Quantum Optical Implementations

SUSSP Summer School AUG 2011

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Structure

Lecture 1: 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

Lecture 2: Experimental implementations

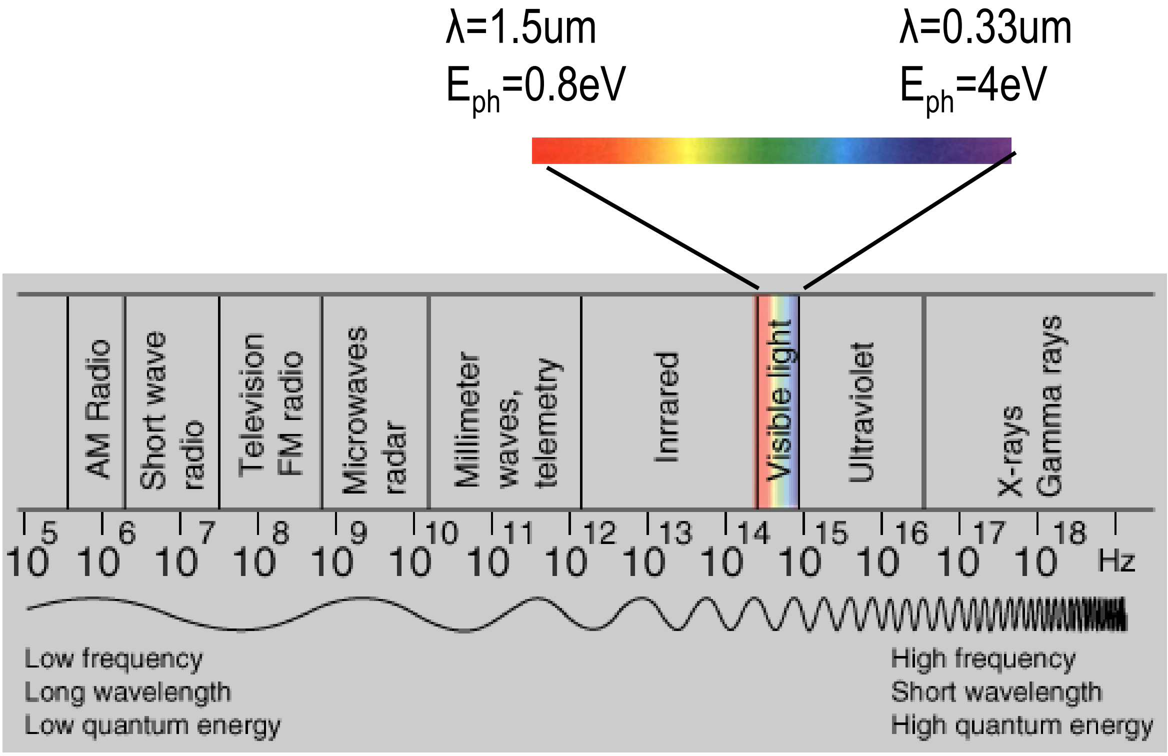
- Detection
- Single photon sources
- Pair photon sources
- Entangled state sources
- Single photon detection
- Gate realisations and experiments
- N00N states

Structure

Lecture 3: More efficient gates, hybrid QIP.

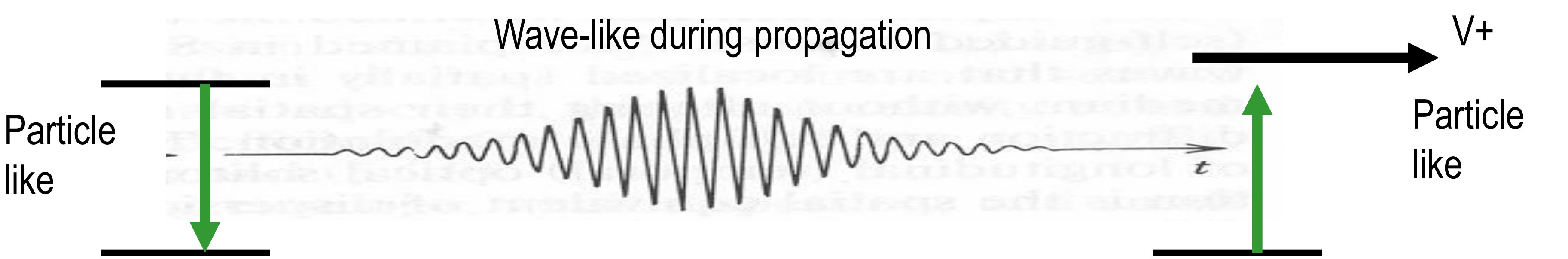
- 2-level system in a cavity
- Charged quantum dots in cavity
- Spin-photon interface
- Quantum repeater
- Progress towards experiment

The electro-magnetic spectrum



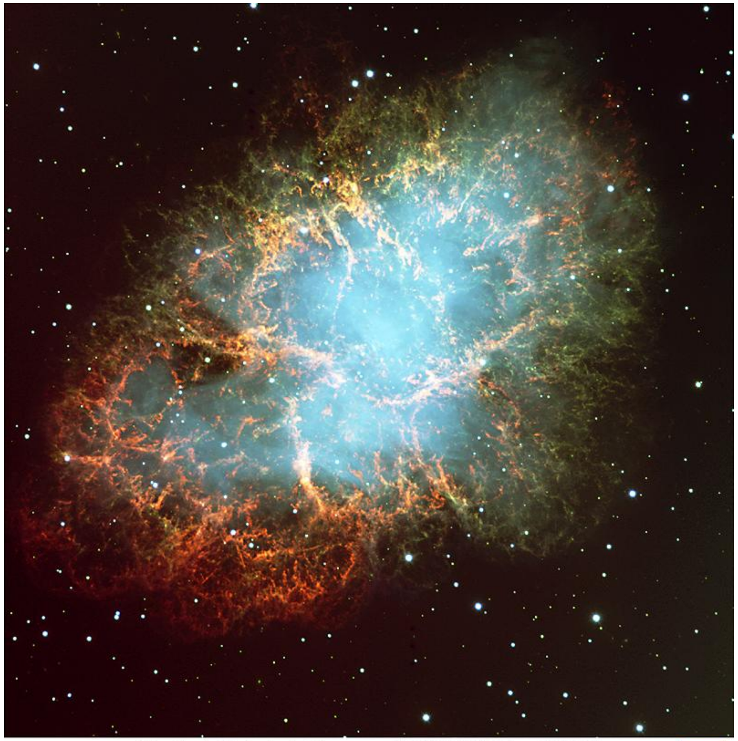
Optical Photon energy

$E_{ph}=hf>>KT$



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**

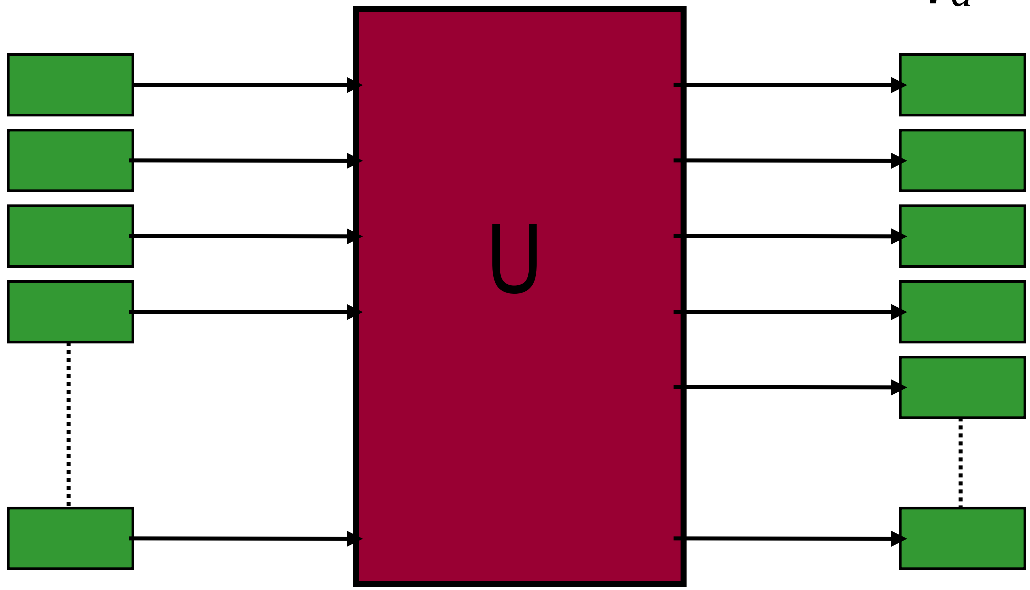


The Crab Nebula in Taurus (VLT KUEYEN + FORS2)

ESO PR Photo 40f/99 (17 November 1999)

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 η<0.5 F>0.99
Non-linear optics η~1 F>0.9?

Detectors

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

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

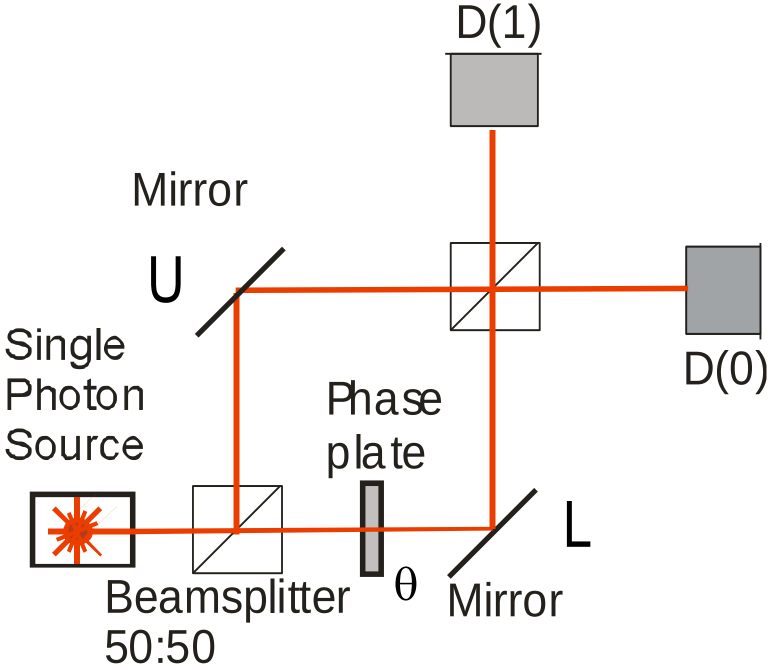
Manipulating single photons as qubits

Interference effects with single photons

Single photon can only be detected in one detector

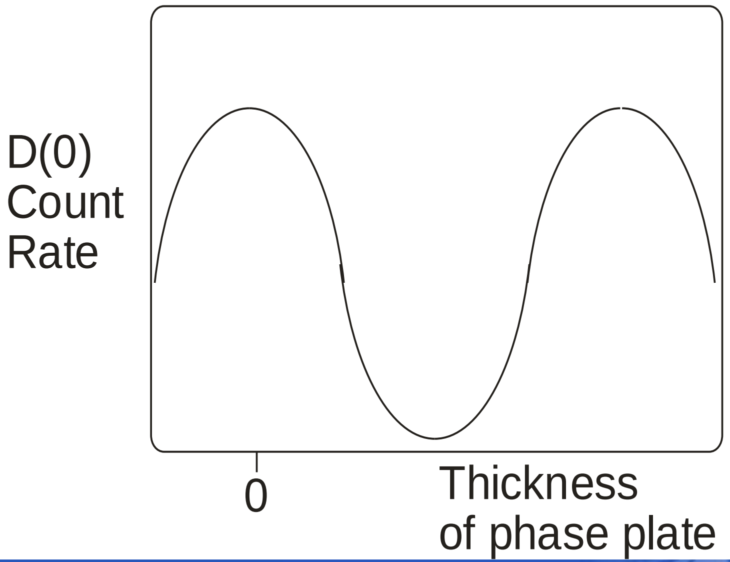
However interference pattern built up from many individual counts

P. Grangier et al, Europhysics Letters 1986



In the interferometer we have superposition state

$$|\Psi\rangle = \frac{1}{\sqrt{2}}\left(|1\rangle_U + e^{i\theta}|1\rangle_L\right)$$



Simple analysis:

$$r = i/\sqrt{2}, t = 1/\sqrt{2} \rightarrow$$

$$|\Psi\rangle = 1/\sqrt{2}\,(i|1\rangle_U + e^{i\theta}|1\rangle_L)$$

$$\rightarrow$$

$$|\Psi\rangle_{out} = 1/2\left[i(1+e^{i\theta})|0\rangle + (1-e^{i\theta})|1\rangle\right]$$

$$|\Psi\rangle_{out} = ie^{i\theta/2}\left[\cos\tfrac{\theta}{2}|0\rangle + \sin\tfrac{\theta}{2}|1\rangle\right]$$

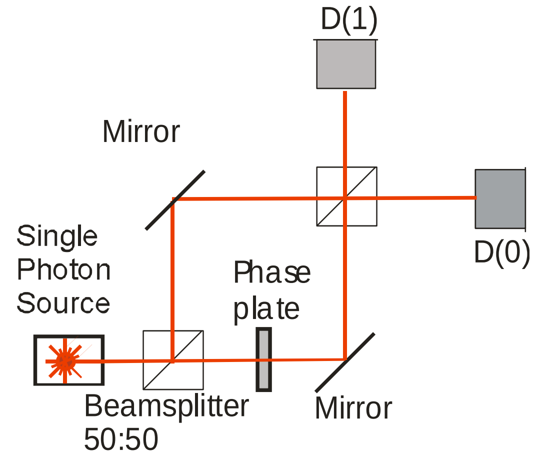
In general

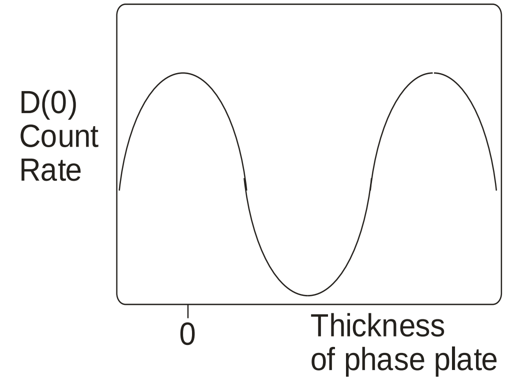
$$|\Psi\rangle = \alpha|0\rangle + \beta|1\rangle \qquad |\alpha|^2 + |\beta|^2 = 1$$

Detection probability $|\alpha|^2$

$$P(0) = (1+\cos\theta)/2$$

$$P(1) = (1-\cos\theta)/2$$





Encoding one bit per photon and single qubit rotations

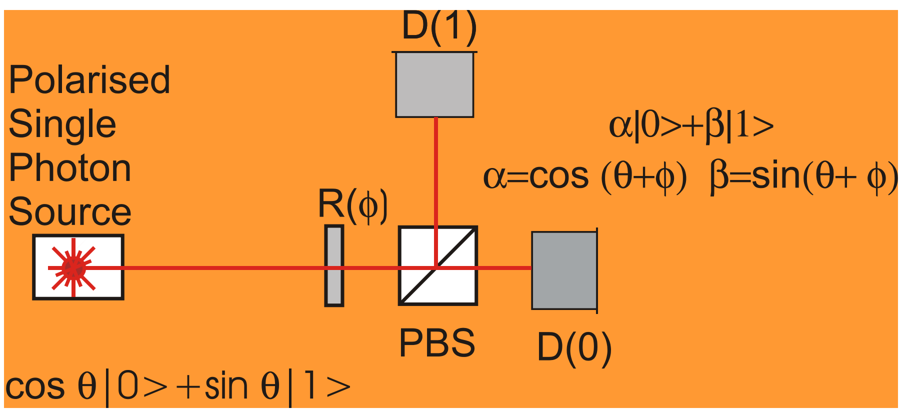
Encoding single photons using two polarisation modes

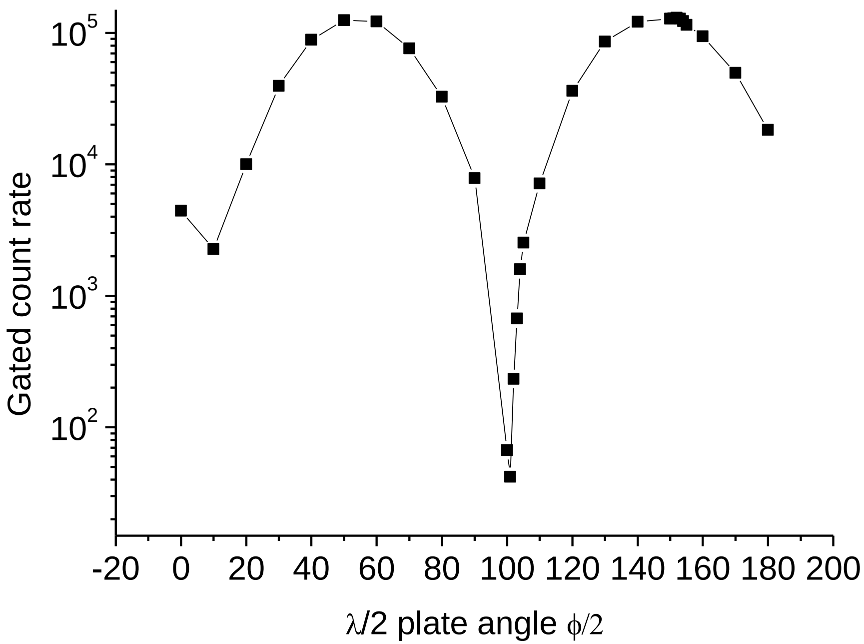
Superposition states of ‘1’ and ‘0’

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

Probability amplitudes α , β

Detection Probability: $|\alpha|^2$



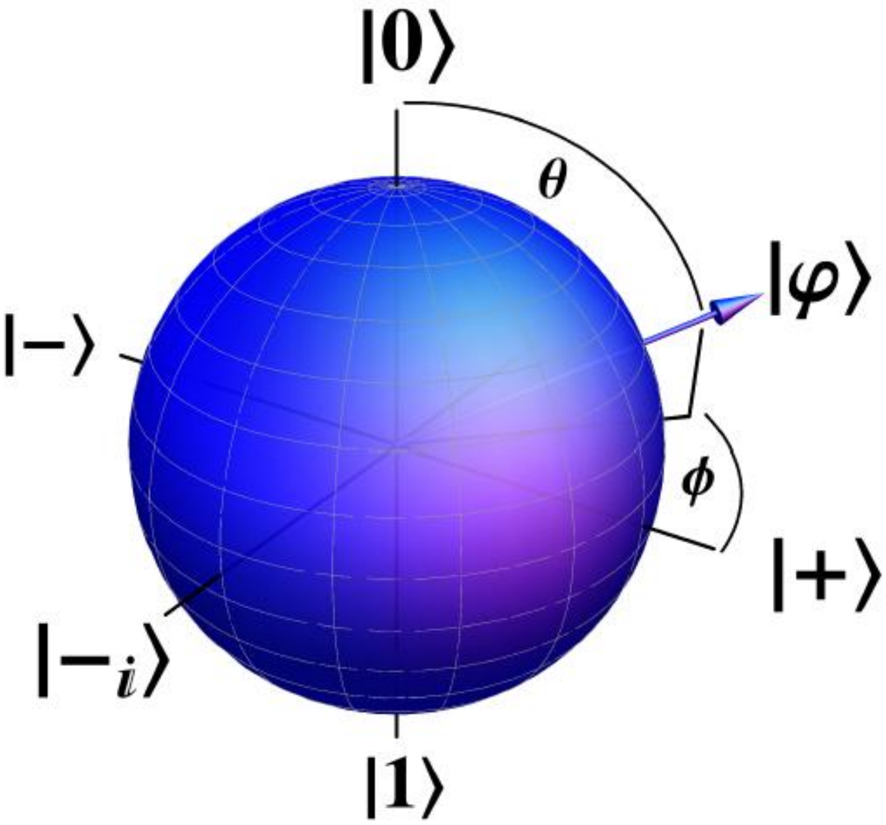


Single photon encoding showing QBER<5.10^{-4} (99.95% visibility)

Bloch Sphere Representation of a Qubit

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

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

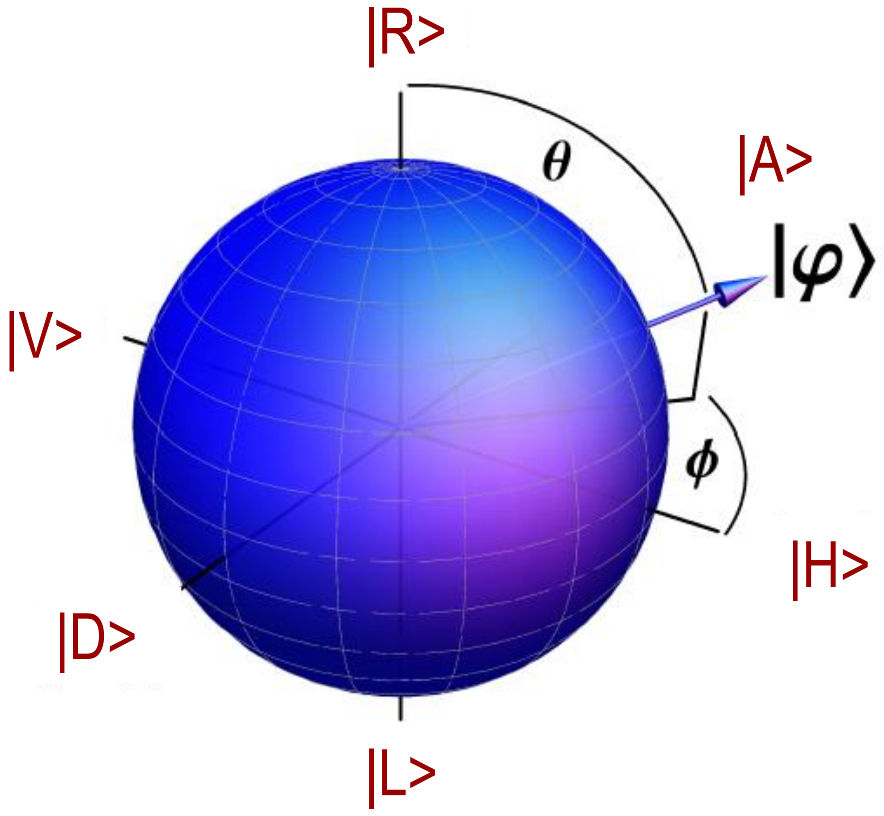


Simple problem: write the states

|+i>, |-i>

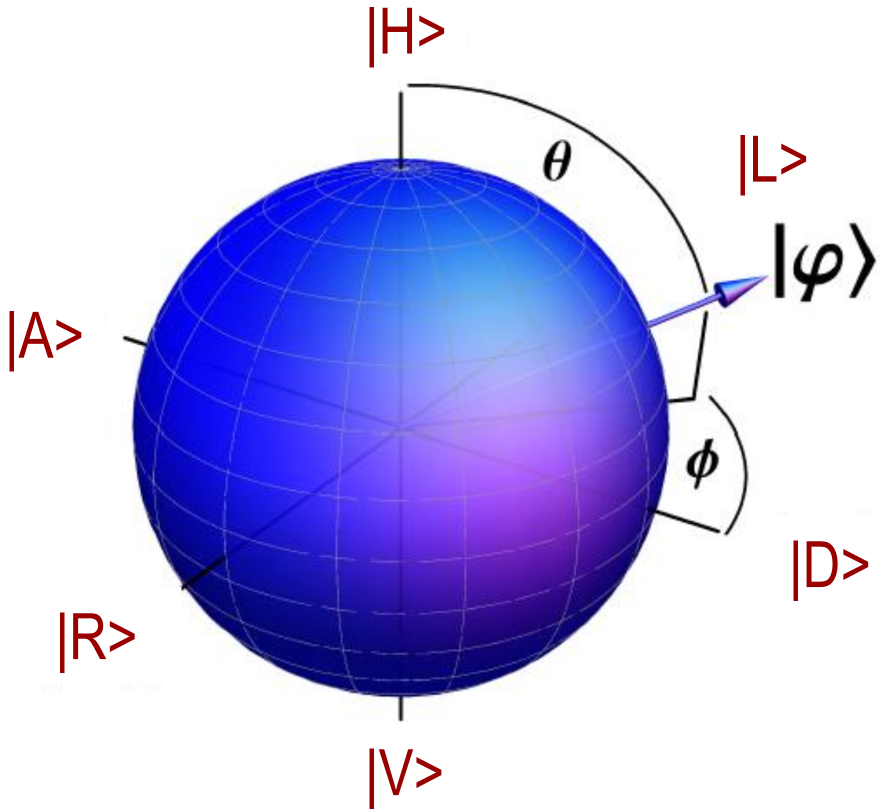
Bloch Sphere: computational basis = circular polarisation states

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



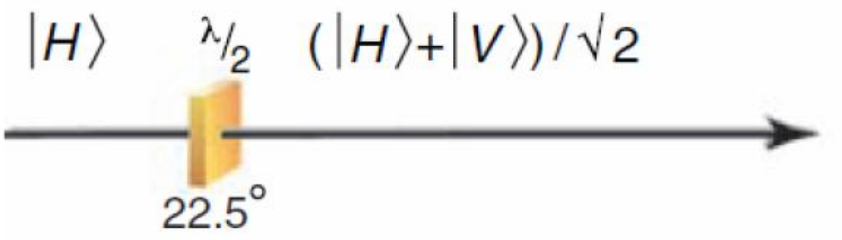
Bloch Sphere: computational basis = linear polarisation states

$$\left|\Psi\right\rangle = \cos\tfrac{\theta}{2}\,|\,H > + e^{i\phi}\sin\tfrac{\theta}{2}\left|V\right\rangle$$

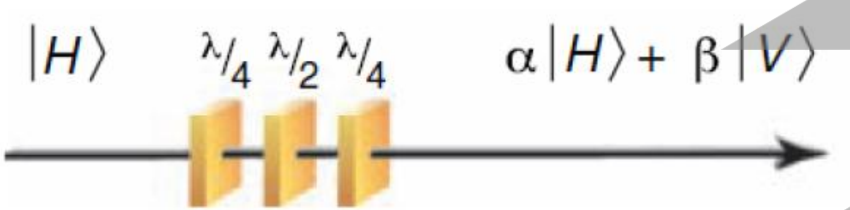


Arbitrary rotations

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



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



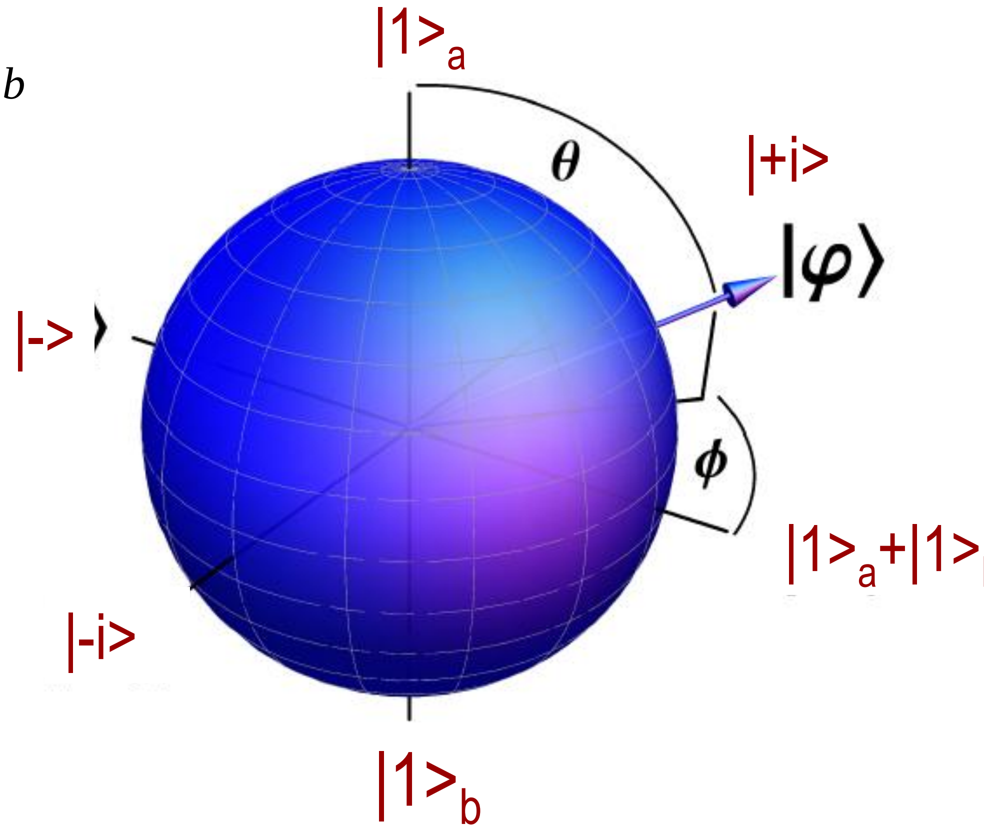
$$Q\hat{W}P = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 + i\cos(2\varphi) & i\sin(2\varphi) \\ i\sin(2\varphi) & i - \cos(2\varphi) \end{pmatrix}$$

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

Bloch Sphere: computational basis = path a/b

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



Waveguide based interferometer to create arbitrary path encoded states

50:50 beamsplitter

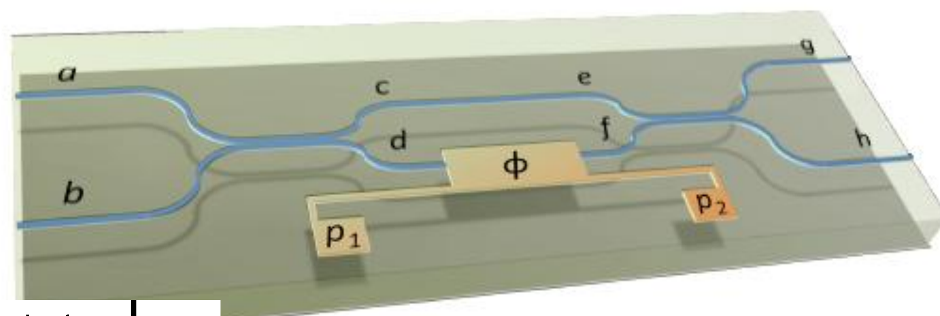
$$H_c \doteq \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & i \\ i & 1 \end{pmatrix}$$

Phase shift

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

$$a_a^\dagger |0\rangle \xrightarrow{H_c} \frac{1}{\sqrt{2}} \left(a_c^\dagger + i a_d^\dagger\right) |0\rangle$$

$$\xrightarrow{Z(\phi)} \frac{1}{\ } \left(a_c^\dagger + i e^{i\phi} a_d^\dagger\right) |0\rangle$$



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

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

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 (see Padgett):
  - 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

$$\left|\Psi^{+}\right\rangle = \left|01\right\rangle + \left|10\right\rangle$$

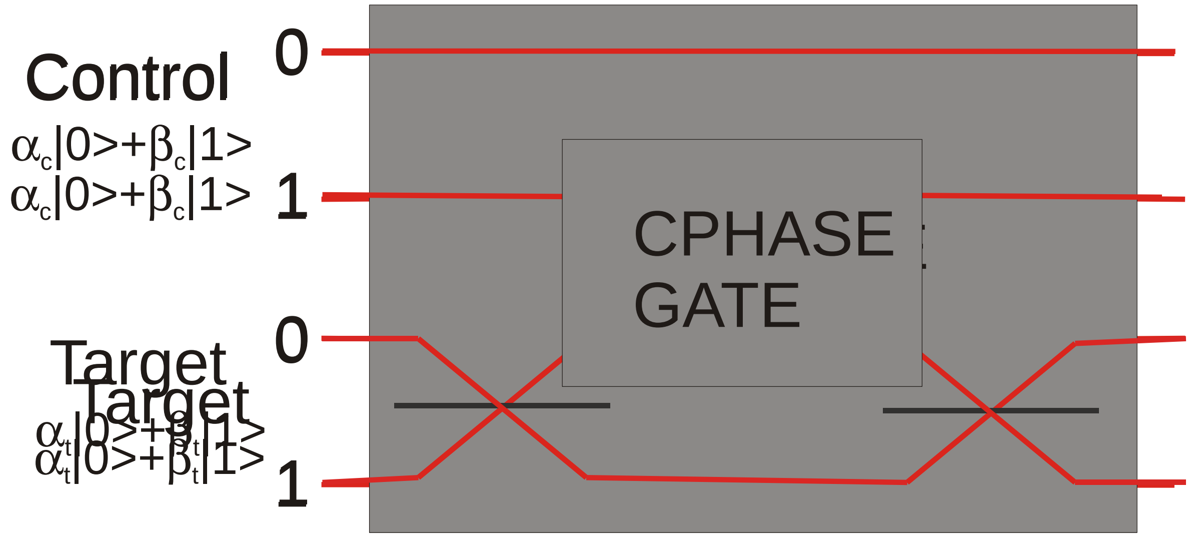
$$\left|\Psi^{-}\right\rangle = \left|01\right\rangle - \left|10\right\rangle$$

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

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

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)

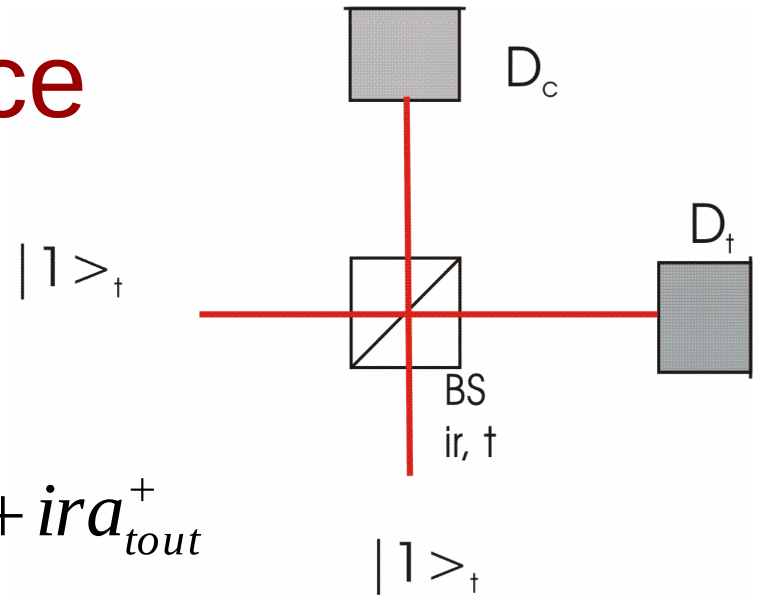
Solid state: J. P. Reithmaier/ A. Forchel, Nature 432, Nov 2004.

Young, Rarity et al arXiv

ALSO

Quadratic interactions thus need TOP HAT photons

2-photon interference



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

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

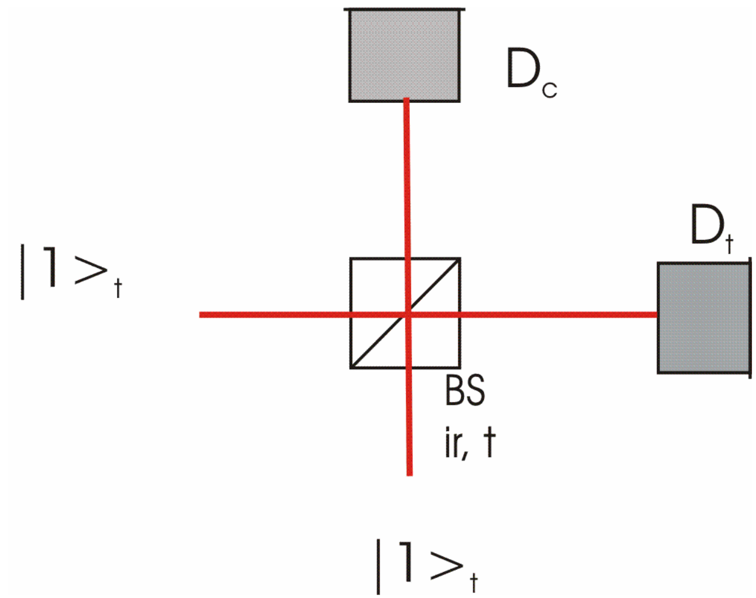
$$\left|\Psi_{out}\right\rangle = (t a_{tout}^+ + ir a_{cout}^+)(t a_{cout}^+ + ir a_{tout}^+)\left|0\right\rangle$$

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

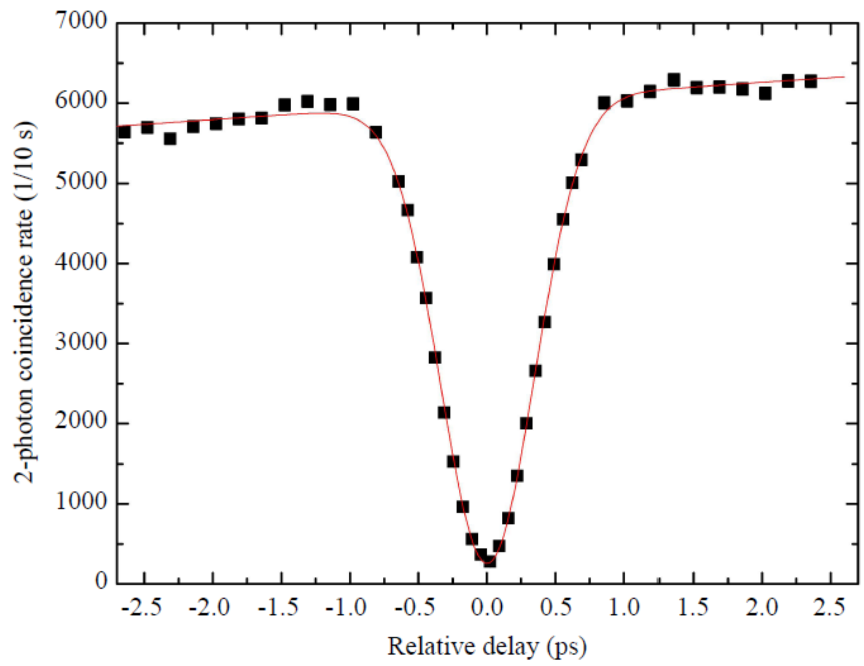
When t=r=1/√2

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

$$= \frac{1}{\sqrt{2}}\left|2\right\rangle_{t} + \left|2\right\rangle_{c}$$



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



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

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

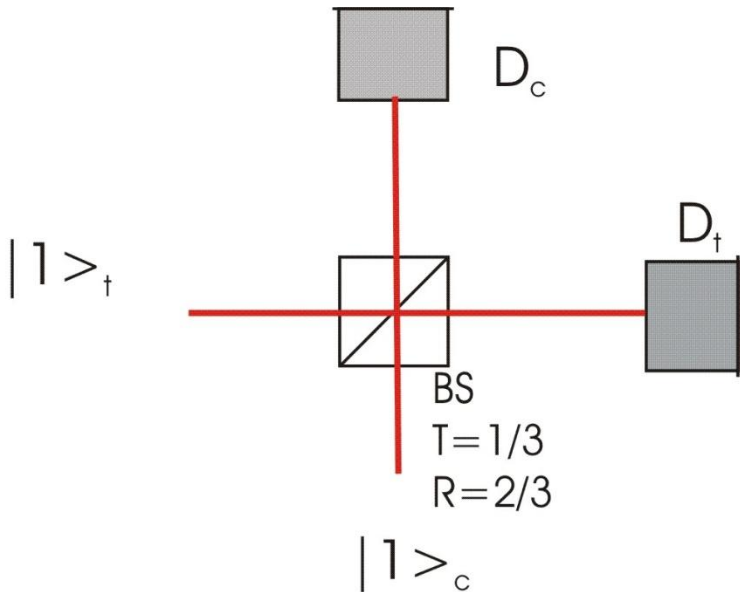
$$|\Psi_{out}\rangle = \frac{1}{8}(a_{tout}^{+} + ia_{cout}^{+})^2 (a_{cout}^{+} + ia_{tout}^{+})^2 |0\rangle$$

?

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

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

Probabilistic phase gate

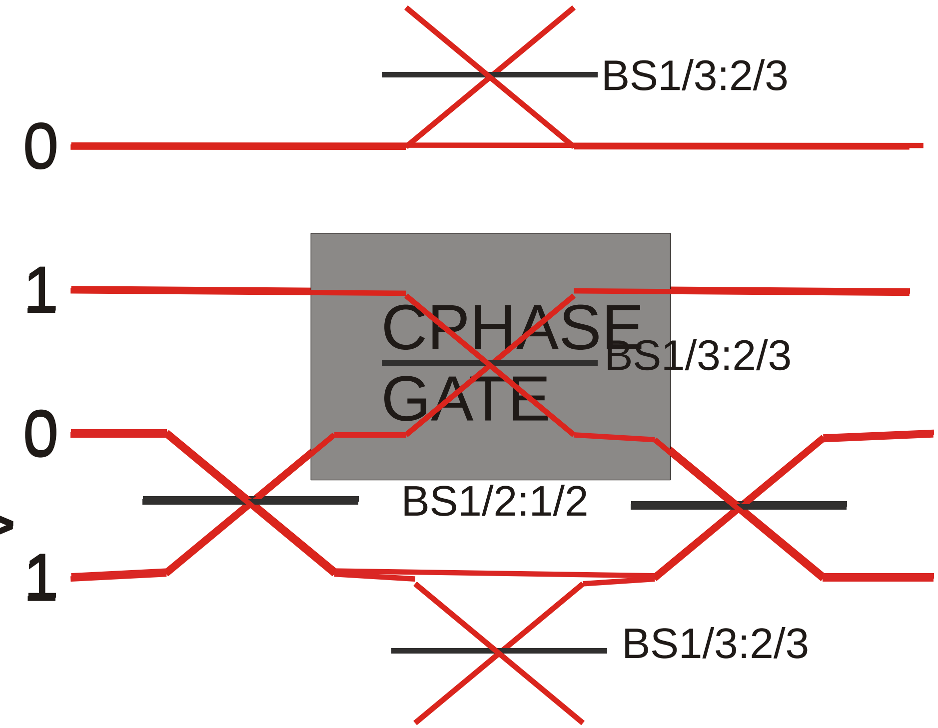


$$|\Psi_{in}\rangle = |1\rangle_t |1\rangle_c$$

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

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

U =universal quantum gate (CNOT)= ‘entangler’



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

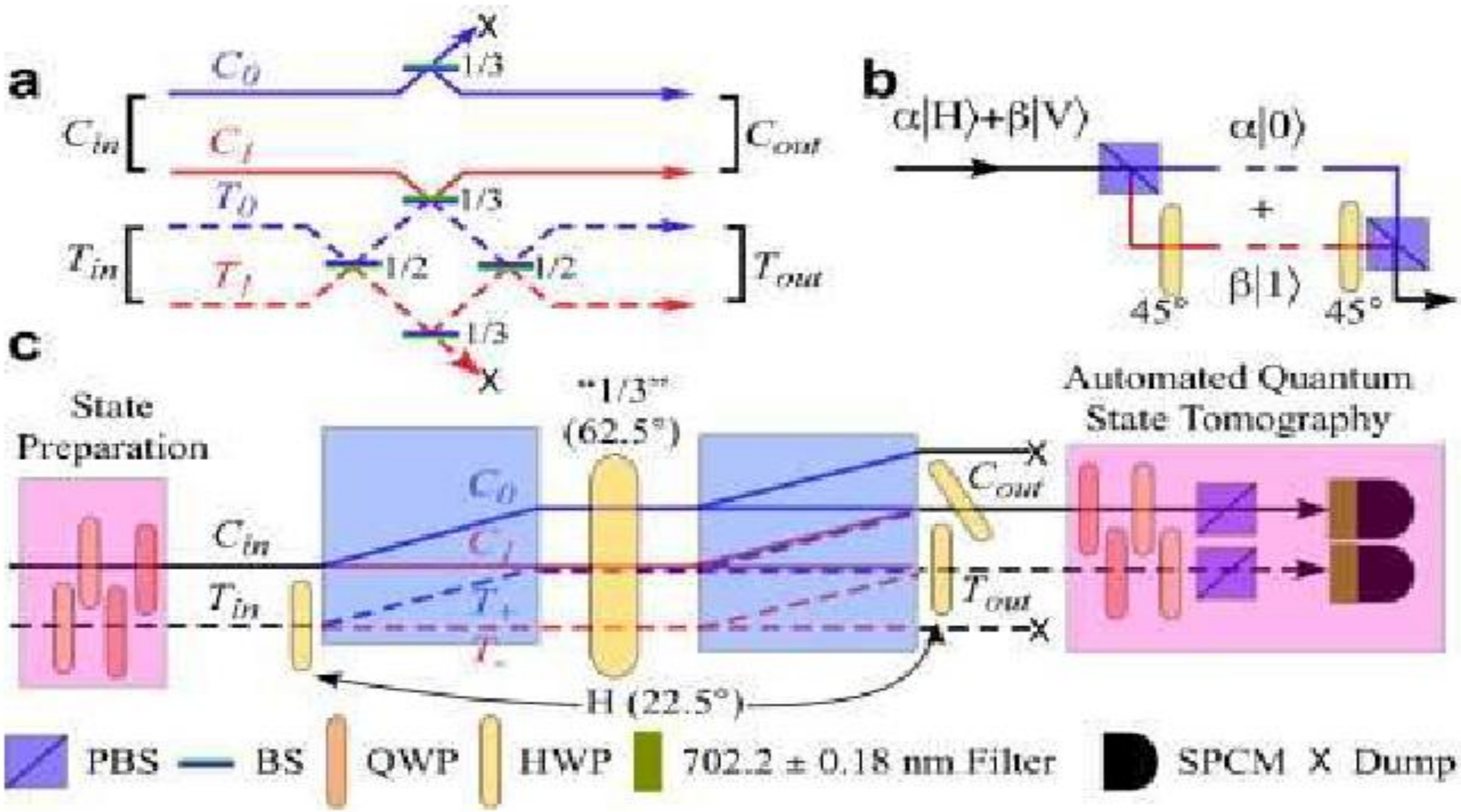
KLM CNOT gate

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

University of BRISTOL

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

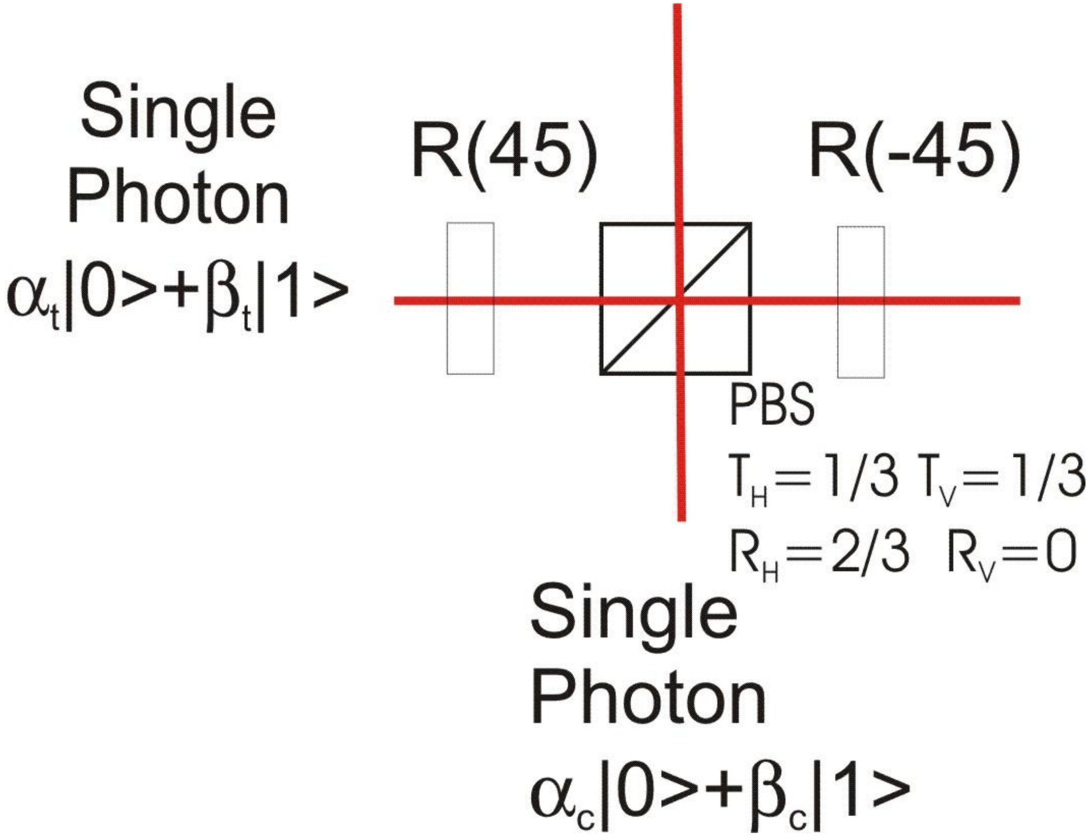
First experimental all-optical quantum controlled-NOT gate



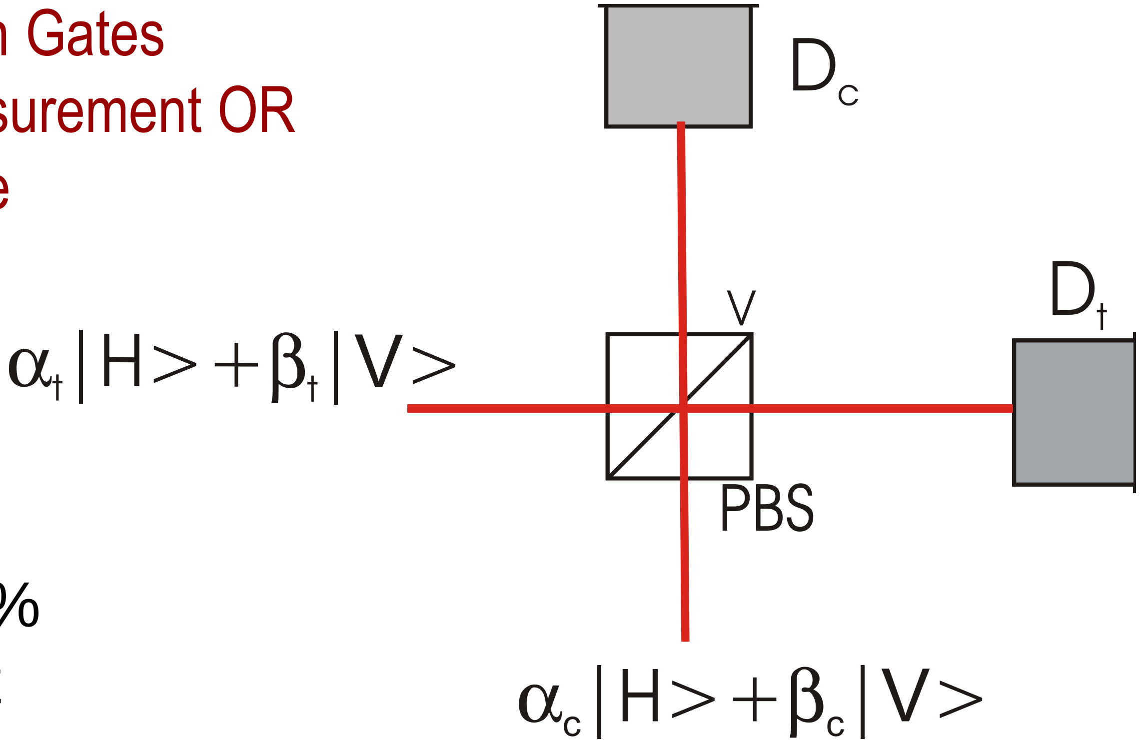
Knill et al Nature 409, 46–52 (2001)

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

Polarisation KLM gate



Polarisation Gates
Parity Measurement OR
Fusion gate

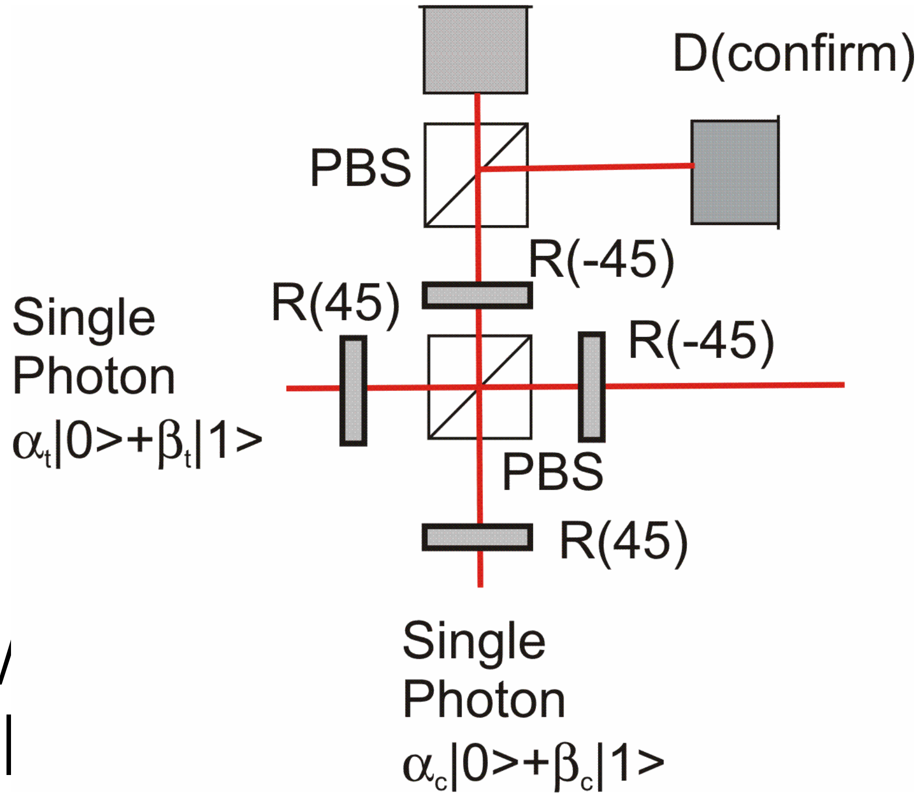


Up to 50% efficient

Notes?

Franson conditional CNOT

Pittman et al (2002) PRL 88, 257902



Target V-->H+V Control H-->H-V

Parity-->HH-VV -45--> H(H+V)+V(H-V

Confirm click is H-->(H+V) out -45--> |

Lecture 2: Experimental techniques

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

Detection

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

The number operator

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

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

Counting single photons

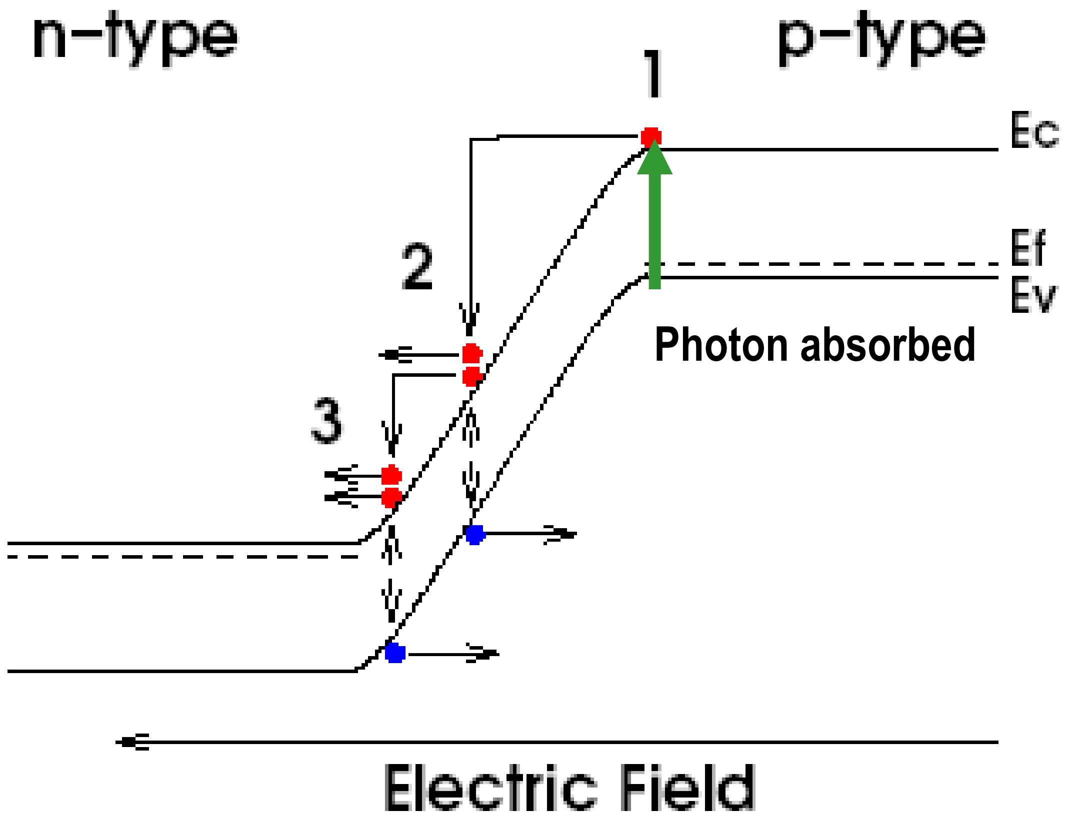
$$ \langle \Psi | a_i^+ a_i | \Psi \rangle = |\alpha|^2 \qquad i = a $$

Coincidence detection

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

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

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

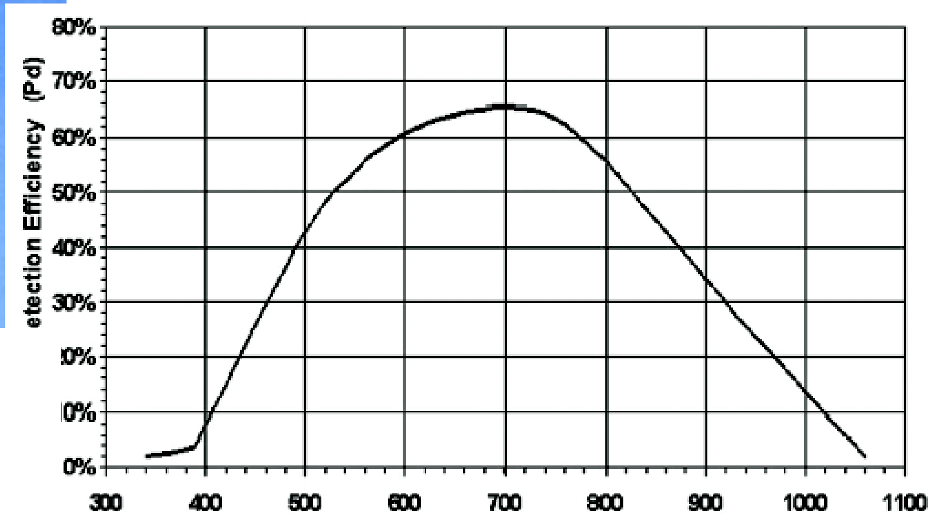
Commercial actively quenched detector module using Silicon APD

Efficiency ~70% (at 700nm)

Timing jitter~400ps (latest <50ps)

Dark counts <50/sec

www.perkinelmer.com



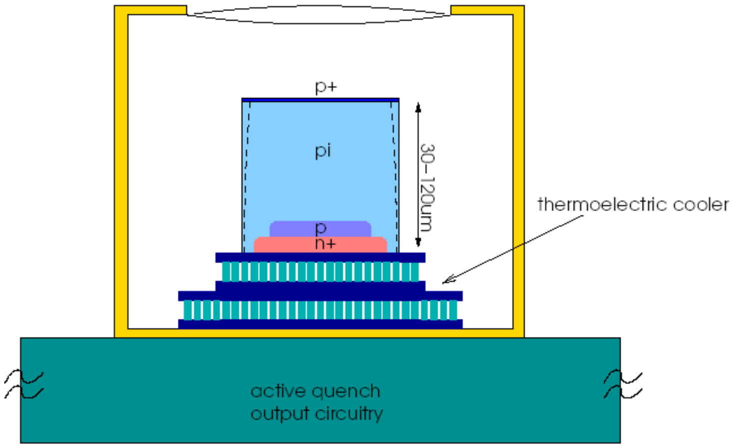


Figure 2.10: Single photon counting module (SPCM).

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

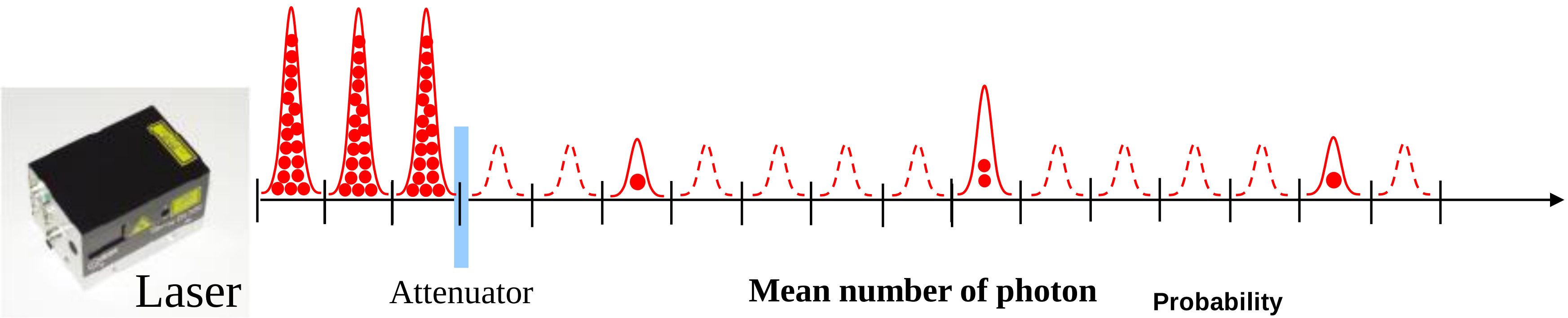
Single and pair photon sources

Approximate single photon source

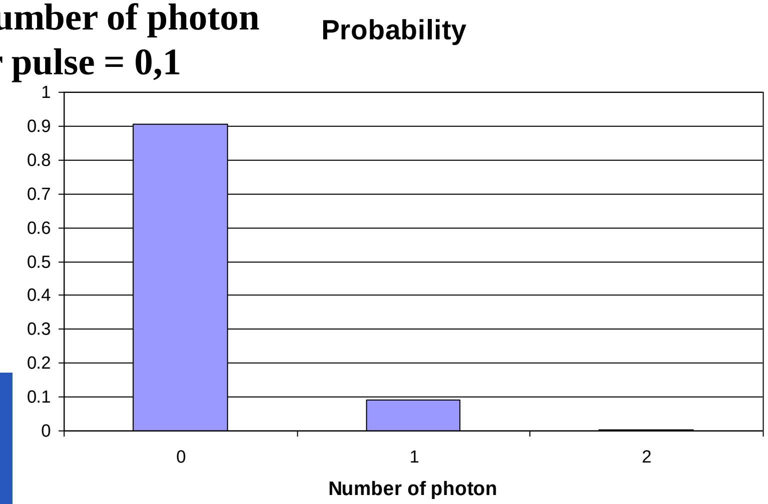
Attenuated laser = Coherent state

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

$$|\alpha|^2 = <n>$$



Mean number of photon per pulse = 0,1



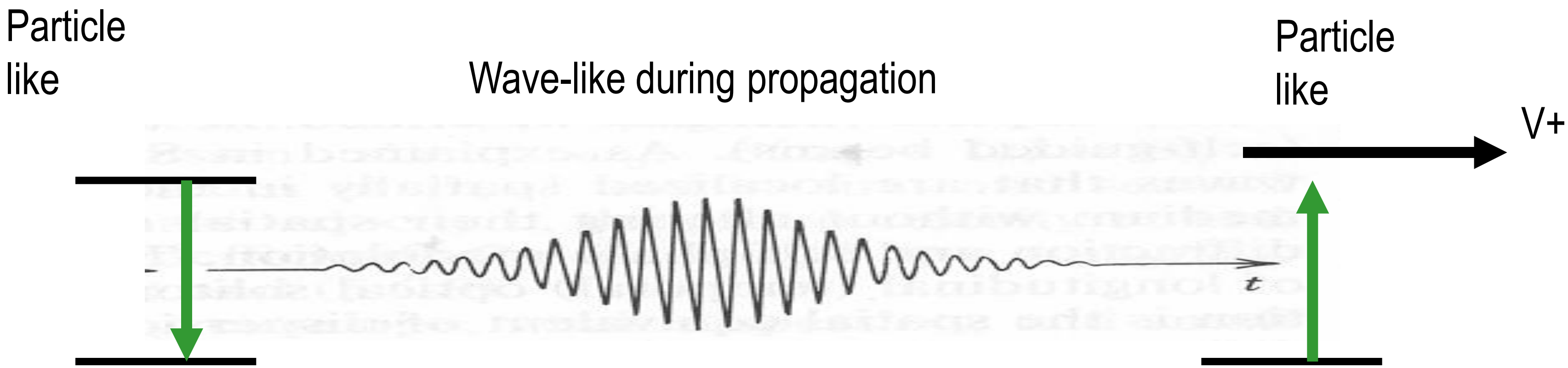
Coherent state shows

Poisson distribution of photons

$$p(n,<n>) = \frac{<n>^n e^{-<n>}}{n!}$$

$$\text{variance} = <n^2> - <n>^2 = <n>$$

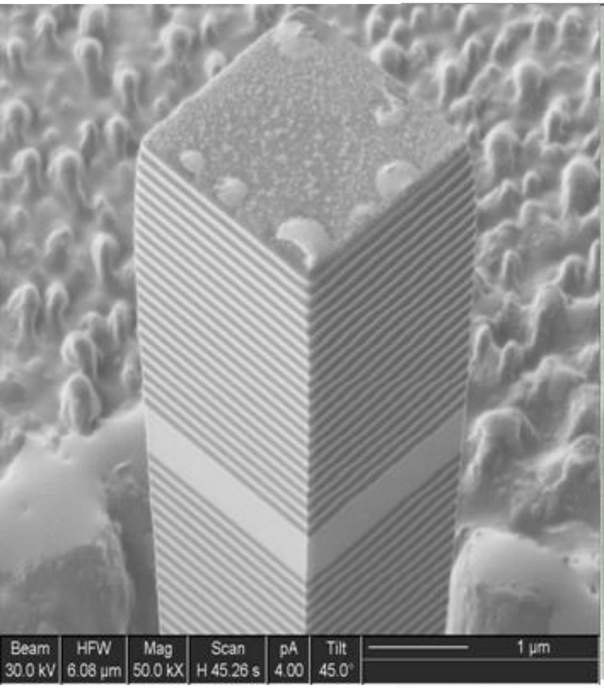
True single photon sources

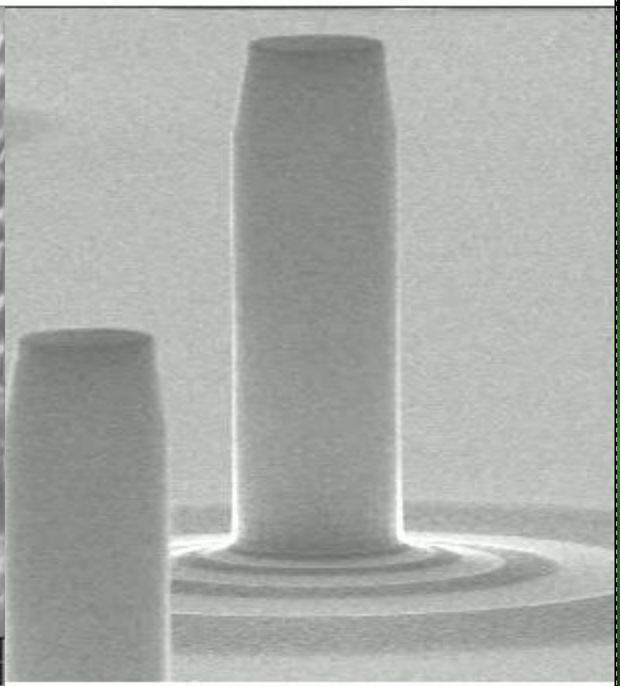


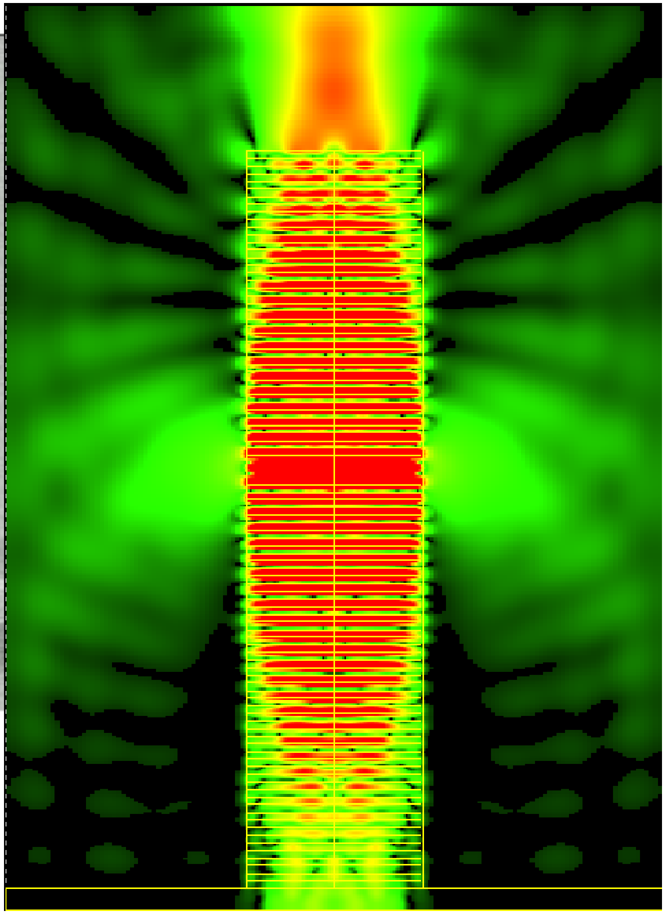
Single atom or ion (in a trap)
Single dye molecule
Single colour centre (diamond NV)
Single quantum dot (eg InAs in GaAs)

Key problem: how to get single photons from source efficiently coupled into single spatial mode

Pillar microcavities for enhanced out-coupling of photons from single quantum dots



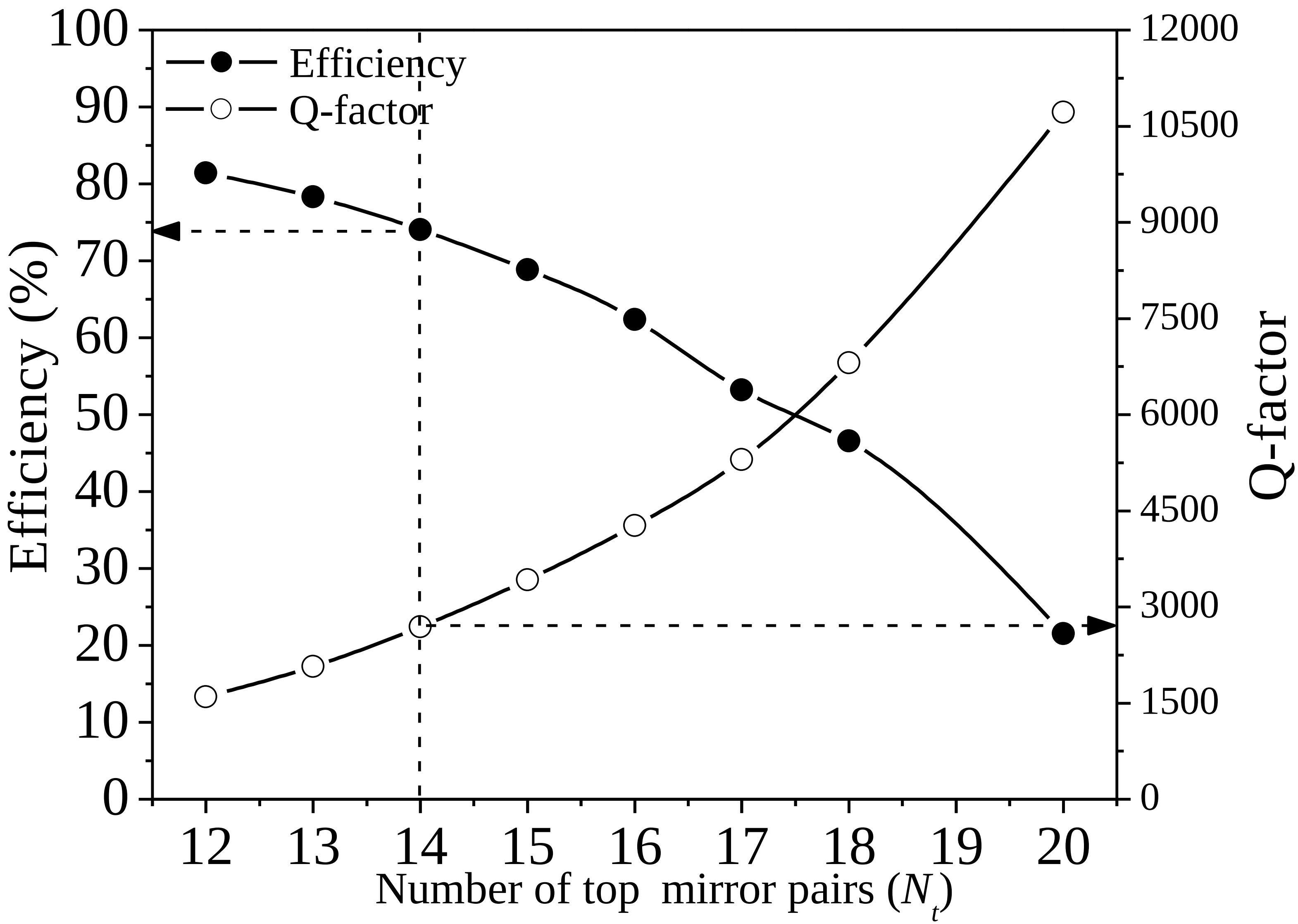




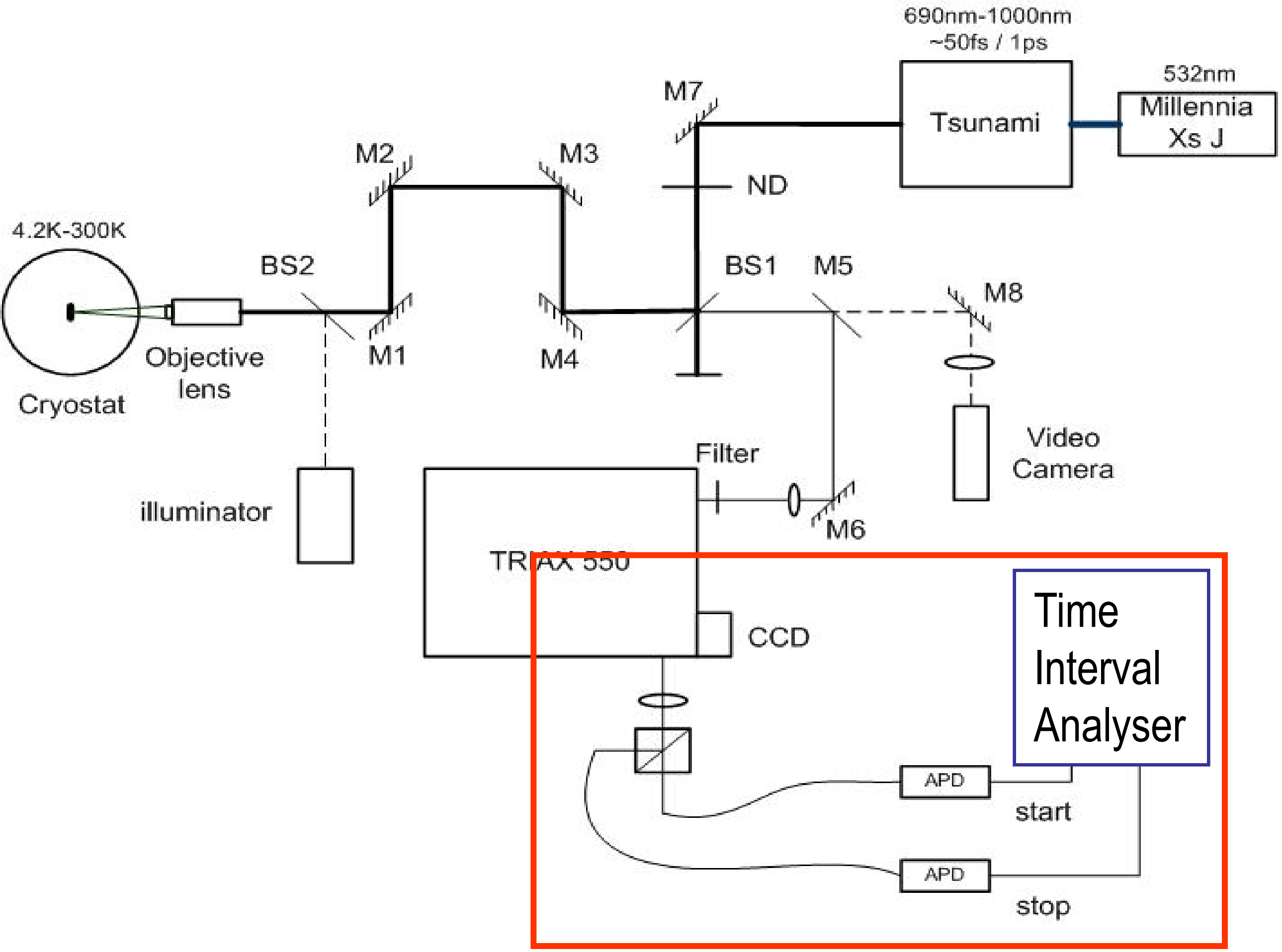
FIB etching

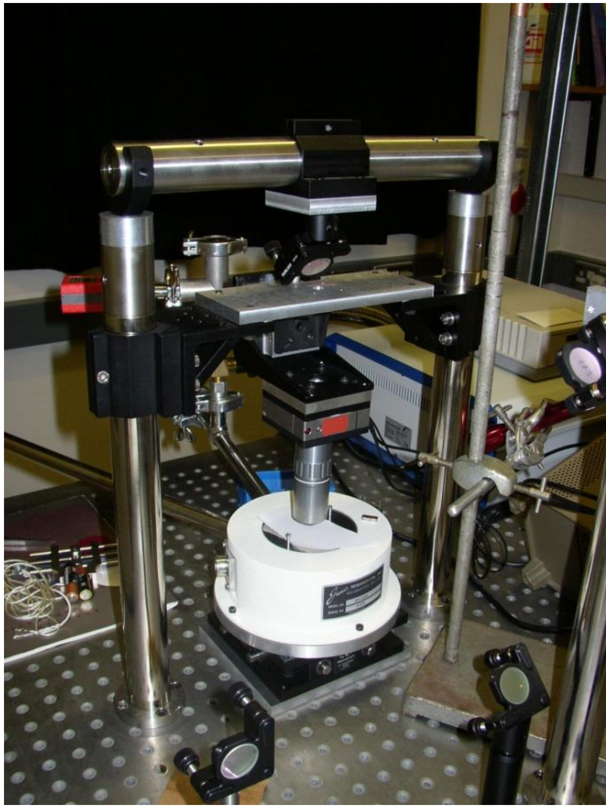
ICP/RIE etching

FDTD simulations: 0.50µm



Experimental Setup

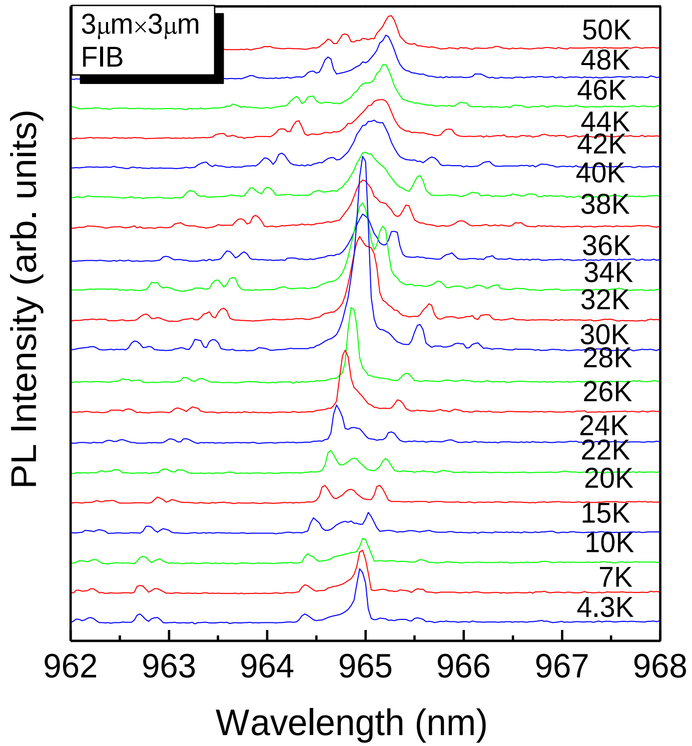


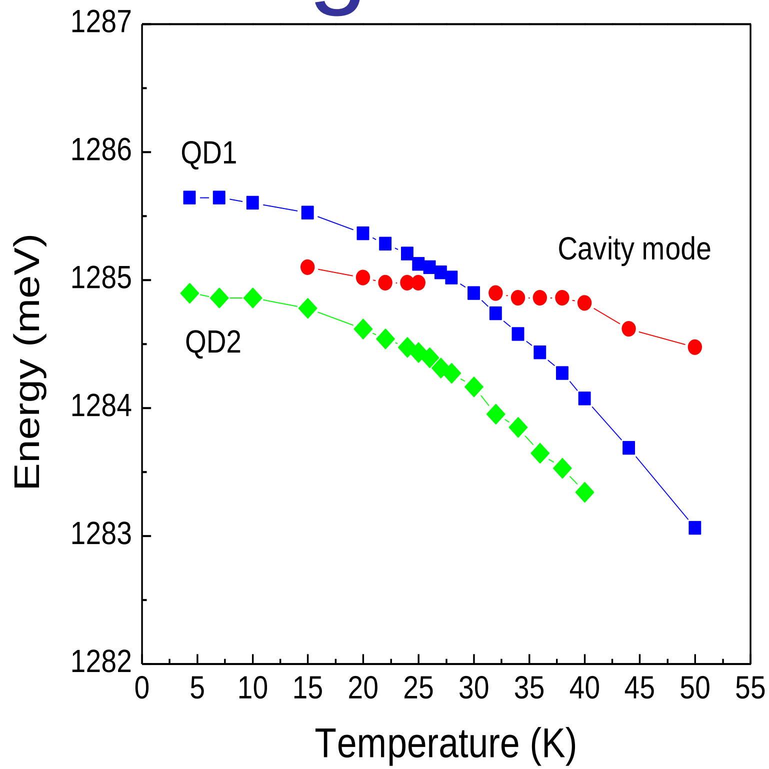


Hanbury-Brown Twiss measurement

$$g^{(2)}(\tau) = \frac{< n(t)n(t+\tau) >}{< n >^2} \sim \frac{p(t : t+\tau)}{p(t)}$$

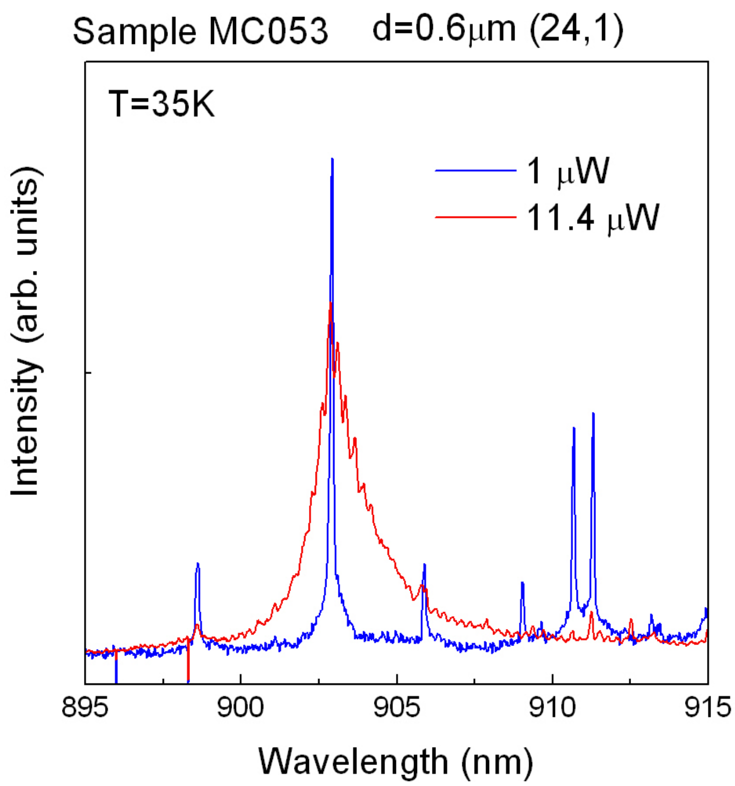
Single QD emission and temperature tuning

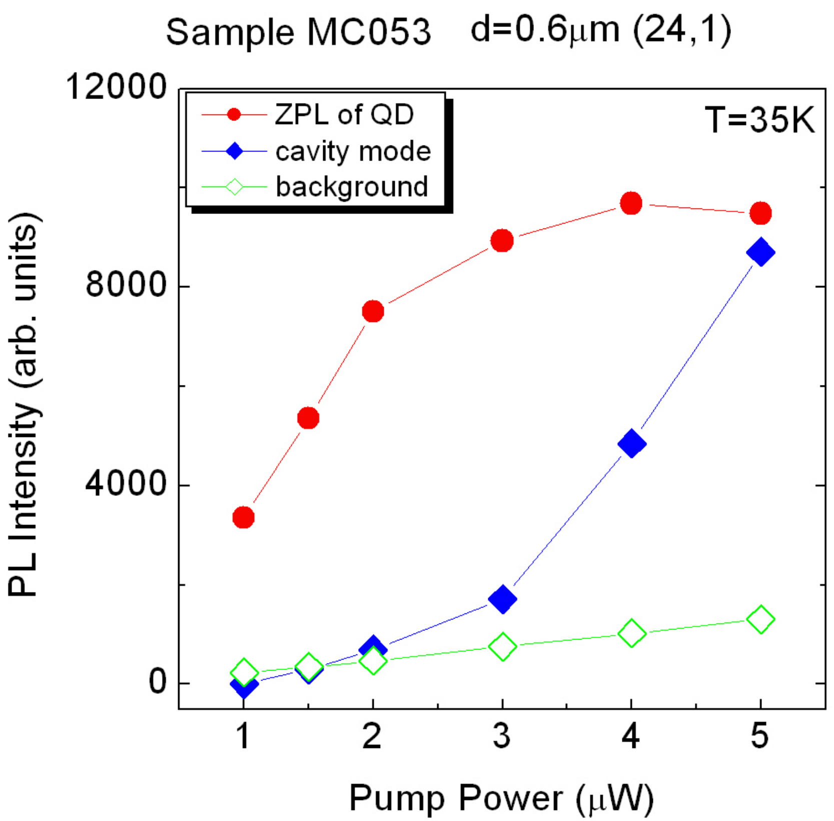




- Single QD emission can be observed in smaller pillar at low excitation power
- QD emission line shifts faster than cavity mode

Single photon generation in circular pillars

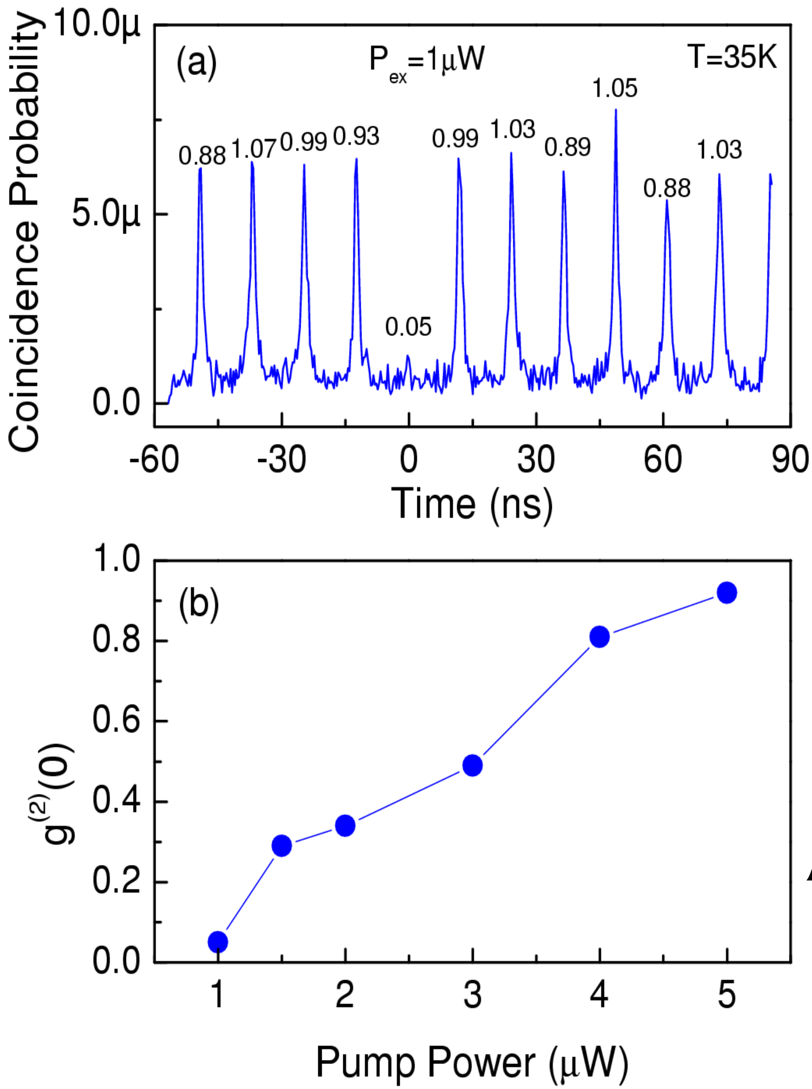




With increasing excitation power

- QD emission intensity turns saturated
- Cavity mode intensity develops

Single photon generation in circular pillars



- $g^{(2)}(0)=0.05$ indicates multi-photon emission is 20 times suppressed.
- $g^{(2)}(0)$ increases with pump power due to the cavity mode

$$g_b^{(2)}(\tau) = \rho^2\left(g^{(2)}(\tau) - 1\right) + 1$$

$$\rho = \frac{I_{signal}}{I_{signal} + I_{cavity} + I_{background}}$$

$$g_b^{(2)}(0) = 1 - \rho^2$$

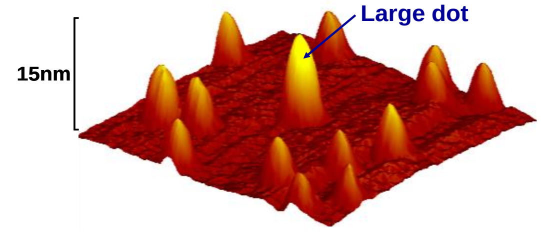
Progress

Single-photon sources

- Optically driven with multiphoton emission <2%
- Optical fibre wavelength emission (1.3µm) – Quantum Key Distribution demonstrated over 35km
- Electrically driven single-photon sources – compact
- Interference demonstrated between pairs of photons from (i) the same QD and (ii) a QD and a laser

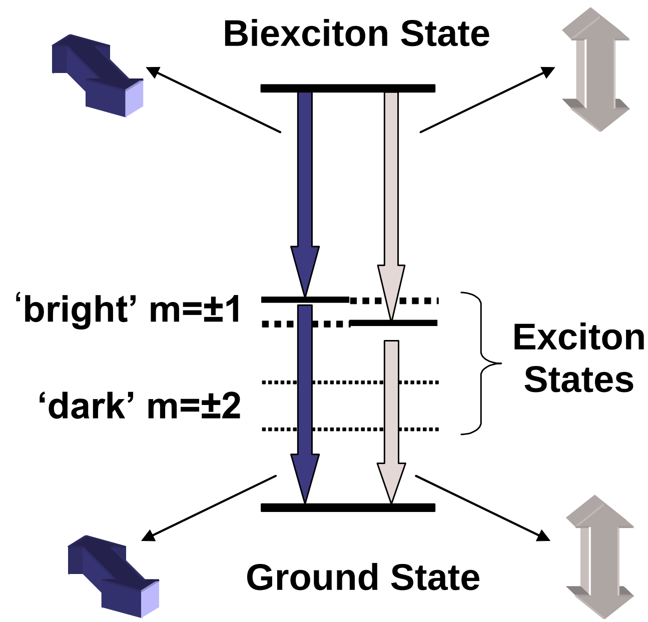
Bennett et al, Optics Exp 13, 7778 (2005)

Journal of Optics B **7,** 129-136 (2005).

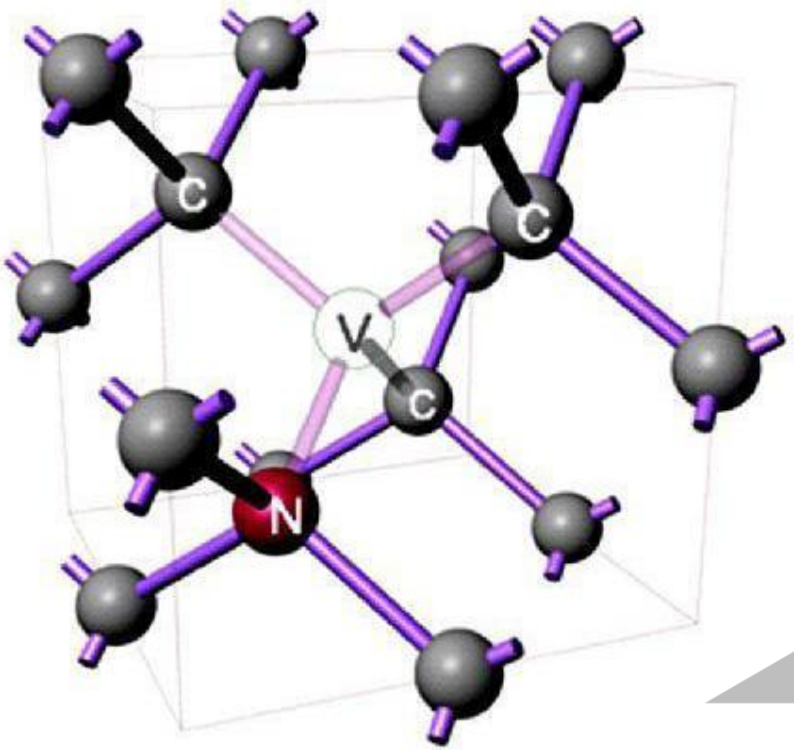


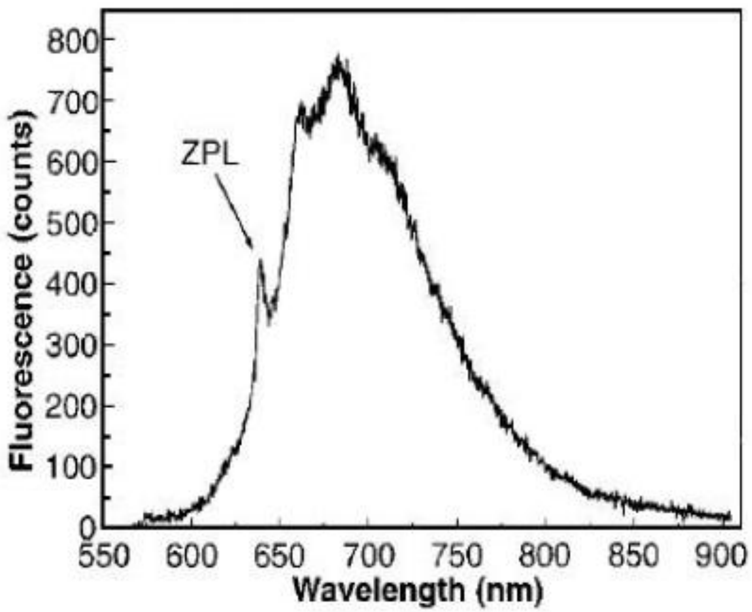
Entangled photon pairs from Biexciton Exciton cascaded emission

(see , Nature **439**, 179-182, PRL 102, 030406 (2009)

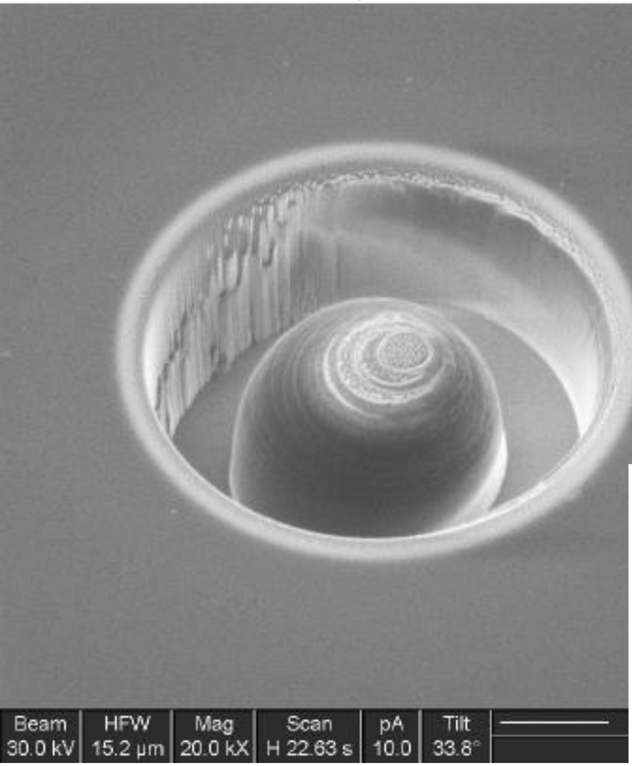


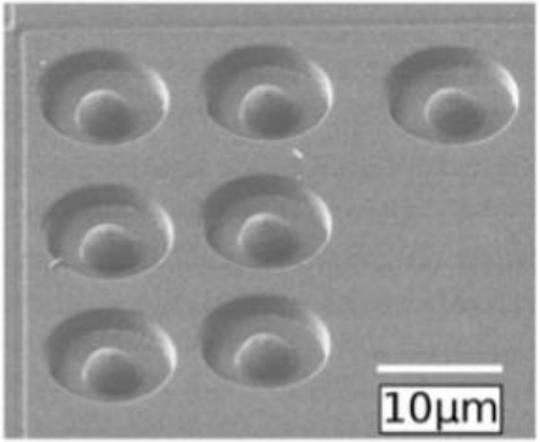
Single photons from NV⁻ centres in diamond

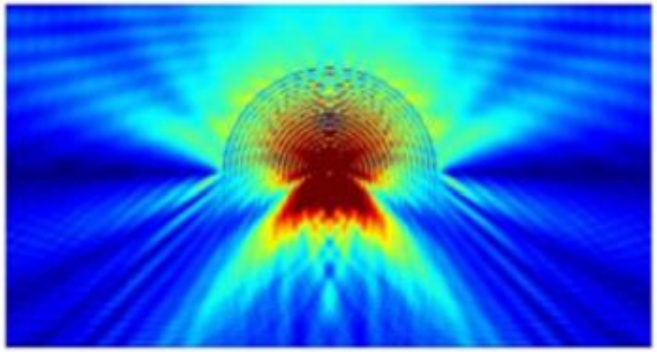




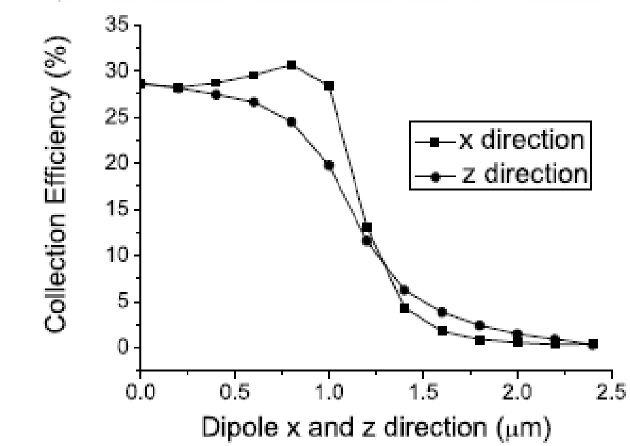
Solid immersion lens fabricated on diamond using focussed ion beam

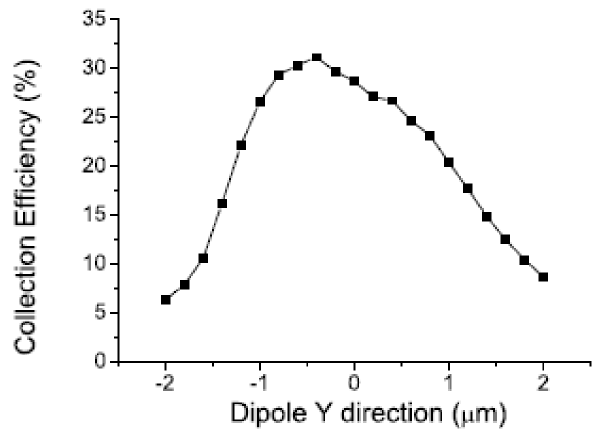






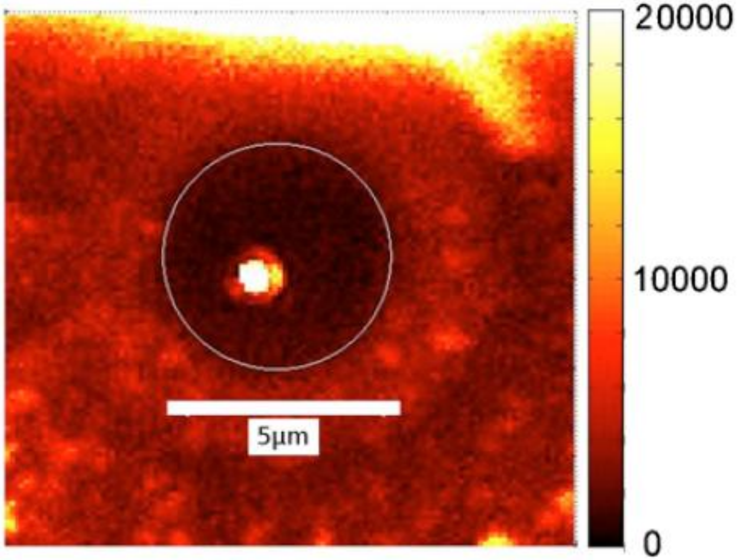
FDTD simulation

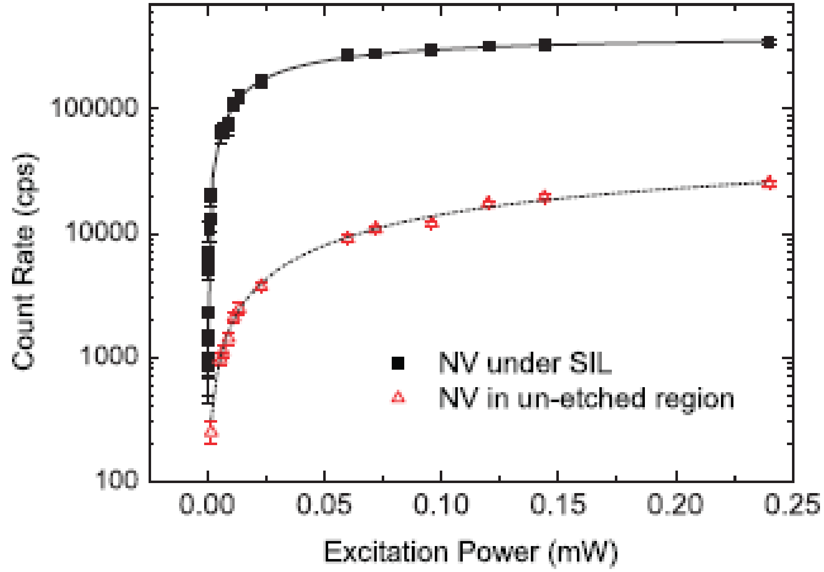




~5% collection into 0.9NA lens from flat surface

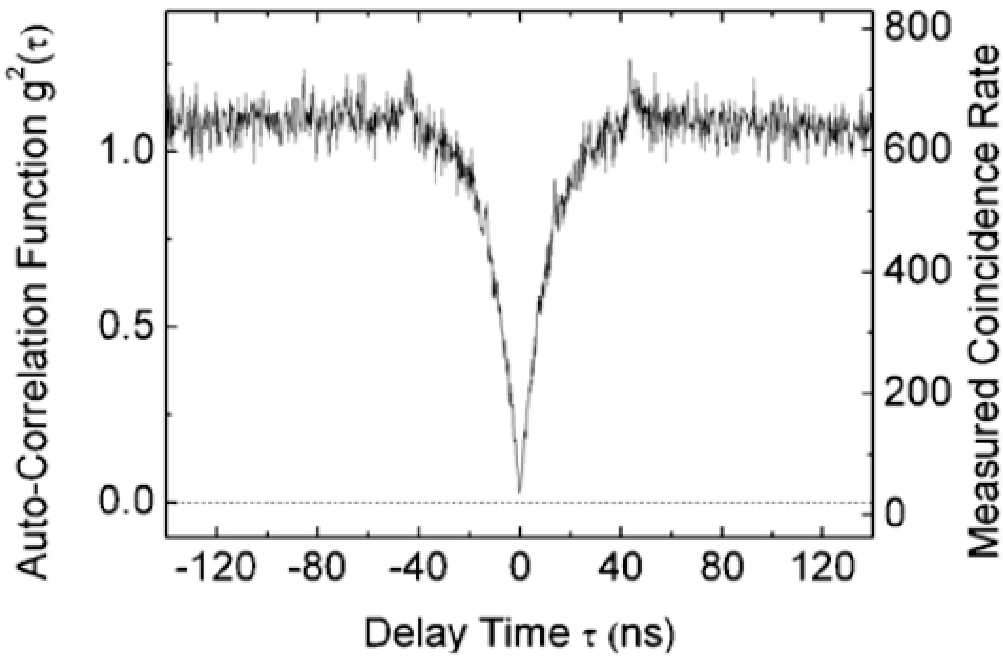
~30% collection into SIL + 0.9NA lens





- Serendipitous discovery of single NV centres under SILs
on Polycrystalline diamond (E6)

J.P. Haddon et al
APL **97**, 241901 2010



Parametric sources of pair photons and entangled photons

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

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

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

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

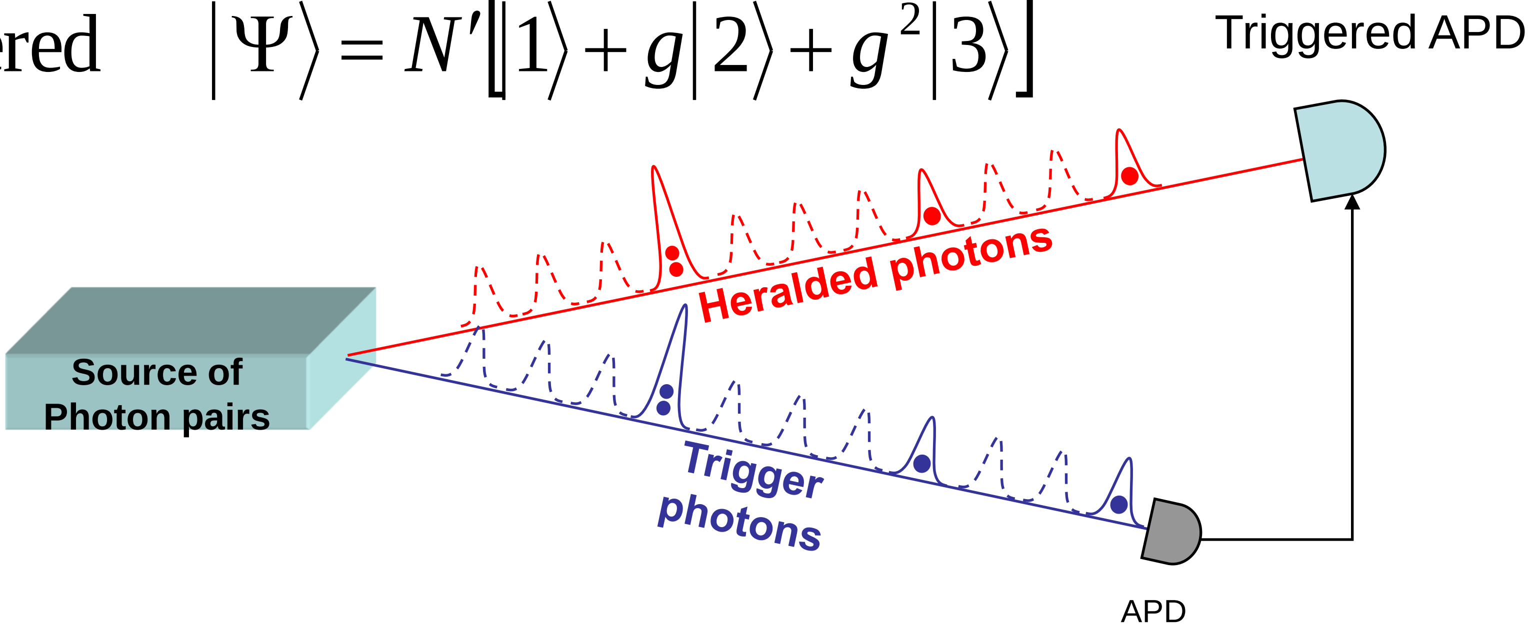
Why photon pairs?

JGR,JMO 1998, 45, 595-604

- Heralded single photon source

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

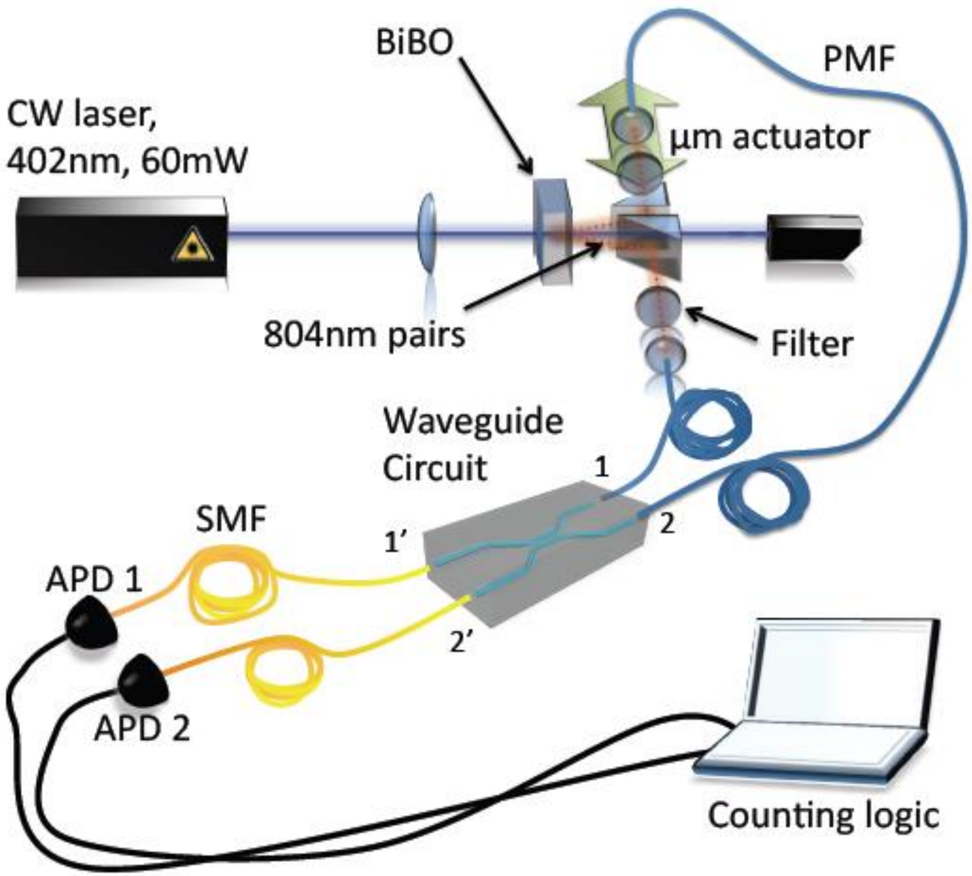
$$\text{Triggered} \quad |\Psi\rangle = N'\left[|1\rangle + g|2\rangle + g^2|3\rangle\right]$$

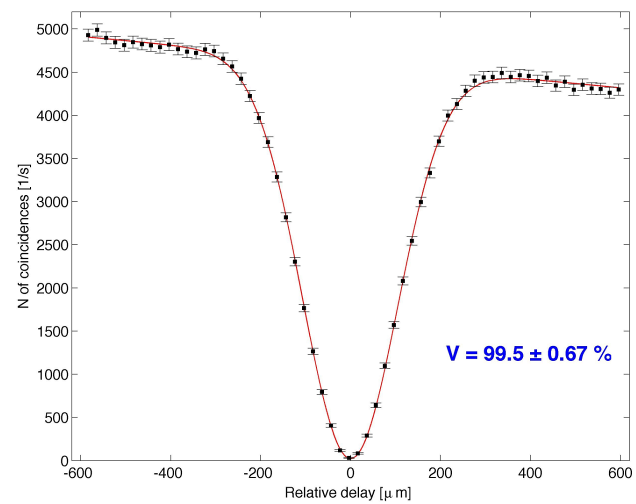


Experimental realization of a localized one-photon state, C. K. Hong and L. Mandel, Phys. Rev. Lett. **56**, 58 (1986)

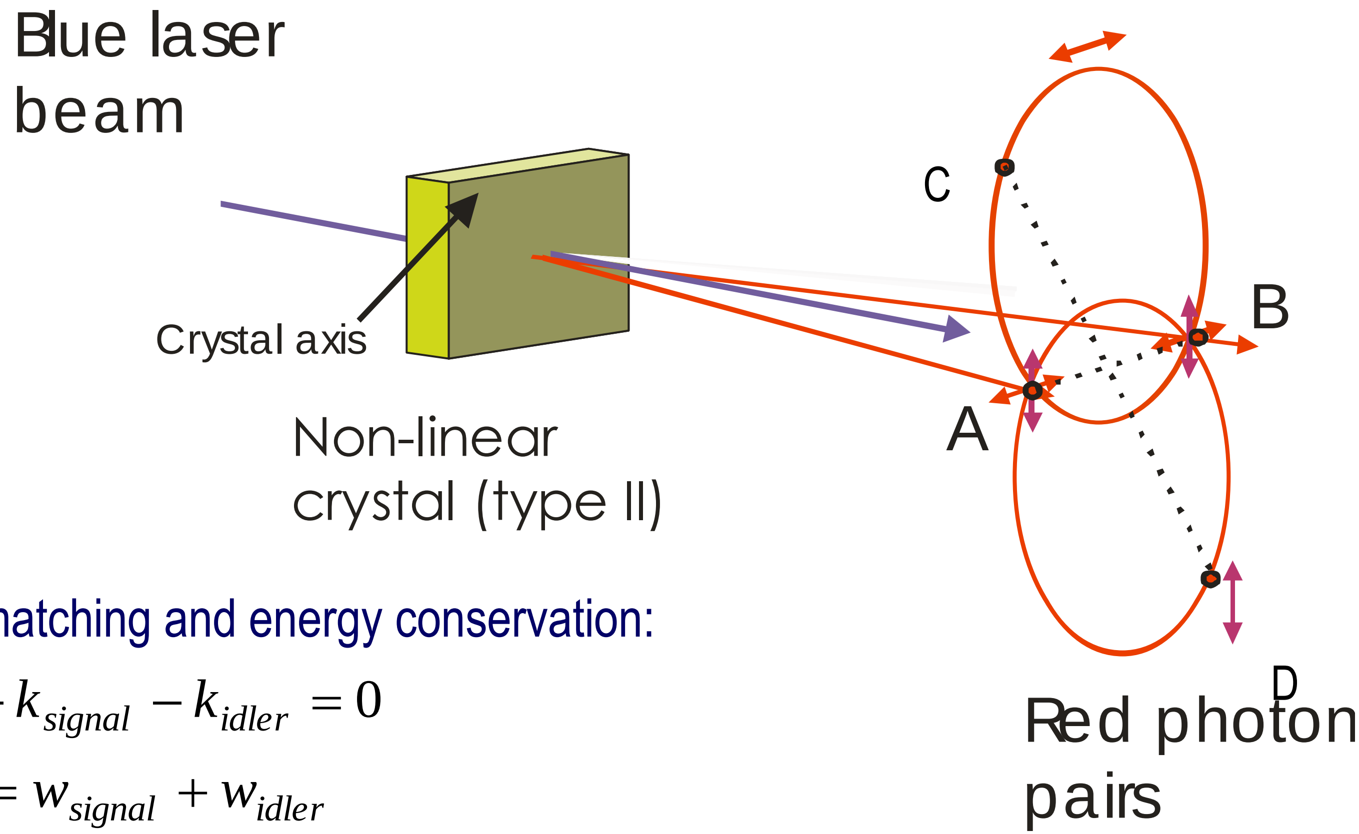
Observation of sub-poissonian light in parametric downconversion. J.G. Rarity, P.R.Tapster and E. Jakeman, Opt. Comm., 62(3):201, 1987.

Source for integrated quantum photonics





Creating Entangled Photon Pairs



Phase matching and energy conservation:

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

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

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

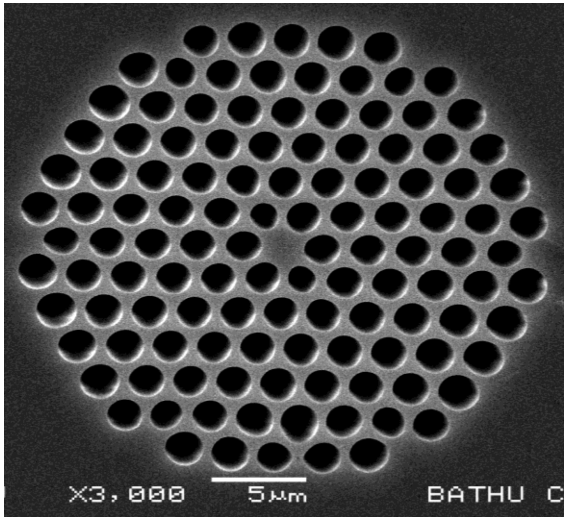
$$\text{Pairs A - B} \quad |\Psi\rangle = \tfrac{1}{\sqrt{2}}\left(|H\rangle_A |V\rangle_B + e^{i\phi}|V\rangle_A |H\rangle_B\right)$$

(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

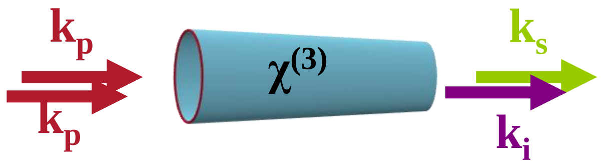
$$\frac{\partial \Psi}{\partial t} = -\frac{i}{\hbar} H \Psi$$

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

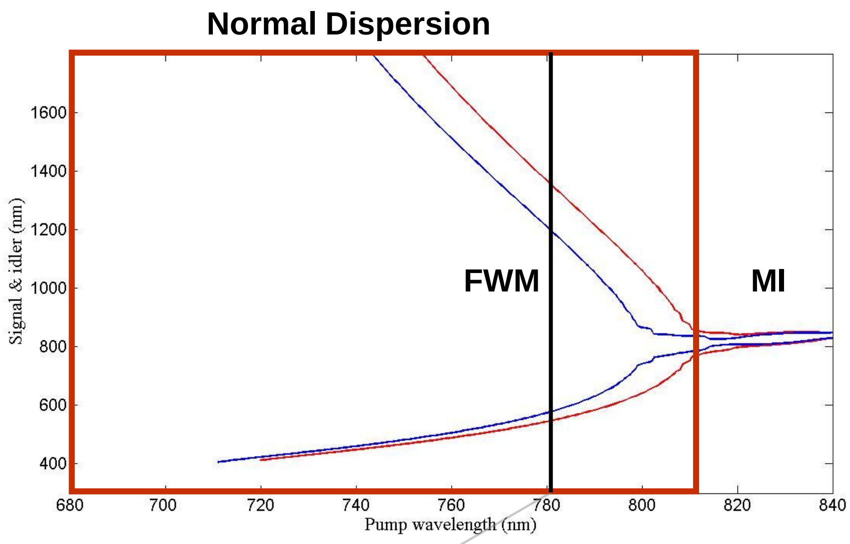
$$|\Psi\rangle = \exp\left[-i g a_s^+ a_i^+\right] |vac\rangle \qquad g = E_p^2 g'$$

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

FOUR-WAVE MIXING PROCESS

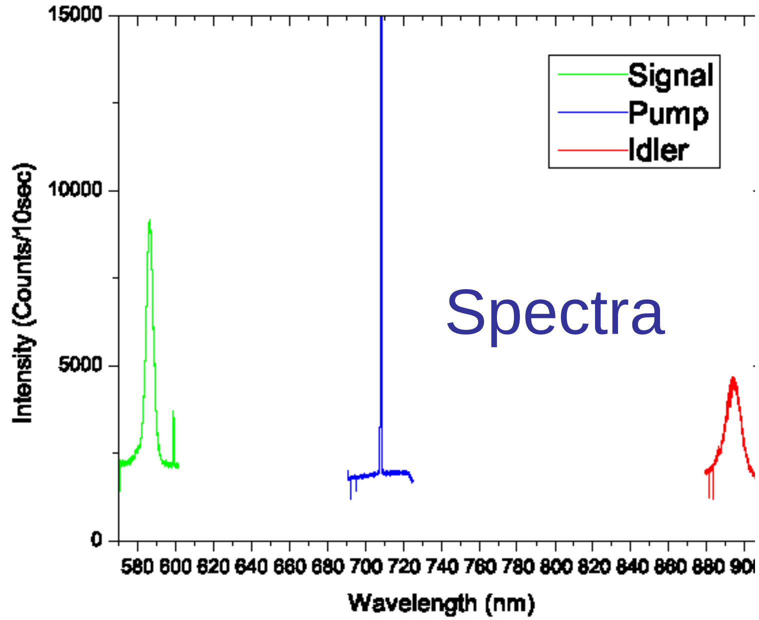


$$\begin{cases} 2k_{pump} - k_{signal} - k_{idler} - 2\gamma P_p = 0 \\ 2\omega_{pump} = \omega_{signal} + \omega_{idler} \end{cases}$$

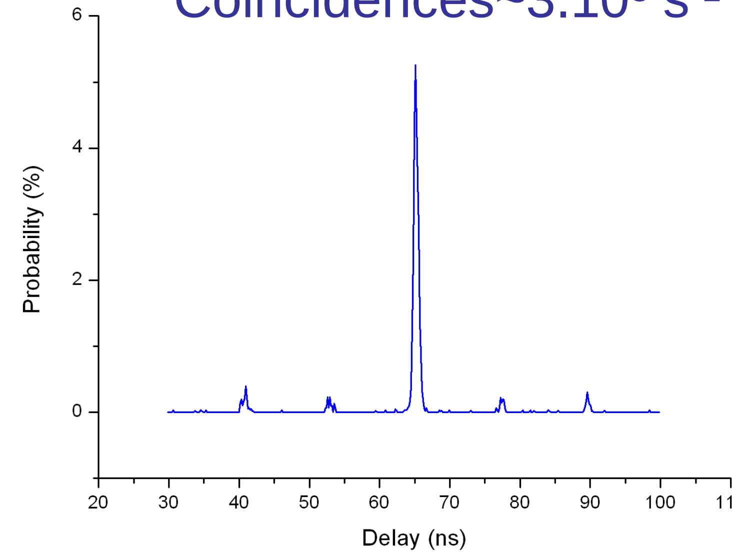


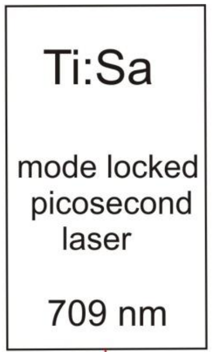
- Pump the fibre in the normal dispersion region
- Produce wavelengths widespread and away from the pump and Raman background effects

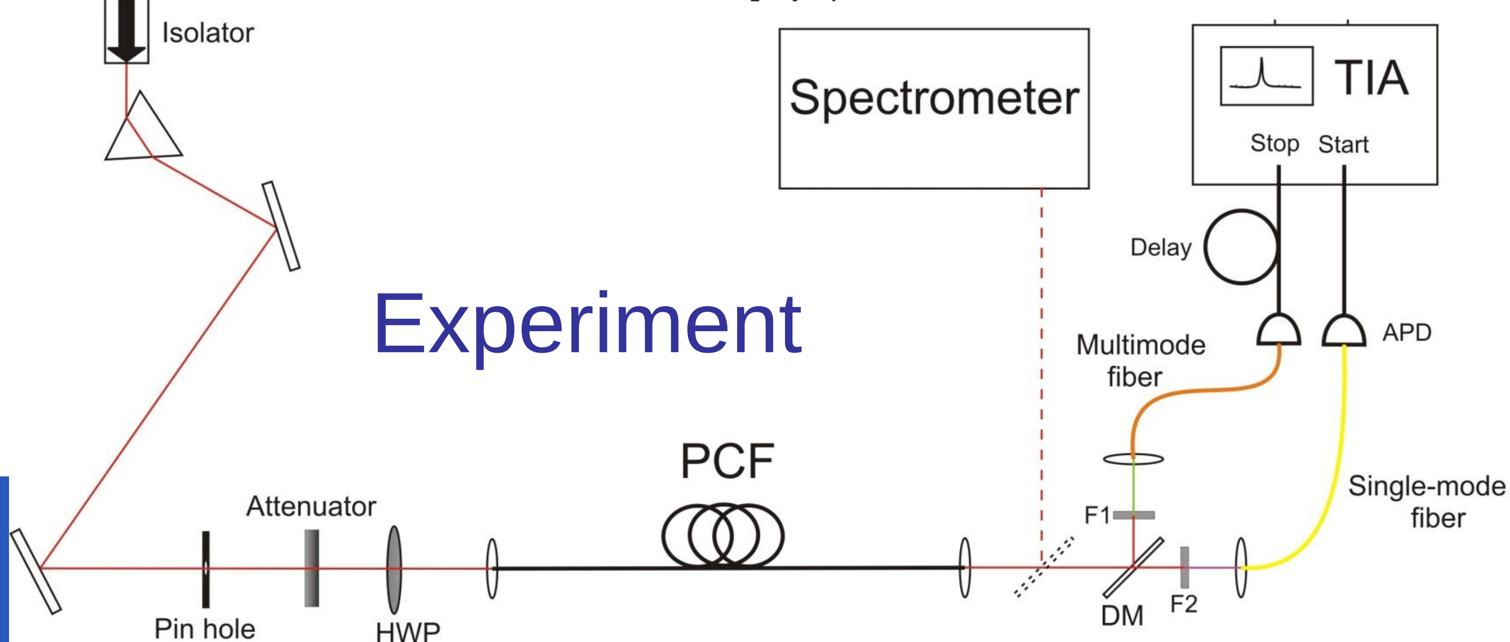
J. Fulconis, O. Alibart, W. J. Wadsworth, P. S. Russell and J. G. Rarity, Opt. Express **13**, 7572 (2005)

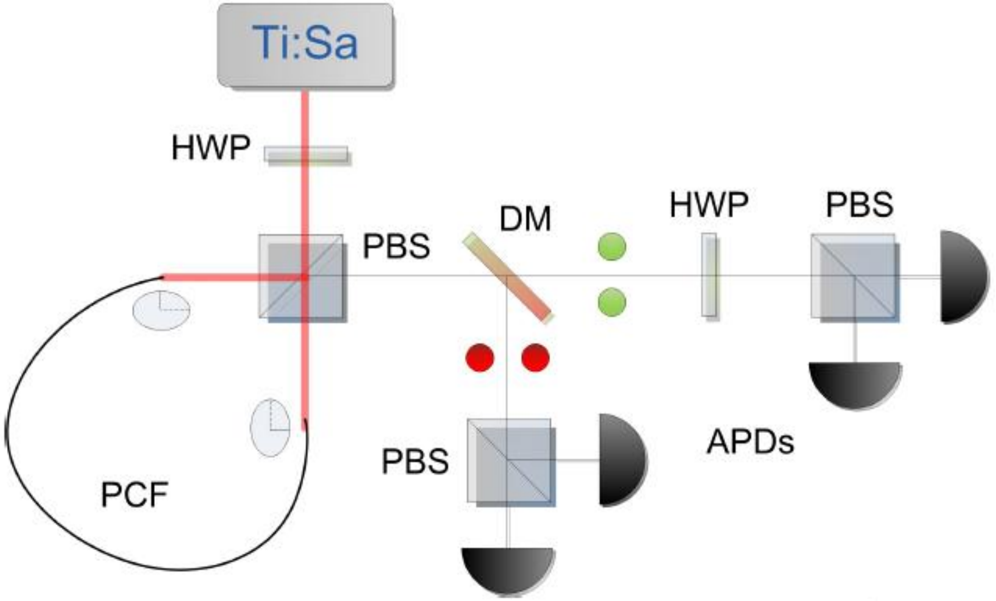


Coincidences~3.10^5 s^{-1}



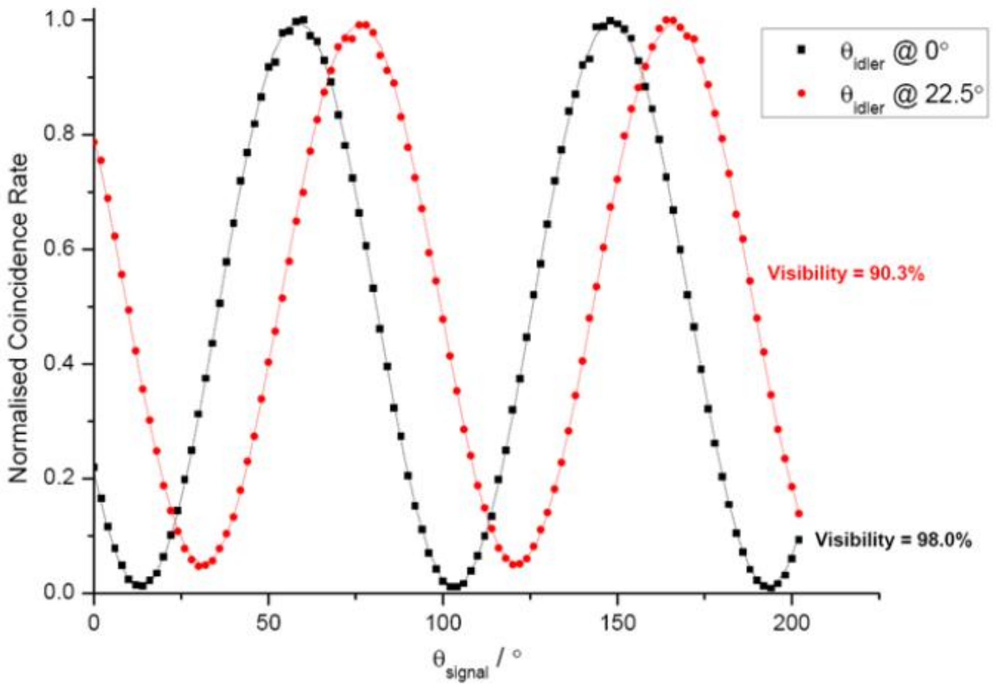






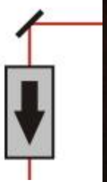
Entanglement

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



Example QIP experiments

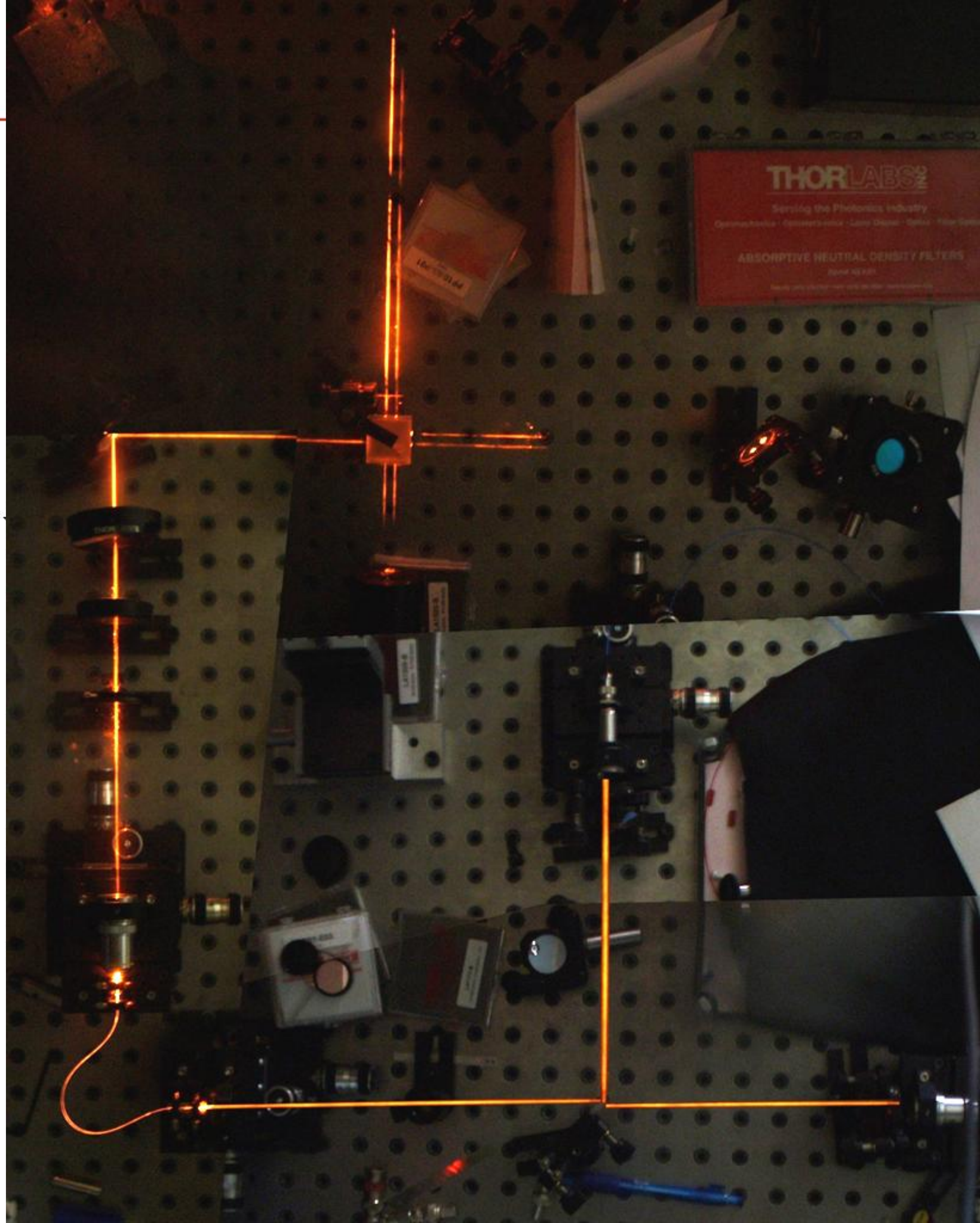
fering
endent



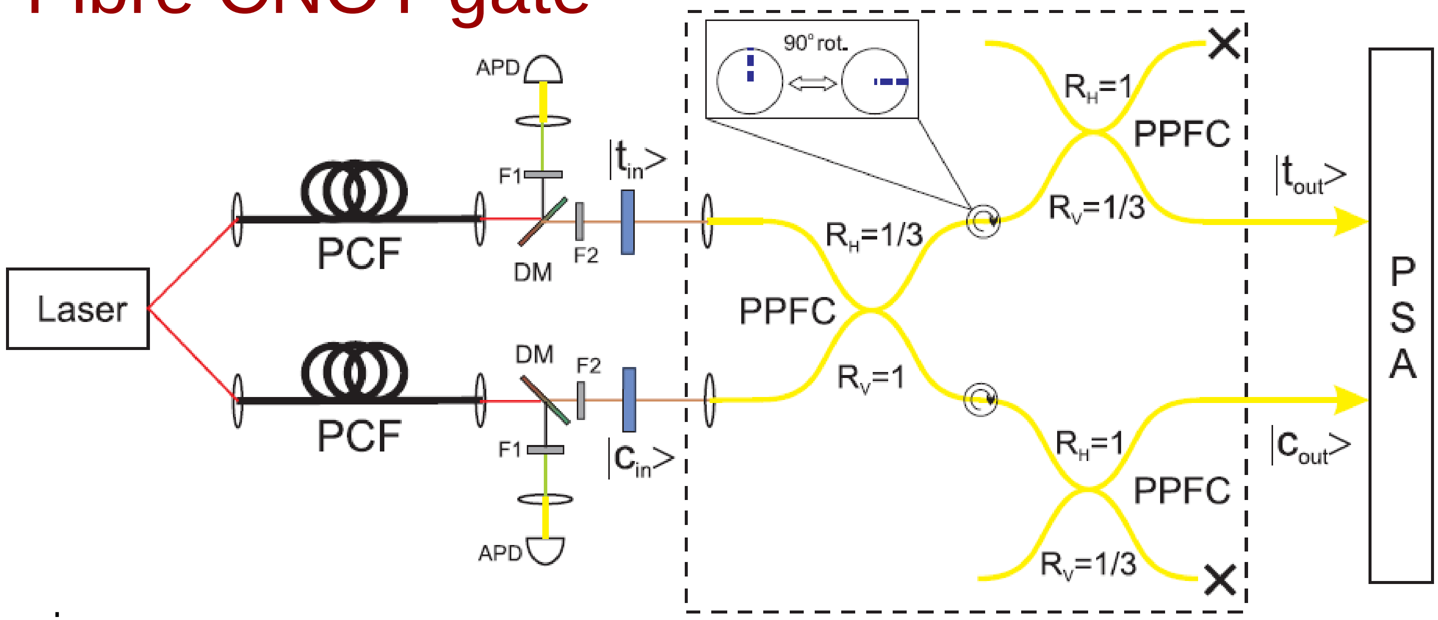
50:50
Beam-splitter

Attenuator
&
half wave-plate

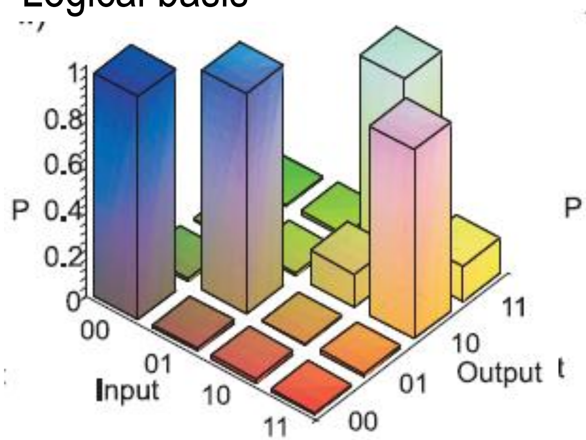
PCF

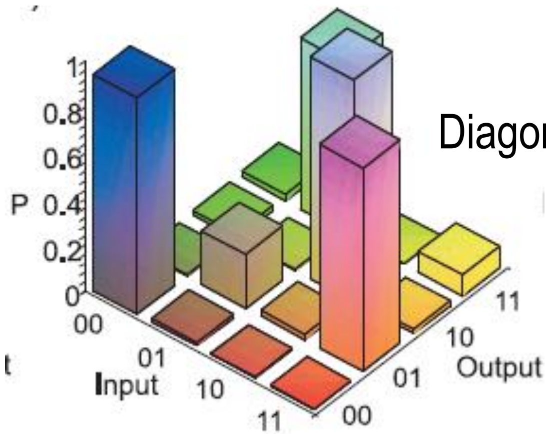


Fibre CNOT gate



Logical basis



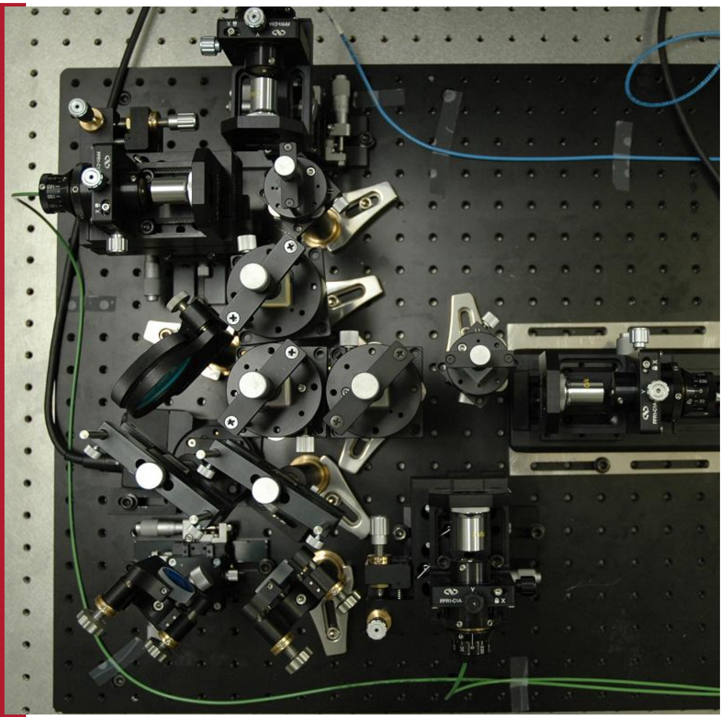


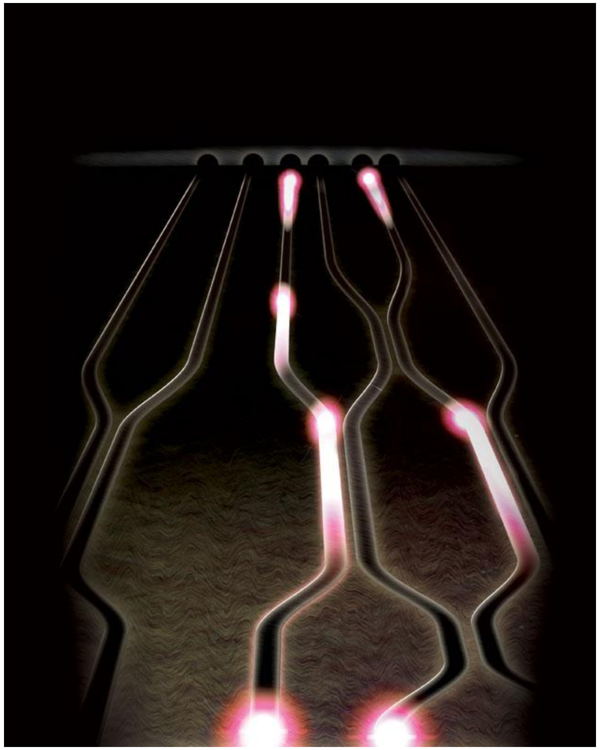
Diagonal basis

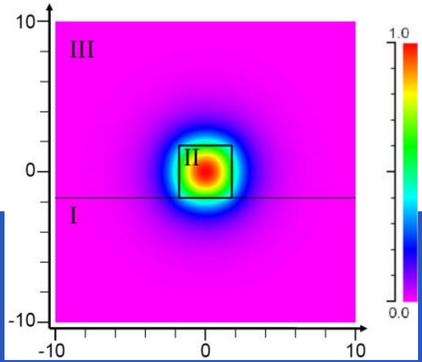
Clark et al Phys Rev A,

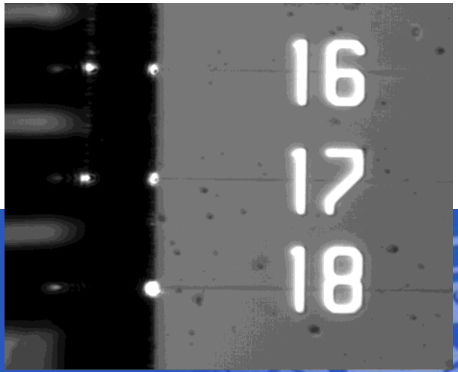
Integrated quantum photonics

Reduce quantum circuits to integrated optics realisations



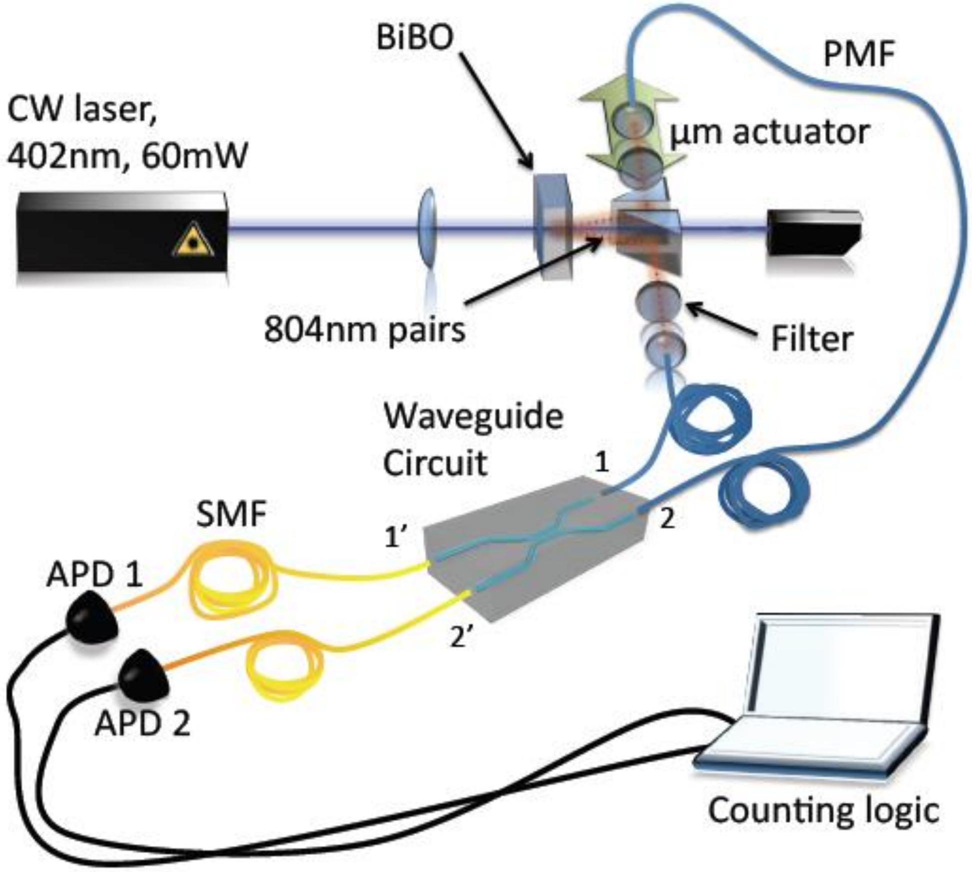




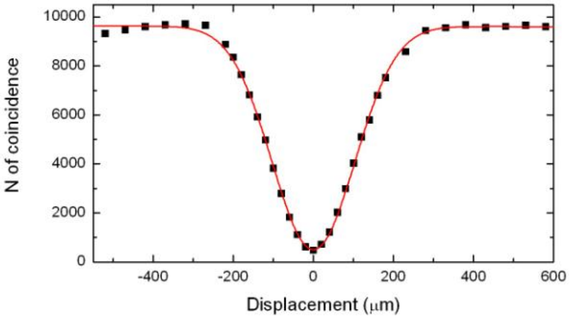


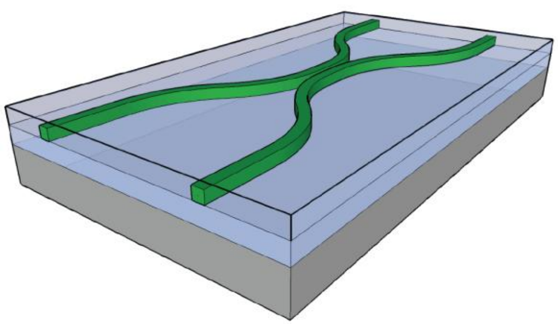
University of BRISTOL

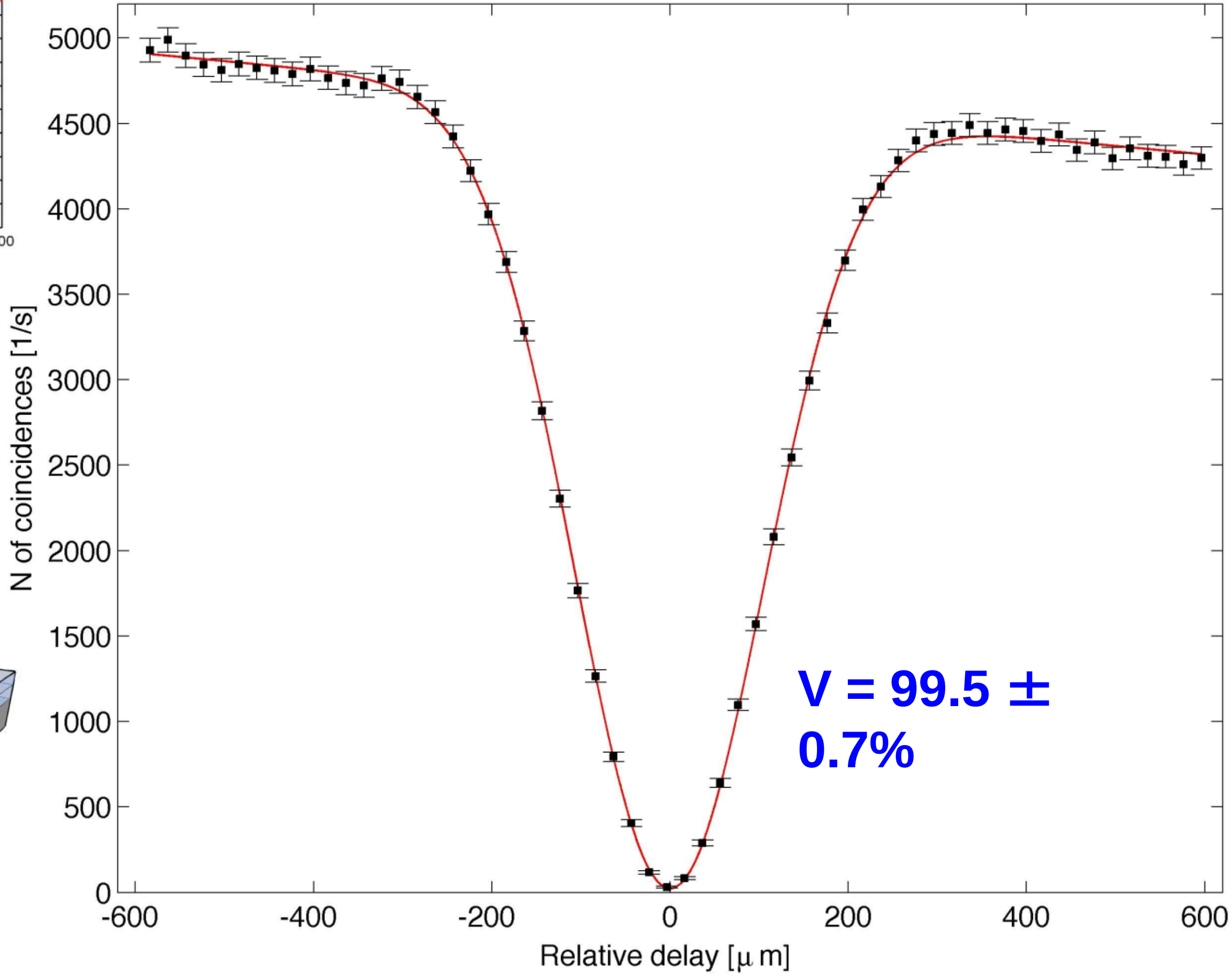
Integrated Quantum Photonics



Integrated Coupler



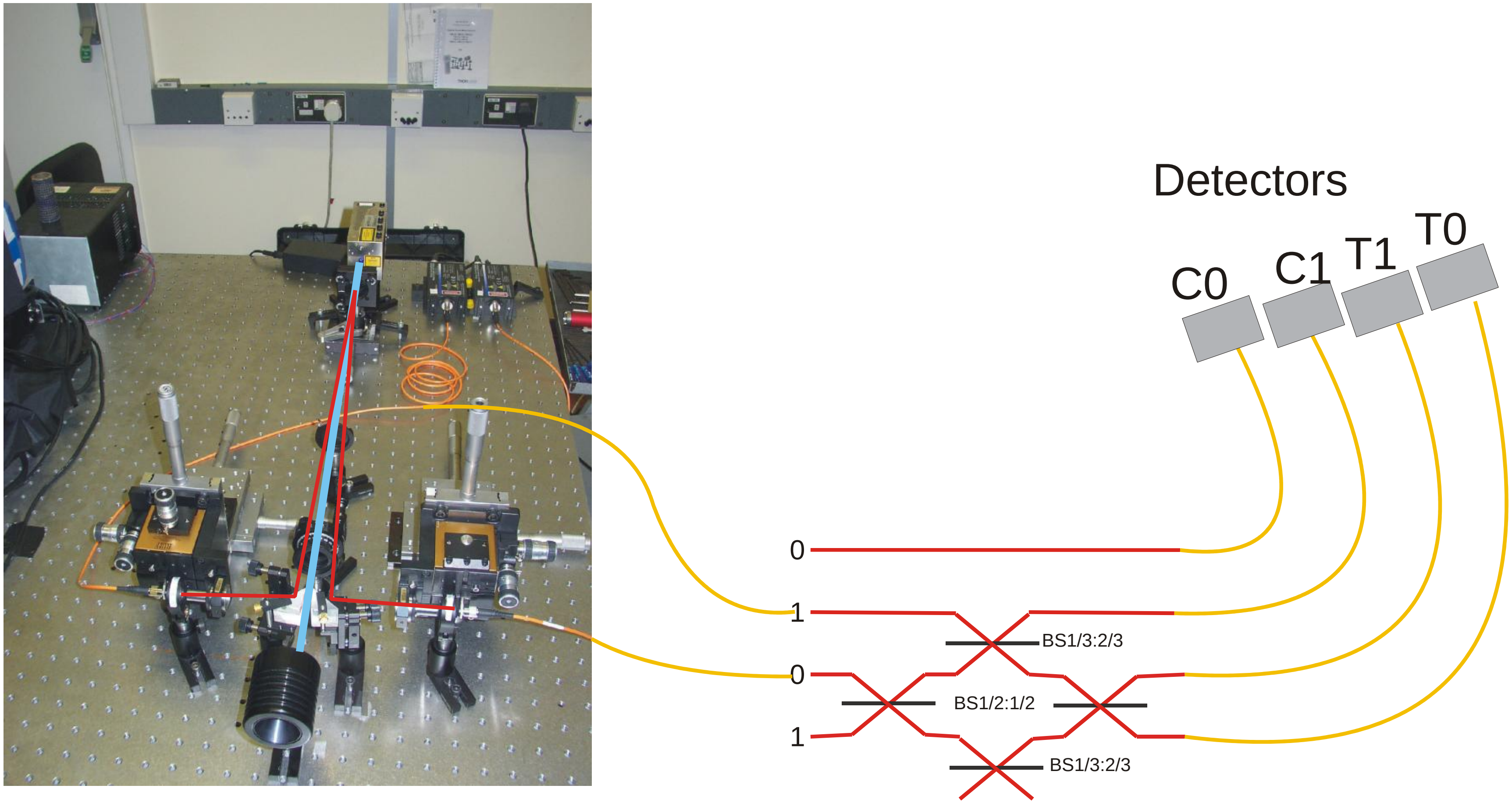




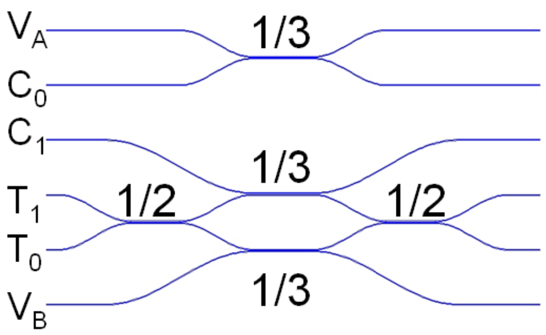
A. Politi, M. J. Cryan, J. G. Rarity, S. Yu, and J. L. O’Brien,. *Science,* **320**, 5876 (2008)

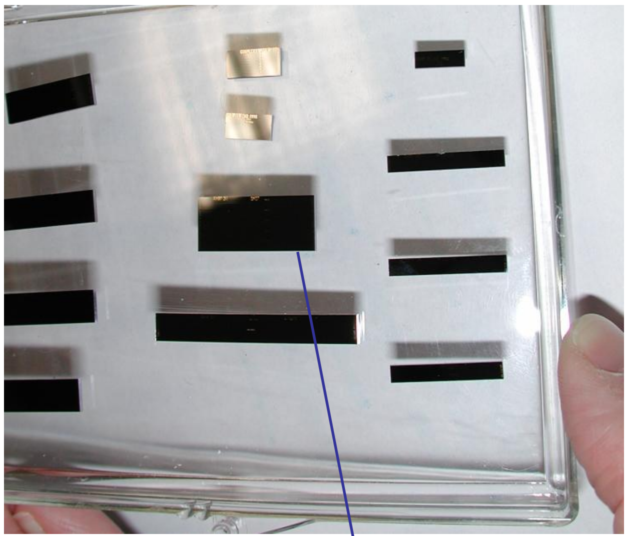
A Laing, A Peruzzo, M Rodas, A Politi, M Thompson, J L O’Brien, *in preparation*

CNOT Gate Experiment



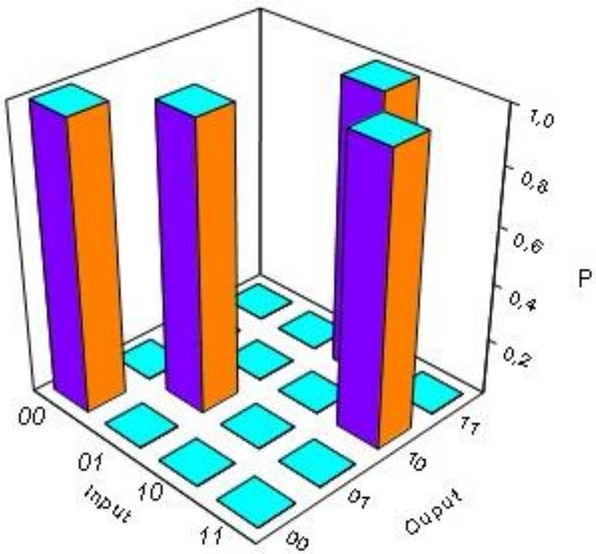
Integrated CNOT gate



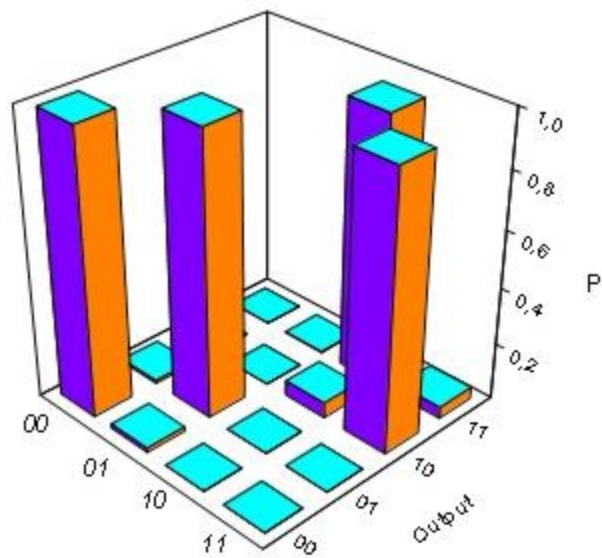


5 CNOT devices on the same chip

Ideal:



Measured:



$$\mathbf{F}_{zz} = \mathbf{96.9 \pm 0.1\ \%}$$

$$\mathbf{S}_{zz} = \mathbf{99.0 \pm 0.1\ \%}$$

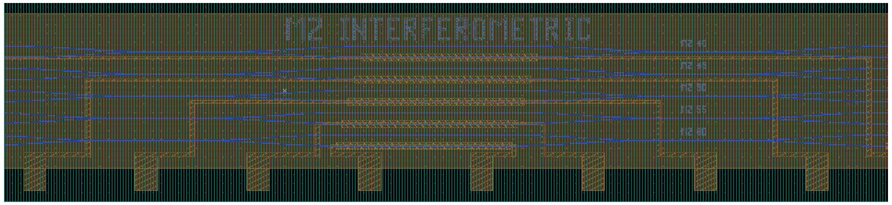
A. Politi, M. J. Cryan, J. G. Rarity, S. Yu, and J. L. O'Brien,. *Science*, **320**, 5876 (2008).

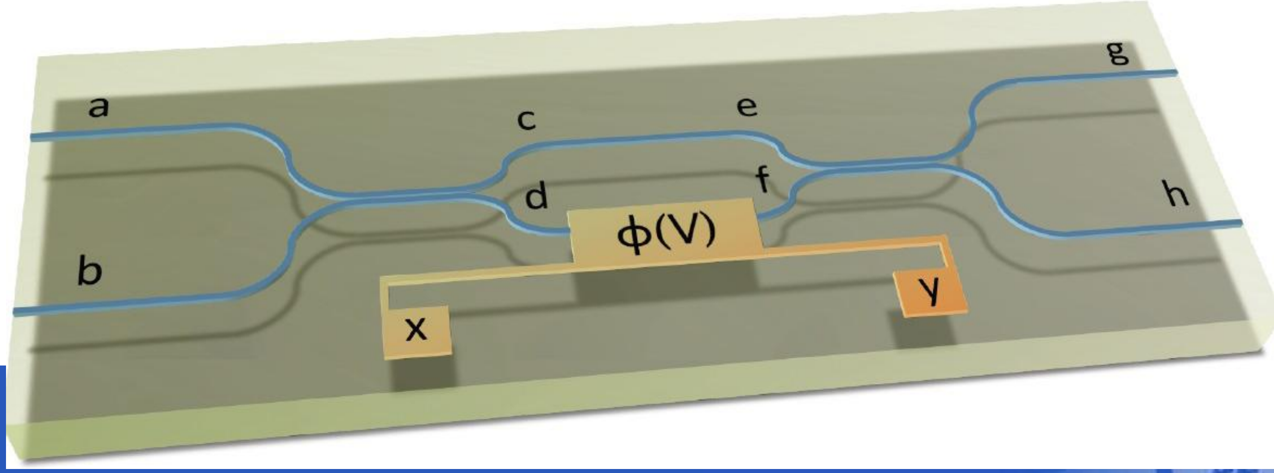
Quantum state manipulation

With resistive heater

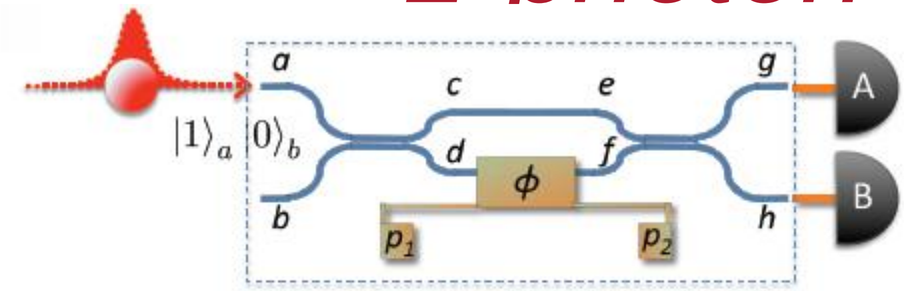
Change refractive index of the WG.

Choose splitting ratio of exit ports.

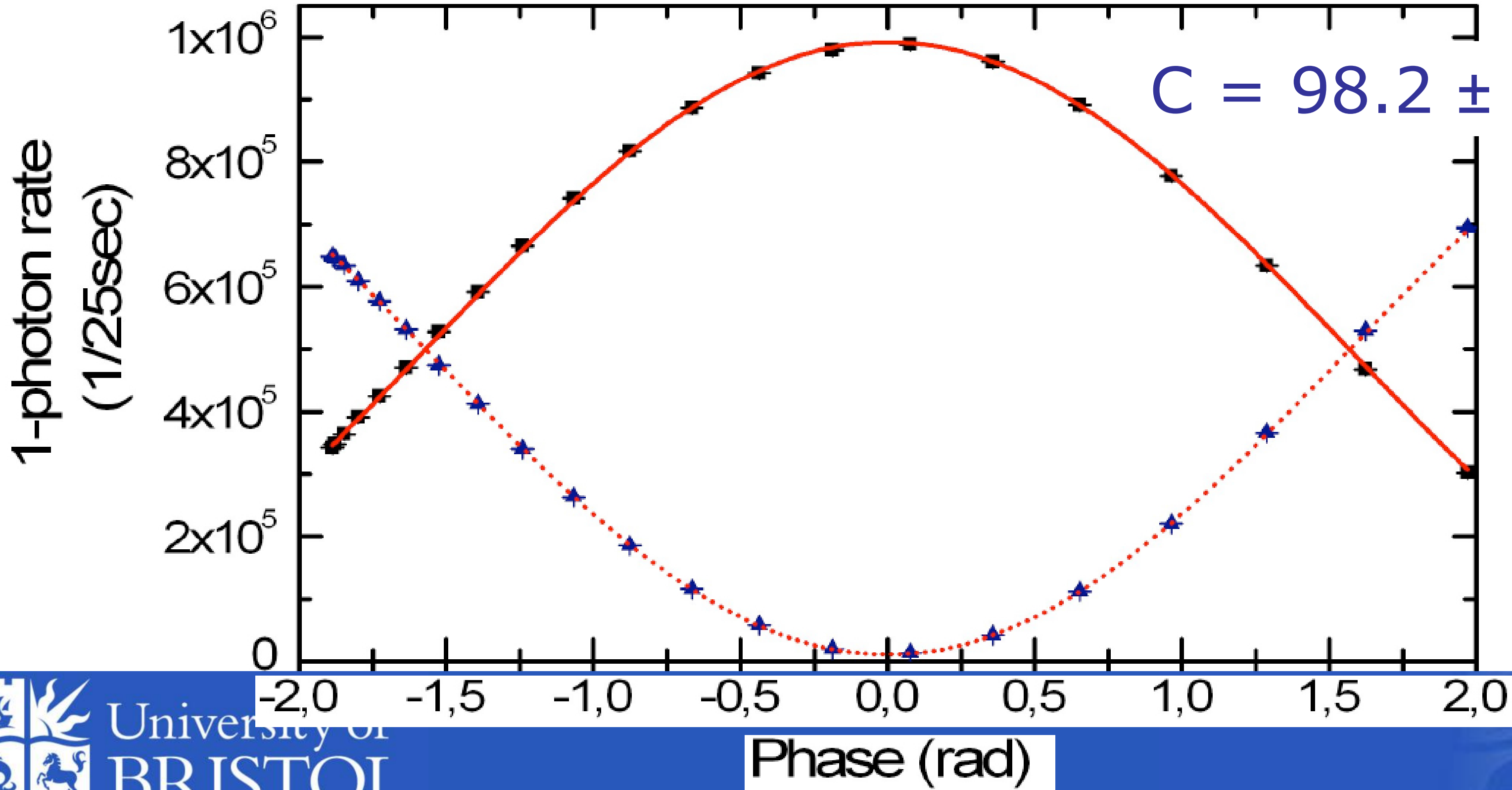




Integrated Phase Control
1-photon

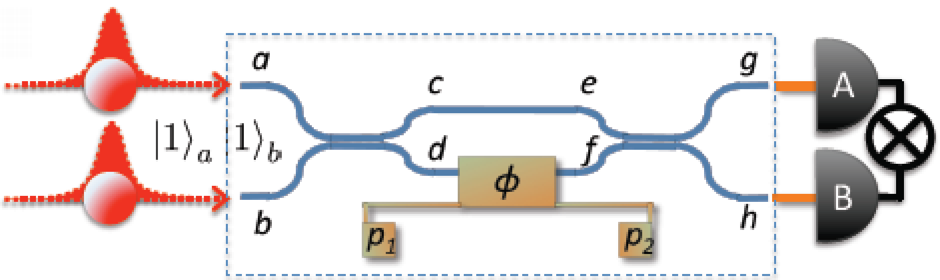


$$P_g = 1 - P_h = \frac{1}{2}\left[1 - \cos(\phi)\right]$$



C = 98.2 ± 0.3 %

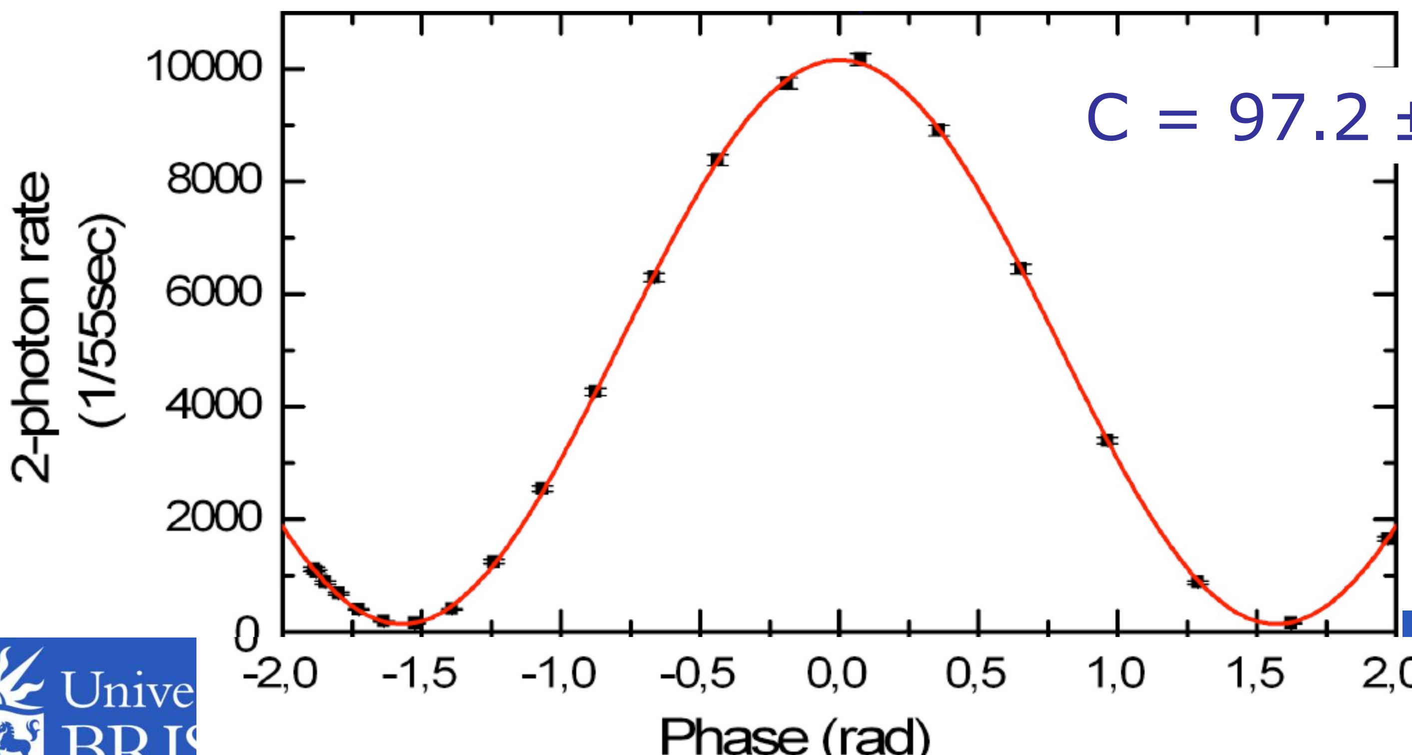
Integrated Phase Control
2-photon



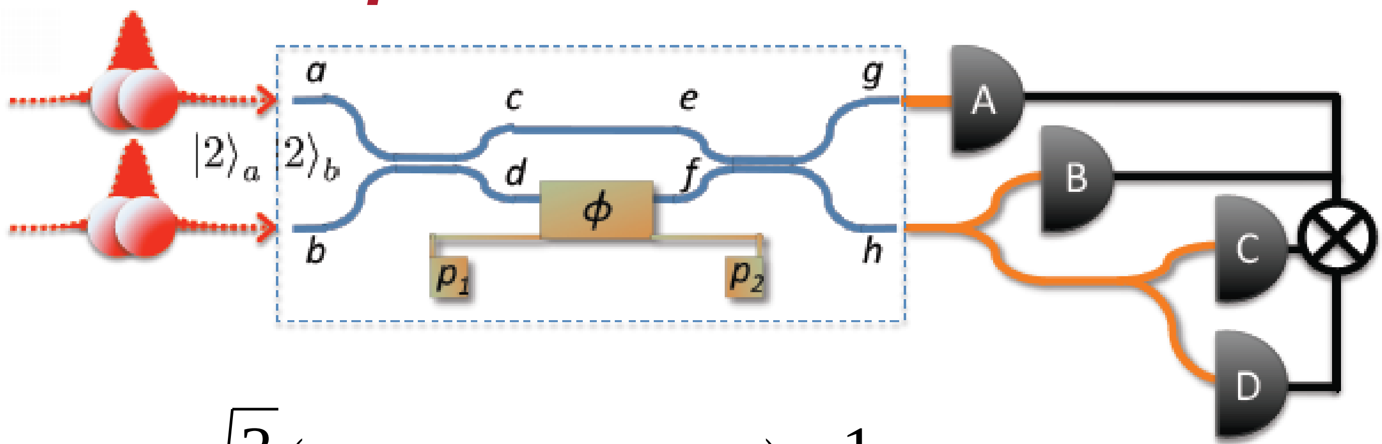
$$|1\rangle_a |1\rangle_b$$

$$\frac{1}{\sqrt{2}}\left(|2\rangle_c |0\rangle_d - |0\rangle_c |2\rangle_d\right)$$

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



Integrated Phase Control
4-photon



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

$$P_{3e,f} = P_{e,3f} = \frac{3}{8}(1 - \cos 4\phi)$$

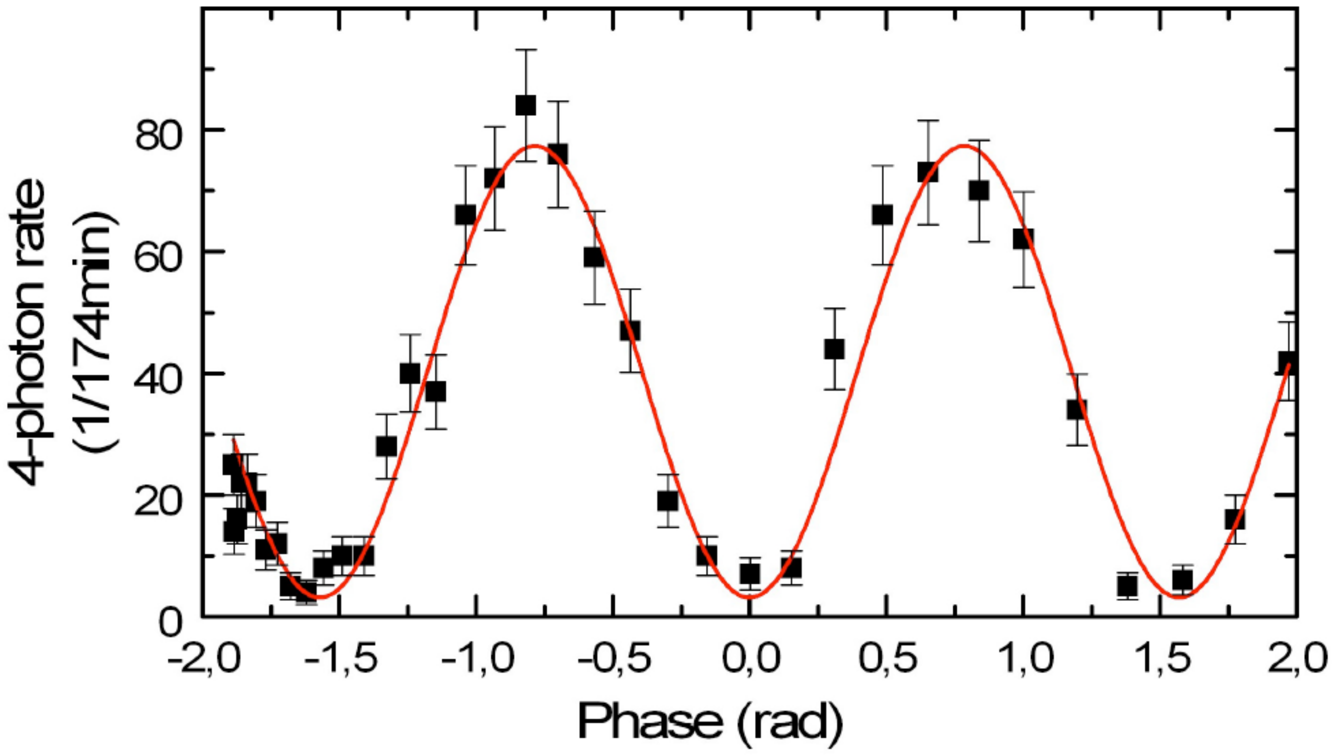
Quantum Metrology:

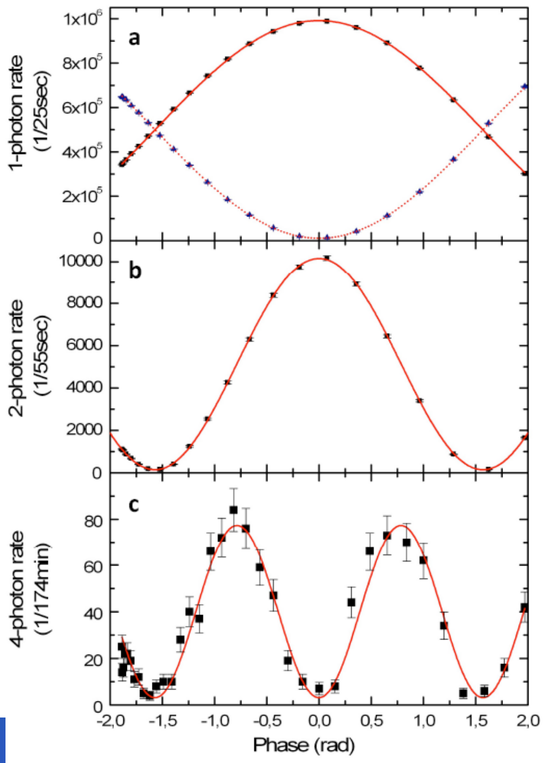
Precision: $\Delta\phi = 1/N$ against $\Delta\phi = 1/\sqrt{N}$

Heisenberg limit

Shot noise limit

Integrated Phase Control
4-photon





C = 92 ± 4 %

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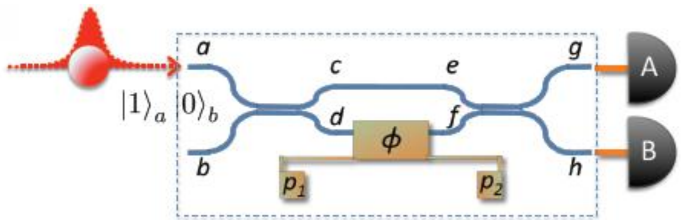
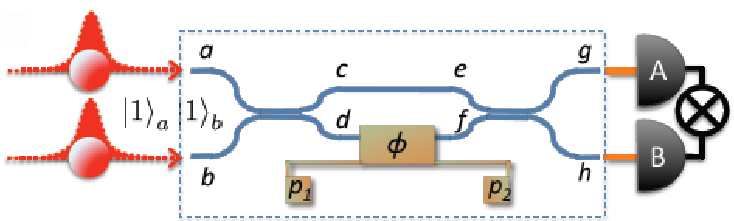
J. F. C. Matthews, A. Politi, A. Stefanov, J. L. O'Brien, to appear in *Nature Photonics*

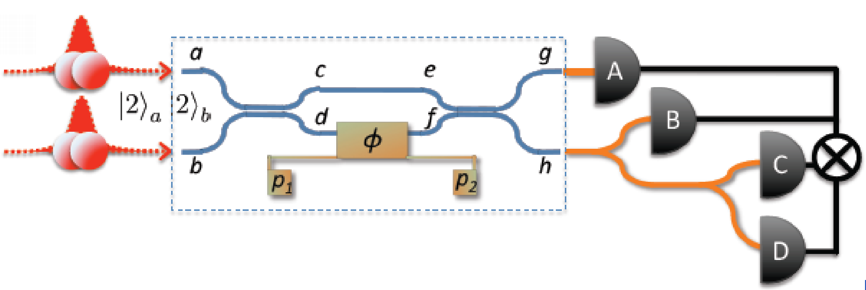
Integrated Phase Control



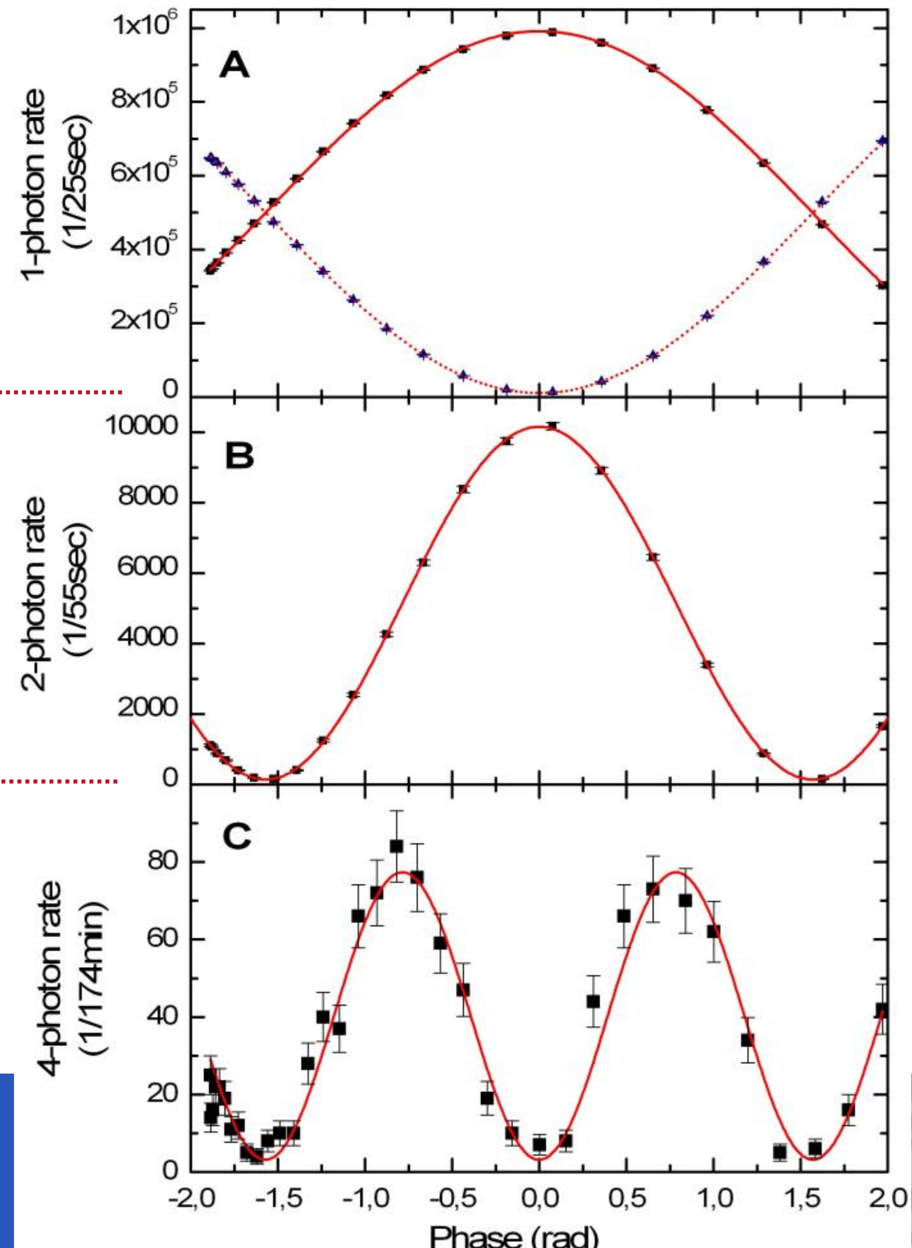
C = 98.2 ± 0.3 %



C = 97.2 ± 0.4 %



C = 92 ± 4 %



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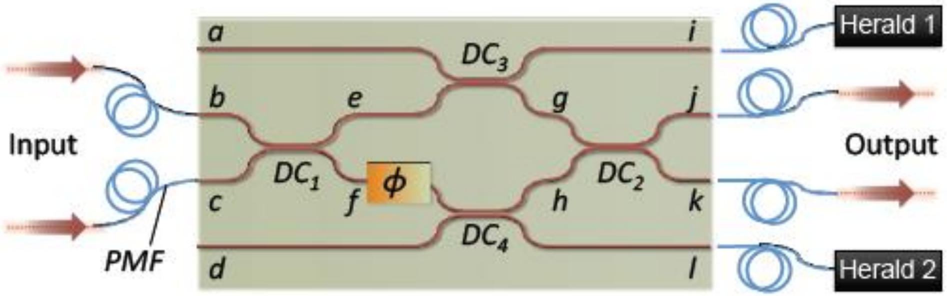
Heralded N00N states



In interferometer

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

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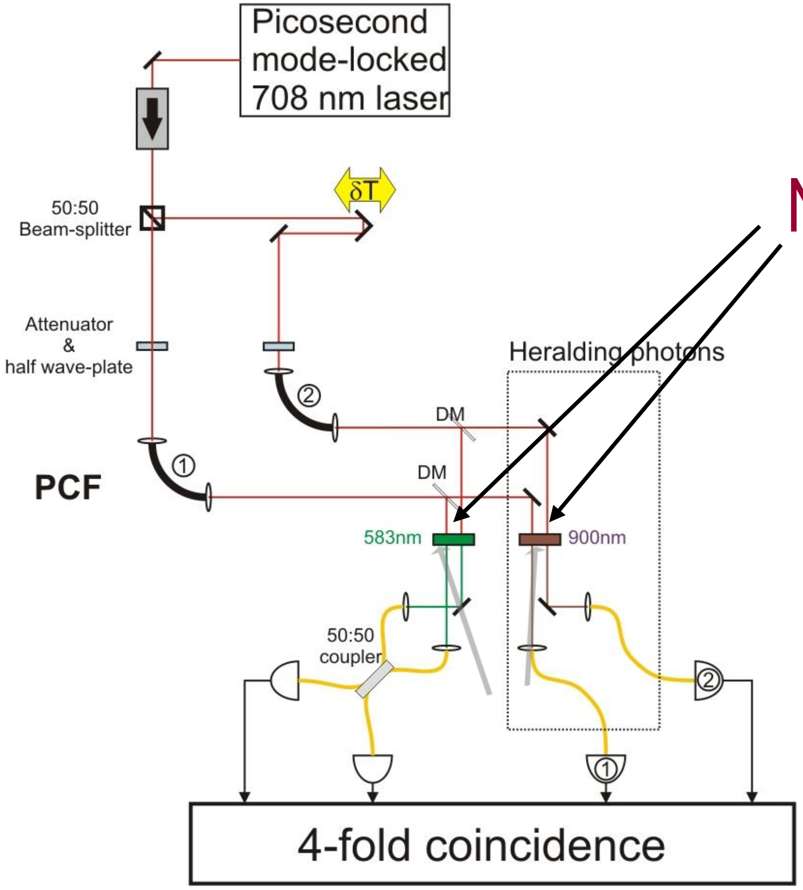
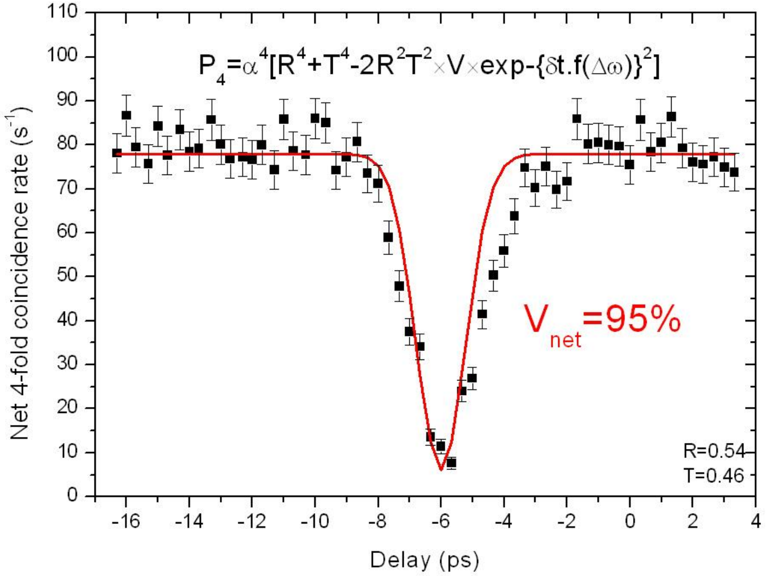
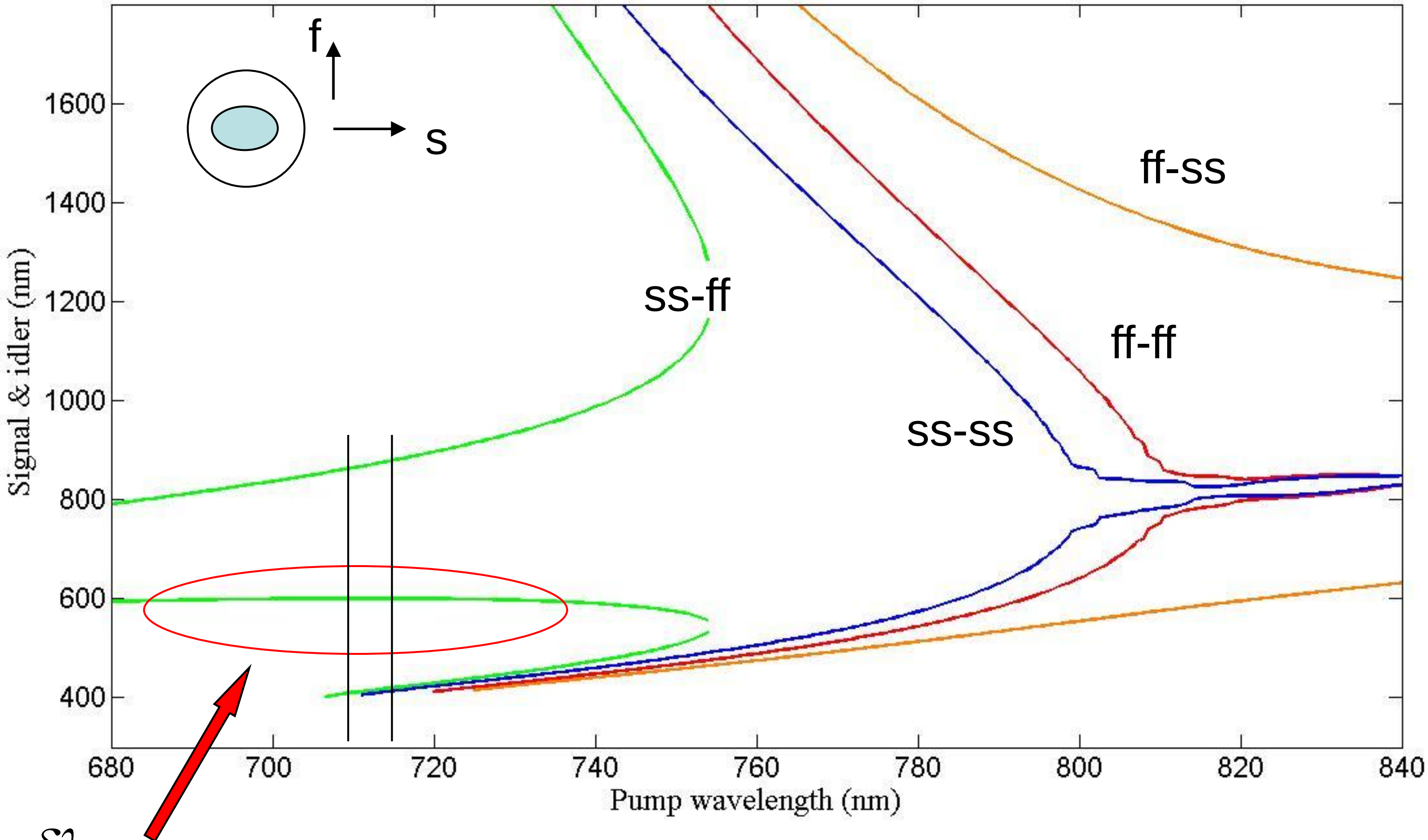
Improved efficiency through pure state generation



Narrowband filters T~60%



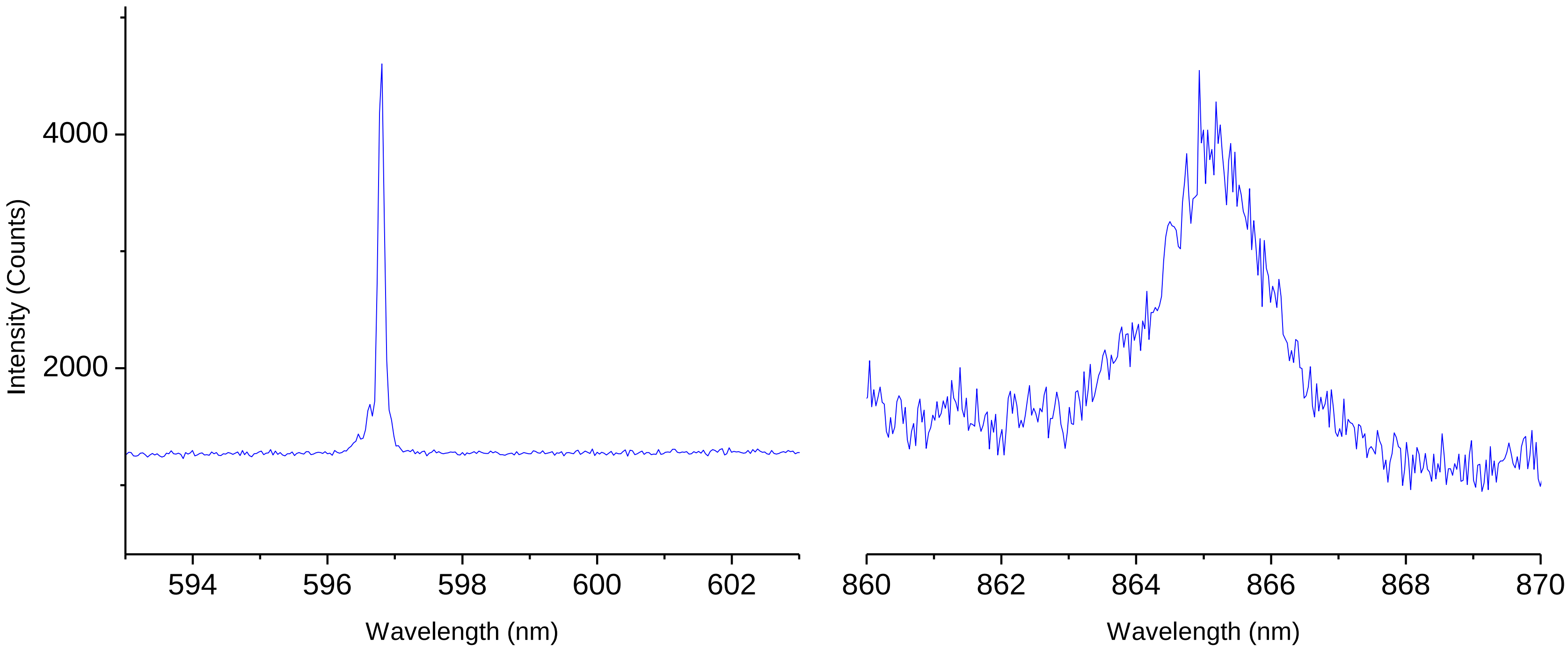
PHASE-MATCHING CONDITION



$$\frac{\delta\lambda_s}{\delta\lambda_p} = 0$$

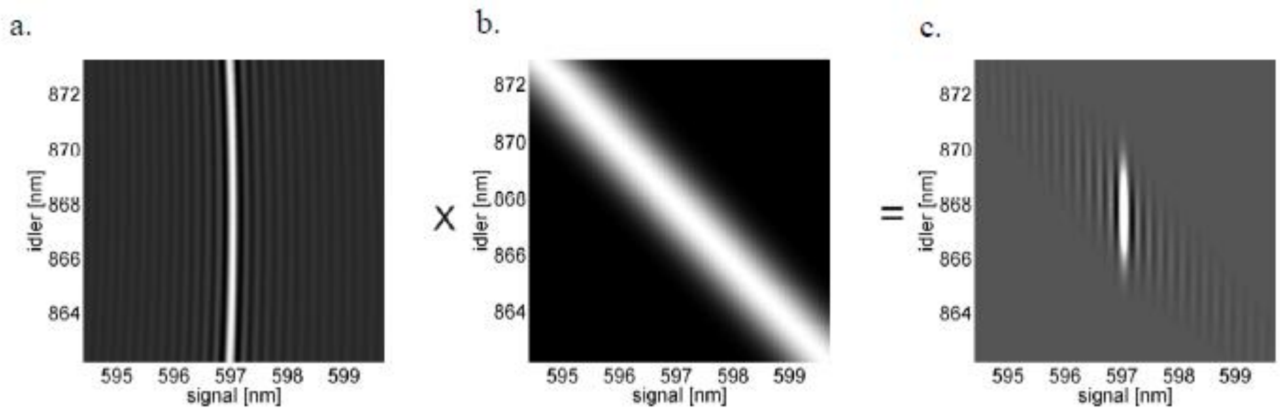
Copolar and Crosspolar birefringent phase matching curves

CHARACTERISTICS OF THE EMISSION



- Time-Bandwidth Limited with **no filters** Signal / Idler FWHM ~ 0.12nm / 2nm
- Single mode
- Polarized
- Total Lumped Efficiency η≈20%

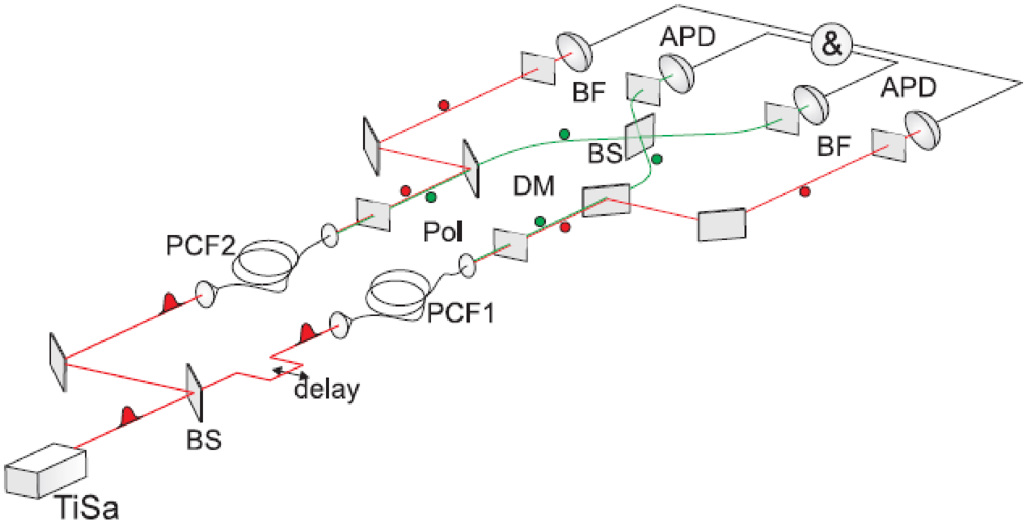
Joint spectral distribution, state factorability and interference visibility

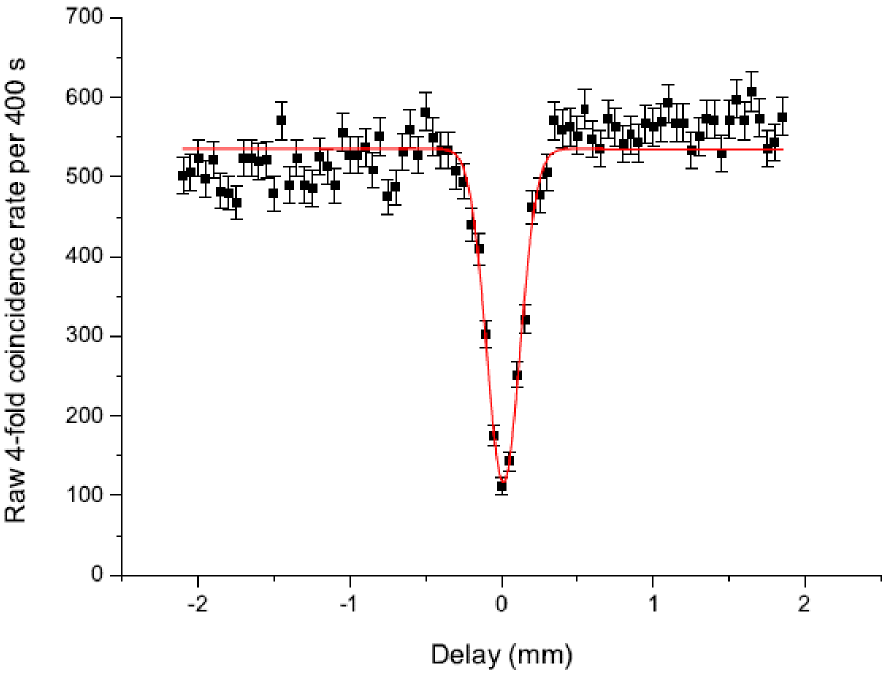


$$F(\omega_s, \omega_i) = \sum_j \sqrt{\lambda_j} f_j(\omega_s) g_j(\omega_i) \qquad \sum_j \lambda_j = 1$$

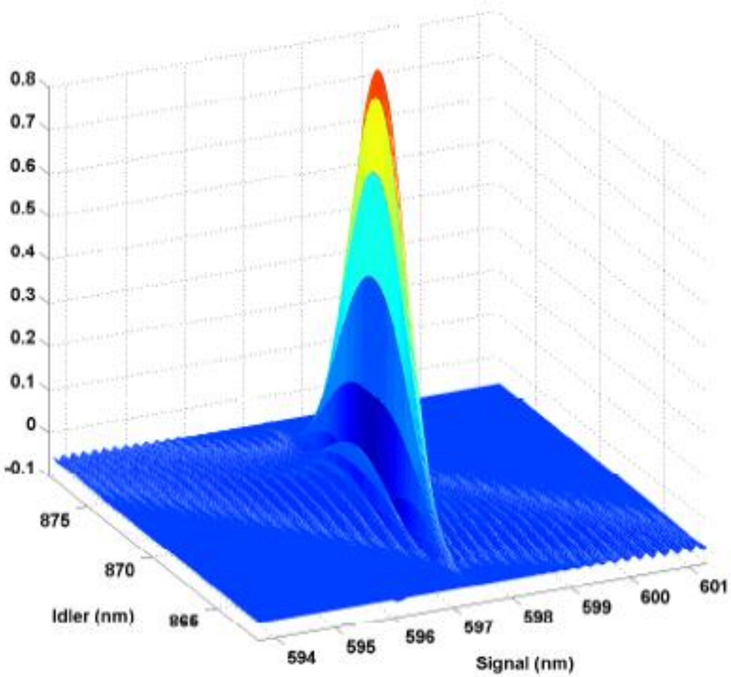
Schmidt number $$K = \frac{1}{\sum_j \lambda_j^2}$$ Max Visibility < 1/K

HOM DIP : RESULTS

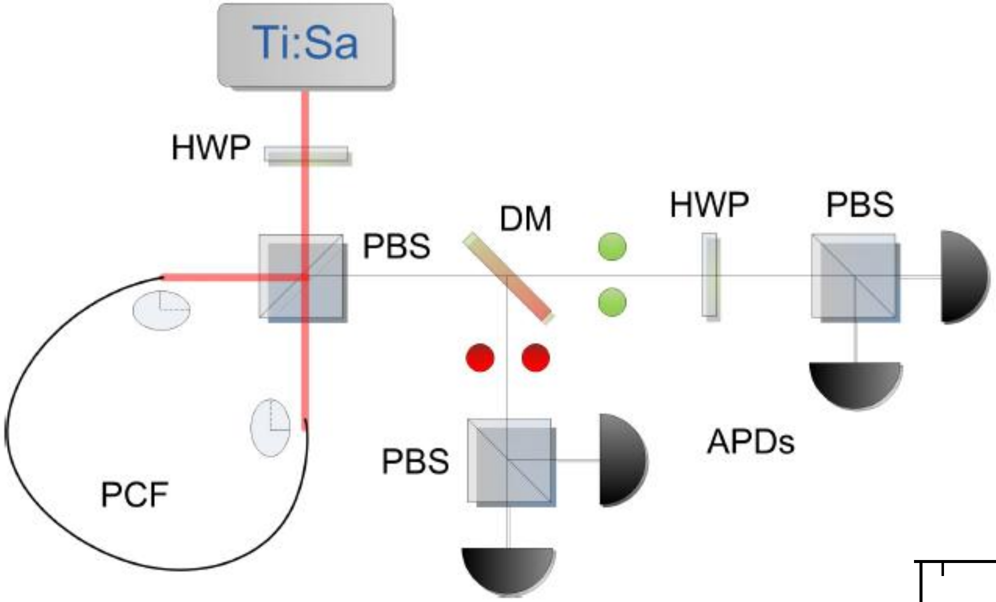




- Purity issue → ripples in JSA due to phasematching function
- Spectral distinguishability between separate sources

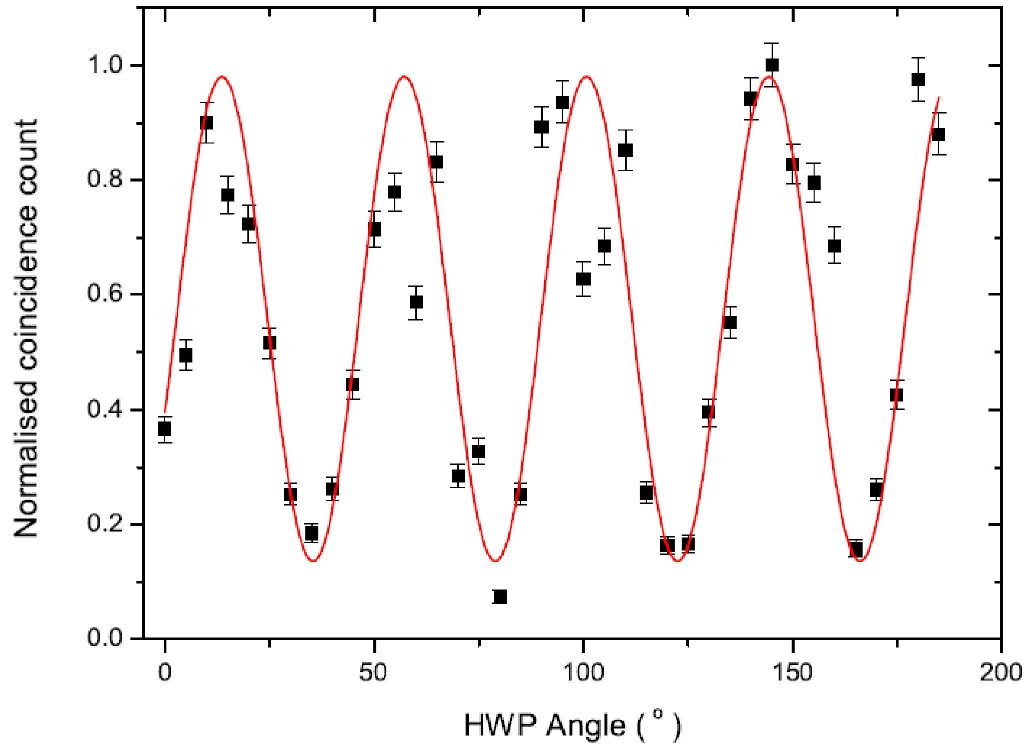


M. Halder,et al, Optics Express **17**, 4670, 2009
A. Clark et al NJP, xx, xxx, 2011

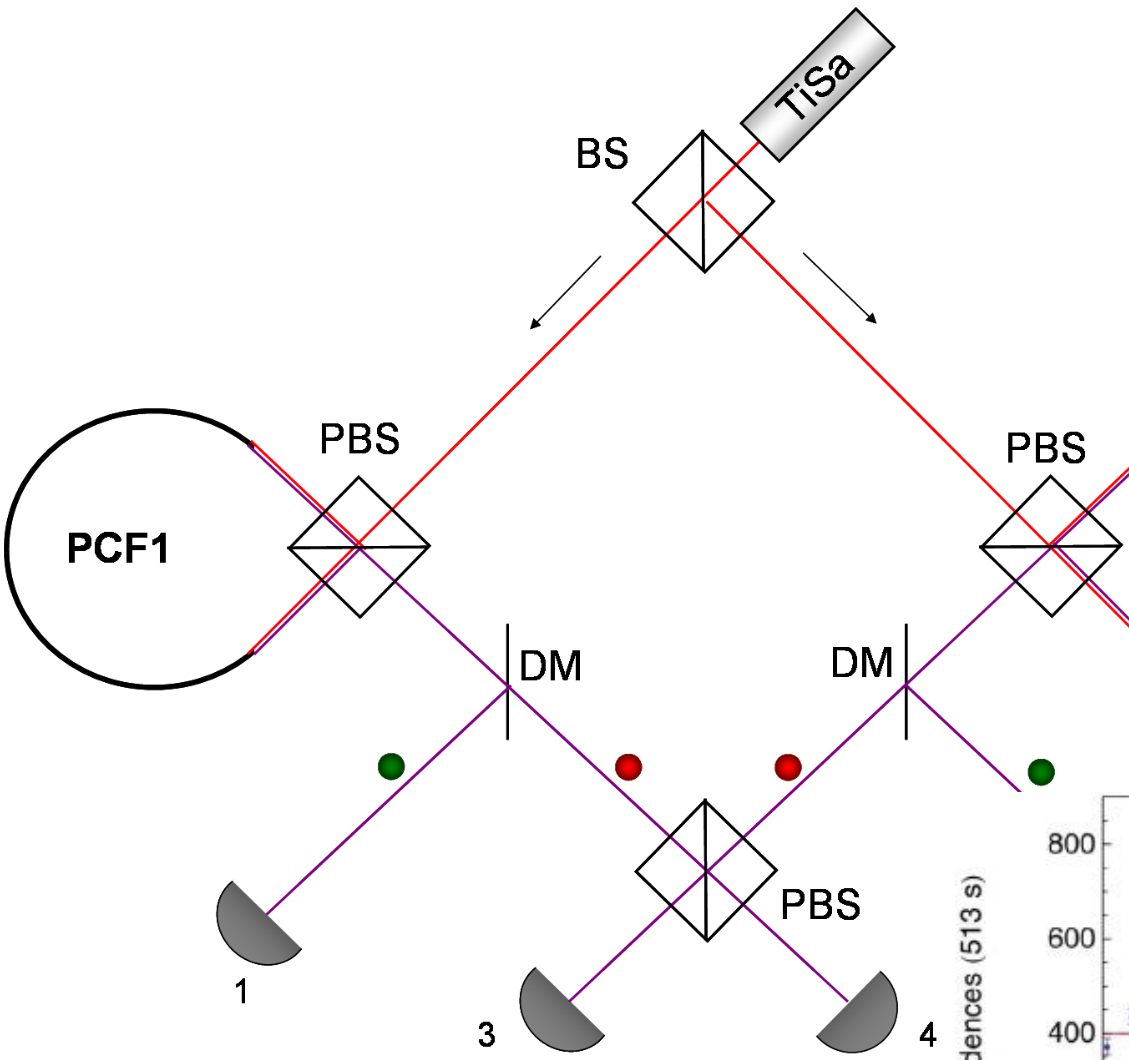


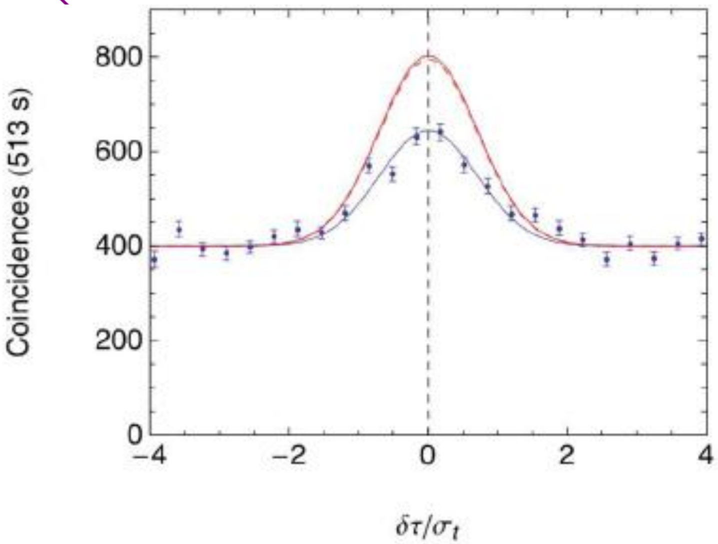
HOM from same fibre

- Create $|H_s H_i V_s V_i\rangle$
- Visibility again limited to ~80%
- May be improved by optimising pump BW?



Cluster/GHZ state generation





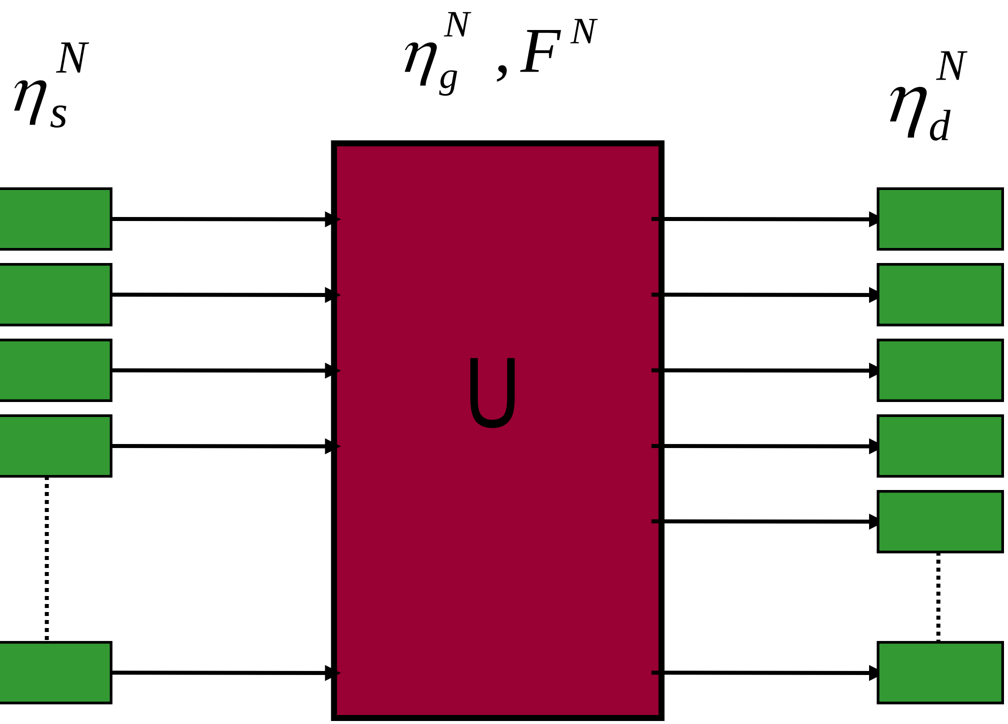
Lecture 3

Structure

Lecture 3: More efficient gates, hybrid QIP.

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

The PROBLEM: many qubits quantum processor



Single Qubit source

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

Unitary transform

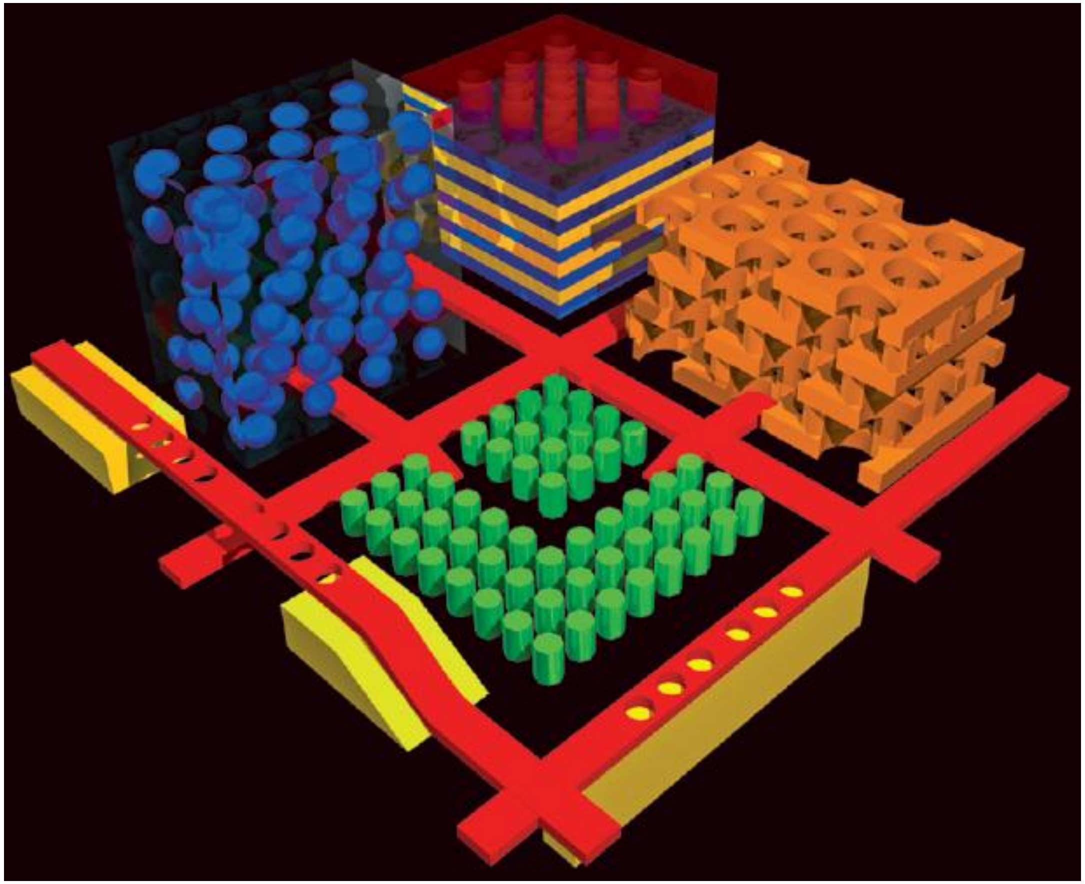
Linear gates η<0.5 F>0.99
Non-linear optics η~1 F>0.9?

Detectors

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

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

Confining light: periodic dielectric structures
Photonic crystals

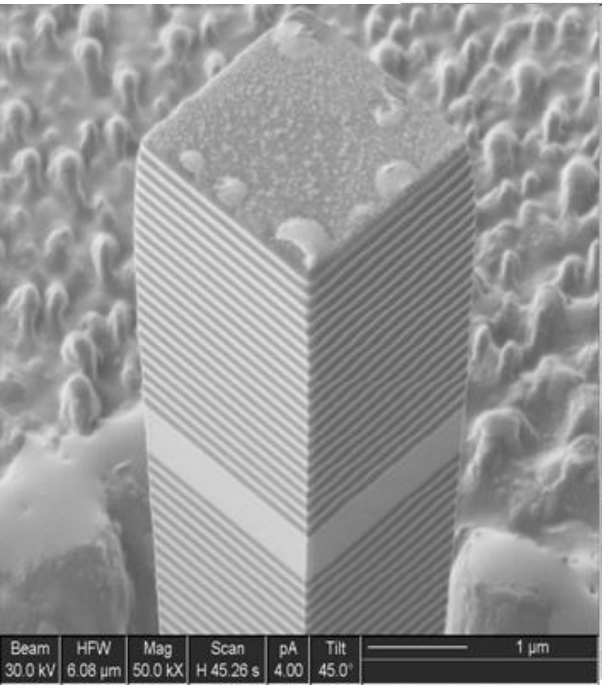


From; Photonic Crystals: Moulding the Flow of Light, Joannopoulos et al, 2008, Princeton University Press

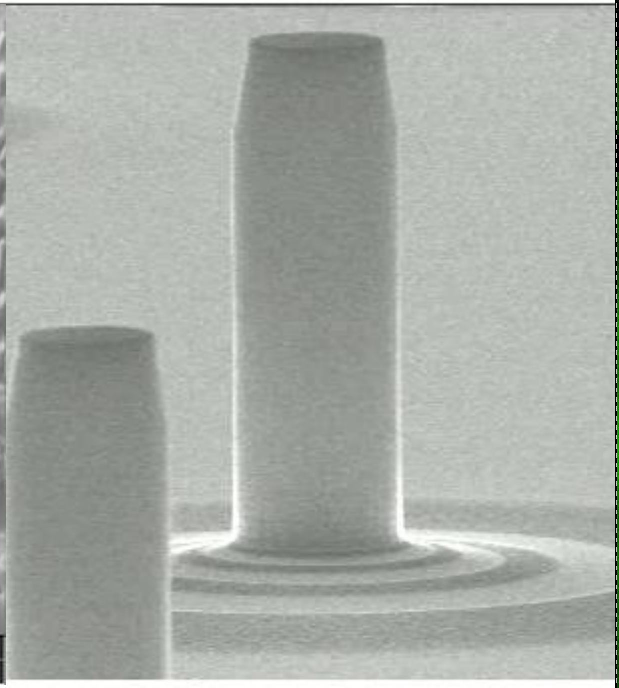
Spin photon interface using charged quantum dots in microcavities

C.Y. Hu, A. Young, J. L. O'Brien, W.J. Munro, J. G. Rarity, Phys. Rev. B 78, 085307 (08)
C.Y. Hu, W.J. Munro, J. G. Rarity, Phys. Rev. B 78, 125318 (08)
C.Y. Hu, W.J. Munro, J. L. O'Brien , J. G. Rarity, Arxiv: 0901.3964(09)
C.Y. Hu, J. G. Rarity, Arxiv: 1005.5545, PRB XX, XXX (2011)

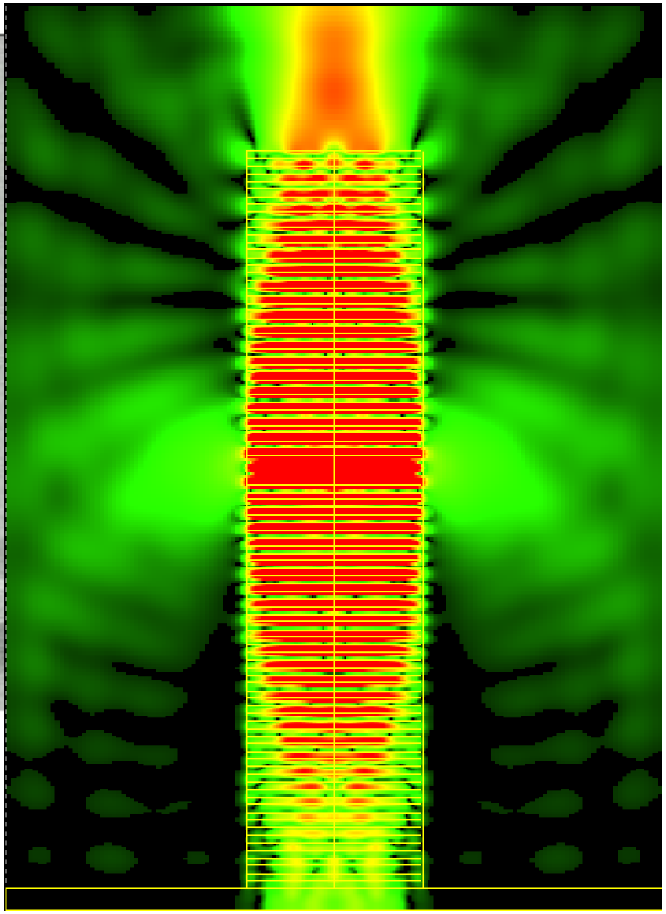
Pillar microcavities for strong coupling of photons with spins in quantum dots



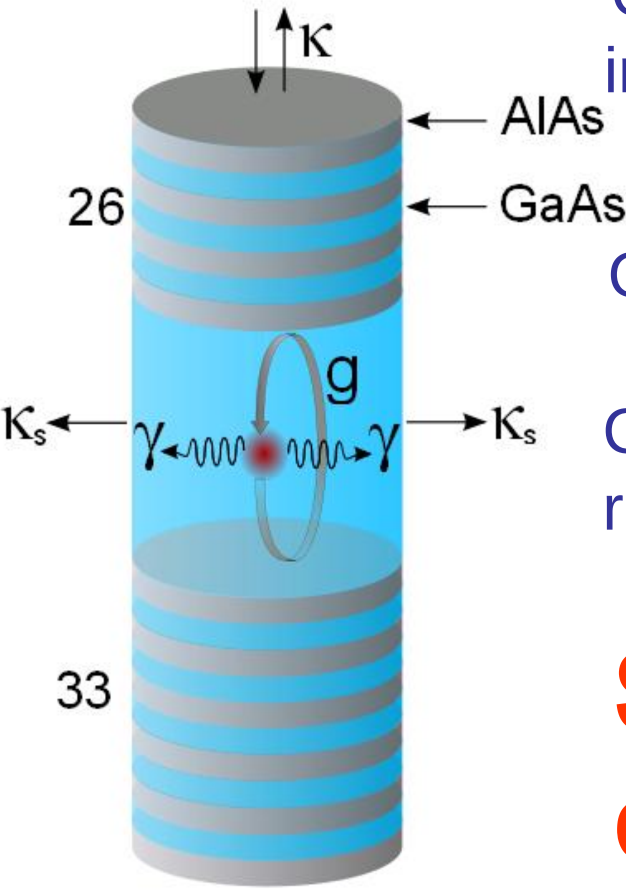
FIB etching



ICP/RIE etching



Cavity Quantum Electrodynamics (CQED)



QD-cavity interaction

$$g = \sqrt{\frac{\hbar^2}{4\pi\varepsilon_r\varepsilon_0}\frac{\pi e^2 f}{mV_{\text{eff}}}}$$

f=oscillator strength
m= electron effective mass
V= cavity volume

QD dipole decay rate γ

Cavity decay rate

$$\kappa + \kappa_s = \frac{\hbar\omega}{Q}$$

Strong coupling

$$g > \frac{\kappa + \kappa_s}{4}$$

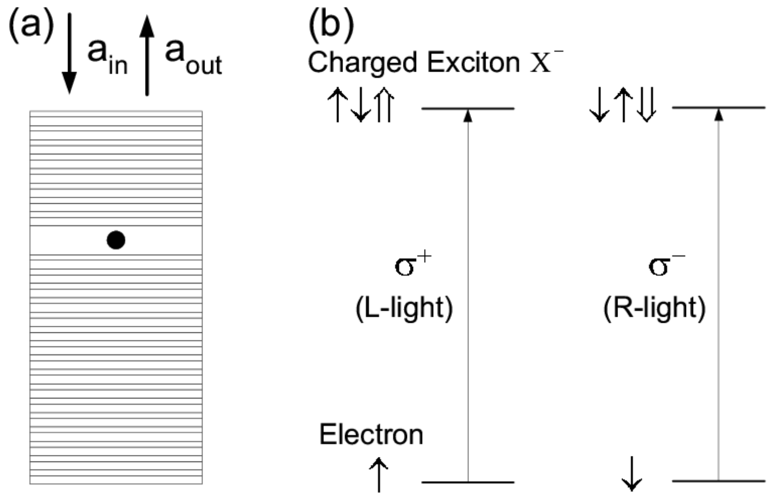
To optimise g/κ

Maximise $\boldsymbol{Q/V^{1/2}}$

Giant optical Faraday rotation

C.Y. Hu, Rarity et al, Phys. Rev. B 78, 085307 (08)
C.Y. Hu, Rarity et al, Phys. Rev. B 78, 125318 (08)

Single-sided cavity



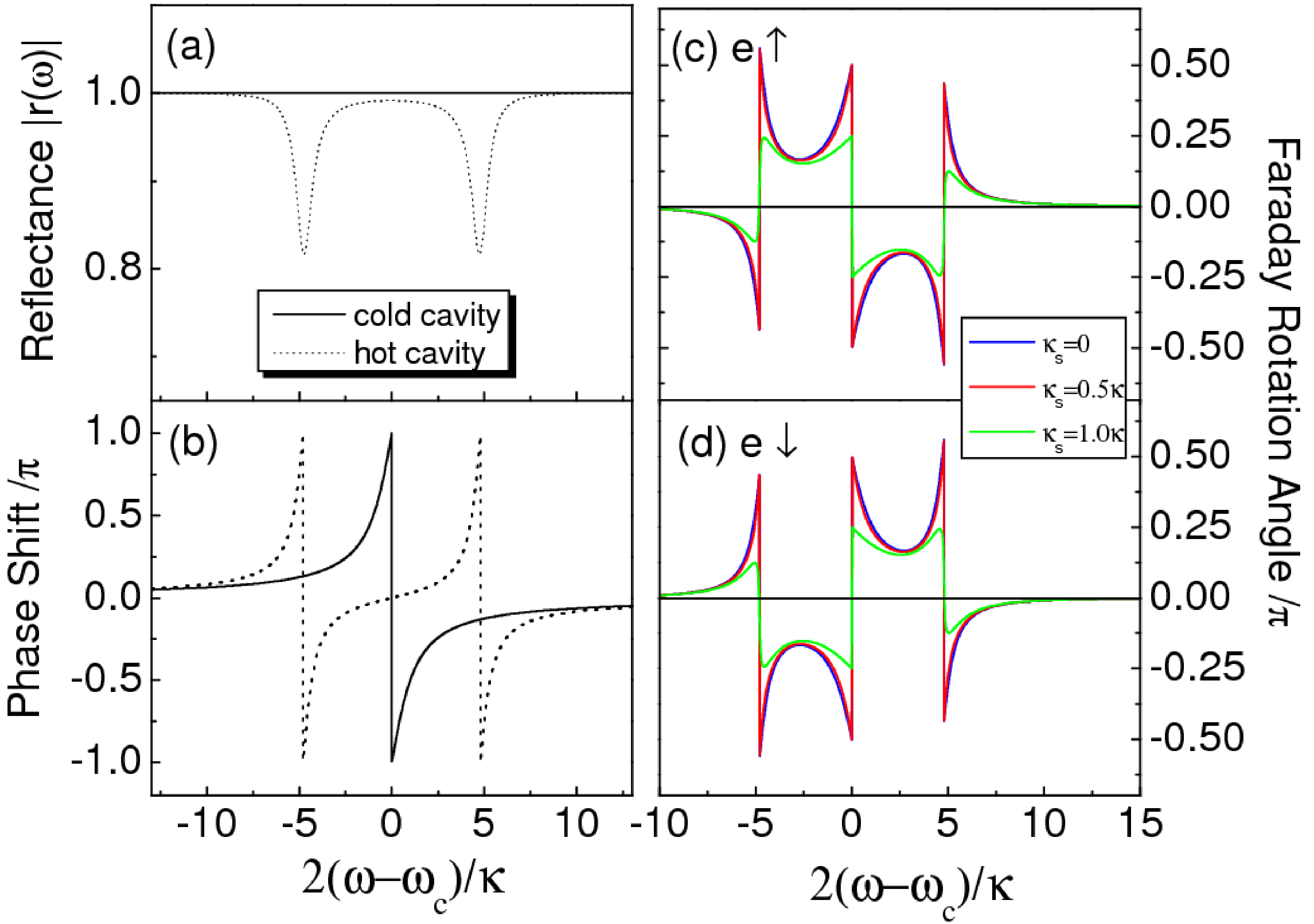
Reflection coefficient

Cold Cavity $g = 0 \quad |r(\omega)| = 1 \quad \varphi_0(\omega) = \pm\pi + 2\tan^{-1}\dfrac{2(\omega - \omega_c)}{\kappa}$

Hot cavity $g >> \kappa, \gamma \quad r(\omega \sim \omega_c) = 1$

Phase shift gate

$$\hat{U}(\Delta\varphi) = e^{i\Delta\varphi\left(|L\rangle\langle L|\otimes|\uparrow\rangle\langle\uparrow| + |R\rangle\langle R|\otimes|\downarrow\rangle\langle\downarrow|\right)}$$



(a)
Reflectance |r(ω)|
1.0
0.8
cold cavity
hot cavity
(b)
Phase Shift /π
1.0
0.5
0.0
-0.5
-1.0
-10
-5
0
5
10
2(ω–ω_c)/κ
(c) e↑
(d) e↓
0.50
0.25
0.00
-0.25
-0.50
Faraday Rotation Angle /π
κ_s=0
κ_s=0.5κ
κ_s=1.0κ
-10
-5
0
5
10
15
2(ω–ω_c)/κ

Giant optical Faraday rotation

- Electron spin ↑, L-light feels a hot cavity and R-light feels a cold cavity
- Electron spin ↓, R-light feels a hot cavity and L-light feels a cold cavity
- By suitable detuning can arrange orthogonal, Giant Faraday rotation angle

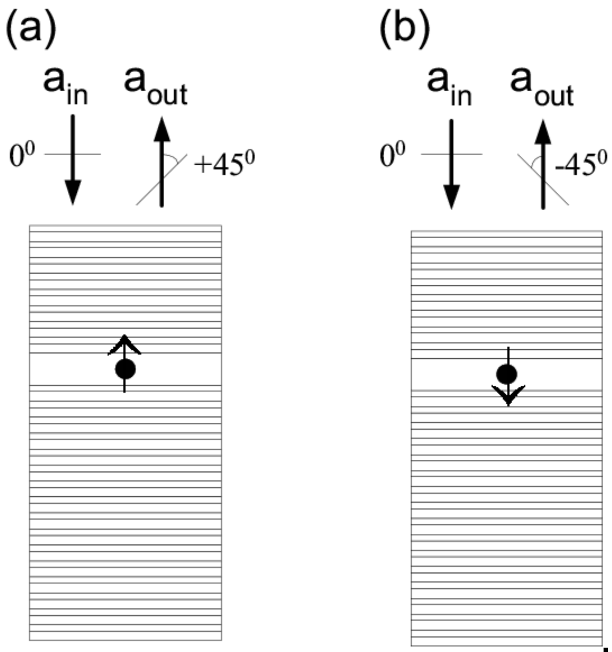
$$\theta_F^{\uparrow} = \frac{\varphi_0 - \varphi}{2} = -\theta_F^{\downarrow} = 45^0 \qquad \Delta\varphi > \frac{\pi}{2}$$

Achievable with

$$\frac{g}{(\kappa + \kappa_s)} > 0.1 \qquad \kappa / \kappa_s \sim 1$$ Low efficiency

$$\frac{g}{(\kappa + \kappa_s)} > 1.5 \qquad \kappa / \kappa_s >> 1$$ High efficiency

Quantum non-demolition detection of a single electron spin



Input light $|H\rangle = \frac{1}{\sqrt{2}}(|R\rangle + |L\rangle)$

Spin up

$$|H\rangle \otimes |\uparrow\rangle \xrightarrow{\dot{U}(\pi/2)} \frac{1}{\sqrt{2}}|+45^0\rangle|\uparrow\rangle$$

Spin down

$$|H\rangle \otimes |\downarrow\rangle \xrightarrow{\dot{U}(\pi/2)} \frac{1}{\sqrt{2}}|-45^0\rangle|\downarrow\rangle$$

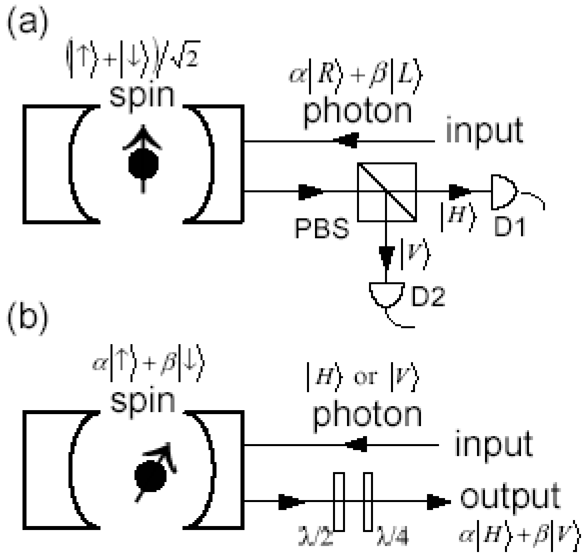
Spin superposition state $\alpha|\uparrow\rangle + \beta|\downarrow\rangle$

$$|H\rangle \otimes (\alpha|\uparrow\rangle + \beta|\downarrow\rangle) \rightarrow \frac{1}{\sqrt{2}}\left\{\alpha|+45^0\rangle|\uparrow\rangle + \beta|-45^0\rangle|\downarrow\rangle\right\}$$

A photon spin entangler!

C.Y. Hu, et al, Phys. Rev. B 78, 085307 (08)

Photon-spin quantum interface



(a)

State transfer from photon to spin

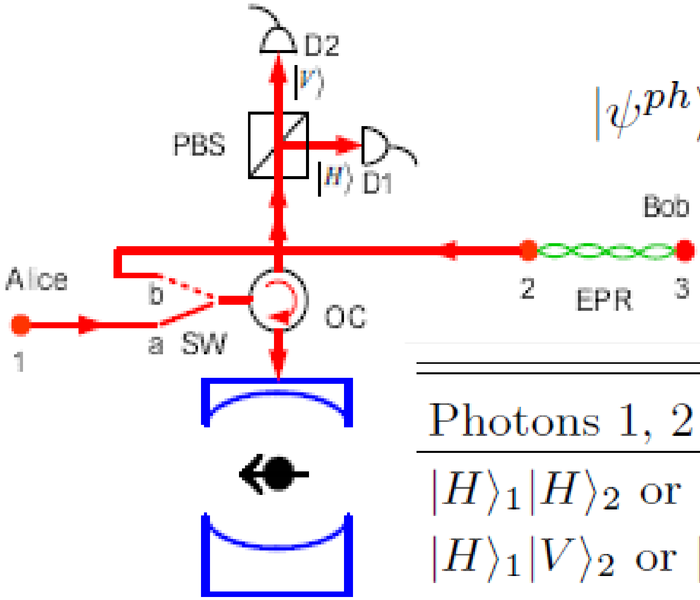
(b)

State transfer from spin to photon

- Deterministic
- High fidelity
- Two sided cavity makes an entangling beamsplitter (Phys Rev B 80, 205326, 2009)

Quantum Repeater: arXiv1005.5545

$$|\psi^{ph}\rangle_1 = \alpha|R\rangle_1 + \beta|L\rangle_1$$

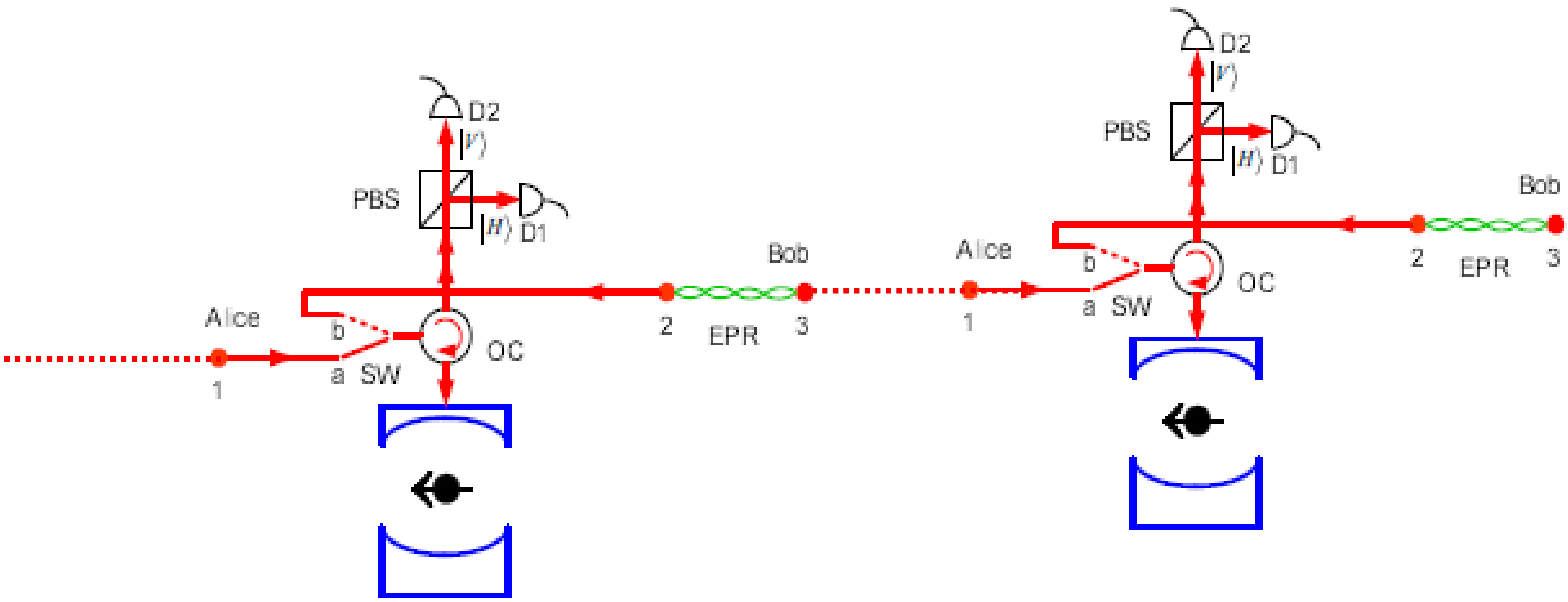


$$|\psi^{ph}\rangle_{23} = (|R\rangle_2|L\rangle_3 + |L\rangle_2|R\rangle_3)/\sqrt{2}$$

$$|\psi^s\rangle = (|\uparrow\rangle + |\downarrow\rangle)/\sqrt{2}$$

Photons 1, 2	Spin	Photon 3
$\|H\rangle_1\|H\rangle_2$ or $\|V\rangle_1\|V\rangle_2$	$\|-\rangle$	$\alpha\|L\rangle_3 - \beta\|R\rangle_3$
$\|H\rangle_1\|V\rangle_2$ or $\|V\rangle_1\|H\rangle_2$	$\|-\rangle$	$\alpha\|L\rangle_3 + \beta\|R\rangle_3$
$\|H\rangle_1\|H\rangle_2$ or $\|V\rangle_1\|V\rangle_2$	$\|+\rangle$	$\alpha\|R\rangle_3 + \beta\|L\rangle_3$
$\|H\rangle_1\|V\rangle_2$ or $\|V\rangle_1\|H\rangle_2$	$\|+\rangle$	$\alpha\|R\rangle_3 - \beta\|L\rangle_3$

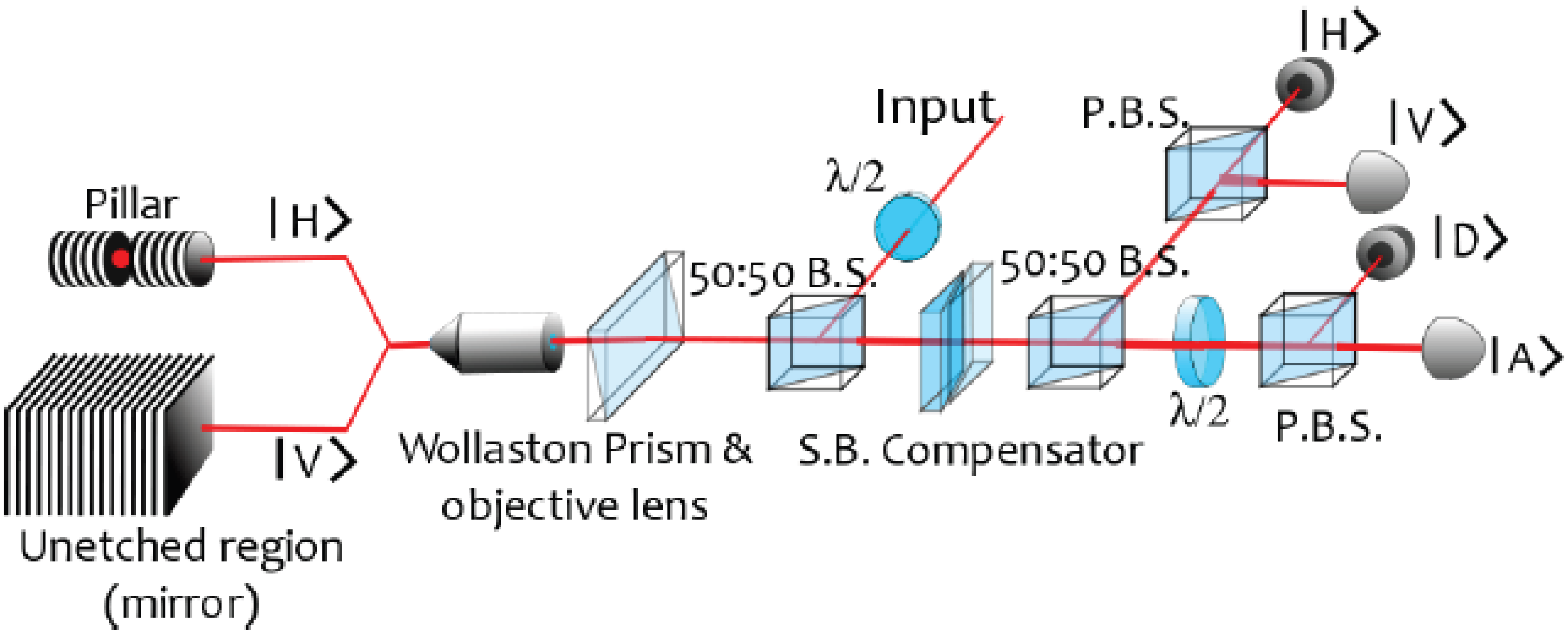
Quantum Repeater: arXiv1005.5545



Experiments

- Strong coupling seen in resonant reflection experiment
- Phase shift between resonant and non-resonant case ~0.2 radians
- Young, Rarity et al arXiv 1011.384

Reflection spectroscopy
Conditional phase shift interferometer

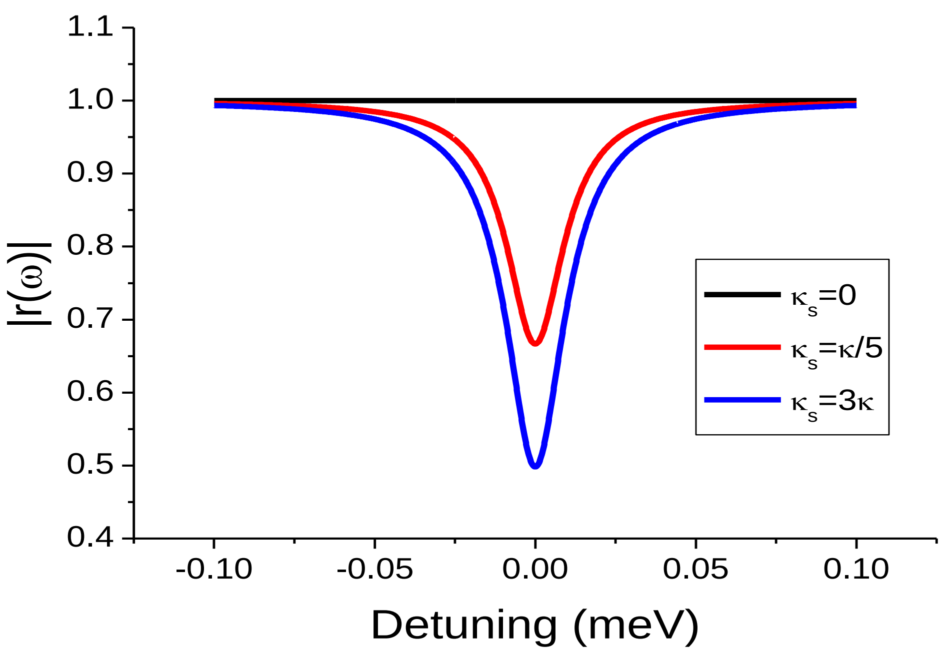


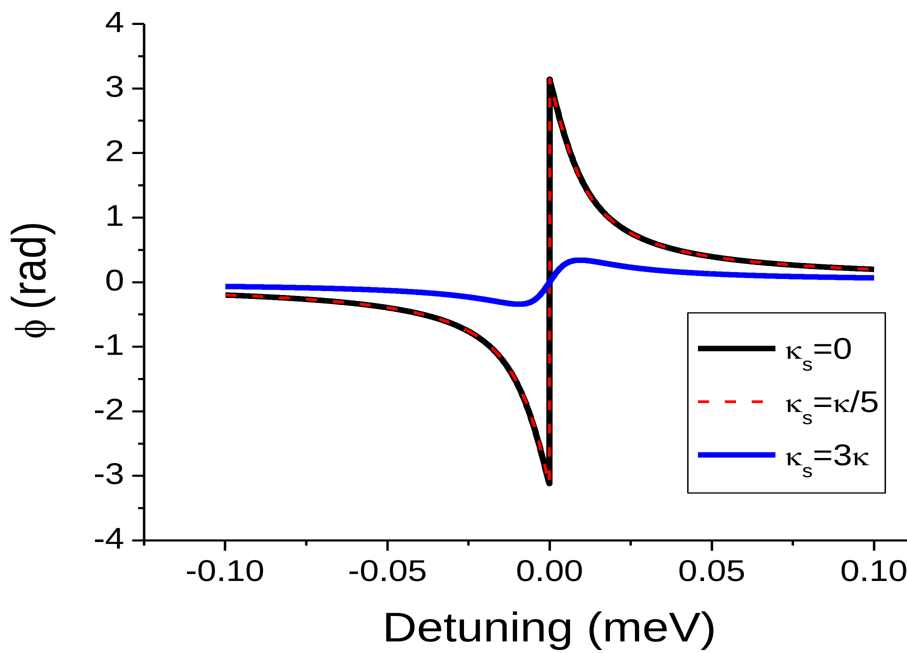
$$\frac{D-A}{\sqrt{V\times H}}=\sin\phi(\omega)$$

Empty cavity

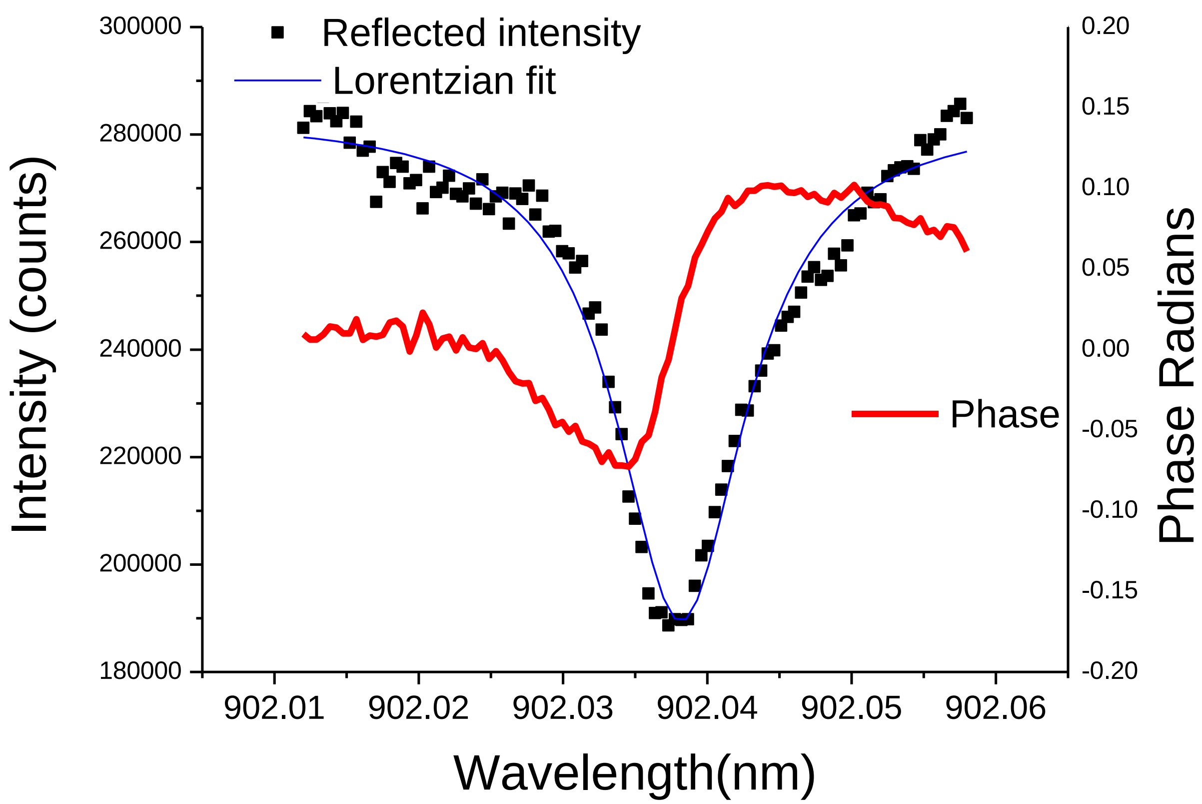
$$r(\omega) = |r(\omega)|e^{i\phi}$$

$$= 1 - \frac{\kappa\left(i(\omega_{qd} - \omega) + \frac{\gamma}{2}\right)}{\left(i(\omega_{qd} - \omega) + \frac{\gamma}{2}\right)\left(i(\omega_c - \omega) + \frac{\kappa}{2} + \frac{\kappa_s}{2}\right) + g^2}$$

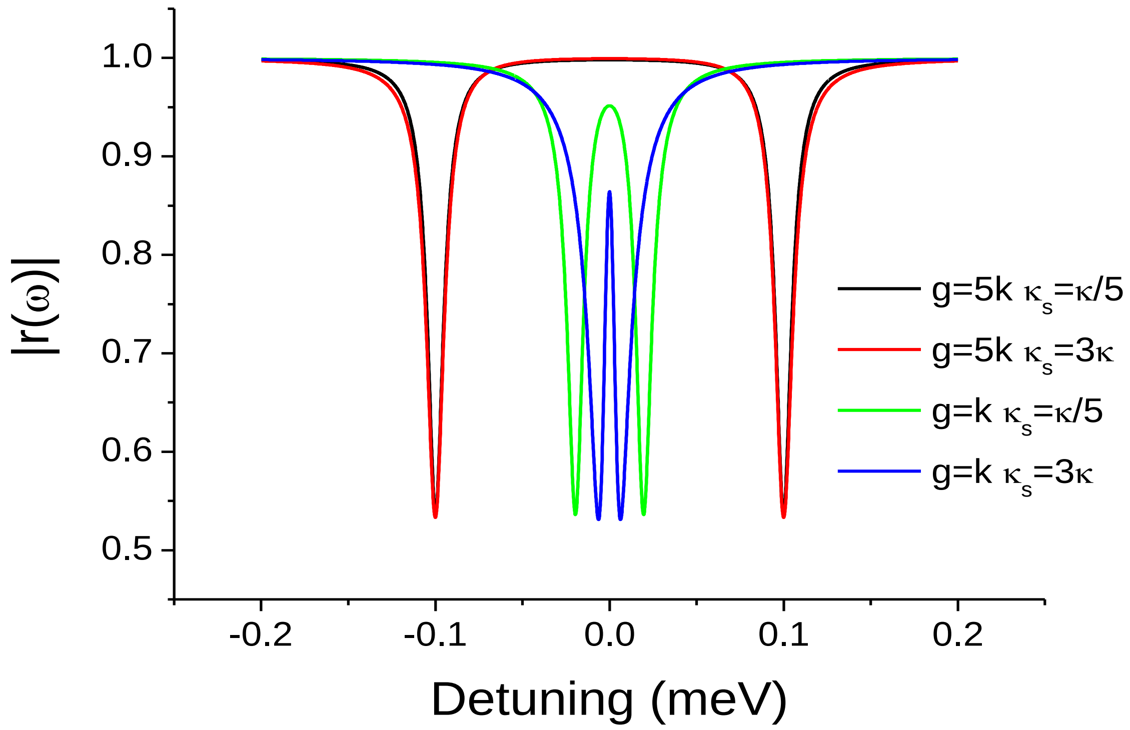




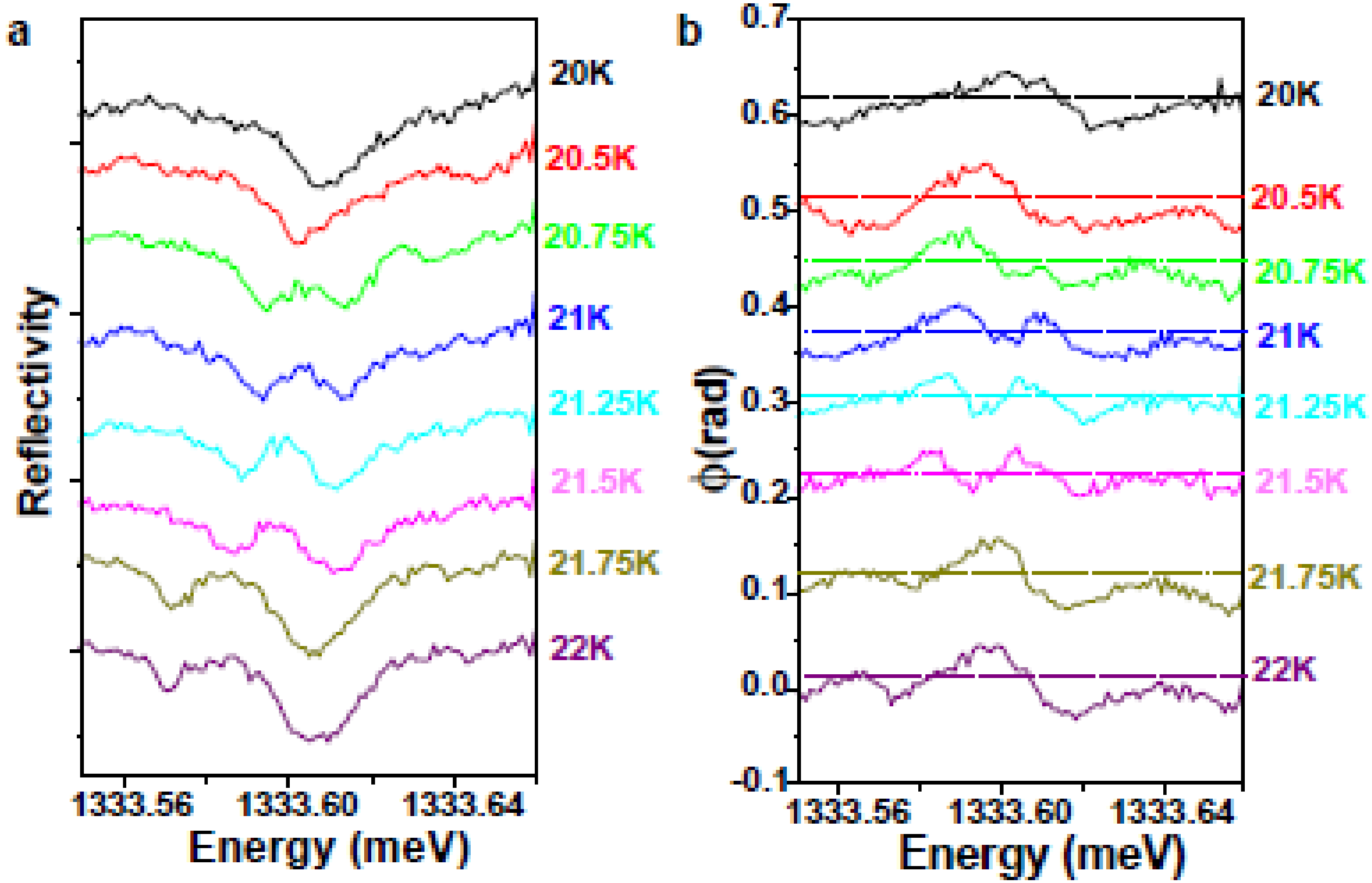
Resonant reflection spectra of an empty 4μ pillar (Q~84000)



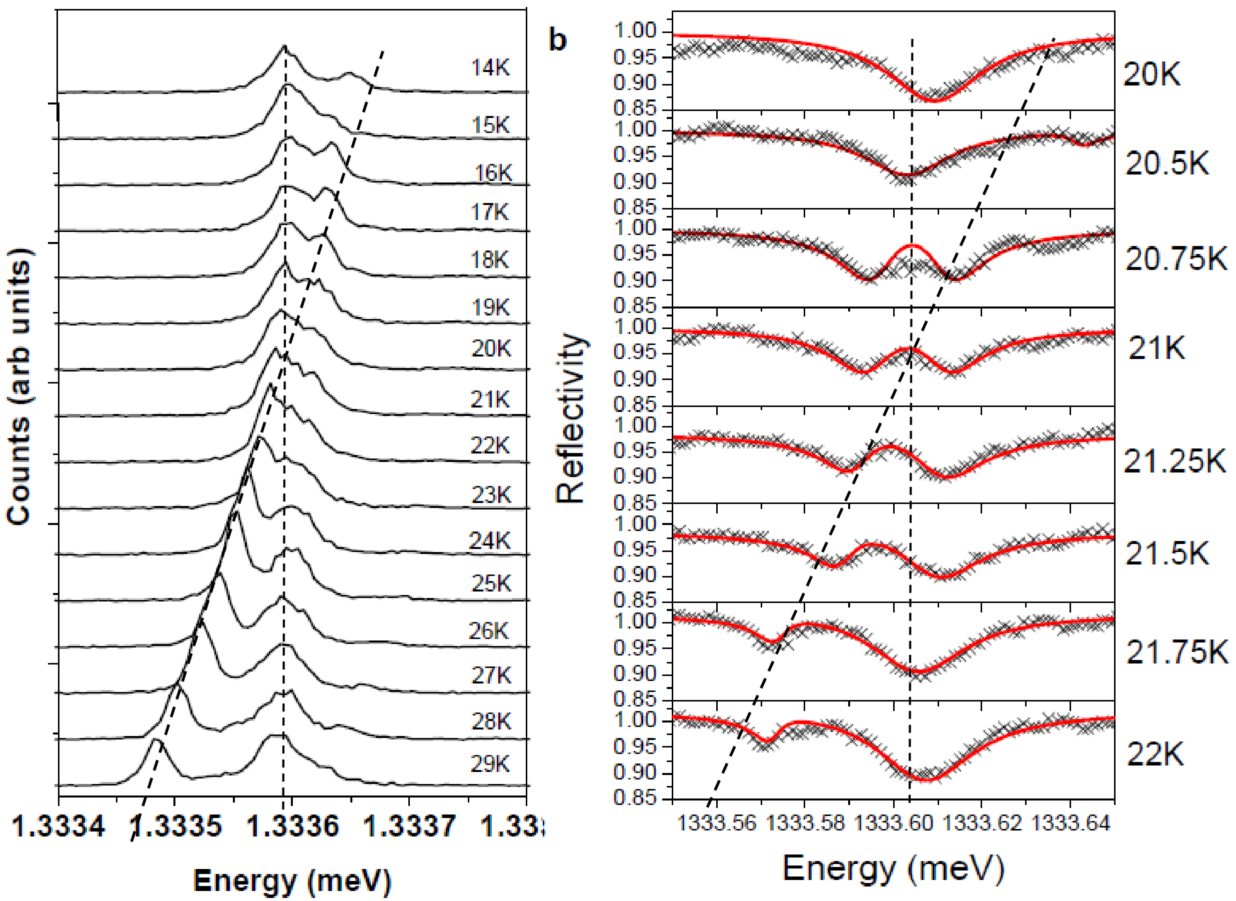
Strongly coupled cavity on resonance



- Resonant reflection spectra of a 2.5μ pillar containing a single dot: temperature tuning to resonance (Q~54000)



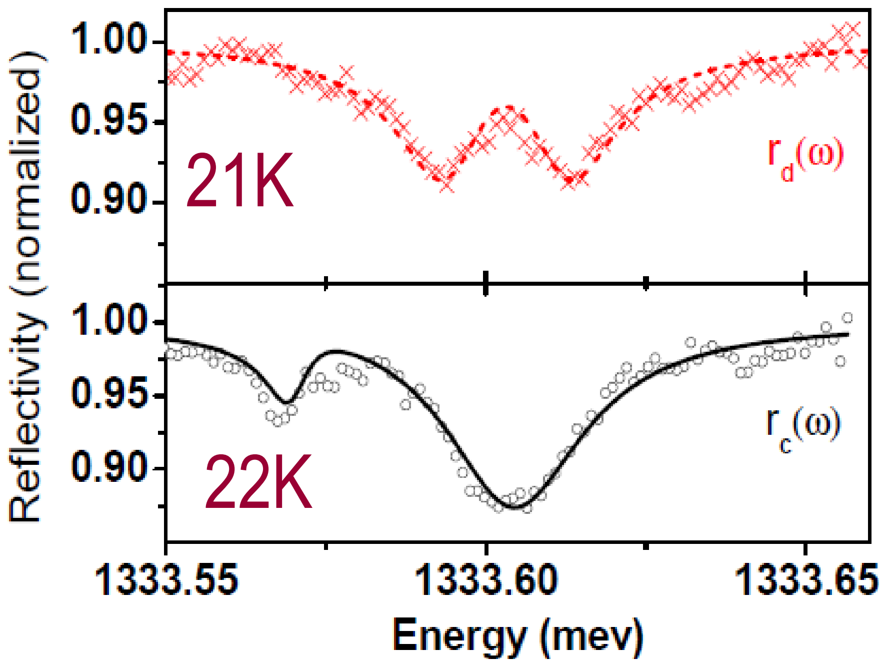
Comparing PL and resonant spectroscopy

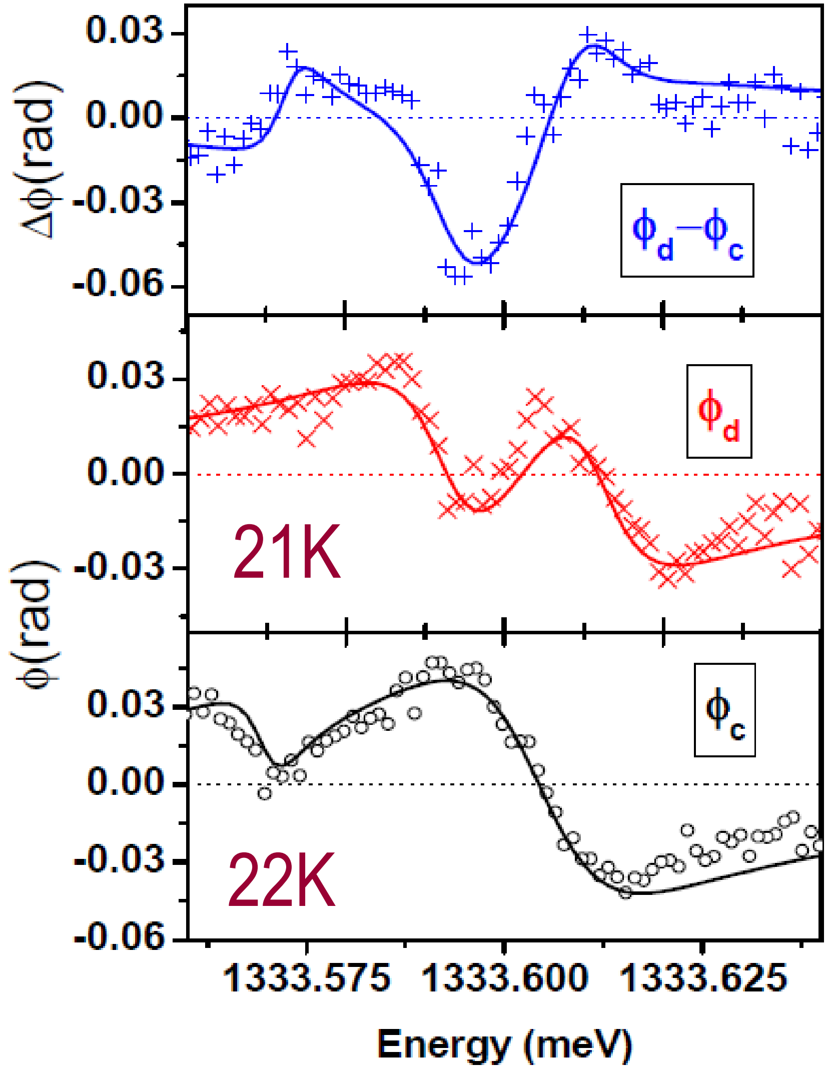


- Conditional phase seen between a dot on and off-resonance with cavity

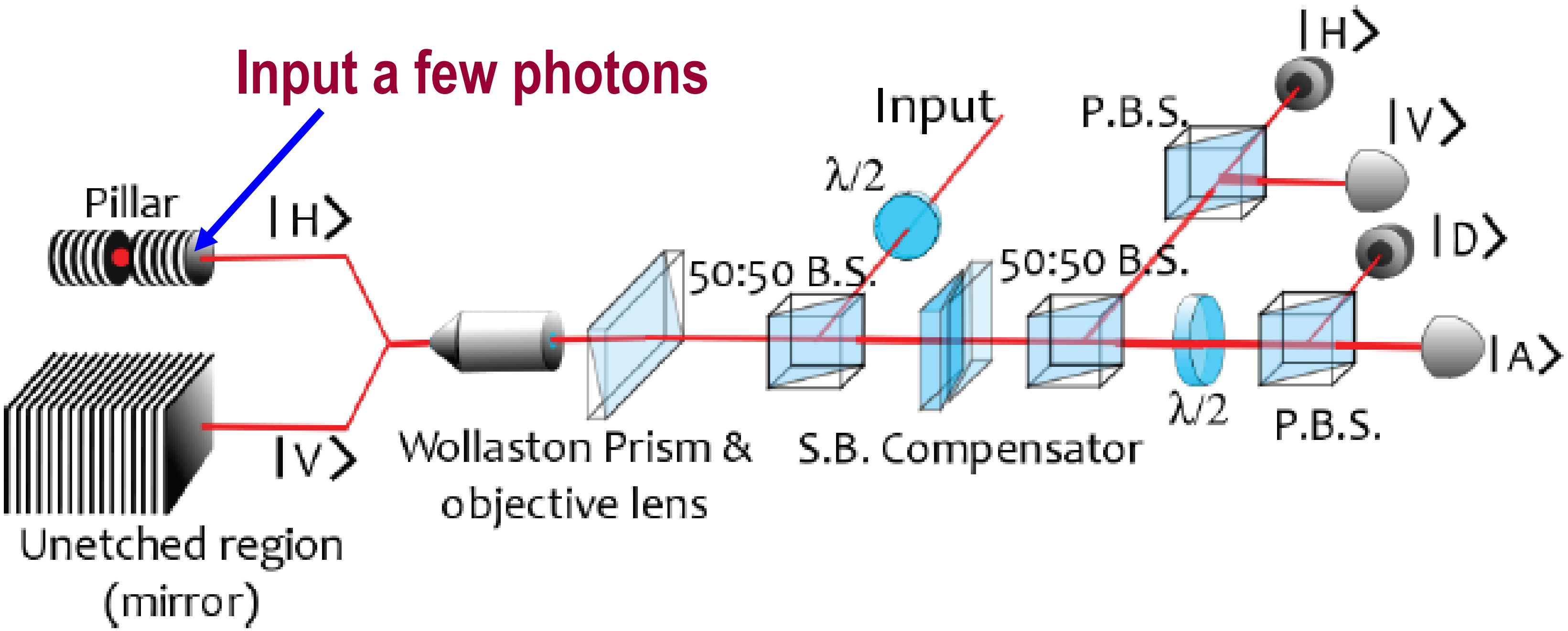
g~9.4ueV *κ*+ *κs* ~ 26ueV *γ*~5ueV

g> (*κ*+ *κs* + *γ*)/4 Δφ~0.05 rad (0.12rad)





Attojoule switch



Input enough photons (1 in principle) to saturate the dot and return to weak coupling.

Change phase of reflection, modulate D and A

All optical switch (1 photon ~0.1 attojoule)

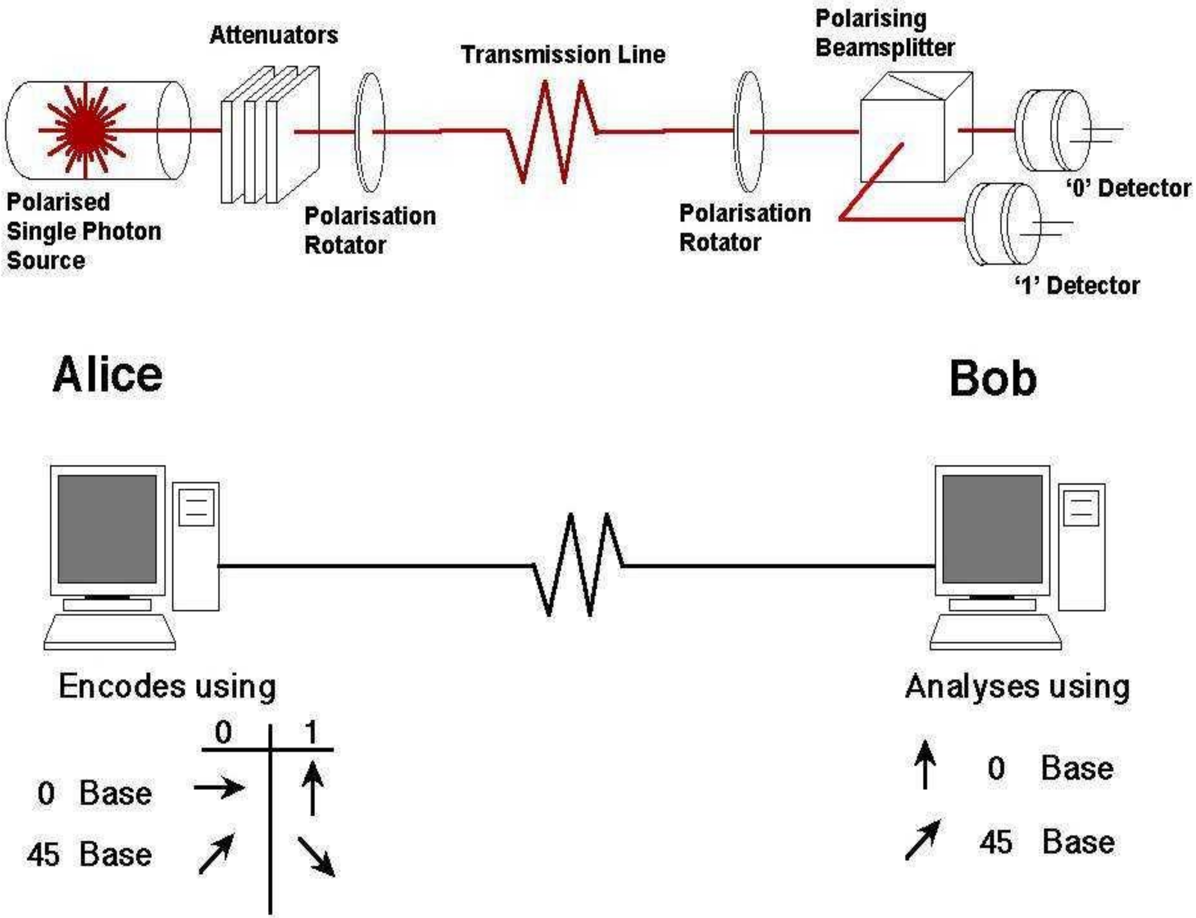
Future:

- Improve coupling and reduce losses to achieve phase shift > pi/2
- Establish strong coupling with charged dots.
  - modulation doped
  - electrically charged
- Investigate dynamics of spin via Faraday rotation
  - We cool the spin by measurement
  - Creating spin superposition states (hard)
  - Rotating spin around equator for spin echo (easy=U(φ))
- Spin coherence times (of microseconds?)
- Nuclear 'calming' to extend coherence times

Bennett and Brassard 1984 secure key exchange using quantum cryptography

Sends

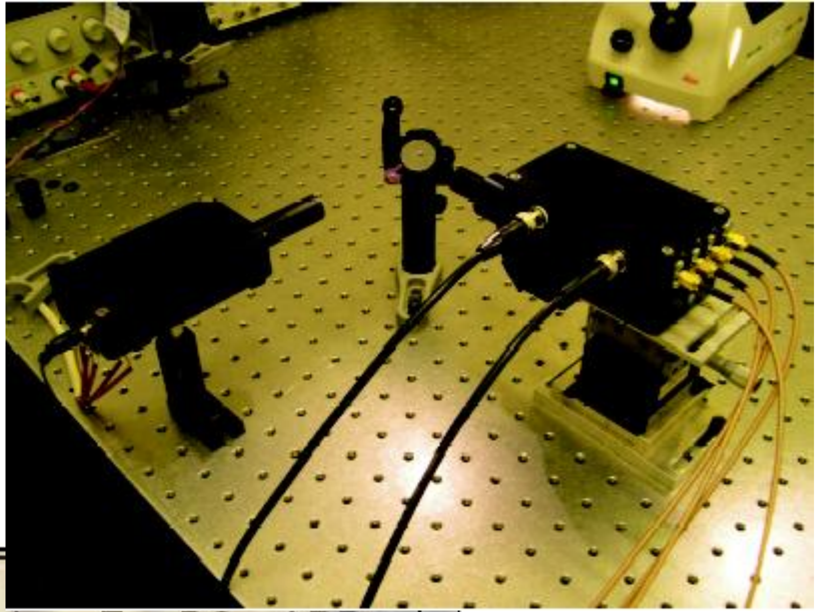
no.	bit	pol.
1	1	45
2	0	45
3	0	0
4	1	45
5	1	0
6	0	45
7	1	45
…		
1004	0	45
1005	1	0
….		
3245	1	45
…		

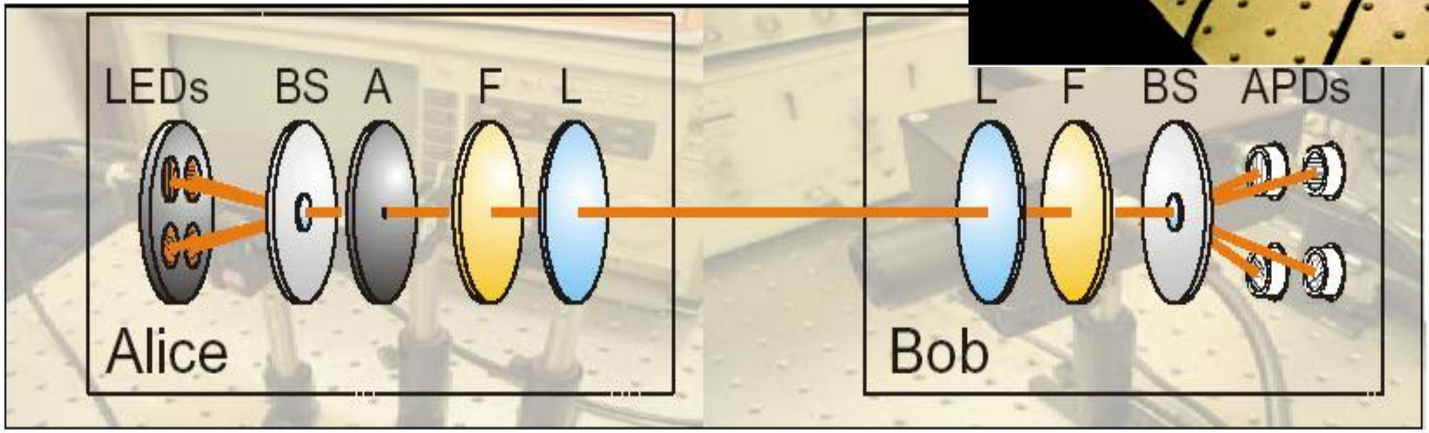


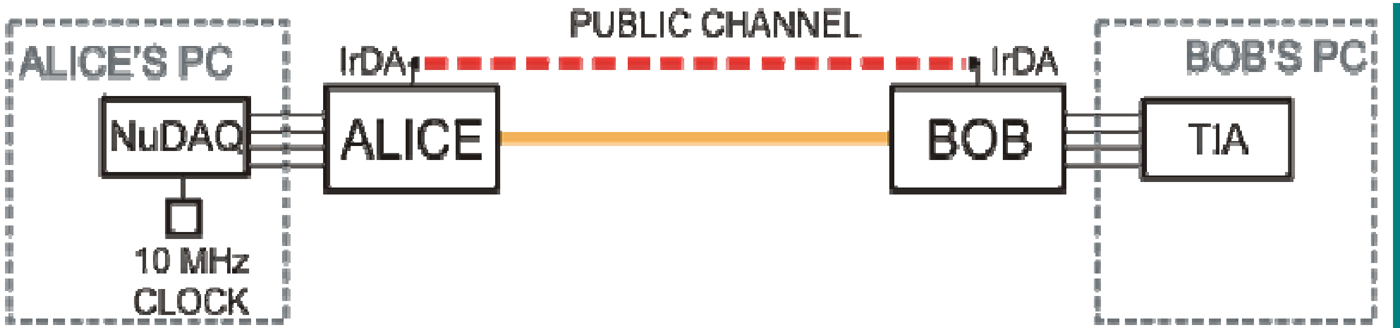
Receives

no.	Bit	Pol.
246	1	45
1004	0	45
2134	0	0
3245	0	0
4765	1	0
5698	0	45

Low cost short range quantum key exchange

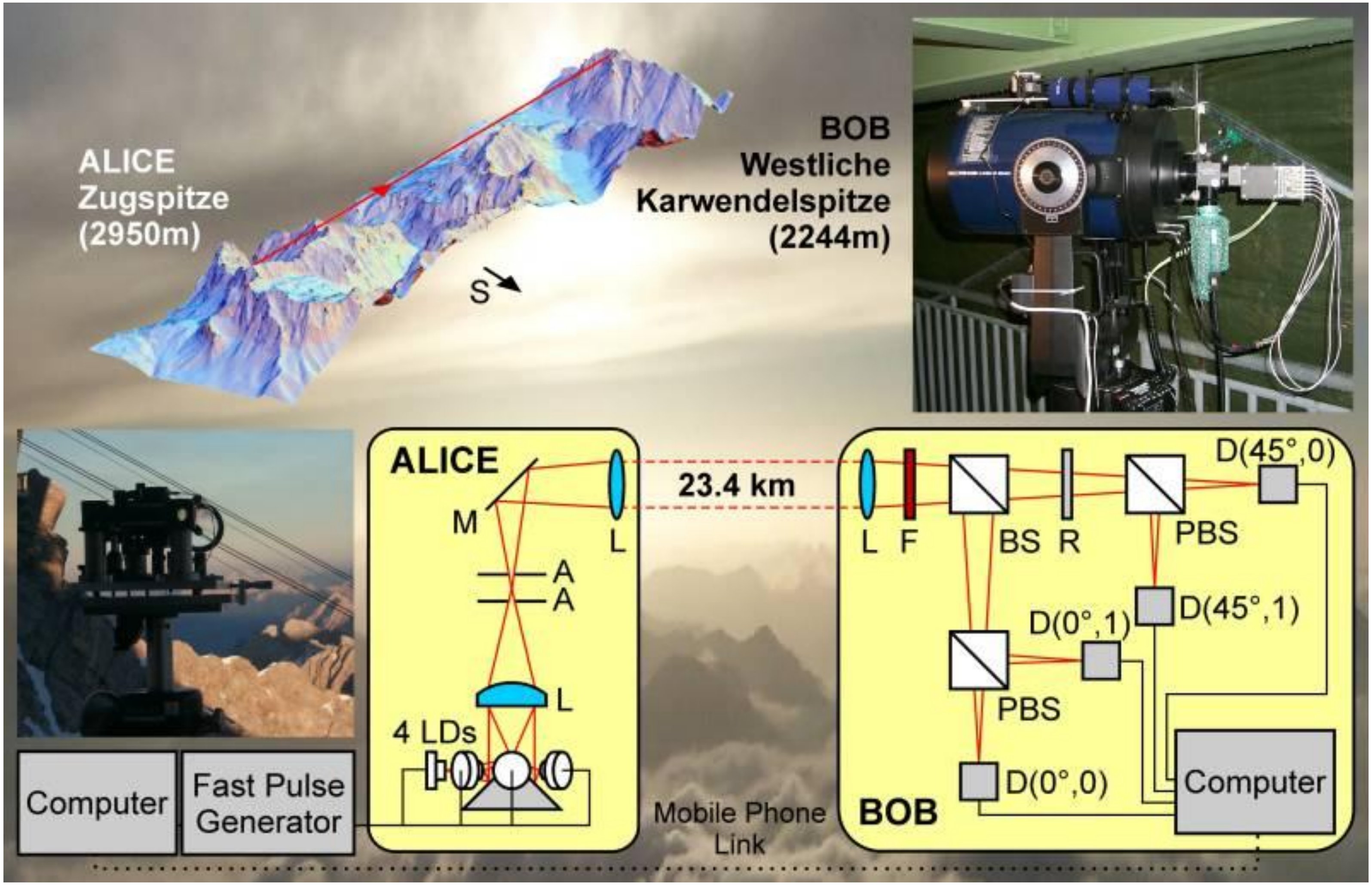






experiment over 23.4km

Kurtsiefer et al, (2002), *Nature*, **419**,



Experimental Demonstration of Decoy State Quantum Key Distribution over 144 km,
Tobias Schmitt-Manderbach, et al Quant-ph 0608***

Recent experiments

Free-Space distribution of entanglement and single

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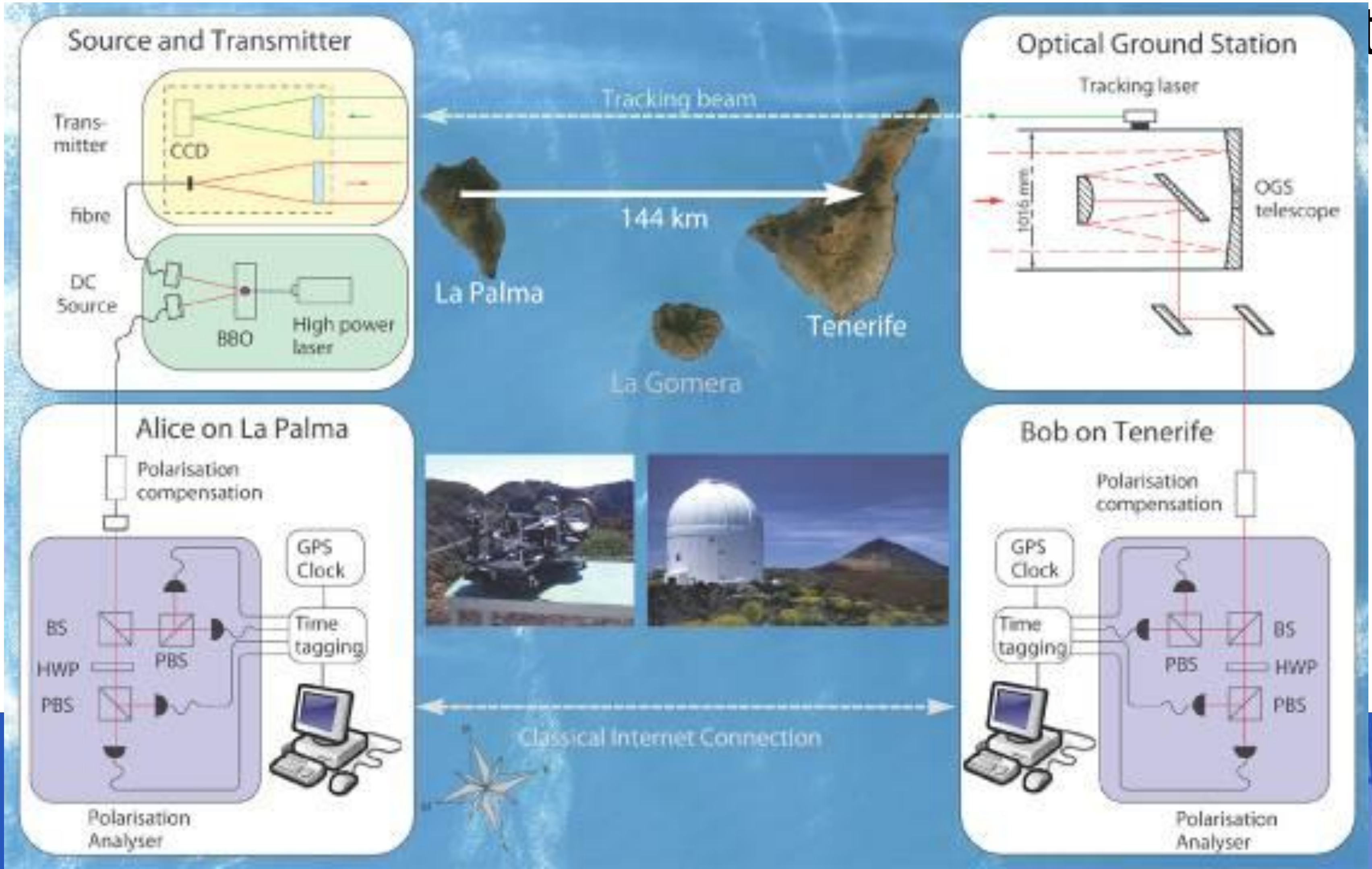
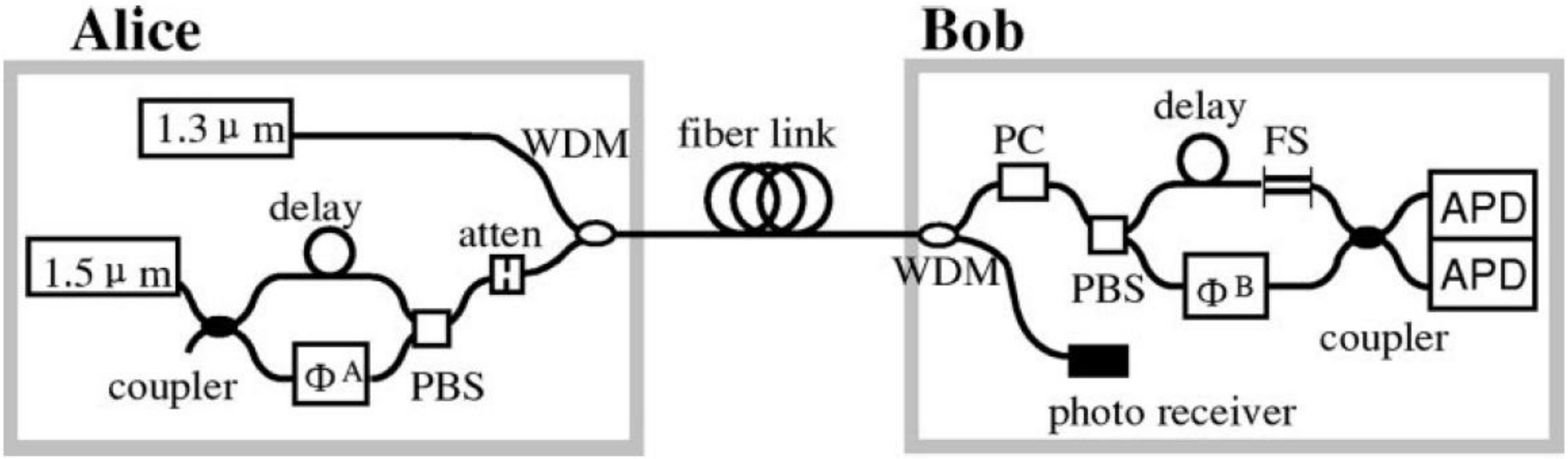


Fibre based systems operating at 1.55 um,



Z. L. Yuan and A. J. Shields C. Gobby, "Quantum key distribution over 122 km of standard telecom fiber," Applied Physics Letters **84** (19), 3762 (2004).