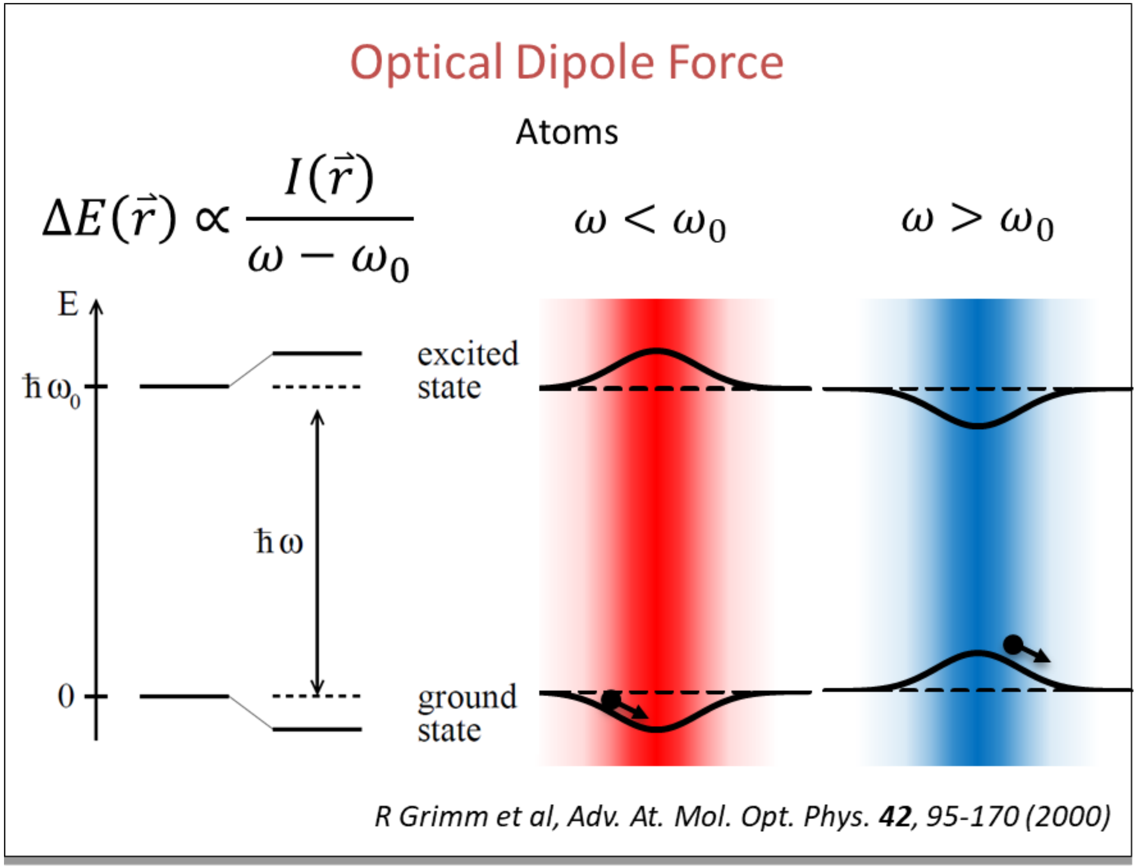
Quality progression within 10 iterations.

Can use atoms as a probe!

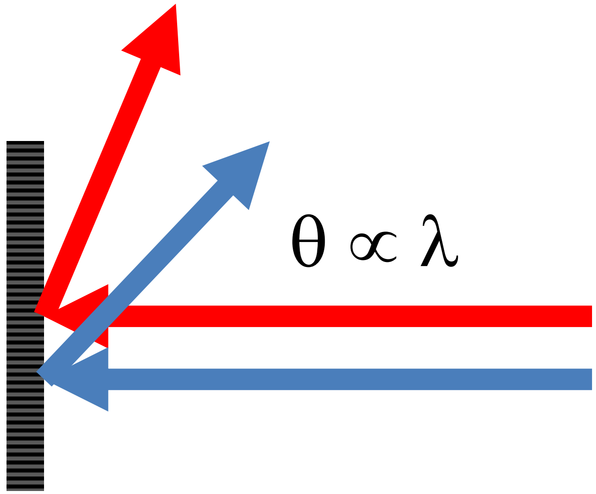


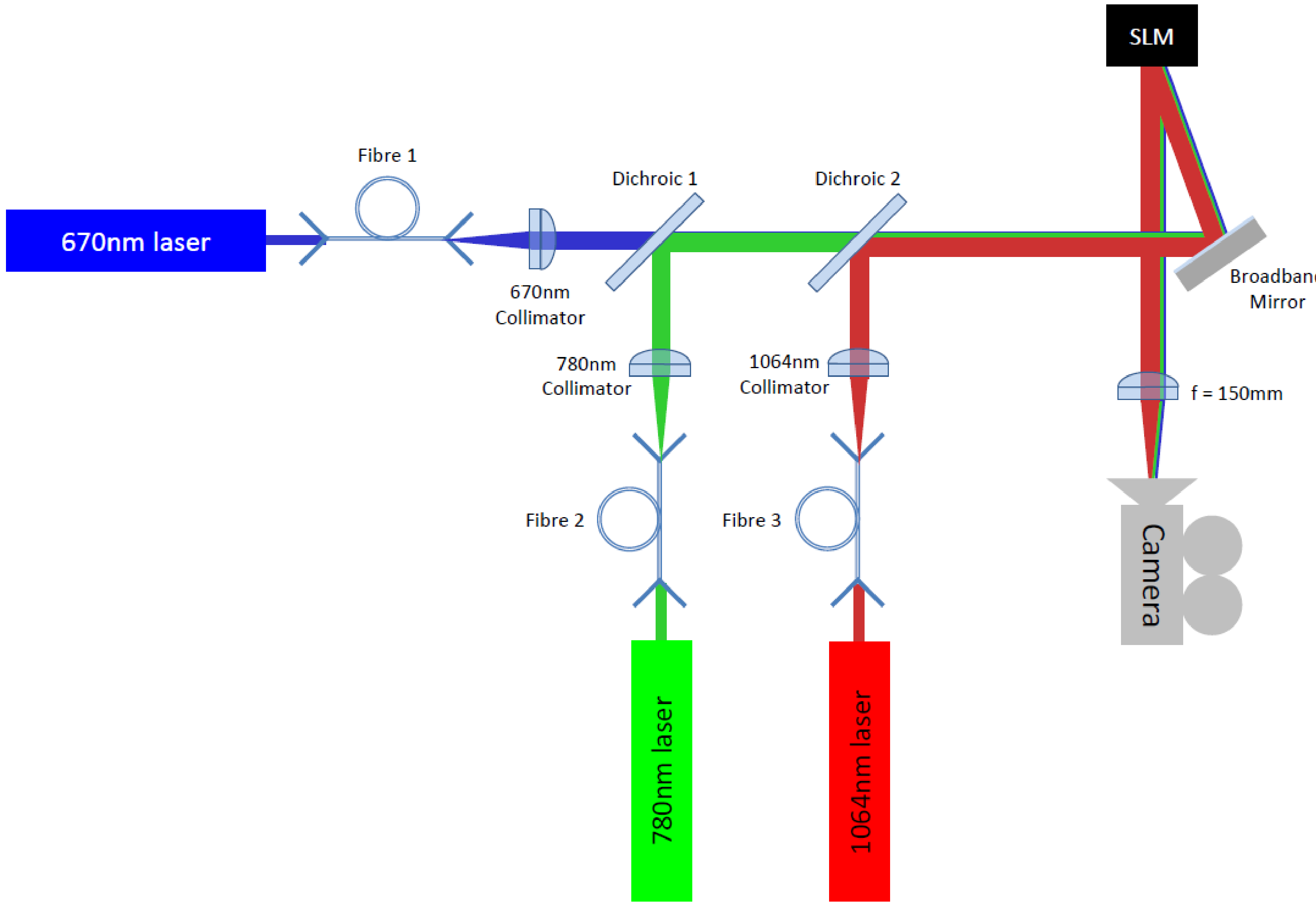
^{87}Rb BEC, 10^5 atoms, T/T_c ~ 0.1

Multi-wavelength holography

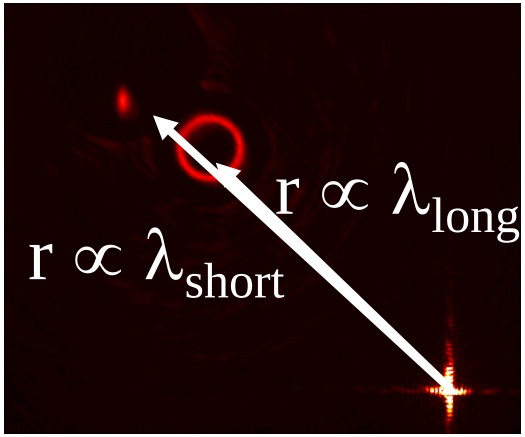


Remember, we use the SLM like a diffraction grating, and separate our pattern of interest from the unmodulated light

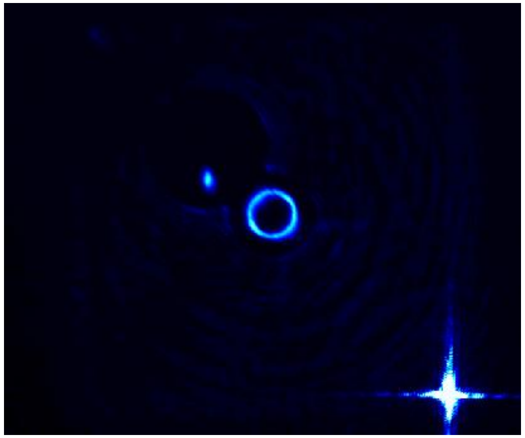



SLM
Fibre 1
Dichroic 1
Dichroic 2
670nm laser
670nm
Collimator
Broadband
Mirror
780nm
Collimator
1064nm
Collimator
f = 150mm
Fibre 2
Fibre 3
Camera
780nm laser
1064nm laser

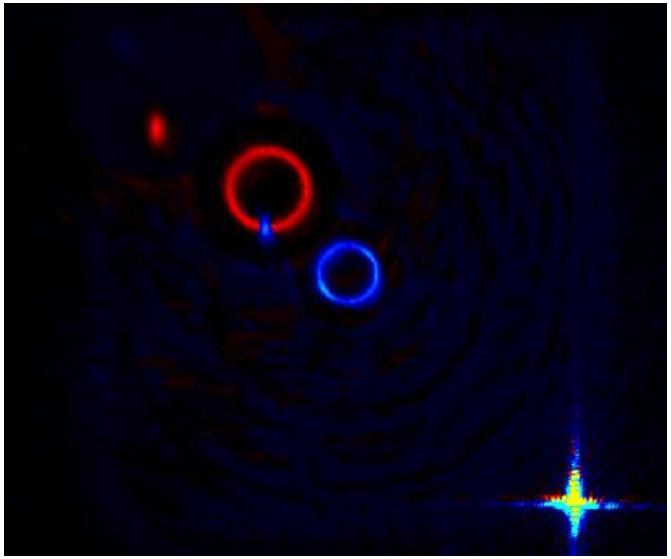
Multi-wavelength holography

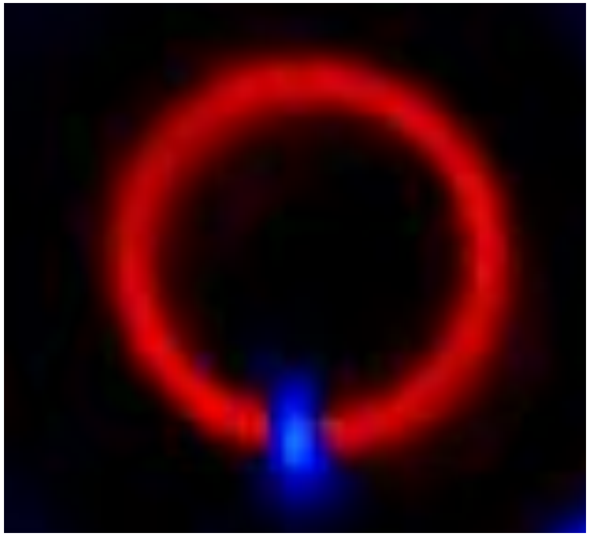


λ = 1064nm



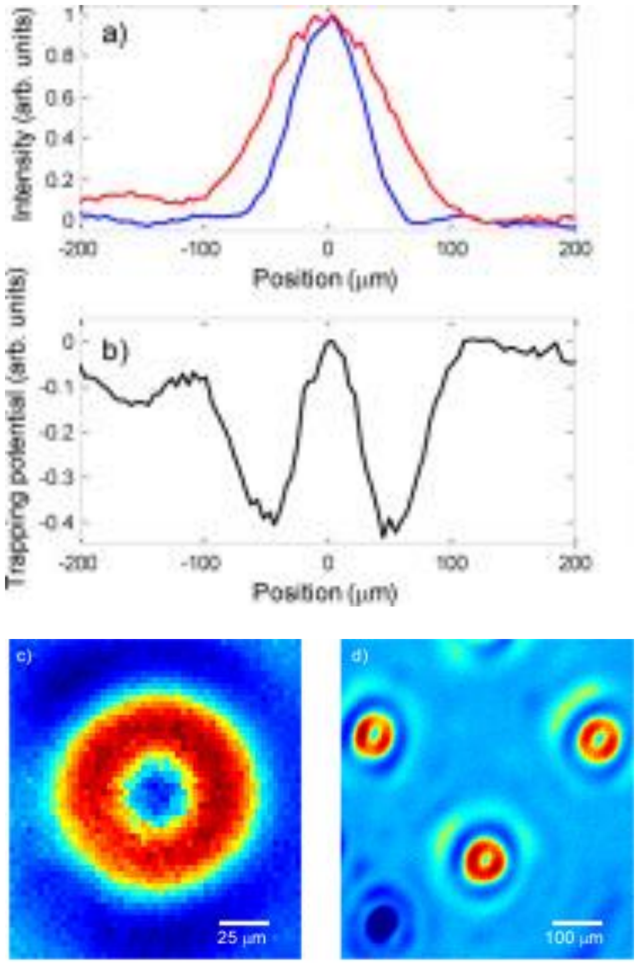
λ = 780nm

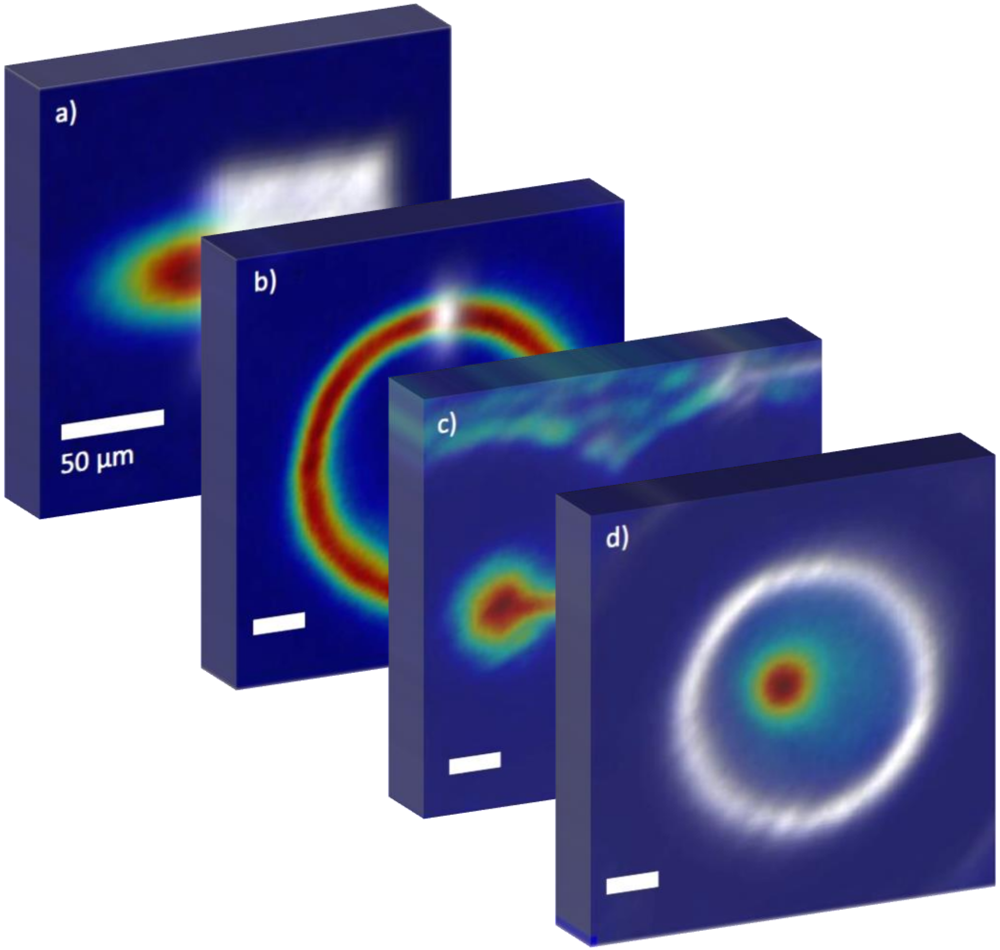




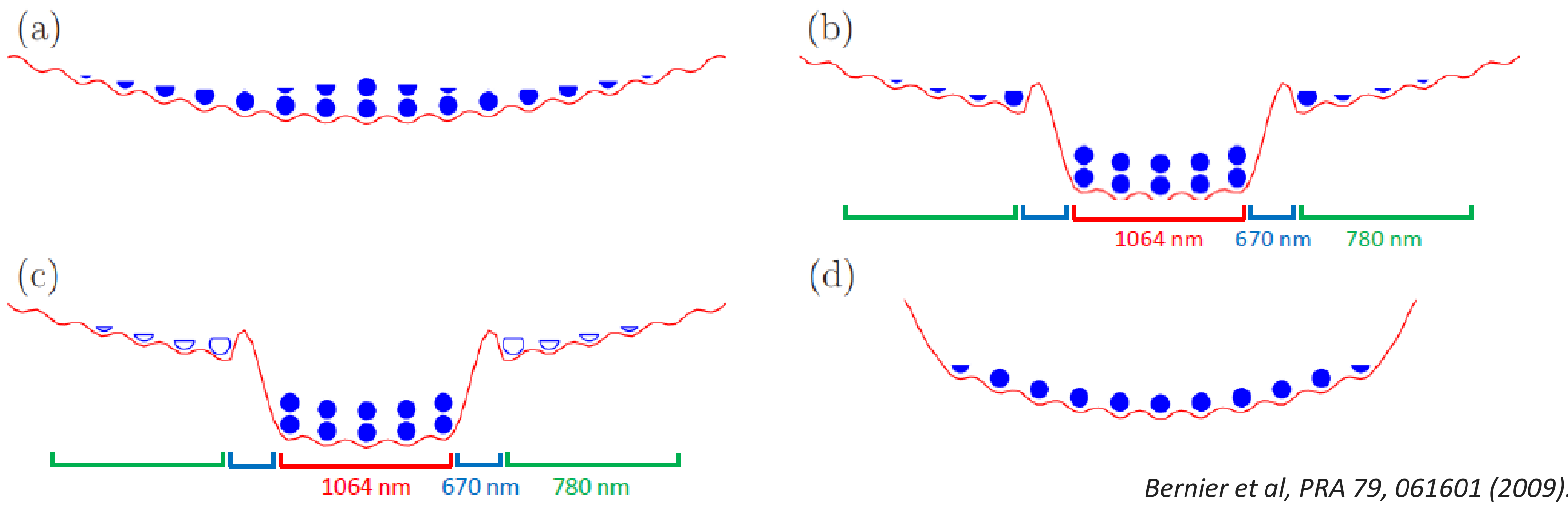
D Bowman et al Opt Express ***23,*** *8365 (2015)*

Multiwavelength Holography

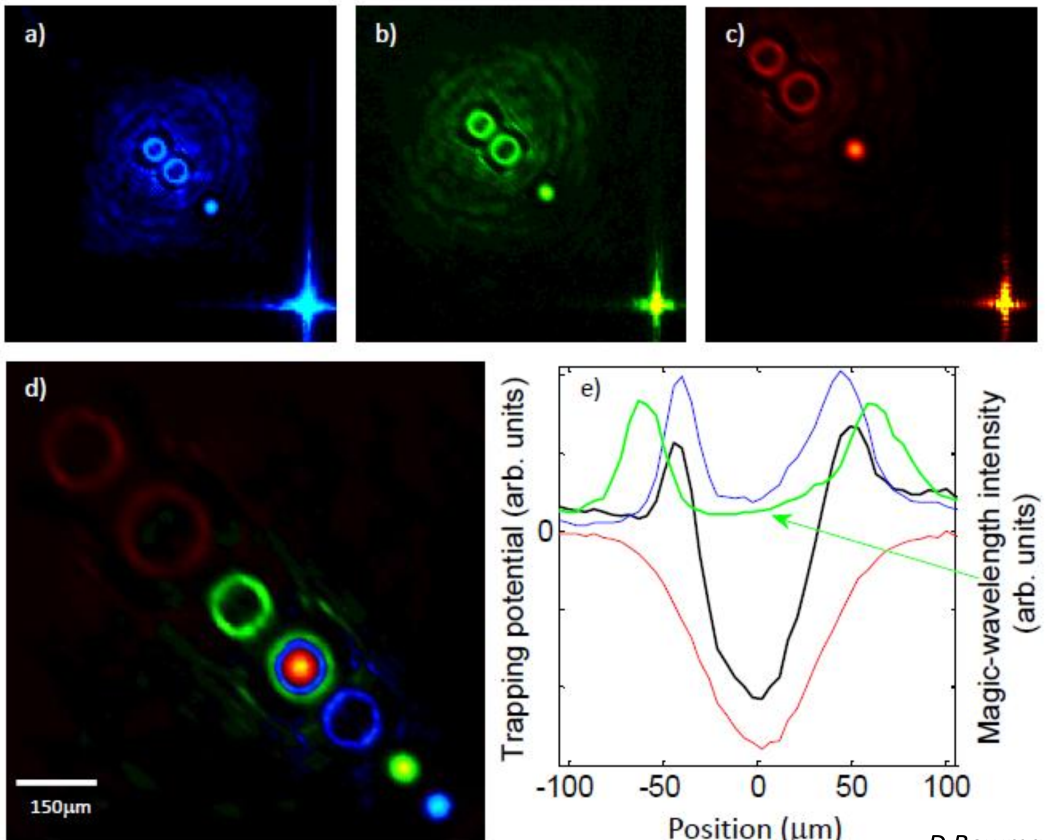




D Bowman et al., Opt Express ***23,*** *8365 (2015)*



Bernier et al, PRA 79, 061601 (2009).

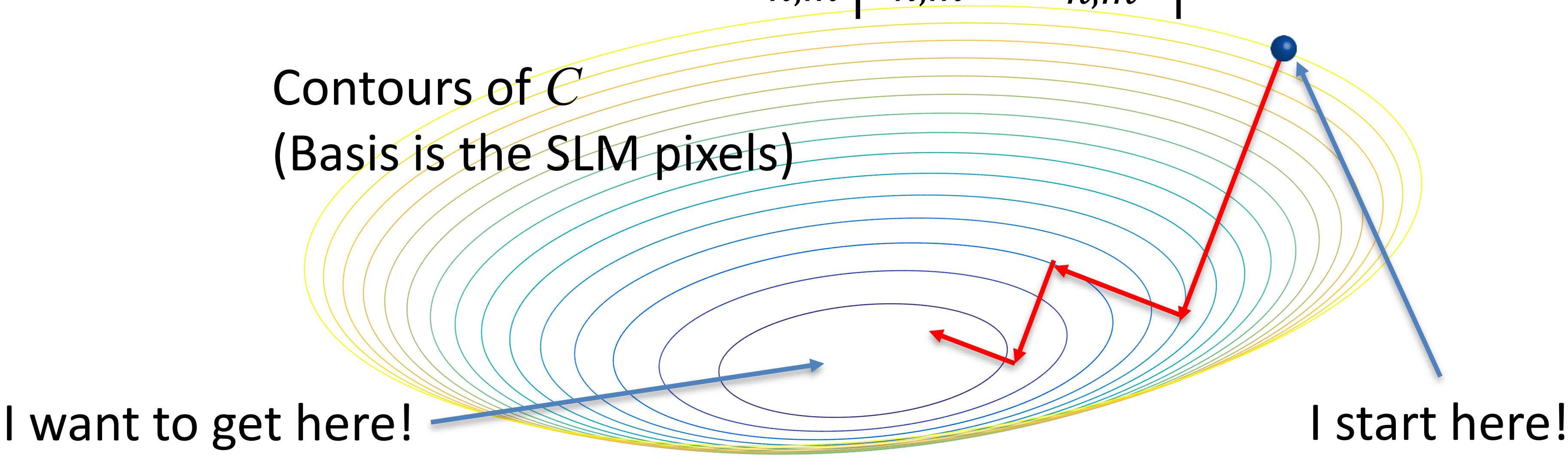


*D Bowman et al Opt Express **23,** 8365 (2015)*

Steepest Descent

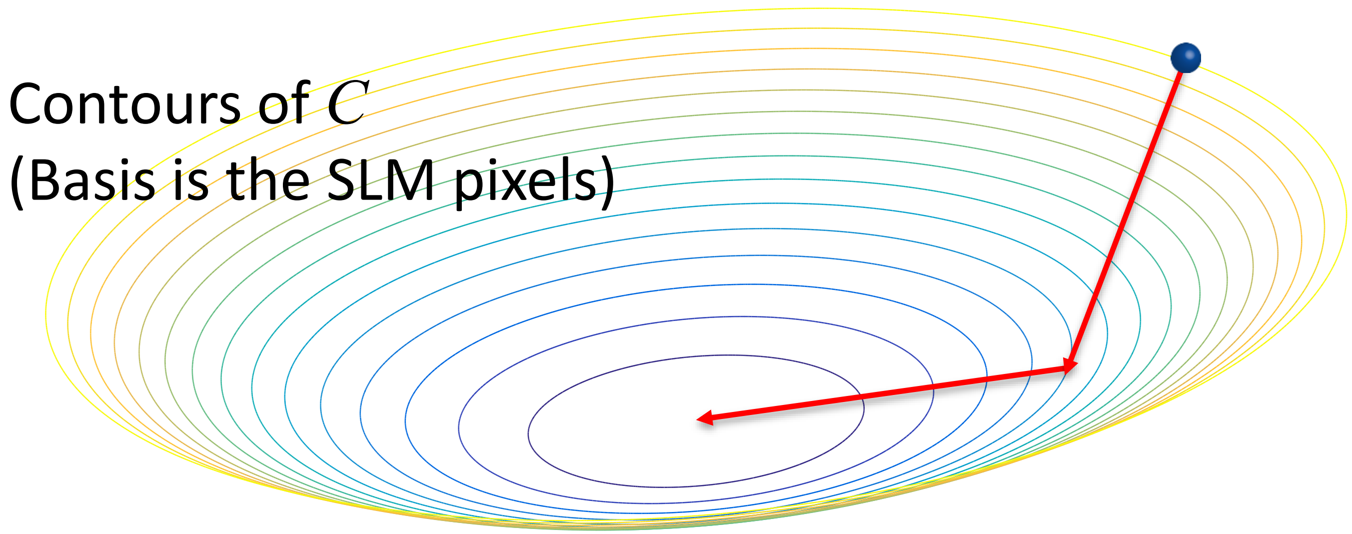
Cost Function Minimisation

Example cost function: $C = \sum_{n,m} \left| T_{n,m} - E_{n,m}^{(\mathrm{out})} \right|^2$



1. Move along a line, initially perpendicular to the contour (steepest descent)
2. Stop when I am parallel to nearest contour
3. Change direction to move perpendicular to contour and repeat until I reach the minimum

Conjugate gradient

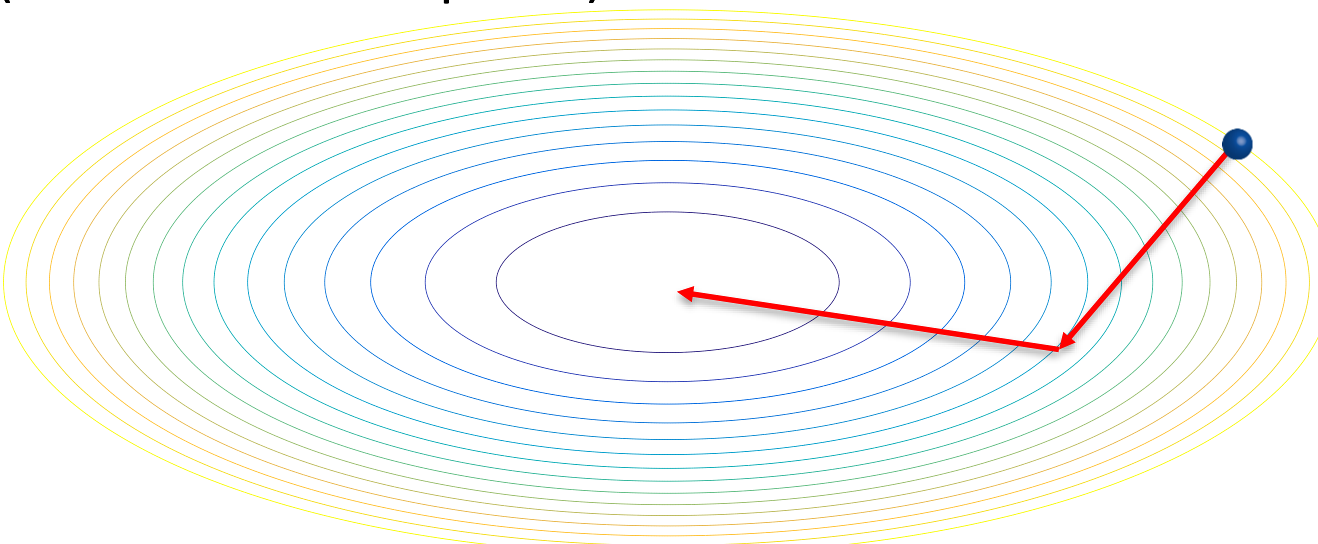


Wouldn’t it be better if we could avoid going back over the same directions?

We could take the conjugate direction!

Conjugate gradient

Contours of C
(Basis is the SLM pixels)



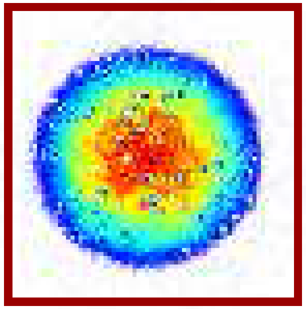
(also known as the C-orthogonal direction)

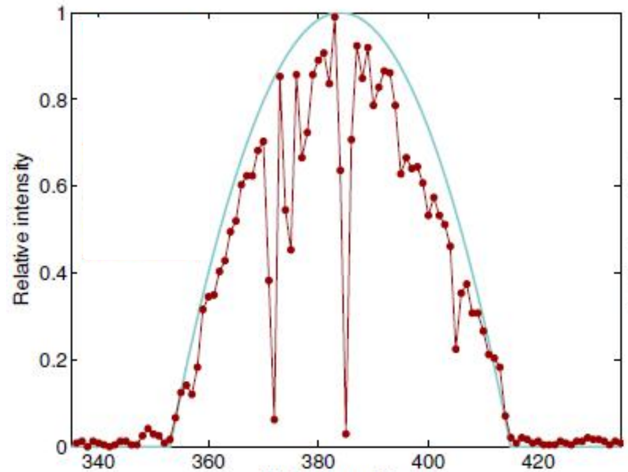
- Guarantees convergence in fewer than *N* steps, where *N* is the size of my basis vector (number of SLM pixels)
- Robust against initial position

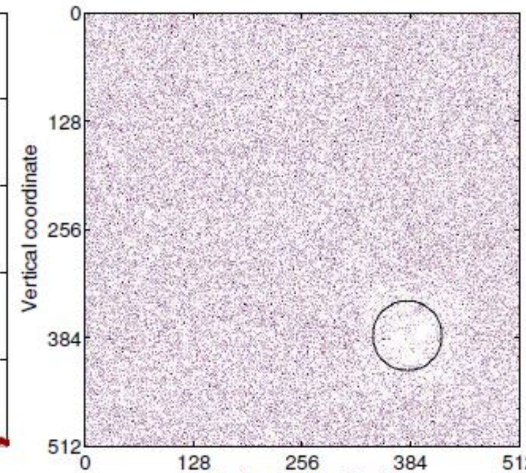
Cost Function Choice

The power of this approach is flexibility in cost function choice.

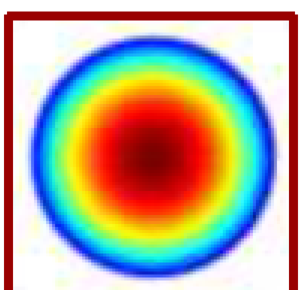
$$C = \sum_{nm} \left(T_{nm} - |E_{out,nm}|^2 \right)^2$$

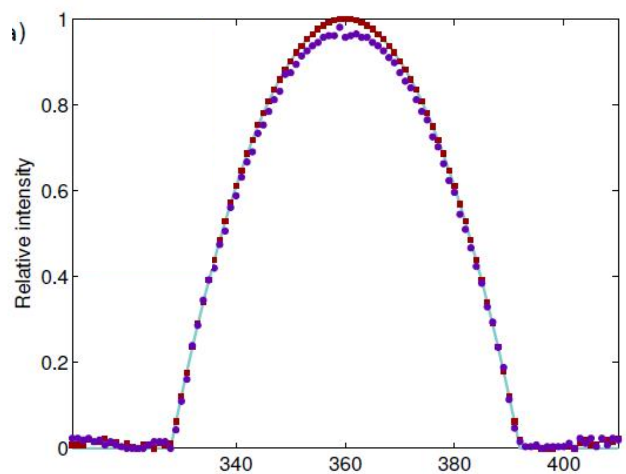


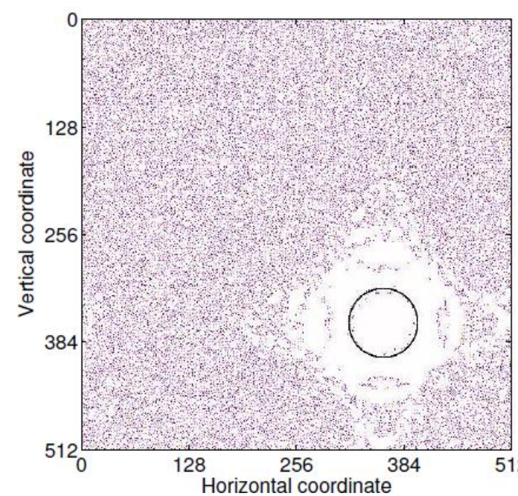




$$C_b = \sum_{nm} \left\{ \left(T_{nm} - \left|E_{nm}^{(out)}\right|^2 \right)^2 + \left[\left(\left|E_{nm}^{(out)}\right|^2 - \left|E_{n(m\pm1)}^{(out)}\right|^2 \right)^2 + \left(\left|E_{nm}^{(out)}\right|^2 - \left|E_{(n\pm1)m}^{(out)}\right|^2 \right)^2 \right] \right\}$$







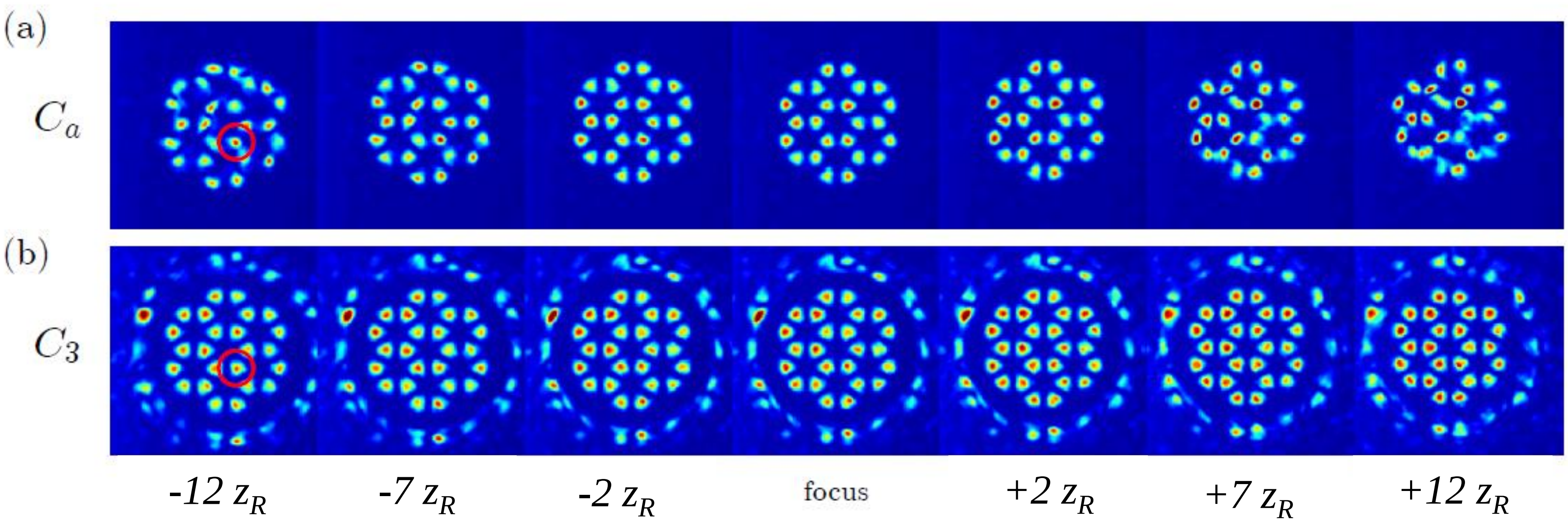
T Harte et al., Opt Express ***22****, 26548 (2014)*

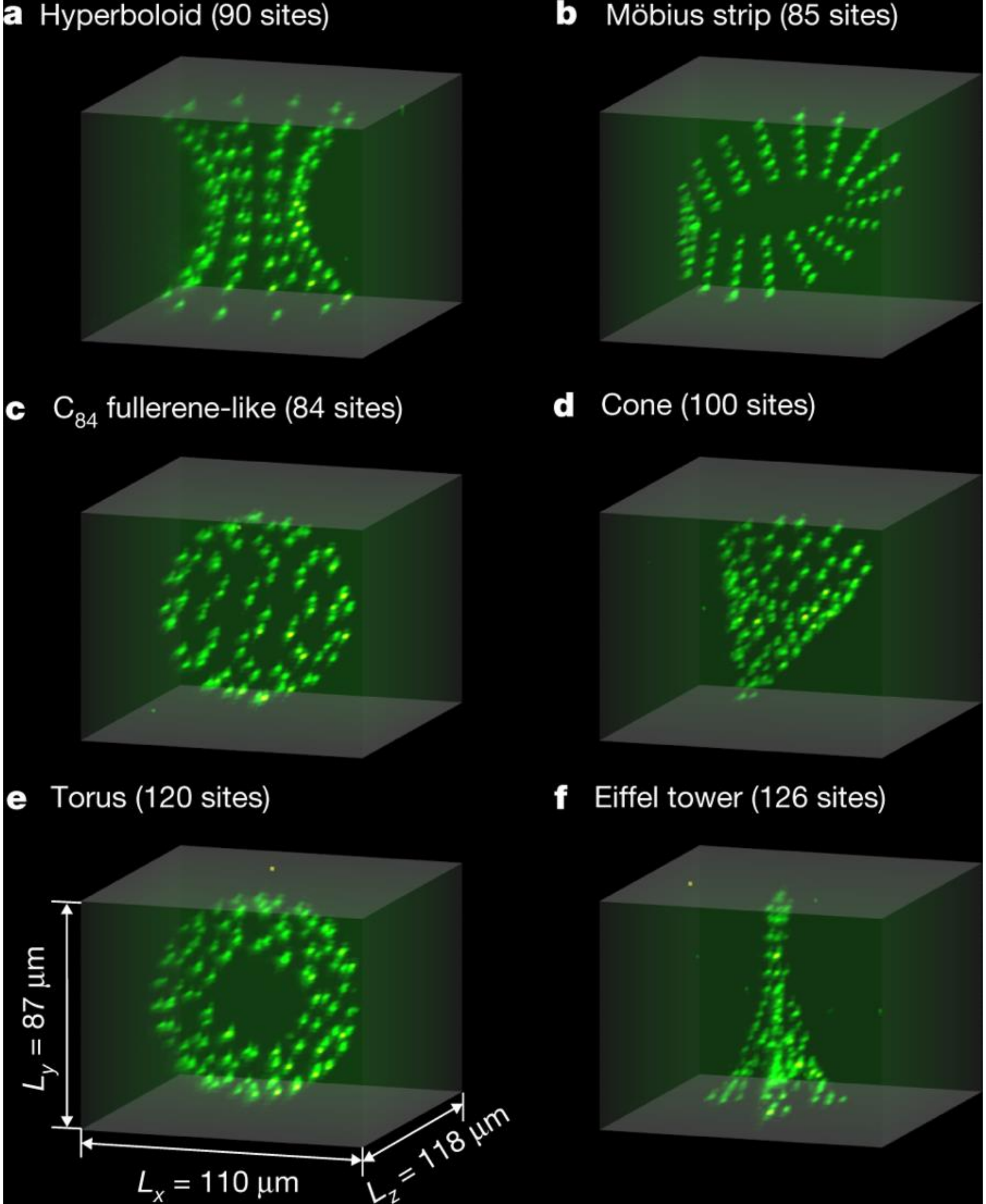
Controlling Amplitude and Phase

- Clearly, to achieve smooth potentials, control over amplitude and phase is desirable

$$C_a = \sum_{nm} \left(T_{nm} - |E_{out,nm}|^2 \right)^2$$

$$C_3 = 10^d \left(1 - \sum_{n,m} \mathrm{Re}\left\{ \left| \tilde{\tau}^*_{n,m} \tilde{E}^{\mathrm{out}}_{n,m} \right| \right\} \right)^2 , \\ = 10^d \left(1 - \sum_{n,m} \sqrt{\tilde{I}_{n,m} \tilde{T}_{n,m}} \cos\left(\Phi_{n,m} - \varphi_{n,m} \right) \right)^2$$

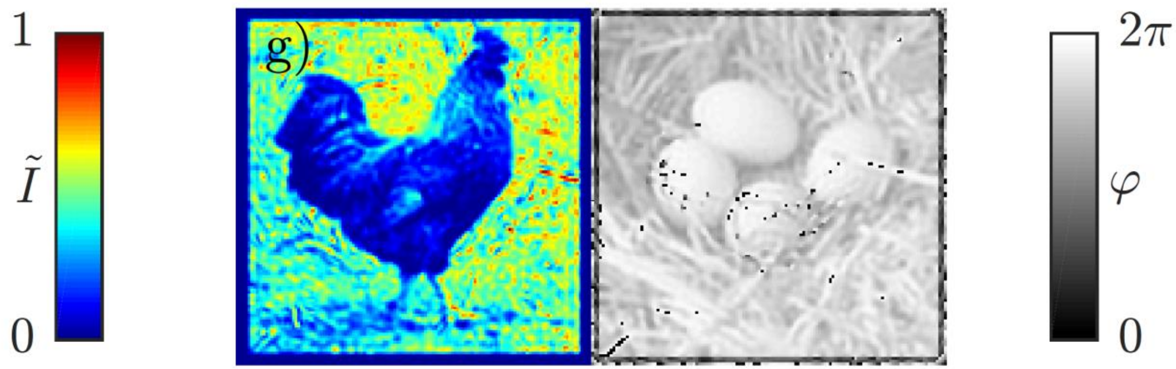




Barredo, et al, Nature 561, 79–82 (2018)

Controlling Amplitude and Phase

- With this method, we can produce completely uncorrelated images in amplitude and phase

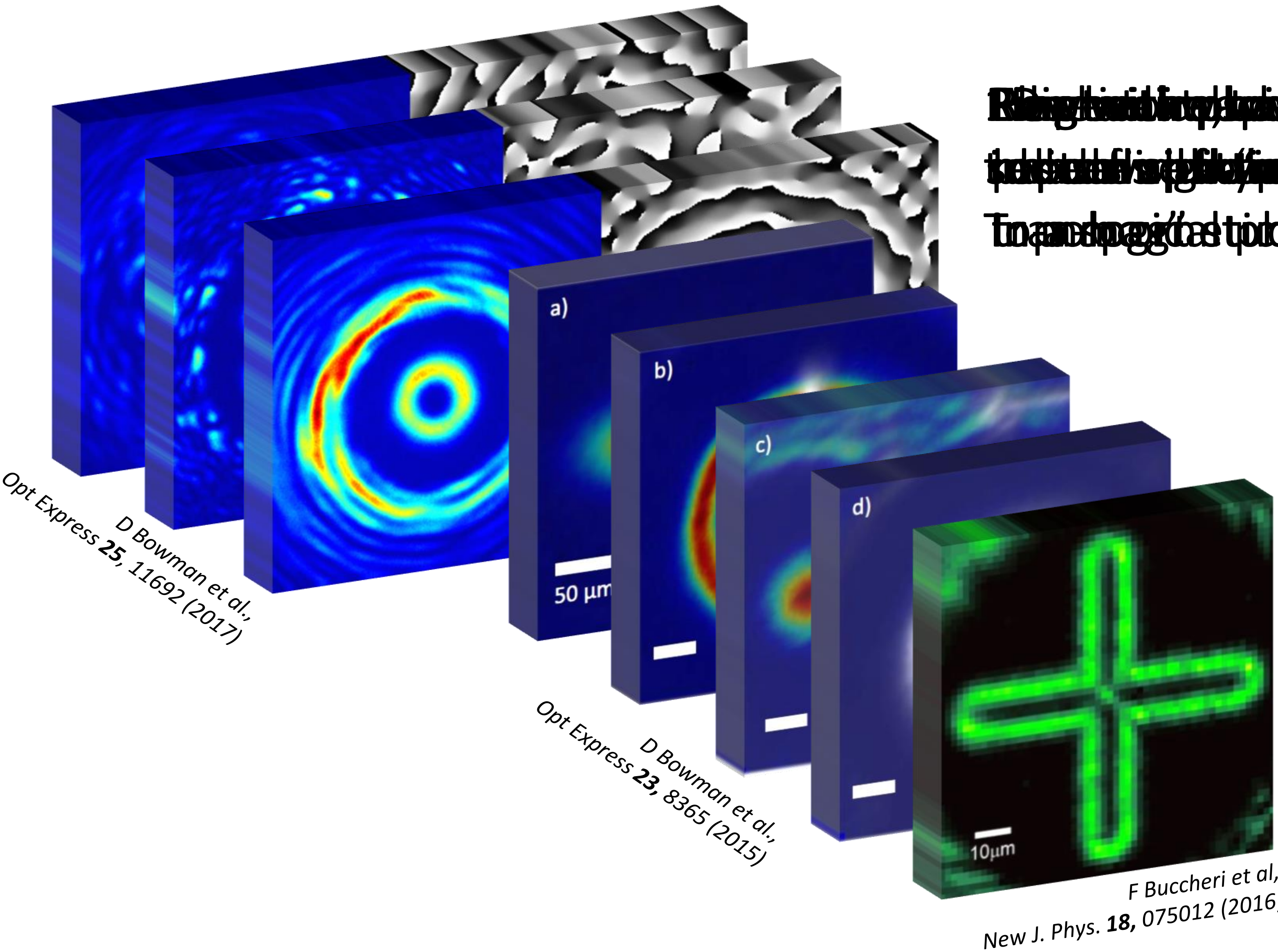


Calculated fidelity: 0.999997 – highest in the literature

- Furthermore, phase can be used to provide additional forces on trapped objects

D Bowman et al., Optics Express 25, 11692 (2017)

Holographic Optical Potentials



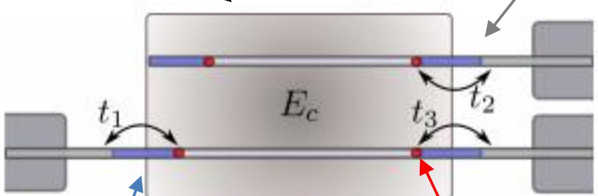
Topological Kondo Qubits

$$H^{\alpha} = \int_0^L dx \left[\frac{\hbar^2}{2m} \partial_x \Psi_\alpha^+(x) \partial_x \Psi_\alpha(x) + \frac{c}{2} \Psi_\alpha^+(x) \Psi_\alpha^+(x) \Psi_\alpha(x) \Psi_\alpha(x) \right],$$

$$H = -i \frac{\hbar v_F}{2\pi} \sum_{\alpha=1}^{M} \int dx \, \psi_\alpha^+(x) \partial_x \psi_\alpha(x) - \lambda \sum_{\alpha \neq \beta} \gamma_\alpha \gamma_\beta \psi_\alpha^+(0) \psi_\beta(0)$$

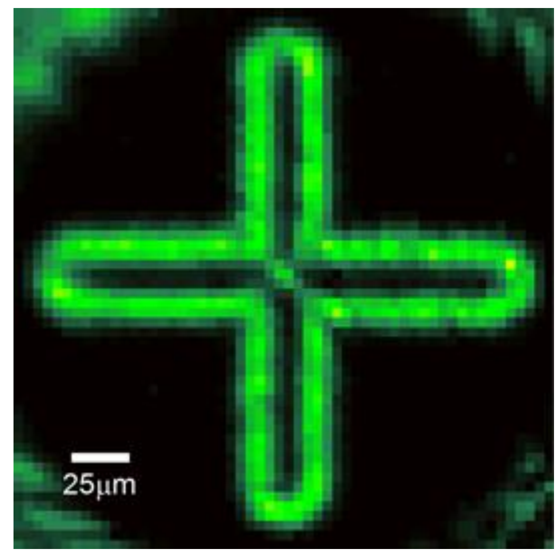
Superconducting island

Semiconductor wires



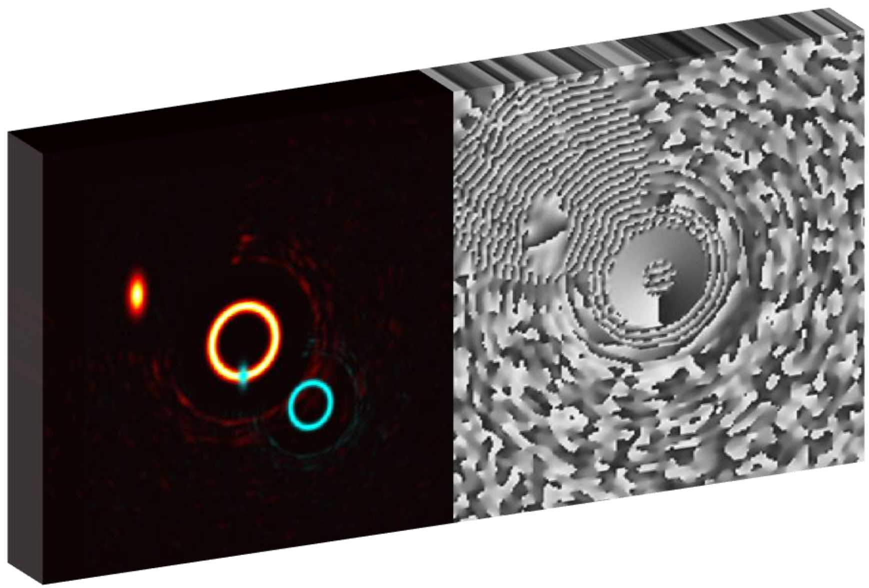
Tunnelling junctions

Majorana fermion



F Buccheri et al, New J. Phys. ***18,*** *075012 (2016)*

Can you put it all together?



How can phase exert a force?

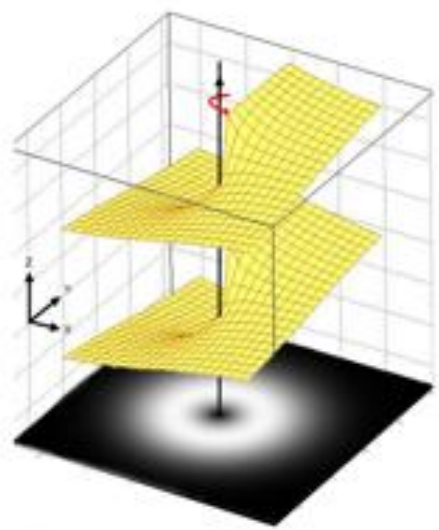
Structured light can possess angular momentum: rotation

$$j = \varepsilon_o \left[r \times \langle E \times B \rangle \right]$$

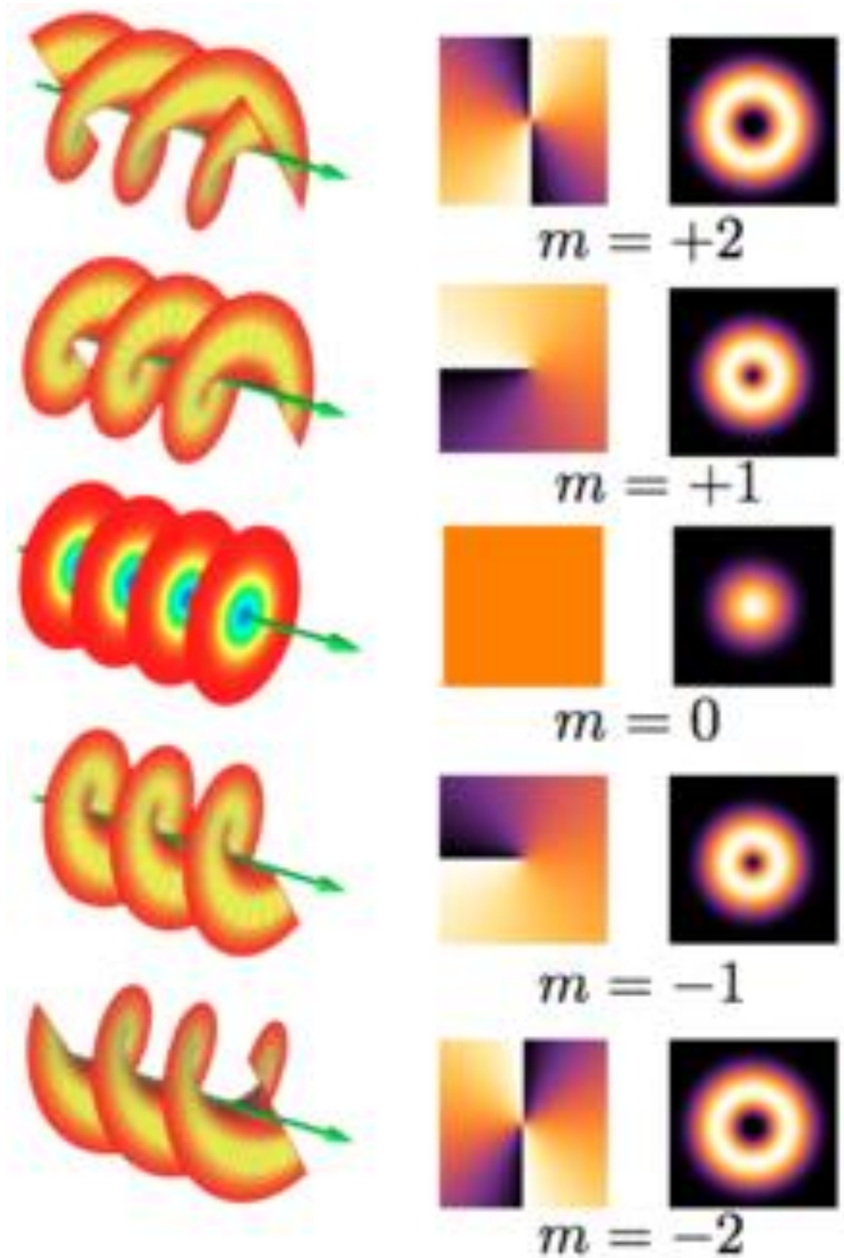
Allen et al Phys Rev A (1992)

Orbital: due to inclined wavefronts

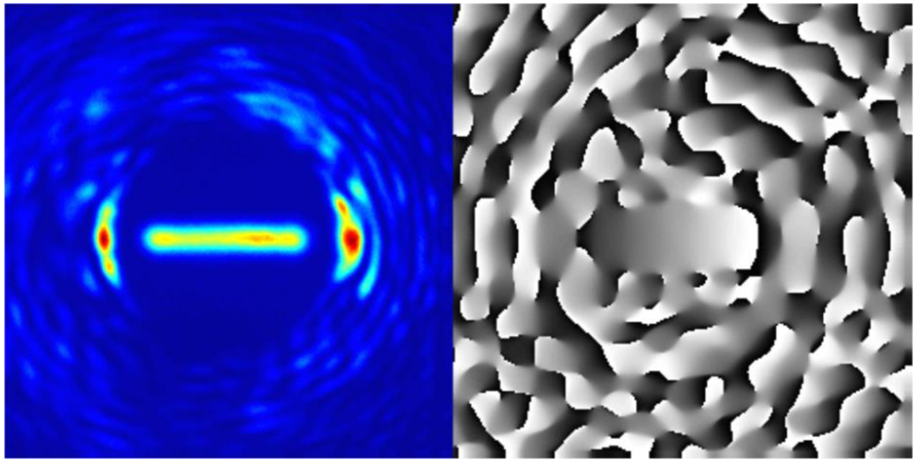
lħ per photon

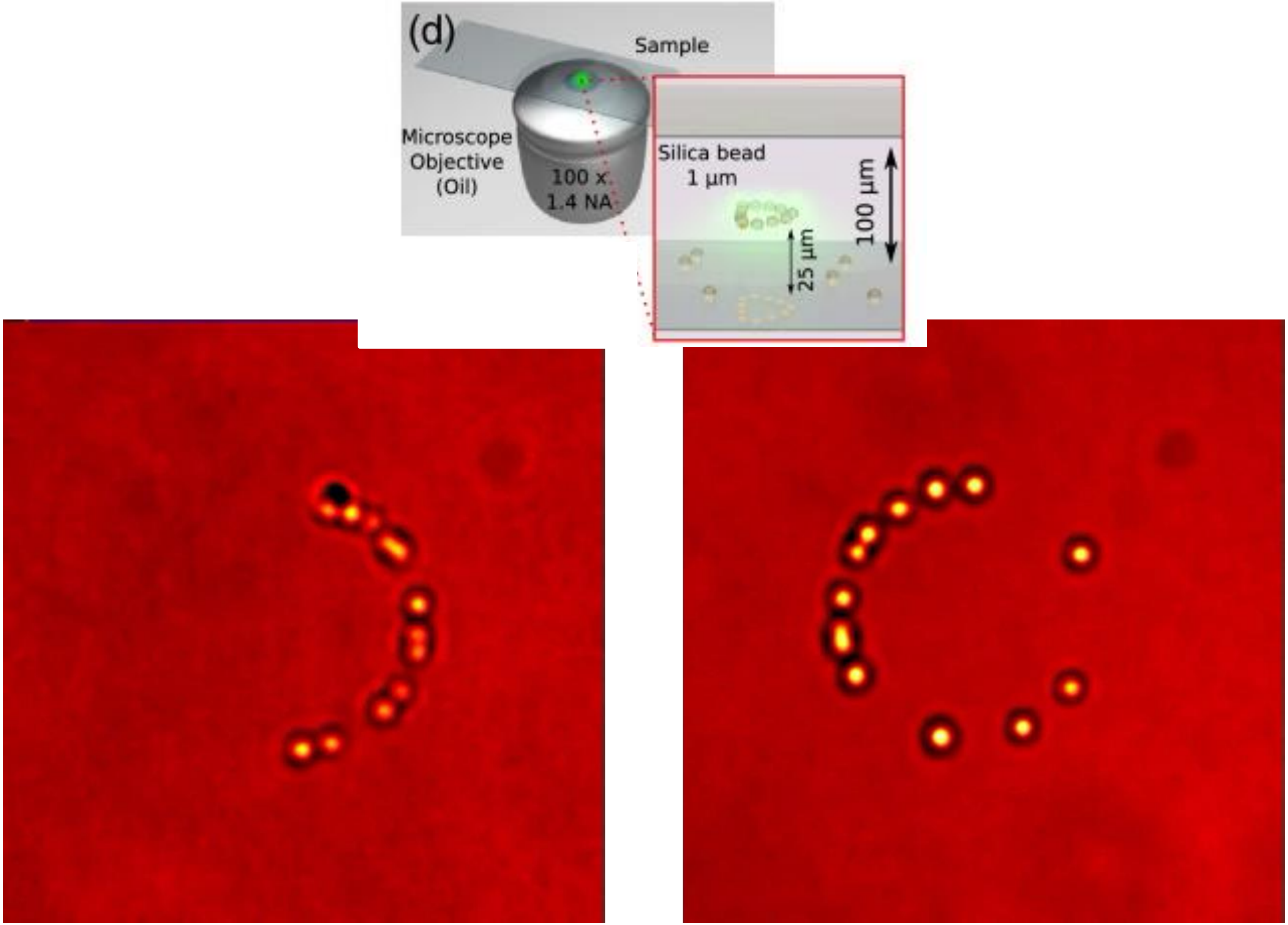


Laguerre-Gaussian (LG) beam


$m = +2$
$m = +1$
$m = 0$
$m = -1$
$m = -2$

These tilted phase fronts can also exert linear momentum





Rodrigo et al, Optica 2, 812-815 (2015)

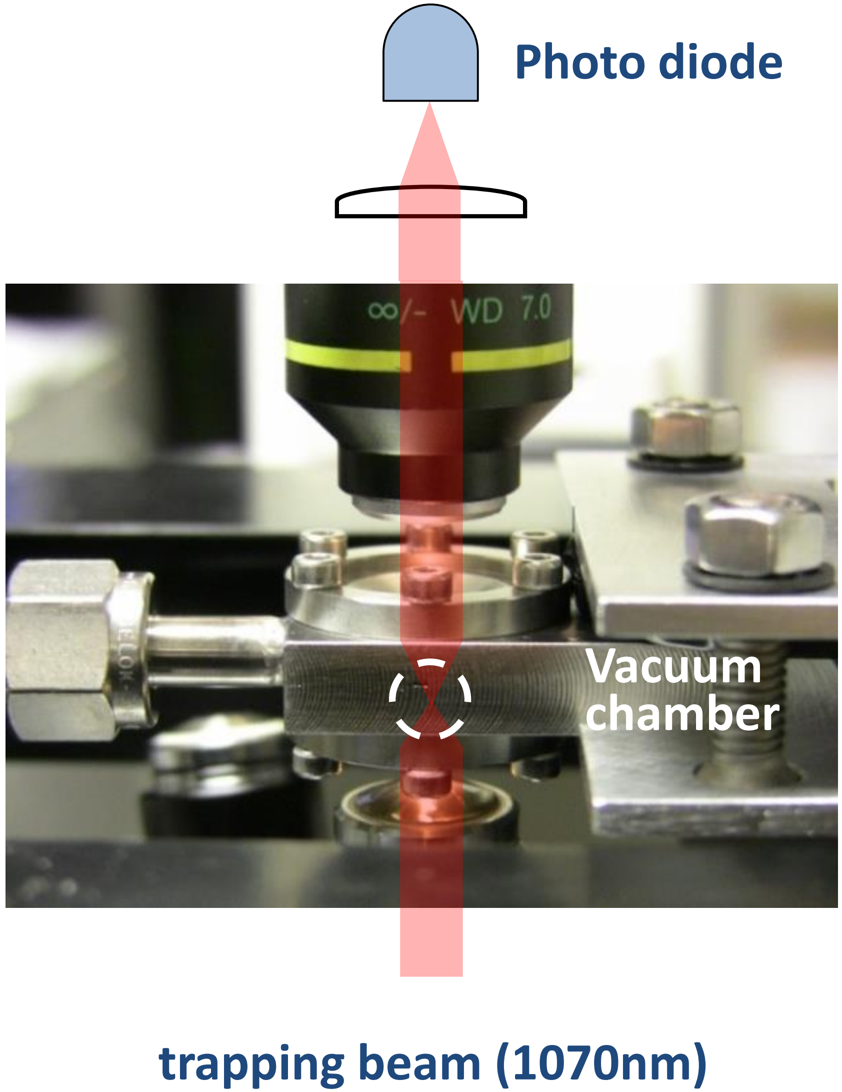
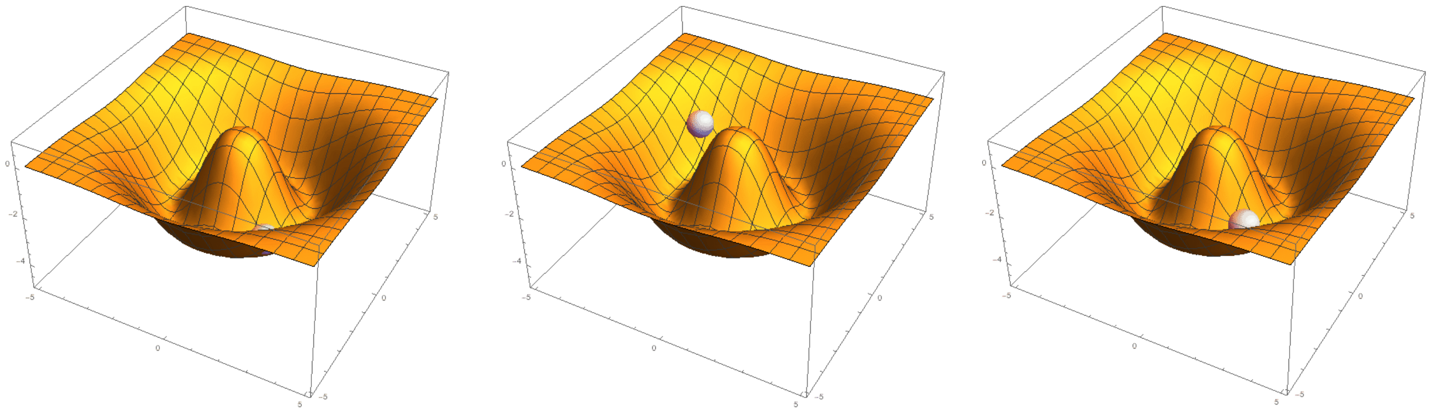
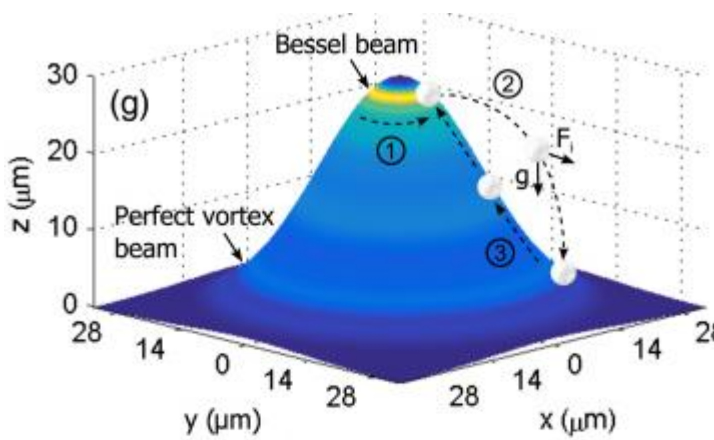


Photo diode
∞/- WD 7.0
Vacuum chamber
trapping beam (1070nm)

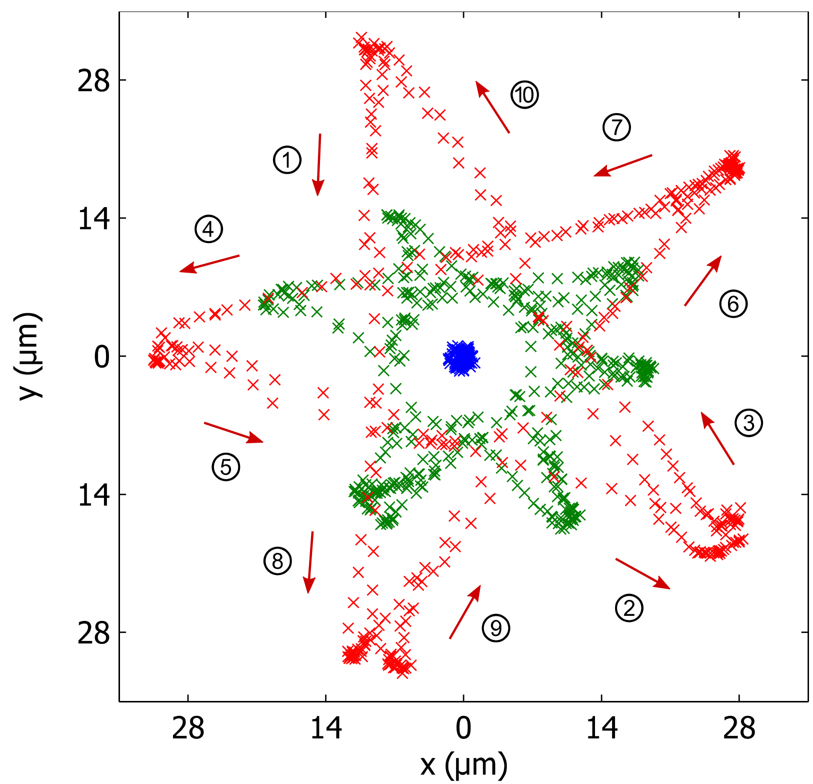


Mazilu et al., Phys Rev A 94, 053821 (2016)

Particle trajectories for
ℓ = 3 (blue)
ℓ = 10 (green)
ℓ = 30 (red)



Arita et al. JOSA B (2017)



Structured light can possess angular momentum: rotation

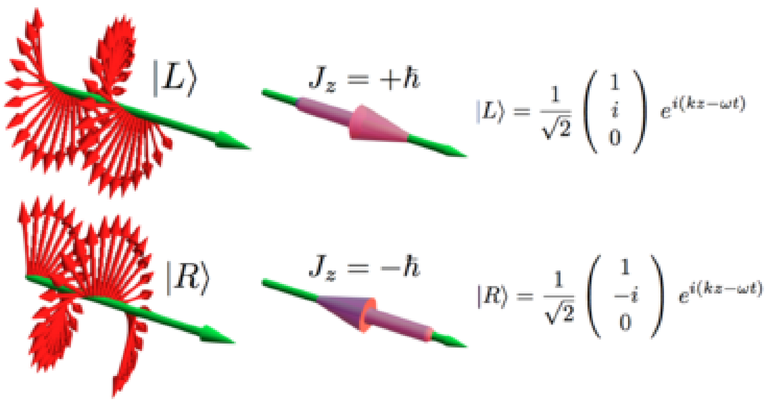
$$j = \varepsilon_o \left[r \times \langle E \times B \rangle \right]$$

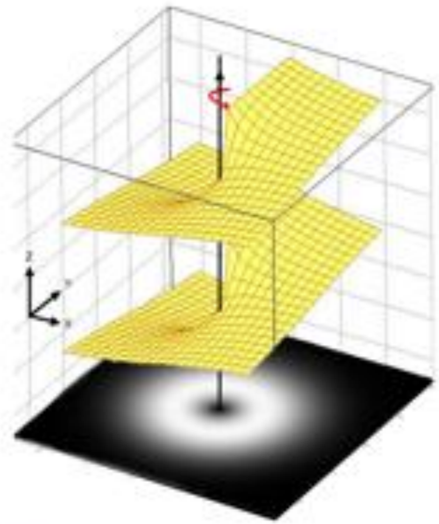
Allen et al Phys Rev A (1992)

Spin: due to polarisation state (rotating E-field)

Orbital: due to inclined wavefronts

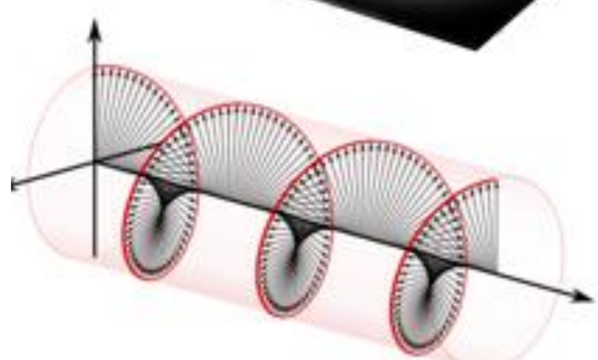
lħ per photon





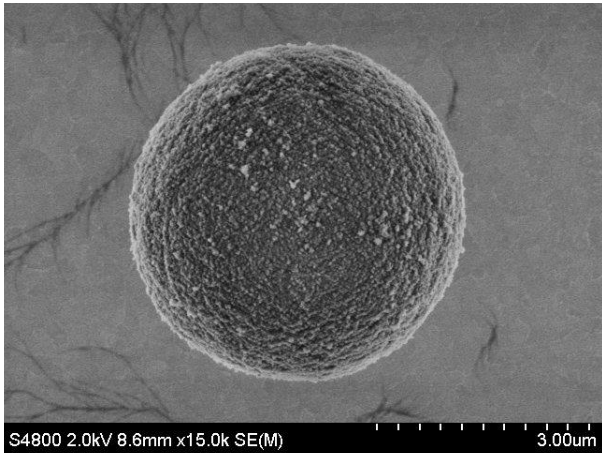
Laguerre-Gaussian (LG) beam

±ħ per photon



Circularly polarized beam

Spin angular momentum




BBC NEWS EDINBURGH, FIFE & EAST SCOTLAND

28 August 2013 Last updated at 16:27

University of St Andrews scientists create 'fastest man-made spinning object'

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Cow v camel


NBC NEWS SCIENCE

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QUANTUM PHYSICS Scientists create fastest-spinning man-made object ever

Scientists create fastest-spinning man-made object ever

Tia Ghose, LiveScience

Aug. 29, 2013 at 12:39 PM ET

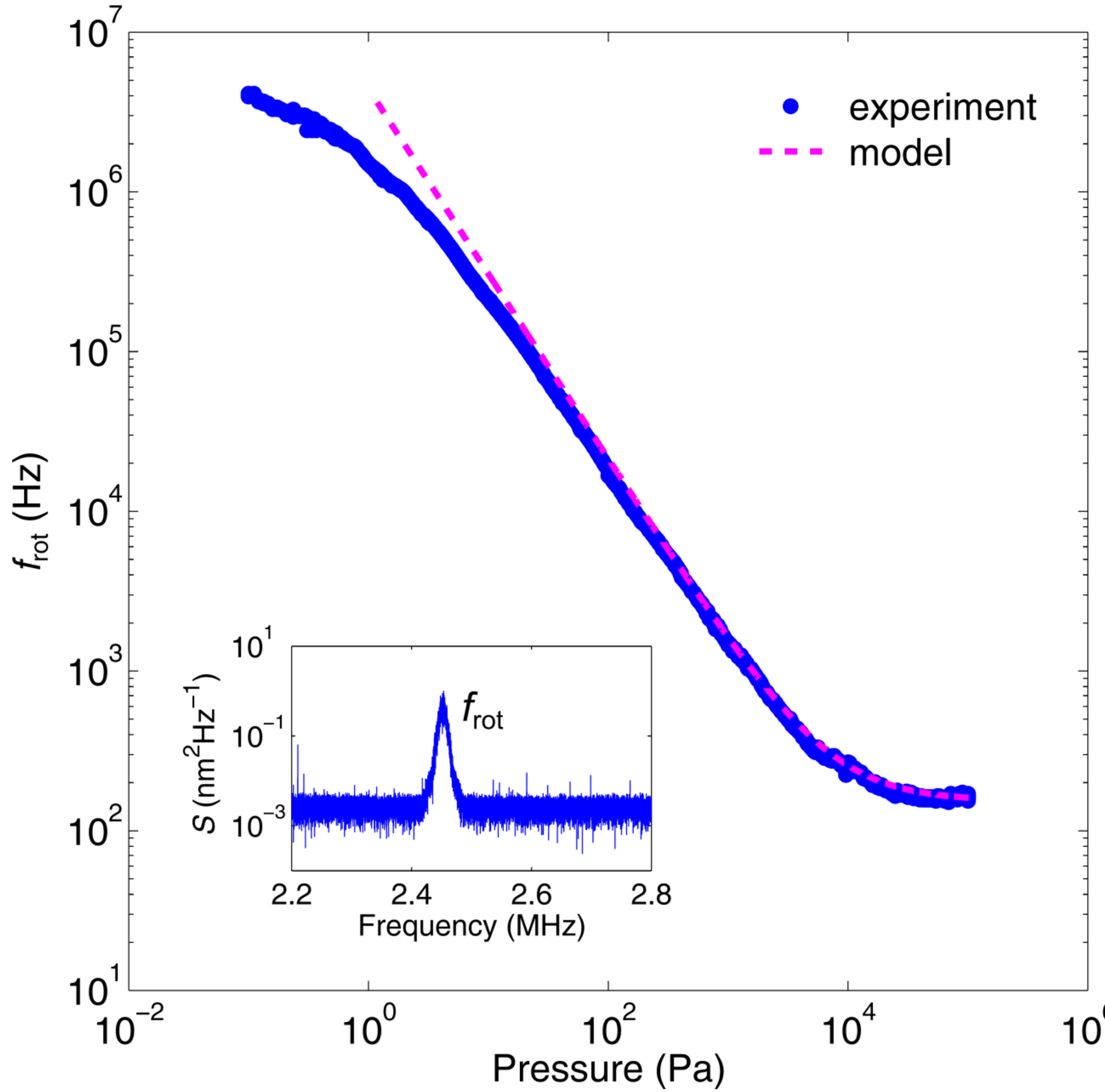
Scientists have created a microscopic sphere and set it awhirl at a blistering 600 million rotations per minute.

The sphere, which rotates 500,000 times faster than the average washing machine, is the fastest-spinning object ever made.

COSMIC LOG How Ground Zero's supertower rose above New York's 9/11 nightmare

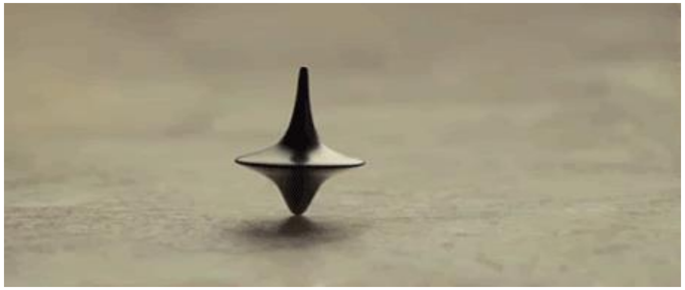
NEW SPACE

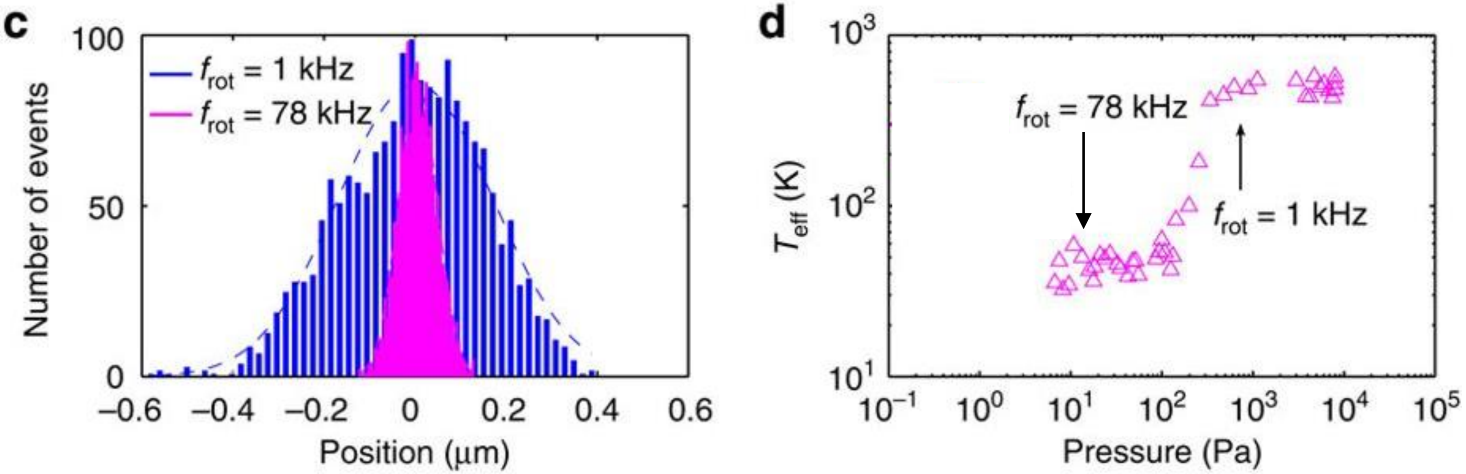
Arita et al. Nature Comm 4, 2374 (2013)



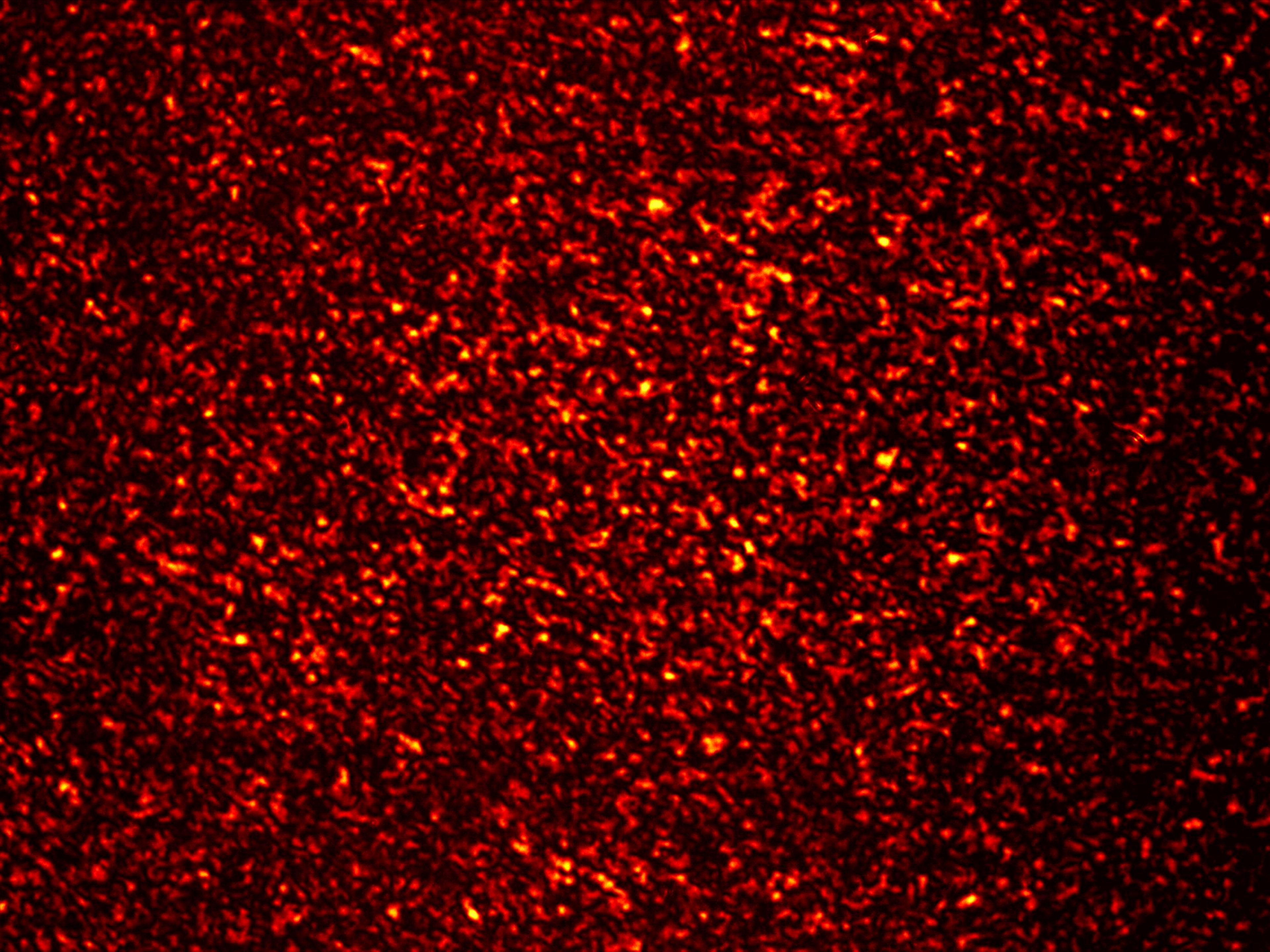
OFFICIALLY AMAZING

Guinness book of world records 2015 (fastest man-made rotation)



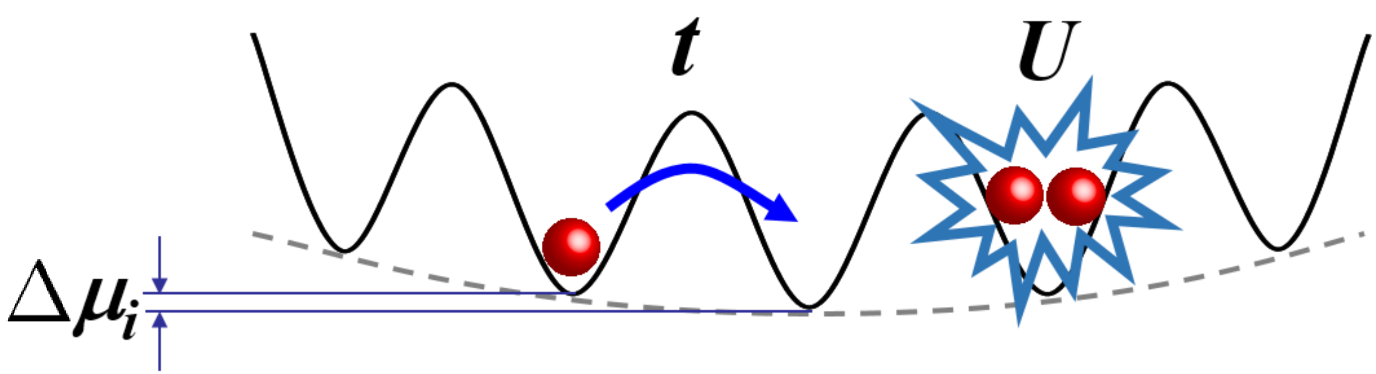


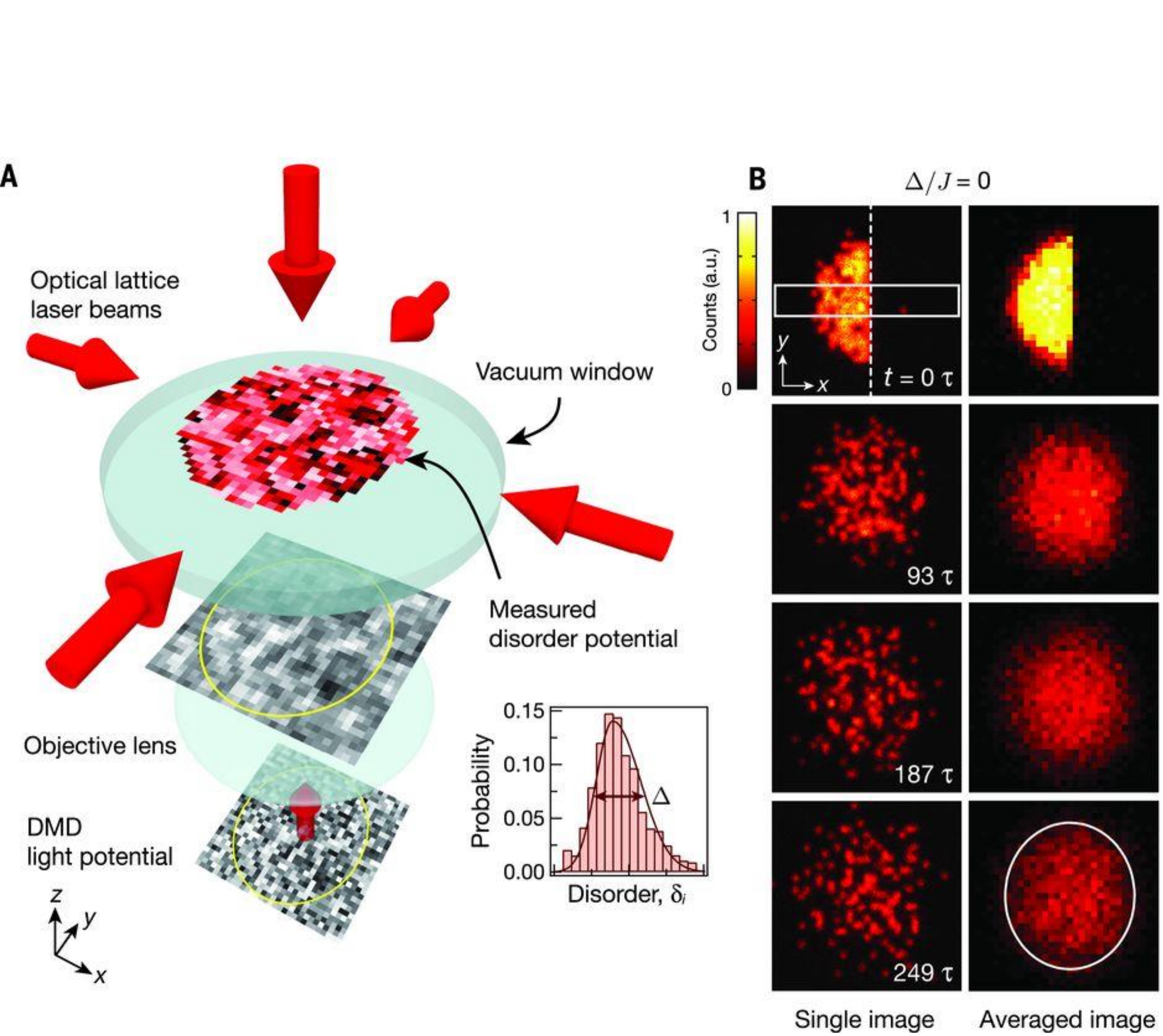
c
100
50
0
f_{rot} = 1 kHz
f_{rot} = 78 kHz
Number of events
−0.6 −0.4 −0.2 0 0.2 0.4 0.6
Position (μm)
d
10^3
10^2
10^1
T_{eff} (K)
f_{rot} = 78 kHz
f_{rot} = 1 kHz
10^{-1} 10^0 10^1 10^2 10^3 10^4 10^5
Pressure (Pa)



The Bose-Hubbard Model

$$\mathcal{H}_B = -t \sum_{\langle ij \rangle} (\hat{b}_i^\dagger \hat{b}_j + \hat{b}_j^\dagger \hat{b}_i) - \mu \sum_i \hat{n}_i + \frac{U}{2} \sum_i \hat{n}_i (\hat{n}_i - 1)$$



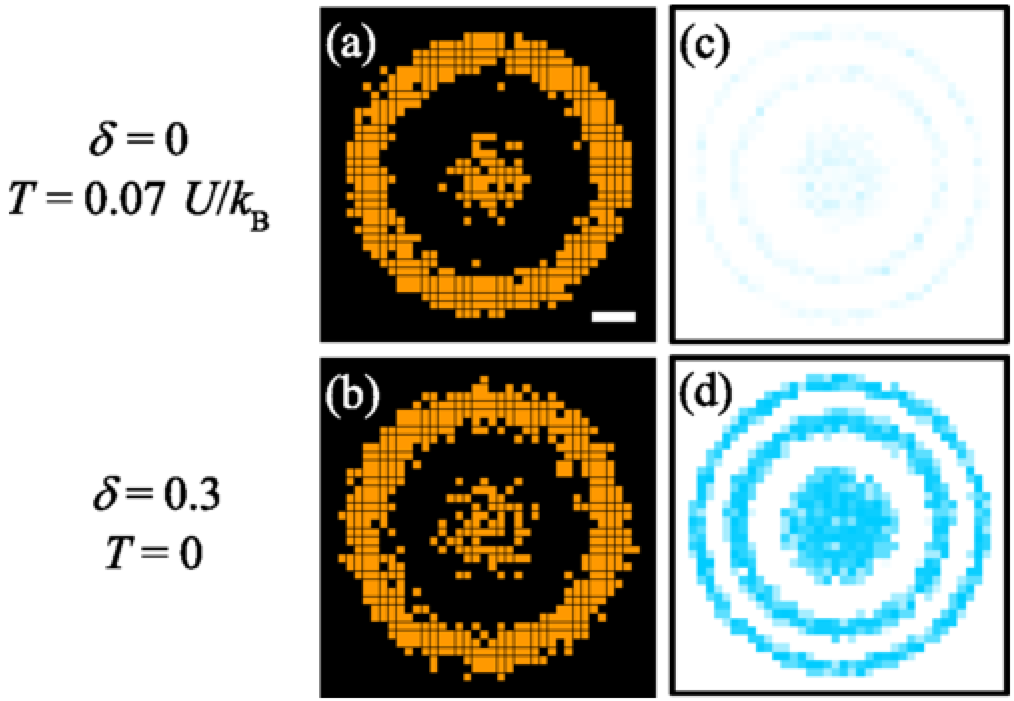


*Choi et al, Science **352**, 1547-1552 (2016)*

shameless plug…

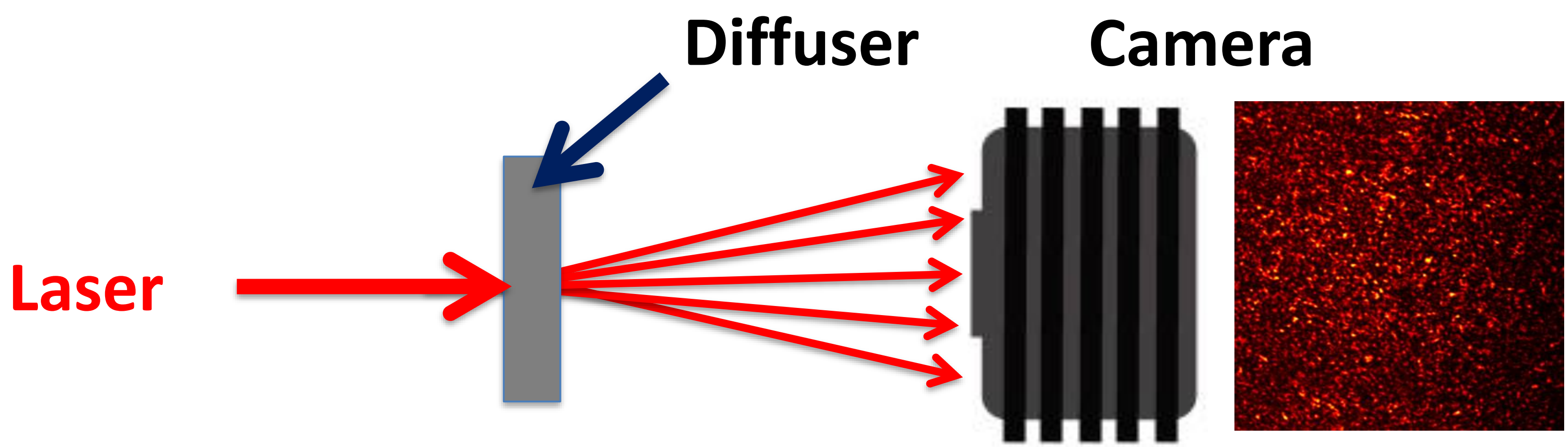
Parity-sensitive density

$Q_{EA} = [\langle n_i^2 \rangle]_{av} - [\langle n_i \rangle]_{av}^2$

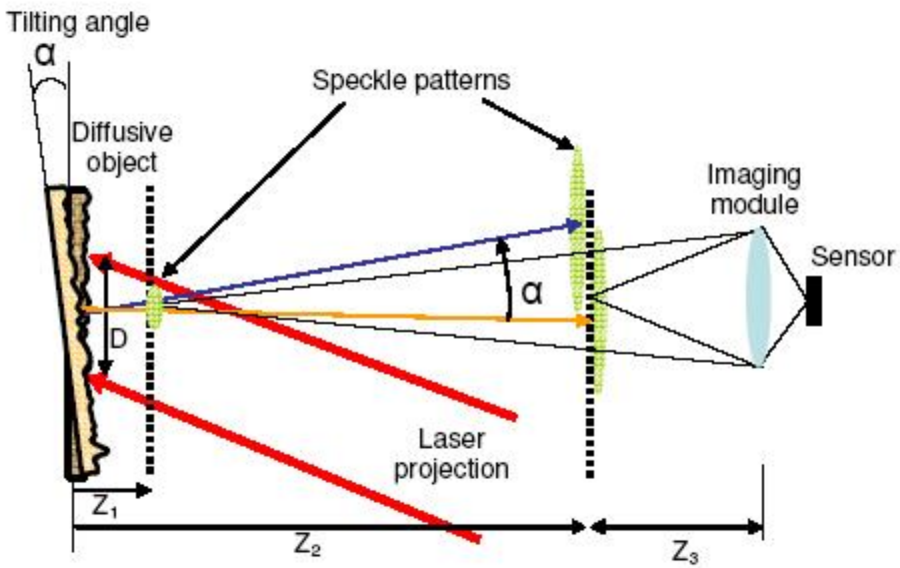


S. J. Thomson, et al, Phys. Rev. A ***94****, 051601(R) (2016)*

Is speckle useful for anything other than just adding disorder?



Measuring motion of a subject



(a).

Imaged at a distance of 30m

Zalevsky et al, Opt Express **24** 21566 (2009)

Alternatively, apply a vibration to the subject and measure response. Used in detecting:

Faults in airplane wings

Breast tumours

Voids behind walls

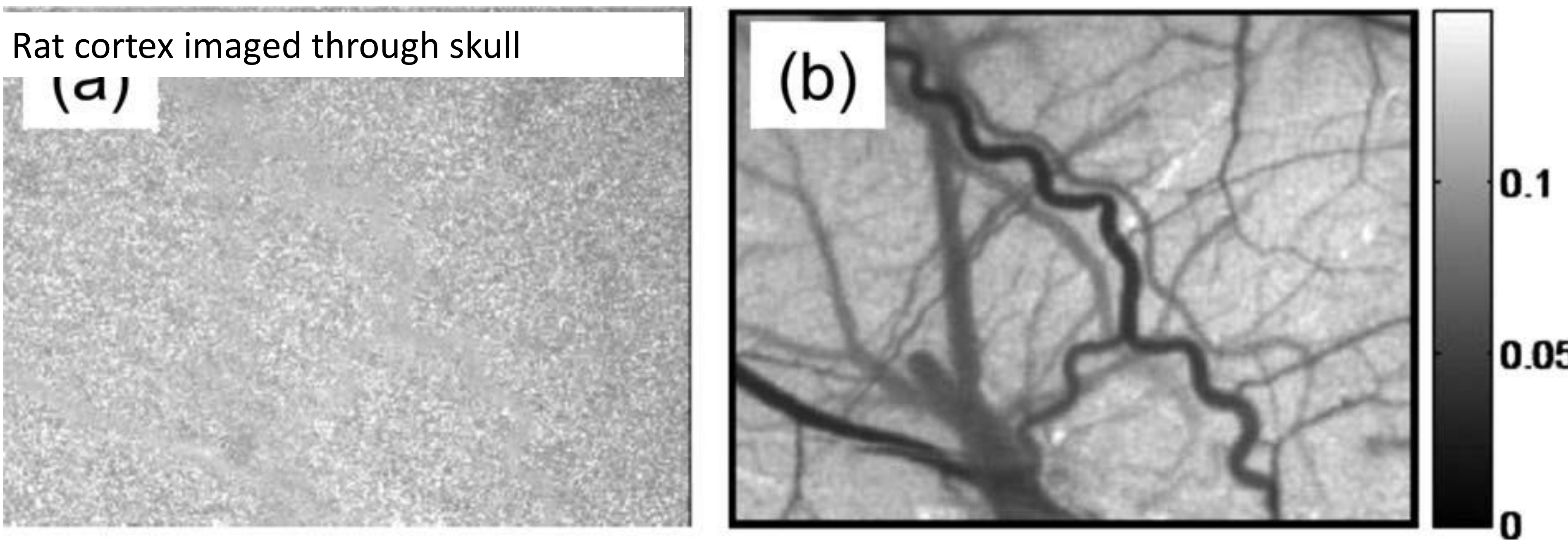
X-Box Kinect

Measuring motion within the subject

https://youtu.be/iH90scynV8Q?t=45s

$$K = \frac{\sigma}{\langle I \rangle}$$

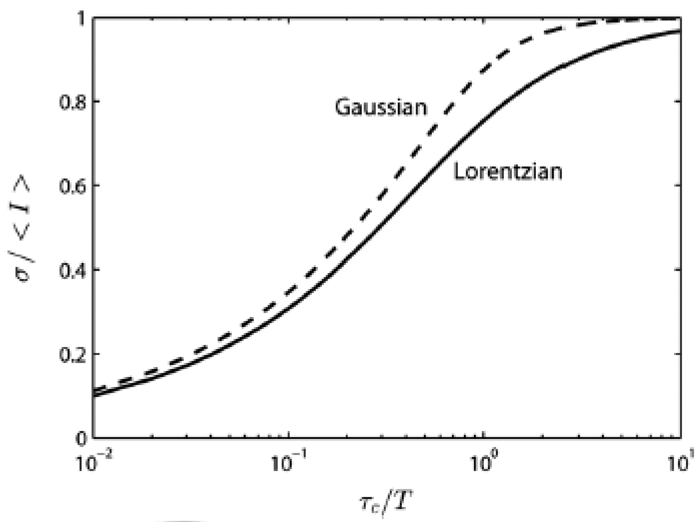
<u>Laser Speckle Contrast Imaging / The Biospeckle Laser:</u>
direct, non-destructive, wide-field image
-> velocity distribution map

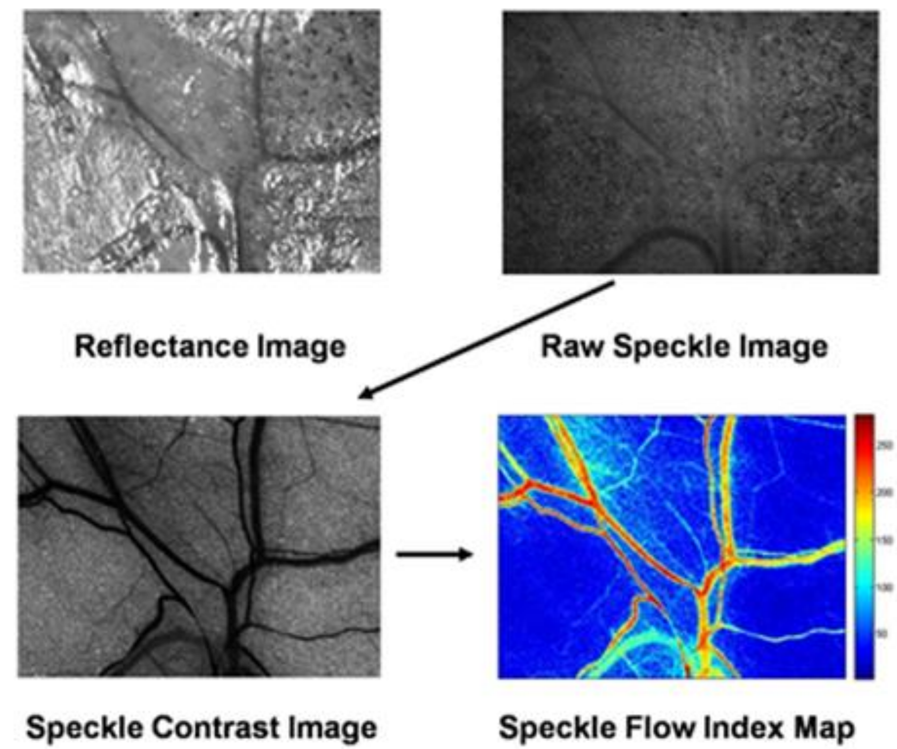


Boas and Dunn, JBO **15** 011109 (2010)

Measuring motion within the subject

Briers et al, JBO **18** 066018 (2013)



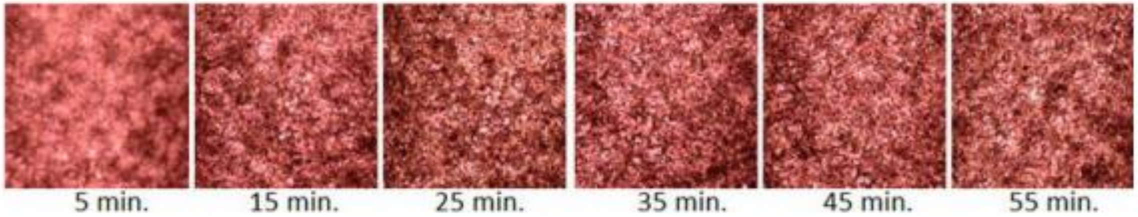


Application areas:

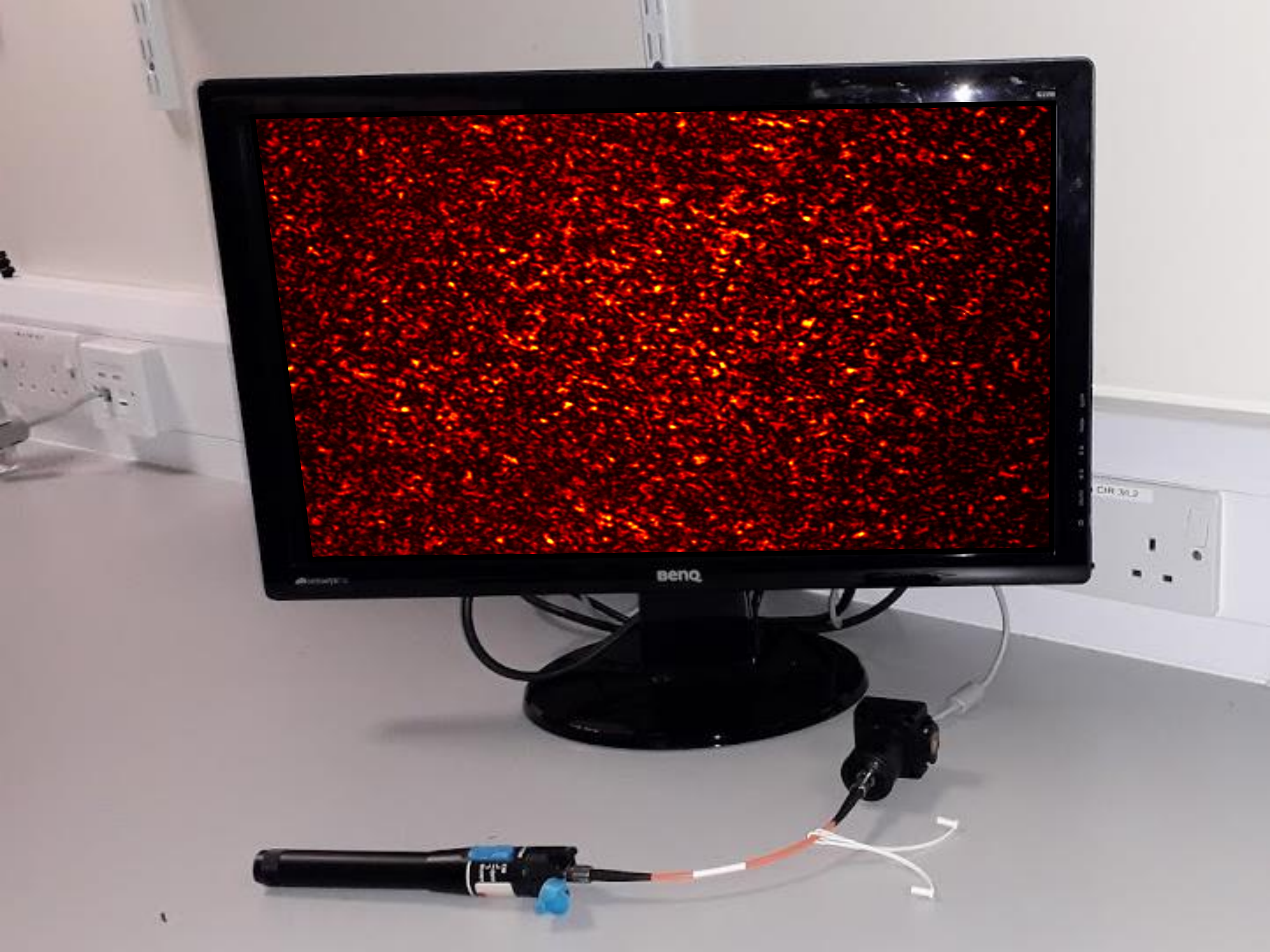
- Cerebral Blood Flow
- Micro-circulation
- Opthalmology
- Migraine studies
- Dentistry
- Wound and burn assessment
- Monitoring seeds
- Vehicle velocimetry

Measuring motion within the subject

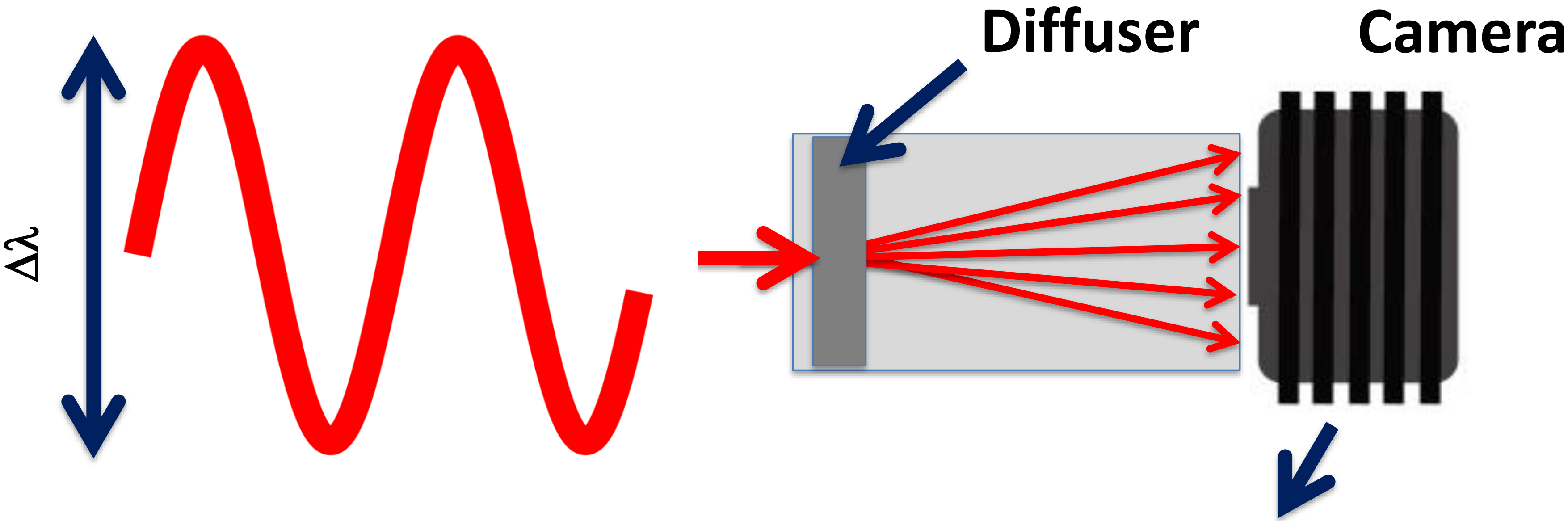
Watching paint dry…



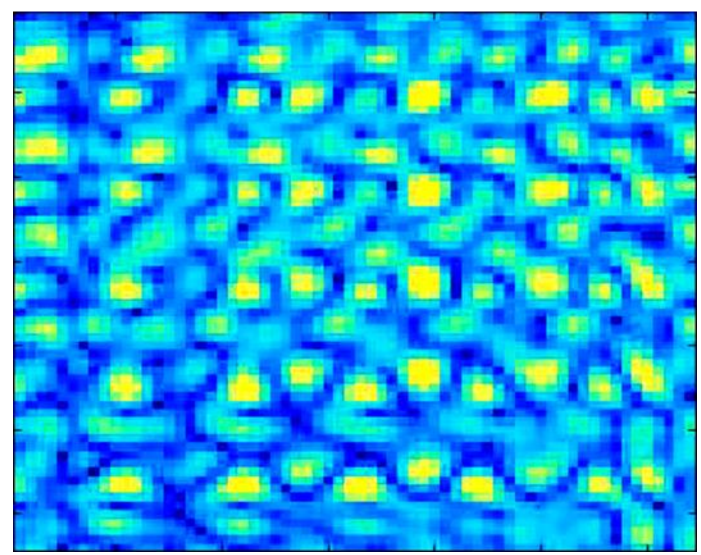
Moreira et al, Opt. Las. Engin. **61** 8 (2014)


BenQ

Concept



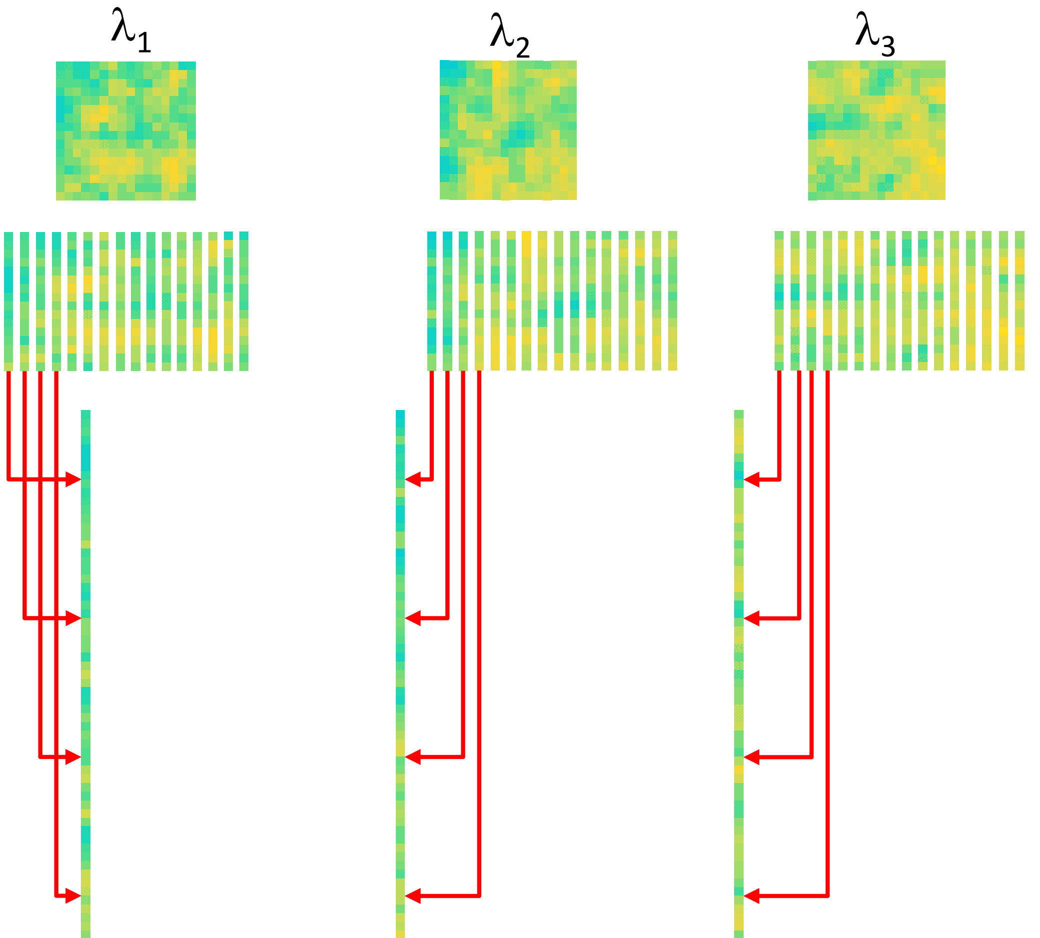
- **Speckle pattern 'randomization'**
  → Coherence of field preserved
  → Interference marker for wavelength
- **Interference changes with Δλ**
  yields unique speckle pattern



But how can we extract λ from the pattern?

Wavelength Measurement ABOVE the Correlation Bandwidth

- **What is the relationship between the speckle pattern and the wavelength?**
  It depends on the microscopic detail of the scattering medium
- **Take a <u>data-driven</u> approach to the analysis**



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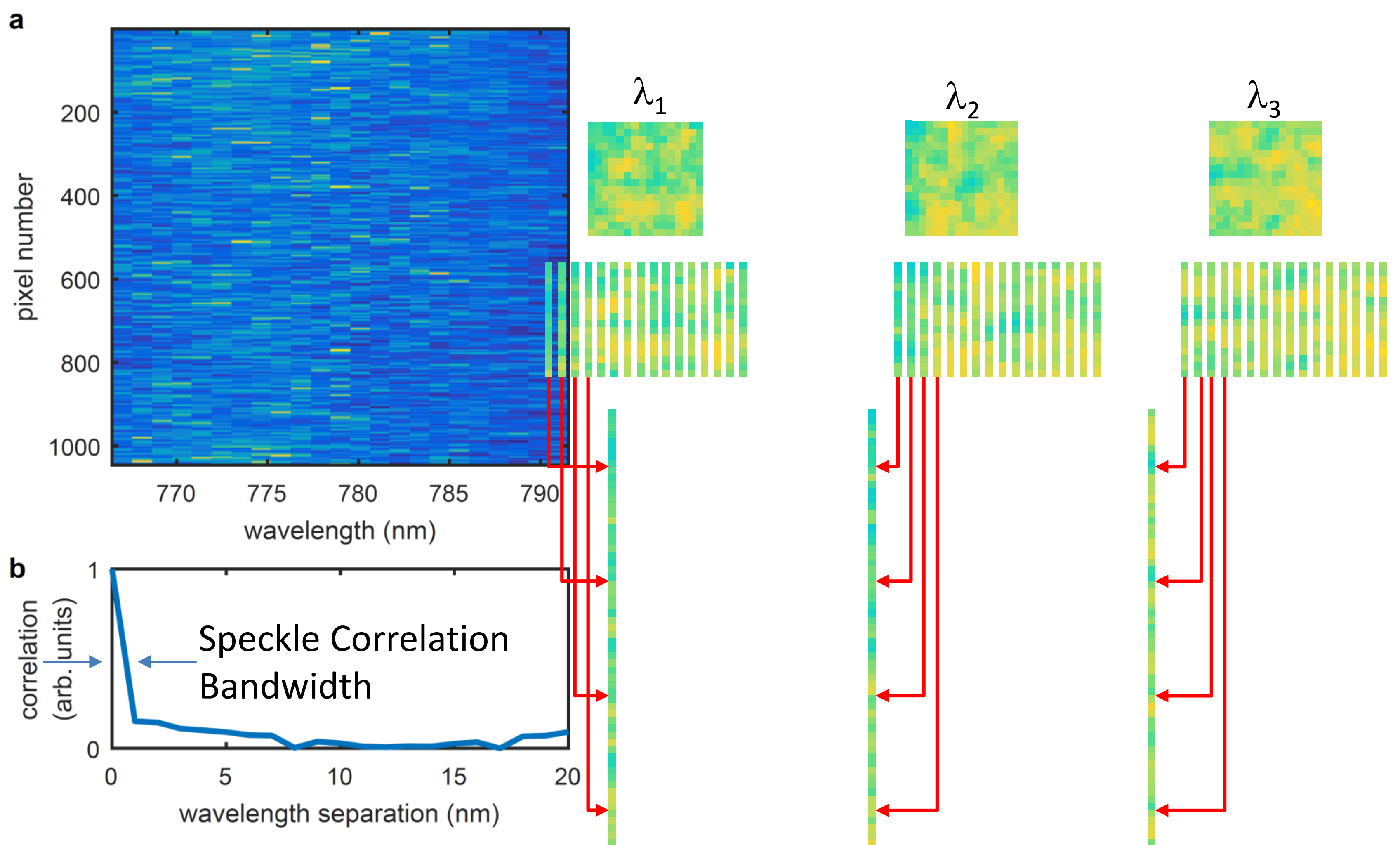

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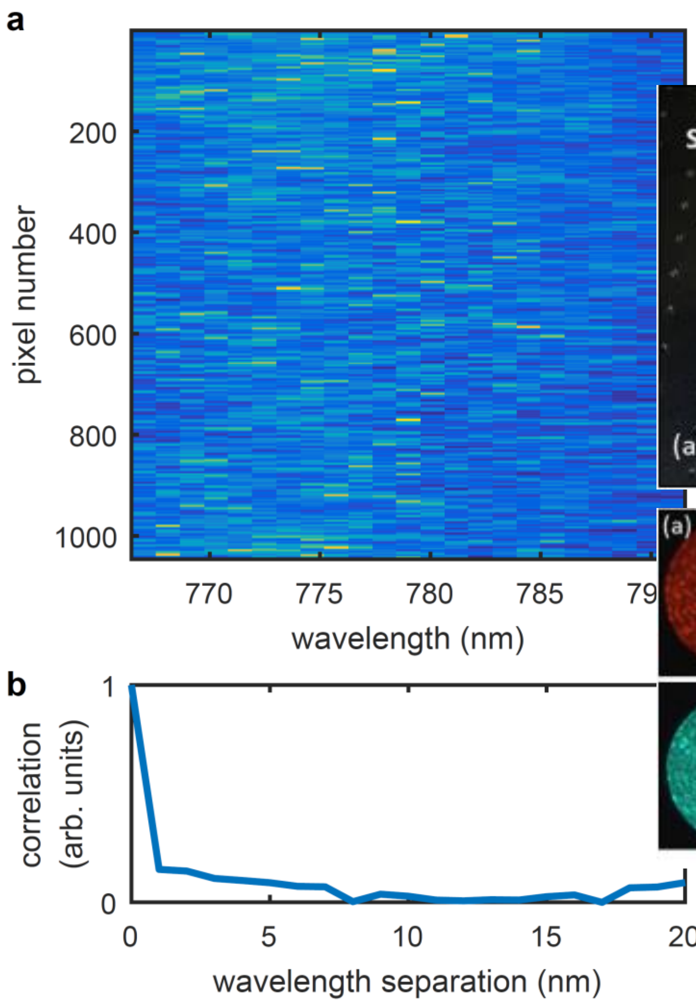
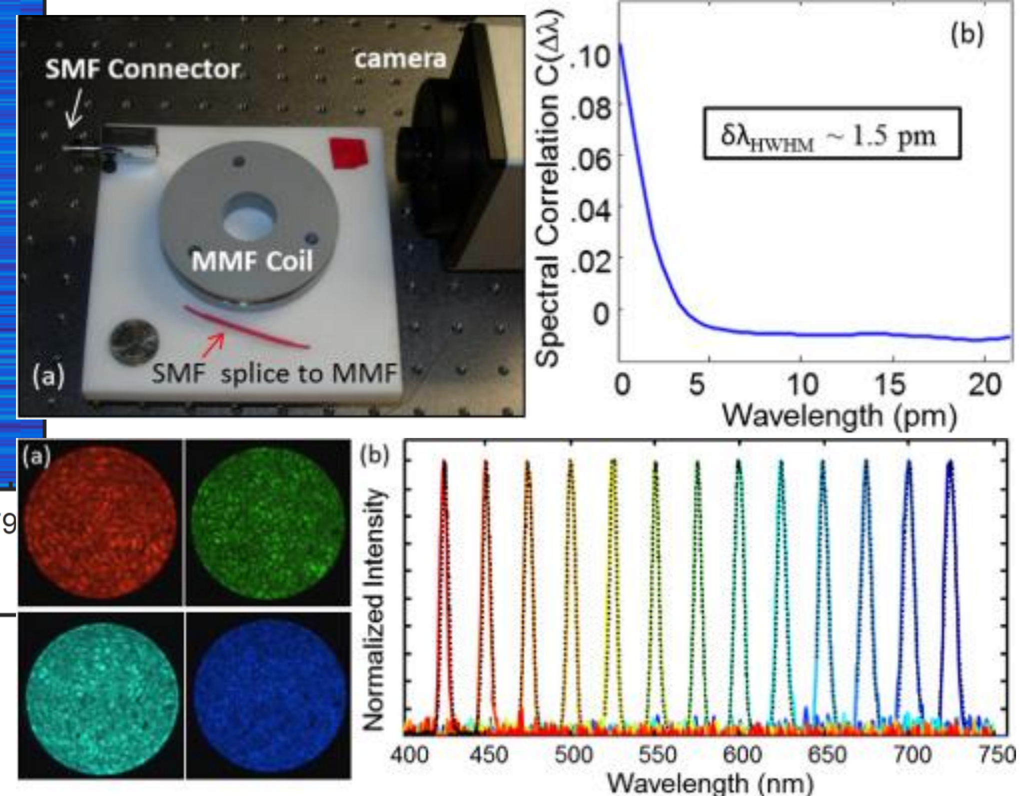
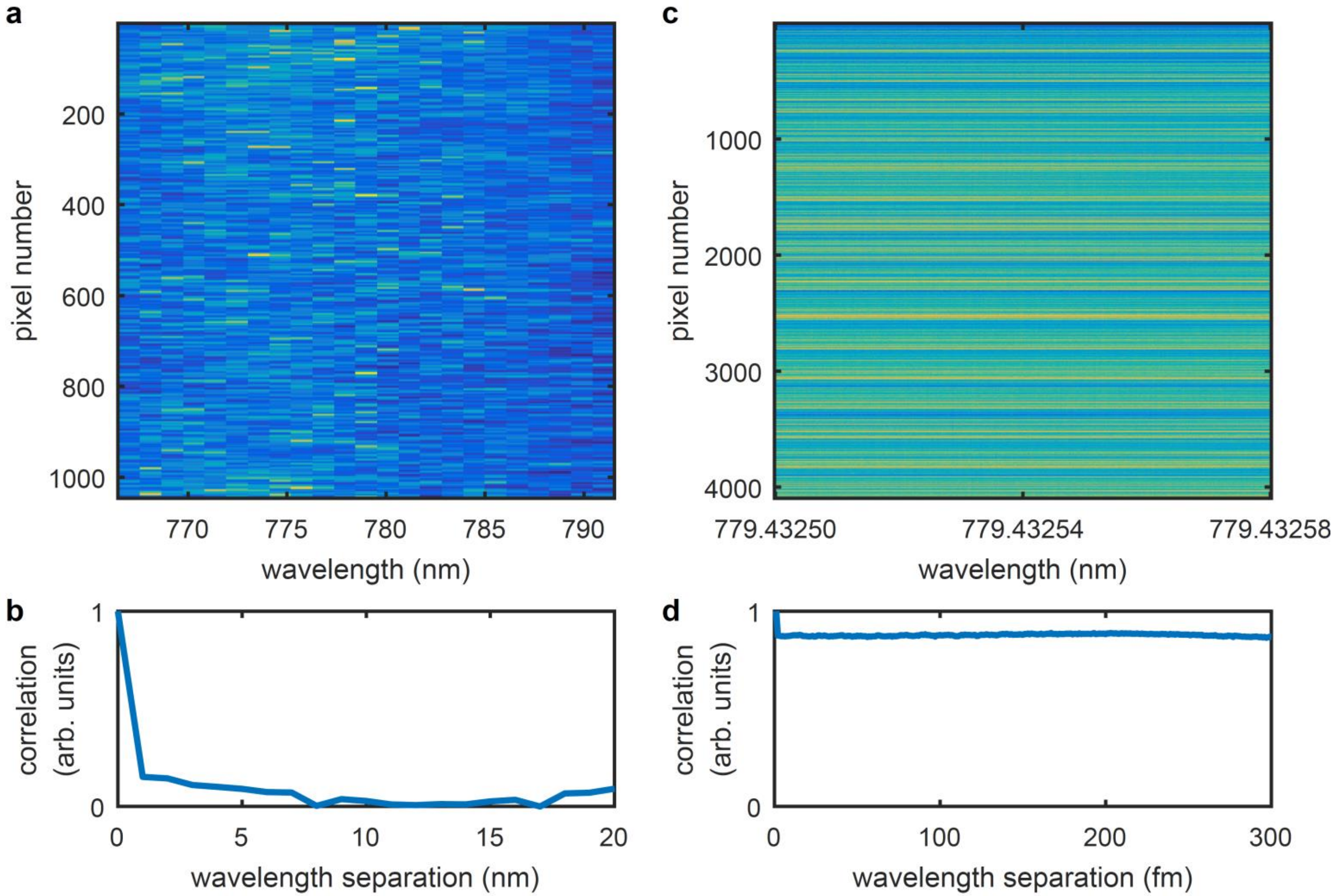




*B Redding, et al, Optica **3**, 175 (2014)*

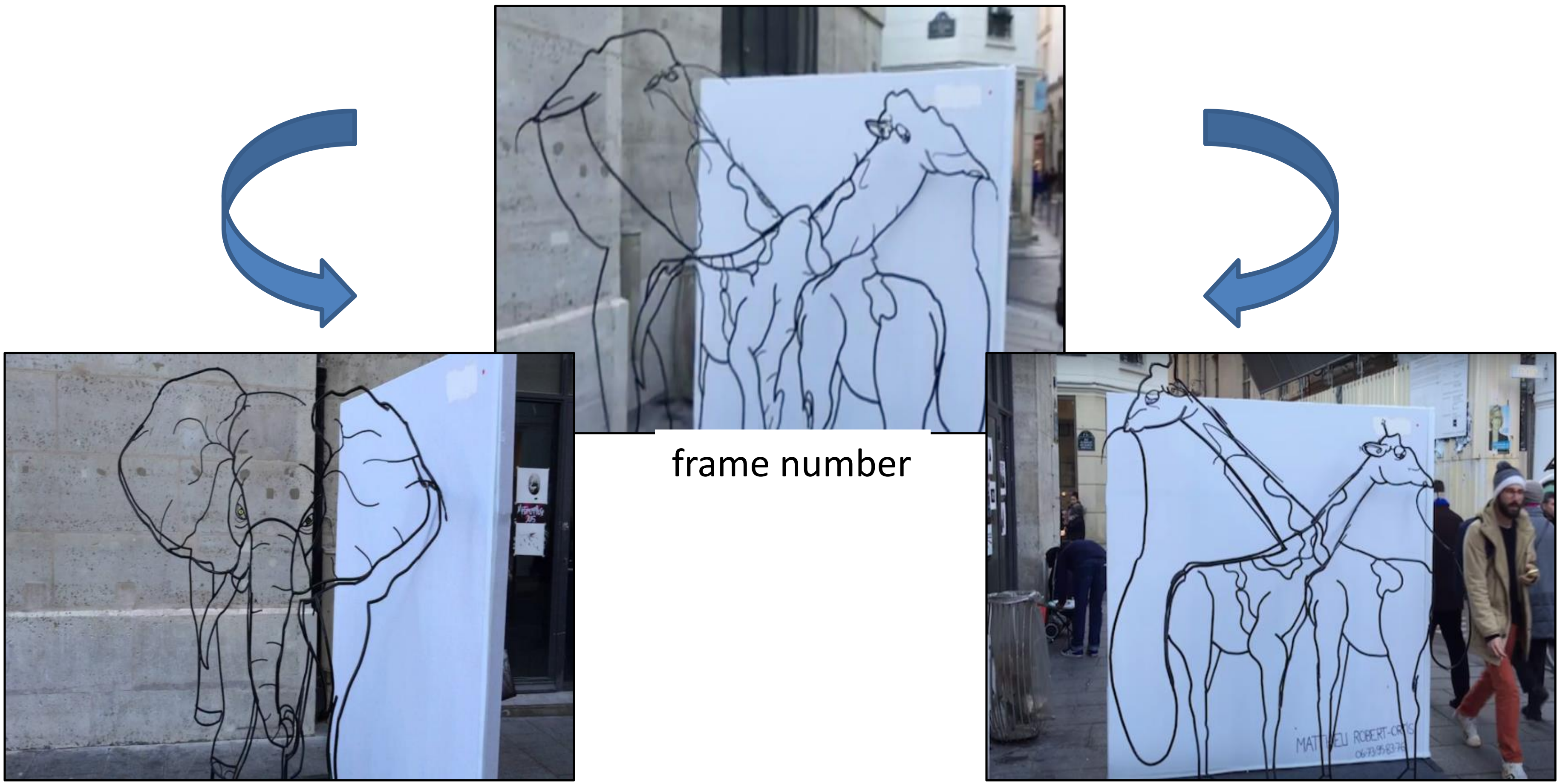
Limitations of TMM

- **What is the relationship between the speckle pattern and the wavelength?**
  It depends on the microscopic detail of the scattering medium
- **Take a <u>data-driven</u> approach to the analysis**



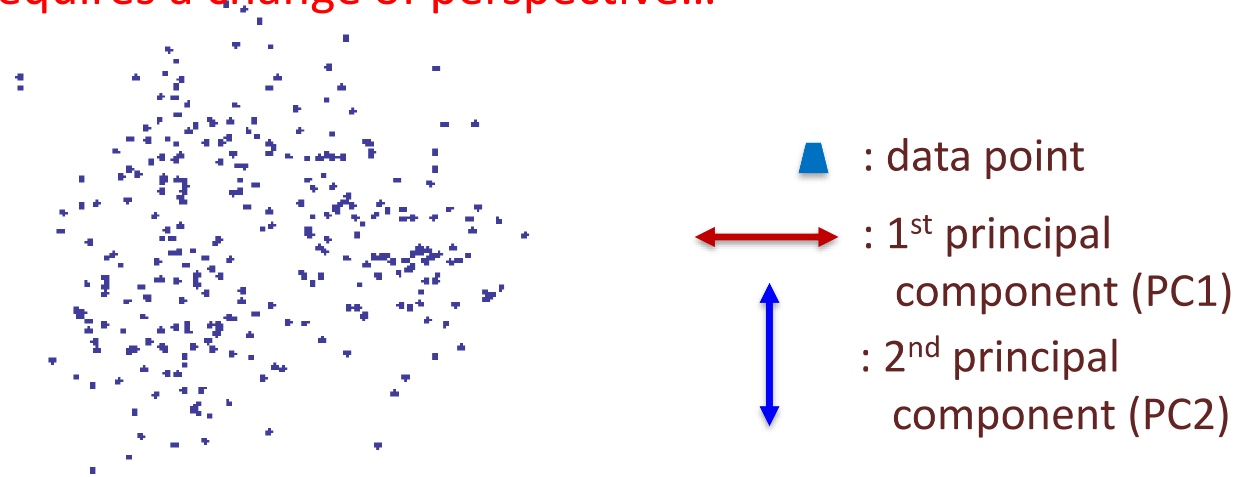
Can we beat the correlation bandwidth?

- **What is the relationship between the speckle pattern and the wavelength?**
  It depends on the microscopic detail of the scattering medium
- **Take a <u>data-driven</u> approach to the analysis**
  Sometimes the answer requires a change of perspective…



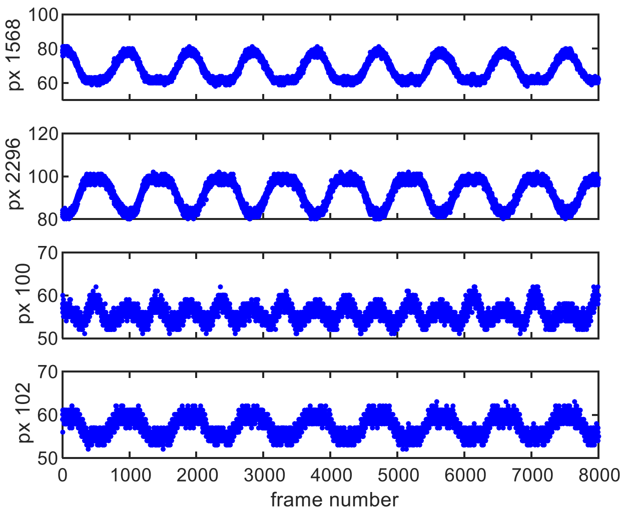
Principal Component Analysis

- **What is the relationship between the speckle pattern and the wavelength?**
  It depends on the microscopic detail of the scattering medium
- **Take a <u>data-driven</u> approach to the analysis**
  Sometimes the answer requires a change of perspective…



Principal Component Analysis is a mathematical process that is defined as a rotation that transforms the data to a new coordinate system, such that the greatest variance by any projection of the data comes to lie on the first coordinate (called 1st Principal Component), and so on..

Principal Component Analysis



- We need to consider the covariance matrix:

$$\sigma_{AB}^2 = \frac{1}{n} AB^T$$

$$\begin{pmatrix} 0.646 & -0.621 & -0.004 & 0.189 \\ -0.621 & 0.630 & 0.010 & -0.189 \\ -0.004 & 0.010 & 0.055 & -0.010 \\ 0.189 & -0.189 & -0.010 & 0.076 \end{pmatrix}$$

- We want to find a new basis, where covariances are zero, and variances are ranked from smallest to largest

  i.e. the eigenbasis!

Principal Component Analysis

$$\sigma_{AB}^2 = \begin{pmatrix} 0.646 & -0.621 & -0.004 & 0.189 \\ -0.621 & 0.630 & 0.010 & -0.189 \\ -0.004 & 0.010 & 0.055 & -0.010 \\ 0.189 & -0.189 & -0.010 & 0.076 \end{pmatrix}$$

Diagonalize

Eigenvalues:

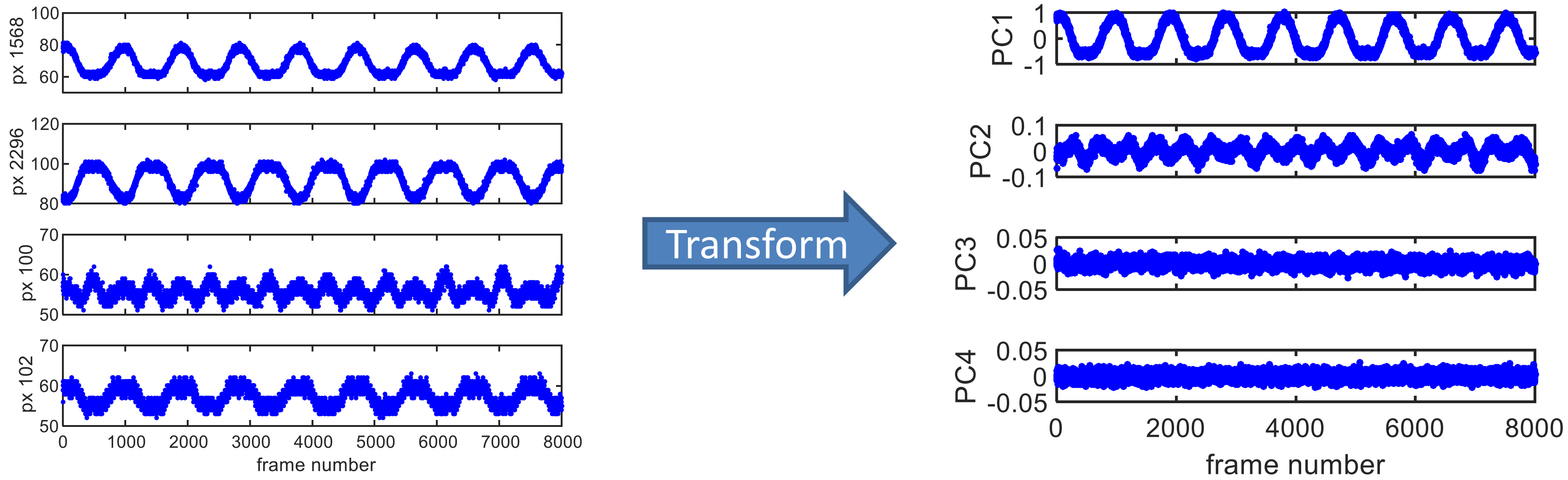
$$\begin{pmatrix} 0.691 & 0 & & \ddots \\ 0 & 0.030 & & \\ & \ddots & 0.009 & 0 \\ & & 0 & 0.009 \end{pmatrix}$$

Basis vectors:

$$\begin{pmatrix} 0.696 \\ -0.687 \\ -0.009 \\ 0.211 \end{pmatrix} \begin{pmatrix} -0.124 \\ -0.053 \\ -0.972 \\ 0.193 \end{pmatrix} \begin{pmatrix} -0.456 \\ -0.209 \\ -0.235 \\ 0.833 \end{pmatrix} \begin{pmatrix} 0.542 \\ 0.694 \\ -0.013 \\ 0.474 \end{pmatrix}$$

Projecting the data onto the new basis gives the **principal components**

Extracting the Wavelength

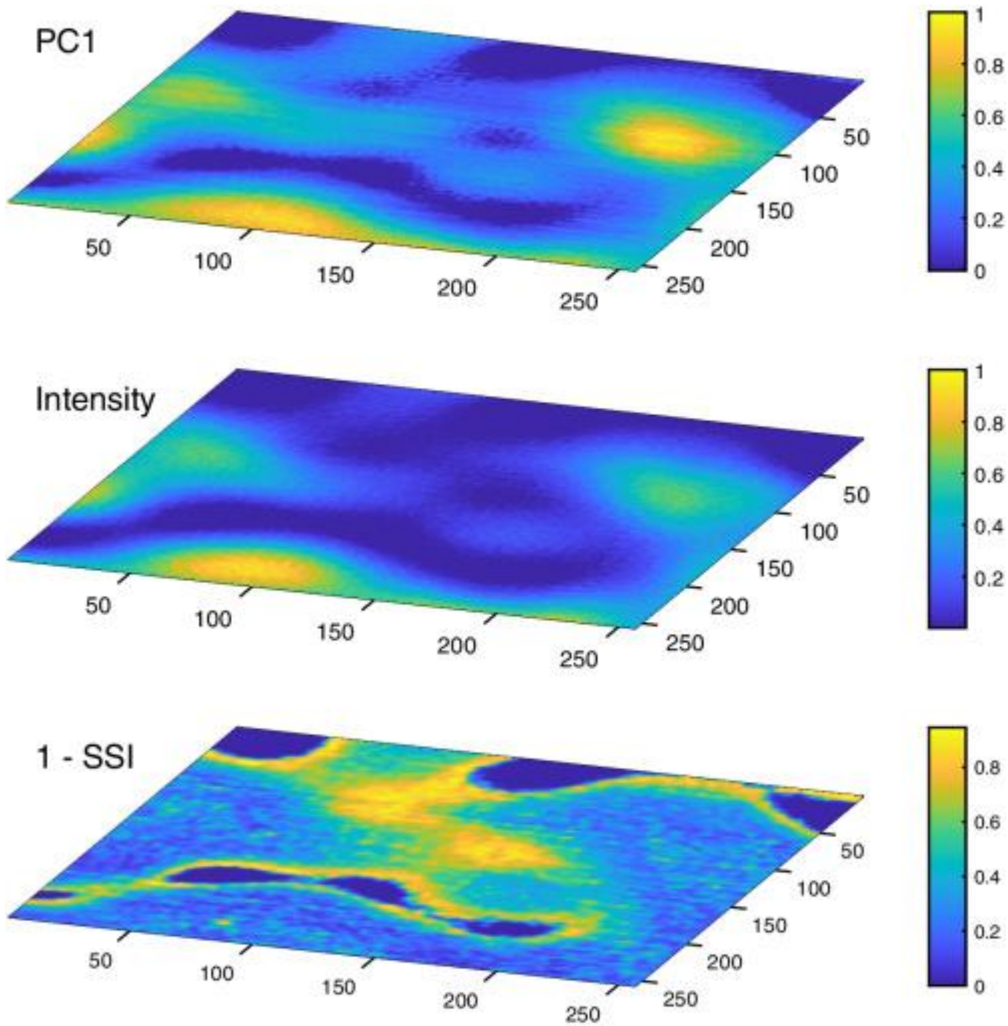


We transform our data to the new basis, comprising its principal components (PCs)

PC1 varies linearly with wavelength
(Proportionality constant acquired through a calibration measurement)

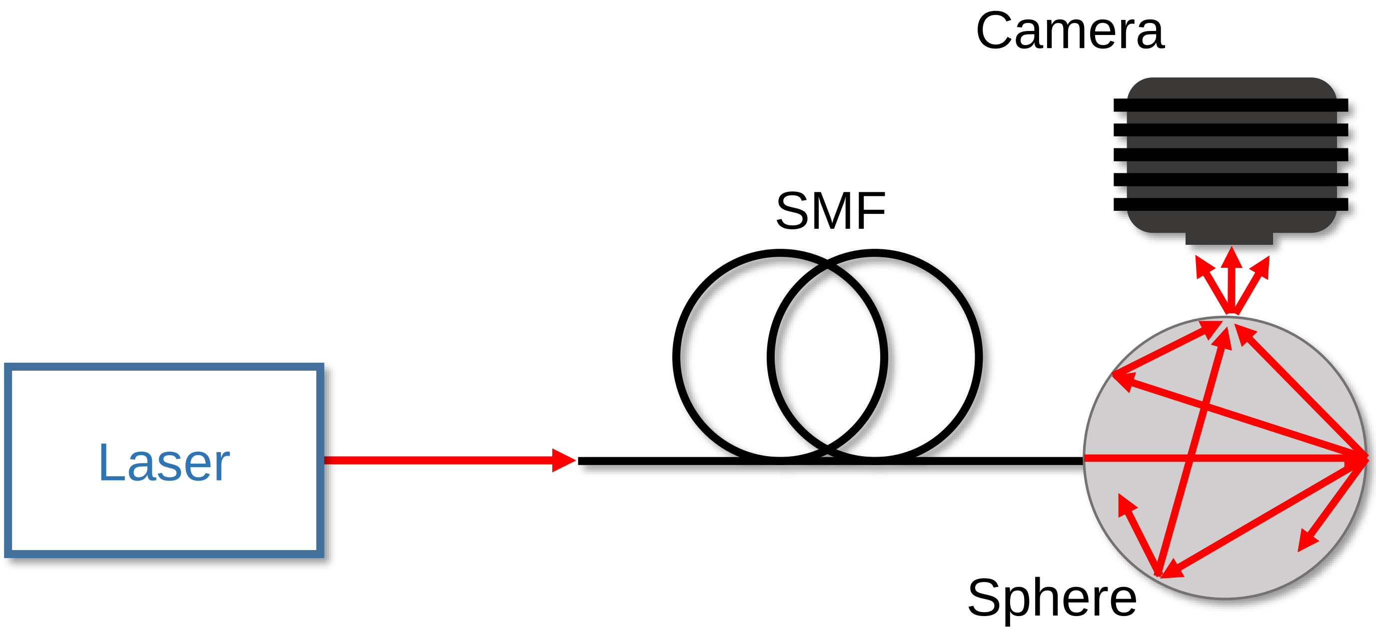
Importantly, the linear dependence means we can interpolate between calibration points

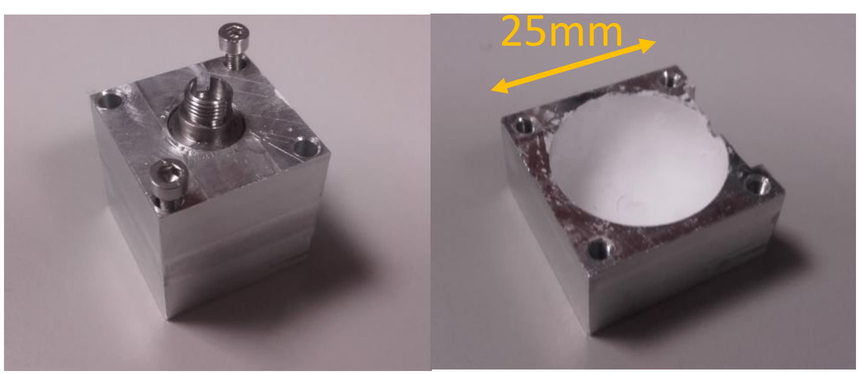
So what's being measured?

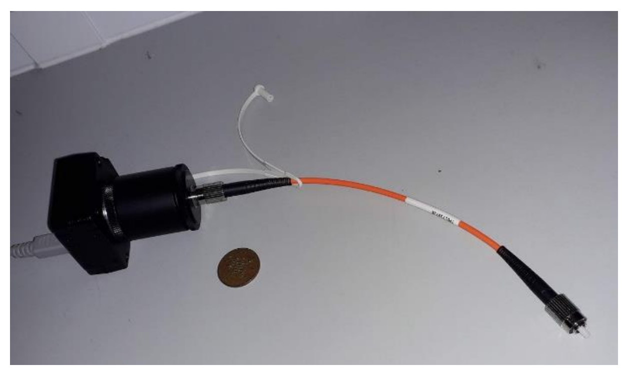


Speckle Wavemeter

Setup



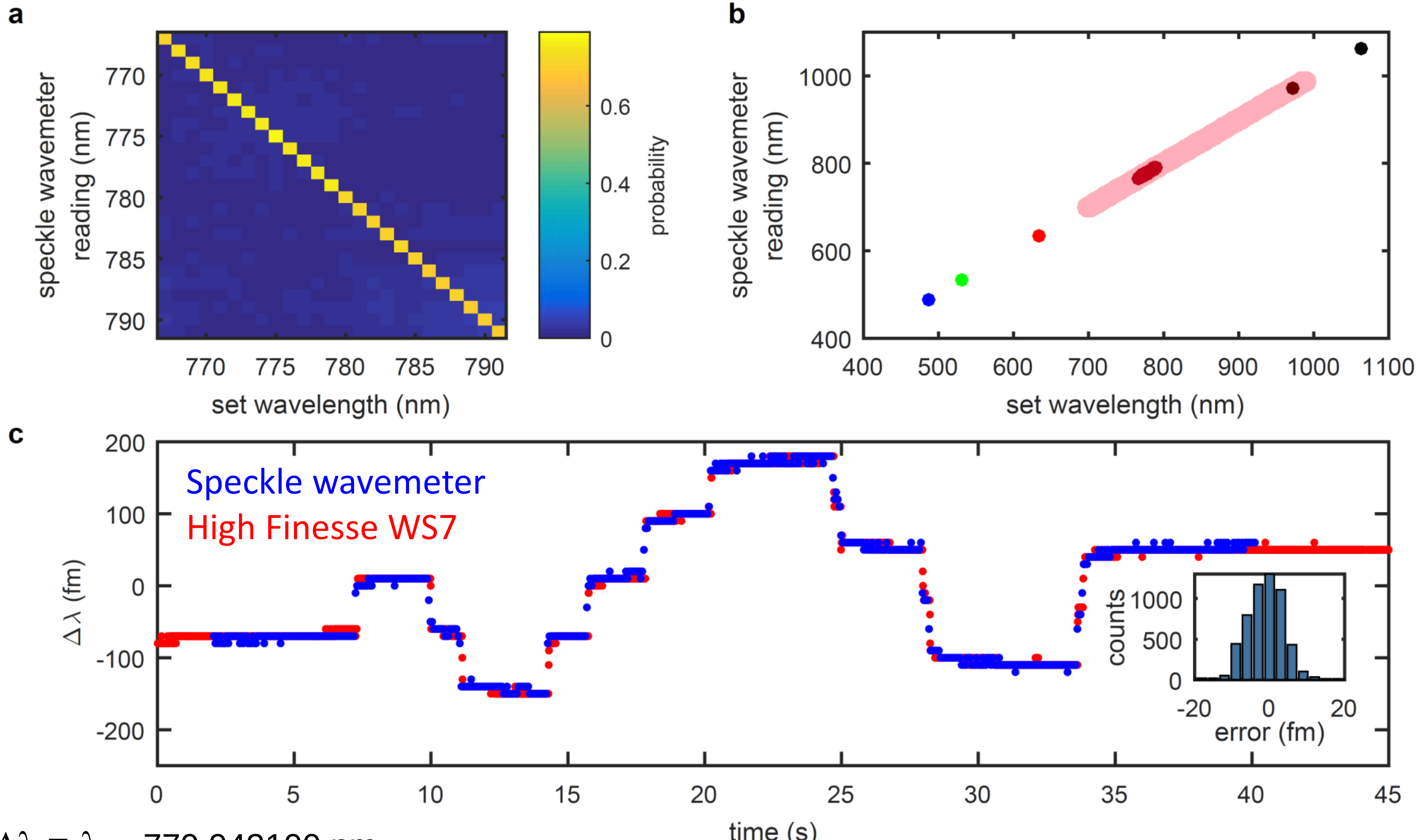




*NK Metzger, et al, Nature Comm **8**, 15610 (2017)*

Speckle Wavemeter

Broadband performance (using TMM)



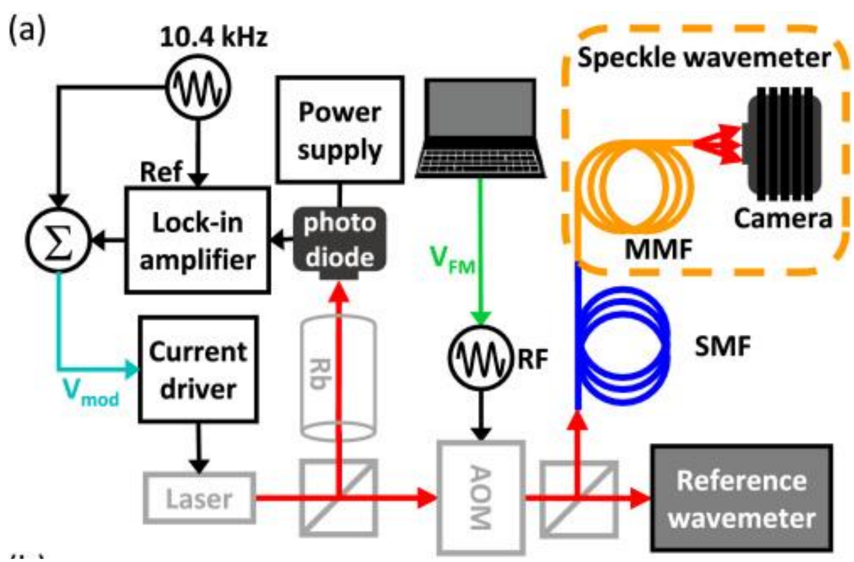
$\Delta\lambda = \lambda - 779.943100$ nm

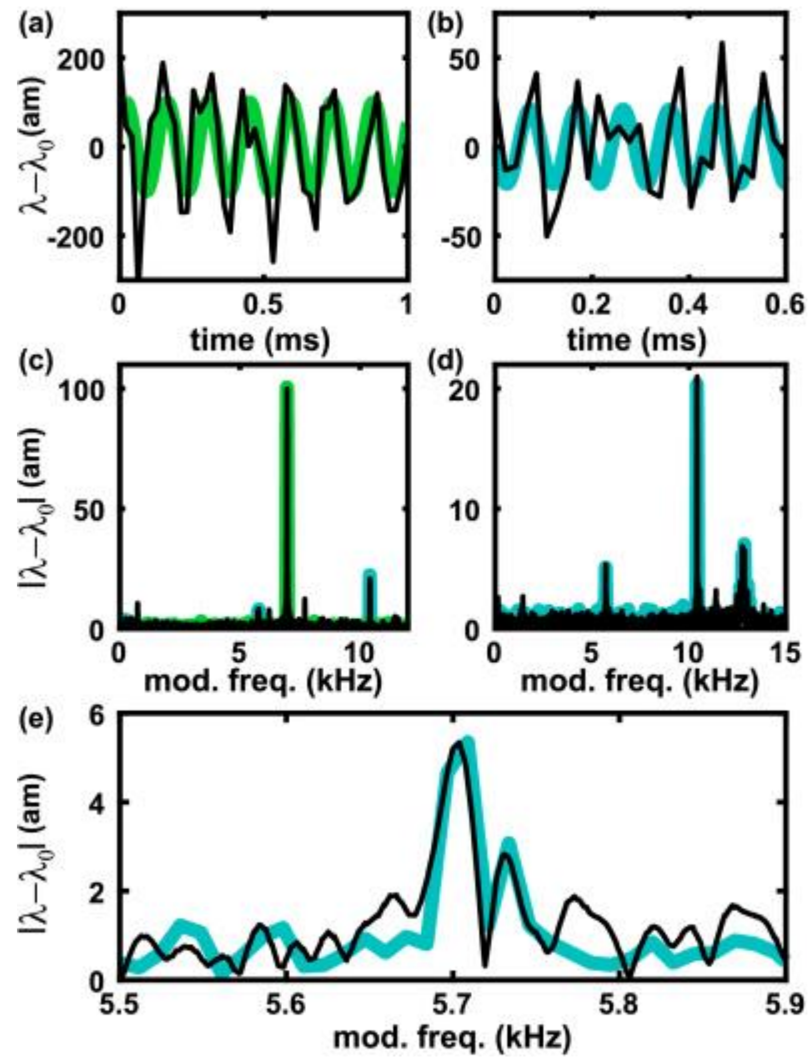
*NK Metzger, et al, Nature Comm **8**, 15610 (2017)*

Speckle Wavemeter

Precision

Sinusoidal current modulation of an ECDL



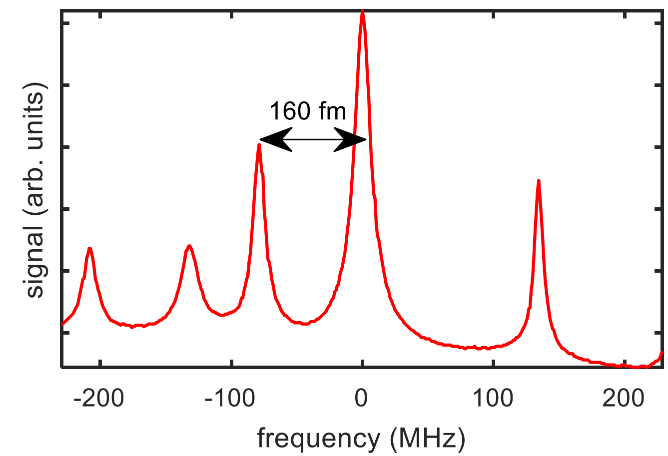


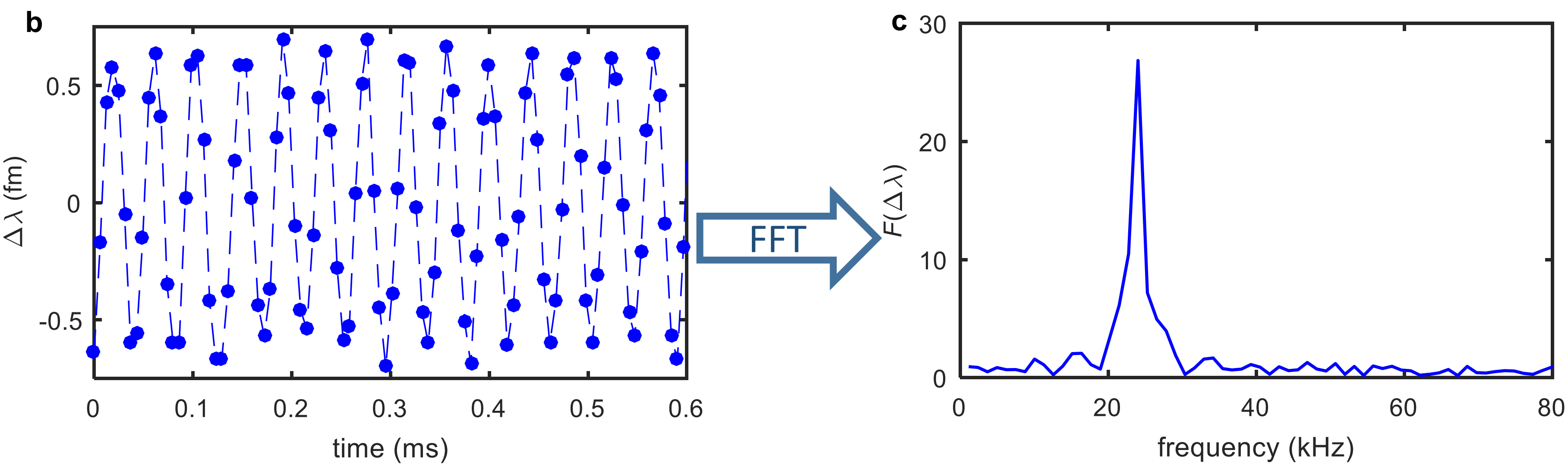
GB et al Opt. Lett. 44, 1367-1370 (2019)

Integrating Sphere Wavemeter

Acquisition Rate

Ti:Sa top-of-fringe locked to rubidium spectroscopy with 24 kHz dither to laser current.

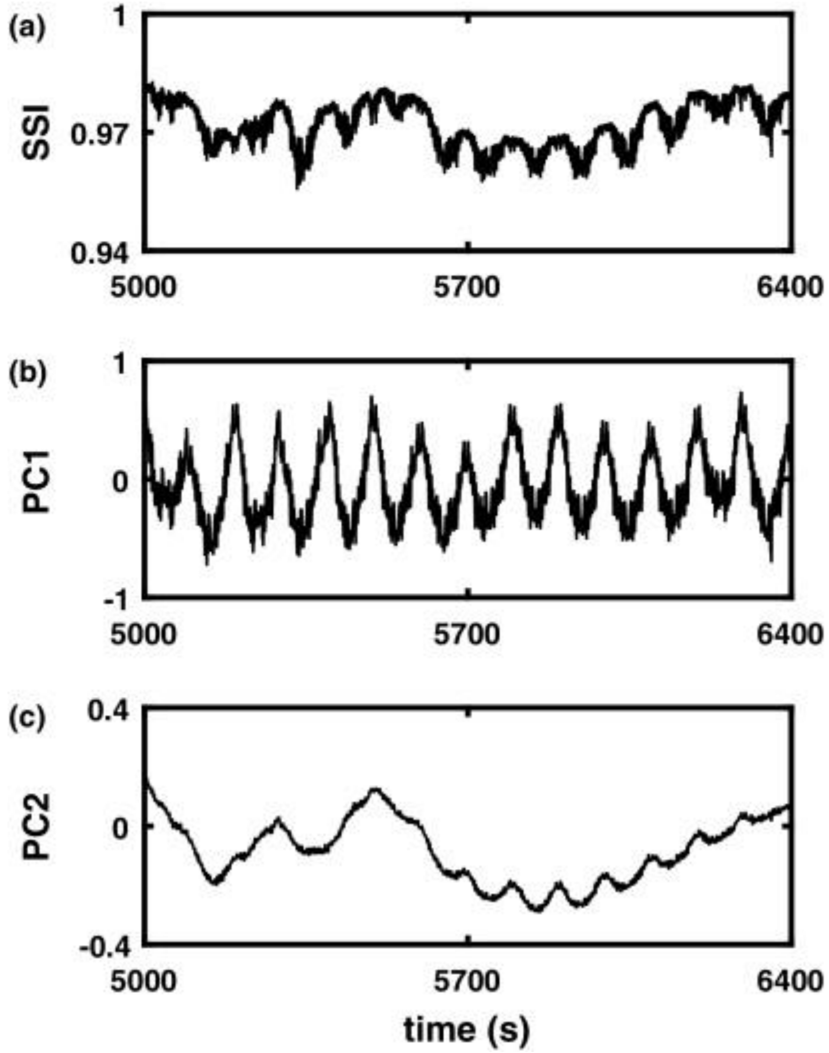




*NK Metzger, et al, Nature Comm **8**, 15610 (2017)*

Speckle Wavemeter

Environmental insensitivity

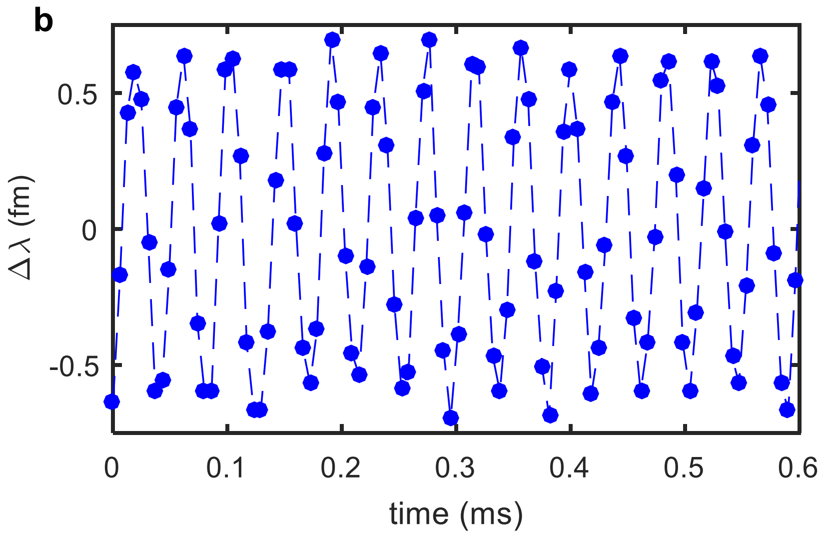


GB et al Opt. Lett. 44, 1367-1370 (2019)

Integrating Sphere Wavemeter

Summary

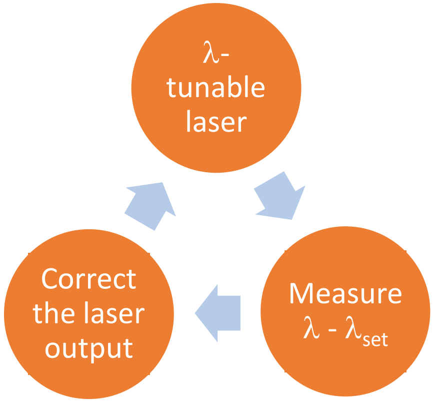
Resolution: 5 am at 780nm
Operating range: vis-nir
(488 - 1064nm demonstrated)
(200 – 2500nm theoretical)
Min input power: < 300 μW
Max acquisition rate: > 200 kHz
Calibration stability: 1.5fm/hr
Vibration dependence: not measured
Footprint (typical): 6 x 6 x 13 cm

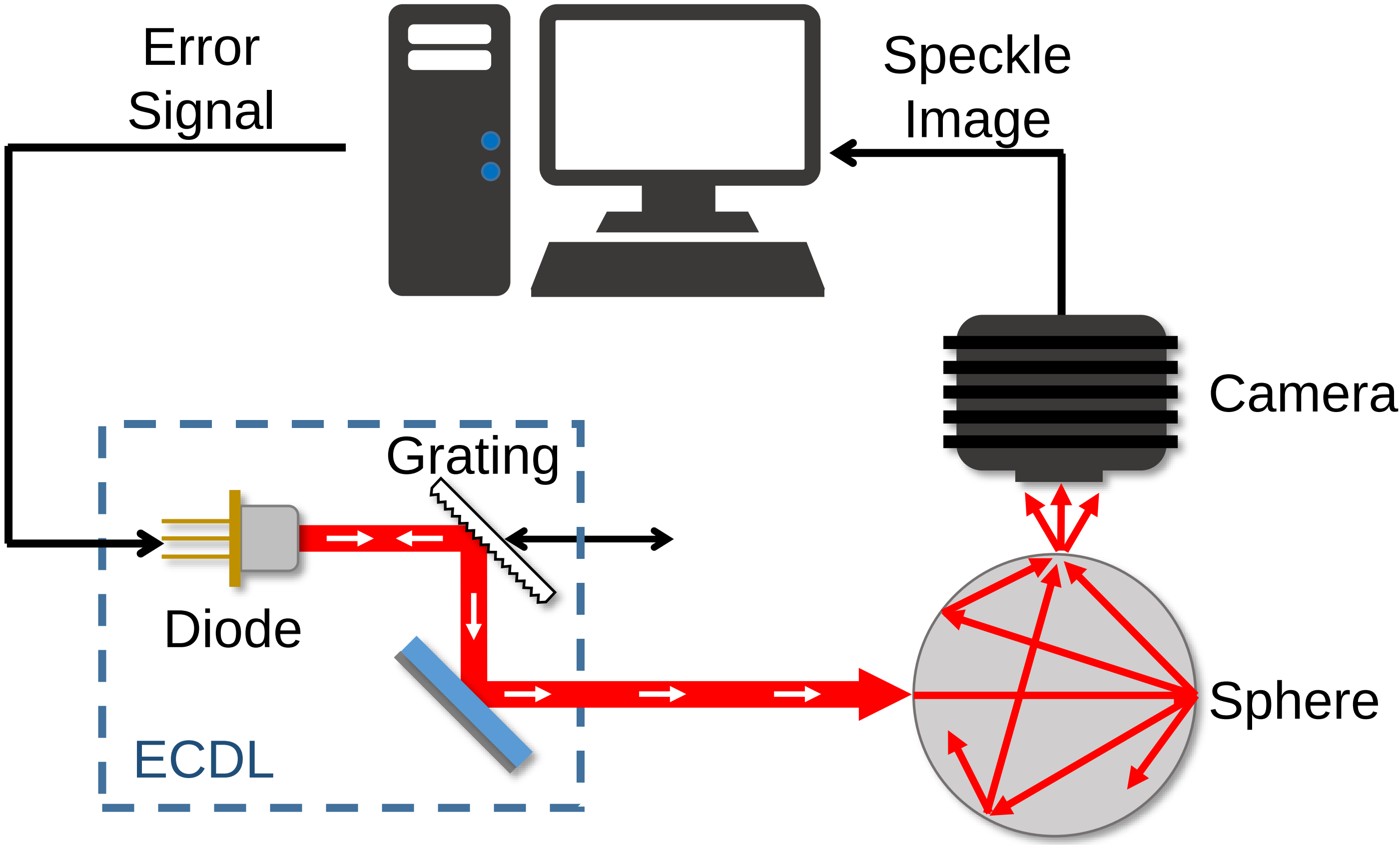


*NK Metzger, et al, Nature Comm **8**, 15610 (2017)*
*GB et al Opt. Lett. **44**, 1367 (2019)*

Speckle Stabilization

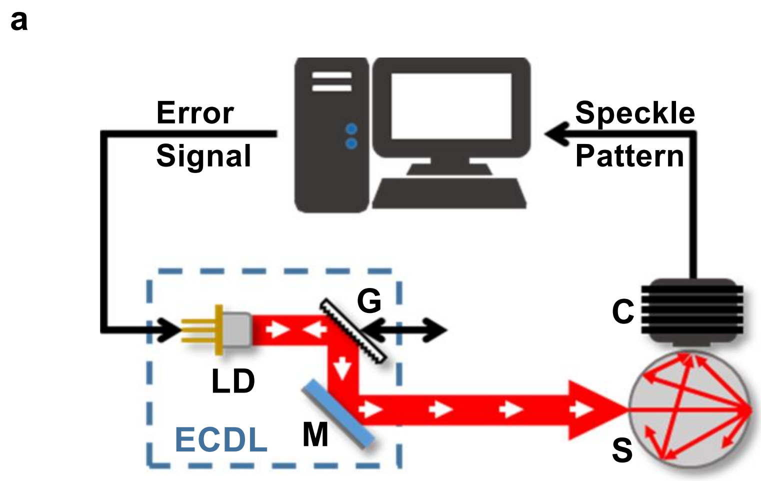
Sometimes, just knowing the wavelength isn't enough, and we really want to control it!

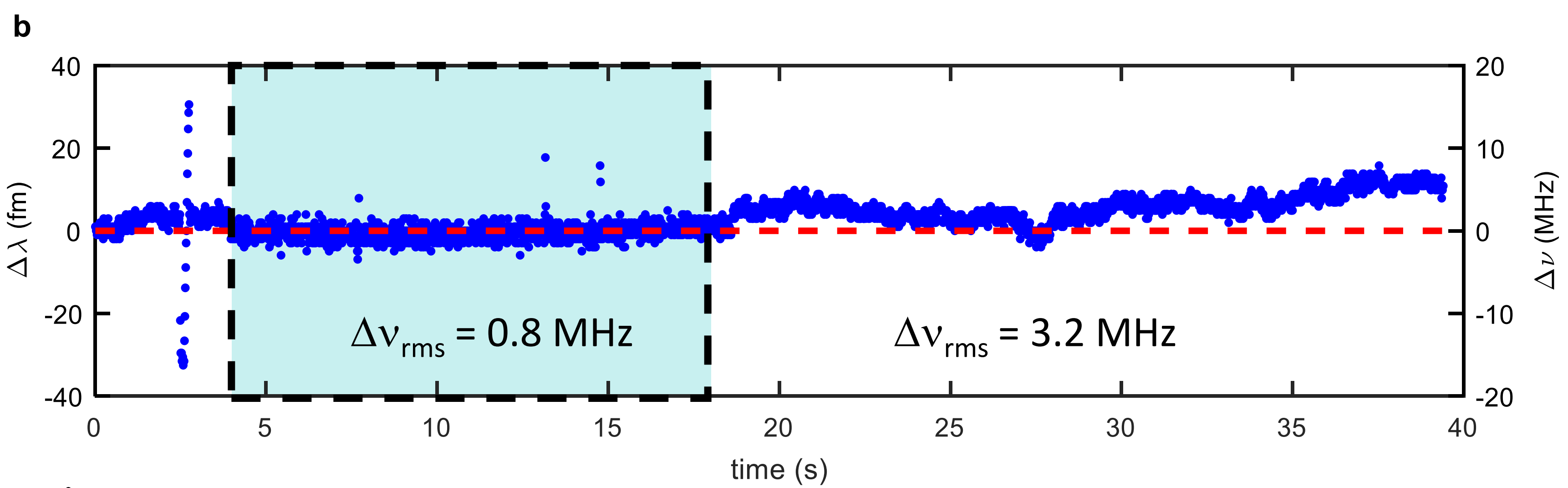




NK Metzger, et al, Nature Comm ***8****, 15610 (2017)*

Speckle Stabilization



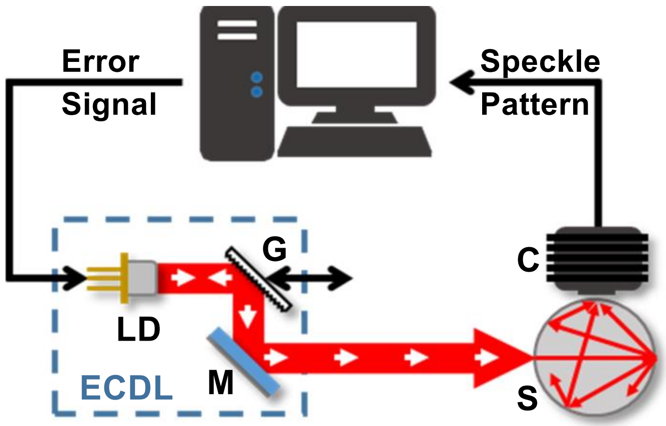


$\Delta\lambda = \lambda - 780.243700$ nm

*NK Metzger, et al, Nature Comm **8**, 15610 (2017)*

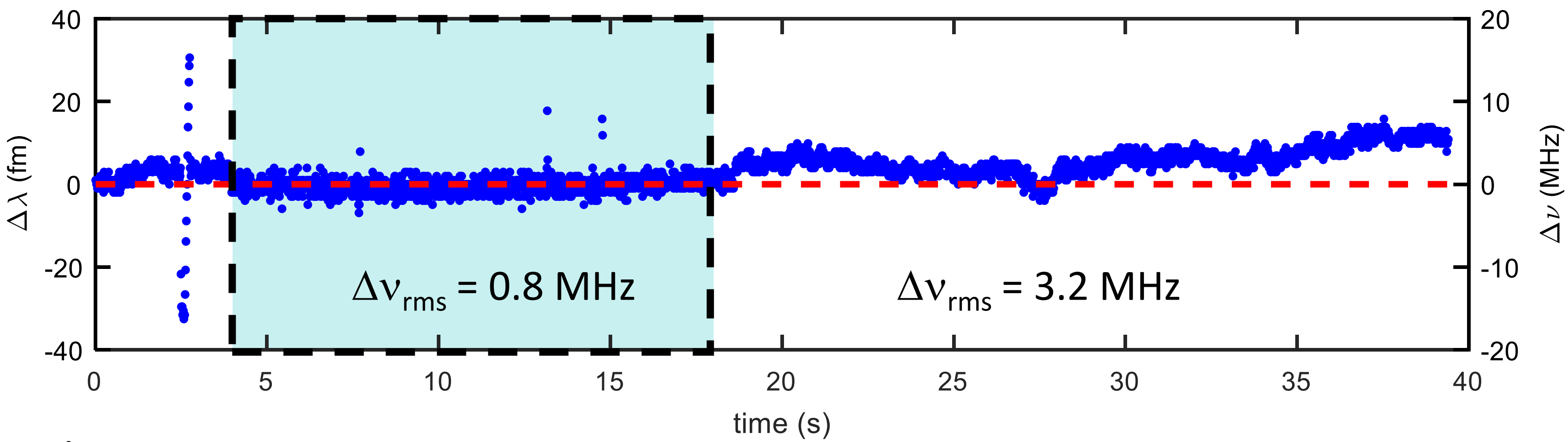
Speckle Stabilization

a



- Tuning Range: Infinite (arbitrary lock point)
- Capture Range: 30 MHz
- Linewidth: 800 kHz over 10s
- Instability: 2×10^{-9} over 10s, without thermal or vibration management
- Lock Update Rate: 200 Hz

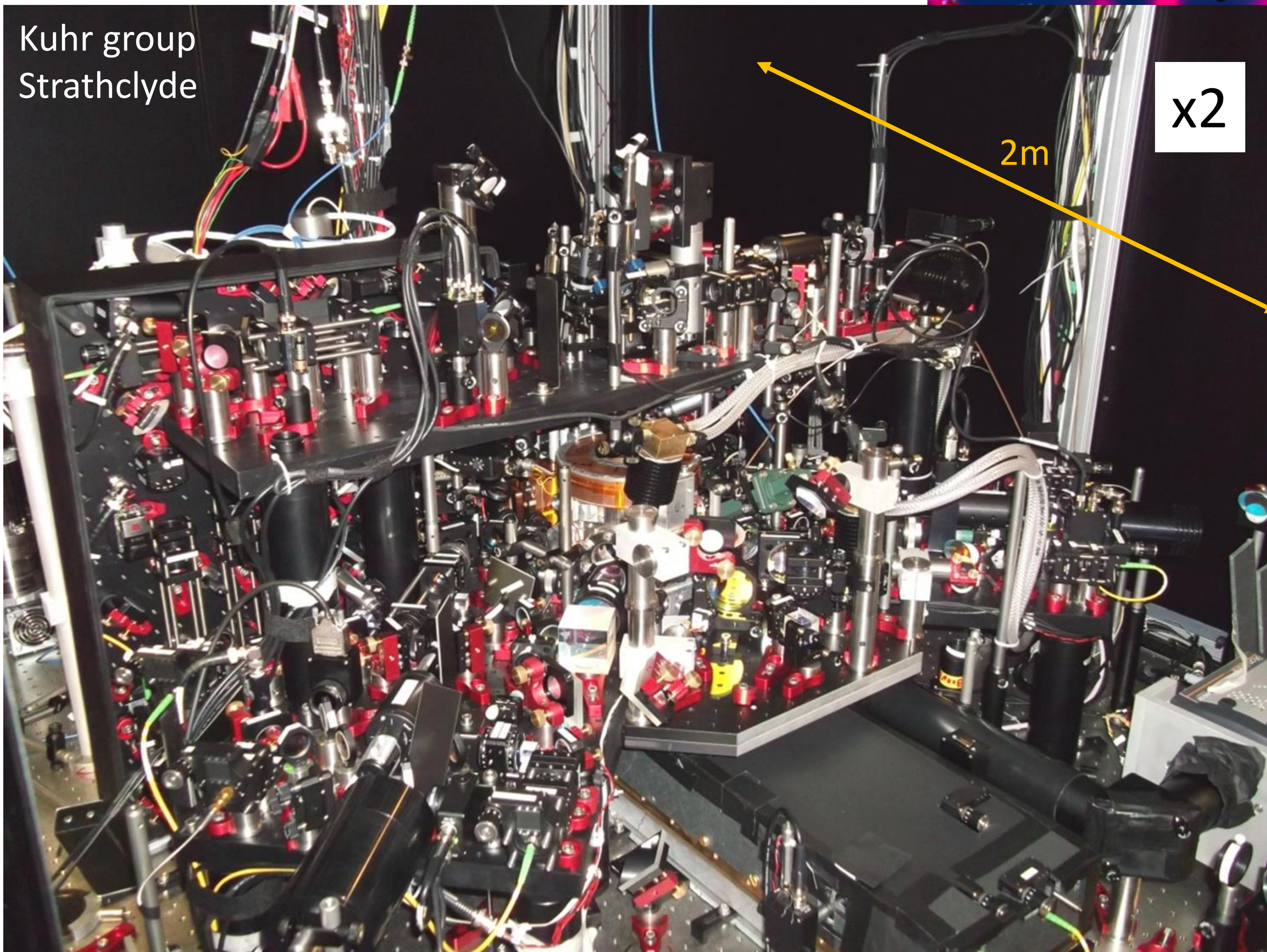
b



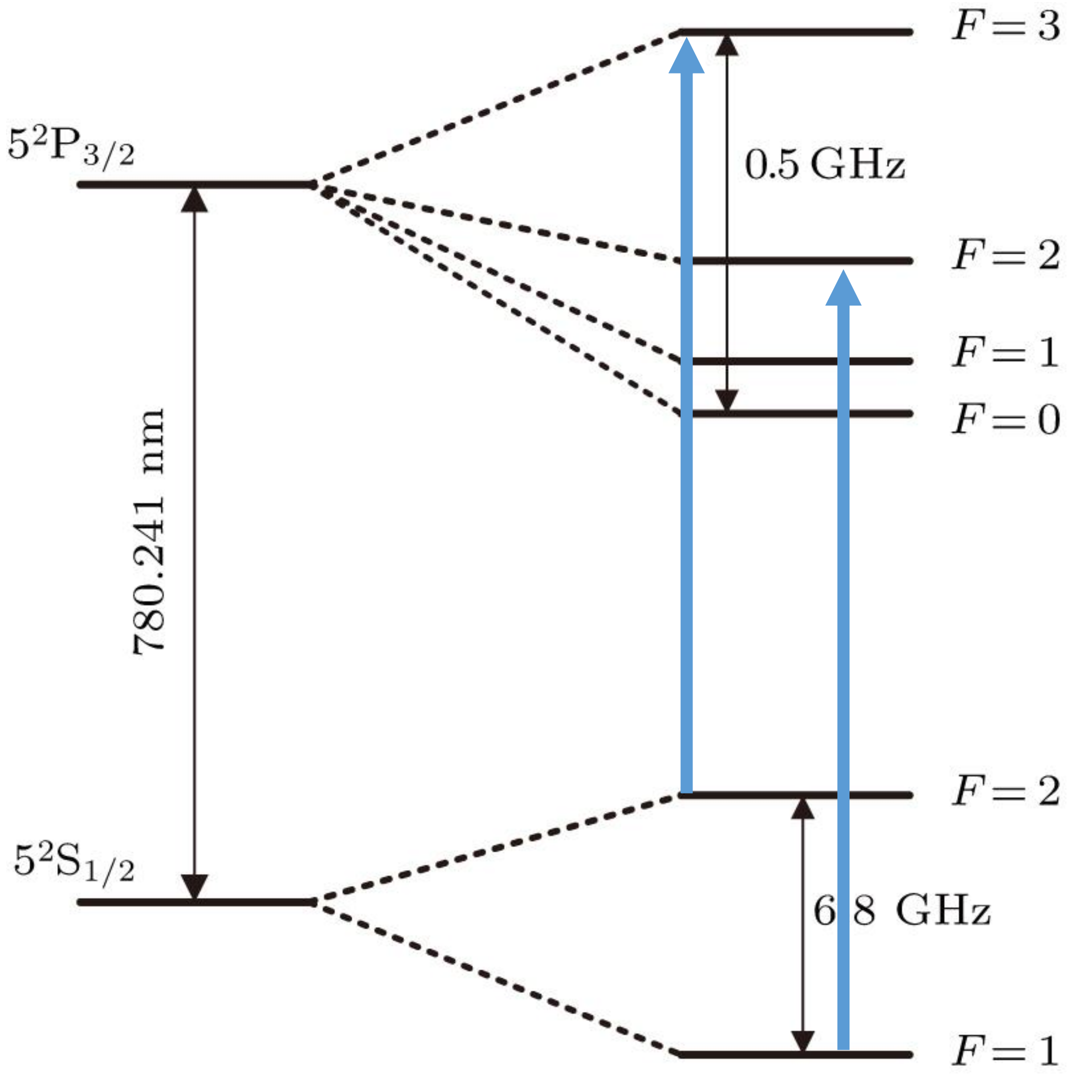
$\Delta\lambda = \lambda - 780.243700$ nm

NK Metzger, et al, Nature Comm ***8****, 15610 (2017)*

Speckle Stabilization:



Tracking multiple wavelengths



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