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WINTER COLLEGE
on
QUANTUM AND CLASSICAL ASPECTS
of
INFORMATION OPTICS

30 January - 10 February 2006

Introduction to Photonic Quantum Logic

J.G. RARITY

Department of Electrical & electronic Engineering
University of Bristol
Bristol
UK

Strada Costiera 11, 34014 Trieste, Italy - Tel. +39 040 2240 111; Fax +39 040 224 163 - sci_info@ictp.it, www.ictp.it

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Introduction to Photonic Quantum Logic

Trieste Winter School FEB 2006

J. G. Rarity
University of Bristol
john.rarity@bristol.ac.uk

Bristol: Daniel Ho, J. Fulconis, J. Duligall, C. Hu, R. Gibson, O Alibart
Bath: William Wadsworth, Philip Russell
Sheffield: M. Skolnick, D. Whittaker, M. Fox, J. Timpson
Toshiba: A. Shields, A. Bennett Cambridge: D. Richie

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Structure

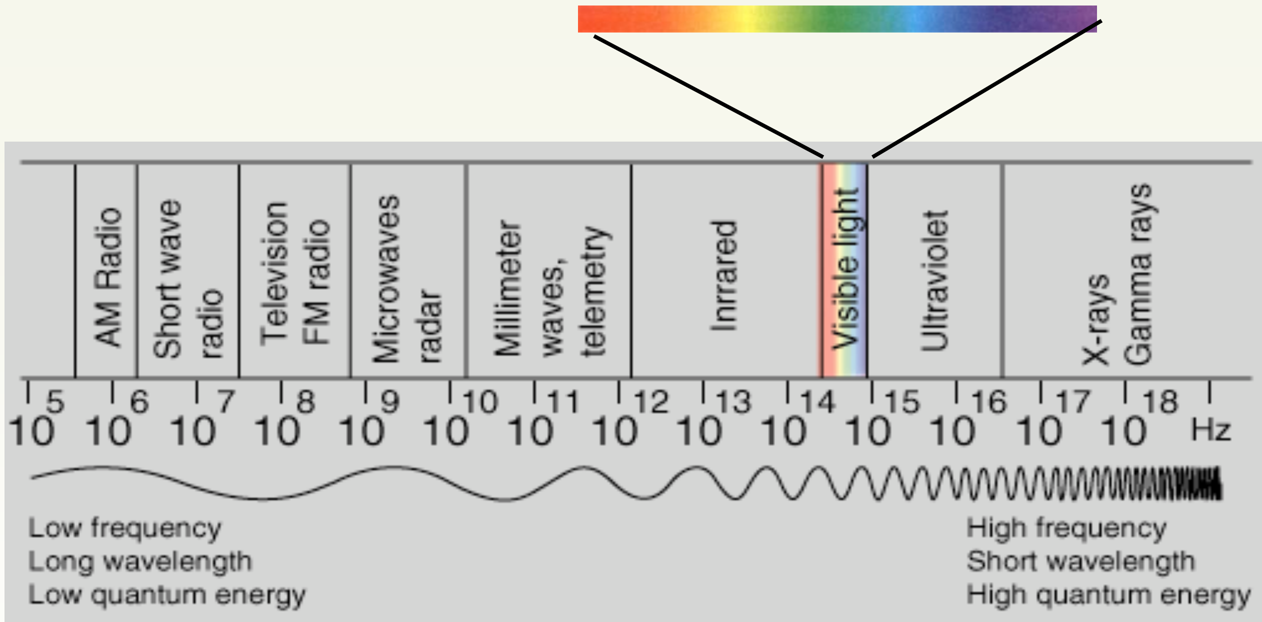
- Lecture 1
  - What is light?
  - Decoherence of photons
  - Single photon detection
  - Encoding bits with single photons and single bit manipulation.
  - Single photon sources
  - Entangled state sources
- Lecture 2
  - Free Space Quantum Cryptography
- Lecture 3
  - Linear logic, efficiency and scalability
  - Towards single photon non-linearity.

The electro-magnetic spectrum

λ=1.5um
E_{ph}=0.8eV

λ=0.33um
E_{ph}=4eV

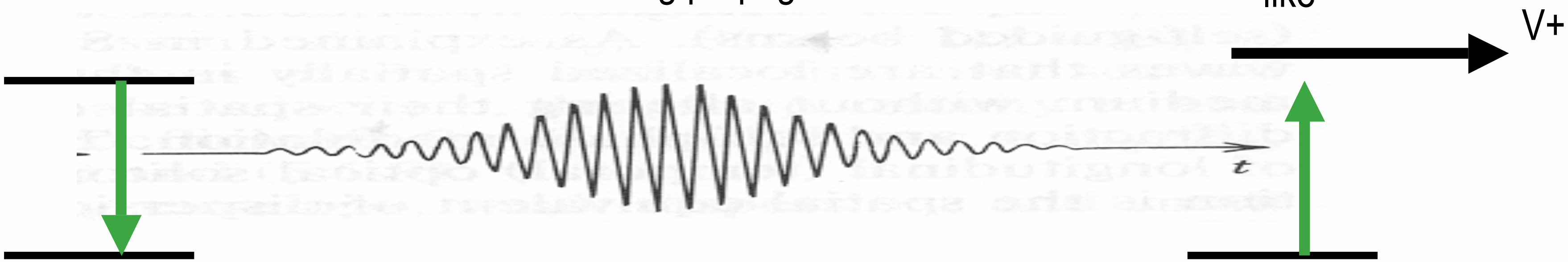
Optical Photon energy
E_{ph}=hf>>KT



Particle like

Wave-like during propagation

Particle like



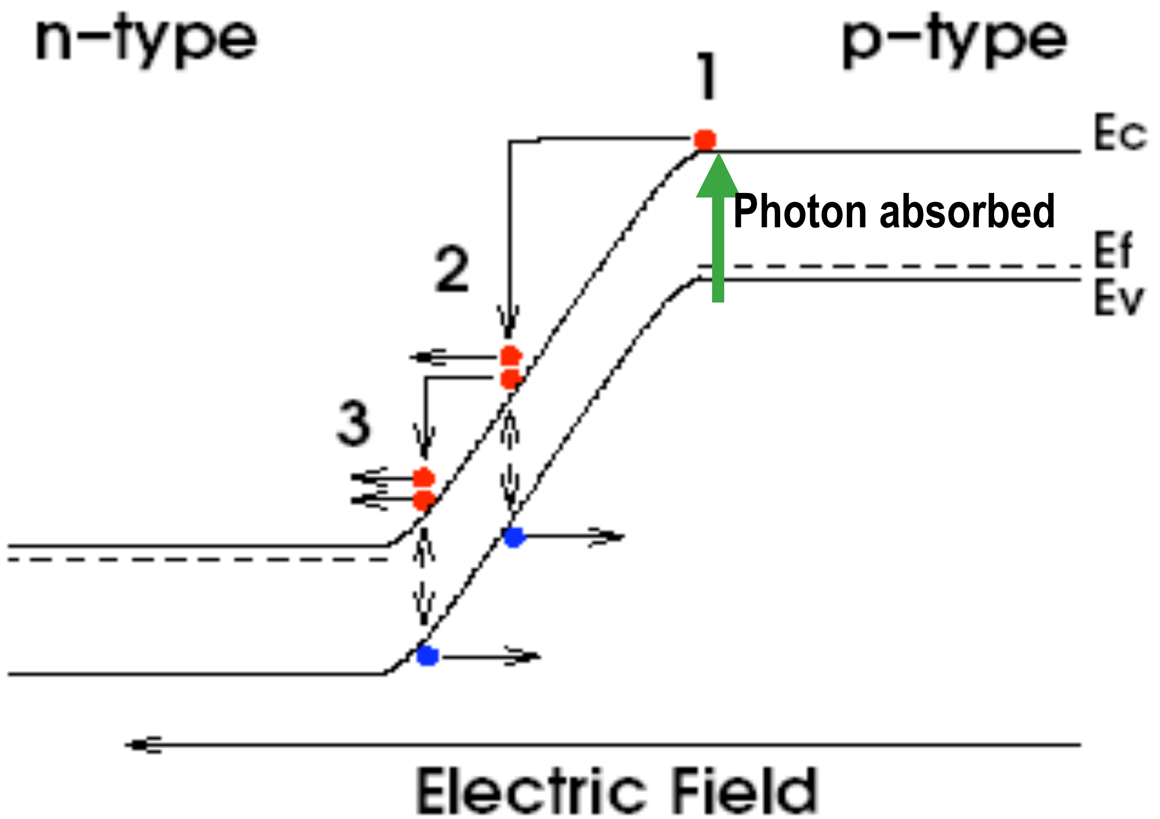
Decoherence of photons: associated with loss

- Storage time in fibre 5μs/km, loss 0.17 dB/km (96%)
- Polarised light from stars==Storage for 6500 years!

The Crab Nebula in Taurus (VLT KUEYEN + FORS2)

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

Photon counting using avalanche photodiodes



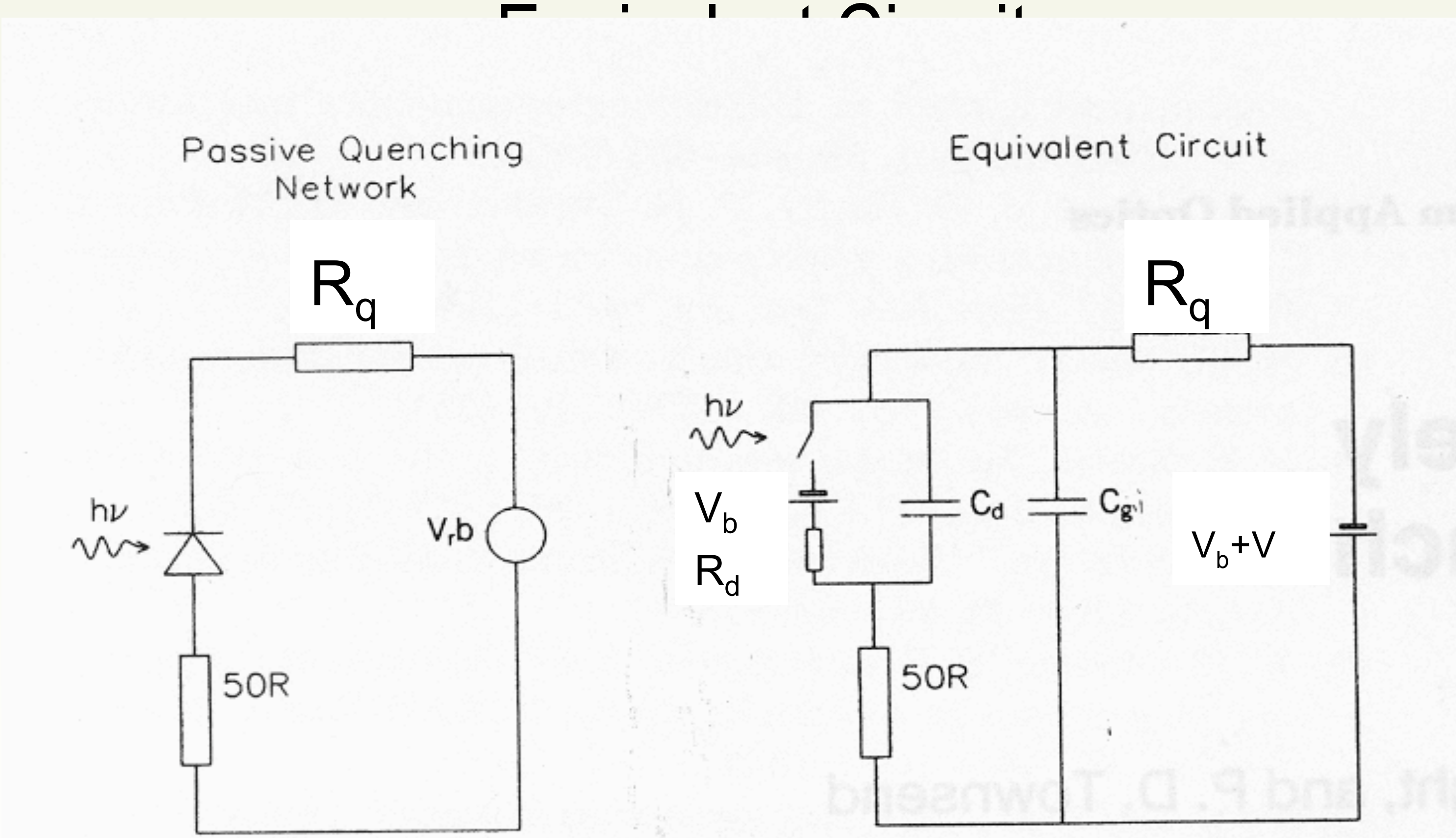
Photon is absorbed in the avalanche region to create an electron hole pair

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

Equivalent Circuit



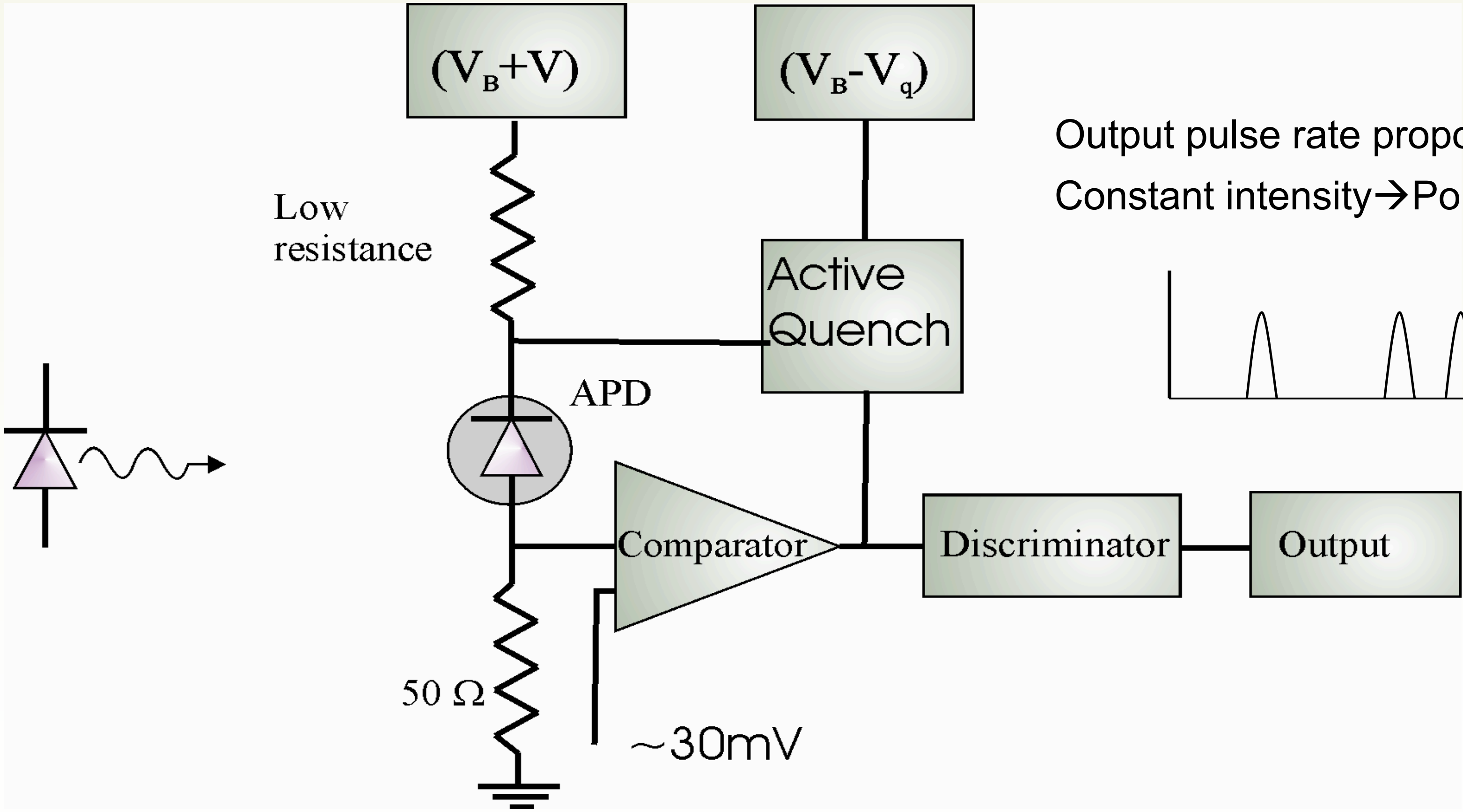
Total charge released on breakdown $(C_d+C_g)V$

Recharge time (dead time) $\tau_D = (C_d+C_g)R_q$

Silicon devices total capacitance ~10pF and R_q~250-400Kohm τ_D 3-5us

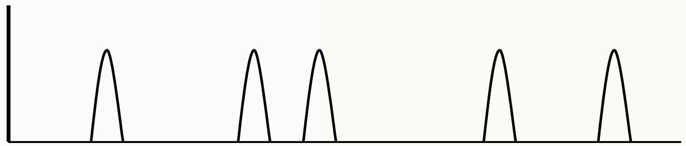
Ge 5pF and 33Kohm, τ_D 150ns, InGaAs 2pF, ~56Kohm

Actively Quenching photon counting module



Output pulse rate proportional to intensity

Constant intensity→Poisson distributed



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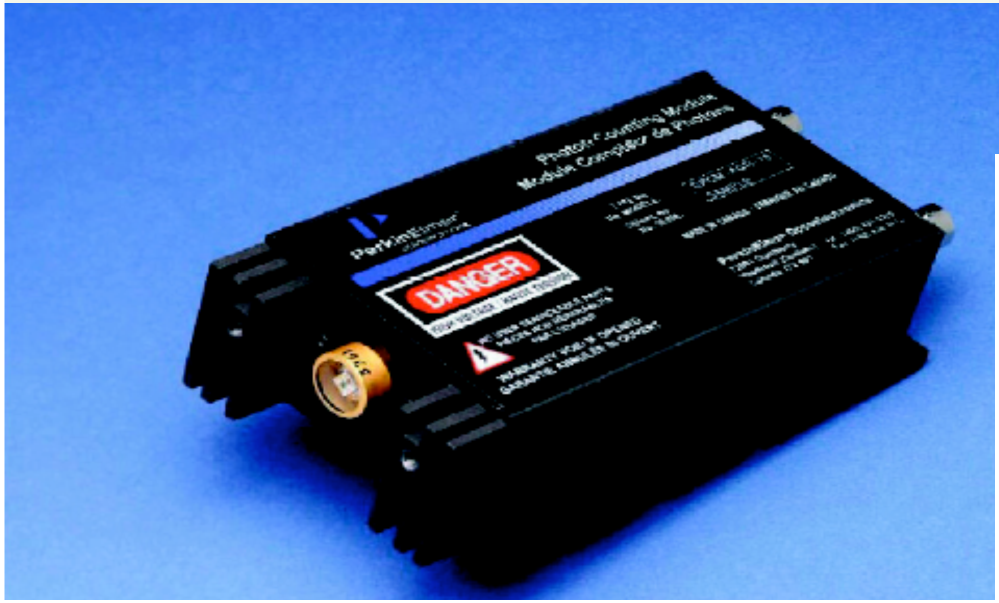
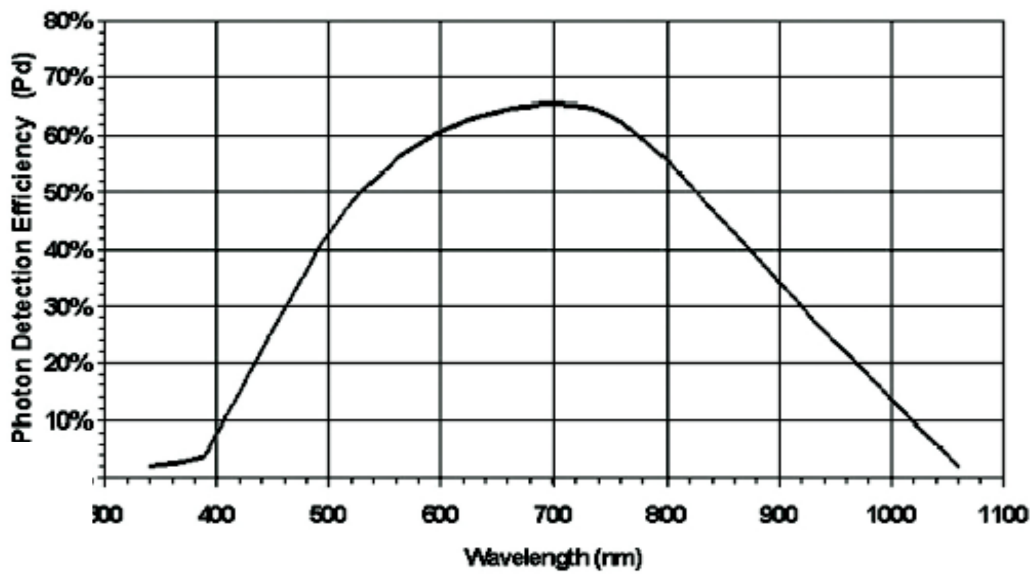
Commercial detector module using Silicon APD

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





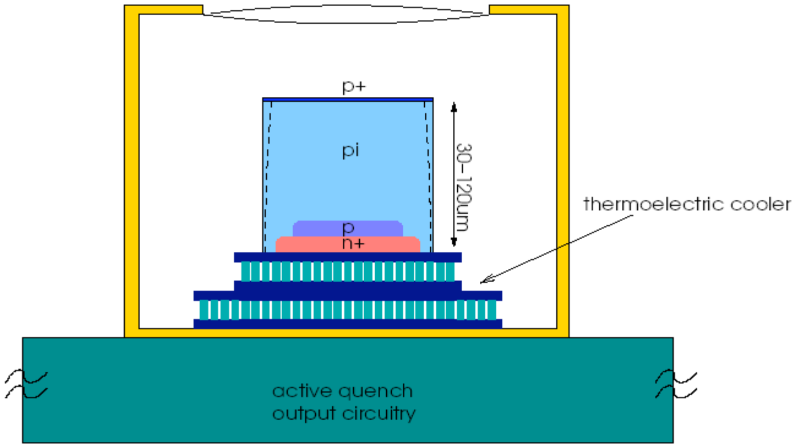


Figure 2.10: Single photon counting module (SPCM).

InGaAs avalanche detectors:
Gated modules operation at 1550nm
Lower efficiency
Higher dark counts
Afterpulsing
www.idquantique.com

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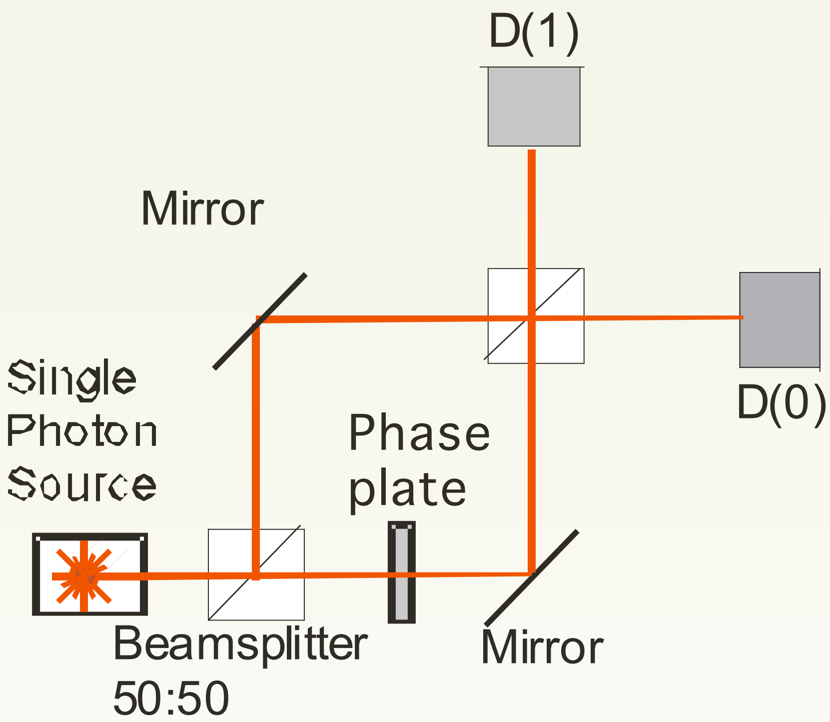
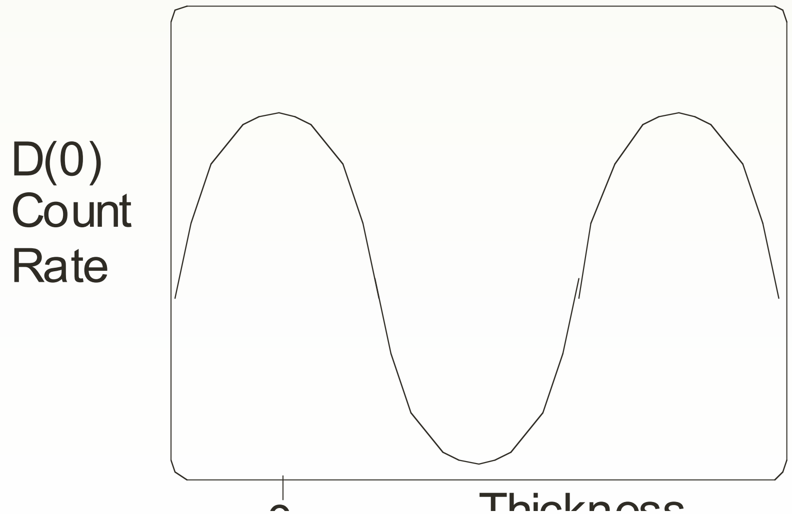
Interference effects with single photons



Single photon can only be detected in one detector
Can only appear in one detector.
However interference pattern built up from many individual counts

Grangier et al 1986

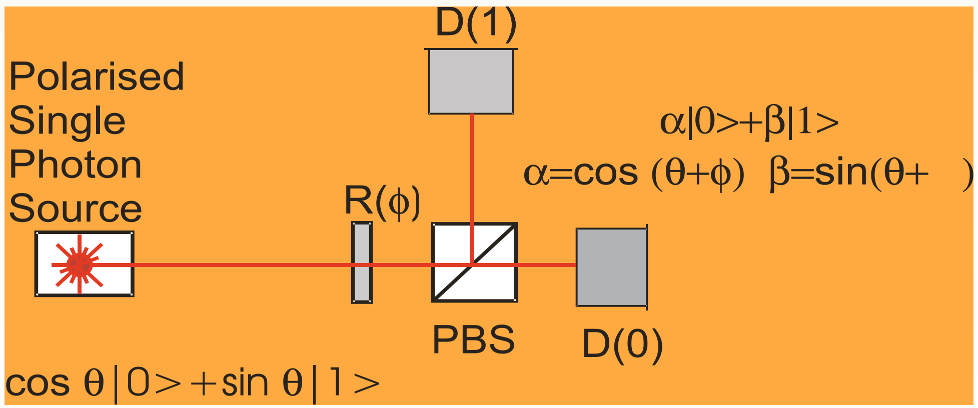


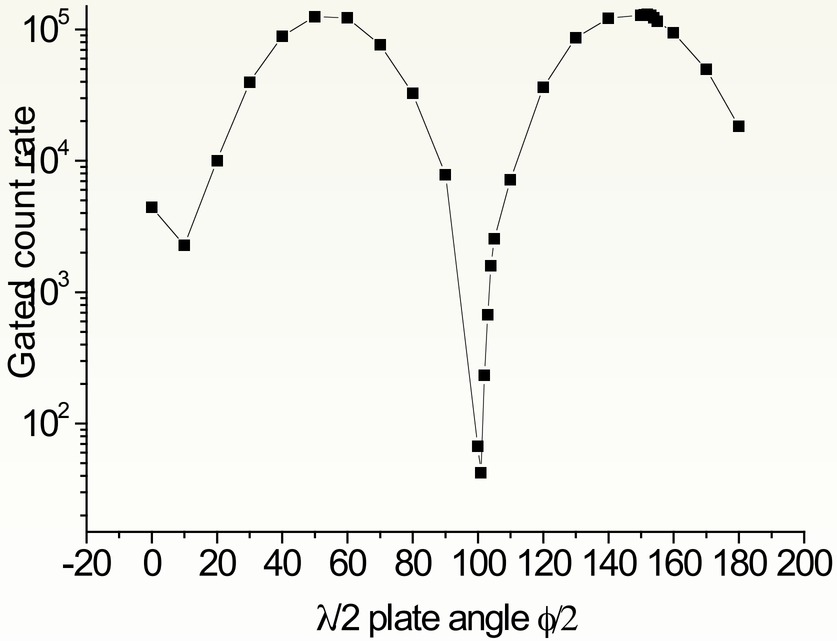
Encoding one bit per photon and single qubit rotations

Encoding single photons using two polarisation modes
Superposition states of '1' and '0'

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

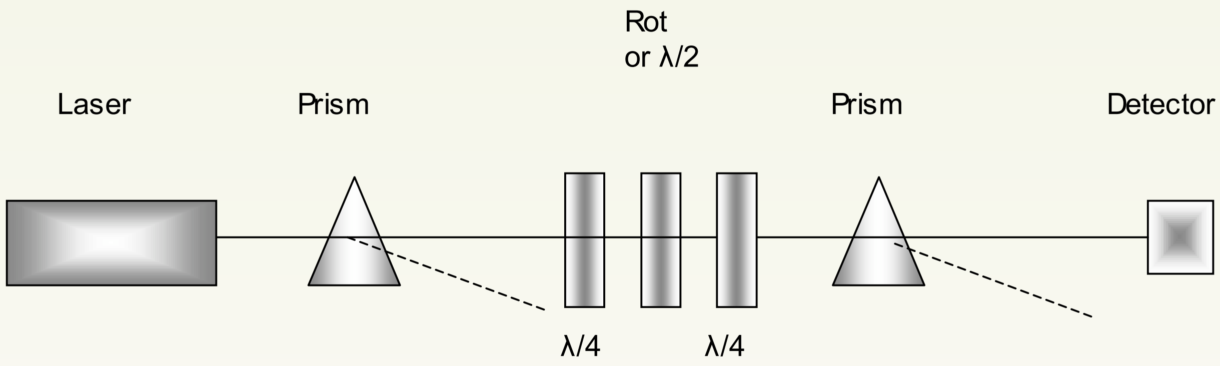
Probability amplitudes α , β
Detection Probability: $|\alpha|^2$



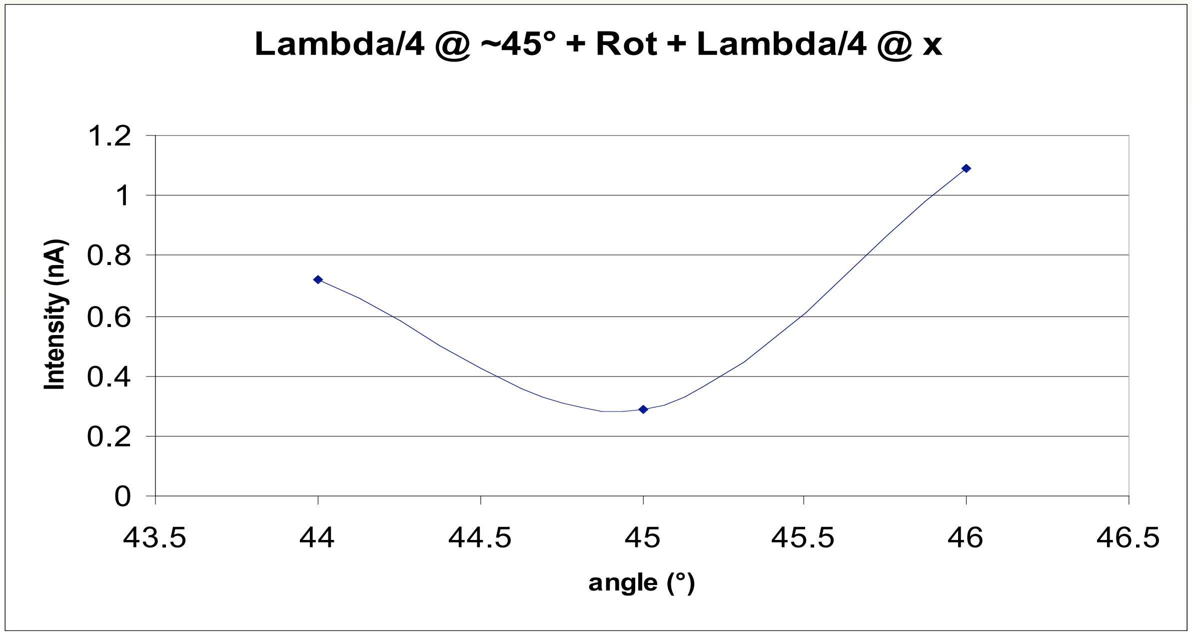


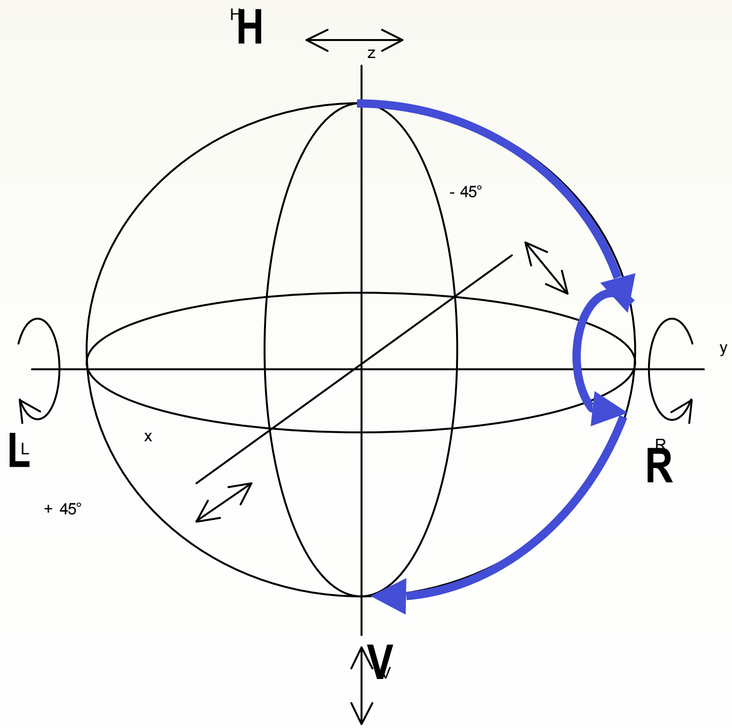
Single photon encoding showing QBER<5.10^{-4} (99.95% visibility)

Multiple waveplates



Max~ 1400 nA, Min~ 0.3 pA, QBER ~2×10^{-4}





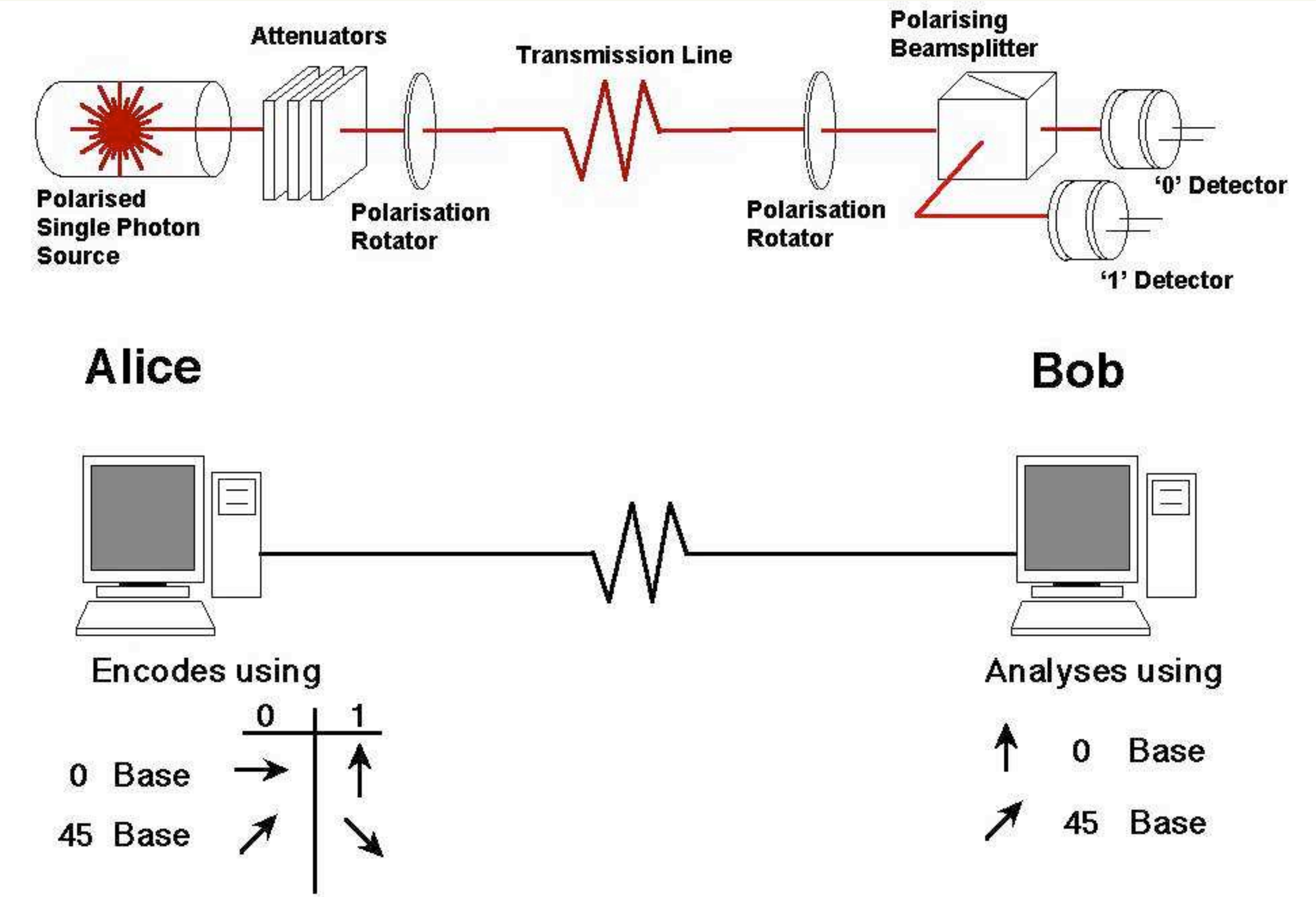
See next lecture:

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

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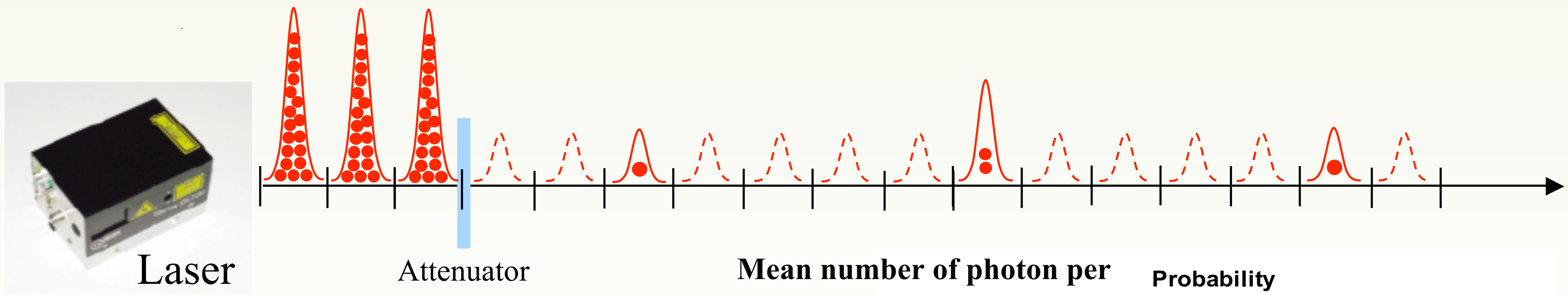
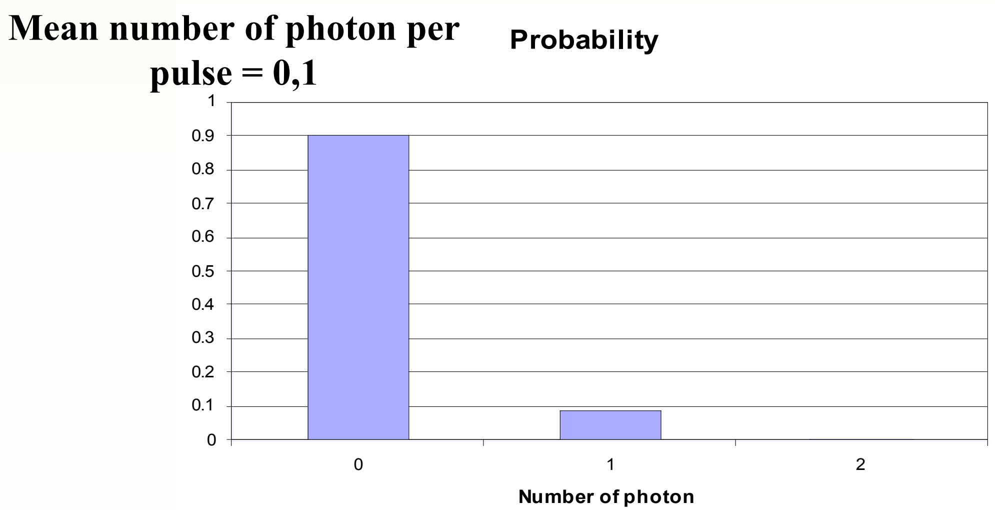
Approximate single photon source

- Attenuated laser





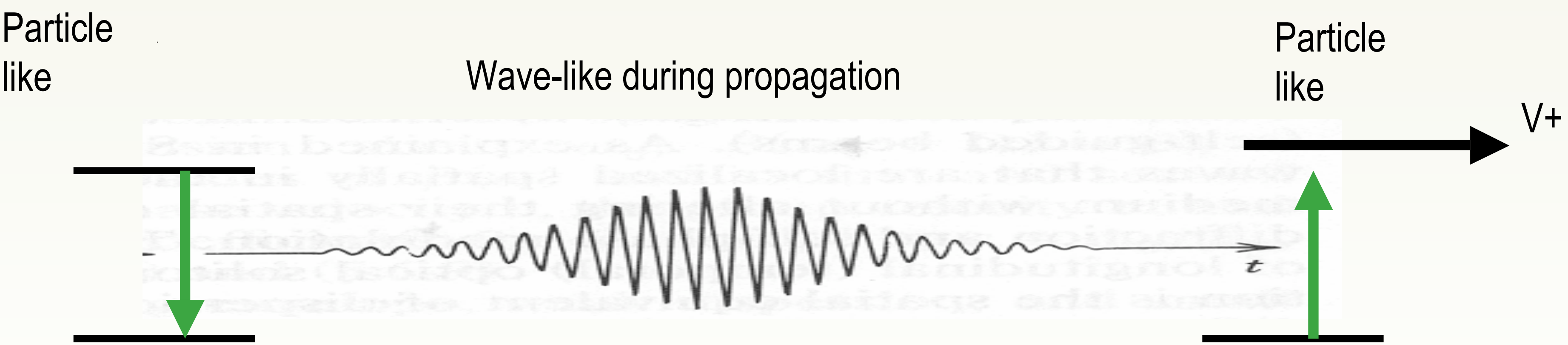
Coherent state shows

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)

Motivations

Quantum cryptography and linear-optics quantum logic needs single-photon sources with

- High generation rate
- High efficiency emission into single mode
- Small multi-photon probability ($g^{(2)}(0) \rightarrow 0$)
- Quantum indistinguishability (time-bandwidth limited, single mode, one polarization, etc.) see lecture 3

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Motivations

Self-assembled InAs/GaAs QDs for single photon source

Advantages:

- No bleaching effect and long-term stability
- High generation rate (exciton lifetime~1ns)
- Embedded in microcavity by in-situ growth
- Standard semiconductor processing
- Solid-state source

Drawbacks: low extraction efficiency (~2%) due to high refractive index of GaAs (n=3.5)

Cavity effects

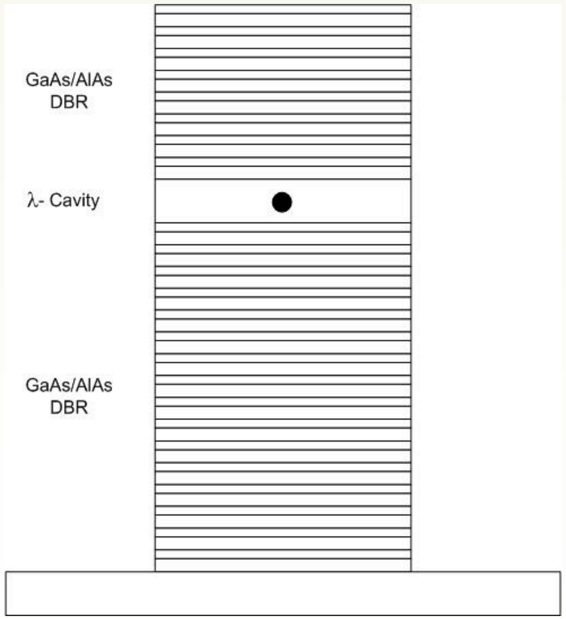
Single photon generation of QDs in 3D microcavity can be improved by Cavity Quantum Electrodynamics (CQED) see lecture 3

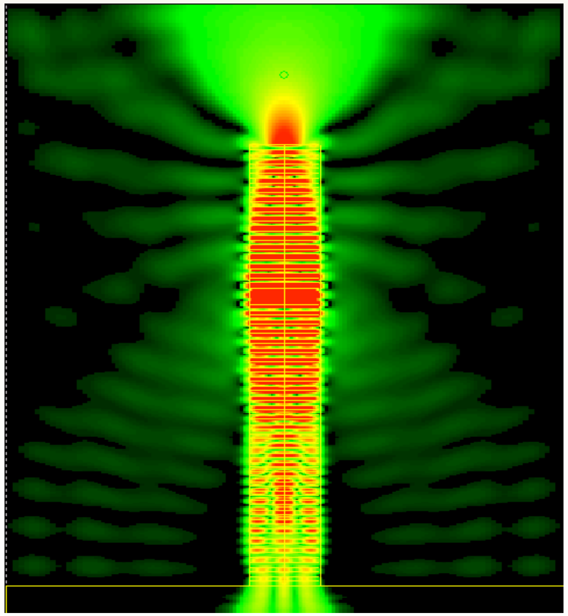
- Enhance spontaneous emission (Purcell effect)
- Improve both coupling and extraction efficiency
- Couple to a single cavity mode
- Toward time-bandwidth limited photon pulse

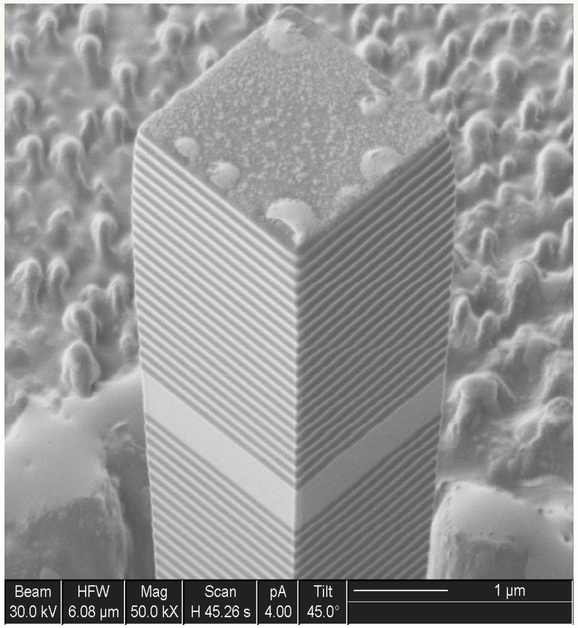
lifetime $T_1 << $ dephasing time T_2

Samples

- λ cavity between two $GaAs/Al_{0.9}Ga_{0.1}As$ DBRs, 20 pairs top 27 pairs bottom
- One layer of self-assembled InAs QD at the cavity center
- Circular / elliptical pillars etched by inductively coupled plasma etching (ICP) [focused ion beam etching (ICP) for a comparison]



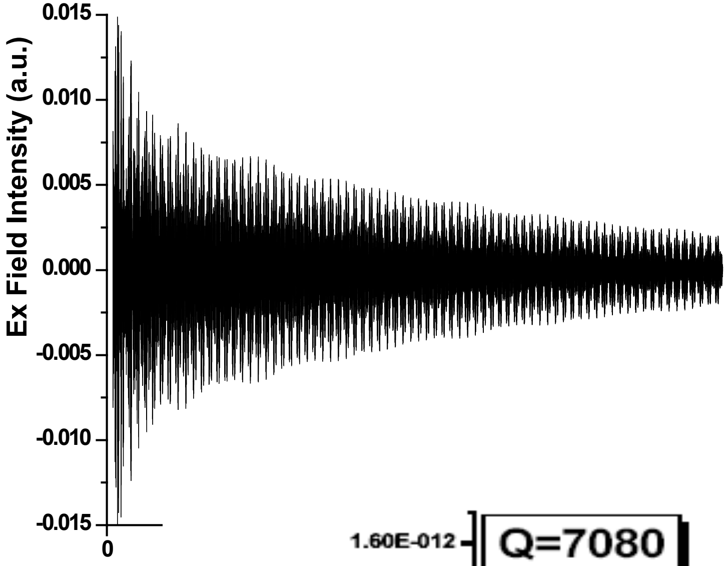


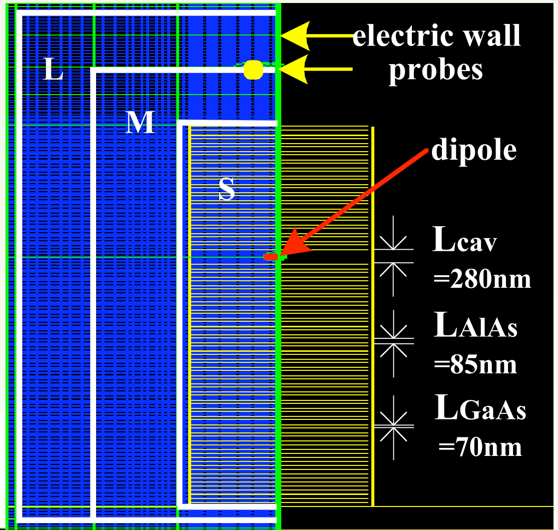


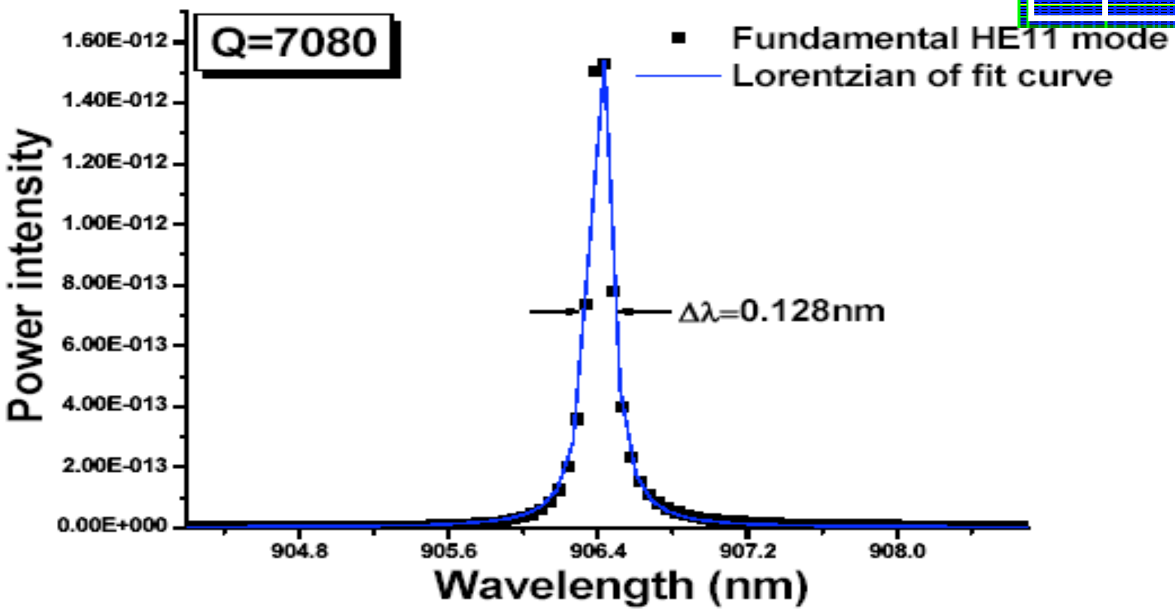
FDTD simulations: 0.50μm radius micropillar microcavity:

Plane wave resonance=1001 nm

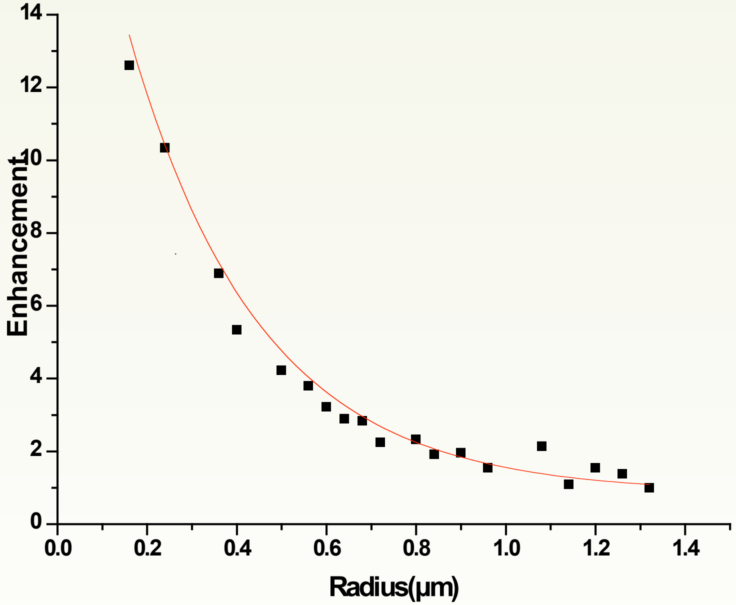
15 mirror pairs on top and 30 bottom

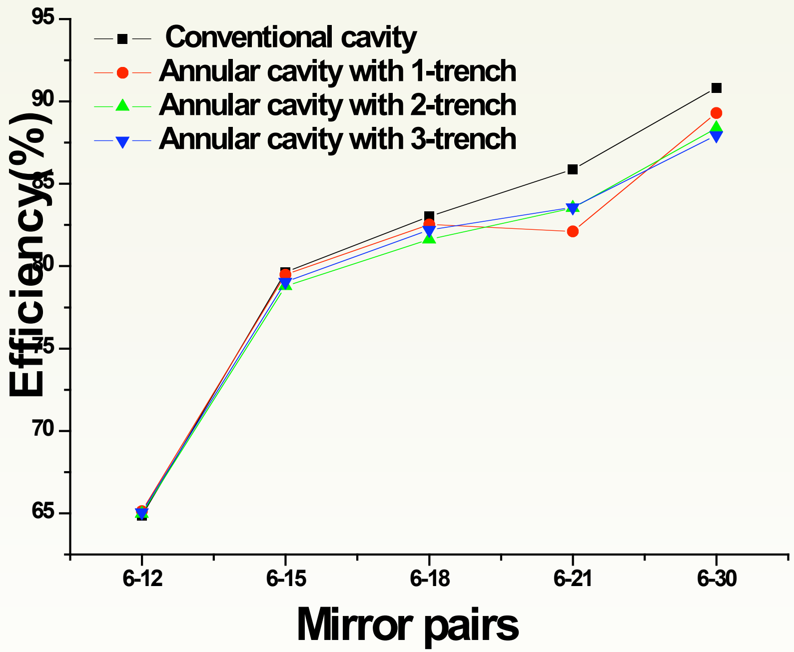






FDTD simulations of micropillar microcavity 6-12 pairs



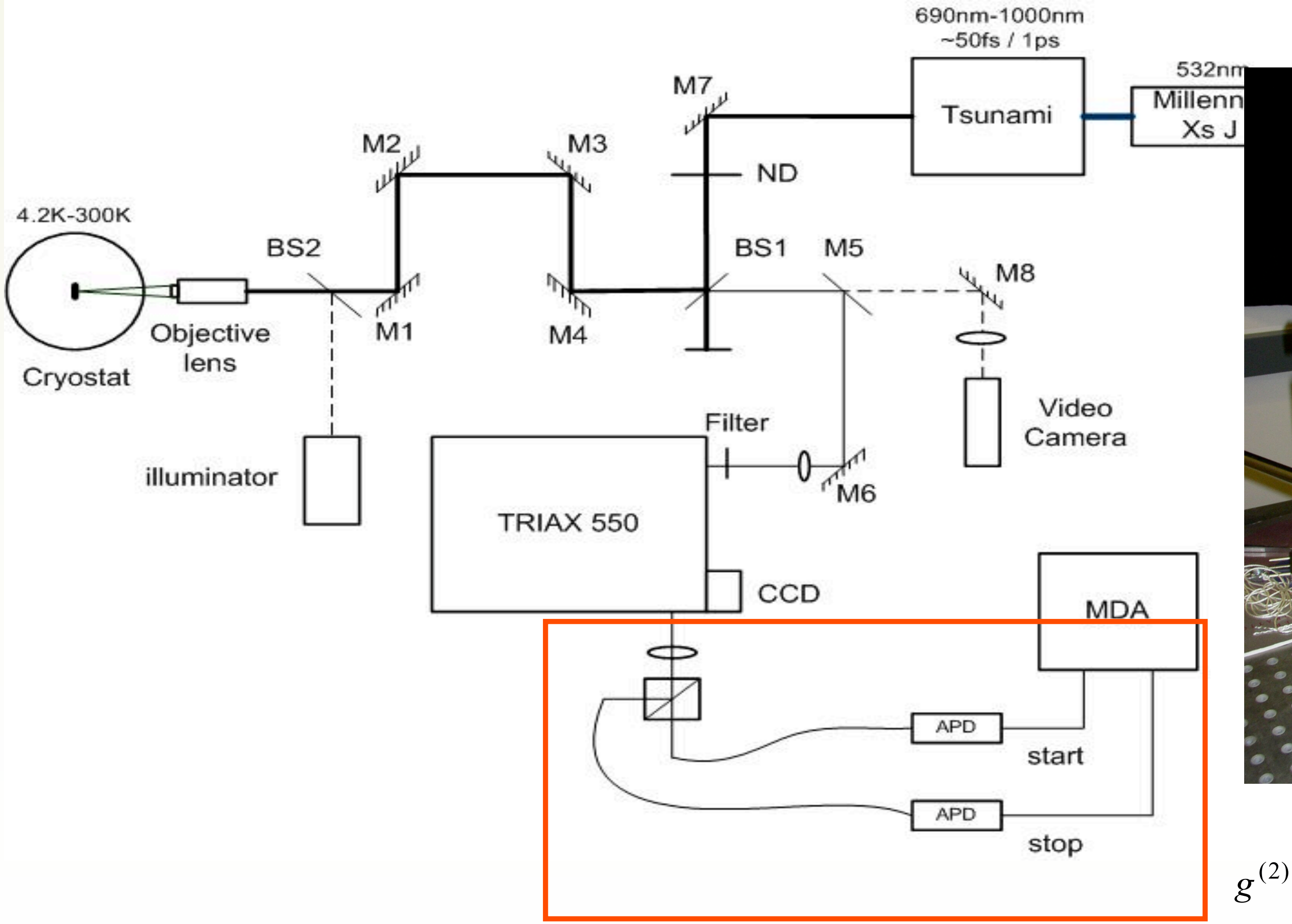


Spontaneous emission enhancement

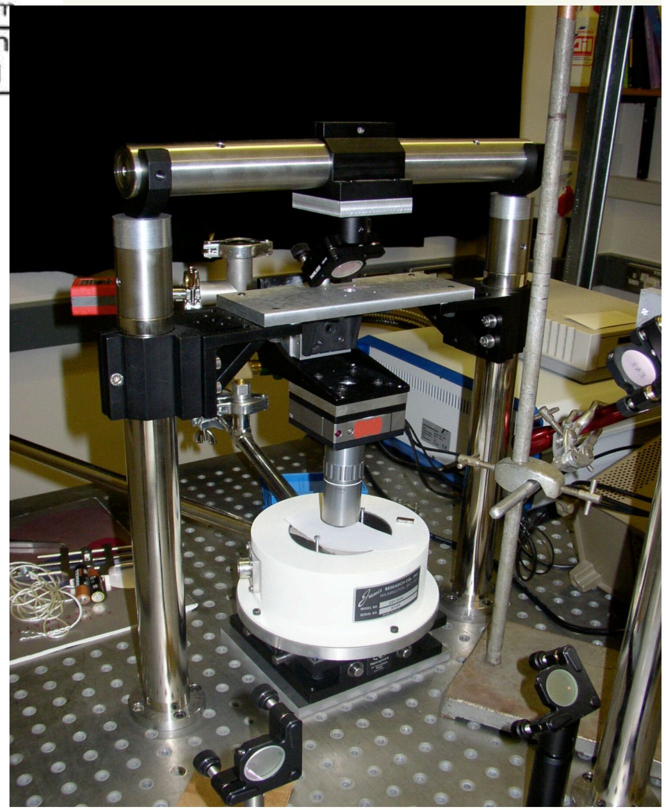
Purcell factor= $\frac{\text{Total emission in cavity}}{\text{Emission into infinite GaAs}}$

>90% efficiency
Into cavity mode!

Experimental Setup

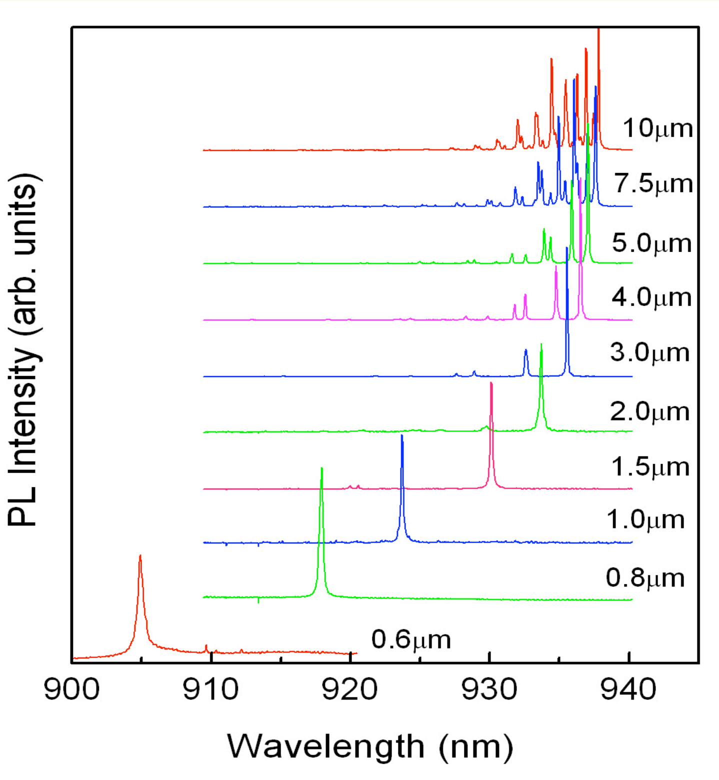


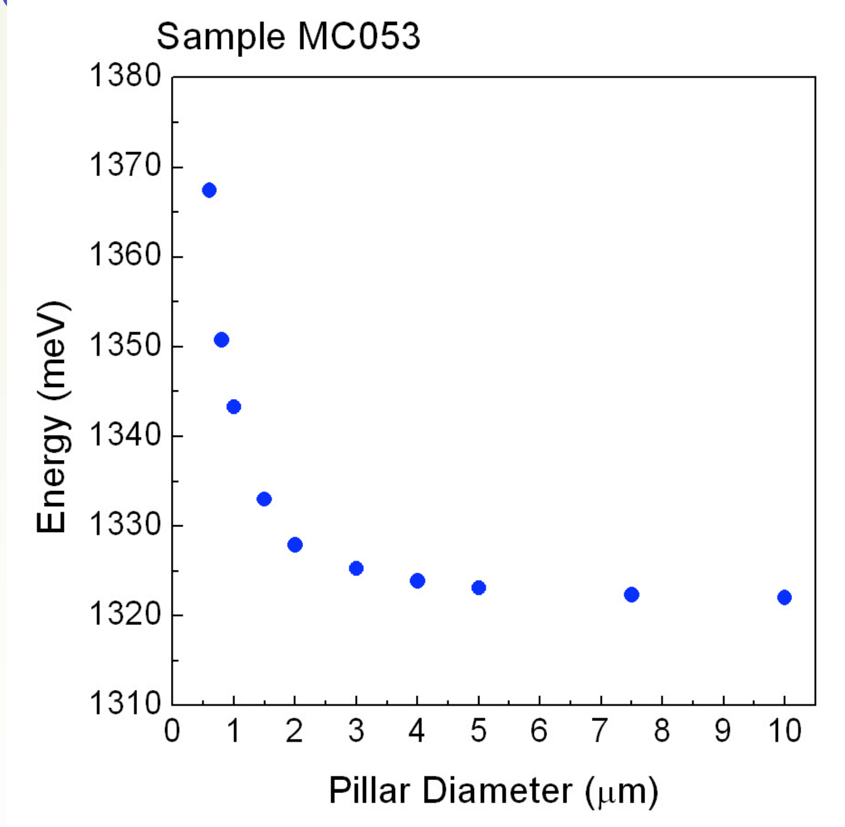
Hanbury-Brown Twiss measurement



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

Pillar-diameter dependent cavity mode





Cavity mode shifts to higher energy with decreasing pillar size

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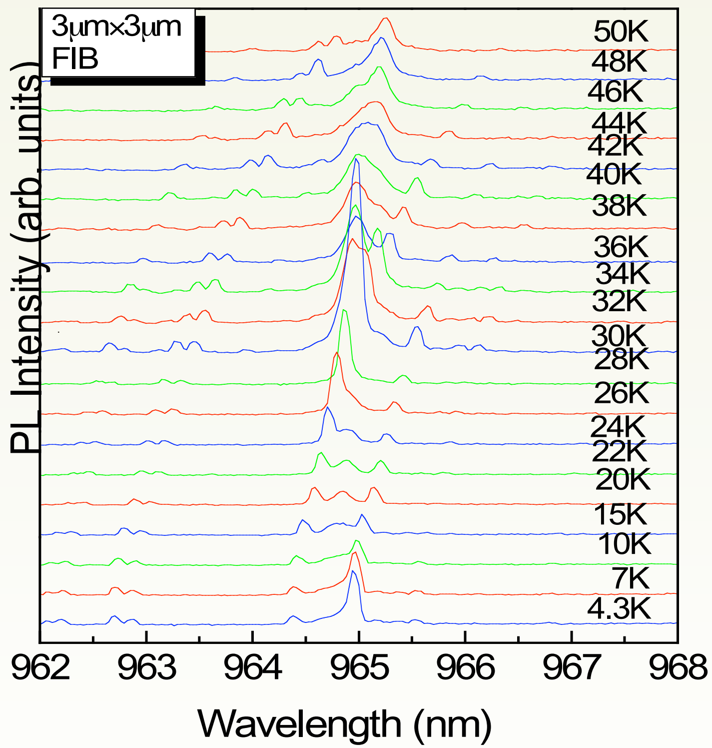
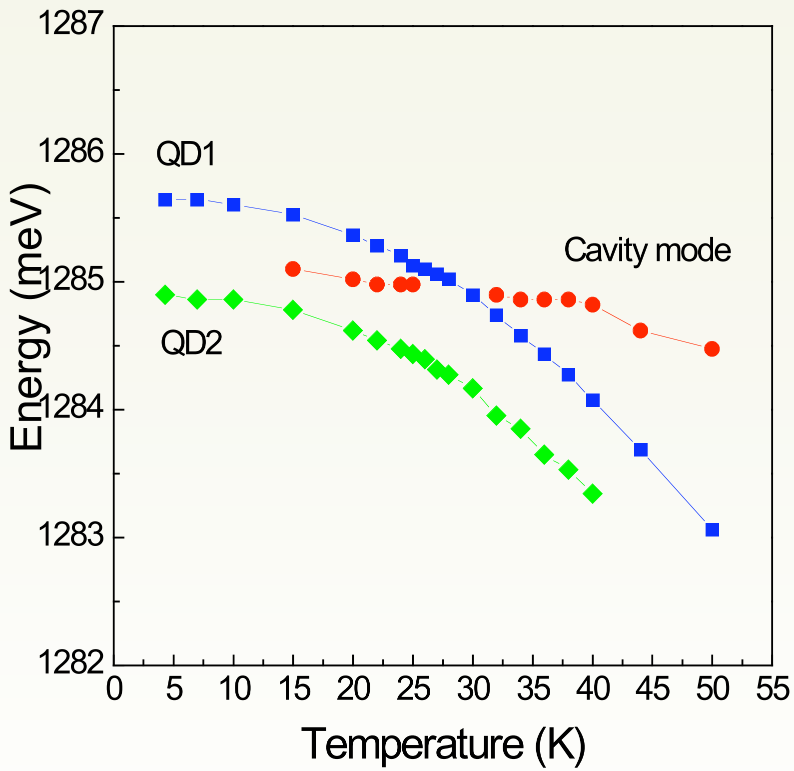
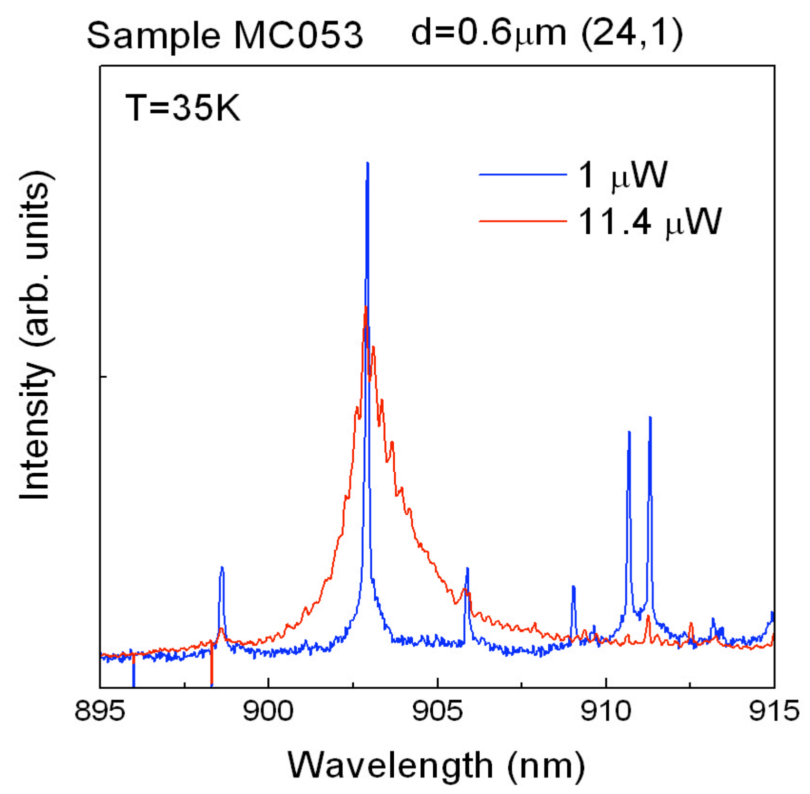
Single QD emission and temperature tuning

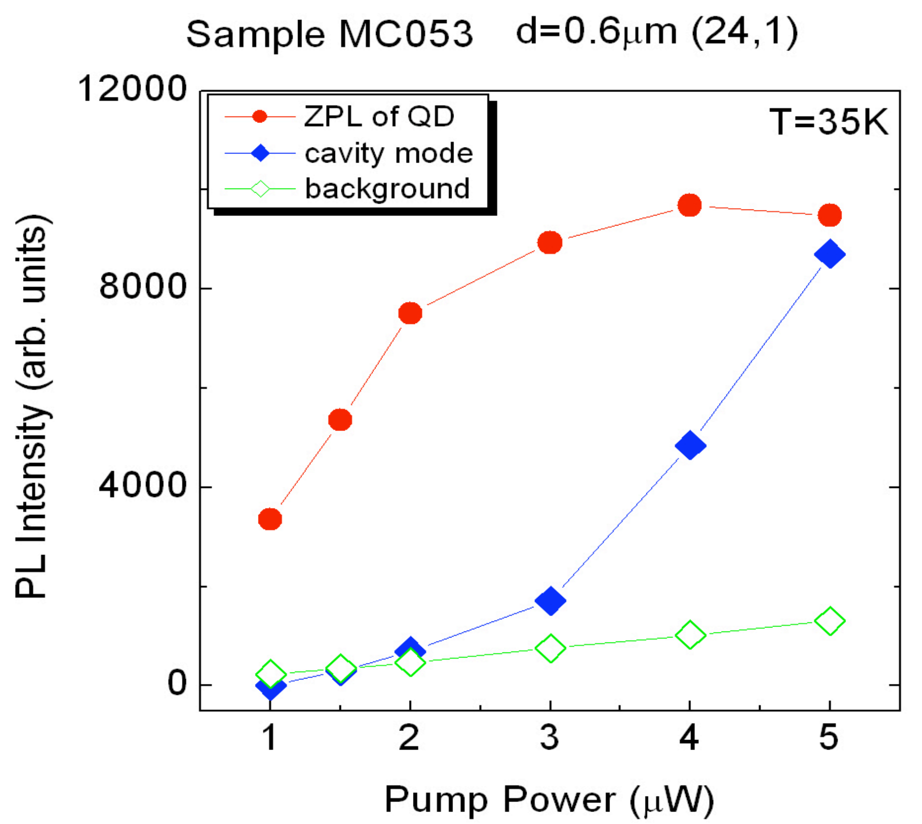




- Single QD emission can be observed in smaller pillar at low excitation power
- QD emission line shifts faster than cavity mode

Single photon generation in circular pillars





With increasing excitation power

- QD emission intensity turns saturated
- Cavity mode intensity develops

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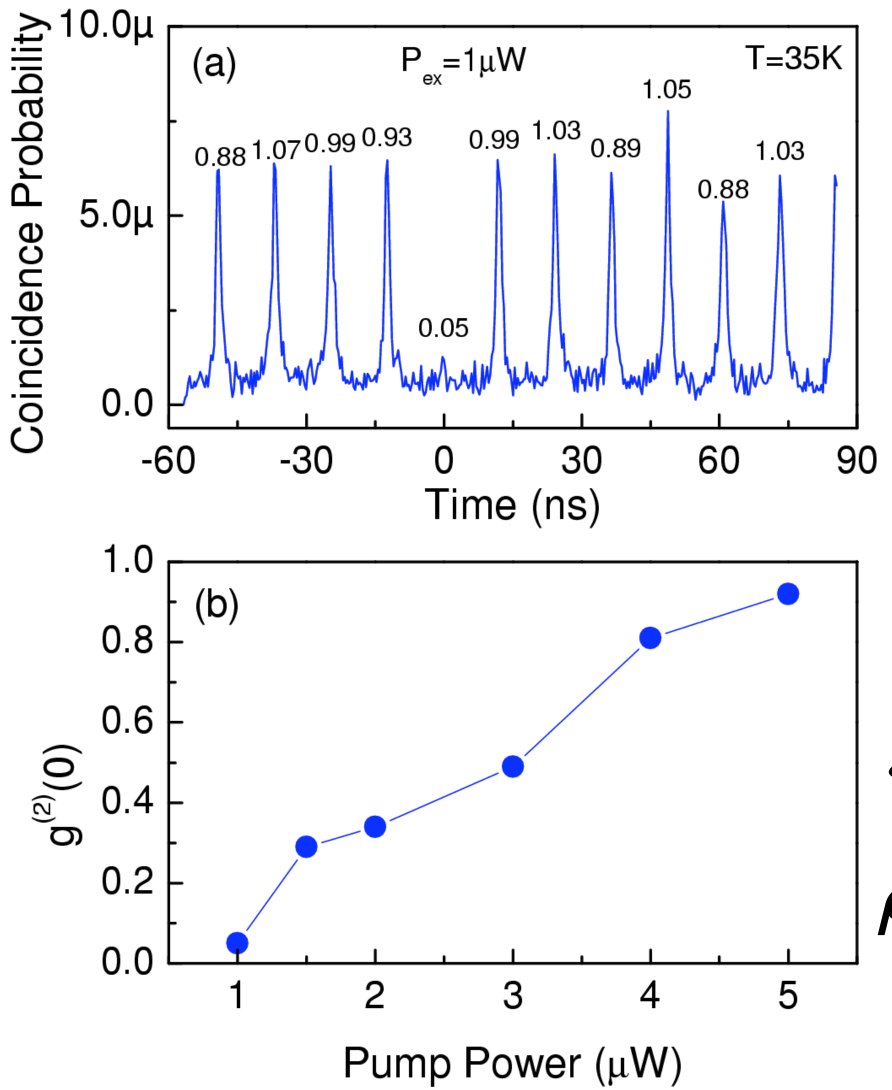
Single photon generation in circular pillars



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

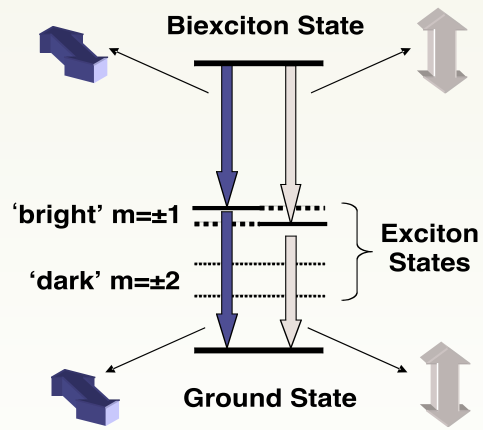
$$g_b^{(2)}(\tau) = \rho^2 \left(g^{(2)}(\tau) - 1\right) + 1$$

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

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

Beyond this:

- Time bandwidth limited single photons on demand from pillar microcavities (Journal of Optics B **7,** 129-136 (2005).
- Entangled photon pairs from Biexciton-Exciton cascaded emission (see , Nature **439**, 179-182).
- Linear gates mixing single photons/ entangled states (lecture 3).
- Entangled solid state/atomic qubits after emission (Knight, Cirac).



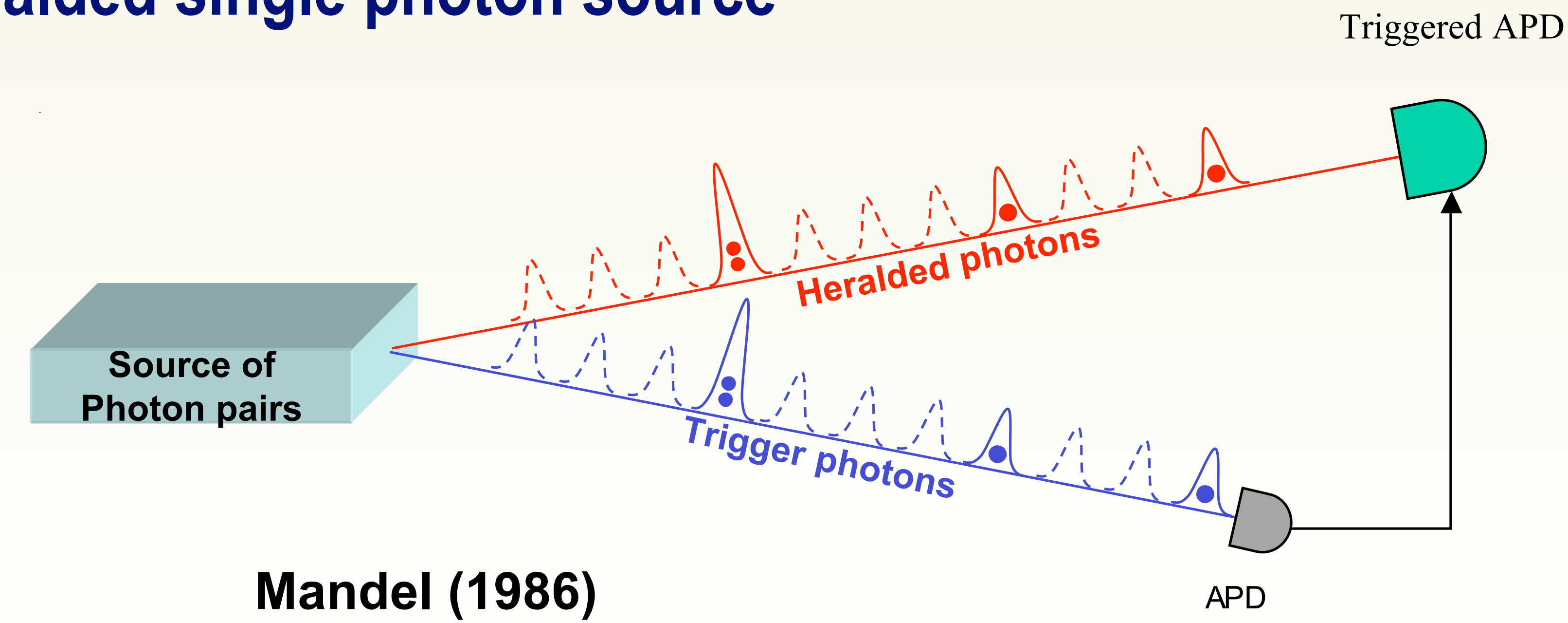
Long term

- Inter-conversion to/from solid state $V_{eff} \sim (\lambda/n)^3$ Strong coupling, non-linear phase gates.

Pair photons and entangled photons

Why photon pairs?

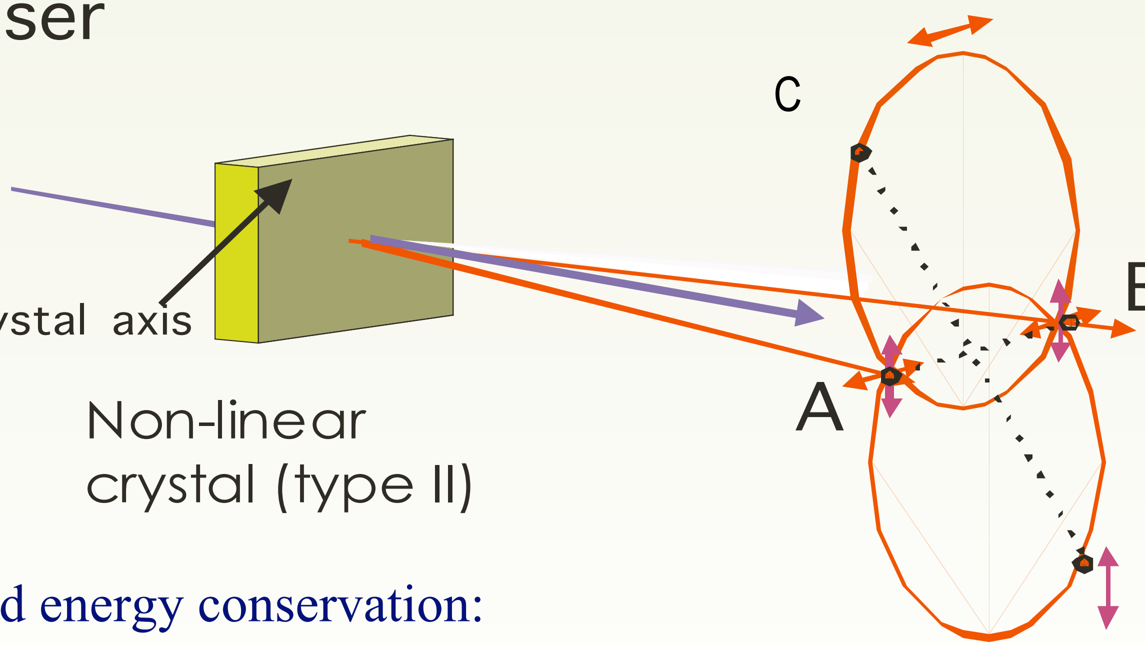
- Heralded single photon source



Mandel (1986)

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

Creating Entangled Photon Pairs



Phase matching and energy conservation:

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

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

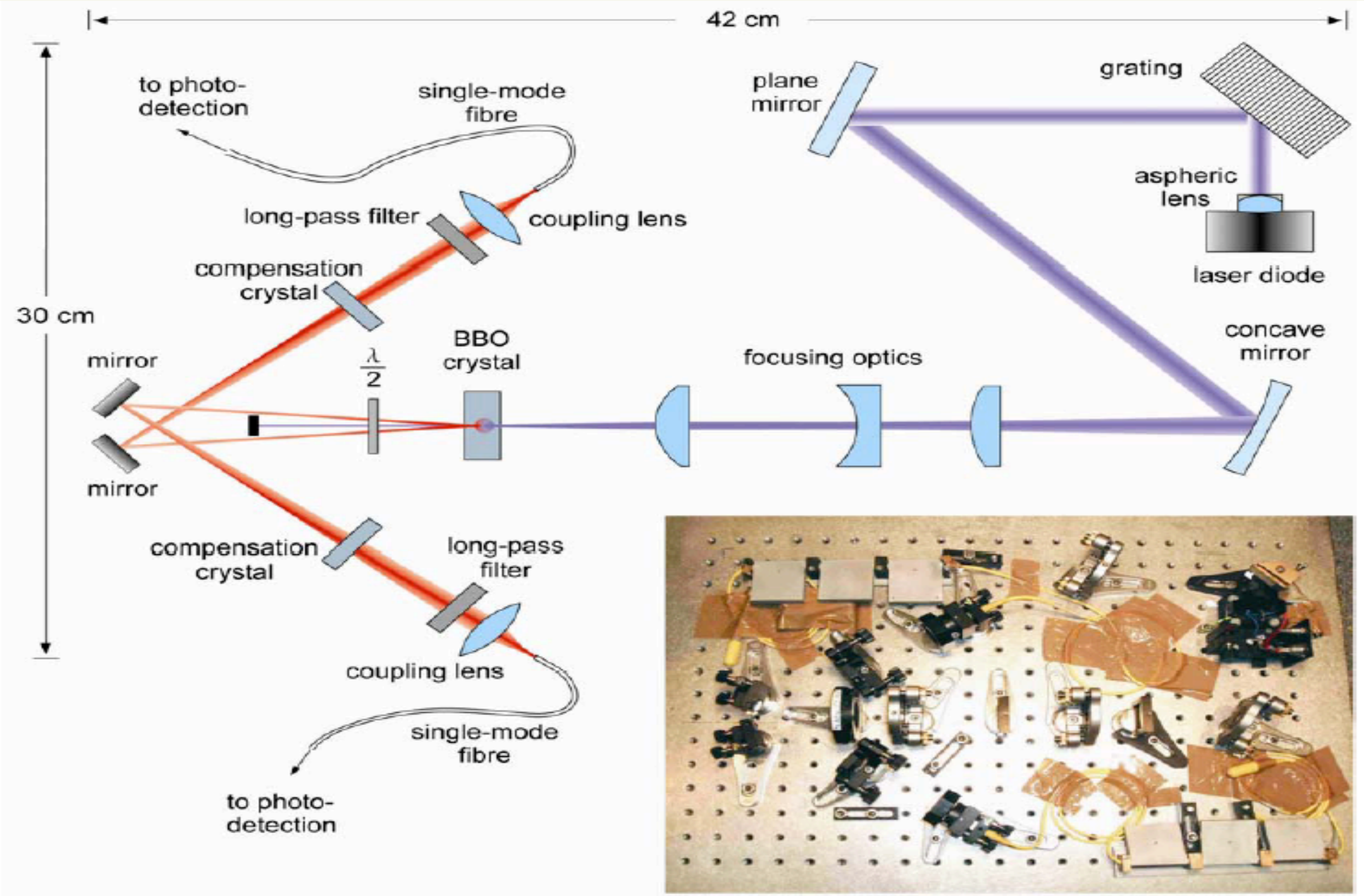
Pairs C - D $\quad |\Psi\rangle = |H\rangle_C |V\rangle_B$

Pairs A - B $\quad |\Psi\rangle = \frac{1}{\sqrt{2}}\left(|H\rangle_A |V\rangle_B + |V\rangle_A |H\rangle_B\right)$

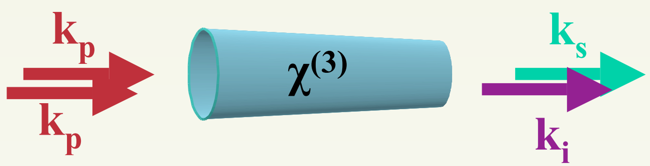
Portable Crystal based entangled pair source

150mW diode

70000 detected coincidences/sec

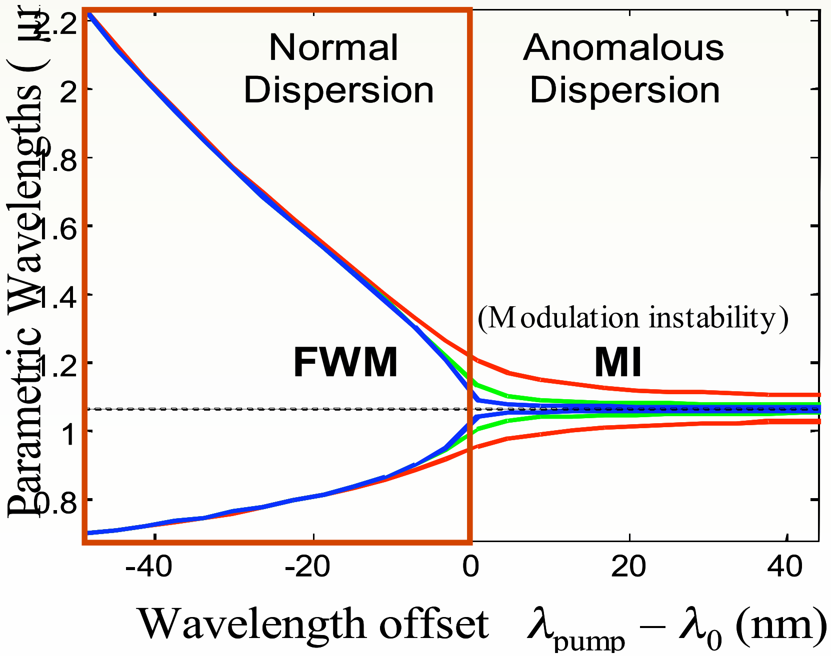


- Non-linear process in $\chi^{(3)}$
- 2 pump photons → 2 emitted photons



Phase matching and energy conservation:

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



Use of the normal dispersion region:

- no pump power dependence
- wavelengths created far from the pump
- Raman and fluorescence amplification effects reduced

W. J. Wadsworth et al. (Opt. Express 2004)

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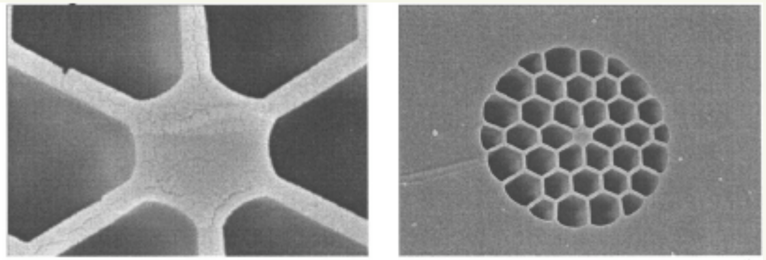
Experiment:

Fulconis et al Opt. Express 13, 7572 (2005)

Fiber specifications

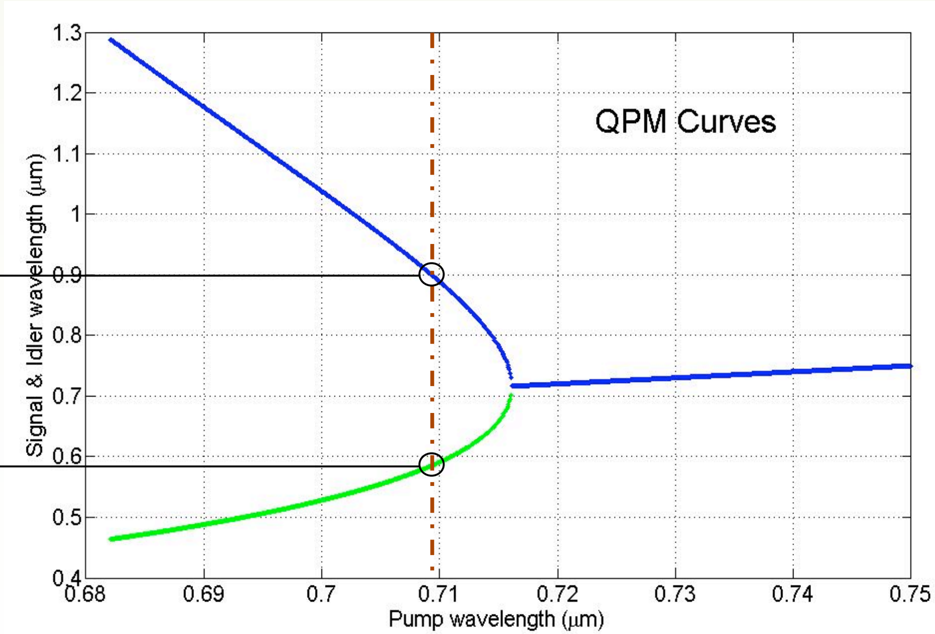
- made of silica and air
- core diameter: ~2mm
- length: 30cm
- zero dispersion wavelength: l_o=715nm



l_{pump}=709nm

l_{idler}=897nm

l_{signal}=587nm



Characteristics of the parametric emission

- Fiber birefringent

  Þ control of the pump polarization needed

  Þ photon pair polarized, aligned with the pump

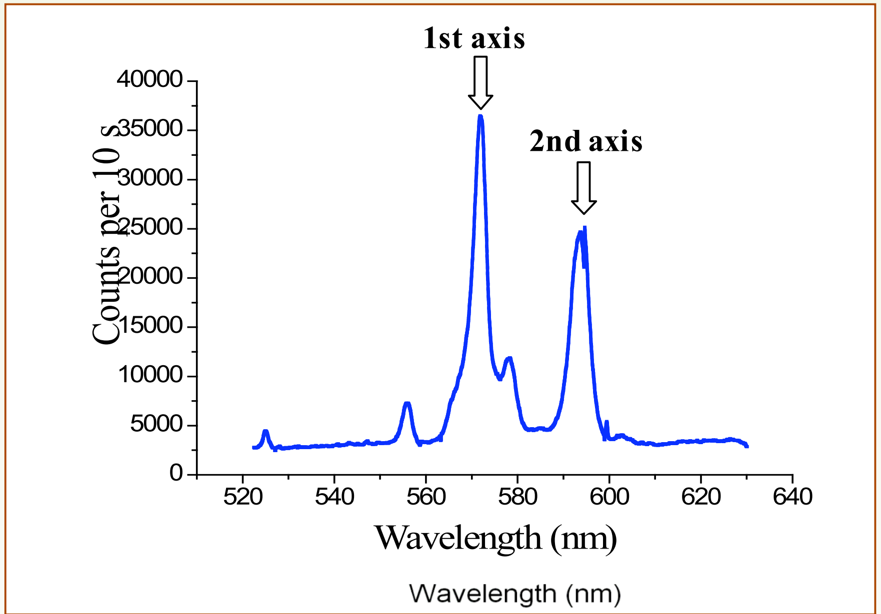
- Narrow band:

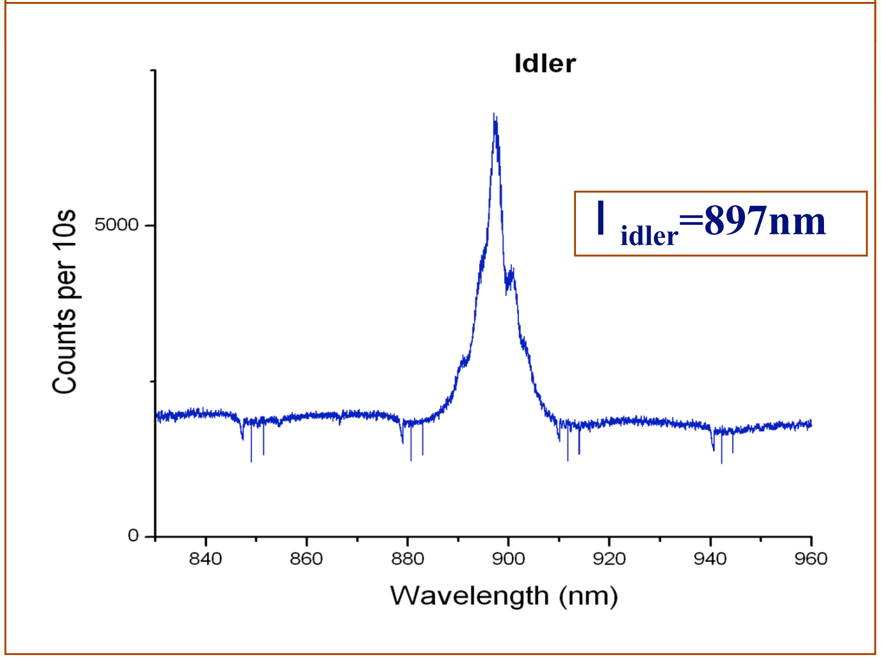
  signal/idler FWHM ~5nm/10nm

- Tunable using fiber parameters and pump wavelength

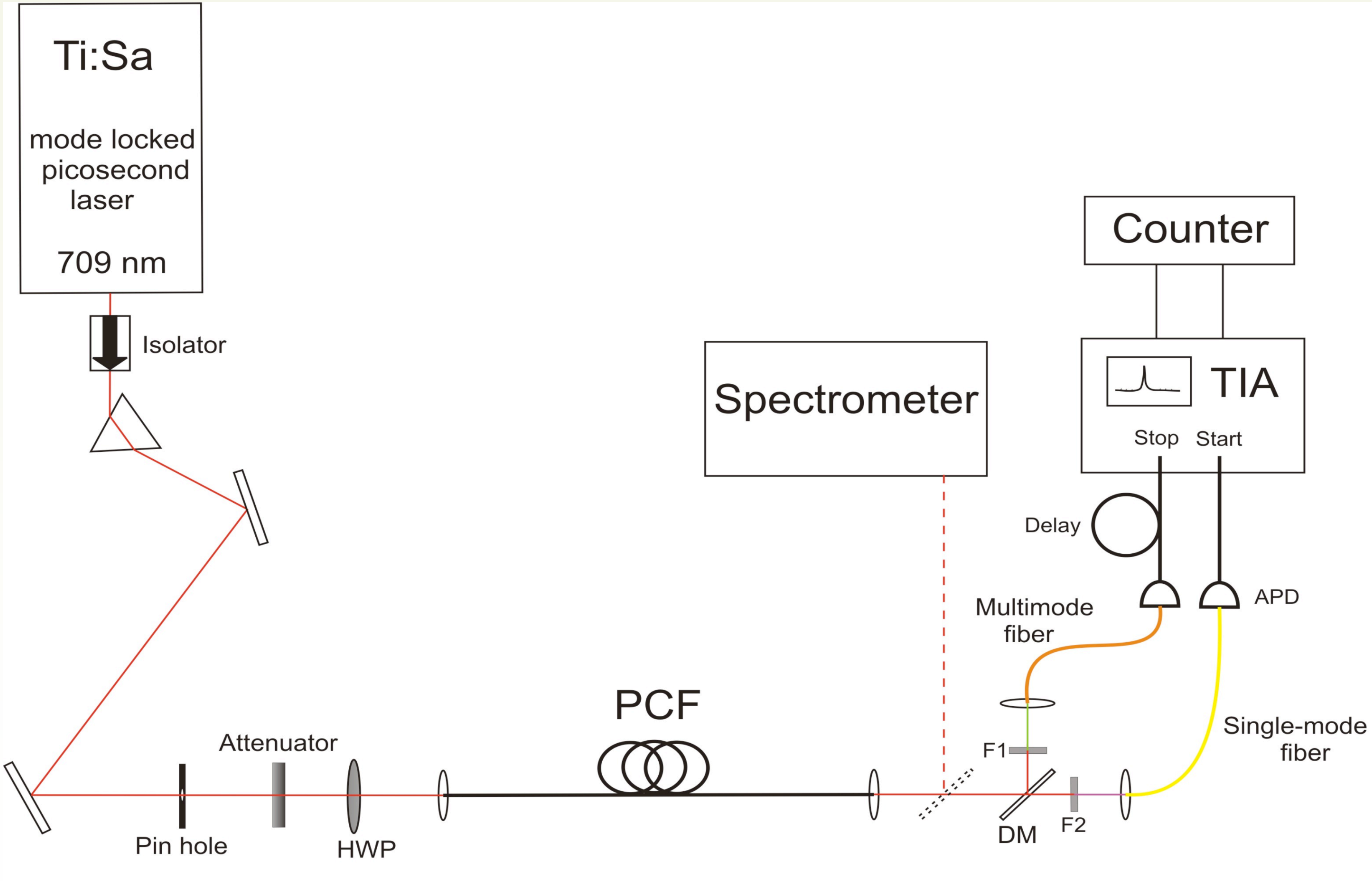
- Highly efficient thanks to the confinement in the fiber

- Single circular mode





Setup



Ti:Sa
mode locked picosecond laser
709 nm
Isolator
Spectrometer
Counter
TIA
Stop
Start
Delay
APD
Multimode fiber
PCF
Attenuator
Single-mode fiber
F1
F2
DM
Pin hole
HWP

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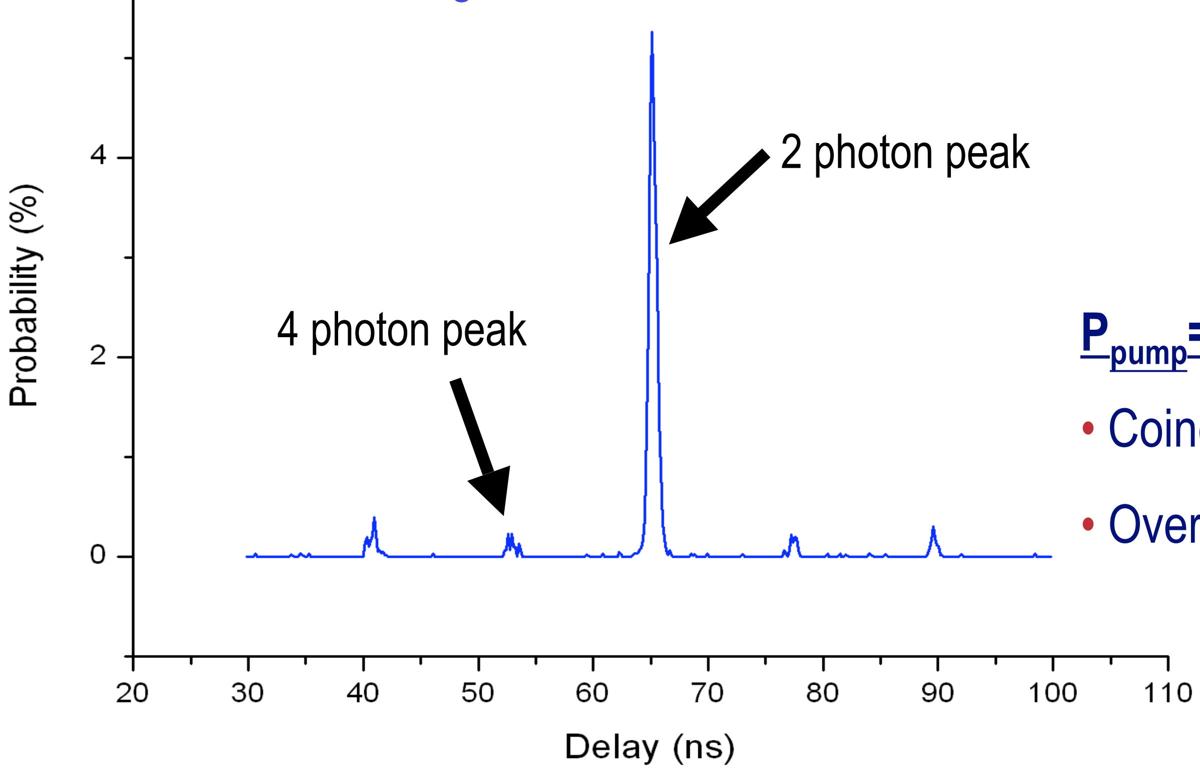
Coincidence results

Idler (895nm): single-mode fiber → ~ 14% of coincidences

Signal (583nm): multimode fiber → ~ 33% of coincidences

: single-mode fiber → ~ 22% of coincidences



P_{pump}=540µW:

- Coincidence rate: **~3.5.10^{5} s^{-1}**
- Overall coupling efficiency in SMF **60%**

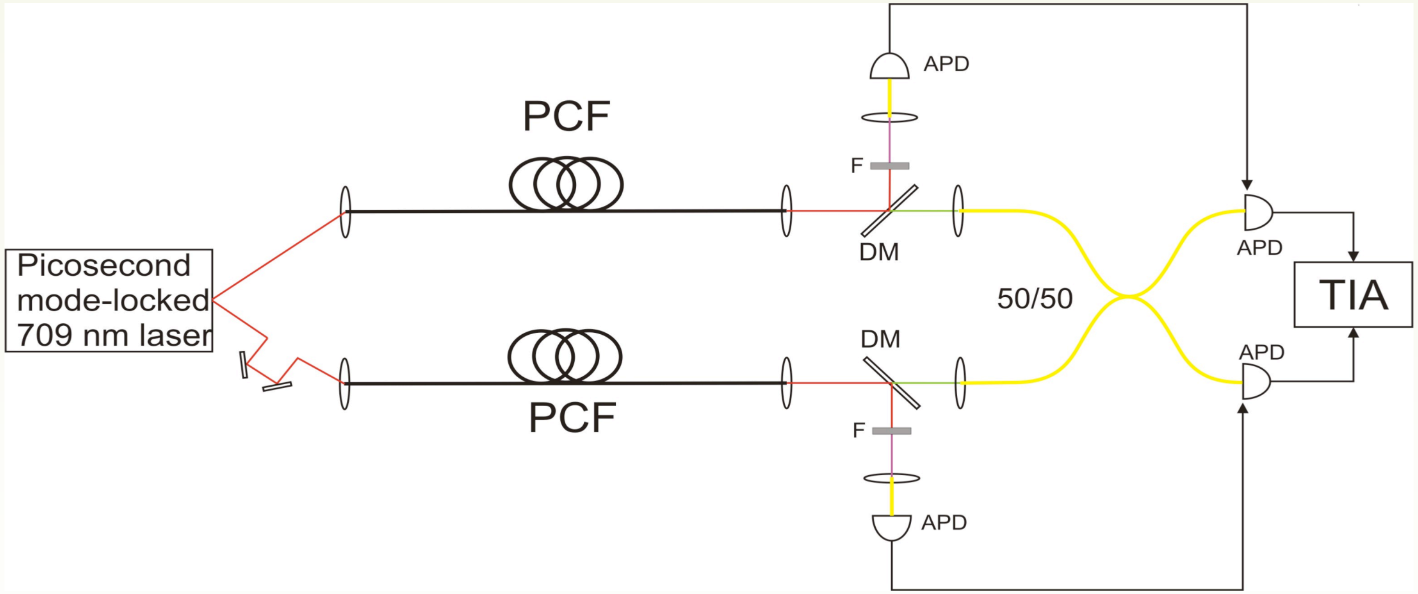
Confirmation of bright pair photon emission:

-potential for 80% coupling to SMF

Future work: see lecture 3

• Improvement of the coincidence rate using narrow band filters and single mode fibers in both channels.

• Four-photon experiment using two PCF



Aim to show a Hong-Ou-Mandel dip between separate gated single photons => requires filtering to less than 0.2nm

Using ~2mW pump (30cm fibre) we expect a coincidence rate >10000/s within this bandwidth

=> 1 four photon events /s

Co-workers

- Universiy of Bristol: Daniel Ho,

J. Fulconis, J. Duligall, C. Hu, R. Gibson

Fibres

- University of Bath: W. Wadsworth, P. Russell

Quantum dots and microcavities

- University of Sheffield: M. Skolnick, D. Whittaker, M Fox
- Toshiba Europe: A. Shields, A. Bennett
- Univ Cambridge: D. Ritchie

Linear optics RAMBOQ IST38864:

Vienna, LMU, HP Bristol, Geneva, Erlangen, Queensland, Toshiba, Cambridge, Thales, MPQ, IdQ, ….