The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

IAEA International Atomic Energy Agency

2037-17

Introduction to Optofluidics

1 - 5 June 2009

Computer generated holograms: multi-point, interactive 3D optical traps

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Computer generated holograms: multi-point, interactive, 3D optical traps

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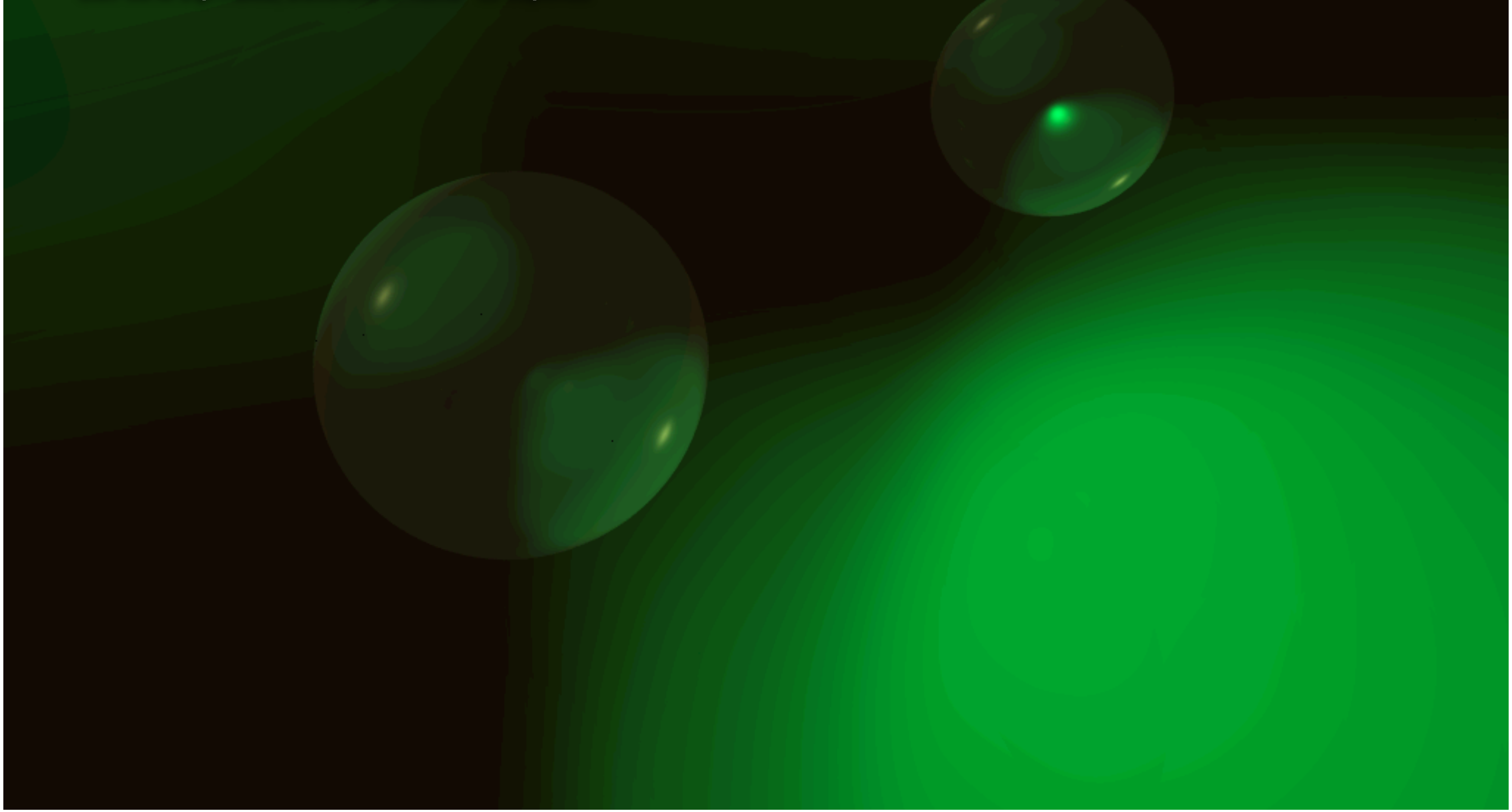
CNR-INFM Dip. Fisica, Università di Roma “La Sapienza”



Plan of today lectures

Optofluidics

1. LIGHT TO MANIPULATE FLUIDS
2. FLUIDS TO MANIPULATE LIGHT
3. LIGHT TO UNDERSTAND FLUIDS

1st Part — HOLOGRAPHIC TRAPPING AS A TOOL FOR FLUID MANIPULATION

2nd Part — HOLOGRAPHIC TRAPPING AS A TOOL TO INVESTIGATE BASICS PHYSICS AT THE MICRON SCALE

MESOSCOPIC

- inertialess dynamics
- noisy environment
- surface forces
- light pushes

Optical tweezer

288 OPTICS LETTERS / Vol. 11, No. 5 / May 1986

Observation of a single-beam gradient force optical trap for dielectric particles

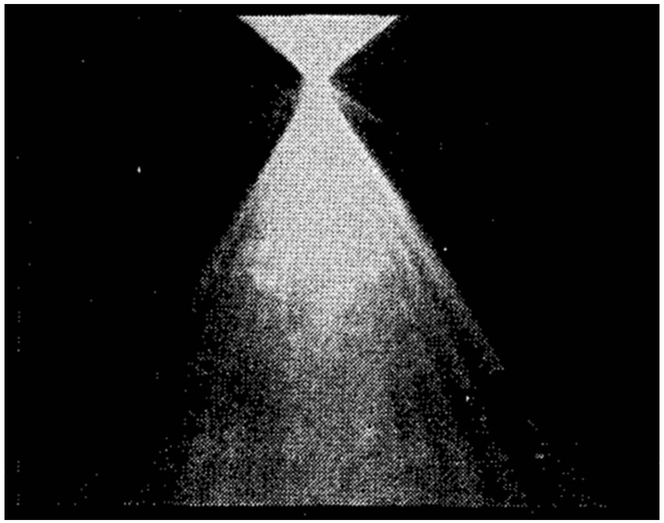
A. Ashkin, J. M. Dziedzic, J. E. Bjorkholm, and Steven Chu

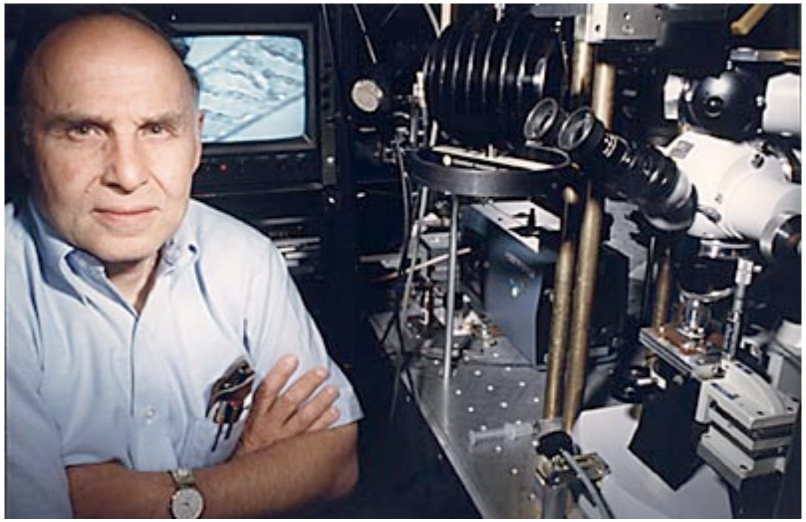
AT&T Bell Laboratories, Holmdel, New Jersey 07733

Received December 23, 1985; accepted March 4, 1986

s by a single-beam gradient force trap was demonstrated for the first reported
egative light pressure due to the gradient force. Trapping was observed over
10 μm to ~25 nm in water. Use of the new trap extends the size range of
tical trapping and manipulation well into the Rayleigh size regime. Applica-
ı trapping is considered.

Optical trapping of dielectric particle
time. This confirms the concept of n
the entire range of particle size from
macroscopic particles accessible to op
tion of this trapping principle to aton





Multi-particle trapping

Why?

- physical interactions between colloids
- biochemical interactions between cells
- assembly of photonic/fluidic micro-devices

How?

Time sharing:

Acousto-Optic Deflectors (AOD), EOD, Galvanometric Mirrors

:)

- fast (~100 kHz)
- precise (Å)

: (

- 2D
- no phase control

Holography:

Spatial Light Modulators (SLM)

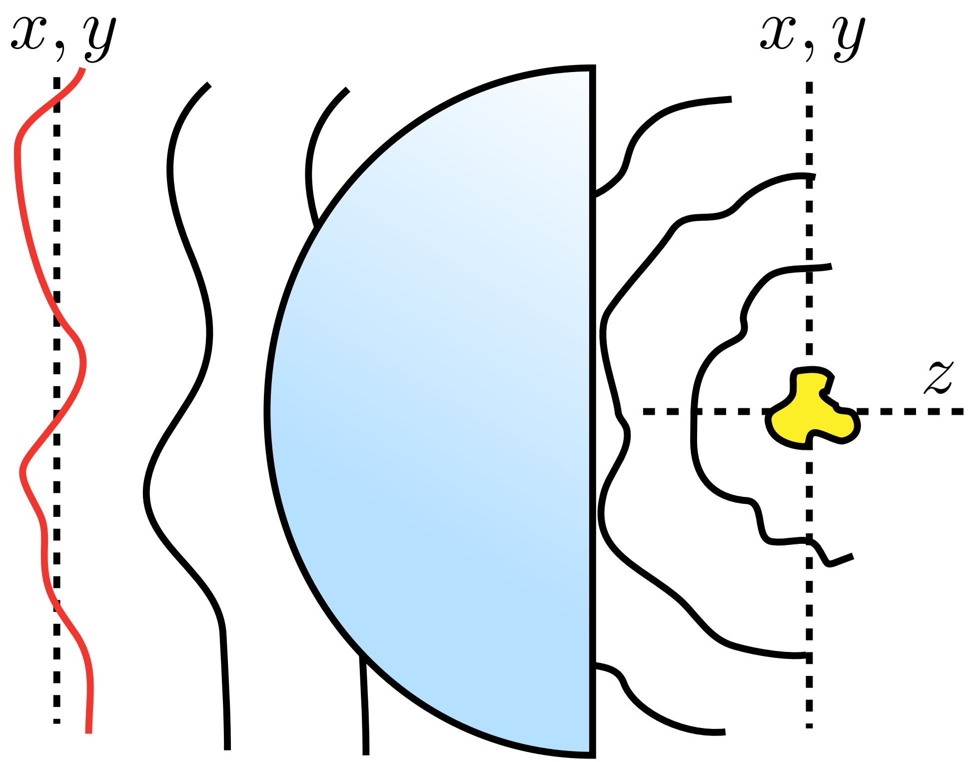
:)

- 3D
- phase control
  aberration correction
  exotic beams,
  vortices, light bottles

: (

- slow (~20 Hz)
- complex algorithms

Computer generated holograms



$u(x, y)$

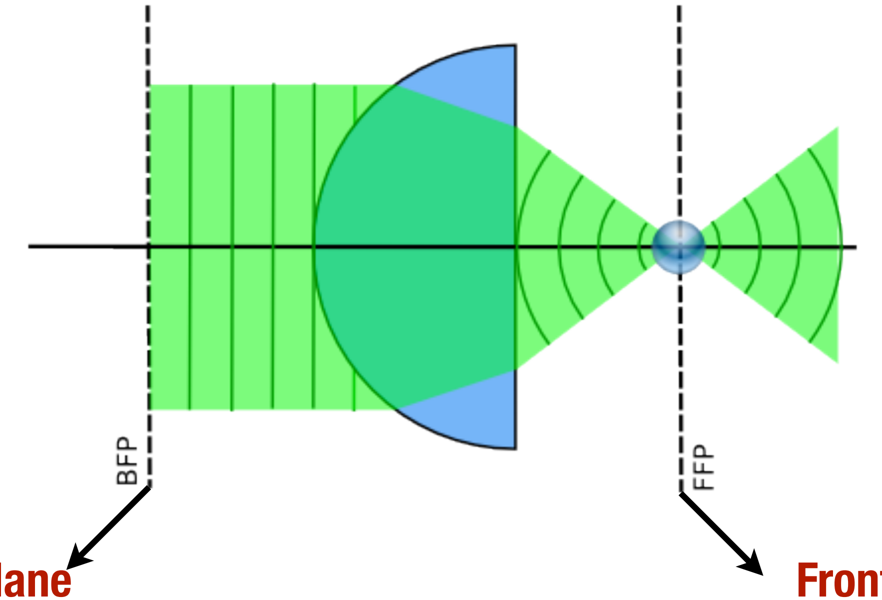
complex amplitude
on the hologram plane

?

$I(x, y, z)$

volumetric intensity distribution
around the focal plane

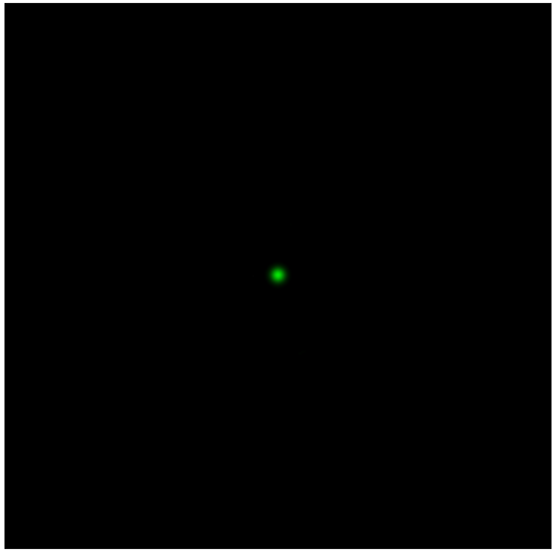
Wavefront modulation in the Fourier plane



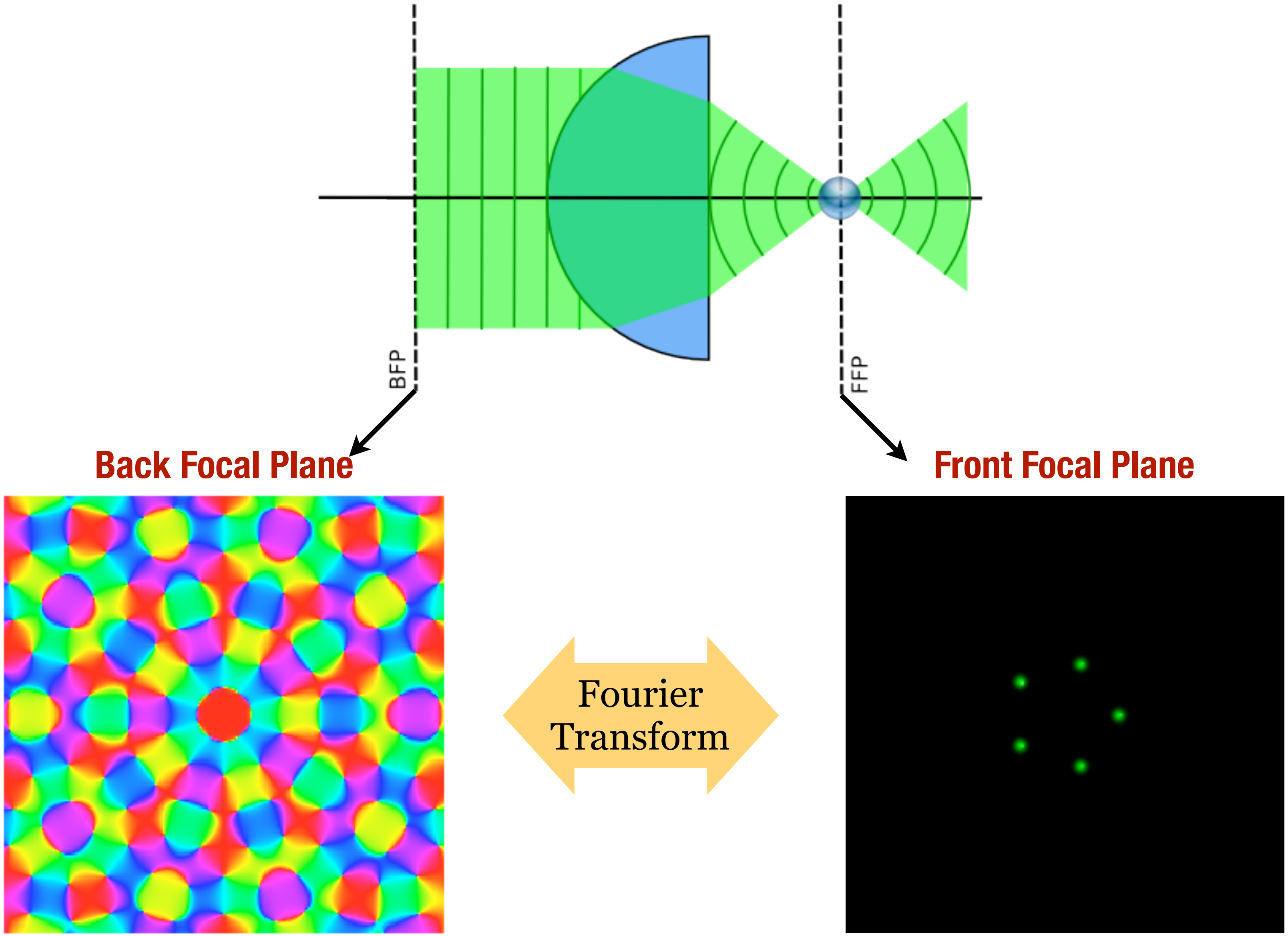
Back Focal Plane

Front Focal Plane

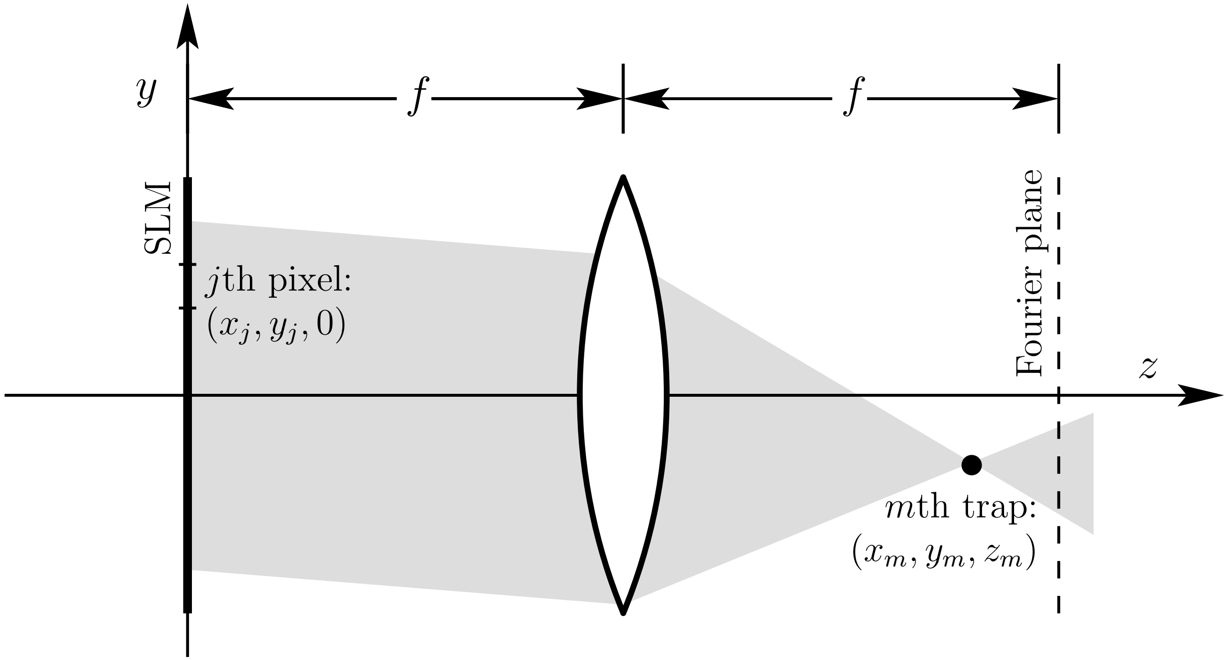
Fourier Transform



Wavefront modulation in the Fourier plane



Wavefront modulation in the Fourier plane

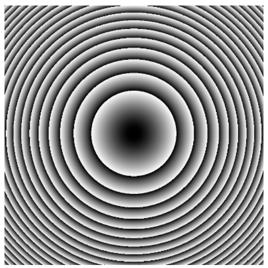


COMPLEX AMPLITUDE ON Jth PIXEL

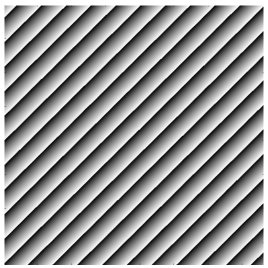
$$u_j = e^{i\Delta_j^m}$$

PHASE SHIFT DUE TO PROPAGATION BETWEEN Jth PIXEL AND Mth TRAP

$$\Delta_j^m = \underbrace{\frac{\pi z_m}{\lambda f^2}(x_j^2 + y_j^2)} + \underbrace{\frac{2\pi}{\lambda f}(x_j x_m + y_j y_m)}$$



lens



grating

Superposition (S)

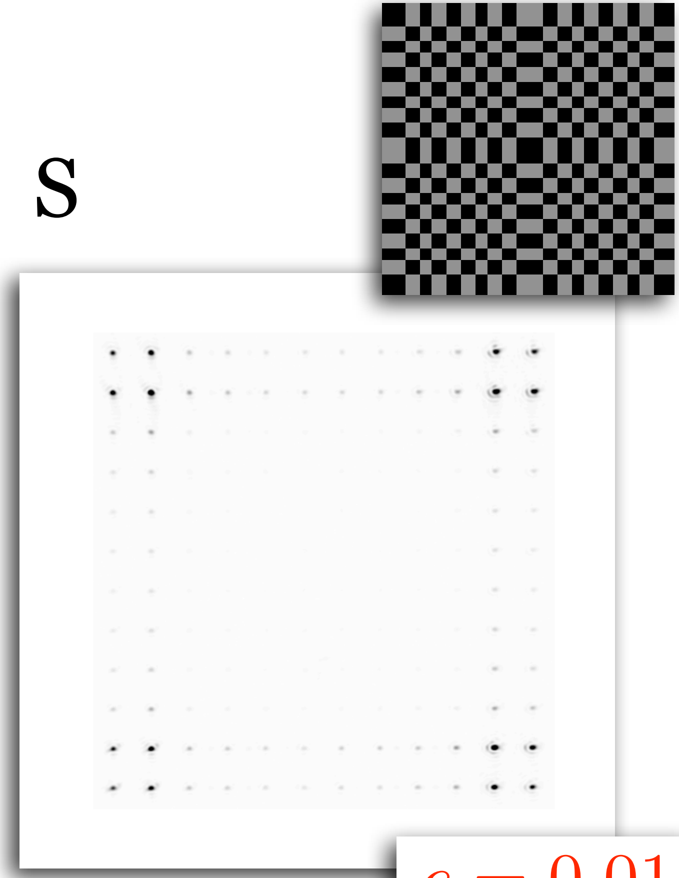
SUPERIMPOSE AND NEGLECT AMPLITUDE

$$\phi_j = \arg\left[\sum_m e^{i\Delta_j^m}\right]$$

EFFICIENCY $e = \sum_m I_m \in [0,1]$

UNIFORMITY $u = 1 - \frac{\max[I_m] - \min[I_m]}{\max[I_m] + \min[I_m]} \in [0,1]$

S



$e = 0.01$

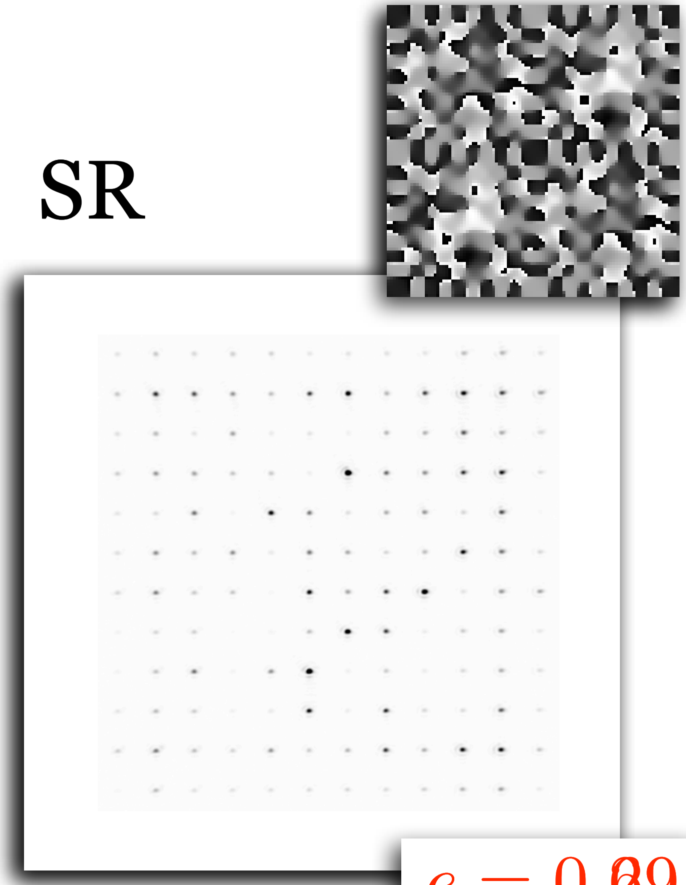
$u = 0.58$

Random Superposition (SR)

KINOFORM WITH PHASE RANDOMIZATION

$$\phi_j = \arg\left[\sum_m e^{i(\Delta_j^m + \theta_m))}\right]$$

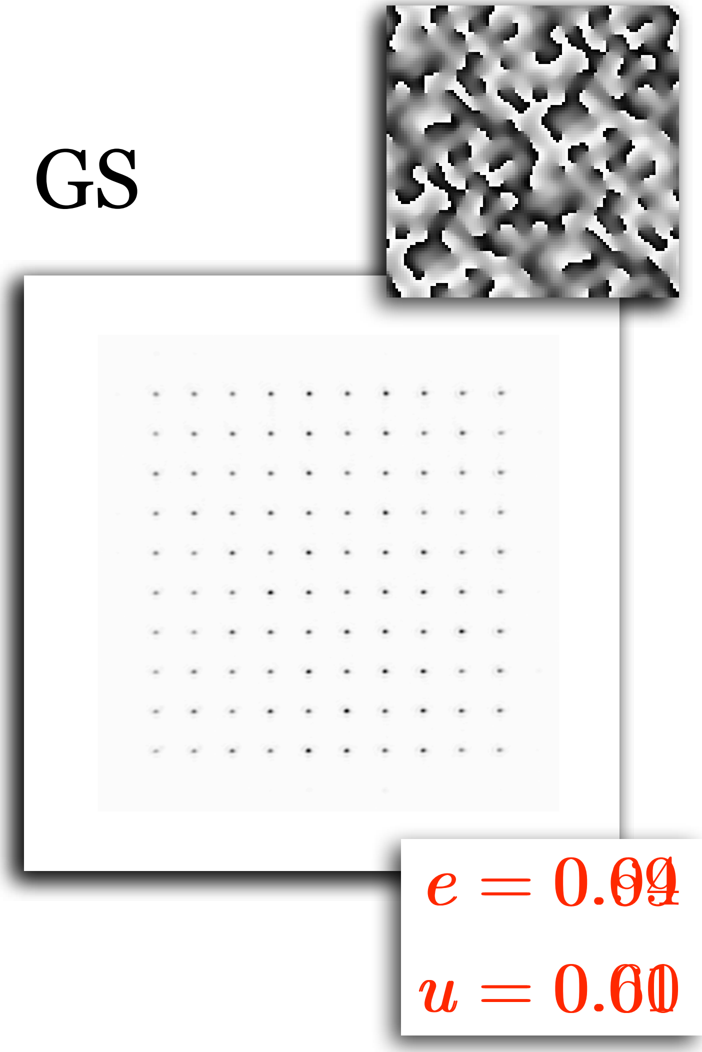
θ_m RANDOMLY CHOSEN PHASE



KINOFORM WITH OPTIMIZED IMAGINARY WEIGHTS

$$\phi_j = \arg\left[\sum_m e^{i(\Delta_j^m + \theta_m))}\right]$$

θ_m ITERATIVELY SEARCH FOR A BEST PHASE COEFFICIENT



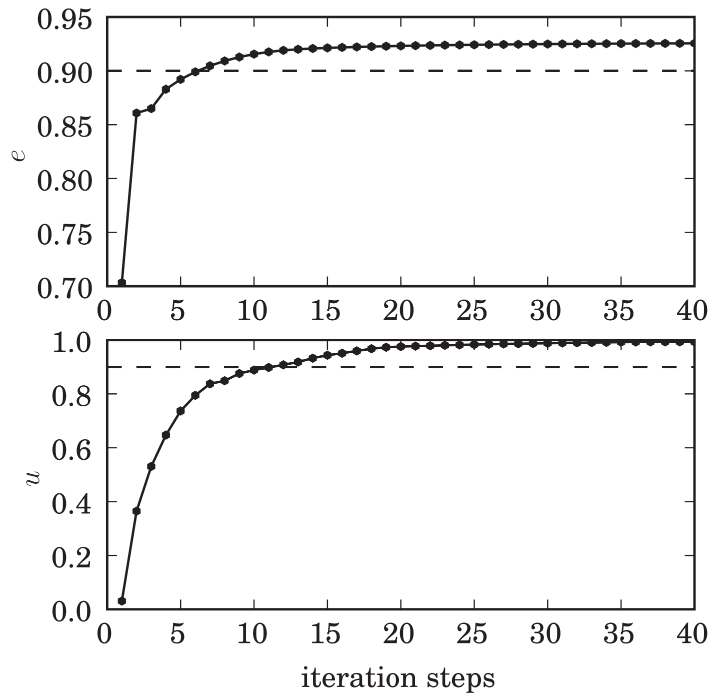
GSW algorithm

DI LEONARDO et al., OPT. EXPRESS (2006)

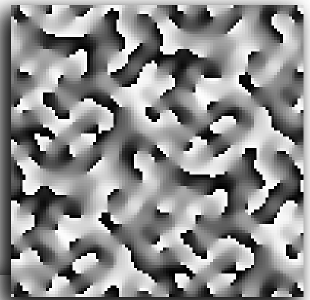
KINOFORM WITH OPTIMIZED COMPLEX WEIGHTS

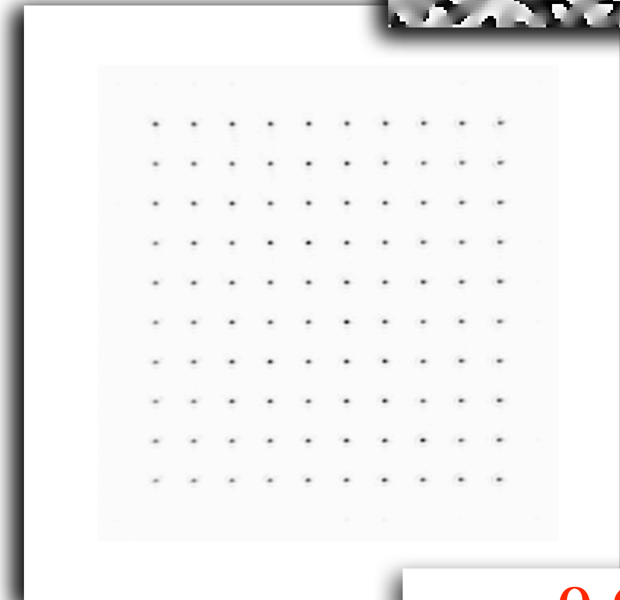
$$\phi_j = \arg\left[\sum_m w_m e^{i(\Delta_j^m + \theta_m)}\right]$$

$w_m e^{i\theta_m}$ ITERATIVELY SEARCH FOR A BEST COMPLEX COEFFICIENT



GSW

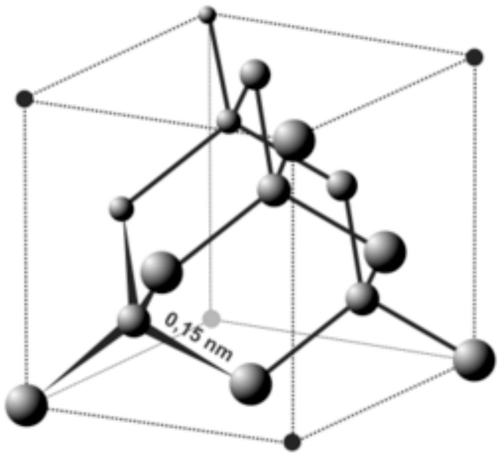




$e = 0.93$

$u = 0.99$

GSW performance in 3D

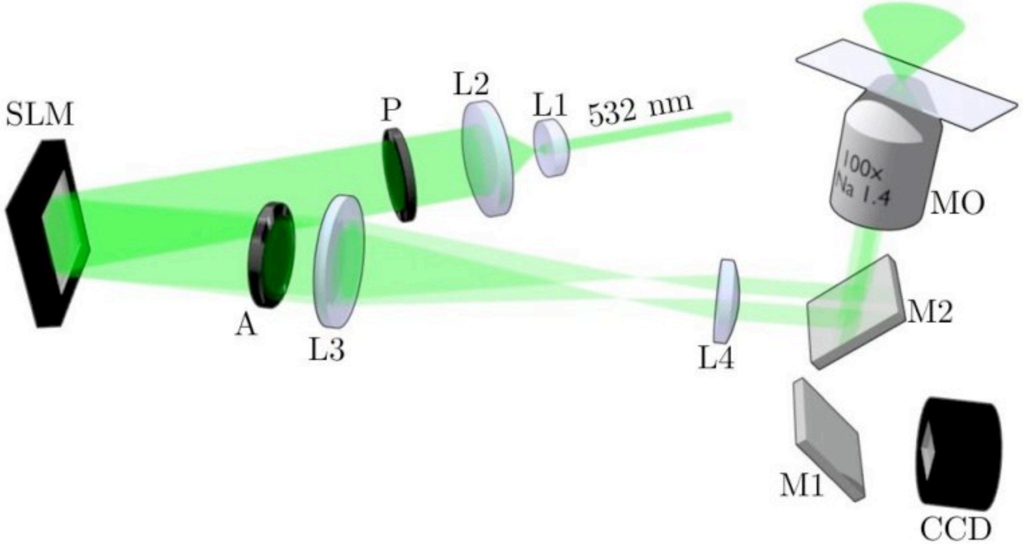


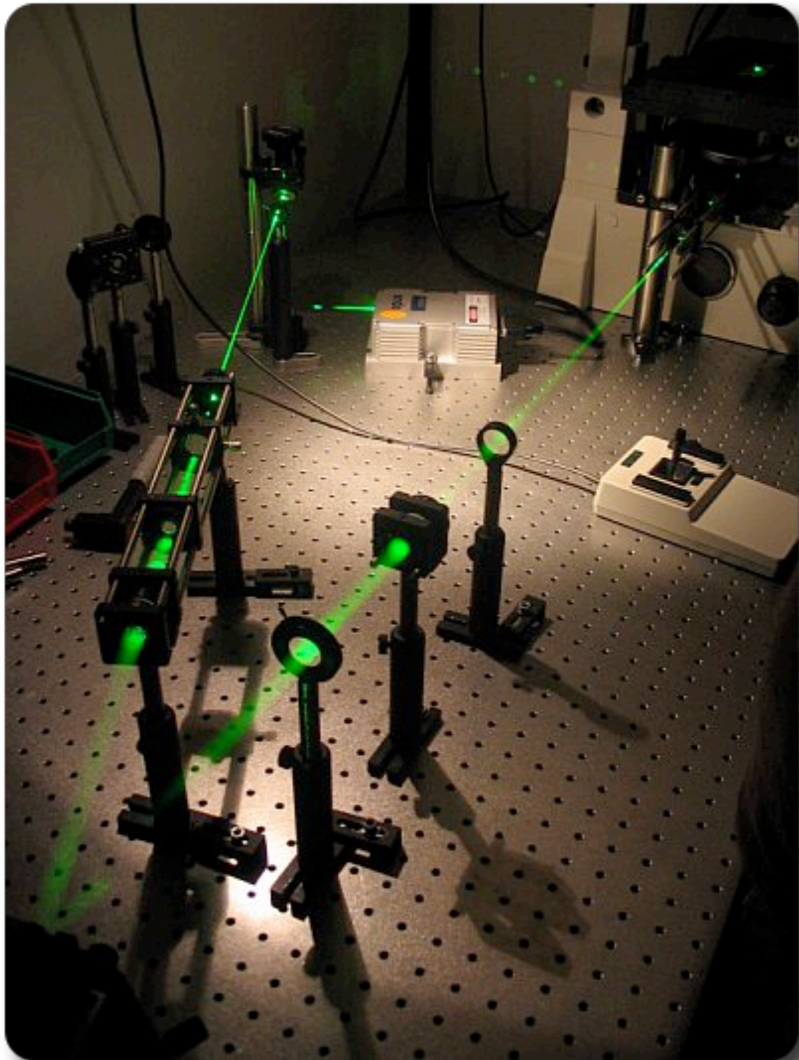
algorithm	e	u	$\sigma(\%)$	K
RM	0.07	0.79	13	-
S	0.69	0.52	40	-
SR	0.72	0.57	28	-
GS	0.92	0.75	14	30
GAA	0.92	0.88	6	30
DS	0.67	1.00	0	$1.7\ 10^5$
GSW	0.93	0.99	1	30

HOT setup

HOLOEYE LCR2500

- 1024x768
- 8 bit
- 75 Hz





HOT reviews

First published in *Nature* **424** August 2003
doi:10.1038/nature01935

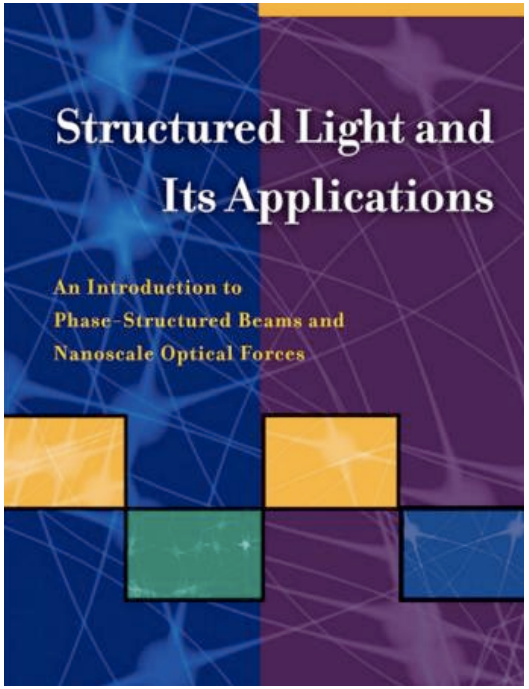
A revolution in optical manipulation

David G. Grier[1]

Optical tweezers: the next generation

Kishan Dholakia, Gabriel Spalding and Michael MacDonald

PHYSICS WORLD OCTOBER 2002



Chapter 6

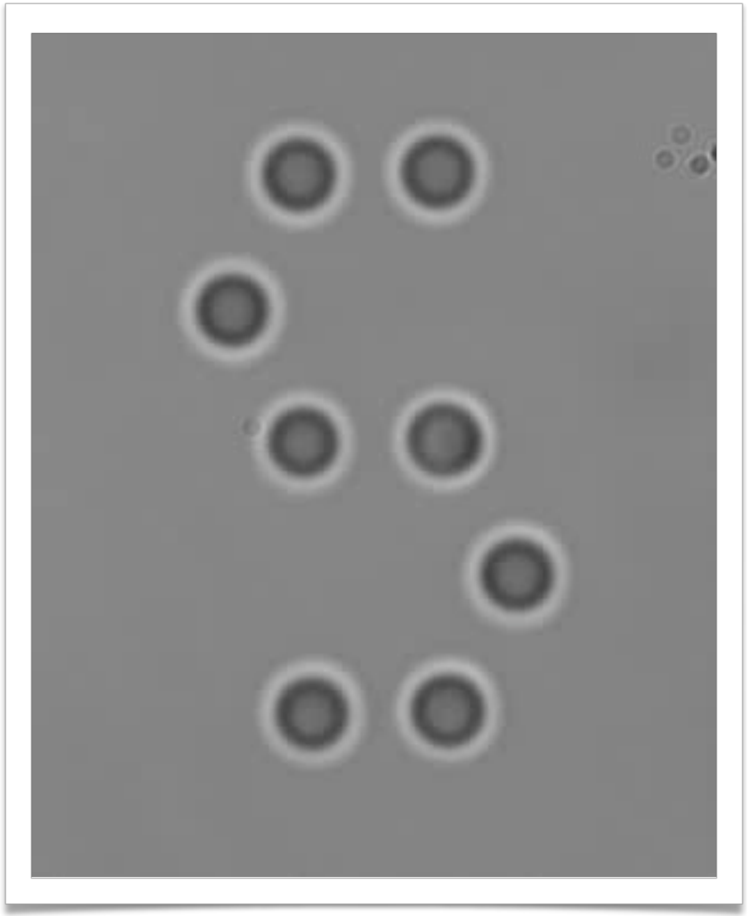
Holographic Optical Tweezers

Gabriel C. Spalding[1], *Johannes Courtial*[2], *and Roberto Di Leonardo*[3]

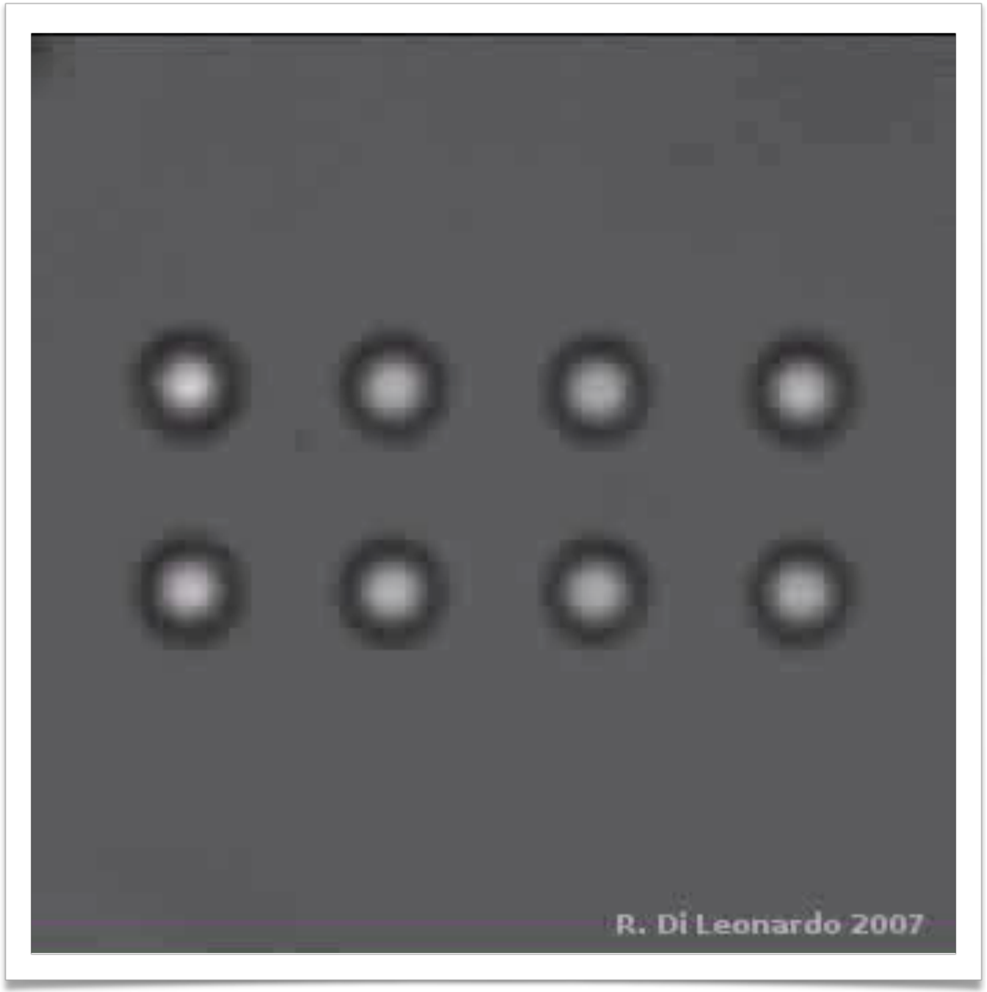
[1] *Illinois Wesleyan University, Bloomington, IL, USA*
[2] *University of Glasgow, United Kingdom*
[3] *Università di Roma, Italy*

Demo

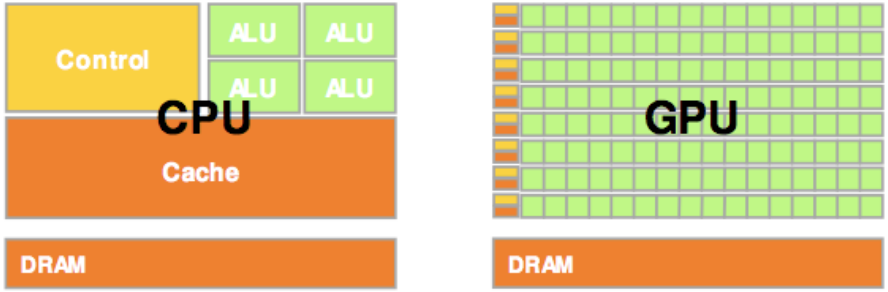
S-O-F-T ANIMATED LOGO

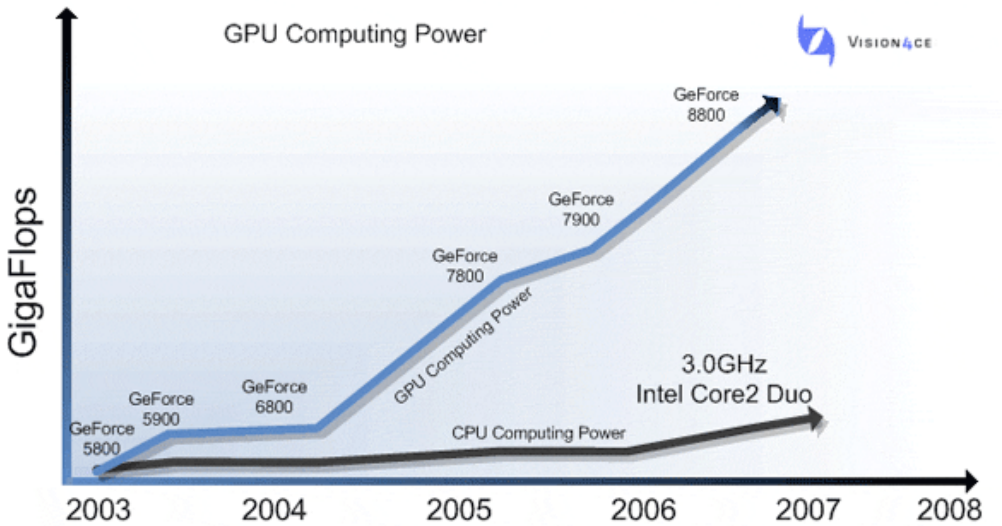


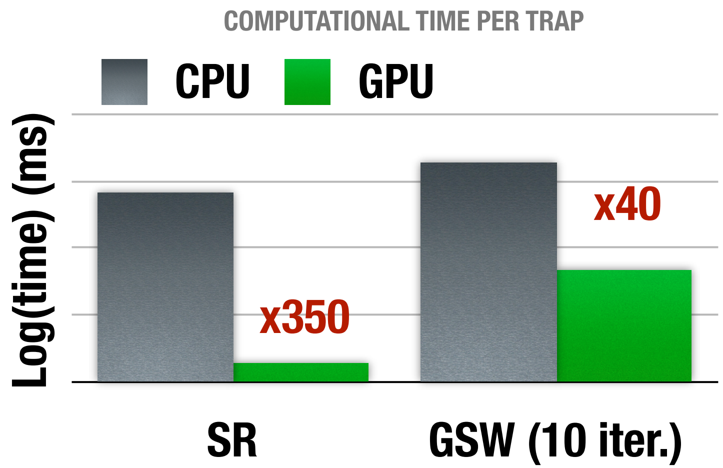
3D SPINNING CUBE



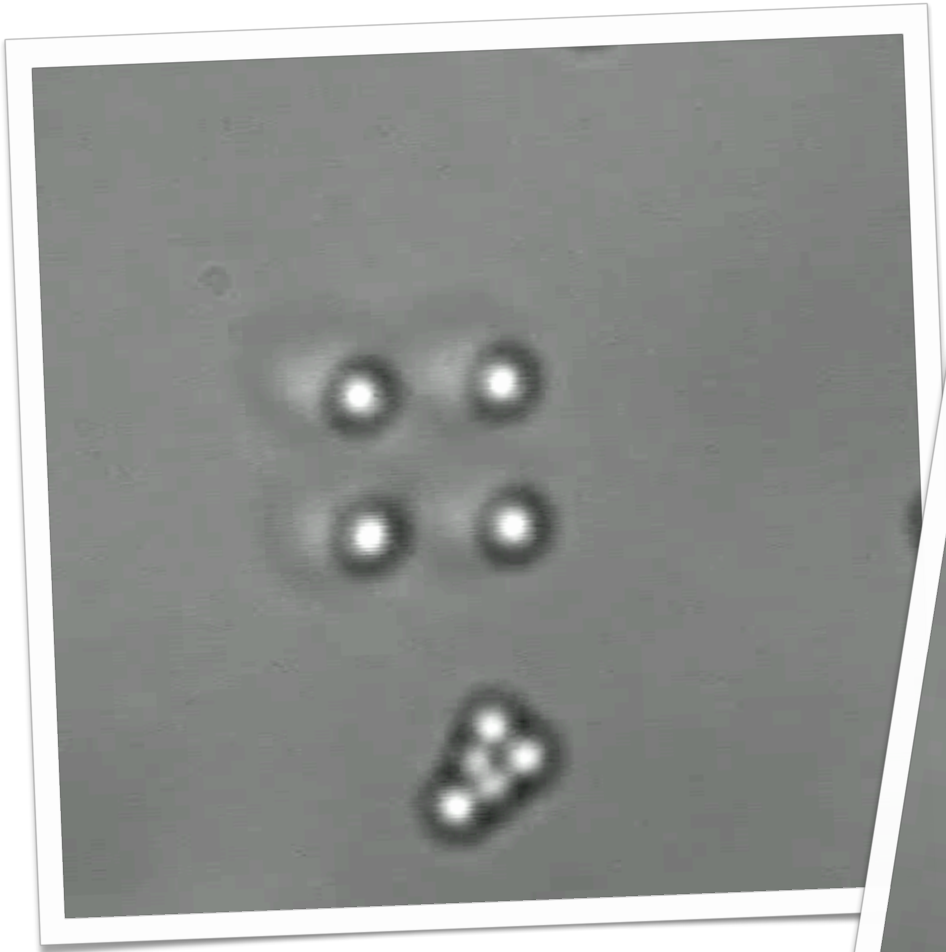
Interactive holographic trapping using GPU

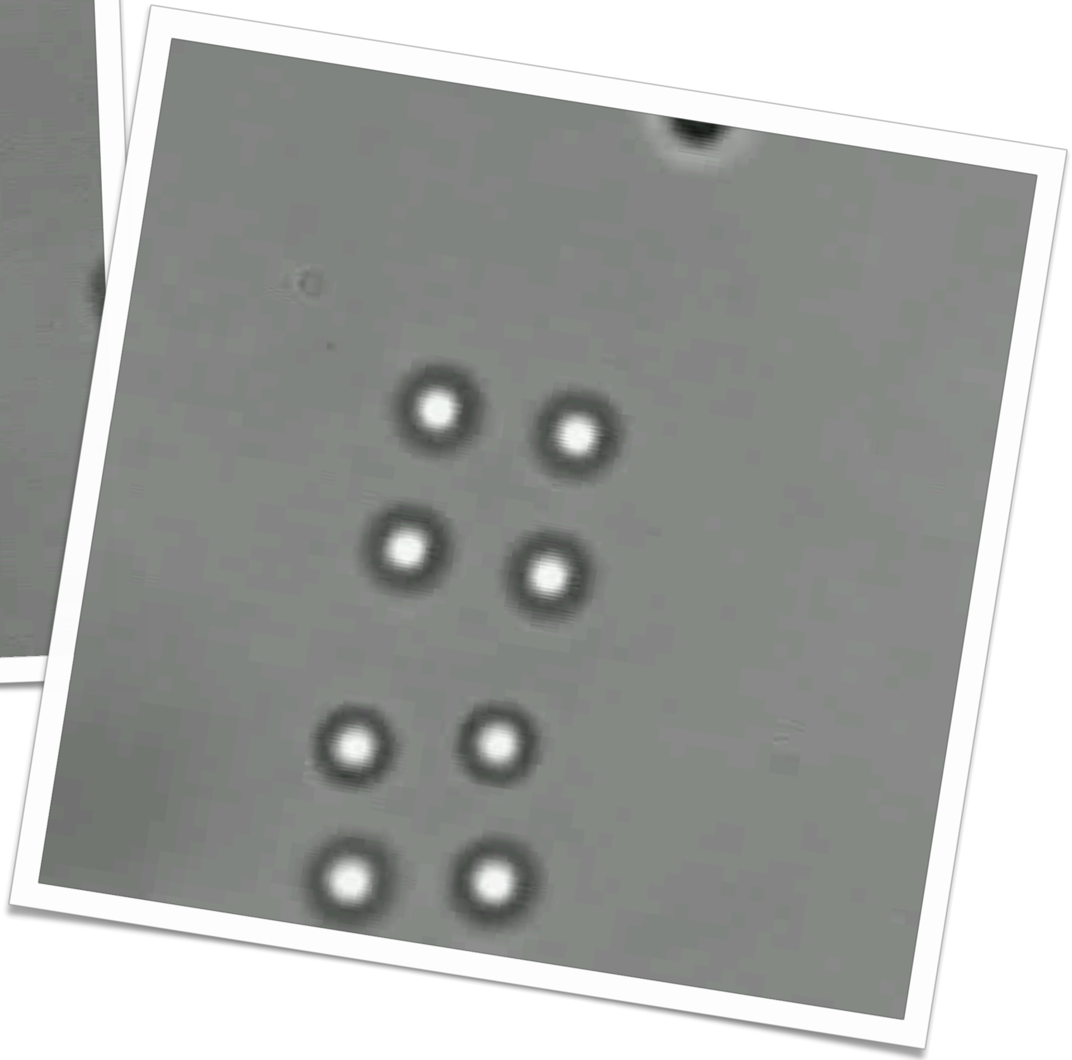






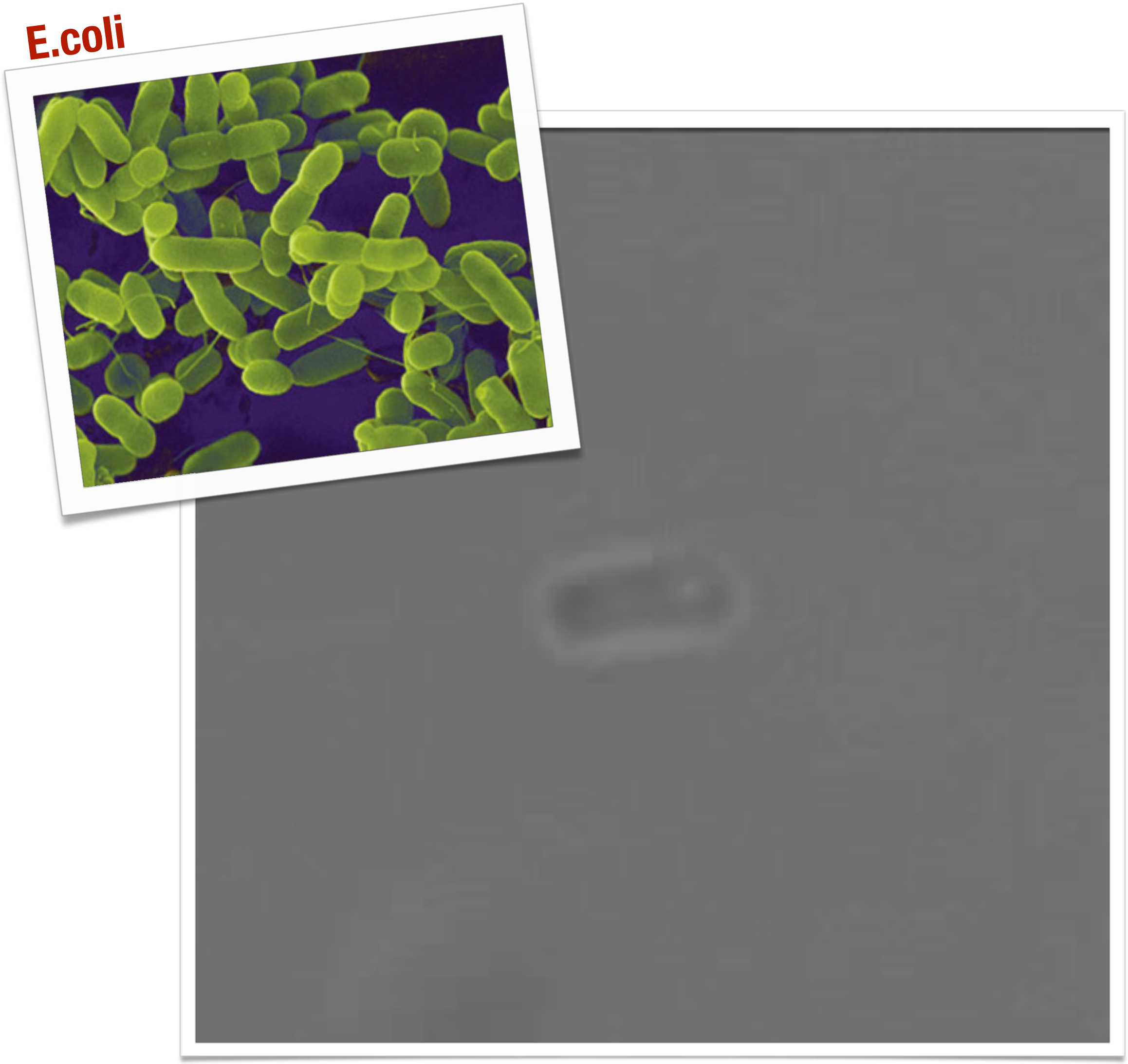
Interactive holographic trapping using GPU

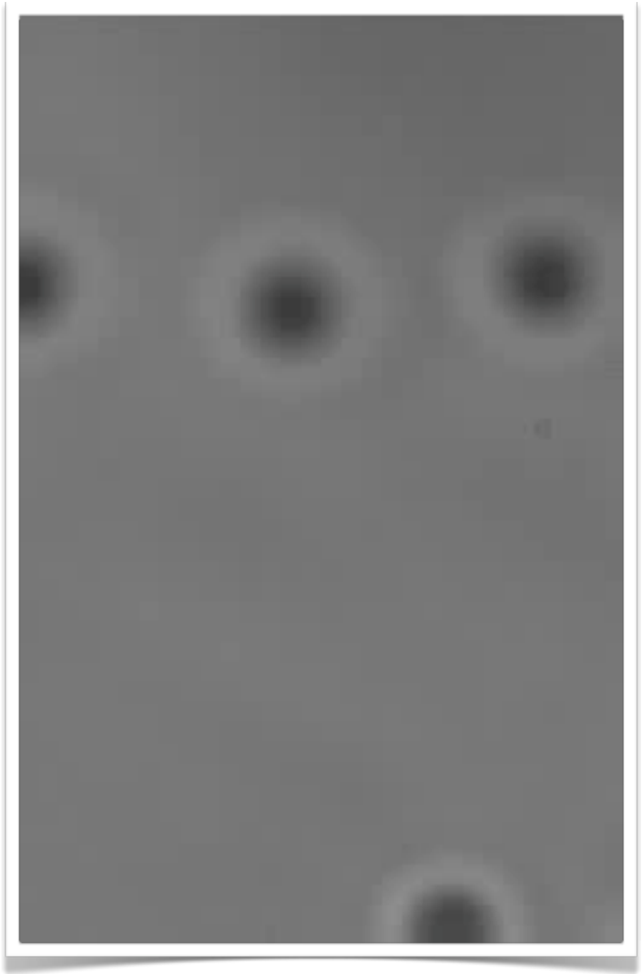




Full 3D manipulation of bacterial cells

E.coli

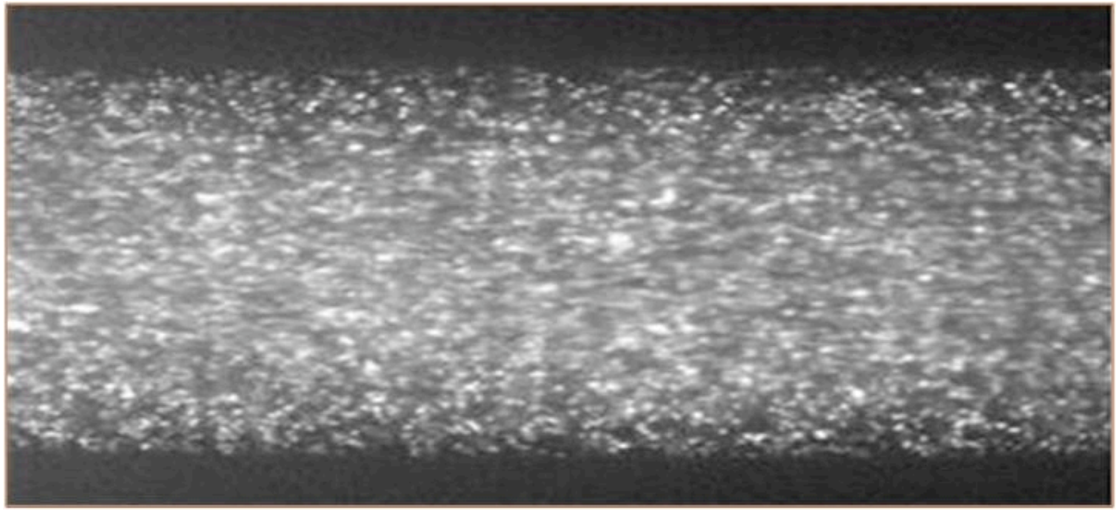




Optofluidics

light driven devices and sensors

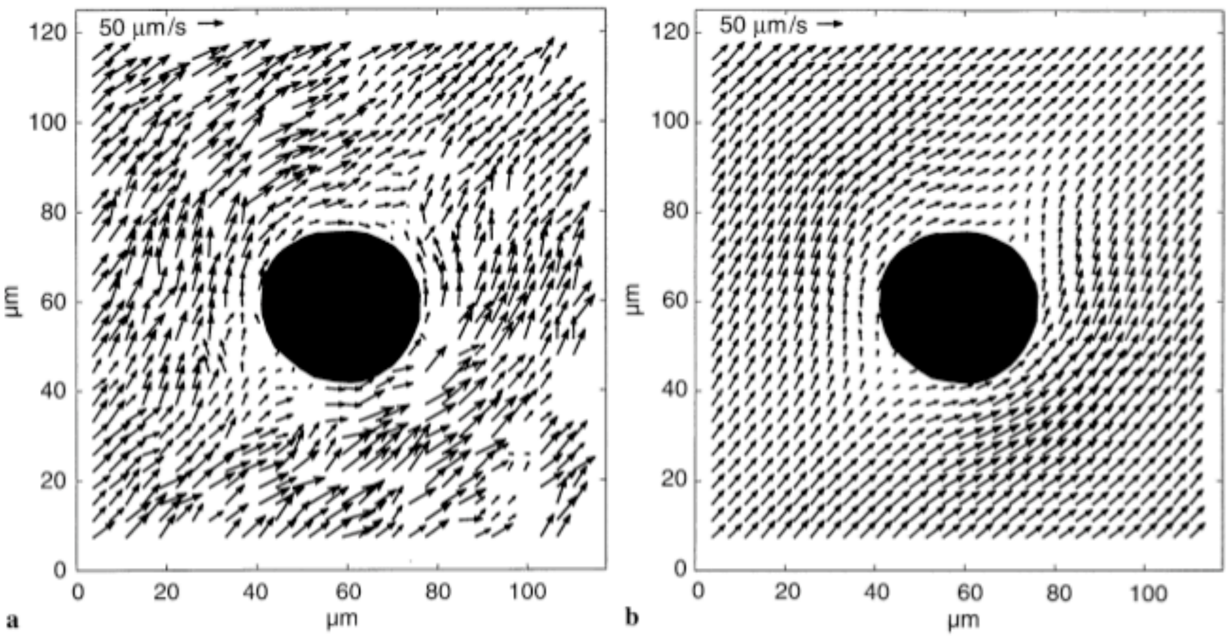
µPIV



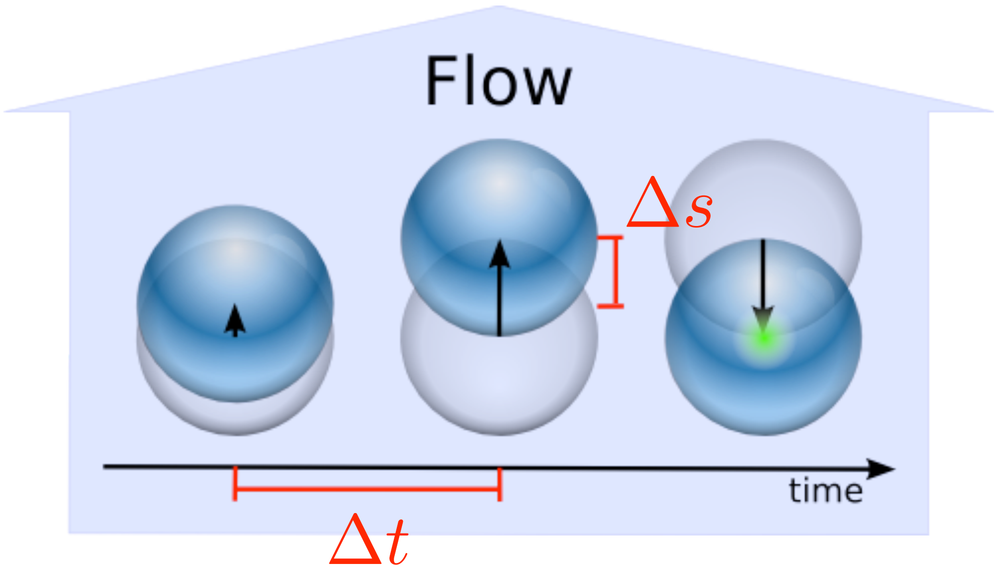
PARK ET AL. EXP. FLUIDS (2004)

µPIV:
track tracer particles

SANTIAGO et al. EXP. FLUIDS (1998)



Blinking tweezers in fluid flow

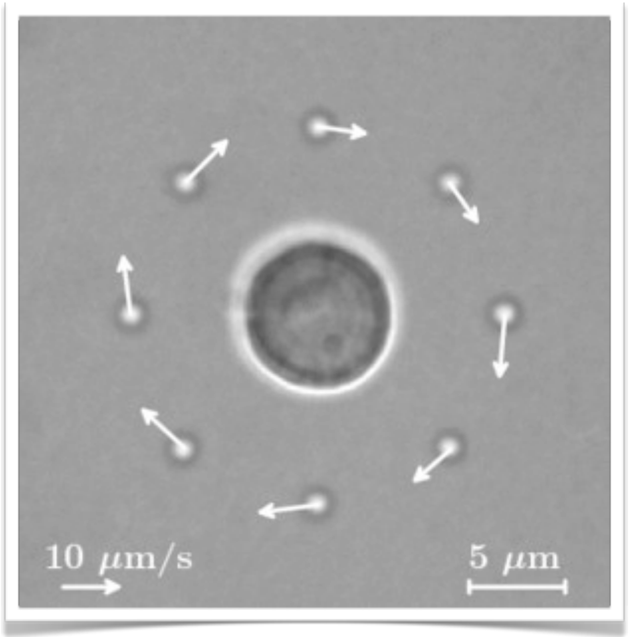


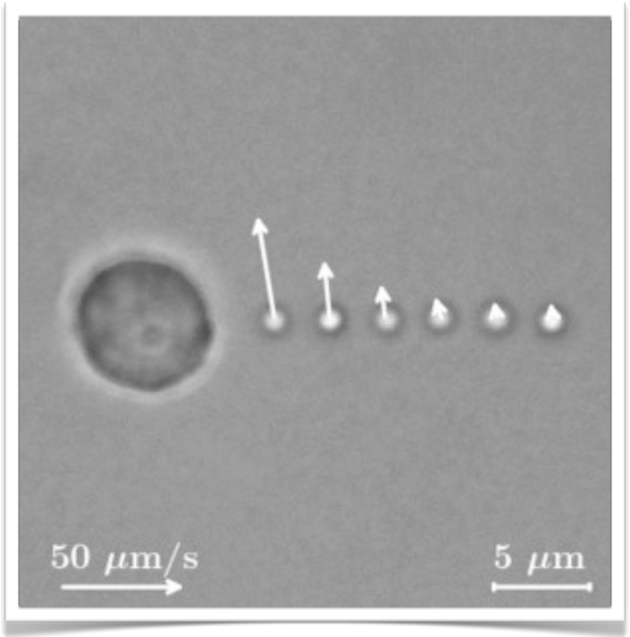
$$v = \frac{\Delta s}{\Delta t}$$ direct velocity measurement

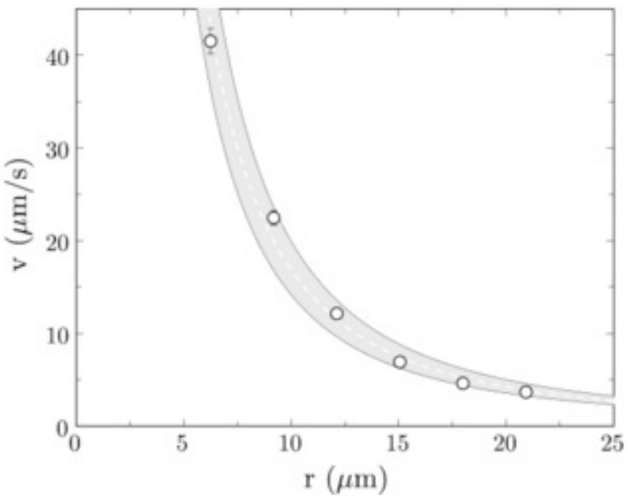
Holographic micro-velocimetry

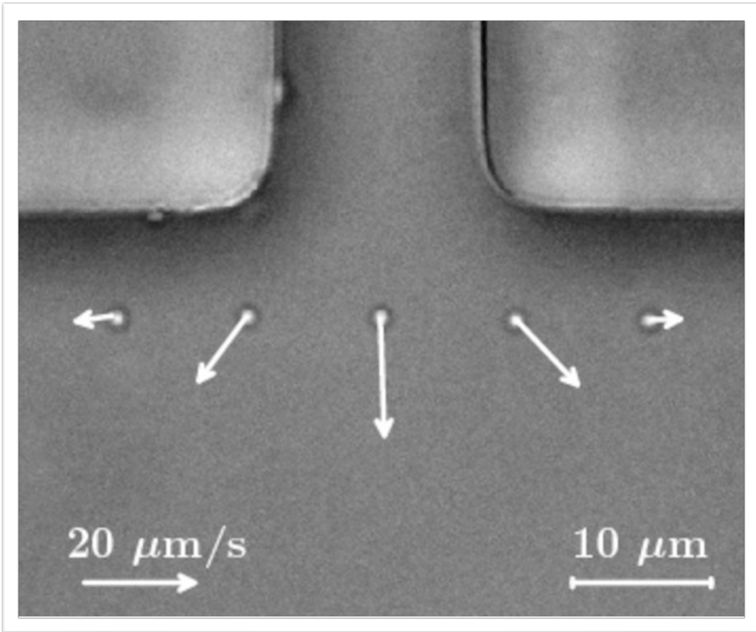
R. DI LEONARDO et al. PRL (2006)

nature RESEARCH HIGHLIGHTS





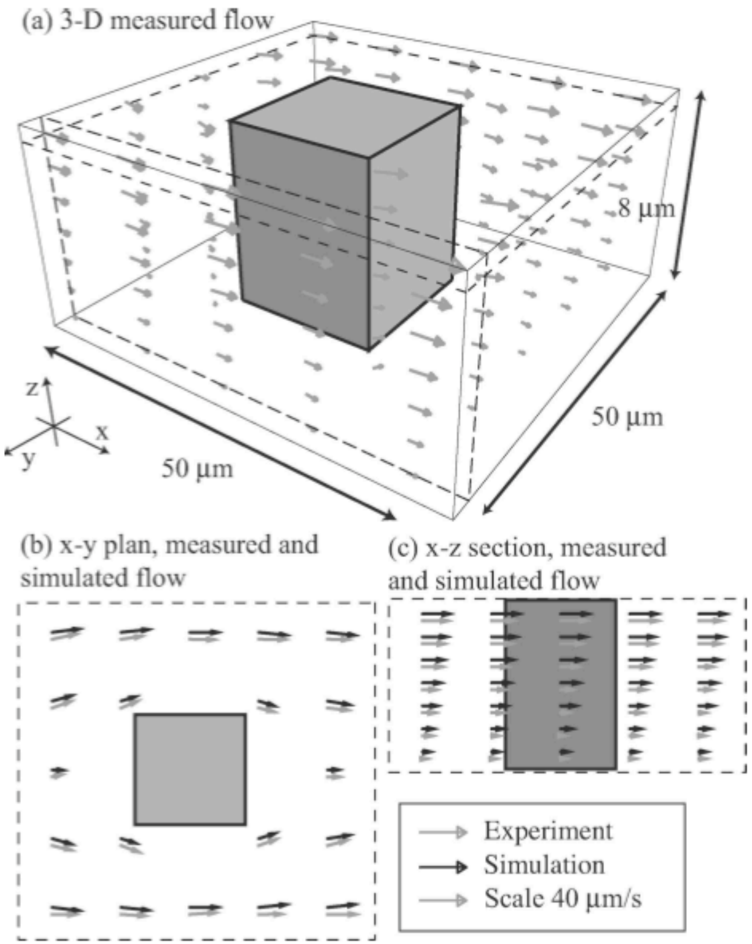




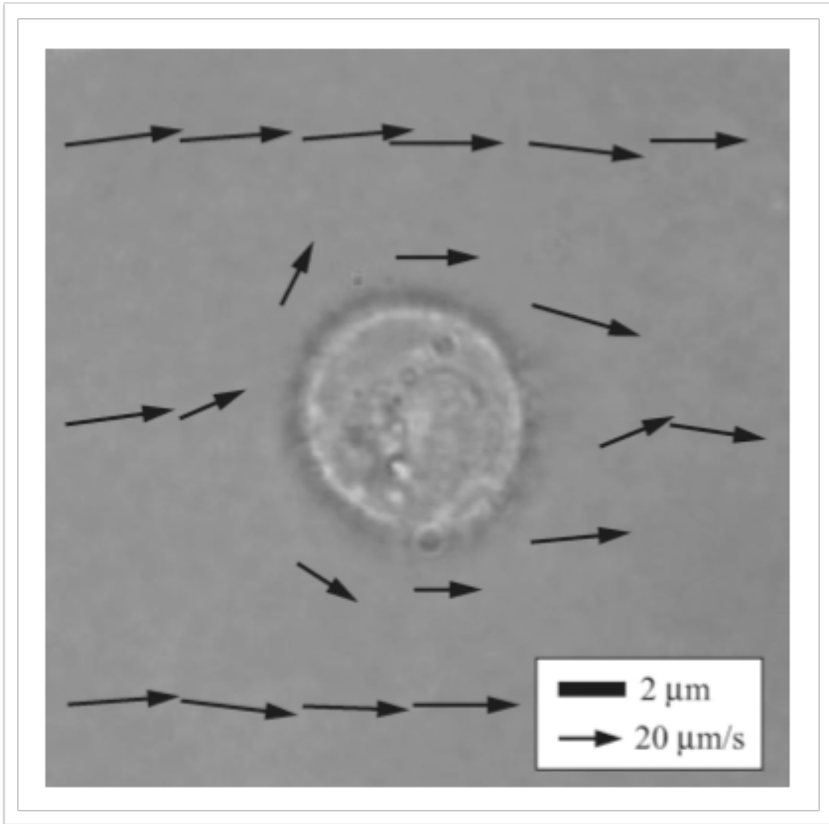
Holographic micro-velocimetry

H. MUSHFIQUE et al. ANAL. CHEM. (2008)

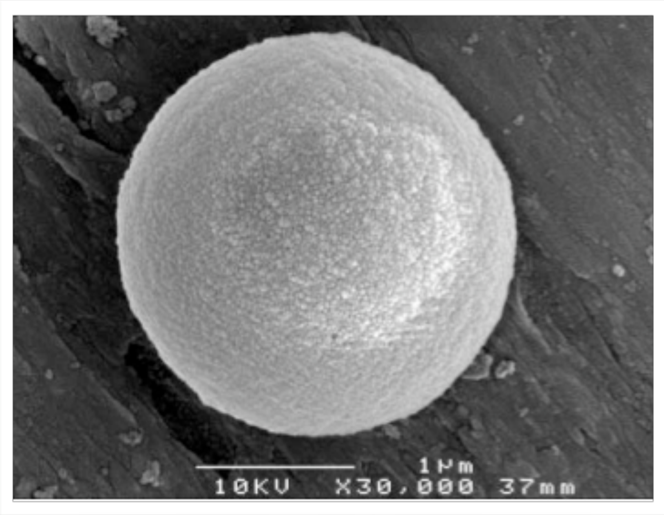
3D FLOW MAP AROUND A PDMS CUBOID



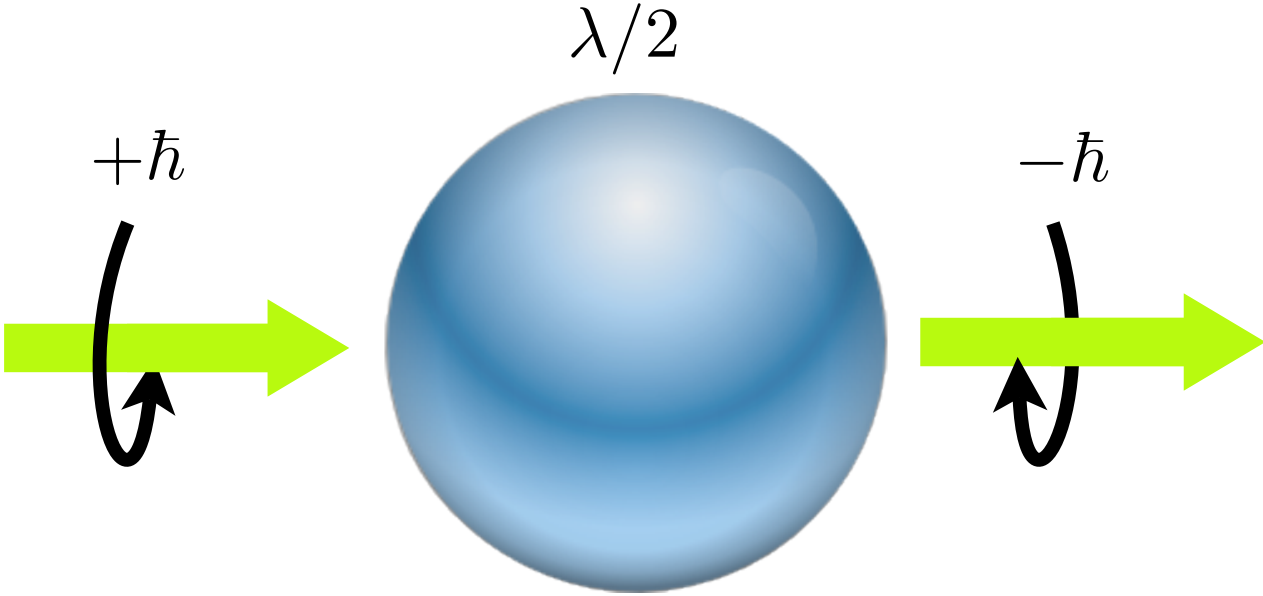
2D FLOW MAP AROUND A CHO CELL



VATERITE SPHERE (CaCO3)



H. RUBINSZTEIN-DUNLOP, AIP (2006)



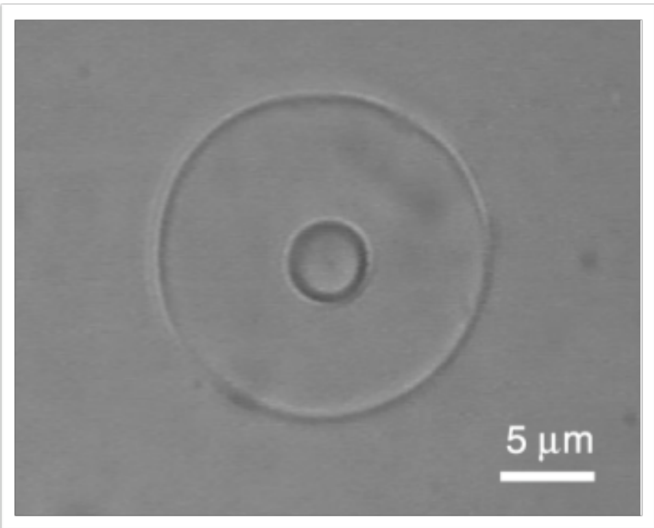
$$T = -\frac{dL}{dt} = 2\hbar\,\frac{P}{\hbar\omega} = \frac{1}{\pi}\,\frac{P}{c}\,\lambda \sim \text{pN}\;\mu\text{m}$$

MAX TORQUE

PHOTON FLUX

MICRON SIZED PARTICLE IN WATER

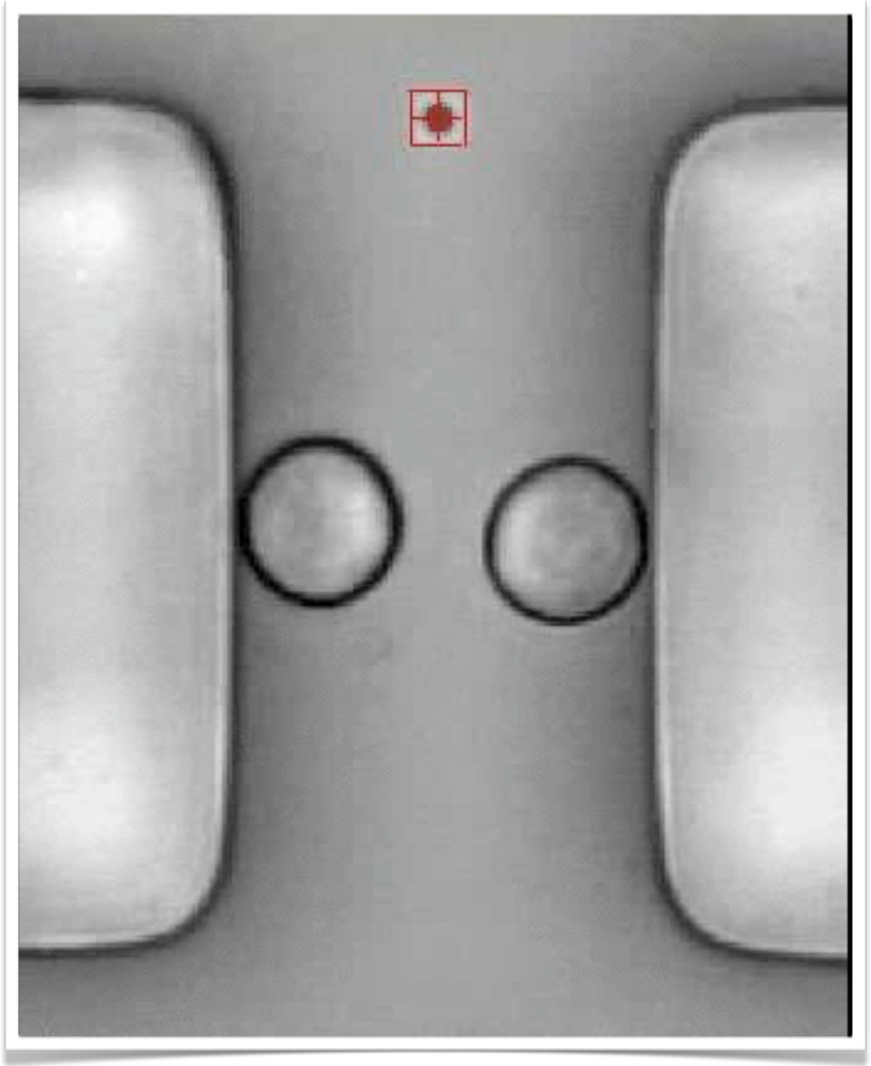
$$\Omega = \frac{T}{8\pi\eta a^3} \sim kHz$$



BISHOP et al. PRL (2004)

An optical driven pump

J LEACH, et al. LAB ON A CHIP (2006)



Summary

Phase only modulation is enough to efficiently split a laser beam into a 3D array of optical traps.

Optimized holograms can be generated by a PC at an high enough framerate to allow interactive micro-manipulation.

The ability to grab and move matter at the micron scale can be used to drive sensors and devices for microfluidics