QDs: a base for quantum devices

Permanent Staff: Anna Vinattieri, Massimo Gurioli

Post Doc: Lucia Cavigli

Ex PhD student: Marco Abbarchi (now in NIMS, Japan)

Ex Master student: Carmine Mastrandrea (now in Galileo)

In collaboration with

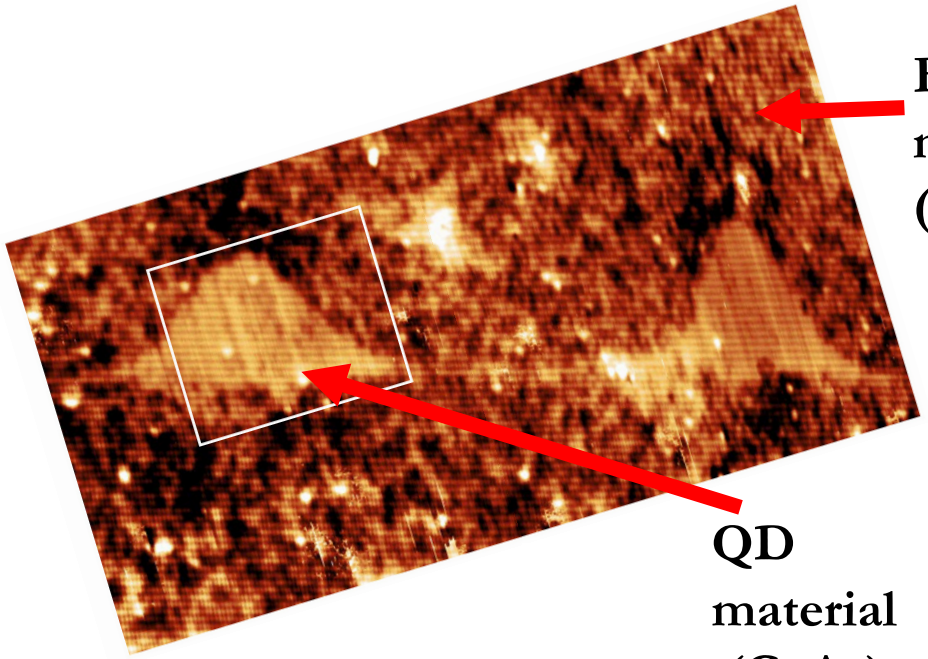
NIMS

Tsukuba, Japan

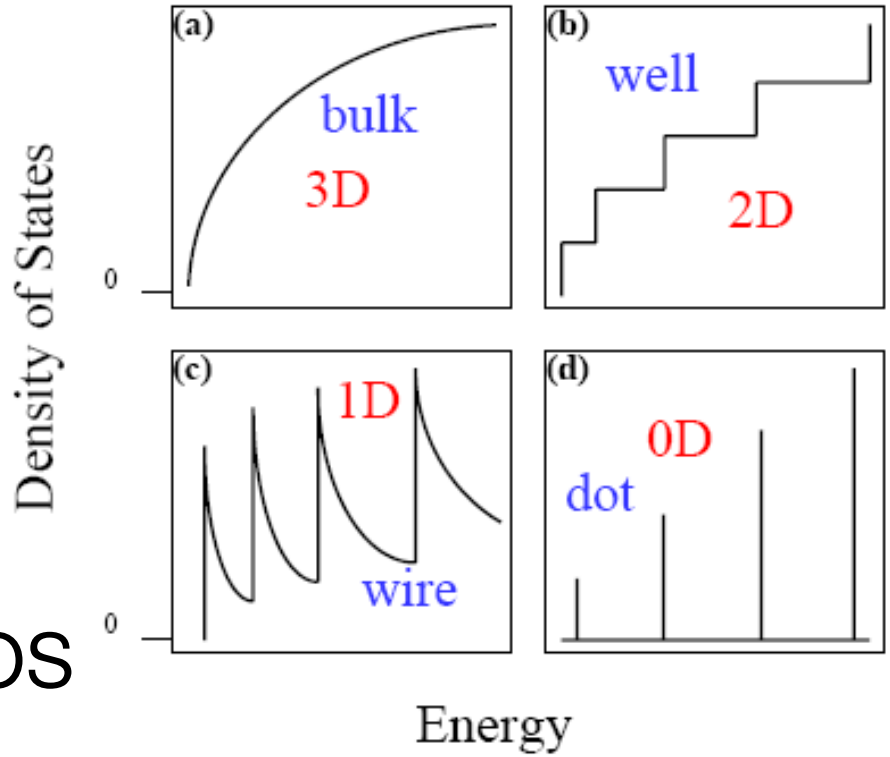
Materials Devices Systems

Eindoven, NL

Introduction

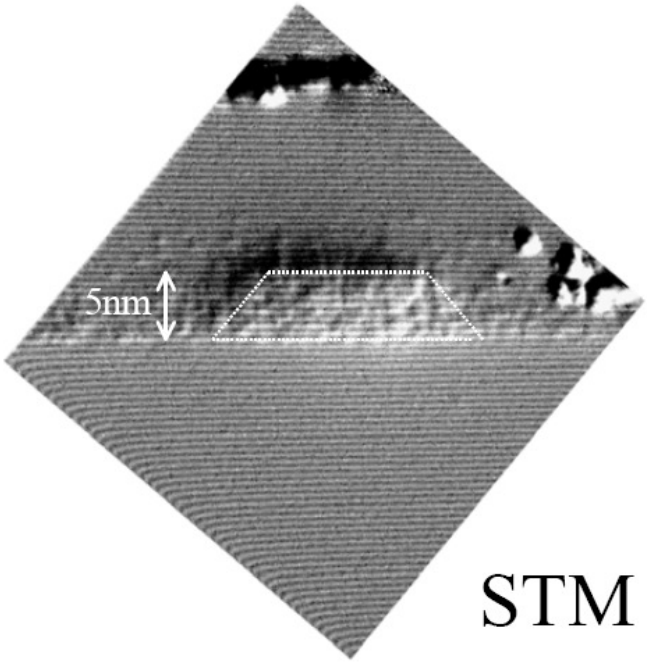


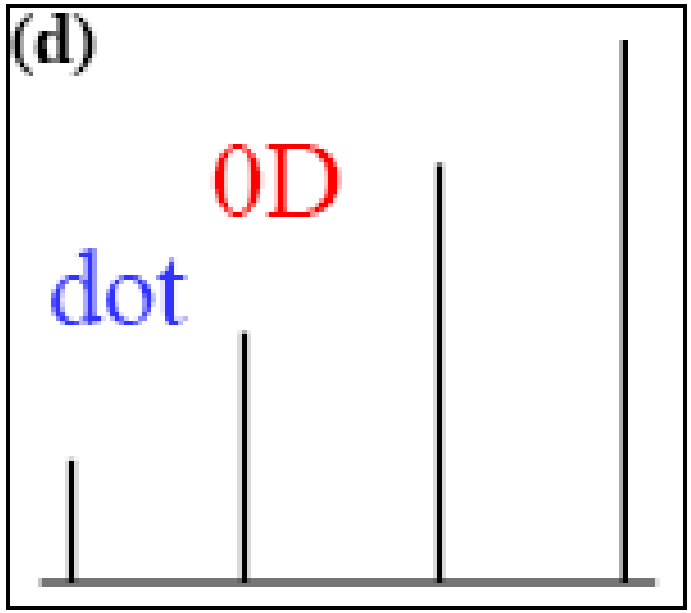
QD=Nano-crystal



- Quantum confinement modifies the electronic DOS

Introduction

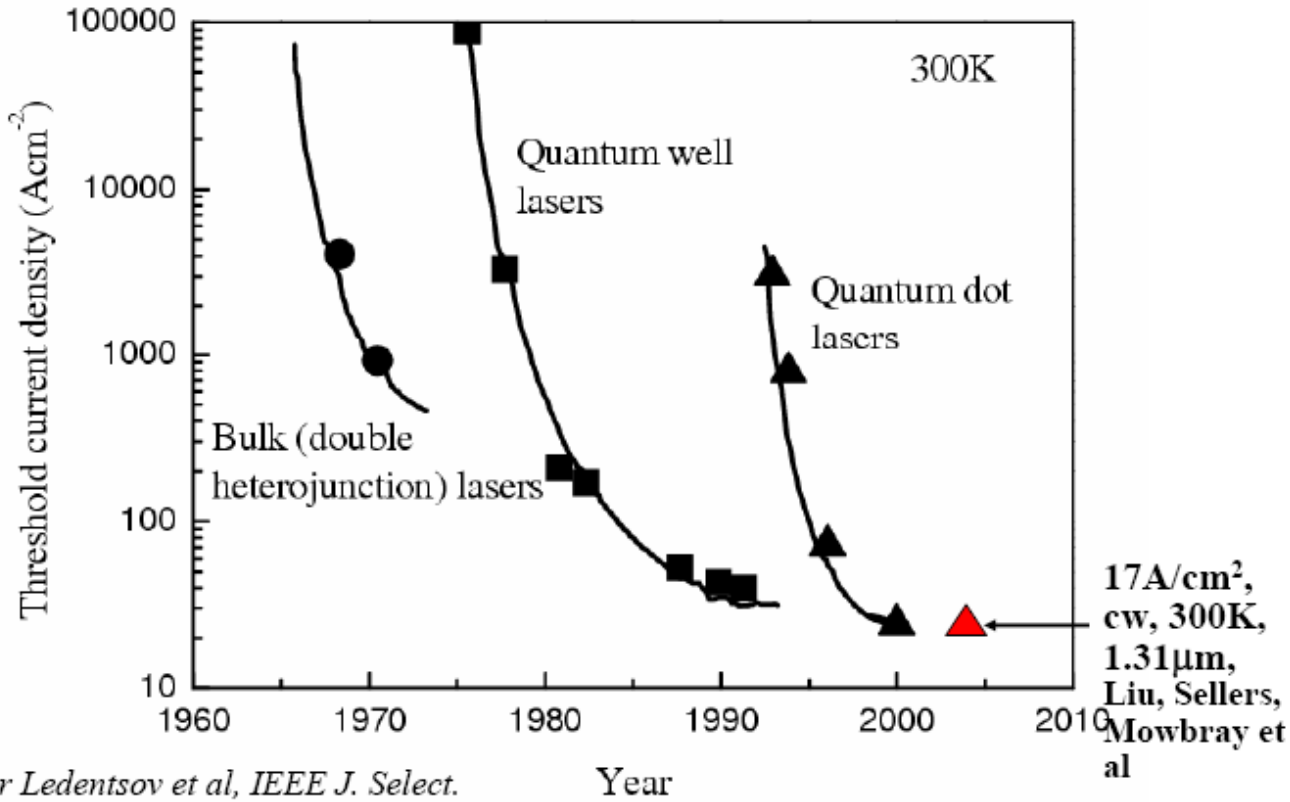




- QDs have atomic-like DOS,
  but with nearly 10^5 -10^6 unit cells in the crystalline clusters
  and embedded in semiconductor environment (devices)

Traditional devices

Semiconductor Laser Performance Versus Year



after Ledentsov et al, IEEE J. Select. Topics Quant. Electron. 6, 439 2000

Quantum devices

PHYSICAL REVIEW A VOLUME 57, NUMBER 1 JANUARY 1998

Quantum computation with quantum dots

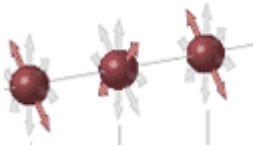
Daniel Loss[1,2,*] and David P. DiVincenzo[1,3,†]

Quantum bits

Quantum gates

Quantum memories

} Quantum computation



Flying Qubits

Quantum emitters

Quantum repeaters

} Quantum communication

QD quantum communication

Already a reality
but
still a lot of new physics

IDQ
FROM VISION TO TECHNOLOGY

REDEFINING SECURITY

CERBERIS

THE BEST OF CLASSICAL AND QUANTUM WORLDS

CERBERIS

LAYER 2 LINK ENCRYPTION
WITH QUANTUM KEY DISTRIBUTION

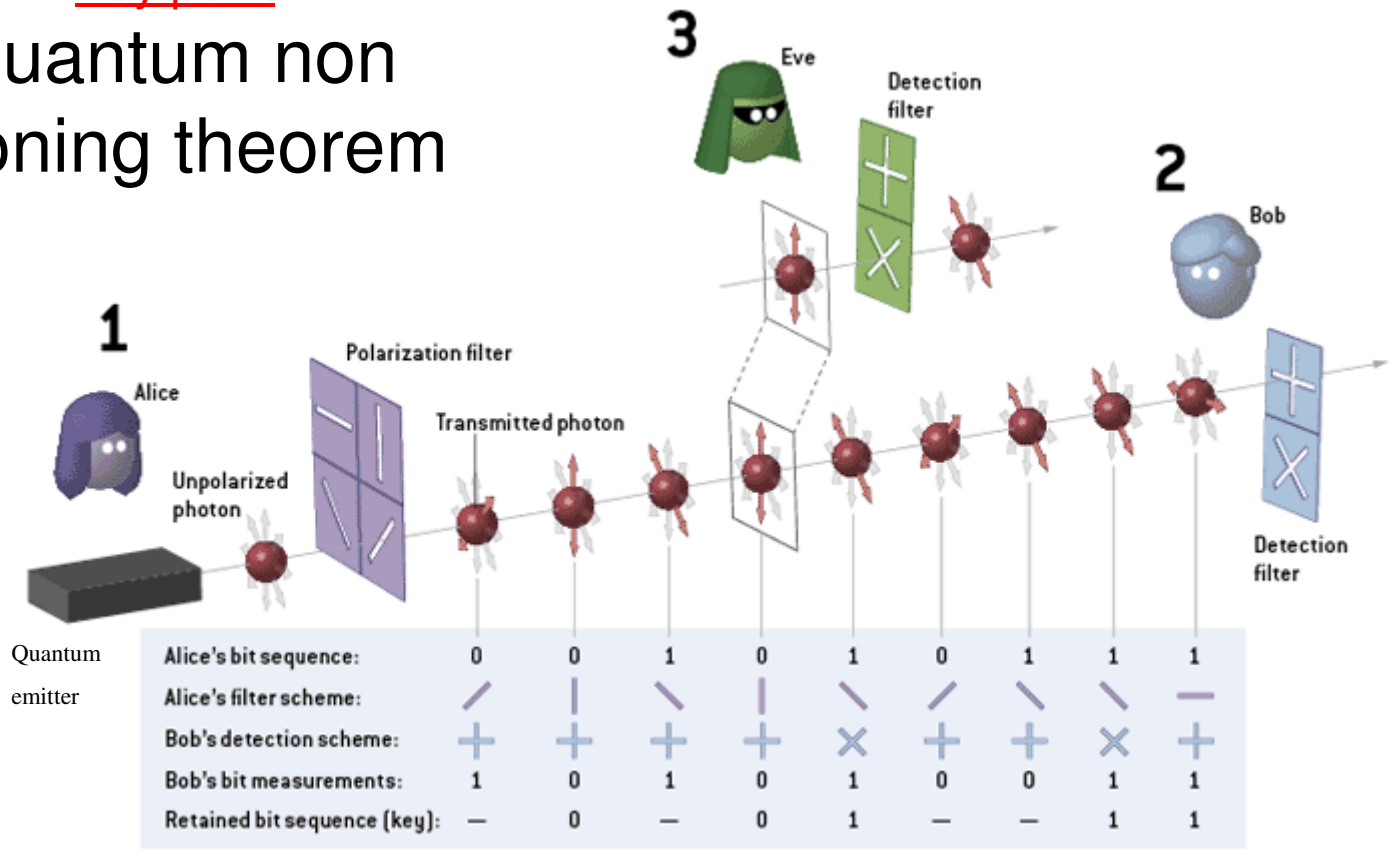
WHY QUANTUM CRYPTOGRAPHY?

- High secrecy of cryptographic keys
  Intrisically guaranteed by quantum physics
  Dual key agreement
- Reveals eavesdropper's presence
  Observation causes perturbation
- Future-proof data confidentiality and integrity
- High key-refresh rate

Quantum cryptography

Key point:

Quantum non cloning theorem



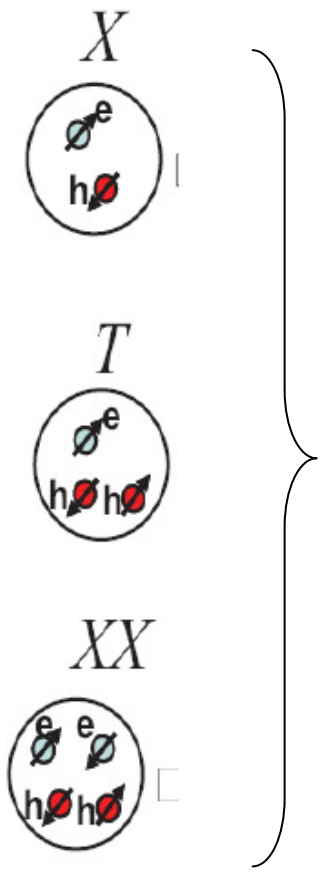
Need for a single photon source

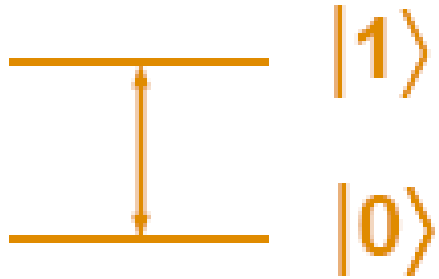
QDs is a QUbit?

Neutral exciton

Charged exciton (trion)

Biexciton



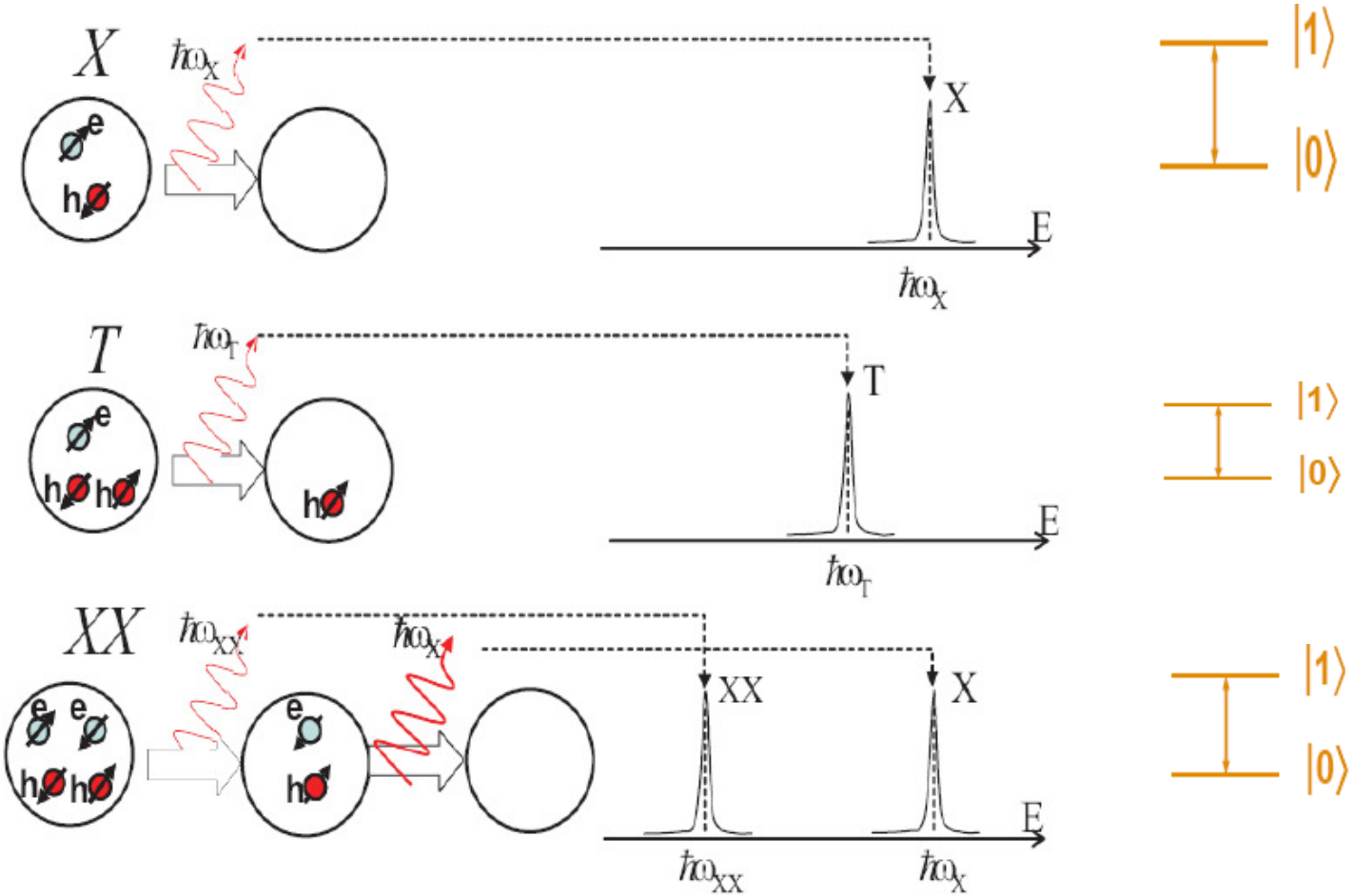


QDs is a multi-QUbit

Neutral exciton

Charged exciton (trion)

Biexciton (multi body System)



Problem of Line attribution:

PHYSICAL REVIEW B 79, 035330 (2009)

JOURNAL OF APPLIED PHYSICS 106, 053504 (2009)

QDs is a quantum emitter

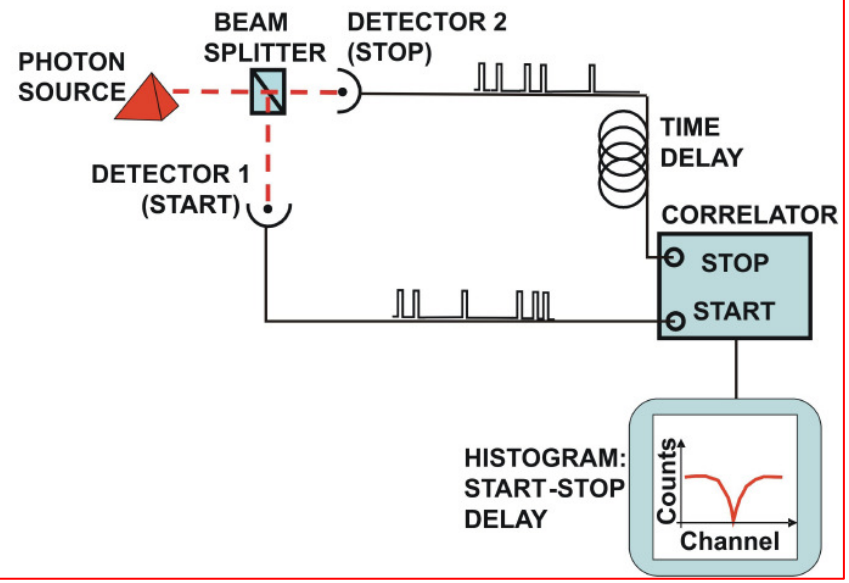
Second order Autocorrelation function:

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

$g^{(2)}(0)$
- =2 Single mode thermal source
- =1 Coherent source
- =0 Single Photon Emitter

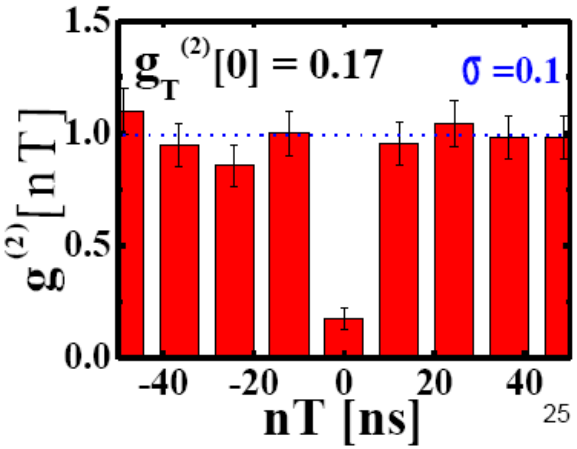
quantum theory: $0 \leq g^{(2)}(0) < 1$

Hanbury Brown and Twiss Interferometer



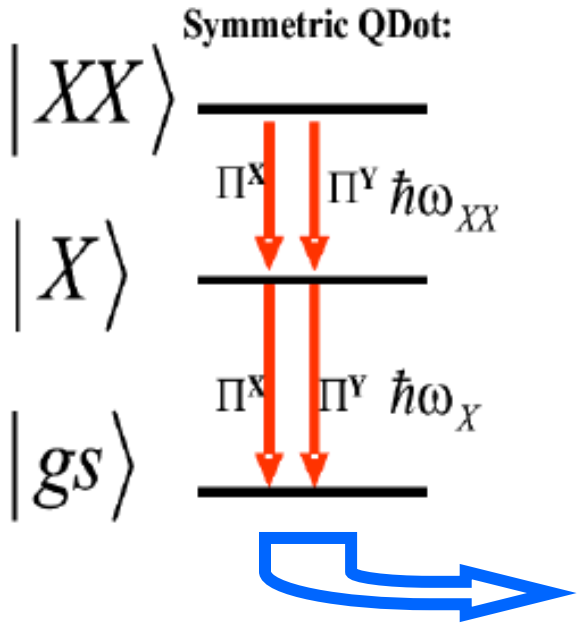
Applied Physics Express 1 (2008) 042001

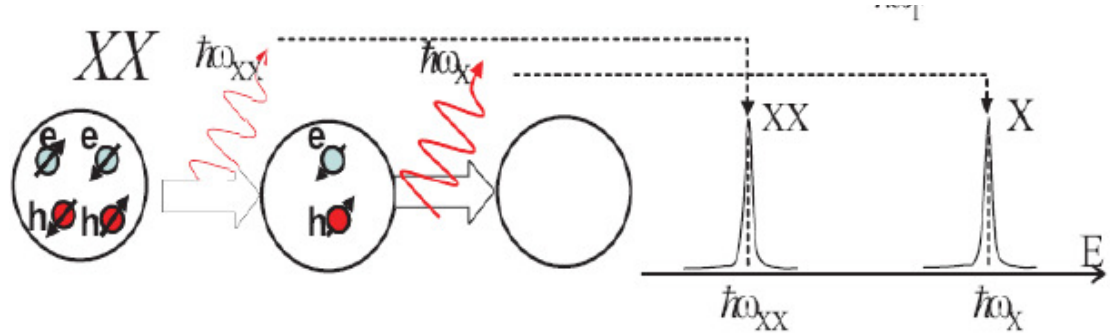
PHYSICAL REVIEW B 79, 085308 (2009)



QD is a multicolor single photon emitter

QDs and entangled photon pairs





$$|\psi_f\rangle = \frac{|\Pi^X, \hbar\omega_X; \Pi^X, \hbar\omega_{XX}\rangle + |\Pi^Y, \hbar\omega_X; \Pi^Y, \hbar\omega_{XX}\rangle}{\sqrt{2}} =$$

$$\frac{|\Pi^X; \Pi^X\rangle + |\Pi^Y; \Pi^Y\rangle}{\sqrt{2}} * |\hbar\omega_X; \hbar\omega_{XX}\rangle = \frac{|11\rangle + |00\rangle}{\sqrt{2}}$$

X and XX can be entangled

PHYSICAL REVIEW B 78, 125321 (2008)

PHYSICAL REVIEW B 79, 035330 (2009)

Quantum Comm.: what next?

- Increase the repetition rate
- Increse the emission efficiency
- Electrical injection
- Indistinguishable single photons (Hong-Mandel interference)

Increase the radiative efficiency

Purcell Effect - Control Spontaneous Emission

B10. Spontaneous Emission Probabilities at Radio Frequencies. E. M. PURCELL, *Harvard University*.—For nuclear magnetic moment transitions at radio frequencies the probability of spontaneous emission, computed from

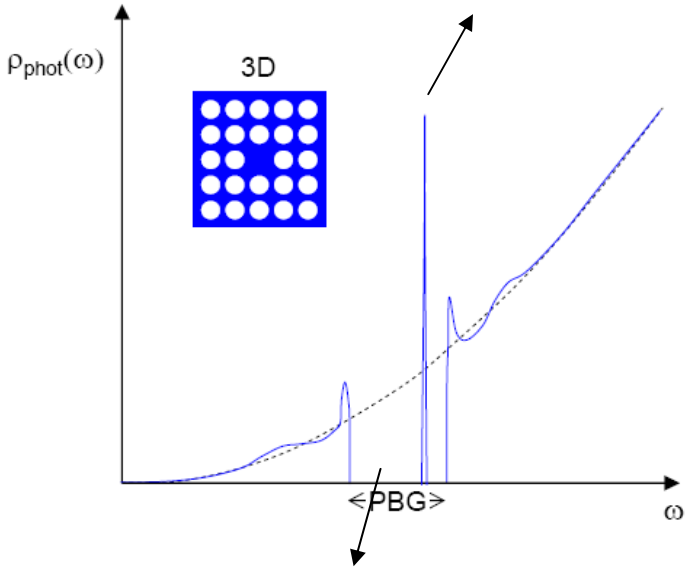
$$A_\nu = (8\pi\nu^2/c^3)h\nu(8\pi^3\mu^2/3h^2)\ \text{sec.}^{-1},$$

is so small that this process is not effective in bringing a spin system into thermal equilibrium with its surroundings. At 300°K, for $\nu = 10^7$ sec.$^{-1}$, $\mu = 1$ nuclear magneton, the corresponding relaxation time would be 5×10^{21} seconds! However, for a system coupled to a resonant electrical circuit, the factor $8\pi\nu^2/c^3$ no longer gives correctly the number of radiation oscillators per unit volume, in unit frequency range, there being now *one* oscillator in the frequency range ν/Q associated with the circuit. The spontaneous emission probability is thereby increased, and the relaxation time reduced, by a factor $f = 3Q\lambda^3/4\pi^2V$, where V is the volume of the resonator. If a is a dimension characteristic of the circuit so that $V\sim a^3$, and if δ is the skin-depth at frequency ν, $f\sim\lambda^3/a^2\delta$. For a non-resonant circuit $f\sim\lambda^3/a^3$, and for $a<\delta$ it can be shown that $f\sim\lambda^3/a\delta^2$. If small metallic particles, of diameter 10^{-3} cm are mixed with a nuclear-magnetic medium at room temperature, spontaneous emission should establish thermal equilibrium in a time of the order of minutes, for $\nu = 10^7$ sec.$^{-1}$.

Purcell, Phys. Rev. **69**, 681 (1946).

$$A(\nu) = C\frac{8\pi\nu^2}{c^3} = C\rho_{ph}(\nu)$$

Acceleration of the emission



Suppression of the emission

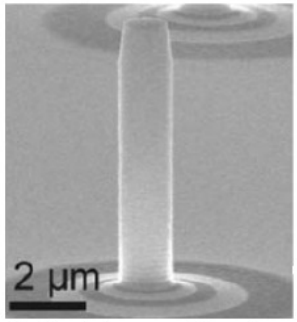
See talk Intonti on PhC-MCs

High repetition rate

Purcell effect

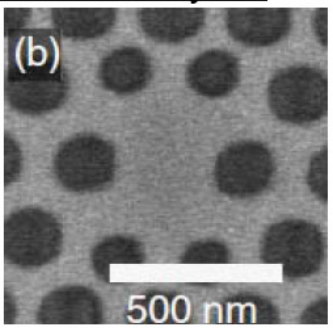
$$A(\nu) = A_0 F_P$$

Micropillar



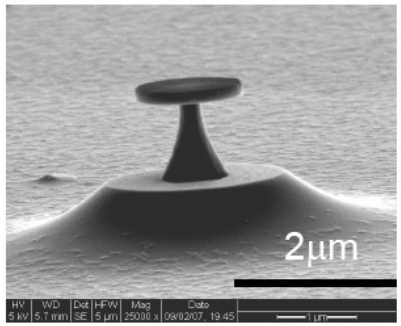
A. Forchel group, Wuerzburg

Photonic Crystal



J. Vuckovic group, Stanford

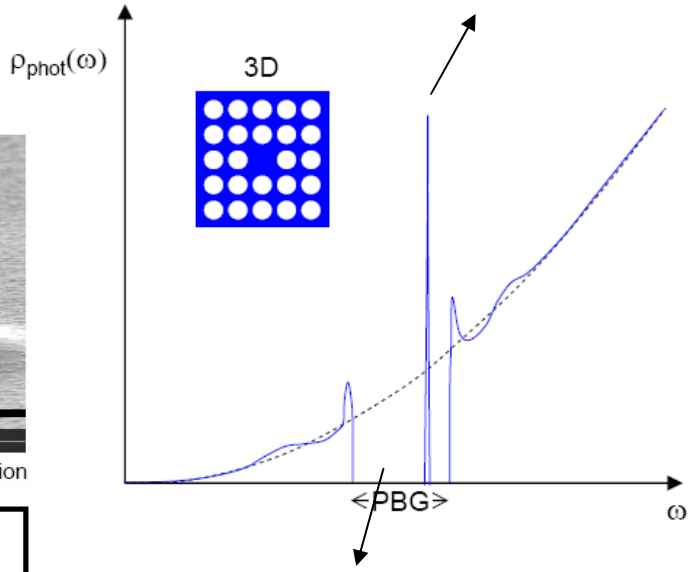
Microdisk



Our Fabrication

	Micropillar	Photonic Crystal	Microdisk
Q @930nm	23000	30000	20000
V	5 $(\lambda/n)^3$~	0.5 $(\lambda/n)^3$~	5 $(\lambda/n)^3$~
Fp	61	145	125

Acceleration of the emission



Suppression of the emission

100 MHz→10 GHz

Purcell effect in micropillars with oxidized Bragg mirrors

L. Cavigli[1,*], L. Lunghi[2], M. Abbarchi[1], A. Vinattieri[1] B. Alloing[3], C. Zinoni[3] A. Fiore[3], A. Gerardino[2]
P. Frigeri[4] L. Seravalli[4], S. Franchi[4], and M. Gurioli[1]

QD quantum computation

A long (never-ending ?) route
but
with a lot of new physics

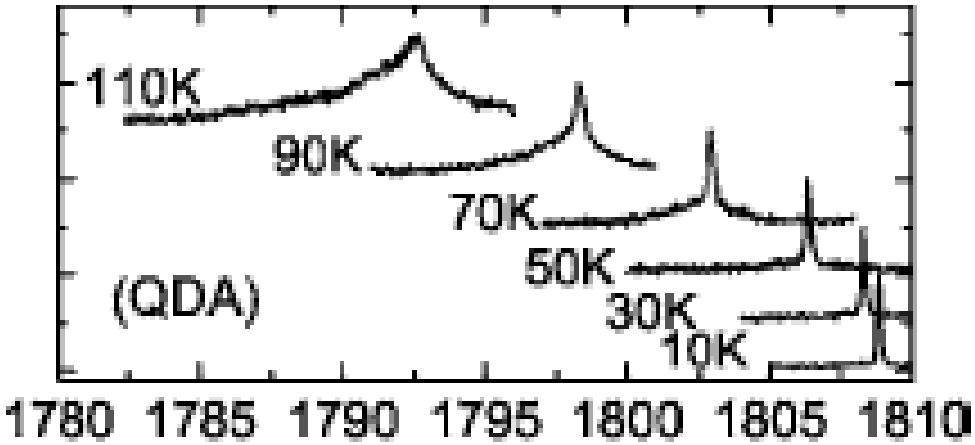
Quantum computer

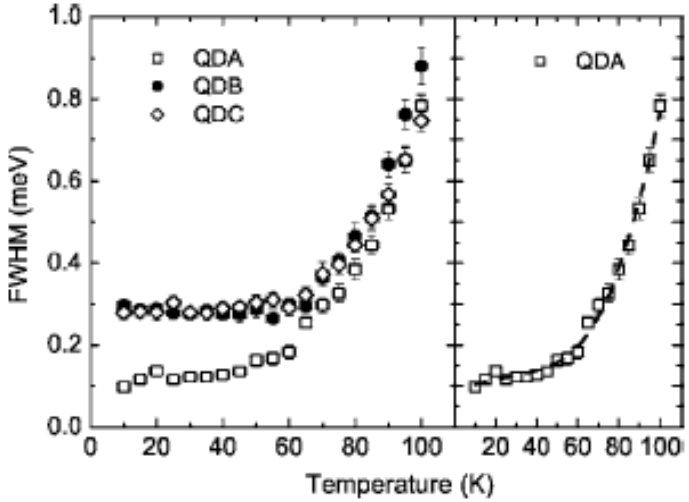
Di Vincenzo's criteria

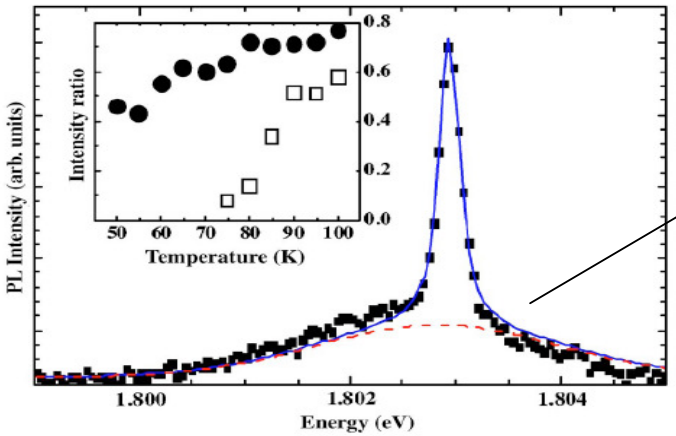
	Good	Bad
1. Scalability	Semic. Tech. Electrical control	Self Assemb. Low Control of size
2. Faithful initialization	OK	
3. Manipulation	Optical, electric	Very fast
4. Readout	Optical	Electronic coupling
5. Long dephasing time	Fast manipulation Cavity effect	Too short May be with spin

Decoherence

Homogeneous broadening: phonon interaction







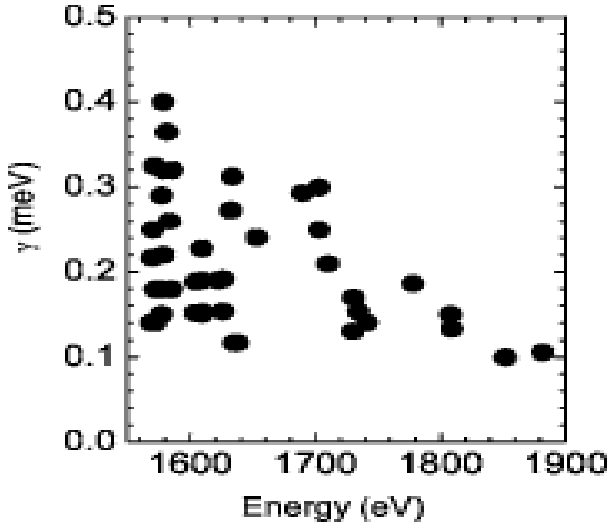
Non Lorentzian homogeneous broadening

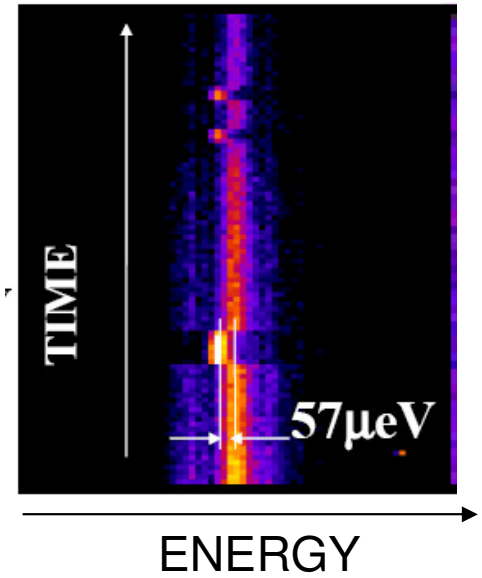
PHYSICAL REVIEW B 73, 125342 (2006)

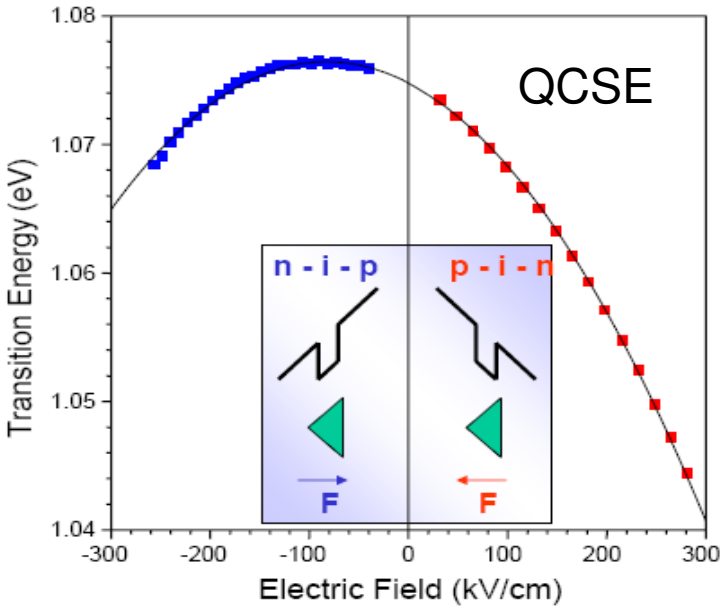
JOURNAL OF APPLIED PHYSICS 104, 023504 (2008)

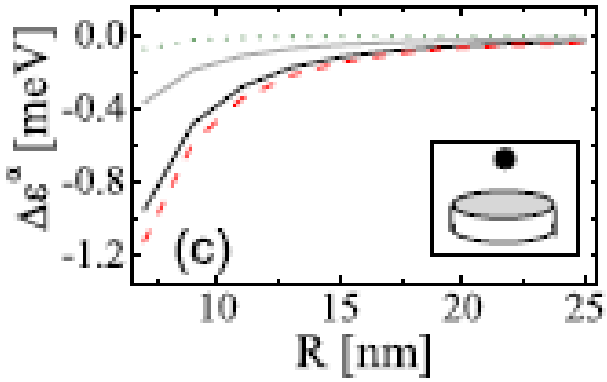
Decoherence

Inhomogeneous broadening









APPLIED PHYSICS LETTERS 93, 162101 (2008)

Decoherence

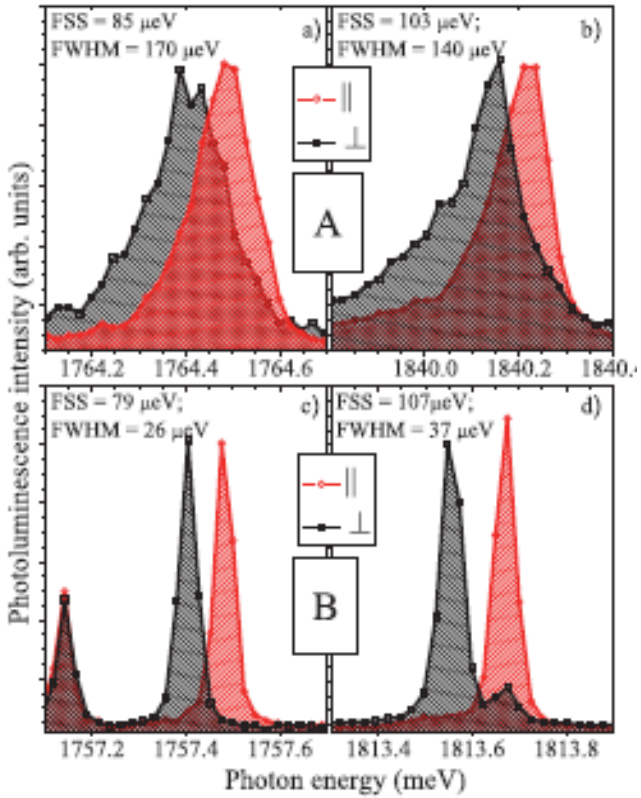
~~*Inhomogeneous broadening*~~

IOP PUBLISHING NANOTECHNOLOGY
Nanotechnology 20 (2009) 395601 (5pp) doi:10.1088/0957-4484/20/39/395601

Ultra-narrow emission from single GaAs self-assembled quantum dots grown by droplet epitaxy

T Mano[1], M Abbarchi[1,2], T Kuroda[1], C A Mastrandrea[2], A Vinattieri[2], S Sanguinetti[3,4], K Sakoda[1] and M Gurioli[2]

At 10 K almost at the radiative limit
≈ 1 ns



Magnetic QDs: a base for quantum spin devices

Permanent Staff: Massimo Gurioli
Roberta Sessoli, Andrea Caneschi
Dante Gatteschi

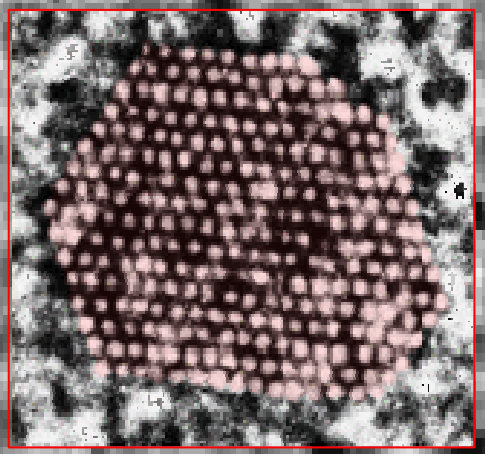
Post Doc: César de Julián Fernández
Francesco Pineider

PhD student: Giulio Campo

Ex Ph D student: Lucia Cavigli,
Rafael Novak Lapo Bogani

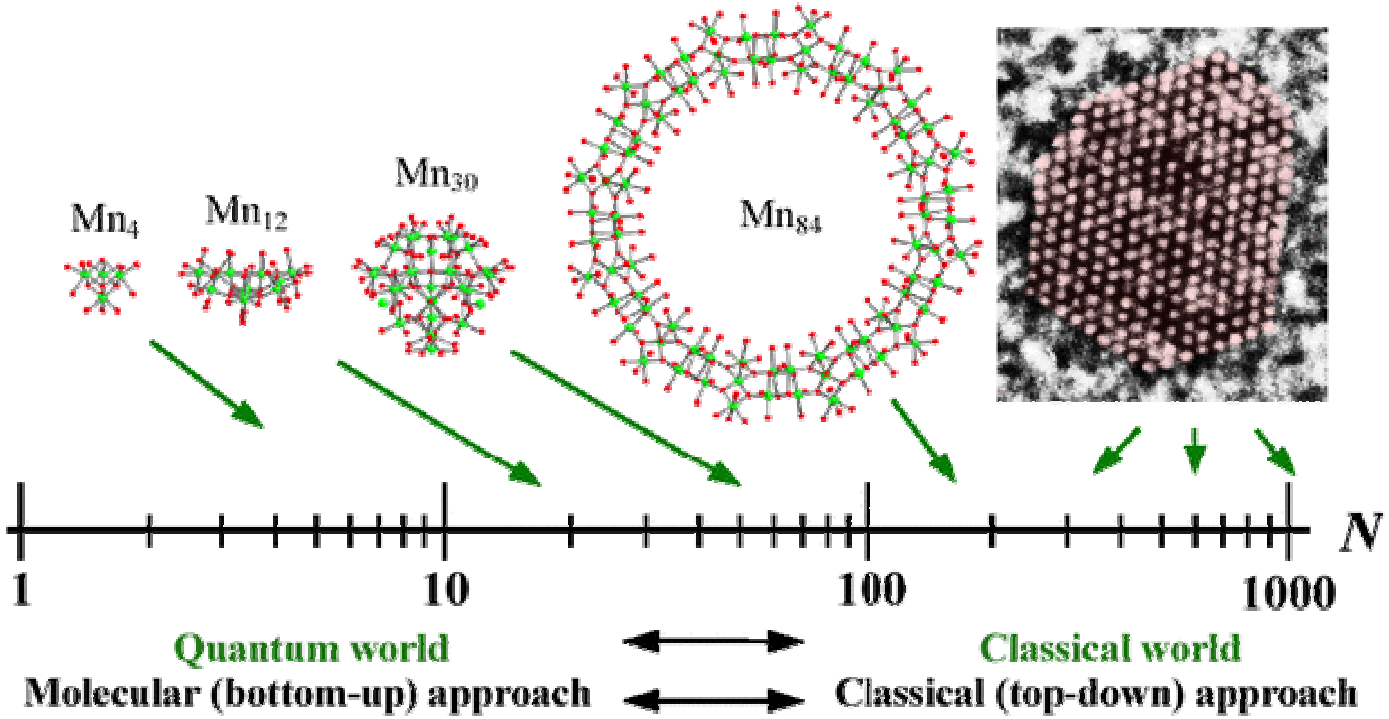
MAGMANet
NETWORK OF EXCELLENCE

INSTM



Molecular Magnets

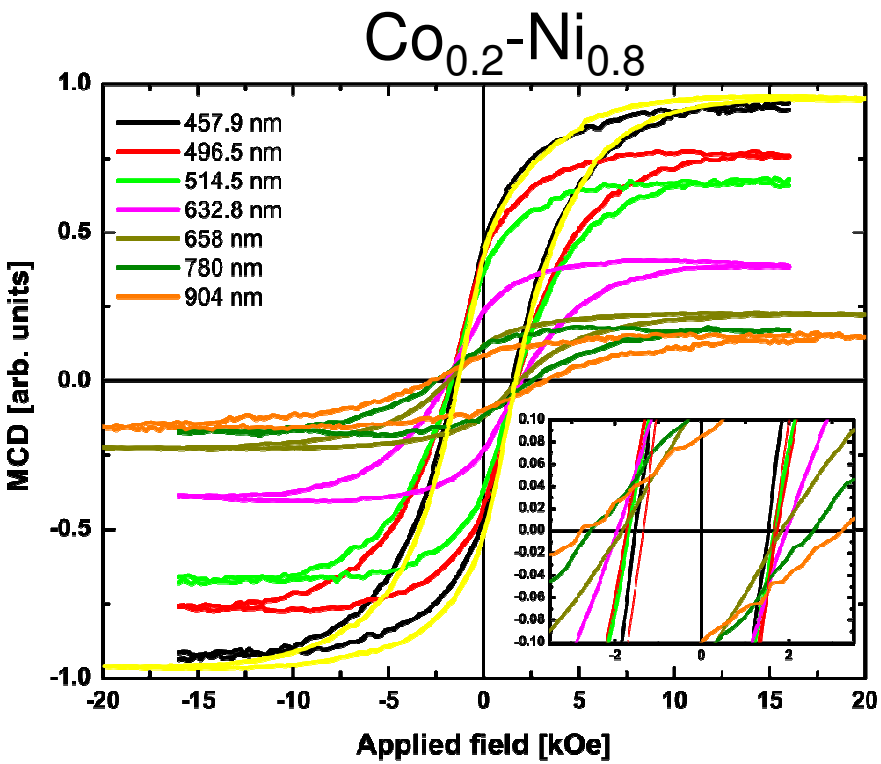
- Molecular clusters containing exchange-coupled transition metal ions
- Behave like small magnets (nanoparticles) under suitable conditions (low T, for example)
- Monodispersed (no size distribution)

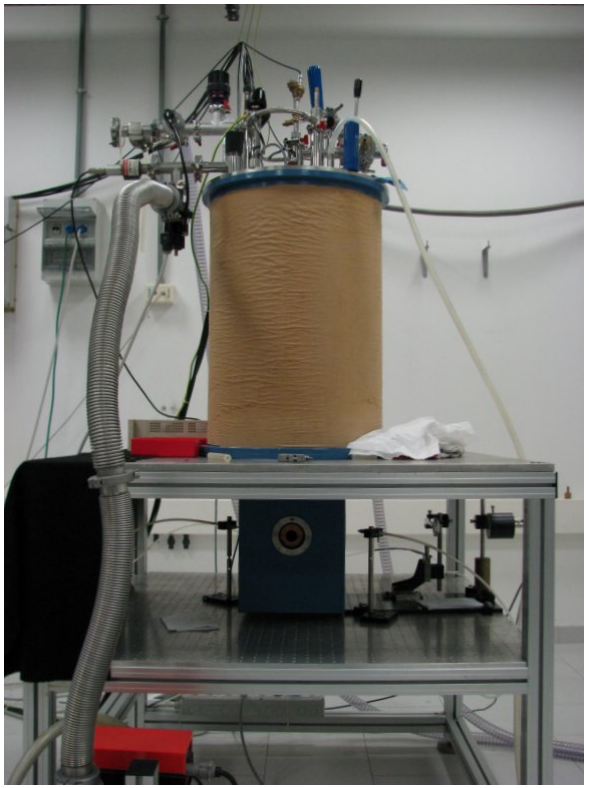


• Slow relaxation of the magnetization → Hysteresis of dynamic origin
• Macroscopic quantum tunneling of the magnetization

Coexistence of quantum and classical phenomena

Magneto Optical set-up





Magnetic field → up to 10 T
Temperature → 1.5 K to RT
Wavelength → 400 nm - 950 nm

Configurations: MCD, Faraday & Kerr
Co-irradiation experiments

Adv. Mater. **2007**, *19*, 3906–3911

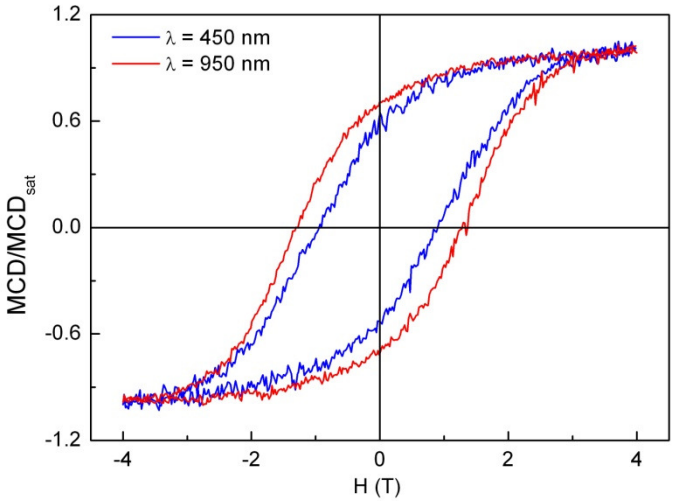
J. Mater. Chem., 2008, **18**, 109–115 | 109

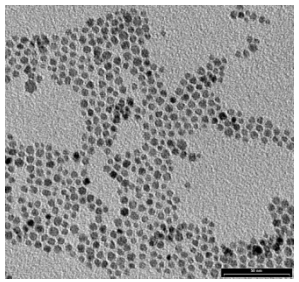
Nanotechnology **21** (2010) 165701

New magneto-optical effects

Ligth assisted demagnetization in oxide nanoparticles

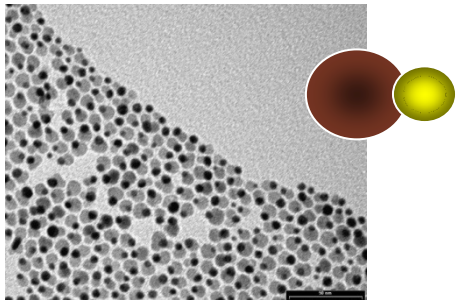
$CoFe_2O_4$

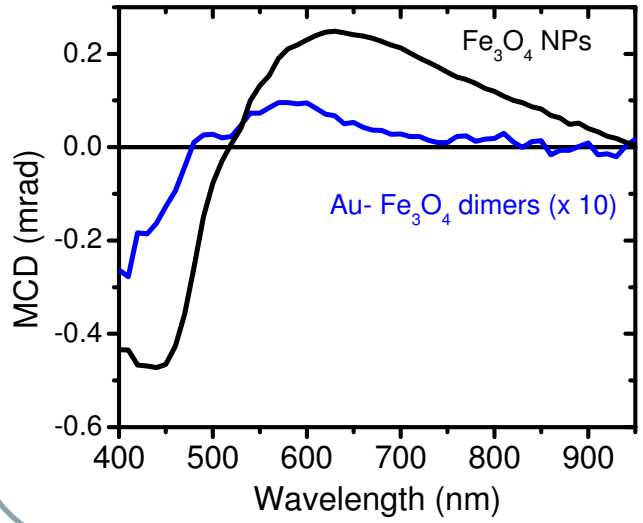




Magneto-plasmonics

Hetero-dimers & core-shell





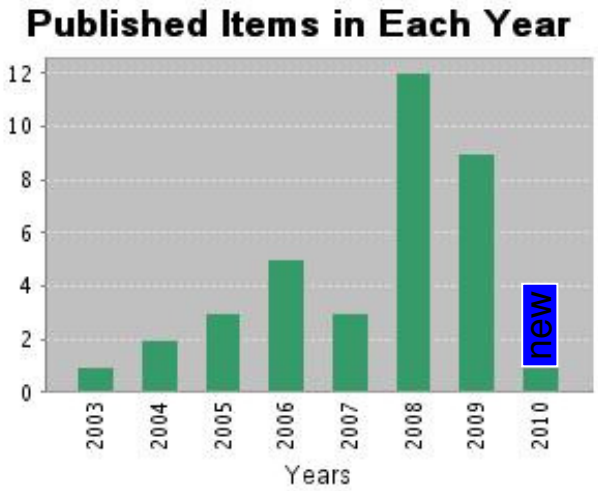
Group assessment

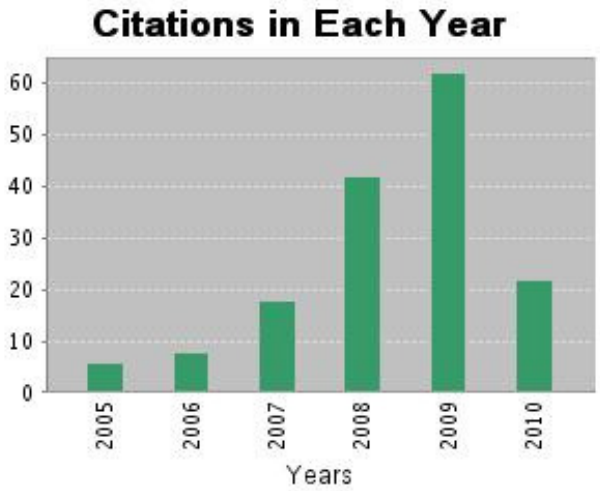
- Papers
- Citations
- Fundings

Results

Gurioli M.&Abbarchi+Gurioli M.&Cavigli

QDs



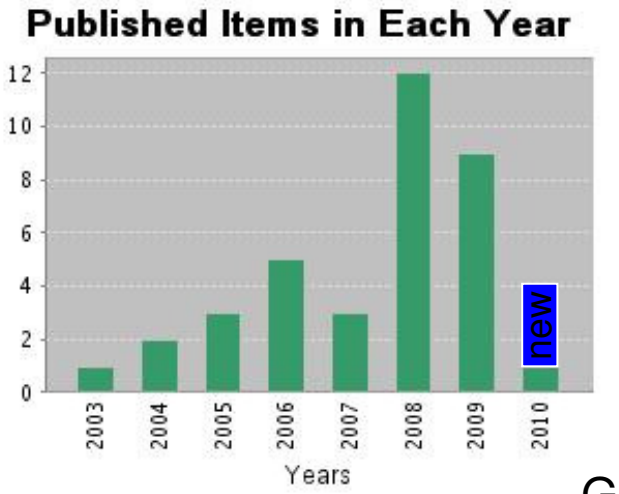


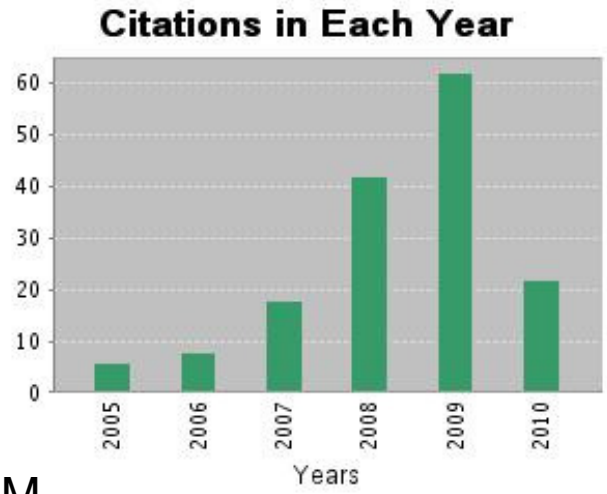
http://apps.isiknowledge.com/

Results

Gurioli M.&Abbarchi+Gurioli M.&Cavigli

QDs

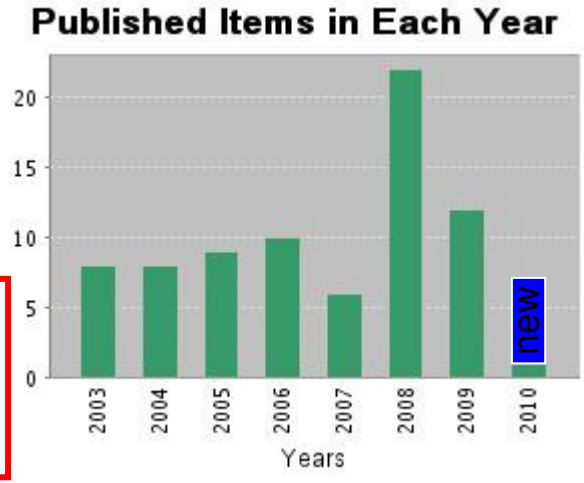


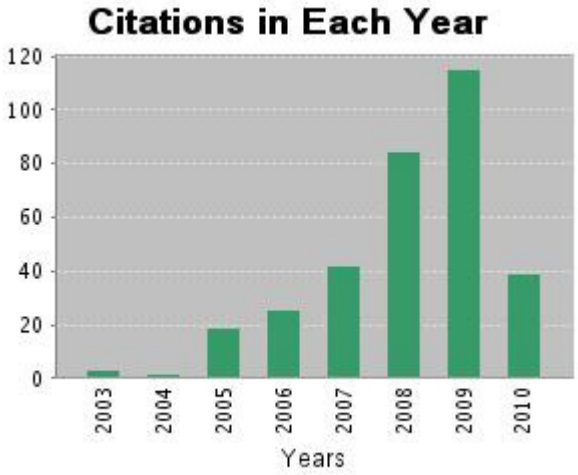


Gurioli M.

All

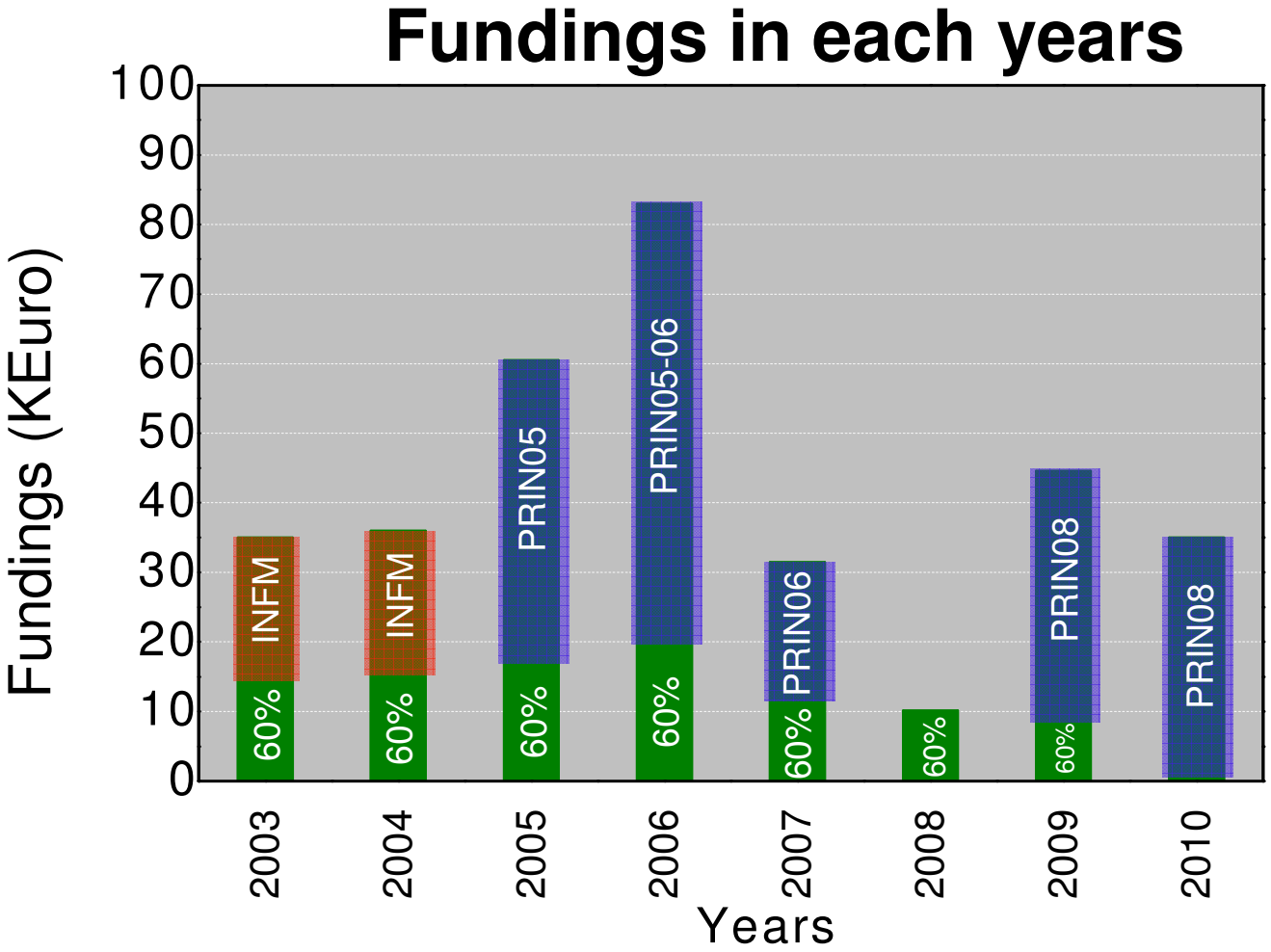
47 Articles
32 Conf. Pr.s
332 Citations





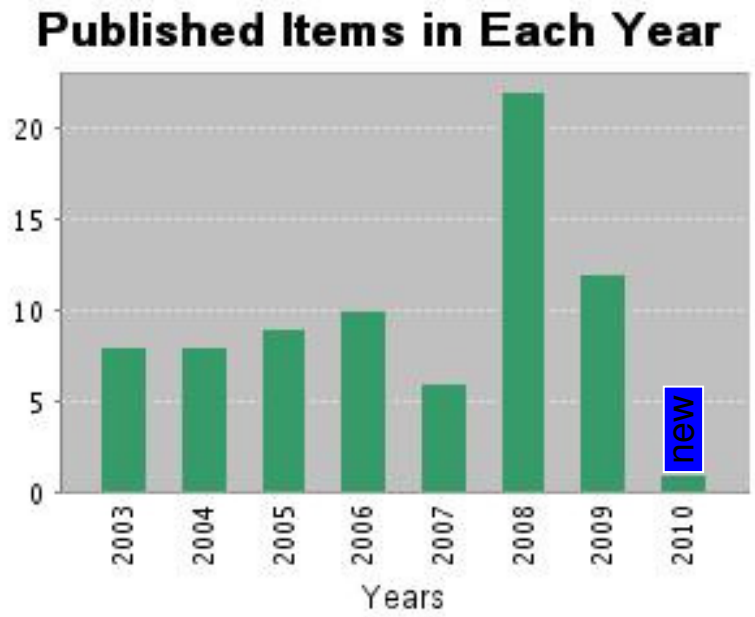
http://apps.isiknowledge.com/

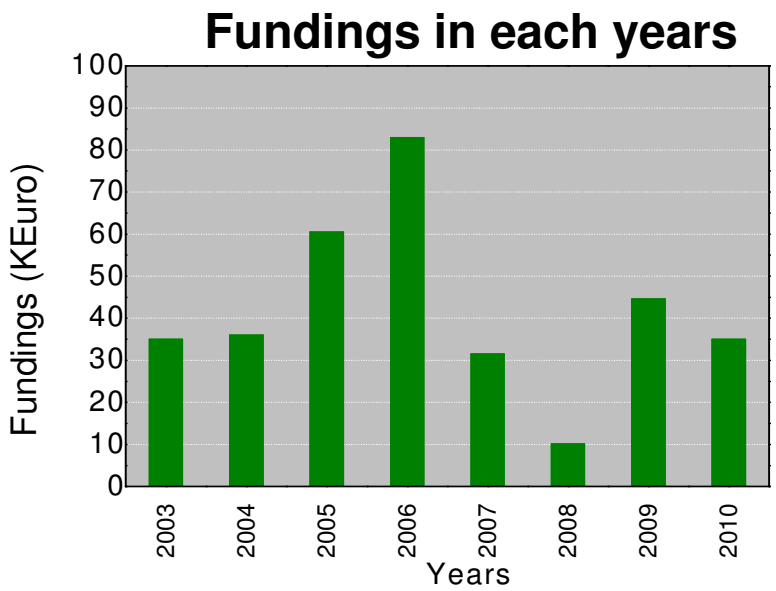
Fundings

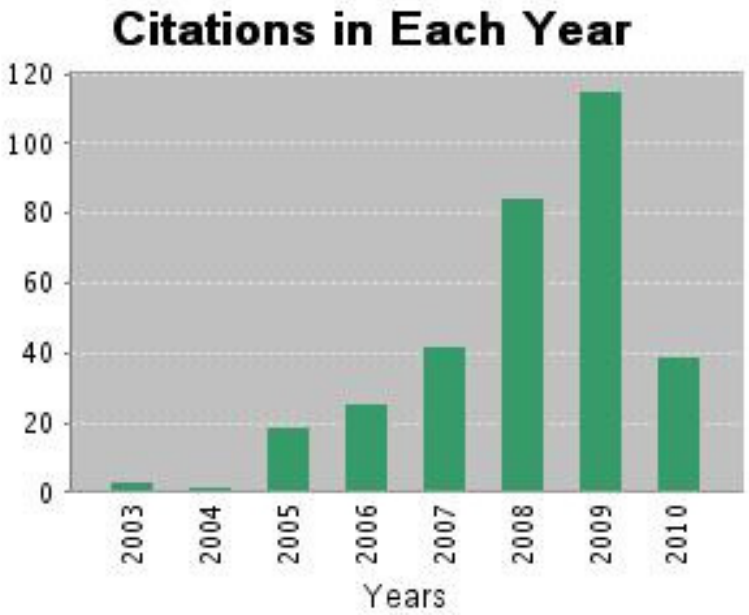


Lack of funds for new investement

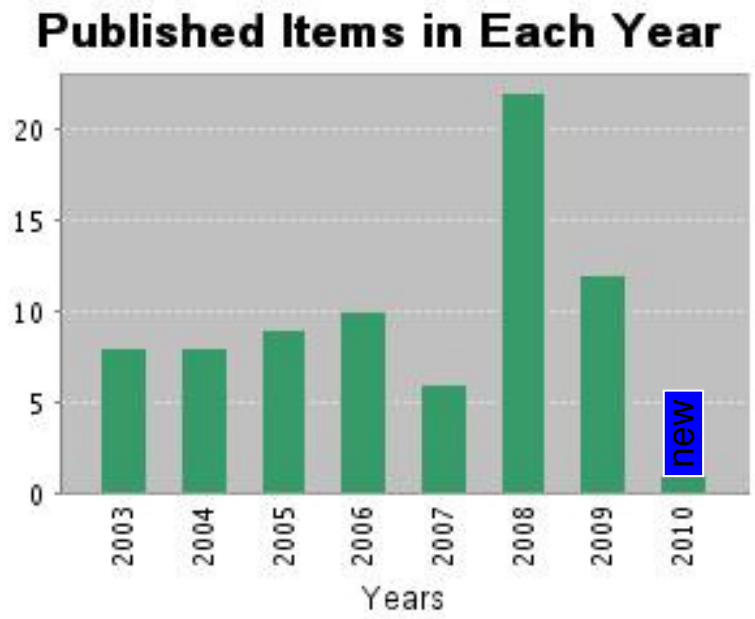
Comparison

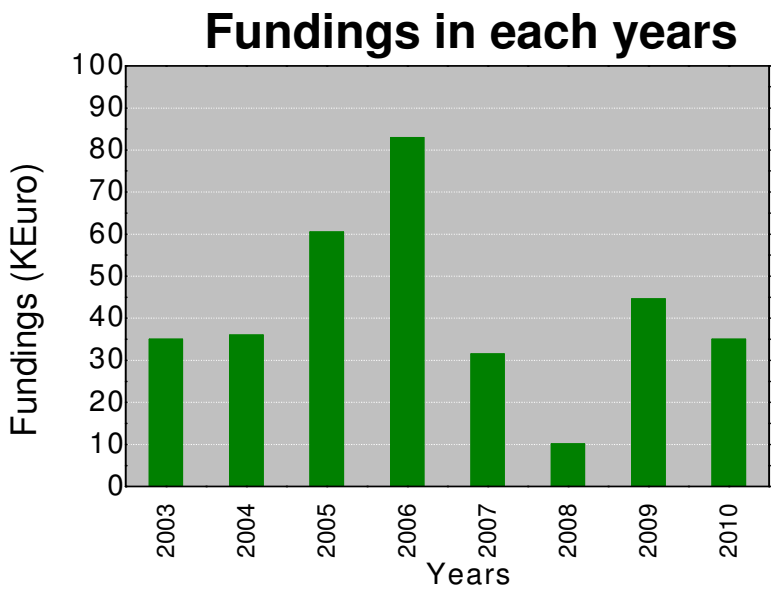

Published Items in Each Year
20
15
10
5
0
new
2003
2004
2005
2006
2007
2008
2009
2010
Years

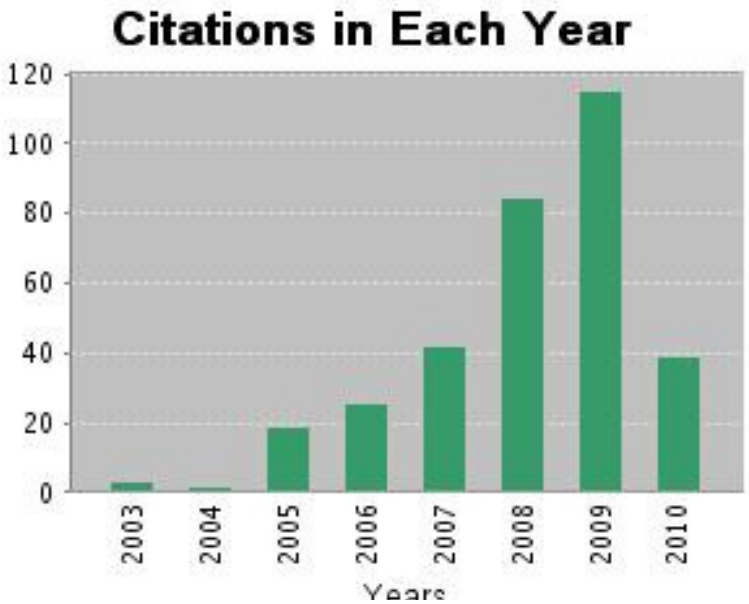

Fundings in each years
Fundings (KEuro)
100
90
80
70
60
50
40
30
20
10
0
2003
2004
2005
2006
2007
2008
2009
2010
Years


Citations in Each Year
120
100
80
60
40
20
0
2003
2004
2005
2006
2007
2008
2009
2010
Years

Comparison





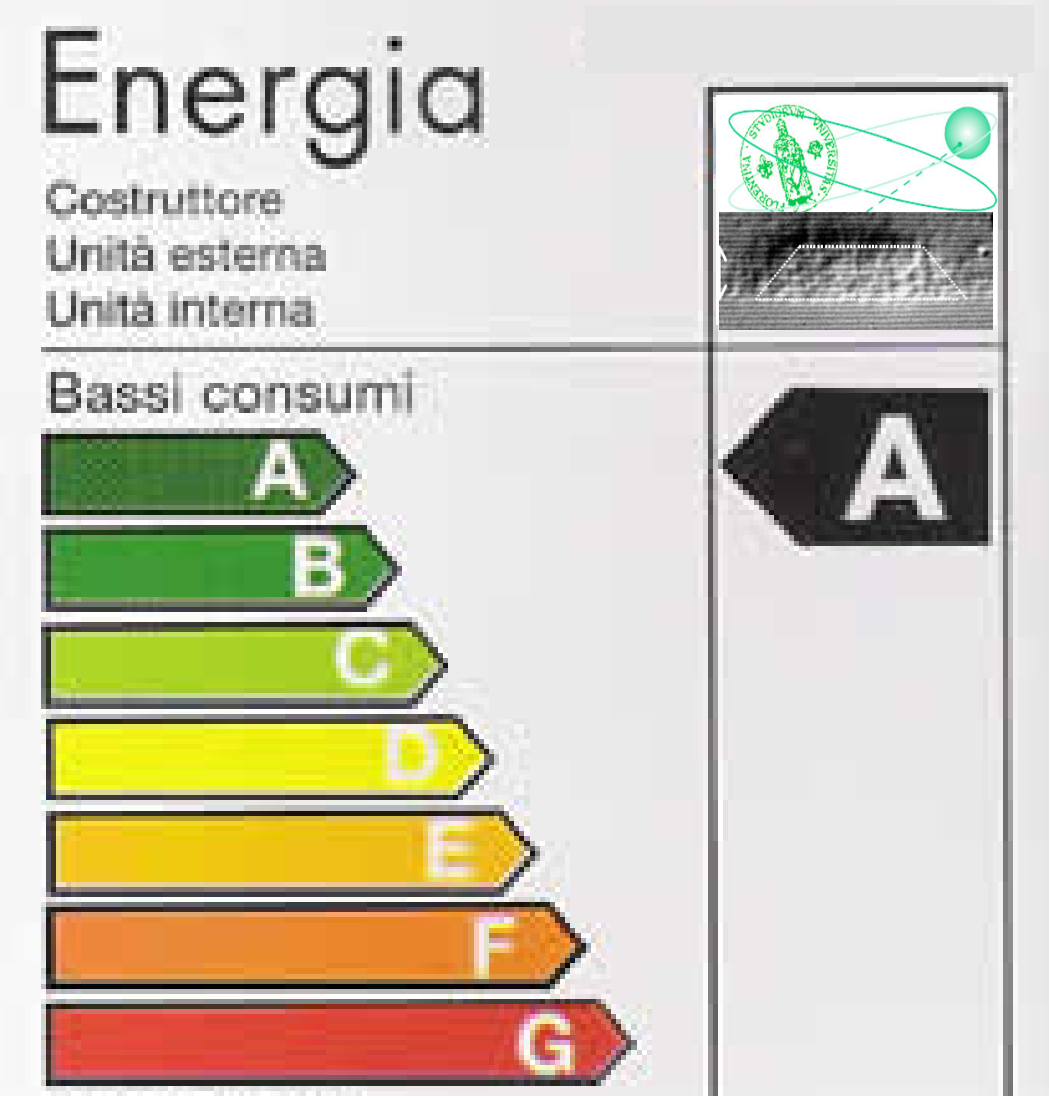


Efficiency

η_1 = 0.23 papers/Keuro

η_2 = 1 citations/Keuro

Conclusions



Efficiency

η_1 = 0.23 papers/Keuro

η_2 = 1 citations/Keuro