OQA module

Classical description of a quantum emitter

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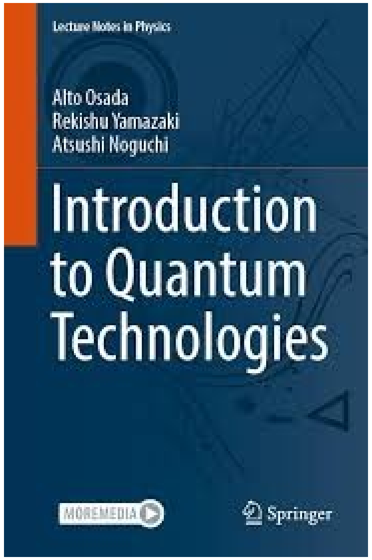
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Alto Osada
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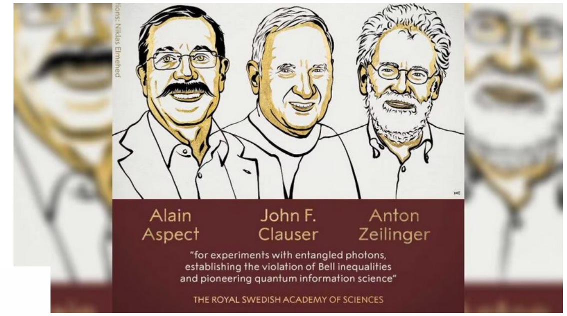
Alain Aspect
John F. Clauser
Anton Zeilinger
"for experiments with entangled photons, establishing the violation of Bell inequalities and pioneering quantum information science"
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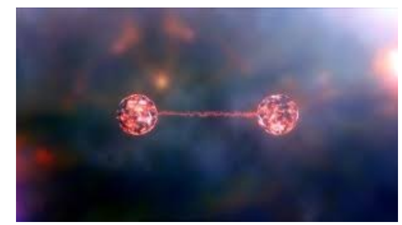

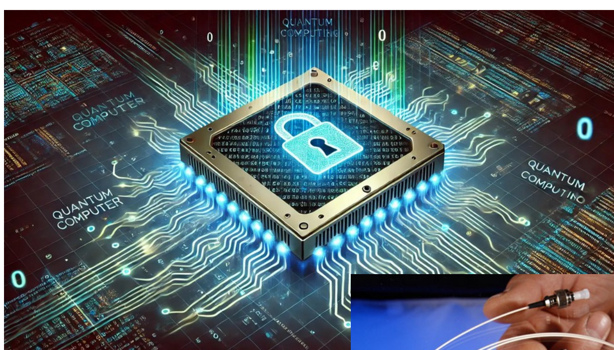
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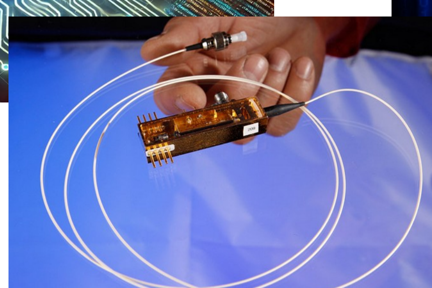
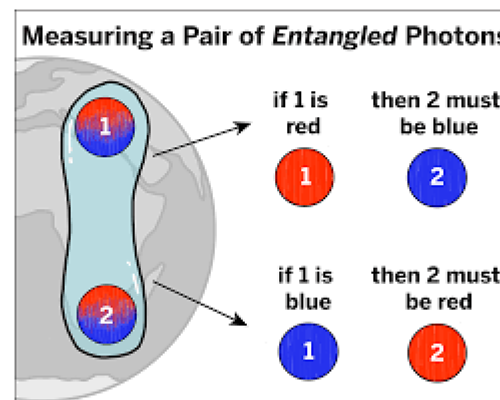



Measuring a Pair of *Entangled* Photons
if 1 is red
then 2 must be blue
if 1 is blue
then 2 must be red

Quantum technologies

OPTICS/ Photons

Manipulation of single

tons

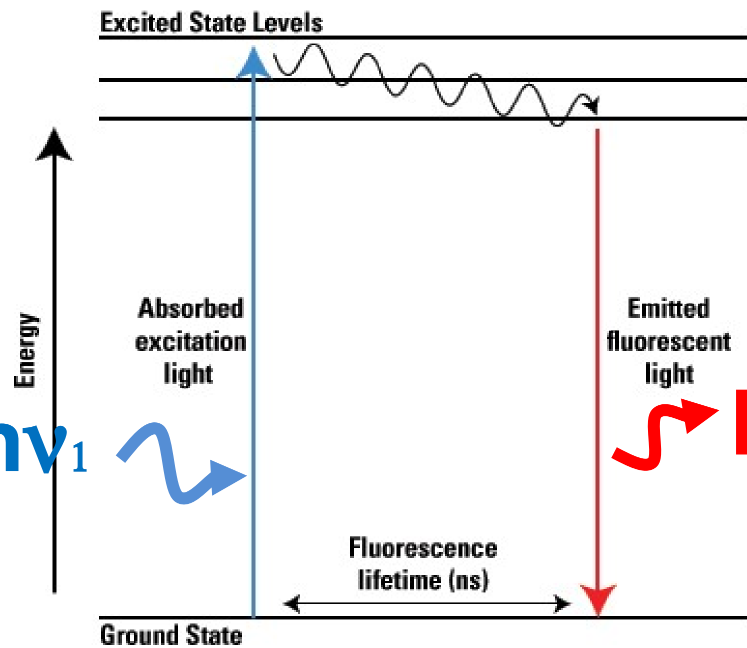
Where do they come from ???
Single photon generator ???

Single photon emission: **fluorescence**

A model of a fluorescent emitter:

➔2 energy levels (2 states: fundamental / excited)

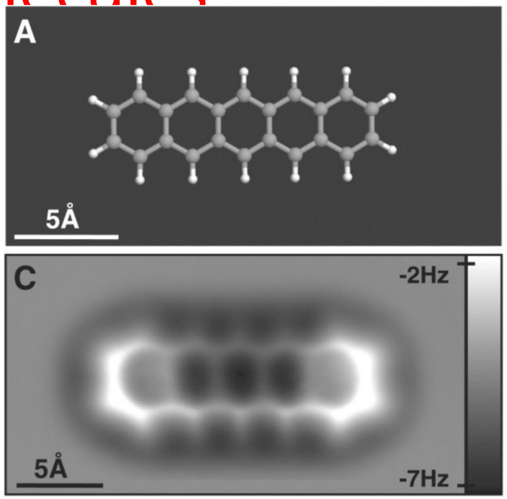
1 photon absorbé $h\nu_1$



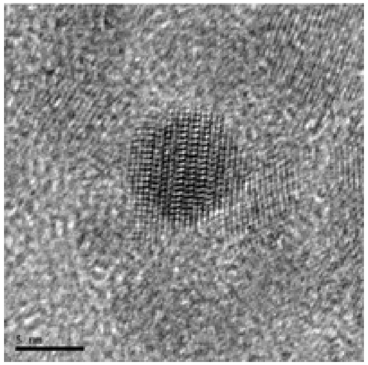
1 emitted phot $h\nu$

$$\nu_1 > \nu_2$$

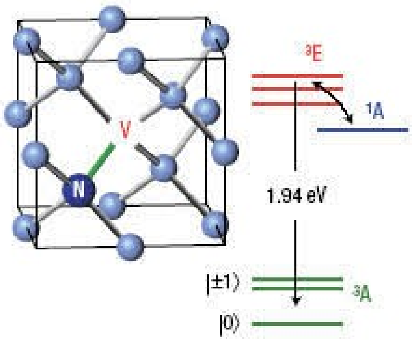
- Fluorescence molecules



- Colloidal quantum dots



- NV color centers in diamond



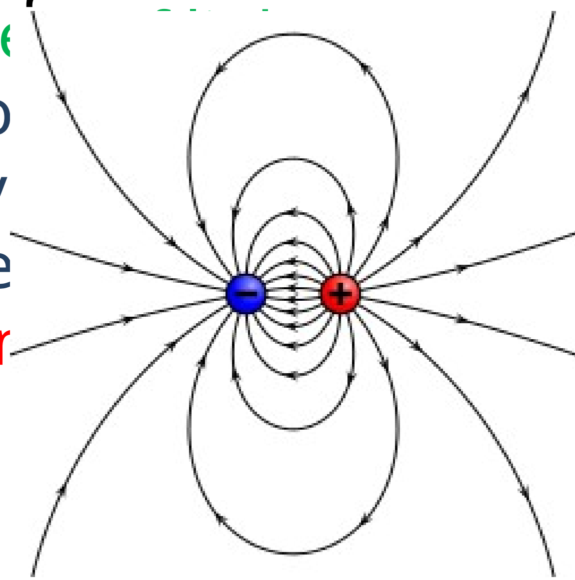
Quantum emitters

- Point-like emitters of light (nanometer scale) : atoms, molecules , nanoparticules.
- Internal energy levels ➔ light matter interaction: ground and excited states: emission shows discrete spectral peaks
- Spontaneous emission of photons (no stimulated emission)

Quantum emitters

From a classical point of view ??

- Point-like emitte… …eter scale) : atoms, molecules , nano…
- Internal energy … …er interaction: ground and excited state… …discrete spectral peaks
- Spontaneous er… …(no stimulated emission)



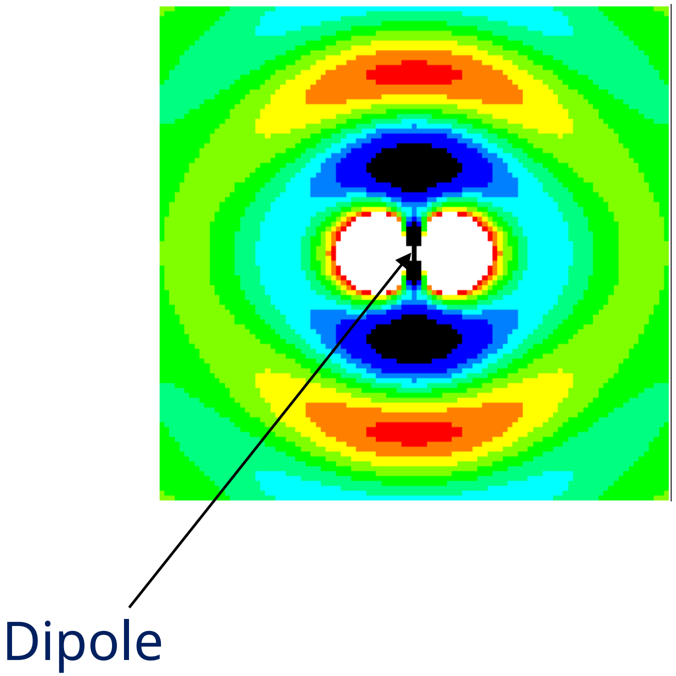
The dipole

Radiation of a dipole

Numerical simulation

FDTD method

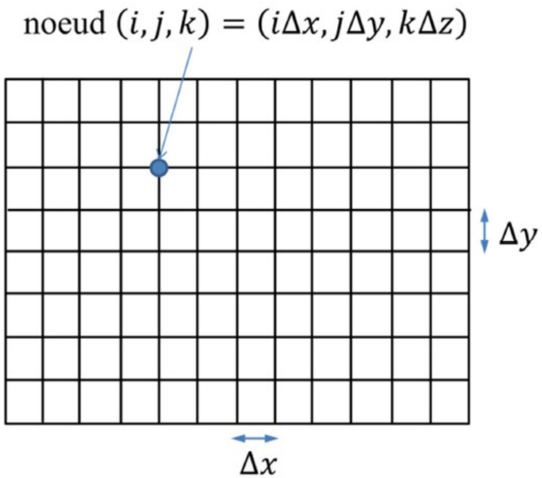
Fullwave (Synopys)



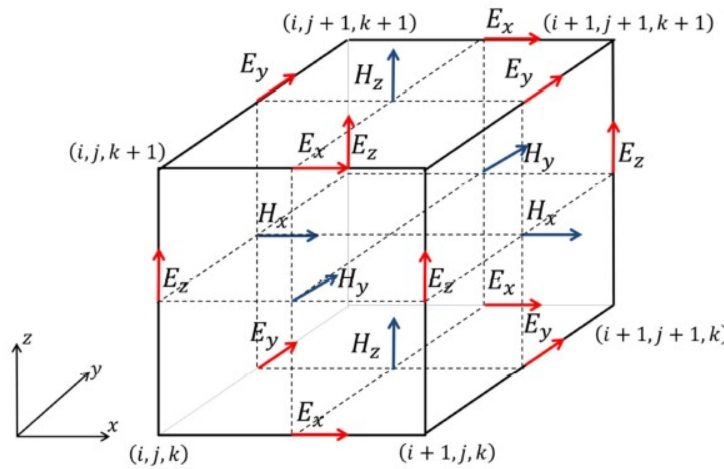
FDTD method: Finite Difference Time Domain

- Maxwell’s equations resolved in space and time.
- Developed for the first time by Yee in 1966 for the low frequencies (microwaves, etc.)
- The acronym FDTD has been given by Taflove in his reference book, extension to optics
- Widely used in optics for the design and simulations of nano-optical structures.

Discretization of the Maxwell's equations in space and time



Space gridding

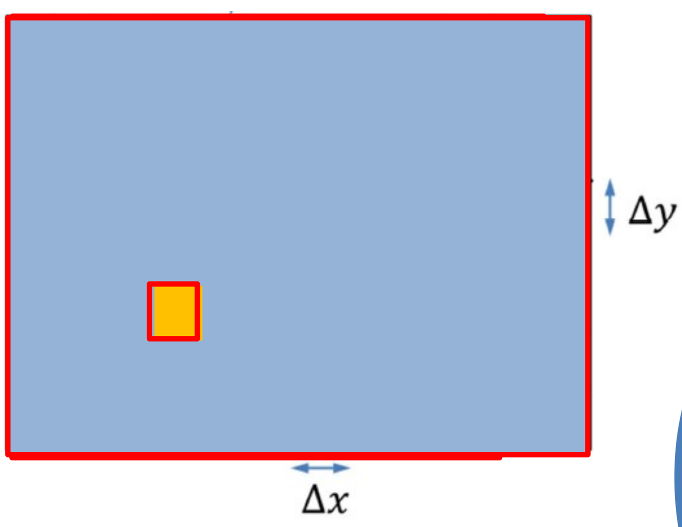


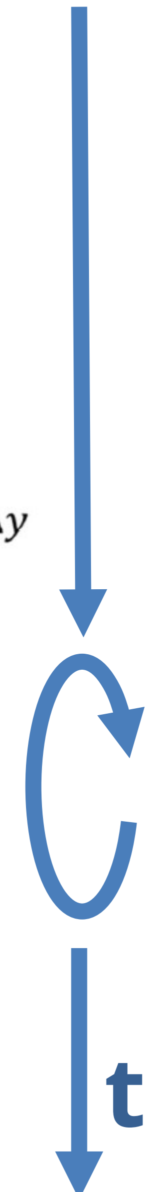
View of the field components in a single cell : the Yee cell

$$\frac{\partial H_x}{\partial t}(\mathbf{r},t) = \frac{1}{\mu}\left(\frac{\partial E_y}{\partial z}(\mathbf{r},t) - \frac{\partial E_z}{\partial y}(\mathbf{r},t)\right)$$

$$\frac{H_x^{n+1/2}(i,j,k) - H_x^{n-1/2}(i,j,k)}{\Delta t} = \frac{1}{\mu(i,j,k)}\left[\frac{E_x^n(i,j,k+1) - E_x^n(i,j,k)}{\Delta z} - \frac{E_z^n(i,j+1,k) - E_z^n(i,j,k)}{\Delta y}\right]$$

How does it work ? The algorithm





- The space and meshgrid (in space and time) ➔ computation volume

- We define objects: Ɛ defined in each ce

- We place the EM source: source term =

- generates et dans in the cell (Maxwell's equations)

- Boundary conditions with neighbourin

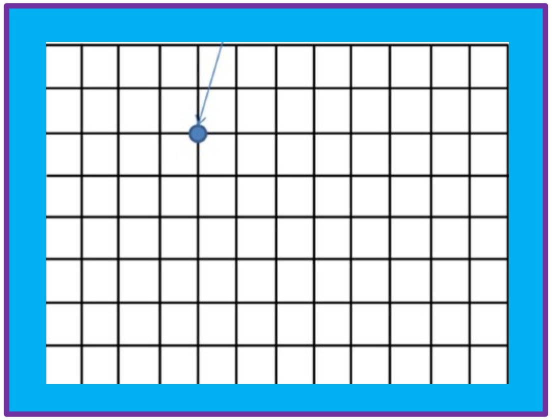
- Field propagation in the cell (finite diff.)

- Stationnary regime reached: we stop

Comments

1- Finite computation volume

➔ the optical waves are reflected at the edges !!!!!!



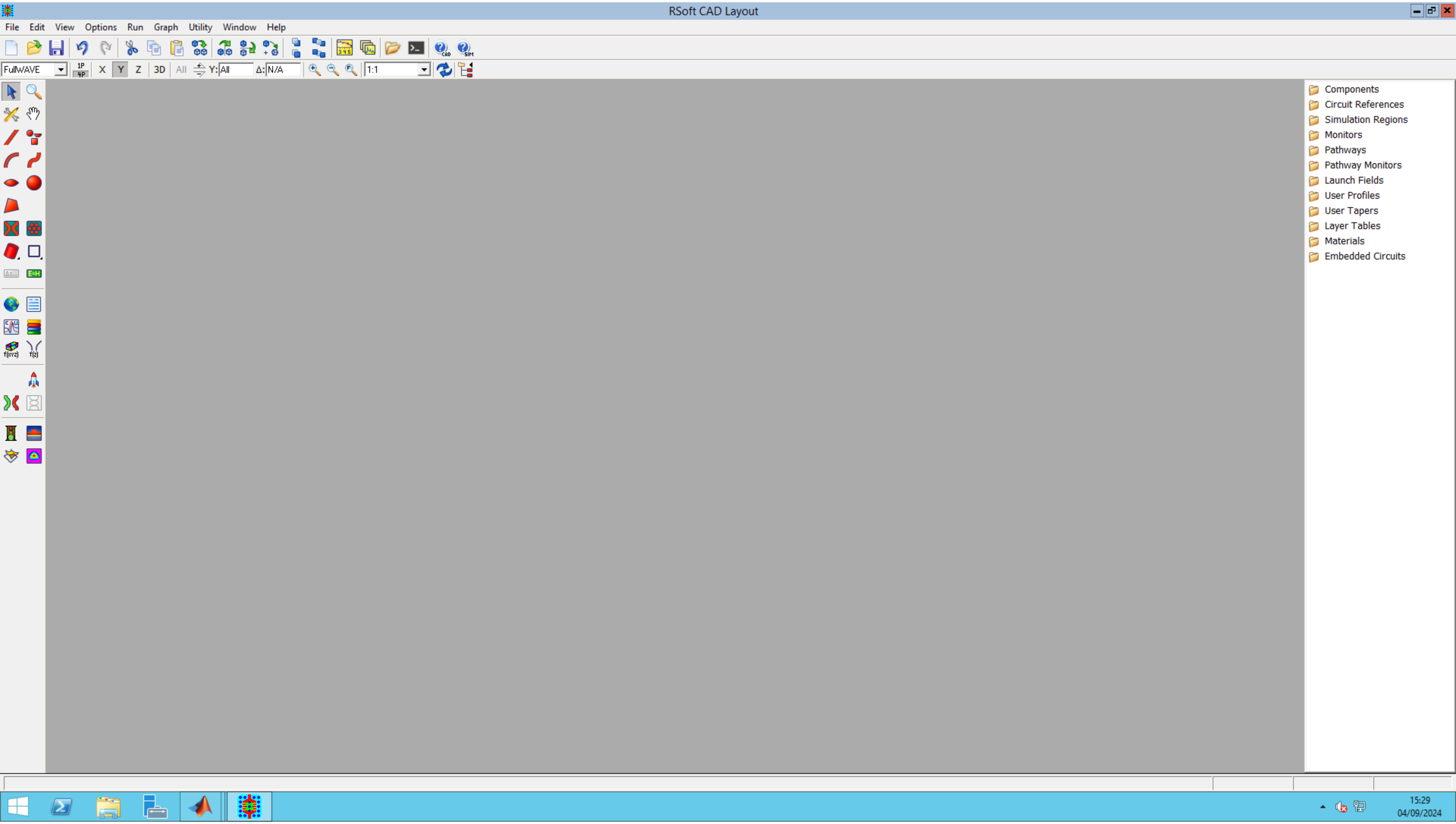
Absorbing layer:
PML (Perfectly Matched layer)

2- Spatial and temporal discretizations are linked

➔ A rule must be fulfilled !! ➔ stability criterion

$$\Delta t \leq \frac{1}{v_{max}\sqrt{\frac{1}{\Delta x^2} + \frac{1}{\Delta y^2} + \frac{1}{\Delta z^2}}}$$

FDTD, commercial software « Fullwave »



MISSION #1

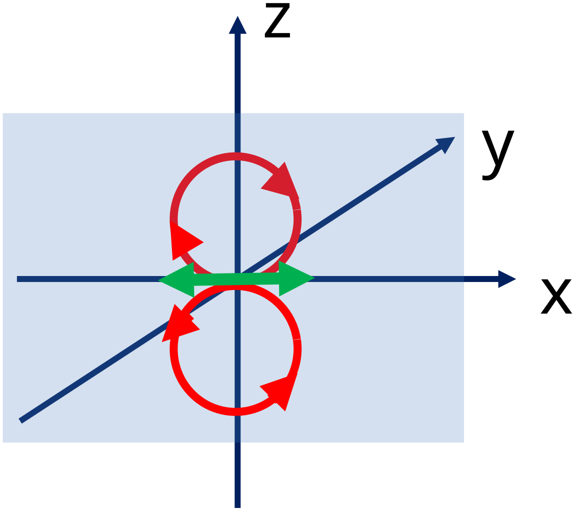
Characterize the EM field around the dipole

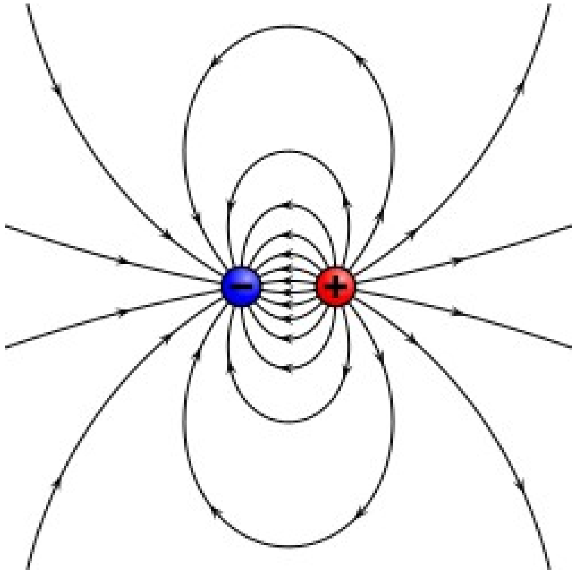
- E-field
- H-field

Dipole: classical analog of a quantum emitter (that is, a point-like source)

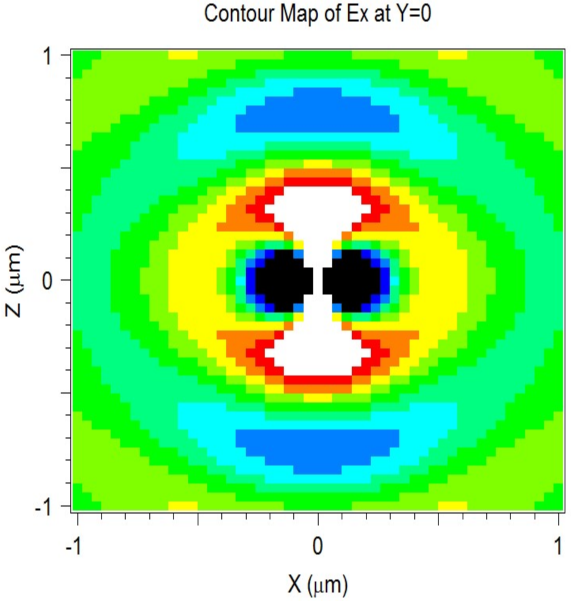
➔ Take the user’s guid👍

E-field

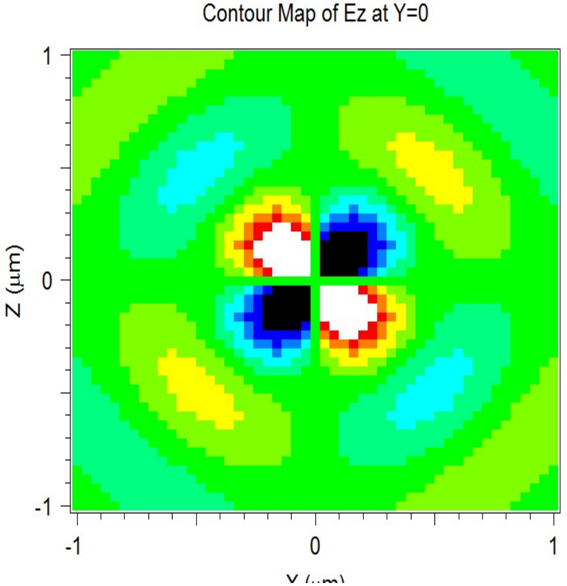

z
y
x



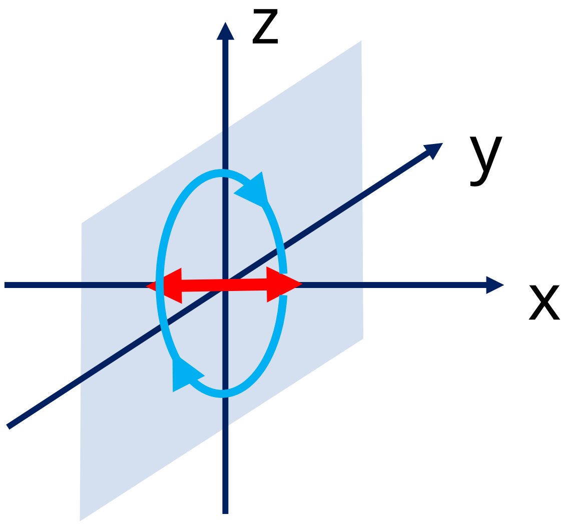
Ex


Contour Map of Ex at Y=0
1
0
-1
Z (μm)
-1
0
1
X (μm)

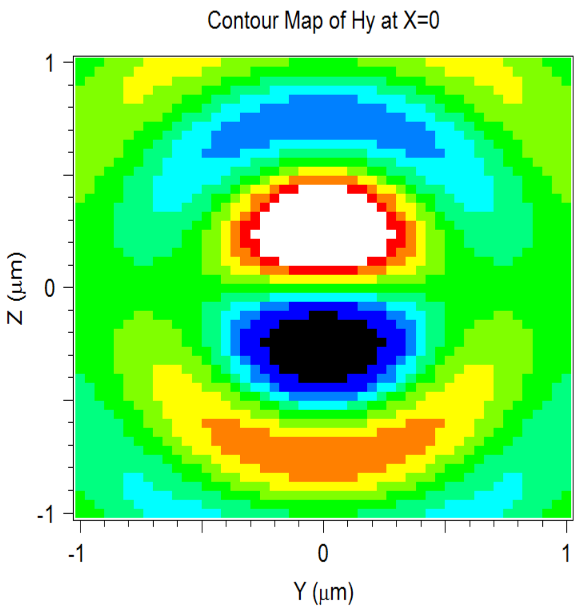
Ez


Contour Map of Ez at Y=0
1
0
-1
Z (μm)
-1
0
1

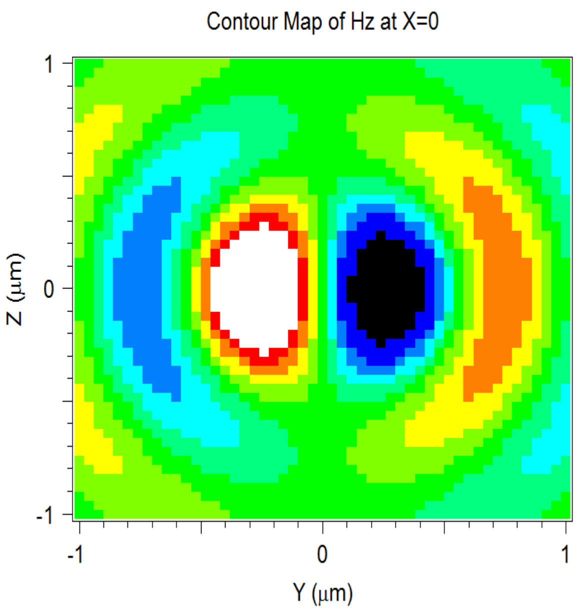
H-field



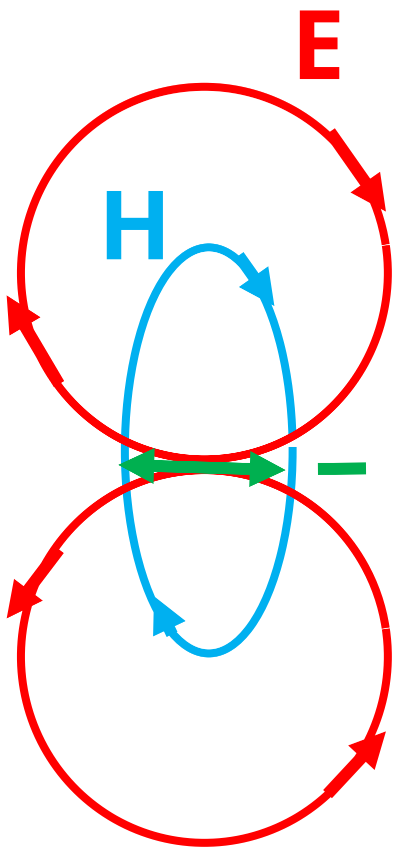
z
y
x

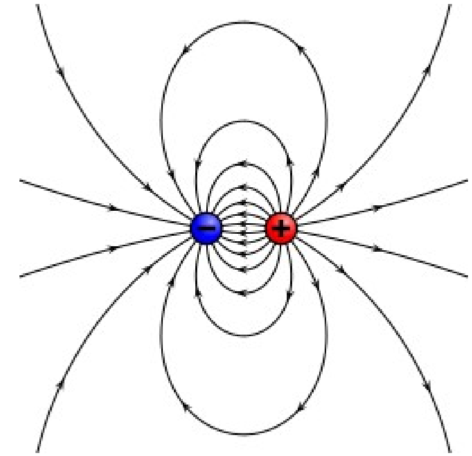


Contour Map of Hy at X=0
Z (μm)
Y (μm)
1
0
-1
-1
0
1

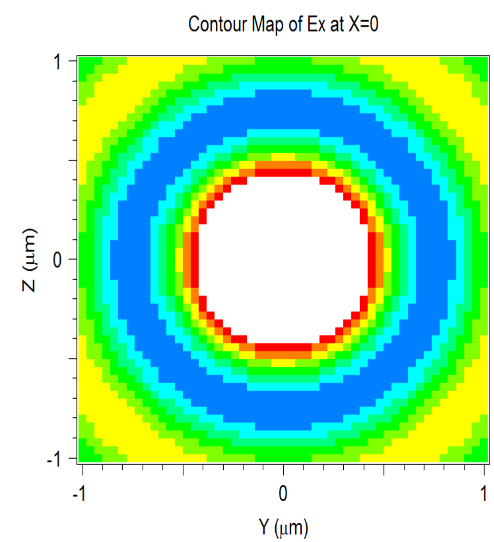


Contour Map of Hz at X=0
Z (μm)
Y (μm)
1
0
-1
-1
0
1





Axial symmetry



MISSION #2

Calculate the power radiated by a dipole

1- Dipole in vacuum
2- Dipole near an object

E and H fields (FDTD)

Power

➔ Poynting theorem (cf. Novotny's book)

Poynting theorem

In a **linear and non dispersive** medium

$$\oint_S \underbrace{\left(\vec{E}\times\vec{H}\right)}_{\text{Poynting}}\cdot\overrightarrow{dS}+\frac{\partial}{\partial t}\int_V \frac{1}{2}\left[\vec{D}\cdot\vec{E}+\vec{B}\cdot\vec{H}\right]dV=-\int_V \vec{j}\cdot\vec{E}\,dV$$

Net energy flow through the surface S delimiting a volume V

Rate of change of the energy inside the volume

Rate of energy dissipation within the volume (by the Lorentz force (**F**= ρ**E**) acting on charges densities ρ)

$$\delta W=P(t)\,\delta t=\delta t\int_V \rho\vec{v}\cdot\vec{E}\,dV$$

The exerted work

Poynting theorem

In a **linear and non dispersive** medium

$$\oint_S \underbrace{\left(\vec{E} \times \vec{H}\right)}_{\text{Poynting}} \cdot \overrightarrow{dS} + \frac{\partial}{\partial t} \int_V \frac{1}{2}\left[\vec{D} \cdot \vec{E} + \vec{B} \cdot \vec{H}\right] dV = -\int_V \vec{j} \cdot \vec{E}\, dV$$

Net energy flow through the surface S delimiting a volume V

Rate of change of the energy inside the volume

RADIATION AND ABSORPTION (joule effect)

Poynting theorem

- Harmonic fields in time (stationary regime), linear and non dispersive fields
- <u>Time-averaged quantities</u>

$$\oint_S \left\langle \vec{E} \times \vec{H} \right\rangle \cdot \overrightarrow{dS} = -\int_V \left\langle \vec{j} \cdot \vec{E} \right\rangle dV$$

In complex notation

➔

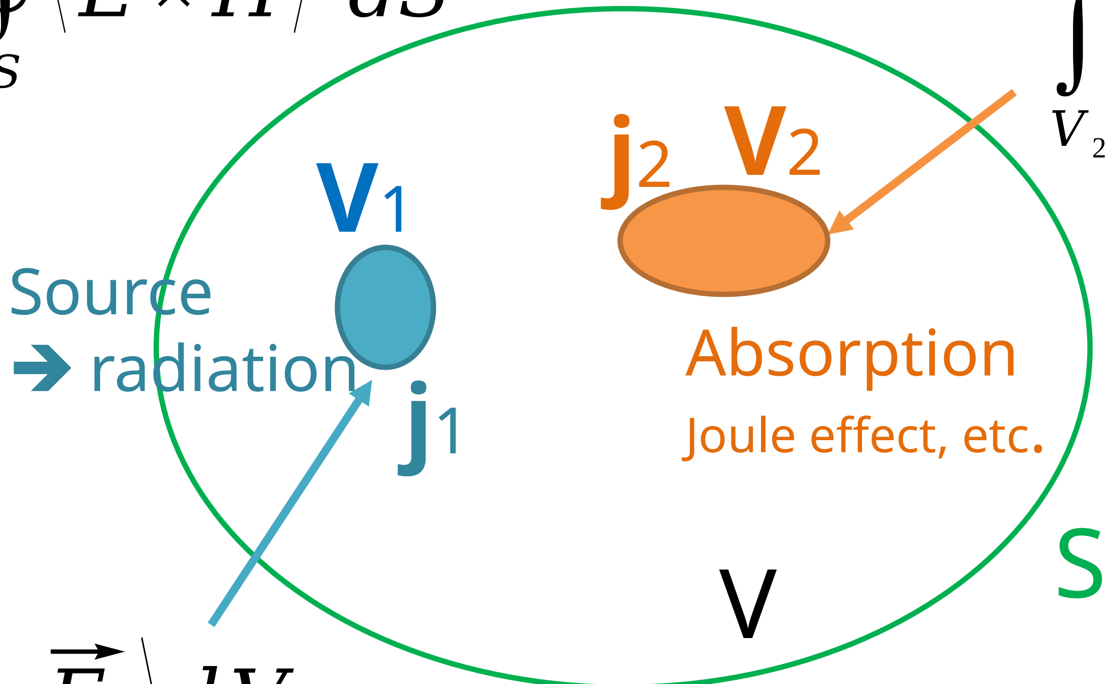
Time averaged Poynting vector

➔ =

An example

$$\oint_S \langle \vec{E} \times \vec{H} \rangle \cdot \overrightarrow{dS}$$

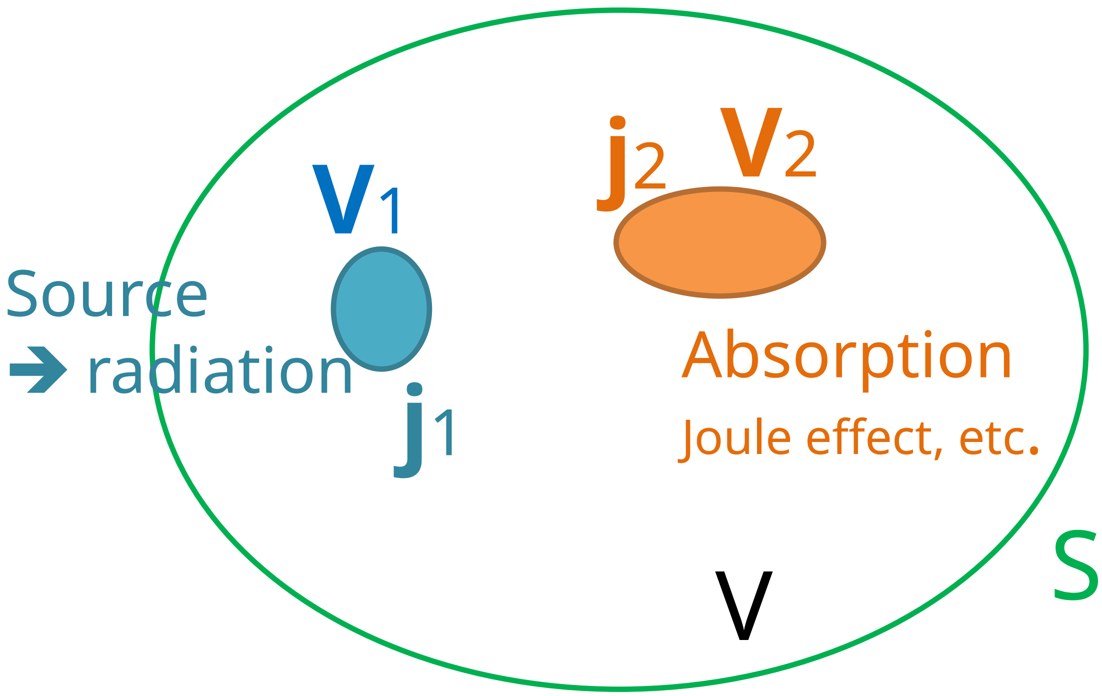
$$\int_{V_2} \langle \vec{j}_2 \cdot \vec{E}_2 \rangle dV$$



$$\int_{V_1} \langle \vec{j}_1 \cdot \vec{E}_1 \rangle dV$$

$$\oint_S \langle \vec{E} \times \vec{H} \rangle \cdot \overrightarrow{dS} = -\int_{V_1} \langle \vec{j}_1 \cdot \vec{E}_1 \rangle dV - \int_{V_2} \langle \vec{j}_2 \cdot \vec{E}_2 \rangle dV$$

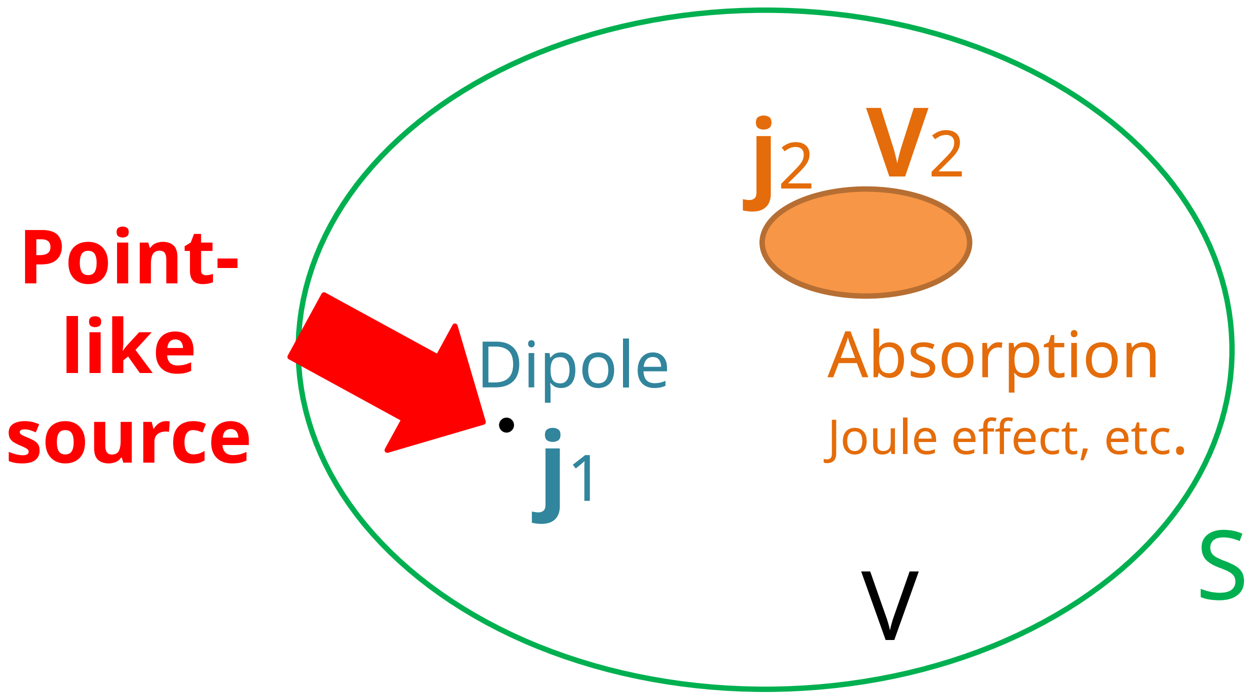
An example



ower outside V

Power radiated inside V – Power absorbed inside

The source = dipole

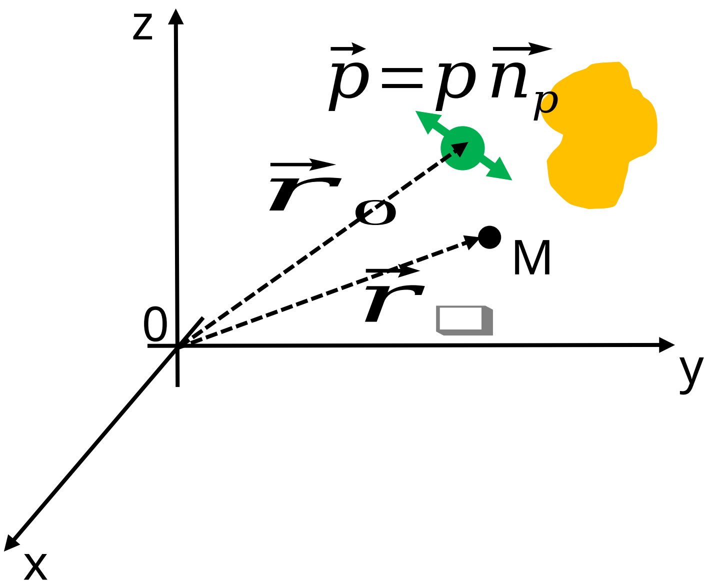


ower outside V

Power radiated inside V – Power absorbed inside

Radiating dipole

(in Harmonic regime)



Dipole moment

$$\vec{p}(\vec{r},t) = Re\{\vec{p}(\vec{r})\exp[-i\omega t]\}$$

$$\vec{p}(t) = q(\vec{r}(t) - \vec{r}_o)$$

Current density

$$\vec{j}(\vec{r},t) = Re\{\vec{j}(\vec{r})\exp[-i\omega t]\}$$

Due to a charge distribution q of coordinate

In first approximation, we have:

$$\boldsymbol{\vec{j}(\vec{r},t) = -i\omega\vec{p}\,\delta(\vec{r} - \vec{r}_o)}$$

From the Poynting theorem

$$\frac{dW}{dt} = -\frac{1}{2}\int_V Re\left[\vec{j}^* \cdot \vec{E}\right] dV$$

Dissipated energy by time unit **= radiated power**

Volume of the source

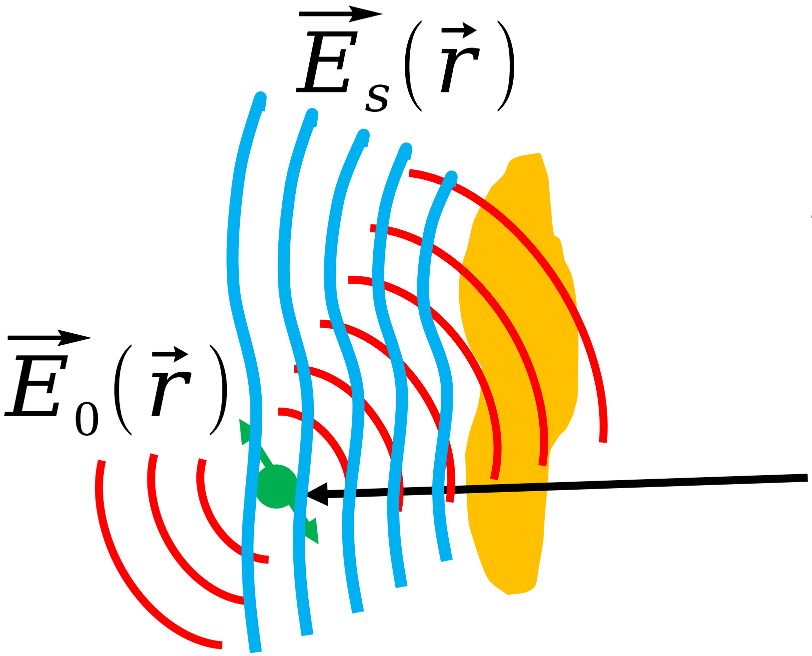
For a dipole, is replaced by $\boldsymbol{i\omega}\,\vec{\boldsymbol{p}}^*\,\boldsymbol{\delta}\left(\vec{\boldsymbol{r}}-\vec{\boldsymbol{r}}_{\mathbf{0}}\right)$

:

$$\boxed{P = \frac{dW}{dt} = \frac{\omega}{2} Im\left[\vec{p}^* \cdot \vec{E}\left(\vec{r}_0\right)\right]}$$

Radiated electric optical field **at the dipole position**

Dipole in an inhomogeneous medium



$$P = \frac{\omega}{2} Im\left[\vec{p}^{\,*} \cdot \vec{E}(\vec{r}_0)\right]$$

$$\vec{E}(\vec{r}_0) \text{¿} \vec{E}_0(\vec{r}_0) + \vec{E}_s(\vec{r}_0)$$

$$\boxed{\frac{P}{P_0} = 1 + \frac{6\pi\varepsilon_0\varepsilon}{|\vec{p}|^2}\frac{1}{k^3} Im\left[\vec{p}^{\,*} \cdot \vec{E}_s(\vec{r}_0)\right]}$$

The back-scattered field changes the powe

Cf. *Principle of nano-optics*, L. Novotny, Cambridge, 2e Ed. 2012, p239

An oscillating charge produces an electromagnetic radiation

Mediates the energy dissipation from the dipole source

Has an influence back onto the oscillating charge (!!)

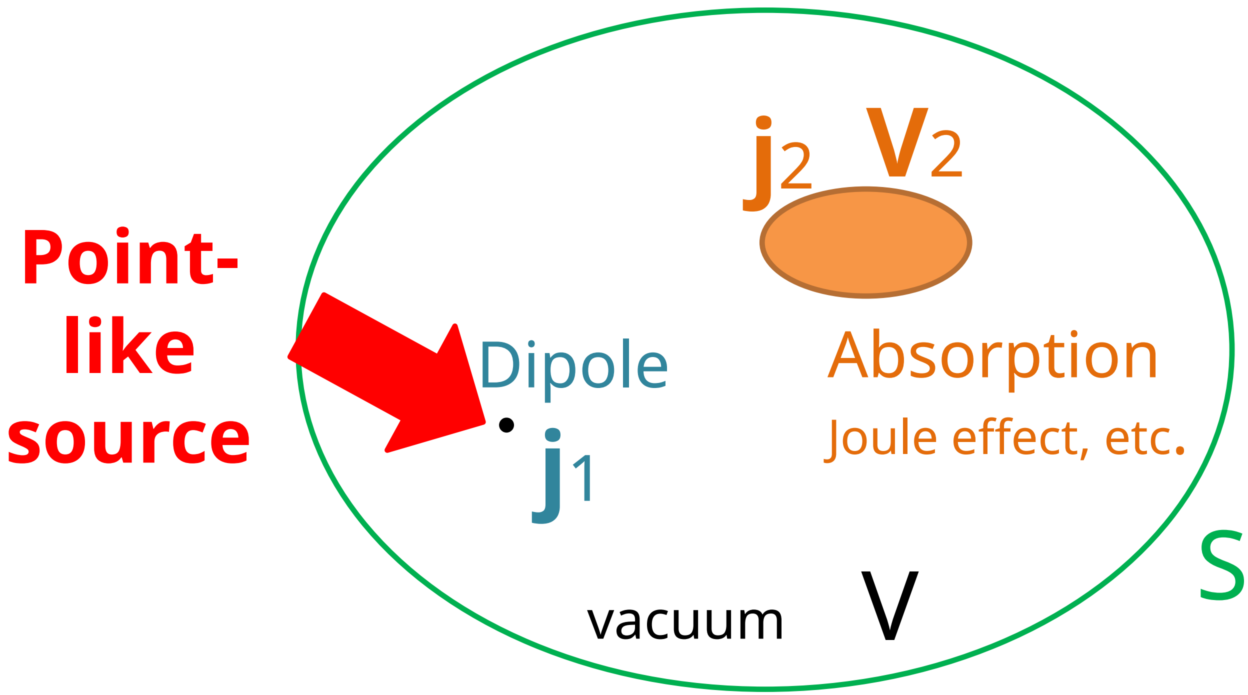
Retroaction of the radiating dipole on itself due to the environment

MISSION #2

Calculate the power radiated by a dipole

1- Dipole in vacuum
2- Dipole near an object

The source = dipole



$$P = \frac{dW}{dt} = \frac{\omega}{2} Im\left[\vec{p}^{\,*} \cdot \vec{E}(\vec{r}_0)\right]$$

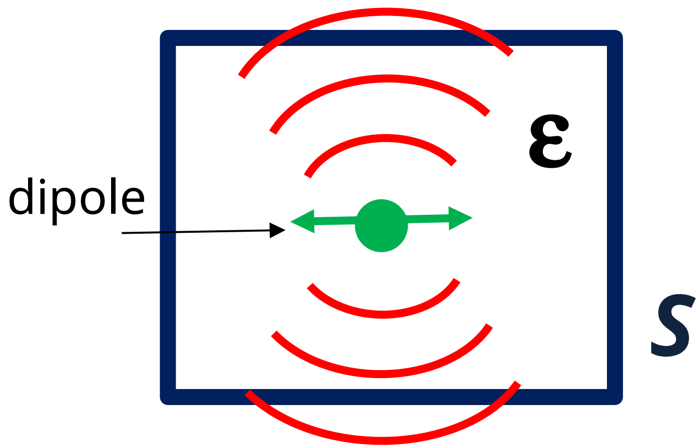
?

Power outside V

= Power radiated inside V – Power absorbed inside V

Power outside V = Power radiated inside V

Calculation of the Poynting vector flow !



Poynting's theorem

$$P_{\mathbf{o}} = \oint_S \left\langle \vec{E} \times \vec{H} \right\rangle dS$$

Time averaged

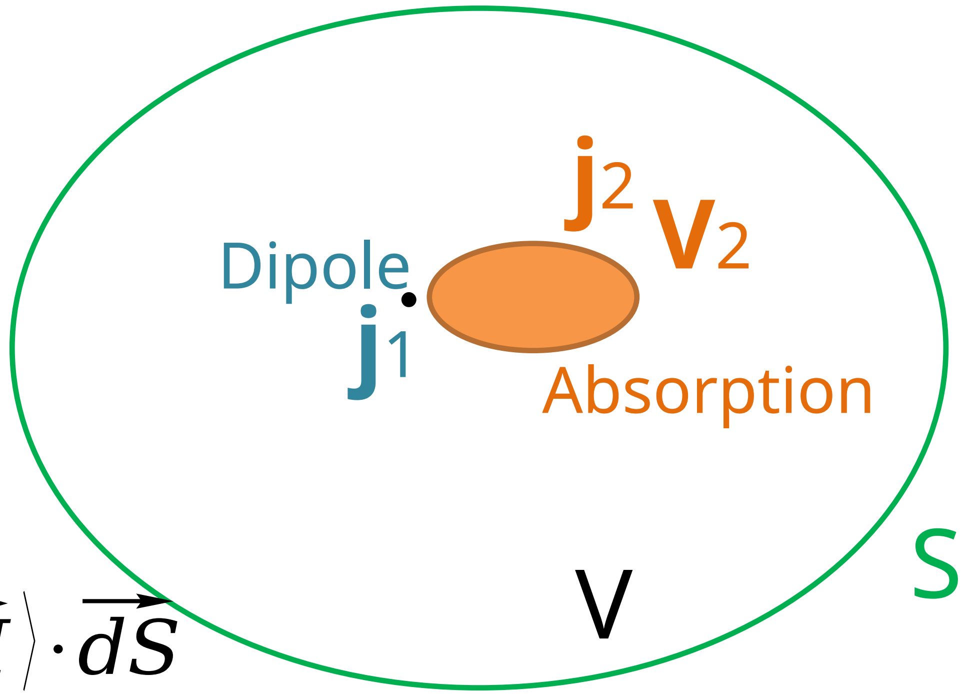
MISSION #2

Calculate the power radiated by a dipole

1- Dipole in vacuum

2- Dipole near an object

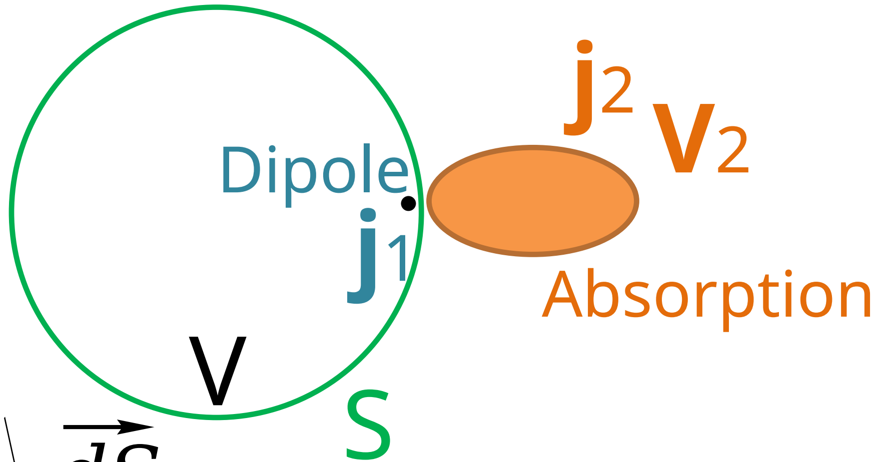
Poynting vector flow ?



$$\oint_S \langle \vec{E}\times\vec{H}\rangle\cdot\vec{dS}$$

Power radiated by the system « dipole+ ct »

Poynting vector flow ?



$$\oint_S \langle \vec{E} \times \vec{H} \rangle \cdot \overrightarrow{dS}$$

Power radiated by the dipo

BUT… numerical artifacts when the distance DIPOLE-OBJECT is small… OU

CASE

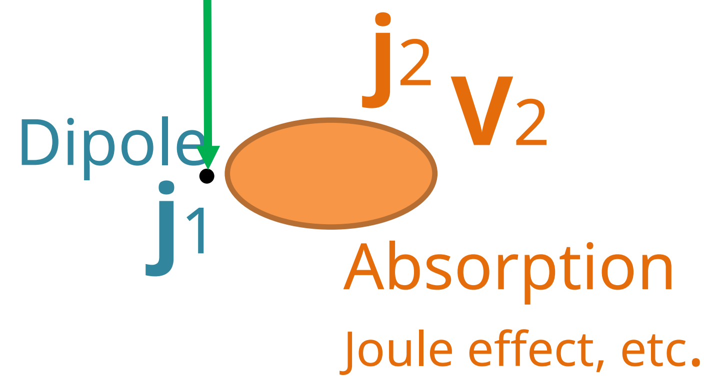
No Choice !!!!

$$\vec{p} = |\vec{\boldsymbol{p}}| e^{-i(\omega t + \boldsymbol{\varphi})}$$

?

FDTD

$$P = \frac{\omega}{2} Im\left[\vec{p}^{\,*} \cdot \vec{E}(\vec{r}_0)\right]$$



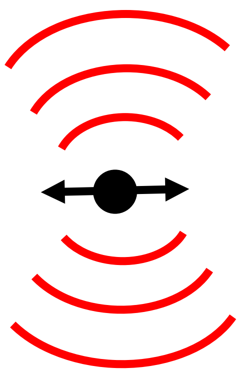
$$\vec{E}_0(\vec{r}_0, t) = \vec{E}_0(\vec{r}_0) e^{-i\omega t}$$

Calculation of

➔ Dipole in a <u>homogeneous medium</u>

Whose permittivity **ε** matches that of the medium at the dipole position, when the dipole interacts with the nanostructures

ε



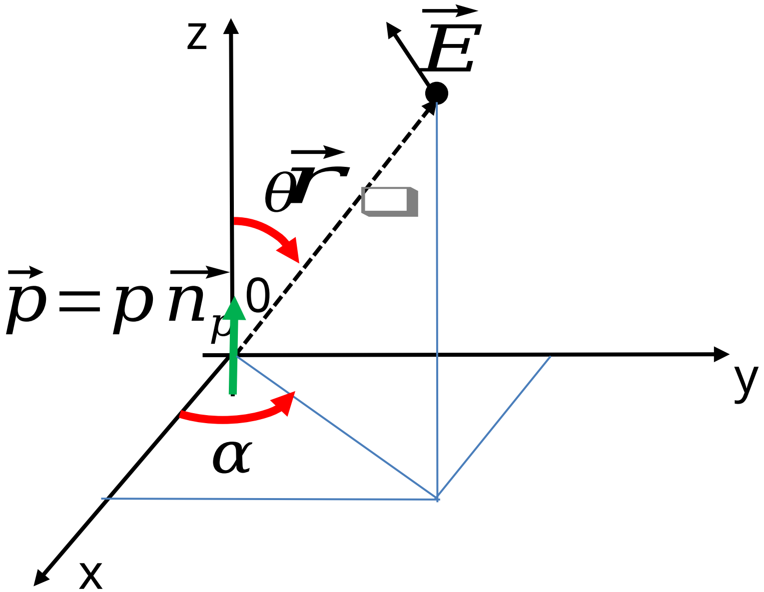
<u>STEP #1 :</u> $\vec{p} = |\vec{\boldsymbol{p}}| e^{-i(\omega t + \varphi)}$

<u>STEP #2 :</u> $\vec{p} = |\vec{p}| e^{-i(\omega t + \boldsymbol{\varphi})}$

STEP #1 : $\vec{p} = |\vec{\boldsymbol{p}}| e^{-i(\omega t + \varphi)}$

n a homogeneous medium ➔ analytical expression of E

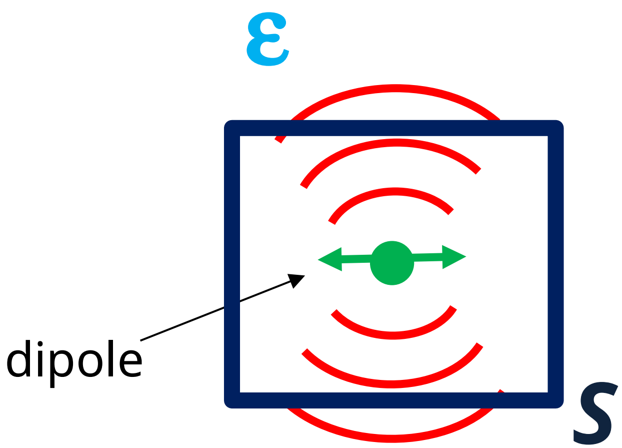
$$E_z = \frac{|\vec{p}|}{4\pi\varepsilon_0\varepsilon} \frac{e^{ikR}}{R} \left[k^2 \sin^2\theta + \frac{1}{R^2}\left(3\cos^2\theta - 1\right) - \frac{ik}{R}\left(3\cos^2\theta - 1\right) \right]$$



$$\boxed{P_0 = \frac{|\vec{p}|^2}{12\pi} \frac{\omega}{\varepsilon_0 \varepsilon} k^3}$$

Cf. *Principle of nano-optics*, L. Novotny, Cambridge, 2e Ed. 2012, p239

STEP #1 : $\vec{p} = |\vec{\boldsymbol{p}}| e^{-i(\omega t + \varphi)}$



$$|\vec{p}|^2 = \frac{12\pi \varepsilon_0 \varepsilon}{\omega k^3} P_0$$

From analytical expression of the E-field

$$P_0 = \oint_S \vec{E} \times \vec{H} \, dS$$

From FDTD calculation

STEP #2 : $\vec{p} = |\vec{p}| e^{-i(\omega t + \boldsymbol{\varphi})}$

➔ In a homogeneous medium

- Normally =0 ➔ and are in phase

- With the FDTD (not null...)

➔ In a inhomogeneous medium, remains unchanged

STEP #2 : $\vec{p} = |\vec{p}| e^{-i(\omega t + \boldsymbol{\varphi})}$

➔ Dipole in vacuum (a homogeneous medium)

$$P = \frac{\omega}{2} Im\left[\vec{p}^{\,*} \cdot \vec{E}(\vec{r}_0)\right]$$

$$\oint_S \langle \vec{E} \times \vec{H} \rangle \cdot \vec{dS}$$

Dipole along (0x)

,)

There are two solutions, only one is correct, to be tested by recalculating P

Dipole interacting with nanostructures

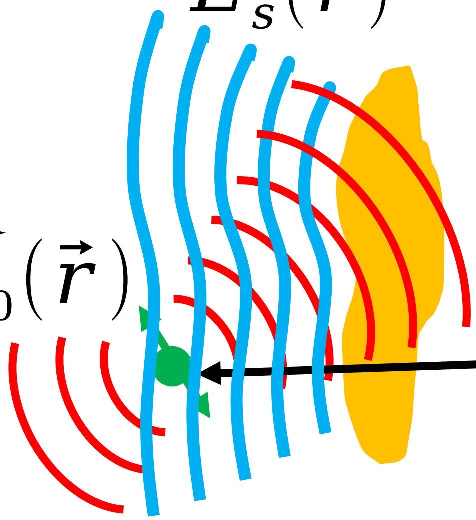
$$\boxed{P = \frac{dW}{dt} = \frac{\omega}{2} Im\left[\vec{p}^{\,*} \cdot \vec{E}\left(\vec{r}_0\right)\right]}$$

know
n

FDT
D

$\vec{E}_s\left(\vec{r}\right)$

$\vec{E}_0\left(\vec{r}\right)$



$$\vec{E}\left(\vec{r}_0\right) = \vec{E}_0\left(\vec{r}_0\right) + \vec{E}_s\left(\vec{r}_0\right)$$

OQA module

Classical description of a quantum emitter

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I. Introduction
   - Definition of a quantum emitter (QE)
   - 3 types of emitters
II. Individual QE in an inhomogeneous environment
III. Description via the quantum ElectroDynamics (ED) (just basic considerations…)
   - Description of the spontaneous emission
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I- Introduction

Quantum emitter:

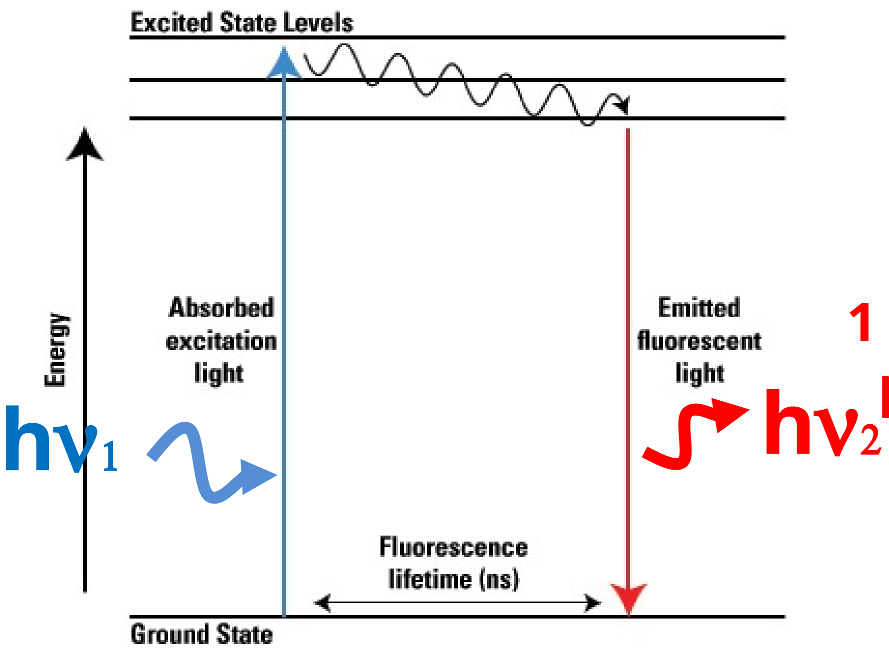
- Light emitter (in our case)
- Point-like emitter (nanometer scale) : atoms, molecules , nanoparticules.
- Internal energy levels ➔ light matter interaction: ground and excited states: emission shows discrete spectral peaks
- « states » ➔ electrons in orbitals defined by quantum numbers (n,l, m_l, m_s)
- Single photon emissions
- Spontaneous emission of photons (no stimulated emission)
- central in nano-optics or nano-photonics

Single photon emission: **fluorescence**

The model of a fluorescent emitter:

➔2 energy states (fundamental / excited states)

1 photon absorbé



1 emitted photon

$$\boxed{\nu_1 > \nu_2}$$

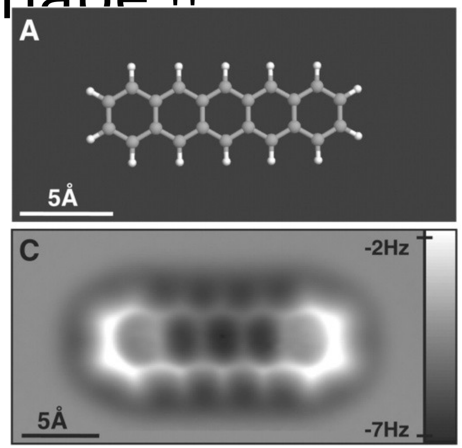
3 families of quantum emitters:

- Fluorescent molecules
- Quantum dots
- Color centers (in diamond)

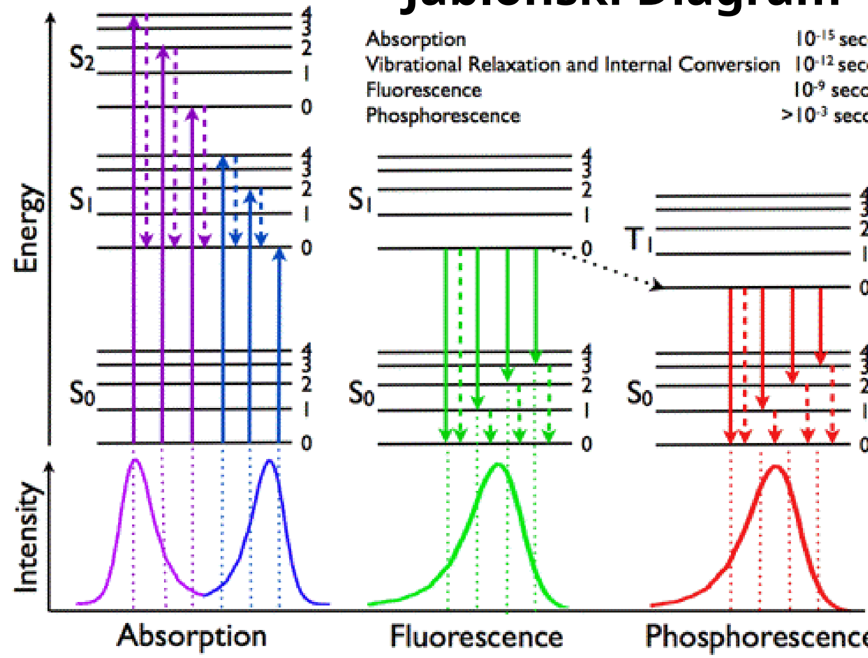
- Fluorescence molecules

➔ Organic molecules

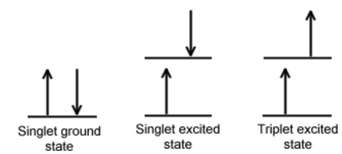
➔ Elongated shape !!

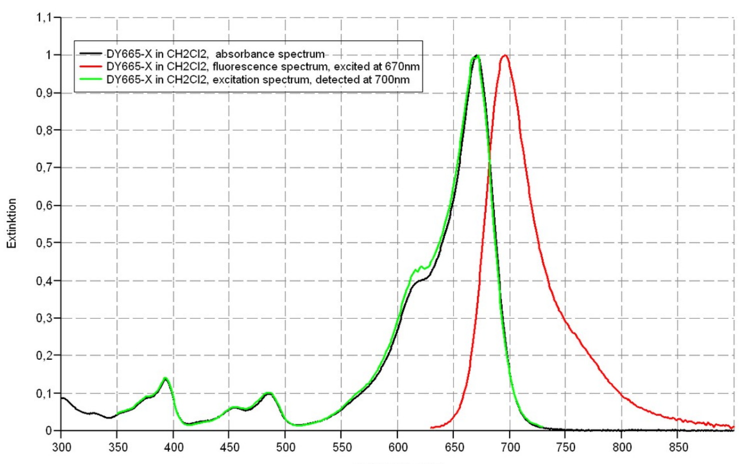


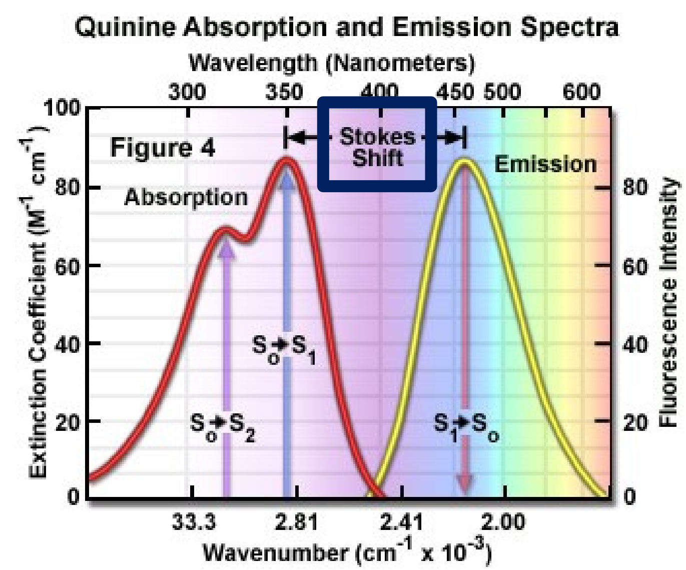
Jablonski Diagram



➔ Energy states

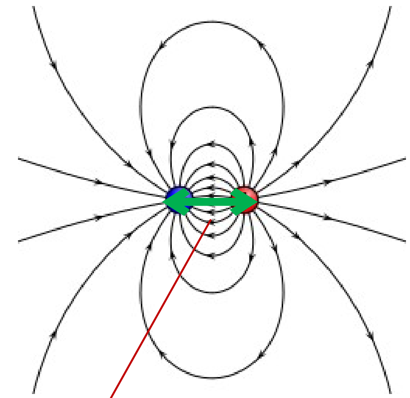




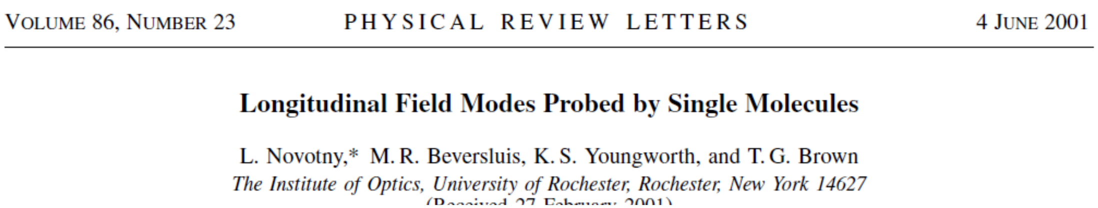


From the spatial point of view...

Point-like fluorescent sources ➔ Dipole sources ➔ Oriented Dipole moment



Transition dipole moment
➔ For absorption and emission

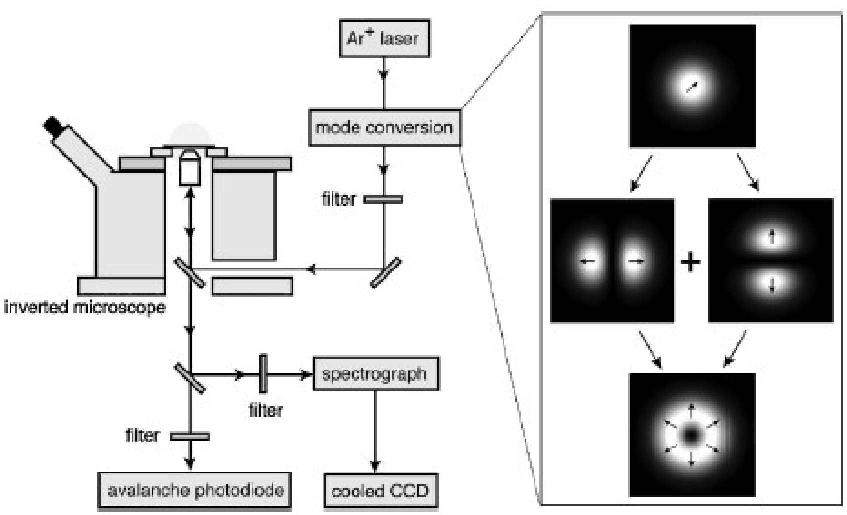

VOLUME 86, NUMBER 23 PHYSICAL REVIEW LETTERS 4 JUNE 2001

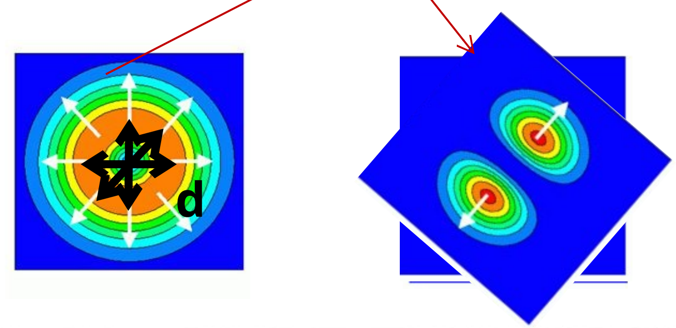
Longitudinal Field Modes Probed by Single Molecules

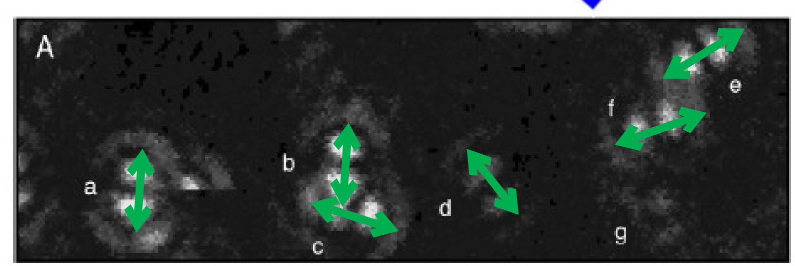
L. Novotny,* M. R. Beversluis, K. S. Youngworth, and T. G. Brown
The Institute of Optics, University of Rochester, Rochester, New York 14627

Taux de fluorescence R

$$\boxed{R(\mathbf{r}) = c|\mathbf{d} \cdot \mathbf{E}(\mathbf{r})|^2,}$$







3 families of quantum emitters:

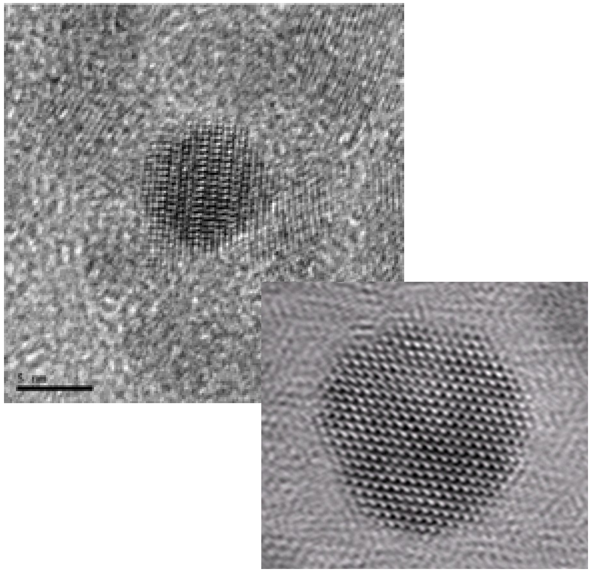
- Fluorescent molecules
- Quantum dots
- Color centers (in diamond)

- Colloidal quantum dots

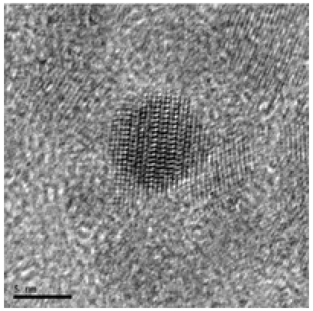
➔ Semiconductor nanocristals in solution

➔ Almost spherical shape

➔ Size: on the nanoscale



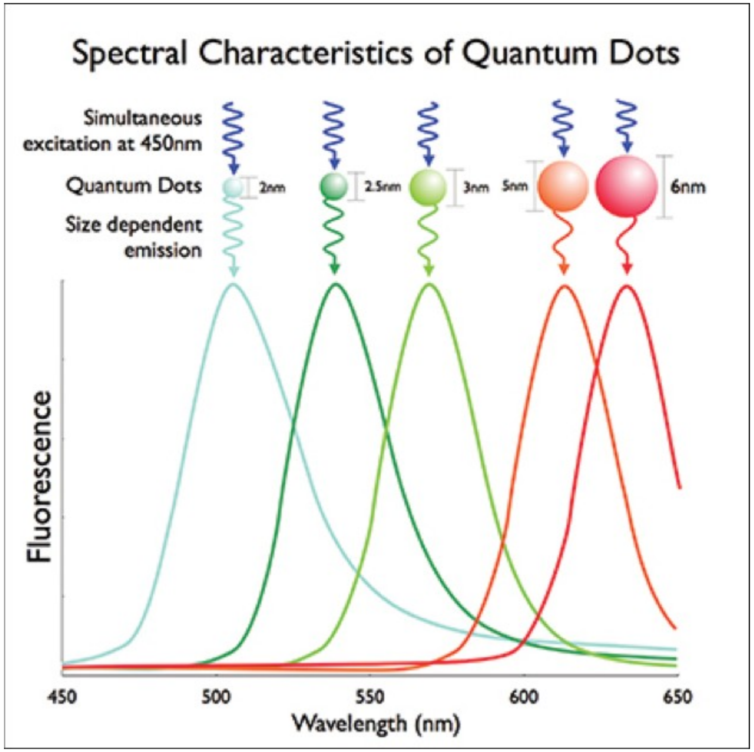
Quantum dots CdSe/Zns of various sizes (1 size per bottle) – UV excitation

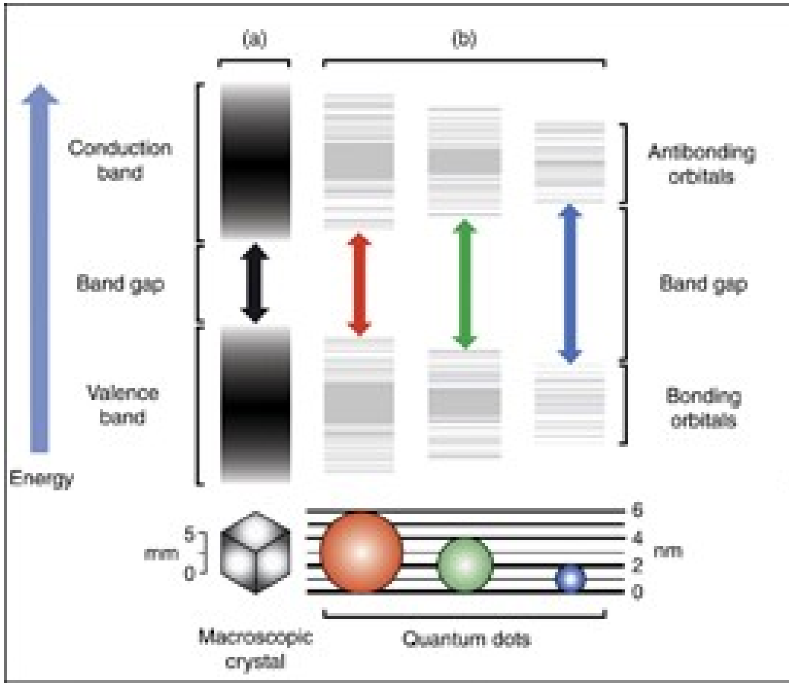


***0,0000001
4**

***0,0000001
4**

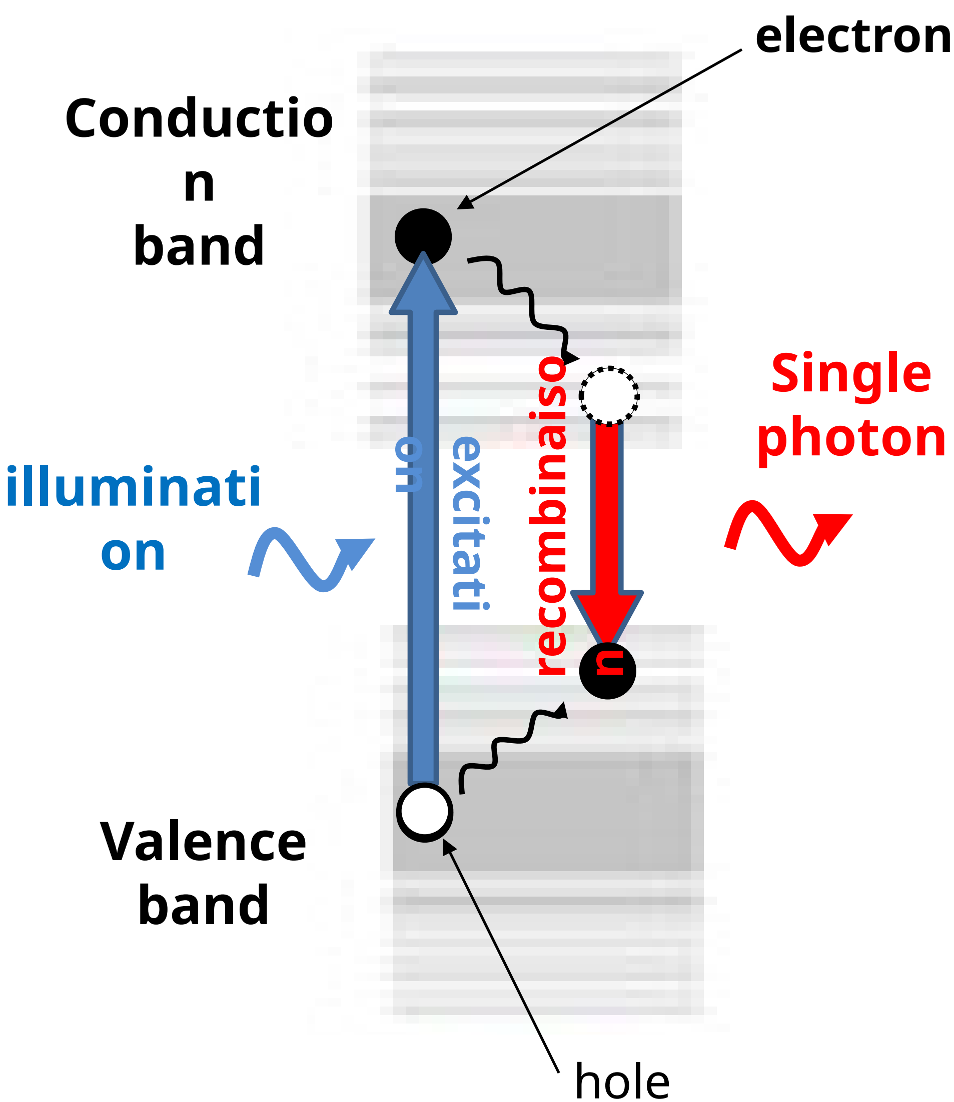
➔ Properties of Semiconductors + « quantum size effect »





➔ QD = « big atom »: two energy state system with a particle of 2-6 nm, i.e., 10 to 100 bigger than an atom ➔ easier manipulation, etc…

Fluorescence: involves an exciton rather than an electron
Exciton = electron-hole pair (semiconductor material)



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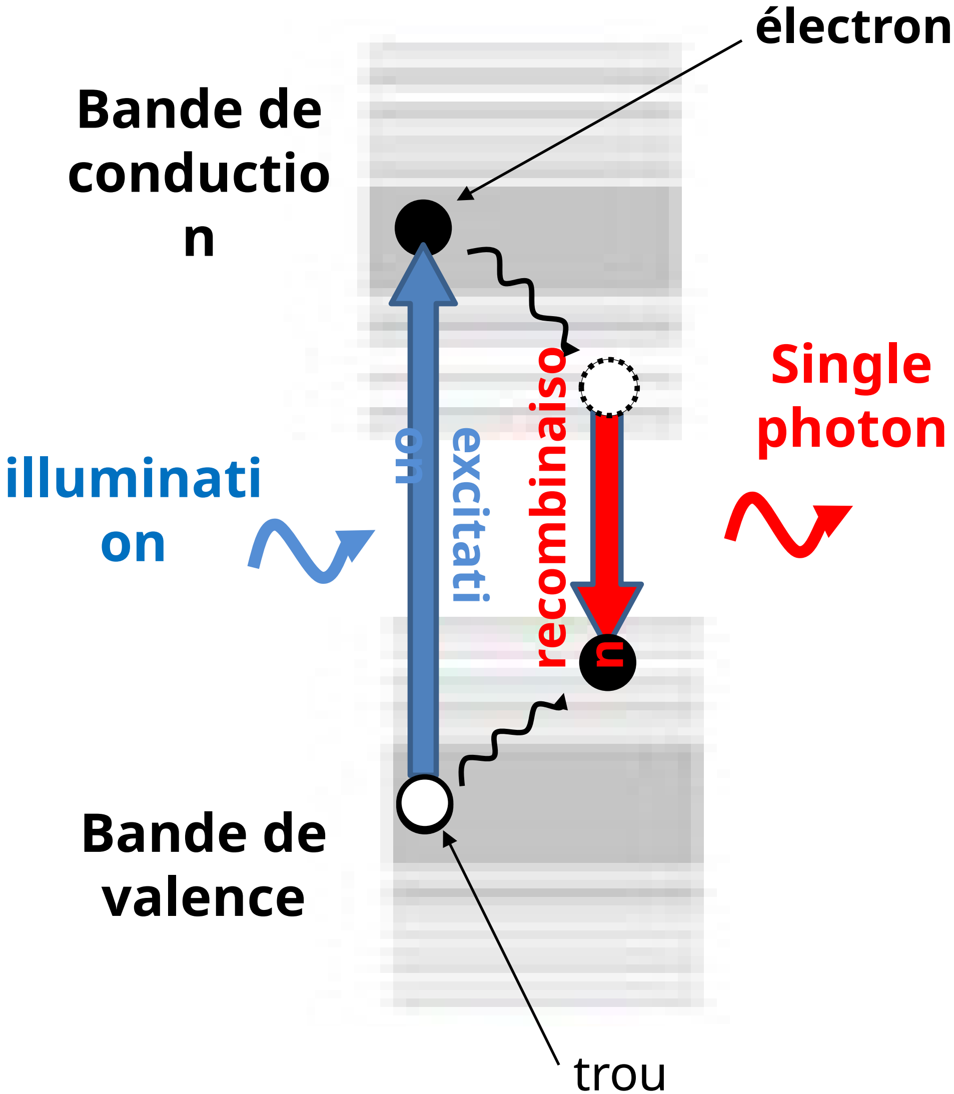
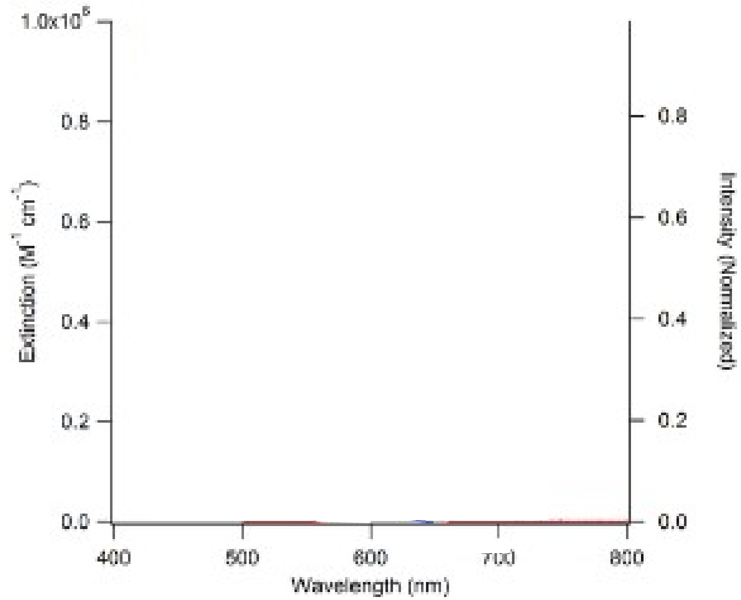
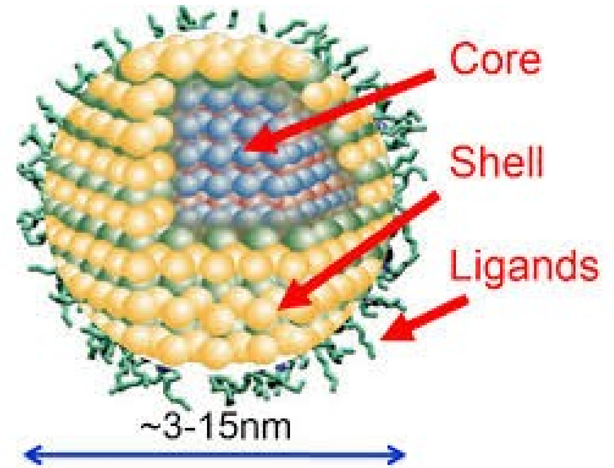




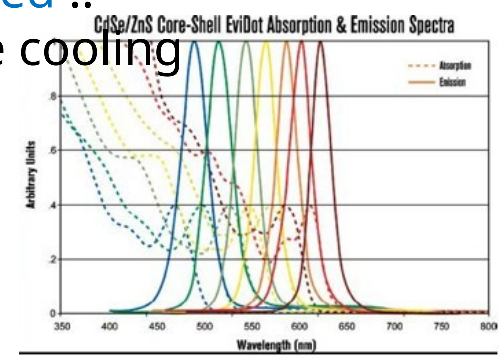
High emission yield/efficiency at room temperat

Photostability at room temperature
➔ QD encapsulation: « core-shell » system

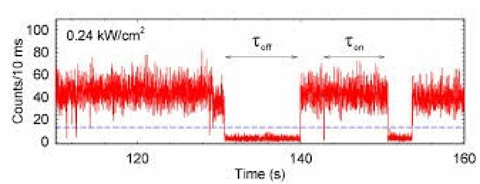


Avantages:

- Broadband absorption (semiconductor)
- quantum size effect: the size defines the emission wavelength
- Photon sources from blue to near and middle infrared !!
- Photostability at room temperature ➔ no expensive cooling



Drawbacks :



- blinking
- In contact to O_2, blueshift of the emission wavelength

Broad application field: biomedical (fluorescent markers), optoelectronics, screens-TV, etc…

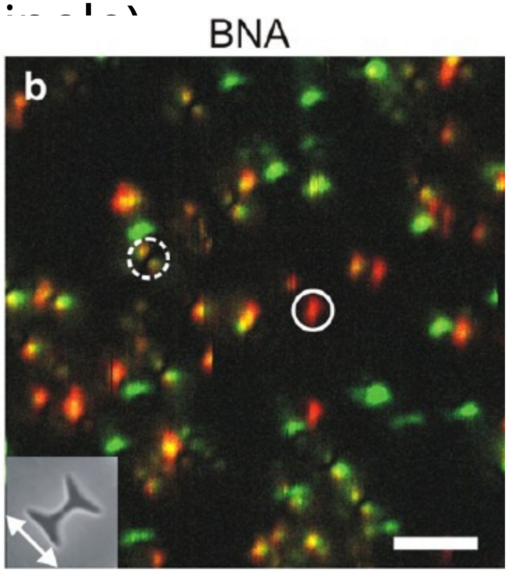
Dipole :

➔ Dipolar transitions for the absorption et emission (as molecules) **excepted that:**

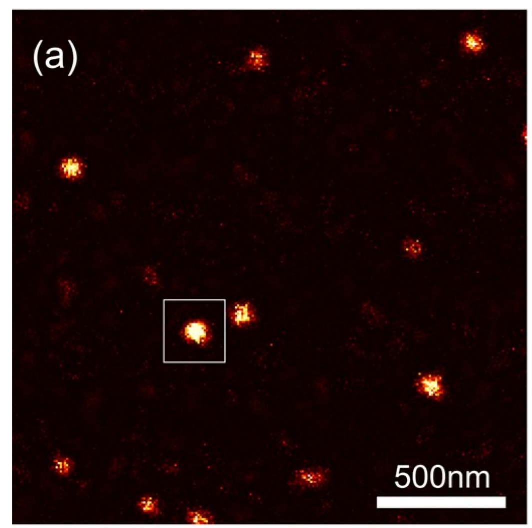
Degenerated dipole moment:

➔Dipolar emission in a 2D plan,

➔Arbitrary orientation of the mission dipole in this plane (no fixed oriented dipole)



Molecule imaging

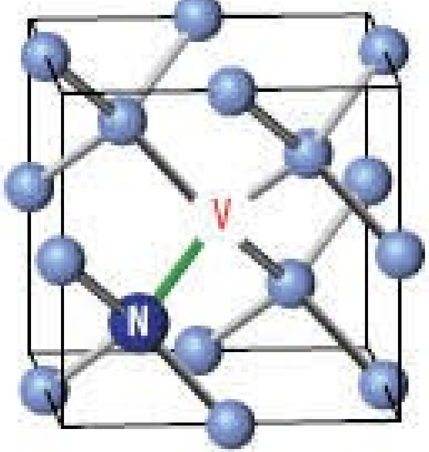


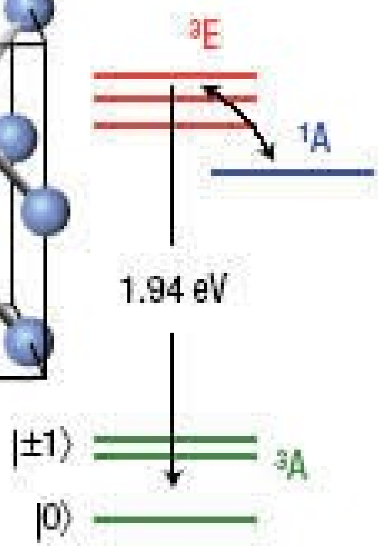
Quantum dot imaging

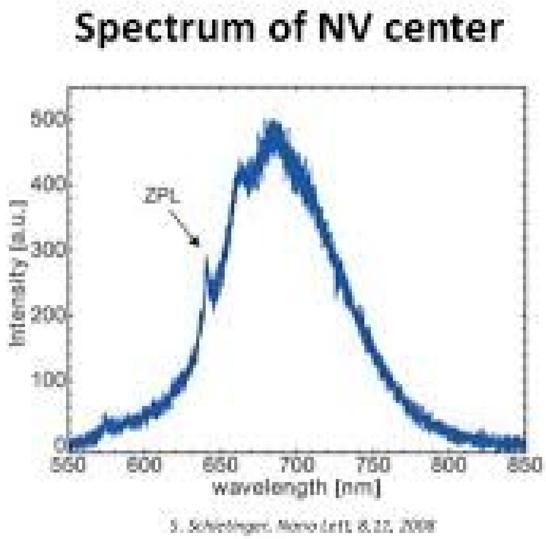
3 families of quantum emitters:

- Fluorescent molecules
- Quantum dots
- Color centers (in diamond)

- Vacancy in a high energy gap (5.5 eV) semiconductor: diamond
- A single nitrogen atom (N) creates on a neighbouring site a vacancy ➔ « NV center »
- Free electron are in play ➔ favorable to fluoresence
- Lifetime of the excited state: 11 ns
- Size: 10-30 nm (size of the diamond fragment which hosts the NV-center)
- Easier manipulation than QDs ➔ attached at the very tip
- No blinking
- Fixed emission wavelength = 690 nm (no wavelength tunability)
- Also used as a probe for magnetometry







The fluorescence, this is…

A two-step process:

→ Absorption of a photon

→ Spontaneous emission of a photon of (usually) lower energy → Stokes shift

These two steps are rigorously described using quantum electrodynamics

Tiny objects on the nanoscale → quantum theory

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Purcell (1946) : spontaneous emission of a QE is modified by its environment

➔ QE coupled to an optical resonator (resonant optical structure such as a FP cavity, etc.)

Purcell Factor:

Quality factor of the resonator

$$F_p = \frac{3}{4\pi^2}\frac{Q}{V}\left(\frac{\lambda}{n}\right)^3$$

Enhancement of the emission rate

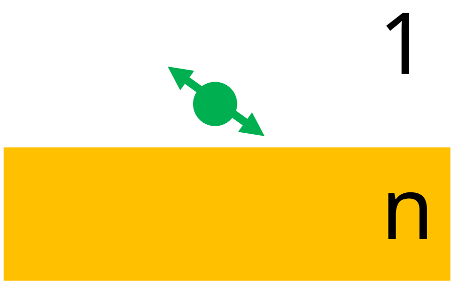
Volume of the resonant optical mode

➔ Purcell effect: if high Q and small V, a QE emits its photon much faster : « super emitter »

Since Purcell (1946)

1966

Fluorescence lifetime modified by a non resonant optical environement



Drexhage et al, 1966

1981-1983

➔ Purcell effect experimentally demonstrated **(Goy et al, 1983)**

➔ Inhibition of the spontaneous emission in a resonant cavity (that is the opposite effect to Purcell's… in a cavity !!) **(Kleppner, 1981)**

Since 2000,

Engineering of the spontaneous emission

By structuring the environment of a QE…

We **modify** its photon absorption/emission properties

20th centery

21th centery

We **control** its photon absorption/emissionproperties

➔ **Nanotechnologies**

New fabrications facilities on the nanoscale

➔ Full control over light-matter interaction

nano-optics

Controlling the Spontaneous Emission Rate of Single Quantum Dots in a Two-Dimensional Photonic Crystal

Dirk Englund,[1] David Fattal,[1] Edo Waks,[1] Glenn Solomon,[1,2] Bingyang Zhang,[1] Toshihiro Nakaoka,[3] Yasuhiko Arakawa,[3]
Yoshihisa Yamamoto,[1] and Jelena Vučković[1]
[1]*Ginzton Laboratory, Stanford University, Stanford, California 94305, USA*
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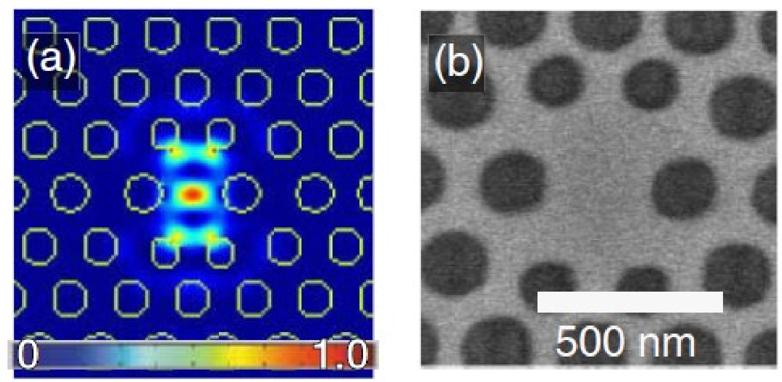
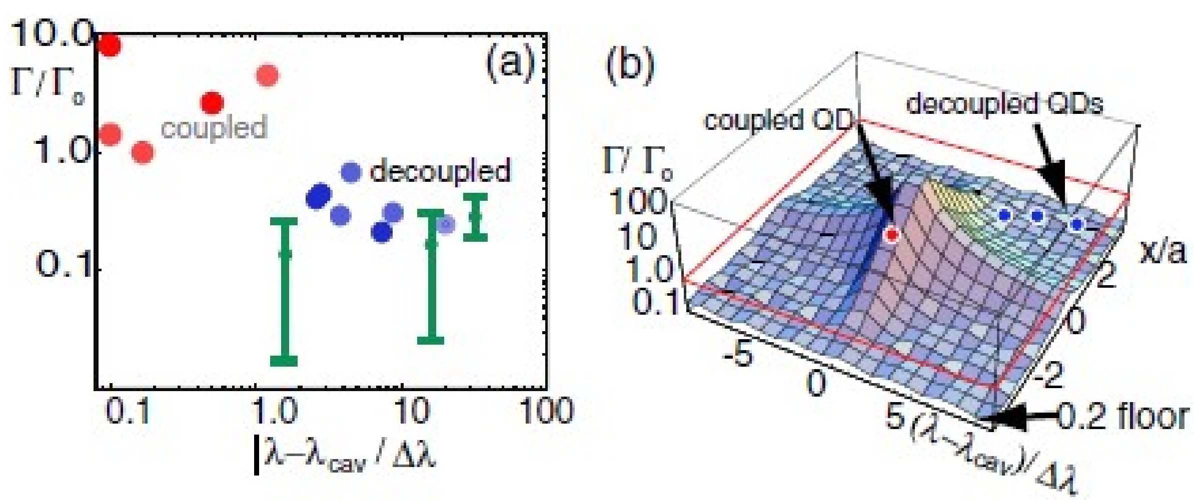
[3]*Institute of Industrial Science, University of Tokyo, Tokyo, Japan*
(Received 17 January 2005; published 1 July 2005)



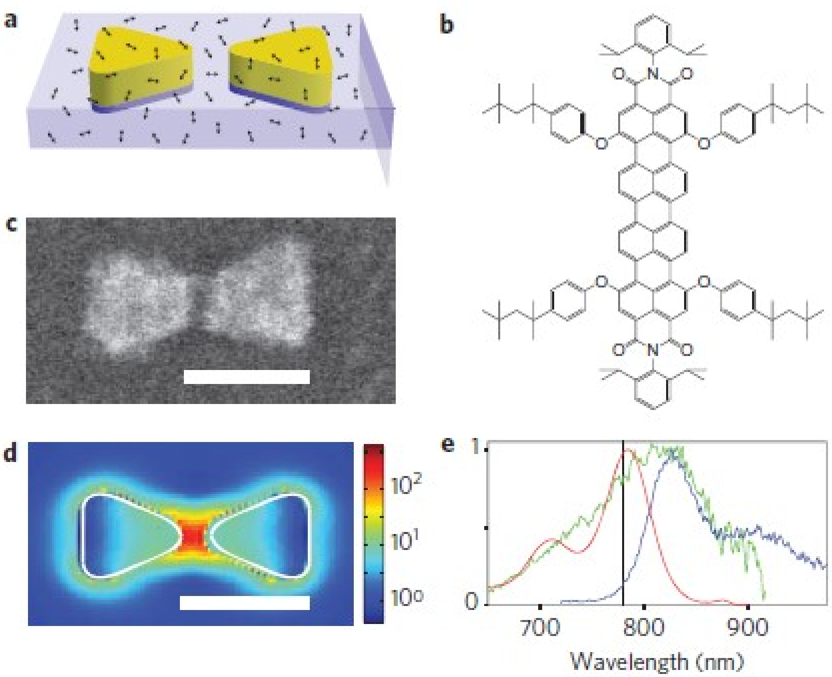


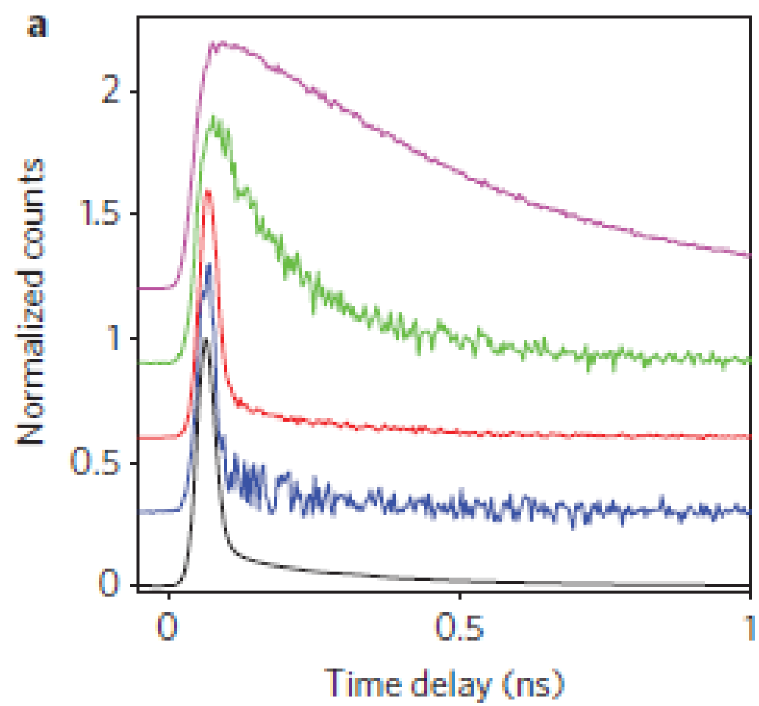
LETTERS
PUBLISHED ONLINE: 18 OCTOBER 2009 | DOI: 10.1038/NPHOTON.2009.187

nature photonics

Large single-molecule fluorescence enhancements produced by a bowtie nanoantenna

Anika Kinkhabwala[1], Zongfu Yu[2], Shanhui Fan[2], Yuri Avlasevich[3], Klaus Müllen[3] and W. E. Moerner[1]*





WHY ?

Quantum emitters ➔ **Single photon sources**

The starting point of future quantum technologies

Need of on-demand single photon sources of controlled properties and performances

➔ nano-photonics could fullfil this requirement by accurately structuring the environment of the QE

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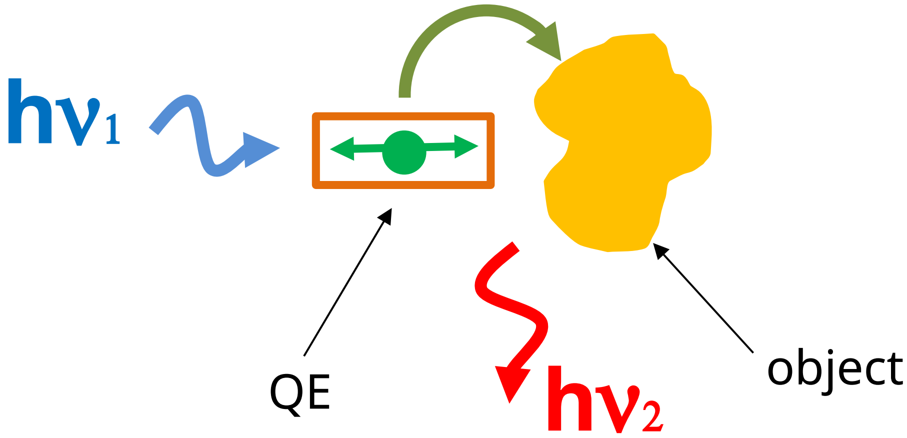
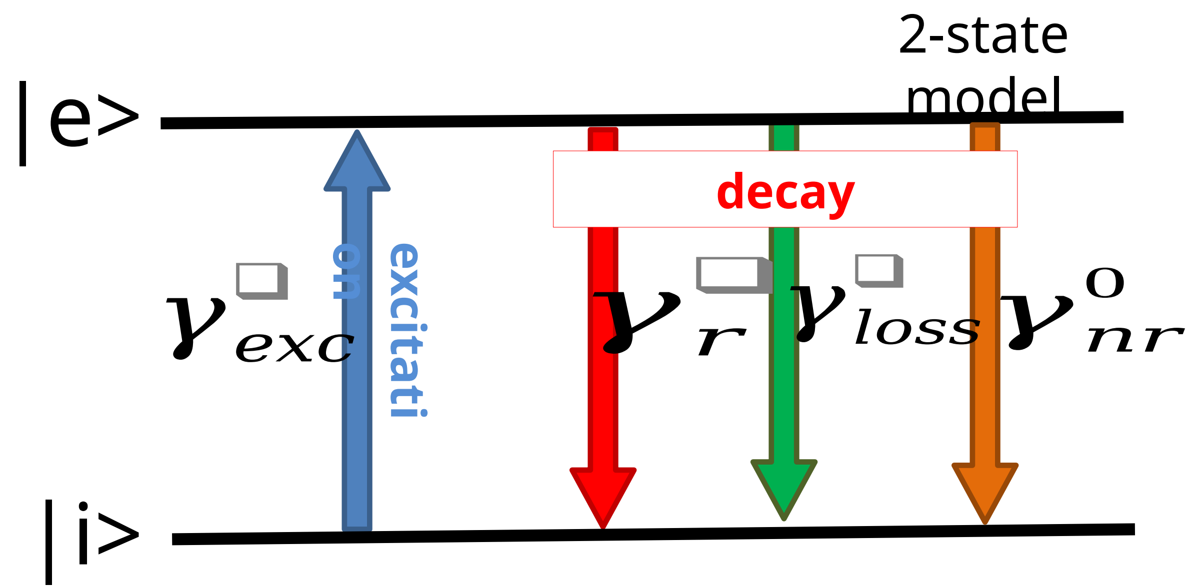
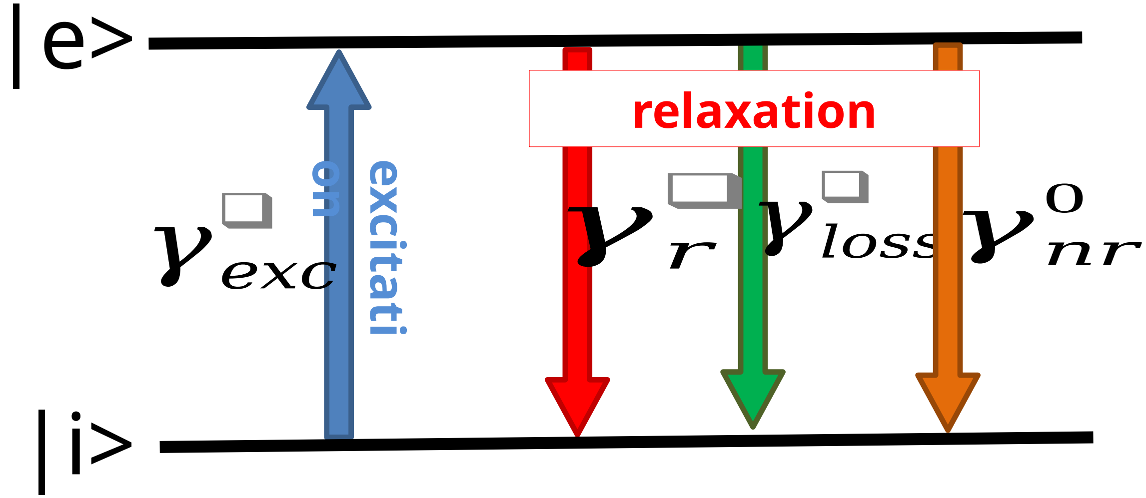
QE in an inhomogeneous environment



3 decay channels



→ only can be experimentally measured



γ_{exc}: excitation rate

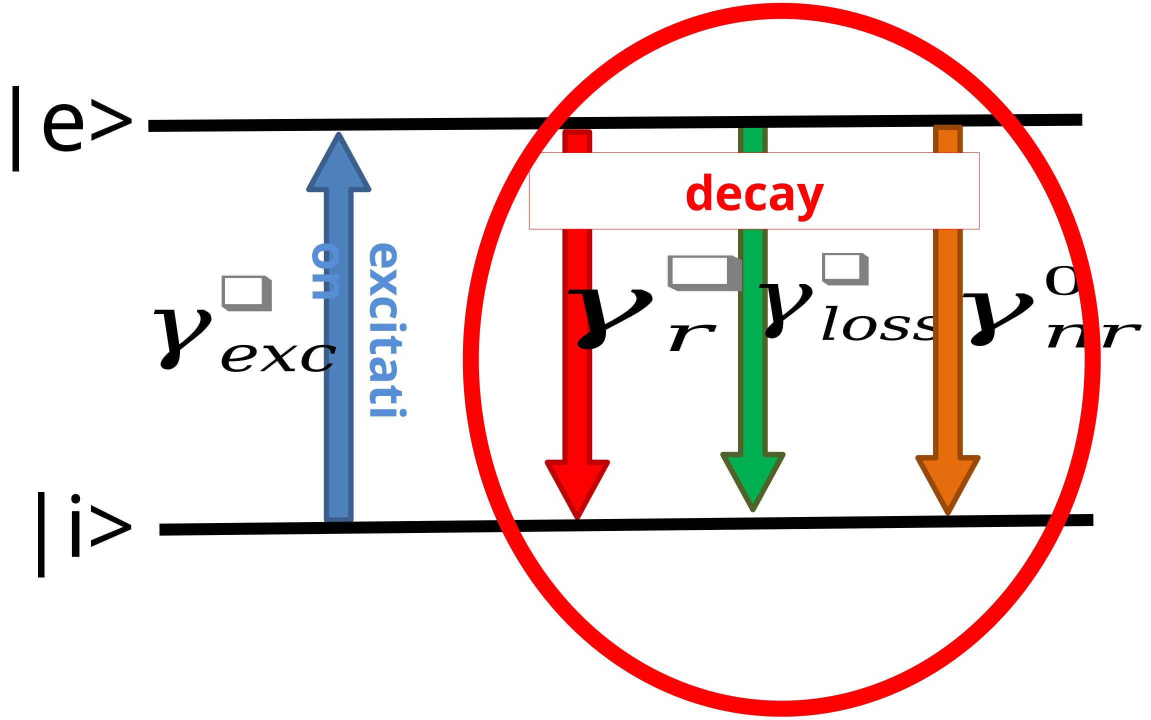
γ_{r}: radiative decay rate → Fluo

γ_{nr}^{0}: intrinsic non-radiative decay rate

γ_{loss}: non-radiative decay rate

→due to losses in the environement

Description of the spontaneous emission



Total decay rate

$$\underbrace{\gamma \;¿\; \gamma_r^{\square} + \gamma_{loss}^{\square} + \gamma_{nr}^{0}}$$

$$¿\; \gamma_{nr}^{\square}$$

Non-radiative decay rate

Particular case, QE in vacuum

vacuum

$$\gamma_{\square}^{0} \;¿\; \gamma_r^{0} + \gamma_{nr}^{0}$$

➔ Intrinsic losses which are independent of the QE env.

$\gamma_r^{\square} \neq \gamma_r^{0}$ ➔ Spontaneous emission influenced by the environment of the QE (Purcell and others)

Lifetime of the excited state

$$\tau \text{¿} \frac{1}{\gamma} = \frac{1}{\gamma_r^{\square} + \gamma_{loss}^{\square} + \gamma_{nr}^{0}} \square \square$$

Emitter in vacuum

$$\tau_0 \text{¿} \frac{1}{\gamma} = \frac{1}{\gamma_r^{0} + \gamma_{nr}^{0}} \square \square$$

Quantum yield (efficiency)

Probability of a radiatively released photon
Probability of a radiative decay

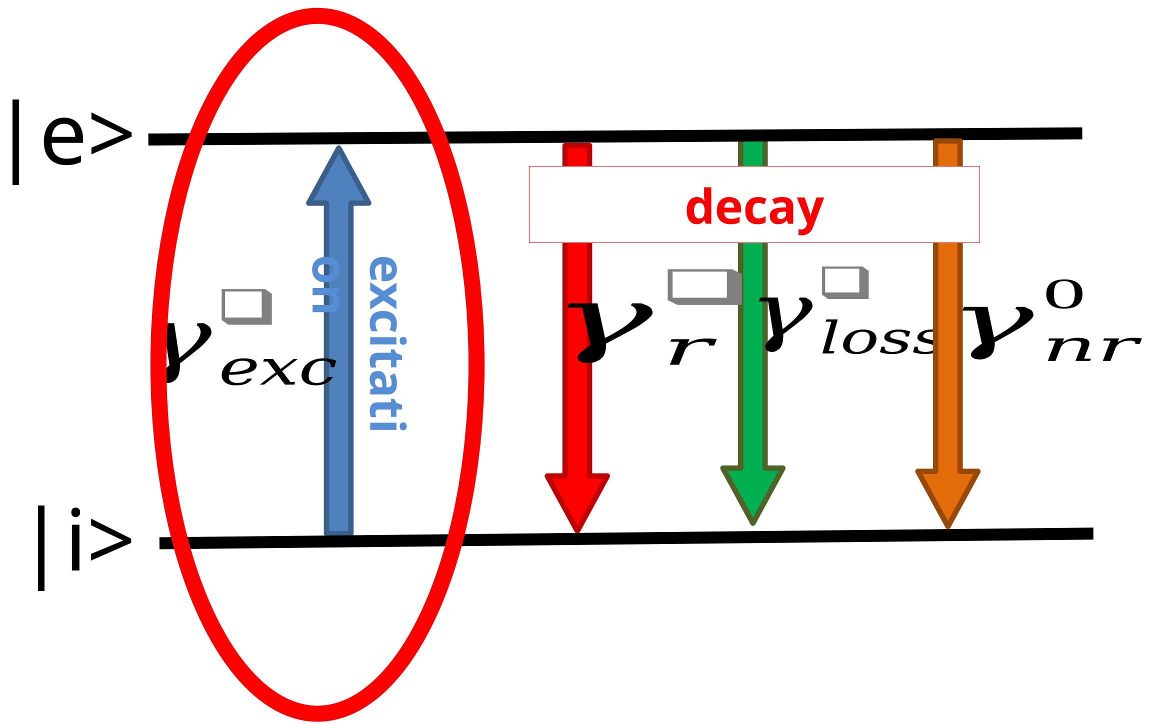
$$q = \frac{\gamma_r}{\gamma} = \frac{\gamma_r}{\gamma_r + \gamma_{loss} + \gamma_{nr}^0}$$

Emitter in vaccum

$$q_i = \frac{\gamma_r^0}{\gamma^0} = \frac{\gamma_r^0}{\gamma_r^0 + \gamma_{nr}^0}$$

Intrinsic quantum yield

Description of the QE excitation

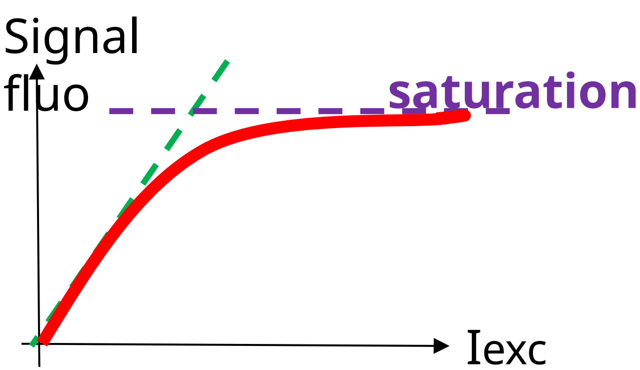


Case of an QE excitation with weak optical power : excitation well below the saturation regime

➔ The QE is most of the time in its ground state

$$\gamma_{exc}^{\square} = \text{¿} \overrightarrow{n_p} \cdot \vec{E}\left(\vec{r}_0, \omega_{abs}\right) \vee \text{¿}^2 \text{¿}$$

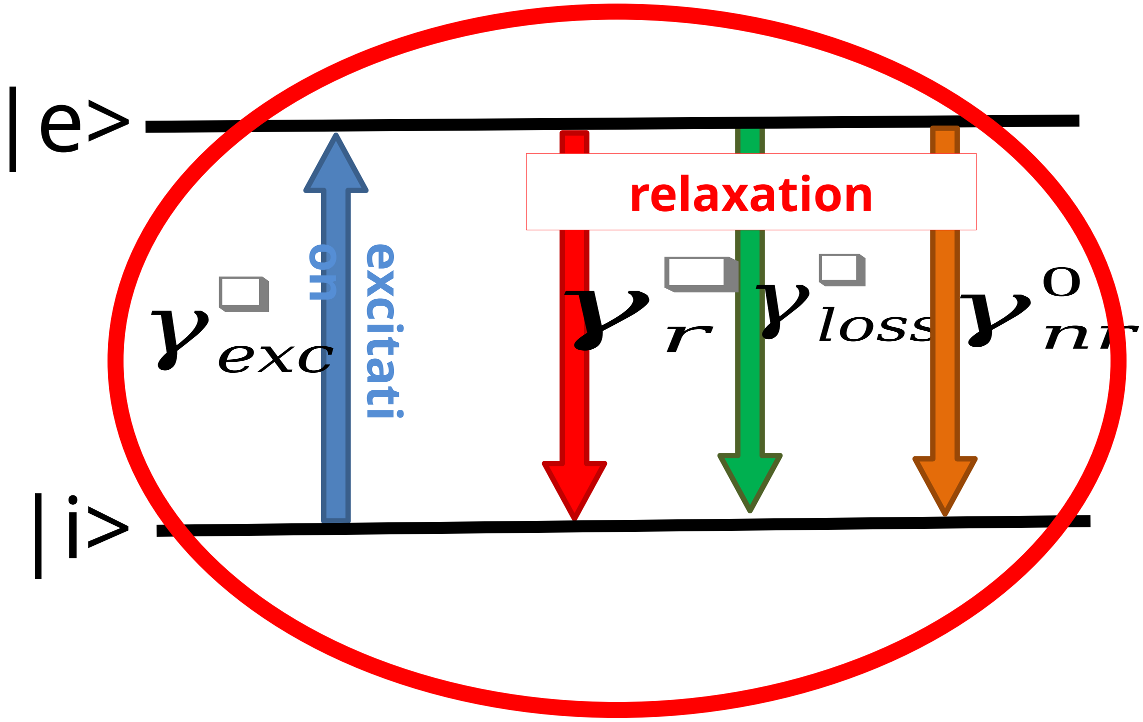
unit vector defining the dipole moment of the QE
: electric optical field for excitation
: position vector of the QE
: angular frequency at excitation



Emitter in vacuum

$$\gamma_{exc}^{0} = \text{¿} \overrightarrow{n_p} \cdot \vec{E}_0\left(\vec{r}_0, \omega_{abs}\right) \vee \text{¿}^2 \text{¿}$$

Description of fluorescence emission



Fluorescence rate

→below saturation threshold

$$\gamma_{em} = q\,\gamma_{exc}$$

Experimentally measurable parameter (with a photon counter)

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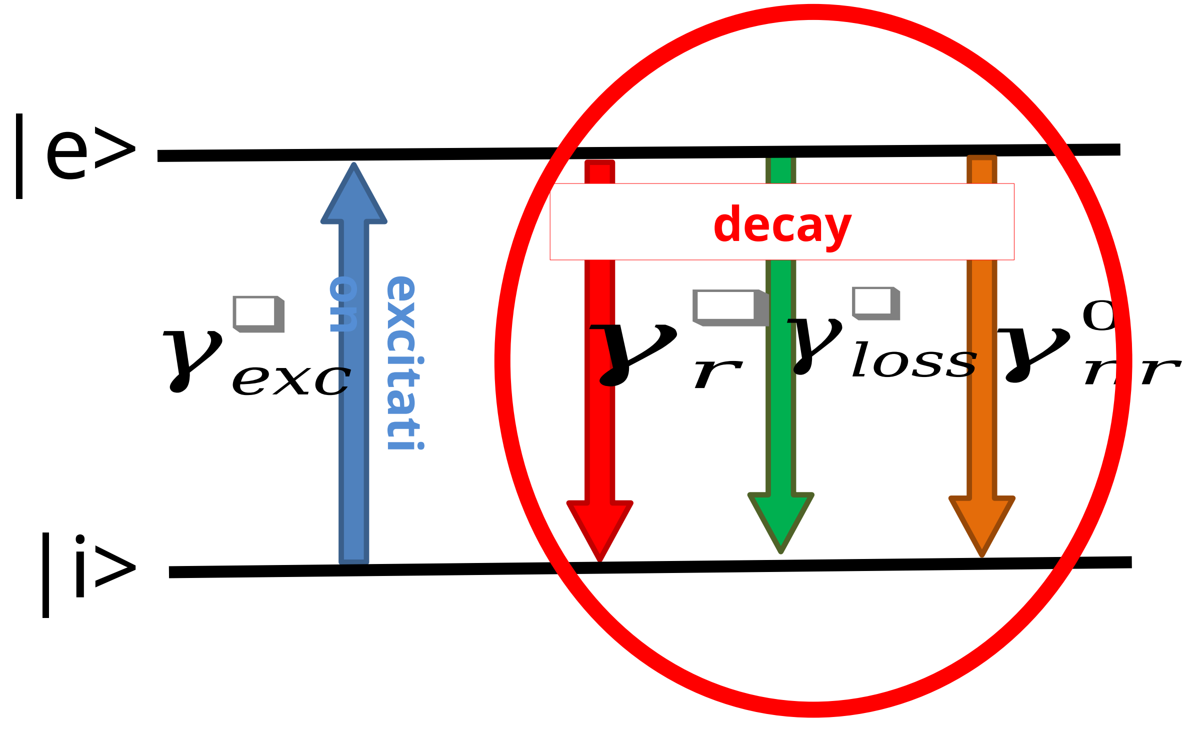


|e>
|i>
excitation
decay
γ_{exc}
γ_{r}
γ_{loss}
γ_{nr}

Why ?

Nanoscale systems : « QE + environment » are often too complex to be rigorously resolved/described by quantum electrodynamics

Classical Electrodynamics is much more simple to implement

➔ Numerous numerical methods based on Maxwell's equations are nowadays commercially available (FDTD, FMM, etc.)

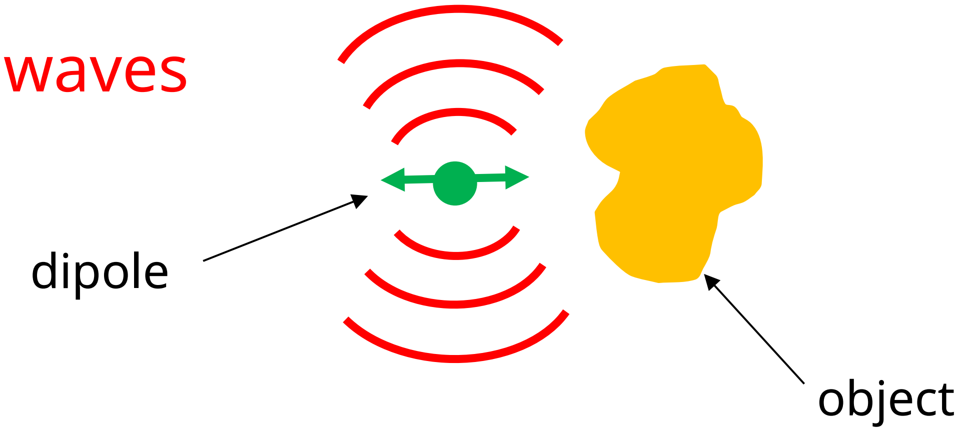
Électrodynamique classique ?

QE ➔ Radiating
dipole

Power calculation from electromagnetic waves

➔ Poynting's theorem

Electromagnetic waves



IMPORTANT !

The link between quantum and classical electrodynamics

In the case of a **« weak coupling »** between the QE and its environment, we have:

$$\boxed{\frac{\gamma}{\gamma^{0}} = \frac{P}{P_{0}}}$$

Quantum formalism of the QE

Classical formalism of the radiating dipole

$$\boxed{\frac{\gamma}{\gamma^{0}} = \frac{P}{P_{0}}}$$

A link between quantum and classical approaches is possible at the expense of a normalisation process

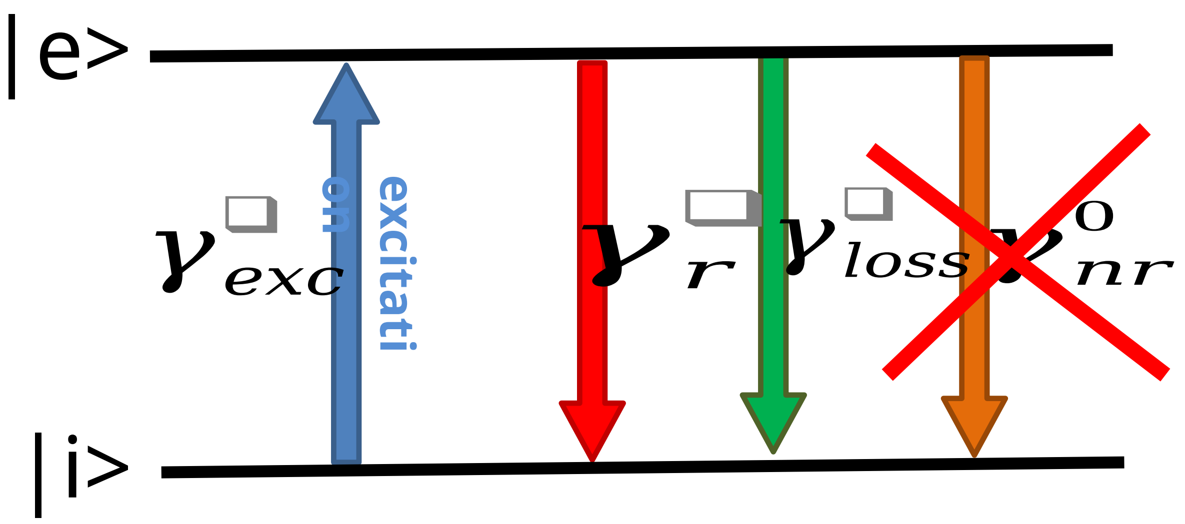
We can **<u>only</u>** predict a ***<u>relative</u>*** spontaneous emission induced by the environment of the QE. No quantitative prediction of the emission rate…

<u>BUT</u> the problem is greatly simplified

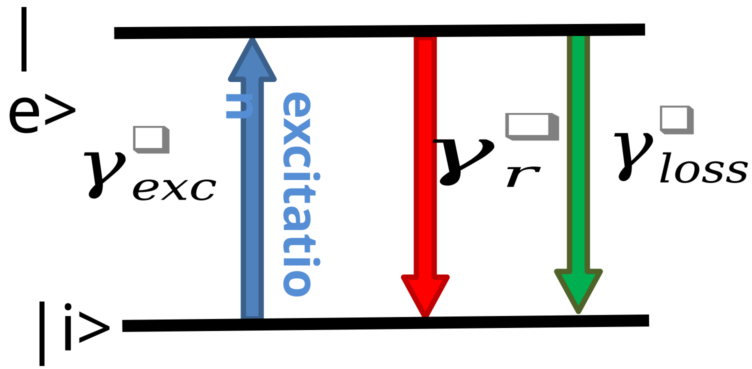
In the following: PERFECT EMITTERS

$$\gamma^{0}_{nr} = 0$$

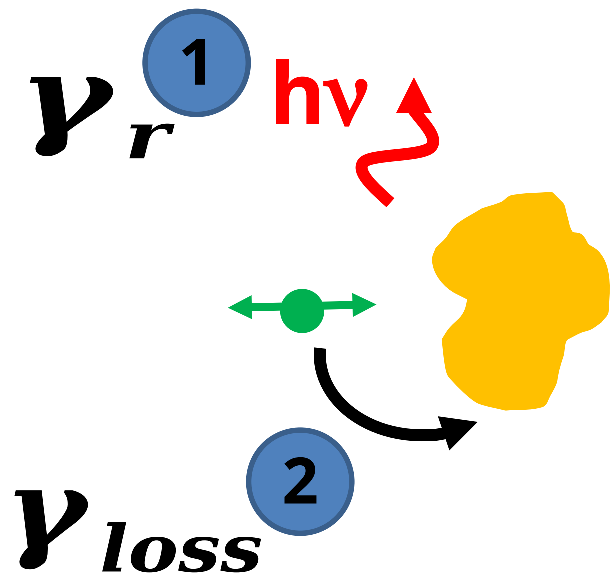
$$q_i = 1$$



Problem to resolve



2 decay channels to simulate



$$\frac{\gamma_r}{\gamma^0}\,?,\ \frac{\gamma_{loss}}{\gamma^0}\,?,\ \frac{\gamma}{\gamma^0}\,?,\ q\,?$$

What do we have ?

➔ $$\boxed{\frac{\gamma}{\gamma^0} = \frac{P}{P_0}}$$

➔ **Classical electrodynamics**

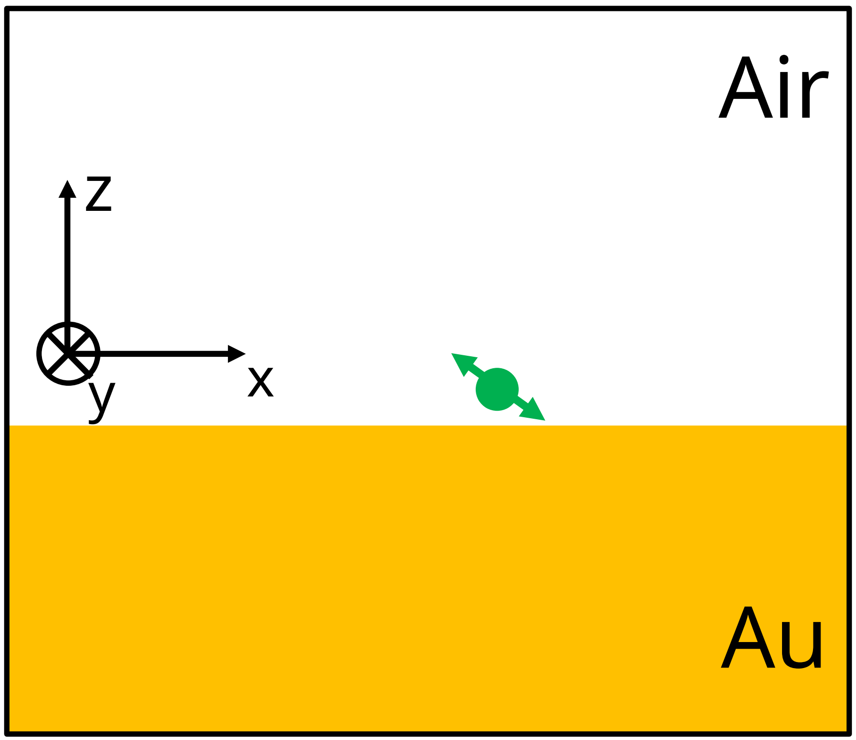
- Numerical methods based on Maxwell's equations
- Analytical description of a radiating dipole
  ➔ dipolar field (analytic formula)
- Poynting's theorem

TP :

Spontaneous emission (SE) of a quantum emitter near a structure : quantum description via classical electrodynamics

Objective

Prediction of the change of SE of a single emitter positioned near a (nano)structure



2 cases under study :

- // (0x)
- // (0z)

Emission at λ = 800 nm

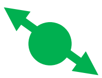
$$\frac{\gamma_r}{\gamma^0}, \frac{\gamma_{loss}}{\gamma^0}, \frac{\gamma}{\gamma^0}, q\ ??$$

Methodology

Quantum formalism of the QE

$$\frac{\gamma}{\gamma^{0}} = \frac{P}{P_{0}}$$

Classical formalism of the <u>radiating dipole</u>



➔ **Power calculation from a radiating dipole**

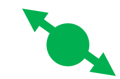
P_0 and P have to be calculated with the dipole positioned in two media of the same permittivity $\boldsymbol{\varepsilon}$!!!

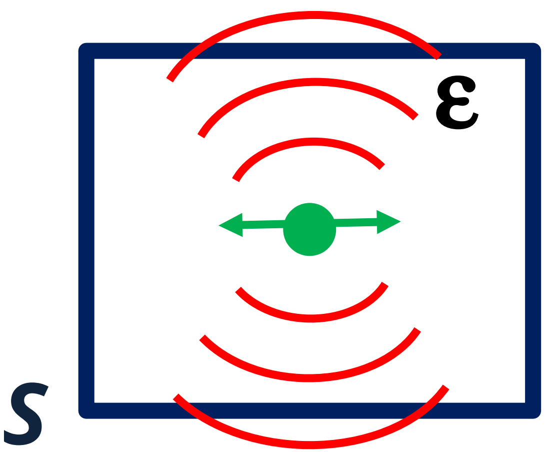
Methodology

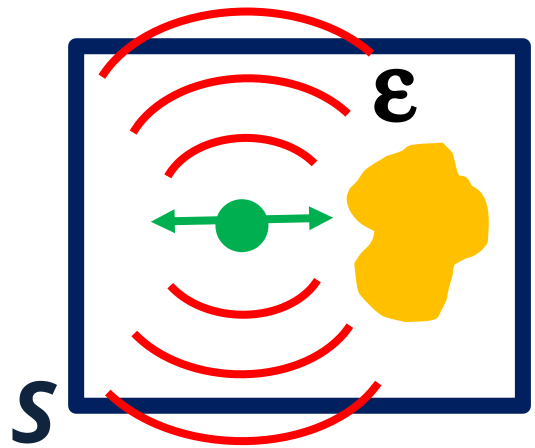
Quantum formalism of the QE

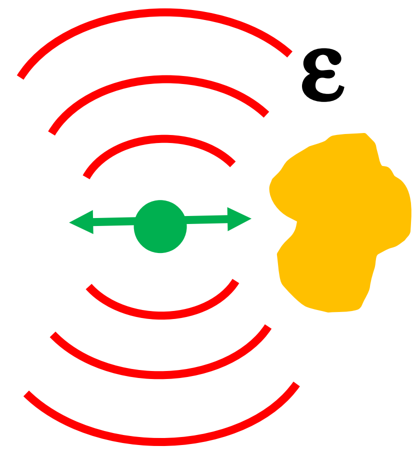
$$\frac{\gamma}{\gamma^{0}} = \frac{P}{P_{0}}$$

Classical formalism of the <u>radiating dipole</u>









$$P_{0} = \oint_{S} \vec{E} \times \vec{H}\, dS$$

$$P_{r} = \oint_{S} \vec{E} \times \vec{H}\, dS$$

$$P = \frac{\omega}{2} Im\left[\vec{p}^{\,*} \cdot \vec{E}(\vec{r}_{0})\right]$$

$$\Rightarrow \frac{\gamma_{r}}{\gamma^{0}}$$

$$\Rightarrow \frac{\gamma}{\gamma^{0}}$$

Methodology

$$\frac{\gamma_r}{\gamma^0}, \frac{\gamma}{\gamma^0}, \frac{\gamma_{loss}}{\gamma^0}, q$$

$$=$$