Single cold atoms for quantum optics and quantum information processing

ICFO
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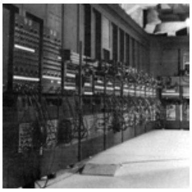
- Quantum technologies: single atoms and photons
- Single-ion quantum computing
- Quantum optical phenomena vs.
  quantum information processing tools
- Atom-photon interfaces @ ICFO

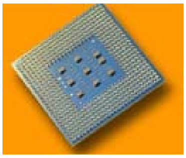
QT Quantum Optical Information Technology

CCQM, Evora, 13th November 2008

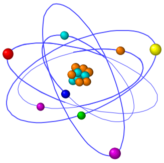
Towards quantum technology (Moore's Law)



ENIAC (1947)

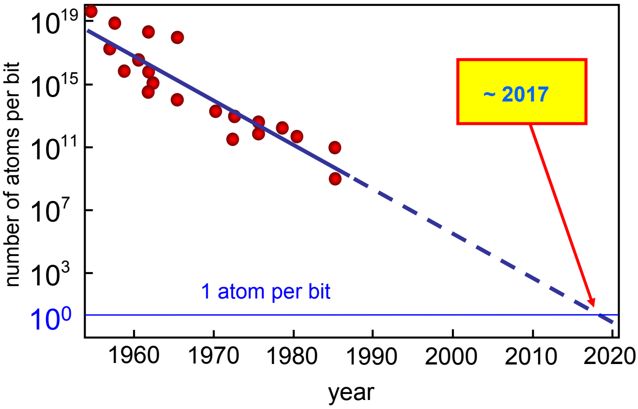


Pentium 4 (2002)



1 atom

How many atoms per bit of information?



- Quantum effects will play a role – and open up new avenues

Quantum information with single quantum systems

Applications in informatics and physics

- P. Shor, 1994: **factorization of large numbers is polynomial on a quantum computer, exponential on a classical computer**
- L. Grover, 1997: **data base search $N^{1/2}$ quantum queries, N classical**
- **simulation of Schrödinger equations or any unitary evolution**
- **quantum cryptography / repeaters / quantum links**
- **improved atomic clocks** (P. Schmidt et al., 2005)
- **(Gedanken-)experiments**
  fundamentals of QM, decoherence, entanglement

Fundamental phenomena ⇔ Quantum information ⇔ Technological applications

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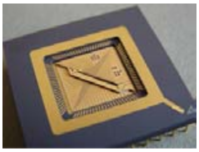
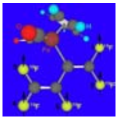
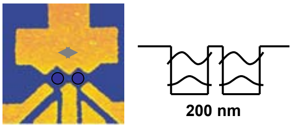
Various approaches



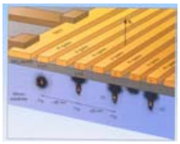
- **Ion traps**
- Neutral atoms in traps (opt. traps, opt. lattices, microtraps)
- Neutral atoms and cavity QED
- **NMR (in liquids)**



- Superconducting qubits (charge-, flux-qubits)
- **Solid state concepts**
  (spin systems, quantum dots, etc.)



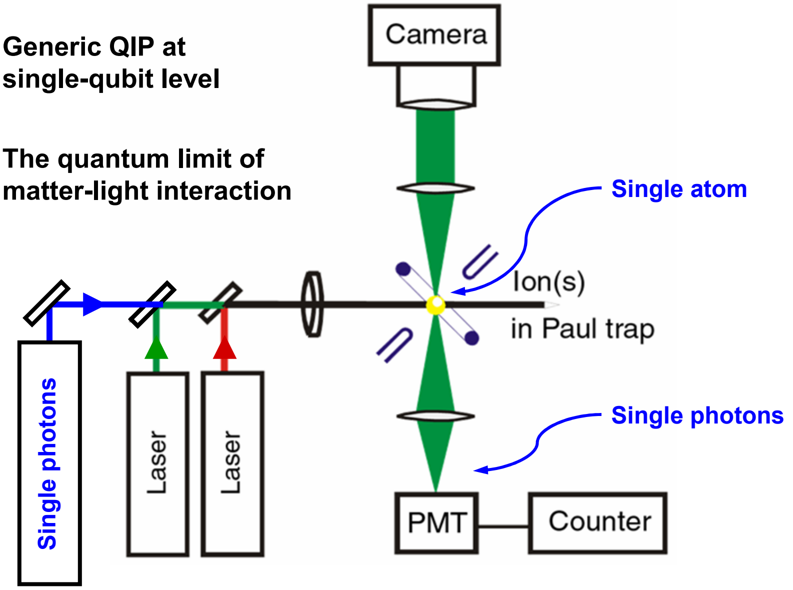
- Optical qubits and LOQC (linear optics quantum computation)
- Electrons on L-He surfaces
- Electrons in Penning trap
- Spectral hole burning in ion-doped crystals
- Colour centers
- …and more



COLD SYSTEMS

Single atom – single photon experiment

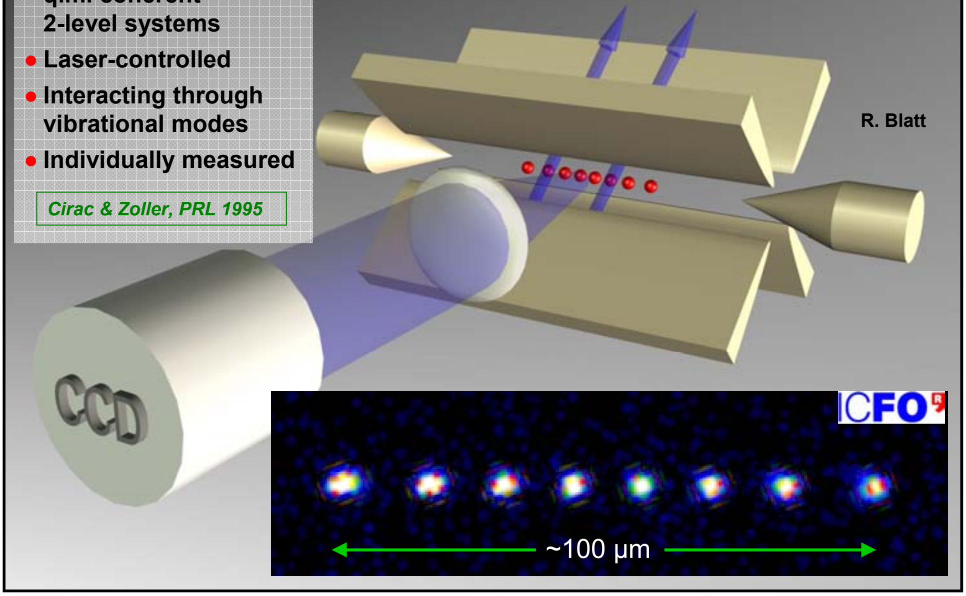
- **Generic QIP at single-qubit level**
- **The quantum limit of matter-light interaction**



String of ^{40}Ca+ ions in a linear Paul trap

- **Ions = "qubits" = q.m. coherent 2-level systems**
- **Laser-controlled**
- **Interacting through vibrational modes**
- **Individually measured**

Cirac & Zoller, PRL 1995



R. Blatt

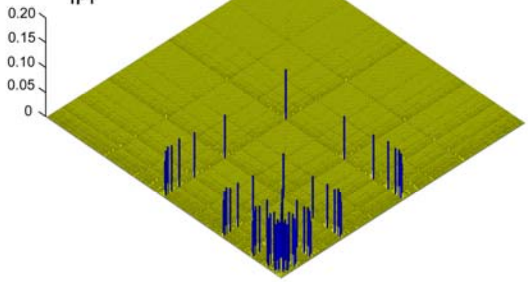
State of the art : The Quantum Byte

- **Entangled W state of 8 ions @ Innsbruck**

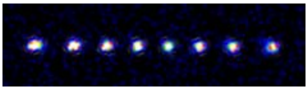
$$|\mathrm{W}\rangle = \frac{1}{\sqrt{N}}(|D\ldots D\,S\rangle + |D\ldots D\,S\,D\rangle + \ldots + |S\,D\ldots D\rangle)$$

Density matrix

|ρ|



Fidelity 72%



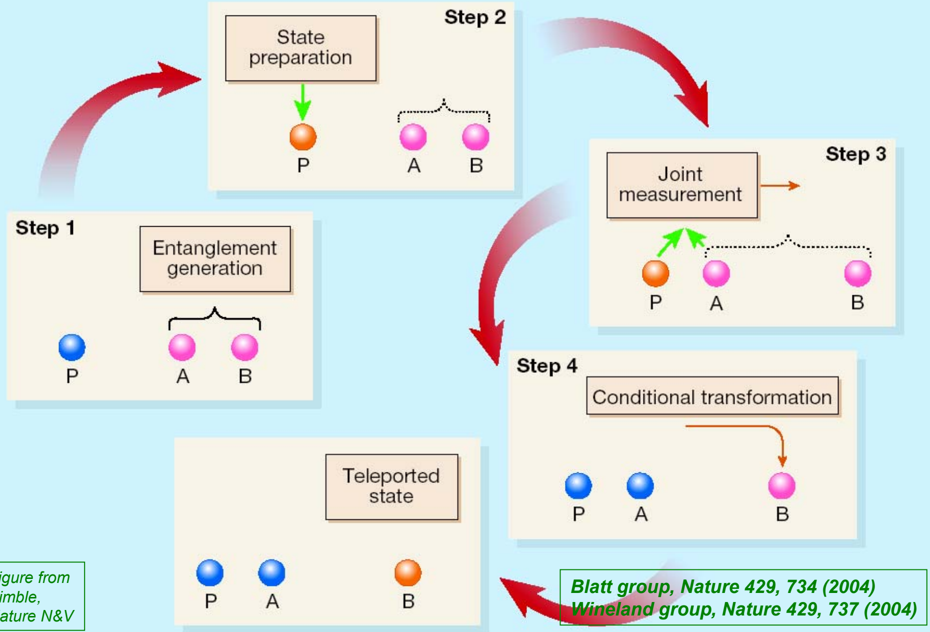
Blatt group, Nature 438, 643 (2005)

- **Entangled GHZ state of 6 ions @ NIST Boulder**

$$|\mathrm{GHZ}\rangle = \frac{1}{\sqrt{2}}(|D\,D\ldots D\rangle + |S\,S\ldots S\rangle)$$

Wineland group, Nature 438, 639 (2005)

State-of-the-art: Quantum Teleportation



Step 1 Entanglement generation

Step 2 State preparation

Step 3 Joint measurement

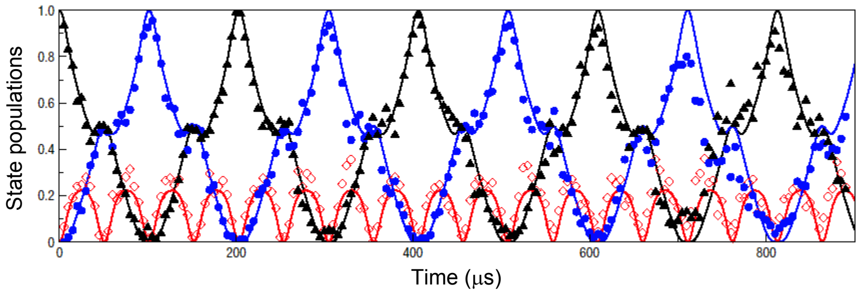
Step 4 Conditional transformation

Teleported state

Figure from Kimble, Nature N&V

Blatt group, Nature 429, 734 (2004)
Wineland group, Nature 429, 737 (2004)

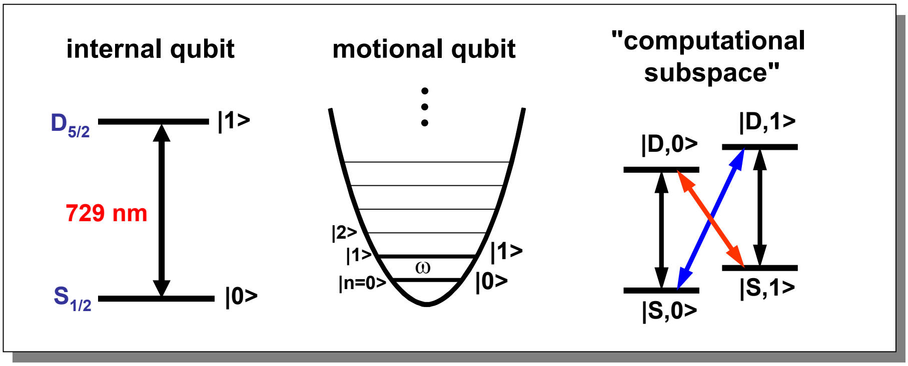
State-of-the-art: High-fidelity quantum gates



- 17 sequential entangling and disentangling operations
- individual entangling fidelity 99.3(1)% for Ψ^+ Bell state

Blatt group, Nature Physics 4, 463 (2008)

Why cold ? Qubits in a single ^{40}Ca$^+$ ion



internal qubit

motional qubit

"computational subspace"

COHERENT LASER MANIPULATION (Rabi oscillations)

⟷ **|S,n> ⇔ |D,n> : carrier transition** $(\Delta = 0)$

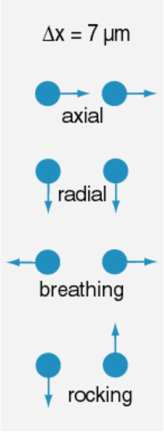
⟷ **|S,n> ⇔ |D,n±1> : sideband transition** $(\Delta = \pm\omega)$

First single-ion quantum gate: Wineland group, PRL 75, 4714 (1995).

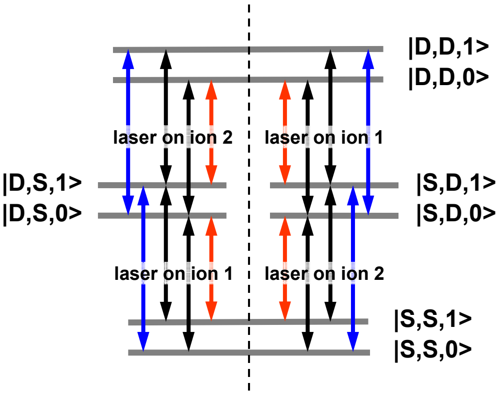
2 ions + motion = 3 qubits

With several ions, the motional qubits are shared
motional qubit acts as the "bus" between the ions

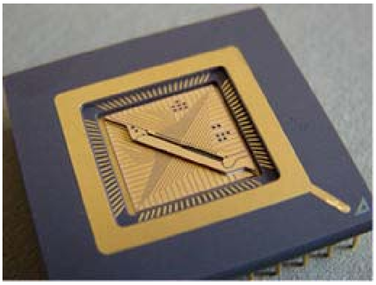
vibrational modes



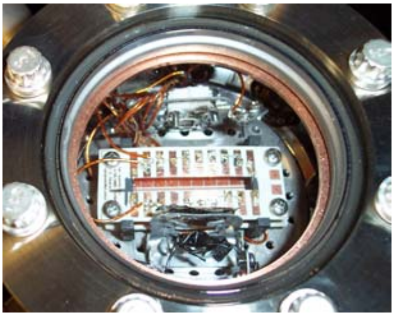
computational subspace: 2 ions, 1 mode



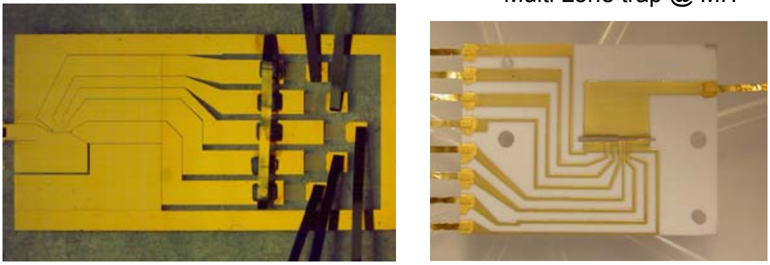
Future: Scaling up quantum processors



www.microtrap.eu

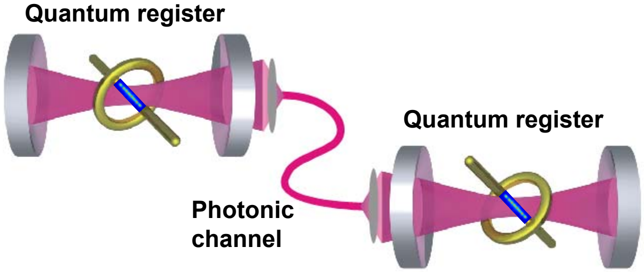


Multi-zone trap @ MIT



Chip-trap and multi-zone trap @ NIST

Future: quantum networks



- Quantum Communication
- Distributed Quantum Computing
- Teleportation, Quantum Repeaters
- Requires: Fully coherent and efficient state transfer between atoms and photons

First specific proposal: J. I. Cirac et al., PRL 78, 3221 (1997)

Quantum optical phenomena

↔

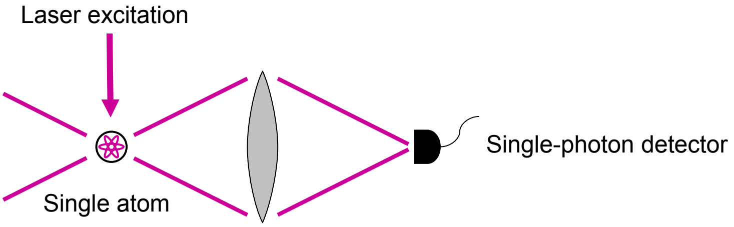
Quantum information tools

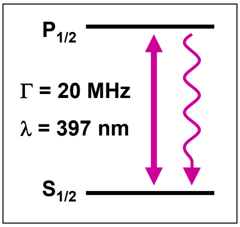
Phenomena to Tools - Examples

- **Photon recoil ⇔ Laser cooling**
- **Quantum jumps ⇔ State discrimination**
- **State reduction (qu. measurement) ⇔ State preparation**
- **Interference ⇔ Quantum phase engineering**
- **Photon indistinguishability ⇔ Entanglement**
- **Quantum correlations ⇔ Entanglement as a resource**

From projective quantum measurement
to distant atom-atom entanglement

Projective quantum measurement

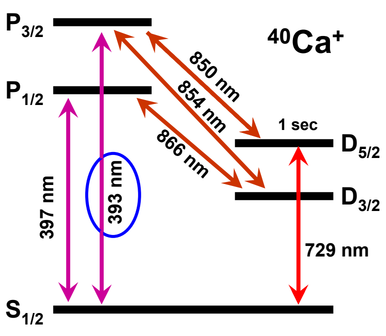


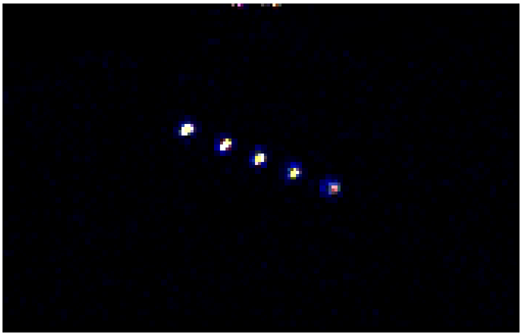


Detected photon
=
State reduction
=
Projective measurement

(von-Neumann measurement)

Quantum jumps & "Quantum amplification"



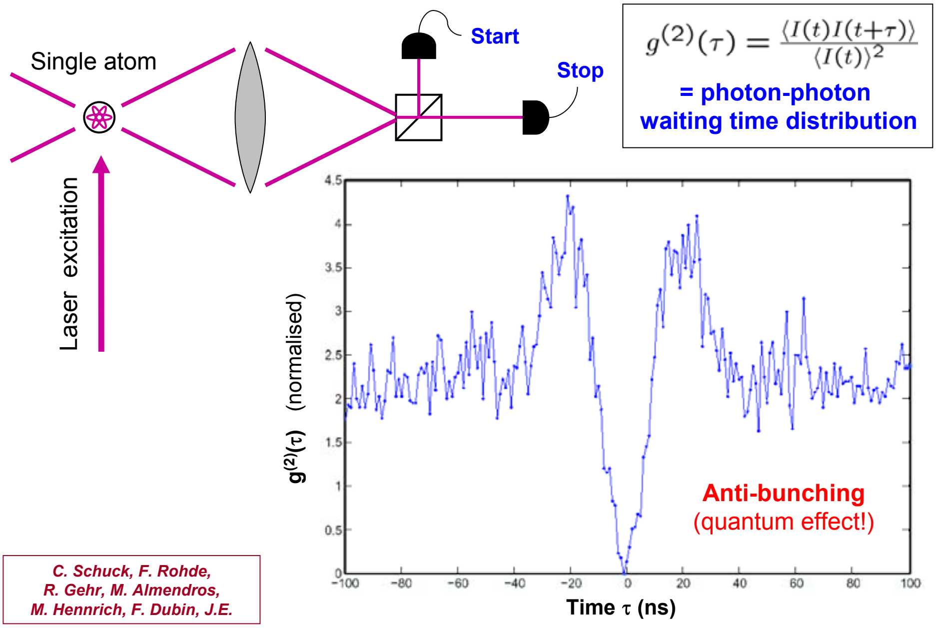


- High power LED for photo ionisation (80 mW @ 385 nm, HWHM 15 nm) excites 393 nm transition
- Ions are pumped into $D_{5/2}$ state (life time ~ 1s) → No fluorescence
- Detection of absorption of < 1 photon/sec

H. Dehmelt 1975

F. Rohde, C. Schuck, M. Almendros, M. Hennrich, J.E.

"Anti-bunching" in $g^{(2)}$ - Correlation



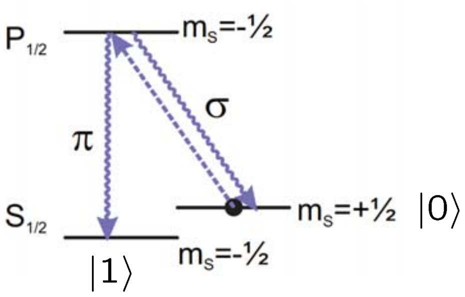
$$g^{(2)}(\tau) = \frac{\langle I(t) I(t+\tau)\rangle}{\langle I(t)\rangle^2}$$

= photon-photon waiting time distribution

Anti-bunching
(quantum effect!)

C. Schuck, F. Rohde, R. Gehr, M. Almendros, M. Hennrich, F. Dubin, J.E.

Atom-photon entanglement



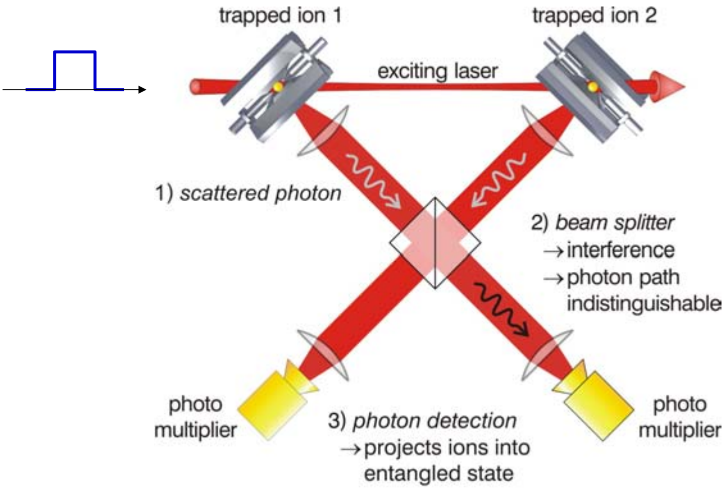
- Atom initially in $|0\rangle$ excited with σ laser pulse
- Emitted photon σ- or π-polarised
- **Entangled atom-photon state**
- **Detected photon prepares atomic state**

$$\boxed{|\psi_f\rangle = |1\rangle|\pi\rangle - |0\rangle|\sigma\rangle}$$

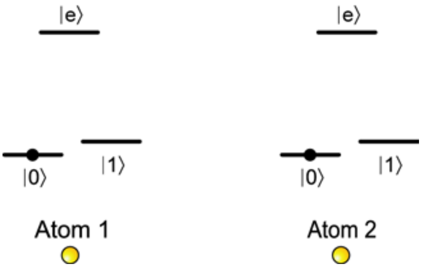
Monroe group, B. Blinov et al., Nature 2004

Schemes for atom-atom entanglement

- **One-photon scheme** ***(Cabrillo PRA 1999)*** **: wave interference**



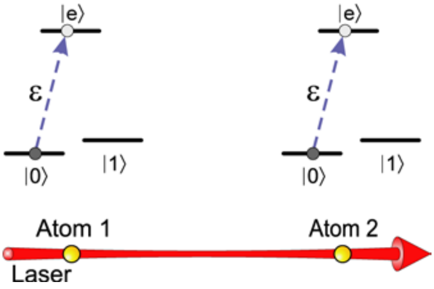
Entanglement scheme step 0



Preparation of initial state

$$|\Psi_{init}\rangle = |0\rangle|0\rangle$$

Entanglement scheme step 1



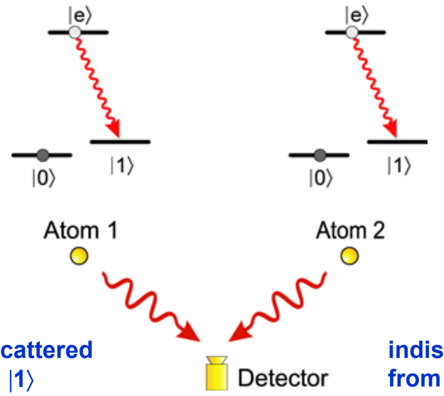
Excitation with probability ε « 1

$$|\Psi_{init}\rangle = |0\rangle|0\rangle$$

$$\downarrow$$

$$|\Psi_e\rangle = |0\rangle|0\rangle \;+\; \epsilon[|e\rangle|0\rangle + |0\rangle|e\rangle] \;+\; \cancel{\epsilon^2|e\rangle|e\rangle}$$

Entanglement scheme step 2



Detection of a scattered photon on |e⟩ → |1⟩

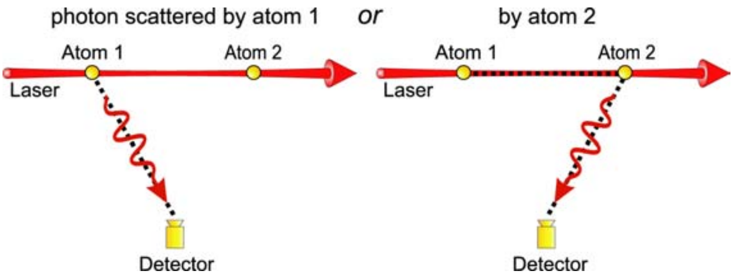
indistinguishable from which atom

$$|\Psi_e\rangle = |0\rangle|0\rangle + \boxed{\epsilon[|e\rangle|0\rangle + |0\rangle|e\rangle]} + \cancel{\epsilon^2|e\rangle|e\rangle}$$

- **Detected photon prepares atom-atom entangled state**

$$\boxed{|\Psi_f\rangle = \frac{1}{\sqrt{2}}[|1\rangle|0\rangle + e^{i\phi}|0\rangle|1\rangle]}$$

Classical vs. quantum phases



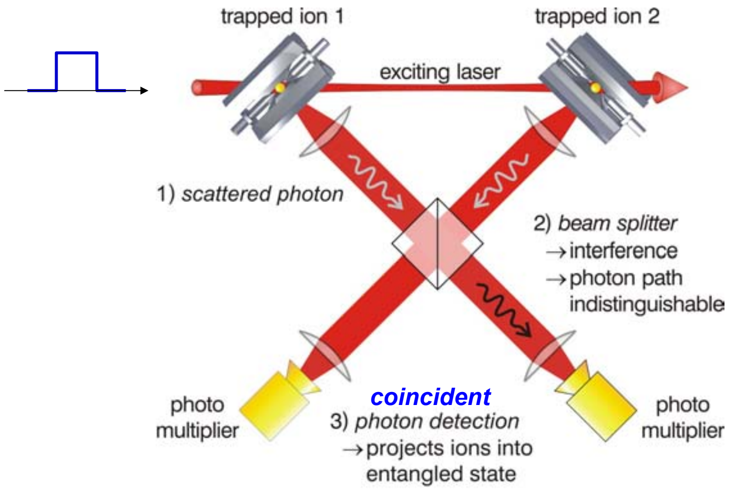
Photon path difference defines the quantum phase *Φ* of the entangled state

$$|\Psi_f\rangle = \frac{1}{\sqrt{2}}[|1\rangle|0\rangle + e^{i\phi}|0\rangle|1\rangle]$$

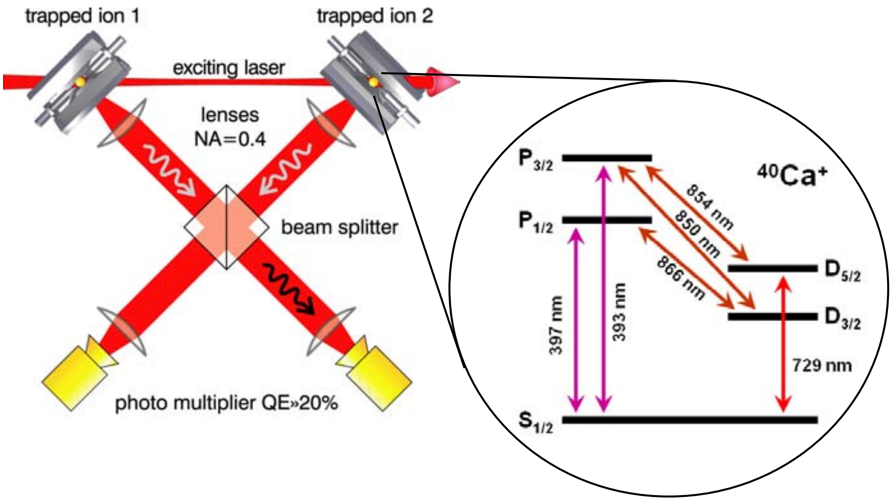
➔ **Ressource for quantum networks**

Schemes for atom-atom entanglement

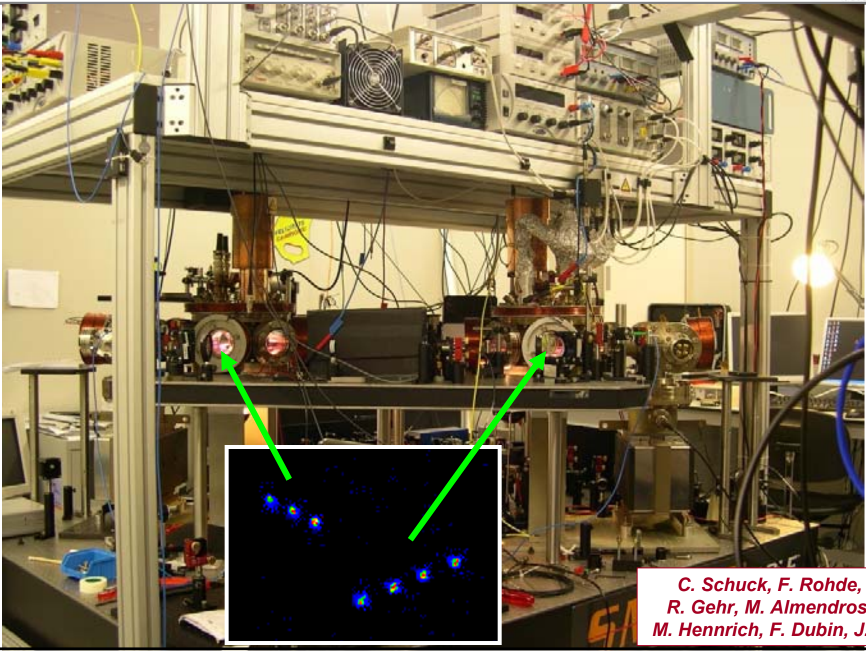
- **Two-photon schemes** ***(Feng / Simon, PRL 2003)*** **: photon interference**



At ICFO : two independent $^{40}Ca^+$ ion traps

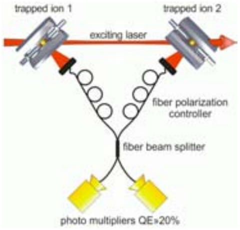


Double trap set-up @ ICFO

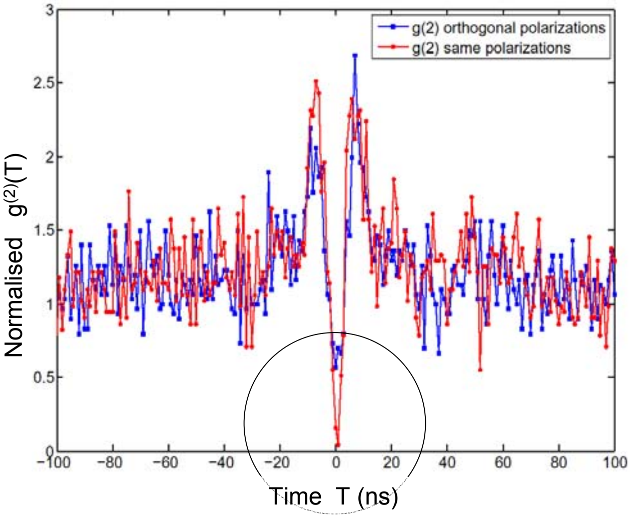


C. Schuck, F. Rohde,
R. Gehr, M. Almendros,
M. Hennrich, F. Dubin, J.E.

Results : Interference

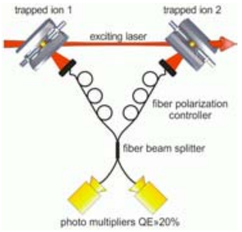


- **Two ions in two traps**
- **Anti-bunching**
- **Photon indistinguishability**



New J. Phys., soon

Results : Interference



- **Two ions in two traps**
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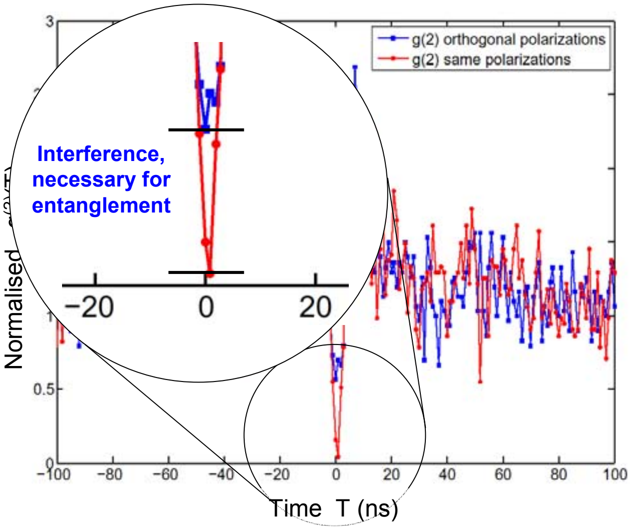


Interference, necessary for entanglement

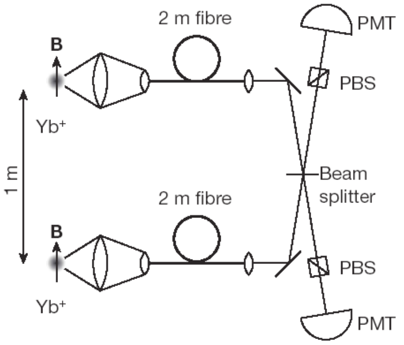
New J. Phys., soon

Highlight : distant entanglement

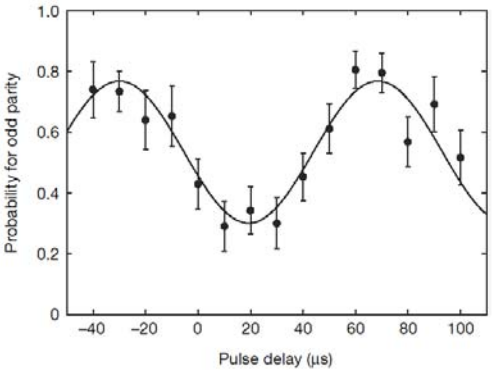
- **2 ions at macroscopic distance @ Michigan**

Monroe group, Nature 449, 68 (2007)

Schematic



Rotated basis result



- **Fidelity 63 %**
- **1 pair / 39 s**

Future: Teleportation between quantum registers

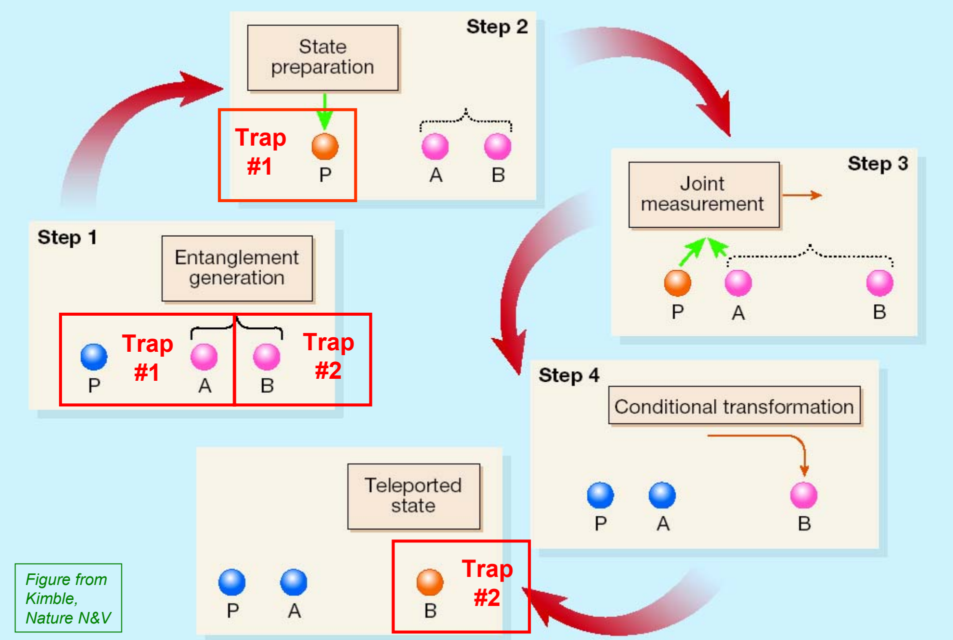
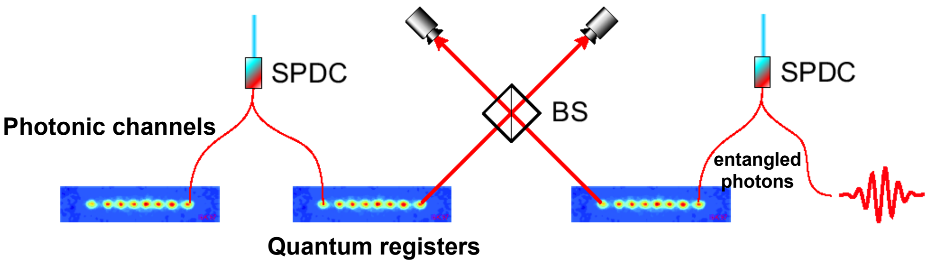


Figure from Kimble, Nature N&V

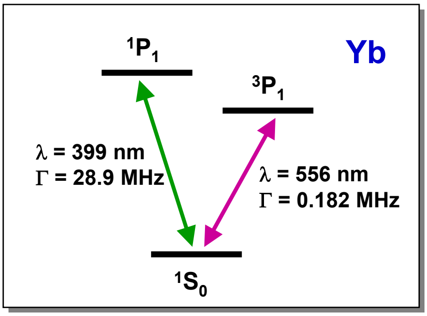
Quantum network experiments @ ICFO

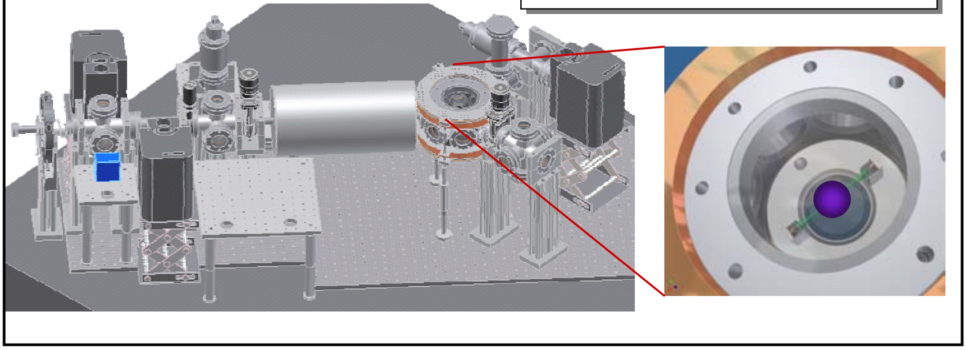


- **Various schemes of distant entanglement**
- **Teleportation**
- **Photon-atom entanglement transfer**

Cavity QED system @ ICFO

- Neutral ytterbium atoms
- MOT @ 399 nm, Zeeman slower
- MOT @ 556 nm
- IR laser dipole trap
- High finesse resonator



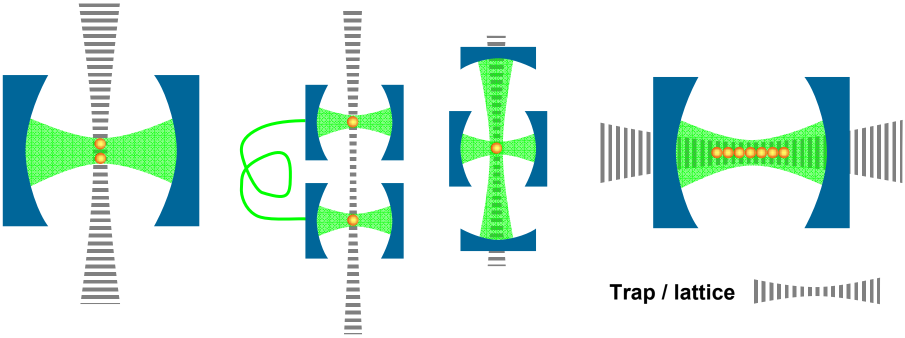


Cavity QED photon-atom interfaces

Atom-atom coupling via cavity

Cavity-cavity coupling (optically or via atom)

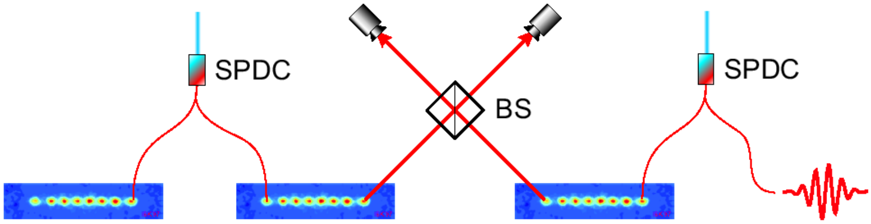
Collective atom coupling with cavity



- Transmission of quantum information *J.I. Cirac et al., PRL 1997*
- Entangled light pulses *G. Morigi et al., PRL 2006*
- Cavity cooling *S. Zippilli et al., PRL 2005*

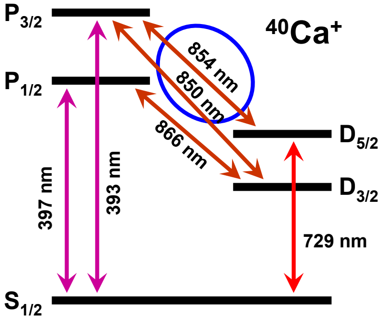
Towards controlled single-photon absorption

long-term objective : photon-atom entanglement transfer

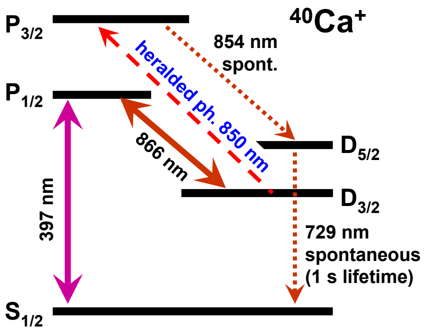


Single photon source resonant with Ca^+

- Entangled photon pairs at 850 nm or 854 nm (Type II collinear parametric down-conversion)
- One photon filtered to Ca^+ absorption bandwidth → partner is resonant
- Strategy: Quantum jumps induced by one photon, correlated with filtered partner photon

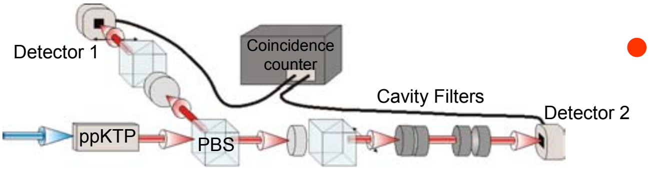


Towards controlled single-photon absorption



- ~ 3000 photons / s @ 850 nm tightly focused onto ion
- Geometrical cross section ~ 2 %
- Absorption probability (oscillator strength): $\frac{1}{150}$
- ~ 6 % of absorbed photons create quantum jump (branching ratio)
- 10-20 % of photons have heralding partner

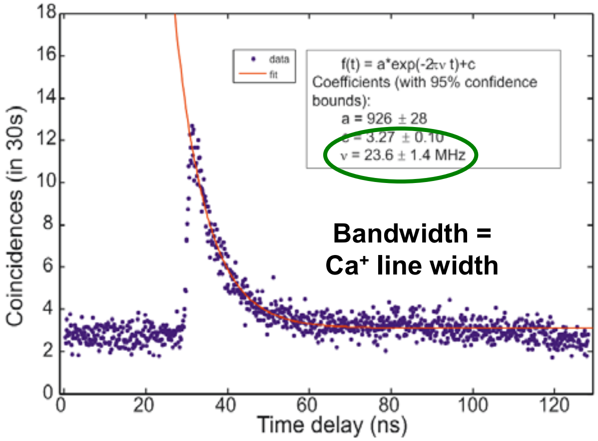
Experiment : Flux and Bandwidth



- Temporal shape of photon wave packet after filtering

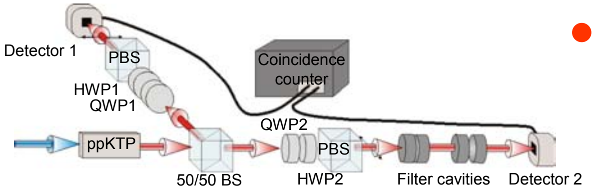
- Absolute brightness (detected) :
  150 pairs/s
  @ 100 mW pump
  @ 24 MHz bandwidth

- Spectral brightness (detected) :
  $3 \cdot 10^4$ pairs /(s mW nm)
  = 60 pairs / (s GHz mW)

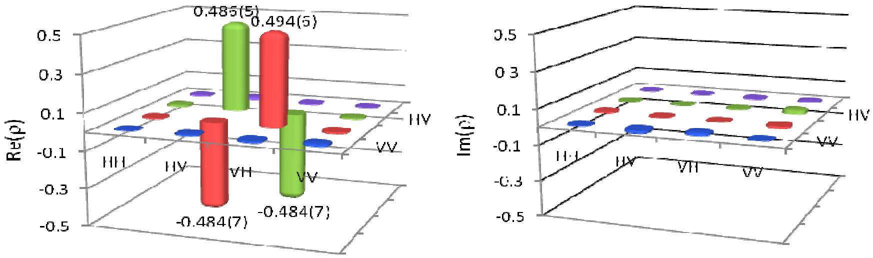


Bandwidth = Ca^+ line width

Experiment : Tomography



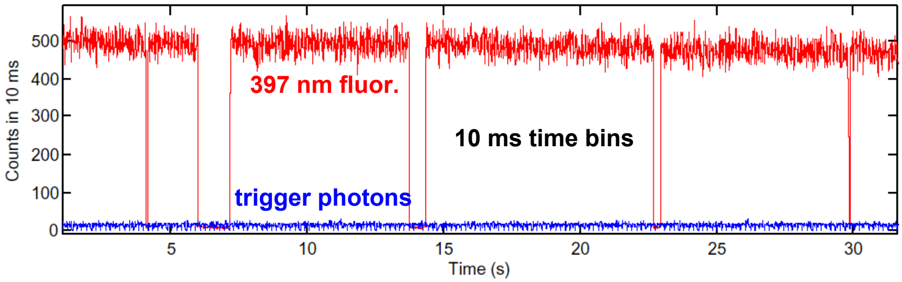
- **Reconstruction of the density matrix**



- **Fidelity** $F = \langle \Psi^- | \rho | \Psi^- \rangle$ **= 97.6 ± 1.1 %**

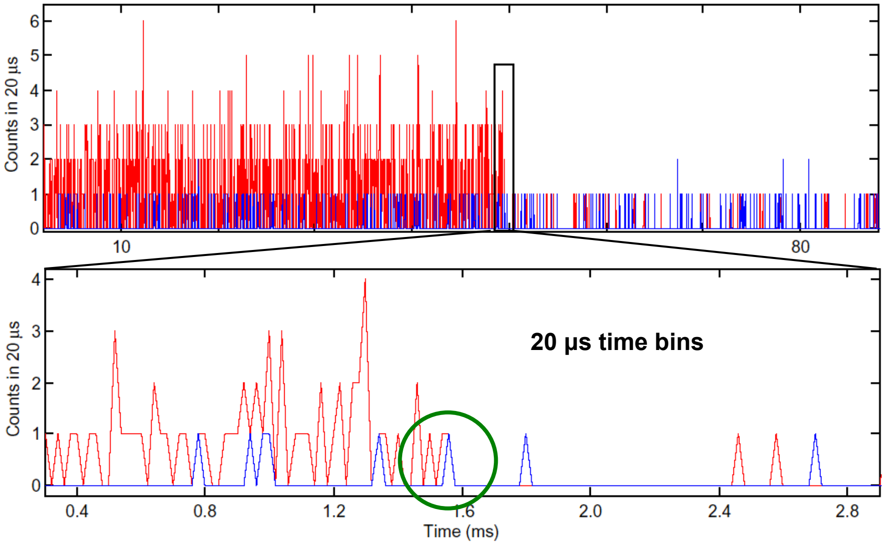
A. Haase et al.
Optics Lett.

Quantum jumps



- **Measured ~ 1 quantum jump / min, compatible with expected rate**

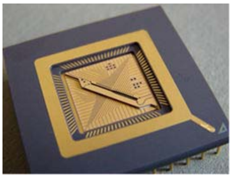
How controlled absorption SHOULD look like

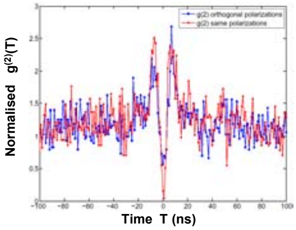


- Now accumulating statistics…

Summary

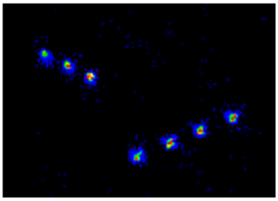
- QIP with cold atoms/ions





- Quantum optics : tool for quantum information and quantum technologies

- Activities & Perspectives @ ICFO:
  Double ion quantum processor
  Single atom – single photon interfaces
  Quantum networks



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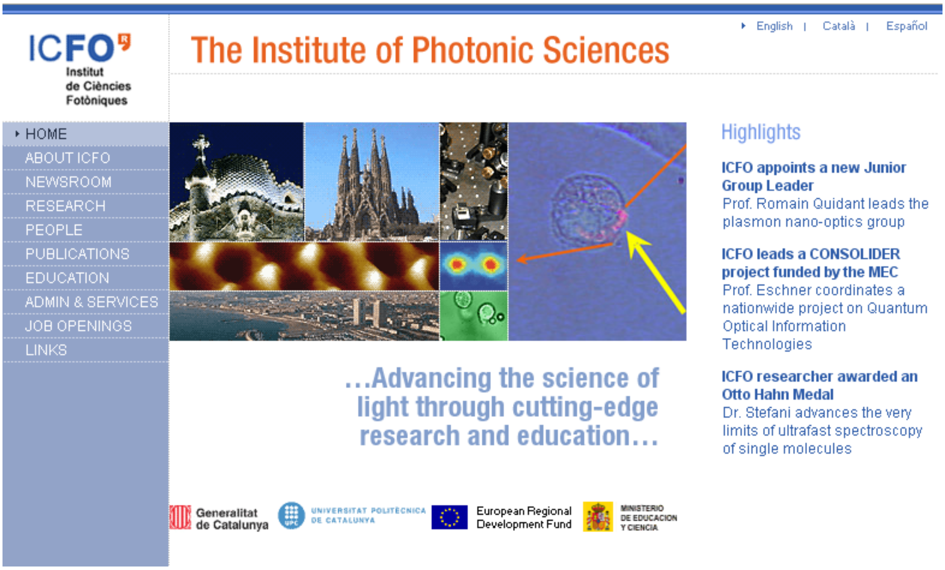
http://www.icfo.es/



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Highlights

ICFO appoints a new Junior Group Leader
Prof. Romain Quidant leads the plasmon nano-optics group

ICFO leads a CONSOLIDER project funded by the MEC
Prof. Eschner coordinates a nationwide project on Quantum Optical Information Technologies

ICFO researcher awarded an Otto Hahn Medal
Dr. Stefani advances the very limits of ultrafast spectroscopy of single molecules

Generalitat de Catalunya | Universitat Politècnica de Catalunya | European Regional Development Fund | Ministerio de Educación y Ciencia

The Team

ICFO Institut de Ciències Fotòniques

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You?

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www.qoit.es

QT
Quantum Optical
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Programa Consolider – Ingenio 2010

MINISTERIO
DE EDUCACIÓN
Y CIENCIA

11 groups in 6 institutions:

UPV (Valencia), UAM, IMM-CSIC (Madrid), UAB, UB, ICFO (Barcelona)

50% Experimental (atoms, photons, solid state)
50% Theory (quantum optics, quantum information)

- **Establish QOIT as an area of cutting-edge competence in Spain**
- **Exploit two-fold complementarities**
  Science – Technology and Experiment – Theory