Single and paired photons from many entangled atoms

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Outline

- Why single (and paired) photons?
- Conditional single-photon generation: how it works.
- Experimental results:
  - Conversion of stored quantized spin gratings into single photons;
  - Narrowband identical photon generation (Hong-Ou-Mandel test);
  - Hong-Ou-Mandel effect with delayed photons: entanglement;
  - Interferometry with photon pairs;
  - Recovery efficiency and Fock state generation.

Why single photons?

- Proposed applications in quantum information processing and quantum communication:
  - Atoms have very long storage time for quantum states (quantum bits), but are difficult to transport.
  - Photons are ideal carriers of quantum information, but are difficult to store.
  - Coherent mapping between atomic and photonic qubits is an important building block for quantum information processing.

Why single photons?

- Proposed applications in quantum information processing and quantum communication:
  - Single-photon sources would enable quantum repeaters to extend entanglement and quantum communication over distances longer than the absorption length of optical fibers.

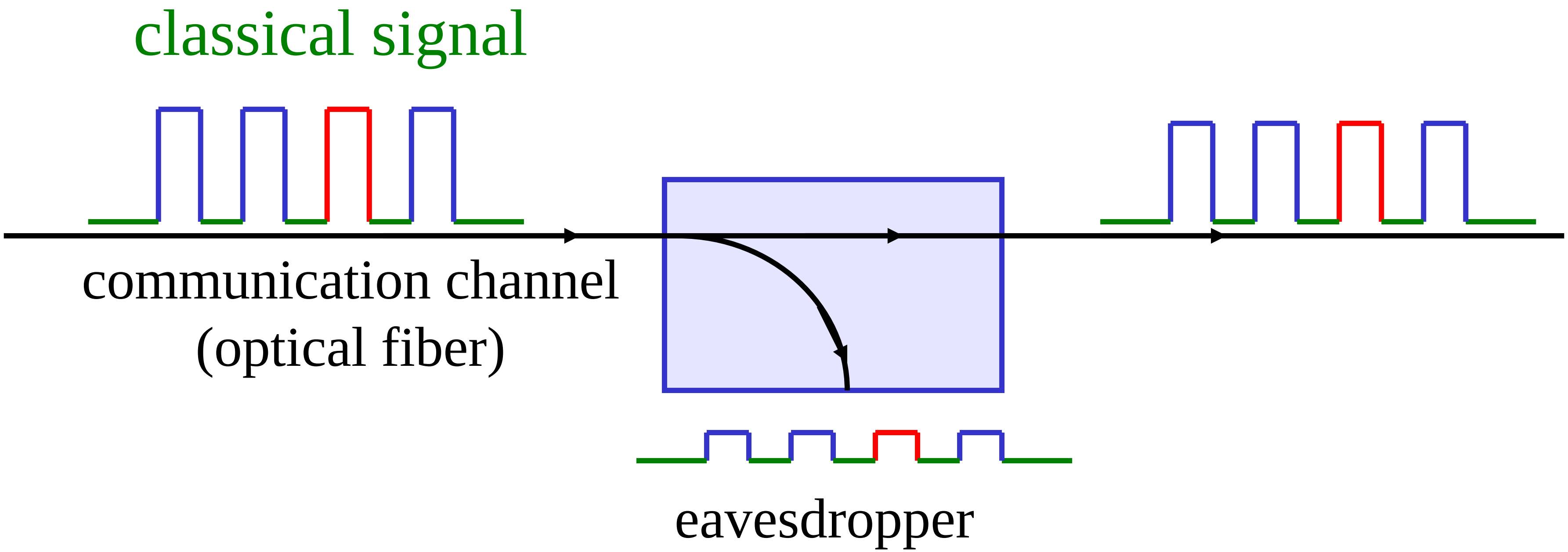
    Duan, Lukin, Cirac, and Zoller, Nature **414**, 413 (2001).

Why single photons?

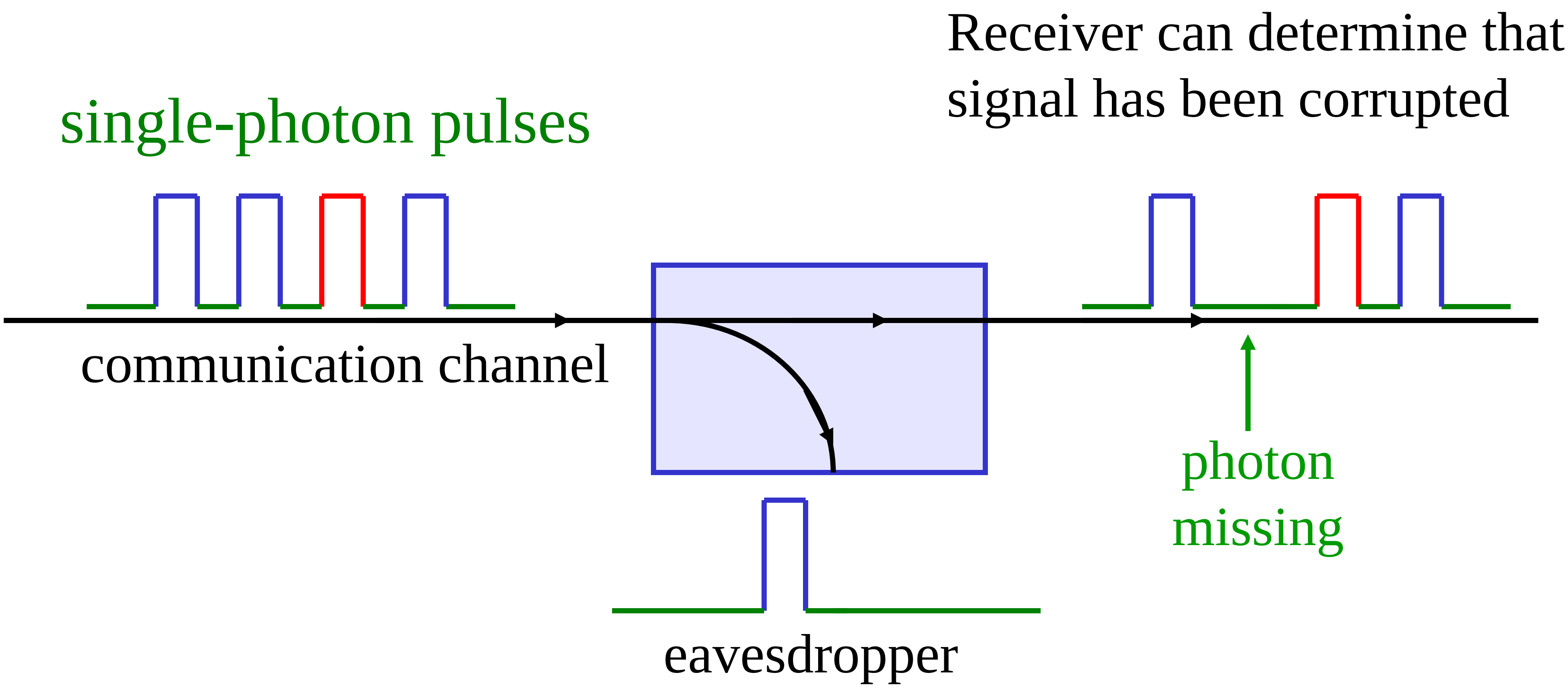
- States of definite photon number *n* (Fock states) are fundamental states in quantum mechanical description of light.
- Fock states are highly non-classical.

  Applications in sub-shot noise interferometry and precision measurements.
- Single-photon state *n*=1 is the simplest Fock state, can serve as building block.

Classical communication

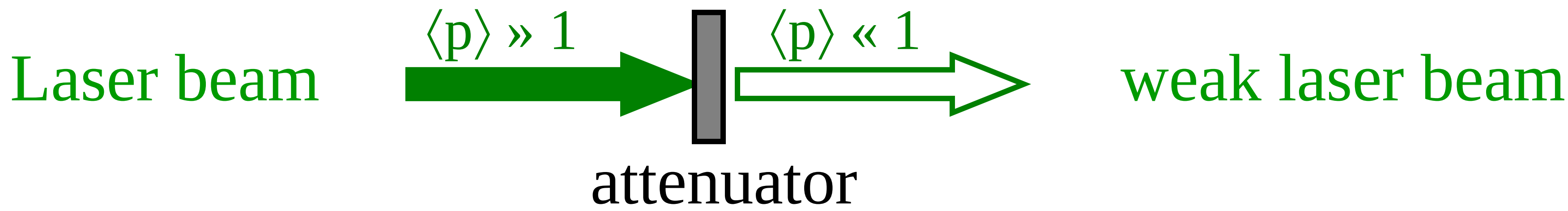


Secure quantum communication



Single-photon states necessary

Poissonian photon source: coherent state



Poissonian source:

Attenuated laser pulse with low average photon number $\langle p \rangle \ll 1$:

$\mathbf{p_0 \approx 1}$ $\mathbf{p_1 \approx \langle p \rangle}$ $\mathbf{p_2 \approx \langle p \rangle^2/2}$

Two-photon events can be suppressed by attenuating beam.

Is it possible to suppress zero-photon events as well?

Desired single-photon source

single-photon emitter single-photon detector

<u>Desired single-photon source</u>:

$p_0 \approx 0$ $p_1 \approx 1$ $p_2 \approx 0$

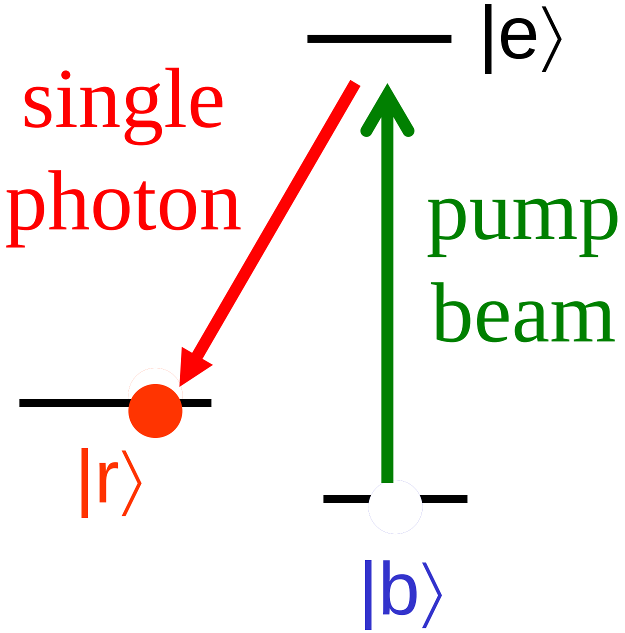
How to overcome inherent randomness in photon generation?

Use single particle or single excitation.

How to achieve directional emission?

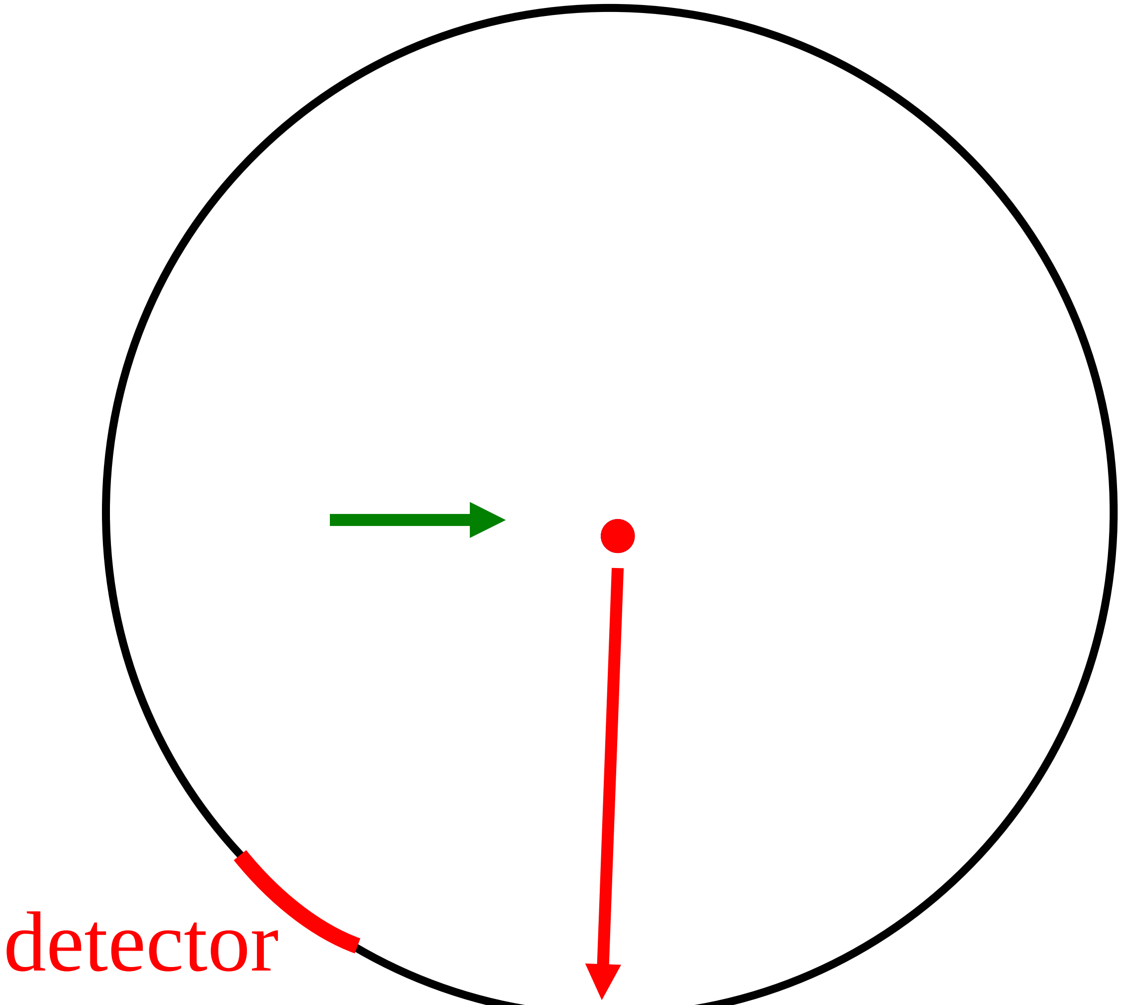
Use collective excitation.

Single three-level (λ) atom emits single photon



Photon emission on demand.

Directionality problem: resonator.

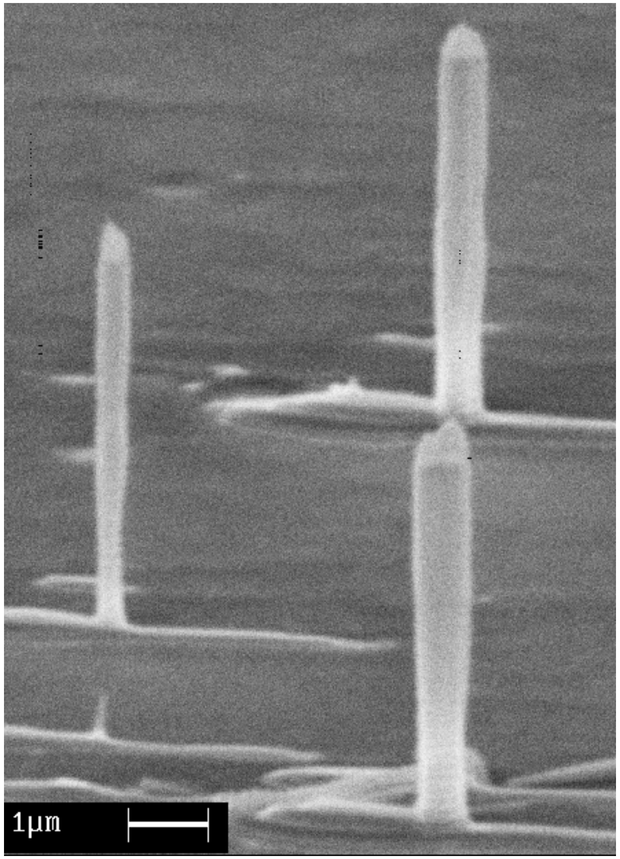


Single-photon sources with resonators

- Single quantum dots with integrated resonator structures. (Stanford).

  Suppression of two-photon events relative to Poissonian distribution by factor 50.

  Broadband photons, collection efficiency to be improved.



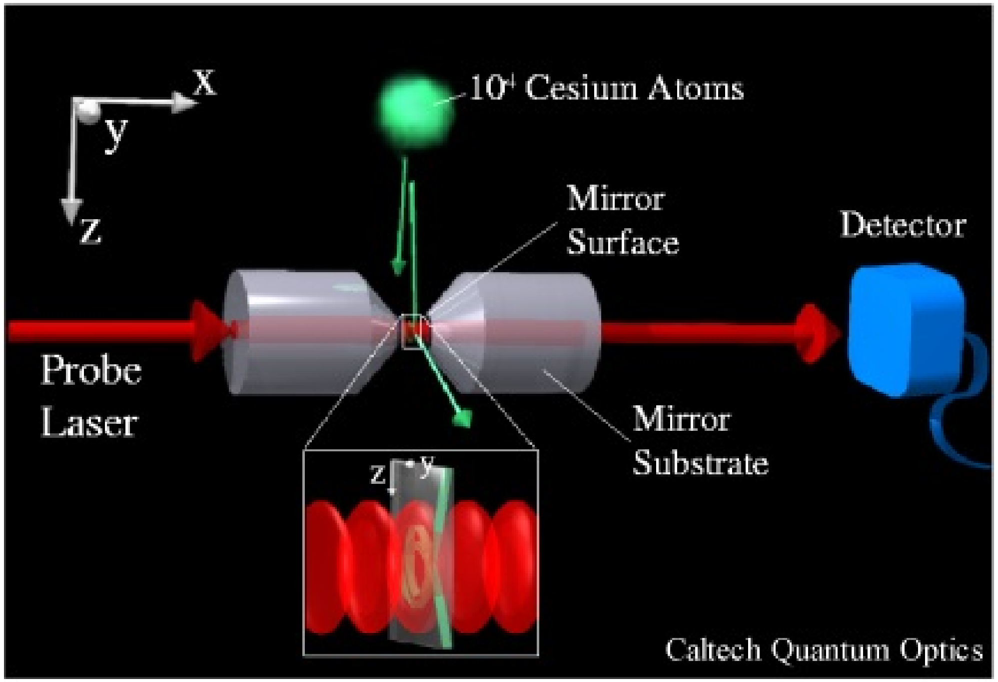
Vuckovic et al., Appl. Phys. Lett. **82**, 3956 (2003).

Single-photon sources with resonators

- Single atoms strongly coupled to a macroscopic resonator produce single photons (Caltech, Max-Planck Institute).
- Requires strong coupling regime (probability of emission into resonator must exceed emission into 4π).

McKeever et al., Science **303**, 1994 (2004).

Kuhn, Henrich, and Rempe, Phys. Rev. Lett. **89**, 067901 (2000).



Single-photon sources with resonators

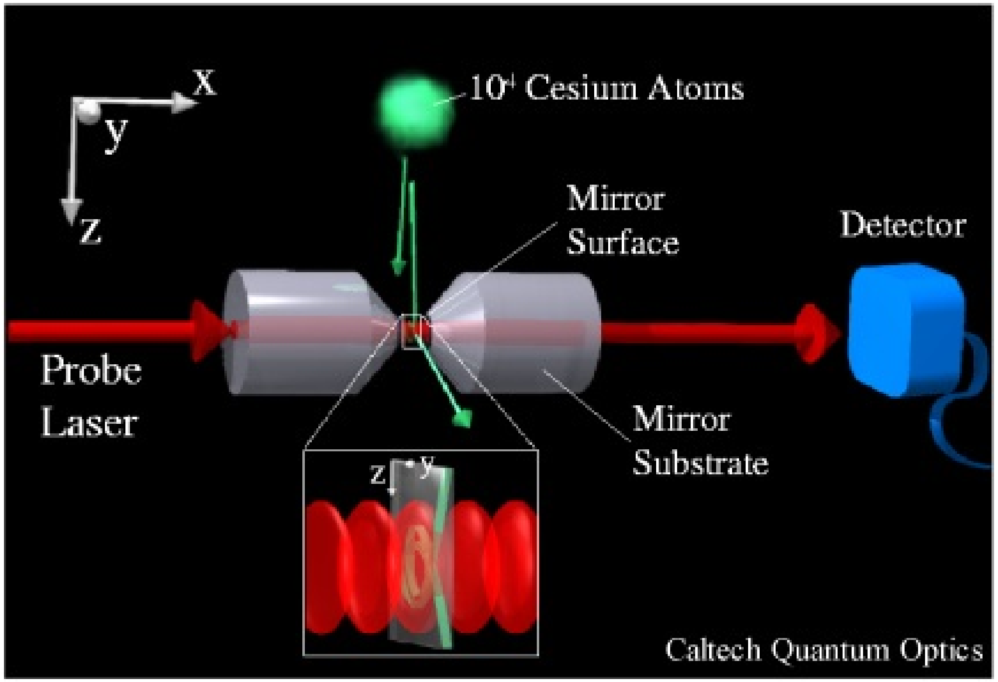
- Single atoms strongly coupled to a resonator can emit single narrowband photons into a well-defined direction, but there are severe technical problems:

Resonator finesse F=400,000;

Control of atomic position with resolution below optical wavelength;

Confinement of atom;

Mirror losses.



Avoiding the strong-coupling regime

- Use many atoms instead to achieve directional emission.

Dicke superradiance, proposal by

Duan, Lukin, Cirac, Zoller, Nature **414**, 413 (2001).

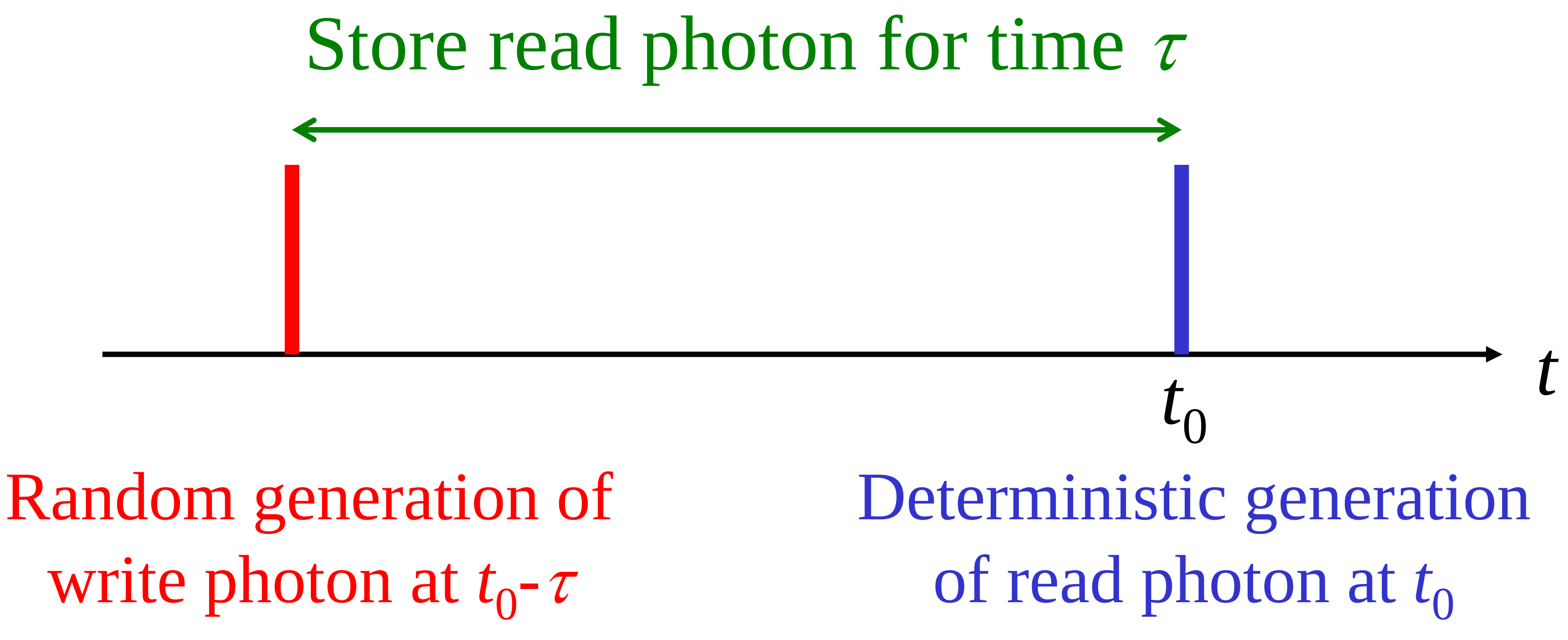
How can we make sample emit into a small solid angle?

How can we make many (10^6) atoms emit exactly one photon?

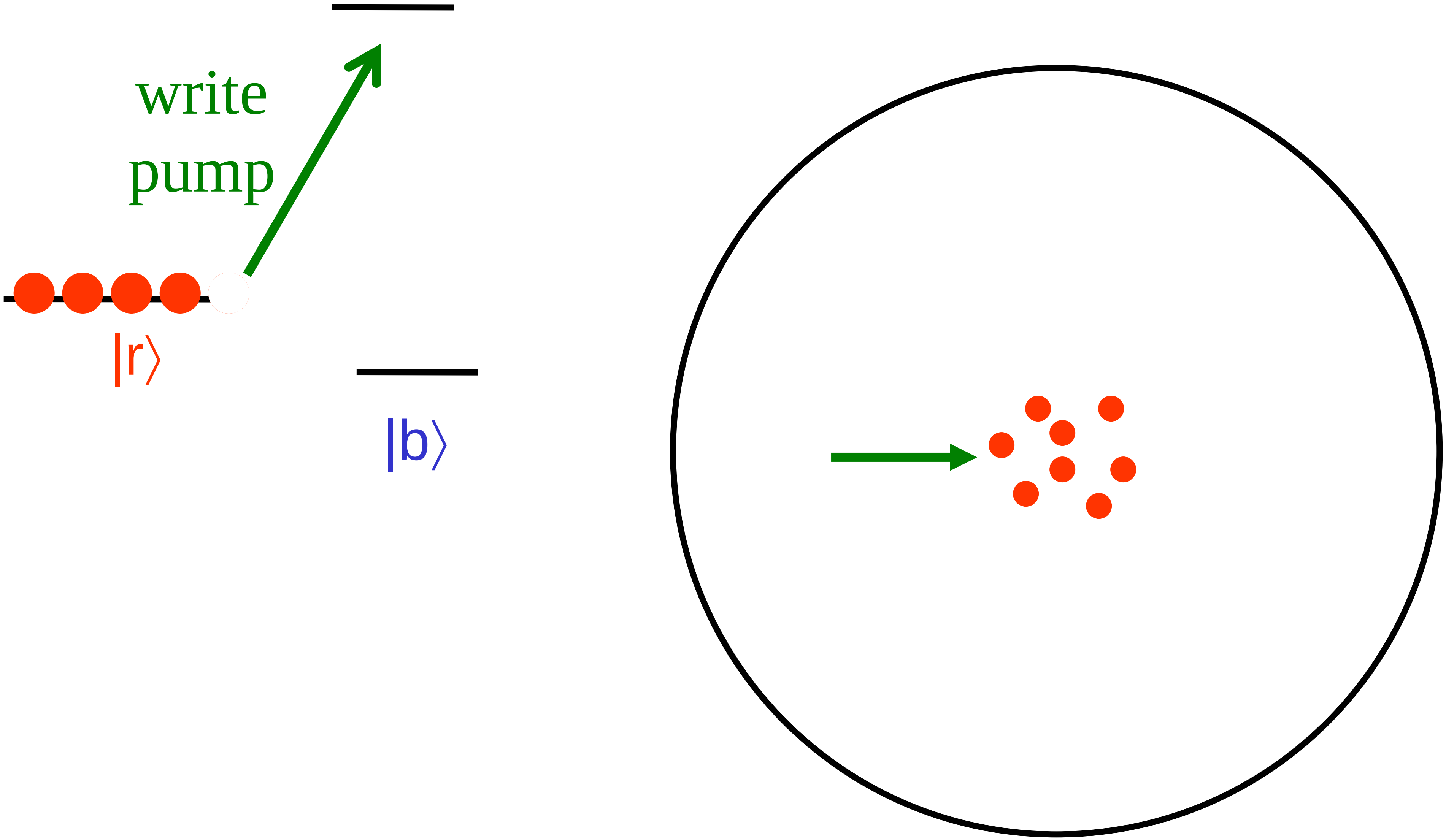
Single-photon generation by many atoms: Semiclassical picture

Poissonian photon pair and memory = single photon on demand

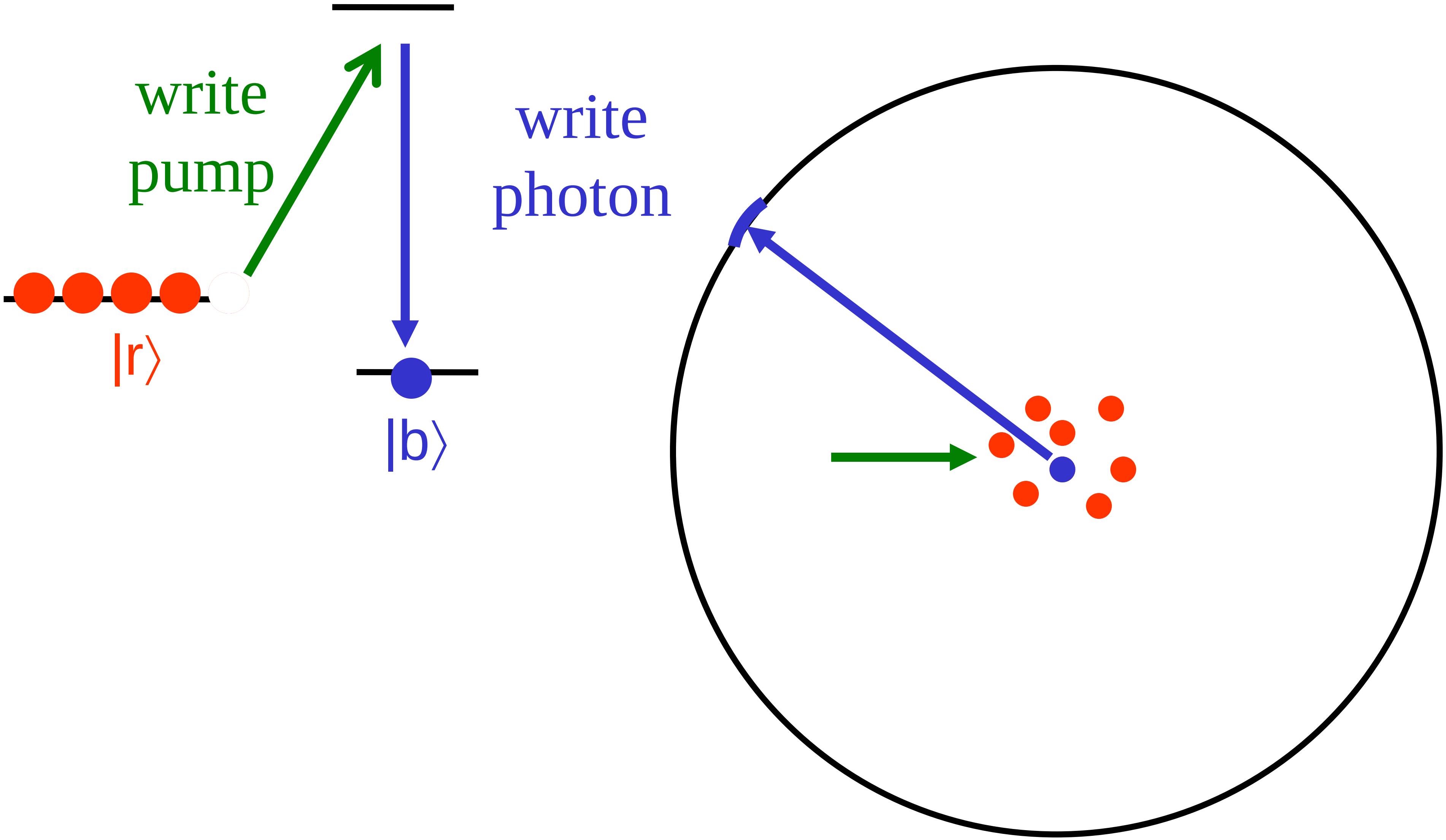
- A Poissonian generator of photon pairs can serve as a deterministic single photon source if a photon can be stored.



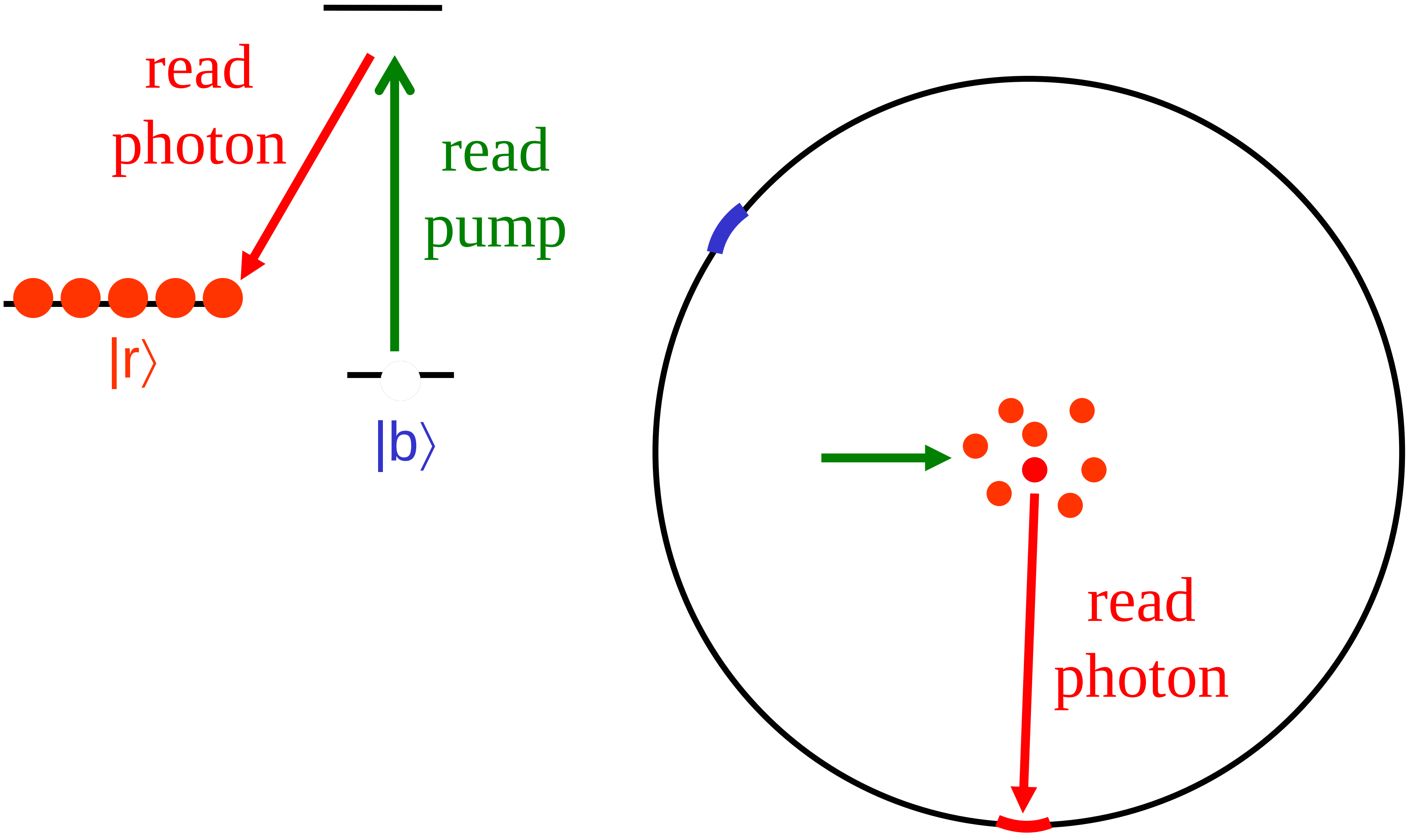
Conditional single-photon emission by many atoms



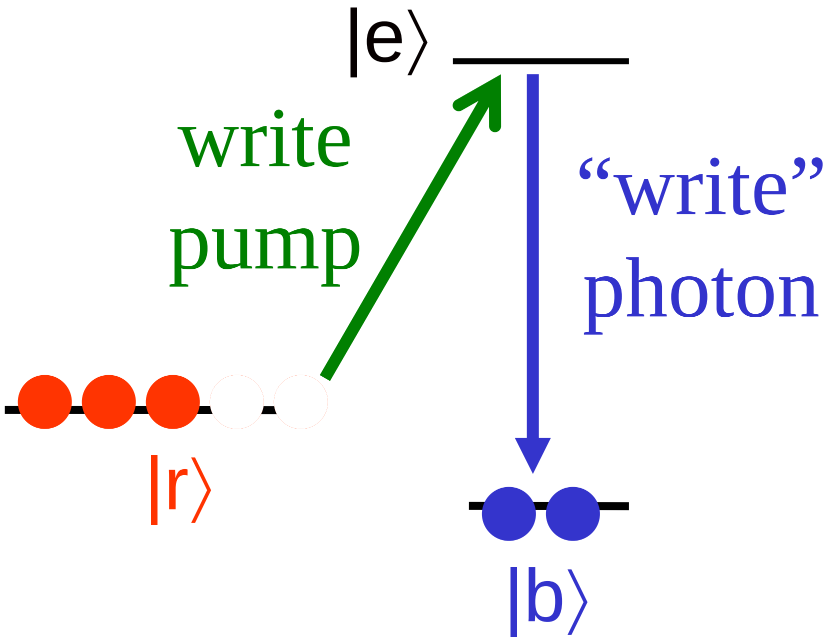
Random generation of “write” photon



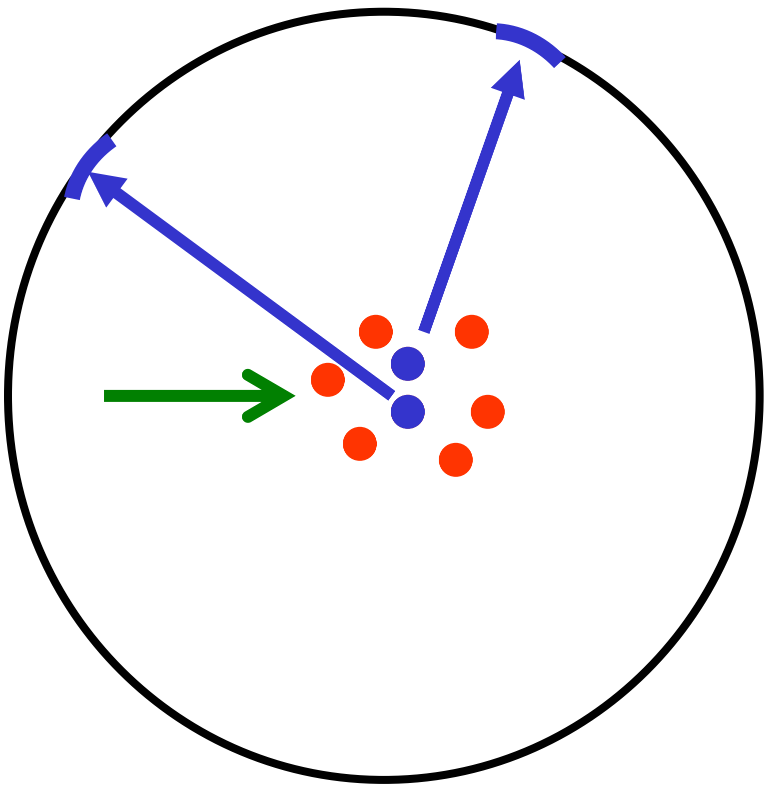
Conditional generation of “read” photon



Two-atom transfer can be suppressed by reducing transfer probability

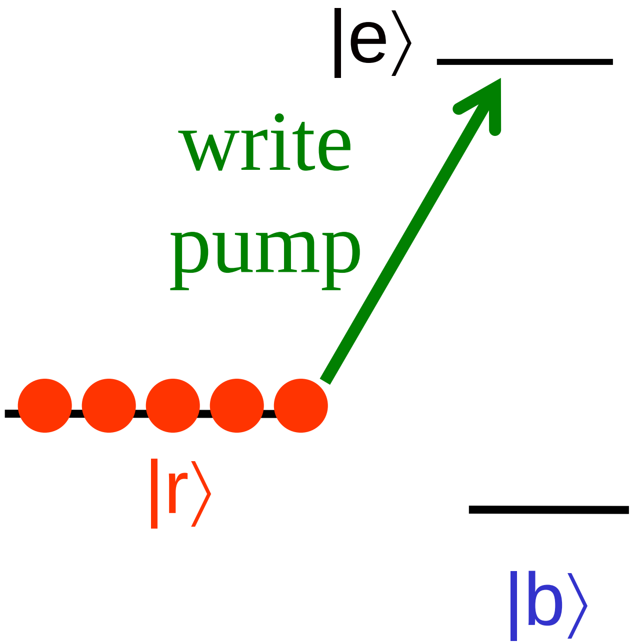


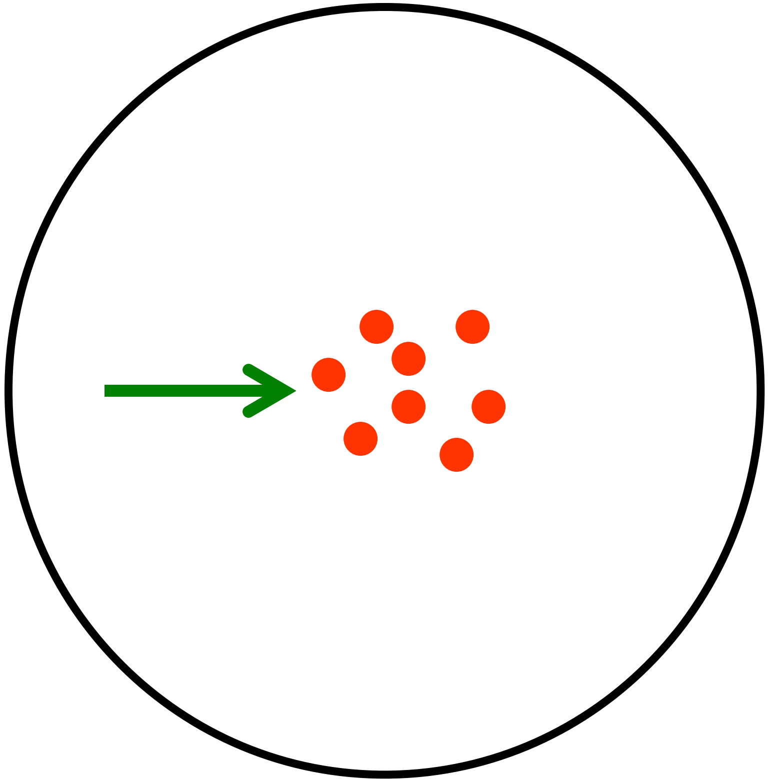
Suppressed as p^2 if transfer probability $p \ll 1$



But: if $p \ll 1$ then large probability for zero-atom transfer

Zero-atom transfer can be reduced conditionally



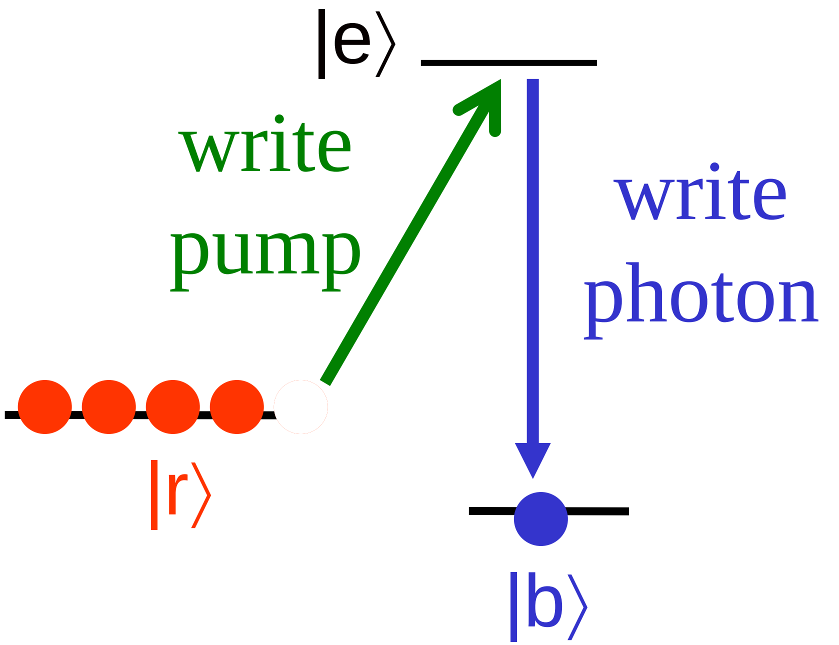


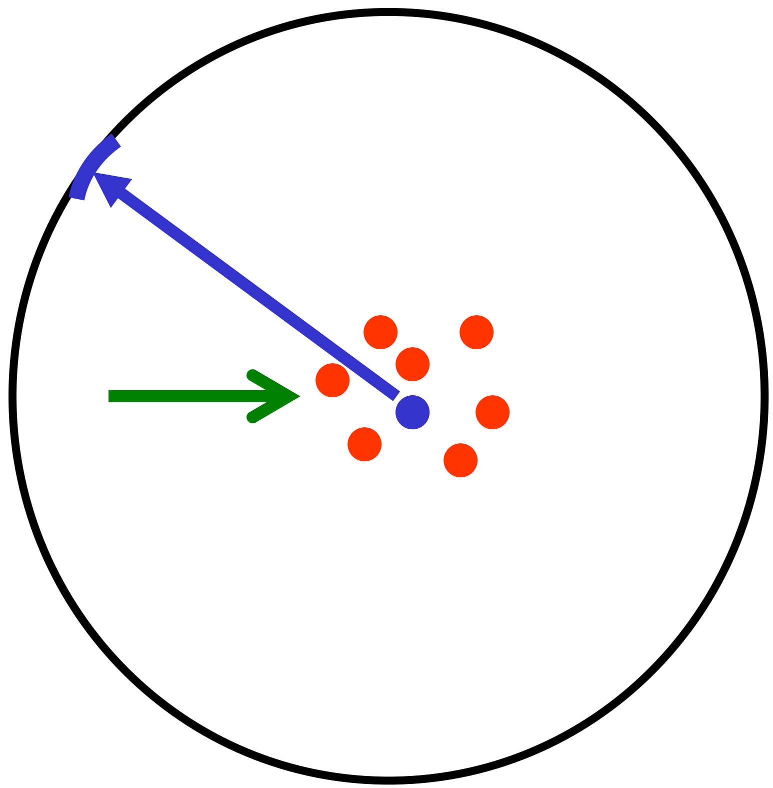
If no write photon detected,
restore original situation and
repeat experiment

(Duan, Lukin, Cirac, Zoller).

Kuzmich, Kimble, Heidelberg groups

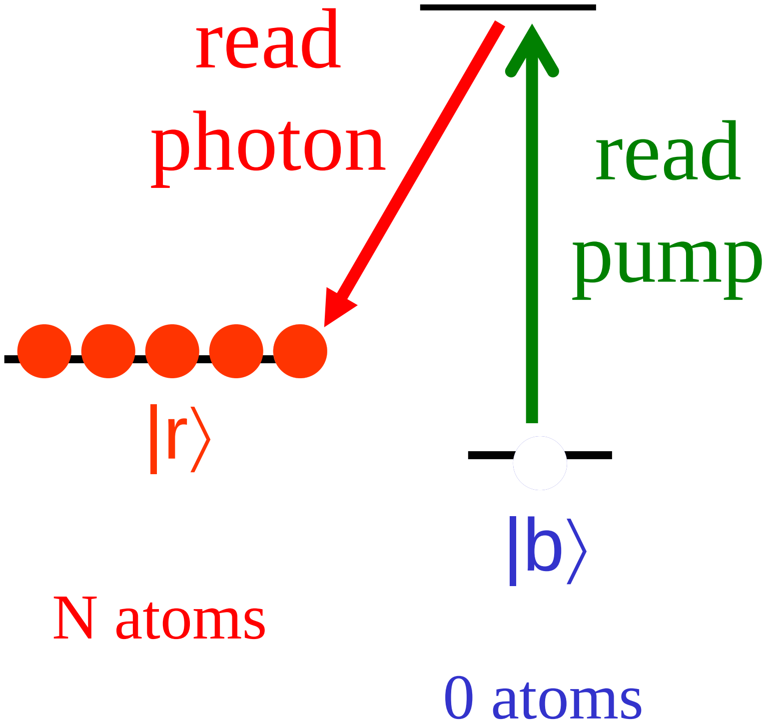
Repeat experiment until successful



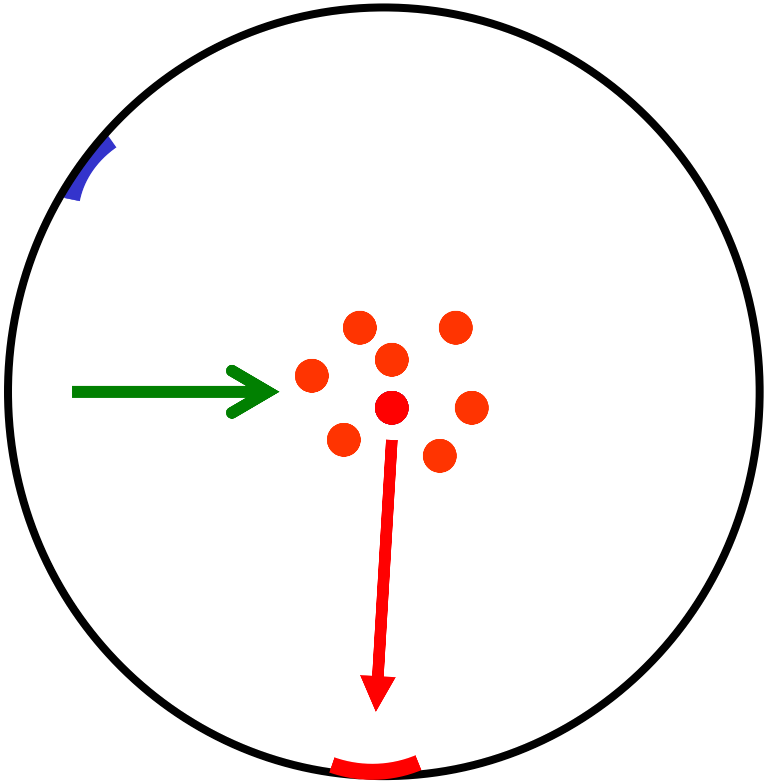


Detection of write photon prepares single-photon source (to be read out at a desired later time).

Triggered (conditional) single-photon generation from single pumped atom

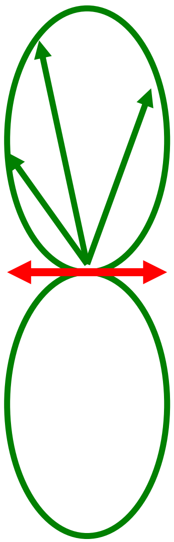


Why many atoms?

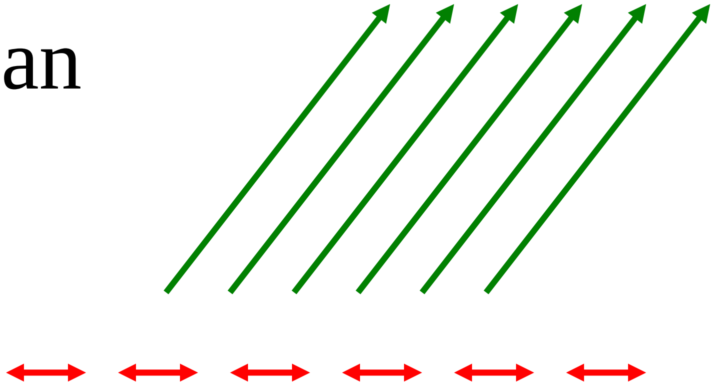


How to create directional source:

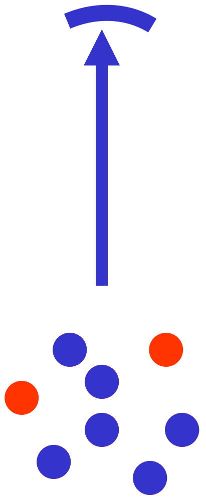
- A single dipole antenna emits dipole pattern.



- An array of dipole antennas can emit in a specific direction.



Collective emission enables directional source



Any atom could have emitted,
we cannot know which one.

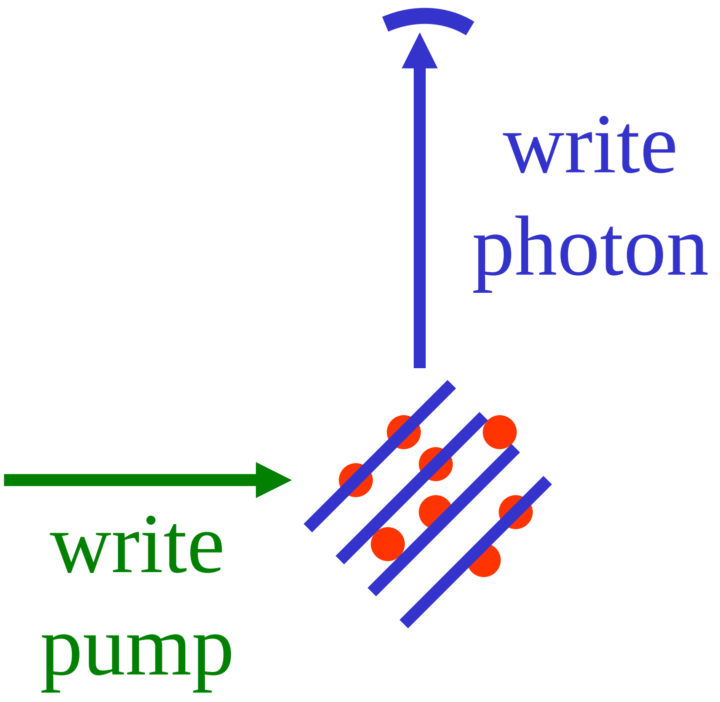
Sample is in an superposition of states (entangled state):

Addition of quantum mechanical amplitudes with correct phases:

Single-photon emission writes polarization grating with a single quantized excitation into many-atom system.

Collective emission enables directional source

Emitted single write photon writes phased array of dipole antennas (holographic grating) into atomic sample.

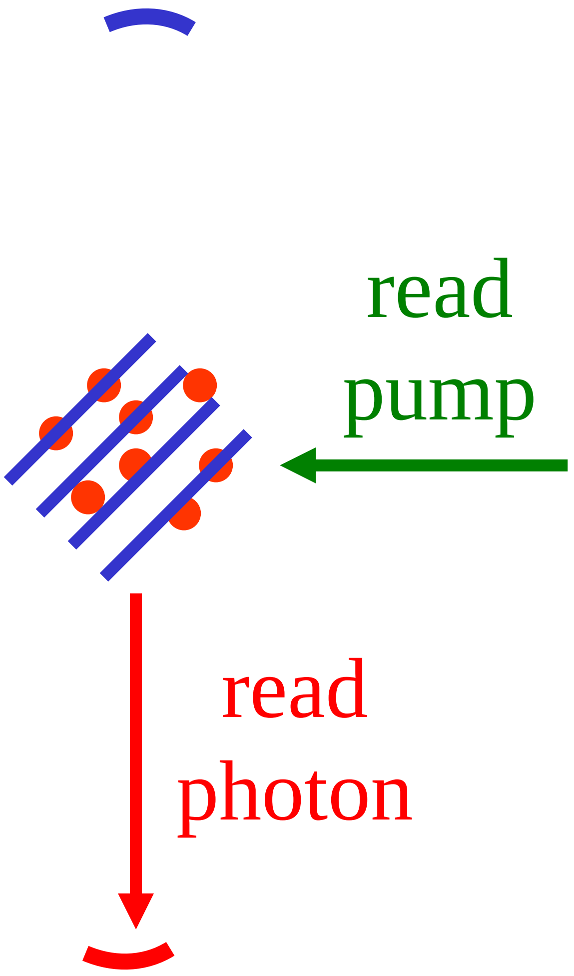


Holographic grating with quantized excitations

Emitted single write photon writes phased array of dipole antennas (holographic grating) into atomic sample.

Grating contains only one excitation (one quantum of atomic spin).

Pump beam Bragg-scatters off the grating into the detector: directional emission.



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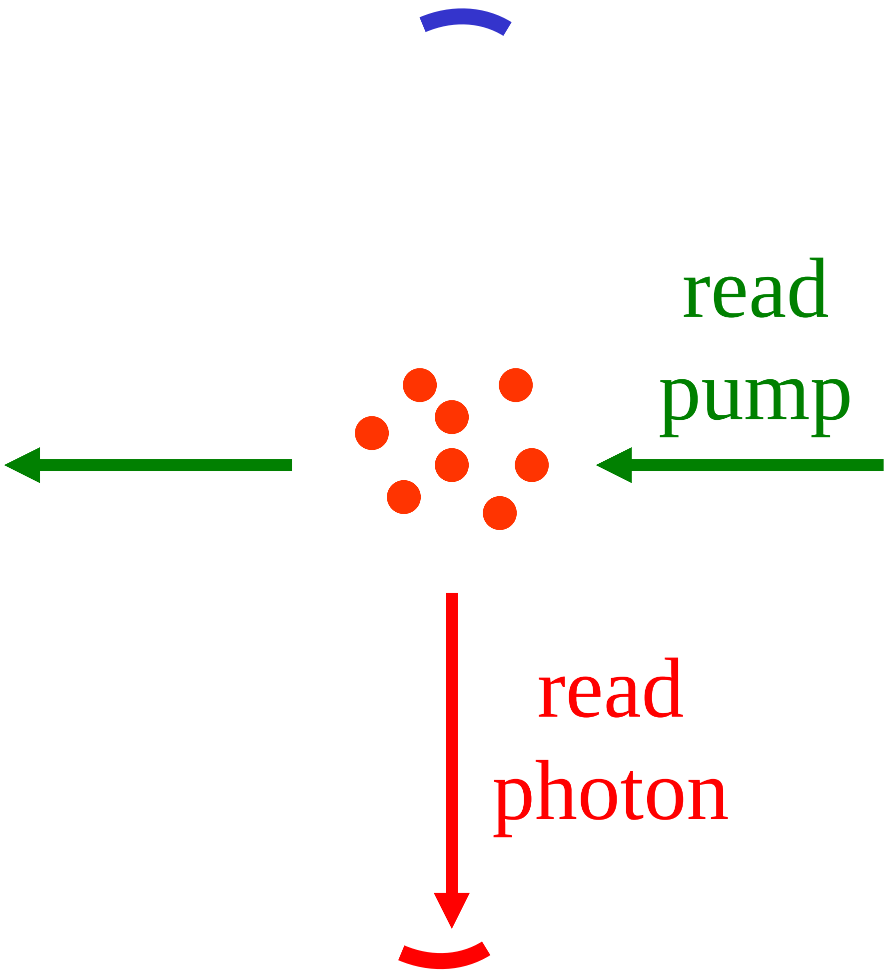
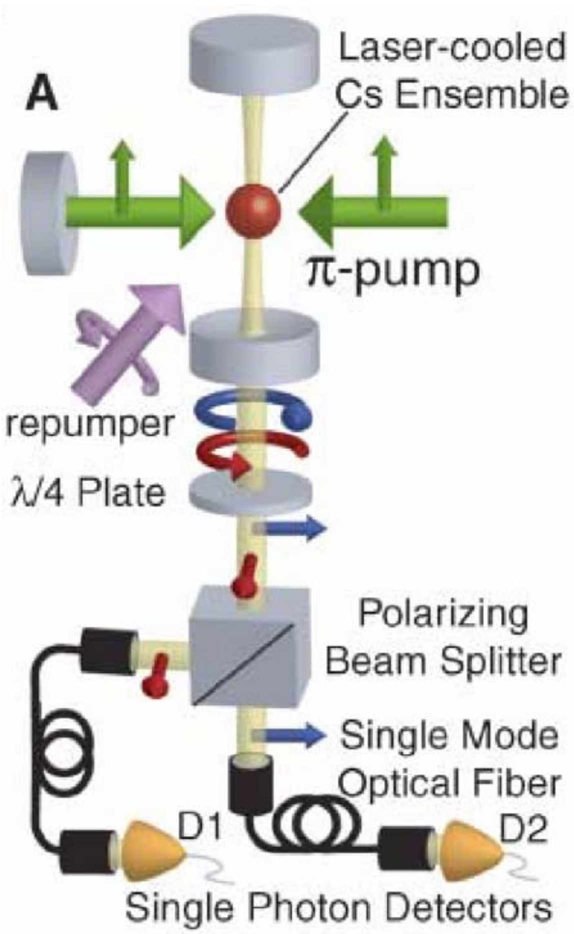


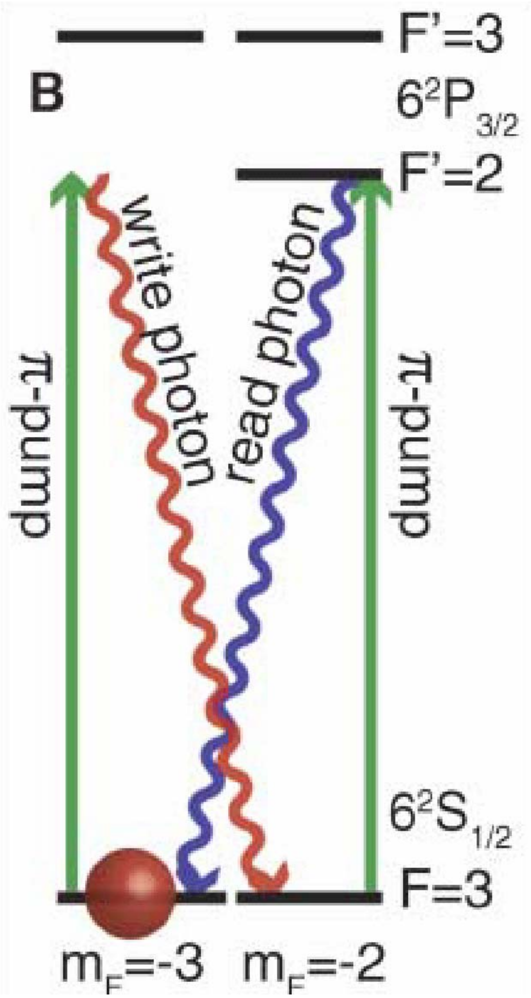
Grating disappears after single photon has been emitted: no further Bragg-scattered photons .

Experimental results:

Near-simultaneous pair generation

Setup photon pair generation

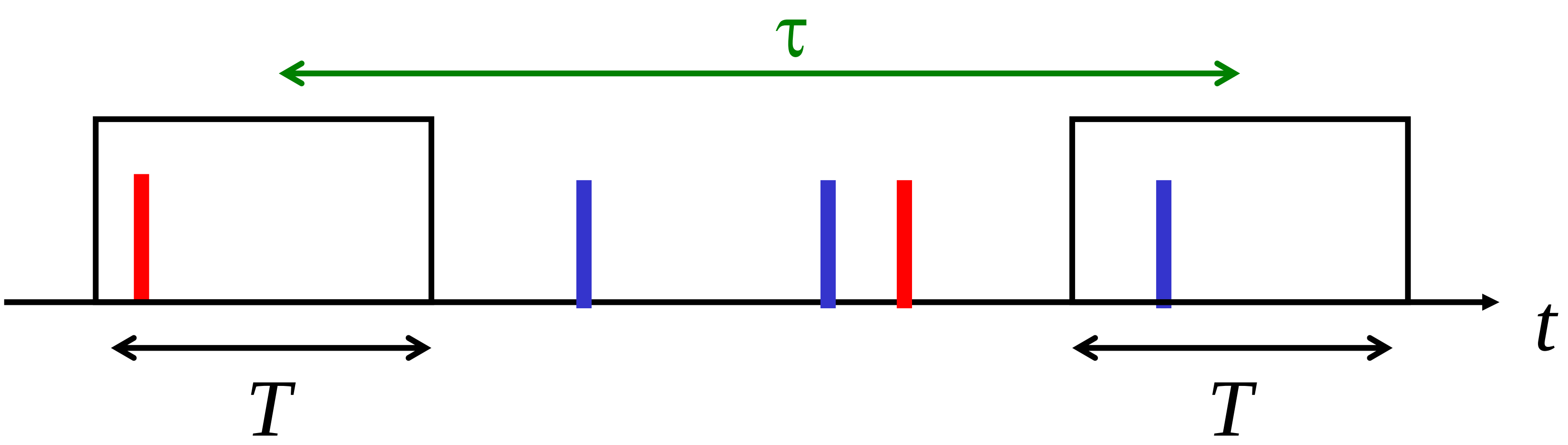




Two-photon correlation functions

$$g_{wr}(\tau) = \langle n_r(\tau)\, n_w(0) \rangle_T \,/\, \langle n_w \rangle_T \langle n_r \rangle_T$$

The two-photon correlation function is the number of coincidences, normalized to the expected number for a Poissonian source.



Correlation functions for classical sources

The two-photon correlation function is the number of coincidences, normalized to the expected number for a Poissonian source.

Classical autocorrelation functions have $g_{aa} \geq 1$:

$g_{rr} = 1$ (Poissonian or laser);

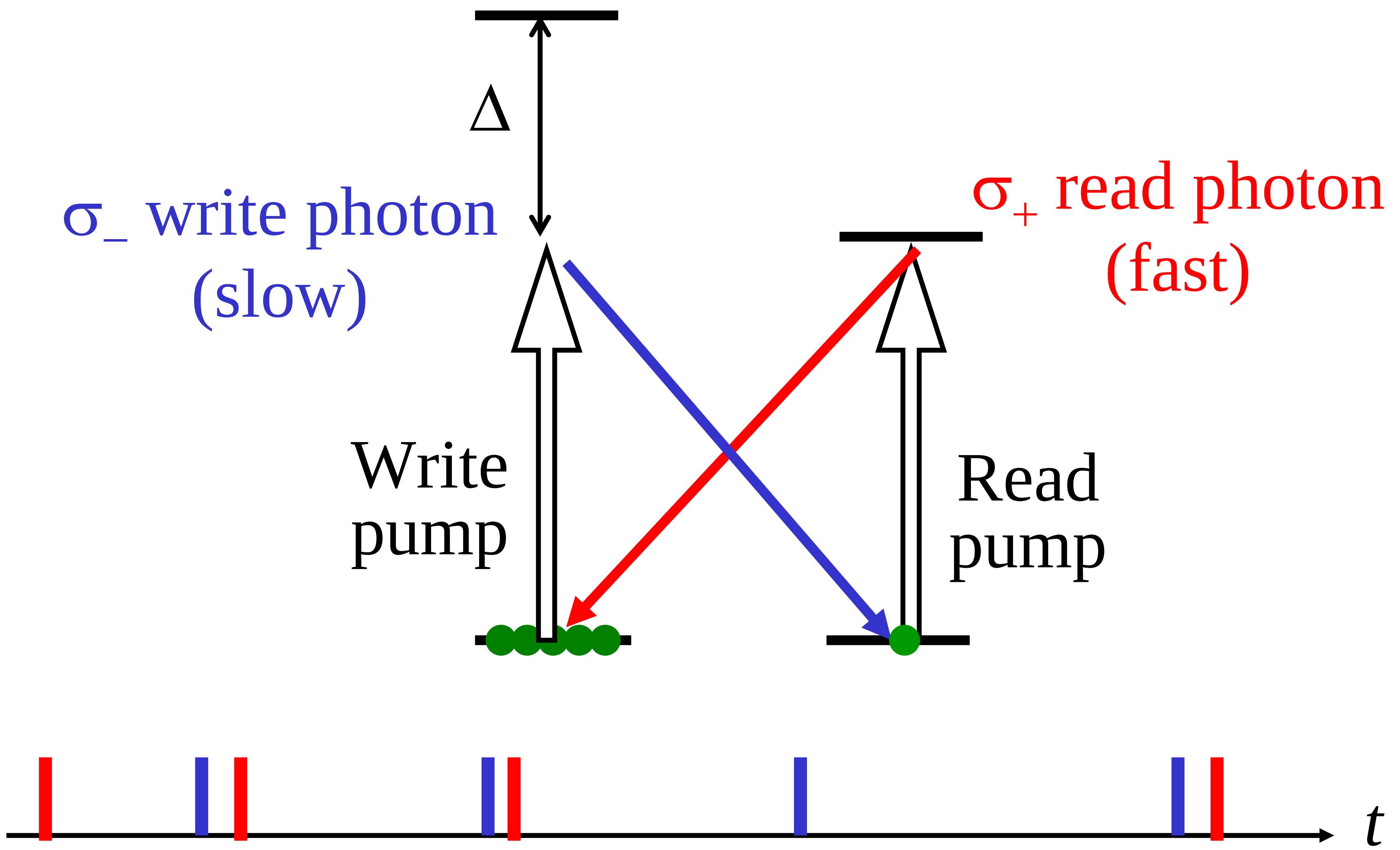
$g_{rr} = 2$ (Classical field);

$g_{rr} > 2$ (intensity noise);

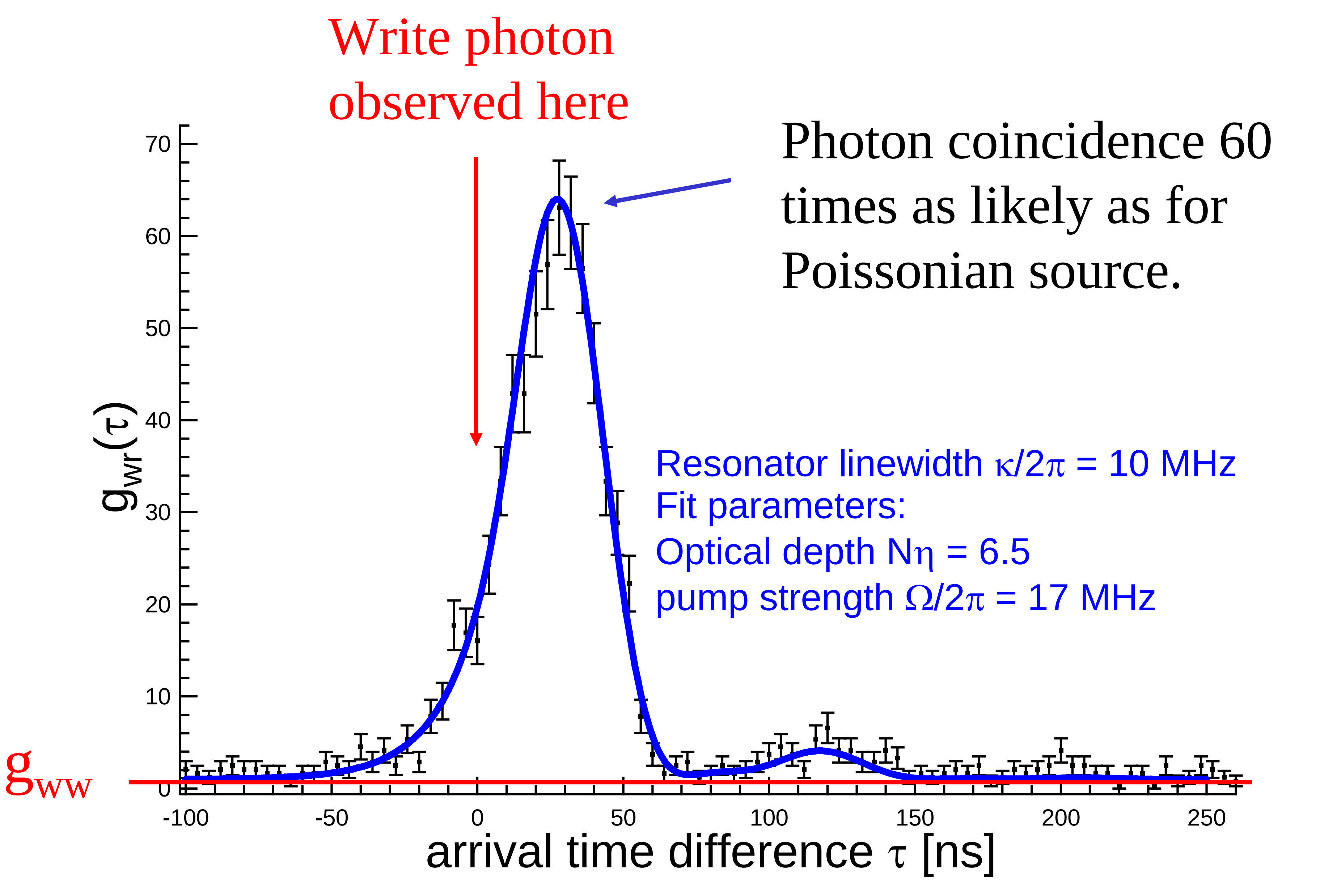
$g_{rr} < 1$ sub-poissonian photon source;

$g_{rr} = 0$ ideal single-photon source.

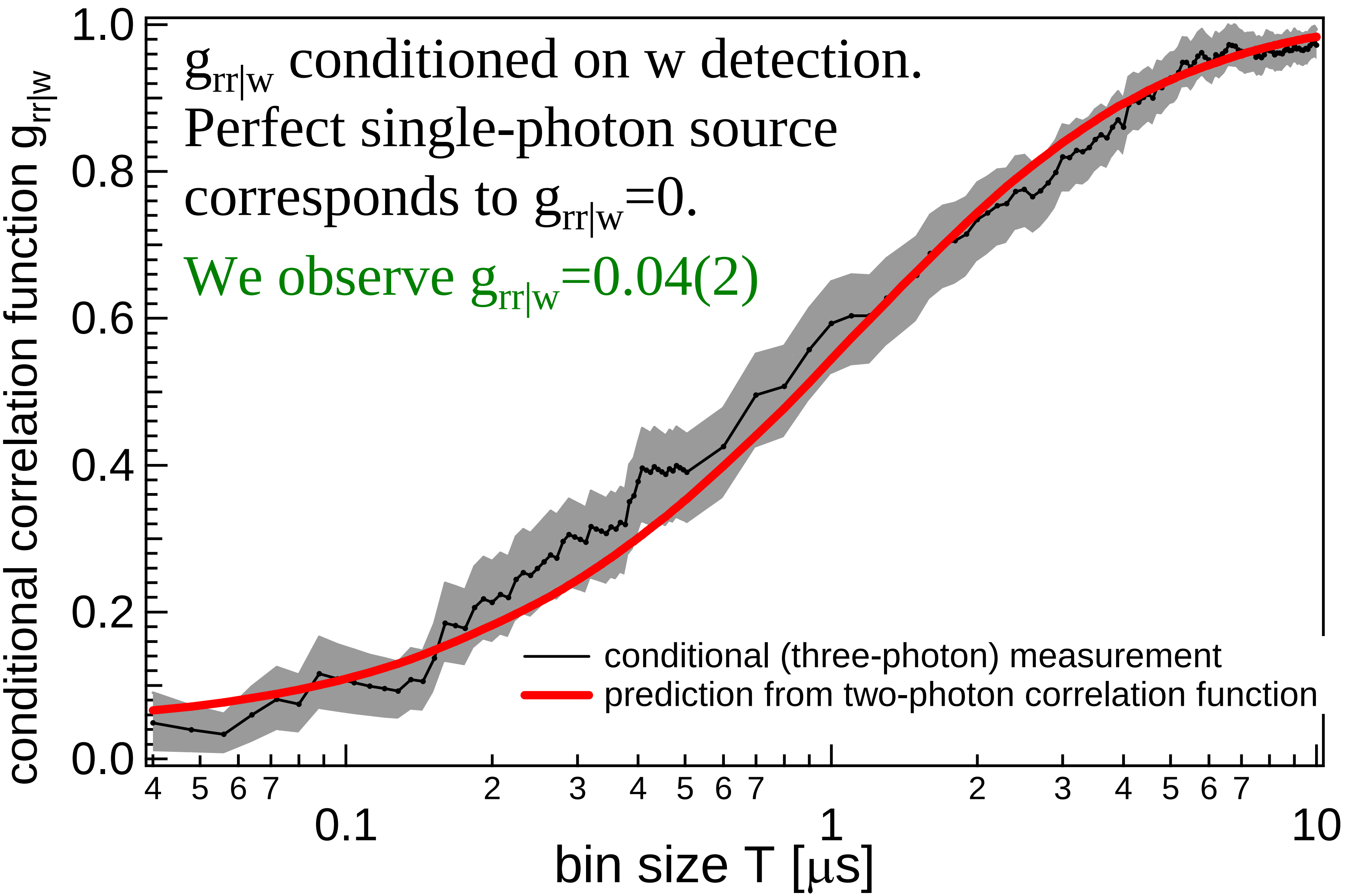
Near-simultaneous photon generation: four-wave mixing at the twin-photon level



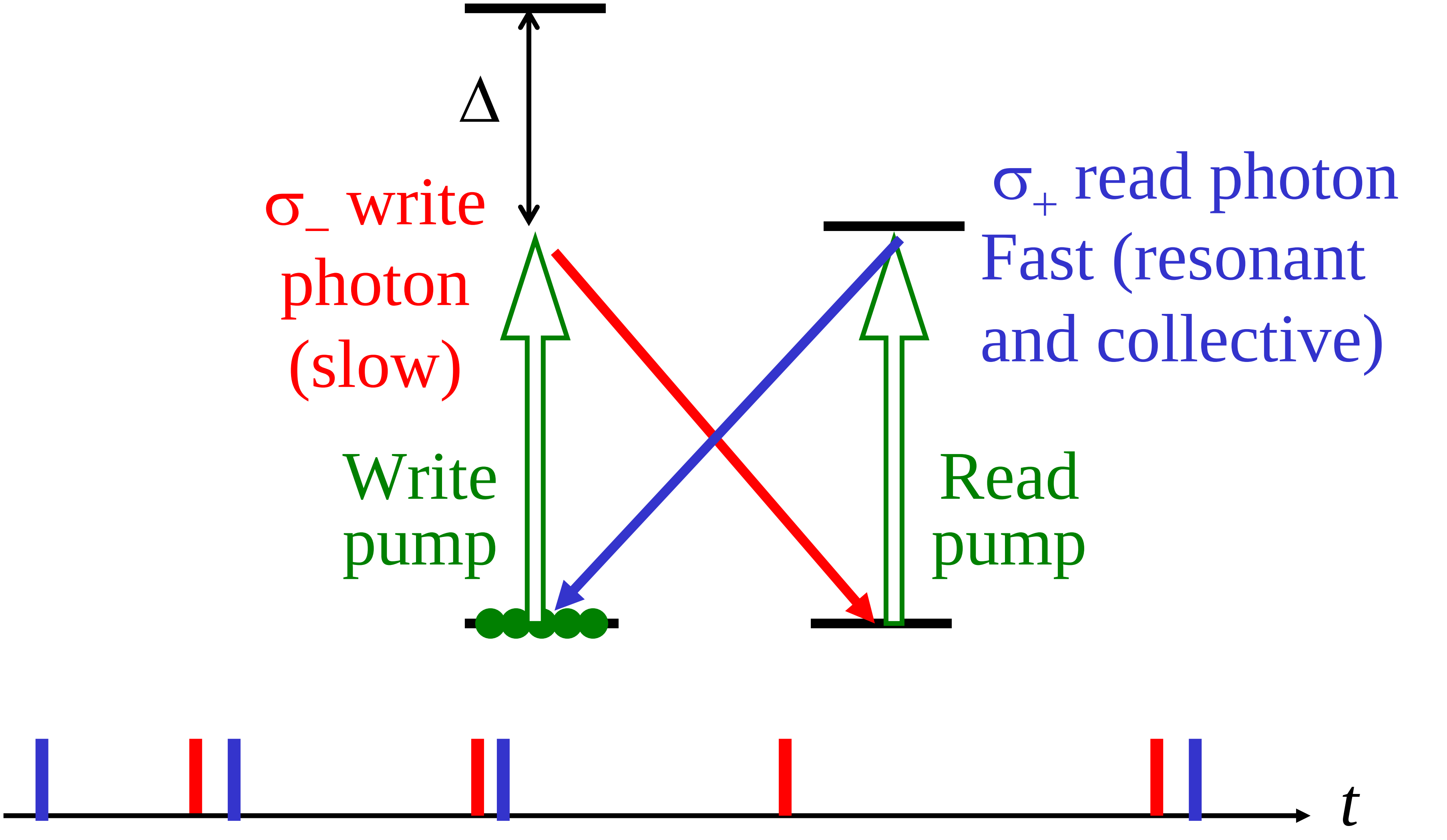
The waveform of the read photon



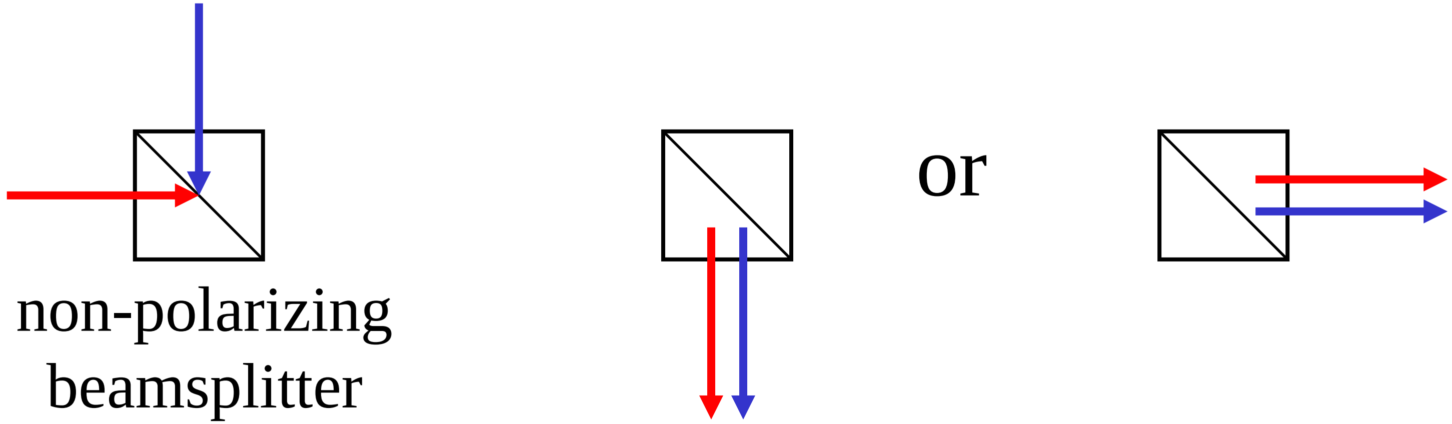
Quality of the conditional single-photon source



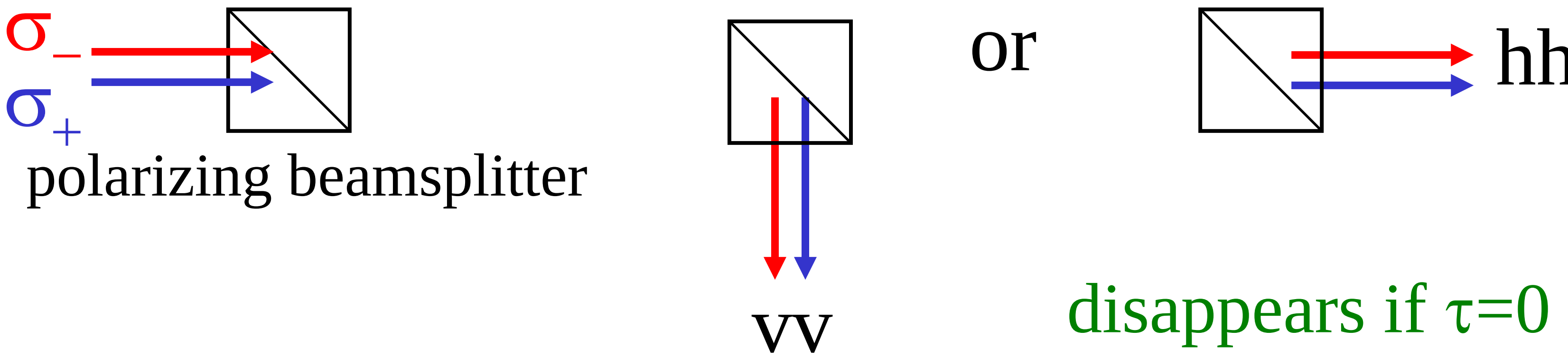
Are the write and read photon identical?



Hong-Ou-Mandel effect for identical photons



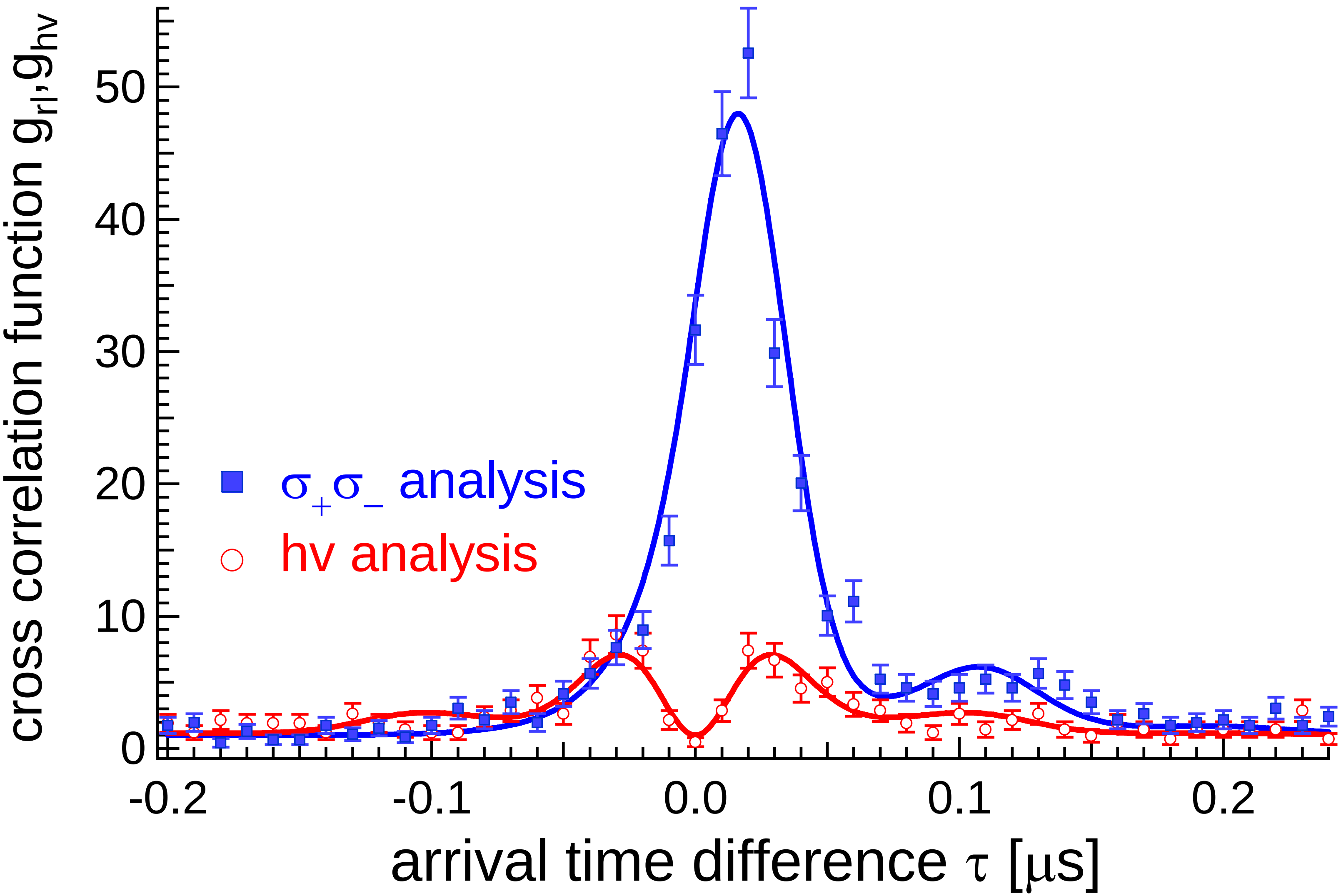
Identical photons always emerge together.



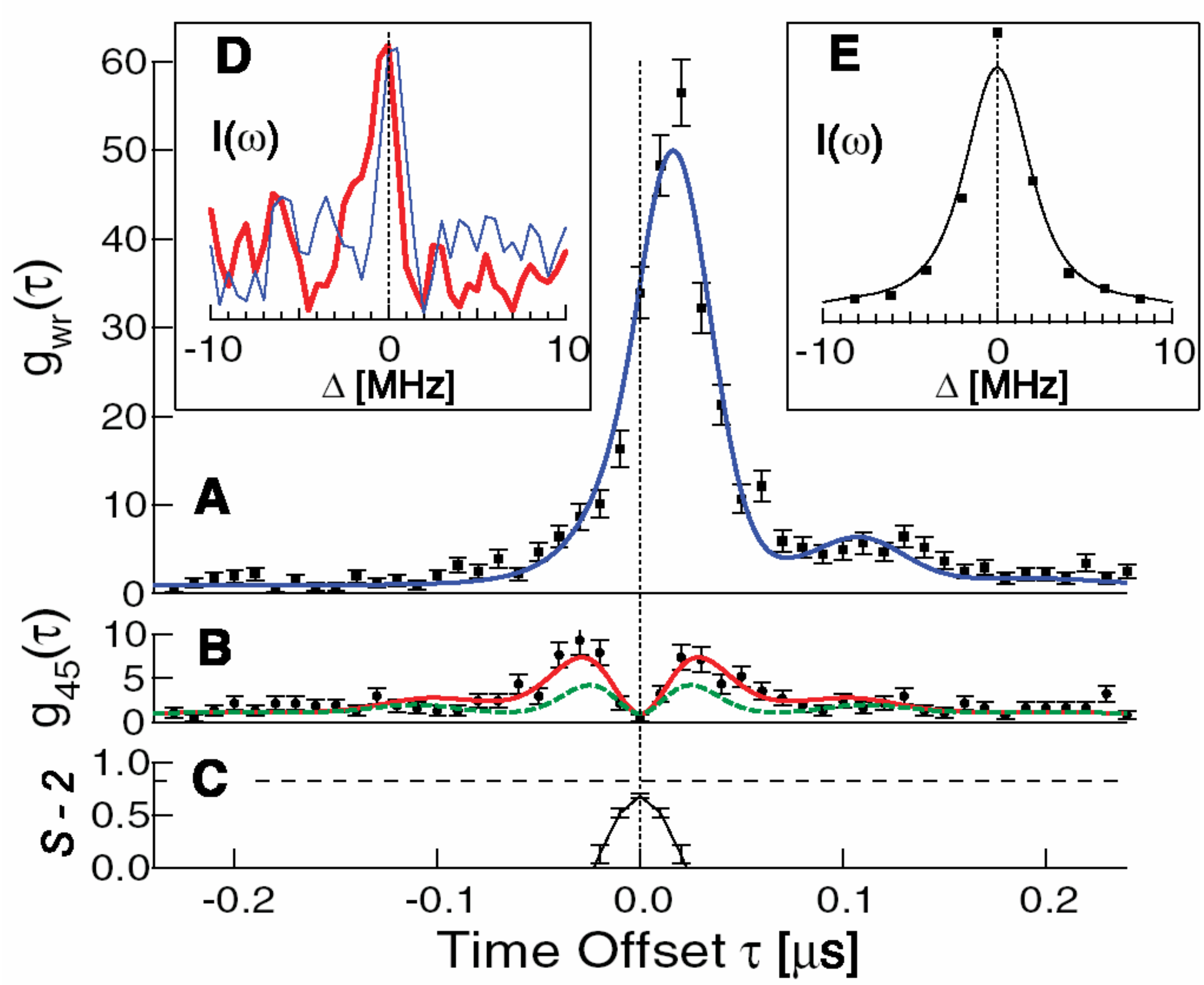
disappears if $\tau=0$ and photons identical

$$\sigma_-(\tau)\,\sigma_+(0) = (h-iv)(h+iv) = hh + vv + i(hv-vh)$$

Hong-Ou-Mandel dip for identical photons

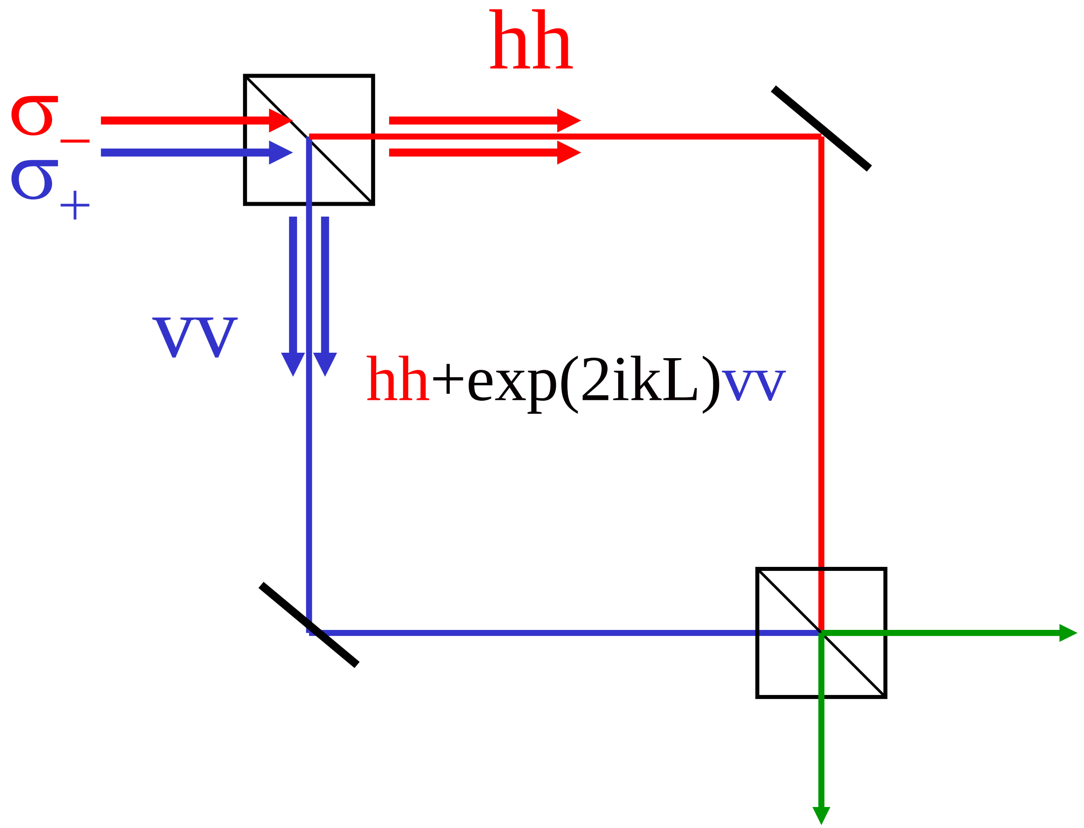


Pair correlation function, Hong-Ou-Mandel dip, photon bandwidth and Bell parameter



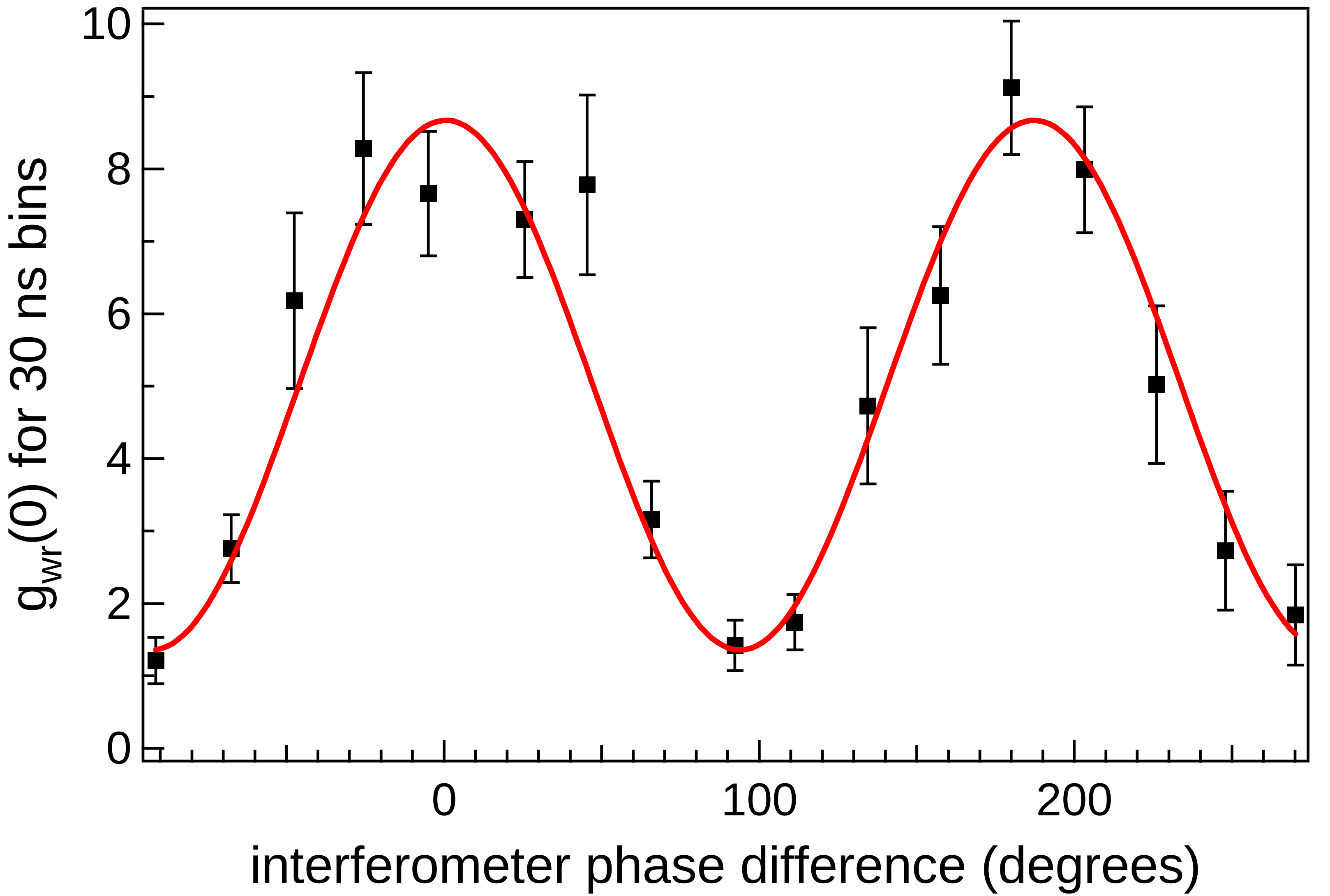
J. Thompson, J. Simon, H. Loh, and V. Vuletic, Science **303**,71 (2006).

Two-photon interferometry below the shot-noise limit

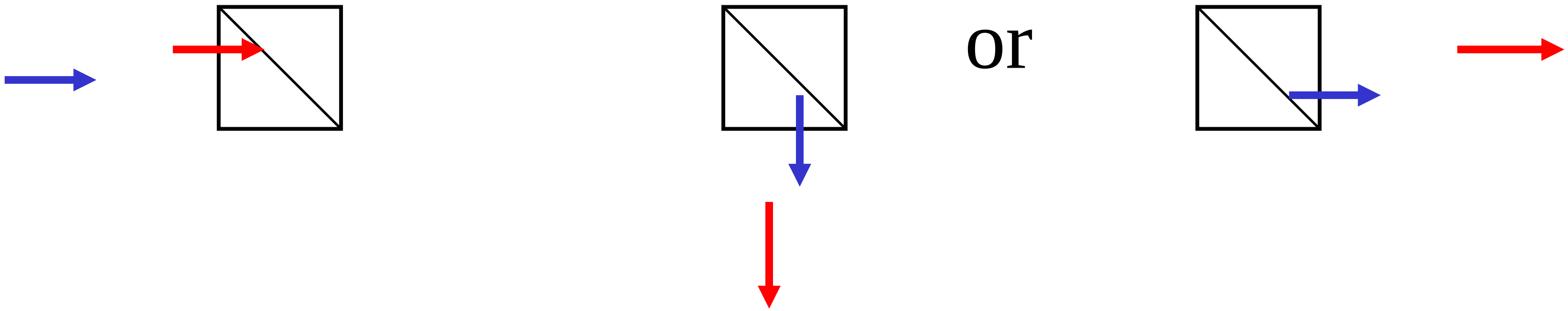


Correlations oscillate twice as fast as single-photon signal

Two-photon interferometer for simultaneously arriving photons



Hong-Ou-Mandel dip for delayed photons?

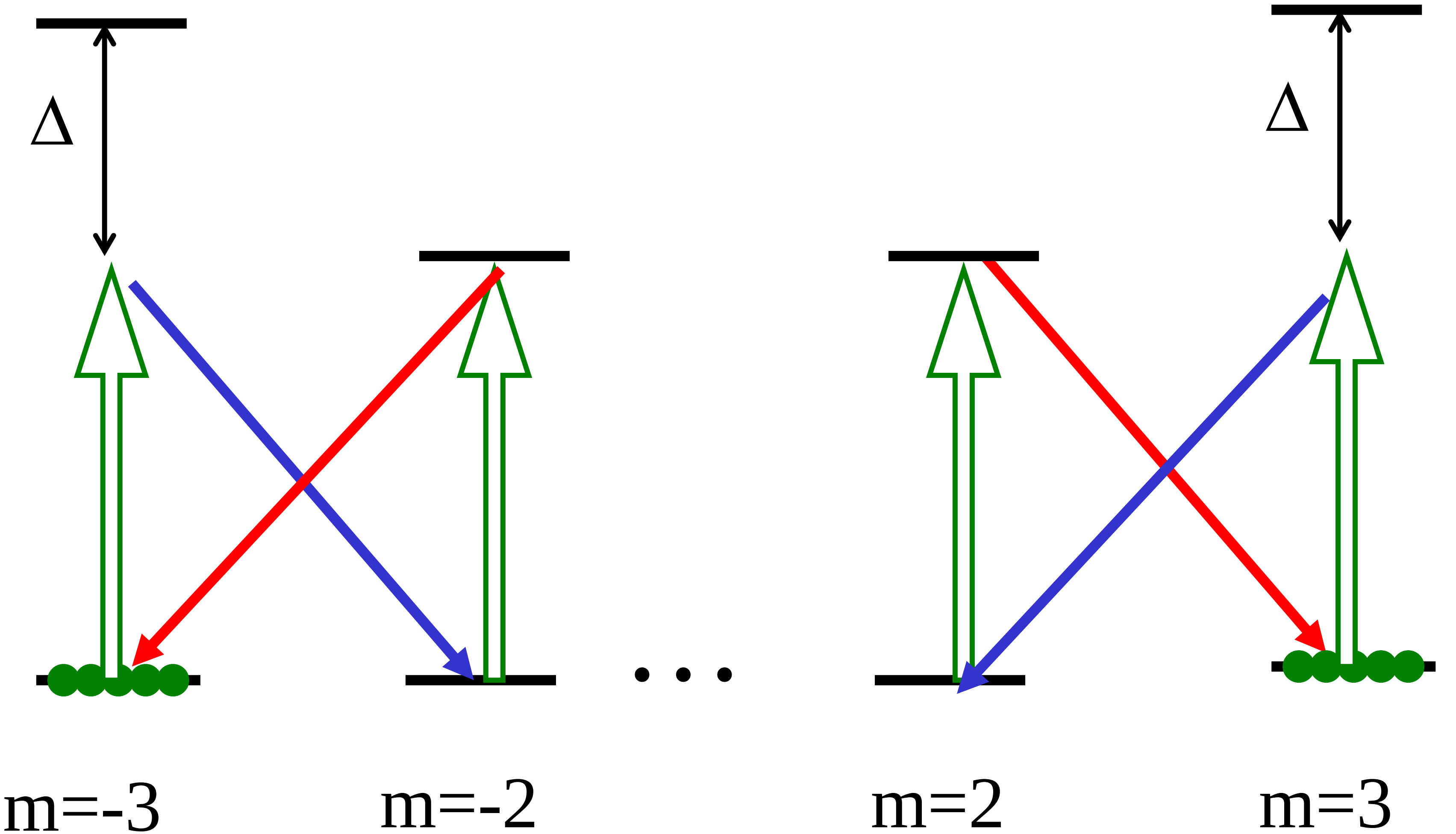


$$\sigma_{-}(\tau)\,\sigma_{+}(0) = (h-iv)(h+iv) = hh + vv + \quad i(hv-vh)$$
$$\sigma_{+}(\tau)\,\sigma_{-}(0) = (h-iv)(h+iv) = hh + vv - \quad i(hv-vh)$$

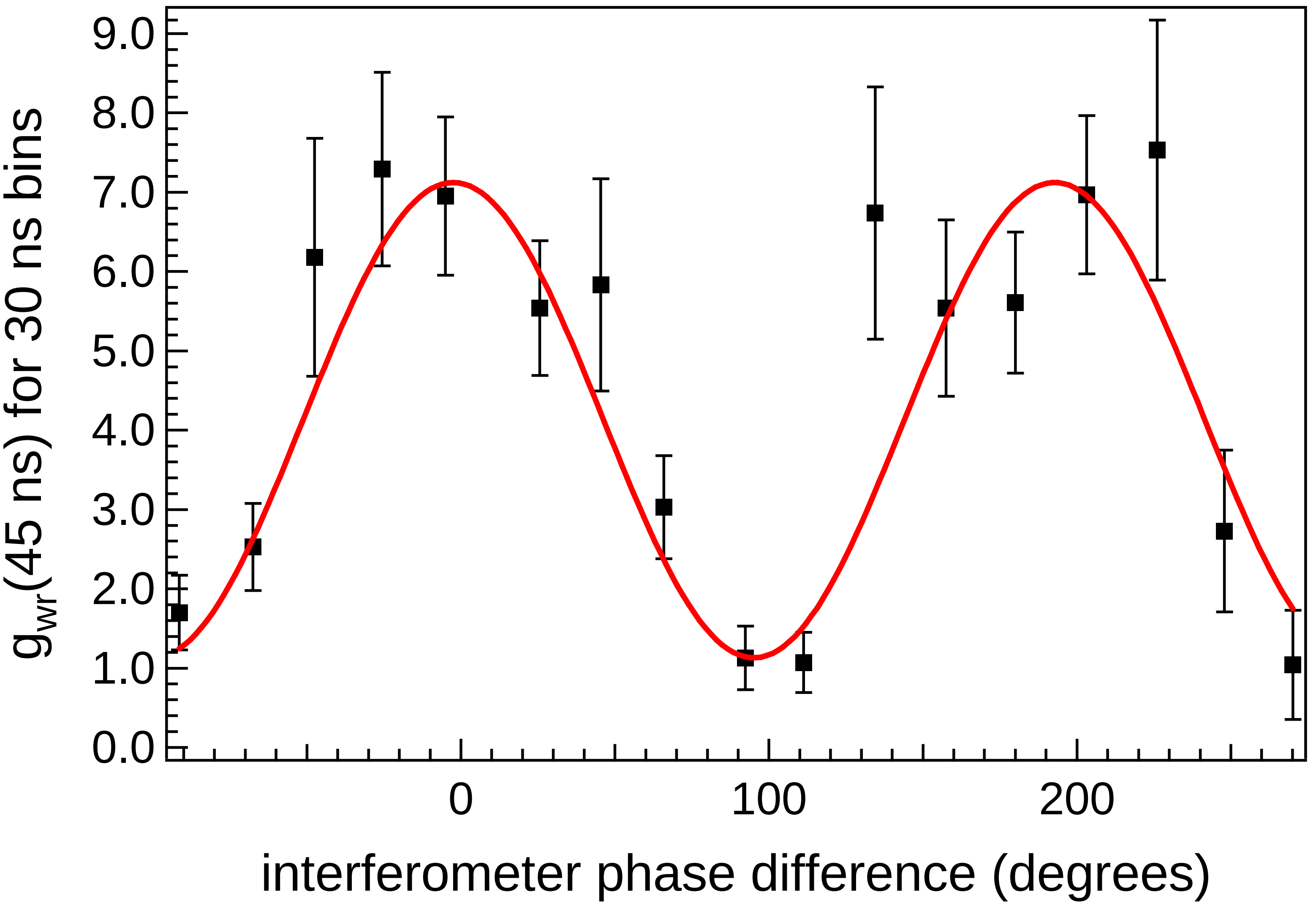
$$\sigma_{-}\sigma_{+} + \sigma_{+}\sigma_{-} = hh + vv$$

Even if the photons arrive at different times.

Entangled photon pair generation



Two-photon interferometer for photons passing the interferometer separately

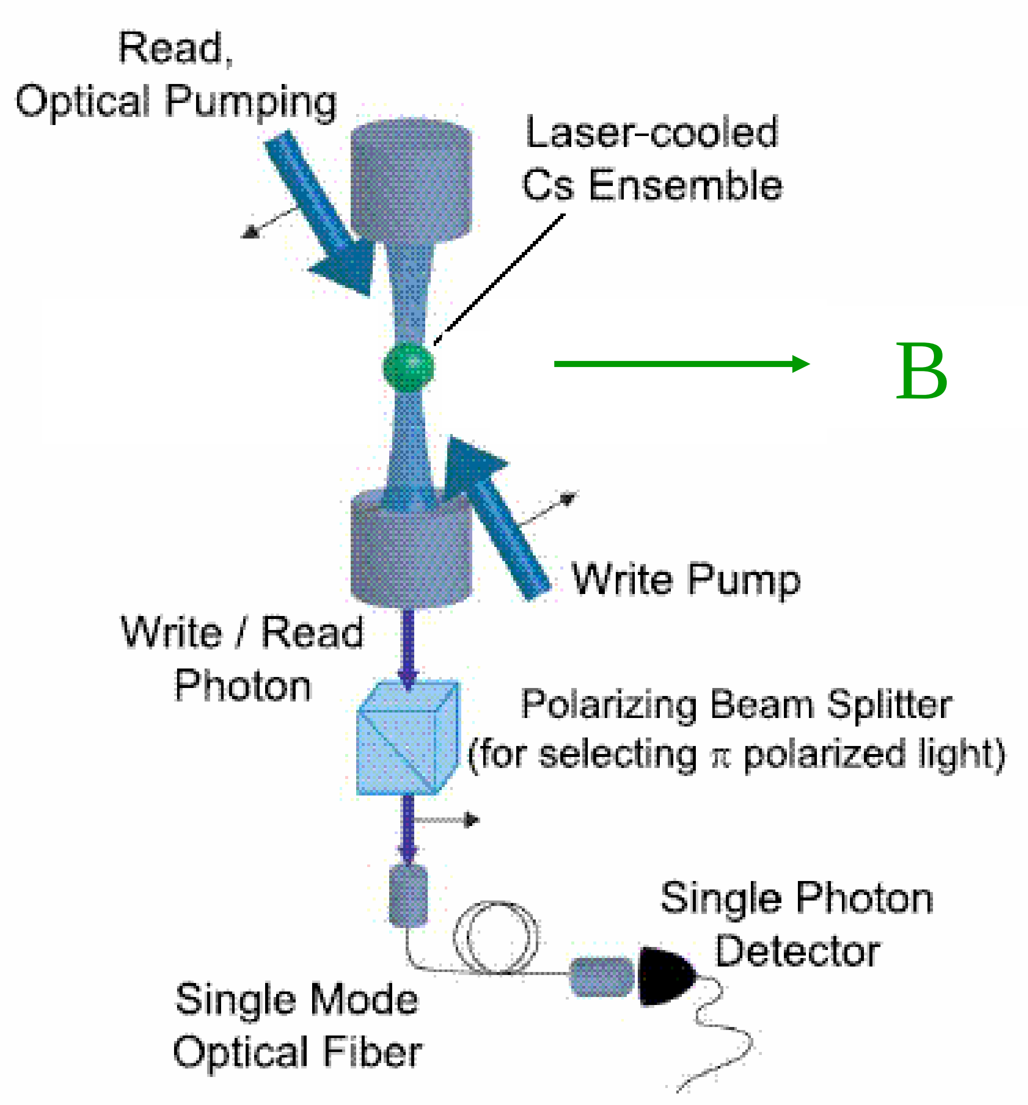


Can we make a single-photon Fock state?

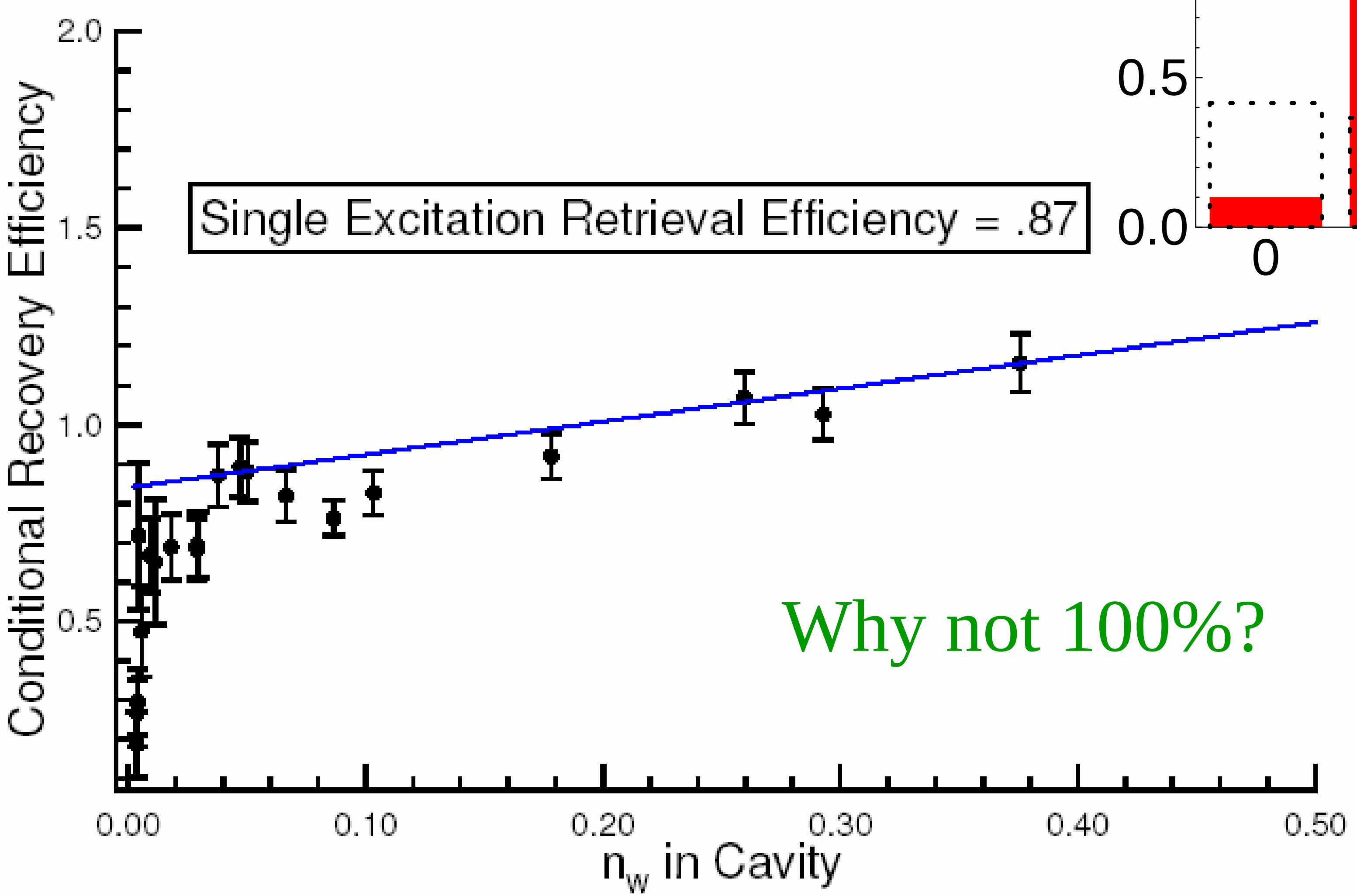
Storage and readout of quantized spin grating

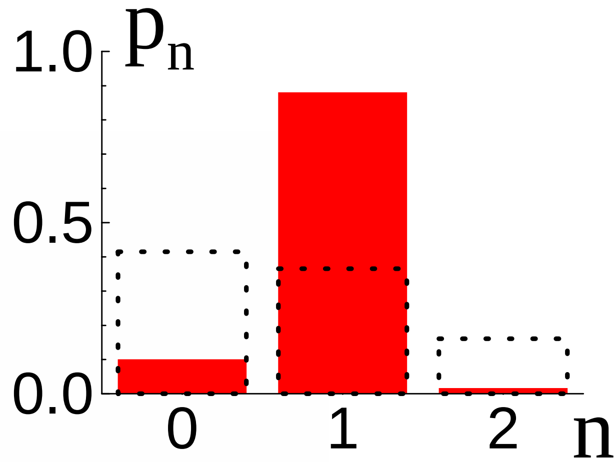
Setup with reduced Doppler effect

Adjustable delay between write and read processes



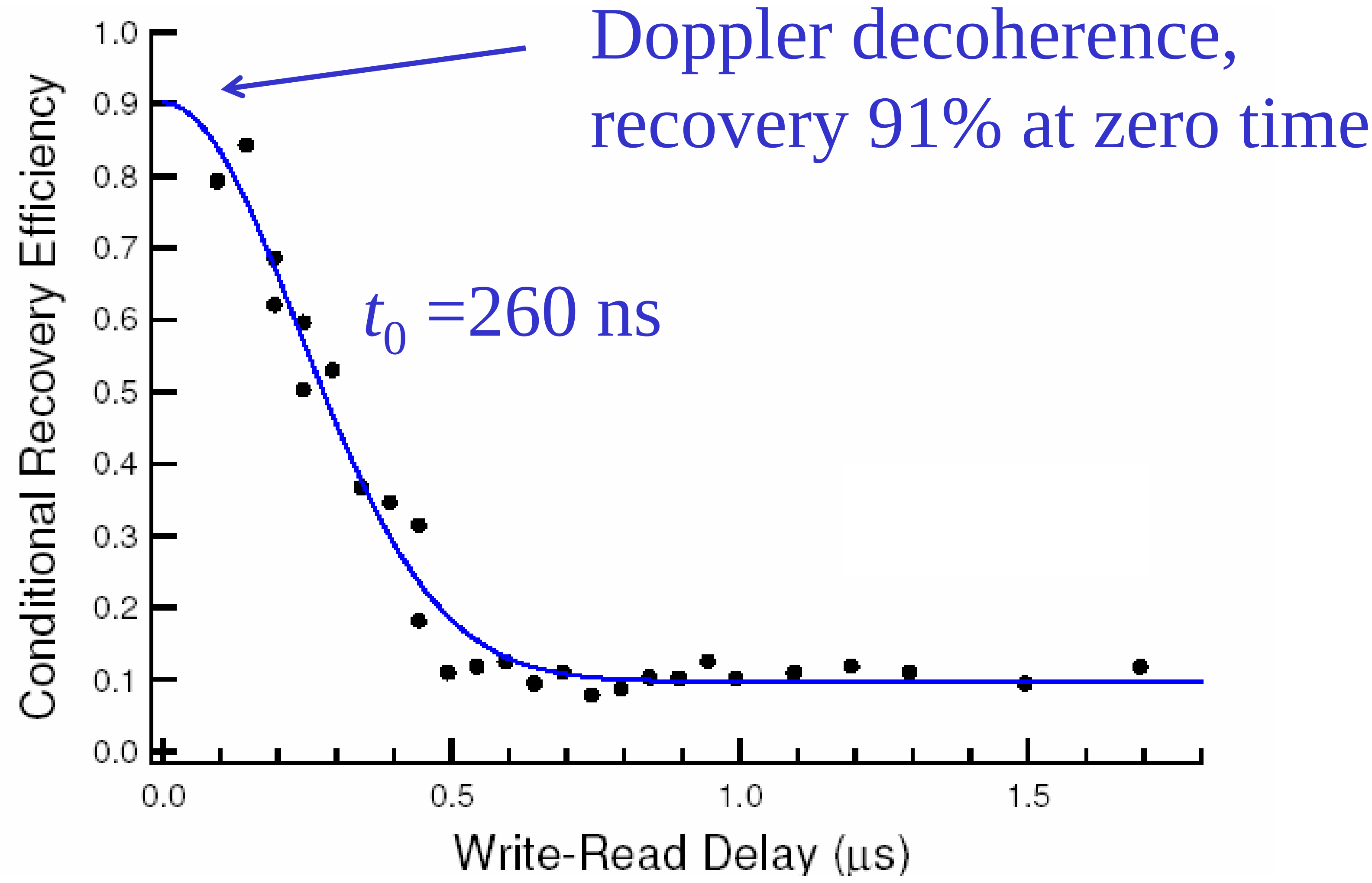
Read efficiency vs. write photon number n_w



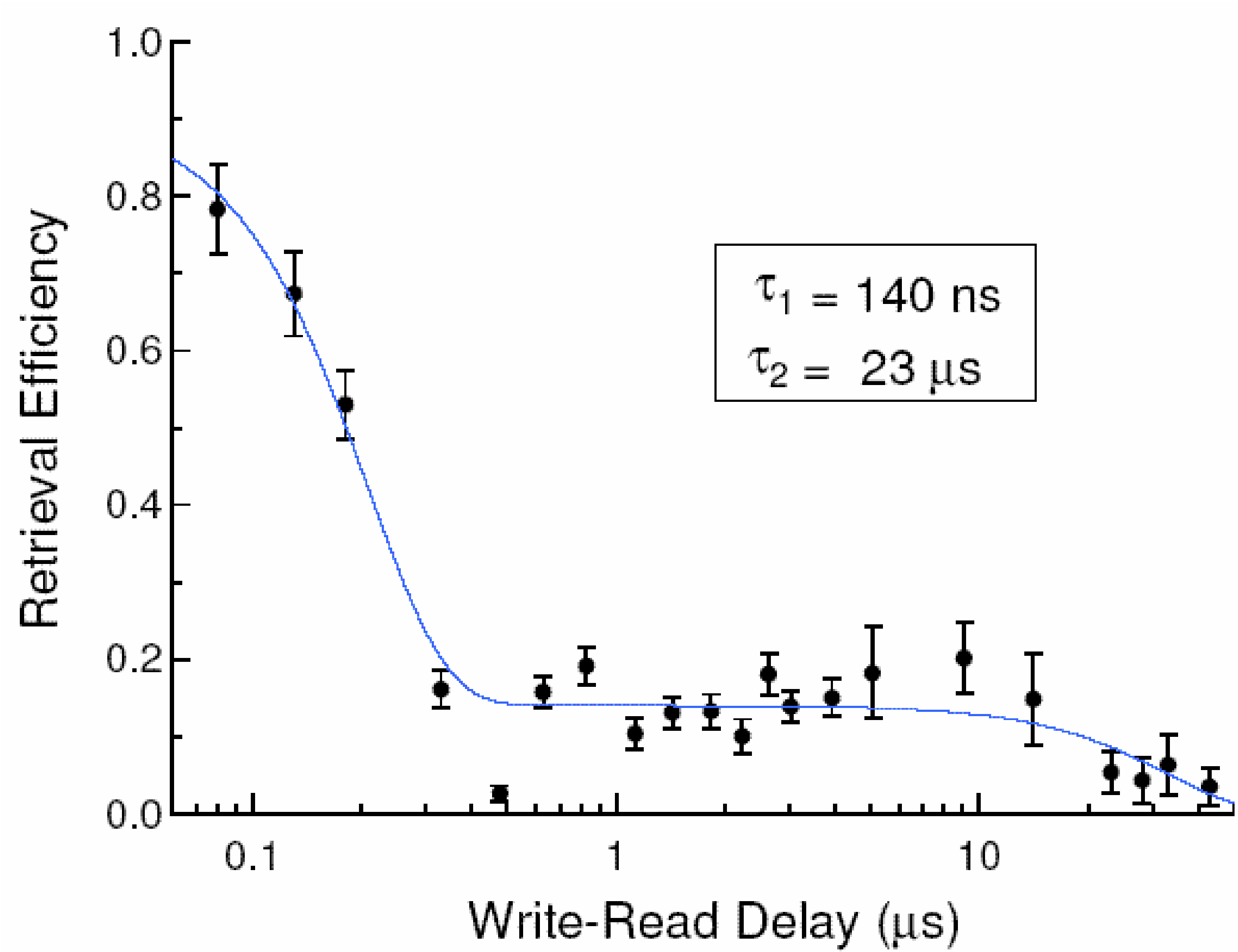


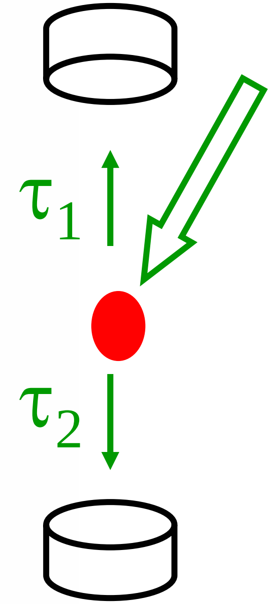
Why not 100%?

Recovery efficiency at short times

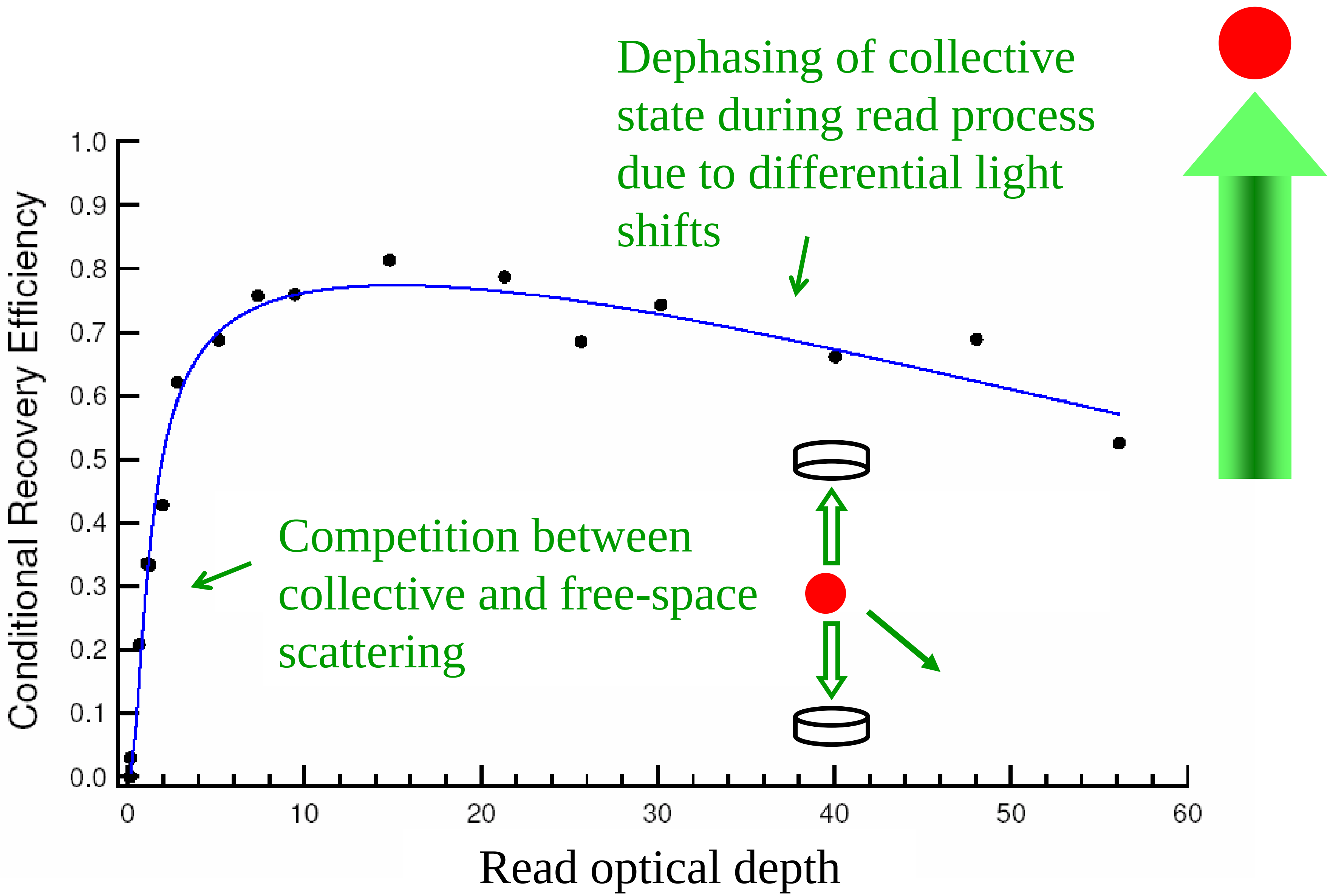


Recovery efficiency with two time constants for standing wave geometry





Recovery efficiency vs. optical depth



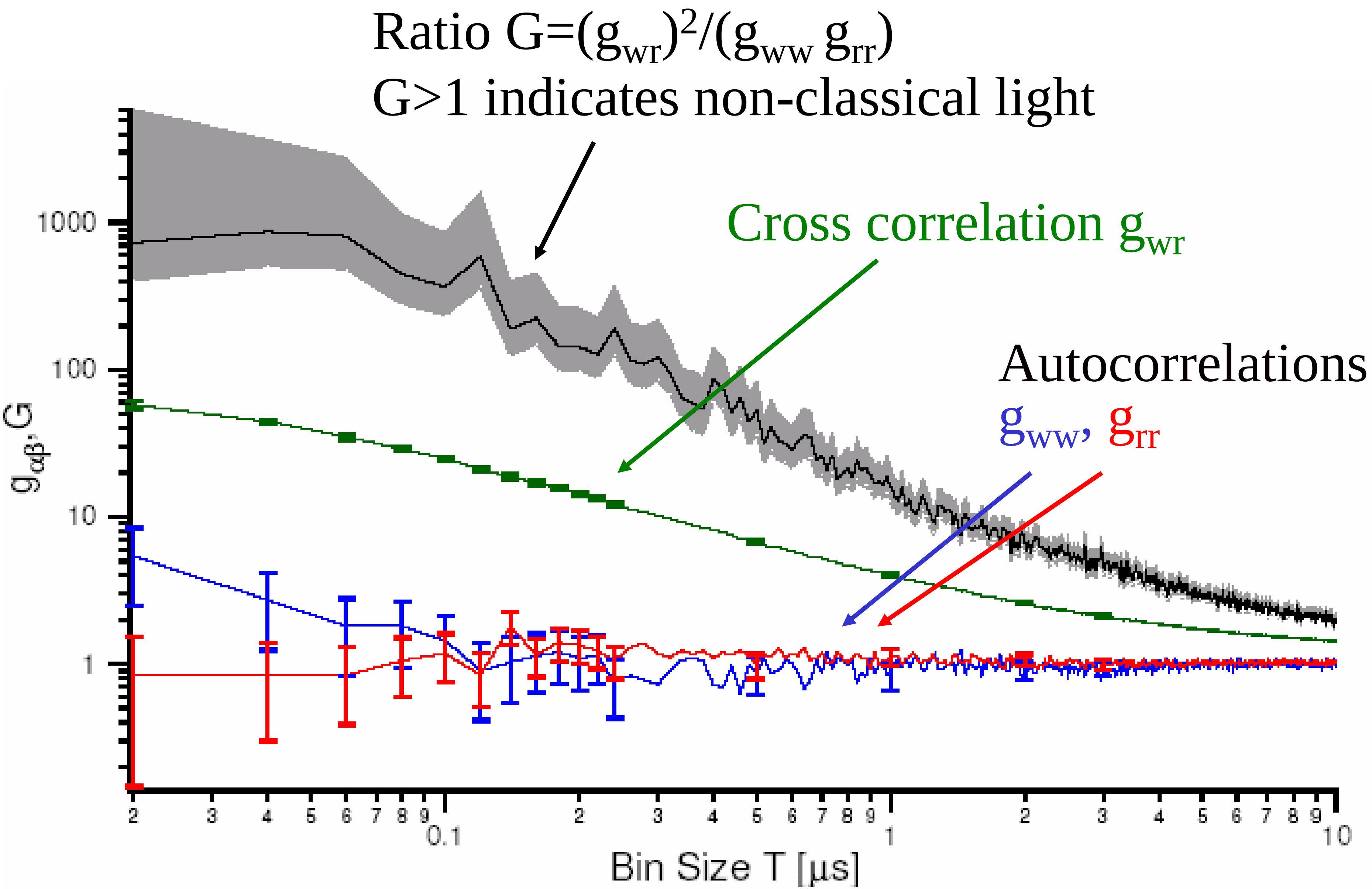
Experimental results with samples in free space

- Lukin group: write/read correlations with many photons van der Wal *et al.*, Science **301**, 196 (2003); storage and retrieval of a single photon, Eisaman *et al.*, Nature **438**, 837 (2005);
- Kimble group: first strongly non-classical light in single-photon regime, Kuzmich *et al.*, Nature **423**, 731 (2003); deterministic entanglement, Chou *et al.*, Nature **438**, 828 (2006).
- Kuzmich group: probabilistic entanglement, storage and retrieval of a single photon, Chaneliere *et al.*, Nature **438**, 833 (2005); enhancement of single-photon generation using feedback, Chaneliere *et al.*, Nature **438**, 833 (2005).
- Harris group: pair generation with large rate, Balic *et al.*, PRL **94**, 183601 (2005).

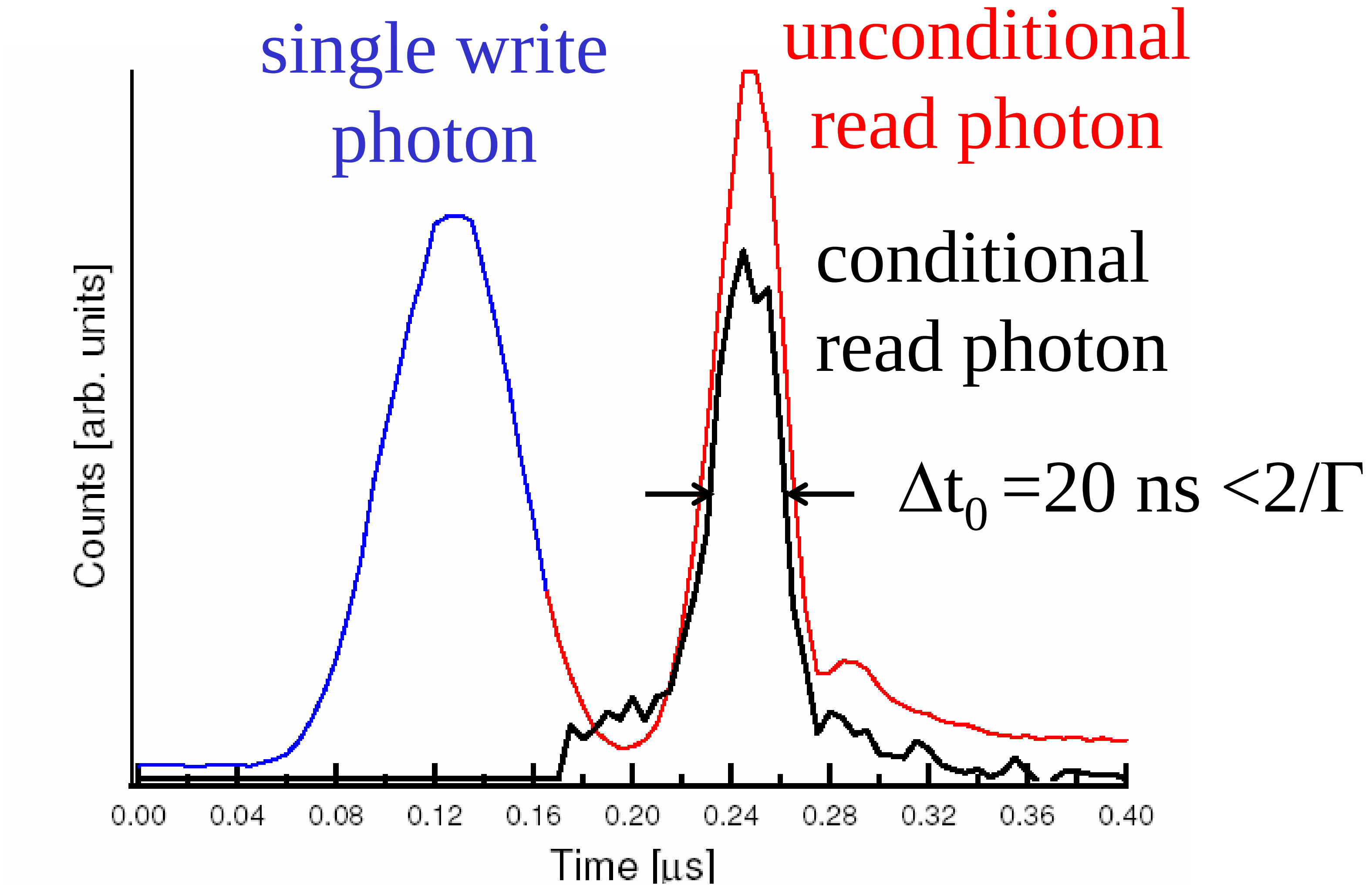
Summary

- Generation of single-excitation quantized spin gratings by detection of one photon
- Storage time of spin grating 20 μs due to thermal motion (Doppler effect)
- Conversion of spin grating into photon with 80% efficiency (intracavity), 65% outside resonator
- High-brightness source of indentical photons (10^3 times brighter than best parametric downconverter)
- Future work:
  - Storage of quantum bits (milliseconds to seconds) in optical lattice
  - Two, three and four-photon generation on demand

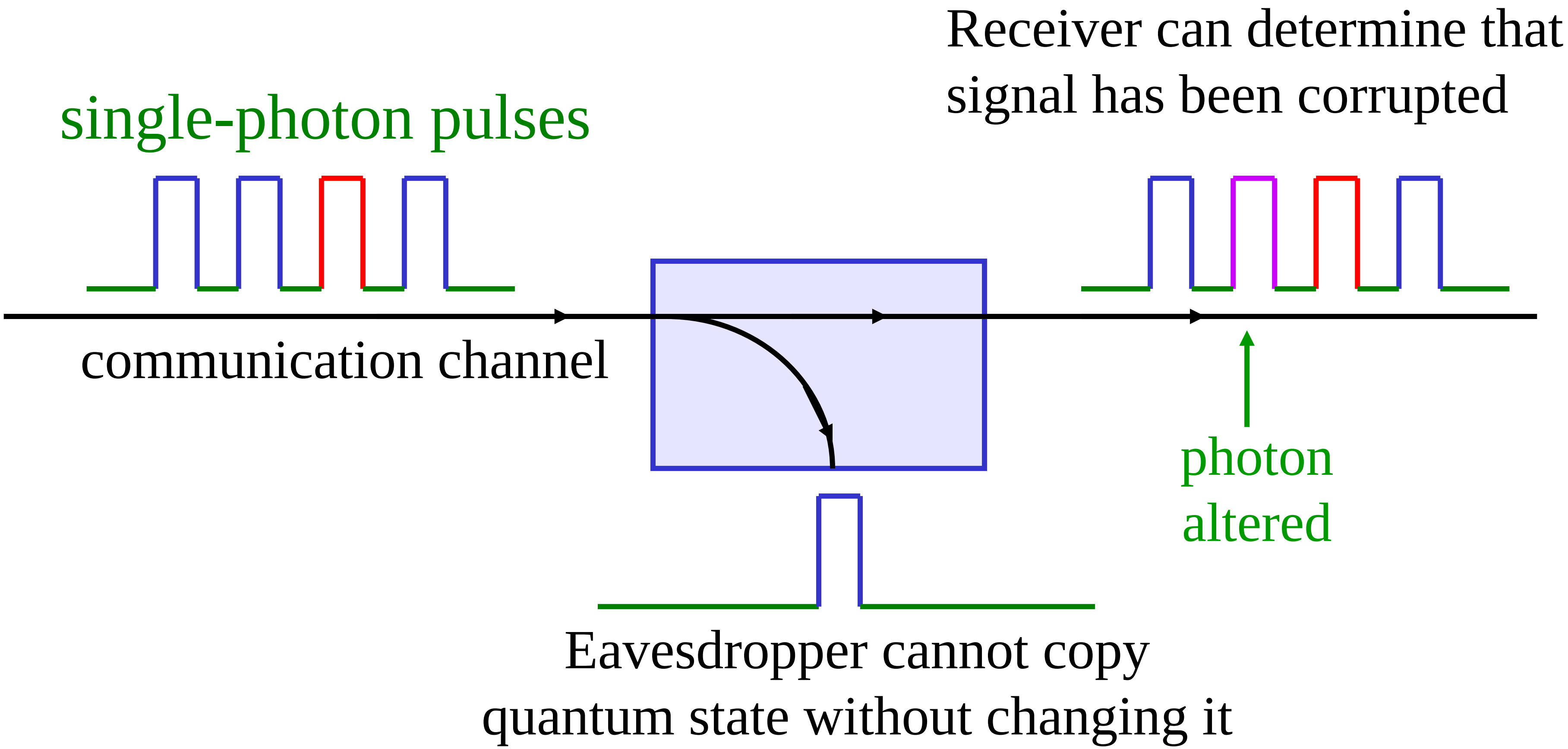
Correlation functions and ratio



Waveforms of write and read photons



Secure quantum communication: no cloning of quantum states



Recovery efficiency of the read photon

Observation of the write photon defines t=0.