Many facets of Polaritons

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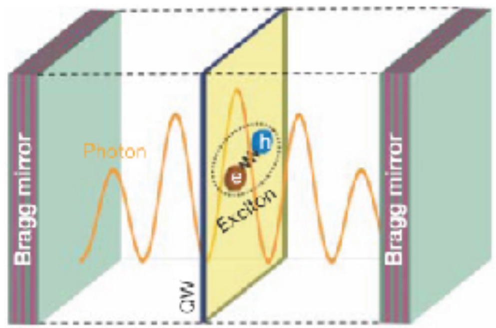
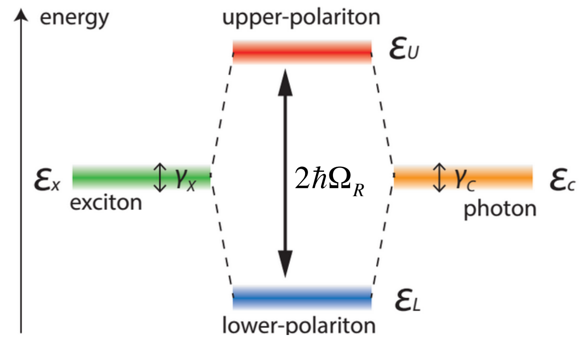
Microcavity Exciton Polaritons

Microcavity polaritons arise from the strong coupling of cavity photons to quantum well excitons



J. Kasprzak *et al.*, Nature (London) **443**, 409 (2006).

The eigenstates of the system are mixed exciton-photon quasi particles: polaritons



Hamiltonian in the strong coupling:

$$\hat{H} = E_X \hat{x}^+ \hat{x} + E_C \hat{c}^+ \hat{c} + \hbar\Omega_R \left(\hat{x}^+ \hat{c} + \hat{c}^+ \hat{x} \right) \quad \rightarrow \hat{H} = \begin{pmatrix} E_C & \hbar\Omega_R \\ \hbar\Omega_R & E_X \end{pmatrix}$$

Diagonalization:

$$\hat{H} = E_{LP} \hat{a}^+ \hat{a} + E_{UP} \hat{b}^+ \hat{b}$$

← polariton basis →

$$\begin{pmatrix} \hat{a} \\ \hat{b} \end{pmatrix} = \begin{pmatrix} X & C \\ -C & X \end{pmatrix} \begin{pmatrix} \hat{x} \\ \hat{c} \end{pmatrix}$$

$$\Rightarrow E_{L,U} = \frac{1}{2} \left(E_C + E_X \mp \sqrt{\left(E_C - E_X \right)^2 + (2\Omega_R)^2} \right)$$

Hopfield coefficients

$$|X|^2 + |C|^2 = 1$$

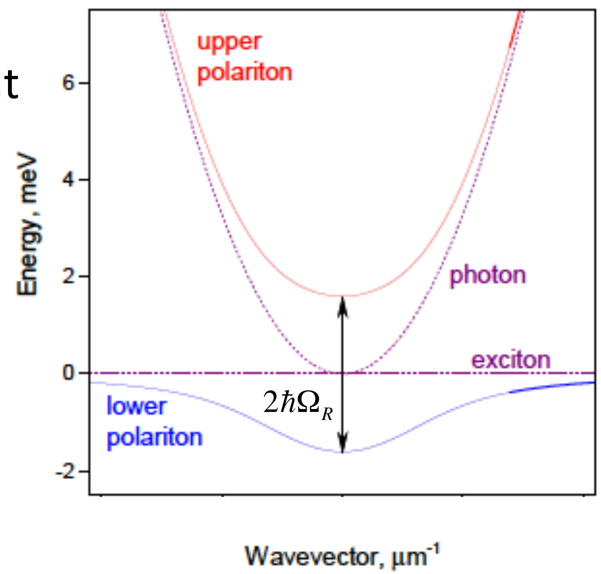
$$\hat{a} = X\hat{x} + C\hat{c}$$

$$\hat{b} = C\hat{x} - X\hat{c}$$

Microcavity Exciton Polaritons

Features

- Polaritons are composite bosons
  - low effective mass provided by their photonic content
  - nonlinearity provided by the excitonic content
- Easily accessible : optical excitation and detection

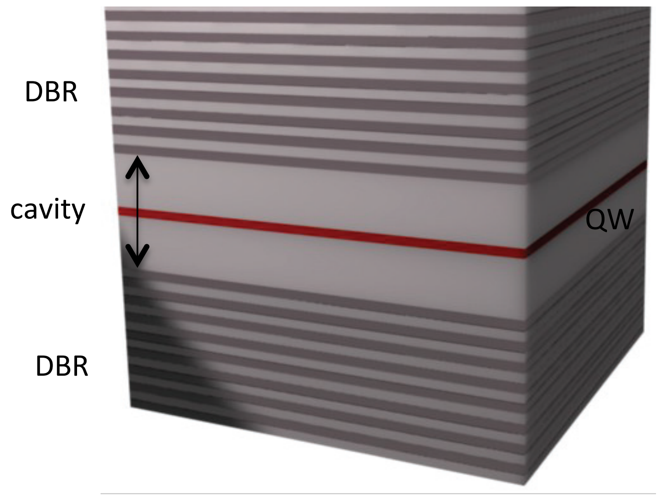


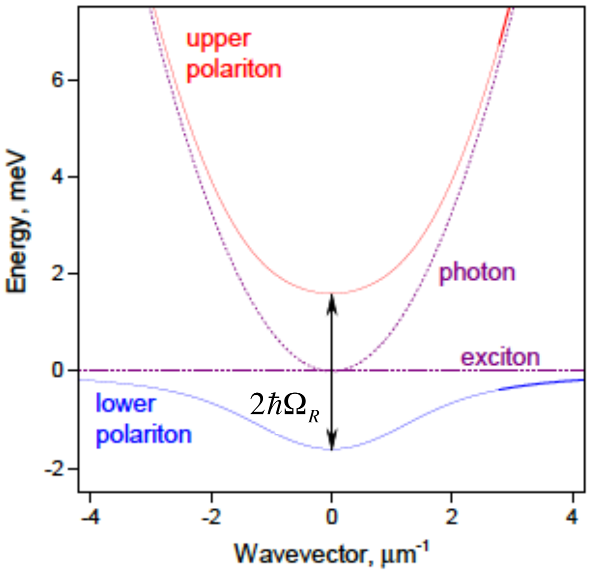
Dynamics $\Longrightarrow$ Gross-Pitaevskii equation

$$i\hbar\frac{\partial\psi}{\partial t}=\left[E-\frac{\hbar^2}{2m}\nabla^2+\alpha_1|\psi|^2-i\gamma\right]\psi$$

Microcavity Exciton Polaritons

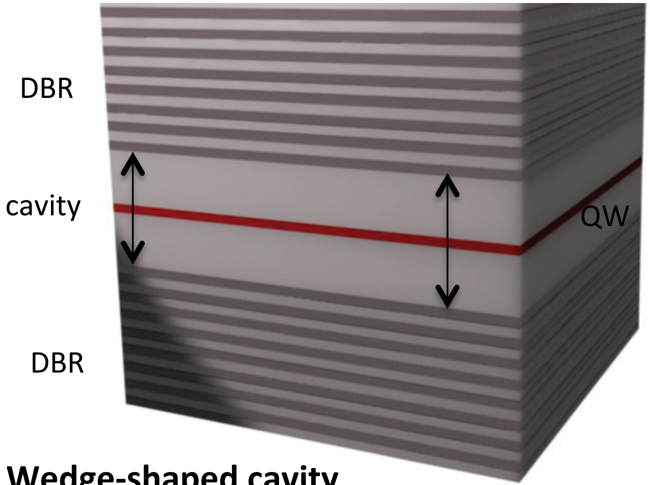
Polaritons in planar microcavity



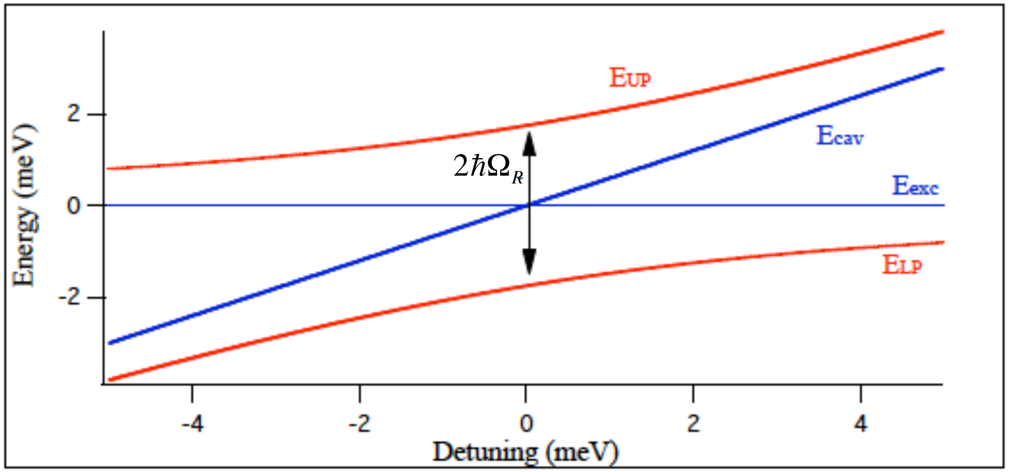


Microcavity Exciton Polaritons

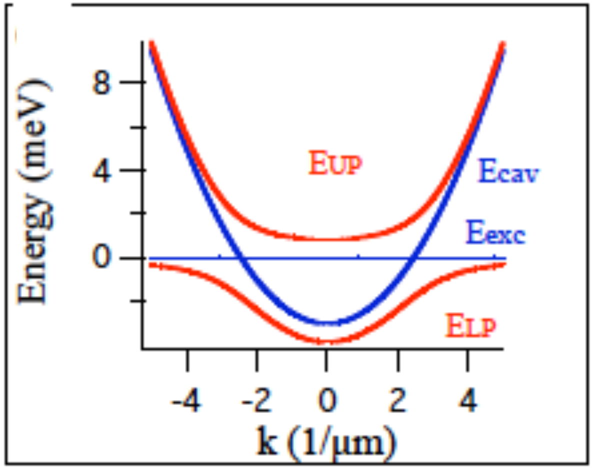
Polaritons in planar microcavity

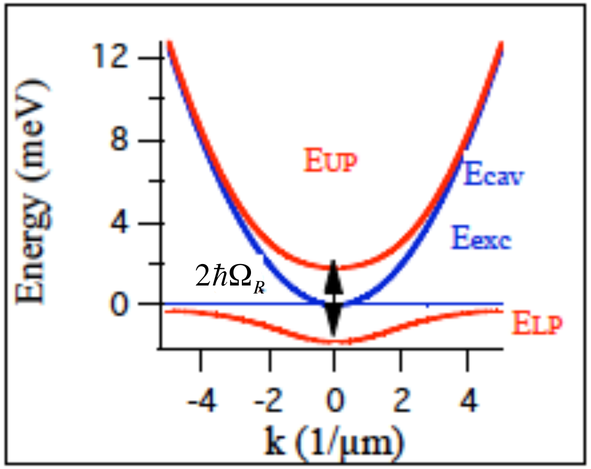


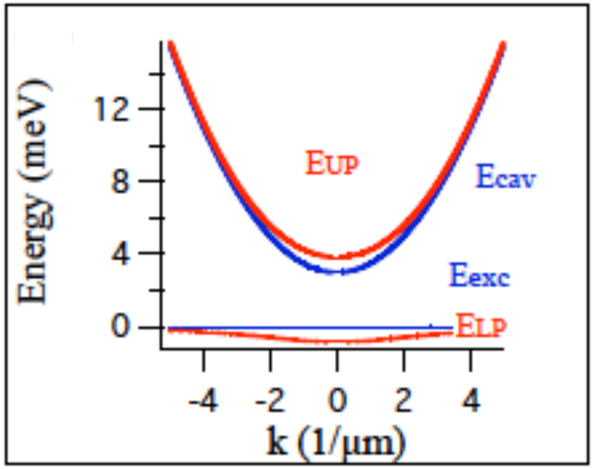
Wedge-shaped cavity



$$E_{LP,UP}(k) = \frac{1}{2}\left(E_X + E_c(k) \mp \sqrt{\delta^2 + 4\Omega_R^2}\right)$$







Cavity detuning

| polariton > = X | exciton > + C | photon >

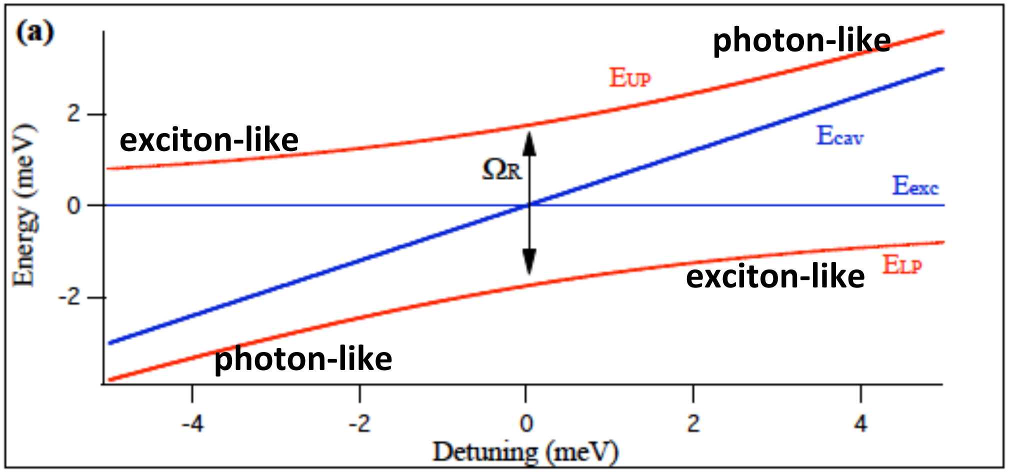
Hopfield coefficients

excitonic fraction

$$|X|^2 = \frac{1}{2}\left(1 + \frac{\delta}{\sqrt{\delta^2 + 4\hbar^2\Omega^2}}\right)$$

photonic fraction

$$|C|^2 = \frac{1}{2}\left(1 - \frac{\delta}{\sqrt{\delta^2 + 4\hbar^2\Omega^2}}\right)$$

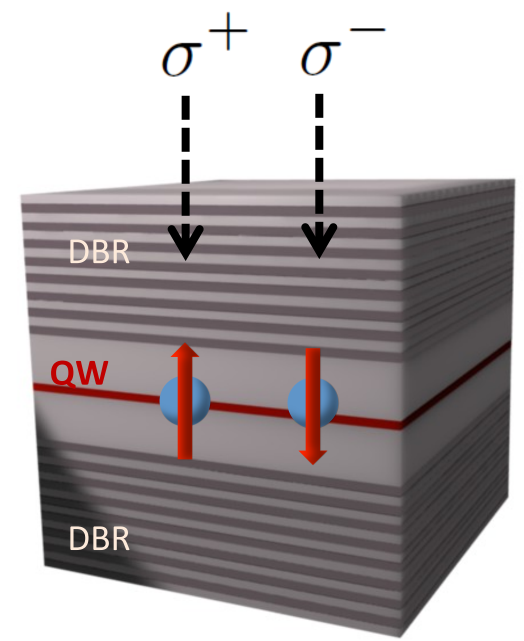


sample position

Two spin states of polariton

Polariton has two spin projections: spin up and down

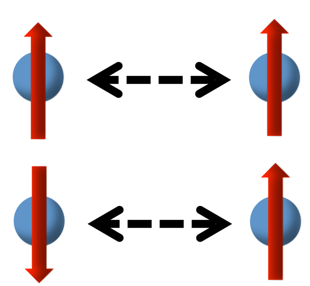
Spin up exciton couples σ^+ cavity photon polarization
Spin down exciton couples σ^- cavity photon polarization



Polariton Spinor Gross-Pitaevskii equation

$$i\hbar\dot{\psi}_\pm = \left[E_\pm - \frac{\hbar^2}{2m}\nabla^2 + \alpha_1|\psi_\pm|^2 + \alpha_2|\psi_\mp|^2 - i\gamma\right]\psi_\pm$$

$\alpha_1|\psi_\pm|^2 \rightarrow \Delta E$ $\quad$ $\alpha_2|\psi_\mp|^2 \rightarrow \Delta E$



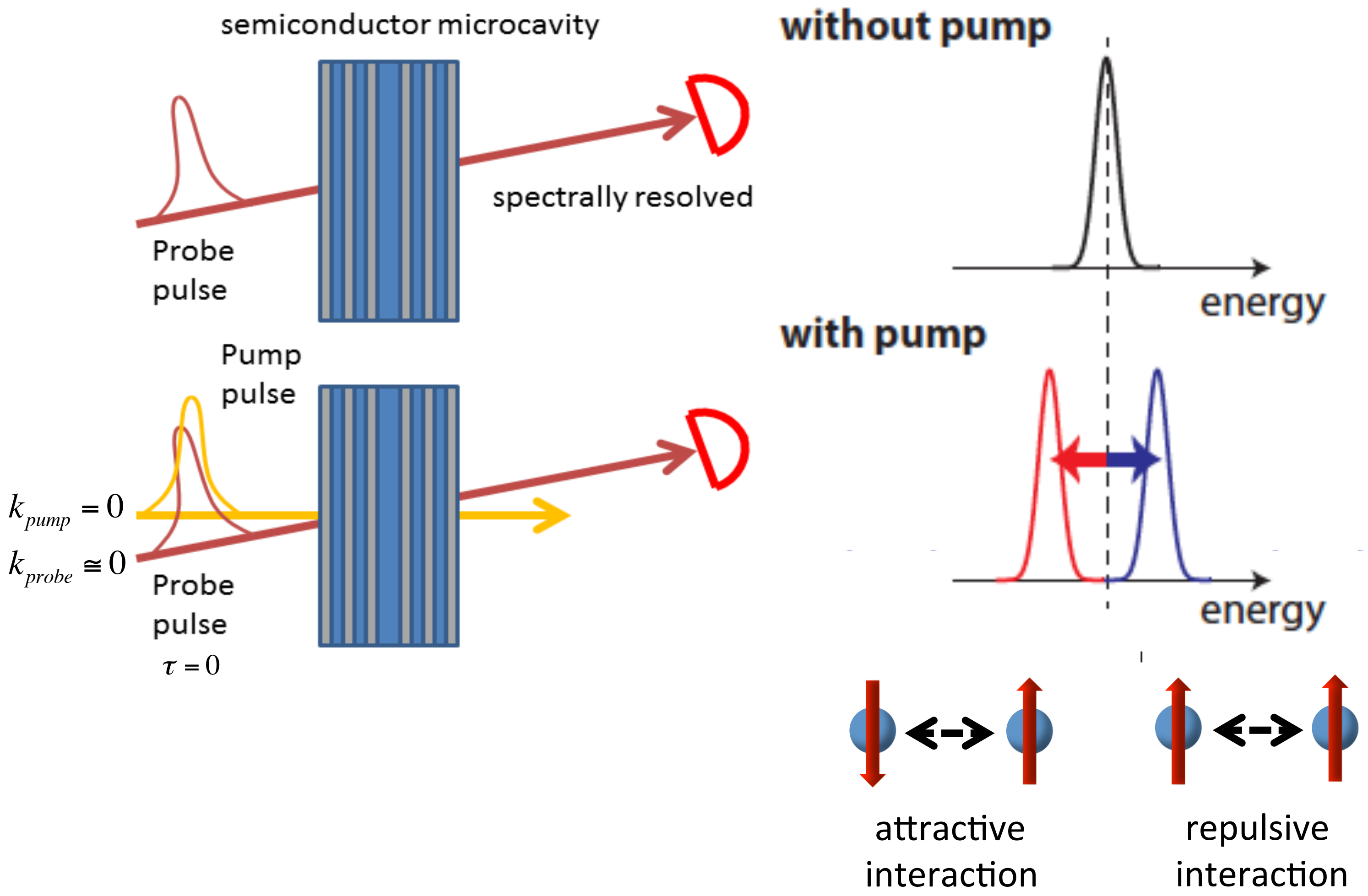
Repulsive polariton interaction with parallel spins

Attractive polariton interaction with anti-parallel spins

N. Takemura *et al.*, Phys. Rev. B 90, 195307 (2014)

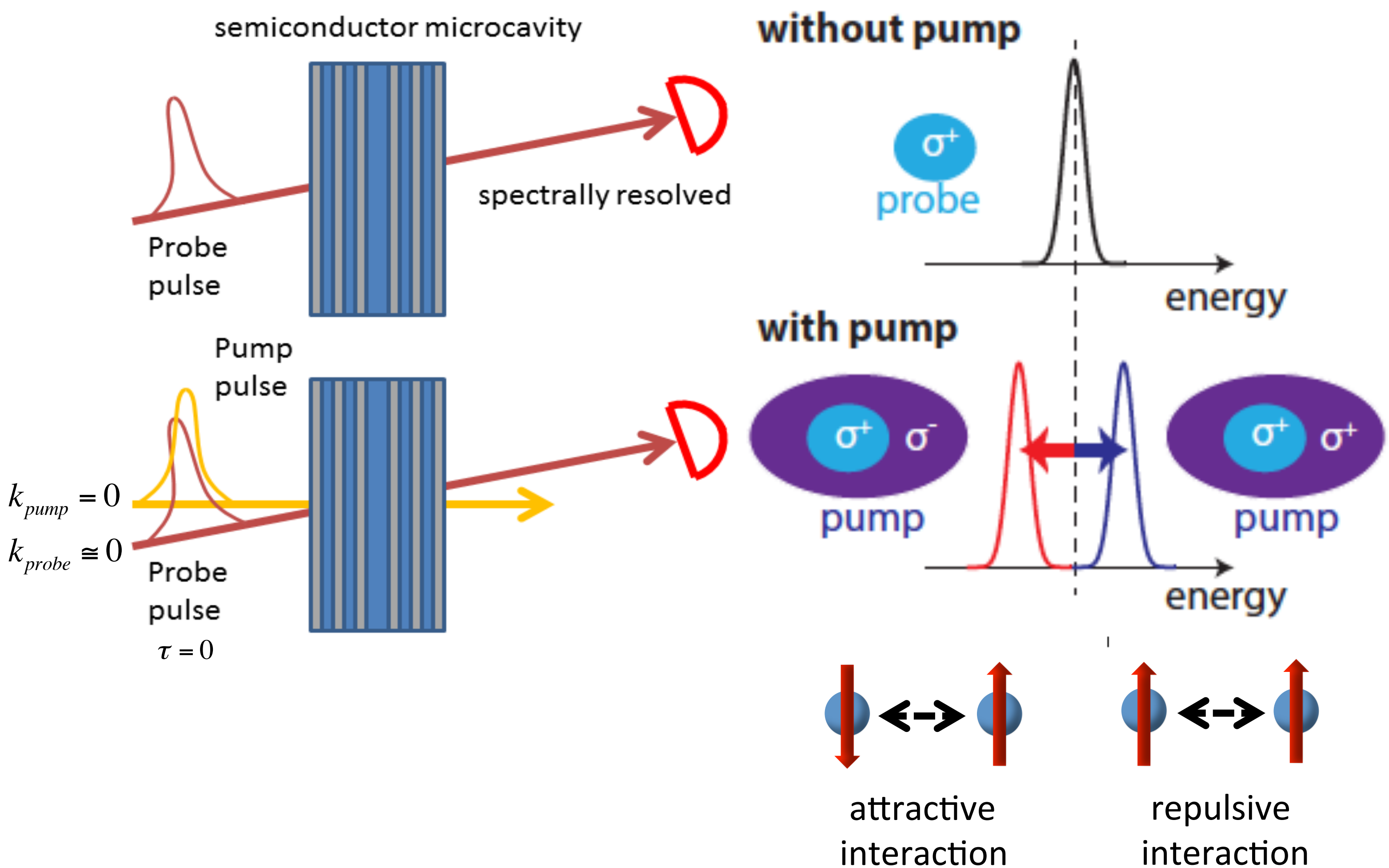
Spectrally resolved pump-probe spectroscopy

Pump-probe spectroscopy



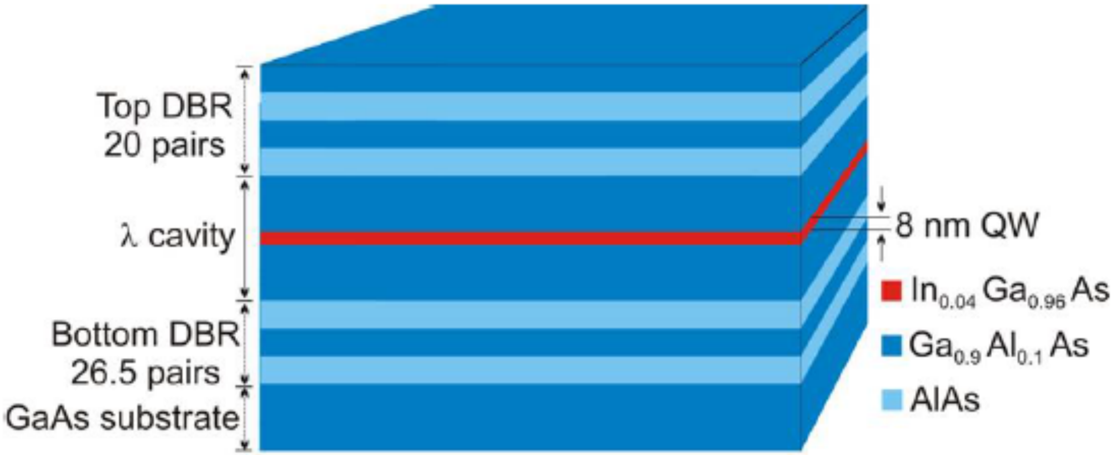
Spectrally resolved pump-probe spectroscopy

Pump-probe spectroscopy

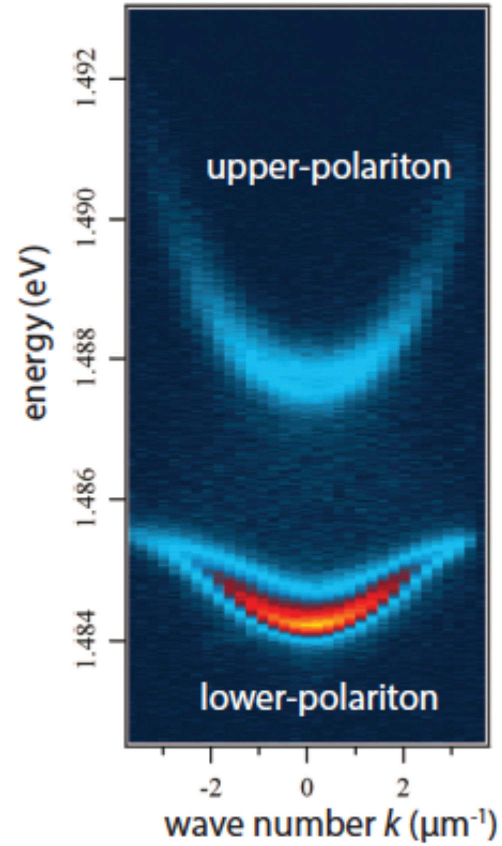


Sample

Microcavity sample



Photoluminescence spectrum

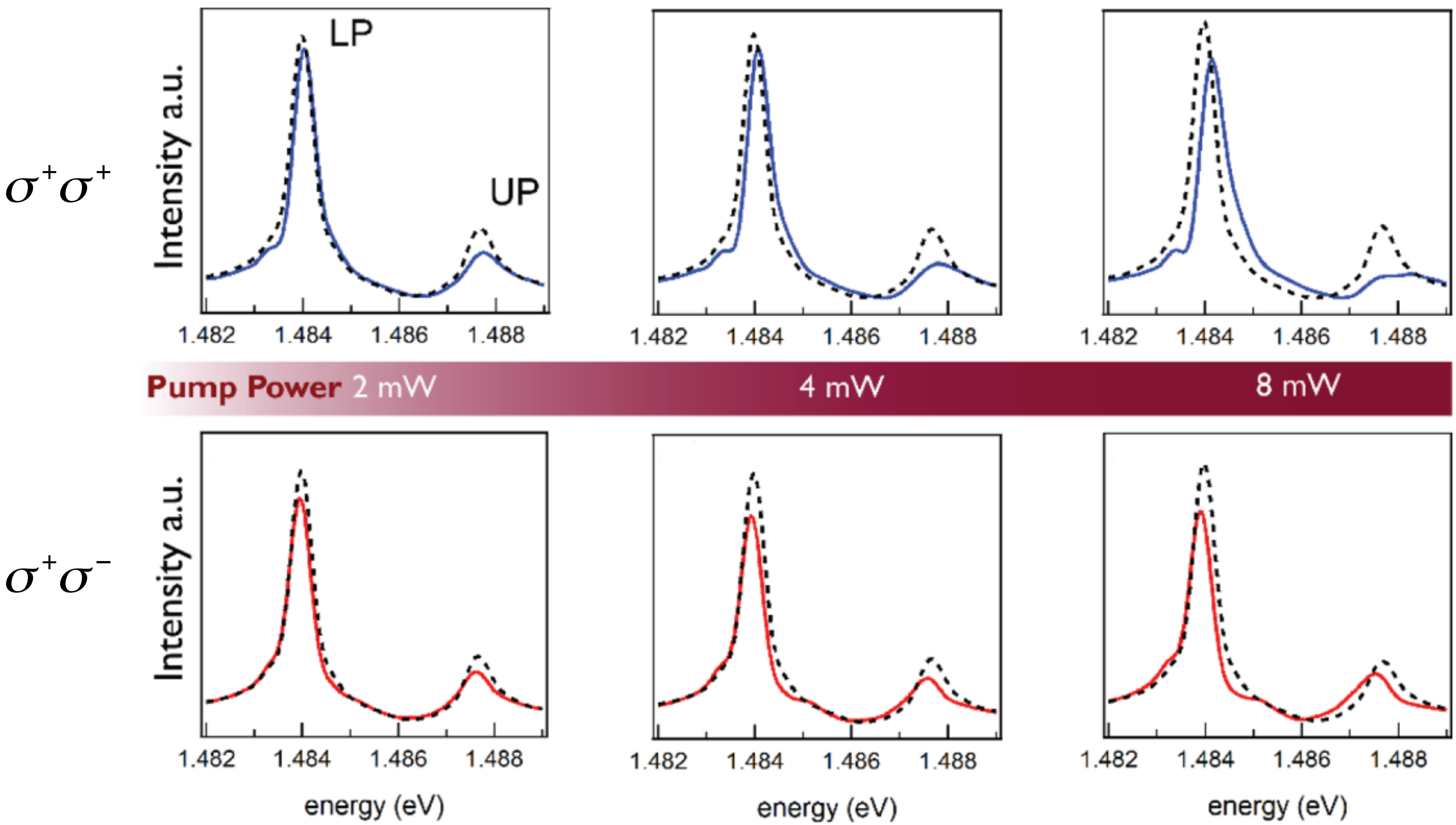


$T = 5K \qquad \delta = -0.8 meV$

R. Stanley *et al*, Appl. Phys. Lett. 65, 1883 (1994)

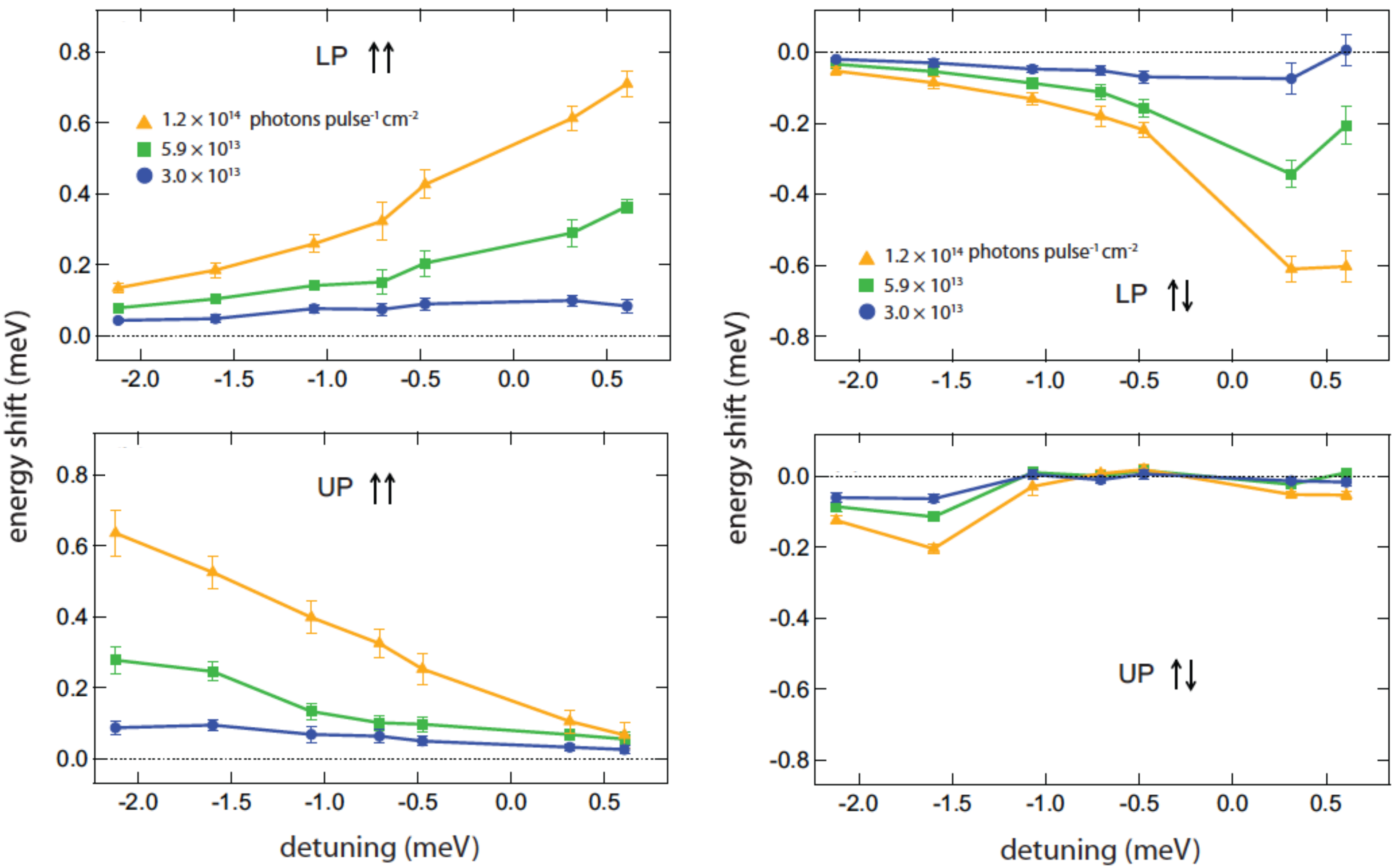
Polariton spinor interactions

Pump probe signal



N. Takemura *et al.*, Phys. Rev. B 90, 195307 (2014)

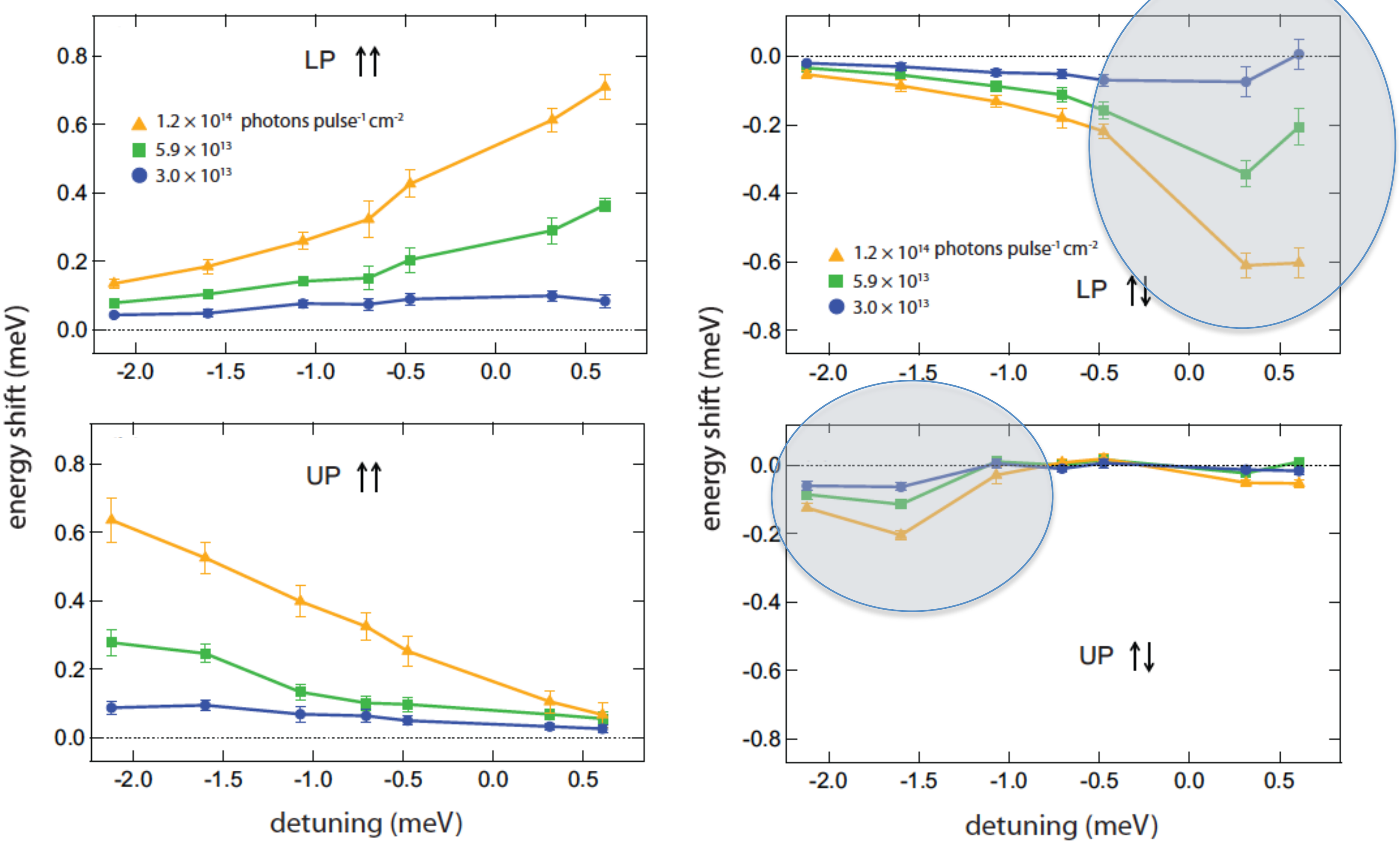
Polariton spinor interactions



N. Takemura *et al.*, Phys. Rev. B 90, 195307 (2014)

Polariton spinor interactions

Deviation from the Hopfield dependence



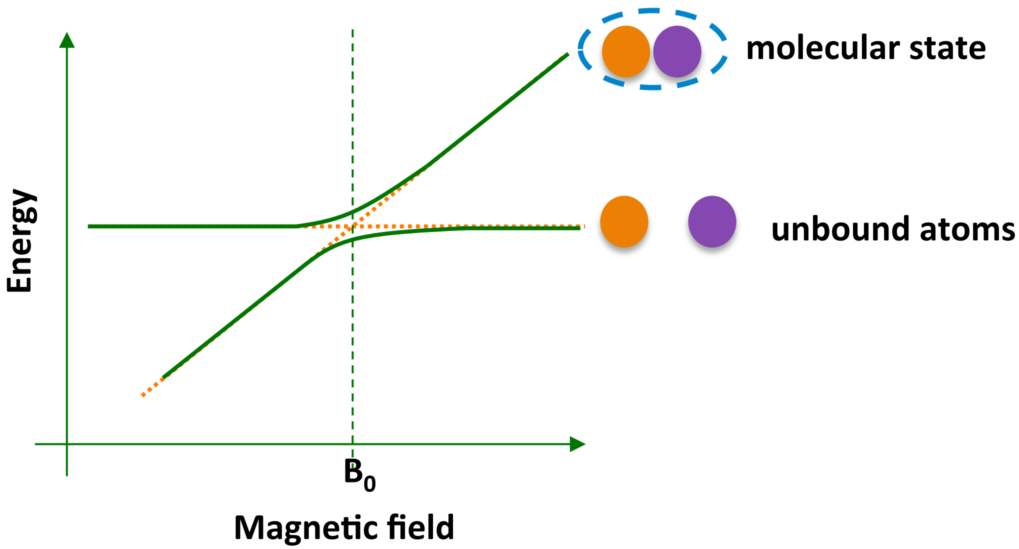
N. Takemura *et al.*, Phys. Rev. B 90, 195307 (2014)

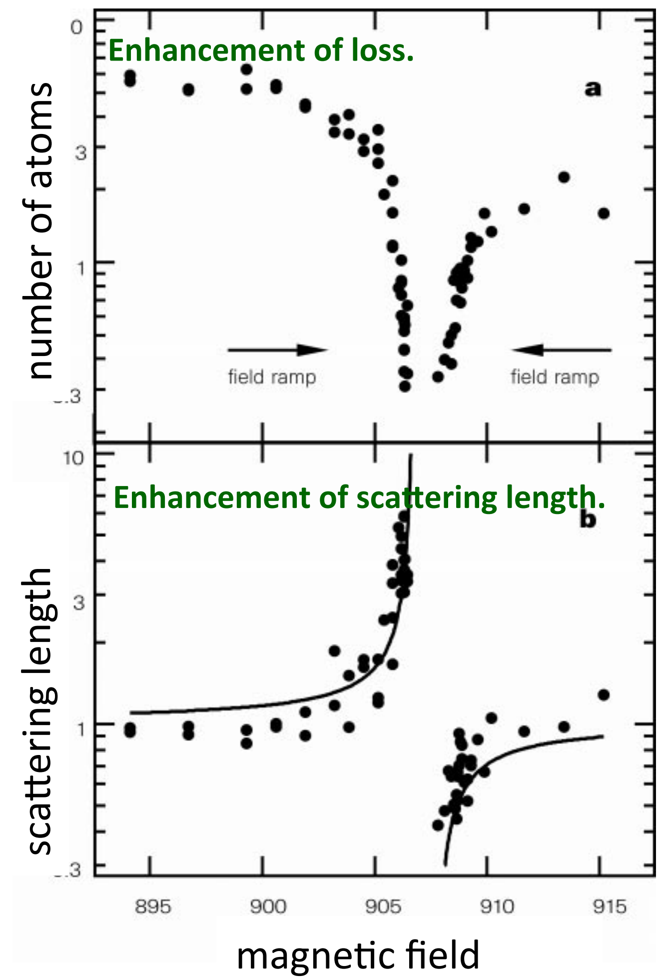
Biexciton effect on opposit spin polariton interaction

Feshbach resonance

Feshbach resonance in cold atoms

A Feshbach resonance occurs when the energy of two interacting free atoms comes to resonance with a molecular bound state.

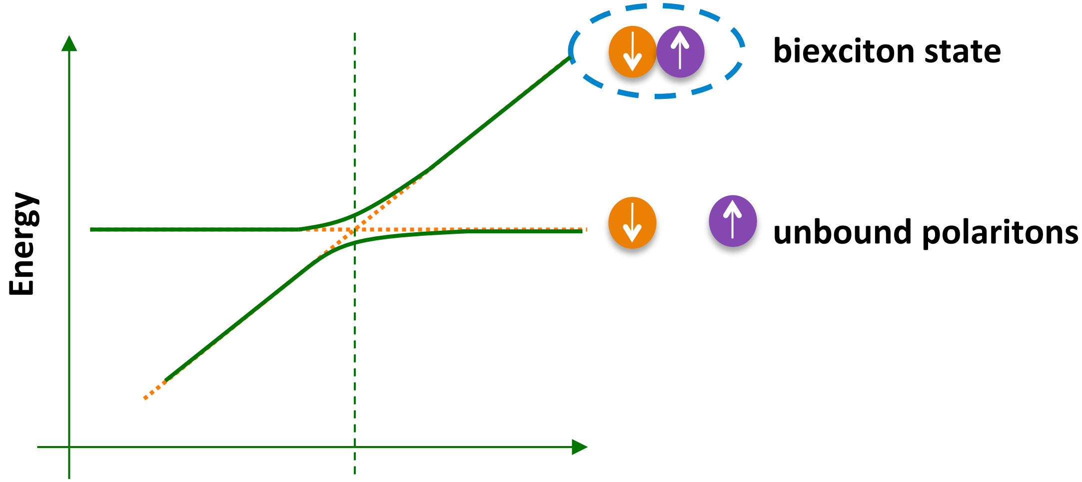


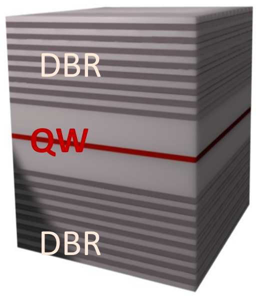


S. Inouye *et al.,* Nature (London) **392**, 151 (1998).

Polaritonic Feshbach resonance

Feshbach resonance in microcavity polaritons



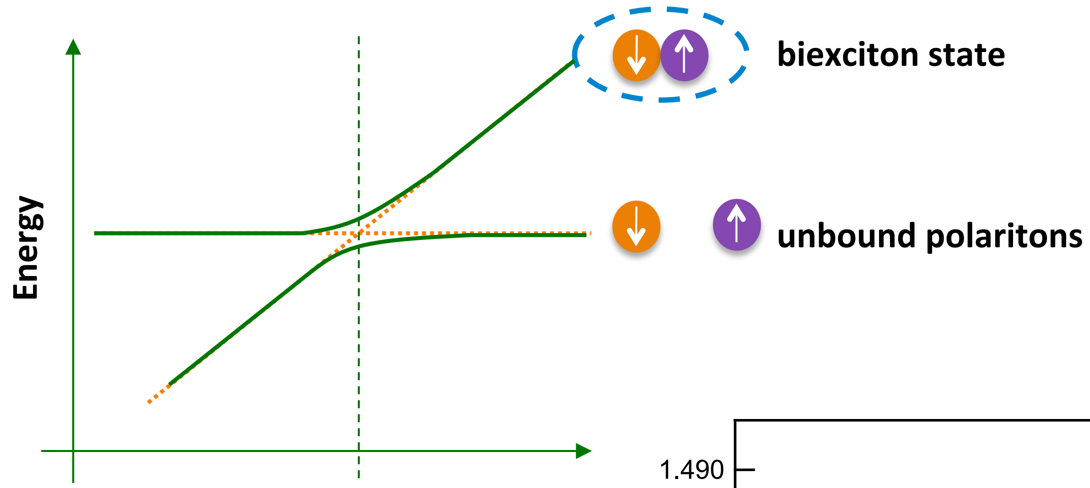


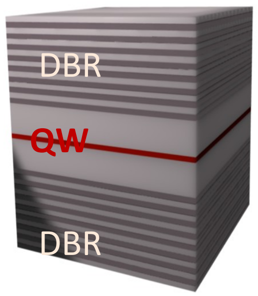
By tuning the relative energy

N Takemura *et al.*, Nature Physics 10, 500 (2014)

Polaritonic Feshbach resonance

Feshbach resonance in microcavity polaritons





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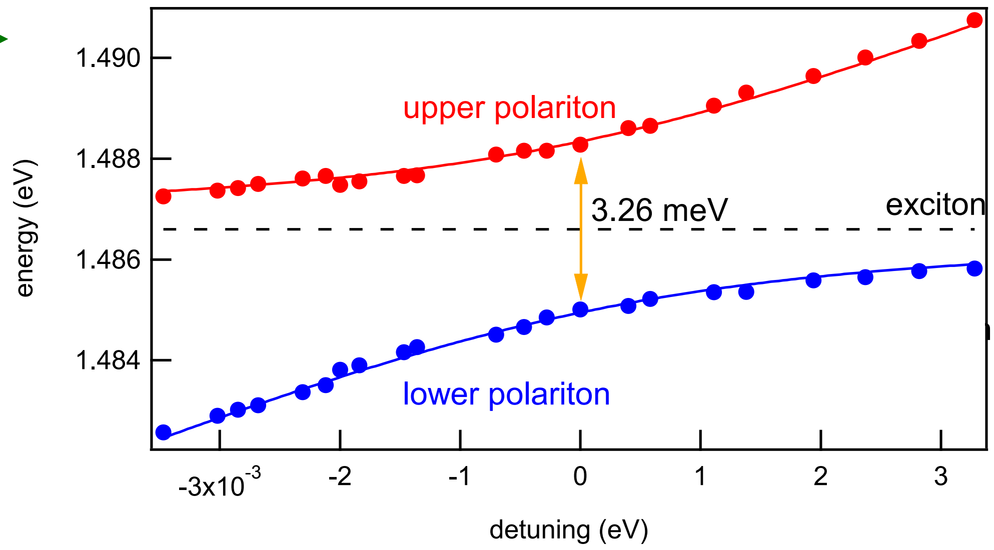

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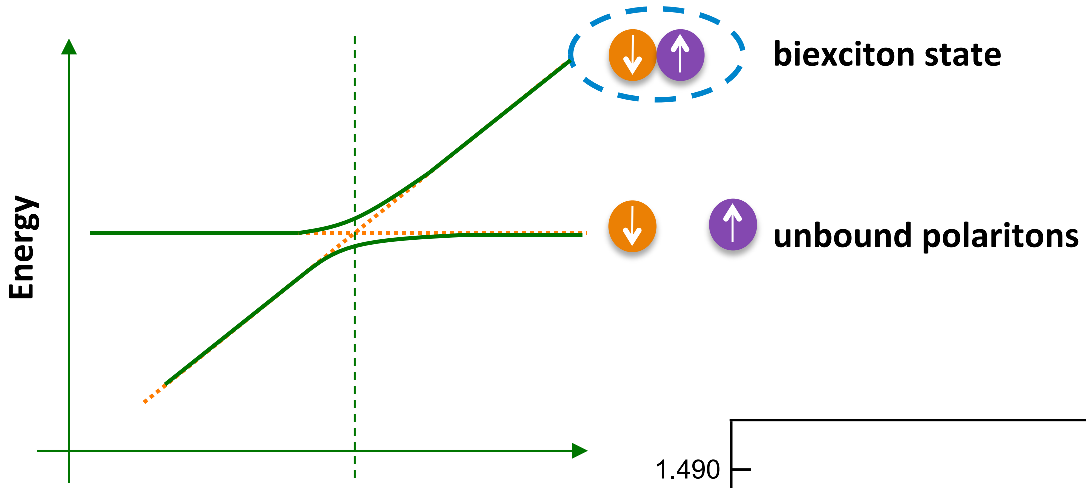
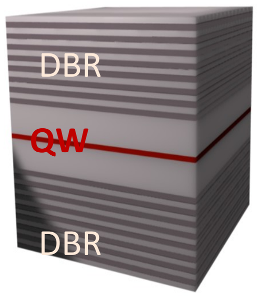
Polaritonic Feshbach resonance

Feshbach resonance in microcavity polaritons





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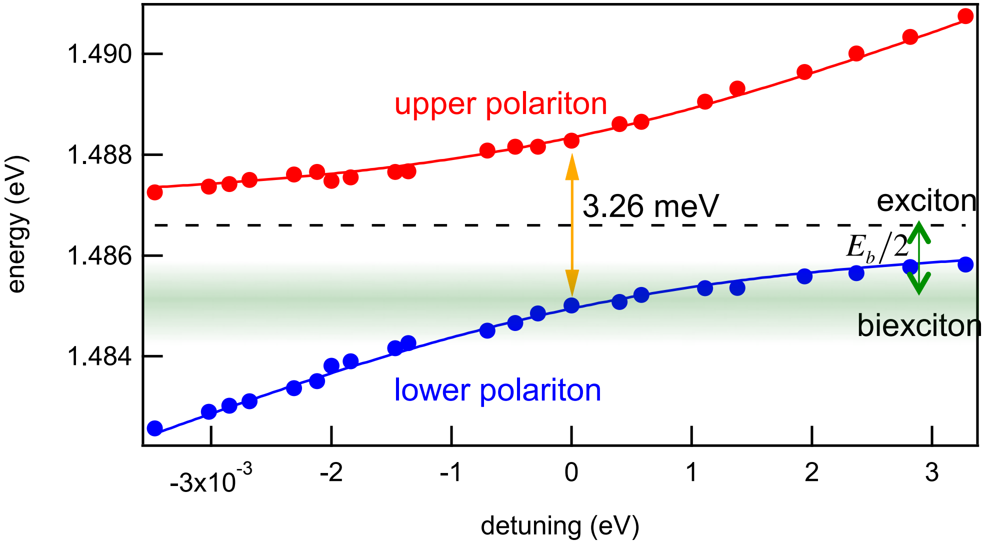

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Polaritonic Feshbach resonance

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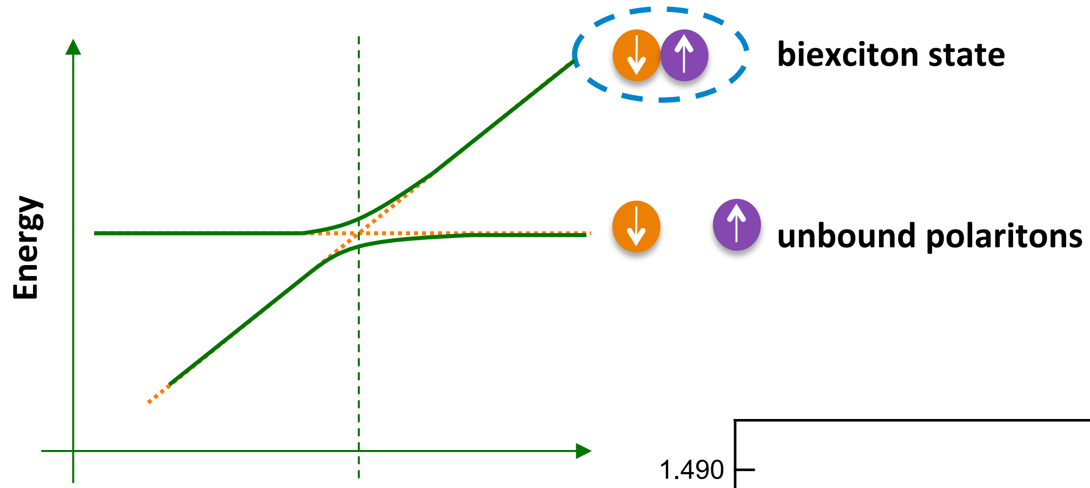
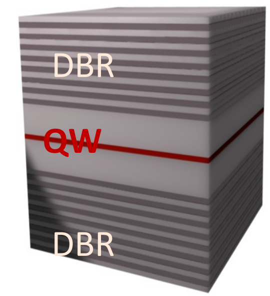
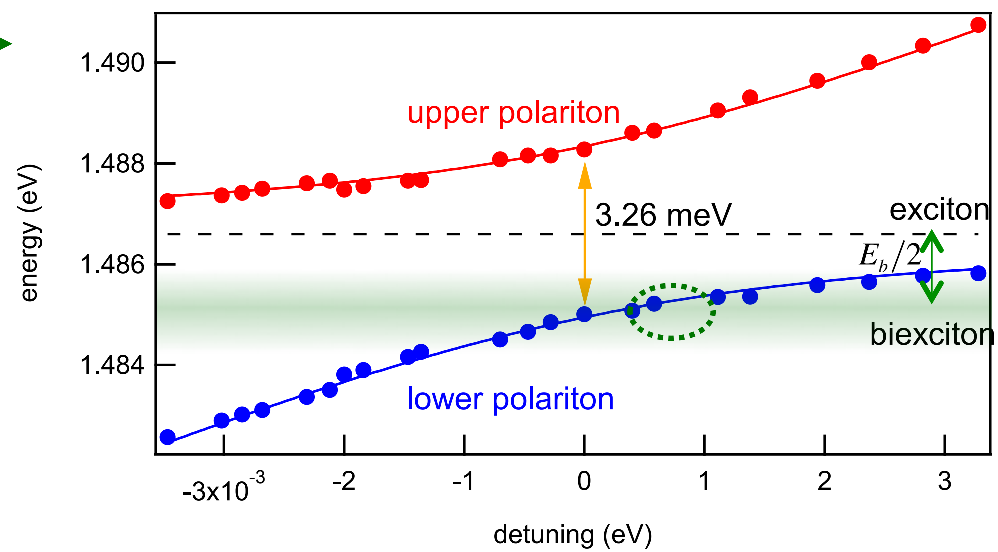




By tuning the relative energy



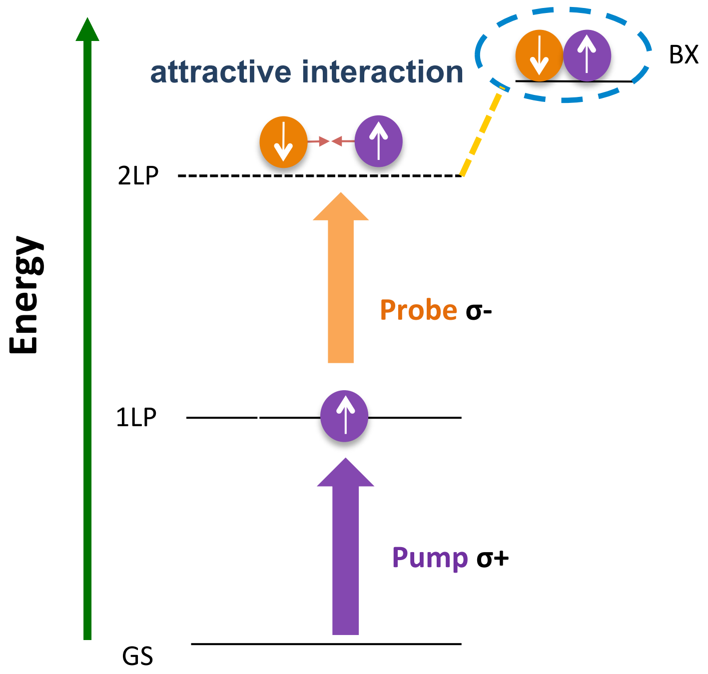
N Takemura *et al.*, Nature Physics 10, 500 (2014)

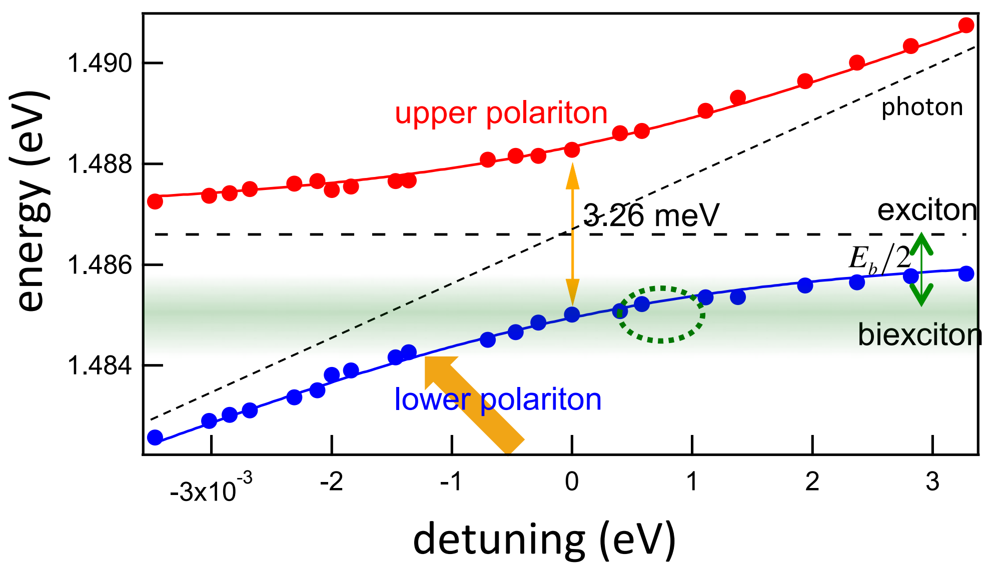
Biexciton effect on opposit spin polariton interaction

Polaritonic Feshbach resonance

The scheme to induce biexcitonic Feshbach resonance

Below BX state

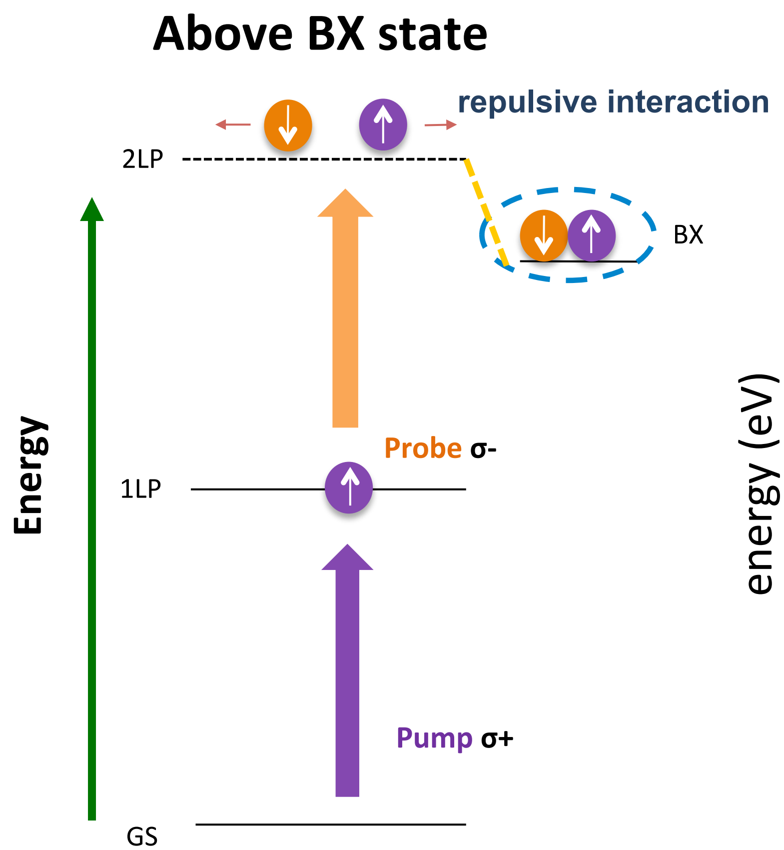


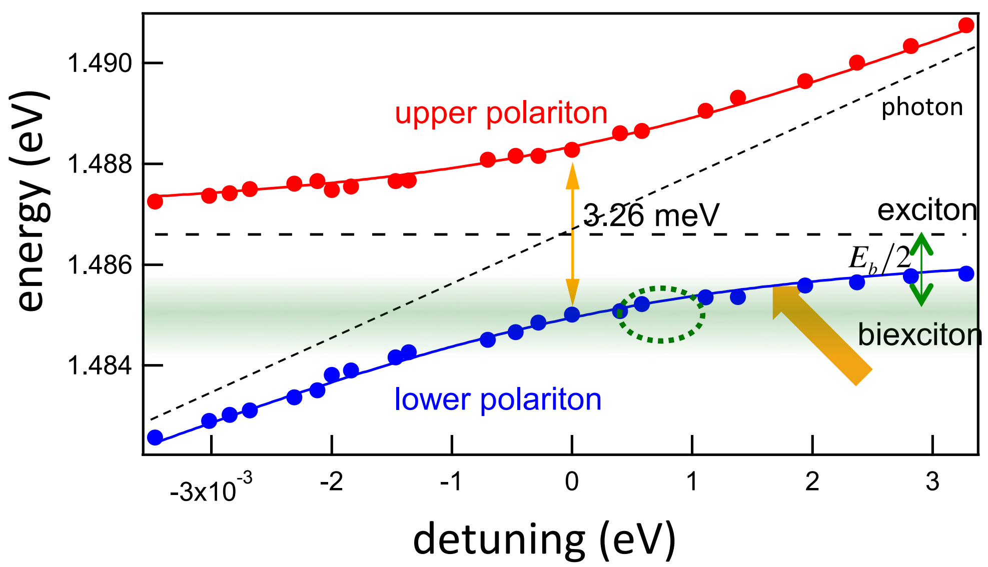


N Takemura *et al.*, Nature Physics 10, 500 (2014)

Polaritonic Feshbach resonance

The scheme to induce biexcitonic Feshabach resonance





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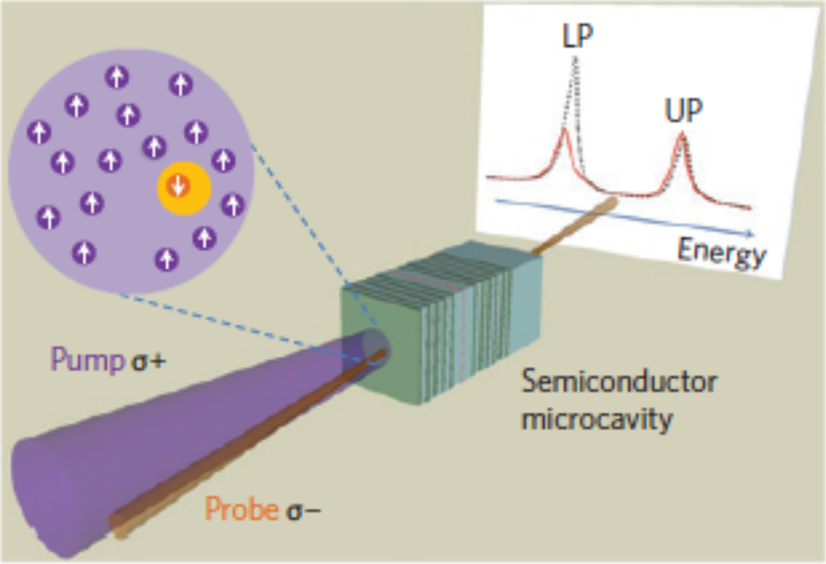
Polaritonic Feshbach resonance

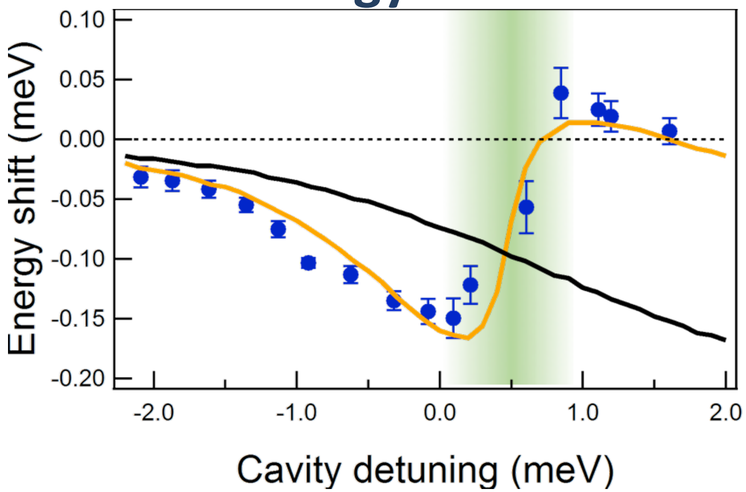
The pump and probe experiment



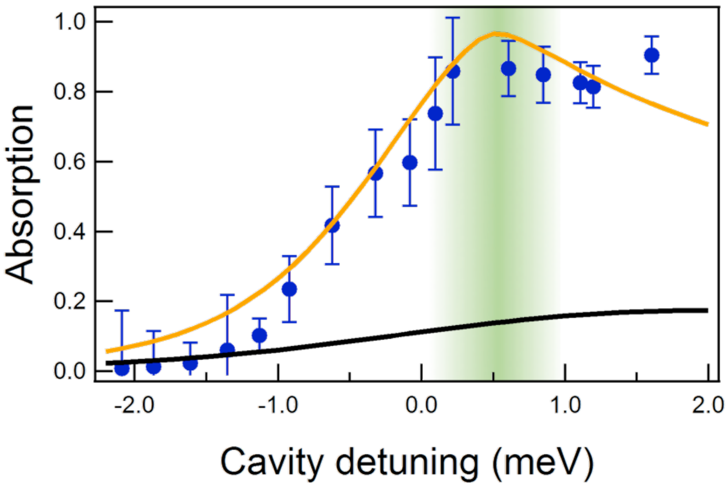
N Takemura *et al.*, Nature Physics 10, 500 (2014)

Polaritonic Feshbach resonance

Energy shift



Absorption

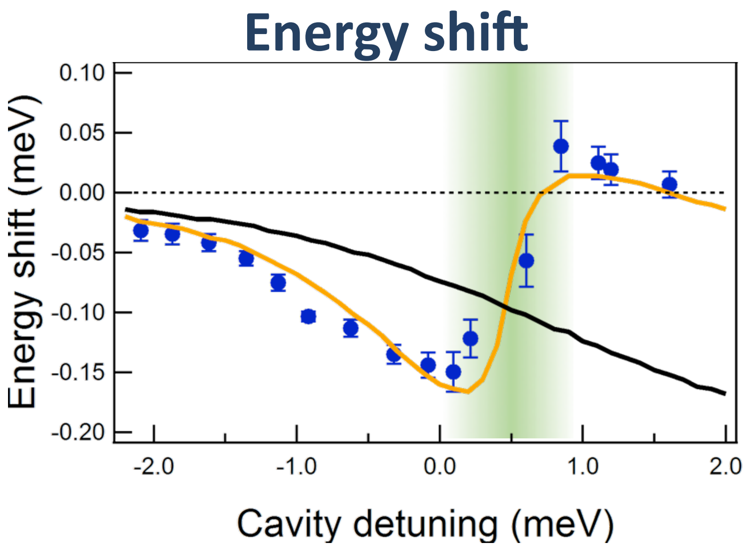


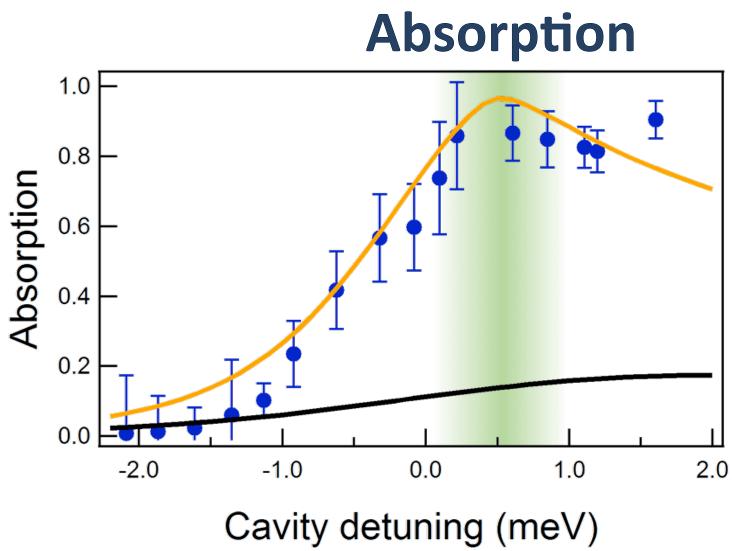
$$H = \Omega_X (a_{c\sigma}\psi^+_{X\sigma,i} + a^+_{c\sigma}\psi_{X\sigma,i}) + \frac{U_{+-}}{2}\left(\psi^+_{X\sigma,i}\psi^+_{X(-\sigma),i}\psi_{X(-\sigma),i}\psi_{X\sigma,i}\right) + g_{BX}(\psi^+_{Bi}\psi_{X\uparrow i}\psi_{X\downarrow i} + \psi_{Bi}\psi^+_{X\uparrow i}\psi^+_{X\downarrow i})$$

photon-exciton **background interaction** **two excitons-biexciton scattering**

N Takemura *et al.*, Nature Physics 10, 500 (2014)

Polaritonic Feshbach resonance





$$H = \Omega_X \left(a_{c\sigma} \psi^+_{X\sigma,i} + a^+_{c\sigma} \psi_{X\sigma,i}\right) + \frac{U_{+-}}{2}\left(\psi^+_{X\sigma,i}\psi^+_{X(-\sigma),i}\psi_{X(-\sigma),i}\psi_{X\sigma,i}\right) + g_{BX}\left(\psi^+_{Bi}\psi_{X\uparrow i}\psi_{X\downarrow i} + \psi_{Bi}\psi^+_{X\uparrow i}\psi^+_{X\downarrow i}\right)$$

photon-exciton **background interaction** **two excitons-biexciton scattering**

$$\Delta E_{L,\downarrow} = g^{+-} X_0^4 \left|\psi^{pu}_{LP,\uparrow}\right|^2 + \mathrm{Re}\left[\frac{g^2_{bx} X_0^4 \left|\psi^{pu}_{LP,\uparrow}\right|^2}{2\varepsilon_{LP} - \varepsilon_B + i\gamma_B}\right]$$

Energy shift

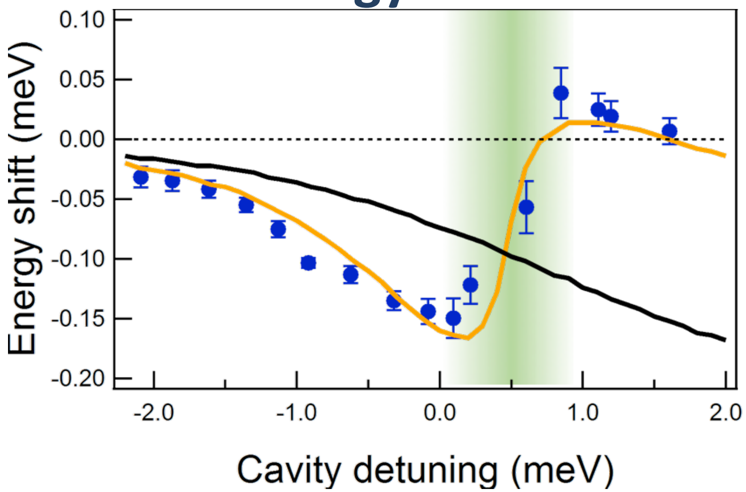
$$\alpha = g^{+-} X_0^4 + g_{bx} X_0^4 \frac{2\varepsilon_L - \varepsilon_B}{\left(2\varepsilon_L - \varepsilon_B\right)^2 + \gamma_B^2}$$

absorption

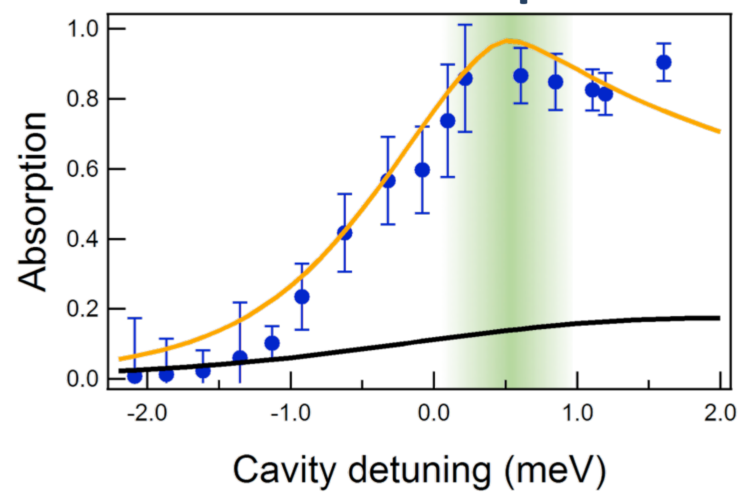
N Takemura *et al.*, Nature Physics 10, 500 (2014)
N Takemura *et al.*, Phys. Rev. B 95, 205303 (2017)

Polaritonic Feshbach resonance

Energy shift



Absorption

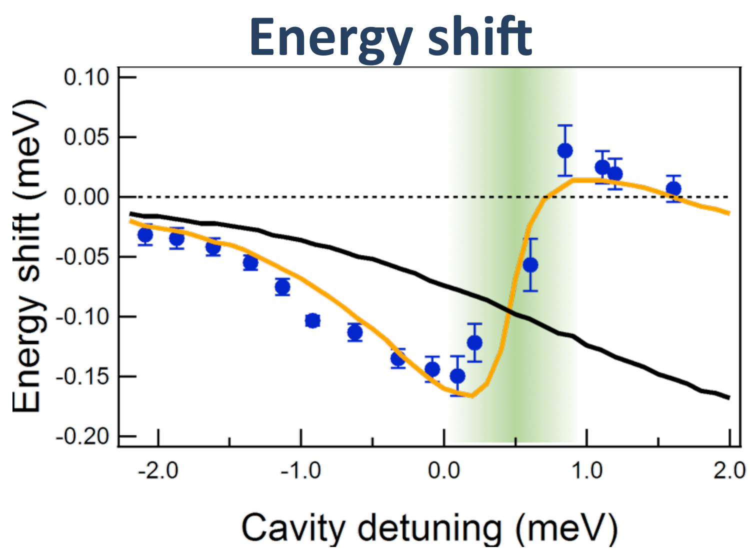


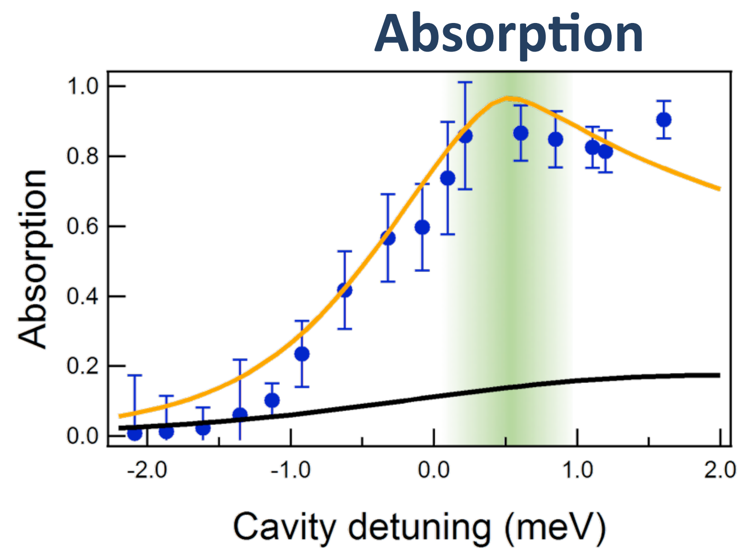
characteristic shape of resonant scattering

- ✓ dispersive shape
- ✓ change of the magnitude and sign of the interaction
- ✓ absorption maximum at resonance region

N Takemura *et al.*, Nature Physics 10, 500 (2014)

Polaritonic Feshbach resonance





characteristic shape of resonant scattering

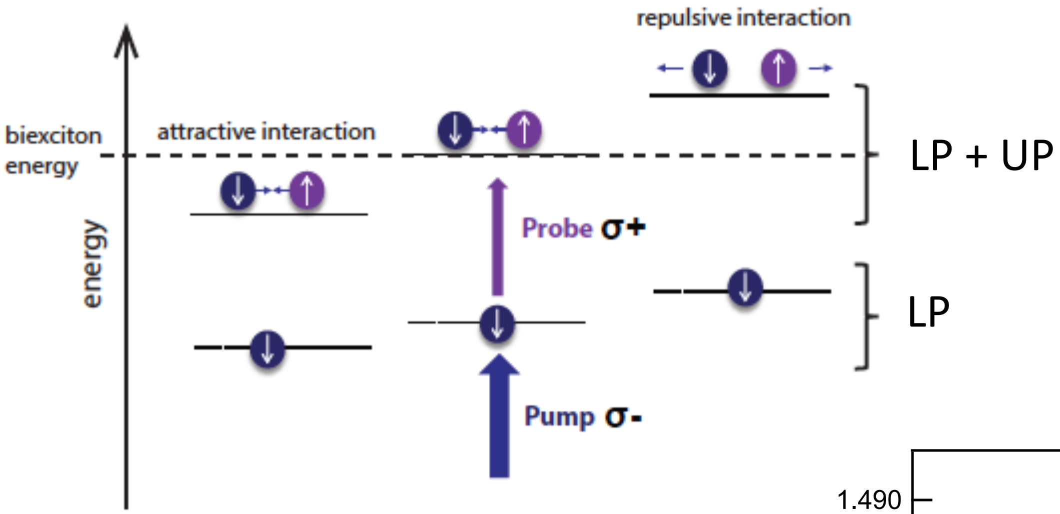
- ✓ dispersive shape
- ✓ change of the magnitude and sign of the interaction
- ✓ absorption maximum at resonance region

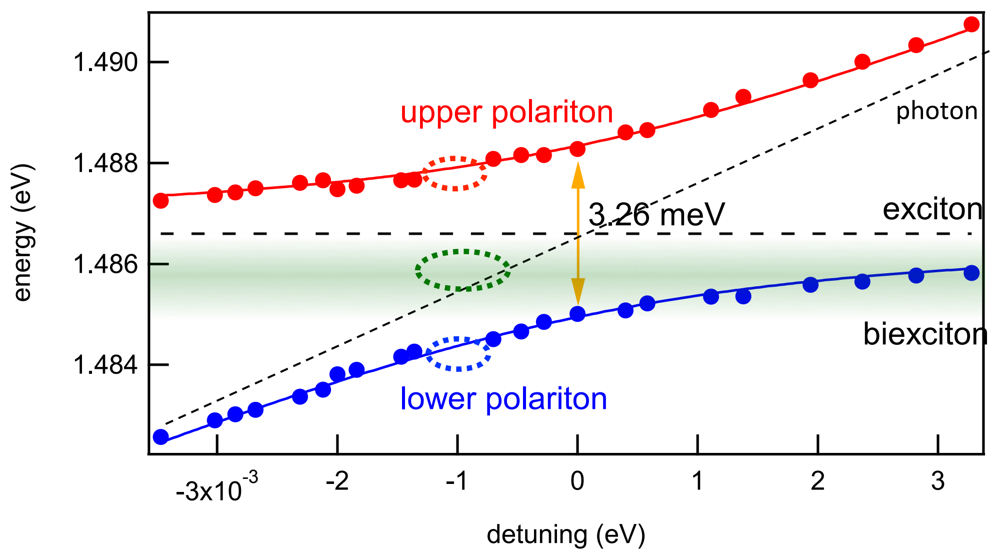
N Takemura *et al.*, Nature Physics 10, 500 (2014)

Control the strength and nature of the interaction

Polaritonic Cross Feshbach resonance

The scheme to induce cross Feshbach resonance

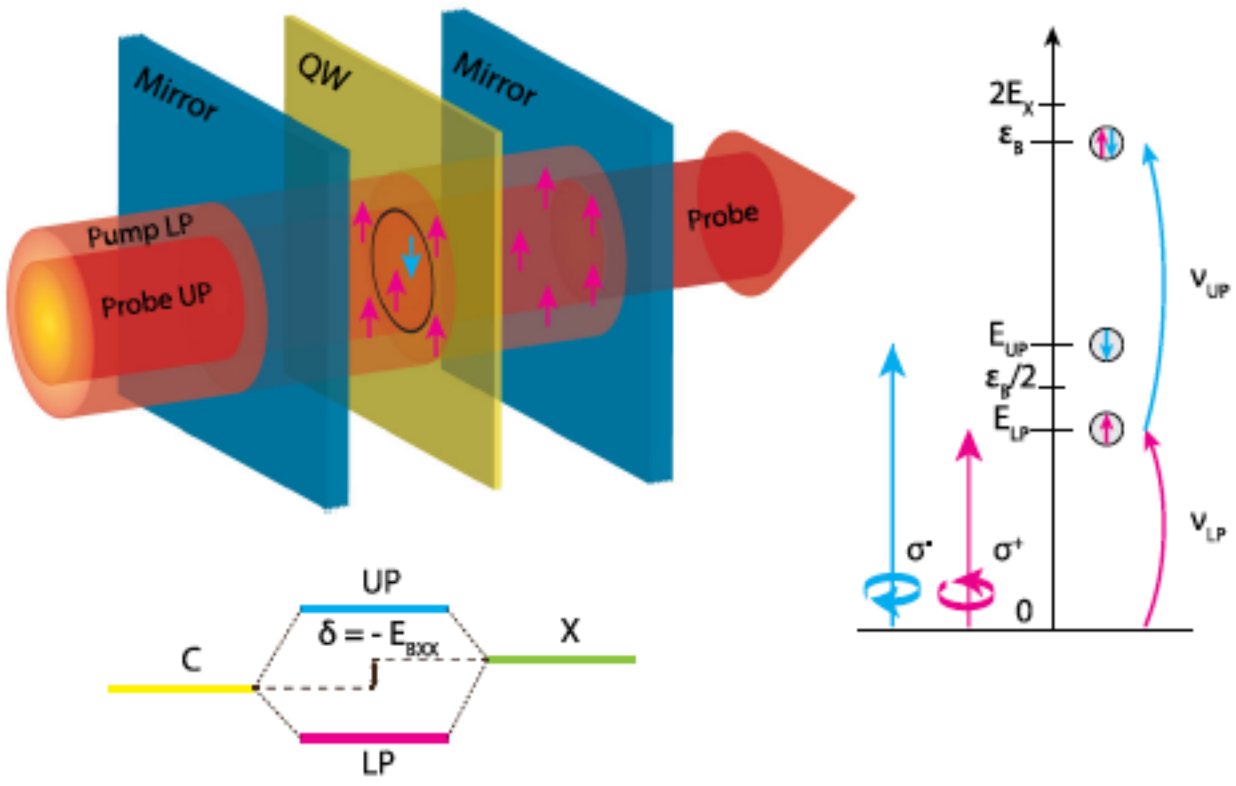




M. Navadeh-Toupchi *et al*, Phys. Rev. Lett. 122, 047402 (2019)

Polaritonic Cross Feshbach resonance

The pump and probe experiment



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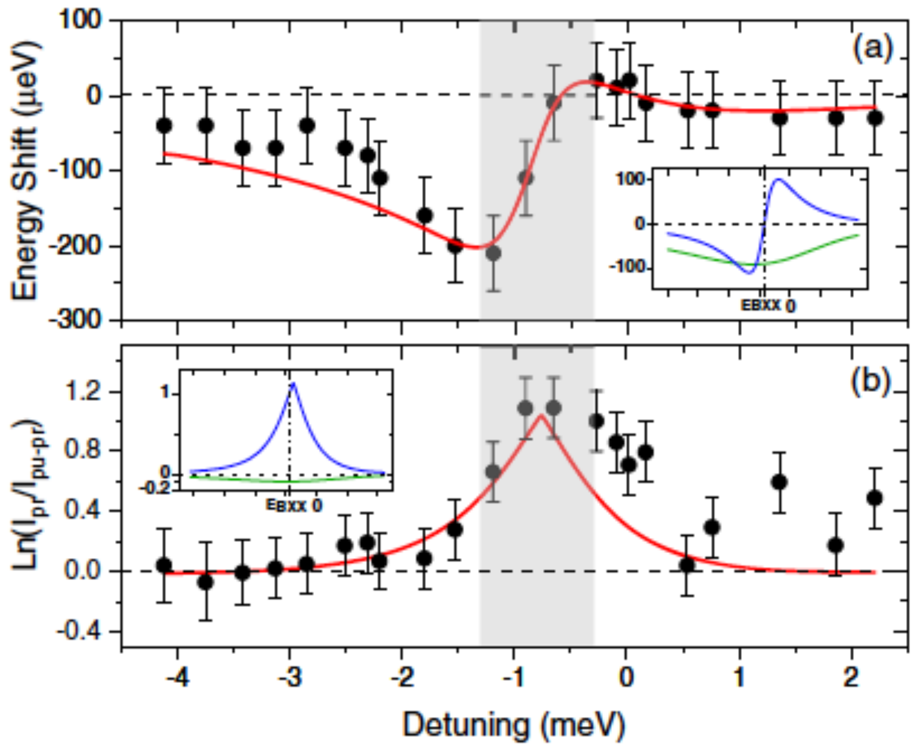


$$\Delta E_{U,\downarrow} = g^{+-} X_0^2 \left|C_0\right|^2 \left|\psi_{LP,\uparrow}^{pu}\right|^2 + \mathrm{Re}\left[\frac{g_{bx}^2 X_0^2 \left|C_0\right|^2 \left|\psi_{LP,\uparrow}^{pu}\right|^2}{\varepsilon_{LP}+\varepsilon_{UP}-\varepsilon_B + i\gamma_B}\right]$$

Energy shift

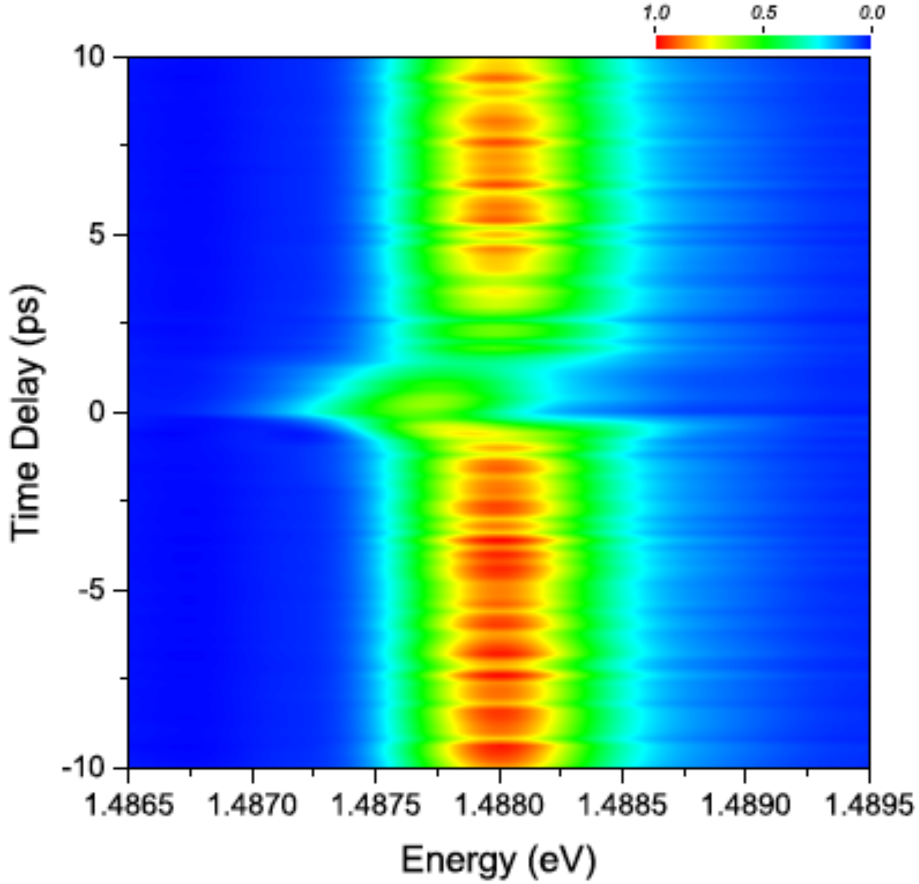
$$\alpha_B = g_{bx}^2 X_0^2 \left|C_0\right|^2 \left|\psi_{LP,\uparrow}^{pu}\right|^2 \frac{\gamma_B}{\left(\varepsilon_{LP}+\varepsilon_{UP}-\varepsilon_B\right)^2+\gamma_B^2}$$

Absorption

M. Navadeh-Toupchi *et al*, Phys. Rev. Lett. 122, 047402 (2019)

Polaritonic Cross Feshbach resonance

Dynamics of the cross Feshbach resonance

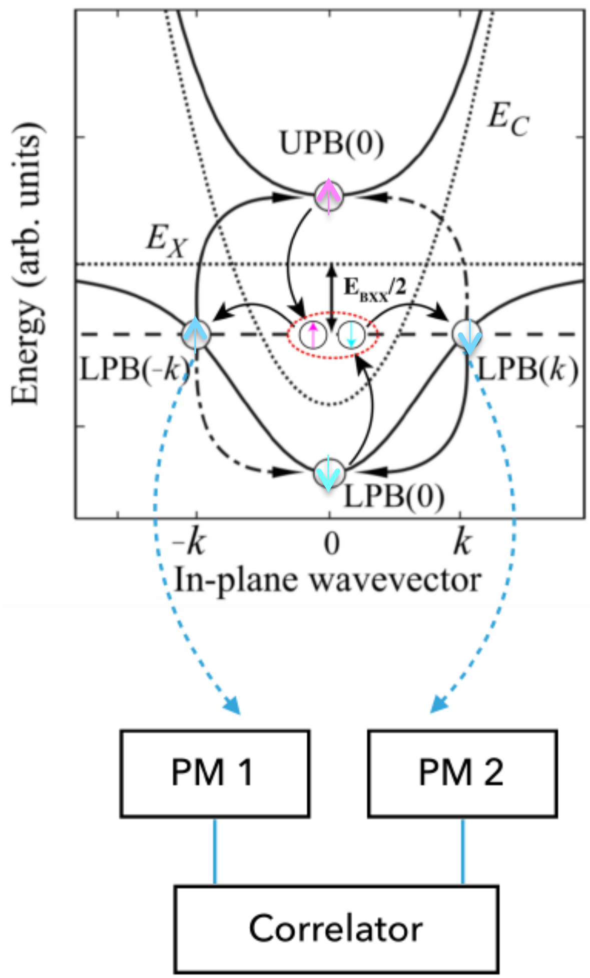


Cavity detuning in the vicinity of the cross FR

$\delta = -1.2meV$

M. Navadeh-Toupchi *et al*, Phys. Rev. Lett. 122, 047402 (2019)

Scheme for generating pairs of entangled photons

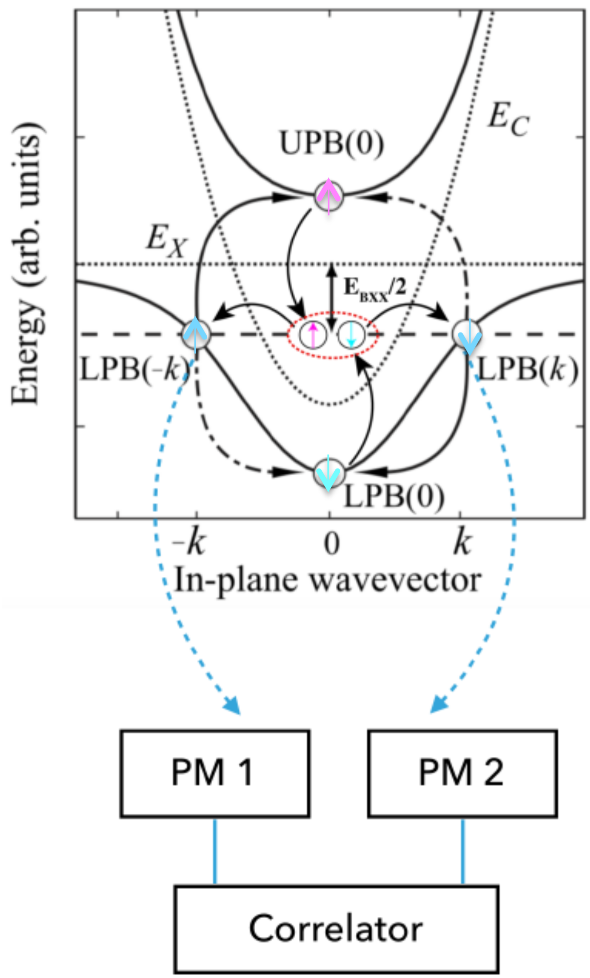


Pair of photons entangled in momentum and polarization

LP(-k) ↑ ↓ LP(-k)

H. Oka *et al*, Appl. Phys. Lett. 94, 111113 (2009)

Scheme for generating pairs of entangled photons



Pair of photons entangled in momentum and polarization

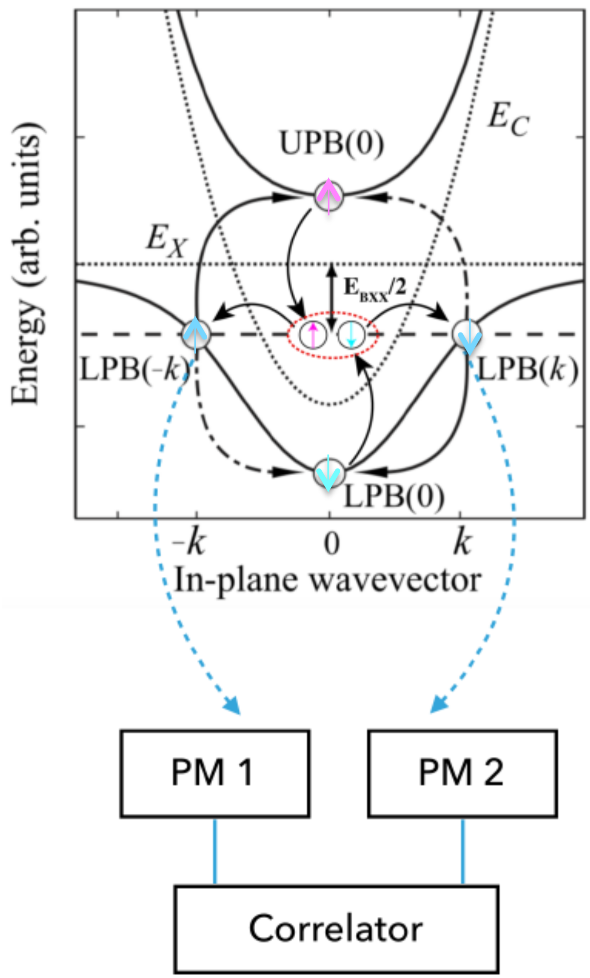
LP(-k) ↑ ↓ LP(-k)

Pair of photons entangled in energy and polarization

UP(k=0) ↑ ↓ LP(k=0)

H. Oka *et al*, Appl. Phys. Lett. 94, 111113 (2009)

Scheme for generating pairs of entangled photons



Pair of photons entangled in momentum and polarization

LP(-k) ↑ ↓ LP(-k)

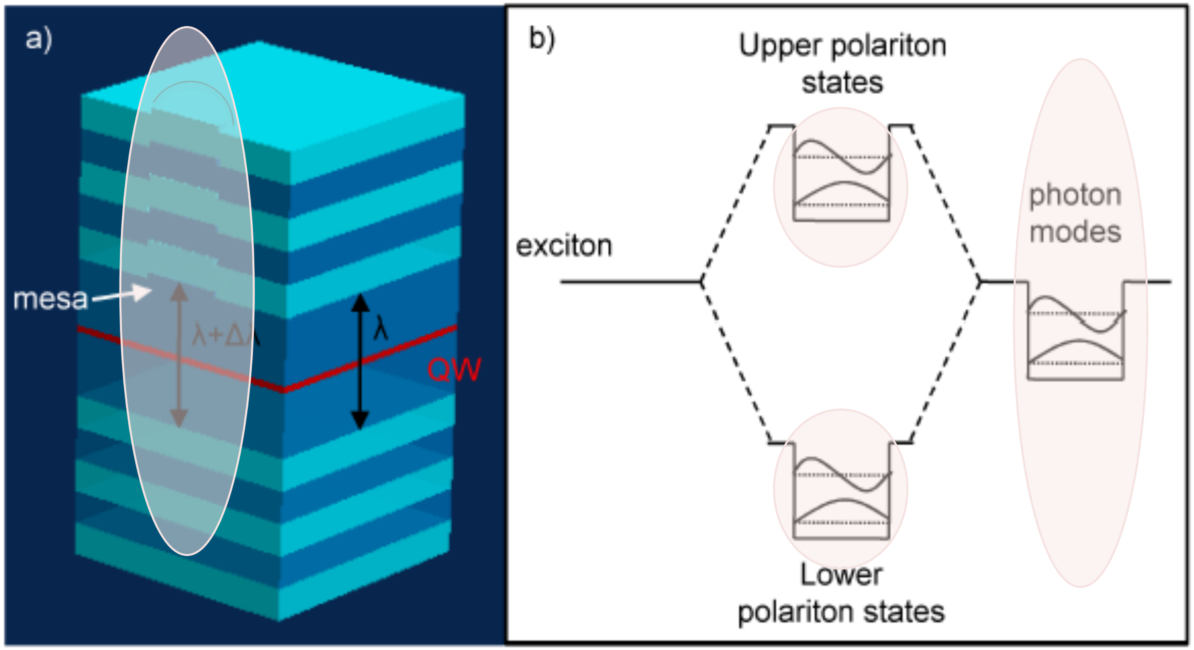
Pair of photons entangled in energy and polarization

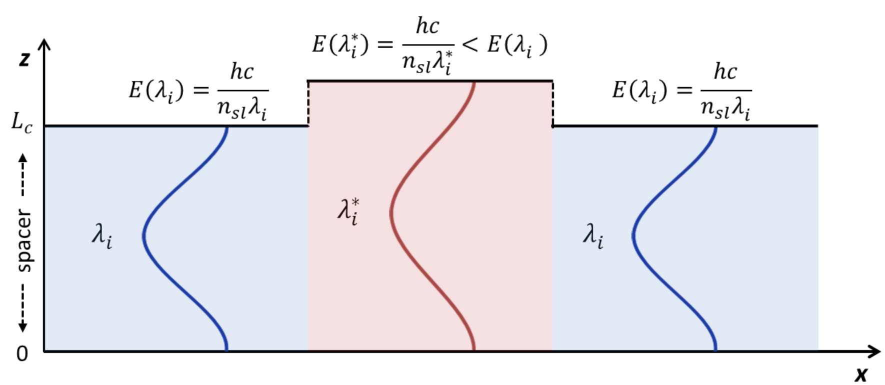
UP(k=0) ↑ ↓ LP(k=0)

The cross FR situation
will permit the entangled photon pairs
to be isolated from the transmitted laser beams

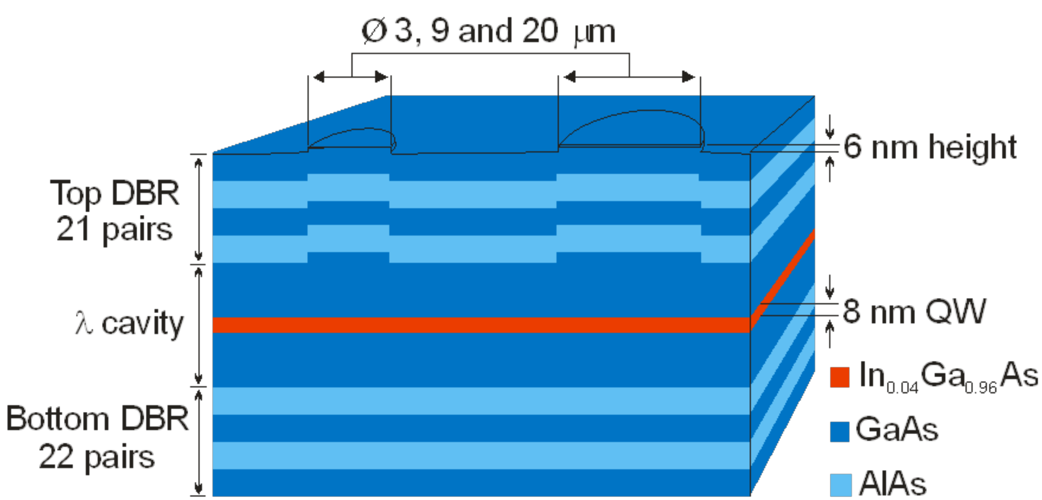
H. Oka *et al*, Appl. Phys. Lett. 94, 111113 (2009)

Confined zero-dimensional polaritons

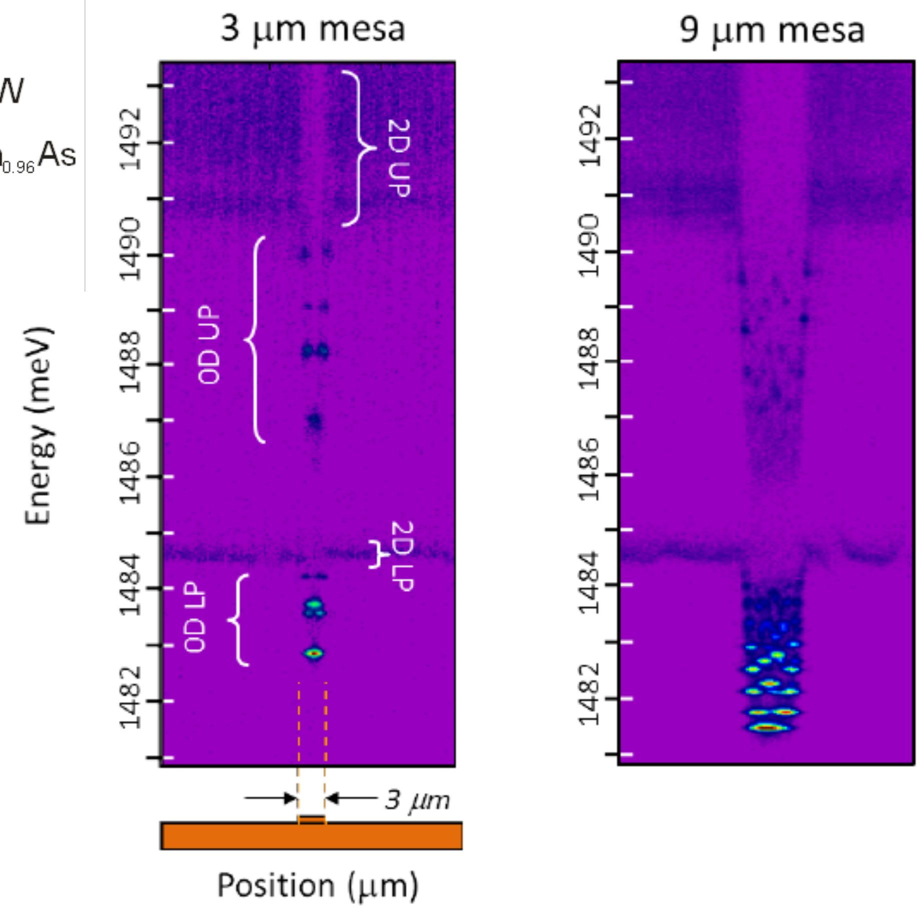




Confined zero-dimensional polaritons

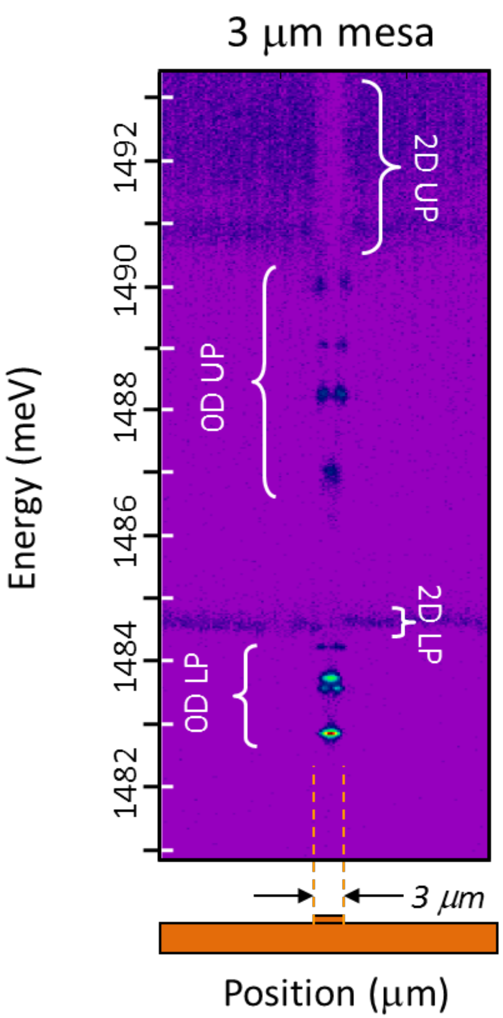


Spatially resoved spectrum



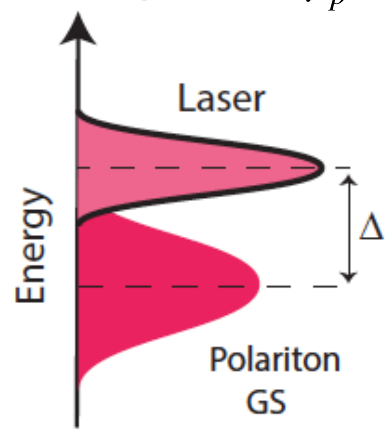
o. El-Daïf *et al.*, Appl. Phys. Lett. 88, 061105 (2006)
R. I. Kaitouni *et al.*, Phys. Rev. B 74, 155311 (2006)

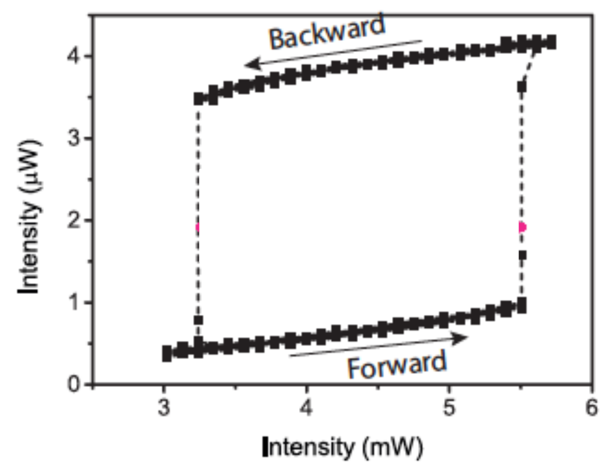
Polariton bistability



Bistability condition

$$\Delta \geq \sqrt{3}\gamma_p$$





$$\gamma_p = 70\mu eV$$

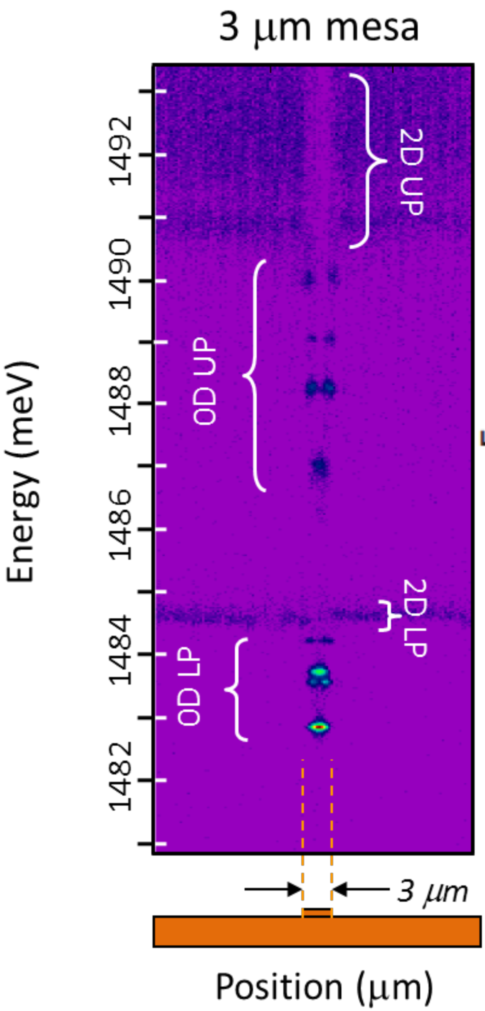
$$\Delta = 0.4meV$$

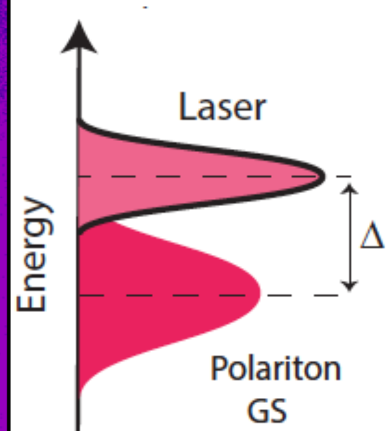
Laser polarization σ^+

$$i\hbar\frac{\partial\psi}{\partial t} = \left[E - \frac{\hbar^2}{2m}\nabla^2 + \alpha_1|\psi|^2 - i\gamma\right]\psi + F$$

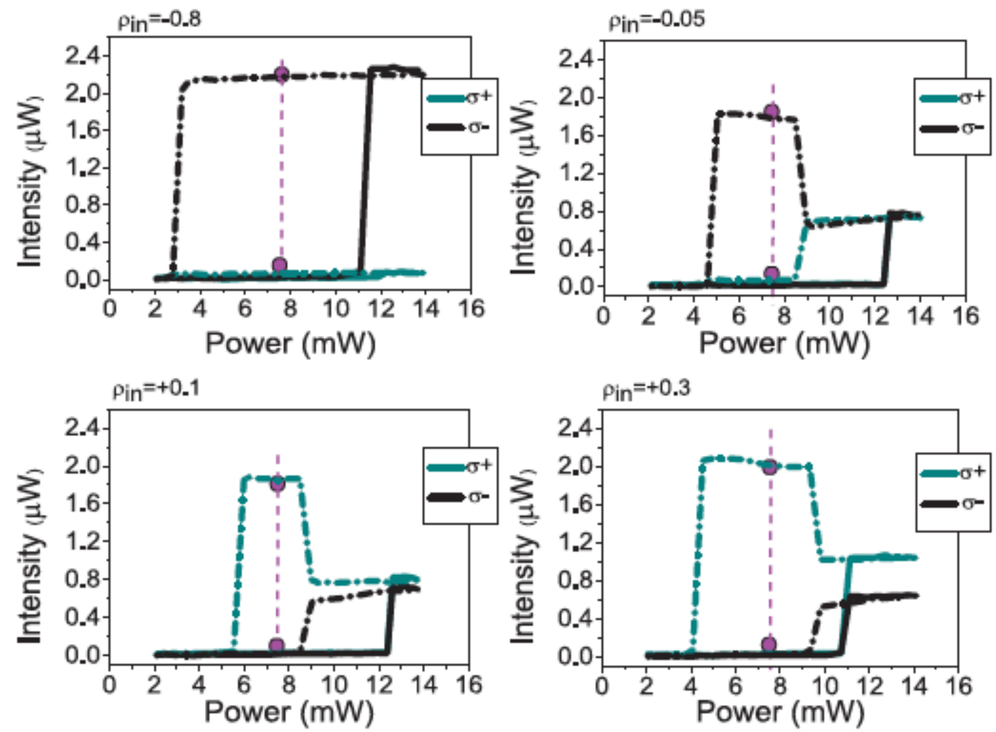
H. Abbaspour *et al.*, Phys. Rev. Lett. 113, 057401 (2014)

Polariton spinor bistability





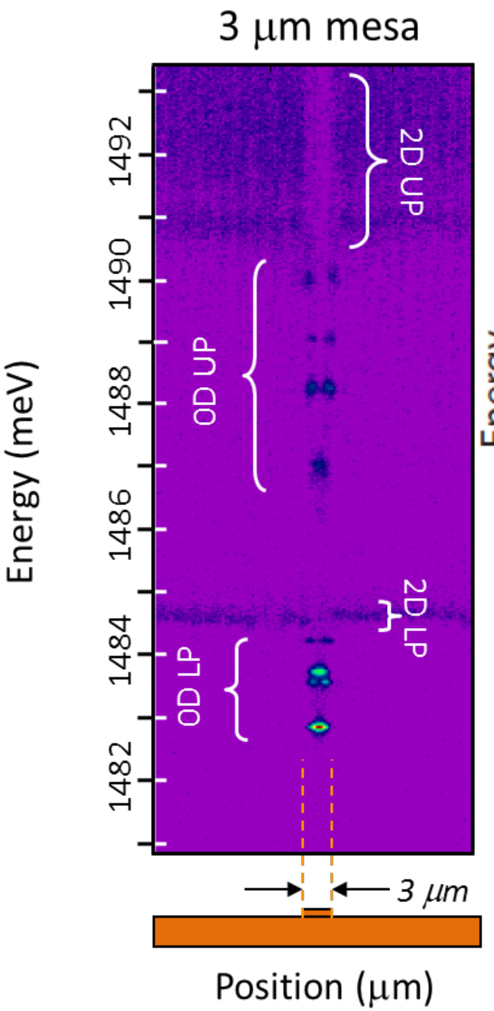
$\Delta = 0.8meV$
biexciton resonance

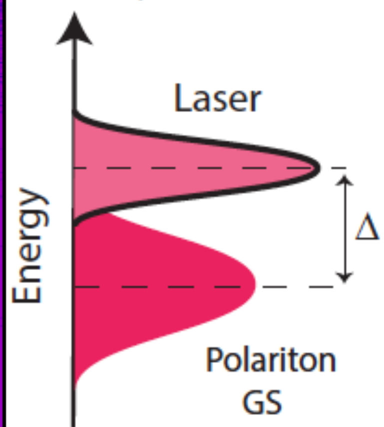


$$i\hbar\dot{\psi}_{\pm} = \left[E_{\pm} - \frac{\hbar^2}{2m}\nabla^2 + \alpha_1|\psi_{\pm}|^2 + \alpha_2|\psi_{\mp}|^2 - i(\gamma + \beta|\psi_{\mp}|^2)\right]\psi_{\pm} + F_{\pm}$$

H. Abbaspour *et al.*, Phys. Rev. B 91, 155307 (2015)

Polariton spinor bistability





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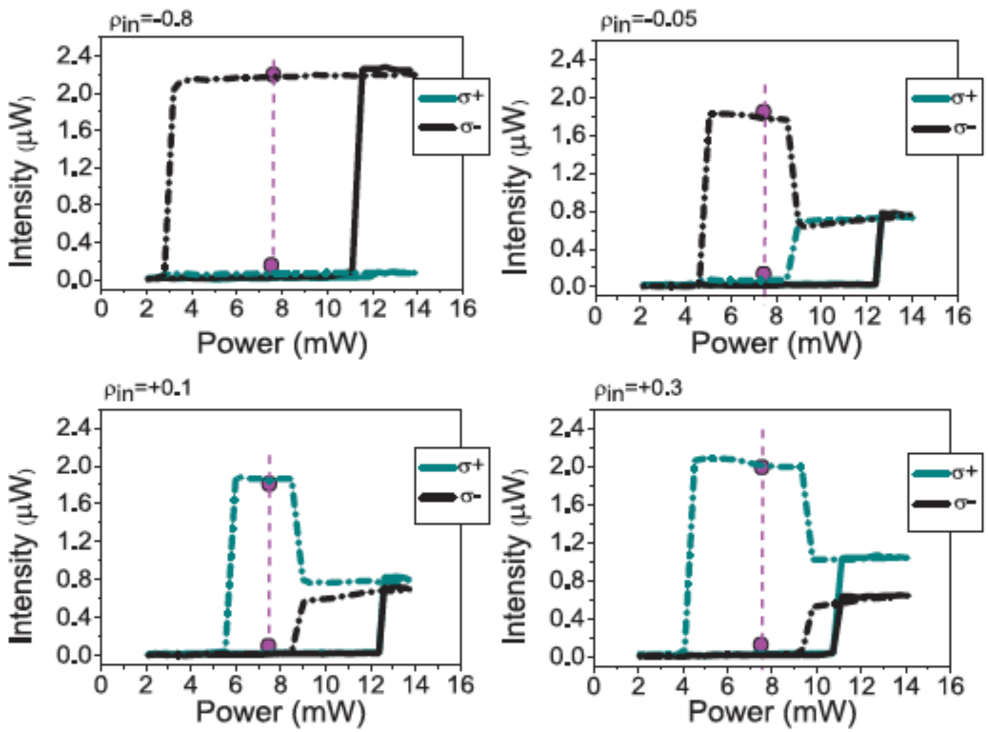


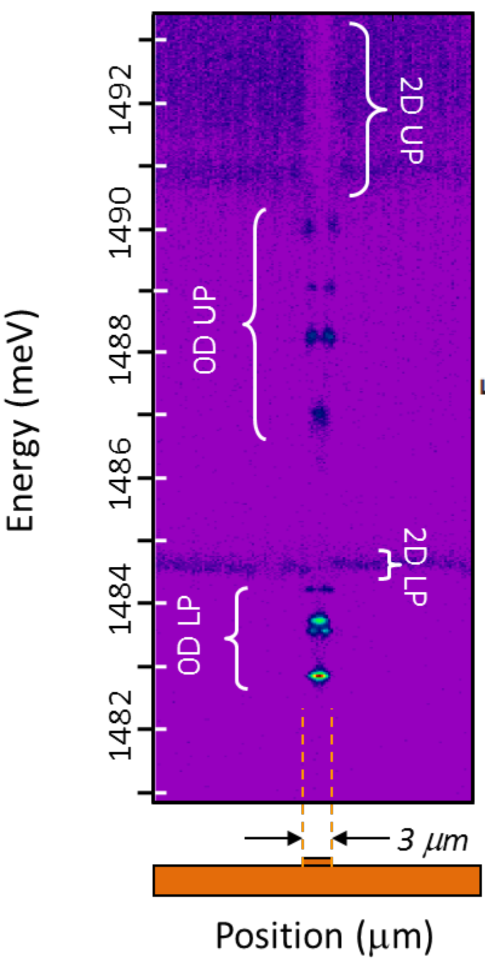
Laser power: 7.8 mW

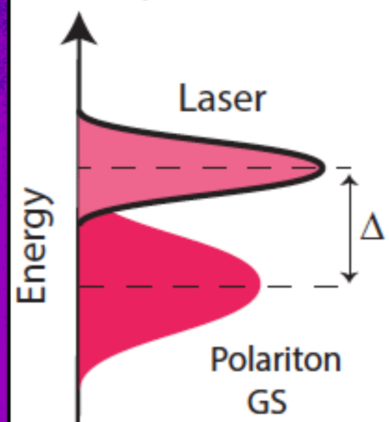
$$\rho = \frac{I_{\sigma+} - I_{\sigma-}}{I_{\sigma+} + I_{\sigma-}}$$

H. Abbaspour *et al.*, Phys. Rev. B 91, 155307 (2015)

Polariton spinor bistability

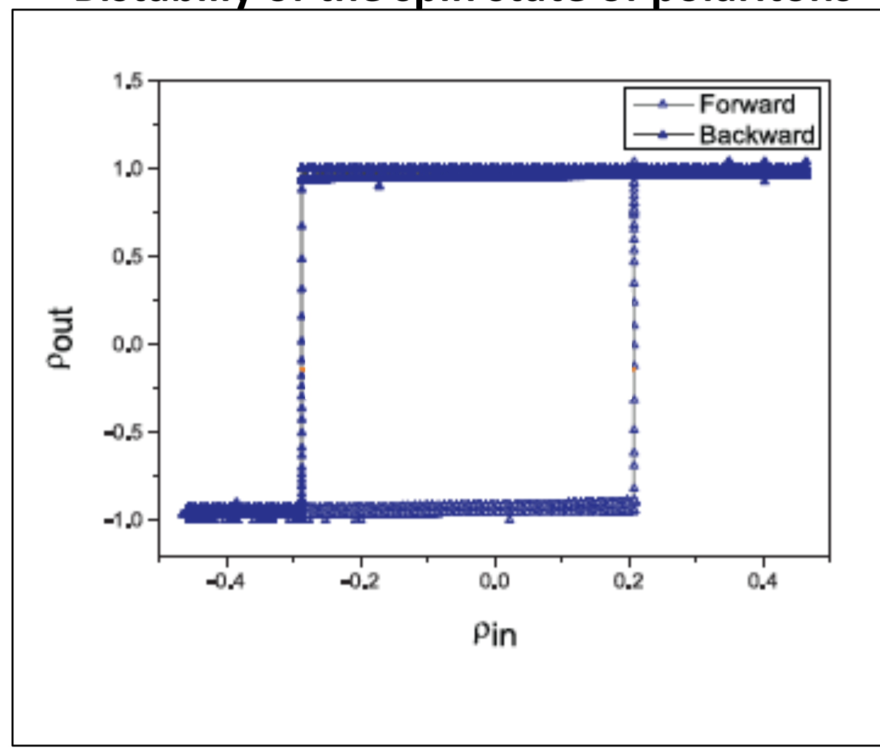
3 μm mesa





$\Delta = 0.8 meV$
biexciton resonance

Bistabiliy of the spin state of polaritons

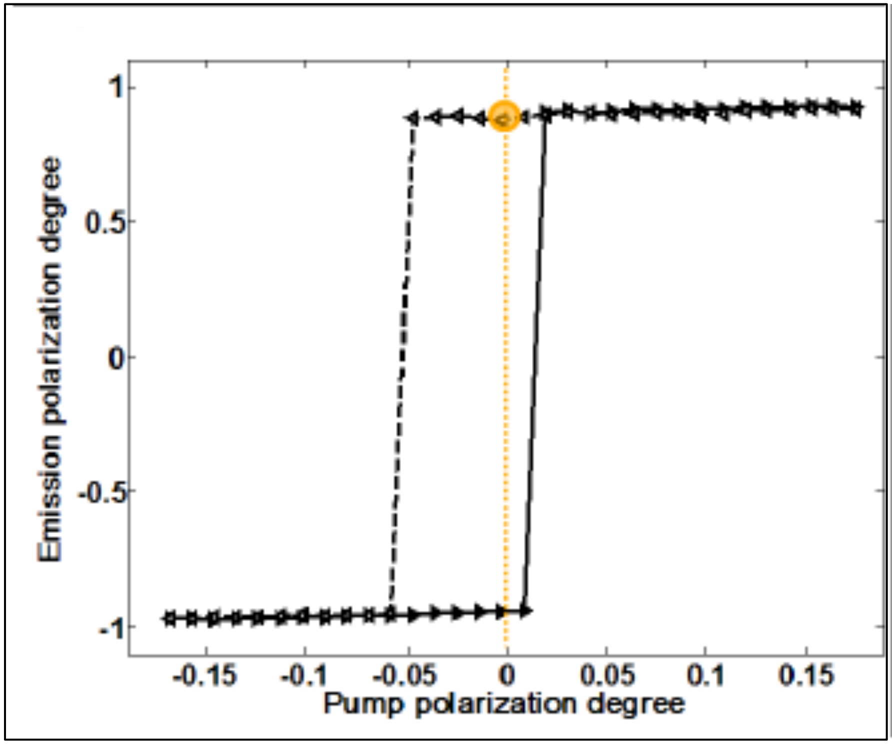


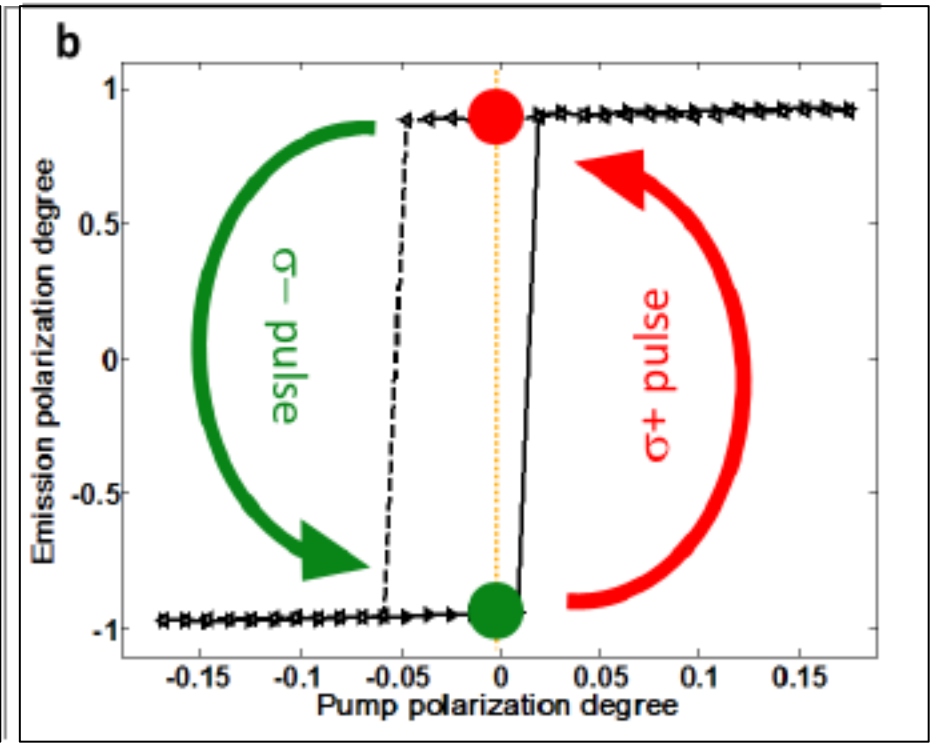
Laser power: 7.8 mW

$$\rho = \frac{I_{\sigma+} - I_{\sigma-}}{I_{\sigma+} + I_{\sigma-}}$$

H. Abbaspour *et al.*, Phys. Rev. B 91, 155307 (2015)

Spin switch



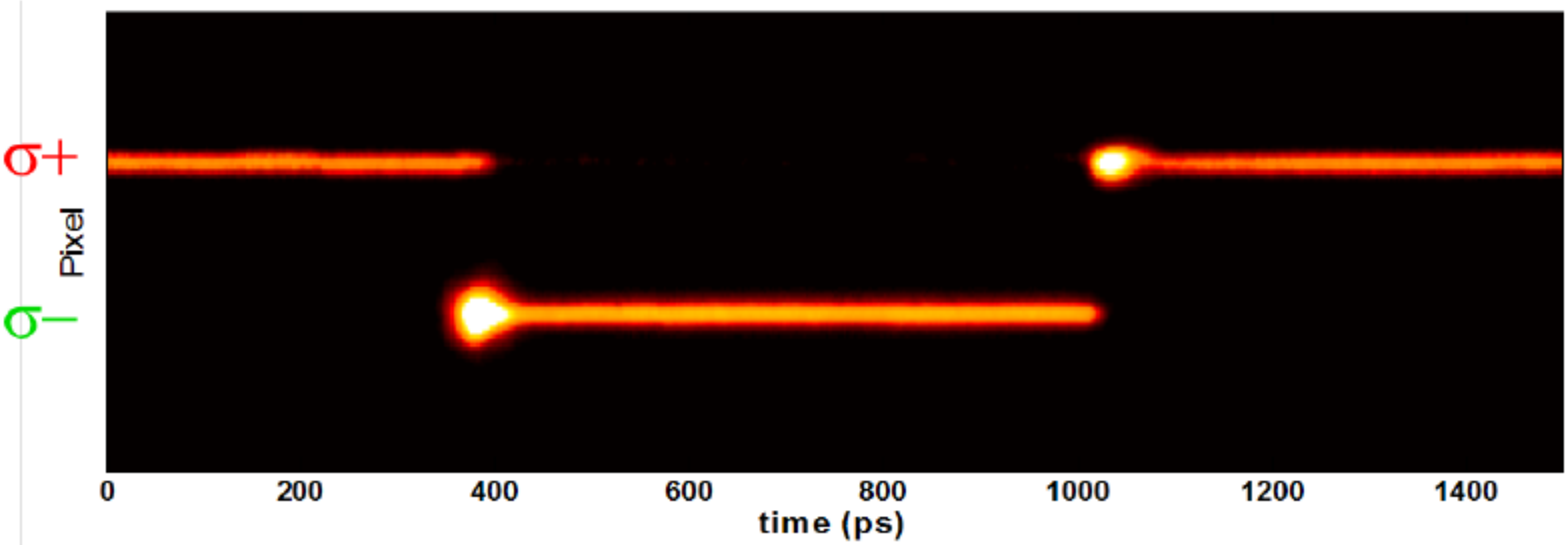


Laser power: 7.8 mW

Emission polarization: $\rho = \frac{I_{\sigma+} - I_{\sigma-}}{I_{\sigma+} + I_{\sigma-}}$

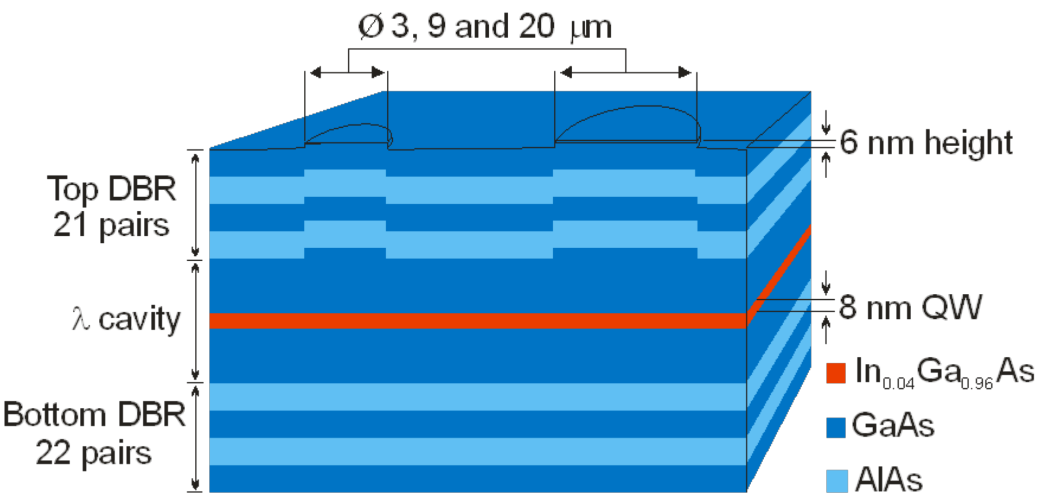
R. Cerna *et al.*, Nat. Commun 4, 2008 (2013)
R. Cerna , Thèse 5014 EPFL 2011

Spin memory

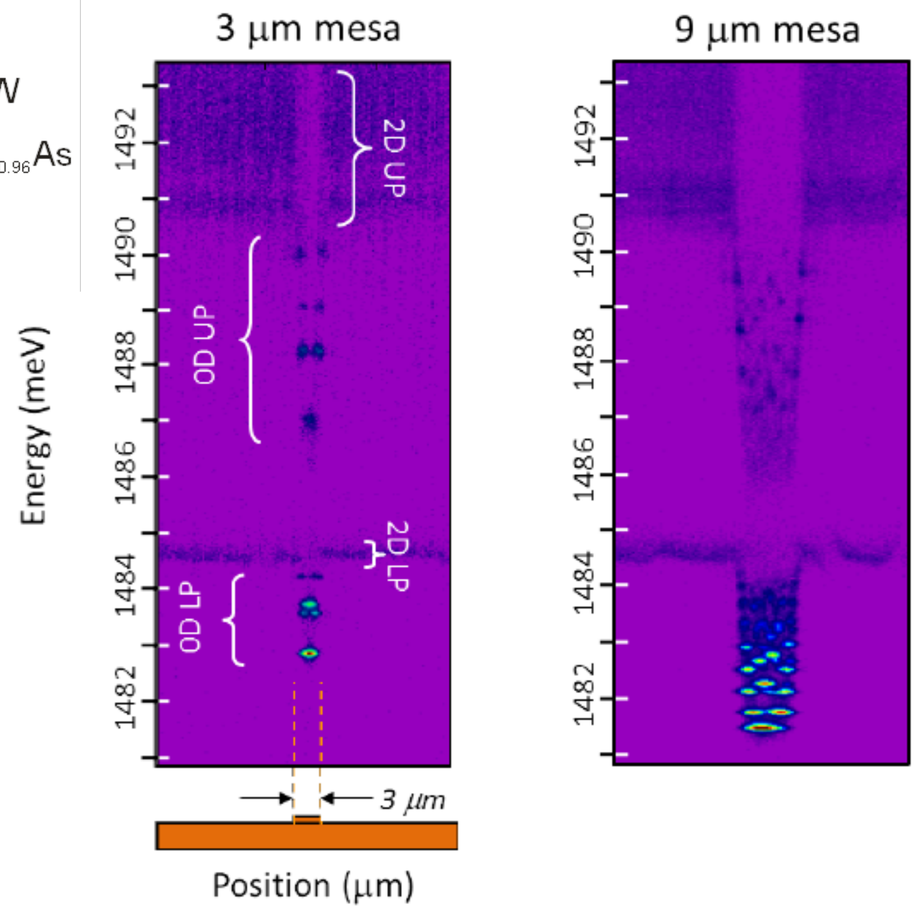


R. Cerna , Thèse 5014 EPFL 2011

Confined zero-dimensional polaritons



Spatially resoved spectrum



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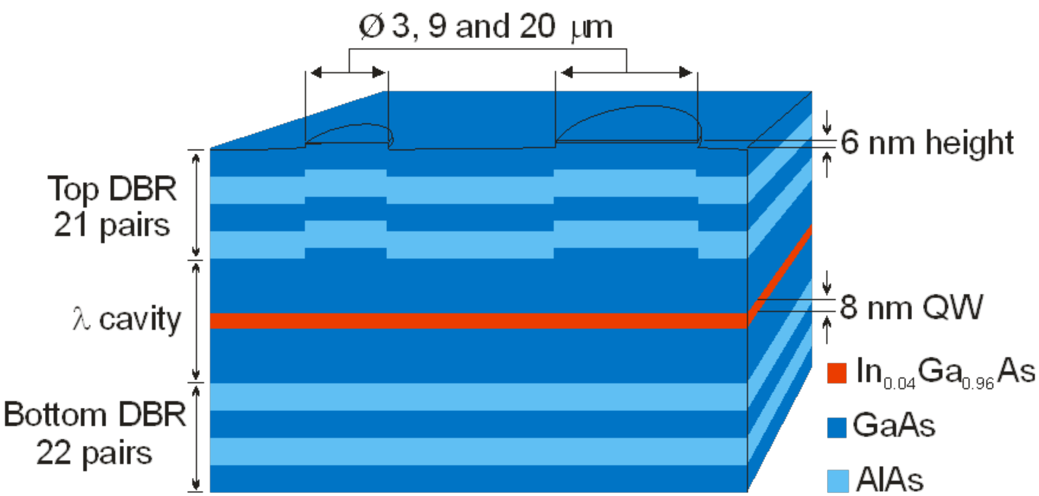
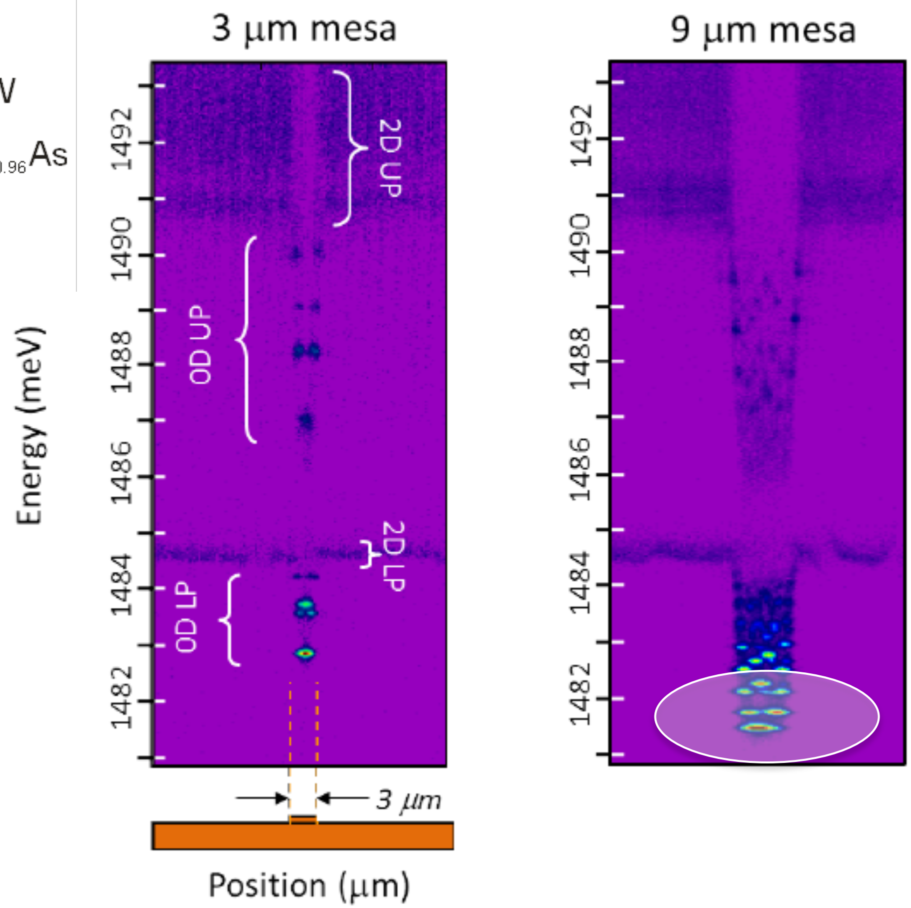
Confined zero-dimensional polaritons



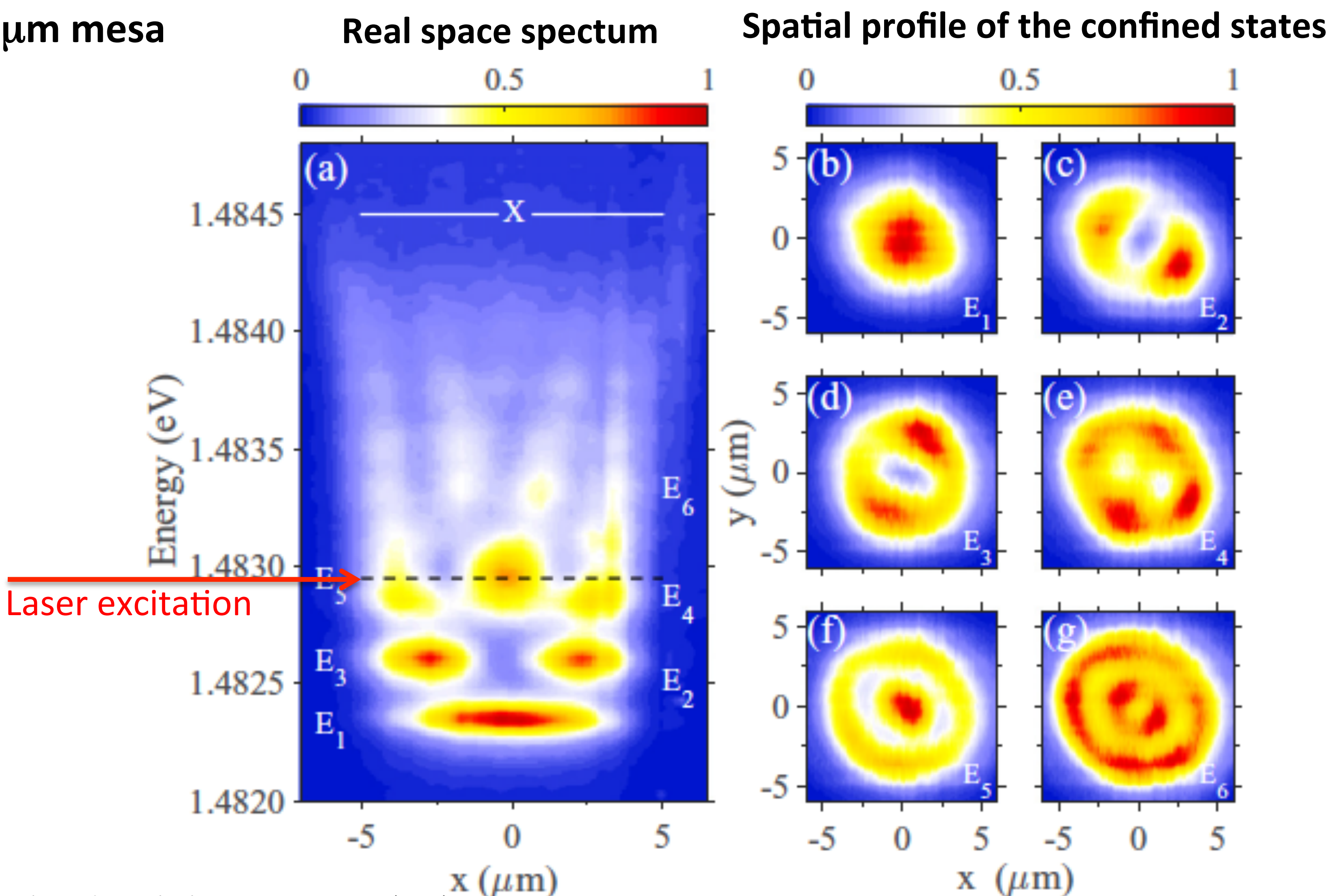
Spatially resoved spectrum



O. El-Daïf *et al.*, Appl. Phys. Lett. 88, 061105 (2006)
R. I. Kaitouni *et al.*, Phys. Rev. B 74, 155311 (2006)

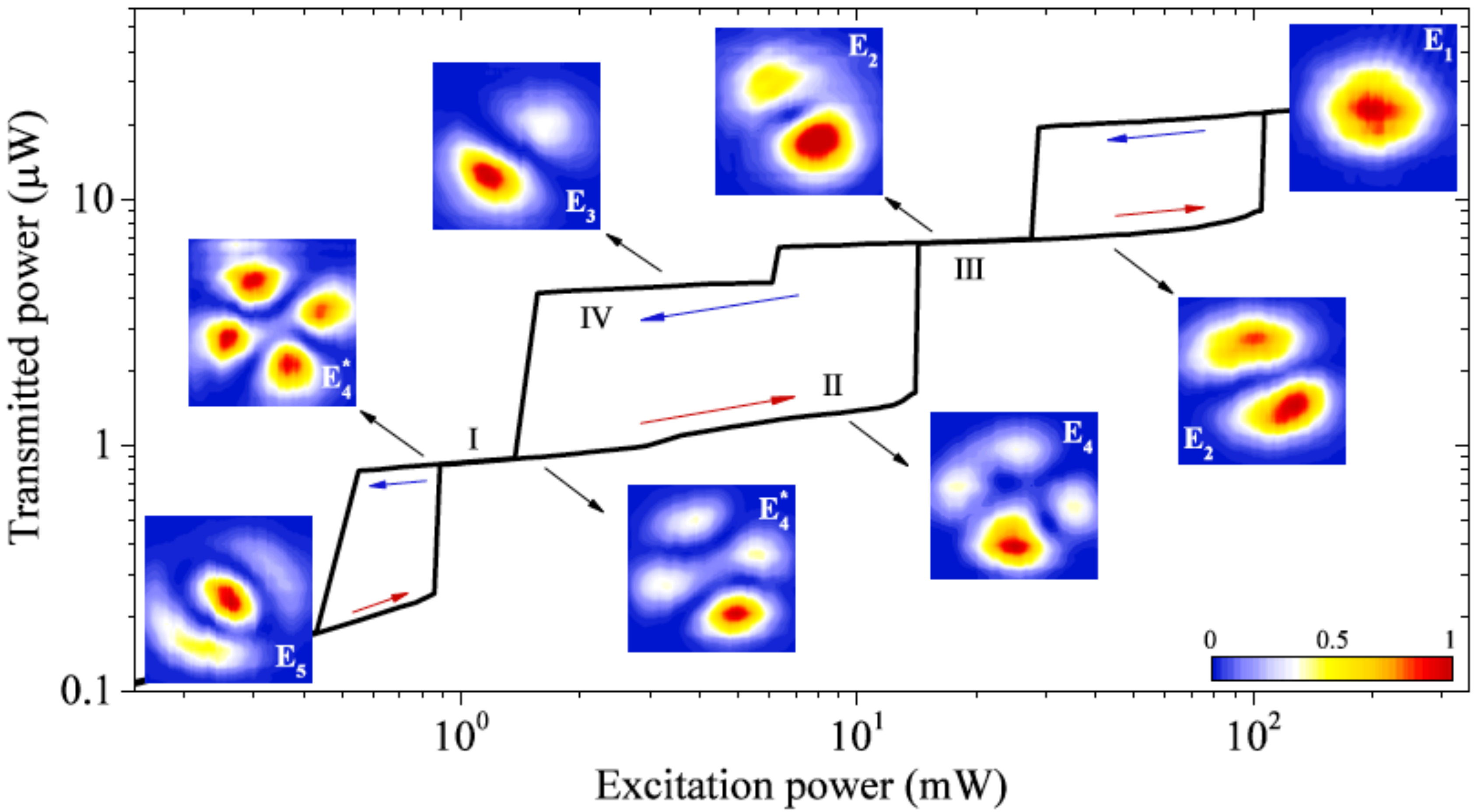
Spatial multistability

9 μm mesa



C. Oullet-Plamondon *et* al., Phys. Rev. B 93, 085313 (2016)

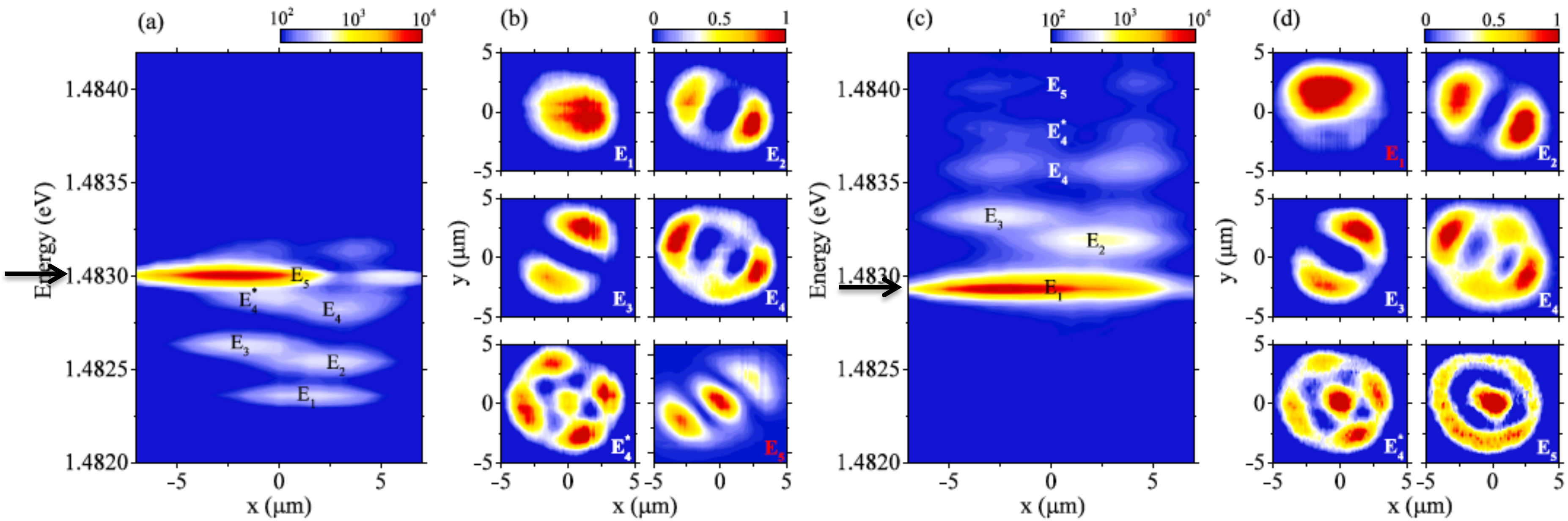
Spatial multistability

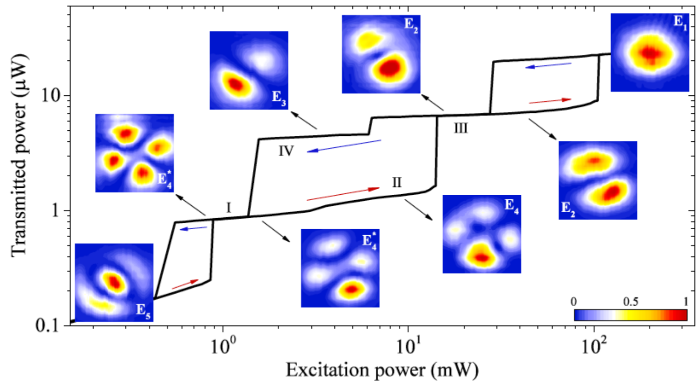


C. Oullet-Plamondon *et* al., Phys. Rev. B 93, 085313 (2016)

Spatial multistability

Botton of the bistability curve **Top of the bistability curve**

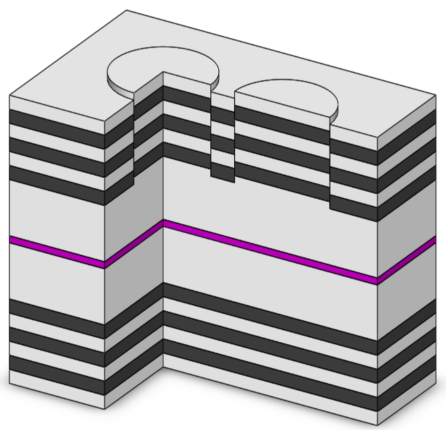


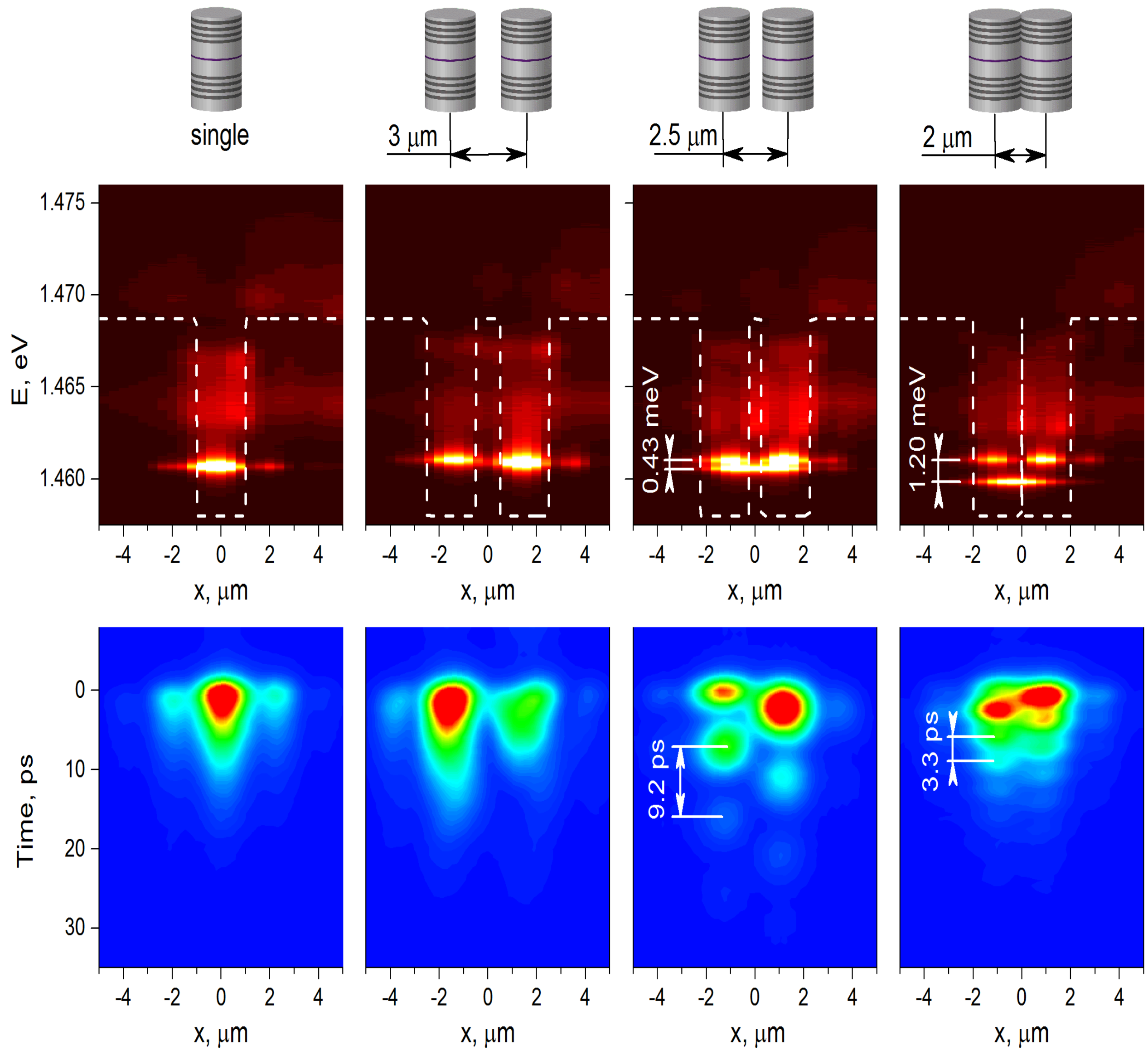


C. Oullet-Plamondon *et* al., Phys. Rev. B 93, 085313 (2016)

Coupled mesas

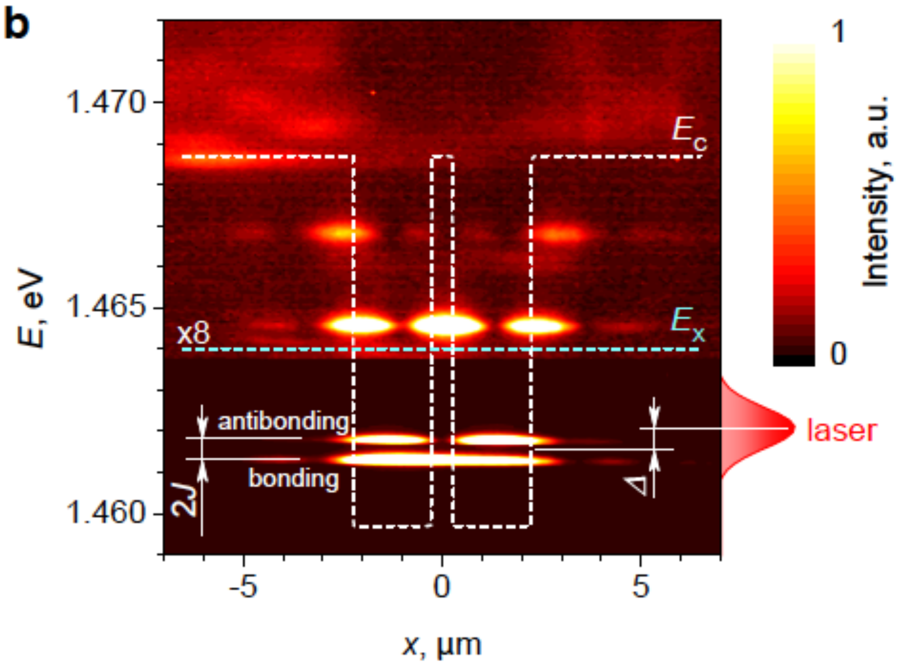
Coupled 2μm mesas



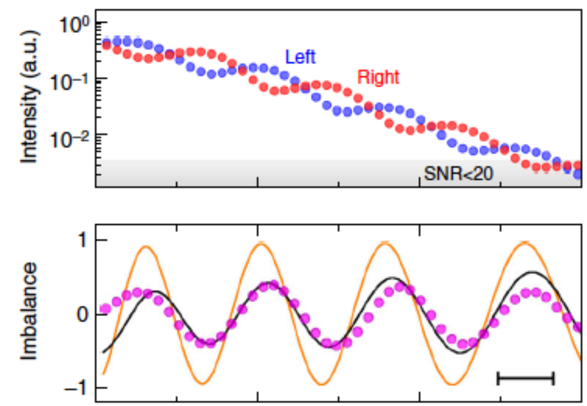


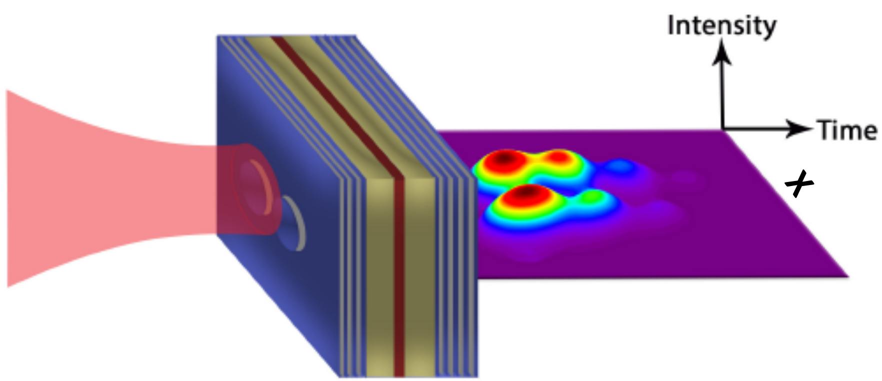
A. Adiyatullin, Thèse 7991 EPFL 2017

Polariton Josephson junction



$$\hat{H} = \sum_{k=L,R}\left[\hbar\omega_c \hat{a}_k^+ \hat{a}_k + U\hat{a}_k^+ \hat{a}_k^+ \hat{a}_k \hat{a}_k\right] - J\left(\hat{a}_L^+ \hat{a}_R + \hat{a}_R^+ \hat{a}_L\right)$$





A. Adiyatullin *et al.*, Nat. Commun. 8, (2017)

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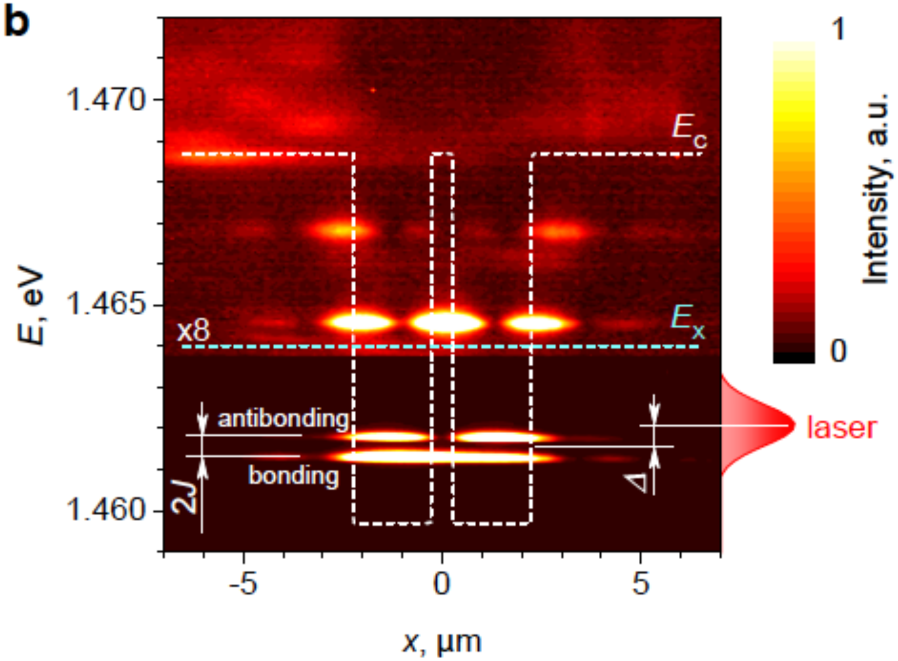

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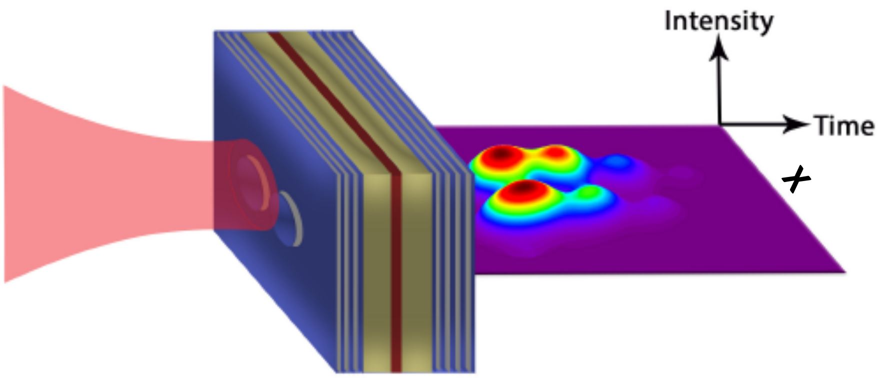
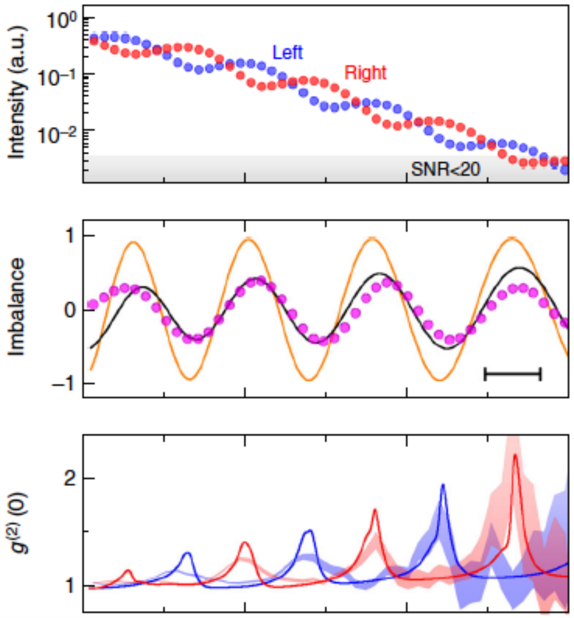
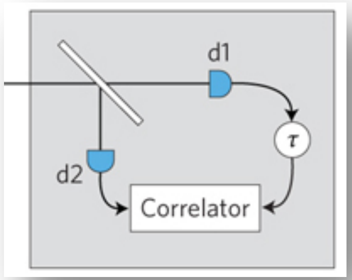


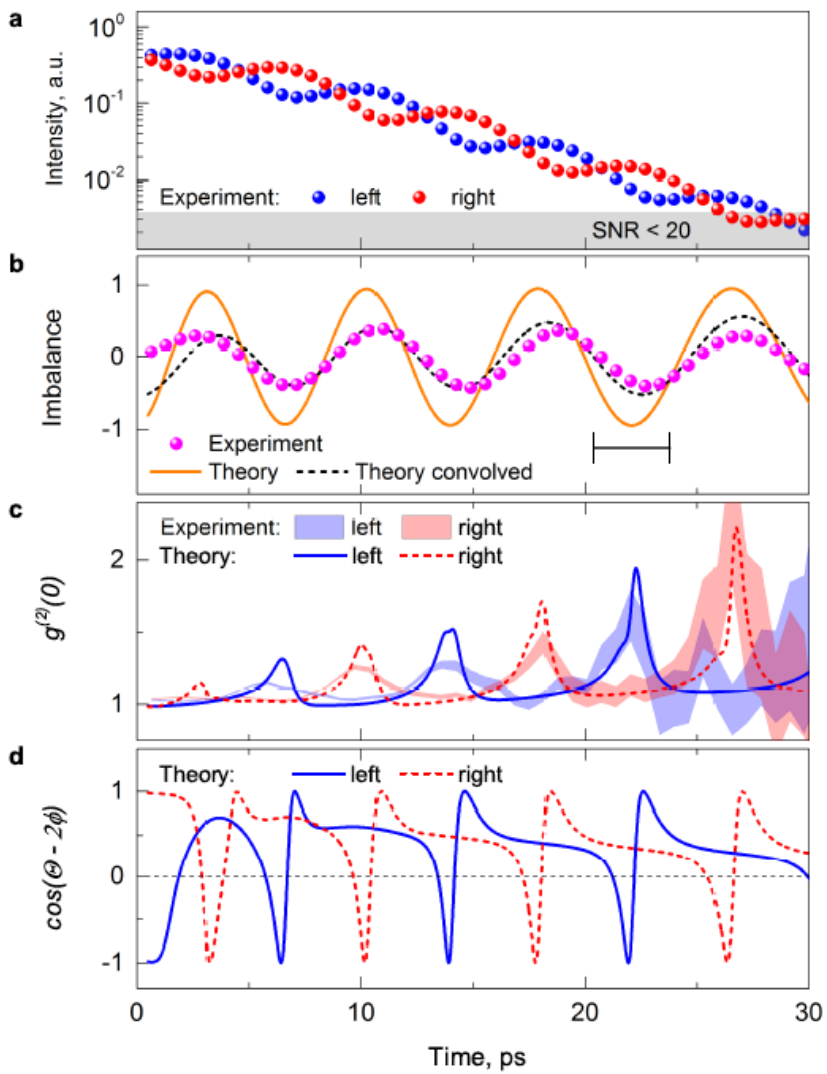




$$g^{(2)}(0) = \frac{\langle \hat{a}^+\hat{a}^+\hat{a}\hat{a}\rangle}{\langle \hat{a}^+\hat{a}\rangle^2}$$

A. Adiyatullin *et al.*, Nat. Commun. 8, (2017)

Periodic squeezing in a polariton Josephson junction



A. Adiyatullin *et al.*, Nat. Commun. 8, (2017)

Model: *H. Flayac and V. Savona, PRA **95**, 043838 (2017)*

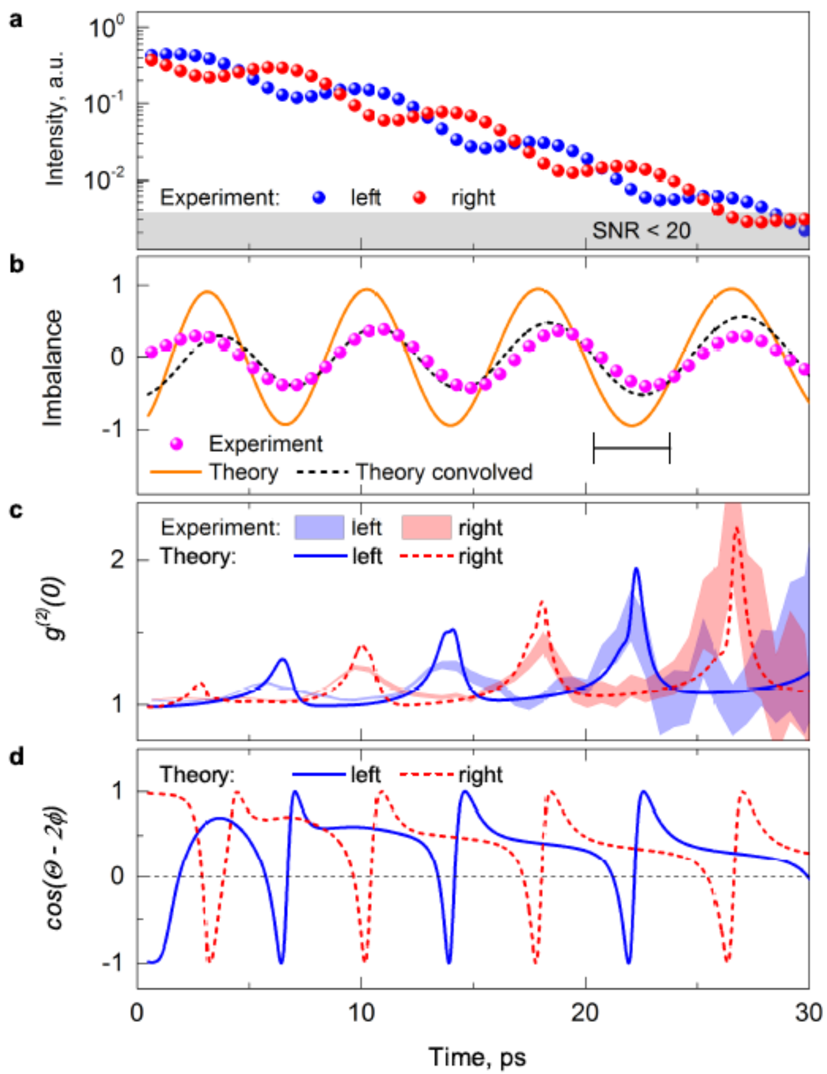
$$\hat{H} = \sum_{k=L,R}\left[\hbar\omega_c \hat{a}_k^+ \hat{a}_k + U\hat{a}_k^+\hat{a}_k^+\hat{a}_k\hat{a}_k\right] - J\left(\hat{a}_L^+\hat{a}_R + \hat{a}_R^+\hat{a}_L\right) + \sum_{k=L,R}\left[P_k(t)\hat{a}_k^+ + P_k^*(t)\hat{a}_k\right]$$

Polariton operators: $\hat{a}_k = \alpha_k + \delta\hat{a}_k$

$\alpha_k = \langle \hat{a}_k \rangle$ coherent mean field operator

quantum fluctuation operator

Periodic squeezing in a polariton Josephson junction



A. Adiyatullin *et al.*, Nat. Commun. 8, (2017)

A. Adiyatullin, Thèse 7991 EPFL 2017

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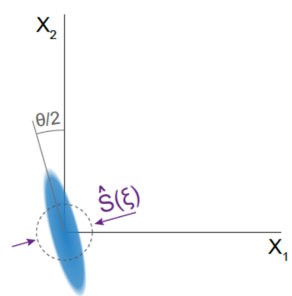
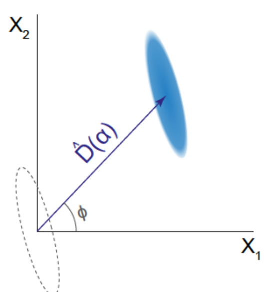
quantum fluctuation operator

$$\Rightarrow g^{(2)}(0) \Rightarrow \cos(\theta - 2\varphi)$$

Squeezing operator $\rightarrow \hat{S} = \exp\left[\xi^* \hat{a}^2 - \xi \hat{a}^{+2}\right]$

Squeezed coherent state $\rightarrow |\xi, \alpha\rangle = \hat{S}|\alpha\rangle$



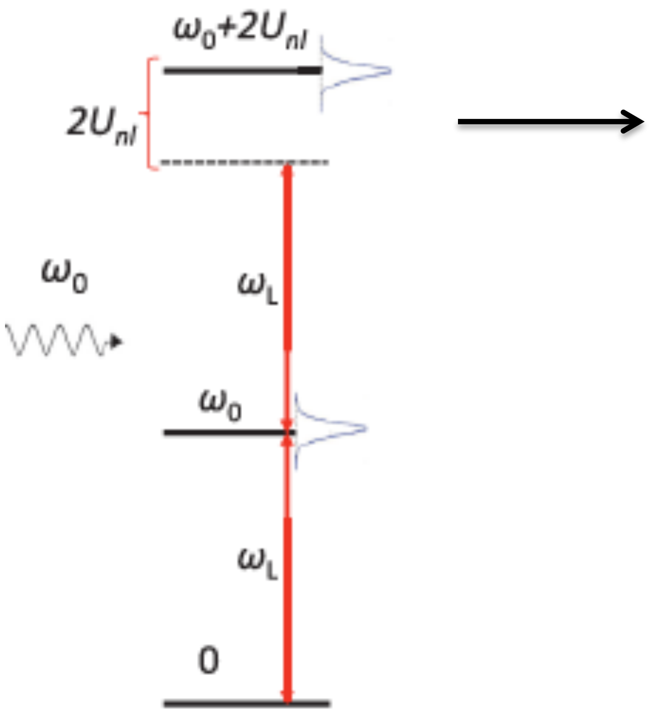


Squeezing $\rightarrow \xi = re^{i\theta}$

Displacement $\rightarrow \alpha = \bar{\alpha}e^{i\varphi}$

Polariton quantum blockade

Towards polariton quantum blockade



Ferretti & Gerace, PRB85, 033303 (2012)

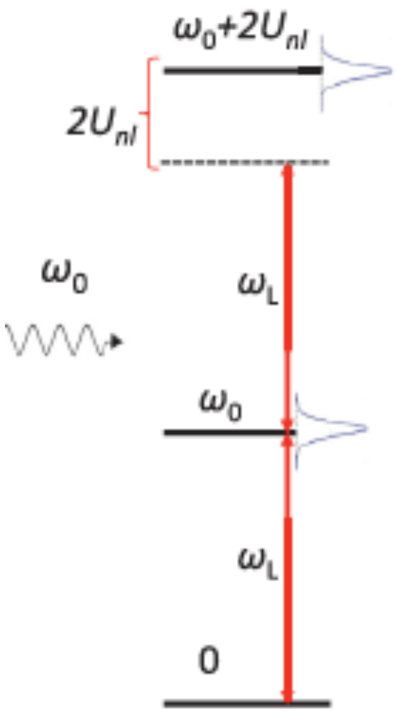
Strong nonlinearity $U_{nl} > \gamma$

The two-polariton state is shifted by $2U_{nl} > 2\gamma$

The presence of a single polariton in the cavity is able to block the entrance of the second one

Polariton quantum blockade

Towards polariton quantum blockade



Ferretti & Gerace, PRB85, 033303 (2012)

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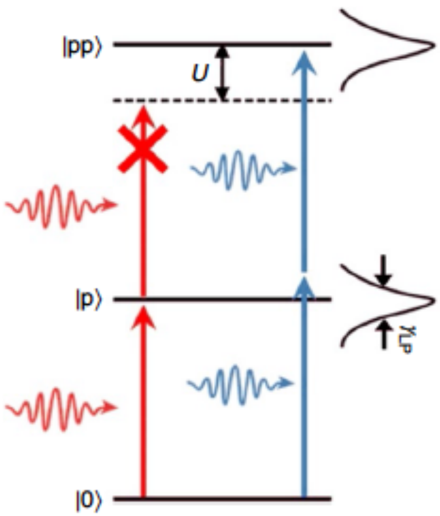
$$U_{nl} \cong \frac{3(\hbar\omega_0)^2}{4\varepsilon_0 V_{eff}} \frac{\chi^{(3)}}{\varepsilon_r^2}$$

$$g^2(0) = \frac{\langle c^+c^+cc\rangle}{\langle c^+c\rangle^2} = \frac{1}{\left(1+4(U/\gamma)^2\right)}$$

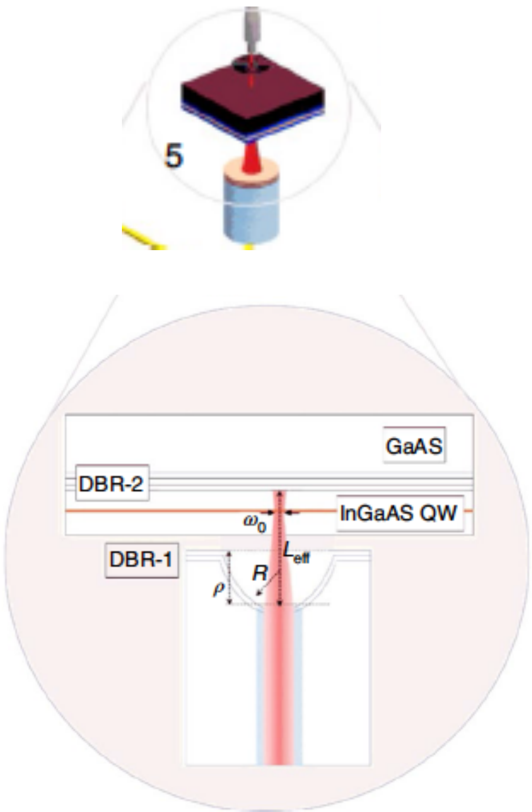
I. Carusotto & C: Ciuti, Rev. Mod. Phys. 85, 299 (2013)

Polariton quantum blockade

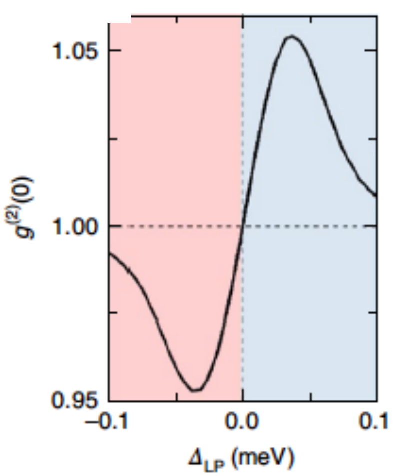
The Experiment

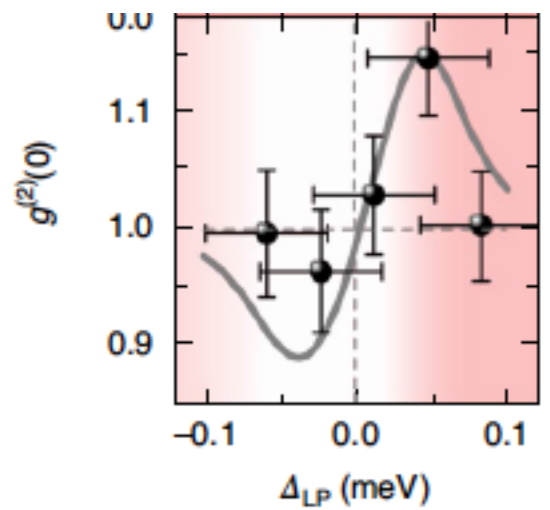


Fibre microcavity



r=1.17μm

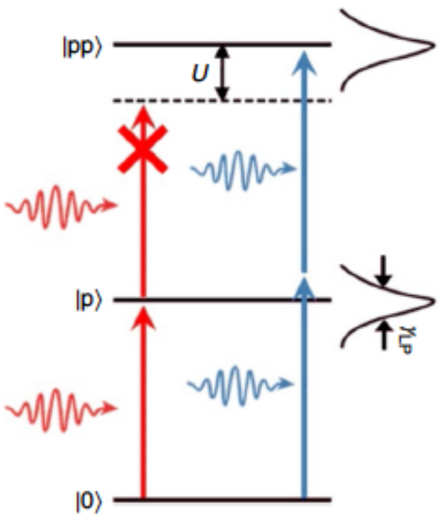


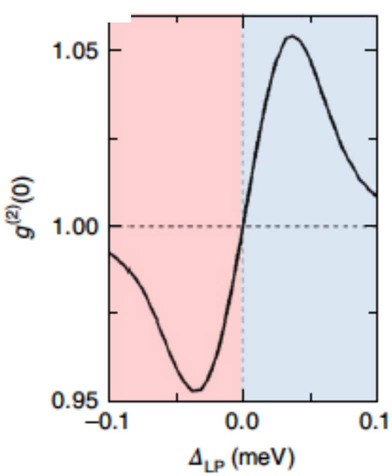


G. Munoz-Matutano et al, Nat. Mat. 18, 21

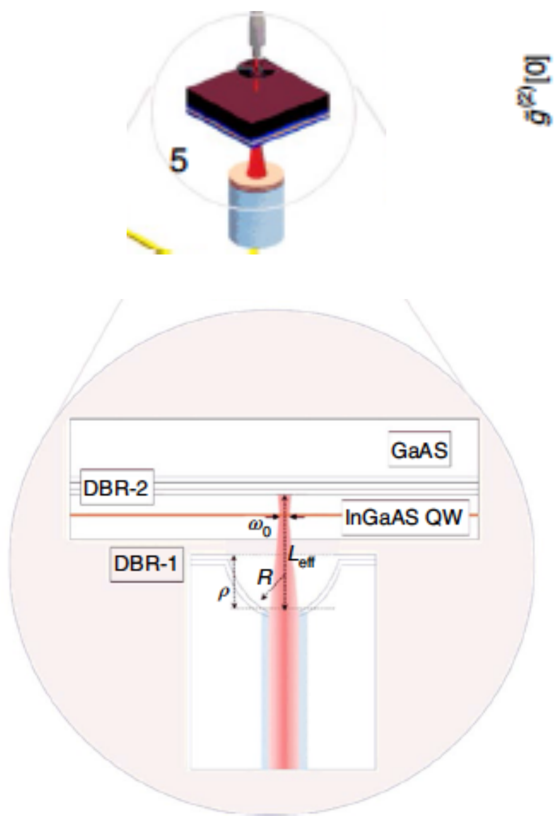
Polariton quantum blockade

The Experiment





Fibre microcavity



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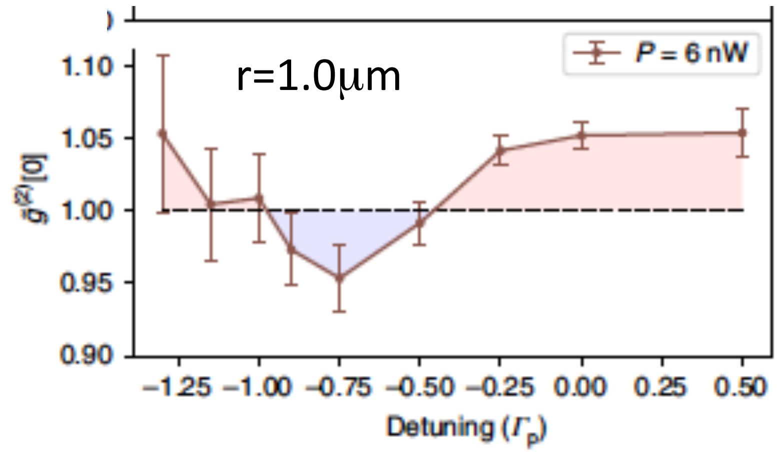
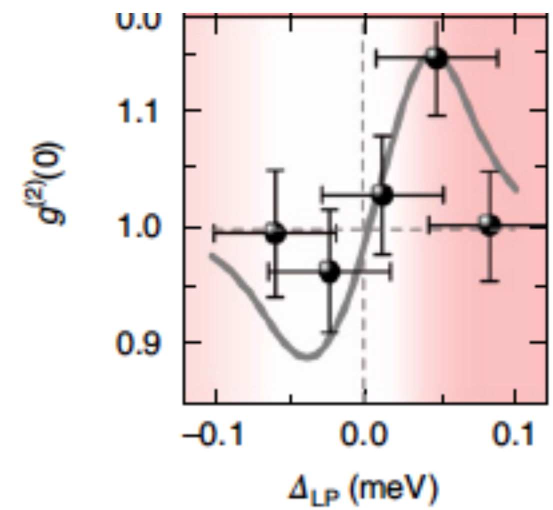
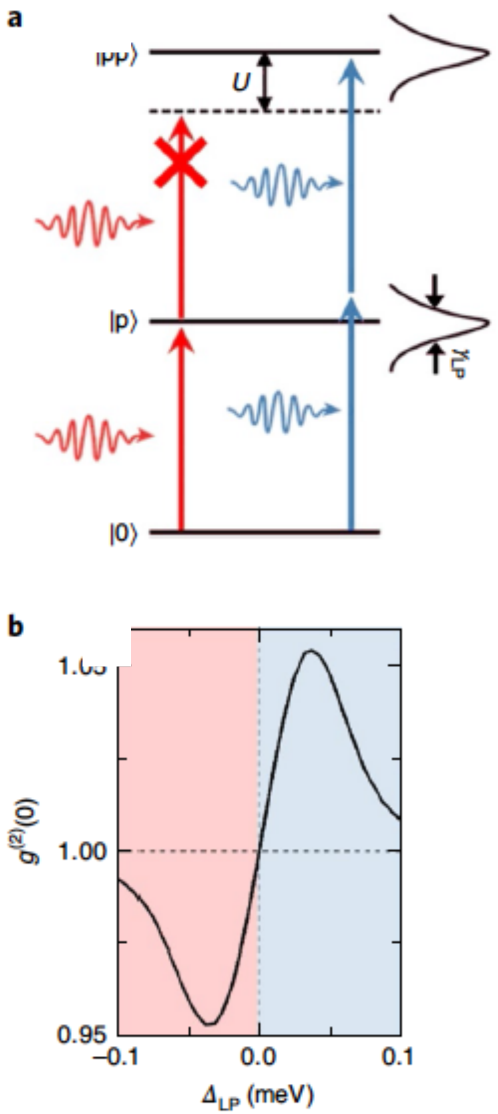
G. Munoz-Matutano et al, Nat. Mat. 18, 21



A. Delteil et al, Nat. Mat. 18, 219 (2019)



Polariton quantum blockade



Sample with smaller diameter:
⟹ smaller volume
⟹ stronger interaction

$$U \cong \frac{3(\hbar\omega_0)^2}{4\varepsilon_0 V_{eff}} \frac{\chi^{(3)}}{\varepsilon_r^2}$$

$$g^2(0) = \frac{1}{\left(1 + 4(U/\gamma)^2\right)}$$

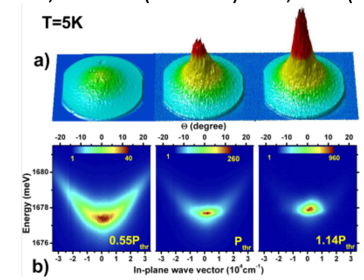
Many facets of Polaritons

| polariton > = Ux | exciton > + Uc | photon >

- **Light effective mass – photonic component**
- **Nonlinear interaction – excitonic component**
- **Spin-dependent interaction**

Bose-Einstein condensation

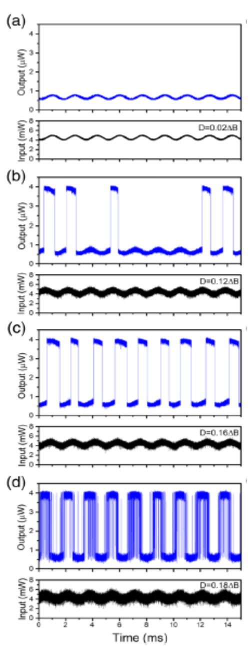
J. Kasprzak *et al.*, Nature (London) **443**, 409 (2006).



Stochastic resonance and Spinor Stochastic resonance

H. Abbaspour *et al.*, Phys. Rev. Lett. 113, 057401 (2014).

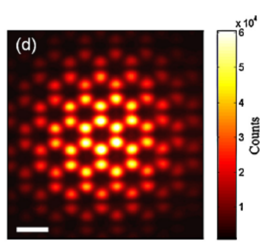
H. Abbaspour *et al.*, Phys. Rev. B 91, 155307 (2015).

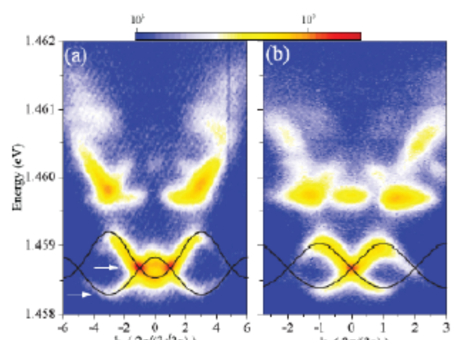


Polariton lattices

T. Jacqmin et al, Phys. Rev. Lett. 112, 116402 (2015)

C. Ouellet-Plamondon, Thèse 7603 EPFL

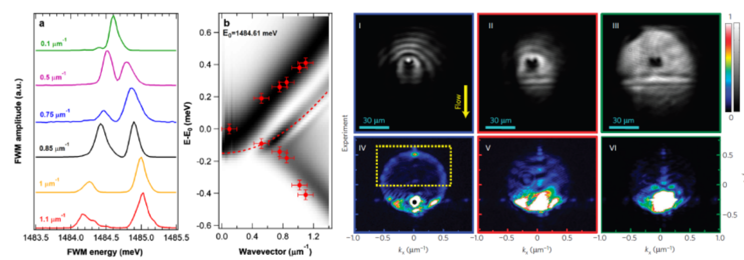




Superfluidity

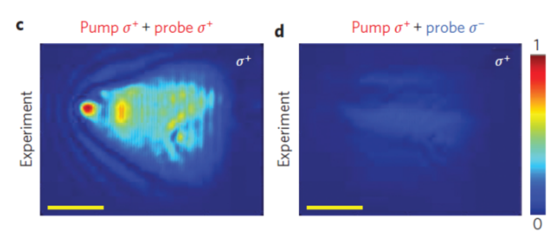
A. Amo *et. al.*, Nature Phys. **5**, 805 (2009).

V. Kohnle *et. al.*, Phys. Rev. Lett. **106**, 255302 (2011).



Spin switching

A. Amo *et. al.*, Nature Photon. **4**, 361 (2010).



Many facets of Polaritons

- **Feshbach resonances**
  Morteza Navadeh Toupchi
  Naotomo Takemura
  Stéphane Trebaol
  Mitchell Anderson
- **Bistability**
  Roland Cerna
  Hadis Abbaspour
  Claudéric Ouellet-Plamondon
  Stéphane Trebaol
  Grégory Sallen
- **Superfluidity**
  Verena Kohnle
  Yoan Léger
- **Polariton squeezing in JJ**
  Albert Adiyatullin
  Mitchell Anderson
- **Samples**
  François Morier-Genoud
  Fauzia Jabeen
  Clauderic Oeullet-Plamondon
  Grégory Sallen
  Morteza Navadeh Toupchi
  Albert Adiyatullin
- Daniel Oberli
- Benoît Deveaud