A cavity-mediated photon-photon gate

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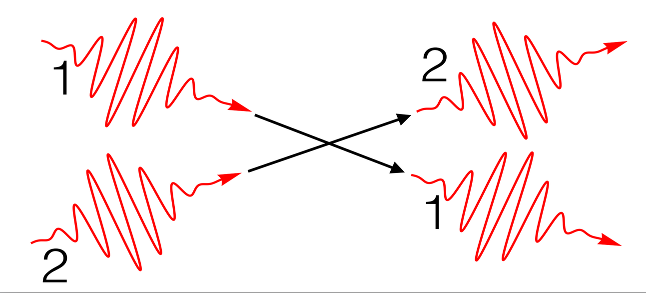
Motivation

- Quantum information processing with single photonic polarisation qubits.
- Implementation of a deterministic gate protocol which is fundamentally different compared to hitherto existing all-optical gates [1] based on linear optics.
- Various applications such as deterministic production of **entangled states**, **cluster states** and scalable **quantum computing** [2].

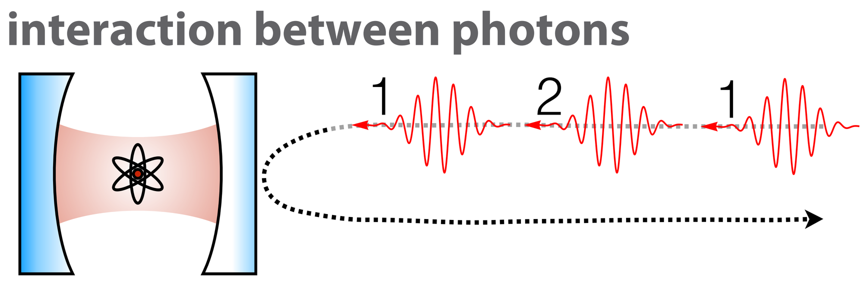
[1] O´Brien, Optical Quantum Computing, Science 318, 1567-1570 (2007).
[2] Duan et al., Scalable Photonic Quantum Computation through Cavity-Assisted Interactions, PRL 92, 127902 (2004).

How to Make Two Photons Interact ?

Free space: No interaction

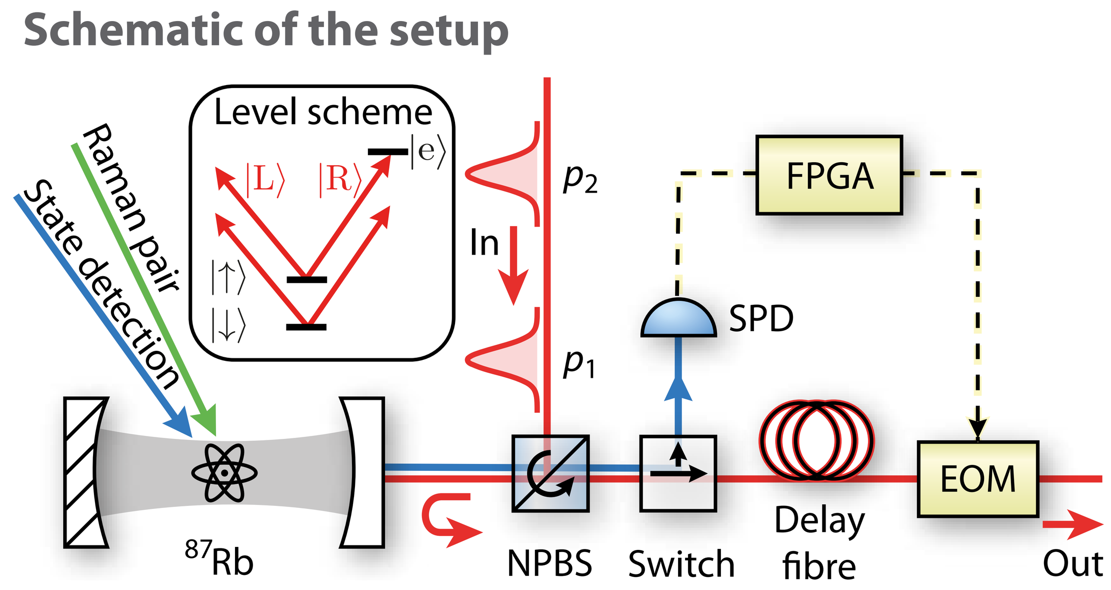


Solution: Atom in cavity mediates interaction between photons



Realization of the Photon-Photon Gate

Schematic of the setup



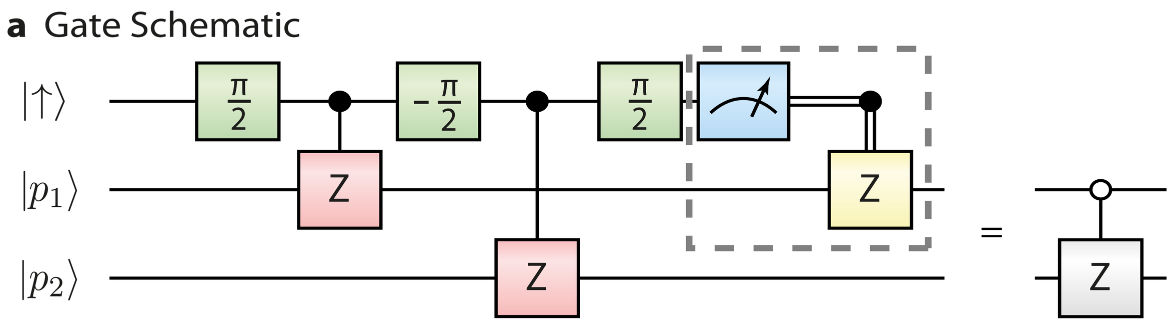
- Reflection of two weak coherent pulses ($\bar{n}$=0.17, Gaussian envelope with 0.6µs FWHM) to probe the gate.

All-optical CPF gate: Truthtable

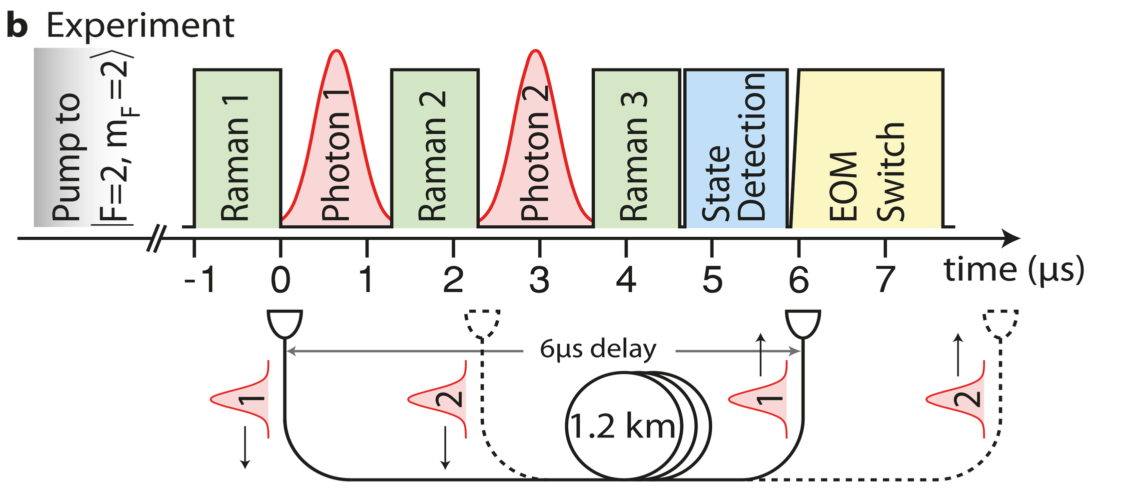
$|RR\rangle \rightarrow \ |RR\rangle$
$|RL\rangle \rightarrow \ |RL\rangle$
$|LR\rangle \rightarrow -|LR\rangle$
$|LL\rangle \rightarrow \ |LL\rangle$

Quantum Circuit Diagram

a Gate Schematic



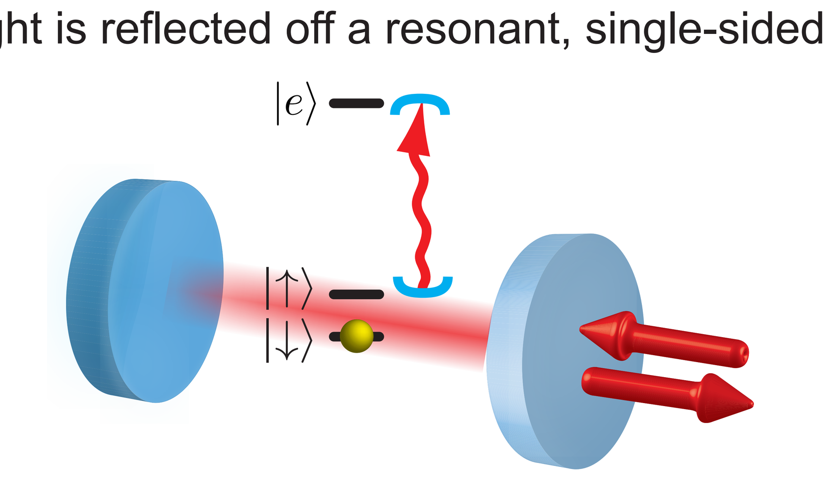
b Experiment



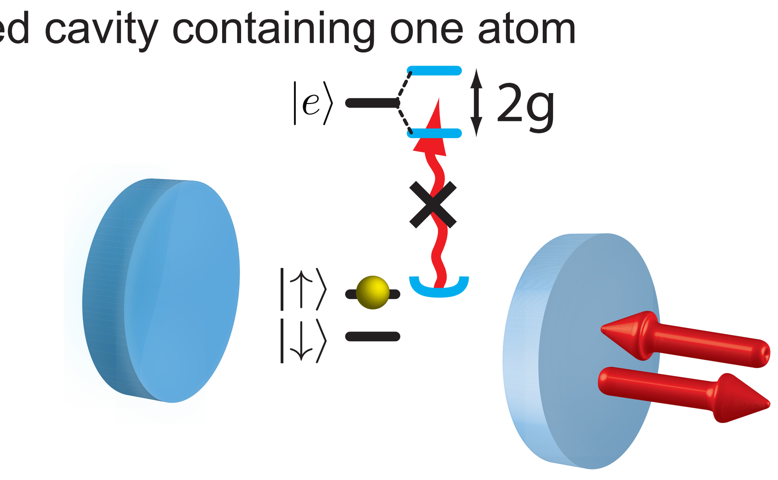
- Second interaction of atom and first photon replaced by atomic state detection and classical feedback onto the photon.
- Photons are sent into a 1.2 km-long delay fibre.
- Feedback via FPGA which activates an EOM-induced polarisation rotation on first photon.

Underlying Atom-Photon Gate Mechanism

Light is reflected off a resonant, single-sided cavity containing one atom



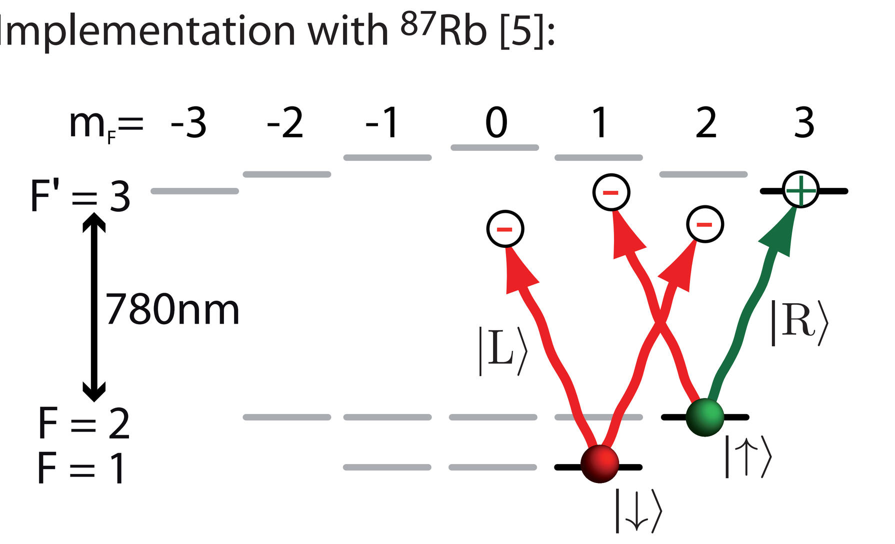
Atom in |↓⟩: Impinging photons can enter the cavity before being reflected.



Atom in|↑⟩: **Strong coupling** splits the resonance such that resonant photons are reflected without entering.

Difference between the two situations: Photon does or does not enter.
→ State-dependent **π phase shift** [4] on the combined atom-photon state
→ **controlled atom-photon phase gate**

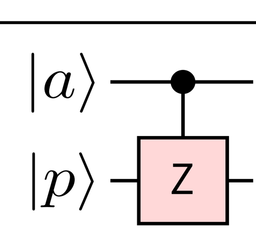
Implementation with ^{87}Rb [5]:



Gate efficiency (total reflection probability): **68%**

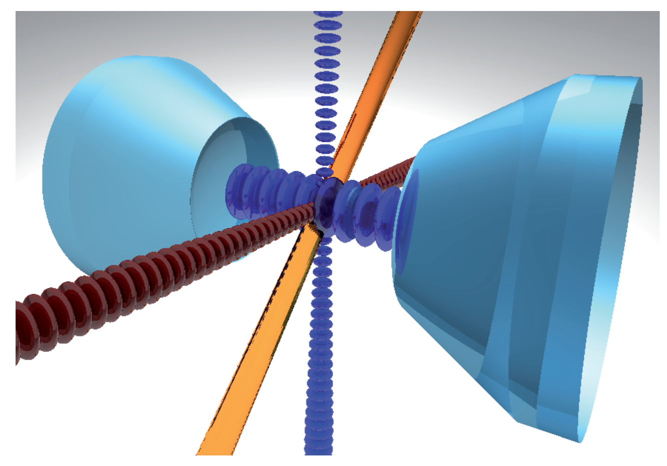
Atom-photon gate: Truthtable

$|\uparrow R\rangle \rightarrow -|\uparrow R\rangle$
$|\downarrow R\rangle \rightarrow \ |\downarrow R\rangle$
$|\uparrow L\rangle \rightarrow \ |\uparrow L\rangle$
$|\downarrow L\rangle \rightarrow \ |\downarrow L\rangle$



[4] Reiserer et al., Nondestructive Detection of an Optical Photon, Science 342, 1349–1351 (2013).
[5] Reiserer et al., A quantum gate between a flying optical photon and a single trapped atom, Nature 508, 237-240 (2014).

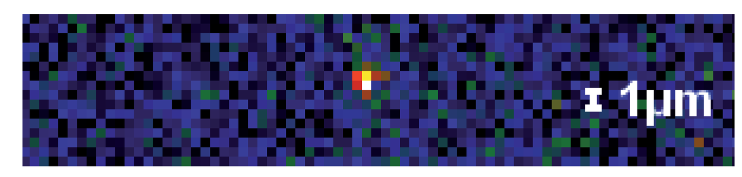
Experimental Setup



Atom trapping in 3D optical lattice: [3]
- High trap frequencies (>100kHz)
- Tight confinement (<15nm)
- Full control over the atomic position

Intra-cavity Sisyphus cooling: [3]
- Fast cooling close to the ground state
- Fluorescence imaging of the atom

Cavity Parameters
T_{M1} = 4 ppm, T_{M2} = 92 ppm,
Losses = 7 ppm, F ≈ 60000, l = 0.5 mm
(g, κ, κ_{out}, γ) = 2 π (8, 2.5, 2.3, 3) MHz

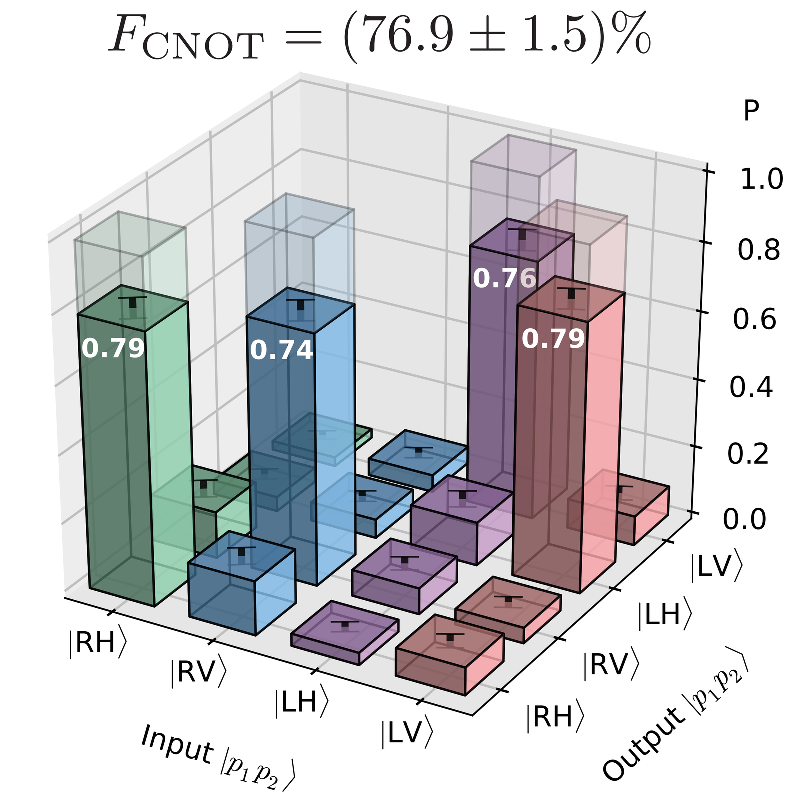


[3] Reiserer et al., Ground-State Cooling of a Single Atom at the Center of an Optical Cavity, PRL 110, 223003 (2013).

Experimental Data

CNOT operation if one photon is circularly and the other is linearly polarized

$$F_{\text{CNOT}} = (76.9 \pm 1.5)\%$$



Average gate fidelity
Measurement of fidelity for all 36 possible polarisation input states with 80 two-photon clicks for each output state

Average fidelity over all output states

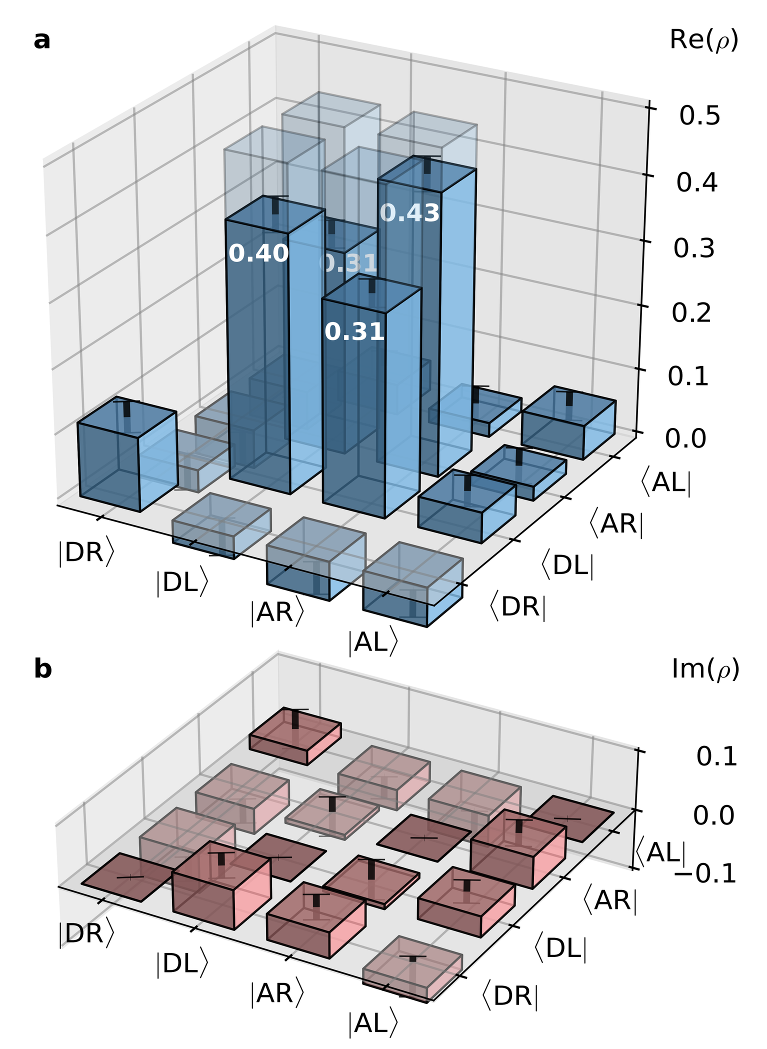
$$\overline{F} = (76.2 \pm 3.6)\%$$

Definition of bases

$$|H\rangle = \frac{1}{\sqrt{2}}(|R\rangle + |L\rangle) \quad |D\rangle = \frac{1}{\sqrt{2}}(|R\rangle + i\,|L\rangle)$$
$$|V\rangle = \frac{1}{\sqrt{2}}(|R\rangle - |L\rangle) \quad |A\rangle = \frac{-1}{\sqrt{2}}(i\,|R\rangle + |L\rangle)$$

Generation of entangled two-photon state
Generation of $|\Psi^+\rangle = \frac{1}{\sqrt{2}}(|DL\rangle + |AR\rangle)$ for input state $|DD\rangle$.

$$F_{\Psi^+} = \langle\Psi^+|\rho|\Psi^+\rangle = (72.9 \pm 2.8)\%$$

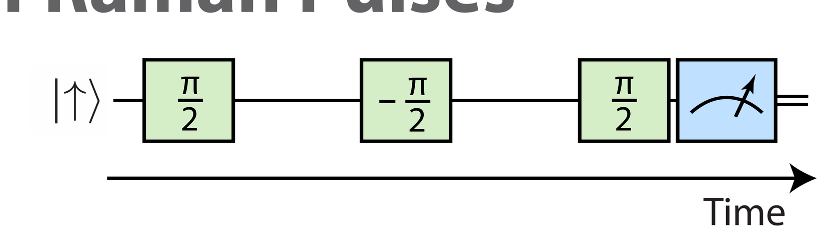


Fidelity postselected on the case |↓⟩:
$$F_{\Psi^+} = (74.4 \pm 3.9)\%$$

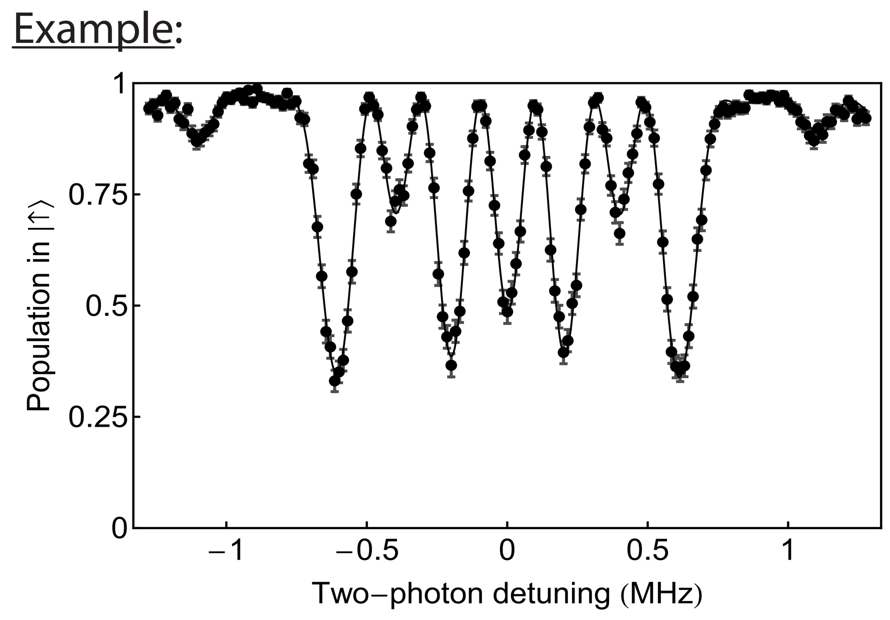
Fidelity postselected on the case |↑⟩:
$$F_{\Psi^+} = (71.5 \pm 4.2)\%$$

Calibration of Raman Pulses

Pulse calibration with Ramsey-like sequence as in the gate protocol:



Example:



Fit reveals residual two-photon detuning (< 3kHz) as well as Rabi frequency (250 kHz) and pulse duraion (1µs).

AC Stark shift caused by Raman lasers (40 kHz) can be compensated by switching to a different two-photon detuning when the lasers are not impinging on the atom.

Efficiency and Error Budget

Transmission probability per photon:

$$67\% \times 40\% \times 81\% = 22\%$$

cavity reflectivity — delay fibre — other optical elements

Total experimental gate efficiency for two input photons

$$(22\%)^2 \approx 5\%$$