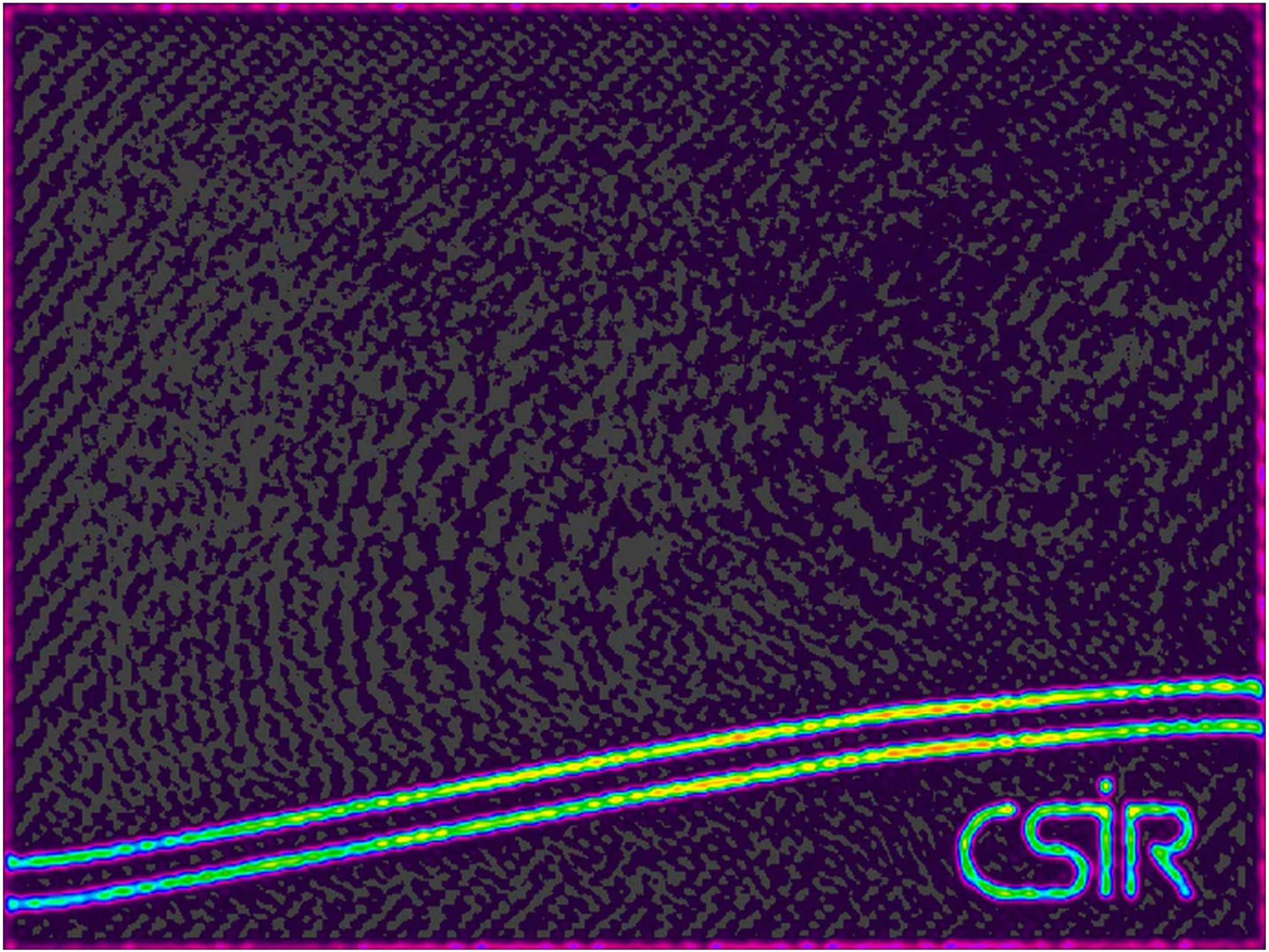
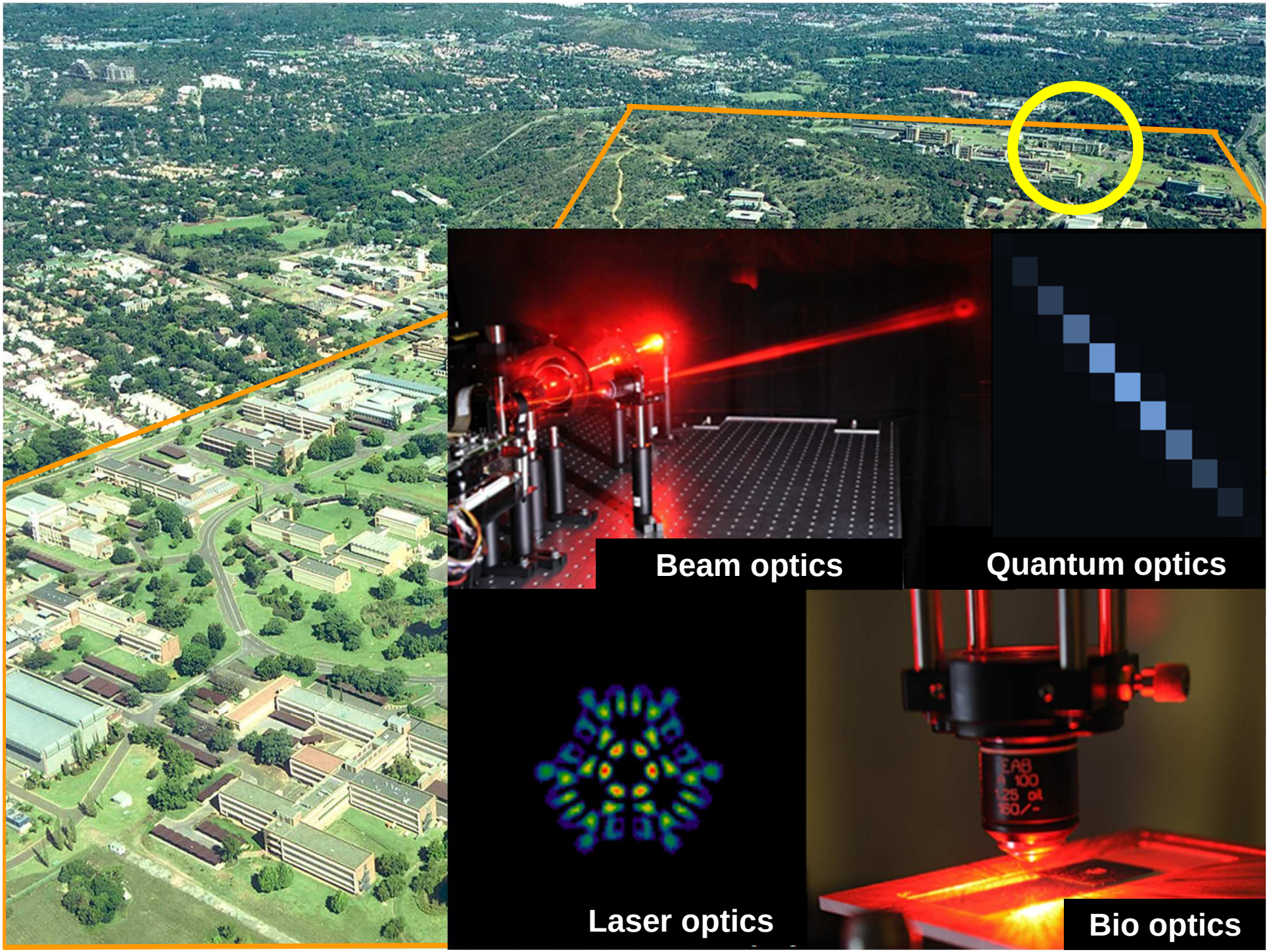
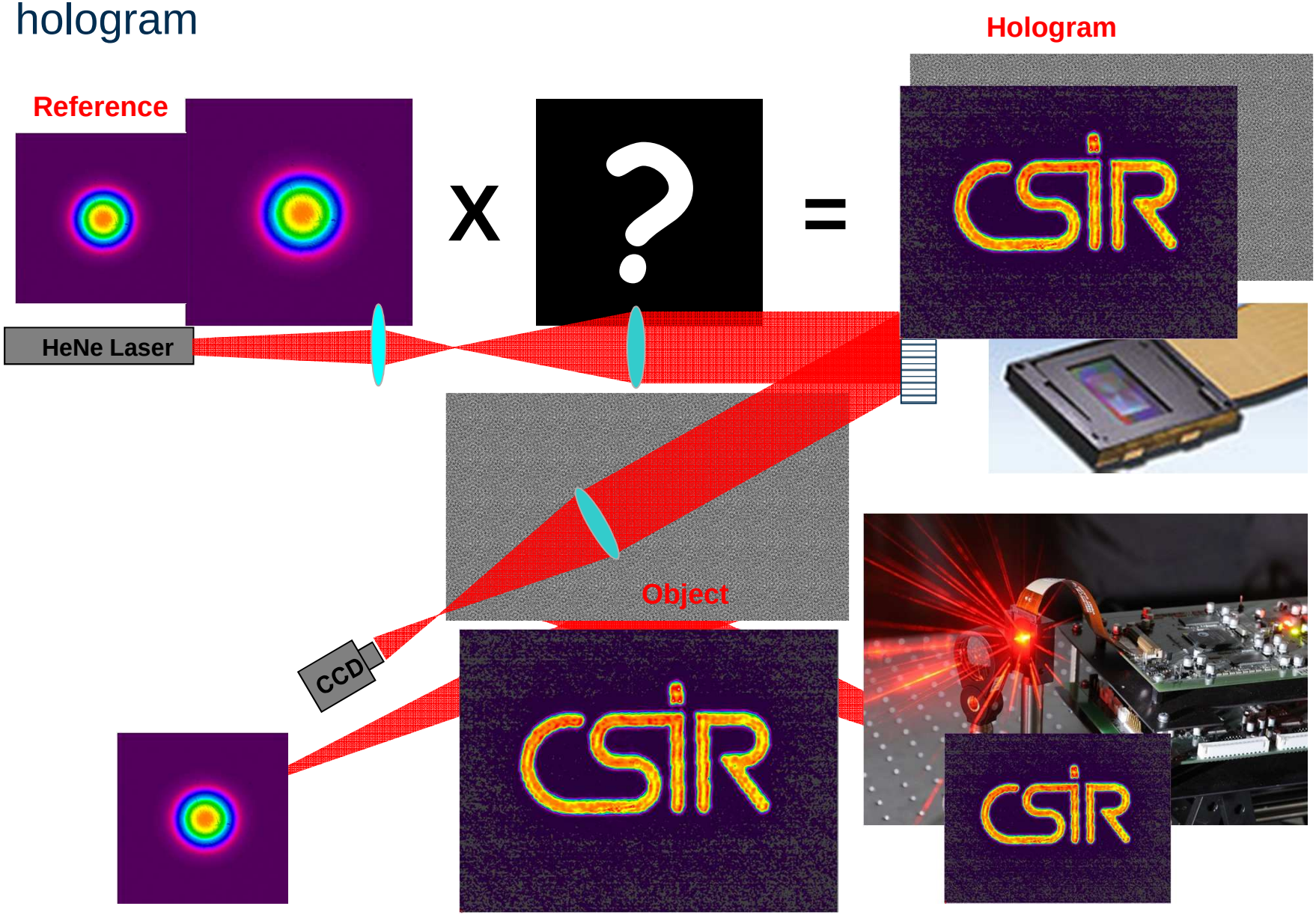
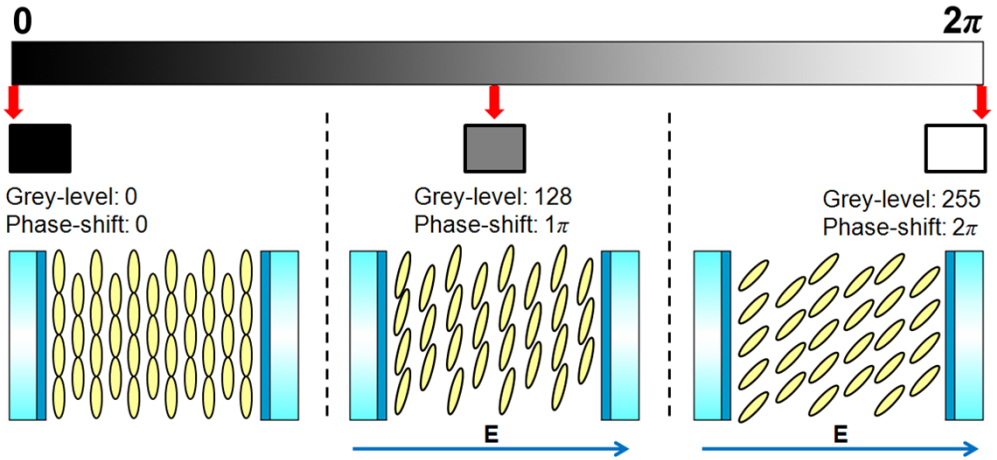

CSIR

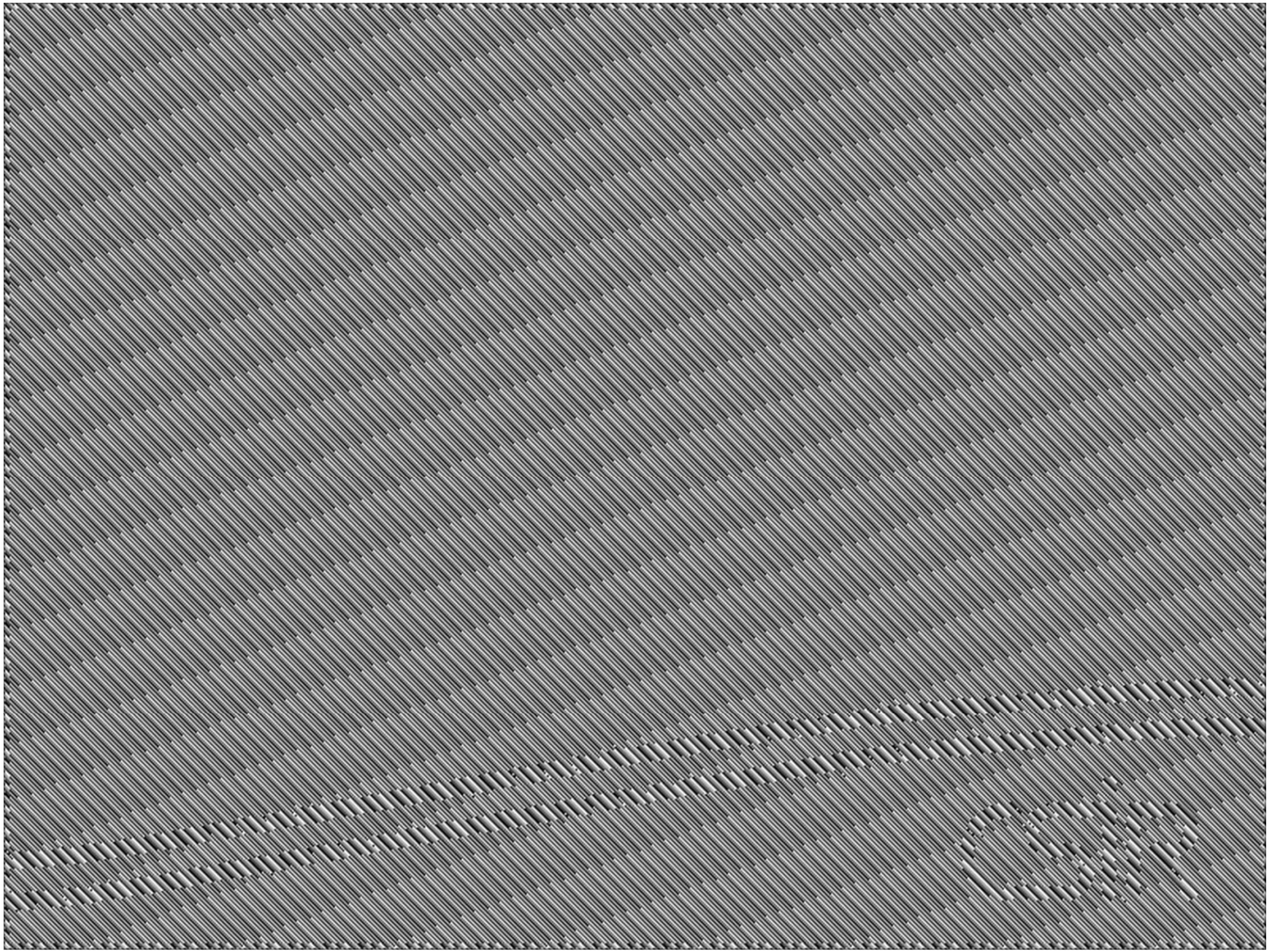

Beam optics
Quantum optics
Laser optics
Bio optics

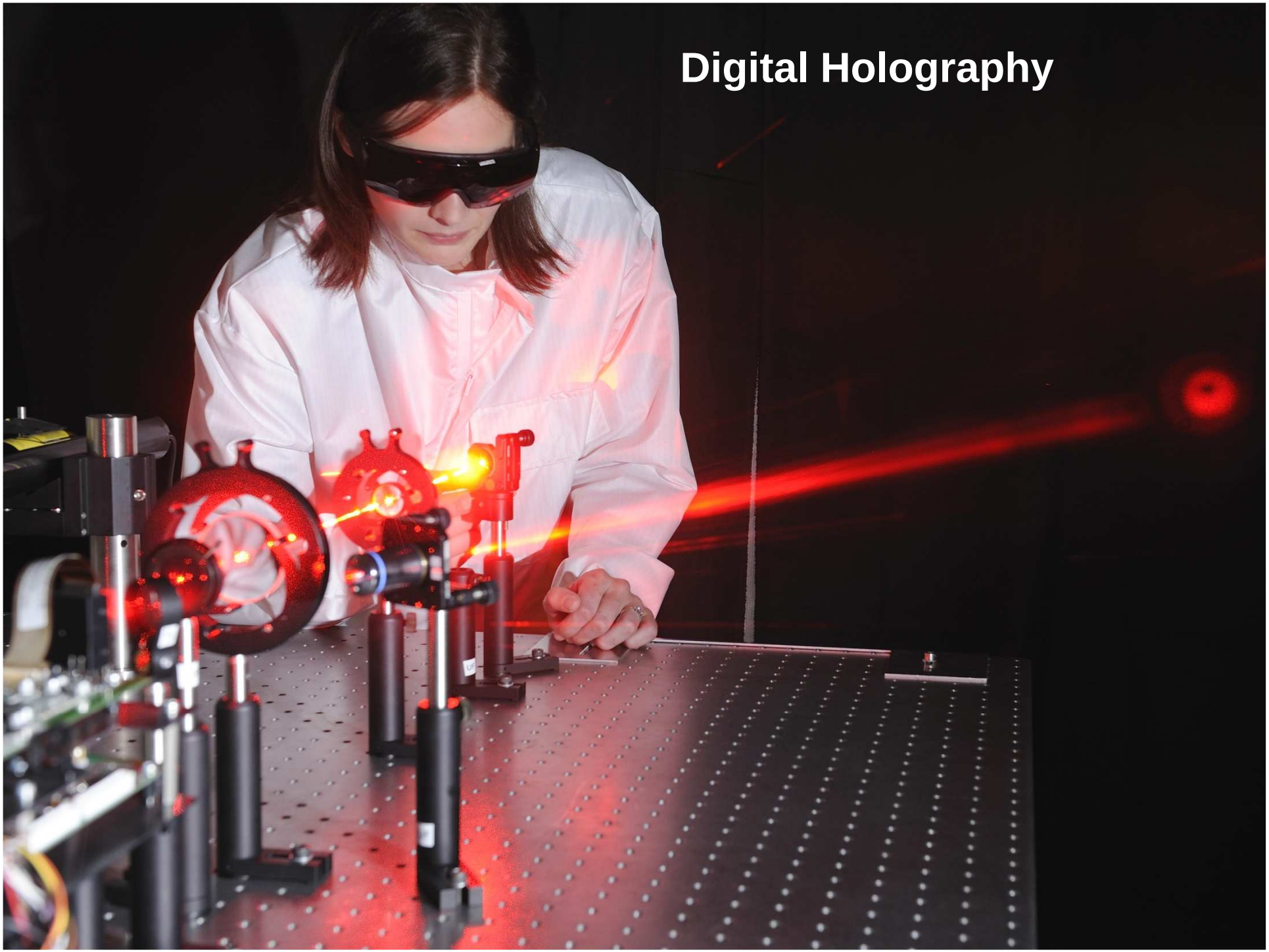
The idea in “digital holography” is to digitally create the desired hologram



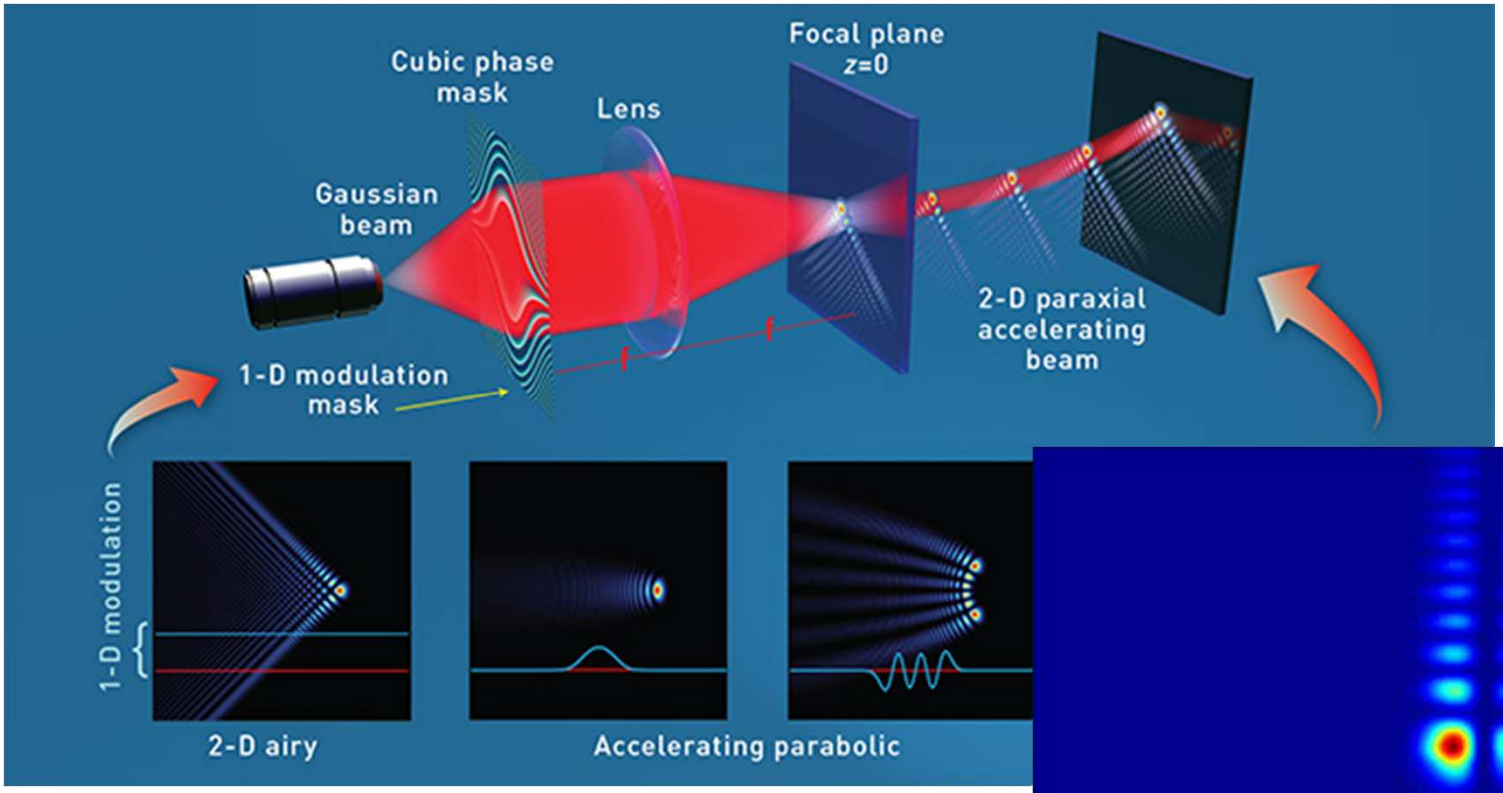
We use Liquid Crystal Displays as our devices to display these holograms: Spatial Light Modulators

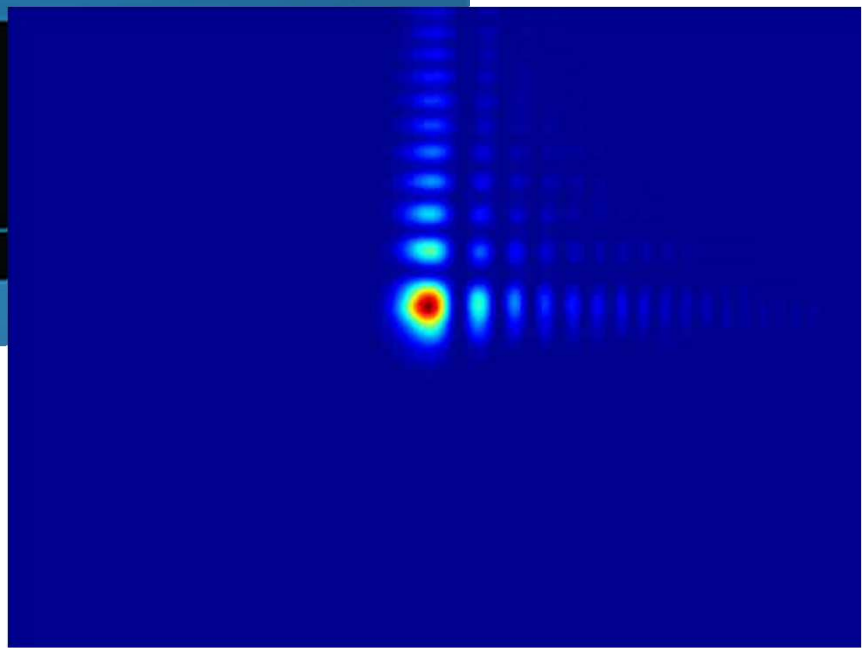





Digital Holography

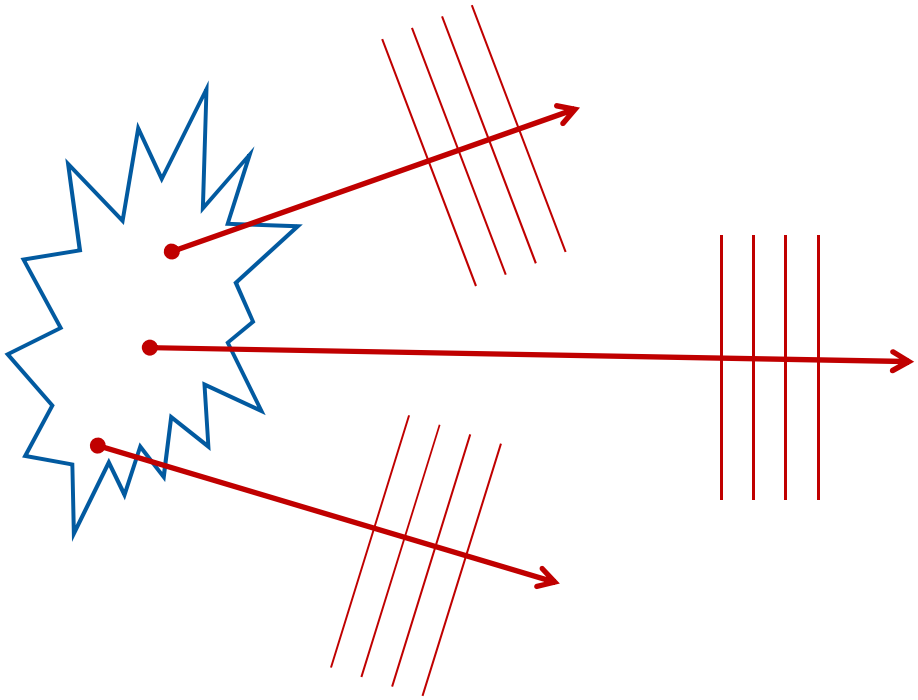
What we want to do is “break the rules” of optics, which can be done if we consider specific features of optical fields

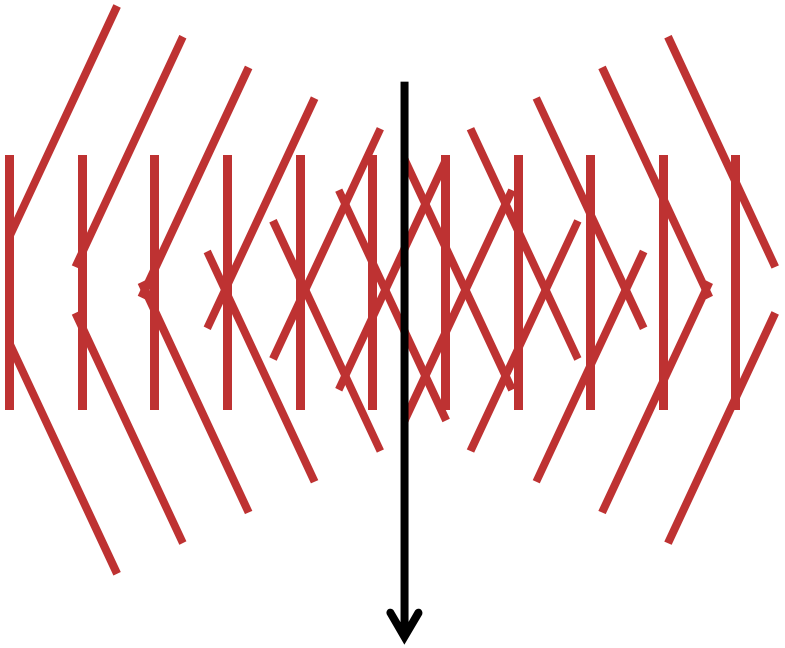




Courtesy: Optics and Photonics News
Phys. Rev. Lett. ***99****, 213901 (2007)*

We will create *non-diffracting* and *angular accelerating* beams

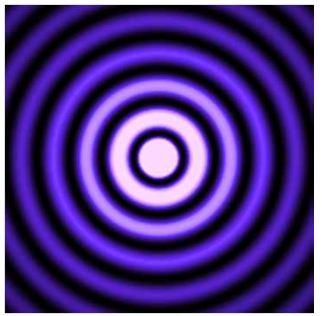




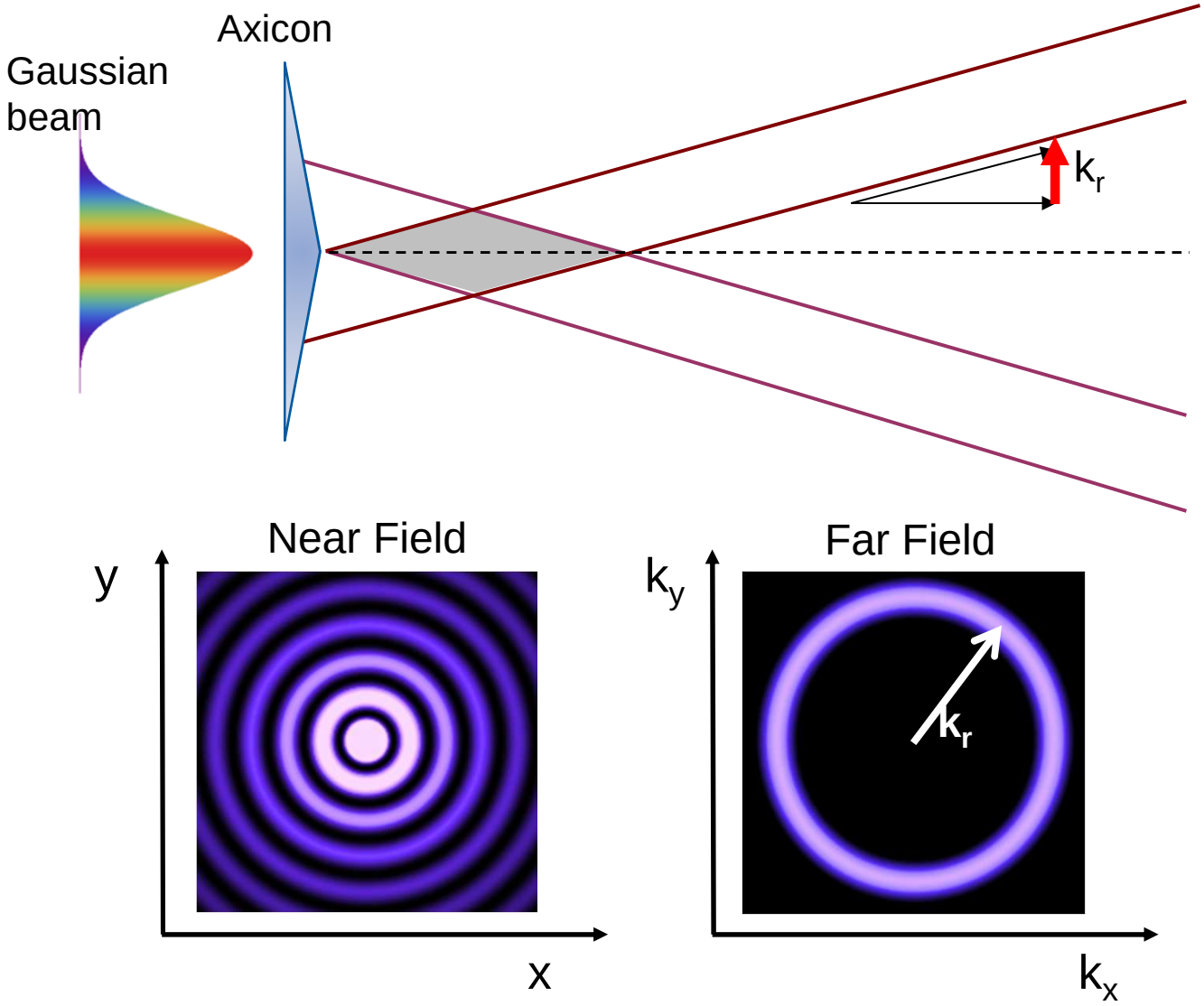
Plane waves

$$U(x,y) = \iint A(u,v)\,\exp(i2\pi(ux+vy))\,dudv$$

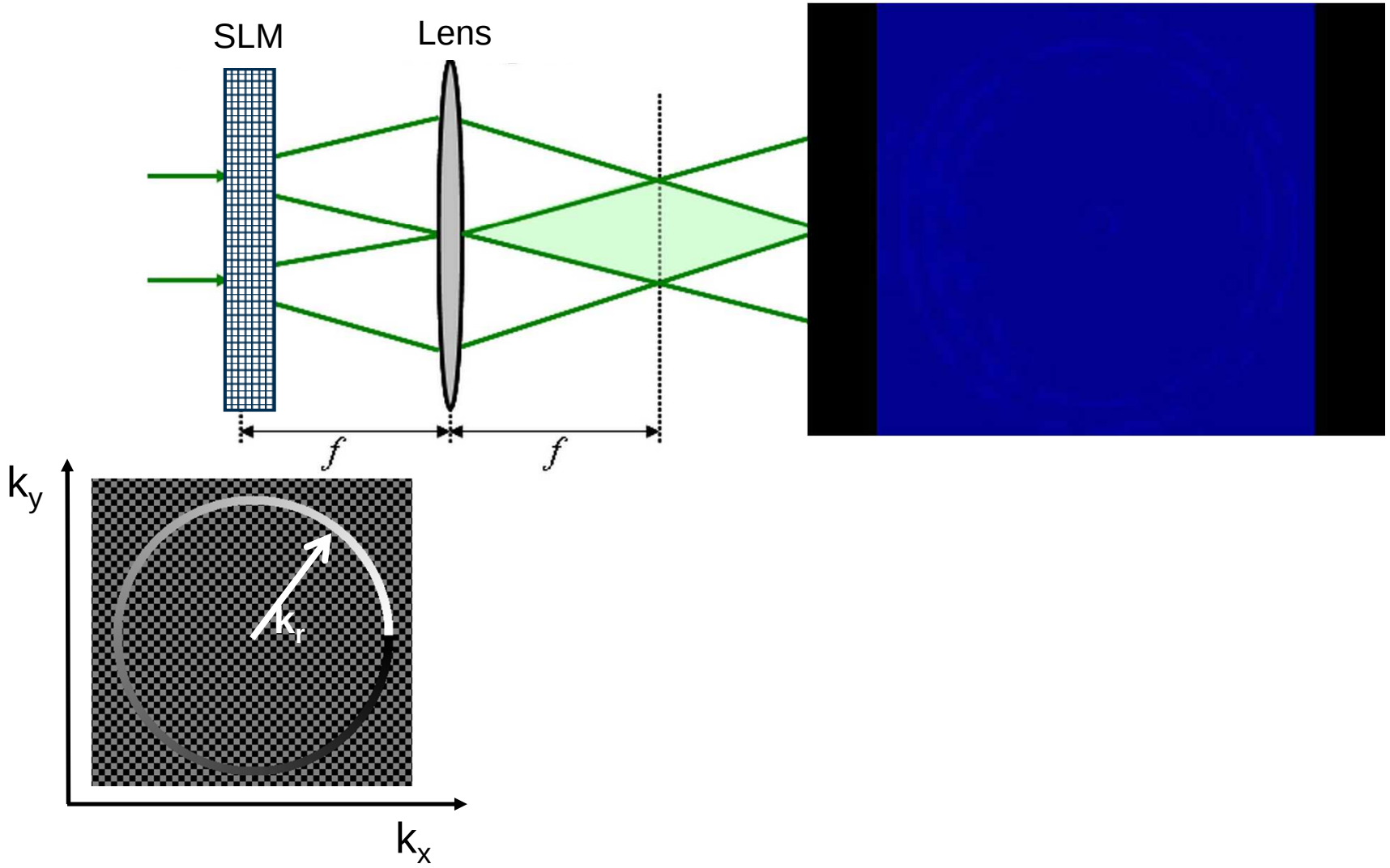
Angular Spectrum
of U(x,y)



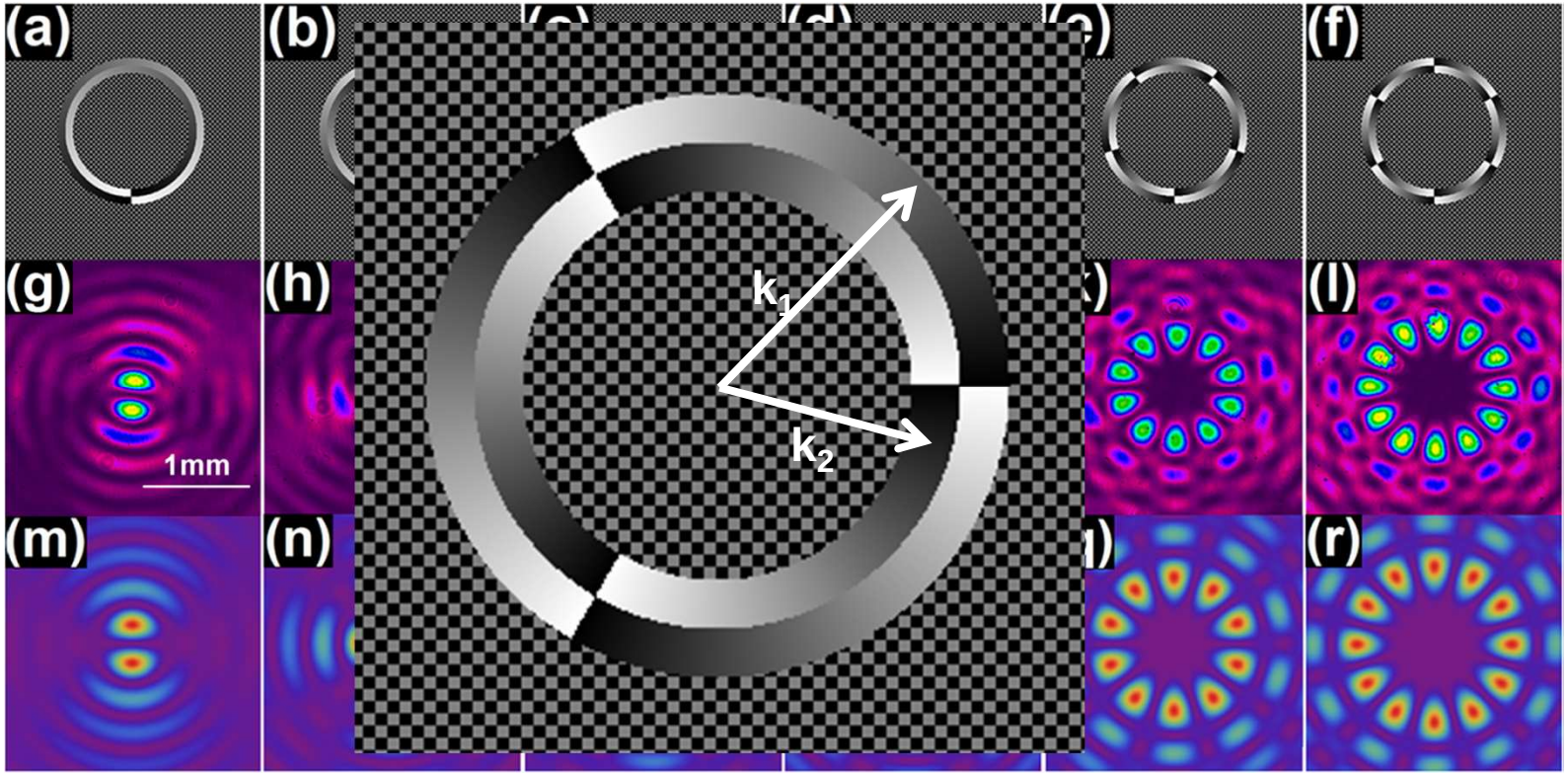
Consider illuminating an axicon with a Gaussian beam



We can place our hologram in the “spatial-frequency” plane to replicate the angular spectrum



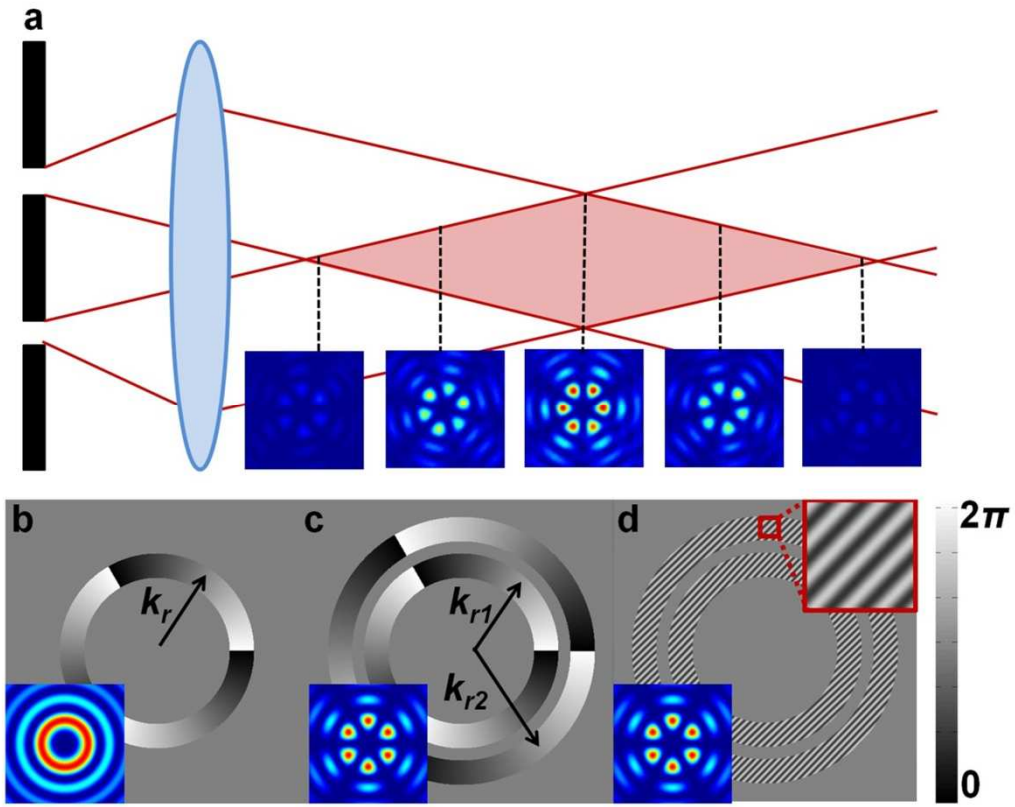
By creating beams with differing phase velocities, the interference pattern changes with propagation distance

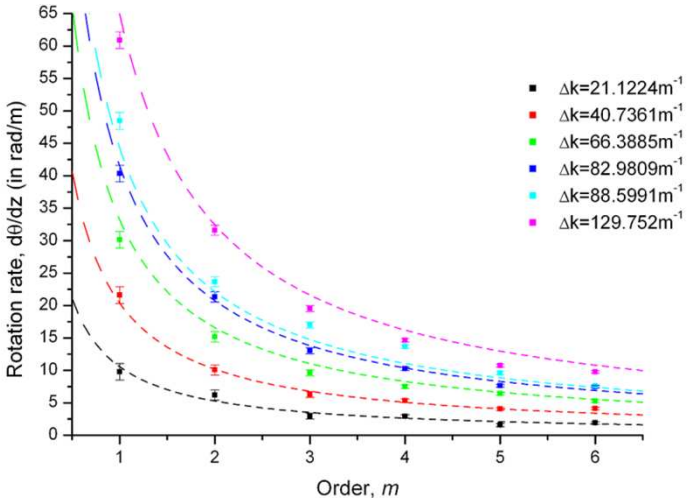


$$H \equiv B_1 e^{ik_{1z}z} e^{-im\varphi} + B_2 e^{ik_{2z}z} e^{im\varphi}$$

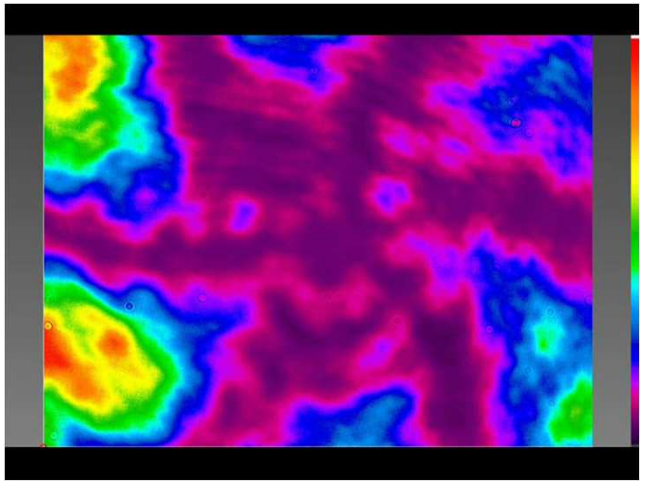
$$I \propto B[1 + \cos(\Delta k z - 2m\varphi)]$$

We can make the pattern rotate during propagation





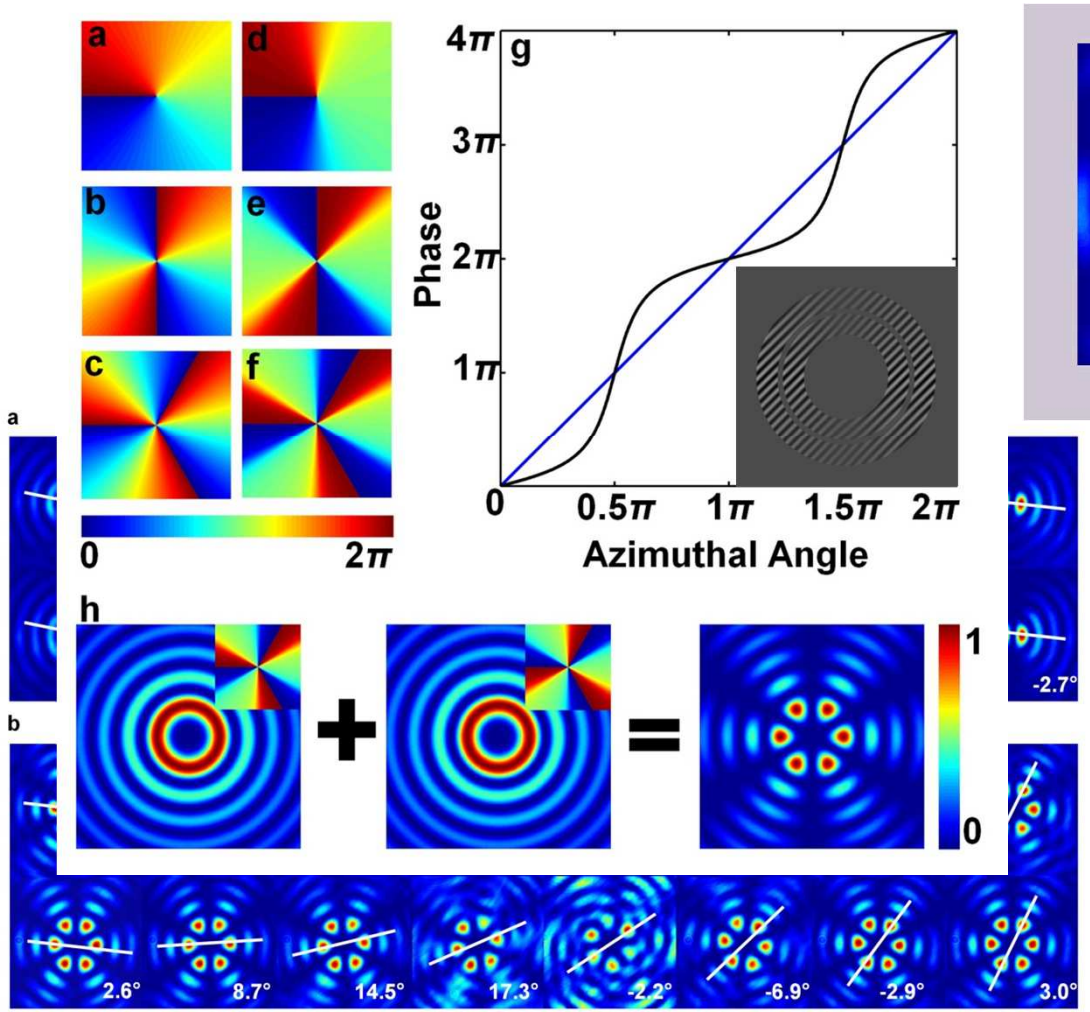
J. Mod. Optics **59**, 259 (2012)
J. Optics **14**, 035702 (2012)

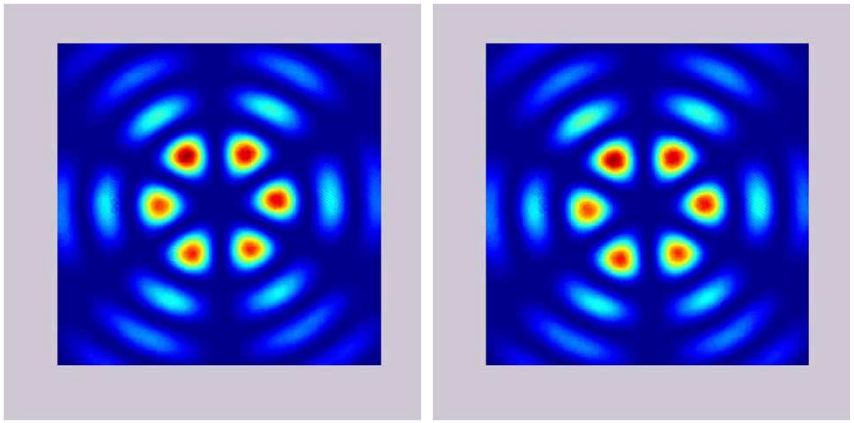


Optics Letters **38**, 3895 (2013)
JOSA A **29**, 567 (2012)

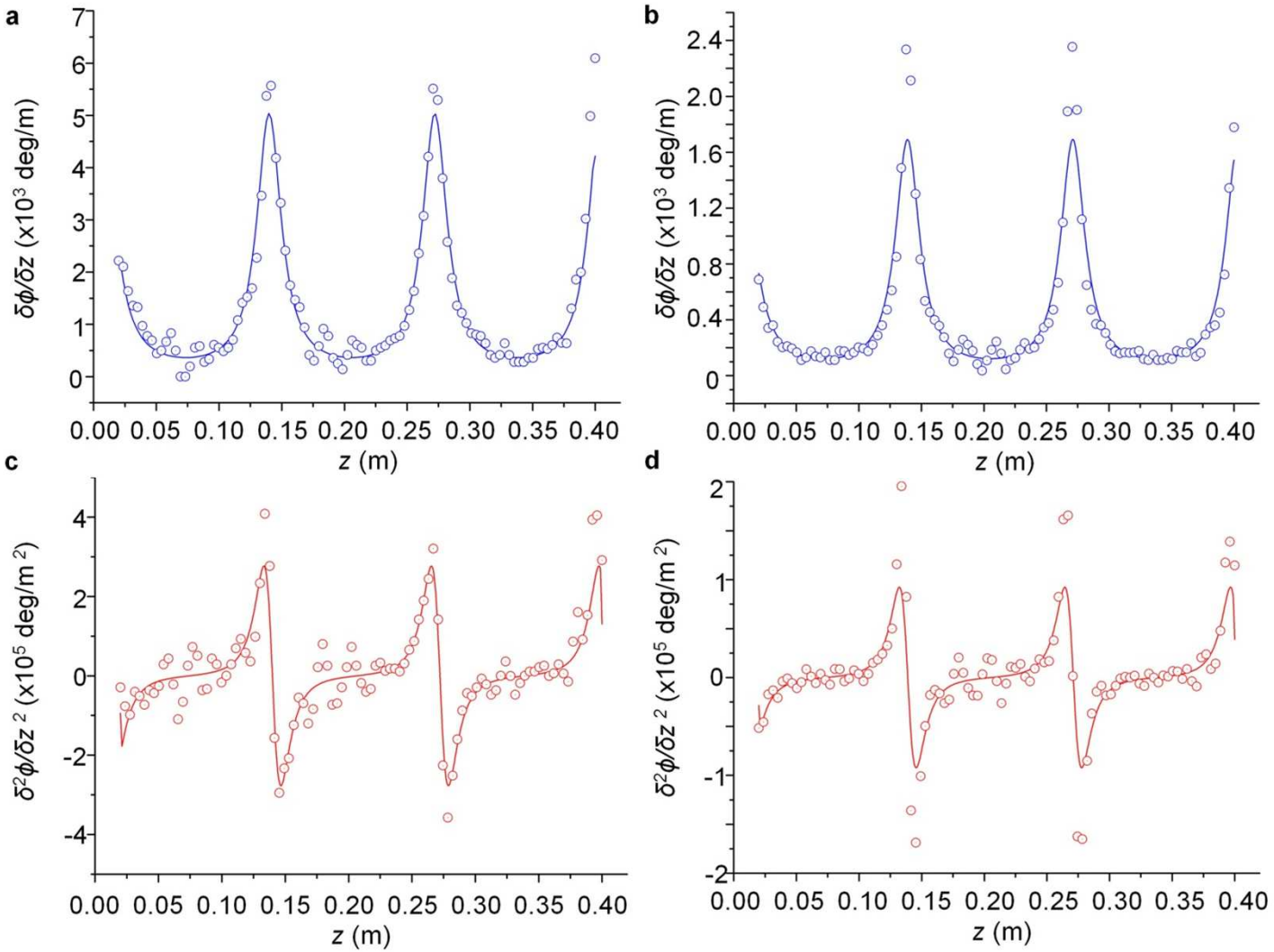
Now let’s create a non-linear variation in the azimuthal phase

... for angular acceleration with twisted light



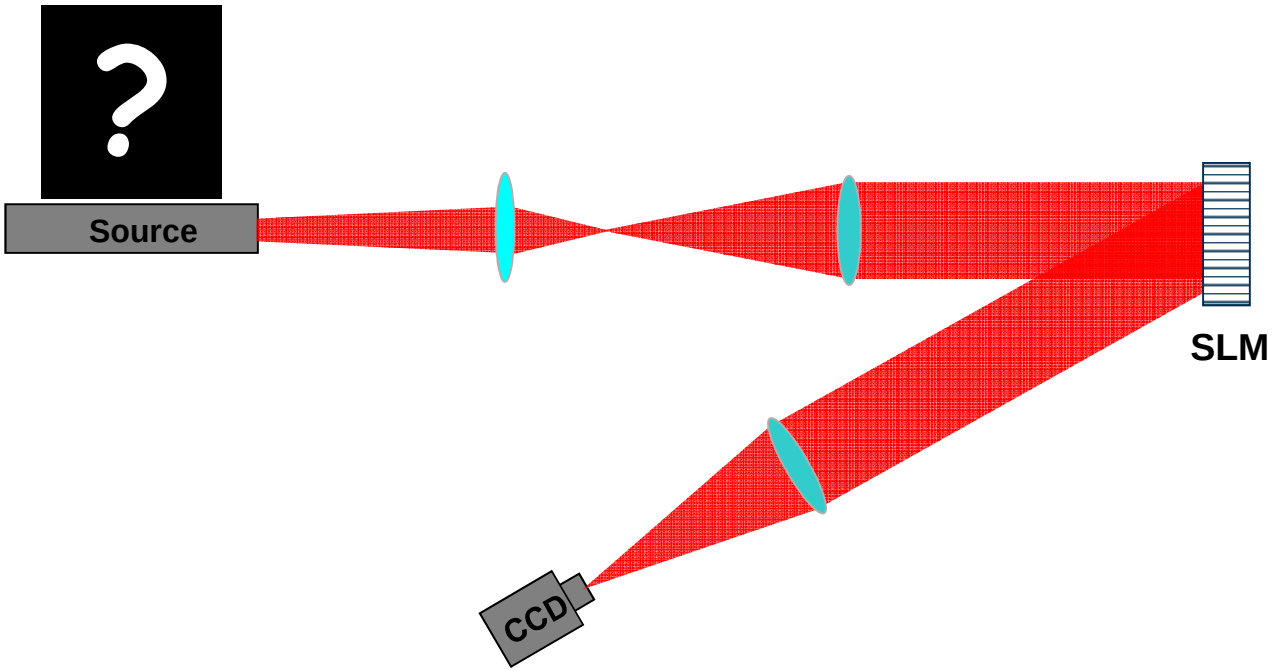


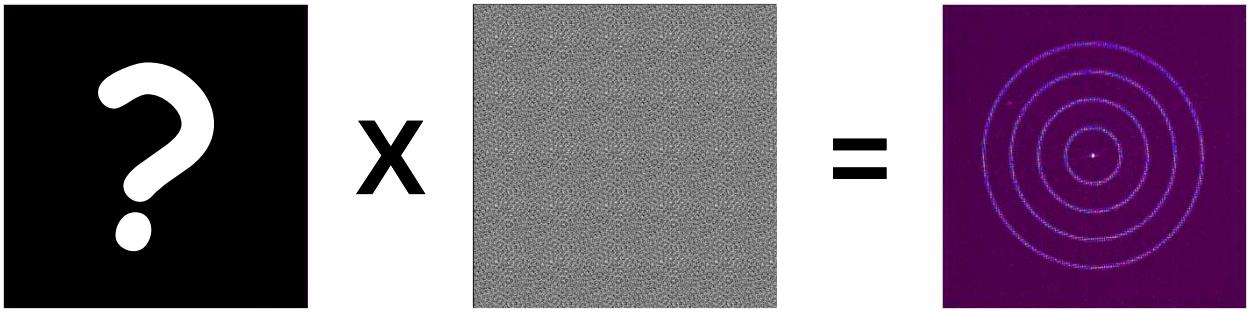
We can demonstrate the angular acceleration of light



arXiv:1405.6547 (2014)

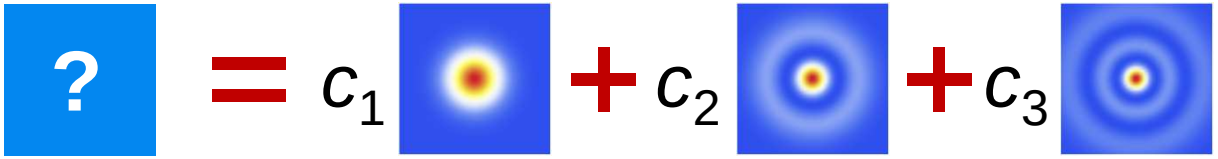
Can we use the SLM as a digital tool for the analysis of optical fields and single photons?

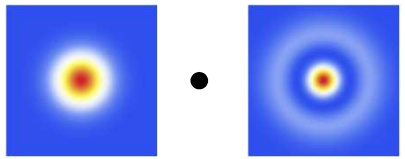


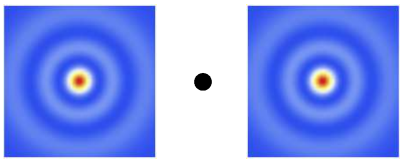


The idea is to expand the unknown field into an orthonormal basis and find the unknown coefficients

$$U = \sum_{n=0}^{\infty} c_n \Psi_n$$





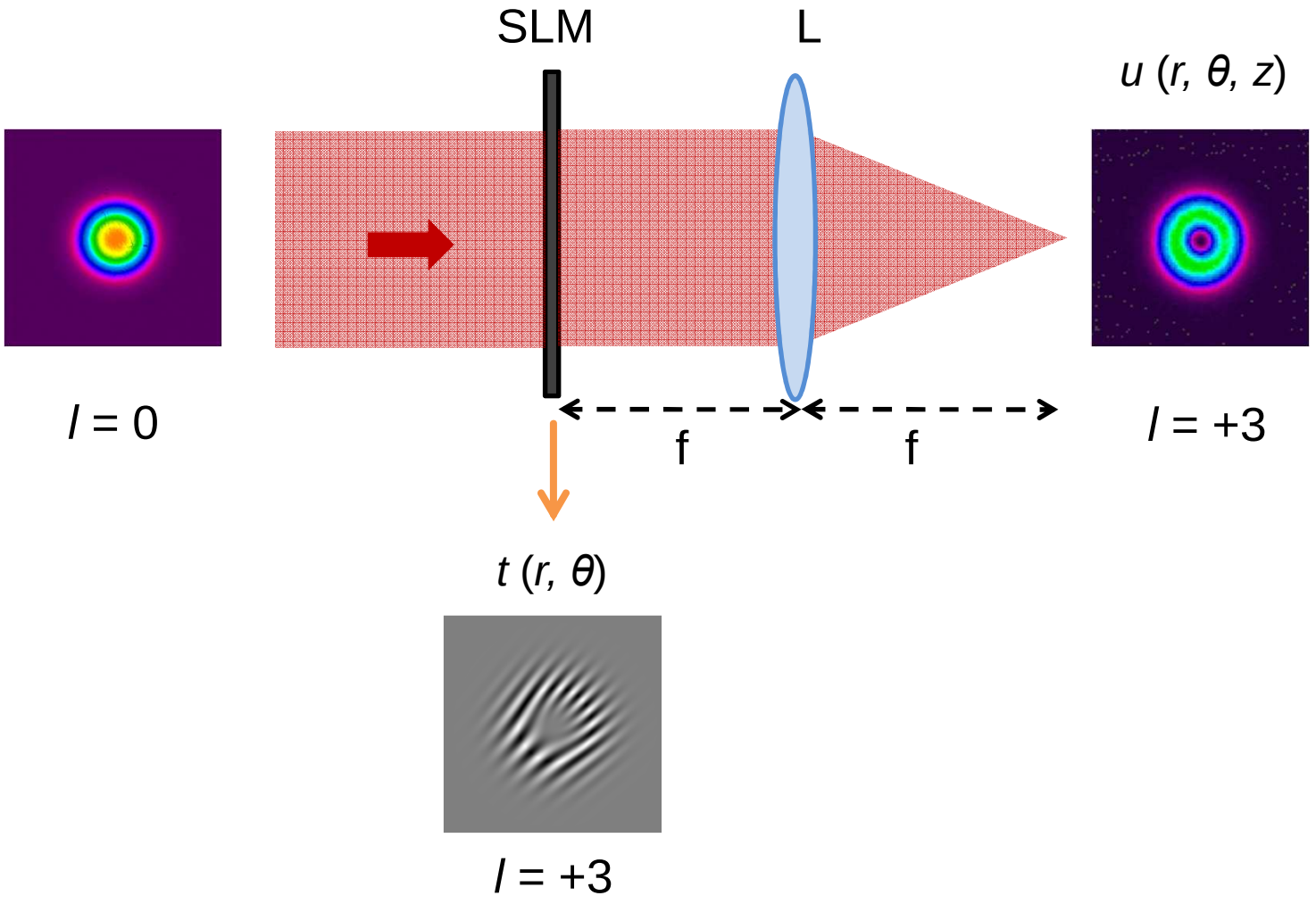


$$c_n = \rho_n \exp(i\phi_n) = \langle U, \Psi_n \rangle = \int\int U \Psi_n^* dxdy$$

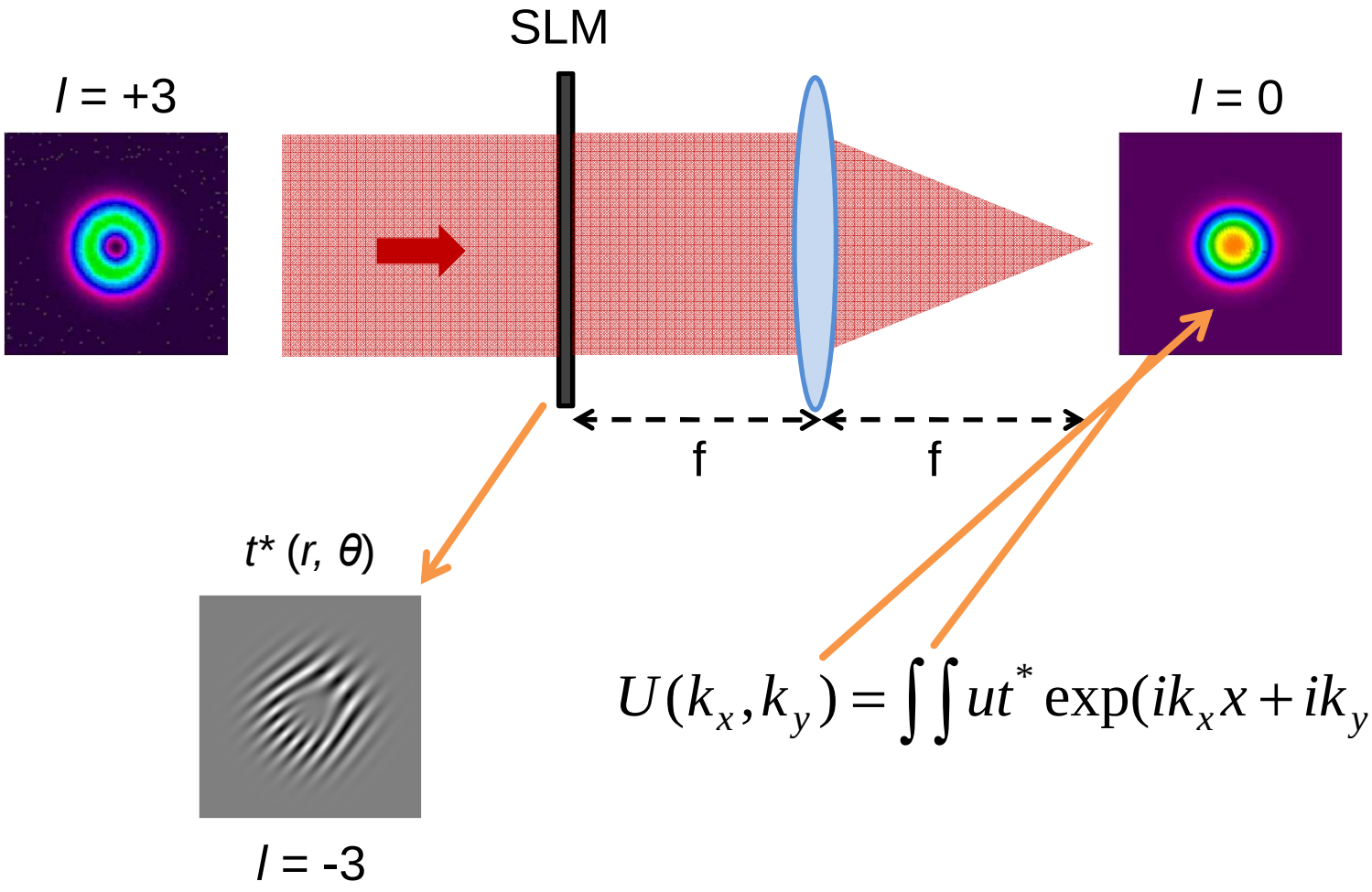
Perform this integral

Create these modes

We know how to create any laser beam with digital holograms written to SLMs

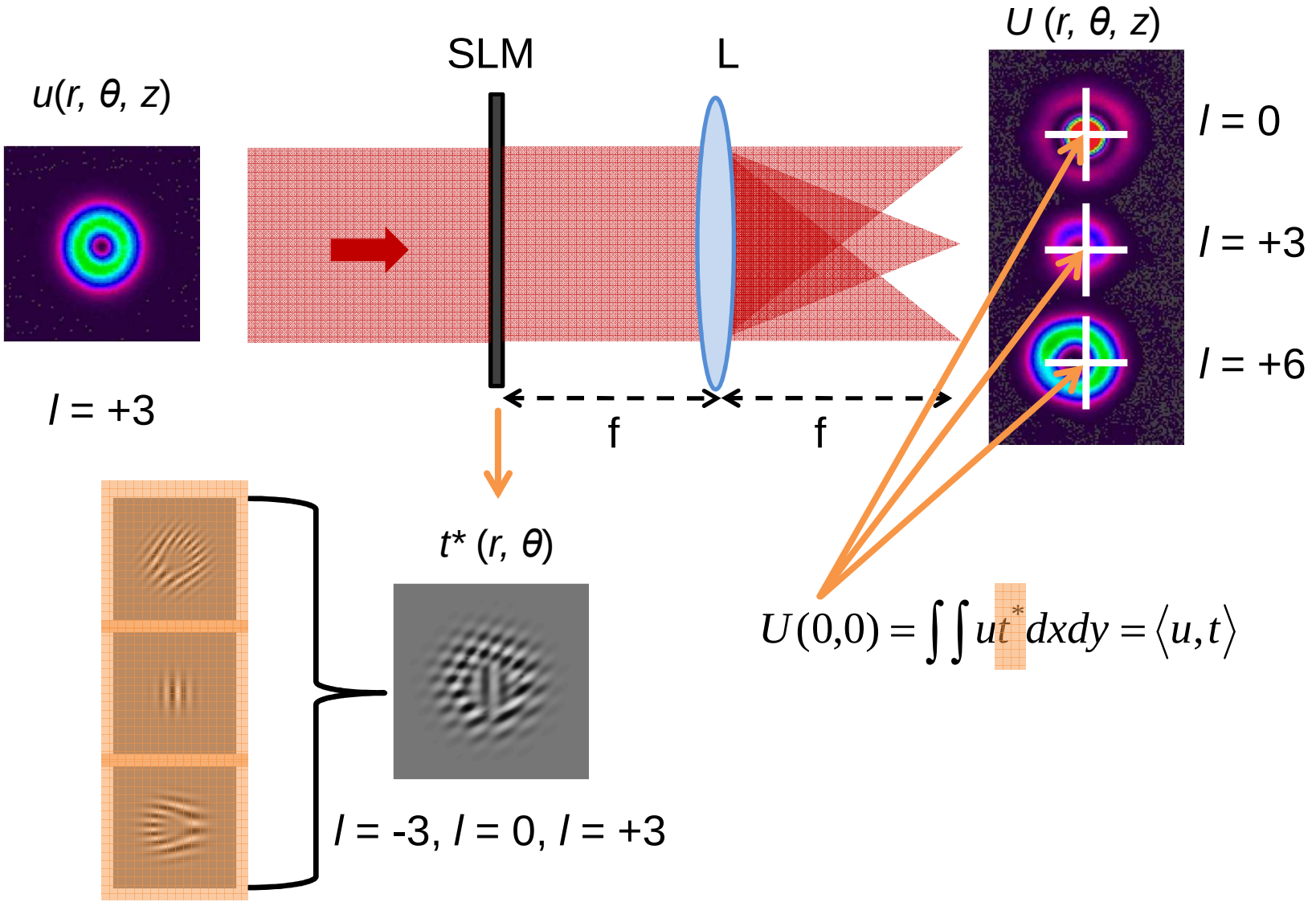


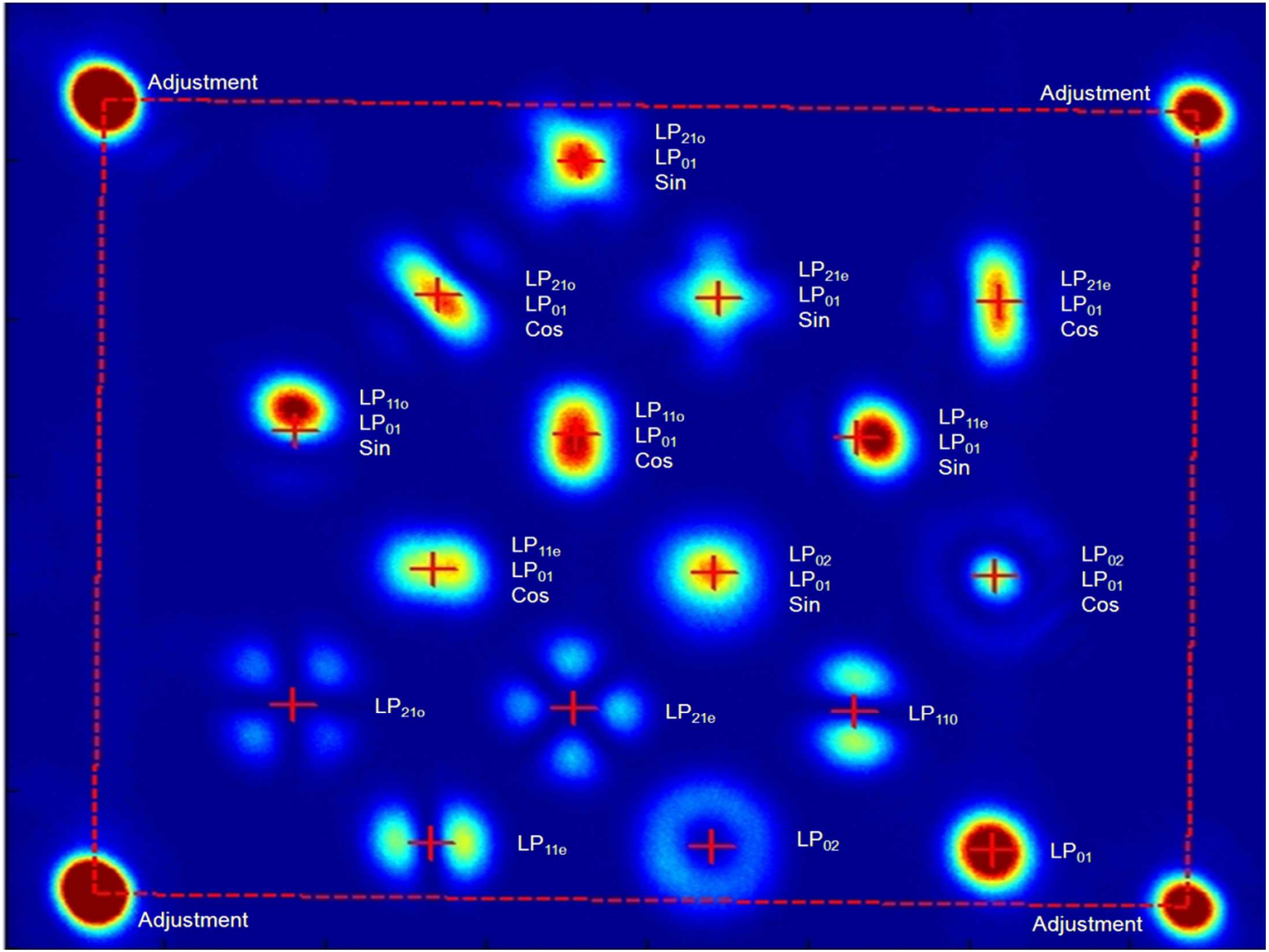
In reverse: we can pass an unknown field through a match filter to find the inner product



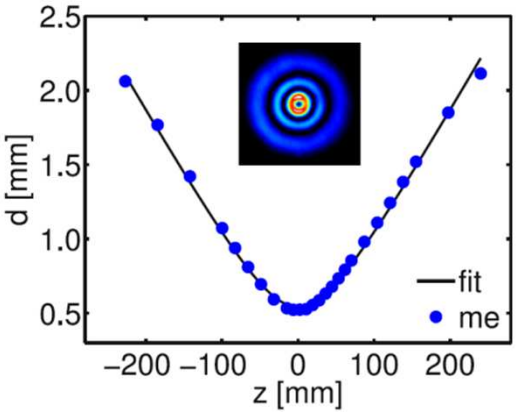
$$U(k_x, k_y) = \int\int ut^* \exp(ik_x x + ik_y y)dxdy$$

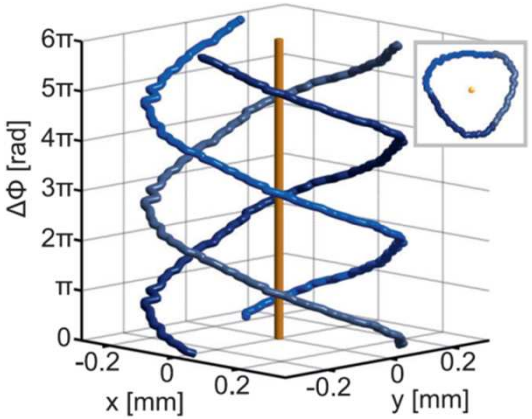
Multiplexing allows many measurements at once

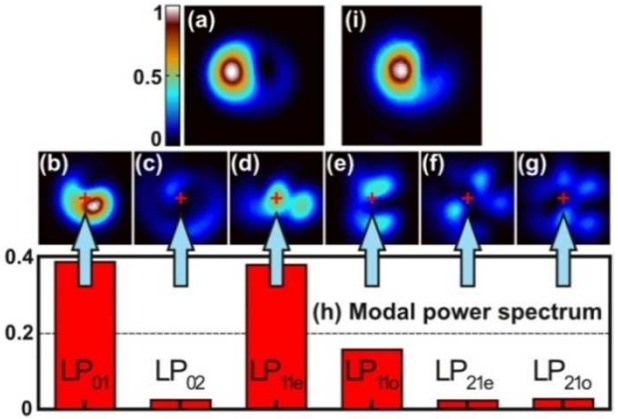


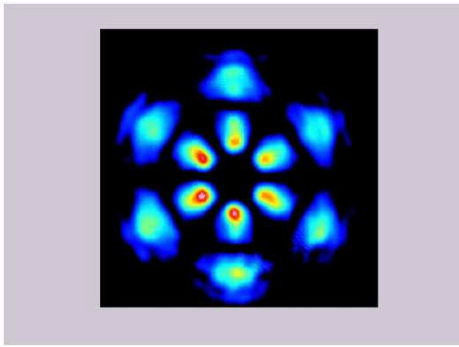

Adjustment
Adjustment
LP21o LP01 Sin
LP21o LP01 Cos
LP21e LP01 Sin
LP21e LP01 Cos
LP11o LP01 Sin
LP11o LP01 Cos
LP11e LP01 Sin
LP11e LP01 Cos
LP02 LP01 Sin
LP02 LP01 Cos
LP21o
LP21e
LP110
LP11e
LP02
LP01
Adjustment
Adjustment

Any physical property of the field can be measured; here are some examples

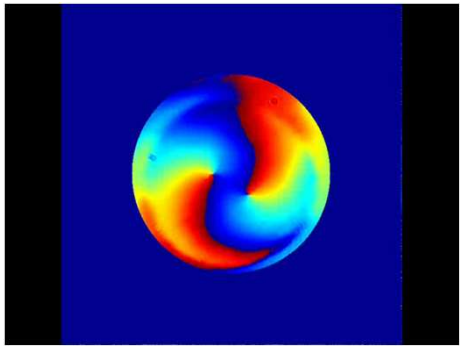








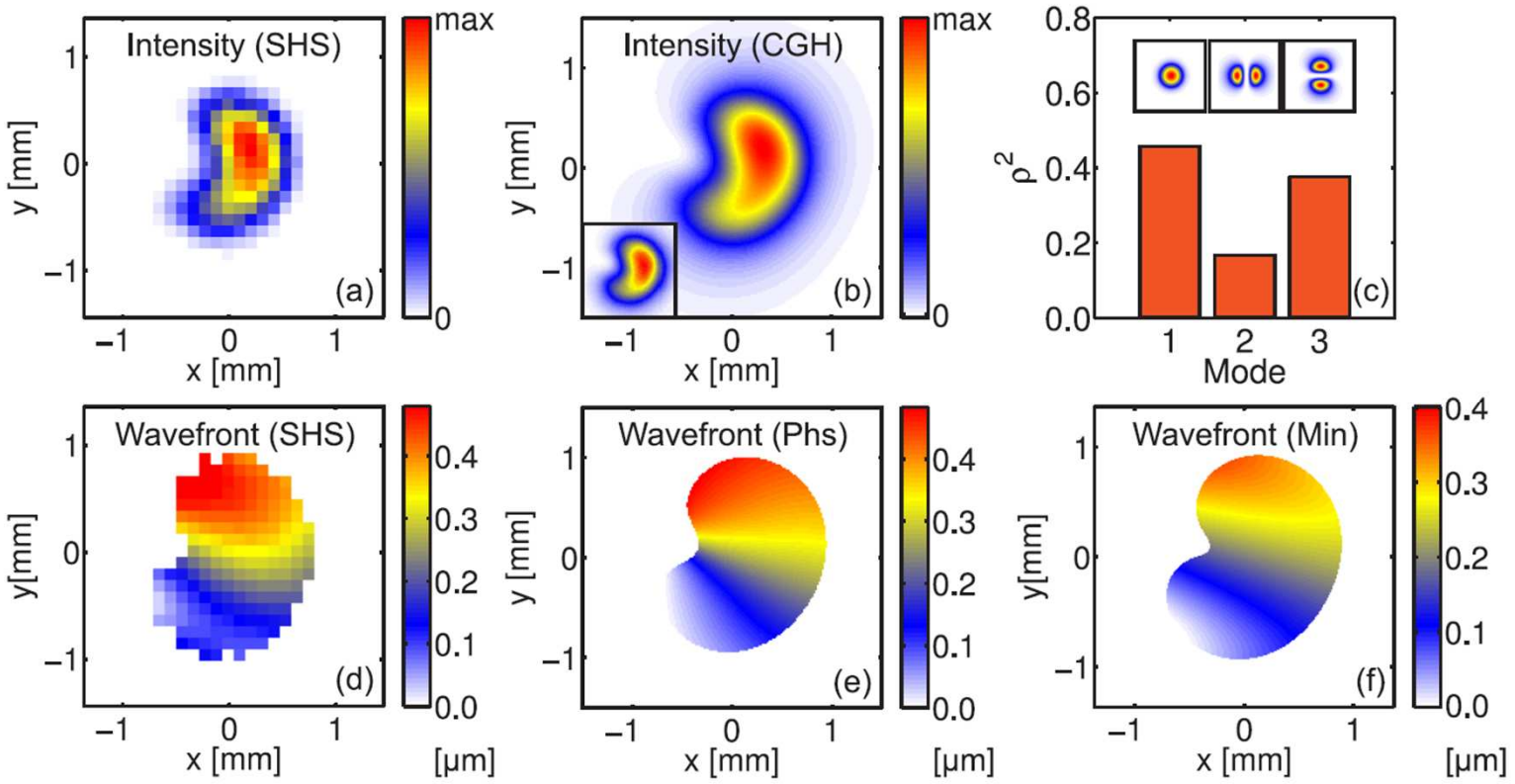
Optics Letters **37**, 4687 (2012)



Optics Express **22**, 14031 (2014)
New J. Physics **15**, 073025 (2013)

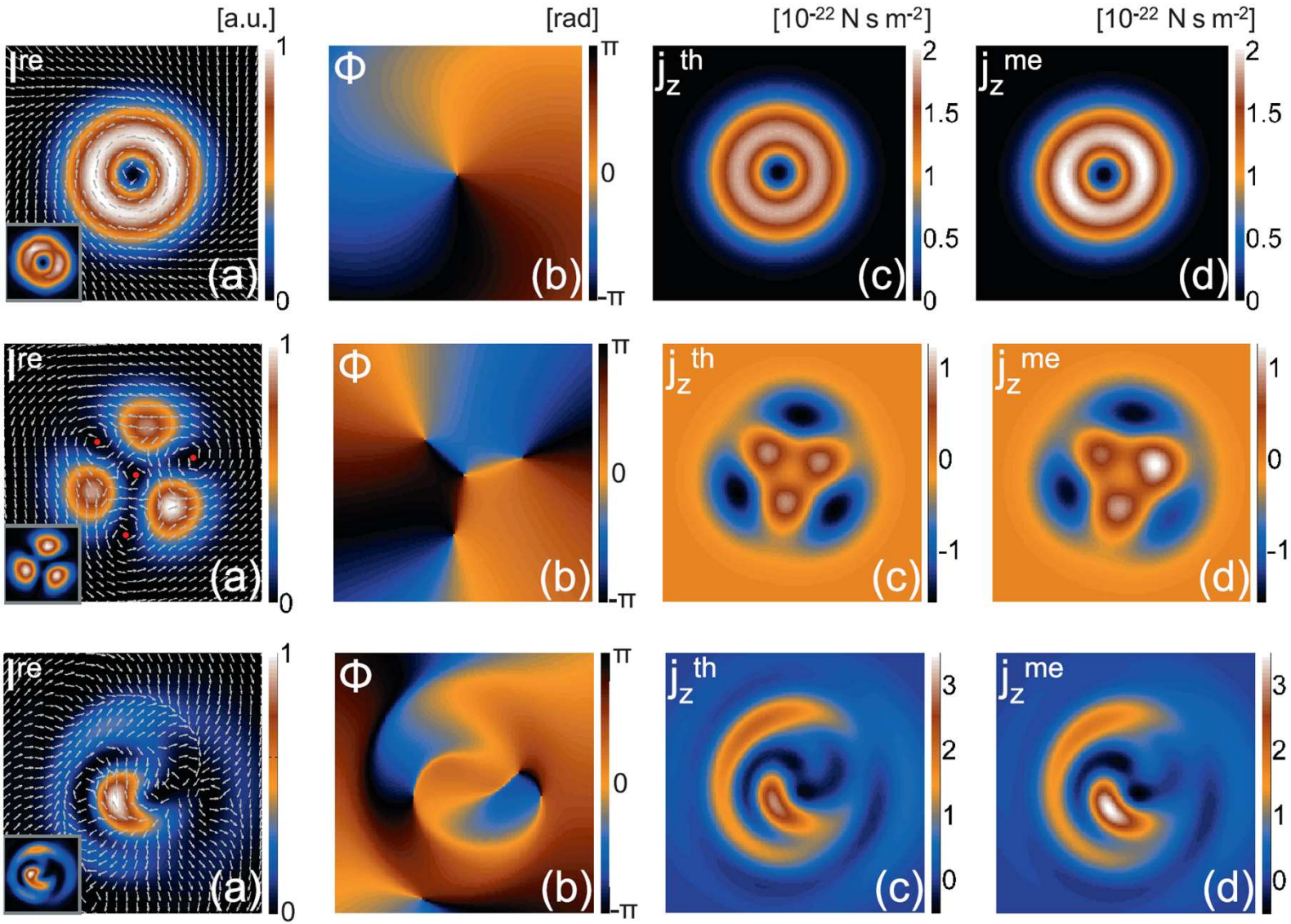
J. Lightwave Tech. **31**, 1023 (2013)
Optics Letters **3**, 2478 (2012)

For example, the wavefront of light … for scalar, vector and vortex beams



Applied Optics **52**, 5312 (2013)
Optics Express **20**,19714 (2012)

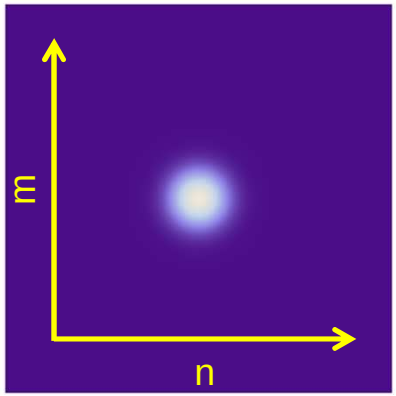
For example, the orbital angular momentum density of light



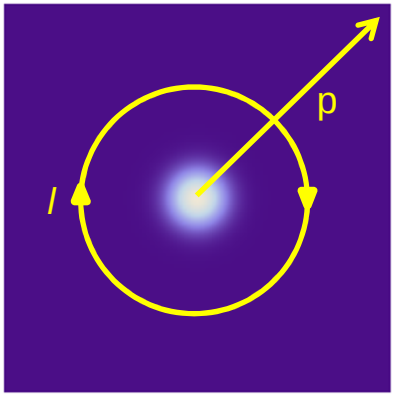
New J. Physics **15**, 073025 (2013)

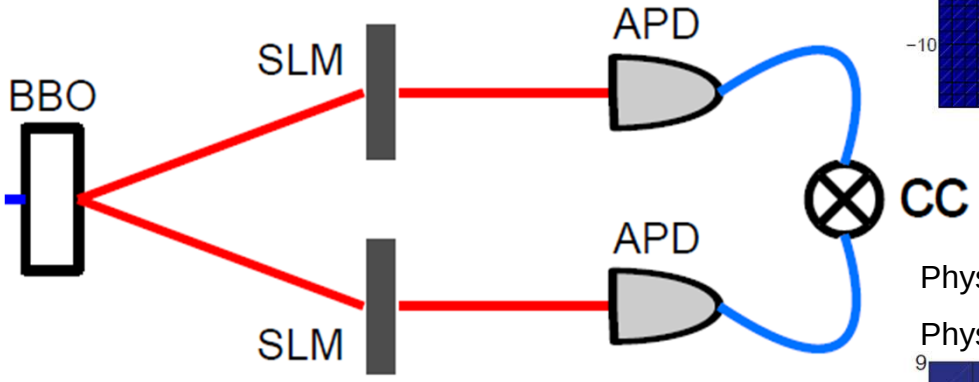
This can also be done at the single photon level … “quantum mechanics with pictures”

Hermite modes

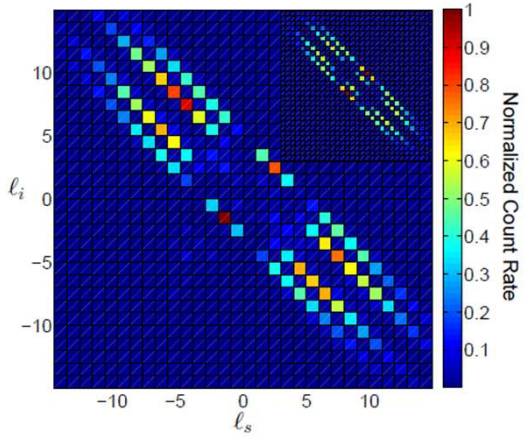


Laguerre modes



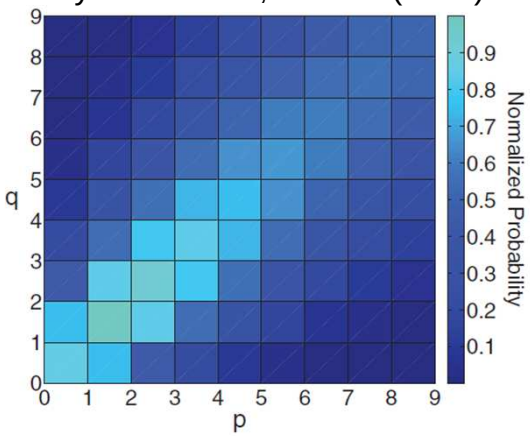


Optics Express **22**, 17039 (2014)

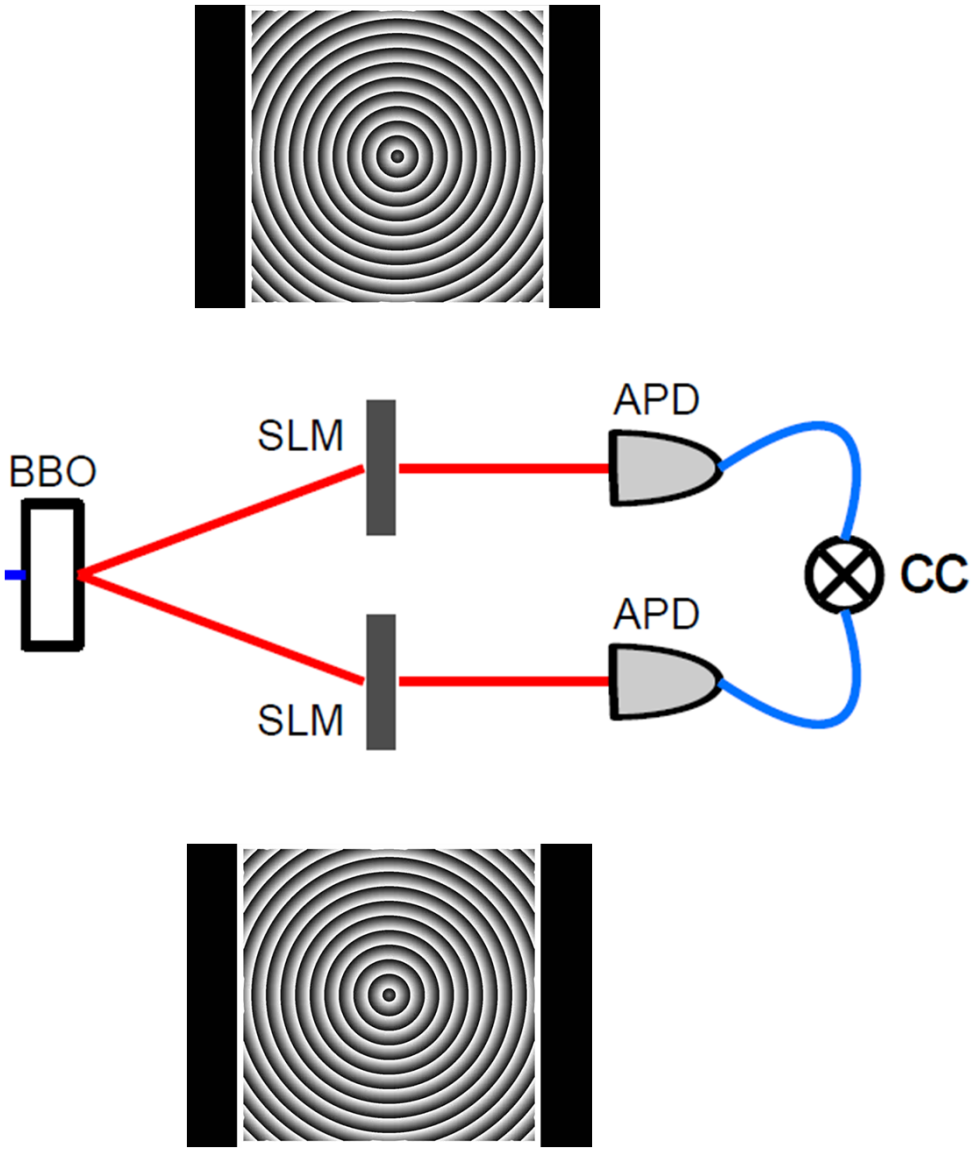


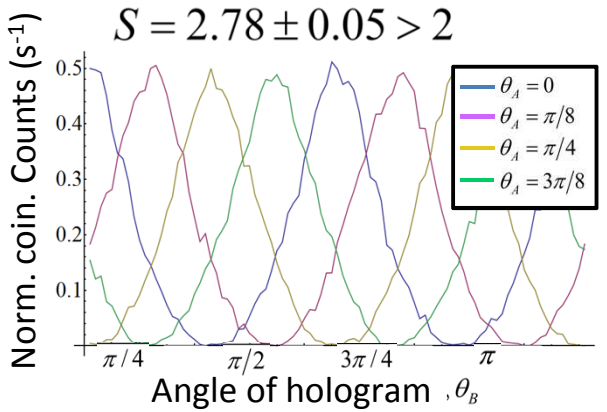
Phys. Rev. A **89**, 063802 (2014)

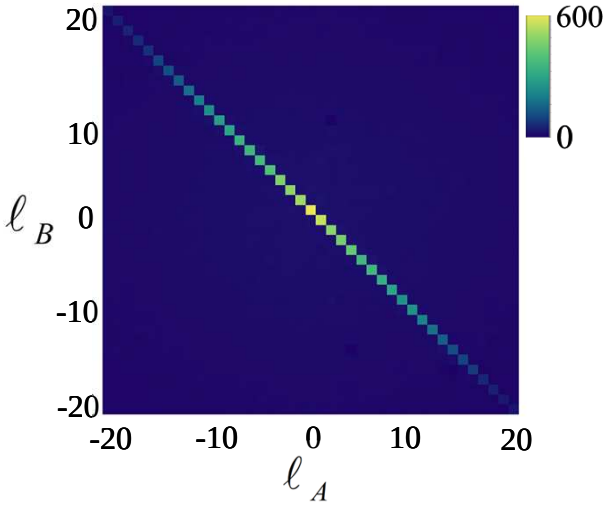
Phys. Rev. A **89**, 043820 (2014)



Entangled Bessel photons using both OAM and radial degrees of freedom

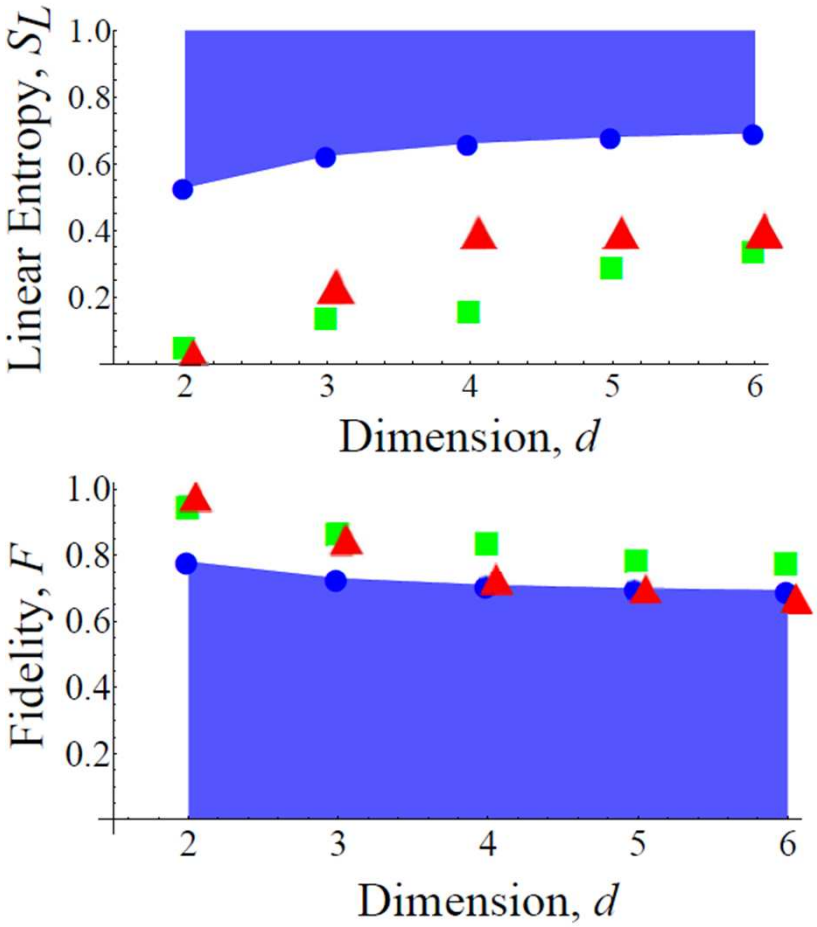


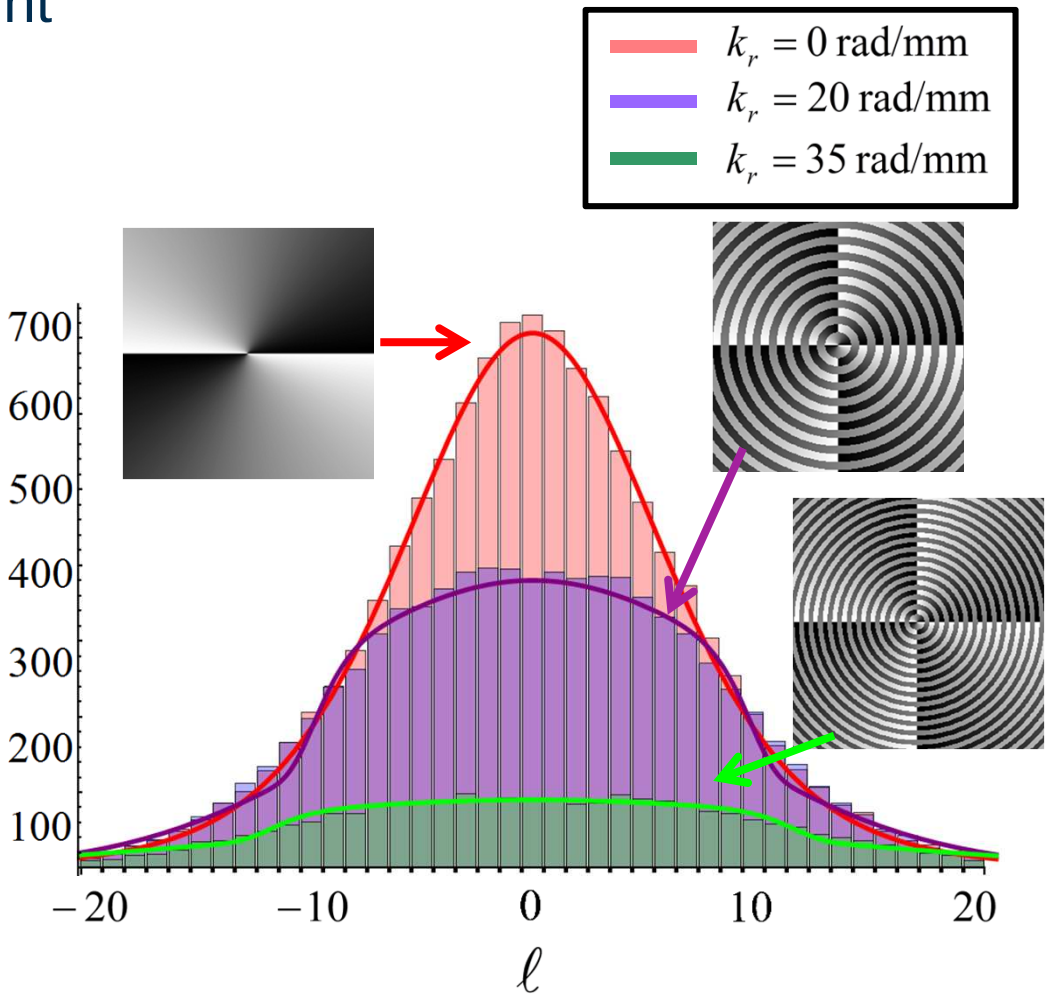




Optics Express **20**, 23589 (2012)

We can tune to higher dimensions and engineered states by using Bessel patterns of light

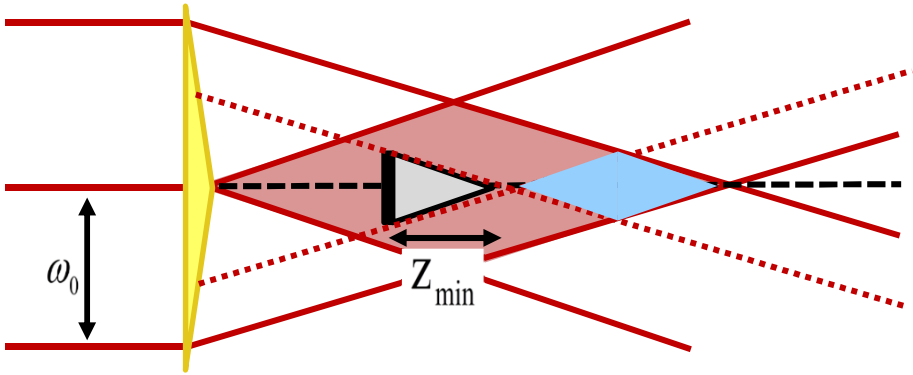


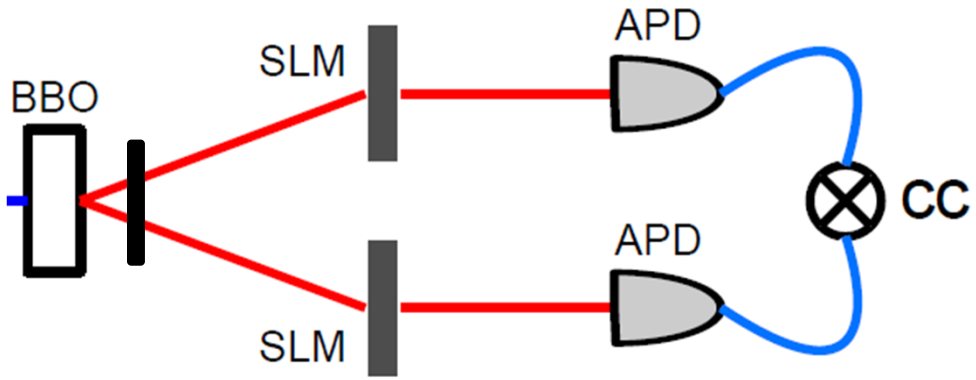


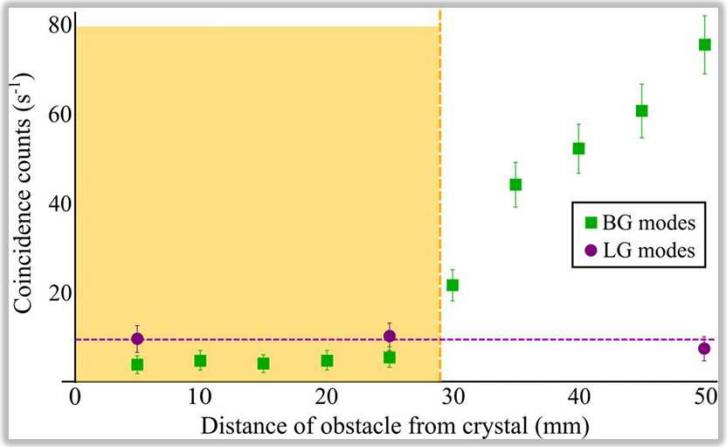
Phys. Rev. A **88**, 033818 (2013)

It is well known that these beams self-heal after an obstruction

… and also in the quantum world?



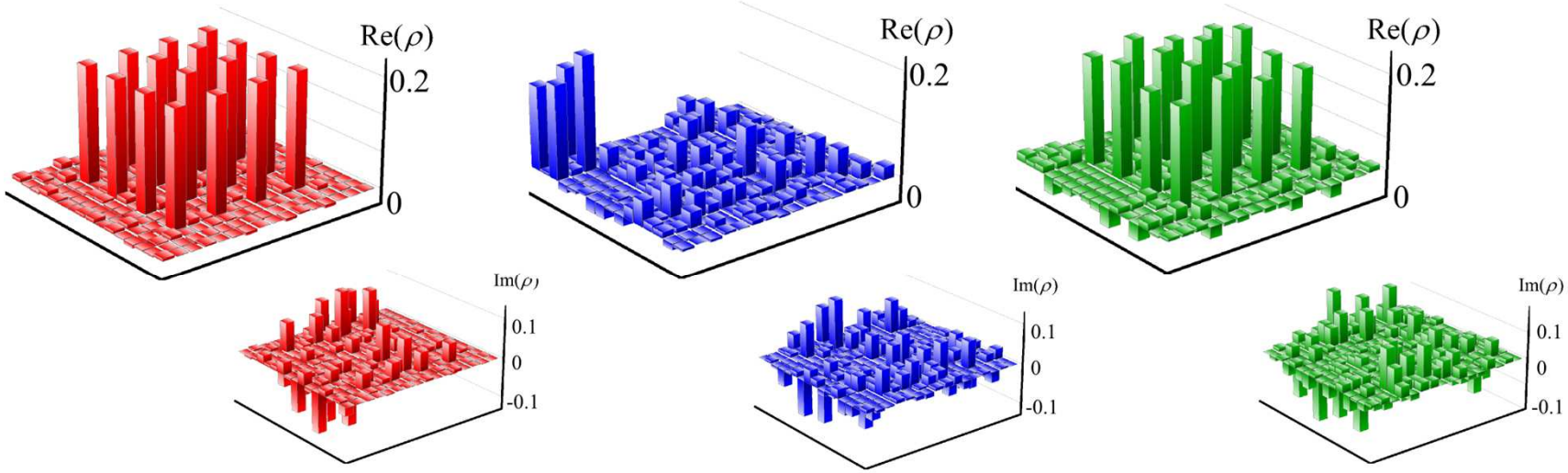




Nature Communications **5**, 3248 (2014)

The self-healing property is applicable to high-dimensional entanglement with Bessel photons

$$d = 4: \quad \ell = \left| -2, -1, 1, 2 \right\rangle$$

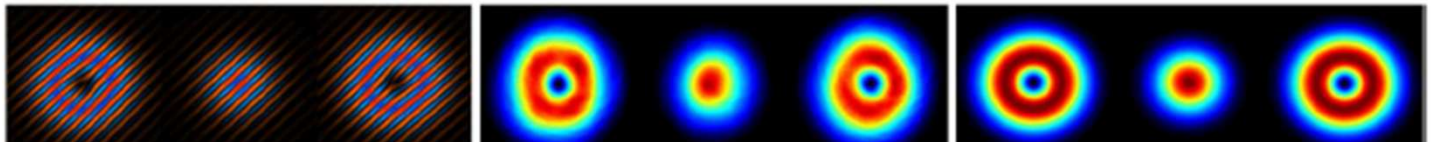


Fidelity as a function of the position of the obstacle

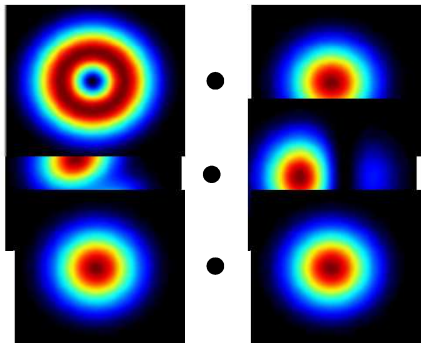
Dimension	5 mm	15 mm	30 mm	50 mm	Unobstructed
2	0.24	0.59	0.79	0.96	0.97
4	0.20	0.45	0.68	0.75	0.79

Nature Communications **5**, 3248 (2014)

Can we customise spatial modes to form Mutually Unbiased Bases (MUBs) from our orthonormal set?



(d + 1) MUBs



= 0

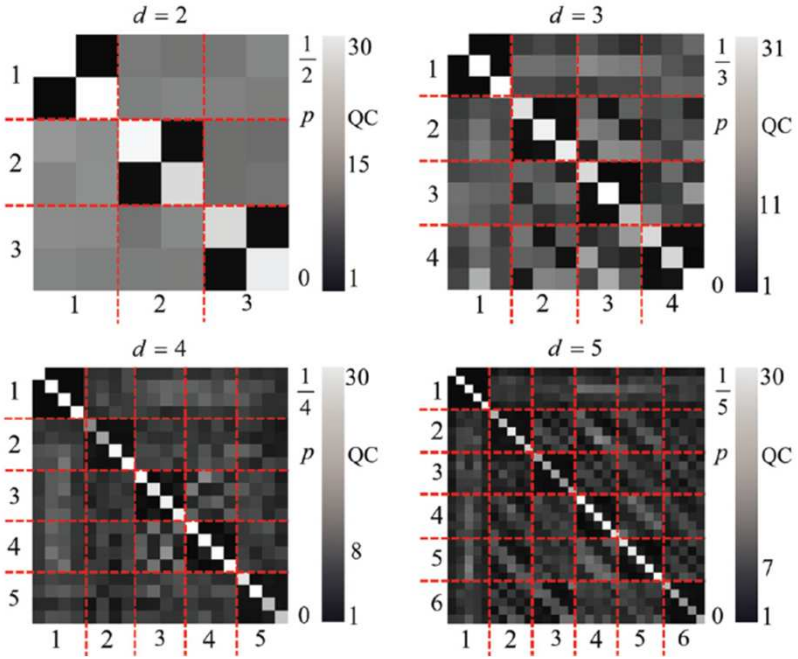
= 1/3

= 1

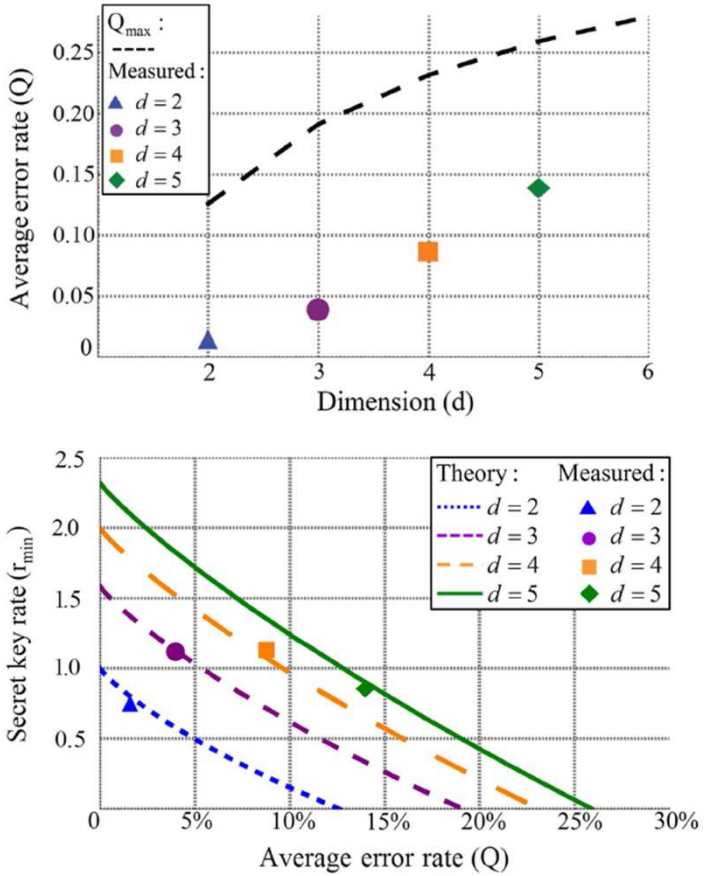
Maybe

Yes/No

We can then execute QKD using high dimensional quantum states

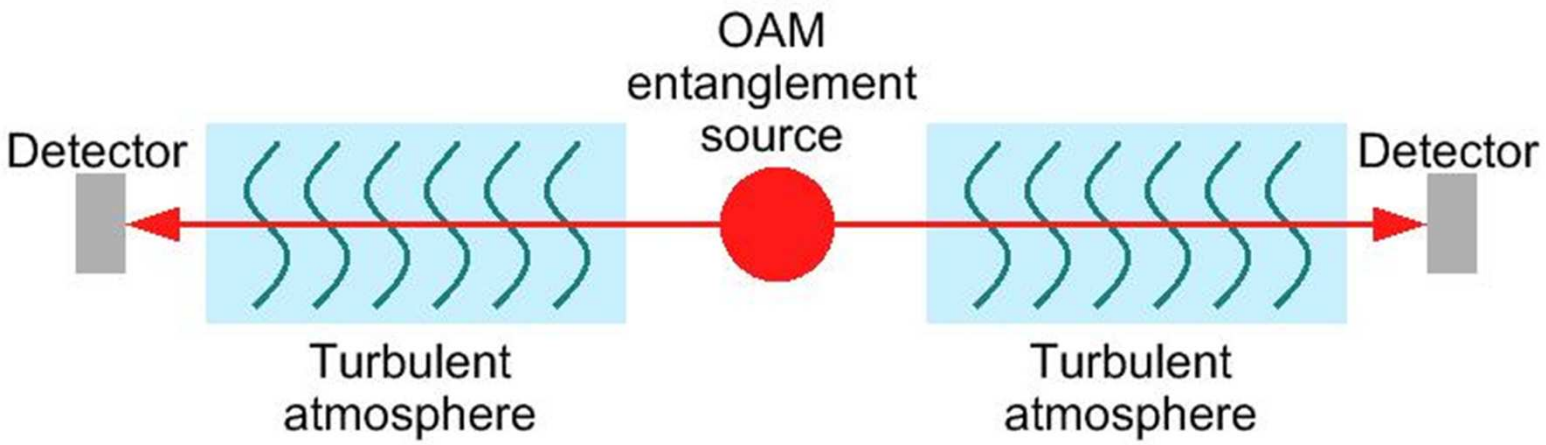


Phys. Rev. Lett. **110**, 143601 (2013)

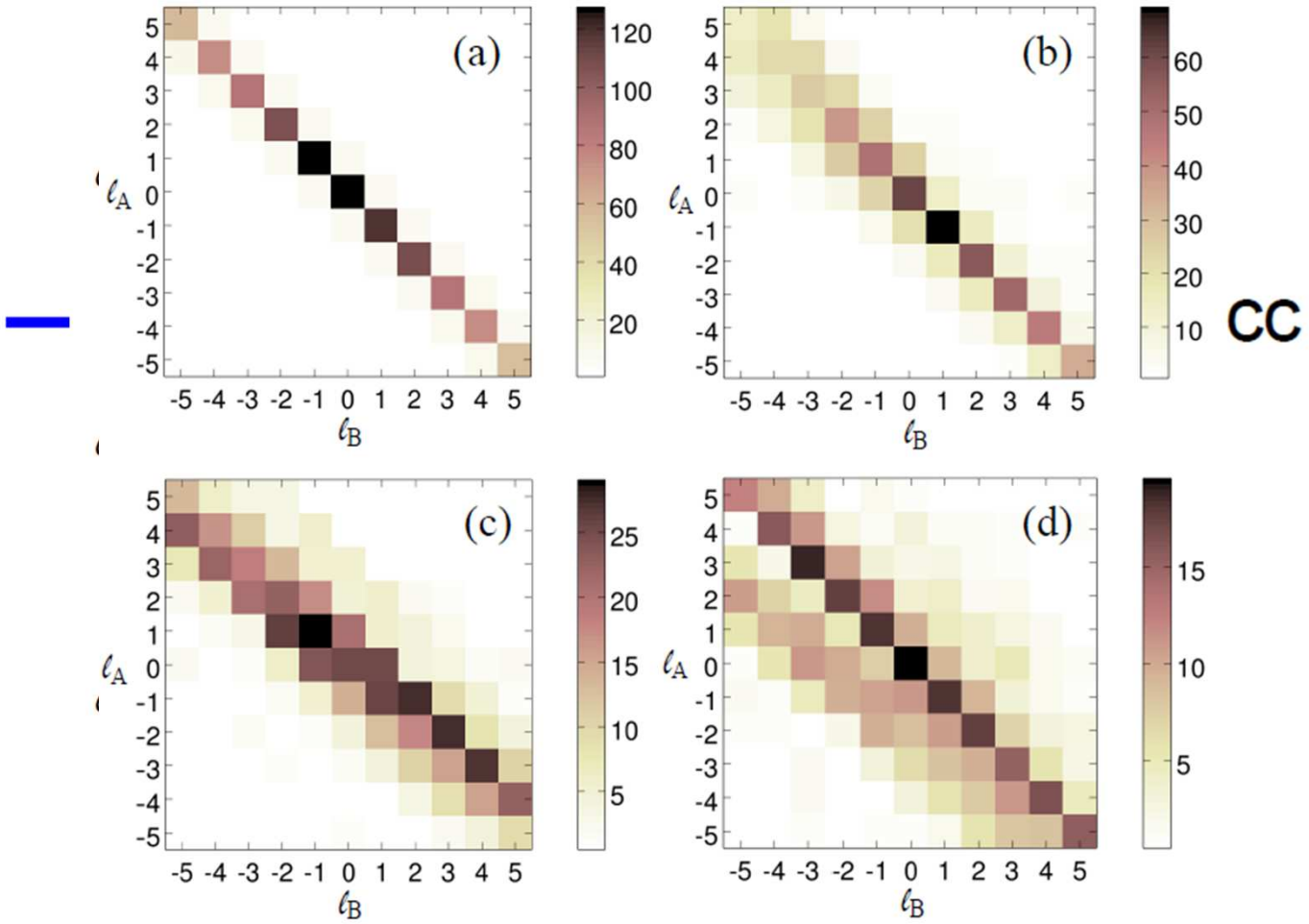


Phys. Rev. A **88**, 032305 (2013)

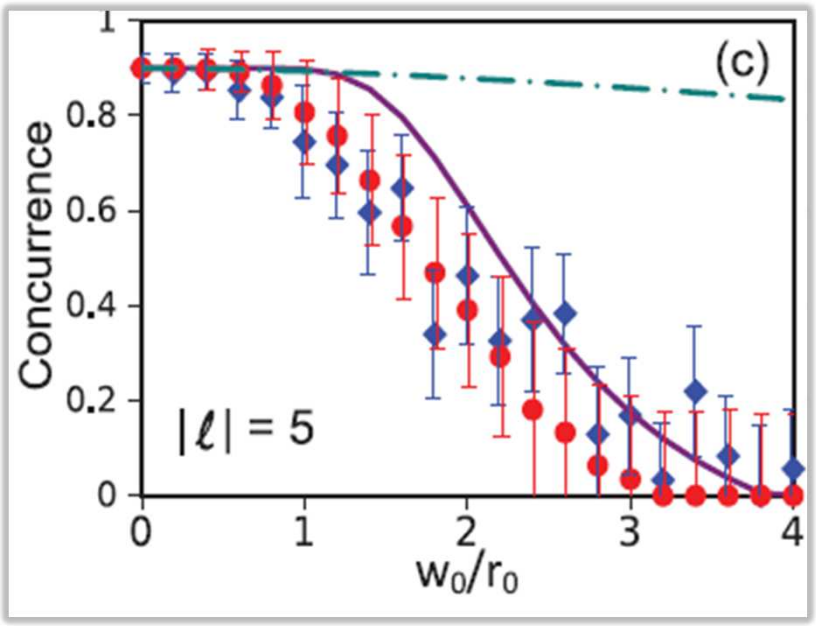
Both the entanglement and the OAM spectrum change during propagation



When turbulence is introduced the modal coupling leads to loss of information



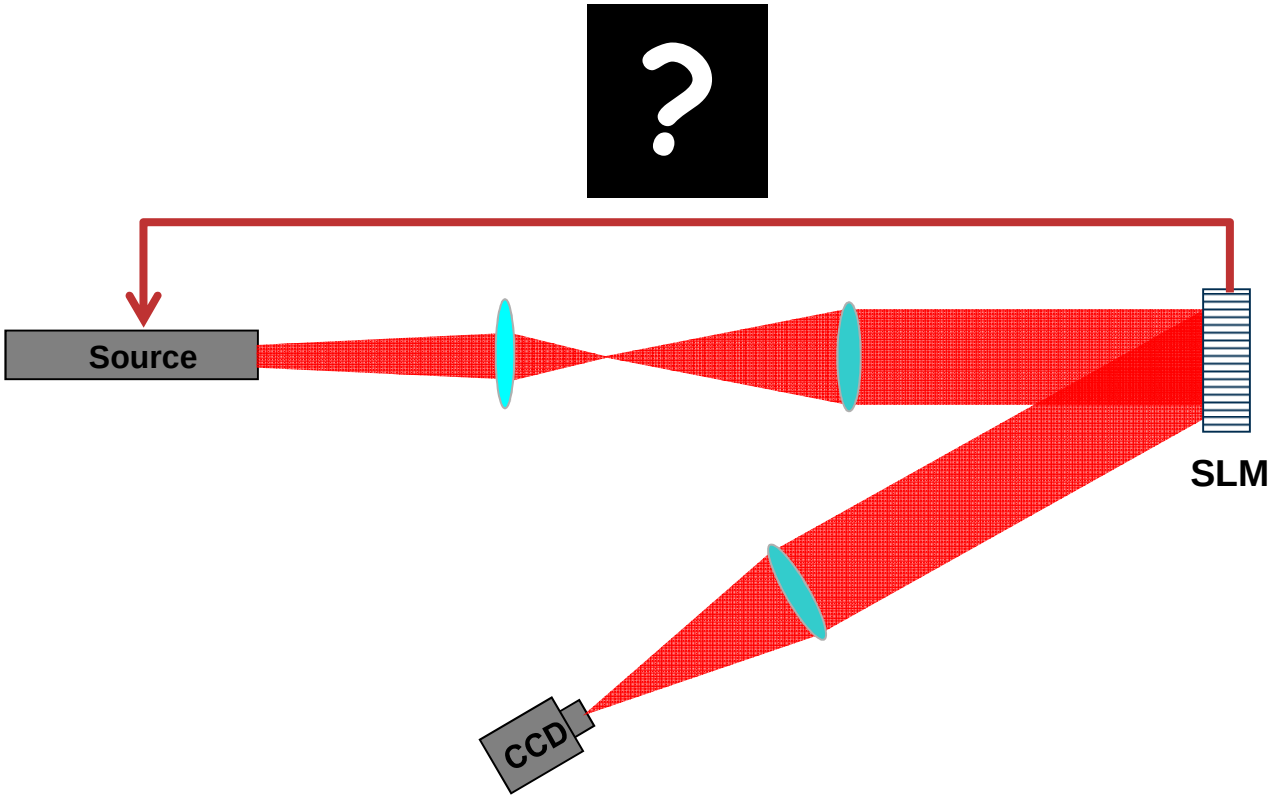
I’m looking for a student to do a crazy experiment …



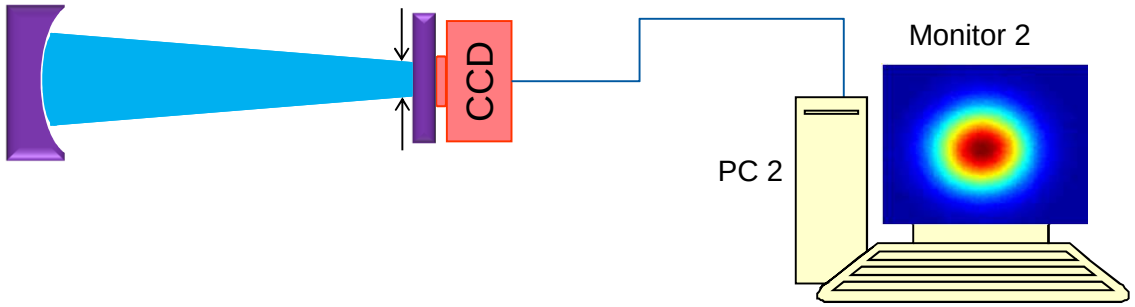
Phys. Rev. A **88**, 012312 (2013)

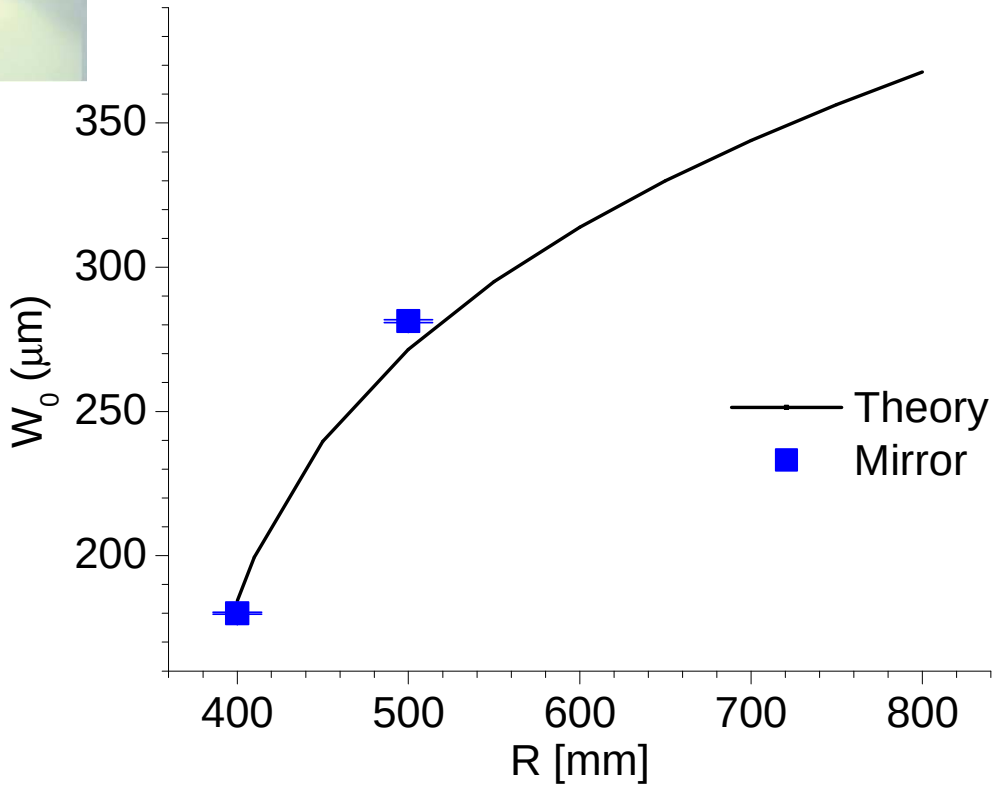
New J. Physics **15**, 063005 (2013)

Can we put the SLM inside the laser to create a holographic mirror that is digitally controlled?

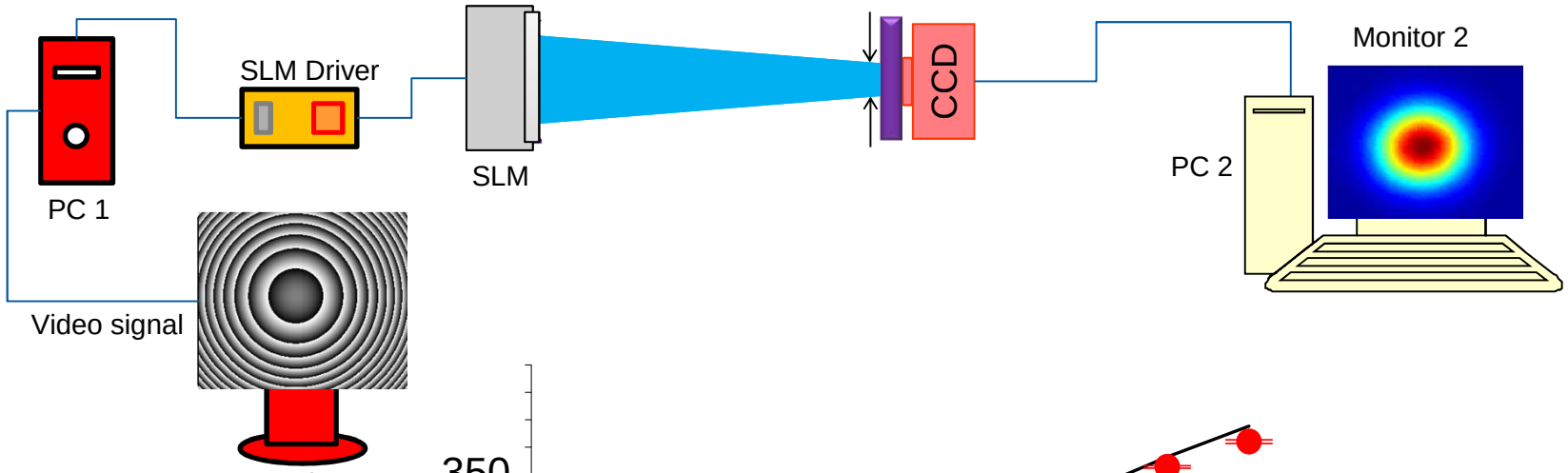


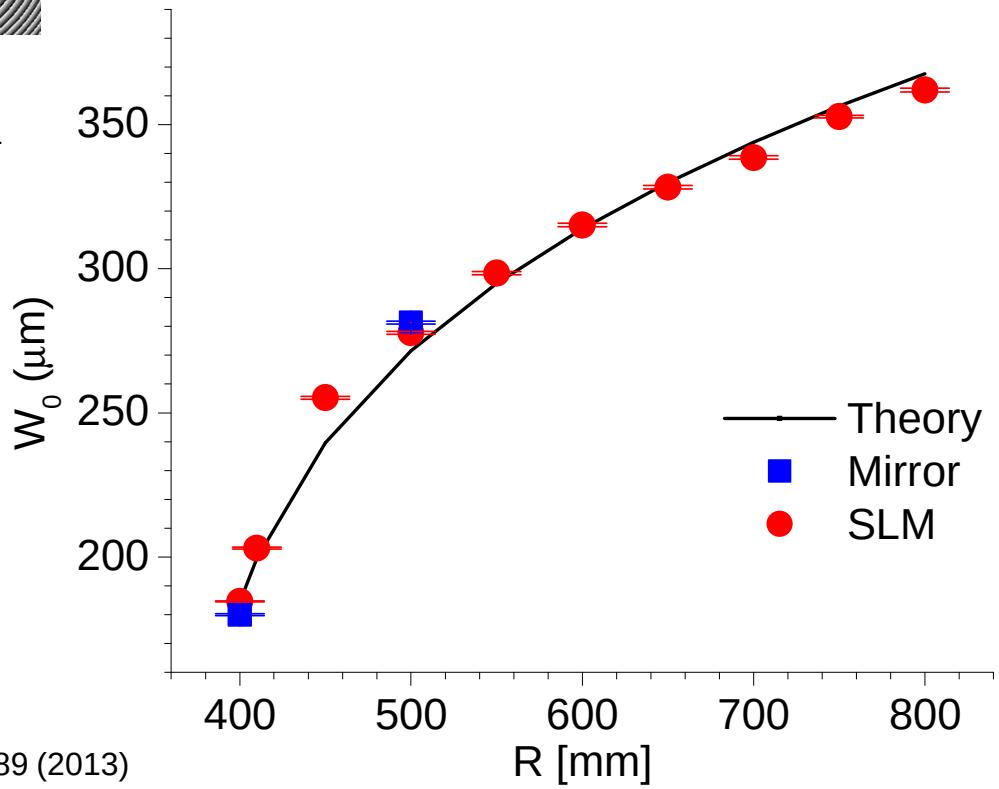
Conventional lasers have fixed, prefabricated mirrors or optics





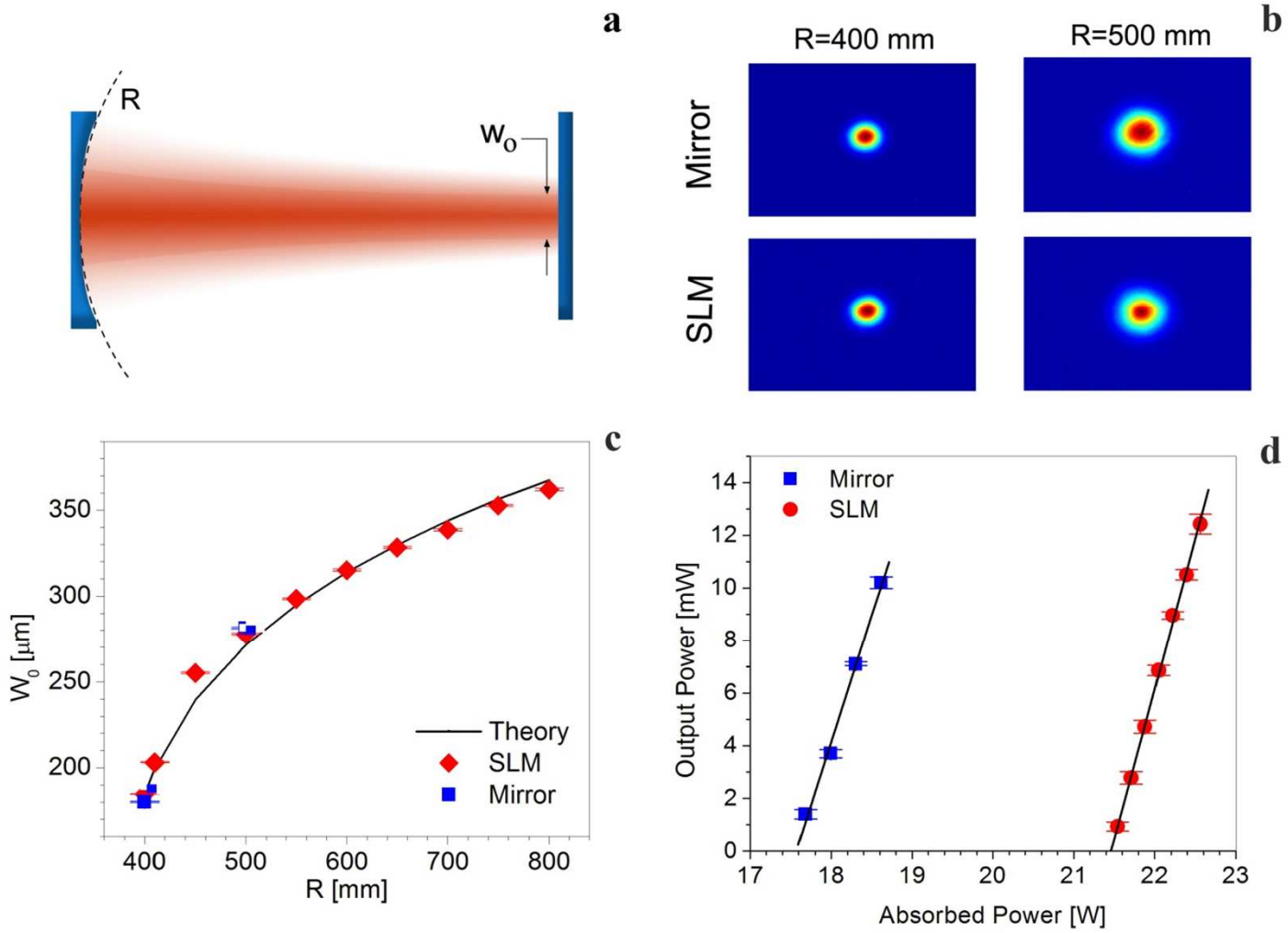
The digital laser concept: very simple



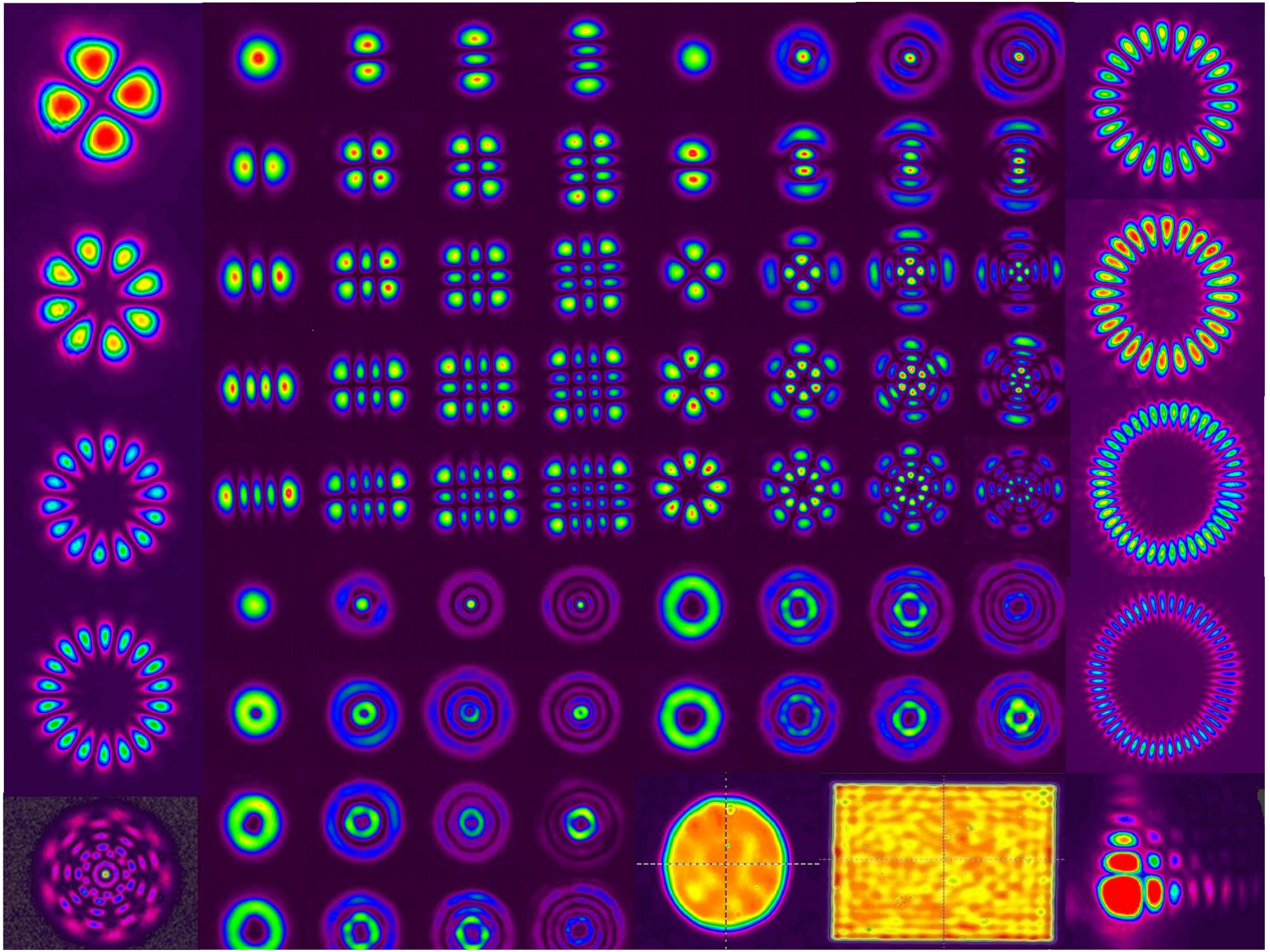


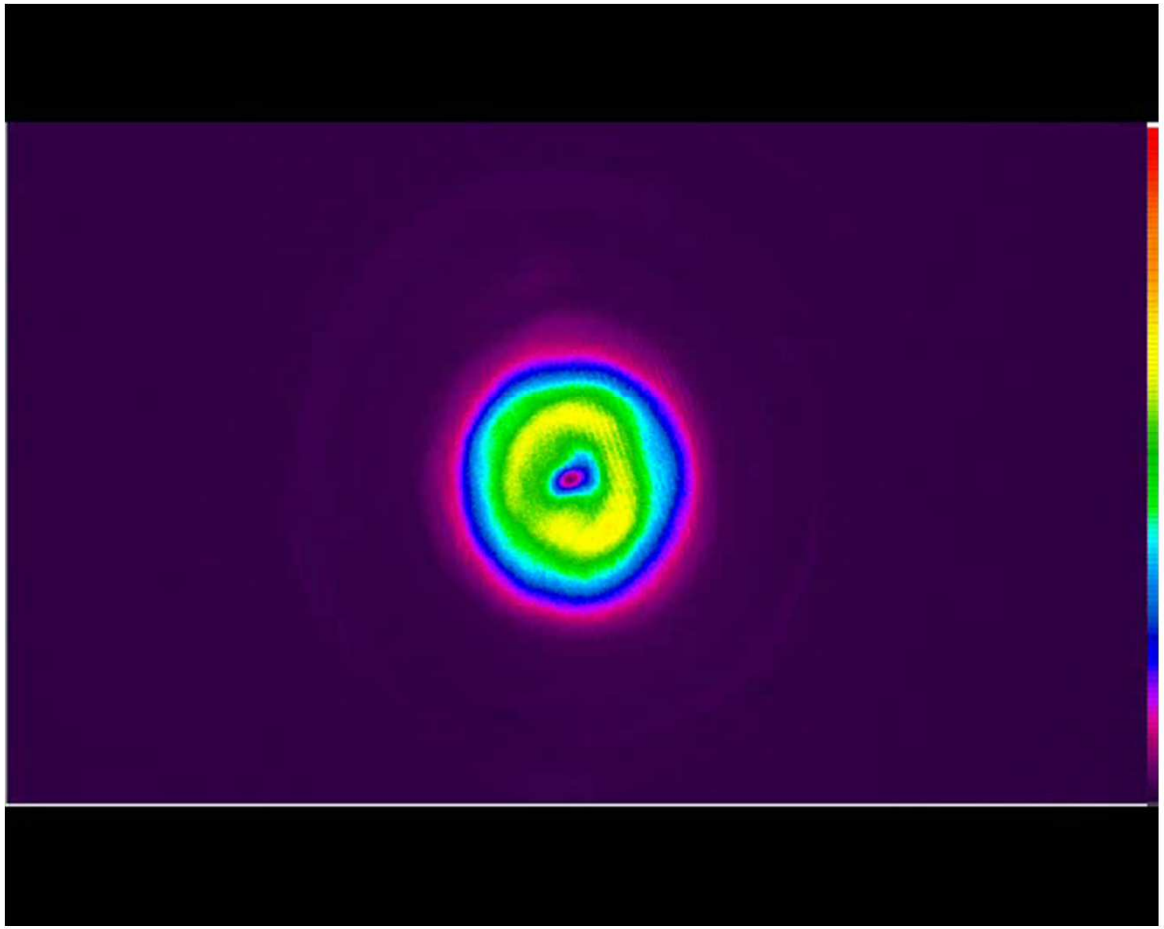
Nature Communications **4**, 2289 (2013)

But there is a cost … the efficiency of the laser



Nature Communications **4**, 2289 (2013)





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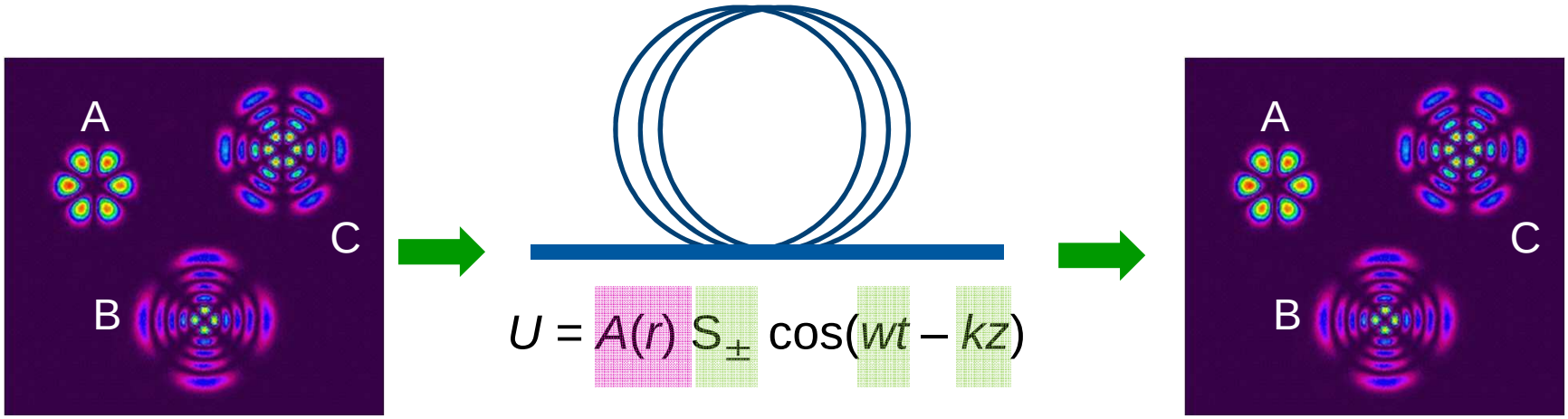
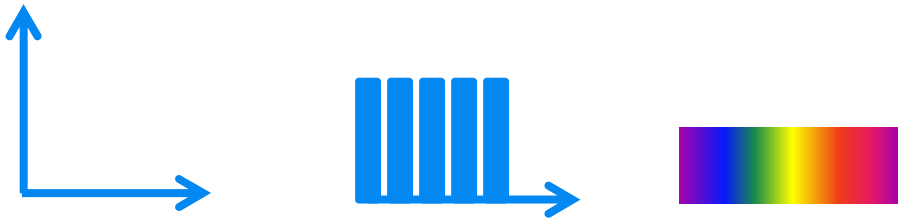
Application: Could we encode information into the patterns of light for increased bandwidth?



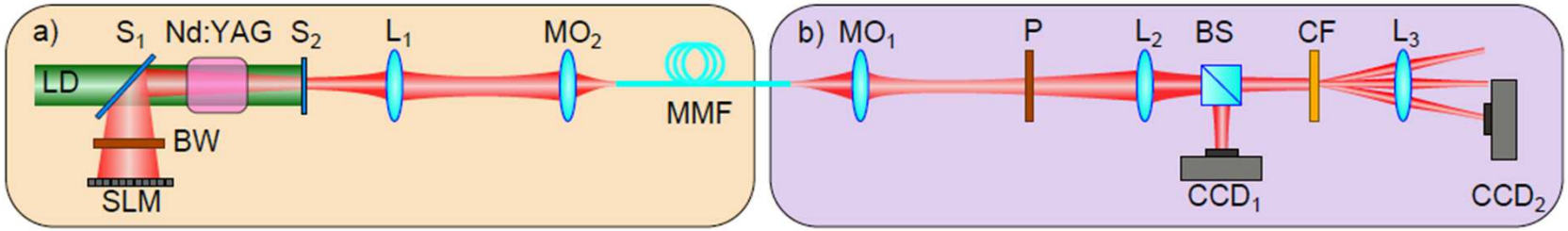


Use the polarisation

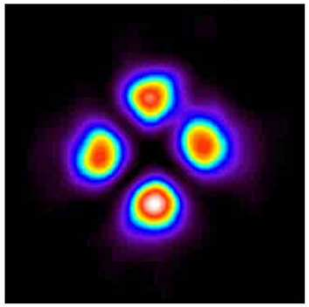
Switch as fast as you can

Pack in lots of colours

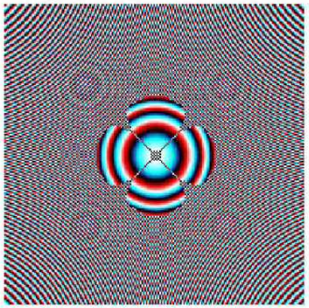
Encoding information into spatial modes and transferring them directly from the source



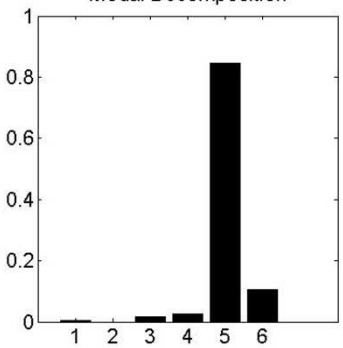
Near Field Intensity



Digital Laser Phase Pattern



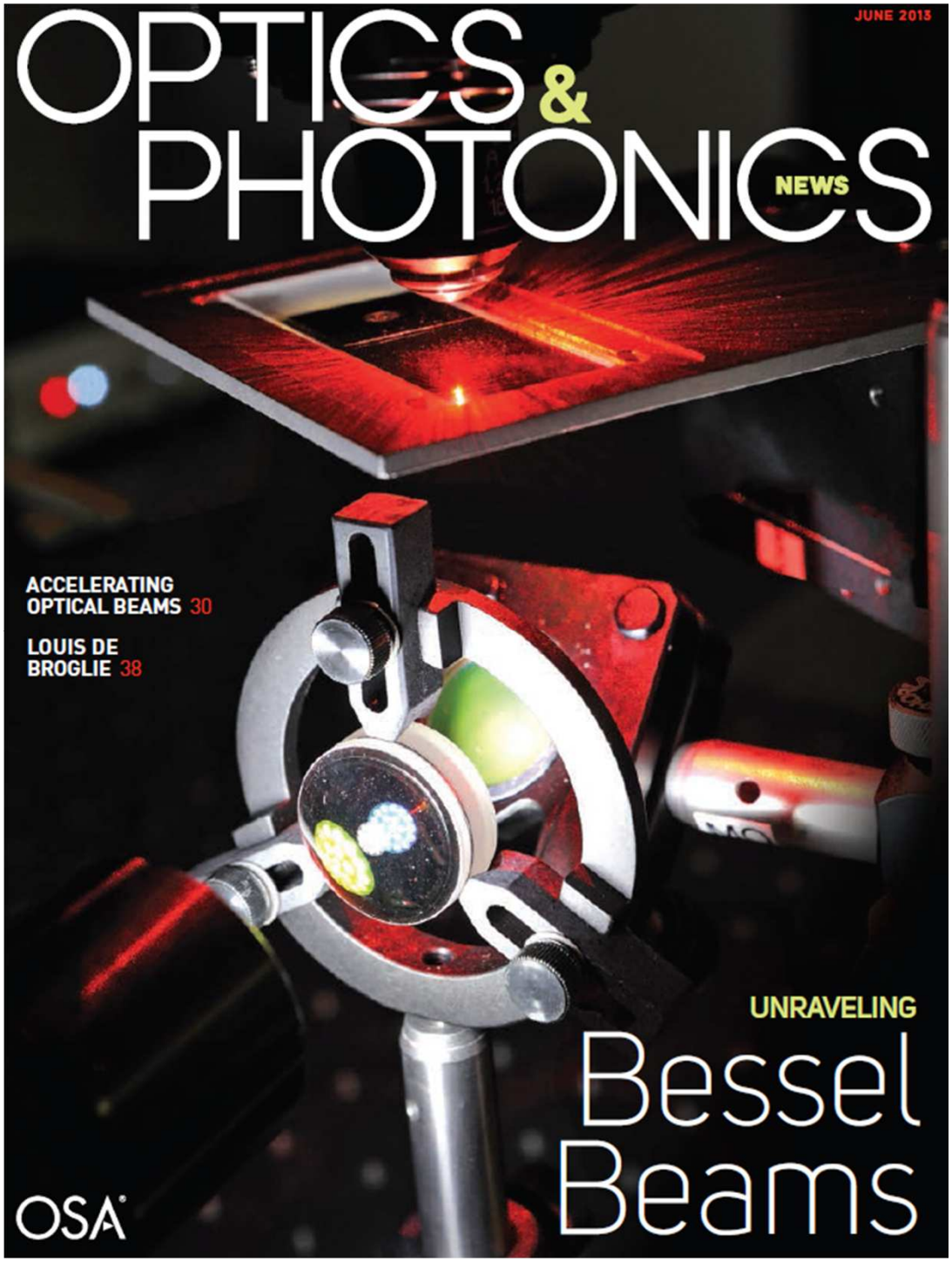
Modal Decomposition



Power Content
$LP_{21e}+LP_{21o}$

95.24%

arXiv:1406.0264 (2014)



“Popular” articles:

Nature Physics **10**, 188 (2014).

Nature Photonics **7**, 592 (2013).

Science&Vie **August**, 44 (2013).

Optics and Photonics News **December**, 30 (2013).

Optics and Photonics News **June**, 22-29 (2013).

Optics.Org **October**, http://optics.org/news/4/10/5 (2013).

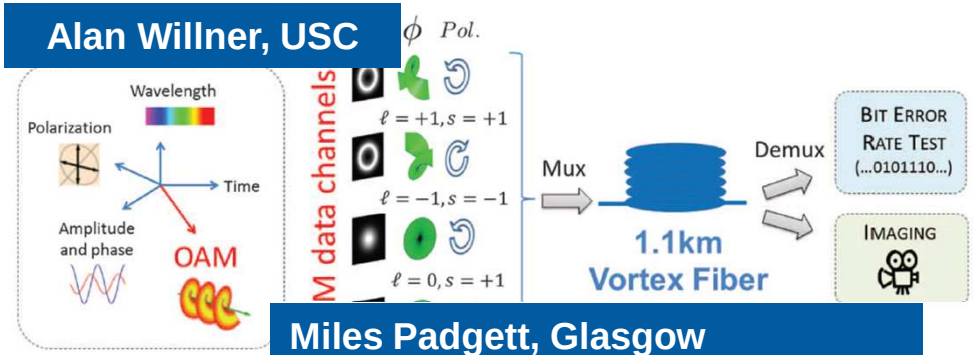
Photonics Spectra **December**, (2013).

Electro Optics **November**, 38 (2013).

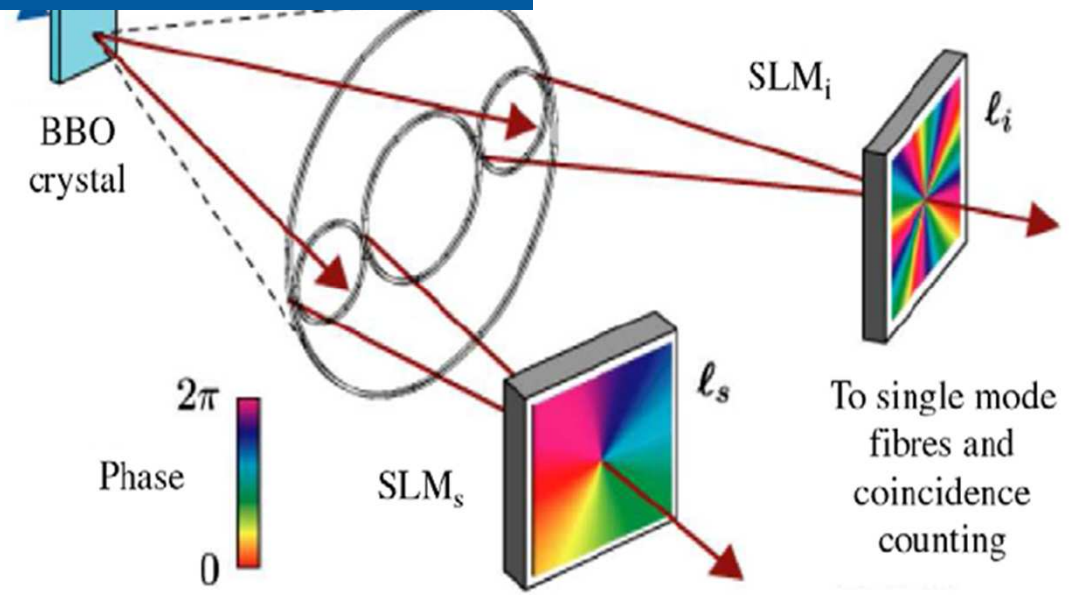
SPIE Newsroom **May**, http://spie.org/x93732.xml (2013).

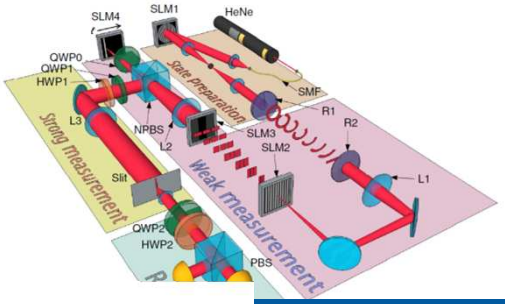
YouTube MathOptics

Alan Willner, USC

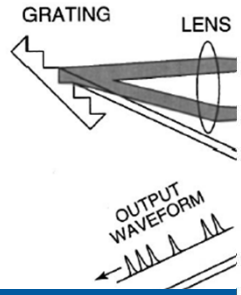


Miles Padgett, Glasgow

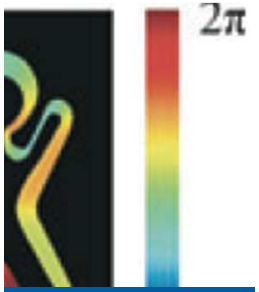




J. Rochester

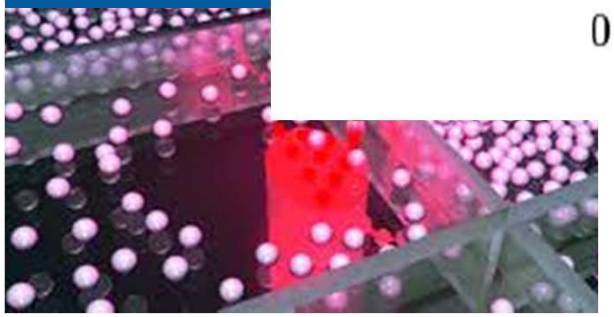


Andrew Wein



Ritch-Marte, Innsbruck

Kishan Dhola



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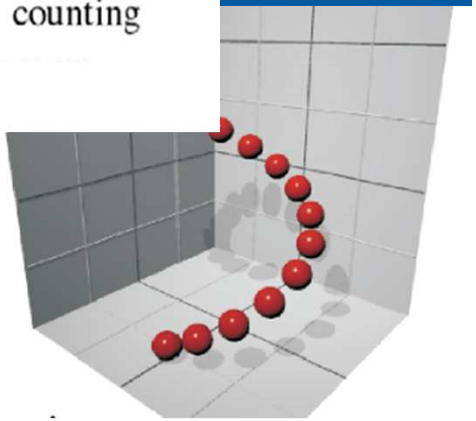

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Theoretical Physics

My nascent group … the people who did the work!

Thank You
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