FLEET

ARC CENTRE OF EXCELLENCE IN FUTURE LOW-ENERGY ELECTRONICS TECHNOLOGIES

Non-equilibrium Bose-Einstein condensation of exciton polaritons

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Outline

- Brief introduction to exciton polaritons
- Fragmented condensation in optical traps
- Exploring non-Hermitian quantum physics with optically-trapped polaritons
- Polariton condensation in the single-shot regime: beyond statistical averaging

Experiment + theory

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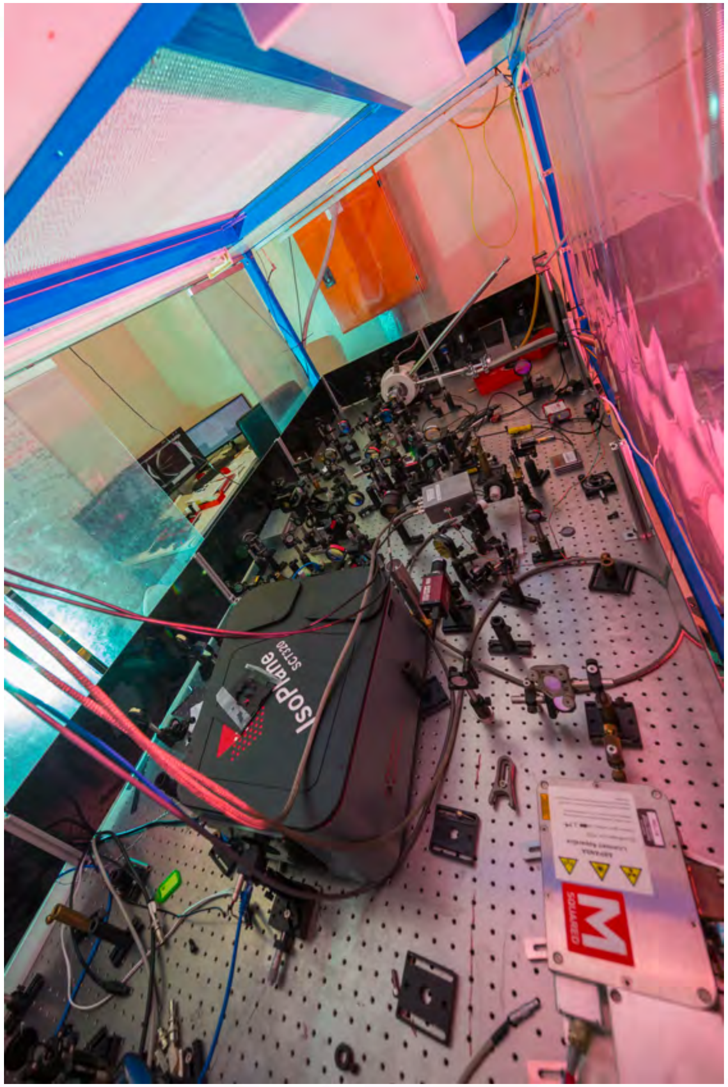
NONLINEAR PHYSICS CENTRE

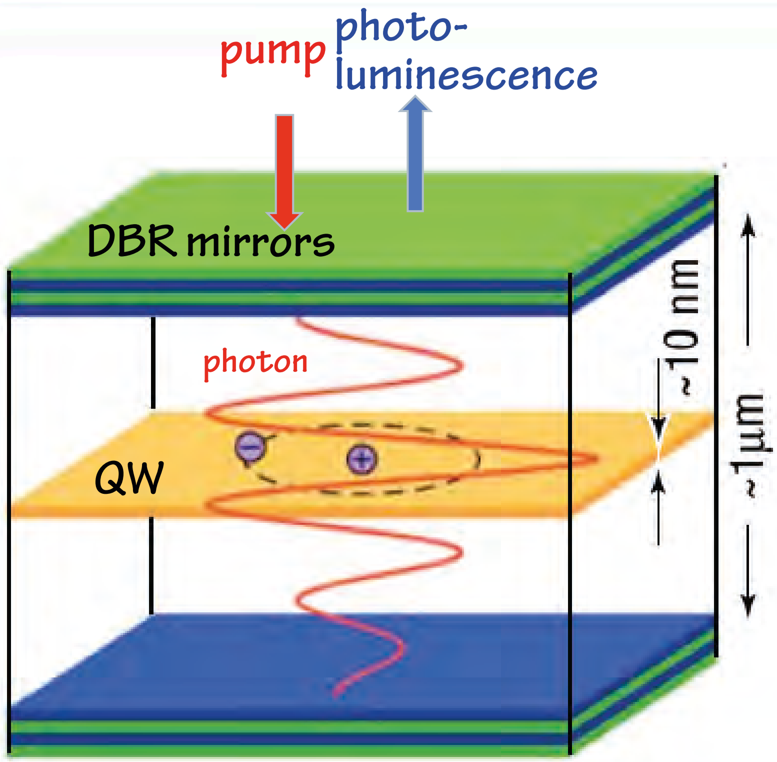
- established in 2013
- unique in Australia

http://polaritonbec.org



Introduction to exciton polaritons

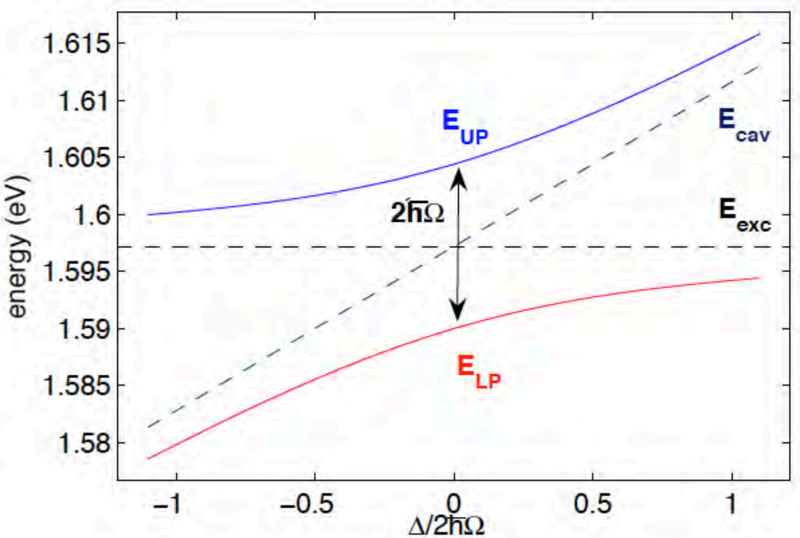
Polariton – half light, half matter



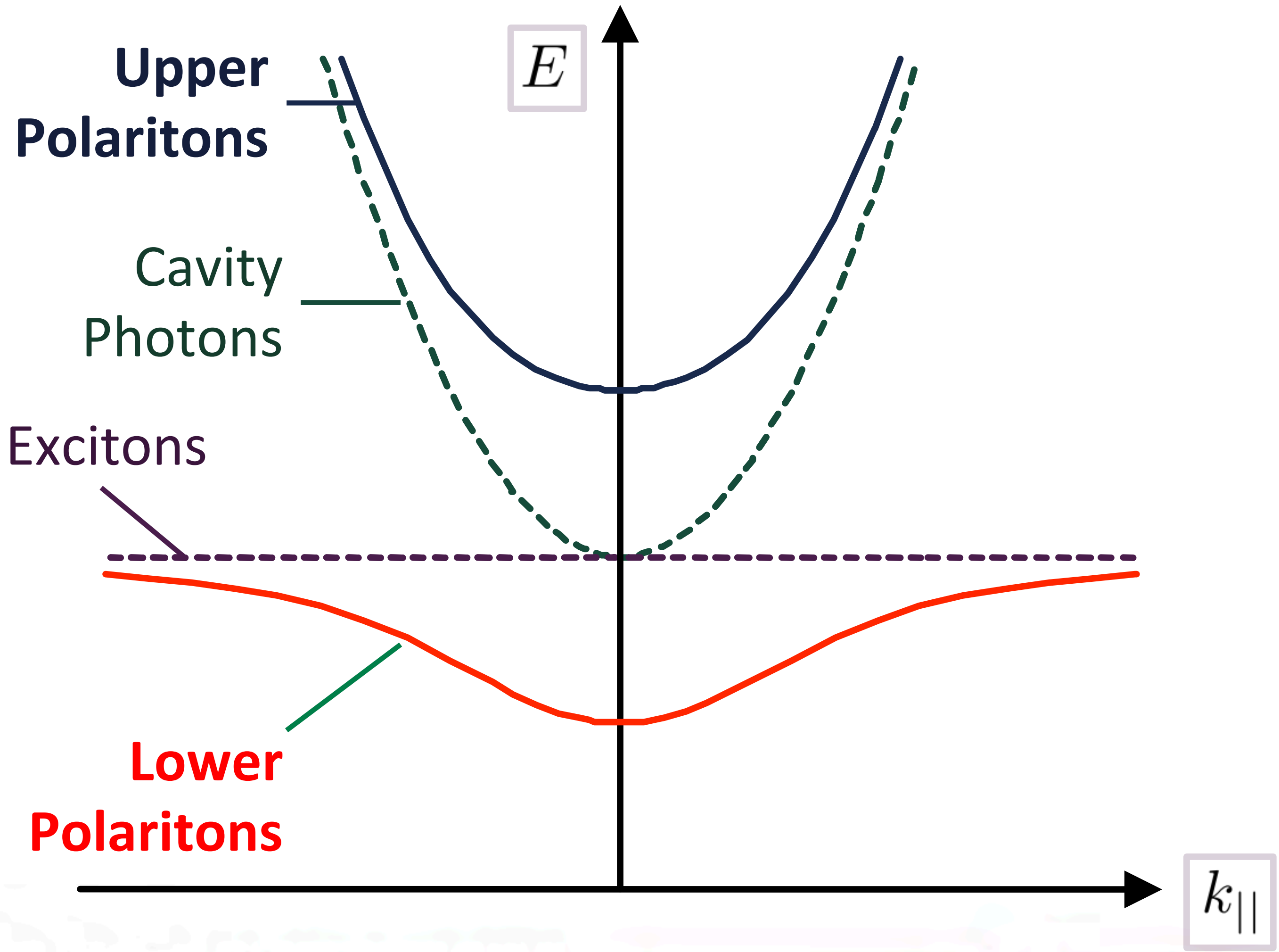
GaAs/AlGaAs

Q~10^6

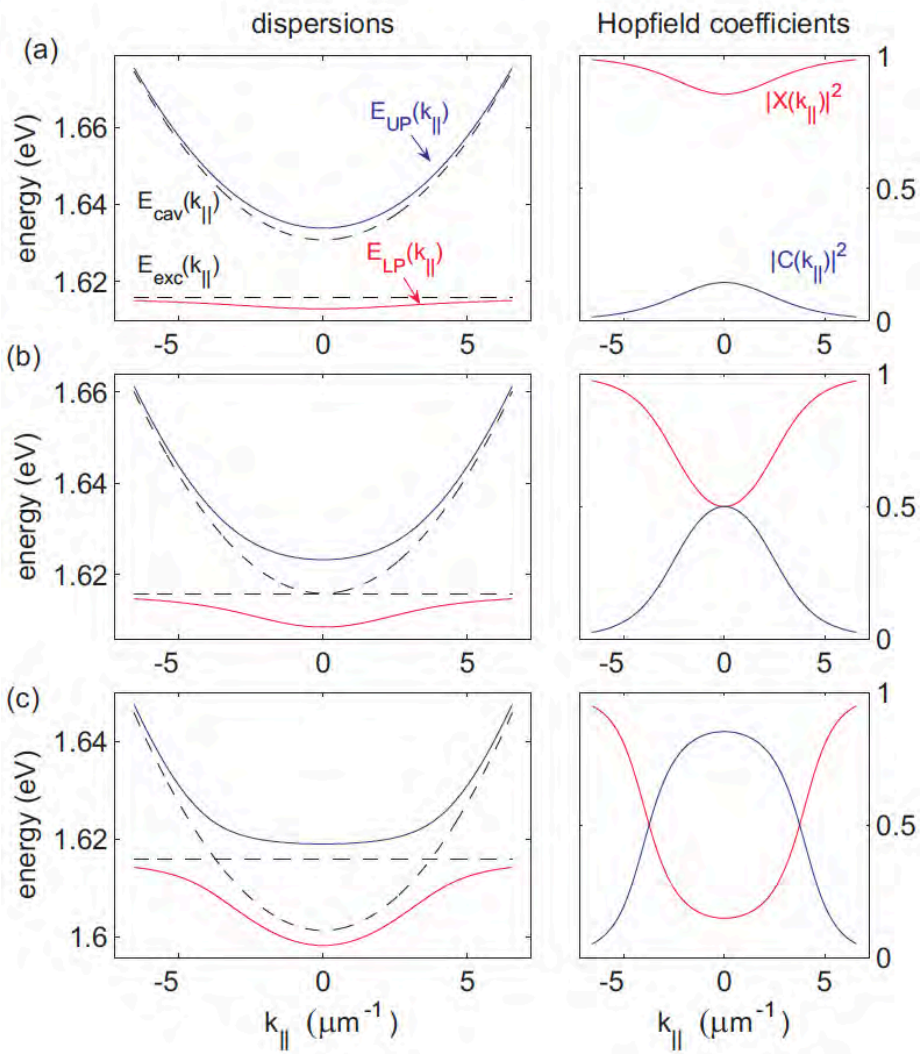
- QWs+DBRs – strong photon and exciton confinement
- Strong light-matter interaction regime
- Exciton and photon form a hybrid state: polariton



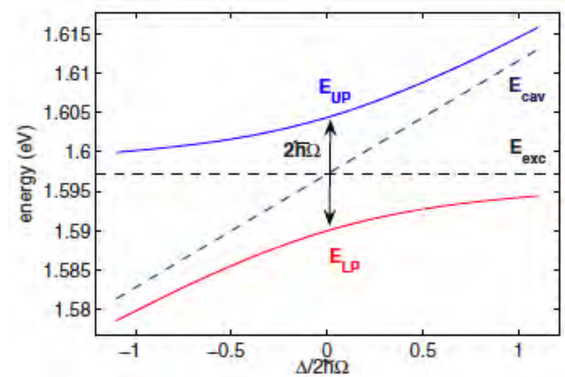
Polariton dispersion



From photon-like to exciton-like polariton



H. Deng et al., Rev. Mod. Phys. 82, 1489 (2010)



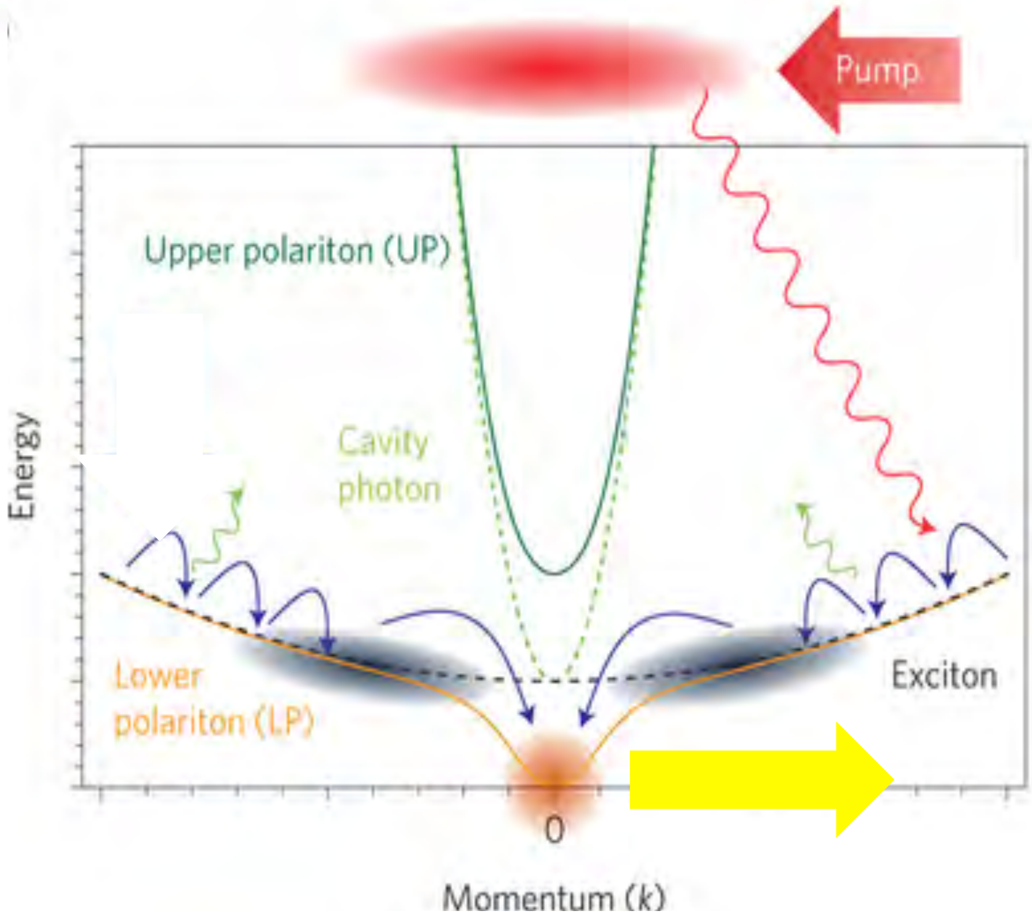
$$m_{LP}(k_{\|} \sim 0) \simeq m_{cav}/|C|^2 \sim 10^{-4} m_{exc}$$

$$m_{UP}(k_{\|} \sim 0) \simeq m_{cav}/|X|^2.$$

Photon part (light):
fast propagation (~μm/ps)
short lifetime (~100 ps)

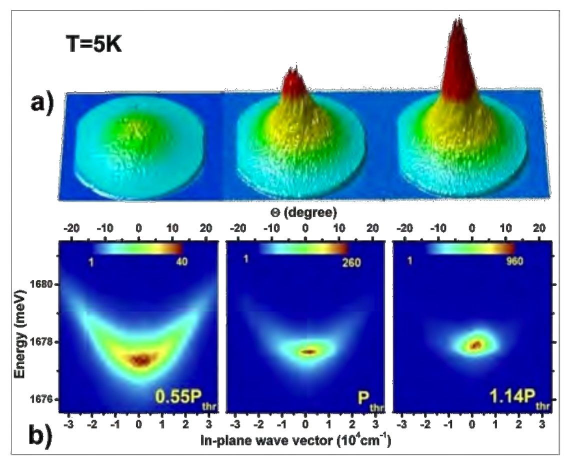
Exciton part (matter):
interactions

Spontaneous condensation of exciton polaritons



- Off-resonant CW pump
- Condensate forms via stimulated scattering into a ground LP state from a thermal excitonic reservoir

PL signal carries all the information about the condensate



Kasprzak et al, Nature (2006)

Polaritons vs other massive bosons

H. Deng et al., Rev. Mod. Phys. 82, 1489 (2010)

TABLE I. Parameter comparison of BEC systems.

Systems	Atomic gases	Excitons	Polaritons
Effective mass m^*/m_e	10^3	10^{-1}	10^{-5}
Bohr radius a_B	10^{-1} Å	10^2 Å	10^2 Å
Particle spacing: $n^{-1/d}$	10^3 Å	10^2 Å	1 μm
Critical temperature T_c	1 nK–1 μK	1 mK–1 K	1–>300 K
Thermalization time/Lifetime	1 ms/1 s $\sim 10^{-3}$	10 ps/1 ns $\sim 10^{-2}$	(1–10 ps)/(1–10 ps)=0.1–10

Critical temperature for condensation is relatively high (up to room temperature)
Highly non-equilibrium system

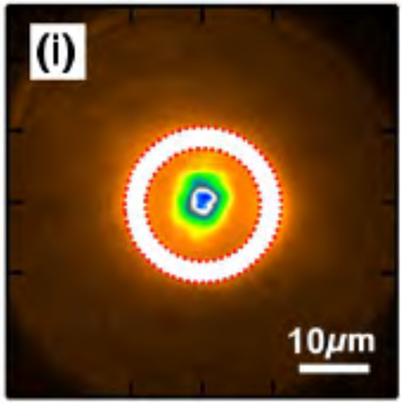
Optical trapping & fragmented condensation

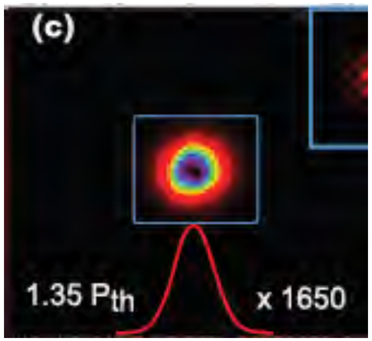
Optically-induced trapping potentials

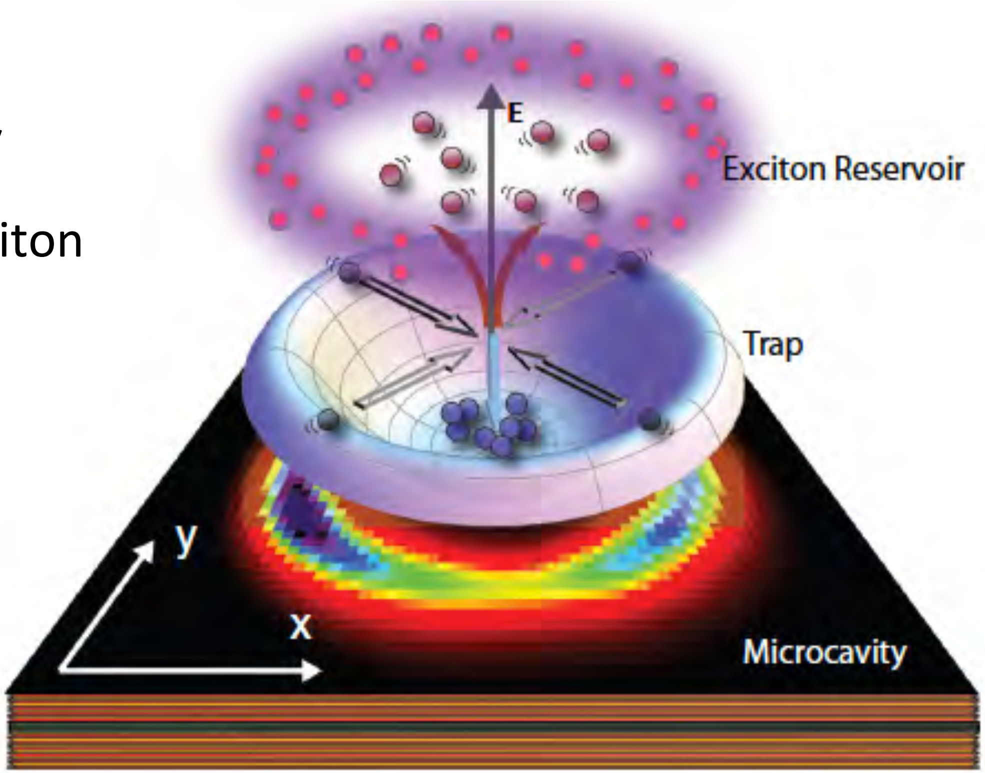
Off-resonant optical pump creates polariton condensate and induces trapping potentials for polaritons

Pump-induced blue shift in energy proportional to the reservoir density

Origin of the blueshift: exciton-polariton interactions





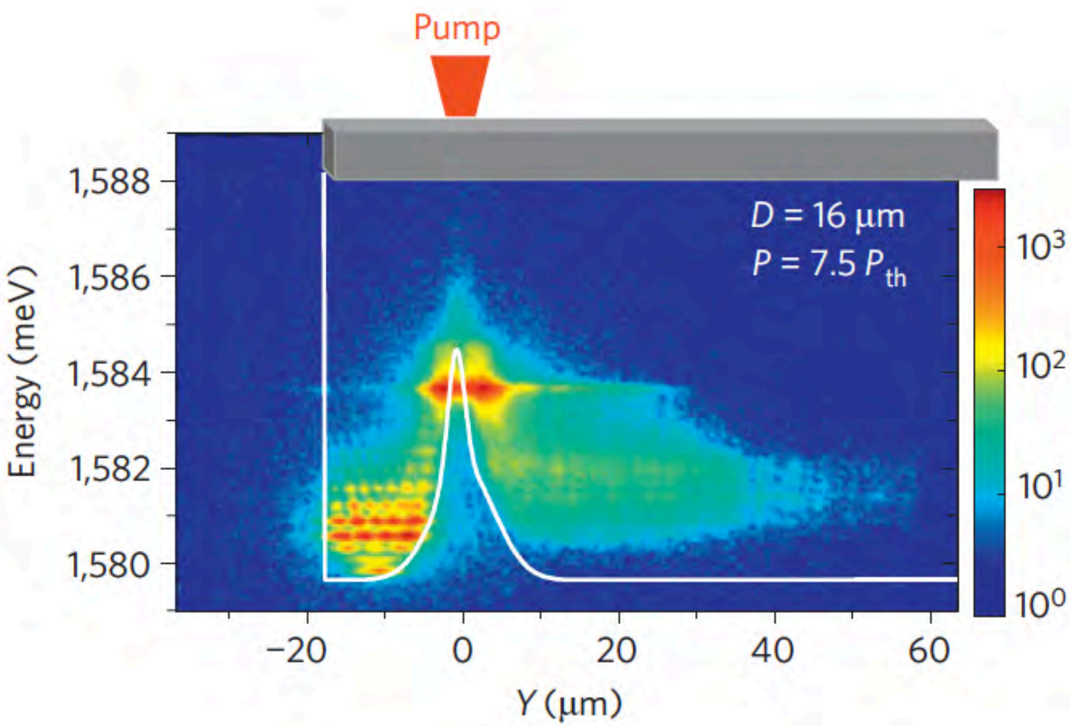


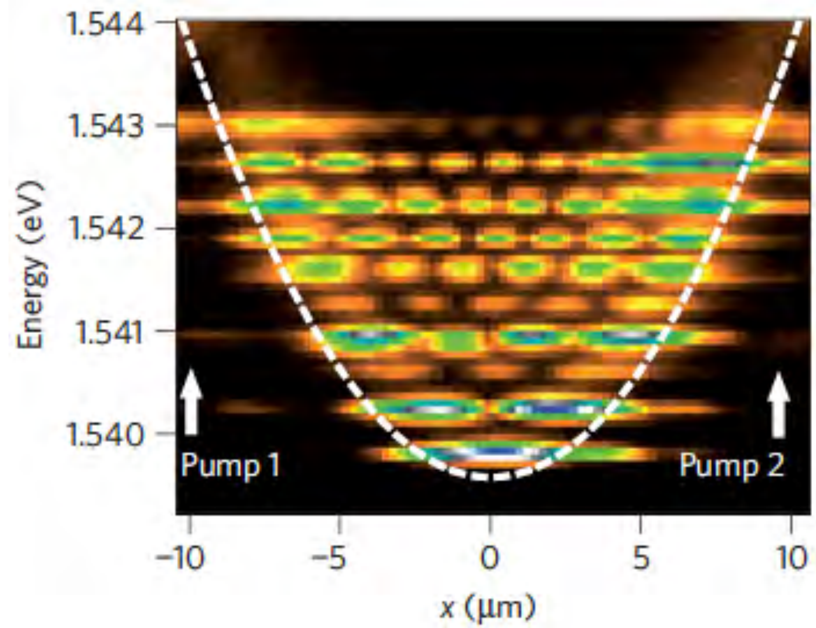
Cristofolini et al., PRL 110, 186403 (2013)

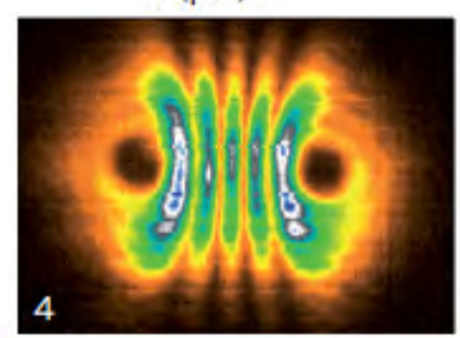
Askitopolous et al., PRB 88, 041308 (R) (2013)

Fragmented condensation in a trap

Fragmented condensates simultaneously occupy several single-particle states in the effective trapping potential



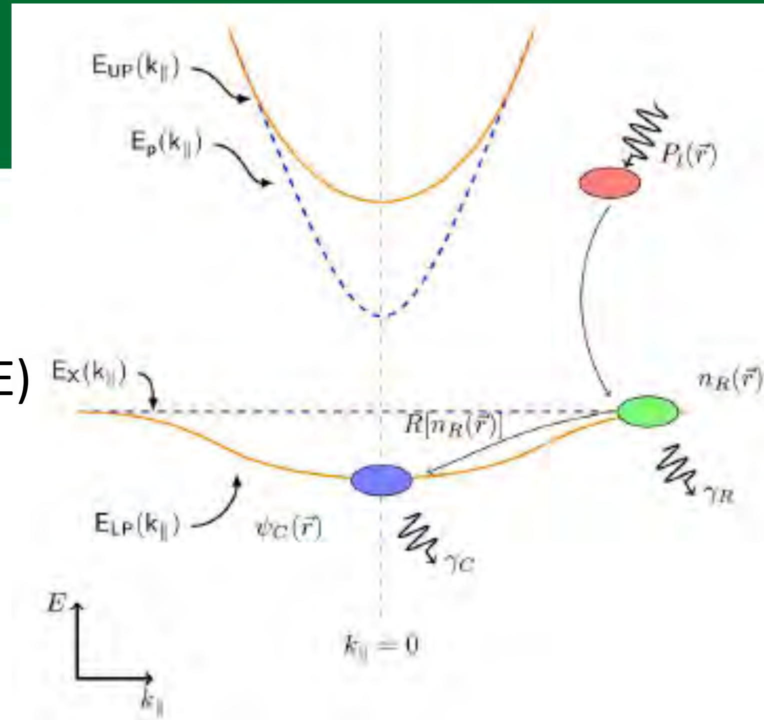




Wertz et al., Nature Physics **6**, 860 (2010)

Tosi et al., Nature Physics **8**, 190 (2012)

The mean-field model



Open-dissipative Gross-Pitaevskii Equation (ODGPE)

Kneer et al. PRA 58, 4841 (1998)
Wouters & Carusotto, PRL 99, 140402 (2007)

condensate & reservoir interactions

stimulated gain

$$i\hbar\frac{\partial\Psi}{\partial t} = \left[-\frac{\hbar^2}{2m}\nabla_\perp^2 + V_{\rm ext}(\vec{r}) + g_c|\Psi|^2 + g_R n_R(\vec{r},t) + i\frac{\hbar}{2}(Rn_R - \gamma_c)\right]\Psi$$

condensate loss

$$\frac{\partial n_R}{\partial t} = -(\gamma_R + R|\Psi|^2)n_R(\vec{r},t) + P(\vec{r})$$

pump rate

reservoir decay

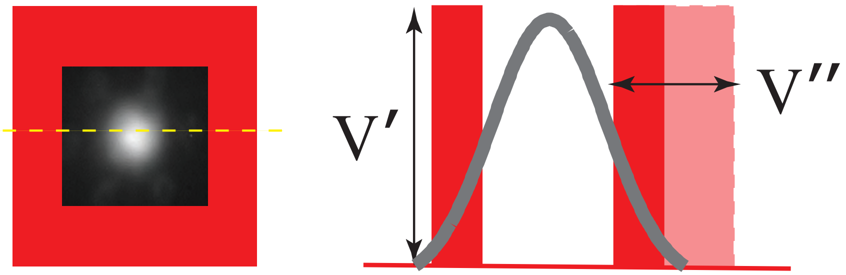
stimulated scattering

Optically-induced potentials are non-Hermitian

- The potential is inherently complex

$$V(\mathbf{r}) = V'(\mathbf{r}) + iV''(\mathbf{r})$$

- Real part is due to exciton-polariton interaction (blue shift) $V' \sim n_R \sim P(\mathbf{r})$
- Imaginary part is due to gain (pump) and polariton decay $V'' = \Gamma(n_R) - \gamma_c$
- Both parts of the potential can be manipulated:



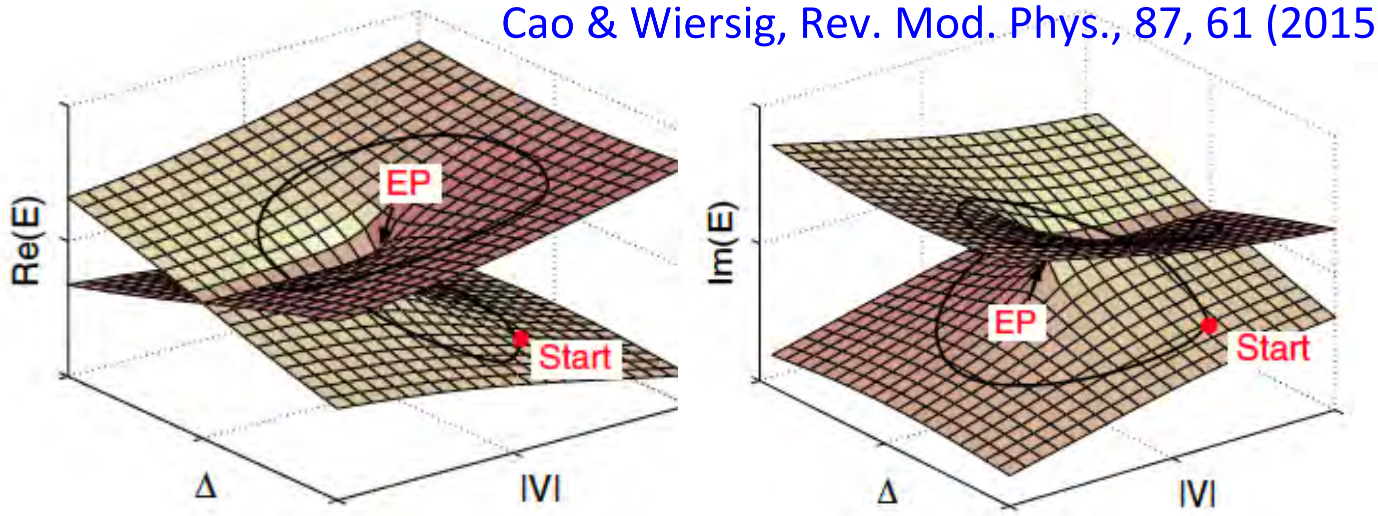
The wall thickness affects overlap between the gain region and the eigenmodes

- Can control both real part (energy) and imaginary part (linewidth) of the complex eigenenergies

Engineering exceptional points for polaritons

Cao & Wiersig, Rev. Mod. Phys., 87, 61 (2015)

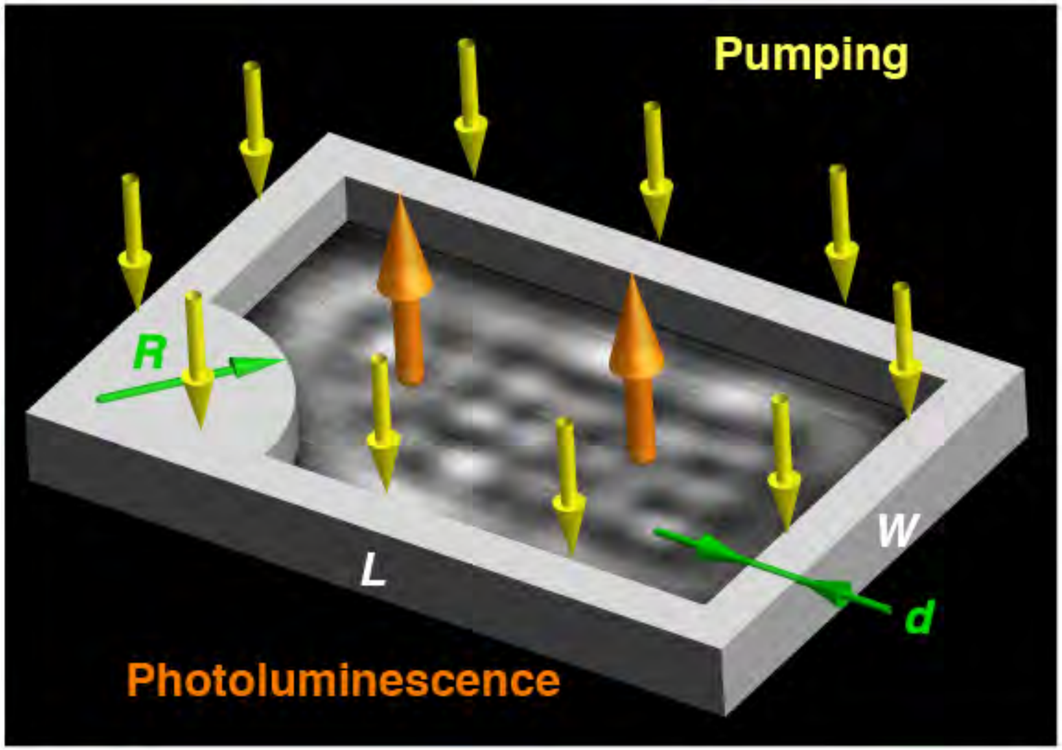
$$\hat{H} = \begin{pmatrix} \tilde{E}_1 & \Delta \\ \Delta & \tilde{E}_2 \end{pmatrix}$$



- EP is a spectral degeneracy: eigenvalues and eigenstates coalesce; branch-point singularity: topological Berry phase
  chiral eigenstate at EP $\psi = \psi_1 + \psi_2 e^{\pm i\pi/2}$

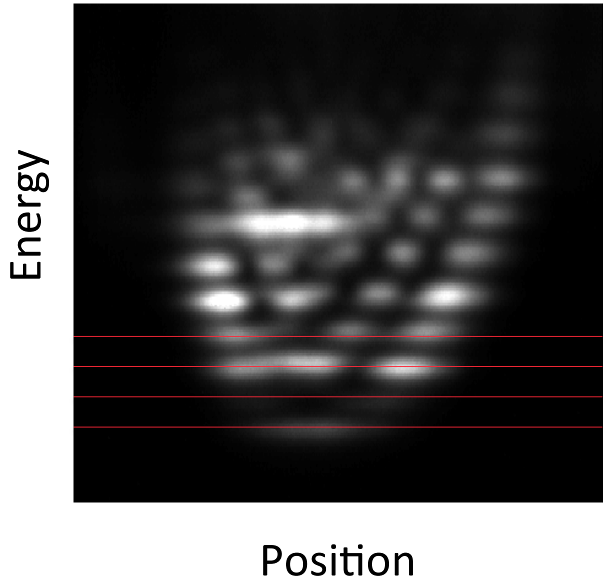
- Create a fragmented polariton condensate
- Use two control parameters to bring two eigenstates to degeneracy
- Test the nontrivial topology of the eigenvalues

Experiment: exciton-polariton Sinai billiard



$$V(\mathbf{r}) = V'(\mathbf{r}) + iV''(\mathbf{r})$$

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



- Sinai billiard: a rectangular area + a scattering corner (23x17 µm)
- Can image eigenmodes (in real space) and eigenvalues
- Energy eigenvalues are complex; finite linewidth

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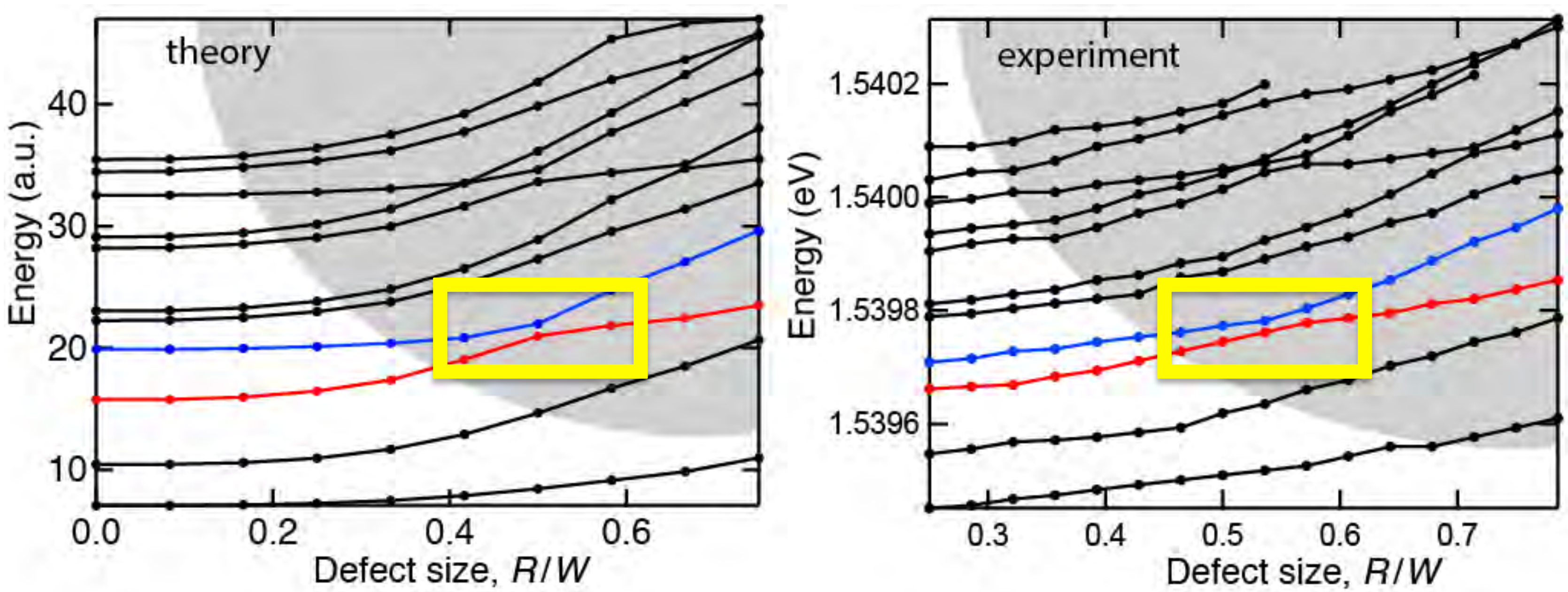
T. Gao, et al., Nature **526**, 554 (2015)

non-Hermitian Sinai billiard: energy spectrum

- Hermitian Sinai billiard exhibits quantum chaos
- Abundance of avoided crossings at low energies
  [M.V. Berry, Ann. Phys. 131, 163 (1981)]
- A non-Hermitian Sinai billiard has both avoided crossings and crossings



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Structure of the eigenvalues near EP

Eigenvalues away from the (near)degeneracy

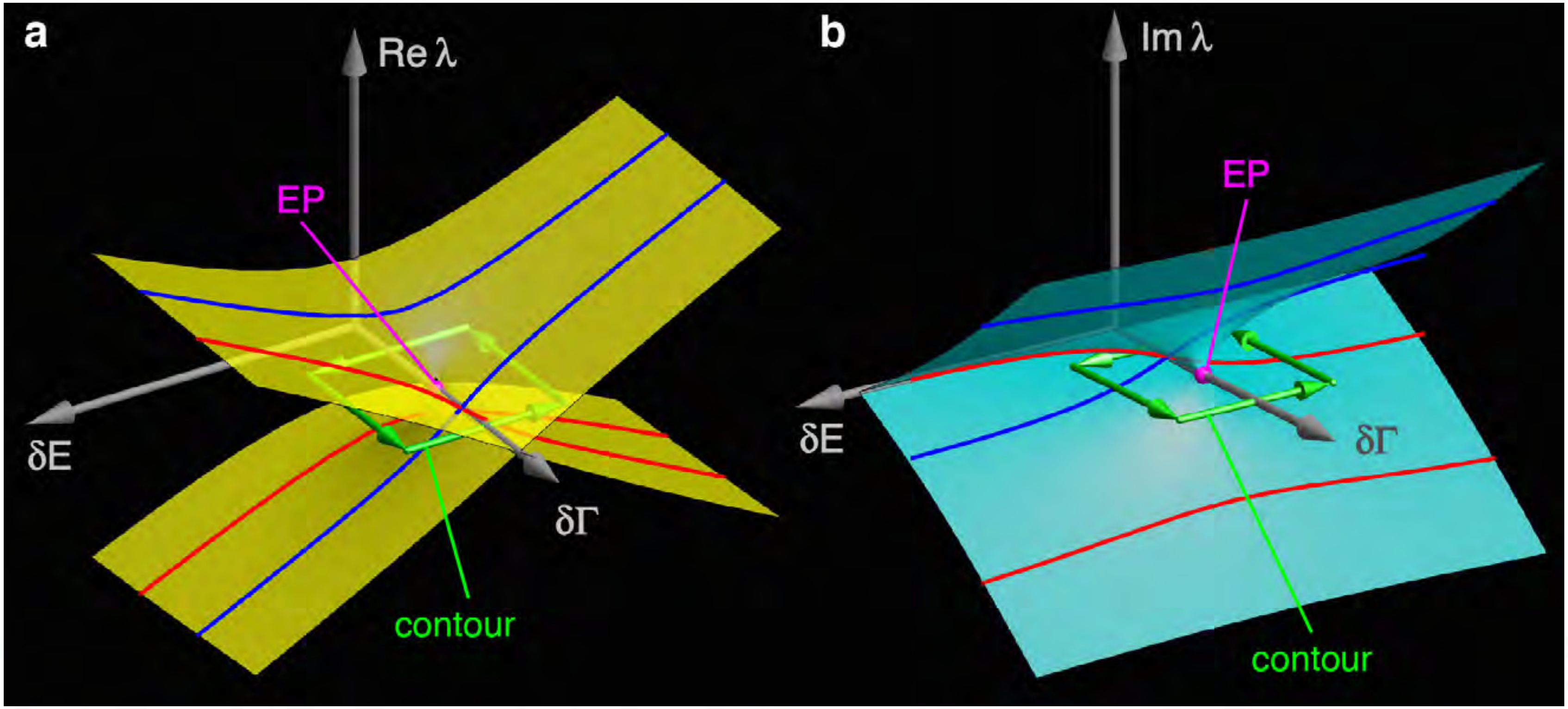
$$\tilde{E}_{1,2} = E_{1,2} - i\,\Gamma_{1,2}$$

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

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

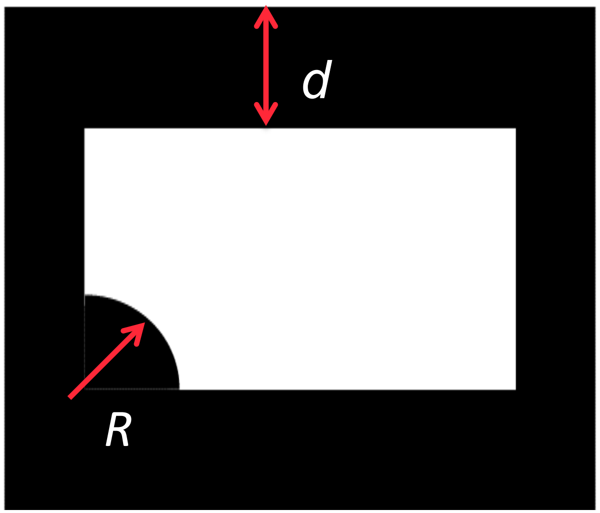
$$\delta\tilde{E} = \left(\tilde{E}_2 - \tilde{E}_1\right)/2 \equiv \delta E - i\,\delta\Gamma$$

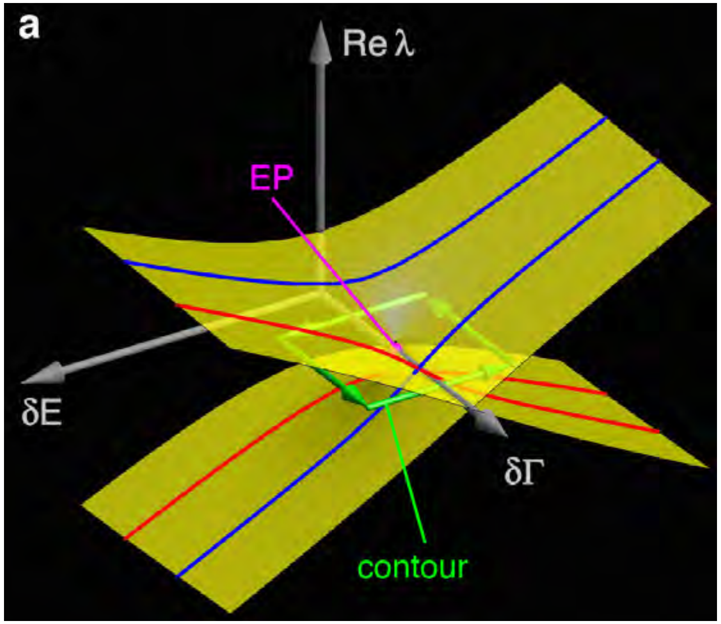
$$\lambda_{1,2} = \tilde{E} \pm \sqrt{\delta\tilde{E}^2 + |q|^2}$$



Moving around the EP

Need two control parameters to move along the contour

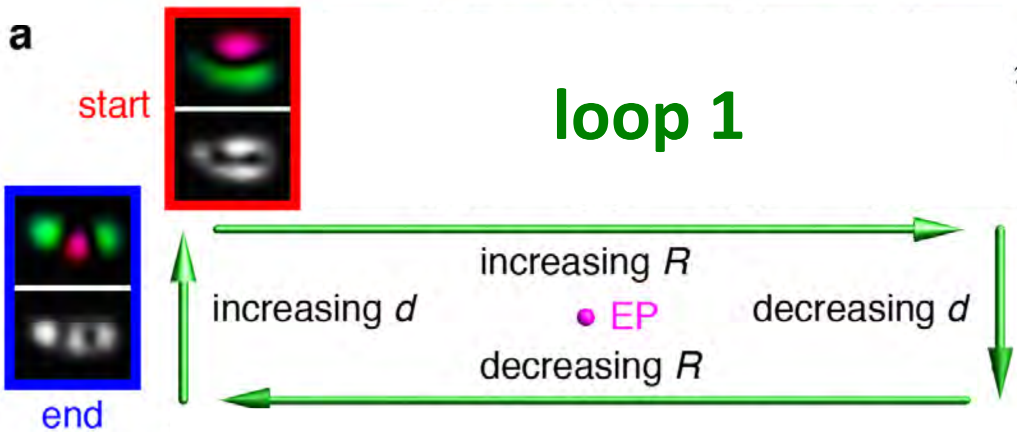


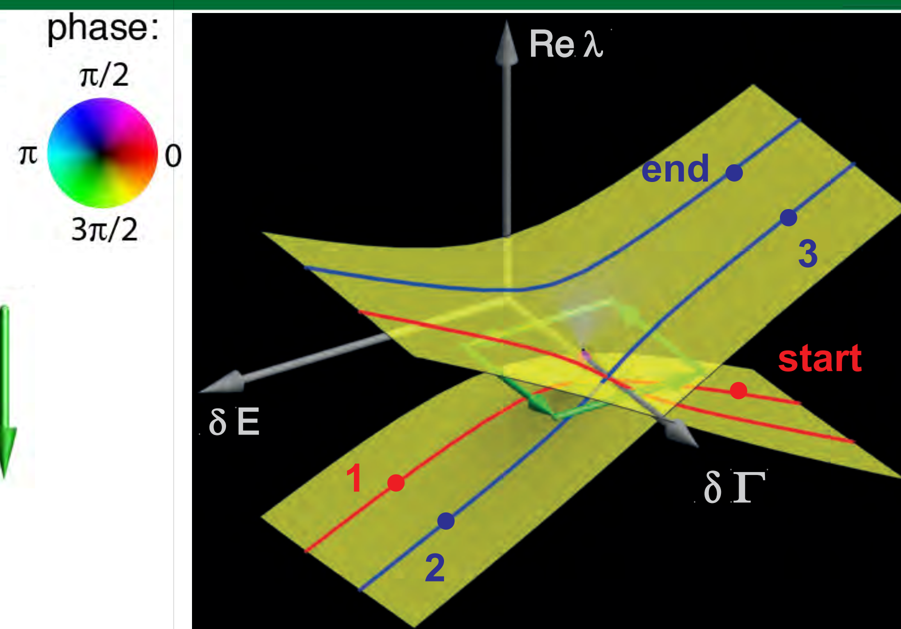


increasing R ➔ decreasing billiard area ➔increasing δE

decreasing d ➔ decreasing overlap between polaritons and walls ➔ increasing $\delta\Gamma$

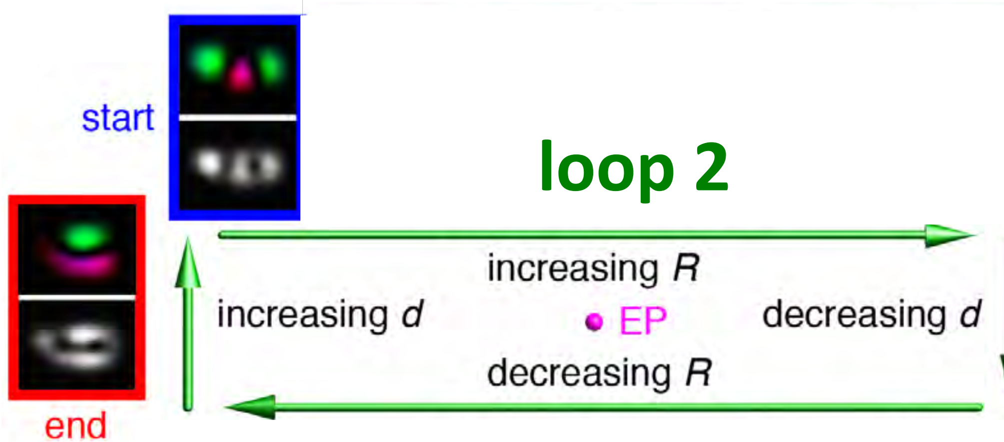
Topological Berry phase





- Two eigenstates: a dipole and a ‘tripole’
- Return to the same red branch and a dipole mode after traversing the contour <u>twice</u>

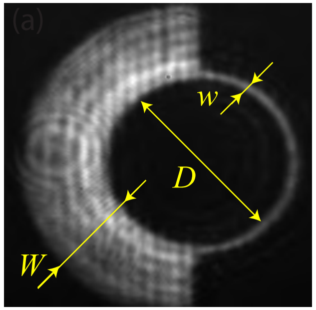
- Topological Berry phase π

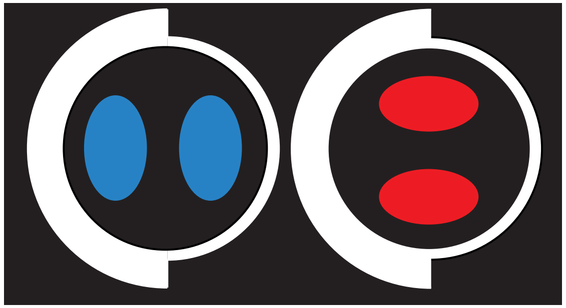


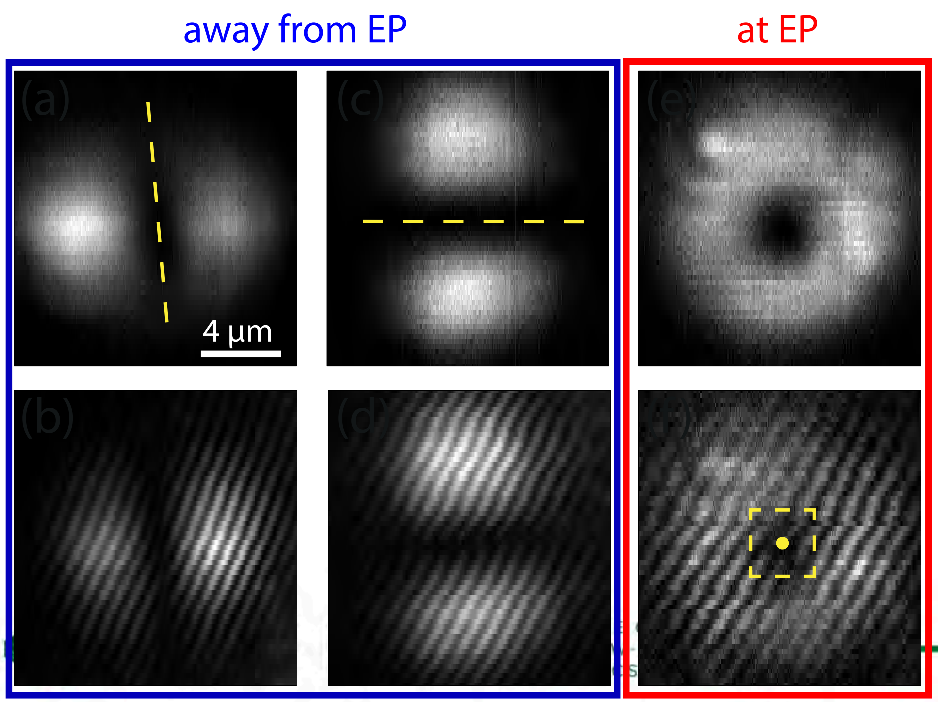
T. Gao, et al., Nature **526**, 554 (2015)

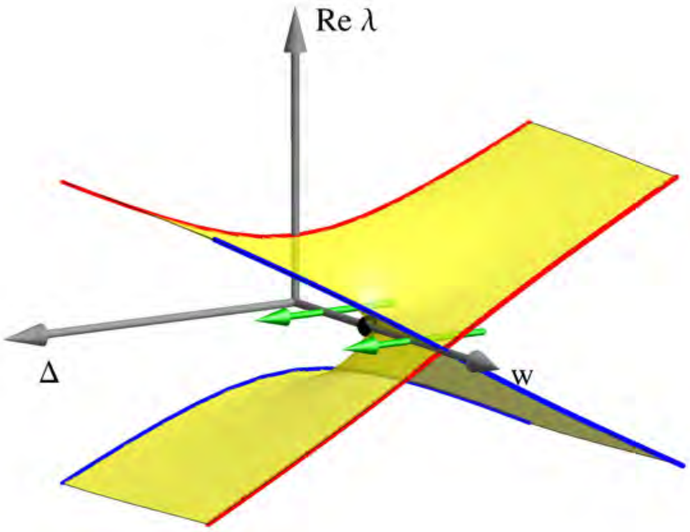
Chiral mode at EP

- Two dipoles in an asymmetric "ring resonator"









$$\psi_{EP} = \psi_1 + \psi_2 e^{\pm i\pi/2}$$

T. Gao, et al., arXiv:1705.09752 (2017)

Polariton condensate coupled to the reservoir

- In optical traps, condensate and reservoir are spatially separated
- What happens if they overlap strongly?
- Reservoir is a source of particles and a source of fluctuations
- What are the properties the condensate coupled to the reservoir?
- Fine details of the condensate formation in the “single-shot regime” without averaging over realisations

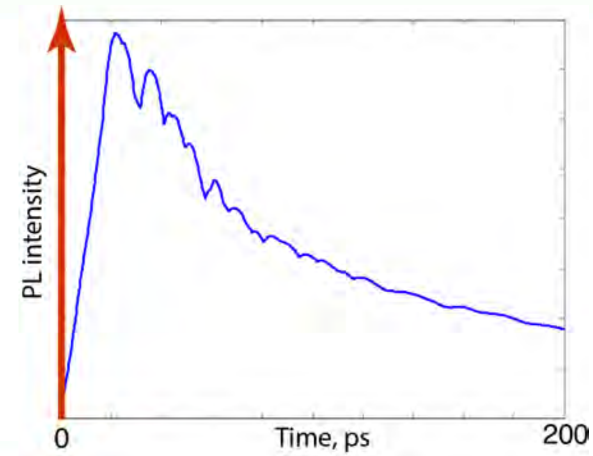
E. Estrecho et al, arXiv:1705.00469 (2017)

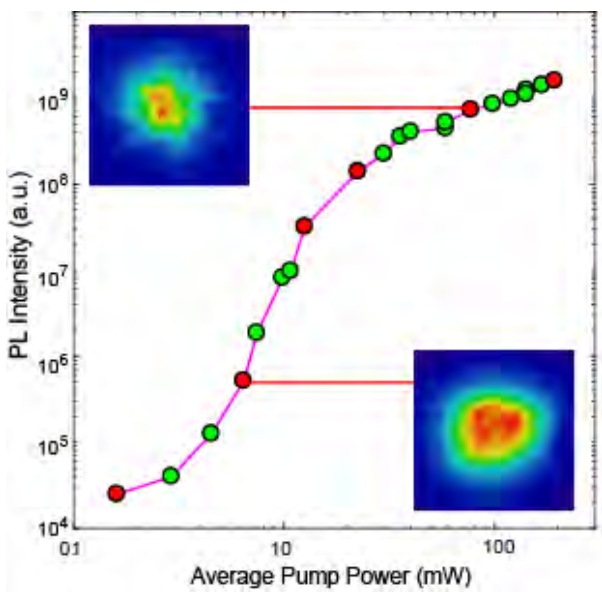
Condensation beyond the statistical average

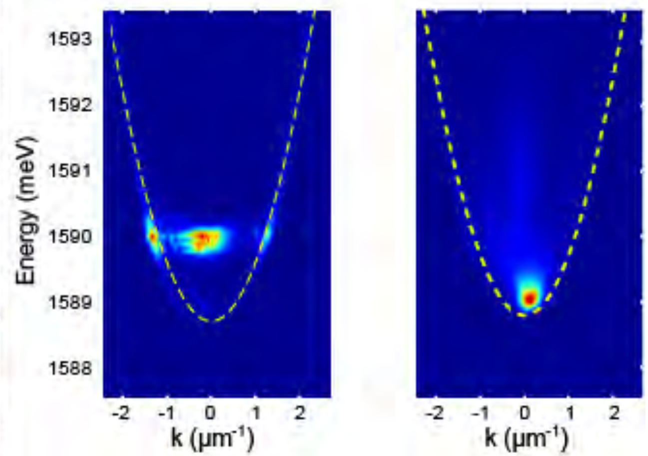
Transition to condensation with growing pump power

Single-shot regime:

- An intense 140 fs pulse
- Gaussian pump
- Only one pulse per life cycle







averaging over 10^6 realisations

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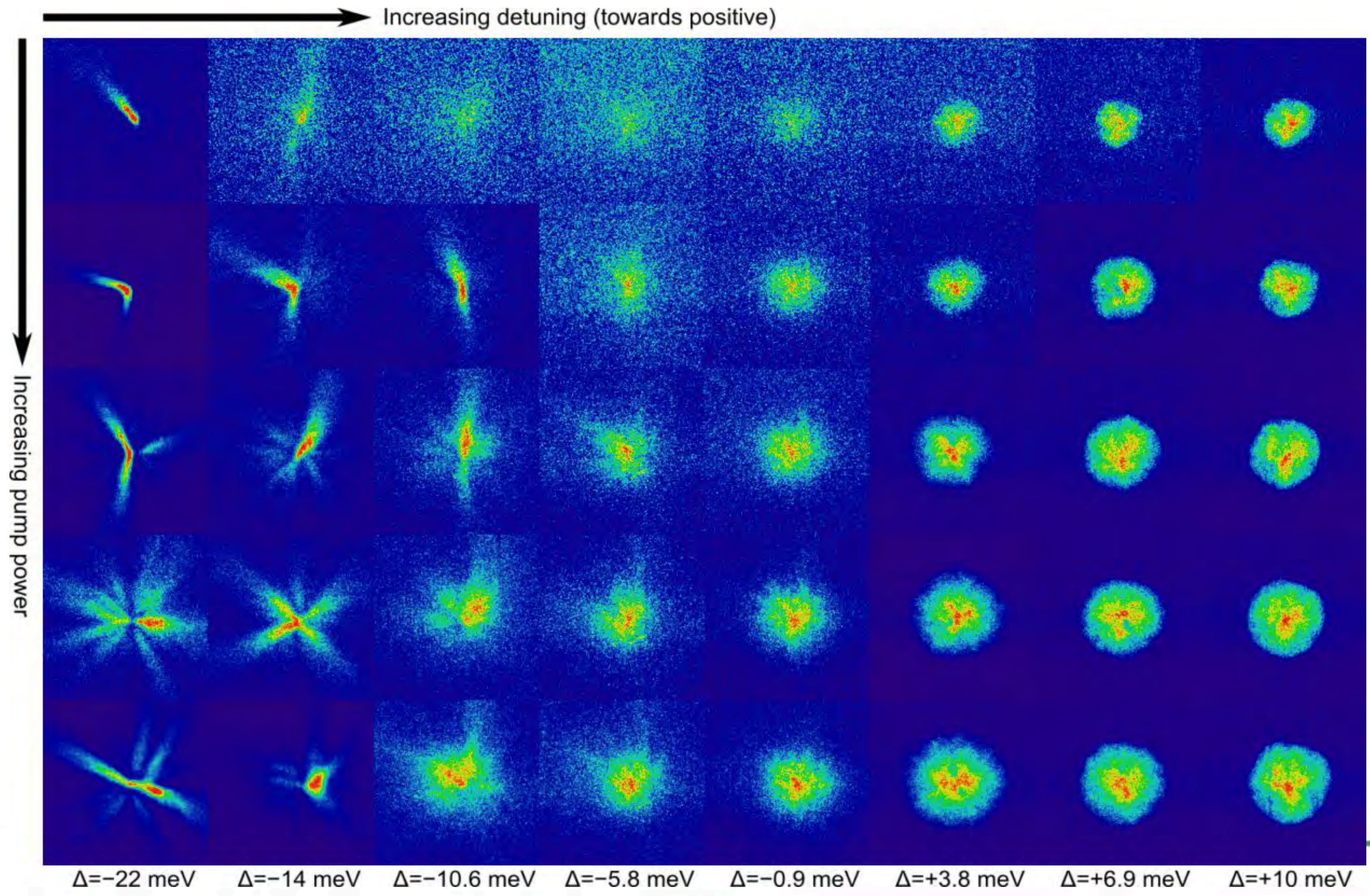
Single-shot experiments with inorganic microcavities

photonic (light) polaritons

excitonic (heavy) polaritons



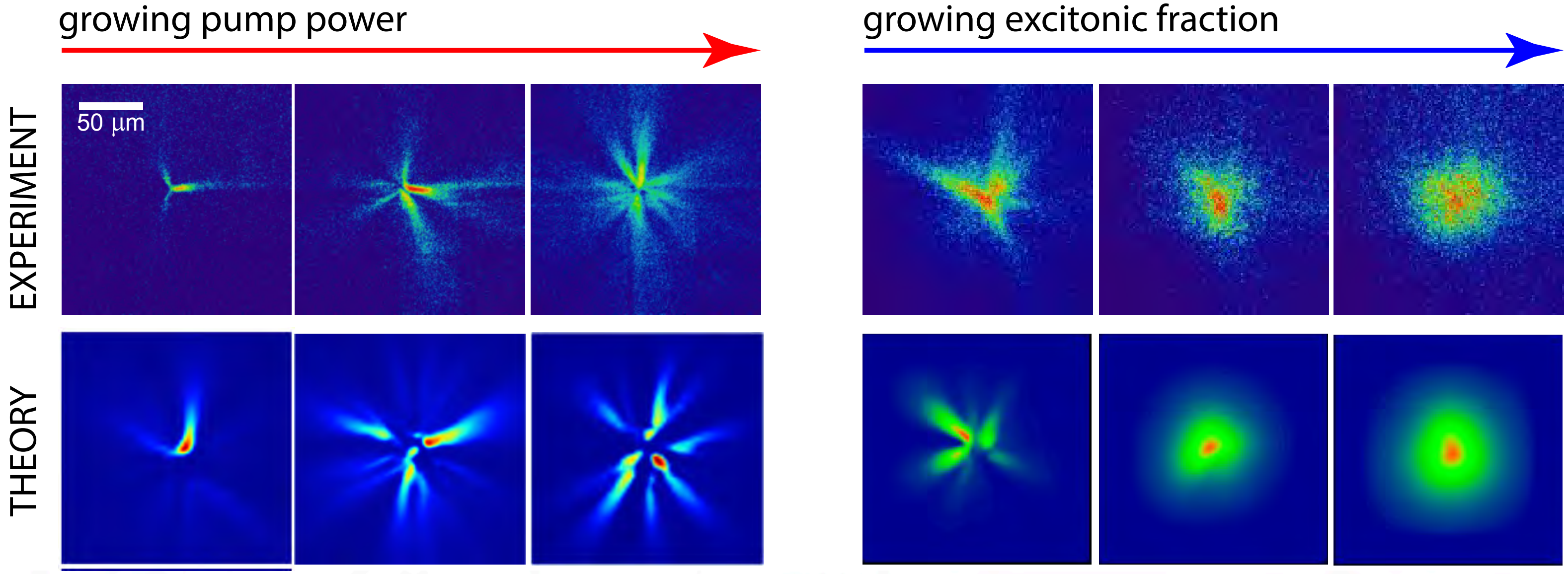
Theory: stochastic classical field model

Essential ingredients: stochastic fluctuations and relaxation of the chemical potential [Wouters & Savona, PRB 79, 165302 (2009)]

$$i\hbar\frac{\partial\psi(\mathbf{r})}{\partial t} = \left[(i\beta-1)\frac{\hbar^2}{2m}\nabla^2 + g_c|\psi|^2 + g_R n_R + i\frac{\hbar}{2}\left(R n_R - \gamma_c\right)\right]\psi(\mathbf{r}) + \frac{dW}{dt}$$

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

$$\langle dW_i^* dW_j\rangle = \frac{\gamma_c + R n_R(\mathbf{r}_i)}{2(\delta x\delta y)^2}\delta_{i,j}dt, \qquad \langle dW_i dW_j\rangle = 0$$



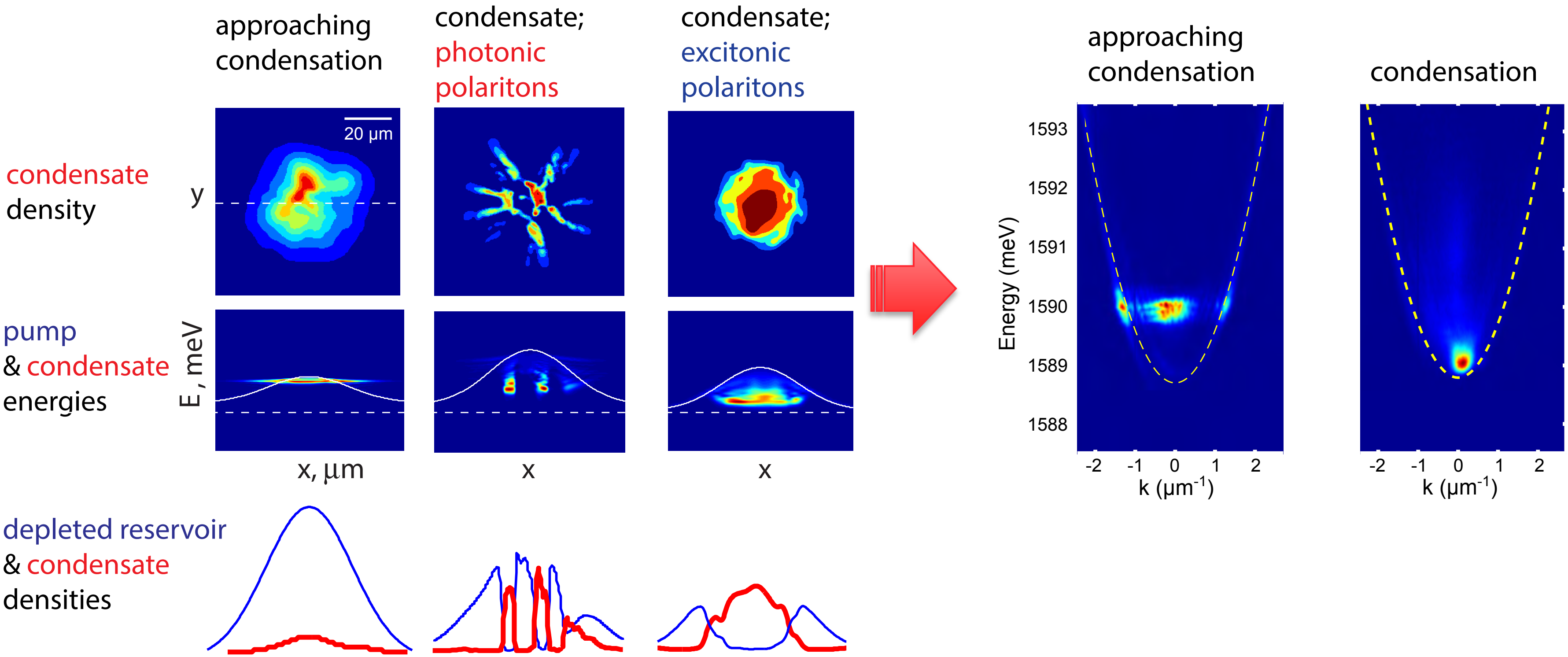
Condensation in the single-shot regime

- Shot-to-shot fluctuations are an inherent feature of spontaneous condensation
- Photon-like polaritons have larger kinetic energy and form filaments
- Exciton-like polaritons are heavy and do not travel far
- No thermal occupation of LP branch
- Energy relaxation and reservoir depletion drives condensation into a ground momentum and energy state
- Energy relaxation (phonon-assisted) is more efficient for exciton-like polaritons

Energy relaxation + reservoir depletion

Transition to condensation in a ground momentum and energy state in a potential induced by the reservoir depletion

$$n_R \sim n_0 e^{-R|\psi|^2}$$



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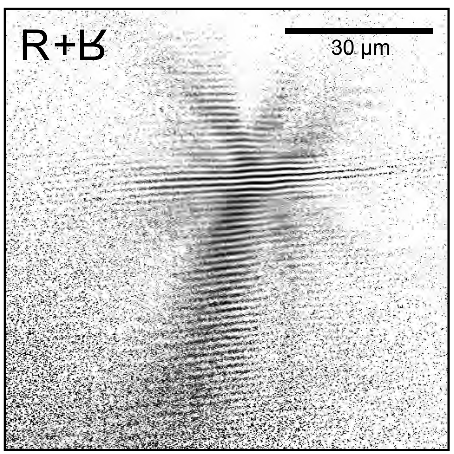
Estrecho et al, arXiv:1705.00469 (2017)

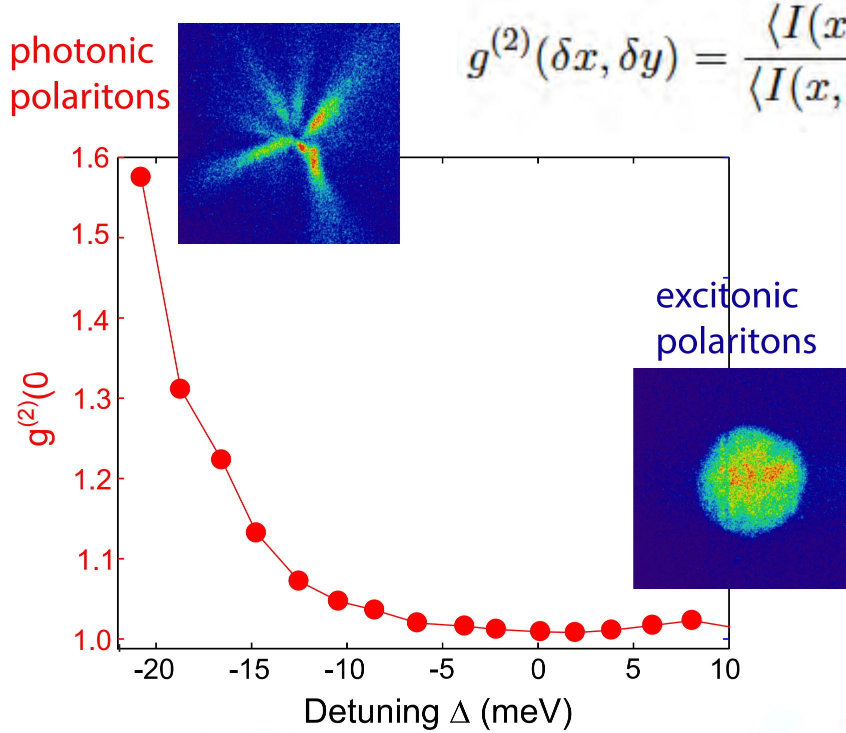
Statistically nontrivial condensate

Condensate of photonic polaritons exhibits long-range order but large density fluctuations: no second-order coherence!
[condensate of photons: Shmitt et al., PRL **116**, 033604 (2016)]

Excitonic polaritons display standard condensation properties

$$g^{(2)}(\delta x, \delta y) = \frac{\langle I(x,y) I(x+\delta x, y+\delta y)\rangle}{\langle I(x,y)\rangle\langle I(x+\delta x, y+\delta y)\rangle}$$





Estrecho et al, arXiv:1705.00469 (2017)

Single-shot imaging: possibilities ahead

- Settling the modulational (dynamical) instability dispute
- Direct evidence of BKT phase – formation of paired phase defects
- Testing Kibble-Zurek scaling laws in an open-dissipative system

Credit where it's due:

Australian National University

- Tingge Gao, Eli Estrecho, Andrew Truscott

RIKEN, Japan

- Michael Fraser, Kostya Bliokh, Franco Nori, Yoshi Yamamoto

Wuerzburg, Germany

- Christian Schneider, Sven Höfling

Pittsburgh, USA

- David Snoke

Southampton, UK

- Guangyao Li, Alexei Kavokin

NTU, Singapore

- Tim Liew

Warsaw, Poland

- Natalia Bobrovska, Michał Matuszewski