Quantum interference between two single photons emitted by two single trapped atoms

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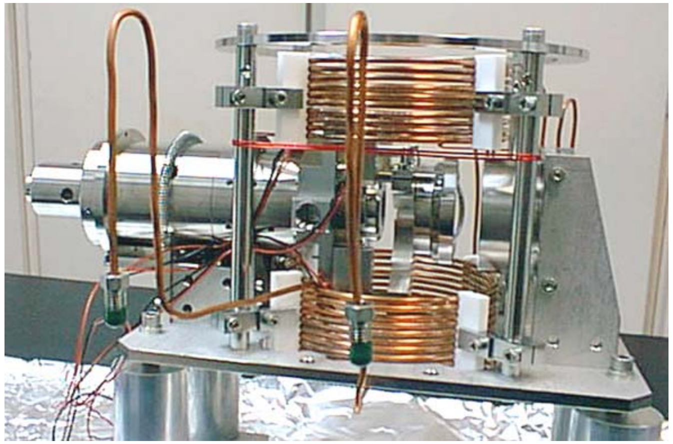
TRAPPING A SINGLE ATOM IN A DIPOLE TRAP

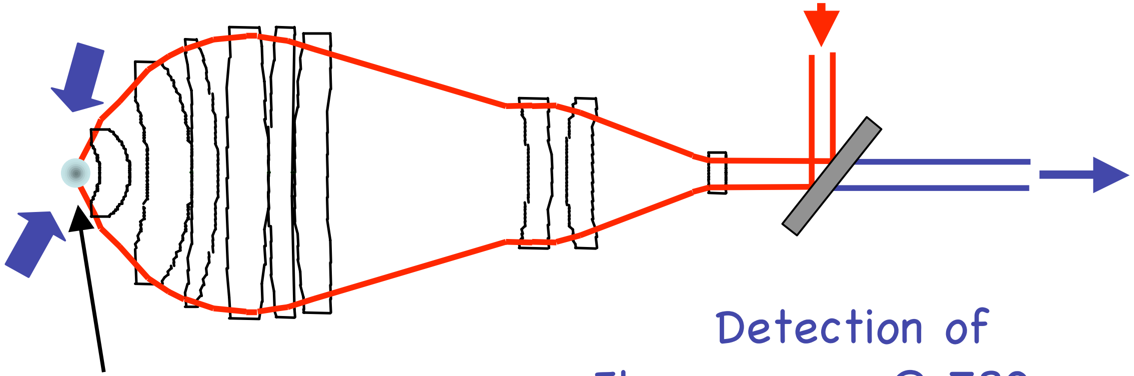
Schlosser *et al.*, *Nature* **411**, 1024 (2001)

TRAPPING SINGLE ATOMS IN AN OPTICAL TWEEZERS



NA = 0.7

w = 0.8 μm

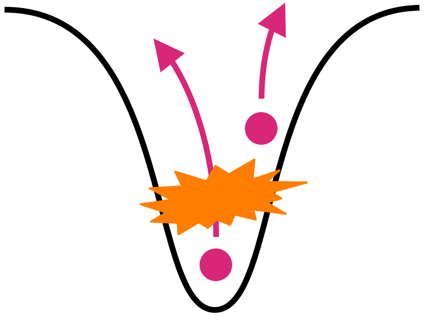


810 nm

Cloud of cold
Rb atoms (≈ 100 μK)

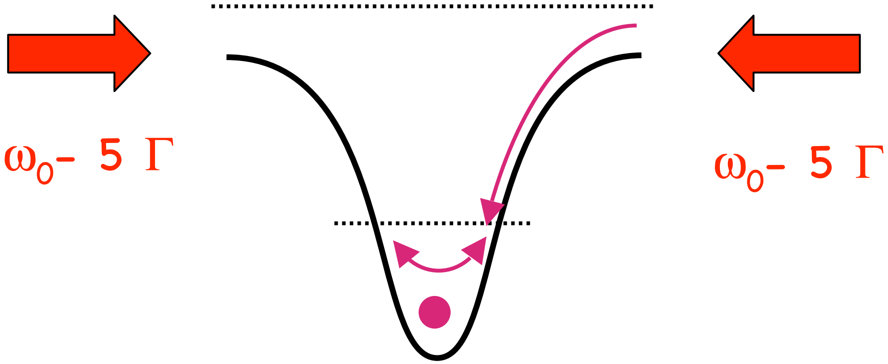
Detection of
Fluorescence @ 780 nm

Single atom ?



Tight trap ⇒
high inelastic collision rate

Loading the tweezers

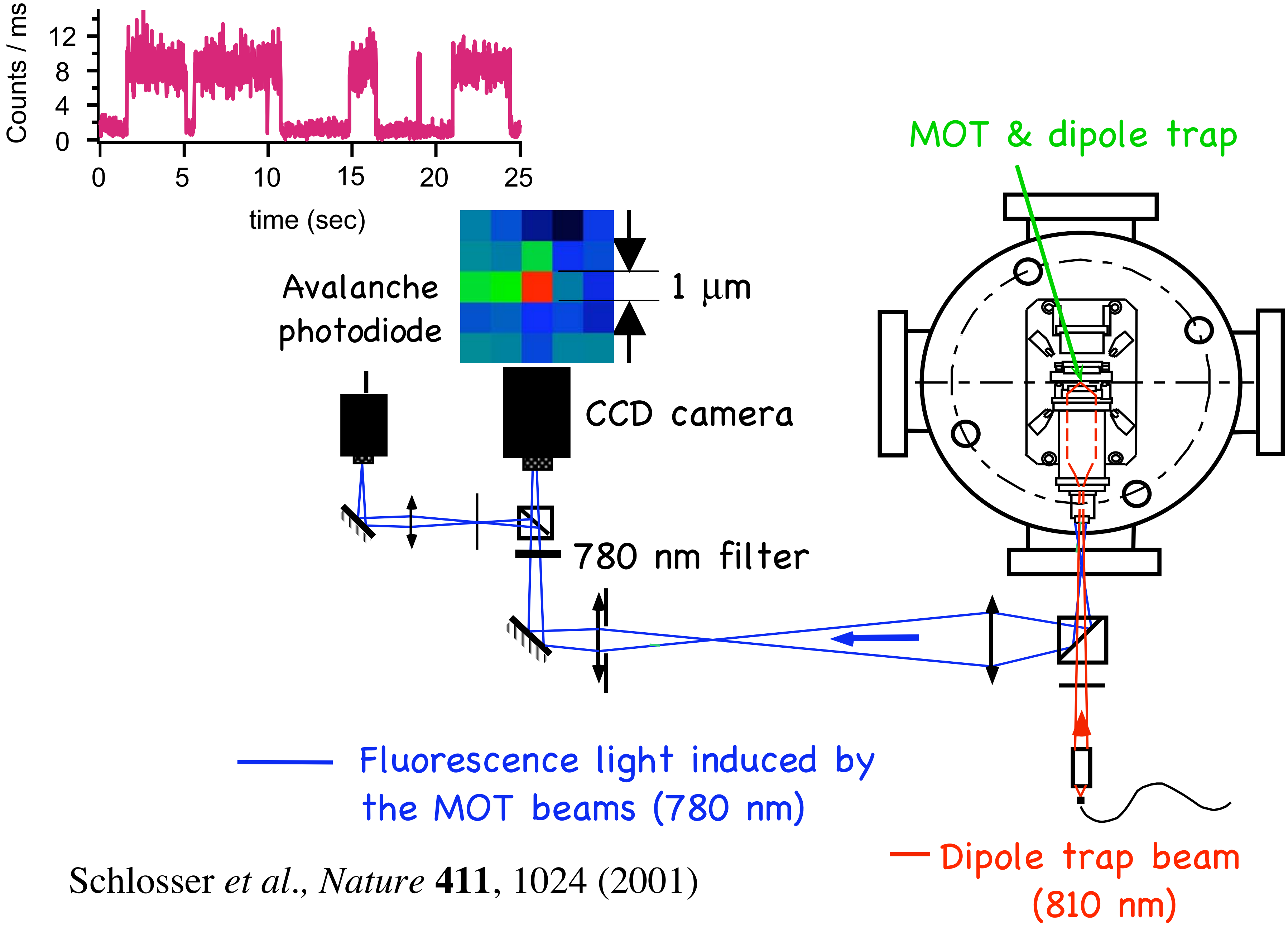


$\omega_0 - 5\,\Gamma$

$\omega_0 - 5\,\Gamma$

Schlosser *et al.*, PRL **89**, 023005 (2002)

DETECTING A SINGLE ATOM



Schlosser *et al.*, *Nature* **411**, 1024 (2001)

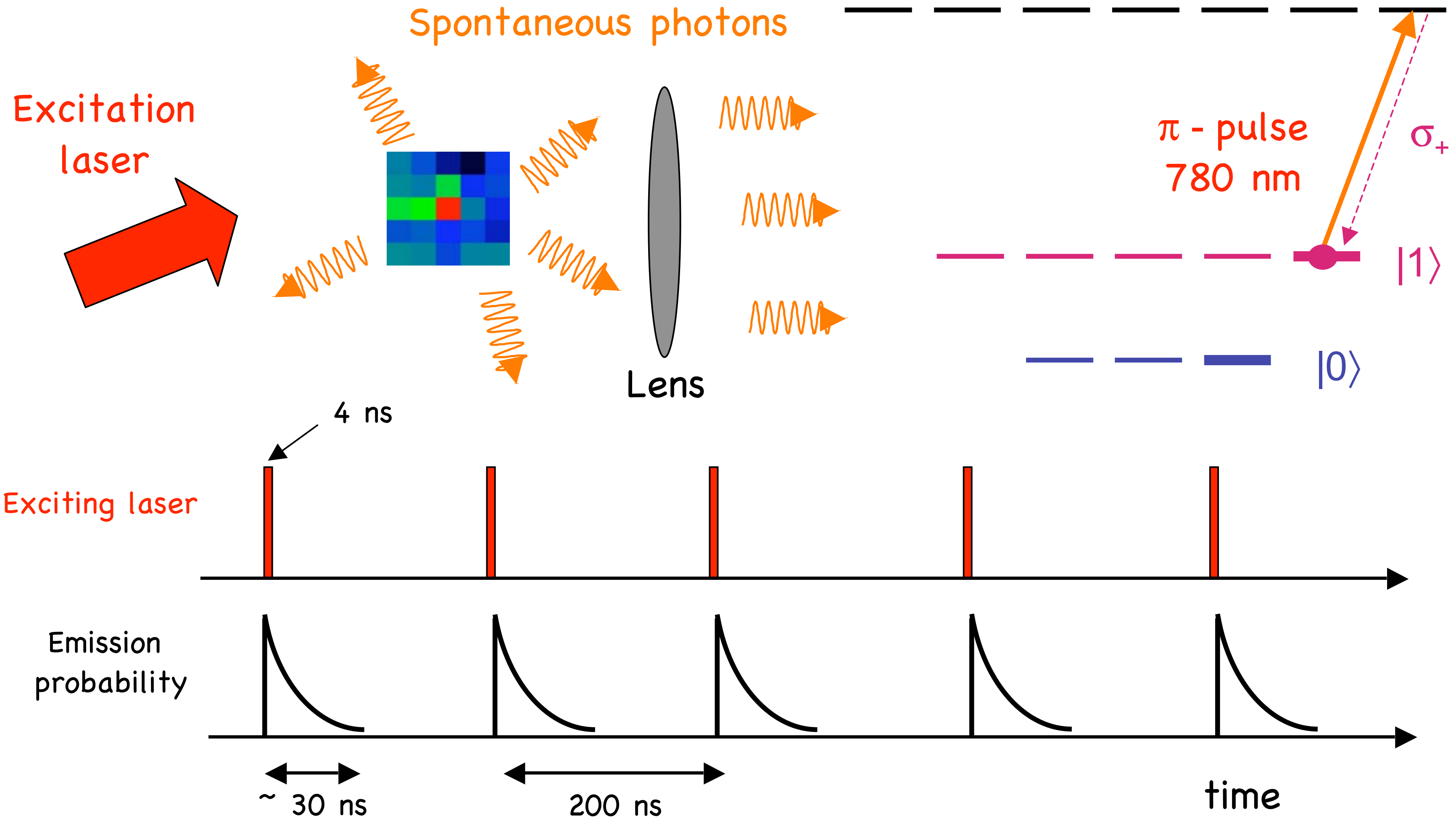
SINGLE PHOTONS

FROM

A SINGLE ATOM

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

THE IDEA

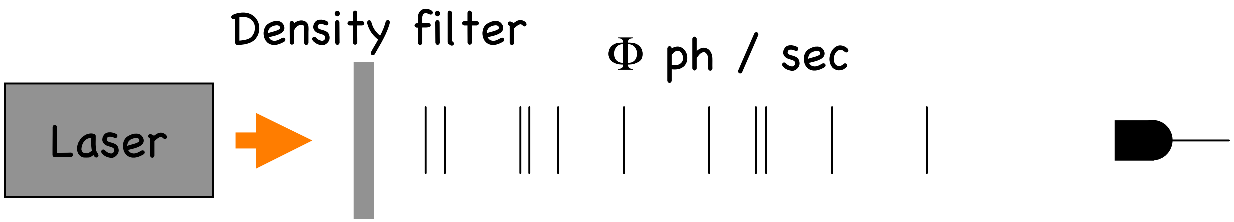


Well defined polarization

In principle = Fourier limited by the 6 MHz linewidth of the transition

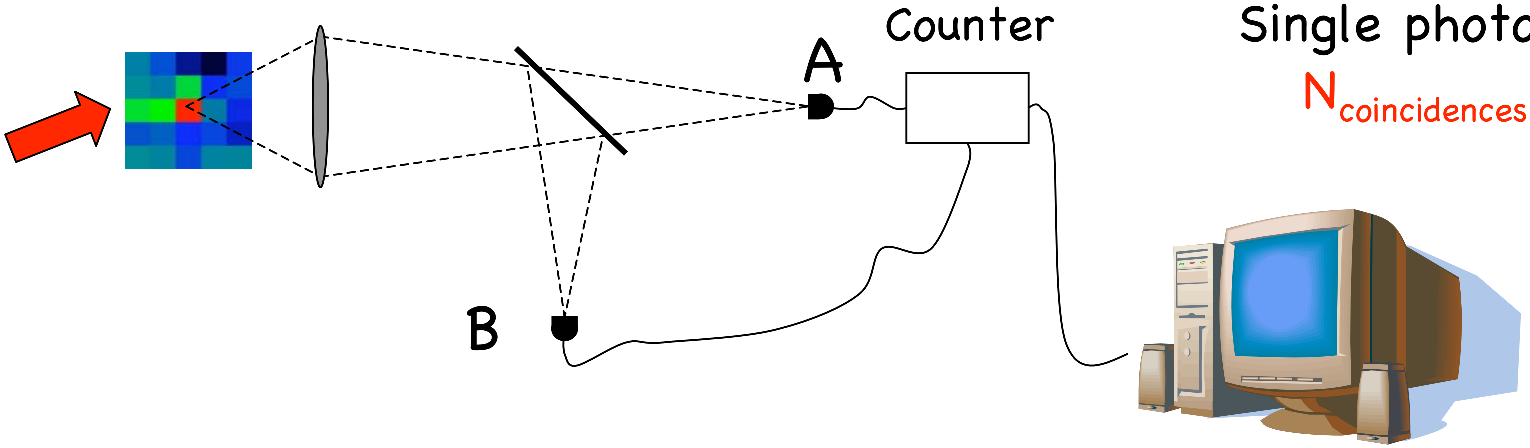
IS IT REALLY A SINGLE PHOTON SOURCE ?

A single photon source **IS NOT** just an attenuated source of « classical » light



Probability to detect 2 photons during $\Delta t = (\Phi\, \Delta t)^2 / 2 \neq 0$

Second-order correlation $G^{(2)}(t,t+\tau) = \langle I(t+\tau)I(t)\rangle \propto N_{\text{coincidences}}(\tau)$



Single photon source:

$N_{\text{coincidences}}(0) = 0$

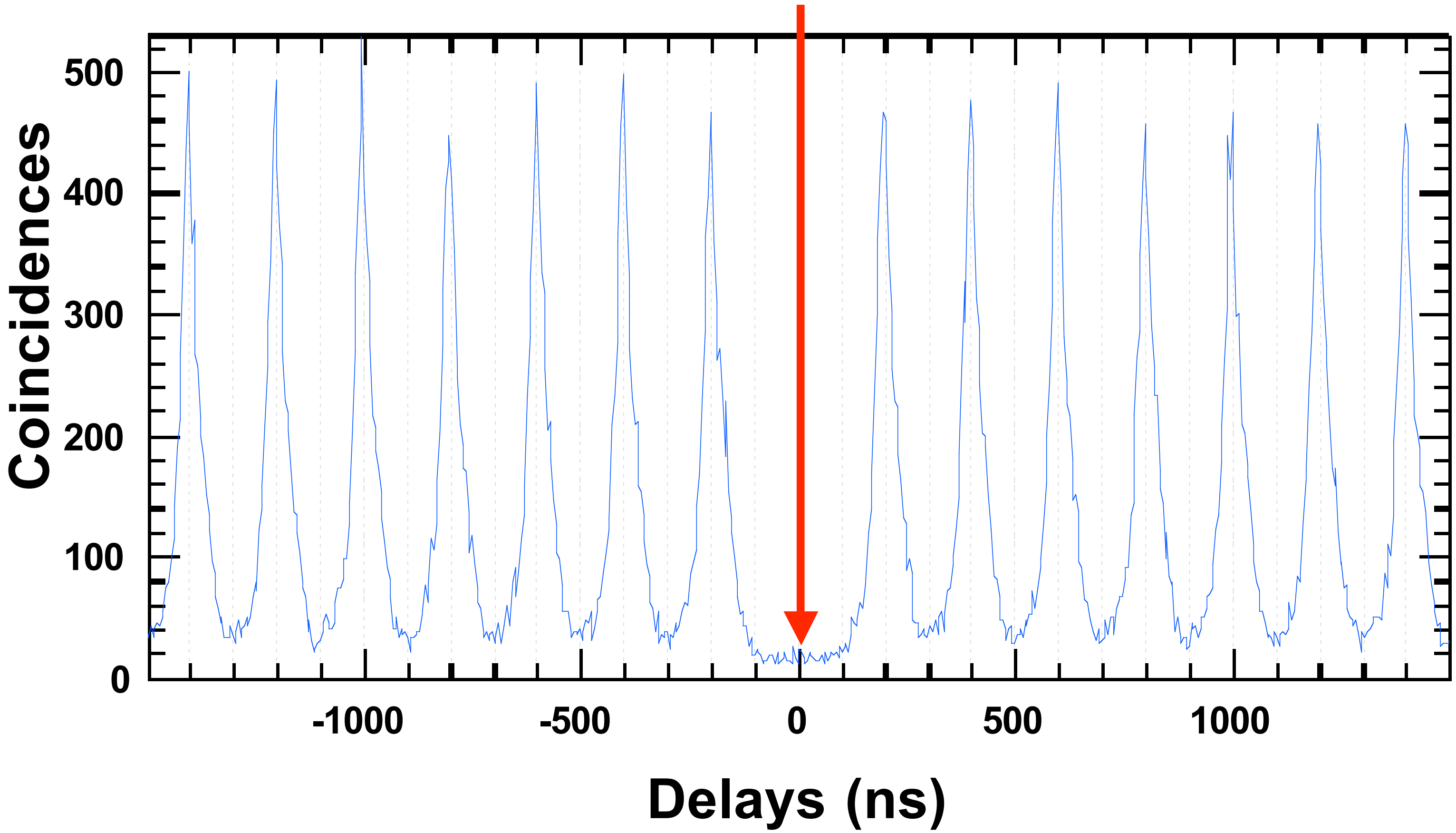
Start - stop configuration: measure the # of coincidences for different delays τ

ANTIBUNCHING

4 - hour acquisition (4×10^6 photons)

Resolution 1 ns, bining × 4

No background correction



Antibunching

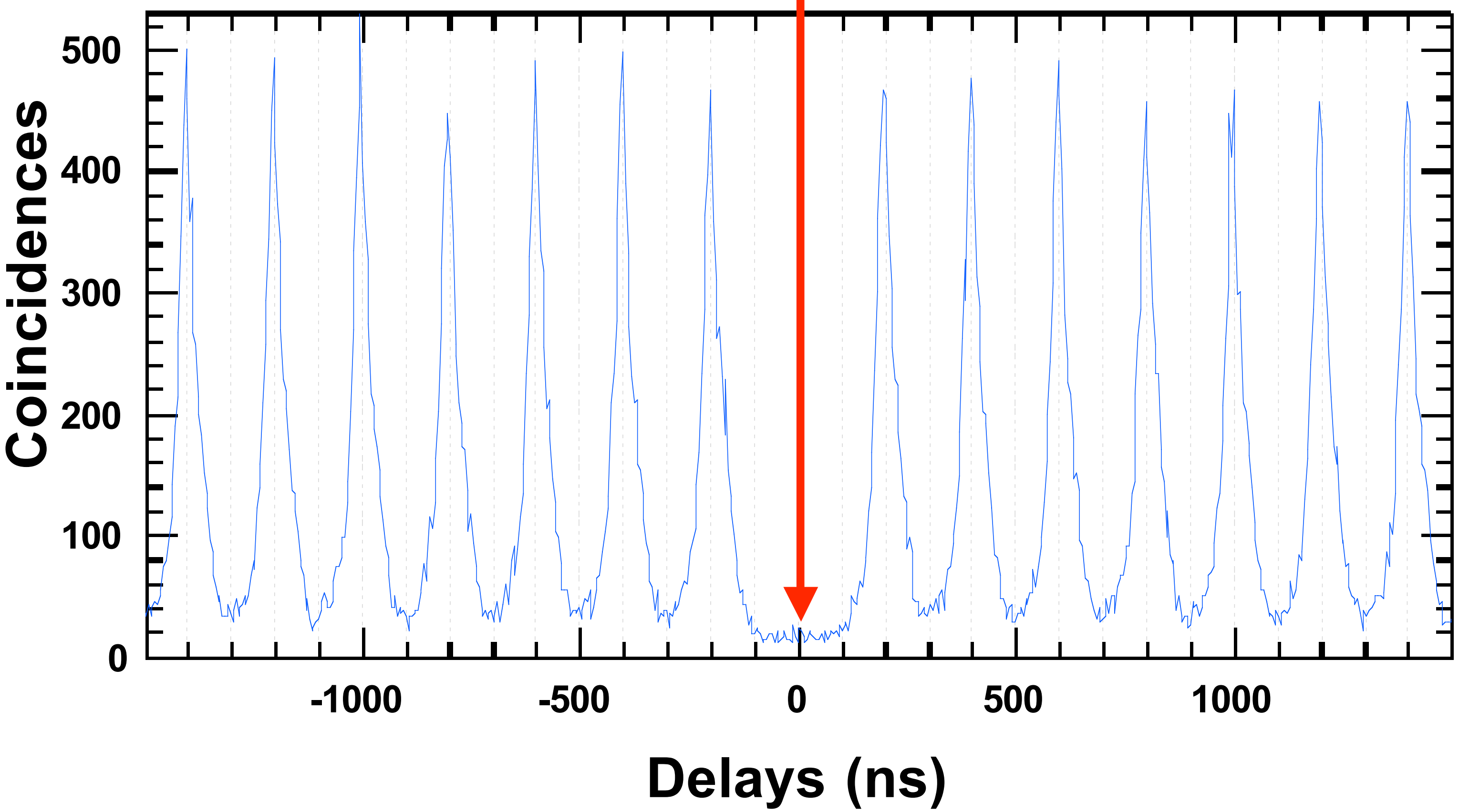
Time between 2 pulses ↔

HOW GOOD A SINGLE - PHOTON SOURCE IS IT?

Area around 0 / Area under a peak = $p(2) / p(1)^2 / 2$

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

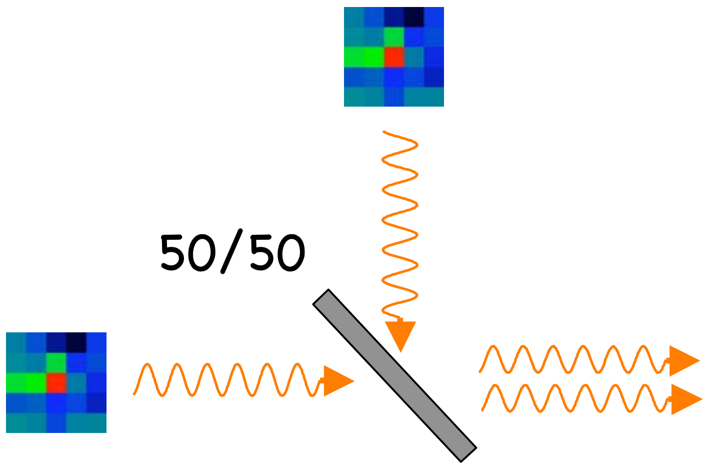
(50 × better than an attenuated light)



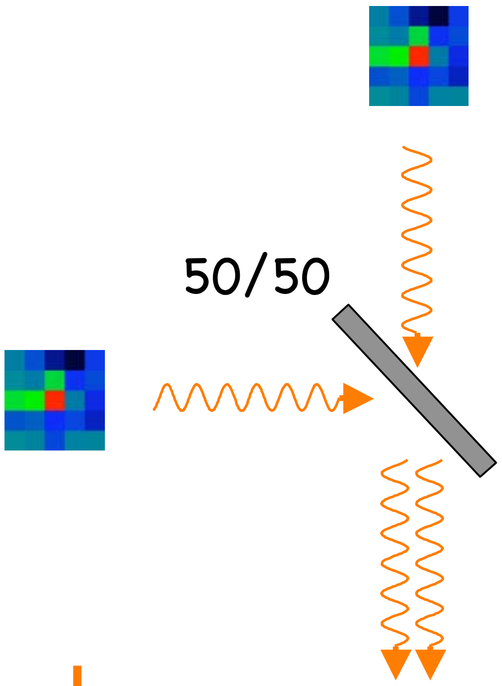
QUANTUM INTERFERENCE BETWEEN TWO SINGLE PHOTONS EMITTED BY INDEPENDENT ATOMS

Beugnon *et al.*, to appear in *Nature* (2006)

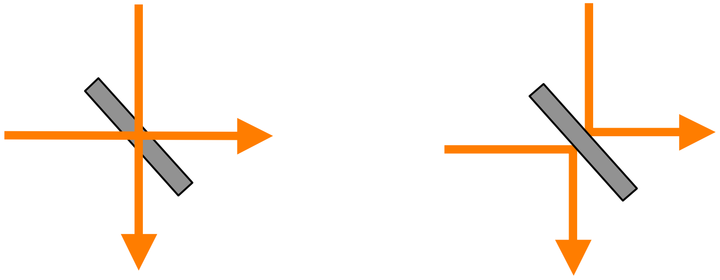
TWO-PHOTON INTERFERENCES ("COALESCENCE")



or



Destructive
quantum
interference



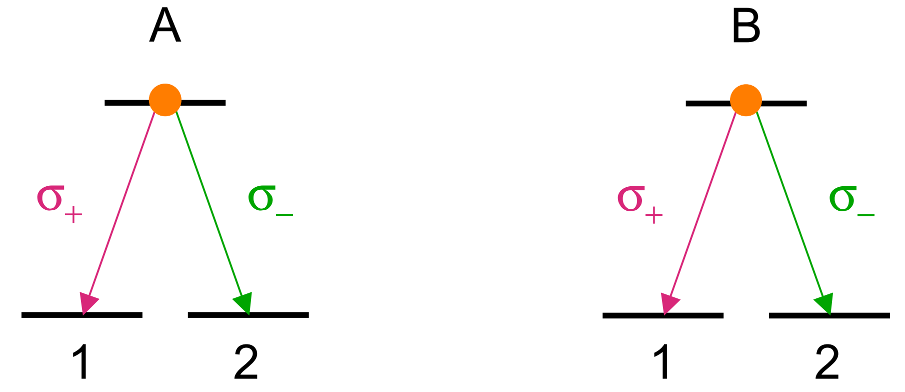
$$| A \quad + \quad -A |^2 \quad = 0$$

Hong, Ou, Mandel *Phys. Rev. Lett.* **59**, 2044 (1987): parametric downconversion

Motivation: CONDITIONAL ENTANGLEMENT

... towards a 2-qubit gate

2 identical atoms emit indistinguishable photons

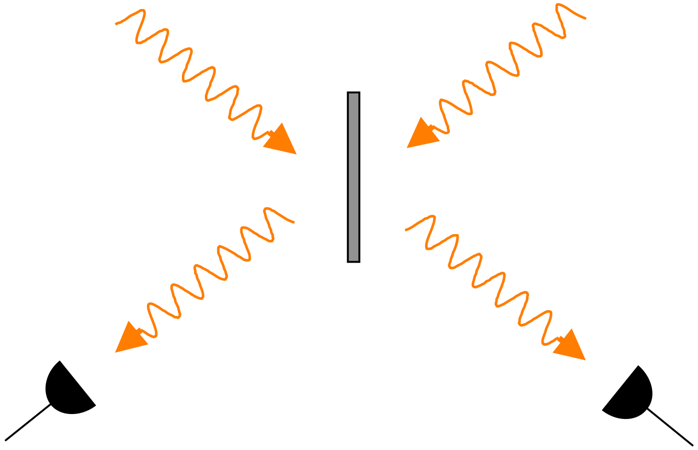


Atom-photon entanglement

Blinov, *Nature* **428**, 153 (2004)

Weinfürter (2005)

$|1_A,\sigma_+\rangle + |2_A,\sigma_-\rangle$ $|1_B,\sigma_+\rangle + |2_B,\sigma_-\rangle$



Two-photon interference

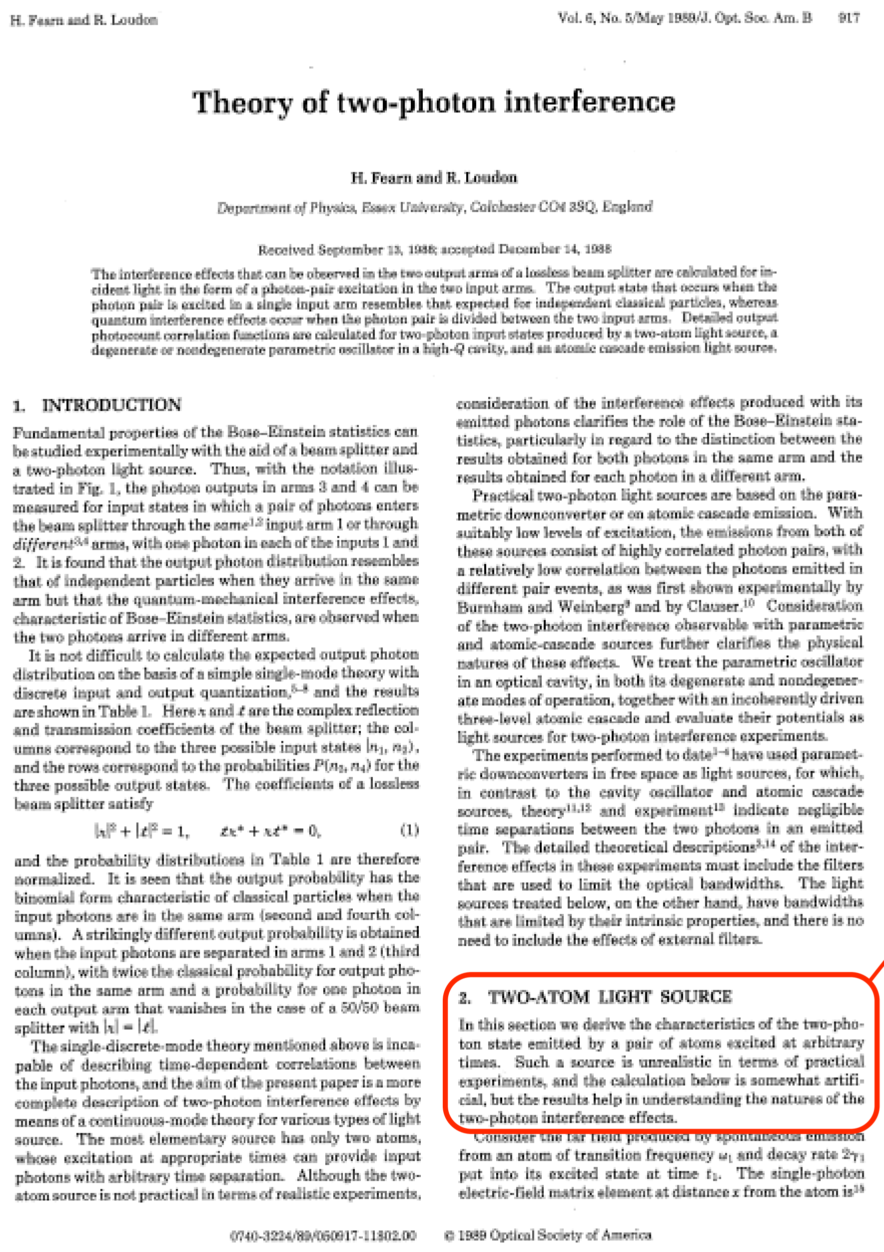
+

Double-clic detection

⇒ entanglement swapping

A double-clic prepares: $|1_A,2_B\rangle + |1_B,2_A\rangle$

ANOTHER KIND OF MOTIVATION…



H. Fearn and R. Loudon Vol. 6, No. 5/May 1989/J. Opt. Soc. Am. B 917

Theory of two-photon interference

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The interference effects that can be observed in the two output arms of a lossless beam splitter are calculated for incident light in the form of a photon-pair excitation in the two input arms. The output state that occurs when the photon pair is excited in a single input arm resembles that expected for independent classical particles, whereas quantum interference effects occur when the photon pair is divided between the two input arms. Detailed output photocount correlation functions are calculated for two-photon input states produced by a two-atom light source, a degenerate or nondegenerate parametric oscillator in a high-Q cavity, and an atomic cascade emission light source.

1. INTRODUCTION

Fundamental properties of the Bose–Einstein statistics can be studied experimentally with the aid of a beam splitter and a two-photon light source. Thus, with the notation illustrated in Fig. 1, the photon outputs in arms 3 and 4 can be measured for input states in which a pair of photons enters the beam splitter through the *same*[1,2] input arm 1 or through *different*[3,4] arms, with one photon in each of the inputs 1 and 2. It is found that the output photon distribution resembles that of independent particles when they arrive in the same arm but that the quantum-mechanical interference effects, characteristic of Bose–Einstein statistics, are observed when the two photons arrive in different arms.

It is not difficult to calculate the expected output photon distribution on the basis of a simple single-mode theory with discrete input and output quantization,[5–8] and the results are shown in Table 1. Here r and t are the complex reflection and transmission coefficients of the beam splitter; the columns correspond to the three possible input states $|n_1, n_2\rangle$, and the rows correspond to the probabilities $P(n_3, n_4)$ for the three possible output states. The coefficients of a lossless beam splitter satisfy

$$|r|^2 + |t|^2 = 1, \qquad t r^* + r t^* = 0, \tag{1}$$

and the probability distributions in Table 1 are therefore normalized. It is seen that the output probability has the binomial form characteristic of classical particles when the input photons are in the same arm (second and fourth columns). A strikingly different output probability is obtained when the input photons are separated in arms 1 and 2 (third column), with twice the classical probability for output photons in the same arm and a probability for one photon in each output arm that vanishes in the case of a 50/50 beam splitter with $|r| = |t|$.

The single-discrete-mode theory mentioned above is incapable of describing time-dependent correlations between the input photons, and the aim of the present paper is a more complete description of two-photon interference effects by means of a continuous-mode theory for various types of light source. The most elementary source has only two atoms, whose excitation at appropriate times can provide input photons with arbitrary time separation. Although the two-atom source is not practical in terms of realistic experiments, consideration of the interference effects produced with its emitted photons clarifies the role of the Bose–Einstein statistics, particularly in regard to the distinction between the results obtained for both photons in the same arm and the results obtained for each photon in a different arm.

Practical two-photon light sources are based on the parametric downconverter or on atomic cascade emission. With suitably low levels of excitation, the emissions from both of these sources consist of highly correlated photon pairs, with a relatively low correlation between the photons emitted in different pair events, as was first shown experimentally by Burnham and Weinberg[9] and by Clauser.[10] Consideration of the two-photon interference observable with parametric and atomic-cascade sources further clarifies the physical natures of these effects. We treat the parametric oscillator in an optical cavity, in both its degenerate and nondegenerate modes of operation, together with an incoherently driven three-level atomic cascade and evaluate their potentials as light sources for two-photon interference experiments.

The experiments performed to date[1–4] have used parametric downconverters in free space as light sources, for which, in contrast to the cavity oscillator and atomic cascade sources, theory[11,12] and experiment[13] indicate negligible time separations between the two photons in an emitted pair. The detailed theoretical descriptions[3,14] of the interference effects in these experiments must include the filters that are used to limit the optical bandwidths. The light sources treated below, on the other hand, have bandwidths that are limited by their intrinsic properties, and there is no need to include the effects of external filters.

2. TWO-ATOM LIGHT SOURCE

In this section we derive the characteristics of the two-photon state emitted by a pair of atoms excited at arbitrary times. Such a source is unrealistic in terms of practical experiments, and the calculation below is somewhat artificial, but the results help in understanding the natures of the two-photon interference effects.

Consider the far field produced by spontaneous emission from an atom of transition frequency ω_1 and decay rate $2\gamma_1$ put into its excited state at time t_1. The single-photon electric-field matrix element at distance x from the atom is[15]

0740-3224/89/050917-11$02.00

Loudon, *J. Opt. Soc. Am. B* **6**, 917 (1989).

2. TWO-ATOM LIGHT SOURCE

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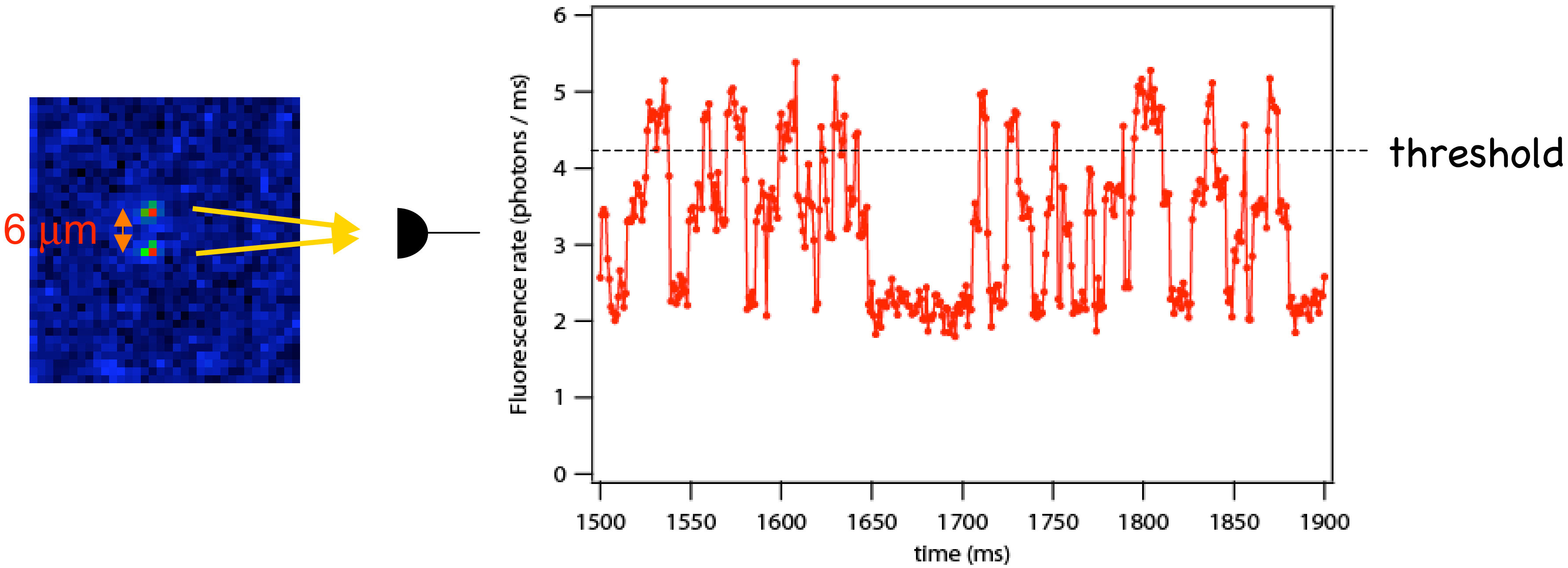
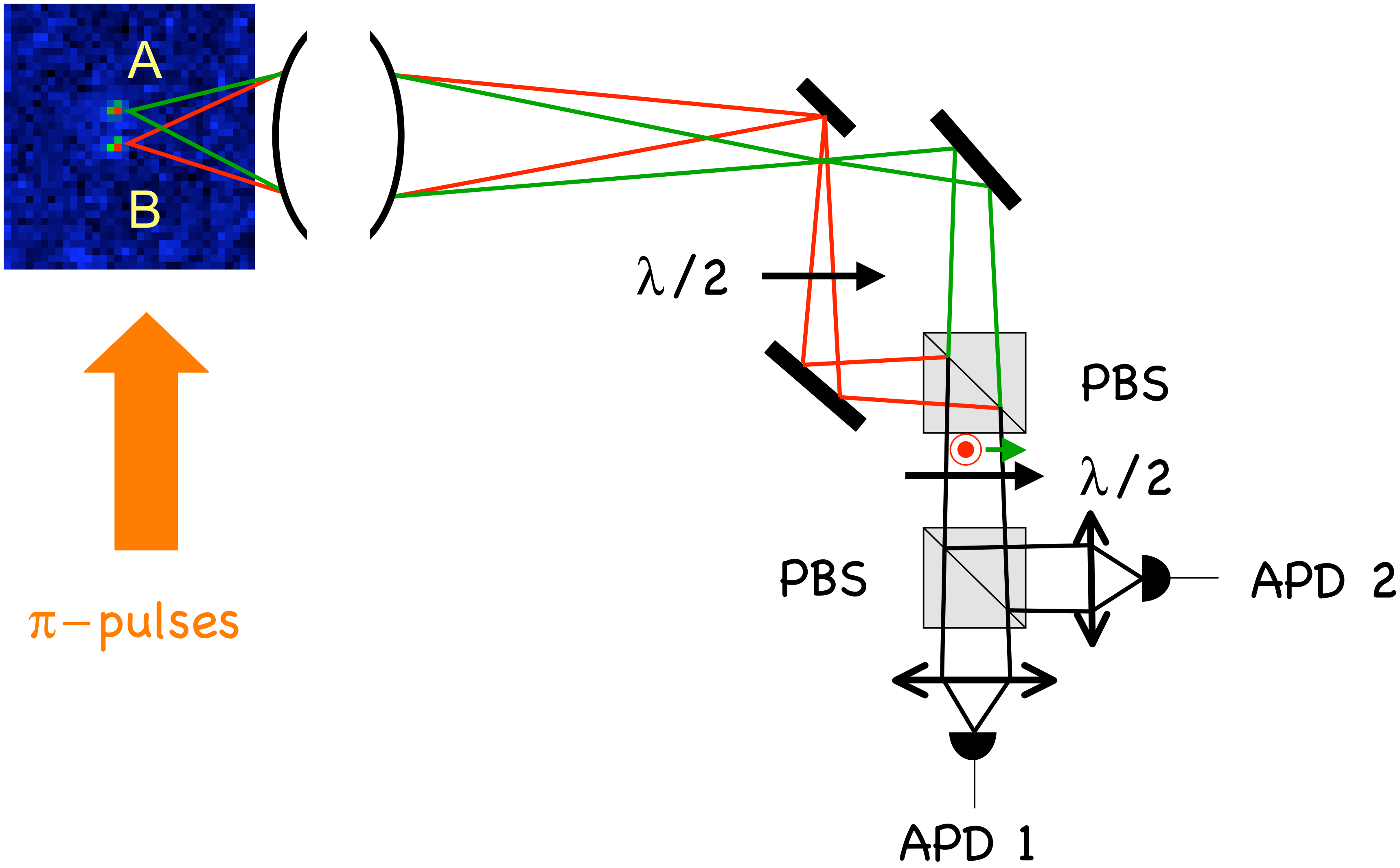
TRAPPING TWO ATOMS

Use two independent optical tweezers

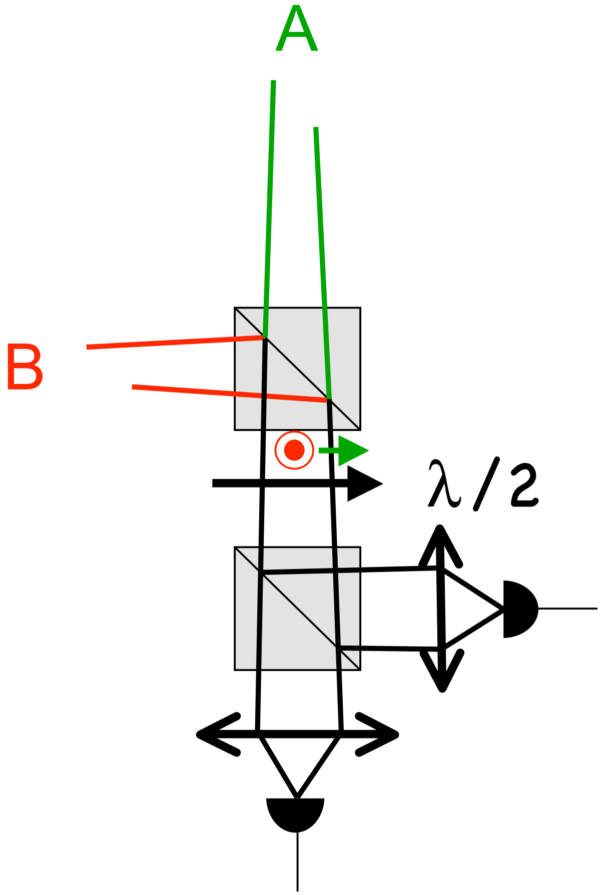


- Detect the presence of two atoms
- Start sequences of excitation (about 9000 pulses)
- Empty the two traps
- Wait until two other atoms are trapped (~ 300 ms)

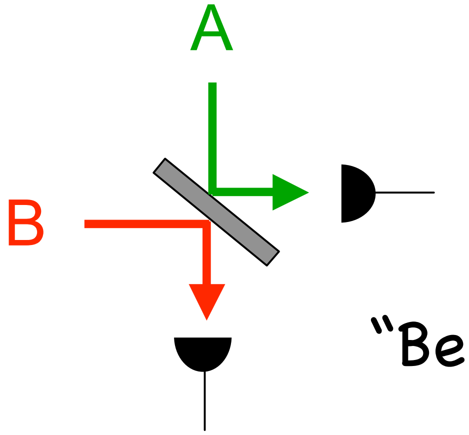
EXPERIMENTAL SETUP



THE 50/50 BEAMSPLITTER

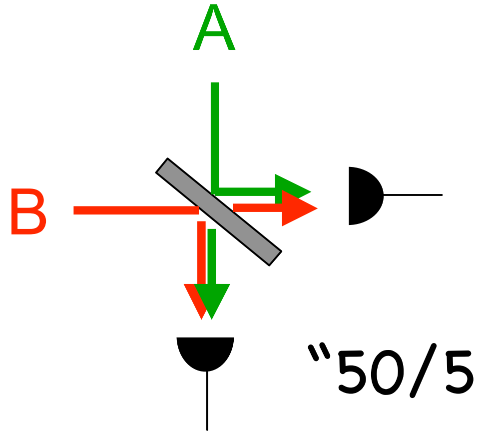


$\lambda/2$ axis // cubes axis

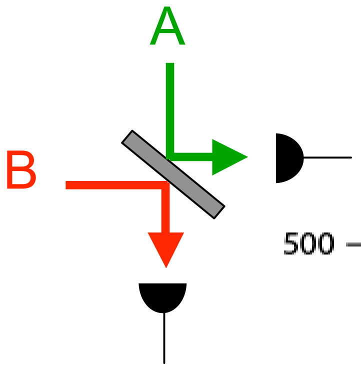


“Beam separator”

$\lambda/2$ axis at 22,5° of cubes axis

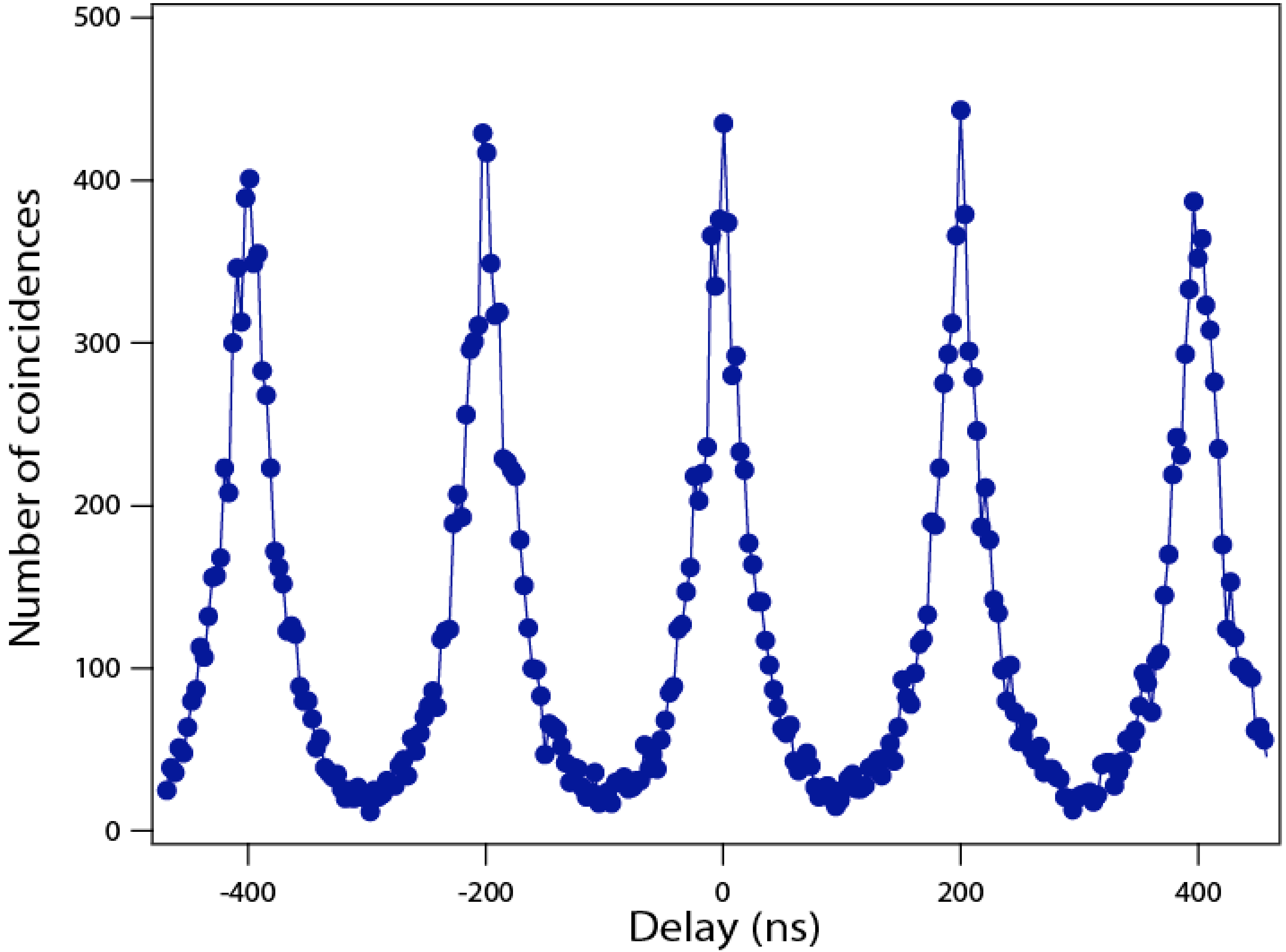


“50/50 beamsplitter”



“BEAM SEPARATOR CONFIGURATION”

(Calibration experiment)

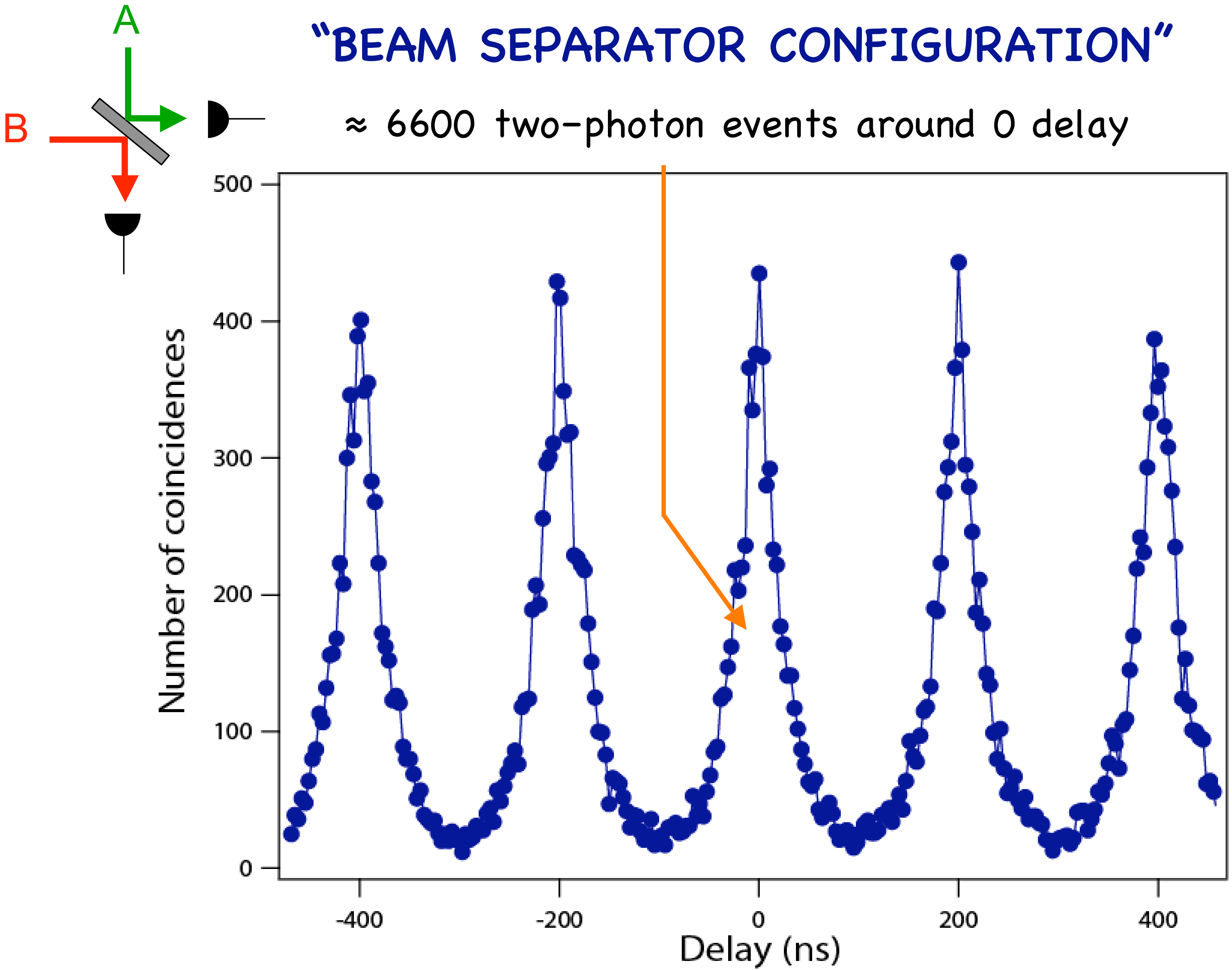


4-hours accumulation

Resolution 3.6 ns

“BEAM SEPARATOR CONFIGURATION”

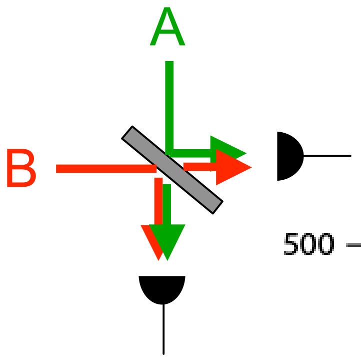
≈ 6600 two-photon events around 0 delay



4-hours accumulation

Resolution 3.6 ns

“50/50 BEAMSPLITTER CONFIGURATION”



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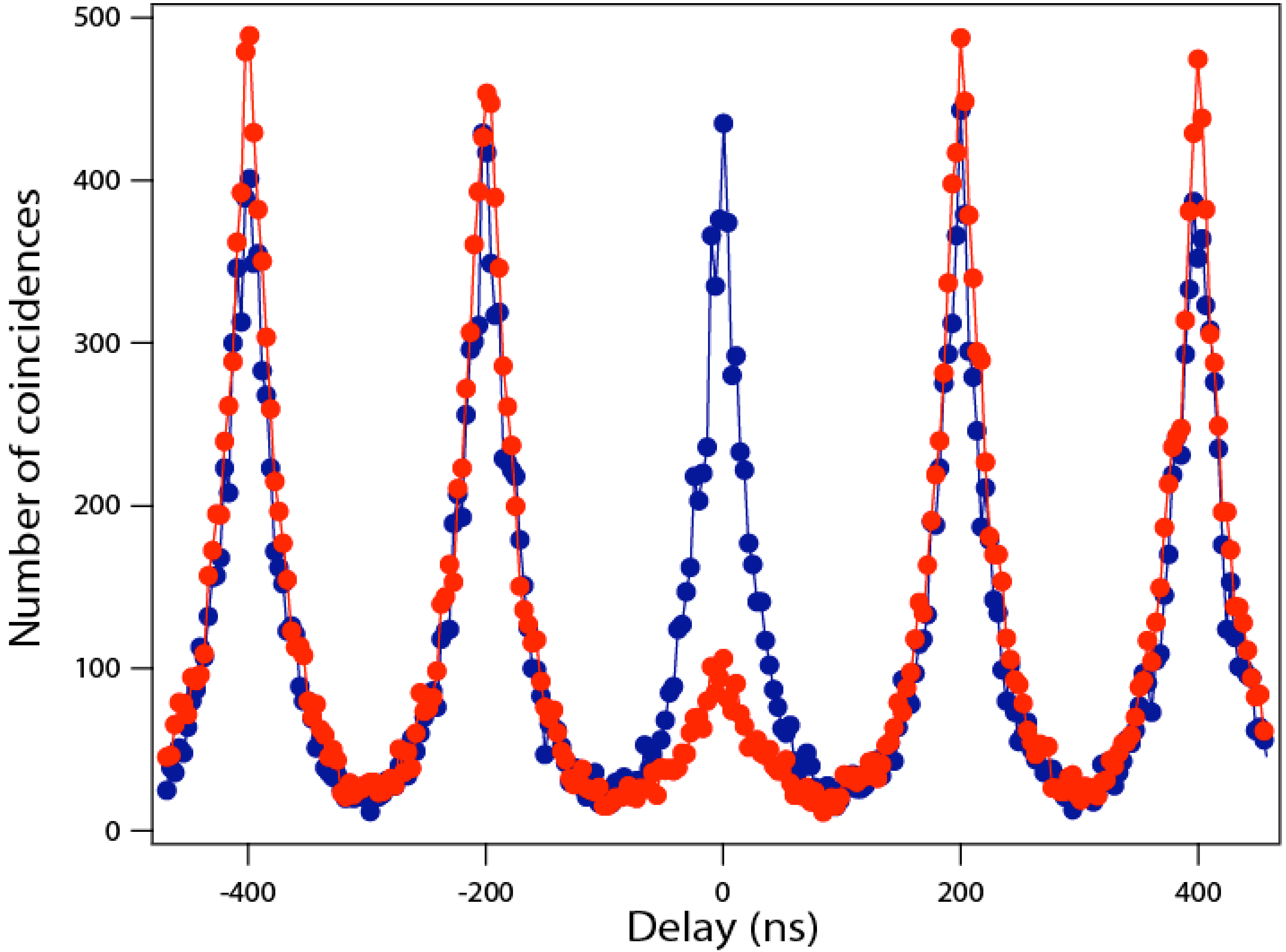
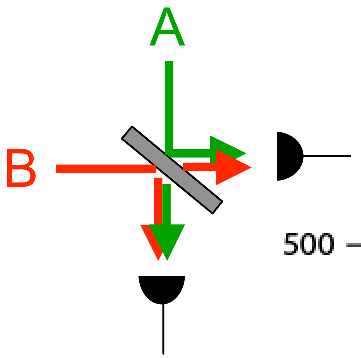


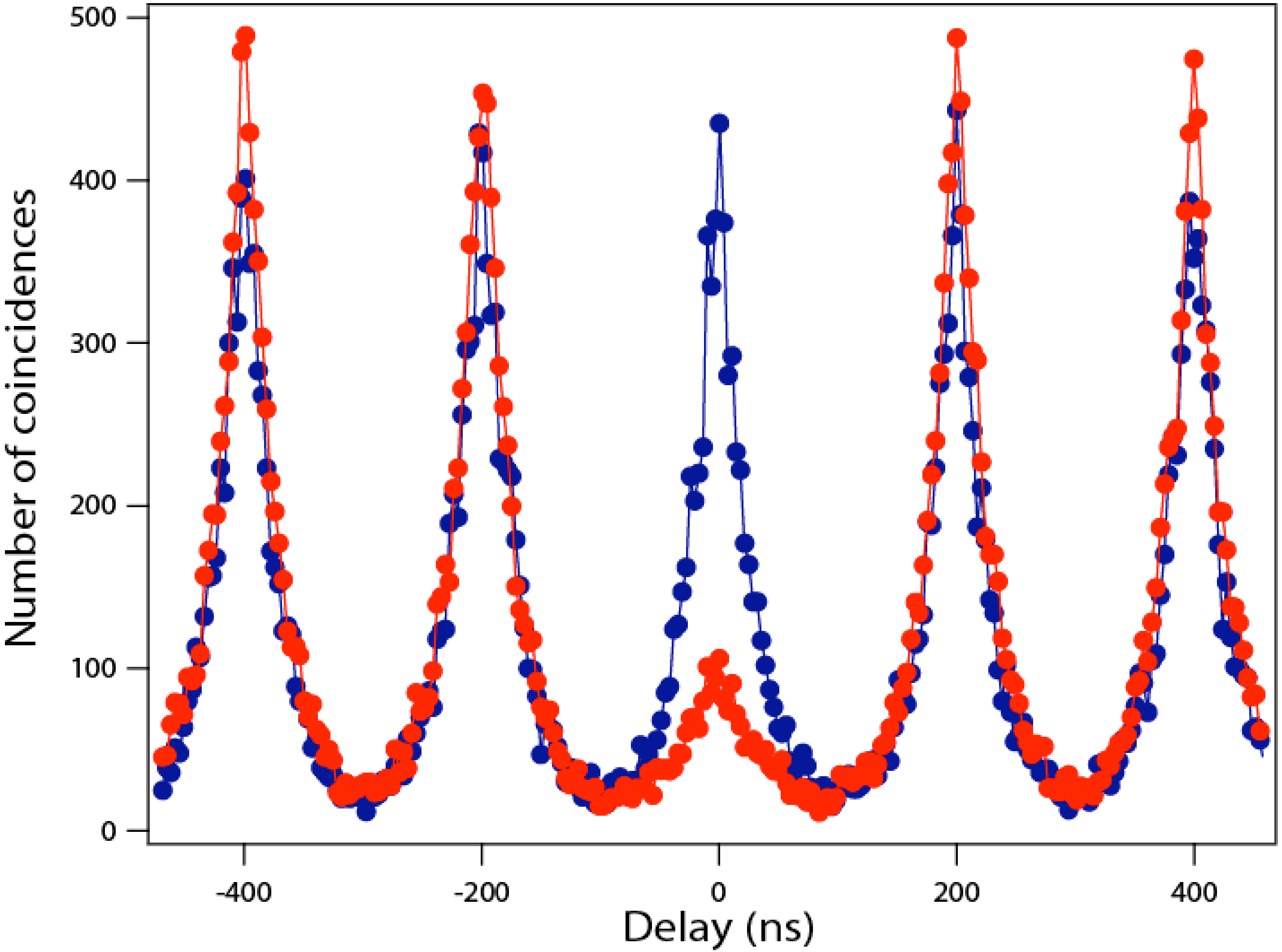
4-hours accumulation

Resolution 3.6 ns

“50/50 BEAMSPLITTER CONFIGURATION”



At non-zero delays, $N_{50/50}$ / N_{cal} ≈ 1 ⇒ 2 atoms trapped

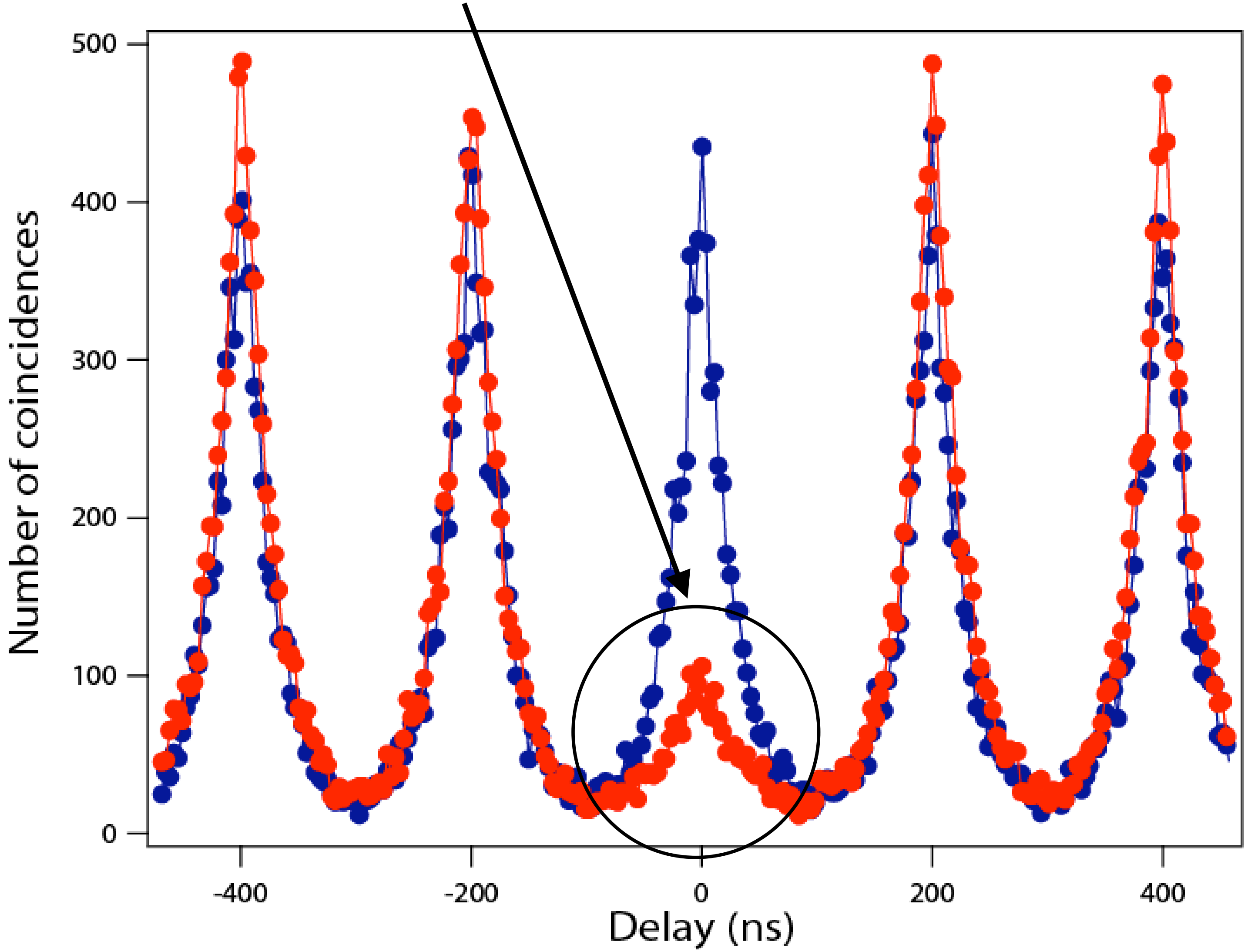


4-hours accumulation

Resolution 3.6 ns

“50/50 BEAMSPLITTER CONFIGURATION”

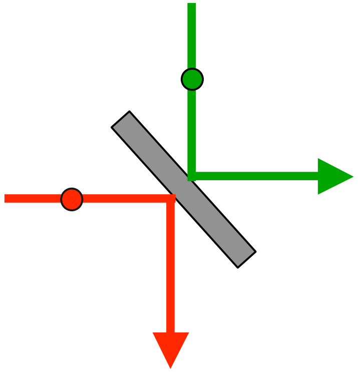
Each photon comes from a different atom (single photon source)



Not to be confused with single atom antibuching

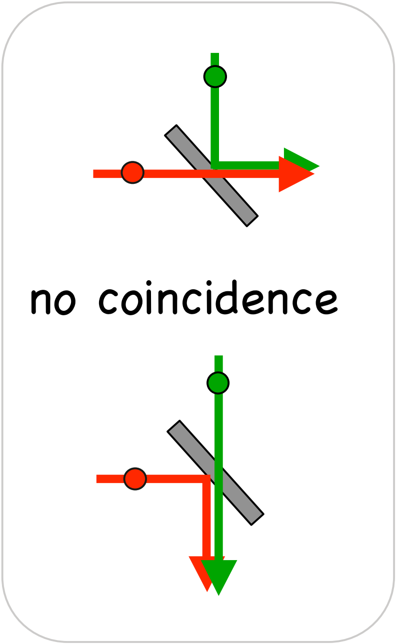
WHAT IF THE TWO PHOTONS DO NOT INTERFERE?

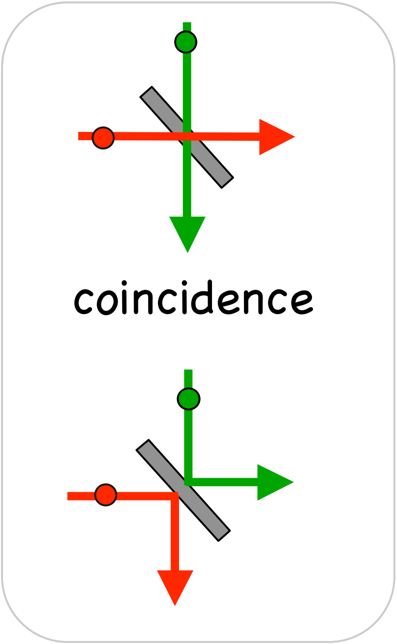
Calibration
($\lambda/2$ axis // cube)



Always a coincidence

$\lambda/2$ axis @ 22,5°
and NO interference



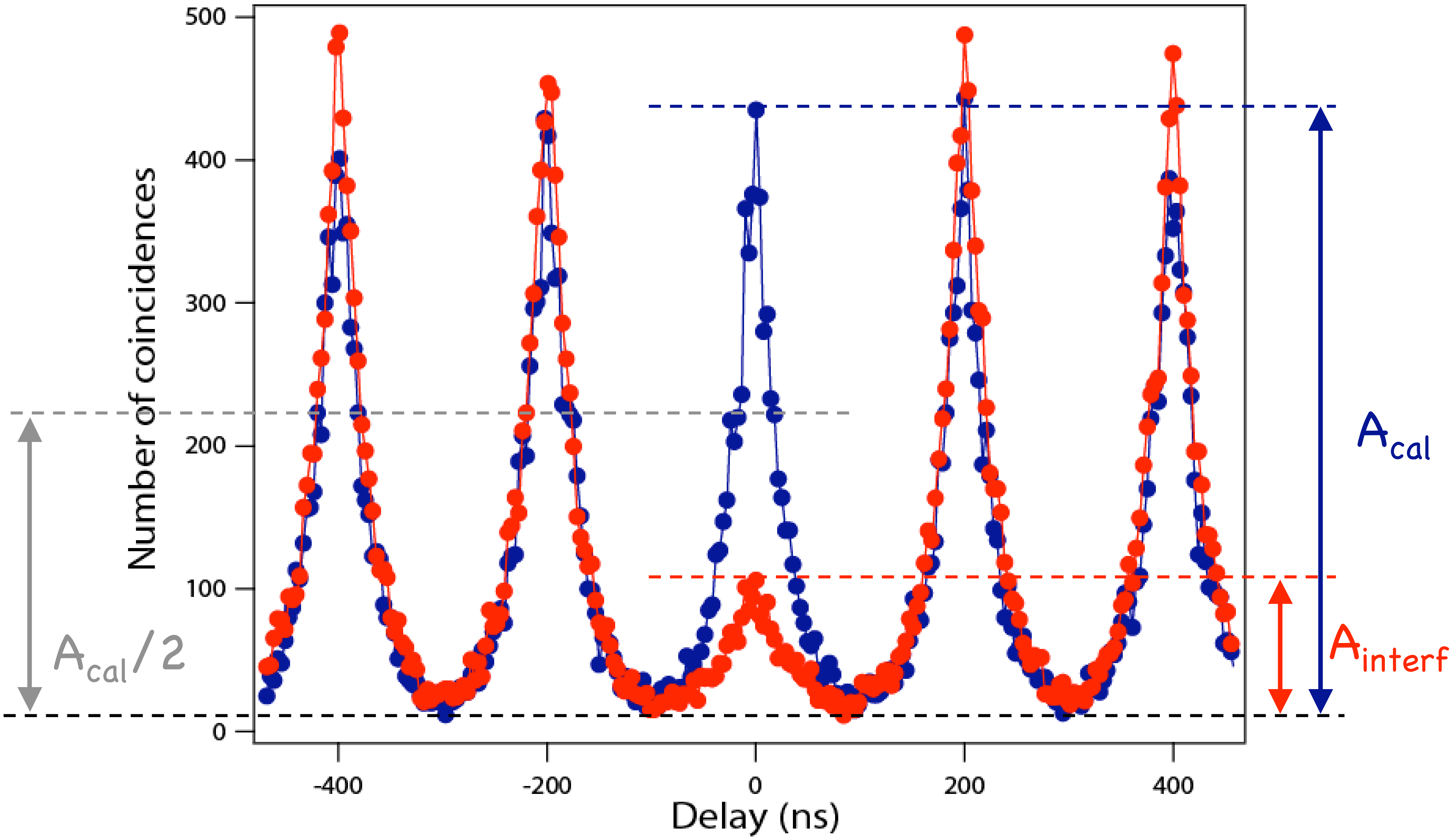


A coincidence half of the time

Comes from the single photon nature of the source

QUANTUM INTERFERENCES

Ratio = A_{interf} / A_{cal} < 1/2



What's next ?

Improve the spatial overlap by coupling into single-mode fibers (losses…?)

Further cooling of the atoms (Raman cooling)

Raman transition to encode the qubit and read out the coherences

Currently : 1 interfering event every 2 / 3 seconds.

⇒ conditionnal entanglement ?

We need to adapt the entanglement schemes to the Rb level structure (time bin…)

The single atom project

Philippe Grangier

Gaétan Messin

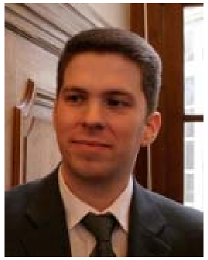
Antoine Browaeys

Jérôme Beugnon

Benoît Darquié

Matt Jones

Jos Dingjan

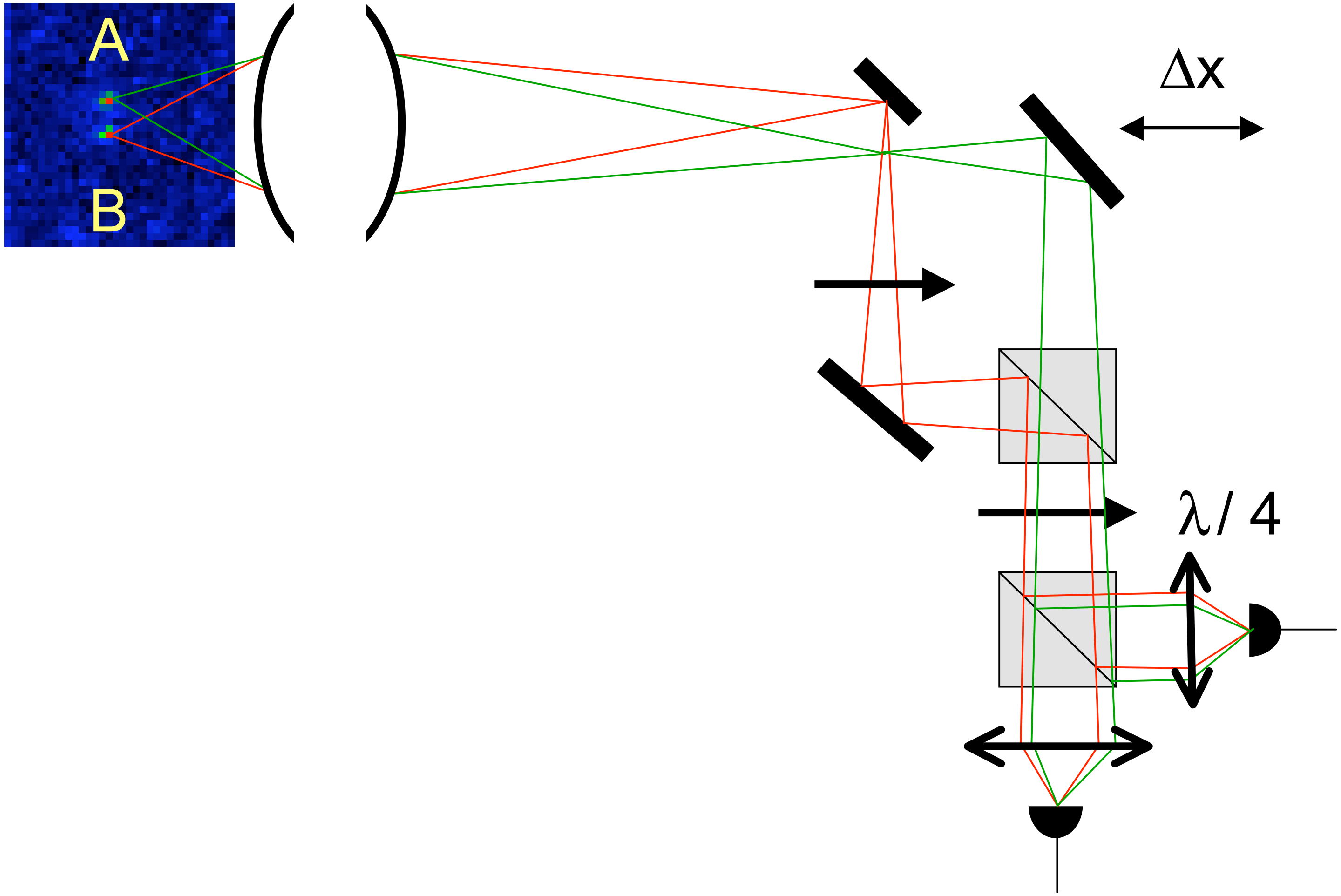


Harold Marion

Yvan Sortais

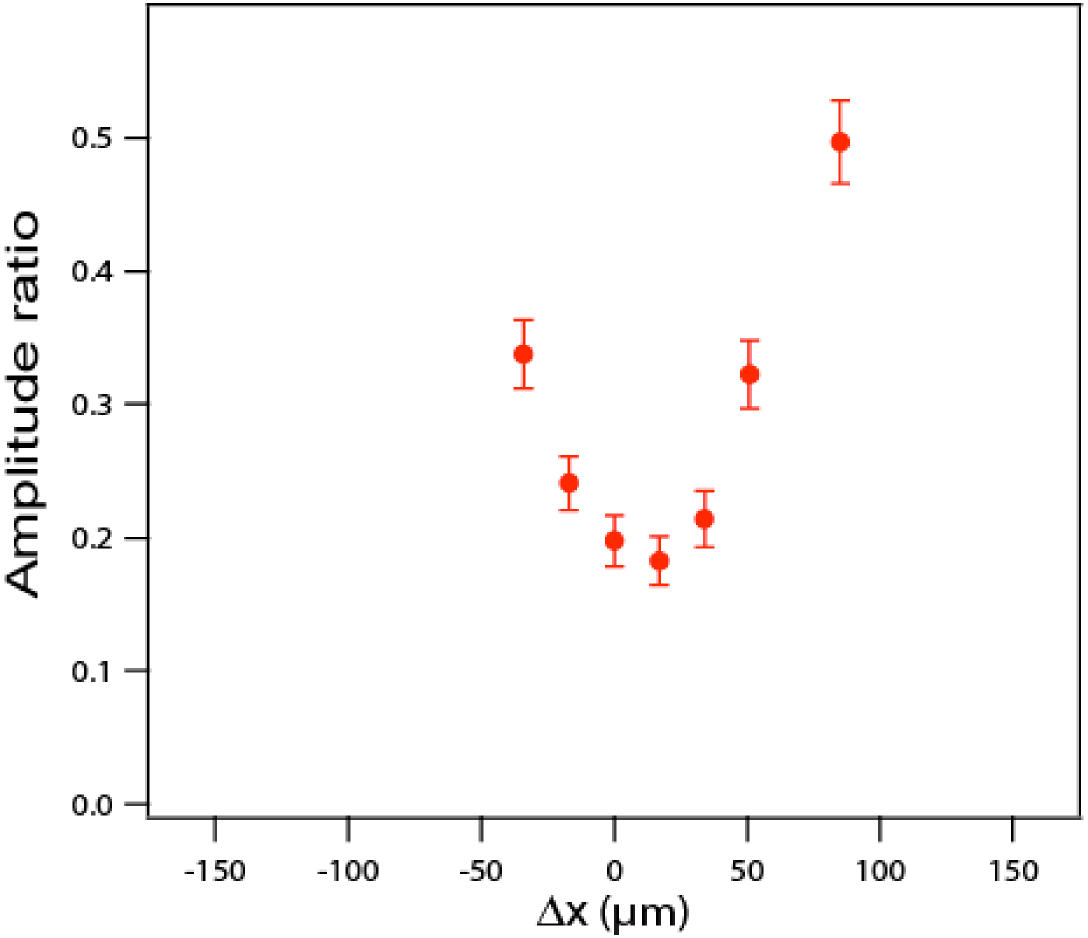
More details…

VARYING THE SPATIAL OVERLAP



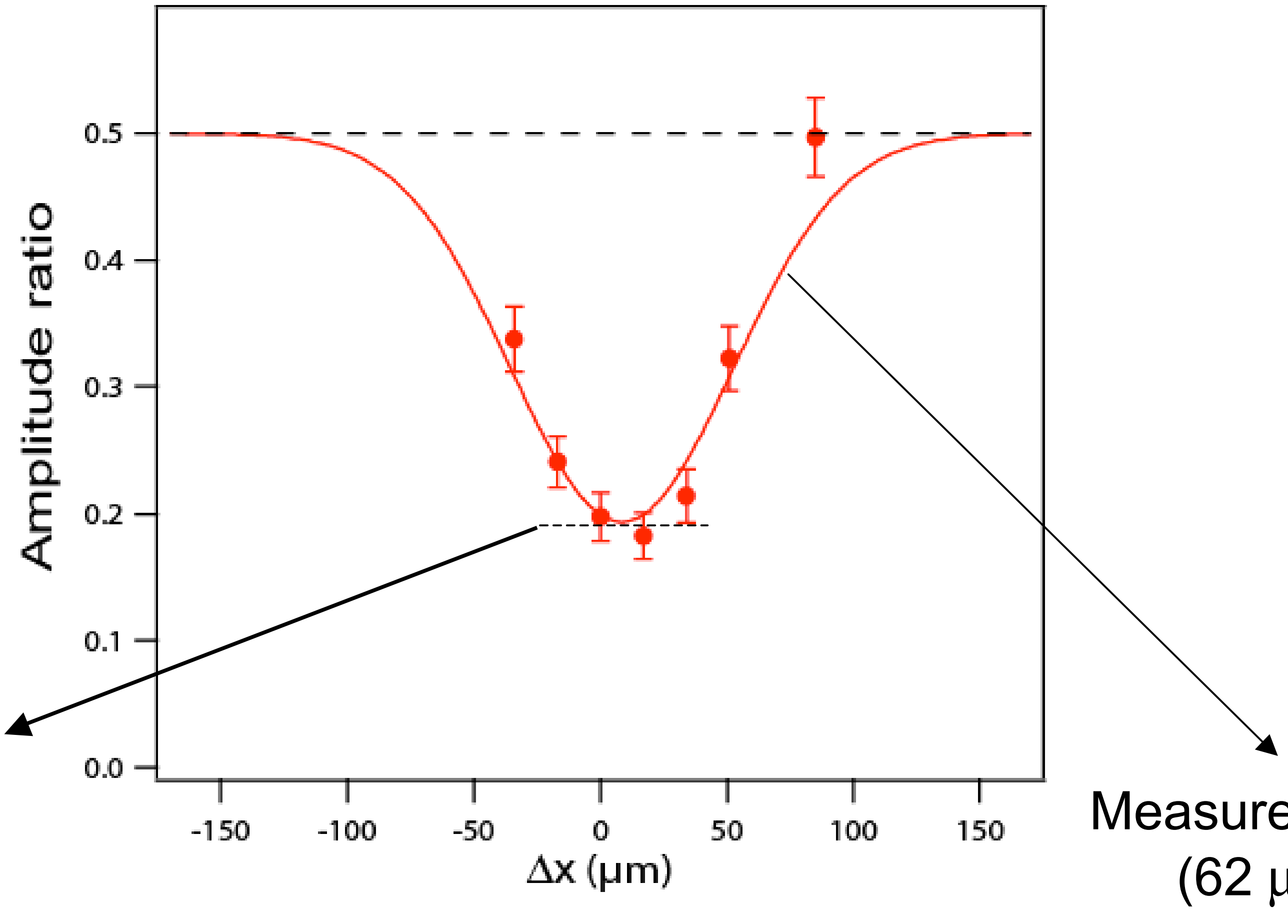
VARYING THE SPATIAL OVERLAP

$$\text{Ratio} = A_{\text{interf}} / A_{\text{cal}}$$



VARYING THE SPATIAL OVERLAP

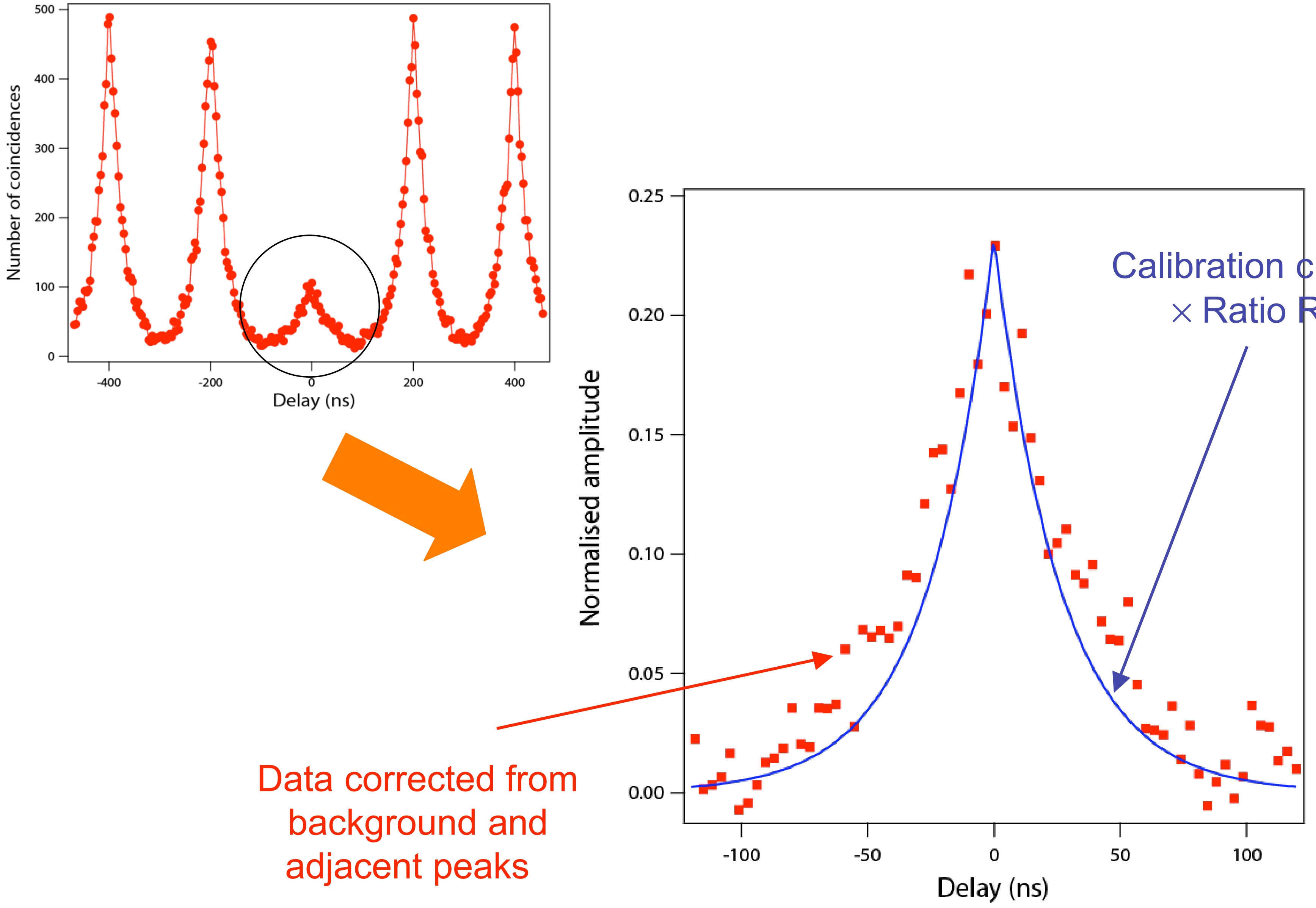
$$\text{Ratio} = \frac{A_{\text{interf}}}{A_{\text{cal}}} = \int \varepsilon_1^*(\mathbf{r})\,\varepsilon_2(\mathbf{r})\,\mathrm{d}^3\mathbf{r}$$



Field amplitude overlap ≈ 80 %

Measured waist (62 μm)

AROUND ZERO DELAY

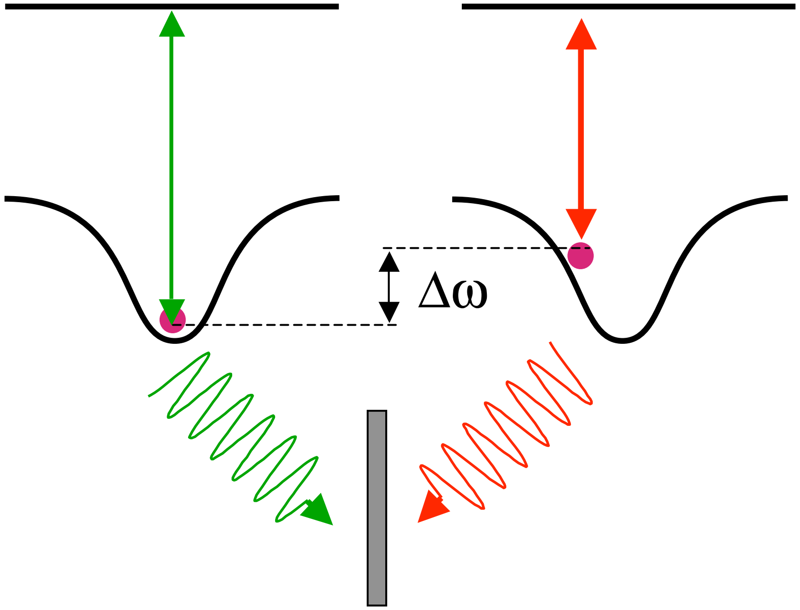


Calibration curve × Ratio R

Data corrected from background and adjacent peaks

THE ATOMS MOVE IN THEIR TRAP …

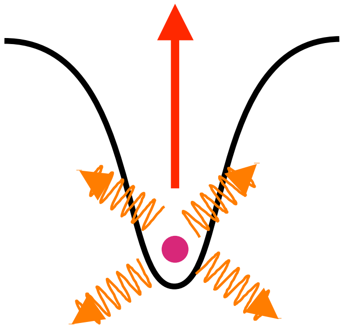
T = 60 µK

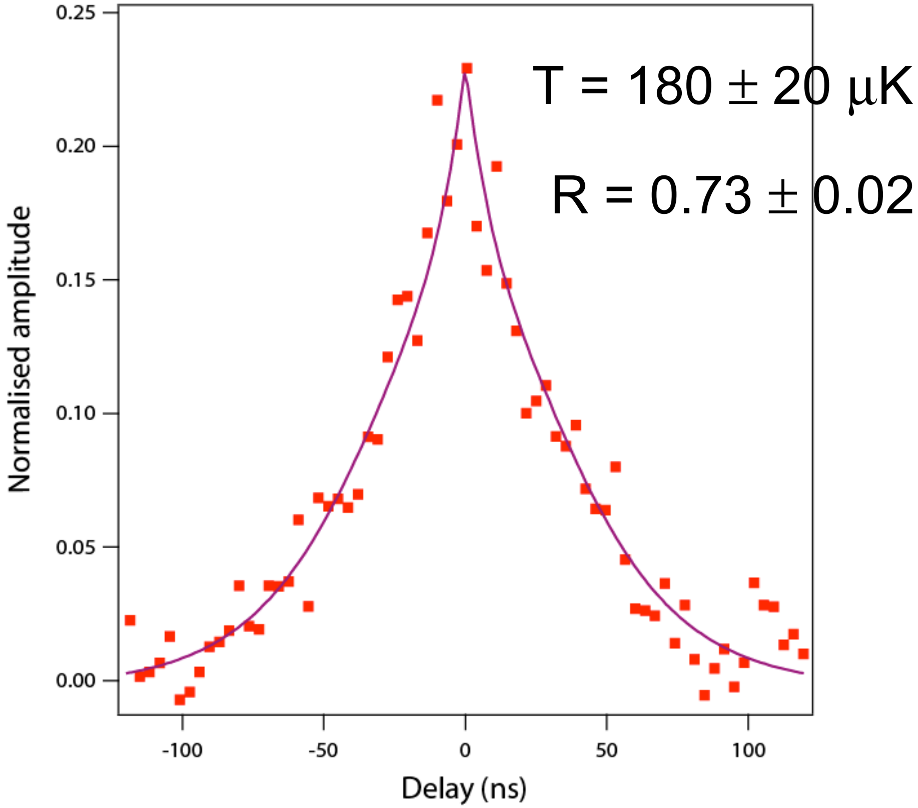


Beat note between the two photons at Δω

Averaging the beatnotes over the lightshifts distribution
⇒ broadening

+ taking into account the heating during the emission

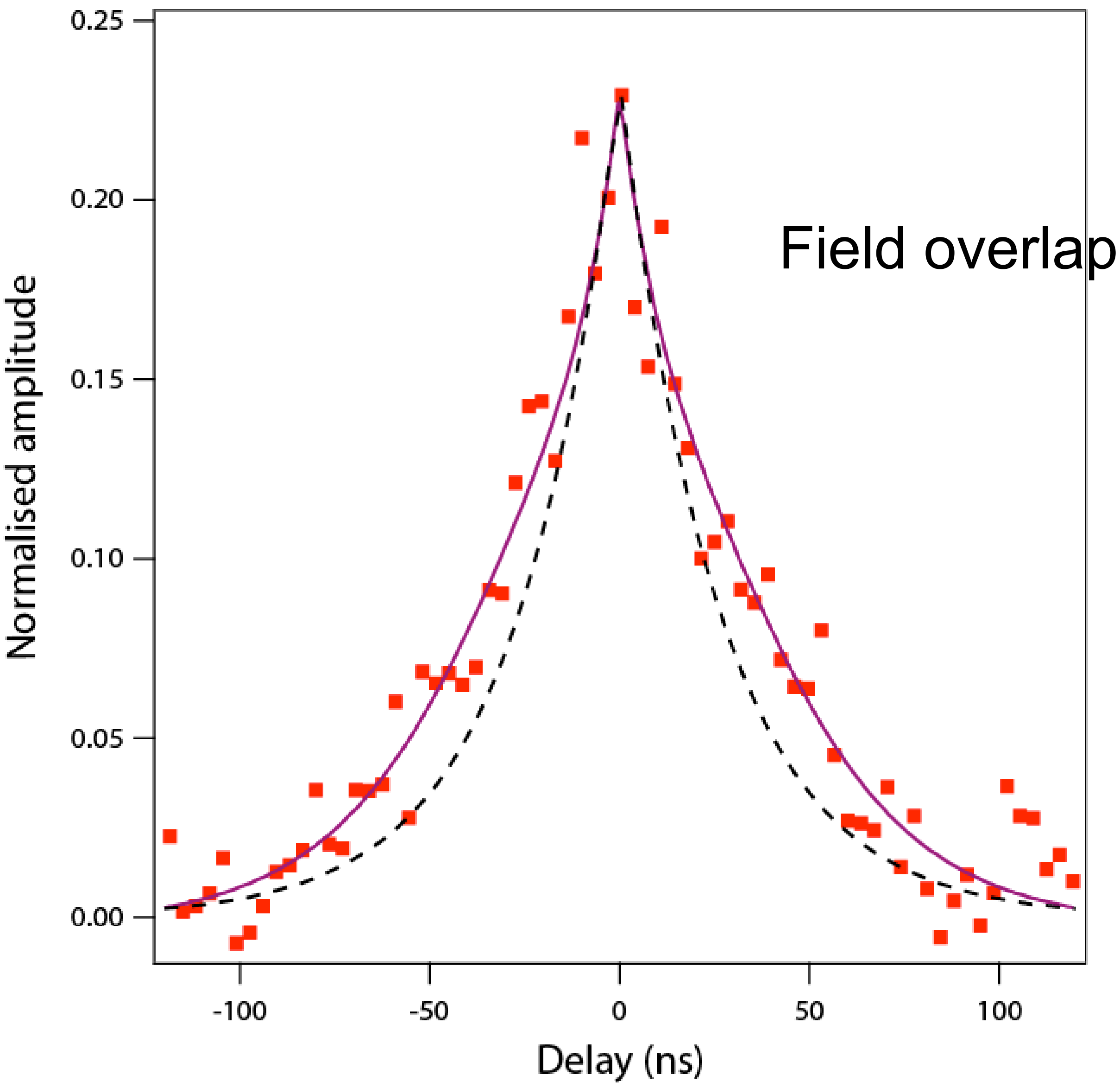




T = 180 ± 20 µK

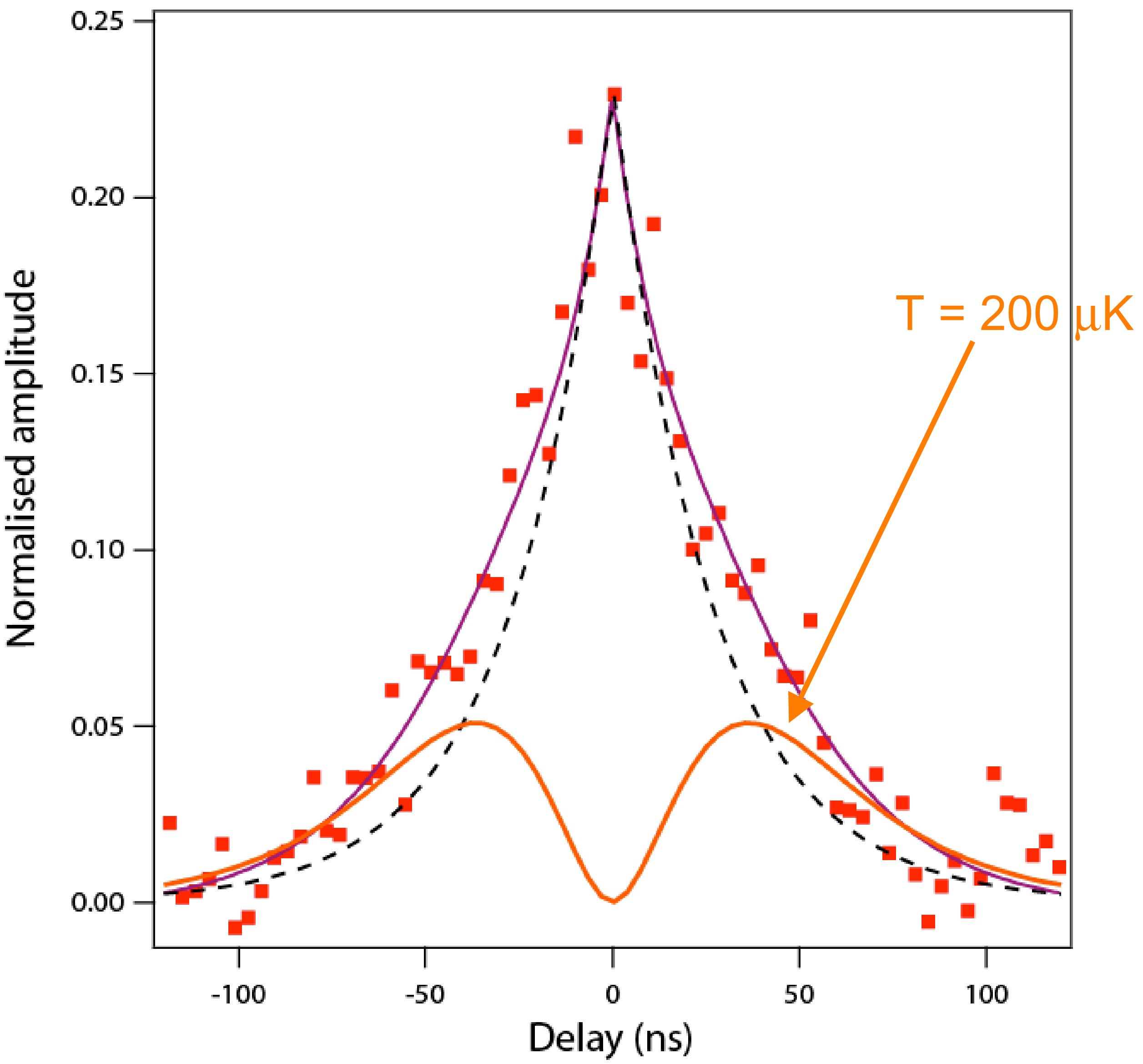
R = 0.73 ± 0.02

WHAT IF THE ATOMS DID NOT MOVE?



Field overlap R = 0.73

AND WHAT IF THE OVERLAP WERE PERFECT?



MUTUAL COHERENCE OF THE SOURCES?

The mutual temporal coherence is limited by

- linewidth of the transition: 6 MHz (T_1)
- motion of the atoms in the trap ⇒ inhomogeneous broadening (T_2^*)

$T = 180$ mK ⇒ $\Delta\nu = 2$ MHz

Depends on the number of excitations, and cooling duty cycle

Contrarily to solid state system, no homogeneous broadening (T_2', dephasing during T_1)

Source suitable for QIP as two atoms can be true « identical » single-photon sources