QUANTUM INFORMATION
with light and atoms

Lecture 2

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MAKING
QUANTUM STATES OF LIGHT

1. Photons
2. Biphotons
3. Squeezed states
4. **Beam splitter**
5. Conditional measurements

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Beam splitter transformation (Heisenberg picture)

- **Quadrature transformation**

$$\begin{pmatrix} \hat{a}_1 \\ \hat{a}_2 \end{pmatrix} = \begin{pmatrix} t & r \\ -r & t \end{pmatrix} \begin{pmatrix} \hat{a}'_1 \\ \hat{a}'_2 \end{pmatrix}$$

where t^2 is the beam splitter transmission, r^2 reflection. $|t|^2 + |r|^2 = 1.$

- If t and r are real, we can assign $t = \cos\theta$; $r = \sin\theta$;

$$\begin{pmatrix} \hat{a}_1 \\ \hat{a}_2 \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \hat{a}'_1 \\ \hat{a}'_2 \end{pmatrix}$$

Also valid for positions, momenta

$$\begin{pmatrix} x_1 \\ x_2 \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} x'_1 \\ x'_2 \end{pmatrix}; \begin{pmatrix} p_1 \\ p_2 \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} p'_1 \\ p'_2 \end{pmatrix}$$

→ Beam splitter transformation = rotation in the phase space ⇒ **entanglement**

Problem: Show that a beam splitter acting on a pair of coherent states will generate a pair of coherent states

Example: Einstein-Podolsky-Rosen state

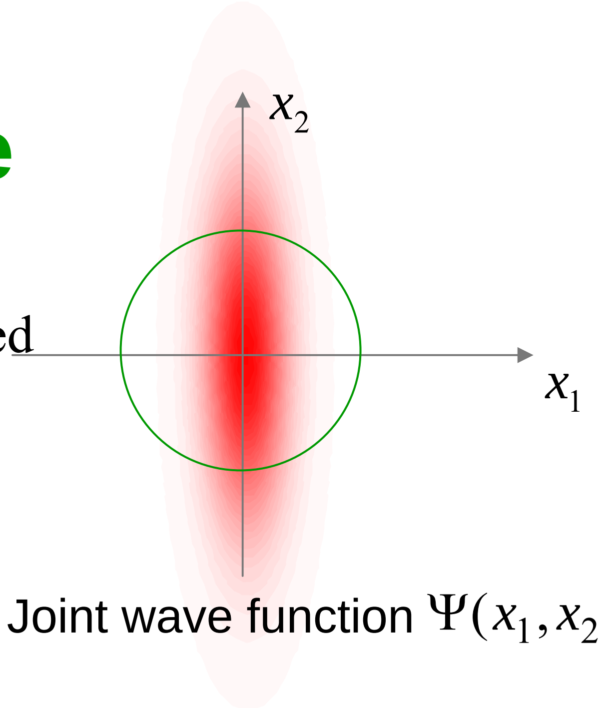
- **State preparation**
  - Overlap X-squeezed $\left(\left\langle \delta x_1^2 \right\rangle < 1/2\right)$ and P-squeezed $\left(\left\langle \delta p_2^2 \right\rangle < 1/2\right)$ vacuum states on a symmetric beam splitter
  - Beam splitter transformation:

$$\begin{pmatrix} X_1 \\ X_2 \end{pmatrix} \to \frac{1}{\sqrt{2}} \begin{pmatrix} X_2 - X_1 \\ X_2 + X_1 \end{pmatrix}; \begin{pmatrix} P_1 \\ P_2 \end{pmatrix} \to \frac{1}{\sqrt{2}} \begin{pmatrix} P_2 - P_1 \\ P_2 + P_1 \end{pmatrix}$$

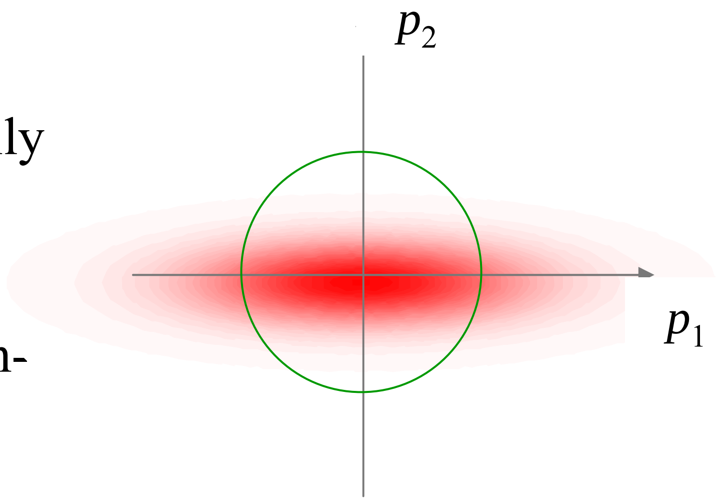
  - After beam splitter:

$$\left\langle \delta(x_1 - x_2)^2 \right\rangle < 1/2; \left\langle \delta(p_1 + p_2)^2 \right\rangle < 1/2$$

  - Both positions and momenta are nonclassically correlated.
  - Entangled state generated!
  - This states approximates the original Einstein-Podolsky-Rosen state.



Joint wave function $\Psi(x_1, x_2)$

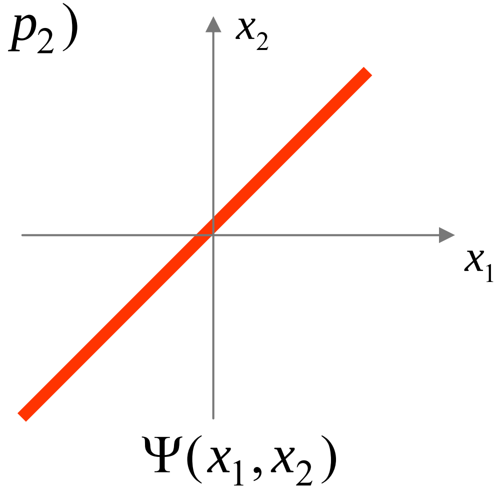


Joint wave function $\Psi(p_1, p_2)$

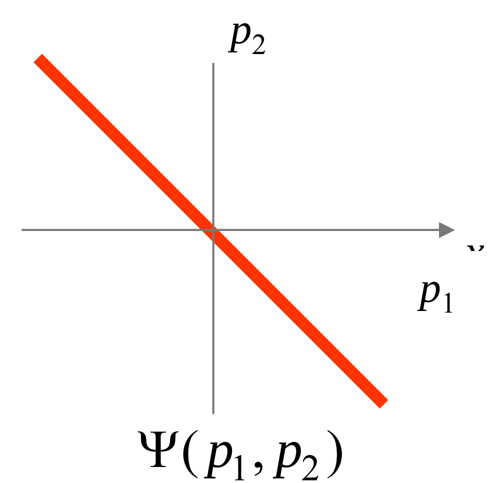
By the way: the original EPR paradox

- **The ideal Einstein-Podolsky-Rosen state**
  - **In position representation:** $\Psi_{\text{EPR}}(x_1, x_2) = \delta(x_1 - x_2)$
  - **In momentum representation:** $\Psi_{\text{EPR}}(p_1, p_2) = \delta(p_1 + p_2)$

Problem: obtain the position representation wave function from the momentum representation

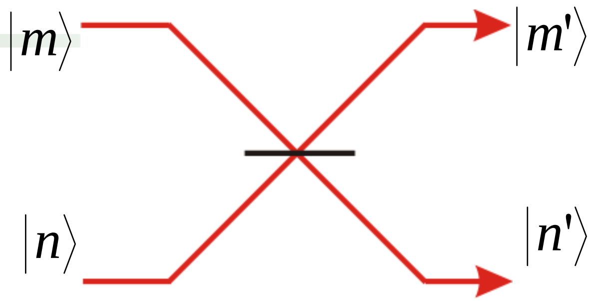


- **If shared between Alice and Bob:**
  - **If Alice measures position** x_1
    $\rightarrow$ **Bob receives a position eigenstate** $|x_2\rangle = |x_1\rangle$
  - **If Alice measures momentum** p_1
    $\rightarrow$ **Bob receives a momentum eigenstate** $|p_2\rangle = |-p_1\rangle$
- **Alice can create two mutually incompatible physical realities at a remote location**



Theory: Einstein, Podolsky, Rosen, PRA **47**, 777 (1935)
Experiment: Z.Y.Ou et al., PRL 68, 3663 (1992)

Beam splitter transformation (Schrödinger picture)



- **Photon number transformation**

$$|m,n\rangle \rightarrow \sum_{j,k=0}^{m,n} \sqrt{\frac{(j+k)!(m+n-j-k)!}{m!n!}} \binom{m}{j} \binom{n}{k} (-1)^k t^{n+j-k} r^{m-j+k} |m+n-j-k, j+k\rangle$$

- **Simplest example: splitting a photon**

$$|1\rangle \rightarrow t|1\rangle_A |0\rangle_B - r|0\rangle_A |1\rangle_B$$

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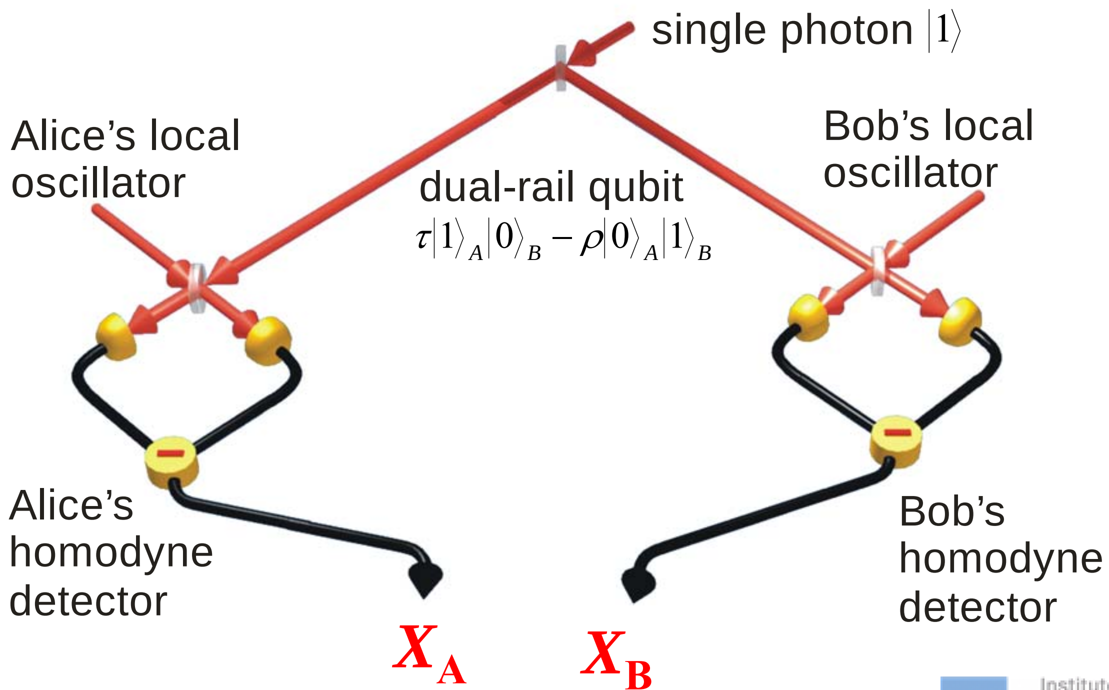
Example: Tomography of a dual-rail qubit

- **Photon hits a beam splitter → a two-mode qubit is generated**

$$|1\rangle \to t|1\rangle_A|0\rangle_B - r|0\rangle_A|1\rangle_B$$

- **Measure quadratures X_A and X_B via homodyne detectors**
- **Phase/dependent quadrature statistics → state reconstruction**



S. Babichev, J. Appel, A. I. Lvovsky, PRL **92**, 193601 (2004)

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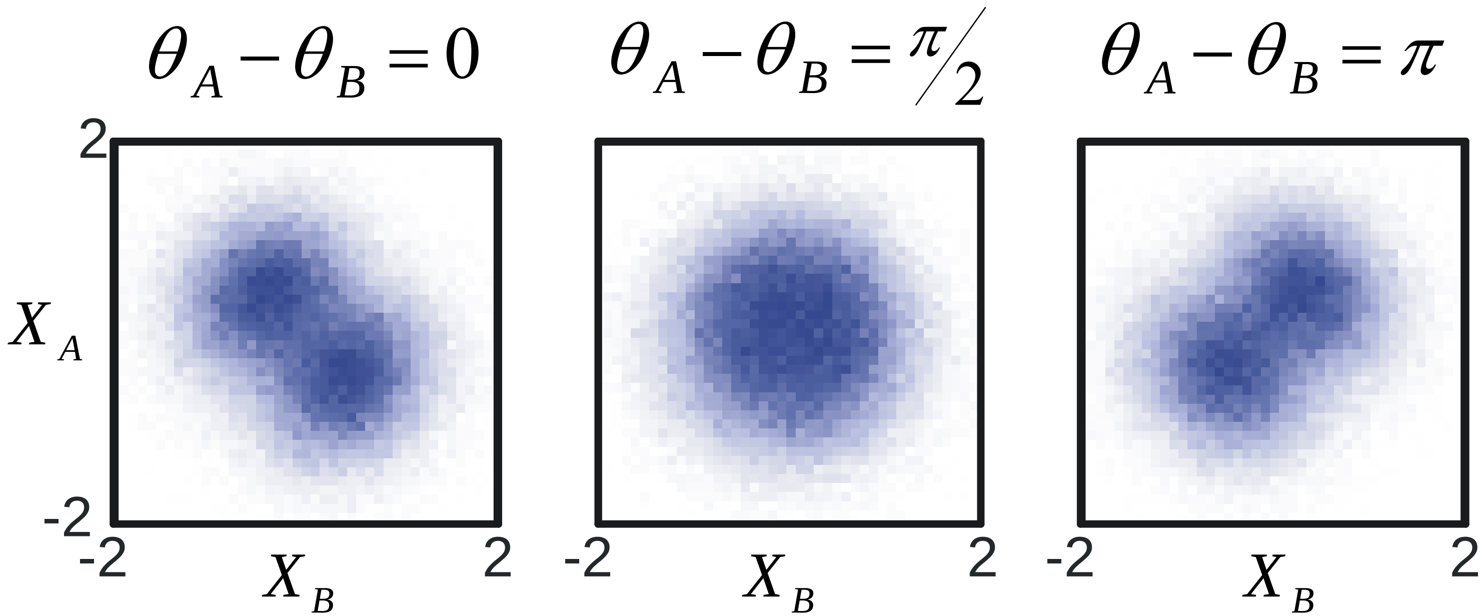
Example:
Tomography of a dual-rail qubit (…continued)

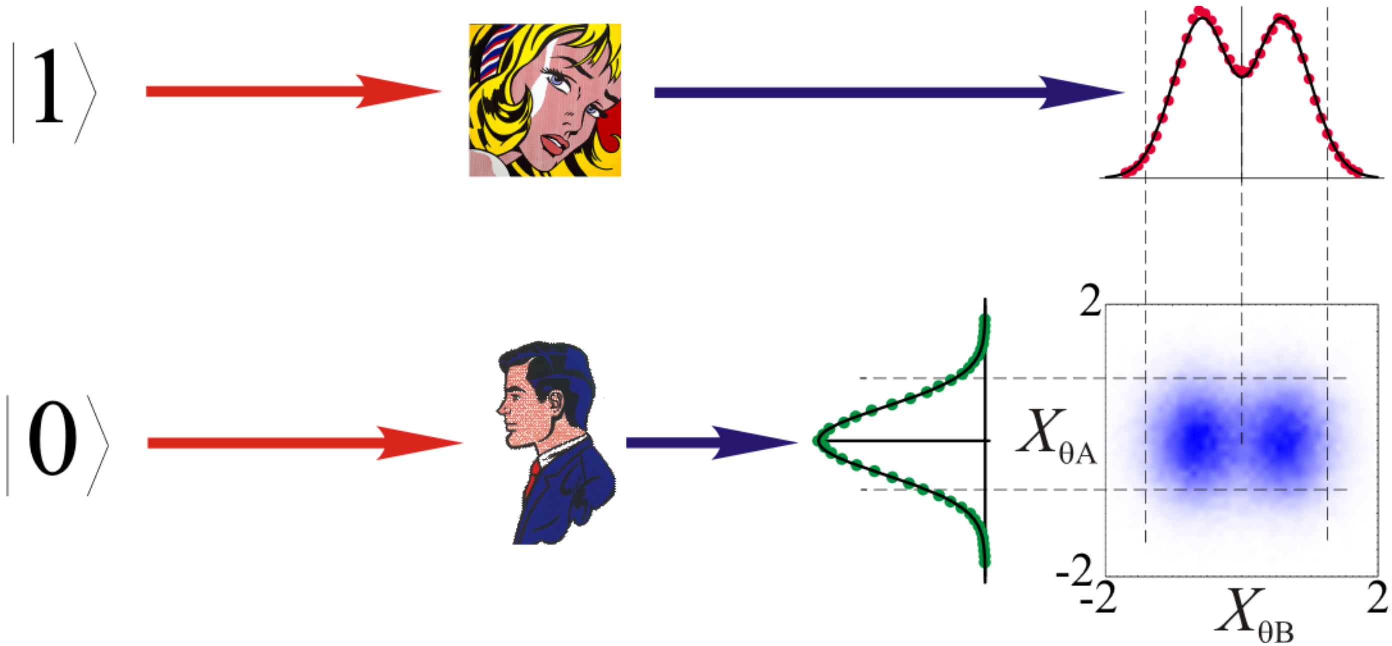
- **Probability distributions** pr(X_A, X_B)
  - **Serve as marginal distributions for the 4-D Wigner function**
  - **Entanglement → Nonclassical, phase-dependent correlations**



- **Probability distributions pr(X_A, X_B) for all θ_A, θ_B → quantum state reconstruction**

Why do we see such distributions?

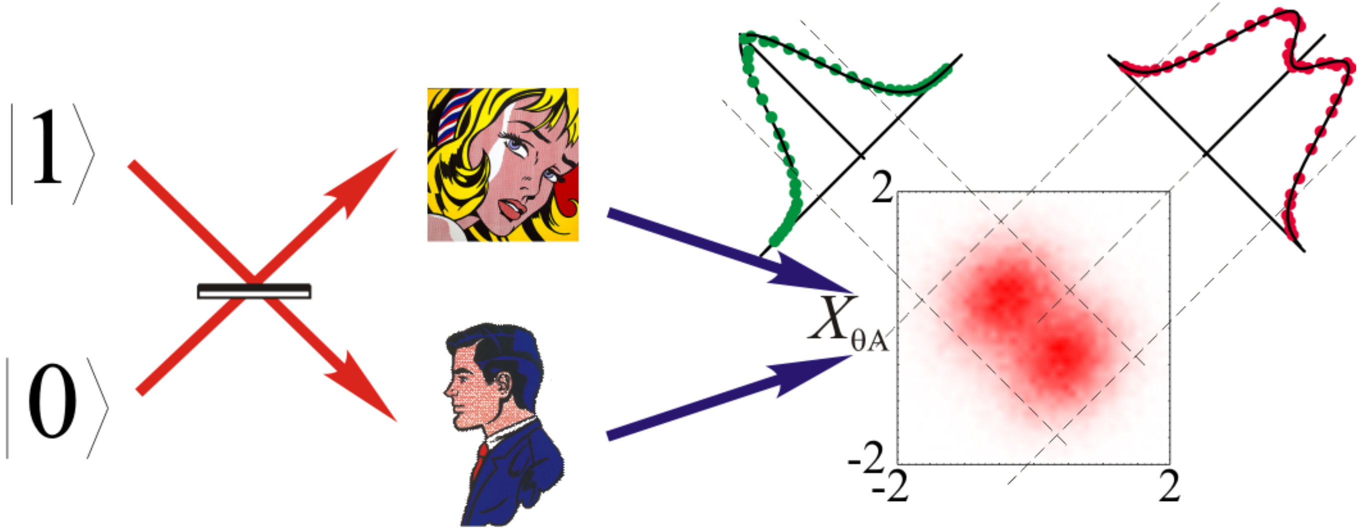
- **If no beam splitter is present**



- Alice measures the single-photon state, Bob measures the vacuum state
- Measurements are uncorrelated → distributions are uncorrelated
- No entanglement
- No information about relative phase θ_A - θ_B

Why do we see such distributions?

- **If beam splitter is present**



- Alice and Bob measure the same quadrature (θ_A - θ_B = 0 or p)
  → uncorrelated distribution rotates by 45°
- Alice and Bob measure different quadratures (θ_A - θ_B = p/2)
  → distribution remains uncorrelated

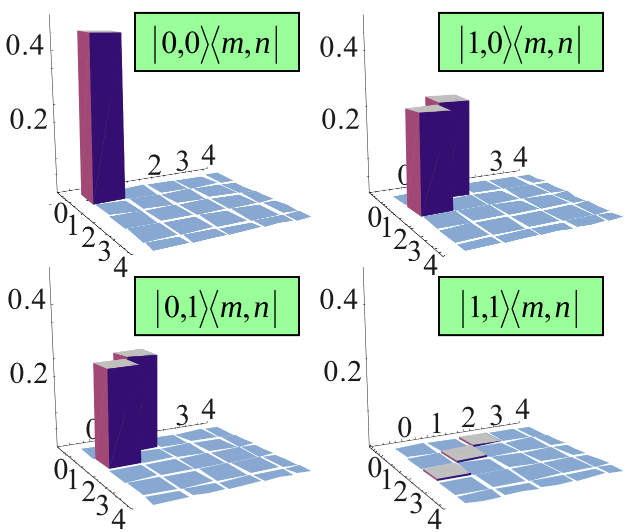
Tomography of an optical qubit

Results

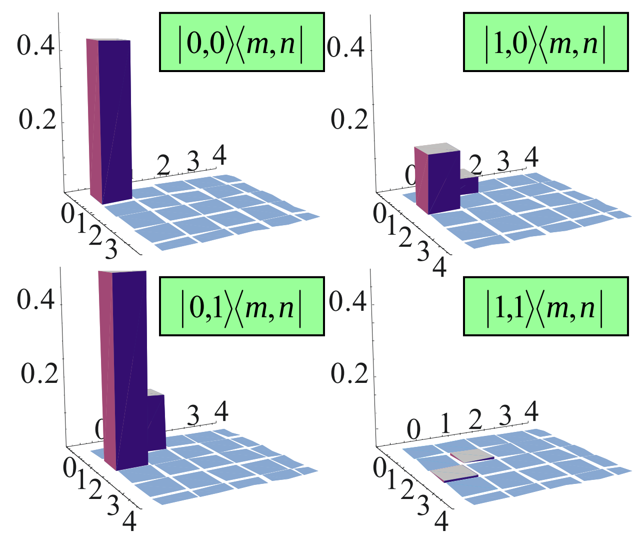
S. Babichev, J. Appel, A. I. Lvovsky, PRL **92**, 193601 (2004)

- **Density matrix**
  - **Serve as marginal distributions for the 4-D Wigner function**
  - **Entanglement → Nonclassical, phase-dependent correlations**

● Beam splitter 50 - 50 %



● Beam splitter 8 - 92 %



First complete (not postselected) reconstruction of an optical qubit

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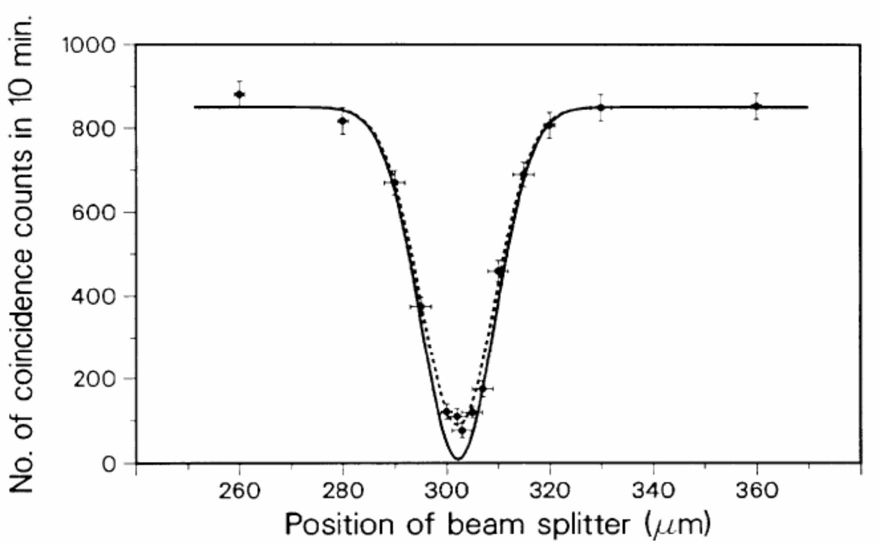
Another example: Hong-Ou-Mandel dip

- **Two photons "colliding" on a beam splitter will stick together**

$$|1,1\rangle \rightarrow \left(|2,0\rangle - |0,2\rangle\right)/\sqrt{2}$$

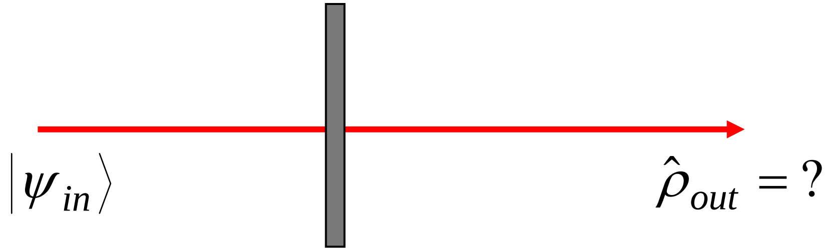
- **Hong-Ou-Mandel effect: correlation count in the beam splitter output vanishes when the two photons arrive simultaneously.**



Hong, Ou, Mandel, PRL **59**, 2044 (1987)

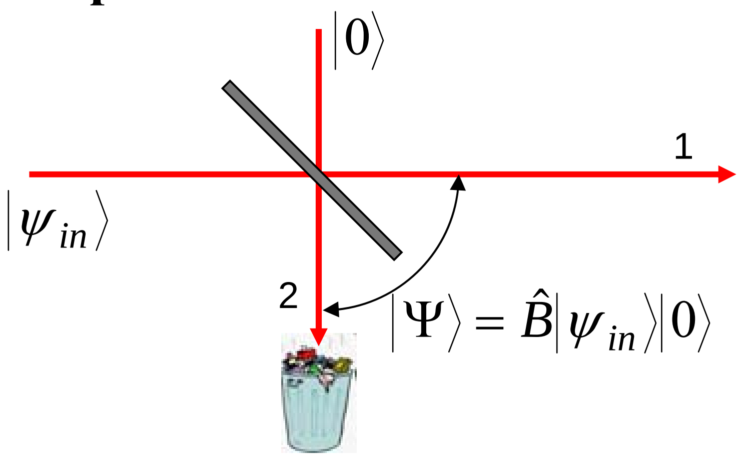
Beam splitter model of absorption

- **The problem**
  - **A quantum state of light propagates through an attenuator. What is the transmitted state?**



Beam splitter model of absorption

- **The solution**
  - **Replace the absorber with a beam splter.**
  - **The second input is vacuum**



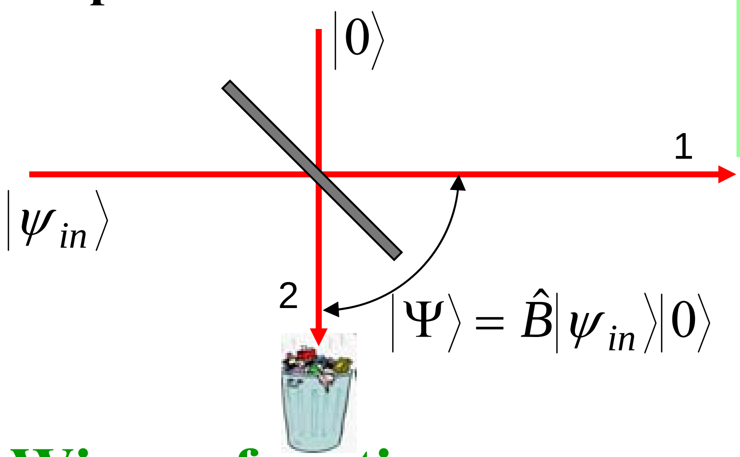
  - **Beam splitter output $|\Psi\rangle$ may me entangled**
  - **Mode 2 in the beam splitter output is lost**
  - **To find $\hat{\rho}_{out}$, trace over the lost mode in the beam splitter output**

$$\hat{\rho}_{out} = \mathrm{Tr}_2 |\Psi\rangle\langle\Psi|$$

Beam splitter model of absorption

- **The solution**
  - **Replace the absorber with a beam spltter.**
  - **The second input is vacuum**

Suppose you have a squeezed state with $\langle x^2 \rangle = 1/4, \langle p^2 \rangle = 1.$ How will these parameters change after propagating through a 50% absorber?



- **In terms of Wigner functions**
  - **Beam splitter input Wigner function:** $W_{|\psi\rangle|0\rangle} = W_{|\psi\rangle}(x_1, p_1) W_{|0\rangle}(x_2, p_2).$
  - **To find the beam splitter output Wigner function** $W_{|\Psi\rangle}(x_1, p_1, x_2, p_2)$ **apply phase-space rotation.**
  - **To find the Wigner finction of mode 1, integrate over mode 2:**

$$W_{out}(x_1, p_1) = \int_{-\infty}^{+\infty} W_{|\Psi\rangle}(x_1, p_1, x_2, p_2) dx_2 \, dp_2.$$

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MAKING QUANTUM STATES OF LIGHT

1. Photons
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5. **Conditional measurements**

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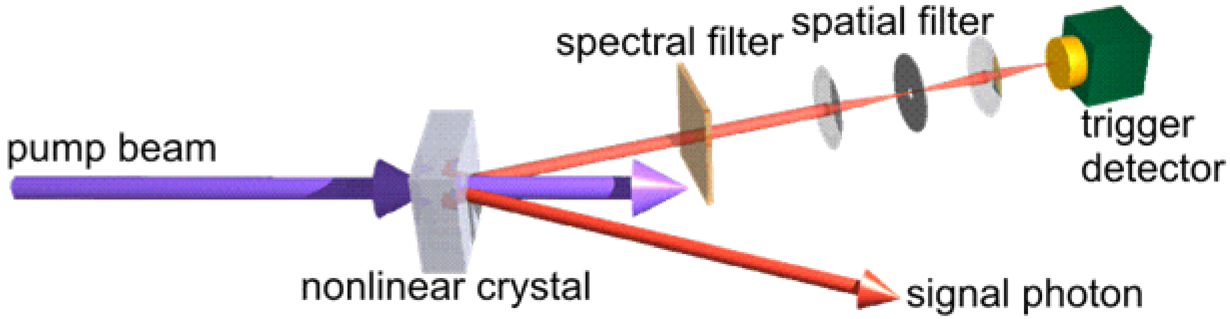
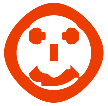
Conditional preparation of a photon

- **Parametric down-conversion**
  - **“Red” photons are always born in pairs**
  - **Photon detection in one emission channel**
    → there must be a photon in the other channel as well



Not a single photon “on demand”



To date, this is the only method which provides a single photon with a high efficiency in a certain spatiotemporal mode

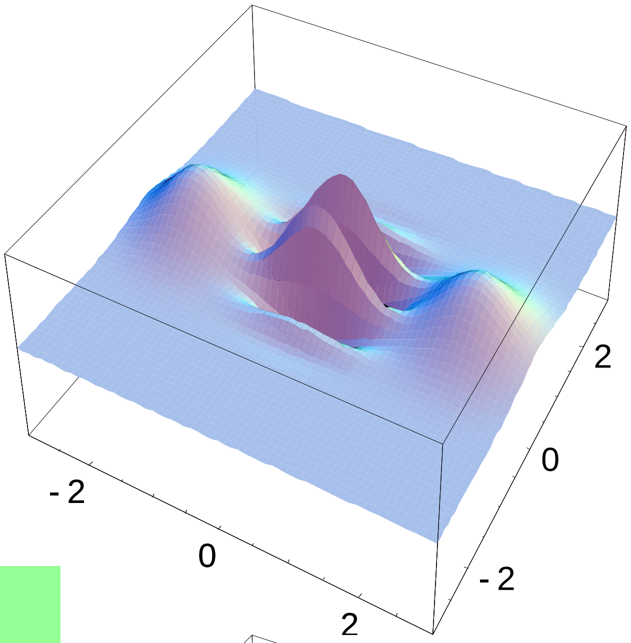
Schrödinger cat

What does it mean in optics?

- **Coherent superposition of two coherent states**

$$\left|\mathrm{cat}_{\pm}\right\rangle = \left|\alpha\right\rangle \pm \left|-\alpha\right\rangle$$

  - **Useful for quantum teleportation quantum computation, and error correction**
  - **Fundamentally important**

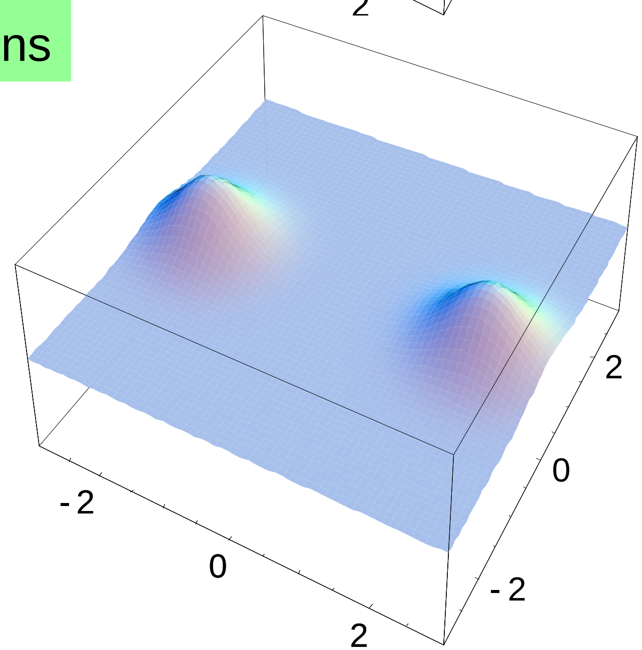


Problem. Calculate these Wigner functions

- **Compare: incoherent superposition of two coherent states**

$$\hat{\rho} = \left|\alpha\right\rangle\left\langle\alpha\right| \pm \left|-\alpha\right\rangle\left\langle-\alpha\right|$$

  - **Boring, classical state**



Schrödinger cat

How to make one?

- **Easy for small α's**

$$|\alpha\rangle = \alpha_0|0\rangle + \alpha_1|1\rangle + \alpha_2|2\rangle + \alpha_3|3\rangle + \ldots$$

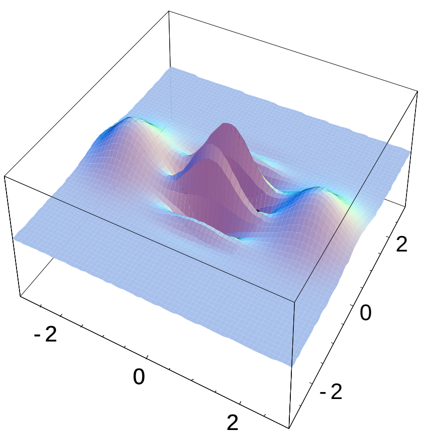
$$-$$

$$|-\alpha\rangle = \alpha_0|0\rangle - \alpha_1|1\rangle + \alpha_2|2\rangle - \alpha_3|3\rangle + \ldots$$

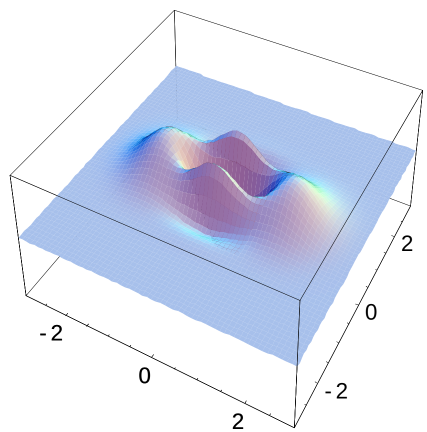
neglect
high-number terms

$$|\text{cat}_-\rangle = \alpha_1|1\rangle - \alpha_3|3\rangle + \ldots$$

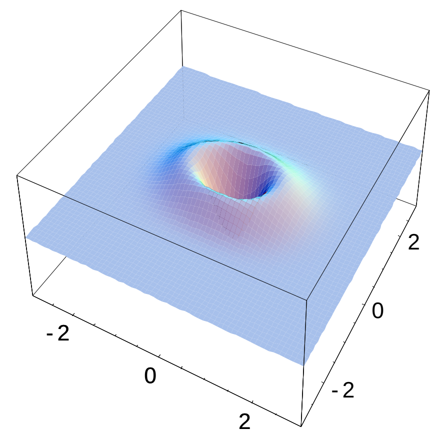
…just a squeezed single-photon state!



$\alpha = 2.1$



$\alpha = 1.4$



$\alpha = 0.7$

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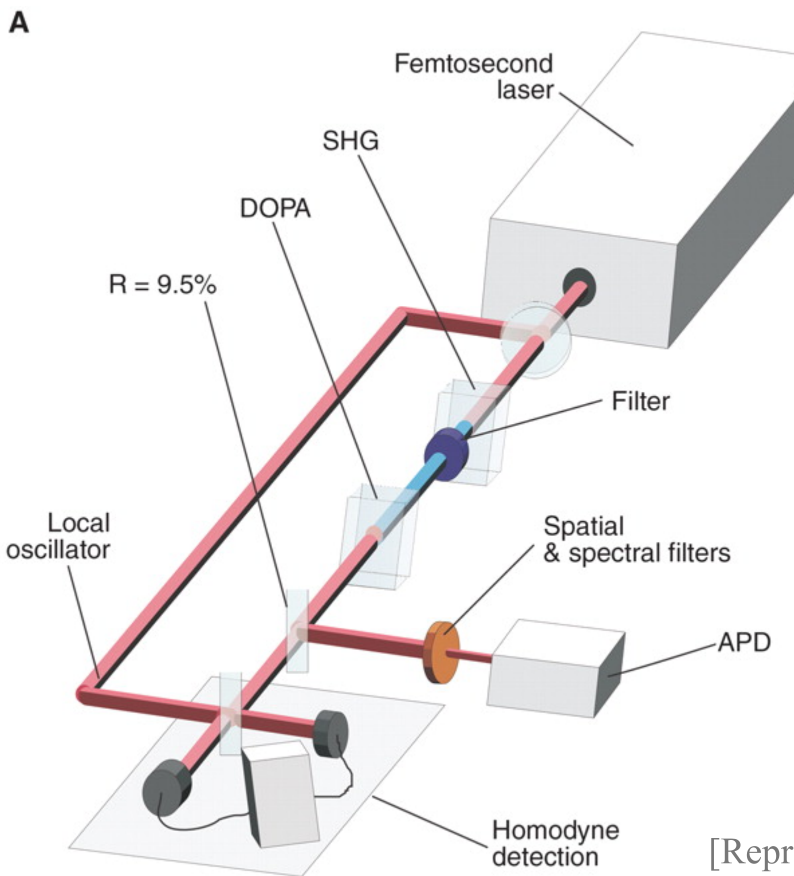
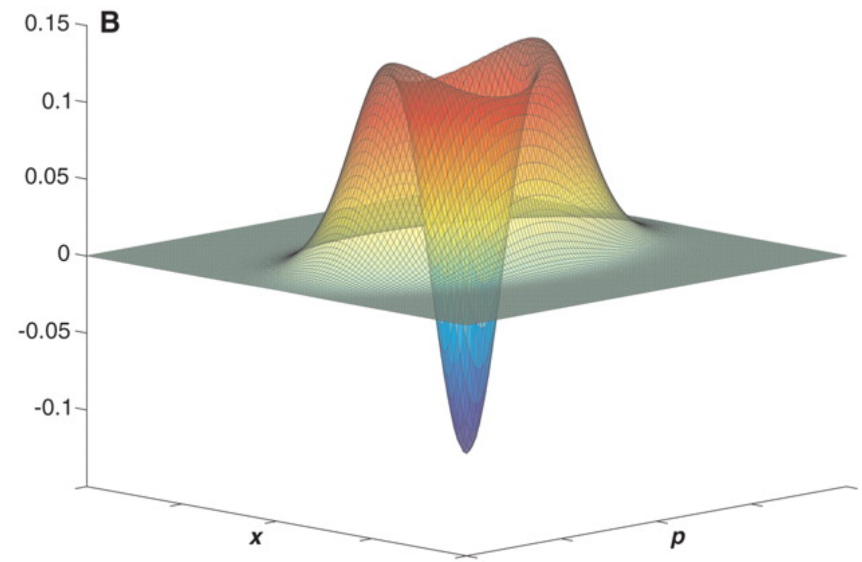
Schrödinger cat

How to make one?

[A. Ourjoumtsev *et al.*, *Science* **312**, 83 (2006)
J. S. Neergaard-Nielsen *et al.*, PRL **97**, 083604 (2006)
K. Wakui *et al.*, quant-ph/0609153]

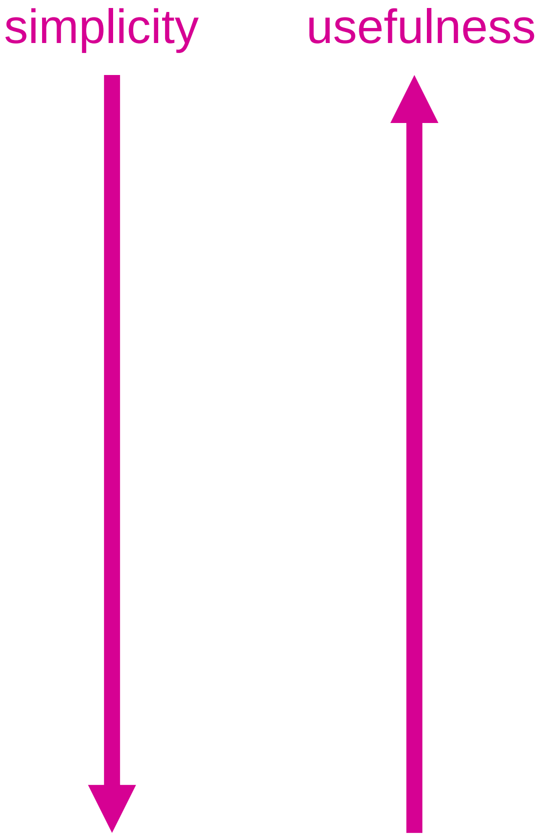
- **Making a squeezed single-photon state**
  - **Create a squeezed state** $|\psi_s\rangle = \beta_0|0\rangle + \beta_2|2\rangle + \beta_4|4\rangle + \ldots$
  - **Subtract a photon** $\hat{a}|\psi_s\rangle = \sqrt{2}\beta_2|1\rangle + 2\beta_4|3\rangle + \ldots$





[Reproduced from A. Ourjoumtsev *et al.*, *Science* 312, 83 (2006)]

Summary to part 2:
Classification of quantum state preparation methods



- **“On demand”:**
  State is readily available when required by the user
  Example: photon from a quantum dot
- **“Heralded”:**
  State produced randomly; system provides user with a classical signal when the state is produced
  Example: heralded single photon
- **“Postselected”:**
  State is not known to have been produced until it is detected
  Example: photon pair from a down-converter

Postselected + conditional measurement = Heralded (maybe)

Heralded + memory = On demand

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QUANTUM REPEATER

and memory for light

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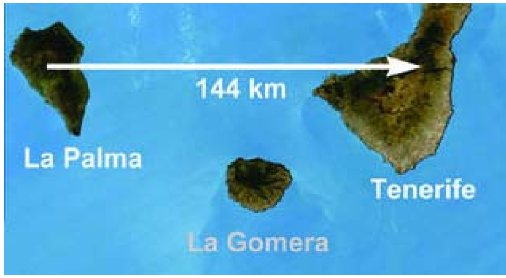
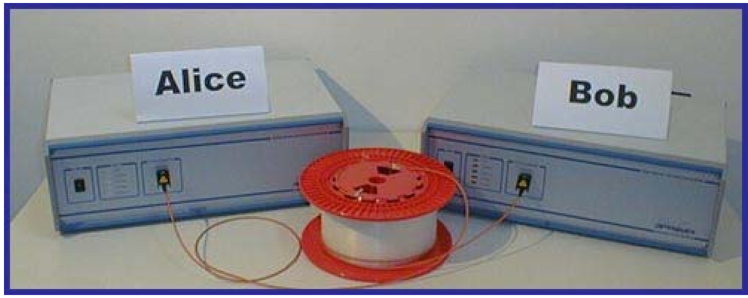
Quantum cryptography: here and now

Secure communication up to 100-150 km



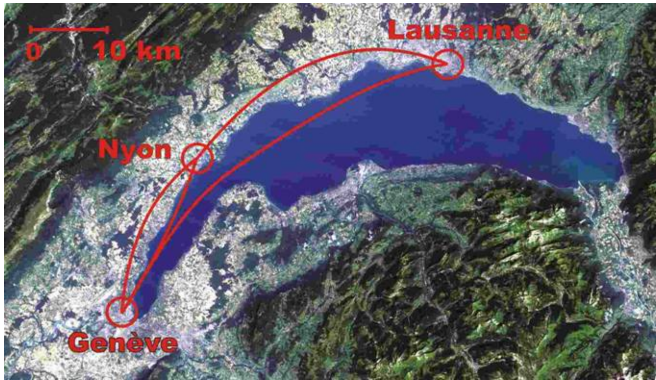
- Free space
- Optical fibers

Commercialization begins



- Id Quantique (Switzerland)
- MagiQ (Boston)
- BBN Technologies (Boston)

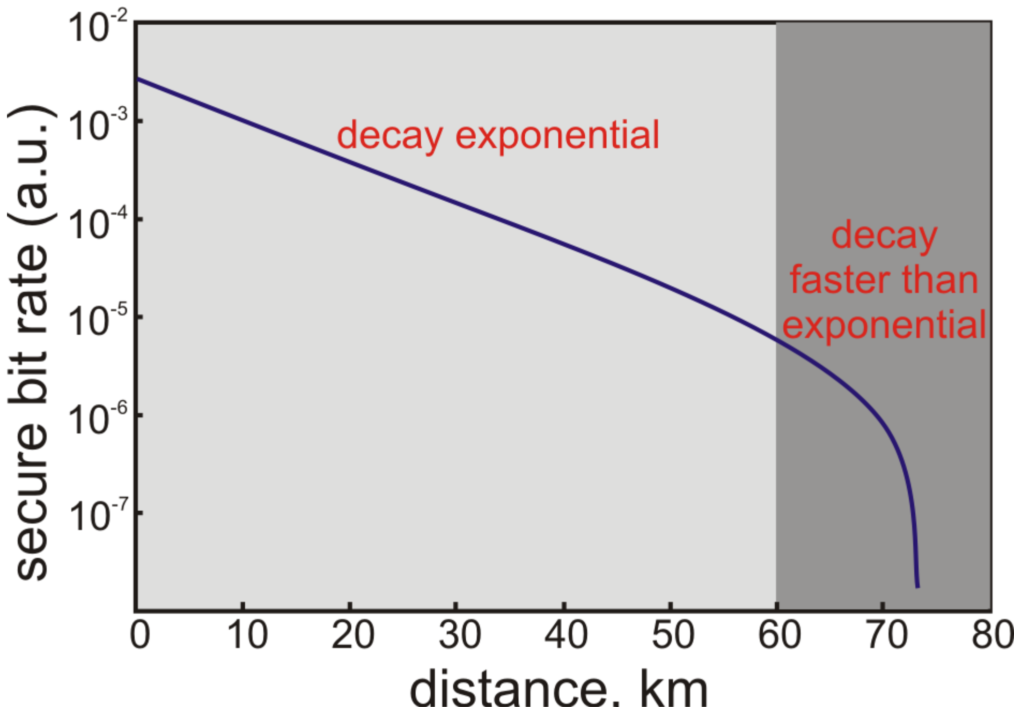
Metropolitan quantum communication networks



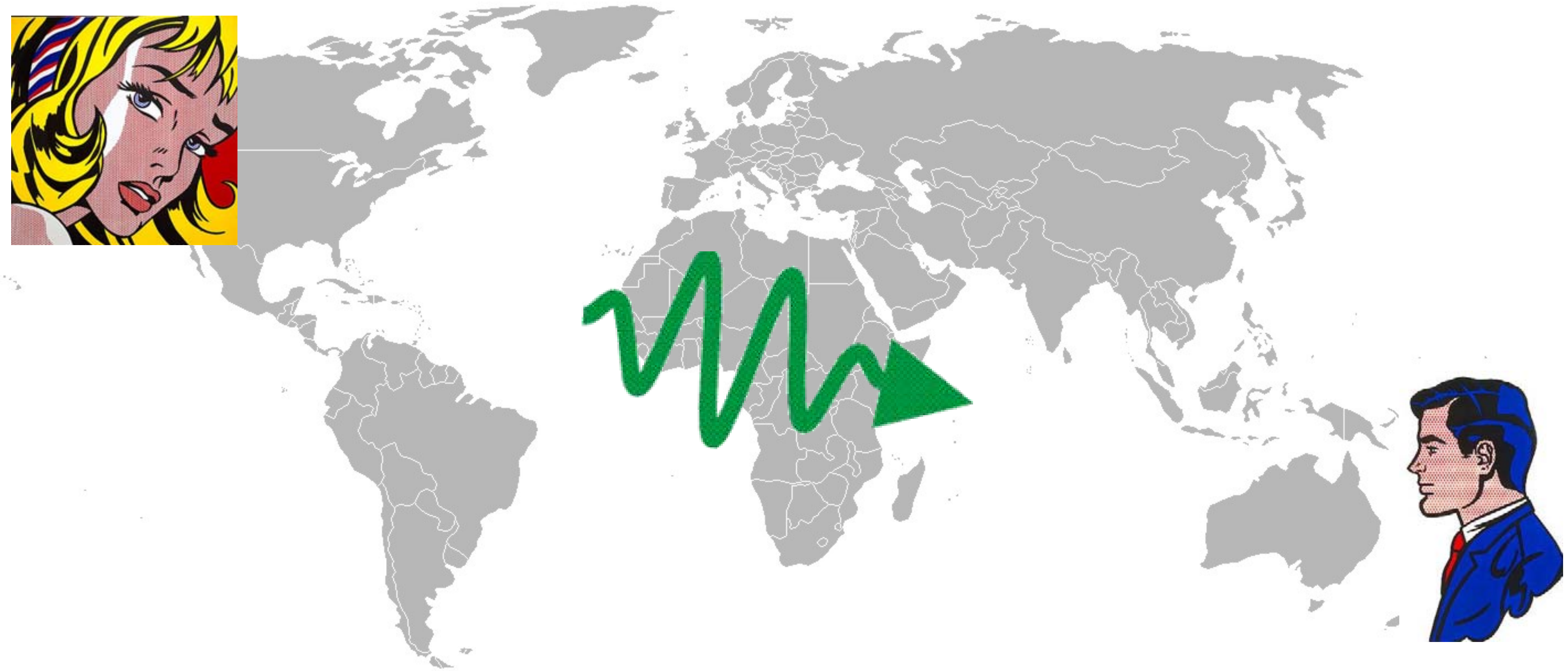
- Geneve
- Boston
- Vienna
- Calgary

Problems with quantum cryptography

- **Preparation of single photons**
  - **Must ensure absence of two-photon pulses**
- **Losses in optical fibers**
  - **0.2-0.3 dB/km: half of photons are lost over 10-15 kilometers.**
  - **Example: Dubai to Kish, 300 km, only 1 in 30,000,000 photons will reach destination**
  - **Can't use amplifiers**
- **"Dark counts" of detectors**
  - **Sometimes a photon detector will "click" without a photon**
  - **Dark clicks cause errors**
  - **Too many errors → can't detect eavesdropping**

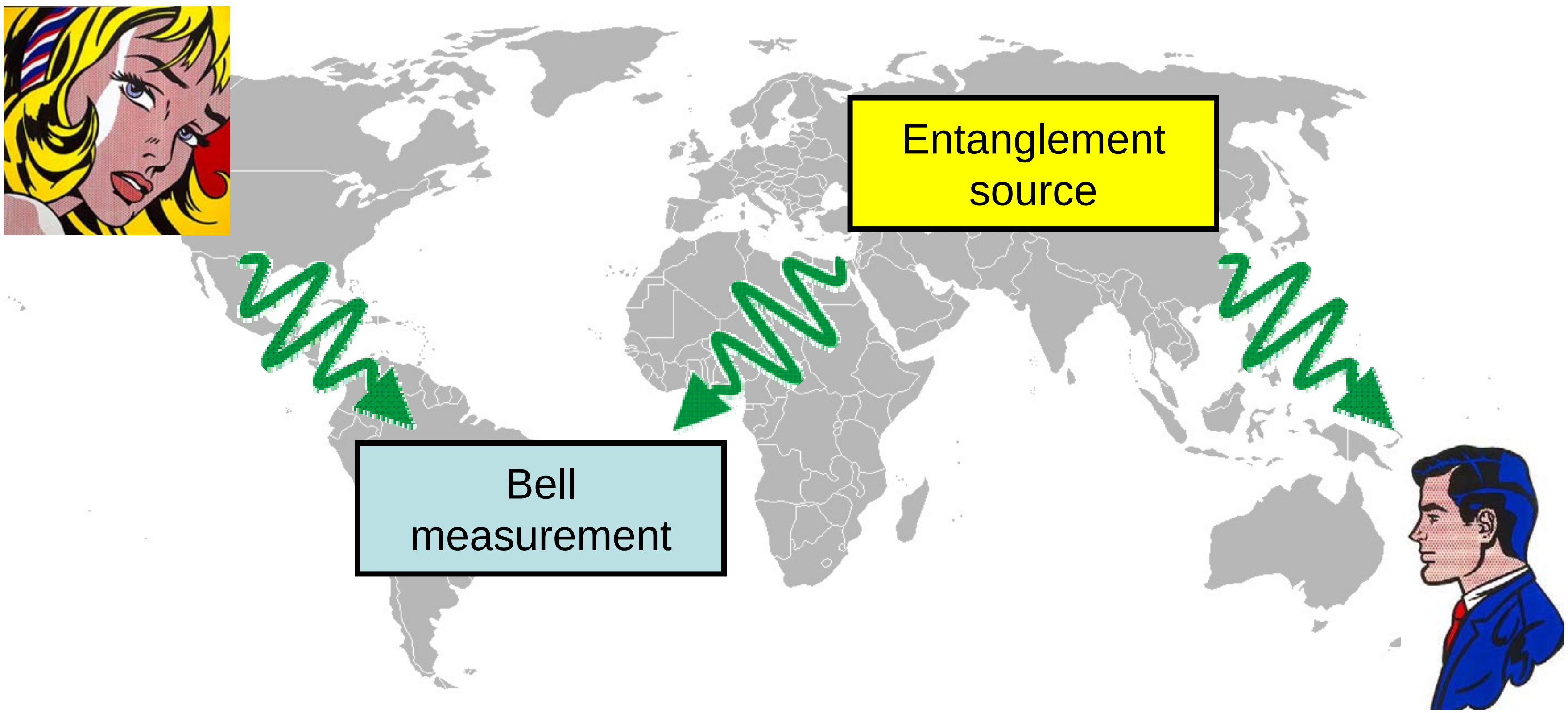


Suppose Alice wants to send a photon to Bob…



- The photon is likely to get lost on its way

Quantum relay



- **If Alice and Bob shared an entangled resource,**

☺ **Alice could *teleport* her photon to Bob**

☹ **But long-distance entanglement is difficult to create**

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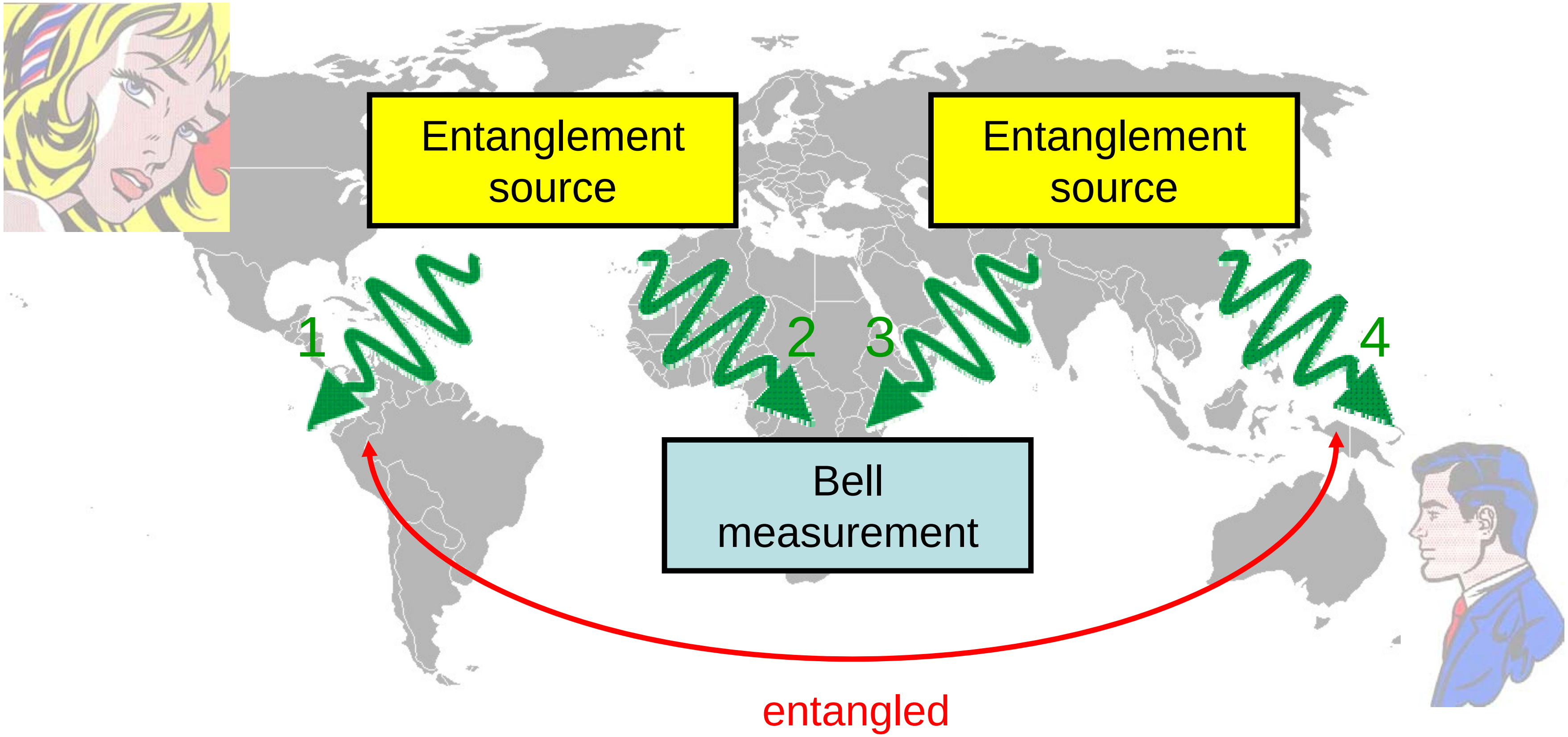
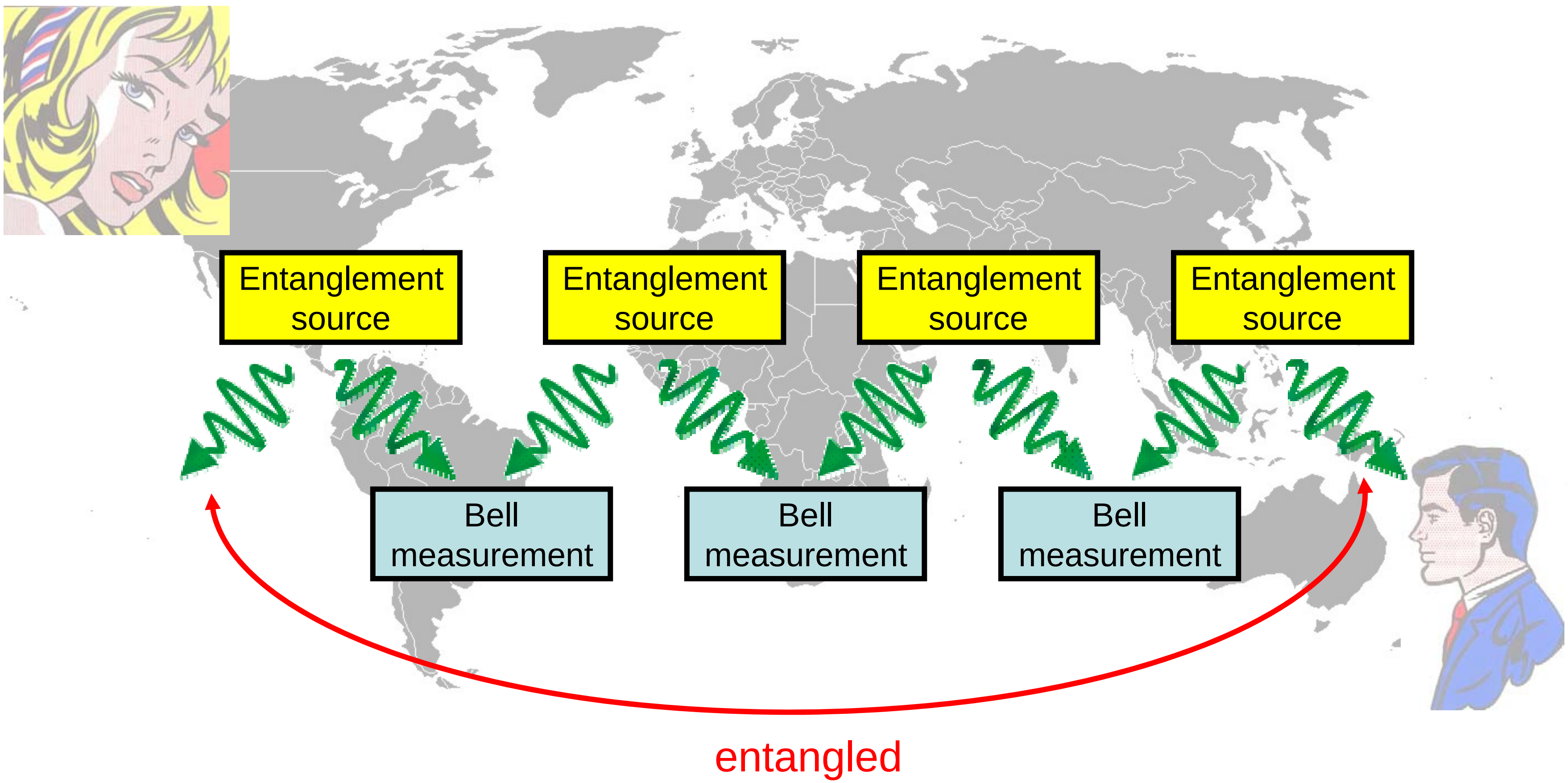
Quantum relay



Long-distance entanglement can be created by *entanglement swapping*

A Bell measurements on modes 2 and 4 entangles modes 1 and 4

Quantum relay

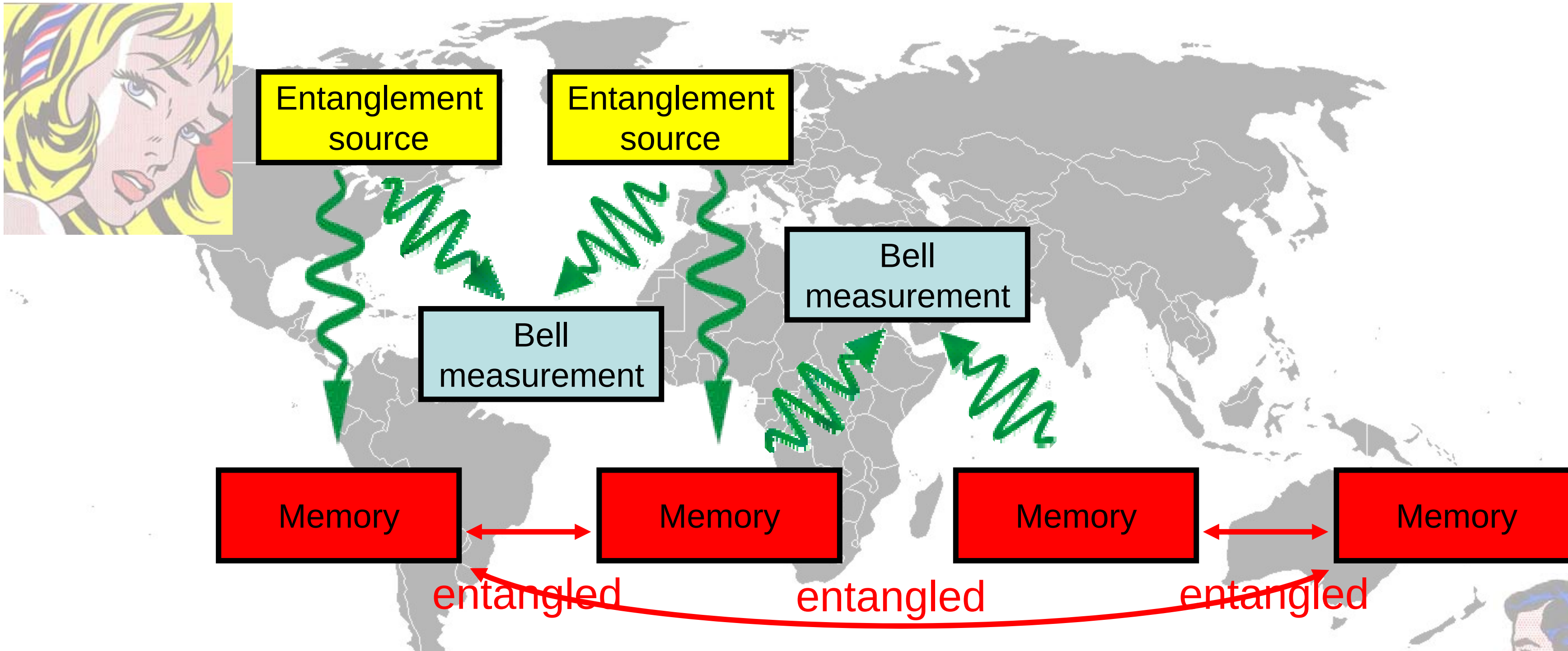


Long-distance entanglement can be created by *entanglement swapping*

☹ **but to succeed, all links must work simultaneously.**

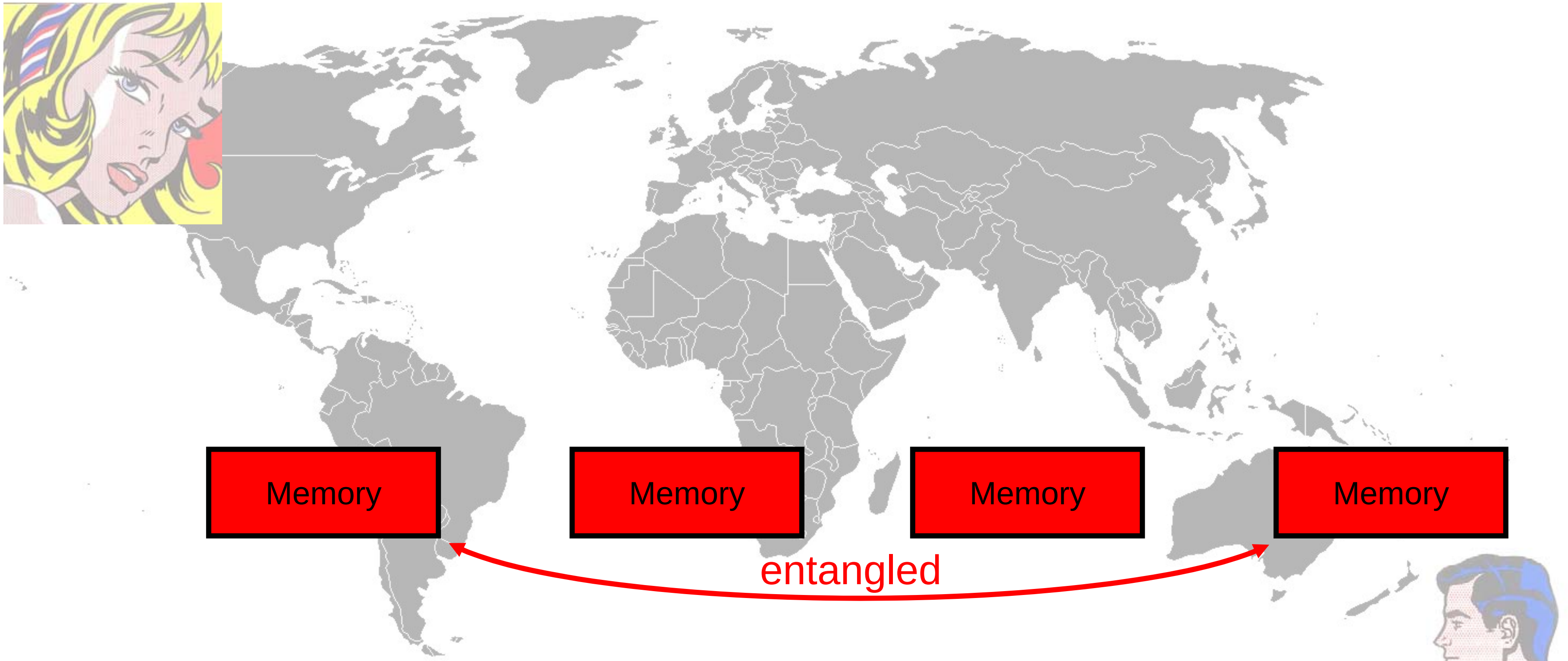
→ success probability still decreases exponentially with distance.

The role of memory



- **But if we had quantum memory,**
  - **entanglement in a link could be stored…**
    until entanglement in other links has been created, too.
  - **Bell-measurement on adjacent quantum memories...**
    will create the desired long-distance entanglement.
  - **Alice can teleport her photon to Bob**

Quantum repeater



- **This technology is called *quantum repeater***
  - **Initial idea: H. Briegel *et al.*, 1998**
  - **In application to EIT and quantum memory: L.M. Duan *et al.*, 2001**
- Quantum memory for light is essential for long-distance quantum communications.

By the way…

- **Quantum memory for light is also useful in quantum computing**
  - **Photon makes an excellent qubit… but does not like to stay put**
  - **Any computer, quantum or classical, needs memory**

ELECTROMAGNETICALLY INDUCED TRANSPARENCY

and memory for light

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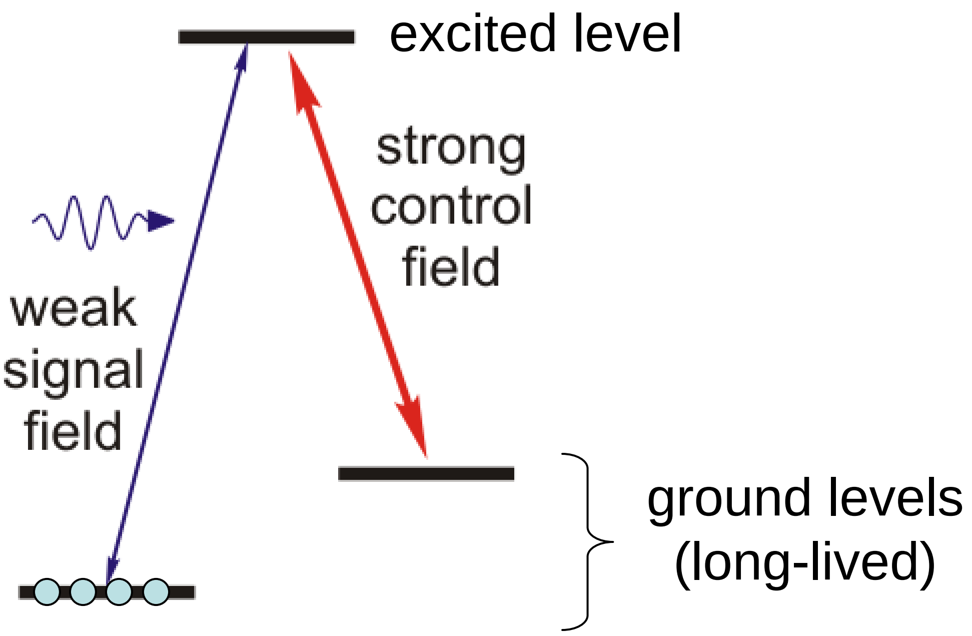
What is EIT?

Quantum interference effect in atoms with Λ-shaped level structure



What will happen to the signal field when we send it through an EIT medium?

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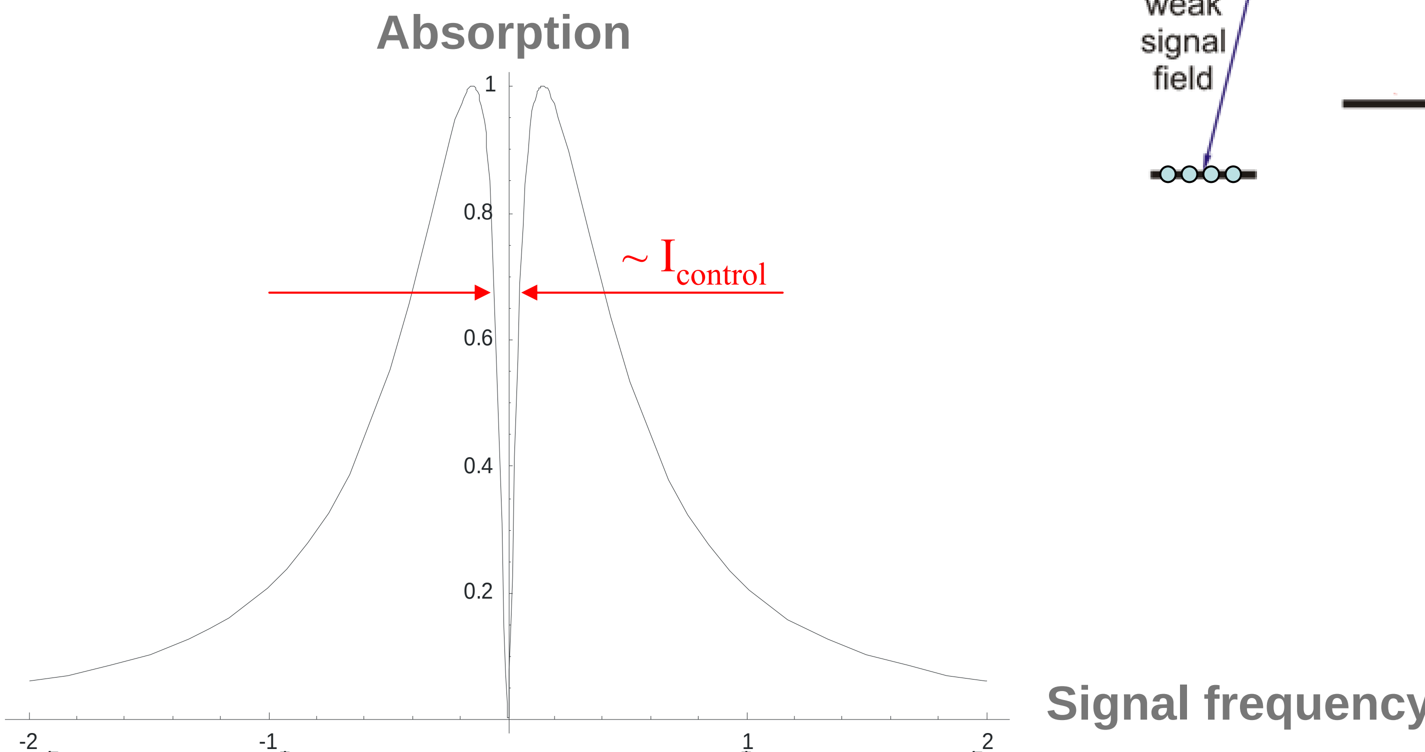
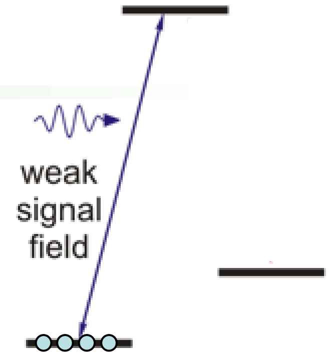
Absorption of the signal field

- Without control field
- With control field





Narrow transparency window on resonance.

- Light propagates through an otherwise opaque medium.

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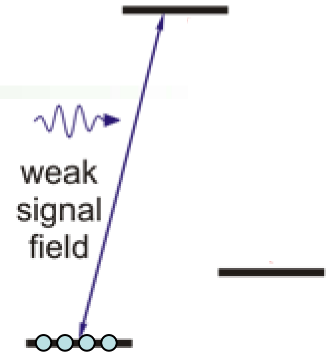
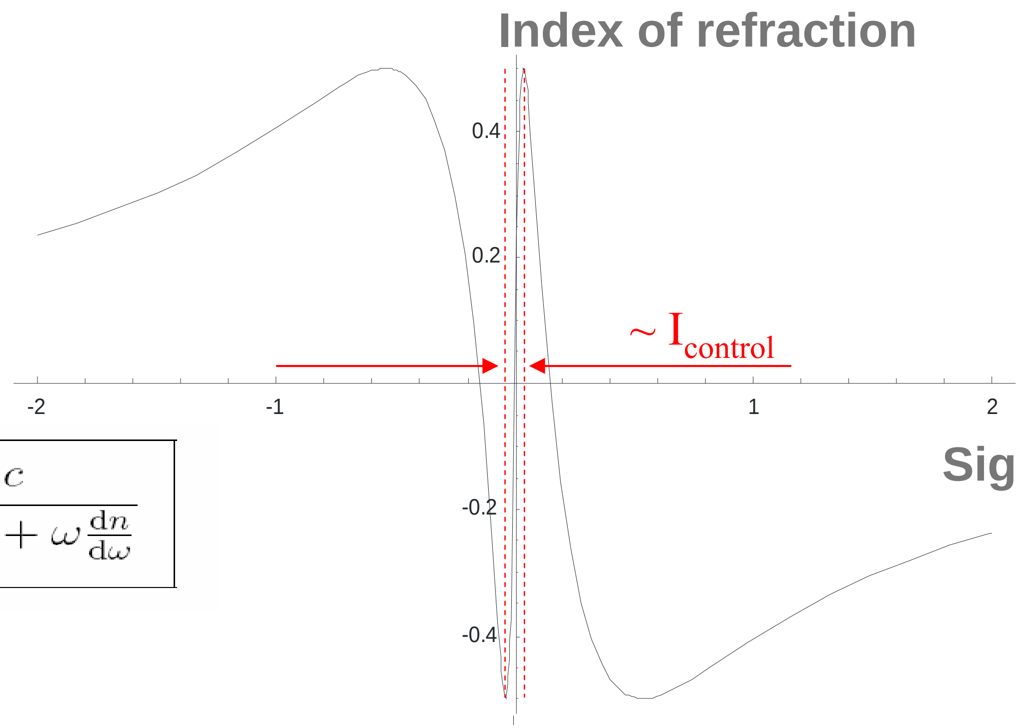
Dispersion of the signal field

- Without control field
- With control field





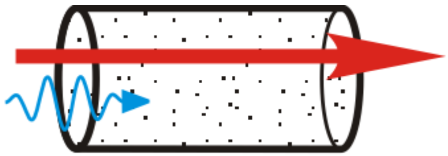
$$v_g(\omega) = \frac{c}{n(\omega) + \omega \frac{dn}{d\omega}}$$

We can enormously reduce the group velocity

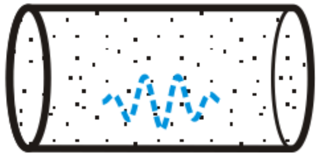
- Group velocity is proportional to the control field intensity

EIT for quantum memory

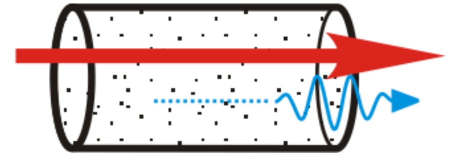
- **The idea**
  - **Turning the control field off will reduce the group velocity to zero**



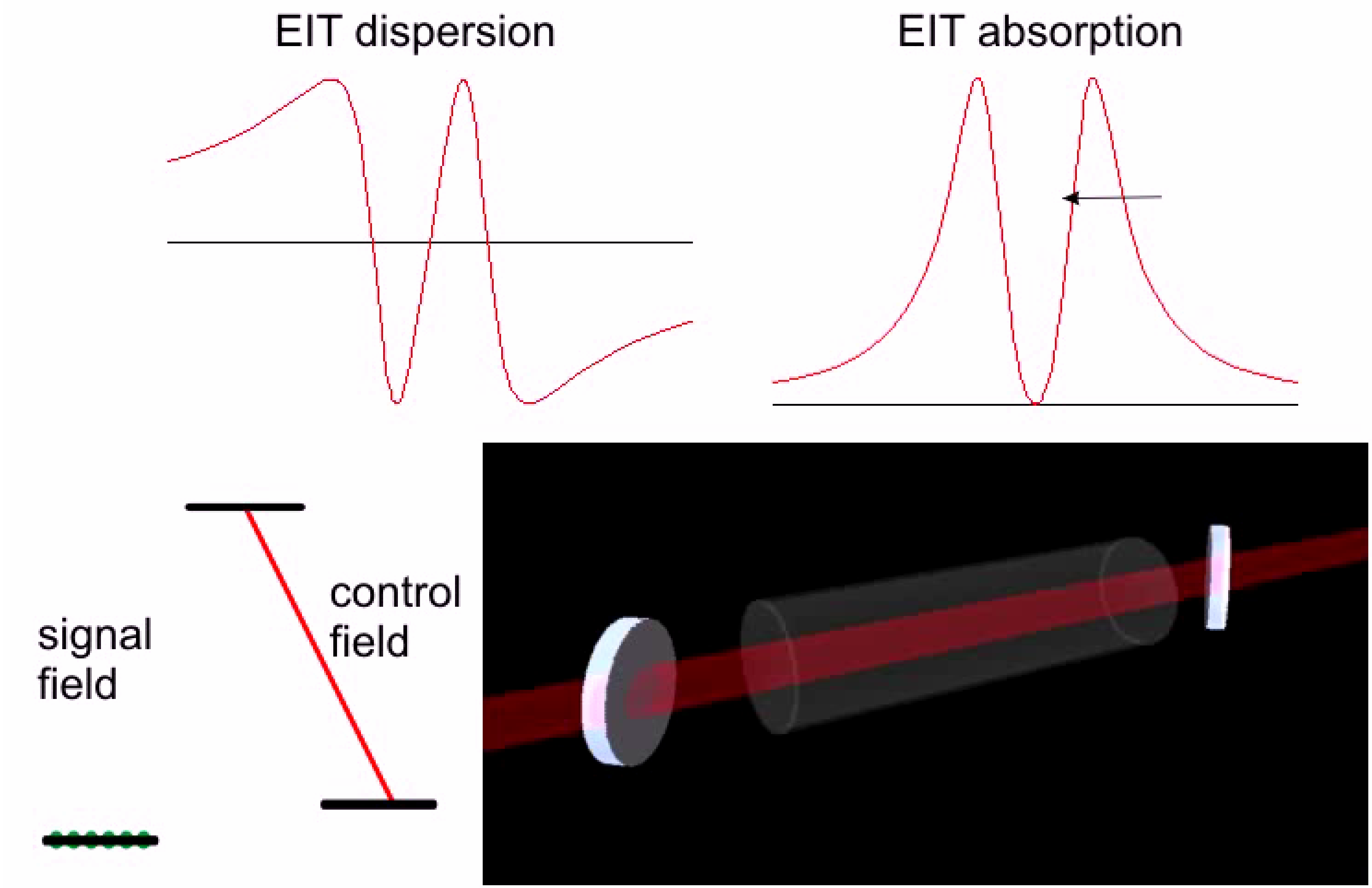
  - **Quantum information contained in the pulse is stored in a collective atomic ground state superposition**



  - **Turning the control field back on will retrieve the pulse in the original quantum state**

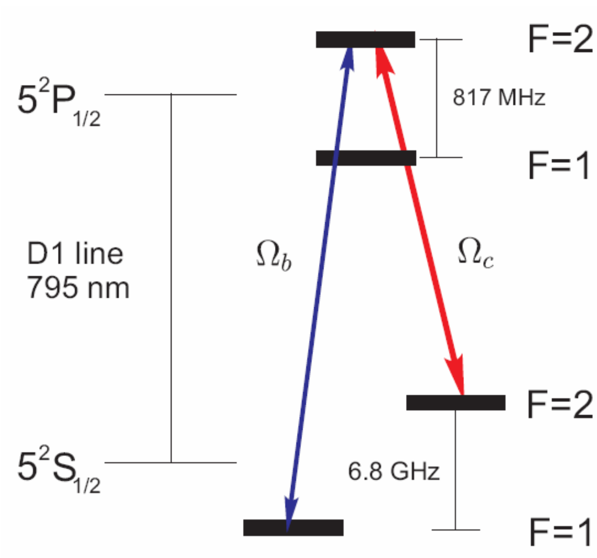


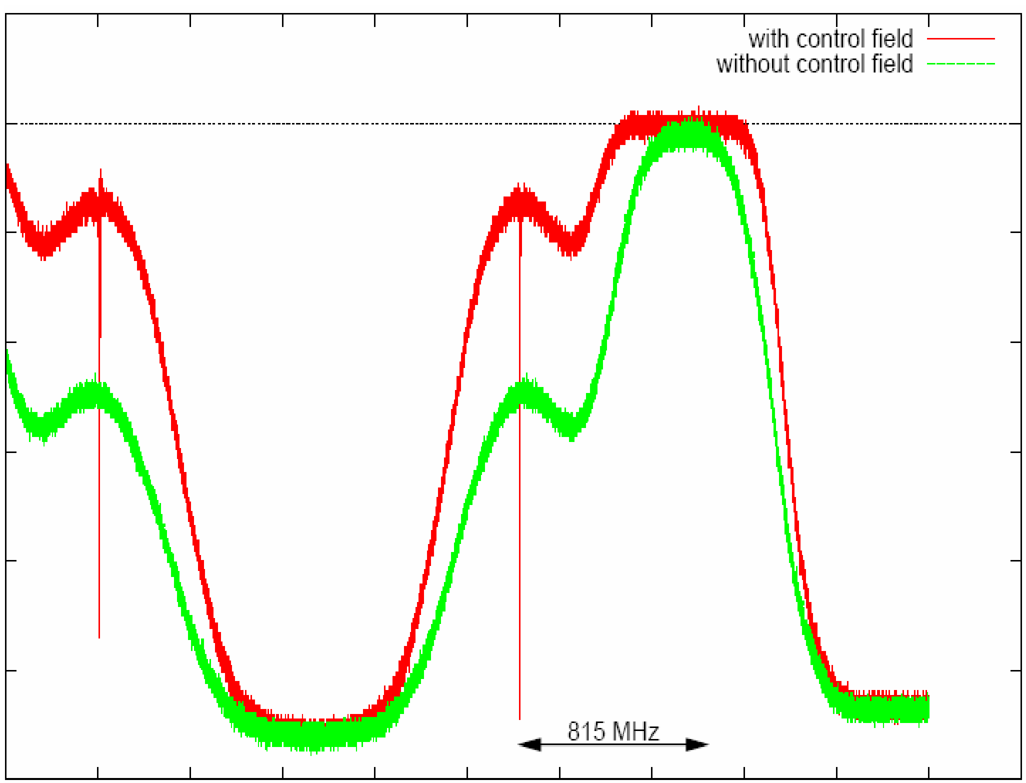
EIT for quantum memory



EIT in our lab

- **Implementation in atomic rubidium**
  - **Ground level split into two hyperfine sublevels → a perfect Λ system**
  - **Control and signal lasers must be phase locked to each other at 6.8 GHz**





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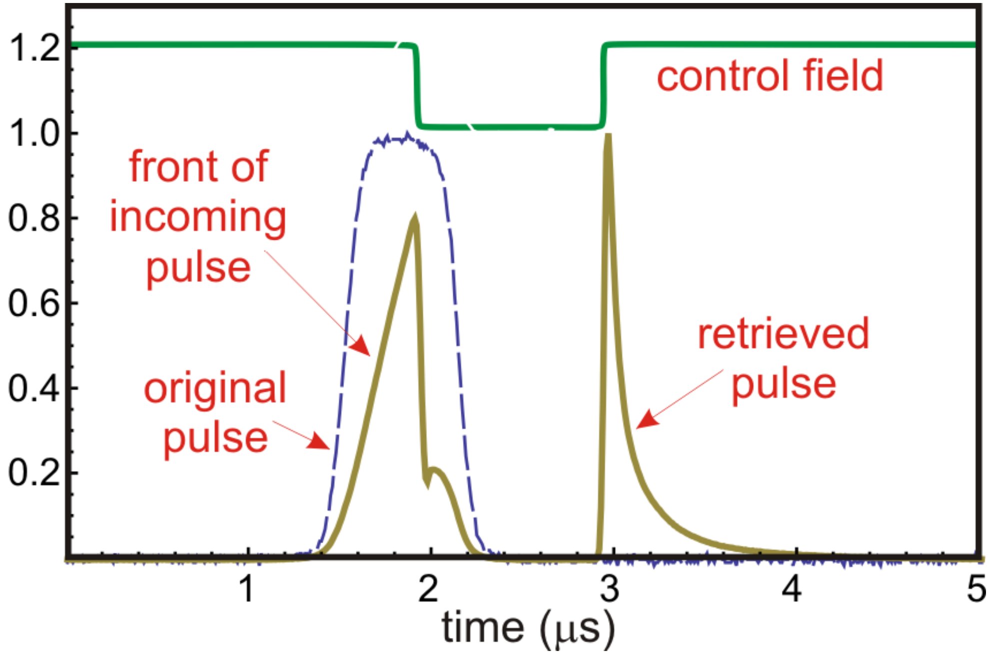
EIT-based memory: practical limitations

- EIT window not perfectly transparent
  → part of the pulse will be absorbed
- Memory lifetime limited by atoms colliding, drifting in and out the interaction region



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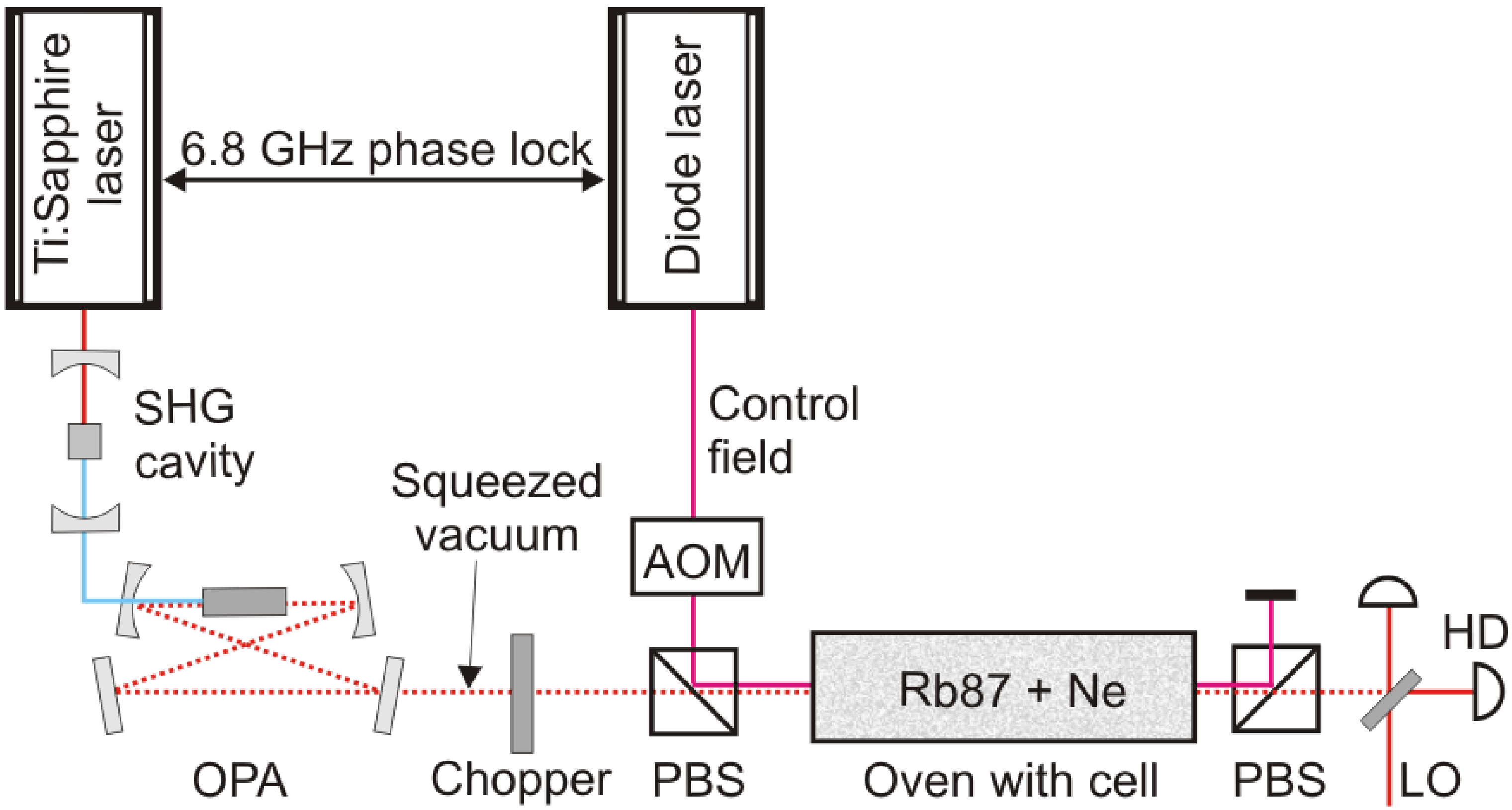
Storage of squeezed vacuum
The setup



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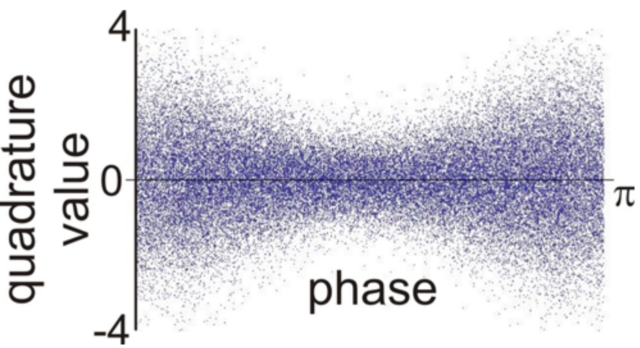
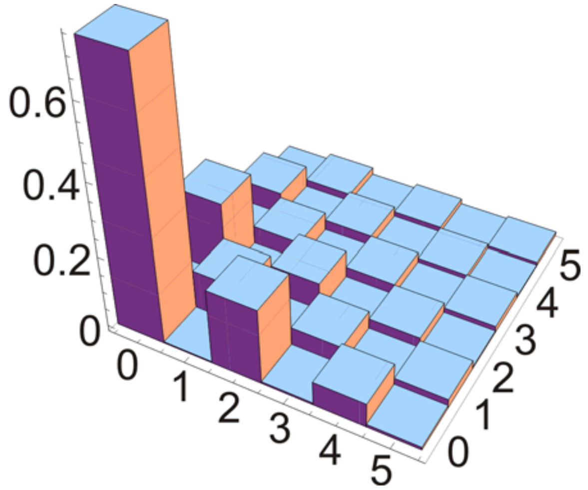
Storage of squeezed vacuum
The initial state

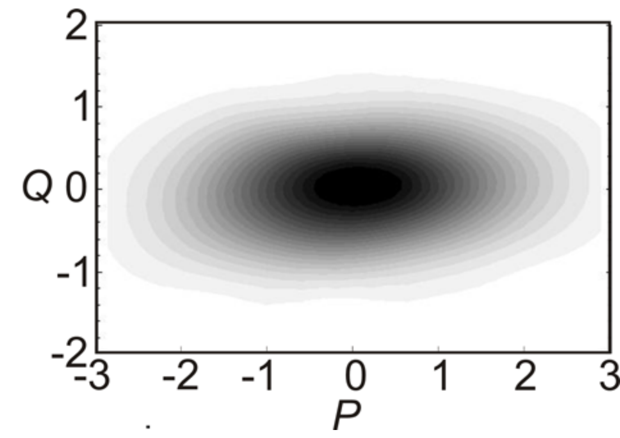
Quadrature data



Density matrix



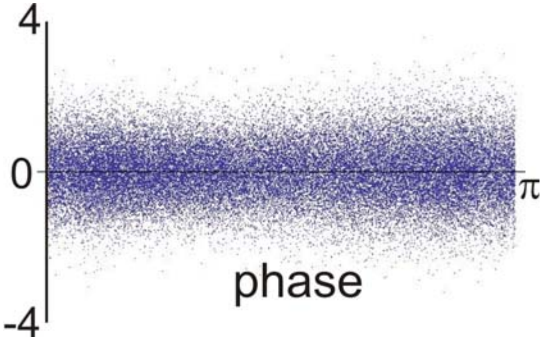
Wigner function



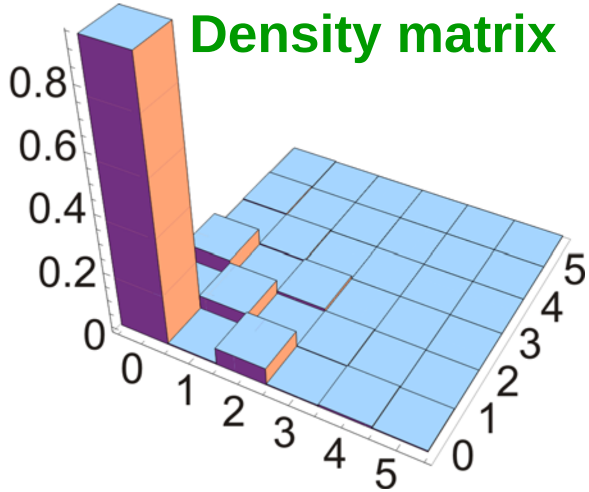
Storage of squeezed vacuum
The retrieved state

J. Appel et al., PRL **100**, 093602 (2008)

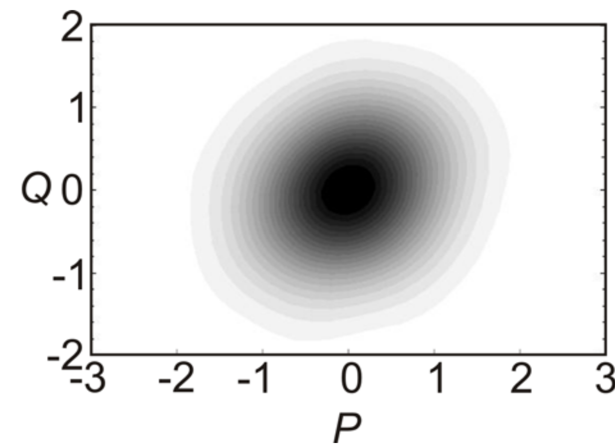
Quadrature data



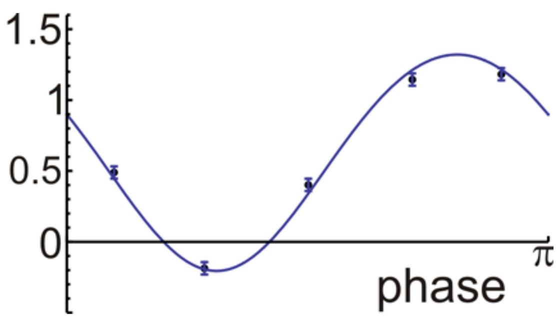
Density matrix



Wigner function



Quadrature noise



- **Maximum squeezing: 0.21±0.04 dB**
- **Squeezing observed in the retrieved state!**

EIT for quantum memory: state of the art

The "holy grail"

- Store and retrieve arbitrary states of light for unlimited time
- State after retrieval must be identical to initial

Existing work

- L. Hau, 1999: slow light
- M. Fleischauer, M. Lukin, 2000: original theoretical idea for light storage
- M. Lukin, D. Wadsworth *et al.*, 2001: storage and retrieval of a classical state
- A. Kuzmich *et al.*, M. Lukin *et al.*, 2005: storage and retrieval of single photons
- M. Kozuma *et al.*, A. Lvovsky *et al.*, 2007: memory for squeezed vacuum

Existing benchmarks

- Memory lifetime: up to milliseconds in rubidium, up to seconds in solids
- Memory efficiency: up to 50 % in rubidium, lower for solids
- Things get much worse when we attempt to store nonclassical states of light

QUANTUM COMPUTATION GATES

1. With EIT

2. Using conditional measurements

An optical C-NOT gate

- **What we need**

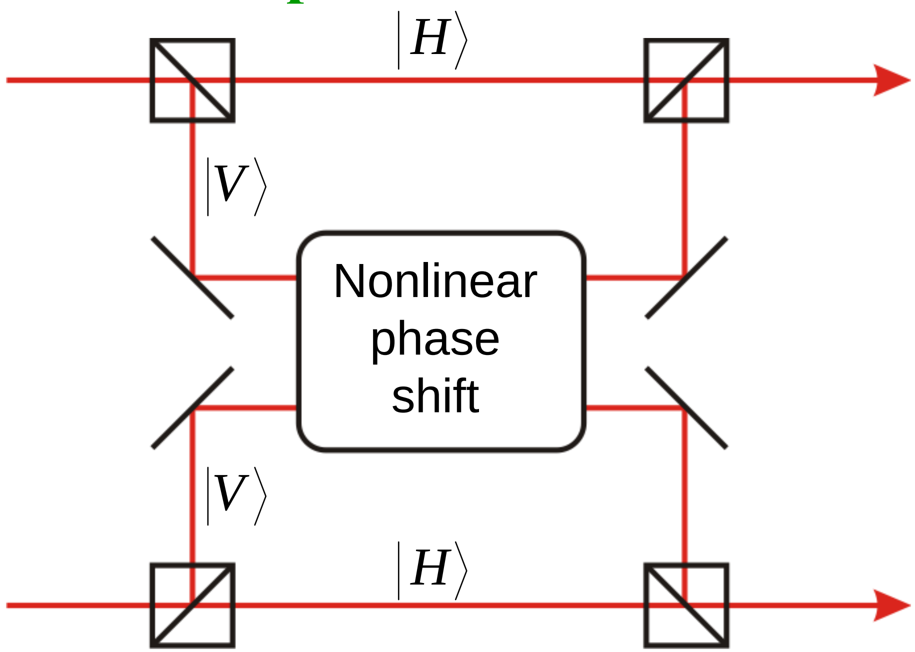
$|H\rangle$ or $|V\rangle$

$|H\rangle$ or $|V\rangle$

$$|H\rangle|H\rangle \rightarrow |H\rangle|H\rangle$$
$$|H\rangle|V\rangle \rightarrow |H\rangle|V\rangle$$
$$|V\rangle|H\rangle \rightarrow |V\rangle|H\rangle$$
$$|V\rangle|V\rangle \rightarrow -|V\rangle|V\rangle$$

An optical C-NOT gate

- **How to implement this**



- **Nonlinear phase shift**

$$|0\rangle|0\rangle \rightarrow |0\rangle|0\rangle$$
$$|0\rangle|1\rangle \rightarrow |0\rangle|1\rangle$$
$$|1\rangle|0\rangle \rightarrow |1\rangle|0\rangle$$
$$|1\rangle|1\rangle \rightarrow -|1\rangle|1\rangle$$

- **Problem**
  - **No materials that exhibit optical nonlinearity at the single-photon intensity level**

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QUANTUM COMPUTATION GATES

1. With EIT

2. Using conditional measurements

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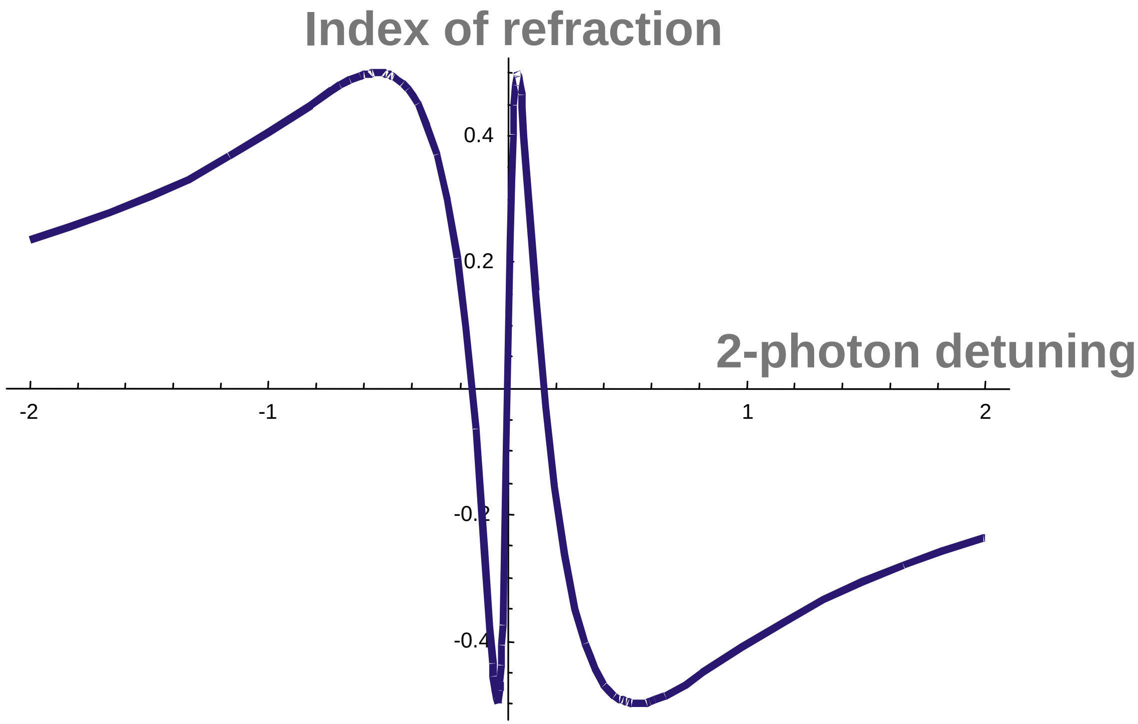
Nonlinear optics with EIT

- **Basic idea: exploit steep dispersion curve to produce large cross-phase modulation**



- **Small change in 2-photon detuning**
  → Large change in transmitted signal phase

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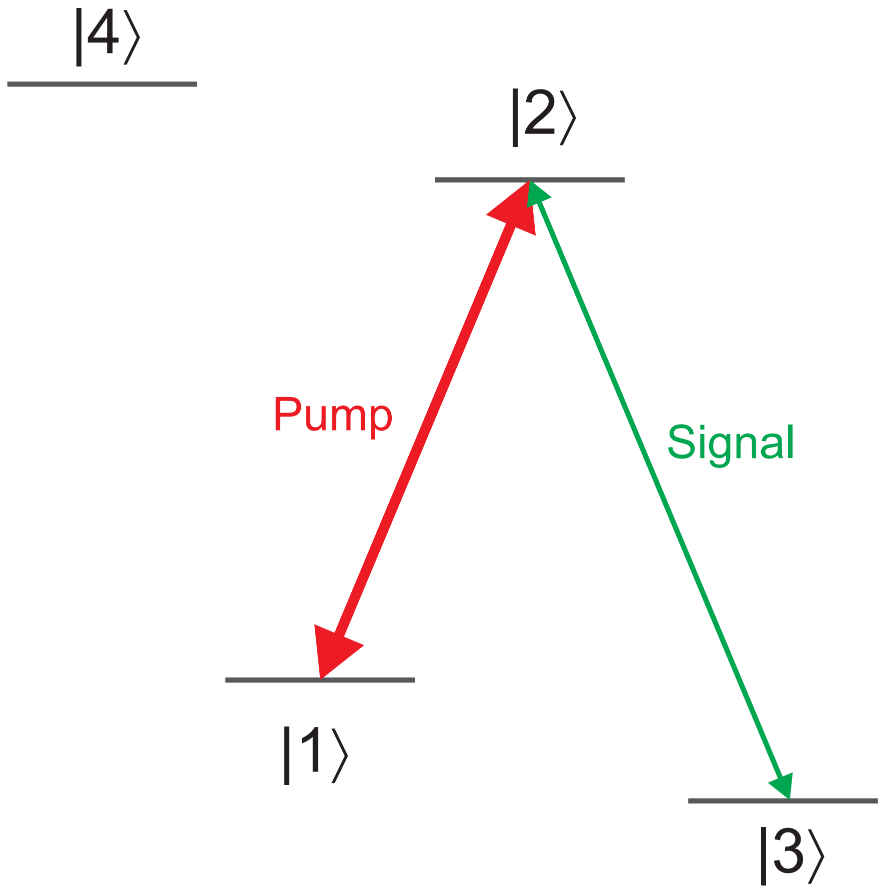
N-type scheme

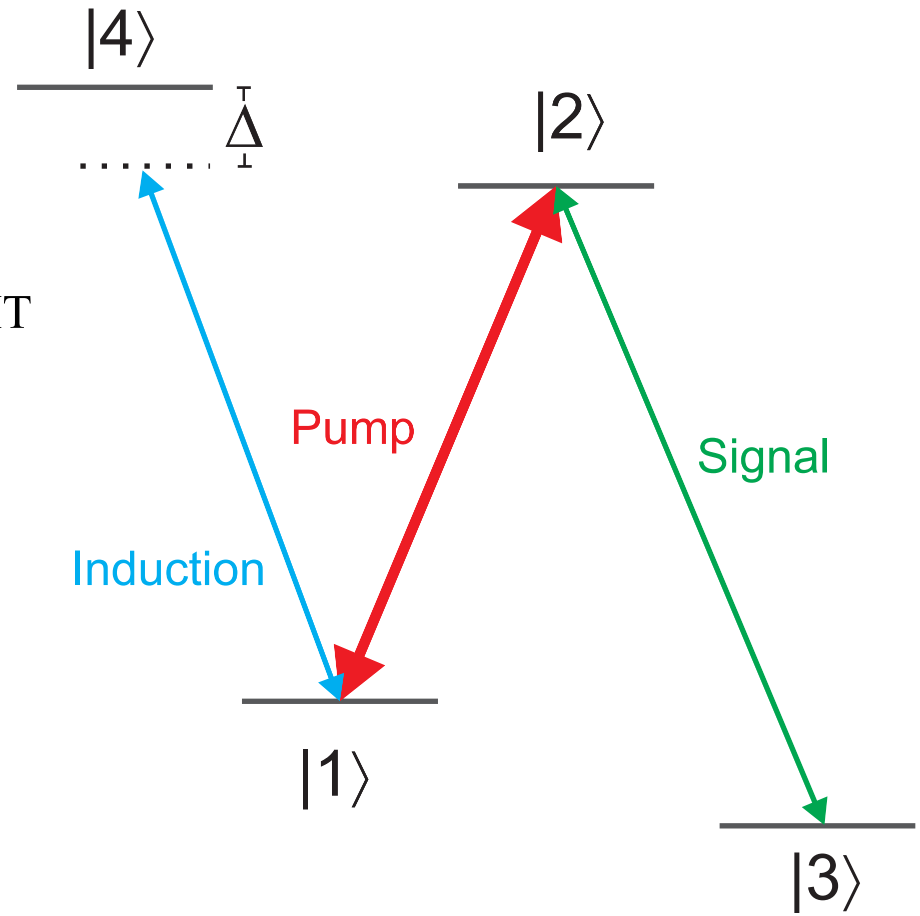
- **EIT on signal field due to $|1\rangle|2\rangle|3\rangle$**



1 Schmidt, Imamoglu. Opt. Lett. **23**, pages 1936-1939 (1996)

N-scheme

- **EIT on signal field due to |1⟩|2⟩|3⟩**
- **Off-resonant coupling of weak induction field produces Stark shift on |1⟩**
  - Changes 2-photon detuning of signal EIT
  - Affects phase of transmitted signal



Schmidt, Imamoglu. Opt. Lett. **23**, 1936 (1996)

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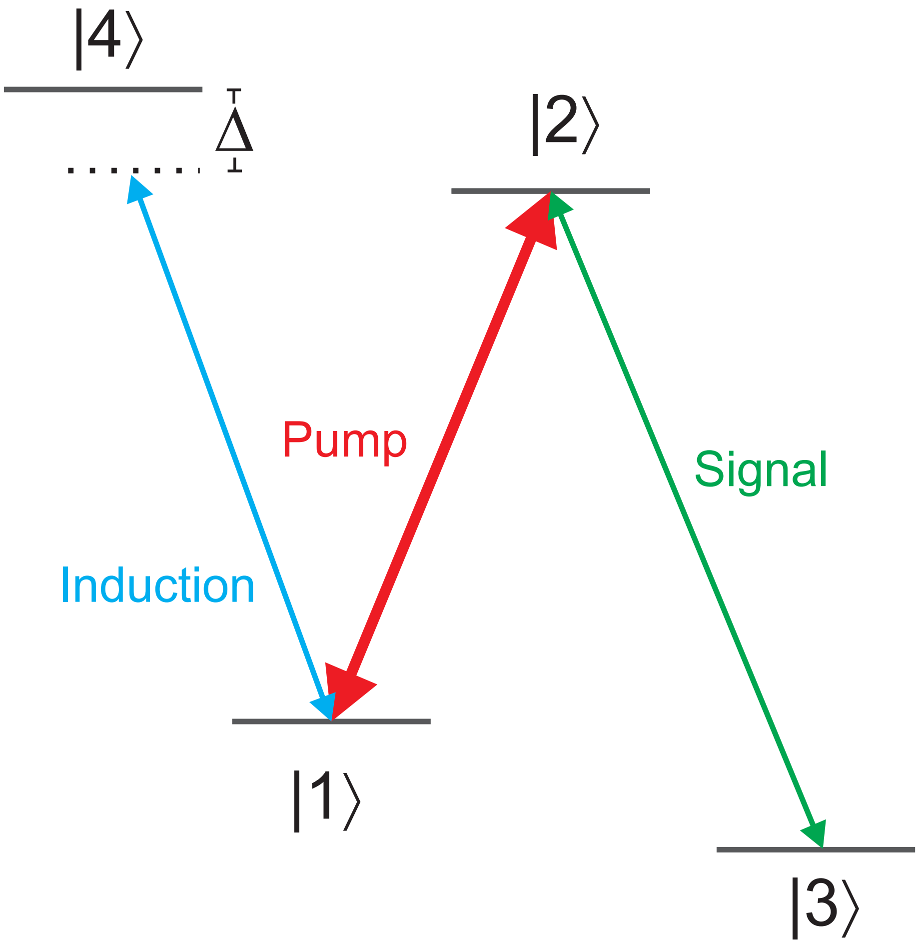
N-scheme
[continued]

- **Problem with N-scheme:**
  - **Only signal field experiences slowdown.**
  - **For pulses, this is a severe limitation.**
- **Solution:**
  - **Slow down induction pulse via another EIT system**
    - Lukin, Imamoglu (2001): use another atomic species (e.g. ^{85}Rb)
    - Wang, Marzlin, Sanders (2006): use double EIT in the same atom



QUANTUM COMPUTATION GATES

1. With EIT

2. Using conditional measurements

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Non-deterministic phase gate: implementation with the beam splitter

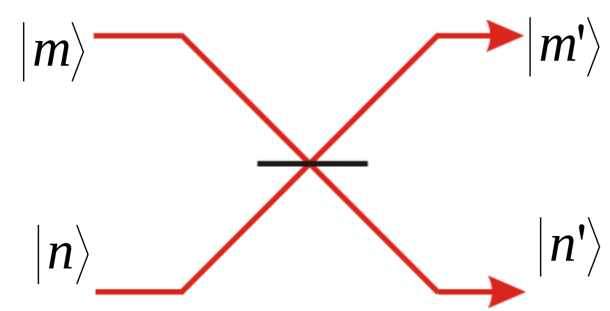
- **General beam splitter transformation**

$$|m,n\rangle \to \sum_{j,k=0}^{m,n} \sqrt{\frac{(j+k)!(m+n-j-k)!}{m!n!}} \binom{m}{j} \binom{n}{k} (-1)^k t^{n+j-k} r^{m-j+k} |m+n-j-k, j+k\rangle$$

Entangles input modes

Entanglement very complicated

Conditional measurement and/or postselection are required to implement computation gates



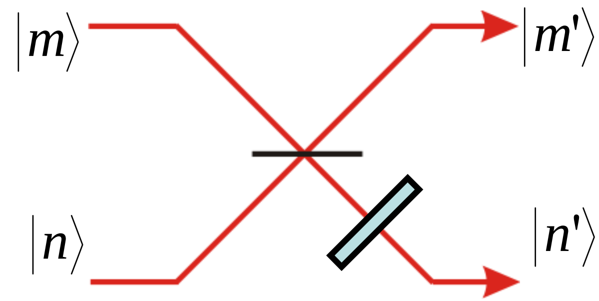
$\Rightarrow$ Linear-optical quantum computing is non-deterministic

Original idea: E. Knill, R. Laflamme, and G. J.Milburn, Nature **409,** 46 (2001).

Non-deterministic phase gate: implementation with the beam splitter

- **Beam splitter with reflectivity 1/3**

$$\left(r=\sqrt{1/3},\ t=\sqrt{2/3}\right)$$



  - **Postselect on events in which the number of photons in the reflected channel is the same as that in the corresponding incident channel**
  - **Neglect all other events**

$$|0,0\rangle \rightarrow |0,0\rangle$$
$$|1,0\rangle \rightarrow \sqrt{1/3}\,|1,0\rangle$$
$$|0,1\rangle \rightarrow -\sqrt{1/3}\,|0,1\rangle$$
$$|1,1\rangle \rightarrow 1/3\,|1,1\rangle$$

Insert π phase shift into the right channel →

$$|0,0\rangle \rightarrow |0,0\rangle$$
$$|1,0\rangle \rightarrow \sqrt{1/3}\,|1,0\rangle$$
$$|0,1\rangle \rightarrow \sqrt{1/3}\,|0,1\rangle$$
$$|1,1\rangle \rightarrow -1/3\,|1,1\rangle$$

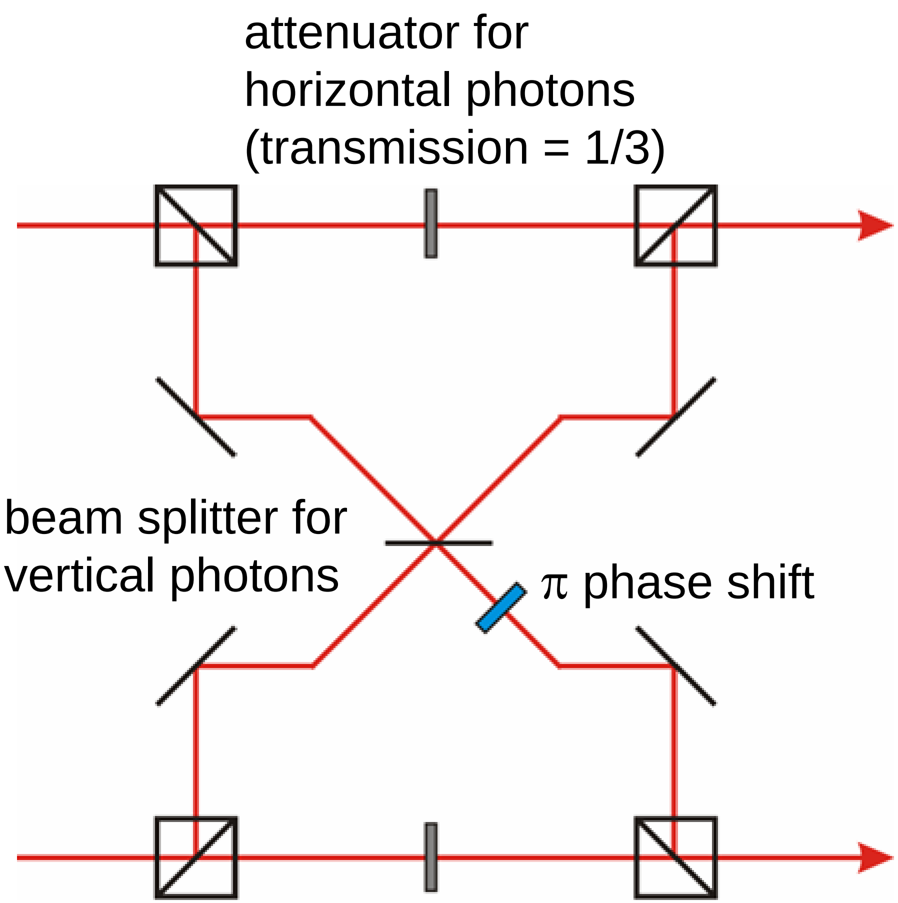
Phase gate implemented!

Non-deterministic (probability = 1/3 per photon)

→ **Need to attenuate horizontal photons, too**

Non-deterministic phase gate
[continued]

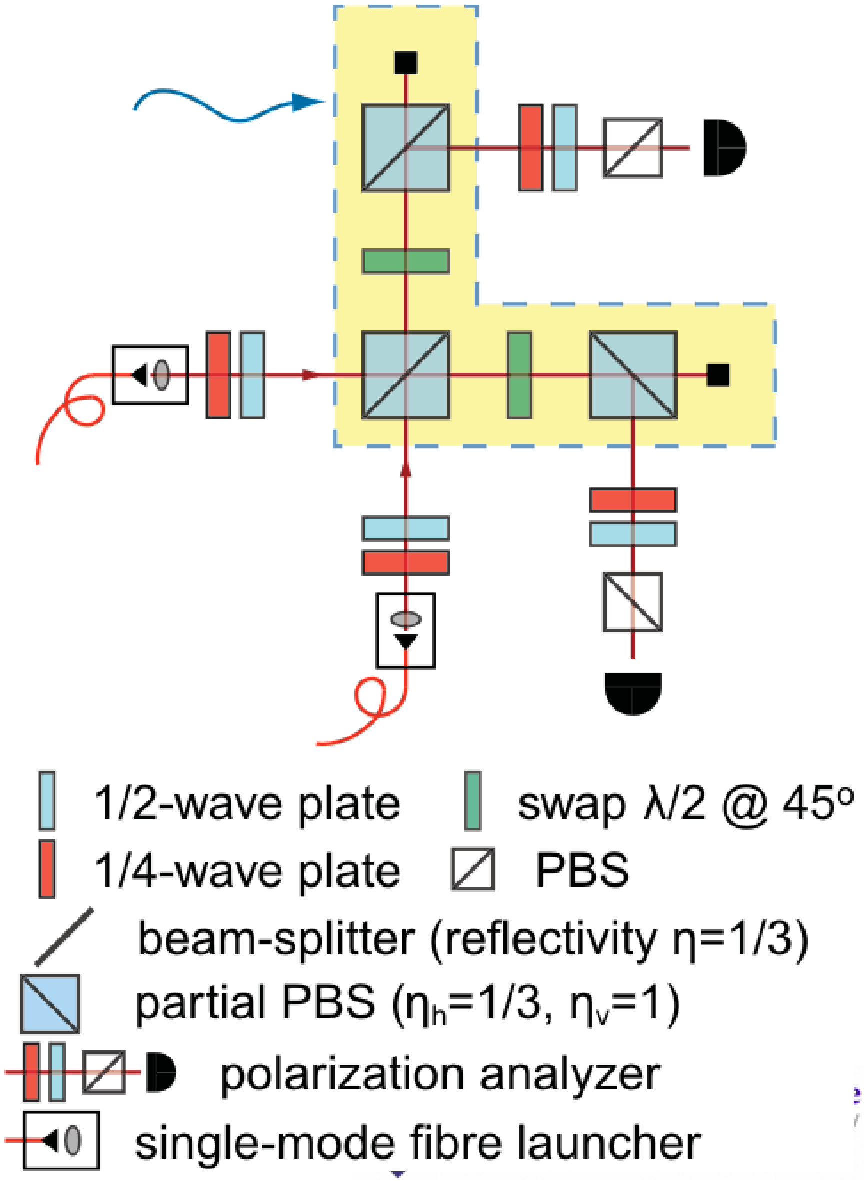
- **Full scheme**



- **Properties**
  - **Works conditioned on detecting 1 photon in each output**
  - **Works with probability 1/9**
  - **Would be useful for quantum computing if we had non-demolition detection of photons**

Non-deterministic phase gate
Experimental implementation

- **The setup**
  - **Partially-polarizing beam splitters used to simplify mode-matching**
  - **Operation of the gate as a Bell-state analyzer verified**



N. K. Langford et al., Phys. Rev. Lett. **95**, 210504 (2005)
N. Kiesel et al., Phys. Rev. Lett. **95**, 210505 (2005)
R. Okamoto et al., Phys. Rev. Lett. **95**, 210505 (2005)

Another example: Conditional preparation of multi-photon entanglement

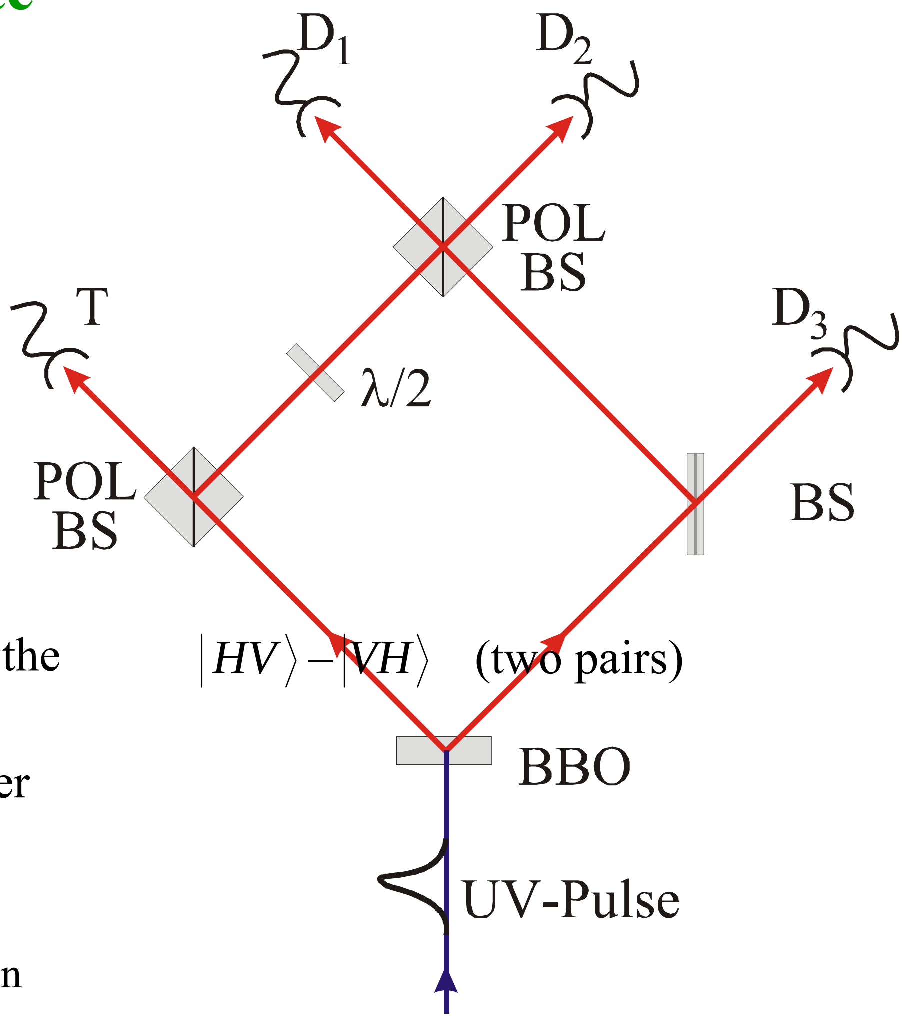
D. Bouwmeester *et al.*, *PRL* **82**, 1345 (1999)

- **Greenberger-Horne-Zeilinger state**

  $|HHV\rangle + |VVH\rangle$

  - **Conditioned on 4-photon coincidence (postselected preparation)**
    - Start from 2 pairs $|HV\rangle - |VH\rangle$
    - Photon that fires T comes from "first pair"
      - $\Rightarrow$ first pair must be $|HV\rangle$
      - $\Rightarrow$ second pair must be $|VH\rangle$
    - Photons transmitted and reflected from BS must be of opposite polarizations
    - Photons detected by D_1 and D_2 must be of the same polarization
    - The state incident on D_1, D_2 and D_3 is either $|HHV\rangle$ or $|VVH\rangle$
    - These possibilities are indistinguishable

      $\Rightarrow$ The output state is a coherent superposition



☹ **We know the state has been generated only after it's detected**

Thanks!

- **Funding:**
  - **CIAR**
  - **NSERC**
  - **AIF**
  - **CFI**
  - **Quantum*Works***

Ph.D. positions available

http://qis.ucalgary.ca/quantech/

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