Coherence in semiconductor nanostructures Part VIII: Exciton-cavity system in the quantum strong coupling regime

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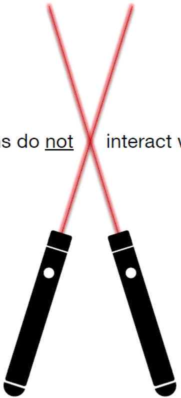
Institut Néel - CNRS
Grenoble France

Warsaw University, October-December 2020

Outline

Motivation

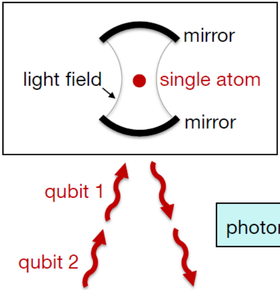
quantum computer based on single photons



photons do not interact with each other!

mediate interactions via

coherent light-matter interface:

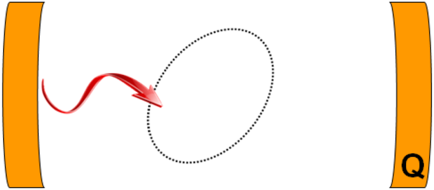


photon-photon gate

Duan & Kimble,
PRL **92**, 127902 (2004)

Strong coupling regime

Reversible temporal exchange of excitation between light & matter



Strong coupling regime

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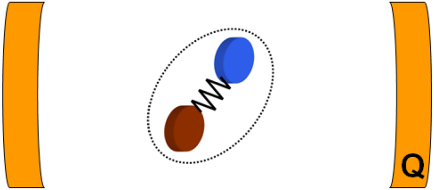

Strong coupling regime

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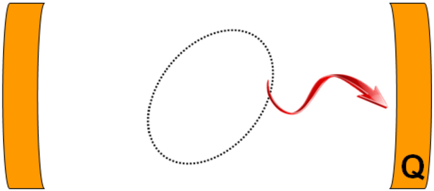

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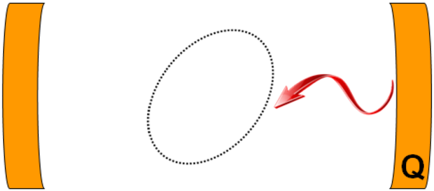
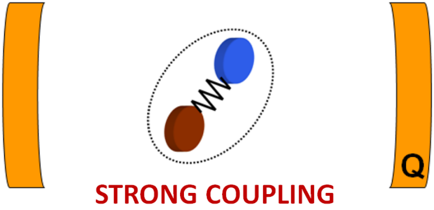


Strong coupling regime

Reversible temporal exchange of excitation between light & matter



Strong coupling regime

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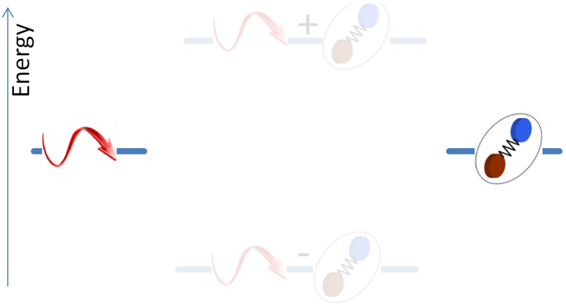

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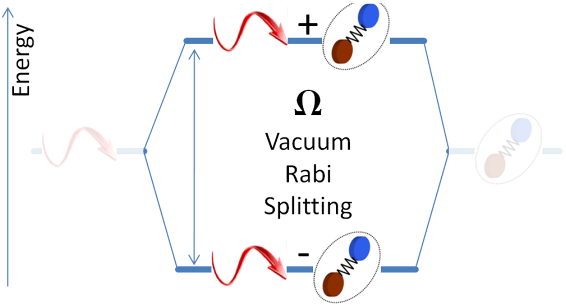


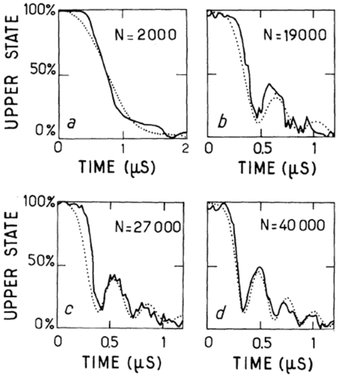
Polaritons: Reversible exchange of excitation $\Leftrightarrow$ energy splitting

Atomic clouds

Volume 51, Number 13 PHYSICAL REVIEW LETTERS 26 September 1983

Observation of Self-Induced Rabi Oscillations in Two-Level Atoms Excited Inside a Resonant Cavity: The Ringing Regime of Superradiance

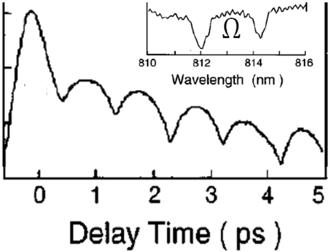
Y. Kaluzny, P. Goy, M. Gross, J. M. Raimond, and S. Haroche



Exciton clouds

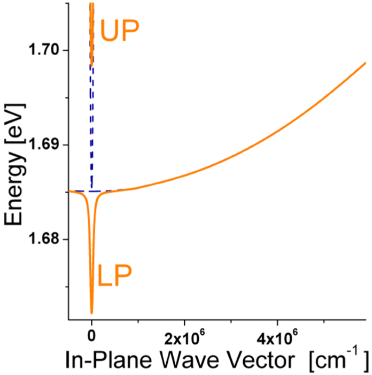
APPLIED PHYSICS LETTERS VOLUME 73, NUMBER 21 23 NOVEMBER 1998

Direct time-domain observation of transition from strong to weak coupling in a semiconductor microcavity ...via Heterodyne Pump-Probe



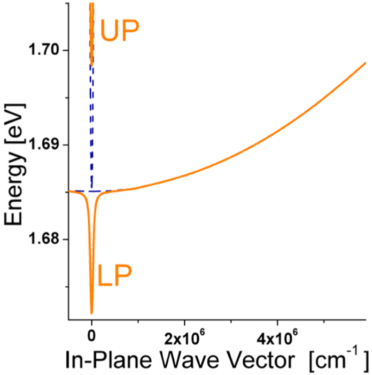
Polaritons: Reversible exchange ⇔ Spectral splitting

Why bother ?



Bosonic degeneracy at hand

Why bother ?



Bosonic degeneracy at hand

Coherent quantum light-matter interface

cavity decay rate

κ $\sim 1/Q$

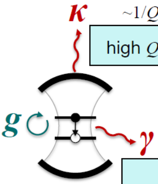
high Q-factor

coherent coupling rate

$1/\sqrt{V}\sim$

low V

(*micro*-cavity)



atom decay rate

$\gamma \sim \gamma_{\text{rad}}$

(radiative channel only)

$g \gg \kappa\,,\,\gamma$: strong-coupling regime

$$\Rightarrow C \gg 1$$

cooperativity

$$C = 2g^2/\kappa\gamma$$

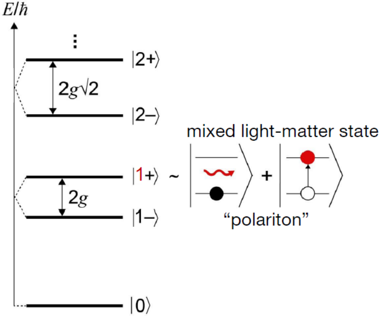
figure-of-merit

Coherent quantum light-matter interface

Jaynes-Cummings Hamiltonian

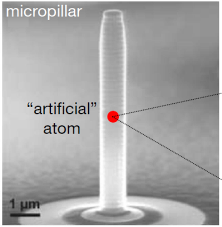
$$H = \underbrace{\hbar\omega_0 b^\dagger b}_{H_{\text{atom}}} + \underbrace{\hbar\omega_0 a^\dagger a}_{H_{\text{cavity}}} + \underbrace{\hbar g(ab^\dagger + a^\dagger b)}_{H_{\text{interaction}}}$$

→ anharmonic "ladder" of eigenstates



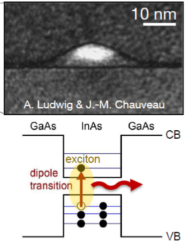
Strong coupling ($C \gg 1$) in the solid state?

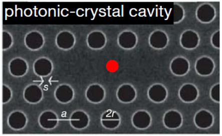
C ~ 1



Reithmaier *et al.*,
Nature **432**, 197–200 (2004)

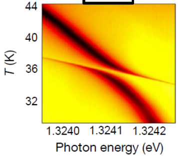
InAs quantum dot





Yoshie *et al.*,
Nature **432**, 200–203 (2004)

C ~ 5



Loo *et al.*,
PRL **109**, 166806 (2012)

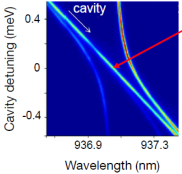
challenges:

- frequency tuning
- dot positioning
- photon collection

limitations:

- solid-state "noise"
- typical Q ~10,000

C ~ 100



Ota *et al.*,
APL **112**, 093101 (2018)

3

Jaynes-Cummings model

Description of fermion-boson interaction on a quantum level

- Coupling of a two-level system (QD) to a harmonic oscillator (fundamental cavity mode)

$$H_{JC} = \omega_c a^\dagger a + \omega_X X^\dagger X + g(aX^\dagger + a^\dagger X)$$

- ω_c: cavity mode frequency, ω_X: exciton transition energy, g: JC coupling, $\delta = \omega_c - \omega_X$: detuning, $a^{(\dagger)}$: bosonic photon ladder operators, $X^{(\dagger)}$: fermionic exciton ladder operators
- Block diagonal with blocks (in $|G, n\rangle$, $|X, n-1\rangle$ subspace)

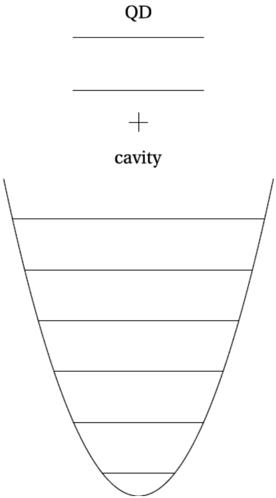
$$H_{JC}^{(n)} = \begin{bmatrix} n\omega_c & g\sqrt{n} \\ g\sqrt{n} & n\omega_c - \delta \end{bmatrix}$$

- Equivalent to a QD driven by a cw-laser with Rabi frequency $2g\sqrt{n}$ and carrier frequency ω_c

Jaynes-Cummings model

Description of fermion-boson interaction on a quantum level

- Eigenstates: exciton-polaritons
- Ground state: $|G, 0\rangle = |G\rangle \otimes |0\rangle$ with $E_0 = 0$
- Excited states (at $\delta = 0, \ n \geqslant 1$): $|n, \pm\rangle = \frac{1}{\sqrt{2}}\{|G, n\rangle \pm |X, n-1\rangle\}$
- Eigenenergies of the excited states ($\delta = 0$): $E_n^{\pm} = n\omega_c \pm g\sqrt{n}$
- Spectrum: JC-ladder, n: rung number



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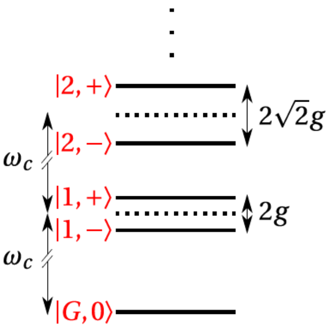
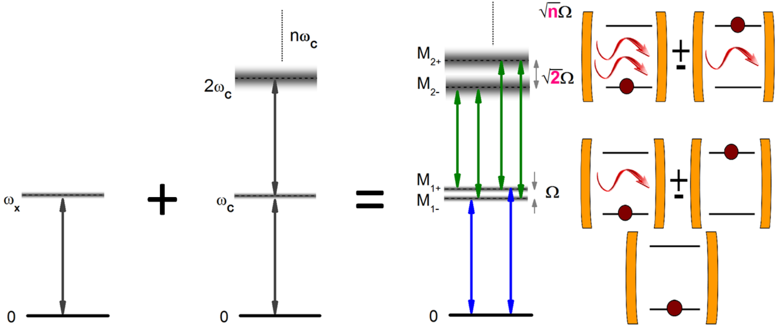


Quantum Strong Coupling

1 photon + cloud of transitions $\neq$ 1 photon + 1 transition



Jaynes-Cummings (JC) nonlinearity: $M_{n+} - M_{n-} \propto \sqrt{n}\Omega$

Quantum Strong Coupling

1 photon + cloud of transitions $\neq$ 1 photon + 1 transition

$$\sqrt{2}$$

Jaynes-Cummings (JC) nonlinearity: $M_{n+} - M_{n-} \propto \sqrt{n}\Omega$

Single atom

VOLUME 76, NUMBER 11 PHYSICAL REVIEW LETTERS 11 MARCH 1996

Quantum Rabi Oscillation: A Direct Test of Field Quantization in a Cavity

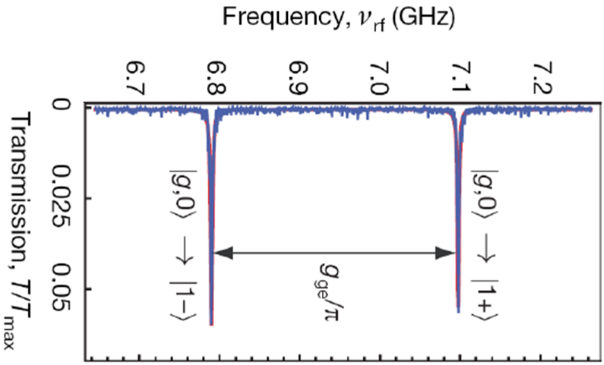
M. Brune, F. Schmidt-Kaler, A. Maali, J. Dreyer, E. Hagley, J. M. Raimond, and S. Haroche
Laboratoire Kastler Brossel, Département de Physique de l'Ecole Normale Supérieure, 24 rue Lhomond, F-75231 Paris Cedex 05, France*
(Received 9 November 1995)

We have observed the Rabi oscillation of circular Rydberg atoms in the vacuum and in small coherent fields stored in a high Q cavity. The signal exhibits discrete Fourier components at frequencies proportional to the square root of successive integers. This provides direct evidence of field quantization in the cavity. The weights of the Fourier components yield the photon number distribution in the field. This investigation of the excited levels of the atom-cavity system reveals nonlinear quantum features at extremely low field strengths.

Superconducting qbits

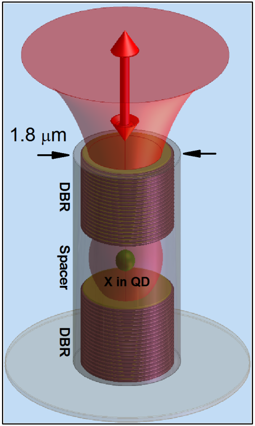
Climbing the Jaynes–Cummings ladder and observing its $\sqrt{n}$ nonlinearity in a cavity QED system

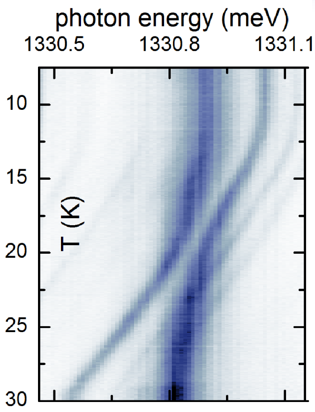
J. M. Fink[1], M. Göppl[1], M. Baur[1], R. Bianchetti[1], P. J. Leek[1], A. Blais[2] & A. Wallraff[1]



Outline

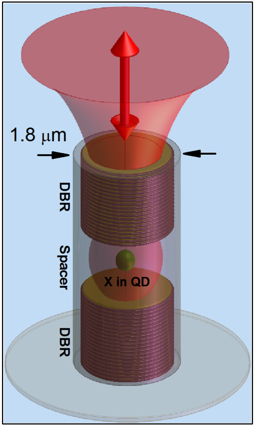
Single exciton in a μ-pillar

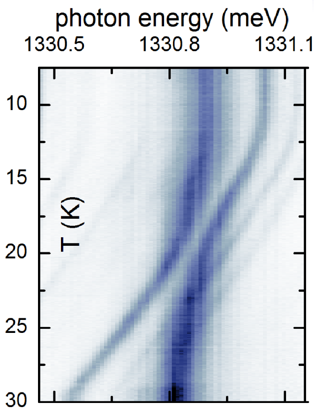




Our Goal: to demonstrate JC nonlinearity in a semiconductor

Single exciton in a μ-pillar





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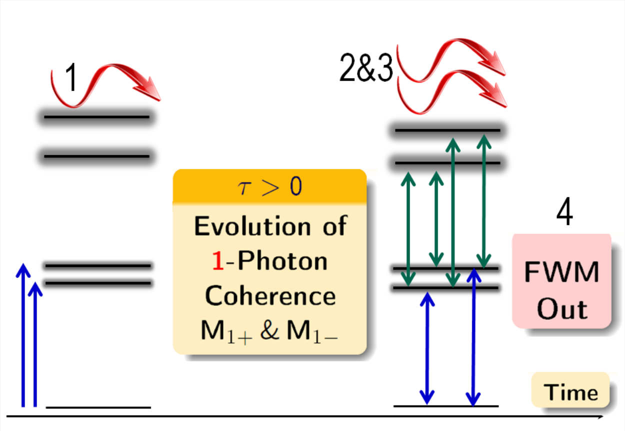
Why FWM for climbing the JC ladder ?



Because it grants a direct access to the 2nd rung via 2-photon coherence

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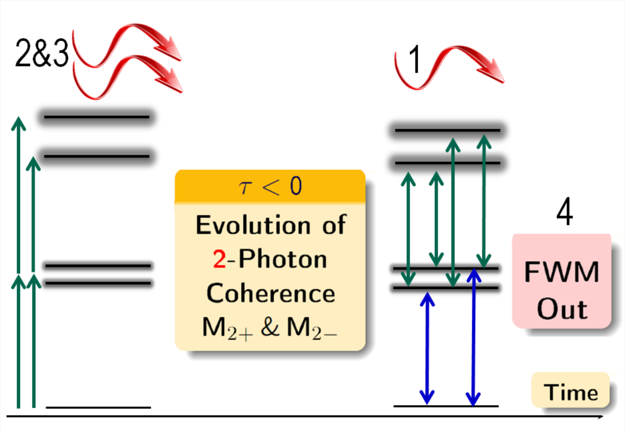

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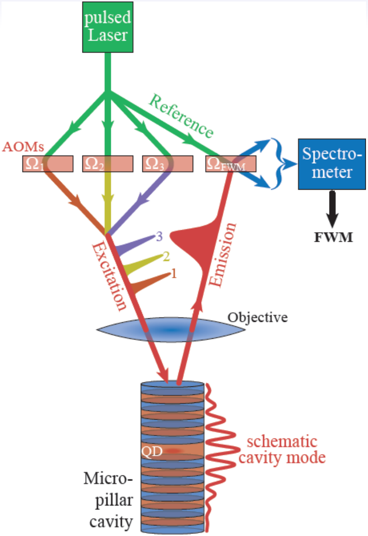
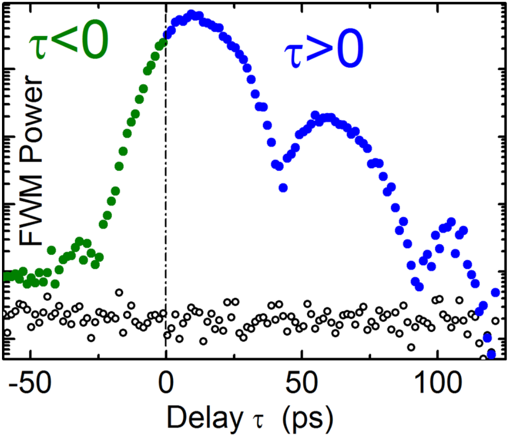
Experimental scheme

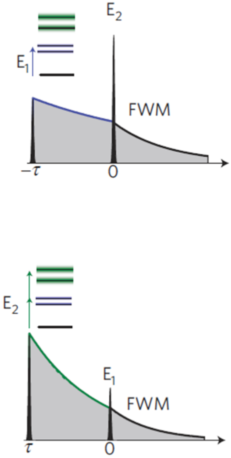


Coherent Dynamics

! $\sqrt{2}$ faster beating of the second rung detected !

JC nonlinearity demonstrated





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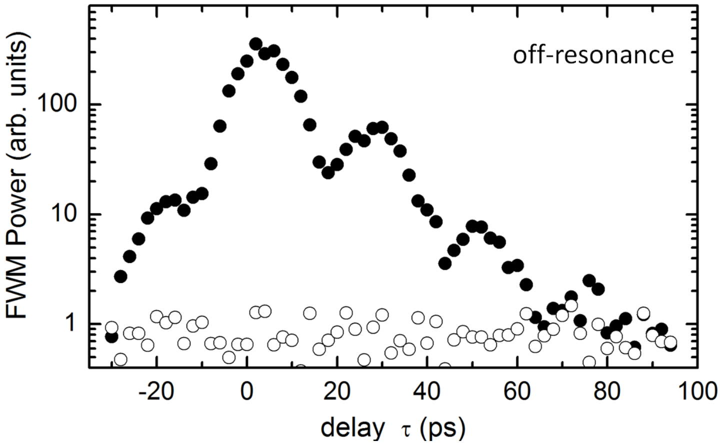

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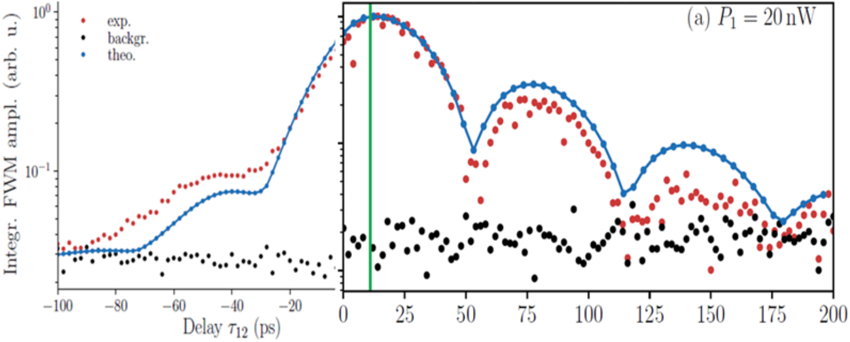
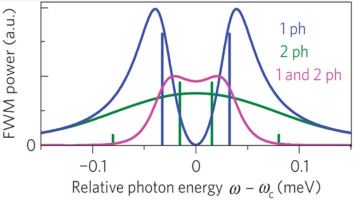
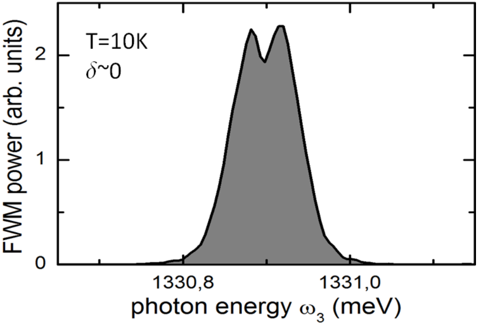


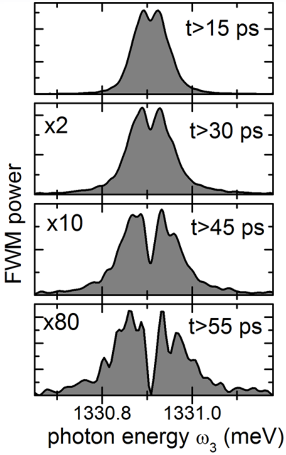
FWM spectrum of an exciton-cavity system





Time Filtering

$M_{1\pm} \leftrightarrow M_{2\pm}$ dephasing is 3 times faster than $0 \leftrightarrow M_{1\pm}$



Spectral recovery of $0 \leftrightarrow M_{1\pm}$ and signatures of $M_{1\pm} \leftrightarrow M_{2\pm}$

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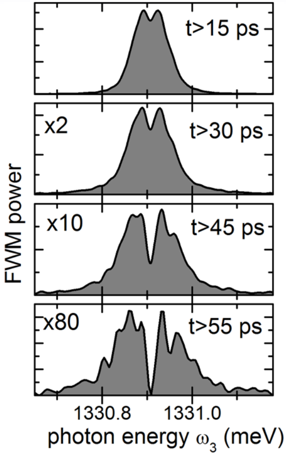
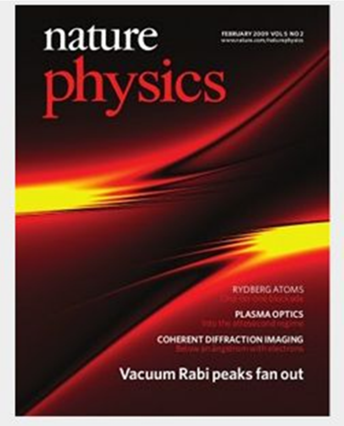
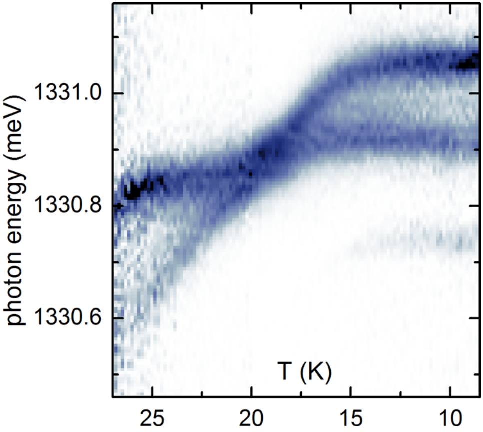


Spectral recovery of $0 \leftrightarrow M_{1\pm}$ and signatures of $M_{1\pm} \leftrightarrow M_{2\pm}$

Tuning curve in FWM

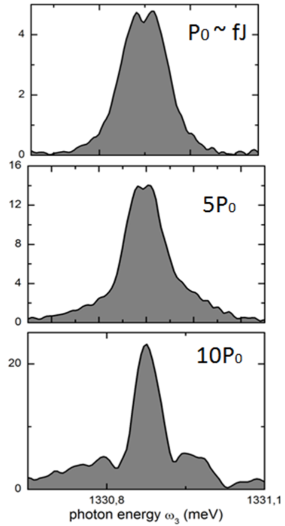
Superconducting Qbits $\Longleftrightarrow$ Semiconductor μ-pillars





Intensity Dependence

Spectral signatures of higher rungs' transitions

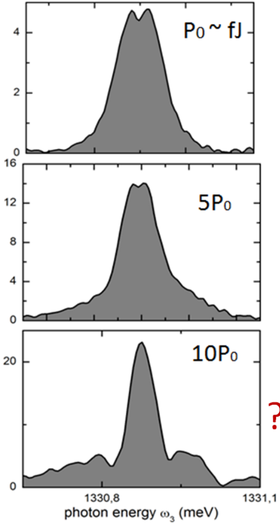


Intensity Dependence

Spectral signatures of higher rungs' transitions

5 levels

n levels

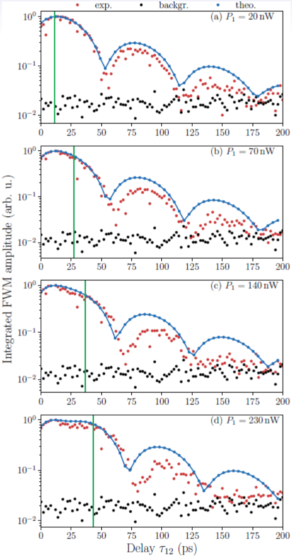


6 transitions

doublet + quadruplet

? Mollow triplet ?

Intensity Dependence

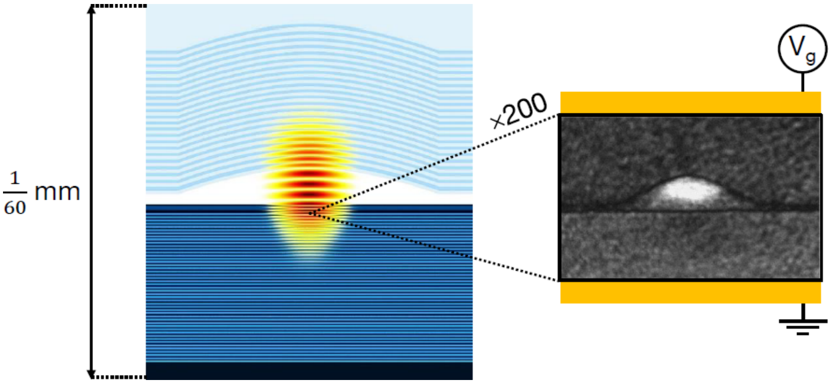


Outline

State of the art: Open Cavity

Cooperativity: $C = \frac{2g^2}{\kappa\gamma} = 150$!!!

Nature 575, 622 (2019)



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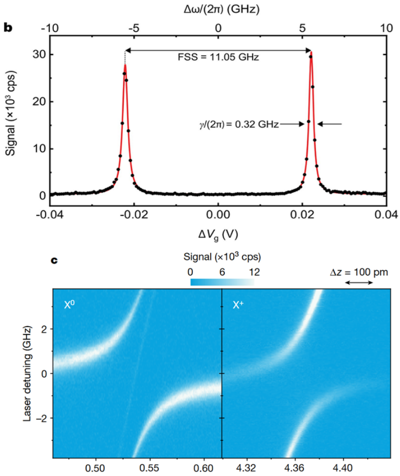

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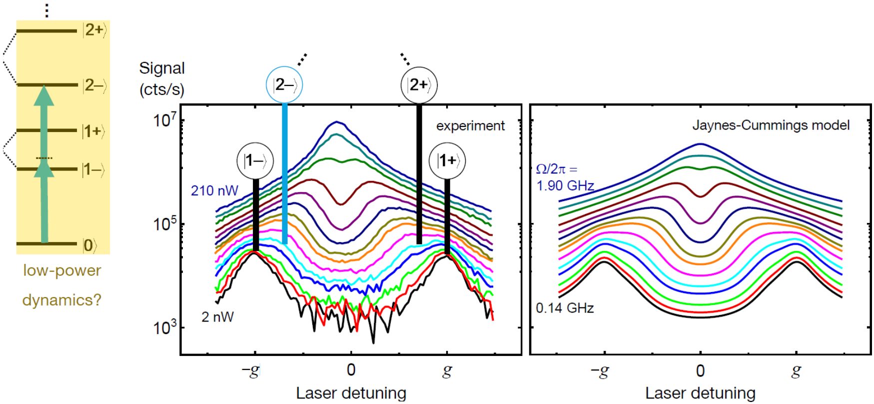
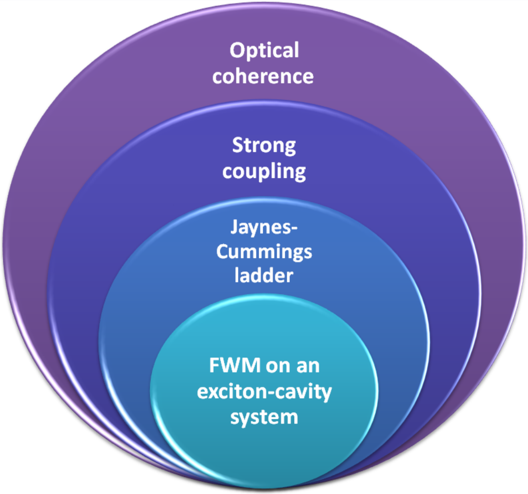
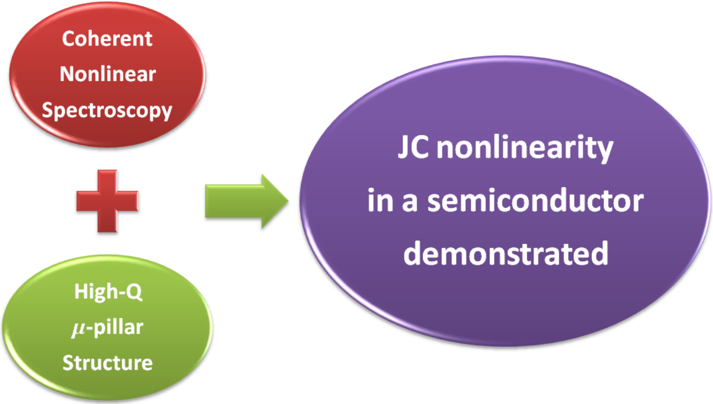


Summary II


Optical coherence
Strong coupling
Jaynes-Cummings ladder
FWM on an exciton-cavity system

Summary II


Coherent
Nonlinear
Spectroscopy
High-Q
μ-pillar
Structure
JC nonlinearity
in a semiconductor
demonstrated