All Optical Quantum Gates

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LOQC People

Staff

T.C.Ralph
A.G.White
G.J.Milburn

Postdocs

J.L.O'Brien
G.J.Pryde
A.Gilchrist
H.Jeong
K.Pregnell

Students

N.K.Langford
T.Weinhold
A.Hayes
A.Lund
P.Rohde
R.Dalton

Collaborators

D.F.V.James ~ Los Alamos
S.Bartlett ~ University of Queensland
C.Myers ~ University of Waterloo
M.Nielsen ~ University of Queensland
D.Branning ~ University of Illinois

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CENTRE FOR QUANTUM COMPUTER TECHNOLOGY
AUSTRALIAN RESEARCH COUNCIL CENTRE OF EXCELLENCE

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Overview

- Introduction
- Optical CNOT gate
  - How it works in theory
  - How it works in practice

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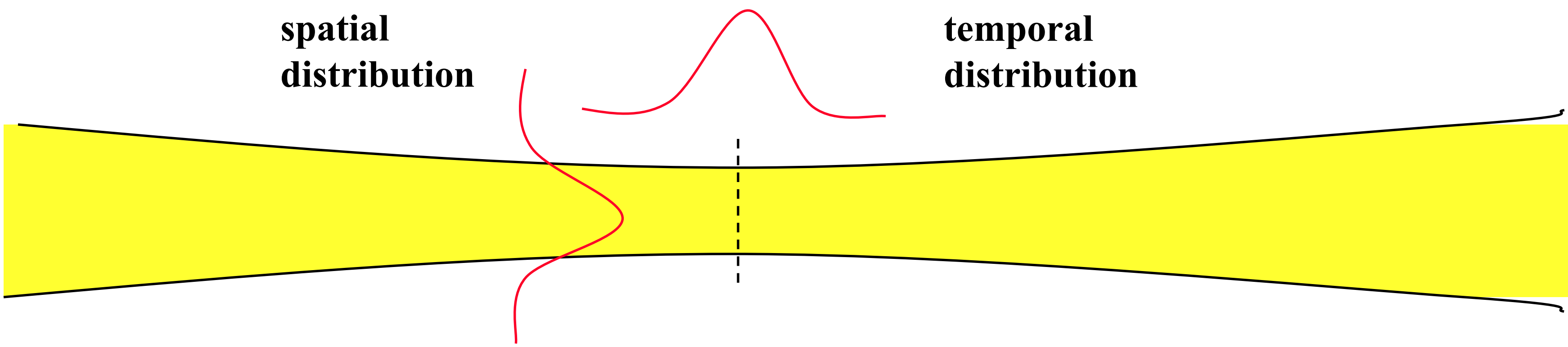
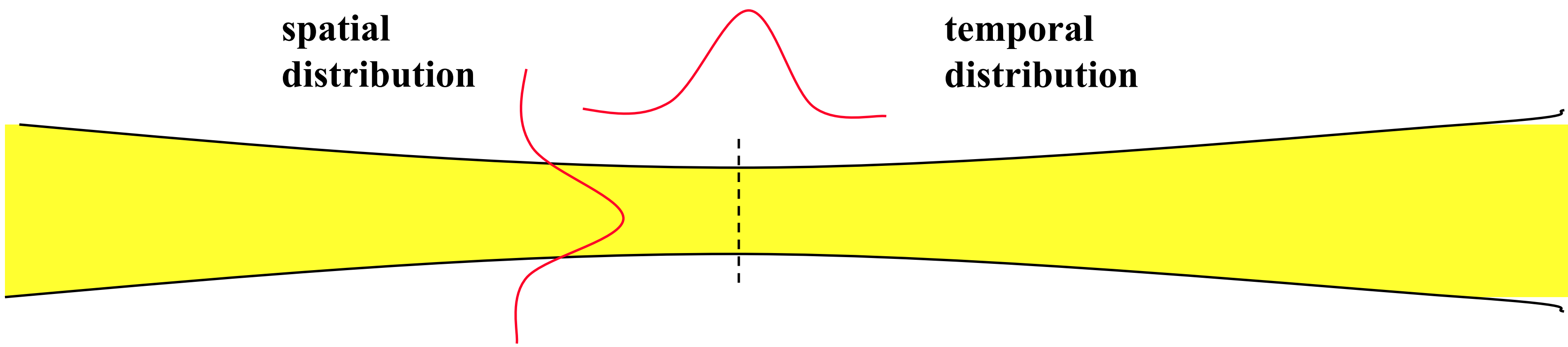
- Optical CNOT gate
  - How it works in theory
  - How it works in practice
- Process Tomography
- Error correction
- Future - scale-up

Single Photon States



single spatio-temporal mode $\equiv$ transform limited

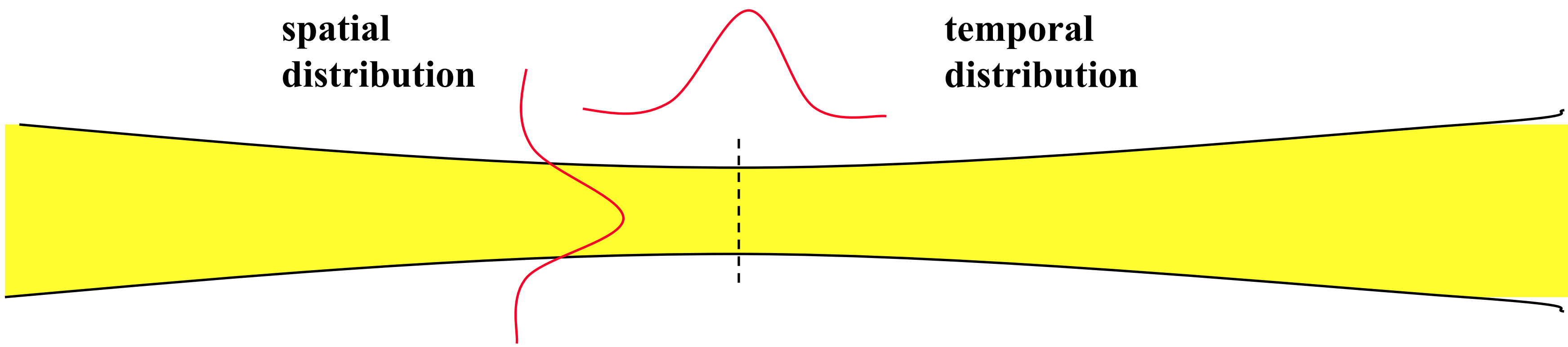
Single Photon States



single spatio-temporal mode $\equiv$ transform limited

If there is exactly 1 quanta of energy in the mode it is a single photon state

Single Photon States



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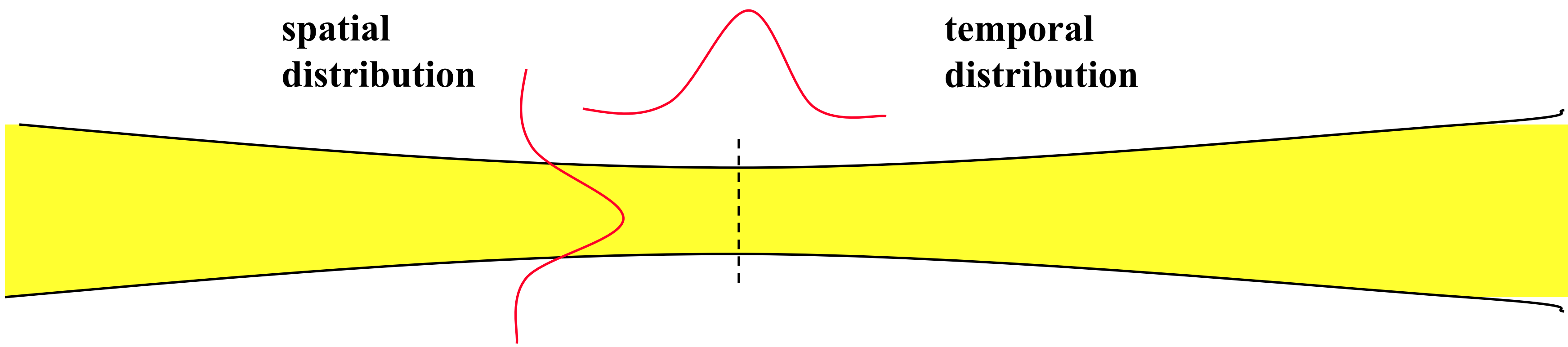
Single Photon States



single spatio-temporal mode $\equiv$ transform limited

If there is exactly 1 quanta of energy in the mode
it is a single photon state

|11>

Experimental Reality Check

- Presently there are no sources of single photon states as just described
- Best that can be done:

$$\rho = P_0 |0\rangle\langle 0| + P_1 |1\rangle\langle 1| \qquad P_1 \approx 60\%$$

A.I.Lvovsky, H.Hansen, T.Aichele, O.Benson, J.Mlynek, and S.Schiller
Phys. Rev. Lett. 87, 050402 (2001)

Experimental Reality Check

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- Best that can be done:

$$\rho = P_0 |0\rangle\langle 0| + P_1 |1\rangle\langle 1| \qquad P_1 \approx 60\%$$

- Also need detectors that can count photons with high efficiency - currently ~ 90% efficiency

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Post-selection

$$|\alpha\rangle = |\mathbf{0}\rangle + \alpha\, |\mathbf{1}\rangle + \mathbf{0.5}\, \alpha^2\, |\mathbf{2}\rangle + \ldots$$

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Post-selection

$\alpha \ll 1$

$$|\alpha\rangle = |0\rangle + \alpha\,|1\rangle + \cancel{0.5\,\alpha^2\,|2\rangle} + \ldots$$

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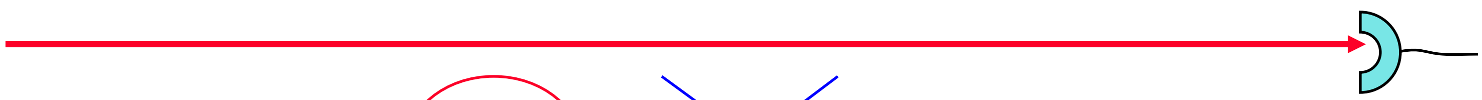
Post-selection

$\alpha << 1$



$$|\alpha\rangle = |0\rangle + \alpha\,|1\rangle + \cancel{0.5\,\alpha^2\,|2\rangle} + \ldots.$$

G.I.Taylor, Proc.Cambridge Phil.Soc.15, 114 (1909).

Post-selection

Down-conversion
splits photons @ 2ω
□□□□□□□□□□□photons @ ω

$\chi << 1$

$$|\phi\rangle = |00\rangle + \chi\,|11\rangle + \ldots$$

Ghosh and Mandel, PRL, 59, 1903 (1987)

Post-selection

$\chi << 1$

Down-conversion splits photons @ 2ω
photons @ ω

$$|\phi> = |00> + \chi\,|11> + \ldots$$

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Post-selection

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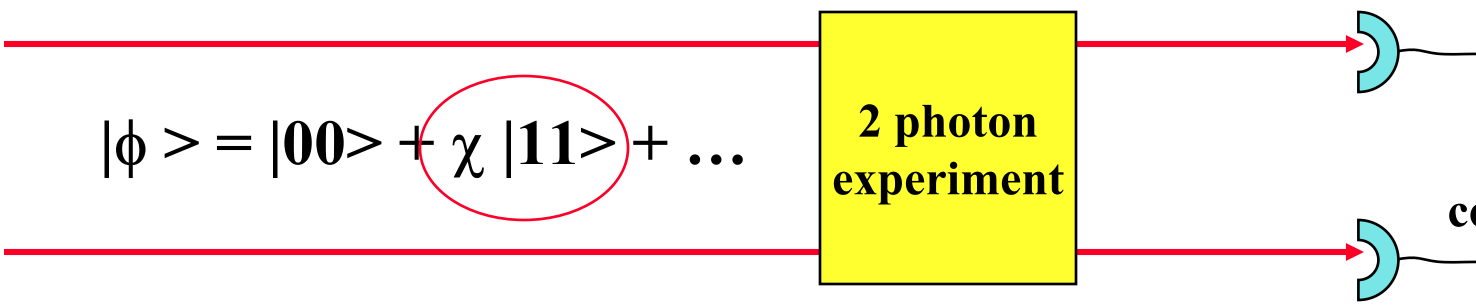
$|\phi\rangle = |00\rangle + \chi\,|11\rangle + \ldots$

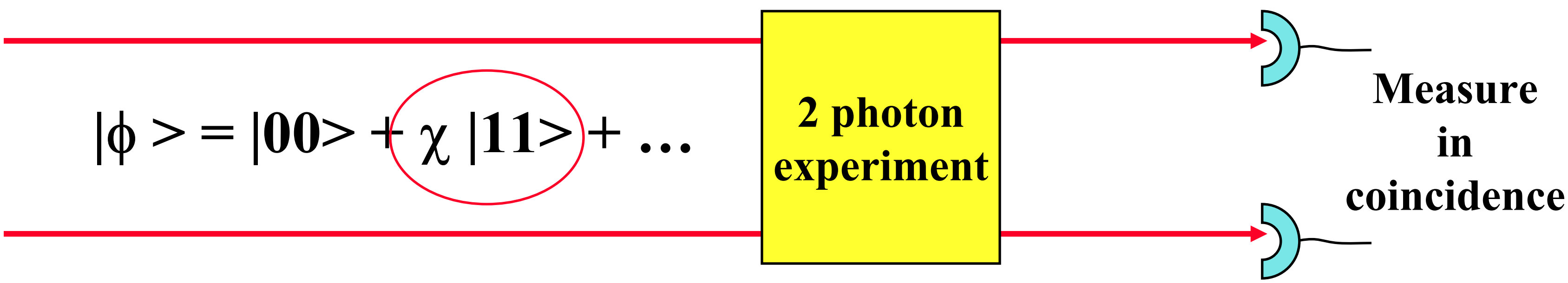


Ghosh and Mandel, PRL, 59, 1903 (1987)

Post-selection

$\chi \ll 1$

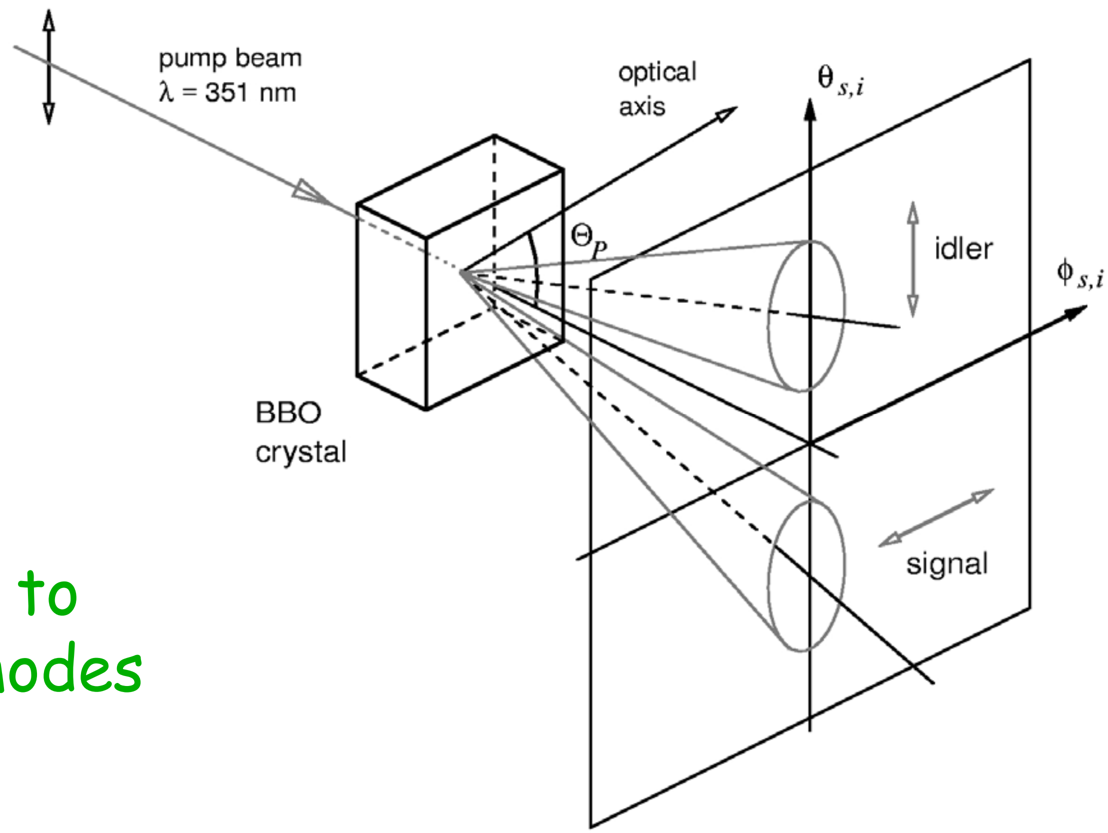
Down-conversion splits photons @ 2ω □□□□□□□□□□□photons @ ω



Ghosh and Mandel, PRL, 59, 1903 (1987)

See also: Santori, Fattal, Vuckovic, Solomon and Yamamoto, Nature, 419, 594 (2002)

Photon source: bright beam-like source



• tune crystal to obtain good modes

S. Takeuchi, *Optics Letters* **26**, 843 (2001); C. Kurstsiefer *et al.*, *J. Mod. Opt.* **48**, 1997 (2001)

Photon source: bright beam-like source

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

- tune crystal to obtain good modes

S. Takeuchi, *Optics Letters* **26**, 843 (2001); C. Kurstsiefer *et al.*, *J. Mod. Opt.* **48**, 1997 (2001)

Photon source: bright beam-like source

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

- tune crystal to obtain good modes
- spatially filter with fibres
- frequency filter (~0.4 nm)

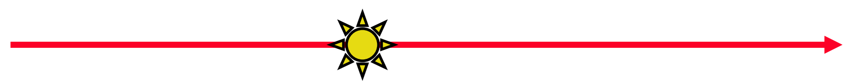
S. Takeuchi, *Optics Letters* **26**, 843 (2001); C. Kurstsiefer *et al.*, *J. Mod. Opt.* **48**, 1997 (2001)

Different CNOT Experiments

- Pittman, Fitch, Jacobs, and Franson,
  PRA **68**, 032316 (2003).
  - 3 photon gate, operates in coincidence.
- O'Brien, Pryde, White, Ralph and Branning,
  Nature **426**, 264 (2003).
  - 2 photon gate, operates in coincidence
- Gasparoni, Pan, Walther, Rudolph, and Zeilinger,
  Phys. Rev. Lett. 93, 020504 (2004)
  - 4 photon gate, operates in coincidence (though in principle could be heralded)

Photons as qubits

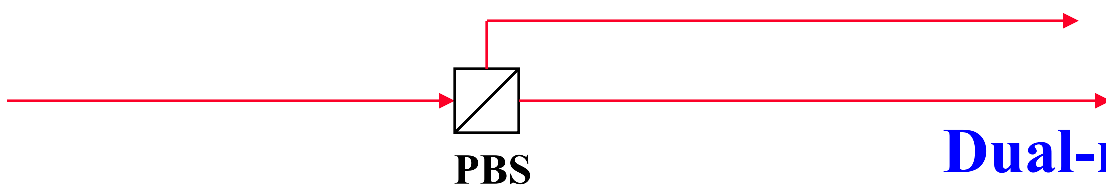
- We can encode qubits as the polarization states of single photons



“0” = |H> **“1” = |V>**

α **|H>** + β **|V>**

- Arbitrary one qubit operations can be realized with half and quarter wave-plates

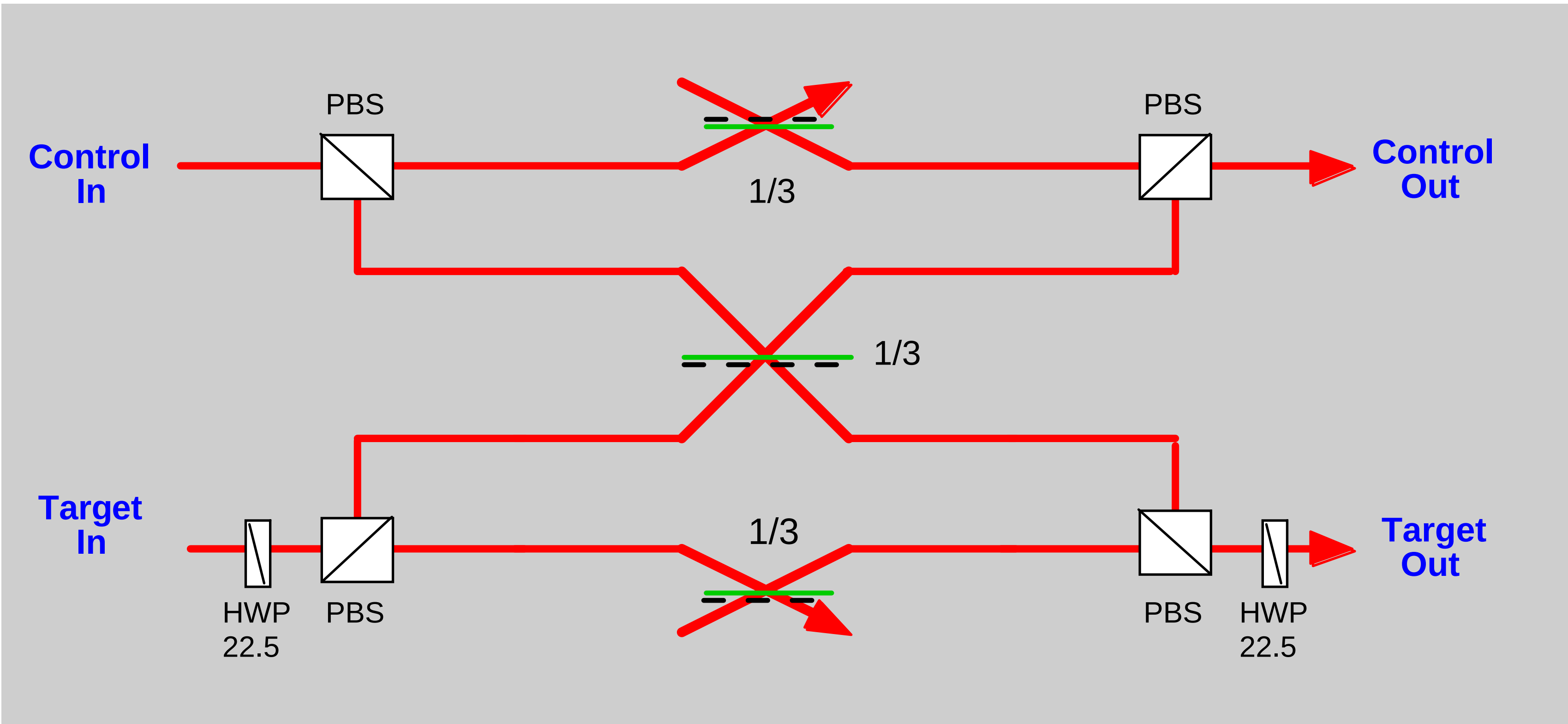


α **|01>** + β **|10>**

Dual-rail encoding

CNOT Gate

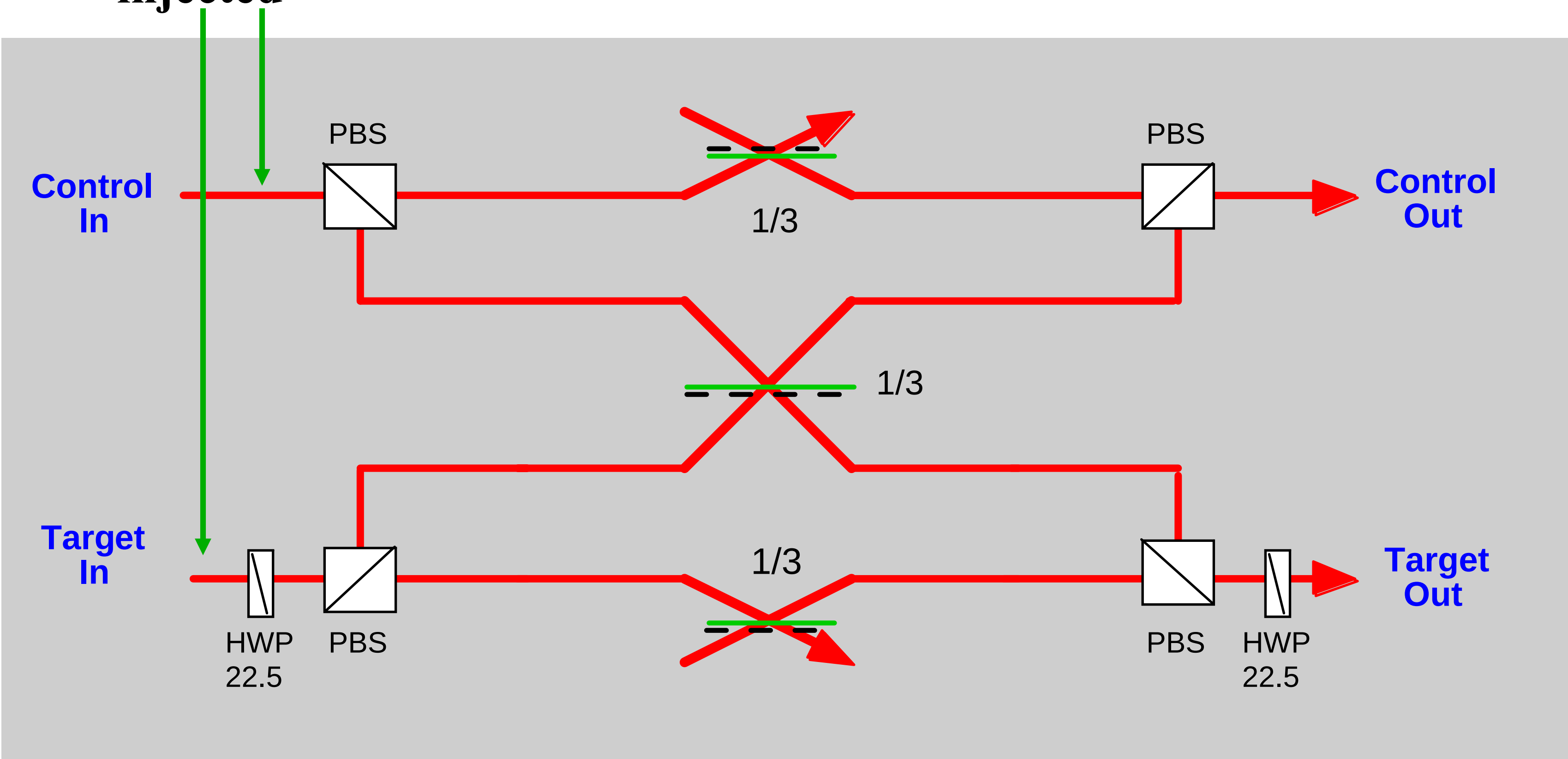
Optical CNOT Gate



T.C.Ralph, N.K.Langford, T.B.Bell and A.G.White, PRA **65**, 062324 (2002)

Optical CNOT Gate

single photons of arbitrary polarization simultaneously injected



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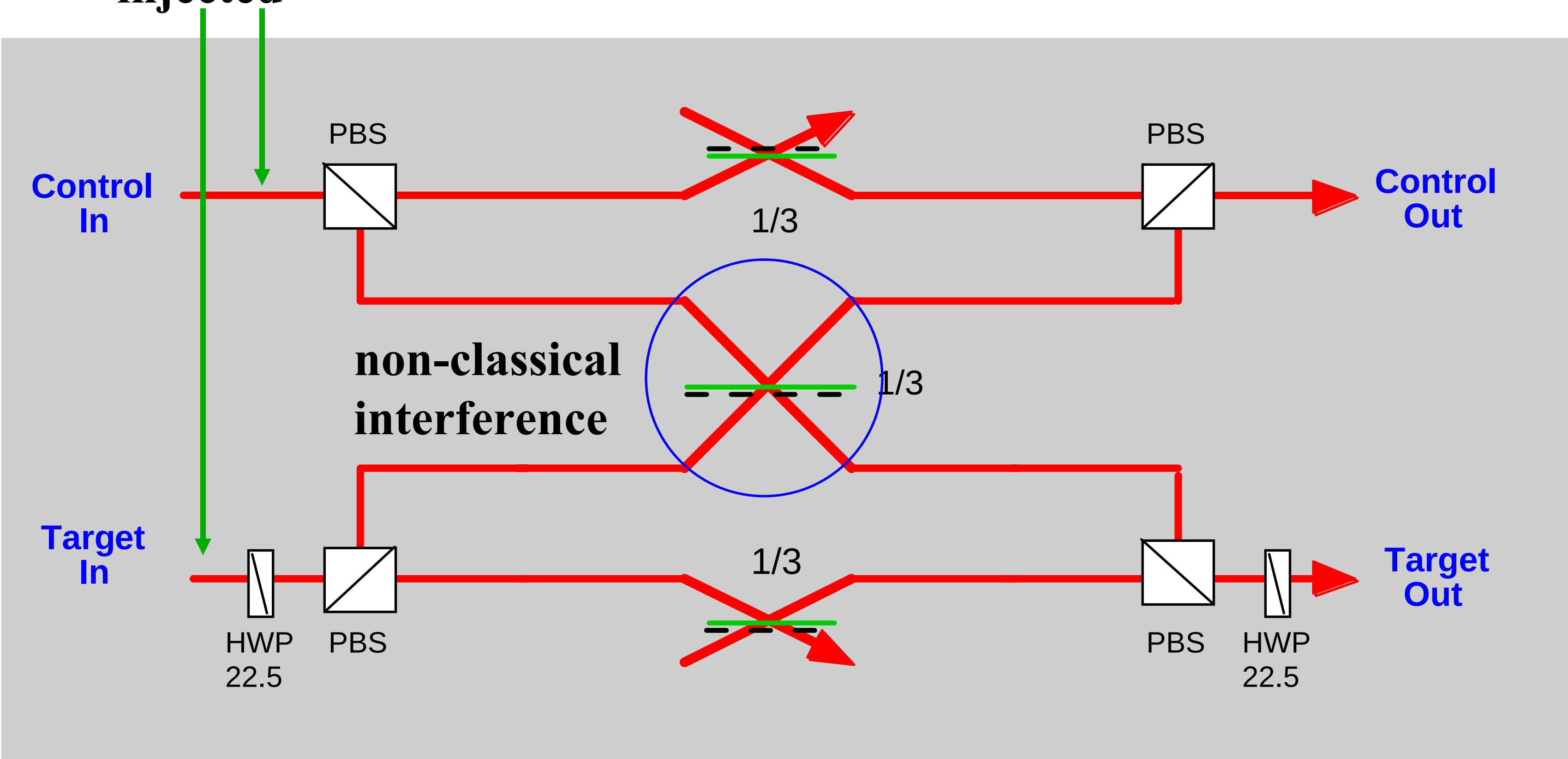
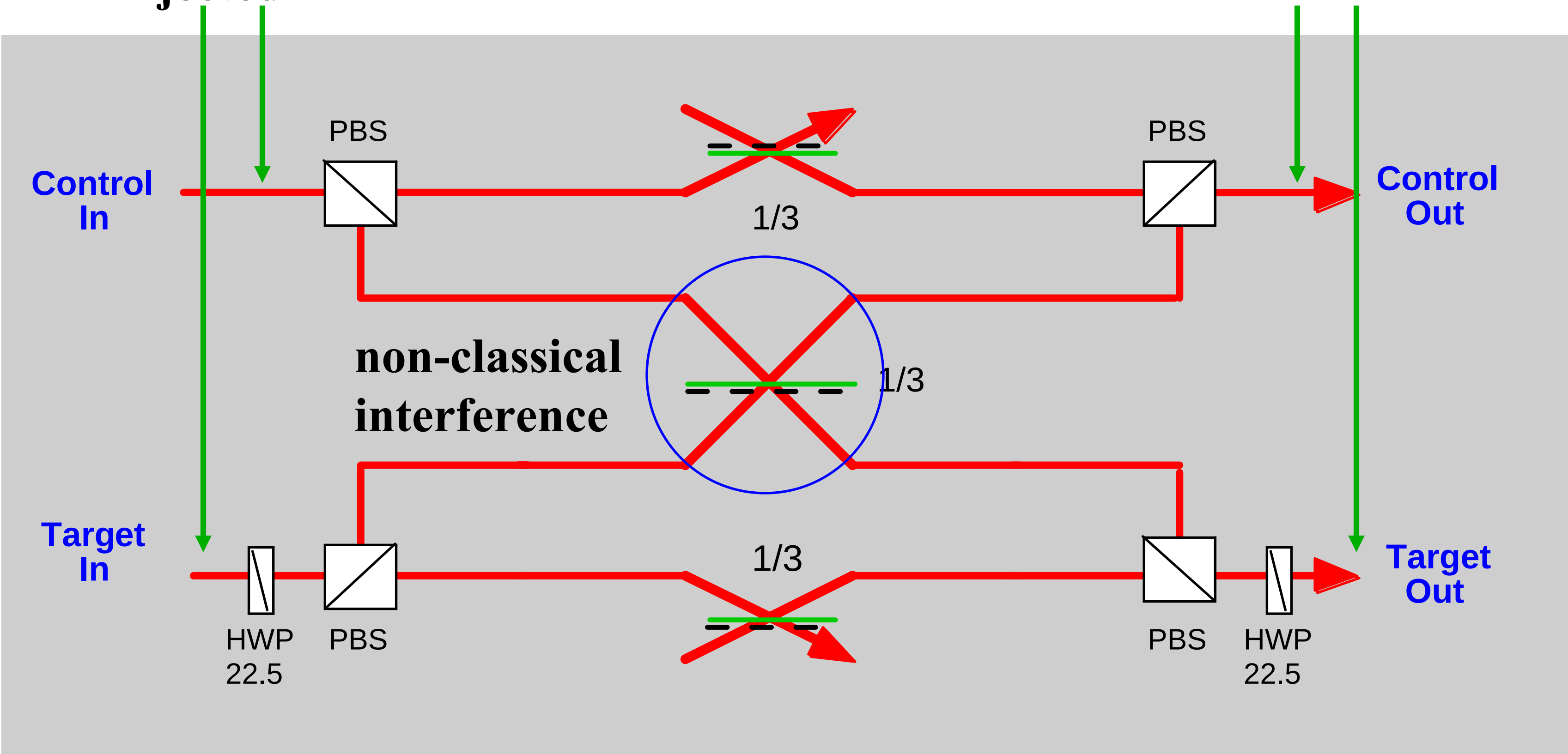


T.C.Ralph, N.K.Langford, T.B.Bell and A.G.White, PRA **65**, 062324 (2002)

Optical CNOT Gate

single photons of arbitrary polarization simultaneously injected

successful events post-selected as simultaneous clicks on photon counters



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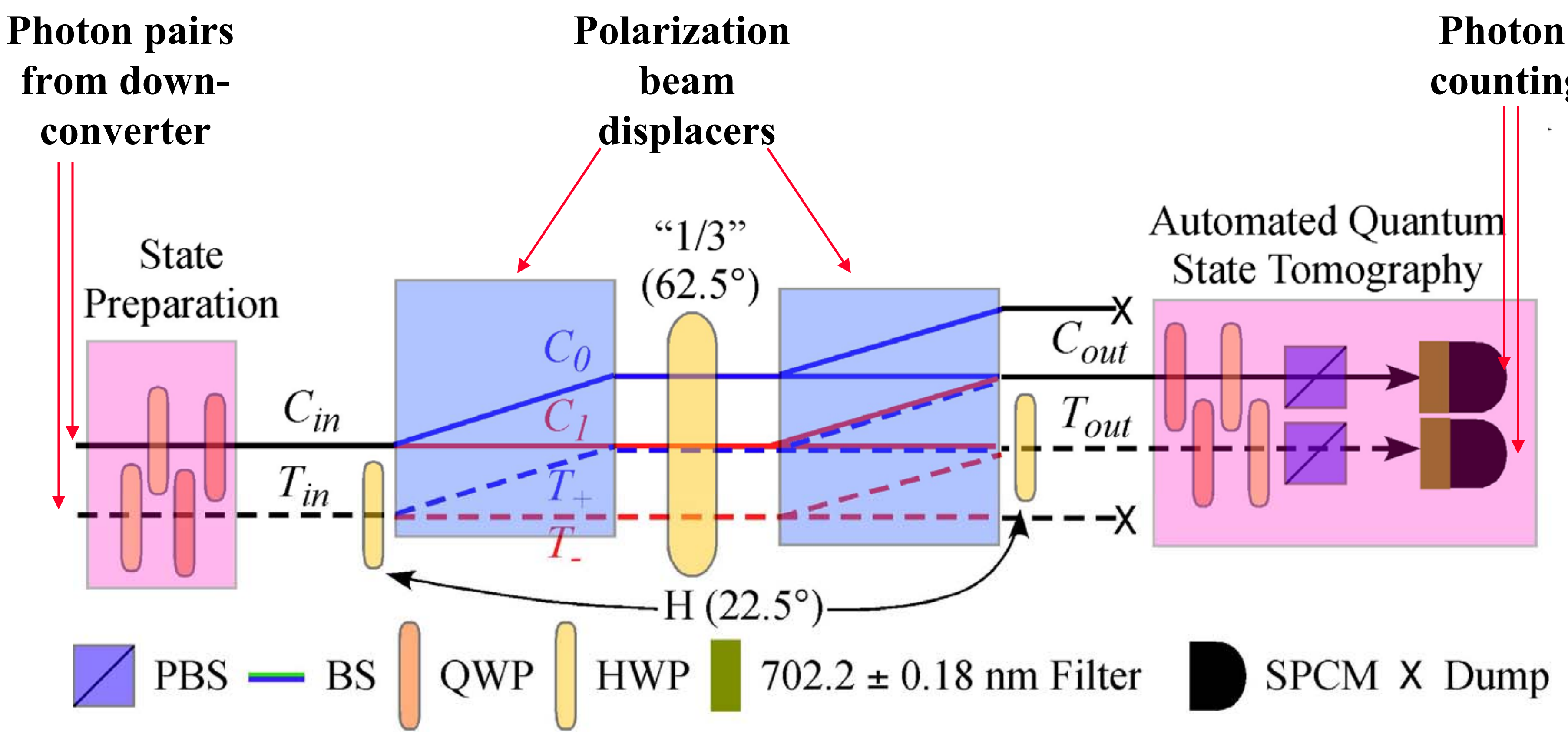
Optical CNOT Gate



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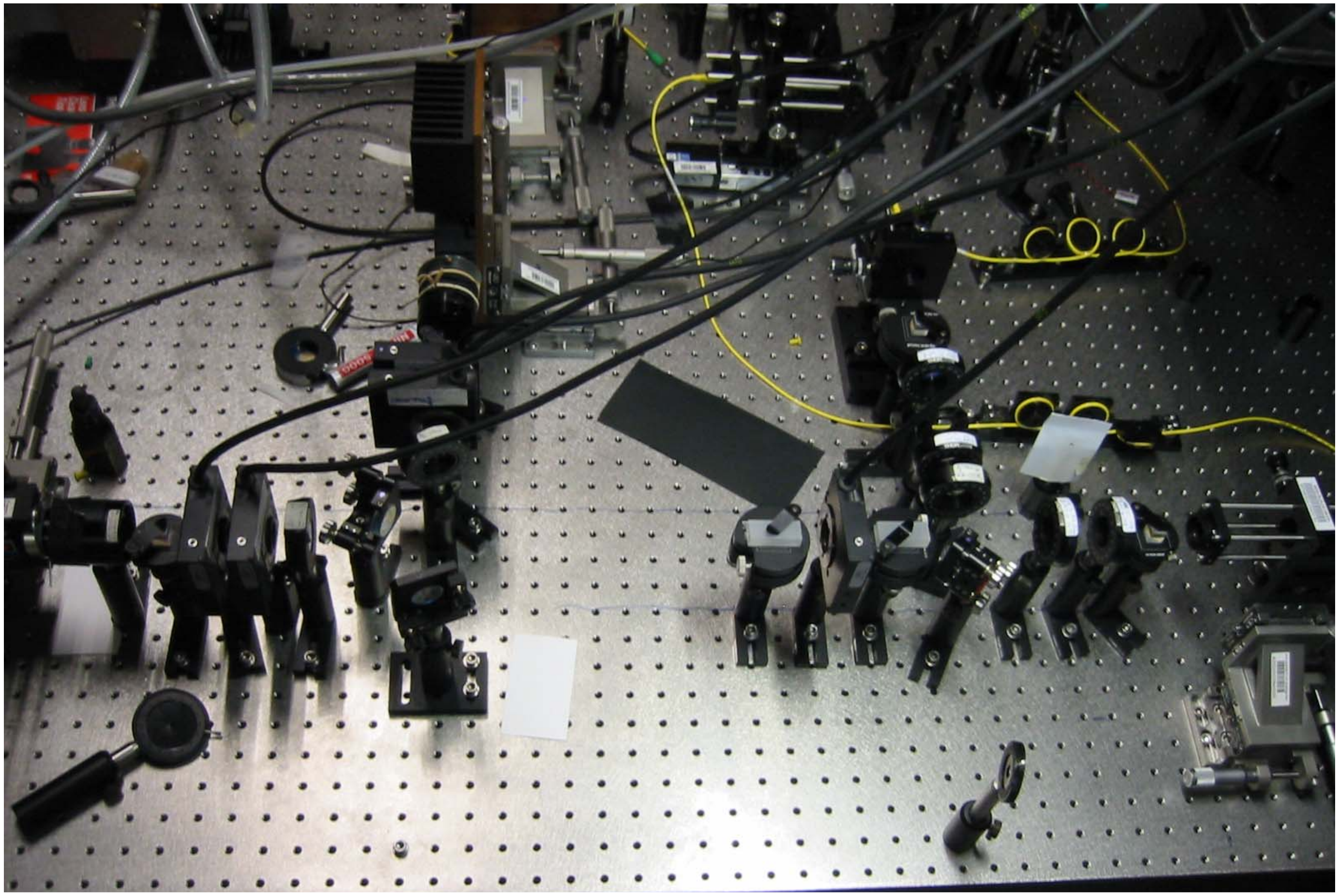
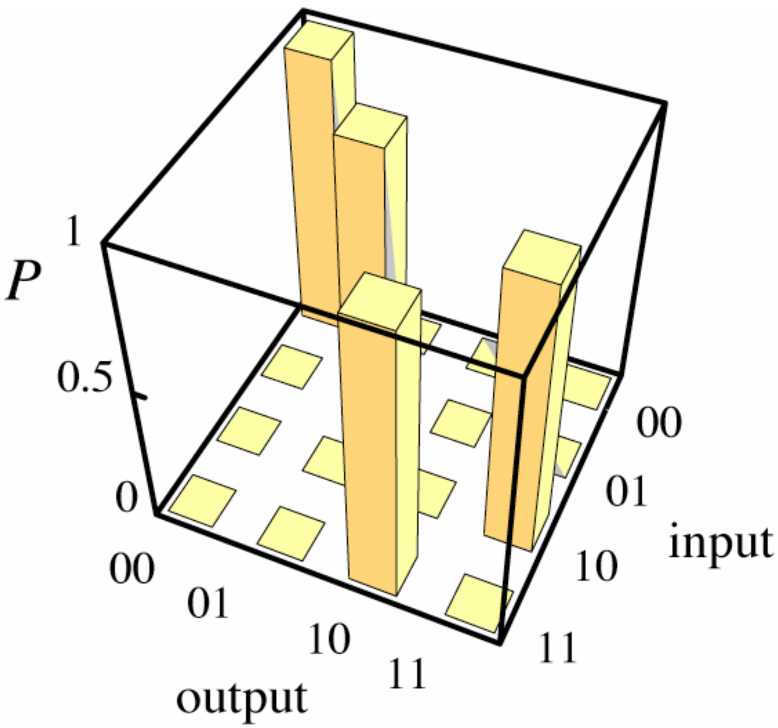
Optical CNOT Gate



J.L.O’Brien, G.J.Pryde, A.G.White, T.C.Ralph, D.Branning,
Nature **426**, 264 (2003).

“Classical” CNOT Operation

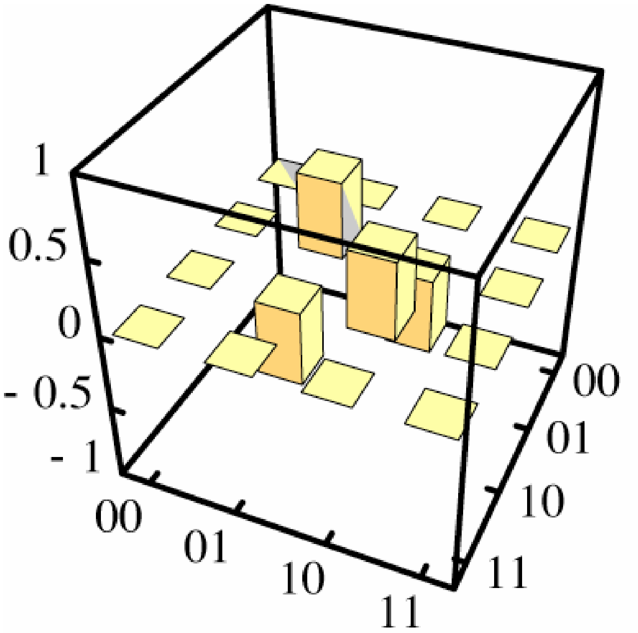


Ideal operation

Truth Table

0,0	0,0
0,1	0,1
1,0	1,1
1,1	1,0

Quantum CNOT Operation



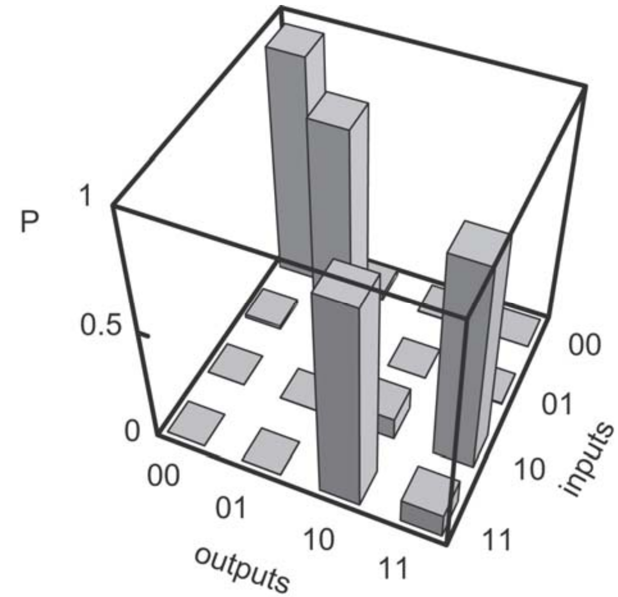
Ideal

Entanglement Production

$$(|0\rangle - |1\rangle)_C |1\rangle_T$$

$$\rightarrow |0\rangle_C |1\rangle_T - |1\rangle_C |0\rangle_T$$

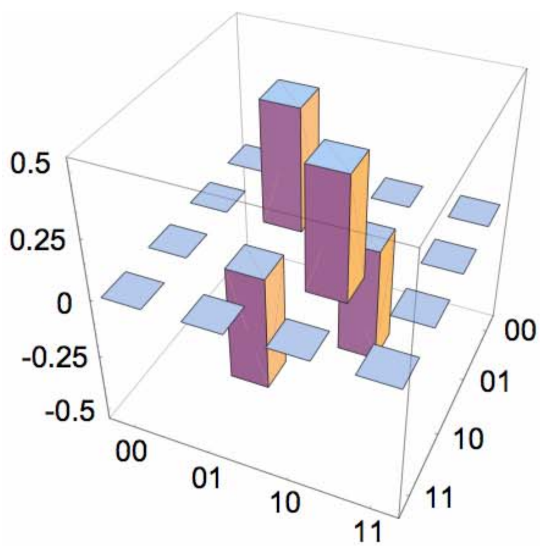
CNOT Truth Table
(average Fidelity = 92%)



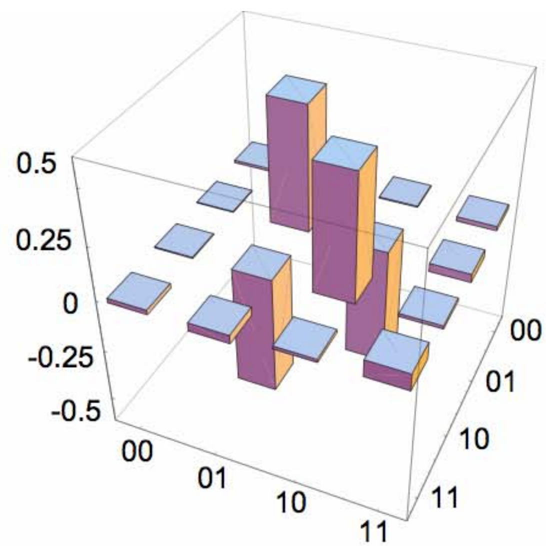
Singlet state from CNOT

|H>|V>-|V>|H>

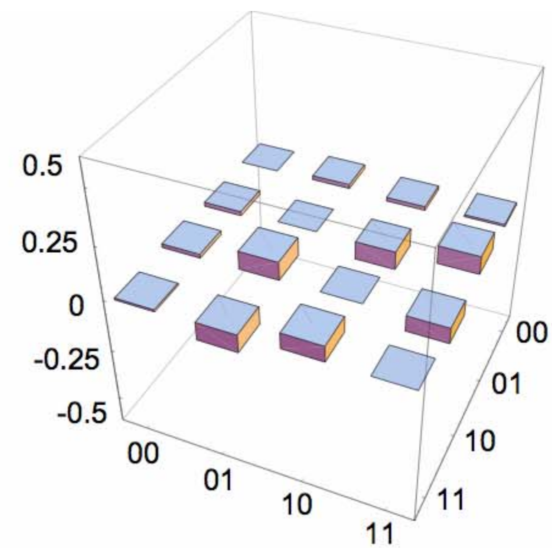
(Fidelity = 94%)



Ideal



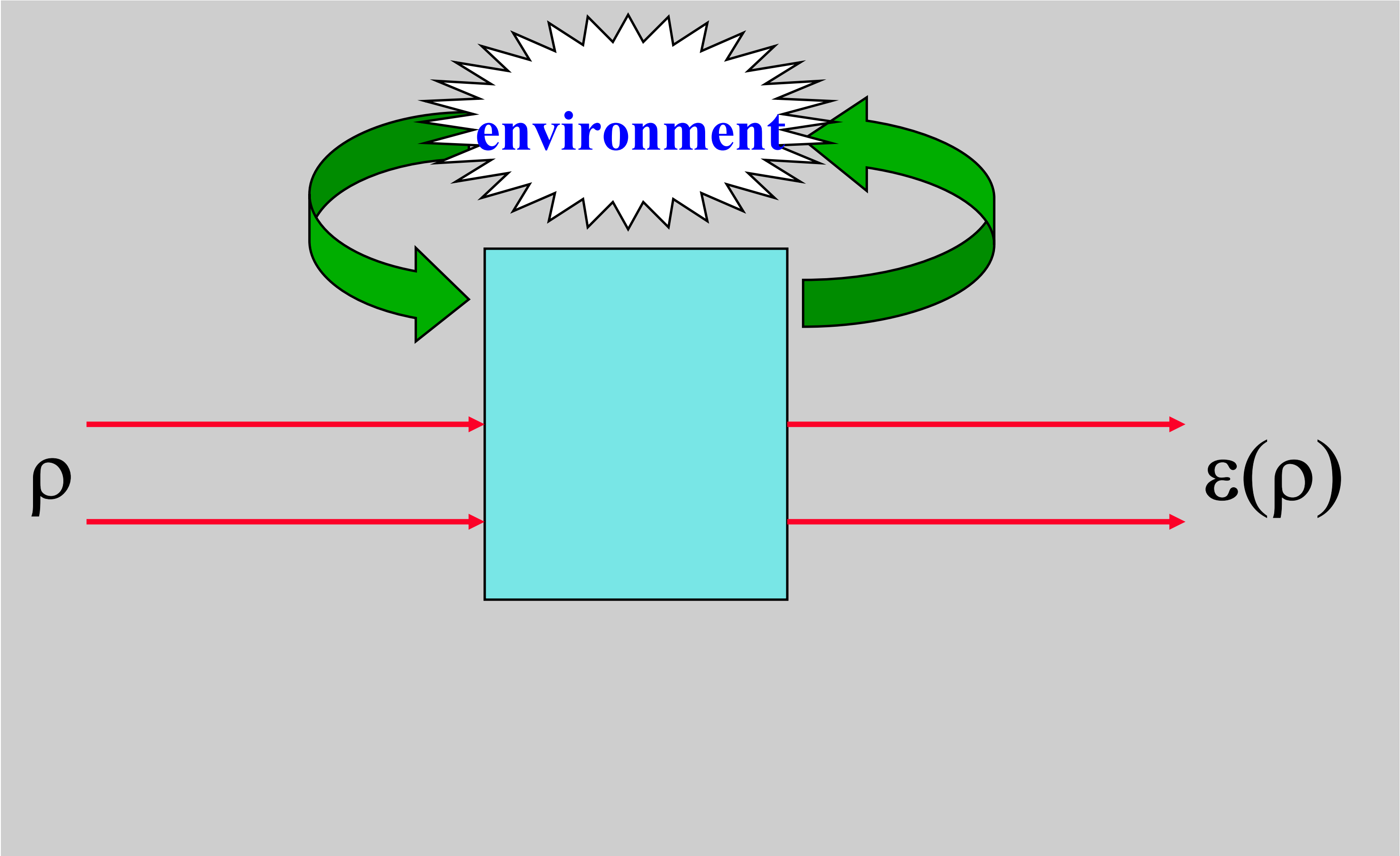
experimental: real



imaginary

Process Tomography

Process Tomography



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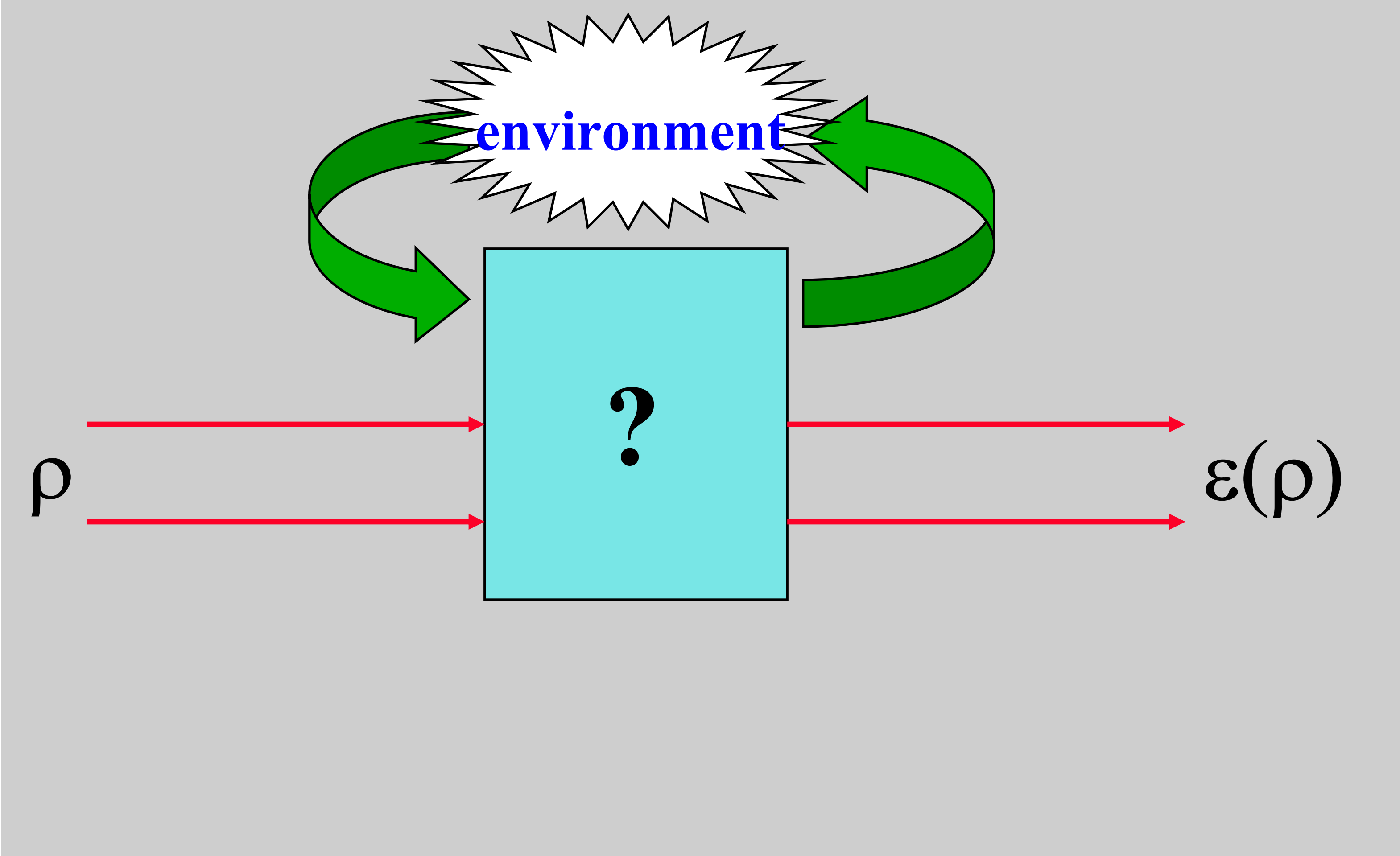

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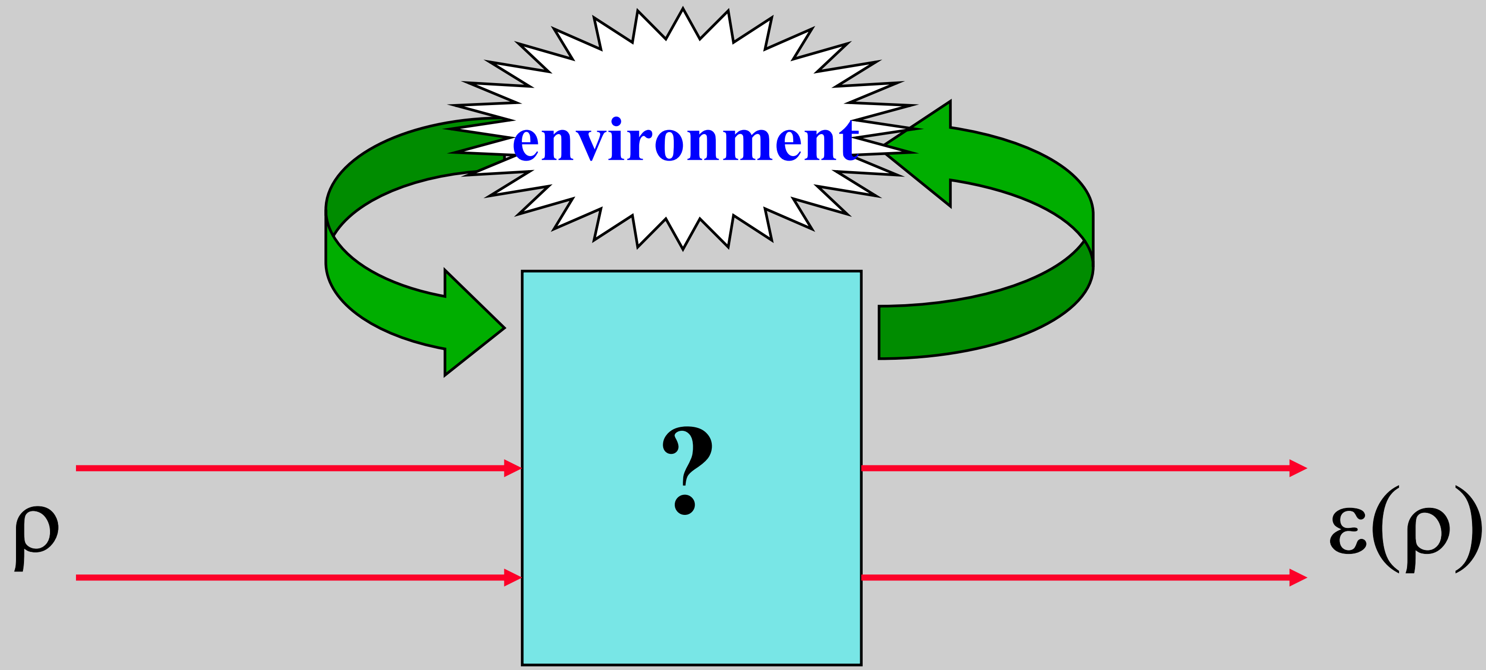
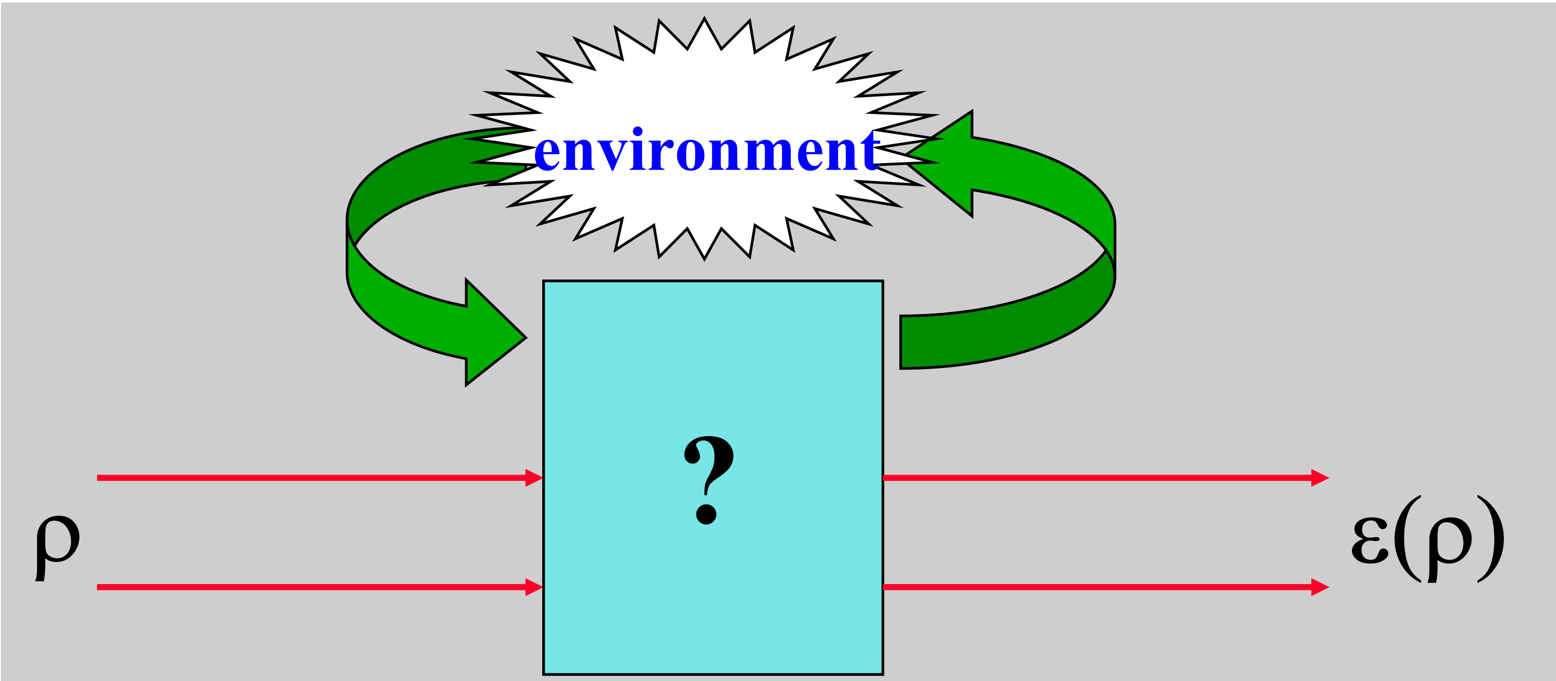


$$\varepsilon(\rho) = \sum \chi_{\square\square} A_{\square}\, \rho\, A_{\square}^{\dagger}$$

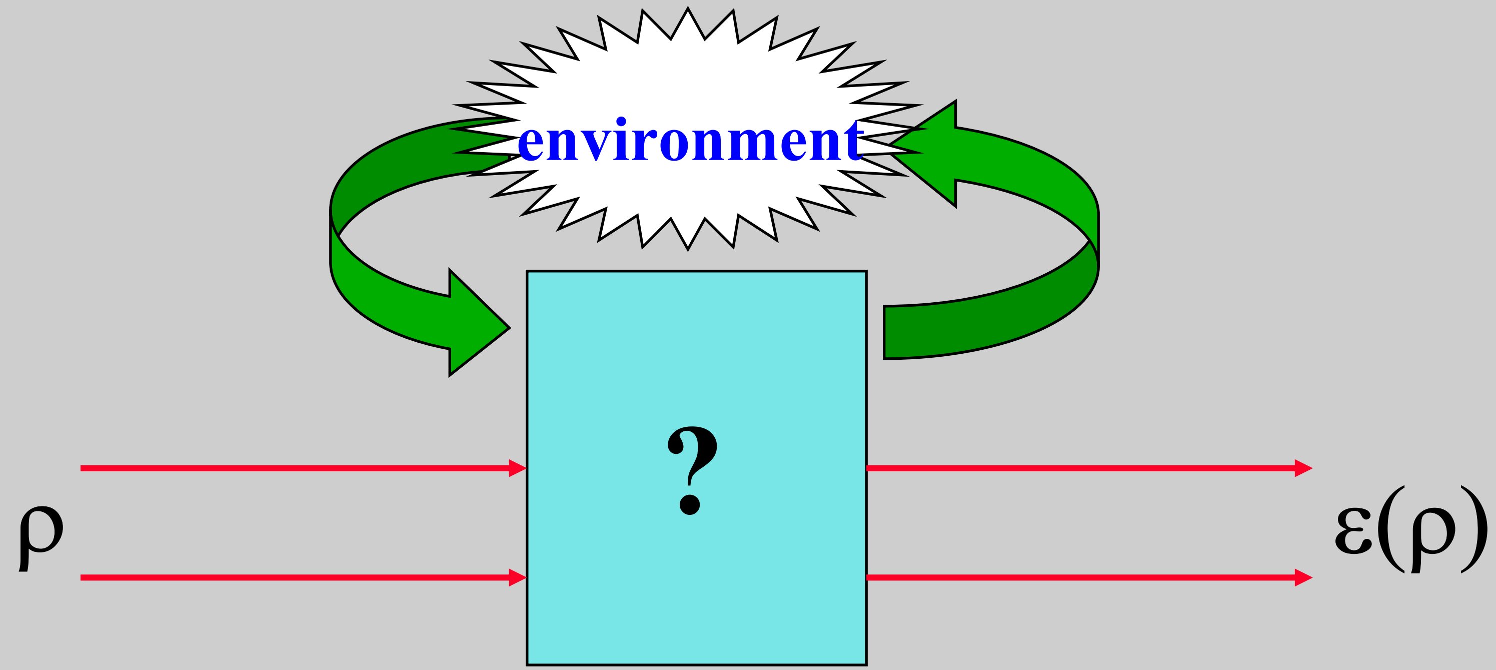
Process Tomography



$$\varepsilon(\rho) = \sum \chi_{\square\square} A_{\square}\, \rho\, A_{\square}^{\dagger}$$

Process matrix

Process Tomography



$$\varepsilon(\rho) = \sum \chi_{\square\square} A_{\square}\, \rho\, A_{\square}^{\dagger}$$

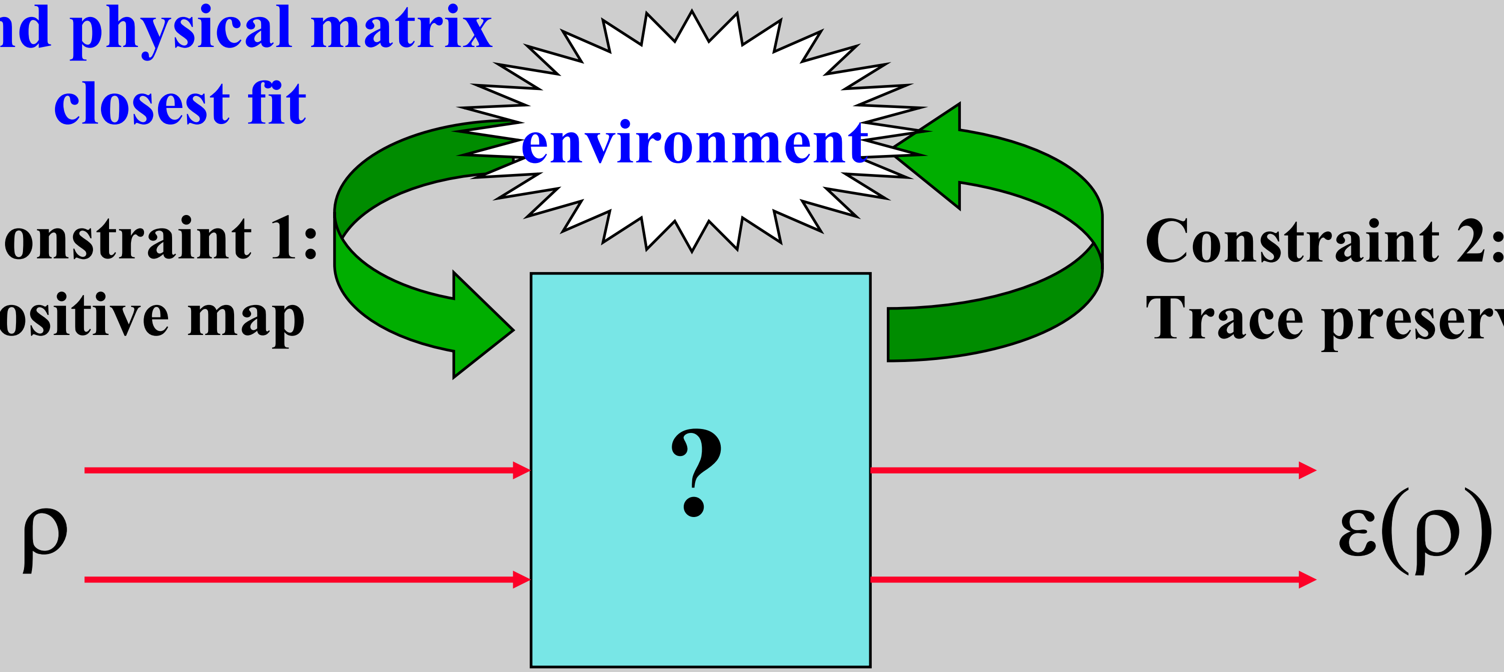
Quantum Computation and Quantum Information, Nielsen and Chuang

Process matrix - determined by 256 measurement combinations

Process Tomography

Find physical matrix closest fit

Constraint 1: Positive map



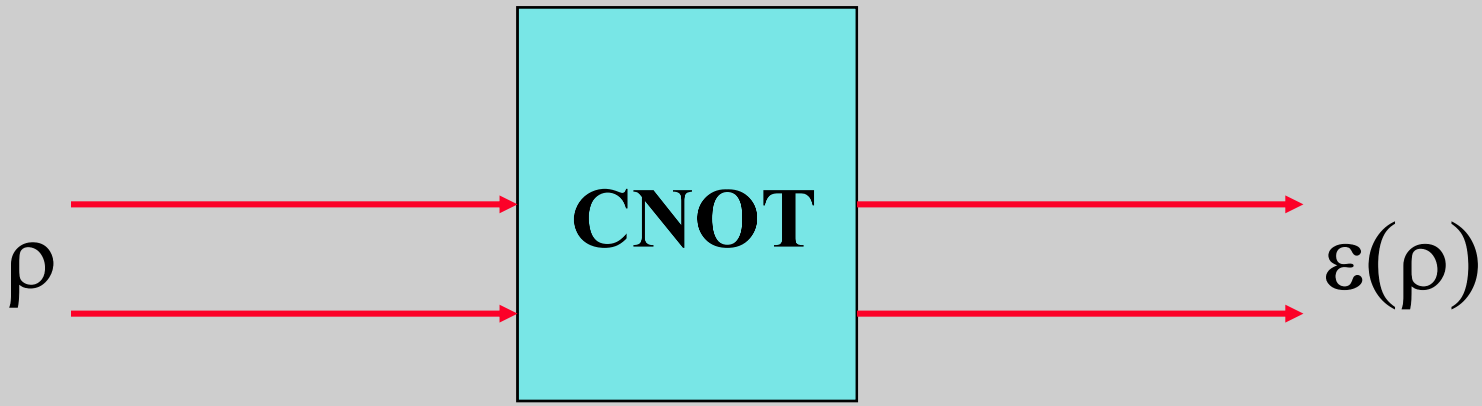
Constraint 2: Trace preserving

$$\varepsilon(\rho) = \sum \chi_{\square\square} A_{\square}\, \rho\, A_{\square}^{\dagger}$$

O'Brien et al, to appear Phys.Rev.Lett. (04) quant-ph/0402166

Process matrix - determined by 256 measurement combinations

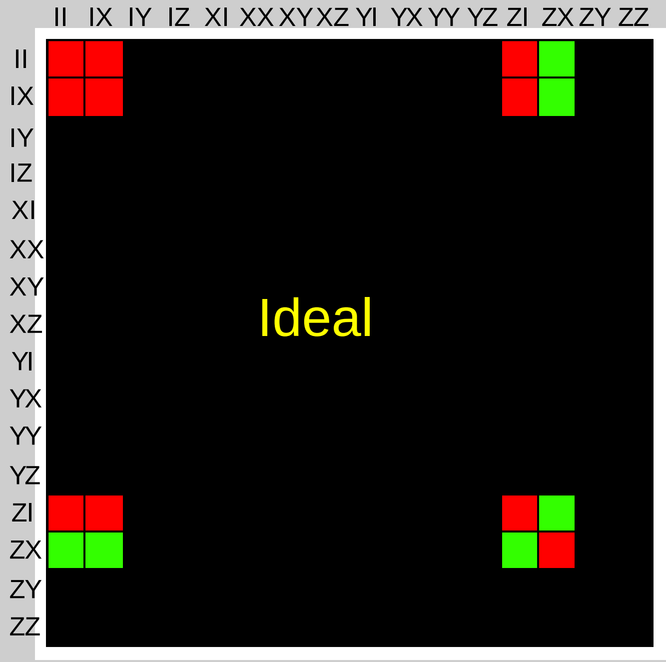
Process Tomography



$$\varepsilon(\rho) = U_{cnot}\, \rho\, \square_{cnot}^{\dagger}$$

$$U_{cnot} = 0.5(II + IX + ZI - ZX)$$

Process Tomography



$$\varepsilon(\rho) = U_{\mathbf{cnot}}\ \rho\ \square_{\mathbf{cnot}}^{\dagger}$$

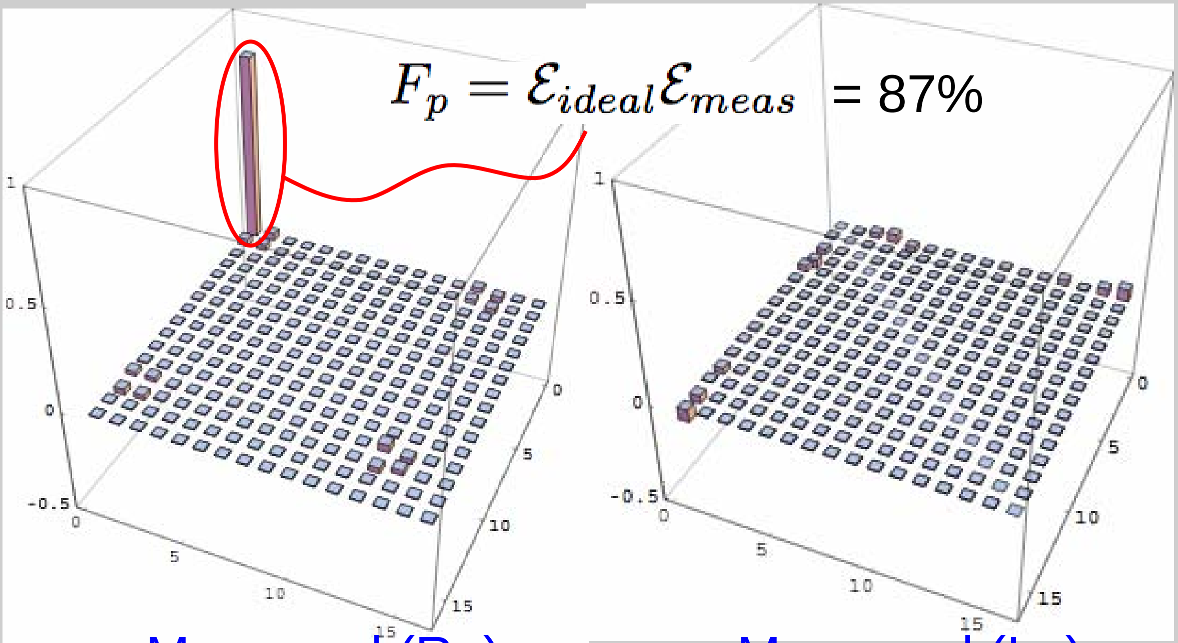
$$U_{\mathbf{cnot}} = \mathbf{0.5(II + IX + ZI - ZX)}$$

Process Tomography

$$\varepsilon(\rho) = U_{cnot}\, \rho\, \square_{cnot}^{\dagger}$$

$$U_{cnot} = 0.5(II + IX + ZI - ZX)$$

Process Tomography



$$F_p = \mathcal{E}_{ideal}\mathcal{E}_{meas} = 87\%$$

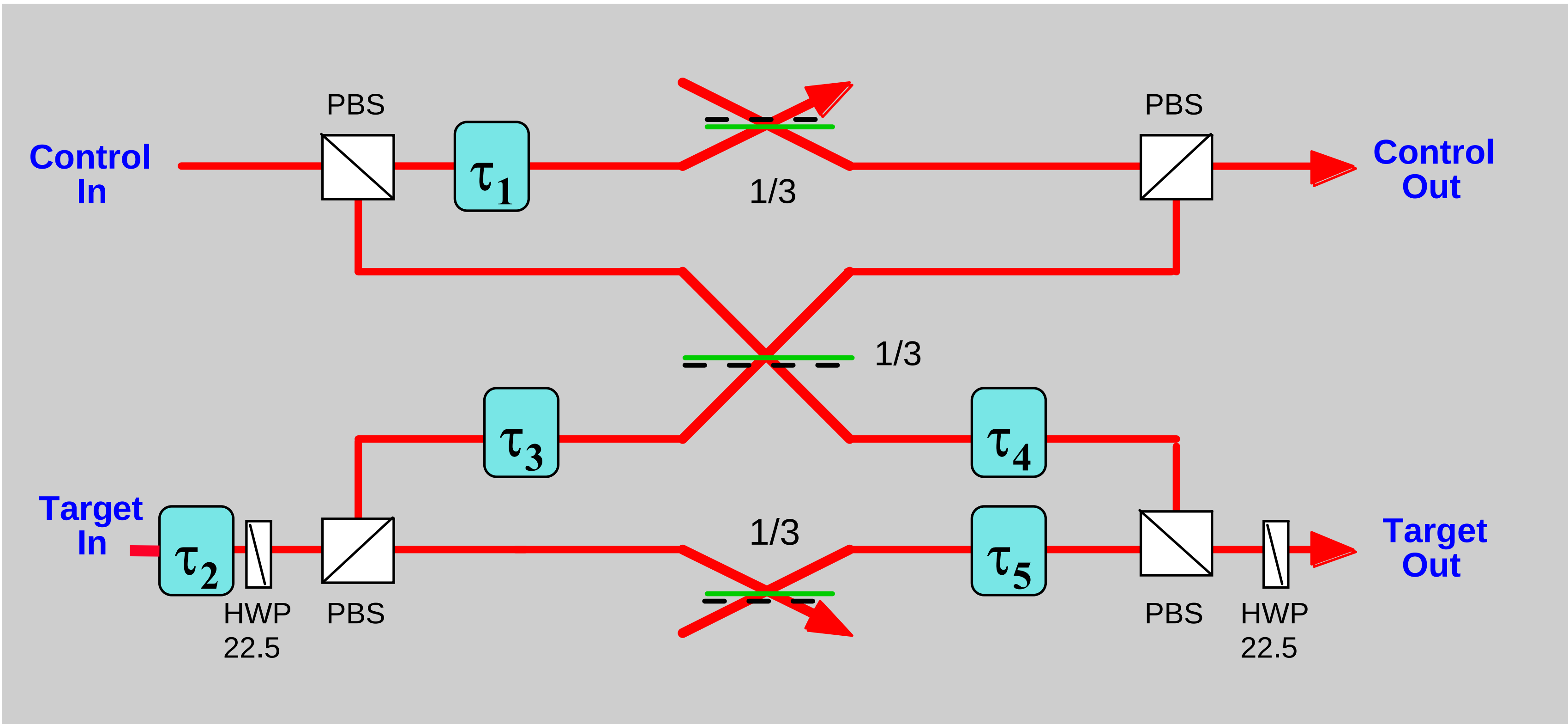
Measured (Re) Measured (Im)

average fidelity = (d F_p +1)/(d+1) = 90%

purity = 0.83 maximum increase in tangle = 0.73

O'Brien, Pryde, Gilchrist, James, Langford, Ralph, White, PRL, 93, 080502 (2004)

Process Tomography II



***Model gate including spatio-temporal structure *Perform tomography on the model - equivalent result for process with less data**

P.P.Rohde, J.L.O'Brien, G.J.Pryde,T.C.Ralph, quant-ph/0411144

Error Correction

Z-measurement Error Correction

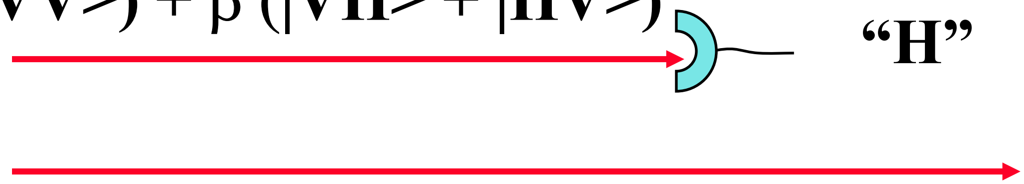
"0" **"1"**

α (**|HH> + |VV>**) + β (**|VH> + |HV>**)

Knill, LaFlamme and Milburn,
Nature 409, 46 (2001)

Z-measurement Error Correction

$\alpha\,(|HH\rangle + |VV\rangle) + \beta\,(|VH\rangle + |HV\rangle)$

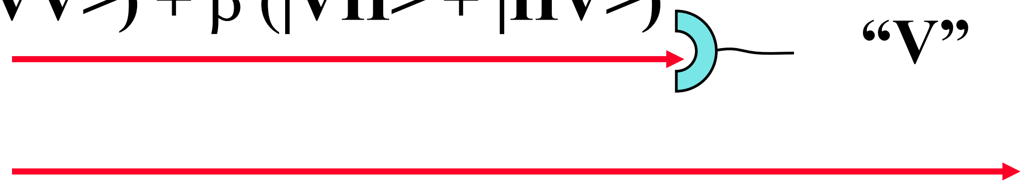


$\alpha\,|H\rangle + \beta\,|V\rangle$

Knill, LaFlamme and Milburn, Nature 409, 46 (2001)

Z-measurement Error Correction

$$\alpha\ (|HH> + |VV>) + \beta\ (|VH> + |HV>)$$



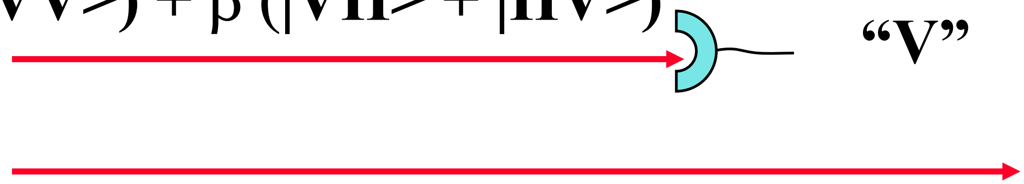
"V"

$$\alpha\ |V> + \beta\ |H>$$

Knill, LaFlamme and Milburn, Nature 409, 46 (2001)

Z-measurement Error Correction

$\alpha\,(|HH\rangle + |VV\rangle) + \beta\,(|VH\rangle + |HV\rangle)$



“V”

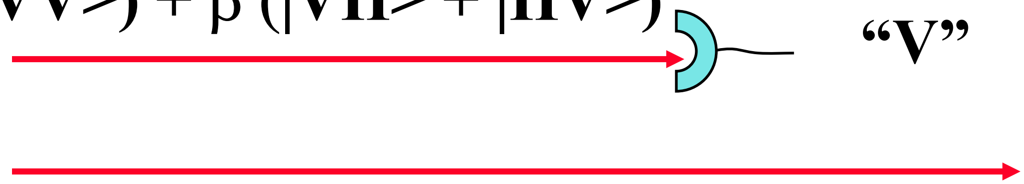
$\alpha\,|V\rangle + \beta\,|H\rangle$

Teleported gates fail by making a Z-measurement

Knill, LaFlamme and Milburn, Nature 409, 46 (2001)
Pittman, Jacobs and Franson, PRA, 64, 062311 (2001)

Z-measurement Error Correction

$\alpha\,(|HH\rangle + |VV\rangle) + \beta\,(|VH\rangle + |HV\rangle)$



“V”

$\alpha\,|V\rangle + \beta\,|H\rangle$

Teleported gates fail by making a Z-measurement	**Knill, LaFlamme and Milburn, Nature 409, 46 (2001)** **Pittman, Jacobs and Franson, PRA, 64, 062311 (2001)**
LOQC cluster states	**Nielsen, PRL, 93, 040503 (04)**

Z-measurement Error Correction

$\alpha\,(|HH\rangle + |VV\rangle) + \beta\,(|VH\rangle + |HV\rangle)$

" ? "

$\alpha\,|H\rangle + \beta\,|V\rangle$ or $\alpha\,|V\rangle + \beta\,|H\rangle$

Photon Loss error correction

Knill, LaFlamme and Milburn, Nature 409, 46 (2001)

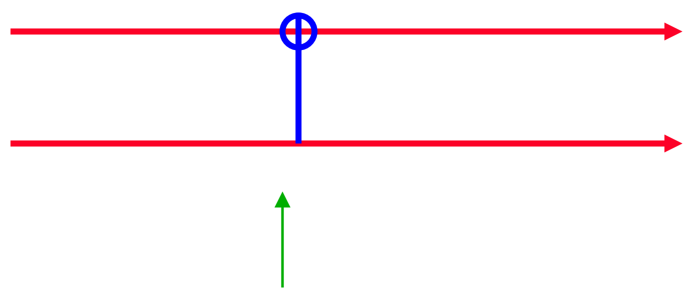
$$|\Phi\rangle_{LL} = \alpha\,|0\rangle_L|0\rangle_L|0\rangle_L + \beta\,|1\rangle_L|1\rangle_L|1\rangle_L$$

Experimental
Z-measurement Error Correction

(i) Encoding

$\alpha\,|H\rangle + \beta\,|V\rangle$

$|H\rangle + |V\rangle$



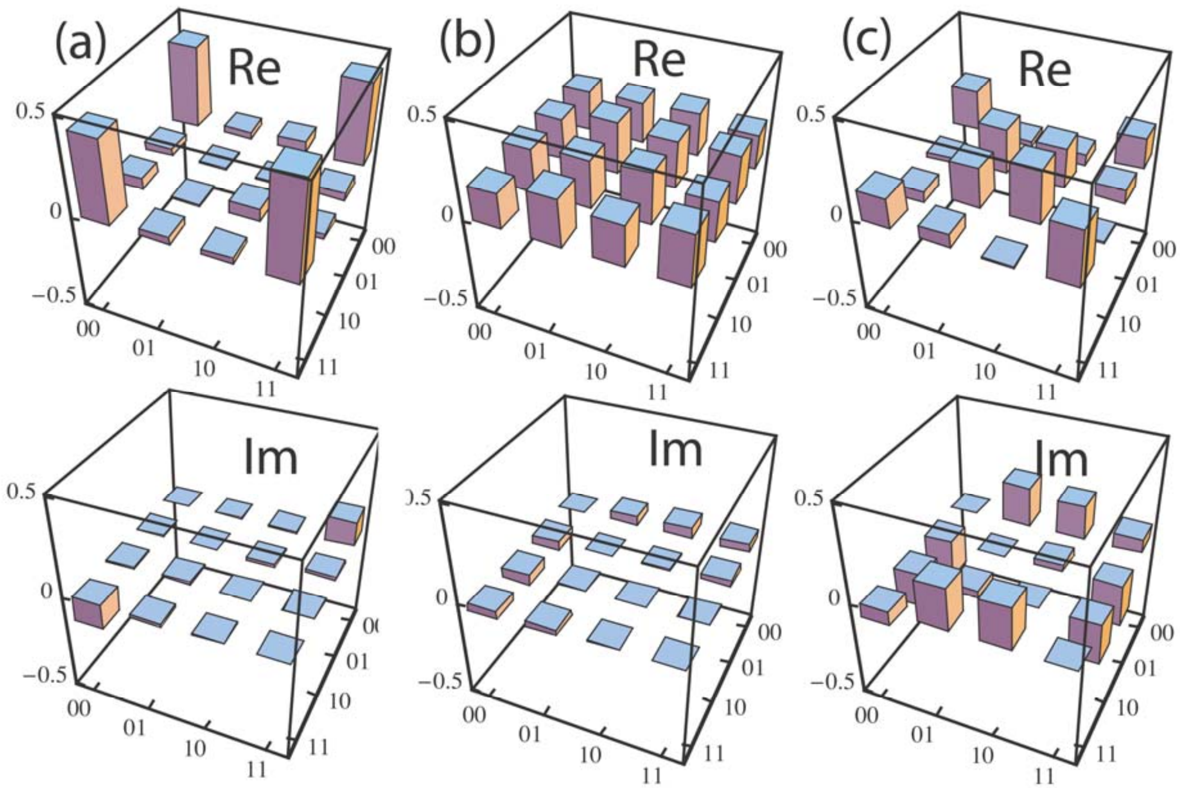
$\alpha\,(|HH\rangle + |VV\rangle) +$
$\beta\,(|VH\rangle + |HV\rangle)$

Non-deterministic CNOT

Experimental
Z-measurement Error Correction

(i) Encoding

Input: |0> |0> + |1> |0> + i |1>



Average Fidelity 88 ± 3%

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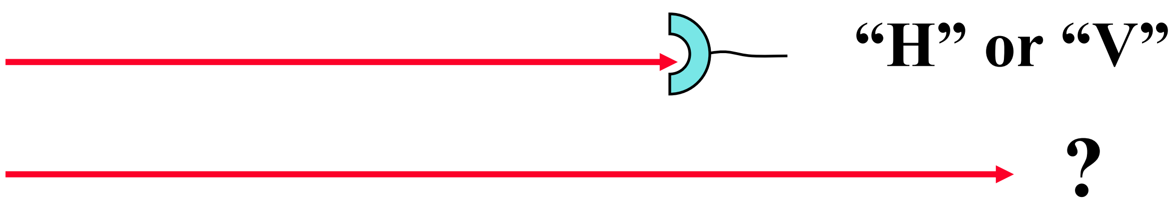
Experimental
Z-measurement Error Correction

(ii) Decoding



$|H\rangle \longrightarrow |V\rangle$

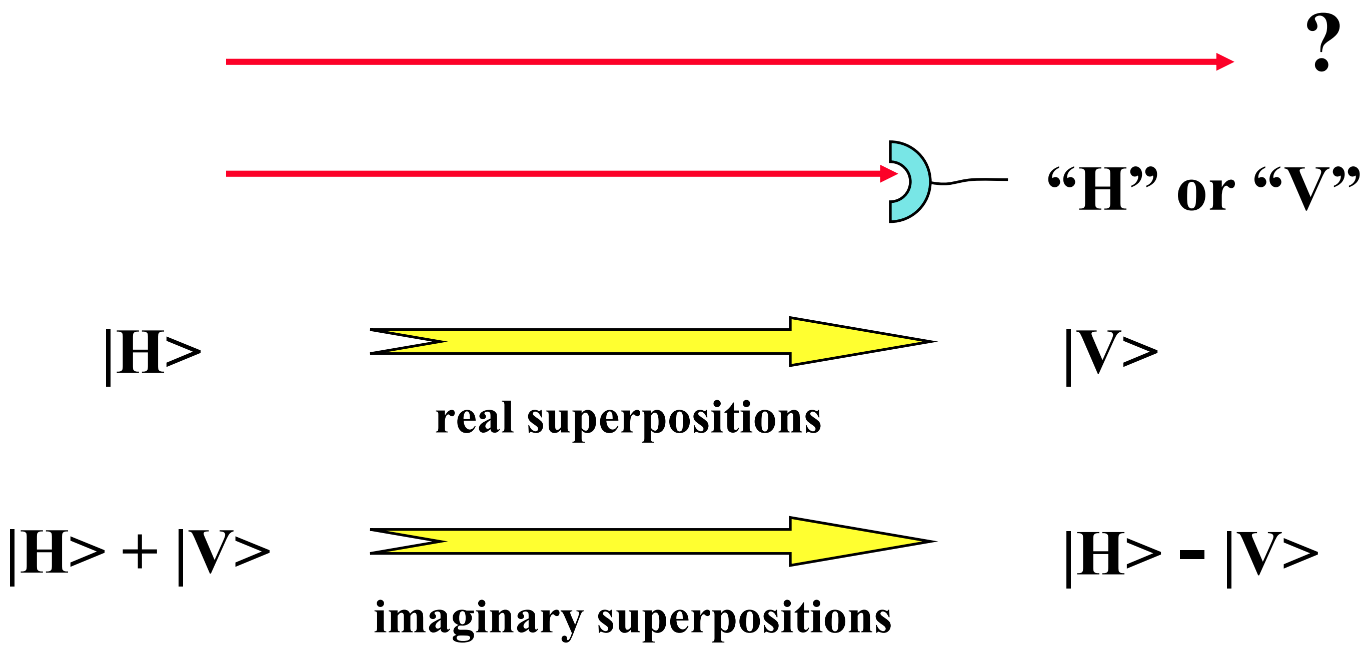
real superpositions

$|H\rangle + |V\rangle \longrightarrow |H\rangle - |V\rangle$

imaginary superpositions

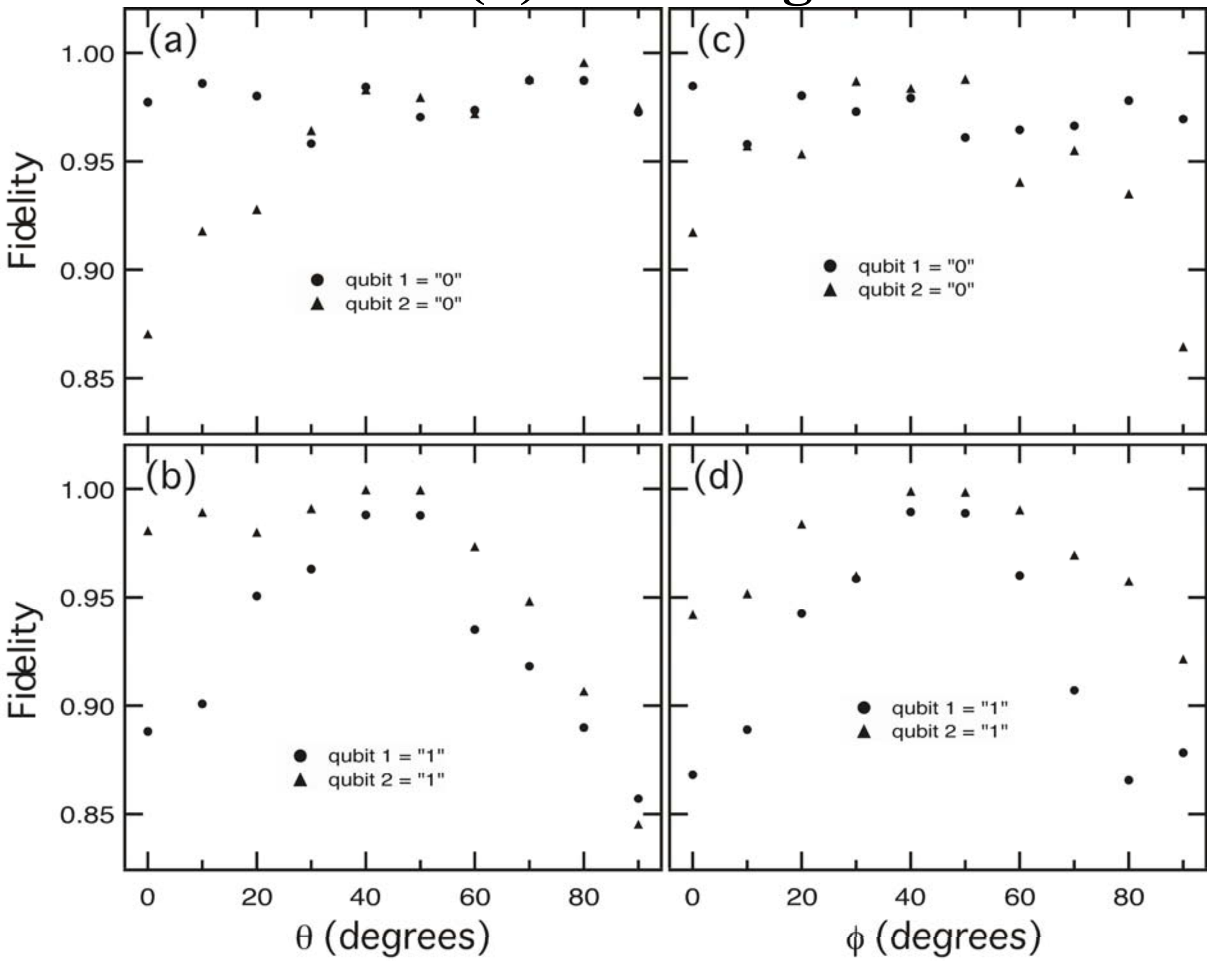
Experimental
Z-measurement Error Correction

(ii) Decoding



Experimental
Z-measurement Error Correction

(ii) Decoding

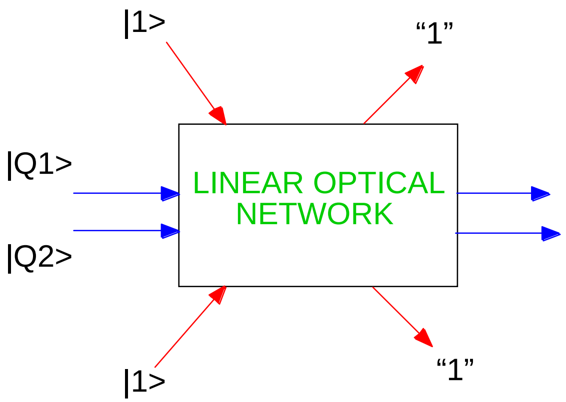


Syndrome measured but not corrected

Average Fidelity 96 ± 3 %

O'Brien, Pryde White and Ralph, quant-ph/0408064

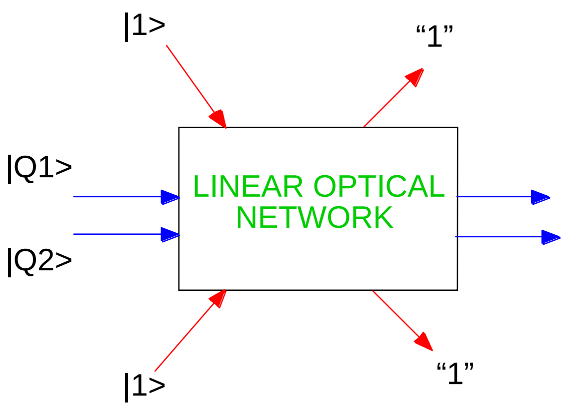
Linear Optics QC~3 main ideas of KLM



***Non-deterministic gates.**
***Don't always work, but heralded when they do.**

Knill, LaFlamme and Milburn, Nature 409, 46 (2001)

Linear Optics QC~3 main ideas of KLM



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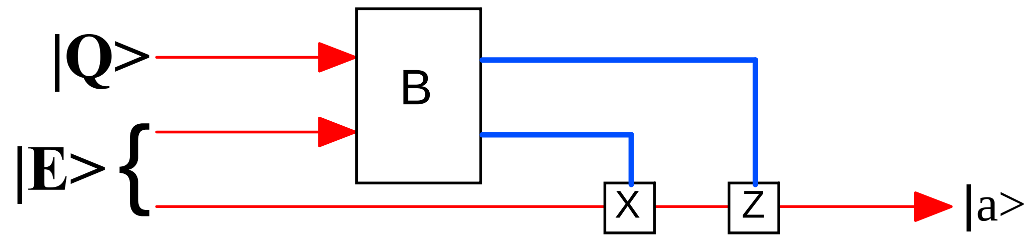
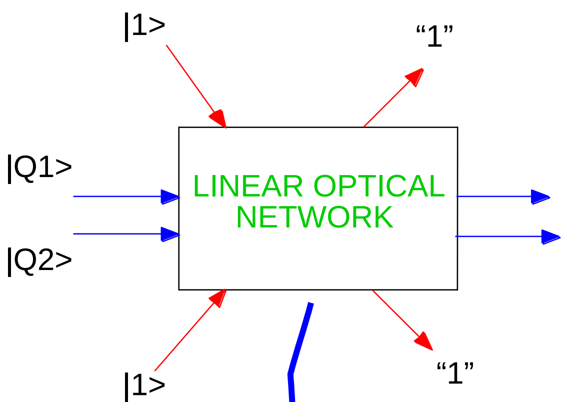
*Non-deterministic teleported gates. When they don't work they measure the qubit.



Knill, LaFlamme and Milburn, Nature 409, 46 (2001)

Linear Optics QC~3 main ideas of KLM



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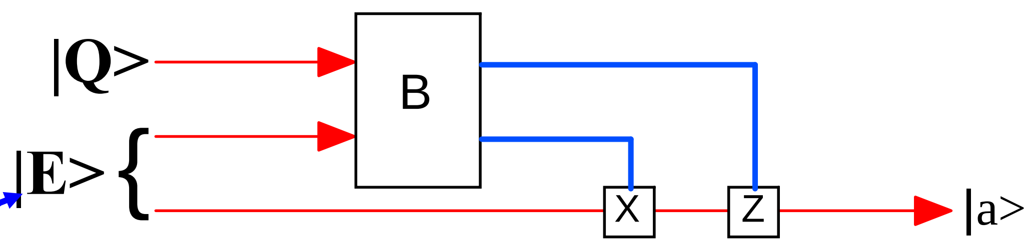

Knill, LaFlamme and Milburn,
Nature 409, 46 (2001)

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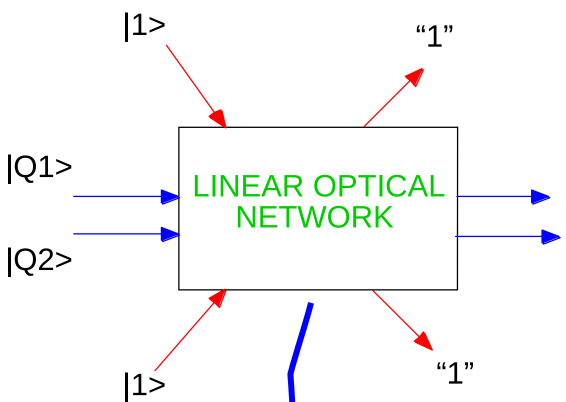
Linear Optics QC~3 main ideas of KLM



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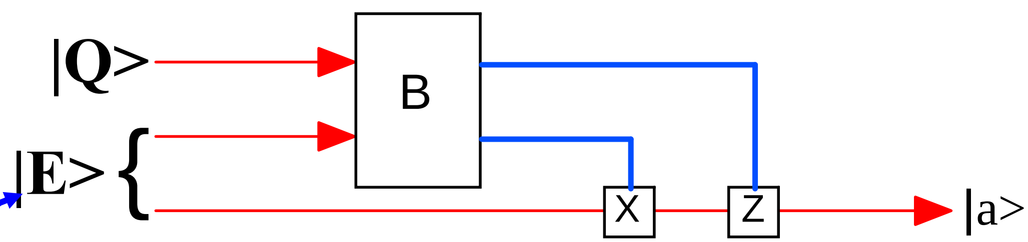
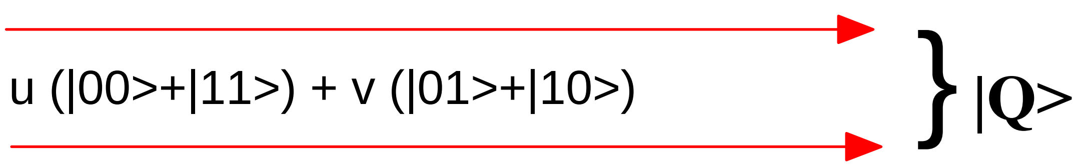
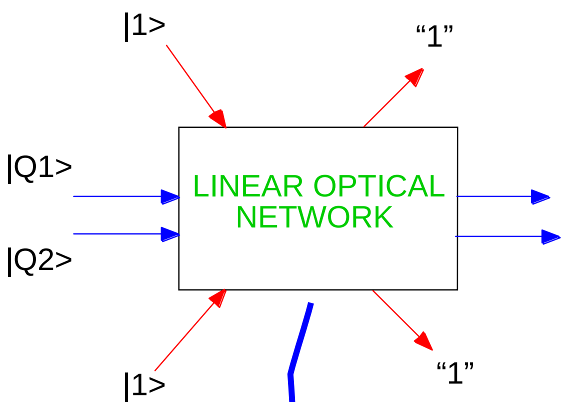




***Error encoding against qubit measurment**

Knill, LaFlamme and Milburn, Nature 409, 46 (2001)

Linear Optics QC~3 main ideas of KLM



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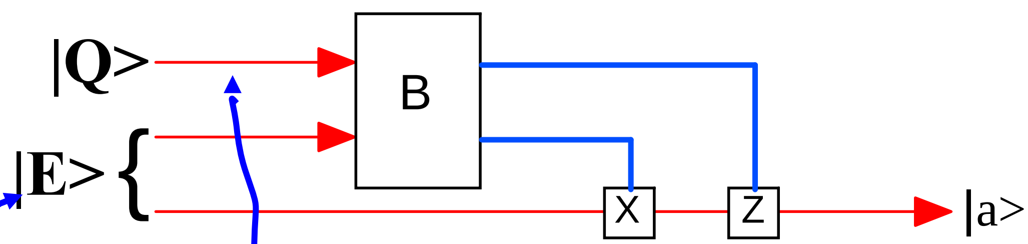

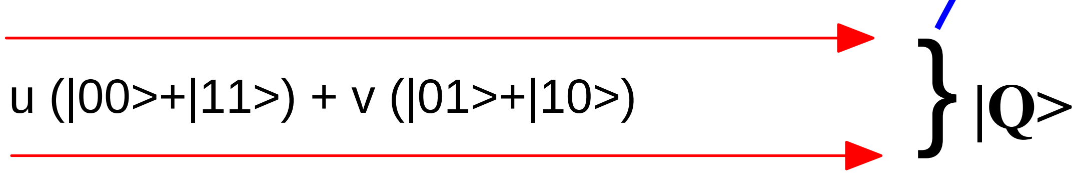

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Knill, LaFlamme and Milburn, Nature 409, 46 (2001)

thanks