Quantum Information:

Manipulating light photon by photon

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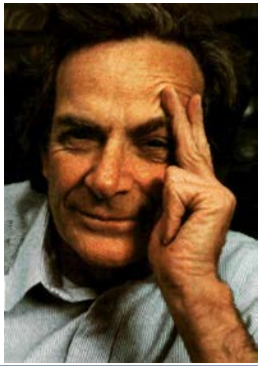
What is Quantum Information?

- Quantum systems exhibit some very strange features
  - Superpositions
  - Uncertainty relations
  - Entanglement
- Instead of working around them, let's use them!



Some examples?

- Quantum computation
  - Exponential speedup over classical protocols
    - Why? Superpositions allow evaluating multiple states at once!

- Quantum cryptography
  - Unconditionally secure key distribution
    - Why? Measurements always affect the state of the system

- Light is excellent for communication
- Light is excellent for testing of fundamental principles

Why?

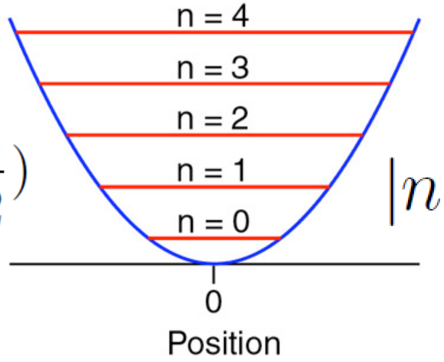
- It travels fast
- It can be easily manipulated…
- It is robust against decoherence

Brief introduction to quantum optics

- Light = single mode of electromagnetic field

  = Harmonic oscillator

$$\hat{H} = \hbar\omega(\hat{x}^2 + \hat{p}^2) = \hbar\omega(\hat{a}^\dagger\hat{a} + \frac{1}{2})$$



$|n\rangle$

- State of light
  - specific superposition of various photon numbers

$$|\psi\rangle = \sum_{n=0}^{\infty} c_n |n\rangle$$

  - Can be also represented by a real function
    - Wigner function $W_\psi(x, p)$

Quantum information processing

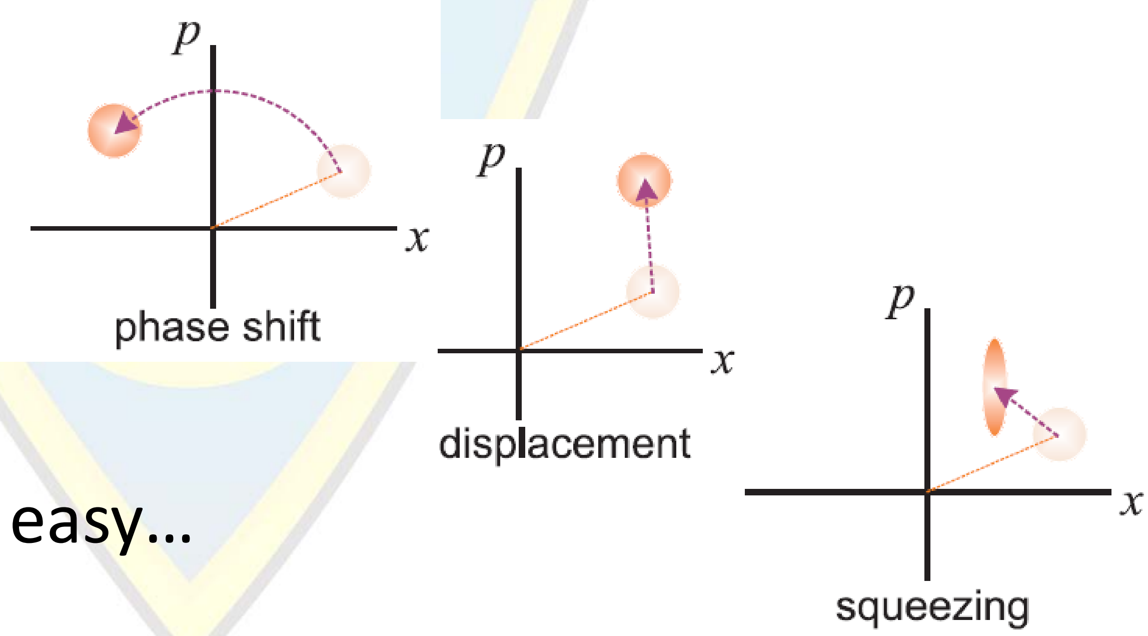
- Preparation of arbitrary states
- Arbitrary manipulation of the states
- Arbitrary measurement of the states

Manipulating light: Gaussian transformations

- Preserve Gaussian nature of Gaussian states

$$W_\psi(x,p) \to W_\psi(x',p')$$

- The basic set of operations
  - Hamiltonians of the second order
  - Phase shift
  - Displacement
  - Squeezing



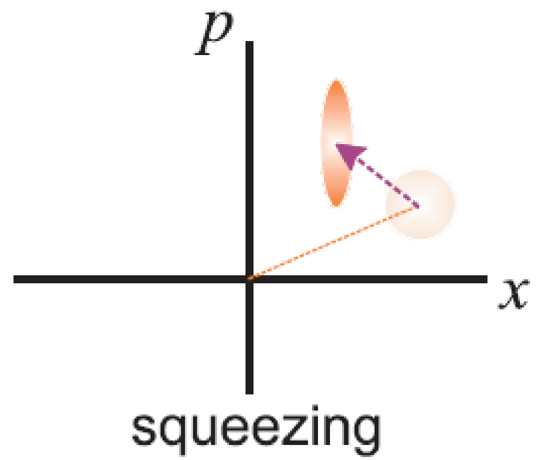
  - the first two are easy…

Squeezing

- Degenerate spontaneous parametric downconversion

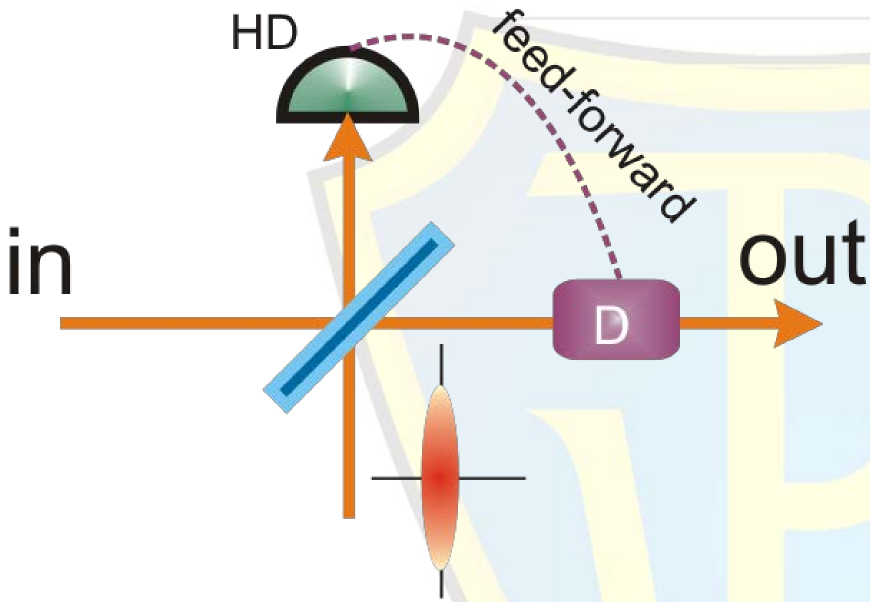
$$\hat{H} = \omega(\hat{x}^2 - \hat{p}^2)$$

$$\hat{x} \rightarrow g\hat{x} \qquad \hat{p} \rightarrow \frac{1}{g}\hat{p}$$



  - Can not be performed in single pass (gain too low)
  - Needs resonator
    - Possible to generate squeezed vacuum
    - Difficult to squeeze other states due to incoupling and outcoupling losses

Squeezing, tricky way



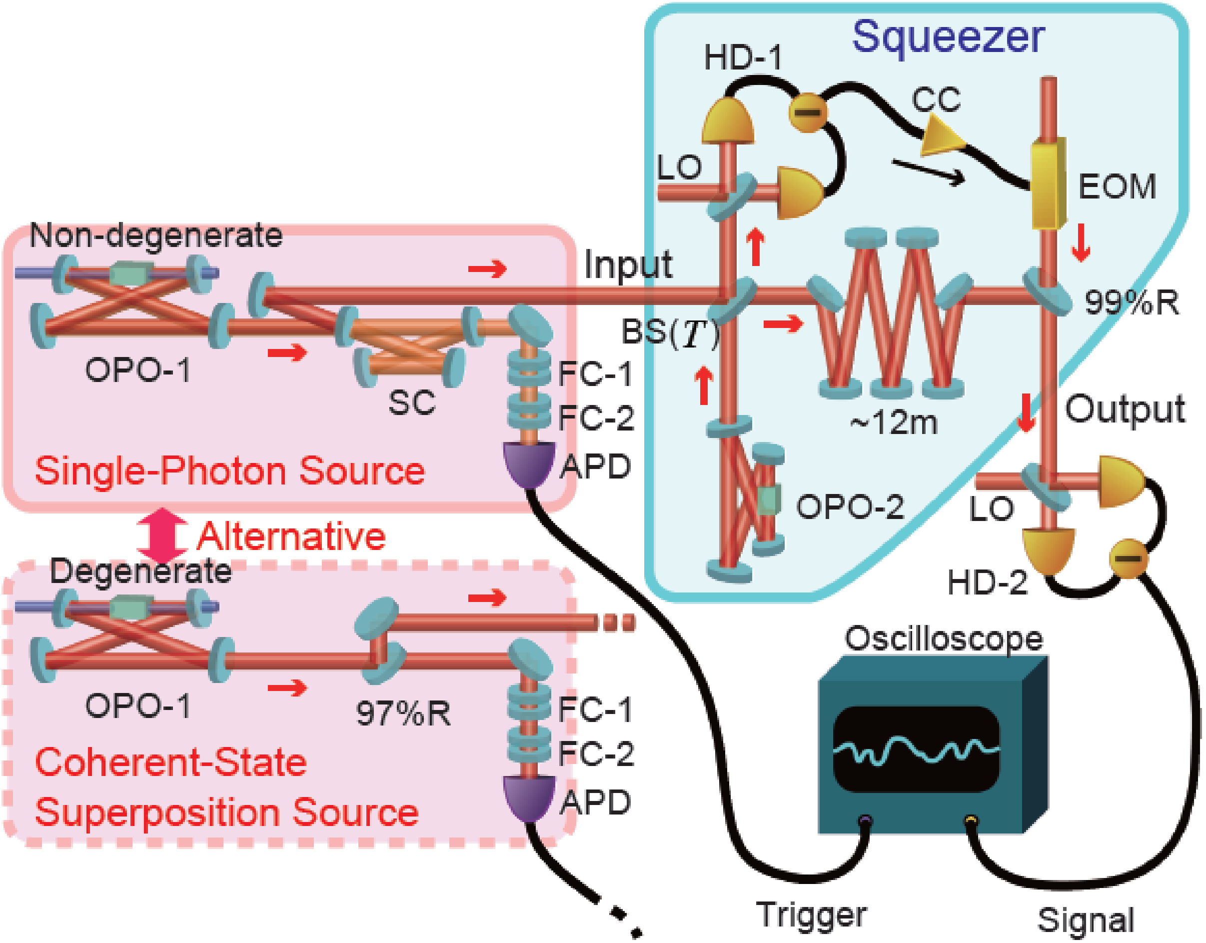
$$\hat{x} \rightarrow g\hat{x} + \hat{N}$$

$$\hat{p} \rightarrow \frac{1}{g}\hat{p}$$

- An unknown state is mixed with a squeezed vacuum
- The vacuum is measured
- Feed-forward is performed

Experimental squeezing of single photon

Y. Miwa, J. Yoshikawa, N. Iwata, M. Endo, P. Marek, R. Filip, P. van Loock, and A. Furusawa, submitted



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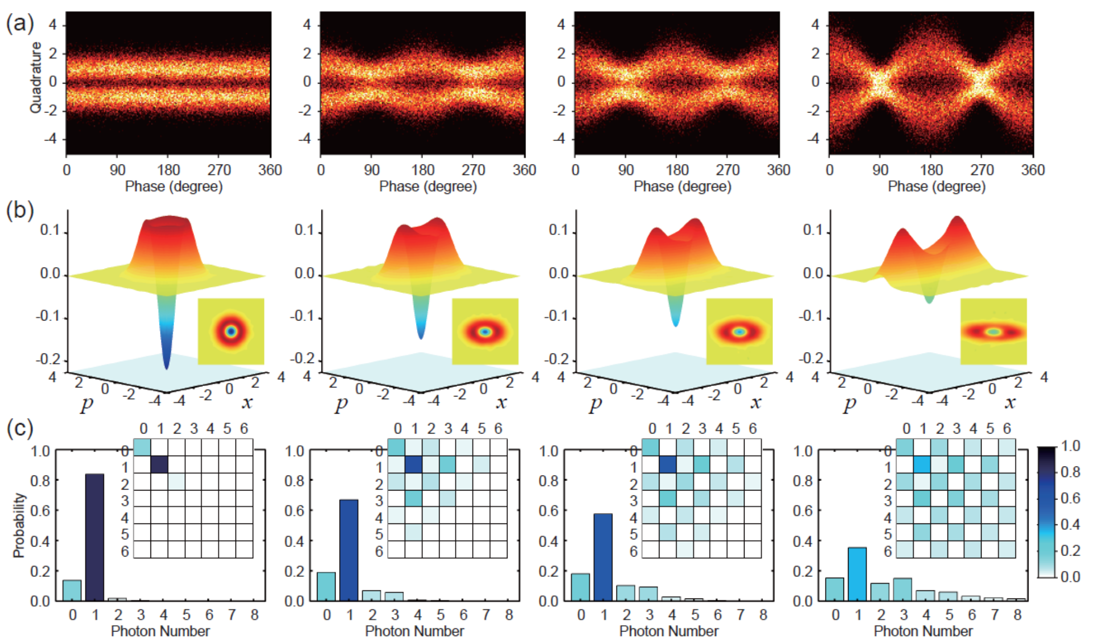
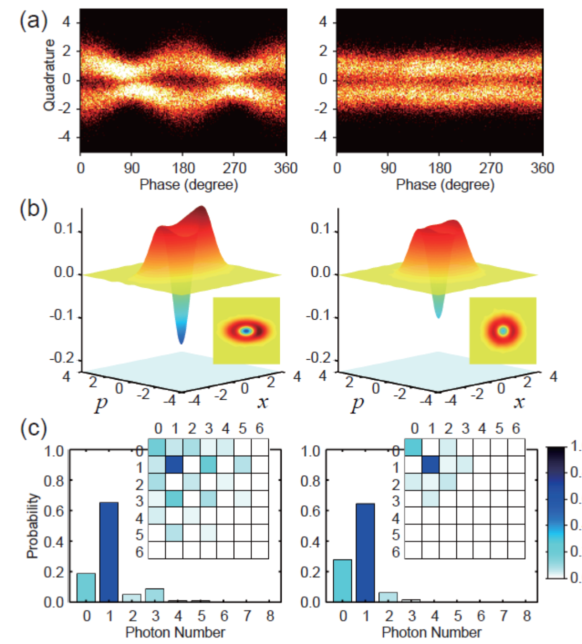


Squeezing of a photon



Unsqueezing of a squeezed photon

High order Hamiltonians

- Necessary for fully universal manipulation
  - And for quantum computation and other fun applications

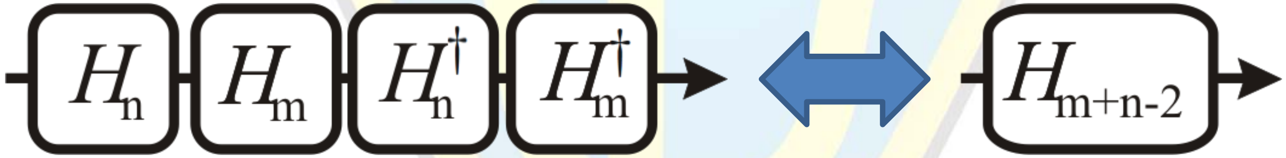
$$\hat{H} = \sum \omega_{jk} \hat{x}^j \hat{p}^k$$

- Not available naturally
  - Too weak,
  - Too noisy
  - Too weak and too noisy and covered by interactions with lower order

Cubic operation

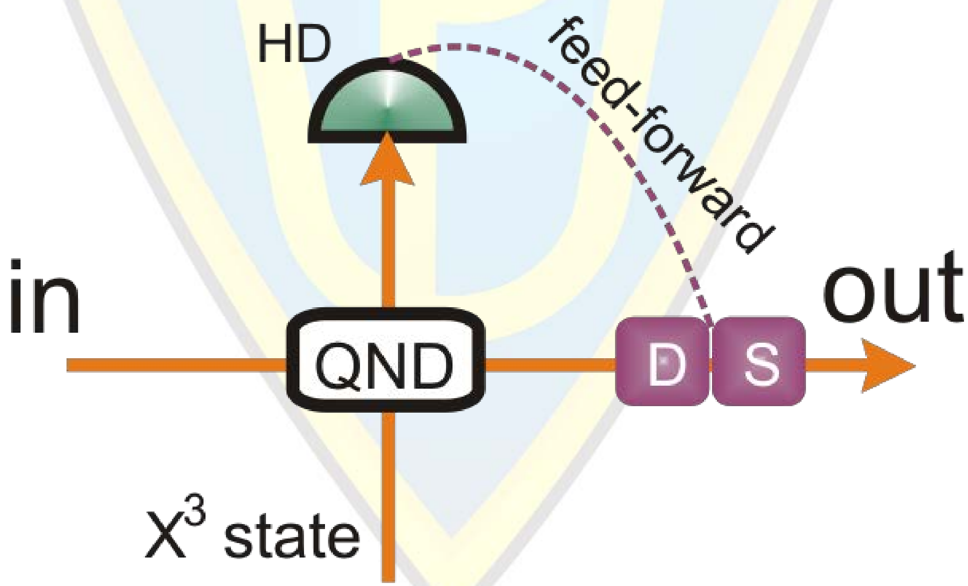
$$\hat{H}_3 = \omega_3 \hat{x}^3$$

- Can be in principle used to implement any operation of higher order



How can cubic nonlinearity be performed?

- Naturally appearing cubic interactions are too weak
- Way around it:
  - Ancilla-and-measurement-and-feedforward:



How can cubic state be generated?

$$|\gamma\rangle = \int e^{i\chi x^3}|x\rangle dx$$

- Unphysical: infinite energy

$$e^{i\chi\hat{x}^3}\hat{S}|0\rangle = \hat{S}e^{i\chi'\hat{x}^3}|0\rangle$$

- Finite energy approximation
  - Squeezing can be disregarded, for the moment

$$(1 + i\chi\hat{x}^3)|0\rangle$$

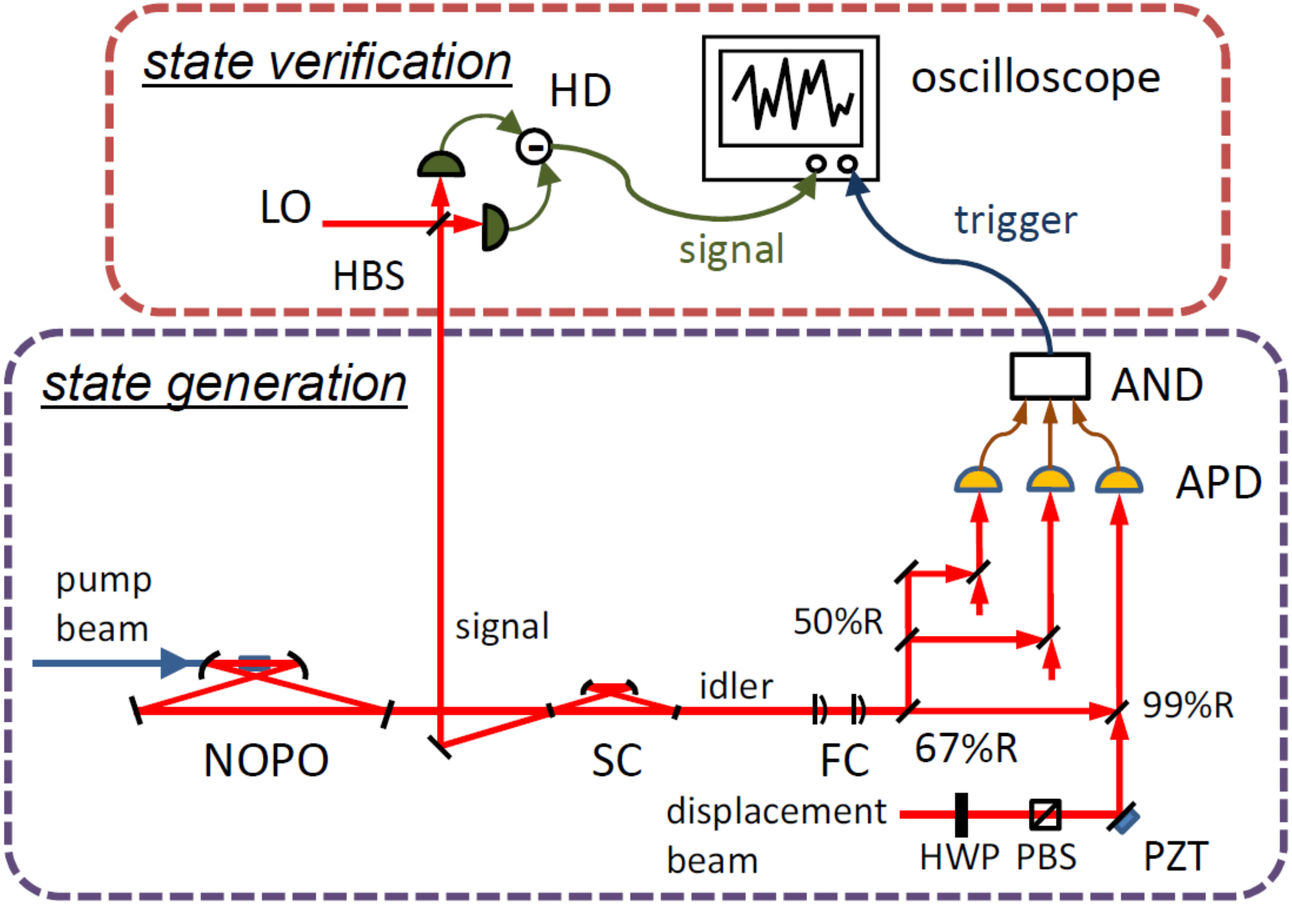
- Weak cubic nonlinearity approximation

$$|0\rangle + i\frac{\chi\sqrt{3}}{2\sqrt{2}}\left(\sqrt{3}|1\rangle + \sqrt{2}|3\rangle\right)$$

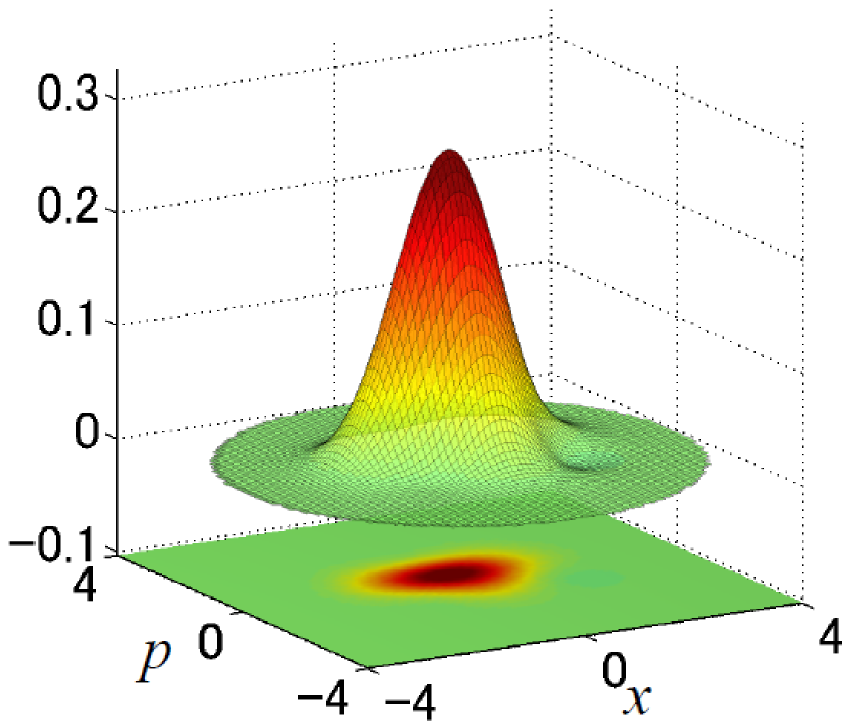
- Can be engineered on the single photon level

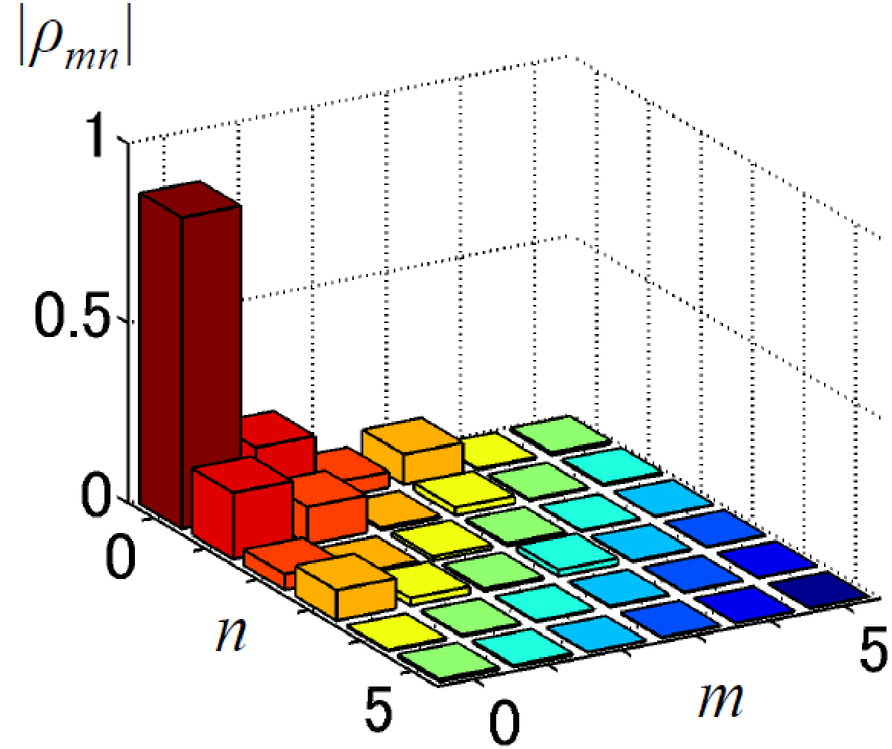
Emulating Quantum Cubic Nonlinearity

Mitsuyoshi Yukawa, Kazunori Miyata, Hidehiro Yonezawa, Petr Marek, Radim Filip, and Akira Furusawa, Phys. Rev. A 88, 053816.



The experimentally generated state



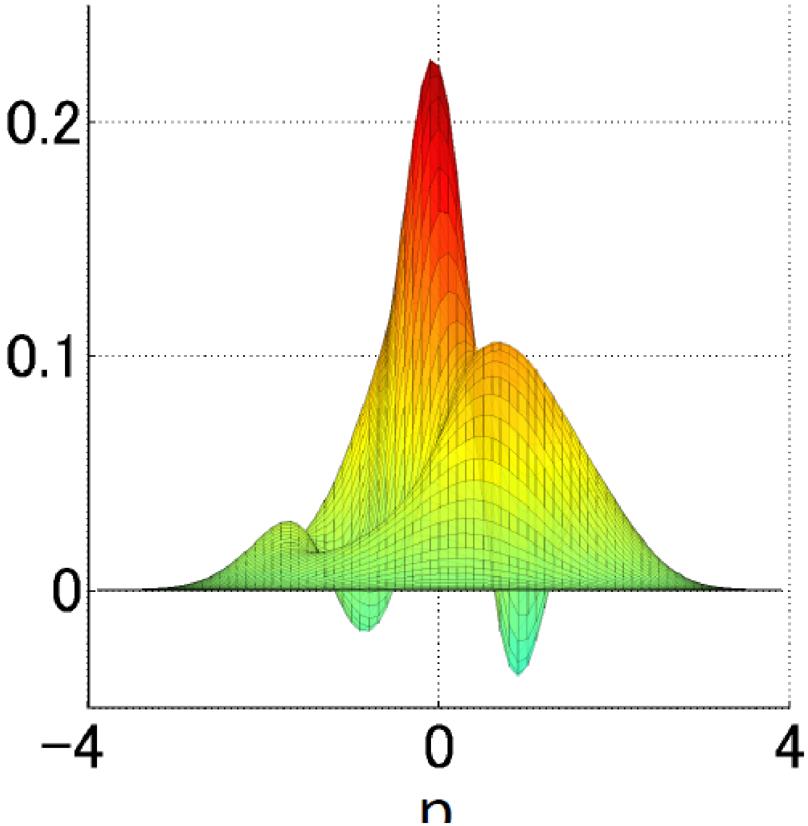


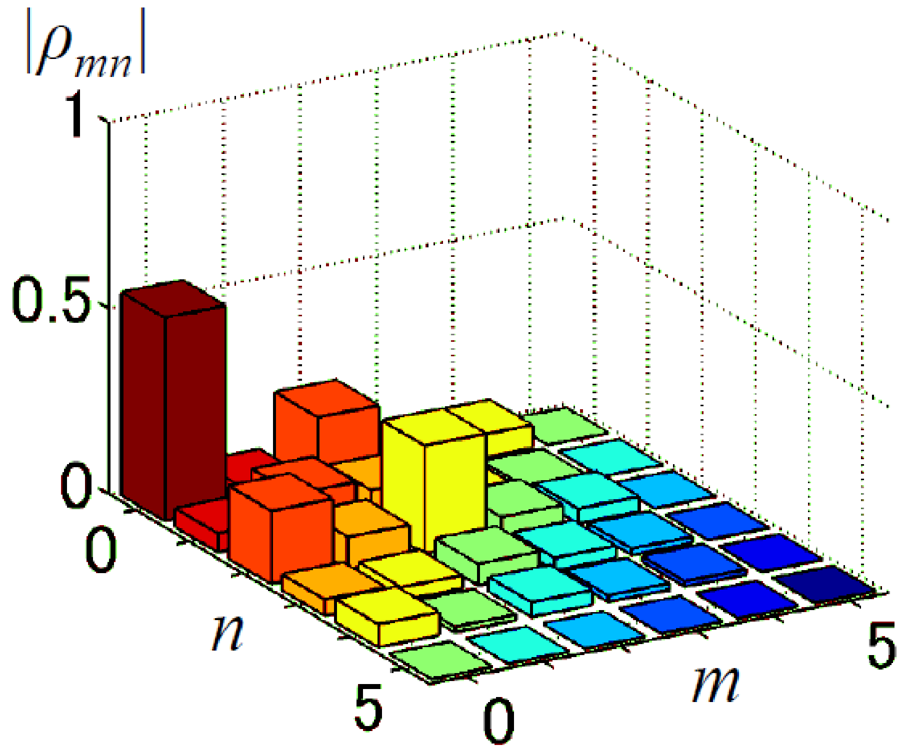
$$|0\rangle + i\frac{\chi\sqrt{3}}{2\sqrt{2}}\left(\sqrt{3}|1\rangle + \sqrt{2}|3\rangle\right)$$

$$F = 0.89$$

$$F_{|0\rangle} = 0.98$$

Single photon subtraction on data





$$\sqrt{3}|0\rangle + \sqrt{6}|2\rangle$$

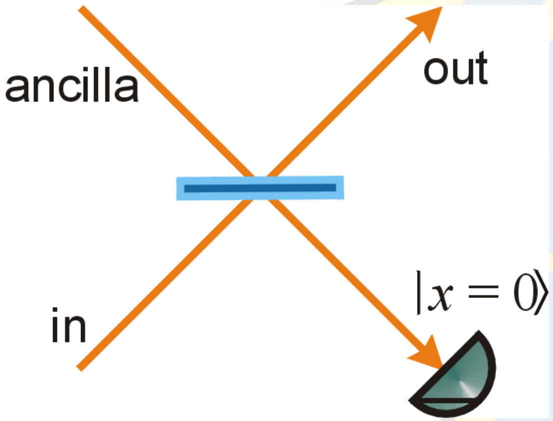
Analysis of cubic behavior

- The state is non-classical
  - It could correspond to the ideal state + noise
  - But does it posses cubic nonlinearity?

- Fidelity is of no use
- We need to look for alternative figures of merit

Inducing cubic operation

- Virtual application of the gate



$$\psi_{\rm out}(x) \approx \psi_{\rm in}(x)\psi_{\rm ancilla}(x)$$

$$\hat{x} \to \hat{x} \quad \hat{p} \to \hat{p} + 3\chi\hat{x}^2$$

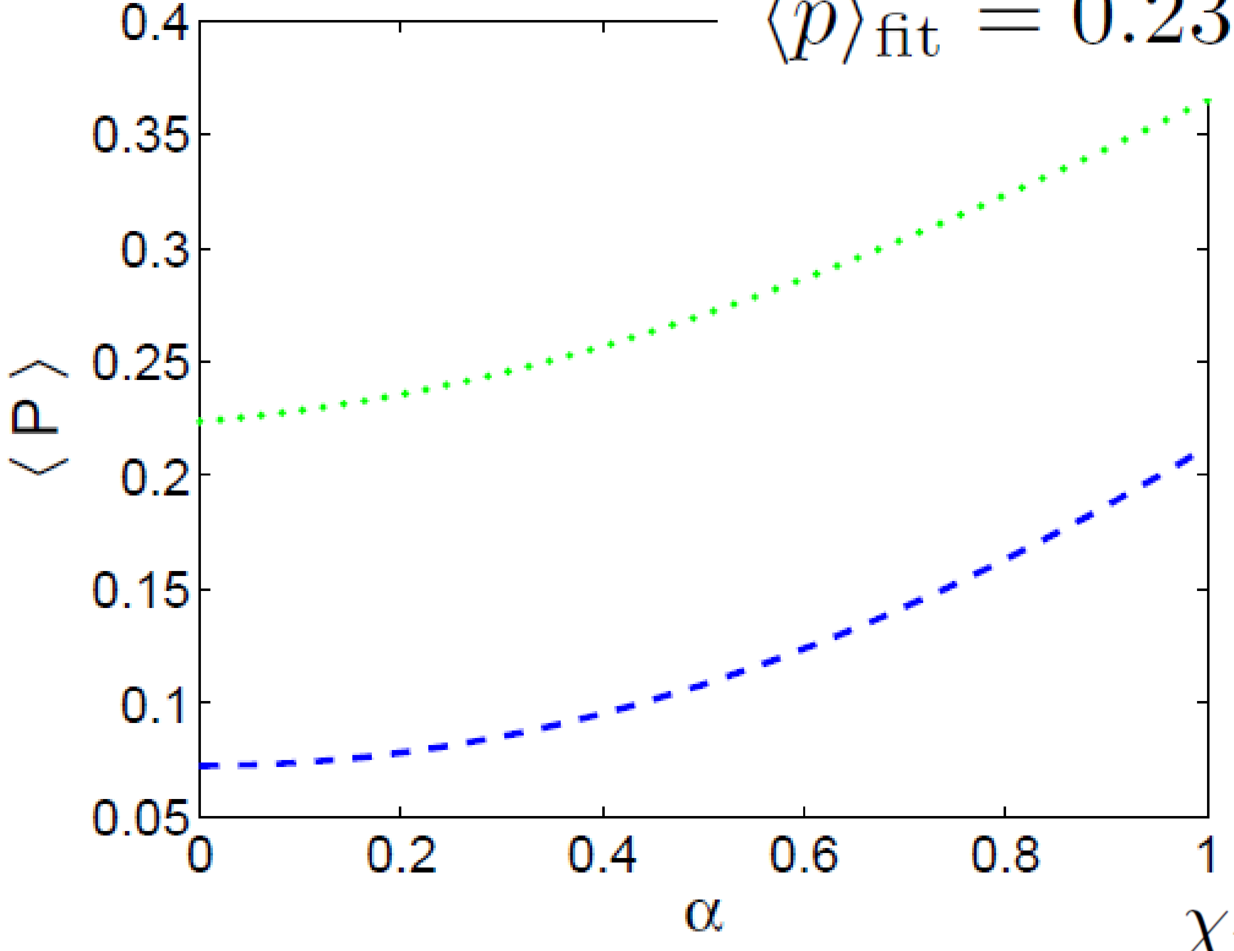
- For a set of coherent states $|\alpha\rangle$:

$$\langle p\rangle \to \langle p\rangle + 3\chi(2\alpha^2 + 1/2)$$

Inducing nonlinearity

$$\langle p \rangle \rightarrow \langle p \rangle + 3\chi(2\alpha^2 + 1/2)$$

$$\langle \hat{p} \rangle_{\text{fit}} = 0.23 + 0.14\alpha^2$$

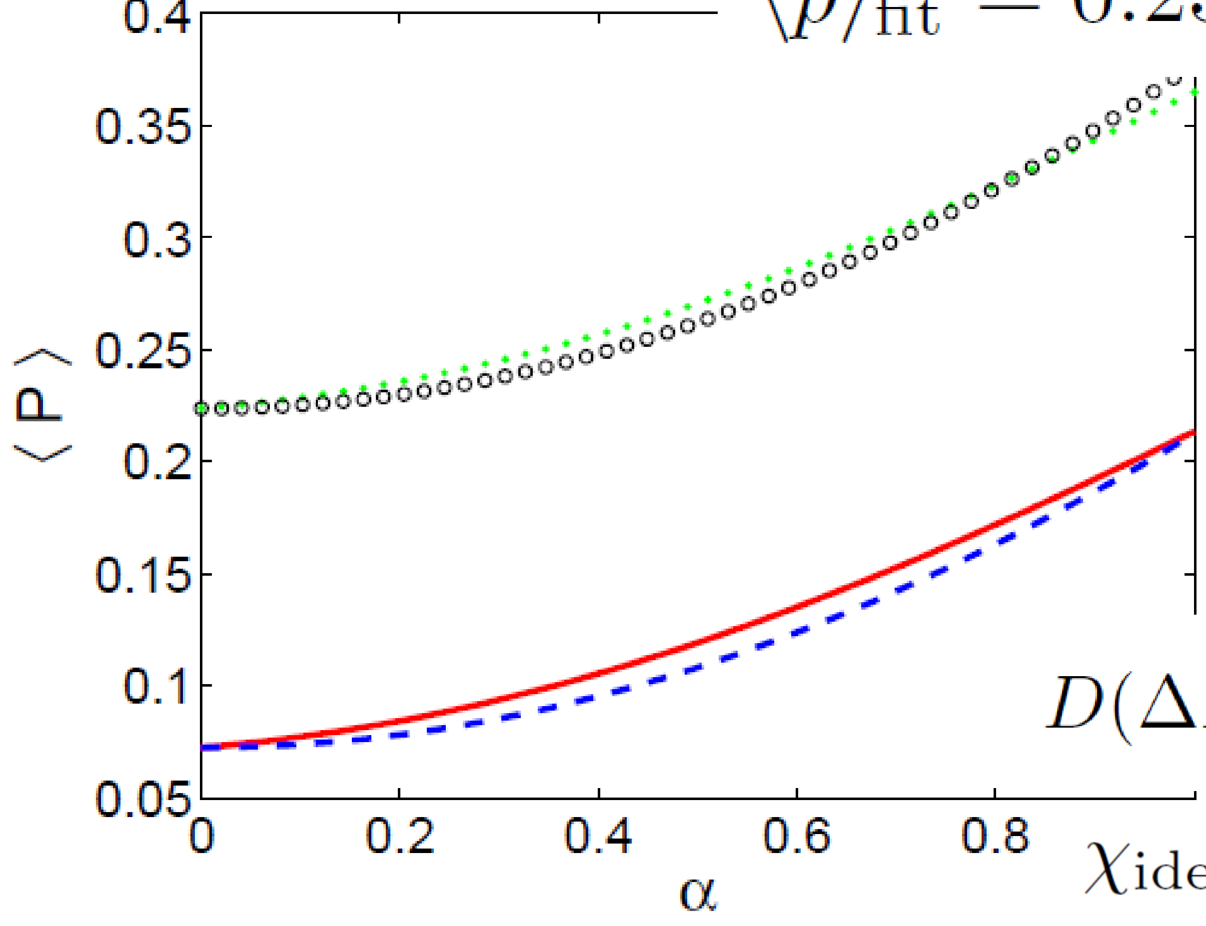


$$\chi_{\text{ideal}} = 0.09$$

Inducing nonlinearity

$$\langle p \rangle \to \langle p \rangle + 3\chi(2\alpha^2 + 1/2)$$

$$\langle \hat{p} \rangle_{\text{fit}} = 0.23 + 0.14\alpha^2$$



$$D(\Delta P) = 0.16$$

$$\chi_{\text{ideal}} = 0.09$$

Observing cubic nonlinearity directly

- Density matrix in position representation

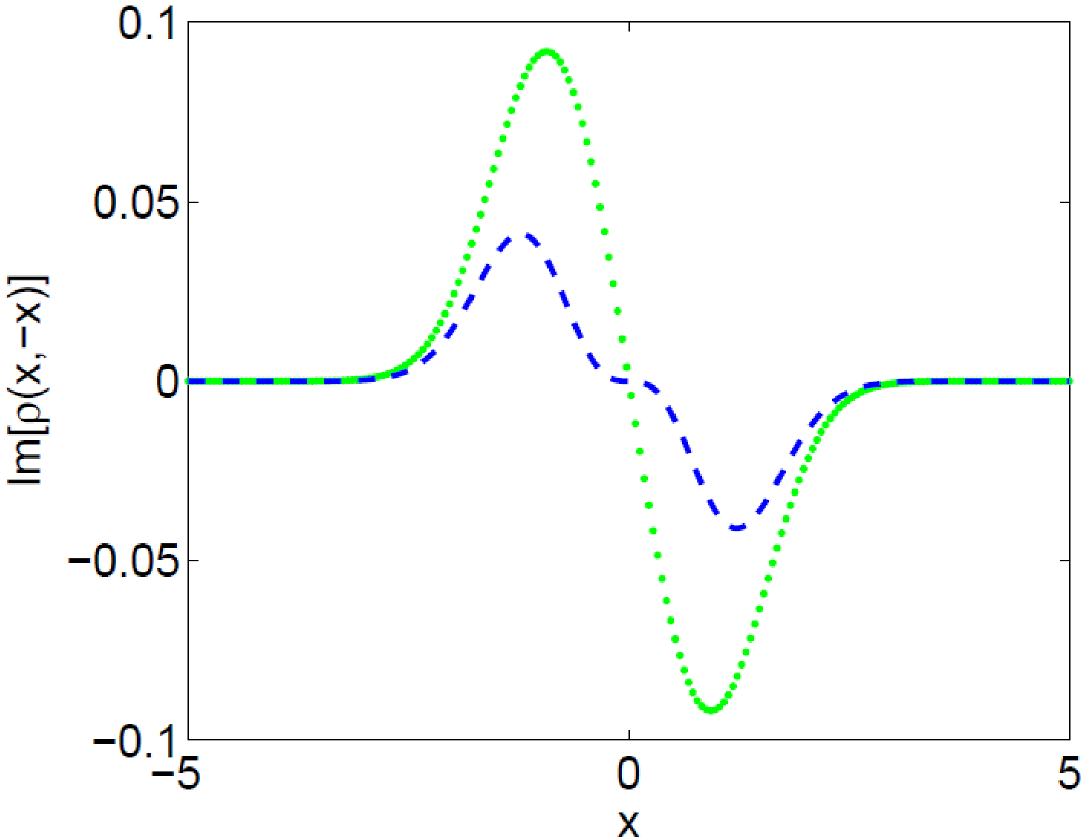
$$\rho(x, x') = \langle x|\hat{\rho}|x\rangle$$

- Looking at the main anti-diagonal:

$$\rho_{id}(x, -x) = \langle x|(1 + i\chi\hat{x}^3)|0\rangle\langle 0|(1 - i\chi\hat{x}^3)| - x\rangle$$
$$= e^{-x^2}(1 - \chi^2 x^6 + 2i\chi x^3)$$

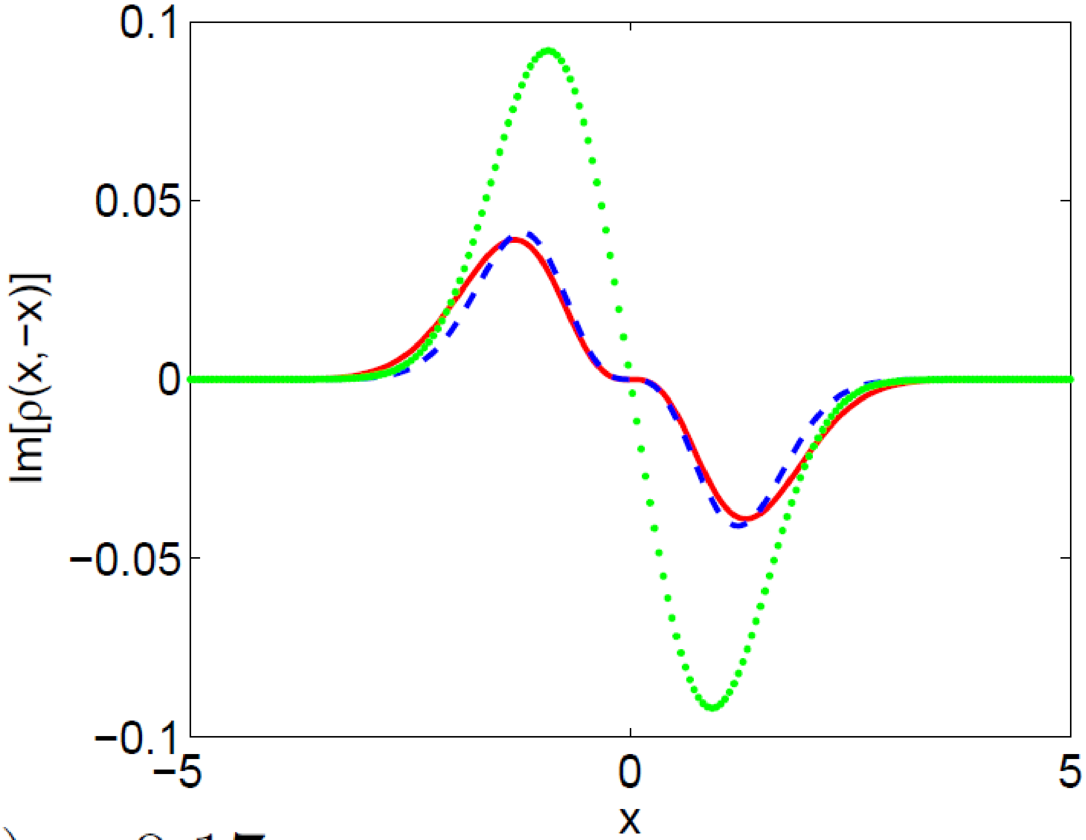
  – Cubic nonlinearity is visible in the imaginary part

Density matrix in position representation



$$\chi_{\rm ideal} = 0.09$$

Density matrix in position representation



$D(\Delta P) = 0.17$ $\chi_{\mathrm{ideal}} = 0.09$

In summary

- Quantum operation can be implemented in a measurement induced way
- Highly nontrivial states, needed for these operations, can be constructed from individual photons

Thank you for the attention!

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