# Interaction of twisted light with semiconductors

**Guillermo F. Quinteiro**

**Departamento de Física**
**Universidad de Buenos Aires**
**Argentina**

# Outline

Introduction

The case of bulk semiconductors

The case of semiconductor structures

Possible applications and experiments

Conclusions

# Twisted Light

What is Twisted Light?
It is a highly *inhomogeneous* light beam carrying *orbital* angular momentum

More familiar:
Spin angular momentum ⟷ Circular polarization

Single photon spin angular momentum: $\pm\hbar$

Single photon Orbital Angular Momentum (OAM): $\ell\hbar$

# Mathematical representation

$$A(\bar{r},t) = A_0 e^{i(kz-\omega t)}[\hat{\varepsilon}_{\pm} F(\bar{r}) + \hat{\varepsilon}_z G(\bar{r})] + c.c.$$

# Mathematical representation

$$A(\bar{r},t) = A_0 e^{i(kz-\omega t)}[\hat{\varepsilon}_{\pm} F(\bar{r}) + \hat{\varepsilon}_z G(\bar{r})] + c.c.$$

Longitudinal polarization

Transverse polarization

# Mathematical representation

$$A(\bar{r},t) = A_0 e^{i(kz-\omega t)}[\hat{\varepsilon}_{\pm} F(\bar{r}) + \hat{\varepsilon}_z G(\bar{r})] + c.c.$$

Longitudinal polarization

Orbital angular momentum

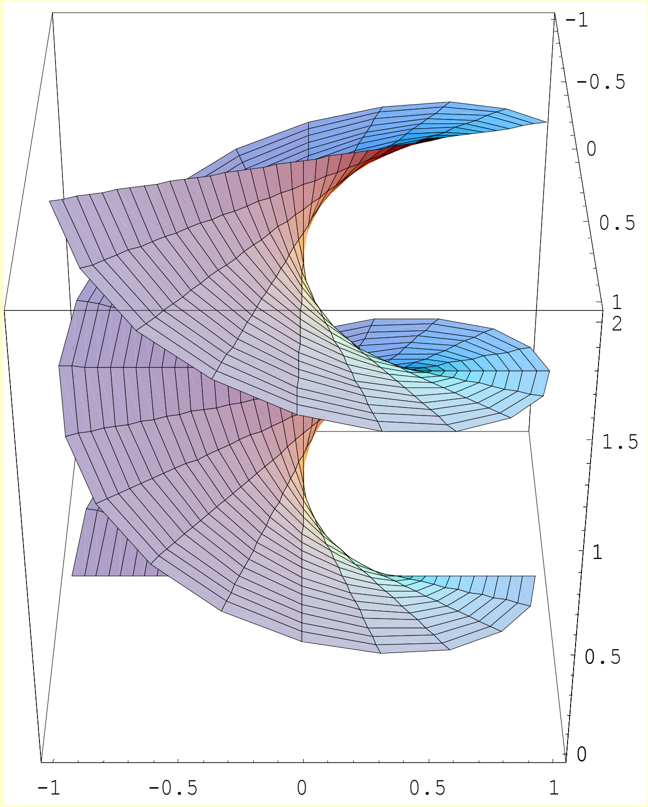
Transverse polarization

$$F(\bar{r}) = e^{il\phi} F(r)$$

Bessel OR Laguerre

$$A(\bar{r},t) = A_0 e^{i(kz-\omega t)}[\hat{\varepsilon}_{\pm} F(\bar{r}) + \hat{\varepsilon}_z G(\bar{r})] + c.c.$$

Helicoidal wave front **!**



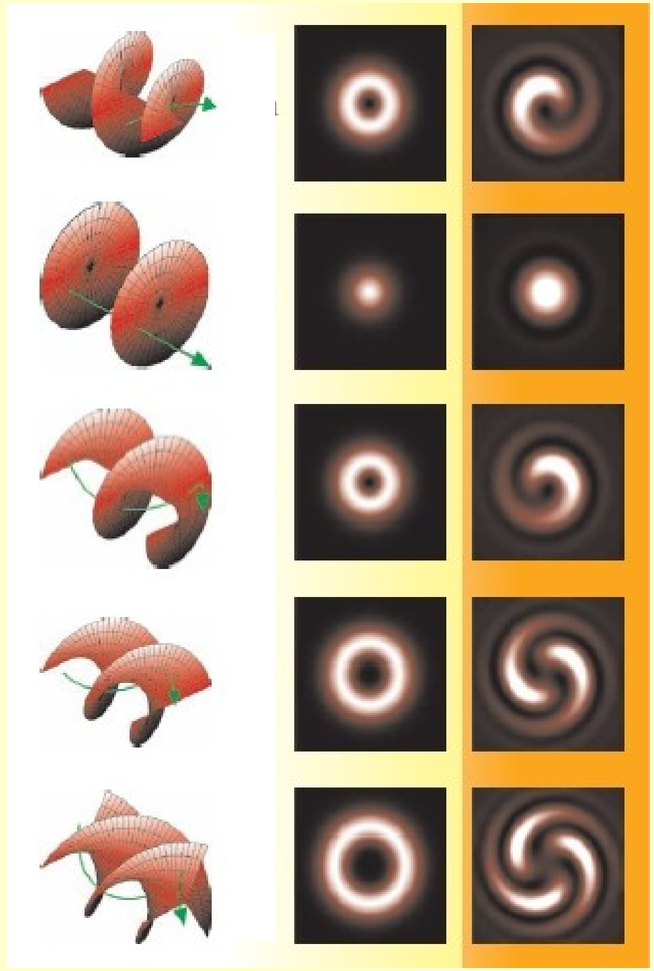
$\ell = -1$

$\ell = 0$

$\ell = 1$

$\ell = 2$

$\ell = 3$

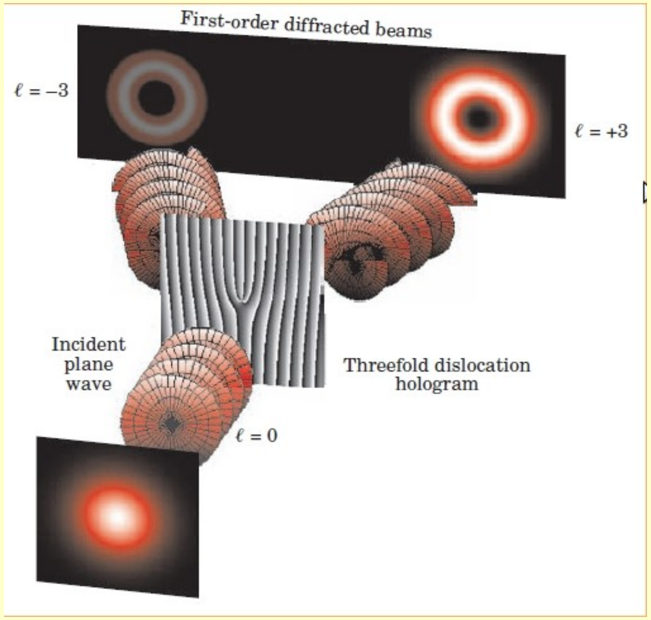


Plane wave

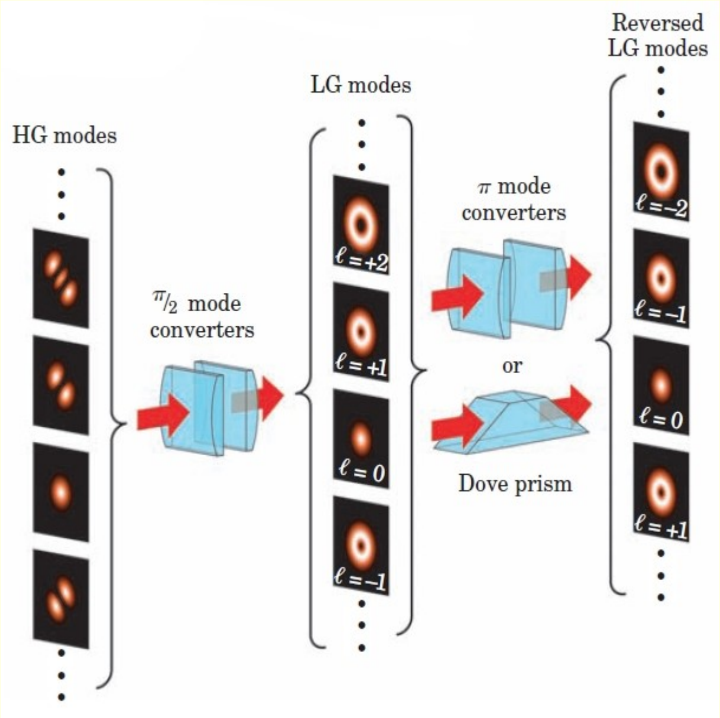
M. Padgett, J. Courtial and Les Allen, Physics Today 35, 2004.

# Generation of twisted light

Holograms




Cylindrical lenses




And other methods...

# Twisted light – semiconductor interaction

Using minimal coupling

$$H_I = \frac{1}{2m}\left[\bar{p} - q\bar{A}(\bar{r},t)\right]^2 + V(\bar{r})$$

$$\frac{1}{2m}\bar{p}^2 + V(\bar{r}) \qquad -\frac{q}{m}\bar{p}\cdot\bar{A}(\bar{r},t) \qquad \frac{q^2}{2m}\bar{A}(\bar{r},t)^2$$

Using minimal coupling

$$H_I = -\frac{q}{m}\,\overline{p}\cdot\overline{A}(\overline{r},t)$$

Using minimal coupling

$$H_I = -\frac{q}{m}\,\overline{p}\cdot\overline{A}(\overline{r},t)$$

Momentum operator

$$A_{\mathrm{q}l\sigma}(\mathrm{r},t) = \hat{\varepsilon}_\sigma A_0 e^{i(kz-\omega t+l\phi)} J_l(\mathrm{r}) + c.c.$$

Using minimal coupling

$$H_I = -\frac{q}{m}\,\overline{p}\cdot\overline{A}(\overline{r},t)$$

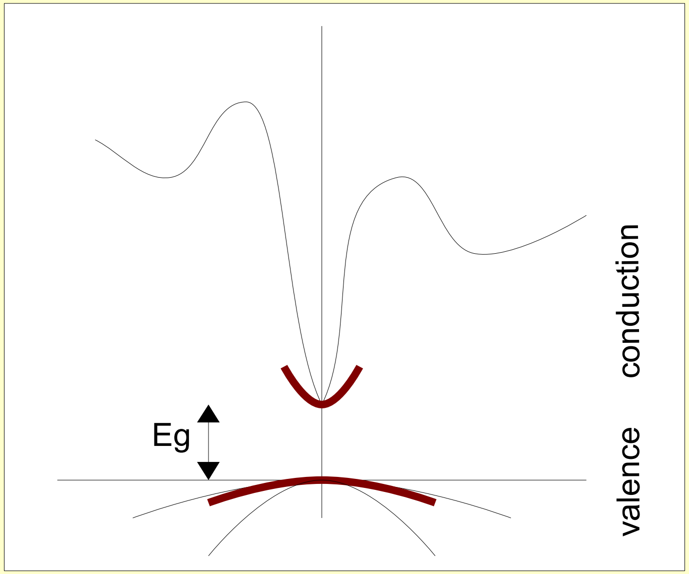
Matrix elements

Single Particle states

Density Matrix

# Bulk semiconductors
## (Single particle)

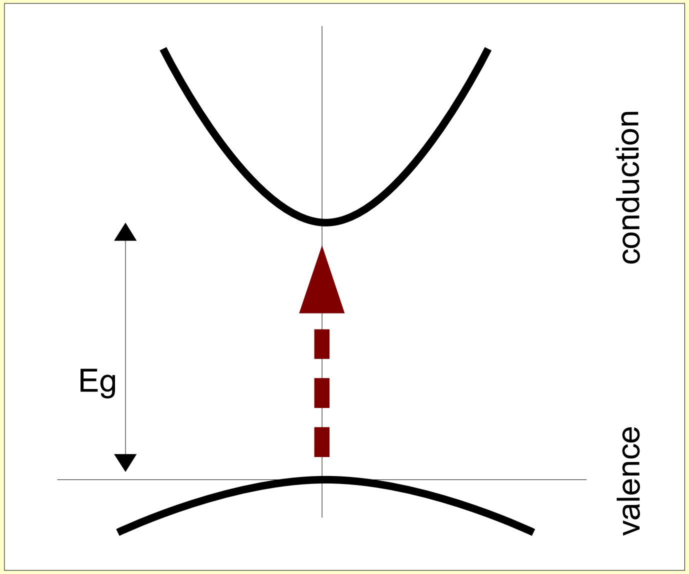
Two-band model:conduction and valence.




Bloch states...

$$\varphi_{\lambda k}(\bar{r}) = \frac{1}{L^{3/2}} e^{\bar{k}\cdot\bar{r}} u(\bar{r})$$

Usually, the light induces *vertical* transitions



We consider the action of $H_I$

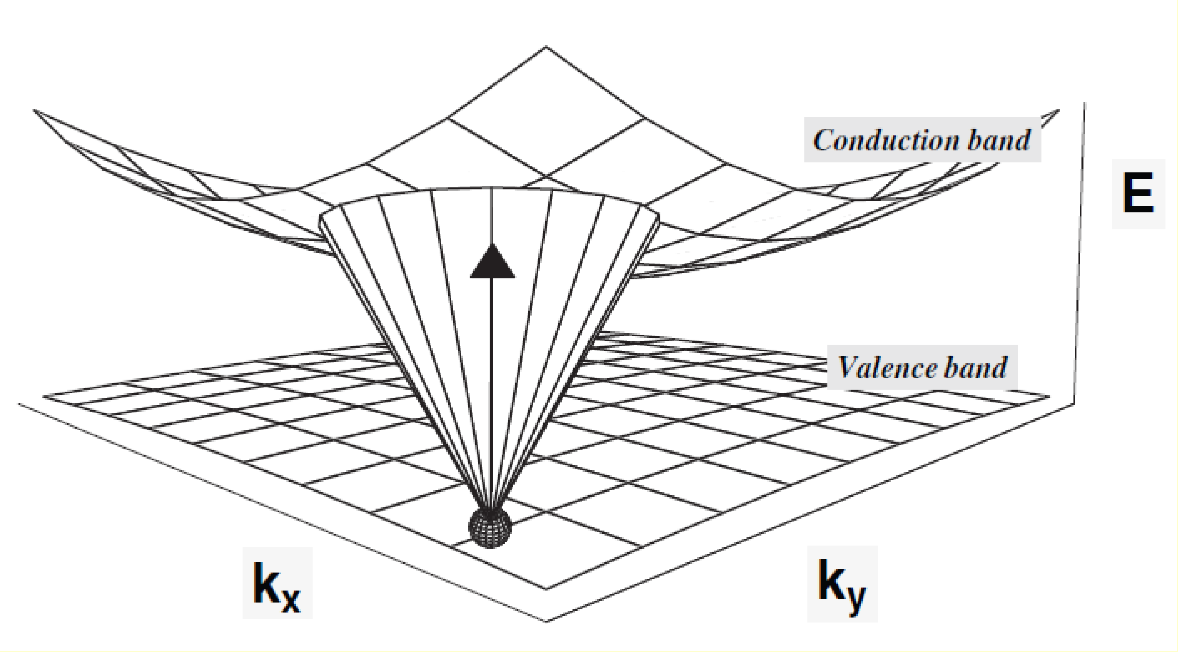
$$H_I$$

$$\varphi_{vk}(r) \to \varphi_{ck'}(r)$$

Allowing for *non*-vertical transitions ...

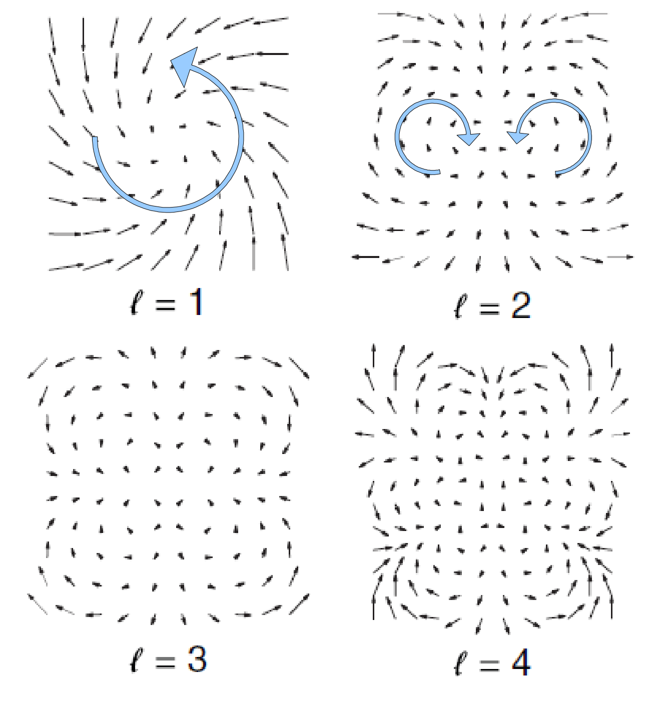
$$H_I^{(+)}\varphi_{vk}(\bar{r}) = \xi\left[i^l e^{iq_z z} J_l(qr) e^{il\phi}\right]\varphi_{ck}(\bar{r})$$

the final state is a superposition:



Electric currents of order *A* and $A^2$ are calculated,

For example to order A:




The current follows the electric field.

To order $A^2$ there is a *net* current:

Top hat profile

Power 3 $\mu$J $s^{-1}$

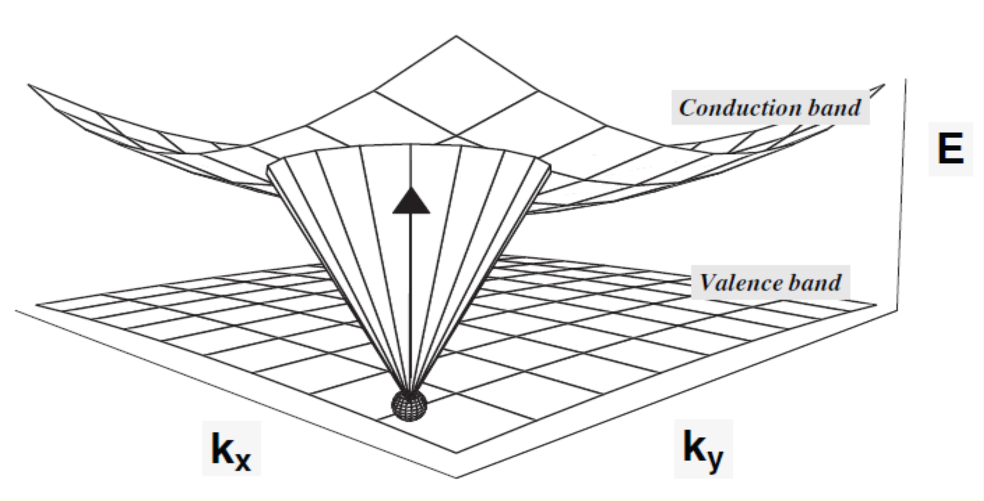
Spot size 0.5 $\mu$m

GaAs

Order $A^2$: $B_z \sim \mu T$

# Bulk semiconductors
## (Density matrix)

We just saw that optical transitions look:




Because cartesian coordinates were used together with a “cylindrical” light field

## Electron states in a cylinder

$$\psi_{bkm}(r) = N e^{ik_z z} J_m(k_r r) e^{im\phi}\ u_b(r)$$

$$\varepsilon_{bkm} = \frac{\hbar^2}{2m_b^*}\left(k_r^2 + k_z^2\right) + \delta_{bc} E_g$$

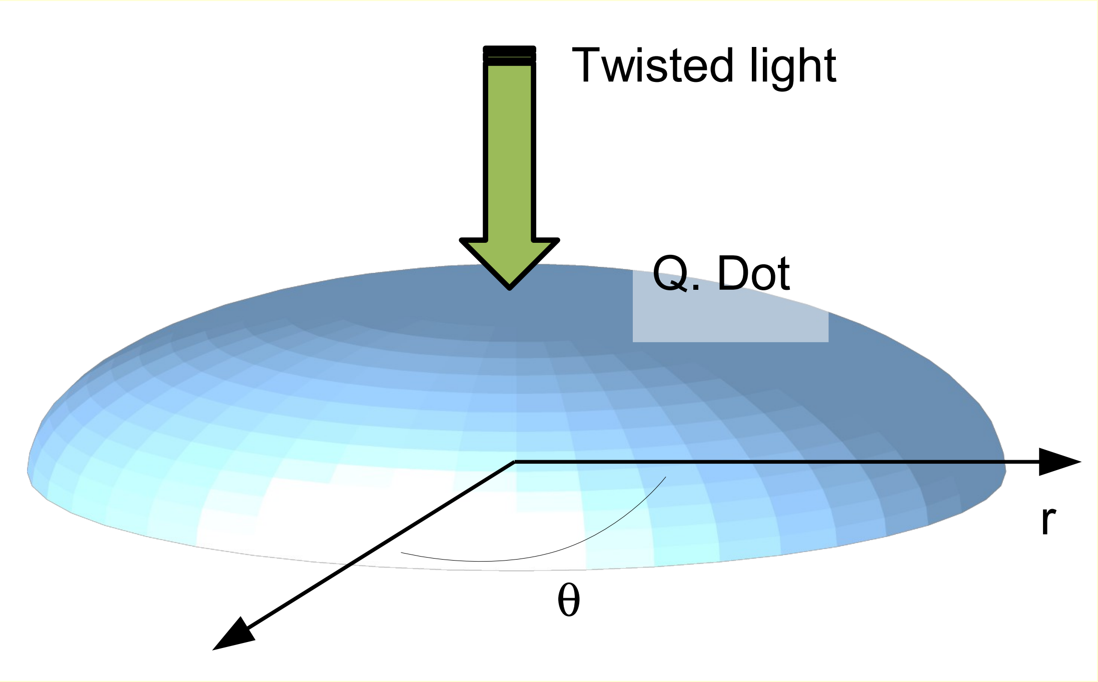
We solve

$$i\hbar \frac{d}{dt}\rho_{b'\alpha',b\alpha} = \left[\rho_{b'\alpha',b\alpha}, H\right]$$

The system of equations is
closed in the subspaces of fixed $\{k_z,m\}$ and $\{k_z+q,m+l\}$

From $\rho_{b'\alpha',b\alpha}$ we can calculate electric currents, etc...

# Semiconductors Structures: Quantum Dots




Disk-shape quantum dot with parabolic confinement

Wave function

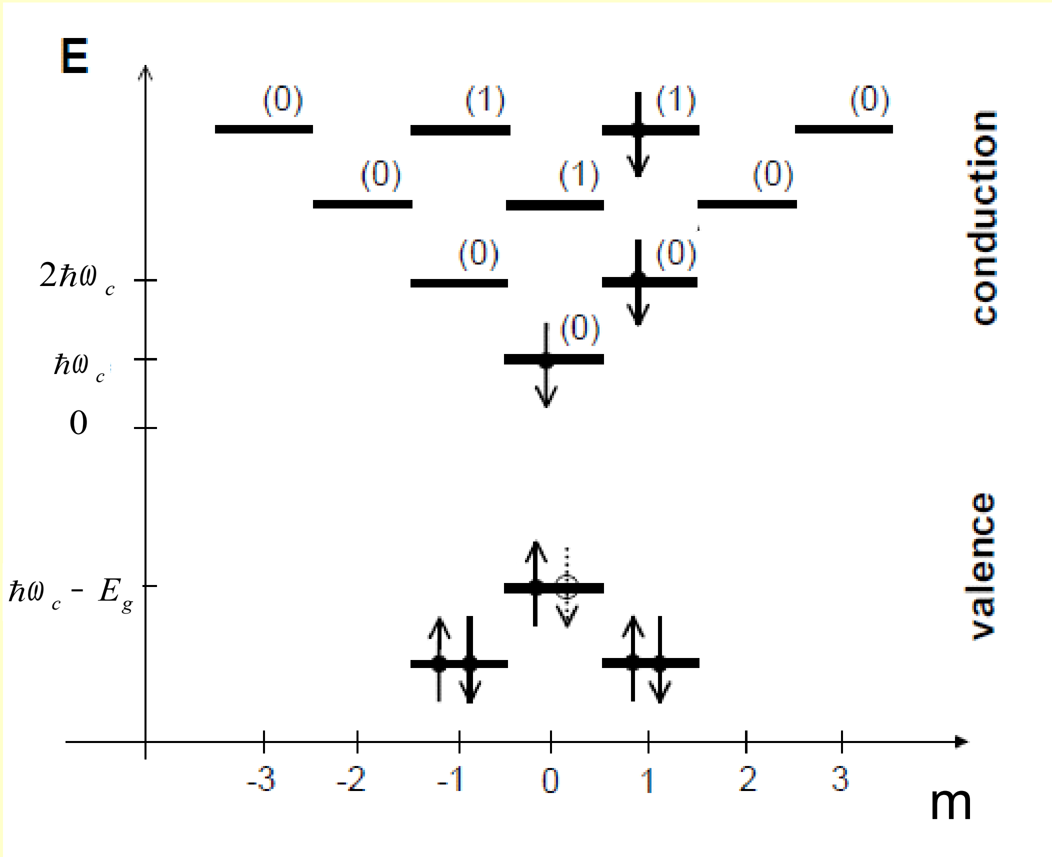
$$\varphi_{bsn}(r,\theta) = Ne^{-Ar^2}\left(\frac{r}{B}\right)^{|n|} L_s^{|n|}(Cr^2)e^{-in\theta}\ u_b(r)$$

Same form as twisted light in Laguerre-Gaussian mode

Transition matrix elements:

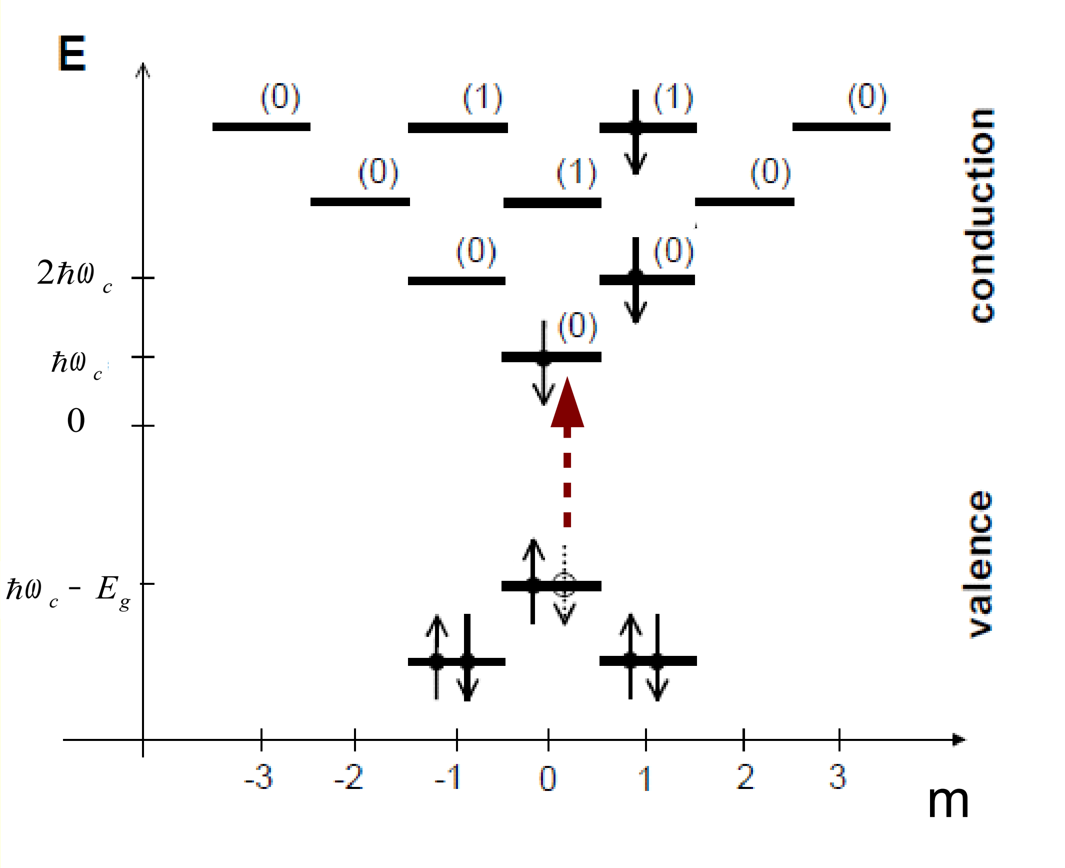
$$\left\langle c\, s'\, m' \middle| H_l \middle| v\, s\, m \right\rangle \propto e^{-i\omega t}\, \delta_{l-(m'-m)}\, h(\zeta)$$

(c) conduction band
(v) valence band
(m) orbital quantum #
(s) radial quantum #
(ζ) QD size / beam waist



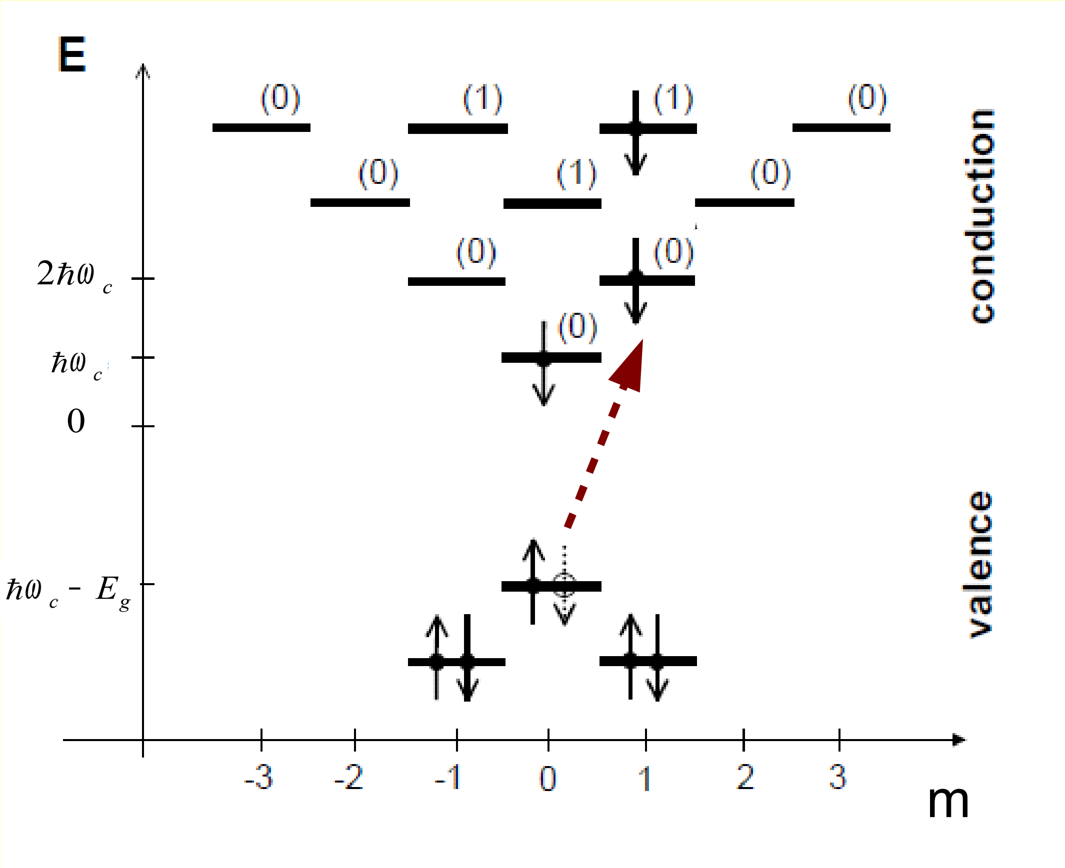

(#) radial quantum #
m orbital quantum #

## Plane wave



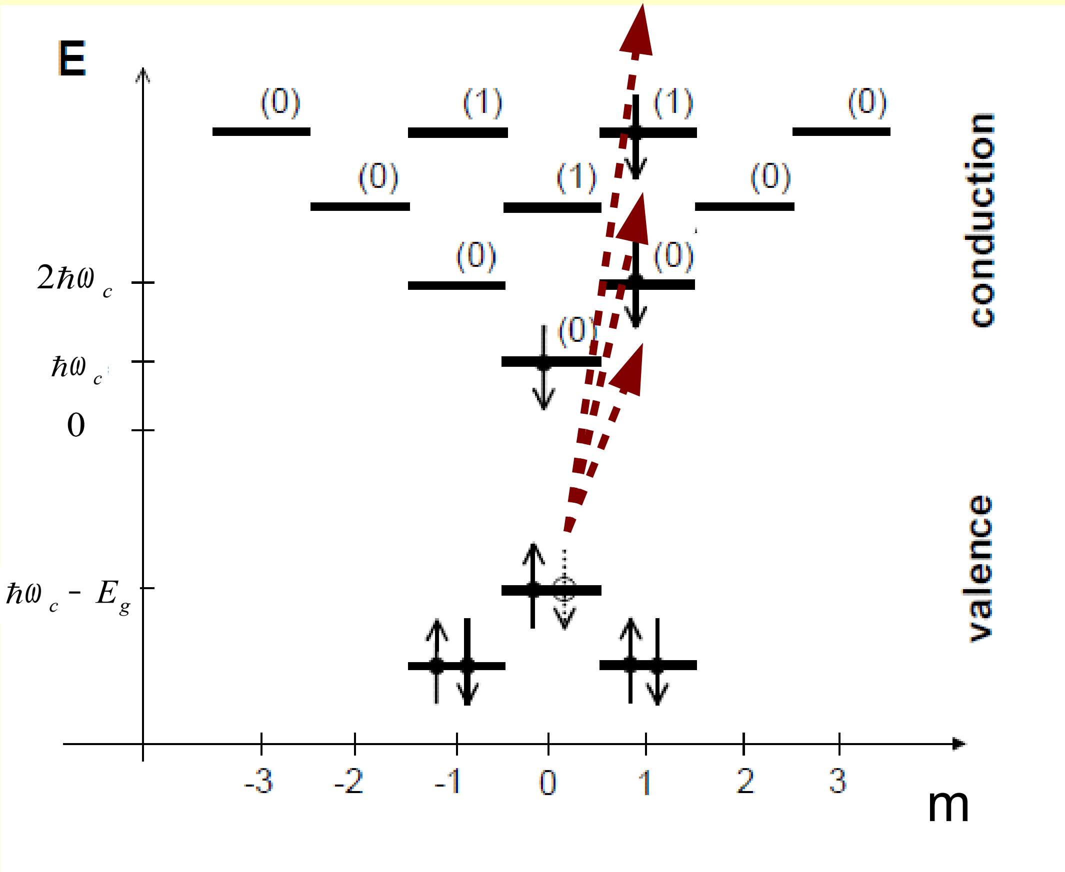

(#) radial quantum #
m orbital quantum #

## Twisted light (L=1)




(#) radial quantum #
m orbital quantum #

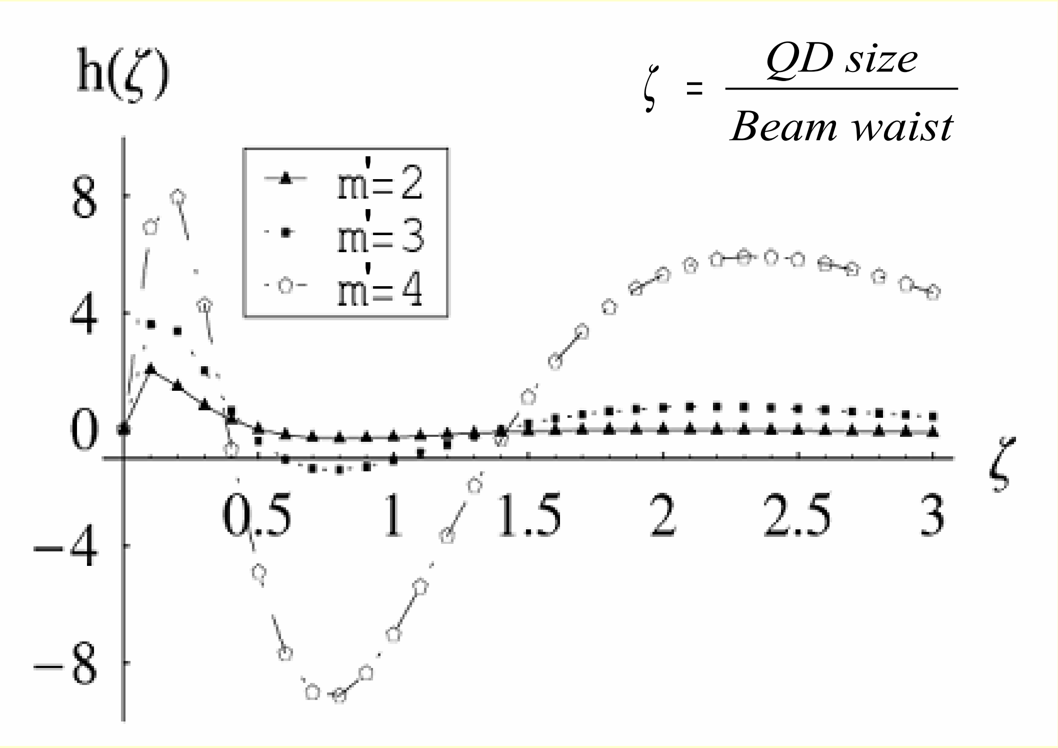
# Changing the radial quantum #

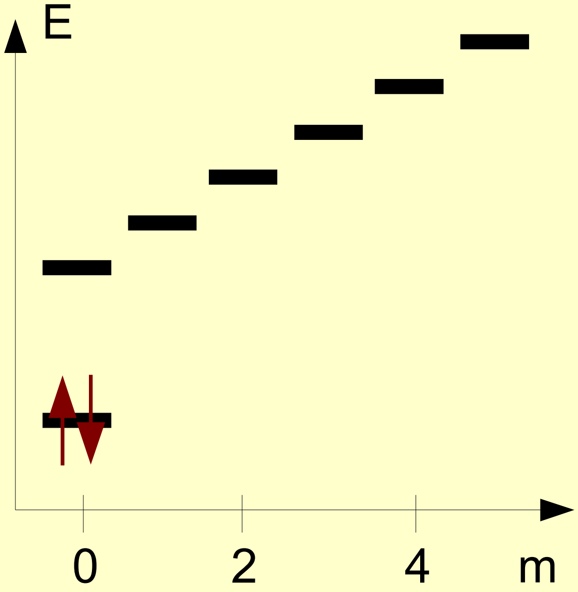



(#) radial quantum #
m orbital quantum #

# Fix m and radial q. #

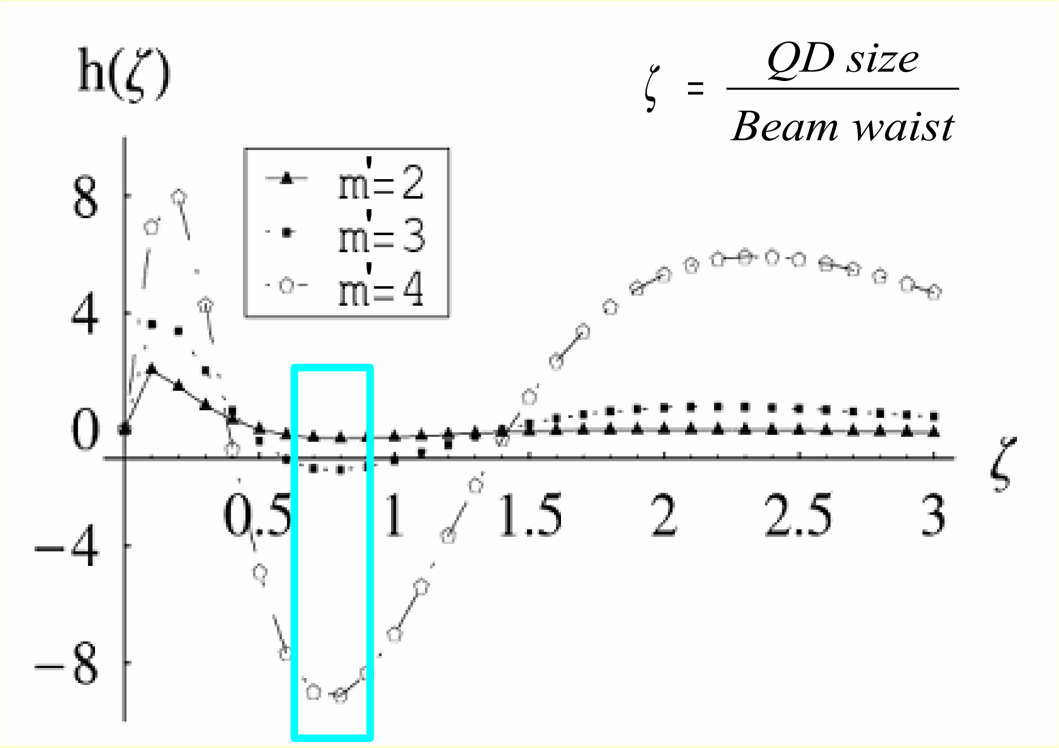
$$\langle c\,s'\,m'|H_l|v\,s\,m\rangle \propto e^{-i\omega t}\,\delta_{l-(m'-m)}\,h(\zeta)$$

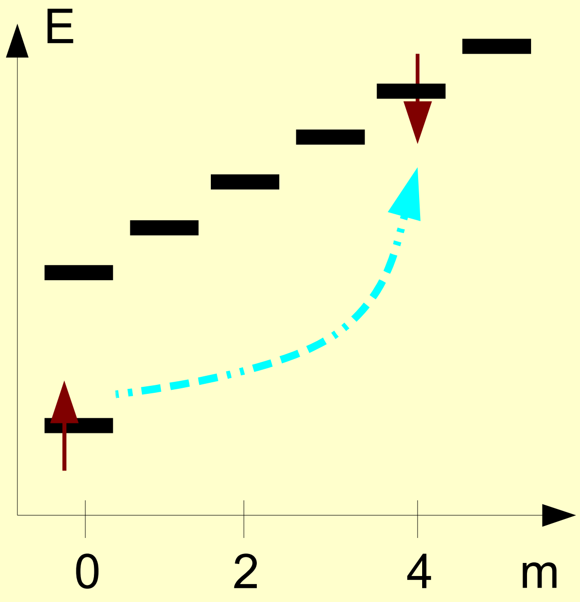


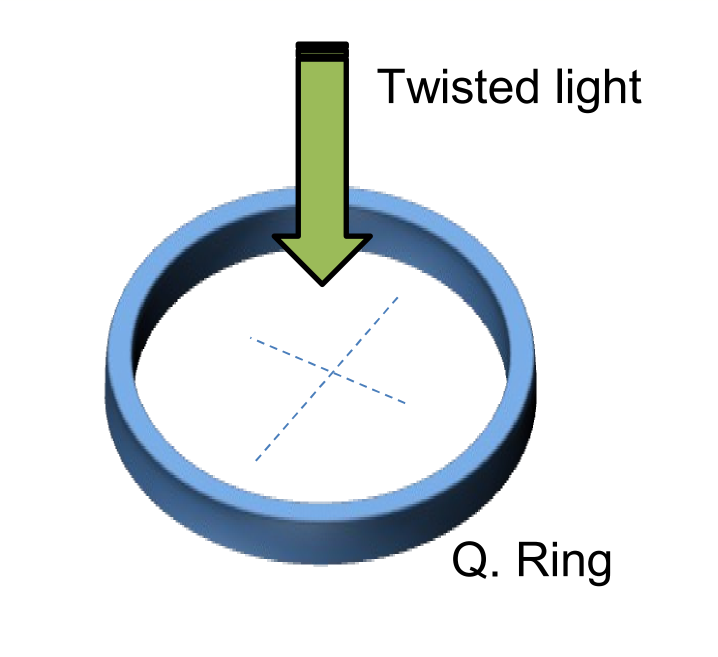
# Fix m and radial q. #

$$\langle c\, s'\, m' | H_I | v\, s\, m \rangle \propto e^{-i\omega t}\, \delta_{l-(m'-m)}\, h(\zeta)$$



# Semiconductors Structures: Quantum Ring




$$\varphi_m(\phi) = Ne^{-im\theta} u_b(r)$$

# Equations for populations and coherences

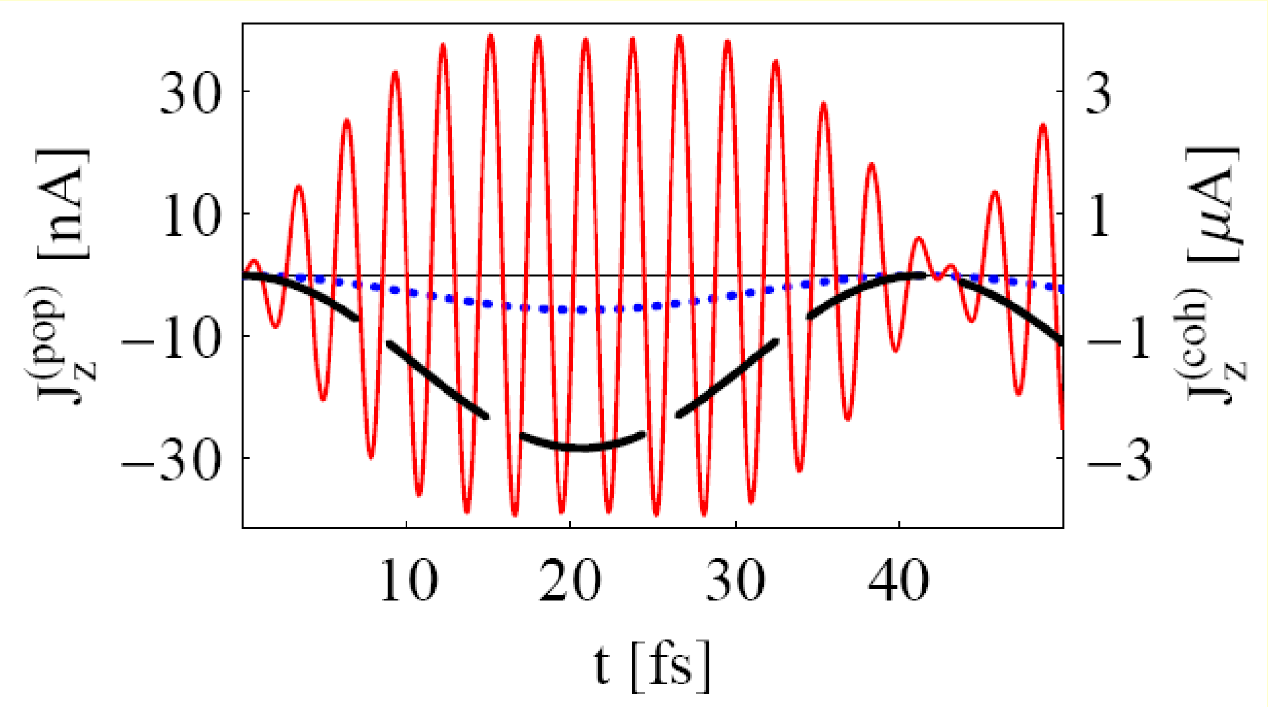
$$\hbar \frac{d}{dt} \rho_{v,mm} = 2\Im\left[\xi^{*} \tilde{\rho}_{vm,cm+l}\right]$$

$$\hbar \frac{d}{dt} \rho_{c,m+lm+l} = -2\Im\left[\xi^{*} \tilde{\rho}_{vm,cm+l}\right]$$

$$i\hbar \frac{d}{dt} \tilde{\rho}_{vm,cm+l} = \Delta_{cm+l,vm} \tilde{\rho}_{vm,cm+l} + \xi\left(\rho_{v,mm} - \rho_{c,m+lm+l}\right)$$

Become decoupled for each {m, m+l}: Tilted Rabi oscillations

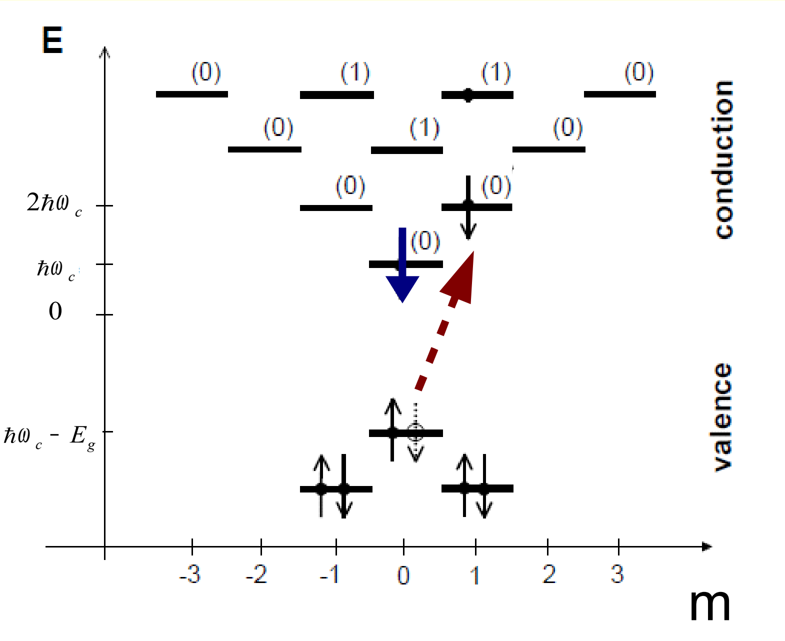
We calculate the current




Two contributions: population- and coherence-based.

# Possible Applications

Manipulation of electronic states to control charged Quantum Dots



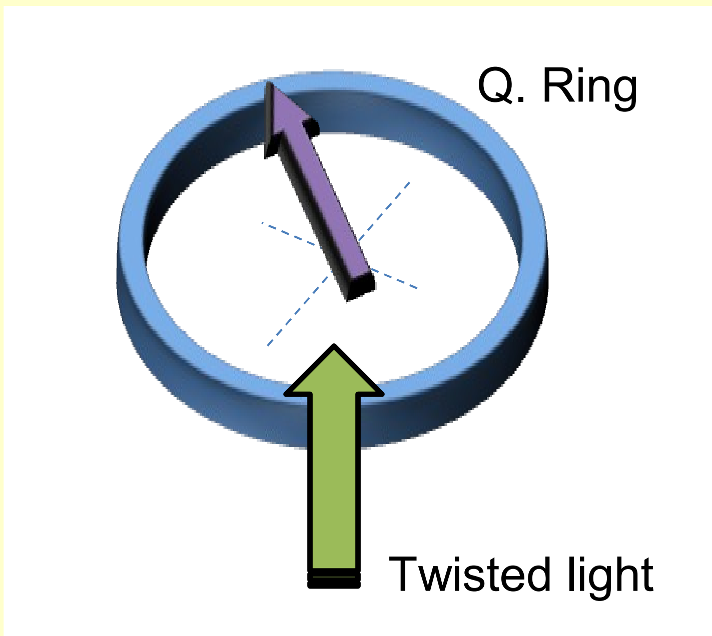


Added electron

Twisted light induced transition

## Possible applications

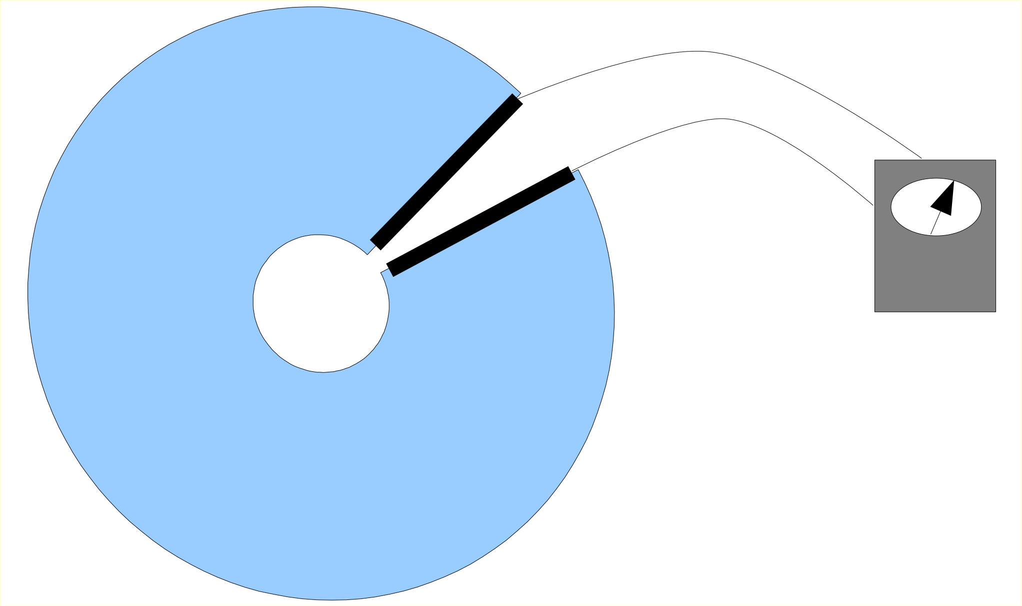
Generation of magnetic fields in Quantum Rings to control spins




Impurity spin

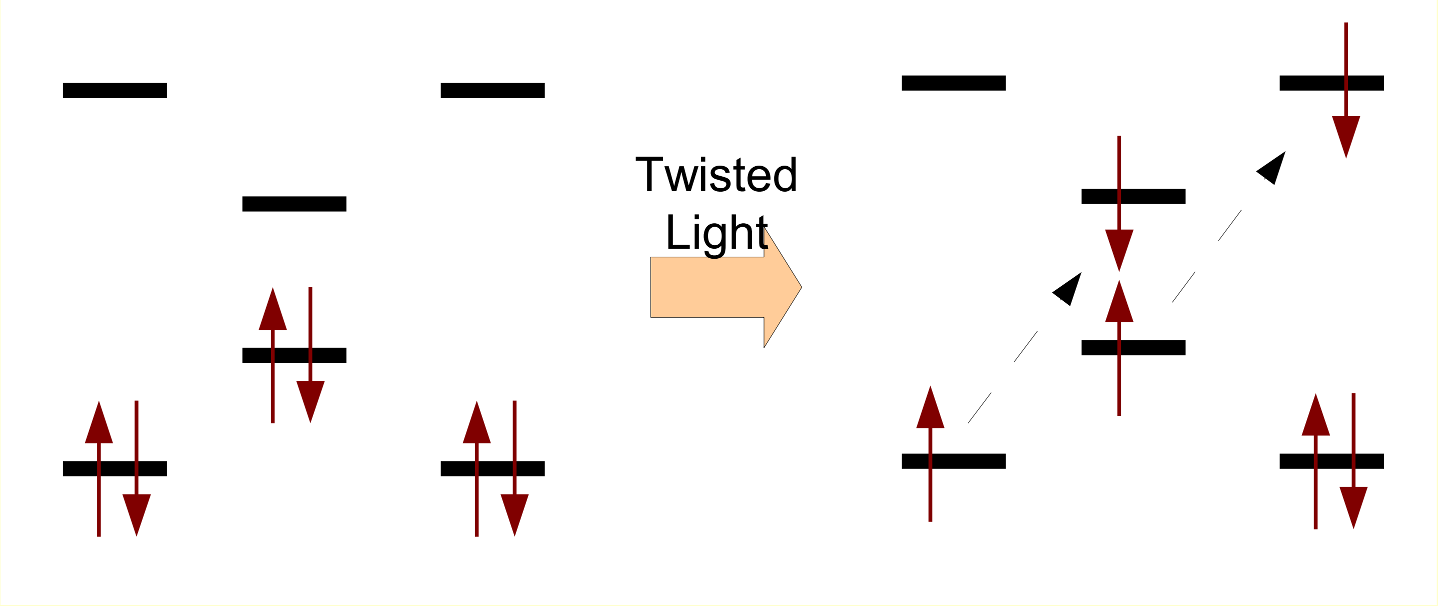
# Possible experiments

In bulk, we suggest measuring the current or voltage in cw excitation



resembling the set-up for photon drag effect.

In quantum dots




Using pump-probe techniques.

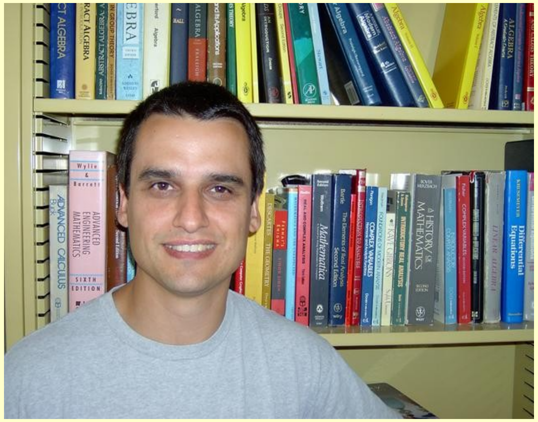
# Conclusions

. Generation of ultrafast electric currents and magnetic field

. New transitions in Quantum Dots

. Possible applications to spintronics

# Bibliography



[1] G. F. Quinteiro and P. I. Tamborenea
***Theory of the optical absorption of light carrying orbital angular momentum by semiconductors***, EPL 85, 47001 (2009).

[2] G. F. Quinteiro and P. I. Tamborenea
***Electronic transitions in disc-shaped quantum dots induced by twisted light***, Phys. Rev. B 79, 155450 (2009).

[3] G. F. Quinteiro and J. Berakdar
***Electric currents induced by twisted light in Quantum Rings,*** Optics Express 17, 20465-20475 (2009).

[4] G F Quinteiro, A O Lucero and P I Tamborenea
***Electronic transitions in quantum dots and rings induced by inhomogeneous off-centered light beams,*** J. Phys.: Condens. Matter 22 (2010) 505802.

[5] G. F. Quinteiro,
**Below-bandgap excitation of bulk semiconductors by twisted light**, EPL 91, 27002 (2010).

[6] G. F. Quinteiro and P. I. Tamborenea
**Twisted-light-induced optical transitions in semiconductors: Free-carrier quantum kinetics**, Phys. Rev. B 82, 125207 (2010).

Vielen Dank Für Ihre Aufmerksamkeit

# Gauge invariance

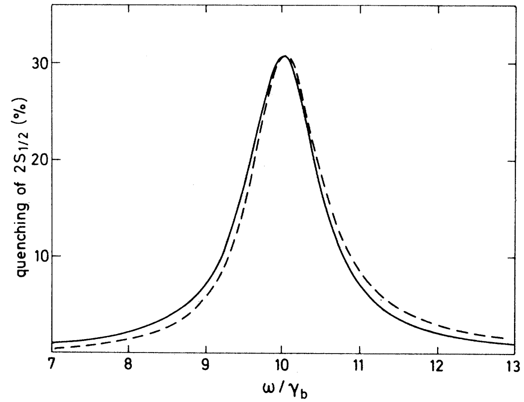



FIG. 1. Quenching of the $2S_{1/2}$ state as a function of the level spacing $\omega$ for a rf frequency $\nu/2\pi = 1000$ MHz and a lifetime of $2P_{1/2}$ $\gamma_b^{-1} = 1.6 \times 10^{-9}$ sec. Solid curve, decay according to Eq. (2.10); dashed curve, decay rate given by Eq. (2.16).

Willis E. Lamb Jr., Rainer R. Schlicher, Marlan O. Scully, Phys. Rev. A 36, 2763 (1987)

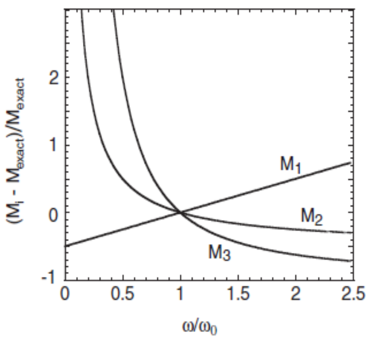



Figure 1. Relative difference between several forms of the Kramers-Heisenberg matrix element $M_i(\omega)$ in the rotating wave approximation and the exact form of $M(\omega)$ for a harmonic oscillator of resonance frequency $\omega_0$. Note that all of the forms agree at the resonance frequency, but that significant differences can occur far from resonance.

K. RZAZEWSKI and R. W. BOYD, journal of modern optics, vol. 51, no. 8, 1137–1147 (2004)

At resonance there are no differences between A.p and E.d