

The Solid-State Quantum Network (SSQN)

An EU/ANR/EPSRC “CHIST-ERA” grant

**Imperial College
London**

Imperial

Terry Rudolf
Ahsan Nazir
Dara
McCutcheon
Sean Barrett
(theory)

Bristol

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J.Rarity,
C.Hu
(spin-photon
interface)



THE BRISTOL CENTRE FOR
NANOSCIENCE AND
QUANTUM INFORMATION



Würzburg



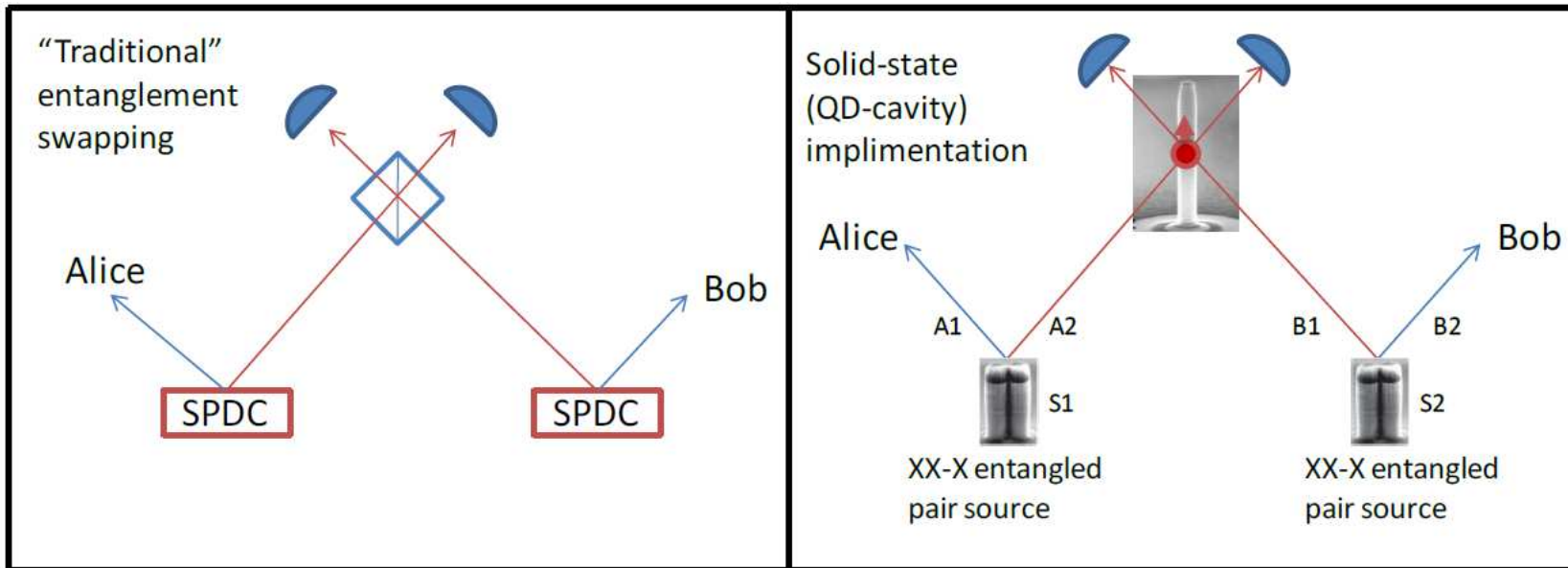
Christian Schneider
Sven Höfling
Martin Kamp
(fabrication of pillars)

LPN (Paris)

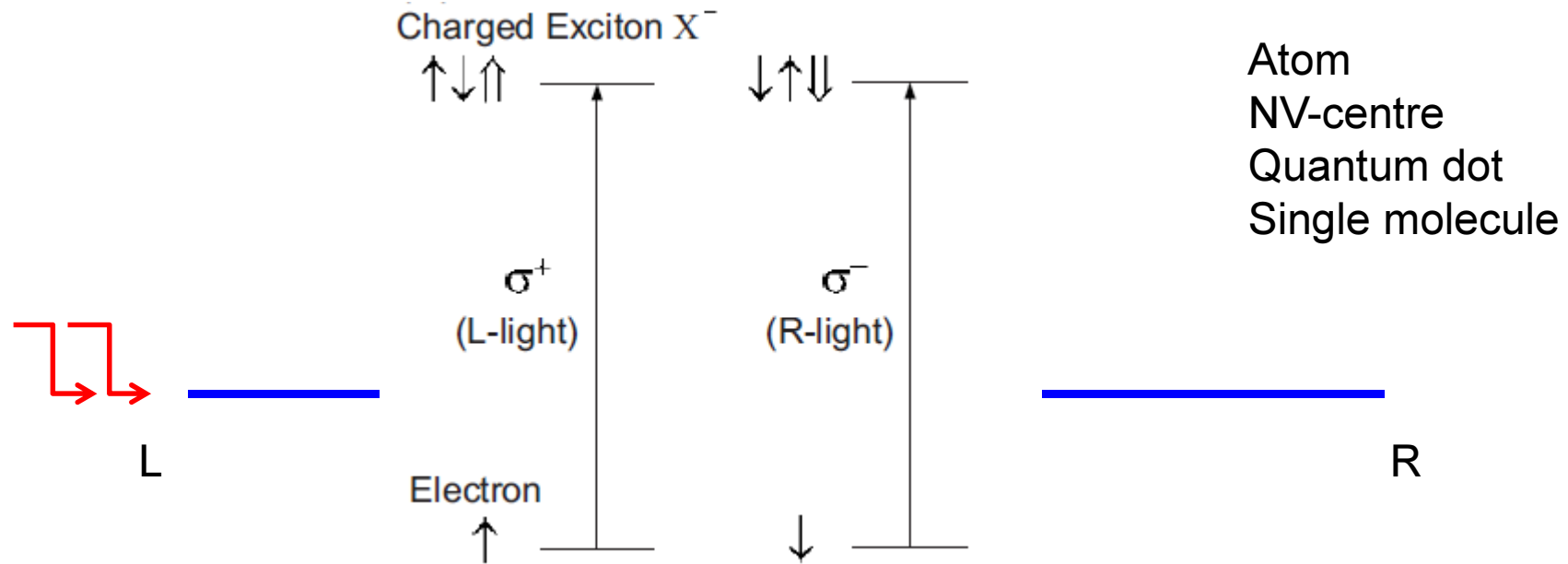


Pascale Senellart
Olivier Krebs
Loïc Lanco
and co
(entangled photon sources)

Outline



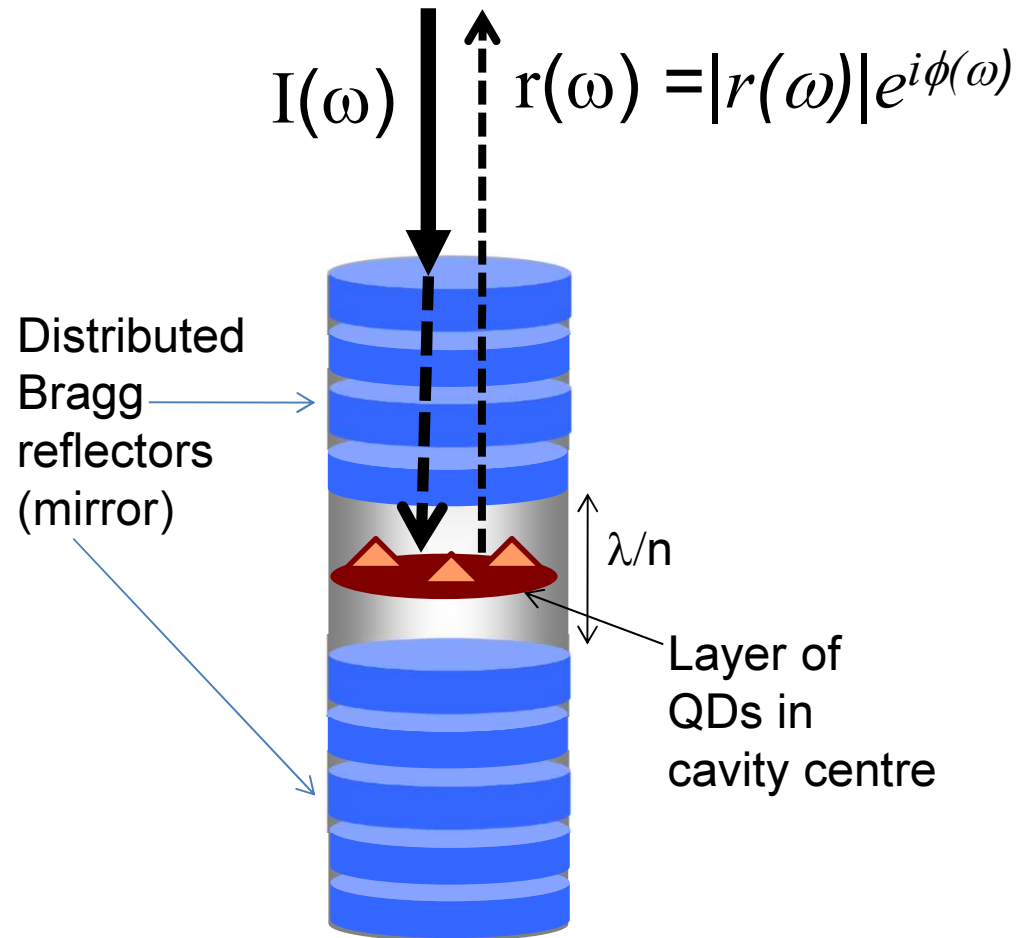
The one dimensional atom



$$\frac{1}{2} \hat{U} |L\rangle \hat{U} |L\rangle (|\uparrow\rangle + |\downarrow\rangle) \rightarrow \frac{1}{\sqrt{2}} (|L\rangle |L\rangle |\uparrow\rangle + |R\rangle |R\rangle |\downarrow\rangle)$$

Realisation in pillar microcavities

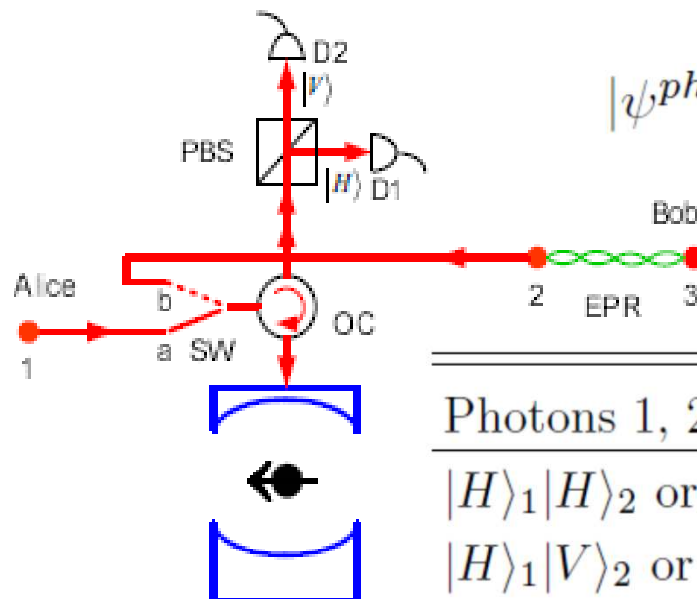
- Based on the quantum dot spin-photon interface, Hu et al PRB83, 115303 (2011)
- Contains an electron spin as an intrinsic memory
- Micropillar increases the light-matter interaction strength and photon extraction efficiency.



Quantum Repeater

arXiv1005.5545

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

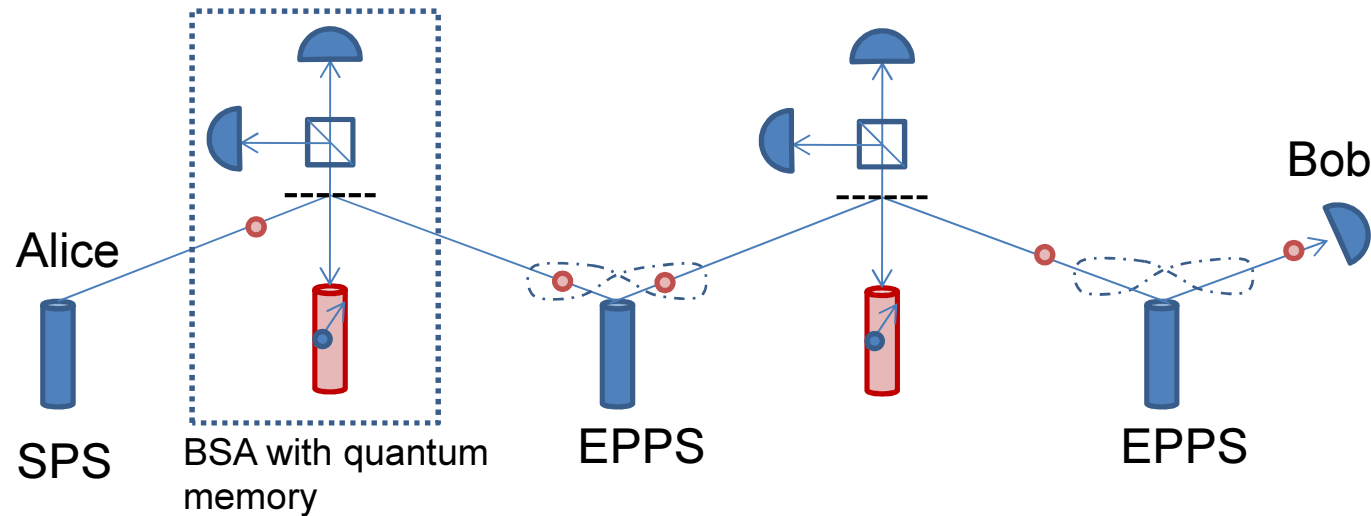


$$|\psi^{ph}\rangle_{23} = (|R\rangle_2|L\rangle_3 + |L\rangle_2|R\rangle_3)/\sqrt{2}$$

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

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$	$\alpha R\rangle_3 - \beta L\rangle_3$

Bringing it all together



- Develop high efficiency indistinguishable single photon sources and entangled pair photon sources.
- Theory from Imperial will aid this by developing protocols to allow development of error correction protocols to deal with photon loss.
- Challenge is in spin preparation and reduction of decoherence mechanisms.

Structure

- **WP1: Fabrication and Sources (UWUERZ, LPN, BRIS, IMP)**
- **WP2: Spin-Photon Interface (BRIS, UWUERZ, LPN, IMP)**
- **WP3: Theory (IMP, BRIS)**
- **WP4: Integration (BRIS, UWUERZ, LPN, IMP)**

‘Deliverables’

D1.3 M6: Charged QD- cavity device with high-Q (BRIS/UWUERZ)

D1.4 M6: Highly-polarization-degenerate high-Q pillars ($\Delta E < 2\mu\text{eV}$) (UWUERZ)

D1.1 M12: Violating Bell inequalities with ultrabright source of entangled pairs (LPN).

D1.5 M18: Spin-photon interface (charged QD strongly coupled to high extraction efficiency, polarization degenerate cavity) (BRIS/UWUERZ/LPN)

D1.2 M24: Entanglement purification of two entangled pairs from photonic molecule (?LPN/BRIS)

D2.1 M12 Demonstrate $\pi/2$ phase shift dependent on spin state (BRIS)

D2.2 M18 Demonstrate arbitrary spin initialisation (BRIS/LPN)

D2.3 M24 Entangled photon-spin interface (BRIS/UWUERZ))

D2.4 M30 Remote spin entanglement (BRIS).

D3.1 M8 Analysis of requirements of photon machine gun (IMP/all).

D3.2 M18 Analysis of multi-dimensional cluster state generation (IMP).

D3.5 M18 Protocols for entanglement purification via surface codes (IMP).

D3.7 M18 Error correcting schemes tailored for non-Markovian noise (IMP).

D3.4 M24 Analysis of fidelities of spin-photon interface repeaters (BRIS/IMP).

D3.3 M36 Schemes for distribution of entanglement via cluster states (IMP/BRIS).

D3.6 M36 Thresholds and overheads for error correction for loss and depolarizing noise using surface codes (IMP).

D4.1 M12 Report on design, feasibility studies and preparation of first integration experiments. (BRIS/LPN)

D4.2 M24 Report on demonstration of photon spin entanglement and relevance to networks (BRIS/LPN)

D4.3 M36 Report on demonstration of key concepts of quantum networks (All).

D4.4 M36 Report on continuous variable schemes for quantum networks (BRIS/IMP)

Potential request for no cost extension to March 31st 2014



Highly successful in publications:

- 16 published papers 3 PRL
- 25 invited conference presentations
- 20 student/postdoc conferences
- Workshop planned at end of SSQN

WP1 Fabrication and Sources Würzburg

Cavity growth: Würzburg

delta Si-doped low density QDs in 25-15 Cavity

SEM image of full structure

top DBR:

15 AlAs/GaAs MPs

InAs QDs

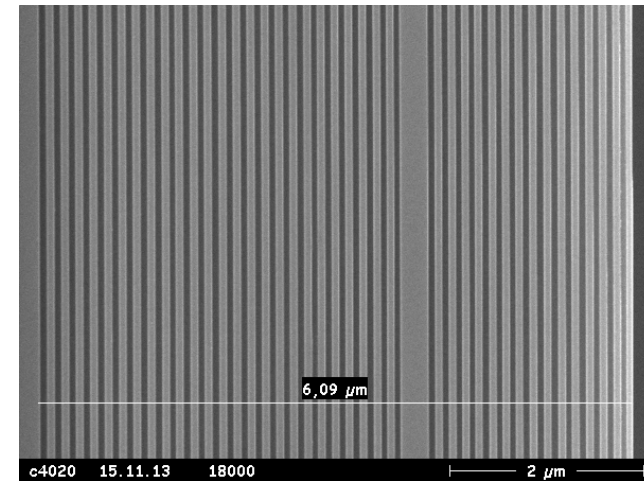
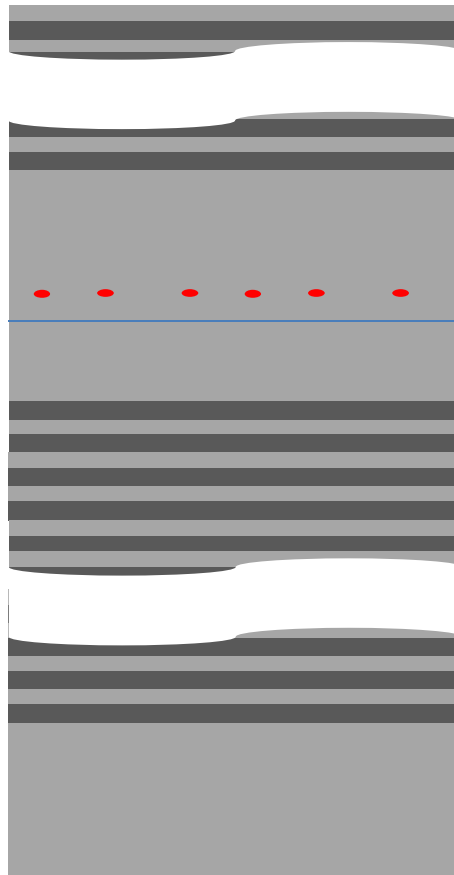
10nm

GaAs

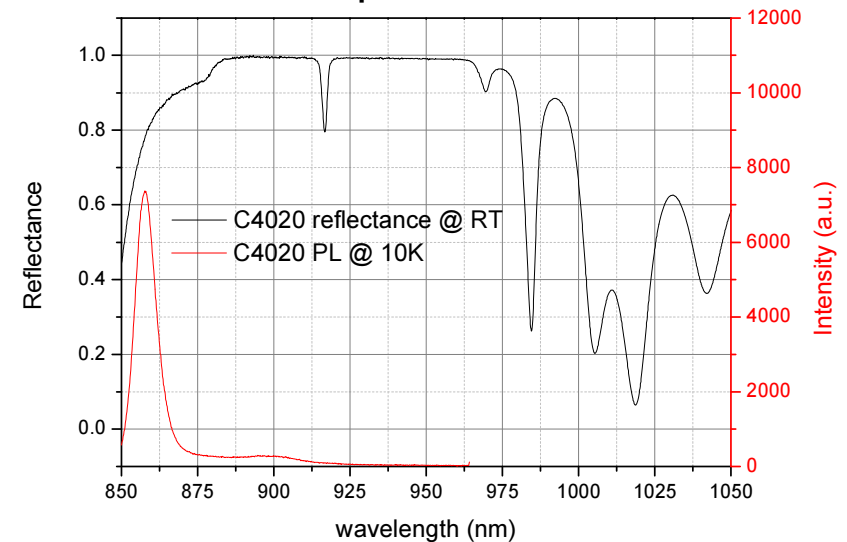
doping

bottom DBR:

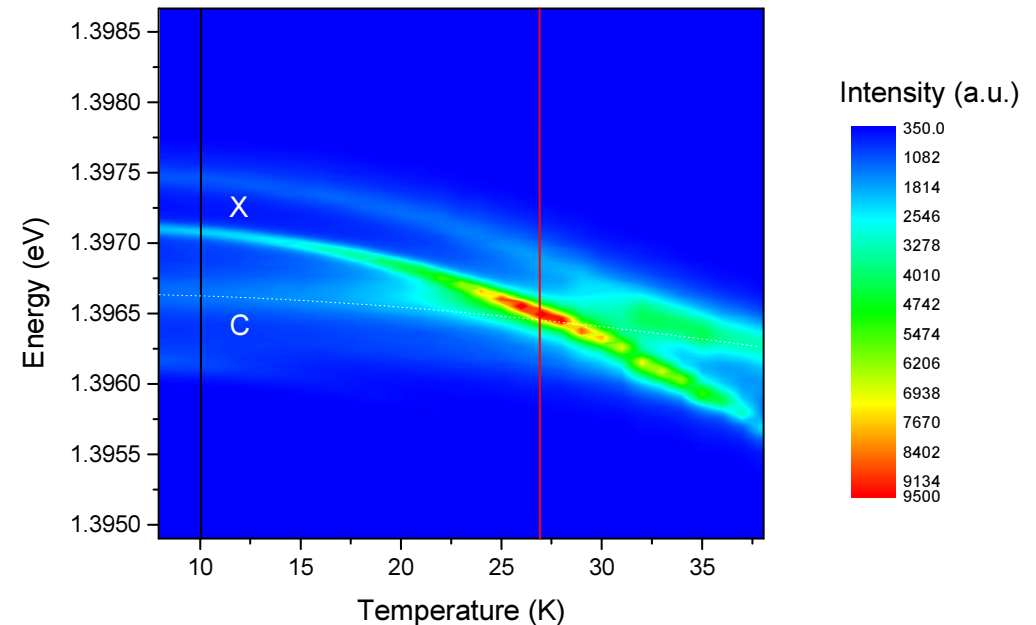
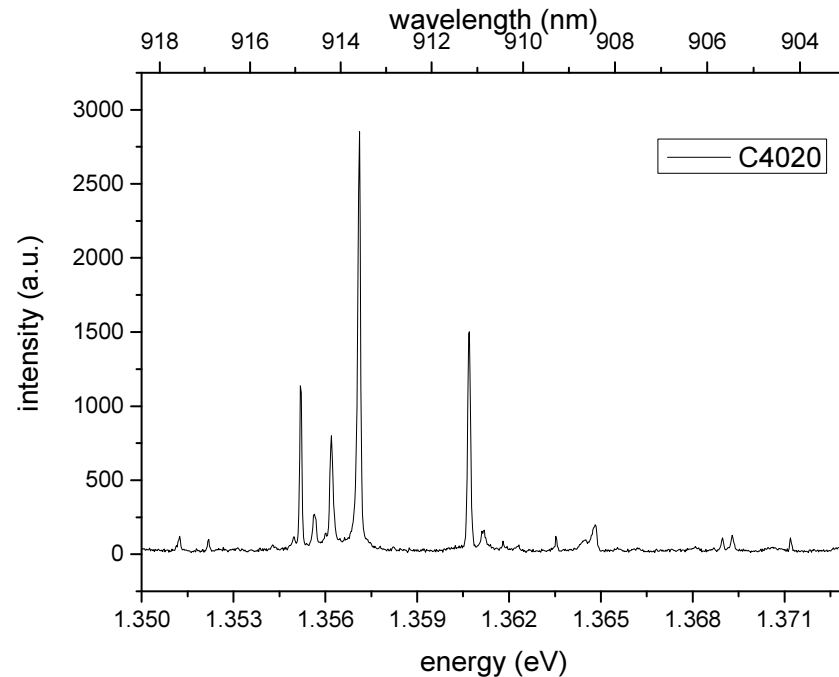
25 AlAs/GaAs MPs



Reflection spectrum and PL of QDs



Spectroscopic investigations



μ PL investigations without top DBR:
Low QD-density (for single QD study)
Narrow and bright QD lines:
reflects high QD quality despite
delta doping

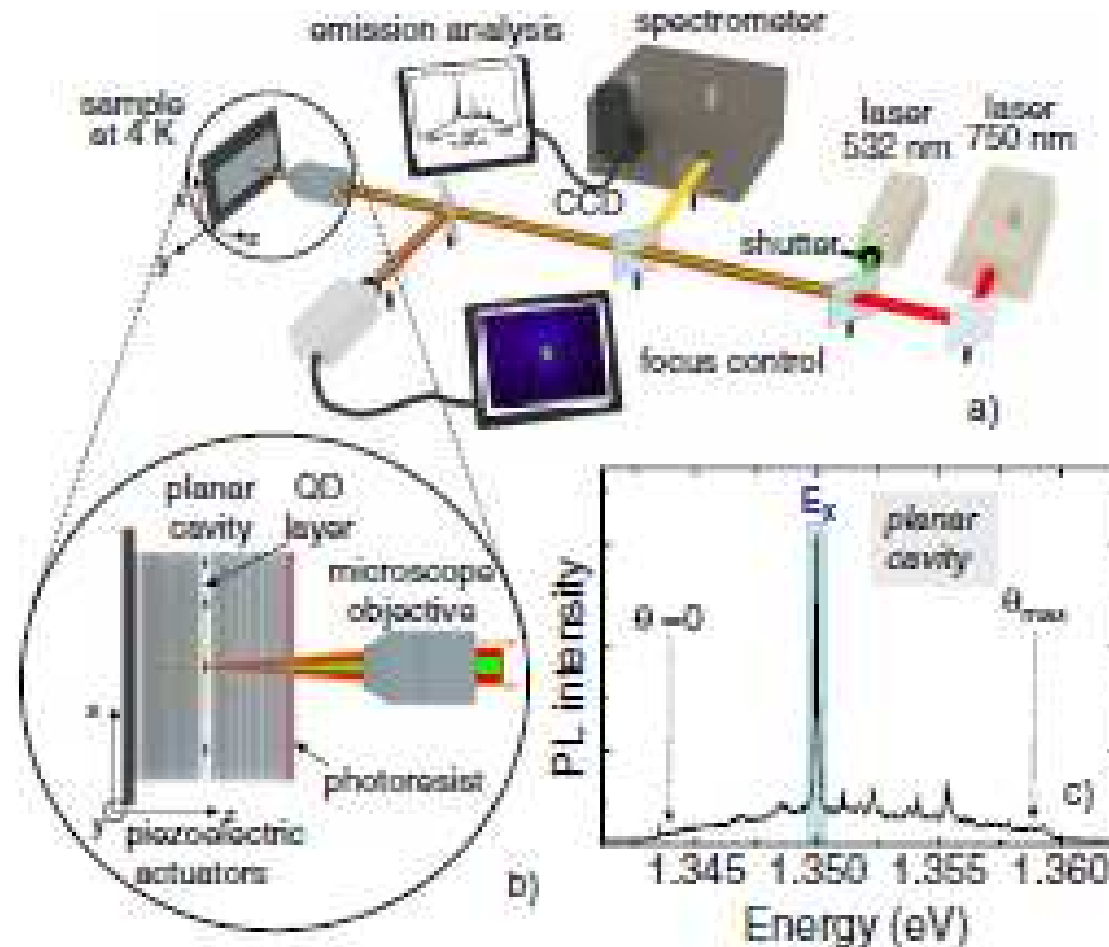
Cavity-QD-coupling:
Strong enhancement of QD signal on
Resonance with cavity mode ($Q \sim 2000$)

Würzburg/LPN: deterministic coupling

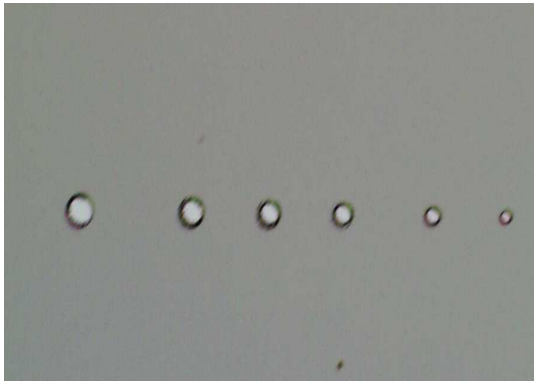
Establishing an in-situ lithography system:

Modification: We couple green (PL) and blue (litho) laser

Through the same fiber to avoid misalignment and preserve a good beam shape



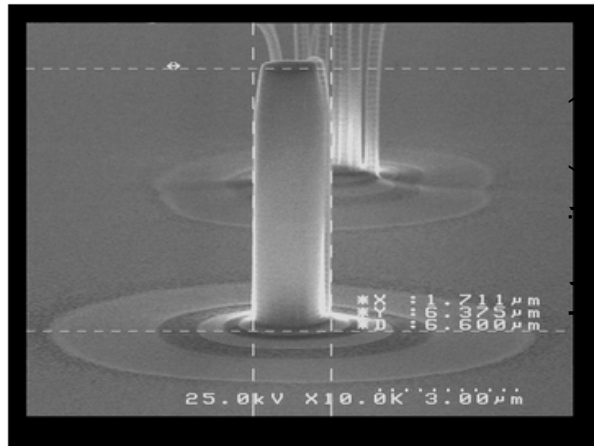
Towards deterministic coupling



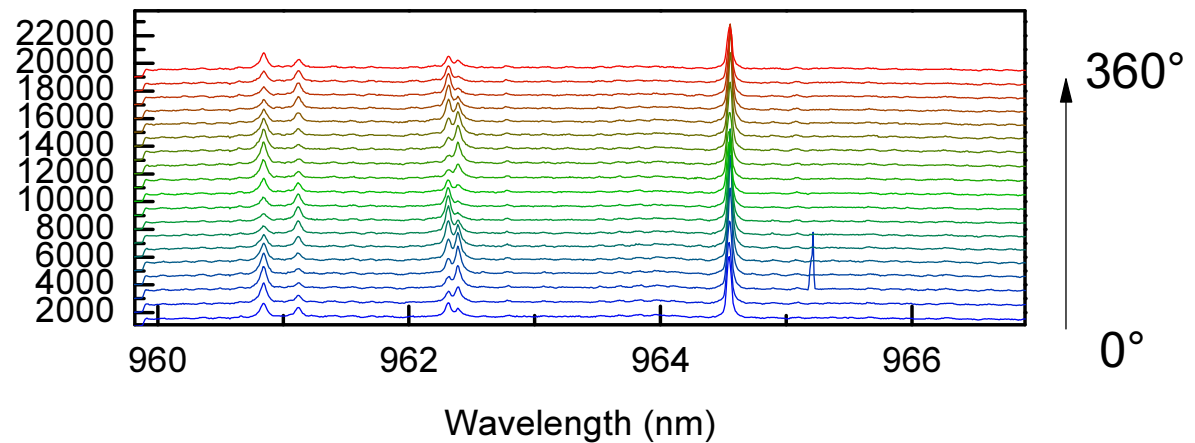
Power: 500 nW (blue laser)
1 sec. Exposure
Holes in optical resist



1 μm sized hole in resist!

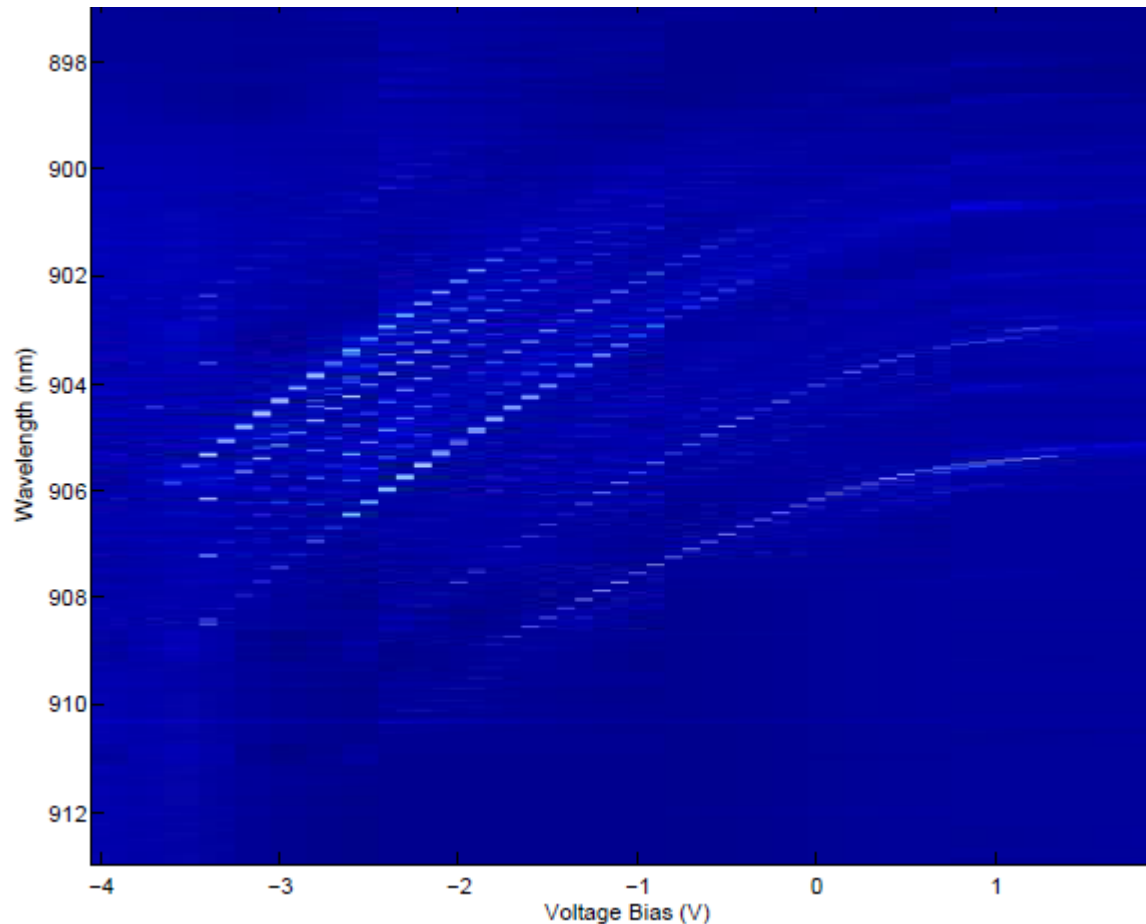


SEM image of pillar fabricated
via in situ lithography

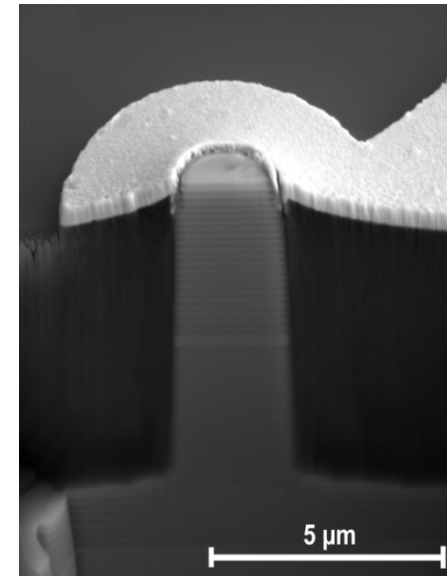


Polarization series on Cavity resonance ($Q \sim 30000$):
splitting $< 15 \mu\text{eV}$!

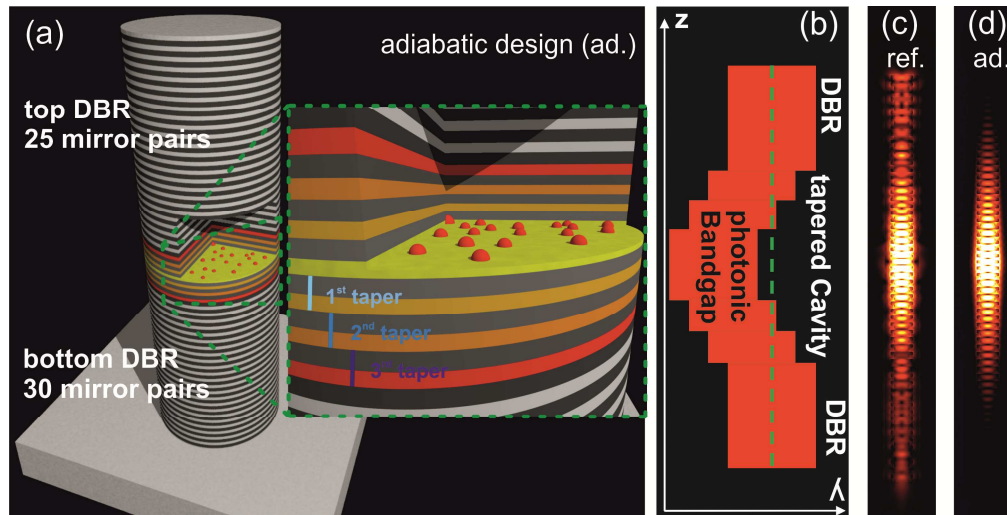
Bristol: Deterministic charging studies



Results from planar sample, contacting pillar microcavity imminent

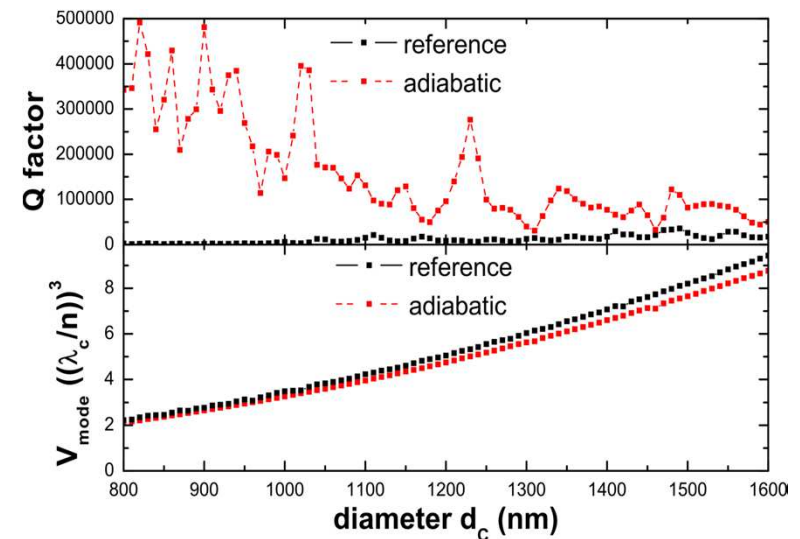


Indistinguishable photons from adiabatic micropillars



Lermer et al., PRL (2012)

Improved mode matching between
localized cavity mode and
evanescent DBR Bloch mode

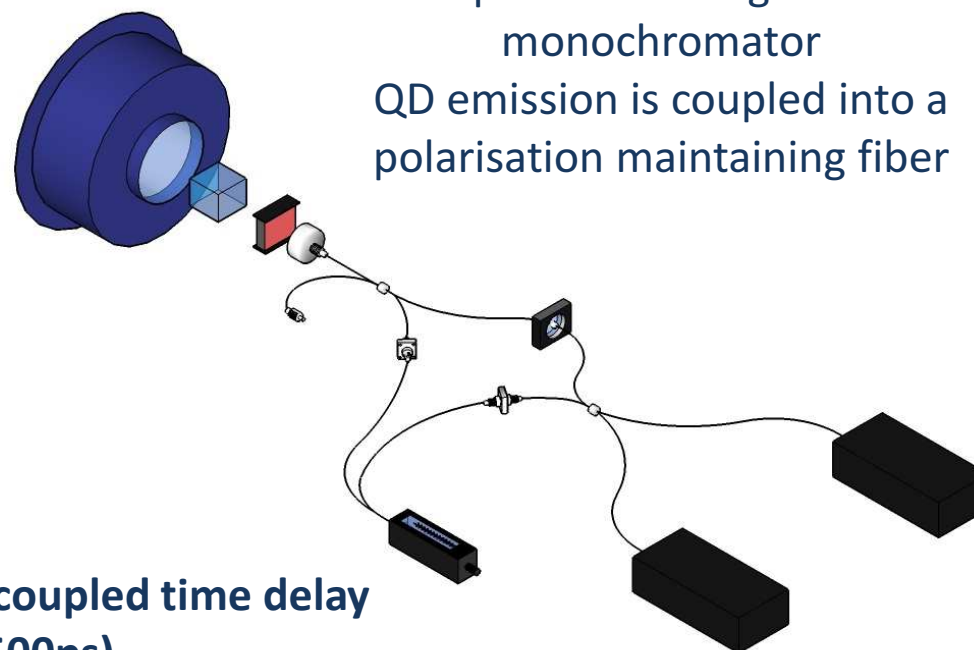


Pronounced cQED effects can be expected

Setup

QD inside a I-He flow cryostat
QD is quasi resonantly pumped via
a Ti:Sa-Laser ($f_{\text{Rep}} = 82 \text{ MHz}$)

Spectral filtering via a
monochromator
QD emission is coupled into a
polarisation maintaining fiber

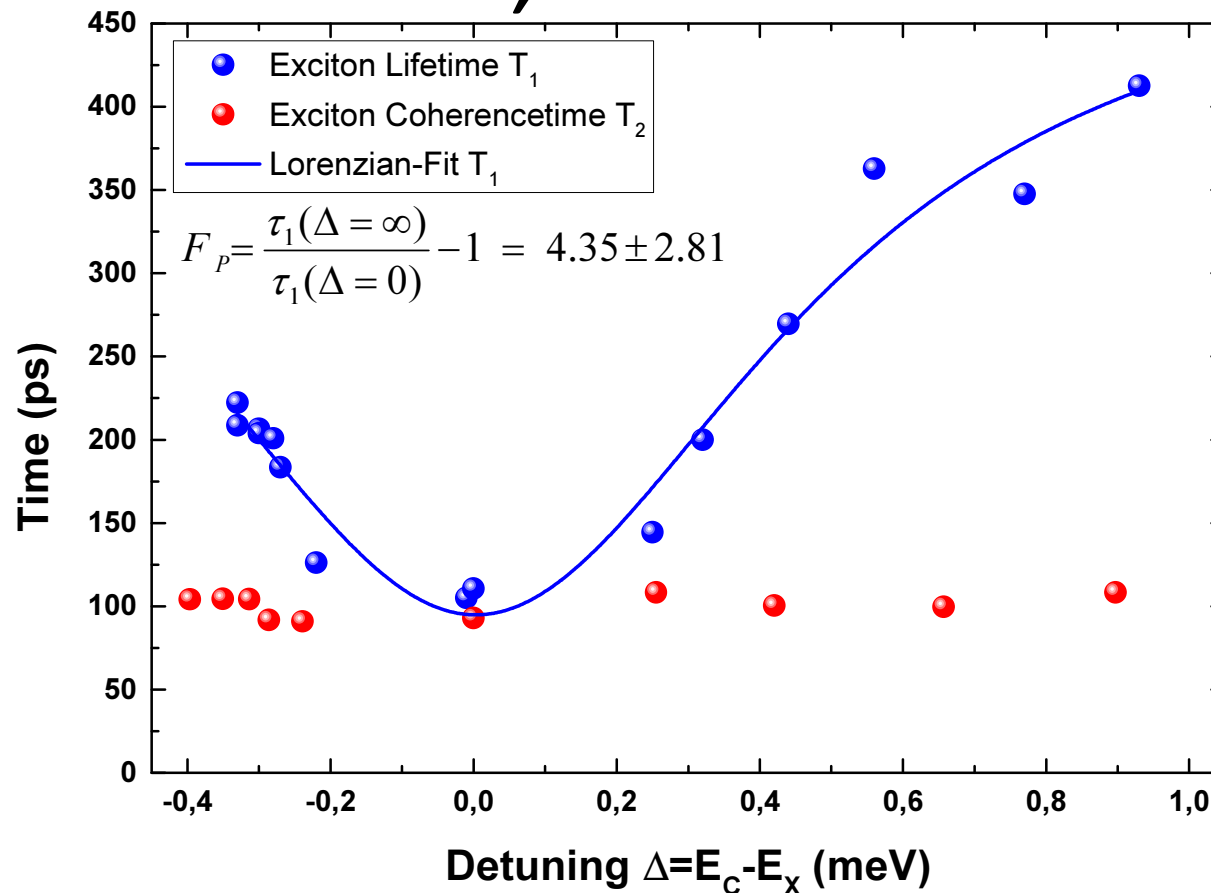


**Variable fiber coupled time delay
(500ps)**

Allows for temporal and spatial
overlap of the wave packets

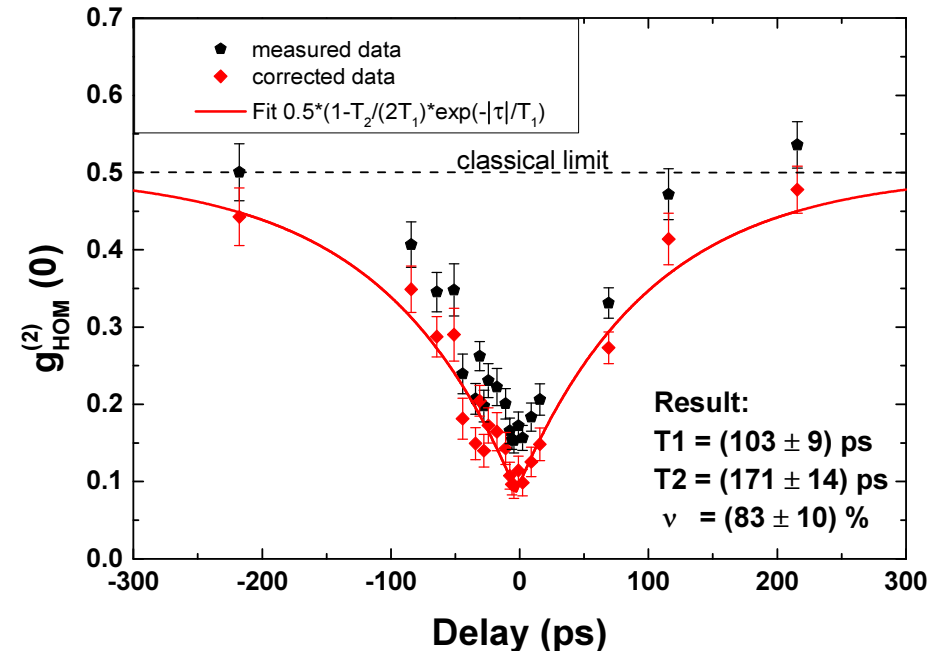
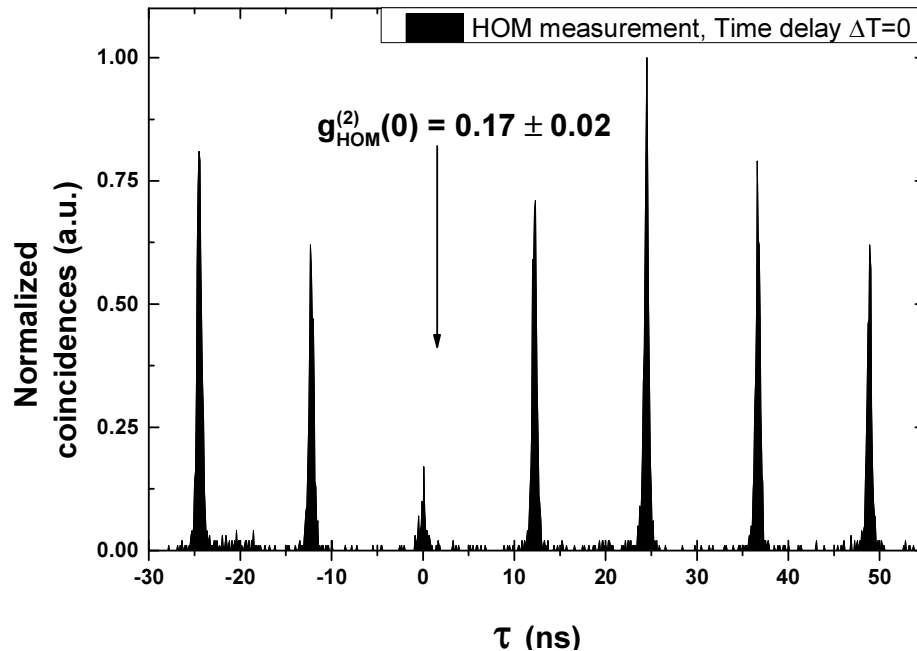
Si-APDs for detection of the
single photons ($\Delta t_{\text{Res}} = 400 \text{ ps}$)

T₁, T₂ vs. Detuning



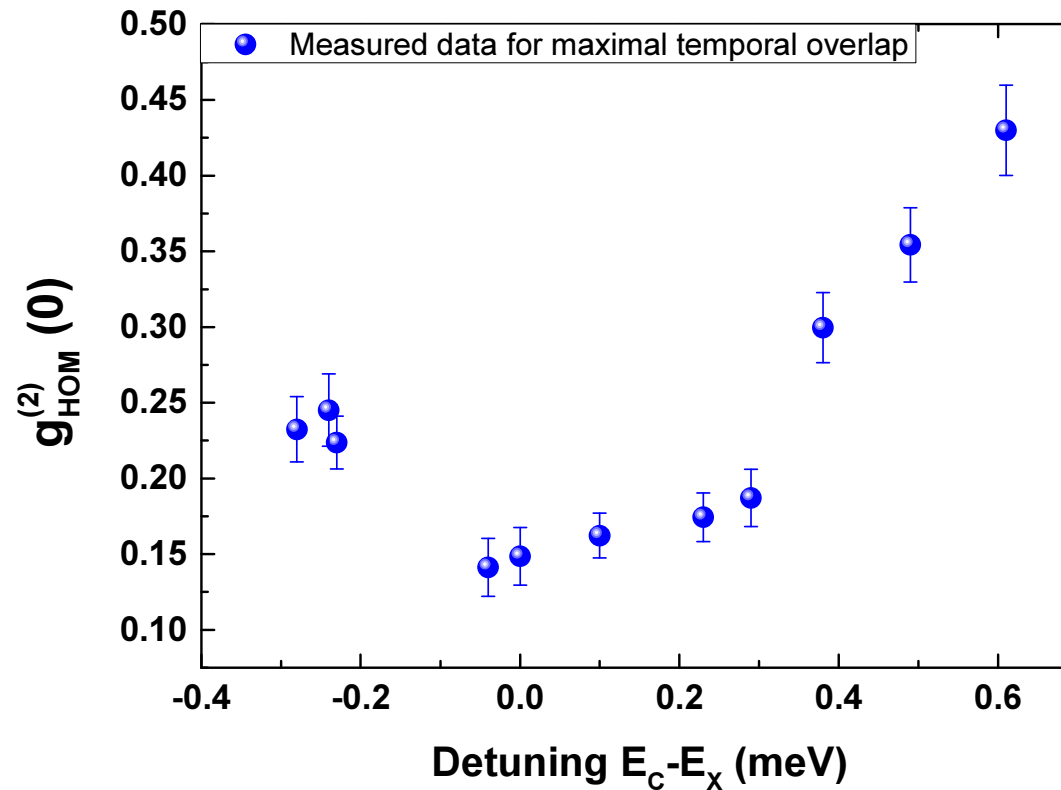
- T_1 was measured via timeresolving μ PL
- Extracted Purcell-factor: $F_p = (4.35 \pm 2.81)$
- T_2 -time was measured via a Michalson-Interferometer
- T_2 stays almost constant while T_1 changes with the exciton-cavity-detuning

Two-photon-interference



- for $\Delta\tau \rightarrow \infty$, $g^{(2)}$ goes slightly above 0.5 due to a non vanishing $g^{(2)}_{\text{HBT}}$
- fitted lifetime T_1 matches the measured lifetime
- fitted coherence time T_2 is higher than the measured one due to spectral diffusion
- fitted visibility $v = (83 \pm 10) \%$

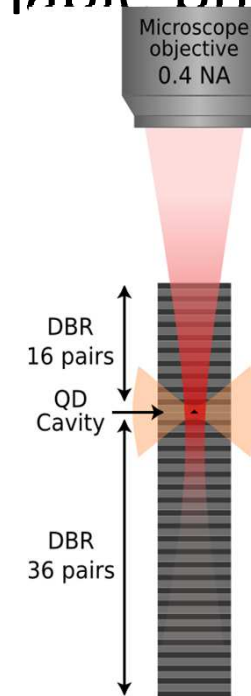
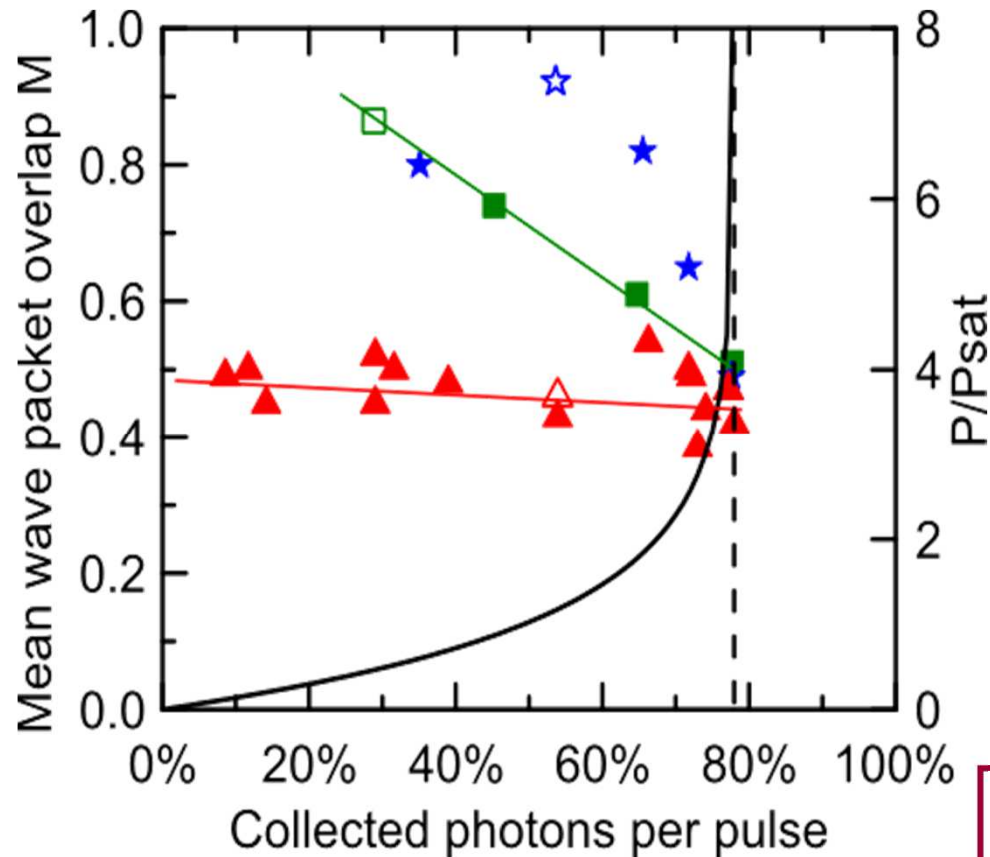
Two-photon-interference vs. detuning



- Datapoints were measured for a maximal temporal overlap
- Due to an increasing lifetime, $g_{\text{HOM}}^{(2)}$ increases also for higher detunings

WP1 Sources(LPN)

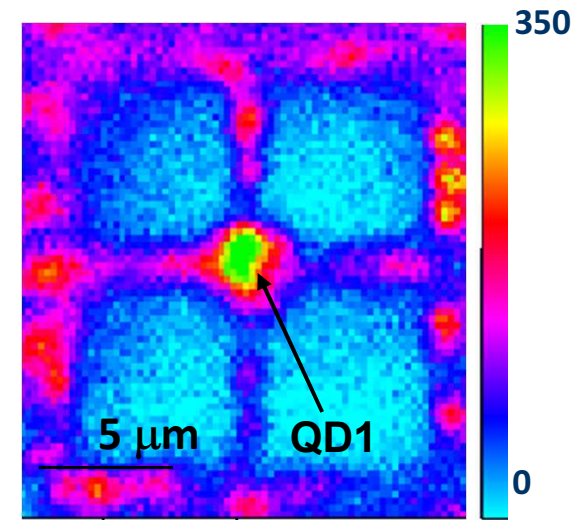
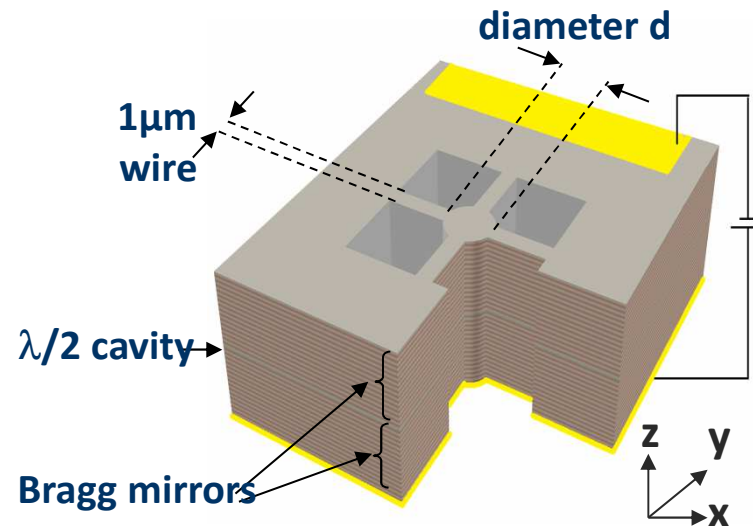
Ultrabright source of indistinguishable photons



**Ultrabright source of
indistinguishable single photons**
**82 % indistinguishability
at 65 % brightness**

Contacted - pillar micro-cavity for electric control

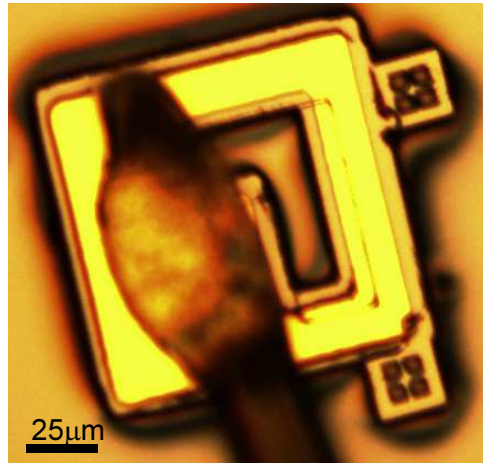
Novel cavity design for electrical
control
of the QD-pillar emission



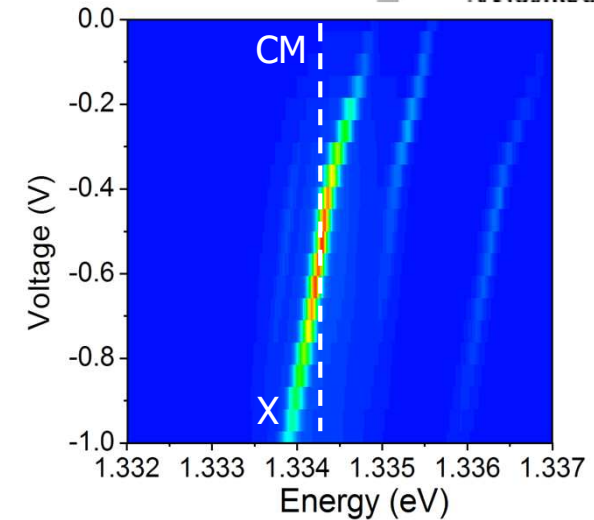
Deterministic coupling of a single
quantum dot to a connected pillar
cavity



Electrically tunable bright single photon source



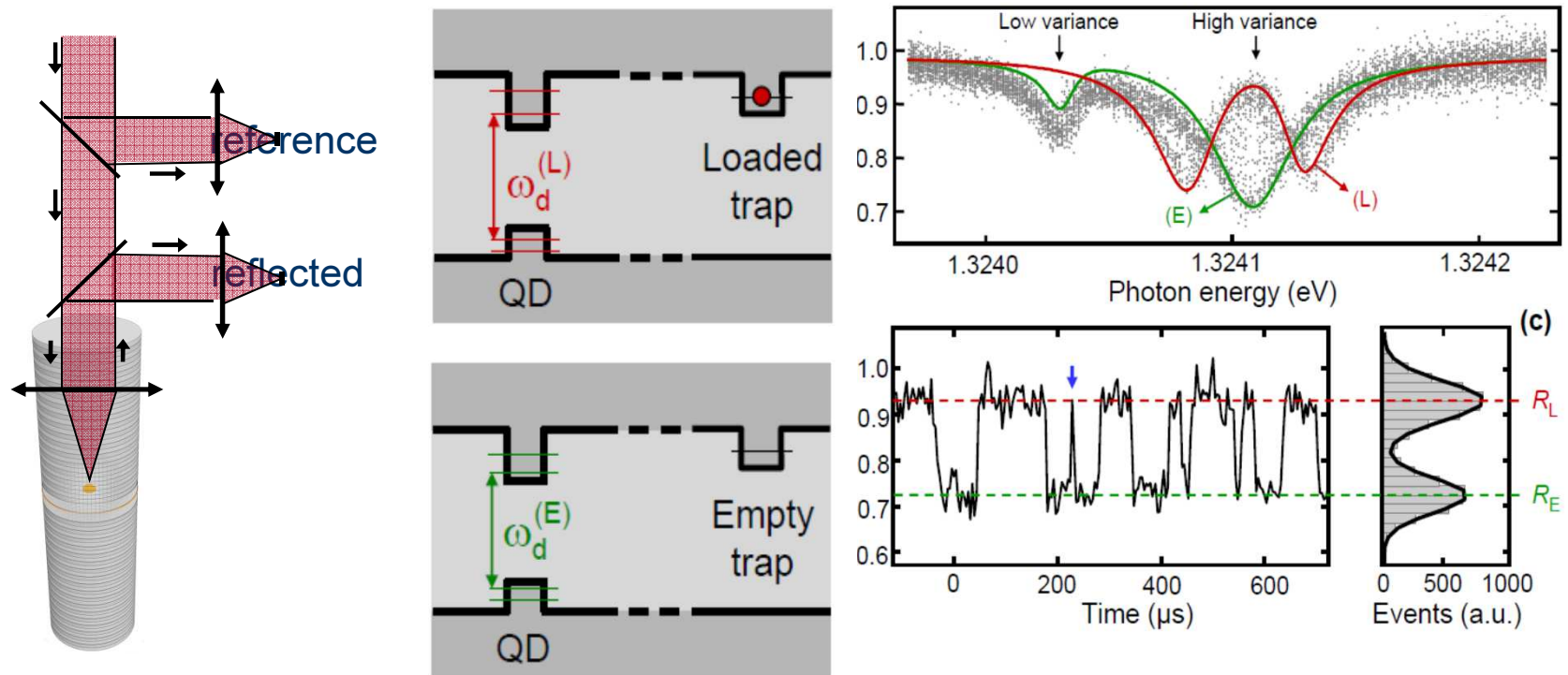
Stark effect:
red-shift up to 1.4 meV for
negative applied electric field.



A. K. Nowak, S. L. Portalupi, V. Giesz, O. Gazzano, C. Dal Savio, P.-F. Braun, K. Karrai, C. Arnold, L. Lanco, I. Sagnes, A. Lemaître & P. Senellart
Nature Communications 5, 3240 (2014)

WP2: Spin-Photon Interface

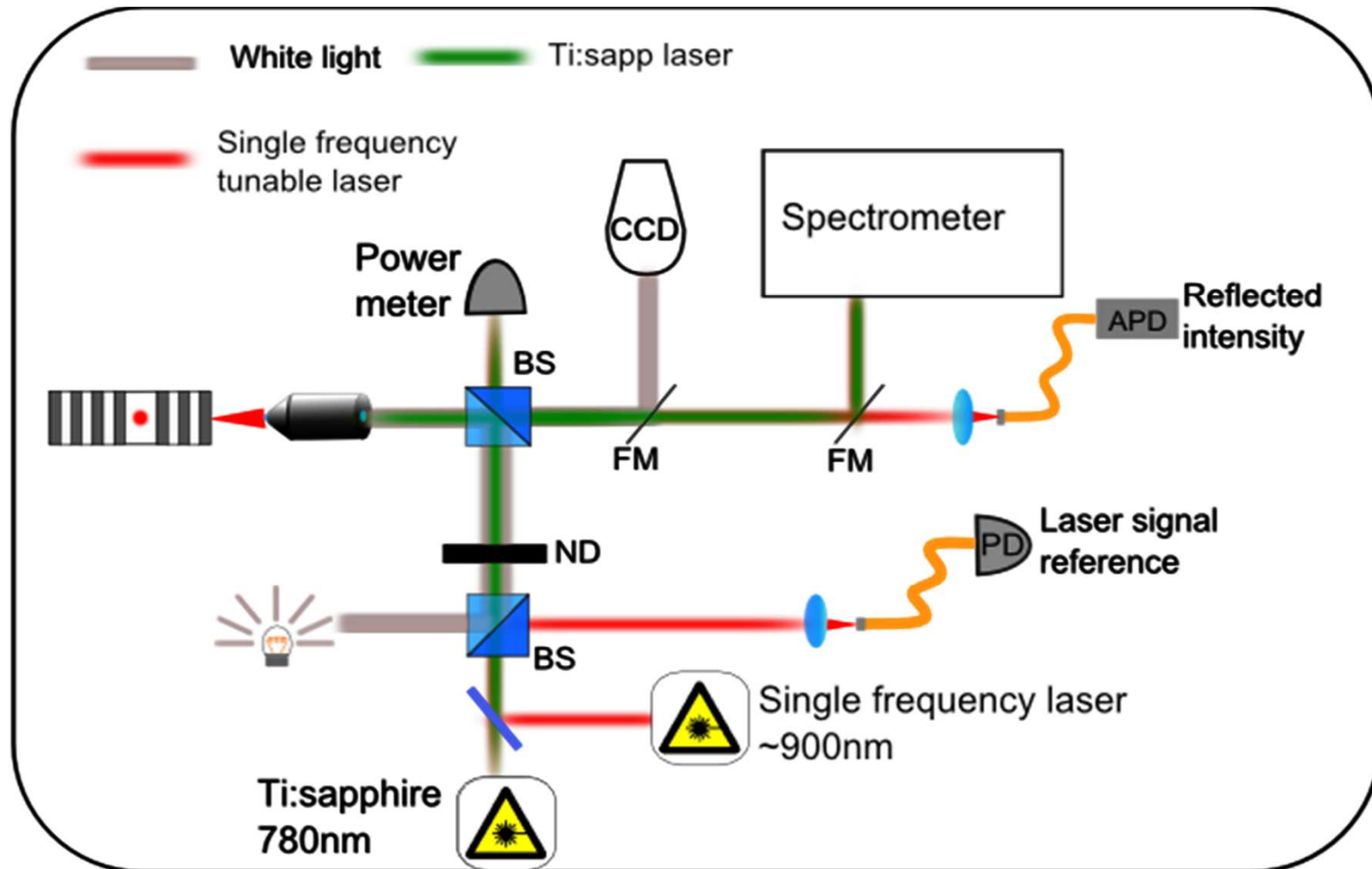
LPN: Cavity enhanced monitoring of single quantum events



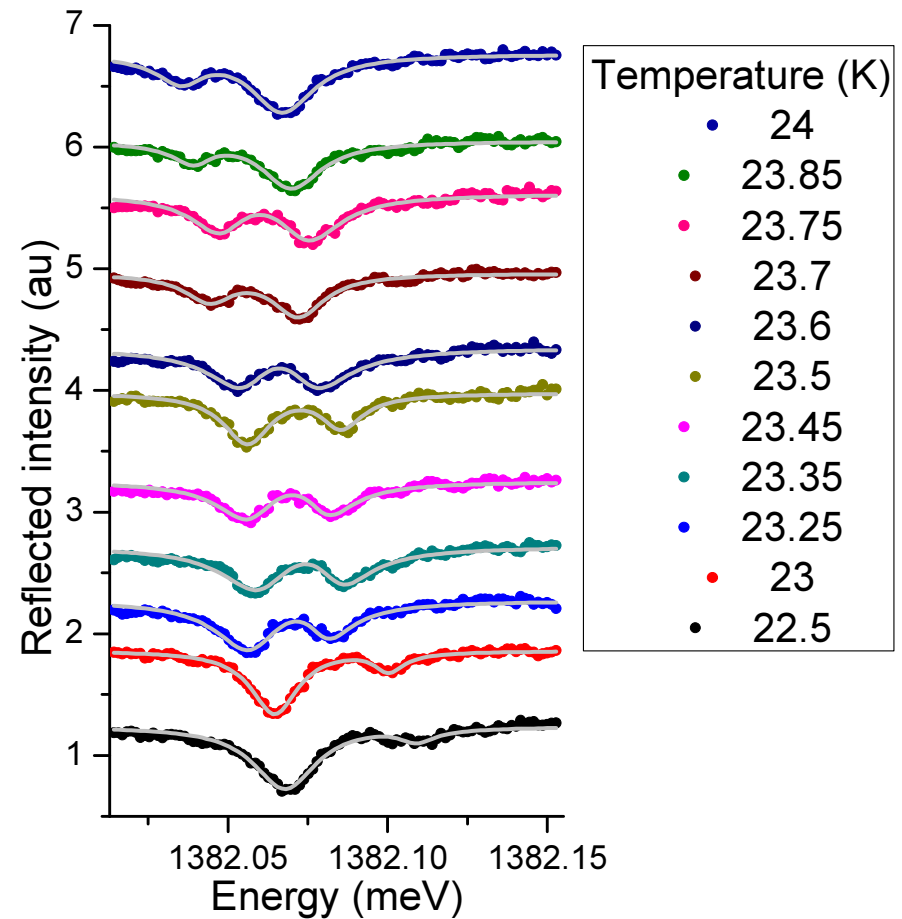
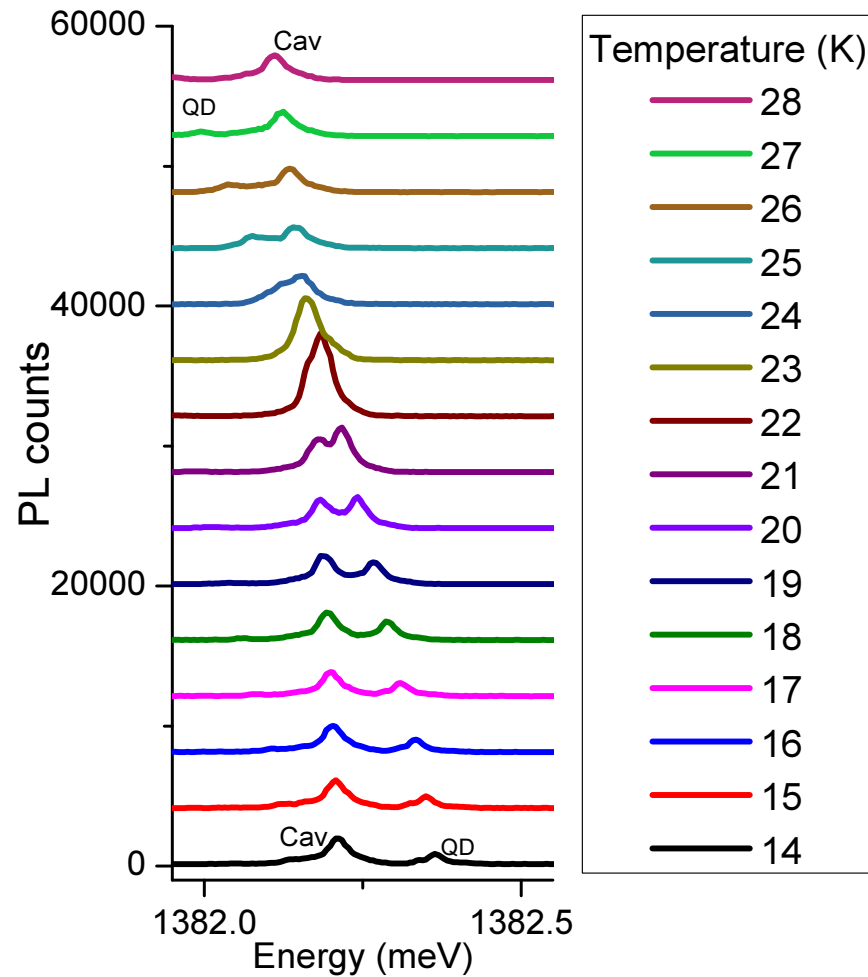
- Real time monitoring of single charge quantum jump
- μs time resolution

Christophe Arnold, Vivien Loo, Aristide Lemaître, Isabelle Sagnes, Olivier Krebs, Paul Voisin, Pascale Senellart, Loïc Lanco
Phys. Rev. X, in press (2014)

Bristol: Resonant reflection characterisation

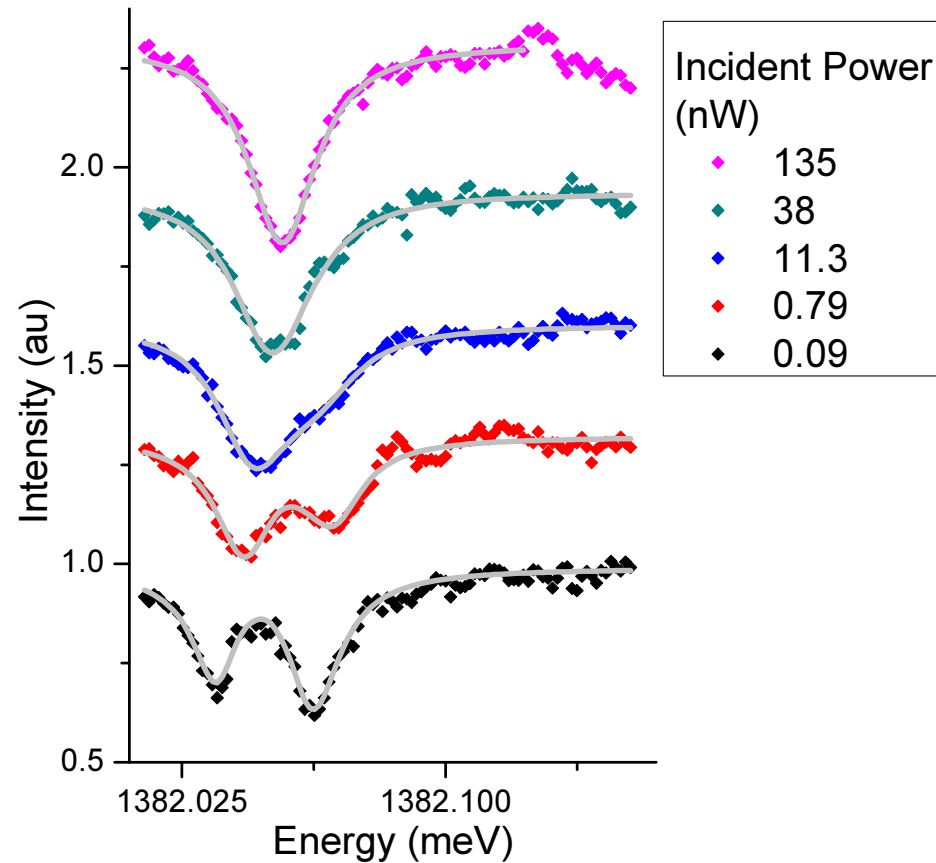


Strong coupling regime

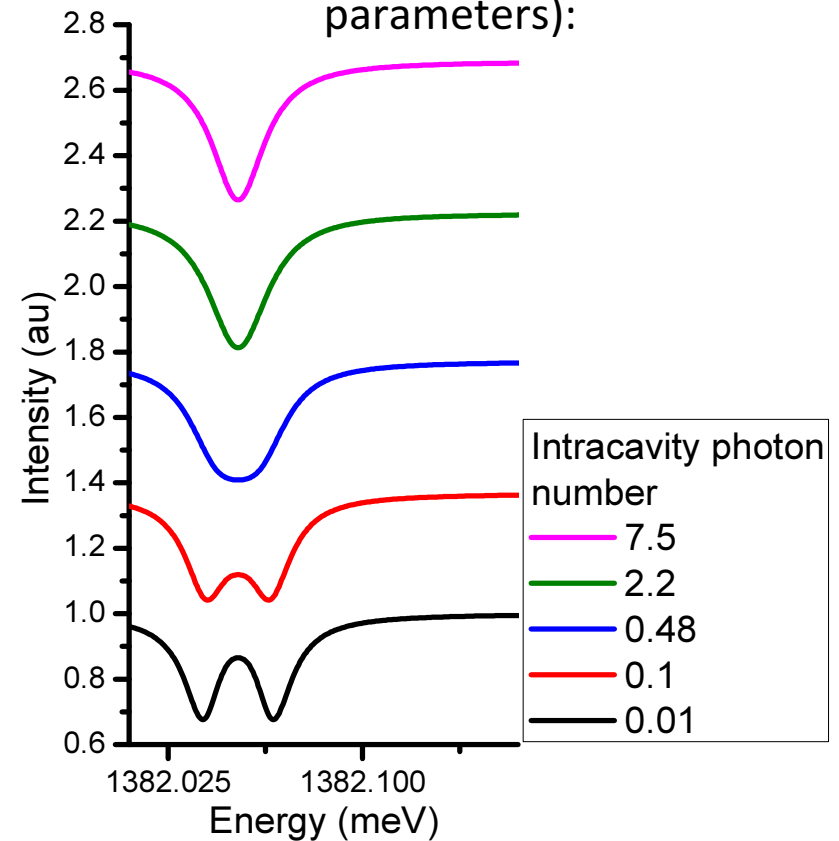


Saturation of QD absorption

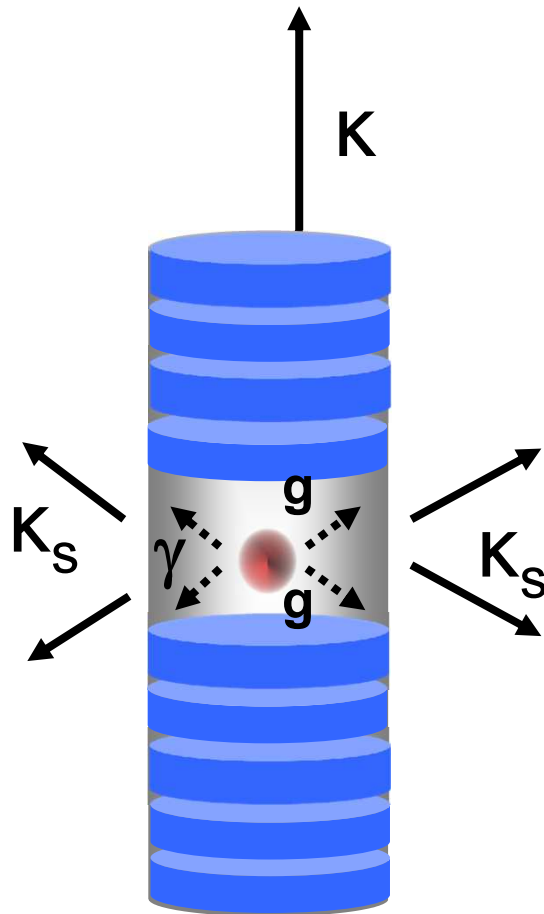
Experimental data:



Expected reflectivity with dot or resonance (based on experimentally obtained parameters):



Switching speed



$$\kappa = 2.85 \mu\text{eV}$$

$$\kappa_s = 20.5 \mu\text{eV}$$

Cavity lifetime = 30ps

Ultrafast switching ~10 GHz

$$g = 13.4 \mu\text{eV}$$

$$\gamma = 9.6 \mu\text{eV}$$

$$n_c = 0.034 = \text{Critical photon number}$$

Satisfies strong coupling condition:

$$g > (\kappa + \kappa_s + \gamma) / 4$$

$$13.4 > 8.2$$

Switching energy

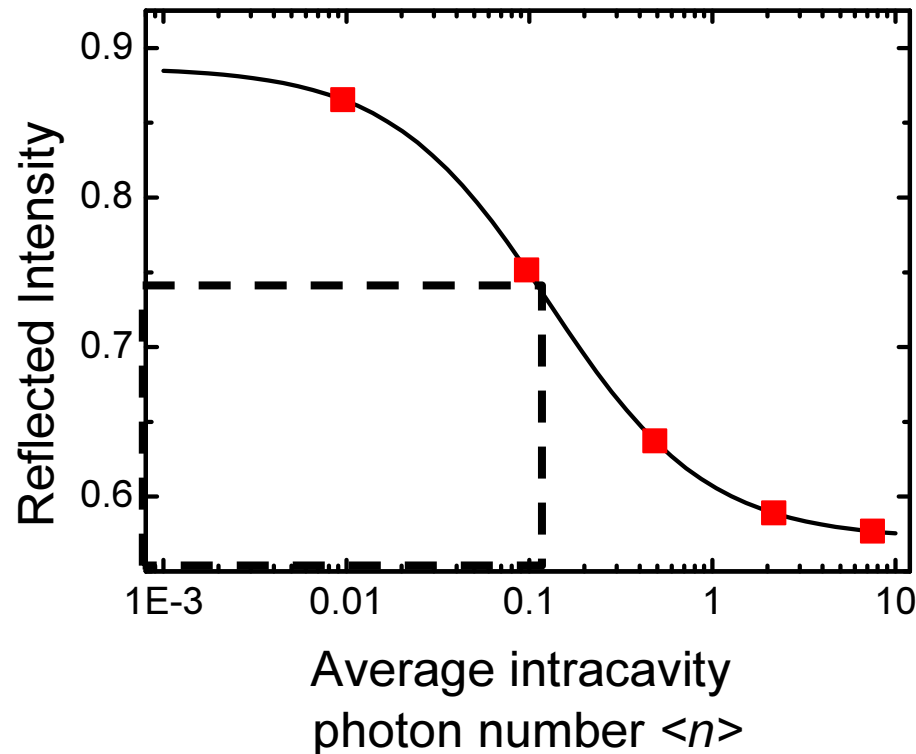
On resonance, equation simplifies to:

$$r(\omega) = 1 - \frac{\kappa \frac{\gamma}{2}}{\frac{\gamma}{2} \left(\frac{\kappa}{2} + \frac{\kappa_s}{2} \right) + g^2 \frac{n_c}{\langle n \rangle + n_c}}$$

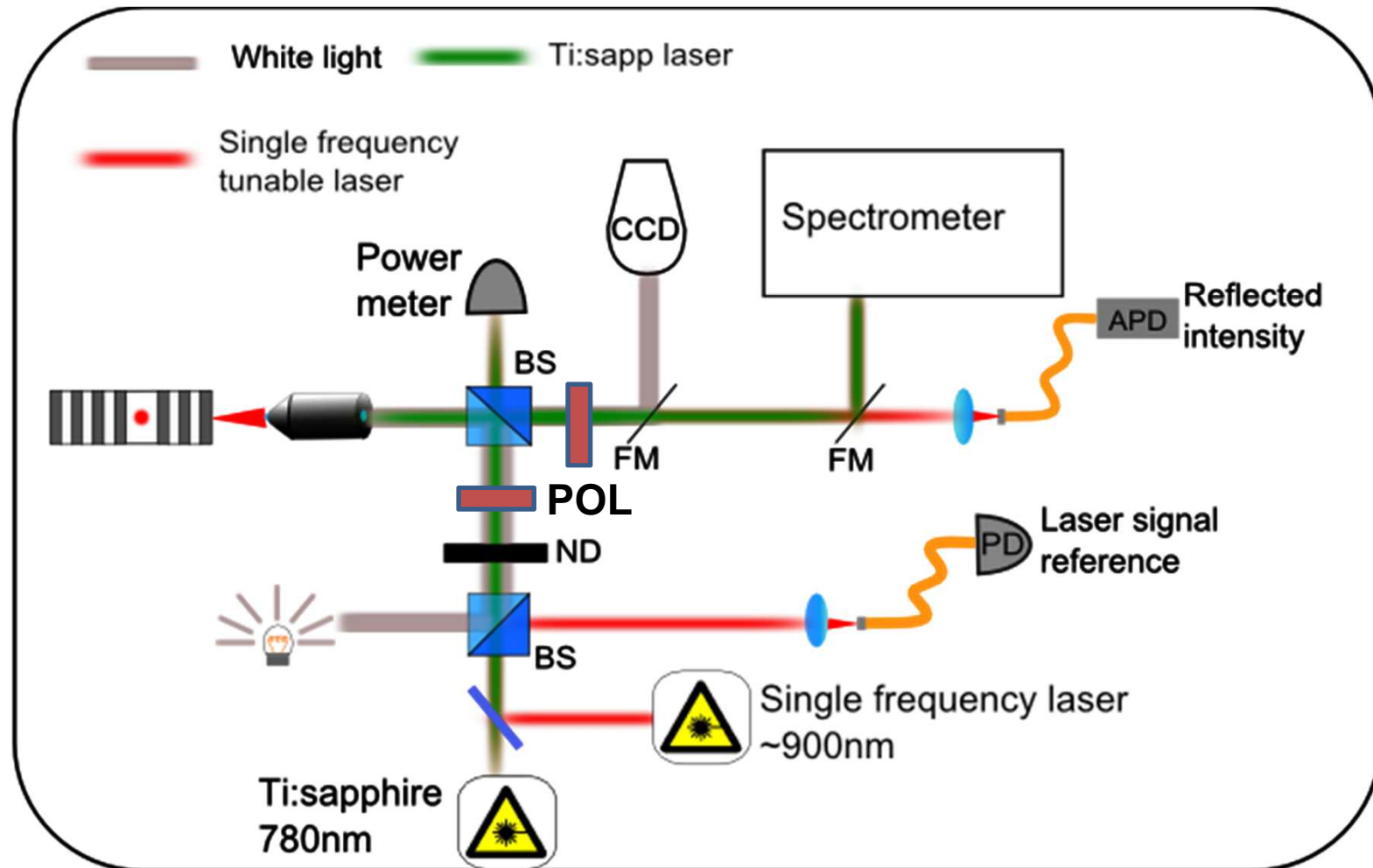
Nonlinear response of reflectivity to intracavity photon number.

Reflectivity drops to 50% of contrast at $\langle n \rangle = 0.13$ = number of intracavity photons required per cavity lifetime to control the switch.

Equivalent to a switching energy = 0.03aJ

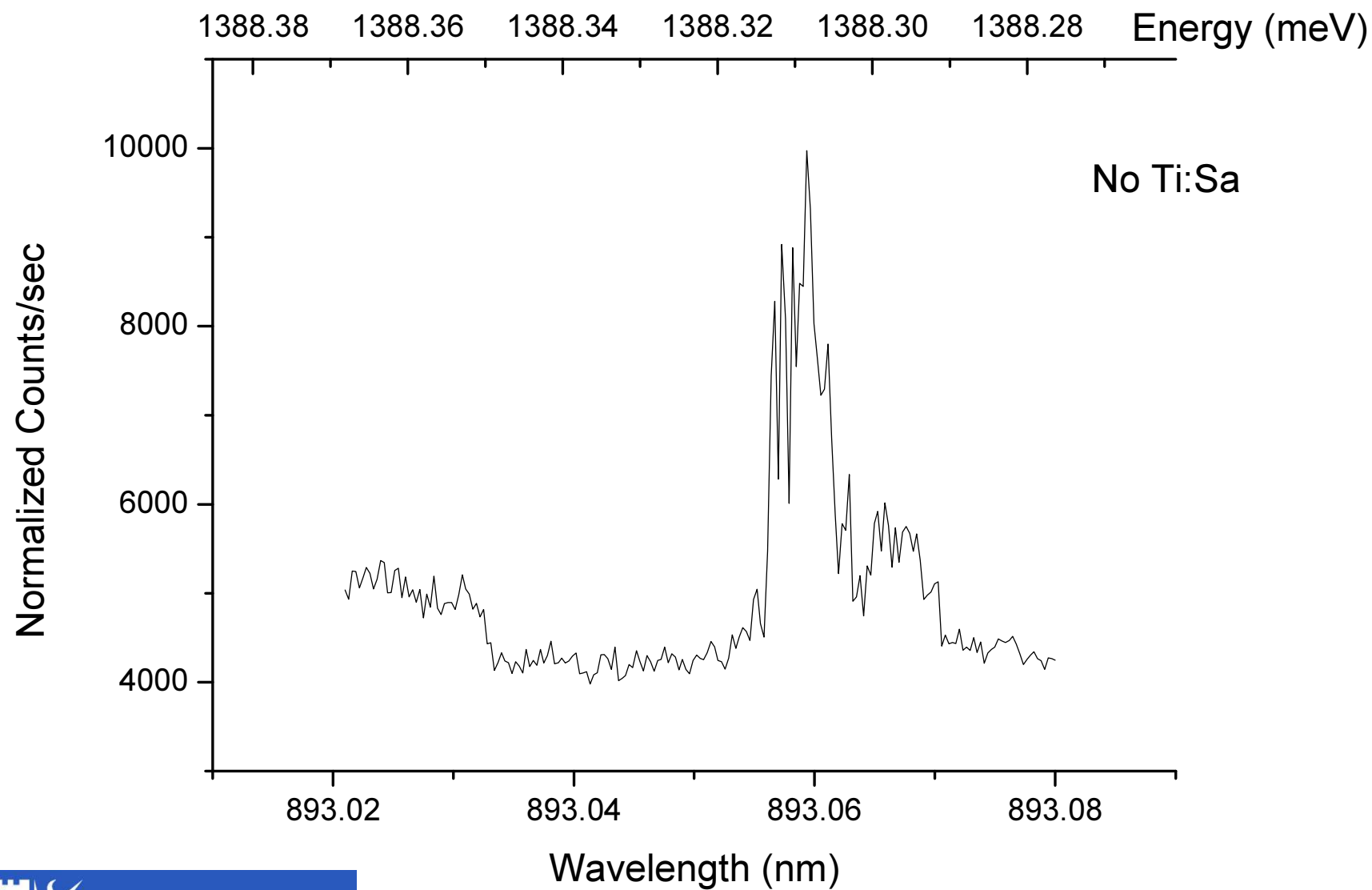


Resonant fluorescence characterisation

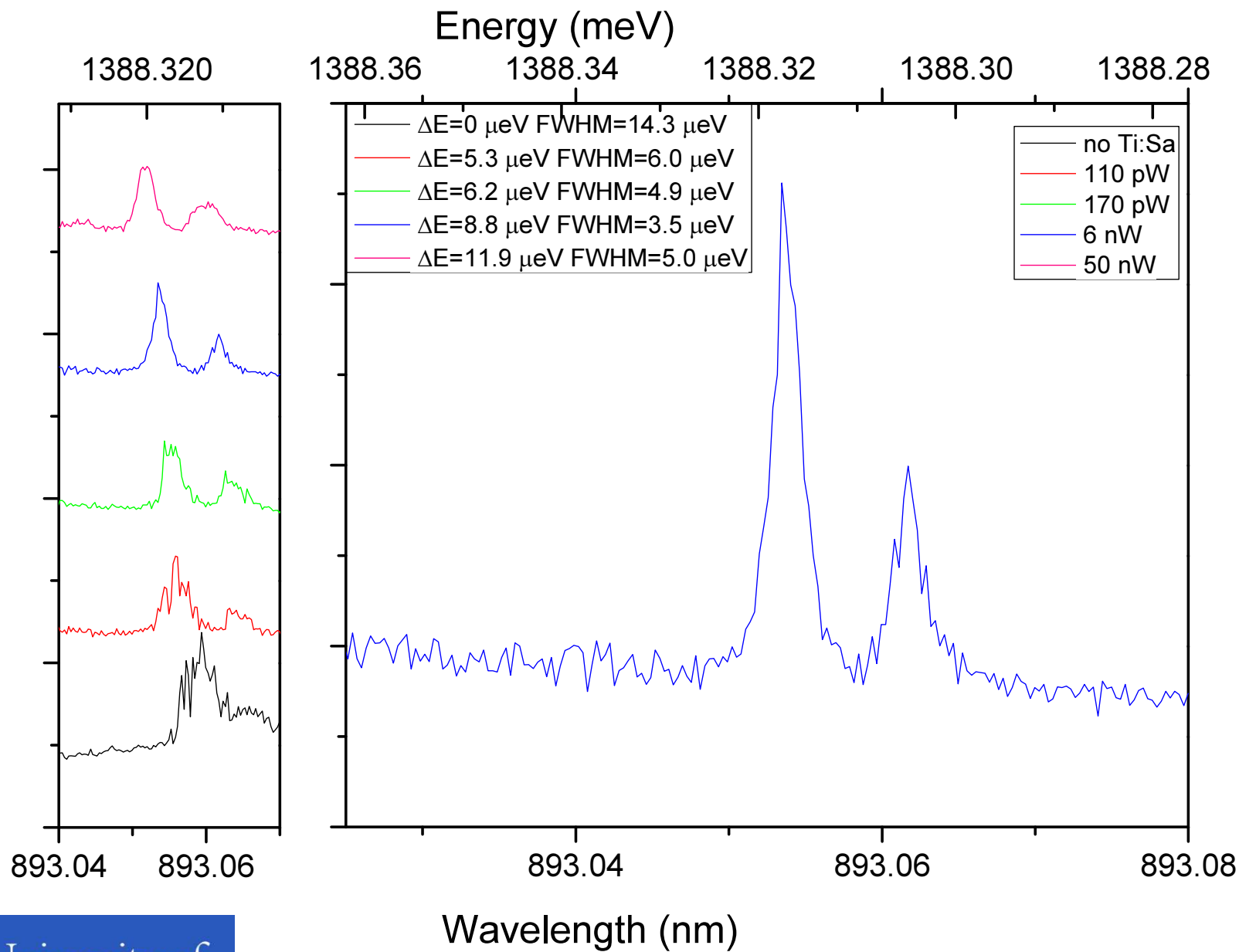


Removing surface charge and cleaning resonance fluorescence

Resonance Fluorescence Scan-C329713.1B



Resonance Fluorescence Scan

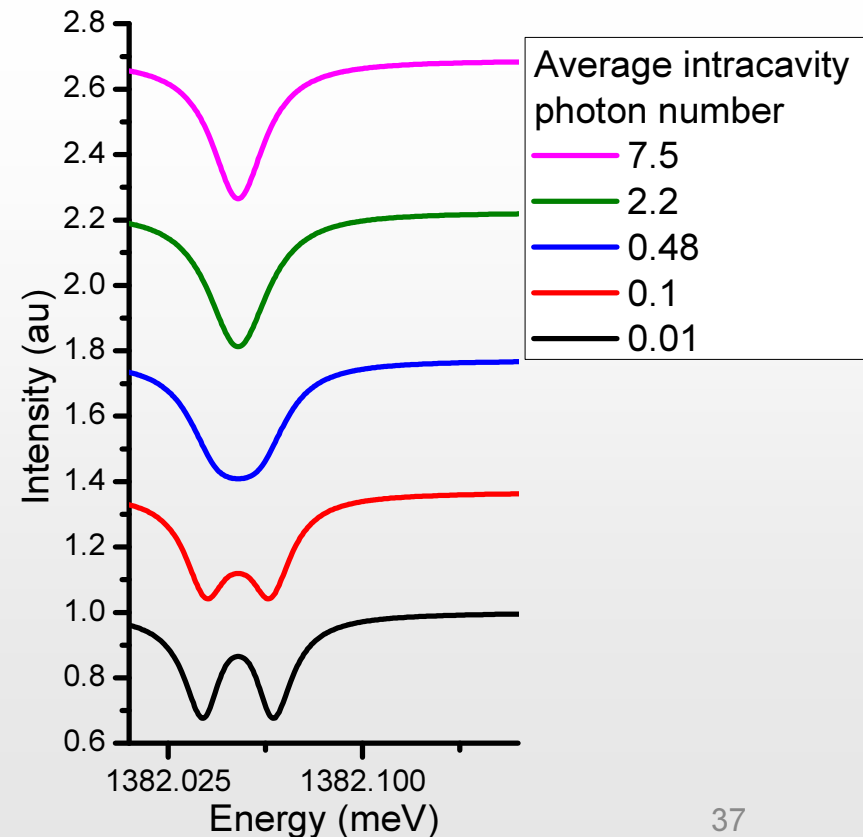


WP3 Theory

Bristol: Semi-analytical model fitting

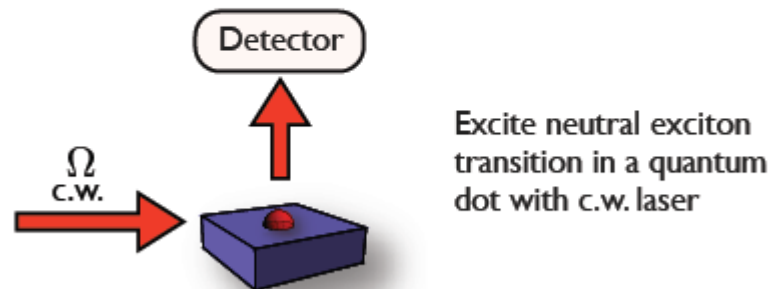
$$r(\omega) = 1 - \frac{\kappa \left[i(\omega_{QD} - \omega) + \frac{\gamma}{2} \right]}{\left[i(\omega_{QD} - \omega) + \frac{\gamma}{2} \right] \left[i(\omega_C - \omega) + \frac{\kappa}{2} + \frac{\kappa_S}{2} \right] + g^2 \frac{n_c \left[\gamma^2 + 4(\omega_{QD} - \omega)^2 \right]}{\langle n \rangle \gamma^2 + n_c \left[\gamma^2 + 4(\omega_{QD} - \omega)^2 \right]}}$$

- Equation represents reflectivity of photons with frequency ω from the cavity, based on cavity and dot parameters (QD linewidth, cavity lifetime etc.)
- Assumes steady state solution. Photons modelled as average intensity of intracavity electric field.
- Master equation solutions support this model so far.



Phonon-enhanced coherent scattering from a driven semiconductor quantum dot

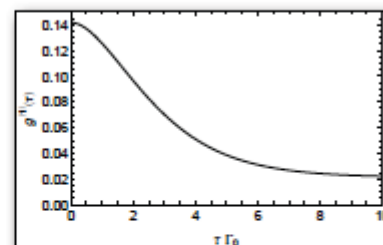
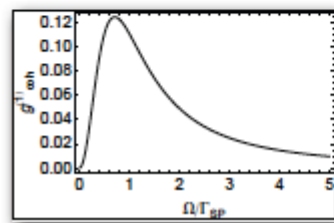
D P S McCutcheon & A Nazir, Phys. Rev. Lett. 110, 217401 (2013)



Consider both the coherent and incoherent emission
Incoherent emission coherence is limited by spontaneous emission rate

Coherent emission:

- Is monochromatic
- Has laser-limited temporal correlations
- Displays anti-bunching
- Good for single photons

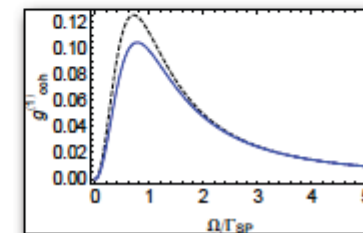


Coherent emission from an atom quickly drops to zero as the c.w. strength is increased

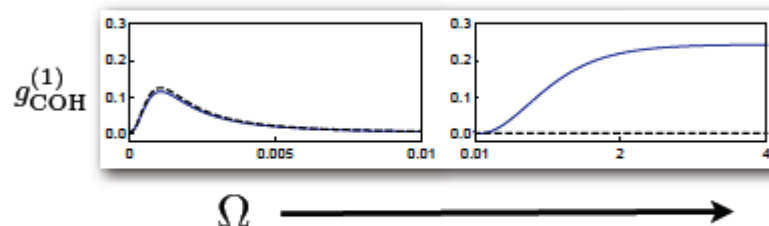
How do quantum dot - phonon interactions change emission?

At weak driving, very little:

— With phonons
- - - Without phonons



At larger driving strengths, quantum dot begins to thermalise with respect to the phonons - coherent scattering increases:

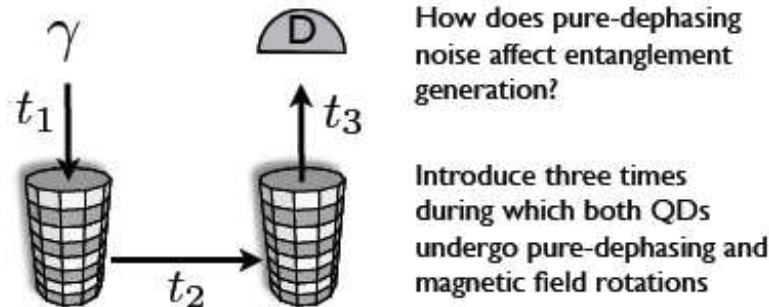


• Quantum dots have a regime of coherent scattering at large driving strengths

• This regime is not present in atoms, since it is caused by exciton-phonon coupling effects

Effect of noise on entanglement generation

A Pineiro-Oriolo, D P S McCutcheon & T Rudolph, Phys. Rev. B, 88, 035315 (2013)

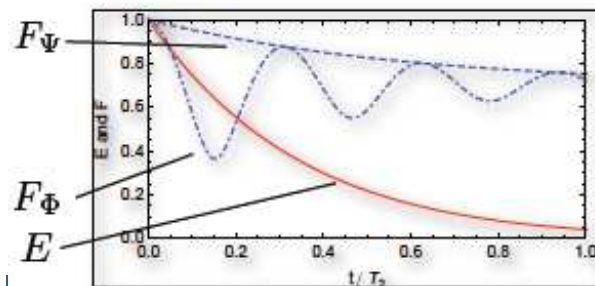


$$\rho_f = e^{\mathcal{L}t_3} [U_2(e^{\mathcal{L}t_2} [U_1(e^{\mathcal{L}t_1} |\phi_{\text{tot}}\rangle\langle\phi_{\text{tot}}|)U_1^\dagger])U_2^\dagger]$$

Liouvillian generates dissipative non-unitary dynamics:

$$\mathcal{L}\rho = -i\frac{\epsilon}{2}[\sigma_z^A + \sigma_z^B, \rho] + \sum_i \left(L_i \rho L_i^\dagger - \frac{1}{2}\{L_i^\dagger L_i, \rho\} \right)$$

$$L_1 = \sqrt{1/T_2}\sigma_z^A \quad L_2 = \sqrt{1/T_2}\sigma_z^B$$



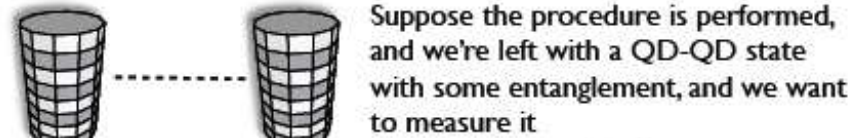
All operation times should be as short as possible for maximum entanglement

$$t = t_1 + t_2 + t_3$$

$$|\Psi\rangle = \frac{1}{\sqrt{2}}(|\uparrow\rangle|\downarrow\rangle + |\downarrow\rangle|\uparrow\rangle)$$

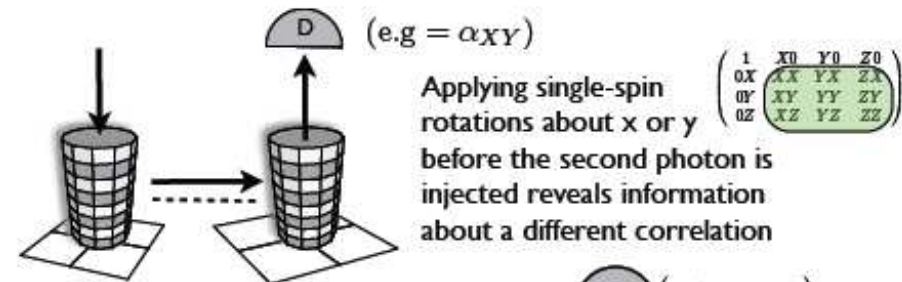
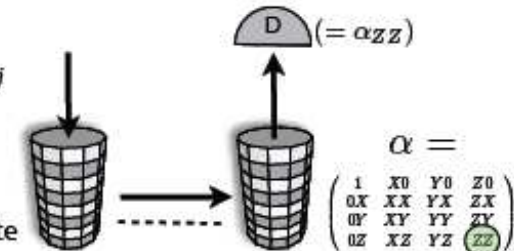
$$|\Phi\rangle = \frac{1}{\sqrt{2}}(|\uparrow\rangle|\uparrow\rangle - |\downarrow\rangle|\downarrow\rangle)$$

Tomography of post-measurement state



$$\rho_{AB} = \sum_{i,j} \alpha_{ij} \sigma_i \otimes \sigma_j$$

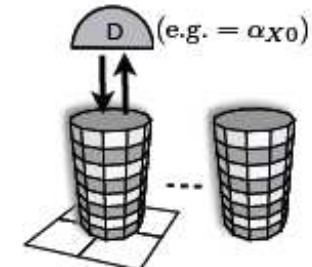
A second photon reveals information regarding the z-z correlation of the QD-QD state



Remaining elements are found by allowing the photon to interact with only one QD

$$\alpha =$$

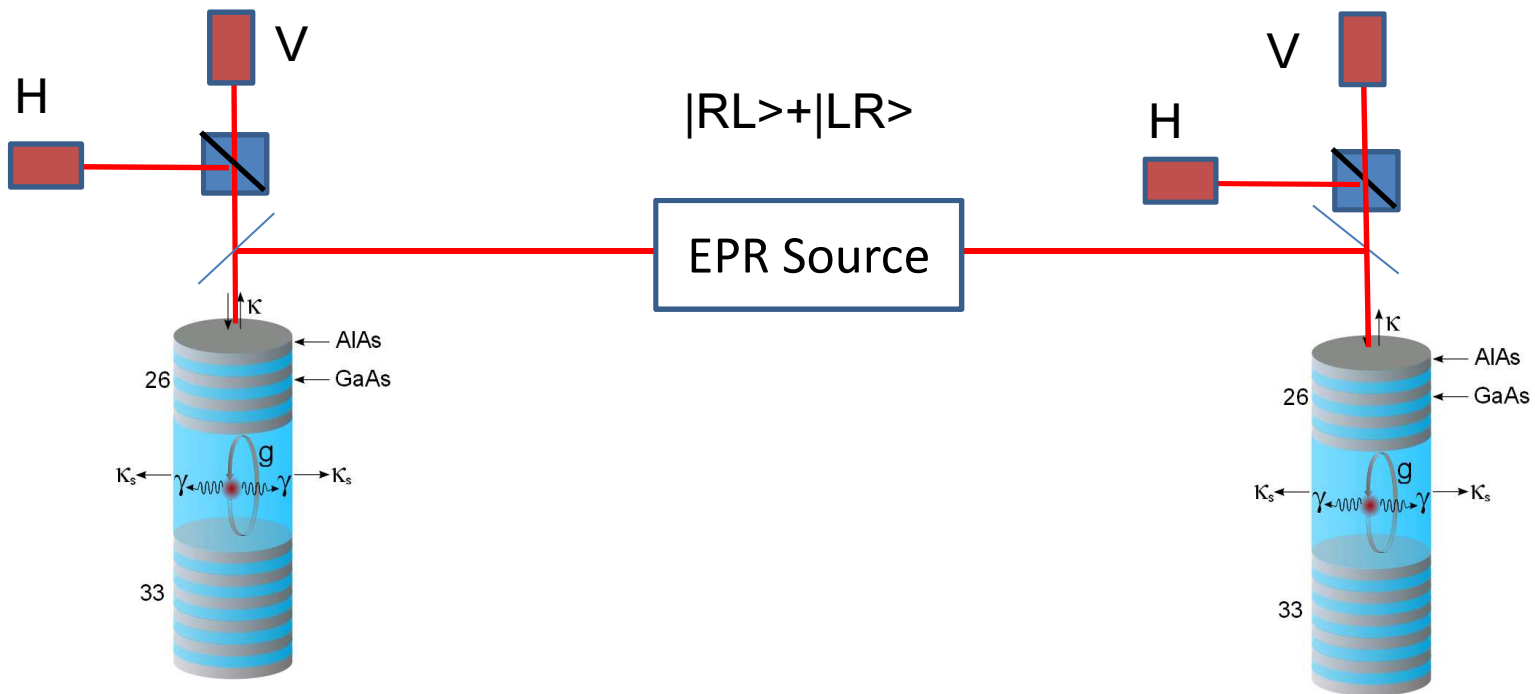
1	x_0	y_0	z_0
$0x$	xx	yx	zx
$0y$	xy	yy	zy
$0z$	xz	yz	zz



- Since z-z correlations are protected from pure-dephasing noise, time for second photon is unimportant
- Second measurement collapses QD-QD state into a protected subspace - more photons can be used

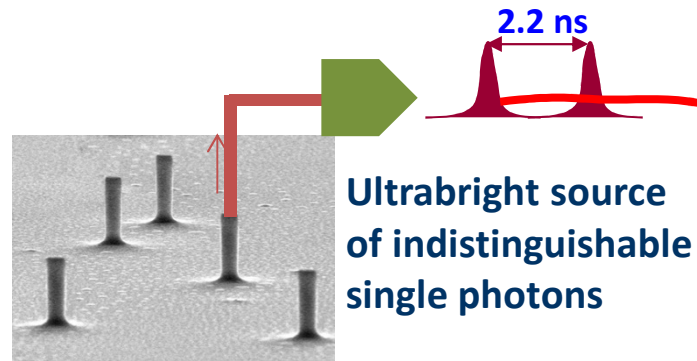
Loophole free Bell test and Device independent QKD

- Detection of an H or V photon heralds the storage of a qbit
- Coincident detection heralds storage of EPR pair spins
- Spin be read out with weak coherent beams $\sim 100\%$ efficiency
- Limited by storage time = decoherence of stored qbit



WP4: Integration

LPN: Controlled NOT gate with a bright single photon source



2.2 ns

Coupling into a
monomode fiber
~90%

Preparation

Gate

Analysis

50/50
coupler

Polar. $\lambda/2$



H,V,D,A

Polar. $\lambda/2$

2.2 ns delay

C-NOT
Gate

$\lambda/4$ $\lambda/2$ Polar.

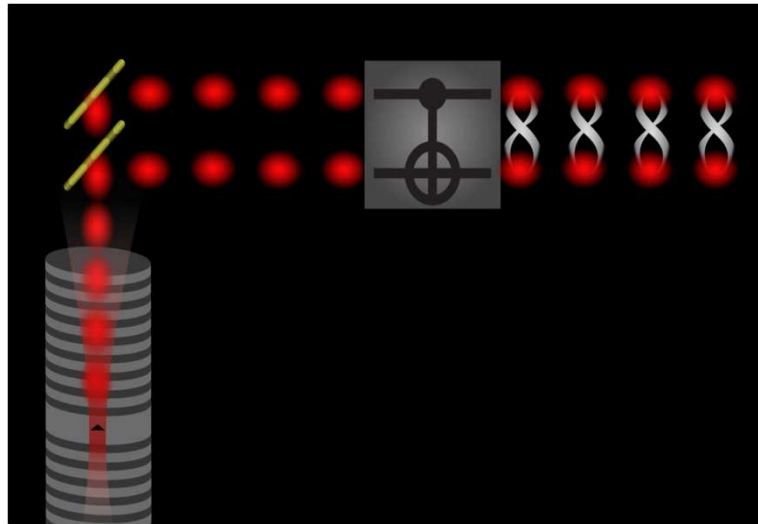
$\lambda/4$ $\lambda/2$ Polar.

Spectro
SPAD

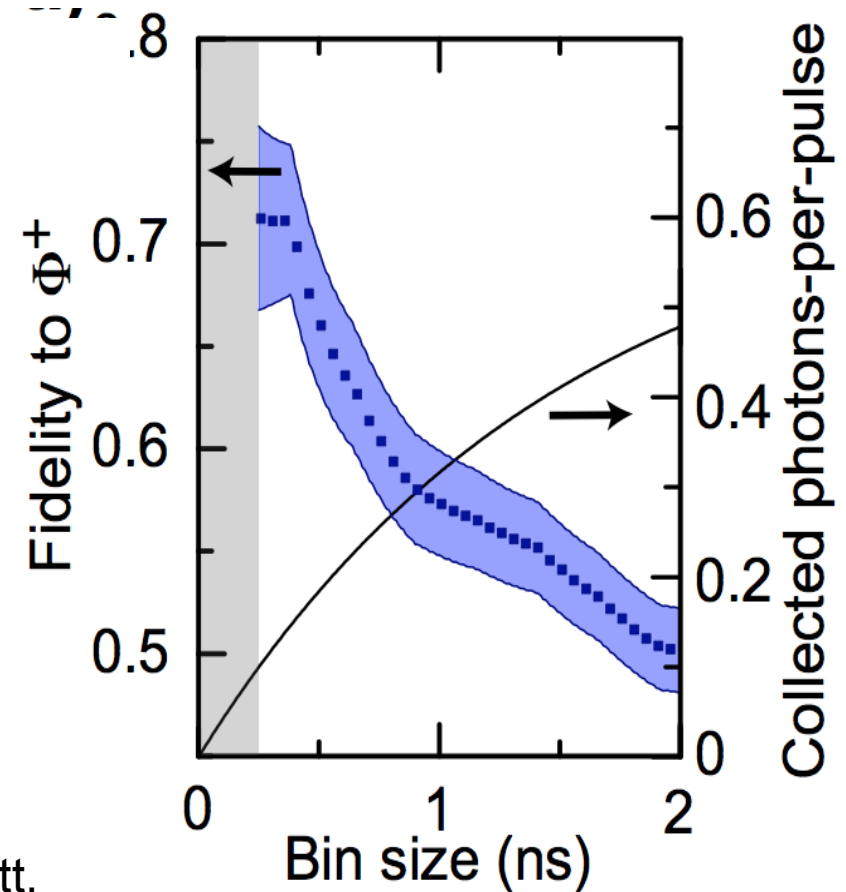
Spectro
SPAD

Correlations

Entangling two photons using a CNOT gate



O. Gazzano, M. P. Almeida, A. K. Nowak, S. L. Portalupi, A. Lemaître, I. Sagnes, A. G. White, and P. Senellart, Phys. Rev. Lett. 110, 250501 (2013)



Summary

SSQN is a European project focussed on replacing key components of a quantum communication network with loss-resistant solid-state ones:

- High efficiency QD-based triggered entangled pair sources (Y1)
- High efficiency indistinguishable photon sources (Y2)
- First integration of sources in linear CNOT gate (Y2)
- Strong coupling saturation/ single photon gates (Y1/Y2)
- Struggling to demonstrate spin-photon effects, but watch this space in (Y3).
- Theoretical understanding of decoherence and phonon effects (Y1/2).
- Loophole free Bell inequalities and device independent quantum key distribution.

Implementation would result in:

- Remove need for synchronised photon arrival and indistinguishability at the Bell-state analyser in the quantum repeater
- Intrinsic heralded quantum memory
- 1000km entanglement distances

Contributors

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