HARVARD
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Photons as Qubits: Amplification and Control

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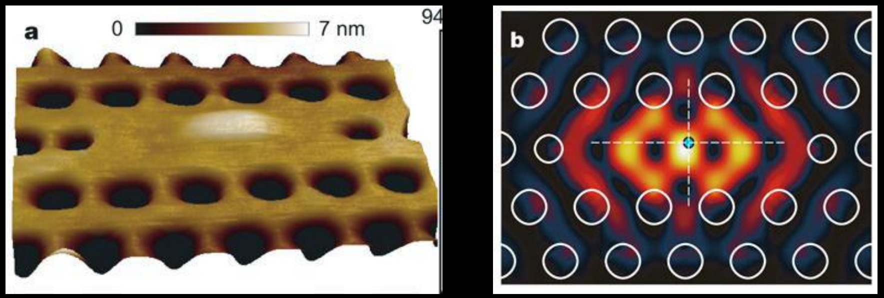
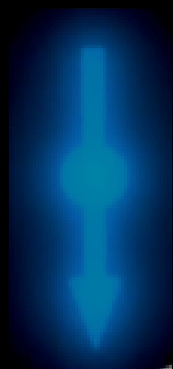


NSF/DOE Quantum Science Summer School (QS3)

June 6, 2019

A NEW MODALITY OF INFORMATION:

"Quantum bit" = qubit



$|0\rangle$ $|1\rangle$

2 basis states

Superposition

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

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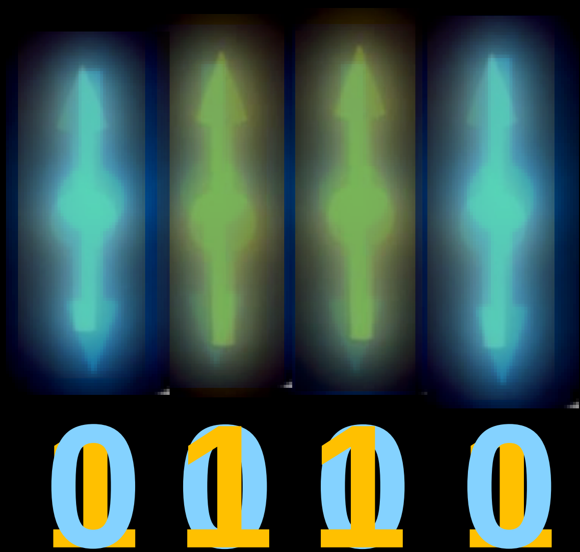
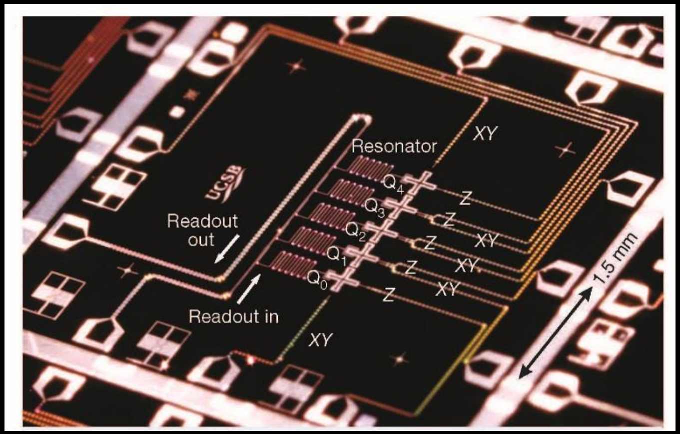


2 or more qubits, physical interaction -> Entanglement

Important Criteria for qubits:

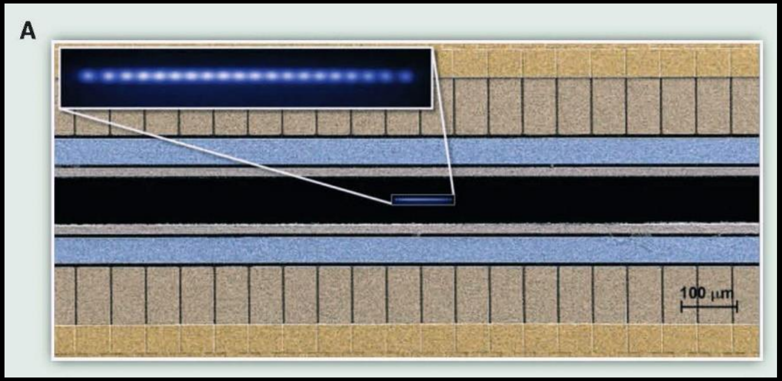
- Coherence
- Control: preparation and read out

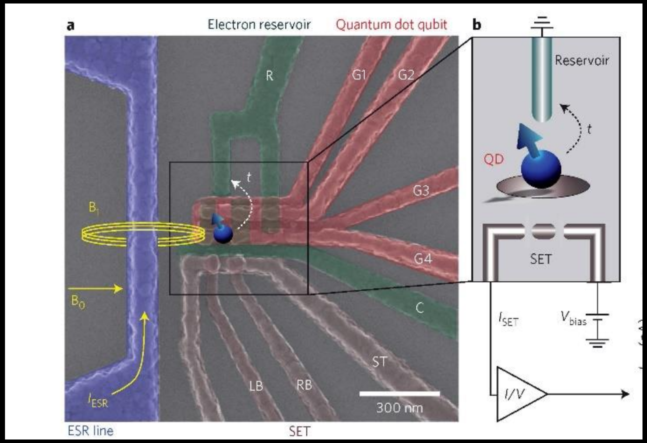
CANDIDATE QUBITS:



Superconductors (Josephson Junctions)
Cleland, Martinis, *Nature* **508** (2014)

Trapped Ions
Monroe & Kim, *Science* **339** (2013)



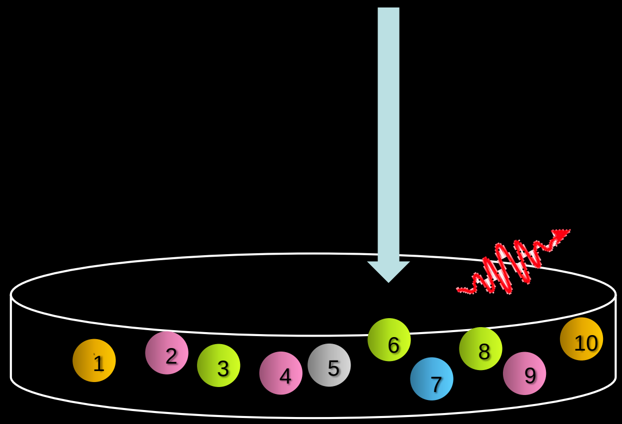


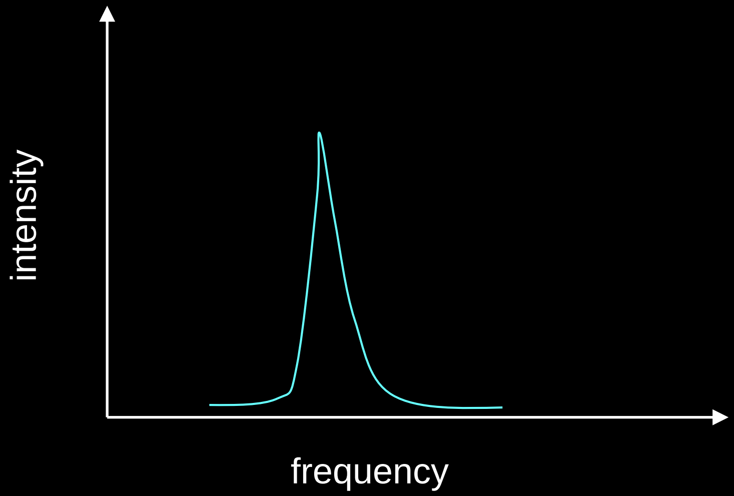
Si Quantum Dots
Veldherst, Dzurak, *Nat. Nanotech.* **9** (2014)

CHOOSING QUBITS, CHOOSING THE “FRAMEWORK”

- How do we initialize and read-out qubit states?
- How do we ensure “coherence” and “isolation” of the qubit?
- How do we “control locally” but “think globally”?

- Identify a QUBIT that has a unique PHOTON signature
- Selectively READOUT that QUBIT : record a ROBUST photon signal





CHOOSING QUBITS, CHOOSING THE “FRAMEWORK”

- How do we initialize and read-out qubit states?
- How do we ensure “coherence” and “isolation” of the qubit?
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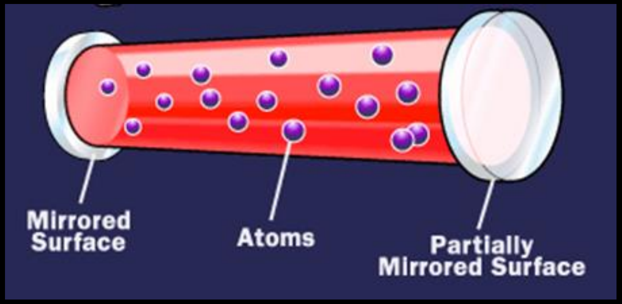
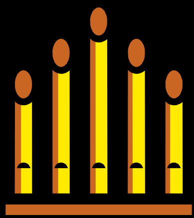
- Selectively READOUT that QUBIT : record a ROBUST photon signal

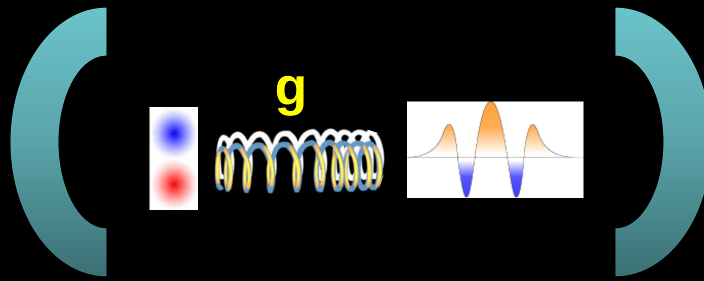
Selective amplification of a light signal:
Perhaps the “framework” can be a CAVITY



https://science.howstuffworks.com/light10.htm

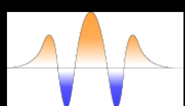
A NANO-SCALE CAVITY FOR “QUBITS”



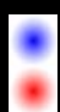


CAVITY

Resonant cavity frequencies determined by geometry



Discrete PHOTON states (from geometry)



A two-level ELECTRONIC system (aka atom)

Design the cavity to achieve a strong interaction (coupling,**g**) between the ELECTRONIC STATES and the PHOTON states, so the cavity can:

- increase the rate of emission of photons from the atom
- control the timing of photon emission
- create a new combined electronic-photonic state

THE TOPICS FOR TODAY

- Semiconductor (GaAs) QUANTUM DOTS
- Photonic Crystal Cavities: structure, fabrication & metrics
- Achieving STRONG COUPLING: new entangled light-matter state

References:

1. Vahala, *Optical Microcavities;*
2. Hennessy et al., *Quantum nature of a strongly coupled single quantum dot-cavity system.*

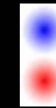
THE TOPICS FOR TOMORROW

- Atomic-scale “defects” in SiC
- Integrated defect-photonic crystal cavity results
- New challenges and opportunities

References:

3. Weber et al., *Quantum computing with defects*
4. Bracher et al., *Selective Purcell enhancement…..*

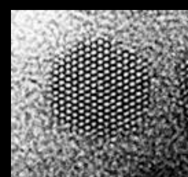
QUANTUM DOTS: ARTIFICIAL ATOMS



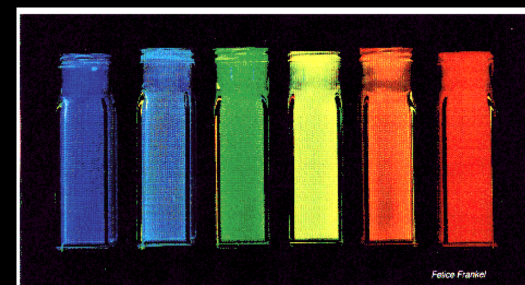
- crystalline semiconductor, 1000’s of atoms
- diameters: few to 10’s of nanometers
- size and shape determines optical properties

Electron Micrograph of quantum dot

Paul Alivisatos, CdSe



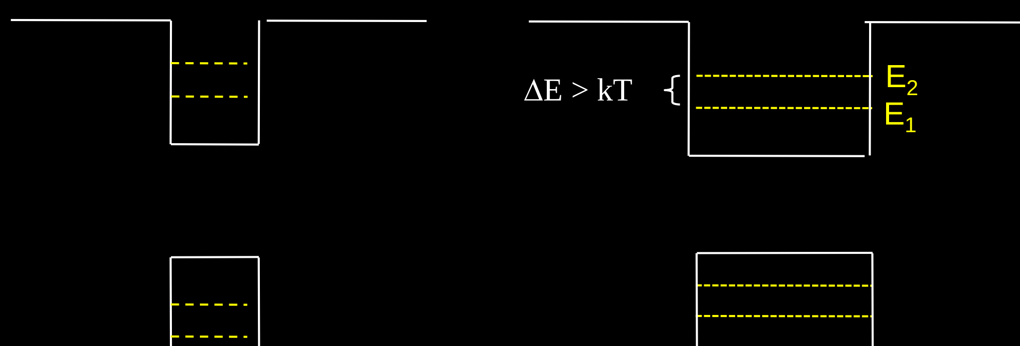
Dabhousi, Bawendi 1997



Colloidal CdSe quantum dots

Conduction band

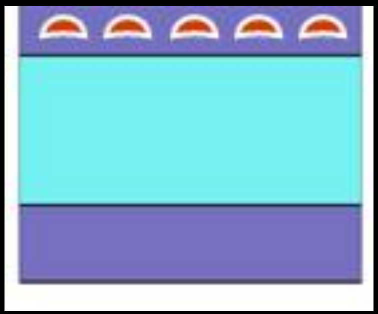
Valence band



small

large

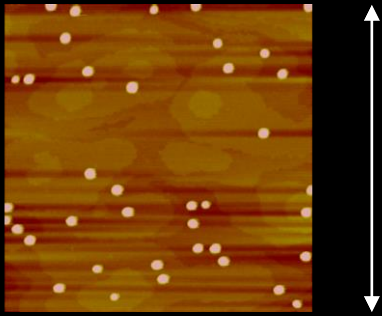
EPITAXIALLY GROWN QDs, INTEGRATED INTO THE STARTING MATERIAL



QD layer

AlAs layer

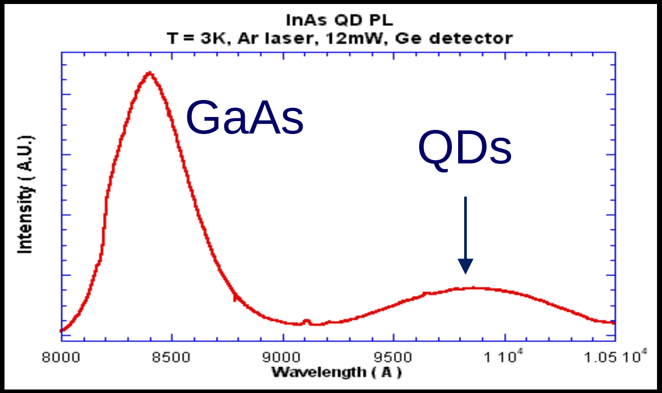
GaAs layer



1 micron

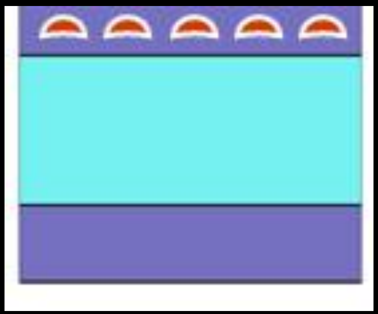
AFM of InAs QDs

We use quantum dots integrated/embedded within the starting material
~ 30 nm diameter, 5 nm height
~ 11% variation in size



- Broad QD peak indicates variation in QD size (30 meV)
- Note measurements made at 3K

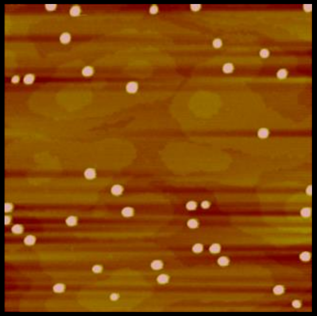
EPITAXIALLY GROWN QDs, INTEGRATED INTO THE STARTING MATERIAL



QD layer

AlAs layer

GaAs layer

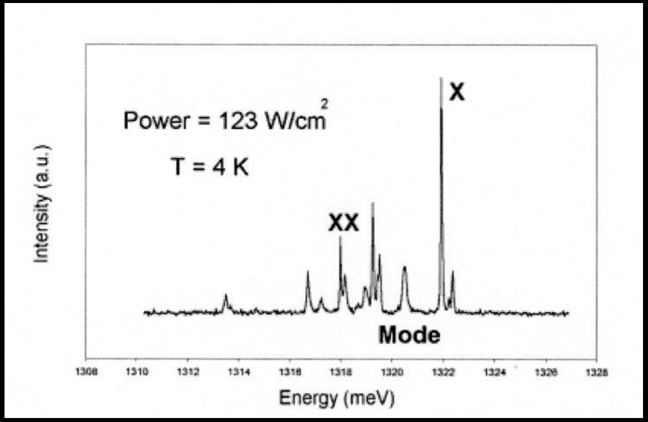


1 micron

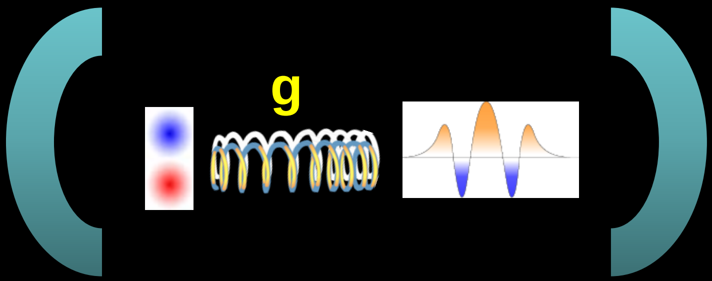
AFM of InAs QDs

We use quantum dots integrated/embedded within the starting material
~ 30 nm diameter, 5 nm height
~ 11% variation in size

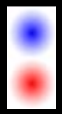
- Focus on single QDs
- Narrow linewidths (10's of μeVs)
- x = exciton, xx = bi-exciton



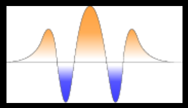
PUTTING TOGETHER THE QD-CAVITY SYSTEM



CAVITY

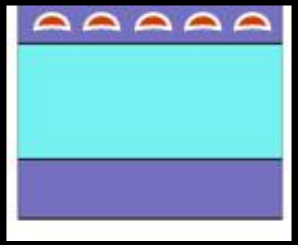


Quantum dots with photons with wavelength 900 nm – 1 μm

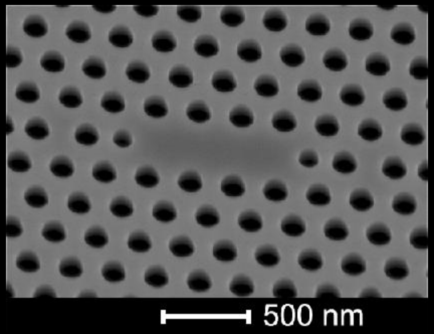


How do we design the cavity?

How do we connect cavity to QD?



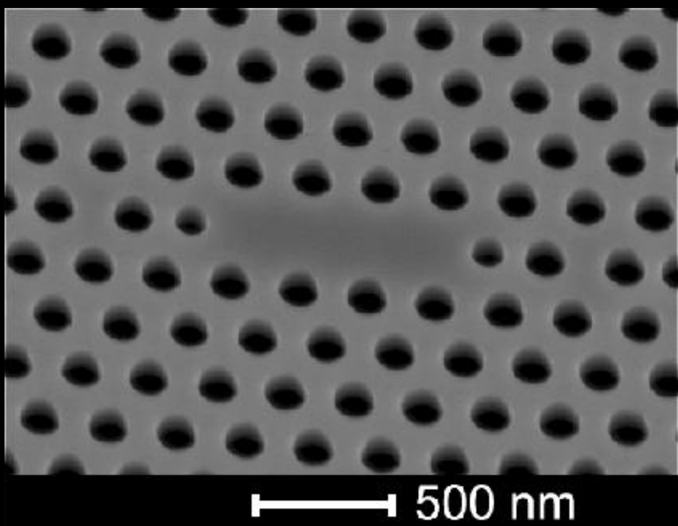
QDs embedded in cavity material



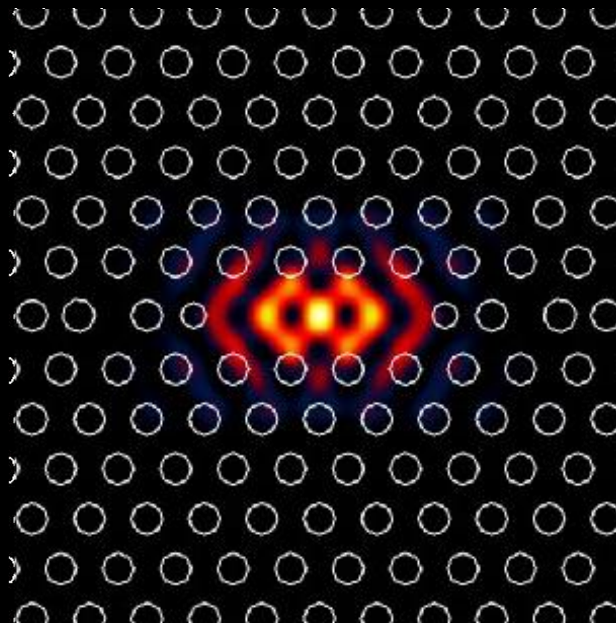
Photonic Crystal Cavity

EPITAXIALLY GROWN QDs, INTEGRATED INTO THE STARTING MATERIAL

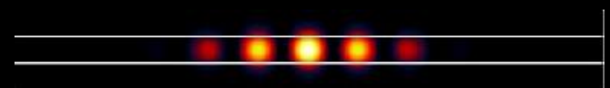
GaAs Photonic Crystal



top



side



Periodic pattern of etched holes -> variation of index of refraction

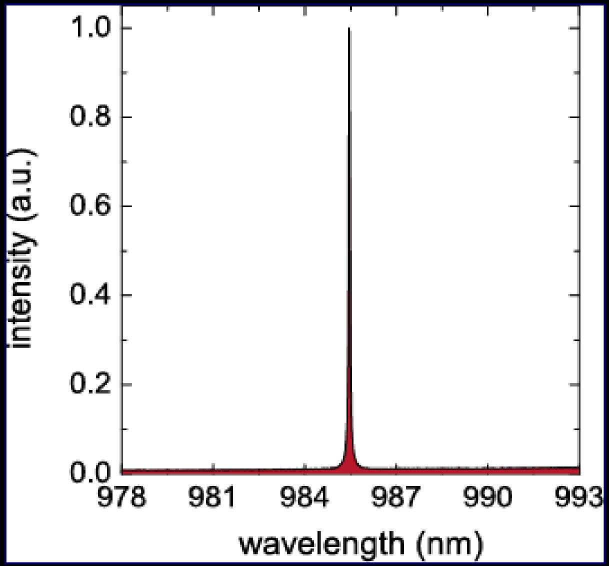
$n_{air} = 1$

$n_{GaAs} = 3.4$

Very high electromagnetic field
Confined within a very small volume; $[\lambda/n]^3$

EPITAXIALLY GROWN QDs, INTEGRATED INTO THE STARTING MATERIAL

A unique frequency/wavelength
associated with this field



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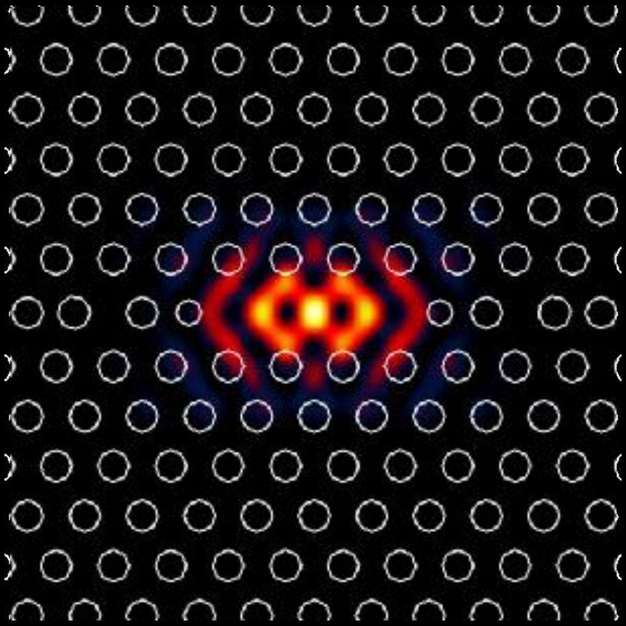
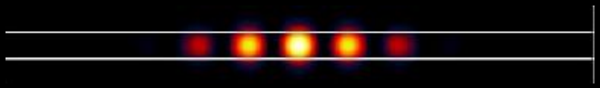


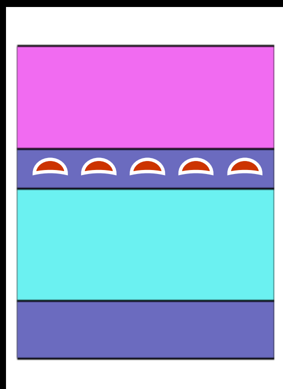
side

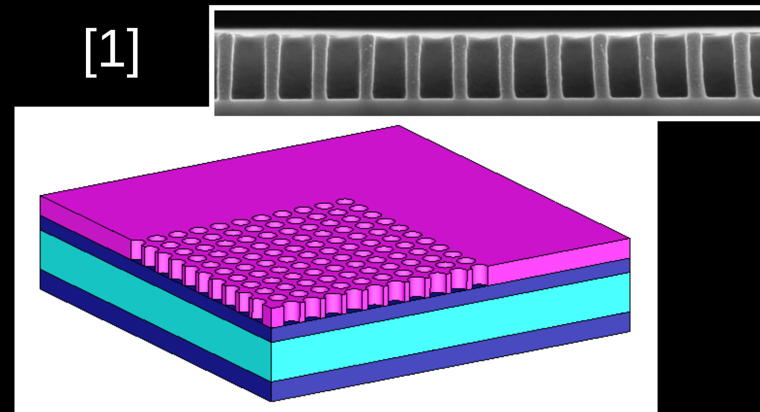


The narrowness of this linewidth is important

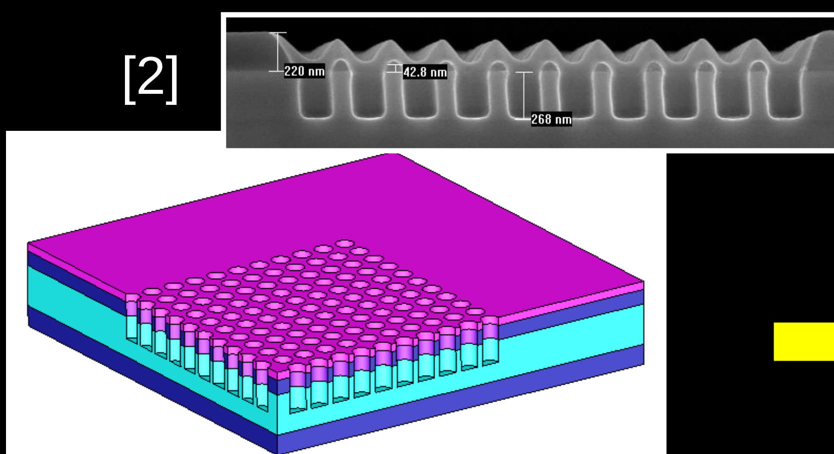
The geometry of the cavity determines its *resonant frequencies*

FABRICATION OF THE CAVITY

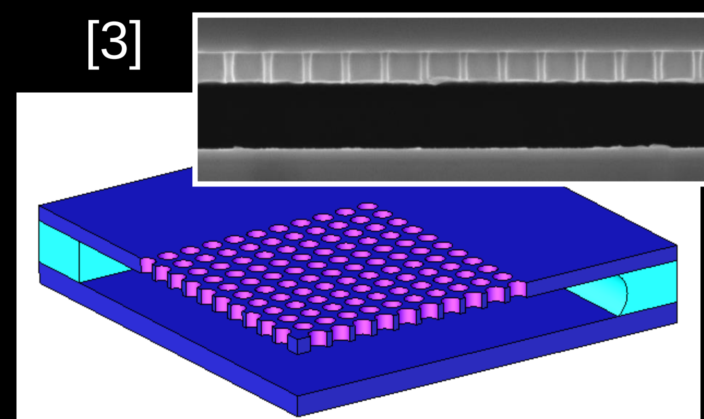




Electron-beam lithography



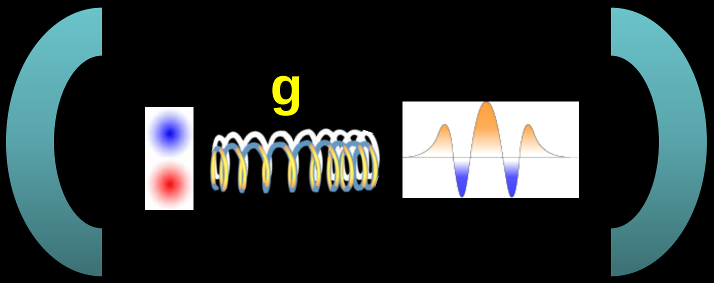
dry anisotropic etching



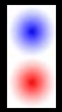
HF selective wet etch

Cavity: a membrane patterned with structures at the 100 nm scale

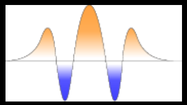
PUTTING TOGETHER THE QD-CAVITY SYSTEM



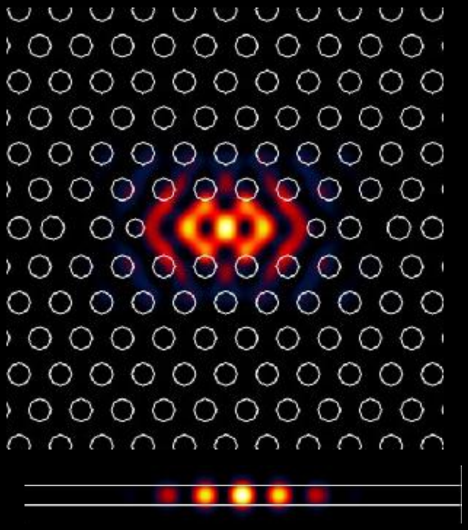
CAVITY



Quantum dots with photons with wavelength 900 nm – 1 μm



How do we design the cavity?



top

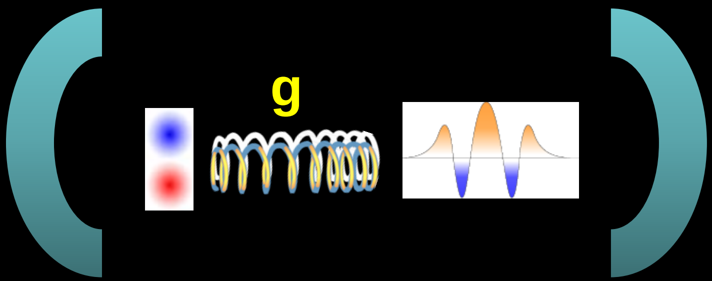
side

TIME OUT

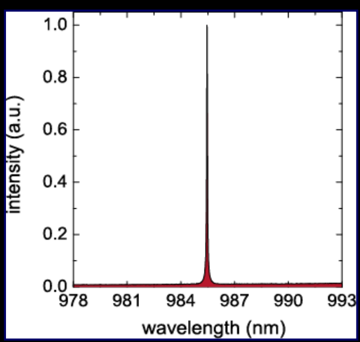
How do we connect (couple) cavity to QD?

PUTTING TOGETHER THE QD-CAVITY SYSTEM:

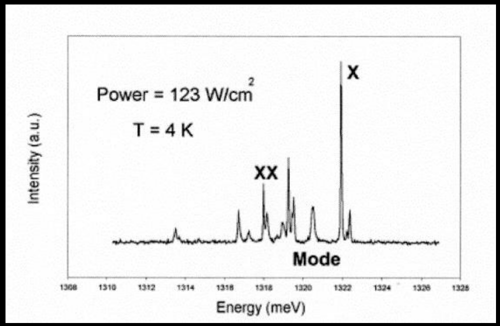
What do you think is important here?



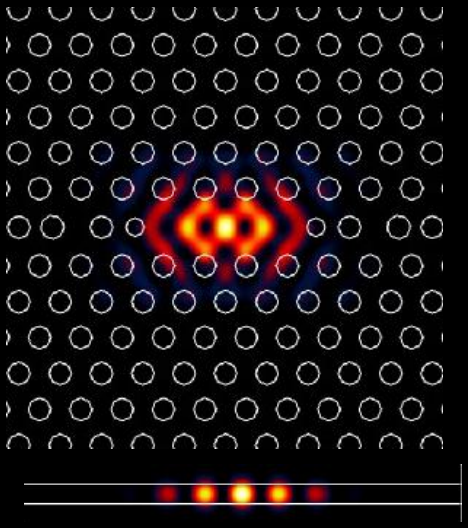
CAVITY



Cavity resonance



Quantum dot spectrum



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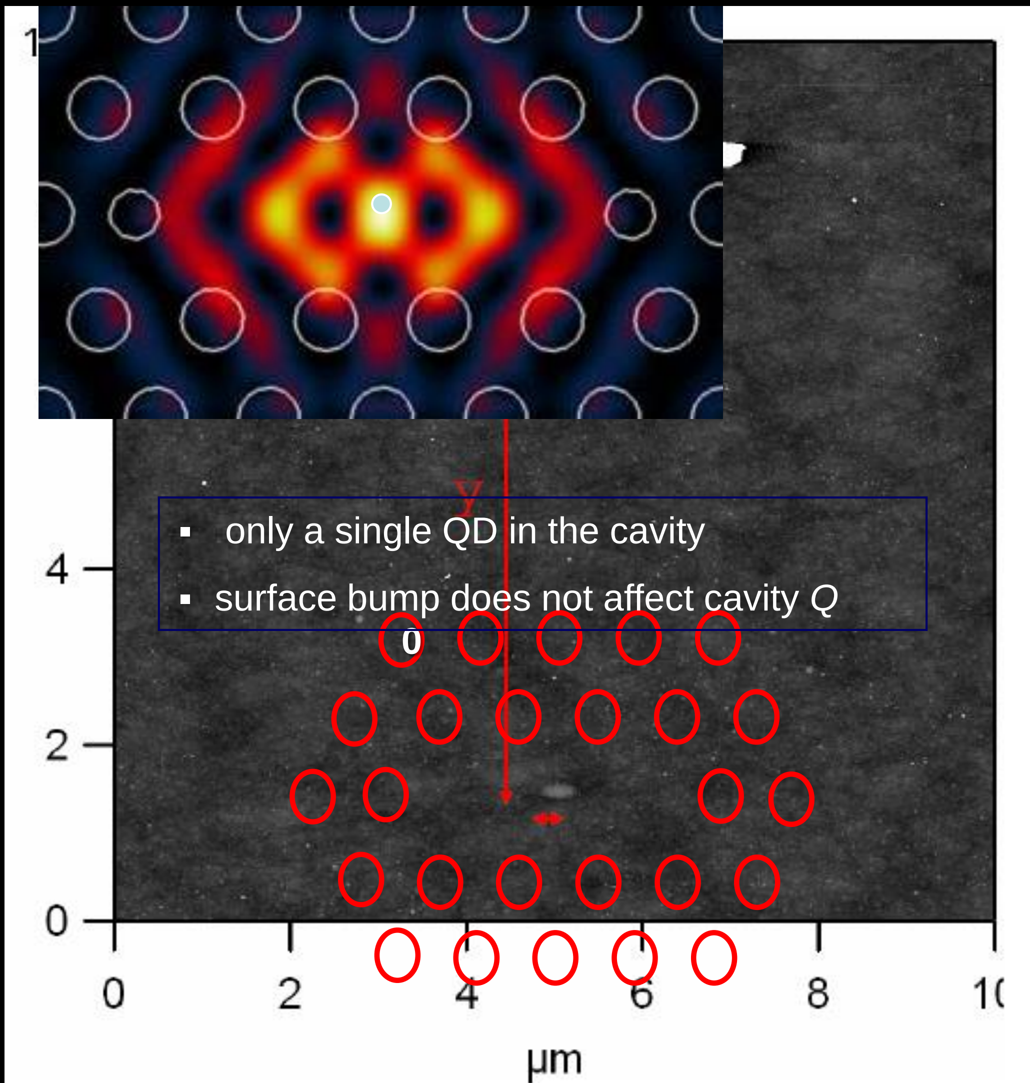
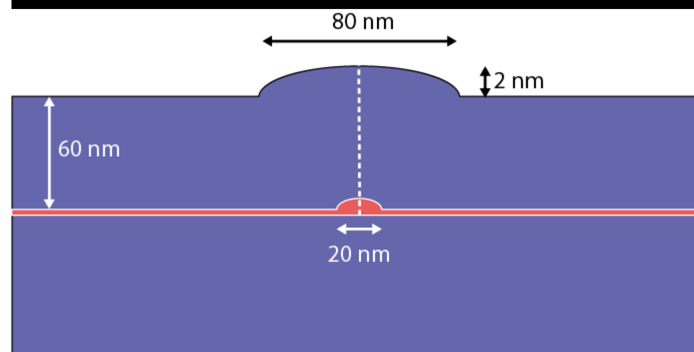
PLEASE TAKE 15 MINUTES WITHIN GROUPS TO DISCUSS THIS, NOTE CONCEPTS THAT ARE UNCLEAR

ALIGNING A SINGLE QD TO THE CAVITY MODE

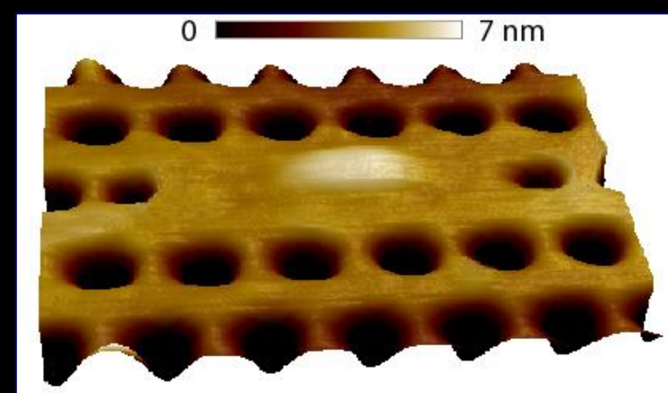


- only a single QD in the cavity
- surface bump does not affect cavity *Q*

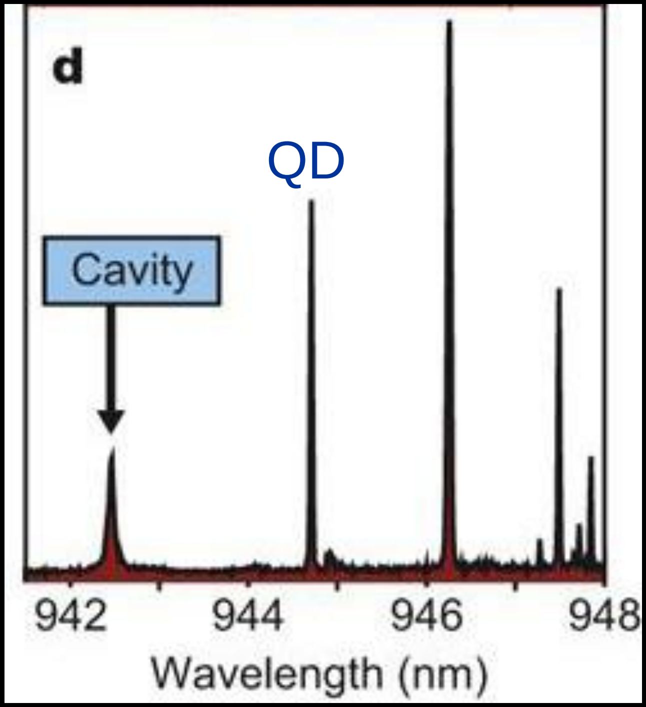
use AFM mapping to detect a single QD beneath the surface!



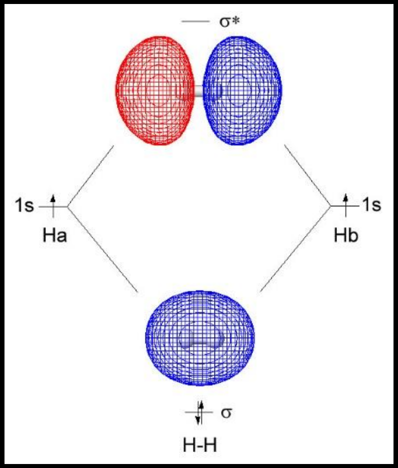
map relative to metal alignment marks



WHAT TO EXPECT IF THERE IS "STRONG COUPLING"

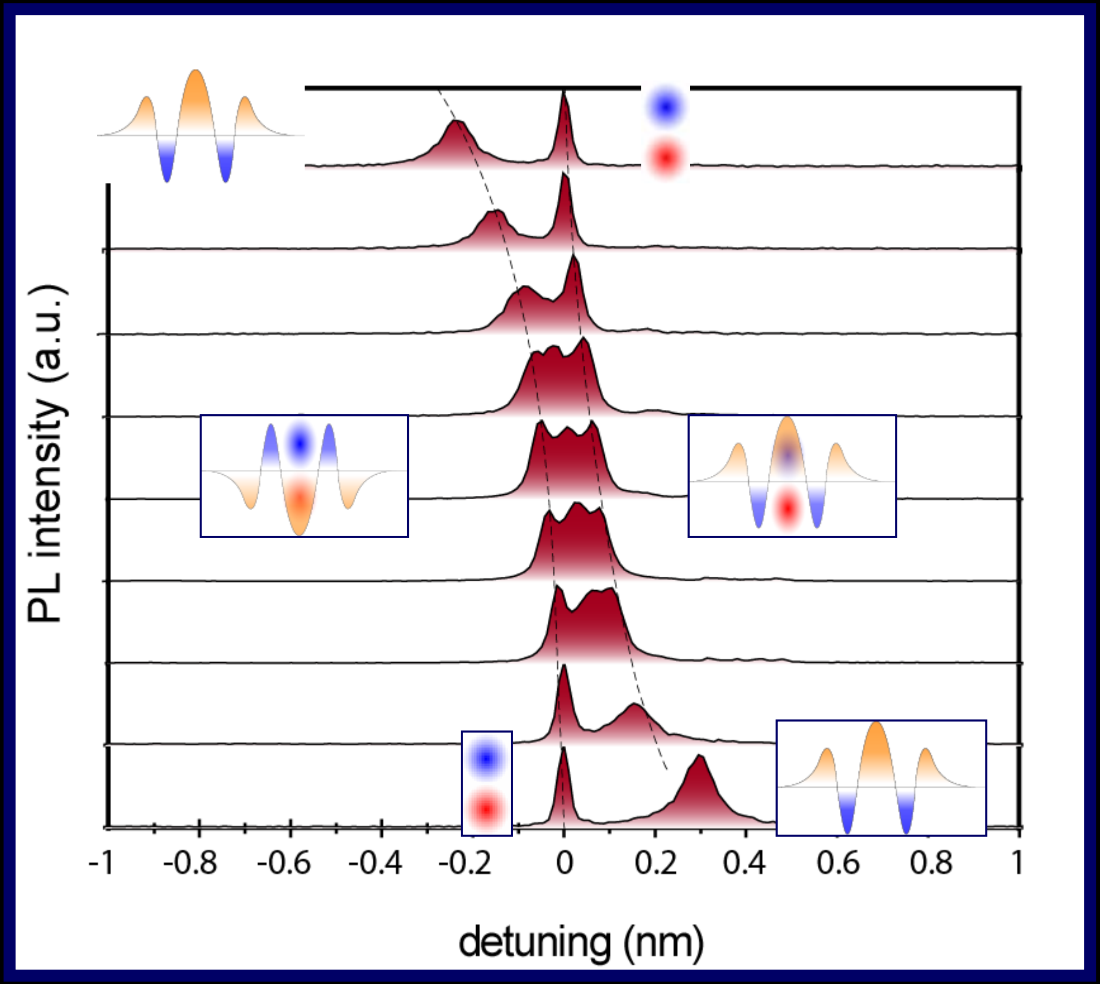


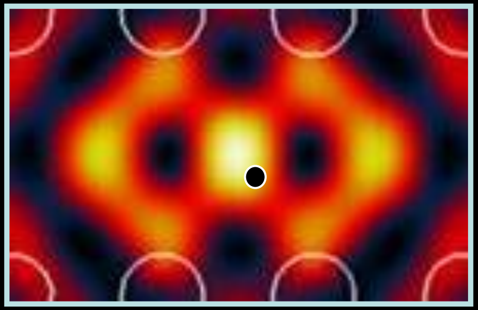
- We can SHIFT the cavity mode in wavelength (condense material onto cavity)
- We can bring the cavity mode closer in wavelength to the QD transition, BUT
- If CAVITY and QD are COUPLED (i.e. same wave function), then they CANNOT have the same energy.



Similar to H atoms within H_2

“ANTI-CROSSING”: THE QD-CAVITY “MOLECULE”





- clear <u>anti-crossing</u>
- only one QD in the cavity

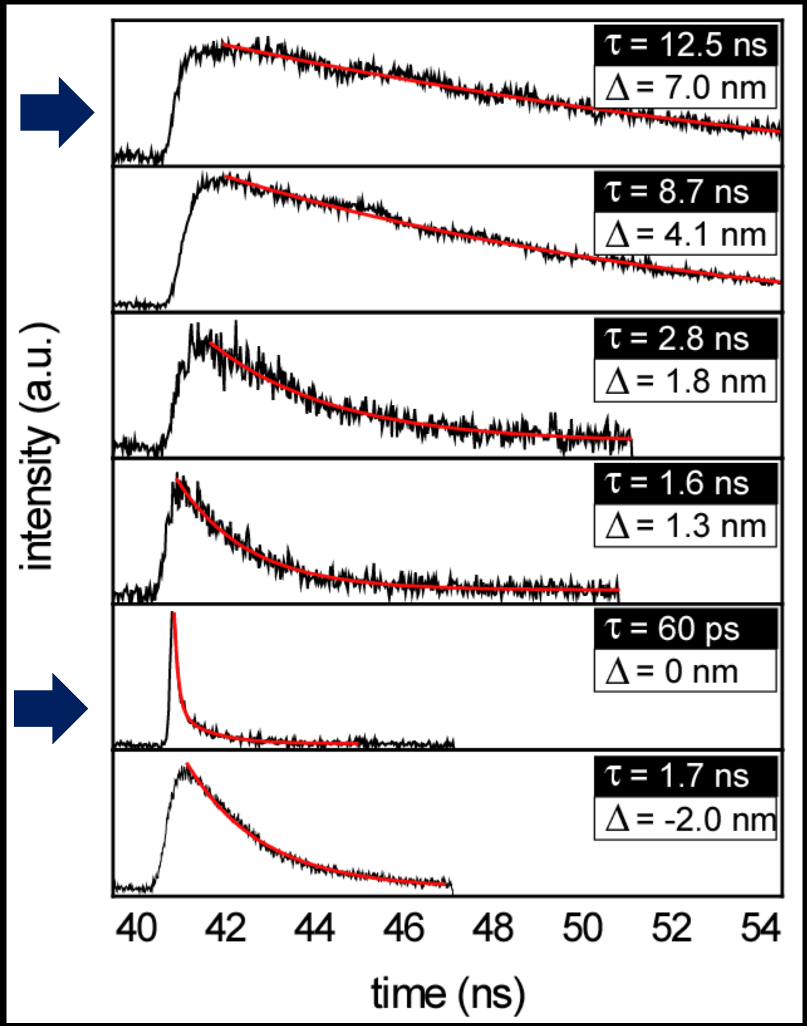
Hennessy et al.,
Nature 445, p. 896-9 (2007)

Tuning the mode through the exciton by monolayer condensation

CAVITY ENGINEERED CHANGES IN LIFE-TIME:

Using the cavity & changing Δ, difference between exciton and mode frequency, can change the radiative lifetime of the exciton

- nominal exciton lifetime in bulk : ~1 ns
- spontaneous emission suppression by a factor of 12 in "detuned" cavity
- at strong coupling, lifetime ~60 ps



SUMMARY

- Semiconductor (GaAs) QUANTUM DOTS: artificial atoms with electronic states
- Photonic Crystal Cavities: standing wave “modes” or photon states
- Interaction of CAVITY with QD: amplified photon signals, new entangled light-matter state

Please read the references,
Send me questions on terms or concepts

ACKNOWLEDGEMENTS

Groups of

Pierre Petroff, UCSB

Atac Imamoglu, ETHZ

Kevin Hennessy

Antonio Badolato