Quantum photonics and its applications

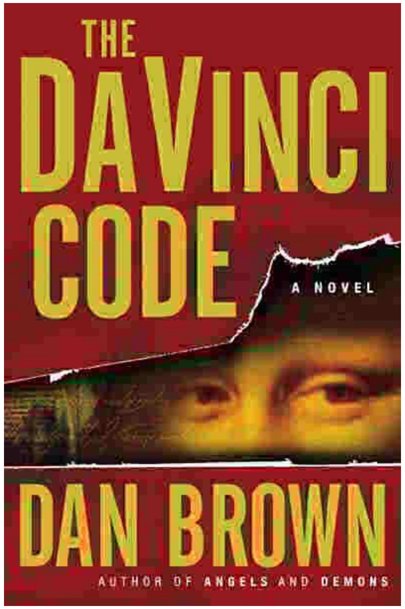
Assoc Prof Christophe Couteau

Laboratory « Light, nanomaterials & nanotechnologies »
CNRS-ERL 7004

University of Technology of Troyes

Location : city of Troyes

History…



& nanotechnology

Birth place of the Templar's knights

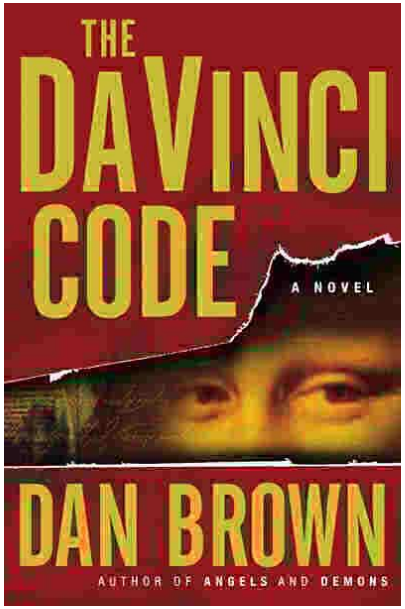
University of Technology of Troyes

Location : city of Troyes

Province name : « Champagne »

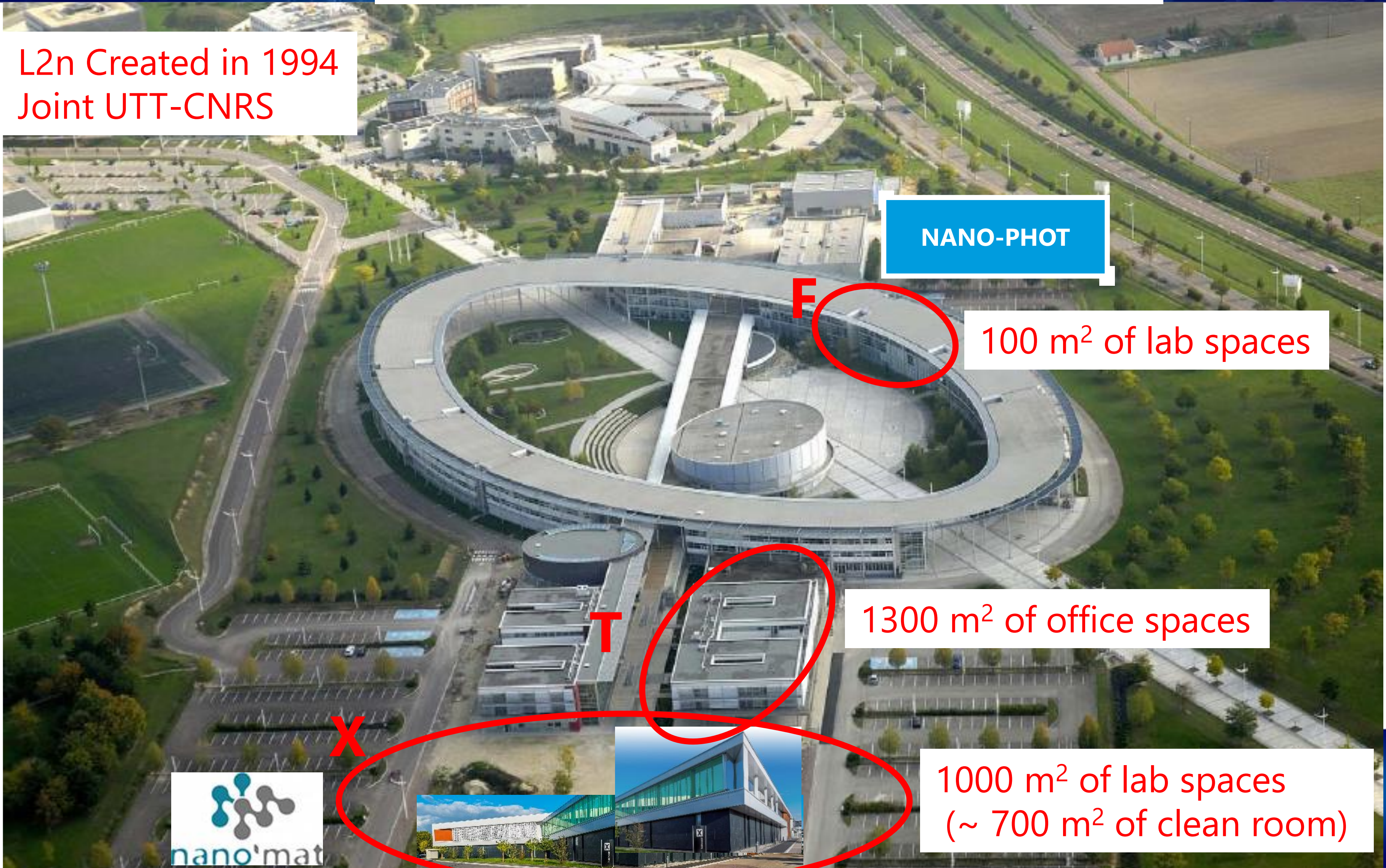
History…

& nanotechnology



Birth place of the Templar's knights

L2n laboratory at the UTT



L2n Created in 1994
Joint UTT-CNRS

100 m^2 of lab spaces

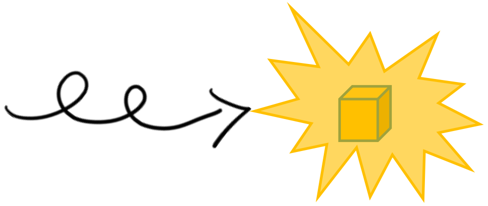
1300 m^2 of office spaces

1000 m^2 of lab spaces
(~ 700 m^2 of clean room)

L2n research signature

Observe Study Control

… light at the nanoscale

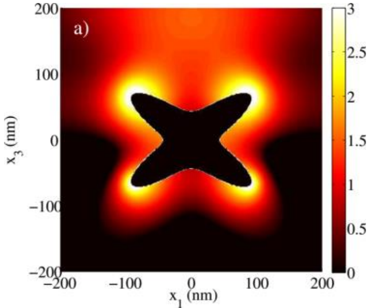


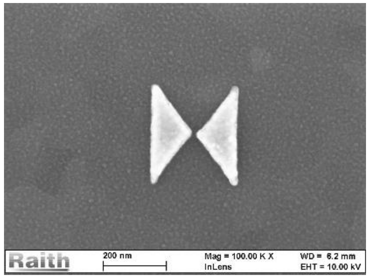
$\ll \lambda$

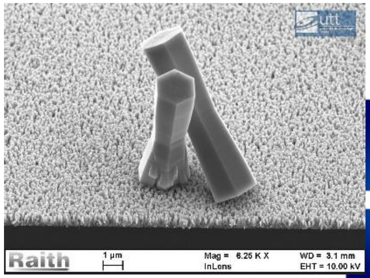
Numerical modeling & simulation

Instrumentation & fabrication

Material growth





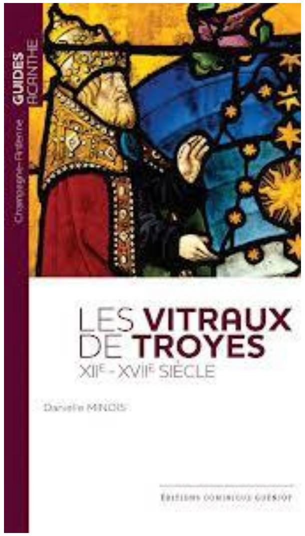


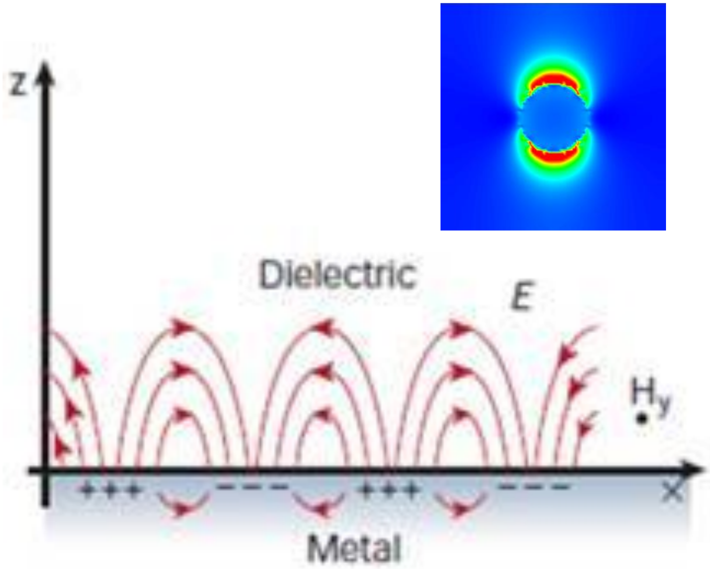
Troyes: city of nano

Troyes: the stain-glass city = city of nano

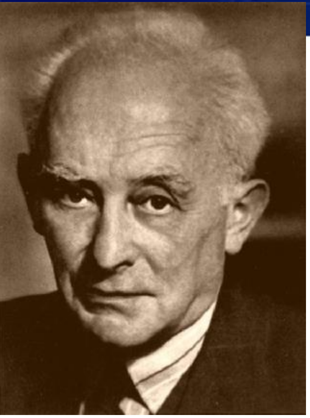
1/3 of medieval stain-glass of France in Troyes

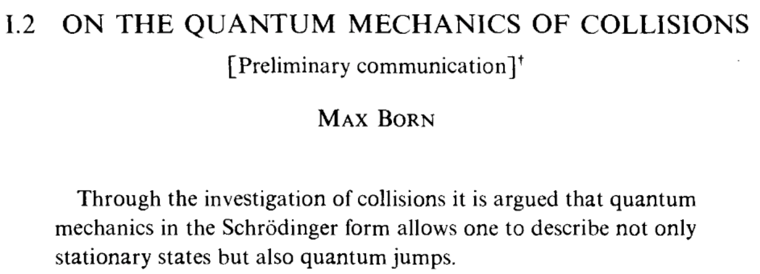
Metallic nanoparticles - plasmonics





Born's rule





I.2 ON THE QUANTUM MECHANICS OF COLLISIONS

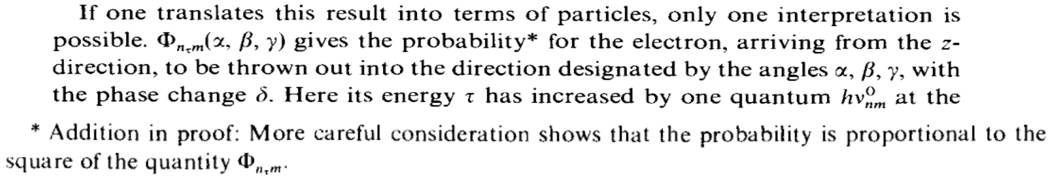
[Preliminary communication]†

MAX BORN

Through the investigation of collisions it is argued that quantum mechanics in the Schrödinger form allows one to describe not only stationary states but also quantum jumps.

$$|\Psi(\mathbf{r},t)|^2 = \Psi^*(\mathbf{r},t)\Psi(\mathbf{r},t)$$

Nobel Prize in 1954



If one translates this result into terms of particles, only one interpretation is possible. $\Phi_{n_\tau m}(\alpha, \beta, \gamma)$ gives the probability* for the electron, arriving from the z-direction, to be thrown out into the direction designated by the angles α, β, γ, with the phase change δ. Here its energy τ has increased by one quantum $h\nu^0_{nm}$ at the

* Addition in proof: More careful consideration shows that the probability is proportional to the square of the quantity $\Phi_{n_\tau m}$.

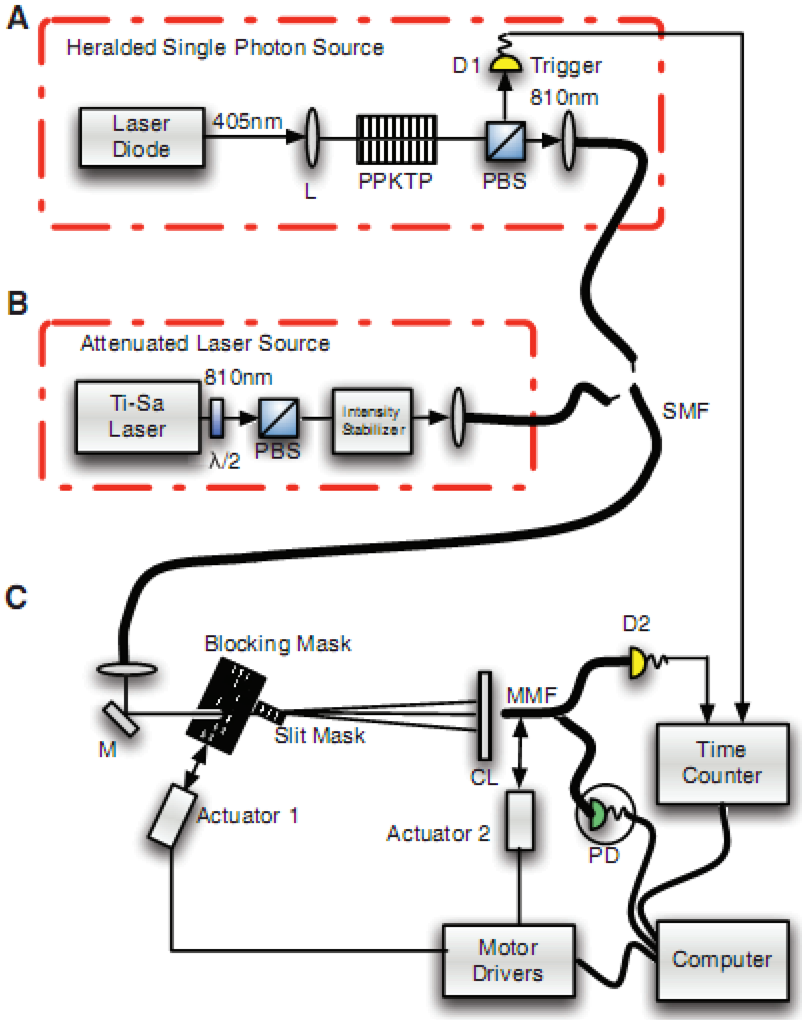
$$I(A) = P(A)$$
$$I(A,B) = P(A \sqcup B) - [P(A) + P(B)]$$
$$I(A,B,C) = P(A \sqcup B \sqcup C) - [P(A) + P(B) + P(C) + I(A,B) + I(A,C) + I(B,C)]$$
$$\vdots$$

REPORTS

Ruling Out Multi-Order Interference in Quantum Mechanics

Urbasi Sinha,[1]* Christophe Couteau,[1,2] Thomas Jennewein,[1] Raymond Laflamme,[1,3] Gregor Weihs[1,4]*

418 23 JULY 2010 VOL 329 SCIENCE www.sciencemag.org



Programme

|1> General context for quantum technologies
- → why should we care?

|2> How is it so different?
- → what about the market?

|3> Quantum technologies and qubits: the photon

|4> The need for a quantum emitter
- → definition of a quantum emitter
- → radiating dipole
- → zoology of quantum emitters

|5> Particular case: the quantum dot
- → semiconductor quantum emitter
- → artificial atom

|6> Application: quantum cryptography

|1> Why should we care?

→ Information technology and communication – ICT is everything !!!

ICT wall

→ suffers from two limitations given by nature: ICT → Quantum Info Tech QIT ?

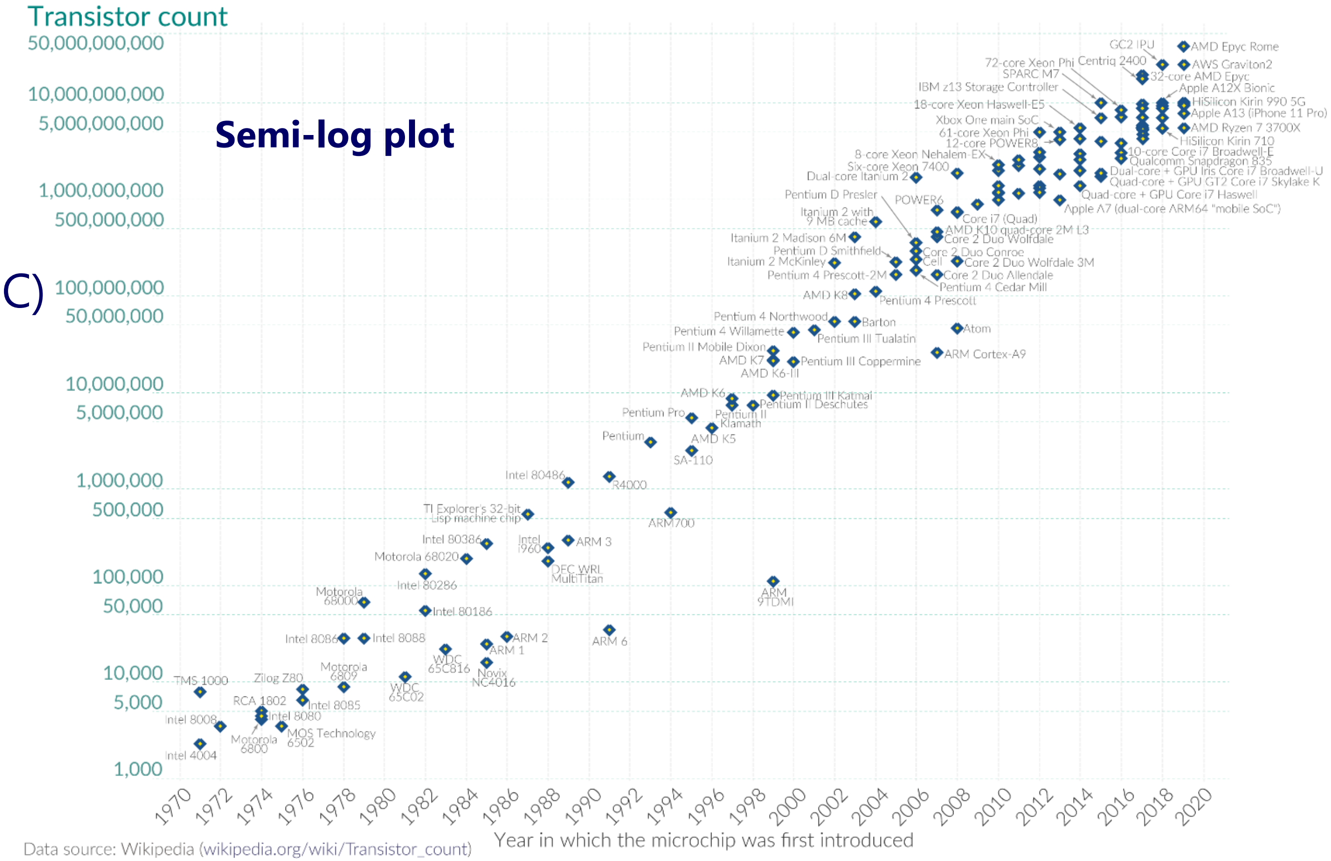
|1 > Why should we care?

→ Limitation 1:
end of Moore’s law

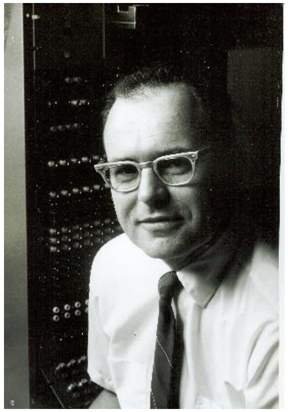
Observation: transistor #
in integrated circuit (IC)
X 2 every 2 years

slow down

Semi-log plot



Data source: Wikipedia (wikipedia.org/wiki/Transistor_count)
OurWorldinData.org – Research and data to make progress against the world’s largest problems.

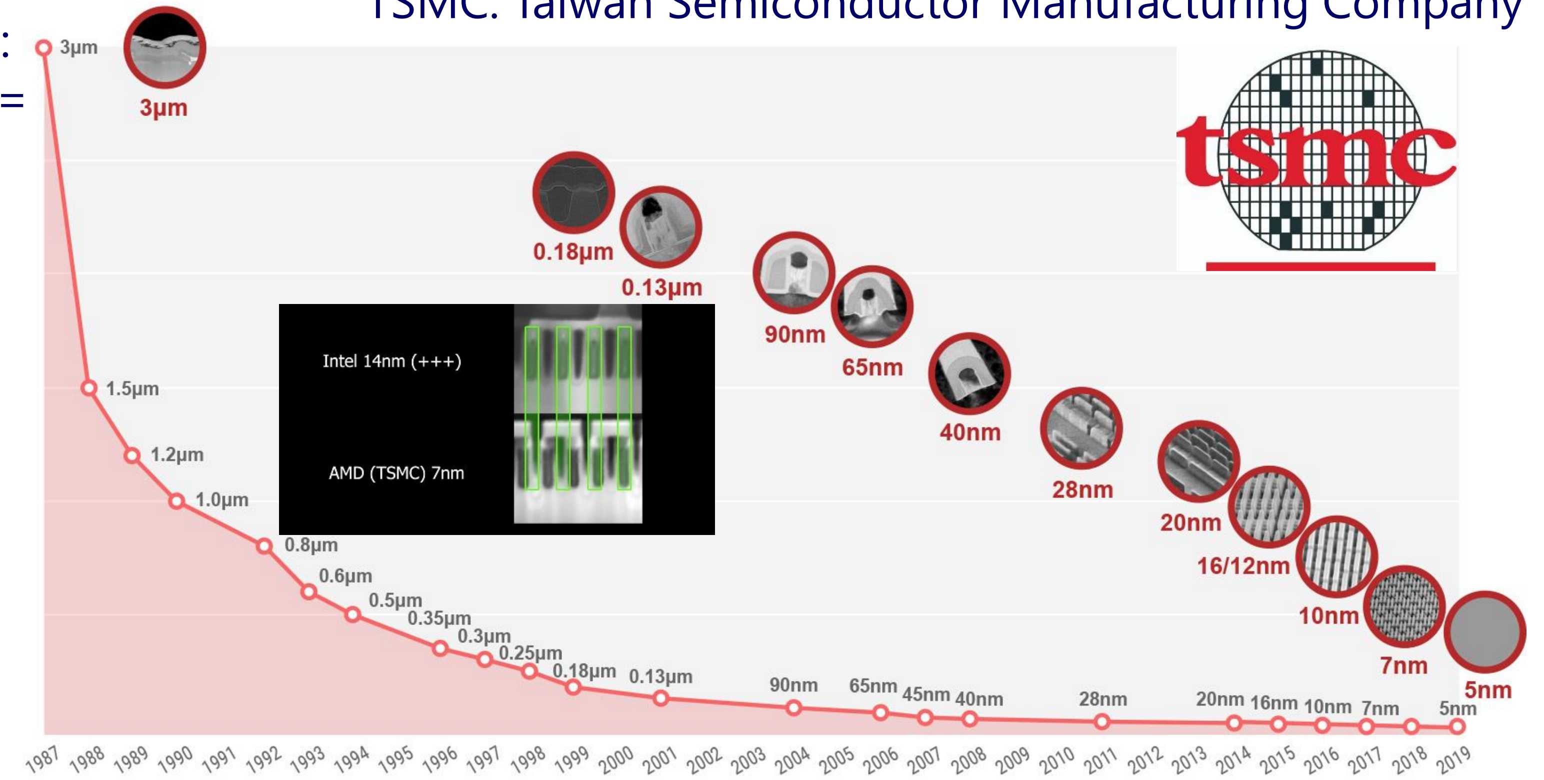


Gordon Moore (1929-):
CEO & co-founder of Intel

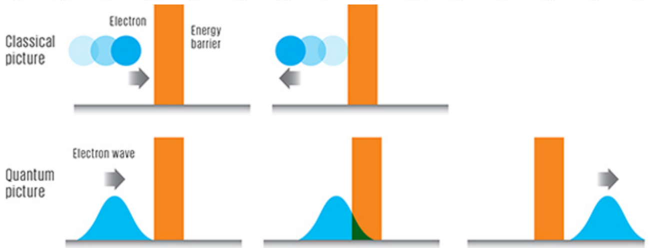
|1> Why should we care?

Size matters: 5 nm technology
TSMC: Taiwan Semiconductor Manufacturing Company

5 nm technology:
Gate oxide layer = Insulating layer



« Quantum tunneling » is the main issue !



|1> Why should we care?

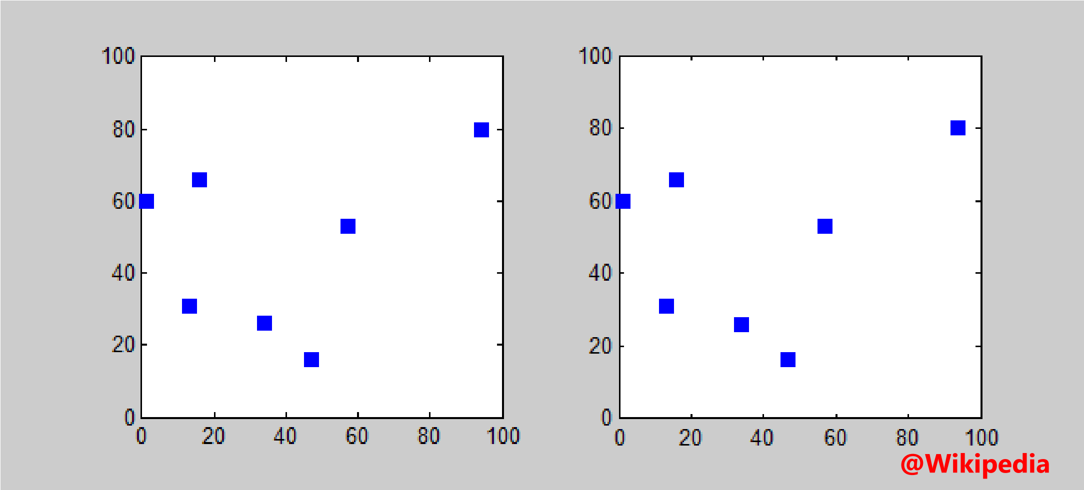
→ Limitation 2:

some problems are « unsolvable »

Traveling salesman problem:

"Given a list of cities and the distances between each pair of cities, what is the shortest possible route that visits each city exactly once and returns to the origin city?"

NP-hard problem in combinatorial optimization

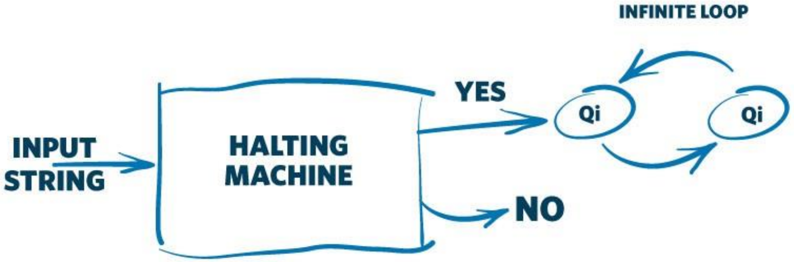


@Wikipedia

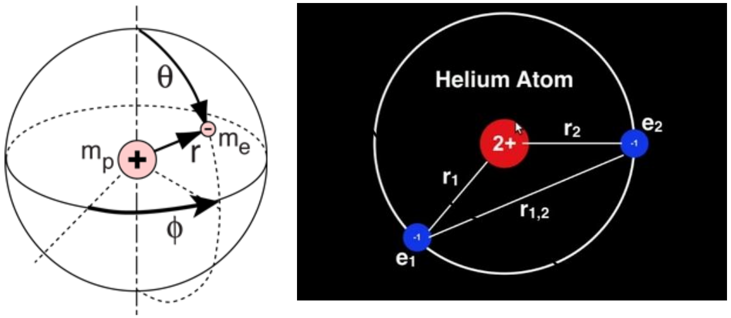
|1> Why should we care?

→ Limitation 2:
some problems are unsolvable

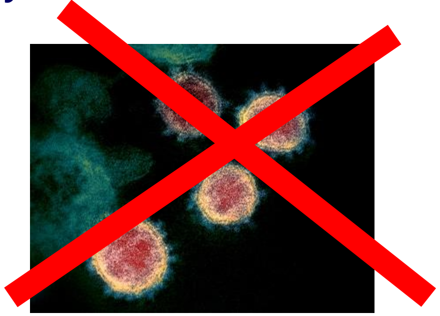
NP-hard = non-polynomial time to be solved



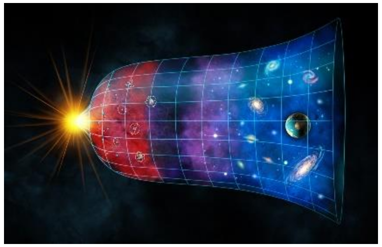
Halting problem



Solving energy levels in molecules



↳ Would take the age of the Universe:

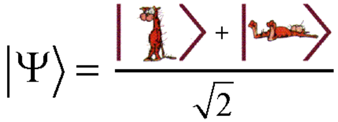


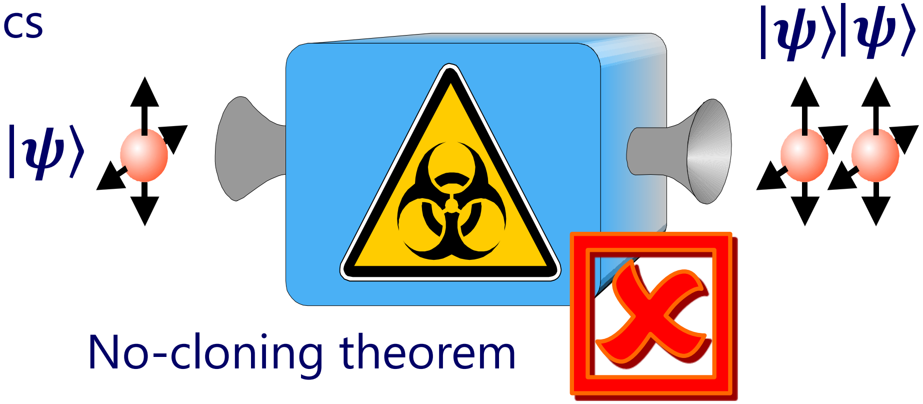
→ no computer now or ever...

|2> How is it so different?

→ Uses the law of quantum physics/mechanics

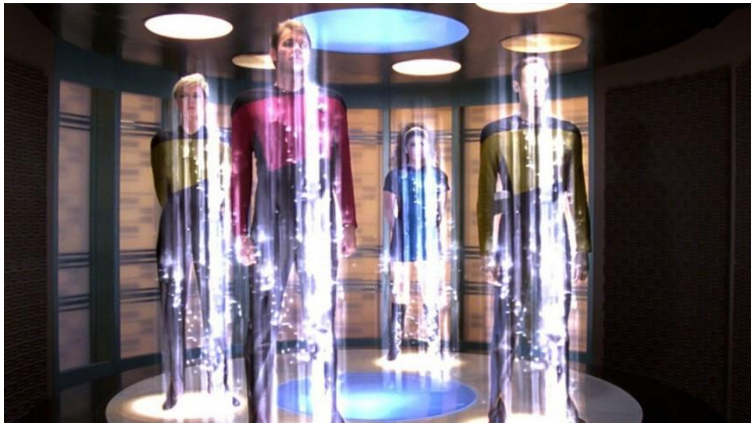

Quantum superposition


$|\Psi\rangle = \frac{|\;\rangle + |\;\rangle}{\sqrt{2}}$



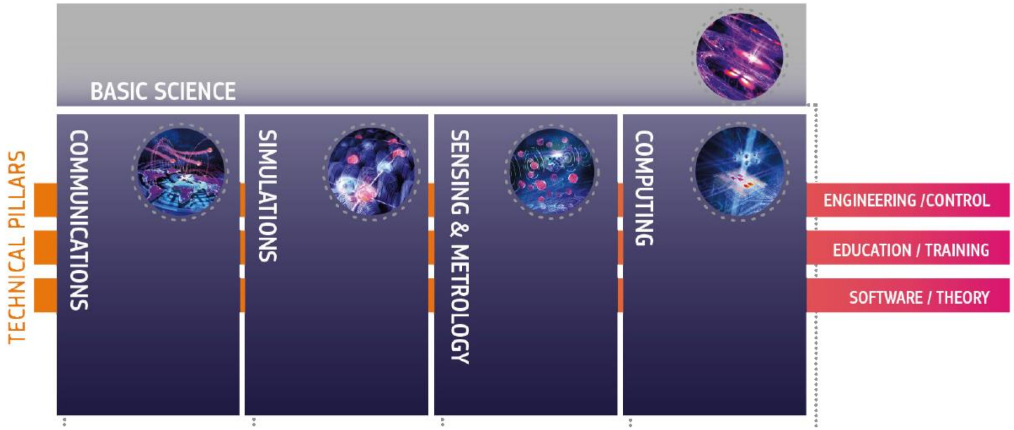
No-cloning theorem


Quantum entanglement


Quantum teleportation

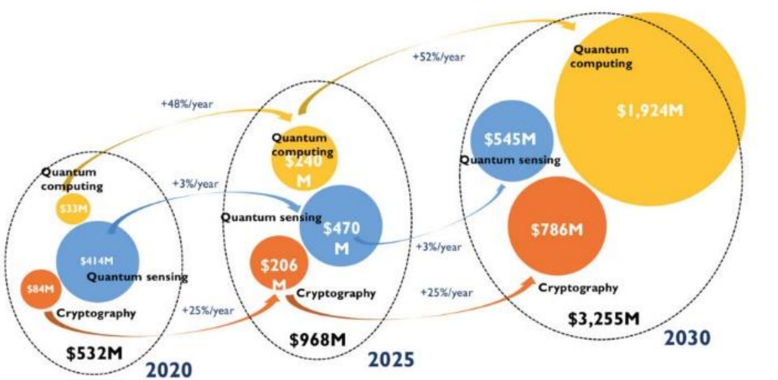
→ Quantum parallelism: concrete example of factoring
Potential applications : AI, optimisation, computation, sensing, communications…

|2> What about the market?



2020 – 2025 – 2030 quantum technologies forecast

(Source: Quantum Technologies report, Yole Développement, 2020)



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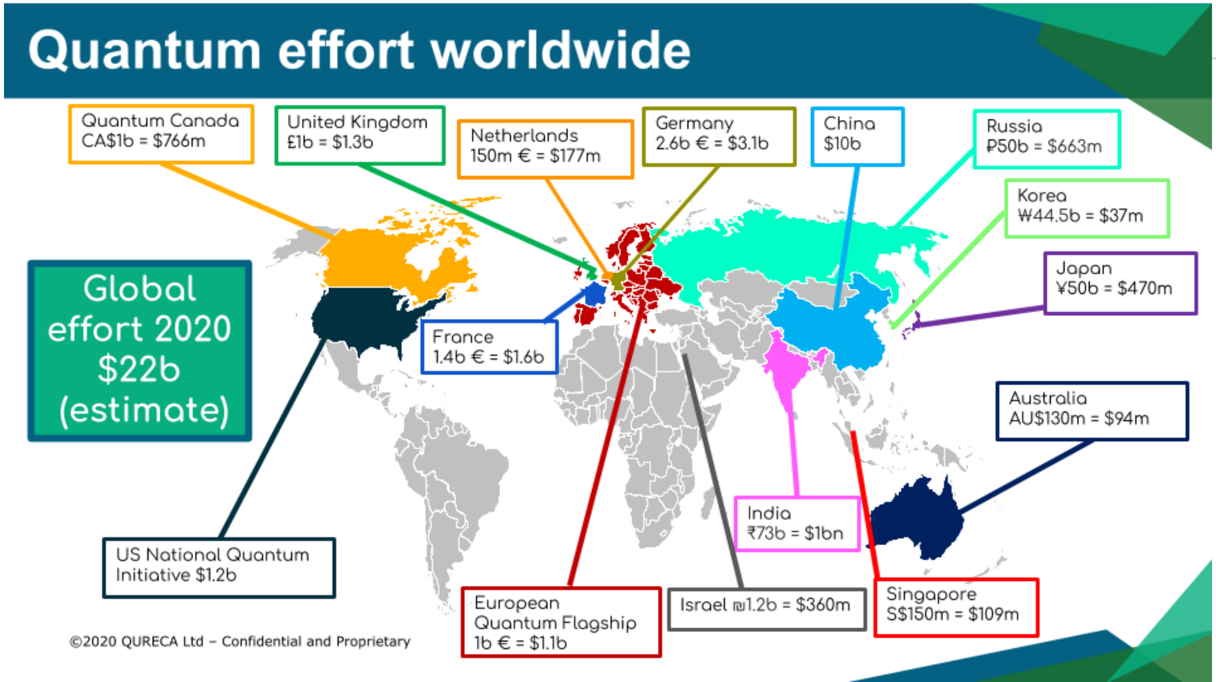
Quantum effort worldwide



Quantum Canada
CA$1b = $766m

United Kingdom
£1b = $1.3b

Netherlands
150m € = $177m

Germany
2.6b € = $3.1b

China
$10b

Russia
₽50b = $663m

Korea
₩44.5b = $37m

Japan
¥50b = $470m

Global effort 2020
$22b
(estimate)

France
1.4b € = $1.6b

Australia
AU$130m = $94m

India
₹73b = $1bn

US National Quantum Initiative $1.2b

European Quantum Flagship
1b € = $1.1b

Israel ₪1.2b = $360m

Singapore
S$150m = $109m

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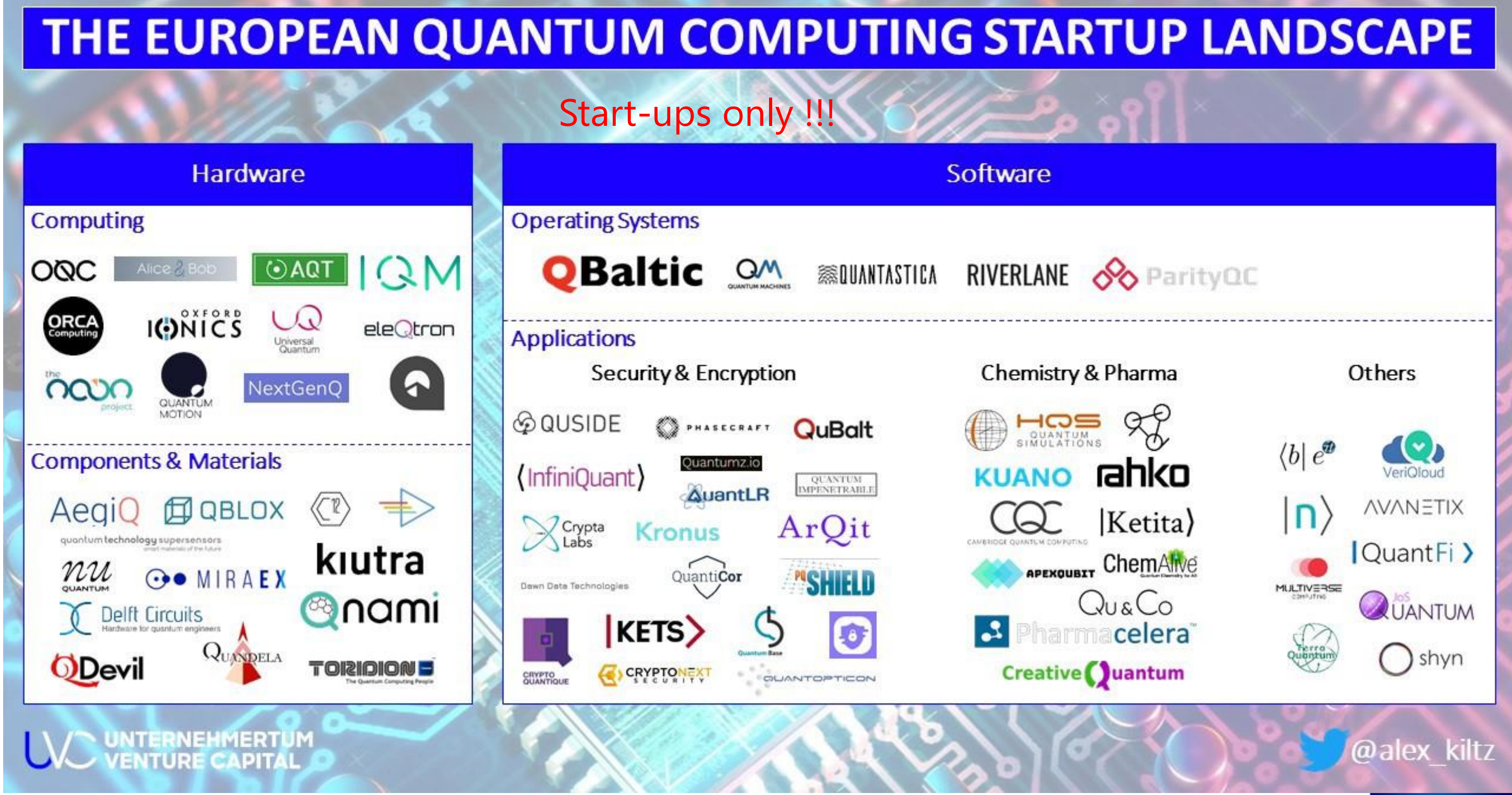
|2> What about the market?



THE EUROPEAN QUANTUM COMPUTING STARTUP LANDSCAPE

Start-ups only !!!

Hardware

Computing

Components & Materials

Software

Operating Systems

Applications

Security & Encryption

Chemistry & Pharma

Others

|2> What about the market?

→ Big ‘major’ companies

Atos
hp
MITSUBISHI
intel
SK telecom
Booz | Allen | Hamilton
LOCKHEED MARTIN
BT
NOKIA
AIRBUS
FUJITSU
TOSHIBA
Google
Alibaba Group
NTT
IBM
Raytheon
Microsoft
THALES
NEC
kpn

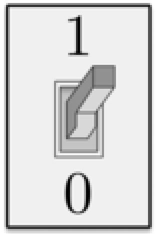
|3> Bits vs qubits

→ Qubit = quantum bits

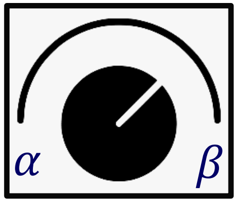
$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle = \frac{\alpha}{\sqrt{|\alpha|^2+|\beta|^2}}|0\rangle + \frac{\beta}{\sqrt{|\alpha|^2+|\beta|^2}}|1\rangle$$

normalised vector → $|\alpha|^2 + |\beta|^2 = 1$

Classical Bit



Qubit $\alpha|0\rangle + \beta|1\rangle$



$$\left.\begin{array}{l}\text{0 state} \rightarrow |0\rangle \\ \text{1 state} \rightarrow |1\rangle\end{array}\right\}$$

qubit is in the two states at the same time !!!

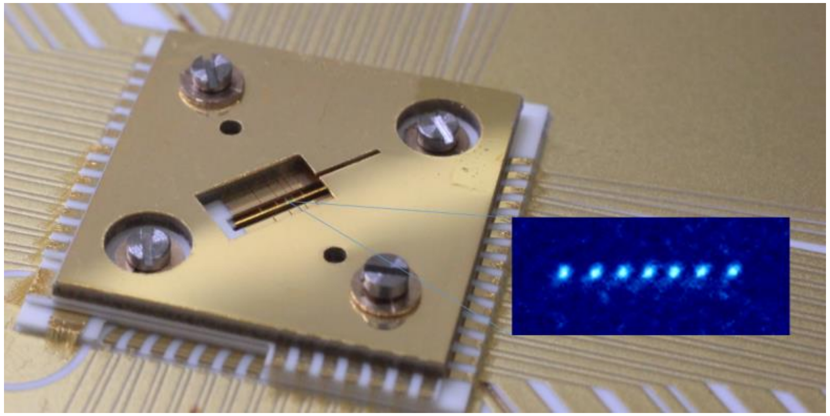
$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

$|\ldots\rangle$: bracket notation = <bra| – |ket> notation → Dirac notation

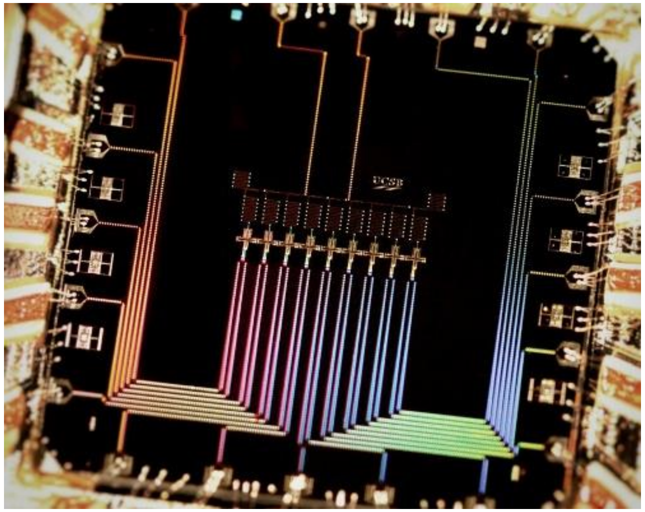
α, β are complex numbers

|3> Quantum technologies

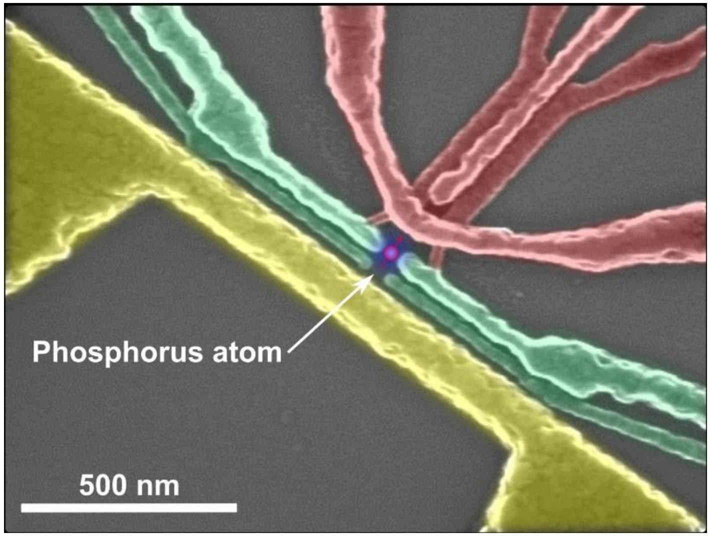
- Different complex technologies



Trapped ions (ETH)



9 Superconducting qubits
Nature 519, 66 (2015)

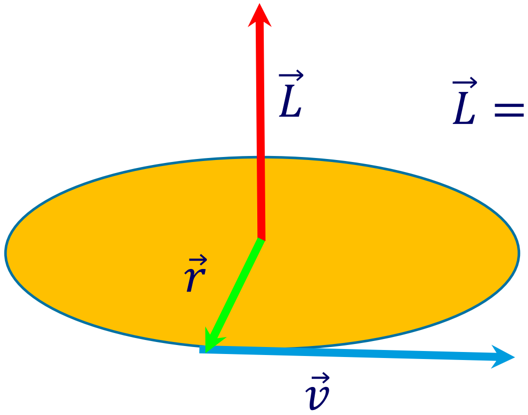


Impurities in Si

→ Use of Photons & condensed matter

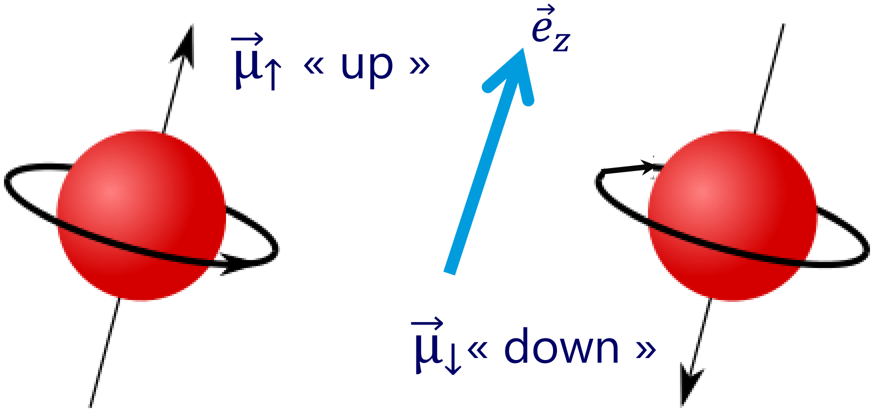
|3> qubits: spin of an electron

→ Notion of spin: angular momentum



$$\vec{L} = \vec{r} \times \vec{p} = \vec{\mathcal{M}} \propto \hbar$$

Electron 'spinning' 2 ways



→ $\vec{\mu}$ is the spin magnetic moment / 'small' magnet
spin is an angular momentum $\propto \hbar$

$$\boxed{\vec{\mu} = \gamma\vec{S} = g\,\frac{q}{2m}\vec{S}}$$

↳ spin operator $\hat{S}_z$ with 2 eigenvalues $+\hbar/2$ and $-\hbar/2$

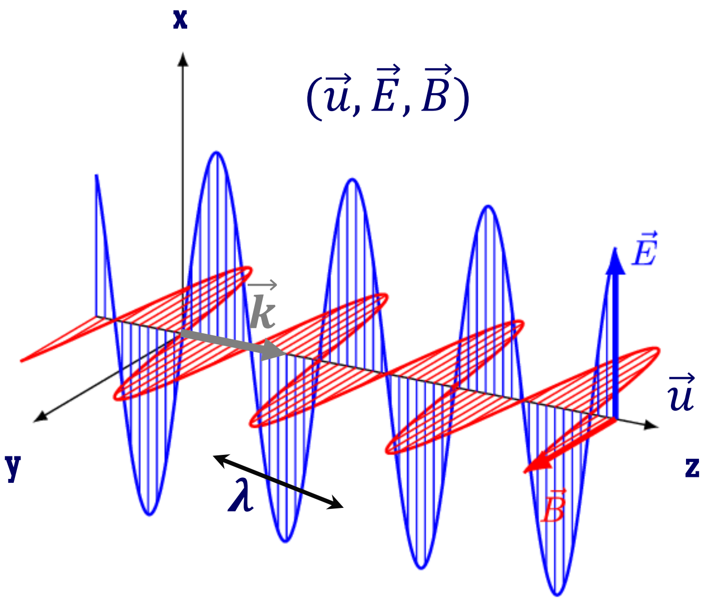
$$\hat{S}_z = \begin{pmatrix} +\hbar/2 & 0 \\ 0 & -\hbar/2 \end{pmatrix} \Rightarrow \alpha|0\rangle + \beta|1\rangle$$

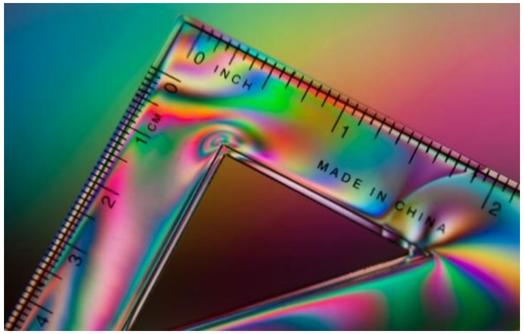
|3> the photon as a qubit

→ A quick reminder: polarisation

monochromatic plane wave (wavelength & frequency) → $\vec{E} = \overrightarrow{E_0}\cos(\omega t - kx)$

light is polarised according to the direction of the $\vec{E}$ field





|3> the photon as a qubit

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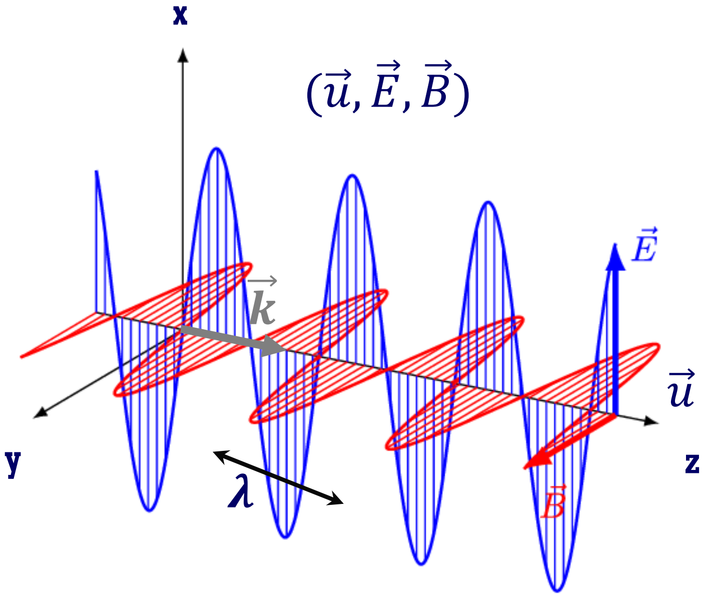


Linear polarisation along x and y:

$$\vec{E} = E_0 \cos(kz - \omega t)\vec{e}_x$$
$$\vec{E} = E_0 \cos(kz - \omega t)\vec{e}_y$$

Linear polarisation at +- 45°:

$$\vec{E} = E_0 \cos(kz - \omega t)(\vec{e}_x + \vec{e}_y)$$
$$\vec{E} = E_0 \cos(kz - \omega t)(\vec{e}_x - \vec{e}_y)$$

Circular polarisation right or left-handed:

$$\vec{E} = E_0 \cos(kz - \omega t)\vec{e}_x + E_0 \cos\left(kz - \omega t + \frac{\pi}{2}\right)\vec{e}_y$$
$$\vec{E} = E_0 \cos(kz - \omega t)\vec{e}_x - E_0 \cos\left(kz - \omega t + \frac{\pi}{2}\right)\vec{e}_y$$

|3> the photon as a qubit

→ A quick reminder: polarisation

Linear polarisation along x and y:

$$\vec{E} = E_0\cos(kz-\omega t)\vec{e}_x$$

$$\vec{E} = E_0\cos(kz-\omega t)\vec{e}_y$$

→ $|\psi\rangle = |0\rangle$ and $|1\rangle$

Linear polarisation at +- 45°:

$$\vec{E} = E_0\cos(kz-\omega t)(\vec{e}_x+\vec{e}_y)$$

$$\vec{E} = E_0\cos(kz-\omega t)(\vec{e}_x-\vec{e}_y)$$

→ $|\psi\rangle = \frac{1}{\sqrt{2}}|0\rangle \pm \frac{1}{\sqrt{2}}|1\rangle$

Circular polarisation right or left-handed:

$$\vec{E} = E_0\cos(kz-\omega t)\vec{e}_x + E_0\cos\left(kz-\omega t+\frac{\pi}{2}\right)\vec{e}_y$$

$$\vec{E} = E_0\cos(kz-\omega t)\vec{e}_x - E_0\cos\left(kz-\omega t+\frac{\pi}{2}\right)\vec{e}_y$$

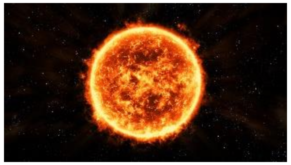
→ $|\psi\rangle = \frac{1}{\sqrt{2}}|0\rangle \pm \frac{i}{\sqrt{2}}|1\rangle$

Note: often we have $|0\rangle = |V\rangle$ and $|1\rangle = |H\rangle$
for vertical & horizontal linear polarisation

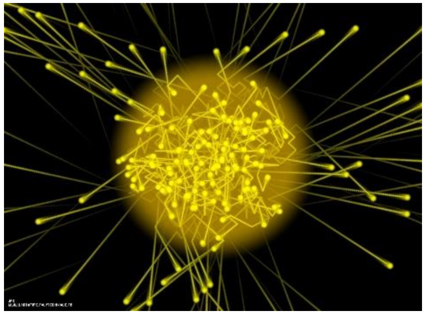
|3> the photon as a qubit

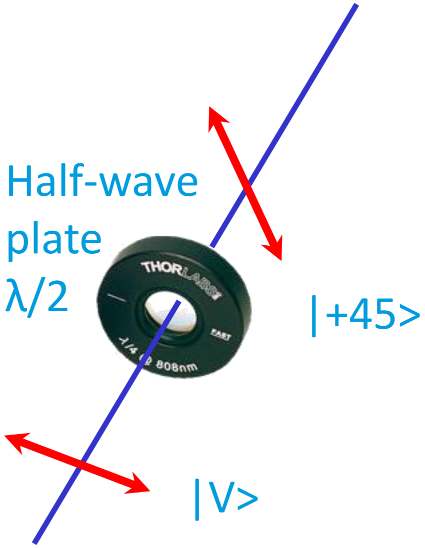
→ A quick reminder: what is a single photon?

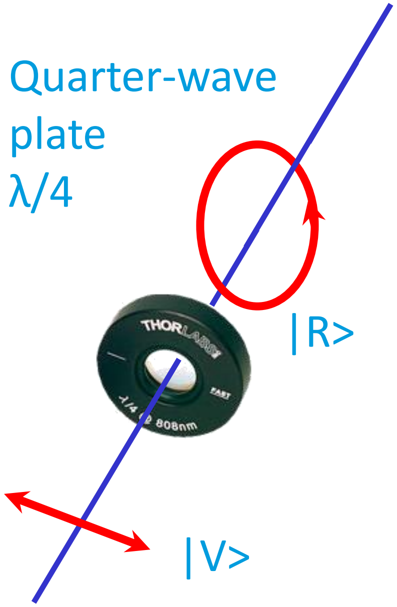
light is an electromagnetic wave

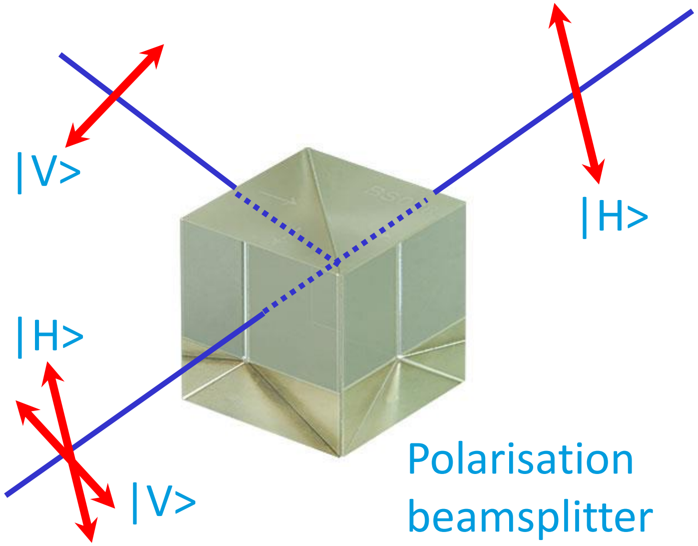


→ also particles = photons





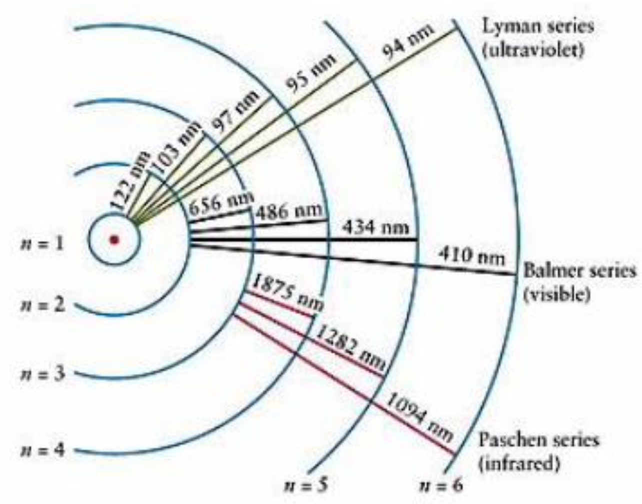




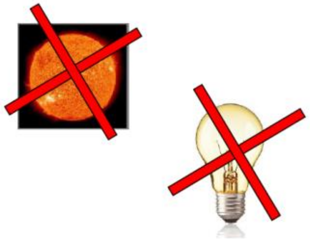
|4> the need for a quantum emitter

Definition of a quantum emitter

→ two level system and single photons



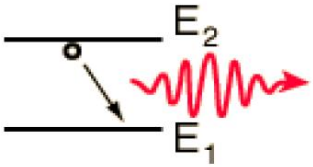
➡ Everything is quantum at its core



Sun, lamp, LED... not OK

A single emitter, not many

AND a two-level system is OK



|4> the need for a quantum emitter

Definition of a quantum emitter

→ Two level system and single photons

- Laser → Poissonian distribution for the photons

↳ Even very attenuated → Proba P_1 for 1 photon

$\frac{1}{2}P_1^2$ for 2 photons

…

- Solution → Single dipole, a 2-level quantised system

↳ isolated atom with
an optical transition
between 2 states

Takes time to reload

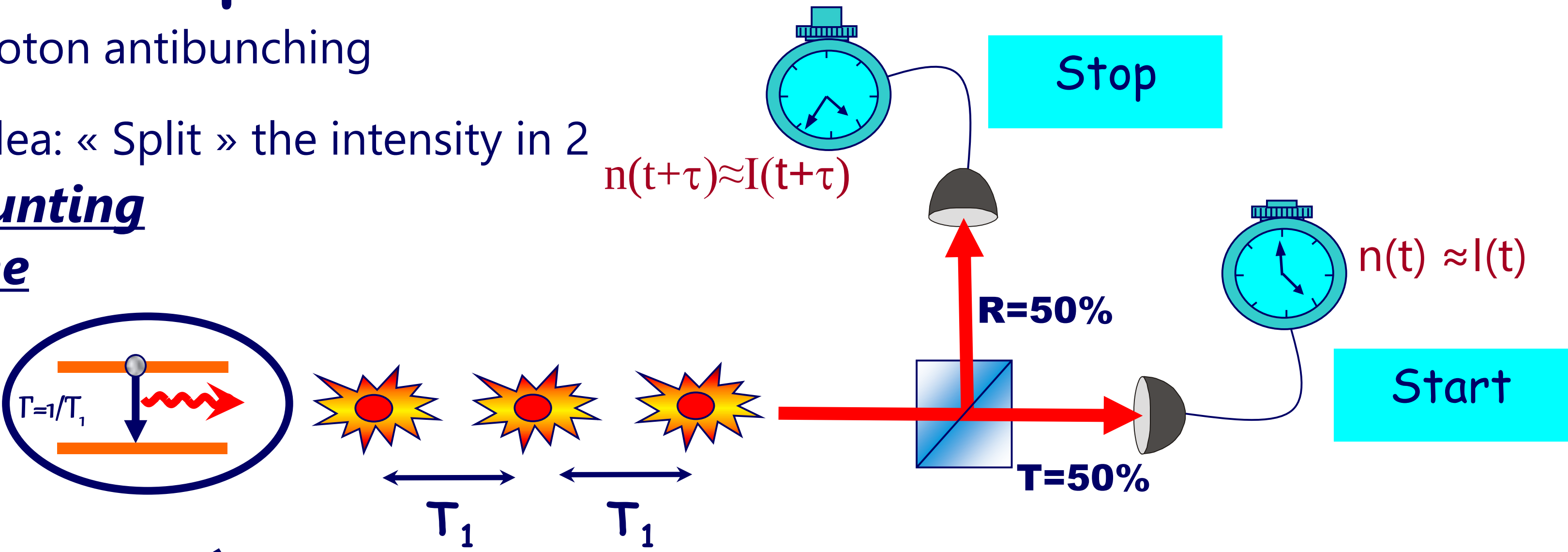
|4> the need for a quantum emitter

Definition of a quantum emitter

→ Photon antibunching

Idea: « Split » the intensity in 2

Photon counting regime



Reflected and ~~transmitted~~ → **but** reflected OR transmitted

Construction of a temporal histogram function of **τ**
Photon correlation function

Quantum optics

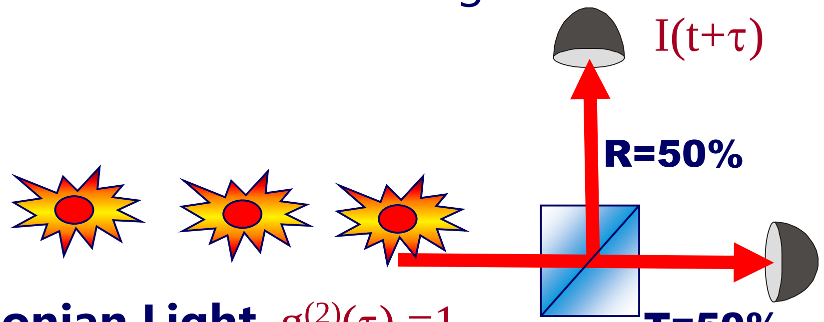
$$\boxed{g^{(2)}(\tau) = \frac{\langle I(t+\tau)I(t)\rangle}{\langle I(t)\rangle^2}} \rightarrow \boxed{g^{(2)}(0)=0}$$

|4> the need for a quantum emitter

Definition of a quantum emitter

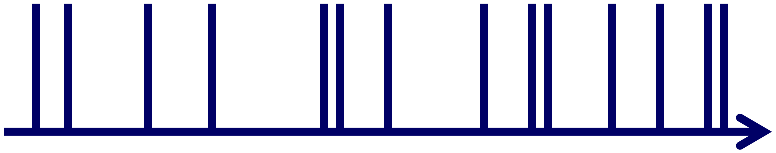
→ Photon antibunching

Photon Counting Regime

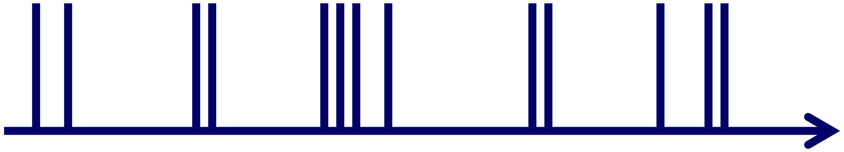


→ $$g^{(2)}(\tau) = \frac{\langle I(t+\tau)I(t)\rangle}{\langle I(t)\rangle^2}$$

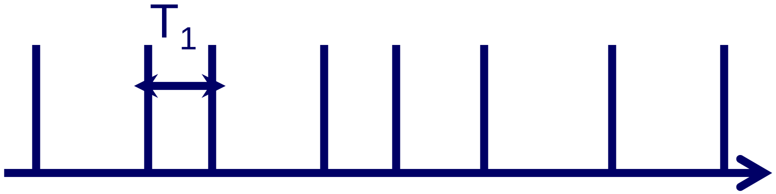
* **Poissonian Light**, $g^{(2)}(\tau) = 1$



* **Bunched Light**, $g^{(2)}(\tau) > 1$

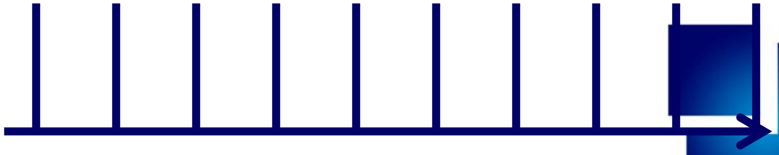


* **Antibunched Light**, $g^{(2)}(\tau) < 1$



Continuous Excitation

* **Single Photons**, $g^{(2)}(\tau) < 1$

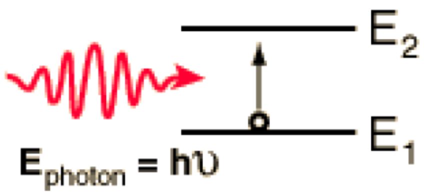


f=80MHz → **Photon Pistol**

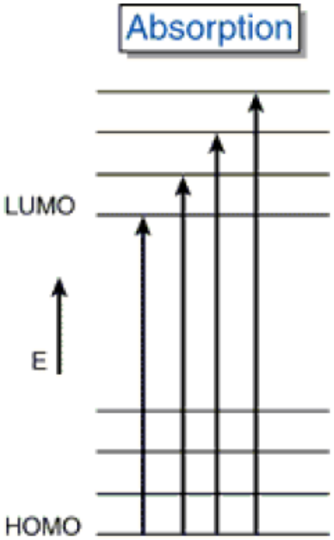
|4> the need for a quantum emitter

Radiating dipole

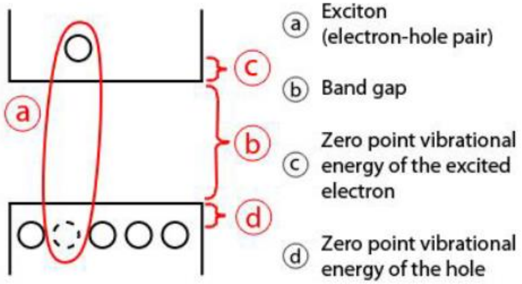
→ Notion of dipole



Absorption in atoms



HOMO-LUMO in molecules



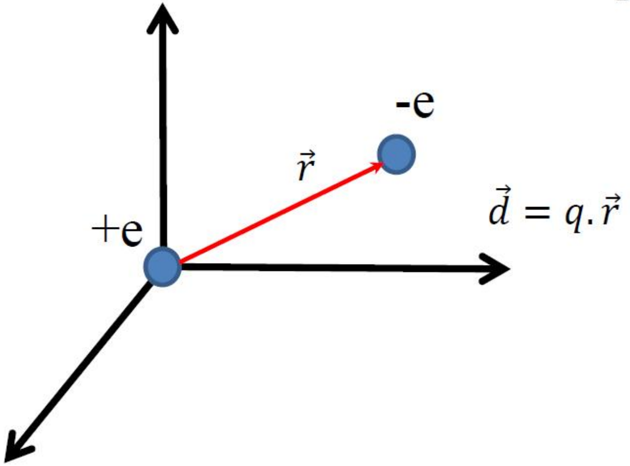
Semiconductors: band structures and excitons

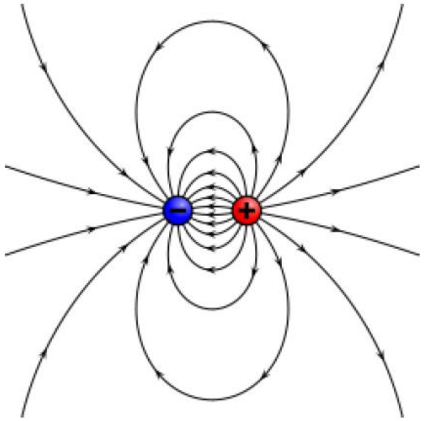
➡ Displacement of charges and creation of a dipole $\vec{d}$

|4> the need for a quantum emitter

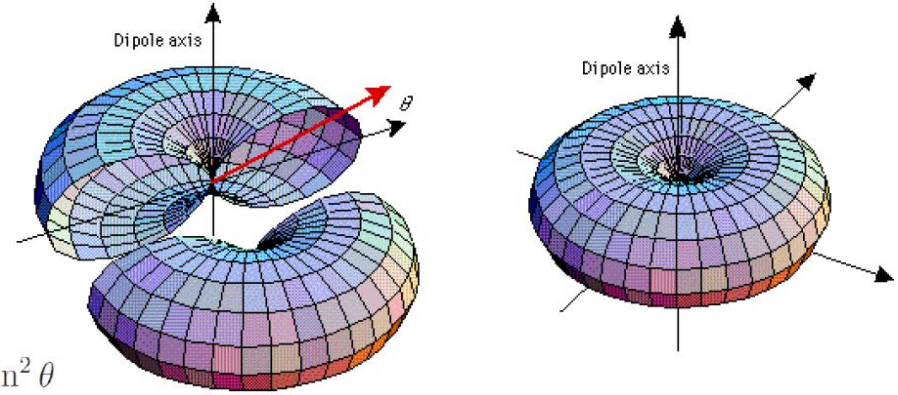
Radiating dipole

→ Notion of dipole





➔ Radiating dipole



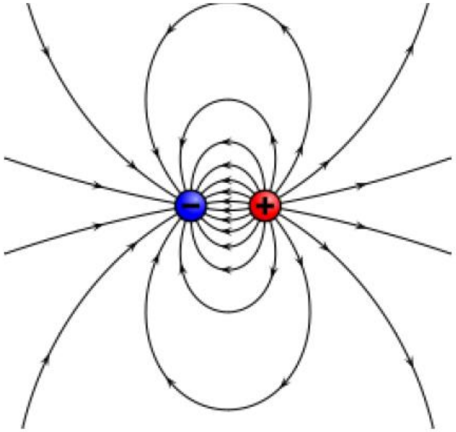
Power/solid angle

$$\frac{d\langle P\rangle}{d\Omega} = r^2\,\hat{\mathbf{r}}\cdot\langle\mathbf{S}\rangle = \frac{ck^4p^2\sin^2\theta}{8\pi} = \frac{p^2\omega^4\sin^2\theta}{8\pi c^3}$$

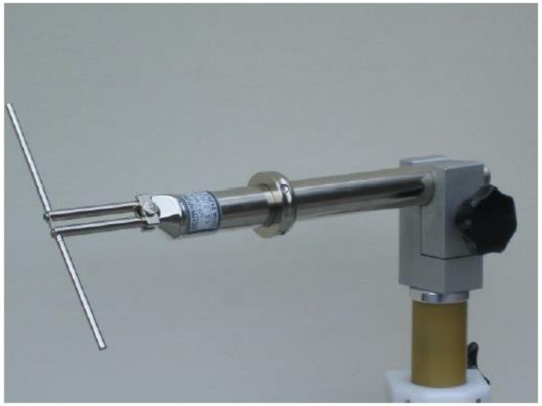
|4> the need for a quantum emitter

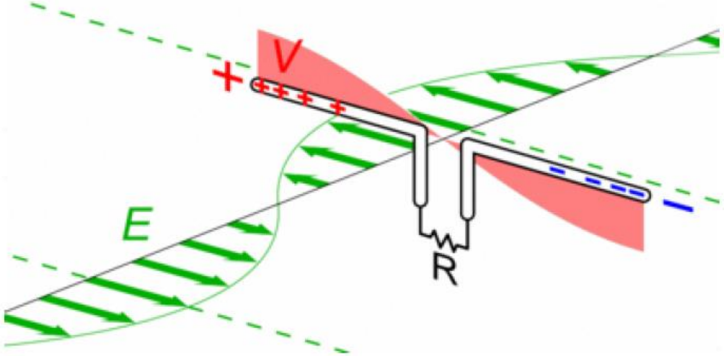
Radiating dipole

→ Notion of dipole



➡ Also used in antennas





|4> the need for a quantum emitter

Radiating dipole

→ Retarded potentials

Define E and B in terms of vector potentials $\vec{A}$ and electrical potential V:

$$\vec{B} = \vec{\nabla} \times \vec{A}$$

$$\vec{E} = -\vec{\nabla} V - \frac{\partial \vec{A}}{\partial t}$$

➡ Maxwell's equations with potentials

$$\nabla^2 \boldsymbol{A} - \frac{1}{c^2}\frac{\partial^2 \boldsymbol{A}}{\partial t^2} = -\frac{\boldsymbol{j}}{\epsilon_0 c^2}$$

$$\vec{A}(M,t) = \frac{\mu_0}{4\pi r}\dot{\vec{d}}\left(t - \frac{r}{c}\right)$$

$$V(r,\theta,t) = \frac{1}{4\pi\varepsilon_0}\frac{\cos\theta}{r^2} d\left(t - \frac{r}{c}\right) + \frac{1}{4\pi\varepsilon_0}\frac{\cos\theta}{rc}\dot{d}\left(t - \frac{r}{c}\right)$$

$$\vec{E}(r,t) \sim \frac{1}{4\pi\varepsilon_0 c^2}\frac{\sin\theta}{r}\ddot{d}\left(t - \frac{r}{c}\right)\overrightarrow{e_\theta}$$

$$\vec{B}(r,t) \sim \frac{1}{4\pi\varepsilon_0}\frac{\sin\theta}{rc^3}\ddot{d}\left(t - \frac{r}{c}\right)\overrightarrow{e_\varphi}$$

Dipole along z

$$\vec{d} = d_0 \cos\omega t\, \overrightarrow{e_z}$$

|4> the need for a quantum emitter

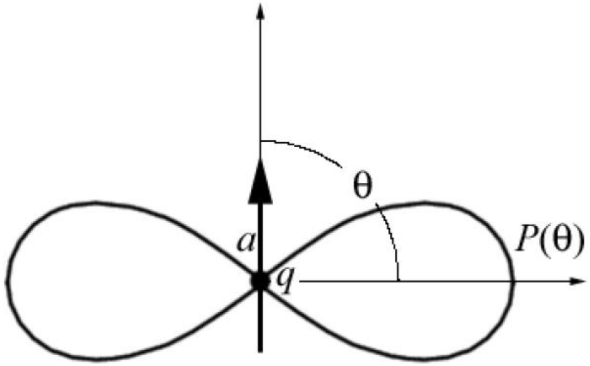
Radiating dipole

→ Poynting vector and radiating power

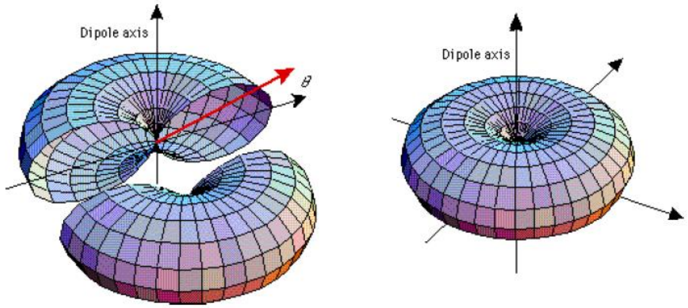
Poynting vector $\vec{S} = \frac{1}{\mu_0}\vec{E}\times\vec{B}$

➡ $\left\langle \vec{S}(r,t) \right\rangle = \frac{\omega^4 d_0^2}{32\pi^2\varepsilon_0 c^3}\,\frac{\sin^2\theta}{r^2}\,\vec{e_r}$

↳ $\wp = \iint \left\langle \vec{S}(r,t) \right\rangle . \vec{dS} = \frac{\omega^4 d_0^2}{12\pi\varepsilon_0 c^3}$



↳



|4> the need for a quantum emitter

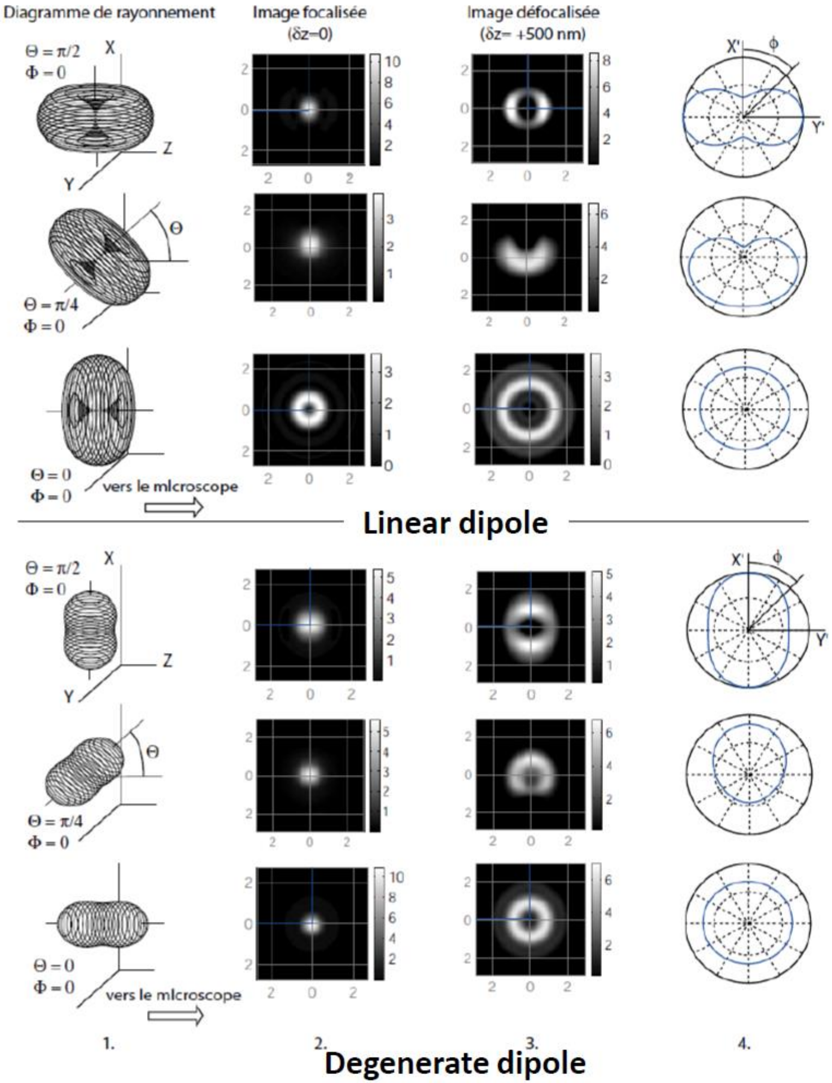
Radiating dipole

→ Poynting vector and radiating power

Radiating dipole

Experimental observations on semiconductor dipoles

PhD X. Brokmann

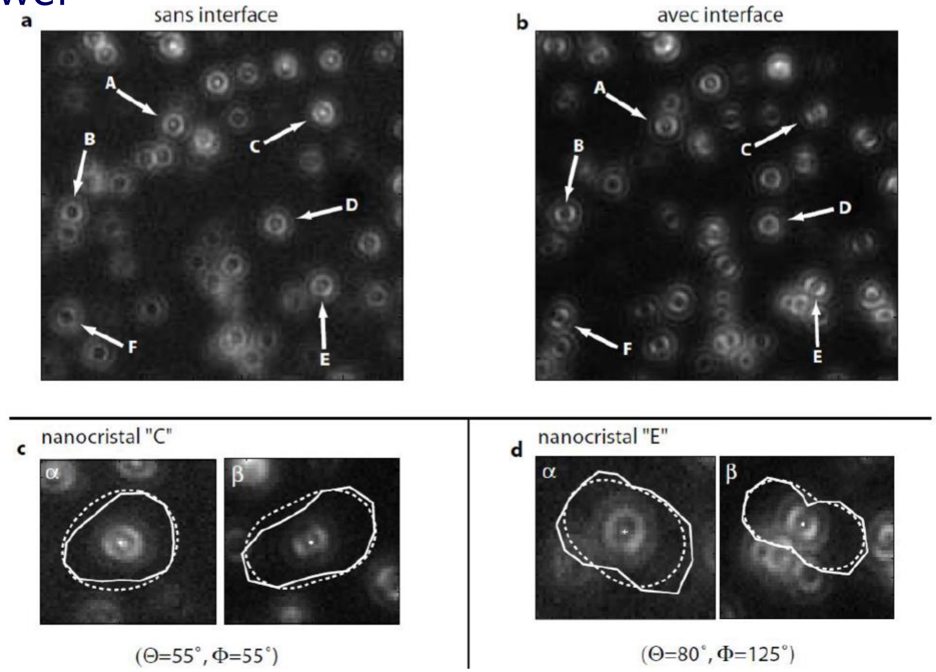


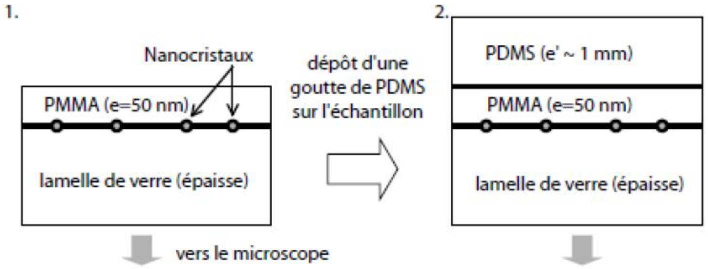
|4> the need for a quantum emitter

Radiating dipole

→ Poynting vector and radiating power

Radiating dipole





1.

Nanocristaux

PMMA (e=50 nm)

lamelle de verre (épaisse)

vers le microscope

dépôt d'une goutte de PDMS sur l'échantillon

2.

PDMS (e' ~ 1 mm)

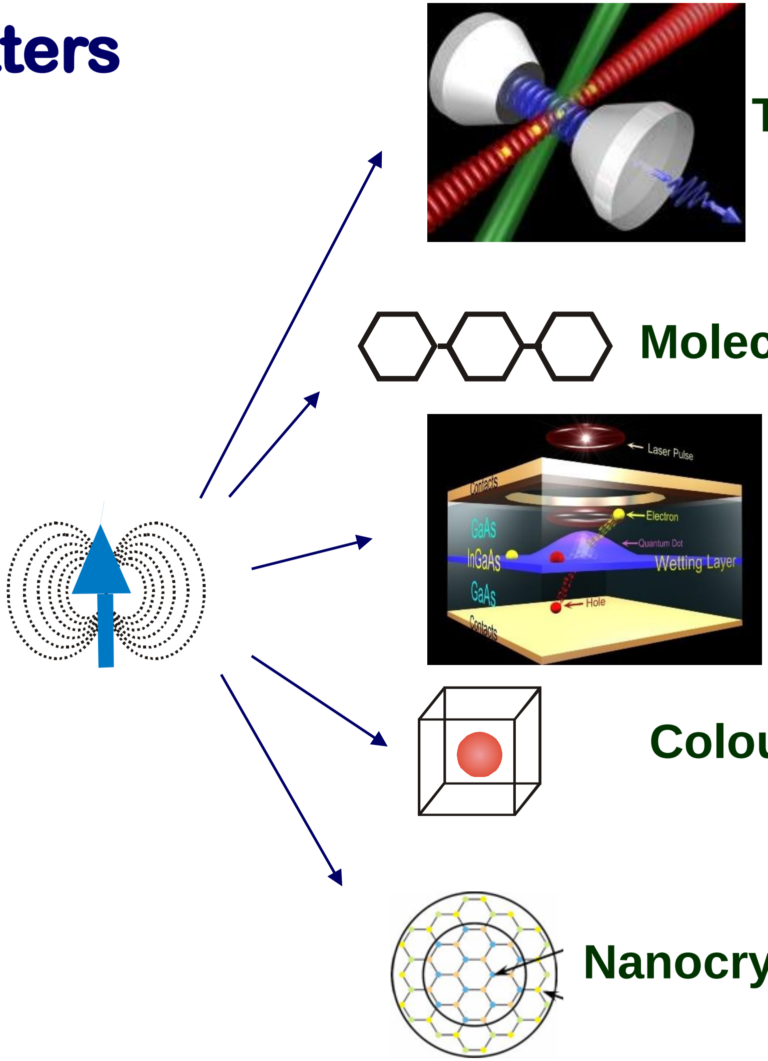
PMMA (e=50 nm)

lamelle de verre (épaisse)

PhD X. Brokmann

|4> the need for a quantum emitter

Zoology of quantum emitters



Trapped atom

Molecule

Quantum dot

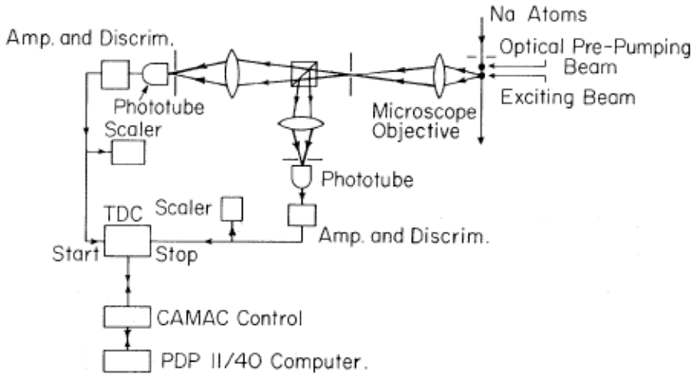
Coloured center

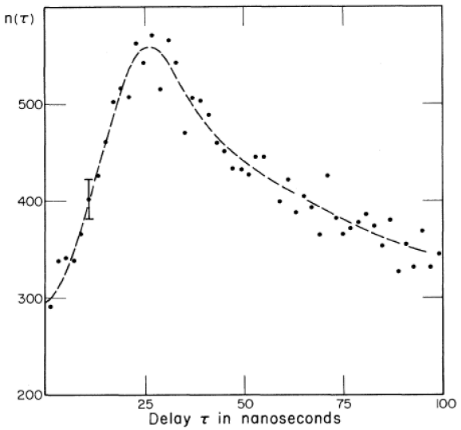
Nanocrystal

|4> the need for a quantum emitter

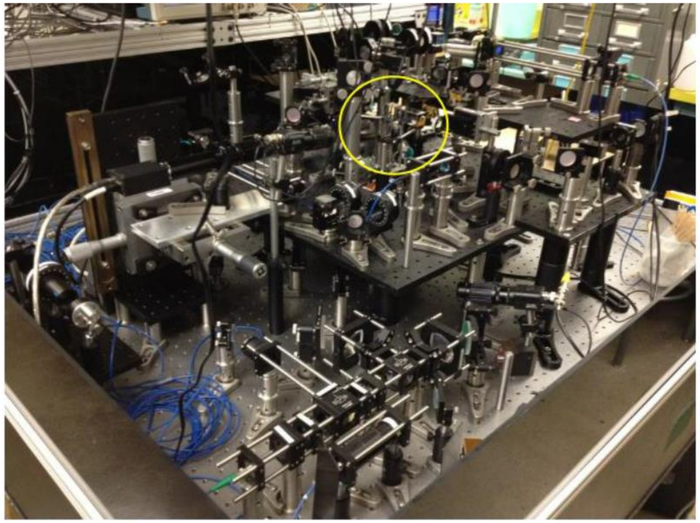
Zoology of quantum emitters

→ Different emitters: atoms

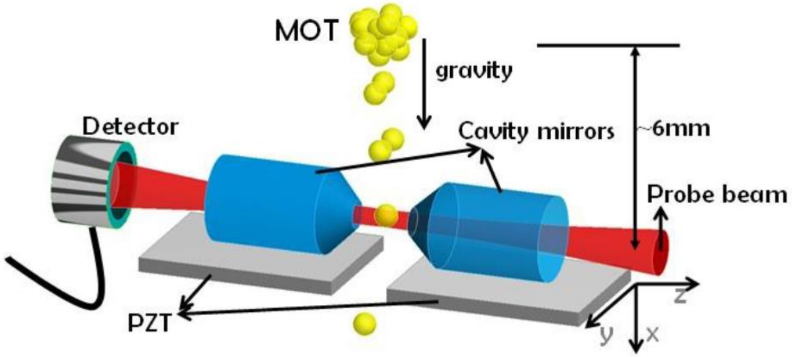




Kimble et al., Phys. Rev. Lett. 39, 691 (1977).



JILA, Boulder, Colorado

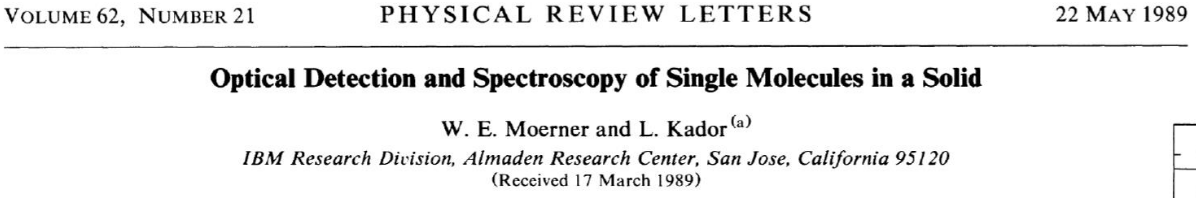


|4> the need for a quantum emitter

Zoology of quantum emitters

→ Different emitters: molecules

Single molecule observation



VOLUME 62, NUMBER 21 PHYSICAL REVIEW LETTERS 22 MAY 1989

Optical Detection and Spectroscopy of Single Molecules in a Solid

W. E. Moerner and L. Kador[a]
IBM Research Division, Almaden Research Center, San Jose, California 95120
(Received 17 March 1989)

- Pentacene in p-terphenyl host matrix
- Low temperature 1.8 K
- Laser frequency modulation spectroscopy
- Electro-optical modulator for side-band excitation

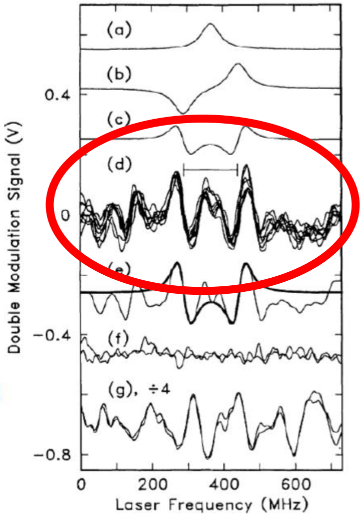
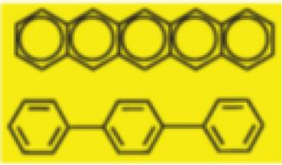
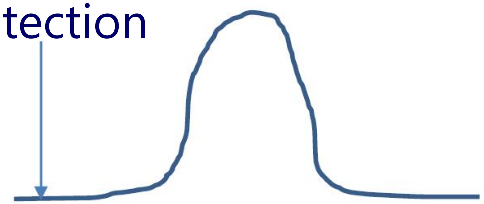


FIG. 1. Illustration of single-molecule spectra using FMS technique. (a) Simulation of absorption line, $\gamma = 65$ MHz. (b) Simulation of FM spectrum for (a), $\nu_m = 75$ MHz. (c) Simulation of FMS line shape. (d) SMD spectra at 592.423 nm, 512 averages, 8 traces overlaid, bar shows value of $2\nu_m = 150$ MHz. (e) Average of traces in (d) (S_2 removed) with fit to the in-focus molecule (smooth curve). (f) Signal far off line at 597.514 nm. (g) Traces of SFS at the O_2 line center, 592.186 nm.



Chemical compound



detection

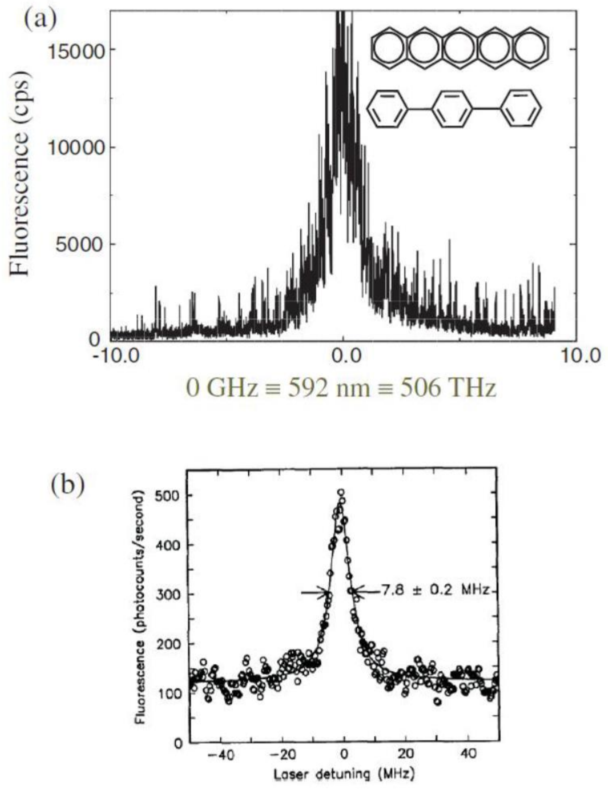
Large spectrum

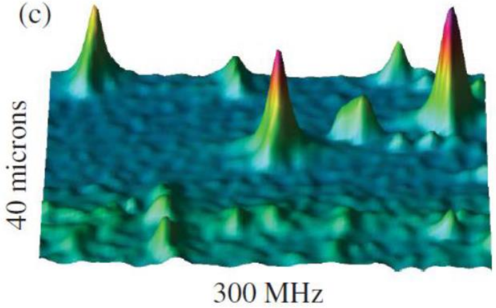
|4> the need for a quantum emitter

Zoology of quantum emitters

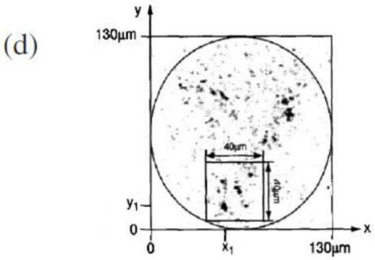
→ Different emitters: molecules

Small bandwidth





Spatial scan: SM measures laser spot size with nm probe!
Freq. scan: Second dimension selects one molecule from many in the same focal volume



W. P. Ambrose, Nature 349, 225

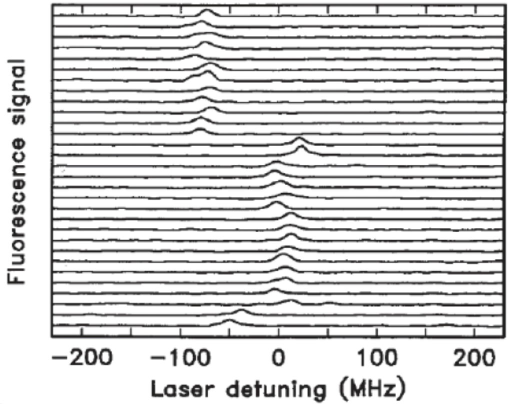
|4> the need for a quantum emitter

Zoology of quantum emitters

→ Different emitters: molecules

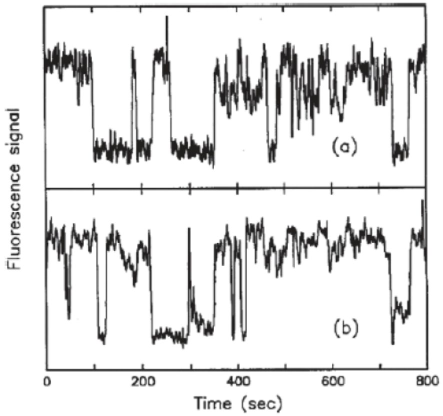
All different

(a) Spectral diffusion, pentacene in p-terphenyl

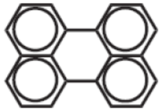


Molecule spontaneously jumps in frequency space due to nearby host dynamics!

(b)

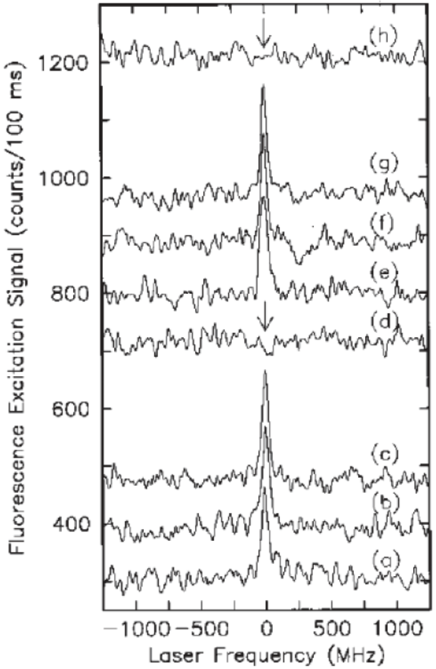


(c)



in $(CH_2\text{-}CH_2\text{-})_n$

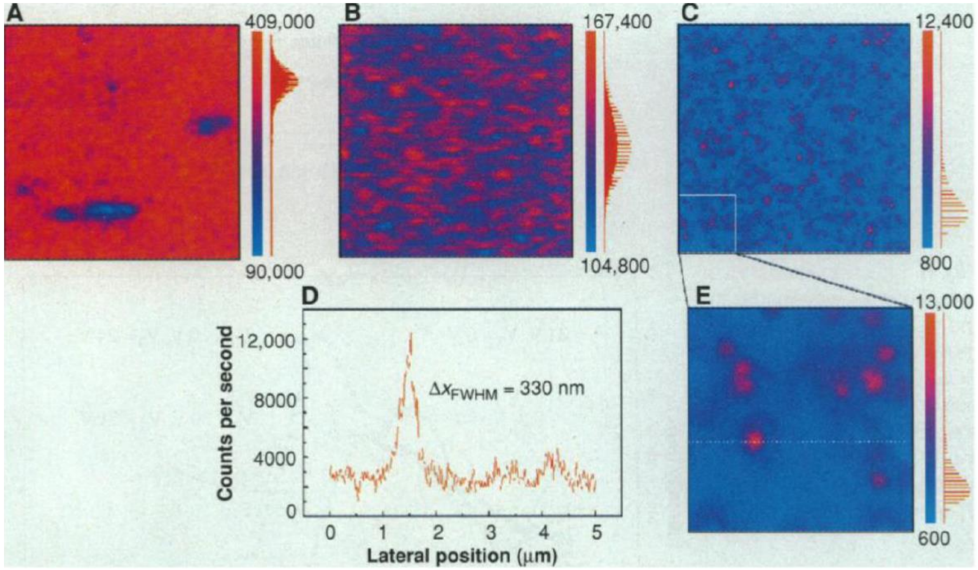
Optically induced spectral shifts!
Poisson kinetics observed

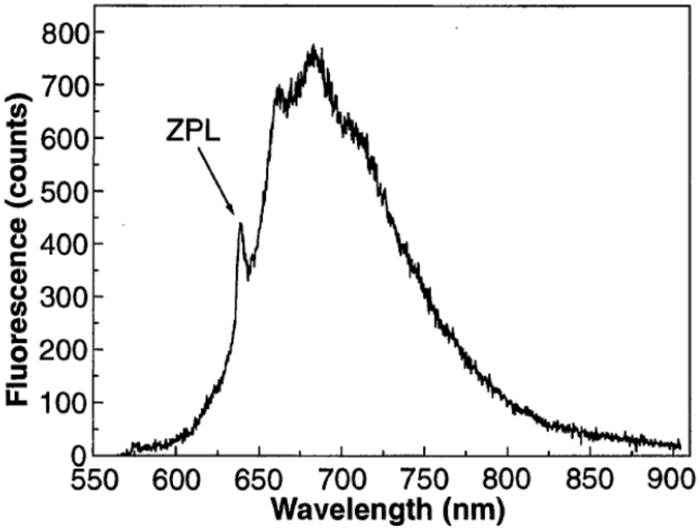


|4> the need for a quantum emitter

Zoology of quantum emitters

→ Different emitters: coloured centers (NV centers in diamond)





Gruber *et al.*, Science 276, 2012 (1997).

|4> the need for a quantum emitter

Zoology of quantum emitters

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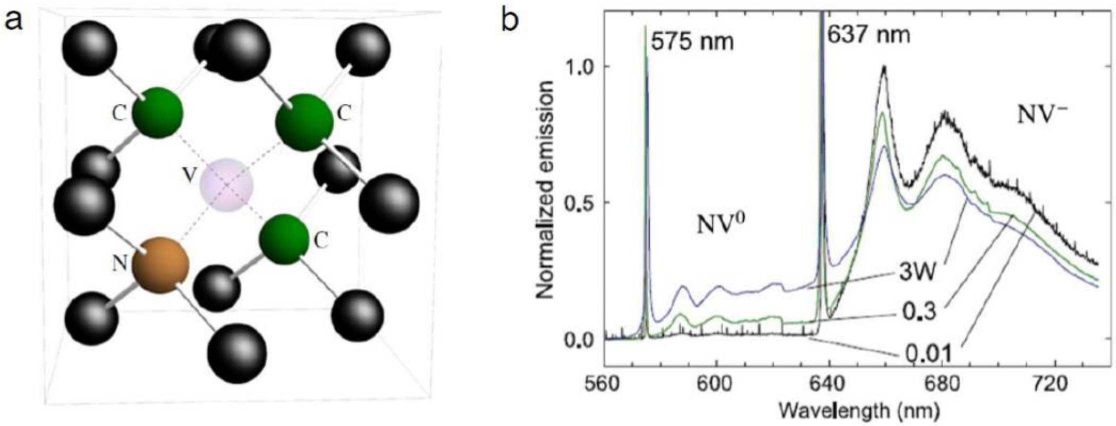
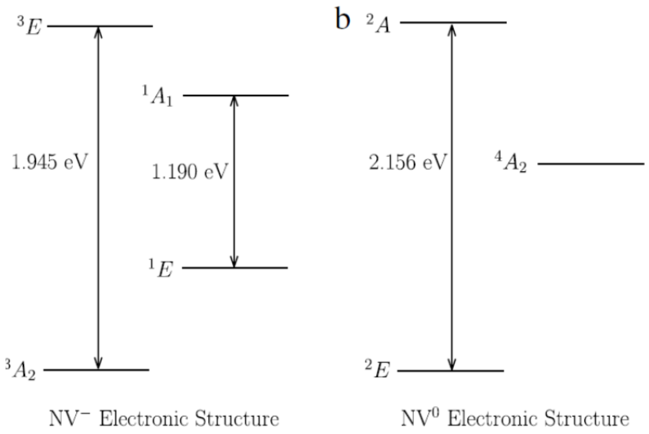


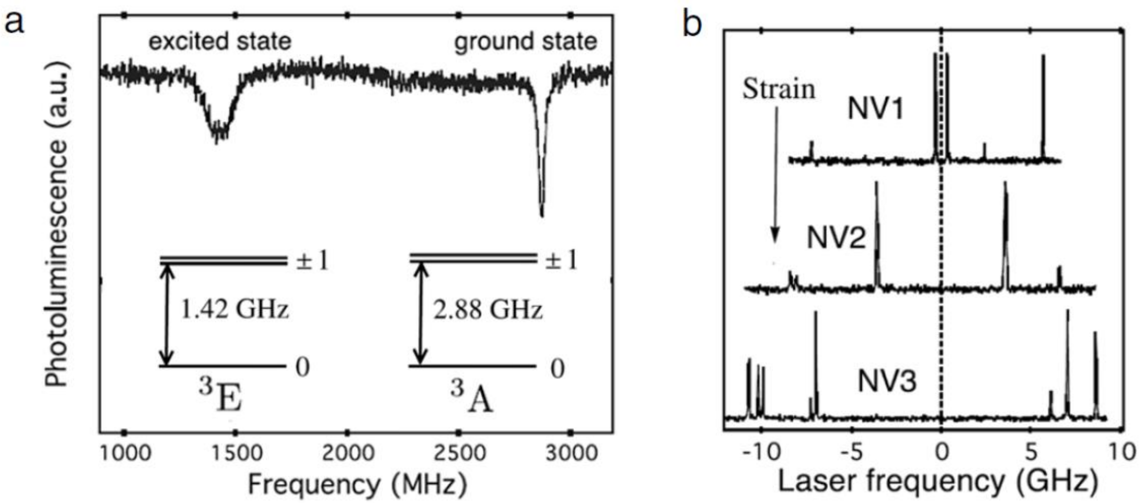


Doherty *et al.*, Phys. Rep. 528, 1,

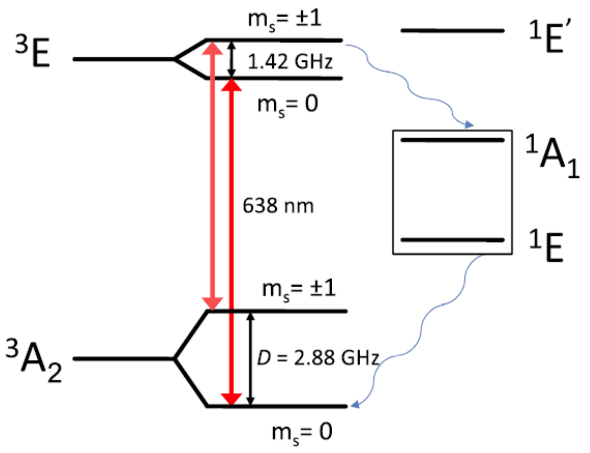
|4> the need for a quantum emitter

Zoology of quantum emitters

→ Different emitters: coloured centers (NV centers in diamond)



Doherty *et al.*, Phys. Rep. 528, 1.



Ivady *et al.*, Phys. Rev. B 90, 235205 (2014)

Splitting ground and excited states: S= 1 and thus $m_s=\pm1$ or $m_s=0$

2 e- → spin-spin interaction with parallel spins $m_s=\pm1$ or antiparallel spins $m_s=0$

Note: There is also a hyperfine structure

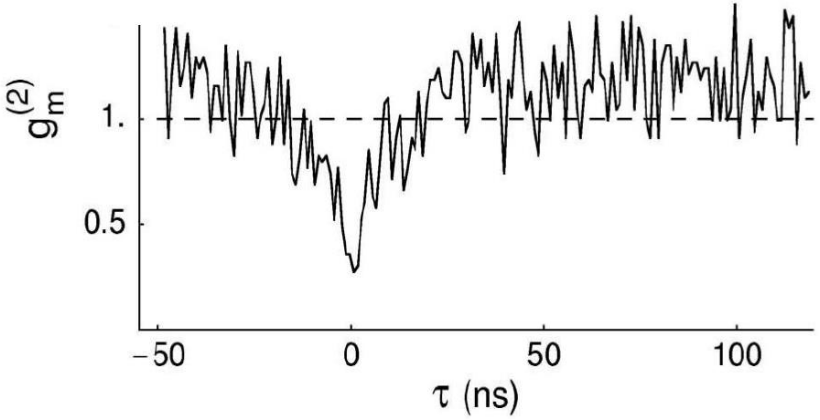
|4> the need for a quantum emitter

Zoology of quantum emitters

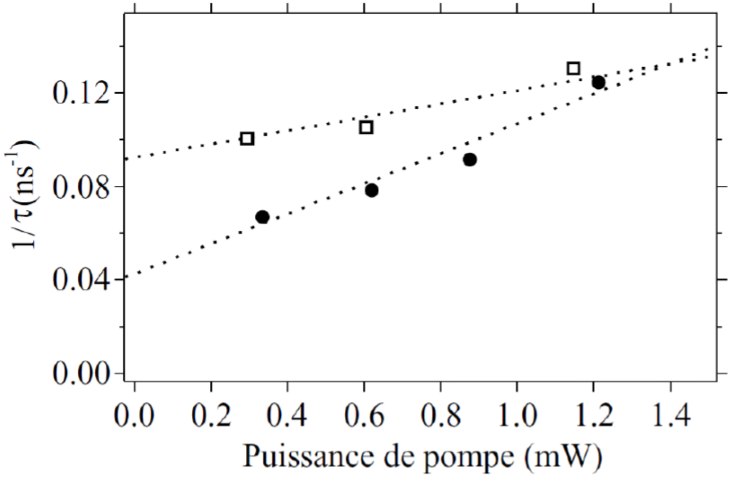
→ Different emitters: coloured centers (NV centers in diamond)

➡ Single photon emission

$$g^{(2)}(\tau) = 1 - e^{-(r+\Gamma)\tau}$$



Kurtsiefer *et al.*, Phys. Rev. Lett. 85, 290 (2000),



Brouri *et al.*, Opt. Lett. 25, 1294 (2000),

↪ Used for quantum technologies

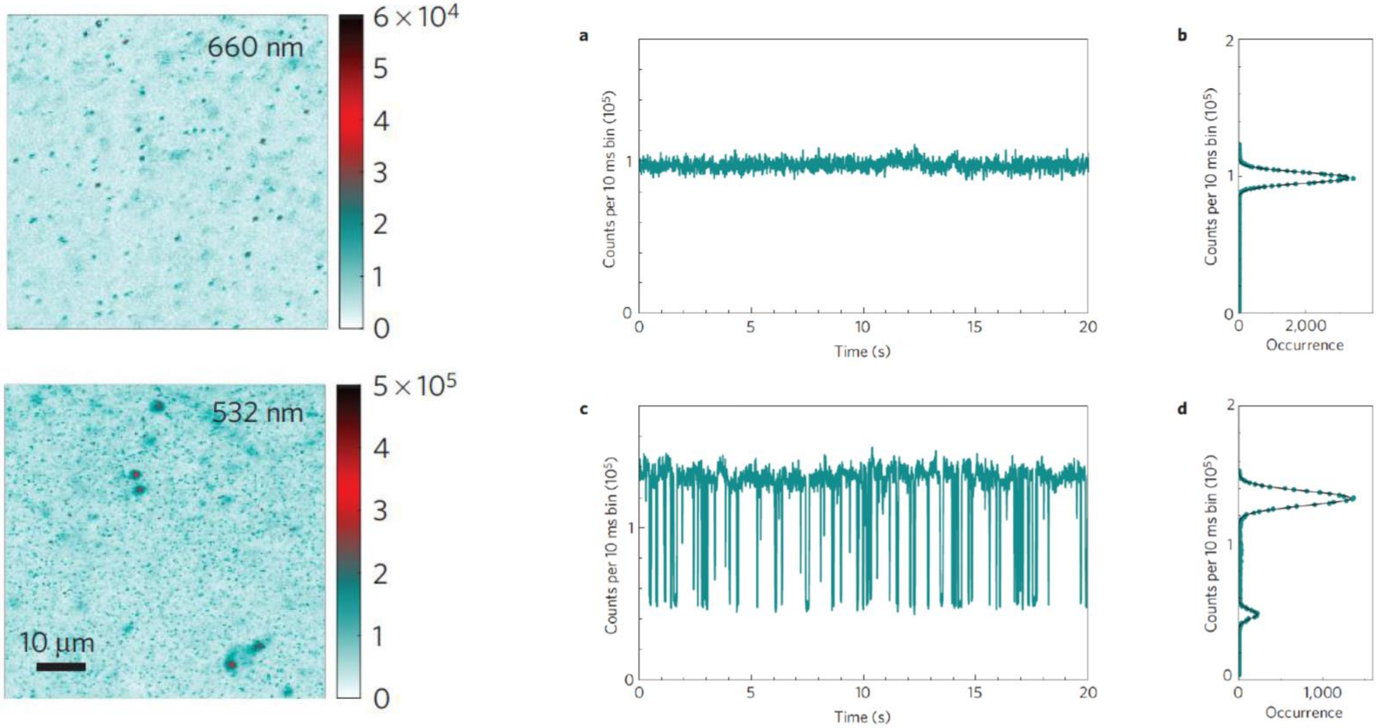
See demo for the correlation function

|4> the need for a quantum emitter

Zoology of quantum emitters

→ Different emitters: coloured centers

➡ High band gad materials: SiC (Eg=3.23 eV and Eg=5.47 eV for diamond)



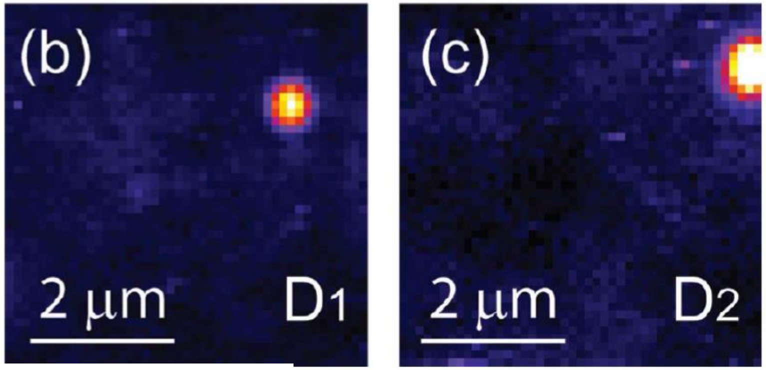
Castelletto *et al.*, Nature Mat. 13, 151 (2014),

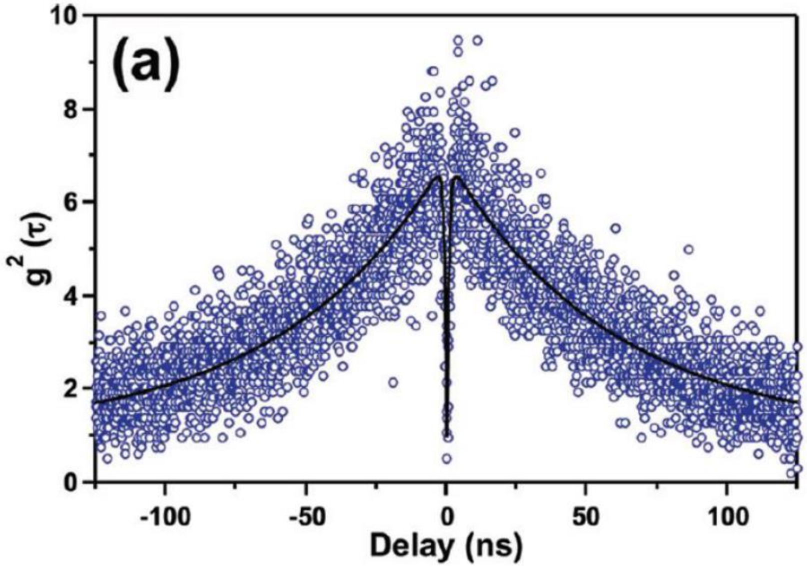
|4> the need for a quantum emitter

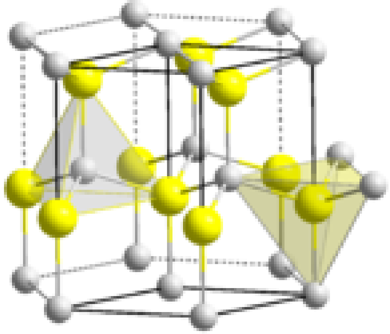
Zoology of quantum emitters

→ Different emitters: coloured centers

High band gap materials: ZnO (Eg=3.37 eV)







Wurtzite structure (hexagonal)

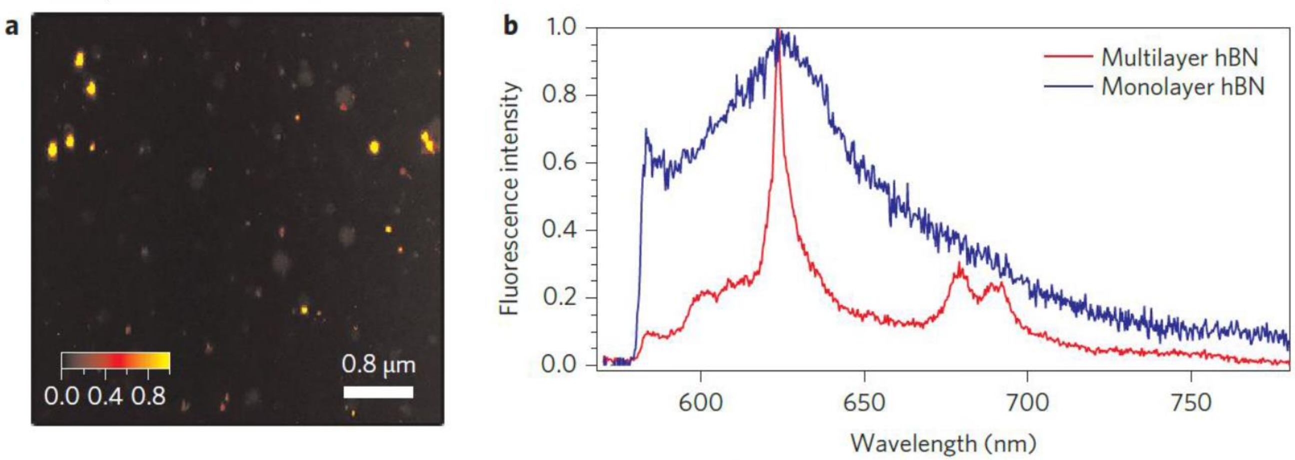
Morfa *et al.*, Nanolett. 12, 949 (2012),

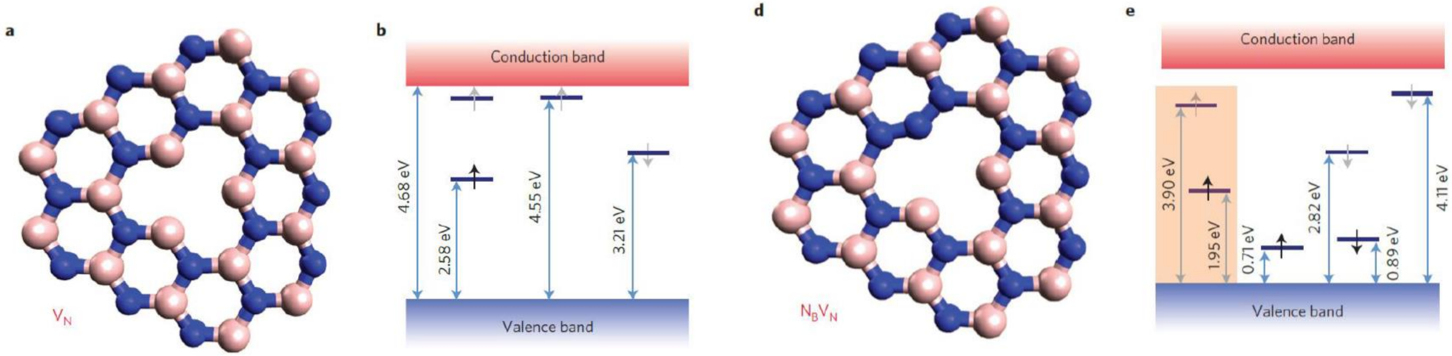
|4> the need for a quantum emitter

Zoology of quantum emitters

→ Different emitters: defects in 2D materials

hBN
Hexagonal
Boron Nitride





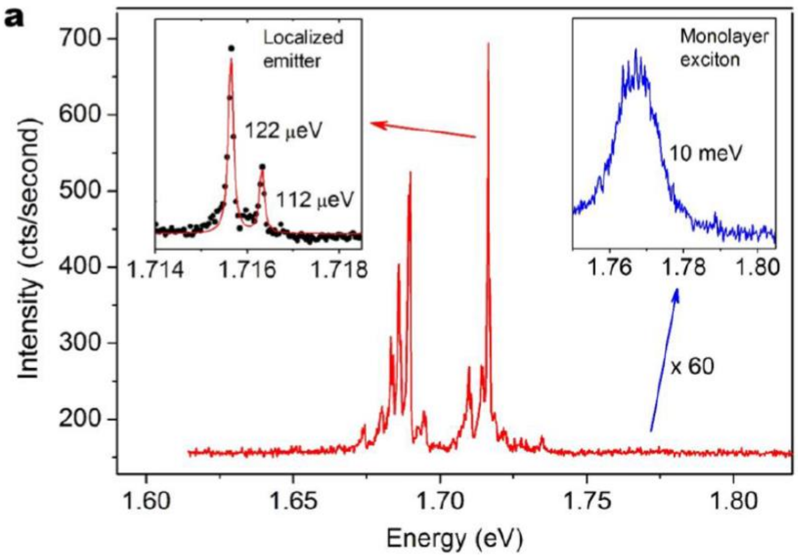
Trong Tran *et al.*, Nature Nanotech. 11, 37 (2016),

|4> the need for a quantum emitter

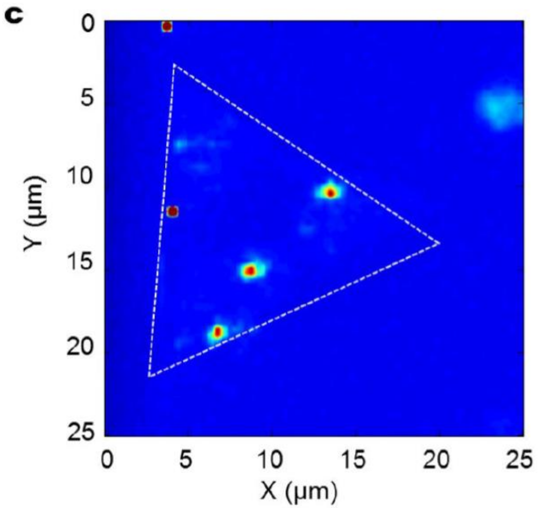
Zoology of quantum emitters

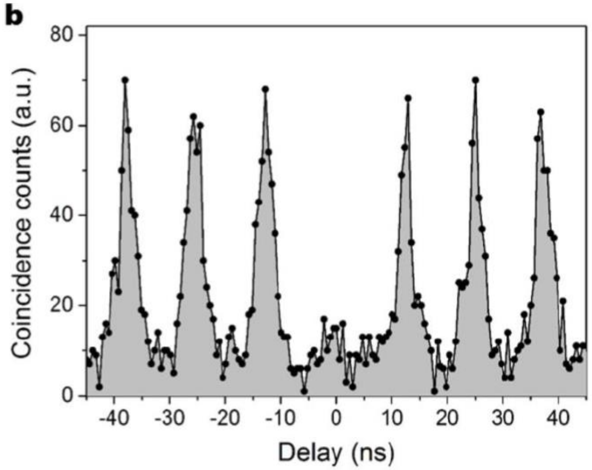
→ Different emitters: defects in 2D materials

WSe$_2$ triangular flakes, atomically thin



He *et al.*, Nature Nanotech. 10, 497 (2015),

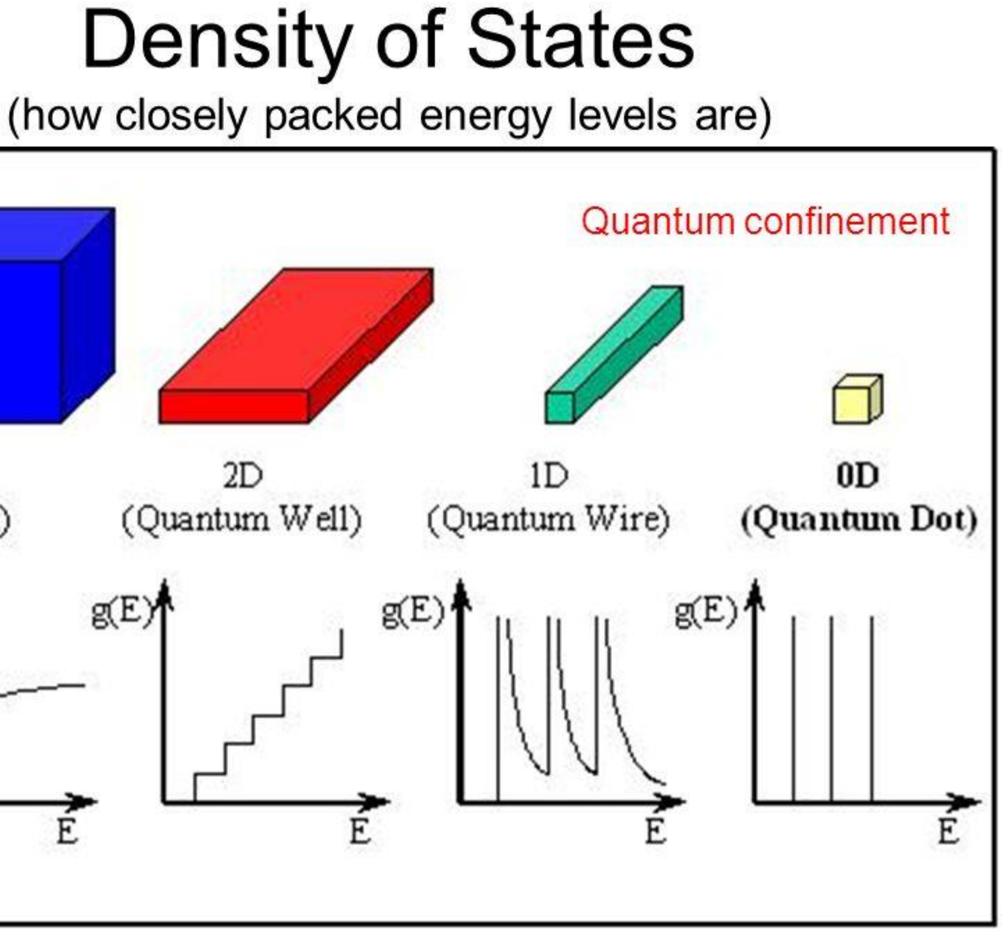




|5> Particular case: quantum dot

Semiconductor quantum emitter

→ Spectroscopy of quantum emitters in semiconductors

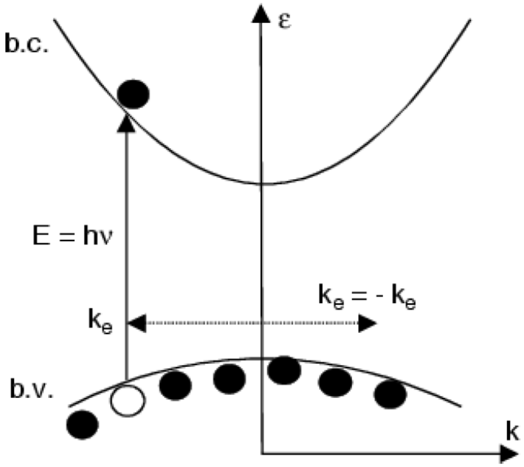


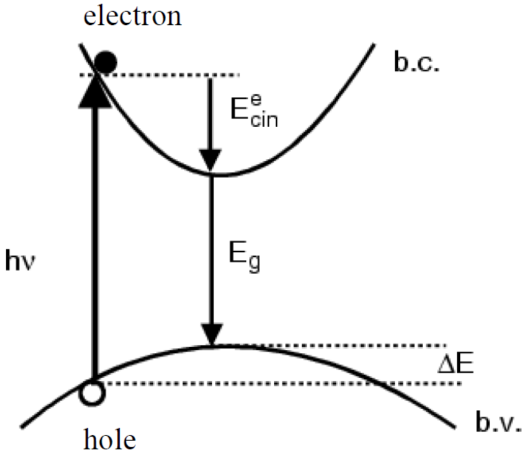
|5> Particular case: quantum dot

Semiconductor quantum emitters

→ Spectroscopy of quantum emitters in semiconductors

Notion of hole and exciton





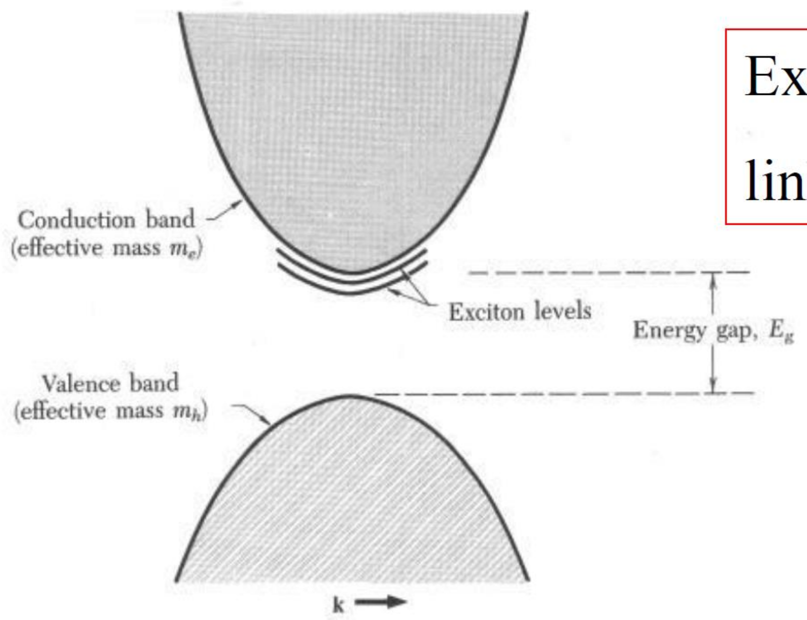
$$\frac{1}{m_h^*} = -\frac{1}{\hbar^2}\frac{\partial^2 \varepsilon_v}{\partial k^2}.$$

|5> Particular case: quantum dot

Semiconductor quantum emitters

→ Spectroscopy of quantum emitters in semiconductors

Notion of hole and exciton

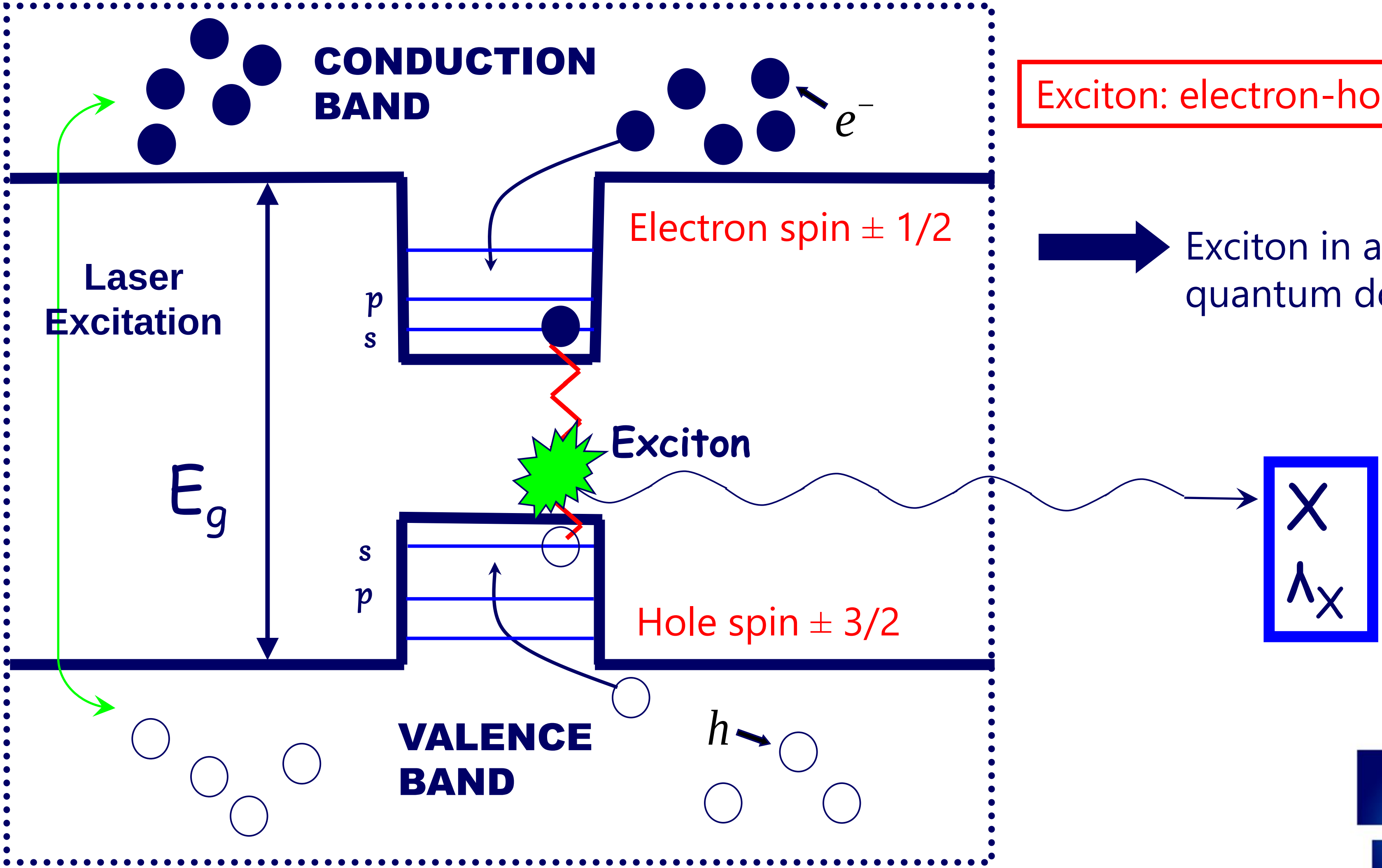


Exciton = Electron-hole pair

link by coulomb interaction

$E_x < E_G$

|5> Particular case: quantum dot



Exciton: electron-hole pair

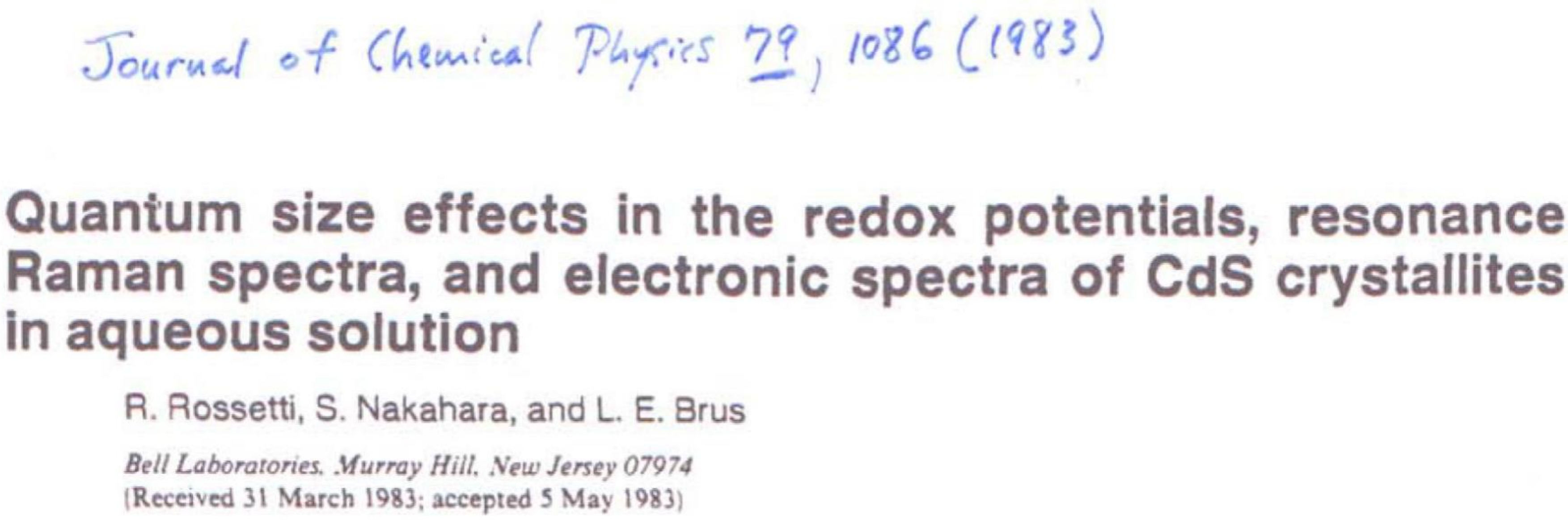
Exciton in a quantum dot

|5> Particular case: quantum dot

Semiconductor quantum emitters

→ Spectroscopy of quantum emitters in semiconductors: nanocrystals

➡ Louis Brus (Columbia University), discoverer of NCs



Journal of Chemical Physics 79, 1086 (1983)

Quantum size effects in the redox potentials, resonance Raman spectra, and electronic spectra of CdS crystallites in aqueous solution

R. Rossetti, S. Nakahara, and L. E. Brus

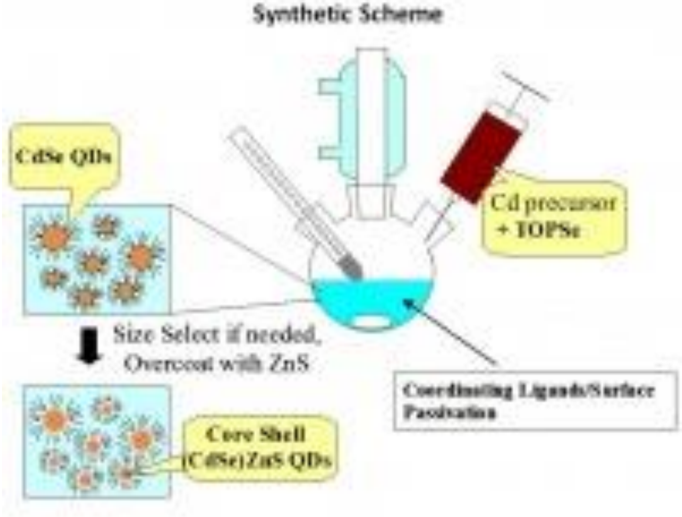
Bell Laboratories, Murray Hill, New Jersey 07974
(Received 31 March 1983; accepted 5 May 1983)

|5> Particular case: quantum dot

Semiconductor quantum emitters

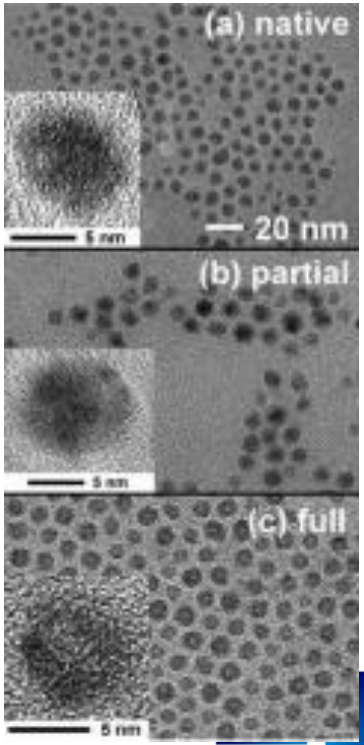
→ Spectroscopy of quantum emitters in semiconductors: nanocrystals

➡ Fabrication of nanocrystals



- Chemical synthesis
- Nice collective properties but poor unity properties
- Unstable

CdSe & CdTe Core-Shell EviDots Span the Entire Visible Spectrum, Ranging from Deep Reds to Bright Blue



TEM pictures

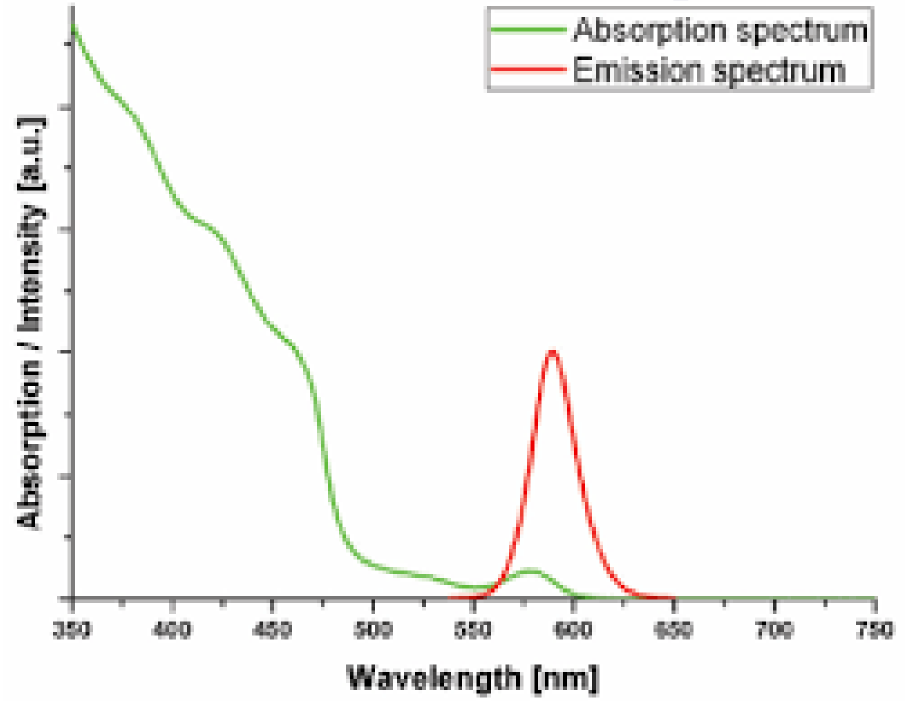
|5> Particular case: quantum dot

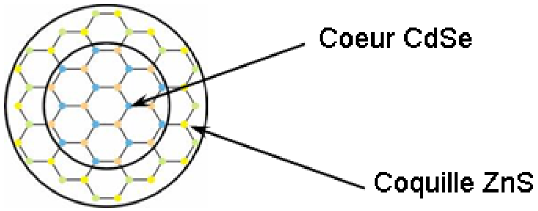
Semiconductor quantum emitters

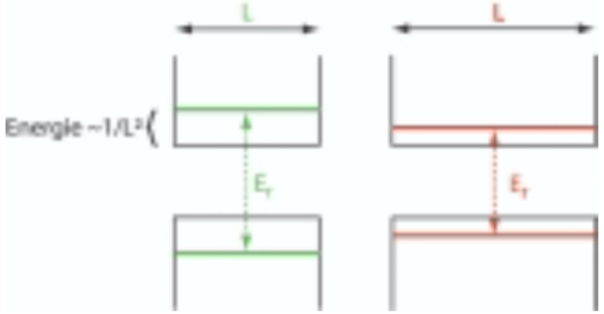
→ Spectroscopy of quantum emitters in semiconductors nanocrystals

Absorption – emission

Φ_1 (green) < Φ_2 (red)





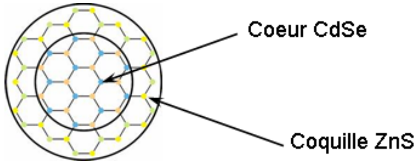


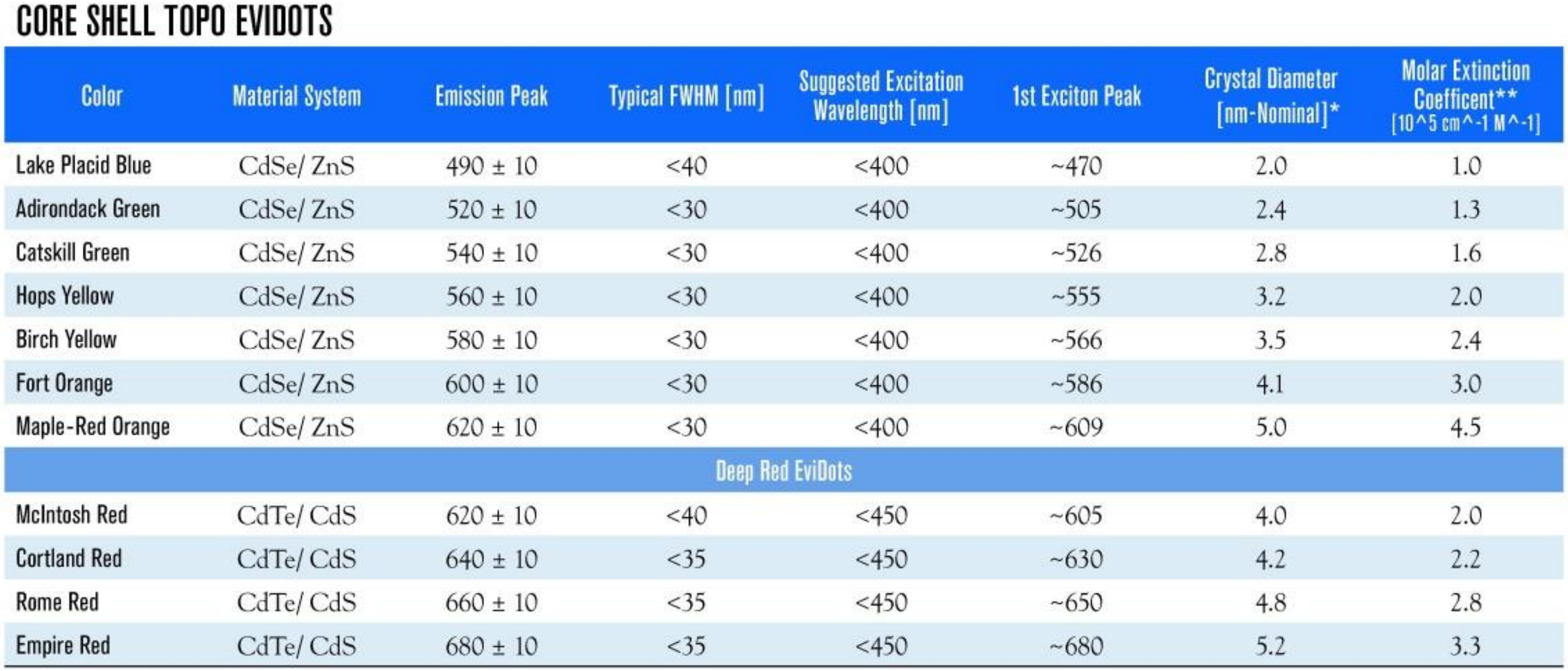
|5> Particular case: quantum dot

Semiconductor quantum emitters

→ Spectroscopy of quantum emitters in semiconductors nanocrystals

Accordability of nanocrystals: from a catalogue





CORE SHELL TOPO EVIDOTS

Color	Material System	Emission Peak	Typical FWHM [nm]	Suggested Excitation Wavelength [nm]	1st Exciton Peak	Crystal Diameter [nm-Nominal]*	Molar Extinction Coefficent** [10^5 cm^-1 M^-1]
Lake Placid Blue	CdSe/ ZnS	490 ± 10	<40	<400	~470	2.0	1.0
Adirondack Green	CdSe/ ZnS	520 ± 10	<30	<400	~505	2.4	1.3
Catskill Green	CdSe/ ZnS	540 ± 10	<30	<400	~526	2.8	1.6
Hops Yellow	CdSe/ ZnS	560 ± 10	<30	<400	~555	3.2	2.0
Birch Yellow	CdSe/ ZnS	580 ± 10	<30	<400	~566	3.5	2.4
Fort Orange	CdSe/ ZnS	600 ± 10	<30	<400	~586	4.1	3.0
Maple-Red Orange	CdSe/ ZnS	620 ± 10	<30	<400	~609	5.0	4.5
Deep Red EviDots							
McIntosh Red	CdTe/ CdS	620 ± 10	<40	<450	~605	4.0	2.0
Cortland Red	CdTe/ CdS	640 ± 10	<35	<450	~630	4.2	2.2
Rome Red	CdTe/ CdS	660 ± 10	<35	<450	~650	4.8	2.8
Empire Red	CdTe/ CdS	680 ± 10	<35	<450	~680	5.2	3.3

* Estimates based upon Yu, Qu, Guo, Peng, February 20, 2003. ** Measured at first exciton peak

|5> Particular case: quantum dot

Semiconductor quantum emitters

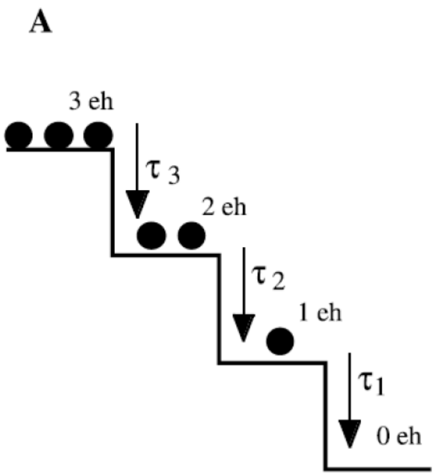
→ Spectroscopy of quantum emitters in semiconductors nanocrystals

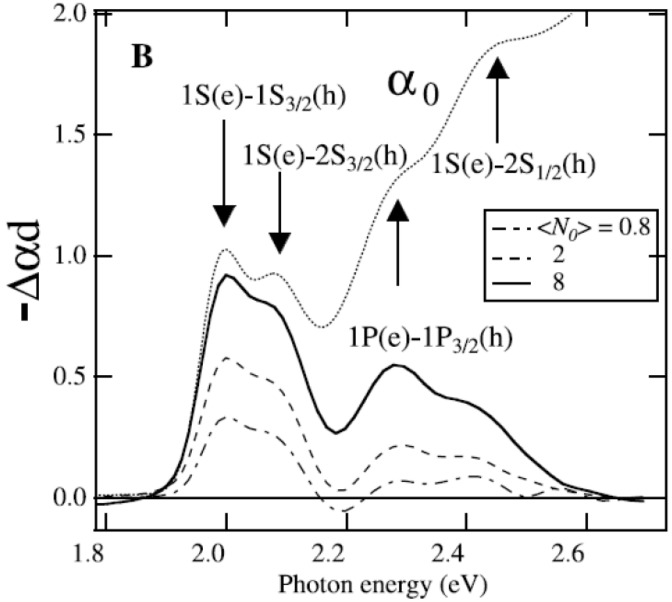
➡ Quantised energies

with Born-Von Karman boundary conditions:

$$\psi(x + L_x, y, z) = \psi(x, y, z)$$

$$E_{\vec{k}} = \frac{2\pi^2\hbar^2}{mL^2}(n_x^2 + n_y^2 + n_z^2)$$





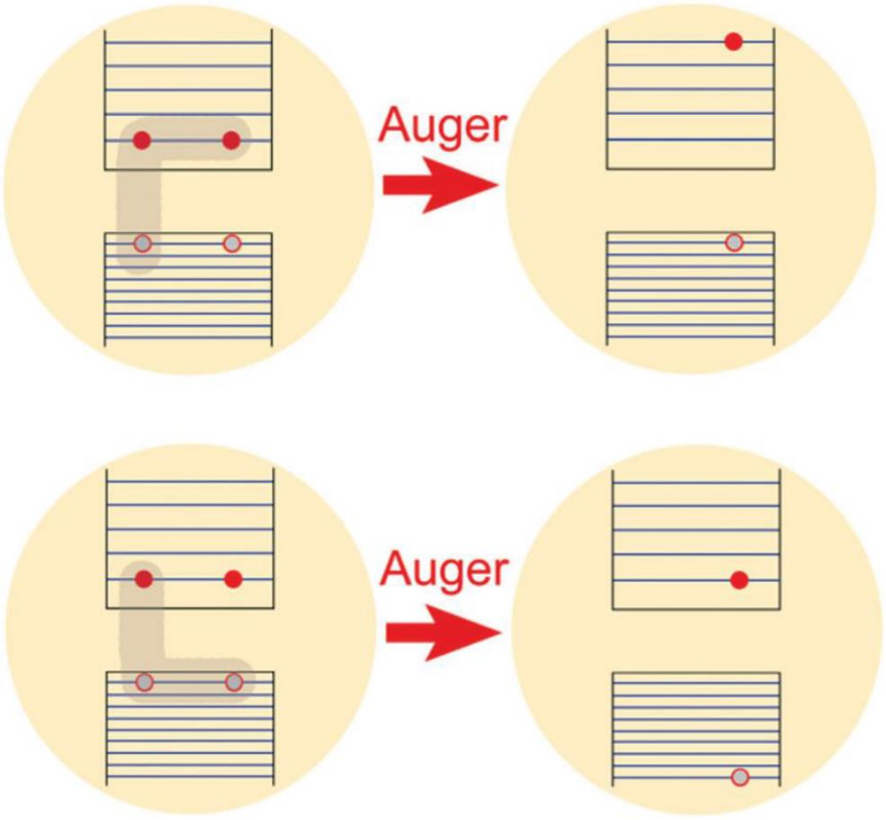
Klimov et al., Science 287, 1011 (2000)

|5> Particular case: quantum dot

Semiconductor quantum emitters

→ Spectroscopy of quantum emitters in semiconductors nanocrystals

➡ Auger effect

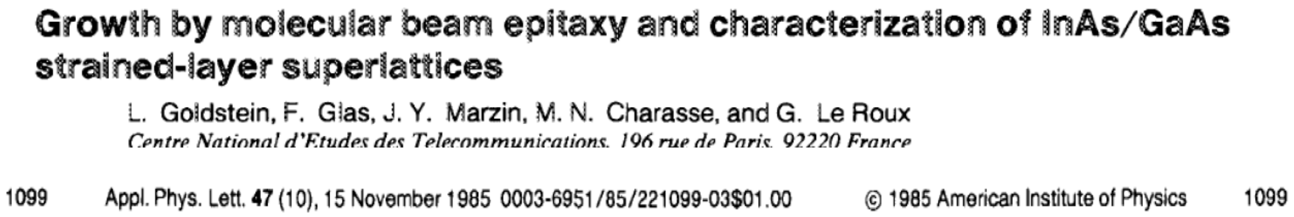


|5> Particular case: quantum dot

Semiconductor quantum emitters

→ Spectroscopy of quantum emitters in semiconductors quantum dots

Quantum 'boxes': physical growth
as opposed to chemical growth



Growth by molecular beam epitaxy and characterization of InAs/GaAs strained-layer superlattices

L. Goldstein, F. Glas, J. Y. Marzin, M. N. Charasse, and G. Le Roux
Centre National d'Etudes des Telecommunications, 196 rue de Paris, 92220 France

1099 Appl. Phys. Lett. **47** (10), 15 November 1985 0003-6951/85/221099-03$01.00 © 1985 American Institute of Physics 1099

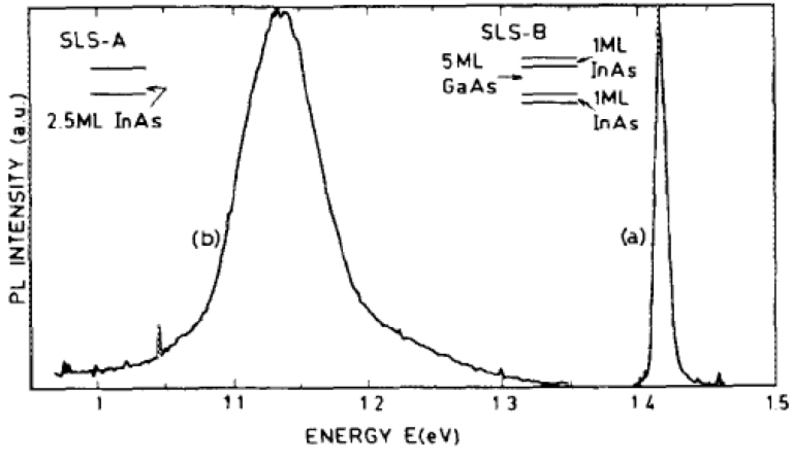


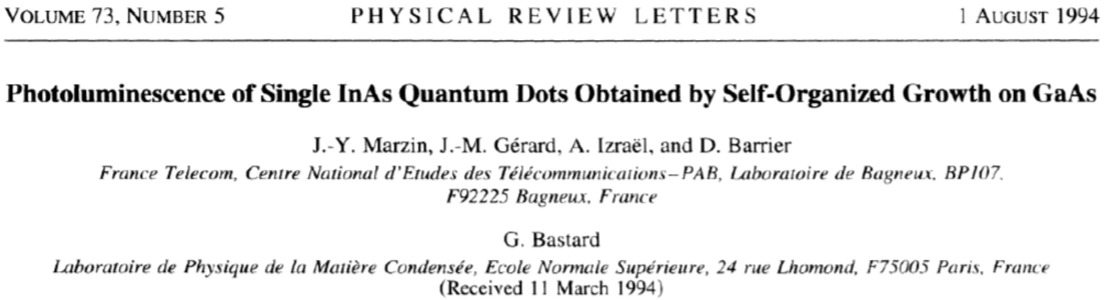
FIG. 3. Photoluminescence at 77 K for (a) 2D and (b) 3D.

|5> Particular case: quantum dot

Semiconductor quantum emitters

→ Spectroscopy of quantum emitters in semiconductors quantum dots

Quantum 'boxes' = quantum dots



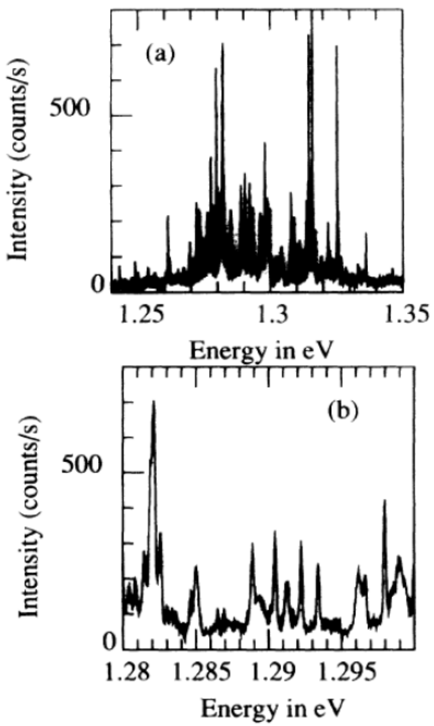
VOLUME 73, NUMBER 5 PHYSICAL REVIEW LETTERS 1 AUGUST 1994

Photoluminescence of Single InAs Quantum Dots Obtained by Self-Organized Growth on GaAs

J.-Y. Marzin, J.-M. Gérard, A. Izraël, and D. Barrier
France Telecom, Centre National d'Etudes des Télécommunications–PAB, Laboratoire de Bagneux, BP107, F92225 Bagneux, France

G. Bastard
Laboratoire de Physique de la Matière Condensée, Ecole Normale Supérieure, 24 rue Lhomond, F75005 Paris, France

(Received 11 March 1994)



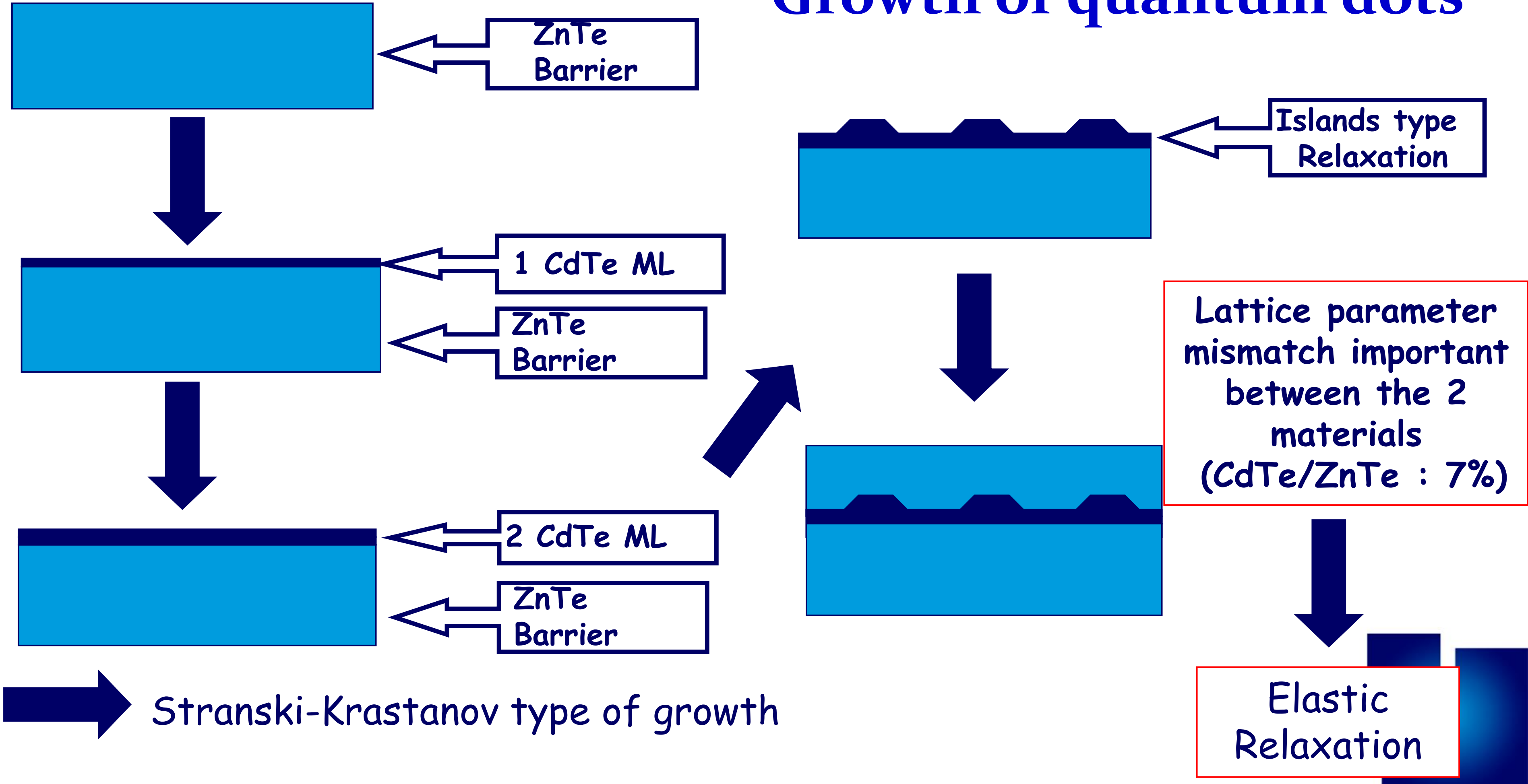
10 K, 500 nm mesa

(also Pierre Petroff at U. Santa Barbara)

|5> Particular case: quantum dot

Molecular Beam Epitaxy (MBE)

Growth of quantum dots



ZnTe Barrier

1 CdTe ML

ZnTe Barrier

2 CdTe ML

ZnTe Barrier

Islands type Relaxation

Lattice parameter mismatch important between the 2 materials (CdTe/ZnTe : 7%)

Elastic Relaxation

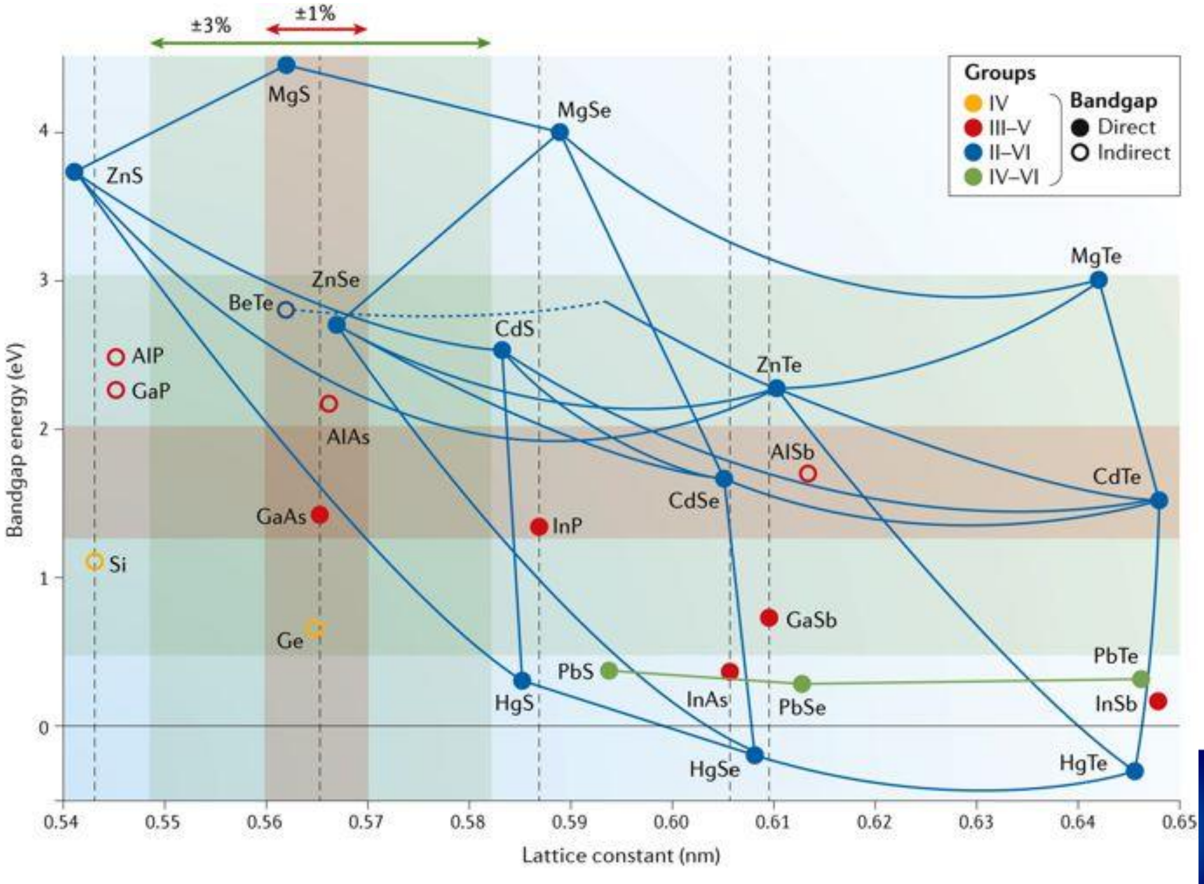
Stranski-Krastanov type of growth

|5> Particular case: quantum dot

Semiconductor quantum emitters

→ Material consideration in semiconductors quantum dots

Bandgap engineering

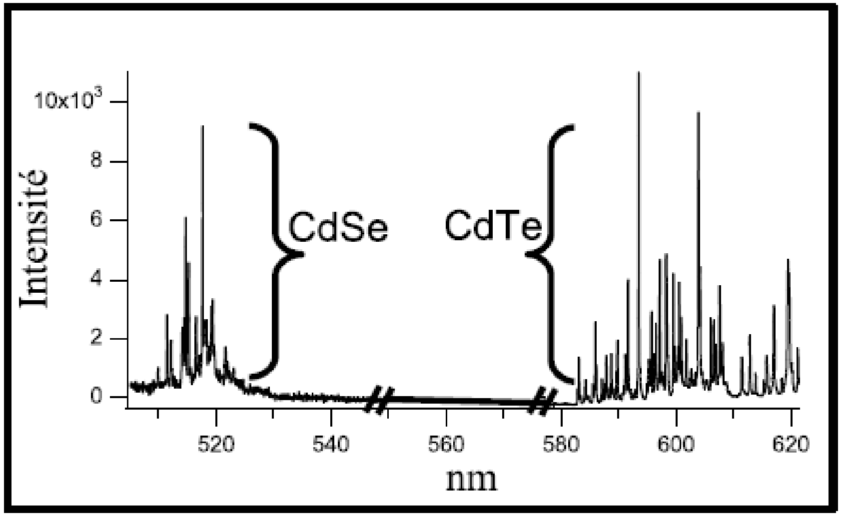


Nature Reviews | Materials

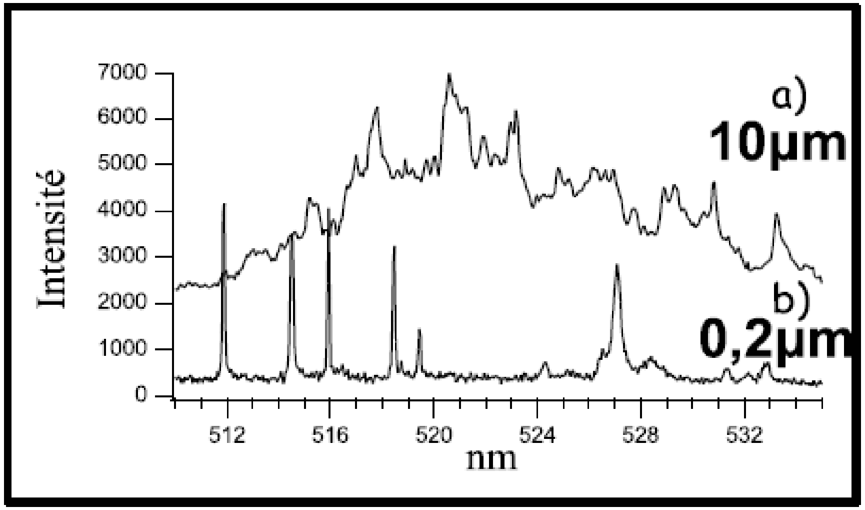
|5> Particular case: quantum dot

Semiconductor quantum emitters

→ Spectroscopy of quantum emitters in semiconductors quantum dots



Material effect…



Confinement effect…

|5> Particular case: quantum dot

Semiconductor quantum emitters

→ Spectroscopy of quantum emitters in semiconductors quantum dots

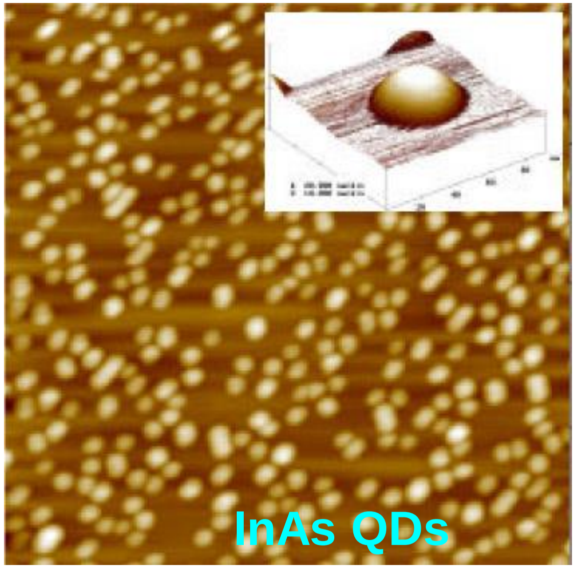
→ Nanoscale islands

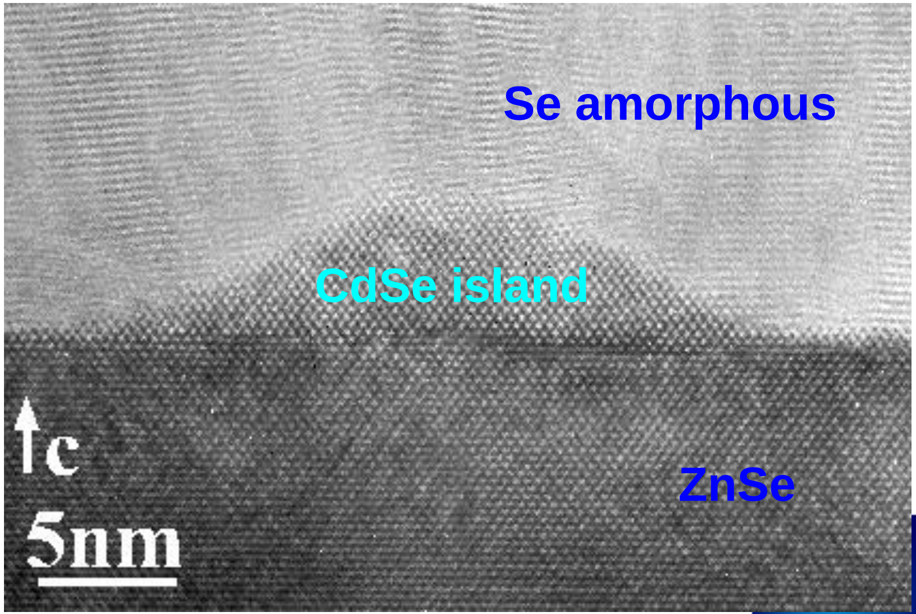
Quantum dots made of II-VI materials like
CdTe/ZnTe or CdSe/ZnSe or III-V like InAs/GaAs

Dim: diameter 20 nm
height 4 nm

Nanometer scale

↳ Quantum confinement effects



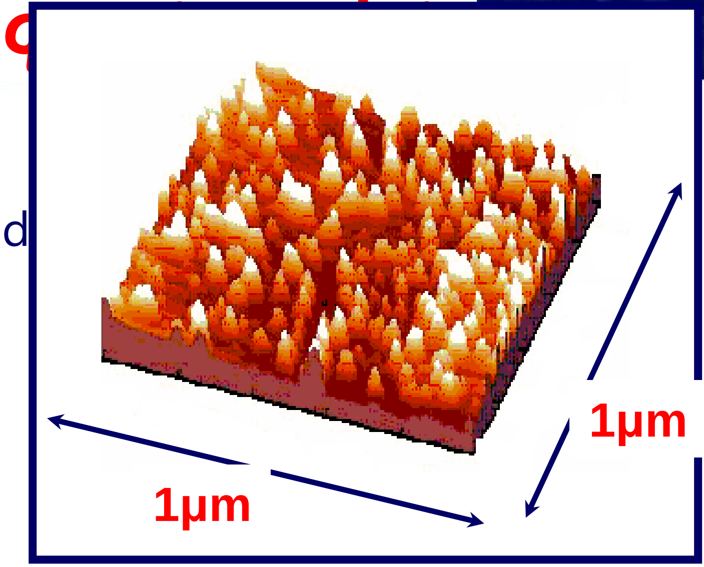


TEM image from C. Bougerol

|5> Particular case: q

Semiconductor quantum emitters

→ Spectroscopy of quantum emitters in semicond



Selection of a single quantum dot

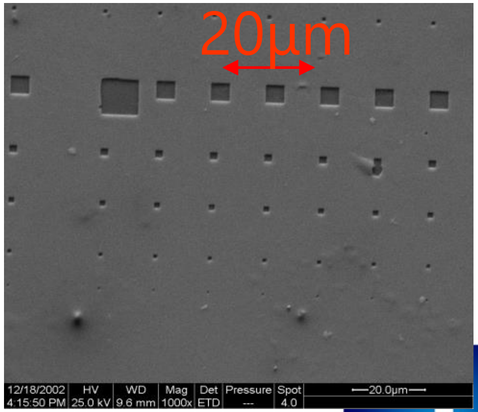
Inhomogeneous repartition of the relaxation

High density of Qds of 10^{10}cm^{-2}

Spatial selection

Deposition of an Al mask of 100 nm thickness

Openings of a=10 µm to 0.1 µm



for a=0.2 µm

≈ 4 excited QDs

Spectral selection

Size fluctuation of QDs

Unique spectrum for each QD

|5> Particular case: quantum dot

Semiconductor quantum emitters

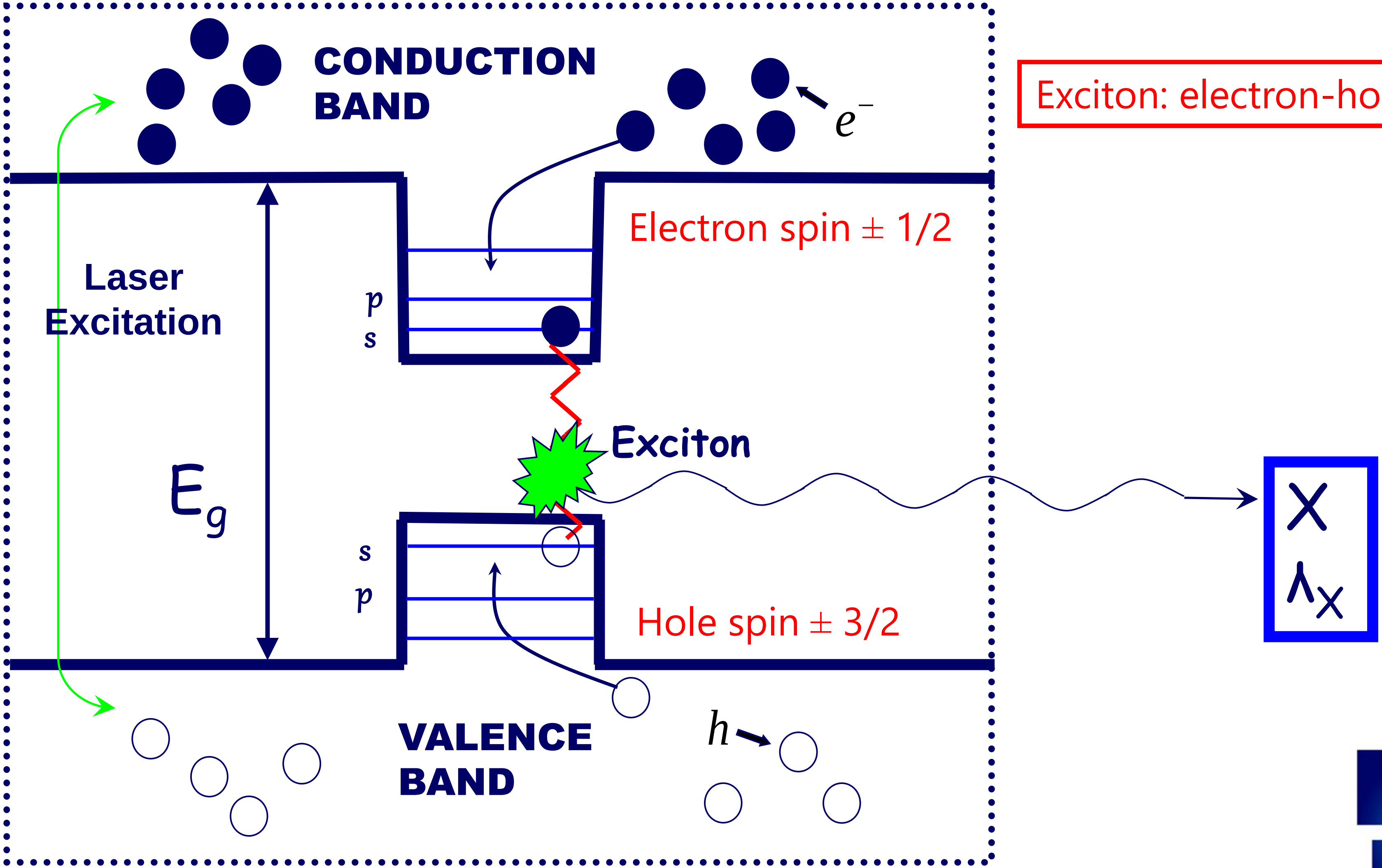
→ Spectroscopy of quantum emitters in semiconductors quantum dots

➡ Quantum dots = artificial atoms

Main difference: no 2 identical quantum dots

as many ‘hydrogen atoms’ as there are quantum dots

|5> Particular case: quantum dot

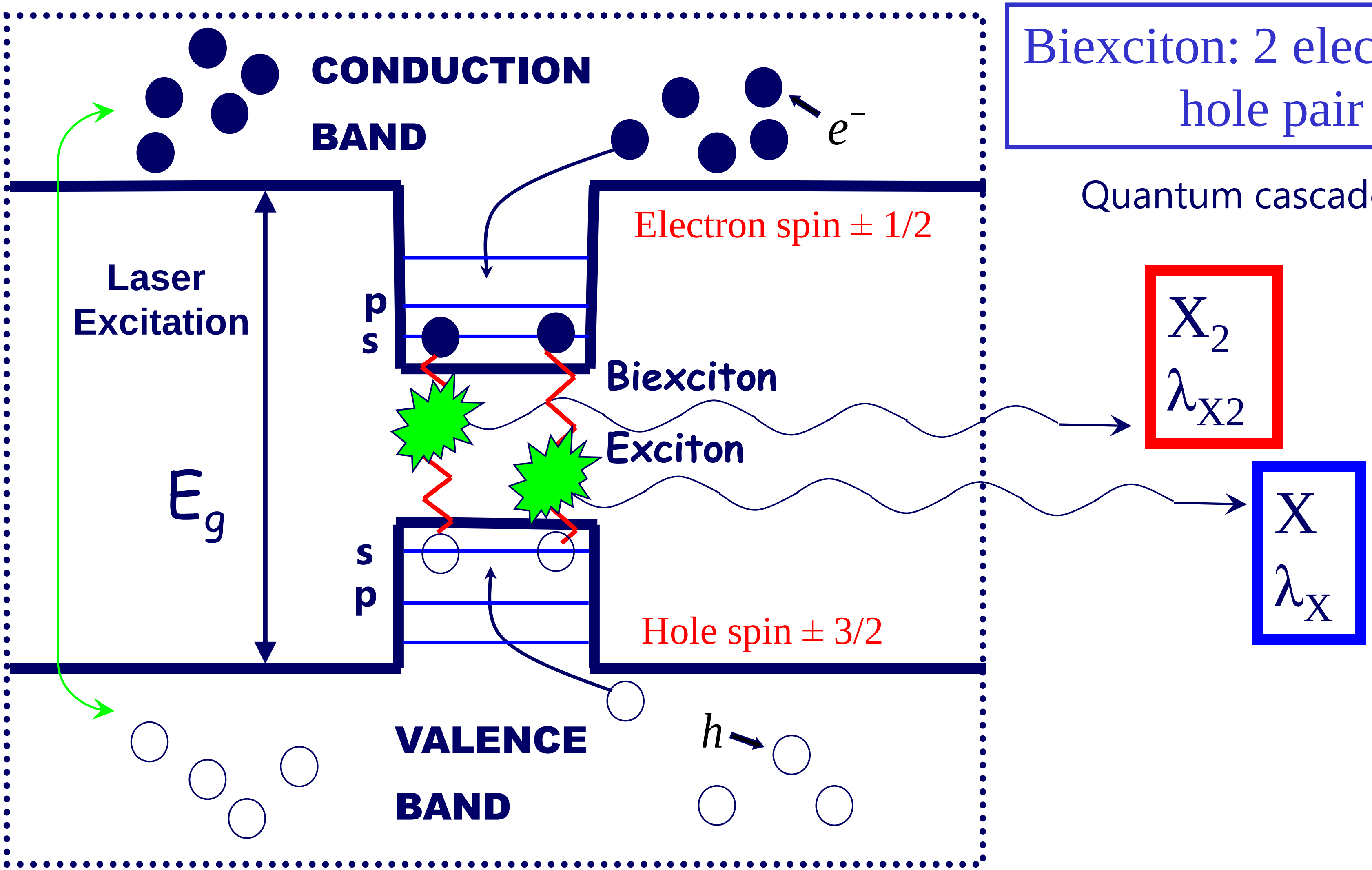


Exciton: electron-hole pair

|5> Particular case: quantum dot

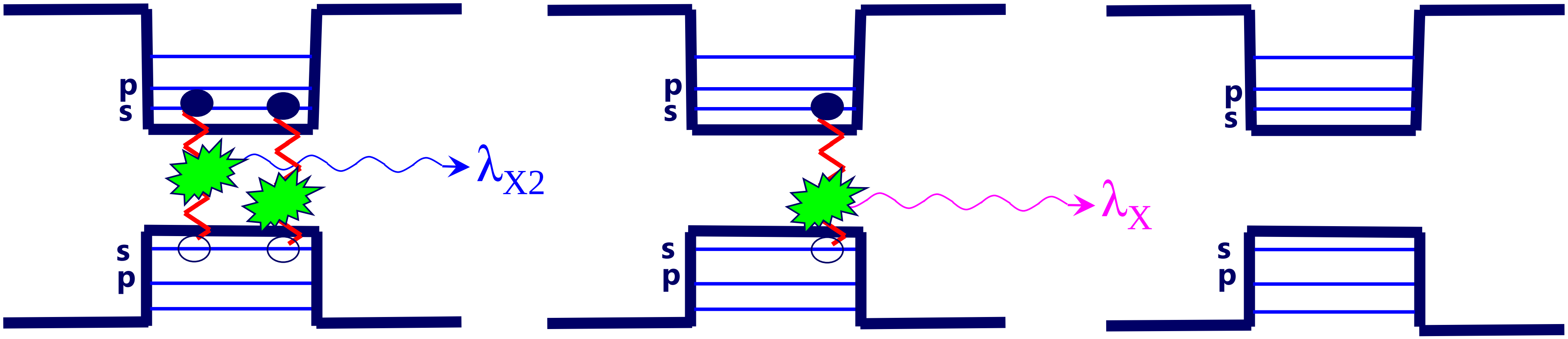
Biexciton: 2 electron-hole pair

Quantum cascade

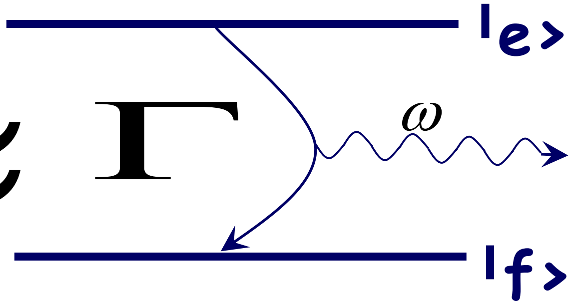


|5> Particular case: quantum dot

➡ Emission of single photons in a cascade



✦Spectral selection of the last exciton $\approx$



Radiative transition of
a 2-level atom

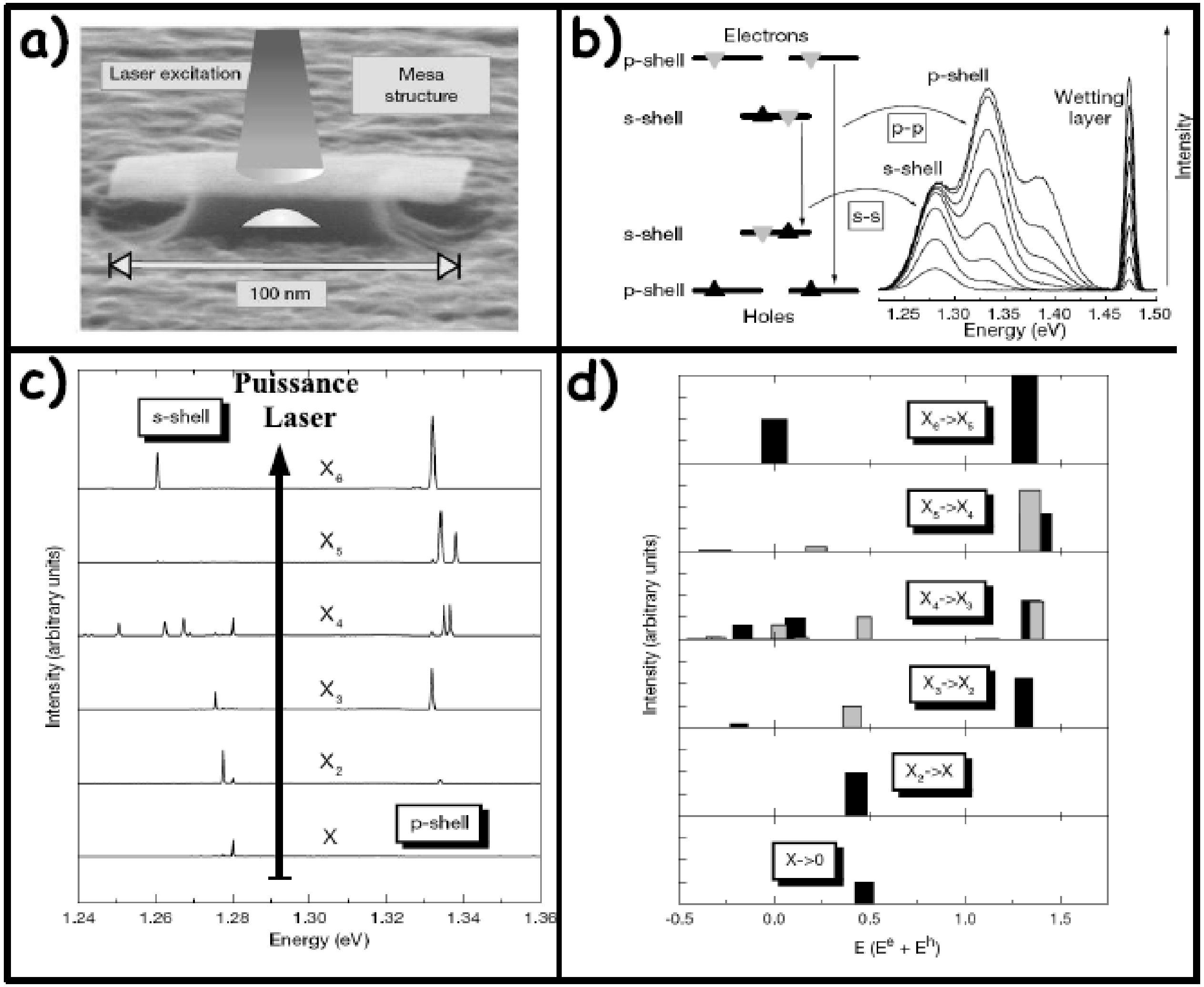
cf. Gayral and Gérard (1999).

|5> Particular case: quantum dot

Semiconductor quantum emitters

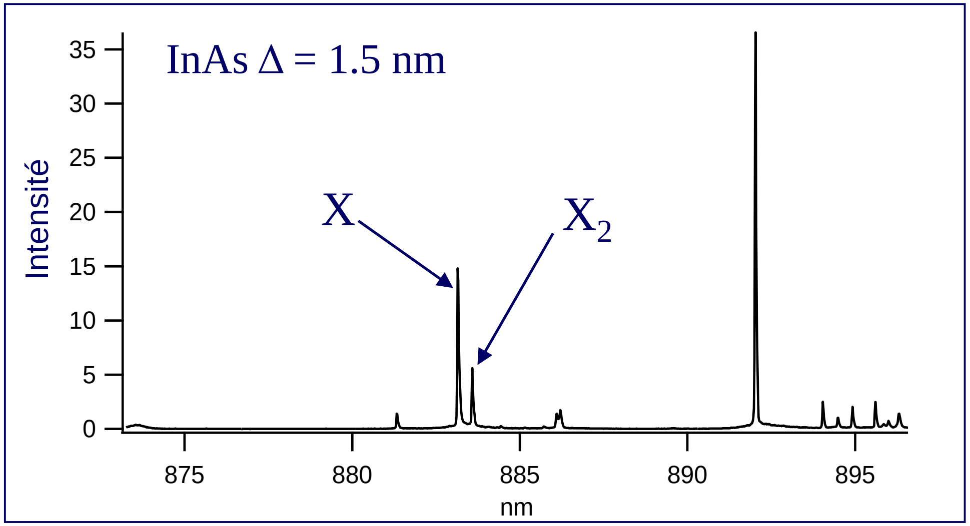
→ Spectroscopy of qu

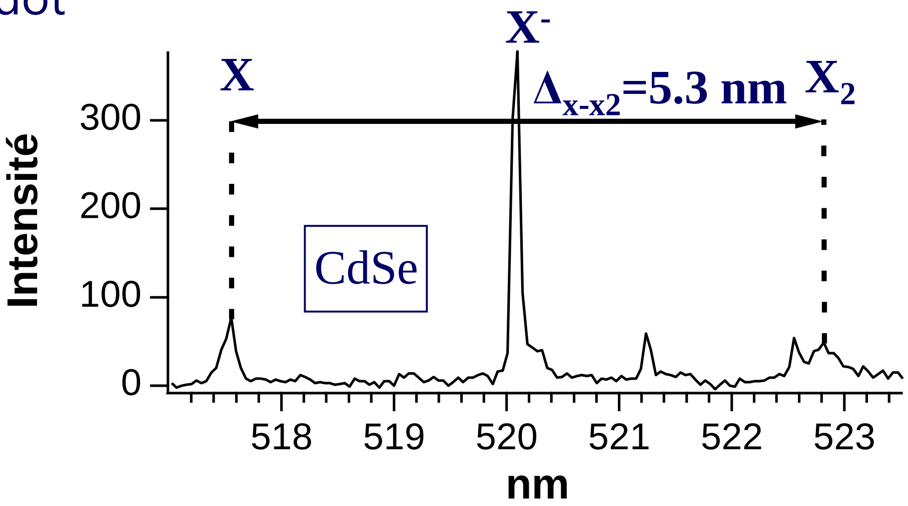
➡ Fine spectroscopy



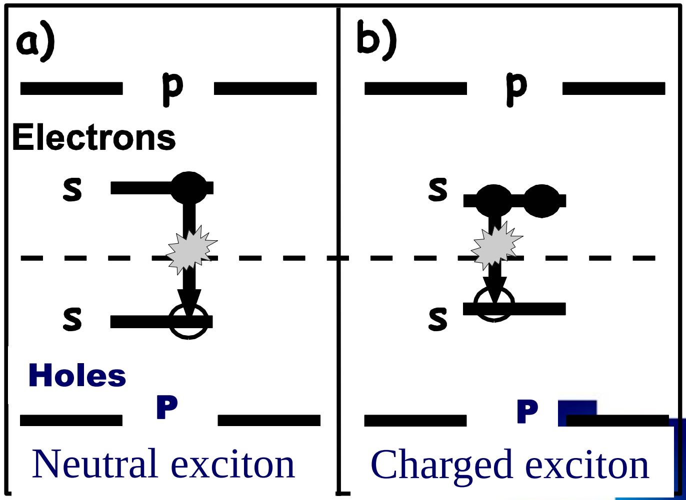
|5> Particular case: quantum dot

- Biexciton and exciton from a same dot





Power dependence (X/X_2)
Magnetic field dependence (X/X^-)



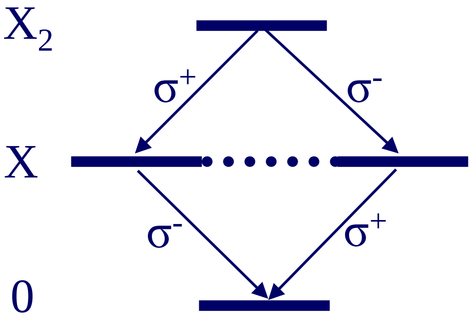
Neutral exciton

Charged exciton

|5> Particular case: quantum dot

- Perfect isotropic quantum dot:

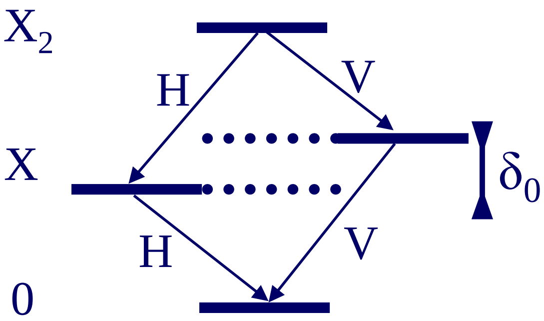
Fine spectroscopy splitting



Entangled state
in polarisation:

$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|\sigma^+\rangle_X|\sigma^-\rangle_{X_2} + |\sigma^-\rangle_X|\sigma^+\rangle_{X_2}\right)$$

- In reality, QDs are anisotropic:

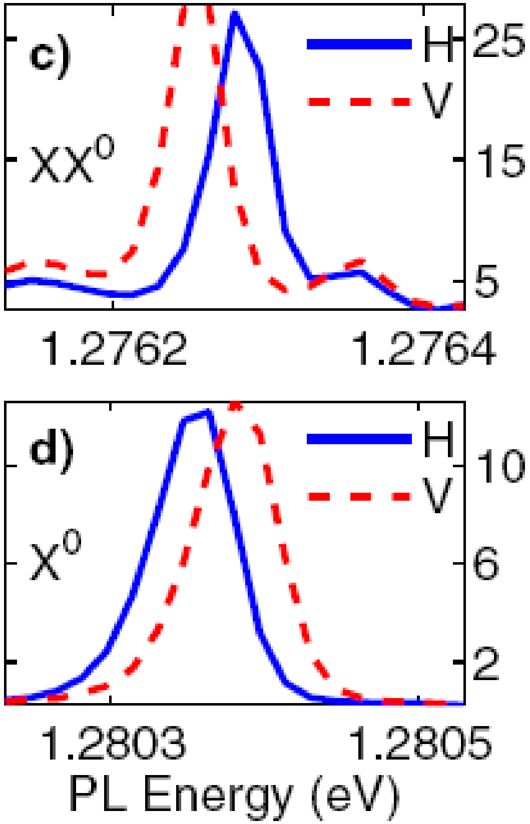


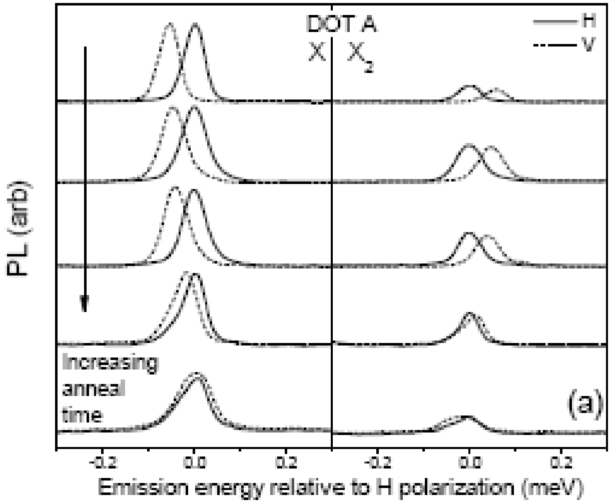
No entanglement,
only correlations

$$\rho = \frac{1}{2}|H_X\rangle\langle H_{X_2}| + \frac{1}{2}|V_X\rangle\langle V_{X_2}|$$

|5> Particular case: quantum dot

✦III-V quantum dots:





Splitting δ_0=1 to 100 µeV
= 0.5 to 40 GHz

Microwave region:
5 to 500 mm

Fine spectroscopy splitting

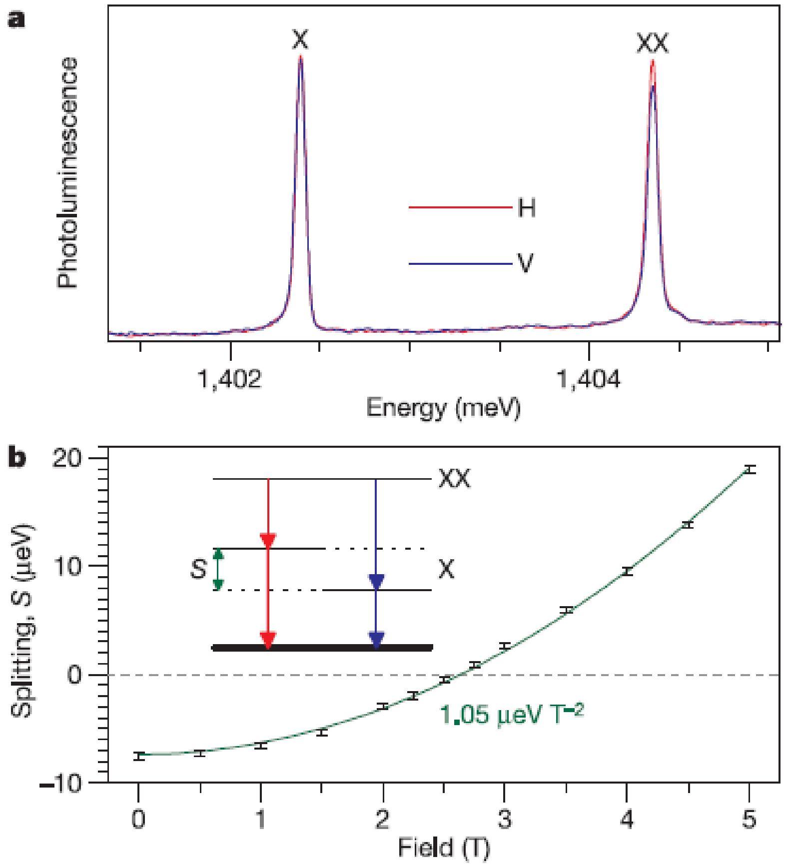
|5> Particular case: quantum dot

✦ III-V quantum dots:

Existing experiments: #1

Shifting of the levels by magnetic field B

Zeeman effect shift:
annihilation of the splitting



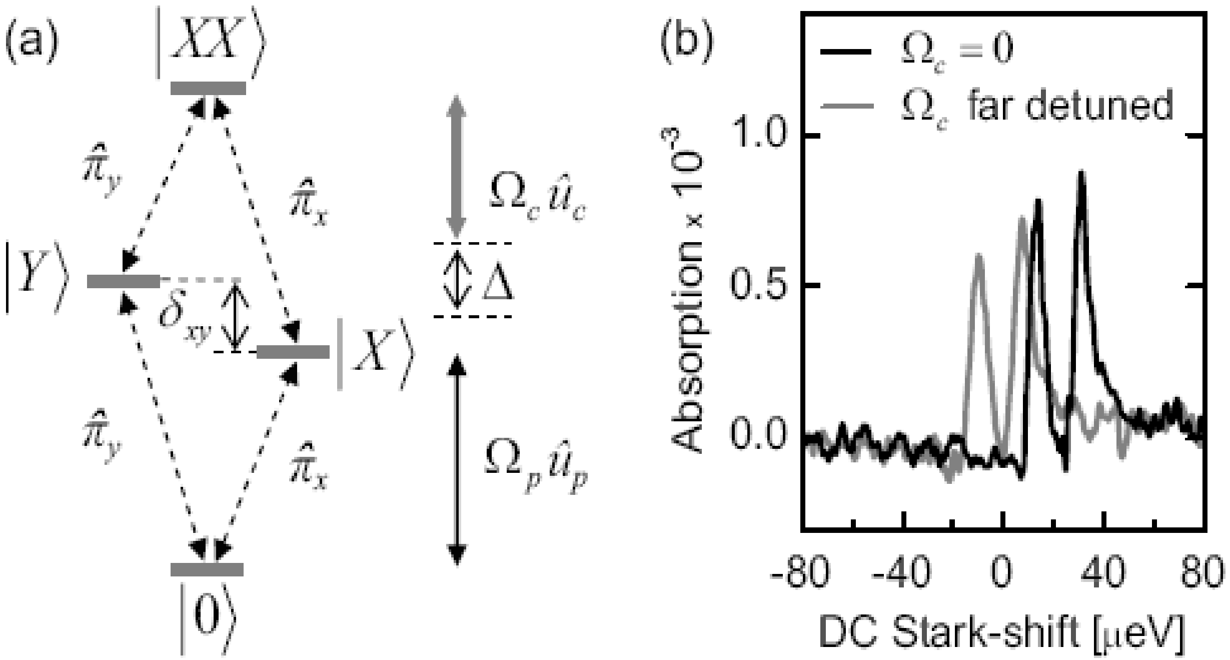
|5> Particular case: quantum dot

✦ III-V quantum dots:

Existing experiments: #2

Detuned lasers

AC Stark shift by virtual photons

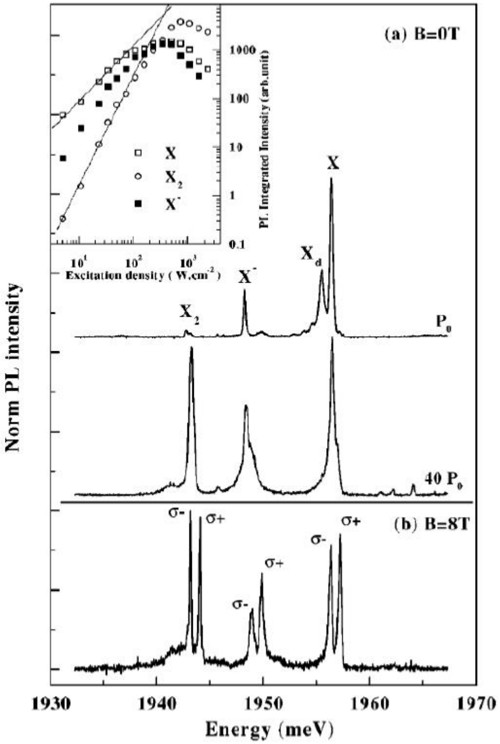


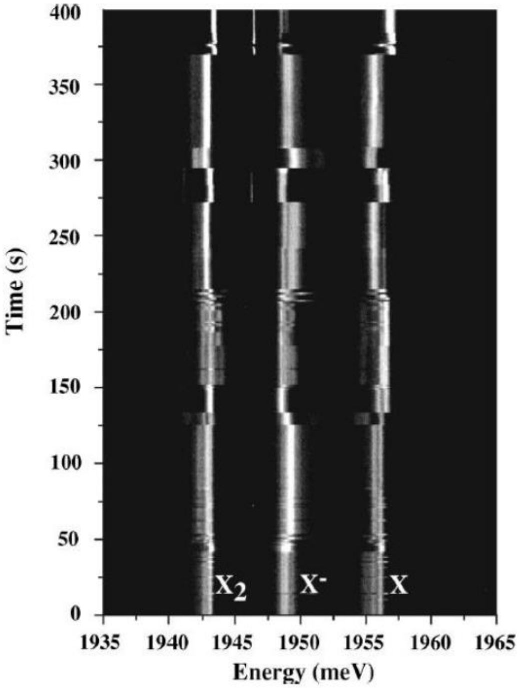
|5> Particular case: quantum dot

Semiconductor quantum emitters

→ Spectroscopy of quantum emitters in semiconductors quantum dots

Stark effect





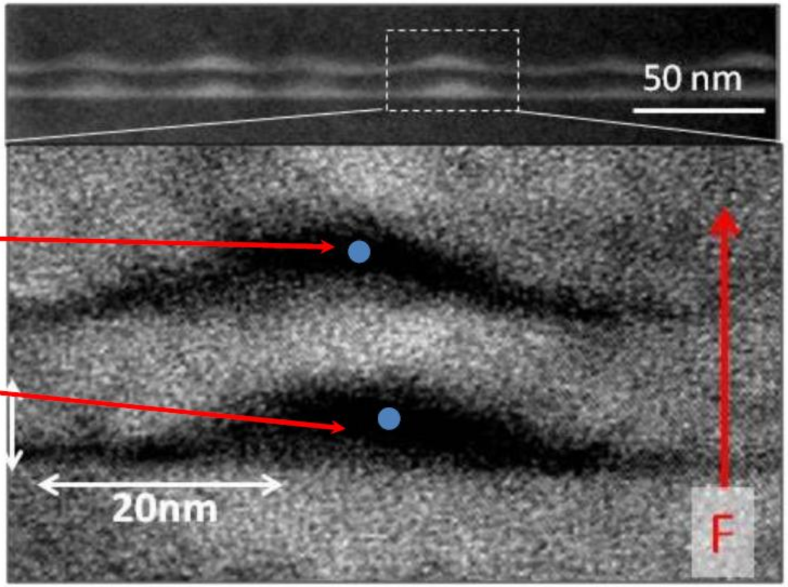
Besombes *et al.*, Phys. Rev. B 65, 121314 (2002)

|5> Particular case: quantum dot

Semiconductor quantum emitters

→ Spectroscopy of quantum emitters in semiconductors quantum molecules

Quantum molecules



✦ Coupled quantum dots or
'quantum molecules'

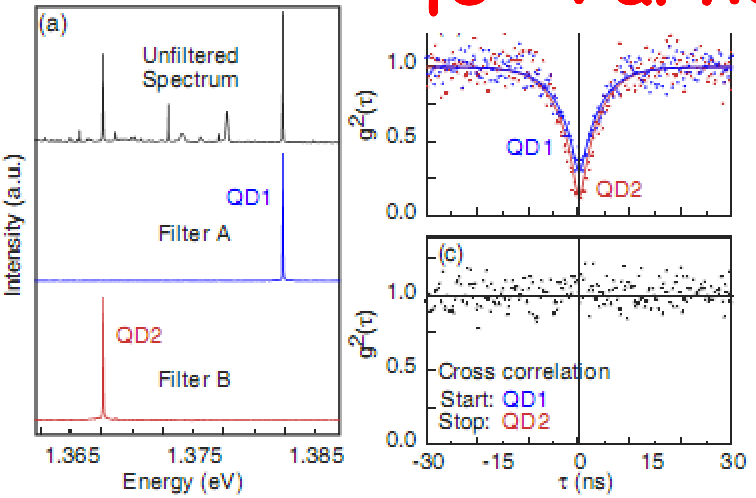
Quantum dot 1

Quantum dot 2

↳ Interaction between excitons in each dots

New levels appear like for a molecule

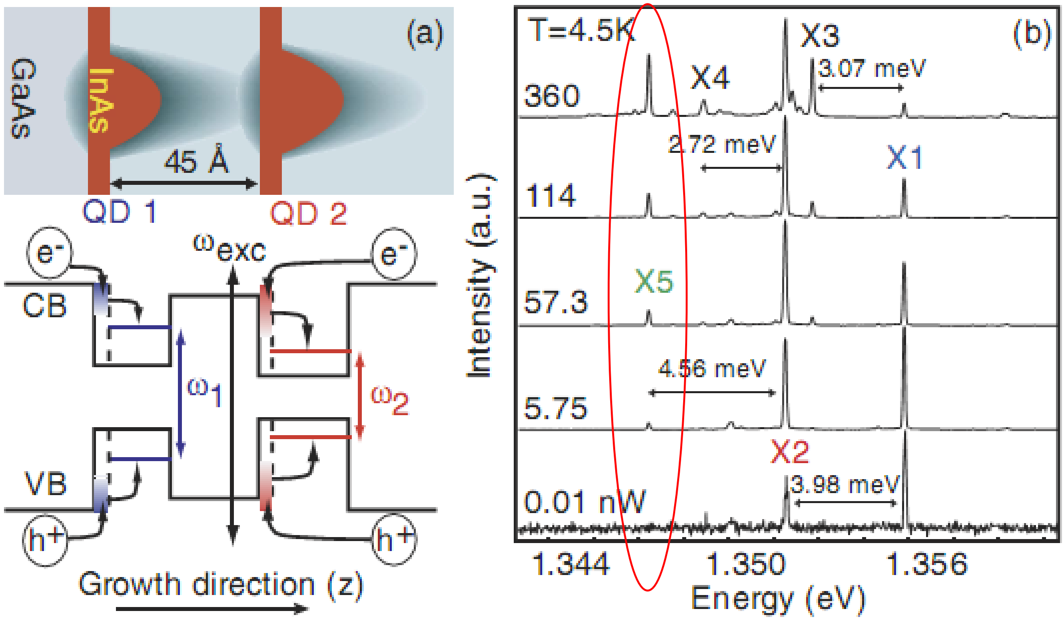
|5> Particular case: quantum dot



No correlations between the QDs laterally

Dipole-dipole coupling with observation of X5

checked by cross-correlations



Quantum molecules

Programme

|1> General context for quantum technologies
- → why should we care?

|2> How is it so different?
- → what about the market?

|3> Quantum technologies and qubits: the photon

|4> The need for a quantum emitter
- → definition of a quantum emitter
- → radiating dipole
- → zoology of quantum emitters

|5> Particular case: the quantum dot
- → semiconductor quantum emitter
- → artificial atom

|6> Application: quantum cryptography

- A bit of history
- Notion of quantum bit
- Photons as qubits
- BB84 Protocol
- Entanglement with photons
- E91 Protocol
- What's next…

ALICE

EVE

BOB

Cryptography

- Cryptography:

  Concept that makes sure information cannot be read by unauthorised people

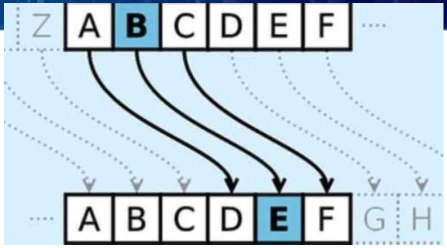
- Oldest known cryptographic system :
  scytale or Plutarque baton (400 before J. C.)

→ 2 identical batons
1 ribbon with letters

A bit of history…

- Ceasar's cipher

UTT= XWW
CHRISTOPHE=FKULVWRKH



- Le Grand Chiffre

Iron mask and Louis XIV (coding syllabes)

- Steganography

Before

After

- Enigma

2nd World War

Vernam cipher (one-time pad)

- Only system proven secure (Vernam & Mauborgne)

ALICE

Message: 0 1 0 0 1 0 1 …
Key: 1 1 0 1 0 0 1 …
XOR: --------------------
Cryptogram: 1 0 0 1 1 0 0 …

Cryptogram: 1 0 0 1 1 0 0 …
Key: 1 1 0 1 0 0 1 …
XOR: --------------------
Message: 0 1 0 0 1 0 1 …

Cryptogram (public)

XOR:
OR exclusive
Boole algebra

0 + 0 = 0
1 + 0 = 1
1 + 1 = 0
0 + 1 = 1

Key requirements:

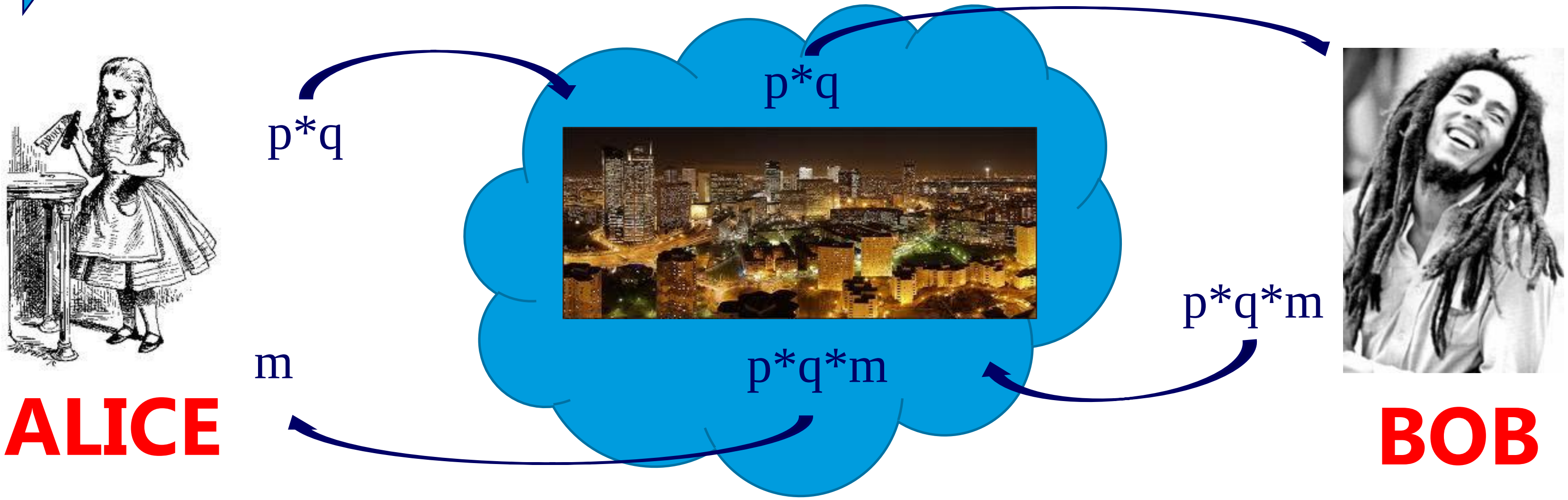
- → Chosen at random
- → Same length as message
- → Used only once

- → Never random?
- → Not easy
- → Costly

Nowadays

- RSA system (Rivest-Shamir-Adleman)

used for e-commerce



Based on the principe that multiplying prime numbers is easy, but finding the prime numbers is difficult !

Limits of cryptography

- More and more data transfer
- A mad mathematician…
- With a quantum computer: end of RSA

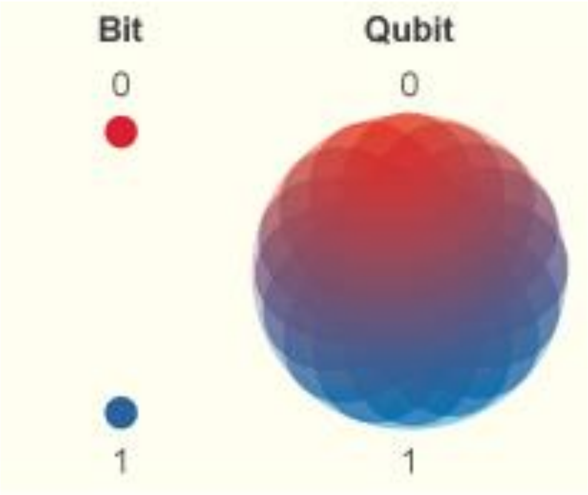
NSA data centre in Utah-USA

→ Mosca's 'threat': store now,
decrypt later…

→ Solution:
<u>quantum cryptography?</u>

Notion of quantum bit

- Comparison: classical & quantum bit



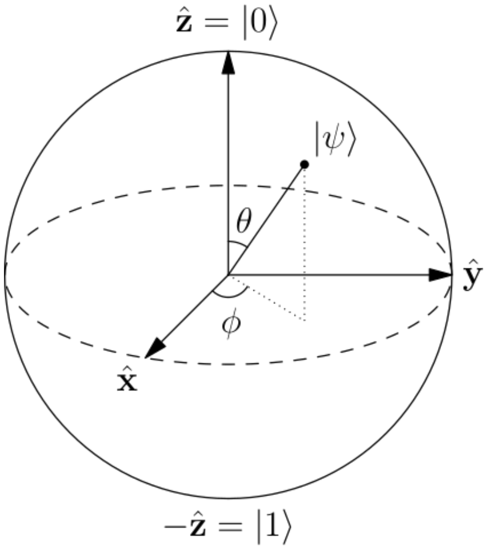
Result:

$\Psi = 0$ OR 1

Result:

$|\Psi\rangle = \alpha|0\rangle + \beta|1\rangle$

Representation on the Bloch sphere



No-cloning theorem in Nature

- Impossible to clone a quantum state

Dolly is OK but no-cloning machine

W. Wootters, W. Zurek, Nature 299, 802–803 (1982). "A Single Quantum Cannot be Cloned".

D. Dieks, Physics Letters A 92, 271–272 (1982). "Communication by EPR devices".

Notions of Electromagnetism

- Photon = electromagnetic wave

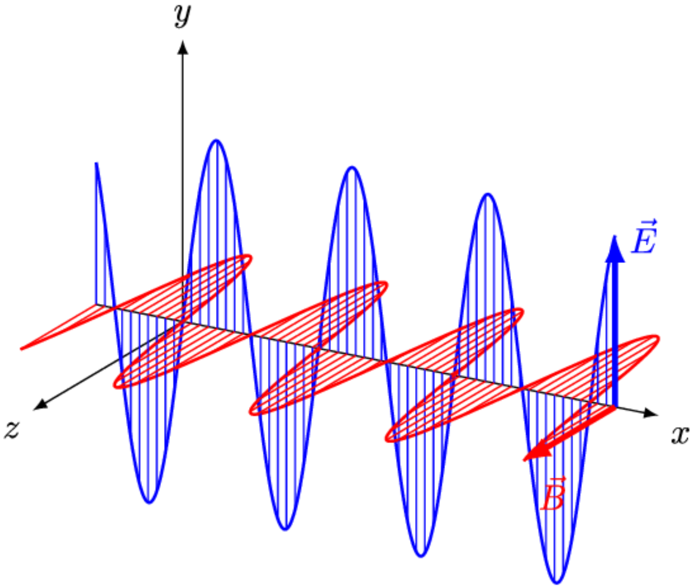
Maxwell's equations

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0}$$

$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J} + \mu_0 \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t}$$



$(\vec{E}, \vec{B}, \vec{u})$

$$\vec{B} = \frac{\vec{u} \wedge \vec{E}}{c}$$

$$\Delta \mathbf{E} = \frac{1}{c^2} \frac{\partial^2 E}{\partial t^2}$$

Wave propagation

Notions of Electromagnetism

Works for single photons

- Photon = electromagnetic wave

Maxwell's equations

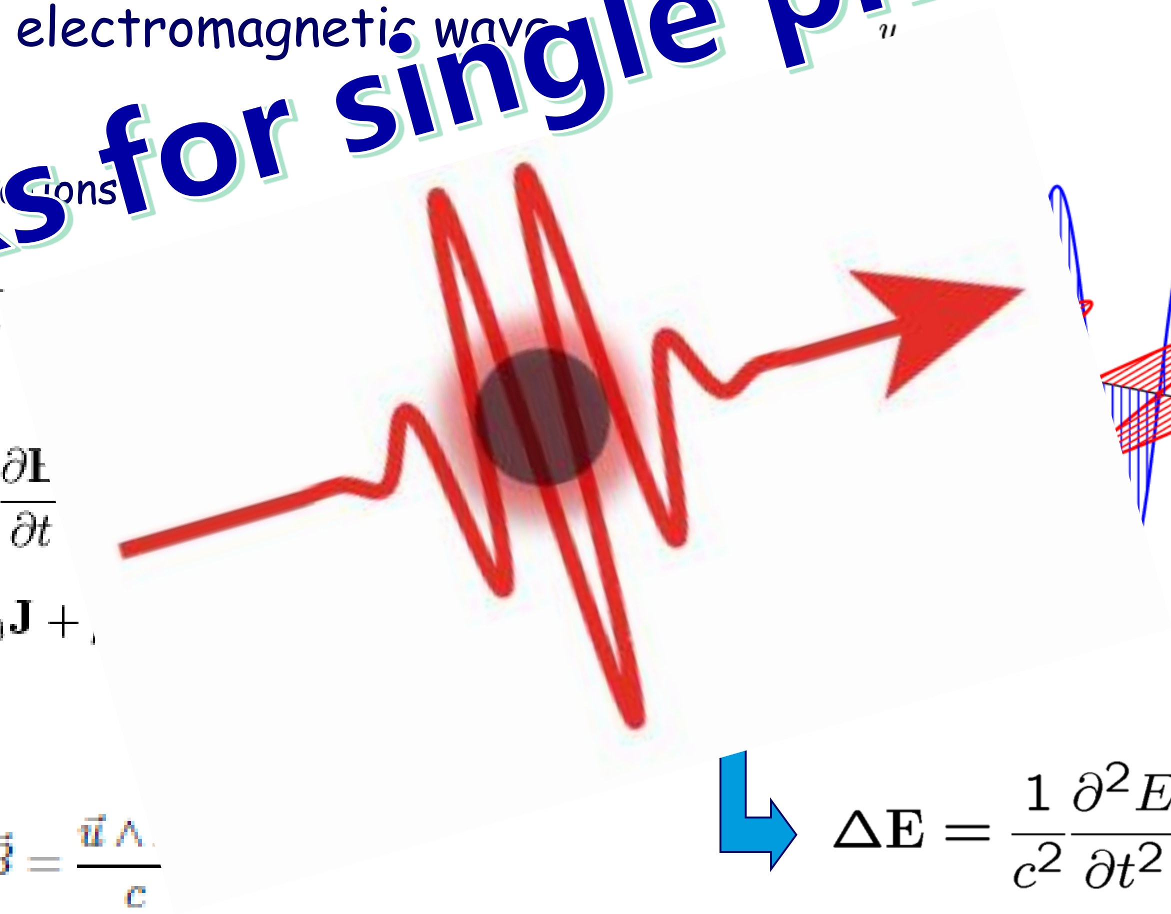
$$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0}$$

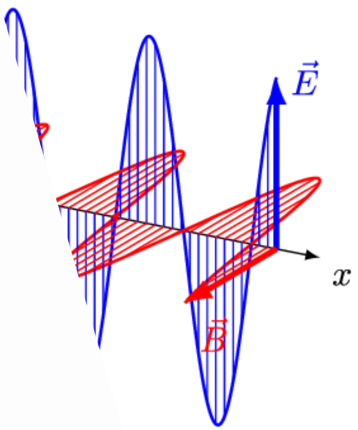
$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J} +$$

$$\vec{B} = \frac{\vec{u} \wedge}{c}$$





$$\Delta \mathbf{E} = \frac{1}{c^2}\frac{\partial^2 E}{\partial t^2}$$

Wave propagation

|3> the photon as a qubit

→ A quick reminder: polarisation

Linear polarisation along x and y:

$$\vec{E} = E_0 \cos(kz - \omega t)\vec{e}_x$$

$$\vec{E} = E_0 \cos(kz - \omega t)\vec{e}_y$$

$$|\psi\rangle = |0\rangle \text{ and } |1\rangle$$

Linear polarisation at +- 45°:

$$\vec{E} = E_0 \cos(kz - \omega t)(\vec{e}_x + \vec{e}_y)$$

$$\vec{E} = E_0 \cos(kz - \omega t)(\vec{e}_x - \vec{e}_y)$$

$$|\psi\rangle = \frac{1}{\sqrt{2}}|0\rangle \pm \frac{1}{\sqrt{2}}|1\rangle$$

Circular polarisation right or left-handed:

$$\vec{E} = E_0 \cos(kz - \omega t)\vec{e}_x + E_0 \cos\left(kz - \omega t + \frac{\pi}{2}\right)\vec{e}_y$$

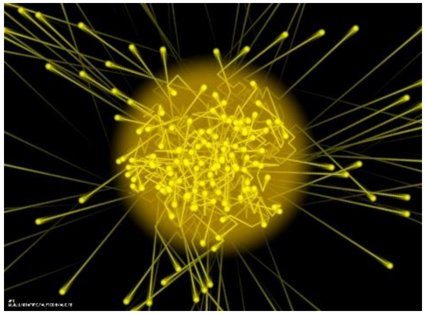
$$\vec{E} = E_0 \cos(kz - \omega t)\vec{e}_x - E_0 \cos\left(kz - \omega t + \frac{\pi}{2}\right)\vec{e}_y$$

$$|\psi\rangle = \frac{1}{\sqrt{2}}|0\rangle \pm \frac{i}{\sqrt{2}}|1\rangle$$

Note: often we have $|0\rangle = |V\rangle$ and $|1\rangle = |H\rangle$
for vertical & horizontal linear polarisation

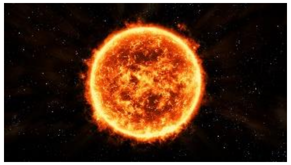
|3> the photon as a qubit

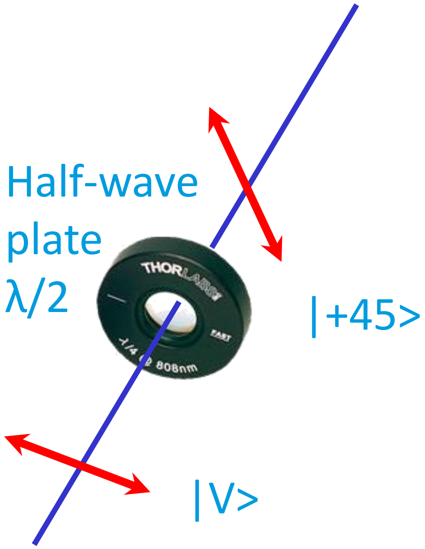
→ A quick reminder: what is a single photon?

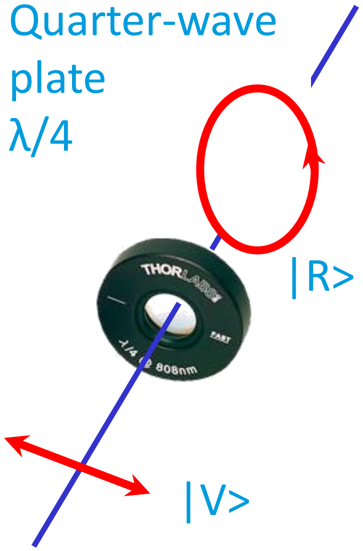


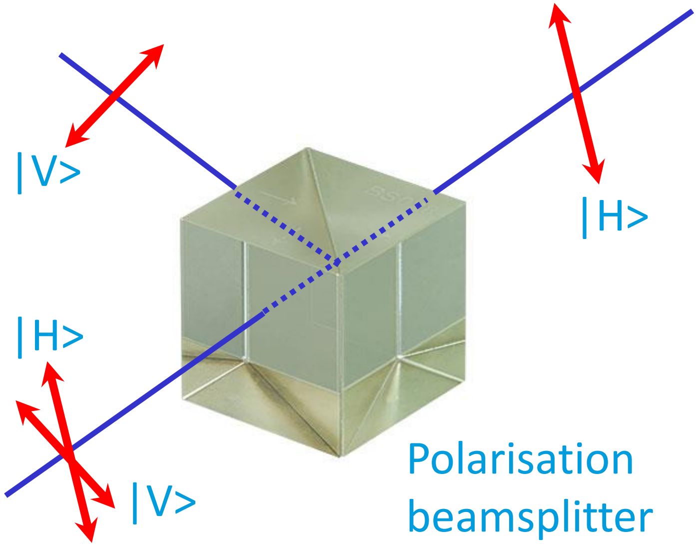
light is an electromagnetic wave

→ also particles = photons



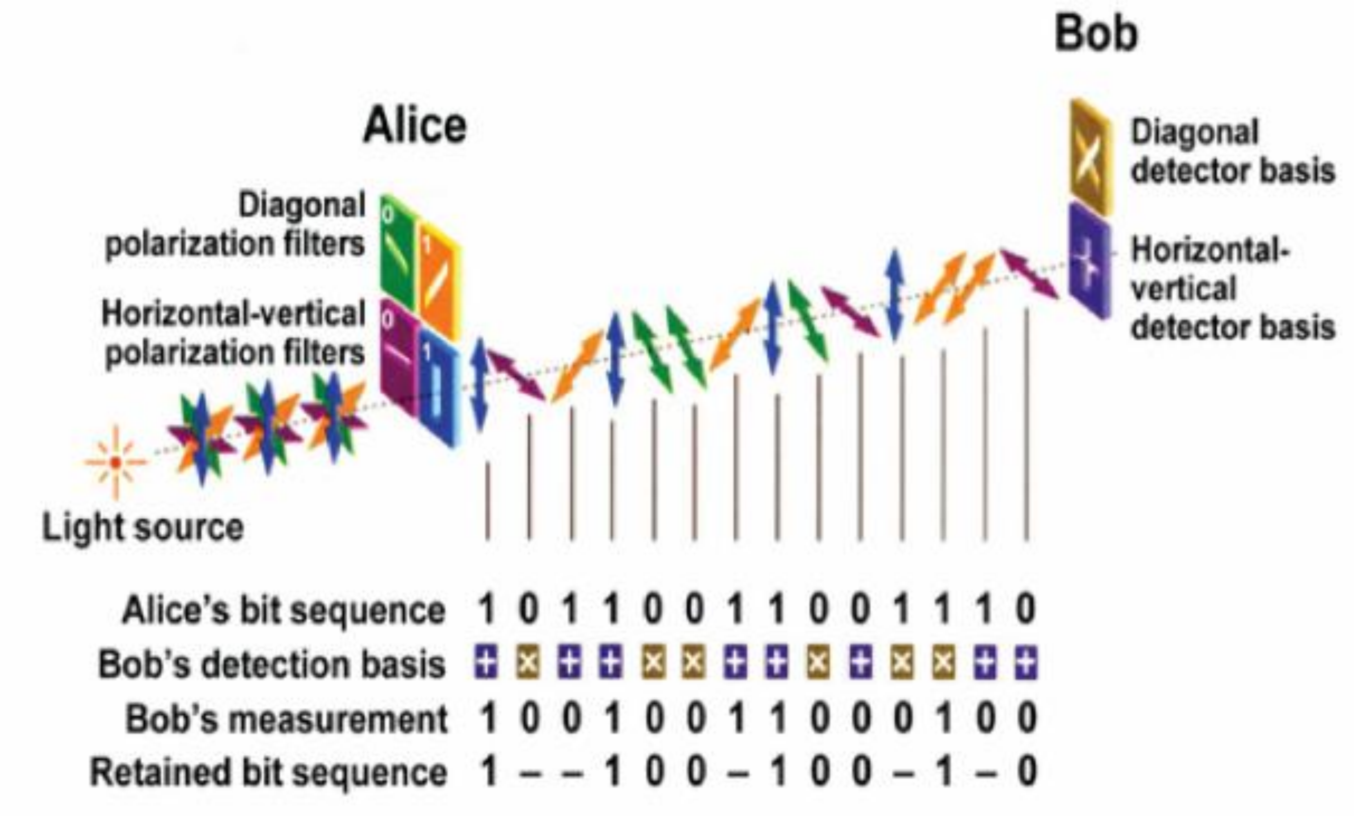






BB84 protocol

- Bennett-Brassard quantum key distribution protocol (1984)

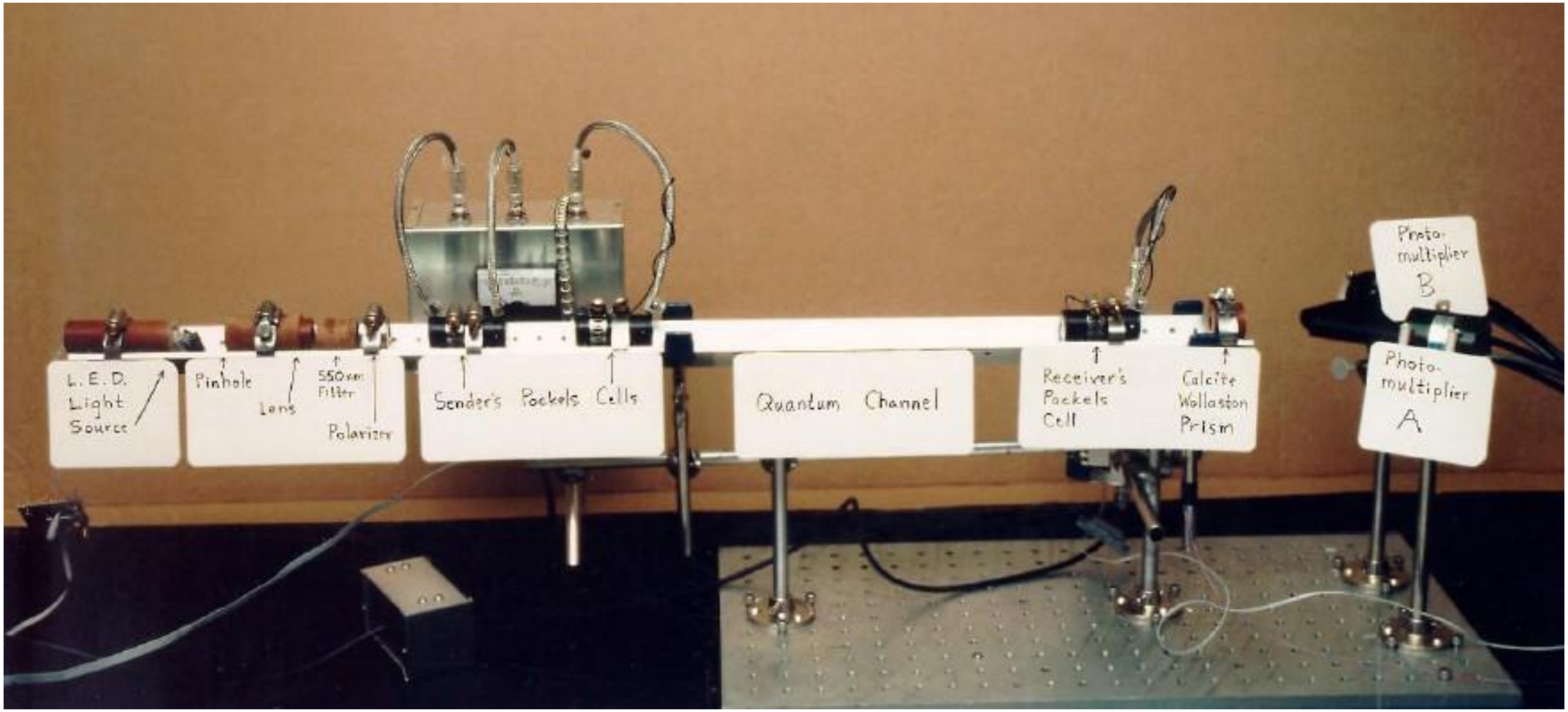


Alice's bit sequence	1	0	1	1	0	0	1	1	0	0	1	1	1	0
Bob's detection basis	+	×	+	+	×	×	+	+	×	+	×	×	+	+
Bob's measurement	1	0	0	1	0	0	1	1	0	0	0	1	0	0
Retained bit sequence	1	–	–	1	0	0	–	1	0	0	–	1	–	0

C. H. Bennett & G. Brassard. "Quantum cryptography: Public key distribution and coin tossing". In Proceedings of IEEE International Conference on Computers, Systems and Signal Processing 175, 8 (1984).

BB84 protocol

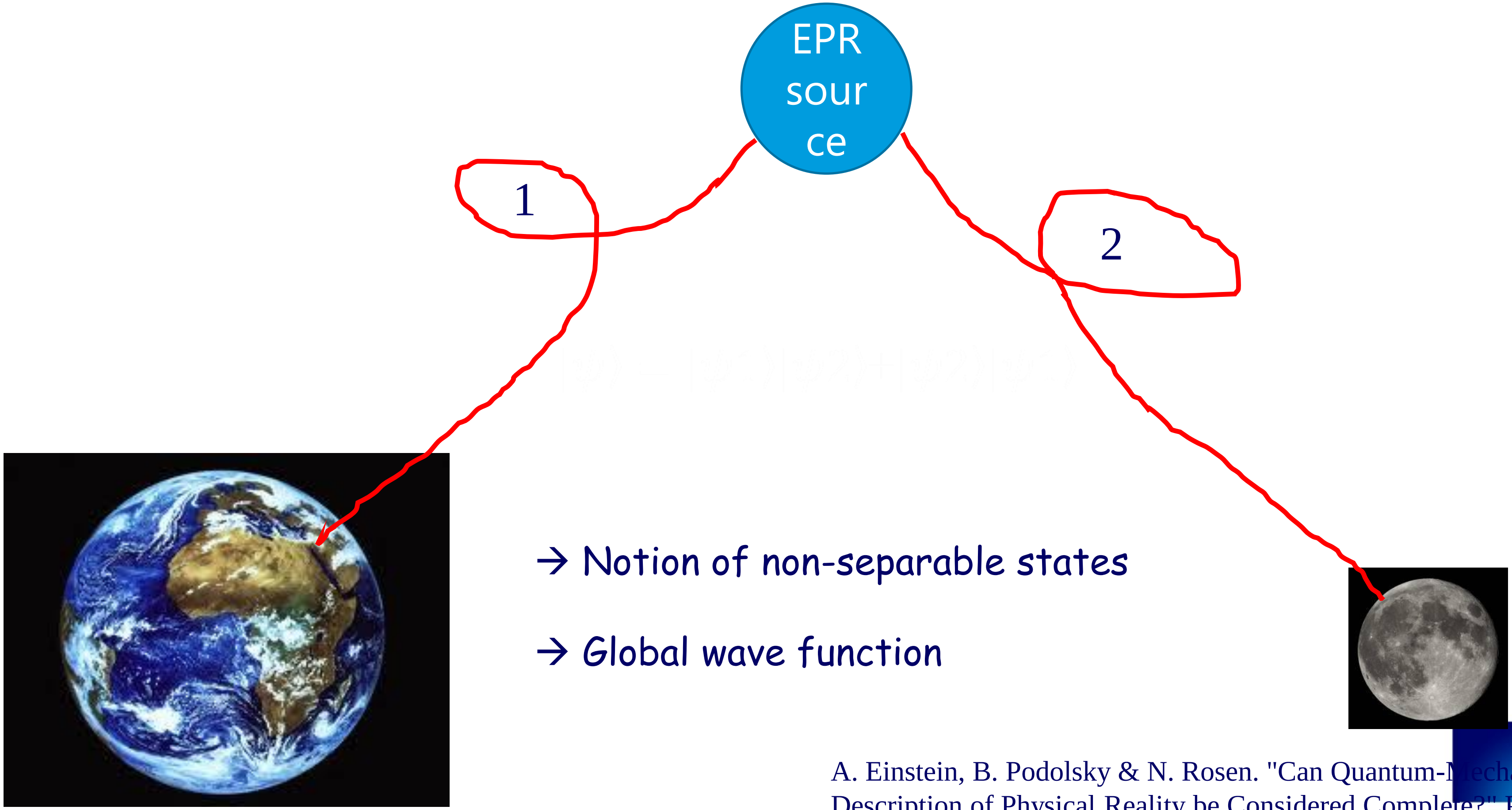
- First experiment



C. H. Bennett, F. Bessette, G. Brassard, L. Salvail & J. Smolin, J. o
Crypt.5, 3, "Experimental quantum cryptography" (1992).

Notion of entanglement

Einstein-Podolski-Rosen paradox (1935)



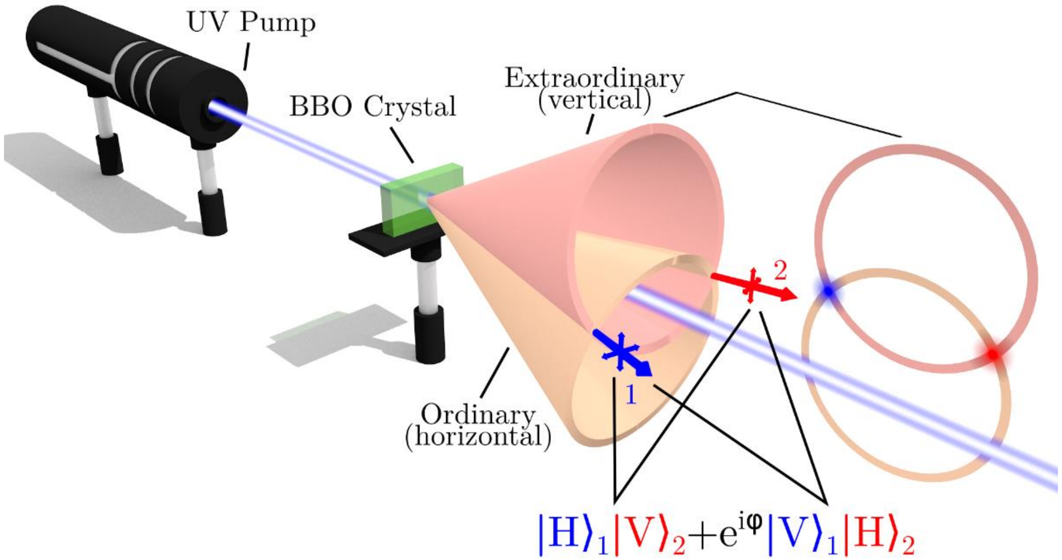
→ Notion of non-separable states

→ Global wave function

A. Einstein, B. Podolsky & N. Rosen. "Can Quantum-Mechanical Description of Physical Reality be Considered Complete?" Physical Review 47, 777–780 (1935).

Photon entanglement

- Polarisation photon entanglement



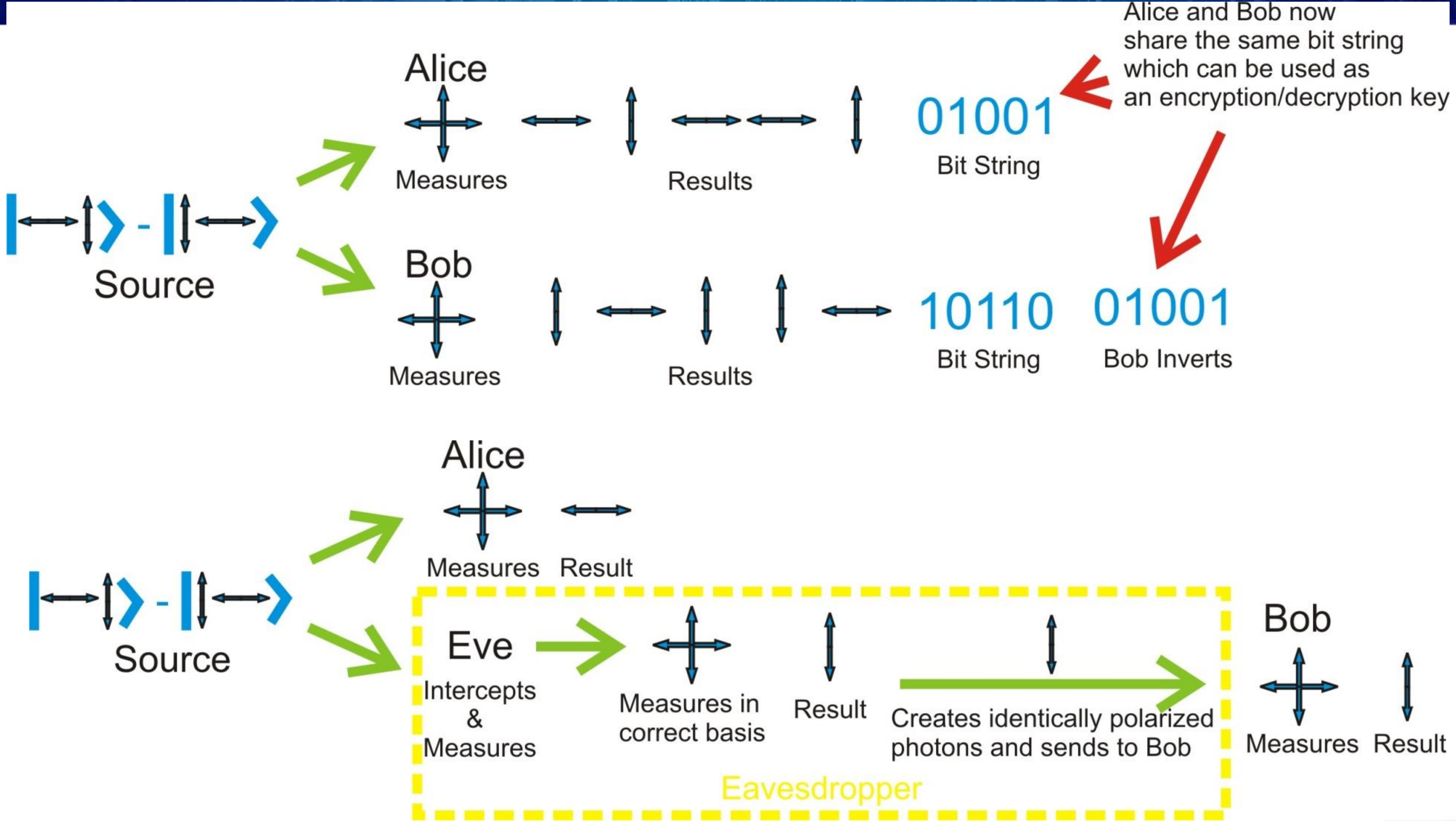
Type II non-linear crystal:

$$\left|\psi^-\right\rangle = \frac{1}{\sqrt{2}}\left(\left|H_1\right\rangle\left|V_2\right\rangle - \left|V_2\right\rangle\left|H_1\right\rangle\right)$$

$$\begin{cases} \vec{k}_p = \vec{k}_1 + \vec{k}_2 \\ E_P = E_1 + E_2 \end{cases}$$

Ekert91 protocol using photon entanglement

E91 protocol



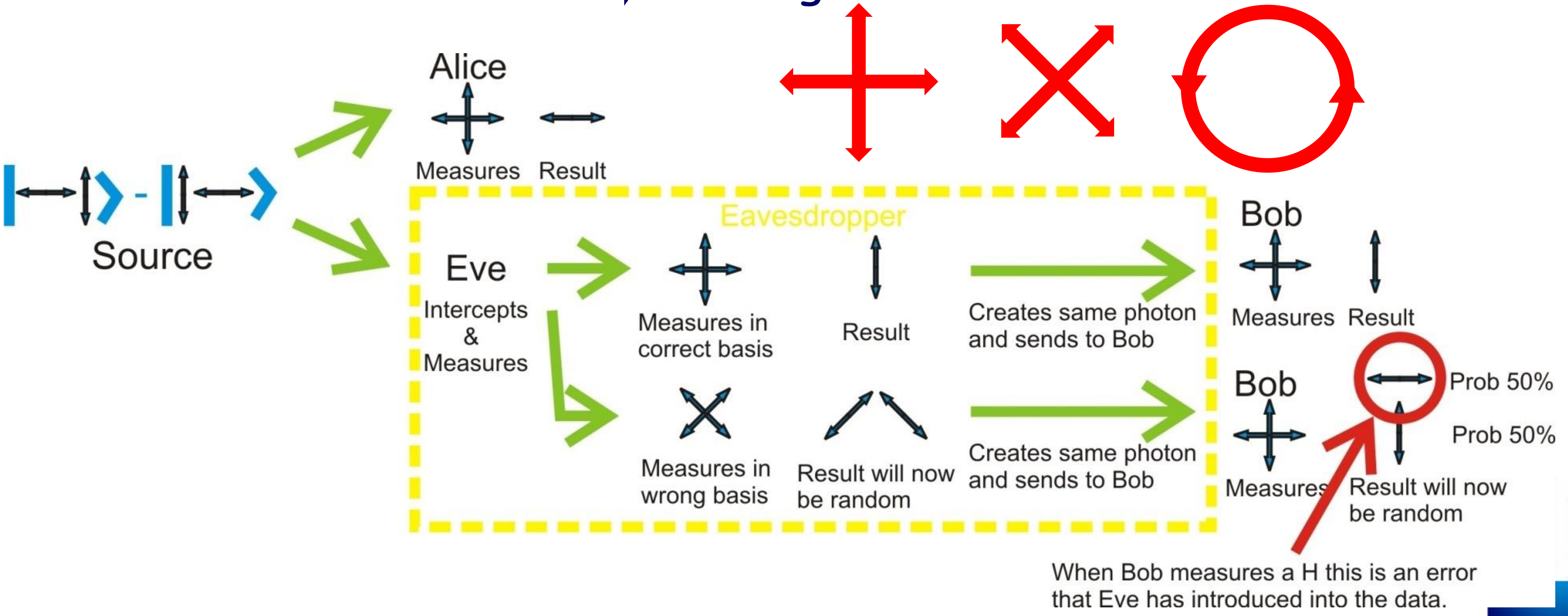
Quantum cryptography based on Bell's theorem
A. K. Ekert, Phys. Rev. Lett. 67, 661 (1991).

E91 protocol

- Eve can be detected

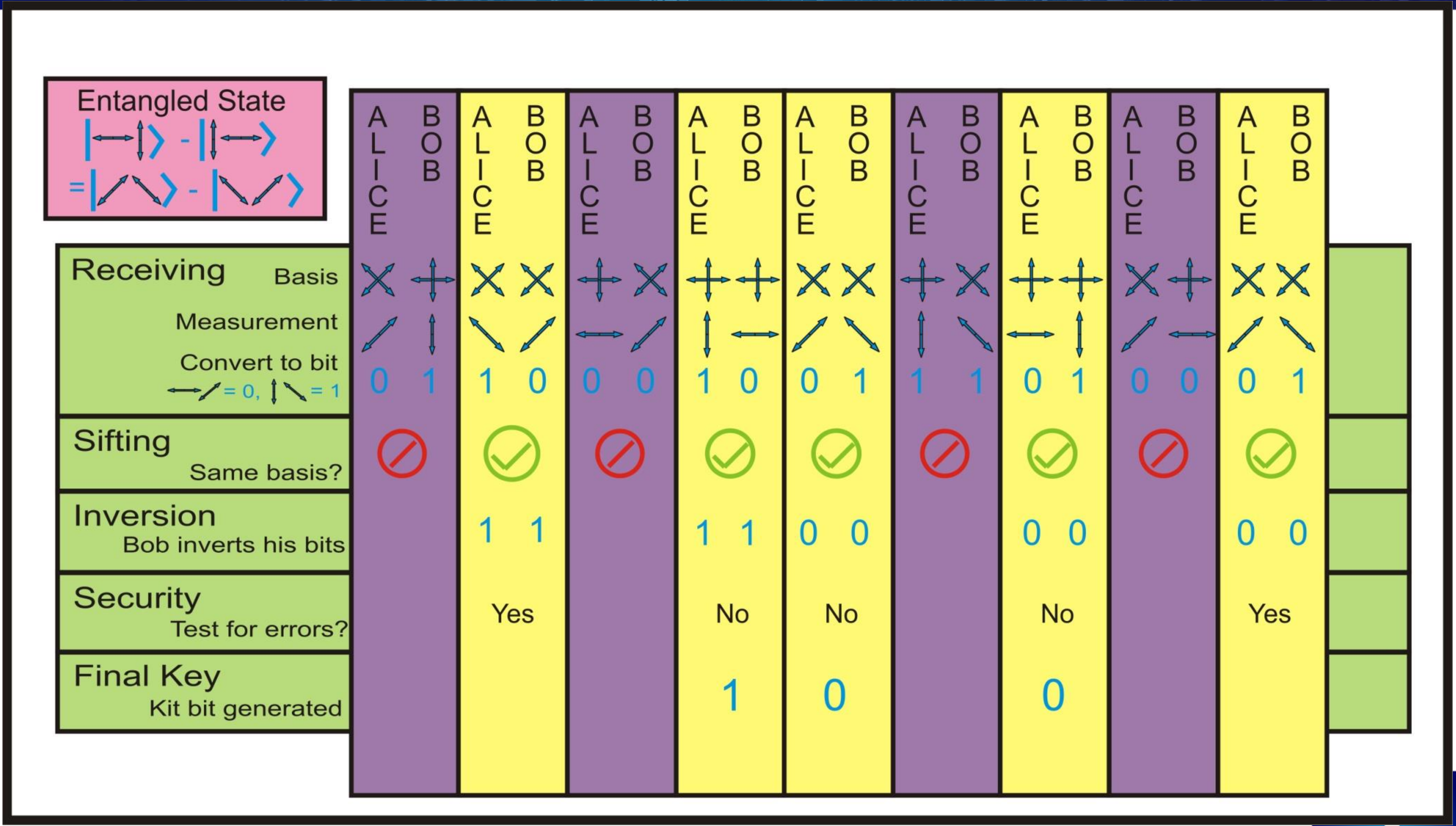
As BB84, use of 2 different basis for Alice and Bob

Entanglement maintained in all basis!



When Bob measures a H this is an error that Eve has introduced into the data.

Quantum key distribution



Entangled State

$|\leftrightarrow\updownarrow\rangle - |\updownarrow\leftrightarrow\rangle = |\nearrow\searrow\rangle - |\searrow\nearrow\rangle$

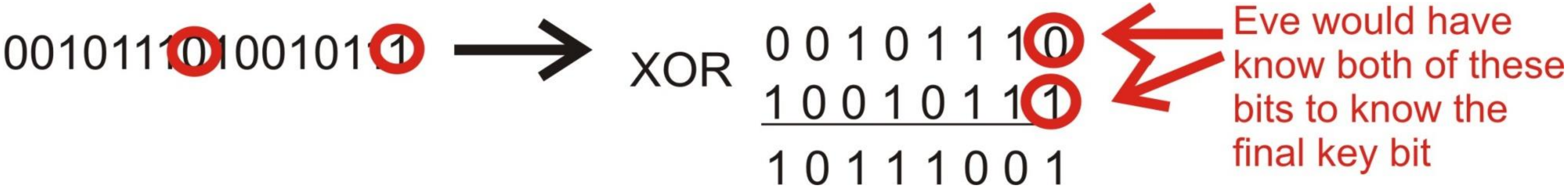
	ALICE	BOB	ALICE	BOB	ALICE	BOB	ALICE	BOB	ALICE	BOB	ALICE	BOB	ALICE	BOB	ALICE	BOB	ALICE	BOB
Receiving Basis	×	+	×	×	+	×	+	+	×	×	+	×	+	+	×	+	×	×
Measurement	↗	↕	↘	↗	↔	↗	↕	↔	↗	↘	↕	↘	↔	↕	↗	↔	↗	↘
Convert to bit ↔ ↗ = 0, ↕ ↘ = 1	0	1	1	0	0	0	1	0	0	1	1	1	0	1	0	0	0	1
Sifting Same basis?	⊘		✓		⊘		✓		✓		⊘		✓		⊘		✓	
Inversion Bob inverts his bits			1	1			1	1	0	0			0	0			0	0
Security Test for errors?			Yes				No		No				No				Yes	
Final Key Kit bit generated							1		0				0					

Private amplification

1- Alice and Bob split their key up in half

2- They then XOR the two halves together

3- In order for Eve to have a bit in the final key, she must have known BOTH bits that were XOR'd together



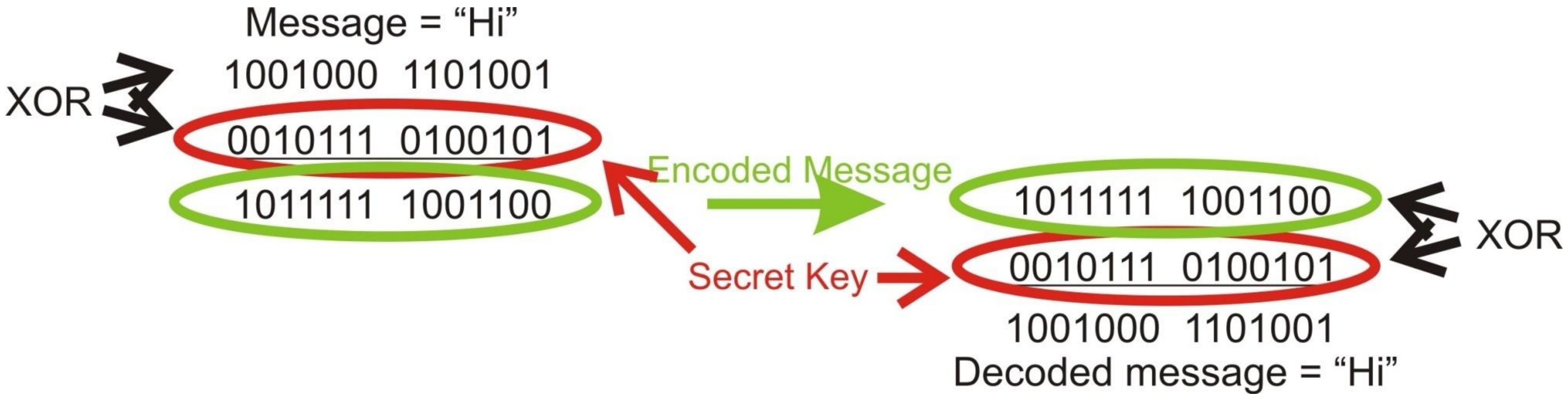
Eve would have know both of these bits to know the final key bit

Usable key

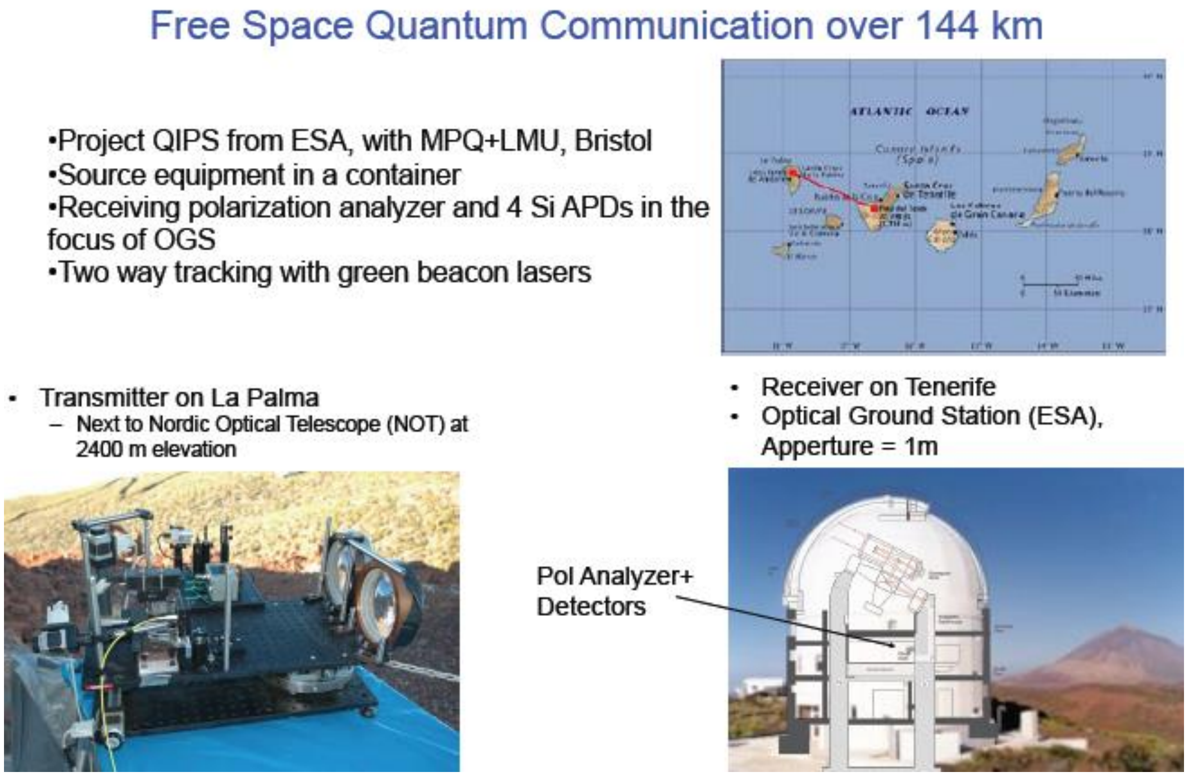
1-Alice encodes her information and sends it to Bob

2- Bob uses his copy of the secret key to decode the message and read what Alice sent

3- The encoding operation is the XOR gate from digital logic



Some records



Free Space Quantum Communication over 144 km

- Project QIPS from ESA, with MPQ+LMU, Bristol
- Source equipment in a container
- Receiving polarization analyzer and 4 Si APDs in the focus of OGS
- Two way tracking with green beacon lasers

- Transmitter on La Palma
  - Next to Nordic Optical Telescope (NOT) at 2400 m elevation

- Receiver on Tenerife
- Optical Ground Station (ESA), Apperture = 1m

Pol Analyzer+ Detectors

Some recent experiments

- 100 km, Vienna
  - Hübel et al Optics Express, Vol. 15, Issue 12, pp. 7853-7862 (2007), arXiv:0801.3620v1 [quant-ph]
- 107km (144 km), Los Alamos
  - Rosenberg et al, Phys. Rev. Lett. 98 010503 (2007), arXiv:quant-ph/0607186v2 (arXiv:0806.3085v1 [quant-ph])
- 200 km, Tokyo
  - Takesue et al, Nature Photonics 1, 343 (2007), arXiv: 0706.0397v1 [quant-ph]
- 250 km Genve
  - arXiv:0903.3907v1 [quant-ph]

Quantum Backbone

- Total Length 2000 km
- 2013.6-2016.12
- 32 trustable relay nodes

  31 fiber links
- Metropolitan networks

  Existing: Hefei, Jinan

  New: Beijing, Shanghai
- Customer: China Industrial & Commercial Bank; Xinhua News Agency; CBRC

Photo ©2016 Vadim Makarov

Shanghai control center of the Chinese
quantum key distribution network and satellite

What about industry

Several start-up companies worldwide and big ones too

- IdQuantiqe (WCP, plug and play, CV system)
- MagiQ (WCP, plug and play)
- BBN (WCP+EPR, Network)
- Toshiba (Fastest gating, quantum dots)
- NTT (WCP, 200km with SSPD)
- Quintessencelabs (CV)
- HP-Labs Bristol (WCP, short range)
- QuTools (Components)
- Qinetiq (EPR, free Space)
- SmartQuantum (WCP, sideband modulation)

Conclusion