Lecture 2 : using single atoms as controlled single-photon sources

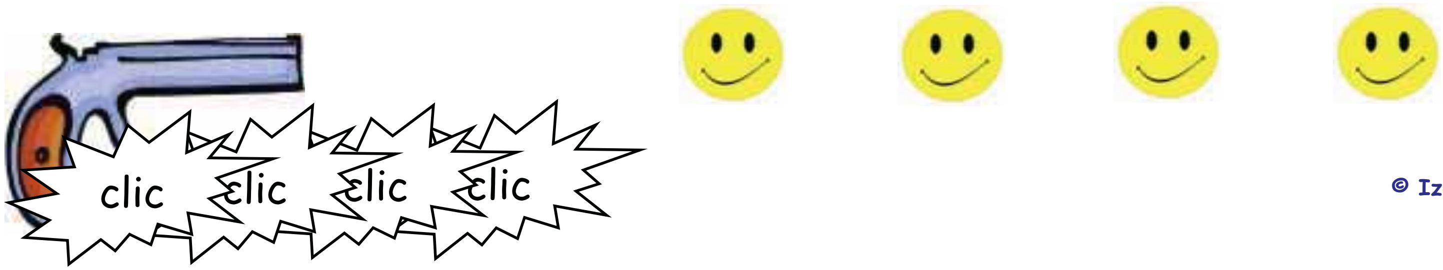
1. Basics of non-classical-light and single photons
2. Generating indistinguishable single photons from single atoms
3. From single atoms to single qubits

Part 1

From heralded single photons (1986)
to single-mode single photons
using a single trapped atom (2005)

Darquié **et al**, Science **309**, 454 (2005)

« Photon gun »



© Izo Abram

Deterministic => photons when we want
Efficient => photons each time we ask
Suitable => photons in the format we require

Different applications require different "qualities" of photons:

Quantum cryptography : the goal is to eliminate "PNS" attacks
must be simple and efficient

Quantum Gates : "KLM" Linear Quantum Computing
requires indistinguishable photons !

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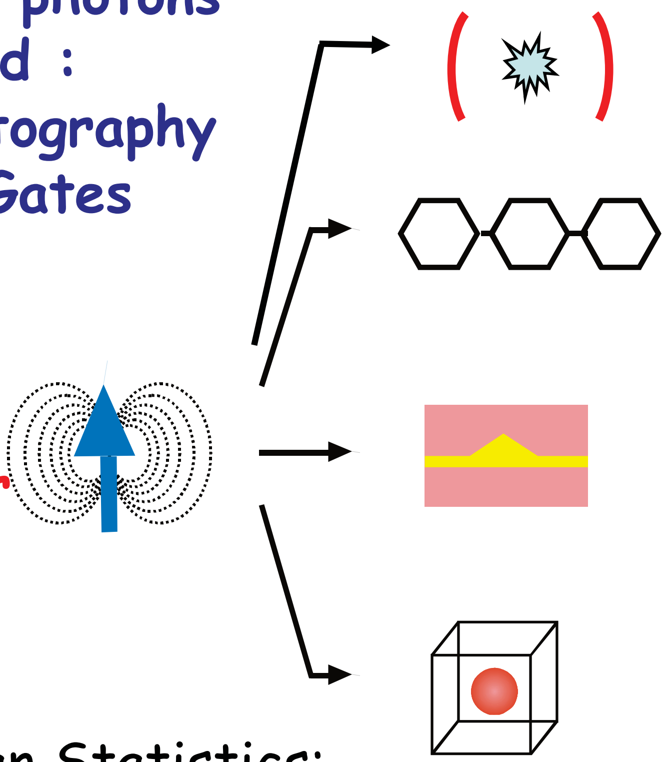
Single Photon Sources

QIPC / S4P

Emitting single photons
on demand :
Quantum cryptography
Quantum Gates

Pulsed
Single Emitter



Single atom or ion in a cavity

Molecule, nanocrystallites

☹ Photobleaching, blinking

Quantum Dot (+ microcavities)
☺ Narrow Spectrum
☹ T = 4K

Color Centers (NV centers)

☺ Stable at Room Temperature
☺ Easy to Produce

☺ Subpoissonian Statistics:

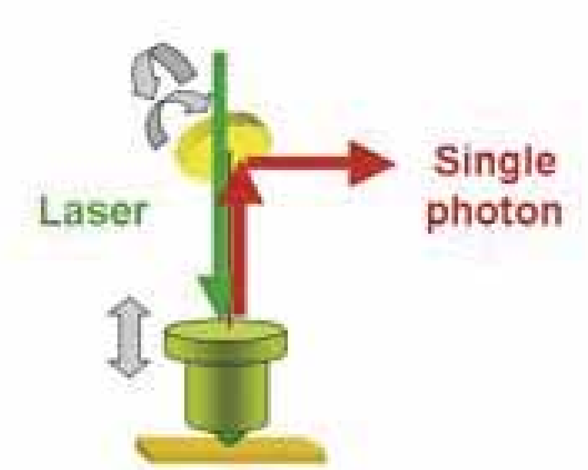
$$p(2) = c_N(0)\frac{p(1)^2}{2}$$

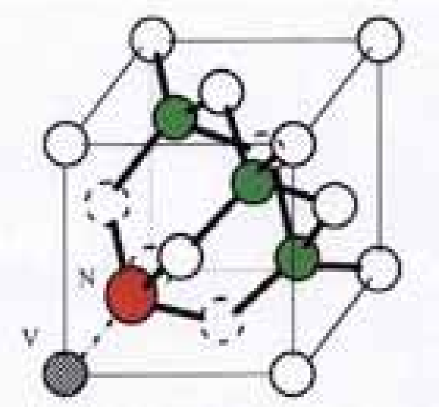
☺ $c_N(0) << 1$

Single photon sources : a simple example

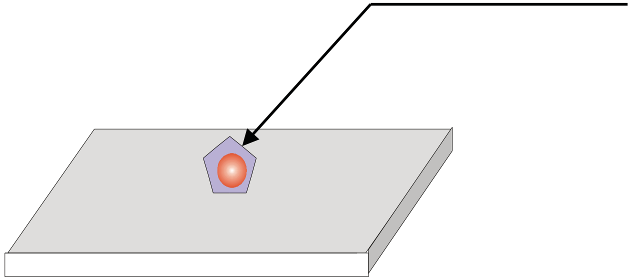
NV centers in diamond nanocrystals

"Single photon quantum cryptography"
A. Beveratos, R. Brouri, T. Gacoin,
A. Villing, J.P. Poizat and P. Grangier
Phys. Rev. Lett. 89 (18), 187901 (2002)

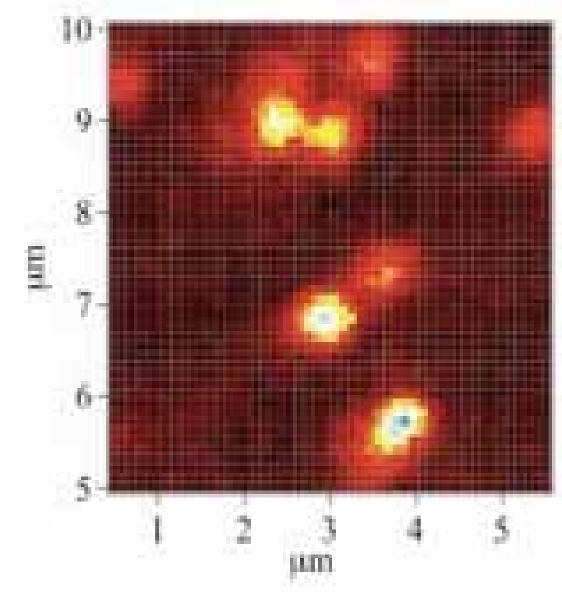




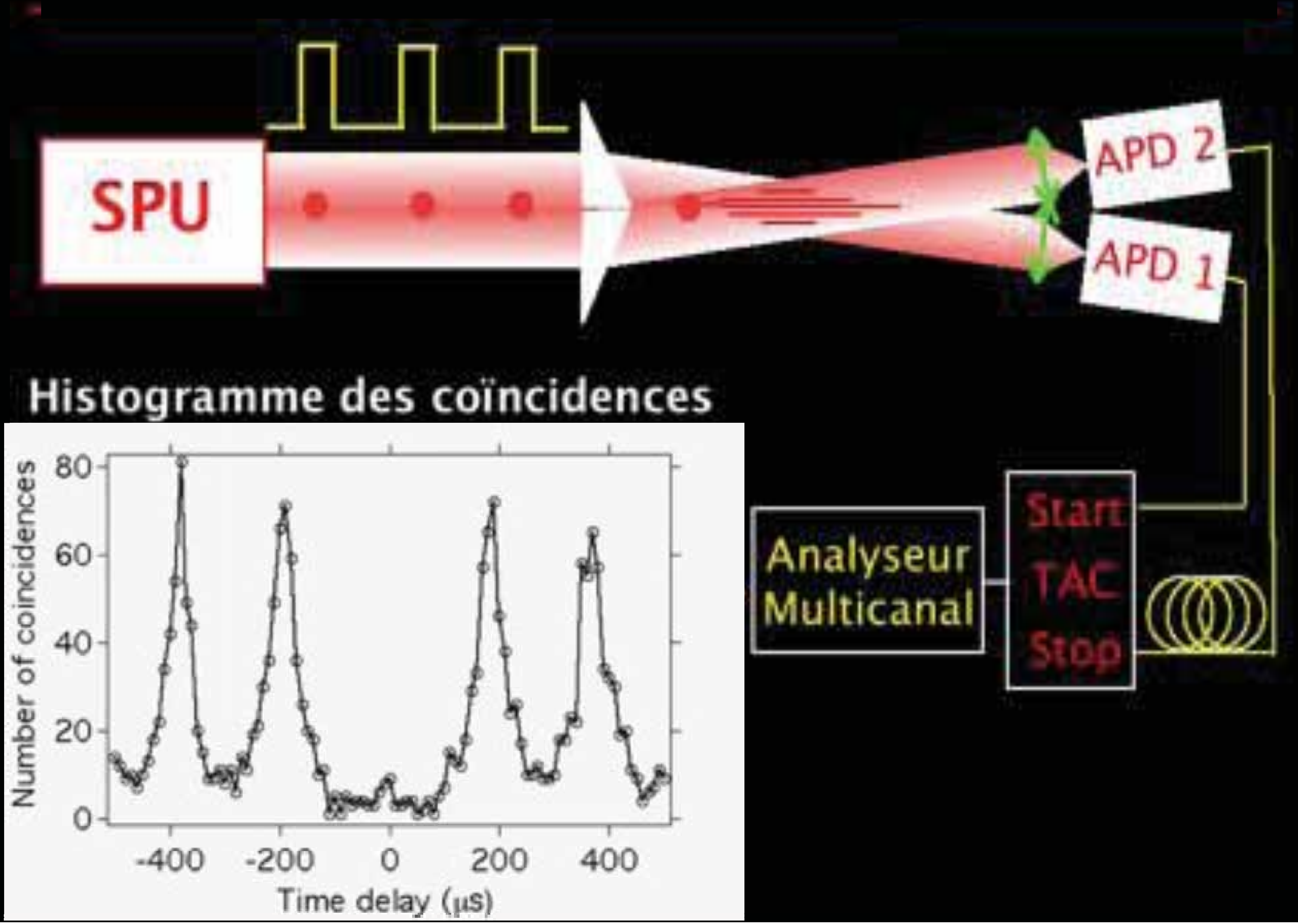
NV = Nitrogen-Vacancy


Ø = 50 nm << λ/n

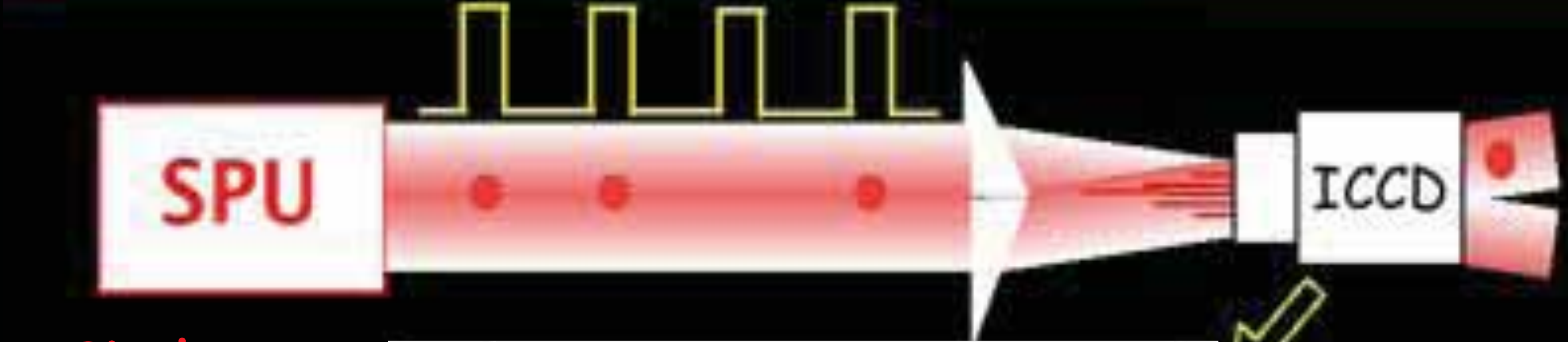
diamond nanocrystal



Which way is followed by the photon ?

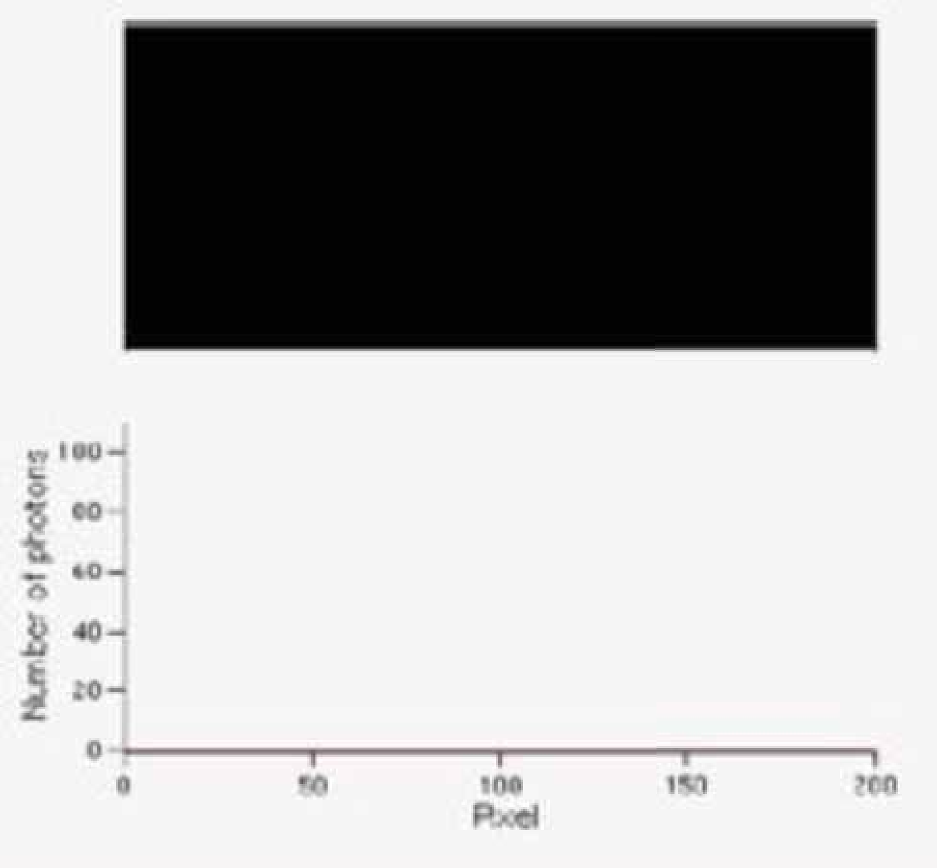


Looking at single photon interferences



Single-photon source :

NV centers in diamond nanocrystals, pulsed excitation



Experiment realized at ENS Cachan :

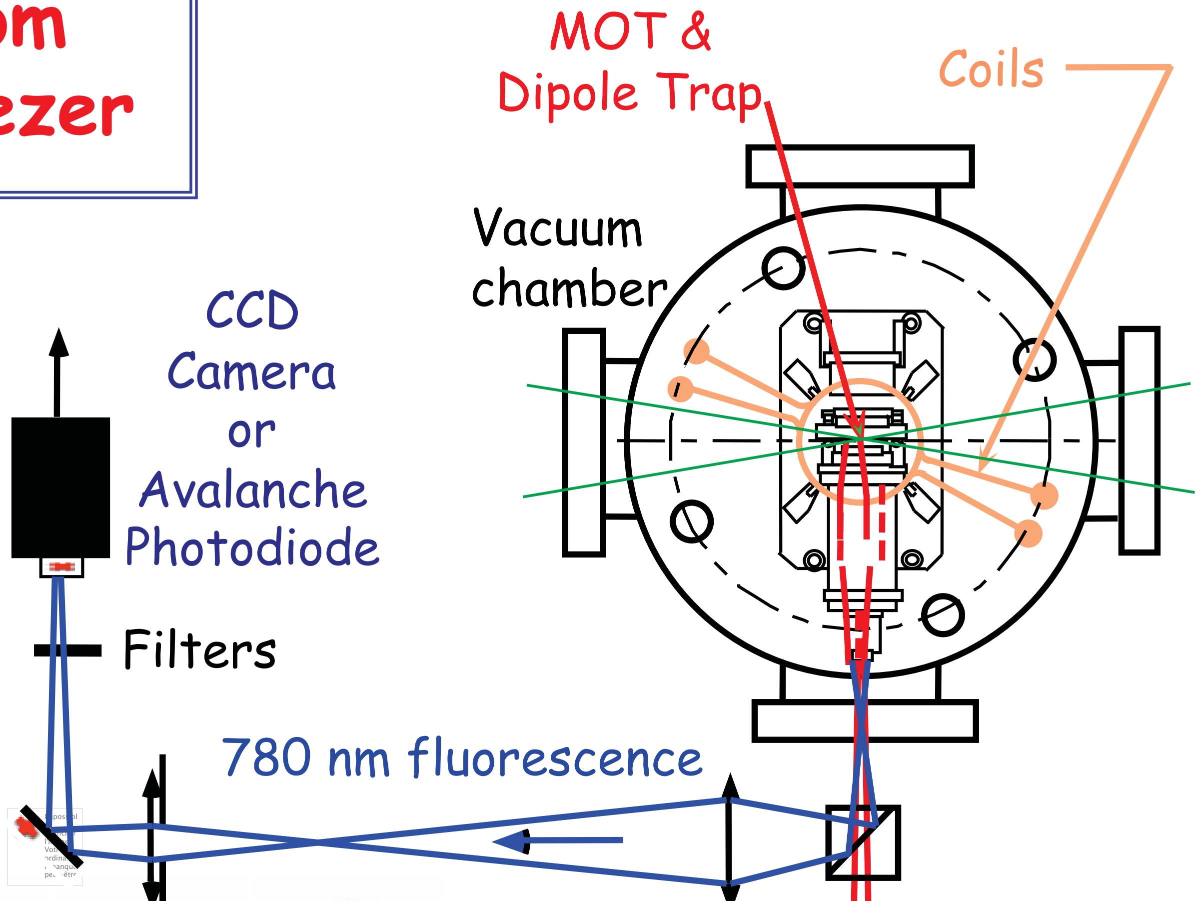
V. Jacques, E. Wu, T. Toury, F. Treussart, A. Aspect, P. Grangier and J.-F. Roch
Eur. Phys. J. D 35, 561-565 (2005)

Free download !

Single atom optical tweezer

Microscopic
dipole trap :
Spot size < 1 μm
Power < 10 mW
Trapping time > 1s

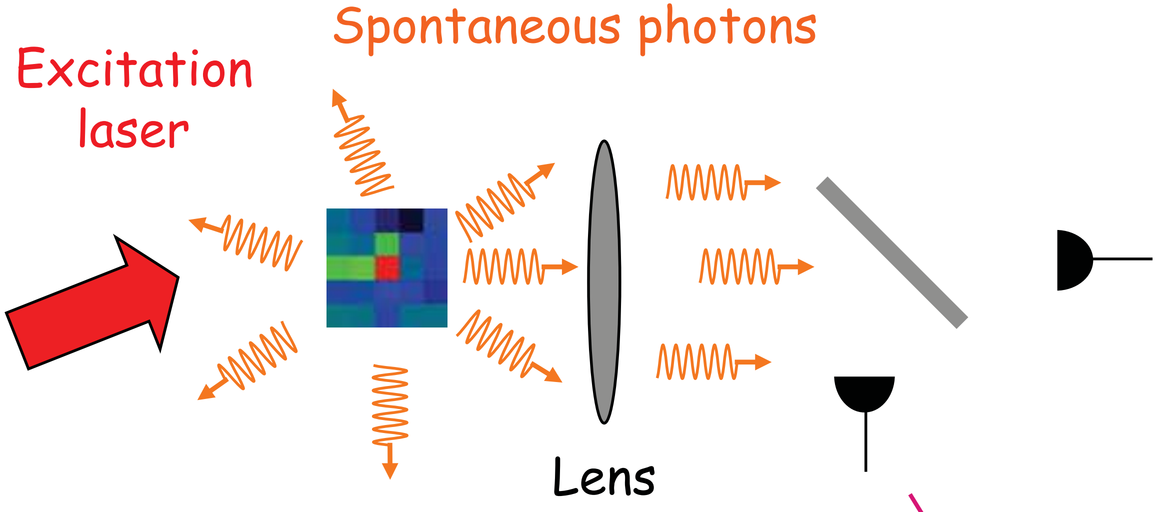
Imaging :1μm/pixel

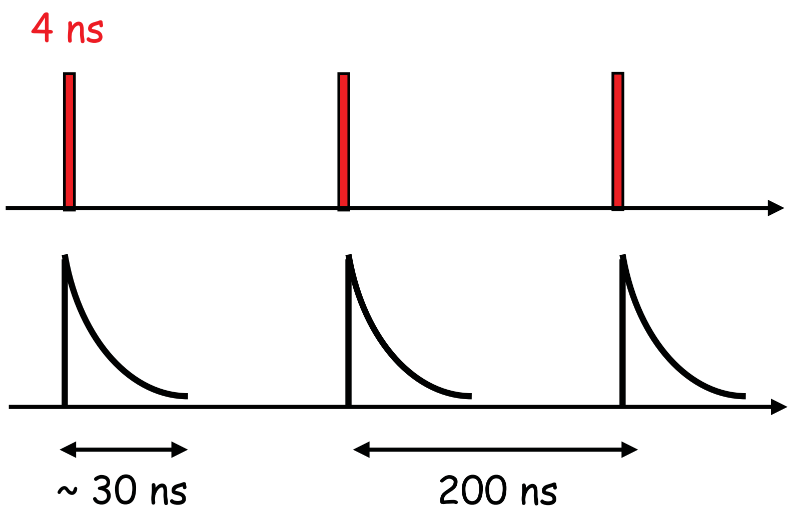


Individual atoms « jumping » in the trap
« Collisionnal blockade » : only one atom !

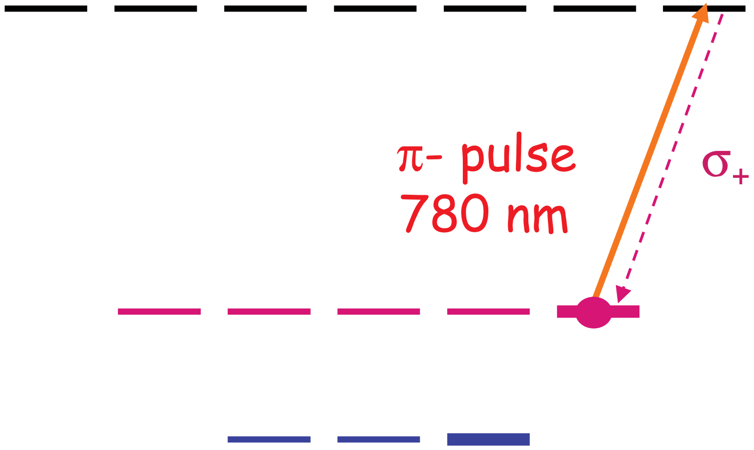
N. Schlosser et al,
Nature 411, 1024 (2001)
PRL 89, 023005 (2002)

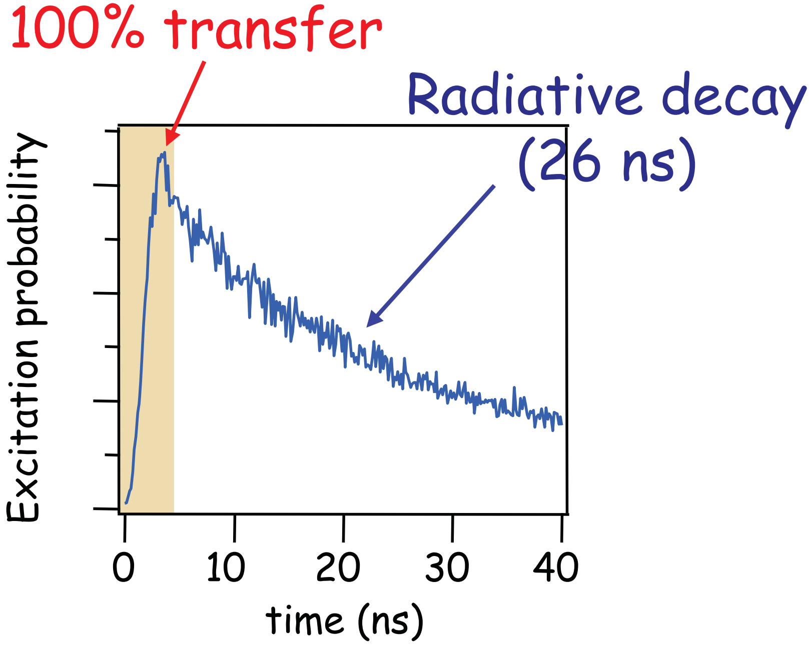
Triggered emission of single photons by an atom





« Coherent » excitation





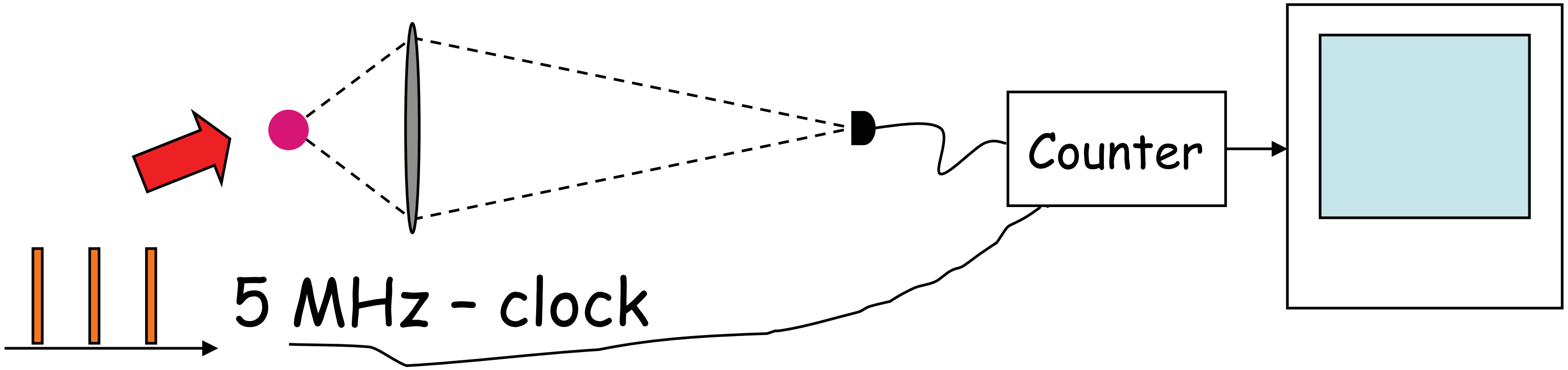
EXCITING THE ATOM

Excitation process based on π – pulse
$\Rightarrow$ test by observing Rabi oscillations on the 780 nm transition

2 – level system model : $P_e \propto \sin^2 \Omega T/2$

Pulse duration (4 ns) << lifetime of the atomic transition (26 ns)

For a fixed pulse duration T = 4 ns, change the laser power $\propto \Omega^2$



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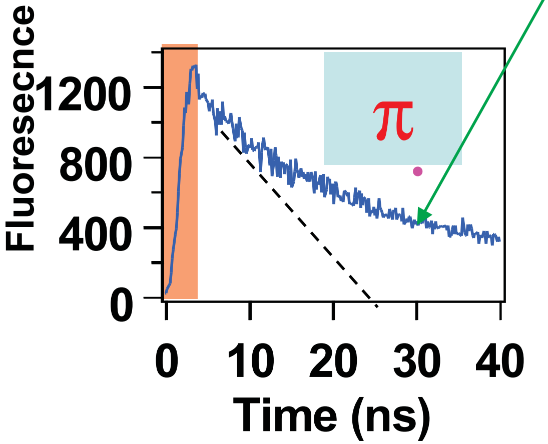
RABI OSCILLATIONS VS TIME

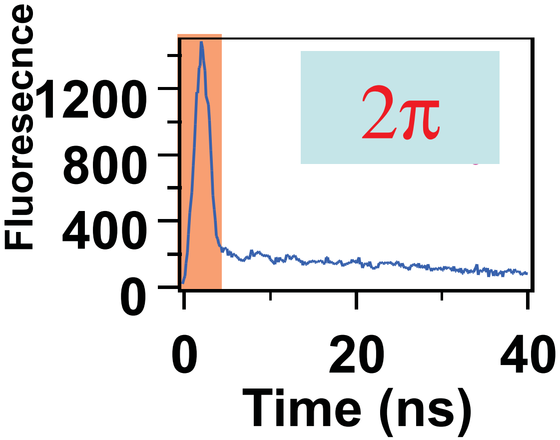
QIPC / S4P

De-excitation (lifetime of the excited state)

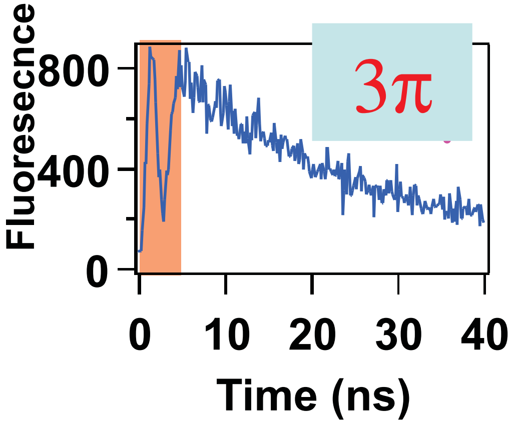
4 ns - pulse



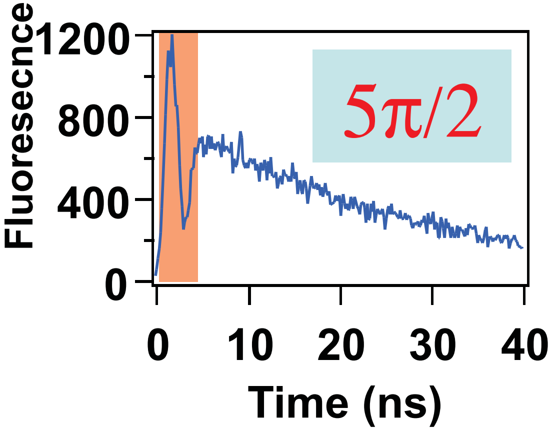
~ 20 W / cm²



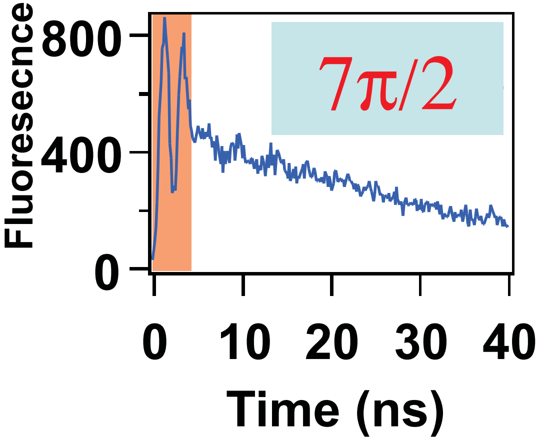
~ 80 W / cm²



~ 180 W / cm²

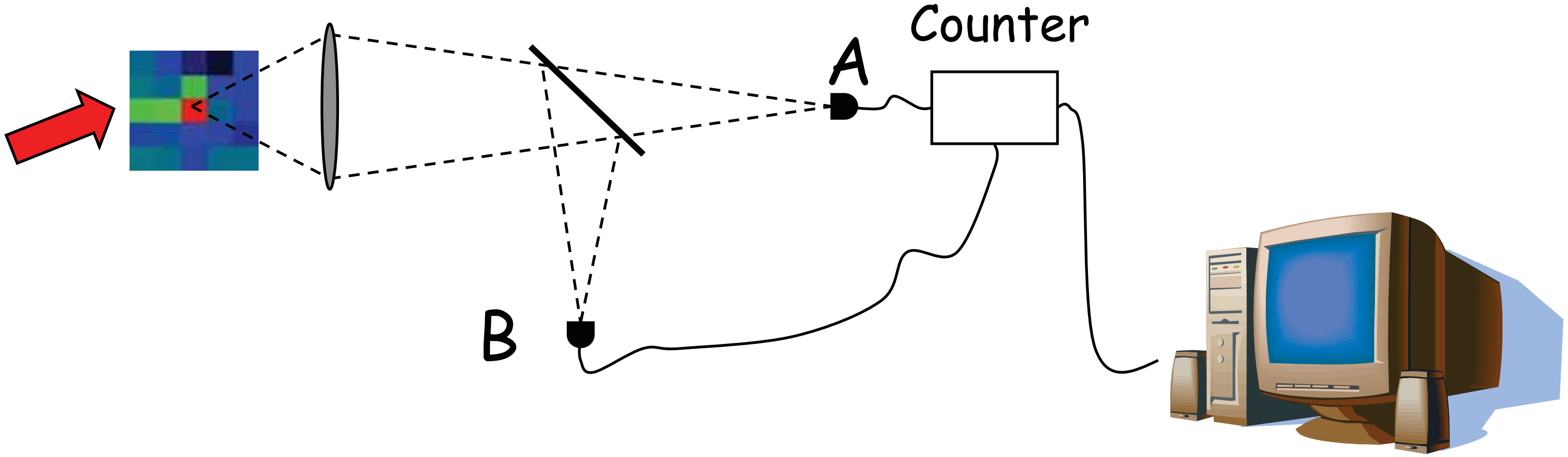


~ 125 W / cm²



~ 250 W / cm²

IS IT REALLY A SINGLE PHOTON SOURCE ?



Start – stop configuration:
measure the number of coincidences for different delays τ

->**second-order intensity correlation function $g^{(2)}(\tau)$**

= Probability to detect one photon at time t,
and another one at time $t+\tau$

Some formulas…

Definition of the intensity correlation function $g^{(2)}(\tau)$:

$$g^{(2)}(t,\ t+\tau) = \frac{P(t,\ t+\tau)}{P(t)P(t+\tau)}$$

Classically P is proportionnal to the intensity :

$$\mathcal{I}(t) = \langle \mathcal{E}^*(t)\mathcal{E}(t)\rangle$$

and thus :

$$g^{(2)}_{class}(\tau) = \frac{\langle \mathcal{E}^*(t)\mathcal{E}^*(t+\tau)\mathcal{E}(t+\tau)\mathcal{E}(t)\rangle}{\langle \mathcal{E}^*(t)\mathcal{E}(t)\rangle^2} = \frac{\langle \mathcal{I}(t+\tau)\,\mathcal{I}(t)\rangle}{\langle \mathcal{I}(t)\rangle^2}$$

En utilisant les inégalités $\langle \mathcal{I}^2(t)\rangle \geq \langle \mathcal{I}(t)\rangle^2$ et $\langle \mathcal{I}^2(t)\rangle \geq \langle \mathcal{I}(t+\tau)\,\mathcal{I}(t)\rangle$ (inégalités de Cauchy-Schwartz), on voit que :

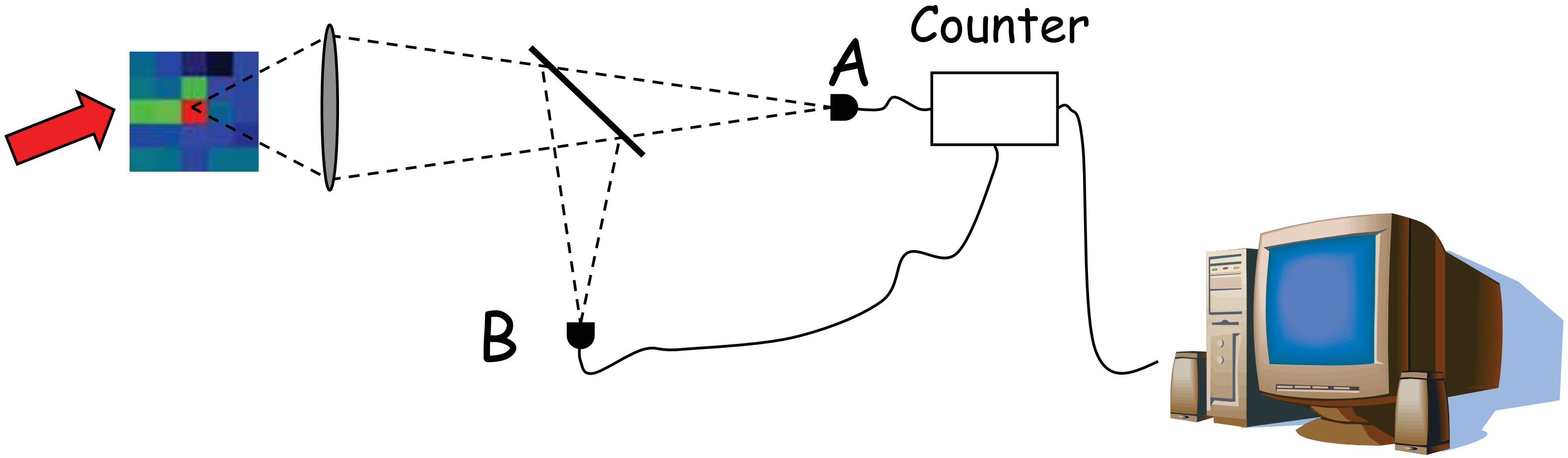
$$g^{(2)}_{class}(0) \geq 1 \qquad g^{(2)}_{class}(0) \geq g^{(2)}_{class}(\tau)$$

Quantum expression of $g^{(2)}(\tau)$:

$$g^{(2)}(\tau,\ \vec{r}) = \frac{\langle \hat{E}^{(-)}(t,\ \vec{r})\hat{E}^{(-)}(t+\tau,\ \vec{r})\hat{E}^{(+)}(t+\tau,\ \vec{r})\hat{E}^{(+)}(t,\ \vec{r})\rangle}{\langle \hat{E}^{(-)}(t,\ \vec{r})\hat{E}^{(+)}(t,\ \vec{r})\rangle^2}$$

For a single photon one can have $g^{(2)}(\tau) = 0$!

IS IT REALLY A SINGLE PHOTON SOURCE ?



Start – stop configuration:
measure the number of coincidences for different delays τ

->**second-order intensity correlation function $g^{(2)}(\tau)$**

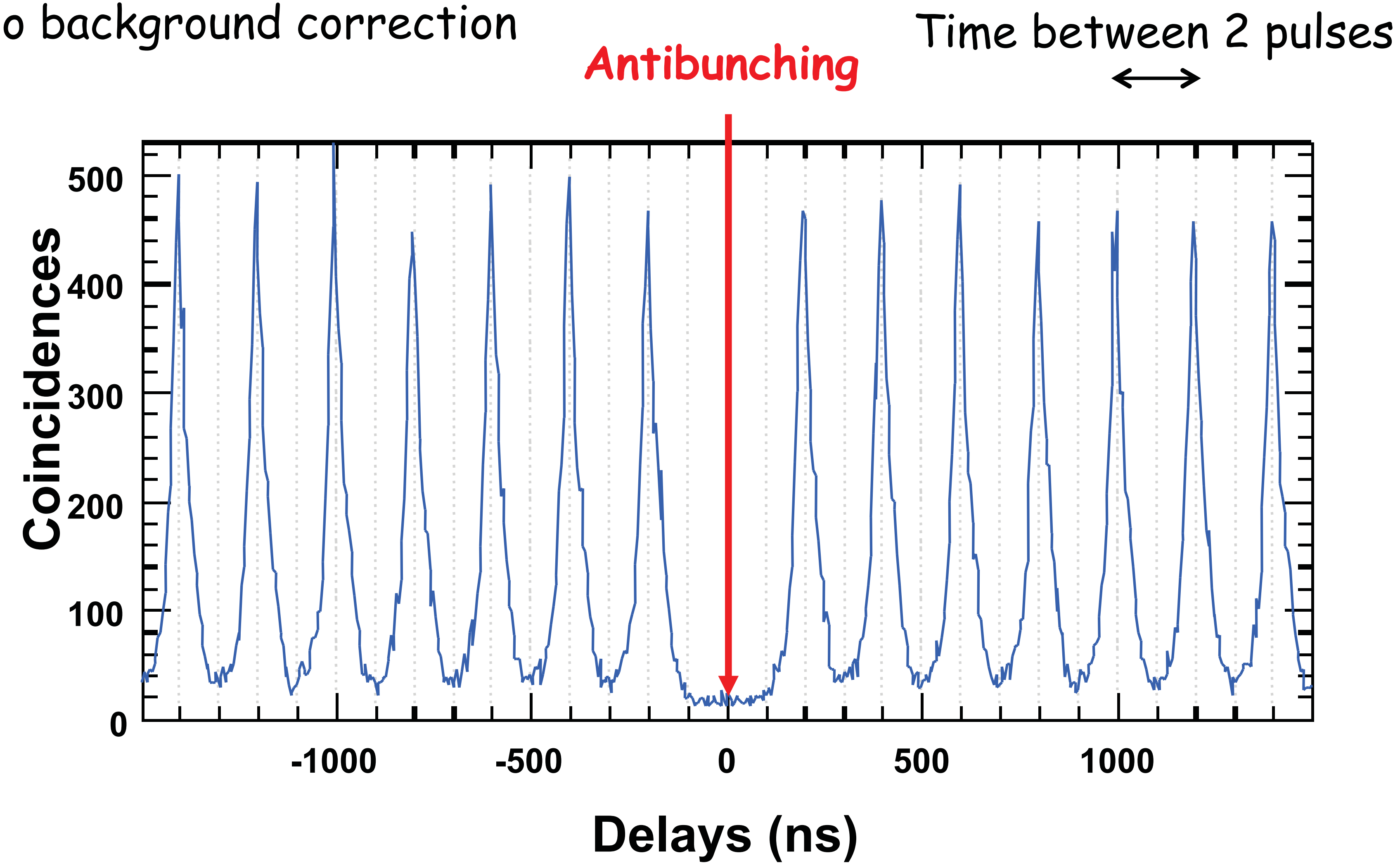
Antibunching : $g^{(2)}(0) < g^{(2)}(\tau)$

Anticorrelation : $g^{(2)}(0) < 1$
(related to sub-poissonian photon statistics)

ANTIBUNCHING : $g^{(2)}(0) < g^{(2)}(\tau)$

QIPC / S4P

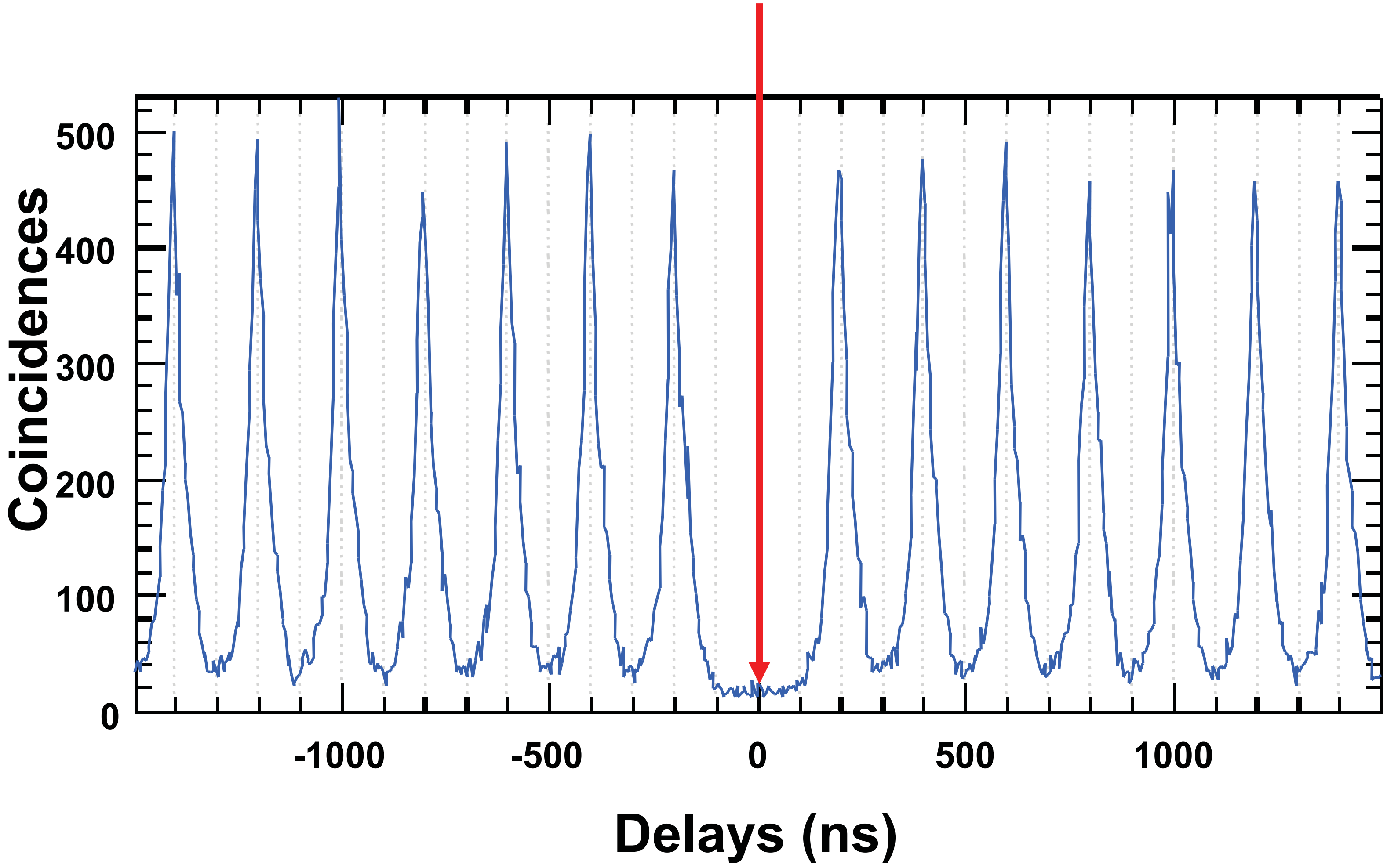
4 – hour acquisition (4×10^6 photons)
Resolution 1 ns, binning × 4
No background correction



ANTICORRELATION : $g^{(2)}(0) < 1$
(sub-poissonian photon statistics)

$C_N(0) = 2\ p(2)\ /\ p(1)^2 = 0.034 = 1/30$

$\Rightarrow$ Probability to emit 2 photons during a pulse, $p(2) = 0.018$



Part 2

Two-photon coalescence

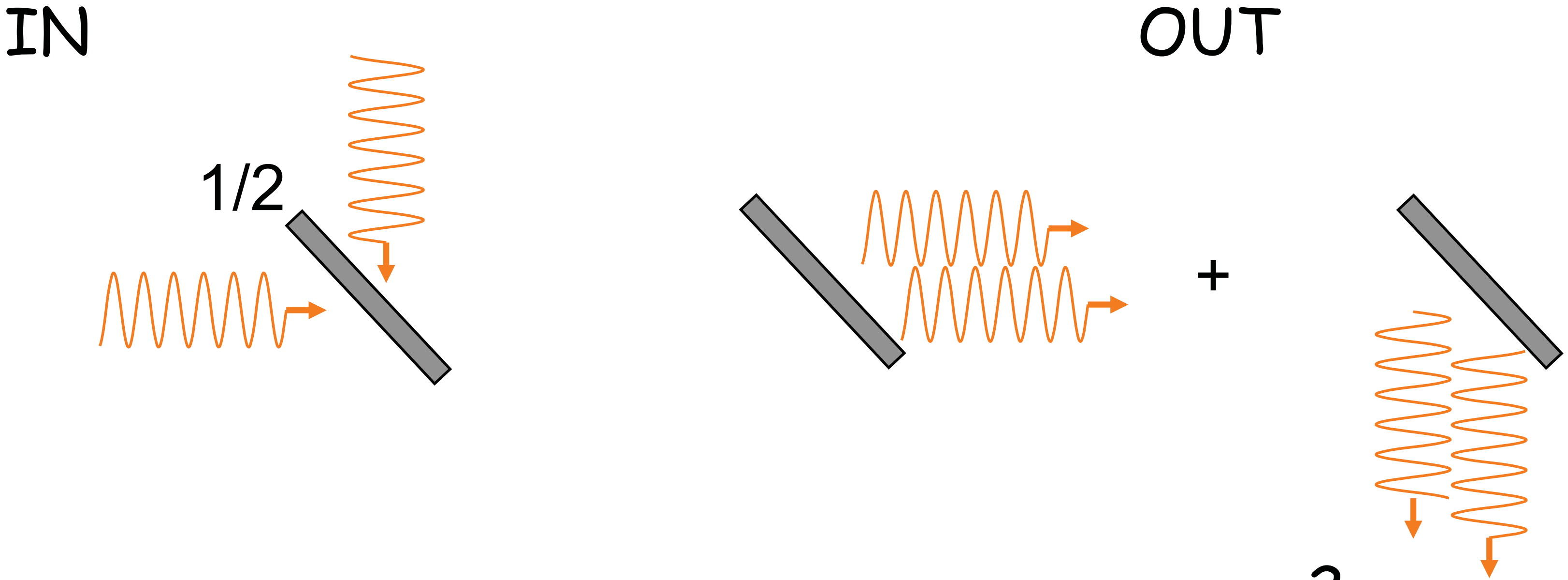
from two independantly trapped atoms

* direct demonstration that the photons are single-mode

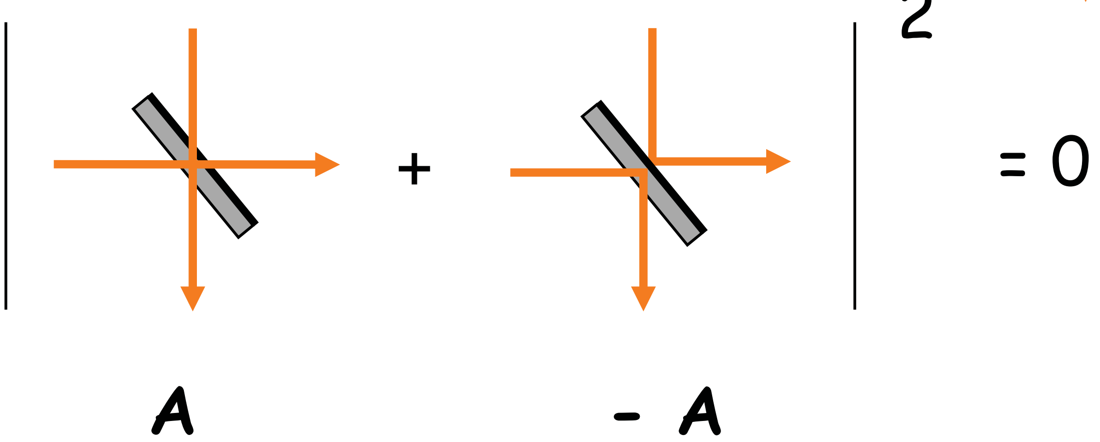
* essential step towards scalability of the KLM scheme

Two-photon interferences
(Hong-Ou-Mandel "HOM" effect)

Rb atoms are all the same -> Indistinguishable photons !

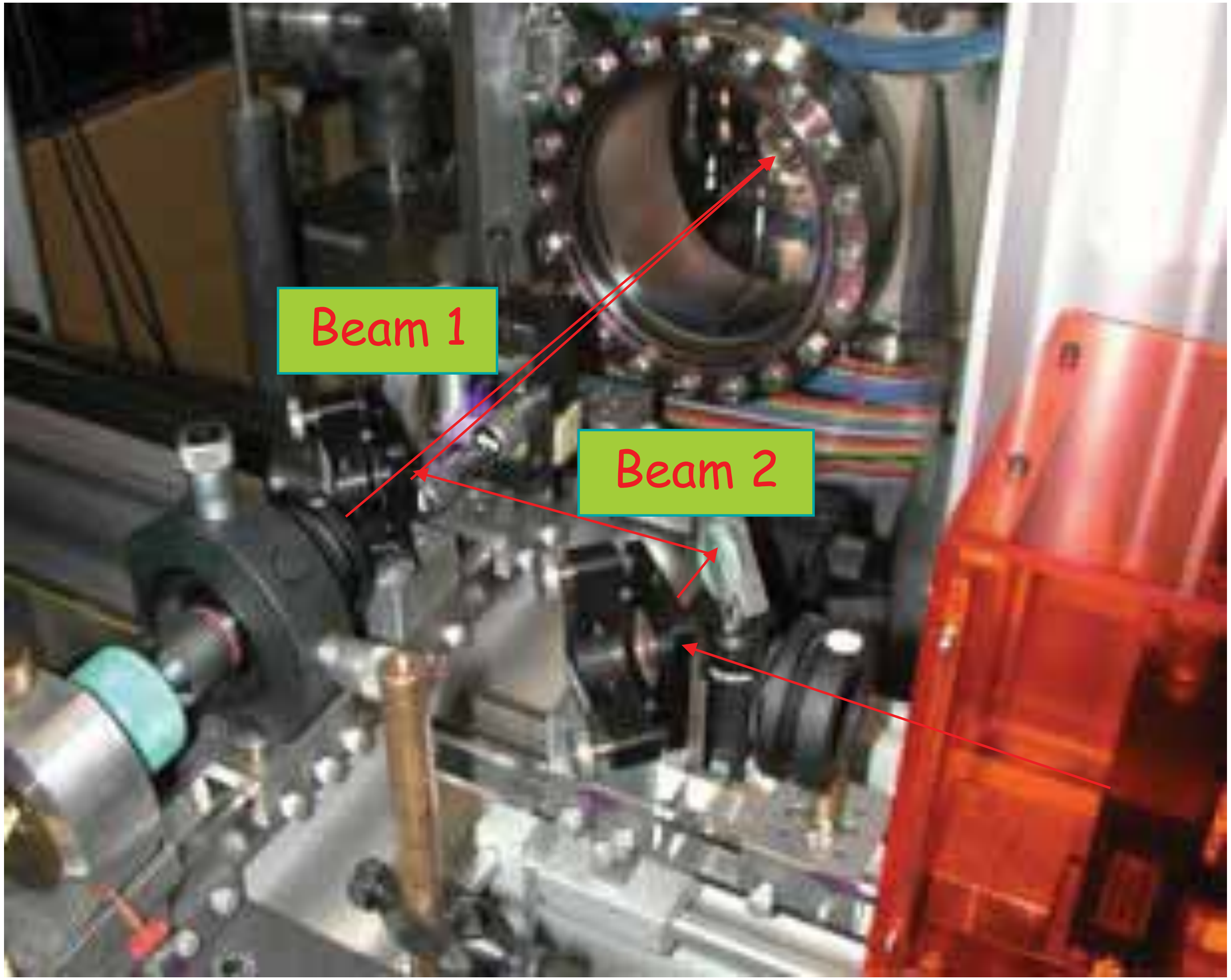


Destructive
interferences
"Coalescence"

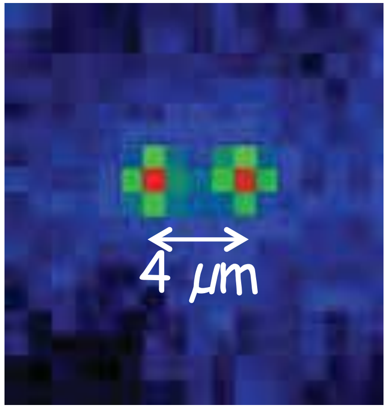


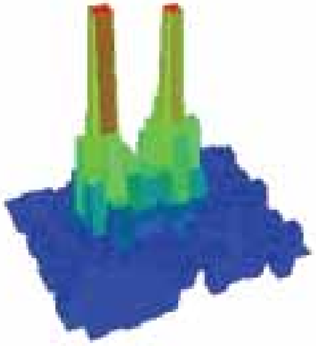
Two atoms at your fingertips

N. Schlosser et al, Nature 411, 1024 (2001)
PRL 89, 023005 (2002)

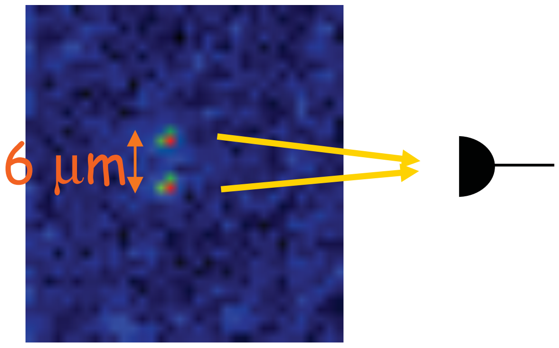


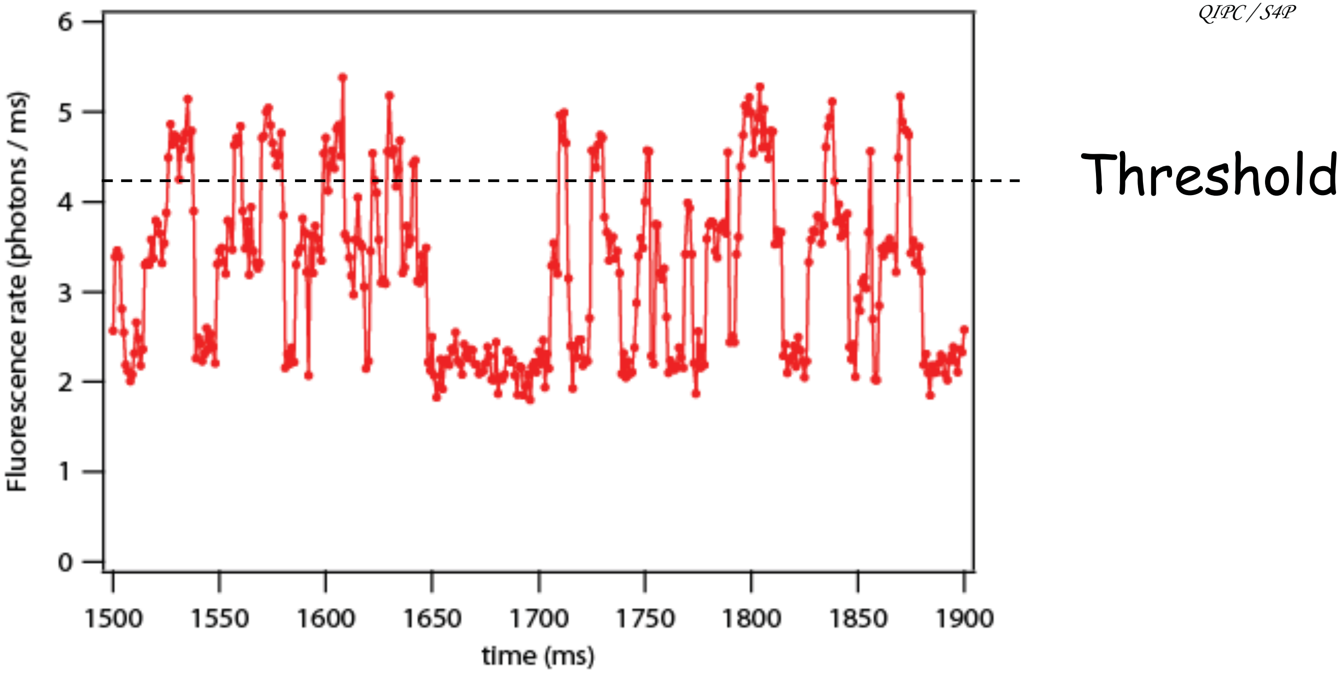
Resolution of the imaging system:
1 micron / pixel





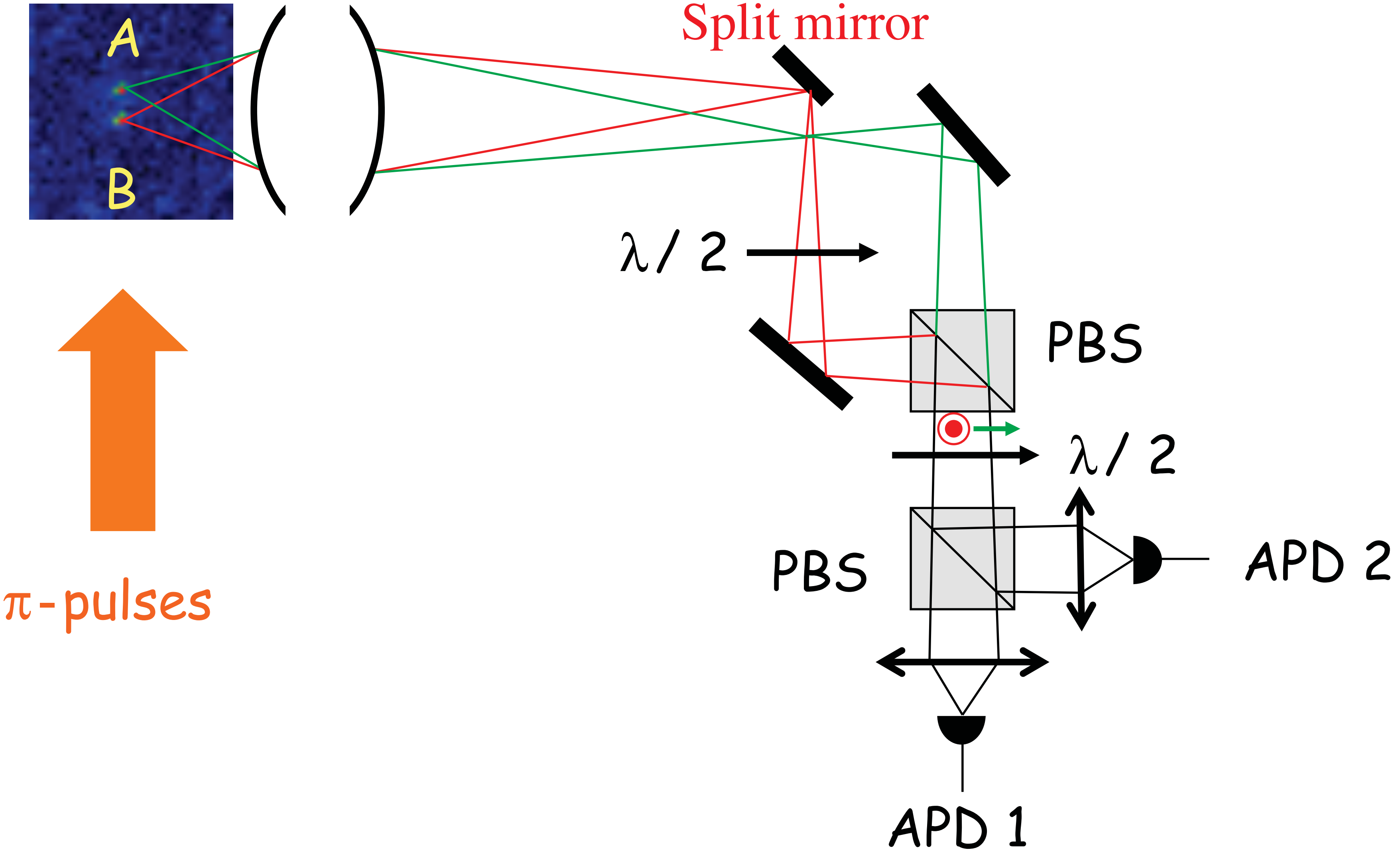
Repeatedly trapping 2 atoms





- Detect 2 atoms (signal above threshold)
- Launch 15 cycles containing 575 pulses (115 µs) followed by 885 µs cooling
- Release the remaining atom(s)
- Catch 2 atoms again (~ 300 ms) and loop

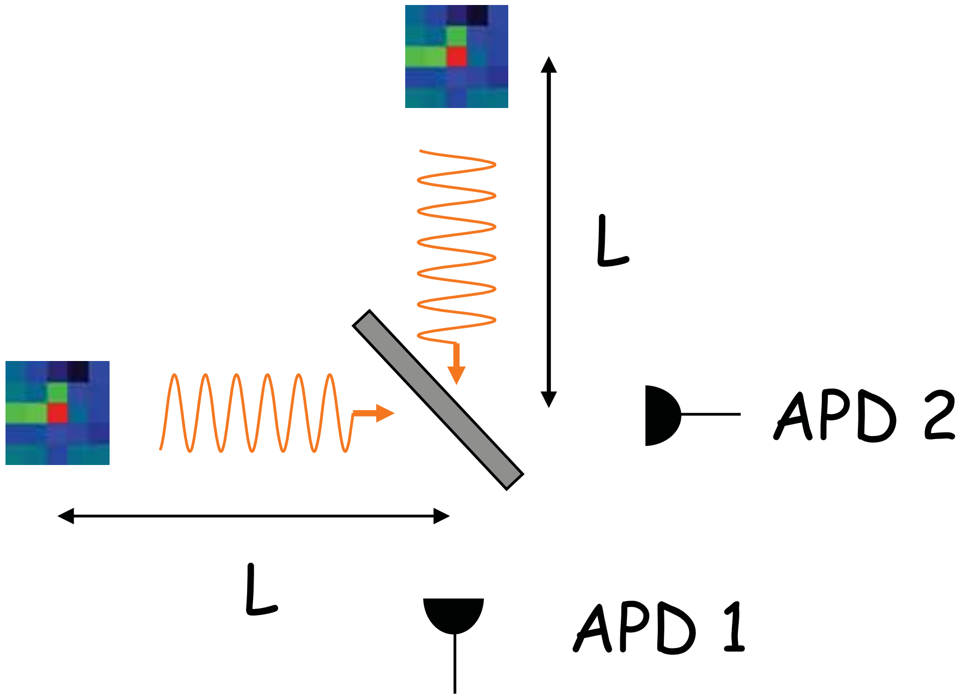
Experimental set-up

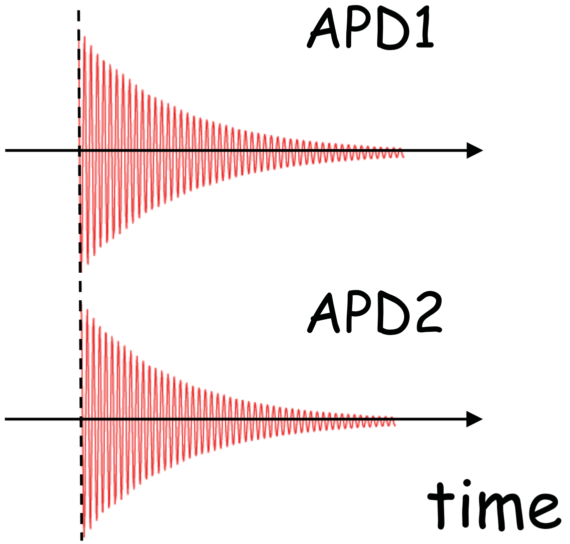


Time-domain matching

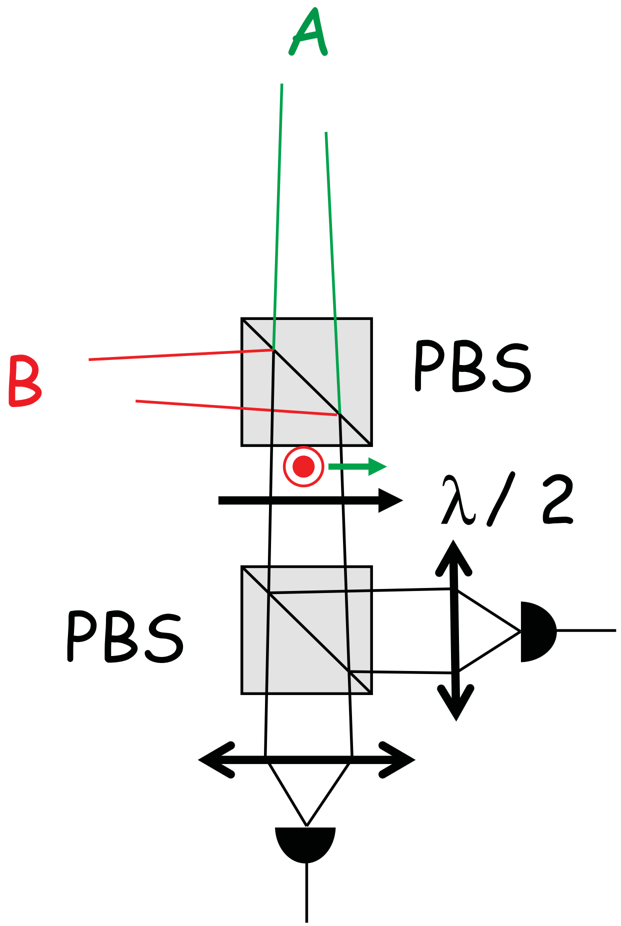
Exactly balanced optical paths

⇒ The two « photon wavepackets » (« 8 m long ») arrive simultaneously onto the detectors

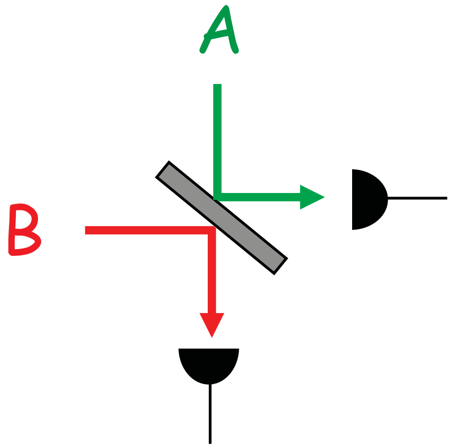




Separation vs recombination

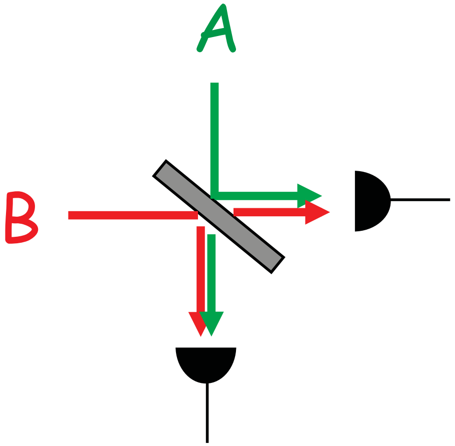


Axis $\lambda/2$ at 0° from pol. axis



Two-sided mirror : uncorrelated counts

Axis $\lambda/2$ at 22,5° of pol. axis

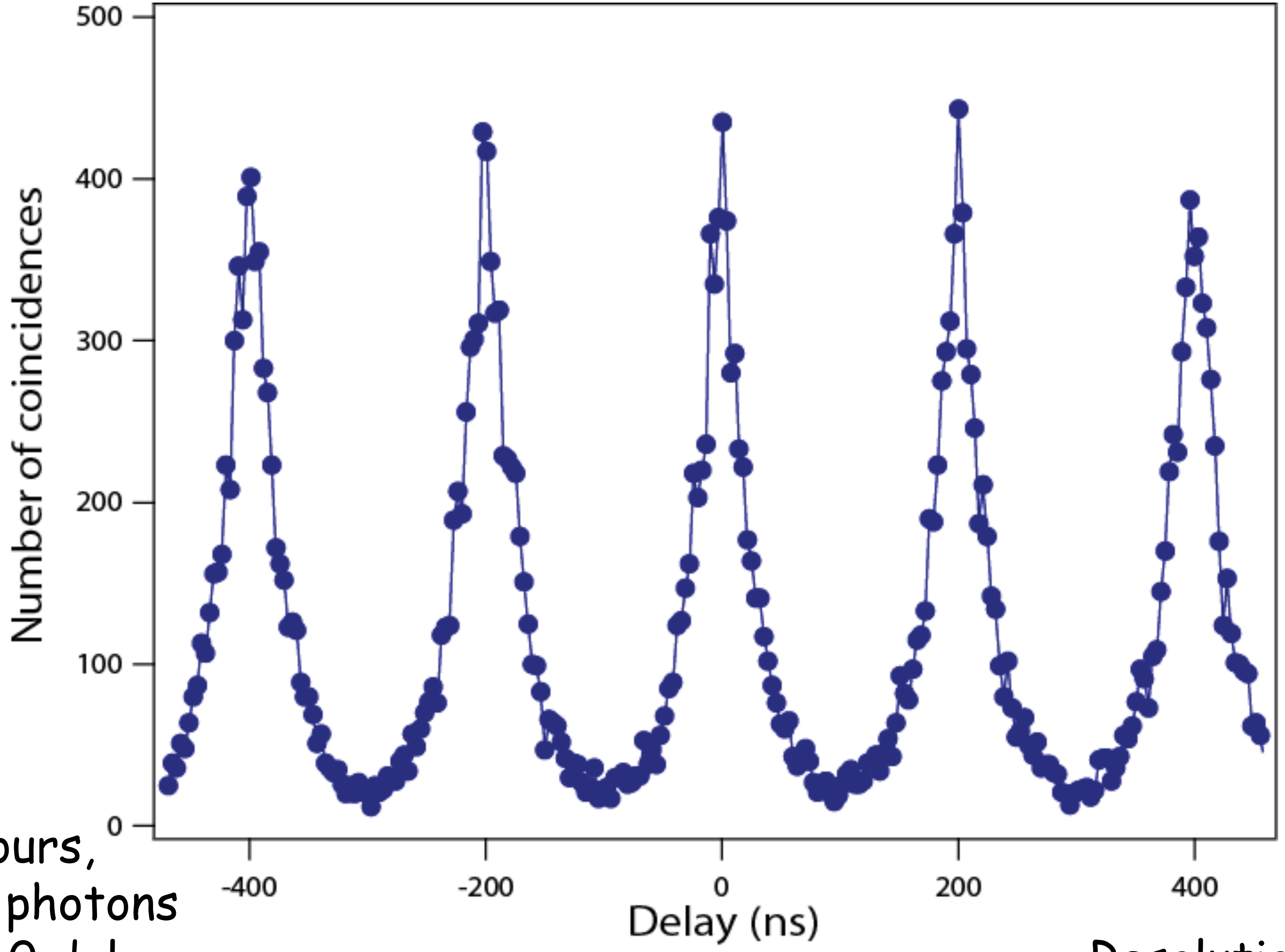


50-50 beamslitter : coalescence

Two-atoms coincidences counting

Calibration : « Distinguishable Photons »

QIPC / S4P



4 hours,
~ 3700 photons
around 0 delay

Resolution 3.6 ns

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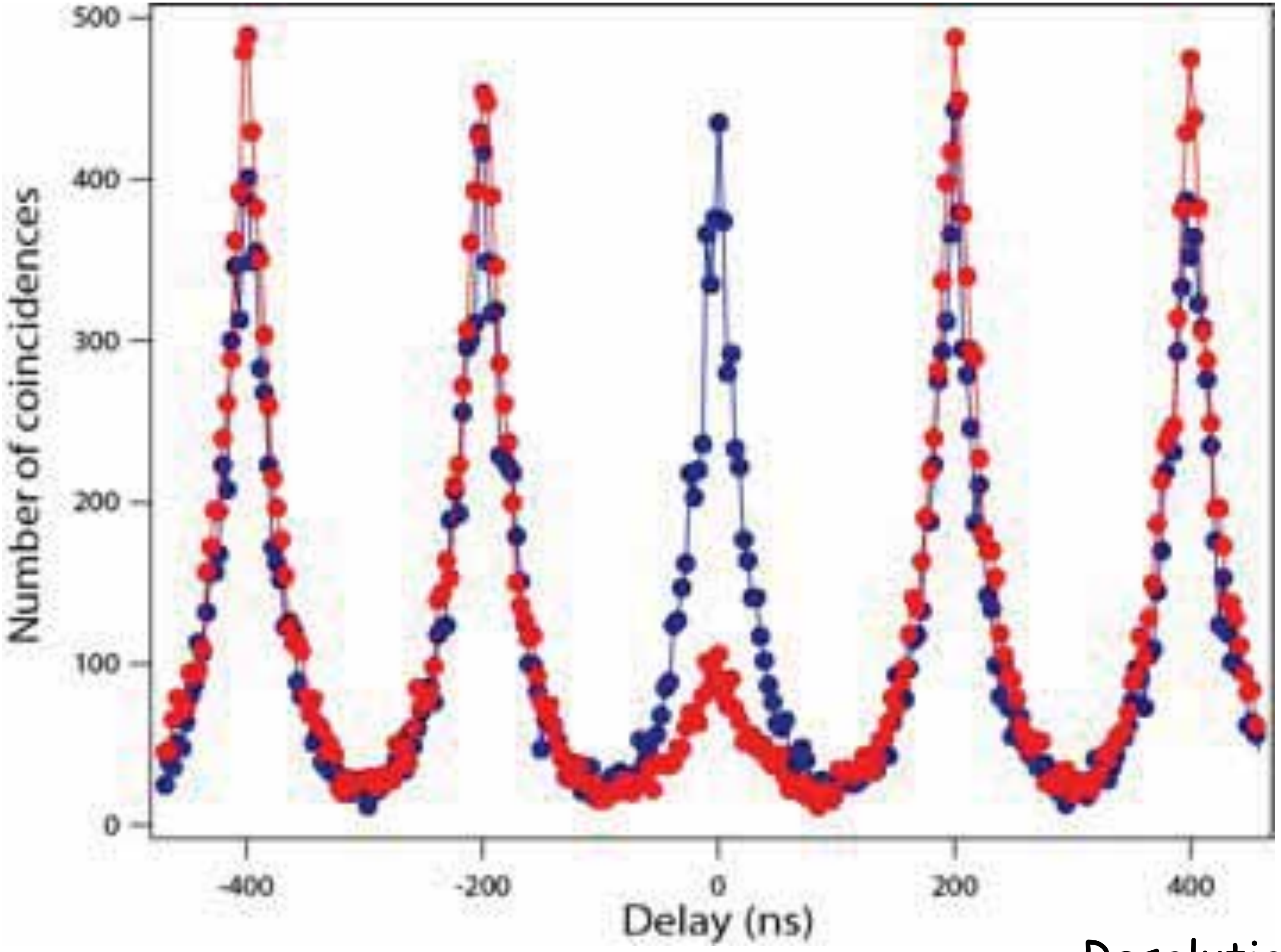
Coincidences counting

« Indistinguishable Photons »

CNRS CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE

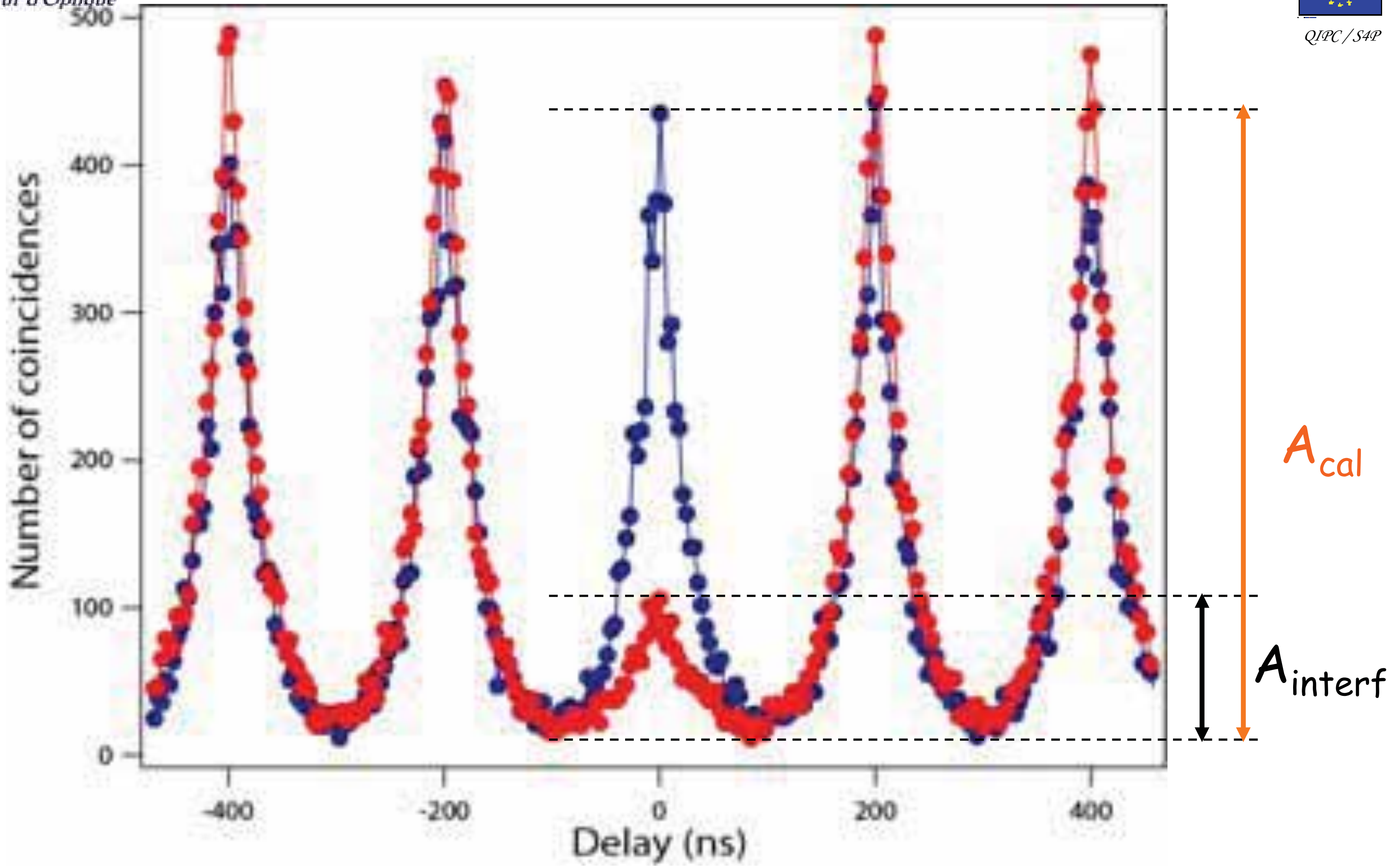
QIPC / S4P



Resolution 3.6 ns

Coincidences counting

QIPC / S4P



Ratio = $A_{interfering} / A_{calibration} = 0.19 \pm 0.02$

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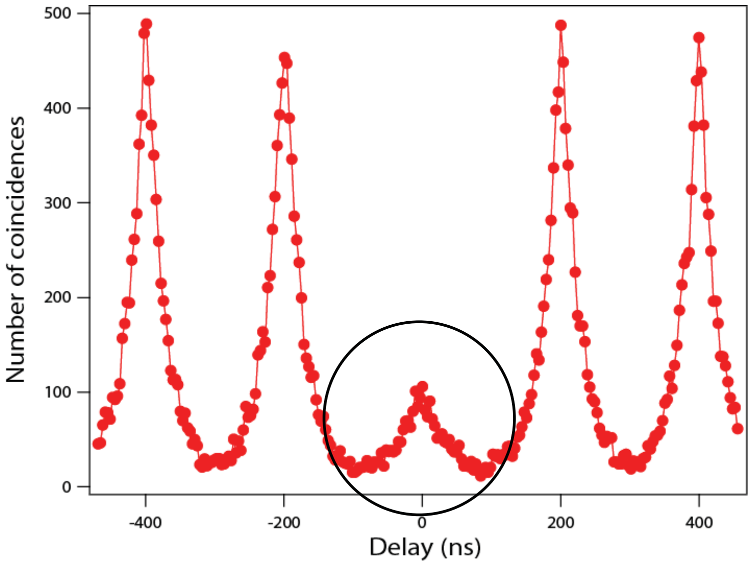
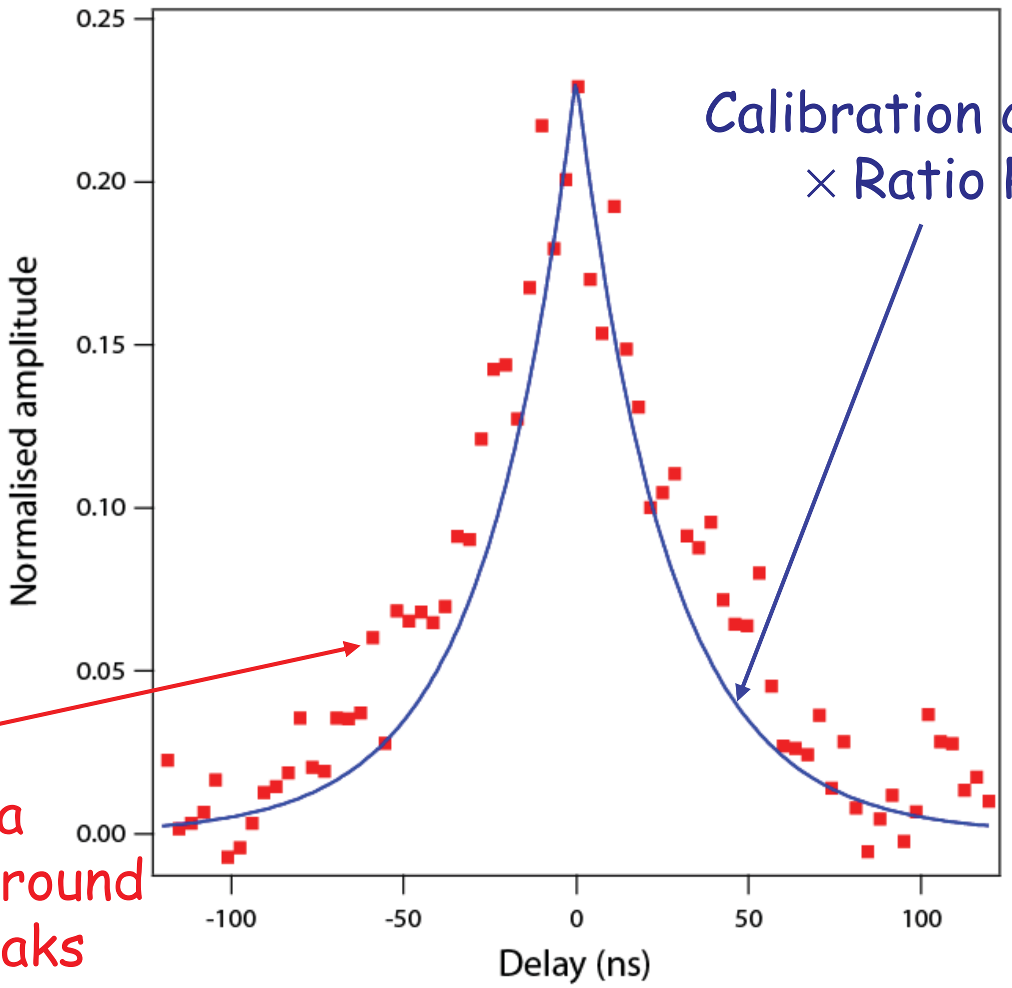
Shape of the peak around zero delay

QIPC / S4P



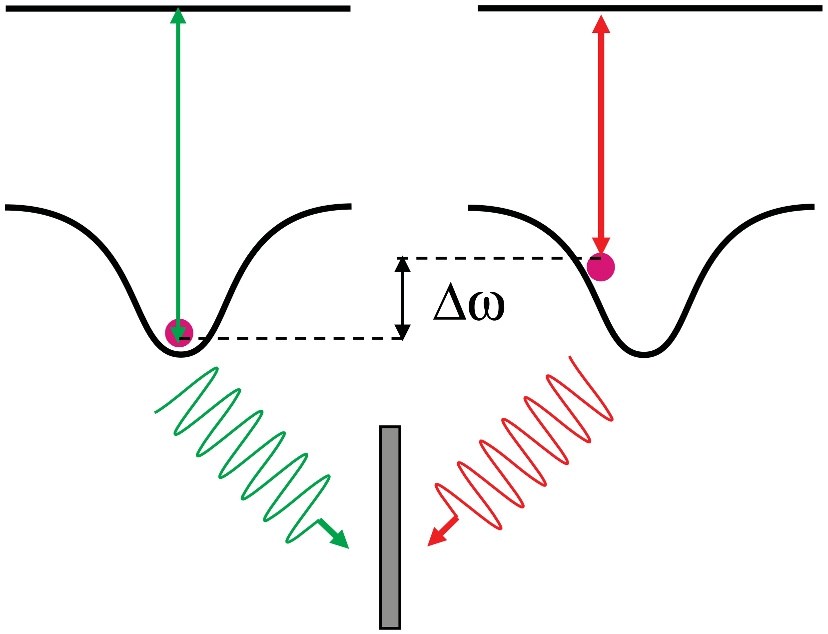


Calibration curve
× Ratio R

Experimental data
corrected from background
and neighbouring peaks

Taking into account the atoms ' motion

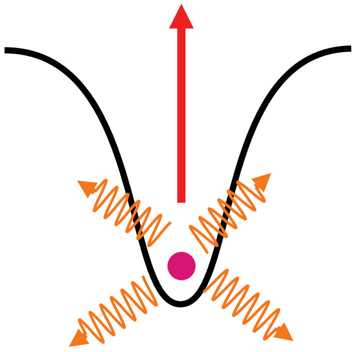
T = 60 μK

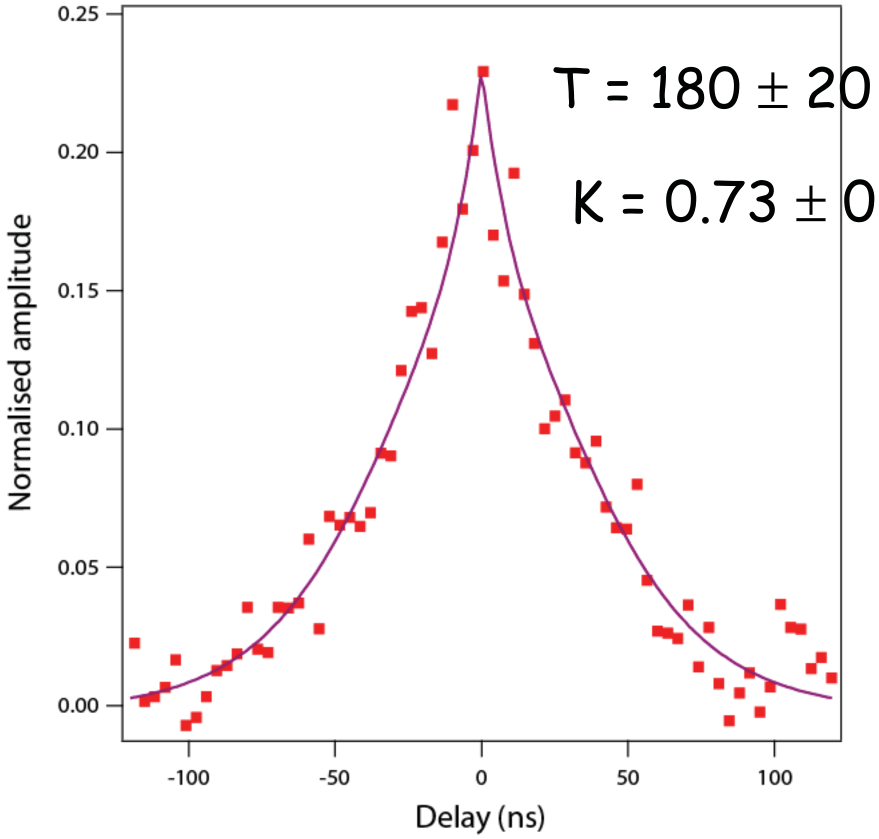


Beat note between the
two photons, frequency Δω

Averaged beat note over
the distribution of light-shifts
⇒ broadening

+ heating effect

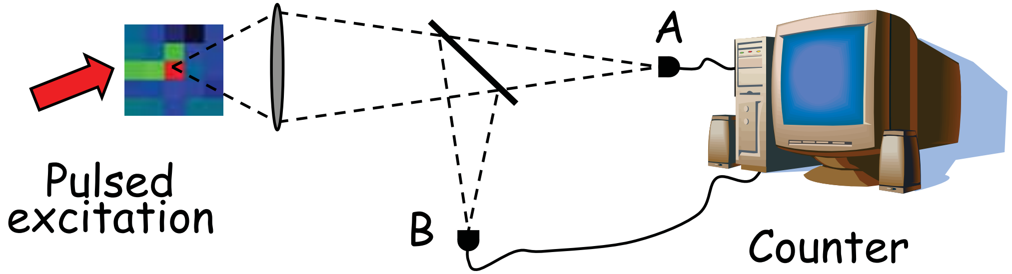




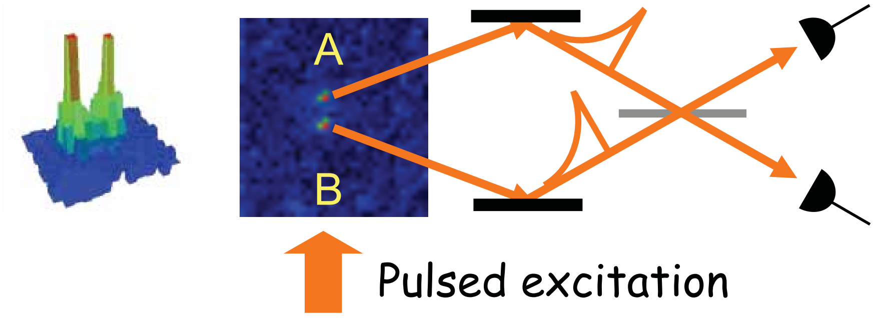
T = 180 ± 20 μK

K = 0.73 ± 0.02

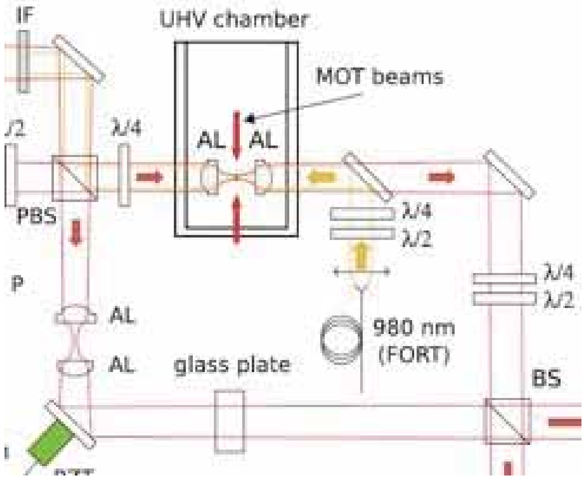
Experiments with single trapped atoms

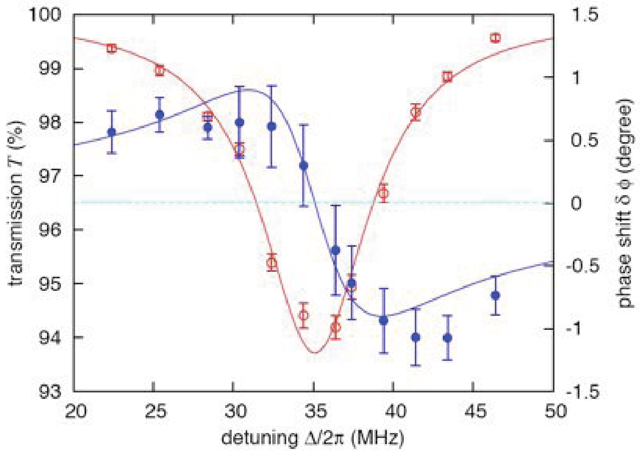


One single atom emits a transform-limited single photon
B. Darquié **et al**,
Science **309**, 454 (2005)



Two single atoms emit two indistinguishable single photons : « coalescence » on a beamsplitter
J. Beugnon **et al**,
Nature **440**, 776 (2006)





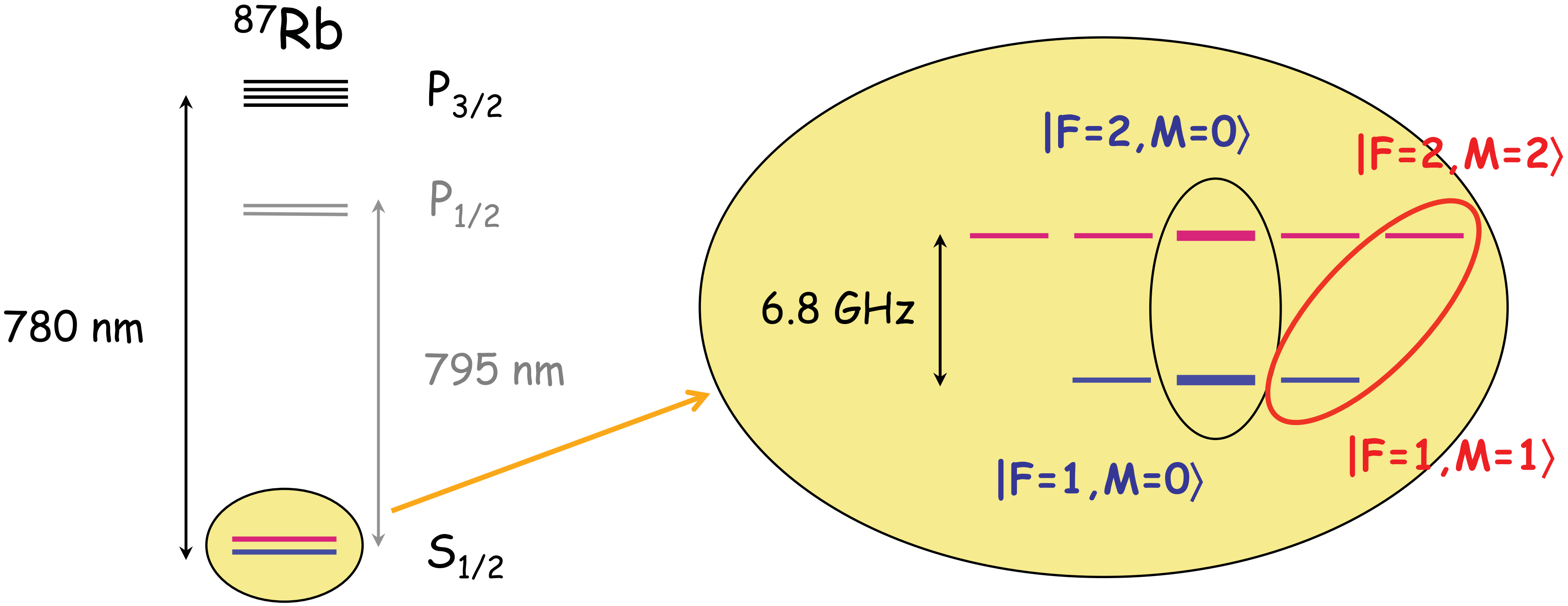
Absorption and dispersion from one single atom
C. Kurtsiefer et al,
arXiv:0905.3734v1
22 May 2009

Part 3

From single atoms to single qubits

The quantum bit

Choose a quantum two-state system with good coherence !



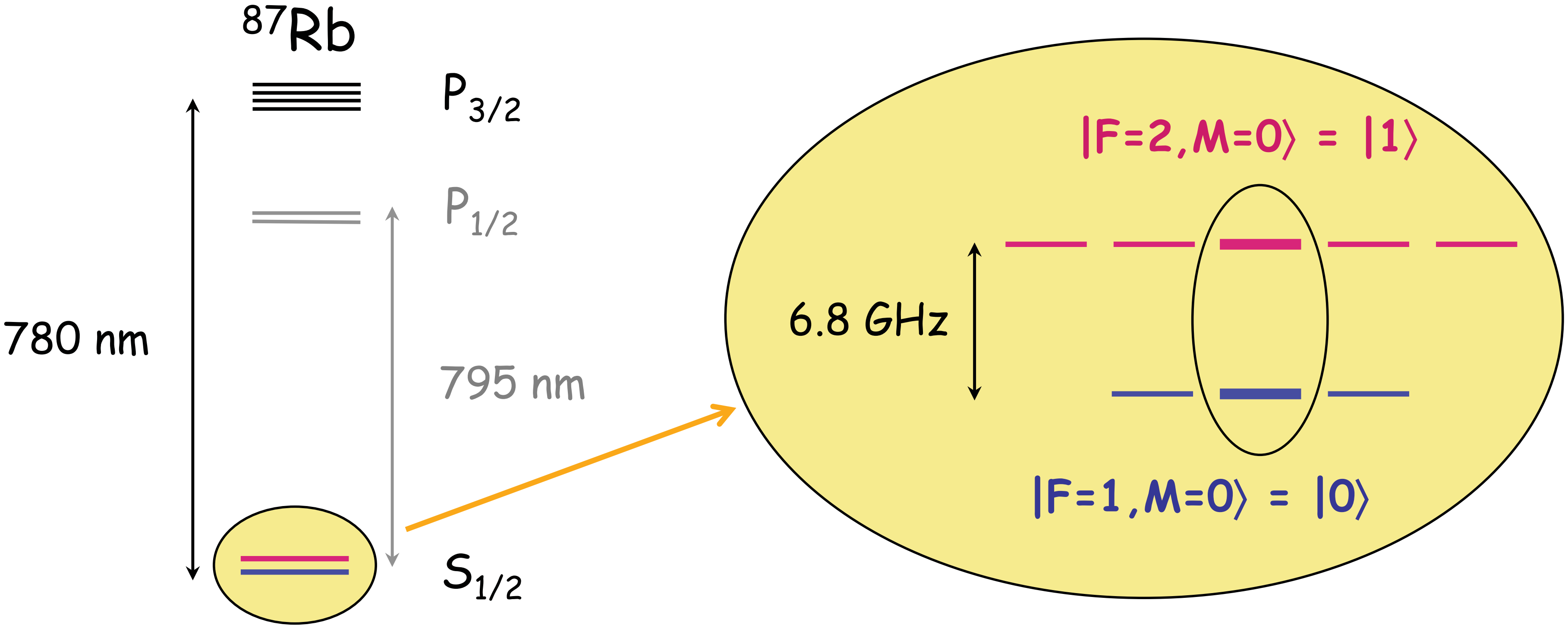
Various choices of M states are possible

0-0, B - insensitive (clock transition)

1-2, easy to prepare (stretched state)

The quantum bit

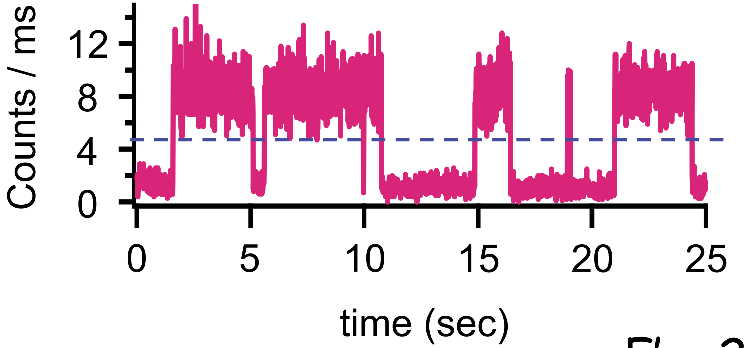
Choose a quantum two-state system with good coherence !

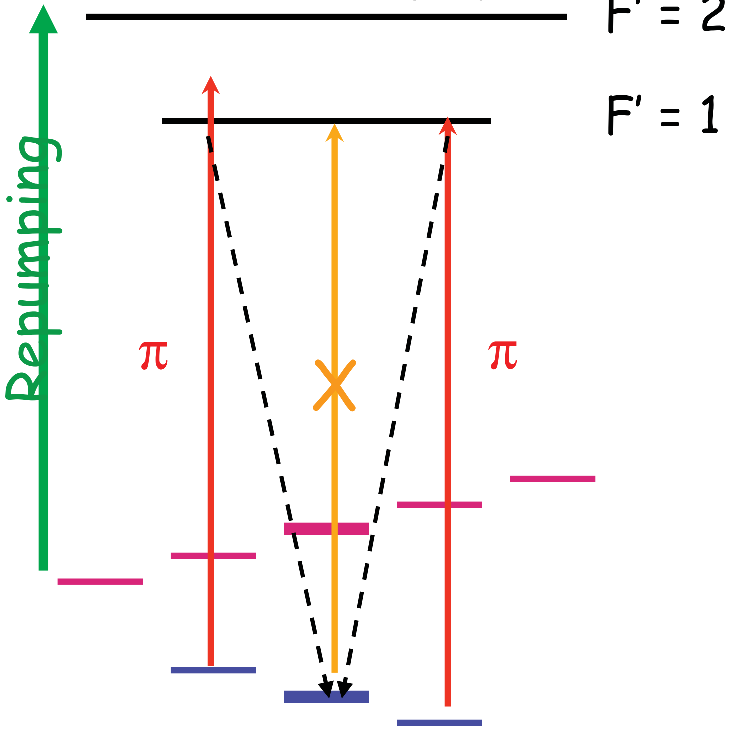


Various choices of M states are possible
Preferred choice : 0-0, B - insensitive
(clock transition)

The toolbox: initialization and readout of the qubit

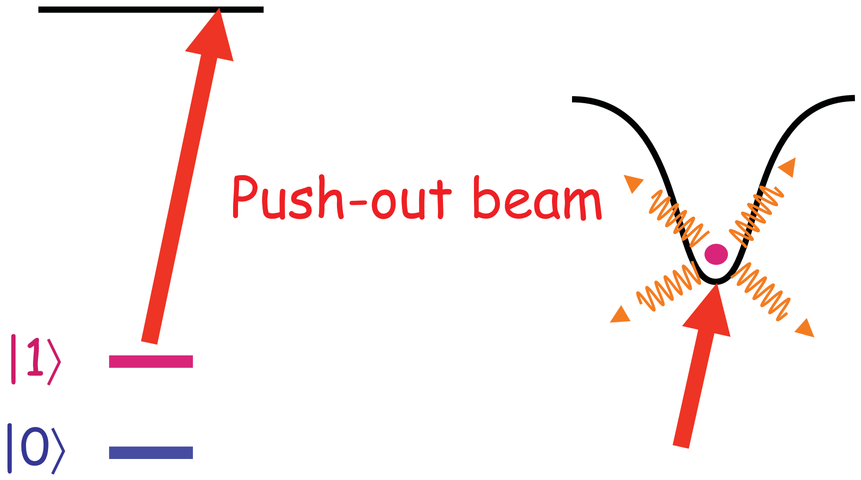
Detection + Initialization





Efficiency: 85% in |0⟩

State-selective detection



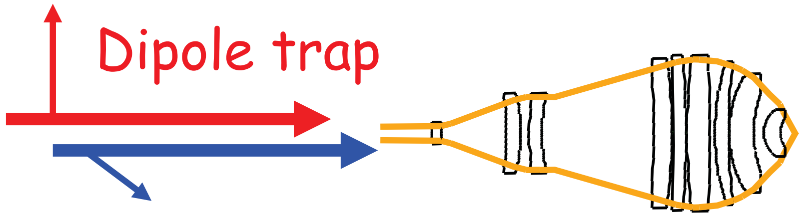
Check for the presence of the atom

No atom ⇒ |1⟩
Atom ⇒ |0⟩

98% efficiency, quantum projection noise limited

Single qubit rotation

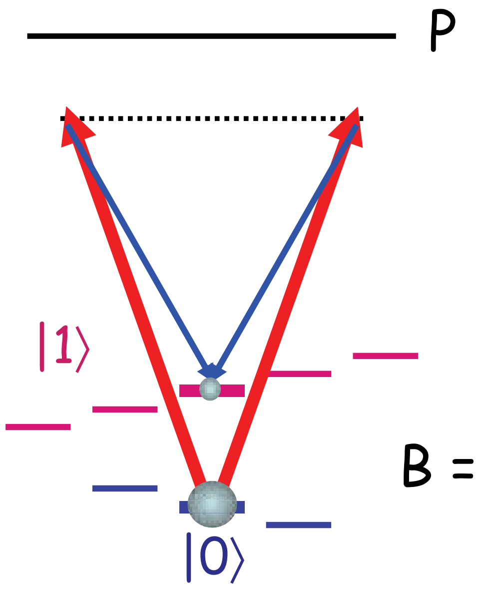
810 nm



Dipole trap

Raman transitions

(2 phase-locked laser diodes

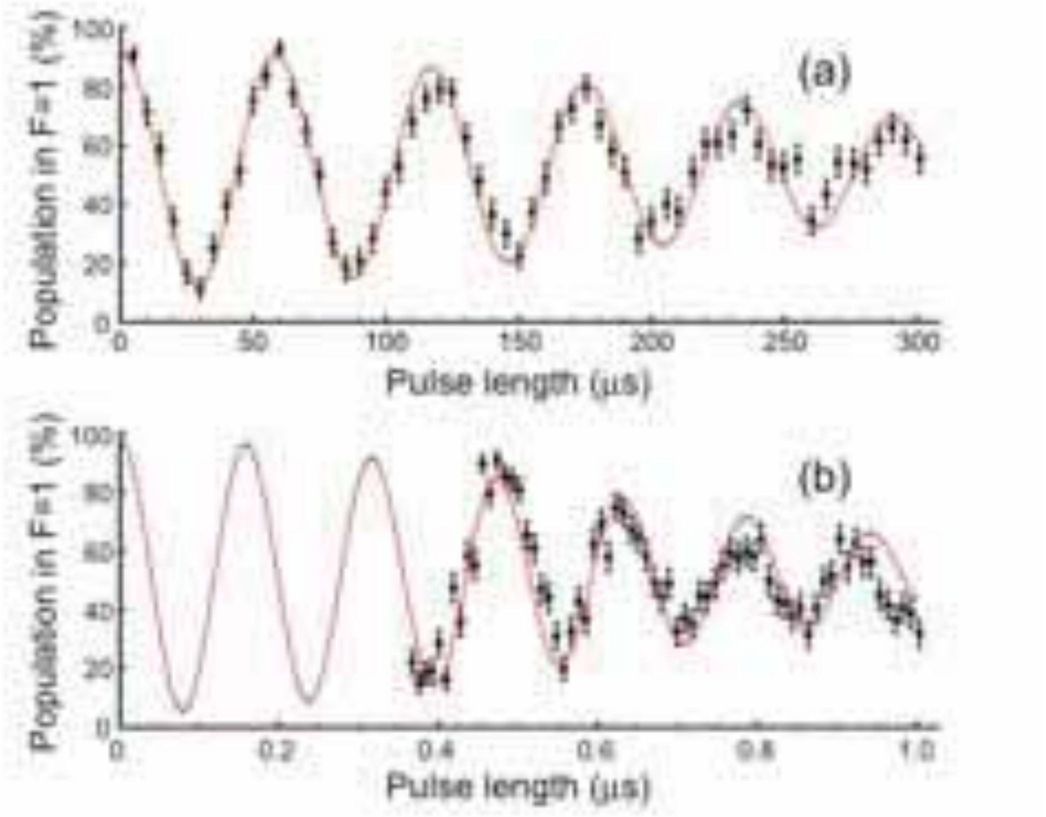


B = 3.6 G

Prepare $|\Psi\rangle = \cos\theta\,|0\rangle + \sin\theta\,|1\rangle$

Average ~ 200 times

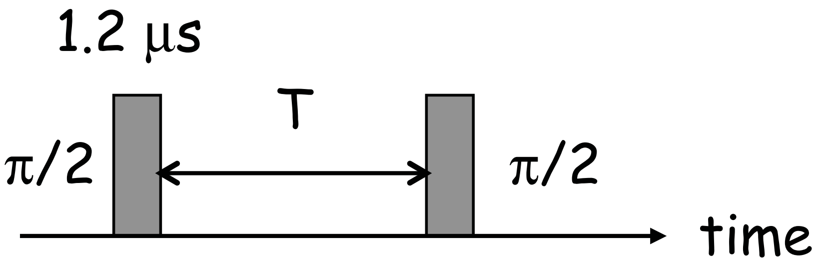
Low intensity: $\pi/2$ pulse in 13 μs

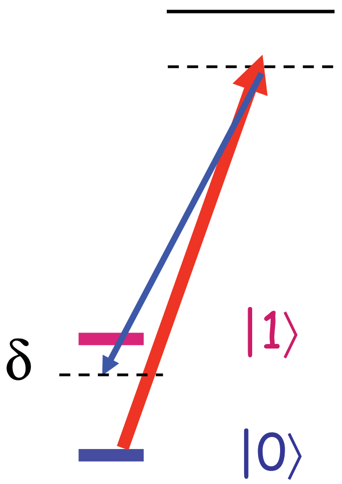


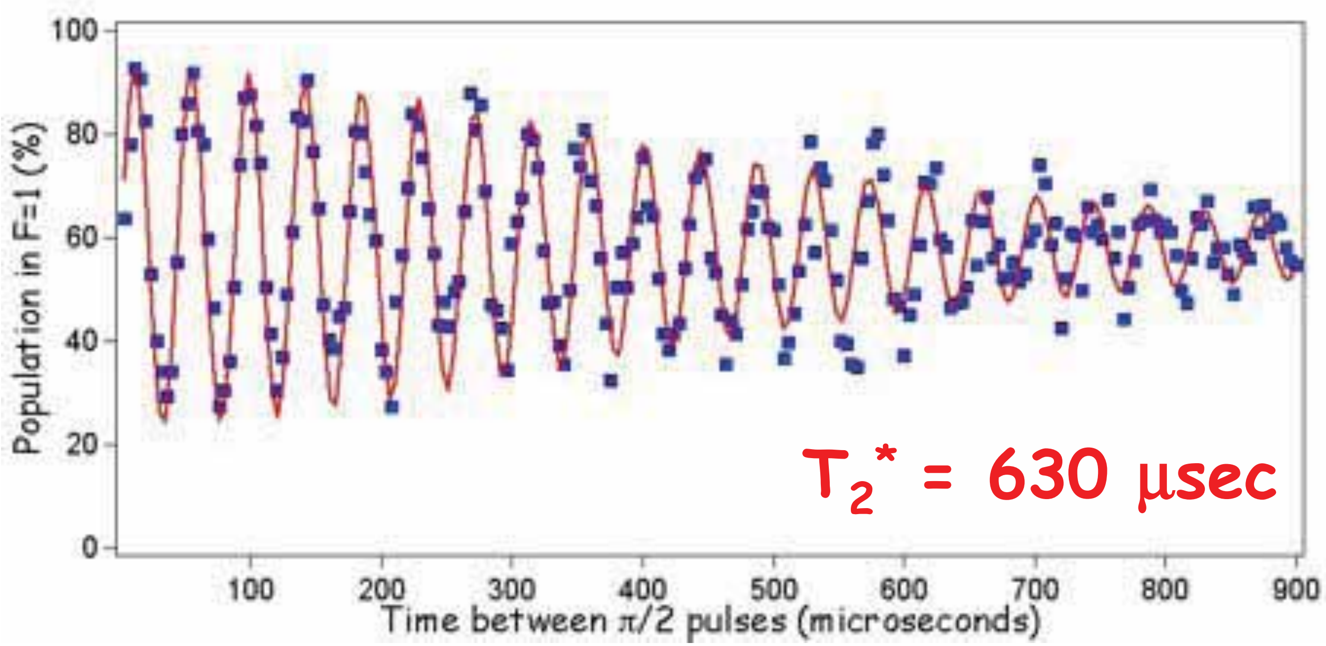
High intensity: $\pi/2$ pulse in 37 ns

Coherence of the qubit: Ramsey spectroscopy

How stable is φ in $\cos\theta\,|0\rangle + \sin\theta\, e^{i\varphi}\,|1\rangle$?



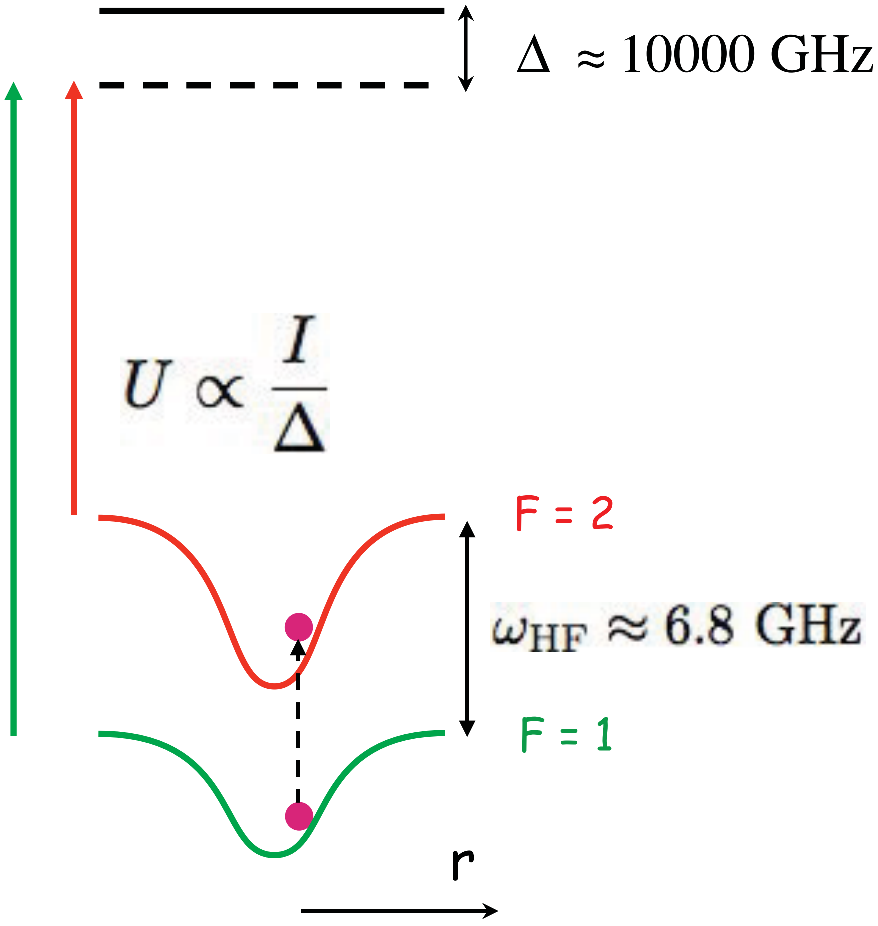




$T_2^* = 630\ \mu\text{sec}$

Decay : limited by residual motion of the atom in the trap

Decay of the Ramsey fringes: coupling external/internal



Differential light shift

$$\propto \frac{\omega_{\mathrm{HF}}}{\Delta} U(r(t))$$

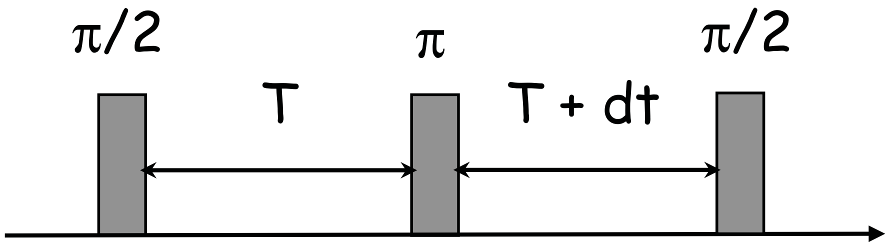
$$\eta = \frac{\omega_{\mathrm{HF}}}{\Delta} \approx 7 \times 10^{-4}$$

Averaged over the motion
of the atom during the pulse
+
Different energy from
one atom to another (thermal)

$$\Delta\omega \sim \eta \frac{k_{\mathrm{B}}T}{\hbar} \sim 700\mathrm{Hz}$$

⇒ « dephasing » : ok

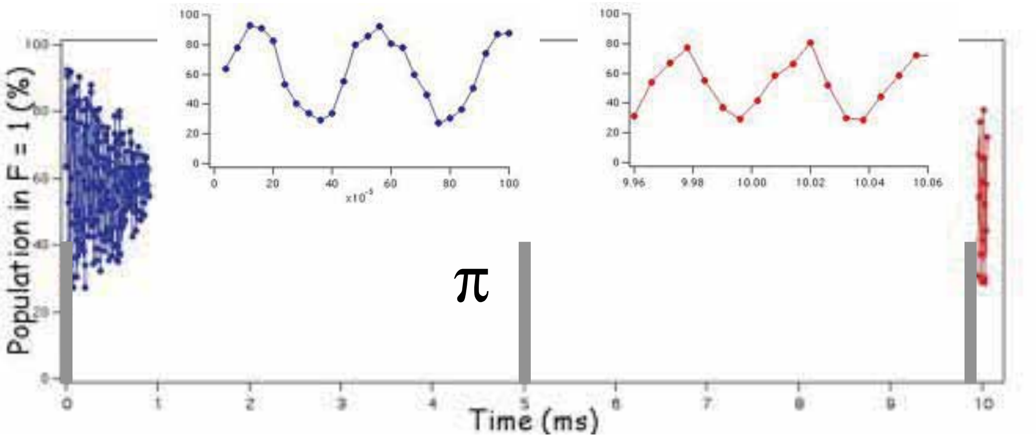
Reversible dephasing: spin echo



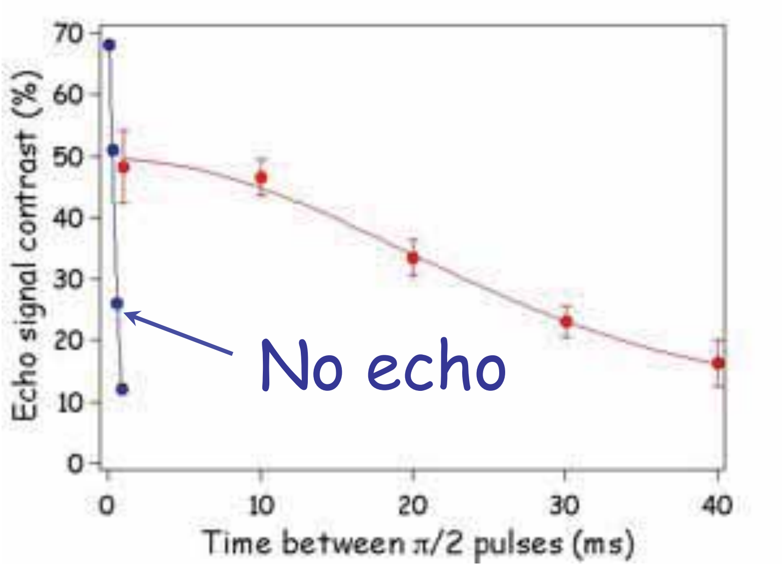
π pulse:

$|0\rangle \rightarrow |1\rangle$

$|1\rangle \rightarrow -|0\rangle$



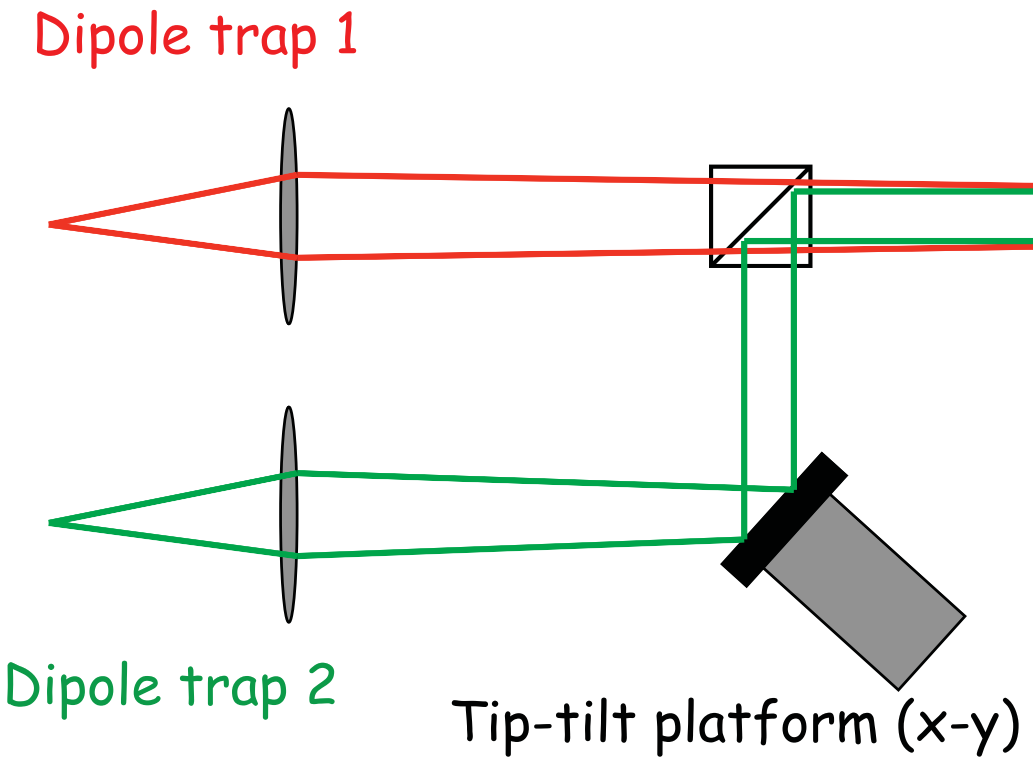
We can « rephase » the atoms after ~ **40 ms** = **70 x coherence time**



Irreversible decoherence time (40 ms) = $10^6 \times$ the $\pi/2$ Rabi flopping time (40 ns)

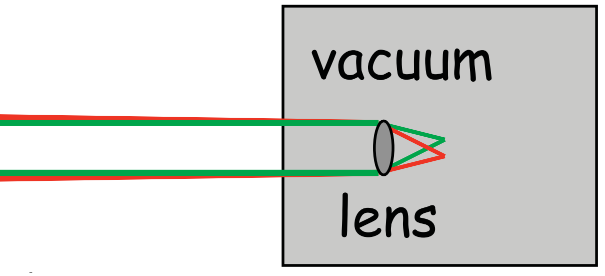
M.P.A. Jones **et al.**, PRA **75**, 040301 (2007)

Moving the qubits

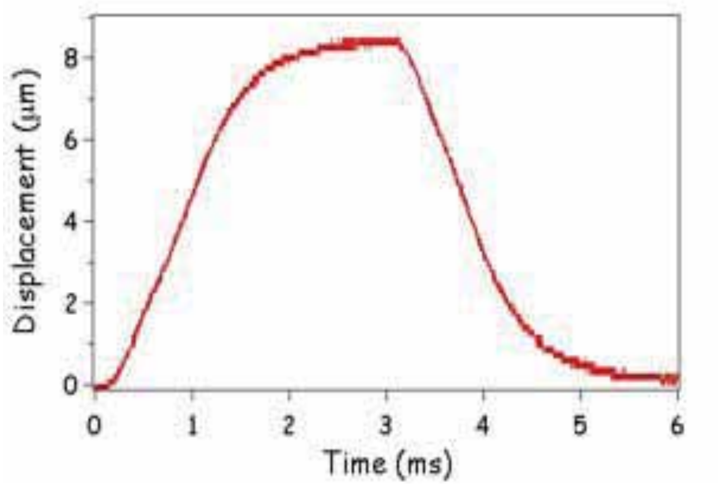

Dipole trap 1

Dipole trap 2

Tip-tilt platform (x-y)


vacuum

lens



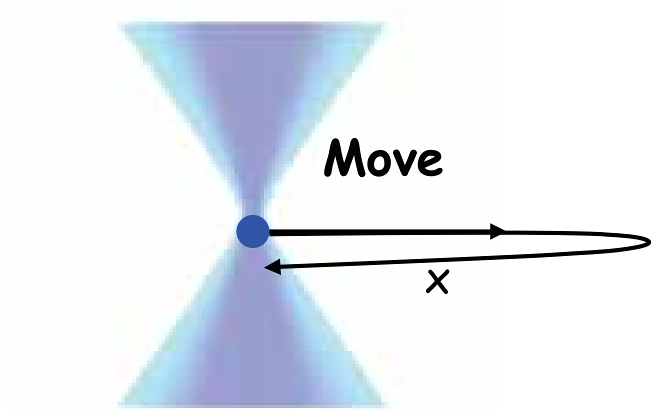
- Scale of the motion :

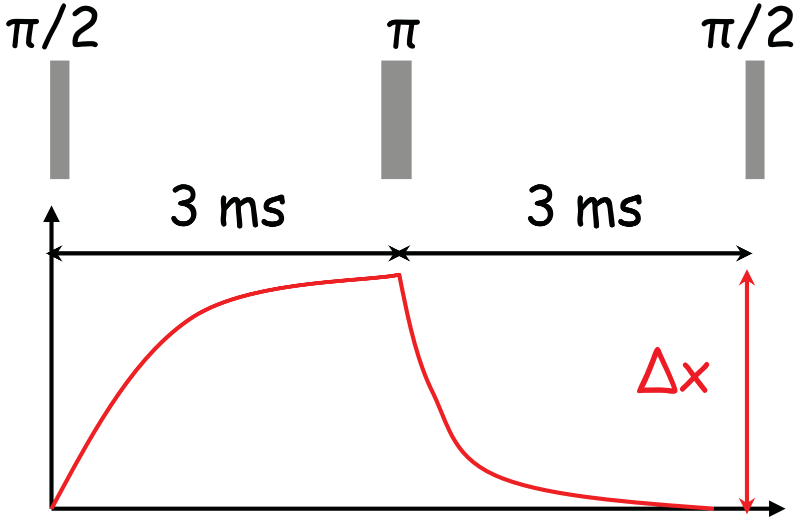
  a few µm in a few ms
- OK for a quantum register

  (coherence time : tens of ms)

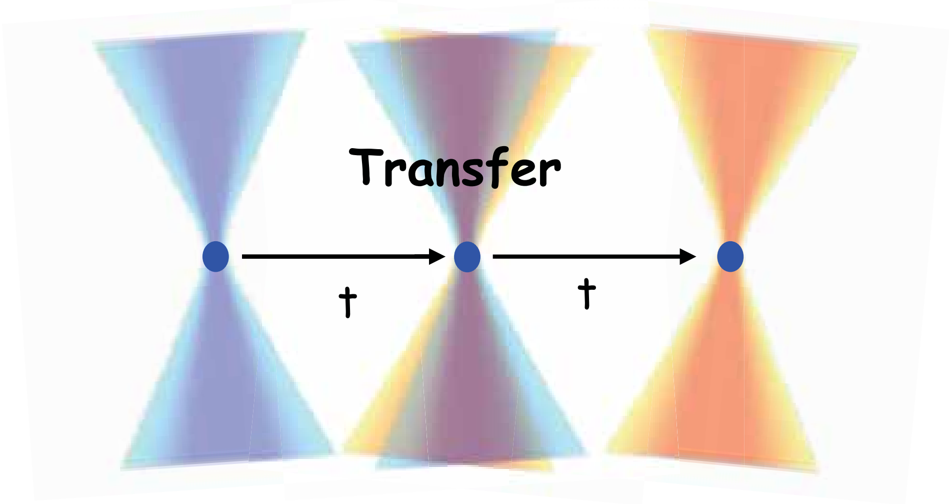
Motion and transfer of single qubits

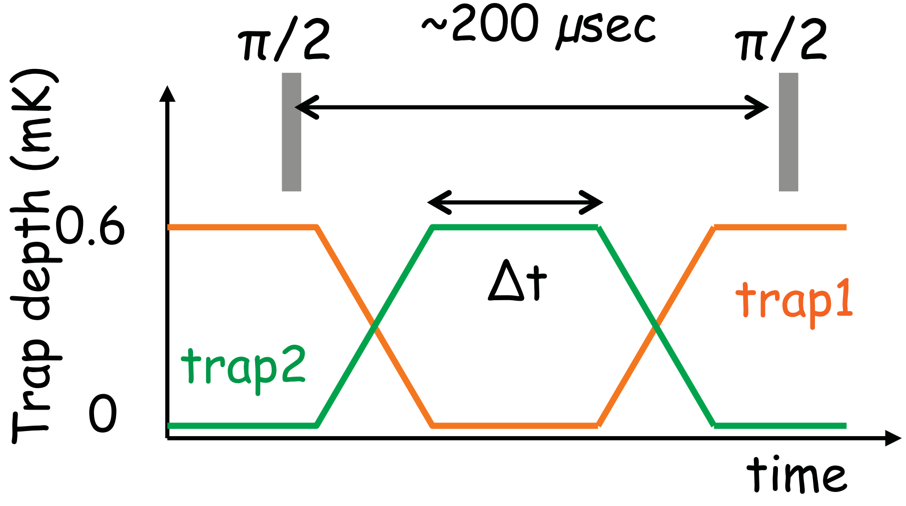
J. Beugnon et al,
Nature Physics **3**, 696 (2007)



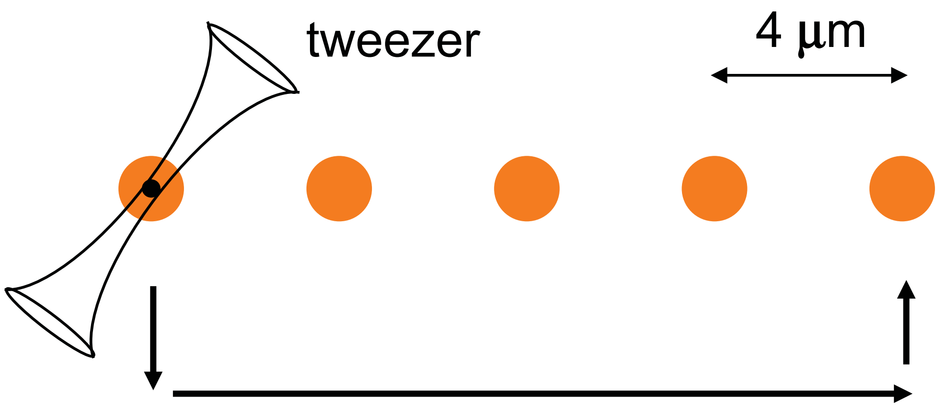


No loss; no heating on motion, little heating on transfer; **no qubit decoherence : OK !**





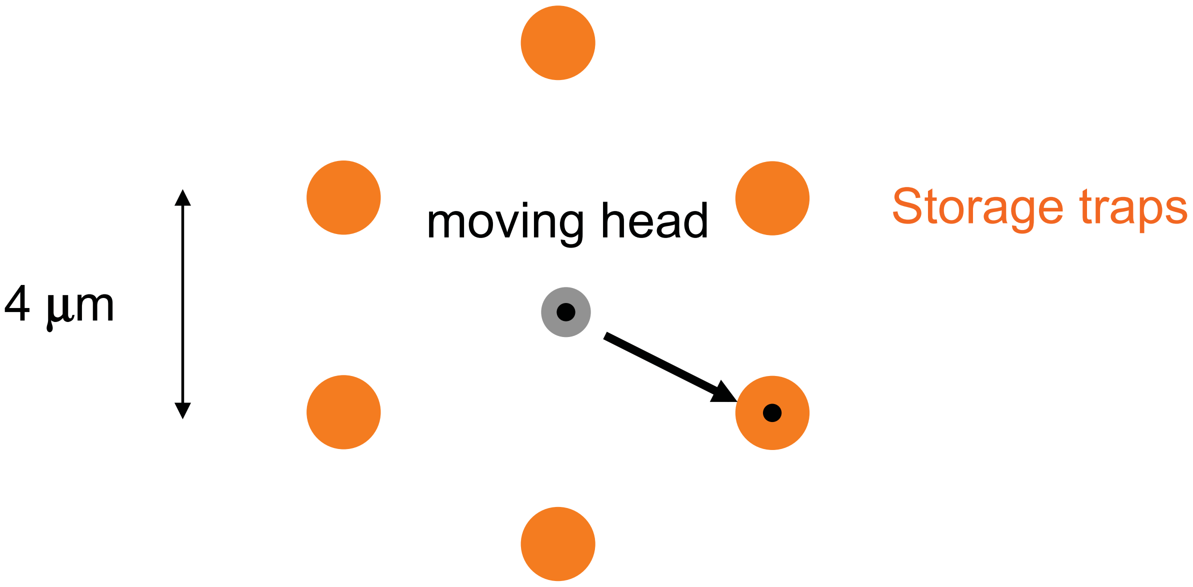
Looking to the future : "quantum register"



tweezer

4 µm

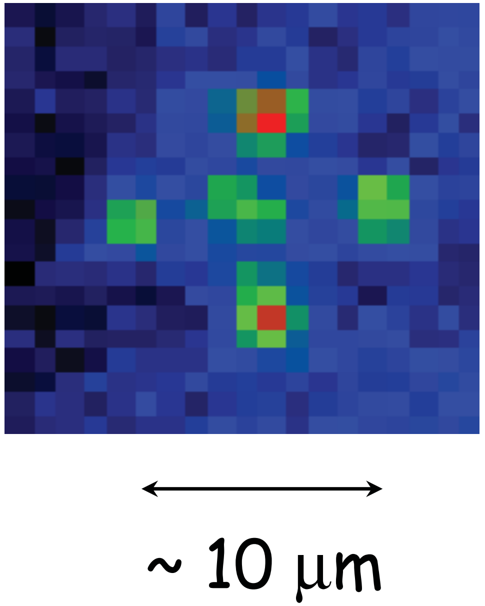
« data bus »



moving head

Storage traps

4 µm



~ 10 µm

Moving head in a quantum register ?
Requires entanglement !

Thank you for your attention…

(and see you tomorrow !)