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JOINT ICTP-INFM SCHOOL/WORKSHOP ON "ENTANGLEMENT AT THE NANOSCALE"

(28 October – 8 November 2002)

" Semiconductor quantum dots : artificial atoms for quantum optics "

presented by:

G. M. Gerard
DRFMC/CEA, Grenoble
France

Semiconductor quantum dots : artificial atoms for quantum optics

Jean-Michel GERARD

Laboratoire Nanophysique et Semiconducteurs, CEA/Grenoble

Work mostly done at CNRS/LPN (Bagneux-> Marcoussis 09/01)
in collaboration with:

E.Moreau, I. Robert, B. Gayral, I. Abram
V. Thierry-Mieg (MBE), L. Manin (RIE)

jmgerard@cea.fr

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Spontaneous emission control in semiconductors

Many attempts to control SE in semiconductors since ~1975
by tailoring...

electronic states	photonic modes
Q wells, Q dots	microcavities, photonic crystals

…for novel/improved optoelectronic devices!

e.g. strained QW lasers (86)	high-efficiency microcavity LEDs (93)
	low-threshold VCSELs (30 µW) (95)
	strong-coupling regime for QWs (92)

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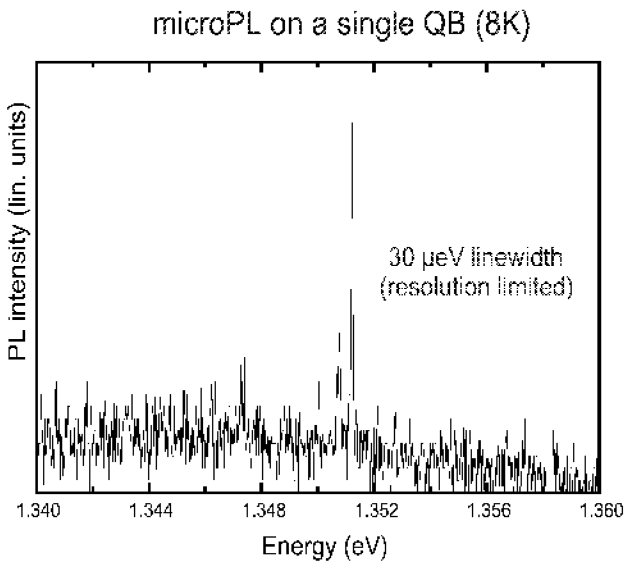
QDs : artificial atoms for quantum optics



Marzin et al,
PRL 73, 1138 (1994)

close analogy with single-atom quantum optics

- e.g. coherent control of QD excitons (2001)

New!

- solid-state CQED : Purcell effect (1997)
- generation of quantum states of light (2000)

ultimate control on SE, on the single photon level

=> first single-mode single-photon source (2001)

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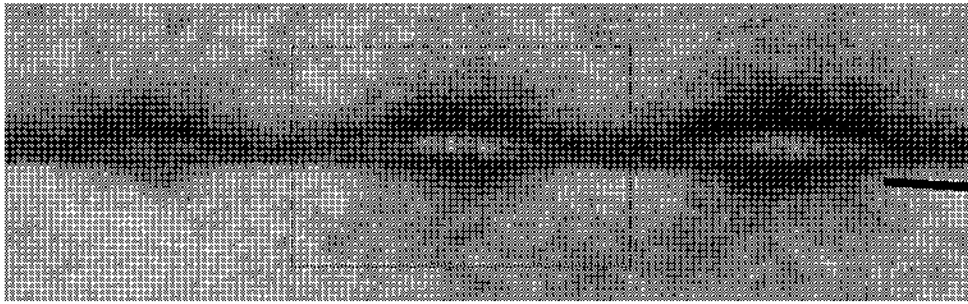
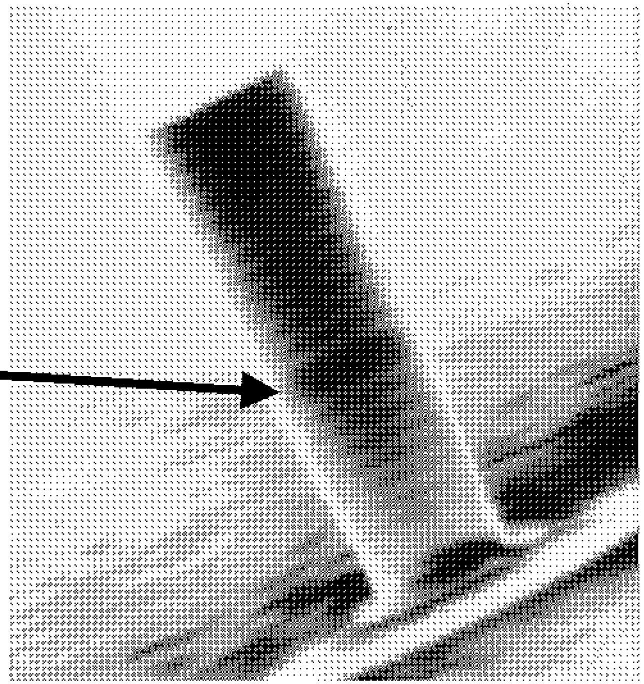
A single-mode single-photon source

Isolated InAs QD

20 nm



GaAs/AlAs micropillar



=> Single-photon emission

⇒ Efficient collection
+
single-mode behavior

E. Moreau et al,
Appl. Phys. Lett. 79, 2865 (2001)

Outline

Single photon sources : applications and requirements

Generation of quantum states of light

QDs in microcavities and the photon collection issue

A single-mode single photon source

Prospects

Single-photon source

Deterministic emission of light pulses containing one and only one photon

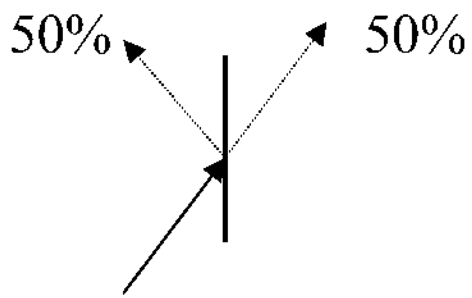
Metrology
flux+energy standard

Quantum Key Distribution
Polarisation-encoded single photons

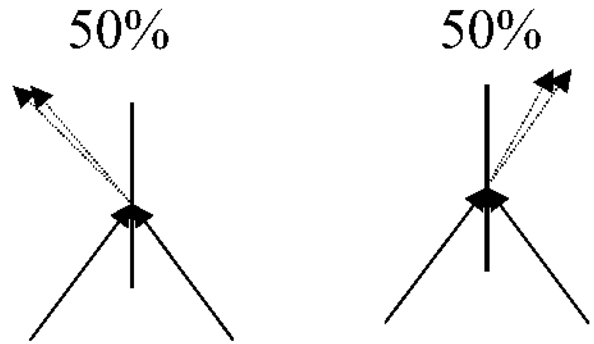
Quantum computing
single photons as Q-bits

Single photons for quantum computing

Knill et al, Nature 409, 46 (01) « Quantum computing using SPs and linear optics »



Single photon on beam-splitter



Two identical photons on BS

Logical optical gate based on single photons!

<u>Requirements:</u>
- same mode +polarisation
- SPS efficiency ~1
- Fourier transform limited ($\Delta\nu.\Delta\tau=1/4\pi$)

Decoherence control !

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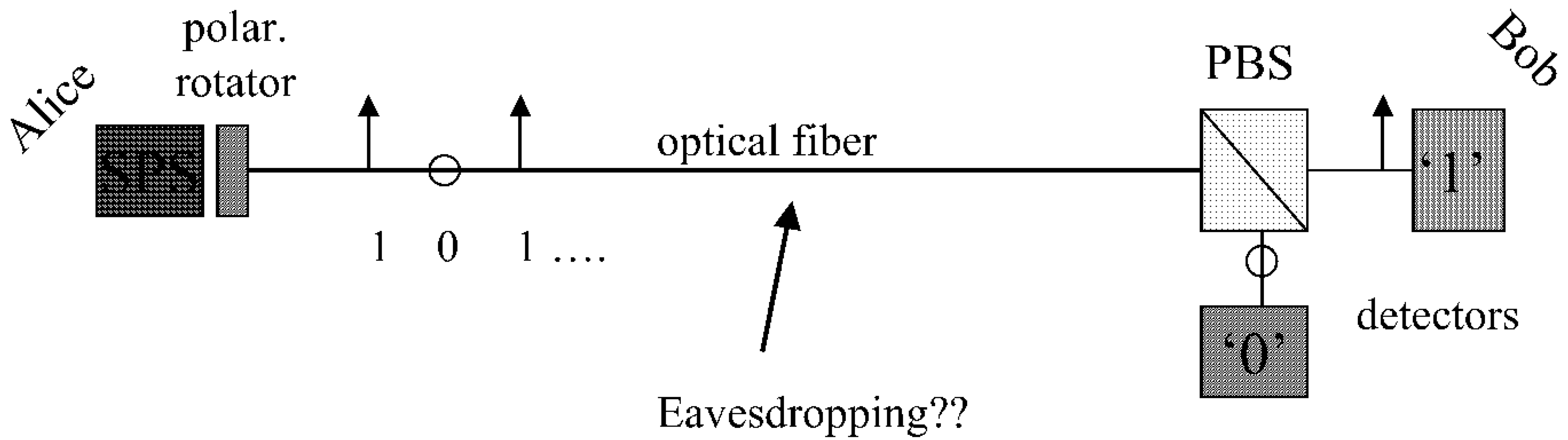
Single photon sources for quantum key distribution



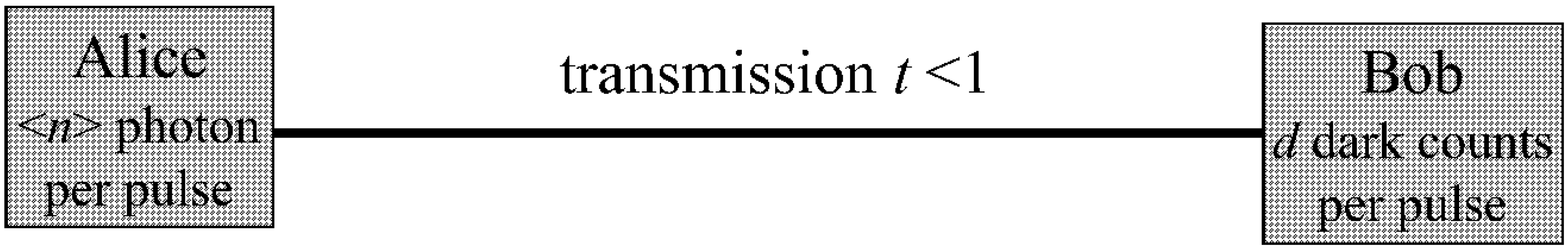
Alice and Bob share a binary key

This protocol can be made intrinsically secure

(Bennett+Brassard 84 : eavesdropping=> more than 25 % errors)

Secure for present as well as future technology

Constraints for secure QKD : 1) dark counts

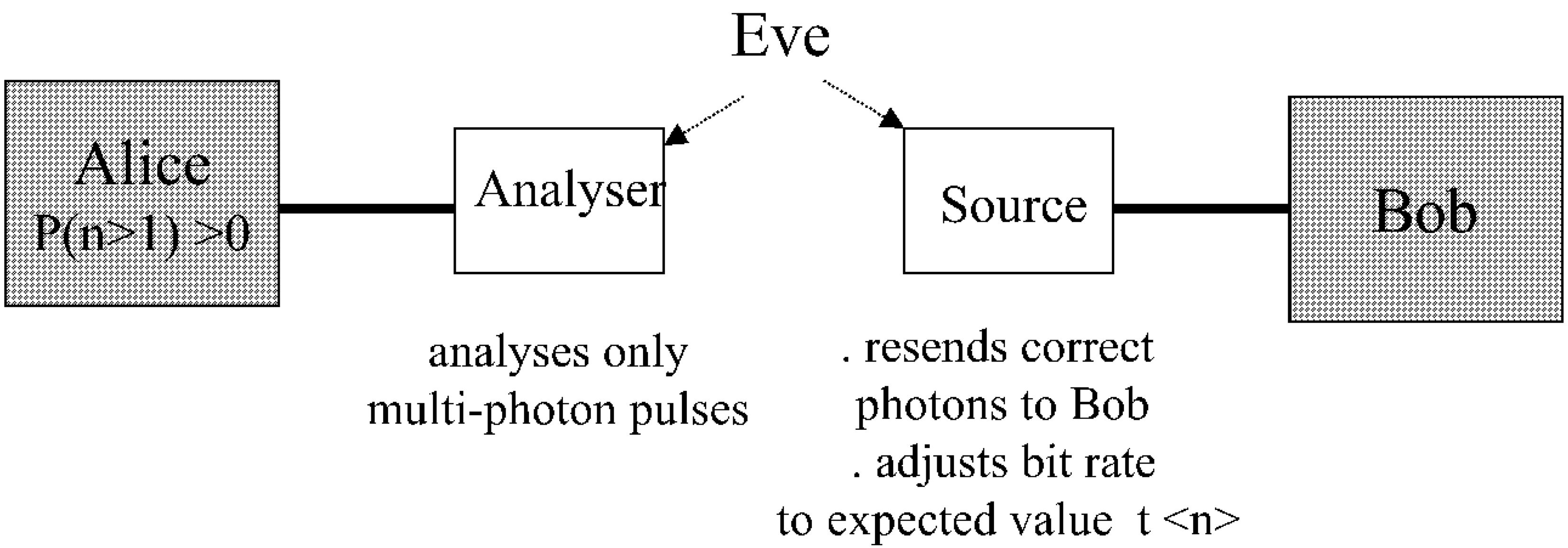


Error correction possible ⇔ $\langle n \rangle\, t > 10\, d$

⇓ limited secure transmission length
(~100km at most at telecom wavelength)

Constraints for secure QKD : 2) multi-photon pulses

Lossy channel => « Photon-Number Splitting » attack



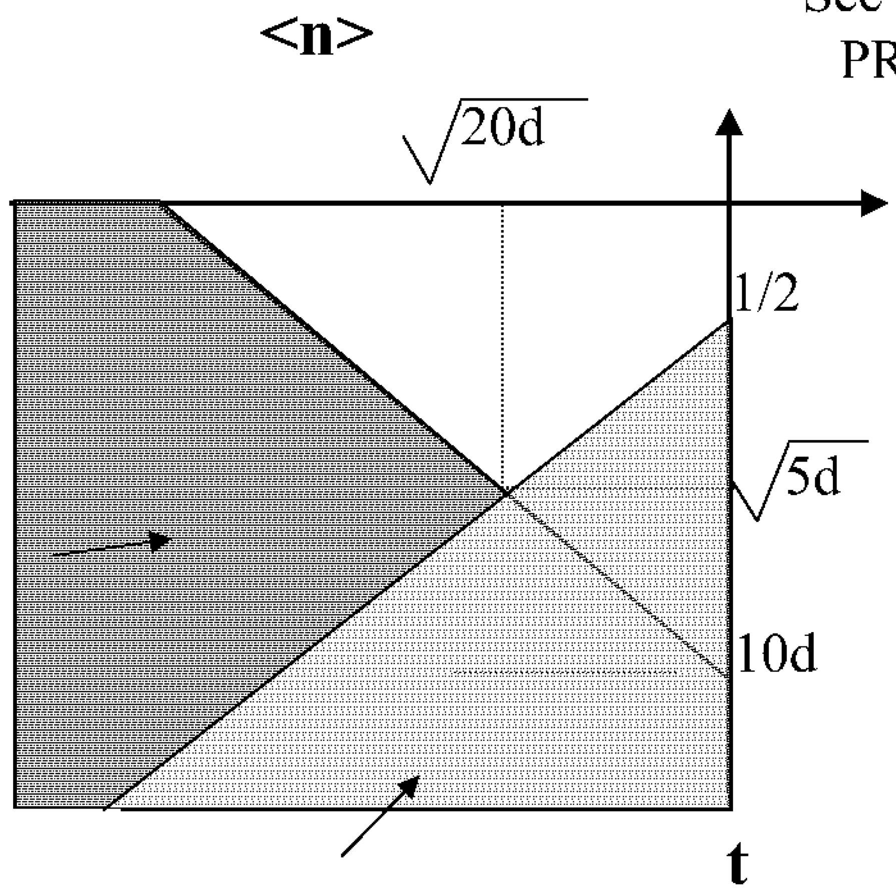
PNS works ⇔ $p(n>1) > t \langle n \rangle$

Secure QKD with weak coherent pulses

$\langle n \rangle \ll 1$

$P(n>1) \sim \frac{\langle n \rangle^2}{2}$

See e.g. Brassard et al PRL 85, 1330 (00)



Too many dark counts

$t.\langle n \rangle < 10\,d$

Too many multi-photon pulses

$\langle n \rangle/2 > t$

$\langle n \rangle_{opt} \sim 4.10^{-3}$ @ 1.3 µm

=> low bit rate

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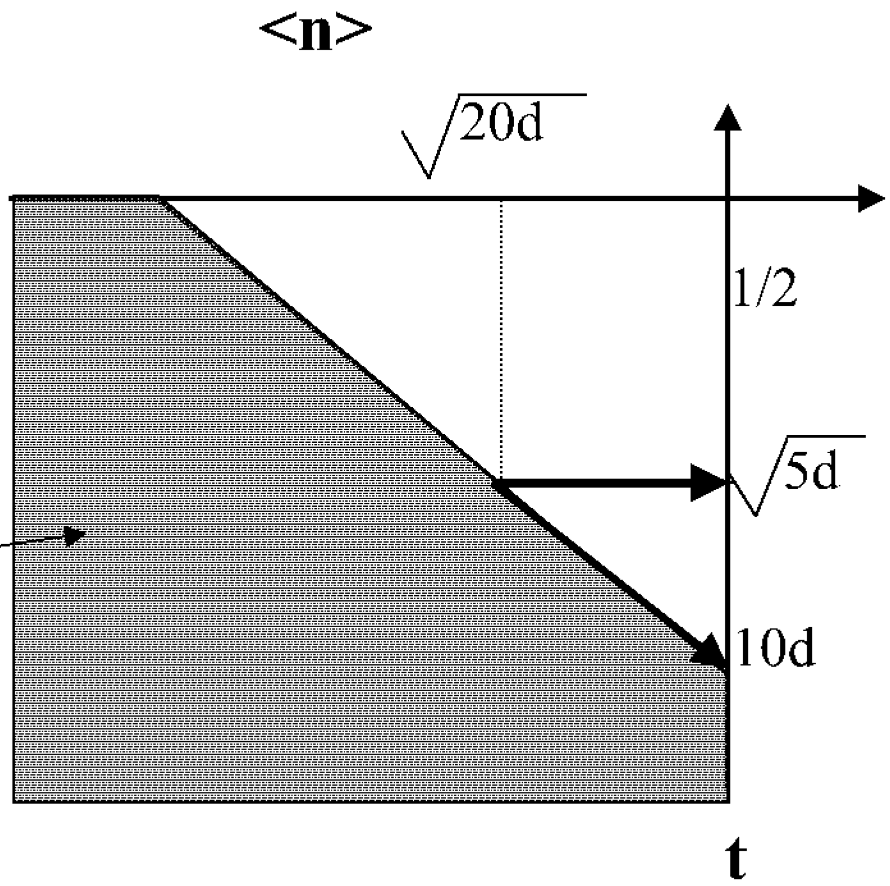
Secure QKD with a perfect SPS



Too many dark counts

$t.\langle n\rangle < 10\,d$

SPS vs weak coherent sources

Replacement of attenuated lasers by a <u>perfect</u> SPS   (@1.3 µm)

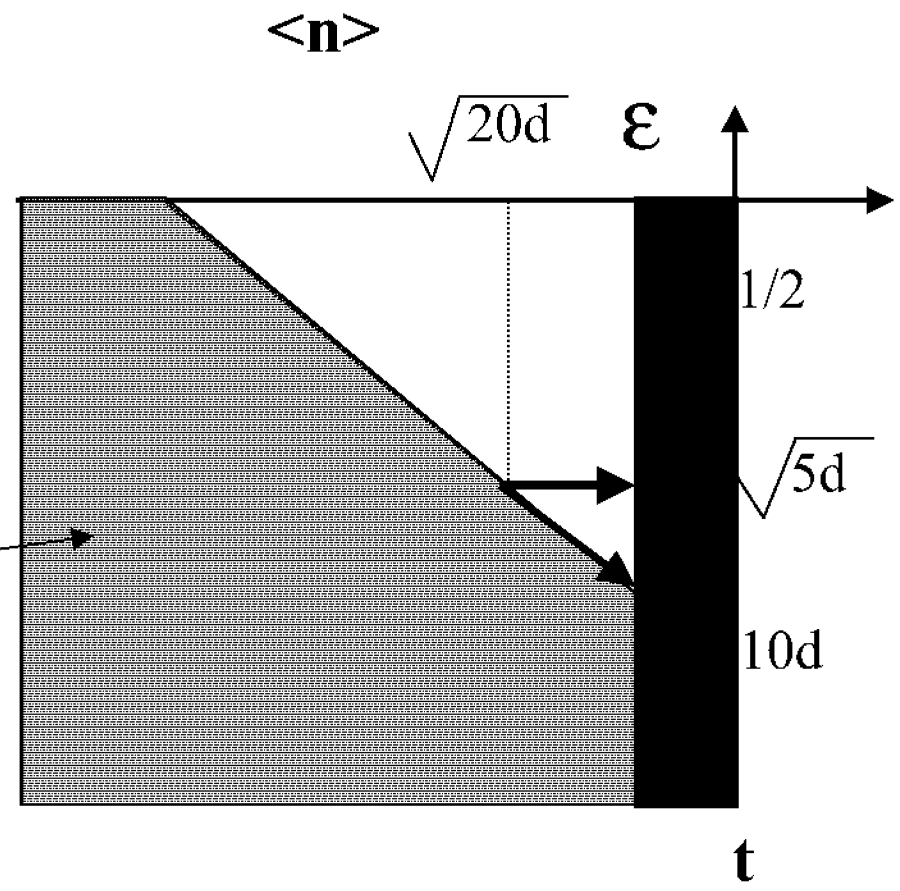
=> secure channel length x 2

=> bit rate x 100

See Brassard et al, PRL 85, 1330 (2000)

What about unperfect single photon sources???

SPS with limited efficiency (ε<1)

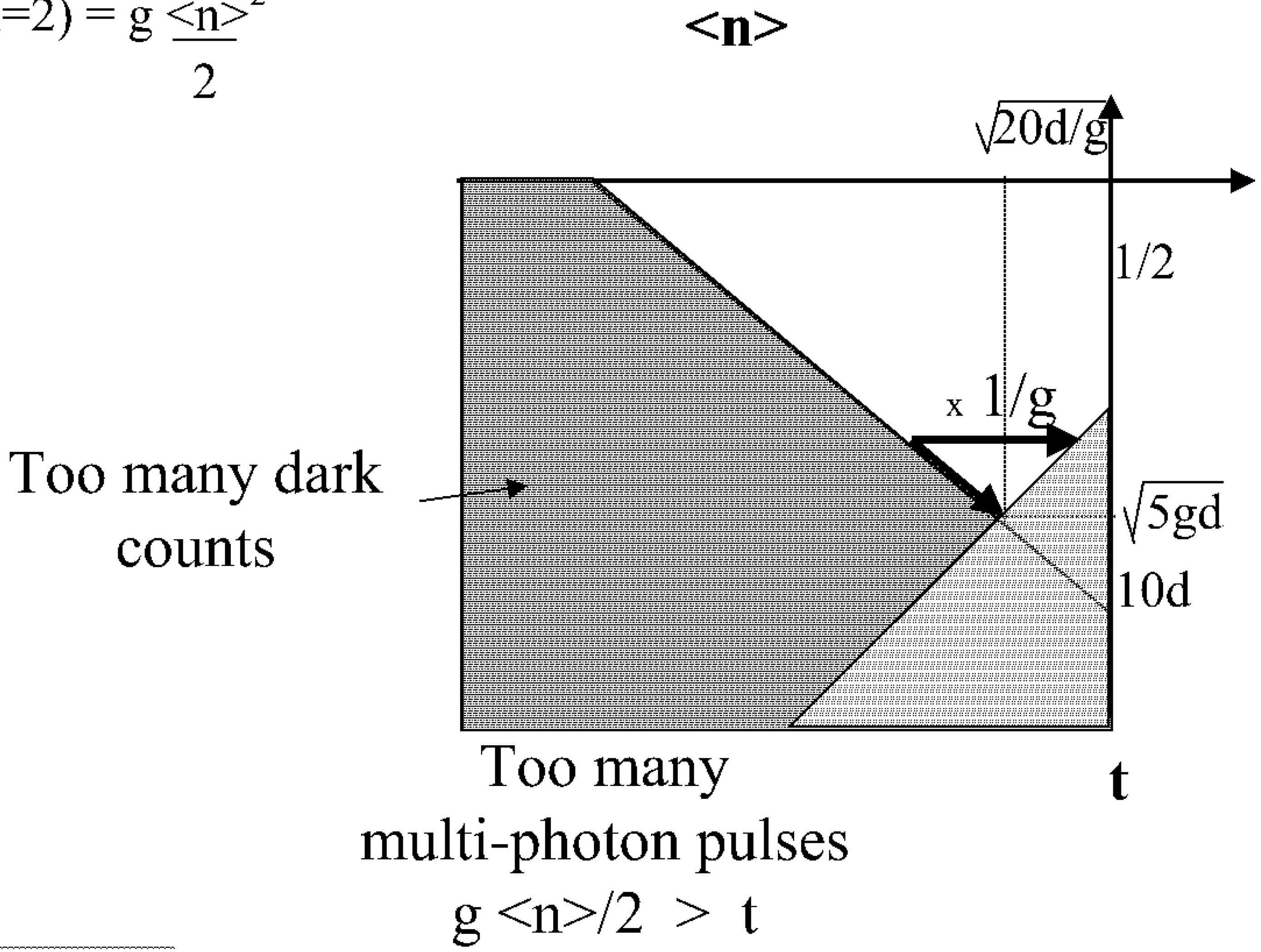


Too many dark counts

$t\,.\langle n\rangle < 10\,d$

Unperfect SPS (0<**g**<1)

$P(n=2) = g \frac{\langle n\rangle^2}{2}$



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Conclusion

It is essential for a practical Single Photon Source to present both

. a large efficiency $p(n=1) = \varepsilon \sim 1$

. a weak probability to emit multi-photon pulses $(g \ll 1)$

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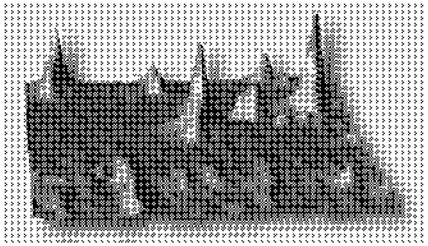
Solid-state single photon emitters

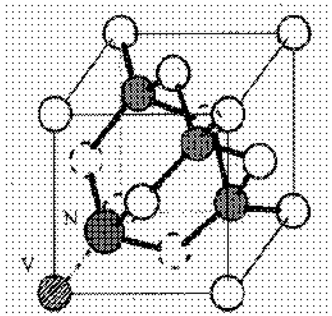
at 300 K !

Molecule



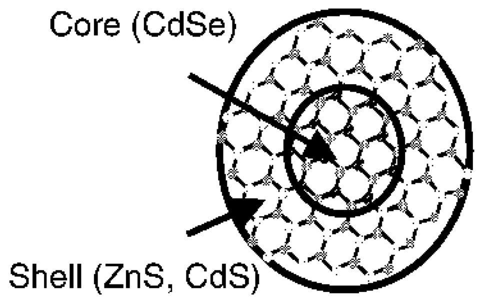
Lounis et Moerner,
Nature 407, 491 (2000)

F center



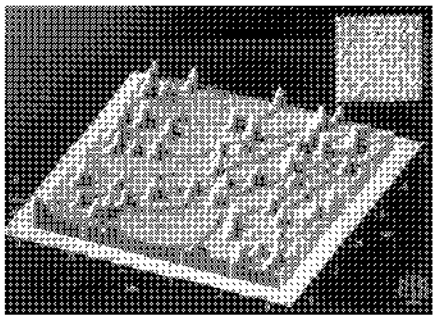
Kurtsiefer et al, PRL 85, 290, 00

Nanocristal



Michler et al, Nature 406, 968, 00

Self-assembled quantum dots



T<50K
until now! →

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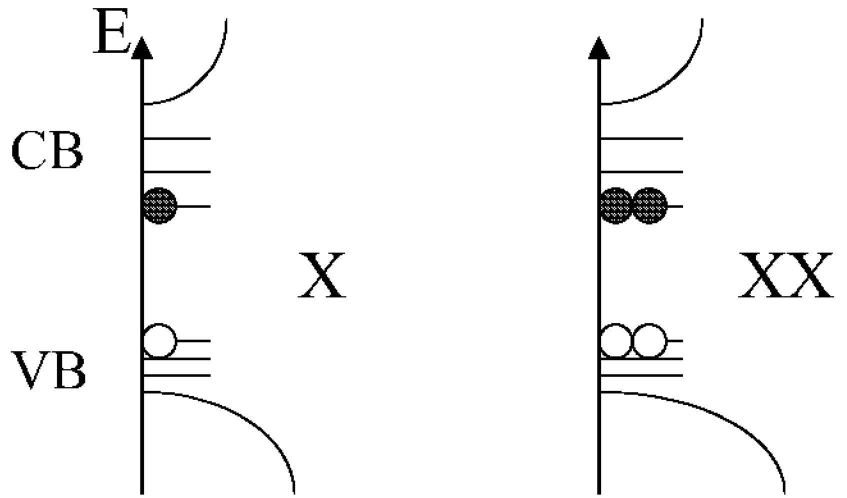
QD assets for single-photon generation

QDs are
- stable (no blinking, no bleaching)
- efficient ($\eta \sim 1$)
- fast ($\tau \sim 1$ns)
- spectrally narrow at low T

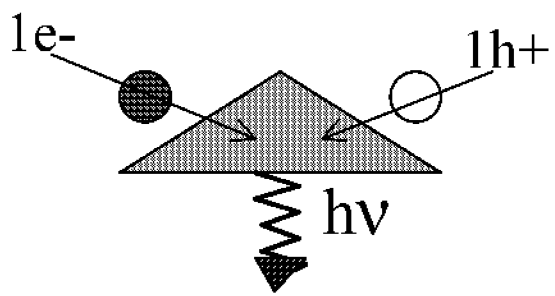
\+ adjustable bandgap/non-resonant pumping OK

Pb: a QD is not a 2-level system!



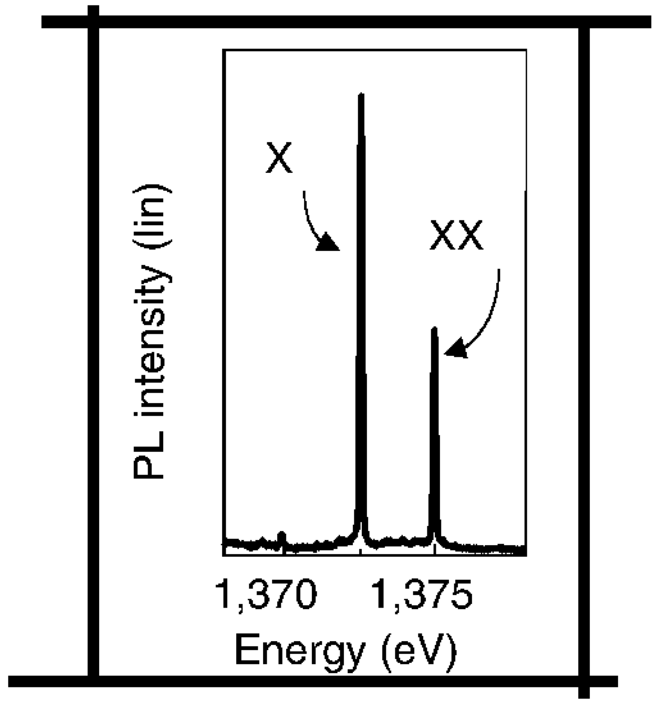
Strategies for single photon generation

Injection controlled by Coulomb blockade (Yamamoto et al, Nature 99)



T<0.1K, no microcavity yet

Implement Coulomb interaction between trapped charge carriers



More efficient!

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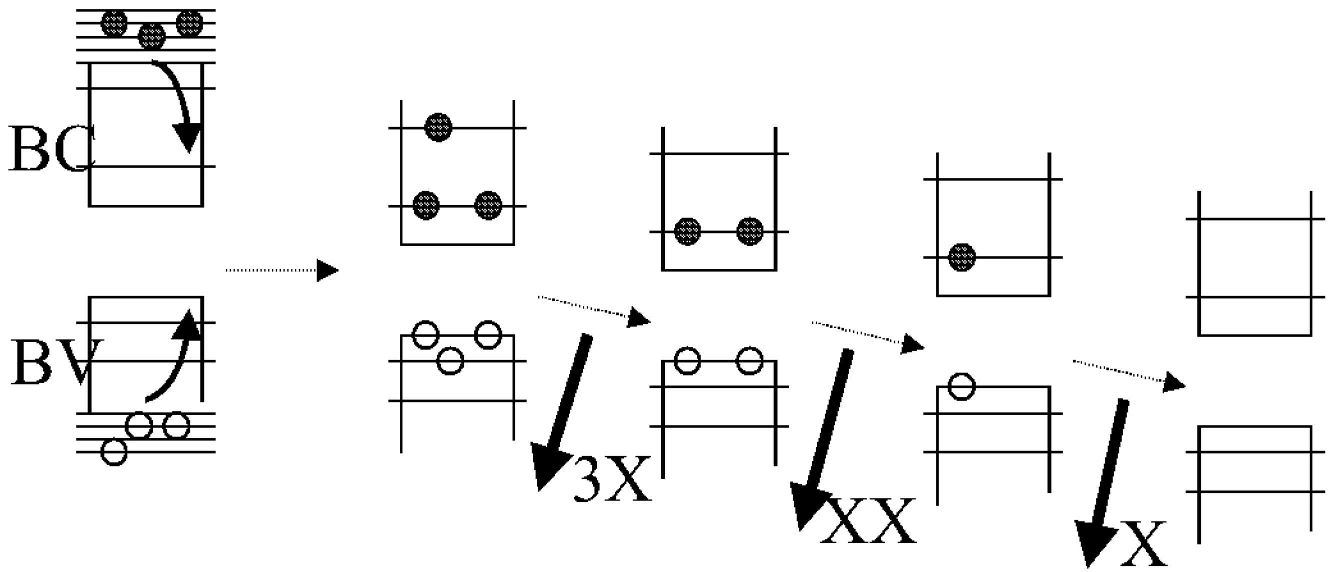
Single photon generation from a QD

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



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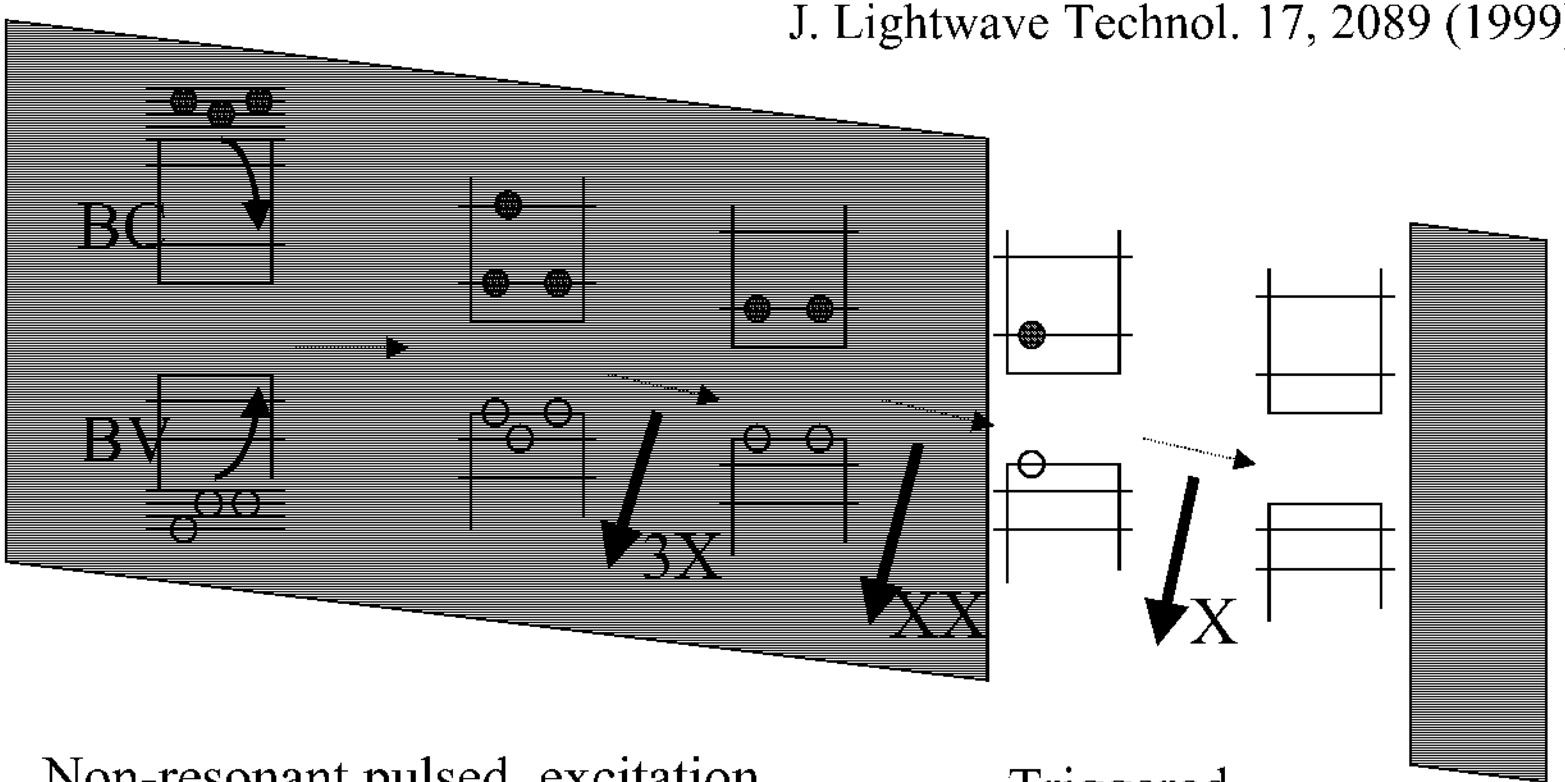

+ Non-resonant pulsed excitation
Spectral filtering

=> Triggered
Single photon

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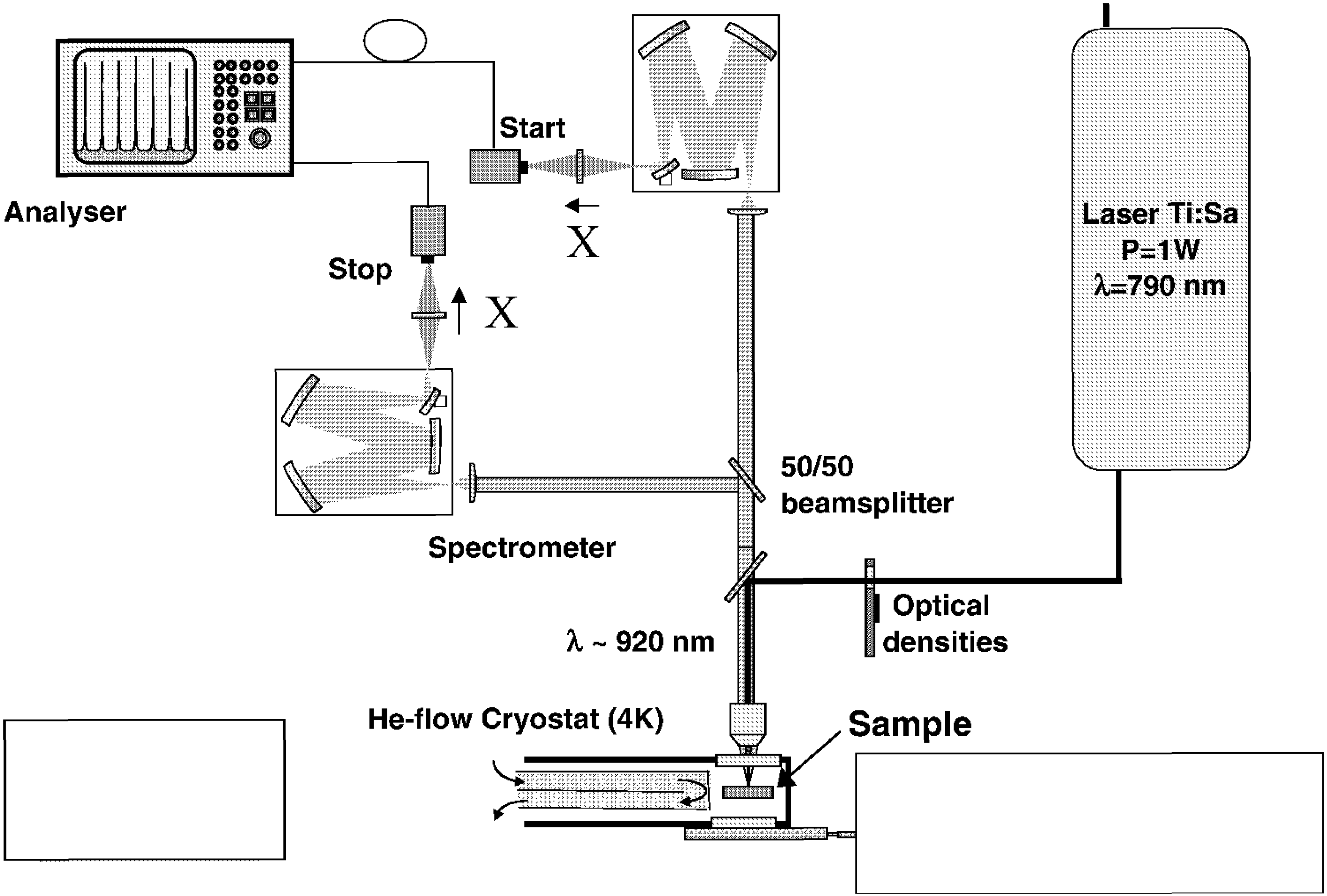
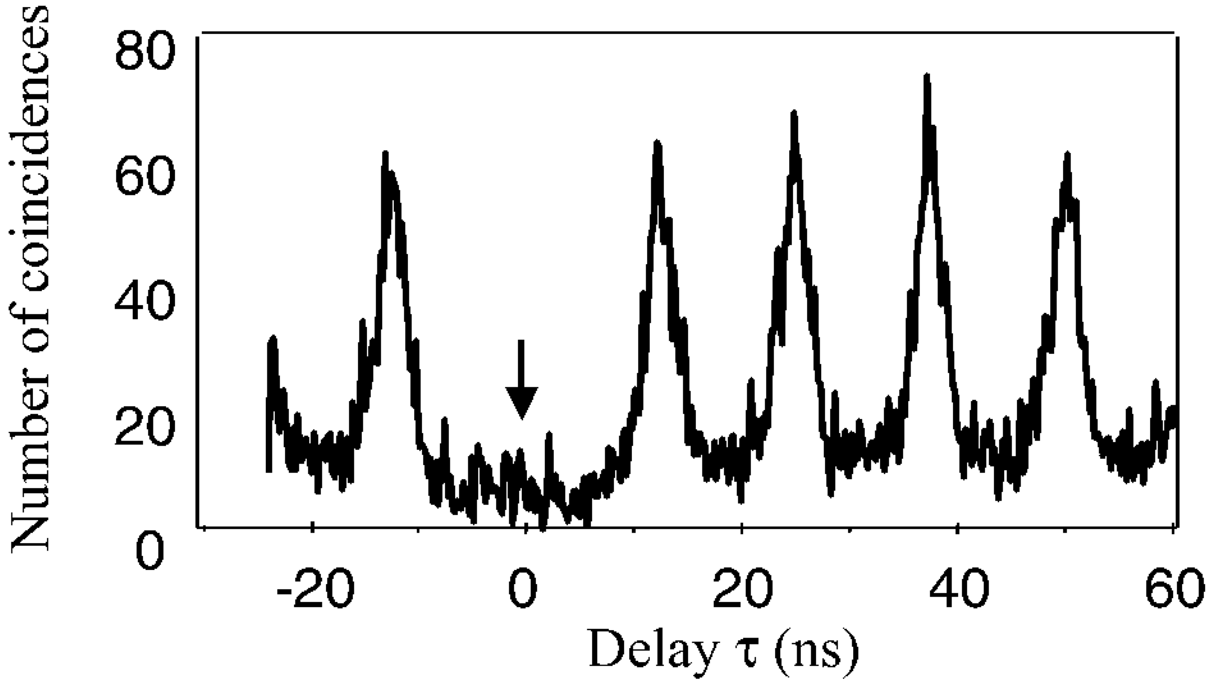
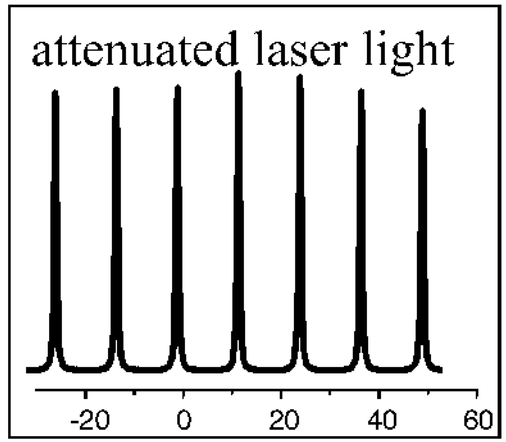
Photon correlation setup



X line correlation histogram

First reports: P. Michler et al, Science 290, 2282 (2000)
C. Santori et al, PRL 86, 1502 (2000)





« X » photons are emitted one by one

Protocol works also for electrical pumping (Yuan et al, Science 195, 102, 2002)

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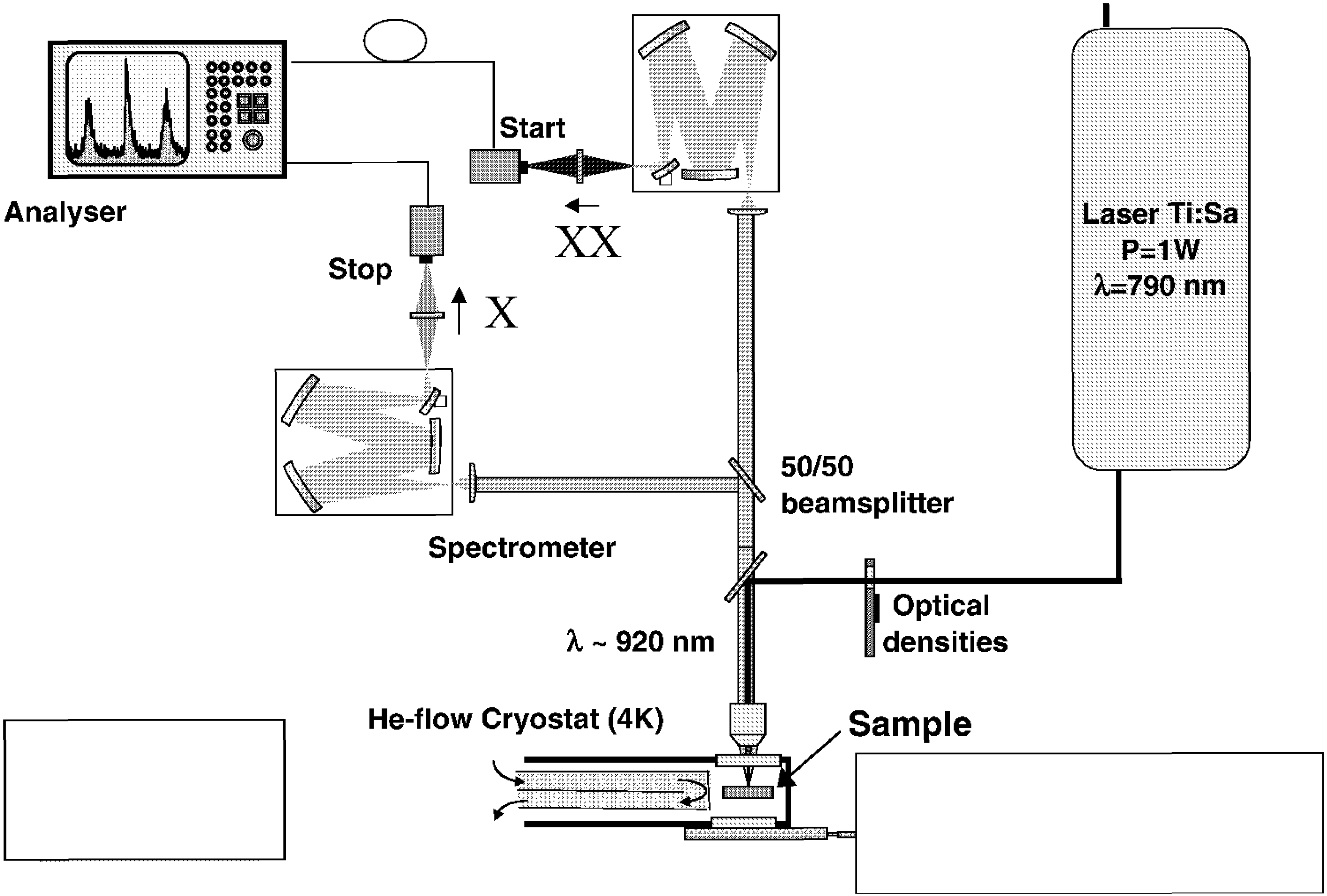
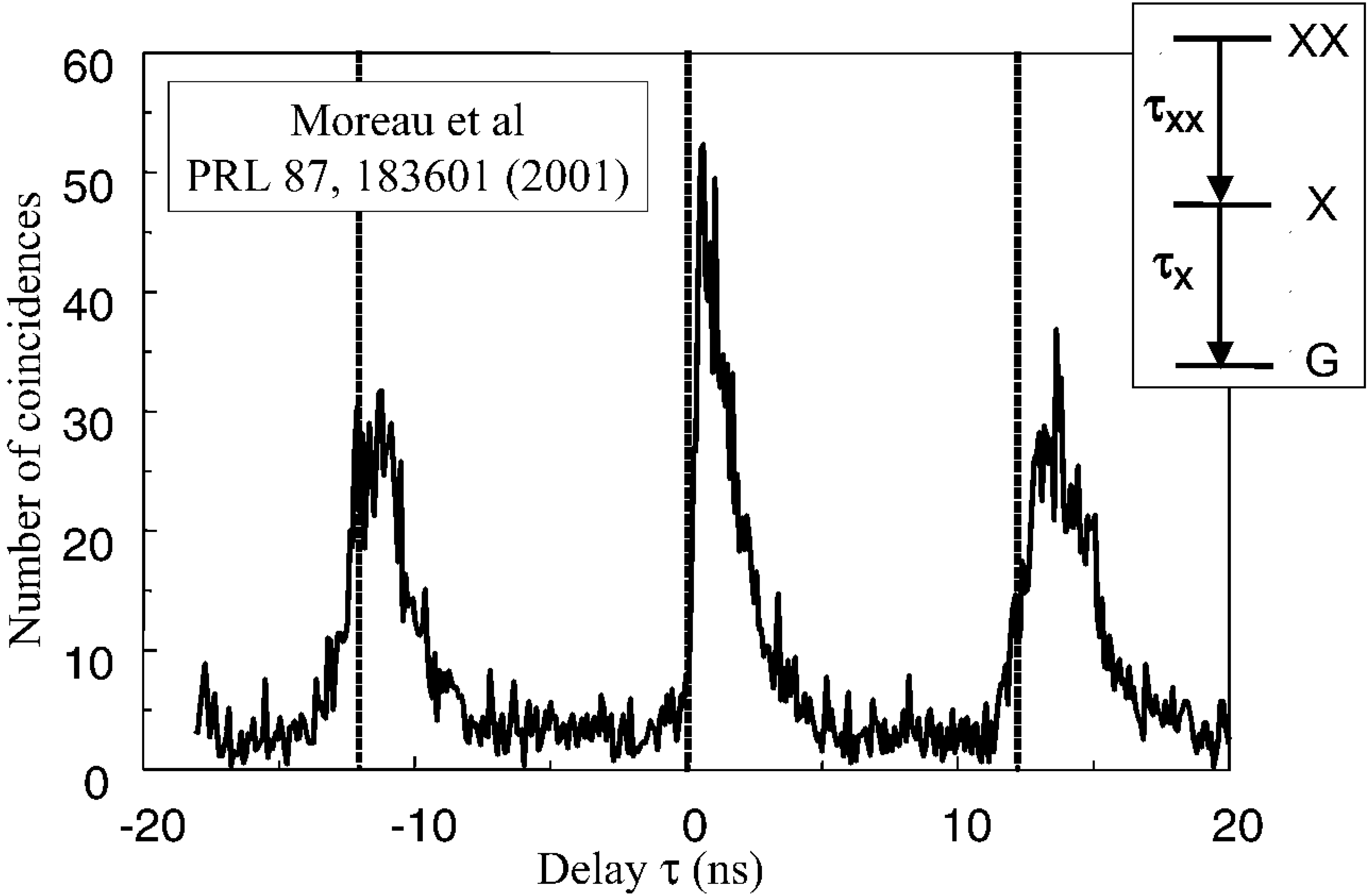
Photon correlation setup



Cross-correlations between X and XX photons



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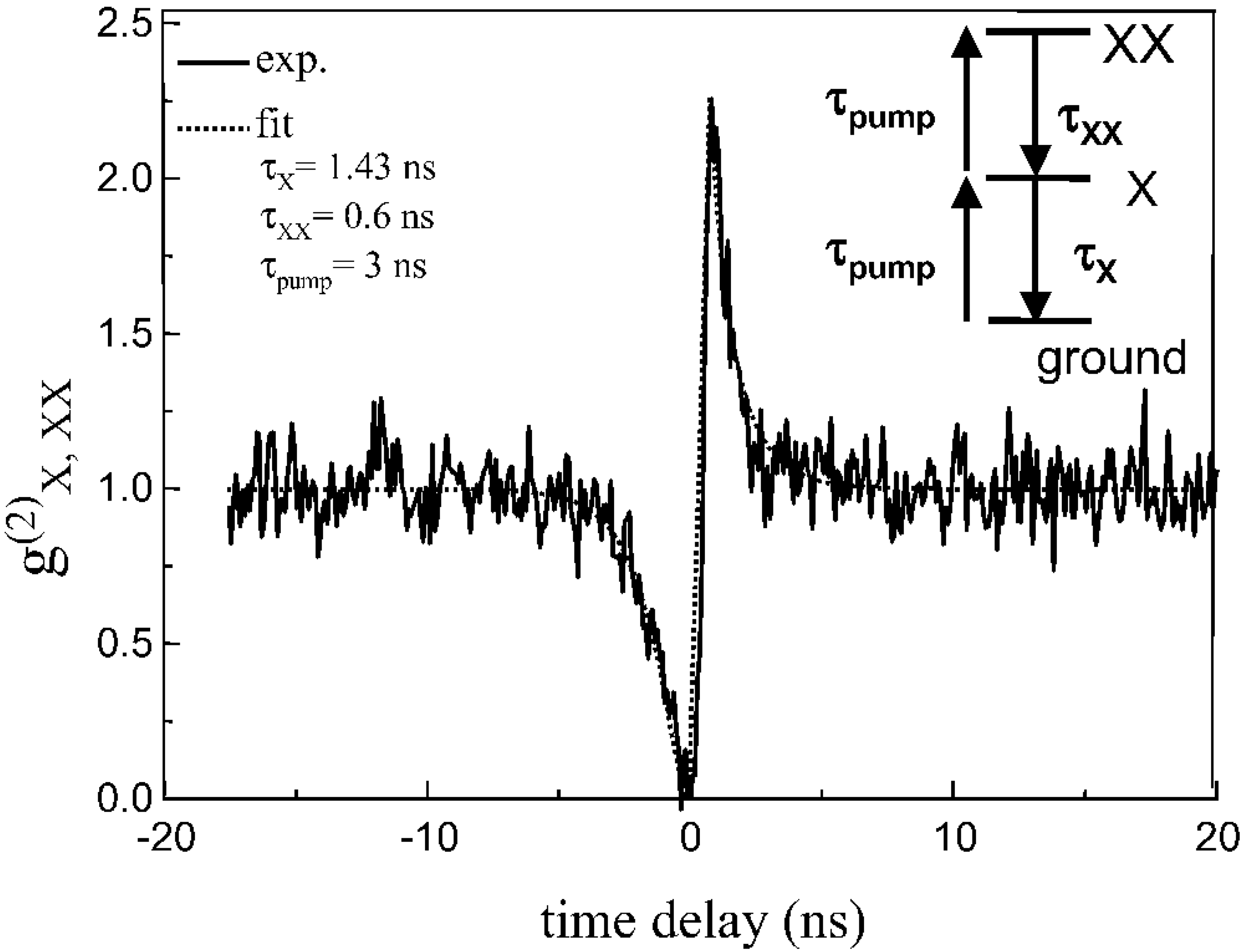
Cross-correlations (cw excitation)

Moreau et al
PRL 87, 183601 (2001)

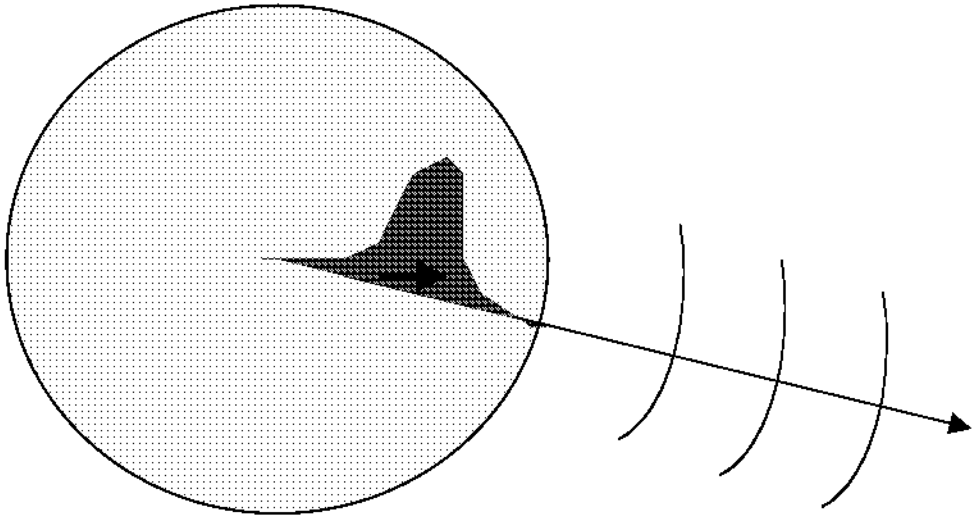


.Both bunching and antibunching

. First observation of a behavior predicted in 1979 ! (Cohen-Tannoudji et al)

How to collect/prepare the single photons?

1) True single-mode cavity = photonic crystal + defect

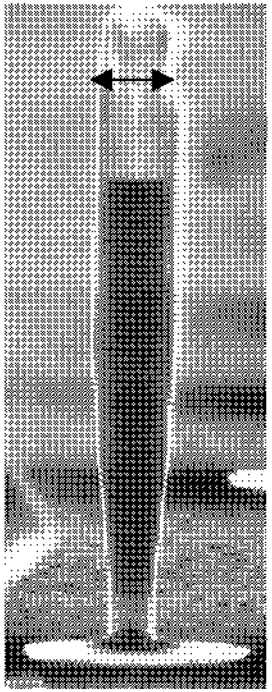


$\beta = 1$

E. Yablonovitch, PRL, 2238 (1991)

Some 3D solid-state microcavities

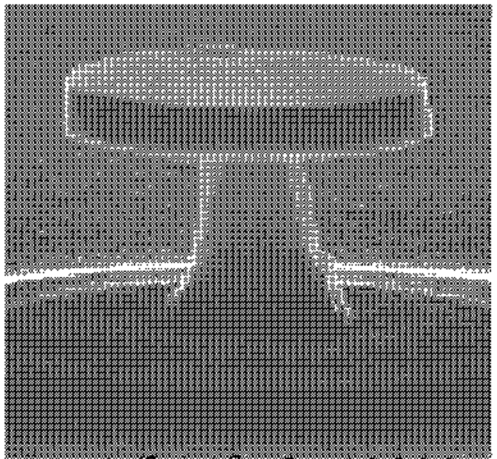
1 µm



V=5 $(\lambda/n)^3$, Q=2100

F_p=32

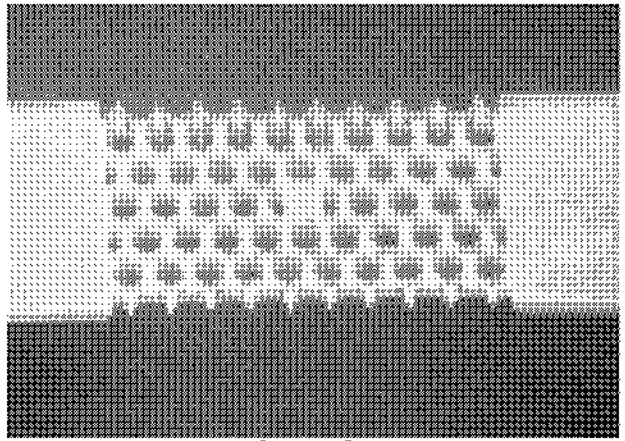
2 µm



V=6 $(\lambda/n)^3$, Q=12000

F_p =150

3 µm



V=0.43$(\lambda/n)^3$, Q=2800

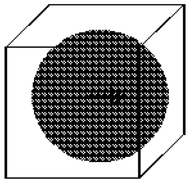
F_p=390 (Caltech)

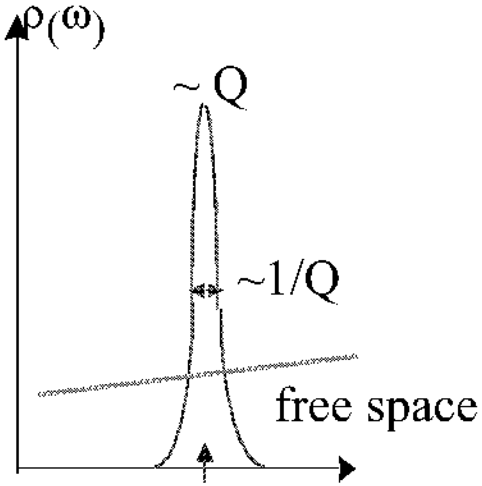
High Q, 3D confined modes

but not perfect « photonic dots » (leaky modes)!

The « Purcell effect »

weak coupling regime ➡ $\frac{1}{\tau} \propto \rho(\omega)\left|\left\langle i\left|\vec{d}.\vec{\varepsilon}\right|f\right\rangle\right|^2$





$F_{p=}$ magnitude for an ideal emitter

.quasi-monochromatic
.spatial matching
.spectral matching

Purcell (1946)

$$\frac{\tau_{free}}{\text{[redacted]}} = \frac{3}{4\pi^2}\frac{Q(\lambda/n)^3}{V}$$

↖ F_p

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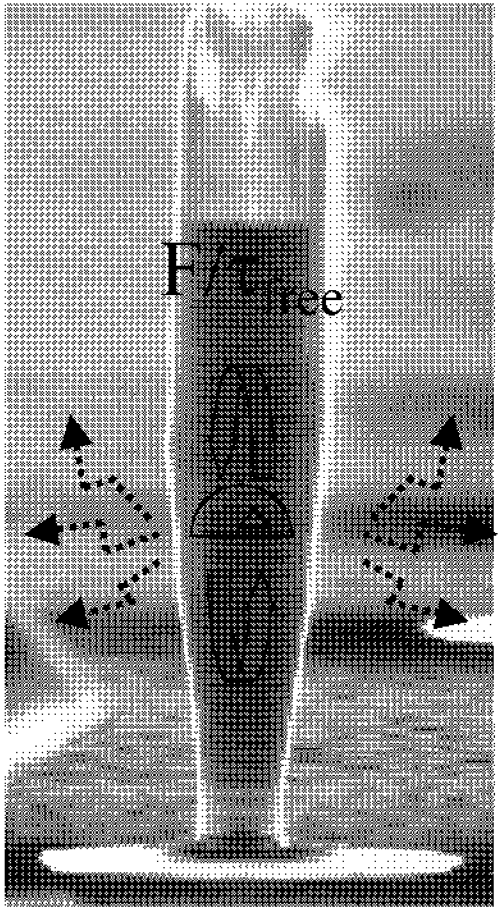
Purcell effect on InAs QDs

1997: First observation of the Purcell effect for a solid-state emitter!

QD array in micropillar	x 5	*J.M. Gérard et al, PRL 81, 1110 (1998)*
QD array in microdisk	x 18	*B. Gayral et al, Physica E7, 641(2000)*
	x 12	*B. Gayral et al, APL 78, 2828 (2001)*
single QD in microdisk	x 6	*A. Kiraz et al, APL 78, 3932 (2001)*
single QD in micropillar	> x 3	*E. Moreau et al, APL 79, 2865 (2001)*
		G. Solomon et al, PRL 86, 3903 (2001)

(Nearly) single-mode spontaneous emission



γ/τ_{free}

(γ~1)

Purcell effect

=

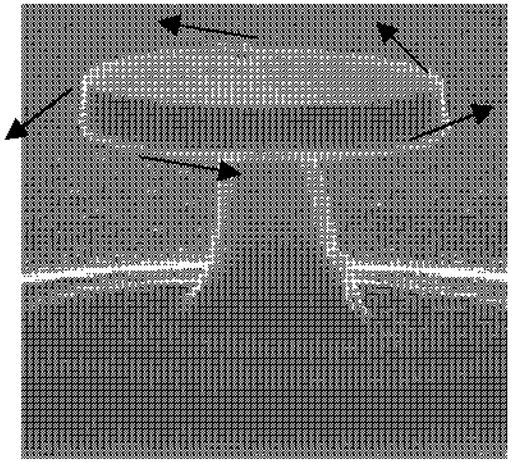
<u>selective</u> enhancement of SE into the resonant mode

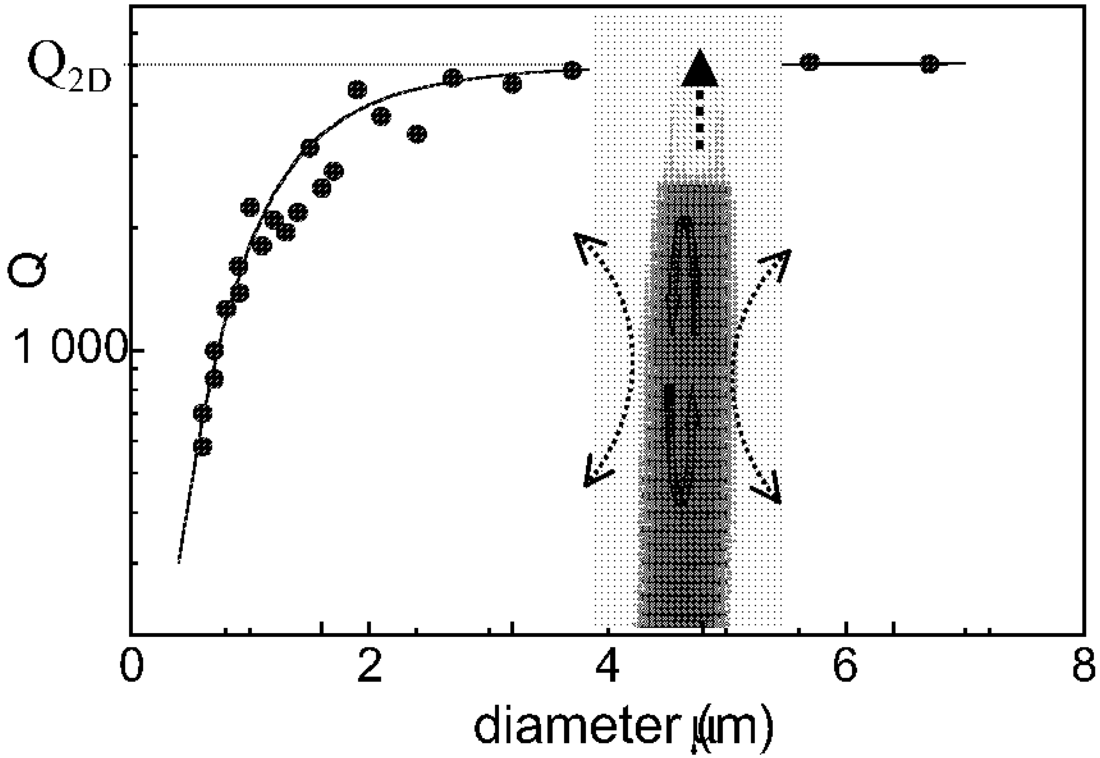
$$\beta = \frac{F}{F+\gamma} \approx 1$$

J.M. Gérard et al, PRL 81, 1110 (1998)

The photon collection issue

Beware !
SPS efficiency ≠ β





scattering by sidewall roughness !

$\varepsilon < \beta$

S

SPS efficiency for GaAs/AlAs micropillars

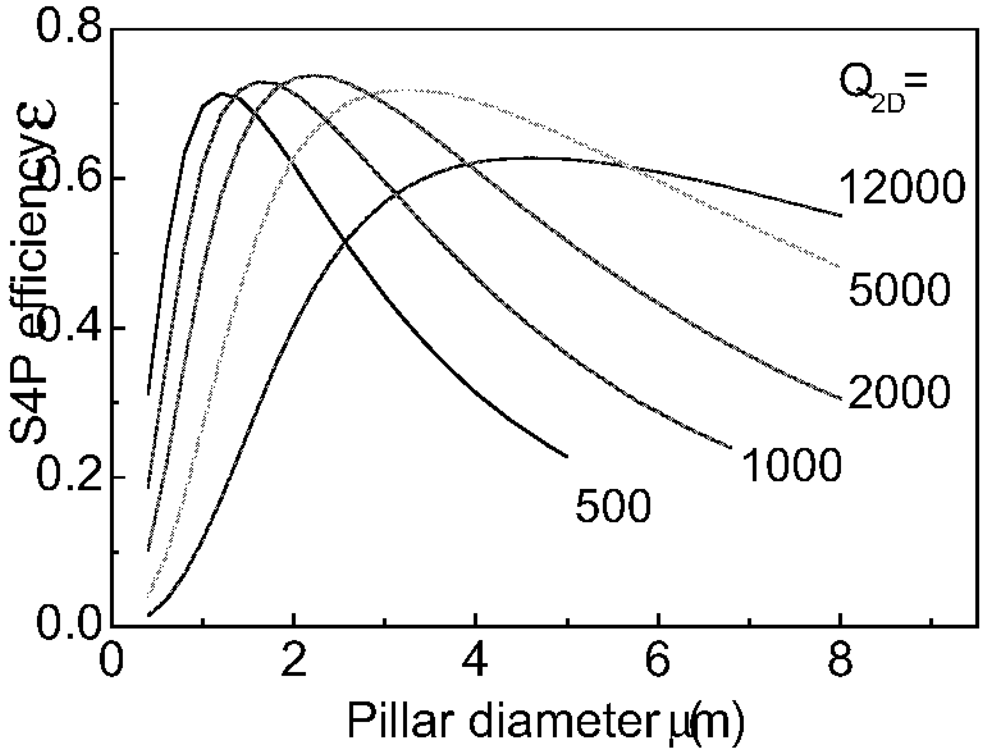
scattering by
sidewall roughness

Q spoiling ↔ $\varepsilon < \beta$

$$\frac{1}{Q} = \frac{1}{Q_{2D}} + \frac{1}{Q_{scat}}$$

⇓

$$\varepsilon = \beta \frac{Q}{Q_{2D}}$$



Efficiencies around 70%
can be reached for state of the art pillars

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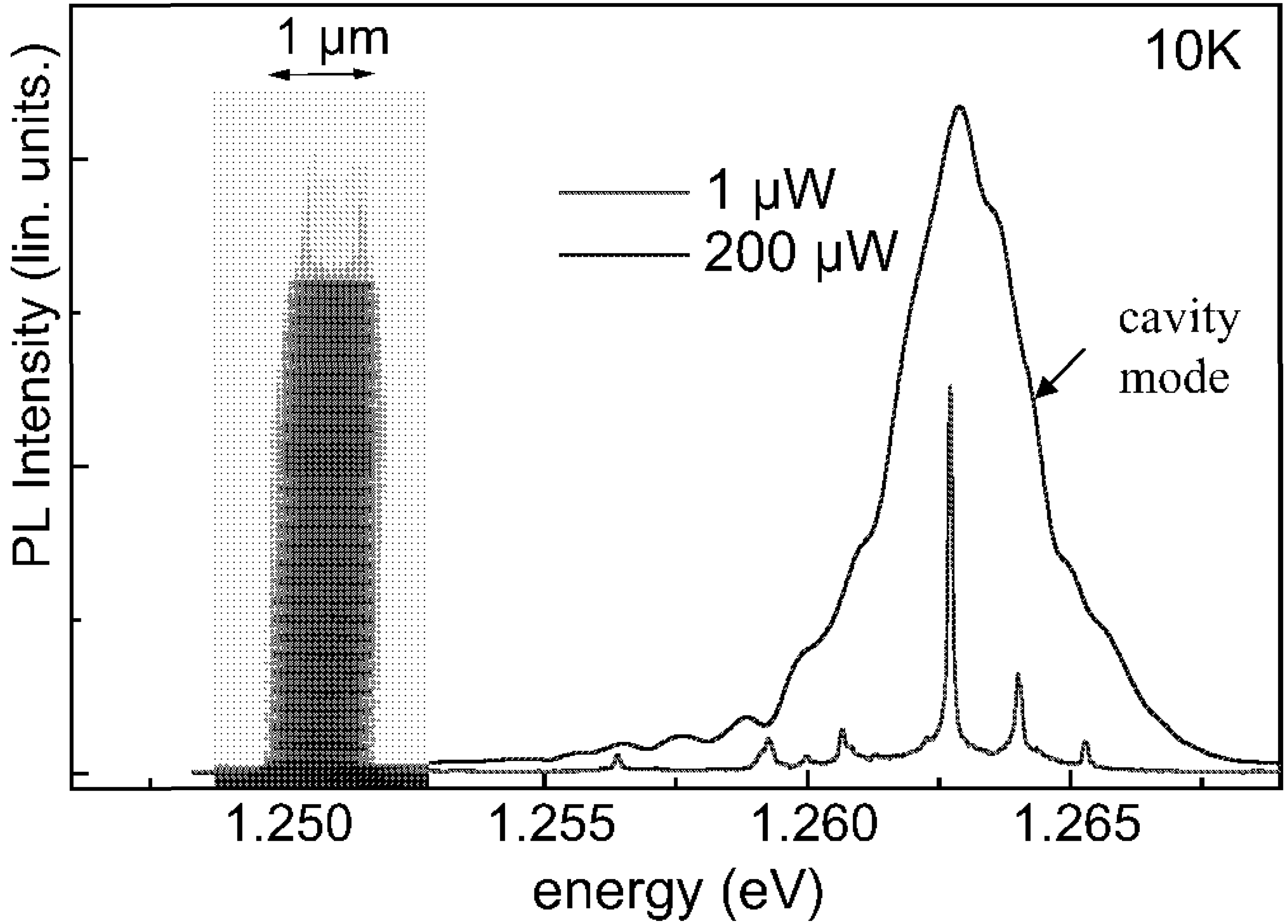
Few QDs in a micropillar



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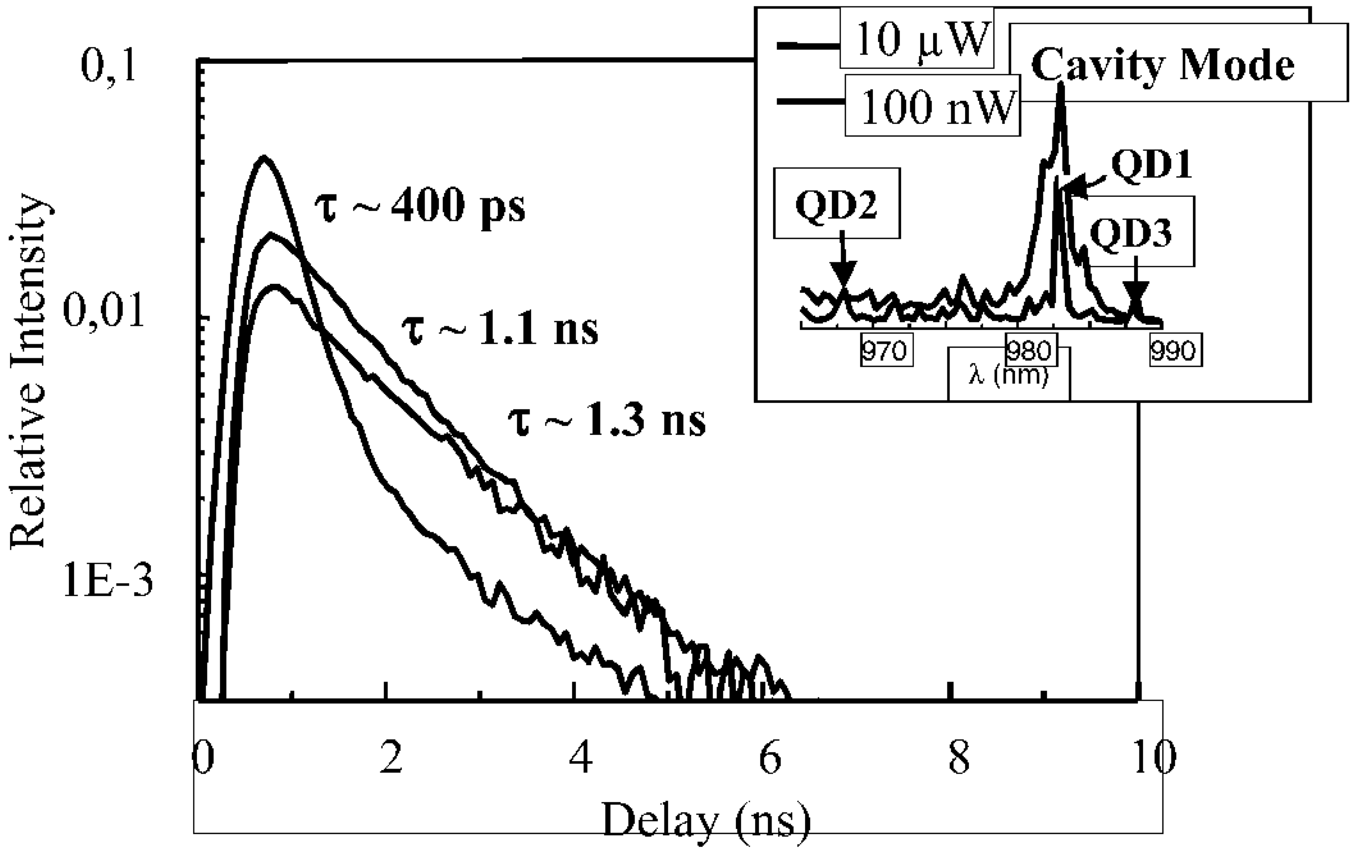
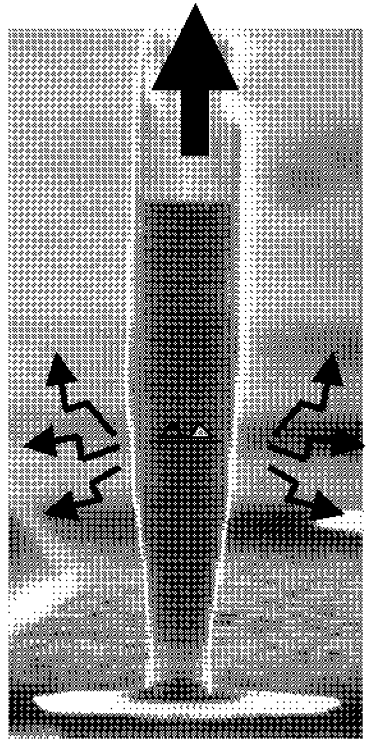
Purcell effect on isolated QDs in a micropillar (Q_{2D}=1000, Q=500, Fp=7)





$F > 3$ $0.66 < \beta < 1$ $0.33 < \varepsilon < 0.5$

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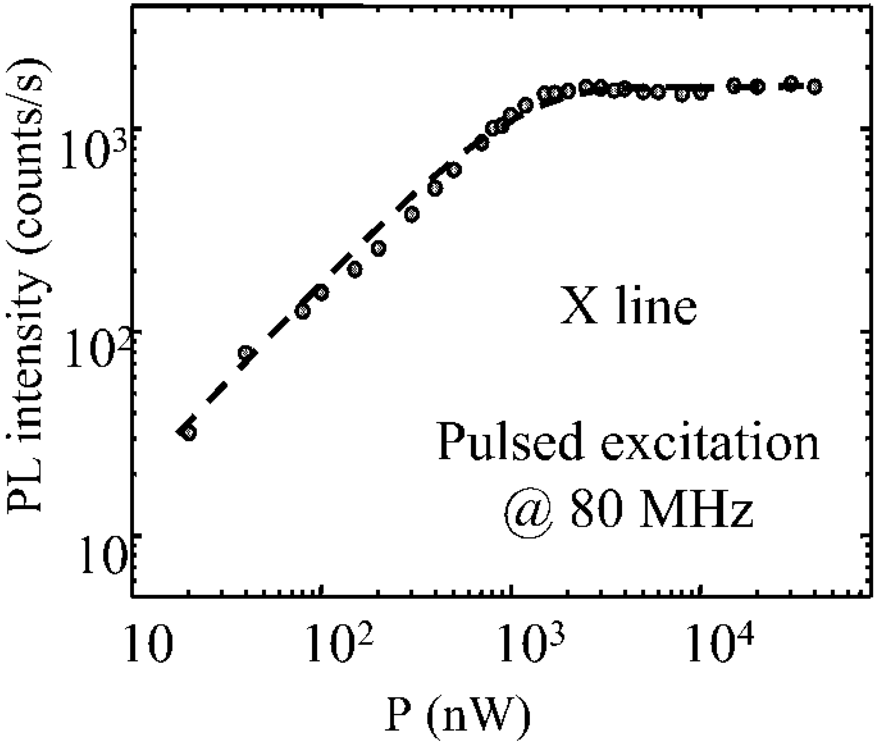
Experimental estimate of the SPS efficiency ε



. Saturation of the X line
=>1 photon emitted per period

. Signal:
4.8 10-4 counts per period

. collection/detection
efficiency of the set-up
~ 1.1 10-3

ε ~ 0.44

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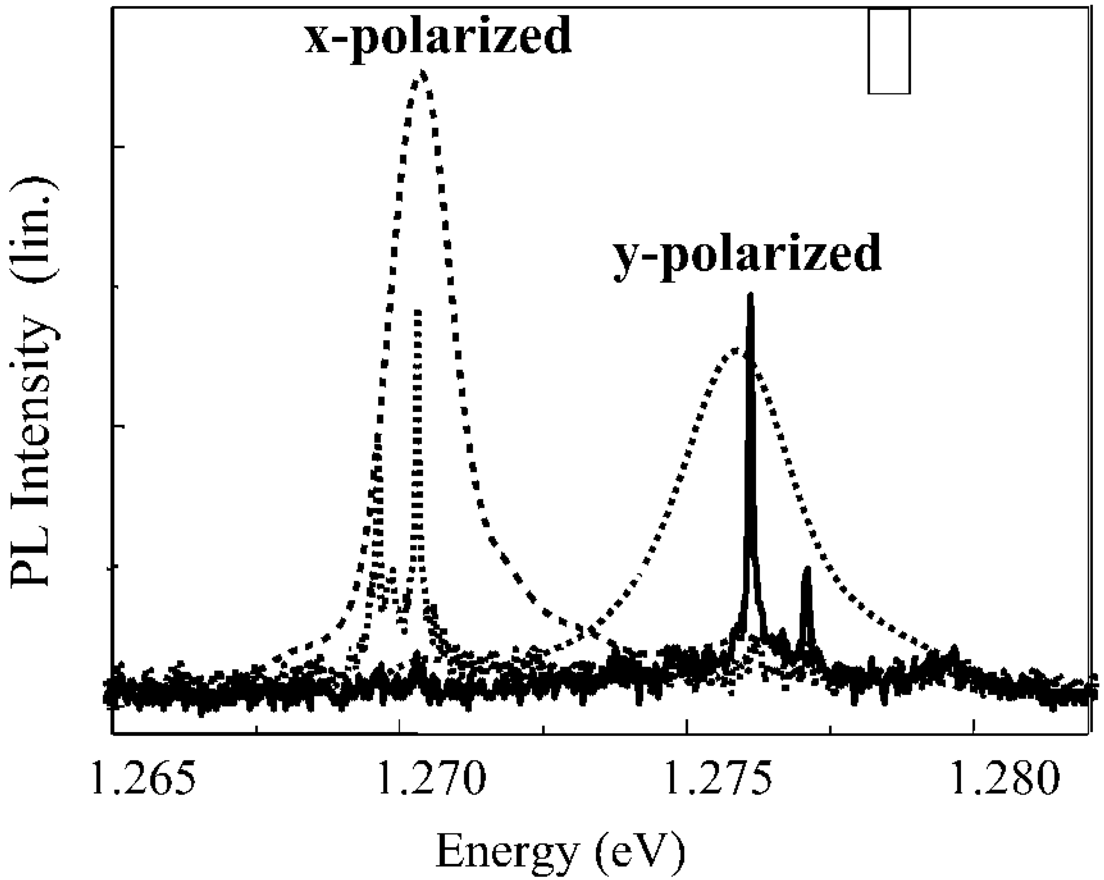
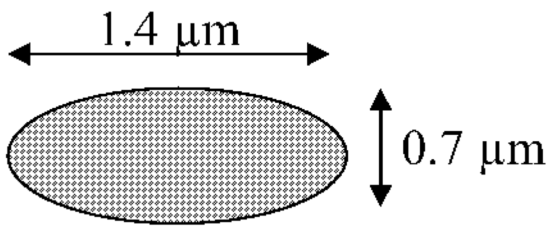
Polarization control in single-mode micropillars



Elliptical cross section



Non degenerate fundamental mode
Gayral et al, APL 72, 1421, 1998

~ 90% linear polarisation degree of single QD emission
Moreau et al, APL 79, 2865, 2001

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Conclusion

Single QD in a micropillar:

-> first single-mode single-photon source

-> first optoelectronic device based on a CQED effect

Already much better for QKD than attenuated laser diodes

-> efficiency > 40% demonstrated (70% within reach)

-> 5-fold reduction of two-or-more-photons pulses

=>secure transmission length↗ , bit rate↗

But T<50K, λ ~1 μm…

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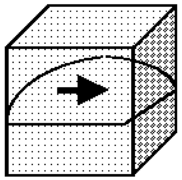
Prospects for QD-SPS

Extension at 1.3 µm   (good InAs/GaAs QDs are available)
Electrical pumping of single QDs in VCSEL like structures

High temperature operation:
. T~77K achievable for truly single InAs QDs
. T~ 300K likely for II-VI single QDs with giant X-XX splitting

Fourier-transform-limited single photons for quantum computing
. Requires $T_2 = T_1/2$!
. Control of decoherence processes $T_2 \uparrow$ (see invited talk by G. Cassabois)
. $T_1 \downarrow$ through the Purcell effect

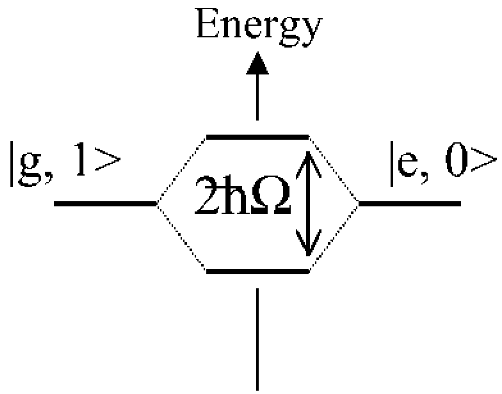
CQED : strong coupling for single QDs?



|ground, 1 photon>

Ω_{rabi}

|excited, 0 photon>



$$\hbar\Omega = |\vec{d} \cdot \vec{\mathcal{E}}_{max}|$$

InAs QD in solid-state cavity :

large dipole (0.6 *e*.nm)

huge vacuum field (10^5 V/cm)

vacuum Rabi splitting observable ⇔ $2\hbar\Omega > \Delta E_{emitter} + \Delta E_{cavity}$

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CNRS cea

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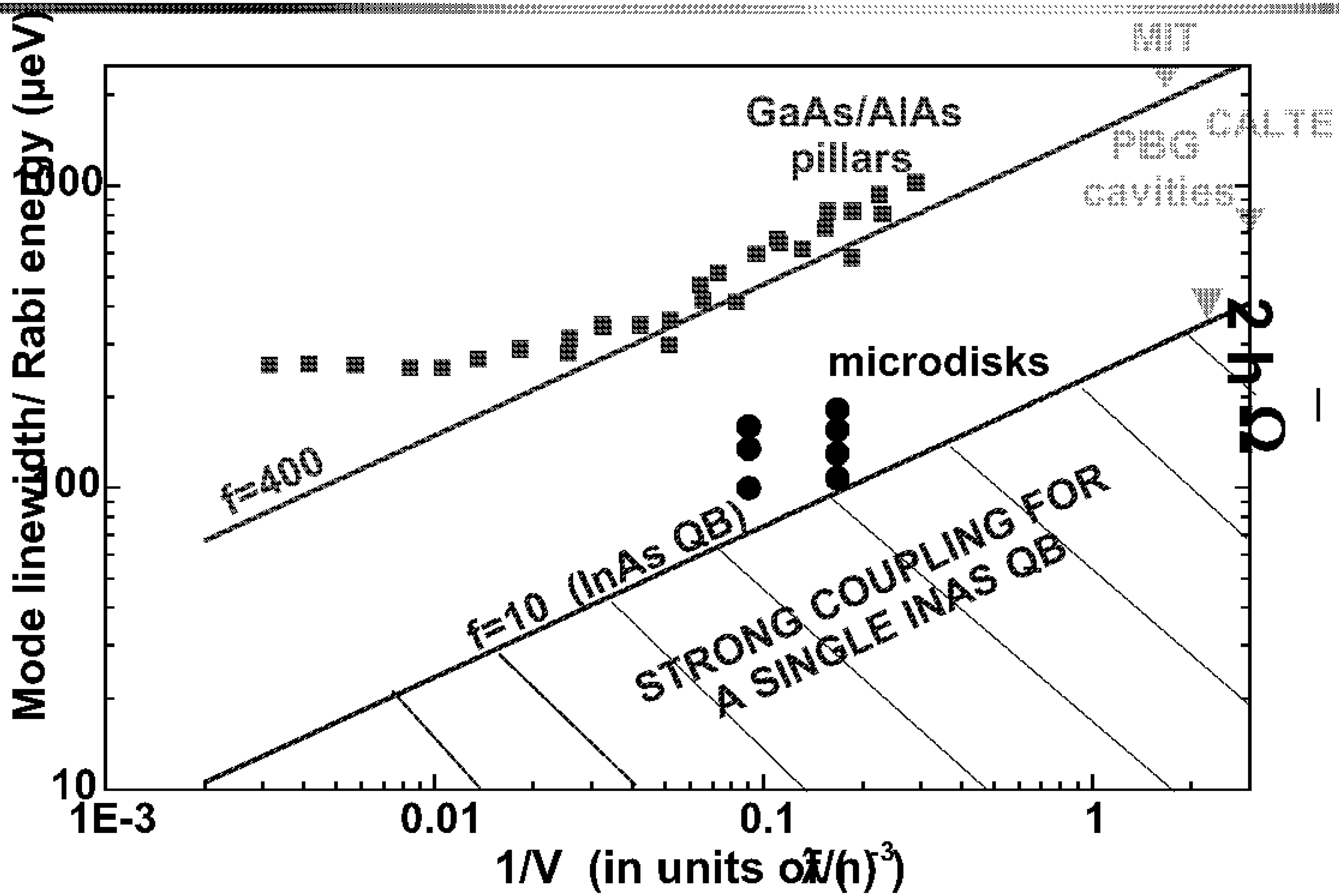
Strong coupling for single QDs ?

Gérard et al, Physica E9, 131 (2001)
Andreani et al, PRB 60, 13276 (1999)



Microdisks are the best candidates for InAs QDs
Interest of QD with larger oscillator strength (QW interface fluctuations)

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