Experimental Quantum Photonics

SFB Summer School

Blaubeuren

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Structure

Background/basics

- What is light?
- Why photons for quantum information
- The goal of an arbitrary quantum processor
- Encoding bits with single photons and single bit manipulation.
- Two qubit logic
- Linear logic schemes

Structure

Experimental implementations

- Single photon detection
- Single photon sources (see 15:00 lecture)
- Pair photon sources
- Entangled state sources
- Gate realisations and experiments
- N00N states, metrology

Quantum optics in wavelength scale structures

Motivation

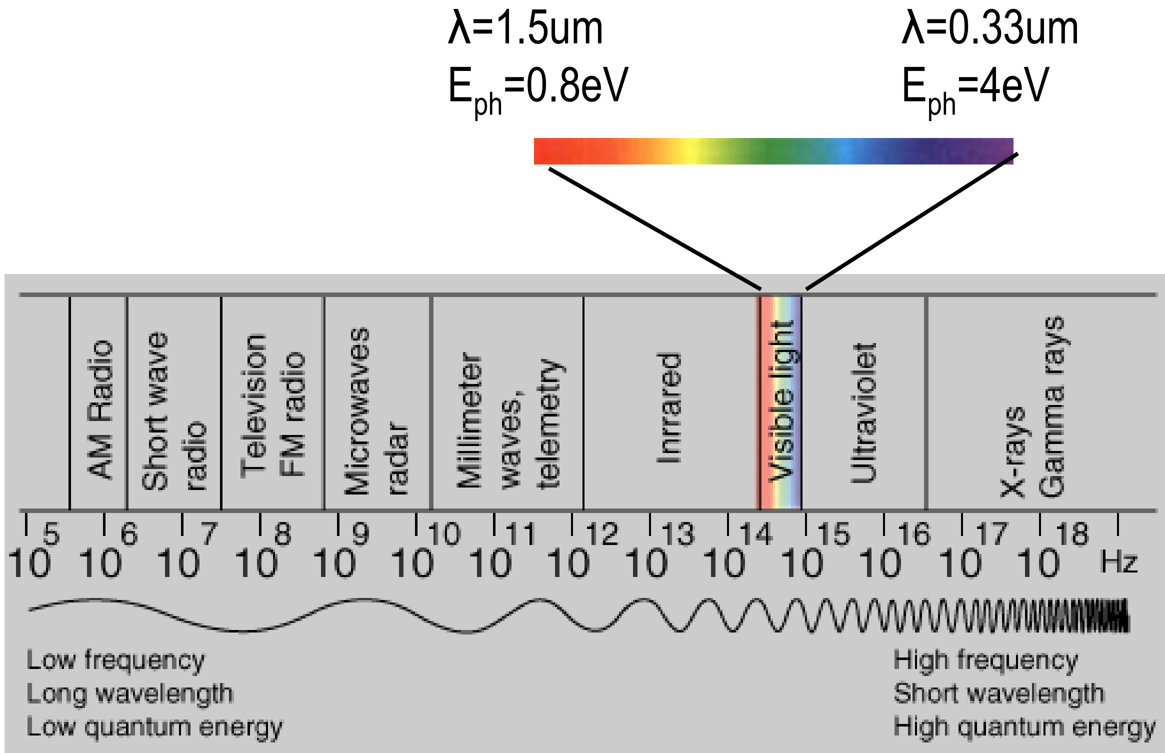
- More efficient gates, Hybrid QIP.

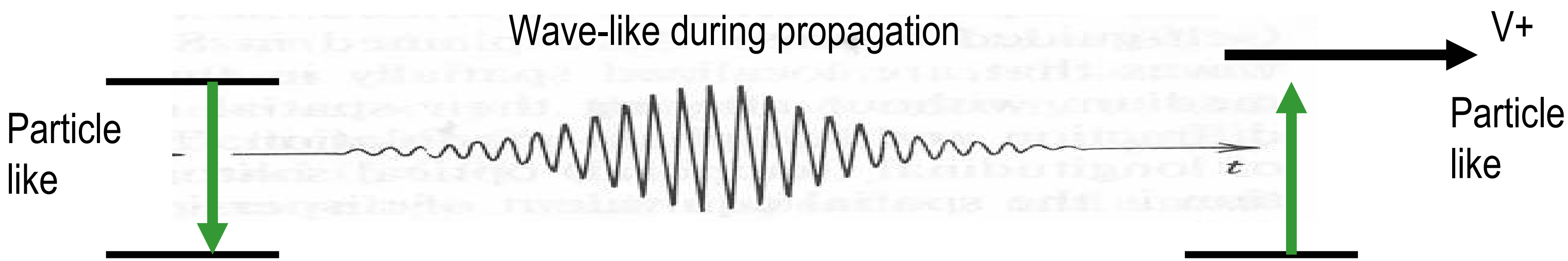
Content

- 2-level system in a cavity
- Charged quantum dots in cavity
- Single photon sources
- Spin-photon interface
- Quantum repeater
- Progress towards experiment

The electro-magnetic spectrum

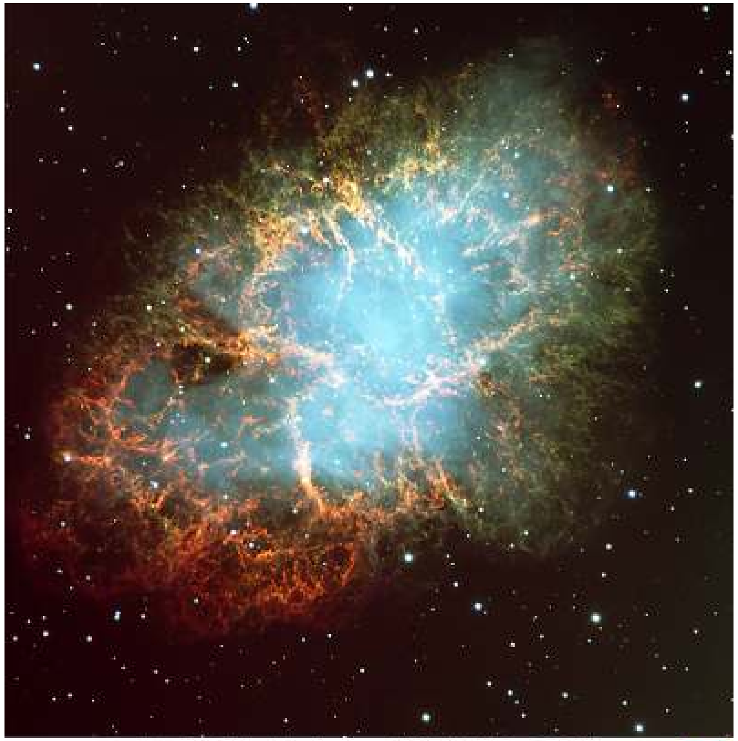
Optical Photon energy
$E_{ph}=hf>>KT$





Decoherence of photons: associated with loss

- Optical Photon energy>>KT
  - Efficient detection
  - Single photons
- Wavelength μm
  - Interference
- Storage time limited by loss
  - Storage time in fibre 5μs/km, loss 0.17 dB/km (96%)
  - Polarised light from stars==Storage for 6500 years!
- **Low non-linearity**
- **Probabilistics gates**

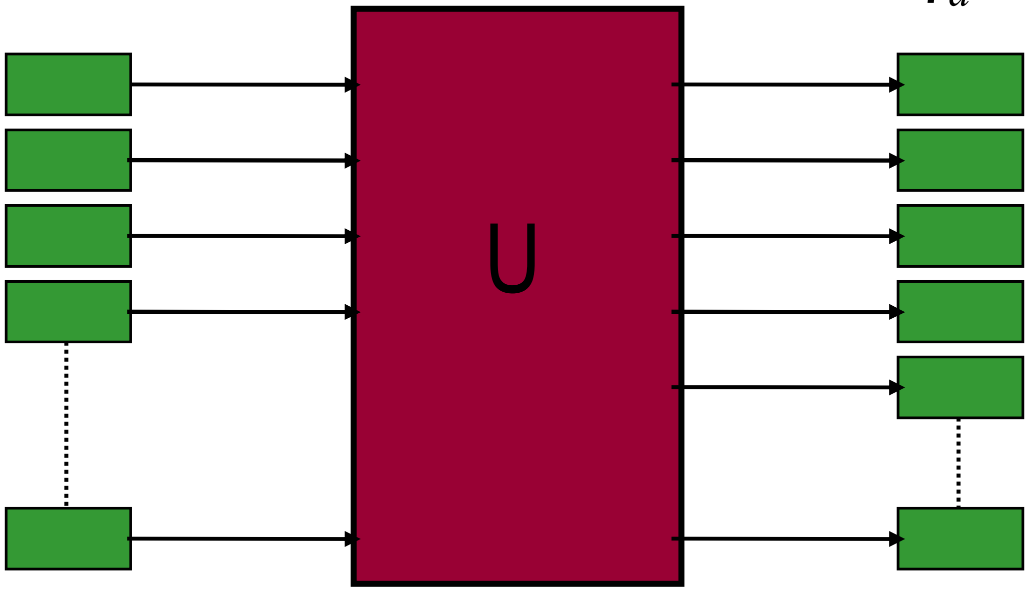


The Crab Nebula in Taurus (VLT KUEYEN + FORS2)

ESO PR Photo 40f/99 (17 November 1999) © European Southern Observatory

The PROBLEM: many qubits quantum processor

η_s^N η_g^N, F^N η_d^N



Single Qubit source

Single 2-level ~ 2-10%
Heralded from pair ~ 80%

Unitary transform

Linear gates $\eta<0.5$ $F>0.99$
Non-linear optics $\eta\sim1$ $F>0.9$?

Detectors

Si 600-800nm ~70% (100%?)
InGaAs 1.3-1.6um ~30%
Superconducting~10-88%

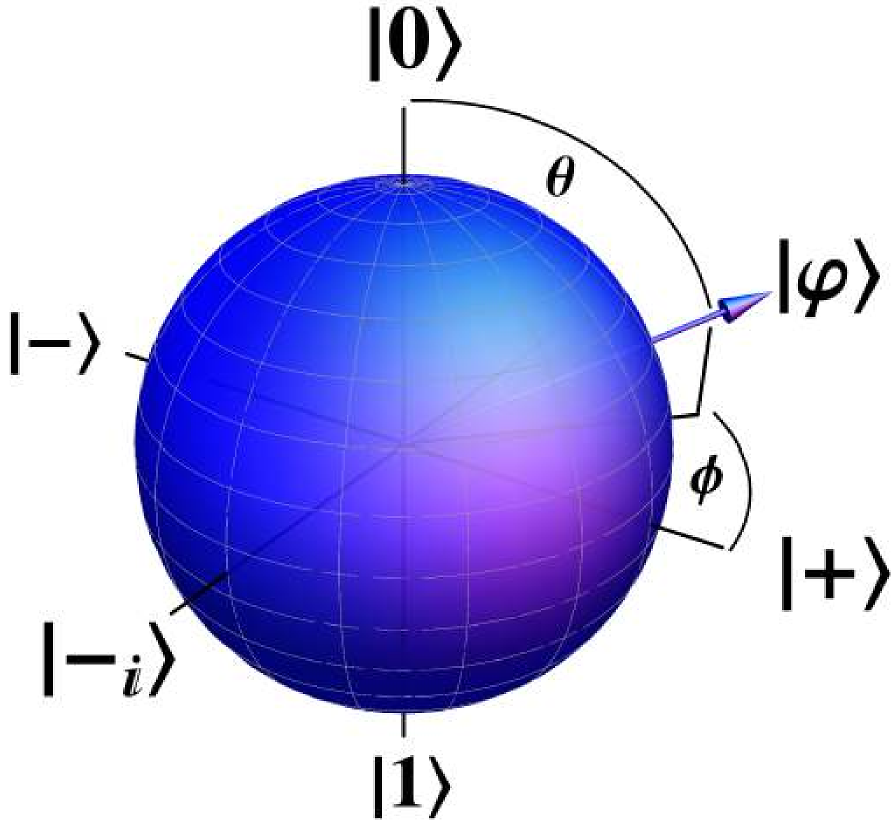
Throughput~ $\eta_s^N \eta_d^N \eta_g^N . f(F).R$

Manipulating single photons as qubits

Bloch Sphere Representation of a Qubit

$$|\Psi\rangle = \cos\tfrac{\theta}{2}|0\rangle + e^{i\phi}\sin\tfrac{\theta}{2}|1\rangle$$

$$|\Psi\rangle = \begin{pmatrix} \cos\tfrac{\theta}{2} \\ e^{i\phi}\sin\tfrac{\theta}{2} \end{pmatrix}$$

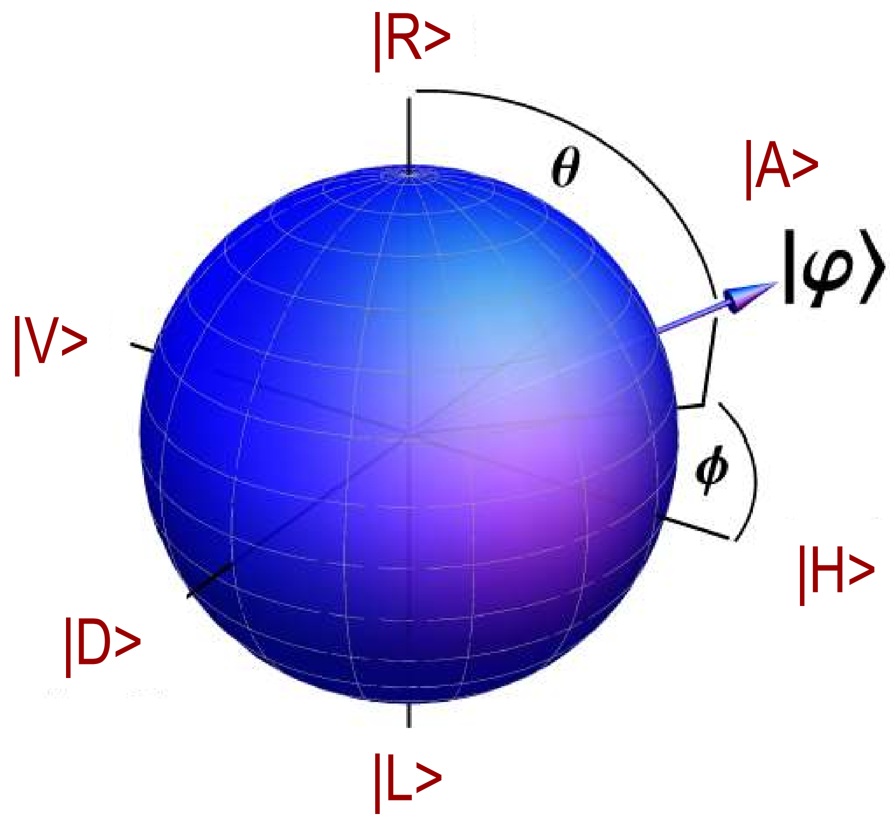


Simple problem: write the states

|+i>, |-i>

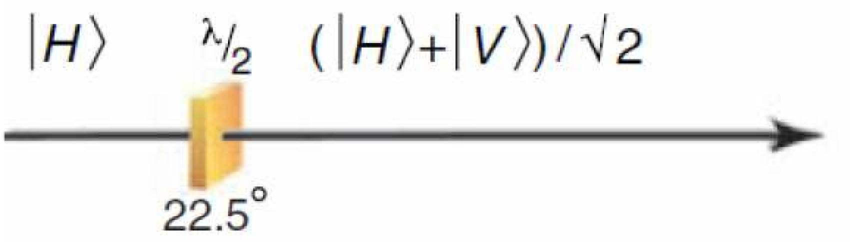
Bloch Sphere: computational basis = circular polarisation states

$$|\Psi\rangle = \cos\tfrac{\theta}{2}|R\rangle + e^{i\phi}\sin\tfrac{\theta}{2}|L\rangle$$

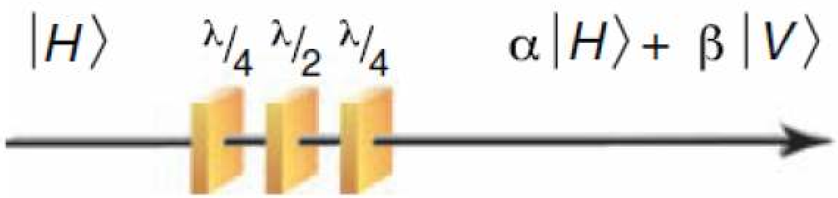


Arbitrary rotations

$$|\Psi\rangle = \begin{pmatrix} \cos\frac{\theta}{2} \\ e^{i\phi}\sin\frac{\theta}{2} \end{pmatrix}$$



$$H\hat{W}P = \begin{pmatrix} \cos(2\varphi) & \sin(2\varphi) \\ \sin(2\varphi) & -\cos(2\varphi) \end{pmatrix}$$



$$Q\hat{W}P = \frac{1}{\sqrt{2}}\begin{pmatrix} 1+i\cos(2\varphi) & i\sin(2\varphi) \\ i\sin(2\varphi) & i-\cos(2\varphi) \end{pmatrix}$$

φ = Angle of waveplate fast axis with respect to H

Combination of three waveplates QWP, HWP, QWP can take you from any arbitrary position on Block sphere to any other

How well can we encode one bit per photon

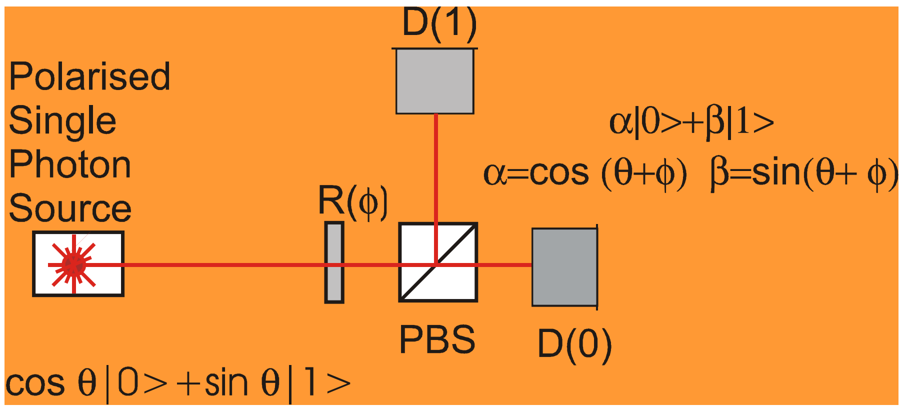
Encoding single photons using two polarisation modes

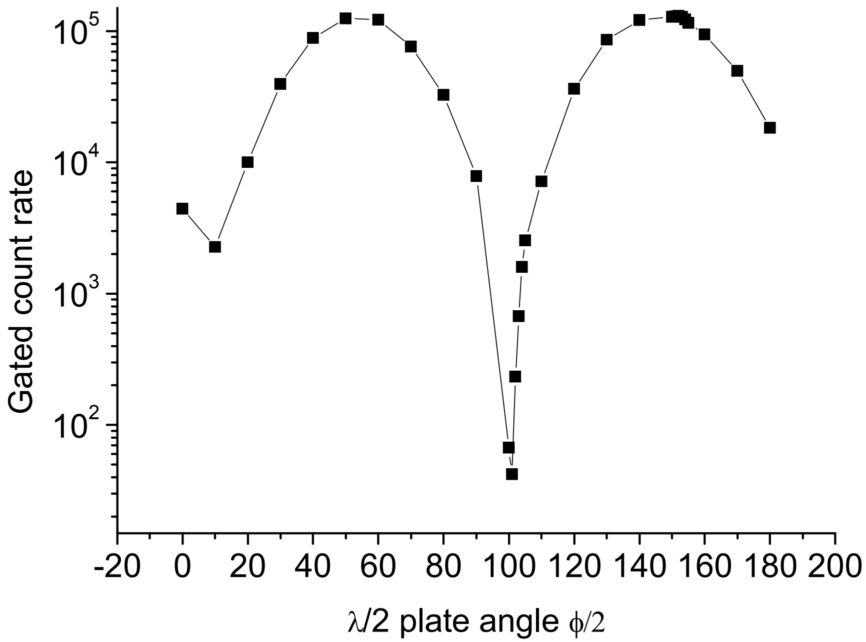
Superposition states of ‘1’ and ‘0’

$$|\Psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

Probability amplitudes α , β

Detection Probability: $|\alpha|^2$



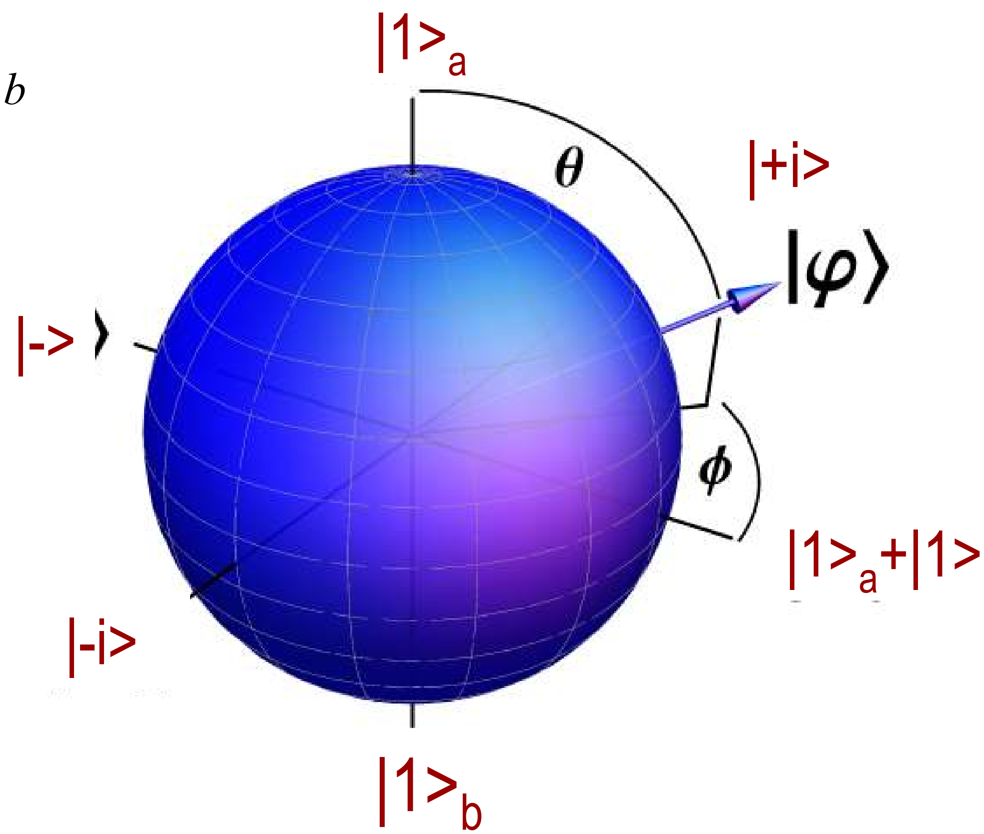


Single photon encoding showing QBER<5.10^{-4} (99.95% visibility)

University of BRISTOL

Bloch Sphere: computational basis = path a/b

$$\left|\Psi\right\rangle = \cos\tfrac{\theta}{2}\left|1\right\rangle_a + e^{i\phi}\sin\tfrac{\theta}{2}\left|1\right\rangle_b$$



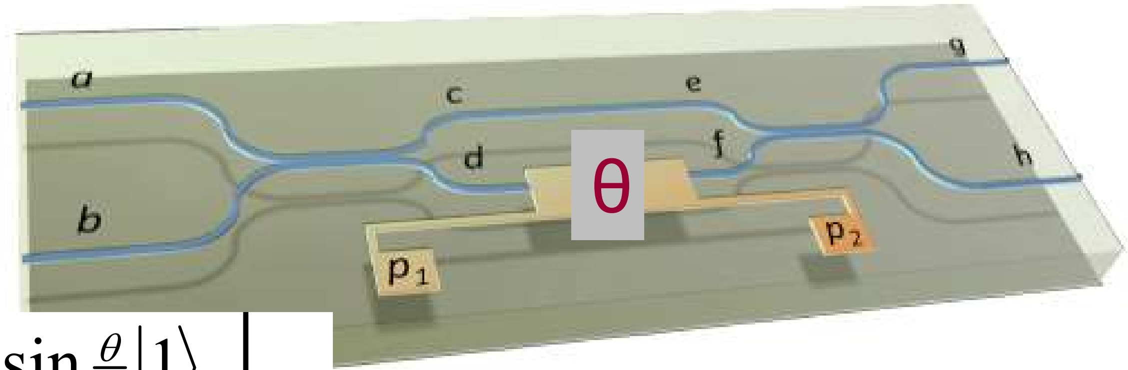
- Waveguide based interferometer to create arbitrary path encoded states

50:50 beamsplitter

$$H_c \doteq \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & i \\ i & 1 \end{pmatrix}$$

Phase shift

$$Z(\theta) = \begin{pmatrix} e^{i\theta/2} & 0 \\ 0 & e^{-i\theta/2} \end{pmatrix}$$



$$|\Psi\rangle_{out} = ie^{i\theta/2}\left[\cos\tfrac{\theta}{2}|1\rangle_g + \sin\tfrac{\theta}{2}|1\rangle_h\right]$$

$$|\Psi\rangle_{out} = ie^{i\theta/2}\left[\cos\tfrac{\theta}{2}|1\rangle_g + \sin\tfrac{\theta}{2}e^{i\phi}|1\rangle_h\right]$$

Need one further phase shift on h-mode to achieve near universal rotation

Have now introduced creation operators for a mode

$$a_i^+ |0\rangle = |1\rangle_i$$

$$i = a, b, c, d.....$$

$$\frac{{a_i^+}^N}{\sqrt{N!}} |0\rangle = |N\rangle_i$$

$$a_i^+ |N\rangle = \sqrt{N+1} |N+1\rangle_i$$

$$a_i |N\rangle = \sqrt{N} |N-1\rangle$$

$$[a_i, a_j^+] = \delta_{ij}$$

And general beamsplitter operator

$$H_{50:50} = \begin{vmatrix} 1 & i \\ i & 1 \end{vmatrix}$$

$$H_t = \begin{vmatrix} t & ir \\ ir & t \end{vmatrix}$$

$$R = r^2$$

$$T = t^2$$

$$R + T = 1$$

The 50:50

beamsplitter can also be

mapped to the Hadamard

$$H = \begin{vmatrix} 1 & 1 \\ 1 & -1 \end{vmatrix}$$

PROBLEM: show how this

can be achieved

Further qubit encoding schemes:

- Time bin
- Frequency
- Spatial mode:
  - Laguerre Gaussian
  - Hermite Gaussian
- Encoding in higher dimensions
  - D -paths, -modes, frequencies, time bins…

2-qubit states: entanglement

Two qubit states that cannot be factorised

The four general Bell states

Notation: QI QO Pol

$$\left|\Psi^{+}\right\rangle = \left|01\right\rangle + \left|10\right\rangle \Rightarrow \left|1_{0}1_{1}\right\rangle + \left|1_{1}1_{0}\right\rangle \Rightarrow \left|HV\right\rangle + \left|VH\right\rangle$$

$$\left|\Psi^{-}\right\rangle = \left|01\right\rangle - \left|10\right\rangle \Rightarrow \left|1_{0}1_{1}\right\rangle - \left|1_{1}1_{0}\right\rangle$$

$$\left|\Phi^{+}\right\rangle = \left|00\right\rangle + \left|11\right\rangle$$

$$\left|\Phi^{-}\right\rangle = \left|00\right\rangle + \left|11\right\rangle$$

N-qubit states

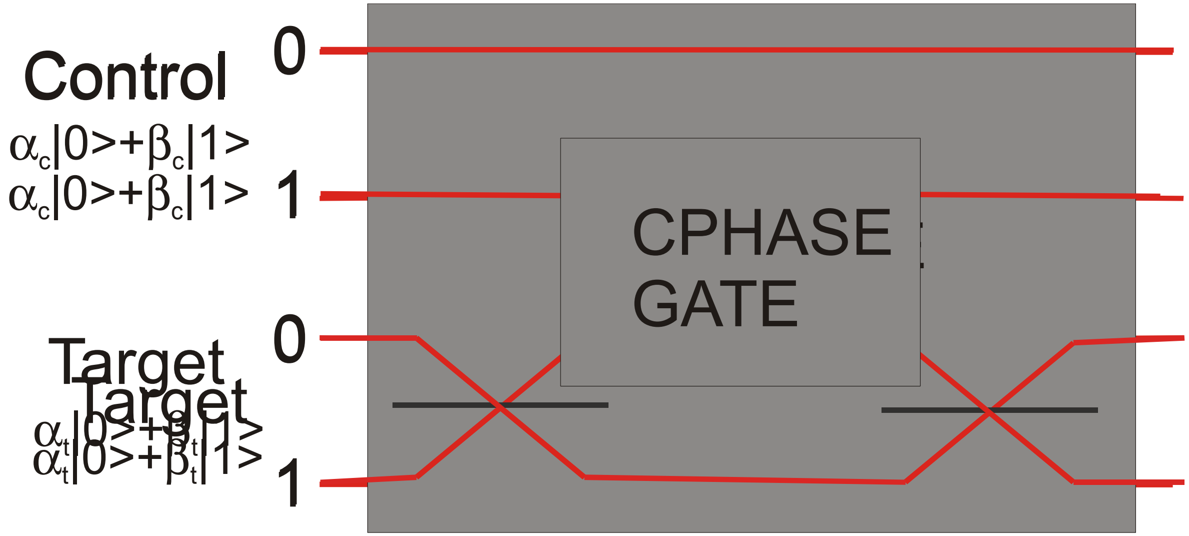
- GHZ states
- Cluster states
- N00N states for interferometry

$$\left|GHZ\right\rangle = \left|1_{0A}1_{0B}1_{0C}....\right\rangle \pm \left|1_{1A}1_{1B}1_{1C}\right\rangle \Rightarrow \left|H_A H_B H_C....\right\rangle + \left|V_A V_B V_C..\right\rangle$$

$$\left|N00N\right\rangle = \left|N_0, 0_1\right\rangle \pm \left|0_0, N_1\right\rangle \Rightarrow \left|N_0, 0_1\right\rangle \pm e^{iN\phi}\left|0_0, N_1\right\rangle$$

2-qubit gates

U =universal quantum gate (CNOT)= 'entangler'



$$\left|\Psi\right\rangle_{in} = \left(\alpha\left|0\right\rangle_t + \beta\left|1\right\rangle_t\right)\left(\alpha_c\left|0\right\rangle_c + \beta_c\left|1\right\rangle_c\right)$$

$$\left|\Psi\right\rangle_{out} = \alpha\alpha_c\left|0\right\rangle_t\left|0\right\rangle_c + \alpha\beta_c\left|1\right\rangle_t\left|1\right\rangle_c + \beta\alpha_c\left|1\right\rangle_t\left|0\right\rangle_c + \beta\,\beta_c\left|0\right\rangle_t\left|1\right\rangle_c$$

2-qubit gates

Requires non-linearity a single photon to iduce a pi phase shift in another photon, extremely difficult to achieve.

PROGRESS

Atoms: Turchette and Kimble PRL1995, (7 degrees per photon)

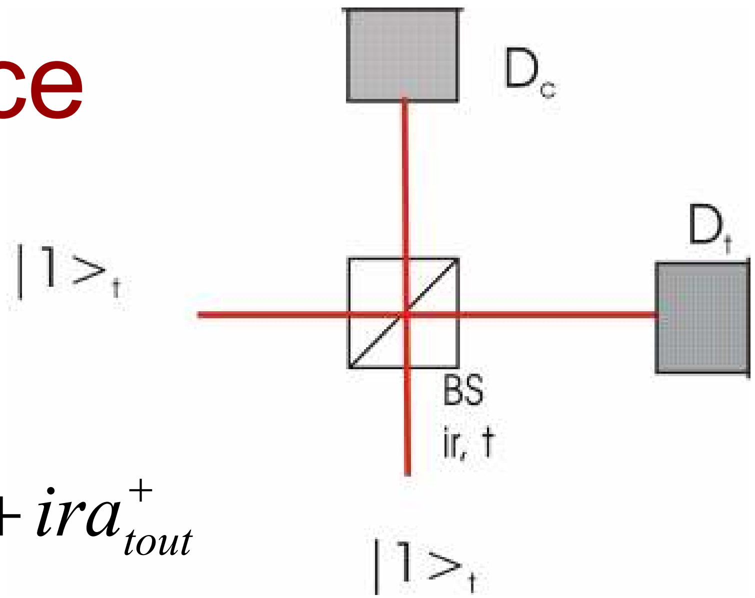
Solid state: J. P. Reithmaier/ A. Forchel, Nature 432, Nov 2004.

Young, Rarity et al Phys Rev B

ALSO

Quadratic interactions thus need TOP HAT photons

2-photon interference



$$|\Psi_{in}\rangle = |1\rangle_t |1\rangle_c = a_t^+ a_c^+ |0\rangle$$

$$a_t^+ \rightarrow t a_{tout}^+ + ir a_{cout}^+ \quad : a_c^+ \rightarrow t a_{cout}^+ + ir a_{tout}^+$$

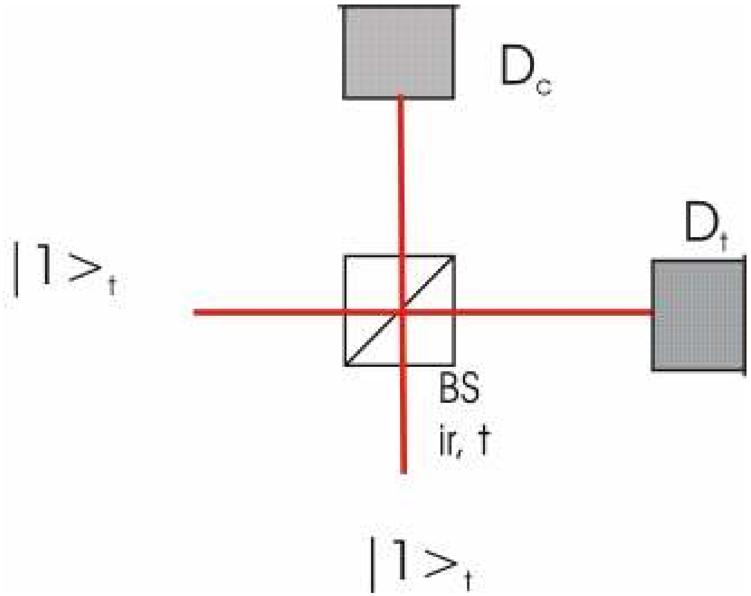
$$|\Psi_{out}\rangle = (t a_{tout}^+ + ir a_{cout}^+)(t a_{cout}^+ + ir a_{tout}^+)|0\rangle$$

$$= (t^2 - r^2)|1\rangle_t |1\rangle_c + \sqrt{2} irt |2\rangle_t + \sqrt{2} irt |2\rangle_c$$

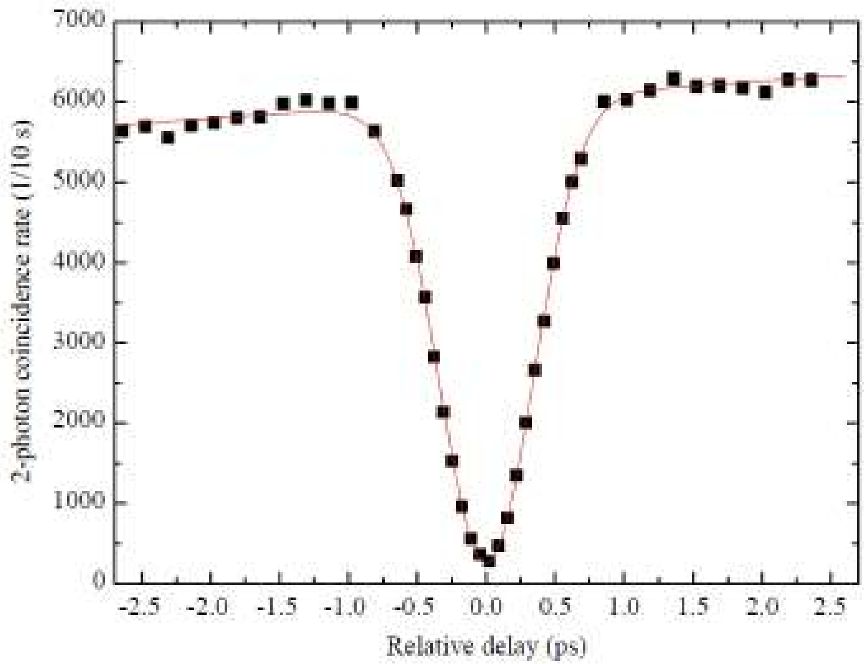
When t=r=1/√2

$$|\Psi_{out}\rangle = \frac{1}{2}(a^+_{tout} + ia^+_{cout})(a^+_{cout} + ia^+_{tout})|0\rangle$$

$$= \frac{1}{\sqrt{2}}|2\rangle_t + |2\rangle_c$$



Hong, Ou, Mandel PRL 1987
Rarity, Tapster, JOSA B, 1989



|2>|2> inputs and generalising the beamsplitter to |N>|M>

$$\left|\Psi_{in}\right\rangle = \left|2\right\rangle_c \left|2\right\rangle = \tfrac{1}{2} a_c^{+2} a_t^{+2} \left|0\right\rangle$$

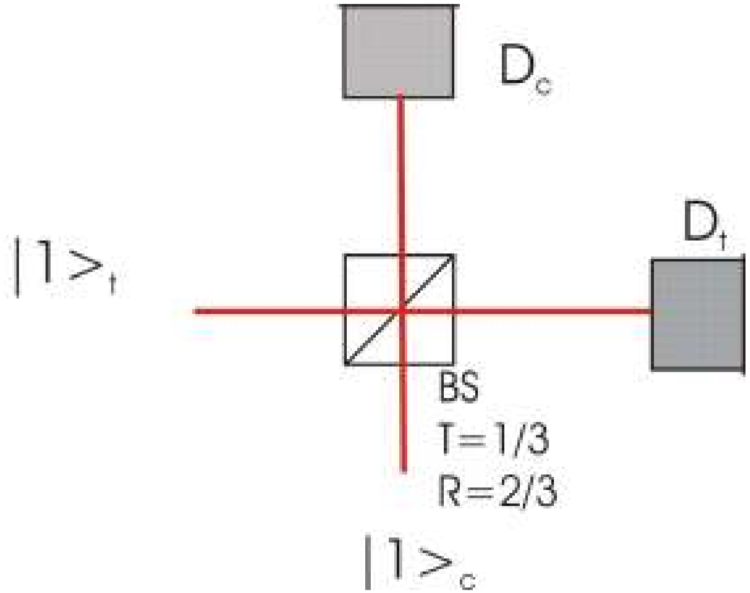
$$\left|\Psi_{out}\right\rangle = \frac{1}{8}(a_{tout}^{+} + ia_{cout}^{+})^2 (a_{cout}^{+} + ia_{tout}^{+})^2 \left|0\right\rangle$$

?

$$= \sqrt{\frac{3}{8}}\left(\left|4\right\rangle_t \left|0\right\rangle_c + \left|0\right\rangle_t \left|4\right\rangle_c\right) + \frac{1}{2}\left|2\right\rangle_t \left|2\right\rangle_c$$

- PROBLEM: |N>|M> state generalised result?

Probabilistic phase gate

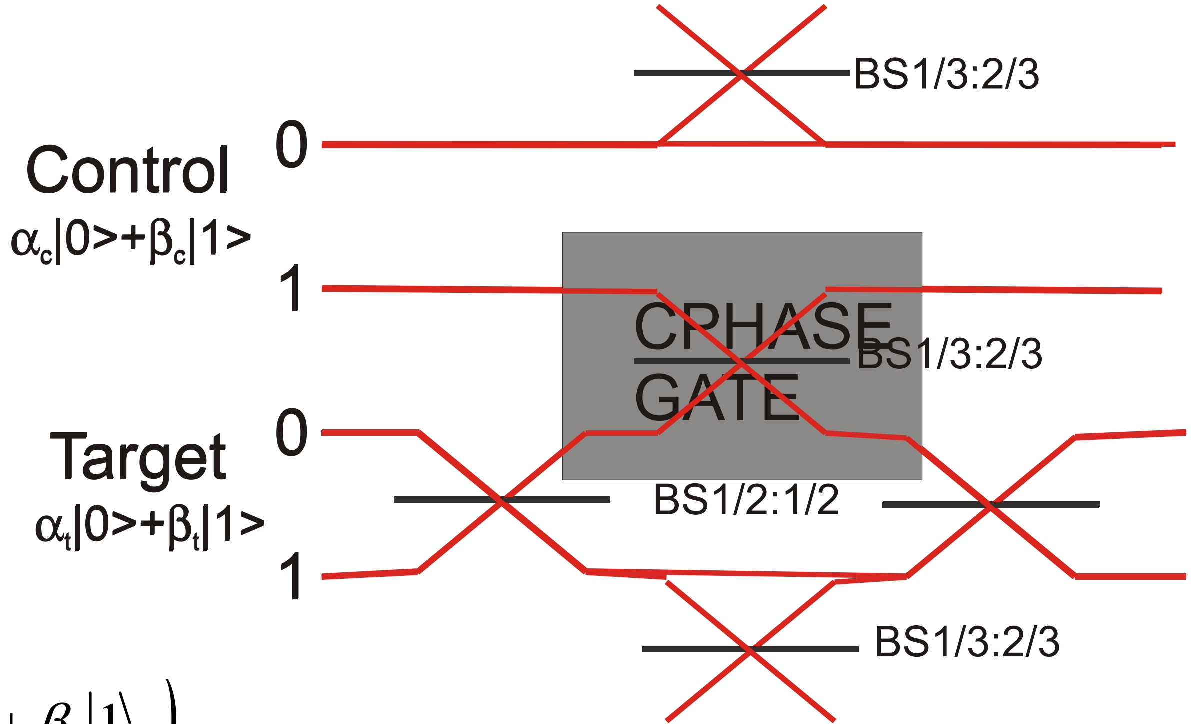


$$|\Psi_{in}\rangle = |1\rangle_t |1\rangle_c$$

$$|\Psi_{out}\rangle = \left((t^2 - r^2)|1\rangle_t |1\rangle_c + \sqrt{2}irt|1,1\rangle_t + \sqrt{2}irt|1,1\rangle_c\right)$$

$$= -\tfrac{1}{3}|1\rangle_t |1\rangle_c$$

U =universal quantum gate (CNOT)= 'entangler'



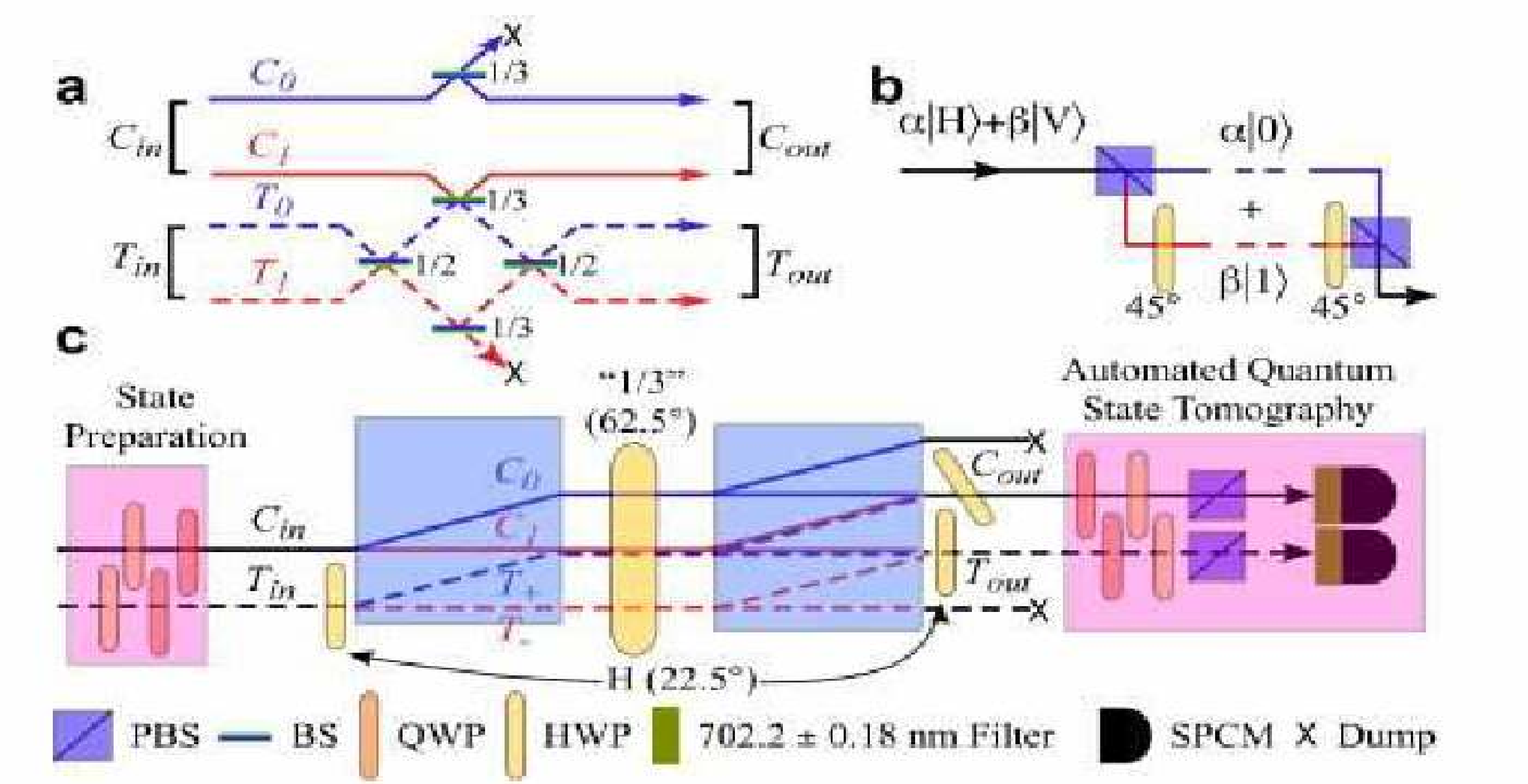
KLM CNOT gate

$$|\Psi\rangle_{in} = (\alpha|0\rangle_t + \beta|1\rangle_t)(\alpha_c|0\rangle_c + \beta_c|1\rangle_c)$$

$$|\Psi\rangle_{out} = \frac{1}{3}(\alpha\alpha_c|0\rangle_t|0\rangle_c + \alpha\beta_c|1\rangle_t|1\rangle_c + \beta\alpha_c|1\rangle_t|0\rangle_c + \beta\,\beta_c|0\rangle_t|1\rangle_c$$

1/9 success probability conditioned on seeing
One photon in control and one in target lines

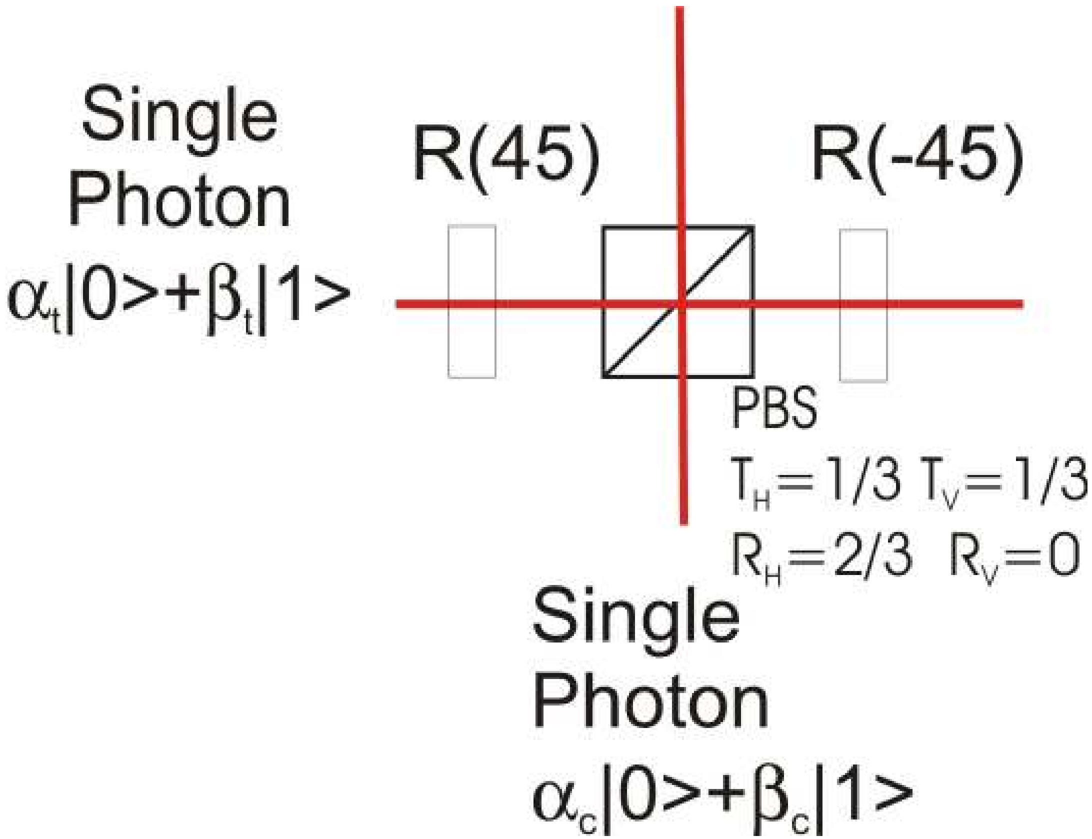
First experimental all-optical quantum controlled-NOT gate



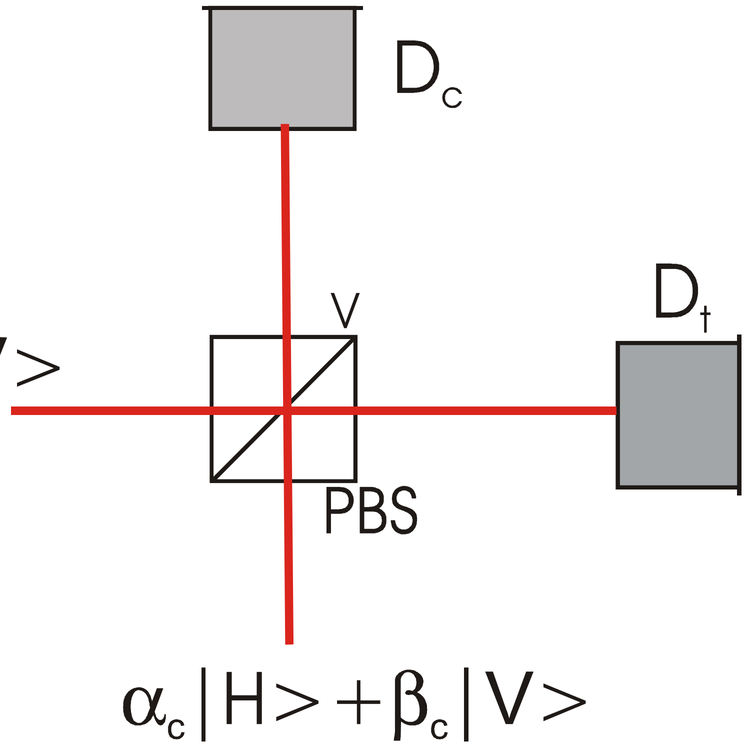
Knill et al Nature 409, 46–52 (2001)

J L O'Brien et al, ***Nature* 426,** 264 (2003) / quant-ph/0403062

Polarisation KLM gate



Polarisation Gates
Parity Measurement OR
Fusion gate



Up to 50% efficient

Notes?

Experimental techniques

- Single photon detection
- Single photon sources
- Entangled state sources
- Gate realisations and experiments
- N00N states and metrology

Detection

The number operator

$$ {}_i\langle 1 | a_i^{+} a_i | 1 \rangle_i = 1 $$

$$ {}_j\langle N | a_i^{+} a_i | N \rangle_j = N\delta_{ij} $$

$$ |\Psi\rangle = \alpha |1\rangle_a + \beta |1\rangle_b $$

Counting single photons

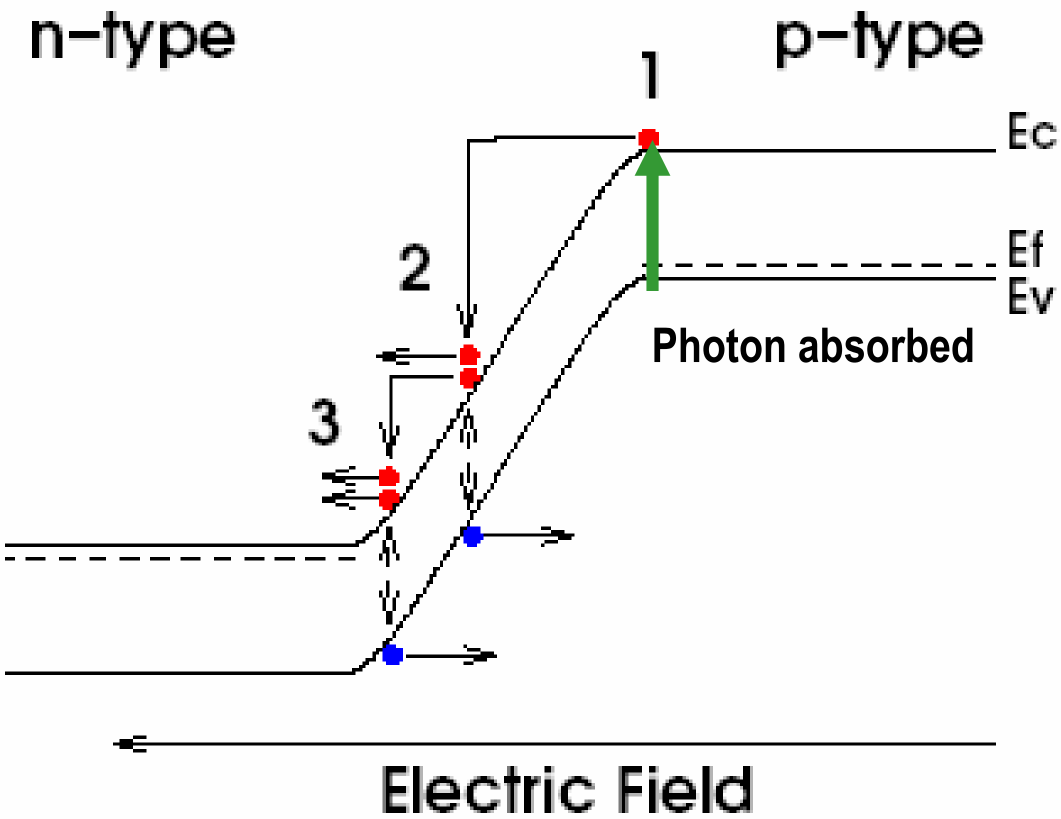
$$ \langle \Psi | a_i^{+} a_i | \Psi \rangle = |\alpha|^2 \qquad i = a $$

Coincidence detection, $g^{(2)}$

$$ |\Psi\rangle = \sqrt{1-\alpha^2}\,|vac\rangle + \alpha |1\rangle_a |1\rangle_b $$

$$ \langle \Psi | a_a^{+} a_b^{+} a_b a_a | \Psi \rangle = |\alpha|^2 $$

Photon counting using avalanche photodiodes



Photon is absorbed in the avalanche region to create an electron hole pair

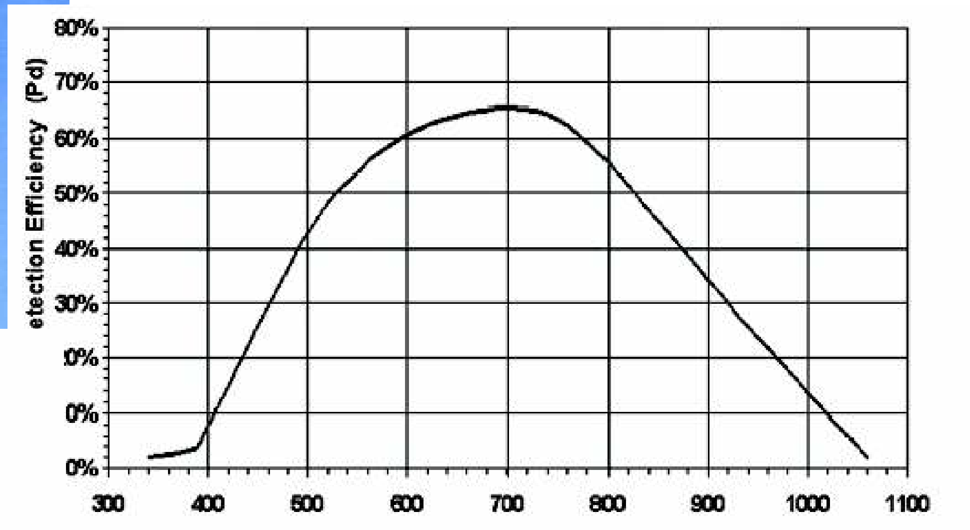
Electron and hole are accelerated in the high electric field

Collide with other electrons and holes to create more pairs

With high enough field the device breaks down when one photon is absorbed

Commercial actively quenched detector module using Silicon APD

Efficiency ~70% (at 700nm)
Timing jitter~400ps (latest <50ps)
Dark counts <50/sec
www.perkinelmer.com



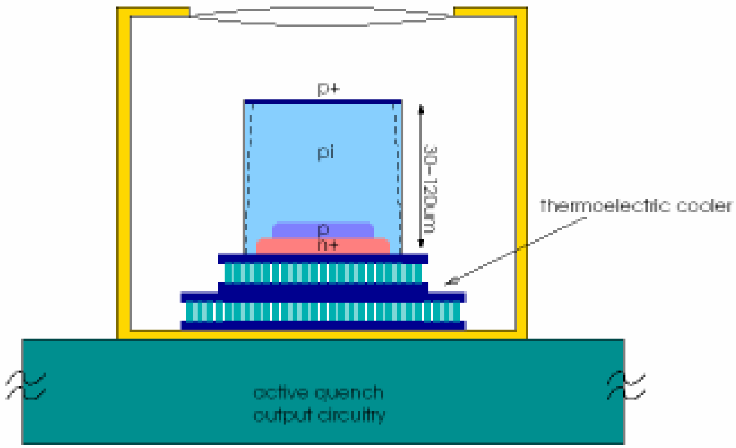


Figure 2.10: Single photon counting module (SPCM).

InGaAs avalanche detectors:

Gated modules operation at 1550nm
Lower efficiency ~20-30%
Higher dark counts ~1E^{4}/sec
Afterpulsing (10 us dead time)
www.idquantique.com

Other detectors

- InGaAs based devices for 1.55 um, gated
- The Geiger mode avalanche diodes count one photon then switch off for a dead time - NOT PHOTON NUMBER RESOLVING
- Photon number resolving detectors may become available in the near future:
  - Superconducting wire detectors, in multiwire configurations Jaspan et al APL 89, 031112, 2006
  - Superconducting transition edge detectors
  - Impurity transitions in heavily doped silicon
  - Self differencing gated detectors

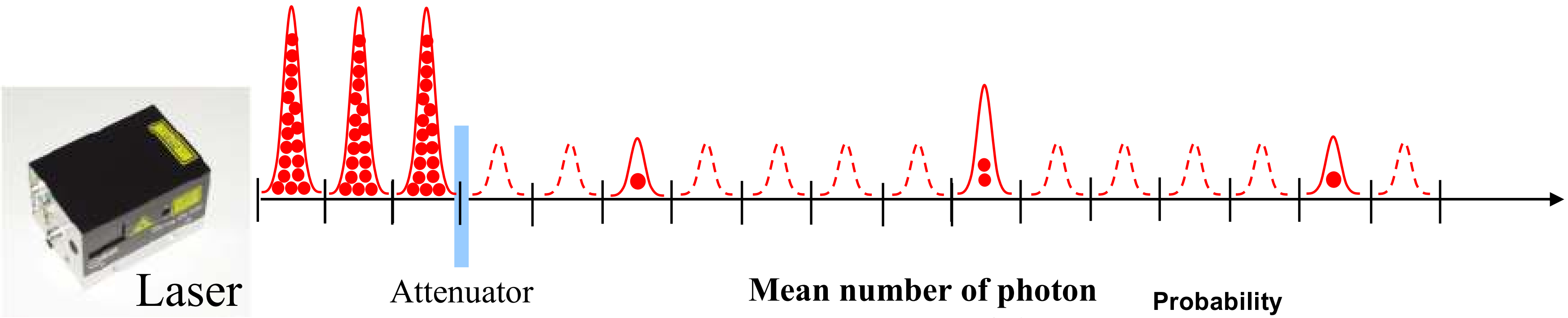
Single and pair photon sources

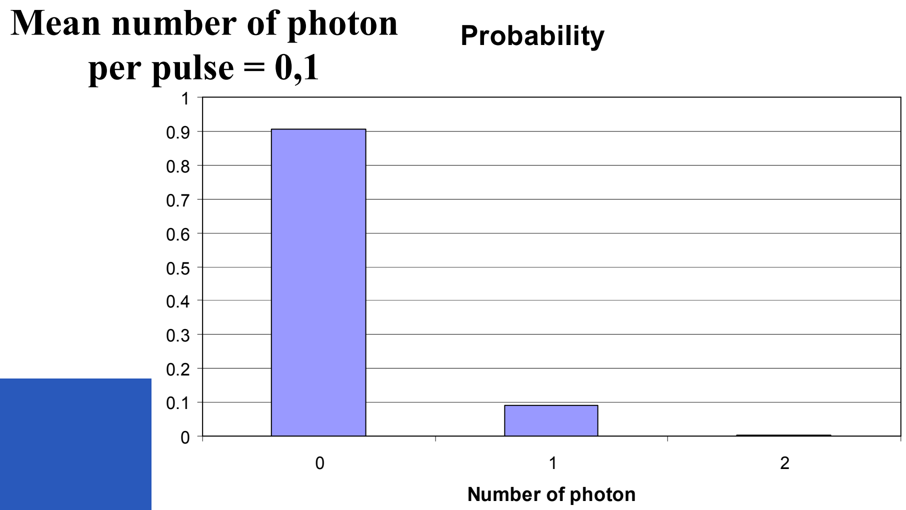
Approximate single photon source

Attenuated laser = Coherent state

$$|\Psi\rangle = e^{-\alpha^2/2}\left[|vac\rangle + \alpha|1\rangle + \alpha^2/\sqrt{2!}\,|2\rangle + \ldots\right]$$

$$|\alpha|^2 = \langle n \rangle$$





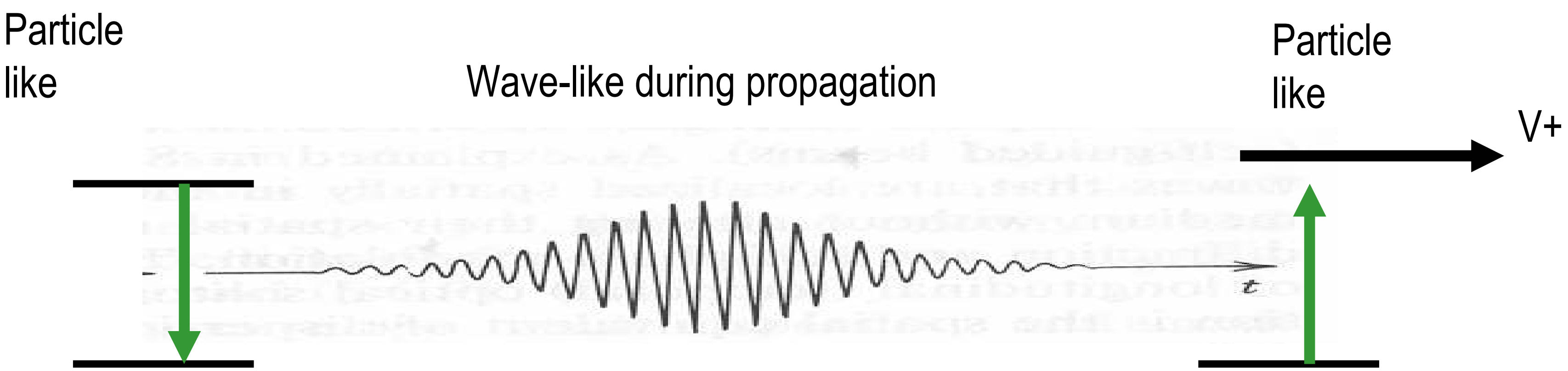
Coherent state shows

Poisson distribution of photons

$$p(n, \langle n \rangle) = \frac{\langle n \rangle^n e^{-\langle n \rangle}}{n!}$$

$$\text{variance} = \langle n^2 \rangle - \langle n \rangle^2 = \langle n \rangle$$

True single photon sources



Single atom or ion (in a trap)
Single dye molecule
Single colour centre (diamond NV)
Single quantum dot (eg InAs in GaAs)

Key problem: how to get single photons from source efficiently coupled into single spatial mode, see this afternoon

Parametric sources of pair photons and entangled photons

$$\frac{\partial \Psi}{\partial t} = -\frac{i}{\hbar} H\Psi$$

$$H = g'(a_s^+ a_i^+ a_p + a_s a_i a_p^+)$$

$$|\Psi\rangle = \exp\left[-iga_s^+ a_i^+\right]|vac\rangle \qquad g = E_p g'$$

$$|\Psi\rangle = N\left[|vac\rangle + g|1\rangle_s|1\rangle_i + g^2|2\rangle_s|2\rangle_i + g^3|3\rangle_s|3\rangle_i \ldots\right]$$

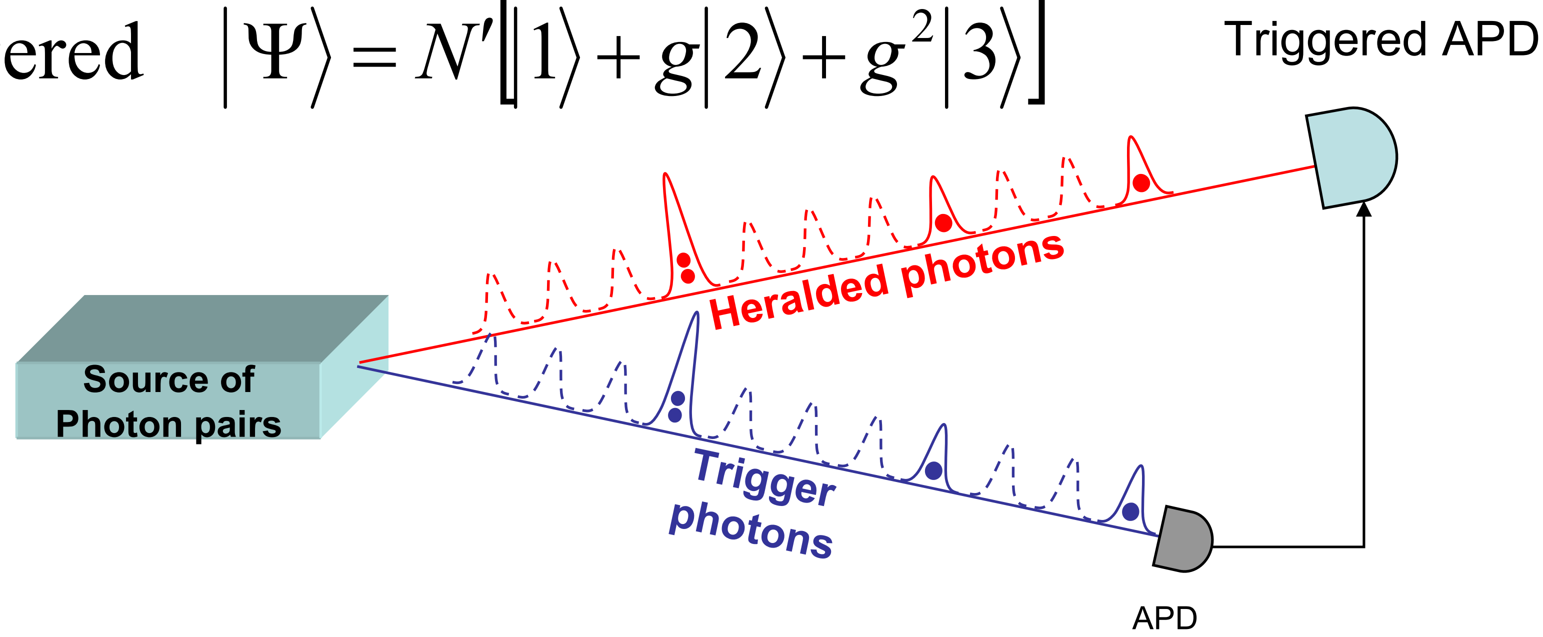
Why photon pairs?

JGR,JMO 1998, 45, 595-604

- Heralded single photon source

$$|\Psi\rangle = N\left[|vac\rangle + g|1,1\rangle + g^2|2,2\rangle + g^3|3,3\rangle \ldots\right]$$

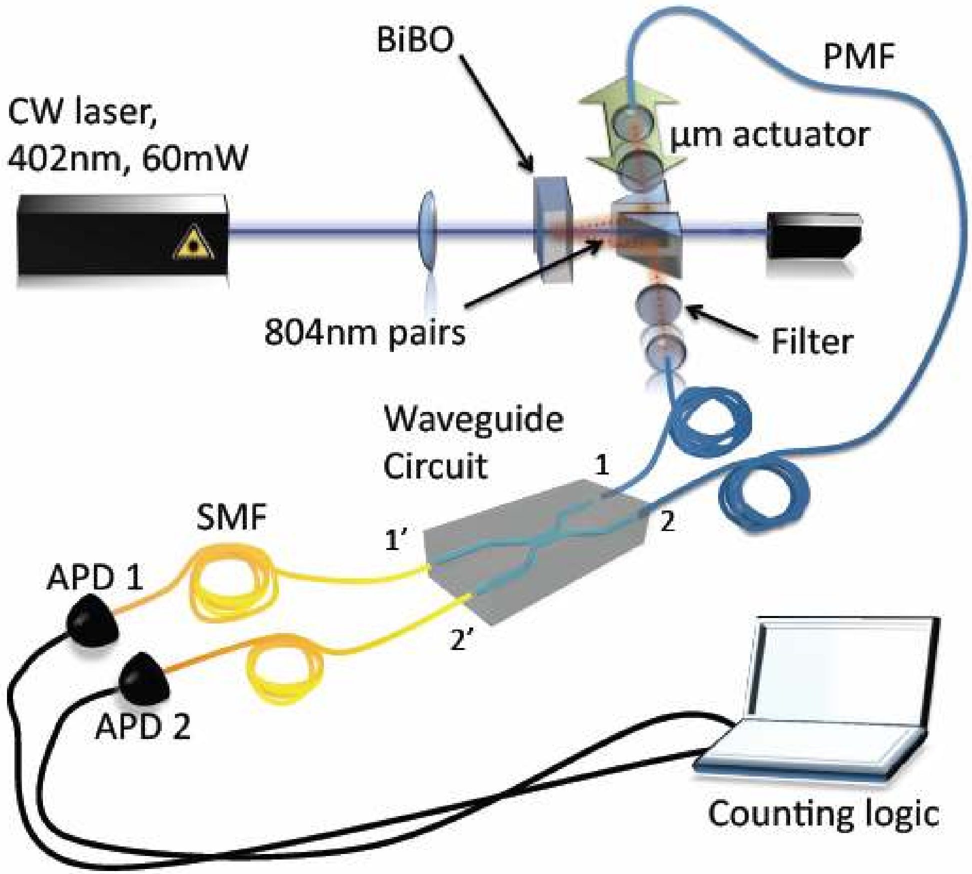
$$\text{Triggered} \quad |\Psi\rangle = N'\left[|1\rangle + g|2\rangle + g^2|3\rangle\right]$$

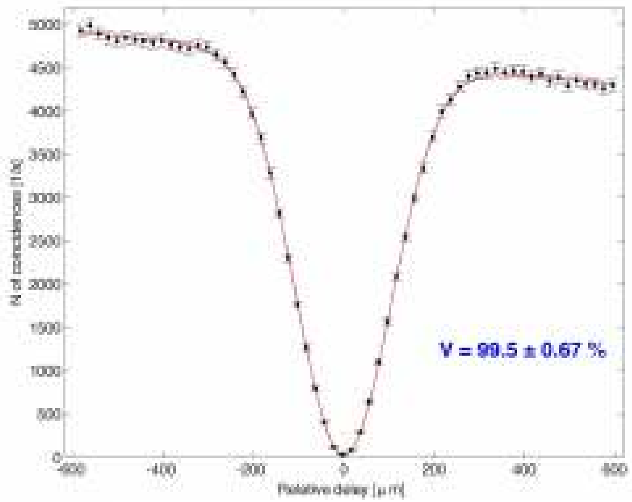


Experimental realization of a localized one-photon state, C. K. Hong and L. Mandel, Phys. Rev. Lett. **56**, 58 (1986)

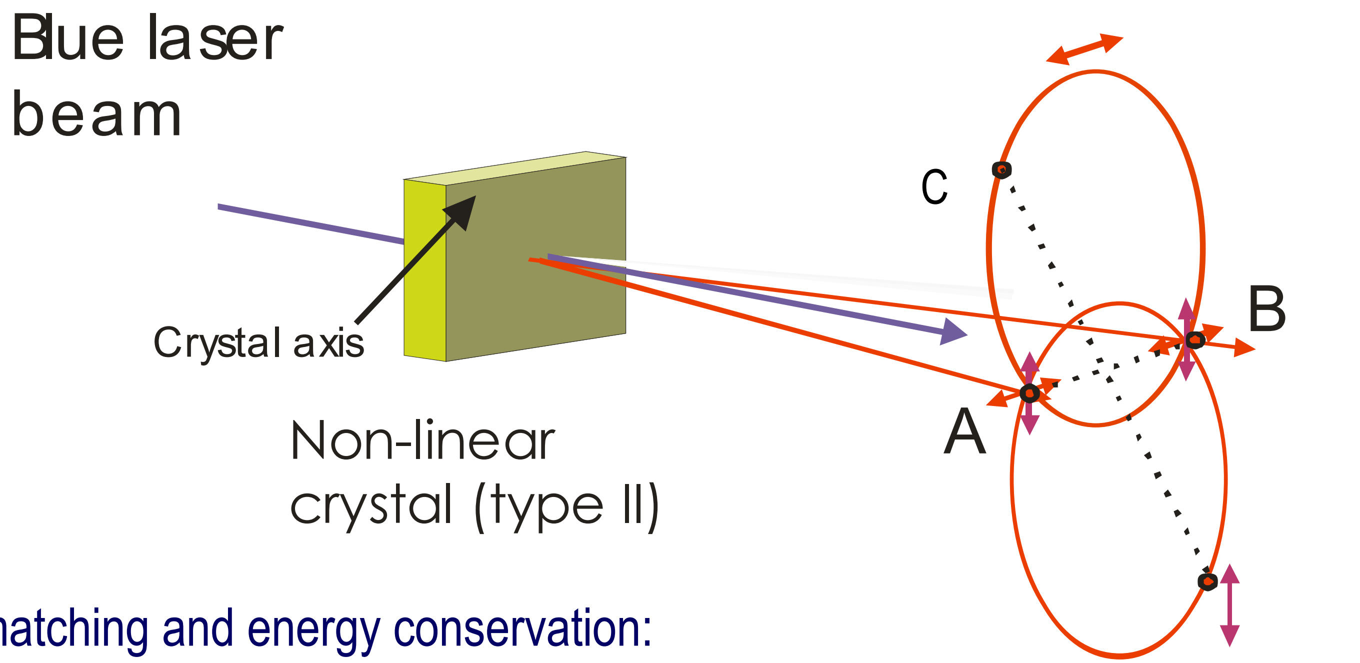
Observation of sub-poissonian light in parametric downconversion. J.G. Rarity, P.R.Tapster and E. Jakeman, Opt. Comm., 62(3):201, 1987.

Source for integrated quantum photonics





Creating Entangled Photon Pairs



Phase matching and energy conservation:

$$k_{pump} - k_{signal} - k_{idler} = 0$$

$$w_{pump} = w_{signal} + w_{idler}$$

$$\text{Pairs C - D} \quad |\Psi\rangle = |H\rangle_C |V\rangle_D$$

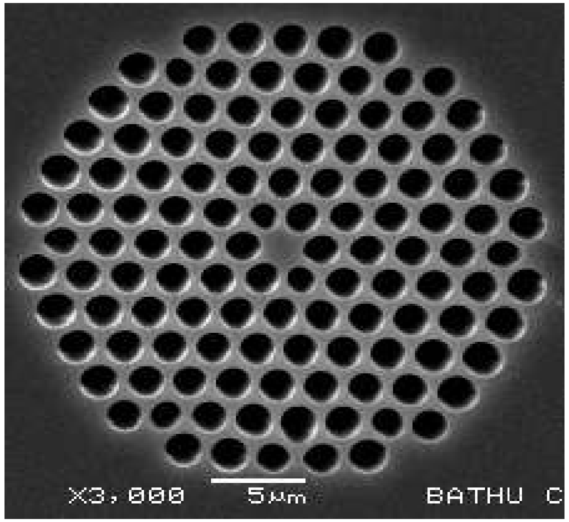
$$\text{Pairs A - B} \quad |\Psi\rangle = \tfrac{1}{\sqrt{2}}\left(|H\rangle_A |V\rangle_B + e^{i\phi}|V\rangle_A |H\rangle_B\right)$$

(ignoring vacuum....why!)

PHOTONIC CRYSTAL FIBRES

SPECIFICATIONS

- Material: silica and air
- Core Diameter: ~2μm
- Zero Dispersion Wavelength: λ_0=810nm
- Birefringent along orthogonal axes



Almost identical properties to three wave process BUT quadratic in pump power

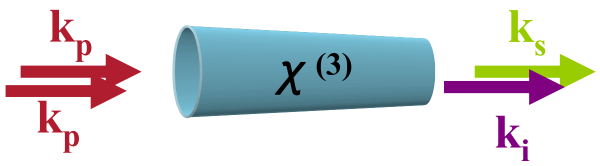
$$\frac{\partial\Psi}{\partial t} = -\frac{i}{\hbar}H\Psi$$

$$H = g'(a_s^+ a_i^+ a_p^2 + a_s a_i a_p^{+2})$$

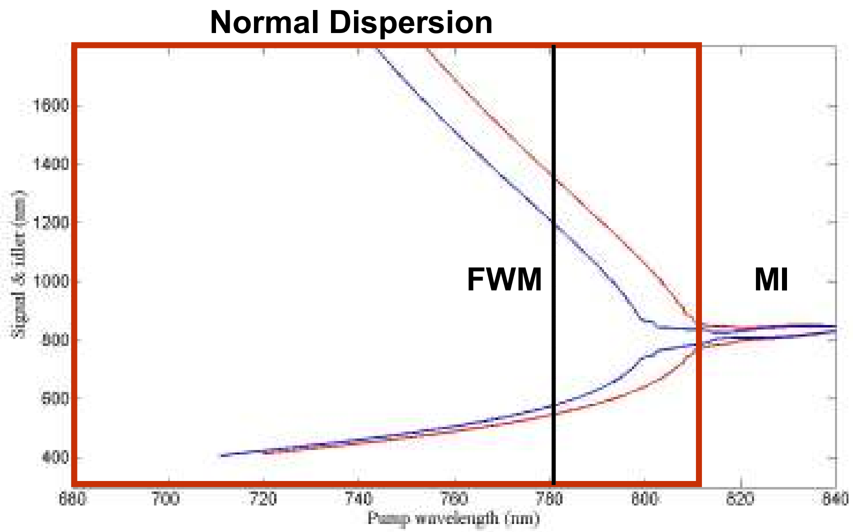
$$|\Psi\rangle = \exp\left[-iga_s^+ a_i^+\right]|vac\rangle \qquad g = E_p^2 g'$$

$$|\Psi\rangle = N\left[|vac\rangle + g|1\rangle_s|1\rangle_i + g^2|2\rangle_s|2\rangle_i + g^3|3\rangle_s|3\rangle_i \ldots\right]$$

FOUR-WAVE MIXING PROCESS



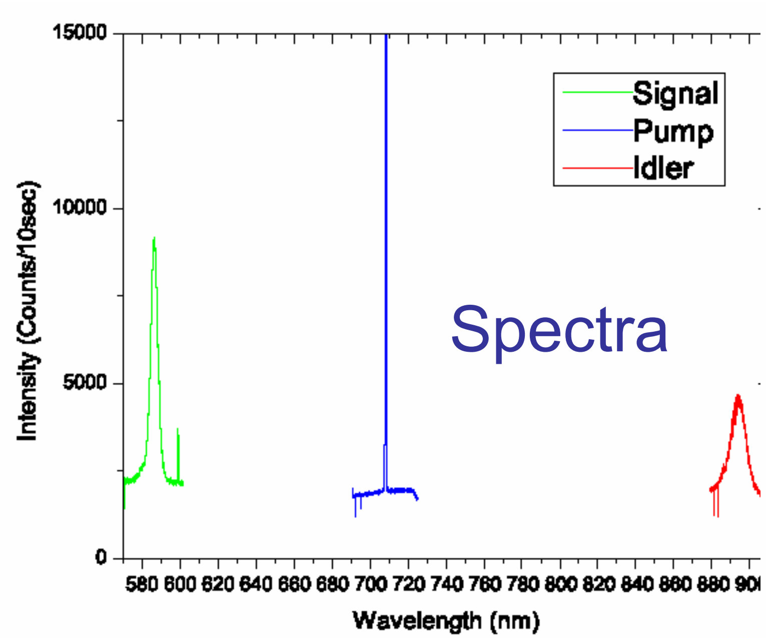
$$\begin{cases} 2k_{pump} - k_{signal} - k_{idler} - 2\gamma P_p = 0 \\ 2\omega_{pump} = \omega_{signal} + \omega_{idler} \end{cases}$$

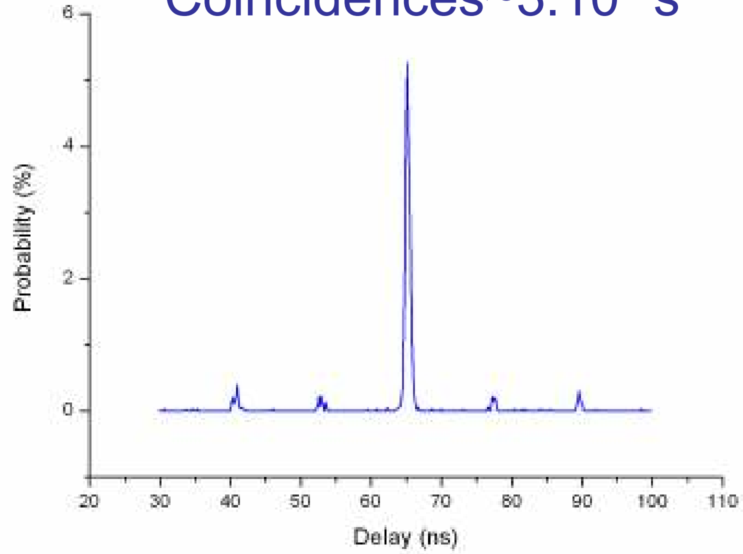


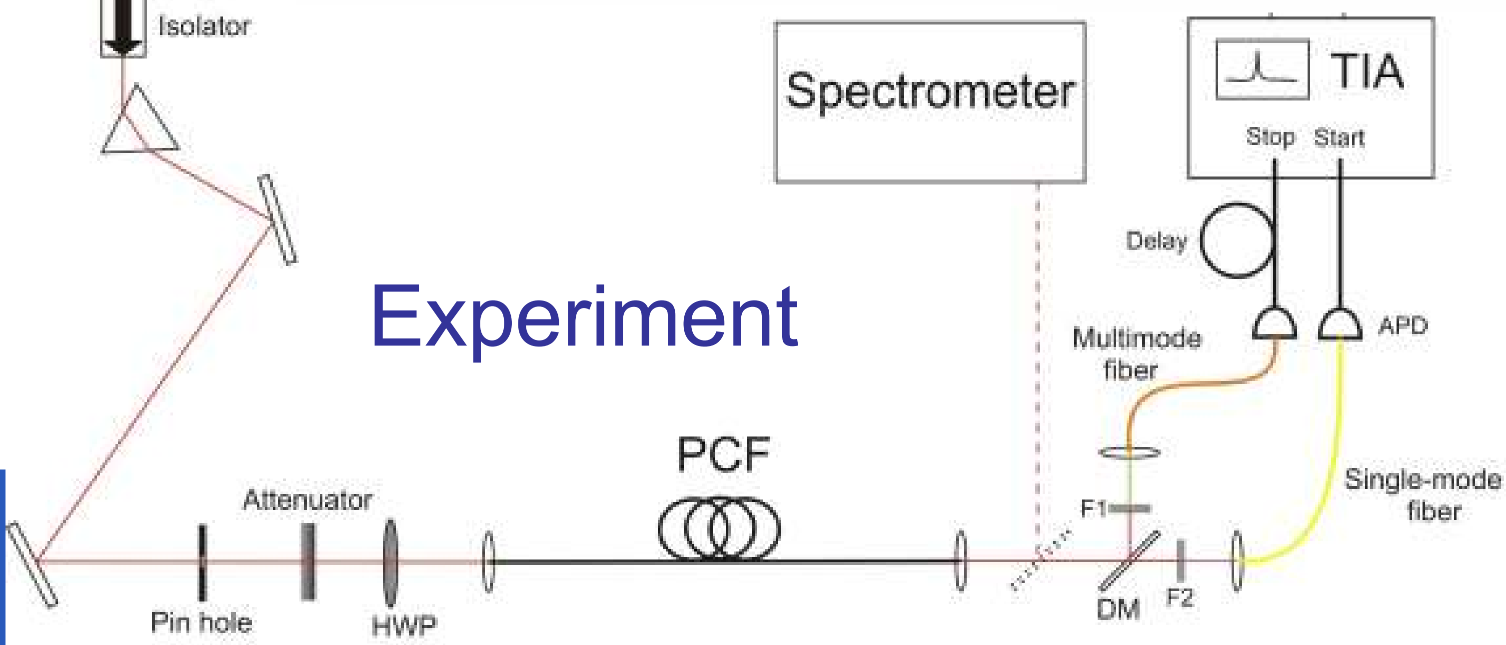
- Pump the fibre in the normal dispersion region
- Produce wavelengths widespread and away from the pump and Raman background effects

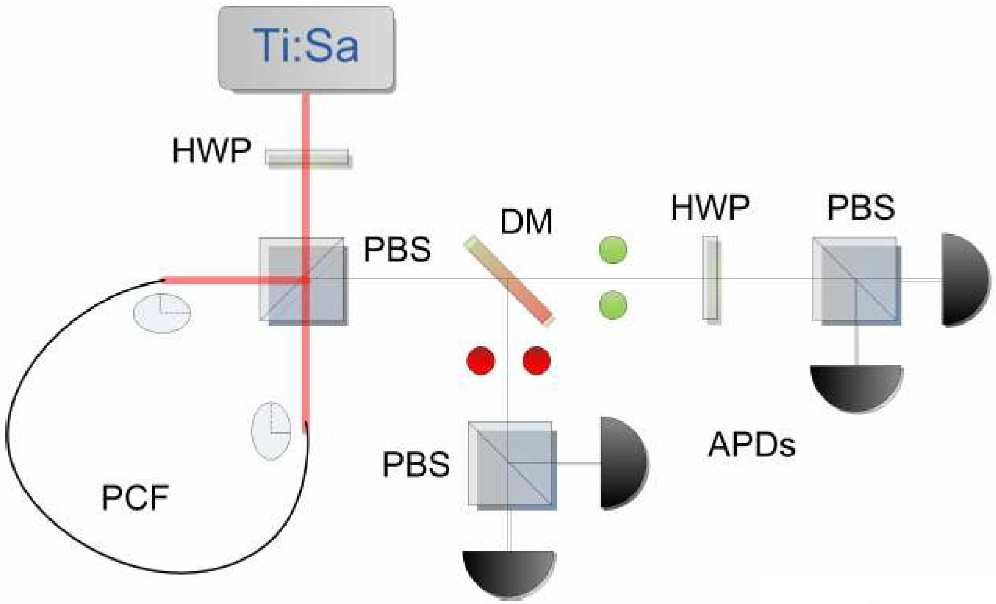
J. Fulconis, O. Alibart, W. J. Wadsworth, P. S. Russell and J. G. Rarity, Opt. Express **13**, 7572 (2005)

Coincidences~3.10^5 s^{-1}



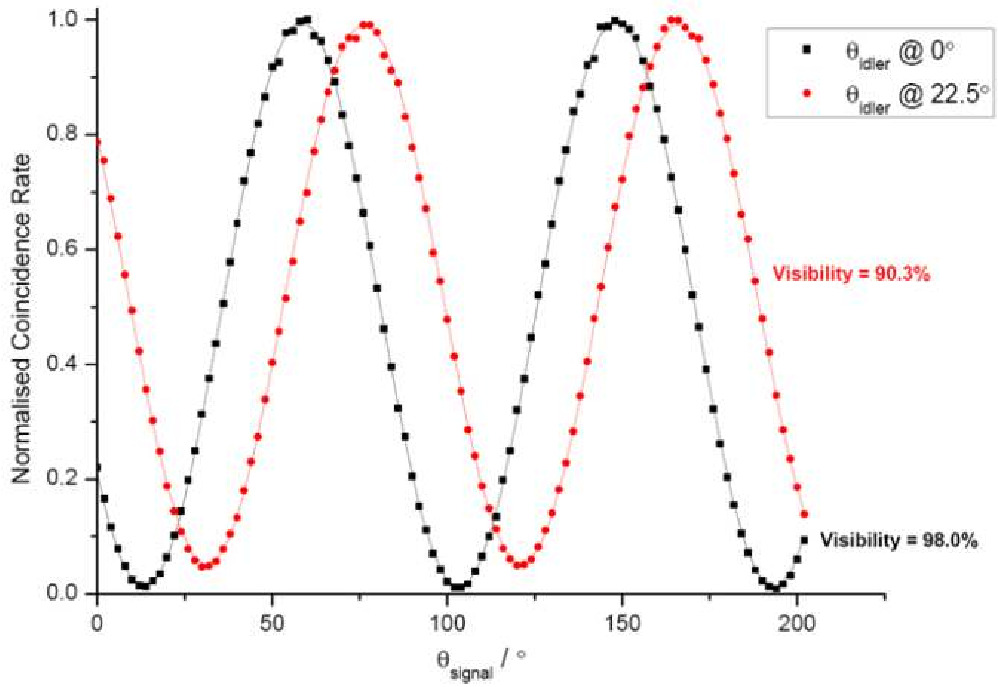






Entanglement

- Create $|H_sH_i\rangle + |V_sV_i\rangle$
- 2-photon fringes visibility >90%



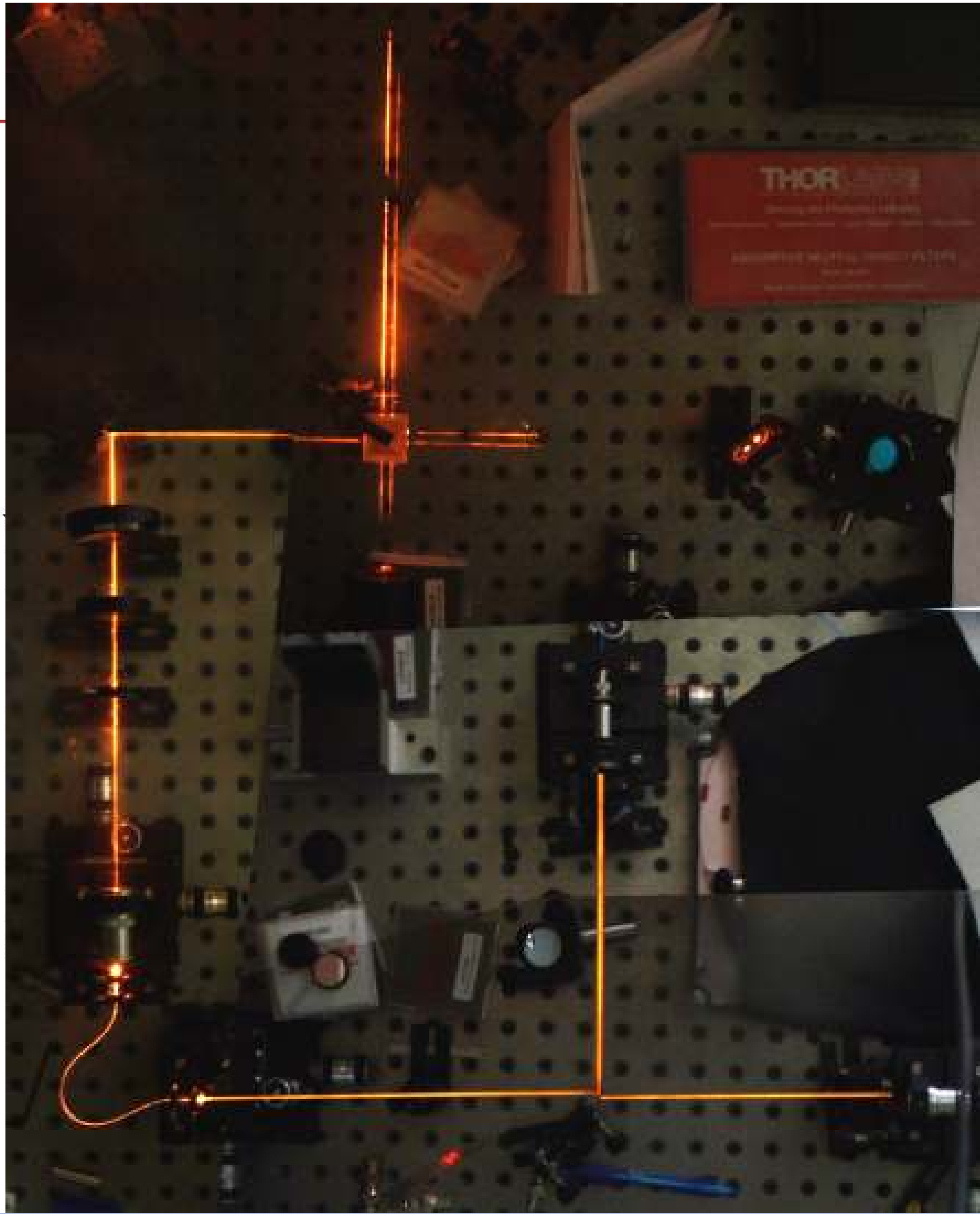
Example QIP experiments

fering
endent

50:50
Beam-splitter

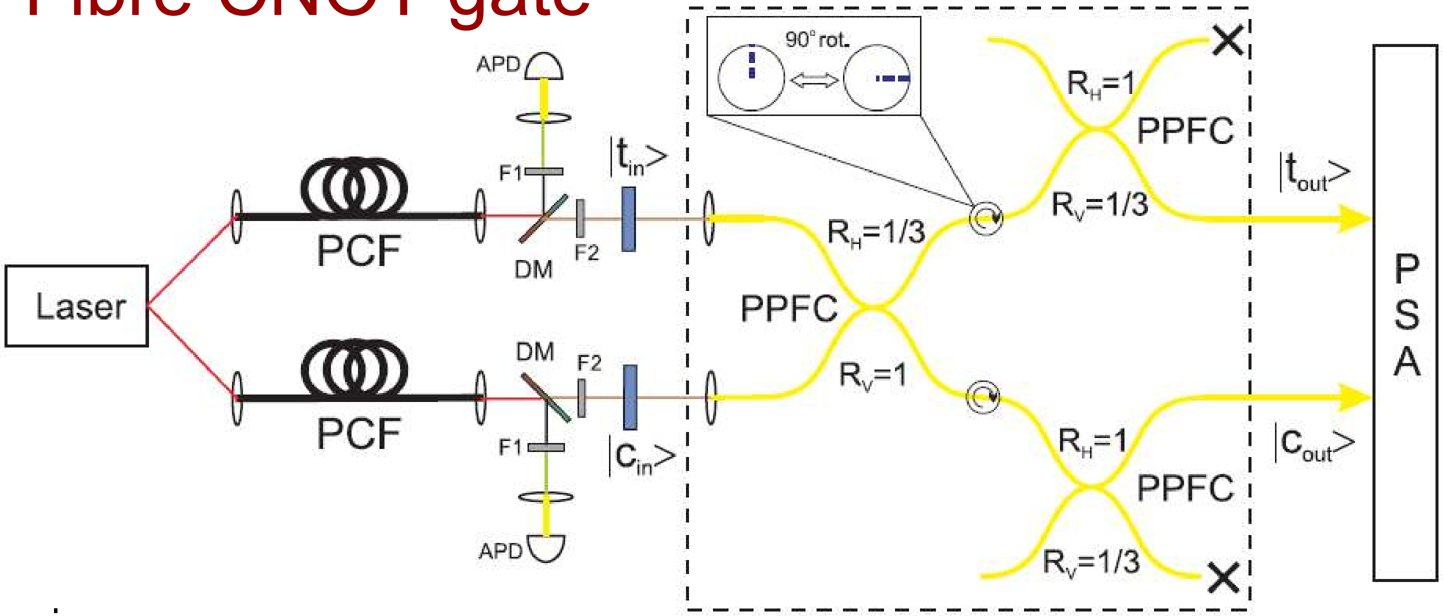
Attenuator
&
half wave-plate

PCF

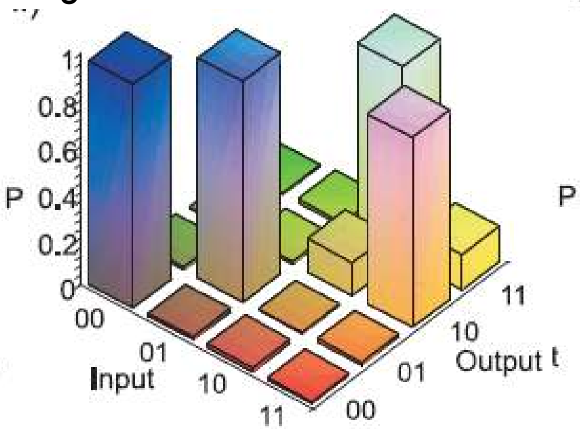


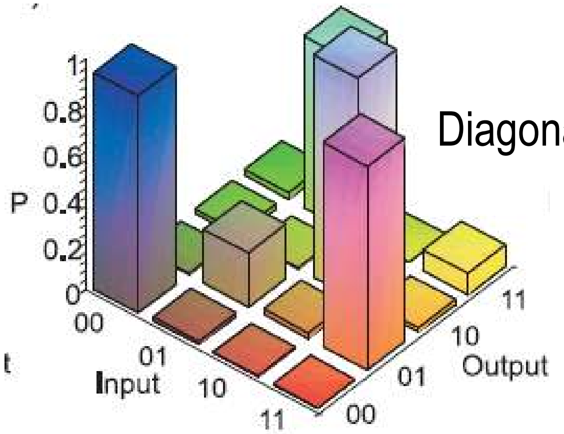
0.54
0.46
4

Fibre CNOT gate



Logical basis

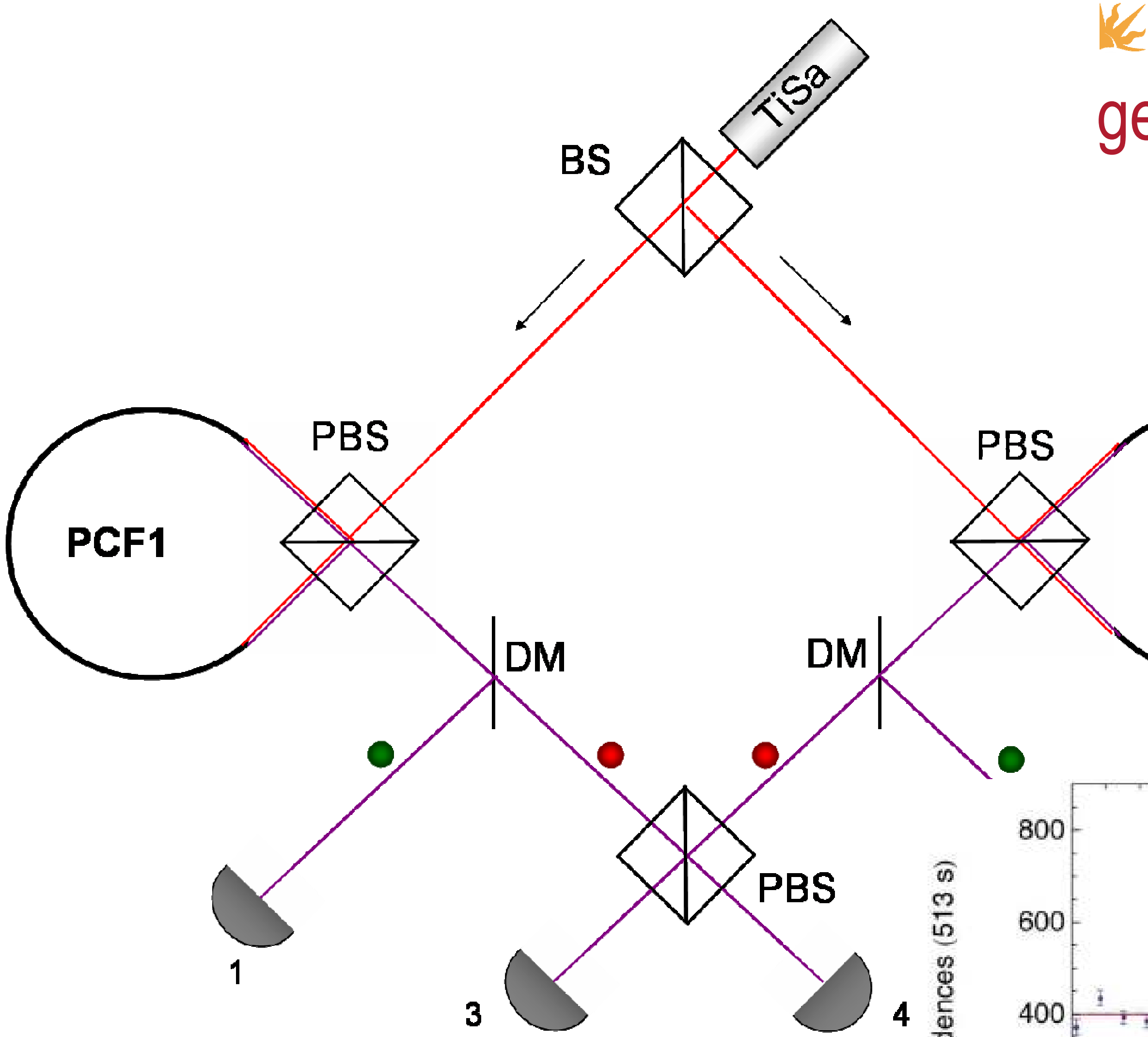


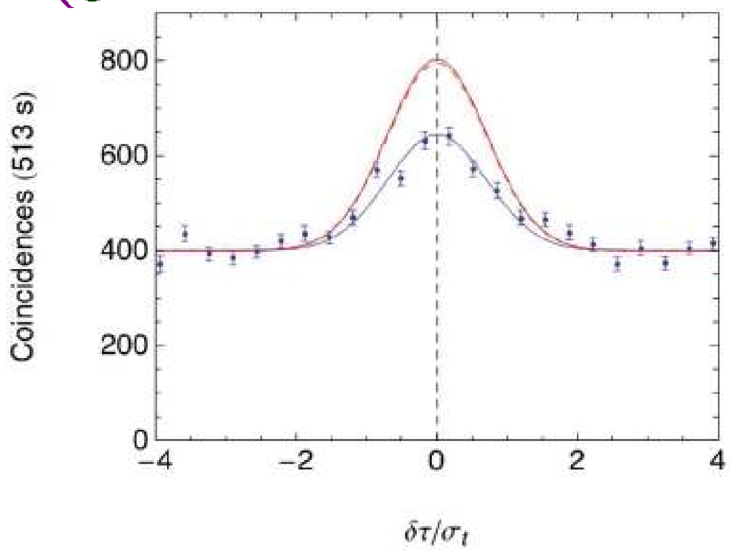


Diagonal basis

Clark et al Phys Rev A,

Cluster/GHZ state generation

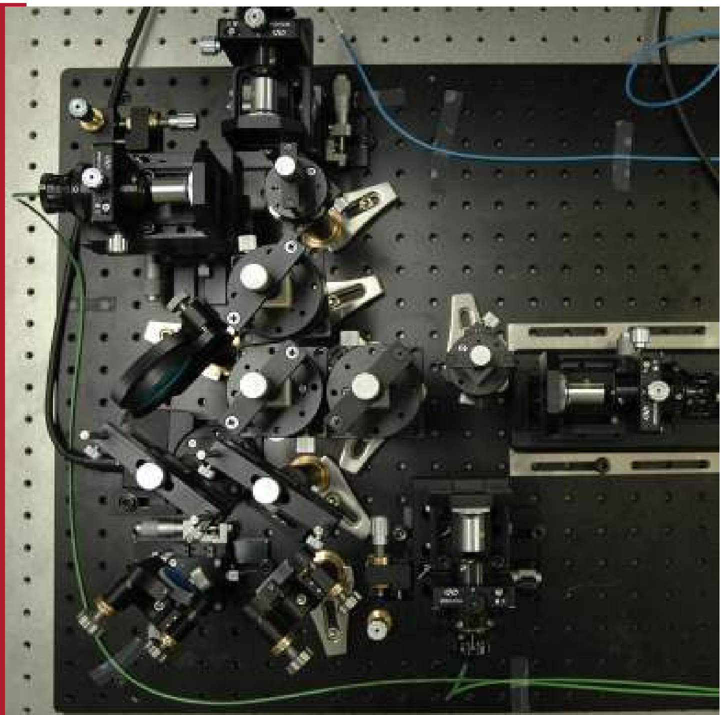


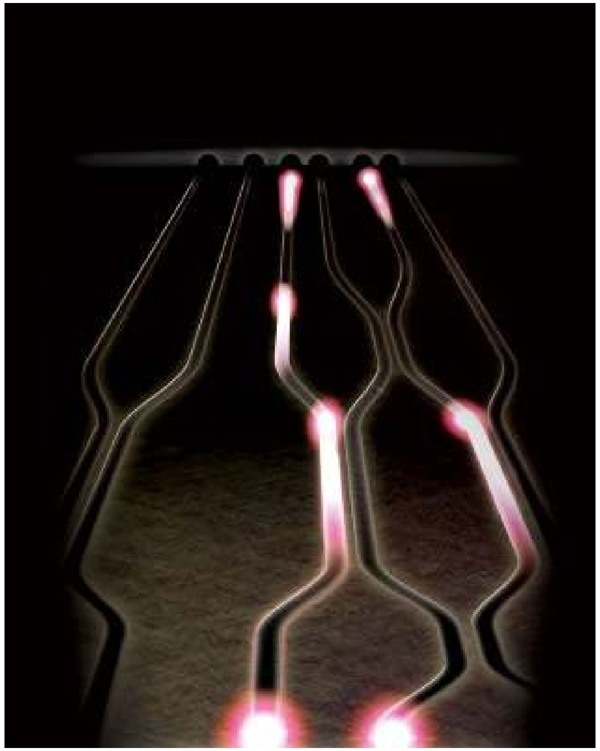


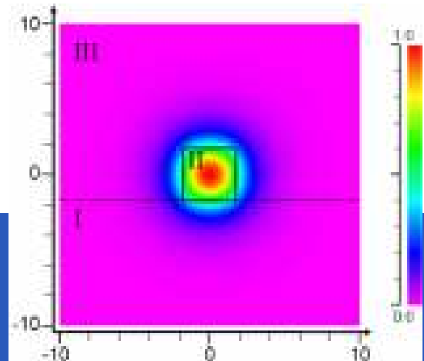
University of BRISTOL

Integrated quantum photonics

Reduce quantum circuits to integrated optics realisations

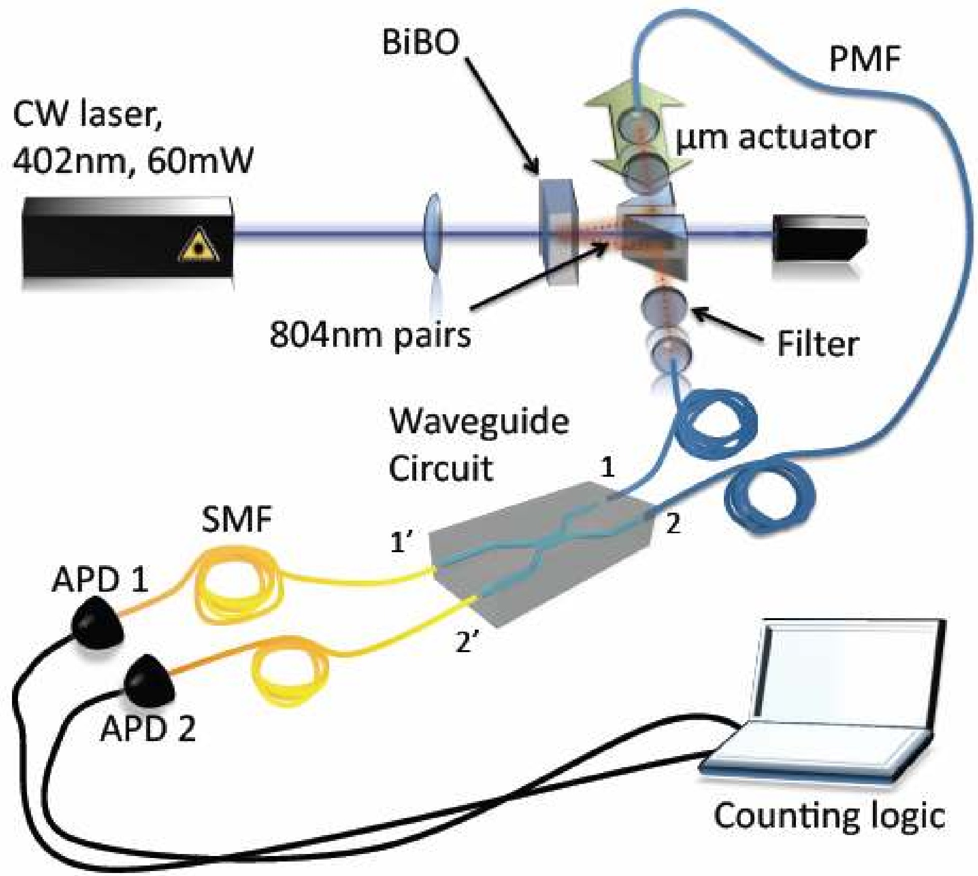




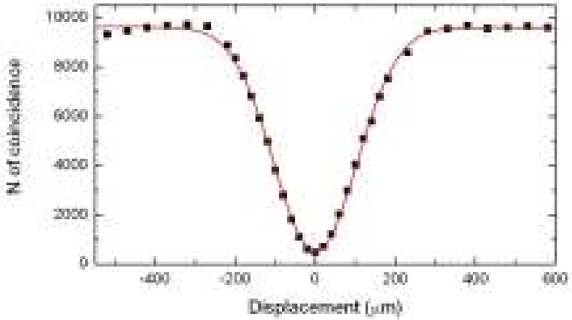


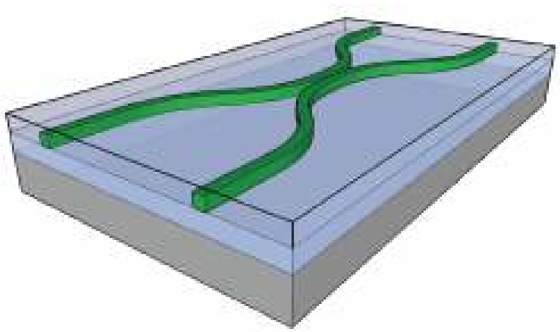
University of BRISTOL

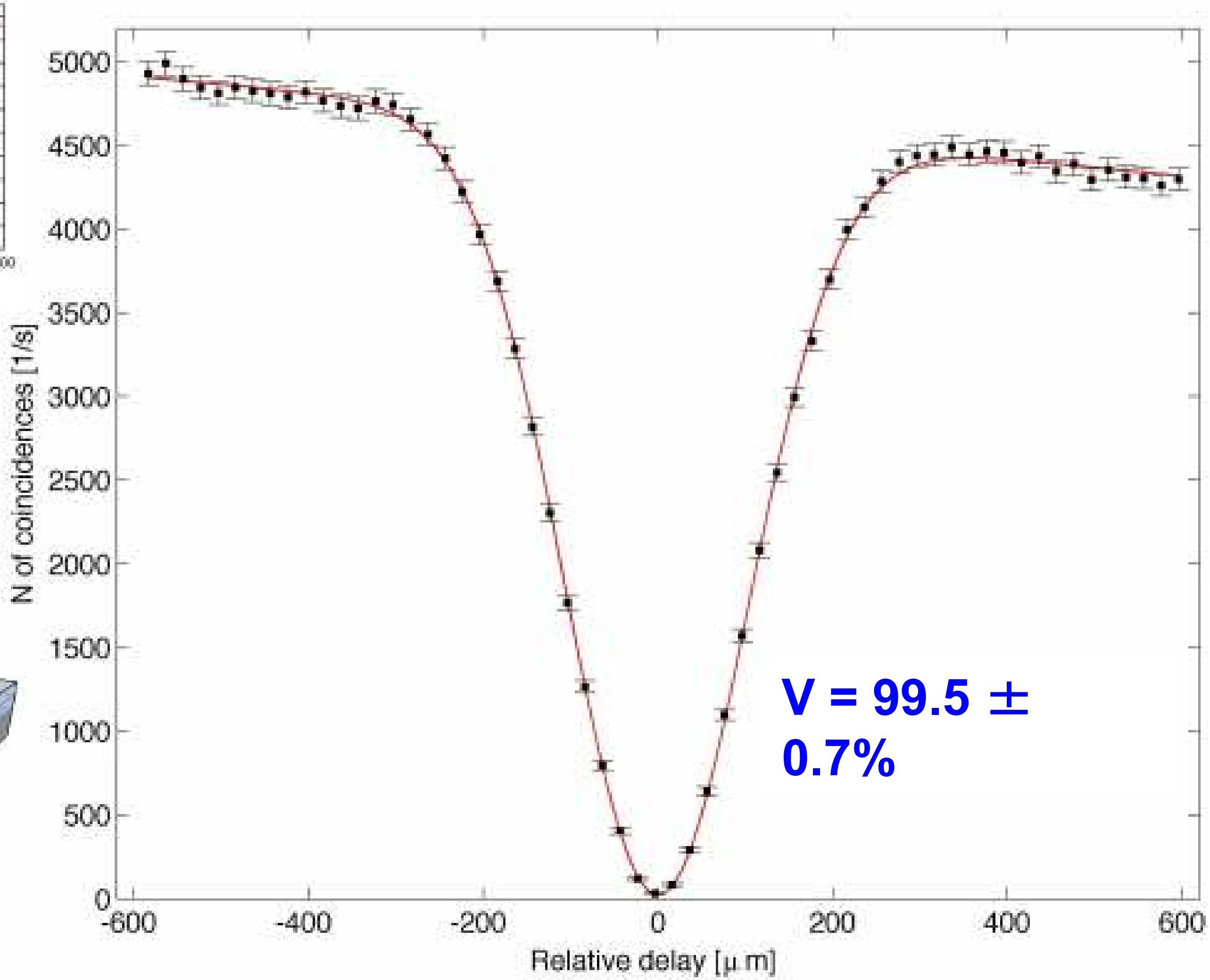
Integrated Quantum Photonics



Integrated Coupler





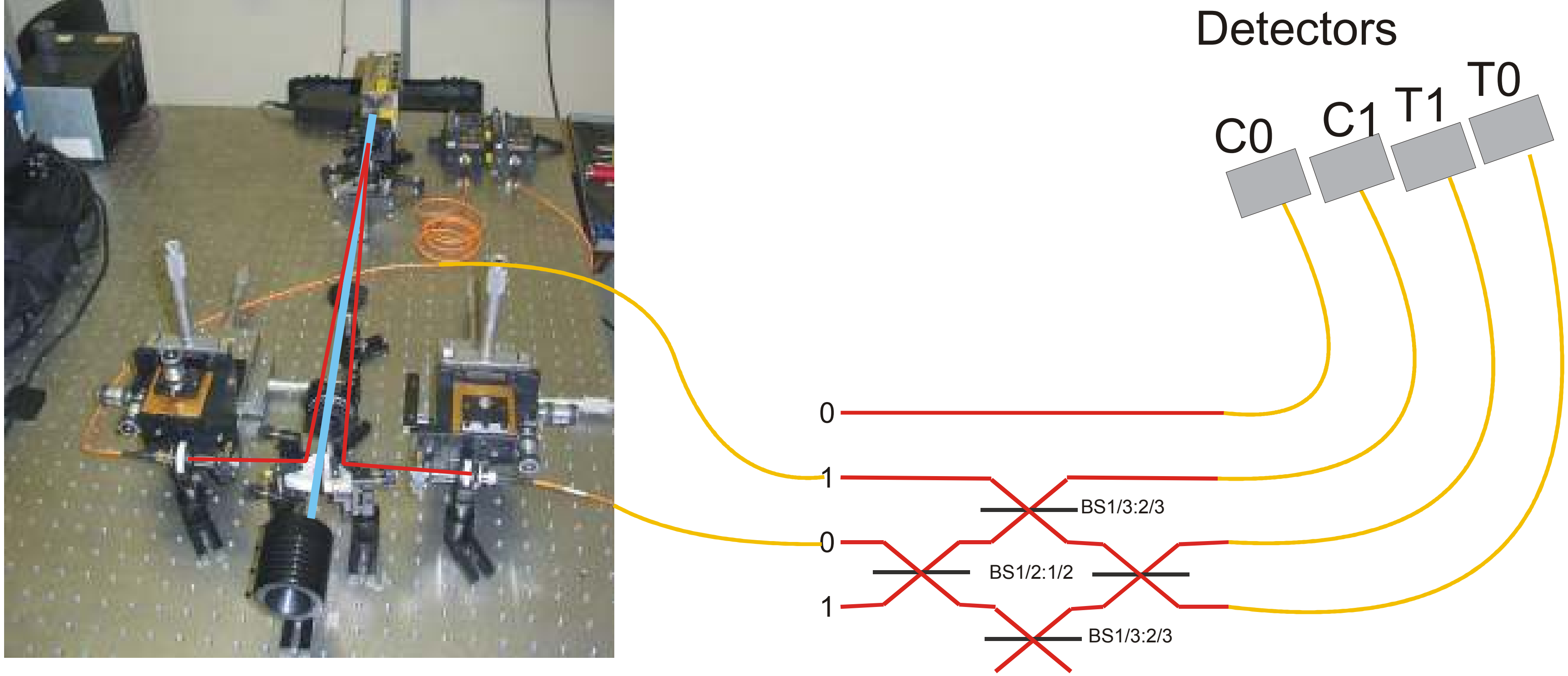


V = 99.5 ± 0.7%

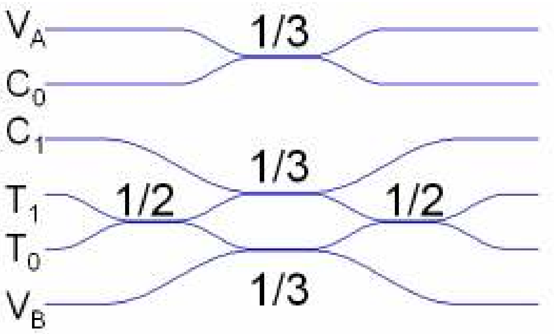
A. Politi, M. J. Cryan, J. G. Rarity, S. Yu, and J. L. O'Brien,. *Science,* **320**, 5876 (2008)

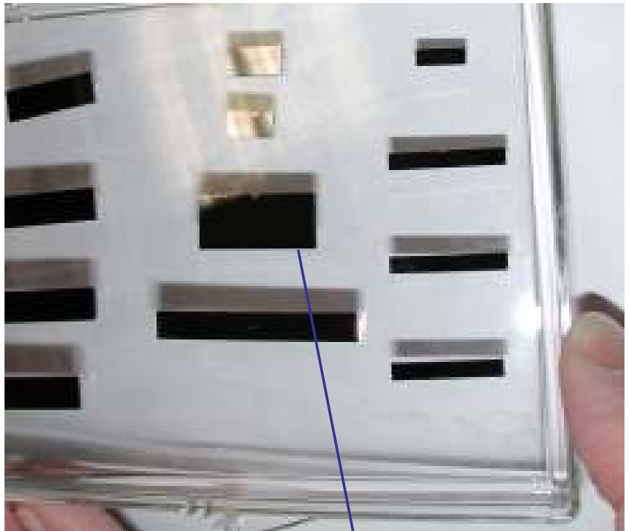
A Laing, A Peruzzo, M Rodas, A Politi, M Thompson, J L O'Brien, *in preparation*

CNOT Gate Experiment



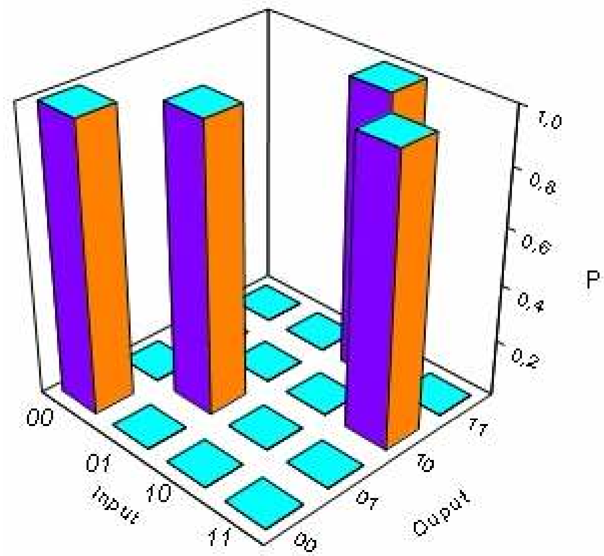
Integrated CNOT gate



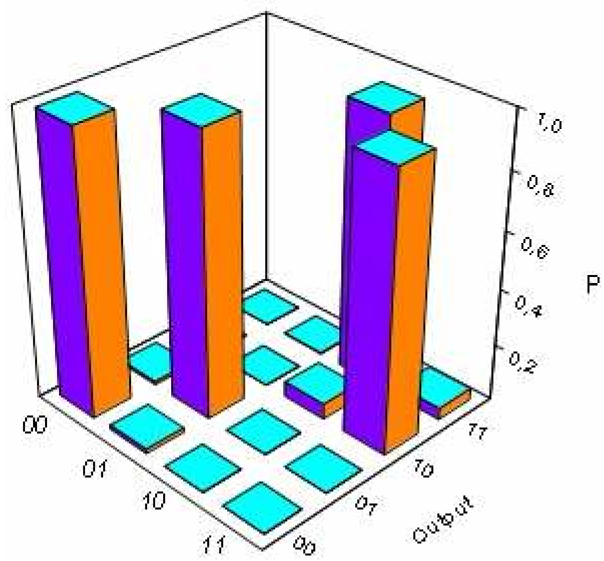


5 CNOT devices on the same chip

Ideal:



Measured:



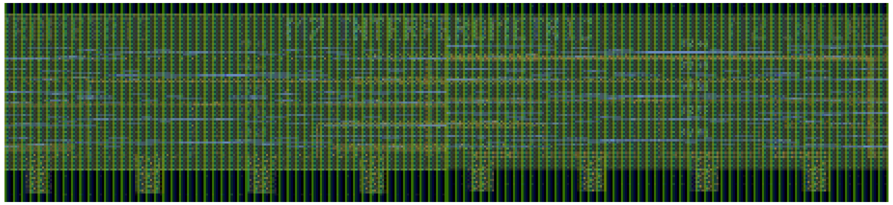
$$F_{ZZ} = 96.9 \pm 0.1 \%$$

$$S_{ZZ} = 99.0 \pm 0.1 \%$$

A. Politi, M. J. Cryan, J. G. Rarity, S. Yu, and J. L. O'Brien,. *Science,* **320**, 5876 (2008).

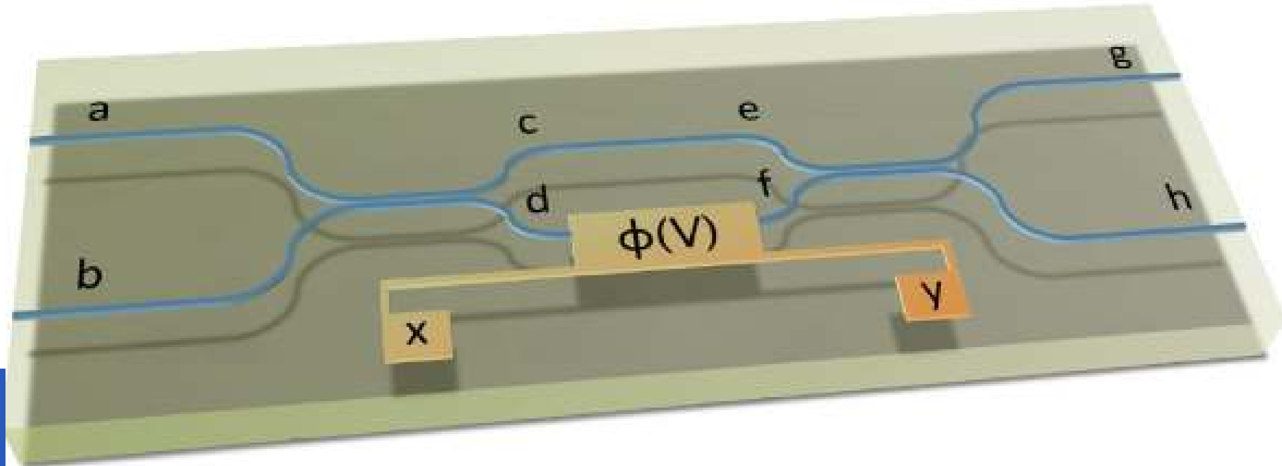
Quantum state manipulation

With resistive heater

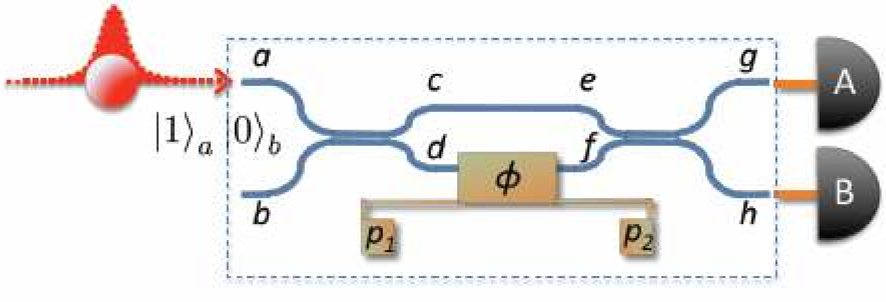


Change refractive index of the WG.

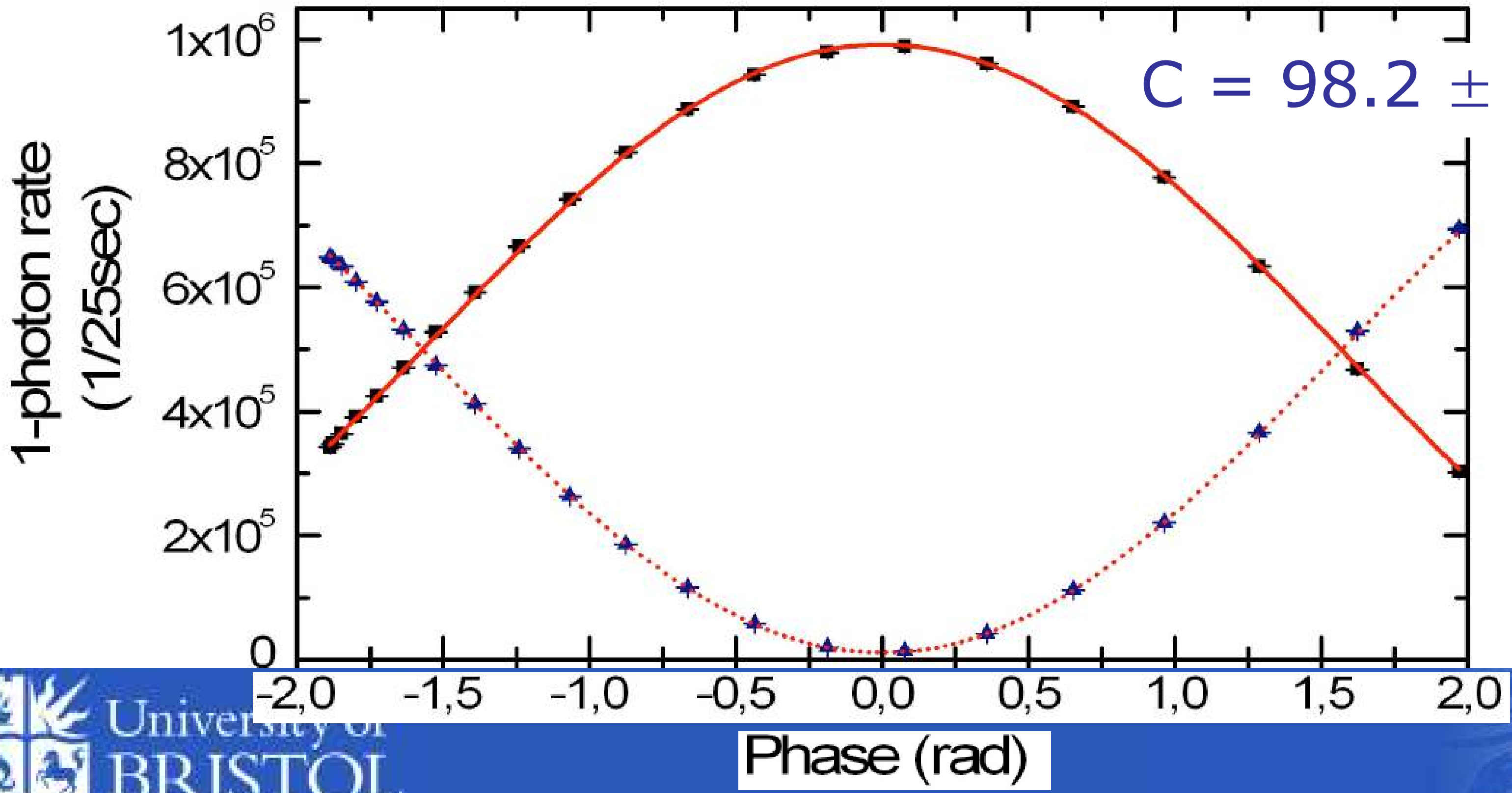
Choose splitting ratio of exit ports.



Integrated Phase Control
1-photon

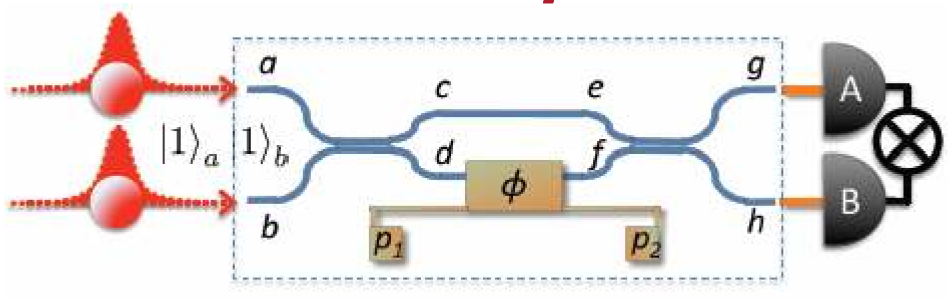


$$P_g = 1 - P_h = \frac{1}{2}\left[1 - \cos(\phi)\right]$$

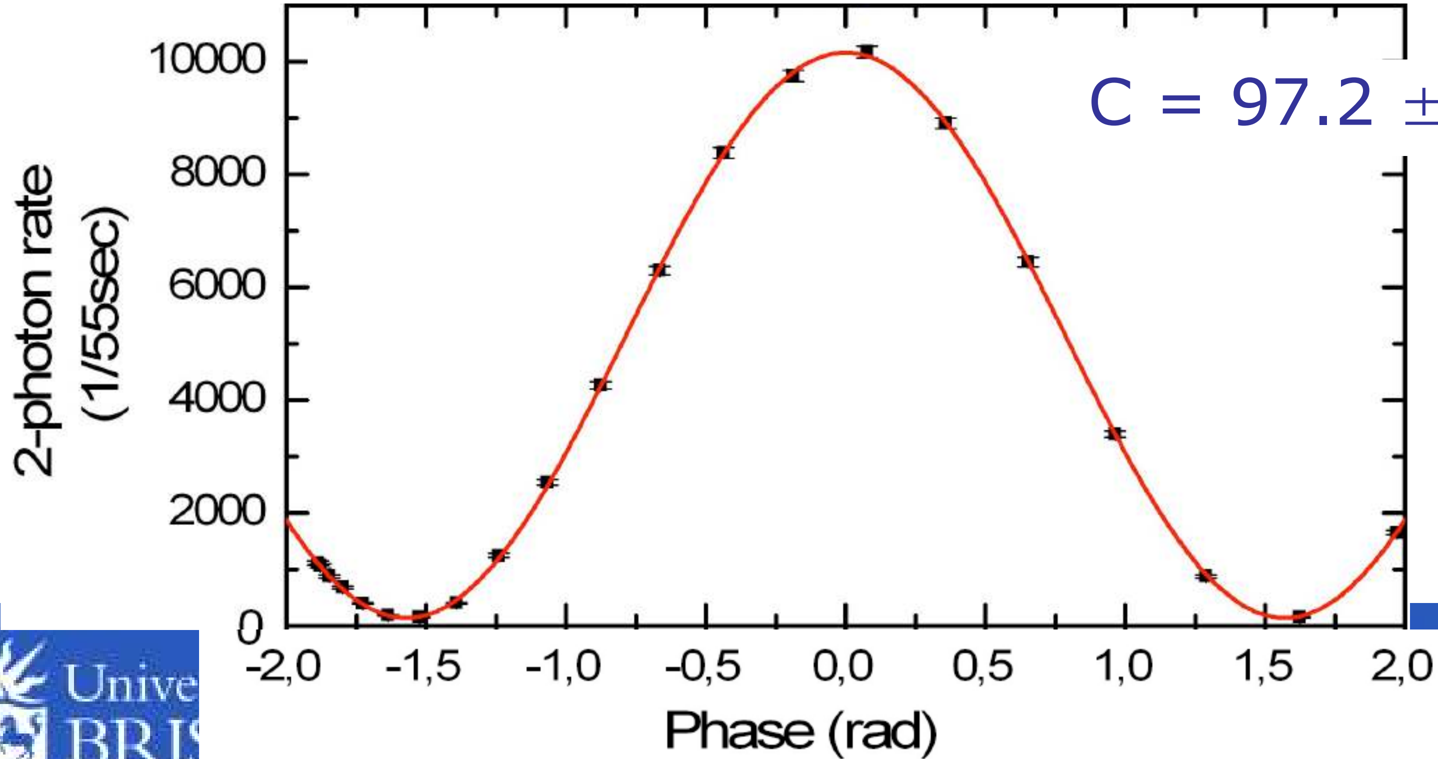


C = 98.2 ± 0.3 %

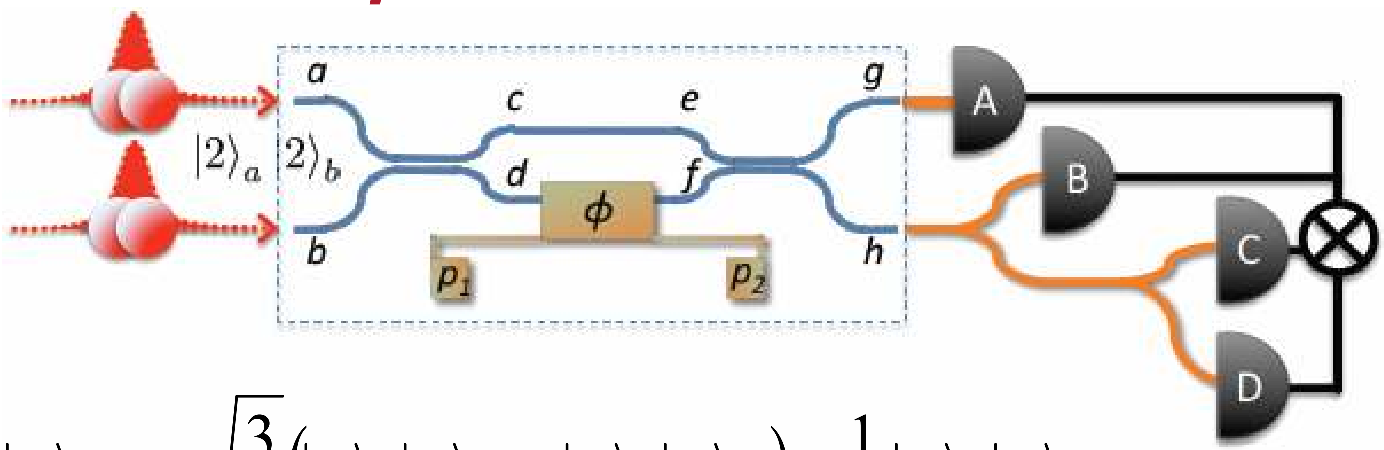
Integrated Phase Control
2-photon



$$|1\rangle_a |1\rangle_b$$
$$\frac{1}{\sqrt{2}}\left(|2\rangle_c |0\rangle_d - |0\rangle_c |2\rangle_d\right)$$
$$\frac{1}{\sqrt{2}}\left(|2\rangle_e |0\rangle_f - e^{2i\phi} |0\rangle_e |2\rangle_f\right)$$



Integrated Phase Control
4-photon



$$|2\rangle_a|2\rangle_b \rightarrow \sqrt{\frac{3}{8}}\left(|4\rangle_c|0\rangle_d + |0\rangle_c|4\rangle_d\right) + \frac{1}{2}|2\rangle_c|2\rangle_d$$

$$P(3g,1h) = P(3g,1h) = \frac{3}{8}\left(1-\cos 4\phi\right)$$

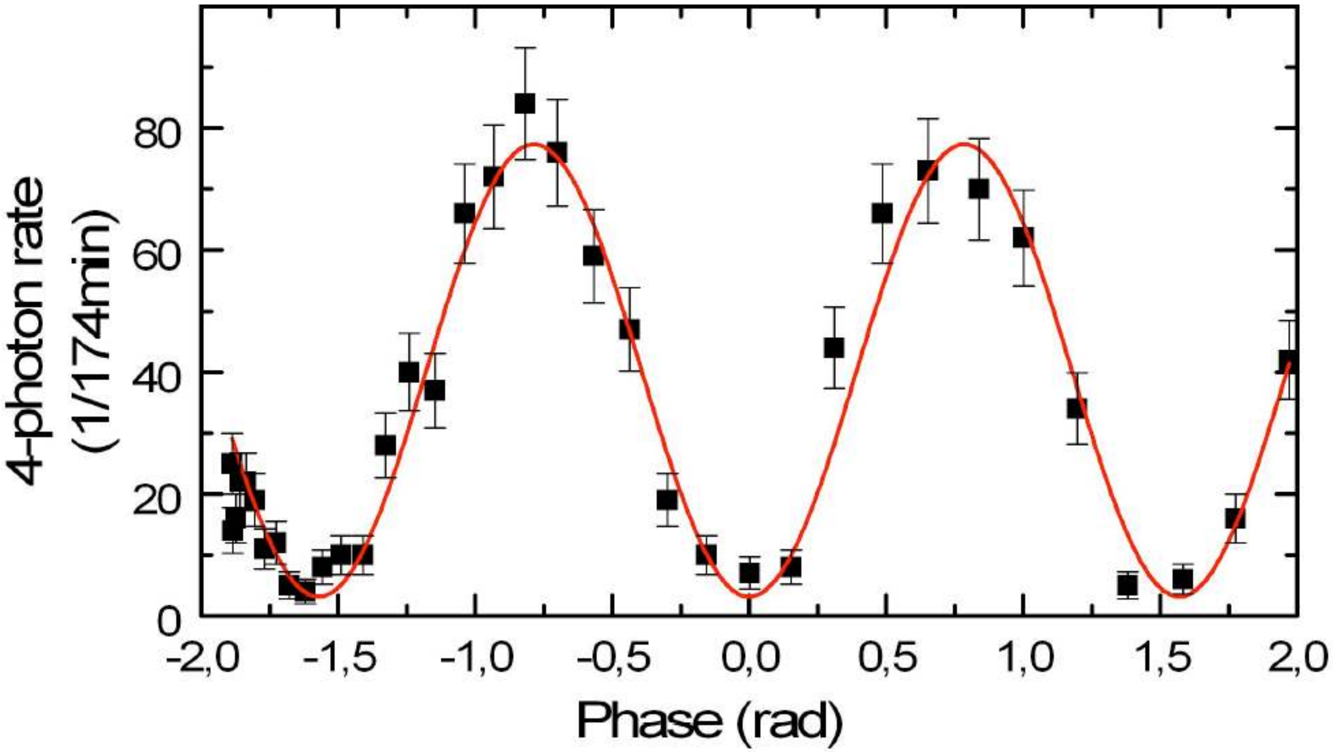
Quantum Metrology:

Precision: $\Delta\phi = 1/N$ against $\Delta\phi = 1/\sqrt{N}$

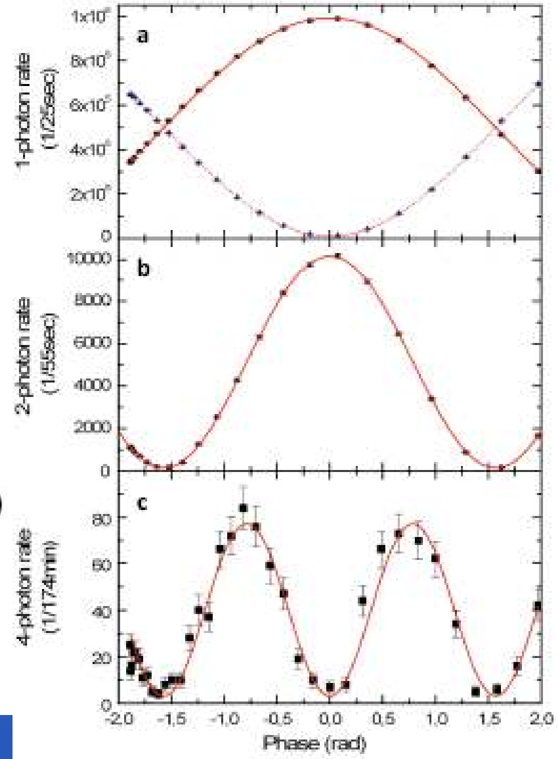
Heisenberg limit

Shot noise limit

Integrated Phase Control
4-photon

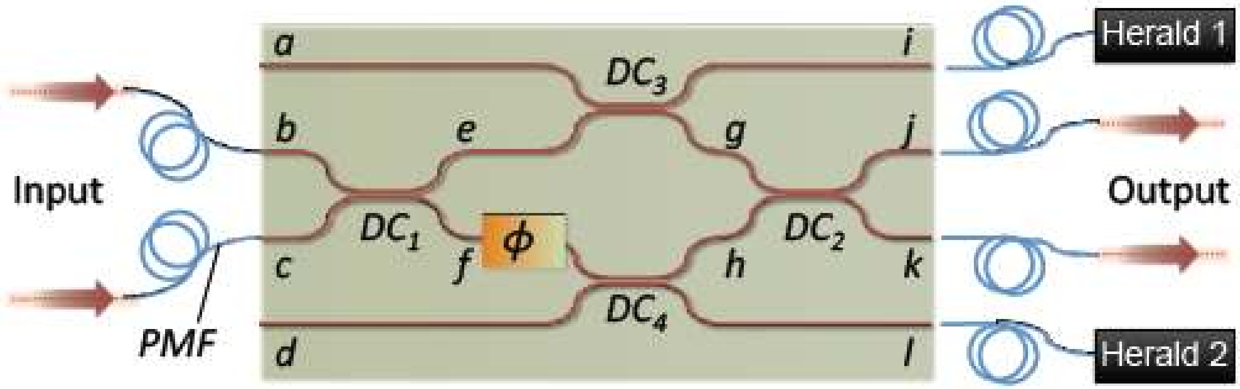


C = 92 ± 4 %



J. F. C. Matthews, A. Politi, A. Stefanov, J. L. O'Brien, to appear in *Nature Photonics*

Heralded N00N states

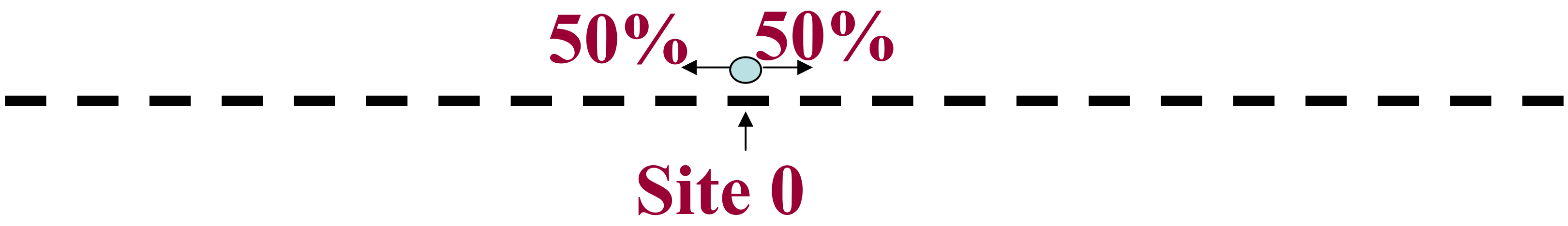


In interferometer

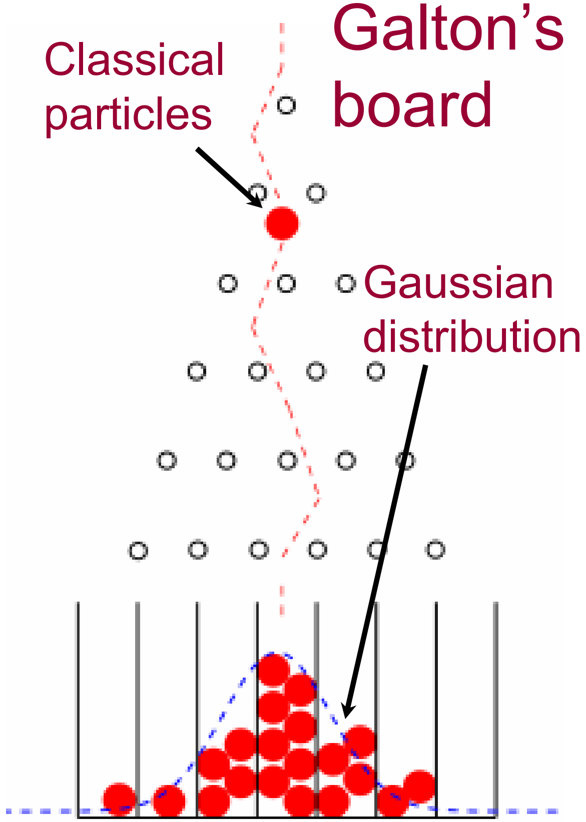
$$|3\rangle_b |3\rangle_c \xrightarrow{DC_1} \sqrt{\frac{5}{8}} |6 :: 0\rangle^0_{e,f} + \sqrt{\frac{3}{8}} |4 :: 2\rangle^0_{e,f}$$

Quantum walks

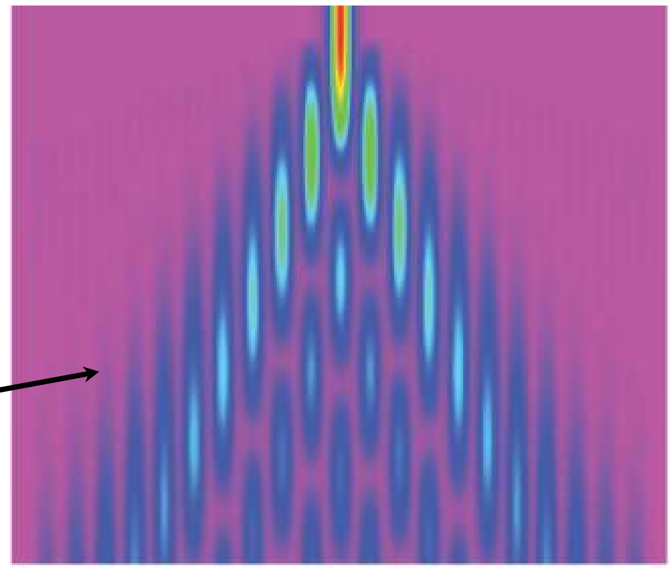
Random walk vs quantum walk

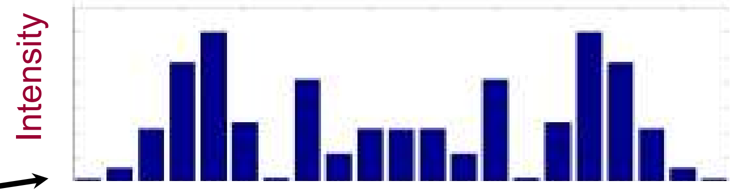


Galton's board



Scatering in waveguide array





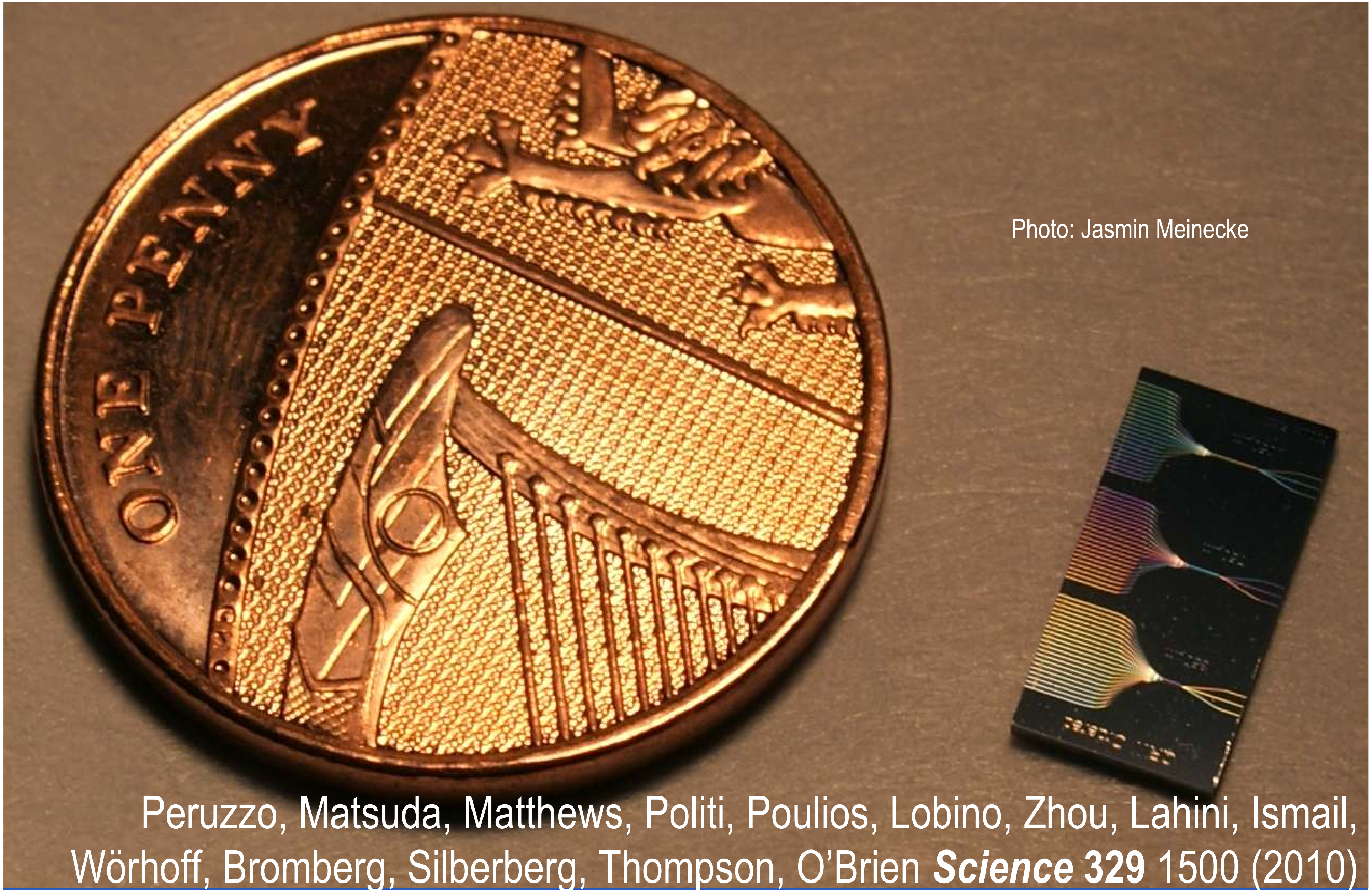
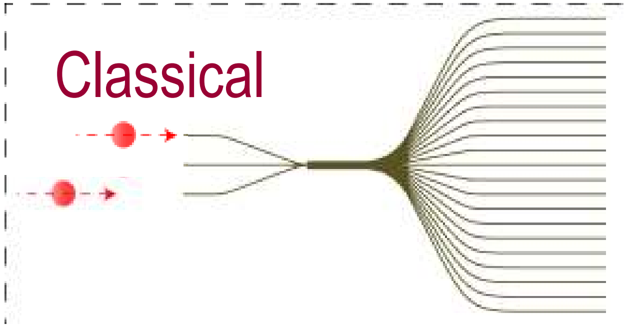
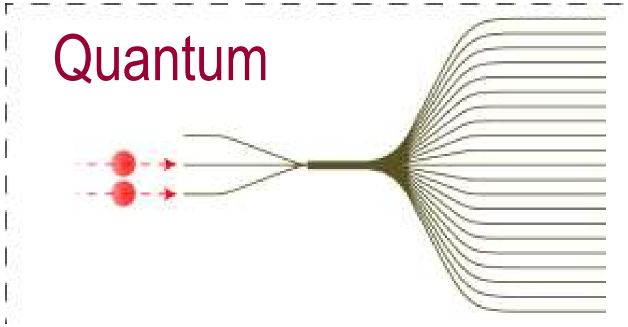


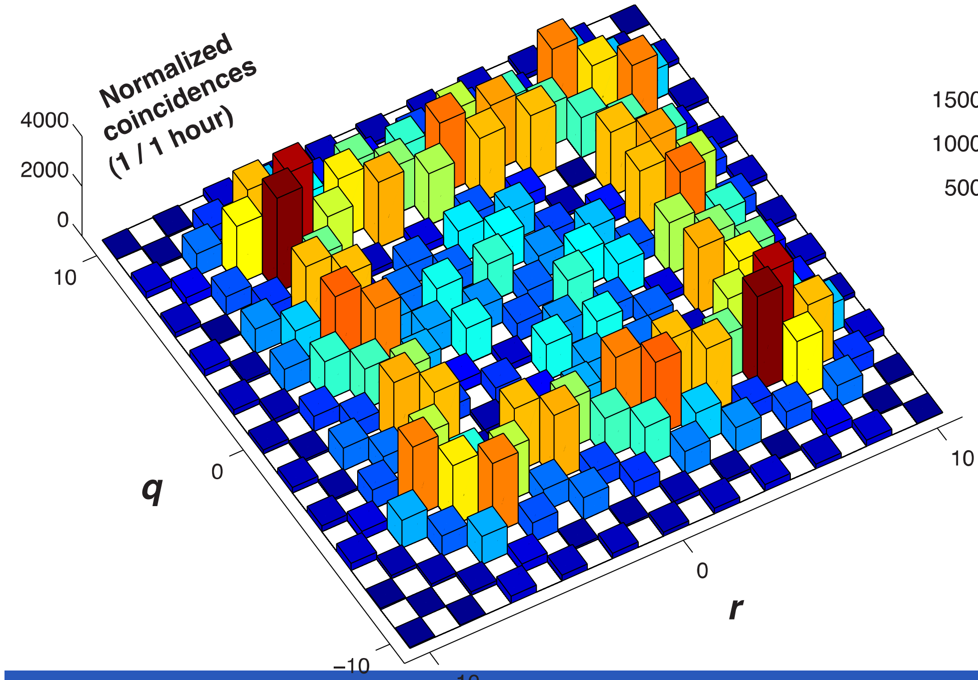
Photo: Jasmin Meinecke

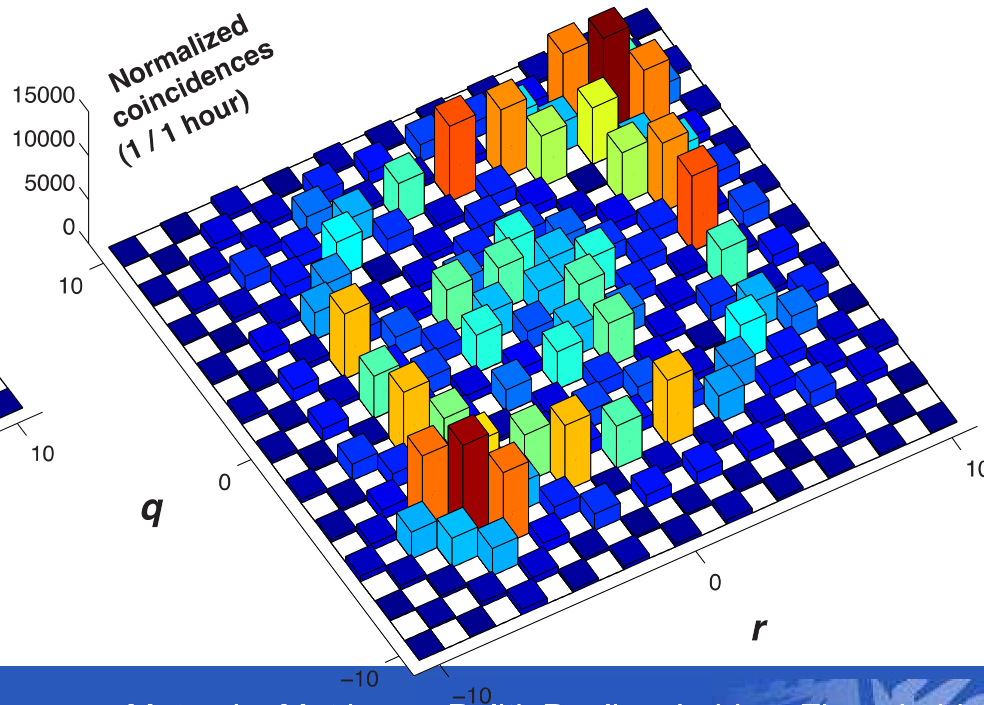
Peruzzo, Matsuda, Matthews, Politi, Poulios, Lobino, Zhou, Lahini, Ismail, Wörhoff, Bromberg, Silberberg, Thompson, O'Brien ***Science* 329** 1500 (2010)

Two-Photon Correlation Matrix (11 state)









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Linear optics prospectives

- Deterministic sources, gates needed
- Unit efficiency detectors
- On-chip generation, manipulation and detection leads to high efficiency
- 10 photons in 100 waveguides = non-computable (? useful)
- Simulation of simple quantum chemistry
- Scalability=High complexity