Observation of non-Hermitian degeneracies in a chaotic exciton-polariton billiard

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Jaewon Shim

Contents

Research Group

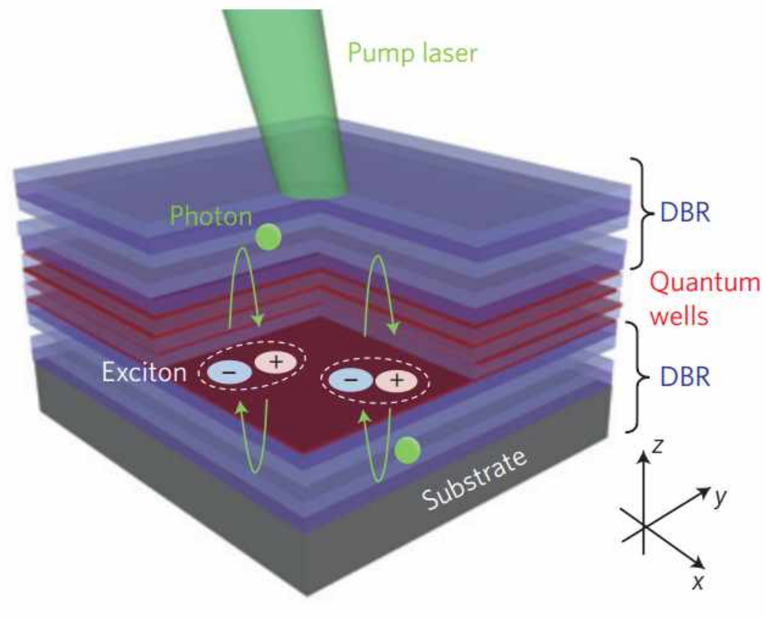
T. Gao(Post-Doc.)
Physical and Mathematical Sciences
(Main author of this paper)
Research School of Physics and Engineering
The Australian National University

Y. S. Kivshar(Head Prof.)
Nonlinear Physics Centre
Research School of Physics and Engineering
The Australian National University

E. A. Ostrovskaya(fellow)
Nonlinear Physics Centre
Research School of Physics and Engineering
The Australian National University

Introduction

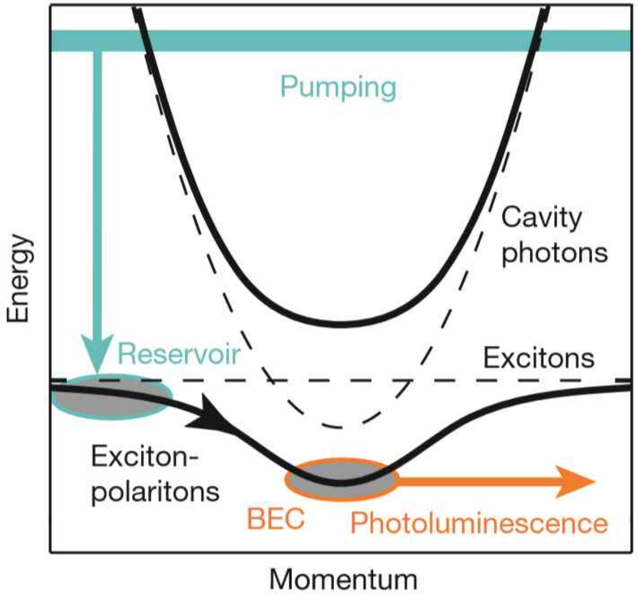
Exciton-Polariton basic structure



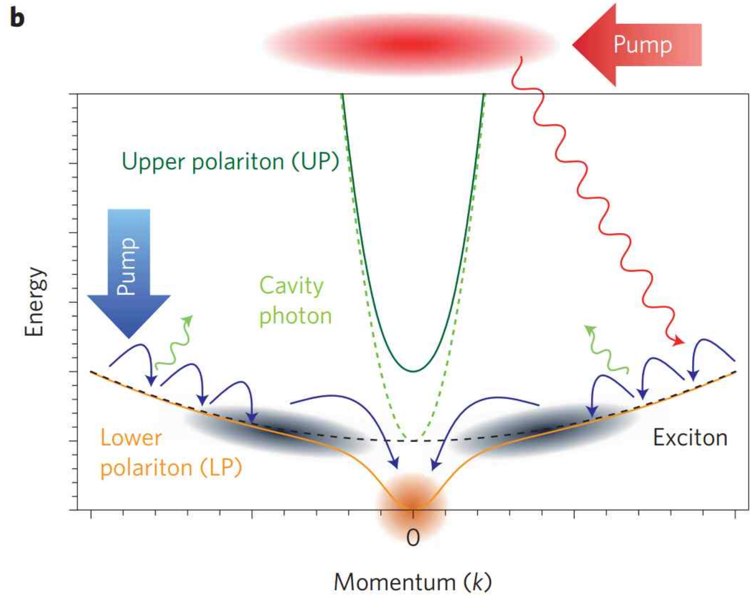
T.Byrnes et al., NRPHY3143

- Excitons exist within quantum well layers.
- Excitons are strongly coupled with photons.
- Sandwiched by 2 DBRs. (distributed Bragg reflectors)
- Can create chaotic exciton-polariton billiard.

Exciton-Polariton BEC



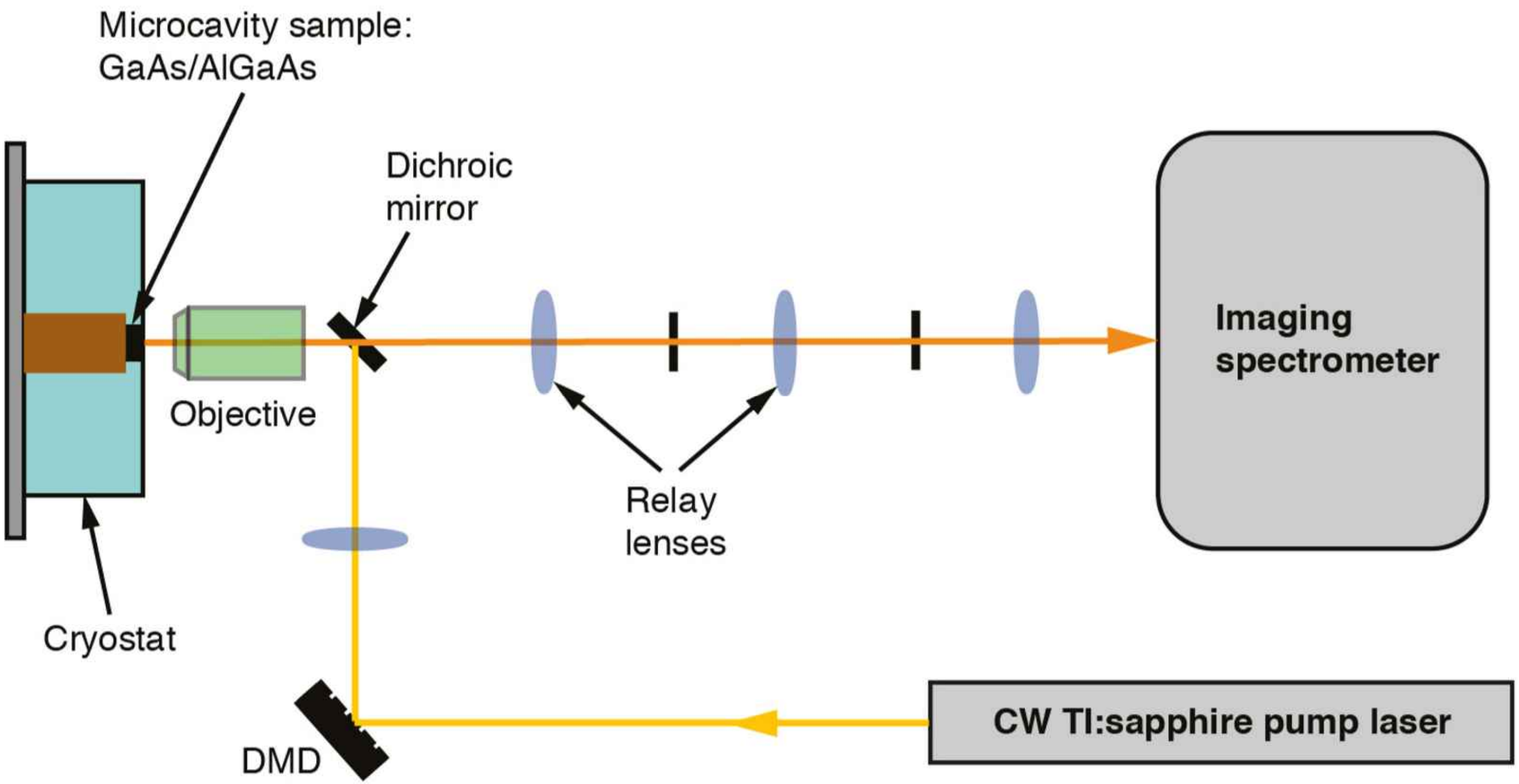
- Creating the chaotic billiard by exciton-polariton BEC using optical pump.
- Hybridization of the cavity photon and exciton modes.
- Optical pump creates an incoherent reservoir of excited exciton-like polaritons.(like a band gap)

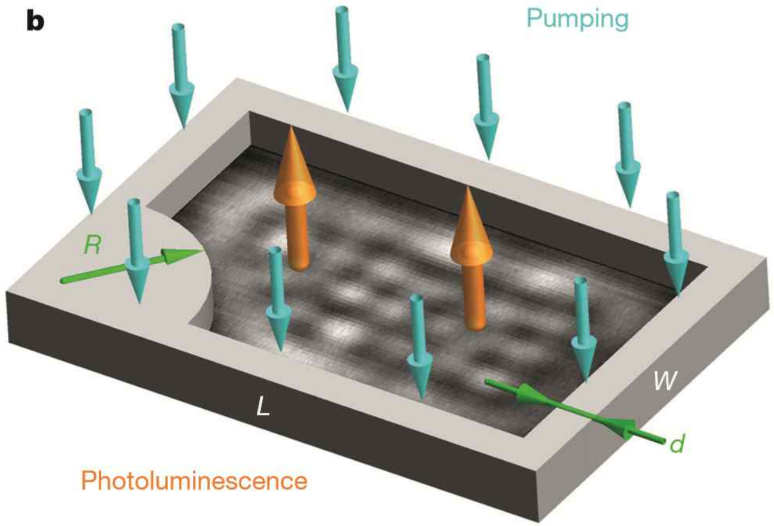


T.Byrnes et al., NRPHY3143

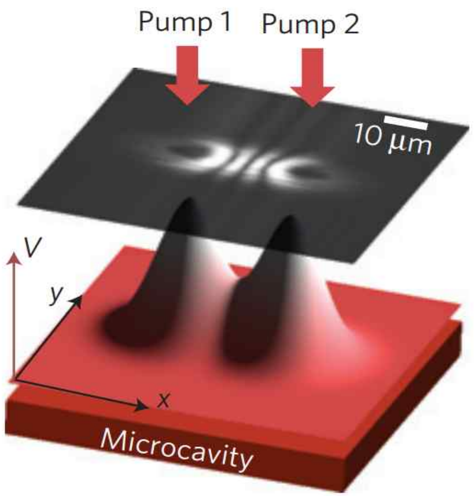
- Continuously pumped condensate decays coherent photons.
- Coherent photons escape the cavity.
- So photoluminescence in BEC is to check the state of condensate.

Experimental Procedure

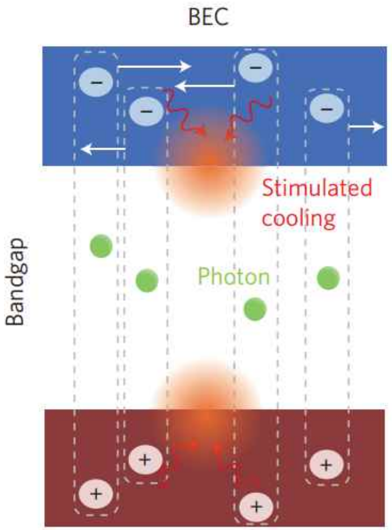




- DMD mirror reflect the spatial Siani billiard pattern.
- Optical pump creates an inhomogeneous distribution of excitons in the plane of quantum well.
- Varying two parameters (R,d) but the area remains same.
- Make cavity with optical pumping.

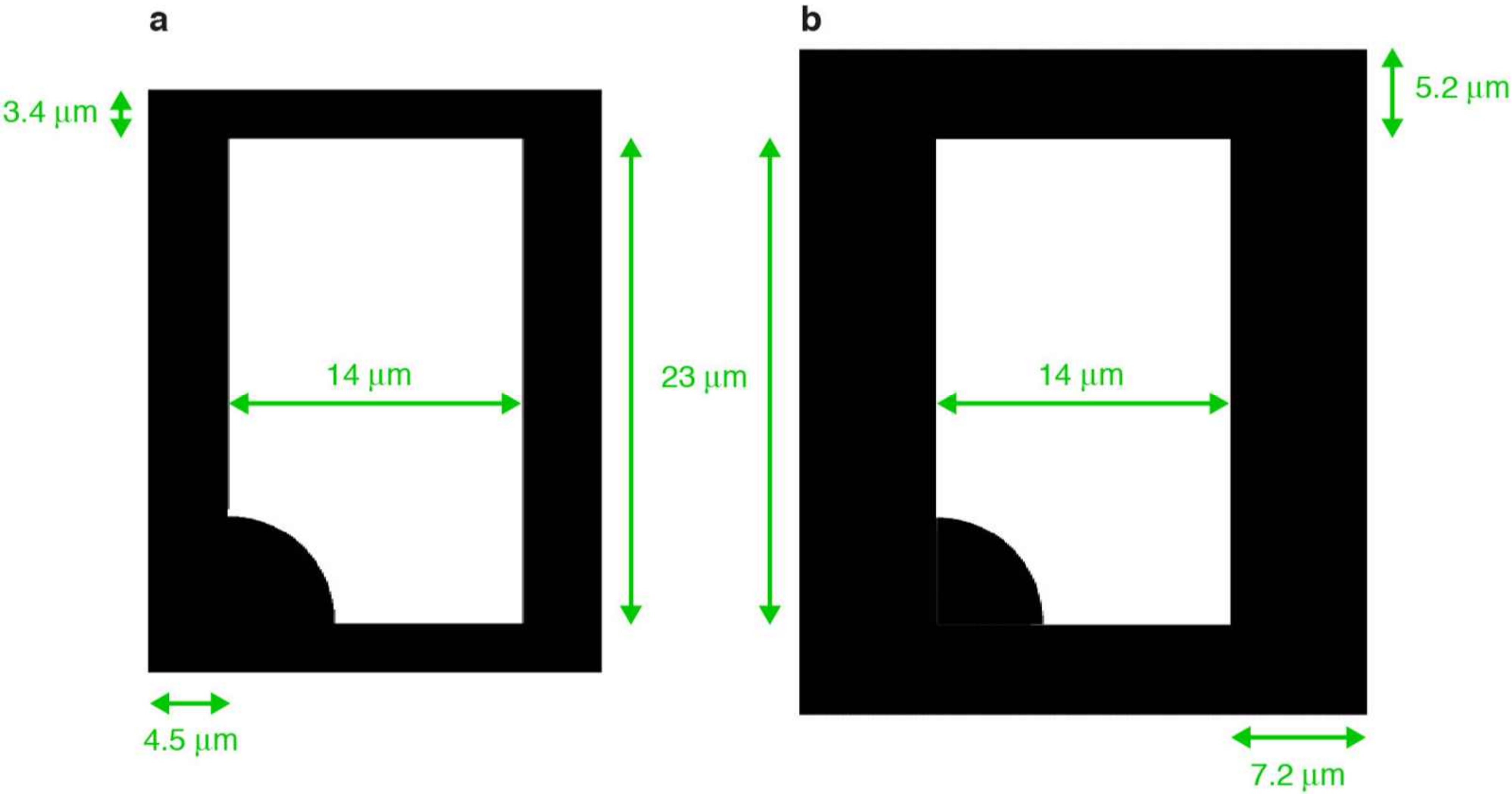


Tosi, G. et al., NRPHYS2182



T.Byrnes et al., NRPHY3143

- Exciton-Quantum well.
  Polariton-wall.
- Strong coupling between the excitons and photons make BEC. (orange cloud)


a
3.4 µm
14 µm
23 µm
4.5 µm
b
5.2 µm
14 µm
7.2 µm

Generation of Exceptional points

Modelling of the billiard

- Gross-Pitaevskii equation

$$i\hbar \frac{\partial \psi(r,t)}{\partial t} = [-\frac{\hbar^2}{2m}\nabla^2 + (g - i\gamma_{nl})|\psi|^2 + (g_R + i\hbar R)n_R(r) - i\hbar\gamma]\psi + i\hbar\Re[\psi(r,t)]$$

- Describes full dyanamics of the exciton-polariton condensation.

- Obtain full structure of spatial modes of the exciton-polariton condensate.

$$\frac{\partial N_R}{\partial t} = P(r) - (\gamma_R + R|\psi|^2)N_R$$

$$\Re[\psi(r,t)] = \alpha n_R[\mu(r,t) - i\hbar\frac{\partial}{\partial t}]\psi(r,t)$$

$$V(r) = V' + iV'' \equiv g_R n_R(r) + i\hbar[R n_R(r) - \gamma]$$

- Coupled-mode model

$$i\frac{\partial \psi_{n,n'}(r,t)}{\partial t} = [-\nabla^2 + V'(r) + iV''(r)]\psi_{n,n'} + \Omega\psi_{n,n'}$$

- For any two non-Hermitian modes of the billiard potential near the degeneracy point

- Anticipate that linear approximation is strongly valid, apply linear Schrodinger equation.

$$\psi_n = a_n(t)\varphi_n(r) \qquad (n,n') = (1,2)$$

$$[-\nabla^2 + V'(r)]\varphi_n(r) = E_\mathrm{n}\varphi_n(r)$$

$$\Gamma_n \propto \int V''(r)\left|\varphi_n(r)\right|^2 d^2 r$$

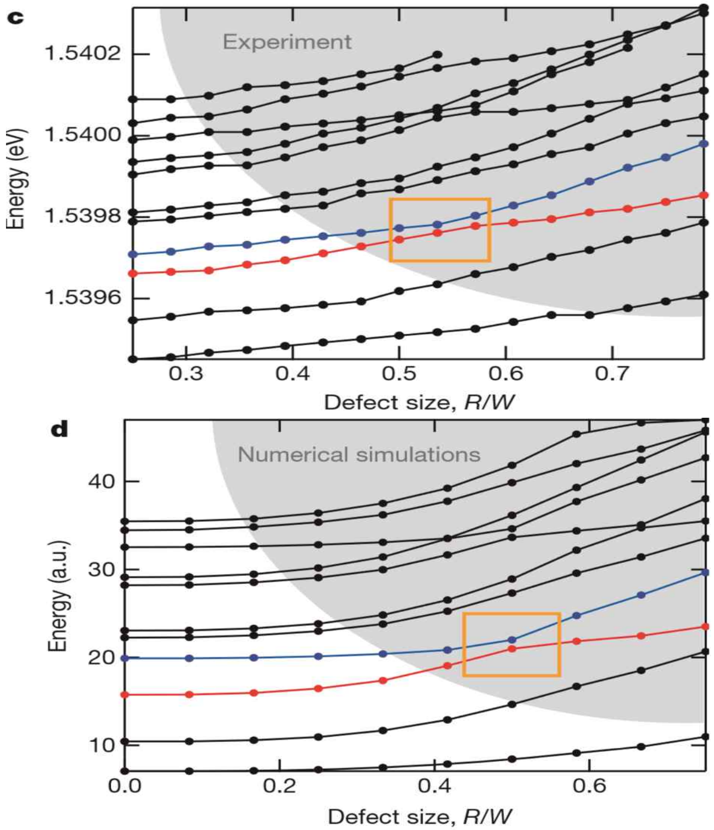
$$q \propto \int \varphi_n^*(r)\varphi_{n'}(r) d^2 r$$

- Separate the temporal and spatial distribution.

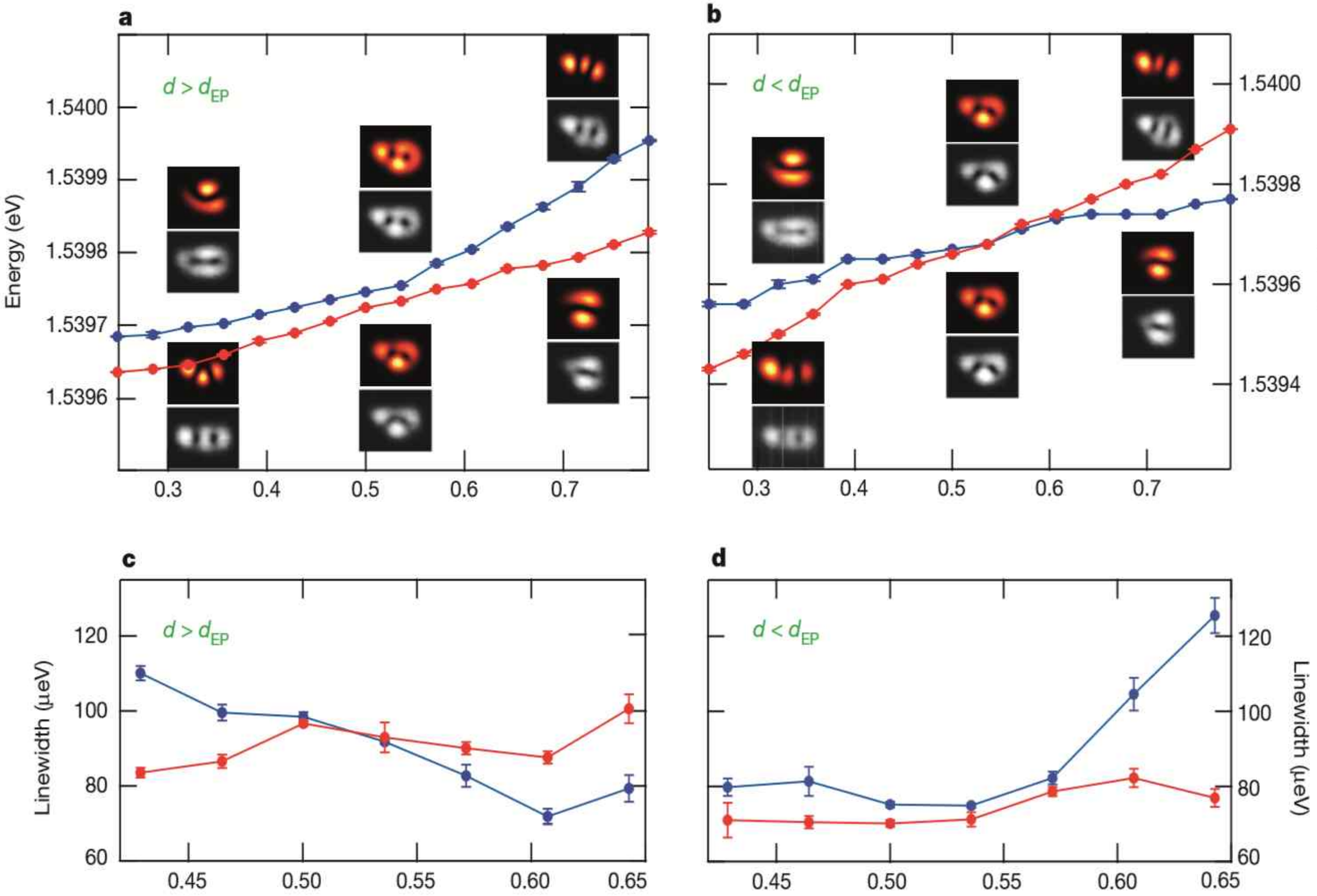
- Spatial overlap q is an off-diagonal term of Hamiltonian and Γ is complex parts of the eigenenergies corresponding to the gain/loss rate.

Results

Varying R parameter



- 11 modes of billiard.
- With growing R, numerous degeneracies and quasi-degeneracies suddenly increase.
- Significant criteria of transition of regular to quantum chaos. (this is soft wall case -> mixed)
- Crossings and anti-crossings of real energy levels are observed.
- However, in order to see the transition between crossing and anti-crossing, we need another parameter->d



- Two billiards with varying d.
- Left pair: for thick wall, anti-crossing for real eigenenergies.
  Crossing for imaginary eigenenergies.
- Right pair: for thin wall, anti-crossing for imaginary eigenenergies.
  Crossing for real eigenenergies.

So transition between crossing and anti-crossing is d dependent.

Linear complex Hamiltonian

$$\hat{H} = \begin{pmatrix} \tilde{E}_1 & q \\ q^* & \tilde{E}_2 \end{pmatrix}$$

$$\tilde{E}_{1,2} = E_{1,2} - i\Gamma_{1,2}$$

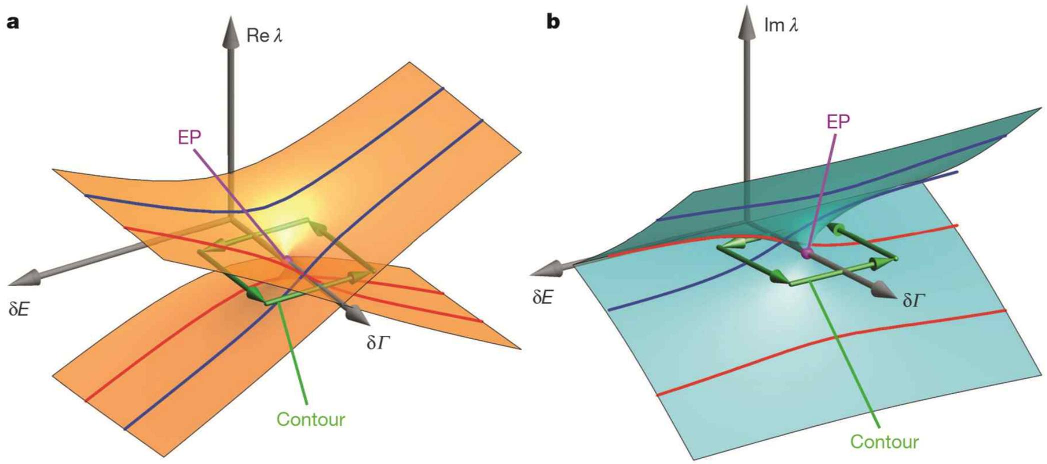
- Linearly approximated Hamiltonian
- The behavior of two billiard modes in the vicinity of a degeneracy ->simple two-level system with effective coupling.

$$\tilde{E} = (\tilde{E}_1 + \tilde{E}_2)/2 \equiv E - i\Gamma$$

$$\delta\tilde{E} = (\tilde{E}_2 - \tilde{E}_1)/2 \equiv \delta E - i\delta\Gamma$$

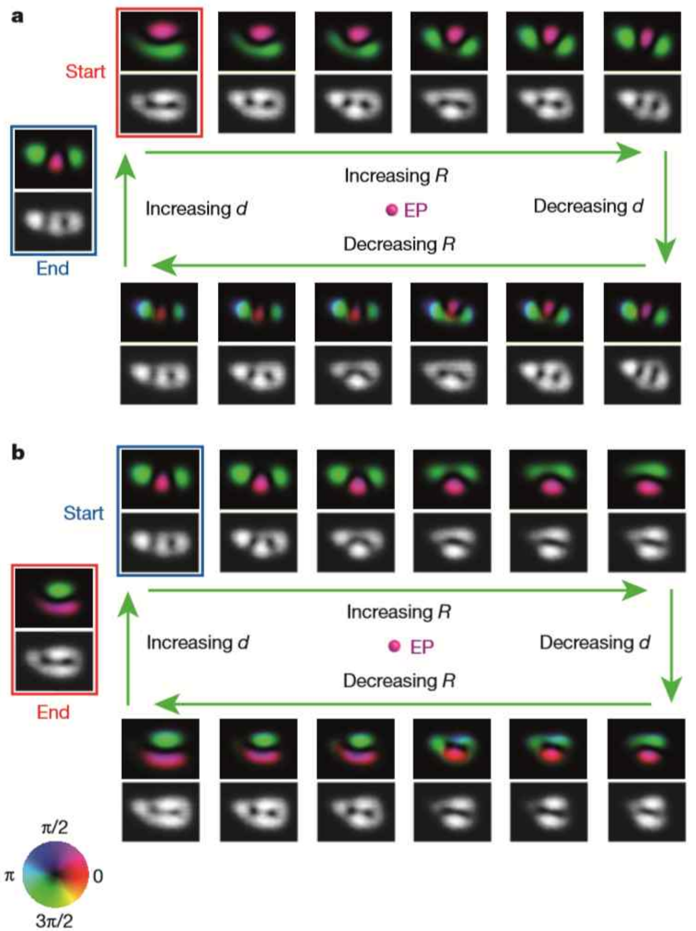
$$\lambda_{1,2} = \tilde{E} \pm \sqrt{\delta\tilde{E}^2 + |q|^2}$$

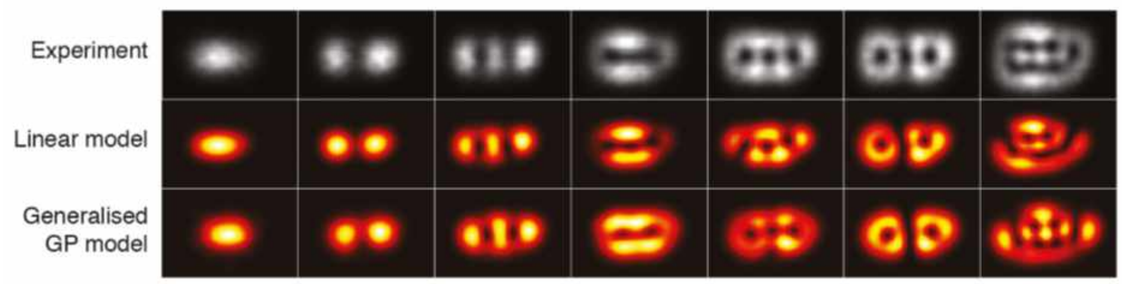
$$\delta\tilde{E} = (\delta E, \delta\Gamma) \Rightarrow (\mathrm{R}, \mathrm{d}) \quad i\delta\tilde{E}_{EP} = \pm|q|$$



- At EP, the eigenvalues coalesce.
- The EP can be encircled in the parameter domain.
- Two parameters approximately arranged (R,d).

Mode Switching





- Left features describe the transmutation of spatial distributions of selected eigenmode along the closed loop.
- Increasing and decreasing R, decreasing and increasing d. First cyle is over
  -> π *phase shift* (topological Berry phase)
- Begin 2nd cycle, repeat above procedure.
  -> π *phase shift* again.
- As a result, when the contour is traversed twice, return to the original mode.
- The experimental and calculated density and phase profiles are matches very well

Q&A