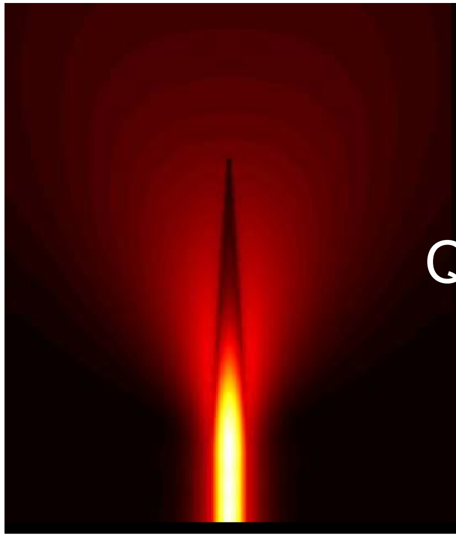


Quantum optics with quantum dots in photonic wires :

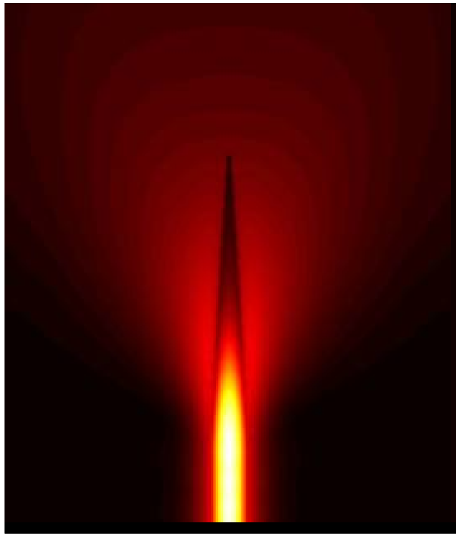
basics and application to ultrabright single-photon sources

Jean-Michel GERARD

Équipe mixte CEA-CNRS Nanophysique et Semiconducteurs

Grenoble

INSTITUT NANOSCIENCES ET CRYOGÉNIE



Quantum optics with quantum dots in photonic wires :

basics and application to ultrabright single-photon sources

J. Claudon, J. Bleuse
N.S. Malik, M. Munsch, E. Dupuy
MBE growth, microfabrication and optics

Nanophysics and Semiconductors
CEA-CNRS joint group
Grenoble, France

P. Lalanne
Modelling

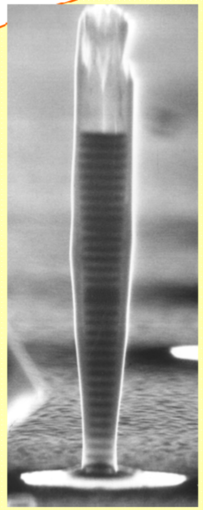
Institut d'Optique
Palaiseau, France

N. Gregersen
Modelling

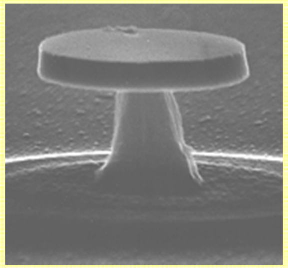
DTU Fotonik
Copenhaguen,Denmark

Work supported by the ANR CAFÉ and WIFO projects

SpE control : an important concept for optoelectronics… since the 80's !

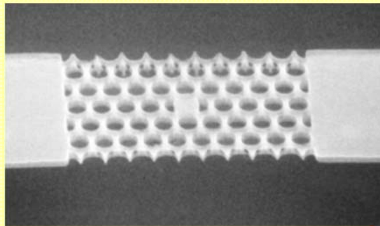


Optical microcavities
1982



Spontaneous emission control

Photonic crystals
1987

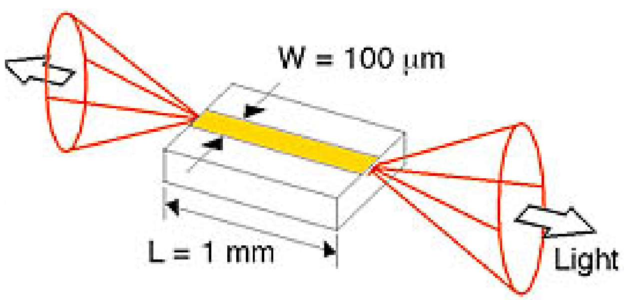


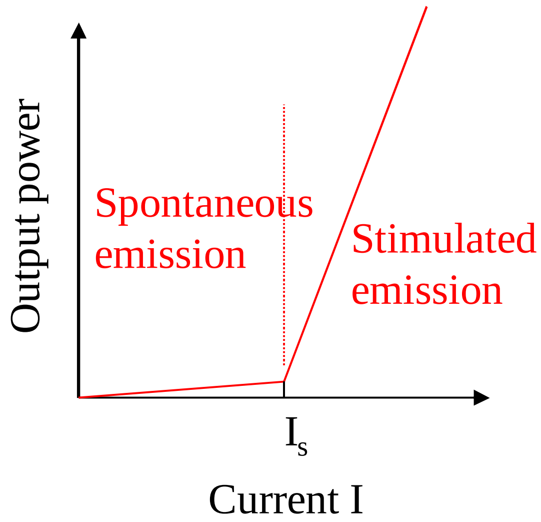
SpE is a key phenomena for LEDs and lasers

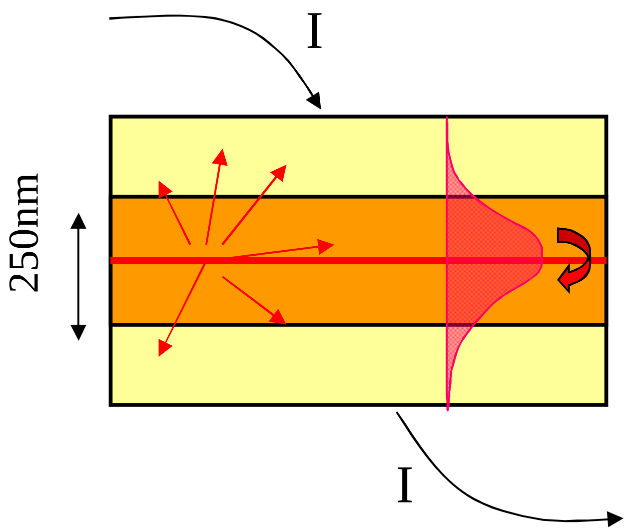
Novel devices based on controled SpE, e.g. single-photon sources

Spontaneous emission control in lasers: why? (as of ~1985)

laser diode







Only a tiny fraction of spontaneous emission is useful!
$\beta \sim 10^{-5}$

100000 times decrease of I_s expected for $\beta \sim 1$!

A novel device based on SpE control : the single photon source

Source able to emit single photons pulses on demand

Non-classical state of light

Applications : quantum cryptography
metrology (energy standard)
optical quantum computing

For most applications, the single photons must be prepared in the same quantum state !!

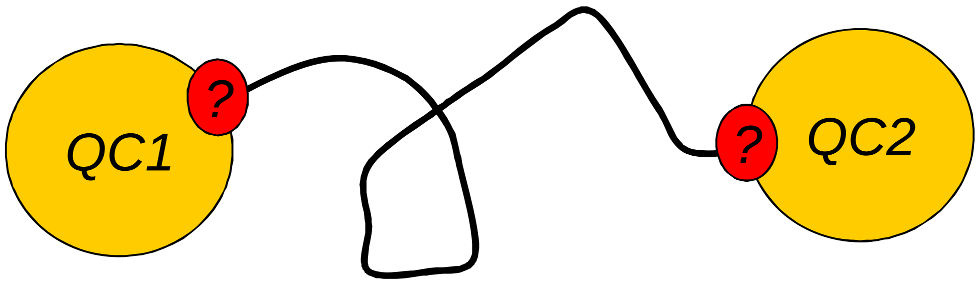
Single mode spontaneous emission wanted !!

SpE control for QIP (2)

Di Vicenzo's two « additionnal » criteria

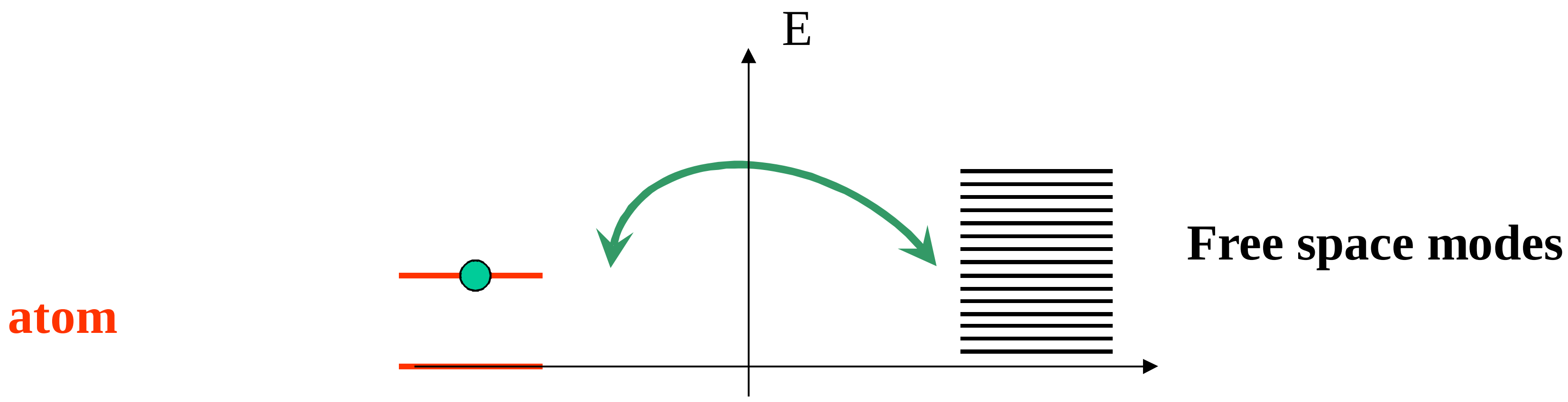
6. The ability to interconvert stationary and flying qubits

7. The ability faithfully to transmit flying qubits between specified locations



Optical fiber

SpE control is not a dream !



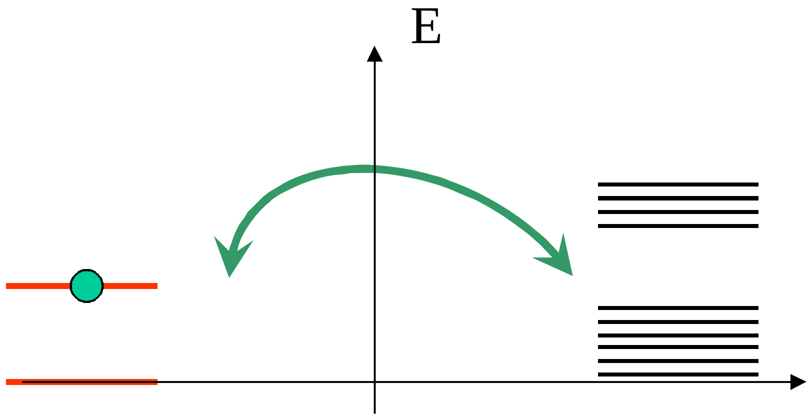
Fermi's Golden Rule : exponential decay

$$1/\tau \propto \text{density of modes per unit volume}$$

One can tailor the spontaneous emission dynamics !

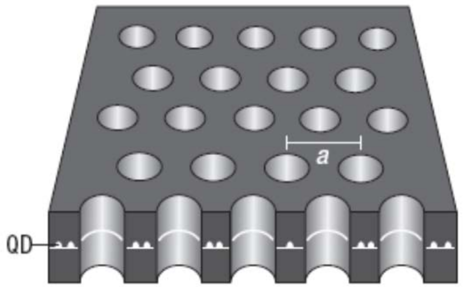
SpE tailoring (1)

atom



« less modes »:

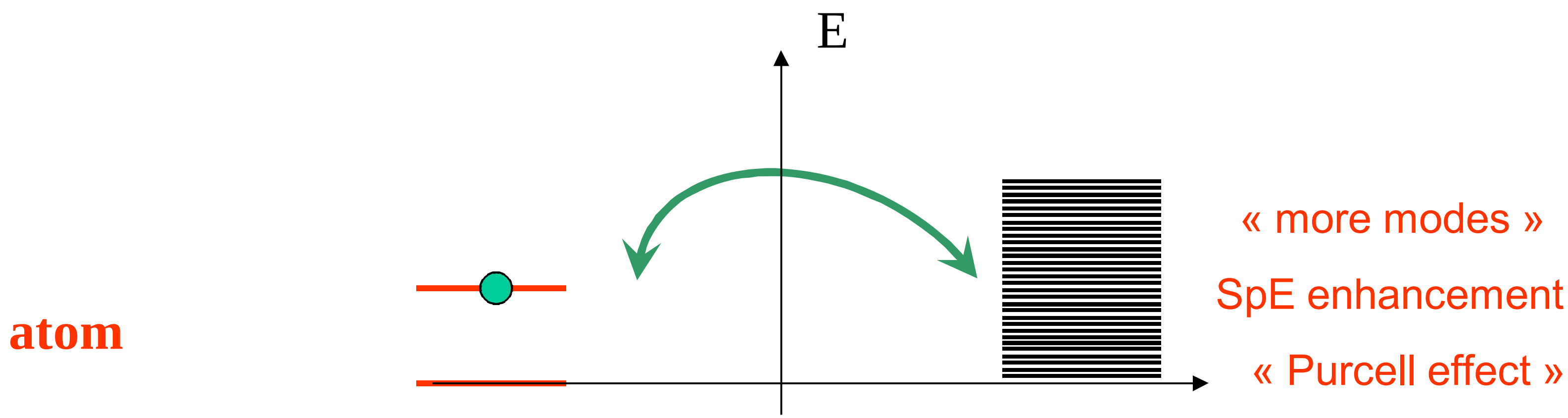
SpE inhibition

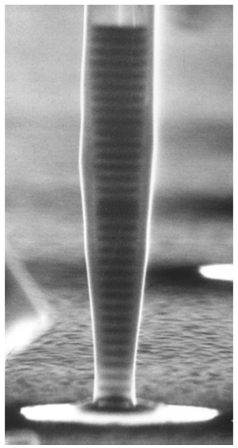


Photonic crystals

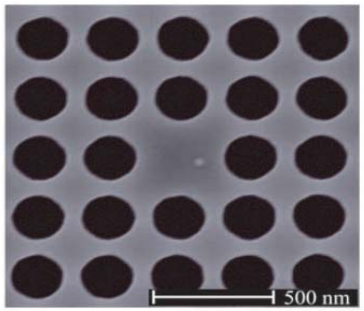
Yablonovitch 1987

SpE Tailoring (2)

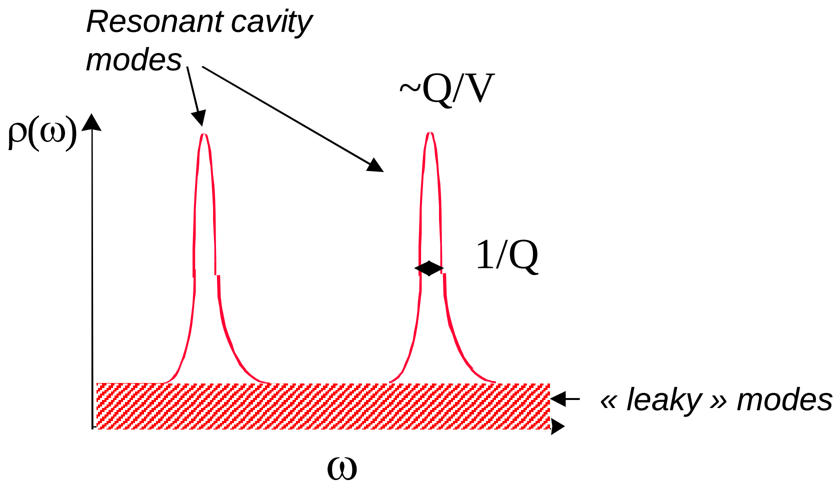




Micropillar cavity

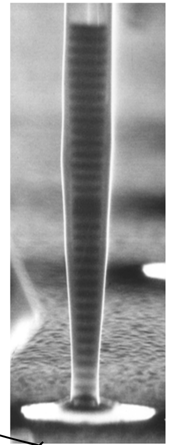


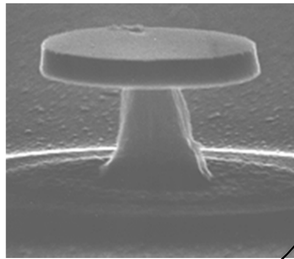
photonic crystal cavity



Quantum dots : artificial atoms for CQED

optical microcavities (90->...)

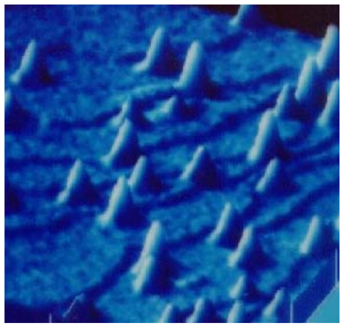


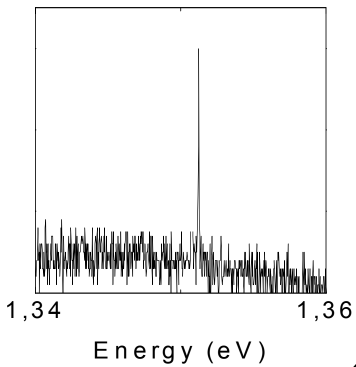


CQED (80->...)

SE can actually be tailored to a large extent for <u>atoms</u> in electromagnetic cavities

self-assembled QDs





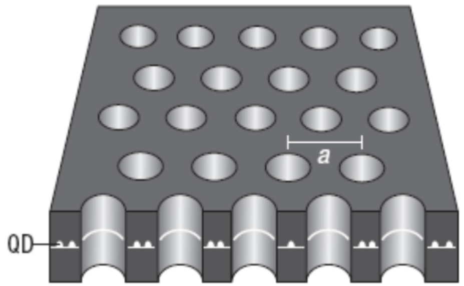
JY Marzin, JMG et al, PRL 94

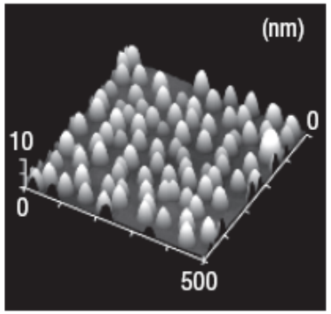
Quantum optics with QDs

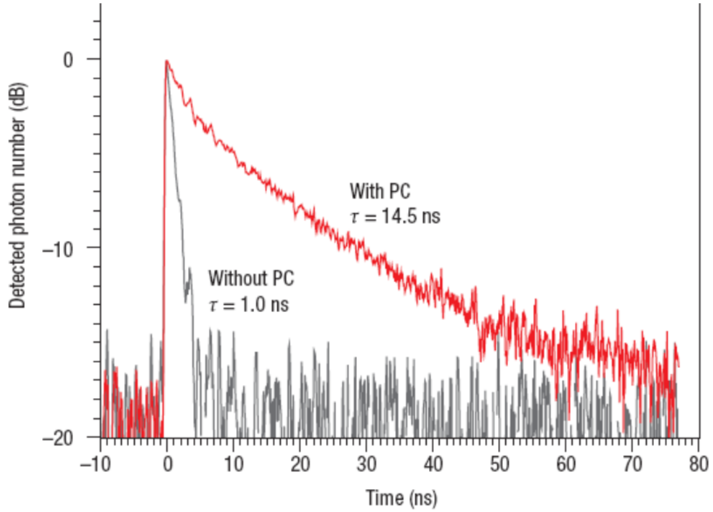
J.M. Gérard et al
(France Telecom R&D)
APL 96, PRL 98

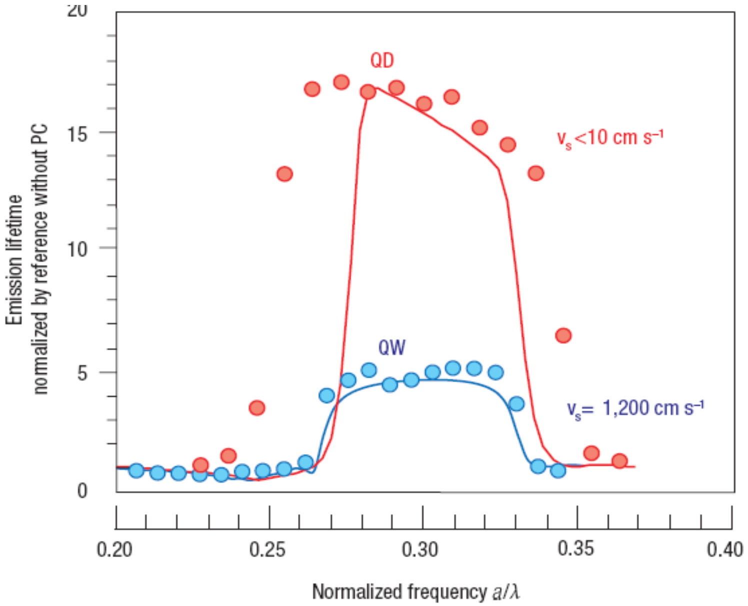
QD SpE inhibition in photonic crystals

From S. Noda et al, Nature Photon. 1, 449, 2007









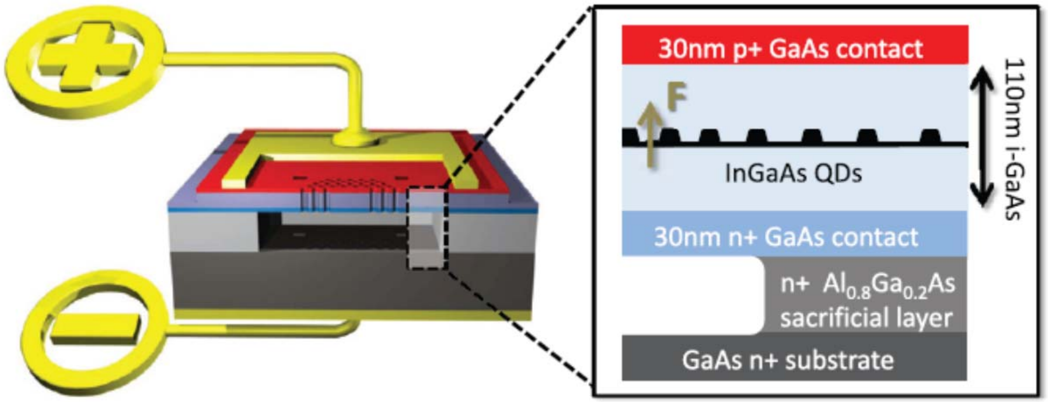
. Strong inhibition (/15) of QD SE in a photonic crystal membrane

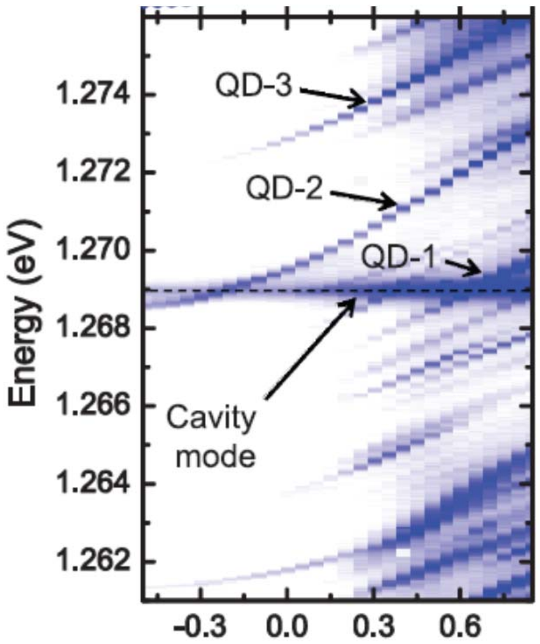
. Effect less visible on quantum wells, due to the lifetime shortening induced by surface recombination

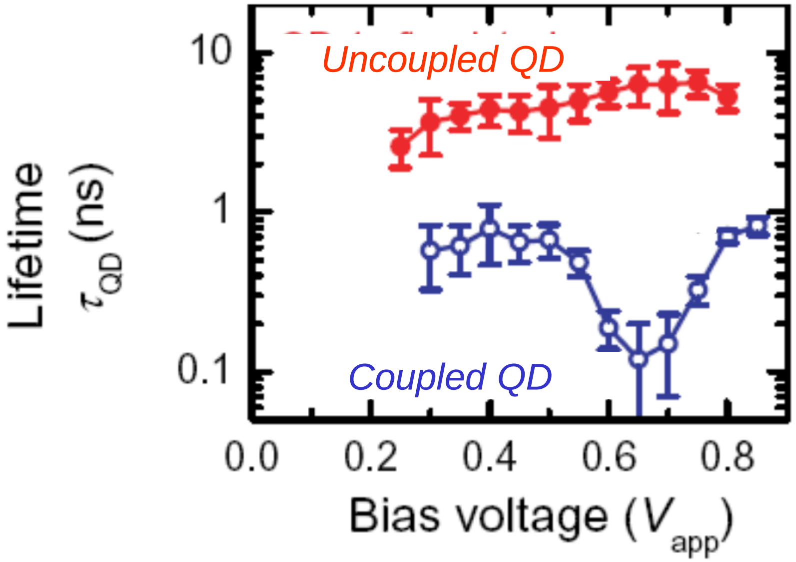
Purcell effect for a single QD in an electrically tunable QD-cavity system

A Laucht et al (WSI),

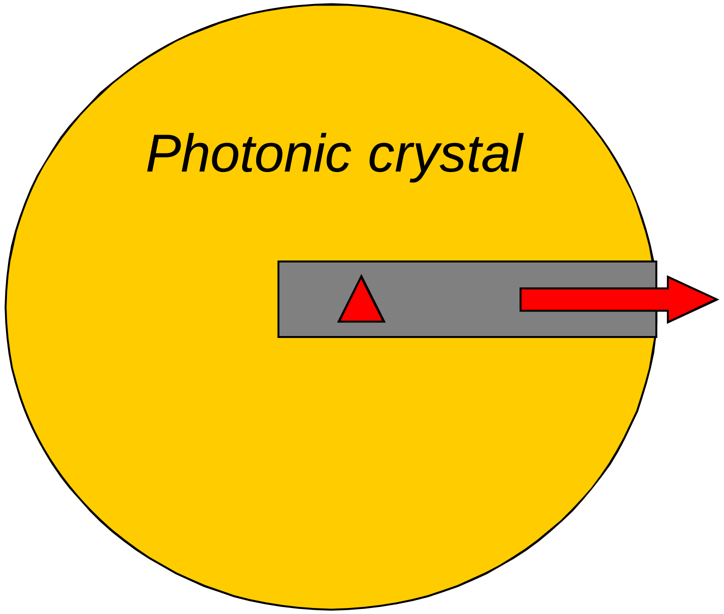
New J Phys, 11 23034 (2009)



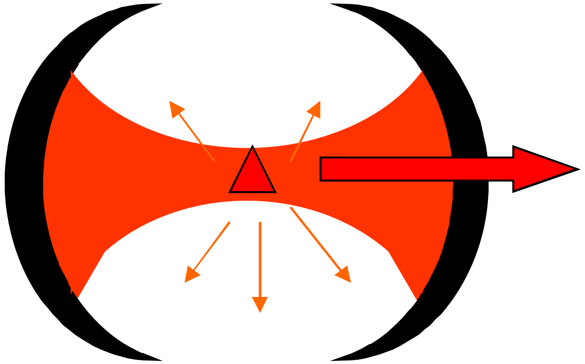




Two avenues toward single-mode SpE

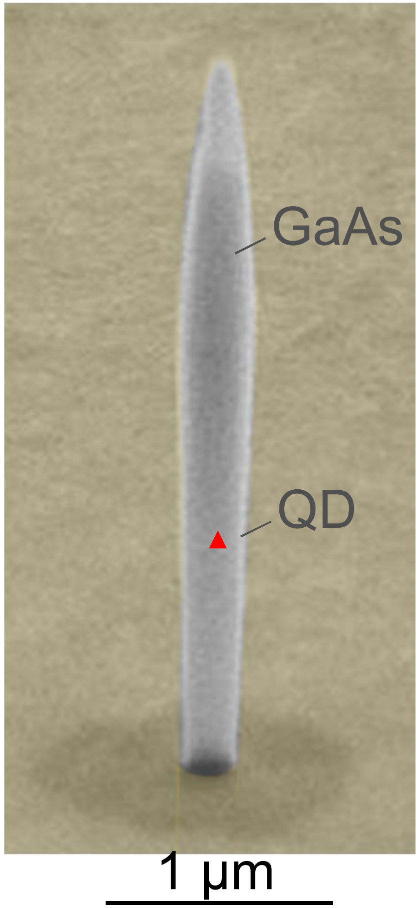


Inhibition of SpE into all useless modes
(proposal E. Yablonovitch ~1990)



Selective enhancement of SpE into a single resonant cavity mode (Purcell effect)

JM Gérard et al, PRL 1998



The dielectric photonic wire :

a very simple photonic microstructure

providing nearly perfect SpE control

=> « novel » template for solid-state CQED

Photonic wires : a novel template for solid-state CQED

Basics of photonic wires

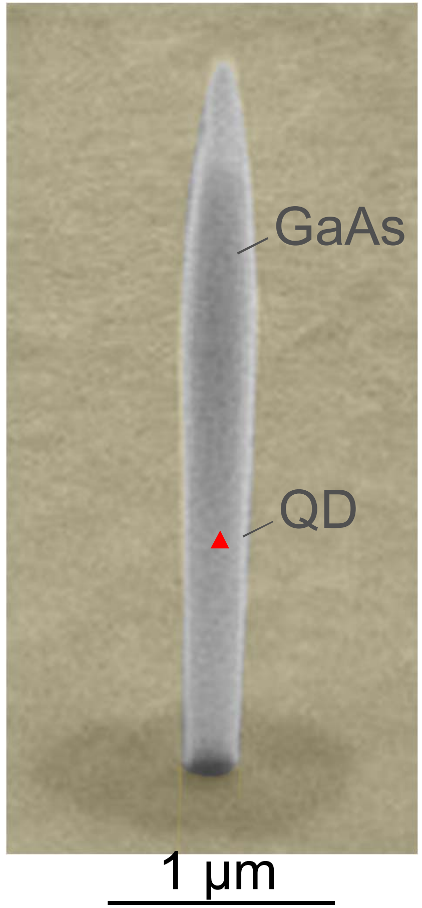
Controling QD SpE with photonic wires

A first practical application :

an « ultrabright » QD single photon source

Perspectives

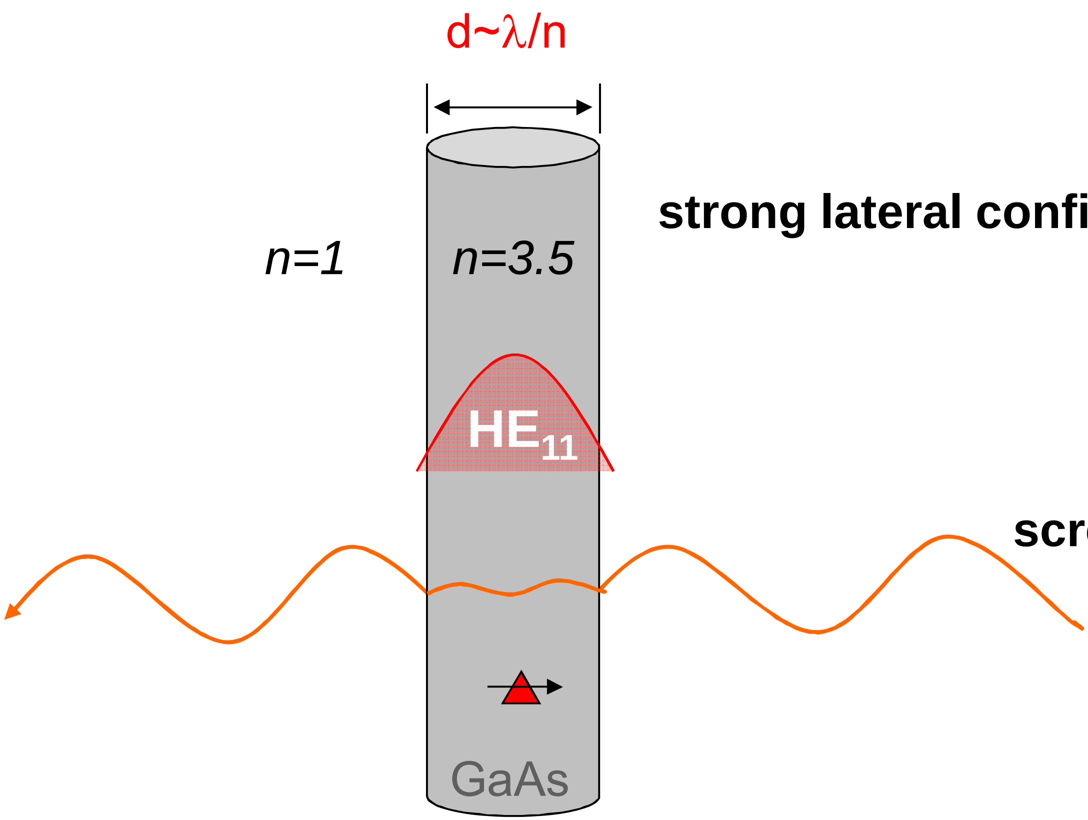
novel opportunities opened by PWs



What is a photonic wire?

First introduced by S.T. Ho et al, see PRL 1995

Single mode optical waveguide with a high refractive index



strong lateral confinement of the guided mode

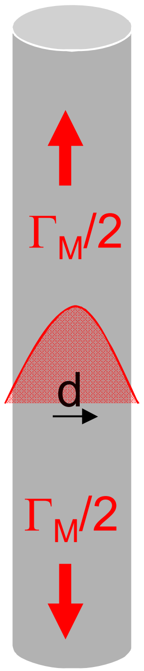
screening of the other modes

=> Highly preferential coupling of QD SpE into the guided mode !

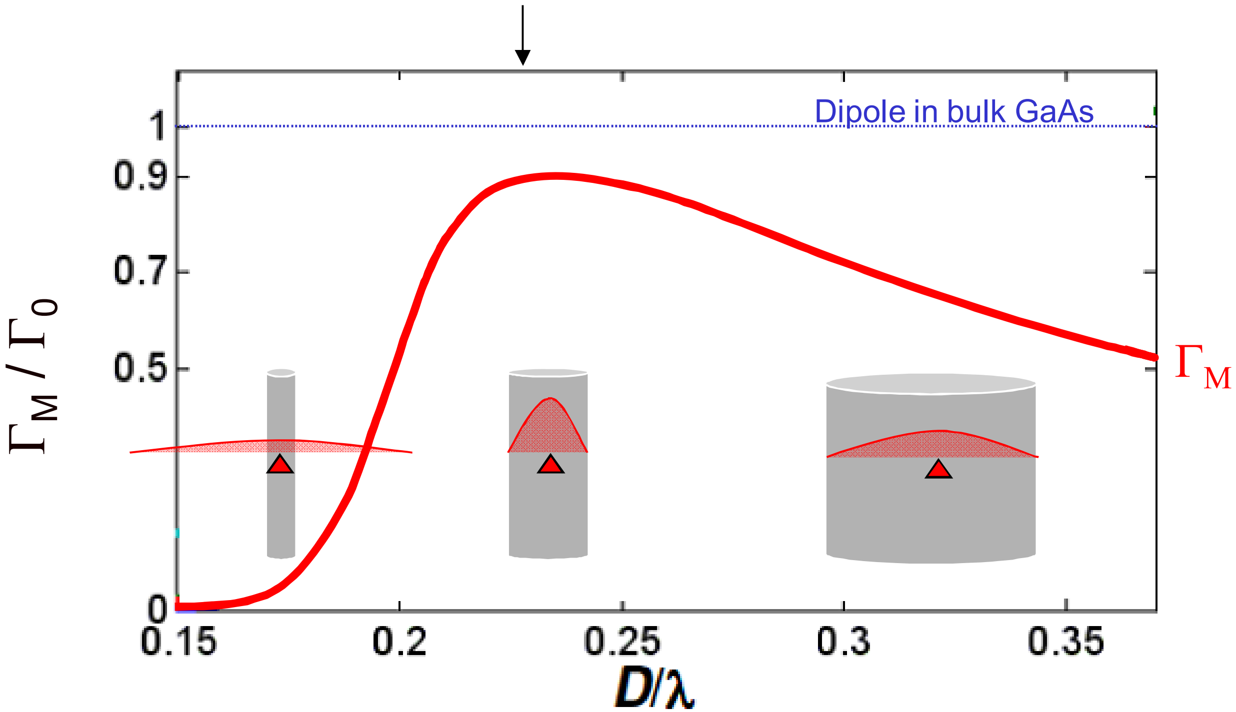
Coupling to the fundamental guided mode

$$\bar{\Gamma}_m = 2 \times \frac{3}{8\pi} \frac{(\lambda/n)^2}{S_{eff}} \frac{n_g}{n}.$$

λ_e = 1 µm
emitter on axis
in-plane dipole



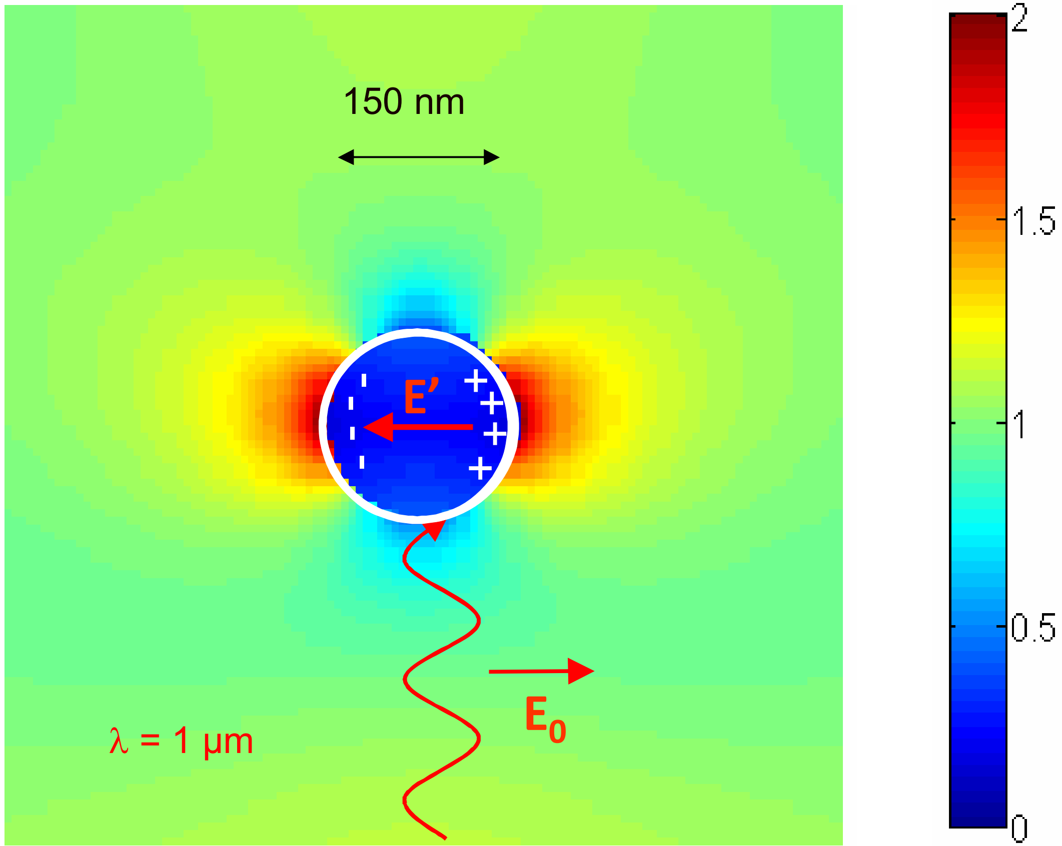
optimum confinement
of the guided mode



I. Friedler et al., Opt. Express **17**, 2095 (2009).

Dielectric screening : simulation

Top view



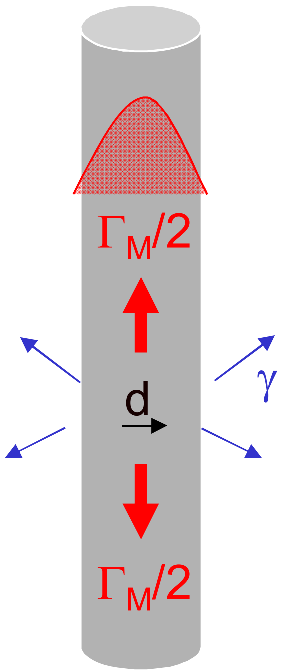
$d \ll \lambda$

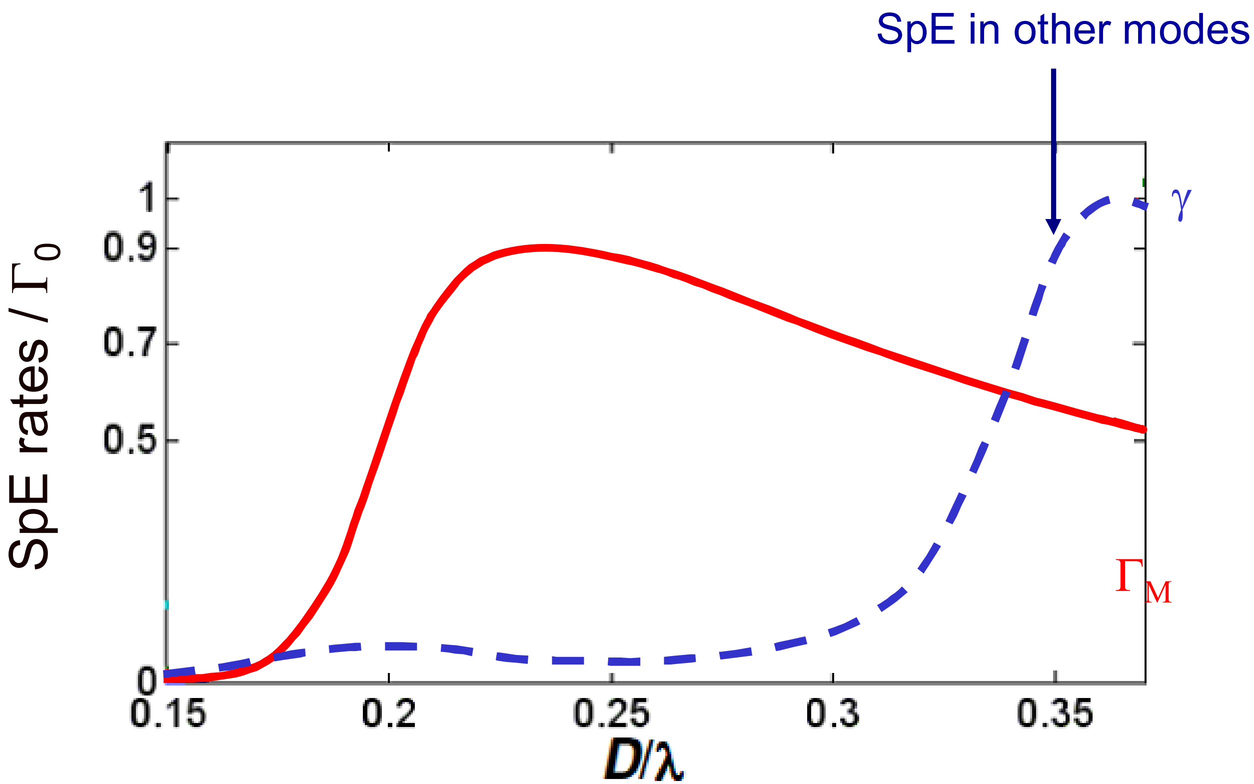
$$\frac{|\vec{E}_{tot}|}{|\vec{E}_o|} = \frac{2}{n^2+1}$$

Strong screening of the incident field
when the polarisation is ⊥ to the wire axis

SpE control in an infinite photonic wire (1)

I. Friedler et al., Opt. Express **17**, 2095 (2009).



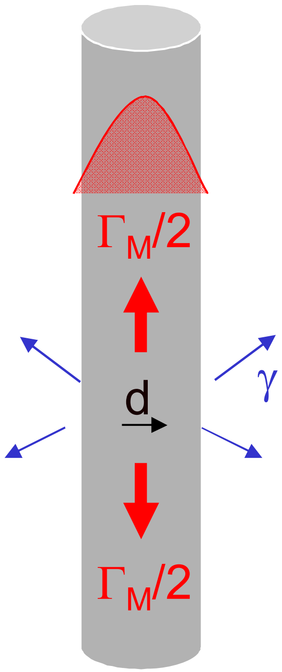


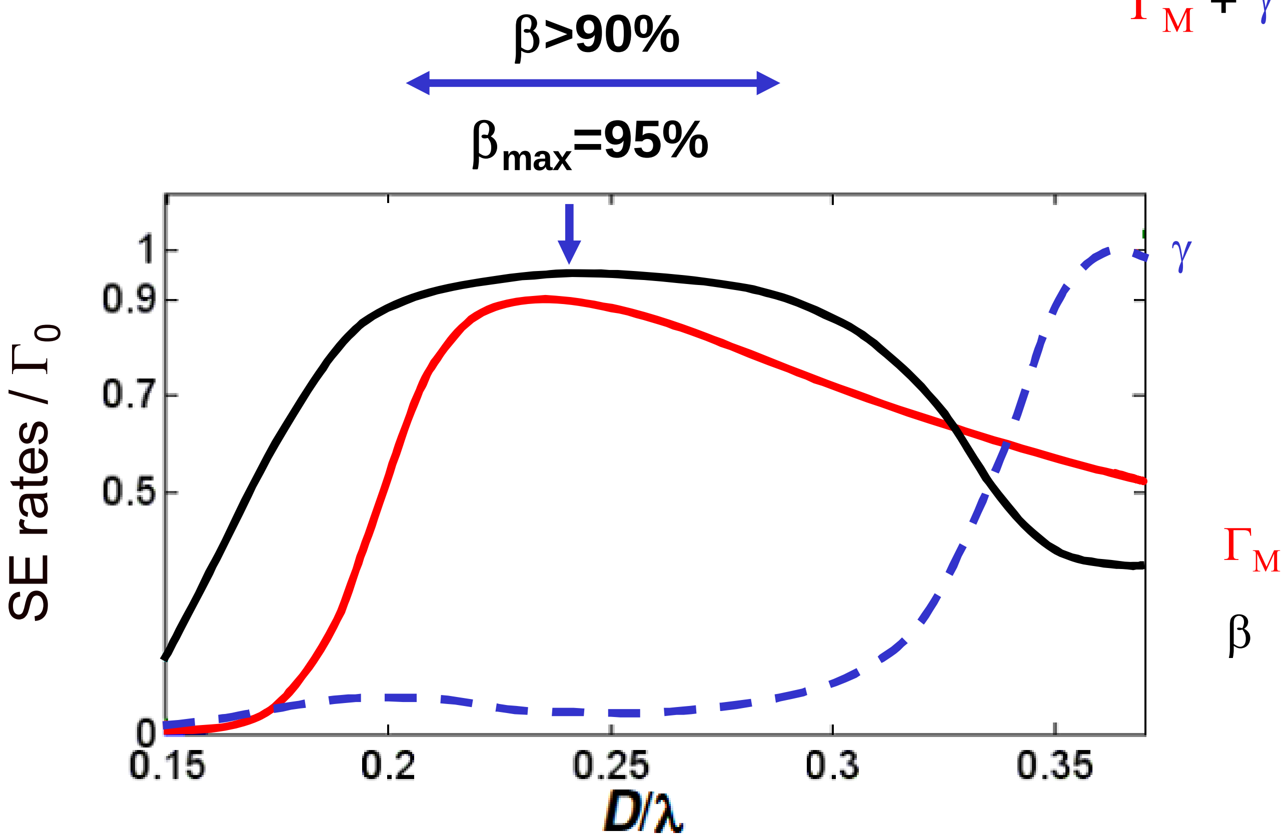
Strong SpE inhibition for small diameter PWs ($d/\lambda < 0.17$)

SpE in the guided mode predominant for $0.2<d/\lambda<0.3$

SpE control in an infinite photonic wire (2)

$$\beta = \frac{\Gamma_M}{\Gamma_M + \gamma}$$

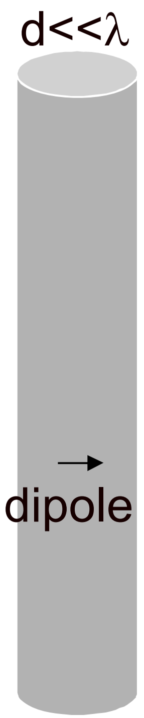


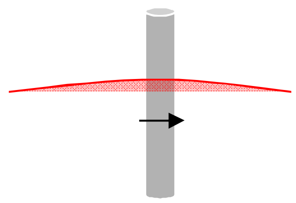


Efficient and broadband SE control

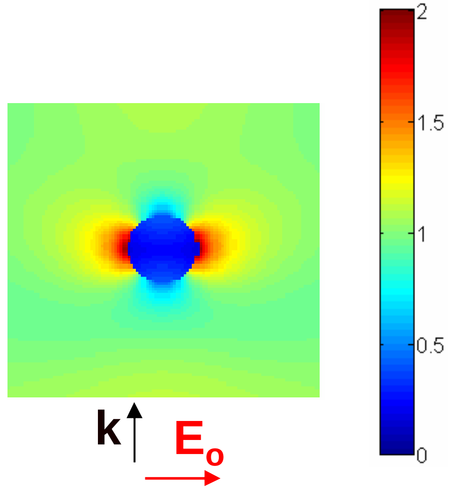
Small diameter ($0.2 < d/\lambda < 0.28$), close to the single mode cut-off

SE inhibition in ultrathin dielectric wires (d/λ < 0.15)





1) *Deconfined guided mode*



2) *Screening of non-guided modes (in plane polar.)*

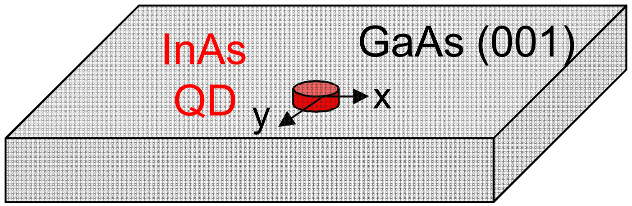
$$\frac{\gamma}{\gamma_0} = \frac{1}{n}\left(\frac{2}{n^2+1}\right)^2$$ ~ *1/150 !!*

Katsenelenbaum 1949 !

Ducloy et al, PRA 2004

Maslov et al, JAP 2006

InAs QDs as test emitters in photonic wires

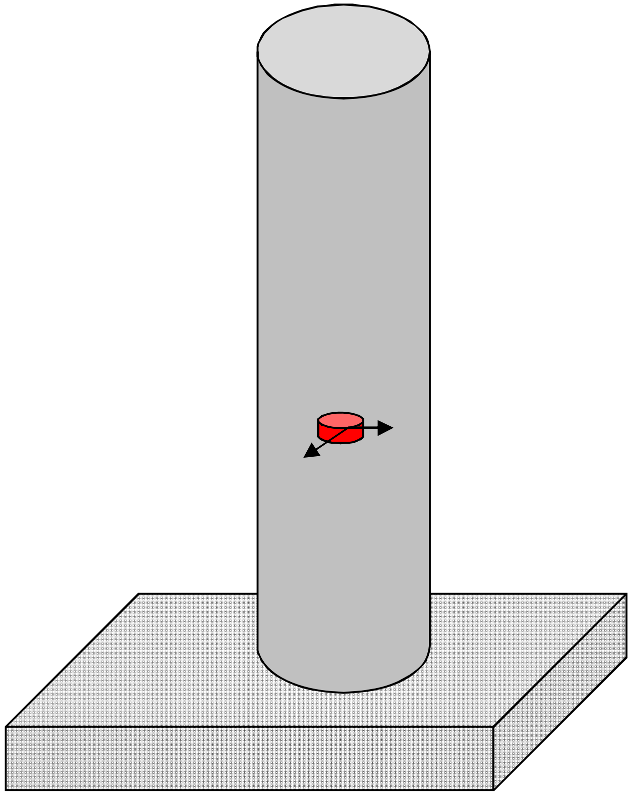


Low energy excitonic complexes have

in plane optical dipoles

Bright X, X-, X+ :   x or y polarized dipole

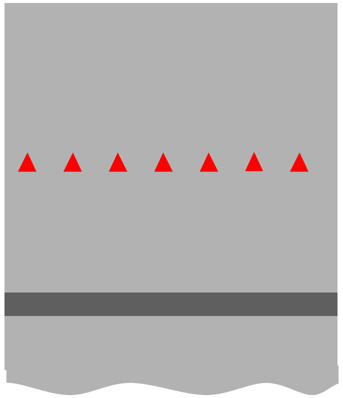
XX : x and y polarized dipoles



=> InAs QDs in vertical PWs

Overview of the fabrication process

1. MBE Growth

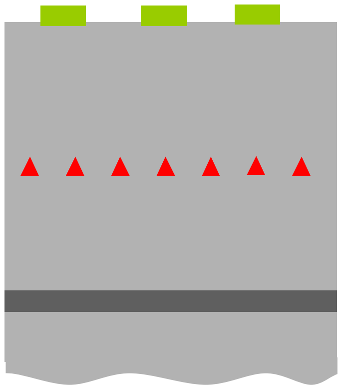


InAs/GaAs QDs

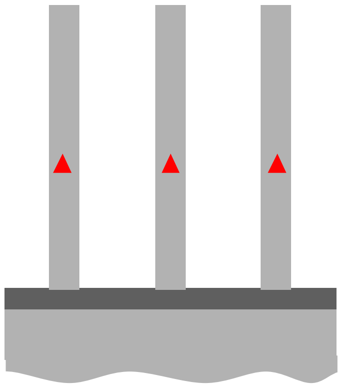
Detection layers for etching

2. **Etching mask definition :**

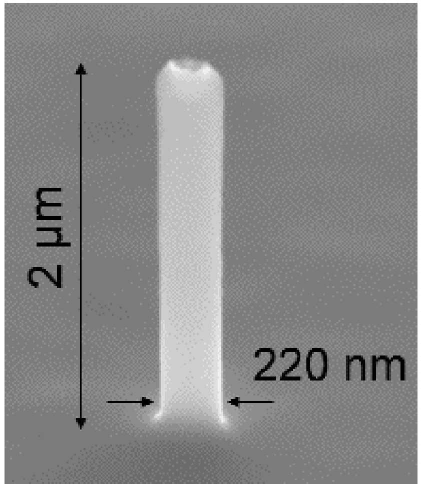
E-beam lithography, Deposition of Ni, lift-off

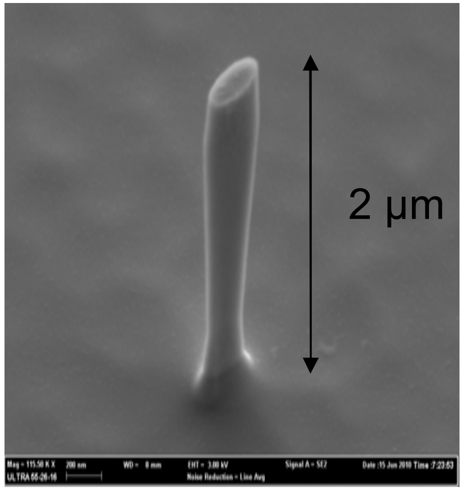


3. **Dry-Etching**

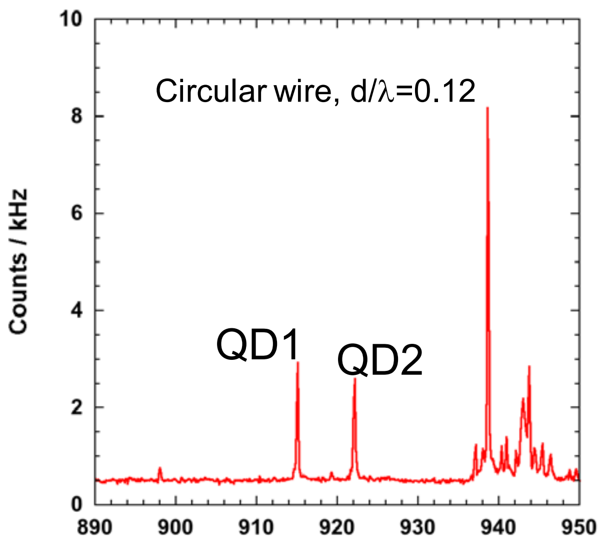


GaAs Photonic Nanowires



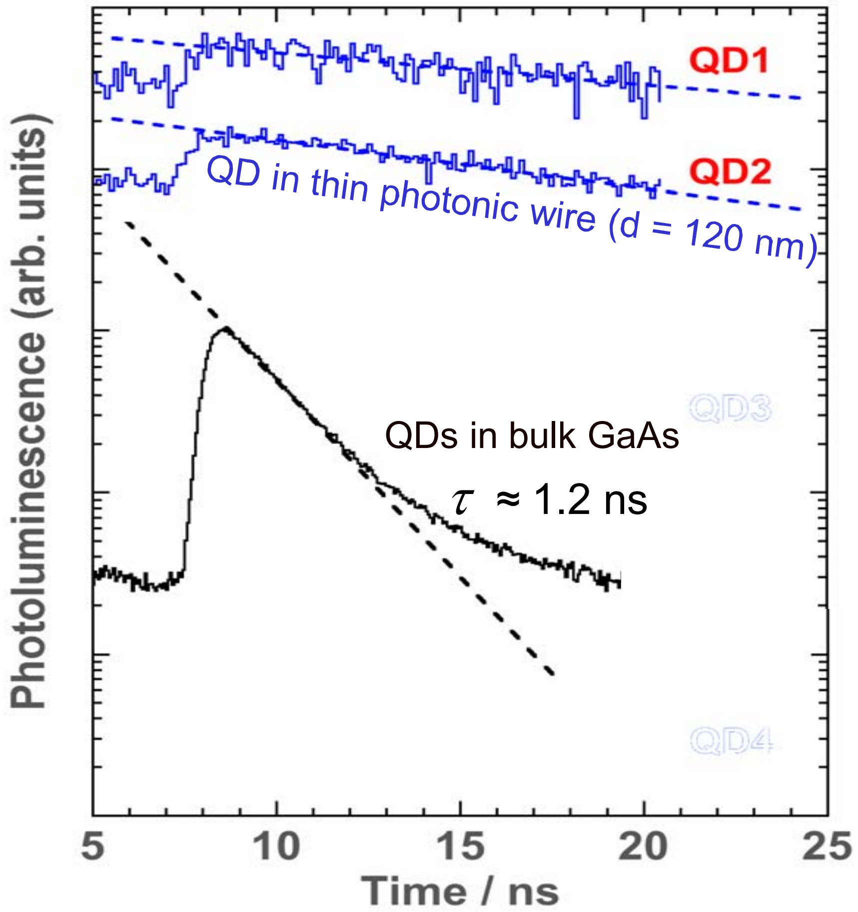


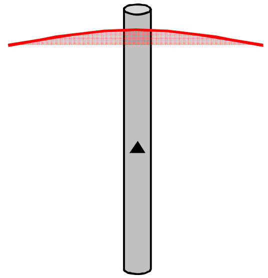
Typical microPL spectrum for few QDs in a photonic wire

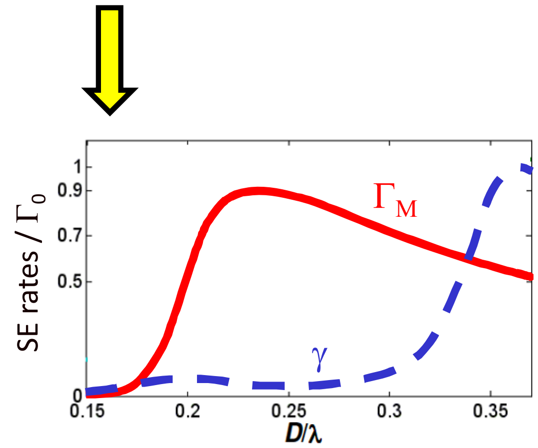


QD properties ?

Time resolved PL for QDs in ultrathin (d<λ/n) PWs







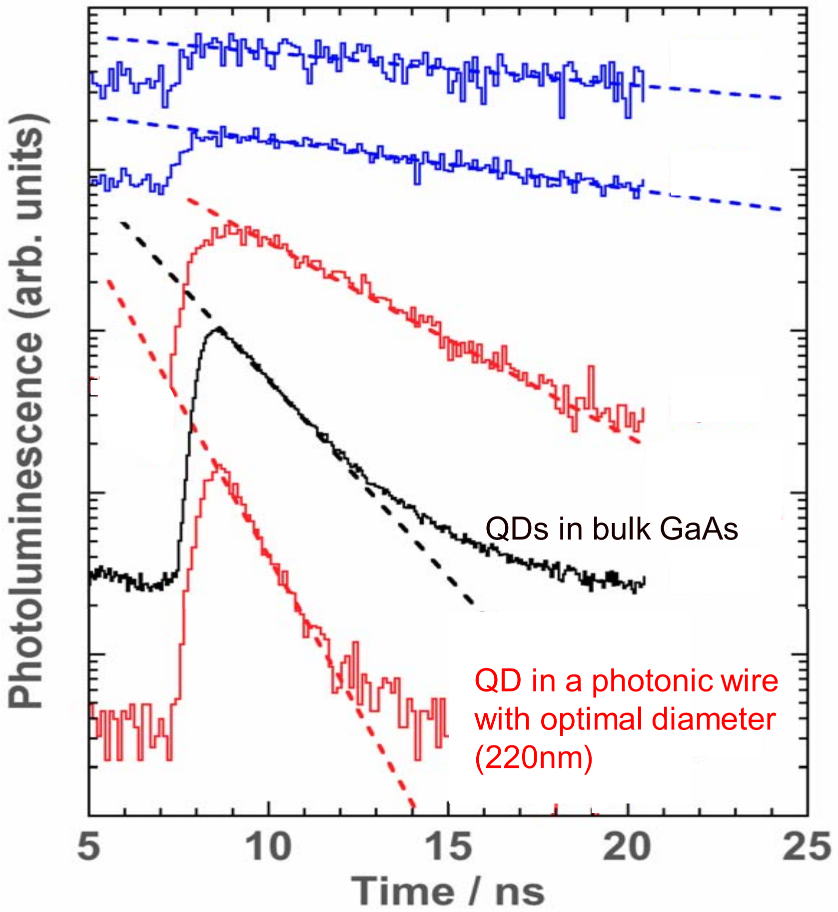
τ ≈ 23 ns for QD1

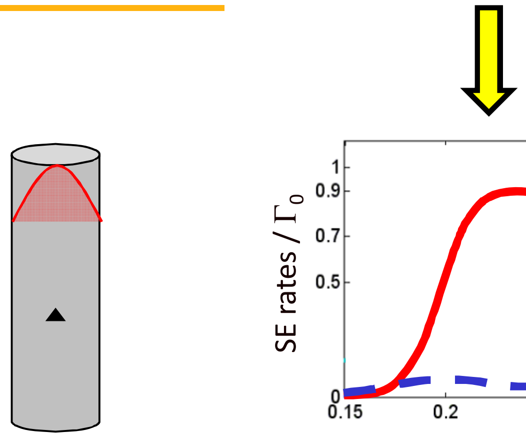
Strong Inhibition (~1/20)
of QD SpE !

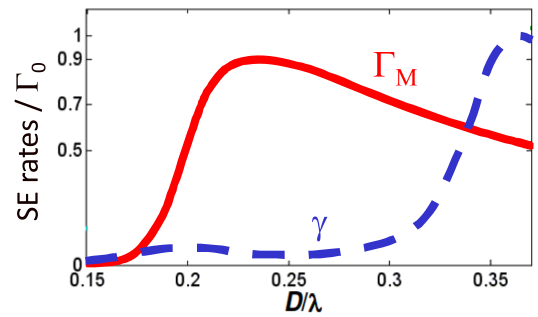
First observation of this effect,
predicted in 1949 !

J. Bleuse et al, PRL 106, 103601 (2011)

Time resolved PL for QDs in PWs





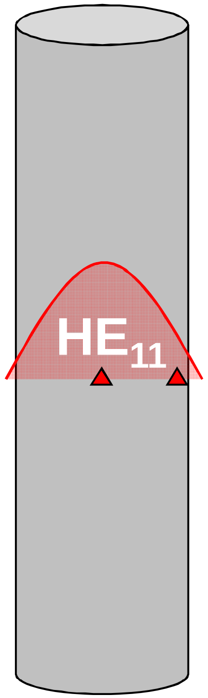


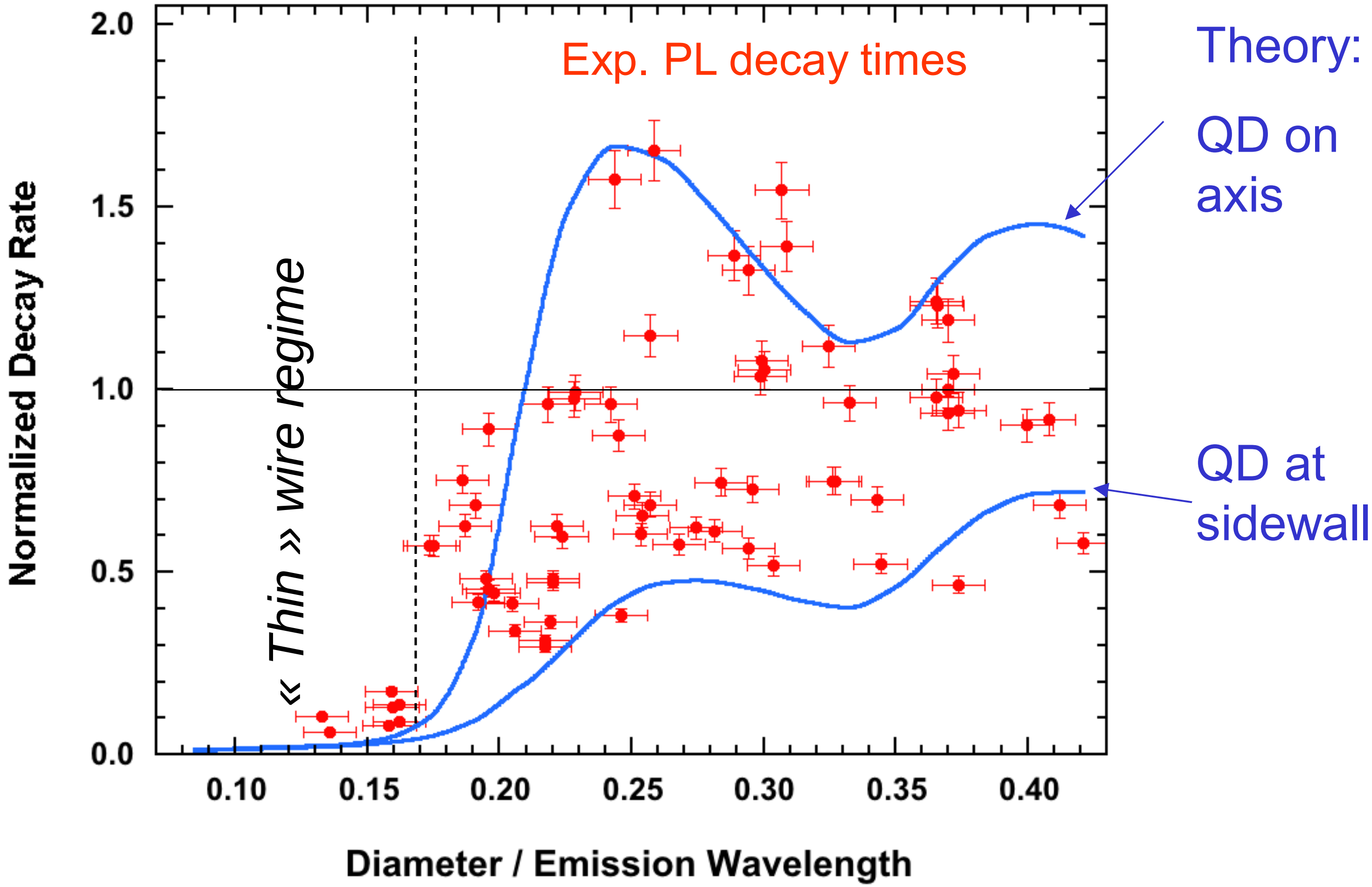
$\Gamma_m >> \gamma$

QD spontaneous emission
is funnelled into the guided mode

J. Bleuse et al, PRL 106, 103601 (2011)

QD spontaneous emission rate in photonic wires



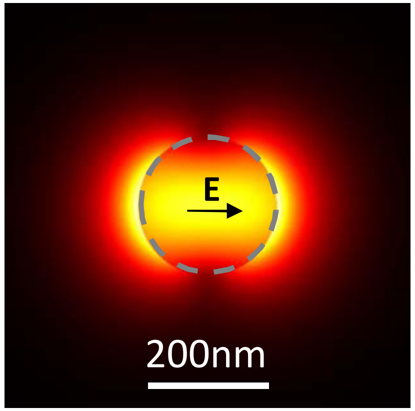


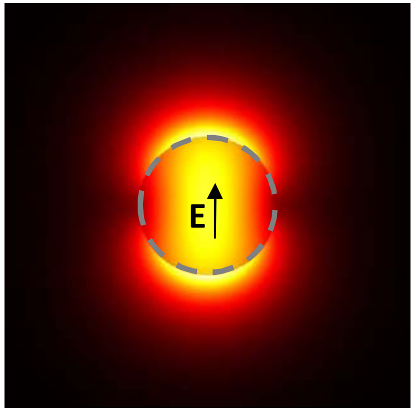
Strong SpE inhibition for all QDs in the « thin wire » regime

Dispersion of QD SpE rates due to random QD position in larger wires

Good agreement between exp. and theory

Cylindrical photonic wires have two polarization-degenerate guided modes





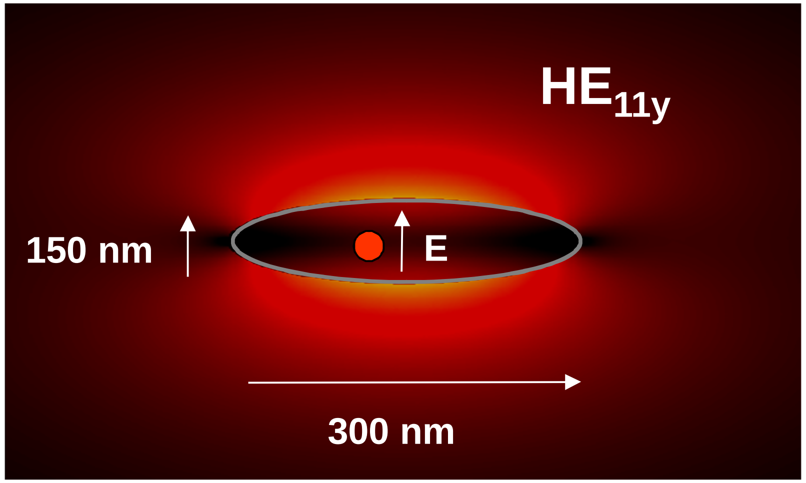
Standard semiconductor nanostructures (QWs, QDs) have both x and y in-plane dipoles

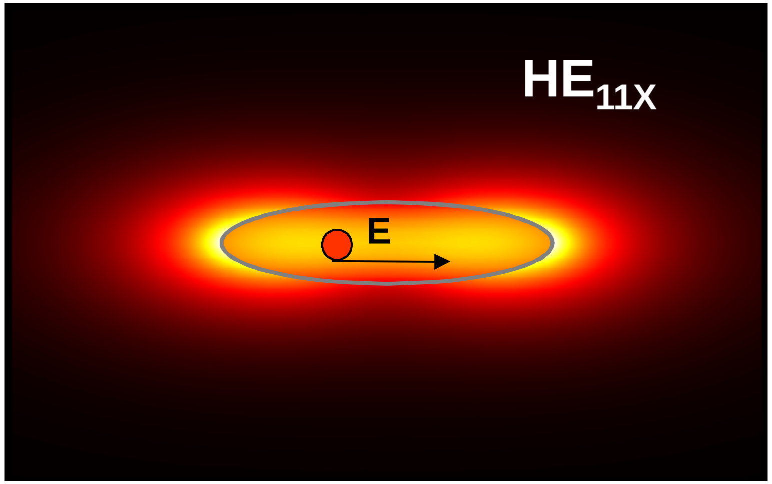
=> Coupling to both guided modes (β ~ 0.5)

How to get true single mode SpE?

Elliptical photonic wires for true single mode SpE

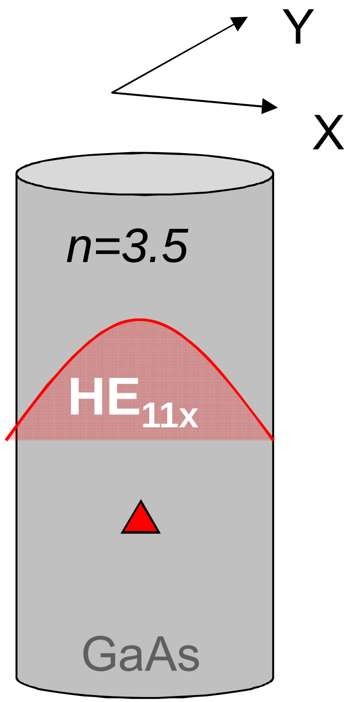
M. Munsch et al, PRL 108, 077405 (2012)





- Selective deconfinement of one guided mode
- β~1 and linearly polarized SpE

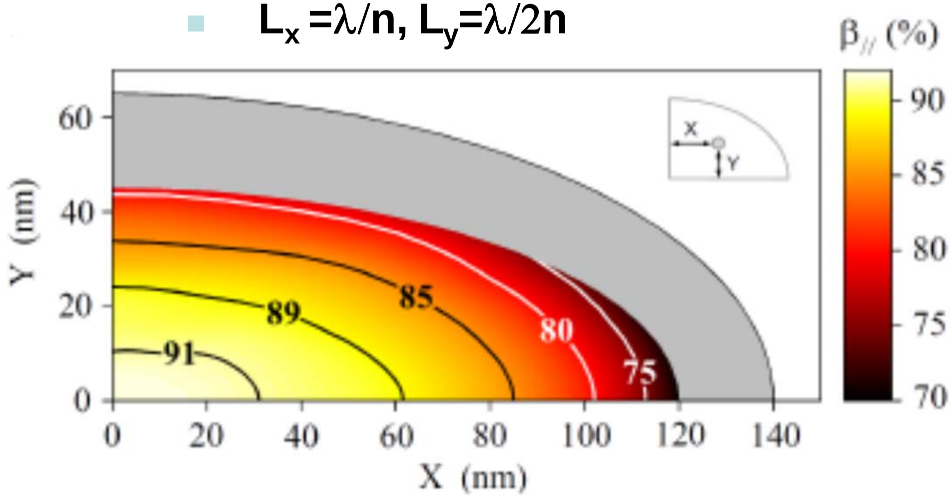
Fraction β_X of SpE emitted in the x-polarized mode



Isotropic, planar dipole

$$\beta_X = \frac{\Gamma_M(X)}{\Gamma_M(X) + \Gamma_M(Y) + \gamma_{leaky}}$$

- $L_x = \lambda/n$, $L_y = \lambda/2n$

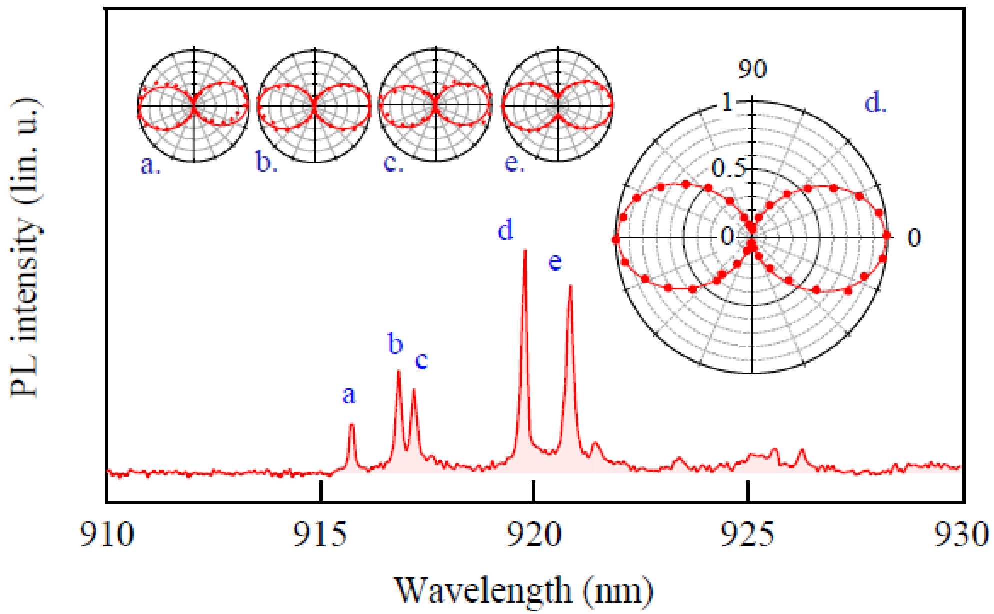


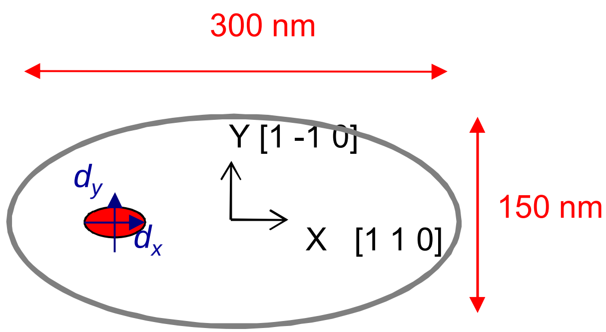
- **β_X > 0.9**
- **Wide choice of (R_x/λ, R_y/λ)**
- **Broadband operation**

QD position vs axis is not critical

Polarization-control in elliptical PWs

Rem: InAs QDs in bulk GaAs display a weak linear polarisation (0-20%)





-**Strong polarization** ratio for all QDs: $0.75 < PR < 0.95$

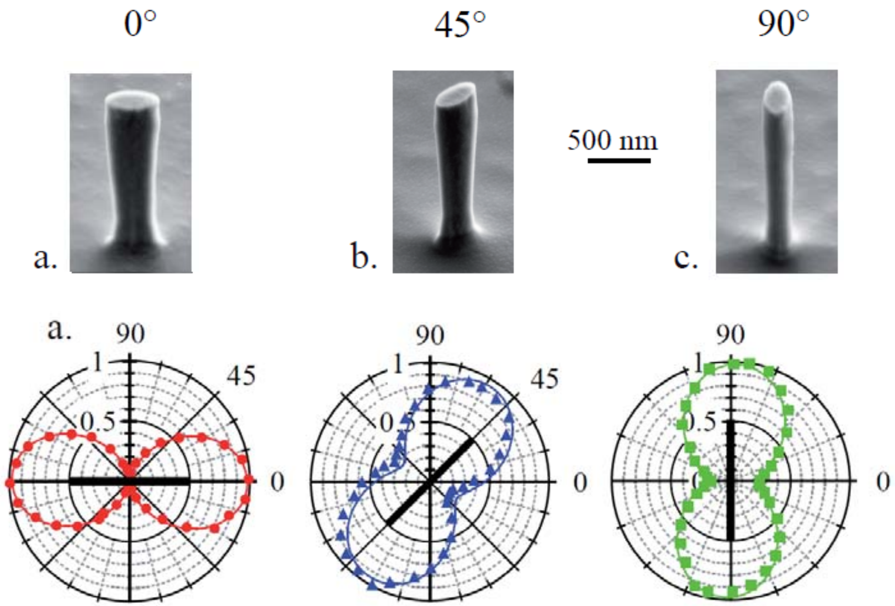
$$PR = \frac{I_{max} - I_{min}}{I_{max} + I_{min}}$$

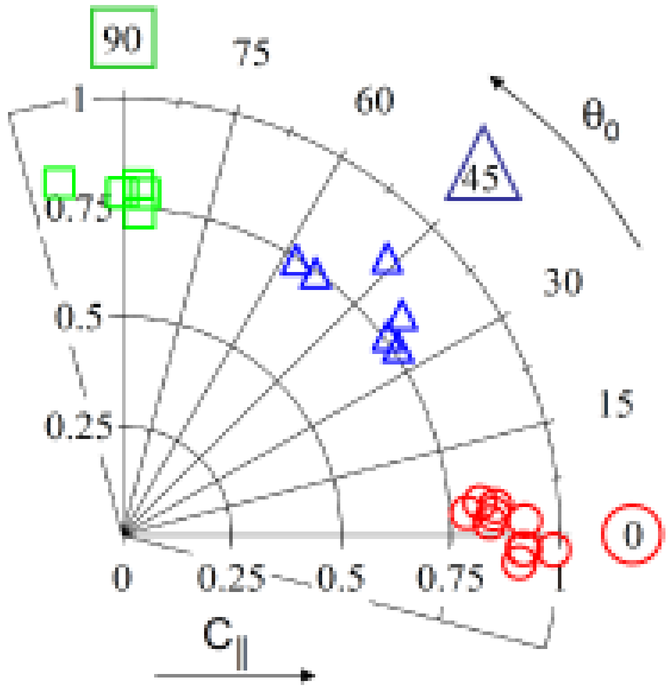
-Polarization angle corresponds to the **wire major axis**

- **Broadband effect**: effect measured on a bandwidth larger than 5 nm

QD polarisation control by PWs (2)

M. Munsch et al, PRL 108, 077405 (2012)





The linear polarization angle is determined by the photonic structure

Application of photonic nanowires to QD single photon sources

What is a single photon source ?

Source able to emit single photons pulses on demand

Non-classical state of light

Applications : quantum cryptography
metrology (energy standard)
optical quantum computing

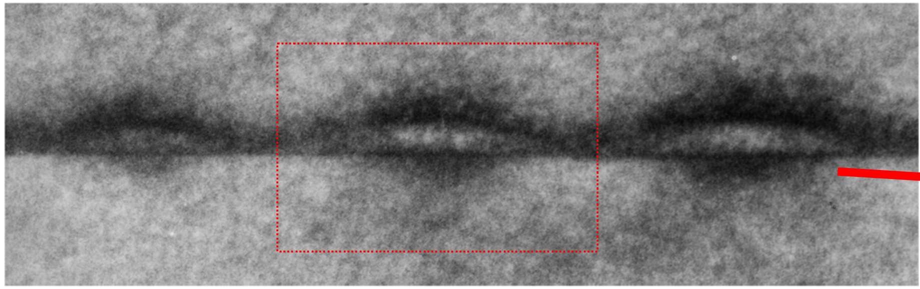
For most applications, the single photons must be prepared in the same quantum state !!

Single mode spontaneous emission wanted !!

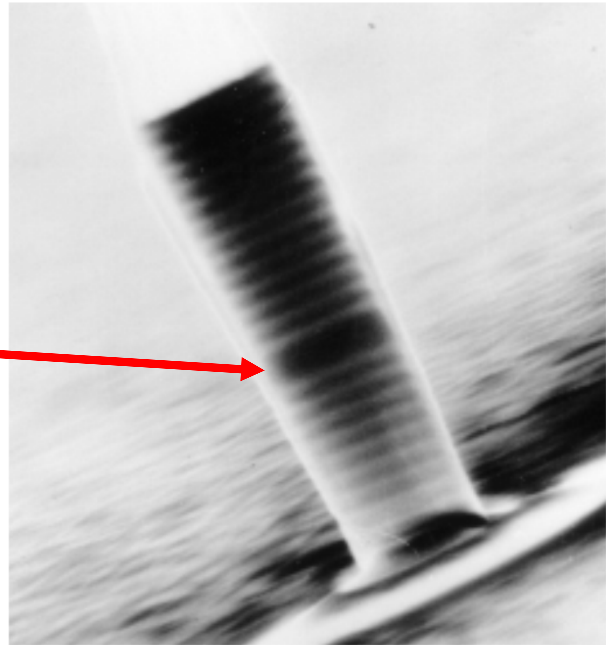
2001 : The first single-mode single-photon source

Isolated InAs QD as « artificial atom »

20 nm



GaAs/AlAs micropillar



=> Single-photon emission

Purcell effect

⇒ Efficient collection
+
single-mode behavior

proposal: *J.M. Gérard et B. Gayral,*
J Lightwave Technol. 17, 2089 (1999)

first exps : E. *Moreau, JMG et al, APL 2001*
Santori et al (Stanford), Nature 2002

QD-microcavity SPS : reported efficiencies

$\mathcal{E}$: average number of photons per pulse

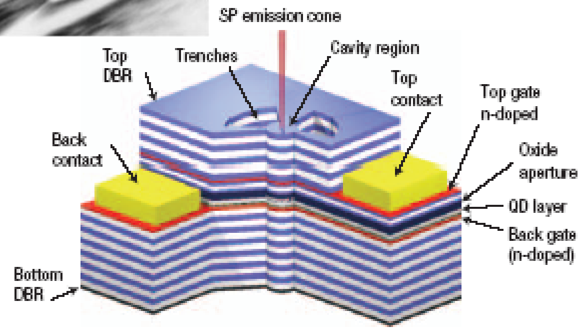
Optically pumped :

$\mathcal{E}$~0.4 for a QD in a micropillar

E.Moreau et al, Physica E13, 418 (2002)
M Pelton et al, PRL. 89, 23 3602 (2002)

$\mathcal{E}$=0.38 in an oxide-apertured planar cavity

S Strauf et al, Nat. Phot. 1, 704 (2007)



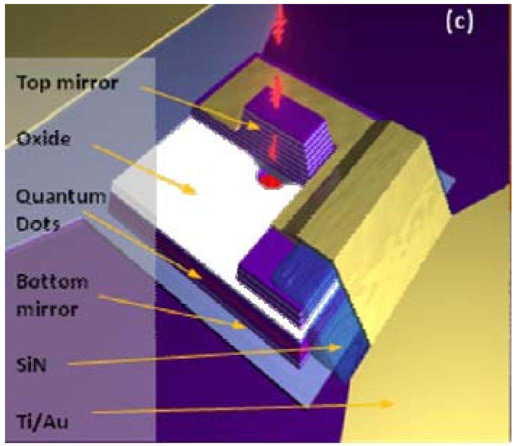
Electrically pumped:

$\mathcal{E}$~ 0.14 in a VCSEL like structure

DJP Ellis et al, New J Phys (2008)

$\mathcal{E}$~ 0.34 for a QD in a micropillar

T Heindel et al, APL 96, 11107 (2010)



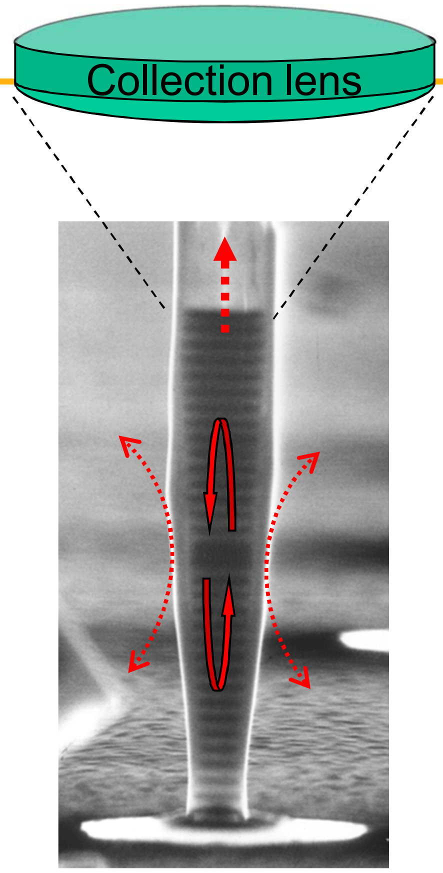
The photon collection issue

Strong Purcell effect => $\beta \sim 1$

but

only part of the single photons are collected !

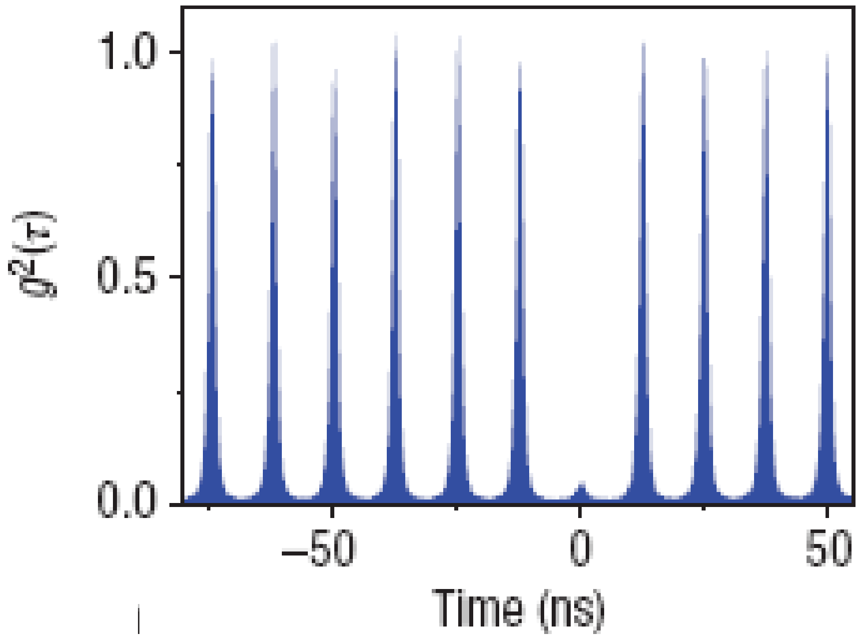
=> SPS efficiency $< \beta$

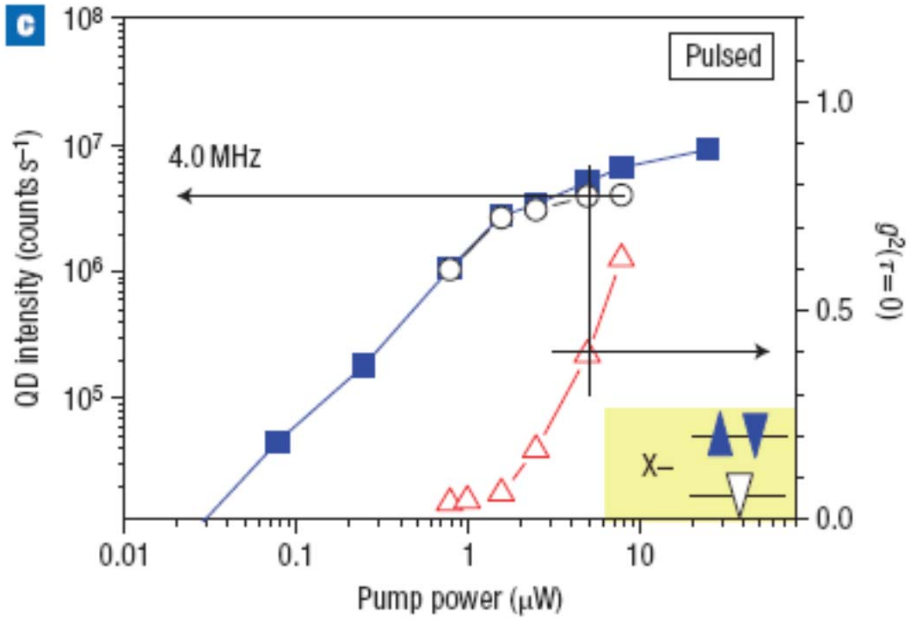


Photon losses due to scattering by sidewall roughness

N.B: The far-field radiation pattern of high Q microcavities is highly sensitive to imperfections !

The $g^{(2)}(0)$ issue for QD-microcavity SPS





From S. Strauf et al, Nat Phot 1, 704 (2007)

See also

Moreau APL 2001, Pelton PRL 2002, Heindel APL 2010

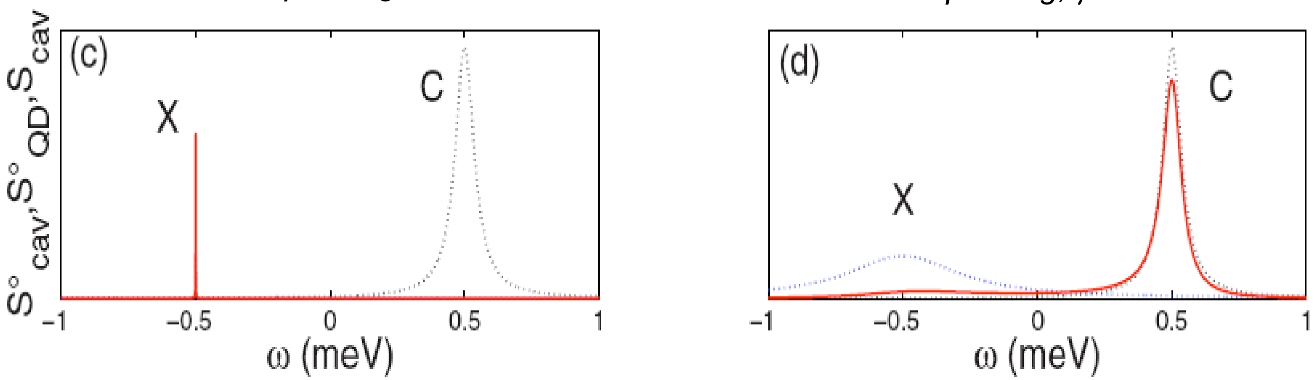
Low $g^{(2)}(0)$ only observed for weak pumping levels

$g^{(2)}(0)>0.5$ at QD saturation level !

Why is $g^{(2)}(0)$ large for QDs in cavities?

1) Cavity feeding by detuned emitters (other QDs, XX and multi X…) due to dephasing

No dephasing *Pure dephasing, γ^* =0.5 meV*



from

A Auffèves et al

PRA 79, 53838 (2009)

Naesby et al, PRA **78** (2008)
Suffczynski *et al*., PRL **103** (2009)
Hohenester *et al*., PRB **80** (2009)
Winger *et al*., PRL **103** (2009)
etc…

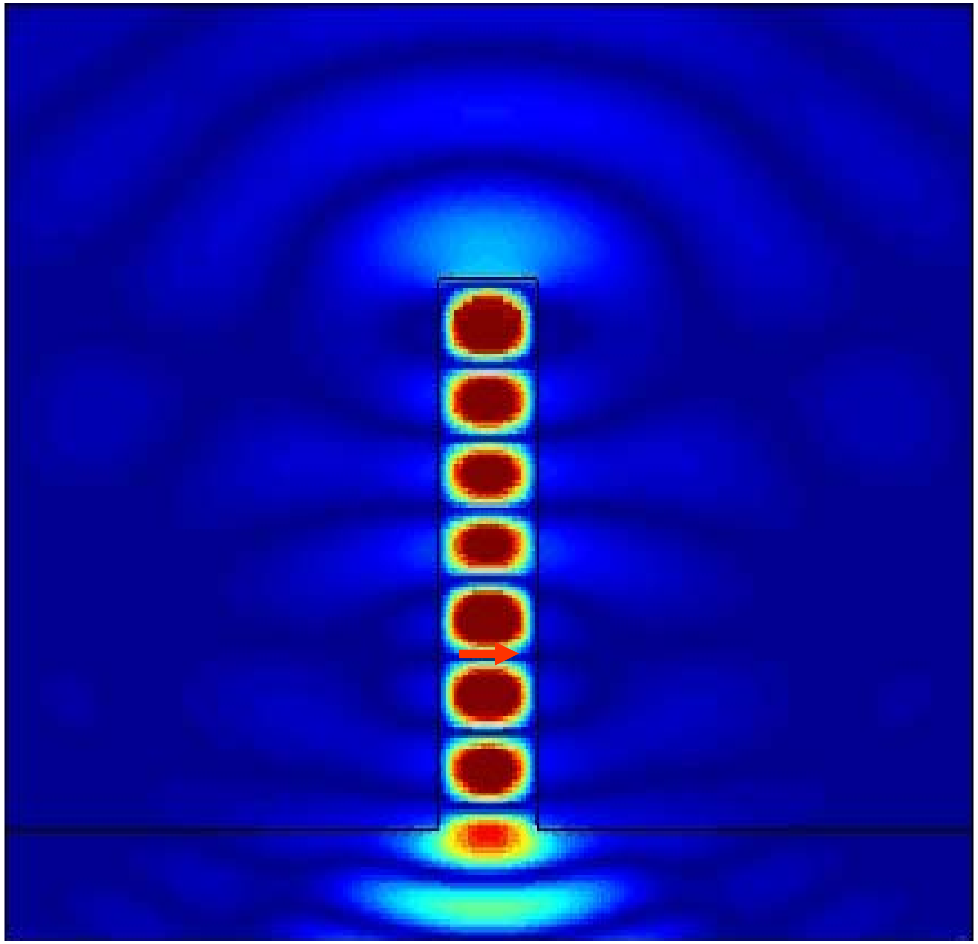
2) Repumping of the QD after the (fast) X emission

Let's get rid of high Q cavities !

~~Selective enhancement of SE in one mode~~ → Inhibition of SE in useless modes

QD in a photonic wire

Courtesy A.L. Henneghien, CEA/LETI/DOPT, Grenoble

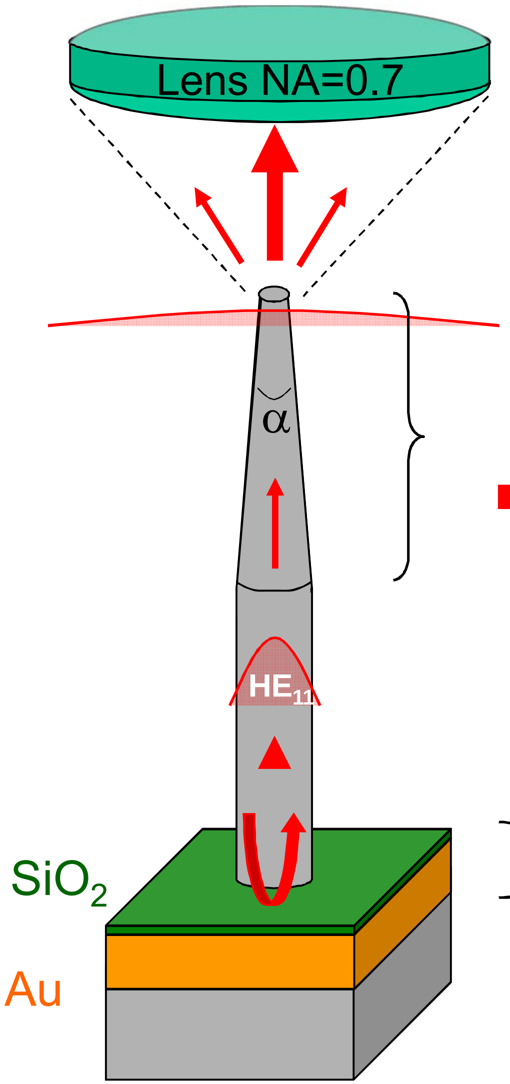


Collection efficiency limited by :

Divergence of the output beam (vs NA)
=> shape engineering

Photon escape toward the substrate
=> integrated mirror

Control of the far field radiation pattern



Needle-like taper

➡ Adiabatic expansion of the guided mode
Reduced far-field divergence

Opt. Lett. ***33***, *1693 (2008)*

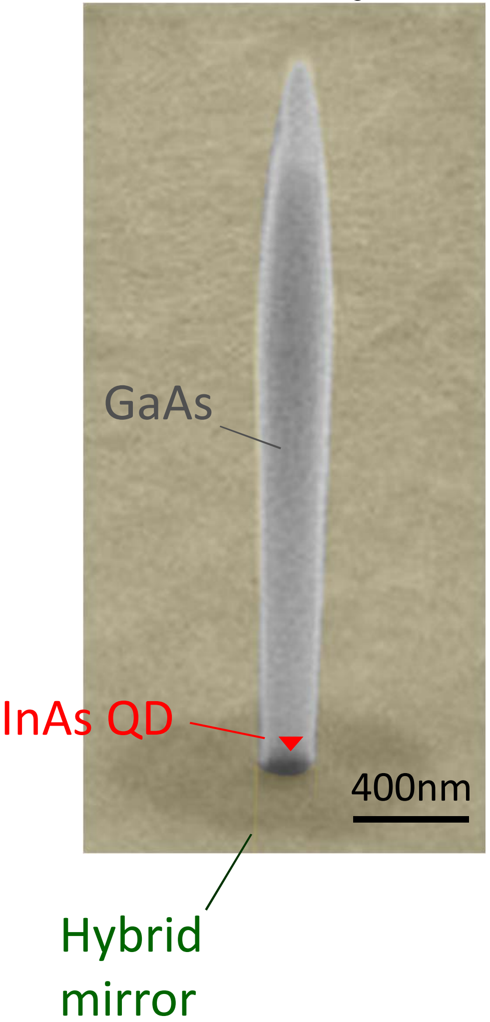
Hybrid metal+dielectric mirror

➡ High modal reflectivity (R~0.95)

Opt. Lett. ***33***, *2635 (2008)*

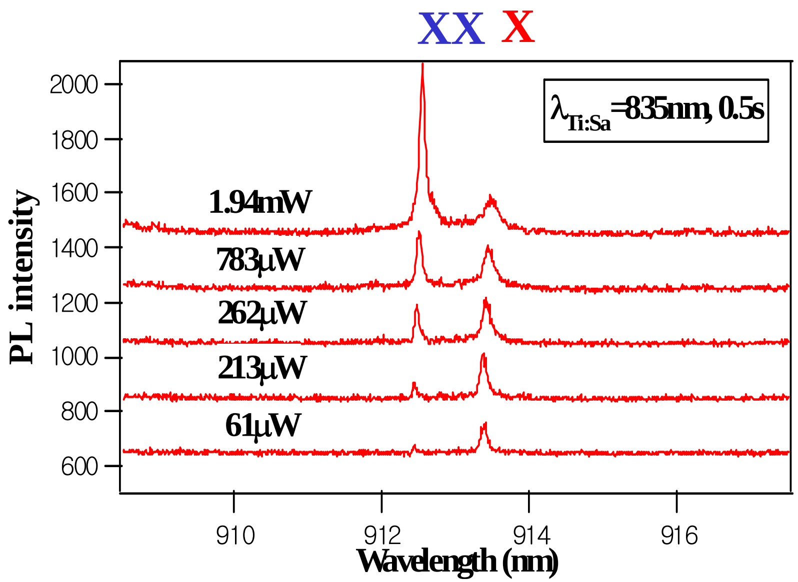
Top-down process

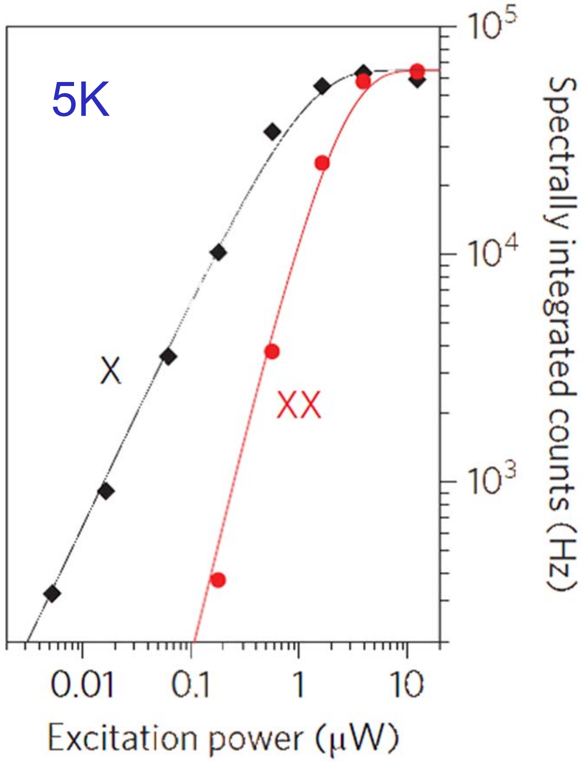
- Mirror deposition
- Flip-chip
- E-beam lithography
- Reactive ion etching



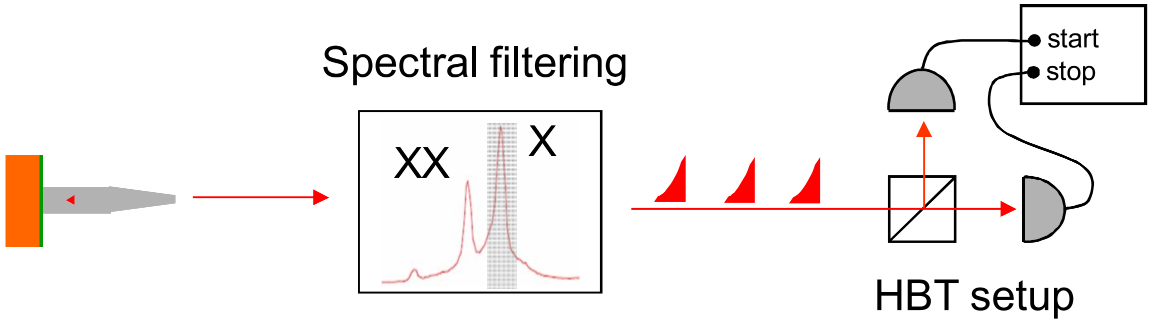
Optical characterization by µPL

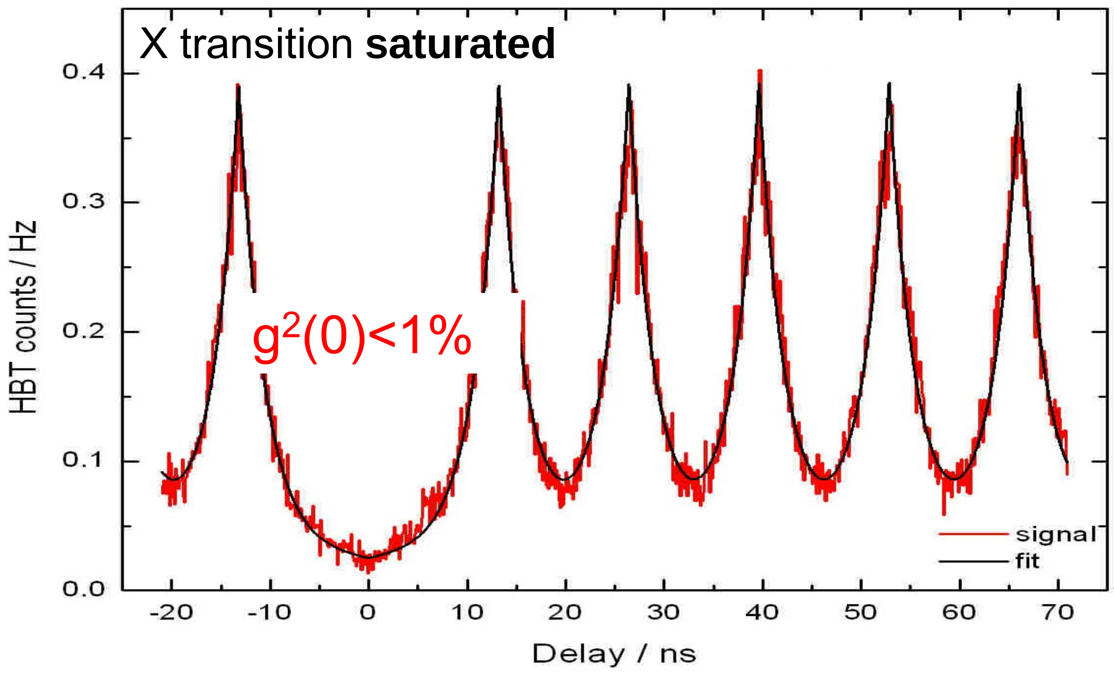
Micro-photoluminescence setup
QD pumping: optical, pulsed, non-resonant (835nm)





A pure single-photon emission



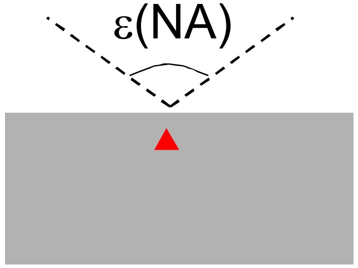


Key difference vs microcavity SPS !

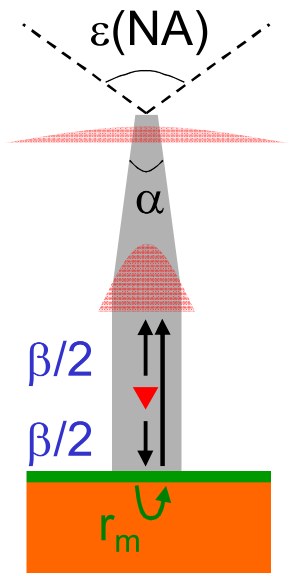
No $g^{(2)}$ spoiling due to cavity-feeding

No repumping (fast capture of excess carriers by surfaces)

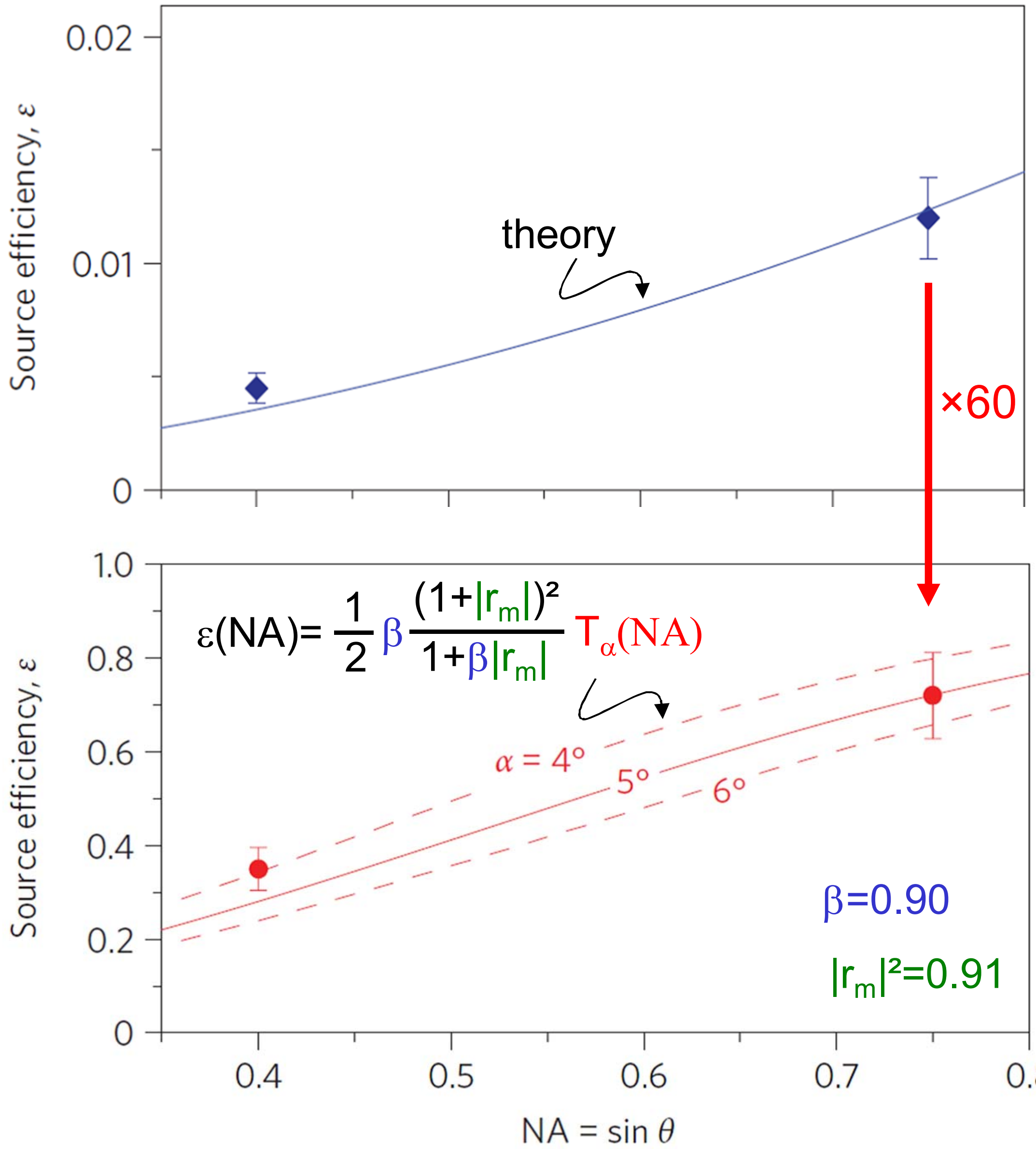
A high-efficiency single-photon source



QD in bulk GaAs



QD in a PW



Assets of photonic wire SPS

o One can get simultaneously

- a high efficiency (0.72 photon per pulse)
- $g^{(2)}(0) < 0.01$

J Claudon et al,

Nature Phot. 4, 174 (2010)

o Efficiency > 0.92 within reach for a QD on axis

I Friedler et al, Opt Exp (2009)

o Many other assets related to the broadband SE control

_ Spectrally tunable QD SPS

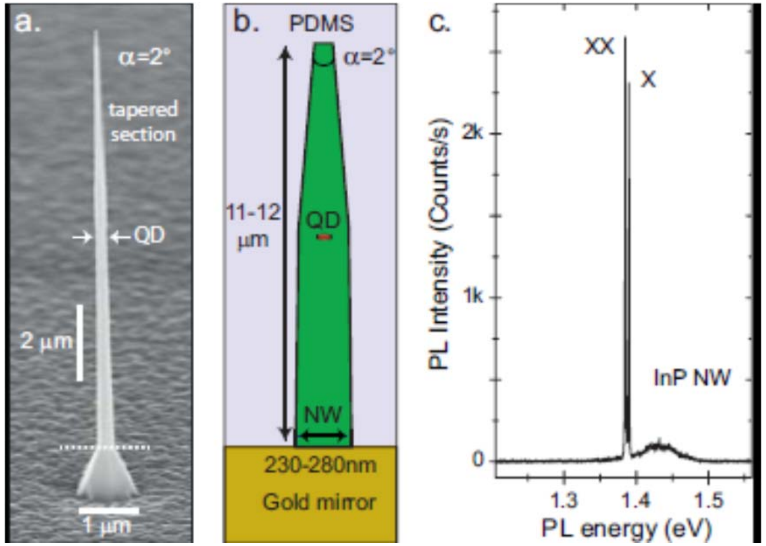
_ Single-mode SPS exploiting a non-monochromatic emitter

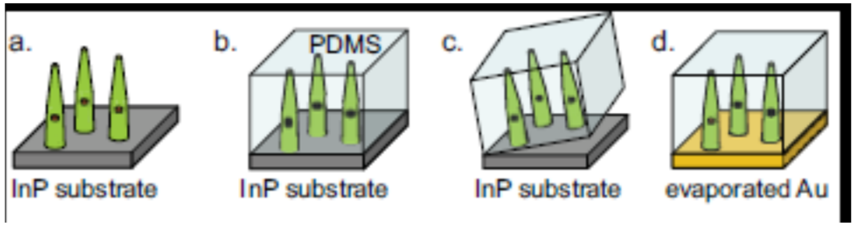
F-center in diamond, QD at high temperature…

_ Efficient source of entangled photon pairs

Bottom-up route toward photonic wire SPS

V. Zwiller's group, U. Deft, Nat. Comm. 2012





Intrinsic assets :

Single QD in the wire

Self-alignement on axis

Sharp tips feasible

Present limitations:

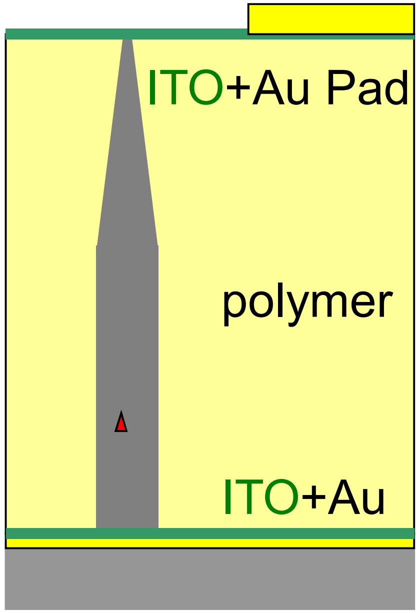
QD blinking (X<-> X-)

control of QD location vs mirror

⇒ Until now, $\varepsilon \sim 0.4$

but clearly a promising approach!

Towards plug-and-play electrically-pumped SPS (1)



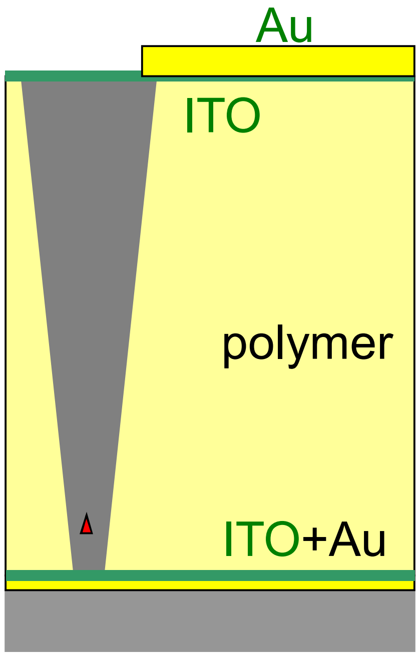
$\varepsilon > 0.8$ for optimized structure

Gregersen et al, Opt. Exp. 2010

… but tricky process!

.

Towards plug-and-play electrically-pumped SPS (2)



Adiabatic mode expansion
inside the photonic wire

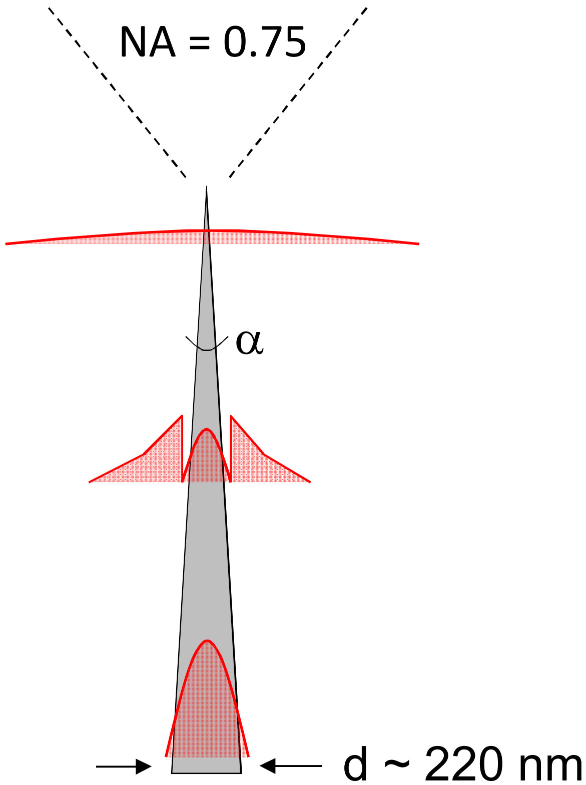
Easier contacting process

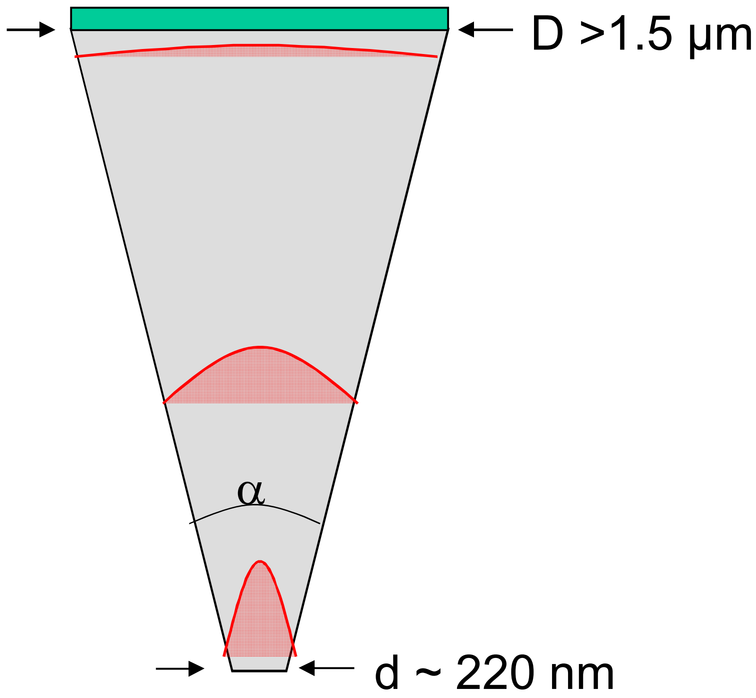
$\varepsilon > 0.9$ for optimized structure

Gregersen et al, Opt. Exp. 2010
CEA+DTU patent 2010

.

Needle-like versus horn-like tapers





α=5° → α=2°
T =78% → T =97%

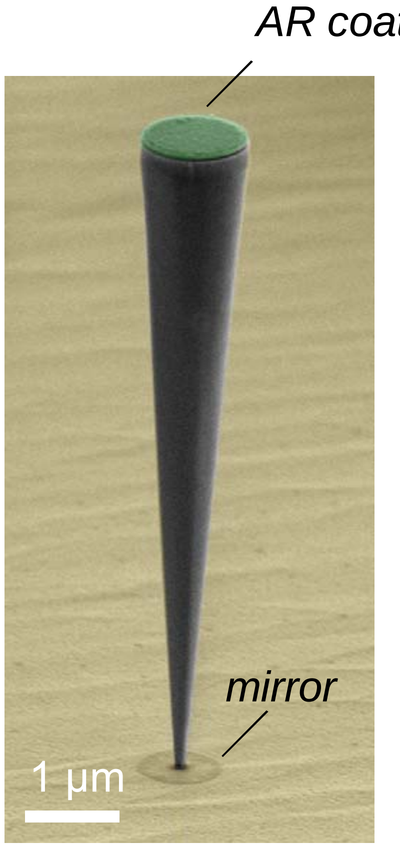
α=10° and D >1.5 μm → T =97%

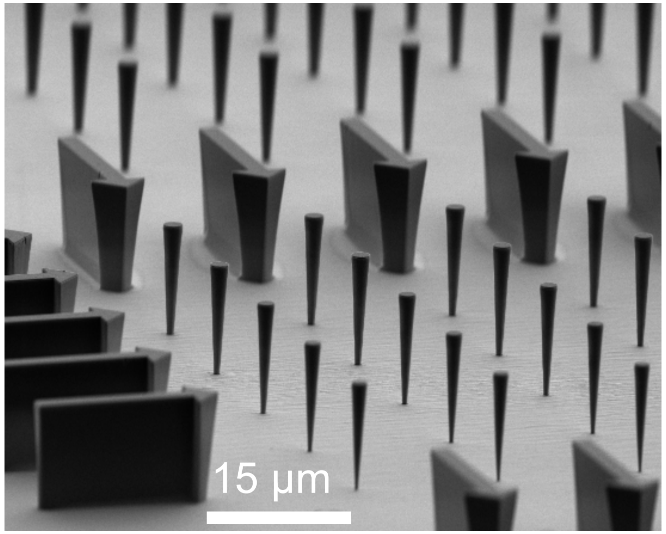
Ultra-sharp needles needed
=> Bottom-up fabrication
e.g. V Zwiller et al, Nat Comm 2012

Weak sensitivity on the taper angle

Far-field divergence defined by the size of the top facet

Photonic wire SPS with inverted tapers





Top down fabrication
e-beam lithography + RIE

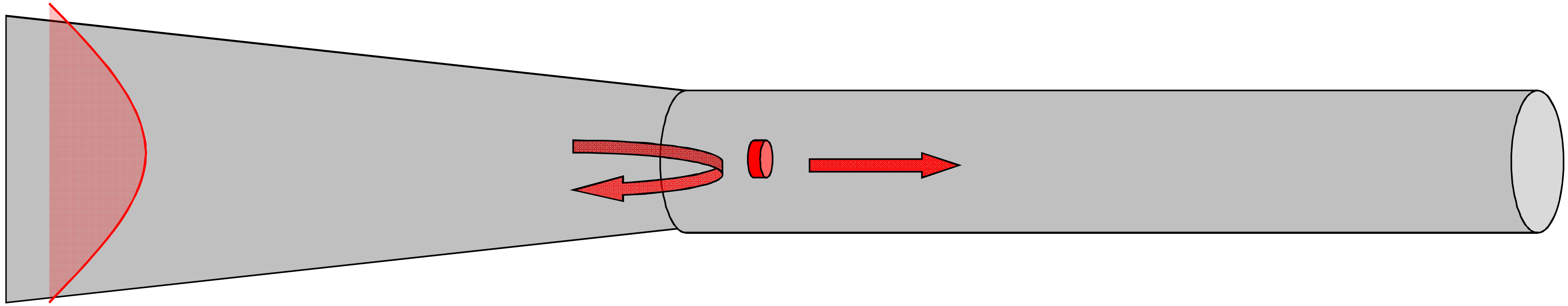
ε> 0.75 photon/pulse demonstrated under optical pumping

J Claudon et al, subm.

A “one-dimensional atom”

Name introduced by Kimble et al in the context of atoms in cavities (PRL 1995)

The artificial atom interacts (~ ONLY) with a 1D photonic channel



Very rich physics, at the single photon level !!!

_ Giant non-linearity at the single photon level => single photon transistor
Auffèves et al, PRA 2007

_ Amplification by the stimulated emission from a single QD *(Valente et al, PRA 2012)* => single photon adder
optimum quantum cloner

Quantum interface for QIP : flying QuBits <-> material QuBits

Conclusion/Prospects

Photonic wires : a new template for CQED experiments with QDs
…or QWs!

Already demonstrated for InAs QDs:

Strong SpE inhibition (x1/20)
Single-mode behavior of SpE
Polarization control

Very promising application prospects in quantum optoelectronics
sources of single-photons
devices exploiting 1D-atom physics
β~1 microlasers