School of Modern Optics

8 May 2013, Puebla, Mexico

Lecture 3

Optical vortex generation using liquid crystals I

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www.loma.cnrs.fr/spip.php?rubrique331

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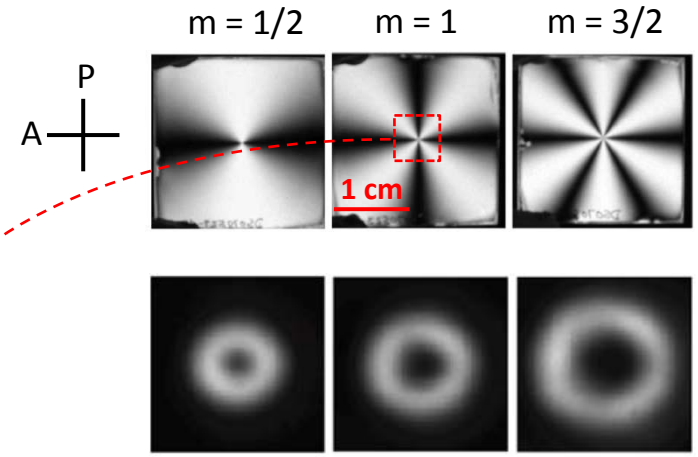
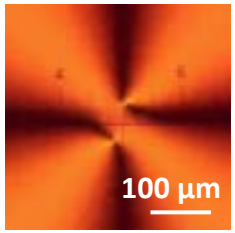
Introduction : artificial liquid crystal spin-orbit vortex generators



S.C. McEldowney *et al.*, Opt. Lett. **33**, 134 (2008)

Topological structure characterization

Optical vortex generation



D. Mawet *et al.*, Opt. Express **17**, 1902 (2009)

Topology is not controlled at microscale

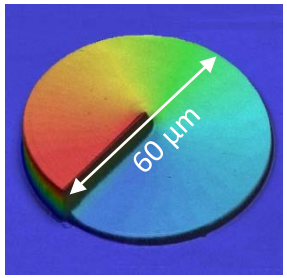
High-tech doable : direct laser writing

In photopolymers

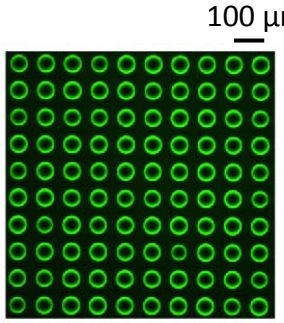
E. Brasselet *et al.*, Appl. Phys. Lett. **97**, 211108 (2010)

In glasses

E. Brasselet *et al.*, Appl. Phys. Lett. **100**, 181901 (2012)



Micro spiral plates



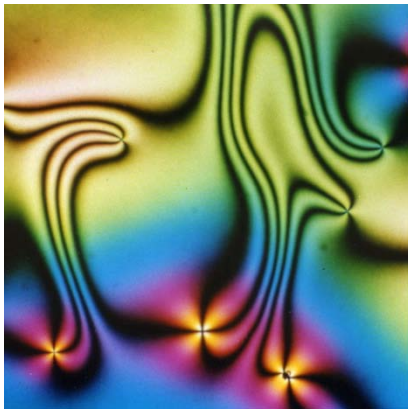
Micro spin-orbit vortex generators

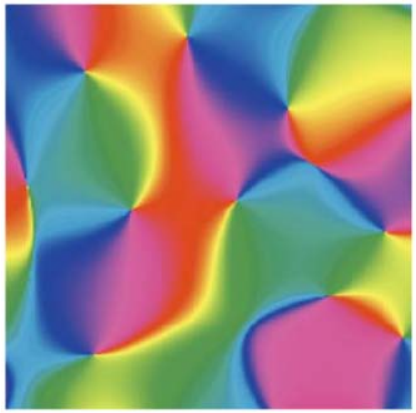
Targeted features towards singular integrated optical elements :

Small size - Easy fabrication
Reconfigurable - Tunable
Large scale integration capabilities (arrays)

Imprinting material topological information on light

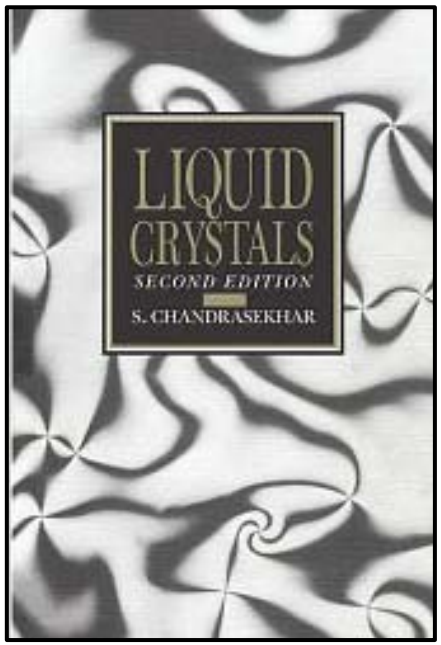
Liquid crystal defects

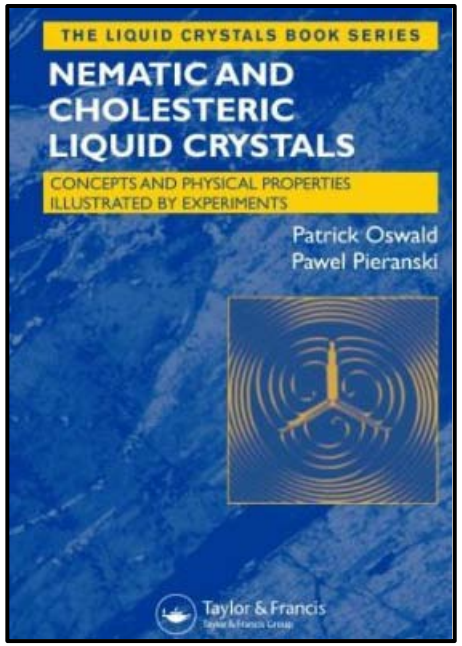


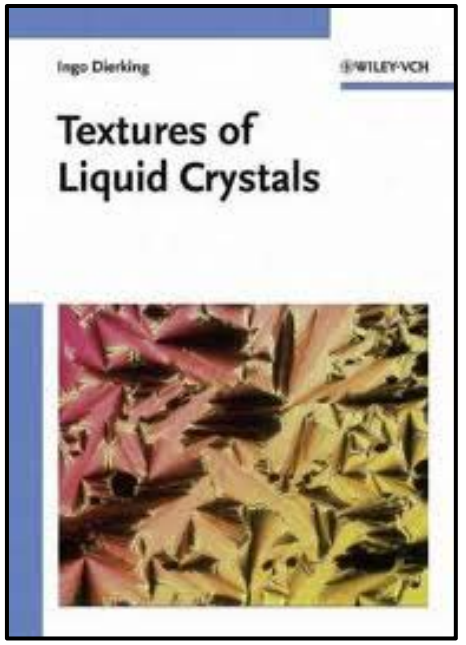


Optical phase singularities

Characteristic feature of self-organization in soft matter







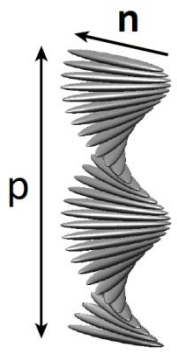
Outline

1. **Self-engineering strategy : nature at work**
2. Material topological diversity benefits
3. Self-engineering strategy : the electrical case
4. Tunable optical vortex arrays from a single defect

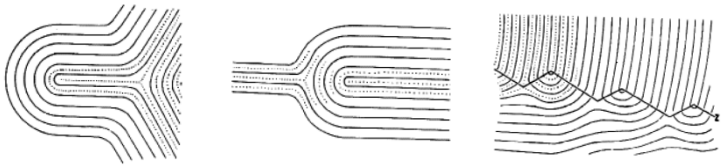
Natural engineering : liquid crystal topological defects

Nematic mesophase + chiral agent = cholesteric mesophase

Helical orientational order with pitch « p »

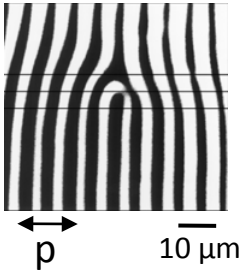


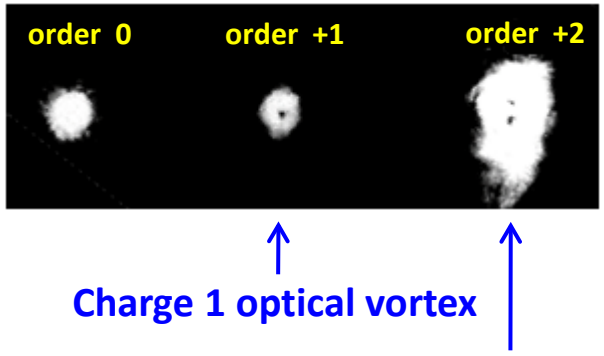
Many kinds of defect structures can be observed



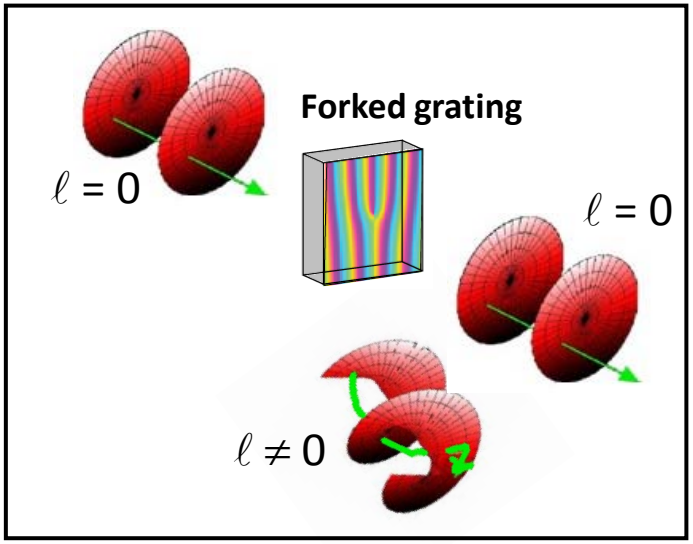
Y. Bouligand, J. Physique (France) **34**, 603(1973)

Dislocations in cholesterics

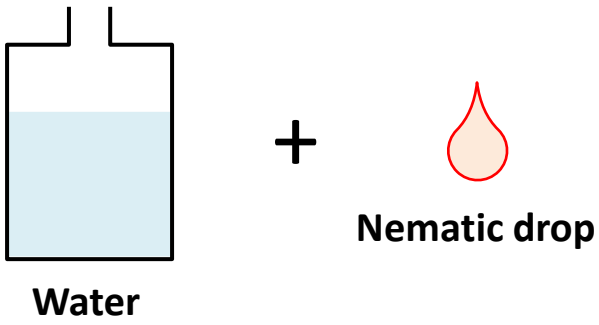




D. Voloschenko *et al.*, Opt. Lett. **25**, 317 (2000)



How to prepare a spherical liquid crystal droplet ?

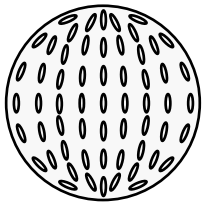


Emulsion of nematic droplets

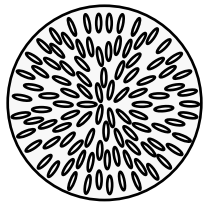
Natural engineering : the case of nematic droplets

Two main kinds of droplets depending on the anchoring boundary conditions

Bipolar droplet



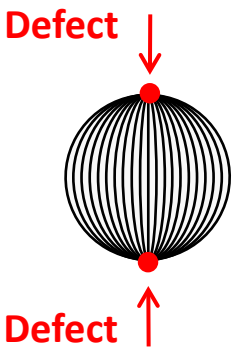
Parallel anchoring

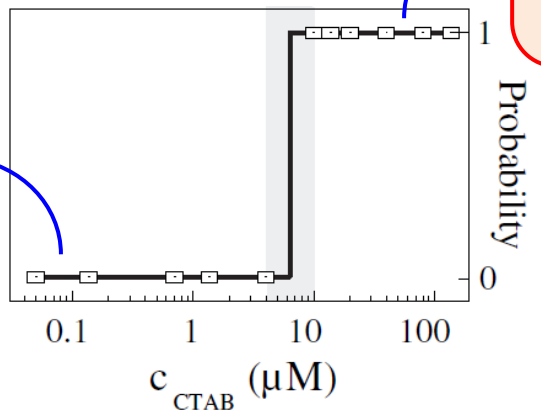


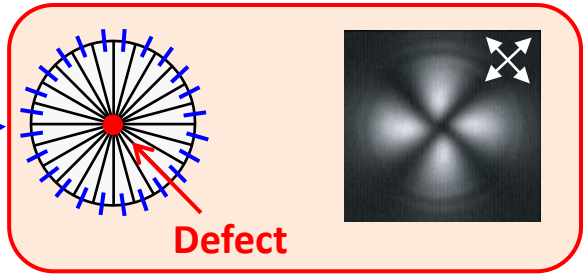
Radial droplet

Perpendicular anchoring

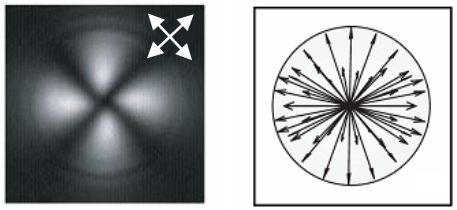
Preparation in water + surfactant

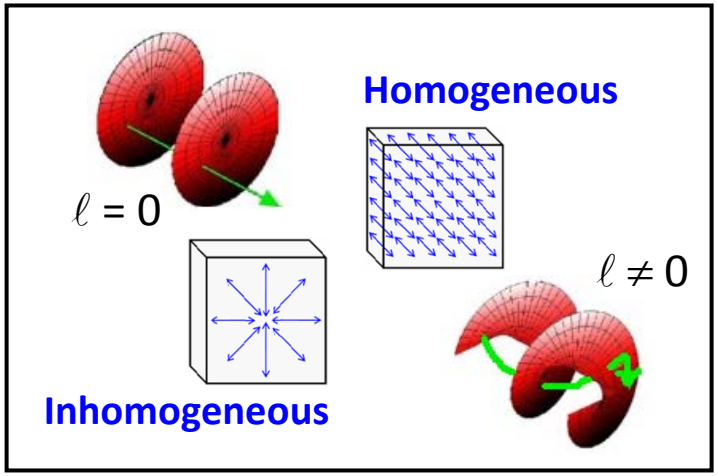






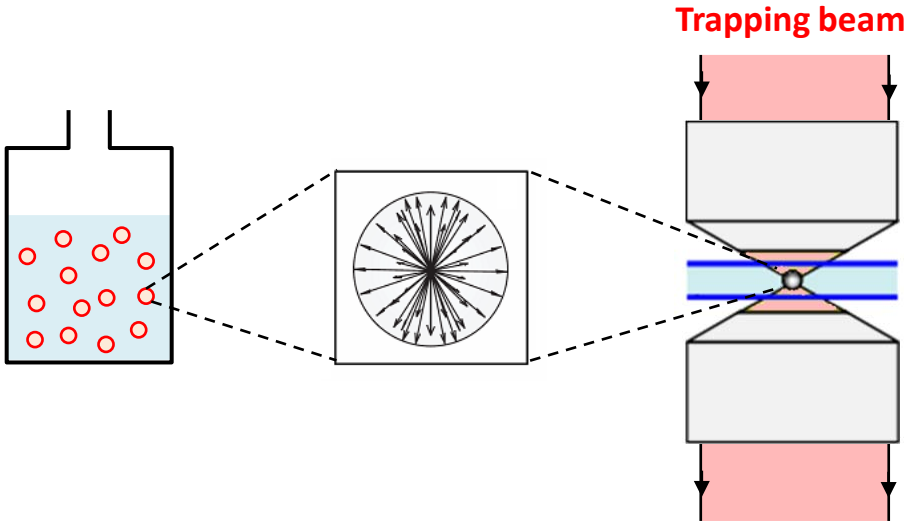
Hedgehog point defects in a radial nematic droplet





Microscopic 3D spin-to-orbital angular momentum converter

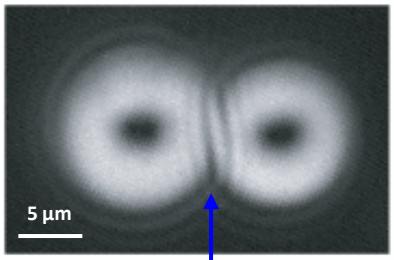
Experiment : qualitative observation



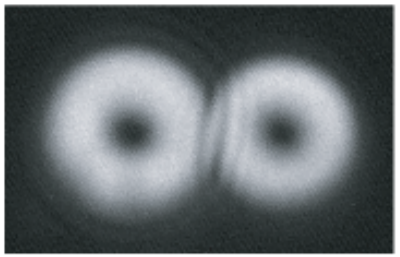
Radial nematic droplet in optical tweezers

TWO-BEAM interference pattern

Left-In / Right-Out



Right-In / Left-Out

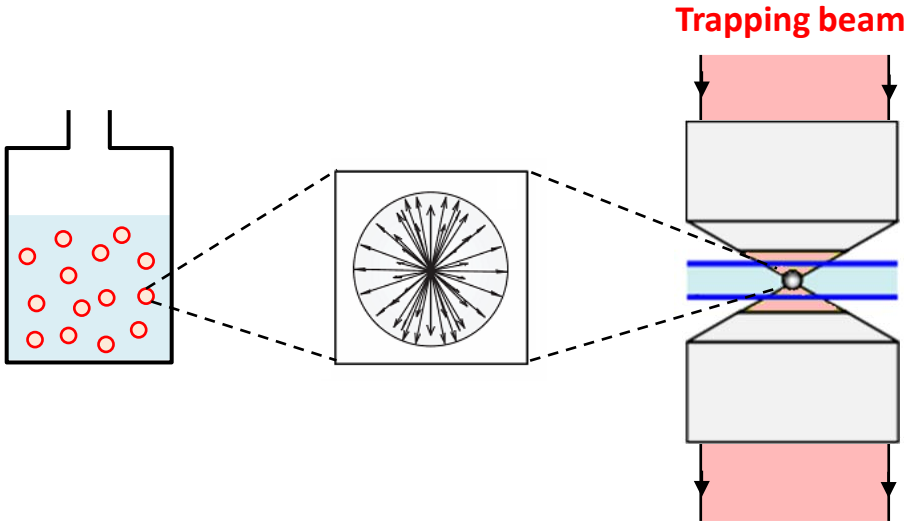


Curved fringes

Signature of azimuthal phase dependence

E. Brasselet *et al.*, PRL **103**, 103903 (2009)

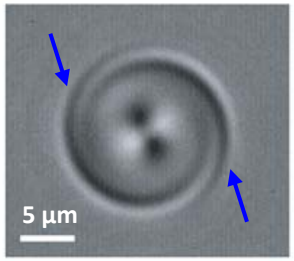
Experiment : qualitative observation



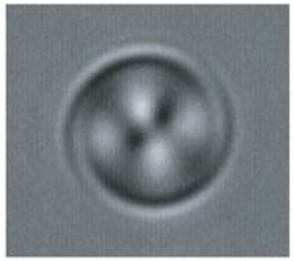
Radial nematic droplet in optical tweezers

SINGLE-BEAM interference pattern

Left-In / Linear-Out



Right-In / Linear-Out



Two-arm spiraling fringes

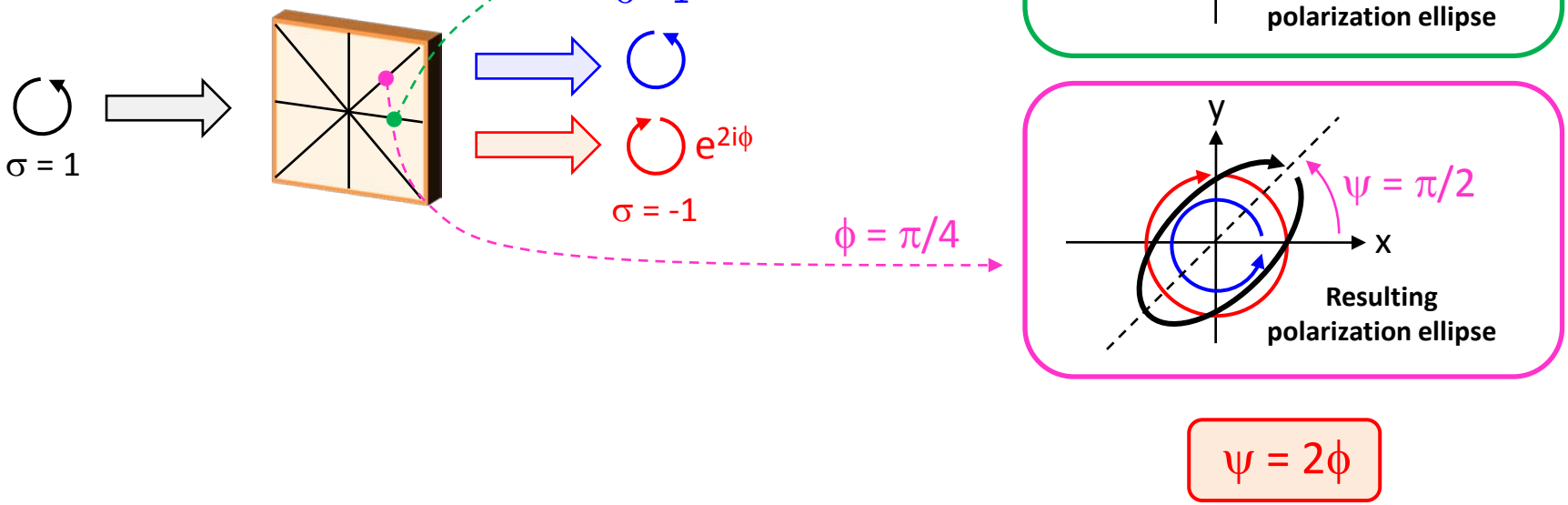
Signature of topological charge ±2

E. Brasselet *et al.*, PRL **103**, 103903 (2009)

Experiment : how to measure quantitatively the vortex phase profile ?

Case study : the radial nematic plate

Inhomogeneous output polarization state



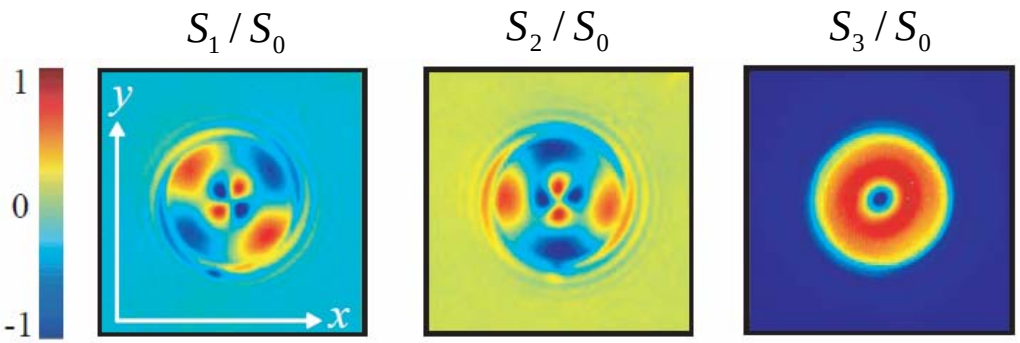
$\psi = 2\phi$

Polarization azimuth gives acces to vortex phase

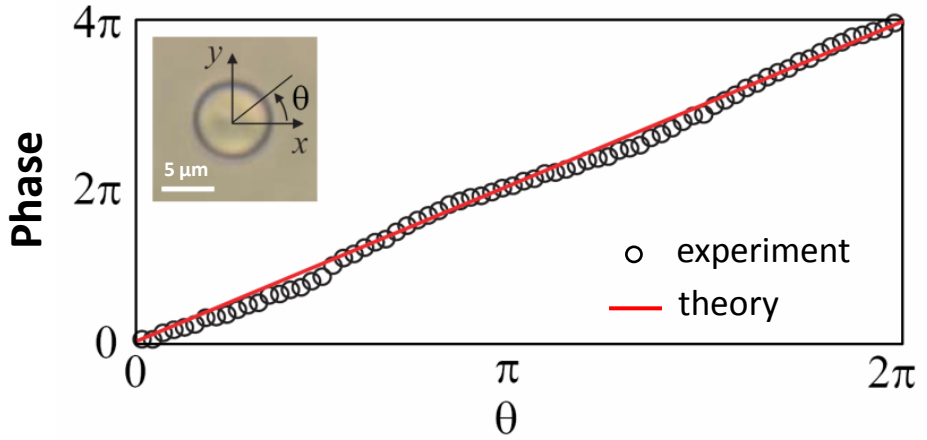
$$\psi = \frac{1}{2}\arctan(S_2/S_1)$$

Experiment : quantitative observation

Spatially resolved polarimetric imaging



Optical vortex phase = arctan(S_2/S_1)

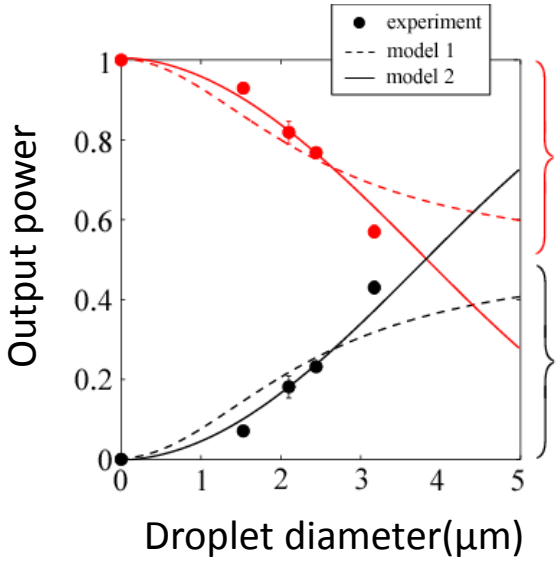


The phase uniformly winds by 4π around the defect : topological charge 2

E. Brasselet *et al.*, PRL **103**, 103903 (2009)

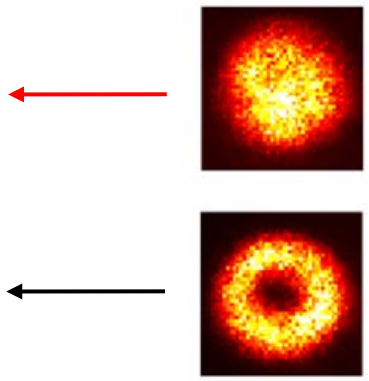
Figures of merit

(1/6) Vortex generation efficiency

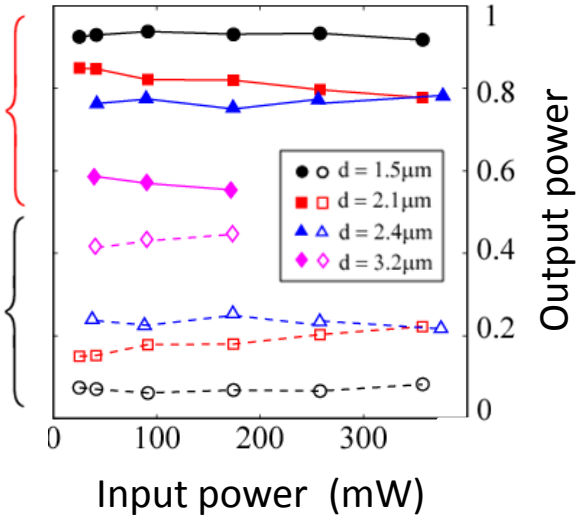


(2/6) Robustness to flux

Unconverted component



Converted component

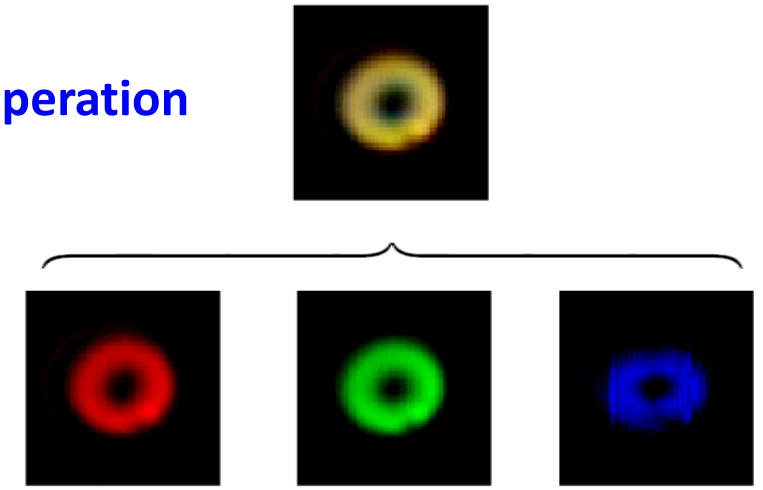


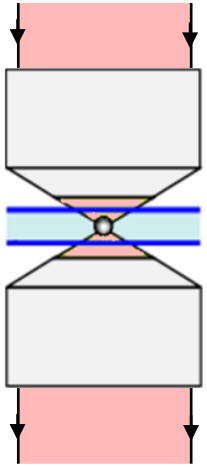
E. Brasselet *et al.*, PRL **103**, 103903 (2009)

Figures of merit

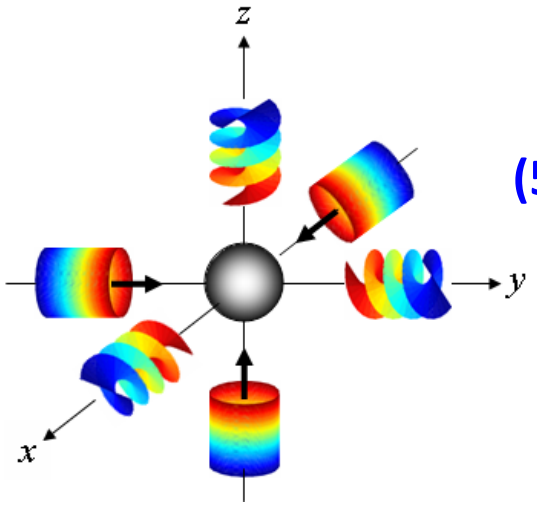
White light vortex

(3/6) Polychromatic operation





(4/6) Self-alignment

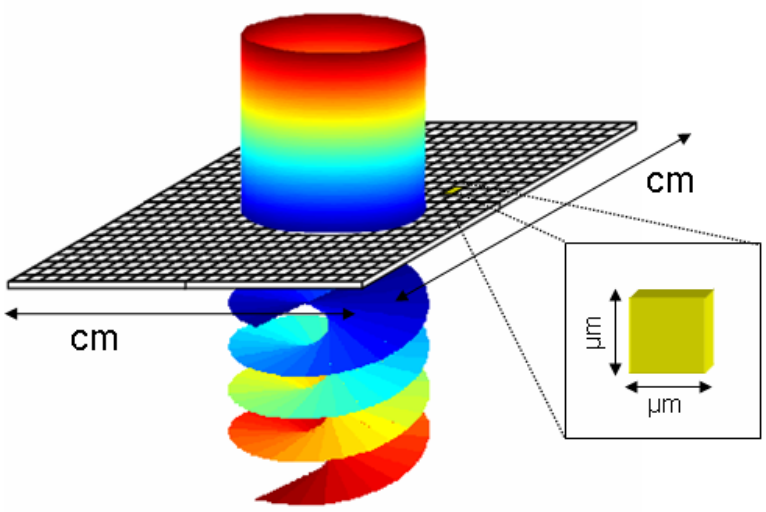


(5/6) Omnidirectionality

E. Brasselet *et al.*, PRL **103**, 103903 (2009)

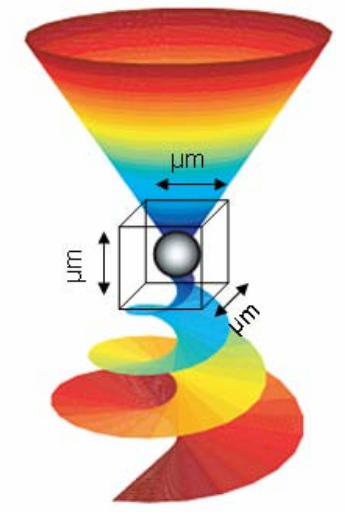
(6/6) Drastic downsizing : macroscale → microscale

Spatial light modulator



1 Megapixel

Self-engineered vortex generator



1 Voxel

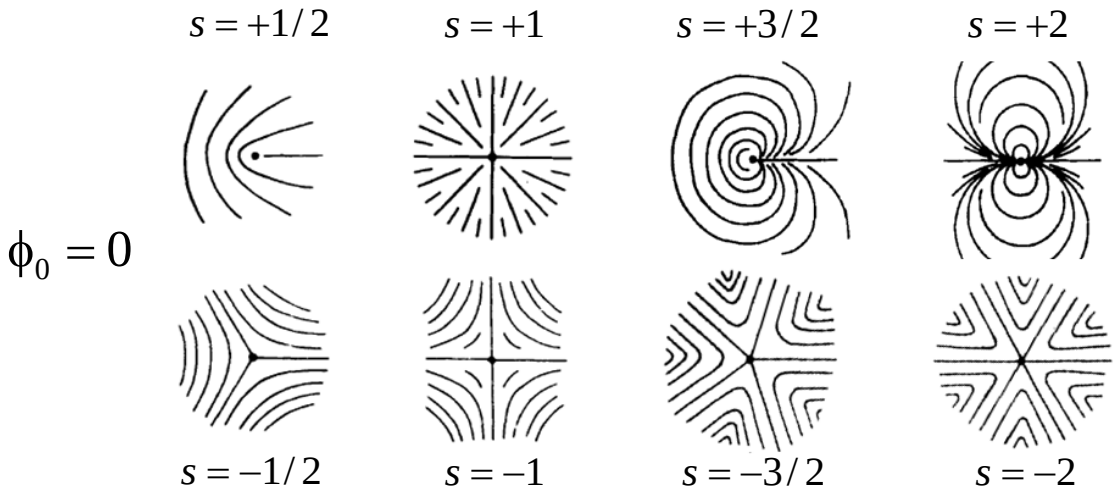
Nevertheless : topological charge limitations

Outline

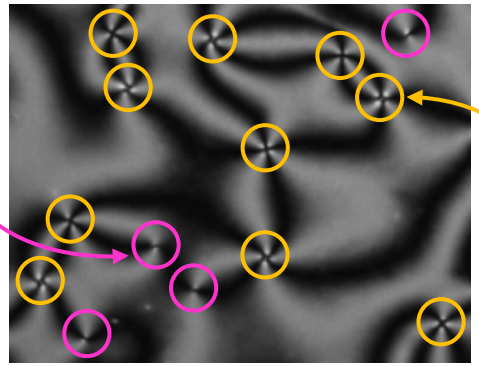
1. Self-engineering strategy : nature at work
2. **Material topological diversity benefits**
3. Self-engineering strategy : the electrical case
4. Tunable optical vortex arrays from a single defect

Azimuthal distribution of the director field

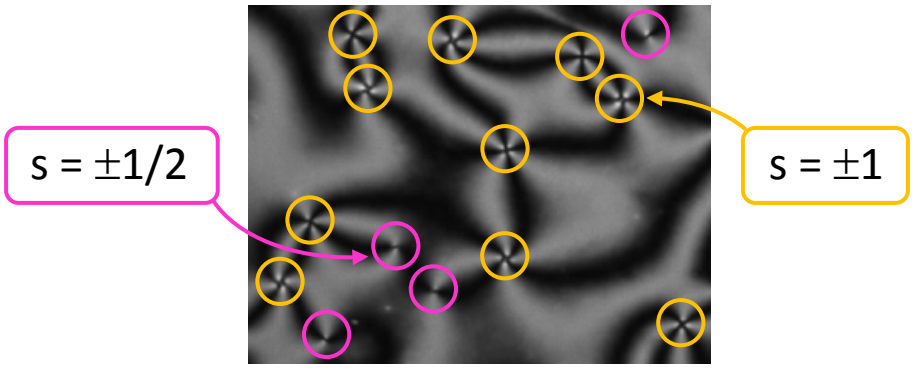
$$\psi = s\phi + \phi_0$$



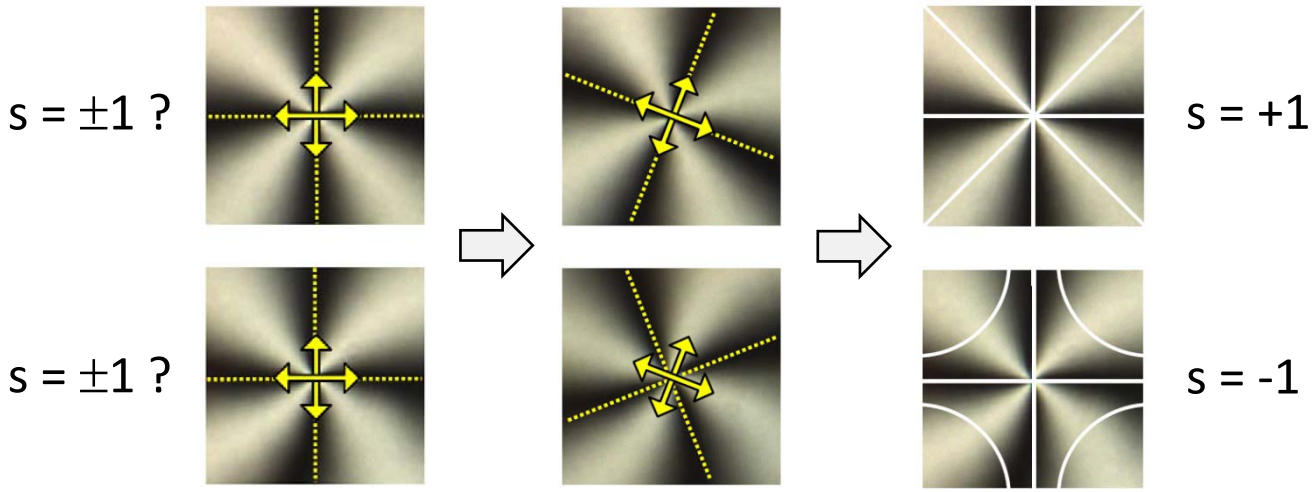
Between crossed polarizers



Between crossed polarizers

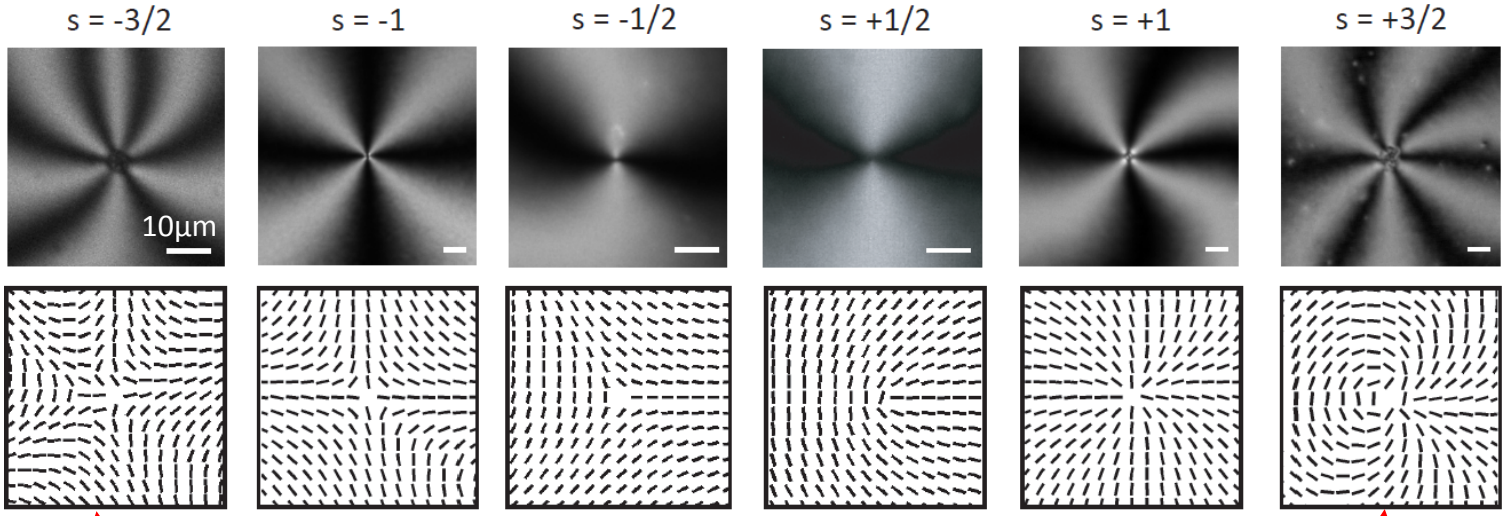


How to discriminate between diferent signs ?



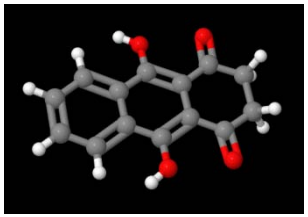
Schlieren spin-orbit micro-optical vortex generators

Experimental structural characterization



Unusual higher-order defects

Trick : doping nematic with a nonmesogenic dopant

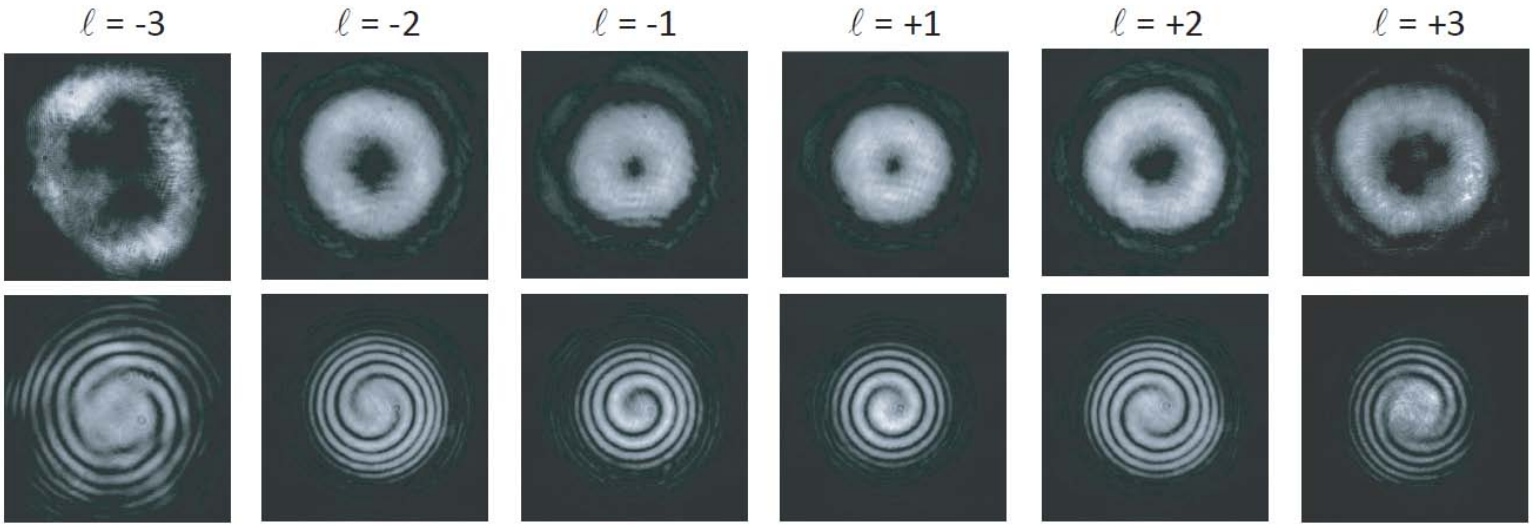


C. Loussert *et al.*, submitted.

Generation of scalar vortex beams

$$\Psi_{\sigma,0} \rightarrow \Psi_{-\sigma,\ell} \quad (\ell = 2\sigma s)$$

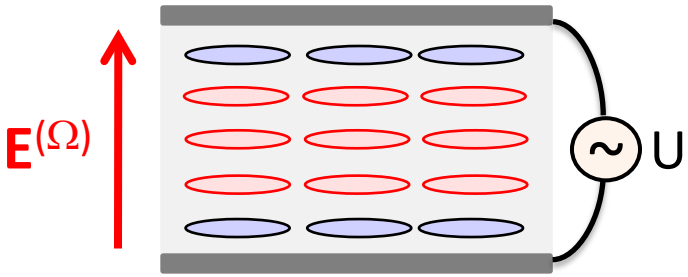
Spin state Orbital state



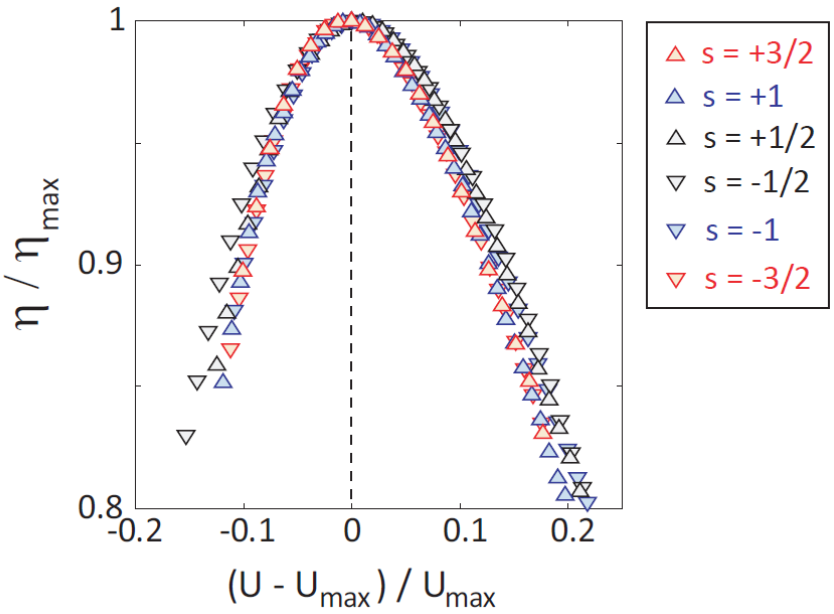
C. Loussert *et al.*, submitted.

How efficient is the vortex generation ?

Local parallel alignment



Electrically tunable efficiency



s	$-3/2$	-1	$-1/2$	$+1/2$	$+1$	$+3/2$
$\eta_{\max}$	94.5%	98.9%	99.1%	99.0%	99.2%	94.2%

C. Loussert *et al.*, submitted.

Generation of vector beams

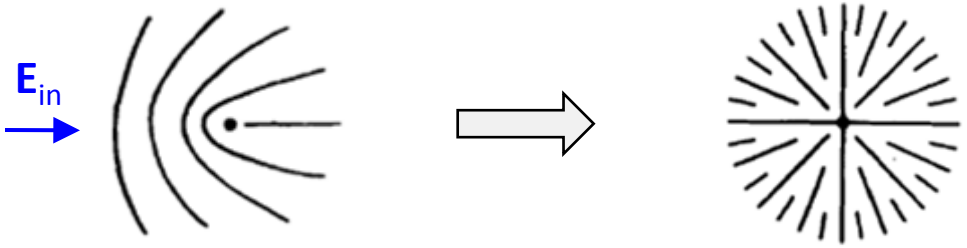
$$\frac{\Psi_{-1,0}+\Psi_{+1,0}}{\sqrt{2}} \rightarrow \frac{\Psi_{-1,\ell}+\Psi_{+1,-\ell}}{\sqrt{2}} \quad (\ell = 2s)$$

Superposition of spin states : linear polarization state

Inhomogeneous linear polarization state

Inhomogeneous λ/2 plate

Radial polarization state

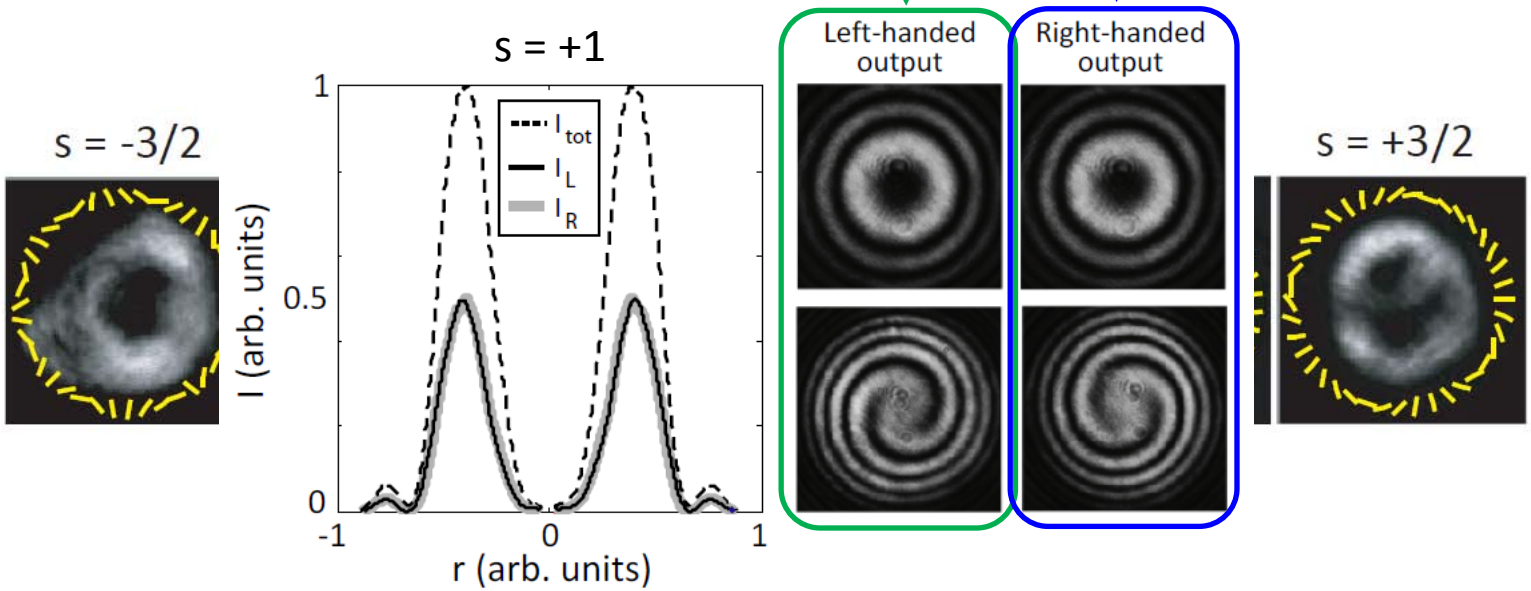


Director field

Electric field

Generation of vector beams

$$\frac{\Psi_{-1,0}+\Psi_{+1,0}}{\sqrt{2}} \rightarrow \frac{\Psi_{-1,\ell}+\Psi_{+1,-\ell}}{\sqrt{2}} \quad (\ell = 2s)$$



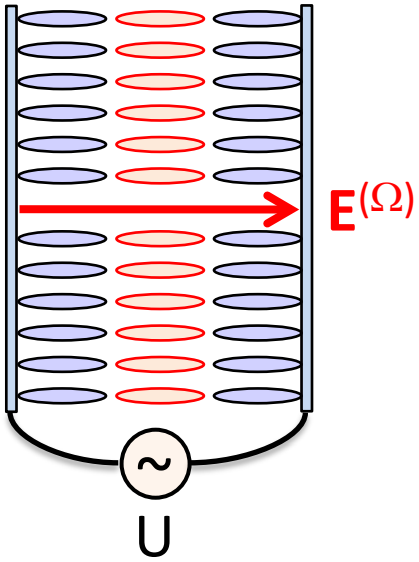
C. Loussert *et al.*, submitted.

Outline

1. Self-engineering strategy : nature at work
2. Material topological diversity benefits
3. **Self-engineering strategy : the electrical case**
4. Tunable optical vortex arrays from a single defect

Electrically induced umbilical defects

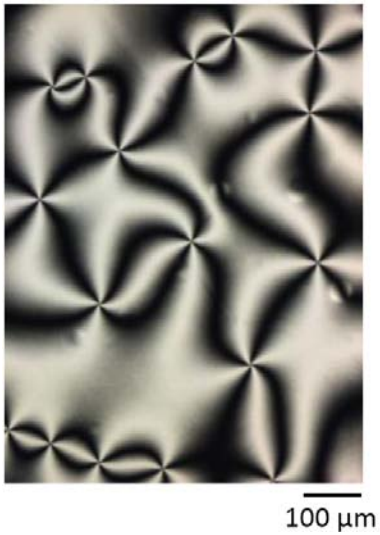
Nematic film at rest



$\varepsilon_a < 0$

$\Omega = 1$ kHz

$$U \gg U_F \sim 1\, V_{rms}$$



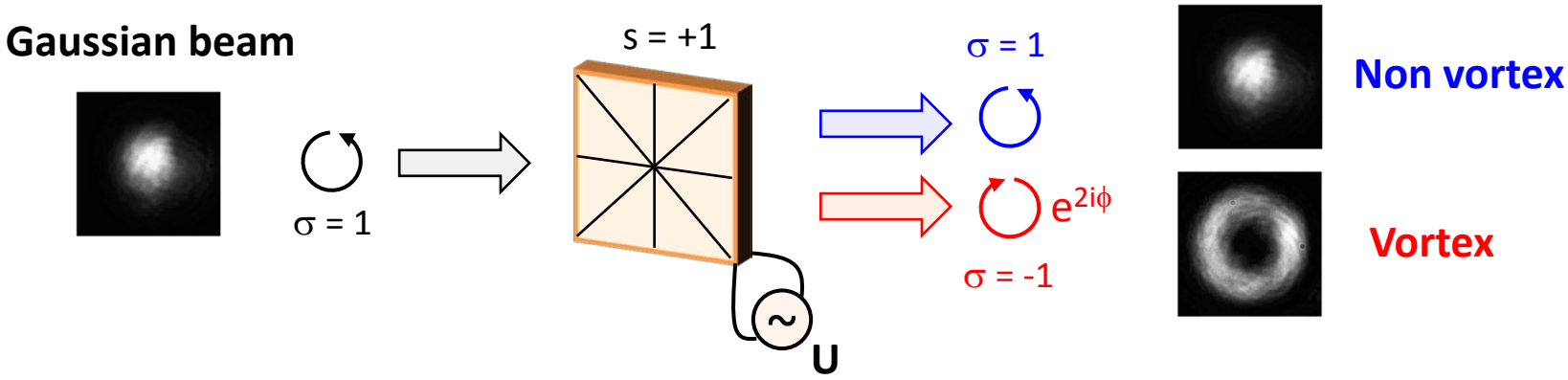
Defect strength : s = ±1

A. Rapini, J. Phys. (Paris) **34**, 629 (1973)

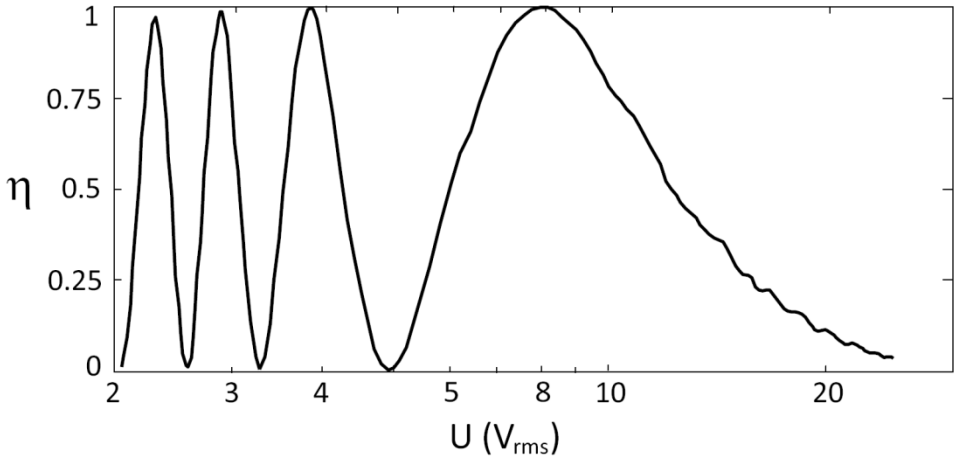
$$\frac{d^2a}{d\rho^2} + \frac{1}{\rho}\frac{da}{d\rho} + \left(1 - \frac{1}{\rho^2}\right)a - a^3 = 0$$

V. L. Ginzburg and L. P. Pitaevskii, Sov. Phys. JETP **34**, 858 (1959)

Electrically tunable optical vortex generation

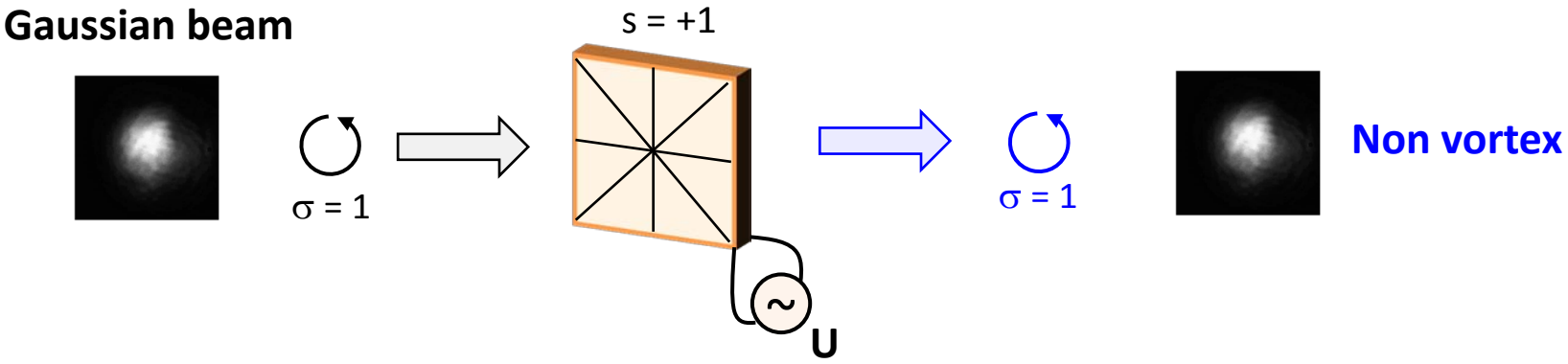


Tunable spin-to-orbital angular momentum conversion

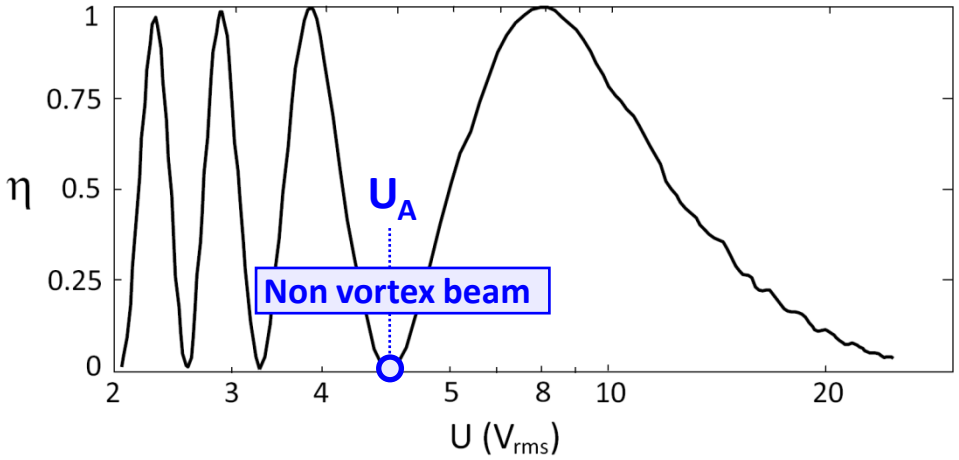


E. Brasselet and C. Loussert, Opt. Lett. **36**, 719 (2011)

Electrically tunable optical vortex generation

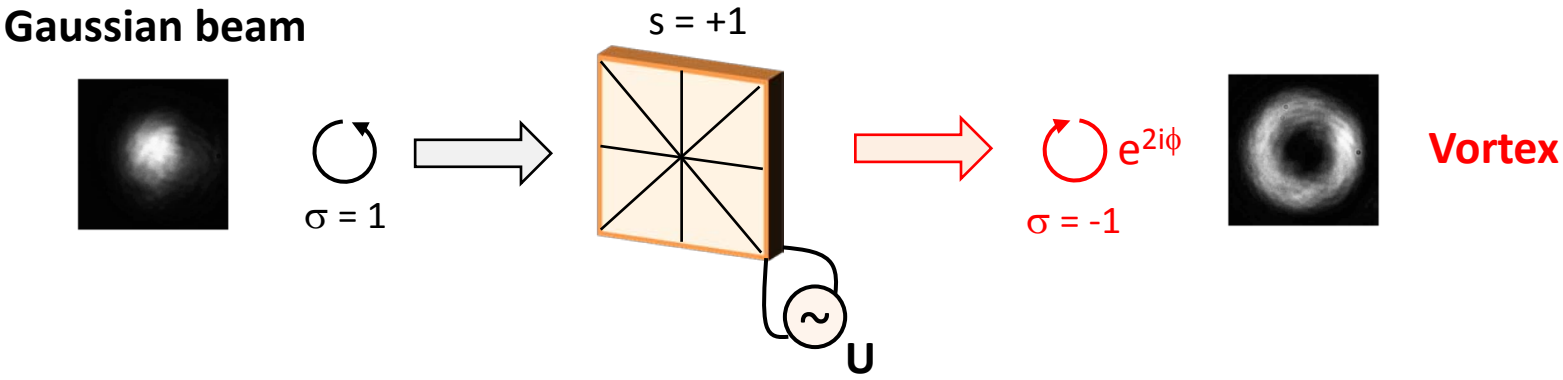


Tunable spin-to-orbital angular momentum conversion

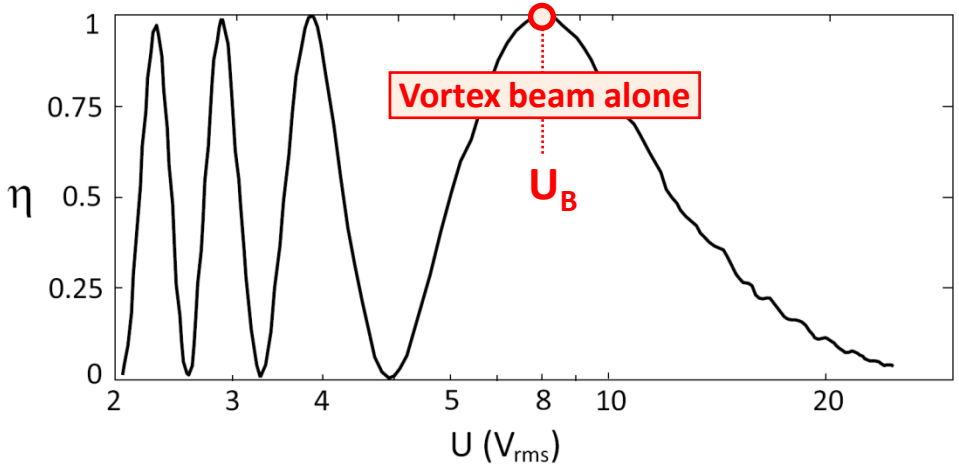


E. Brasselet and C. Loussert, Opt. Lett. **36**, 719 (2011)

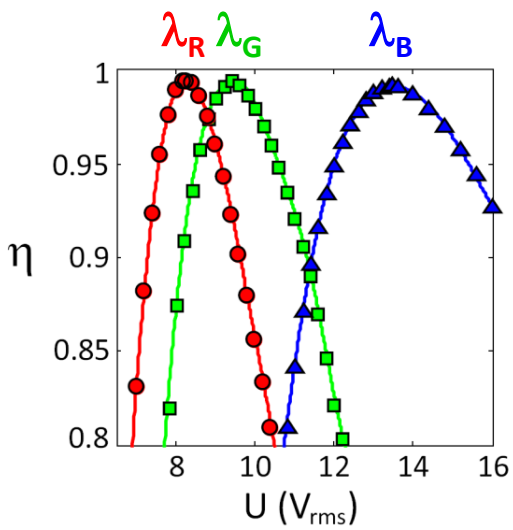
Electrically tunable optical vortex generation



Tunable spin-to-orbital angular momentum conversion



Spectral control



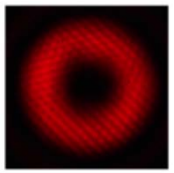
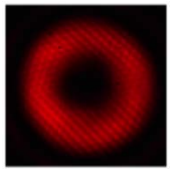
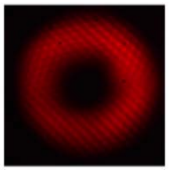
E. Brasselet and C. Loussert, Opt. Lett. **36**, 719 (2011)

Optimal umbilic : polarization encoding of the orbital state

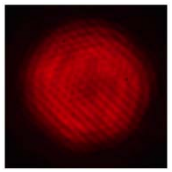
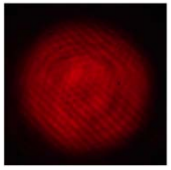
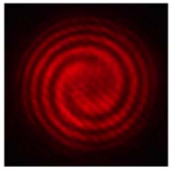
Photons state

$$S \otimes L_2$$

$$\{|-1\rangle, |+1\rangle\}_S \qquad \{|-2\rangle, |+2\rangle\}_{L_2}$$

Input state	$\|-1\rangle_S$	$\|+1\rangle_S$	$\frac{1}{\sqrt{2}}\left(\|-1\rangle_S + \|+1\rangle_S\right)$
Output state	$\|+1\rangle_S \otimes \|-2\rangle_{L_2}$	$\|-1\rangle_S \otimes \|+2\rangle_{L_2}$	$\frac{1}{\sqrt{2}}\left(\|+1\rangle_S \otimes \|-2\rangle_{L_2} + \|-1\rangle_S \otimes \|+2\rangle_{L_2}\right)$
Output beam			

Spin-orbit « tomography »

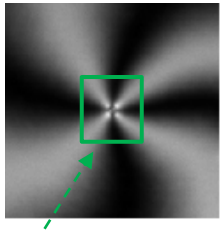
Reference beam $\|-1\rangle_S$			
Reference beam $\|+1\rangle_S$			

Outline

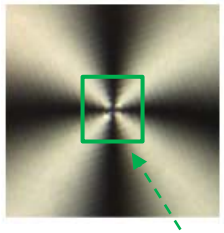
1. Self-engineering strategy : nature at work
2. Material topological diversity benefits
3. Self-engineering strategy : the electrical case
4. **Tunable optical vortex arrays from a single defect**

The importance of the nature of the topological defect

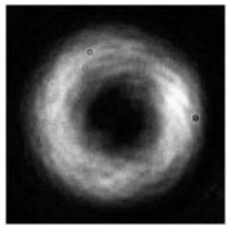
Schlieren defect



Umbilical defect



They look the same



They taste the same

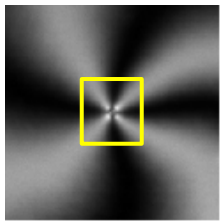
$\ell = 2\sigma$

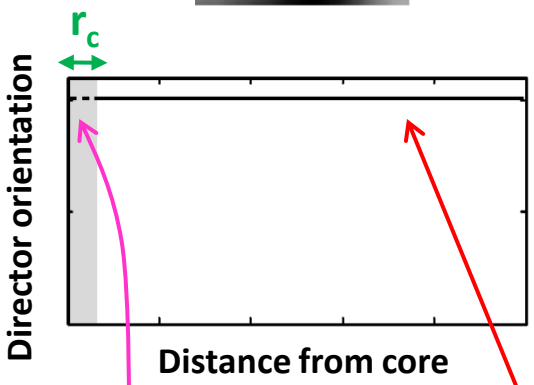
BUT…

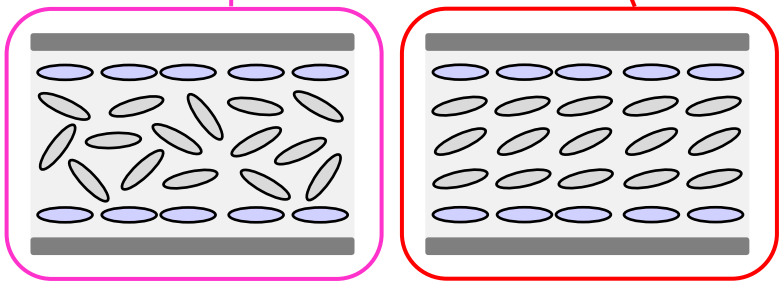
The core are different !

What is making the difference ?

Schlieren defect





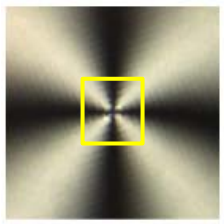


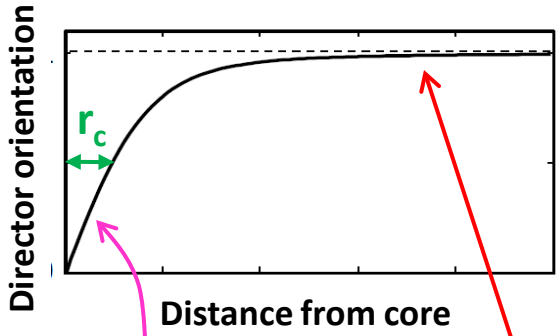
In the core (isotropic)

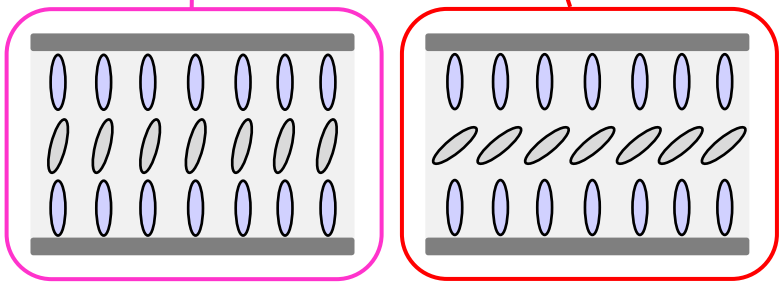
Far from core (nematic)

Singular defect core

Umbilical defect





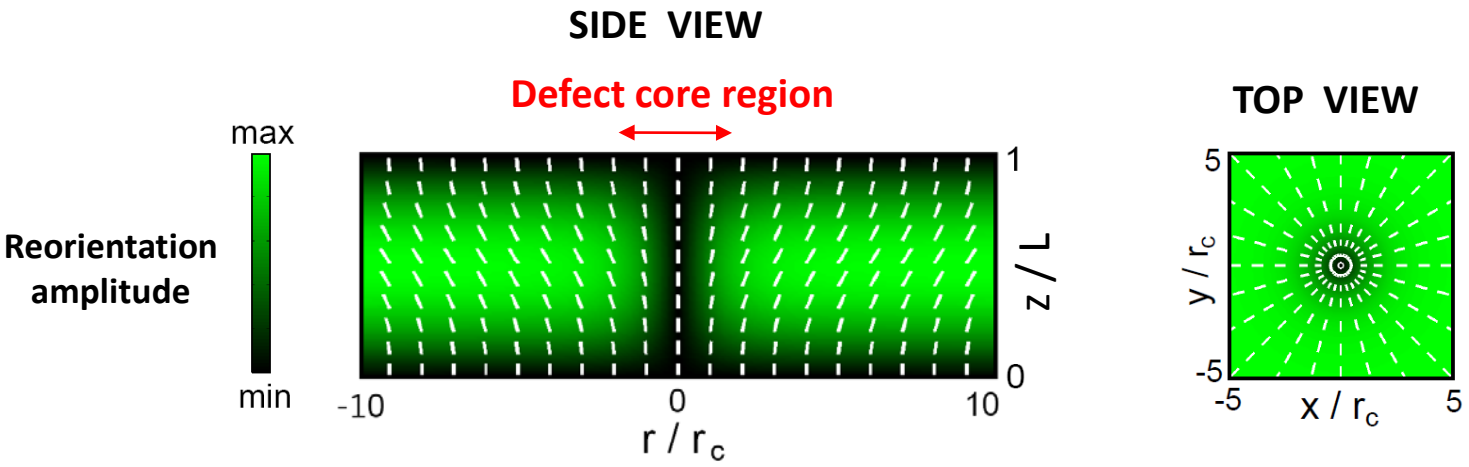


In the core (nematic)

Far from core (nematic)

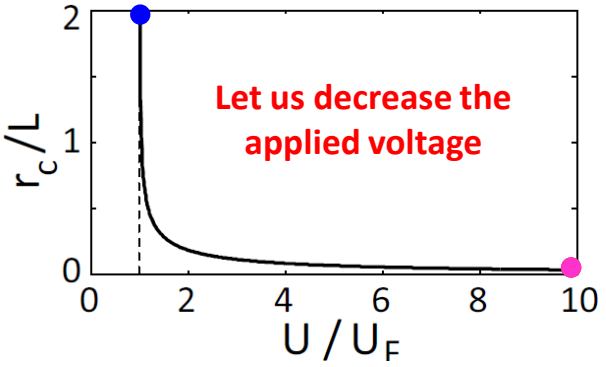
Non singular defect core

Optical vortex generation : so what ?



$$U \sim U_F \Rightarrow r_c \sim L$$

Non-uniform birefringent retardation



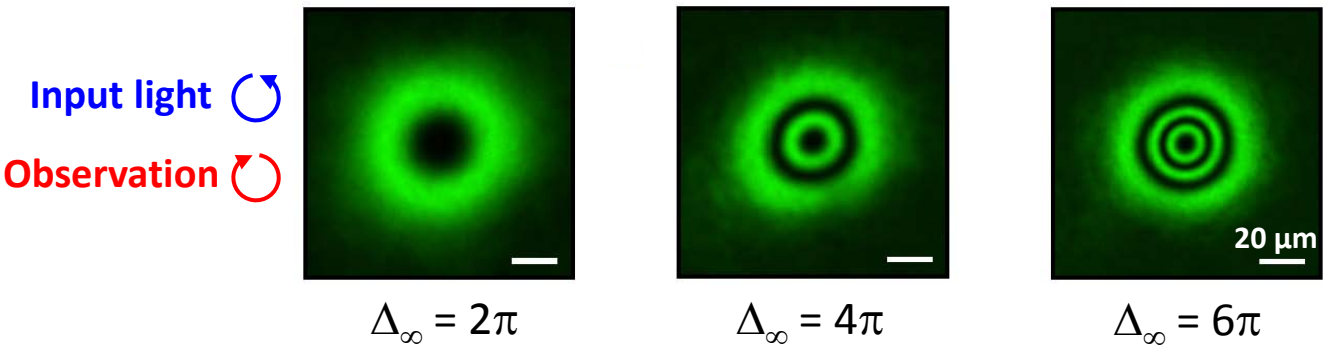
$$U \gg U_F \Rightarrow r_c \ll L$$

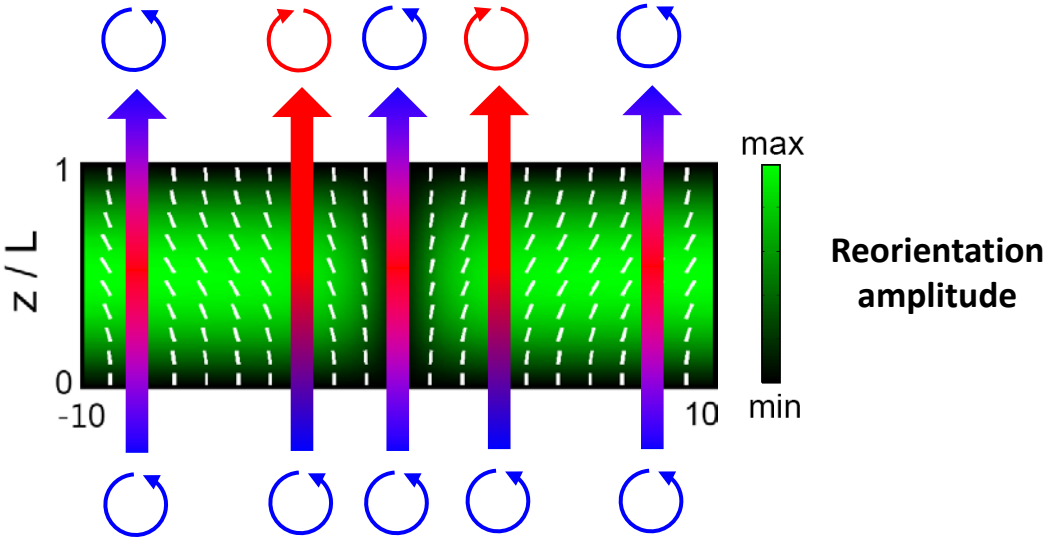
Uniform birefringent phase retardation

A closer look to an umbilic defect with large core

Observation in the circular polarization basis

Optical phase singularity with $\ell = \pm 2$



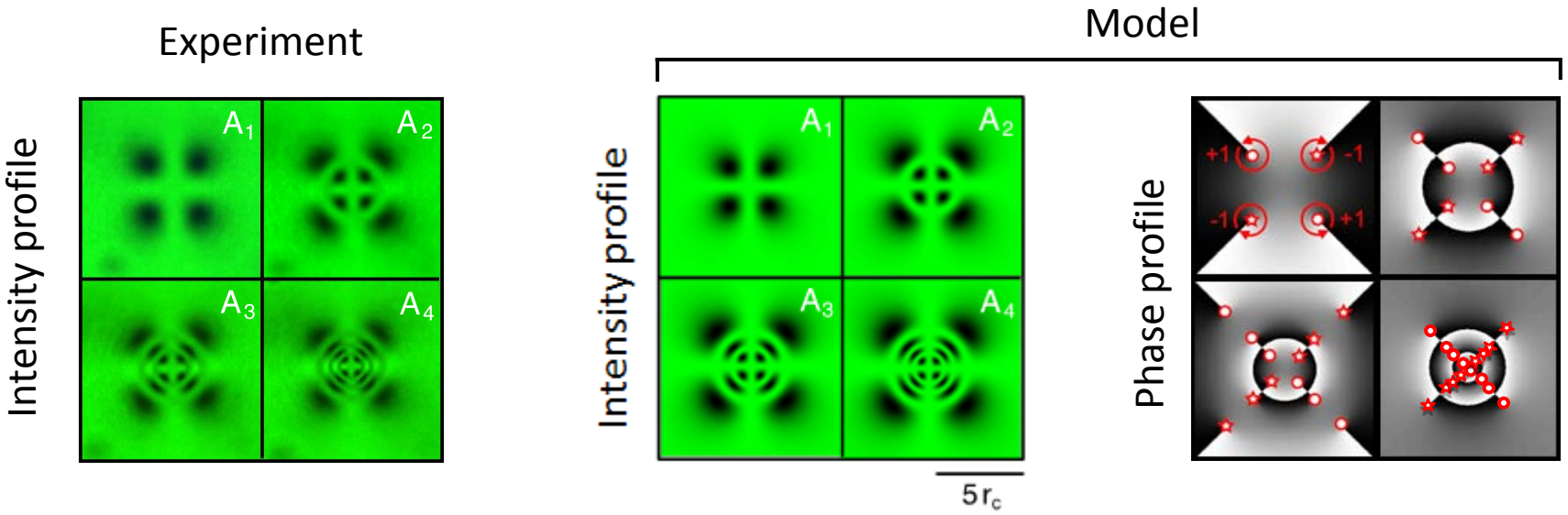


E. Brasselet, PRL **108**, 087801 (2012)

Electrically tunable optical vortex arrays with a single defect

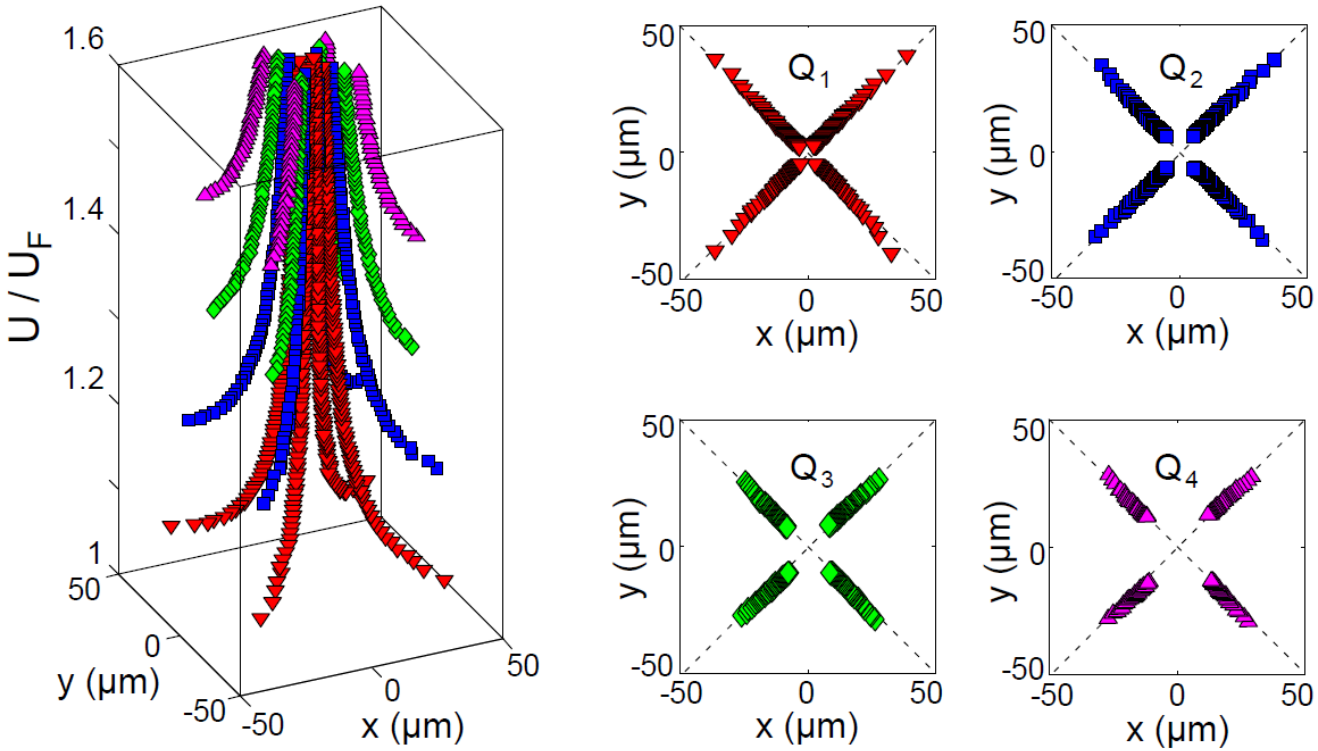
Observation in the linear polarization basis

Optical phase singularities arrays $A_N = \{Q_1, Q_2, \ldots, Q_N\}$



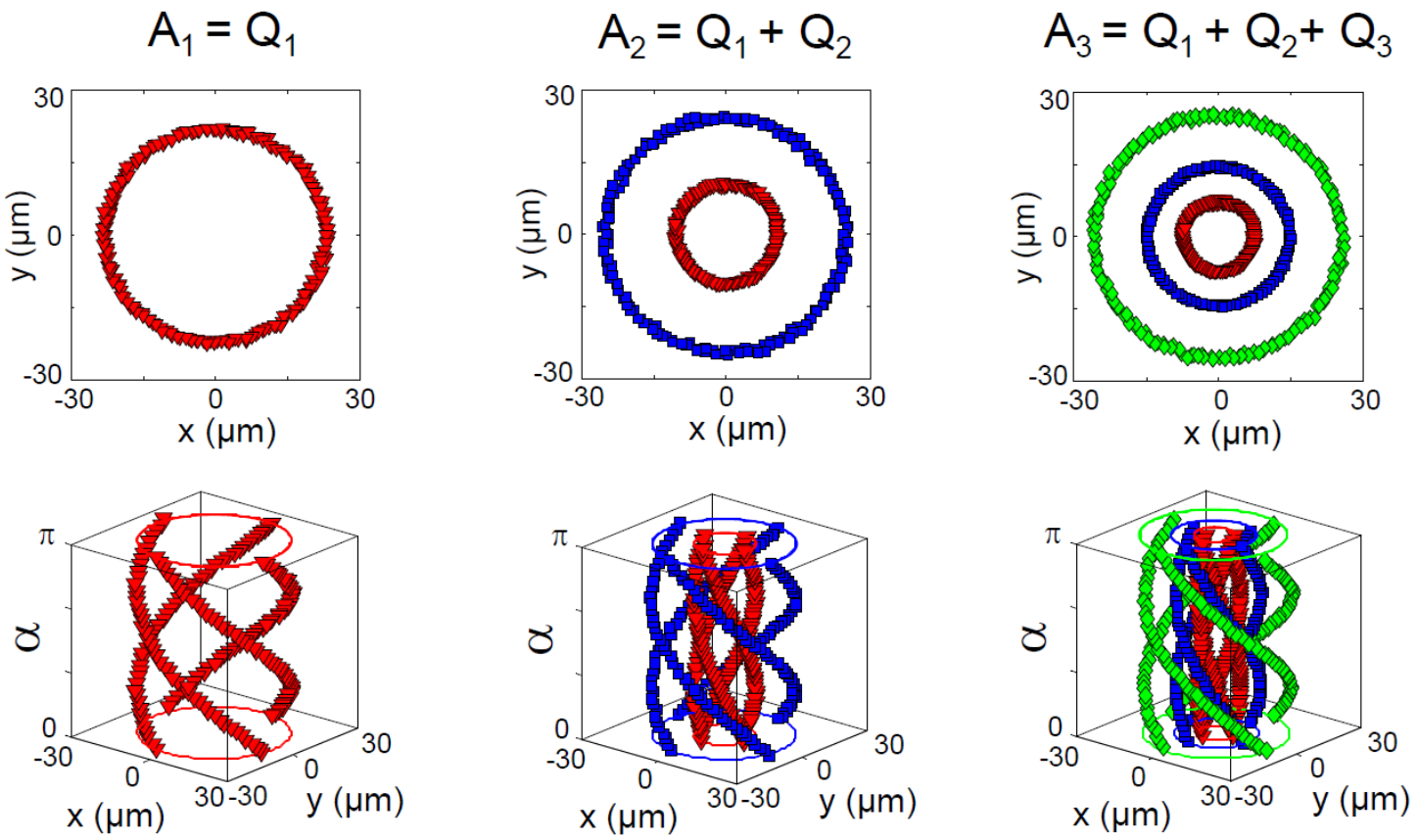
E. Brasselet, PRL **108**, 087801 (2012)

Radial spatial control of the vortex arrays : electrical tuning



E. Brasselet, PRL **108**, 087801 (2012)

Azimuthal spatial control of the vortex arrays : polarizational tuning

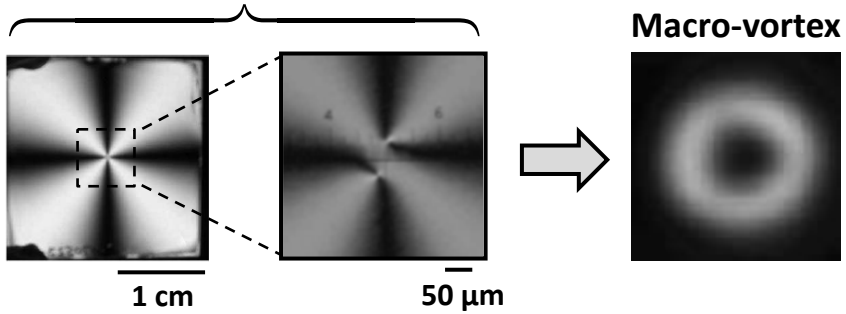


E. Brasselet, PRL **108**, 087801 (2012)

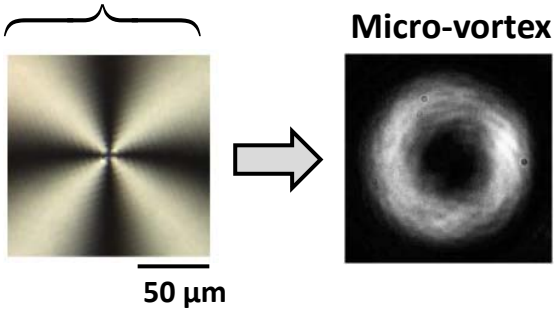
Conclusion: topological interplay between matter and light

Let us remember the initial challenge : integrated singular optical elements

Optical micro-patterning techniques

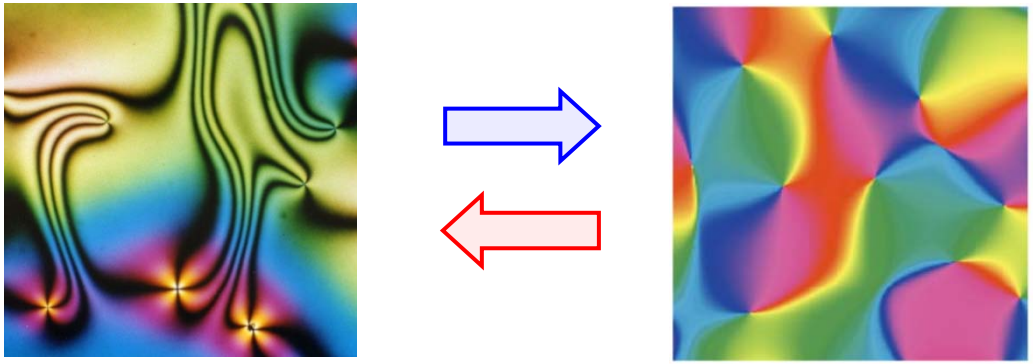


Our approach:
Topological self-engineering



Imprinting material topological information on light

Liquid crystal defects



Optical phase singularities

Imprinting optical topological information on matter

This is for tomorrow !