Optical Vortices in Semiconductor Physics

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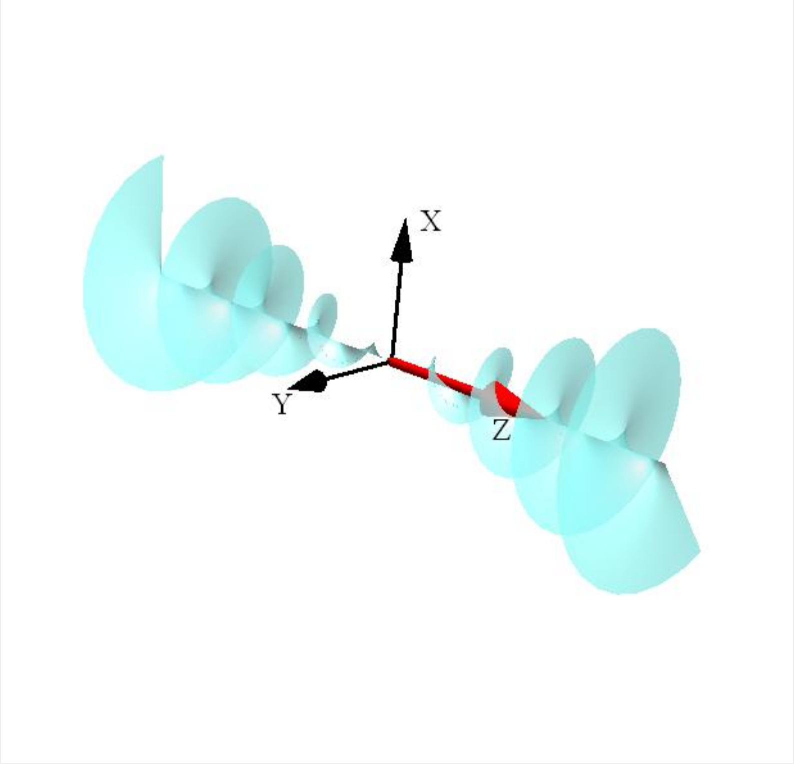
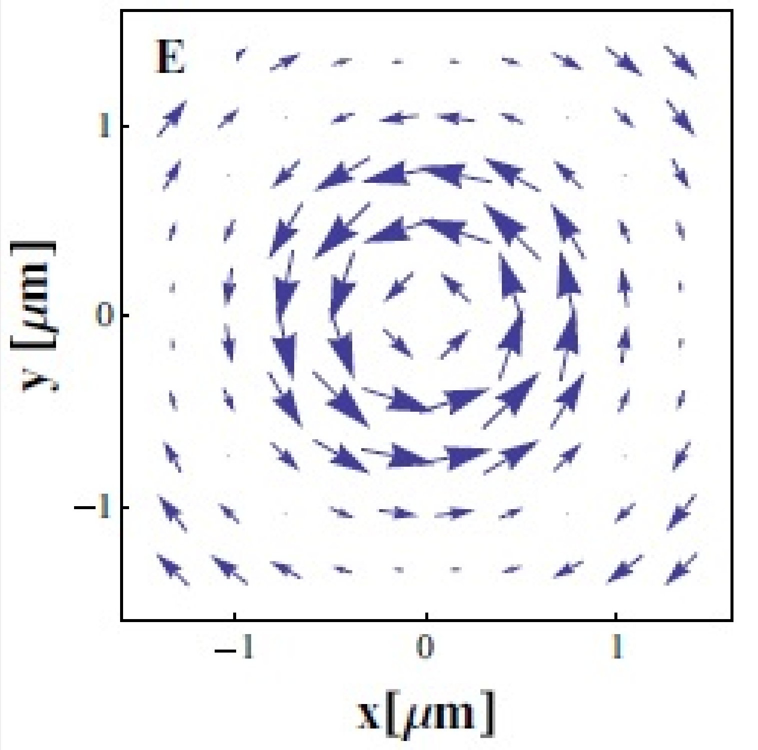
Optical vortex

"twisted light"
"light carrying orbital angular momentum"



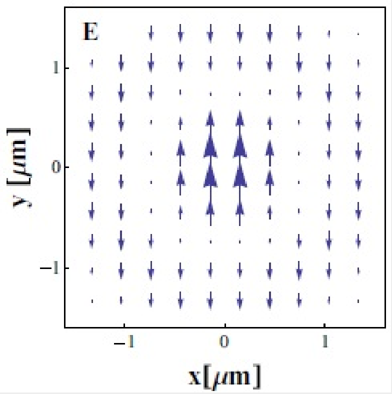
Highly inhomogeneous light field with phase and/or polarization <u>singularities</u>.

Optical Vortex



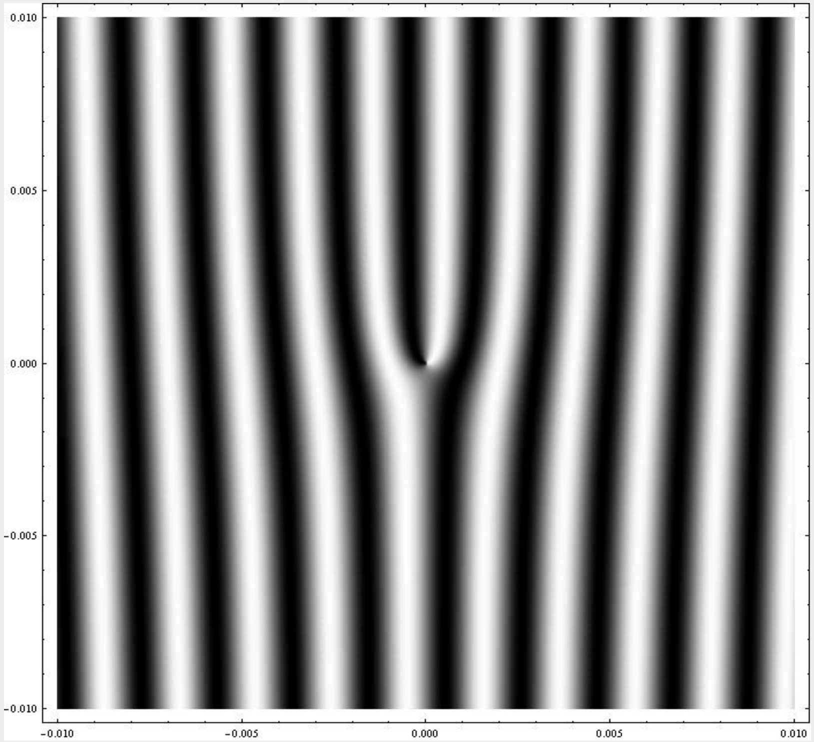
Electric field transverse to propagation direction

Gaussian beam



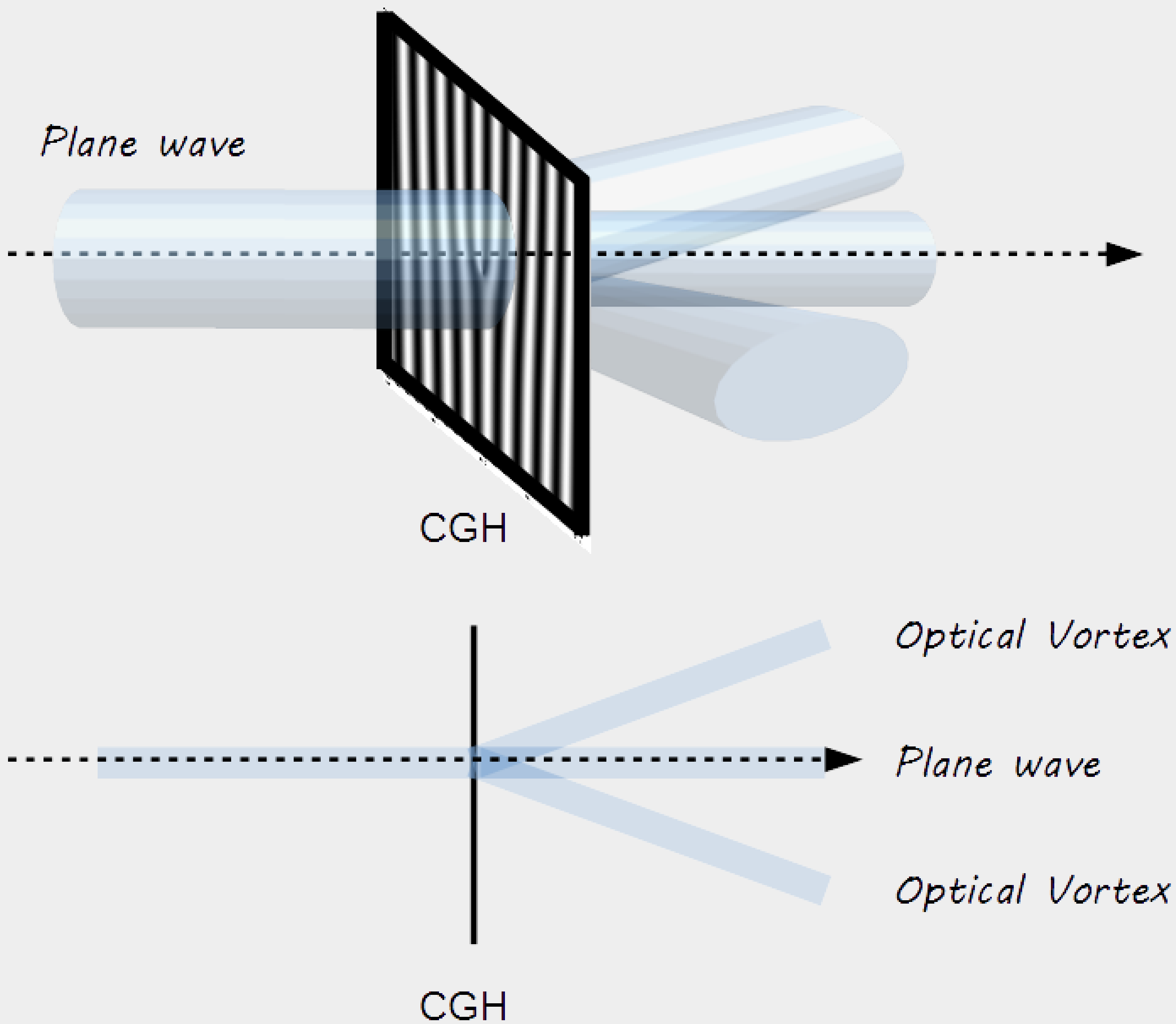
Generation

The simplest and best-known: *Computer generated holograms*

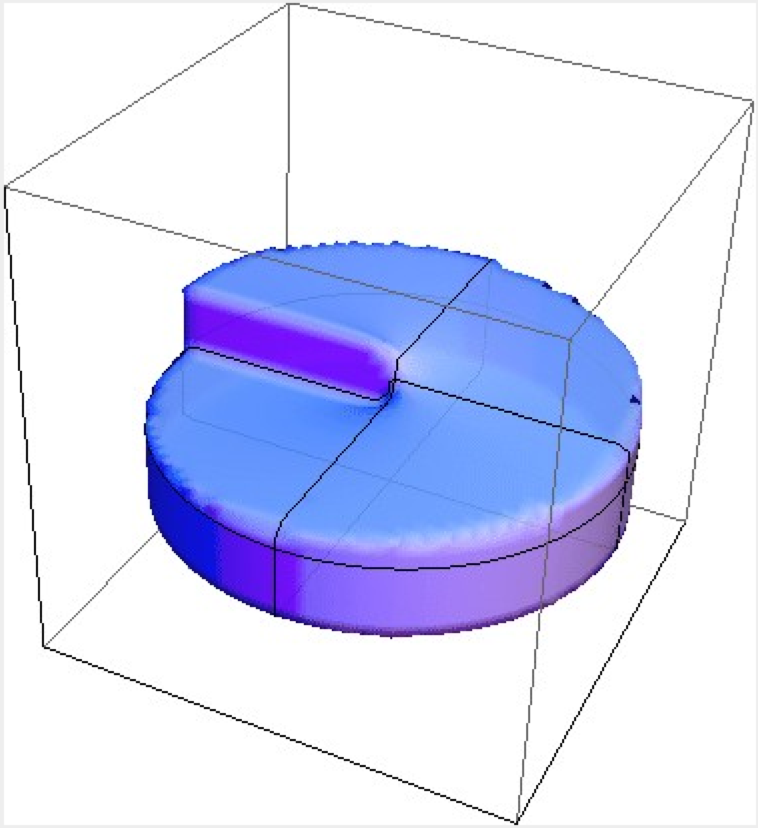


produced by <u>calculating</u> the interference between a plane wave/Gaussian and an optical vortex

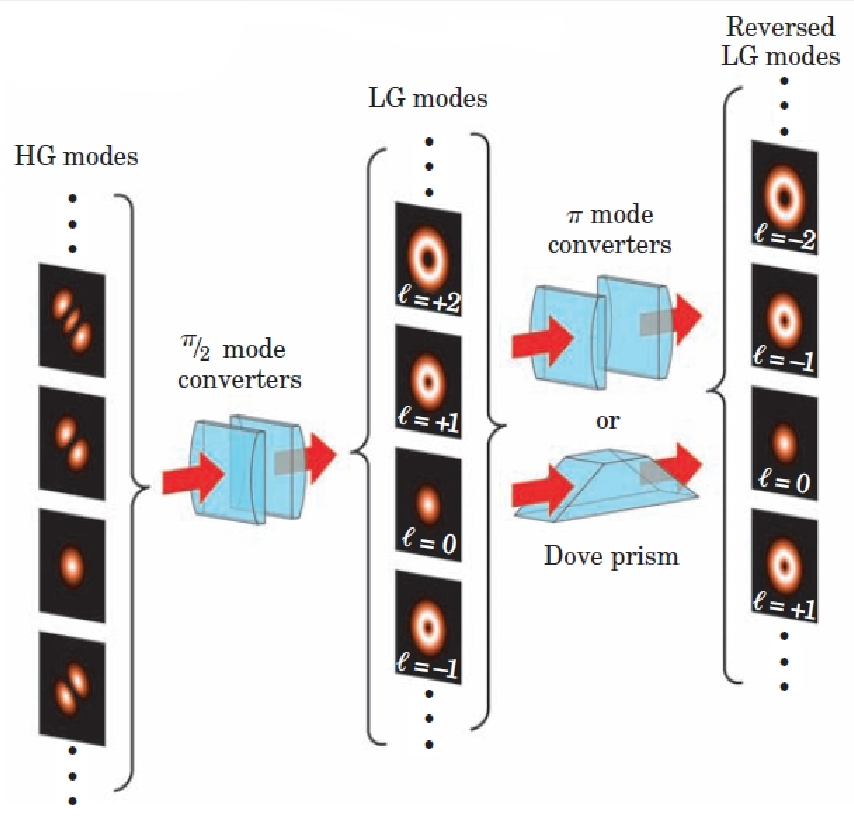
Generation of OVs



Other methods



Spiral phase plate



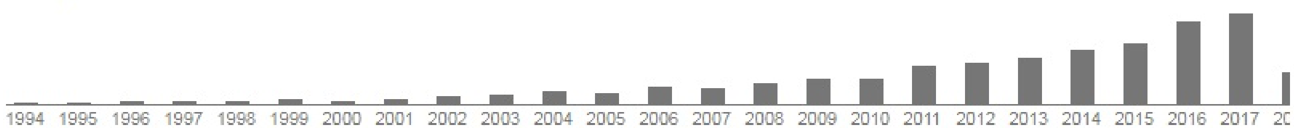
Cylindrical lens

The generation of optical vortices is simple and inexpensive

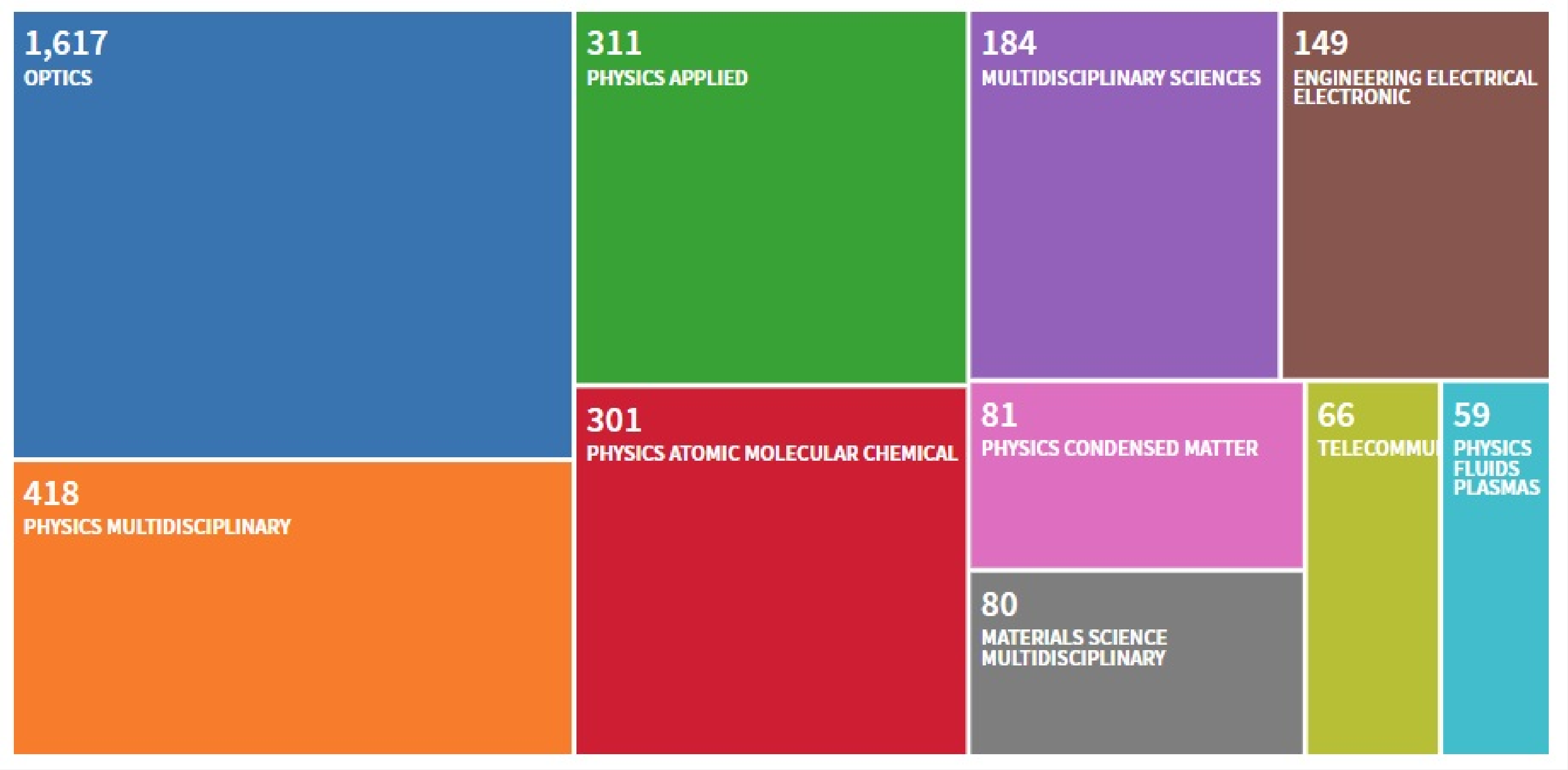
Research in optical vortices

Orbital angular momentum of light and the transformation of Laguerre-Gaussian laser modes

Authors	Les Allen, Marco W Beijersbergen, RJC Spreeuw, JP Woerdman
Publication date	1992/6/1
Journal	Physical Review A
Volume	45
Issue	11
Pages	8185
Publisher	American Physical Society
Description	Laser light with a Laguerre-Gaussian amplitude distribution is found to have a well-defined orbital angular momentum. An astigmatic optical system may be used to transform a high-order Laguerre-Gaussian mode into a high-order Hermite-Gaussian mode reversibly. An experiment is proposed to measure the mechanical torque induced by the transfer of orbital angular momentum associated with such a transformation.
Total citations	Cited by 4623



Scholar articles: Orbital angular momentum of light and the transformation of Laguerre-Gaussian laser modes
L Allen, MW Beijersbergen, RJC Spreeuw... - Physical Review A, 1992
Cited by 4623 Related articles All 10 versions


1,617
OPTICS
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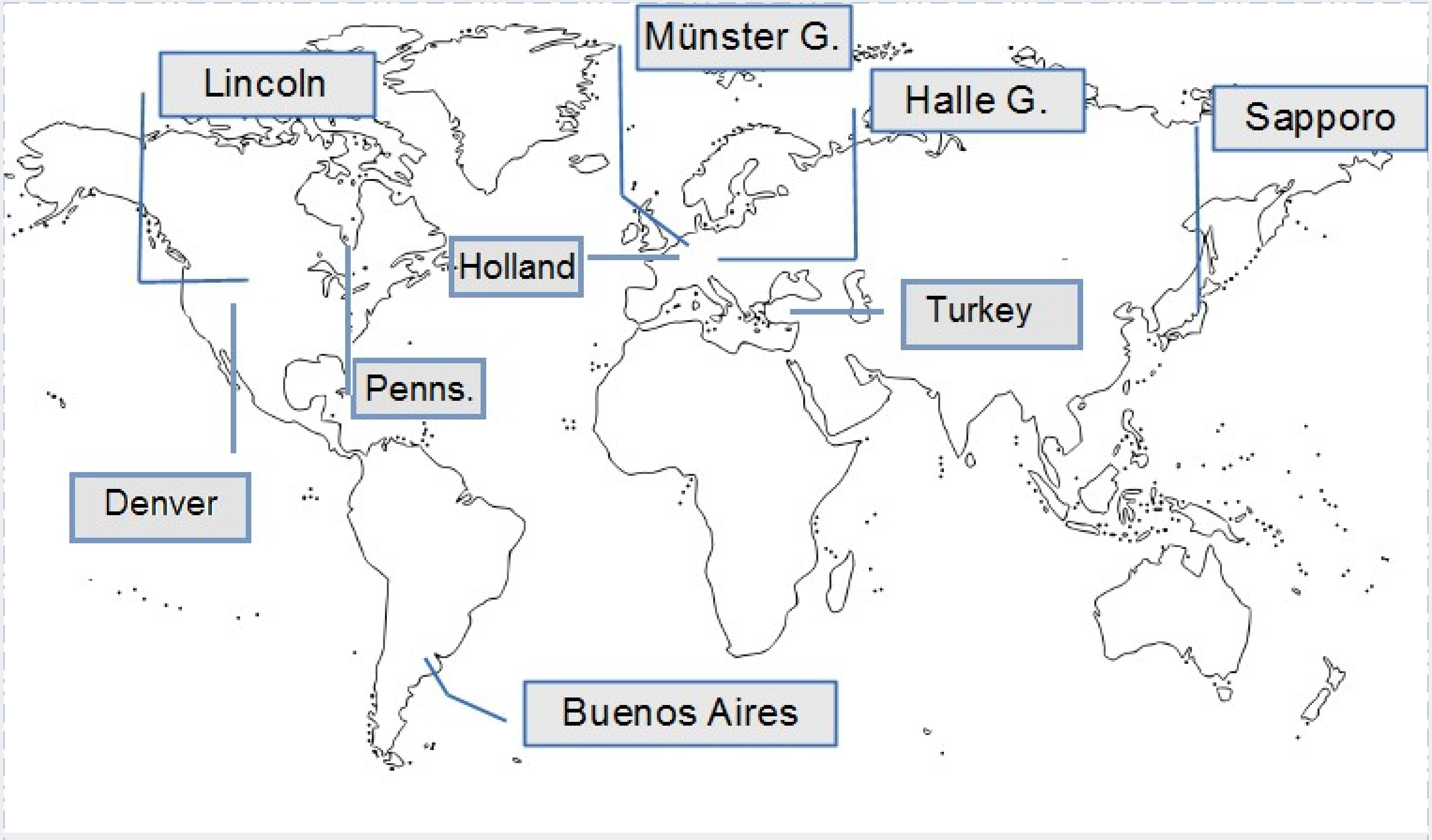
PHYSICS MULTIDISCIPLINARY
311
PHYSICS APPLIED
301
PHYSICS ATOMIC MOLECULAR CHEMICAL
184
MULTIDISCIPLINARY SCIENCES
149
ENGINEERING ELECTRICAL ELECTRONIC
81
PHYSICS CONDENSED MATTER
80
MATERIALS SCIENCE MULTIDISCIPLINARY
66
TELECOMMU
59
PHYSICS FLUIDS PLASMAS

Optical Vortices in Solids

First paper: G. F. Quinteiro and P. I. Tamborenea, EPL, 85 (2009) 47001 **Editor's Choice**



2017

Gaussian beams

How do laser beams look like
and interact with matter?

Fields

Typical laser beams are approximately paraxial

$$\mathbf{E}(\mathbf{r},t) = E_0(\mathbf{r})e^{i(kz-\omega t)}\,\hat{\varepsilon}_\sigma$$

$\hat{\varepsilon}_\sigma = \frac{1}{\sqrt{2}}(\hat{x} + i\sigma\hat{y})$ polarization vector

$\sigma = -1, +1$ Spin angular momentum (polarization index)

with first correction a longitudinal component

$$E_z(\mathbf{r},t) = \frac{1}{w_0 k}\,E_0'(\mathbf{r})e^{i(kz-\omega t)}\,\hat{z}$$

w_0 Beam waist

$k = 2\pi/\lambda$ wave number

for collimated beams ***Ez*** is safely disregarded

Interaction

The dipole interaction suffies

$$H_d = -e\mathbf{r} \cdot \mathbf{E}(t)$$

space dependence of ***E*** and
magnetic interactions are safely neglected

On interaction, light is reducible to a transverse electric field

Optical vortex

Optical vortices are complex
fields with unusual properties...

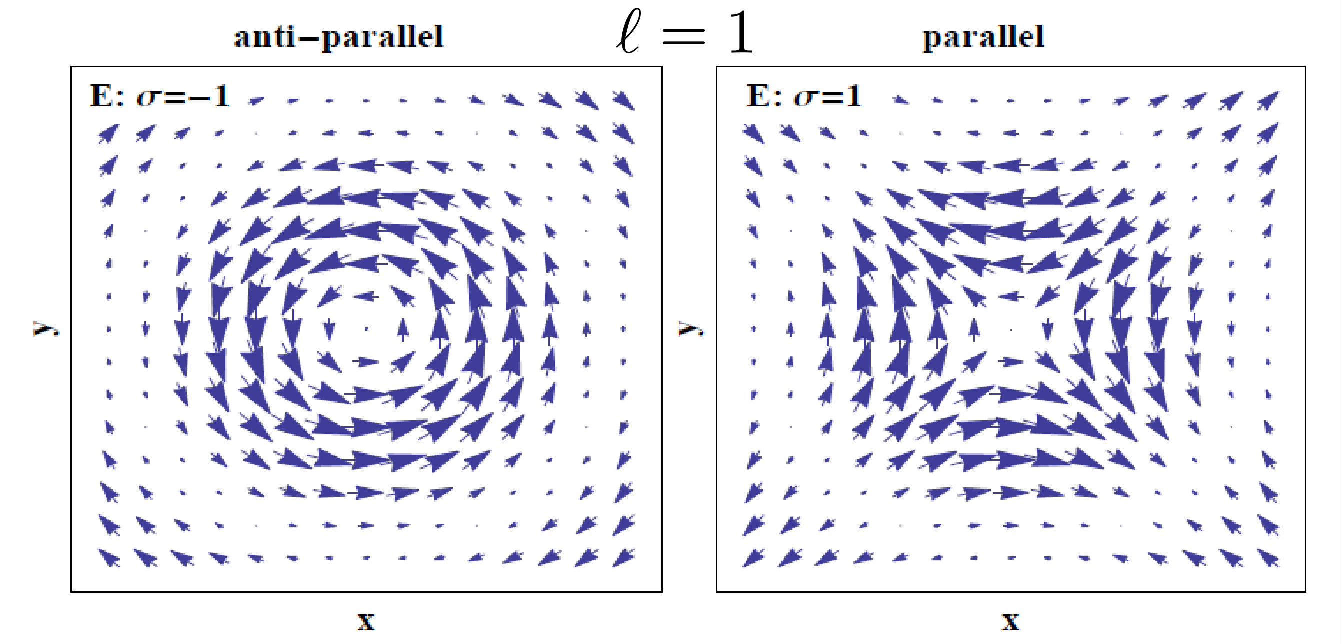
OV are characterized by

Spin angular momentum (polarization index) $\sigma = -1, +1$

Orbital angular momentum (topological charge) $\ell = \ldots\ , -1, +1, \ldots$

$$\mathbf{E}(\mathbf{r}, t) = \left[\hat{\varepsilon}_\sigma F_\perp(\mathbf{r}) e^{i\ell\varphi} + \hat{z} F_z(\mathbf{r}) e^{i(\ell+\sigma)\varphi}\right] \ e^{i(kz-\omega t)}$$

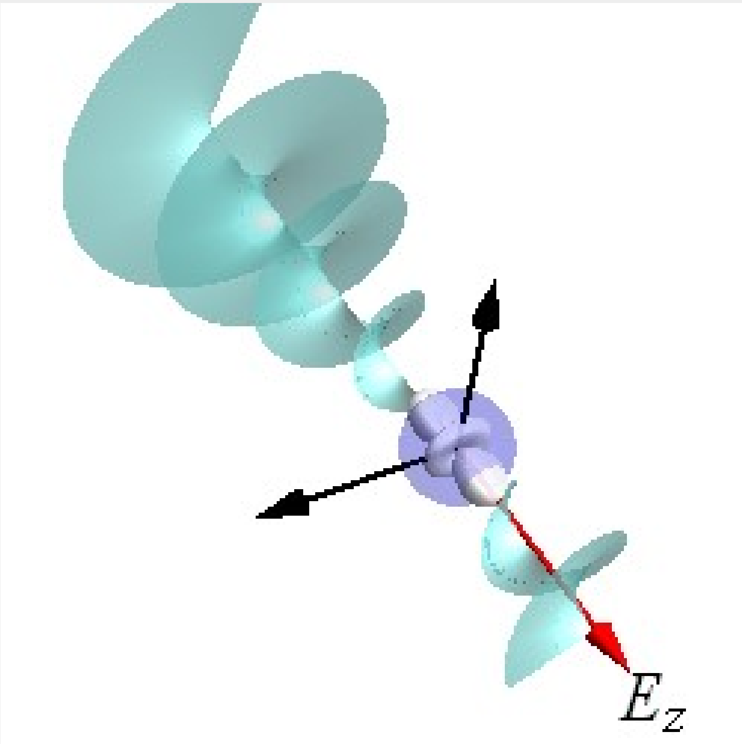
$\hat{\varepsilon}_\sigma = \frac{1}{\sqrt{2}}(\hat{x} + i\sigma\hat{y})$ (Polarization vector)

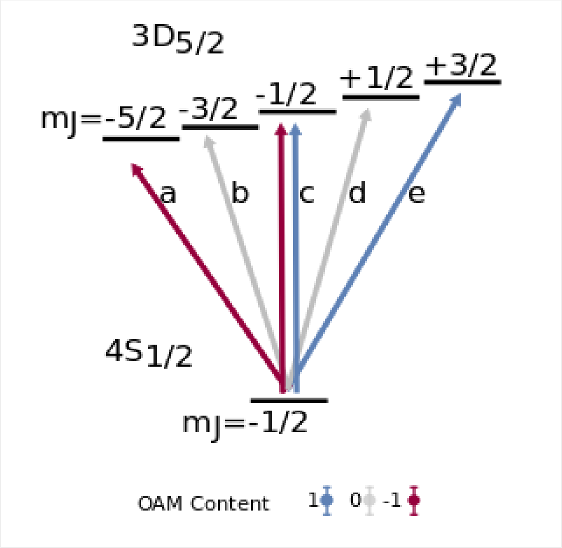


Most unusual things happen for anti-parallel spin and orbital AM

Relevant longitudinal electric field and magnetic field

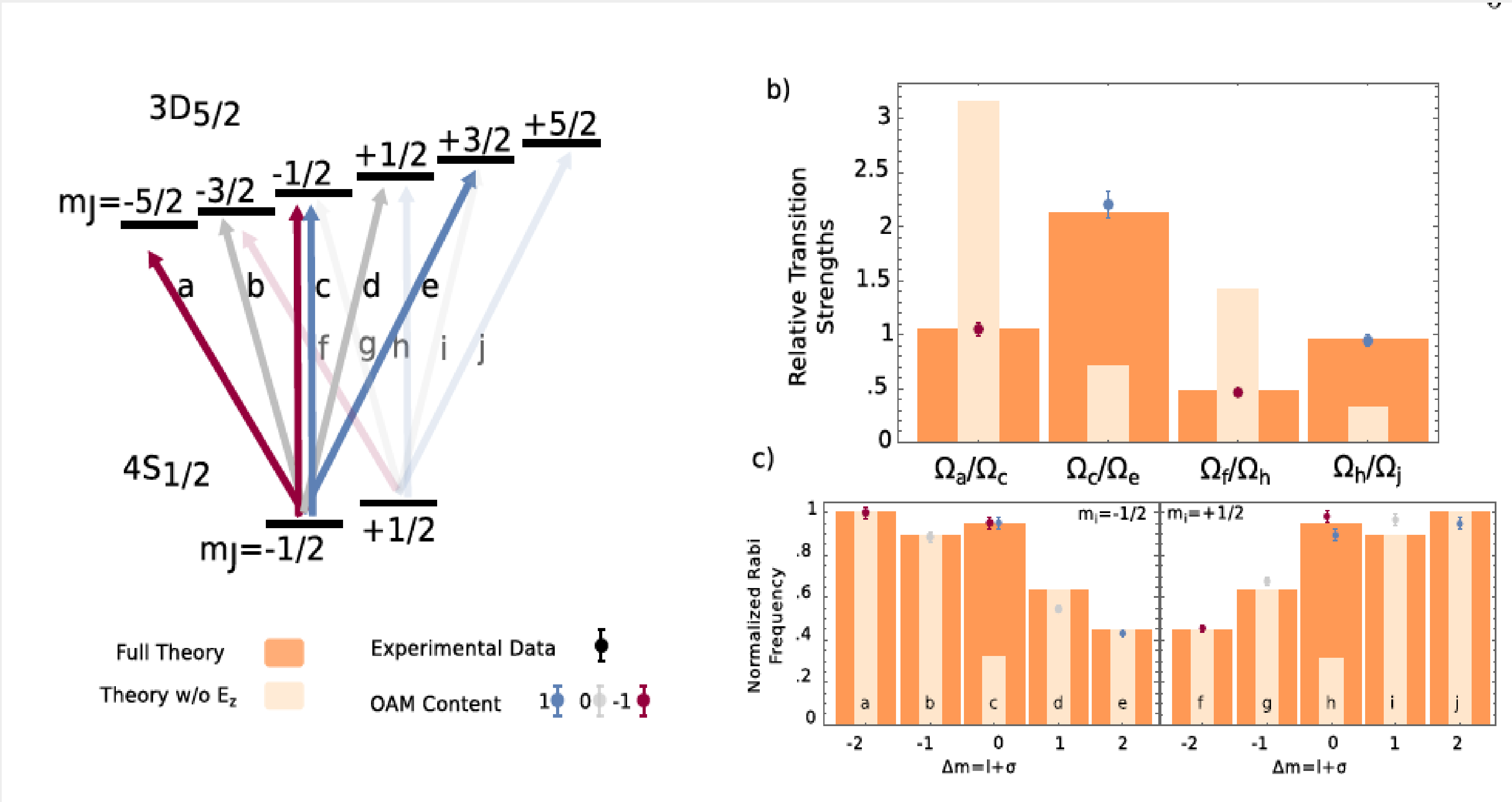
Longitudinal electric field





Experiment: excitation of a Ca ion by a collimated optical vortex

(G. F. Quinteiro et al, *Phys. Rev. Lett. 119, 253203 (2017),* ***Editors' Suggestion***)



Full Theory: includes all components of E

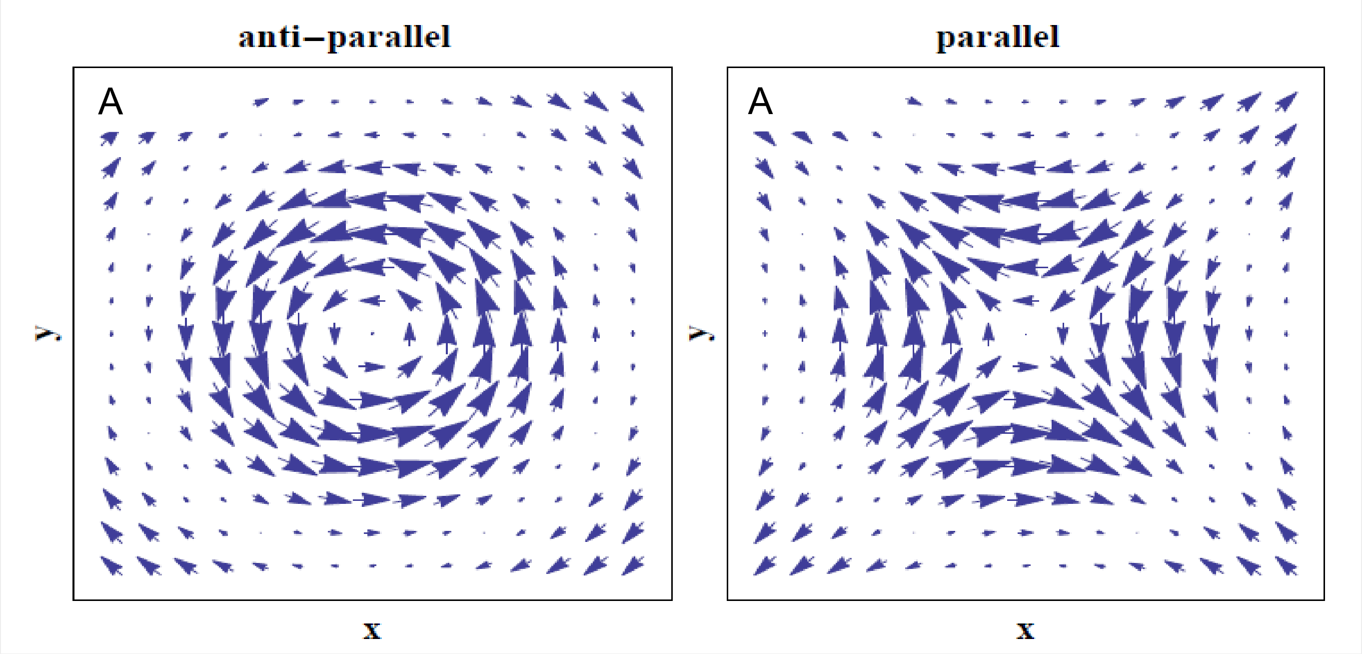
Magnetic interaction

In the Coulomb gauge

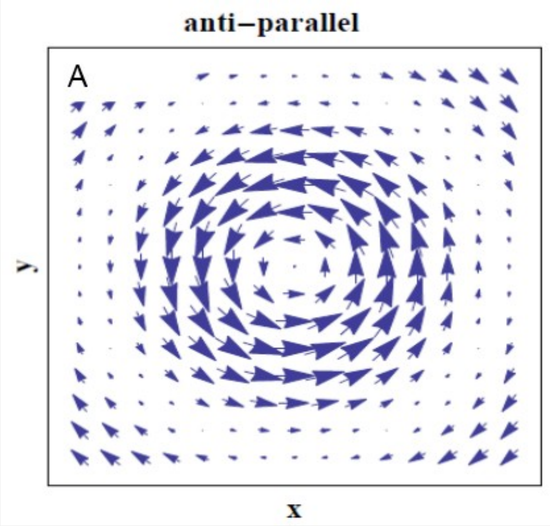
$$\mathbf{A}(\mathbf{r},t) \propto \mathbf{E}(\mathbf{r},t)$$

[**A**(**r**,t) vector potential]

So, the same plot works for **E**(**r**,t) and **A**(**r**,t)



Anti-parallel **A**(**r**,t) clearly has non-vanishing curl
(the field “rotates”)



$$\nabla \times \mathbf{A}(\mathbf{r}, t) \neq 0$$

$$\mathbf{B}(\mathbf{r}, t) = \nabla \times \mathbf{A}(\mathbf{r}, t)$$

$$\mathbf{B}(\mathbf{r}, t) \neq 0$$

one must include the magnetic interaction

$$H_m = \frac{2}{|\ell| + 2 - j} \mathbf{B}_\perp(\mathbf{r}, t) \cdot \mathbf{m} + \frac{2}{|\ell + \sigma| + 2} B_z(\mathbf{r}, t) m_z$$

The terms look like magnetic dipolar,

but is not: there is space dependence

Supporting literature

. G. F. Quinteiro, D. E. Reiter, and T. Kuhn, physical review a **91**, 033808 (2015)

. Marco Ornigotti and Andrea Aiello, optics express 15530 (2013)

. Klimov et al**,** physical review a **85**, 053834 (2012)

. Zurita-Sanchez and L Novotny, JOSA B 19 (2002)

$\ell > 0$

Parallel

$$\tilde{B}_z(\mathbf{r}) \quad \propto \quad \frac{1}{w_0 k}\left(\frac{r}{w_0}\right)^{\ell+1} e^{i(\ell+1)\varphi},$$

Anti-parallel

$$\tilde{B}_z(\mathbf{r}) \quad \propto \quad \frac{1}{w_0 k}\left(\frac{r}{w_0}\right)^{\ell-1} e^{i(\ell-1)\varphi}.$$

For $\ell = 1$ B is constant

For $\ell = 2$ anti-parallel Bxy is constant

On interaction, an optical vortex is a 3D vector field with electric and magnetic contributions

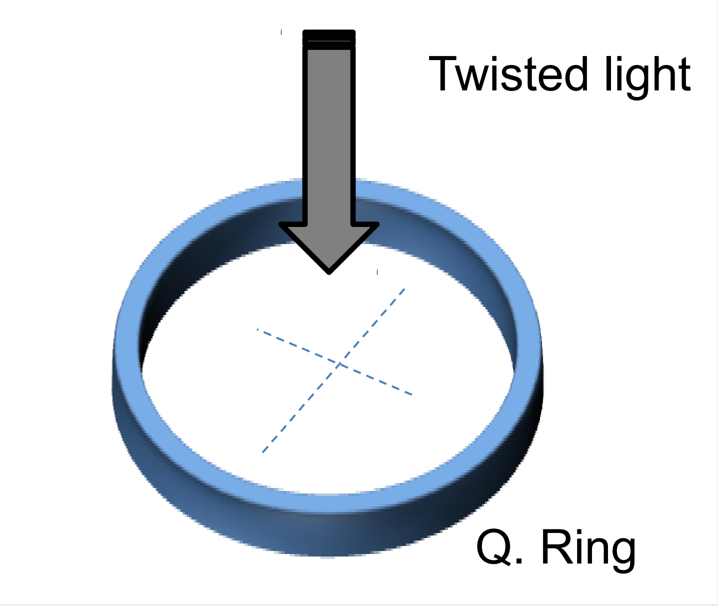
OV – semiconductor interaction

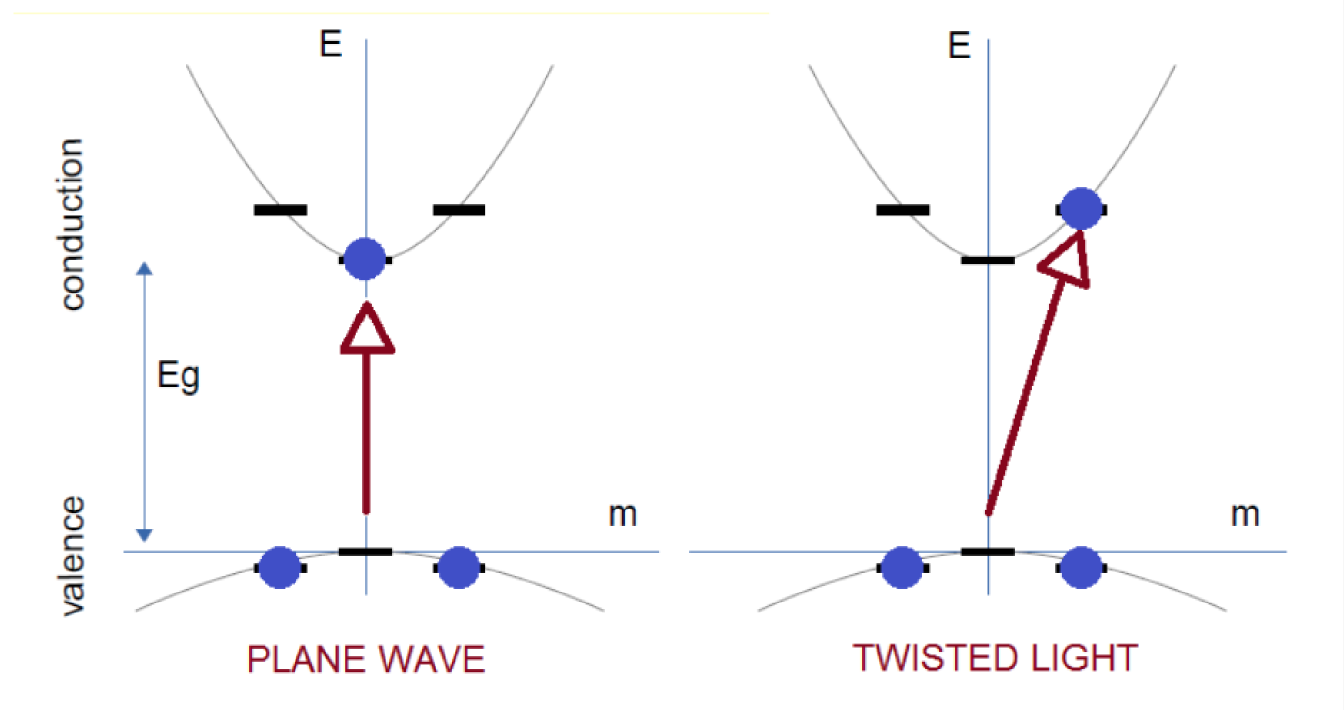
- rotational photon-drag
- generation of local and ultrafast magnetic fields
- new optical transitions in quantum dots
- strong optical-magnetic interactions
- excitation of intersubband states in quantum wells
- spin control with light holes in quantum dots

Photon drag in quantum rings

Quantum rings are 1D structures with the same symmetry as the optical-vortex

$$\varphi_m(\mathbf{r}) = \frac{1}{\sqrt{2}\pi} e^{im\varphi} u_b(\mathbf{r})$$

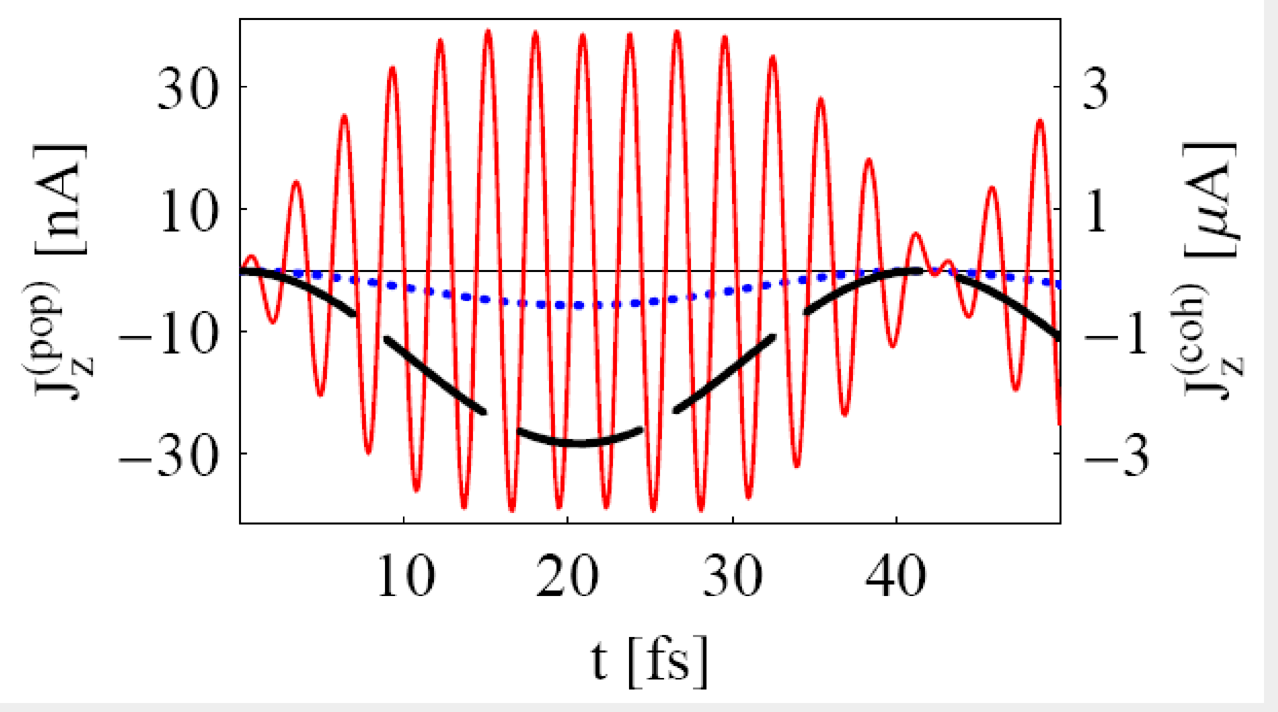




$$\varphi_m(\mathbf{r}) \to \varphi_{m+\ell}(\mathbf{r})$$

Non-vertical transitions are relevant

Induced electric current

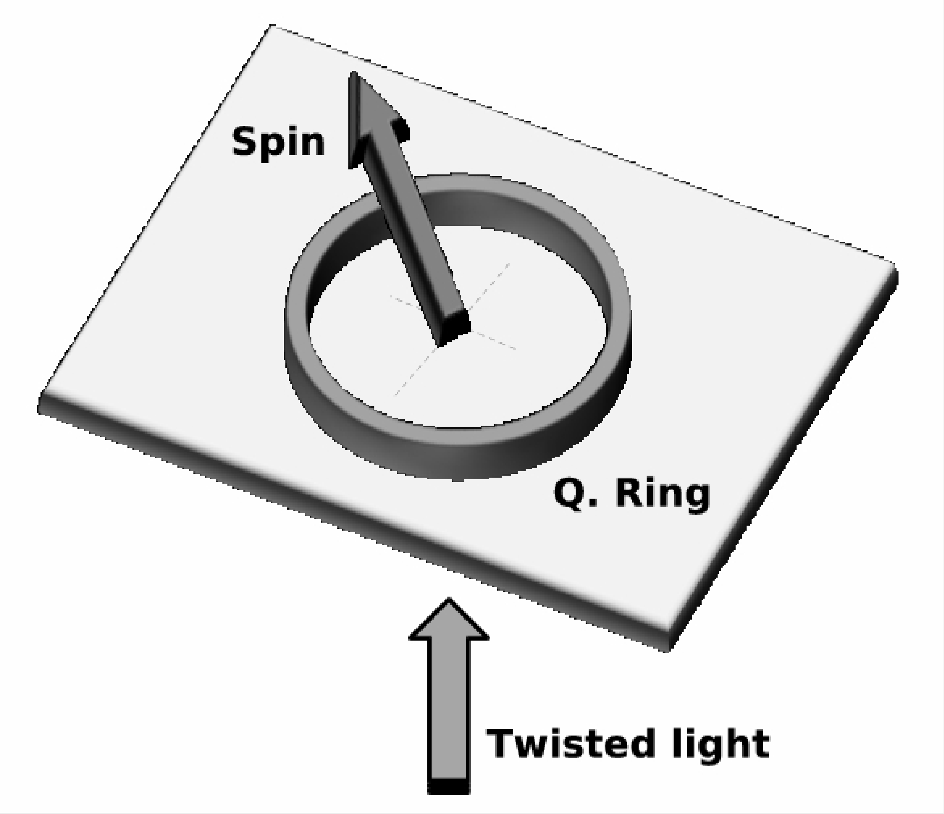


Two contributions:

E : coherence

E^2 : population

A possible application



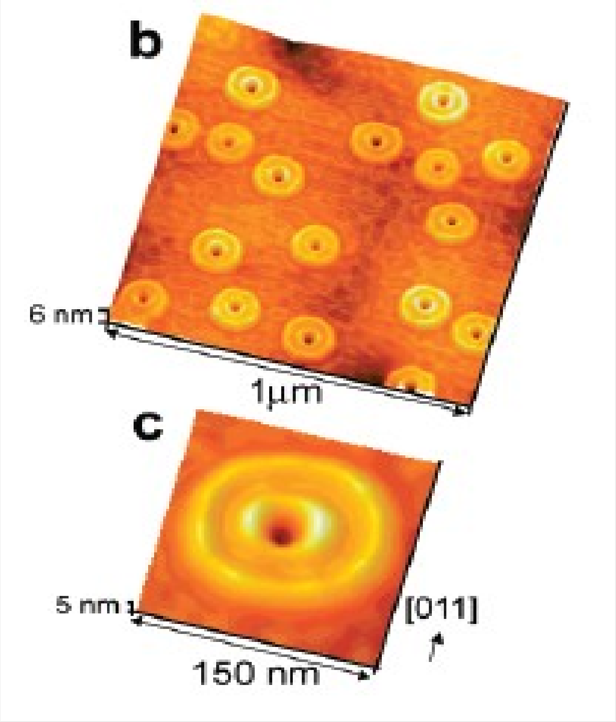
The electric current in the quantum rings produce a magnetic field that may control a spin

Experiments in quantum rings

Ongoing collaboration with:

Dr. Sanguinetti (Milan)
QR fabrication

Dr. Siemens (Denver)
Measurements

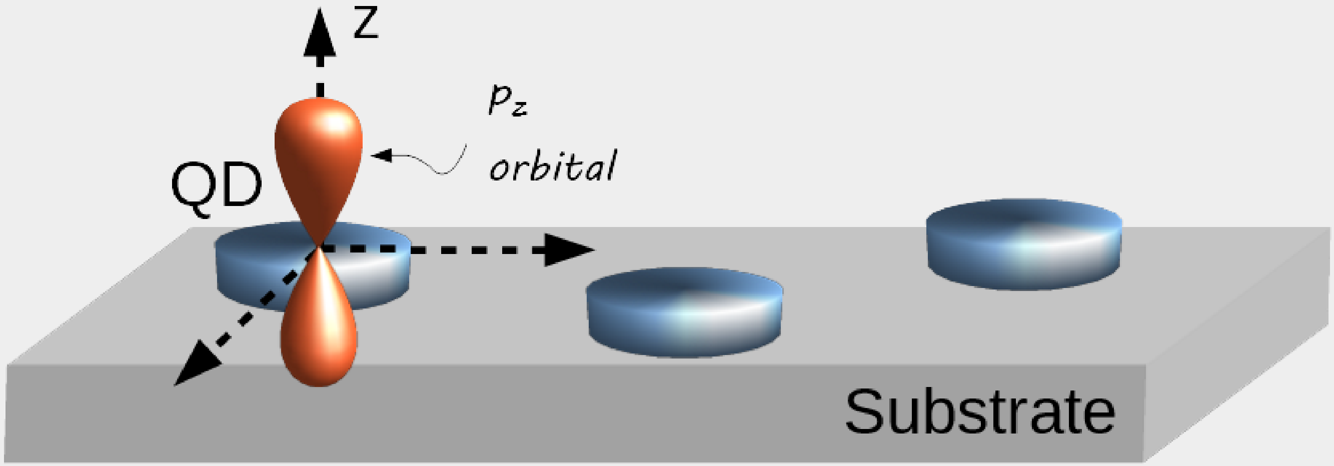


Atomic force microscopy

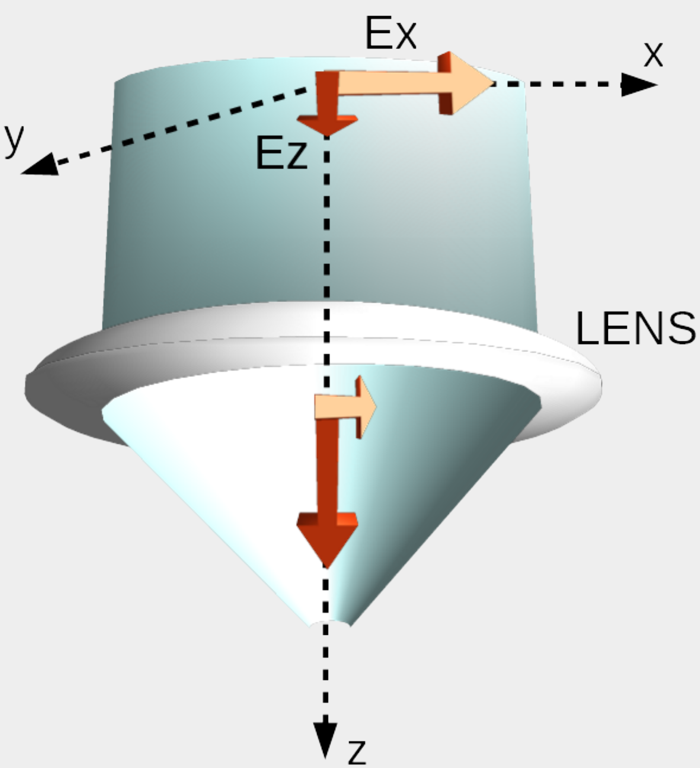
Spintronics with Light-hole in Quantum Dots

Light hole (LH) states have a p_z-like orbital component

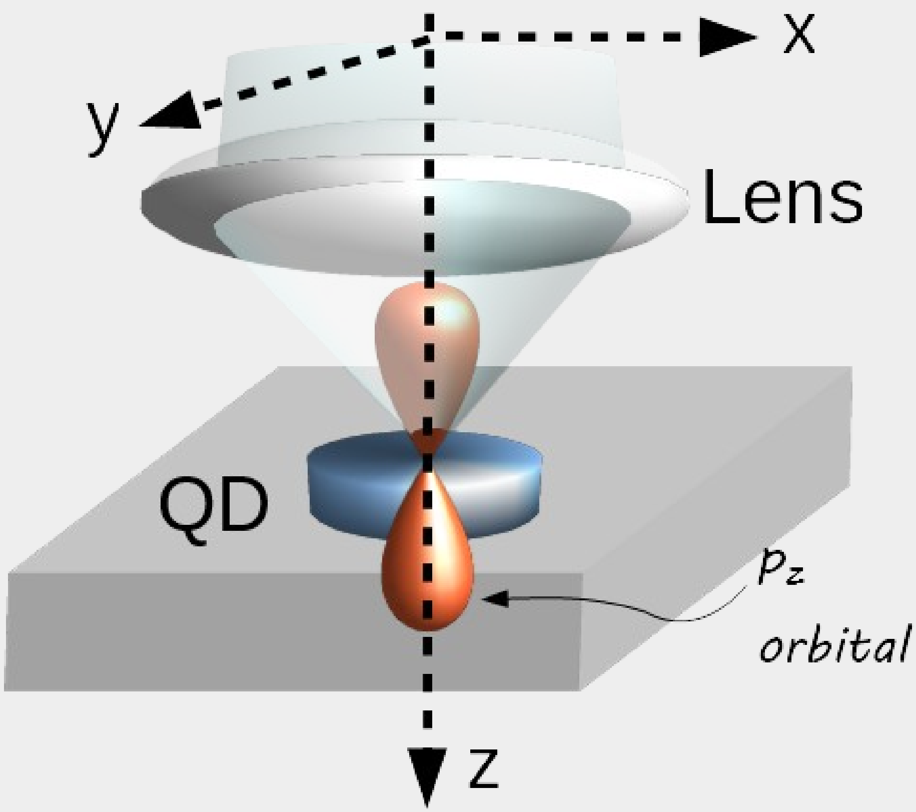
$$|LH+\rangle = -1/\sqrt{6}[(|p_x\rangle + i|p_y\rangle) \downarrow -2|p_z\rangle) \uparrow]$$

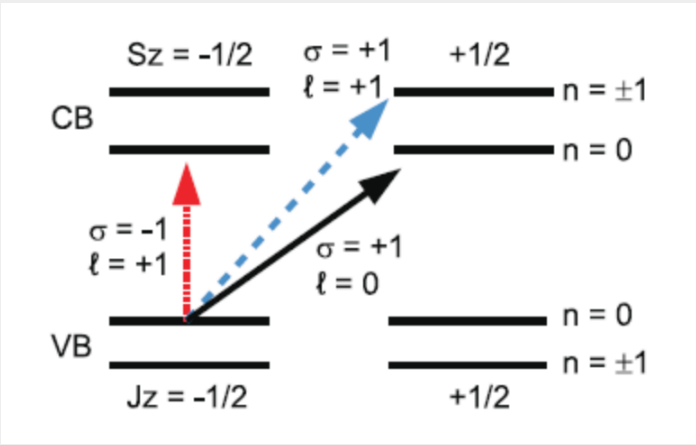


For a focused beam antiparallel beam (ℓ=1 and σ=-1) the longitudinal component $\boldsymbol{E}_z(\mathbf{r},t)$ dominates close to r=0:

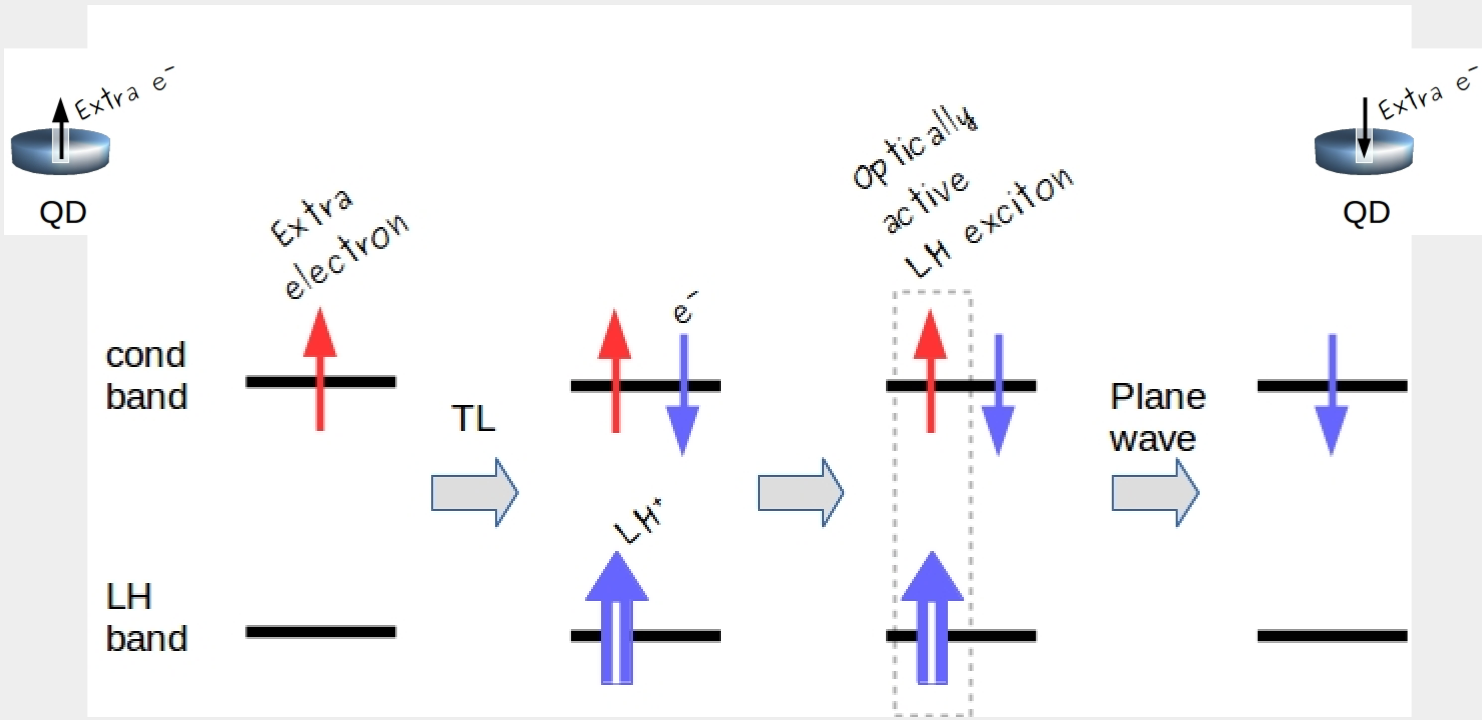


Control the spin state of an extra electron in a QD, by exciting light-holes at normal incidence.





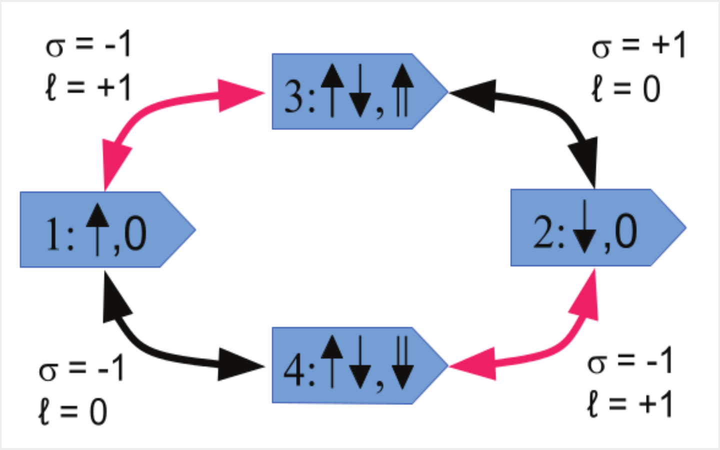
Protocol:

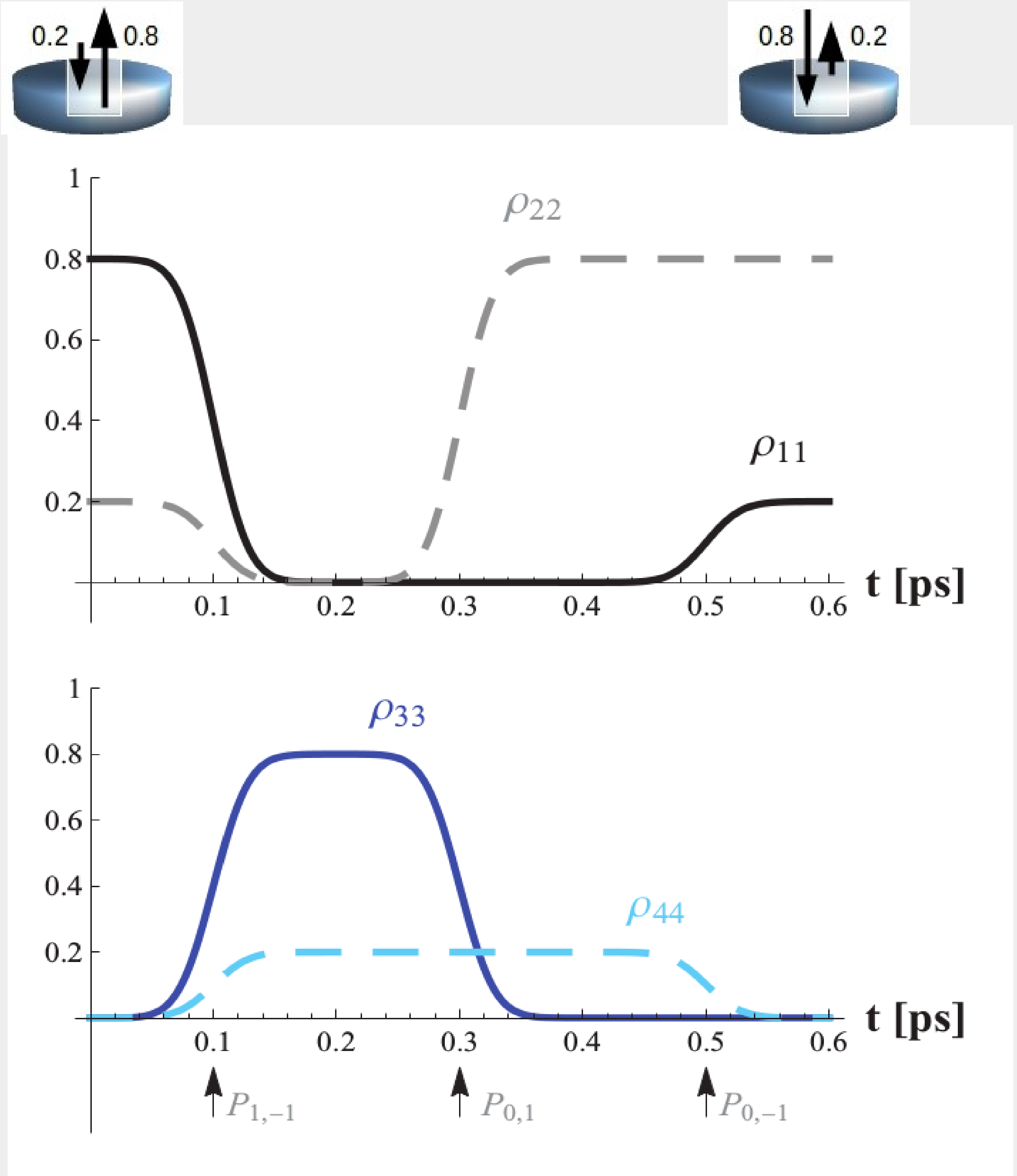


Final state

The spin of the extra electron is flipped by the light

Numerical simulations

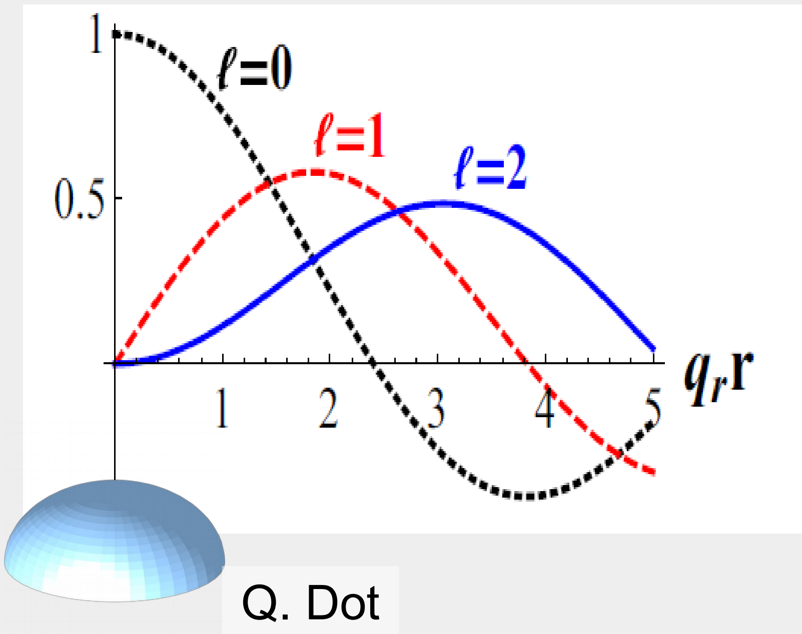




A sequence of 3 pulses ($P_{\ell,\sigma}$)
<u>independent</u> of the initial state
flips the spin

Unexplored directions

- Very few experiments (non in nanostructures)
- Solving the “size” problem with nanostructures



Ways to overcome the problem

There is some theoretical modeling of

- Tight focusing
- Near-field optics

but nothing in the use of

- Large band-gap material
- Longer exposure time

- Realistic study of applications

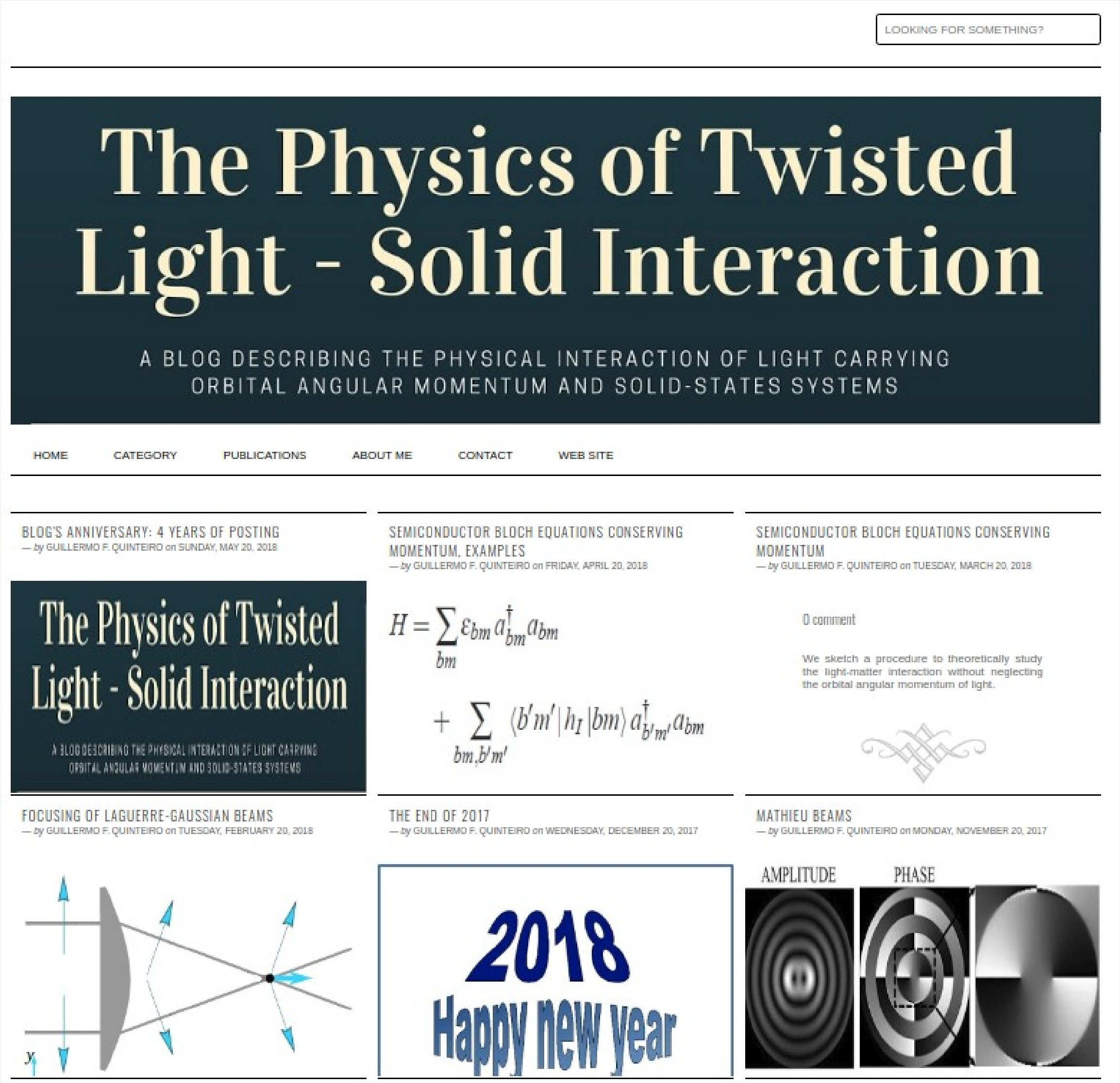
So far mostly theoretical studies with suggestions of possible applications

CONCLUSIONS

Optical vortices brings about new phenomena in semiconductor physics:

- Optical-magnetic interactions
- Strong longitudinal electric fields
- Circular photon drag in nanostructures
- Possible applications to spintronics

more information at:



http://twistedlight-solid.blogspot.com/