Quantum Computation with Spins and Excitons in Semiconductor Quantum Dots (Part III)

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Condensed Matter Theory Group

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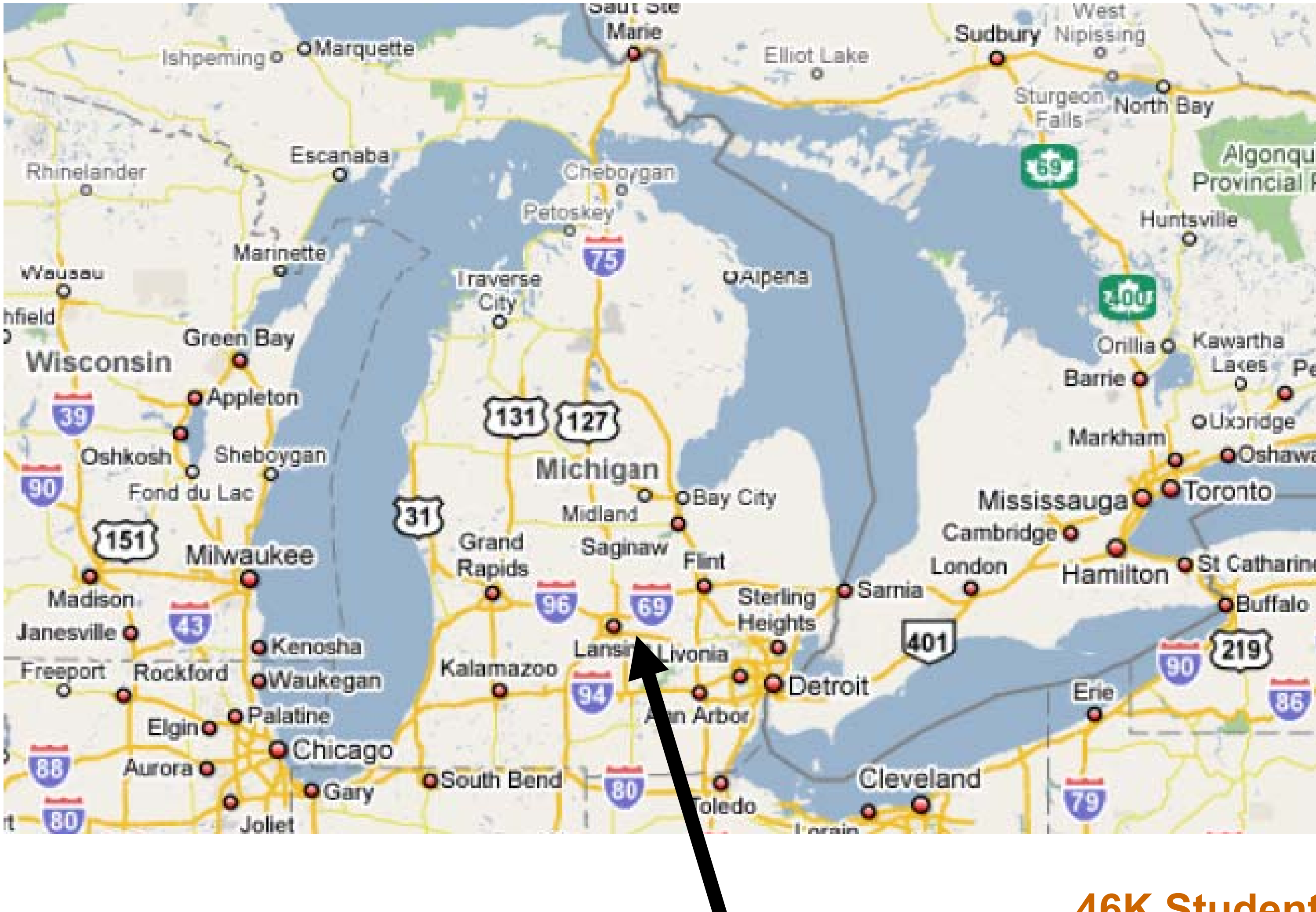
Michigan State University, East Lansing, Michigan

MICHIGAN STATE UNIVERSITY

Dipartimento di Fisica, Pisa, Italy July 11th, 14th, 15th 2008

Where is Michigan State University ?



www.msu.edu

East Lansing

46K Students
10K Graduates
36K Undergraduates

Research Groups

Astronomy / Astrophysics (10 faculty)

Condensed Matter Physics (17)

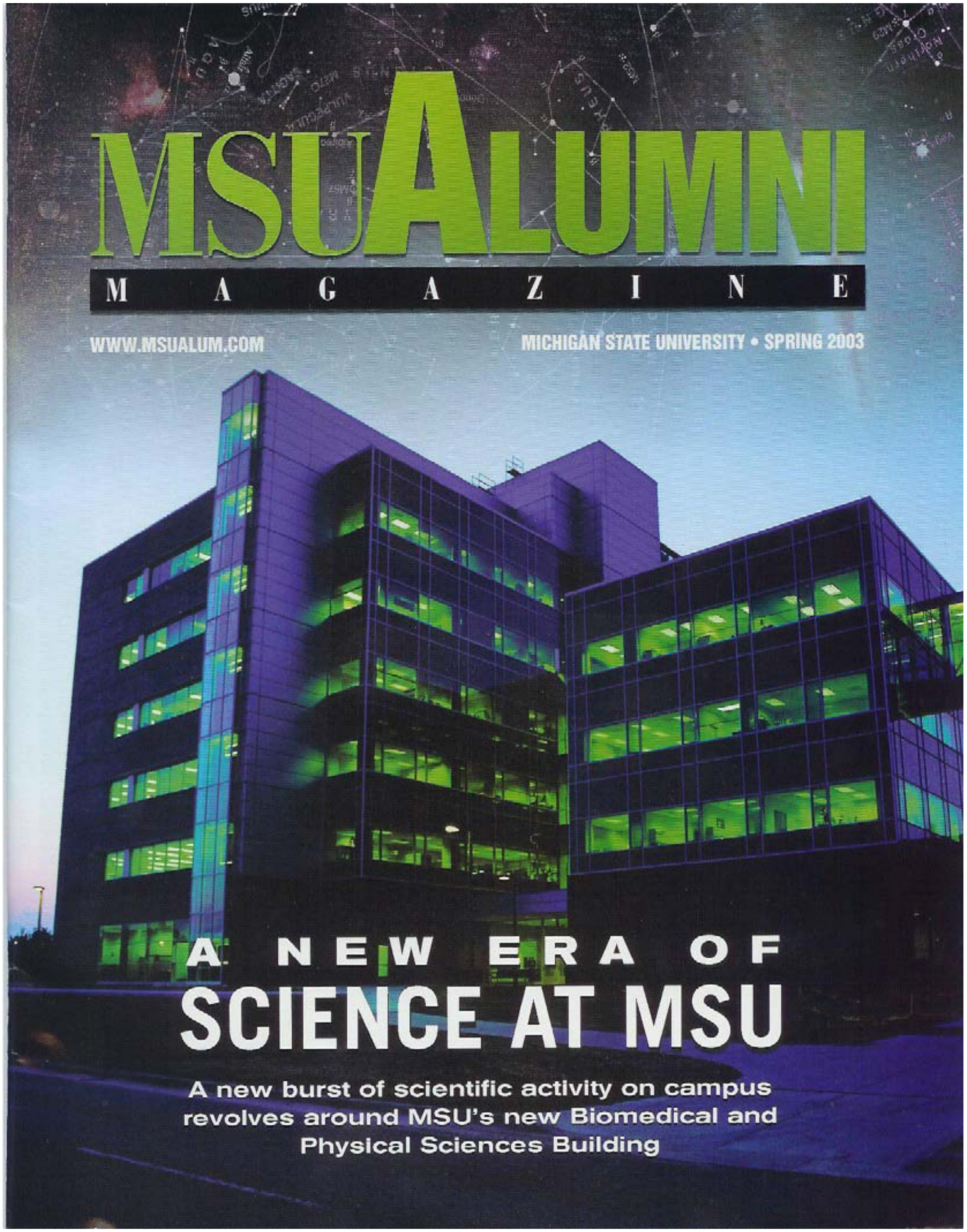
Nuclear Physics (16)

Particle Physics (18)

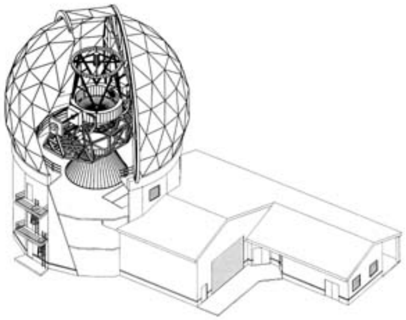
Department of Physics and Astronomy

Department of Physics and Astronomy

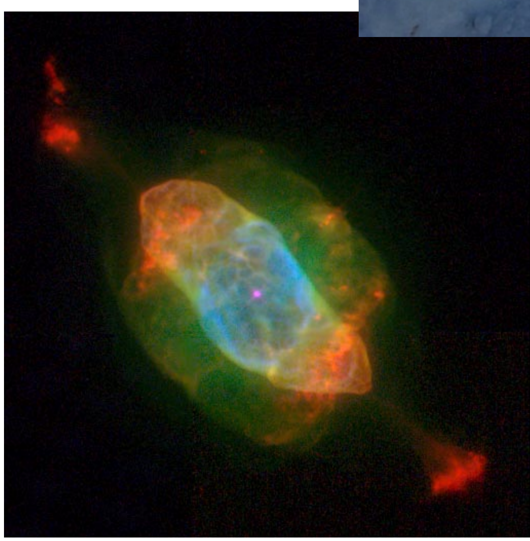
www.pa.msu.edu

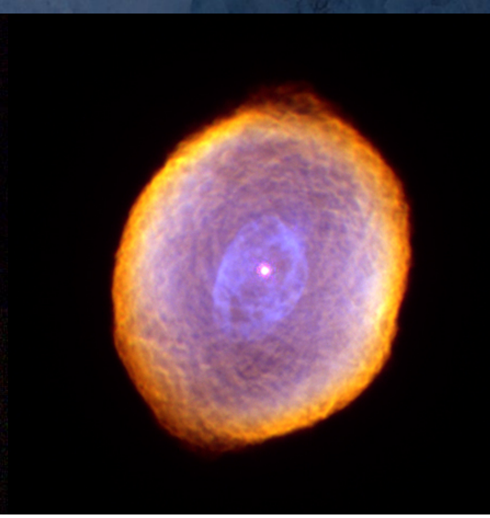


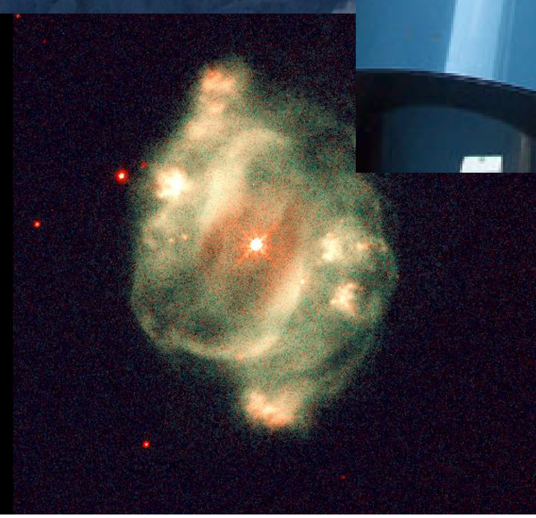
Astronomy / Astrophysics



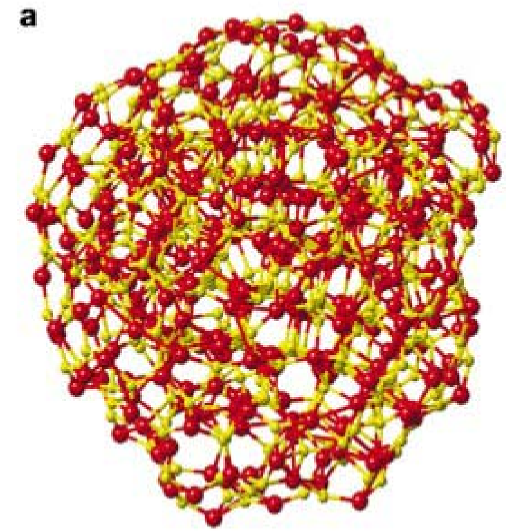
SOAR TELESCOPE



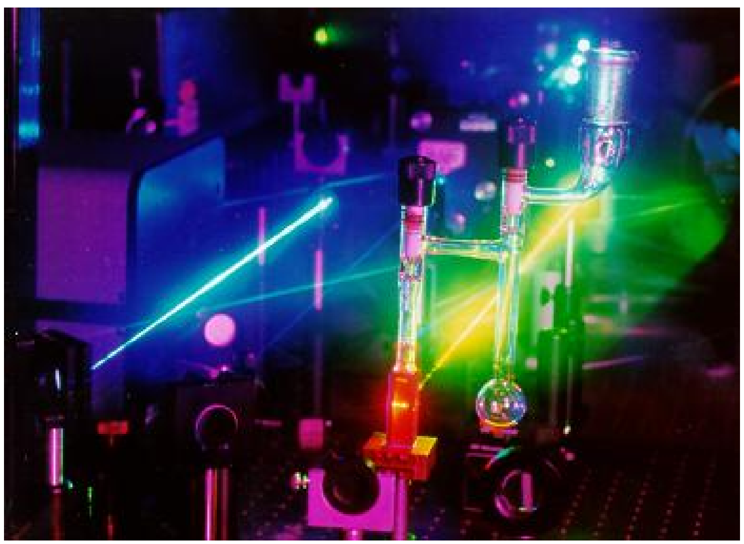


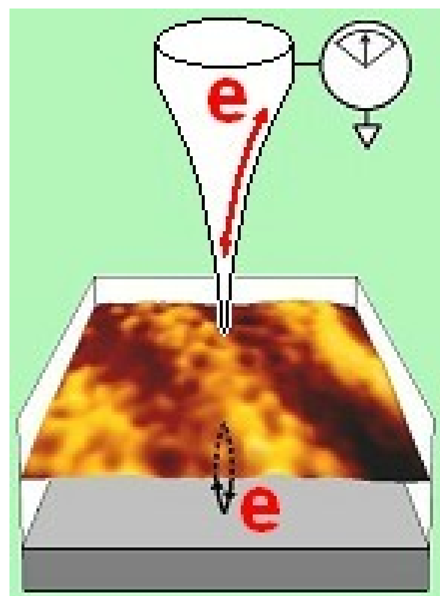


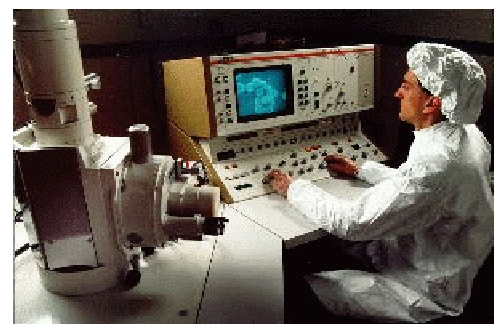
Condensed Matter Physics



Nano-Science
Spintronics
Biophysics
Institute for Quantum Science
W.M.Keck Microfabrication Facility







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Nuclear Physics

National Superconducting Cyclotron Laboratory

Research: basic nuclear physics

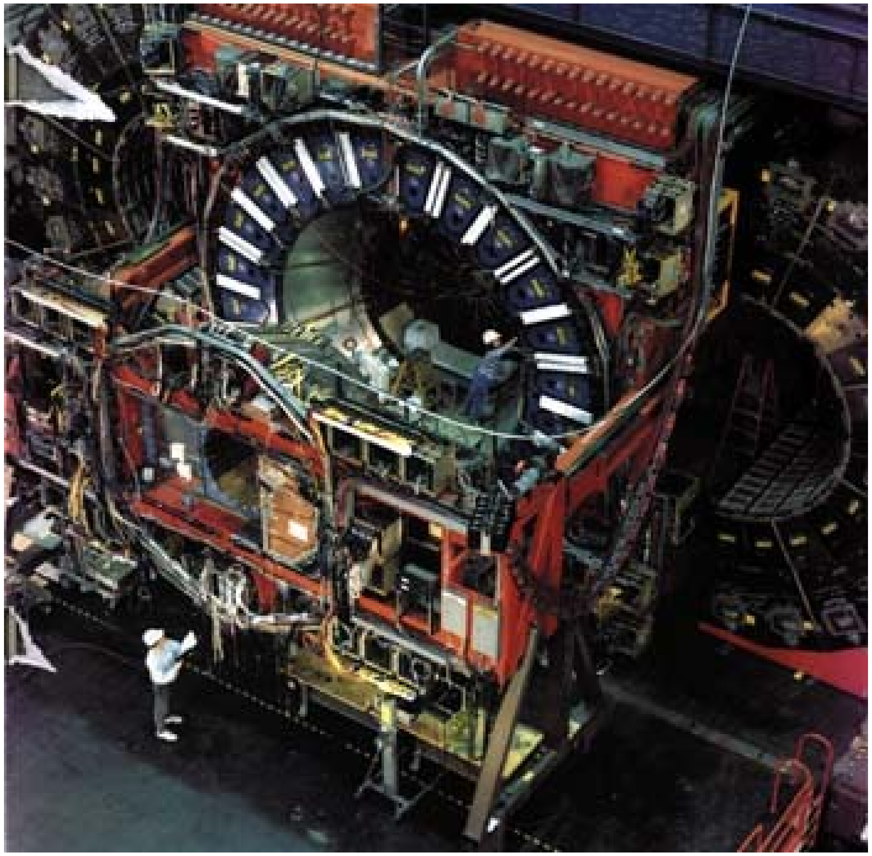
Supported by NSF (~M$15/year)

Faculty: Physics (16), Chemistry (2)

Ph.D. program ranked #2 in USA

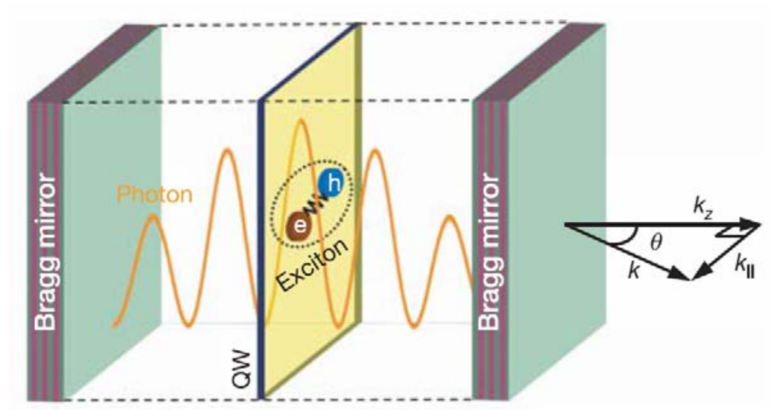
Particle Physics

Experimental group working on detectors (D0 and CDF) at Fermilab and ATLAS (CERN);D0 collaboration spokesperson

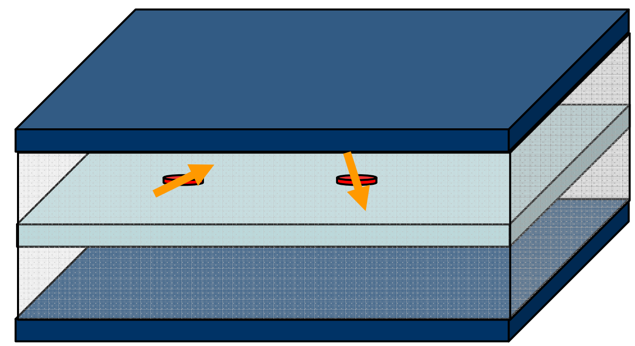


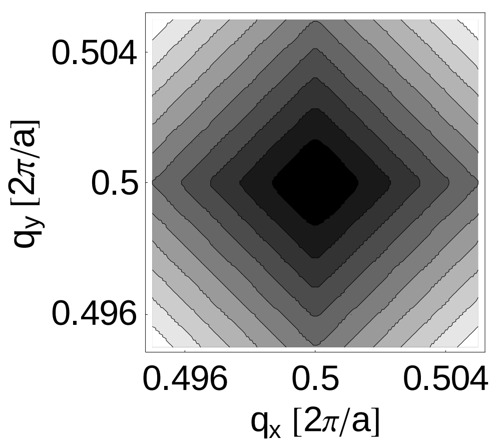
Theory Group

Cavity Polaritons



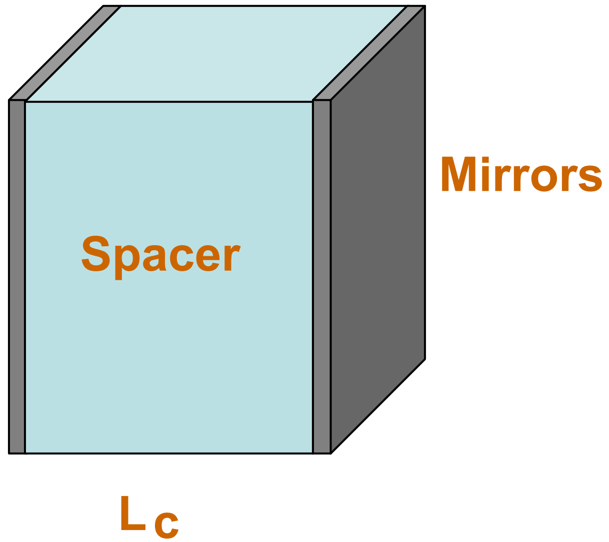
Polaritons and spin coupling in quantum computing architectures





Bragg polaritons in quantum dot lattices

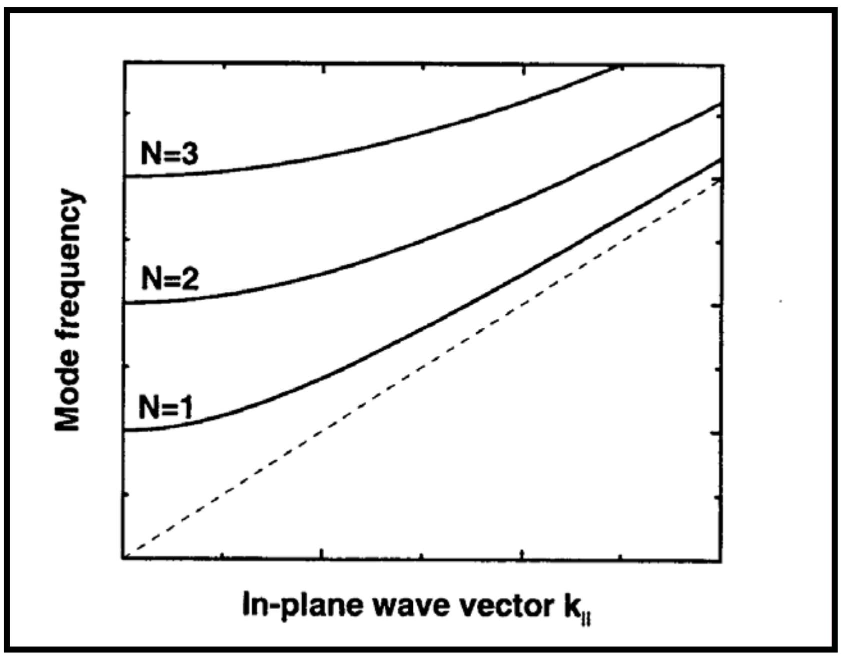
Planar Microcavities



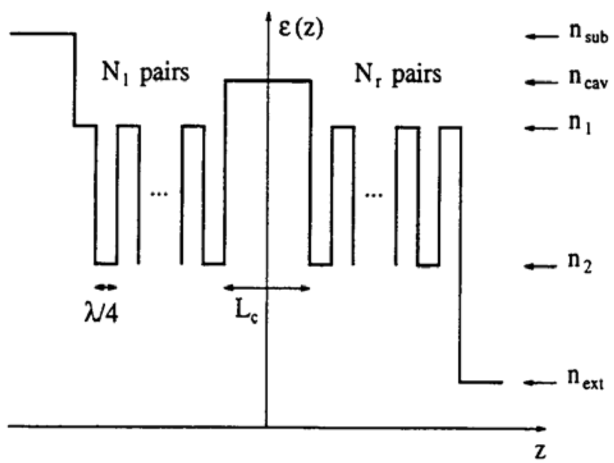
Fabry-Pérot resonator

Quantization of the em field in the z direction

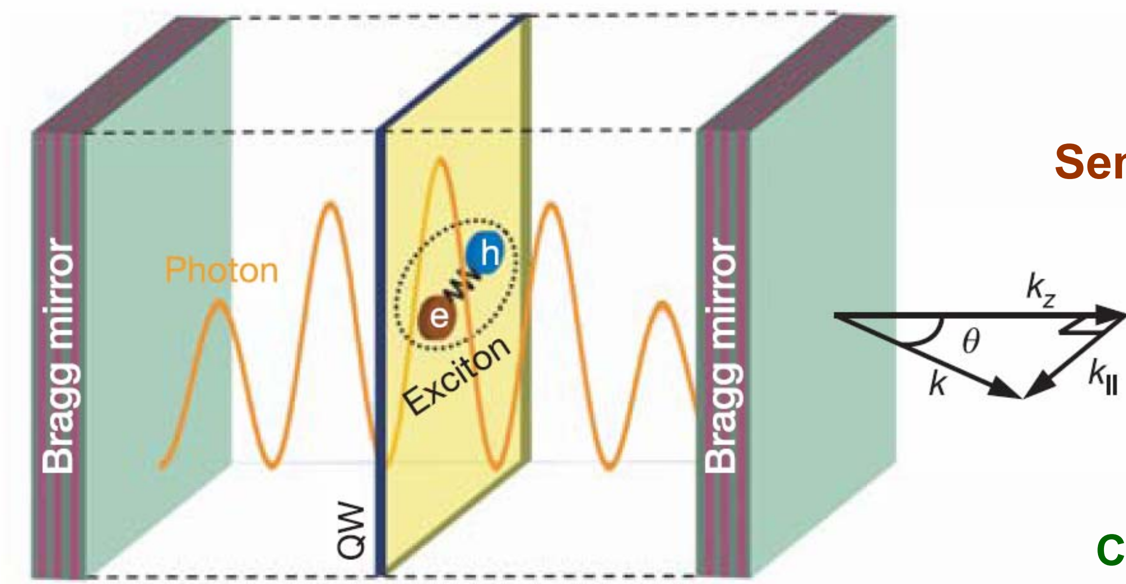
$$K_z = \sqrt{\frac{\omega^2}{c^2} n_{cav}^2 - K_{\parallel}^2} = \frac{N\pi}{L_c}$$



SEMICONDUCTOR MICROCAVITIES

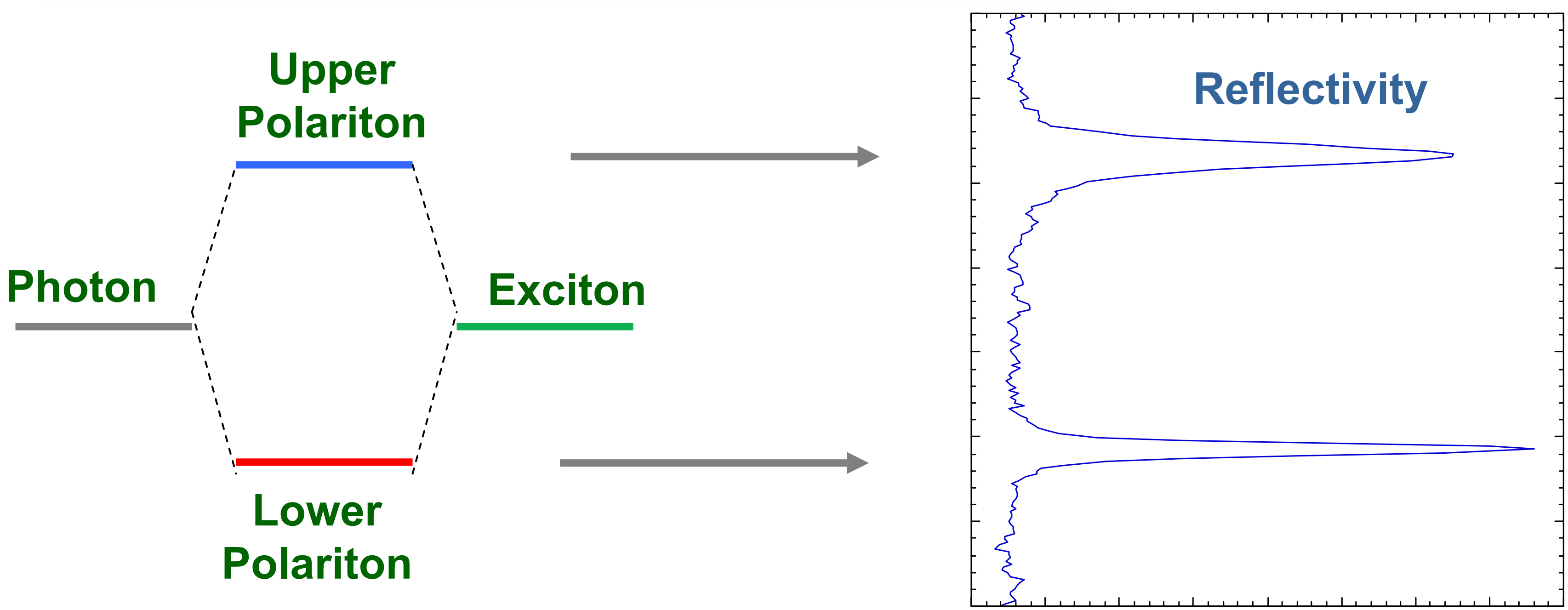


Polaritons: Half-light half-matter particles



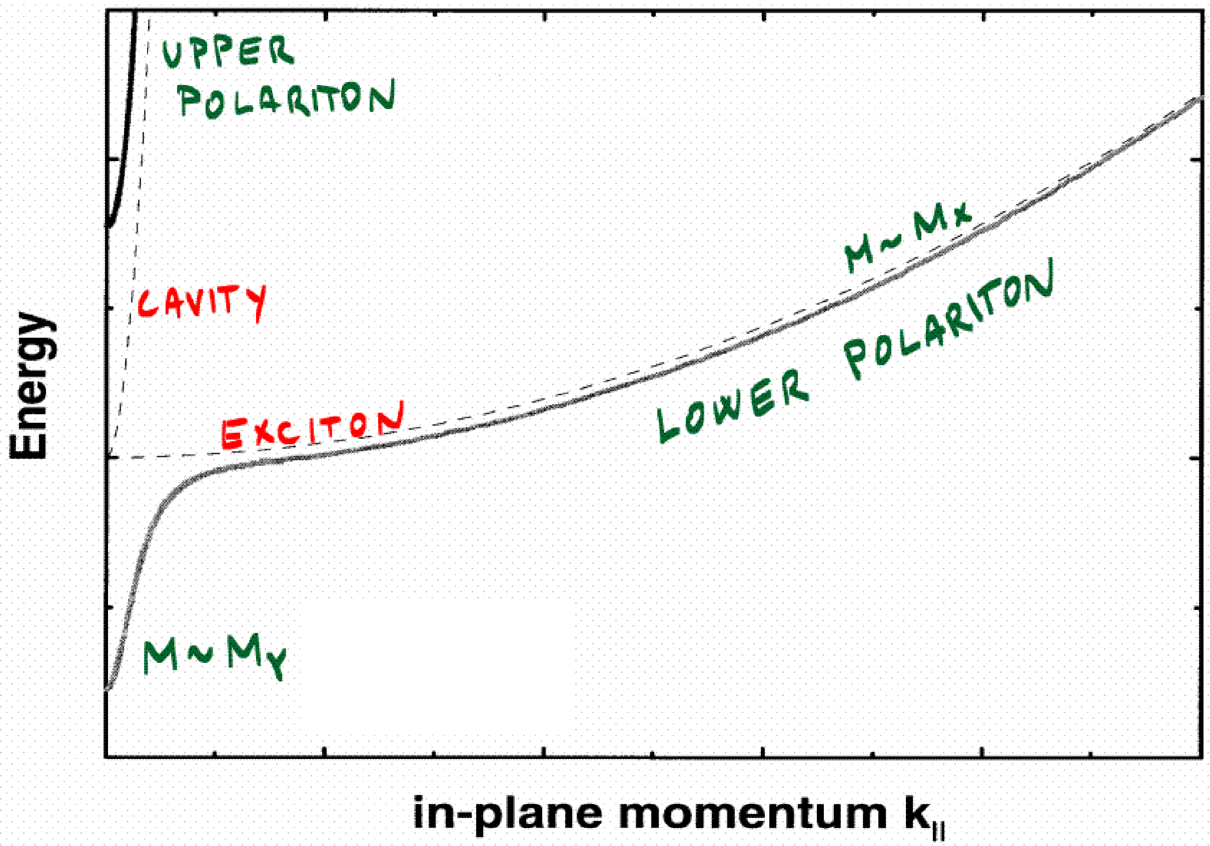
Semiconductor Cavity QED

C. Weisbuch et al. (1992)



Photons in a cavity have a mass

$$E = \hbar c \sqrt{k_{\parallel}^2 + \left(\frac{\pi}{L}\right)^2} \sim E_0 + \frac{\hbar^2 k_{\parallel}^2}{2M_\gamma} \qquad M_\gamma = \frac{\hbar \pi}{cL} \qquad M_\gamma \sim 10^{-5} m_e$$

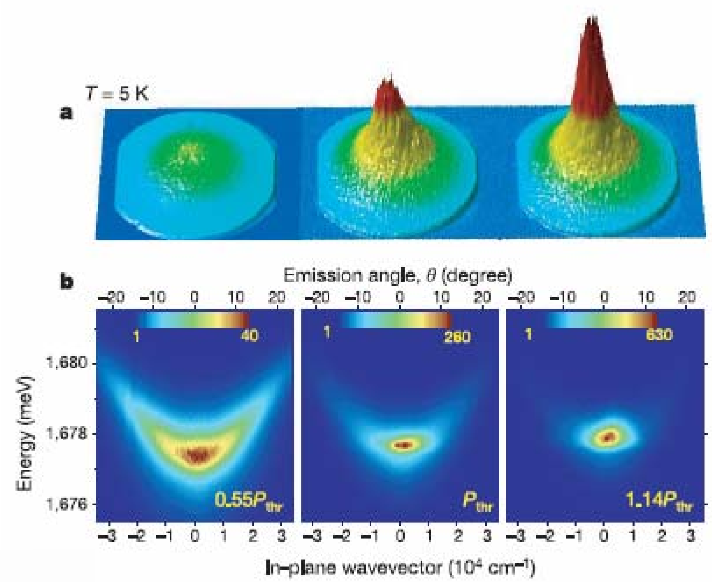


Polariton-mixing is k-dependent (J.J. Hopfield, 56)

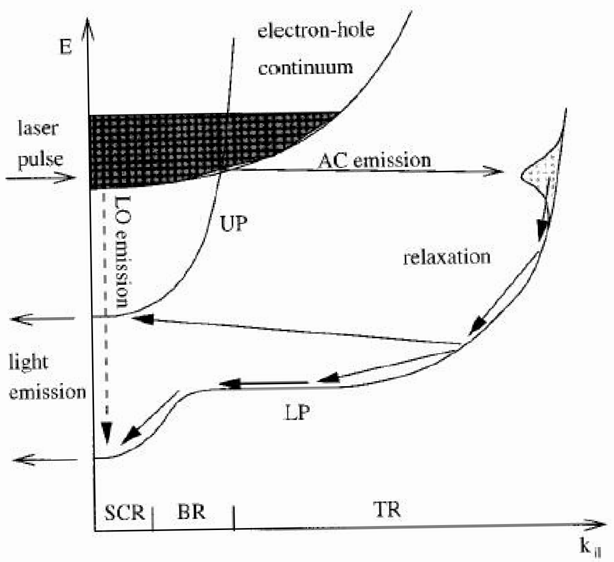
Polaritons have a photon-like mass

Sept 28 2006

Bose Einstein Condensation of Polaritons



J. Kasprzak et al. (2006)

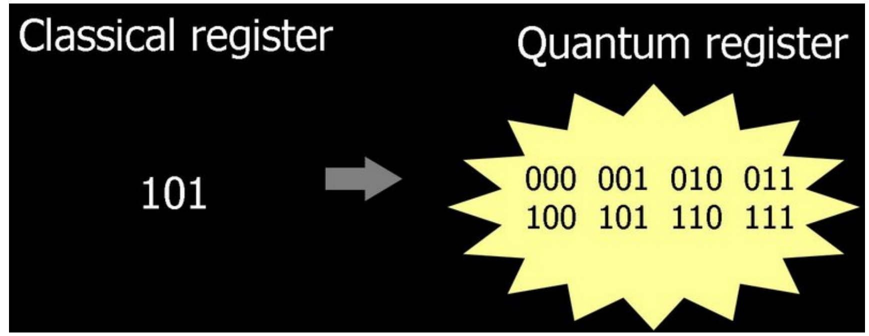


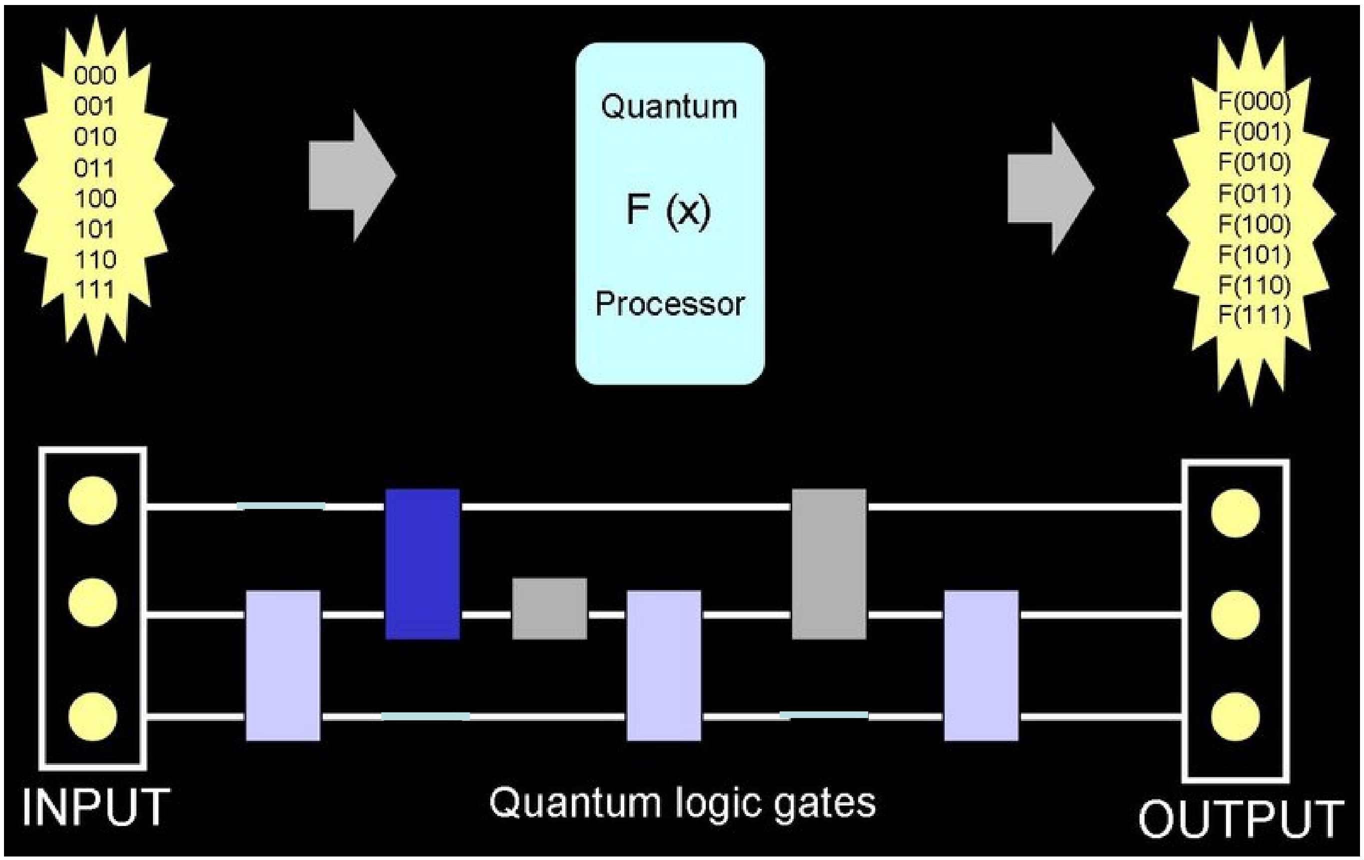
	POLARITONS	BEC ATOMS
Mass	0.00001 x m_0	100,000 x m_0
T	T ~ 100 K	T ~ 10 nK
Lifetime	t ~ 1-10 ps	t ~ 1 s

Bottleneck-effect

F. Tassone, C. Piermarocchi at al. (1997)

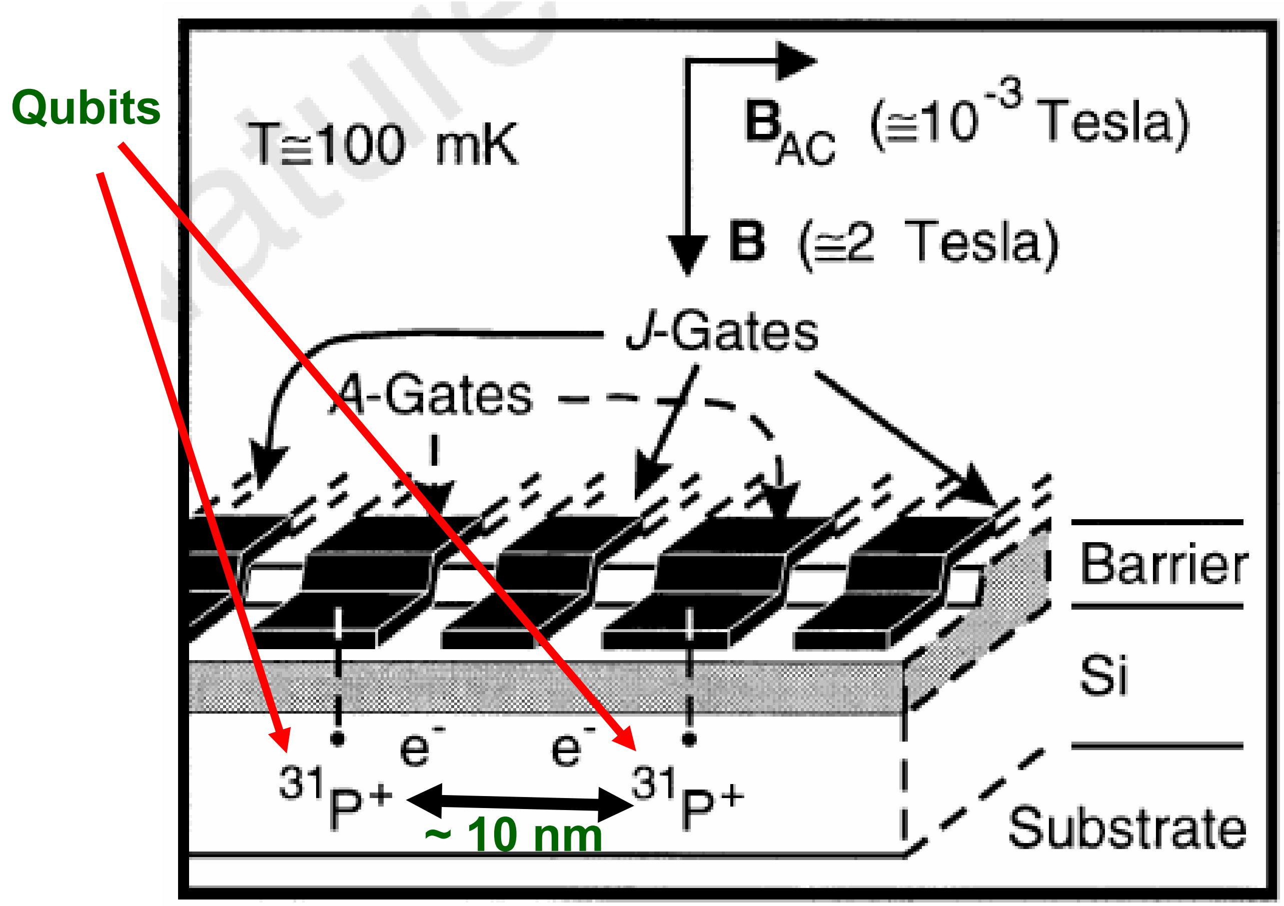
Can polaritons in planar microcavities be useful for Quantum Computing ?





The *Range Problem* in Quantum Computing Architectures

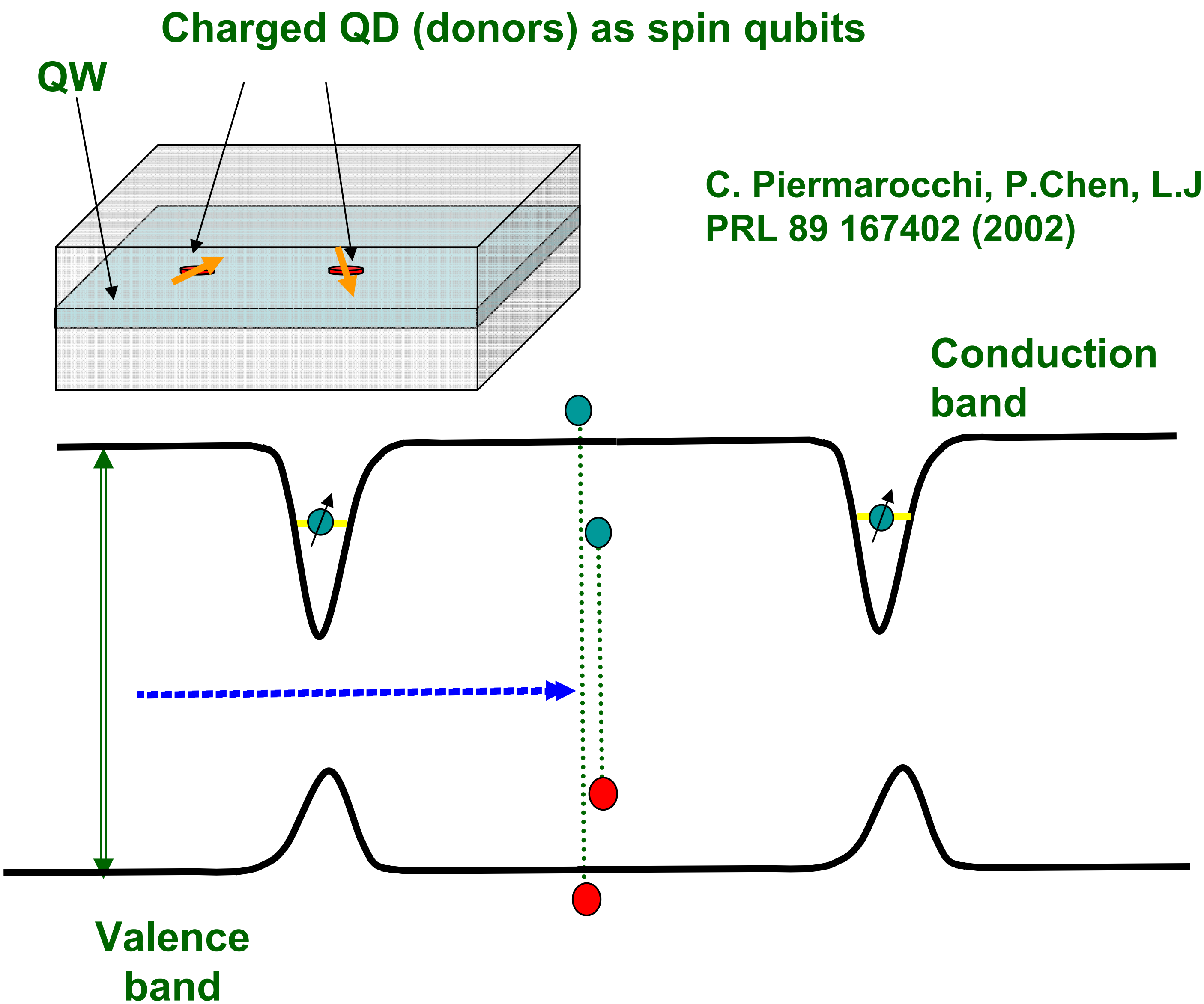
B. Kane Science (1995)



Common problem to many semiconductor spin-qubit architectures

Polaritons can induce a very Long Range Spin-Qubit Coupling

Optical RKKY: Itinerant excitons mediate a spin interaction



C. Piermarocchi, P.Chen, L.J.Sham, G.D.Steel, PRL 89 167402 (2002)

$$-J_{eff} S_1 \cdot S_2$$

$$J_{eff} \sim e^{-R/\kappa}$$

$$\kappa = \frac{\hbar}{\sqrt{2M_X \delta}}$$

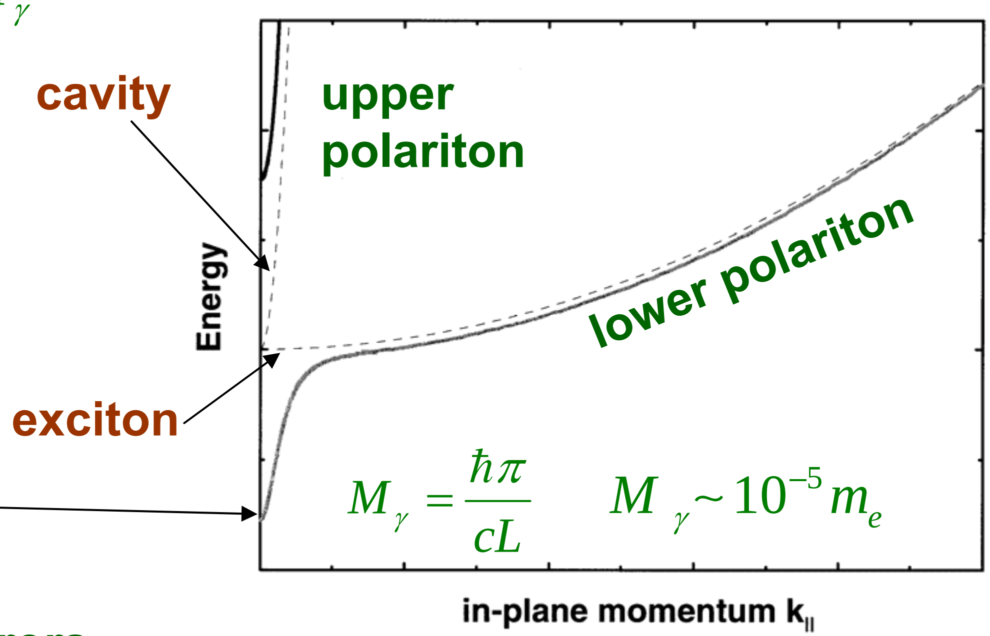
$$\delta = E_X - \hbar\omega_p$$

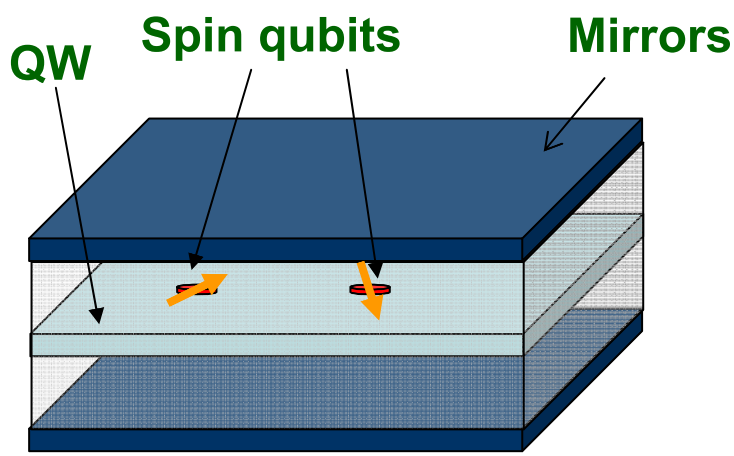
Optical spin coupling with polaritons

$$E = \hbar c\sqrt{k_{\parallel}^2 + \left(\frac{\pi}{L}\right)^2} \sim E_0 + \frac{\hbar^2 k_{\parallel}^2}{2M_\gamma}$$

Polariton-mixing is k-dependent

Polaritons have a photon-like mass



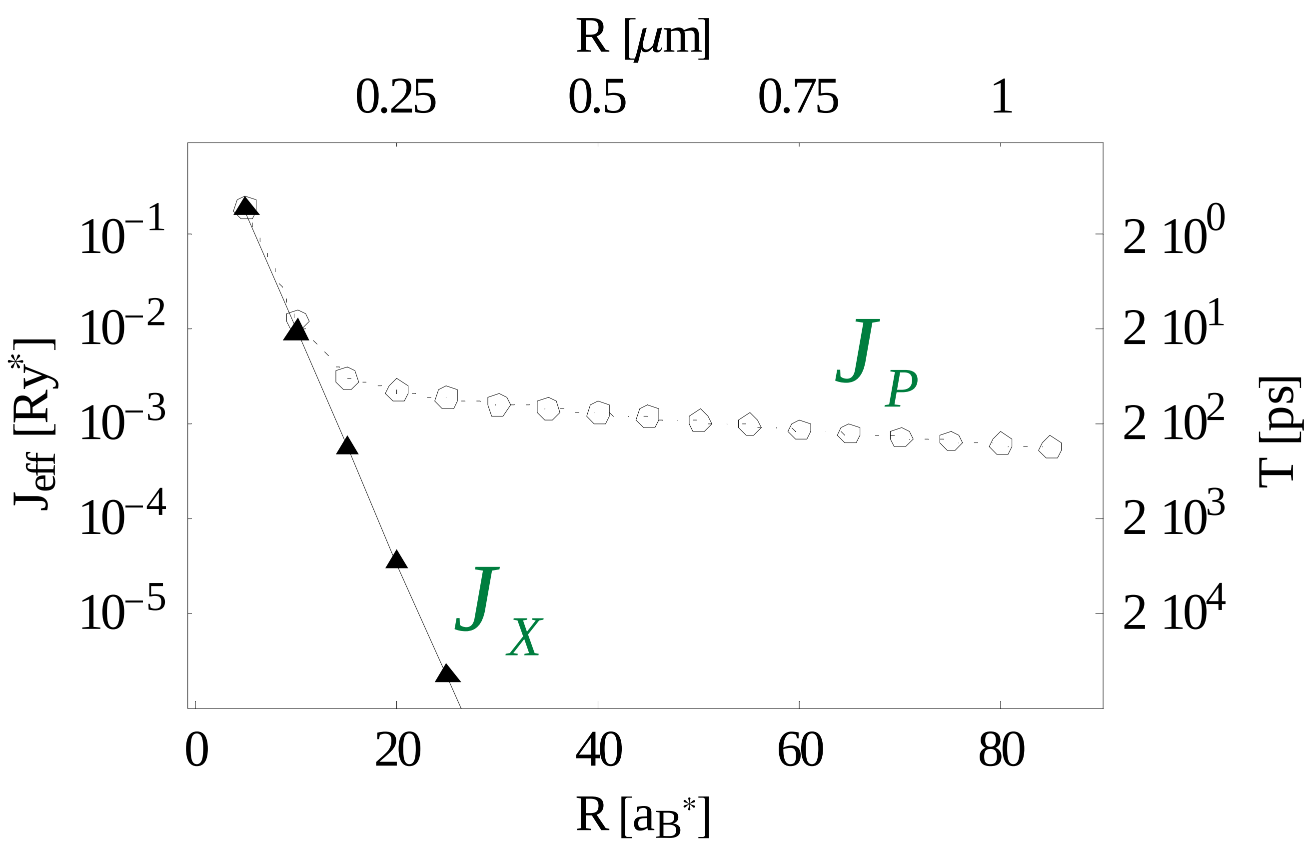


Light polariton mass

⬇

Long range spin coupling

Polariton-mediated Ising component has a very long range

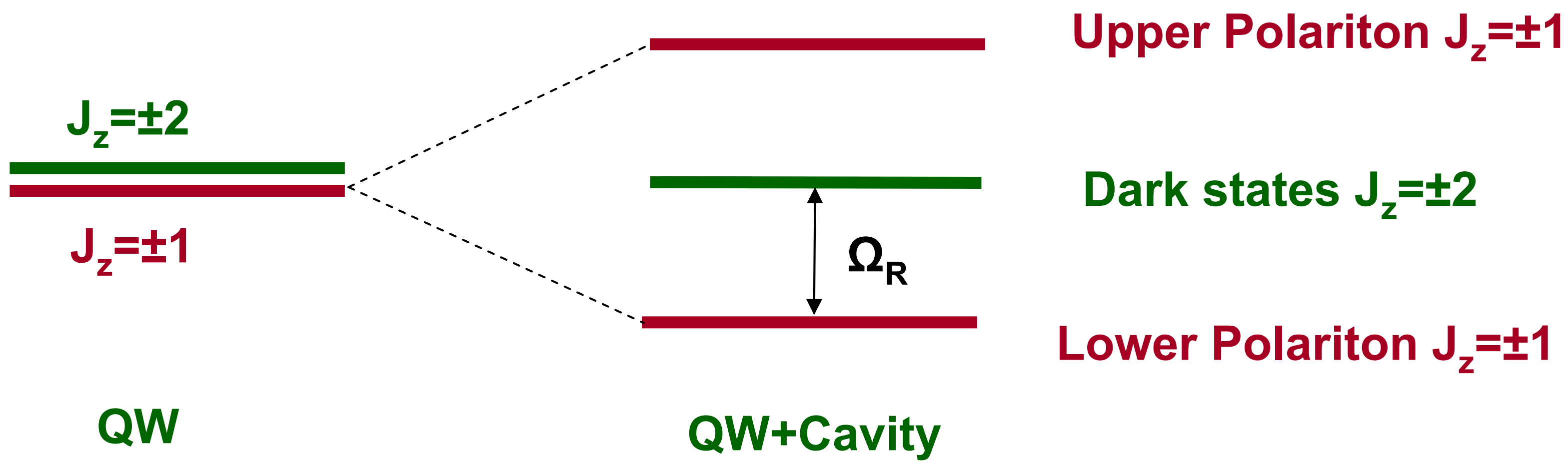


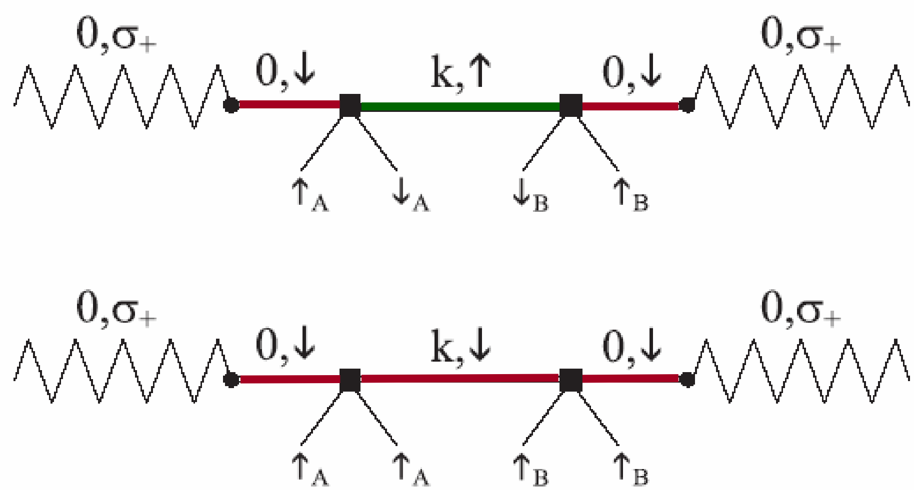
$$H_{eff} = -J_X\left(s_x^1 s_x^2 + s_y^1 s_y^2\right) - J_P s_z^1 s_z^2$$

G. Quinteiro Rosen, J Fernández-Rossier, and C Piermarocchi, PRL 97 097401 (2006)

Polariton splitting causes spin anisotropy

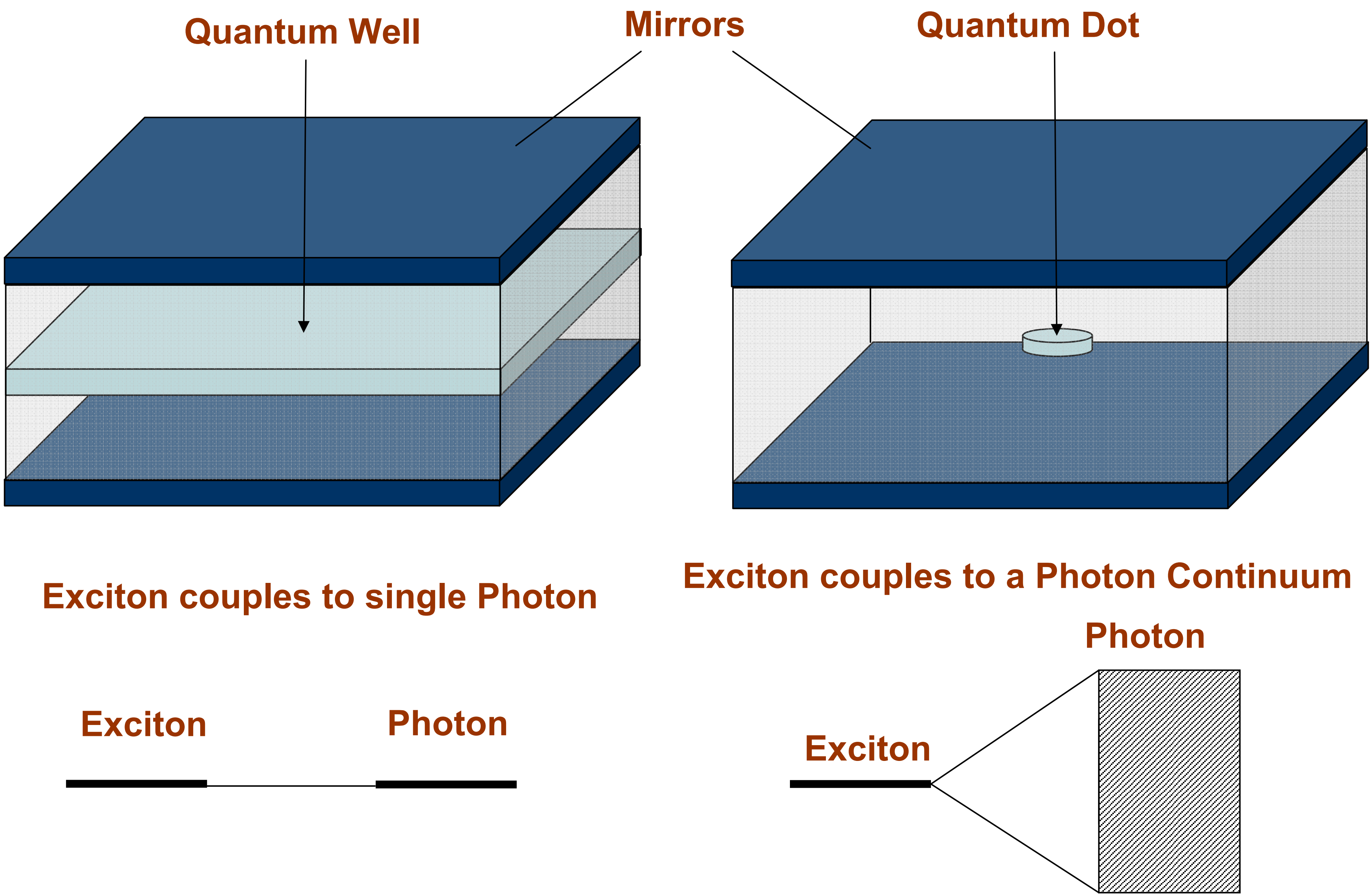
e: $J_z=\pm 1/2$ h: $J_z=\pm 3/2$





A spin flip necessarily implies polariton-dark states mixing

Dimensionality mismatch in light-matter coupling



Quantum Dot Rabi Splitting

0D cavity Photon+0D quantum dot exciton

Strong coupling in a single quantum dot–semiconductor microcavity system

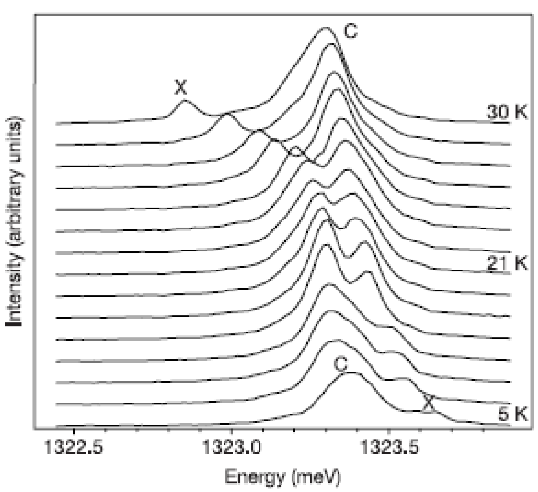
J. P. Reithmaier[1], G. Sęk[1*], A. Löffler[1], C. Hofmann[1], S. Kuhn[1], S. Reitzenstein[1], L. V. Keldysh[2], V. D. Kulakovskii[3], T. L. Reinecke[4] & A. Forchel[1]

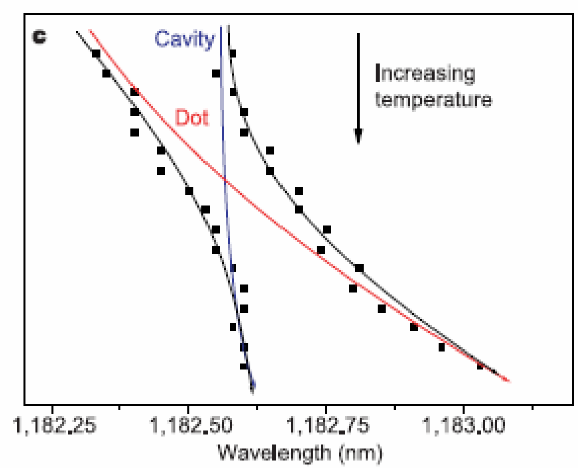
[1] *Technische Physik, Universität Würzburg, Am Hubland, D-97074 Würzburg, Germany*
[2] *Lebedev Physical Institute, Russian Academy of Science, 119991 Moscow, Russia*
[3] *Institute for Solid State Physics, Russian Academy of Science, 142432 Chernogolovka, Russia*
[4] *Naval Research Laboratory, Washington, DC 20375, USA*

Vacuum Rabi splitting with a single quantum dot in a photonic crystal nanocavity

T. Yoshie[1], A. Scherer[1], J. Hendrickson[2], G. Khitrova[2], H. M. Gibbs[2], G. Rupper[2], C. Ell[2], O. B. Shchekin[3] & D. G. Deppe[3]

[1] *Electrical Engineering, California Institute of Technology, Pasadena, California 91125, USA*
[2] *Optical Sciences Center, The University of Arizona, Tucson, Arizona 85721, USA*
[3] *Microelectronics Research Center, Department of Electrical and Computer Engineering, The University of Texas at Austin, Austin, Texas 78712, USA*



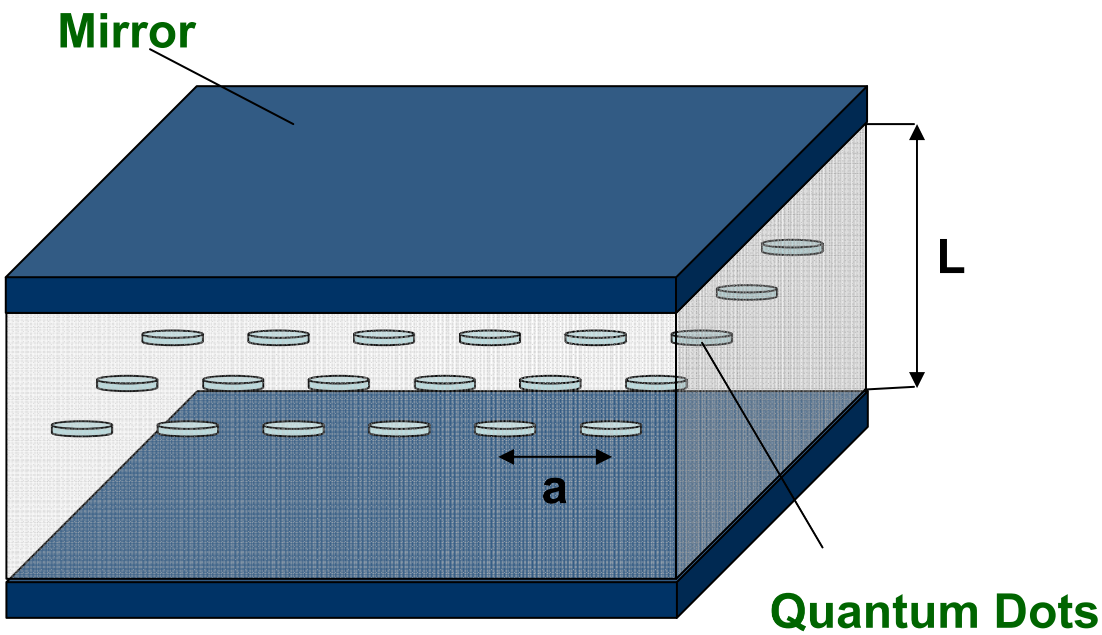


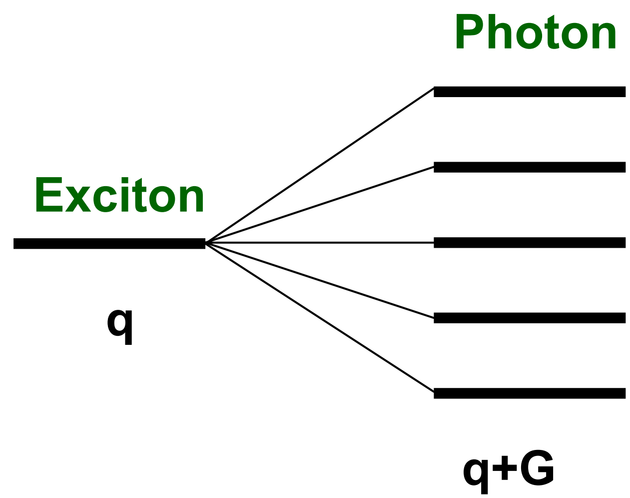
Nature 432 p. 197

p.200

(2004)

2D photons coupled to 2D array of Quantum Dots





Exciton couples to discrete photon modes differing by reciprocal lattice vectors G

Hamiltonian: exciton in QD lattice and 2D photons

Fourier transform of the localized states

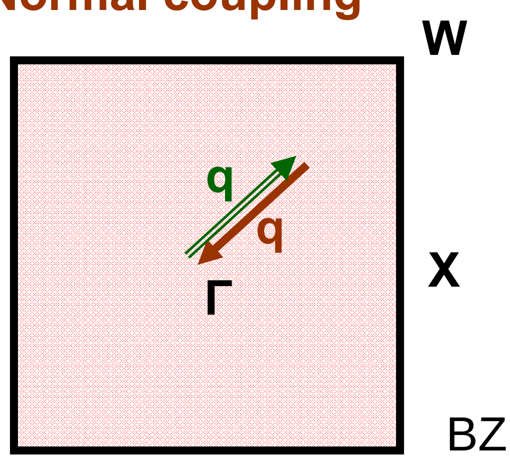
$$\left|\vec{i}\right\rangle \rightarrow \left|\vec{q}\right\rangle = \frac{1}{\sqrt{N}} \sum_{i} e^{i\vec{q}\cdot\vec{R}_i} \left|\vec{i}\right\rangle$$

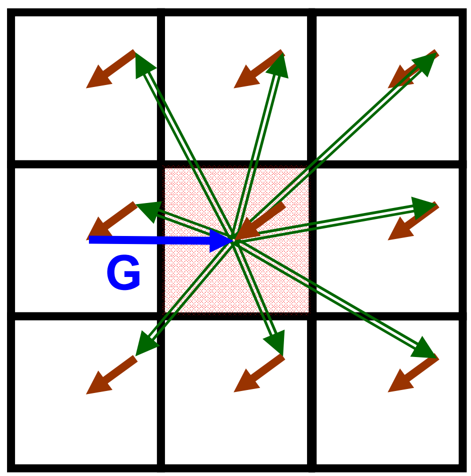
$$H = \sum_{\vec{q}\in BZ} h(\vec{q})$$

Lattice momentum q is in the first Brillouin Zone (BZ) of the dot lattice

$$h(q) = \hbar\omega_x \sigma_{\vec{q}}^{+}\sigma_{\vec{q}}^{-} + \sum_{\vec{G}\in RL} \hbar\omega(\vec{q}+\vec{G}) A_{\vec{q}+\vec{G}}^{+} A_{\vec{q}+\vec{G}} + \left(\hbar g_{\vec{q}+\vec{G}} A_{\vec{q}+\vec{G}}^{+} \sigma_{\vec{q}}^{-} + h.c.\right)$$

Normal coupling



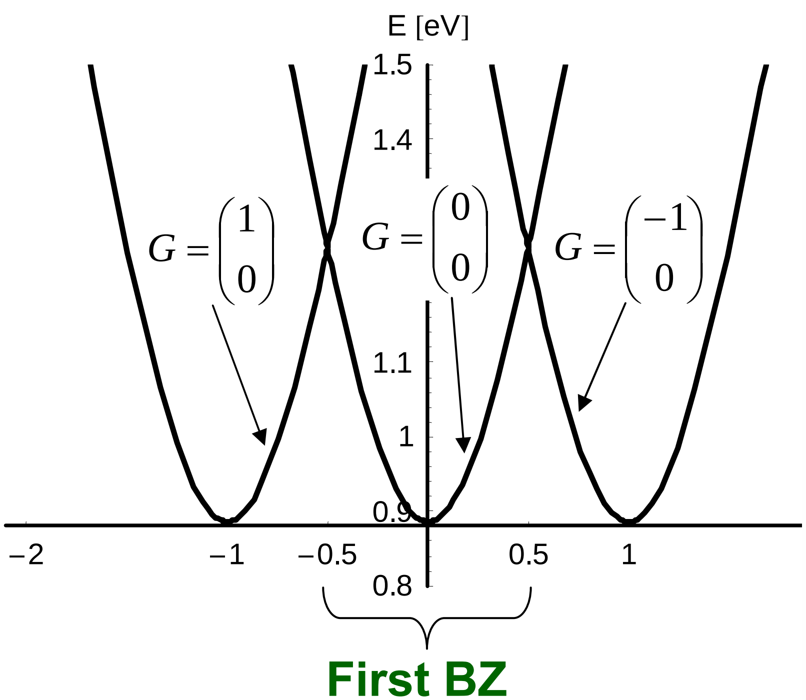


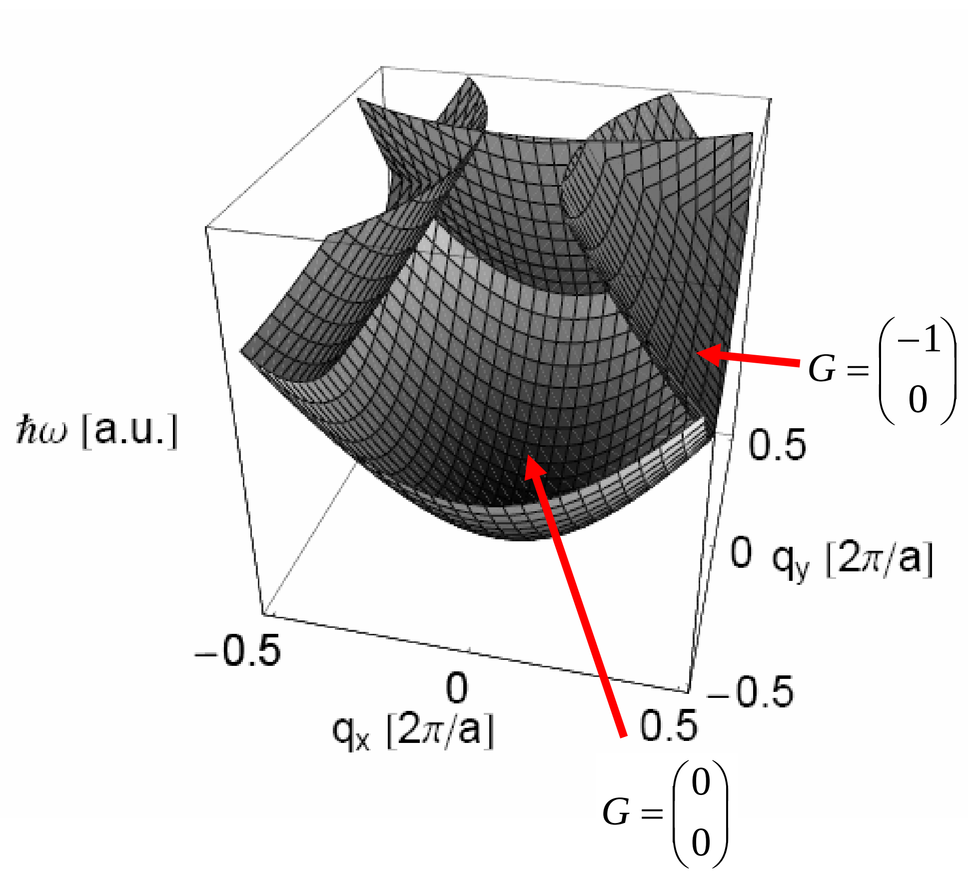
Umklapp exciton-photon coupling

The reduced Zone Scheme

Consider the Photon q+G as quasiparticle labelled by a quantum number G and with momentum q (restricted to 1st BZ)

Umklapp-Photon G has energy dispersion $\omega_G(q) = \omega(q+G)$



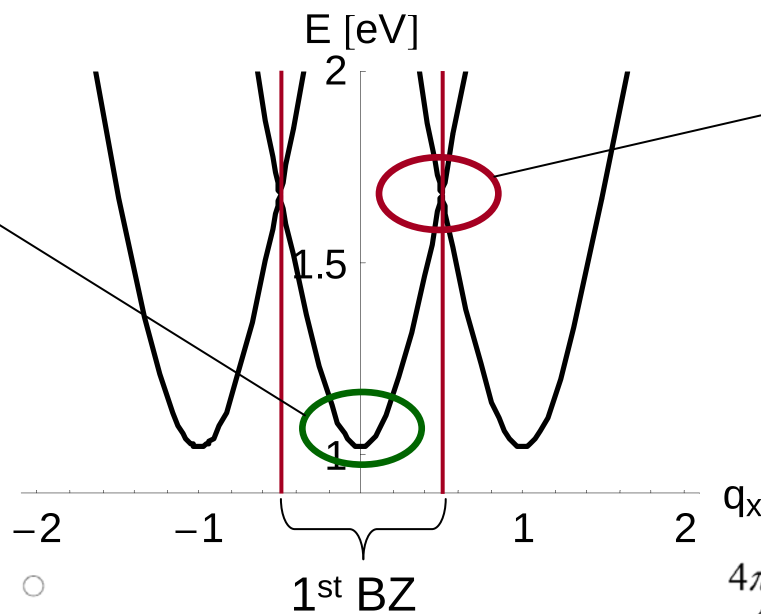


Bragg Polaritons

Idea: Create polaritons in the neighborhood of a Bragg plane!

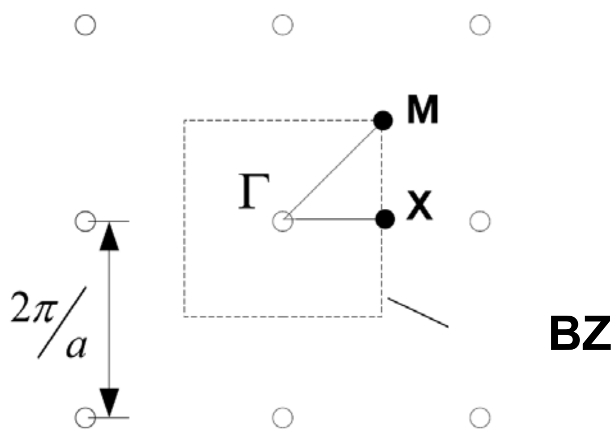
QW-like polaritons

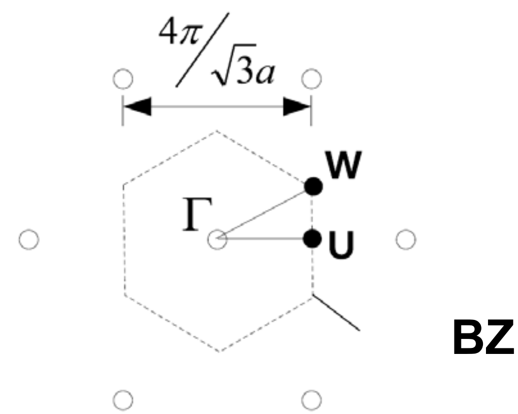
Have small momentum q~0



Bragg polaritons

Have large momentum q at the edge of the BZ

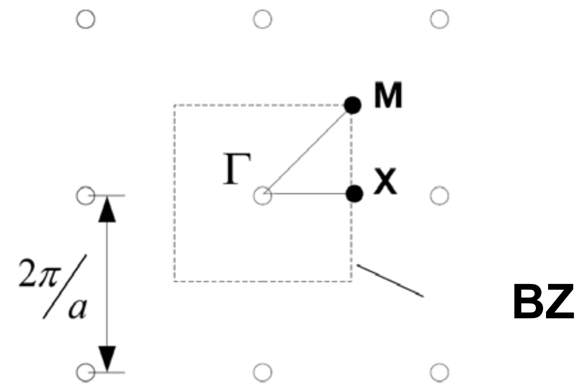




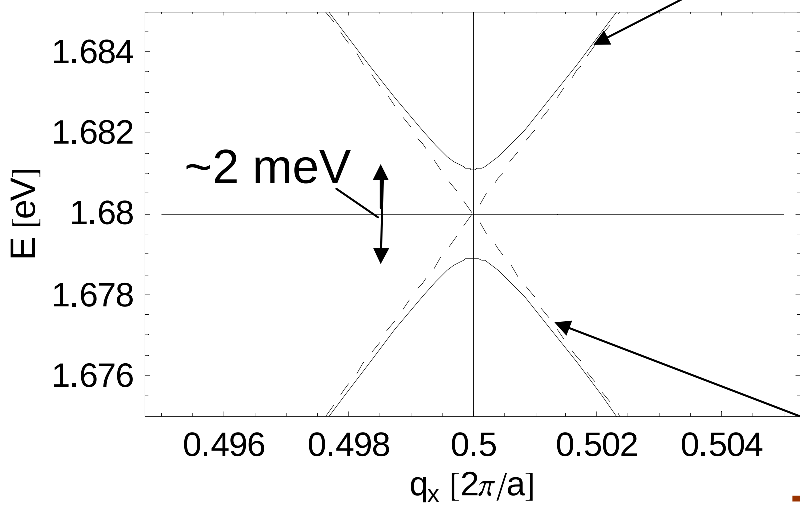
E. M. Kessler, M. Grochol, C. Piermarocchi, Phys. Rev. B 77 072804 2008

Square lattice: X-Point Bragg Polaritons

a=150 nm, dot size= 40 nm, GaAs

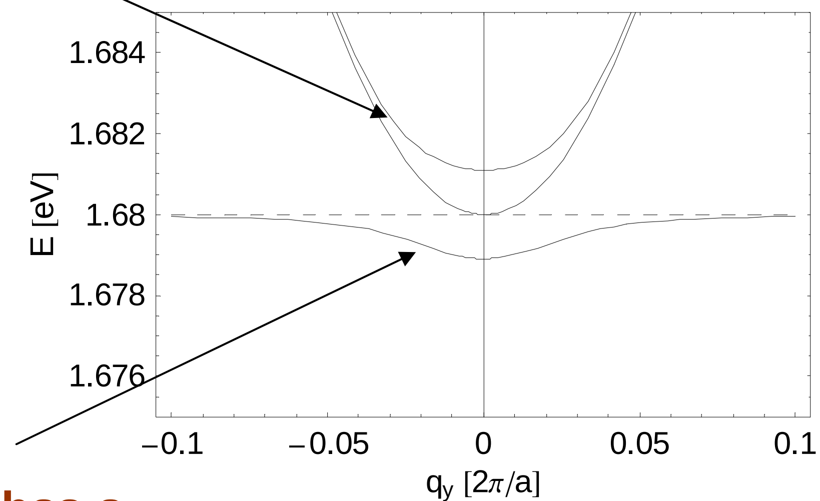


X-direction



The UP has a local minimum

Y-direction

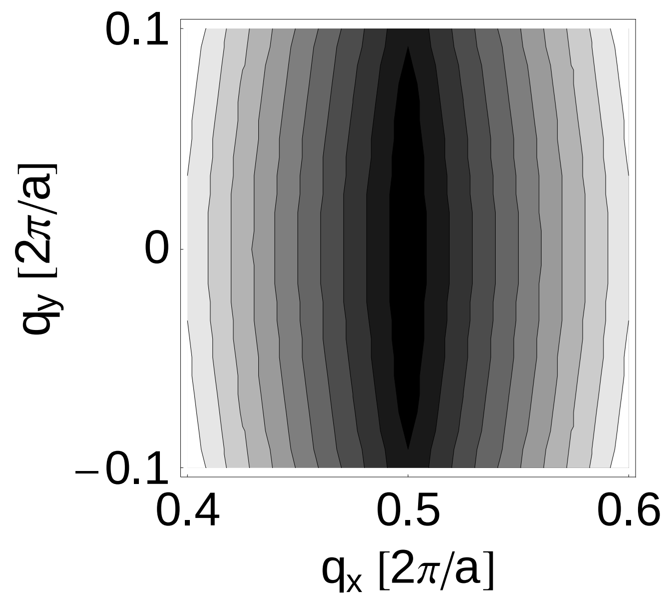


The LP has a saddlepoint

X-Bragg polaritons have strong in-plane asymmetry

The upper polariton (UP) mode

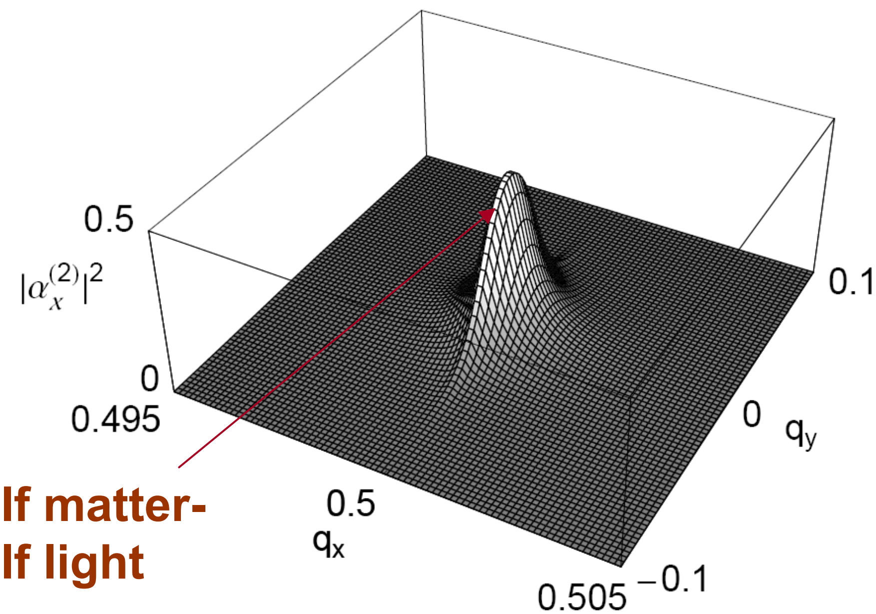
Valley-like dispersion



	UP (1)
m_{xx}/m_{ph}	$1.7 \cdot 10^{-3}$
m_{yy}/m_{ph}	3.32

The excitonic component

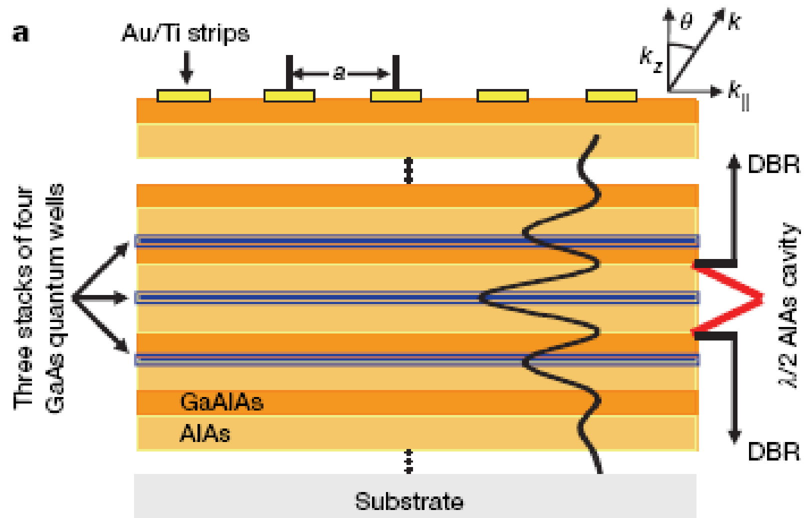
$$\left|P_{\mathbf{q}}^{\xi}\right\rangle = \alpha_x^{\xi}(\mathbf{q})\left|\mathbf{q}\right\rangle + \alpha_{ph1}^{\xi}(\mathbf{q})\left|T_{\mathbf{q}}^{\mathbf{Q}=0}\right\rangle + \alpha_{ph2}^{\xi}(\mathbf{q})\left|T_{\mathbf{q}}^{\mathbf{Q}=(-1,0)}\right\rangle$$



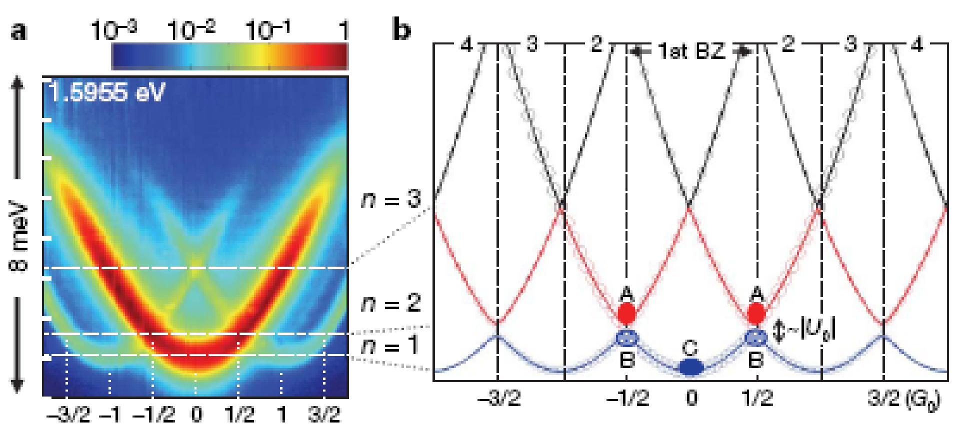
Photon-like mass in y-direction (~10^{-5} m_0)

Even smaller in x-direction (~10^{-8} m_0)

π-polaritons in micro-cavities

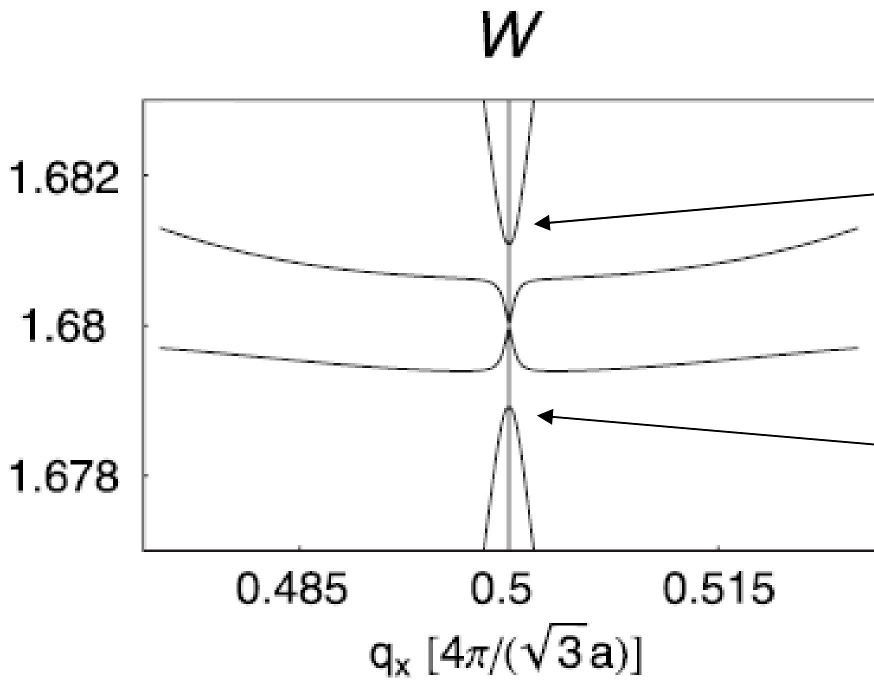


1D Periodic Modulation



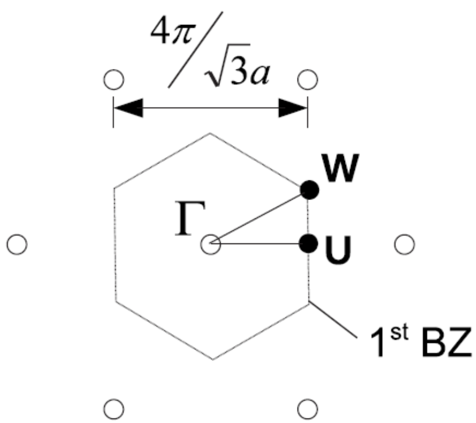
C. W. Lai et al. Nature 450 529 (2007)

Dirac Polaritons

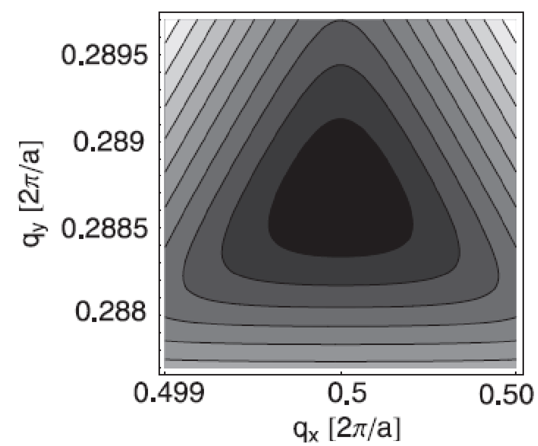


The UP has a local minimum

The LP has a local maximum

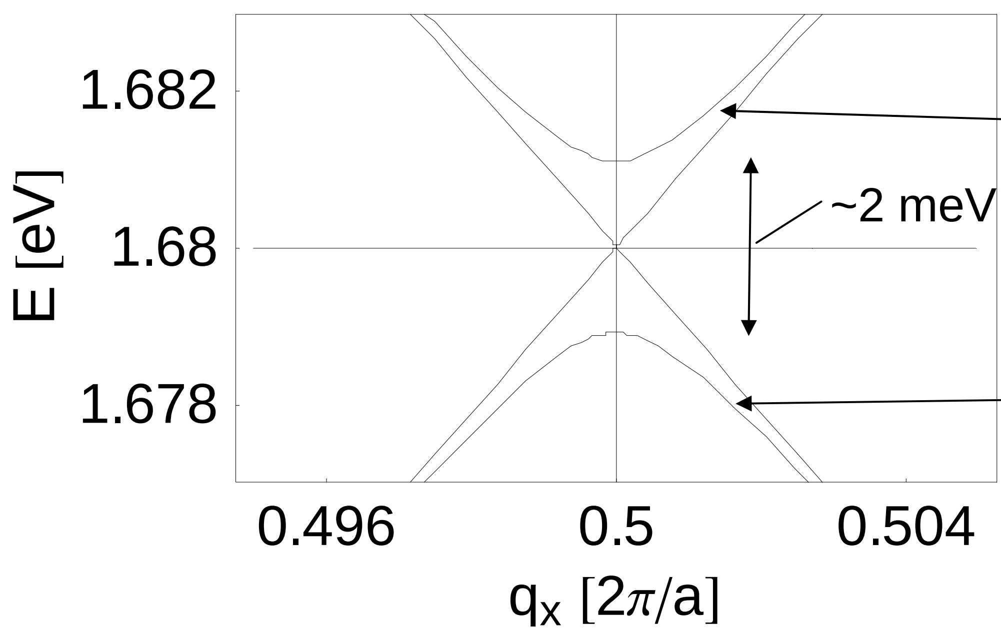


Three photon branches are intersecting



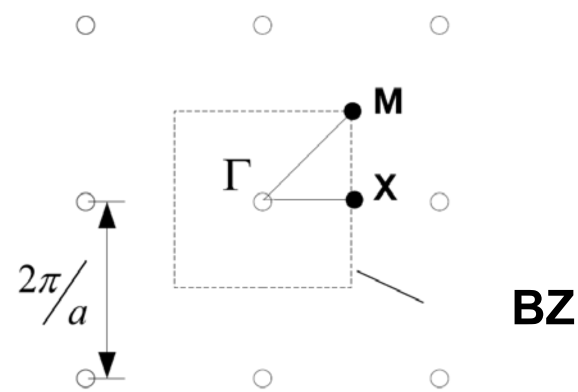
Isotropic mass

Dirac Polaritons on Square Lattices



The UP has a local minimum

The LP has a local maximum

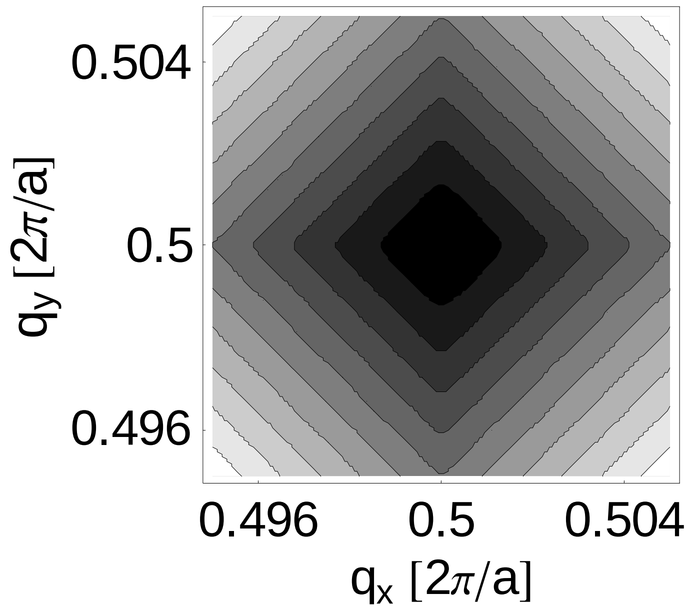


Four photon modes are intersecting

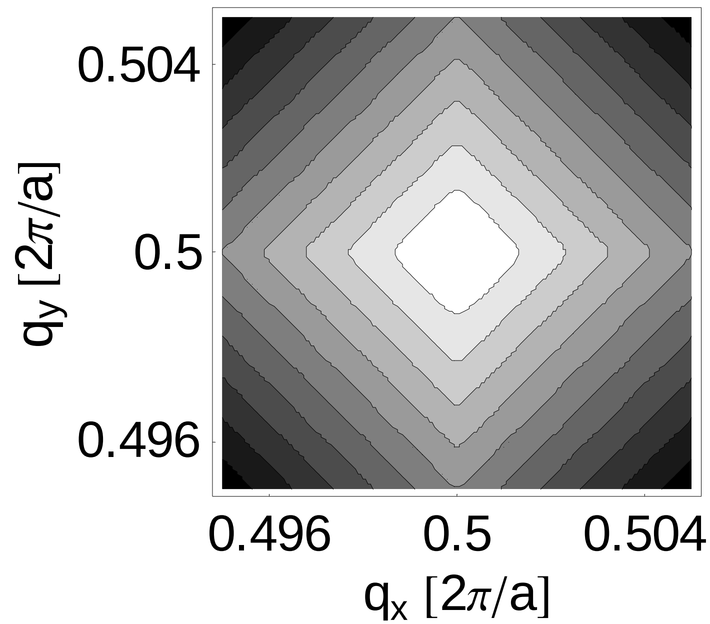
The dot size and lattice spacing can be optimized to maximize the Rabi splitting as at zone boundary

The Upper Polariton and Lower Polariton at M

UP



LP

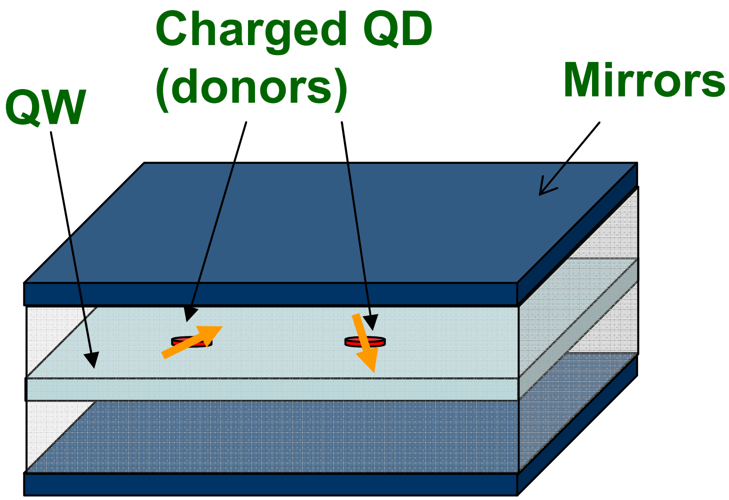


	M1	
	UP (1)	LP (5)
m_{xx}/m_{ph}	$3.43 \cdot 10^{-3}$	$-3.4 \cdot 10^{-3}$
m_{yy}/m_{ph}	$3.43 \cdot 10^{-3}$	$-3.4 \cdot 10^{-3}$

Isotropic extremely small mass for UP and LP

One central polariton mode is slow photon mode, photon mass increase ~L/a

Can polariton effects be useful for Quantum Computing ?

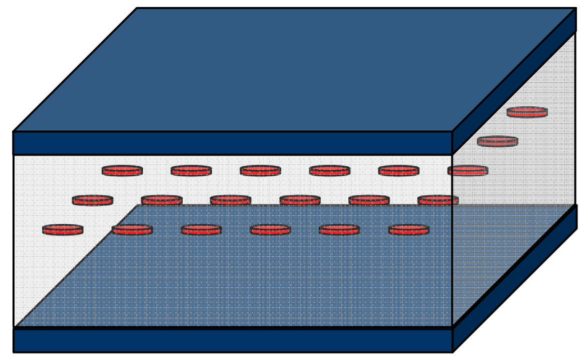


Quantum Well Polaritons

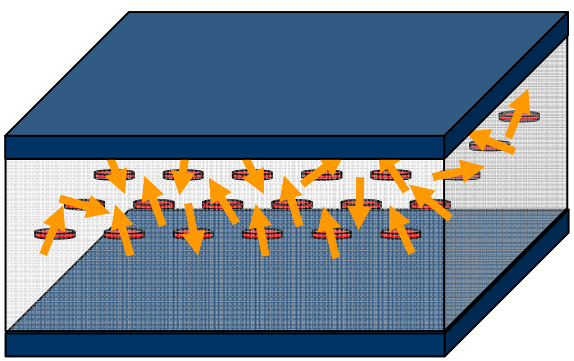
Long range spin coupling

Continuous-discrete mismatch

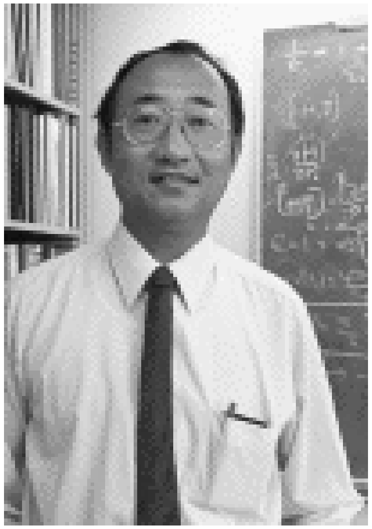
Dirac polaritons



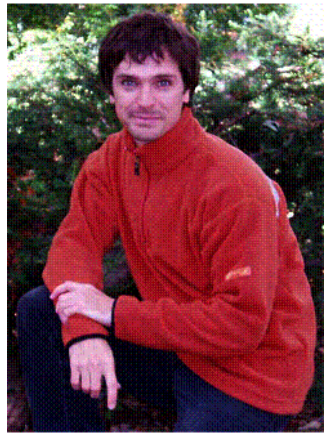
Quantum Dot Lattice



Quantum memory



Lu Sham UC
San Diego



Guillermo Quinteiro
Rosen, Univ. Buenos
Aires, Argentina

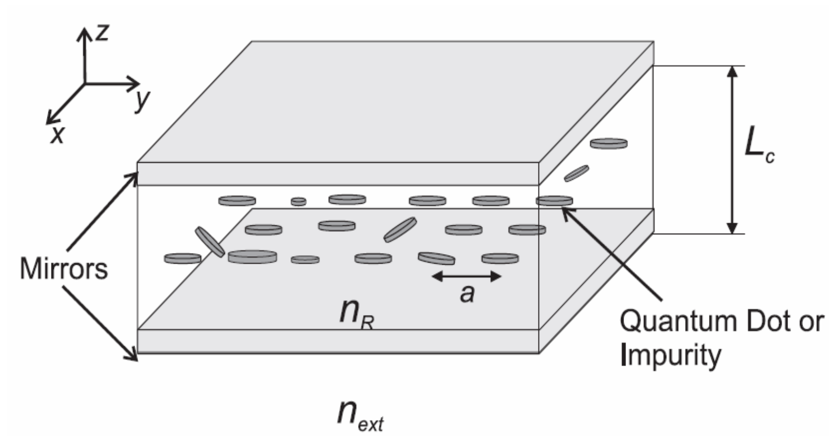
Joaquin Fernandez
Rossier
Alicante, Spain

Po Chung Chen
Tsing-Hua Taipei

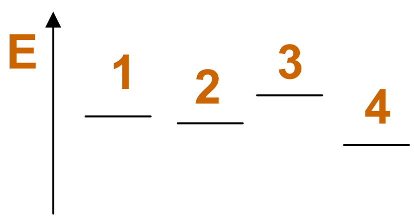
Eric Kessler, MPI
Garching, Germany

Allan MacDonald
U Texas Austin

Disorder

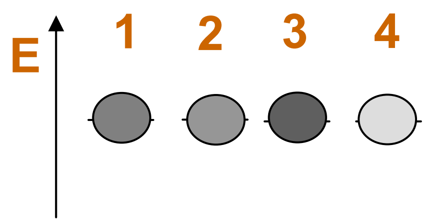


Energy disorder



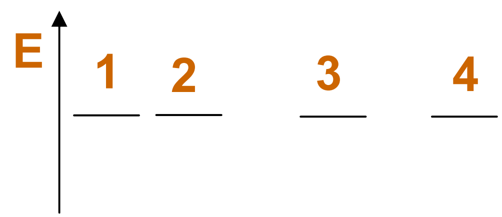
Quantum dots

Oscillator strength disorder



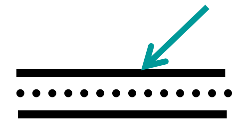
Impurities

Positional disorder

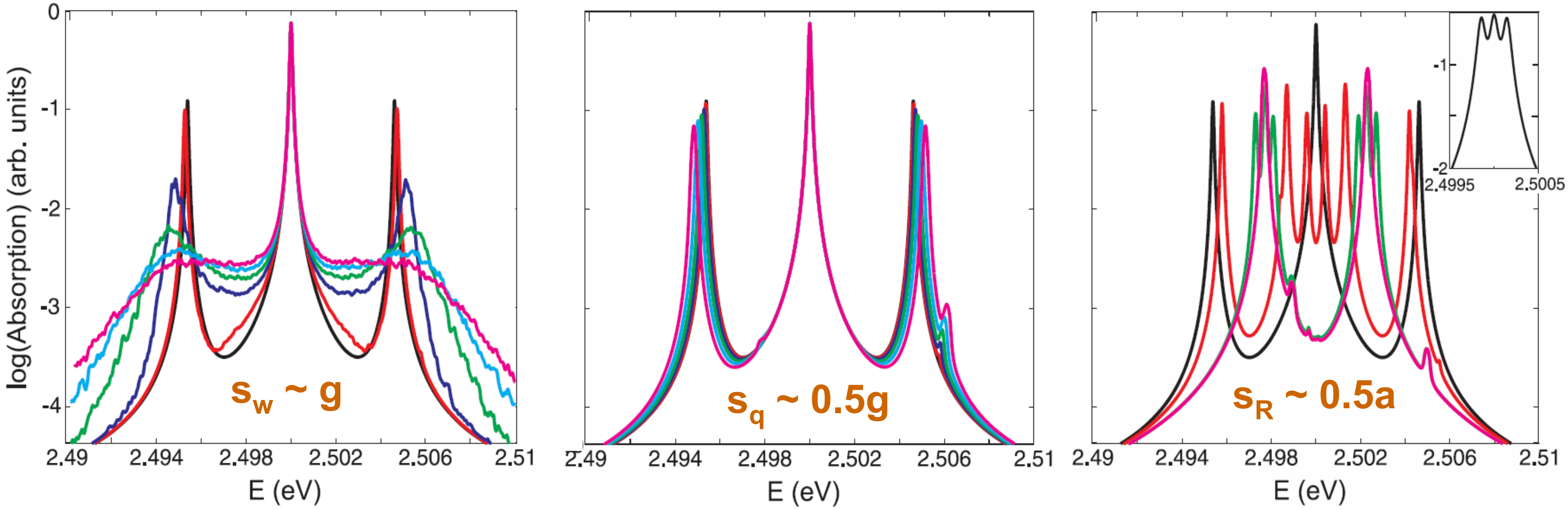


Absorption spectra

M-point



Energy | **Oscillator strength** | **Positional**

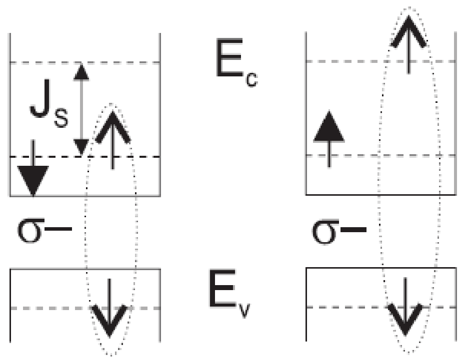


Polaritonic effects the most sensitive to energy disorder.

M. Grochol and C. Piermarocchi, arXiv:0802.3184
(Accepted in Phys Rev B)

Multi-spin coupling

Dot energy levels



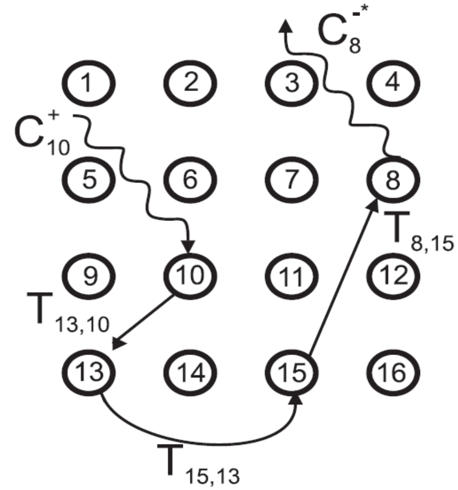
$$\hat{H}_I = J_S \sum_j S_{jz} P_{jz}$$

$$P_{jz} = C^\dagger_{j\uparrow} C_{j\uparrow} - C^\dagger_{j\downarrow} C_{j\downarrow}$$

exciton

Coupling

$$J^{(4)}_{8,15,13,10}$$



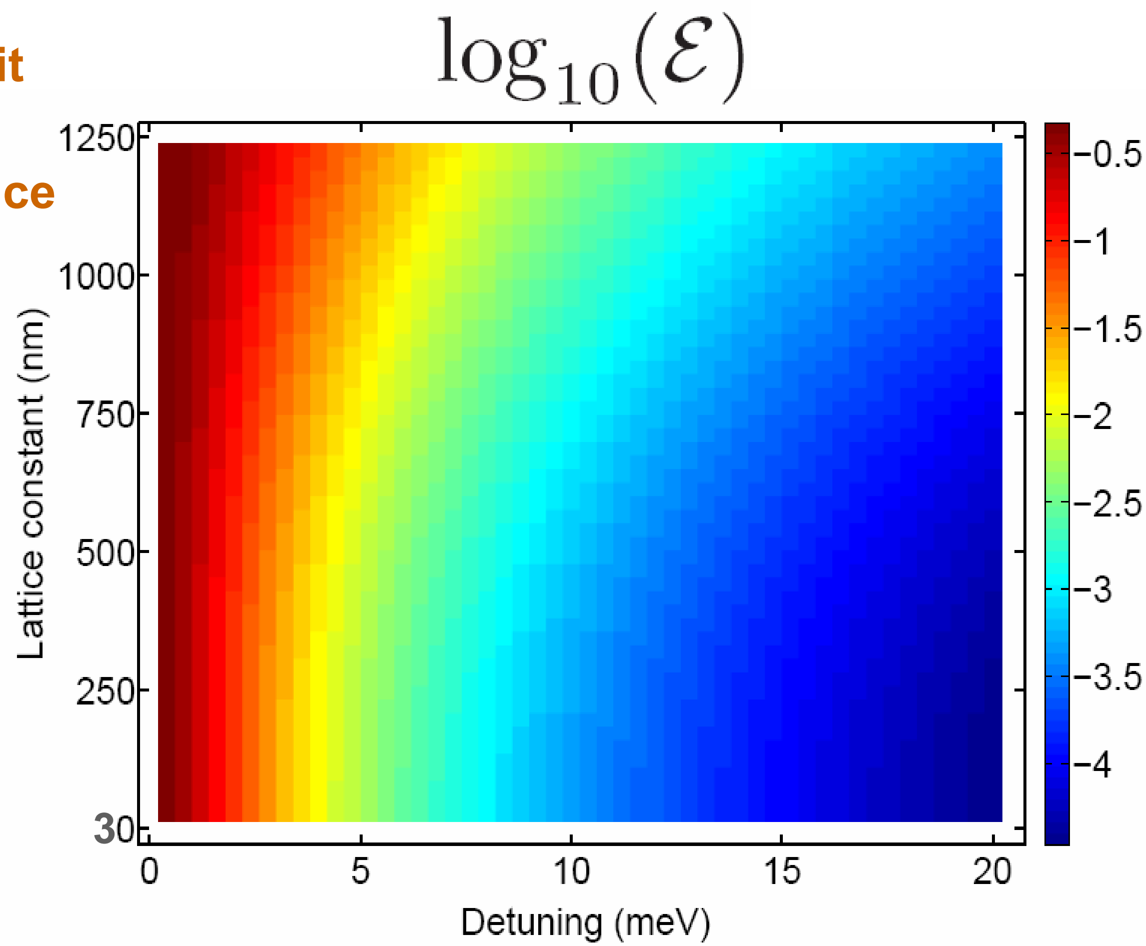
Effective Hamiltonian

$$\hat{H}_T = \sum_{i>j} \tilde{J}^{(2)}_{ij} S_{iz} S_{jz} + \sum_{i>j>k>l} \tilde{J}^{(4)}_{ijkl} S_{iz} S_{jz} S_{kz} S_{lz} + \ldots$$

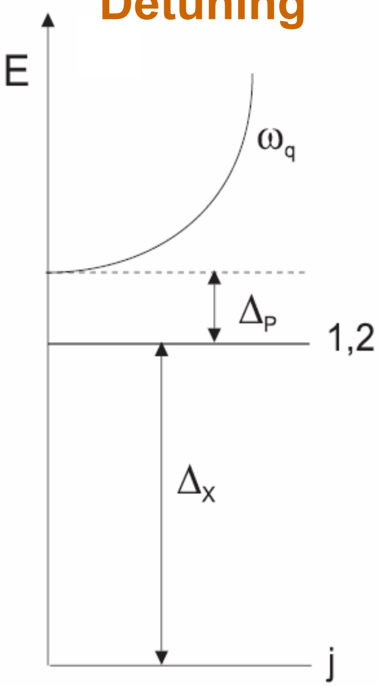
CNOT-gate error

Ideal one-qubit operation

No decoherence



Detuning



High fidelity gate operation in short time ($t_G << T_2$) possible.

M. Grochol and C. Piermarocchi, arXiv:0805.2427