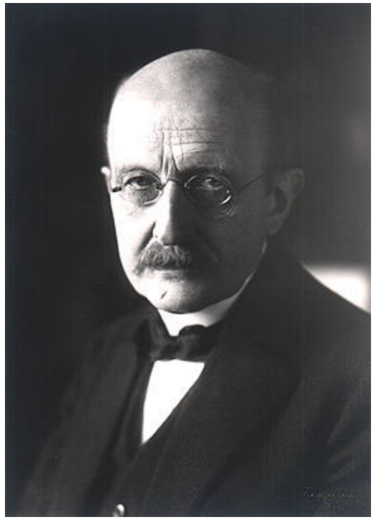
Lecture 2:
Quantum optics at a glance.

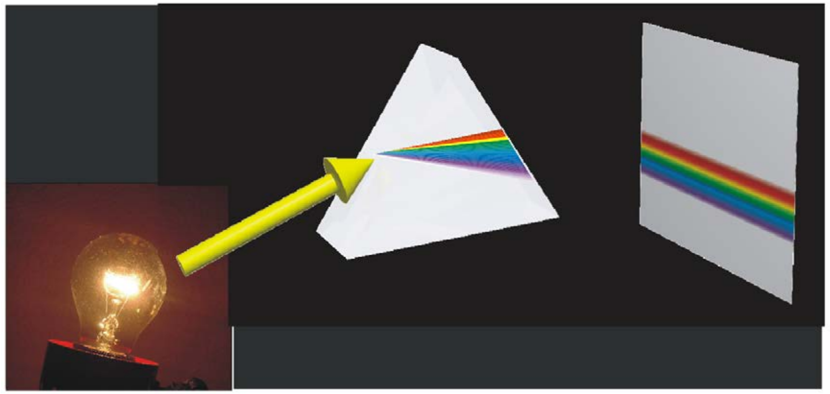
Content

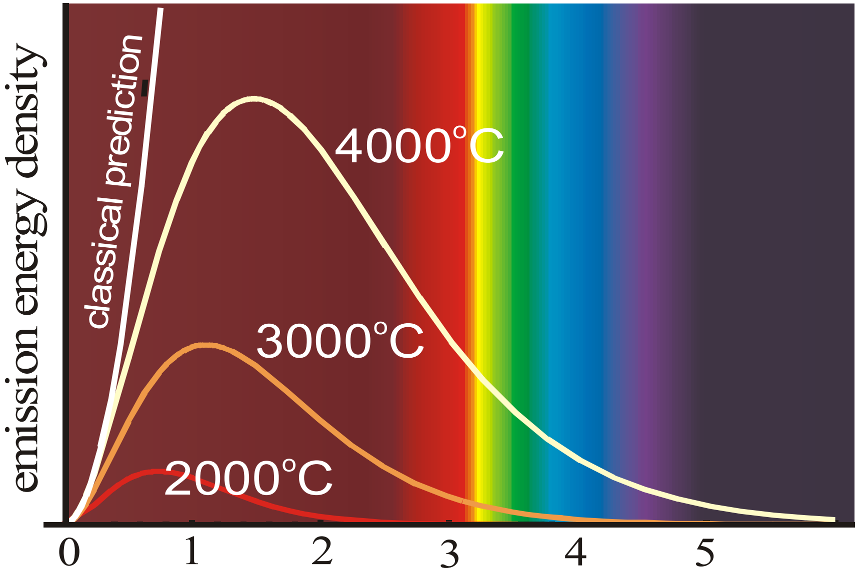
- Few words about light and states
- Wave and particle
- Quantum interference
- Beamsplitter
- States of light
- Entangled state
- Qubit concept
- Bloch sphere

Single photon is beautiful, but we expect from it some practical application

- Thermal radiation
  - All hot objects emit light
  - Emission spectrum can be measured
  - Classical physics predicts infinite intensity







Remind few words about light and states

Plain wave:

$$\vec{E}(\vec{r},t) = \vec{E}_0 e^{i\vec{k}\vec{r}-i\omega t} + c.c.$$

Combination of plain waves makes slowly-varying envelope :

A. I. Lvovsky. Nonlinear and Quantum Optics

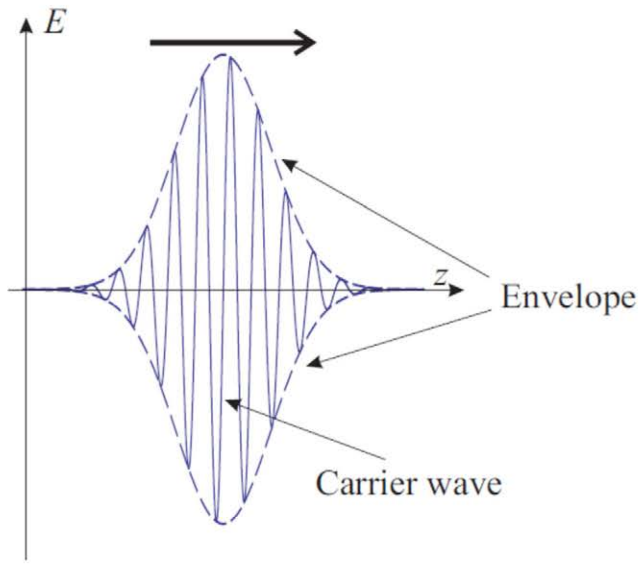
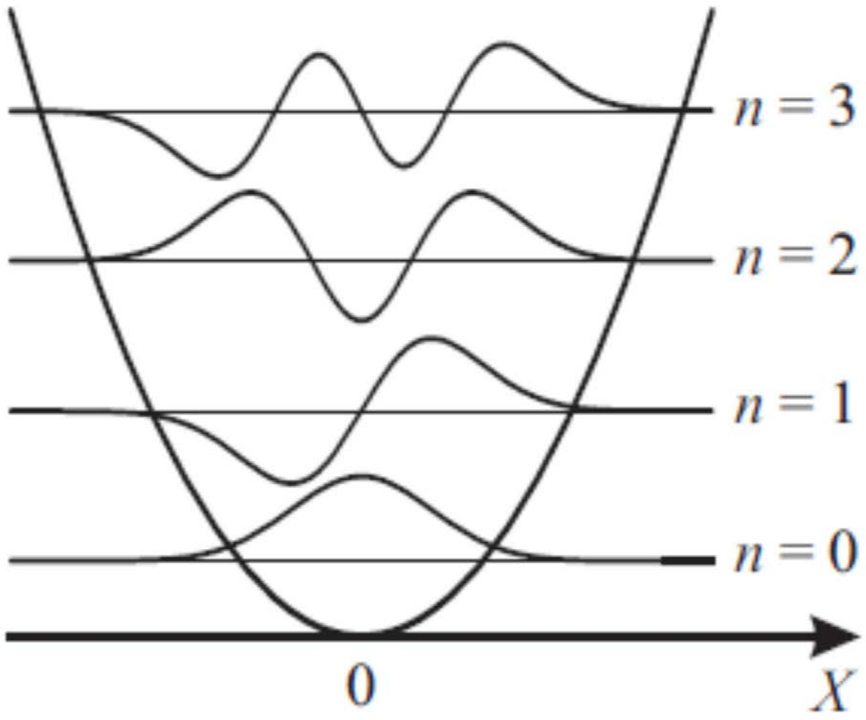


Figure 1.1: A pulse with a slowly varying envelope.

At the same time light can be qauntized:

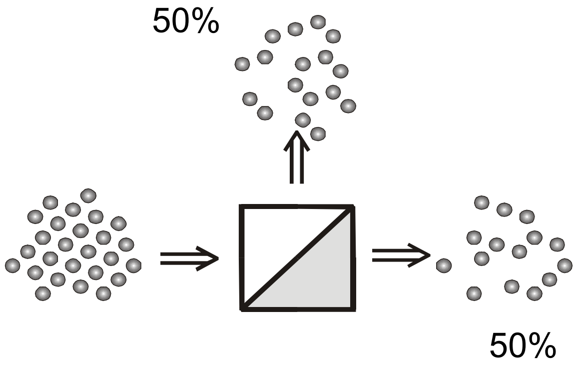


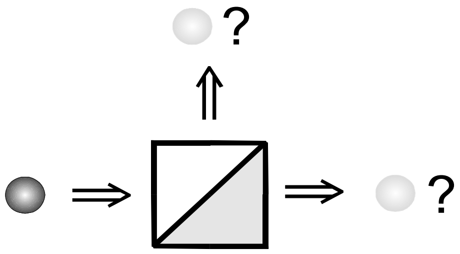
Single-Photons are Elementary Quantum Systems

- A single-photon constitutes an elementary quantum system

- Semi-transparent mirror

It cannot be split





What is the “shape” of the photon?

States of light

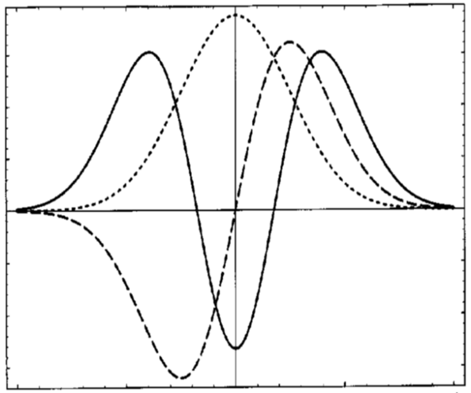
Fock state:
$|n\rangle$ - defined number of photons
Phase is not defined.
What about ΔEΔt ???

$$|n\rangle = \frac{(\hat{a}^\dagger)^n}{\sqrt{n!}}|0\rangle$$

$$\hat{a}^\dagger|n\rangle = \sqrt{n+1}\,|n+1\rangle\,;$$

$$\hat{a}\,|n\rangle = \sqrt{n}\,|n-1\rangle\,;$$

$$\hat{n} = \hat{a}^\dagger\hat{a}$$



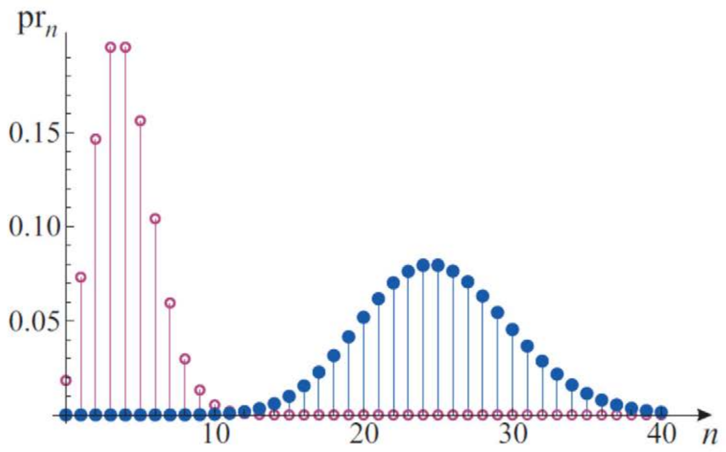
A. I. Lvovsky. *Nonlinear and Quantum Optics*

Coherent state: $|\alpha\rangle$

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

$$\hat{a}\,|\alpha\rangle = \ ?$$

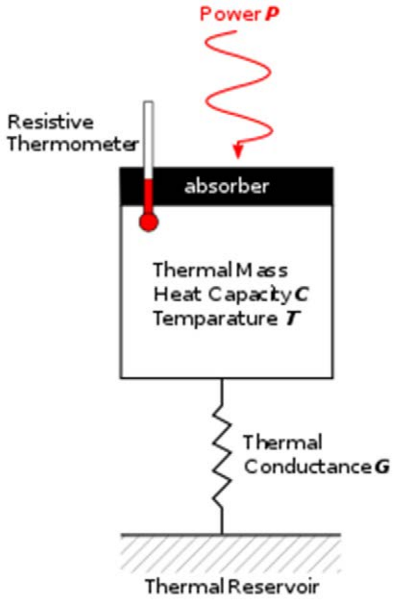
$$\langle n\rangle \ =?$$



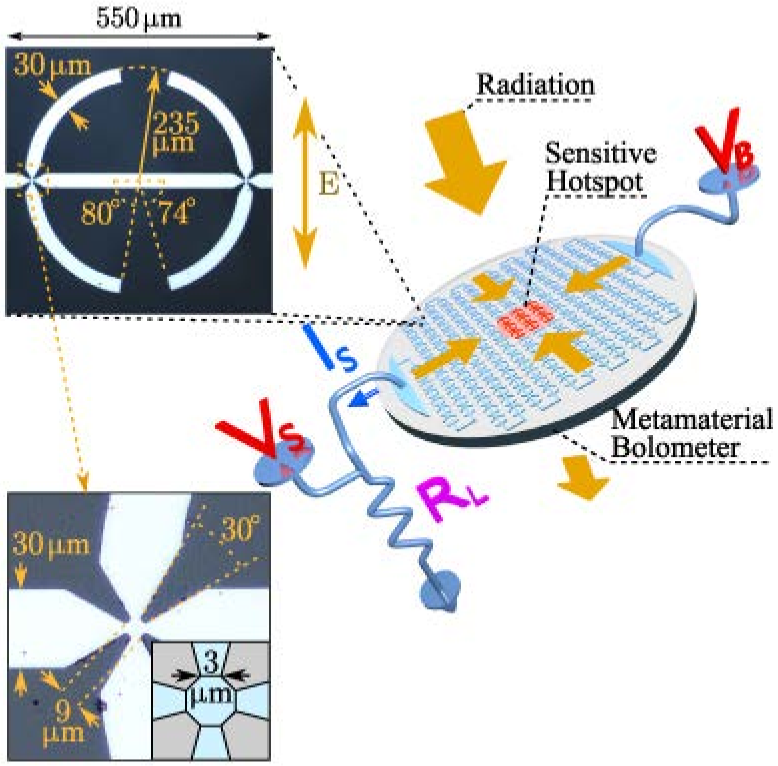
the Poisson distribution with $\langle n\rangle = 4$ (empty circles) and $\langle n\rangle = 25$ (filled circles).

How to observe $\langle n \rangle$?

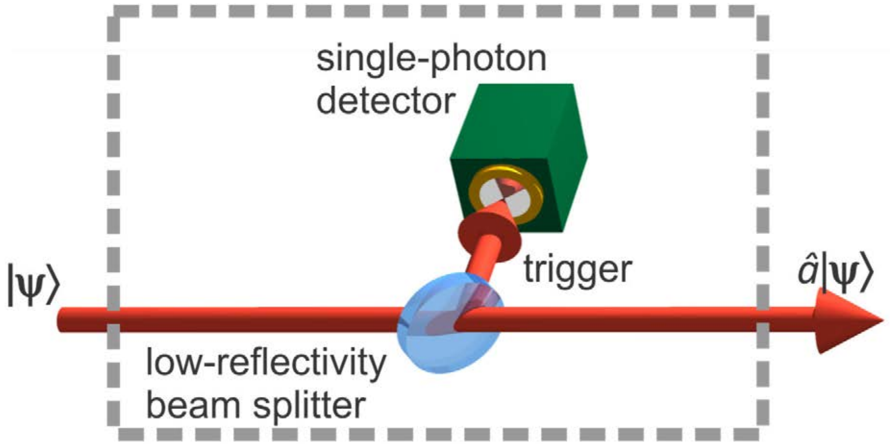
Threshold detector clicks on 1+ photons, we can put many of them



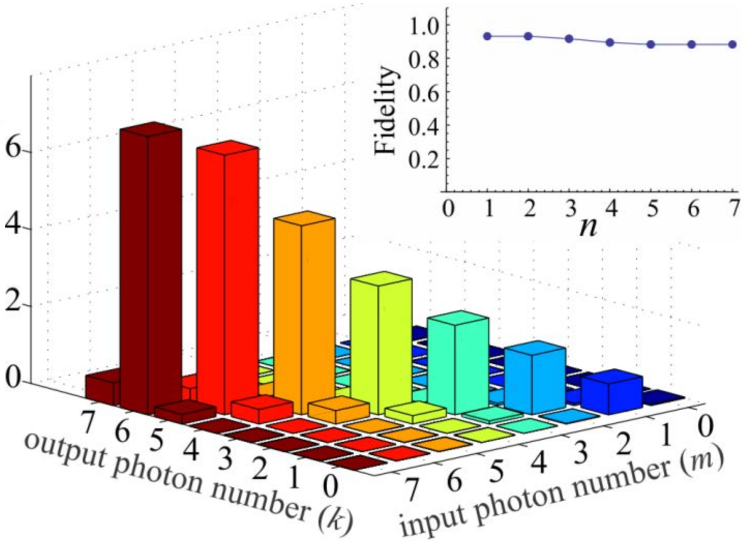
Superconducting nanowire bolometers can distinguish number of photons



How do we implement annihilation operator in the real experiment?



The scheme. A “click” indicates that a photon has been removed from $|\psi\rangle$



Experimental quantum process tomogralphy

R. Kumar, E. Barrios, C. Kupchak and A.L., PRL **110**, 130403 (2013)

Annihilation operator is non-deterministic

- Trace of the process output is given by the “click” probability
- The process involving the annihilation operator can change the state at a distance but cannot be used for faster than light communication because we need to transmit information about click

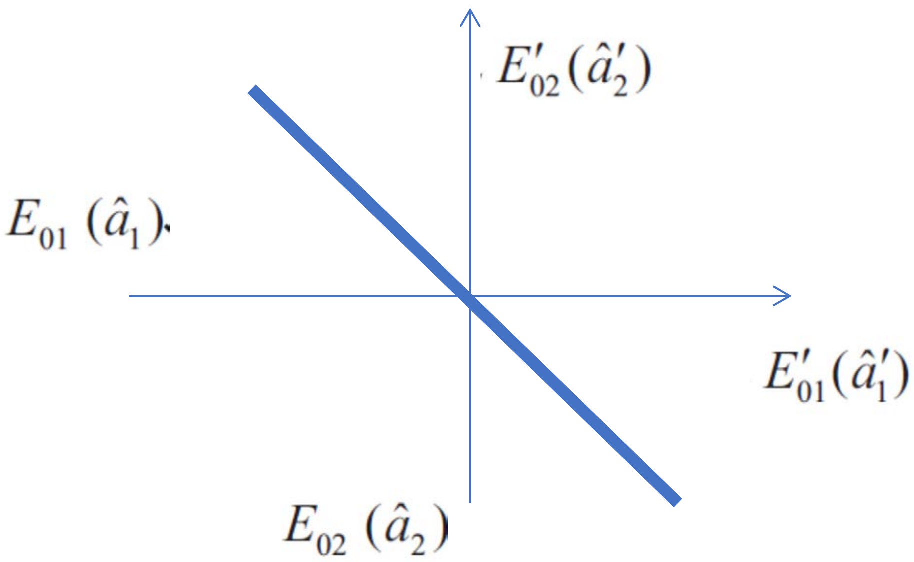
Beamsplitter

$$\begin{pmatrix} E_{01}'^{(+)} \\ E_{02}'^{(+)} \end{pmatrix} = \underline{B} \begin{pmatrix} E_{01}^{(+)} \\ E_{02}^{(+)} \end{pmatrix},$$

$$\underline{B} = \begin{pmatrix} B_{11} & B_{12} \\ B_{21} & B_{22} \end{pmatrix}$$

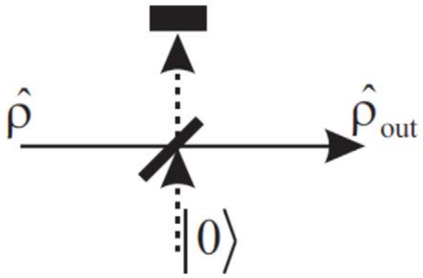
$$\underline{B} = \begin{pmatrix} t & -r \\ r & t \end{pmatrix},$$

$$\begin{pmatrix} \hat{a}_1' \\ \hat{a}_2' \end{pmatrix} = \underline{B} \begin{pmatrix} \hat{a}_1 \\ \hat{a}_2 \end{pmatrix}.$$



How does nature decides where is +r and where –r ?

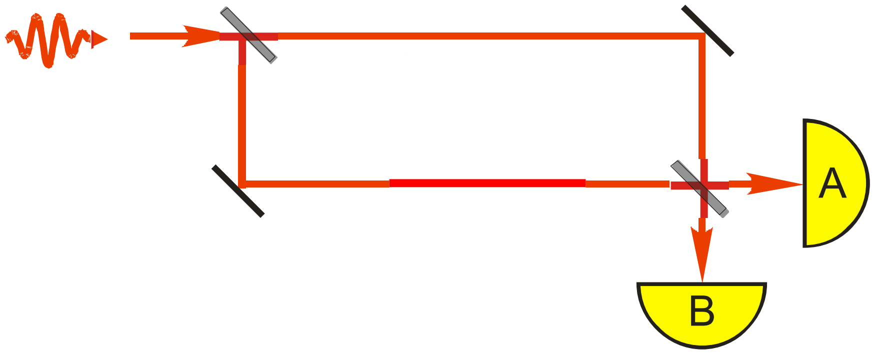
Beamsplitter represents an absorbtion:



The "bomb" paradox

[A. Elitzur and L. Vaidman (1993)]

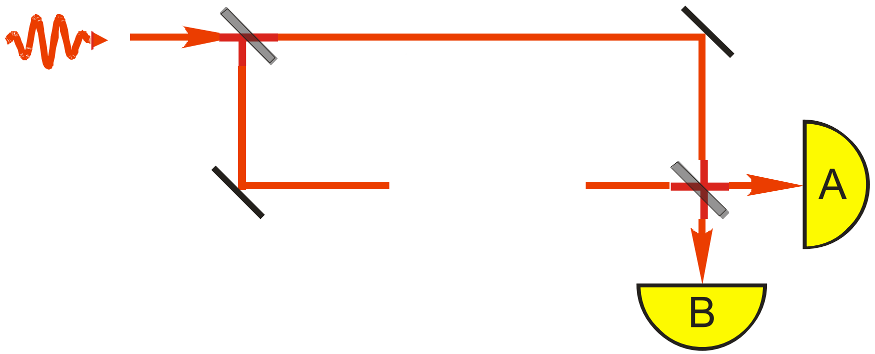
- Mach-Zehnder interferometer tuned to get all signal on A



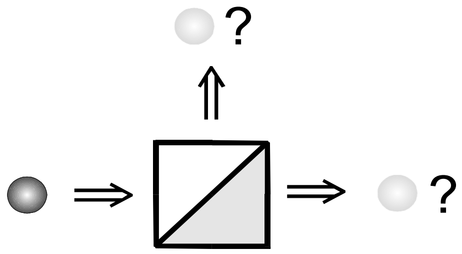
- If we move to single photon signal all clicks will still be on A

The "bomb" paradox
[A. Elitzur and L. Vaidman (1993)]

- Mach-Zehnder interferometer tuned to get all signal on A



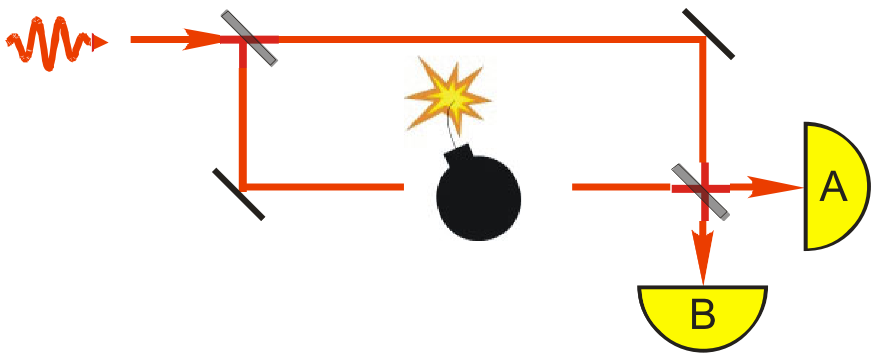
- If cut one arm the signal will be split 50/50



- *Single photon will click random detector*

The "bomb" paradox
[A. Elitzur and L. Vaidman (1993)]

- Interaction-free weapons inspection
  - Insert a single-photon sensitive bomb into one of the interferometer arms



- Bomb absent
  → **interference observed: all photons emerge at A**
- Bomb present
  → **no interference: photons emerge at A or B**
  → **bomb may or may not explode**
- Photon detected at B (what probability ?)
  → **bomb is present**
  → *bomb has been detected without any interaction!*