



# The Solid-State Quantum Network (SSQN)

## An ERC “CHIST-ERA” grant

Imperial College  
London  
(theory)

Bristol  
That's us!  
(spin-photon  
interface)



University of Würzburg  
(fabrication of  
micropillar samples)

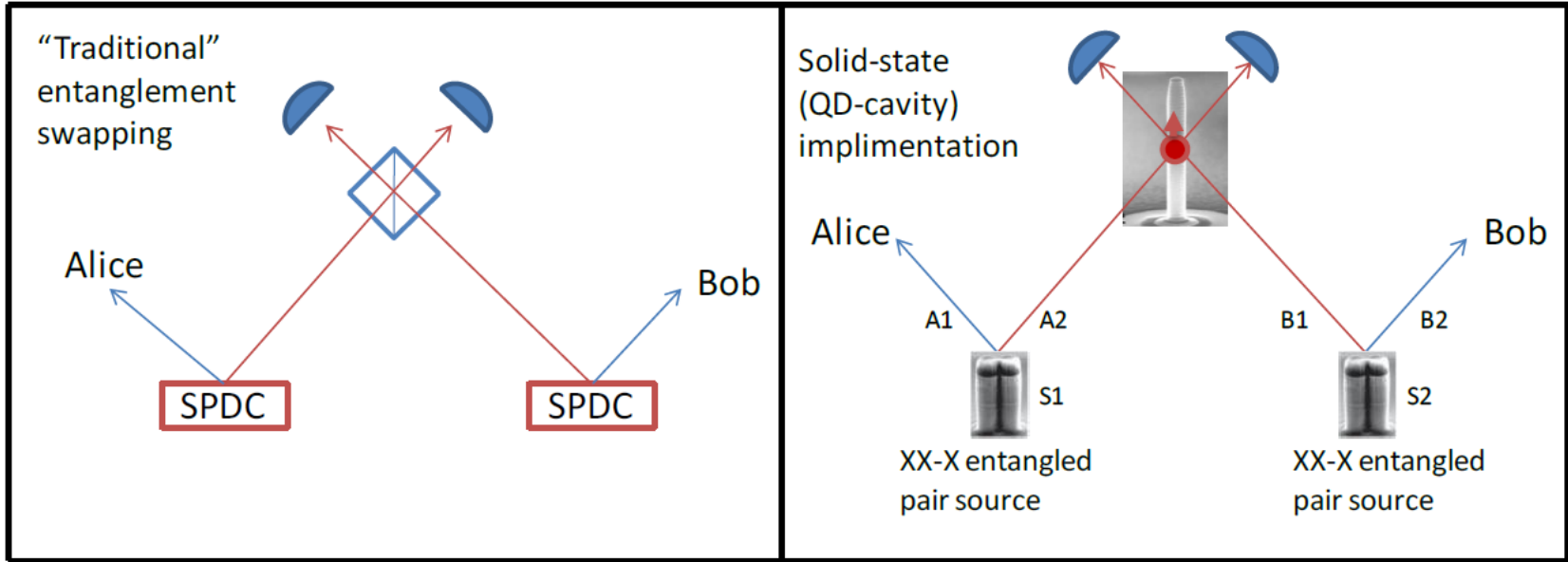
CNRS/LPN Paris  
entangled photon  
sources, spin-photon  
interfaces

# Outline

- Motivation: What we are trying to achieve and why?
- Quantum teleportation: Basic principles and why the traditional approach is so lossy
- Quantum dot-based components: How do they work and what are the problems?
  - Spin-based Bell-state analyser with heralded quantum memory
  - Entangled pair source
- Putting it all together: Conclusions and Outlook

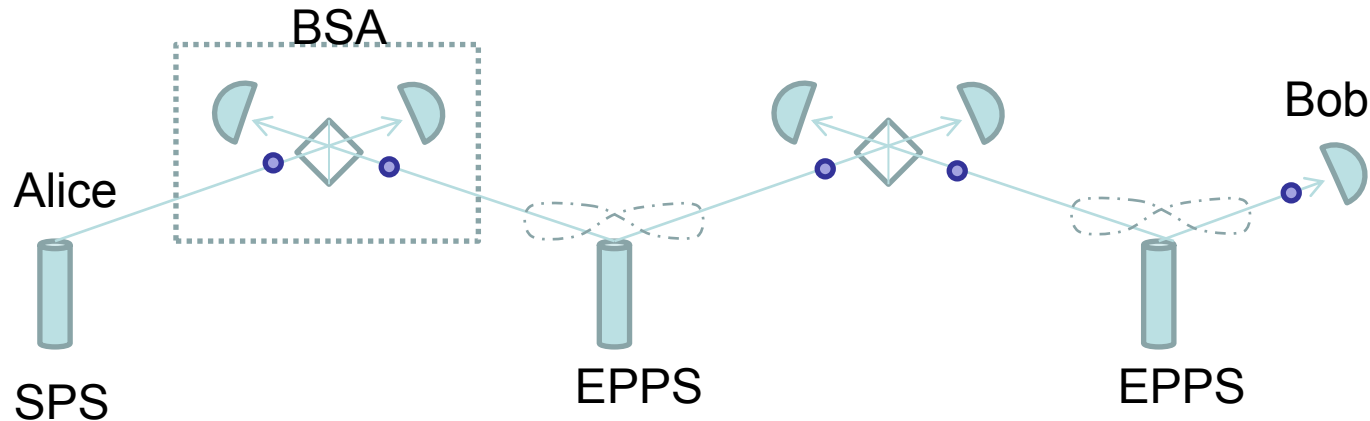


# 🔥 Aim of Project



- Replace “traditional” elements of a quantum teleportation and entanglement swapping module with their solid-state equivalents:
  - ✓ QD-based entangled photon emitter
  - ✓ Spin-based Bell-state analyser

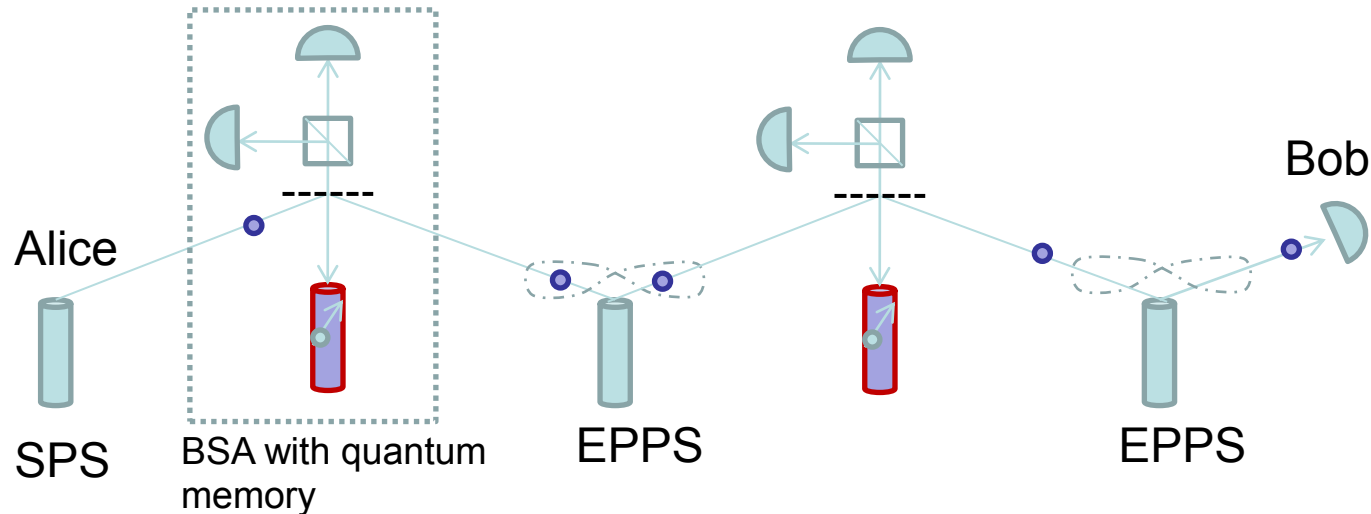
# 🔥 Motivation: Losses in the traditional approach



Intrinsically <5% efficient SPDC entangled pair sources

- Beamsplitter-based Bell state analyser:
  - requires Fourier transform-limited **indistinguishable** photons
  - exactly **synchronous** time of arrival
  - Success rate intrinsically limited to 25%
- Highly sensitive to losses: entanglement swapping distance limited to 200km.

# 🔥 Solid-State Network



- >15% demonstrated efficient QD entangled photon pair sources (100% in principle)
- Spin-photon interface in a micropillar:
  - Intrinsic  $\mu\text{s}$  heralded quantum memory stores photon state: no need for synchronisation
  - Indistinguishability criterion greatly relaxed
- Entanglement swapping distance should reach >1000km and transmission rates should increase by  $10^5$ .

# Solid-state component 1: Bell State Analyser

- Based on the quantum dot spin-photon interface.

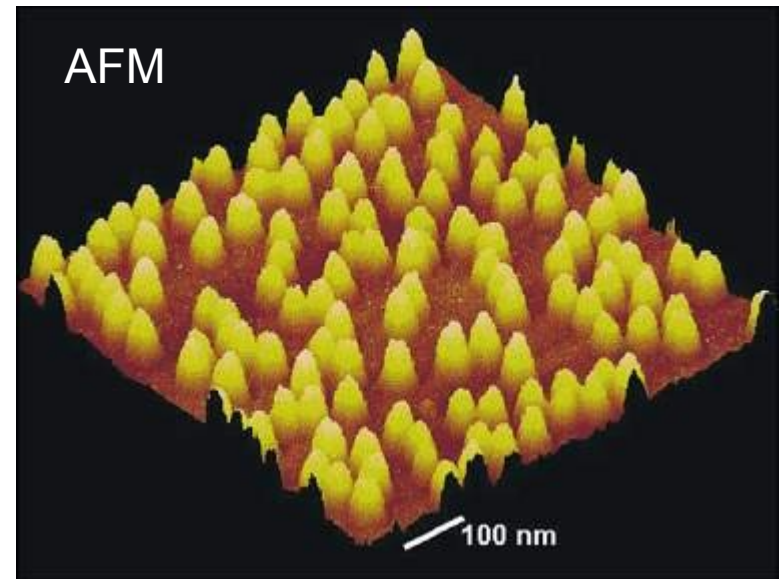
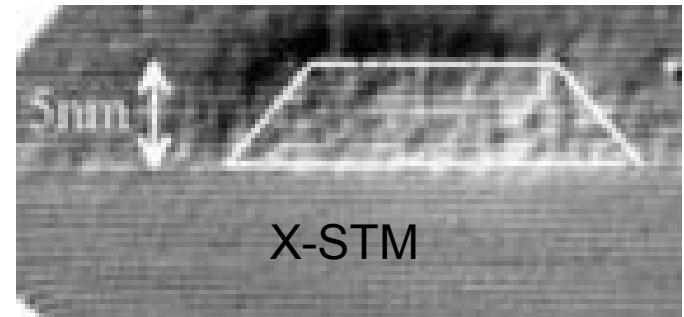
Theory: Hu and Rarity: PHYSICAL REVIEW B **83**, 115303 (2011)

- Contains an electron spin as an intrinsic memory
- Micropillar increases the light-matter interaction strength and photon extraction efficiency.



# 🌟 Quantum Dots as Artificial Atoms

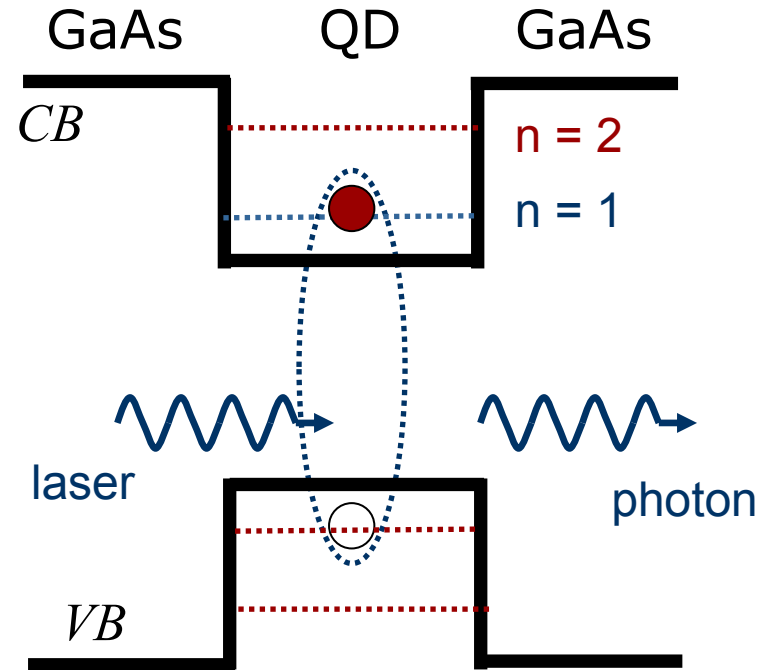
- Quantum Dot (QD) – **small volume** of low bandgap semiconductor
- Size comparable to electron wavefunction
- Energy levels of electrons and holes are quantized
- Undergoes atomic-like transitions with single photons



# 🔥 QD as Two-level System

- Energy levels are analogous to **atomic system**:

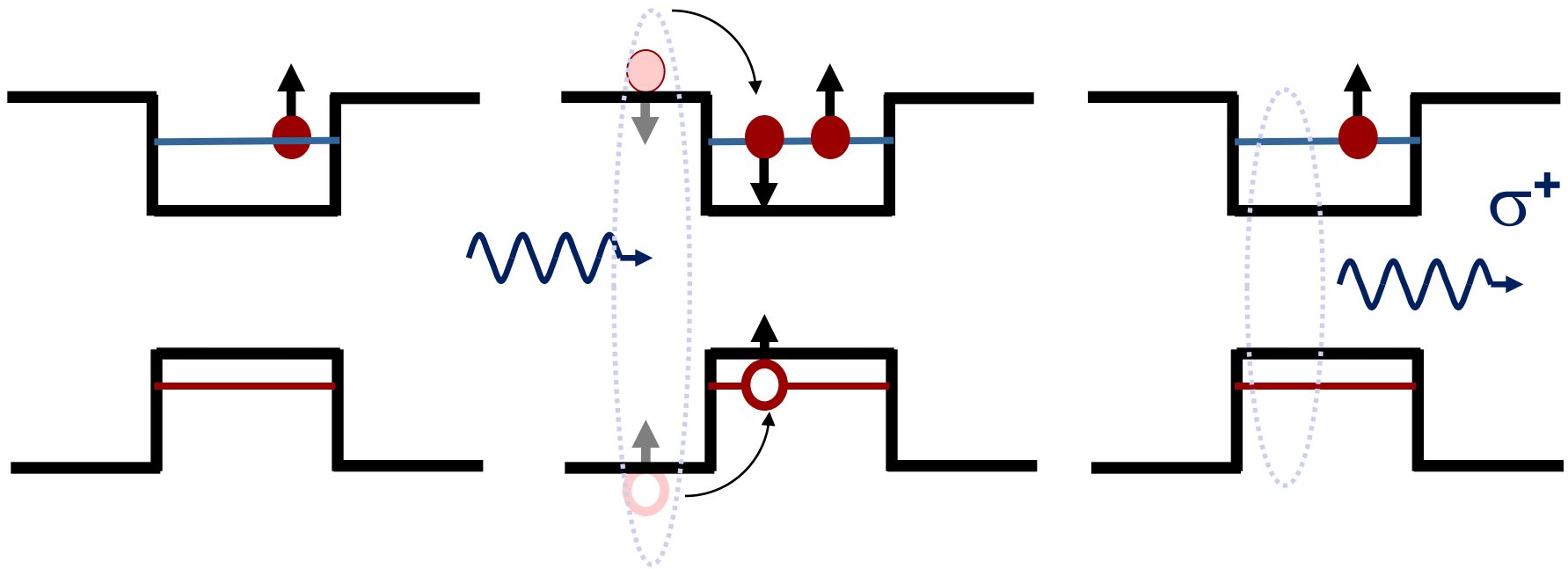
- Well-defined allowed energy levels ( $< 1 \mu\text{eV}$ )
- States separated by several 10's meV
- Isolated from lattice vibrations and decoherence



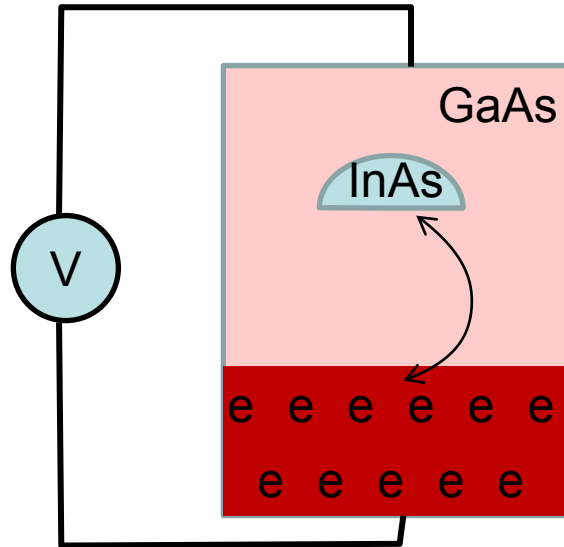
# 🔥 Charged Quantum Dots

Can we use exciton(e-h pair) as a quantum memory?

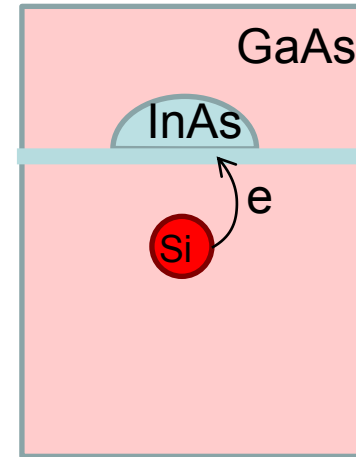
- Problem: lifetime is short ( $< 1\text{ns}$ )
- Use resident electron (spin lifetime  $\sim \mu\text{s}$ )



# 🔥 Doping QDs with Single Electron

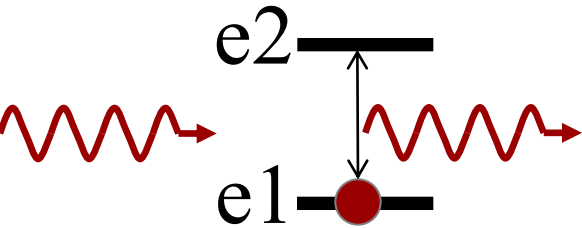


$n^+$  modulation doped  
with Schottky contact

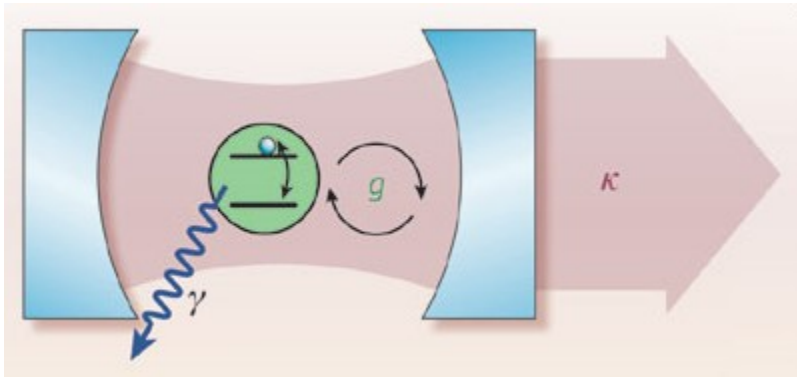


Si delta doped

# 🔥 Atom-Cavity QED

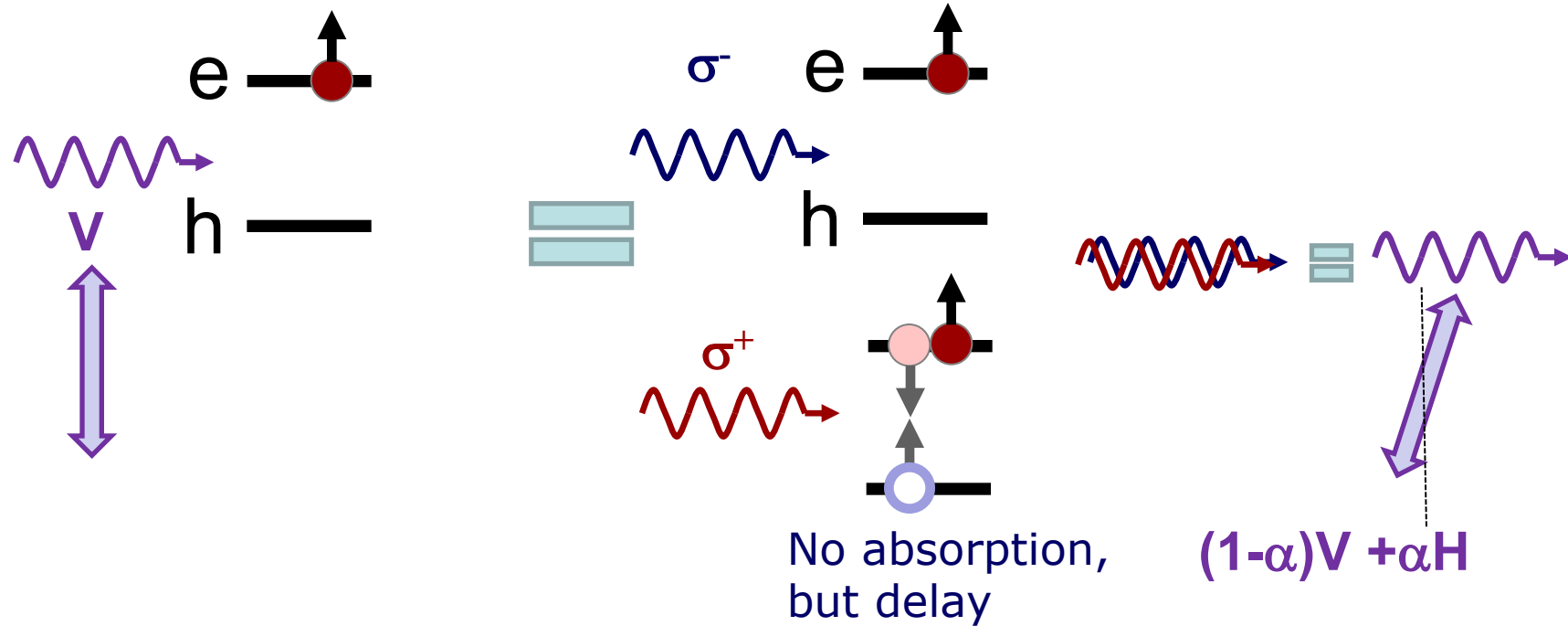


- Aim: transfer photon polarization to excited state of electron, and vice versa
- Optical cavity improves the probability of photon absorption by
  - trapping photon (increases interaction time with atom)
  - reducing modal volume



# 🔥 Faraday Rotation in QDs

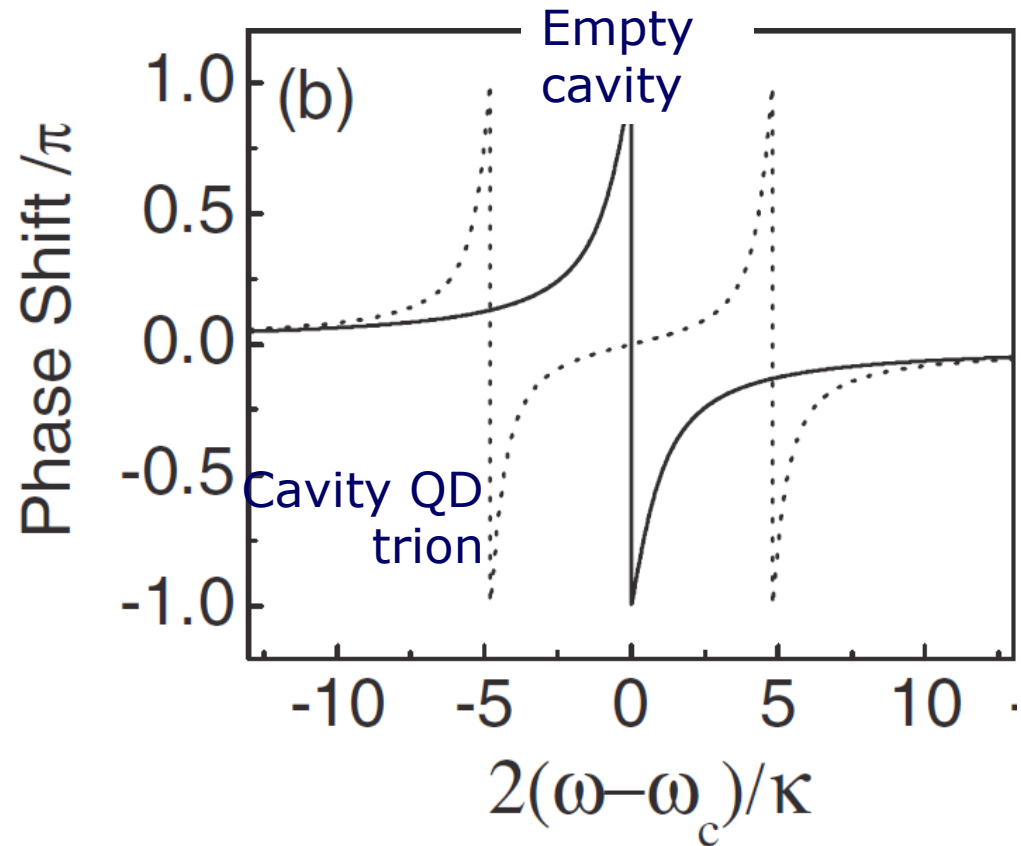
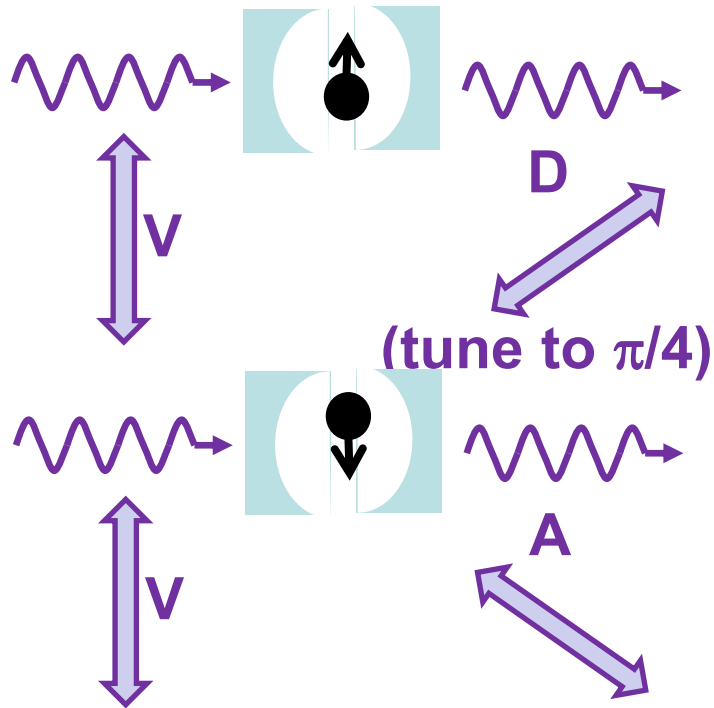
- We need to find an optical method to read out the single electron spin
- Use Faraday Rotation effect:



# 🔥 Faraday Rotation in High Q Cavities

- Use an electron and spin selection rules in QD to perform spin-dependent phase shifts

C.-Y. Hu *et al.*, PRB  
78 085307 (2008)



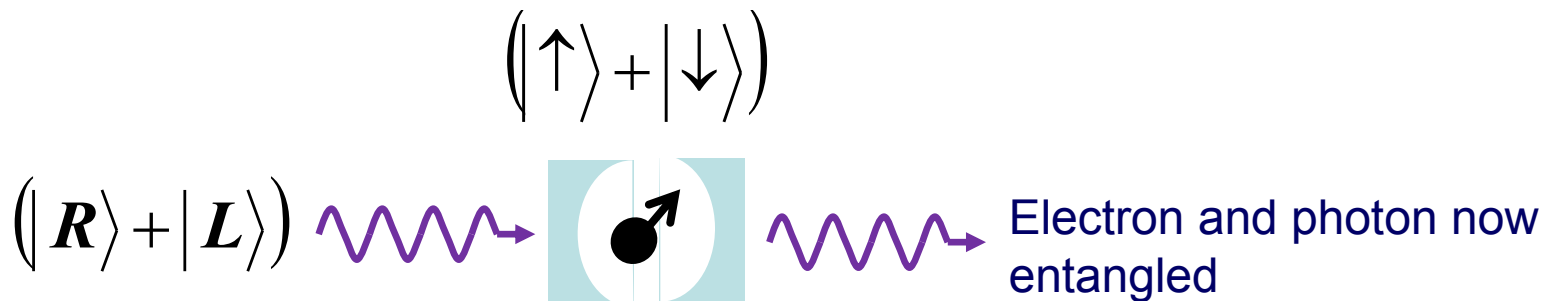
# 🔥 Spin-photon Entangler

$$(|R\rangle + |L\rangle) \otimes (|\uparrow\rangle + |\downarrow\rangle) \mapsto e^{i\phi_0} \{ (|R\rangle + i|L\rangle)|\uparrow\rangle + (i|R\rangle + |L\rangle)|\downarrow\rangle \}$$

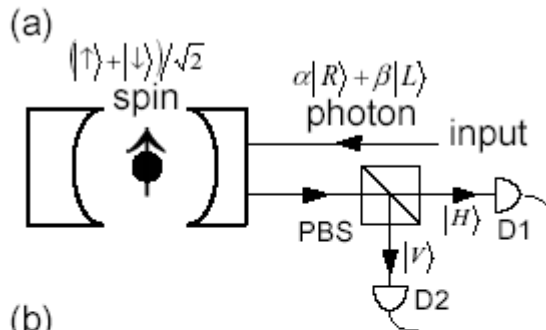
Photon in  
superposition  
of left and right  
circ pol.

Electron in  
superposition  
of up and down  
spin

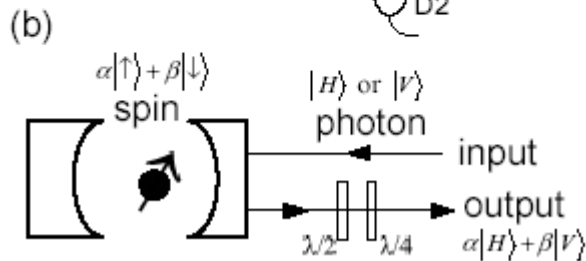
Electron and photon now  
entangled



# 🔥 Spin-Photon State Transfer



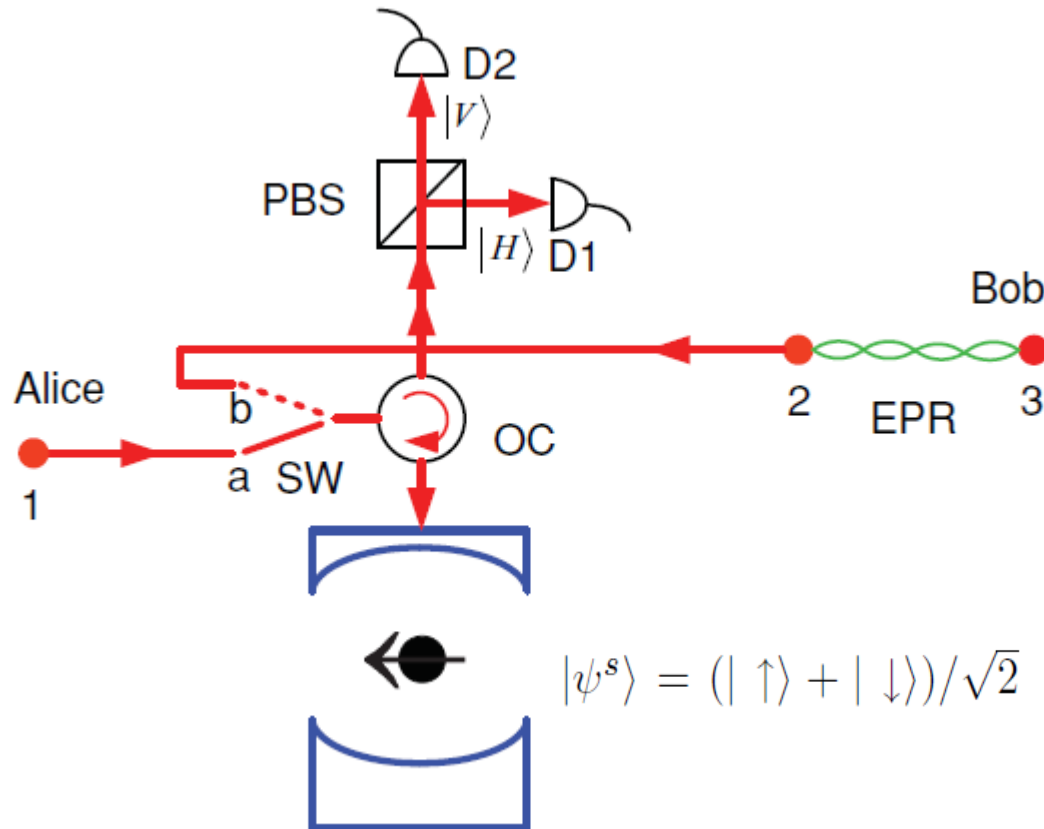
(a)  
State transfer from photon to spin



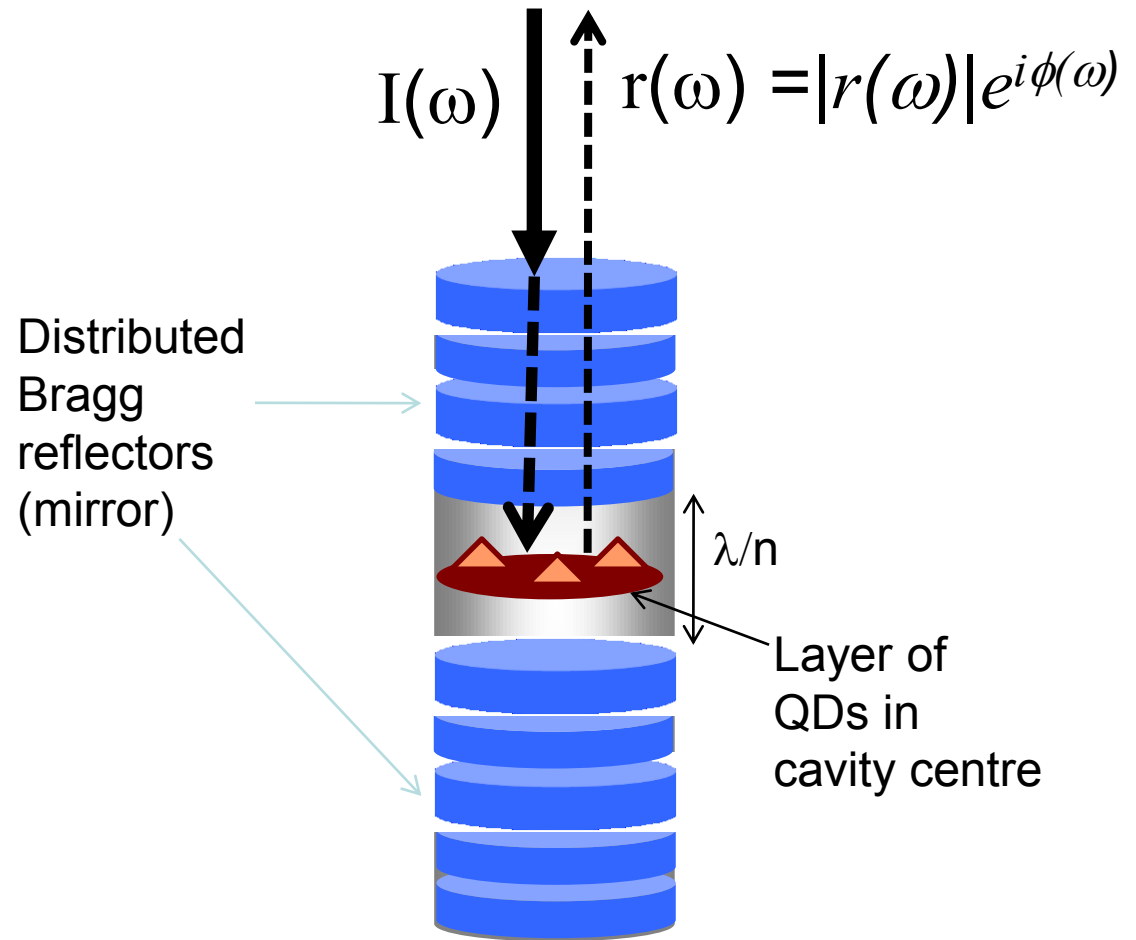
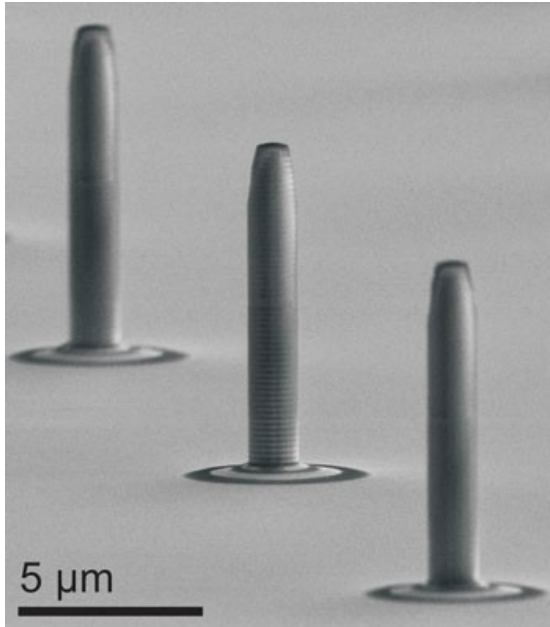
(b)  
State transfer from spin to photon

# Quantum Repeater

arXiv1005.5545

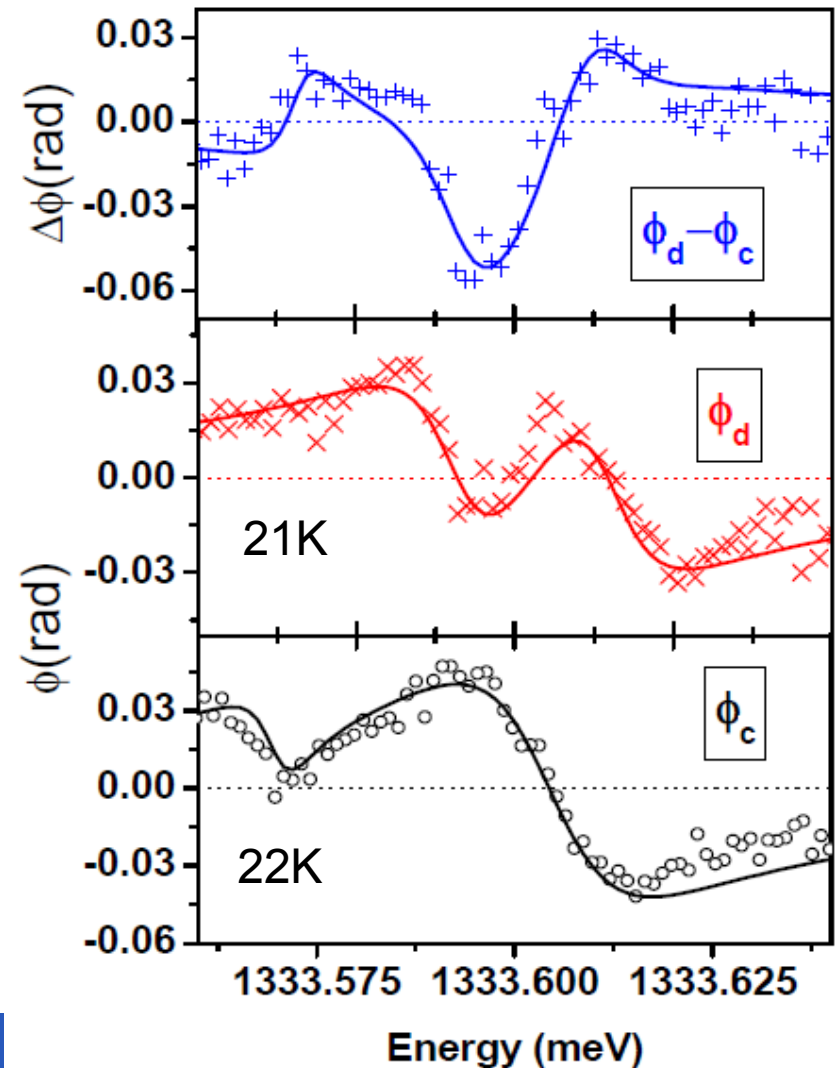
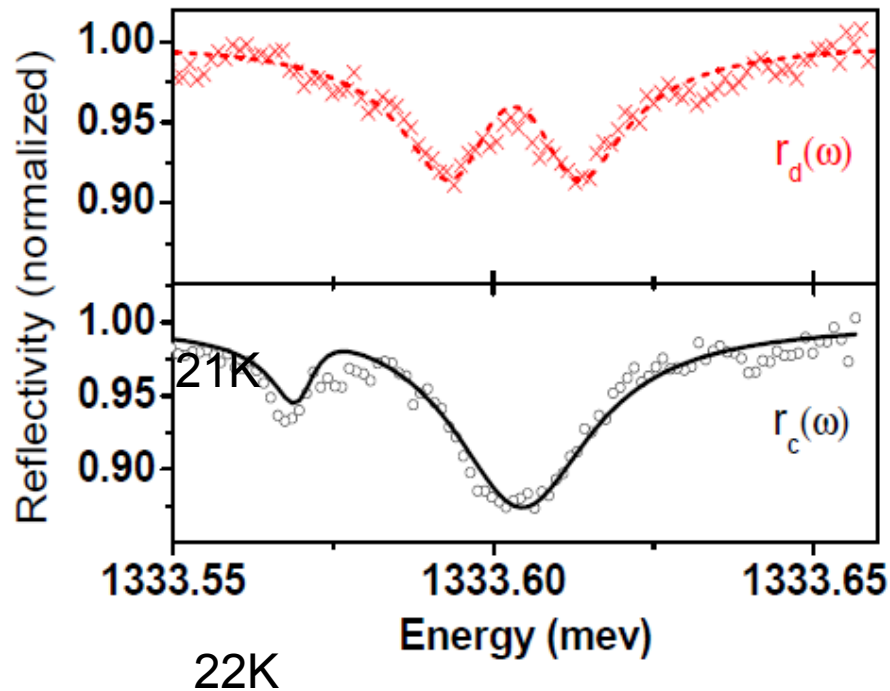


# Quantum dot cavity reflectivity



# Conditional phase shift

$g \sim 9.4 \text{ ueV}$     $\kappa + \kappa_s \sim 26 \text{ ueV}$     $\gamma \sim 5 \text{ ueV}$   
 $g > (\kappa + \kappa_s + \gamma)/4$     $\Delta\phi \sim 0.05 \text{ rad}$  (0.12 rad)



# Challenges

- High Q pillars needed with minimal side leakage (= photon loss) but high photon extraction efficiency (difficult to achieve simultaneously)
- Also need perfectly circular pillars and controlled QD doping
- Spin initialisation protocols to be developed for high-Q cavities
- Need to reduce spin dephasing due to nuclei



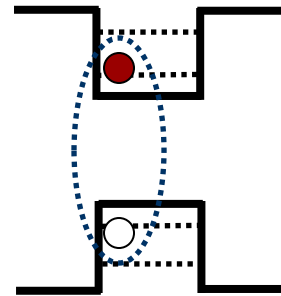
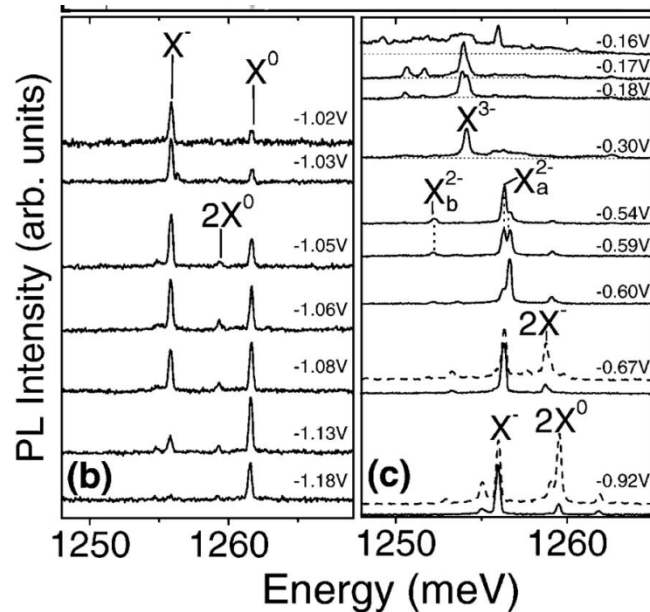
# Solid-state component 2: Single/Entangled Pair Source

- Self-assembled QDs embedded in micropillar cavities:
  - Efficient single photon sources  
31MHz, 39% efficiency sources: Strauf et al., Nat Phot **1**, 704, 2007
  - Efficient entangled pair source achieved by LPN recently

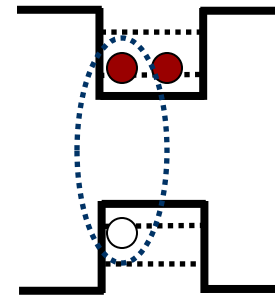
Douce et al., Nature **466**, 217 (2010)



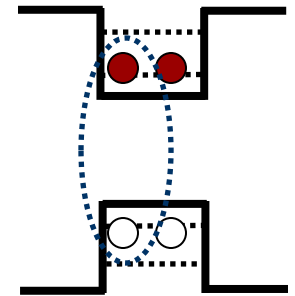
# Single QD Spectroscopy



neutral  
exciton,  $X^0$



Negatively  
charged  
exciton,  $X^-$



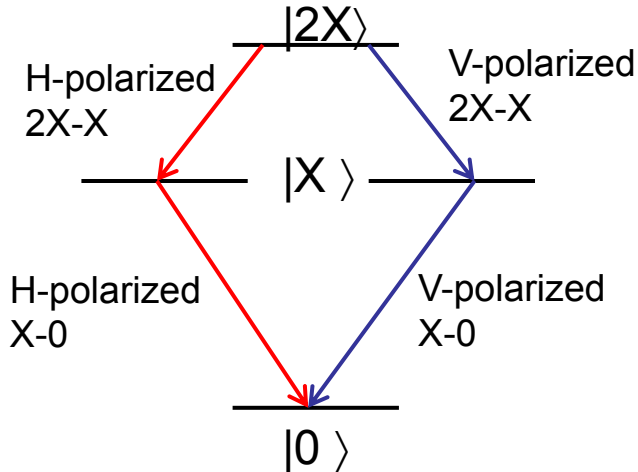
Biexciton,  
 $2X^0$

- Coulomb interactions give each type of exciton a slightly different recombination energy
- Can filter e.g.  $X^0$  or  $X^-$
- Ideal **triggered** single photon source



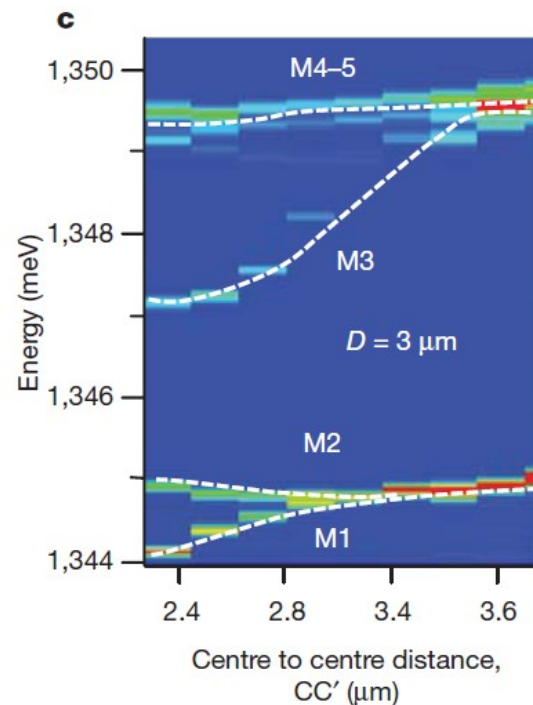
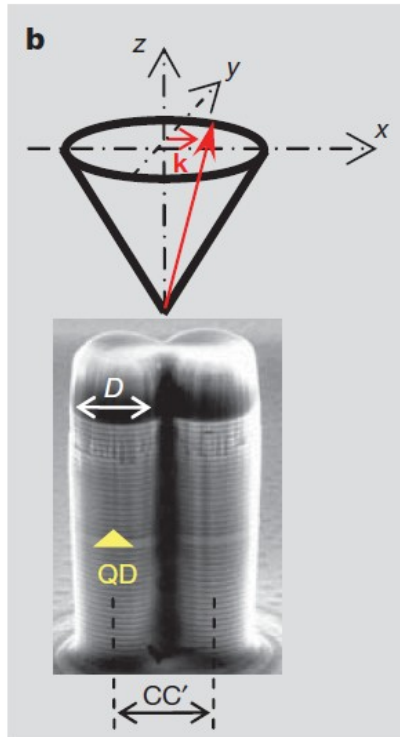
# • Entangled Pair Source

- Create entangled pairs of photons from biexciton-exciton cascade



- Decay of biexciton-exciton and exciton to vacuum state produces two photons
- Photons are entangled in polarization
- Photons differ in emission energy by  $\sim 2\text{meV}$ .

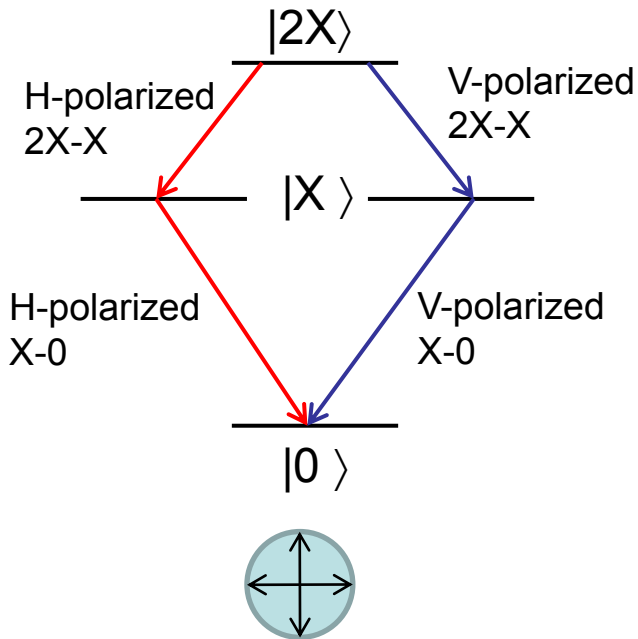
# 🔥 Photonic Molecule



- Non-degeneracy of entangled photon pair means that a micropillar with two modes is needed
- Create two pillars whose modes overlap
- Splitting of modes into two: photonic “molecule”

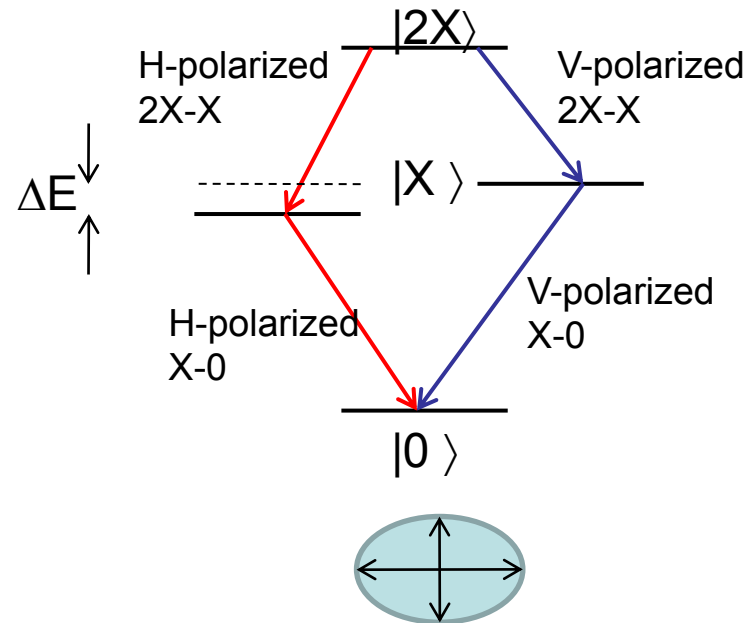
# 🔥 Degeneracy lifting in real QDs

## Cylindrically symmetric QD (rare!)



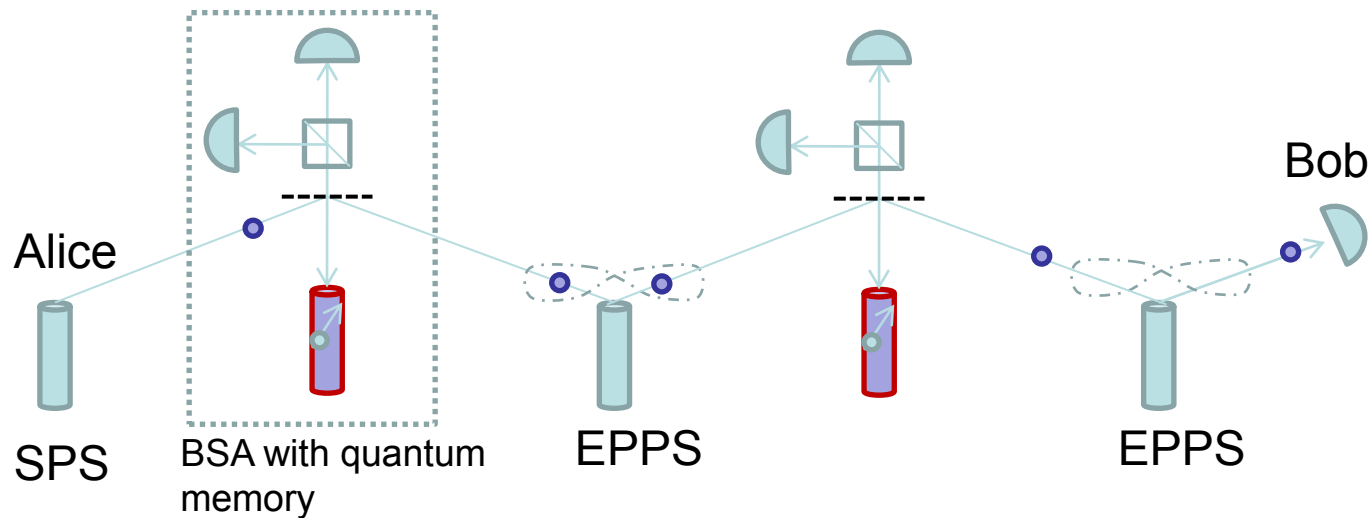
H,V paths for photon indistinguishable

## Asymmetric QD (usual situation!)



H,V paths for photon distinguishable in energy

# 🔥 Bringing it all together



- Components to be developed separately, then brought together to show some simple demonstrators.
- Theory from Imperial will aid this by developing protocols to allow development of error correction protocols to deal with photon loss.
- My input will also help with spin preparation and reduction of decoherence mechanisms.

# Conclusions

- SSQN is a European project focussed on replacing key components of a quantum communication network with loss-resistant solid-state ones:
  - QD-based triggered entangled pair sources
  - QD-based Bell-state analyser with in-built heralded quantum memory.
- Successful implementation would result in:
  - Remove need for synchronised photon arrival and indistinguishability at the Bell-state analyser in the quantum repeater
  - Intrinsic quantum memory and herald increase efficiency
  - >1000km entanglement distances
  - >10<sup>5</sup> increase in data transmission rates



# The SSQN Team



# University of Würzburg

- Technische Physik (TEP), Julius Maximilians Universität Würzburg



Sven Höfling:  
MBE growth and  
fabrication of  
optoelectronic  
devices



Martin Kamp  
Head of TEP,  
spectroscopy of  
semiconductors



Alfred Forchel  
Former head of  
group (now  
President of  
University)

Role: Fabrication of **microcavities** for deterministic charging of QDs with single electron spins in the strong coupling regime for microcavities, optimisation of cavity leakage rate for **spin-photon interface**.



- Optic of Semiconductor nanoStructures Group (GOSS), CNRS Laboratoire de Photonique et de Nanostructures, Paris



Pascale Senellart:  
Entangled  
photon  
sources



Loïc Lanco  
spin-photon  
interface ,  
entangled  
pair sources



Olivier Krebs  
spin physics



Aristide Lemaître  
semiconductor  
growth,  
fabrication



Isabelle Sagnes  
semiconductor  
fabrication



Paul Voisin  
Head of  
group, spin  
physics

Role: Sample design, fabrication and preliminary characterisation, **entangled photon sources**, doped QDs for **spin-photon interface**, monitoring **dynamics of single spins**, **remote spin entanglement**

- Controlled Quantum Dynamics Group



Sean Barrett  
Q. error  
correction,  
repeaters and  
purification



Dara McCutcheon  
spin physics,  
dephasing,  
entanglement  
generation



Ahsan Nazir  
QD phonon  
dephasing, spin  
dynamics, noise in  
open systems



Terry Rudolf:  
Photon Machine  
gun, optical q.  
information  
architectures

Role: Quantum information theory support on topics including: **Photon machine guns**, Optical **cluster states**, **Repeaters** and **purification**, Photonic Loss Tolerance  
Quantum error correction for non-markovian noise

- Centre for Quantum Photonics



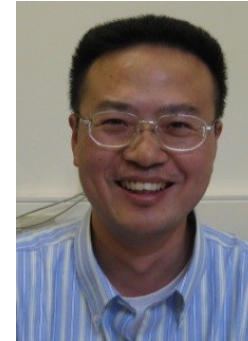
Ruth Oulton:  
Spin-light  
interactions in  
photonics, spin  
dynamics



Andrew Young  
non-linear phase  
shifts in QD-cavity  
systems, protocols



Isobel Piper  
Coherent  
control of QD  
transitions



Chengyong Hu  
experiment-theory  
interface,  
protocols



John Rarity:  
Head of group,  
q.information, q.  
communication

Role: **Project coordination**, experimental implementation, studies of the dynamics of charged and uncharged QD micropillar systems, monitoring dynamics of single spins, **spin photon interface**, FDTD, **integration experiments**.

🌟 Thank you for your attention!

