מכון ויצמן למדע
WEIZMANN INSTITUTE OF SCIENCE

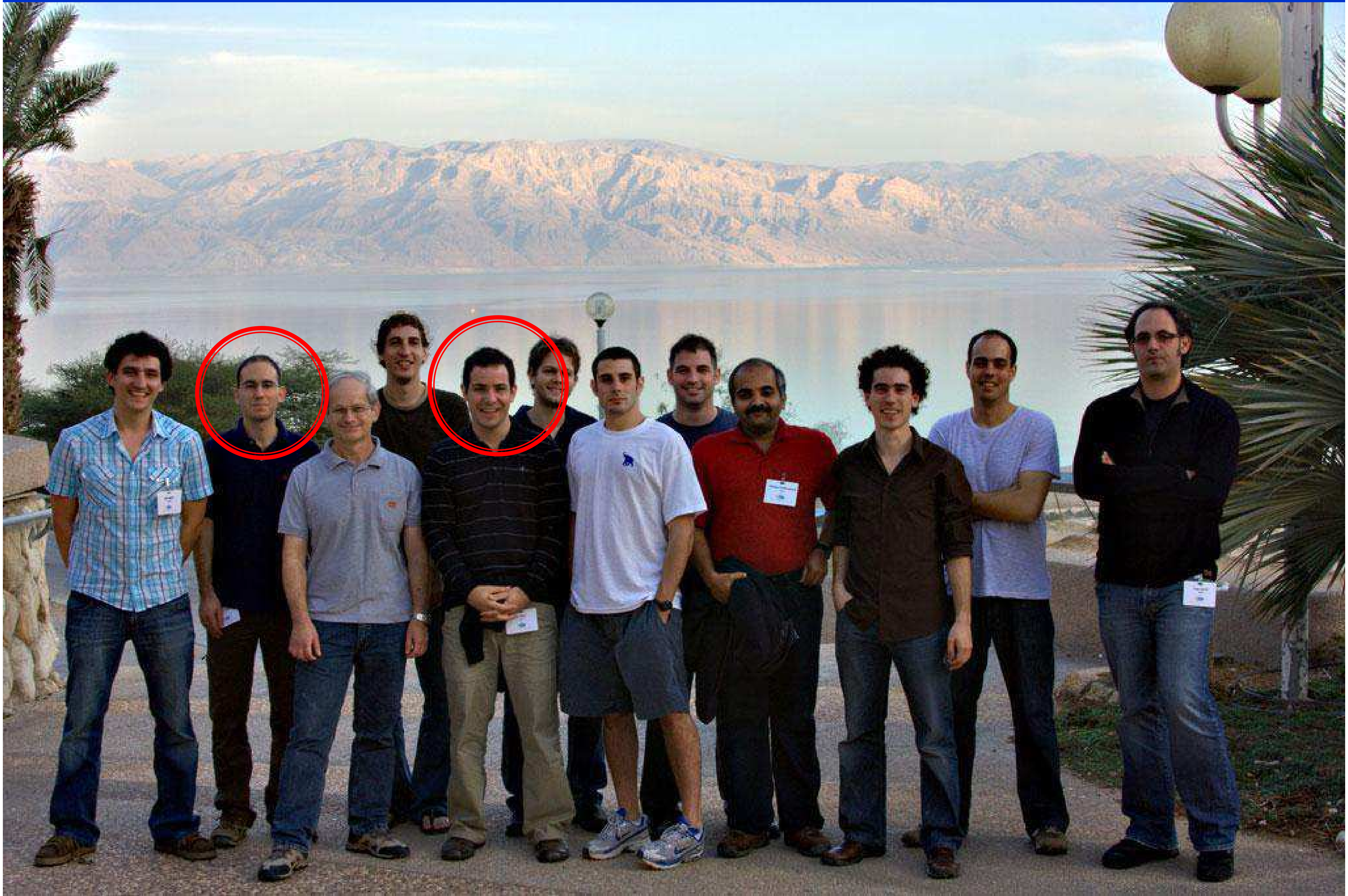
An Easy Road to High-NOON
The photonic Schrodinger's cat

Bonus: Entangled Photon Holes !

Itai Afek, Oron Ambar, Yonatan Israel
Yaron Silberberg

www.weizmann.ac.il/~feyaron

Thanks…



Anti-photon

W.E. Lamb, Jr.

Optical Sciences Center, University of Arizona, Tucson, AZ 85721, USA

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Abstract. It should be apparent from the title of this article that the author does not like the use of the word "photon", which dates from 1926. In his view, there is no such thing as a photon. Only a comedy of errors and historical accidents led to its popularity among physicists and optical scientists. I admit that the word is short and convenient. Its use is also habit forming. Similarly, one might find it convenient to speak of the "aether" or "vacuum" to stand for empty space, even if no such thing existed. There are very good substitute words for "photon", (e.g., "radiation" or "light"), and for "photonics" (e.g., "optics" or "quantum optics"). Similar objections are possible to use of the word "phonon", which dates from 1932. Objects like electrons, neutrinos of finite rest mass, or helium atoms can, under suitable conditions, be considered to be particles, since their theories then have viable non-relativistic and non-quantum limits. This paper outlines the main features of the quantum theory of radiation and indicates how they can be used to treat problems in quantum optics.

afterward, there was a population explosion of people engaged in fundamental research and in very useful technical and commercial developments of lasers. QTR was available, but not in a form convenient for the problems at hand. The photon concepts as used by a high percentage of the laser community have no scientific justification. It is now about thirty-five years after the making of the first laser. The sooner an appropriate reformulation of our educational processes can be made, the better.

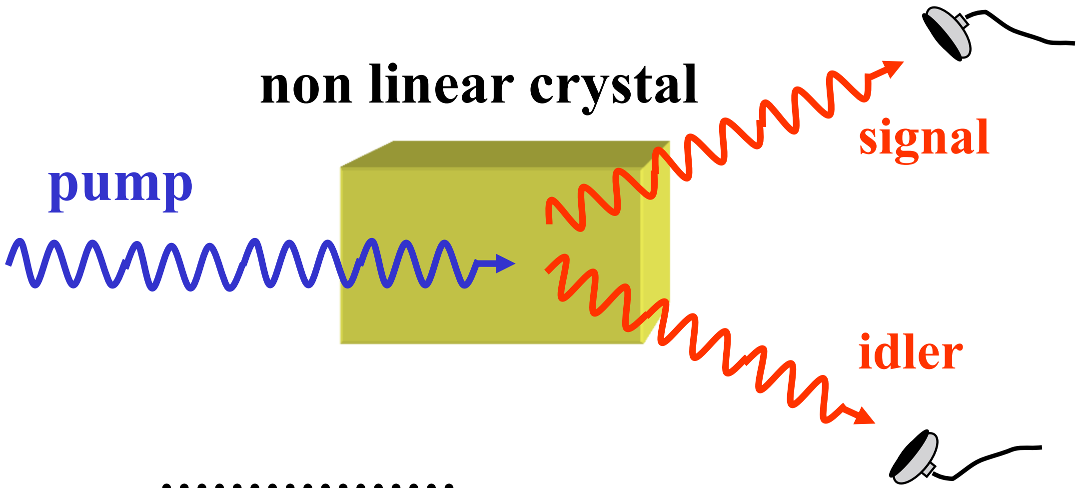
1 A short history of pre-photonic radiation

Modern optical theory [2] began with the works of Ch. Huyghens and I. Newton near the end of the seventeenth century. Huyghen's treatise on wave optics was published in 1690. Newton's "Optiks", which appeared in 1704, dealt with his corpuscular theory of light.

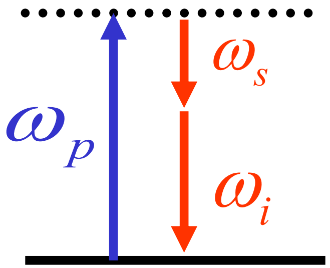
A decisive work in 1801 by T. Young, on the two-slit diffraction pattern, showed that the wave version of optics

Spontaneous Parametric Down-Conversion

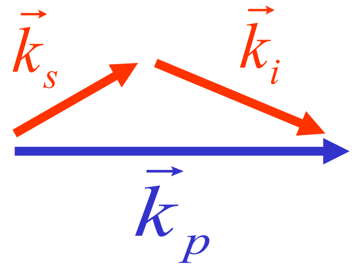
a pump photon is spontaneously converted into two lower frequency photons



energy conservation



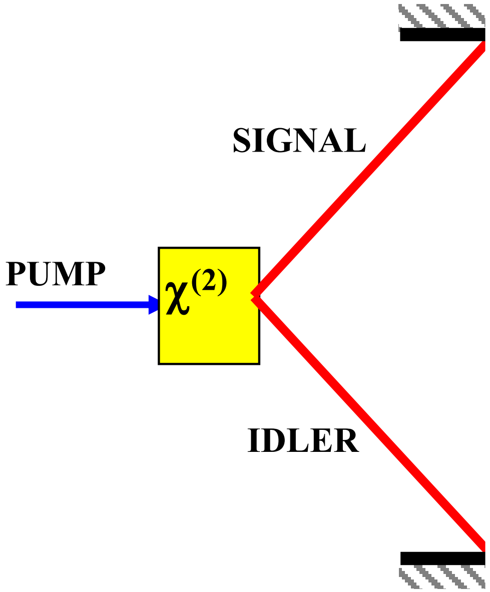
momentum conservation (phase matching)

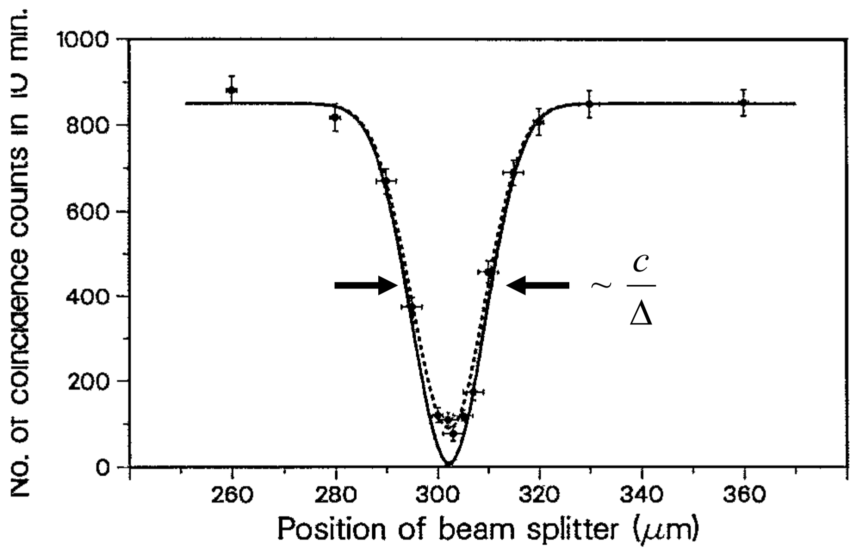


The Hong-Ou-Mandel dip

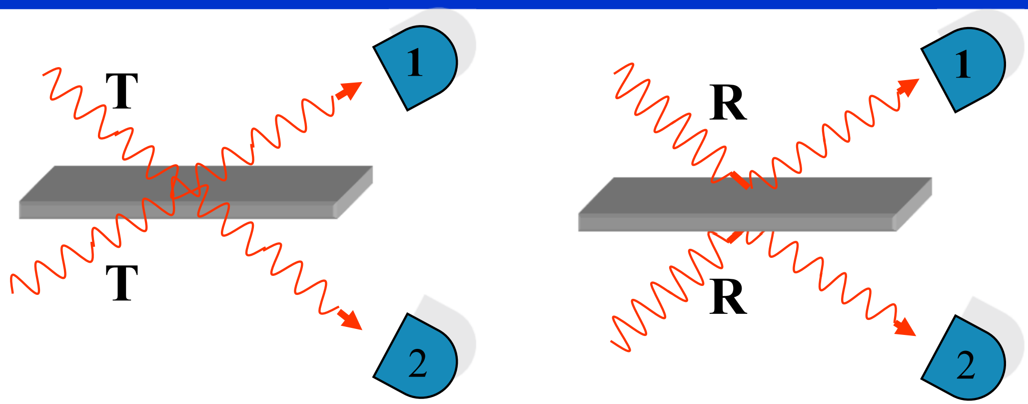
"Measurement of Subpicosecond Time Intervals between Two Photons by Interference"

C.K. Hong, Z.Y. Ou and L. Mandel, PRL 59 (1987)





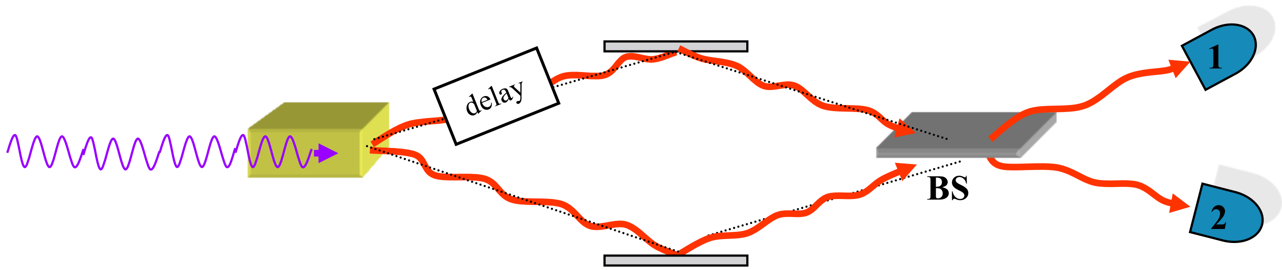
Two-Photon Coincidence Interference



$$\frac{1}{\sqrt{2}} \cdot \frac{1}{\sqrt{2}} \quad + \quad \frac{i}{\sqrt{2}} \cdot \frac{i}{\sqrt{2}} \quad = \quad 0$$

Indistinguishable paths which lead to the same event interfere

→ destructive interference → no coincidence



delay → distinguishable paths → no interference

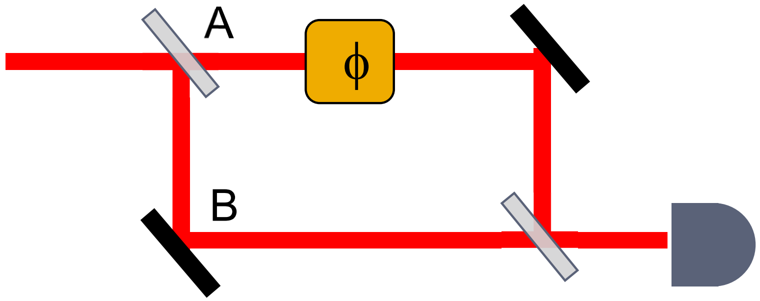
Outline

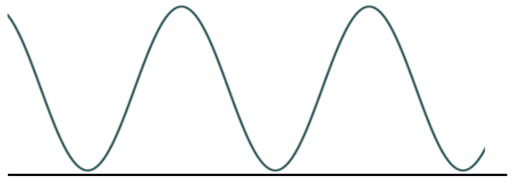
- Short intro to NOON states
- Experimental demonstration of 2- to 5-photon NOON states
- Entangled photon holes

Basics of Optical Metrology

Phase (or distance) Measurement:

$$I(\phi) = \cos^2(\phi/2)$$

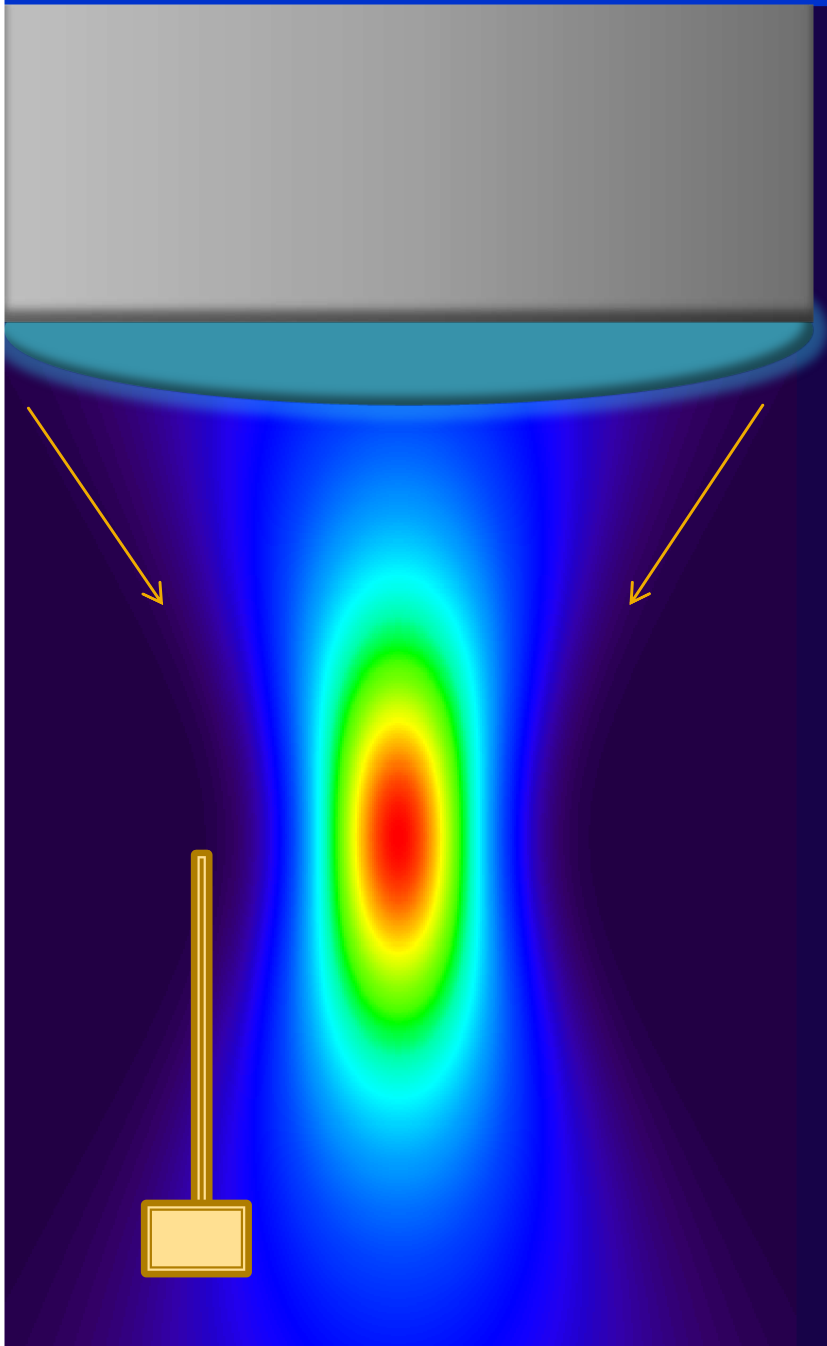




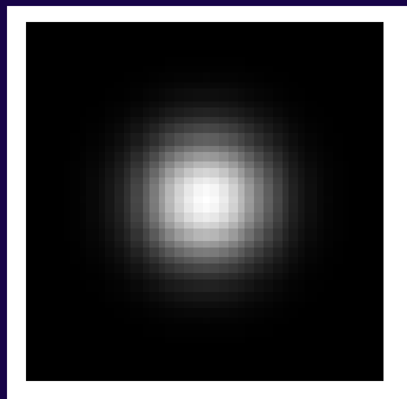
Shot Noise Limited Measurement: $$\Delta\phi = 1/\sqrt{N}$$

Heisenberg Uncertainly limit: $$\Delta\phi = 1/N$$

Interferometry and Imaging

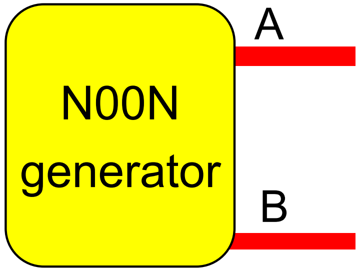


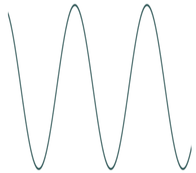
Standard
detector



Diffraction
Limited spot

Enter High-NOON states





$$|N\rangle_A|0\rangle_B + |0\rangle_A|N\rangle_B \rightarrow e^{i\varphi N}|N\rangle_A|0\rangle_B + |0\rangle_A|N\rangle_B \quad \rightarrow \cos^2(N\varphi/2)$$

High-NOON states collect phase N times faster than coherent states – they behave as if their wavelength is N times shorter!

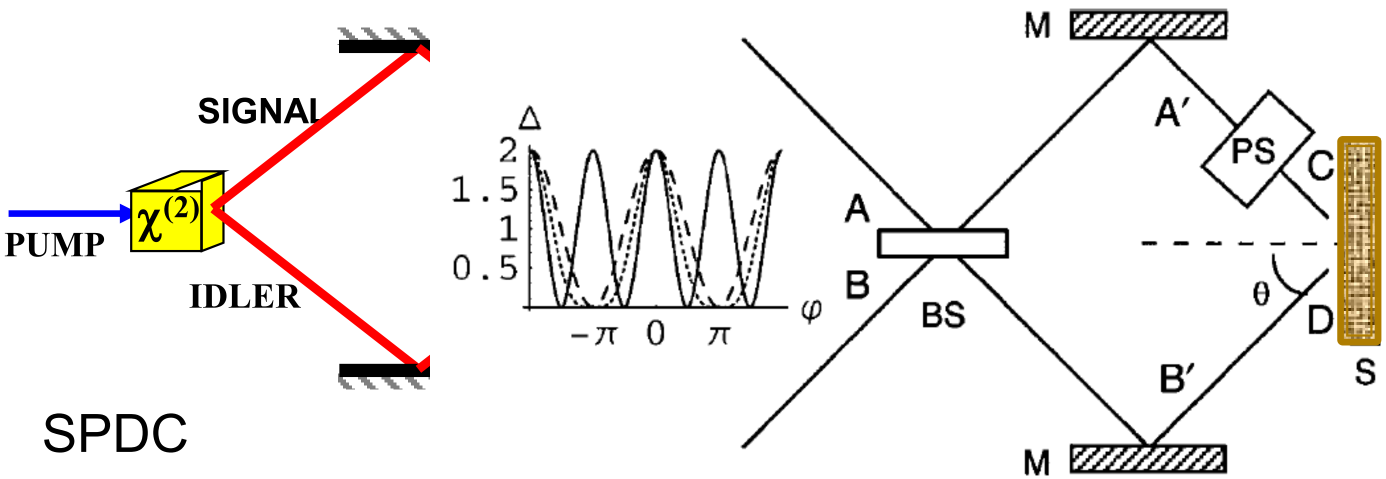
Can reach the Heisenberg limit

NOON states are an example of Schrodinger cat's states – Superposition of two very distinct many-particle states

Quantum Interferometric Optical Lithography: Exploiting Entanglement to Beat the Diffraction Limit

Agedi N. Boto,[1] Pieter Kok,[2] Daniel S. Abrams,[1] Samuel L. Braunstein,[2]
Colin P. Williams,[1] and Jonathan P. Dowling[1,*]

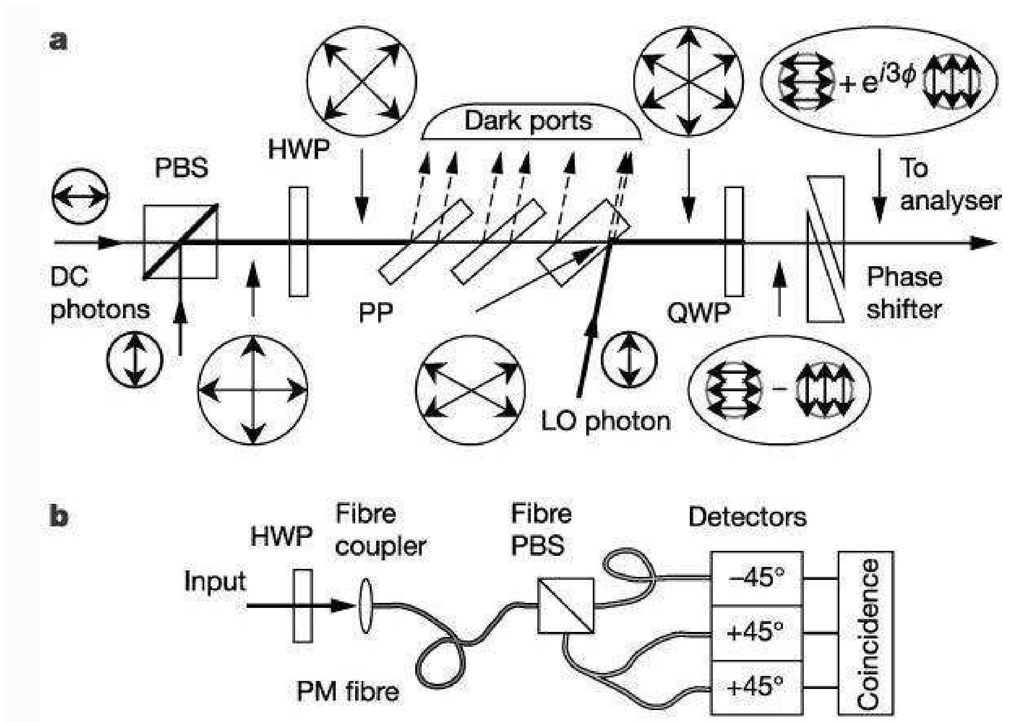
Classical optical lithography is diffraction limited to writing features of a size $\lambda/2$ or greater, where λ is the optical wavelength. Using nonclassical photon-number states, entangled N at a time, we show that it is possible to write features of minimum size $\lambda/(2N)$ in an N-photon absorbing substrate. This result allows one to write a factor of N^2 more elements on a semiconductor chip. A factor of $N = 2$ can be achieved easily with entangled photon pairs generated from optical parametric down-conversion. It is shown how to write arbitrary 2D patterns by using this method.



Previous NOON generation:

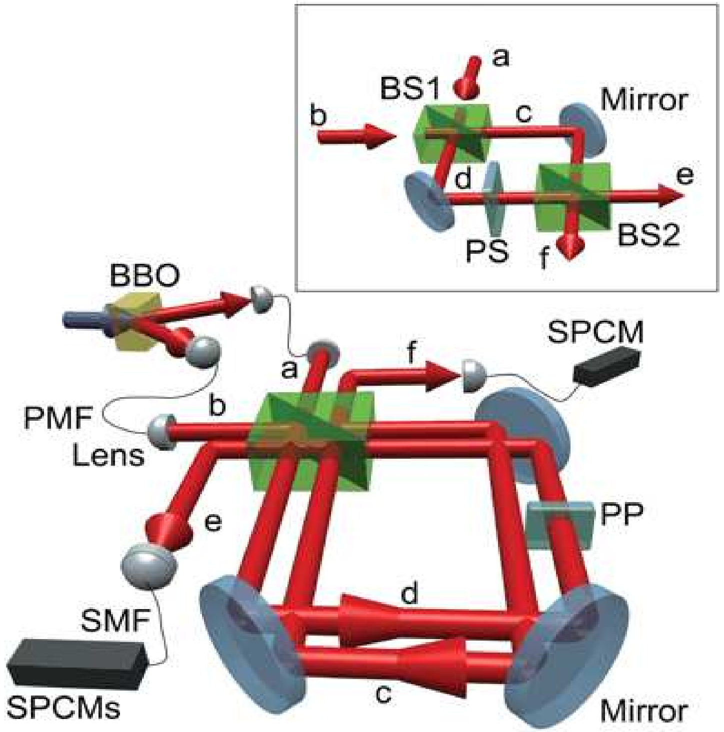
<u>3 photon NOON state</u>
1 SPDC pair + 1 CS photon

M. W. Mitchell et al,
Nature 429, 161 (2004)



<u>4 photon state</u>
2 SPDC pairs - using projection measurement

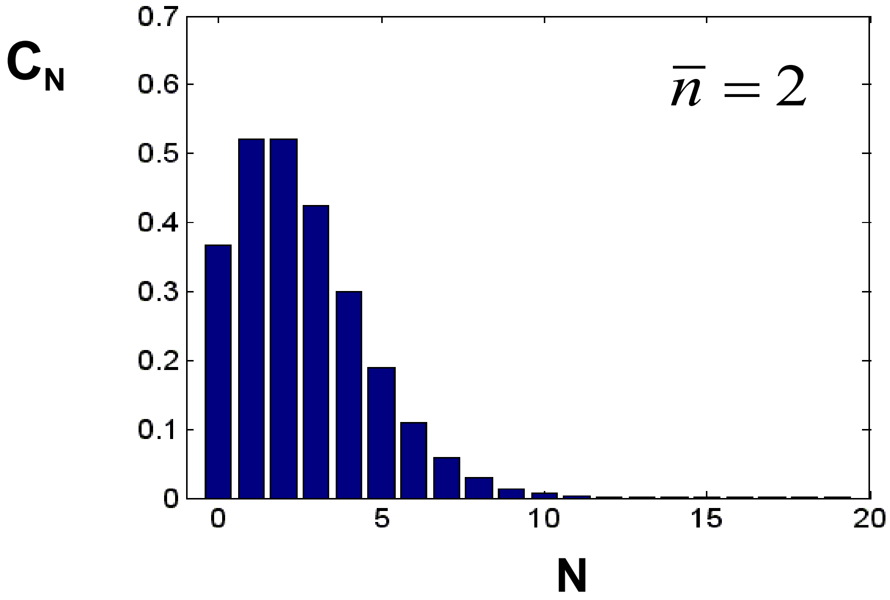
T. Nagata et al,
Science 316, 726 (2007)



Quantum Vs. Classical light statistics

Classical light

Coherent State Amplitudes

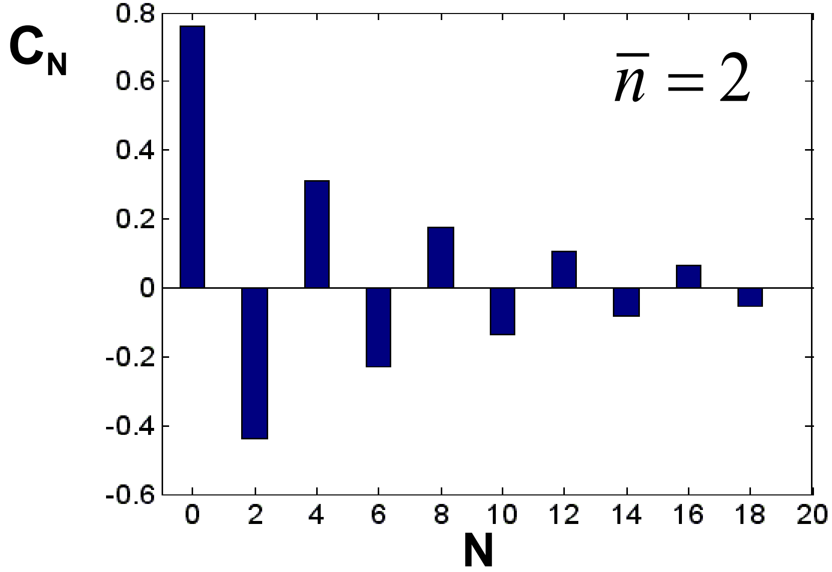


$$|\alpha\rangle = e^{-|\alpha|^2/2} \sum_{n=0}^{\infty} \frac{\alpha^n}{\sqrt{n!}} |n\rangle$$

Poissonian $\quad (\Delta \bar{n})^2 = \bar{n}$

Quantum light

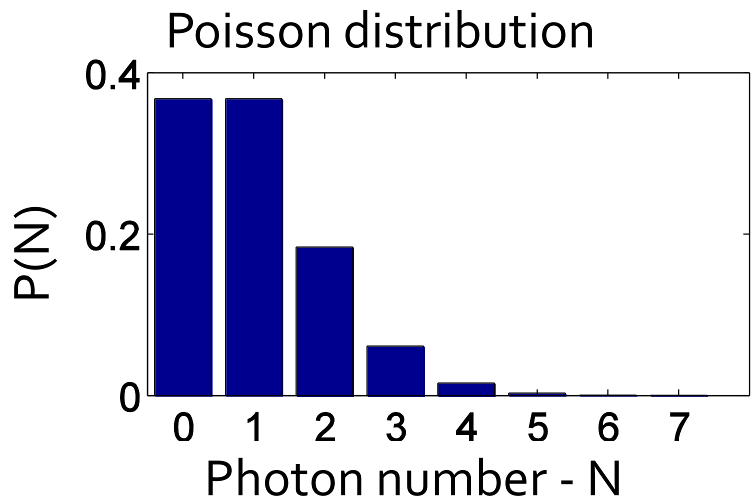
SPDC Amplitudes

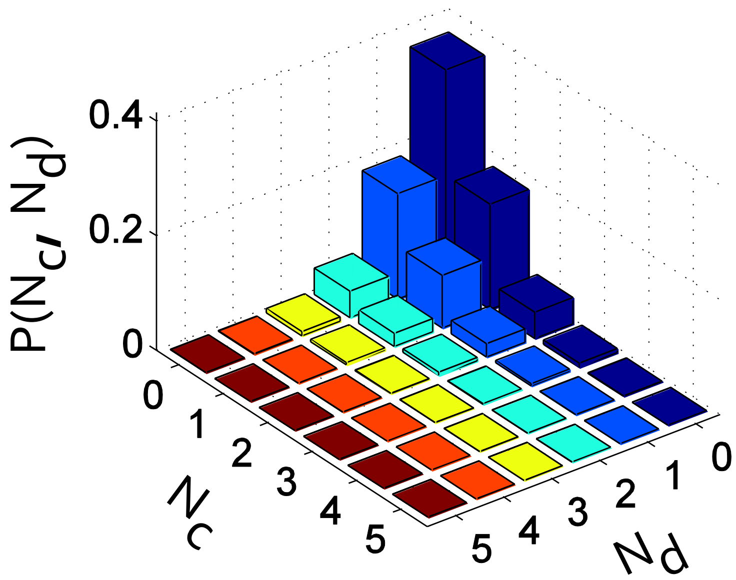


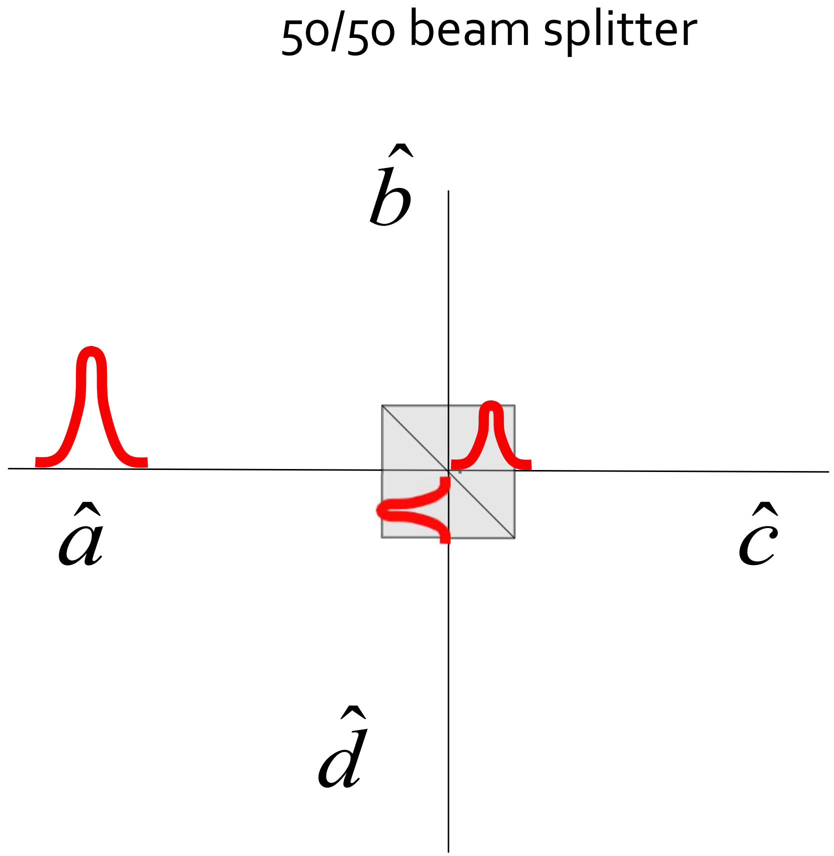
$$|\psi\rangle = \sum_{m=0} (-1)^m \frac{\sqrt{(2m)!}}{2^m m!} r^m |2m\rangle$$

Super-Poissonian $\quad (\Delta \bar{n})^2 > \bar{n}$

Coherent state through a beam splitter

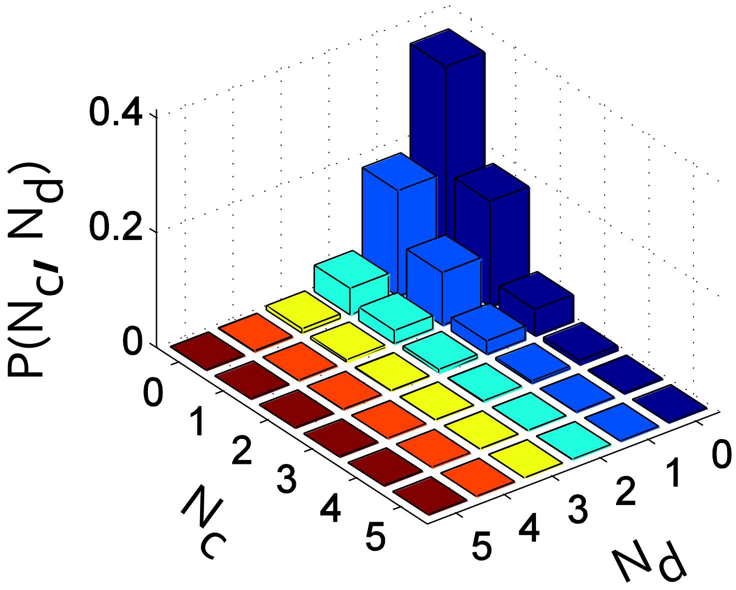






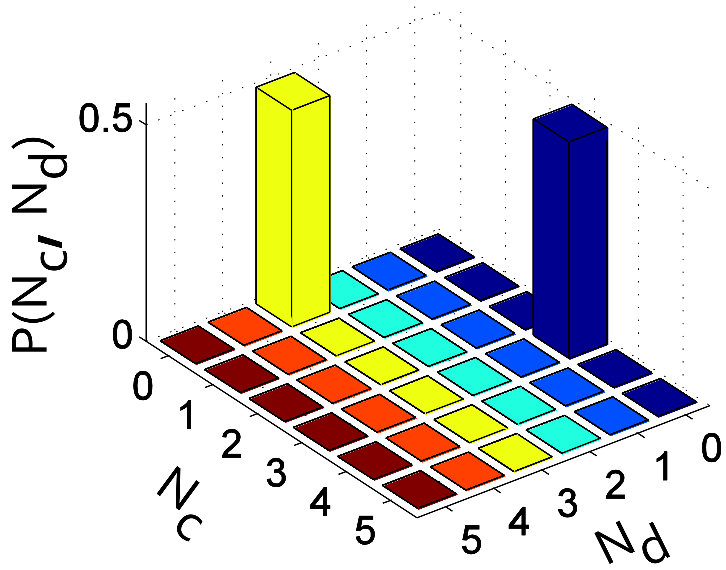
Product state vs. NOON state

Product state



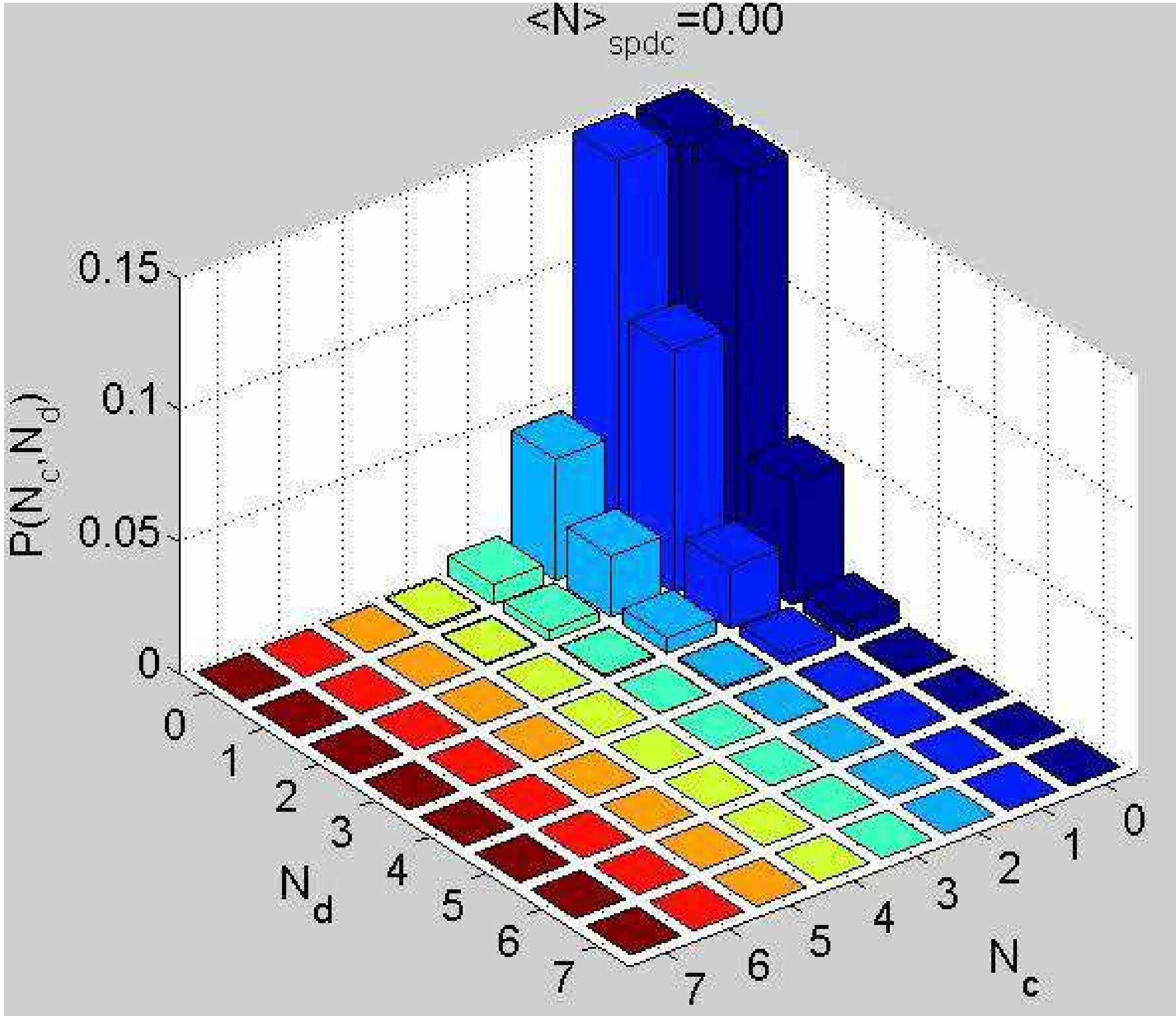
$$|\psi\rangle_{out} = |\alpha\rangle_c \otimes |\alpha\rangle_d$$

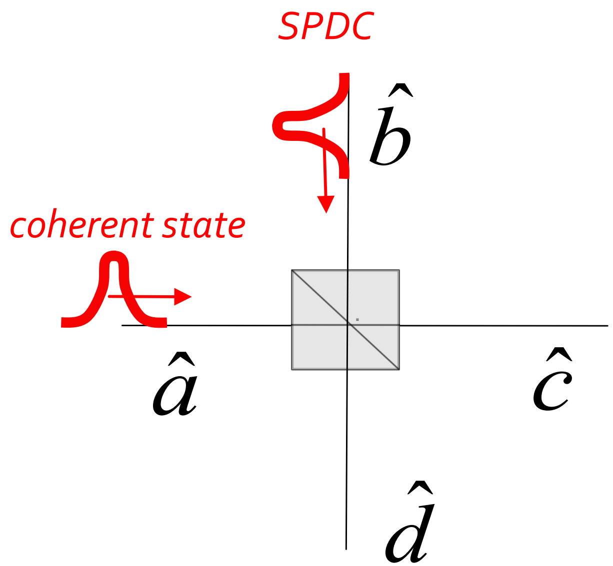
NOON state



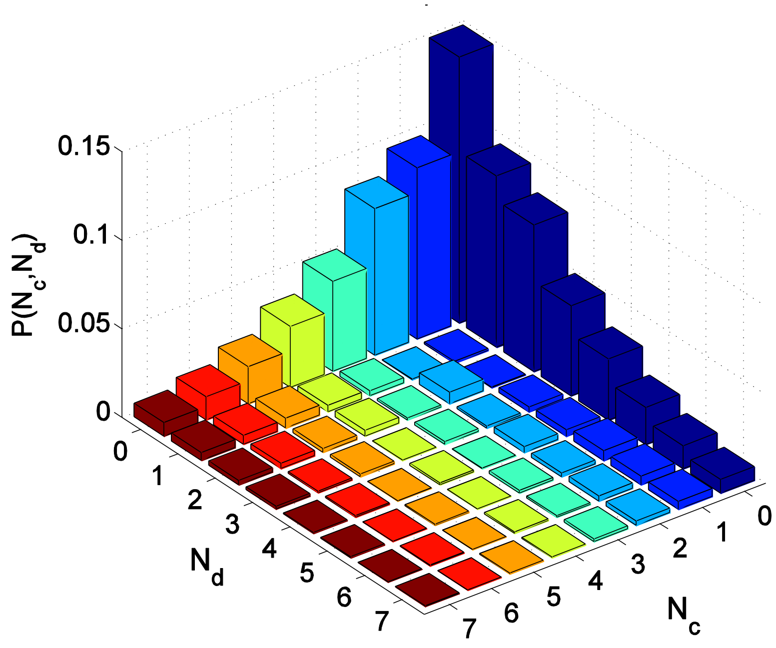
$$|\psi\rangle_{out} = |N\rangle_c |0\rangle_d + |0\rangle_c |N\rangle_d$$

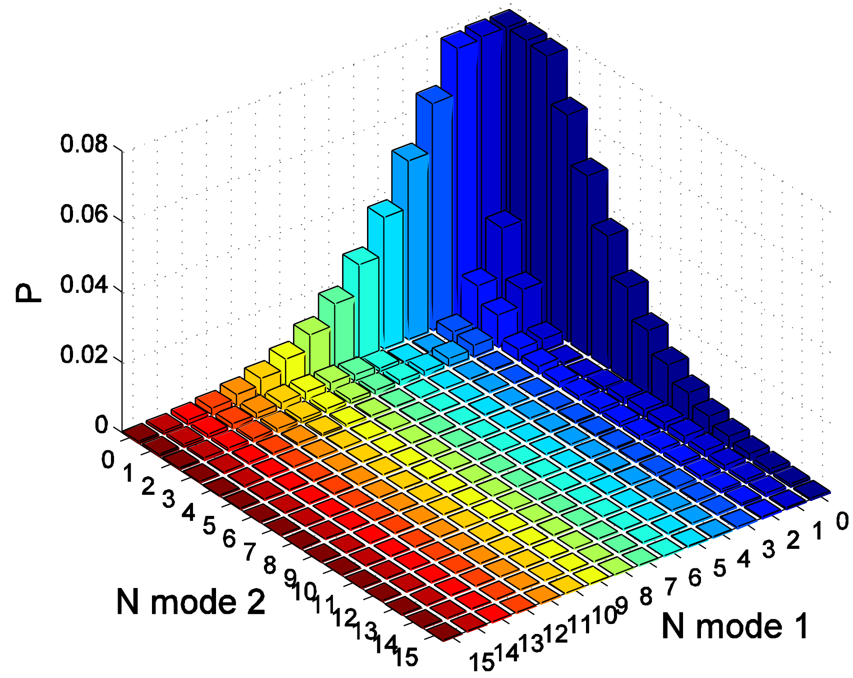
Squeezed vacuum for traffic control





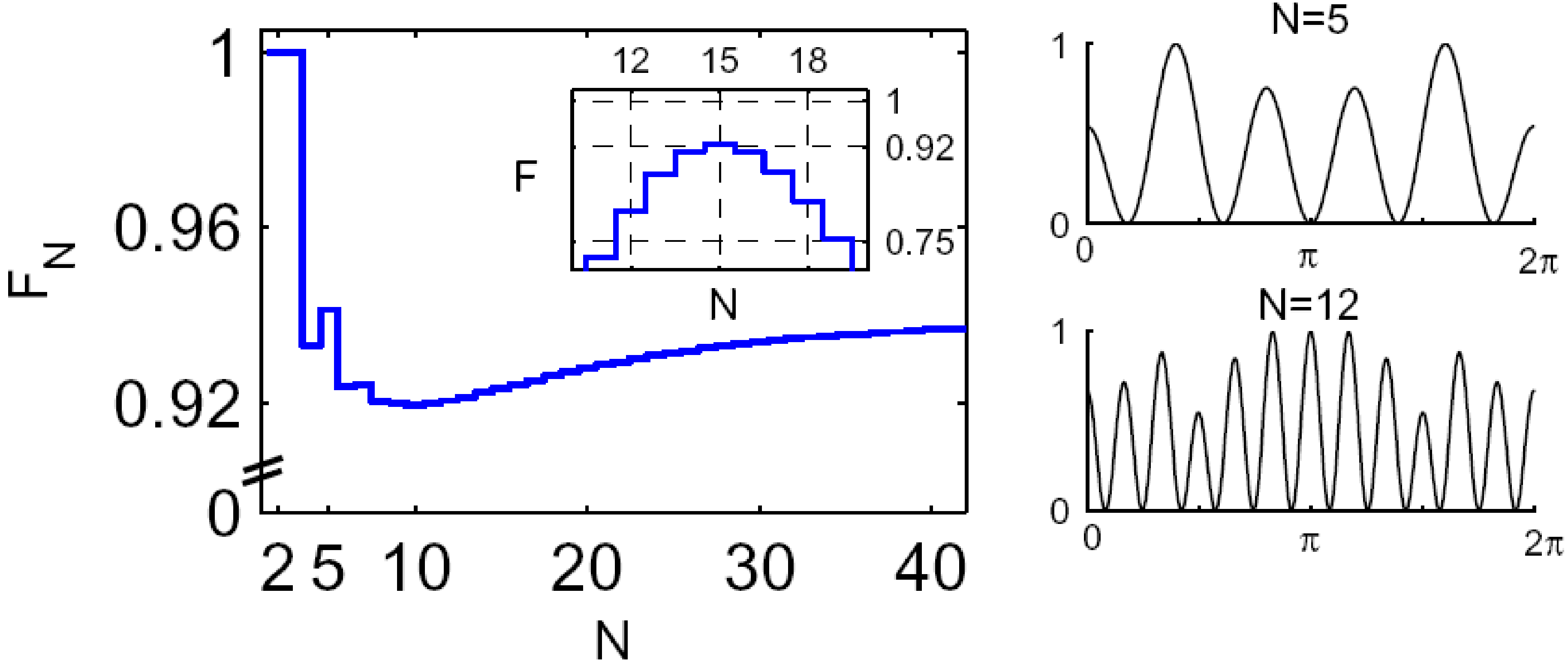
High-fidelity NOON - for any N !



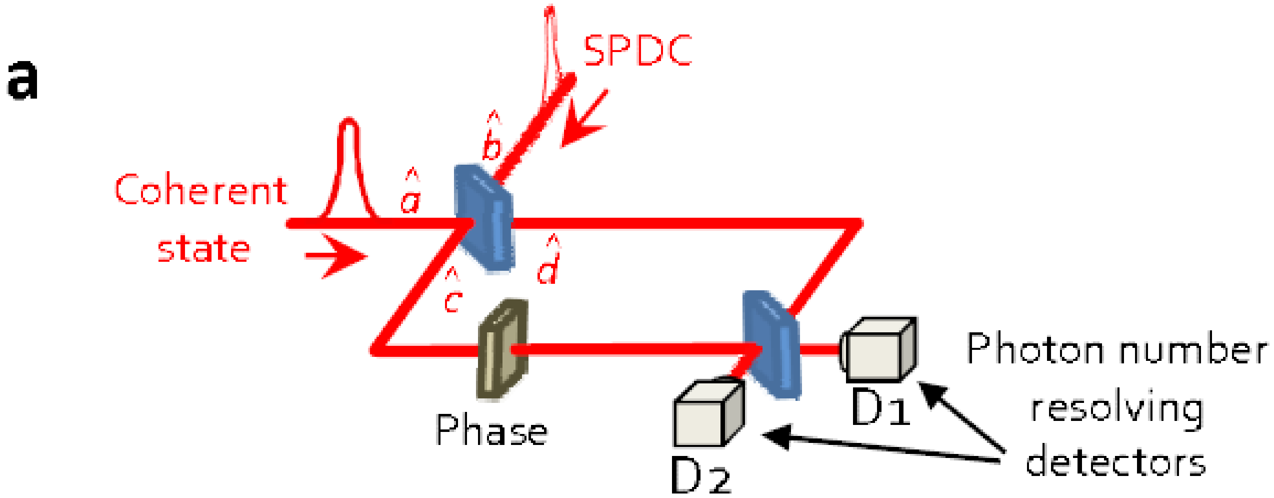


H. F. Hofmann and T. Ono, "High-photon-number path entanglement in the interference of spontaneously down-converted photon pairs with coherent laser light"
Phys. Rev. A **76,** 031806(R) (2007).

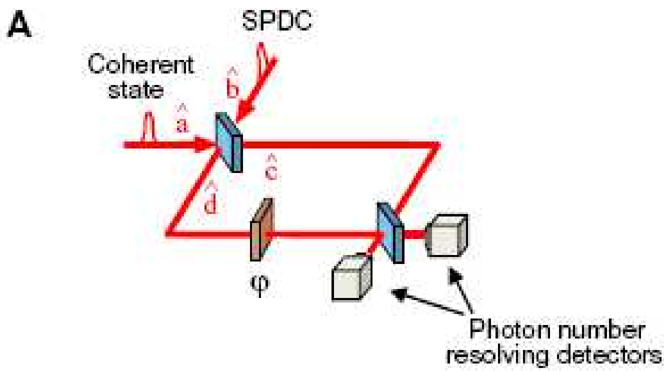
Theoretical fidelity values

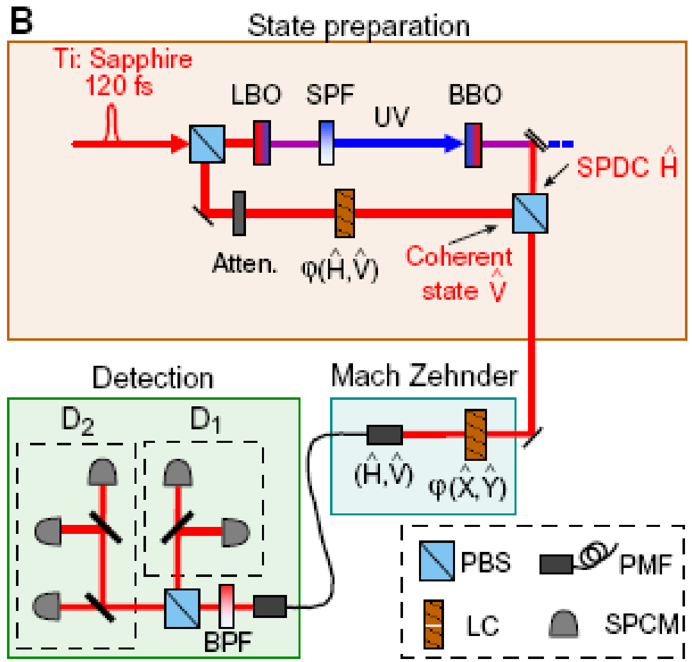


Schematic experimental system

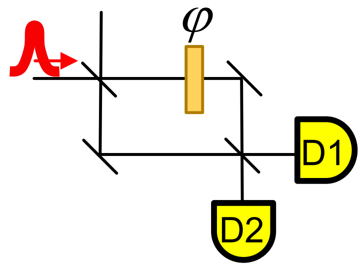


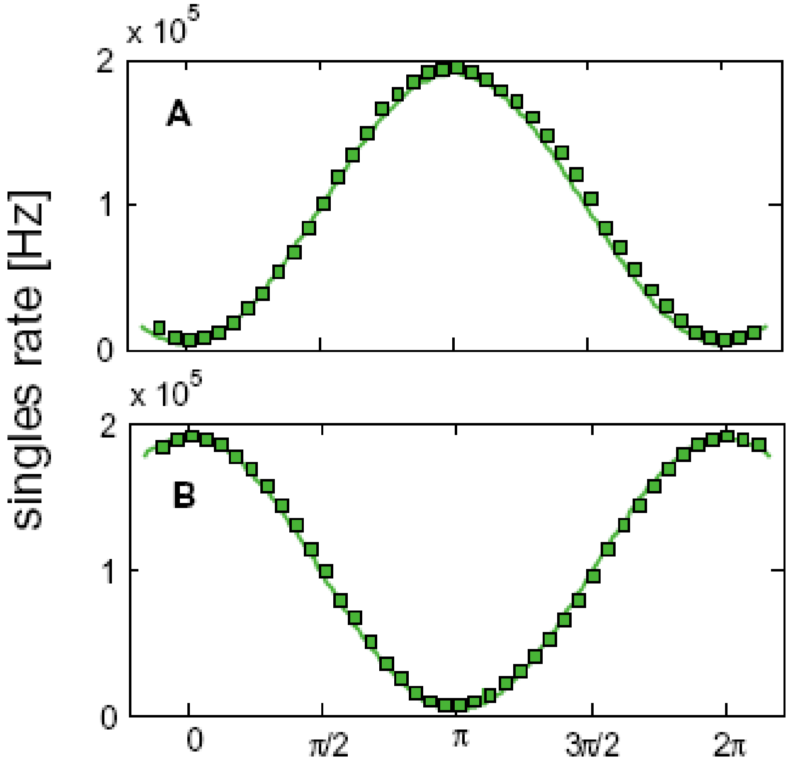
Experimental system





Mach-Zehnder interference measurement

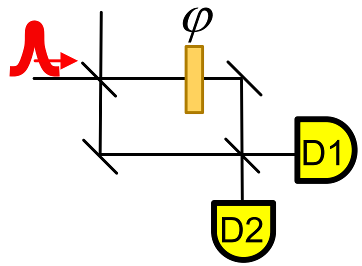


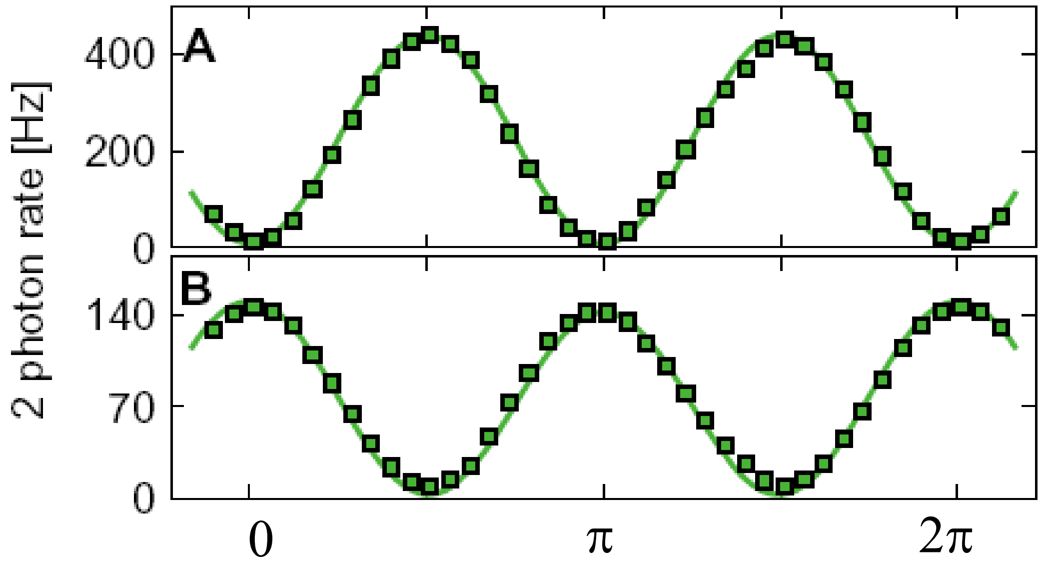


$N_1=1,\ N_2=0$

$N_1=0,\ N_2=1$

2-Photon NOON – de Broglie wave measurement



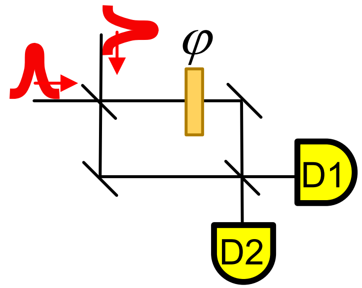


N_1=1, N_2=1

N_1=0, N_2=2

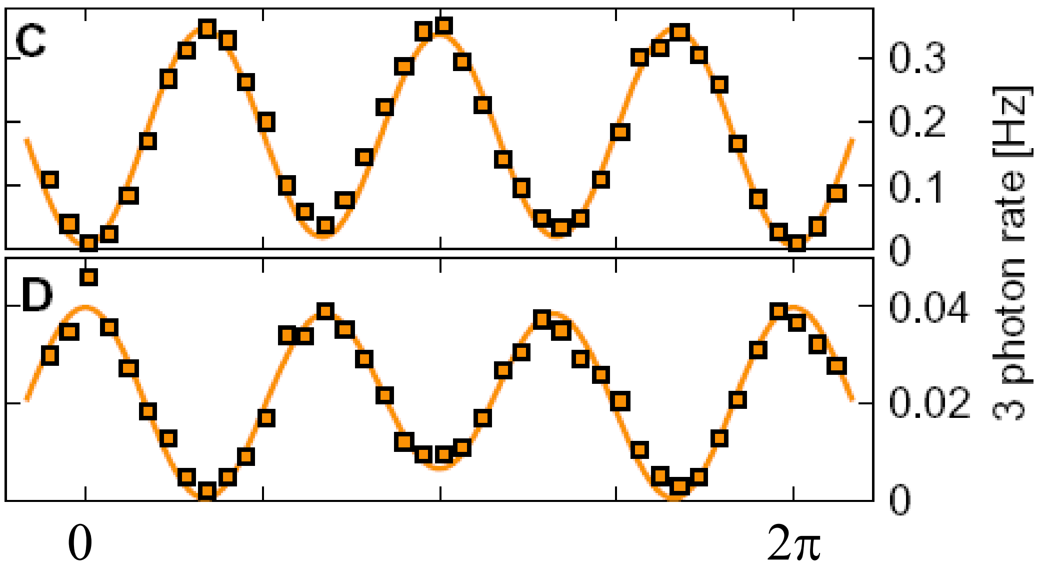
V=95%

3-Photon NOON – de Broglie wave measurement



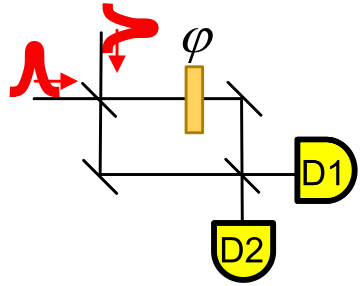
N_1=2, N_2=1

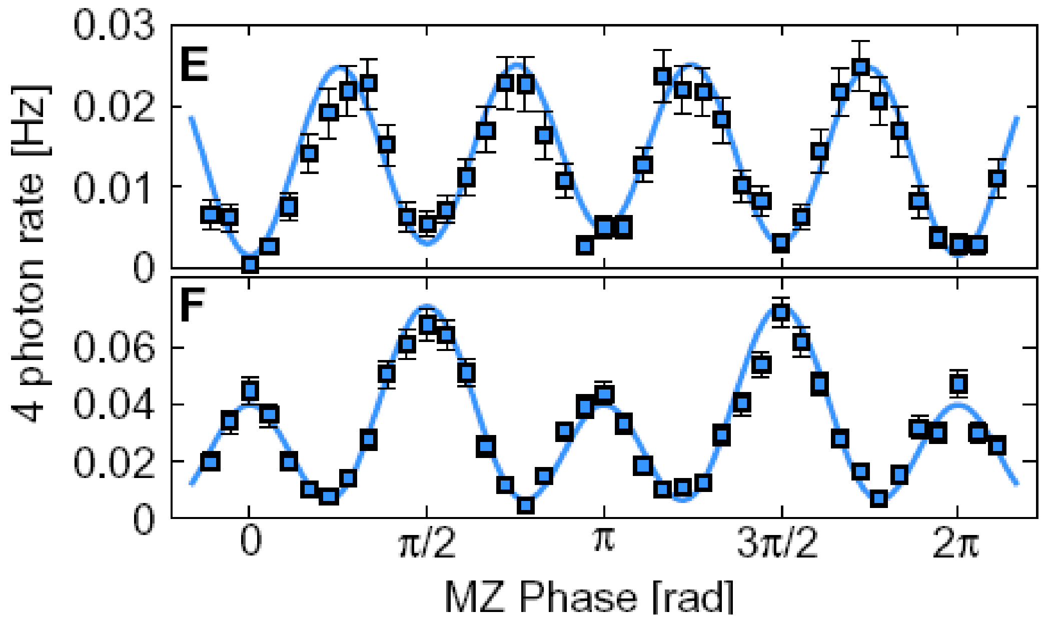
N_1=0, N_2=3



V=88%

4-Photon NOON – de Broglie wave measurement



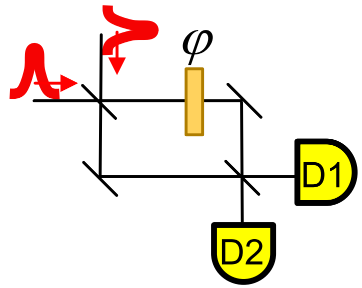


N_1=3, N_2=1

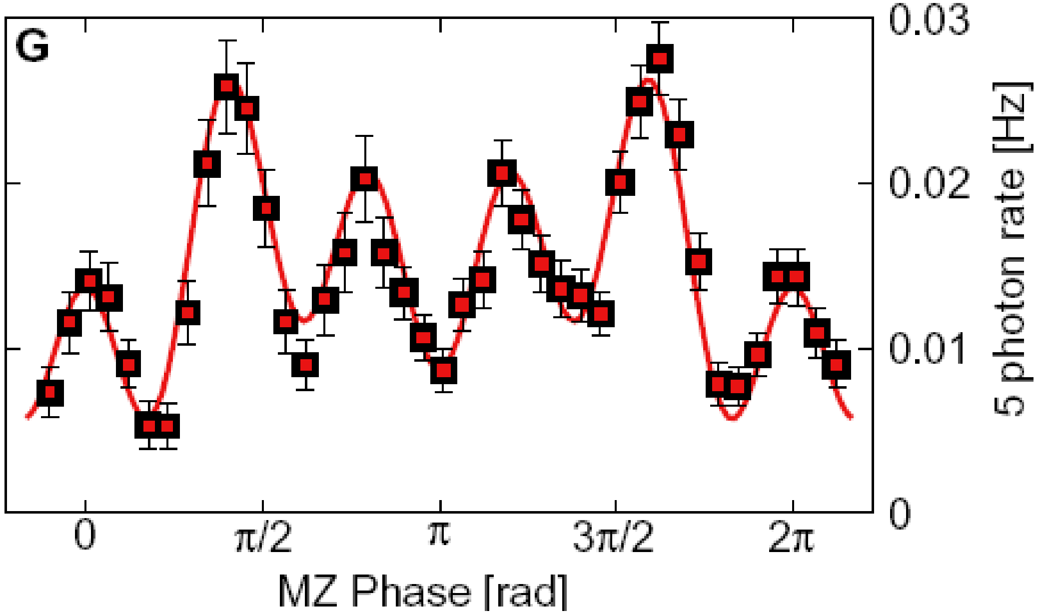
N_1=2, N_2=2

V=75%

5-Photon NOON – de Broglie wave measurement

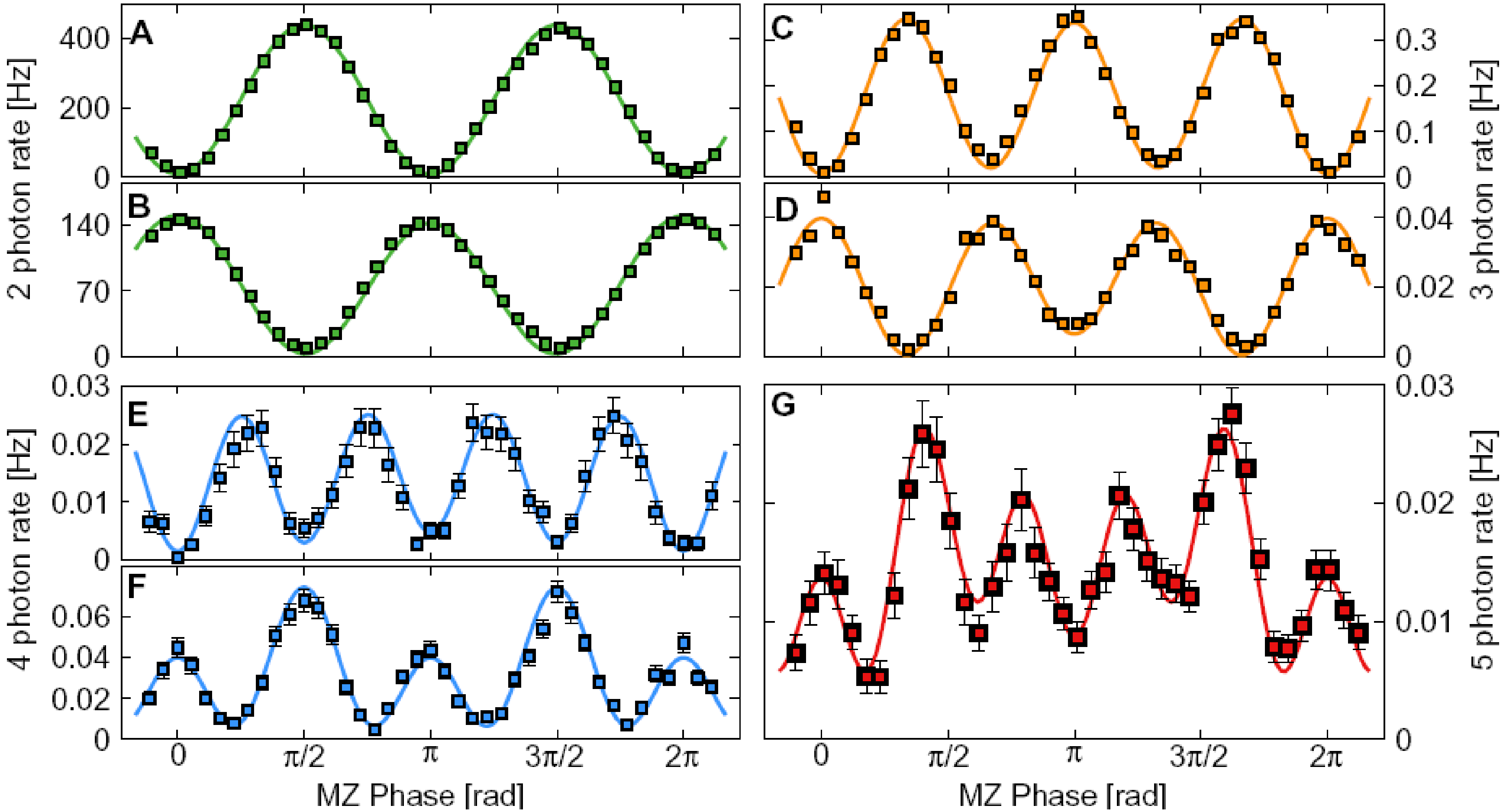


N_1=2, N_2=3



V=42%

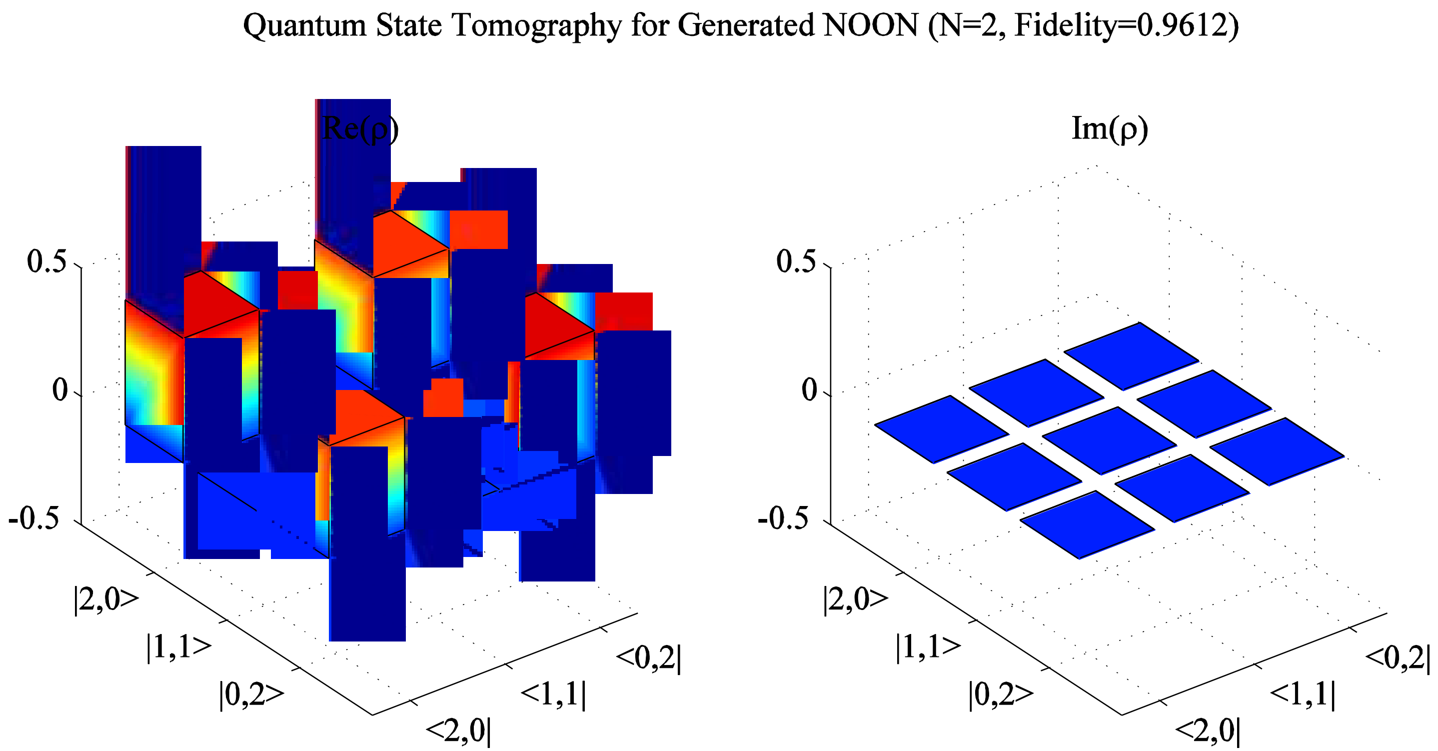
2 to 5 photon NOON states



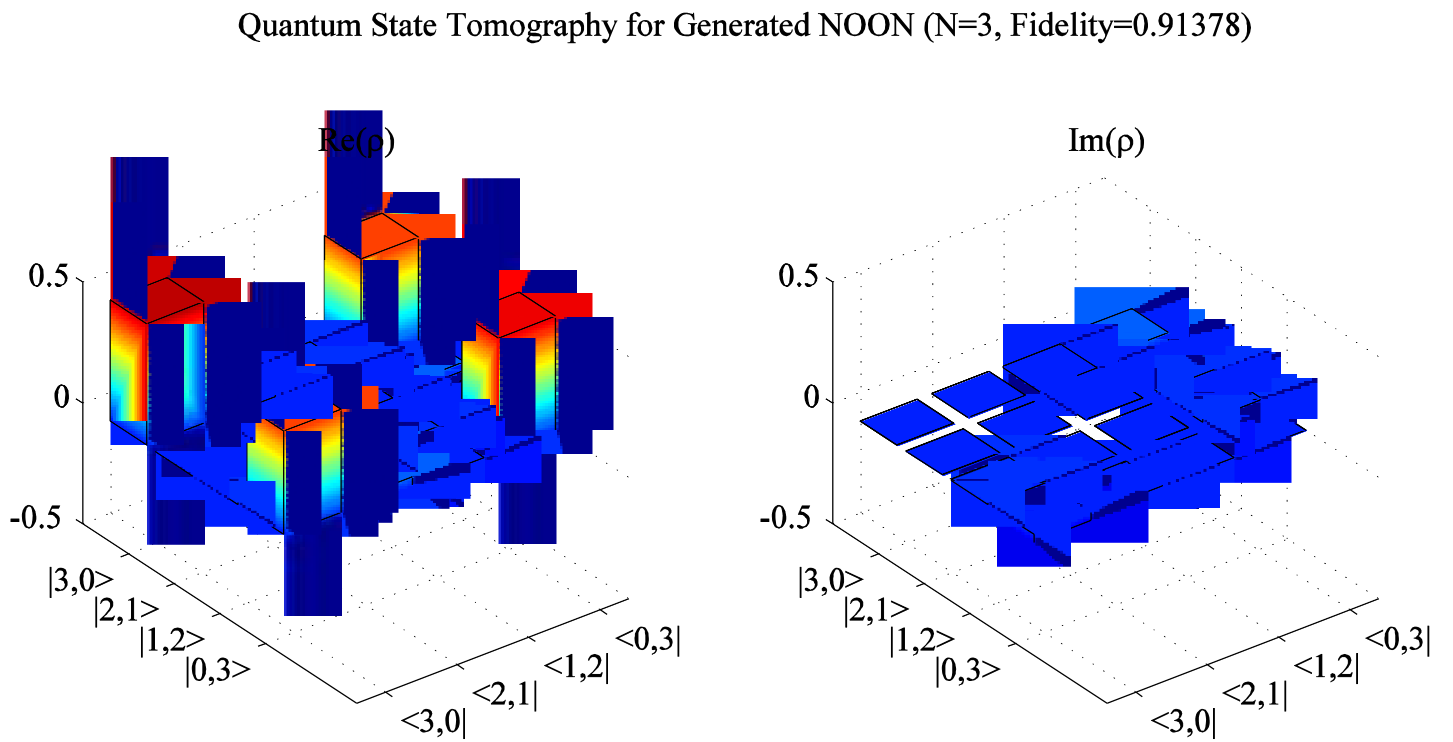
Afek, Ambar, YS, *Science* **328,** 879 – 881 (2010)

PRL **104**, 123602 (2010)

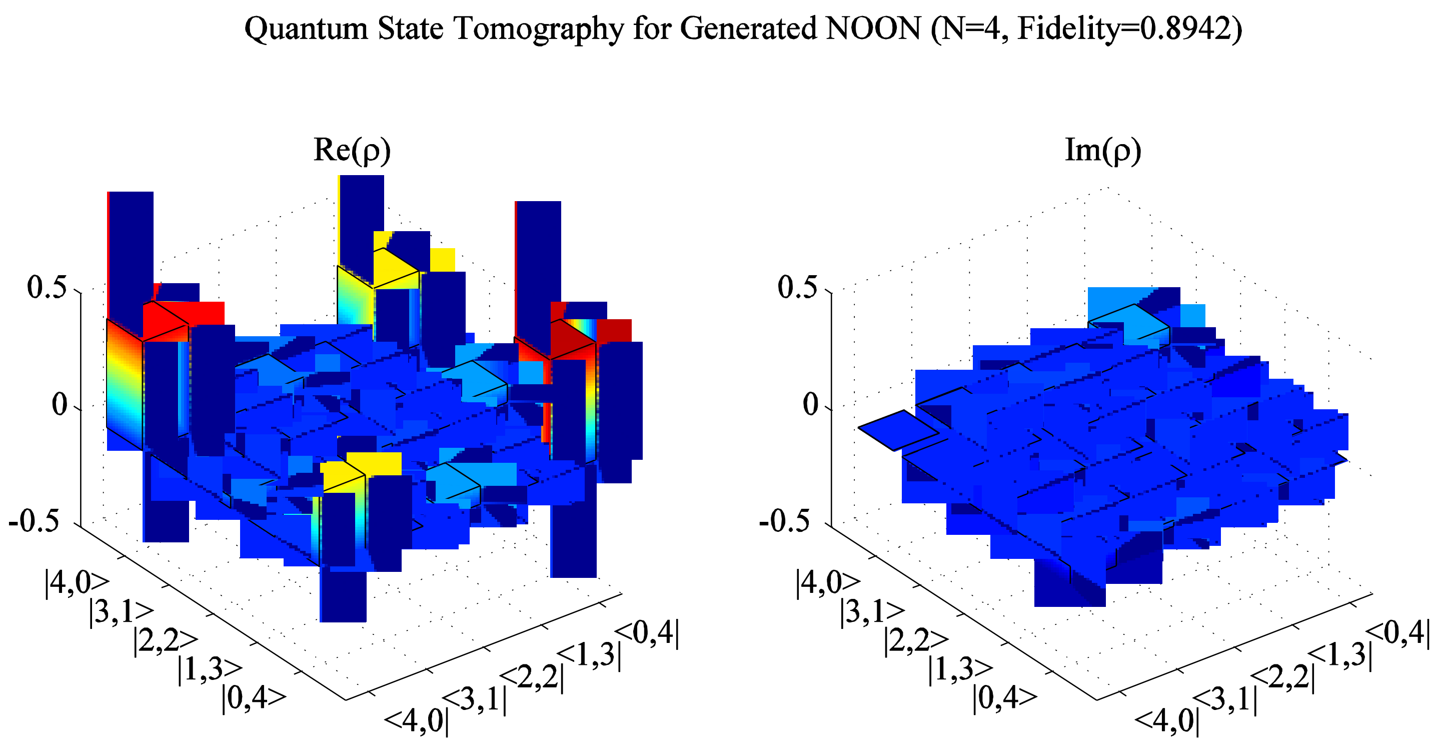
2-Photon NOON state – tomography



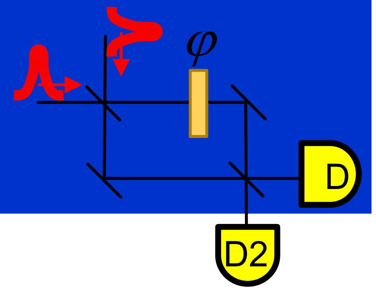
3-Photon NOON state – tomography

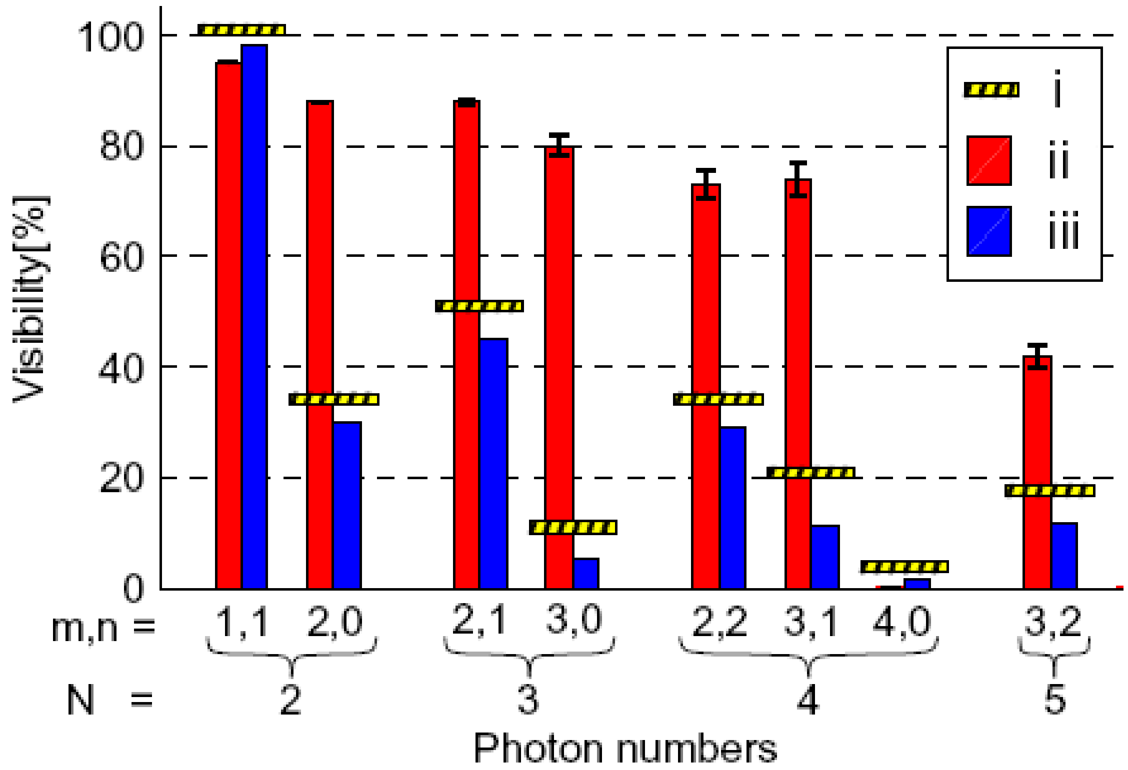


4-Photon NOON state – tomography



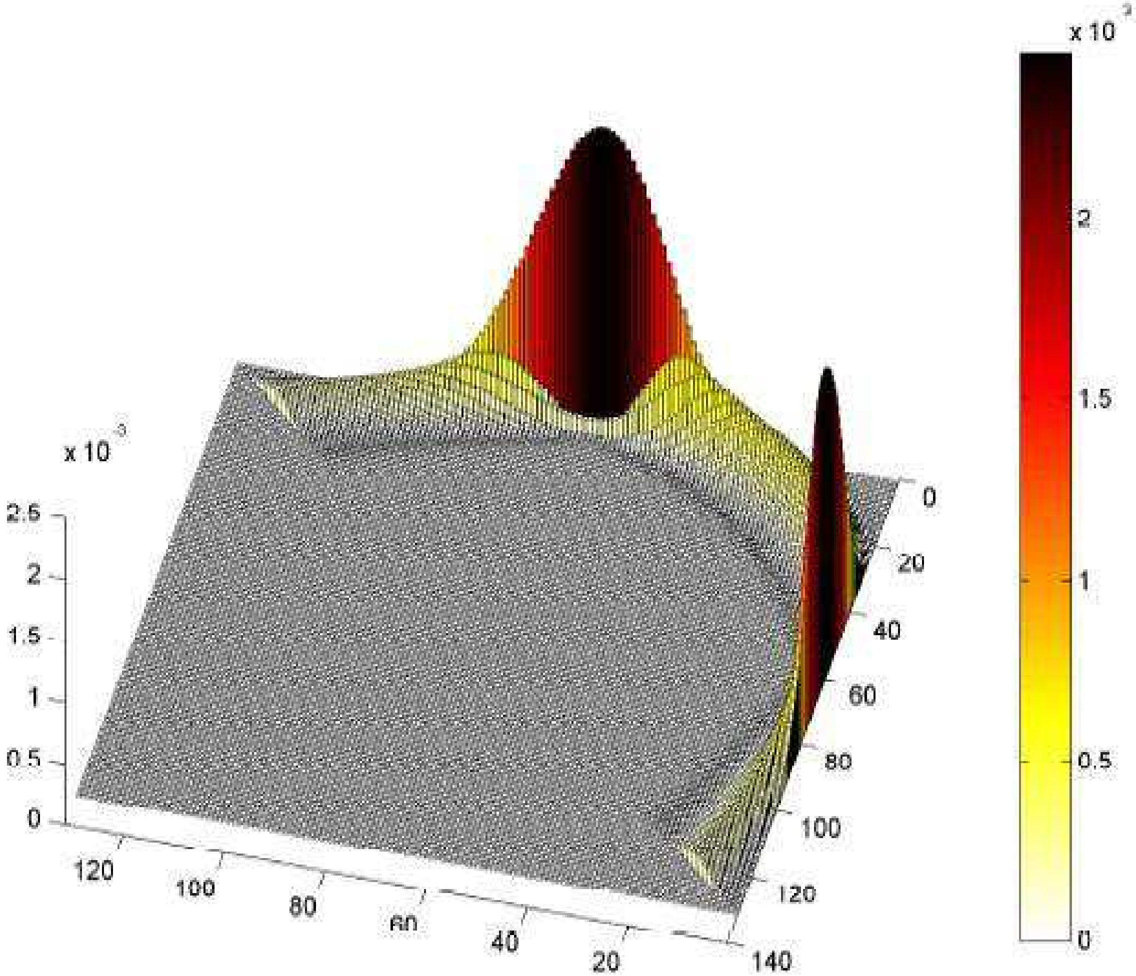
Classical bounds on high frequency visibility





i – Classical bound
ii – experimental NOON states visibility
iii - experimental coherent state visibility using MPPC

30-Photon NOON state



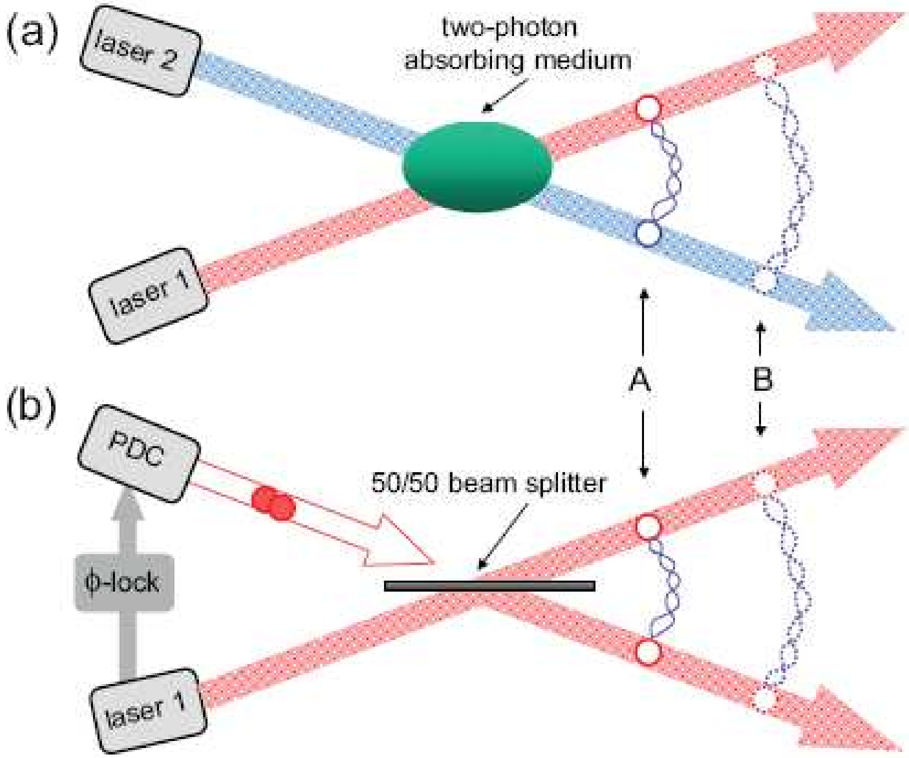
Entangled Photon Holes

Entangled Photon Holes

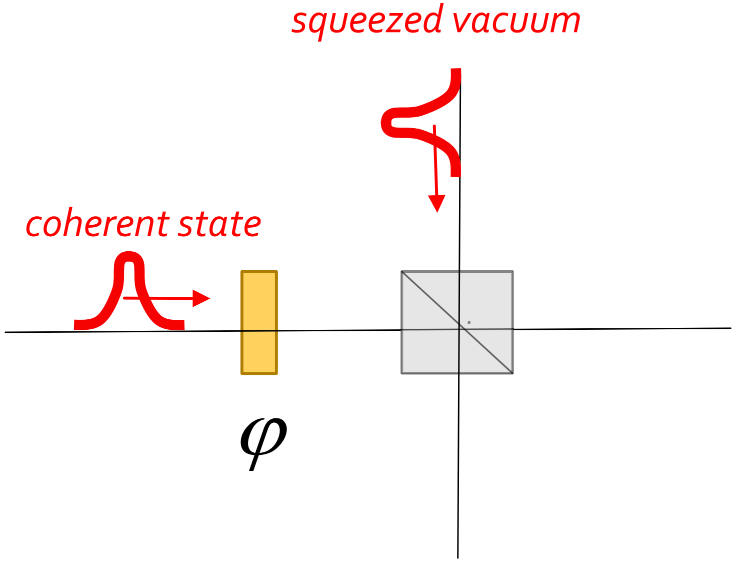
J. D. Franson

Applied Physics Laboratory, Johns Hopkins University, Laurel, Maryland 20723, USA

(Received 24 October 2005; published 6 March 2006)



Arbitrary Entangled Photon Holes !

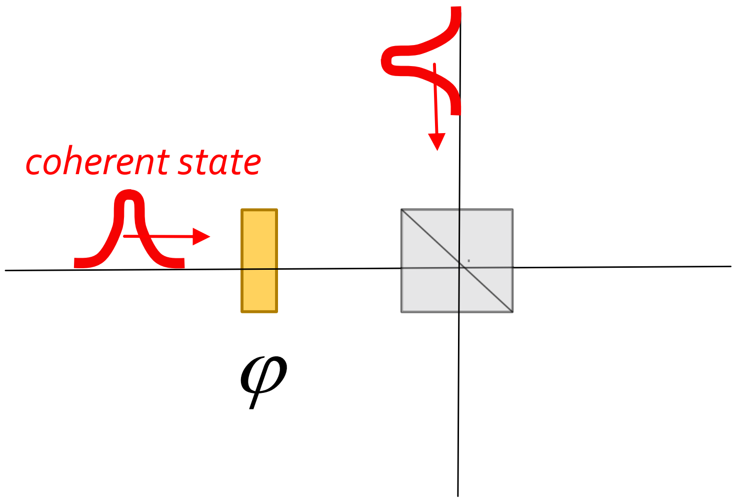


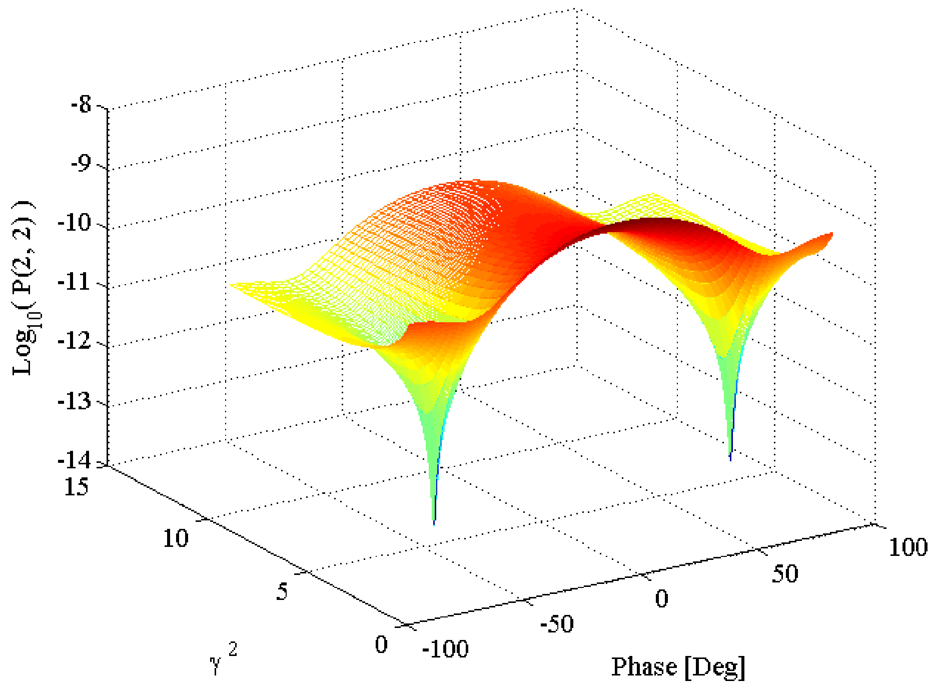
Pair probability ratio

γ^2

By controlling these two parameters one can generate arbitrary photon holes

2,2 Photon Holes



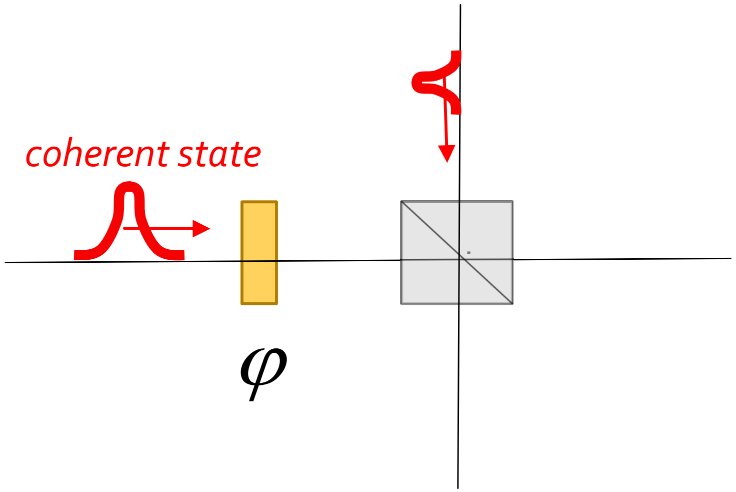


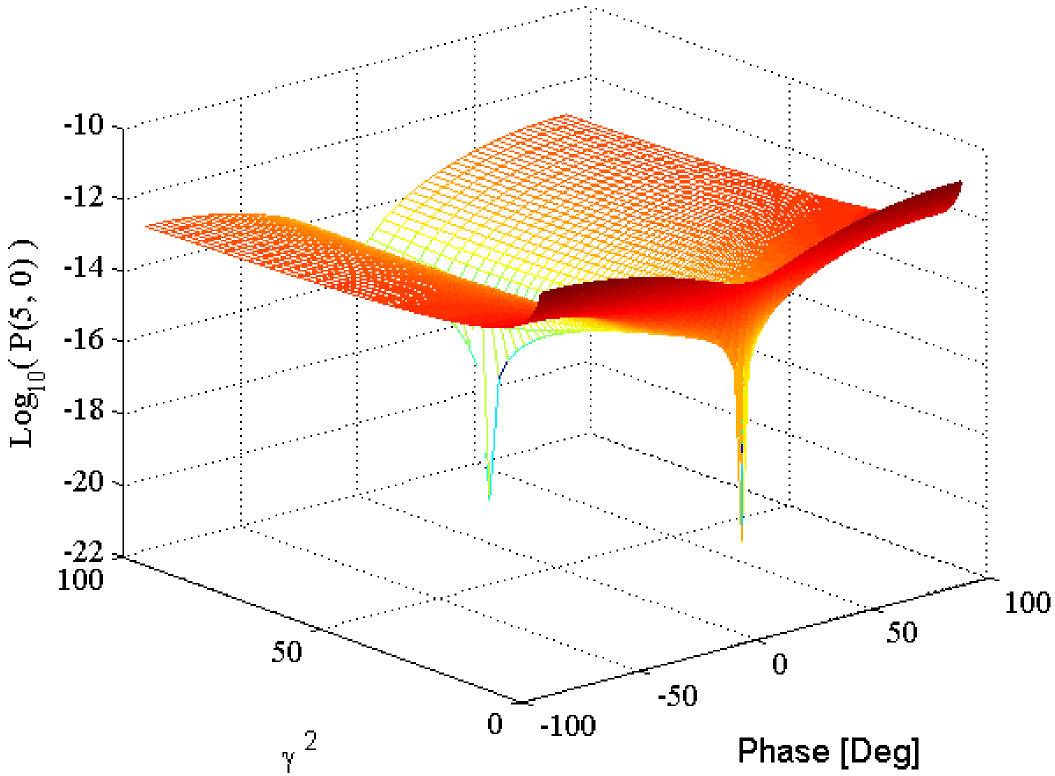
Violation of Cauchy-Schwarz inequality

$$g^{(2,2)}(0) = \frac{\langle I_1^2 I_2^2 \rangle}{\langle I_1 \rangle^2 \langle I_2 \rangle^2} \geq 1$$

$$\gamma^2 = 3$$

5,0 Photon Holes





Violation of Cauchy-Schwarz inequality

$$g^{(5)} = \frac{\langle I_1^5 \rangle}{\langle I_1 \rangle^5} \geq 1$$

$$\gamma^2 = 66$$

High-NOON Summary

- High fidelity generation of **2,3,4,5** photon NOON states in a single setup.
- Most of the photons come from the classical light source - flux is higher than SPDC only sources
- Improving efficiencies by better detectors, spatial mode and eliminating band-pass filter will allow:
  - Measurement of higher order states
  - Heisenberg limited interferometry

Afek, Ambar, YS, *Science* **328,** 879 – 881 (2010)
Phys. Rev. Lett. **104**, 123602 (2010)