Coherent excitation of a strongly coupled quantum dot - cavity system

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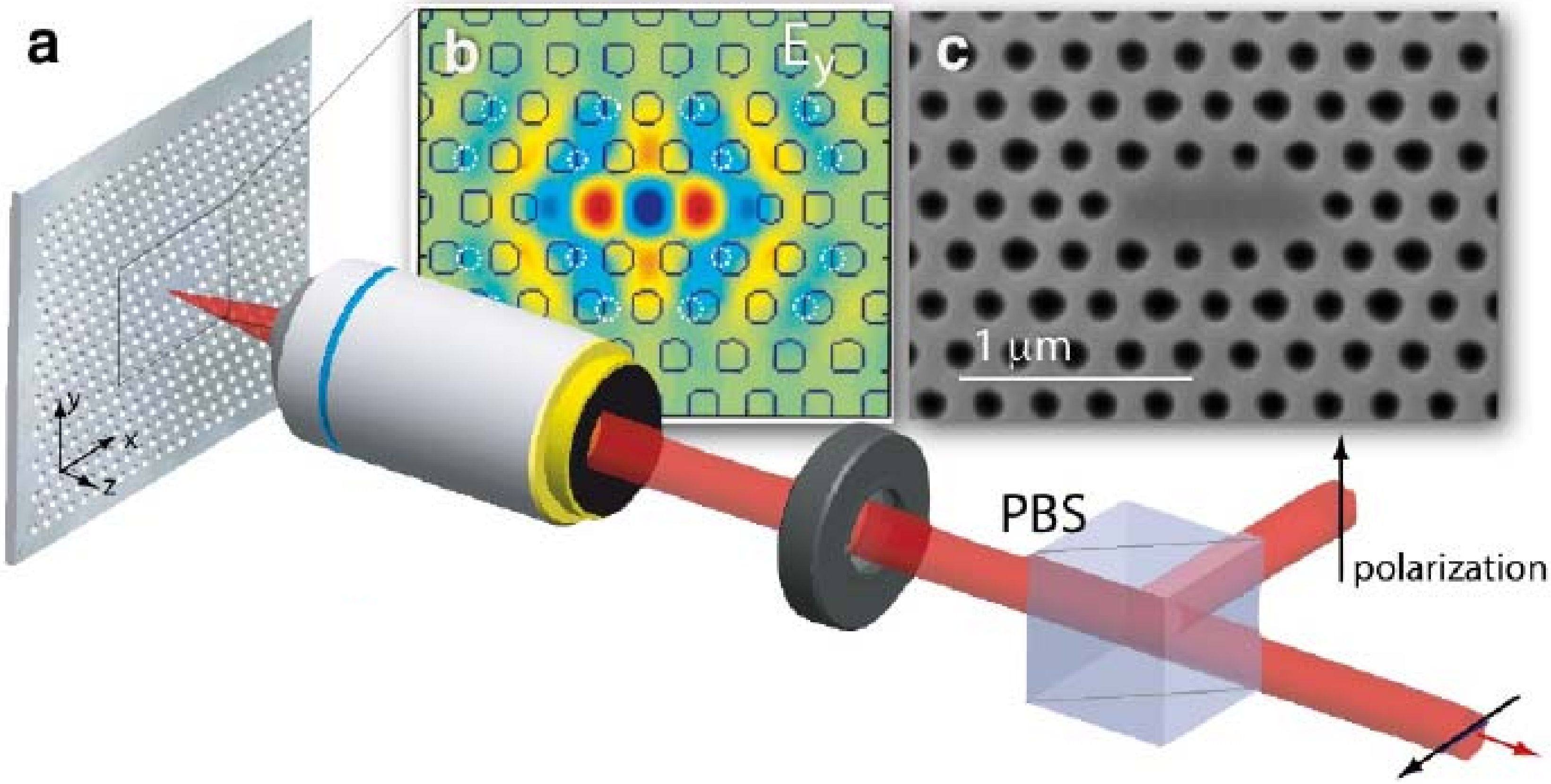
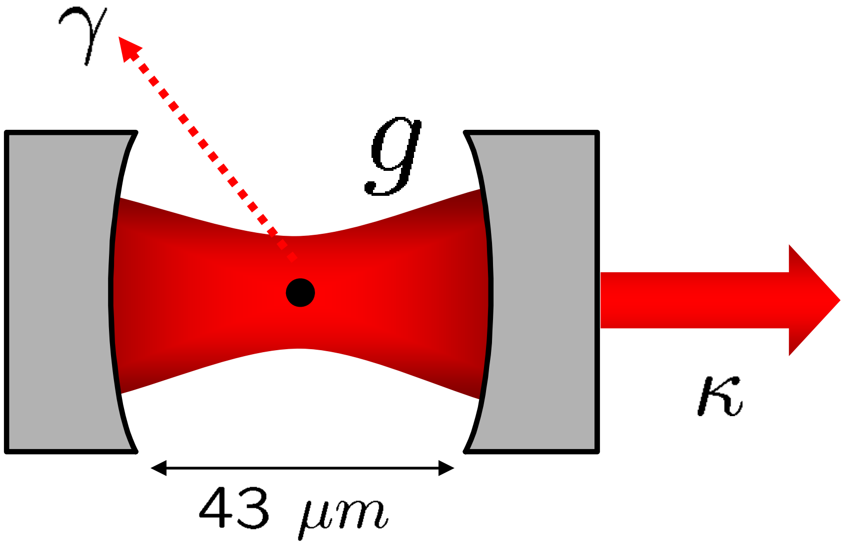


Strong Coupling in Cavity QED



Fundamental quantum optics:
Light-matter interaction is enhanced, accessible, controllable

Quantum Information Science:
Entanglement can be deterministically created between atom and field

2g = Rabi Frequency of a Single Photon

Rate of **coherent exchange** between excitation of
atom and ***field***

Strong Coupling Condition:

$$g \gg (\gamma, \kappa)$$

$$\begin{aligned} g &= 2\pi \times 32 \text{ MHz} \\ \gamma &= 2\pi \times 2.6 \text{ MHz} \\ \kappa &= 2\pi \times 4.2 \text{ MHz} \end{aligned}$$

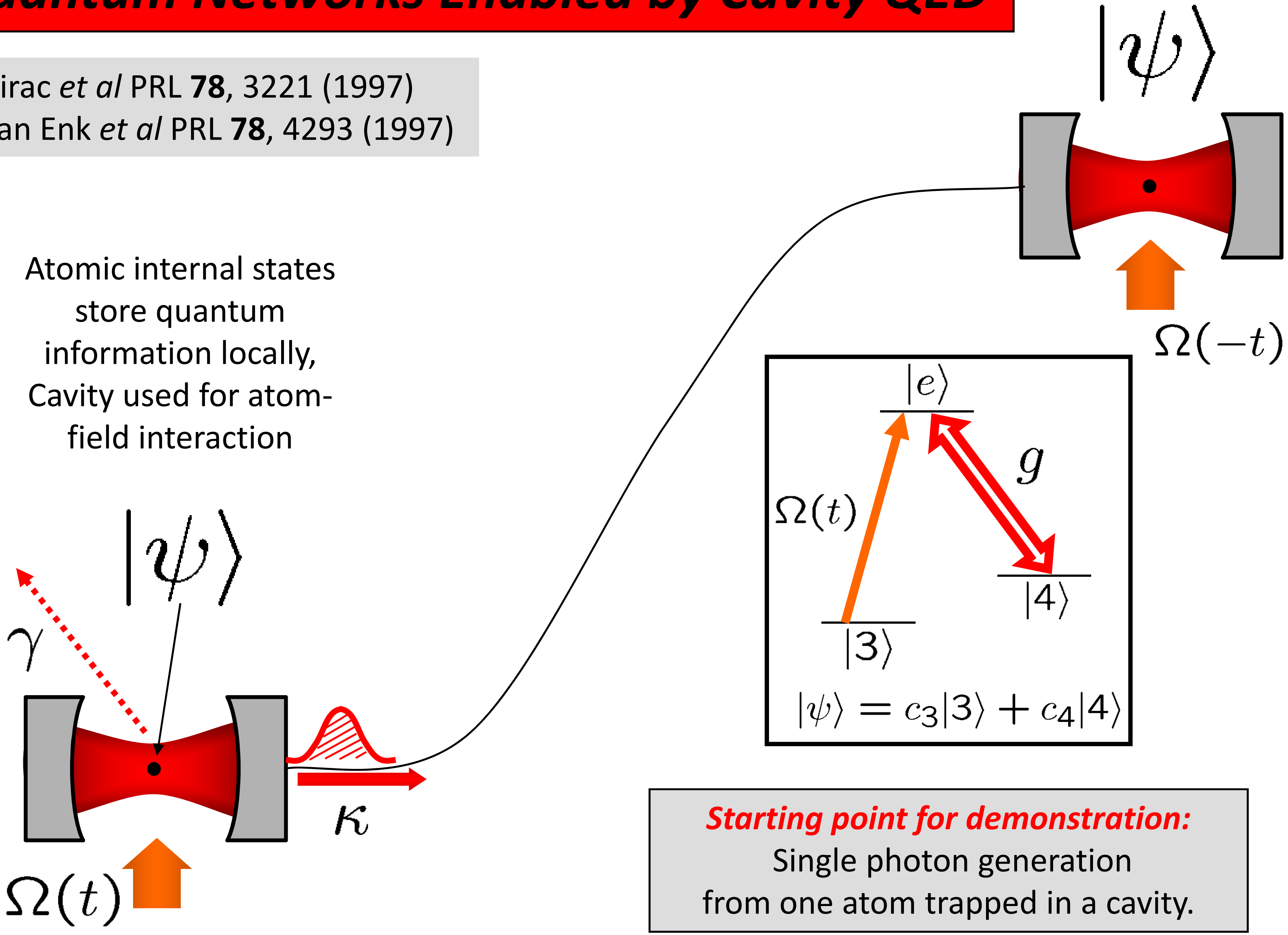
Critical ***photon*** number $n_0 = \frac{\gamma^2}{2g^2} = 0.003$

Critical ***atom*** number $N_0 = \frac{2\gamma\kappa}{g^2} = 0.02$

Quantum Networks Enabled by Cavity QED

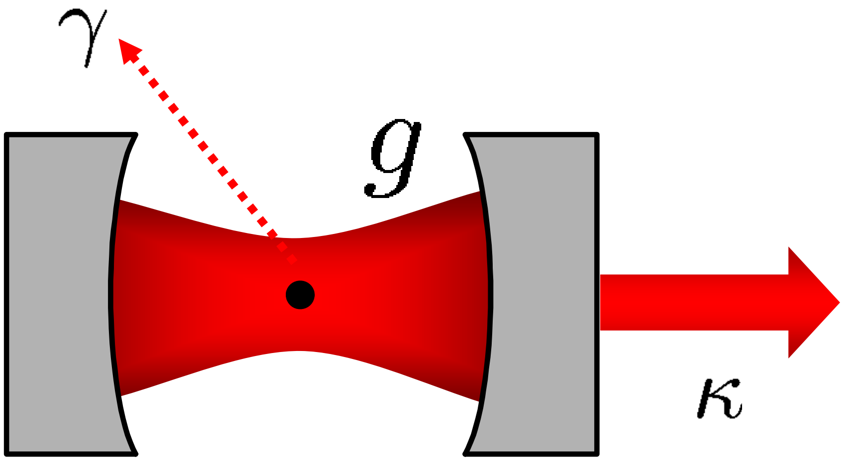
Cirac *et al* PRL **78**, 3221 (1997)
van Enk *et al* PRL **78**, 4293 (1997)

Atomic internal states store quantum information locally, Cavity used for atom-field interaction



Starting point for demonstration:
Single photon generation
from one atom trapped in a cavity.

Atoms vs. Quantum Dots

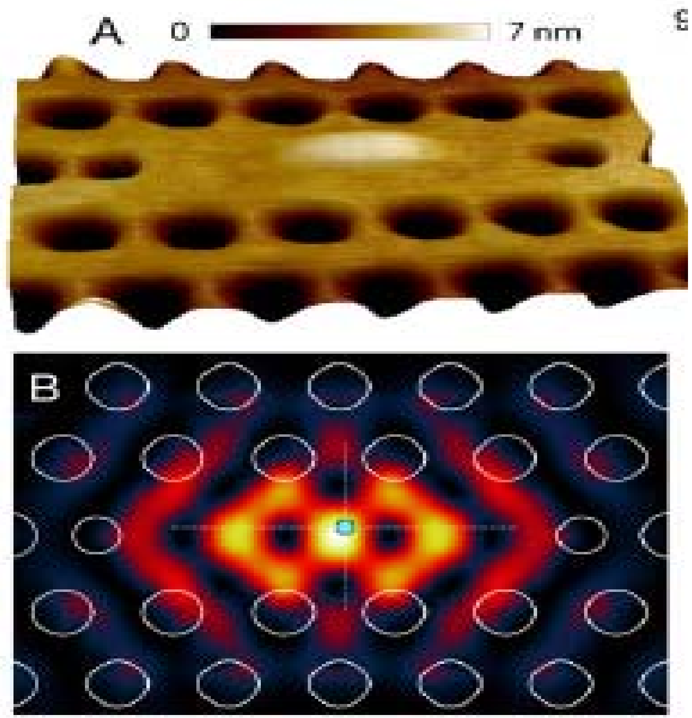


Advantages:

- Internal structure of atoms completely understood.
- Hyperfine structure -> Quantum memory
- Can be (relatively) well isolated from decoherence

Disadvantages:

- Limited atomic storage time
- Difficulty controlling atomic position
- Complexity of laser cooling/trapping apparatus, incl vacuum.



Hennessy,…, Imamoglu, Nature (2007)

Adv.:

- All solid-state system relatively simple, compact, scalable
- Tiny cavities -> huge coupling

Disadv.:

- Decoherence in solid environment
- Cryogenics required
- Quantum dots not all created equal (ok?)
- Input/output coupling techniques?

Englund et al - Highlights

- Goal: Use QD in photonic nanocavity as a building block for quantum information

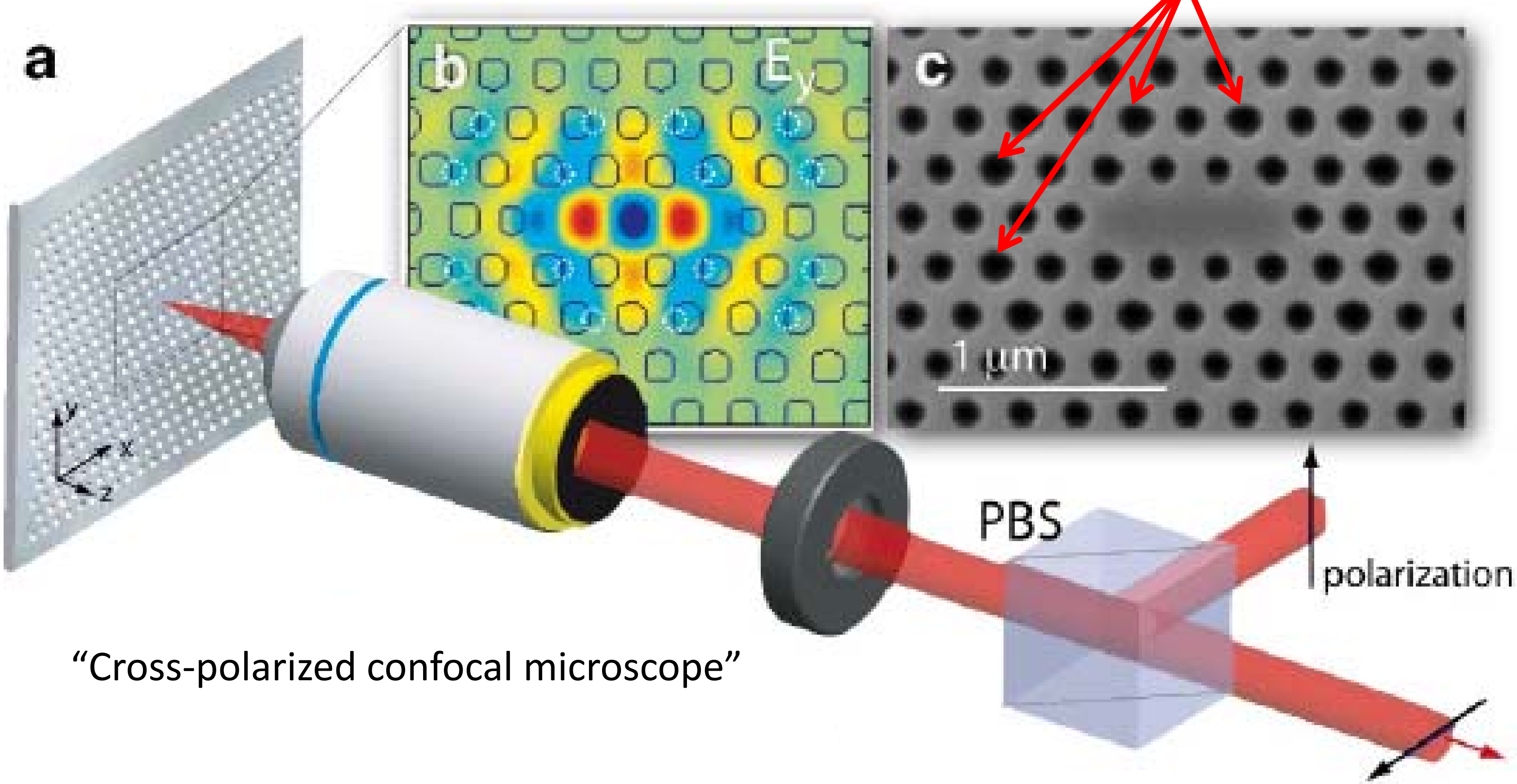
- "One of the key challenges is to ***coherently control the state*** of the quantum dot/cavity system"

- "Here we investigate the ***coherent excitation*** of a strongly coupled InAs quantum dot - photonic crystal cavity system."

- "we observe ***time-domain Rabi oscillation*** in the transmission of a laser pulse"

Main new results seem to be the type of laser excitation used, and the time-domain studies of QD/field dynamics.

Setup



Colour = E_y magnitude

“Perturbed” structure improves in/out coupling & directionality of emission

“Cross-polarized confocal microscope”

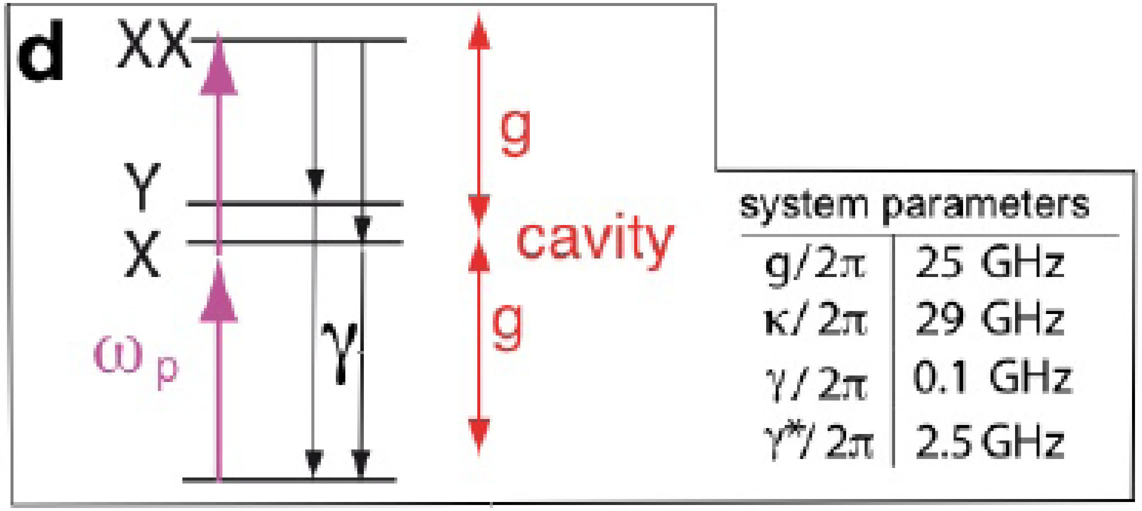
“Cavity is fabricated in a 160-nm thick GaAs membrane, which contains a central layer of self-assembled InGaAs QDs with an estimated density of 50 μm^2.”

… How can they claim “single quantum dot” then?

Energy Levels of Coupled QD/Cavity System

- X and Y are exciton states with different polarization. (What does this mean?)

- XX is a biexciton state



system parameters	
$g/2\pi$	25 GHz
$\kappa/2\pi$	29 GHz
$\gamma/2\pi$	0.1 GHz
$\gamma^*/2\pi$	2.5 GHz

ω_p : pump laser frequency

g : Vacuum Rabi frequency (factor of 2 discrepancy?)

κ : Cavity field decay rate

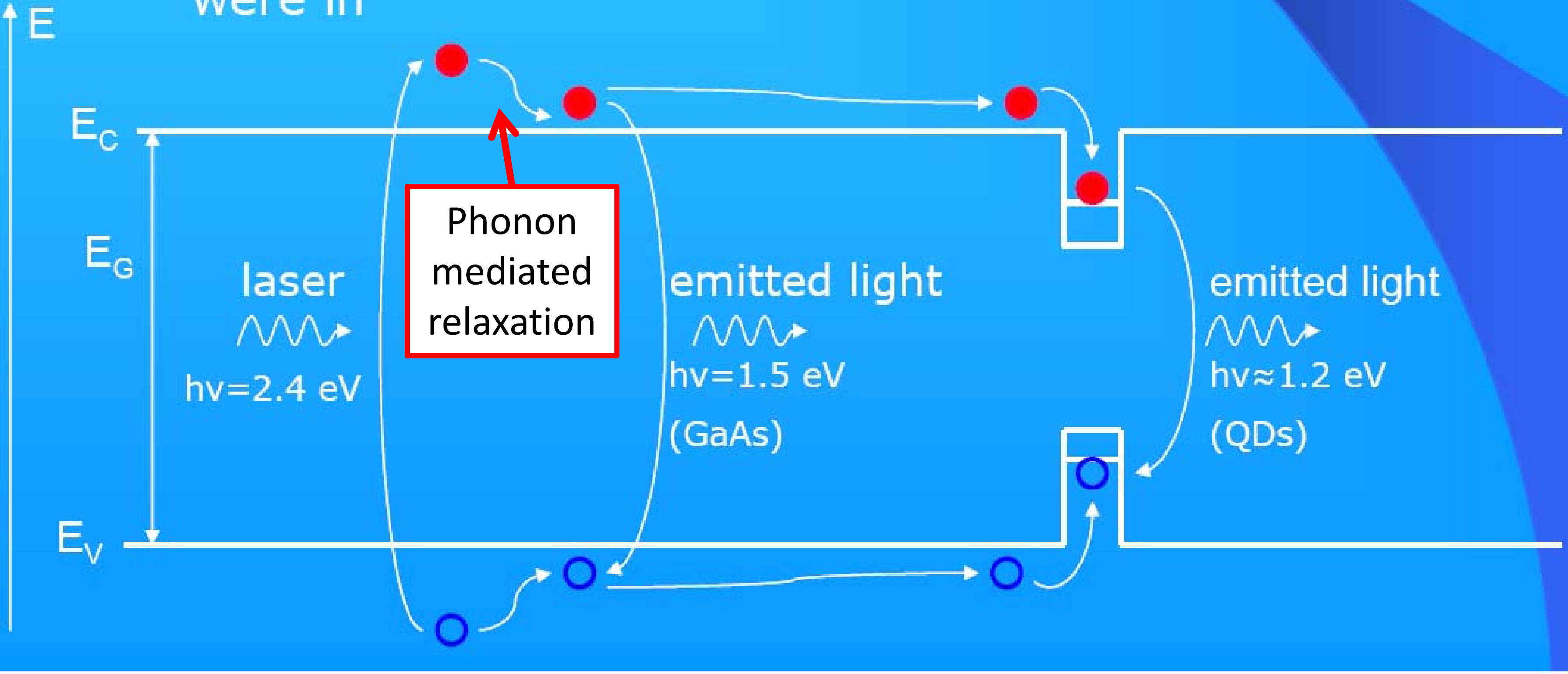
γ : dipole decay rate

γ^* : dipole dephasing rate

These are the same in a 2-level atom (within a factor of 2, I think). In a QD, there is clearly more dephasing.

Photoluminescence

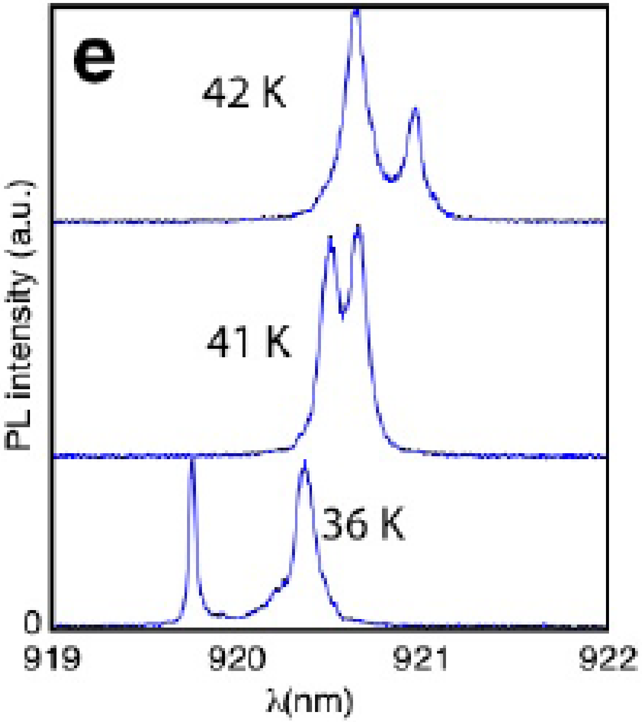
- We can use a laser to excite electrons into the conduction band
- Recombination will often produce a photon – the energy of this photon tells us what state the electron and hole were in

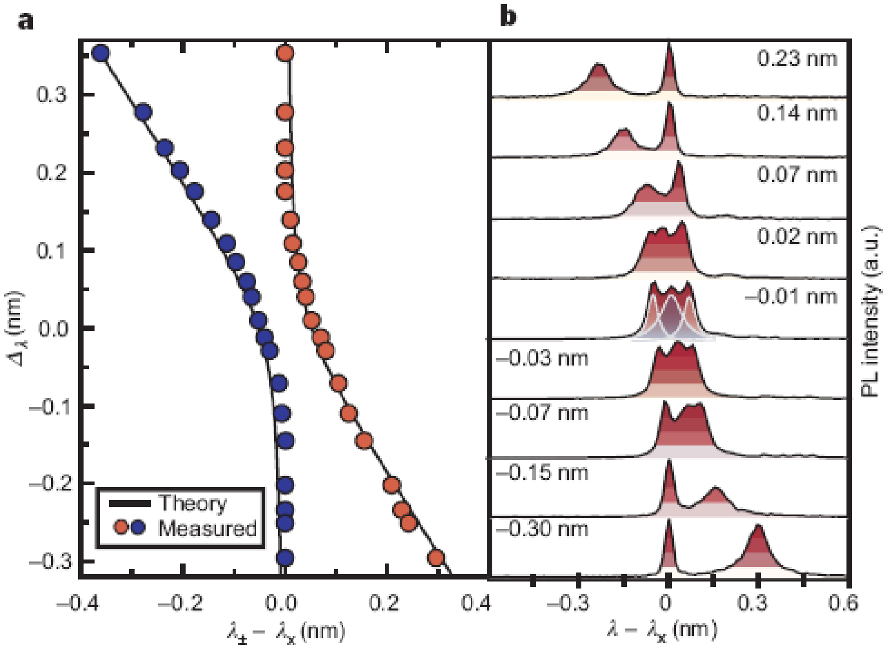


Ariel M’ndange-Pfupfu, Electrical Engineering, Princeton

Photoluminescence (PL) Spectroscopy

- Fixed pump laser wavelength (860 nm cw), $\omega_p > \omega_X$
- Tune the QD via cryostat temperature
- Send photoluminescence to a spectrometer
- See a cavity peak and an exciton peak
- Anti-crossing observed (coupled oscillators)
- g, κ, γ inferred from these spectra





- Analogous data from Imamoglu group, 2007
- Where does third peak come from? “the pure photonic state of the cavity.”
- “As the occupation of charging centres in the vicinity of the QD fluctuates, the exciton energy is renormalized via the Coulomb interaction and the detuning becomes large.”

Resonant Excitation

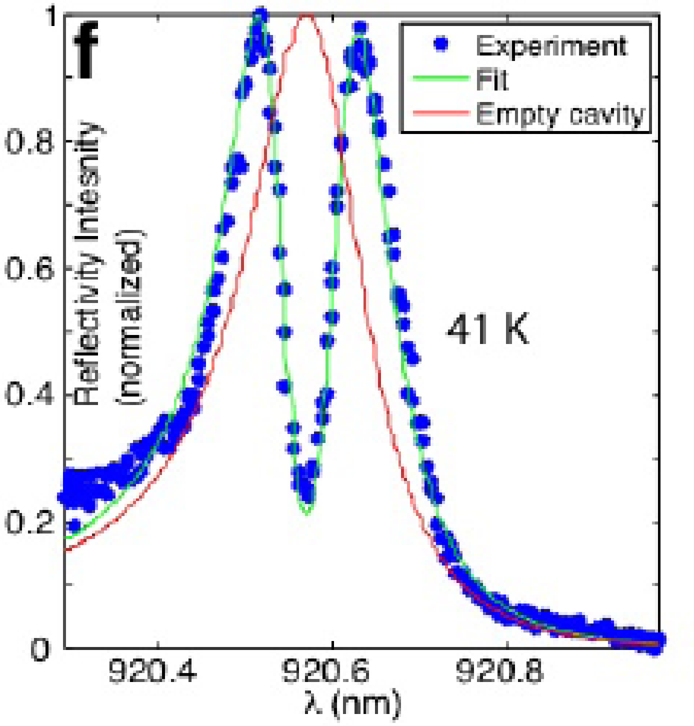
- PL spectroscopy is the usual technique. This resonant driving is more analogous to what's done in atomic CQED, and is an important new feature of this paper.

- Tunable, cw laser is sent in with vertical polarization, and the "reflected" (emitted?) horizontally polarized field in reverse direction is detected.

- Vacuum Rabi splitting is observed. Fit uses (fixed) parameters inferred from PL data. (not sure what the free parameters are…)

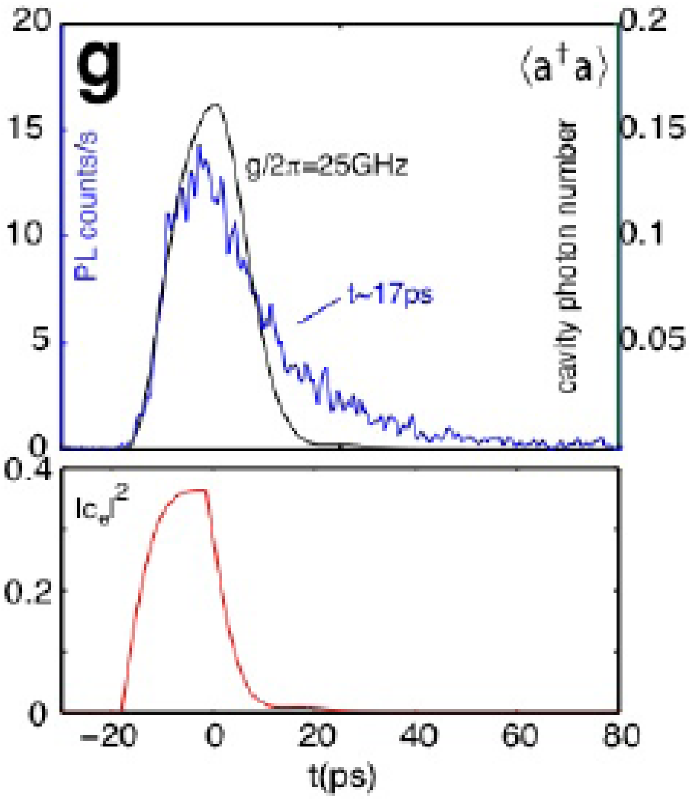
- Signal "nearly vanishes" (down by 80 %) on resonance, "showing that the QD has a very high probability of being in the optically bright state"

- Does this mean the excited state? This is not what happens in the atomic case.



Time-resolved photoluminescence

- Measurement of decay time of the excitation.
- Pump laser at 878 nm, 40 ps pulses
- Measure PL with a streak camera
- Qualitative agreement with a theoretical model (black)
- Model uses previously inferred parameters: Δ, g, γ, κ
- Quantum Monte Carlo simulation, assume 2-level QD
- Timing jitter, based on distribution of relaxation times into the single-exciton excited state (avg 10 ps), is included.
- They "estimate that the QD has a probability of being in an optically dark state of 0.2, meaning that a background signal corresponding to an empty cavity reflectivity must be added."
- This is the "third peak" from Imamoglu data, just not as pronounced.



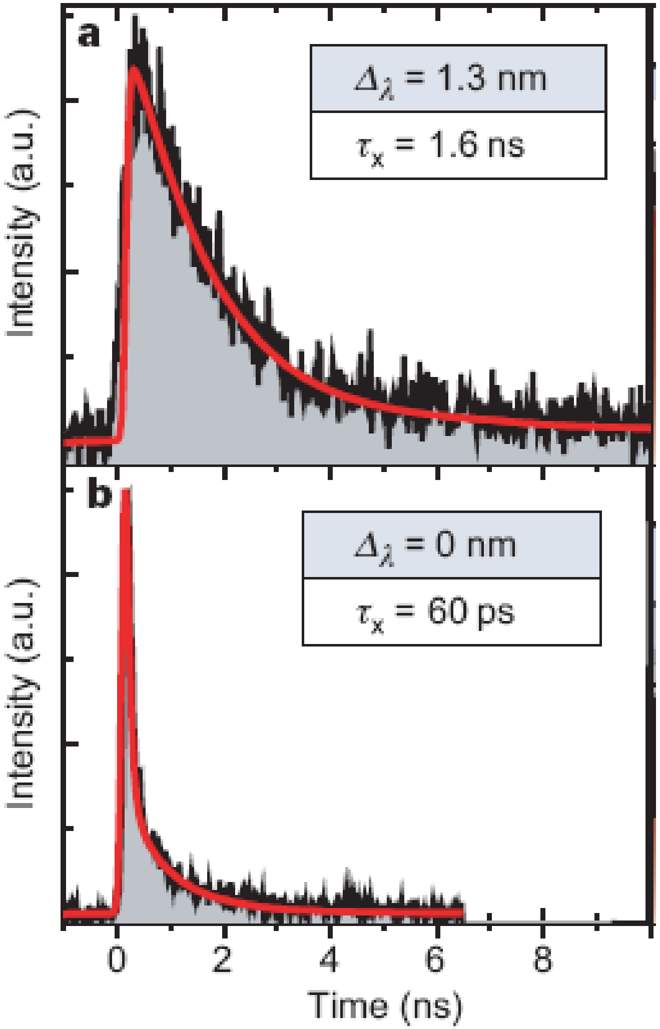
Bottom panel: excited state population from simulation

- "We attribute the short decay time in this case to the observation that nearly all emission collected from the cavity originates from the QD"… this issue does not arise with single atoms!
- "For a very similar system, we previously showed that the cavity mode is strongly antibunched to $g^{(2)}(0)\approx$ 0.05"… strange to quote value for different system….
- Attribute strong QD signal to perturbed cavity design.

Decay dynamics: Comparison to Imamoglu

“Previous measurements of the decay time gave values exceeding 60 ps in the strong coupling regime, which is longer than expected for the strong coupling regime where the decay time should be on the order of the cavity ring-down time of 5 ps for a Q $\approx 10^4$.”

Hennessy,…, Imamoglu, Nature (2007)



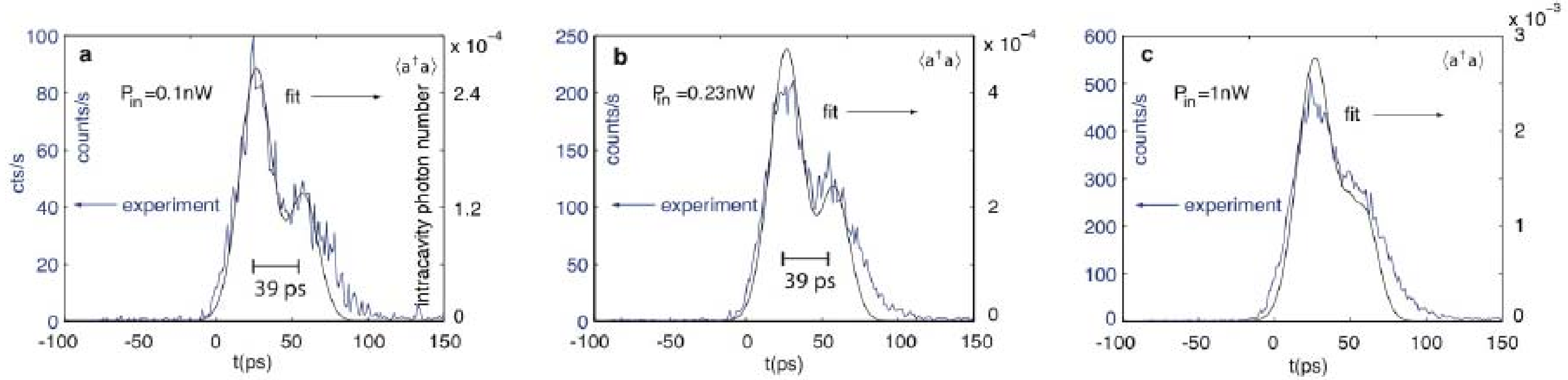
- You don’t need strong coupling to see cavity ring-down time. In fact, you don’t need any coupling.

- Shouldn’t this same argument apply to their own data, for which Q is also 10^4, and they are strongly coupled & on resonance? (although the timing jitter issue is important)

- Imamoglu: Their lifetime is “carrier capture limited” (i.e. time required for relaxation from bulk to QD?). Is this the only difference between two expts?

Confusion comes from the fact that coupling to cavity is always via the semiconductor….

“Vacuum” Rabi Oscillations in the Time Domain



- 40 ps pulses, 80 MHz rep rate, resonant with cavity/QD

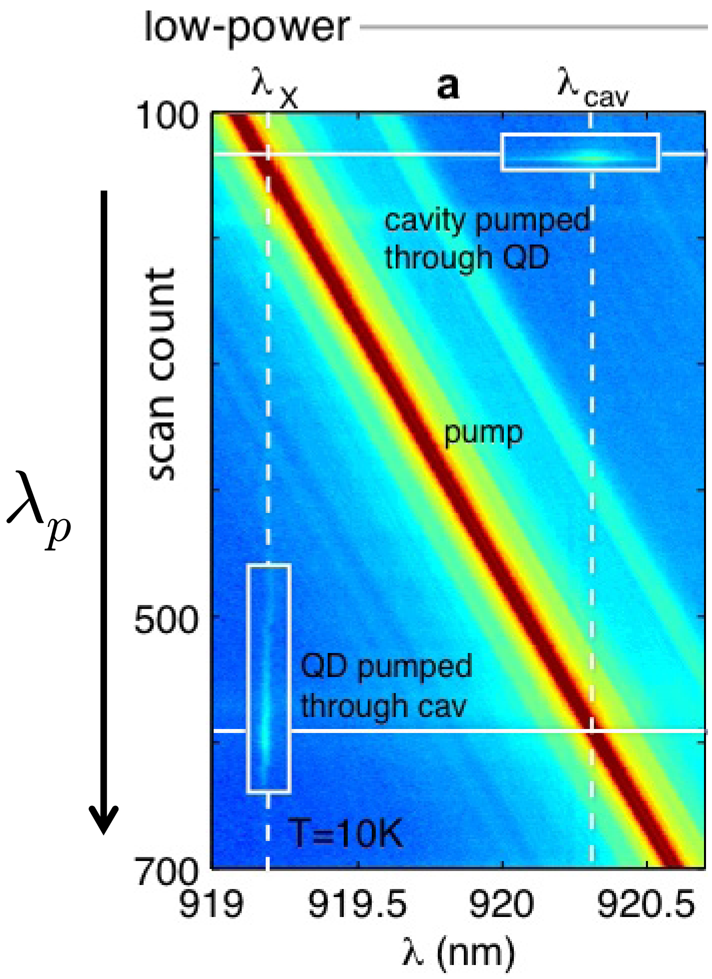
- Observations are “fit” with a full master equation model (g, γ, κ fixed by earlier PL)

- Seemingly the free parameter in the fit is the overall amplitude. This is done for the lowest power data, and then the higher ones are just scaled up appropriately

- Oscillation period of 39 ps closely matches 2π/g=40 ps

- At higher pump power, Rabi oscillation becomes less visible

Resonant Driving For Large Cavity-QD Detunings

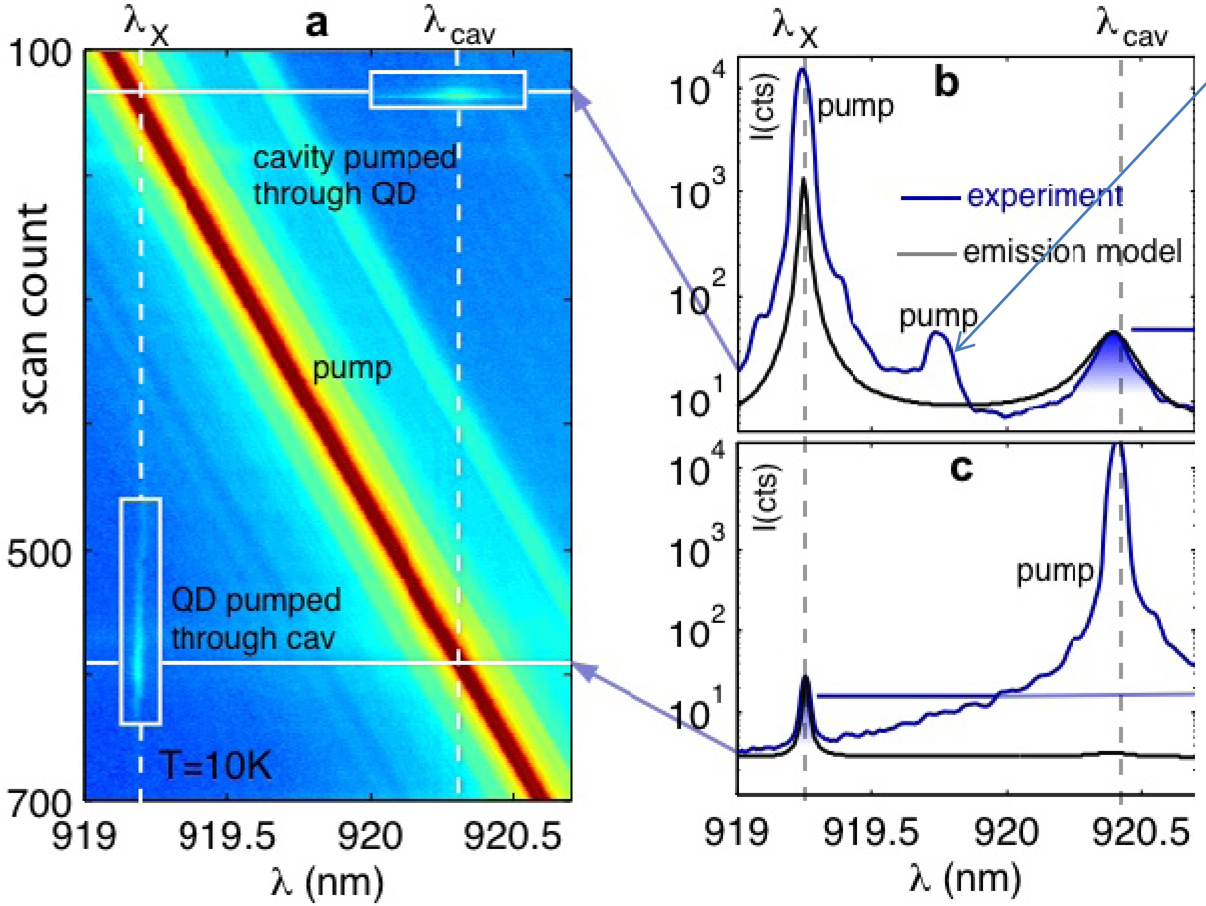


Colour represents PL intensity on spectrometer

- Cavity – QD detuning is 1.17 nm (set by T)
- Laser is polarized at 45 degrees (why?)
- They see a cavity signal when laser hits QD resonance, and vice versa.
- “Cavity represents a strong readout channel for resonant QD spectroscopy”
- Basically since the pump is so far detuned, it can be filtered away and the QD emission can be studied without background pump signal

Resonant Driving For Large Cavity-QD Detunings

Spectra for fixed $\lambda_p = (\lambda_X, \lambda_{cav})$

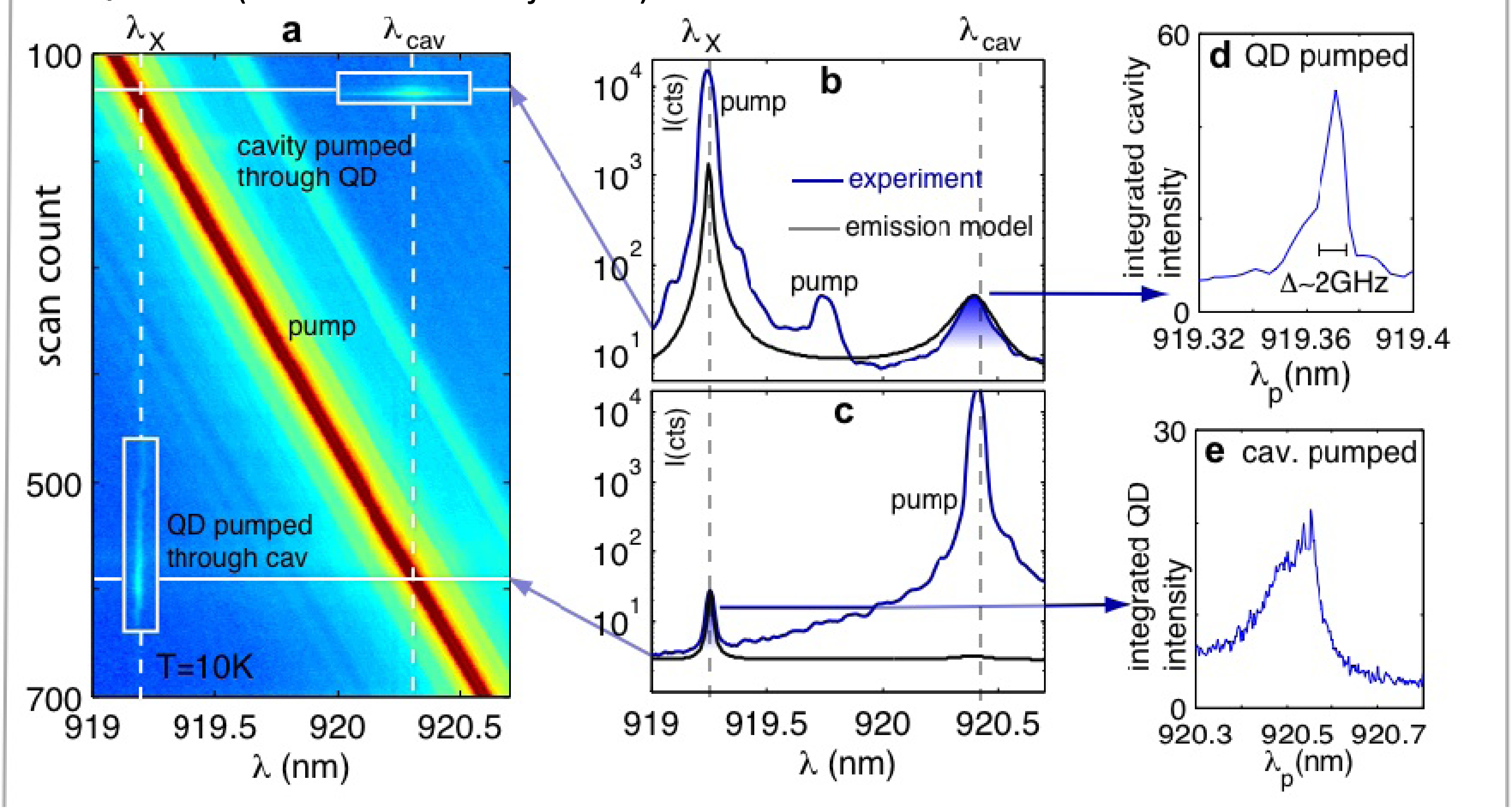


- Middle peak comes from a laser side-mode

- Model the driving mechanism by a pure dephasing process with γ*=0.1 g $\approx 2\pi\times2.5$ GHz

Resonant Driving For Large Cavity-QD Detunings

low-power (12 nW before objective)



Emission wavelength

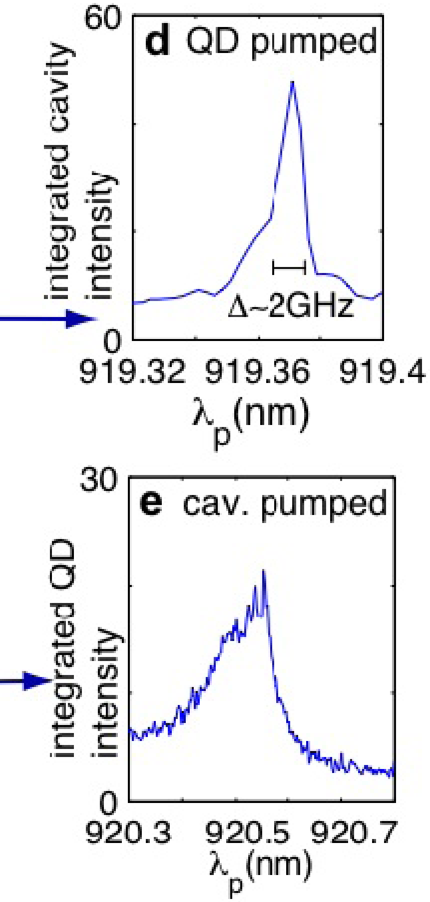
Laser wavelength

d. When laser excites QD, feature at λ_{cav} is resolved to 3 GHz (limited by laser mode hopping)

e. When laser excites cavity, non-lorentzian response is observed at λ_X

- “QD emits with a linewidth that appears limited by our spectrometer resolution” (?)

Resonant Driving For Large Cavity-QD Detunings



- “This cavity-enhanced spectroscopy technique adds an important tool to the repertoire for resonant single quantum dot spectroscopy.”

- “should be universally applicable for solid state cavity QED systems with most cavity designs, so long as the QD has a large enough pure dephasing rate to drive the cavity.”

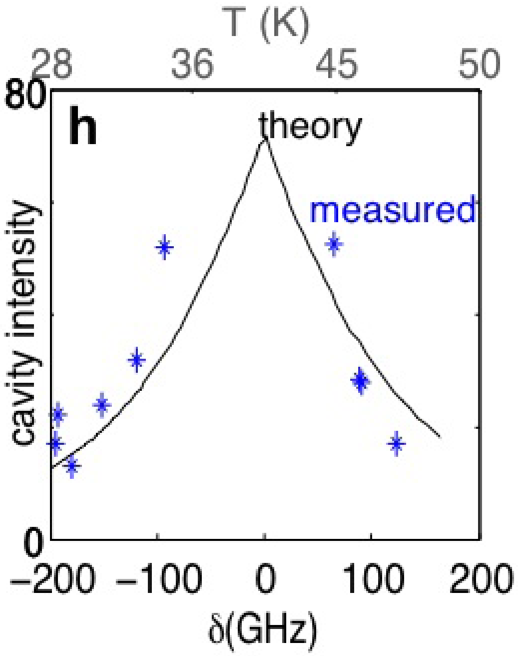
- “The mechanism that allows the quantum dot to drive the far off-resonant cavity is not yet completely clear. It has previously been reported that quantum dots that were pumped through higher excited states or the QD wetting layer can drive the cavity even when it is far detuned. Several recent theoretical models attribute the off-resonant driving of the cavity mode to a pure dephasing mechanism of the quantum dot.”

Cavity Emission via QD Pumping

- Tune QD via temperature.
- Keep laser resonant with QD.
- Measure power emitted at λ_{cav}
- Model: Temperature dependent dephasing

$$\gamma = \gamma_0 + \alpha_0 T, \text{ with } \alpha_0 = 0.5\mu \text{ eV K}^{-1} \text{ and } \gamma_0 = \kappa/100.$$

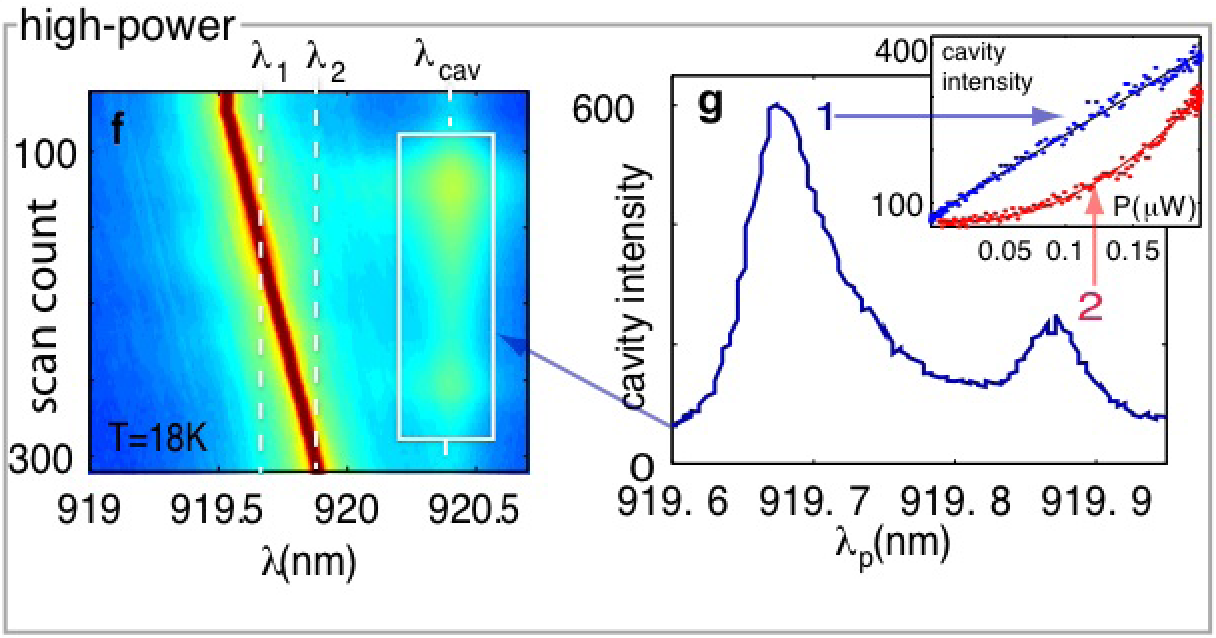
(Ranges from 3.7 to 6.3 GHz, > 0.1 g)



"The theory does not fully explain the observation, suggesting that pure dephasing is only a part of the off-resonant driving mechanism between the QD and cavity. Phonon-mediated and two-photon absorption processes probably also play a role, but are not captured in our model."

Pump Power Dependence of Coherent Excitation

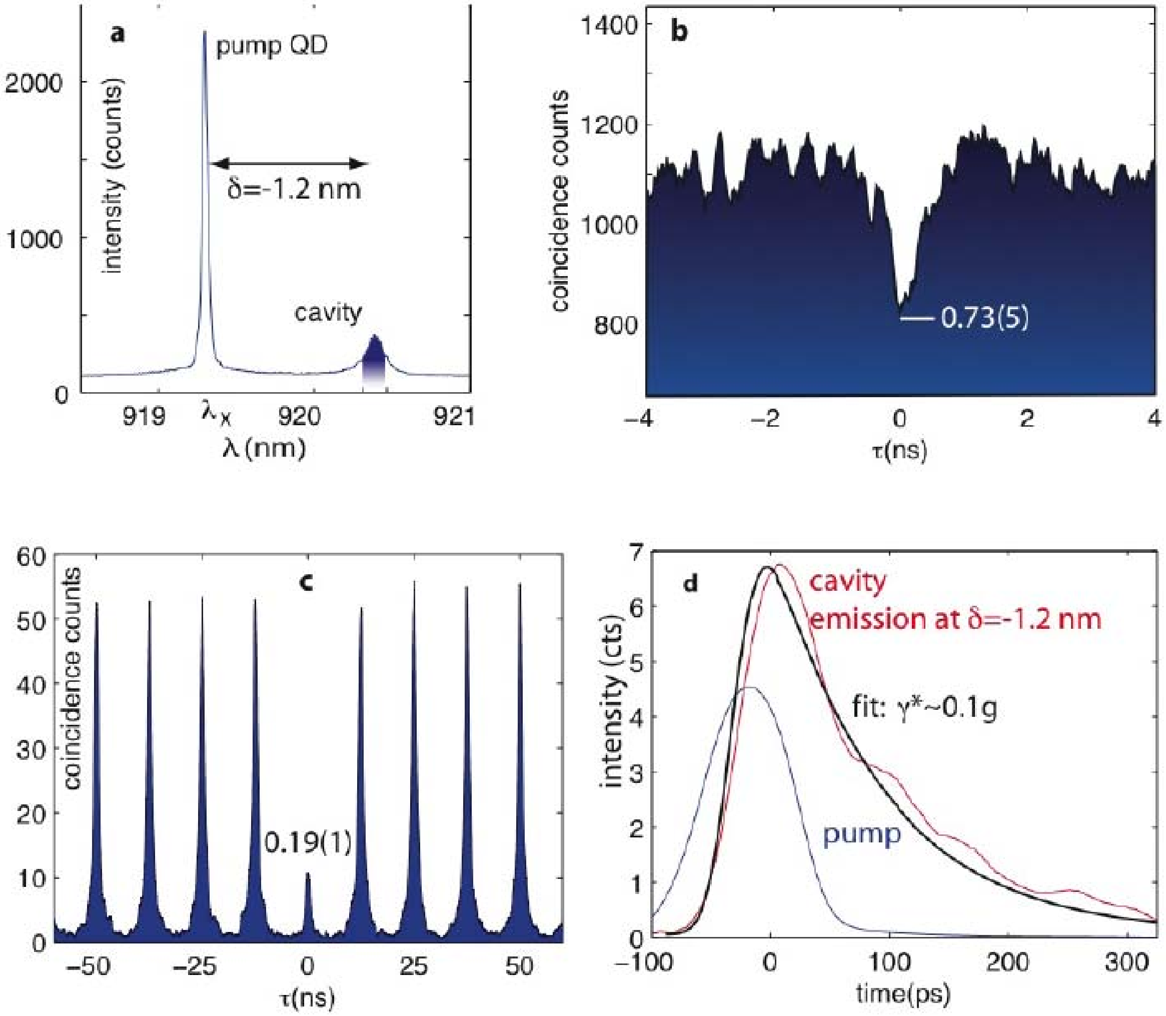
(200 nW before objective, 17 times higher)



- Features far more blurred (attribute to higher spectral diffusion at high intensity) (?)
- Second peak at higher wavelength
- Power dependence of this peak is quadratic, suggesting bi-exciton state resonantly pumped by 2-photon absorption

Second order correlation function

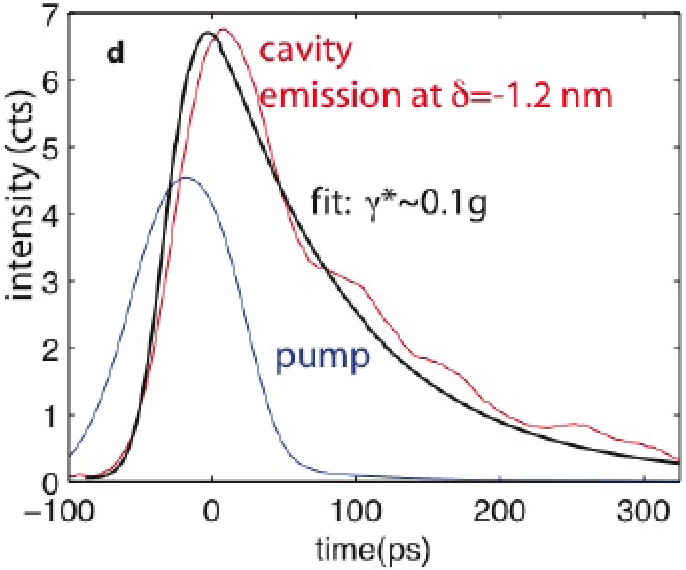
- Check photon statistics to confirm single-emitter character
- Pump QD, off cavity resonance, spectrally filter emission at λ_{cav}
  - Send light to HBT setup
  - For cw driving, depth of antibunching dip is limited by 300 ps time resolution of detectors (vs. excited state lifetime of 118 ps)
  - Go to pulsed driving, resonant with QD (40 ps)
  - Single-photon (ish) source !
  - Main source of coincidences at τ = 0 is residual counts from tail of pump laser.



Better than other QD based single photon sources: no timing jitter from above-resonant, PL type driving. Emission stabilized by cavity frequency (can match frequency, temporal mode profile of different sources). “albeit at the cost of efficiency”… but no efficiency quoted!

Time resolved emission for detuned case

- Drive QD on resonance, with cavity detuned.
- Measure emission at λ_{cav}
- QD-driven cavity emission lifetime is 118 ps for this detuning.
- Use this to infer dephasing rate
- Done with Monte Carlo, with γ^* the only free parameter
- This is how they get γ^*= 0.10(1) g = 2.5 GHz



Conclusions

1. Time-resolved “reflectivity” measurements show Rabi oscillations -> means for observing and manipulating the QD

2. Resonant driving of cavity-detuned dot efficiently populates cavity mode -> new insight, and new tool for for high-res QD spectroscopy

3. On-demand single photon source from resonantly driven QD

4. “In the future, much larger coupling efficiencies will be required. The all-optical techniques discussed here are compatible with integrated photonic crystal structures, where cavities coupled to single QD’s may be connected through networks of waveguides and other chip-integrated elements.”