Observation of Optical Polarization Möbius Strips

or

How to Measure the 3D Field Structure of Tightly Focused Vector Fields

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Experimental Observation of Optical Polarization Möbius Strips

Introduction and Background

Singularities in Optics – Undefined Points in Scalar and Vectorial Light Fields

Optical Möbius Strips – When Light Turns One-Sided and Single-Edged

Theoretical and Experimental Techniques

How to Realize an Optical Möbius Strip with Tightly Focused Light

How to Measure (an Optical Möbius Strip in) a Tightly Focused Light Beam

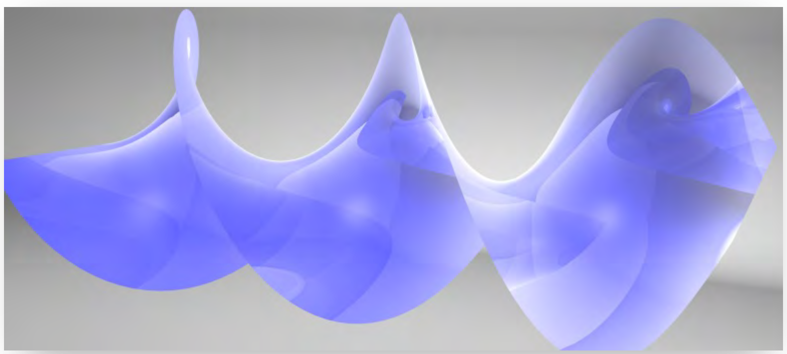
Experimental Results

A Polarization Möbius Strip in the Lab

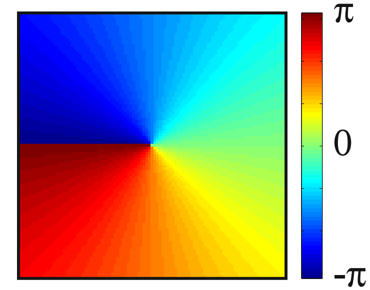
Singularities in Optics

Phase singularities in scalar light beams and scalar wave fields

Laguerre-Gaussian (LG) beams (solutions of the scalar wave equation)



- Phase vortex/singularity in an LG beam
- Spiraling (non-planar) phase front
- Screw dislocation[1]



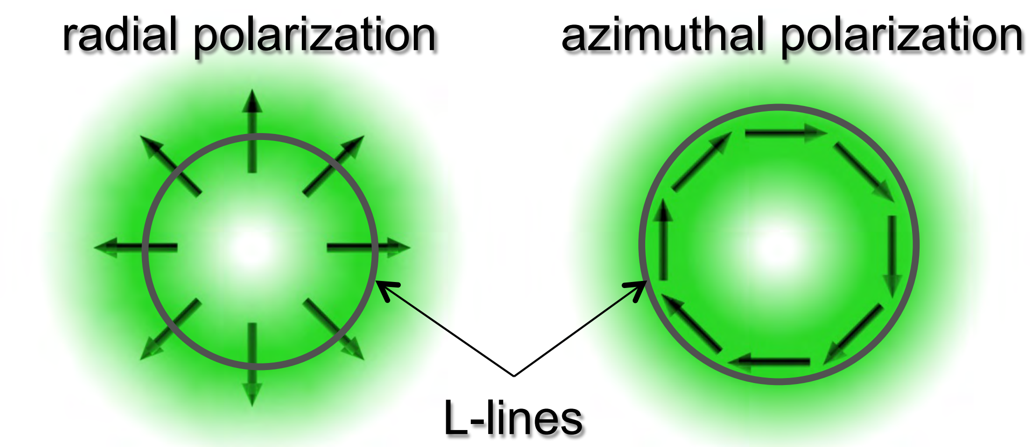
- Helical phase term $e^{im\varphi}$
- m: charge; related to orbital angular momentum[2]
- Singularity is on-axis in a point of zero intensity

[1] J.F. Nye, M.V. Berry, Proc. R. Soc. London A 336 (1974) 165
[2] L. Allen, M. W. Beijersbergen, R. J. C. Spreeuw, and J. P. Woerdman, Phys. Rev. A 45, 8185–8189 (1992)
M. V. Berry, "Singularities in waves and rays," in Les Houches Session XXV - Physics of Defects, R. Balian, M. Kléman, and J.-P. Poirier, eds., (North-Holland, 1981)

Singularities in Optics

Polarization singularities – C (circular polarization) points or L (linear) lines

(Paraxially) propagating vectorial light beams – vortices and L-lines



Each has a polarization singularity at the center

- **Cylindrical vector beams can exhibit polarization singularities on-axis**
- **Non-homogeneous polarization distribution**

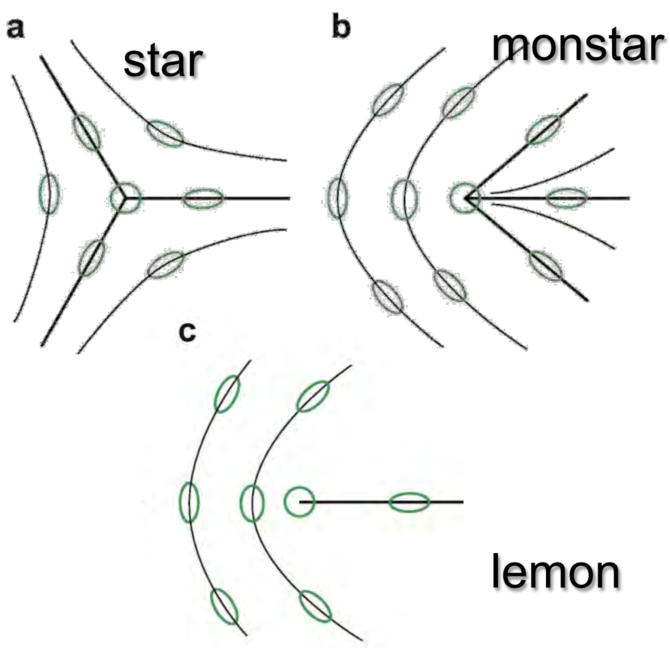
M. R. Dennis, Optics Communications 213, 201-221 (2002)
M. R. Dennis, "Topological Singularities in Wave Fields," PhD thesis, University of Bristol, 2001

Singularities in Optics

Polarization singularities – C points or L lines – introduced by Nye[1-4]

Bright singular points/lines in wave fields or beams

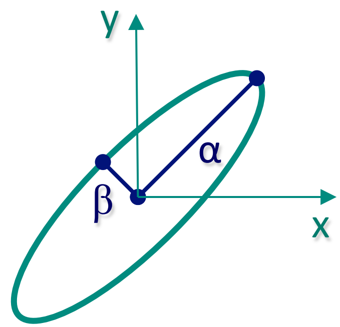
2D Ellipse-fields[5] Each shows a C point)



Definition of polarization ellipse

(Berry's equations[6])

$$\alpha = Re(\mathbf{E}^*(\mathbf{E}\cdot\mathbf{E})^{1/2})$$
$$\beta = Im(\mathbf{E}^*(\mathbf{E}\cdot\mathbf{E})^{1/2})$$
$$\gamma = Im(\mathbf{E}^* \times \mathbf{E})$$



At a C point:

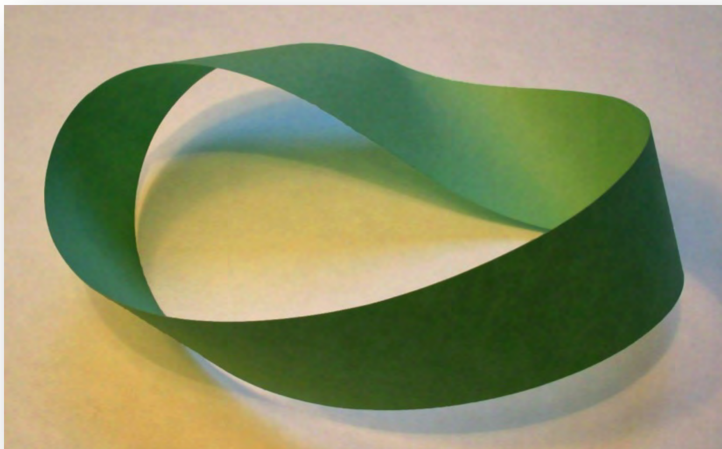
$\alpha = \beta$

Hence, orientation of the polarization ellipse is undefined (singular)

[1] J.F. Nye, Proc. R. Soc. London A 389, 279 (1983)
[2] J.F. Nye, Proc. R. Soc. London A 387, 105 (1983)
[3] J.F. Nye, J.V. Hajnal, Proc. R. Soc. London A 409, 21 (1987)
[4] J.F. Nye, Natural focusing and fine structure of light: caustics and wave dislocations, Institute of Physics Publishing, Bristol, 1999
M.V. Berry, M.R. Dennis, Proc. R. Soc. London A 457, 141 (2001)
[5] I.O. Buinyi, V.G. Denisenko, M.S. Soskin, Optics Communications 282, 143–155 (2009)
[6] M.V. Berry, in: M.S. Soskin, M.V. Vasnetsov (Eds.), Second International Conference on Singular Optics, Proc. SPIE, 4403, 2001, p. 1. etc.

Optical Möbius Strips – When Light Turns One-Sided and Single-Edged

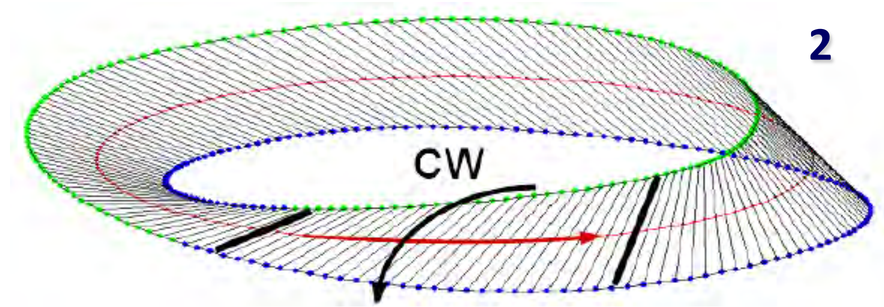
An 'ordinary' Möbius strip



1

A polarization Möbius strip
(introduced by Isaac Freund)

2



Isaac Freund discovered, described, and investiated these unusal objects

- **Optical Möbius strips can be found in light fields**
- **One has to look at a very special field distribution in a very special way**
- **By doing so, one can observe optical Möbius strips in the field structure**

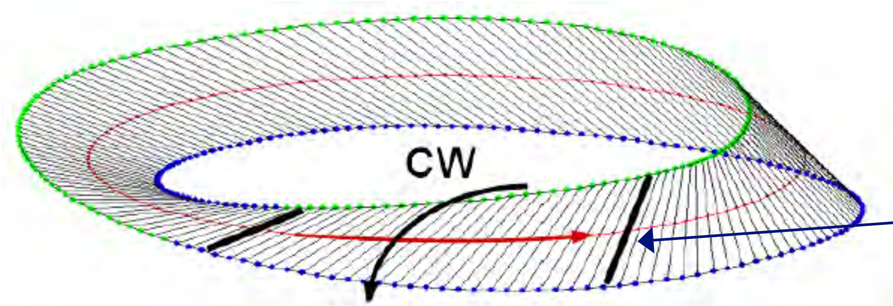
[1] Wikipedia

[2] Isaac Freund, Bar-Ilan Univ., Talk: *Optical Moebius Strips and Twisted Ribbons*, Conf. on Singular Optics, ICTP Trieste, Part II, 30 May 2011

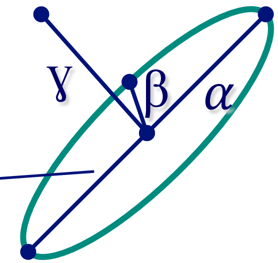
Isaac Freund, Opt. Commun. 242, 65-78 (2004)
Isaac Freund, Opt. Commun. 249, 7-22 (2005)
Isaac Freund, Opt. Commun. 256, 220-241 (2005)
Isaac Freund, Opt. Commun. 283, 1-15 (2010)
Isaac Freund, Opt. Commun. 283, 16-28 (2010)
Isaac Freund, Opt. Lett. 35, 148-150 (2010)
Isaac Freund, Opt. Commun. 284, 3816-3845 (2011)

Optical Möbius Strips – When Light Turns One-Sided and Single-Edged

A polarization Möbius strip



Polarization ellipse



- **Form a circle in the transverse plane around the C-point (think of the star structure) in the 3D electric field distribution**
- **Plot the polarization ellipse along this trace**
- **Look at the twists and turns of the polarization ellipses**
- **Observe a Möbius strip (number of turns depend on the chosen trace and the field)**

Close to the C-point, the orientation of the long axis is undefined (singular)

Optical Möbius Strips – When Light Turns One-Sided and Single-Edged

To the best of our knowledge, such an optical polarization Möbius strip has not previously been demonstrated experimentally.

that increase radially from the C point. These Möbius strips are structurally stable, changing unimportantly when, for example, 3% noise is added to the simulation. Coherent nanoprobe techniques [11–19] capable of determining the field structure on subwavelength scales should permit experimental measurements of these highly unusual objects.

I. Freund, Opt. Lett. 35, Issue 2, 148-150 (2010)
I. Freund, arXiv:0910.1663v1

Our contribution:

- We have developed a (coherent) nanoprobing technique to measure (highly confined) field distributions at the nanoscale
- We adapt the beam configuration proposed by I. Freund to be implement our measurement scheme
- Need either an angle between two beams or one tightly focused beam; we do the latter.

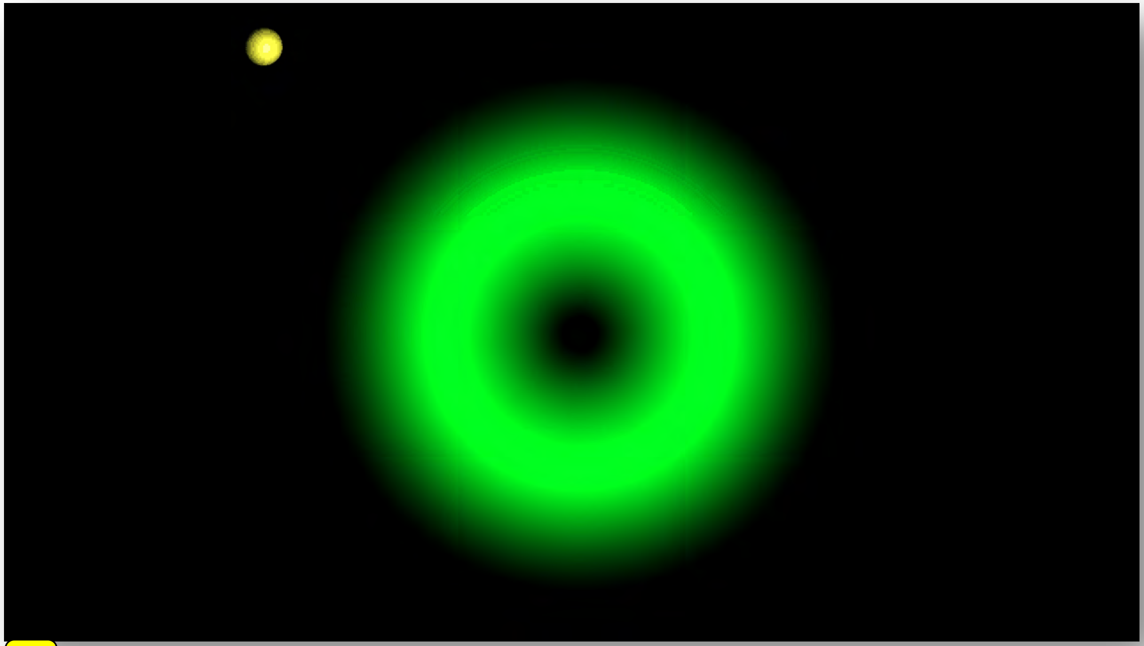
Our recipe:

- **Tight focusing (highly non-paraxial propagation) of a (multimode) light beam with a specially tailored polarization and phase distribution**
- **Generation of a complex 3-dimensional field distribution in the focal plane containing optical polarization Möbius strips**
- **Measurement of the focal field distribution and visualization of the Möbius strip**

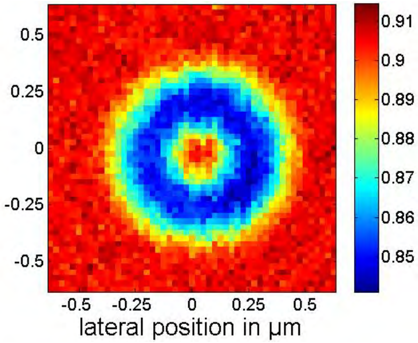
Full vectorial beam measurement on the nanoscale

Nanoparticle-based probing technique for vector beam reconstruction

1. A dipole-like spherical nanoparticle (90 nm diameter) is scanned through the beam
2. The forward- and backward-scattered light for each position of the nanoparticle relative to the beam in the focal plane is measured



measured intensity
(can also measure
polarization and phase)

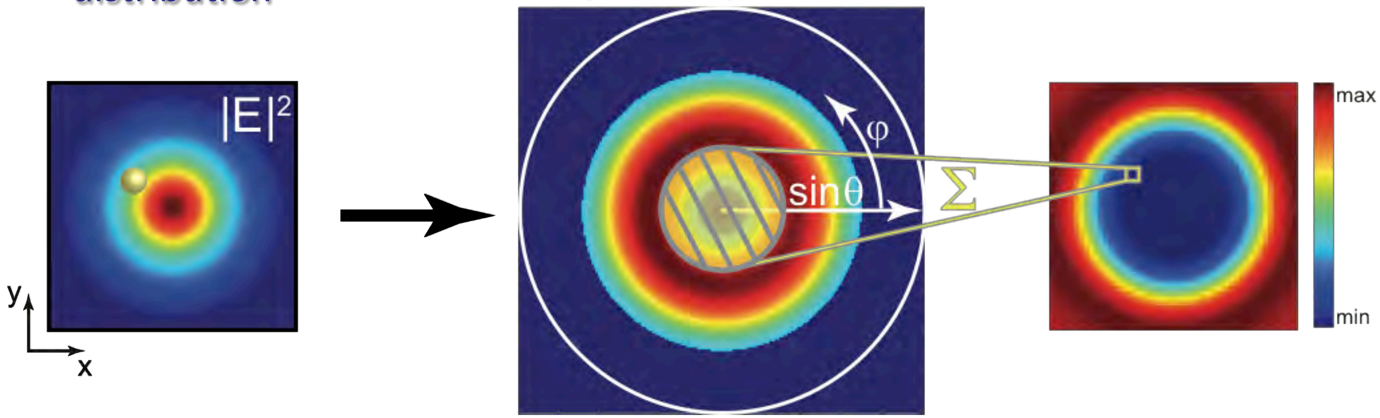


Full amplitude and phase reconstruction scheme:

T. Bauer, S. Orlov, U. Peschel, P. B. and G. Leuchs, "Nanointerferometric Amplitude and Phase Reconstruction of Tightly Focused Vector Beams", Nat. Photon 8, 23 - 27 (2014).

Full vectorial beam reconstruction on the nanoscale

2D-scanning of particle through focal plane:



- Scan scattering particle through focal plane
- Collect k-spectrum of transmitted light (image back-focal plane of objective lens) for each position of the particle relative to the beam in the focal plane $\mathrm{P_T}(\theta,\varphi) = \mathrm{P_{in}}(\theta,\varphi) + \mathrm{P_s}(\theta,\varphi) + \mathrm{P_{int}}(\theta,\varphi)$
- Reduce complexity by integrating over specific sectors
- free parameters: λ, r_{sphere}, ε_m, ε_{gold}, number of multipoles

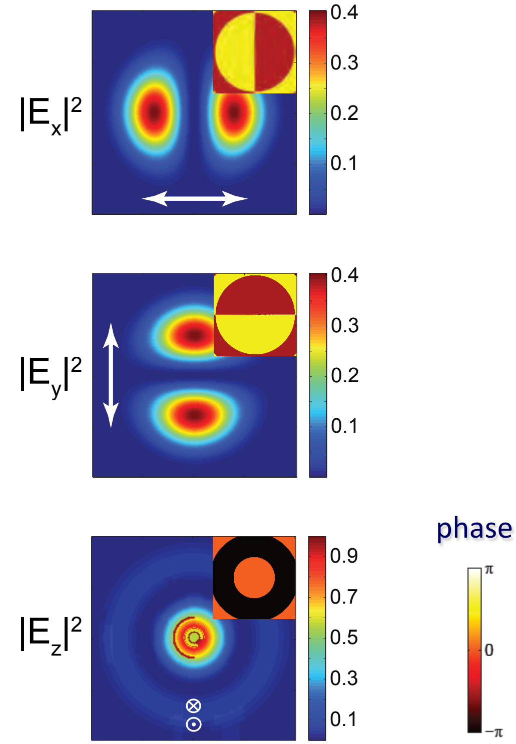
 T. Bauer, S. Orlov, U. Peschel, P. B. and G. Leuchs, Nat. Photon 8, 23 - 27 (2014).

Full vectorial beam reconstruction on the nanoscale

Exemplary result for a <u>tightly focused radially polarized light beam</u>

Full-field (amplitude and phase) distributions reconstructed from experimental nanoprobing data

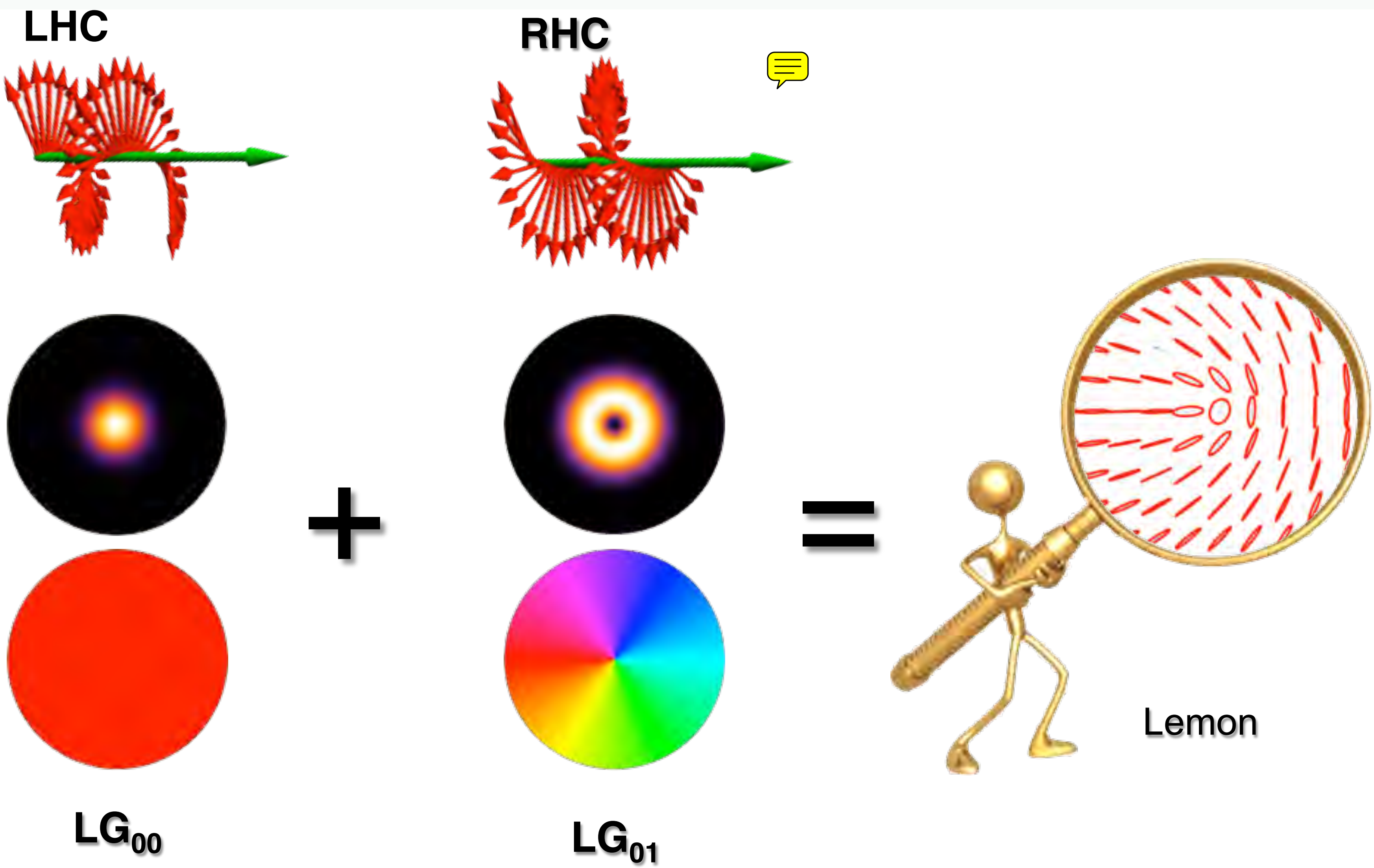
focal field distribution via vectorial diffraction theory



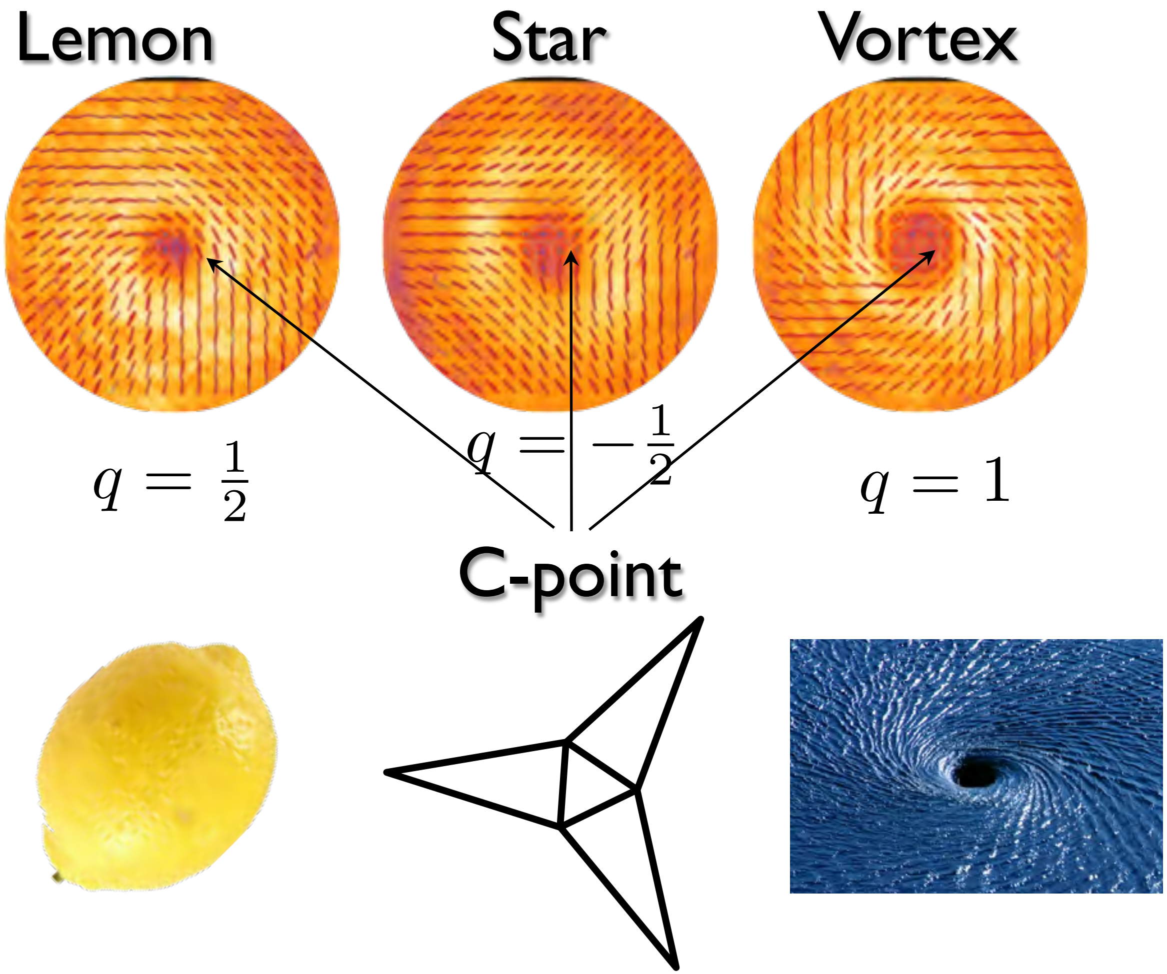
wavelength: 530 nm; particle diameter: 82 nm; focusing numerical aperture: 0.9; 8 multipole orders

 T. Bauer, S. Orlov, U. Peschel, P. B. and G. Leuchs, Nat. Photon 8, 23 - 27 (2014).

Our Experimental Procedure: Superposition of Two Beams



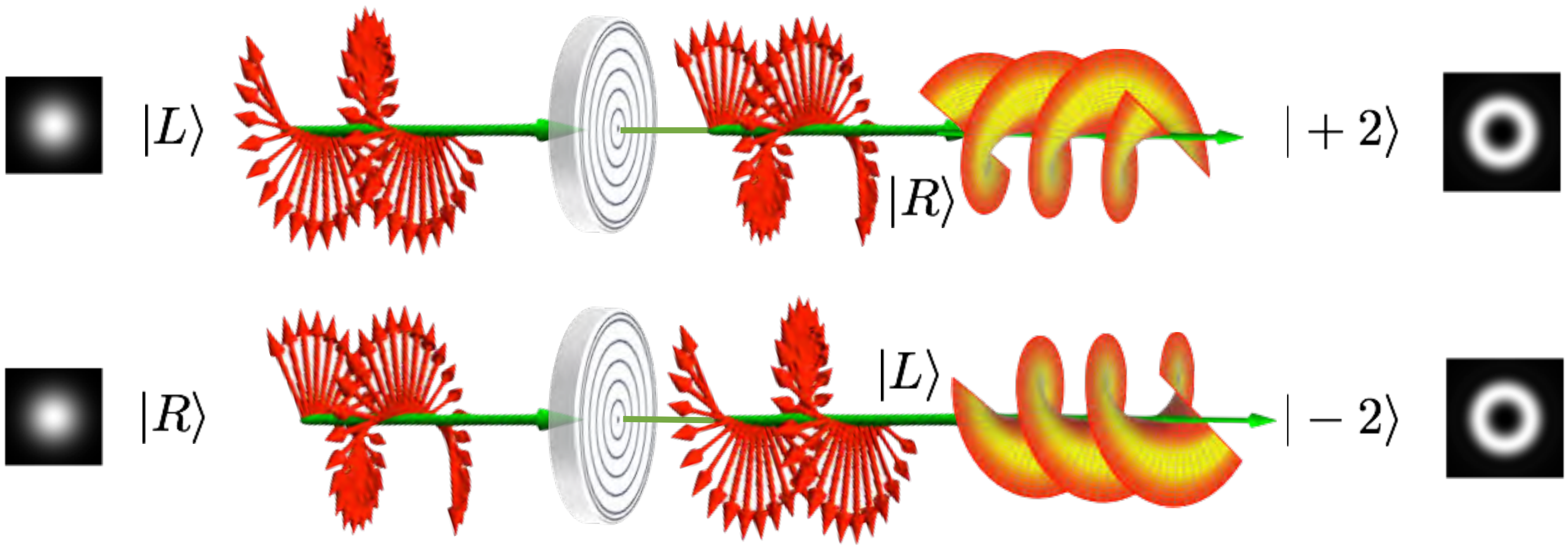
Poincaré Beams
(Vector Beams)



Cardano F, Karimi E, Slussarenko S, Marrucci L, de Lisio C, and Santamato E, *Applied Optics*, **51**, C1 (2012).

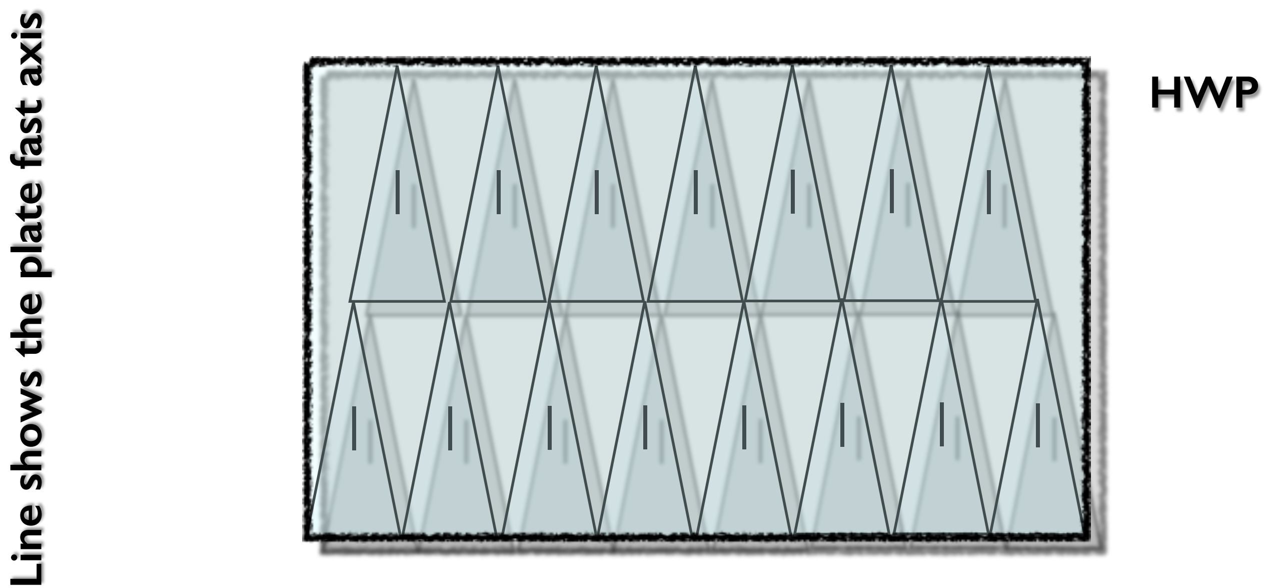
We use q-plates to form vector beams

Action of a q=1 q-plate

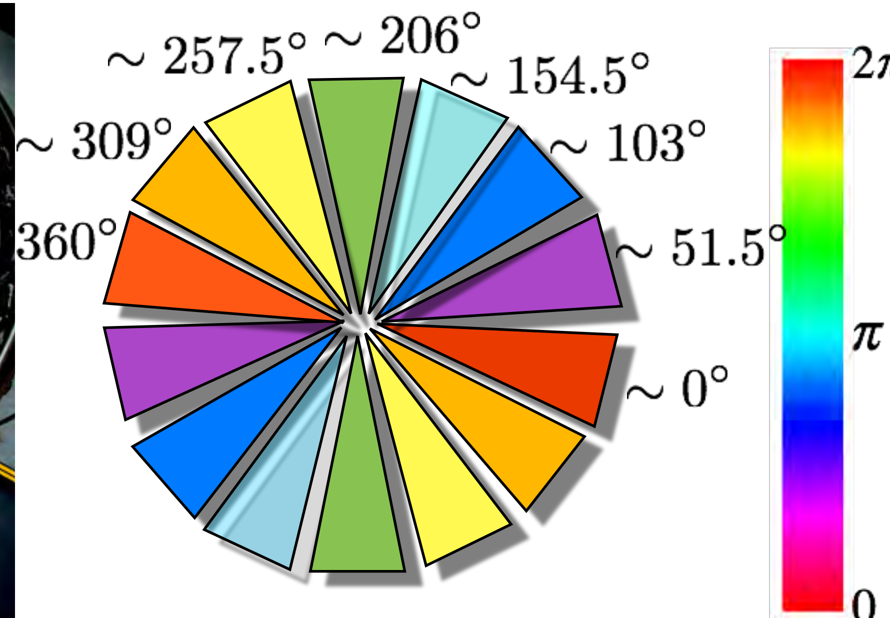


Marrucci L, et al., *PRL* **96**, 163905 (2006).
Karimi E et al., *APL* **98**, 231124 (2009).
Karimi E, et al., *OL* **34**, 1225 (2009).

$q=1$-plate



$q=1$-plate

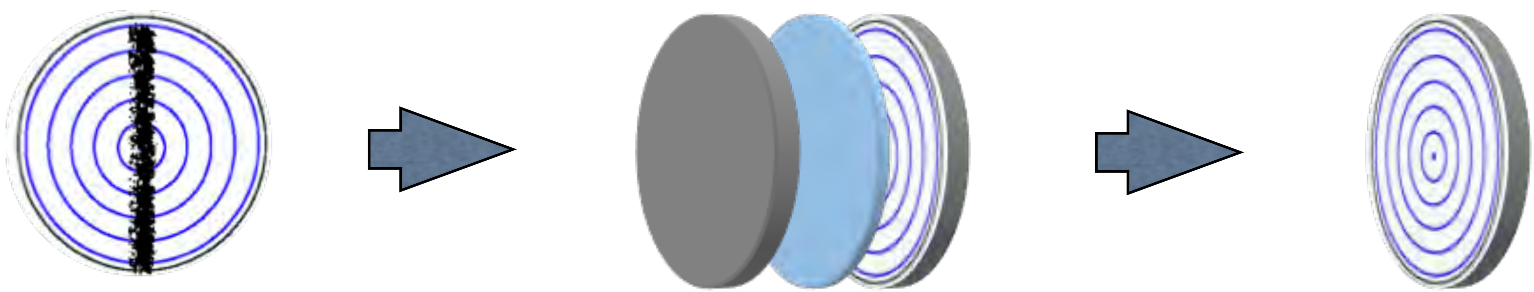


Output phase structure

Marrucci L, et al., *PRL* **96**, 163905 (2006).
Karimi E et al., *APL* **98**, 231124 (2009).
Karimi E, et al., *OL* **34**, 1225 (2009).

Fabricating a $q=1$-plate

How can we generate the *q*-plate? Liquid crystal

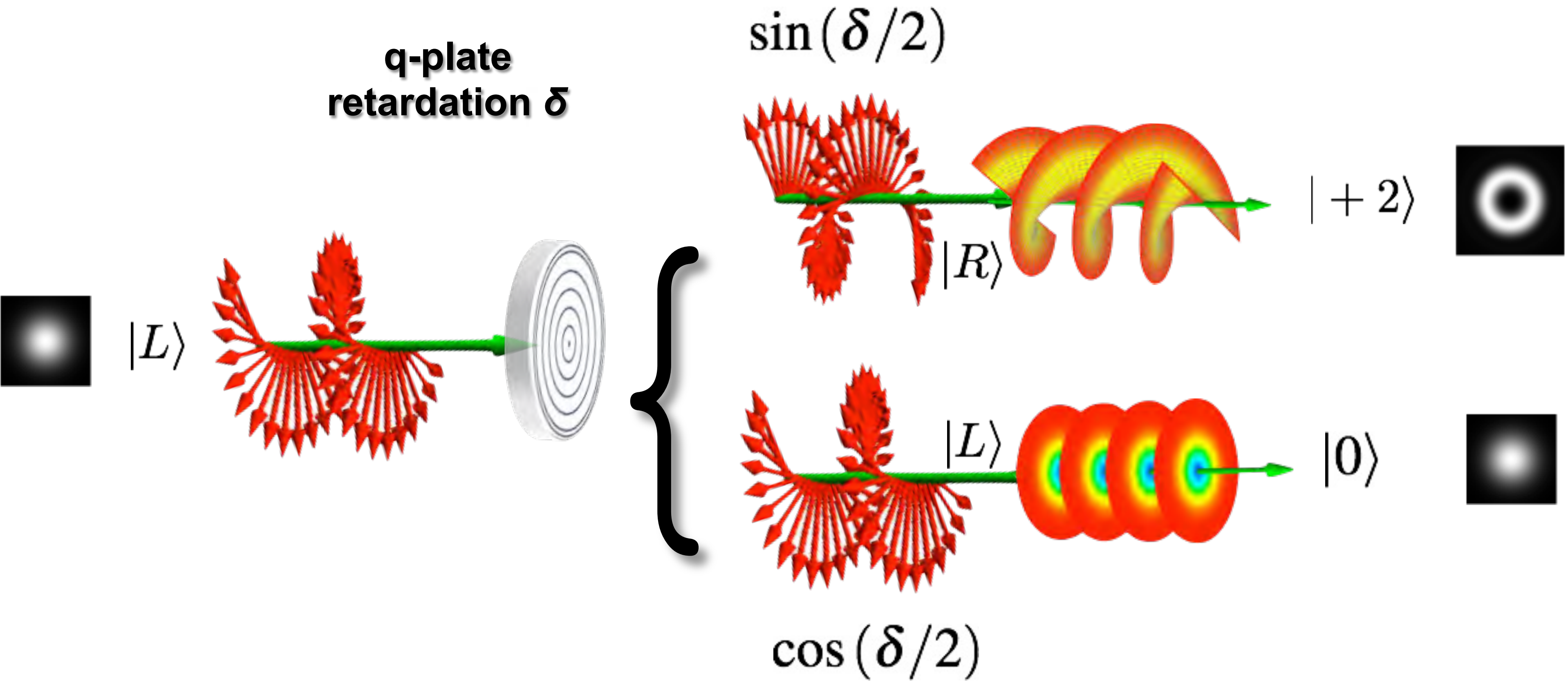


Rubbing technique:
glass coated with polymer

LC

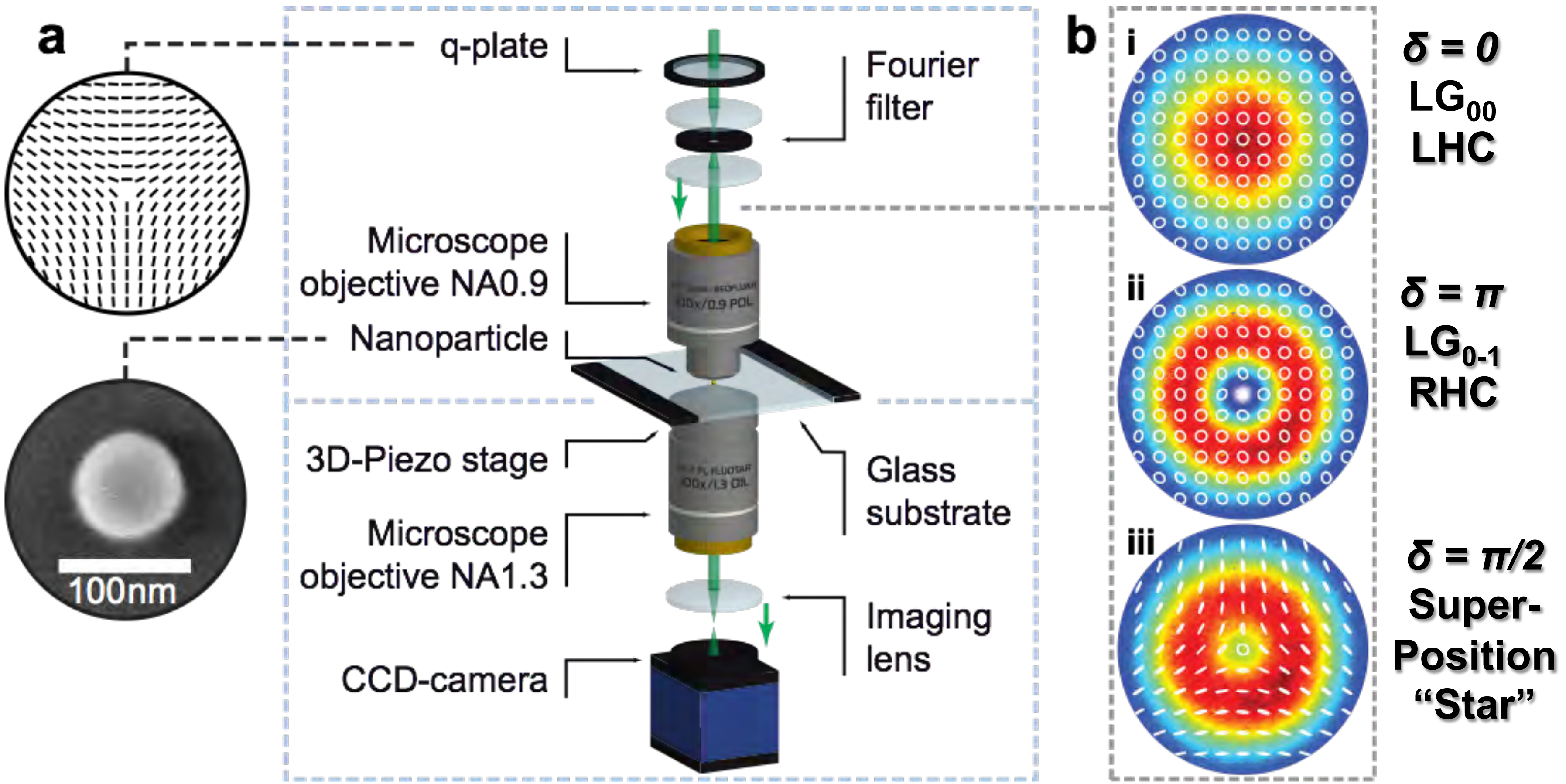
$q=1$ plate

We Use a q-Plate to Form our Vector Beams



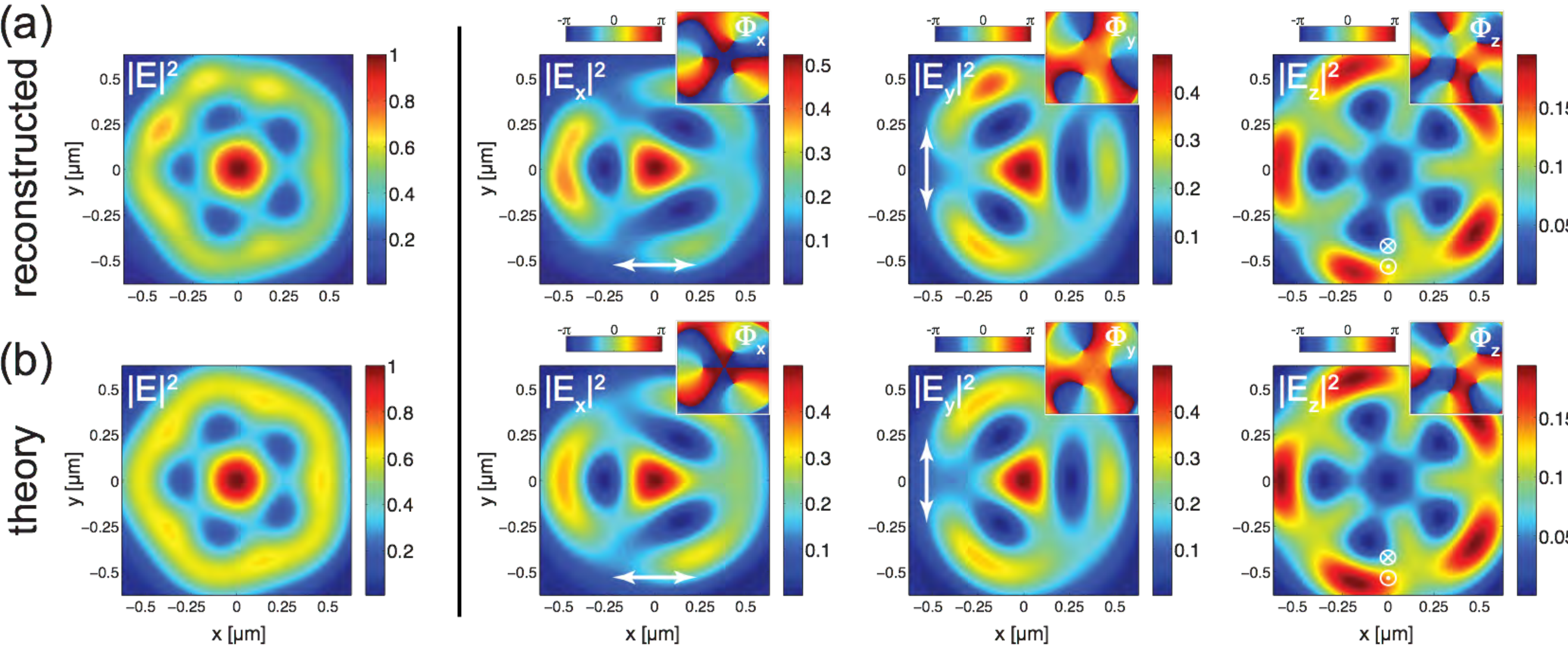
Cardano F, Karimi E, Slussarenko S, Marrucci L, de Lisio C, and Santamato E, *Optics Express* **21**, 8815 (2013)

Observing a Polarization Möbius Strip



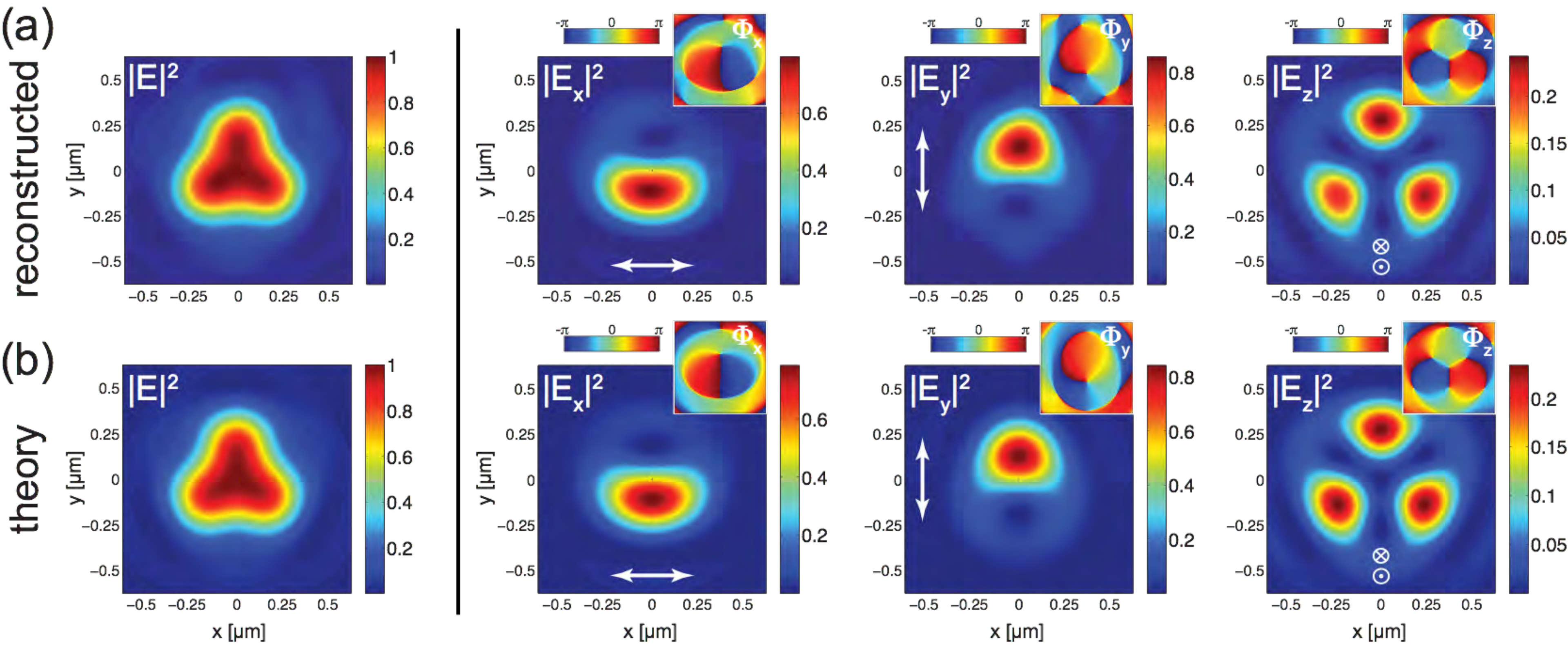
Bauer T, Banzer P, Karimi E, Orlovas S, Rubano A, Marrucci L, Santamato E, Boyd RW, and Leuchs G, *under review.*

Field distribution for “star” beam, q = -3/2



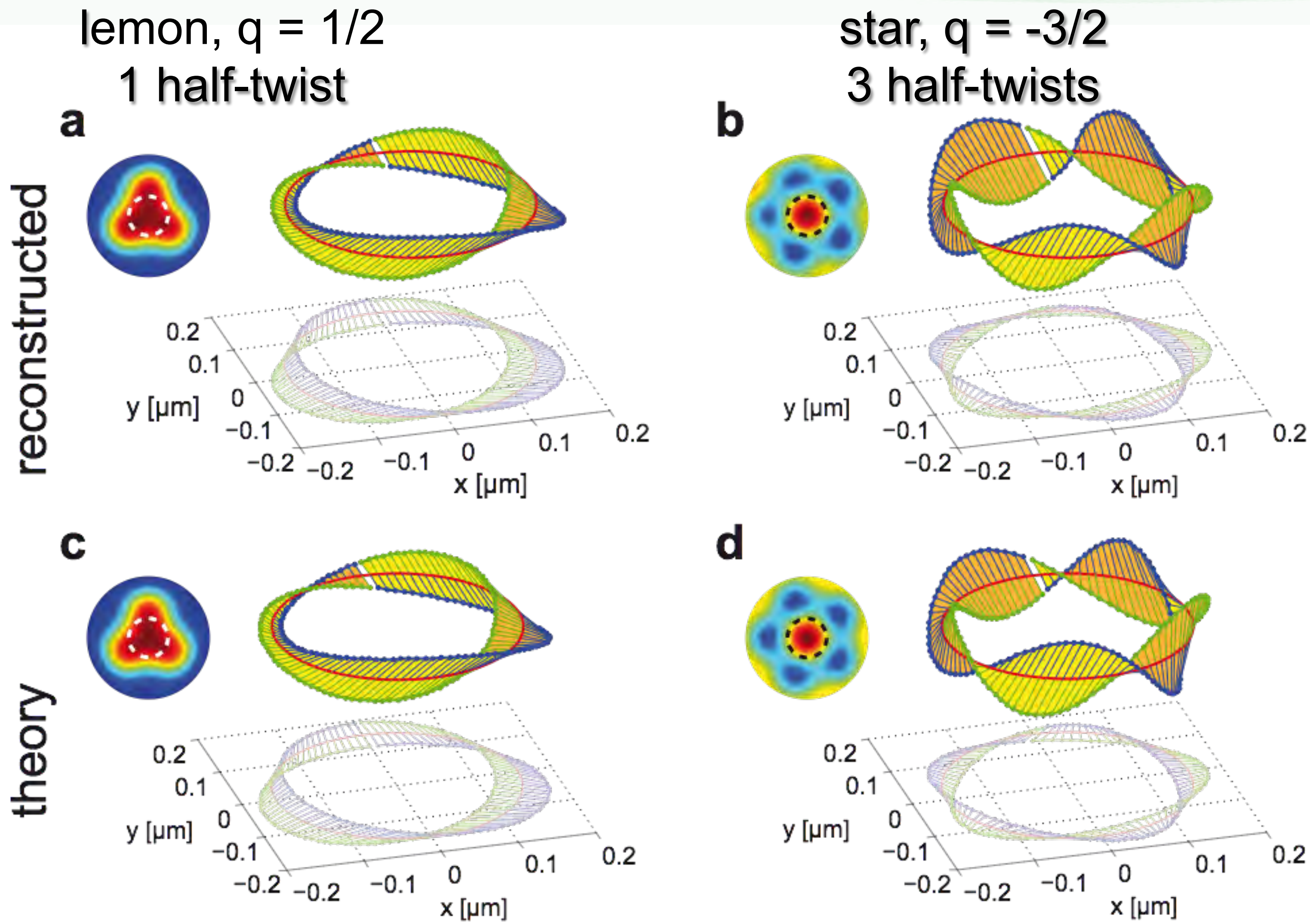
Bauer T, Banzer P, Karimi E, Orlovas S, Rubano A, Marrucci L, Santamato E, Boyd RW, and Leuchs G, *under review*.

Field distribution for “lemon” beam, q = 1/2



Bauer T, Banzer P, Karimi E, Orlovas S, Rubano A, Marrucci L, Santamato E, Boyd RW, and Leuchs G, *under review*.

Möbius strips with half-twists

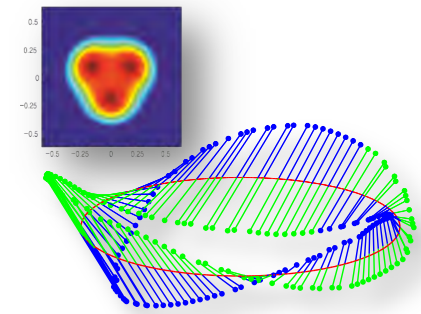


number of half twists= 2|q-1|

Bauer T, Banzer P, Karimi E, Orlovas S, Rubano A, Marrucci L, Santamato E, Boyd RW, and Leuchs G, *in review*.

Conclusions

- **Generation and investigation of an optical polarization Möbius strip in tightly focused light beams**



- **Experimental observation using a particle-based nanoprobing technique**