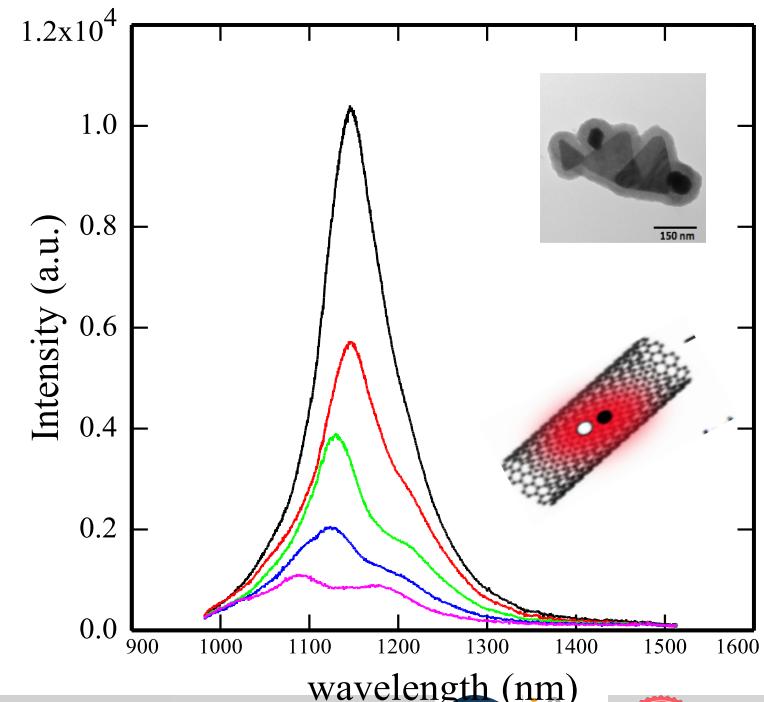




Enhancing carbon-nanotubes luminescence With the help of plasmonic antennas

E. Rousseau
C. Beaufils
G. Cassabois

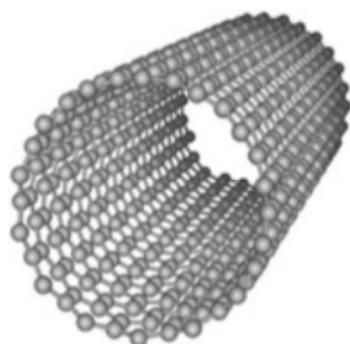
*Laboratoire Charles Coulomb
CNRS- Université de Montpellier
FRANCE*



emmanuel.rousseau@umontpellier.fr

Carbon nanotubes

Well-defined exciton peak @ Room temperature



Telecom-window range : *wavelength* $\sim 1200\text{ nm}$

Small in diameter but quite long \rightarrow single CNT

(Can be excited by current injection)

Nanotube

$d \sim \text{nm}$

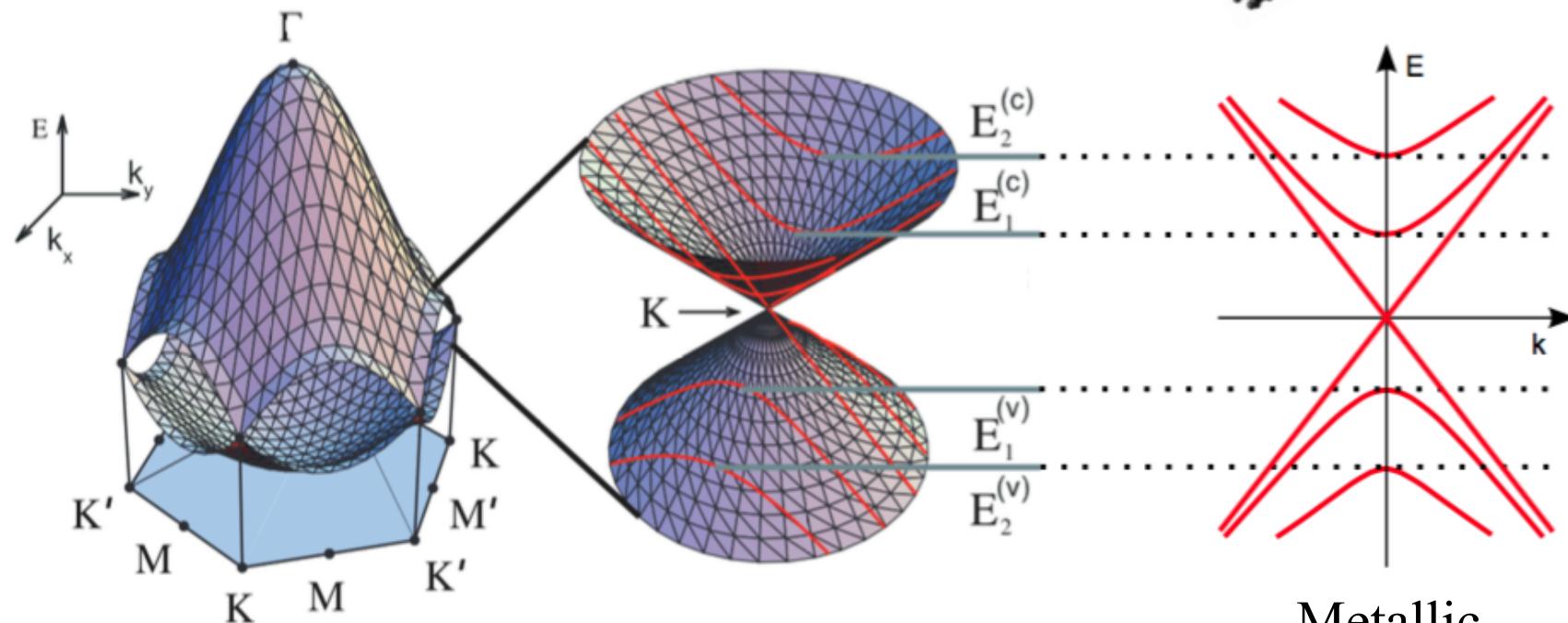
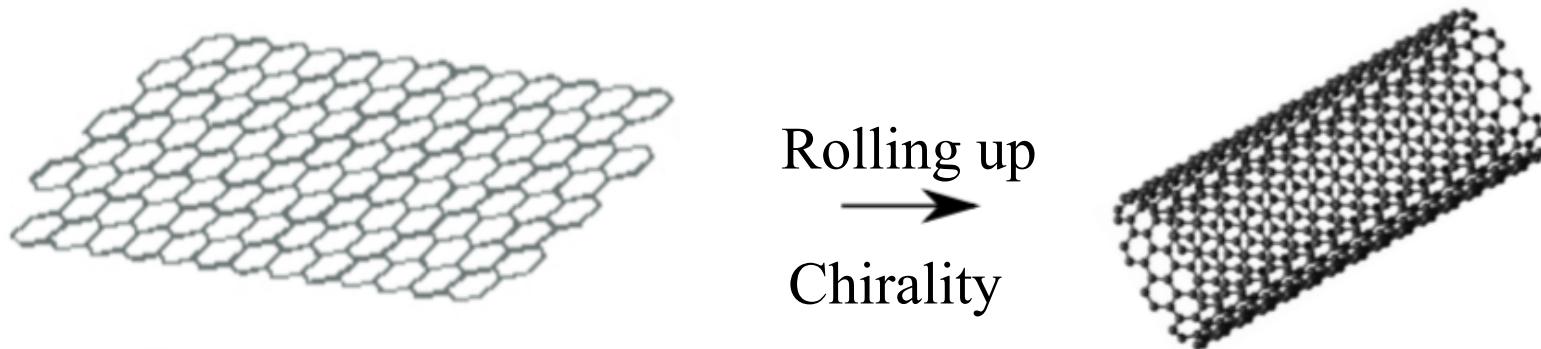
$L \sim \mu\text{m}$

CNT are attractive light source

But...

with a very small quantum yield (less than 1%) !

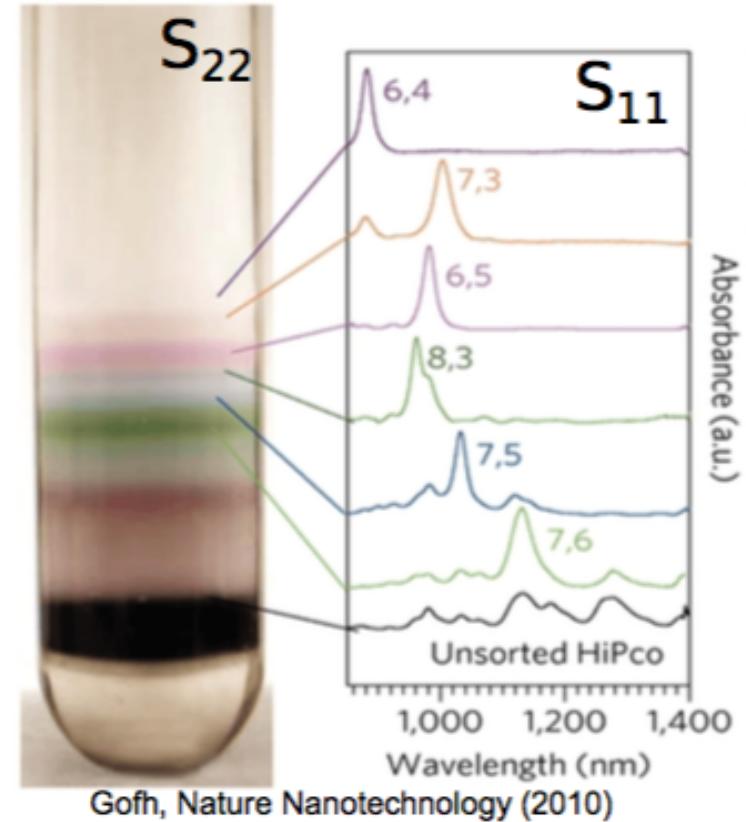
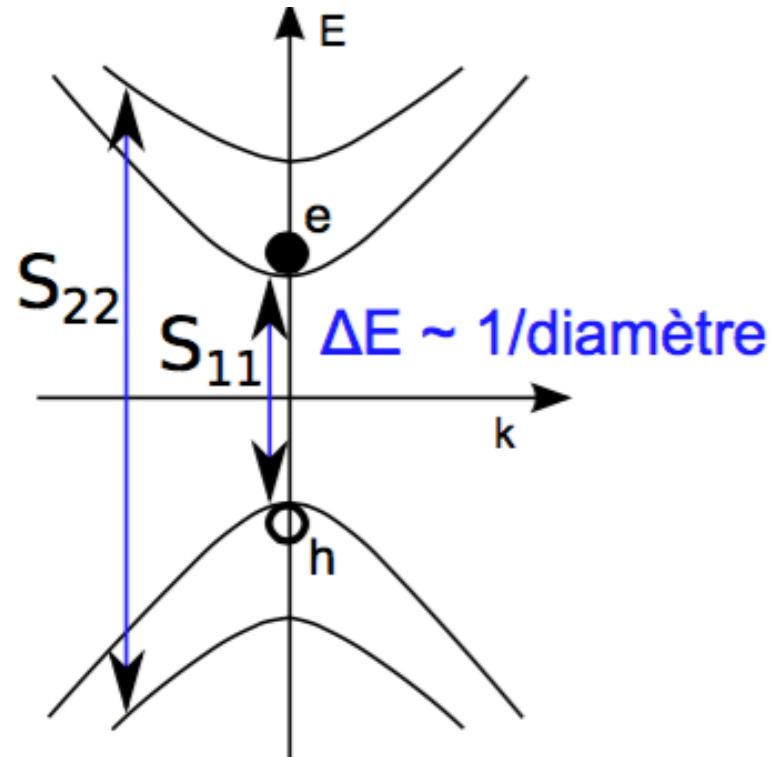
Carbon nanotubes



Dresselhaus, Physica Scripta (2012)

emmanuel.rousseau@umontpellier.fr

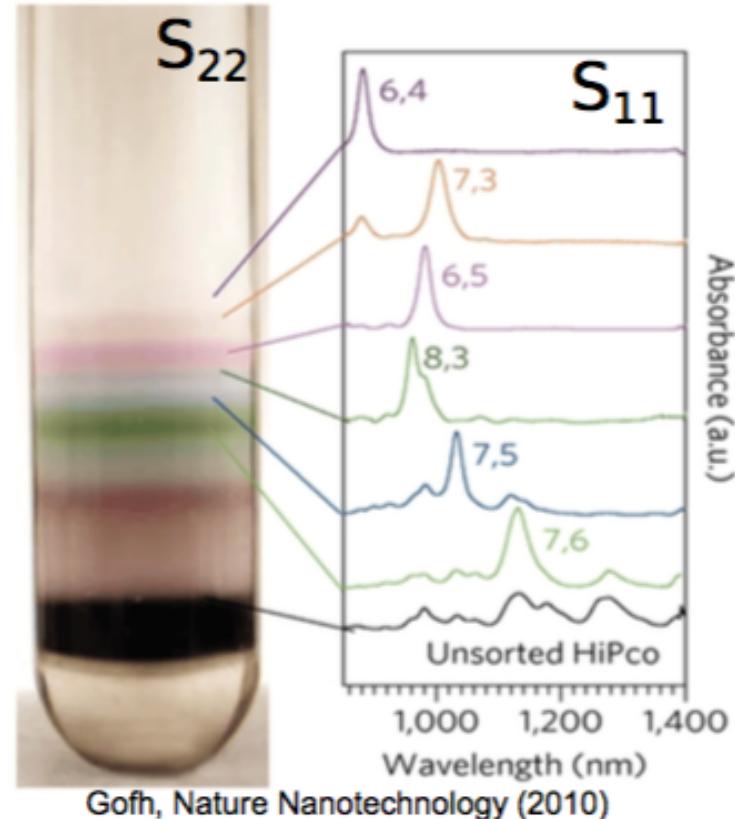
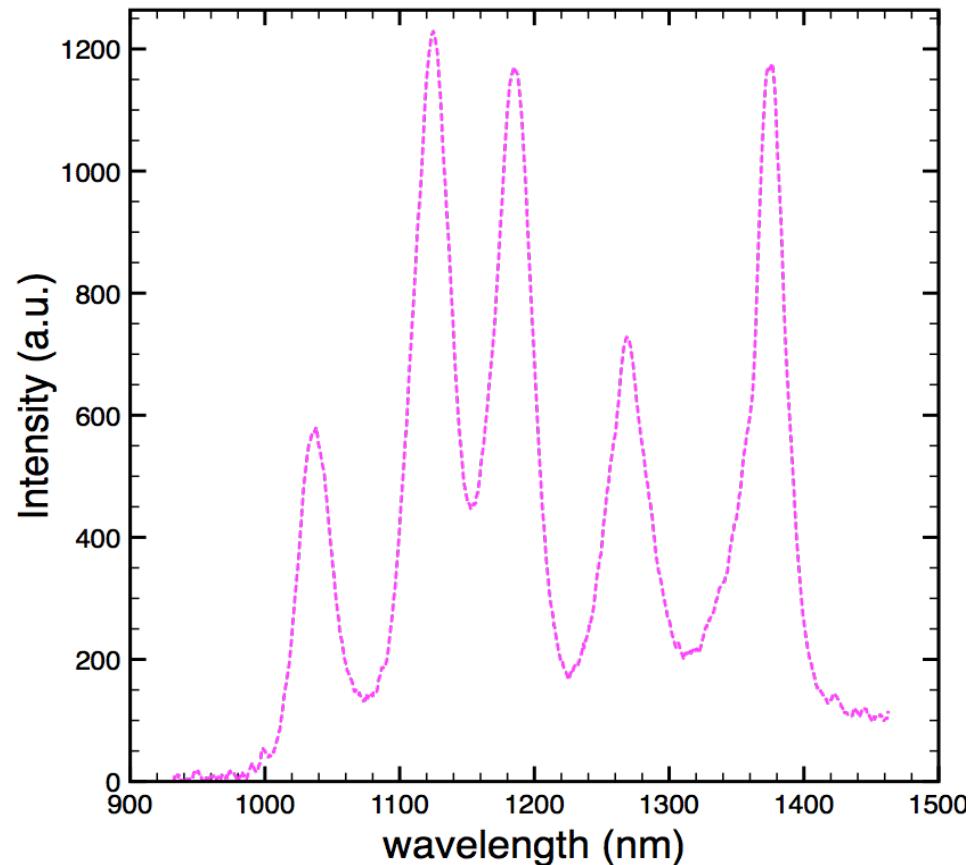
Carbon nanotubes



Typically : in the sample 5 families of semiconducting carbon nanotubes

Characterized by a well-defined exciton peak

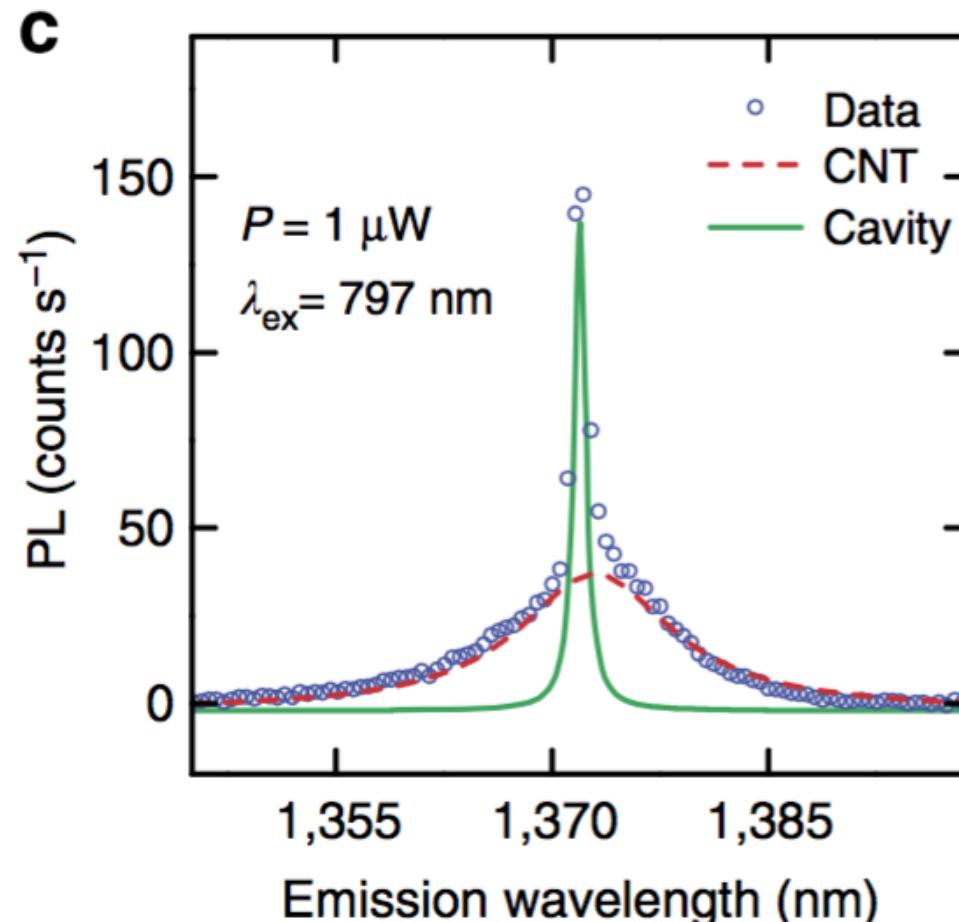
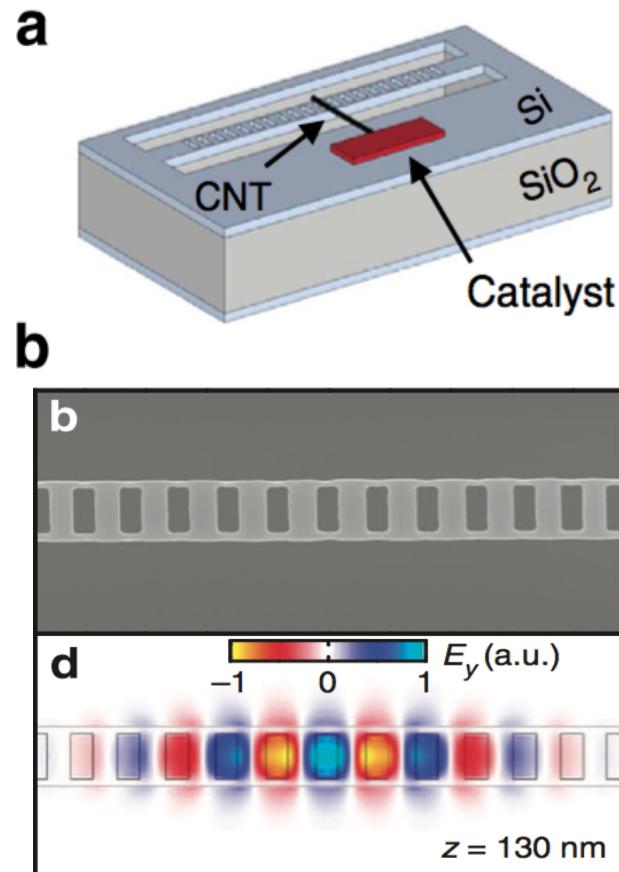
Carbon nanotubes



Typically : in the sample 5 families of semiconducting carbon nanotubes

Characterized by a well-defined exciton peak

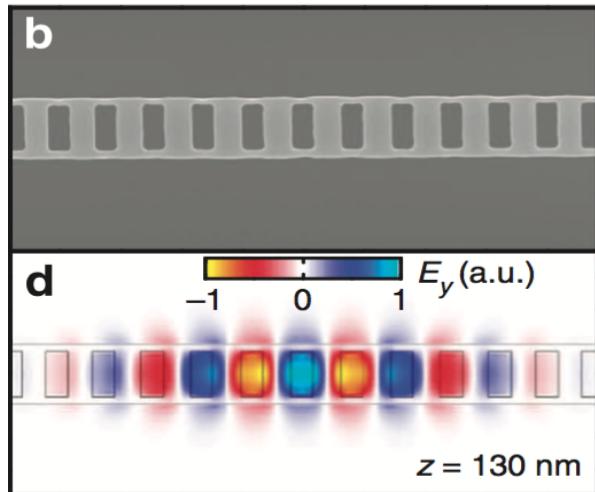
Carbon nanotubes + photonics crystals



Radiative
Enhancement ~ 200

R. Miura et al.
Nature communications 6580 (2014)

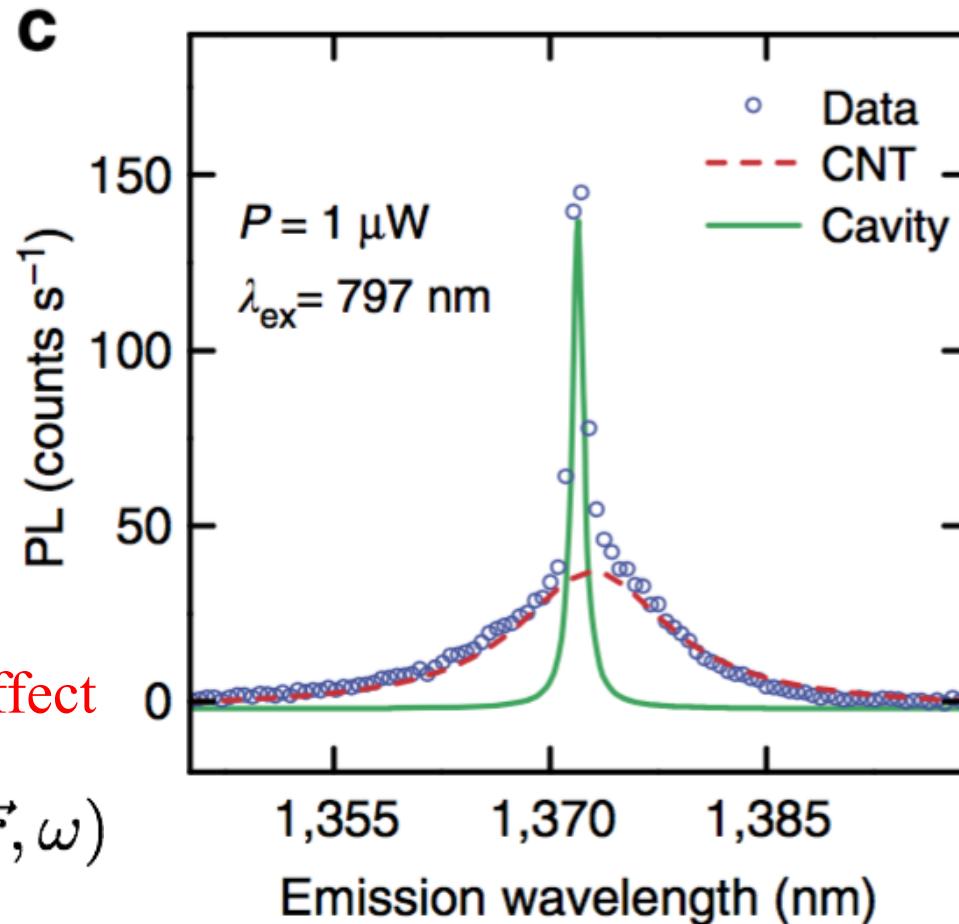
Carbon nanotubes + photonics crystals



Radiative Enhancement :
 → demonstration of the Purcell Effect

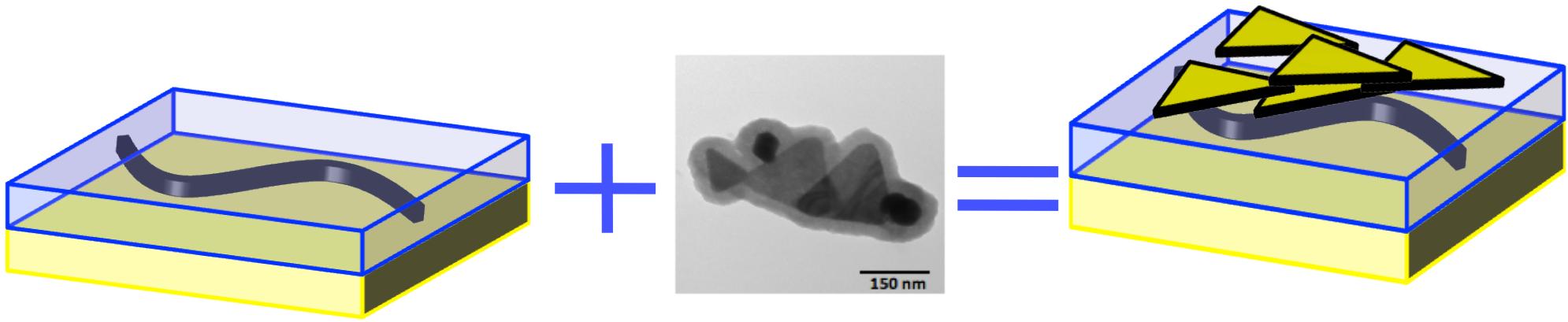
$$\Gamma = \frac{2\pi}{\hbar^2} | <0| -\vec{d} \cdot \vec{E} |1> |^2 \rho(\vec{r}, \omega)$$

→ increased density of elect. states



R. Miura et al.
 Nature communications 6580 (2014)

Carbon nanotubes + plasmonic antennas



Few carbon nanotubes
(1 single)
Quantum emitter

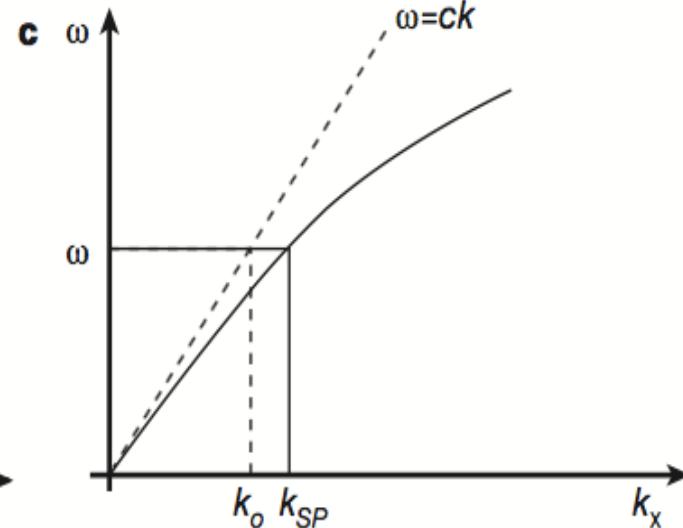
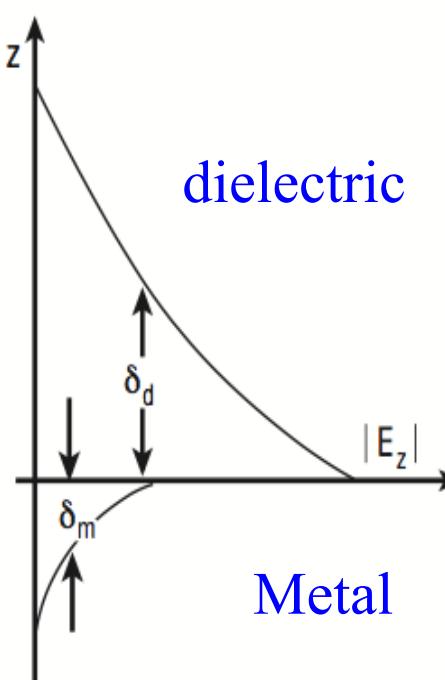
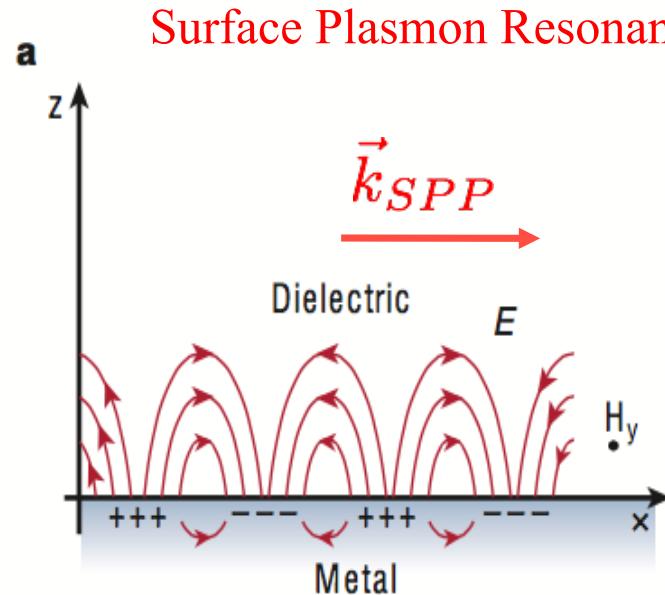
Collection of
Metallic scatterers

Luminescence
Enhancement?

Field of plasmonics (optics of metals)
Purcell effect : how environment modify quantum emitter luminescence

Broad-band enhancement: for the 5 chiralities

Plasmonics and plasmonics antennas



Charge density :

E perpendicular component

Surface wave:

Propagation along the metallic plane

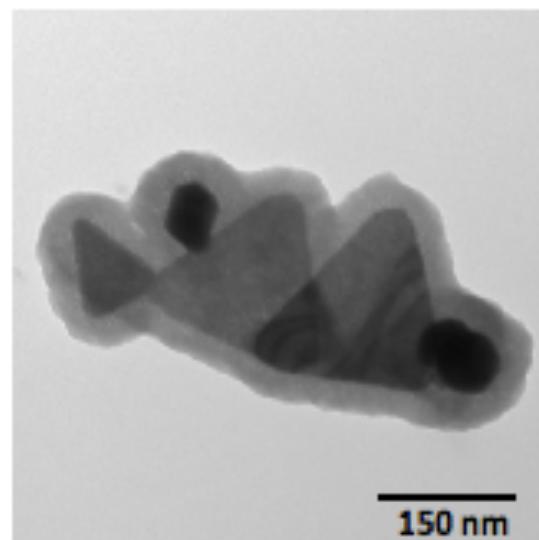
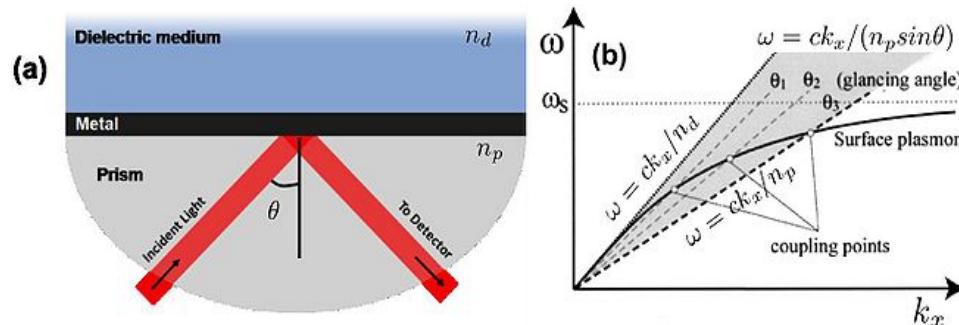
Evanescence field :

Exponential decrease from the metallic interface
Field confinement

Dispersion relation :

Below light cone
Non-radiating mode

Plasmonics and plasmonics antennas



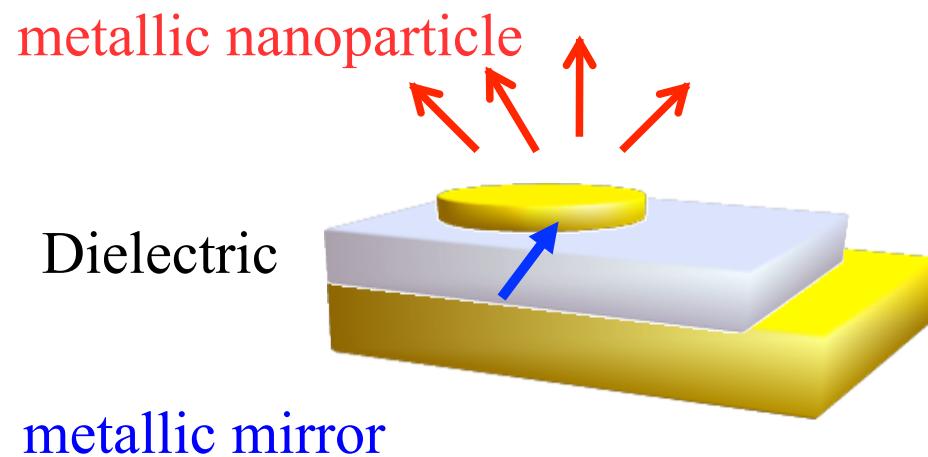
Prism coupling

Metallic nanoparticles
Diffraction => Localized plasmon resonance

Can act as antennas in the visible regime :

- modify radiative pattern (directivity)
- modify luminescence intensity (energy extraction, Purcell effect)

The patch antenna



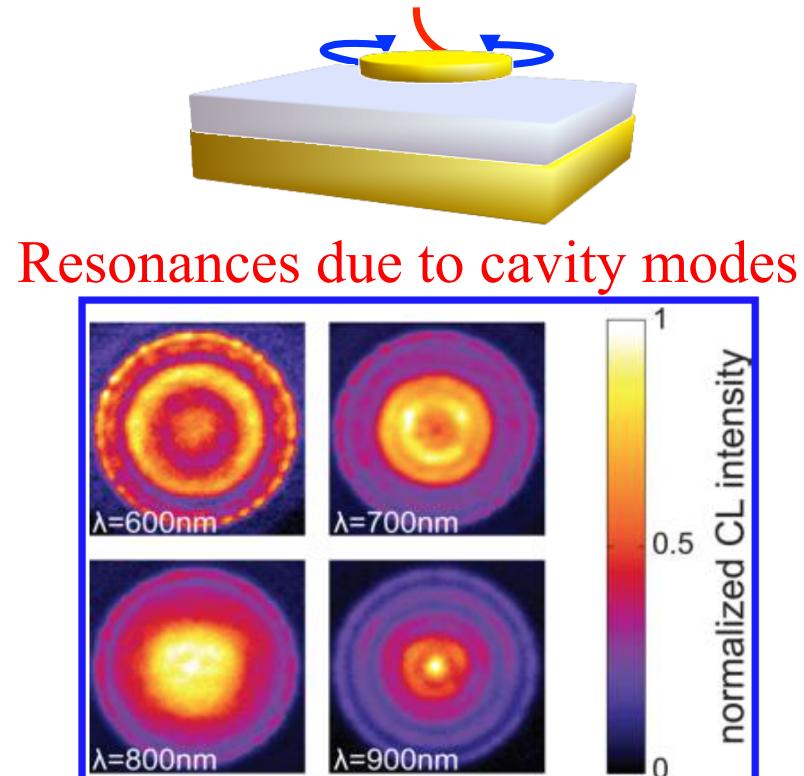
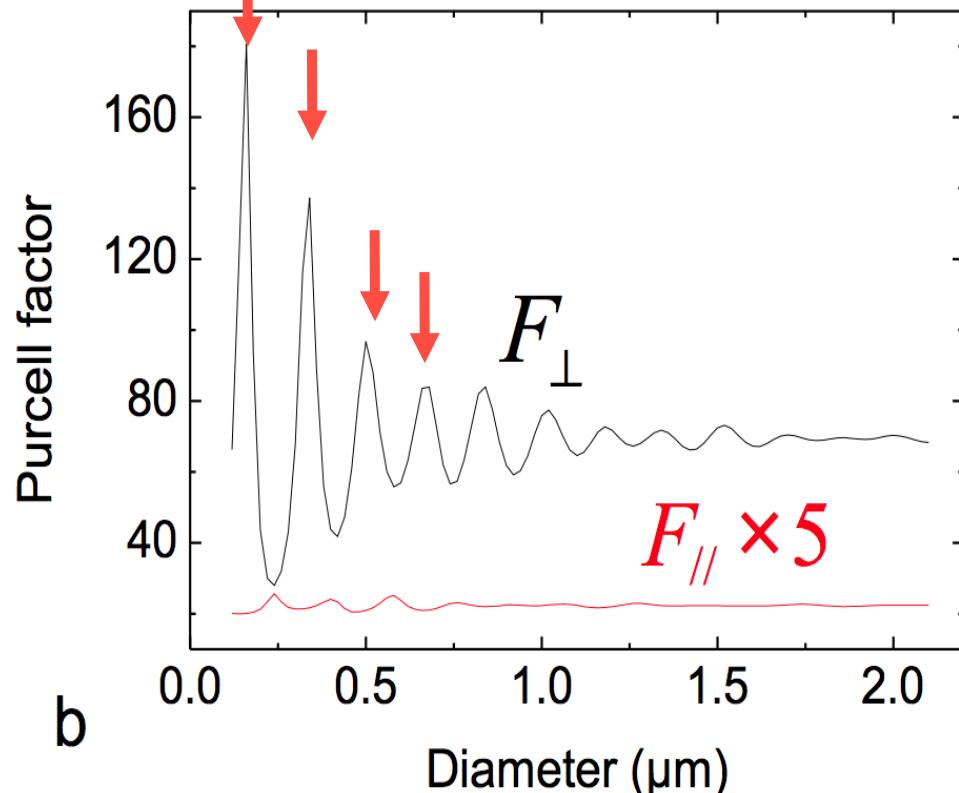
Bottom metallic mirror:

- Light emits in one direction
- Increase electric field confinement

Finite size metallic nanoparticle:

- scatter the near-field
- Can increase of the power radiates by the emitter

The patch antenna: plasmonic cavity modes

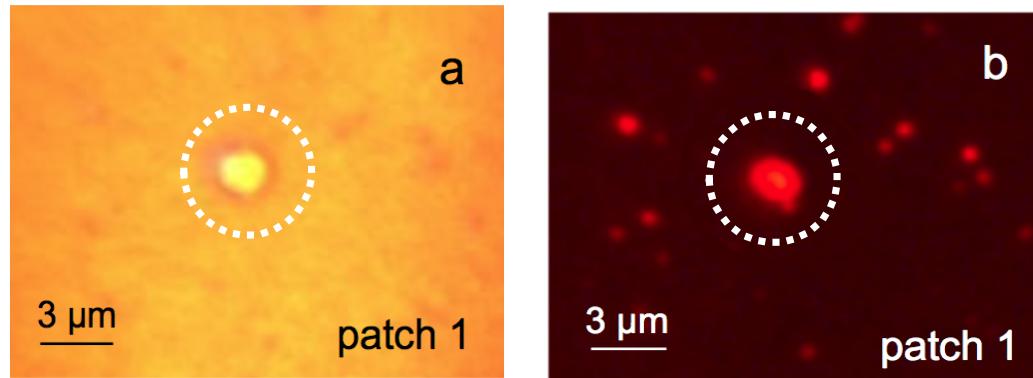


Mohtashami *et al.* ACS Photonics (2014) 1, 1134–1143

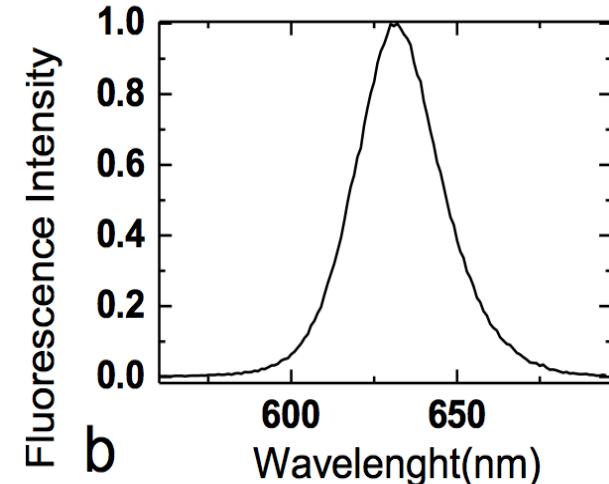
Cavity (plasmonic) modes : cavity geometry defines resonant modes
 Large cavity ($\sim 1\mu\text{m}$) many cavity modes (kind of continuum)

small antennas = high enhancement

The patch antenna : experimental results



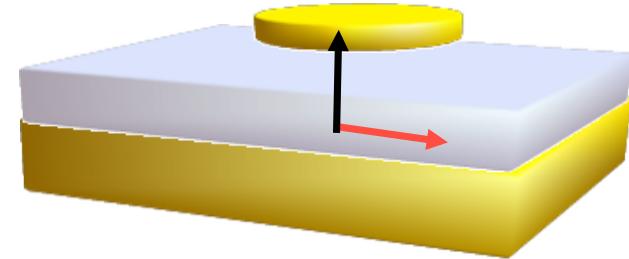
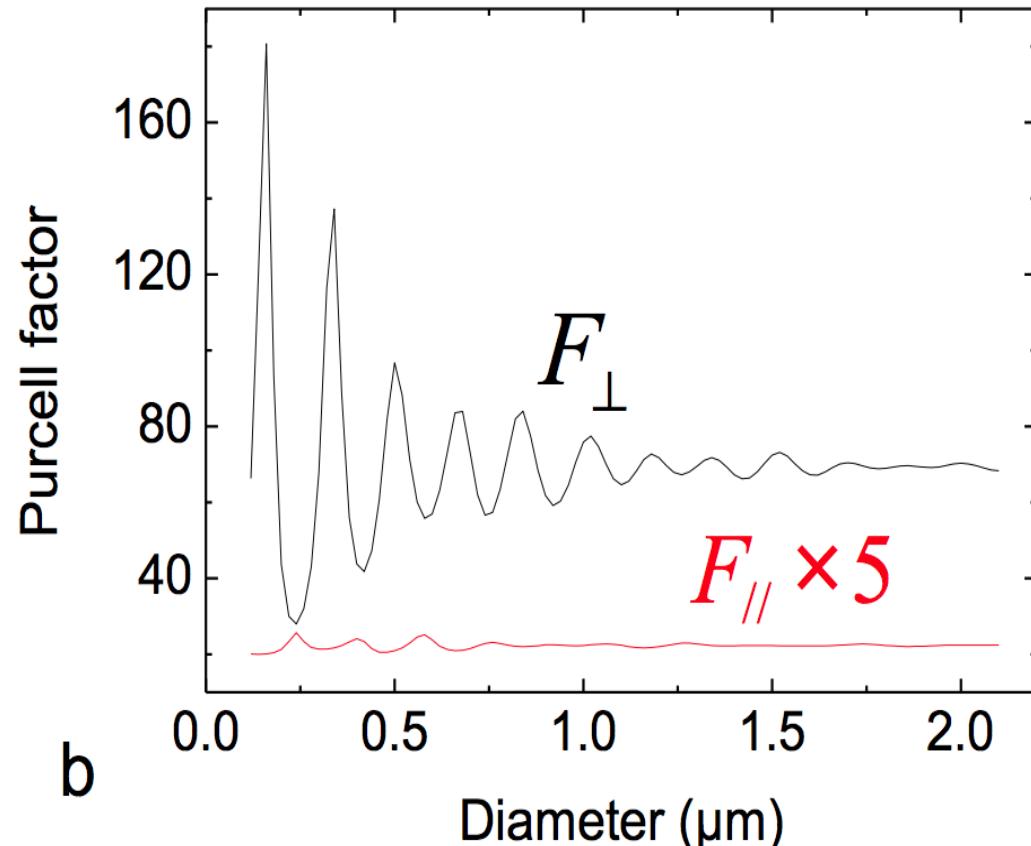
The whole metallic disk radiates
→ the plasmonic mode radiates



Purcell factor ~ 70

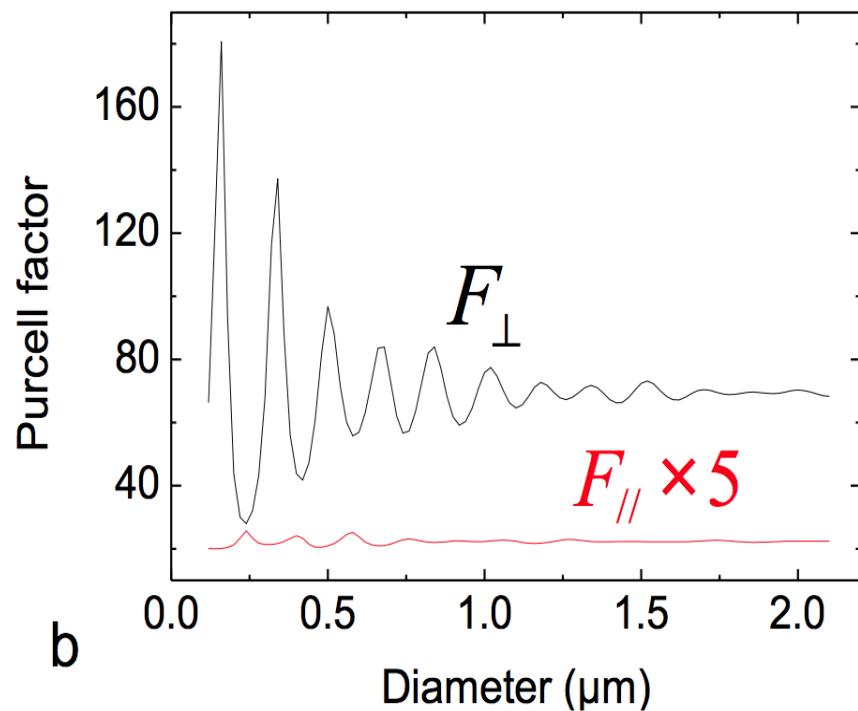
Belacel *et al.* **Nano Lett.**, 2013, 13 (4), pp 1516–1521

The patch antenna: dipole orientation

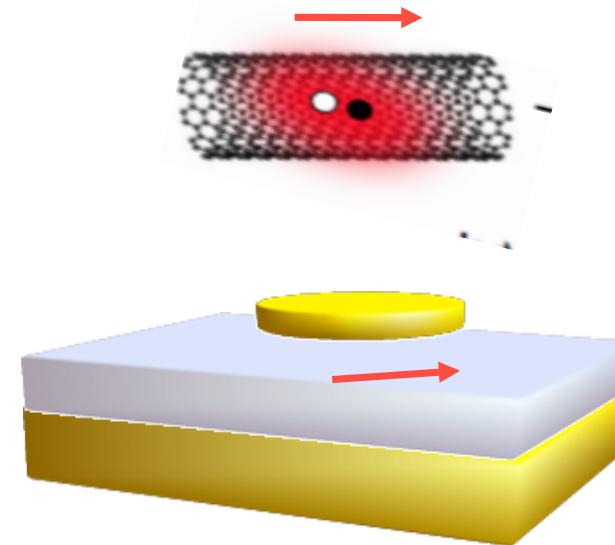


The purcell factor depends drastically on the dipole orientation

The patch antenna: dipole orientation

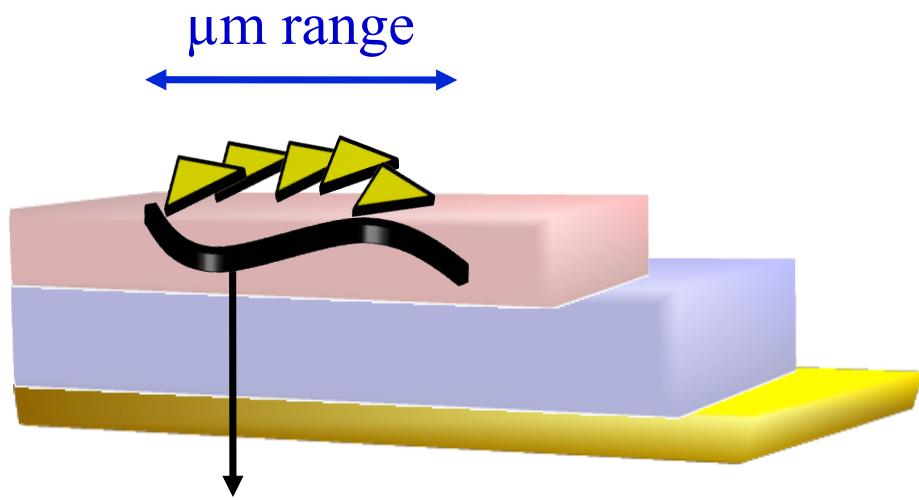


Dipole orientation

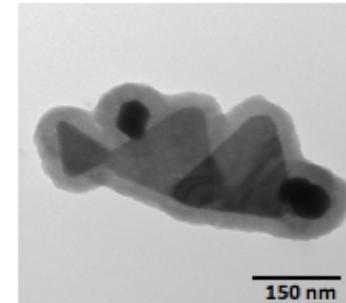


Unfortunately not favorable for CNT !!

Cluster of plasmonics nanoparticles



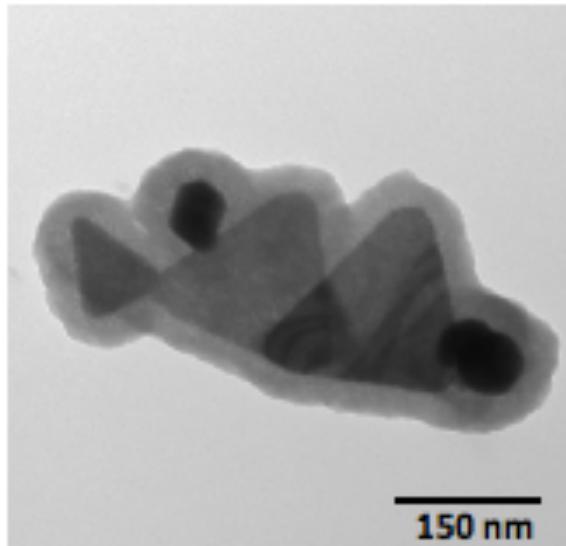
Collection of individual scatterers



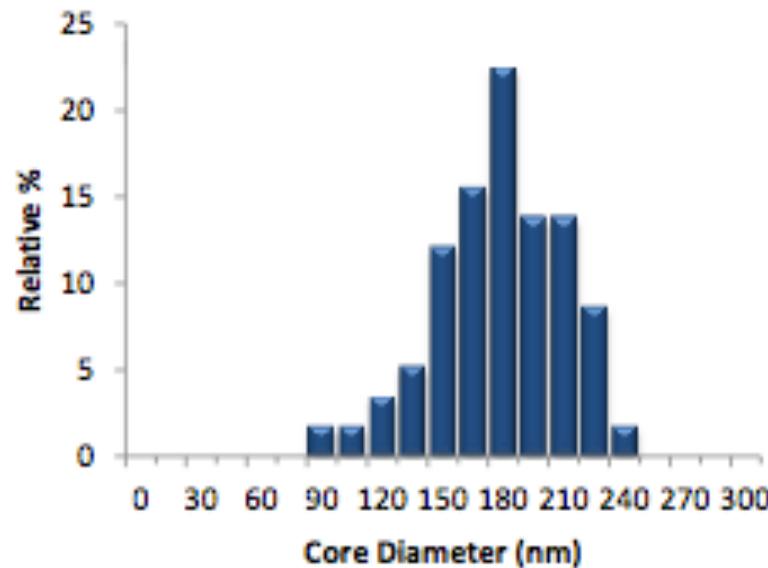
Advantages of both scale:

- Microscopic scale: dipolar resonance
→ Large Purcell factor
- Random distribution of plasmonic nanoparticles
→ relax dipole/metal surface alignment

The sample : the plasmonic nanoparticles



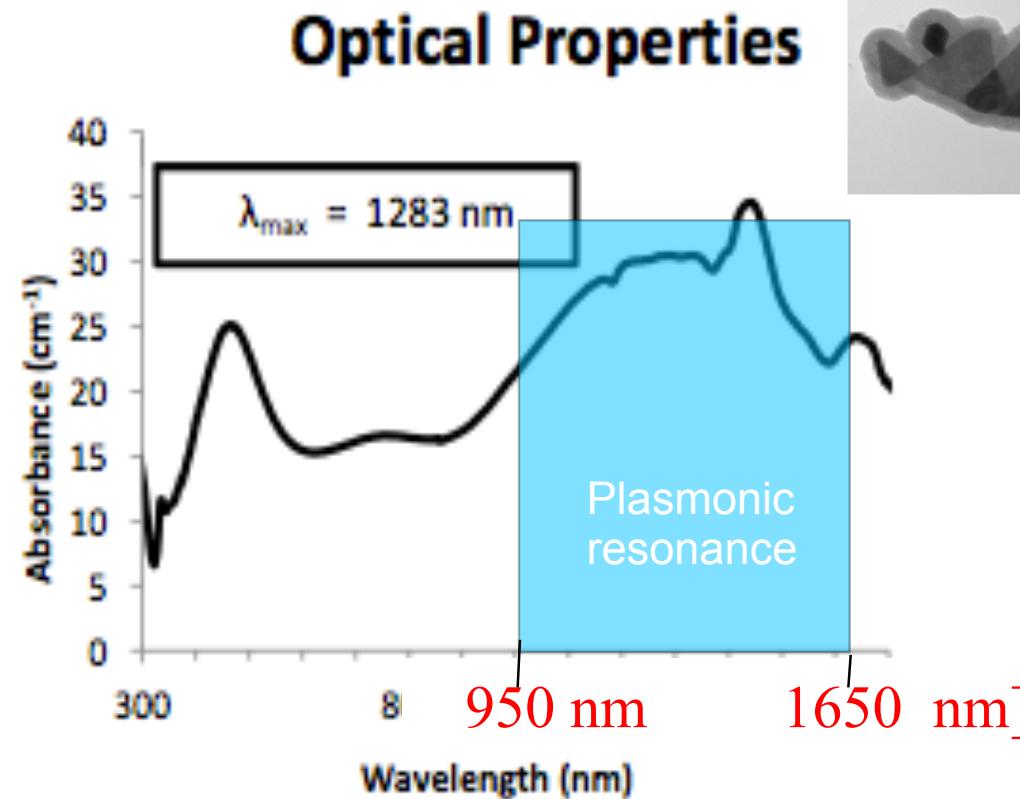
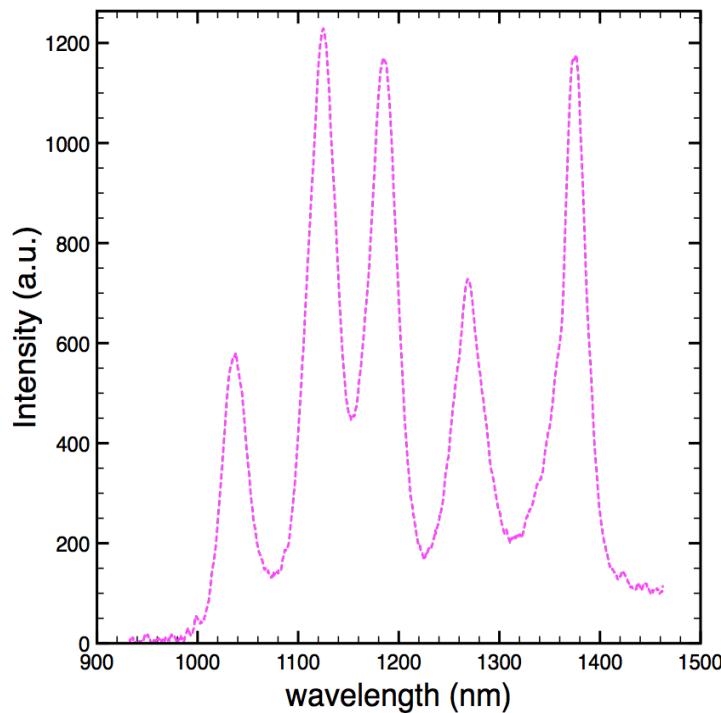
Size Distribution



Patch: Colloidal nano-triangles made on silver coated with silica

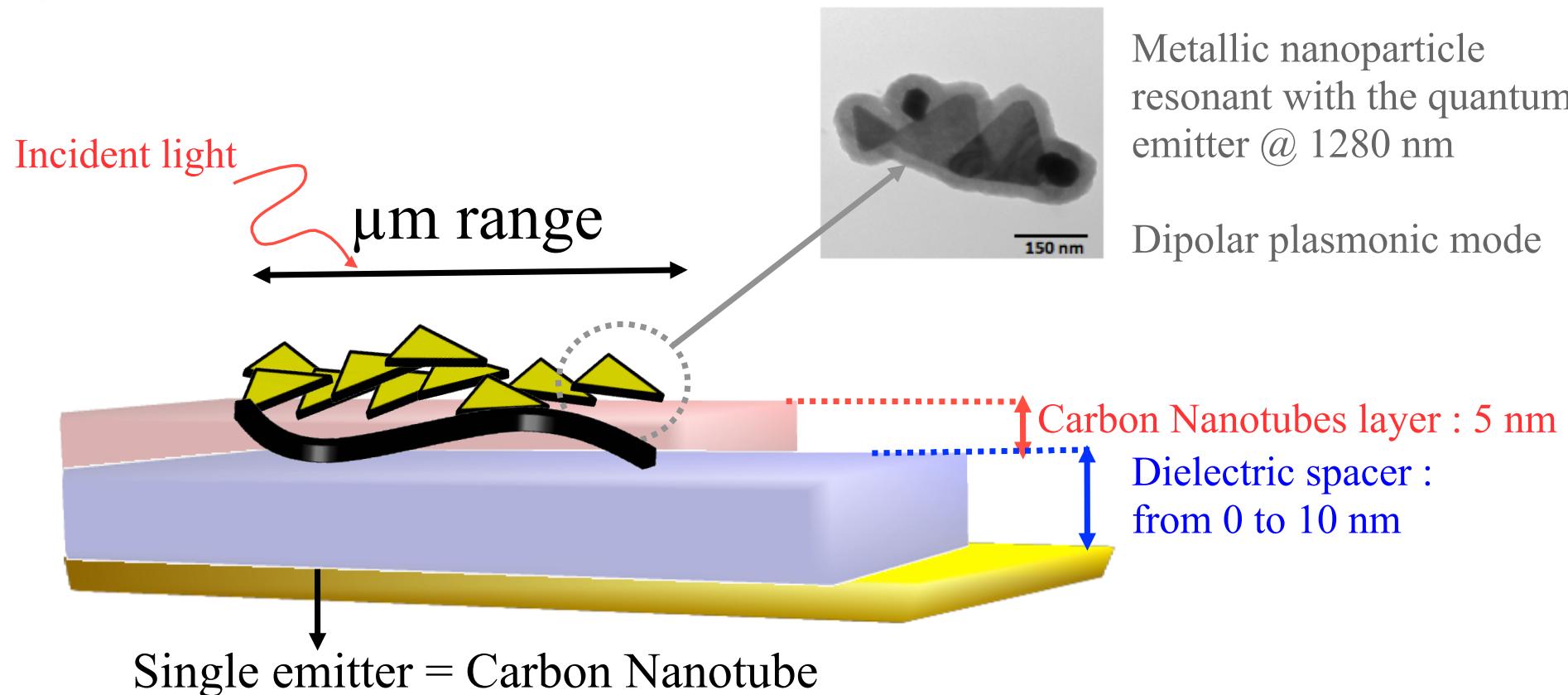
Resonant @ 1280 nm
with broad size dispersion

The sample : the plasmonic nanoparticles



broad size dispersion:
 => broad “resonance” peak (inhomogeneous broadening)
 => broad-band enhancement

Cluster of plasmonics nanoparticles



Metallic nanoparticle resonant with the quantum emitter @ 1280 nm

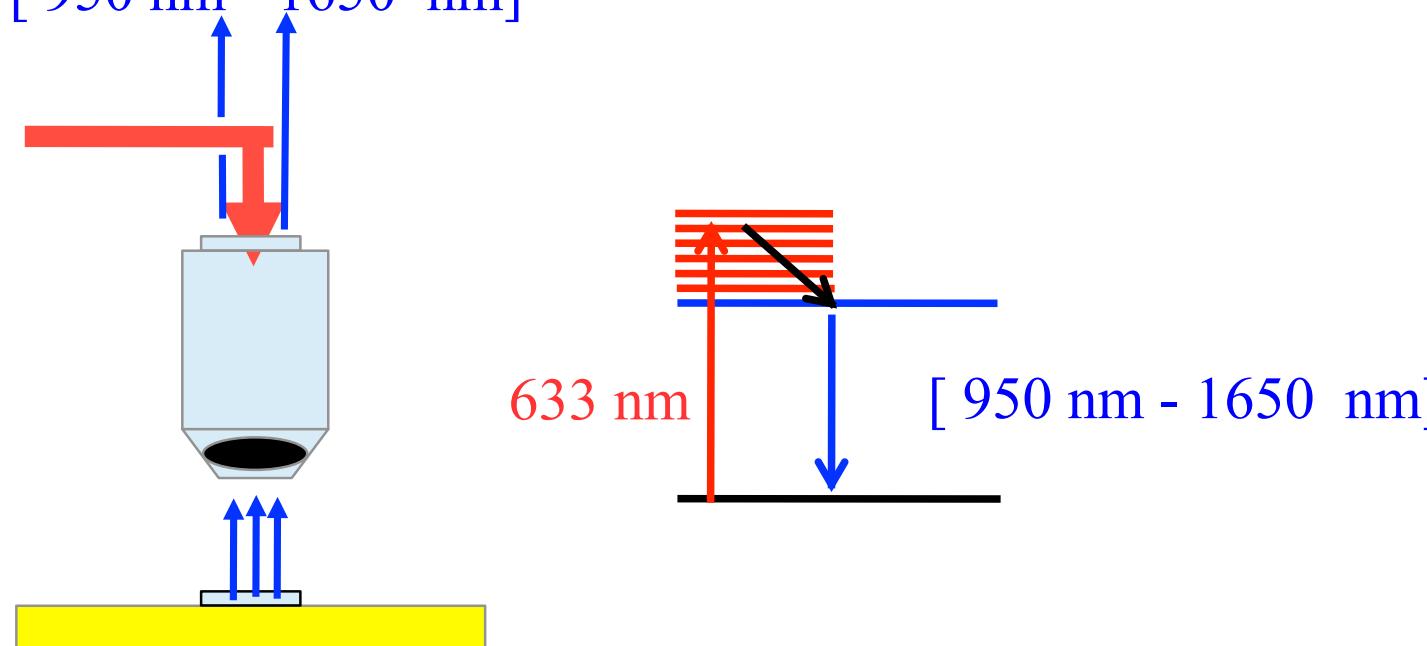
Dipolar plasmonic mode

Carbon Nanotubes layer : 5 nm
Dielectric spacer :
from 0 to 10 nm

The experimental setup:

Luminescence spectrum

Spectrometer :
Luminescence spectrum
[950 nm - 1650 nm]
Excitation laser
@ 633 nm

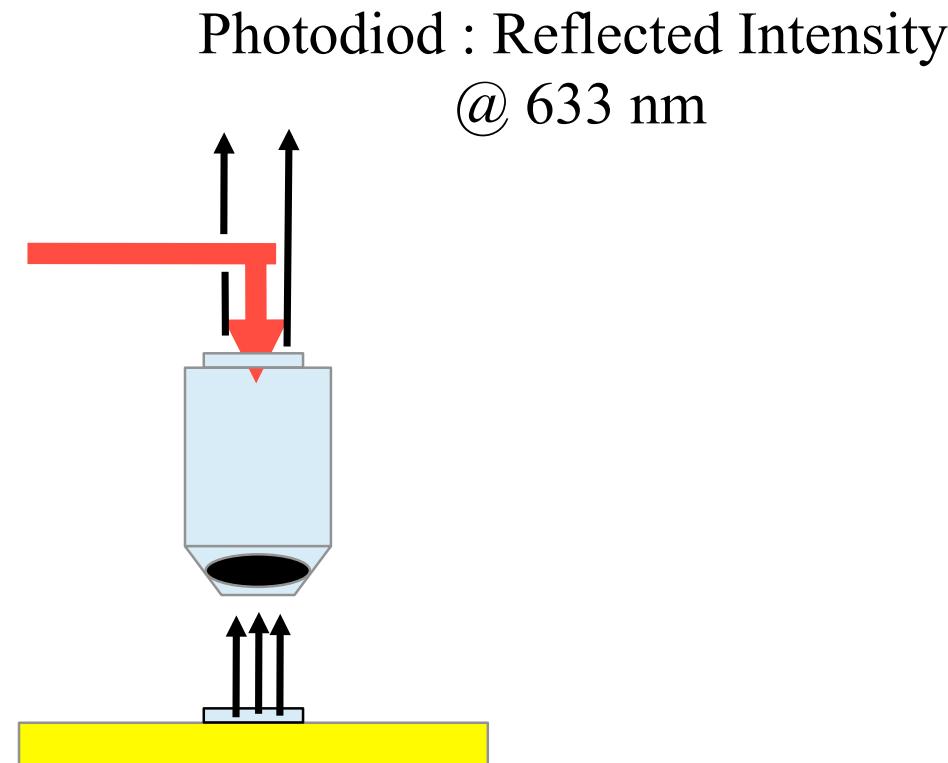


Cartography of the sample luminescence (XY-map)
From room temperature to 4 K

The experimental setup:

Reflectivity

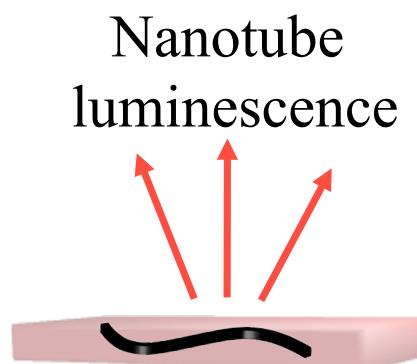
Excitation laser
@ 633 nm



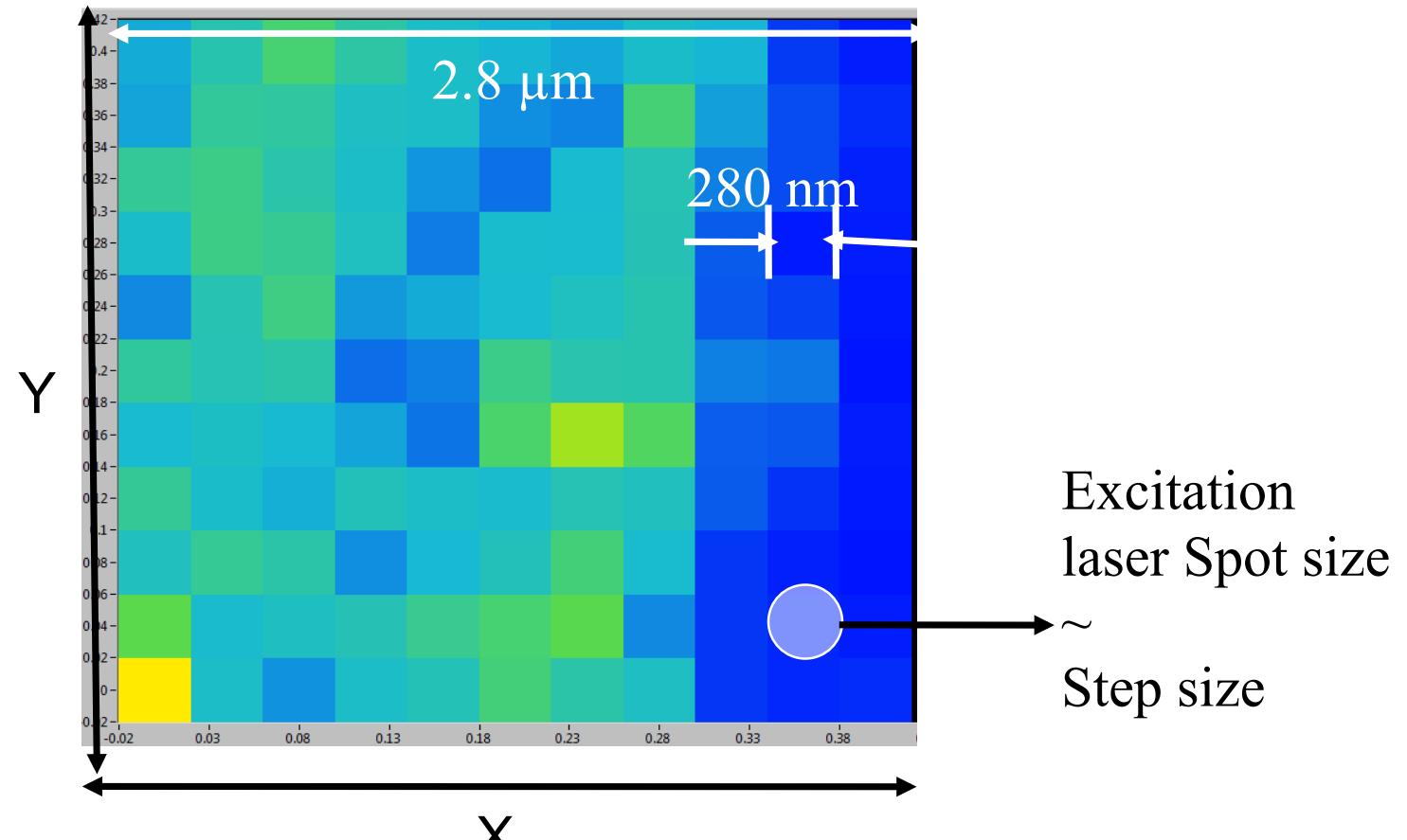
Photodiod : Reflected Intensity
@ 633 nm

Cartography of reflectivity of the sample surface (XY-map)

Map of the sample luminescence



XY-Map of the Total Intensity – **Without particles**



Color scale :

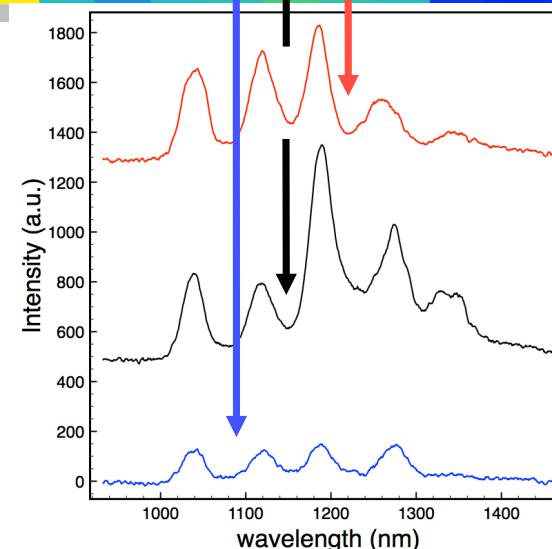
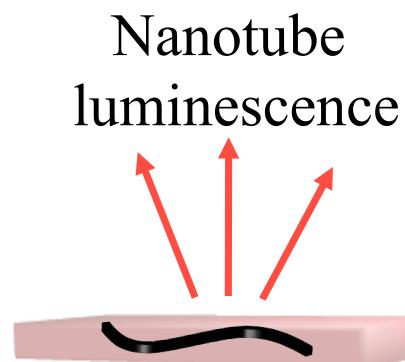
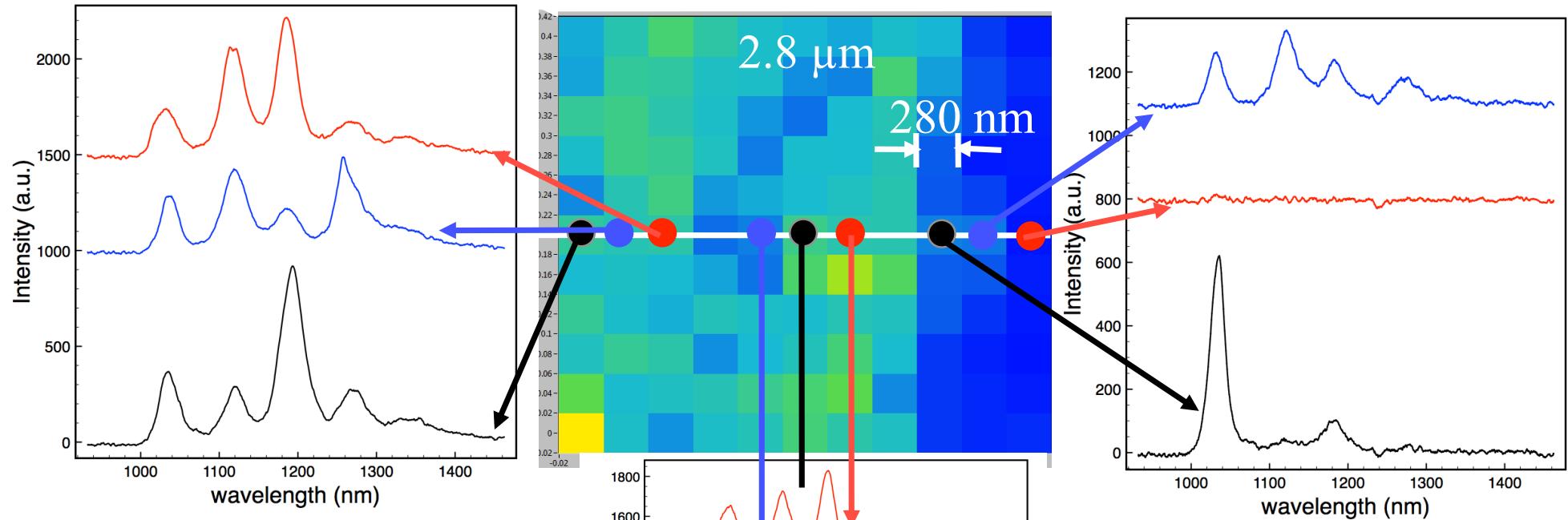
blue → low intensity

orange → moderate intensity

red → high intensity

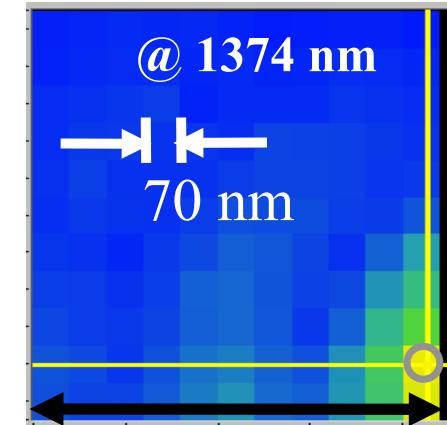
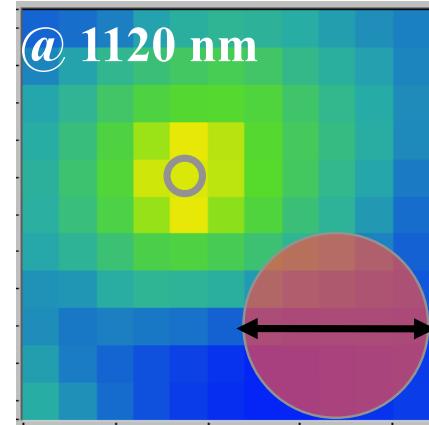
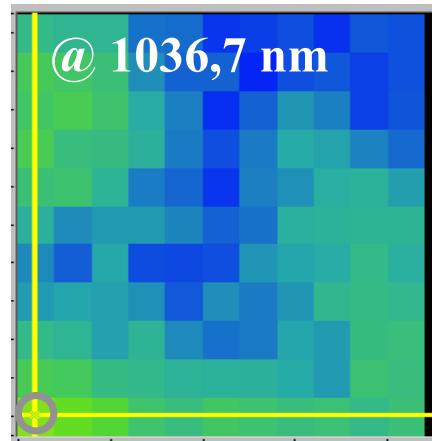
Map of the sample luminescence

XY-Map of the Total Intensity Without particles s



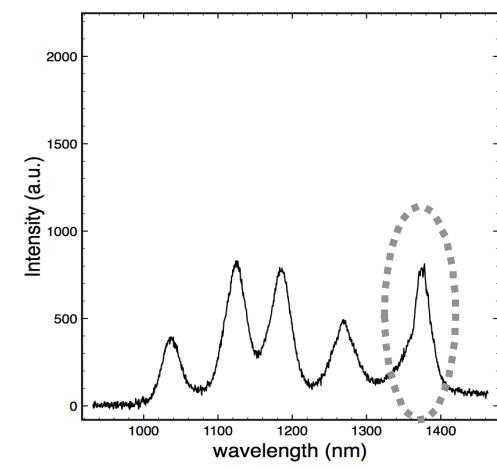
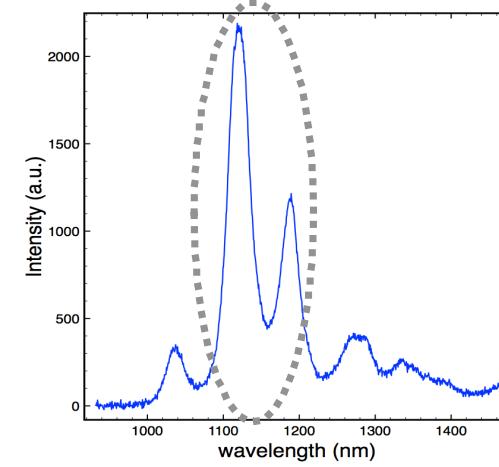
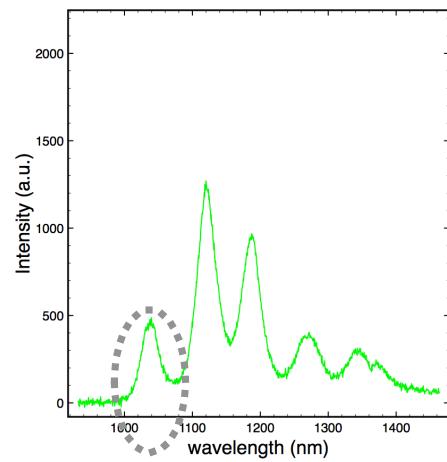
Spectral shape
modification
on the scale $\sim 500 \text{ nm}$

Cartography of the sample : finer scale



Excitation laser Spot size

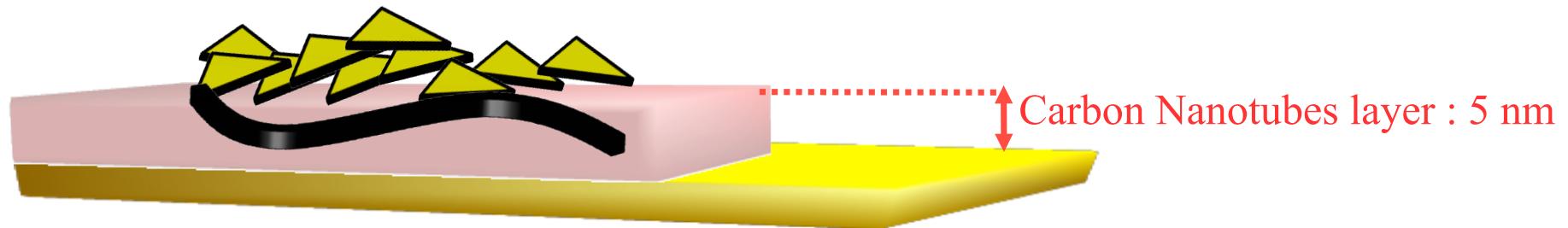
700 nm



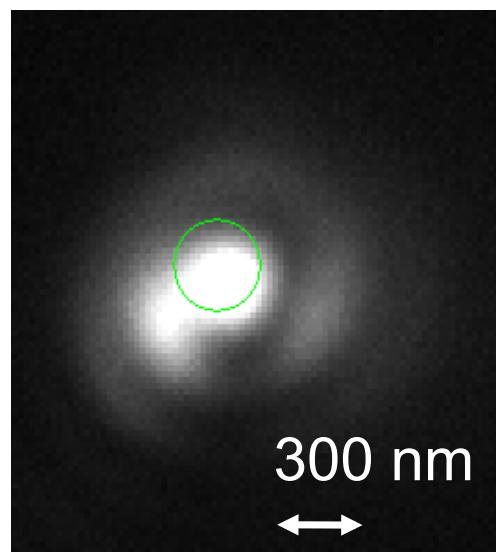
Inhomogeneity characteristic scale ~ 500 nm

emmanuel.rousseau@umontpellier.fr

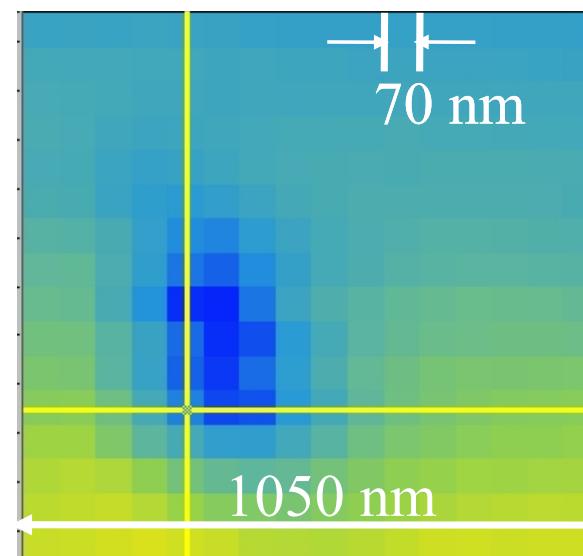
CNT coupled with nanoparticles



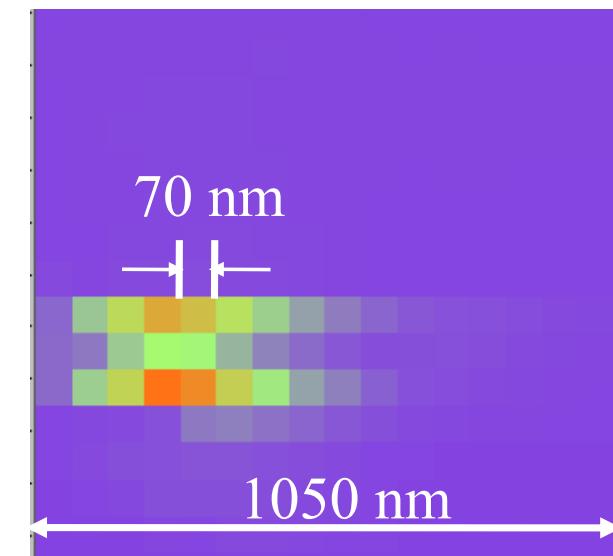
Visualization



reflectivity

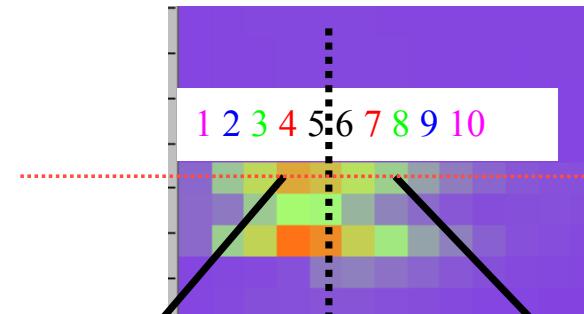
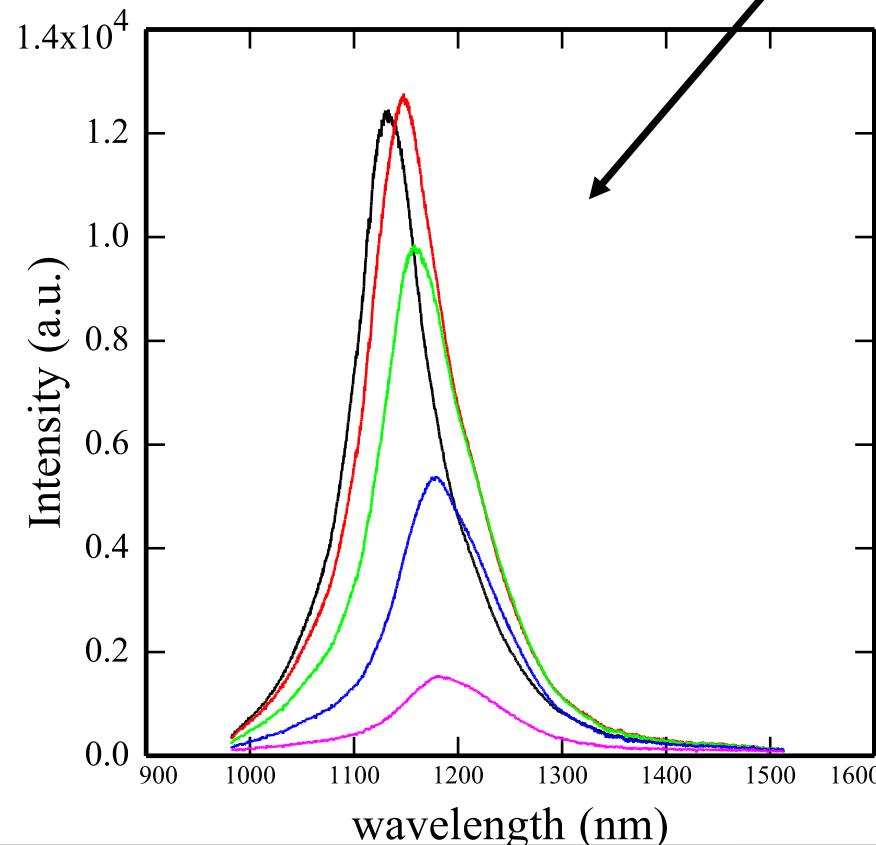


Luminescence



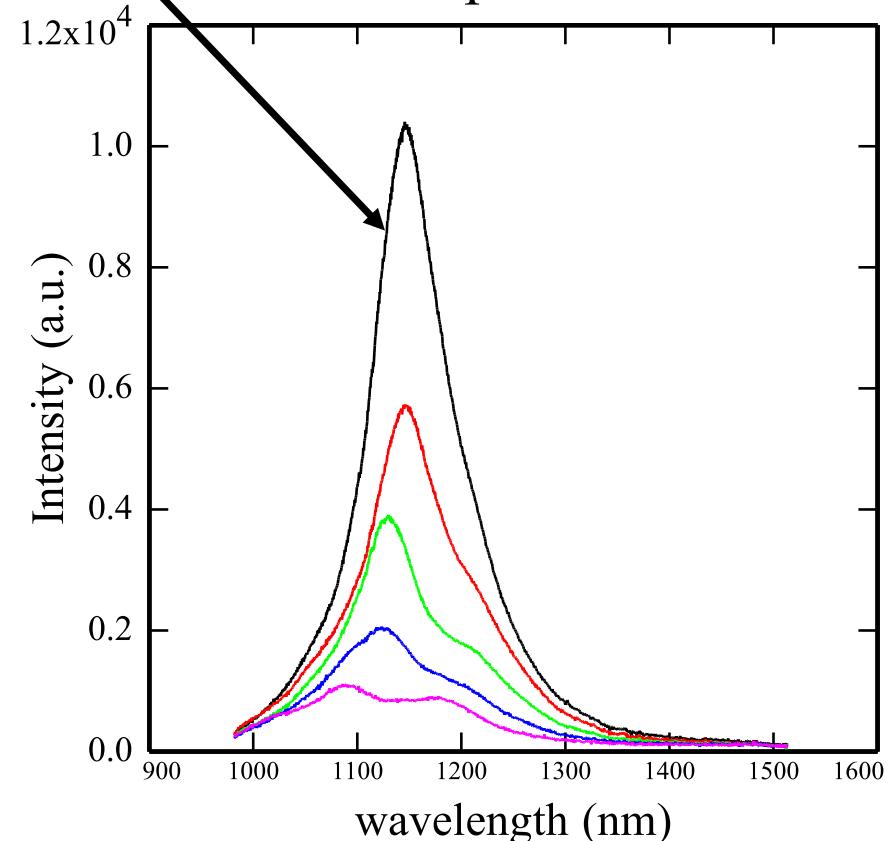
Luminescence enhancement

Spectra evolution
along red line

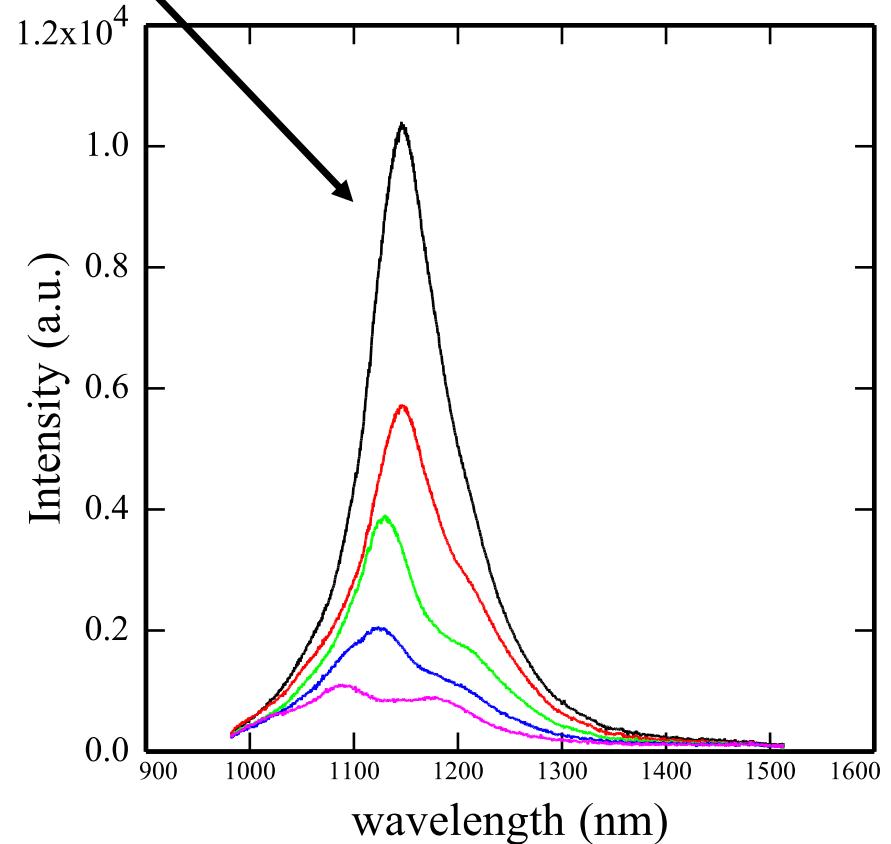
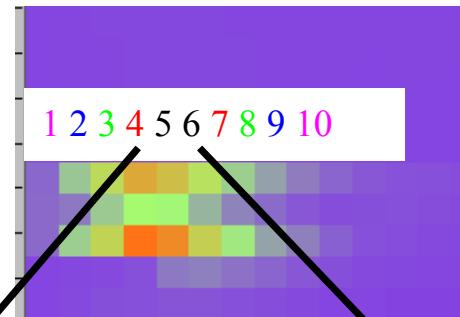
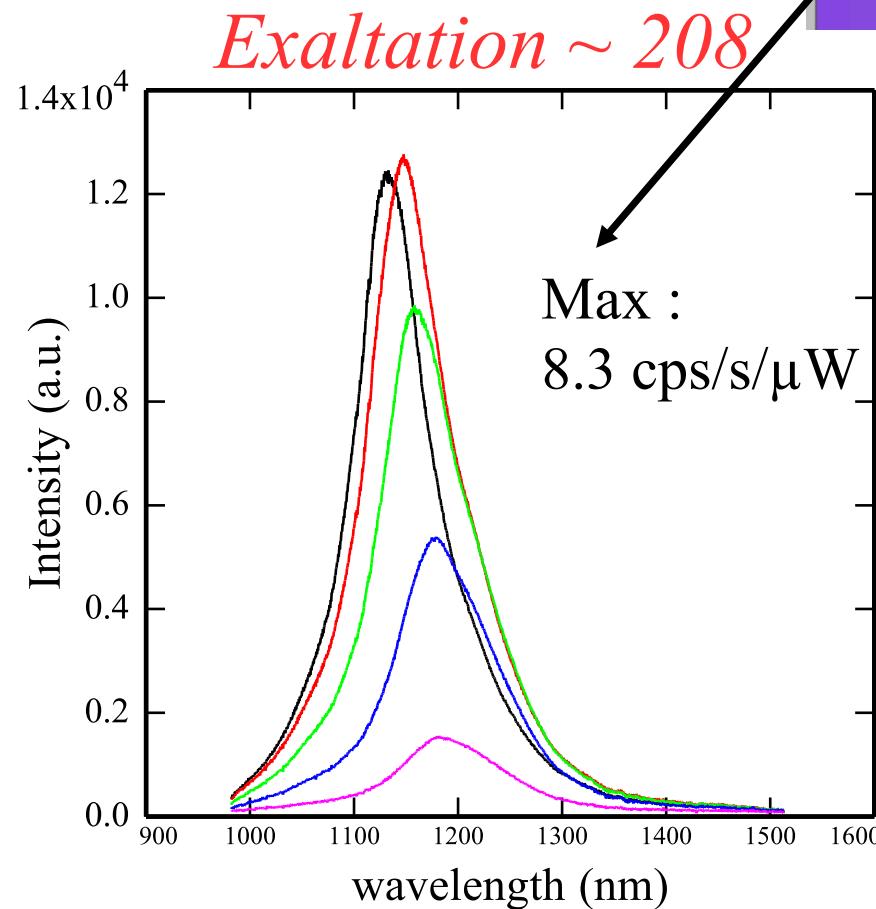


Intensity variation
on 50's nm scale

Coupling with
nanoparticles



Luminescence enhancement



Conclusion

-Strategy

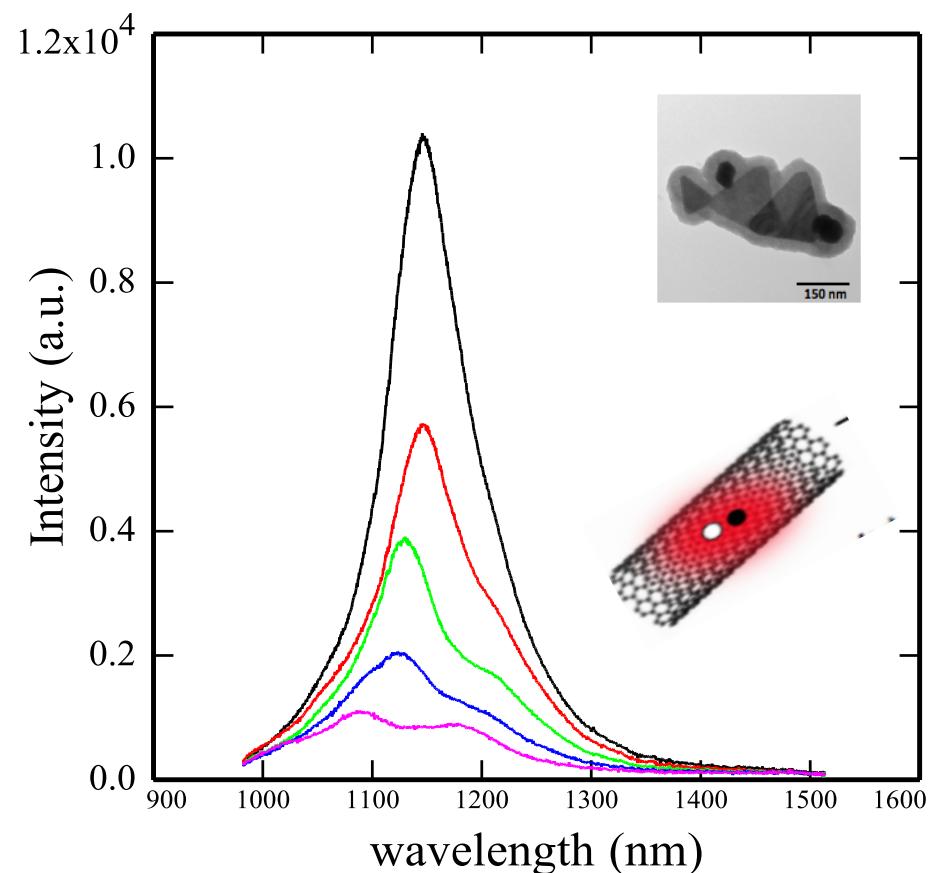
Random antennas/ Random CNT

Improve CNT/antenna dipole matching

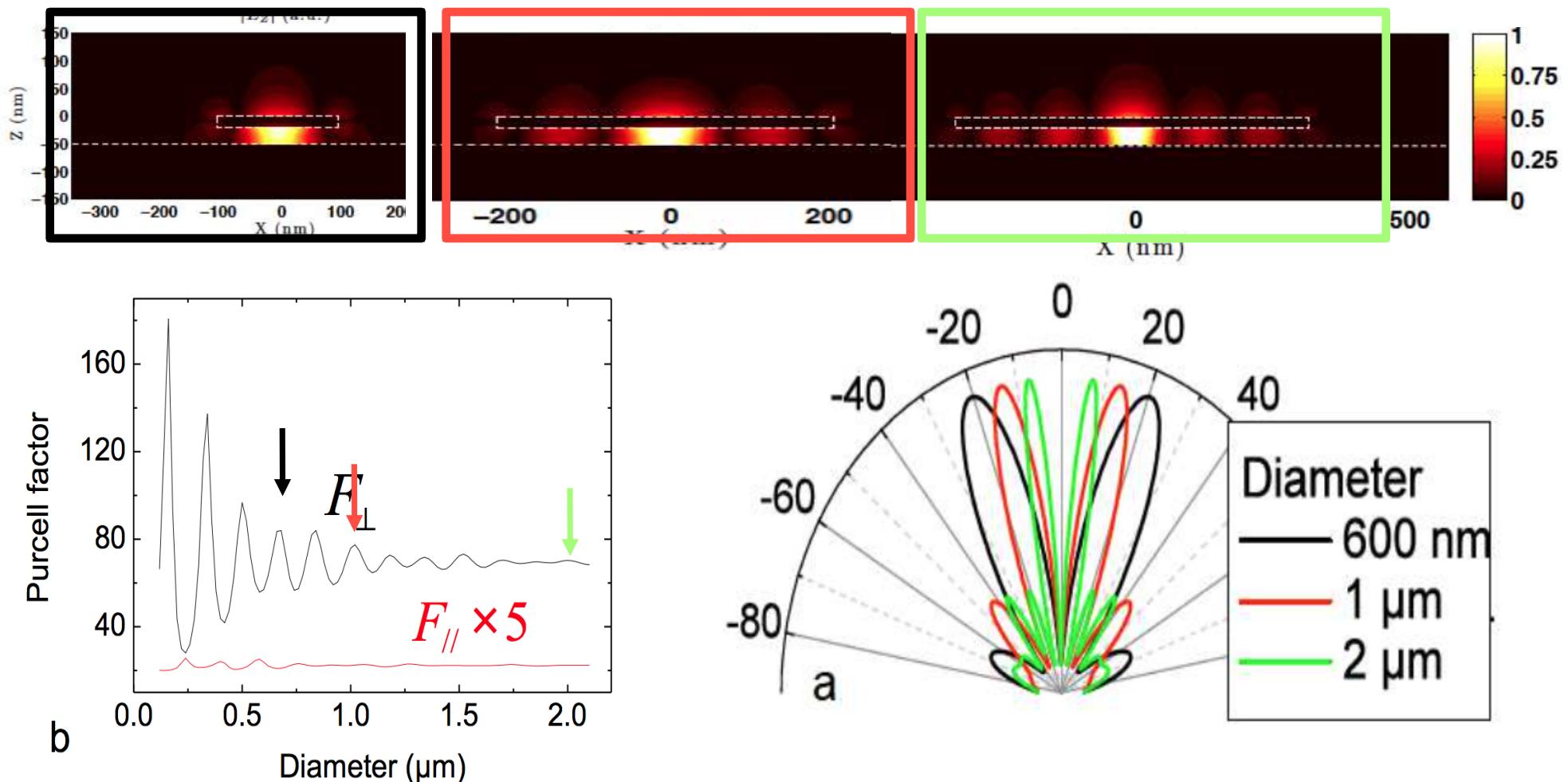
⇒ Radiative enhancement ~ 200

⇒ Usually ~ 50

⇒ length scale ~ 50 nm



The patch antenna: radiation pattern



Large antennas = better directivity

Scattering cross-section

