Acoplamiento fuerte luz-materia en sistemas fuertemente correlacionados

Strong light-matter coupling in strongly correlated systems

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CAOS Y LOCALIZACIÓN EN SISTEMAS CUÁNTICOS DE MUCHOS CUERPOS

Lunes 23 de enero 2022.

DICKE HAMILTONIAN

$$\hat{H}_D = \omega \hat{a}^\dagger \hat{a} + \omega_0 \hat{J}_z + \frac{2\gamma}{\sqrt{\mathcal{N}}} \left(\hat{a}^\dagger + \hat{a} \right) \hat{J}_x .$$

$$\hat{J}_\mu = \frac{1}{2} \sum_{i=1}^{\mathcal{N}} \hat{\sigma}_\mu .$$

$$\mu = x, y, z.$$

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Qubit energy splitting

Atom number

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The **Jaynes-Cummings** model is the Rabi model under the **RWA**.
The **Tavis-Cummings** model is the Dicke under the **RWA**.

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Rotating terms

Counter-rotating terms

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$$\hat{H}_{TC} = \omega \hat{a}^\dagger \hat{a} + \omega_0 \hat{J}_z + \frac{\gamma}{\sqrt{\mathcal{N}}} \left(\hat{a}\hat{J}_+ + \hat{a}^\dagger \hat{J}_- \right) .$$

The TC Hamiltonian commutes with the total number of excitations, hence it is **integrable**.

M. Tavis and, F. W. Cummings, PR 170 (2), 379 (1968).

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POLARITONS

$$\hat{H} = \sum_{\mathbf{k}\sigma} \varepsilon^x_{\mathbf{k}} \hat{x}^\dagger_{\mathbf{k}\sigma} \hat{x}_{\mathbf{k}\sigma} + \sum_{\mathbf{k}\sigma} \varepsilon^c_{\mathbf{k}} \hat{c}^\dagger_{\mathbf{k}\sigma} \hat{c}_{\mathbf{k}\sigma} + \Omega \sum_{\mathbf{k}\sigma} \left(\hat{x}^\dagger_{\mathbf{k}\sigma} \hat{c}_{\mathbf{k}\sigma} + \hat{c}^\dagger_{\mathbf{k}\sigma} \hat{x}_{\mathbf{k}\sigma} \right).$$

Matter excitation **Confined photon** **Strong coupling (TC like interaction)**

A. V. Kavokin, et al., Microcavities, Series on Semiconductor Science and Technology (Oxford University Press, 2017).

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Lower polariton

$$\hat{L}_{\mathbf{k},\sigma} = \mathcal{C}_{\mathbf{k}} \hat{x}_{\mathbf{k},\sigma} + \mathcal{S}_{\mathbf{k}} \hat{c}_{\mathbf{k},\sigma}$$

Upper polariton

$$\hat{U}_{\mathbf{k},\sigma} = -\mathcal{S}_{\mathbf{k}} \hat{x}_{\mathbf{k},\sigma} + \mathcal{C}_{\mathbf{k}} \hat{c}_{\mathbf{k},\sigma}$$

Hopfield coefficients

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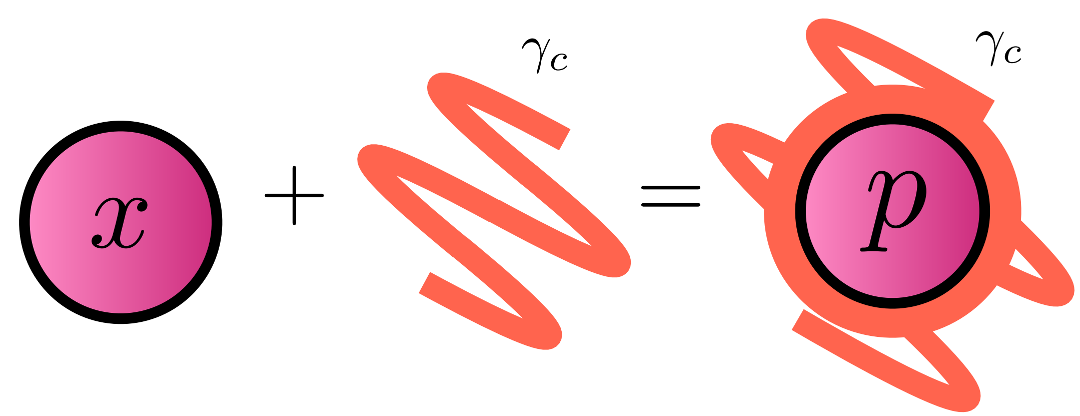

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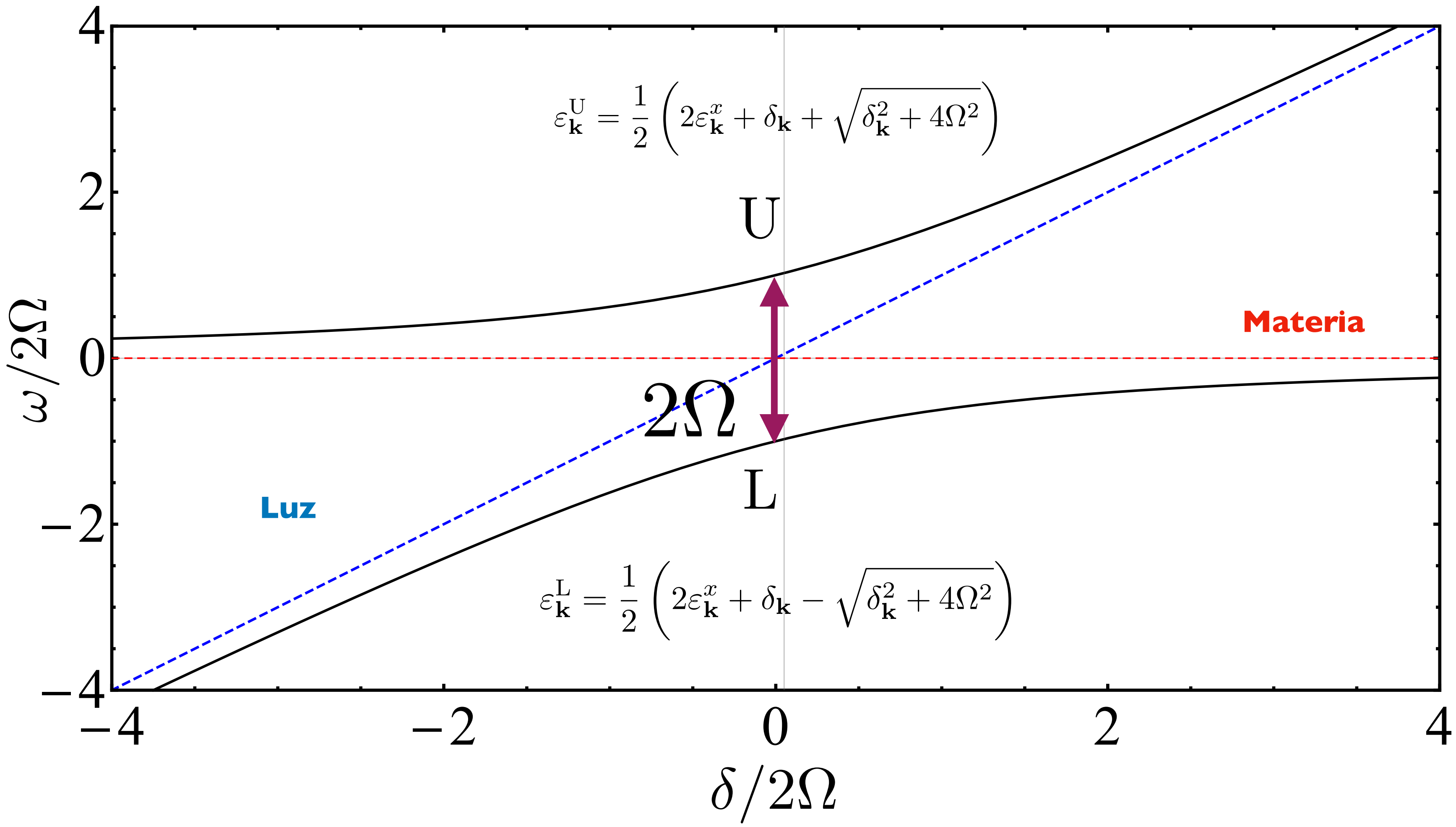

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Light-matter detuning

$$\delta_{\mathbf{k}} = \varepsilon^{x}_{\mathbf{k}} - \varepsilon^{c}_{\mathbf{k}}$$

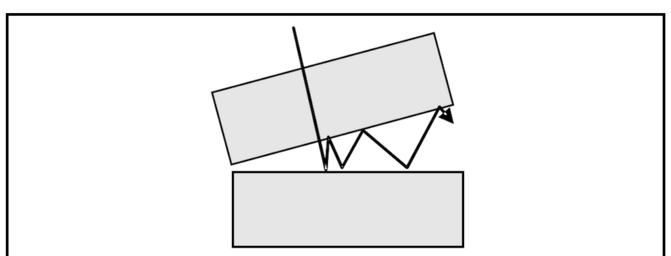
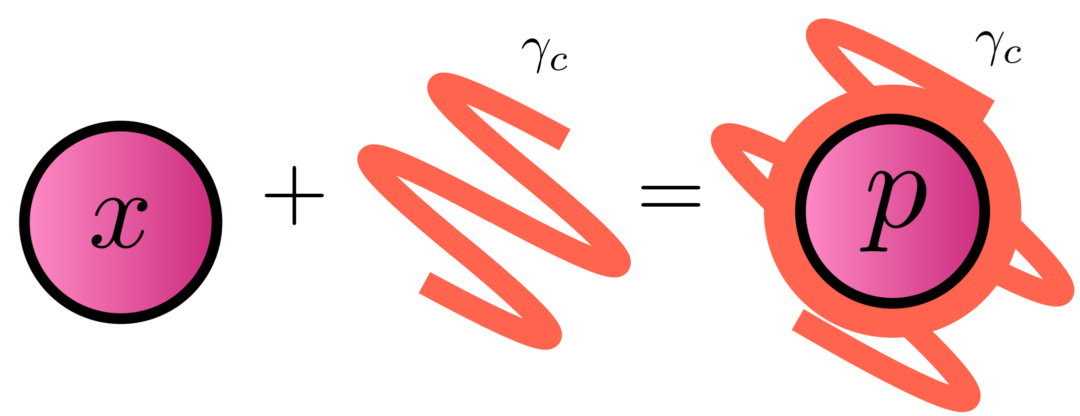


Fig. 1.4: Wedged microcavity, showing walk-off of incident light in multiple reflections.



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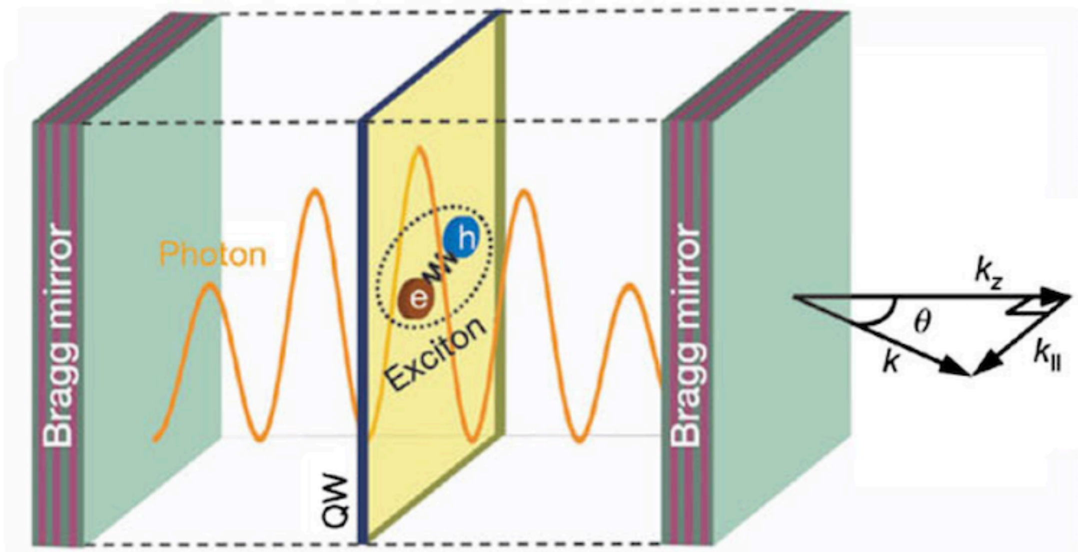
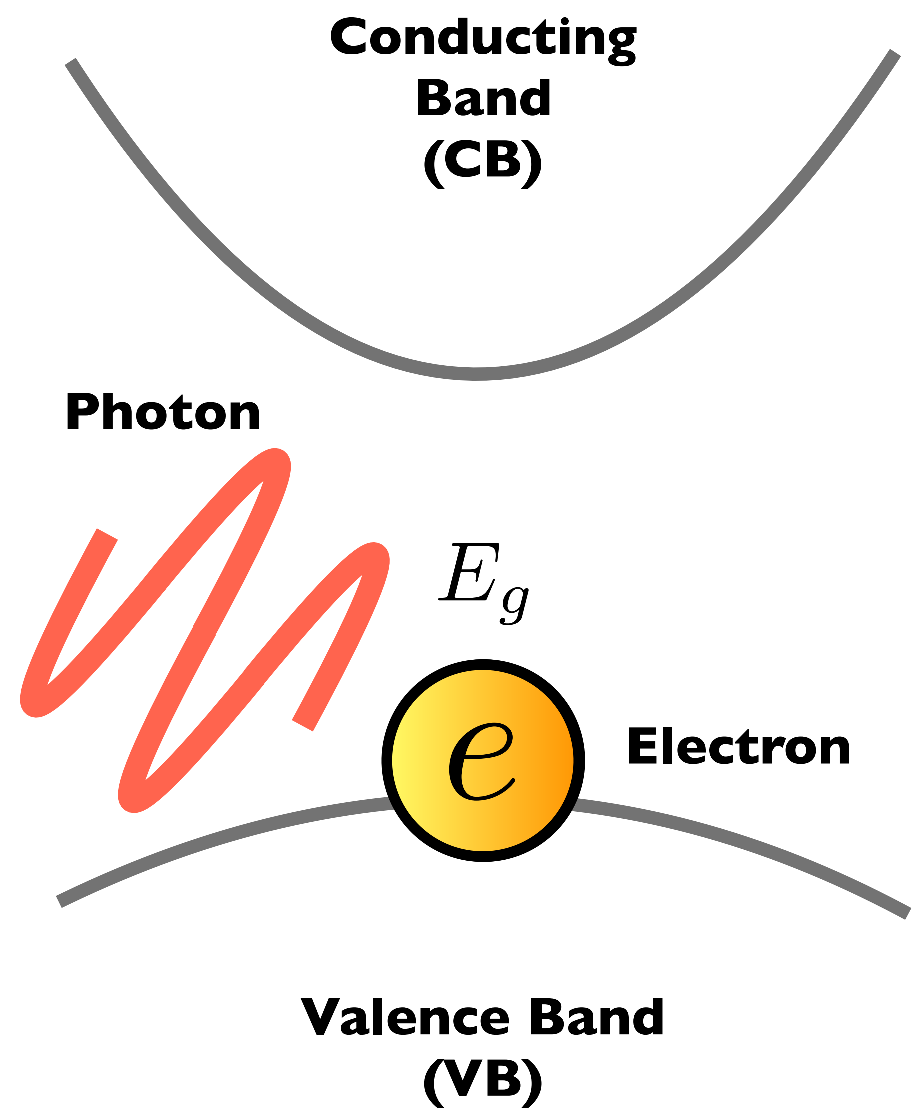
MICROCAVITY SEMICONDUCTORS

Bidimensional materials within a microcavity have become in a new route for the study of fundamental properties of light-matter interaction, as well as a novel platform to explore properties of quantum gases.

GaAs Quantum Well or TMDs





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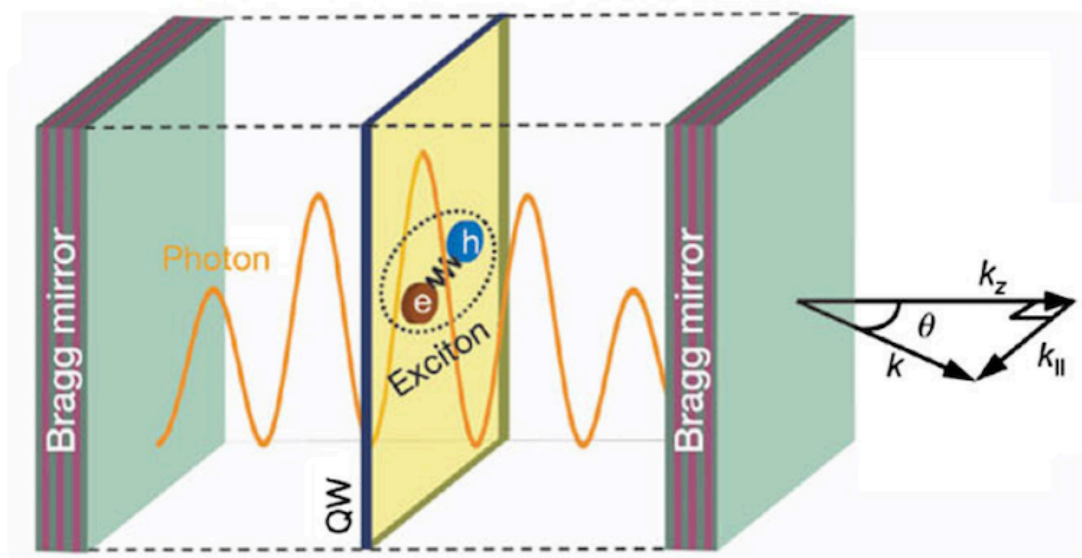

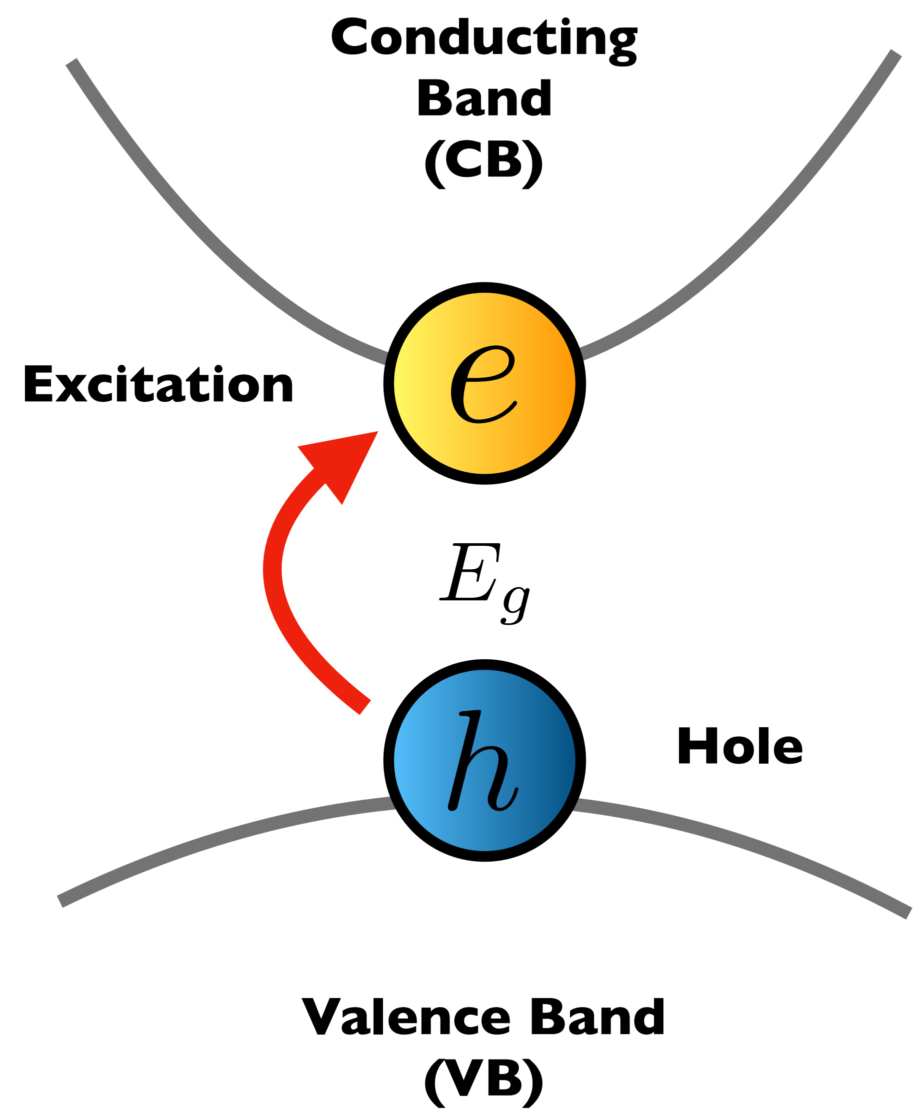

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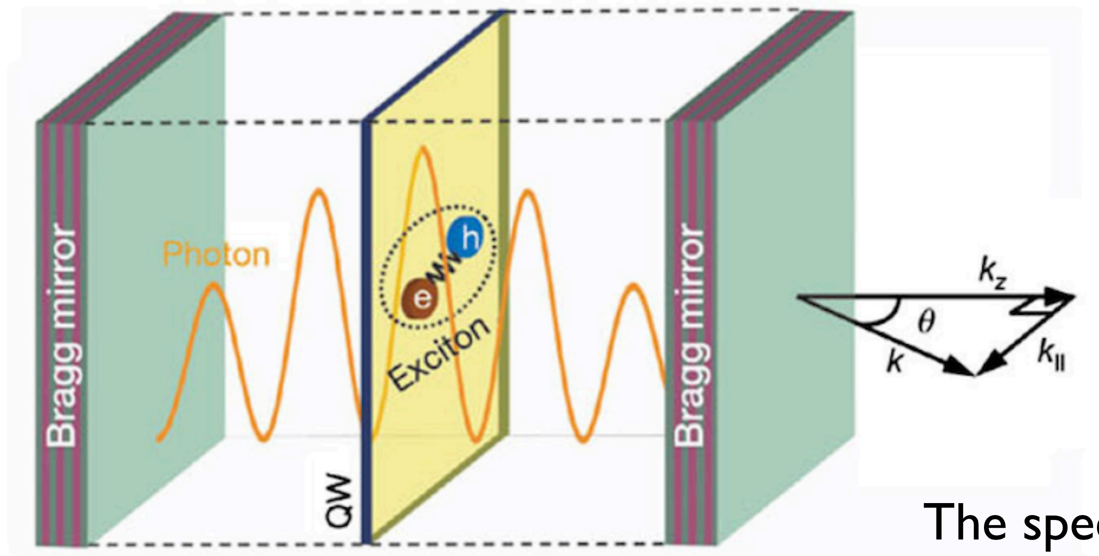
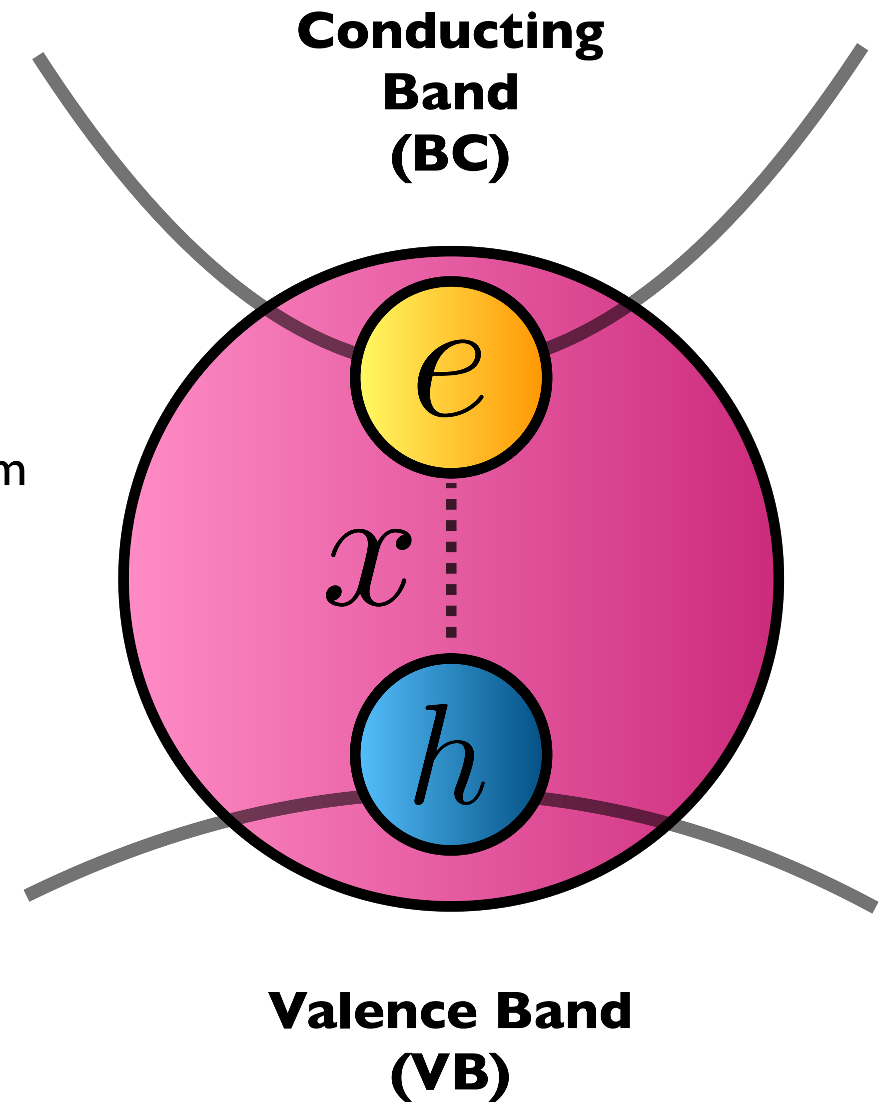


The spectrum is similar to that of an hydrogen atom.



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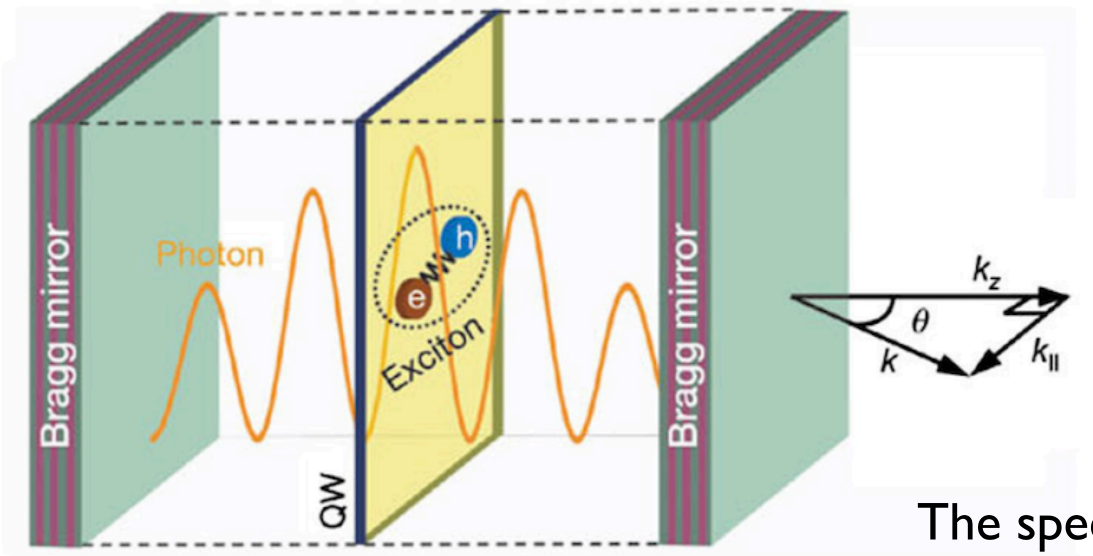

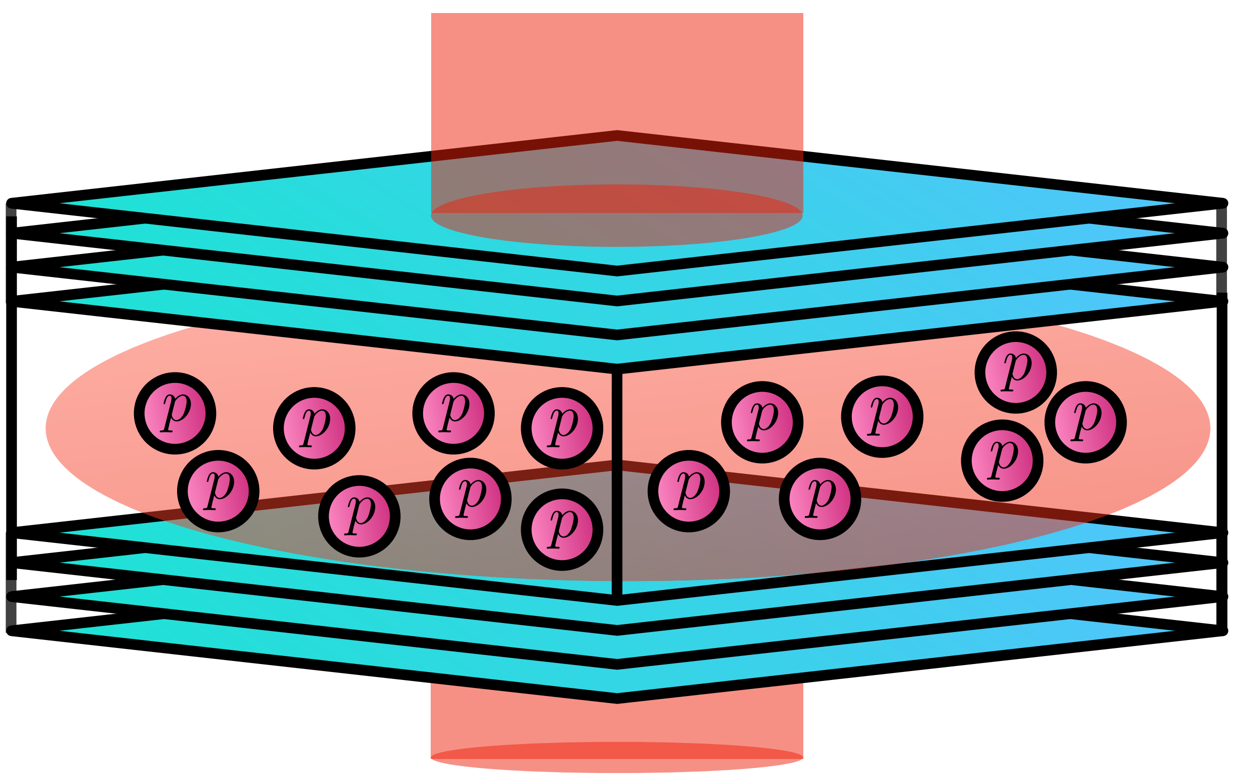

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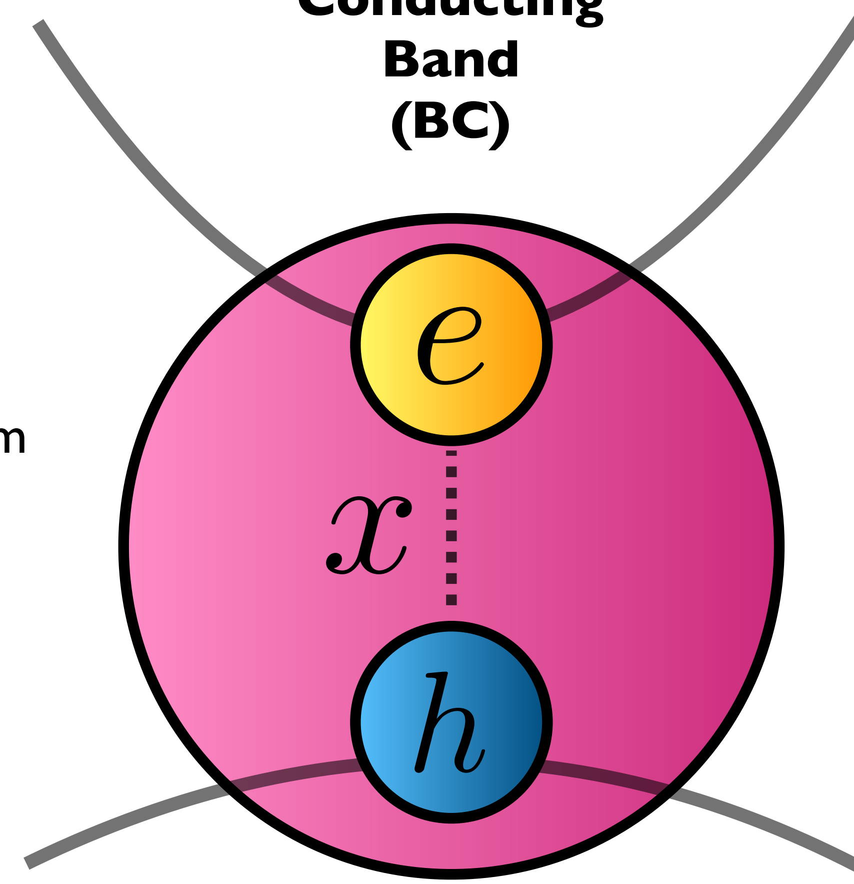
Conducting Band (BC)



Valence Band (VB)

Employing the pump it is possible to create a finite density of excitons that become a quantum gas.

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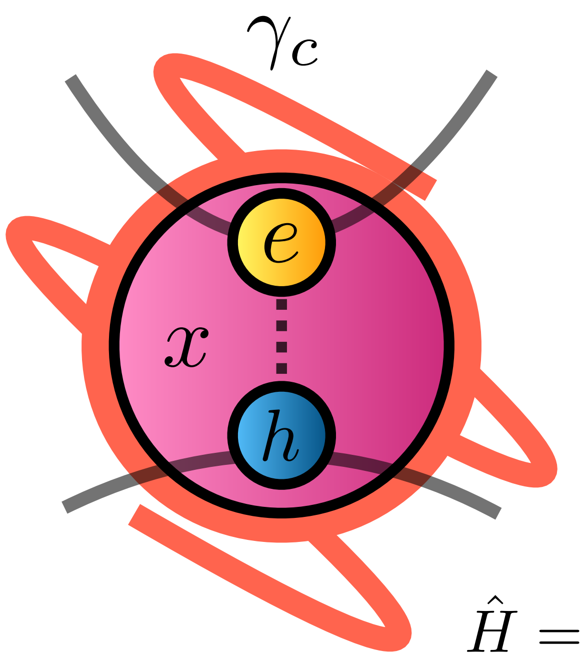
EXCITON-POLARITONS



Microcavity polaritons possess two main features:

- They are good **bosons** within an extended domain of temperature and density thanks to their small masses (of photonic origin).
- Thanks to the **interactions** between them, they can form quantum gases and exhibit condensation, superfluidity and superconductivity.

$$\hat{H} = \sum_{\mathbf{k}} \varepsilon^{x}_{\mathbf{k}} \hat{x}^{\dagger}_{\mathbf{k}} \hat{x}_{\mathbf{k}} + \sum_{\mathbf{k}} \varepsilon^{c}_{\mathbf{k}} \hat{c}^{\dagger}_{\mathbf{k}} \hat{c}_{\mathbf{k}} + \Omega \sum_{\mathbf{k}} \left(\hat{x}^{\dagger}_{\mathbf{k}} \hat{c}_{\mathbf{k}} + \hat{c}^{\dagger}_{\mathbf{k}} \hat{x}_{\mathbf{k}} \right) + \frac{g_{xx}}{2} \sum_{\mathbf{k}\mathbf{k}'\mathbf{q}} \hat{x}^{\dagger}_{\mathbf{k}+\mathbf{q}} \hat{x}^{\dagger}_{\mathbf{k}'-\mathbf{q}} \hat{x}_{\mathbf{k}'} \hat{x}^{\dagger}_{\mathbf{k}}$$

Contact interaction

J. Carusotto and C. Ciuti, Rev. Mod. Phys. 85, 299 (2013).

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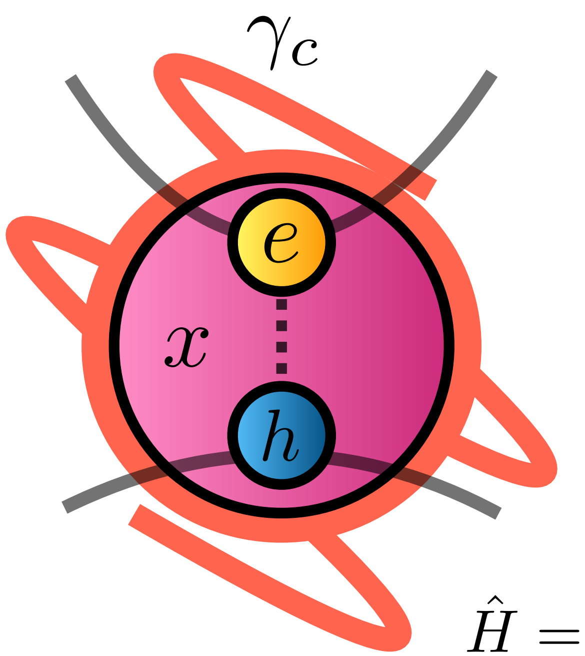

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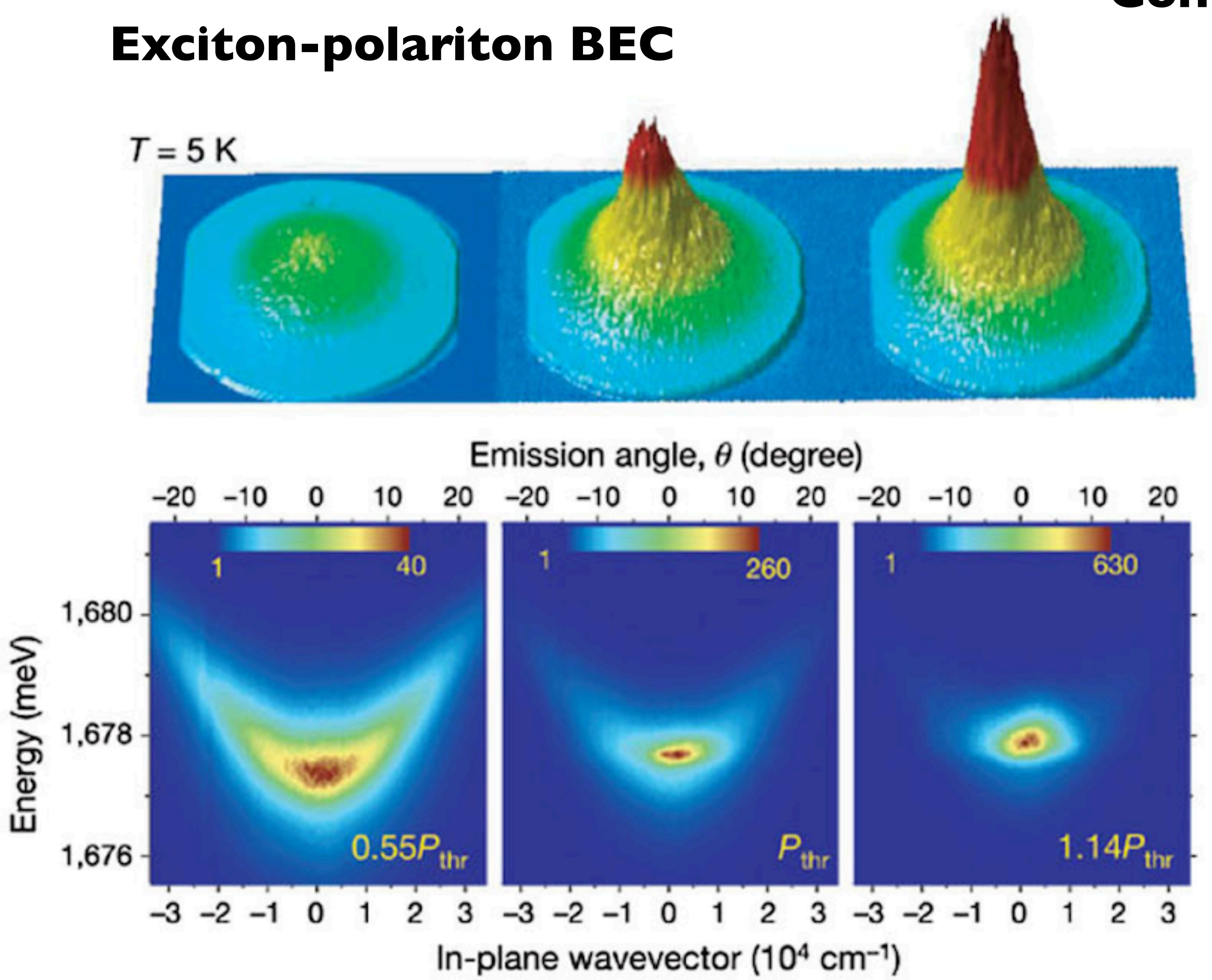
Exciton-polariton BEC



Quantum gases made of exciton-polaritons have a correspondencia with those from atomic physics in the field of ultra-cold atoms in optical lattices. However, they constitute a highly **out-of-equilibrium and strongly** interacting effect resulting from the balance of optical excitations and losses.

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CORRESPONDENCE

Quantum fluids in atomic physics ⟷ **Quantum fluids in solid state physics**

Can we employ what we know in atomic physics to study solid state systems and viceversa?

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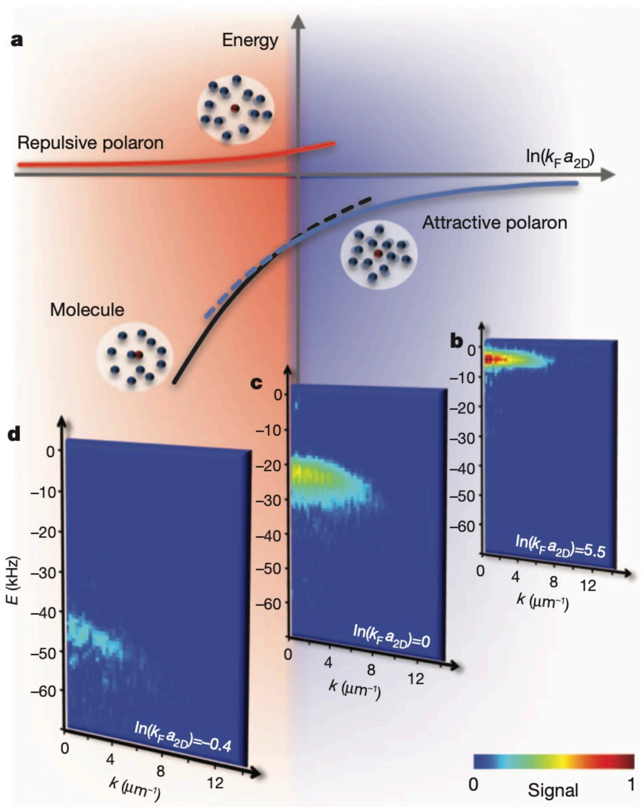

M. Koschorreck, et al., Nature 485, 619 (2012).

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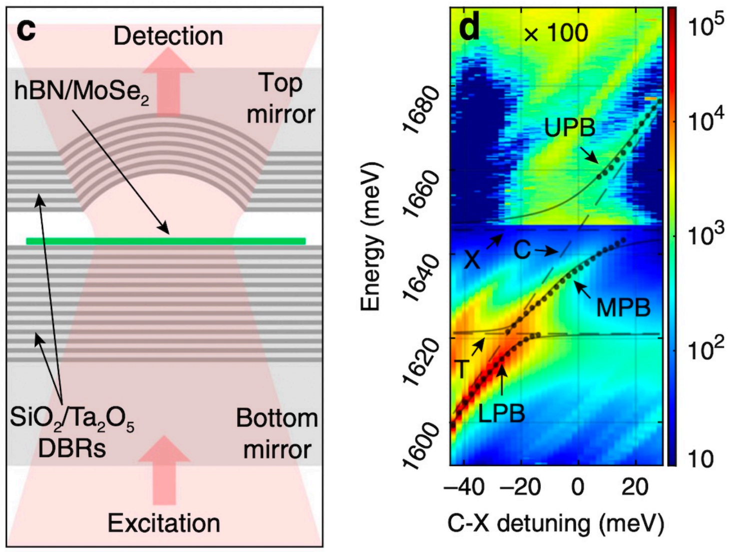

R. P. A. Emmanuele, et al., Nat. Comm. 11, 3589 (2020).

Cold atoms

* Systems that attain equilibrium.
* The two-body interaction can be changed easily by means of changing the scattering length.
* The quasiparticle limits are well-defined.

Microcavity semiconductors

* Out-of-equilibrium systems that can be approximated as stationary.
* The two-body interaction cannot be changed easily (the resonances are given by the binding energy of the semiconductor).
* It is easy to change the light and matter content easily (via the detuning).

EXCITON-POLARITON CONDENSATION

Out-of-equilibrium effects produce a tunable BEC with unique properties.

Polariton Gross-Pitaevskii equation

$$i\hbar\partial_t\Psi_{\mathrm{LP}} = \left[-\frac{\hbar^2}{2m_{\mathrm{LP}}}\nabla^2 + V_{ext}(\vec{r}) + \varepsilon_{\mathrm{LP0}} - i\gamma\right]\Psi_{\mathrm{LP}} + g_{\mathrm{LP}}|\Psi_{\mathrm{LP}}|^2\Psi_{\mathrm{LP}} = iE^{pu}$$

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The interactions depend on the Hopfield coefficients.

$$g_{\rm LP} = g_{xx}\mathcal{C}_{\rm LP\mathbf{k}=0}$$

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$$\Psi_{LP}(\mathbf{r},t) = \Psi^0_{LP}e^{i\mathbf{k}_{pu}\cdot\mathbf{r}}e^{-i\omega_{pu}t}$$

Assuming an stationary solution

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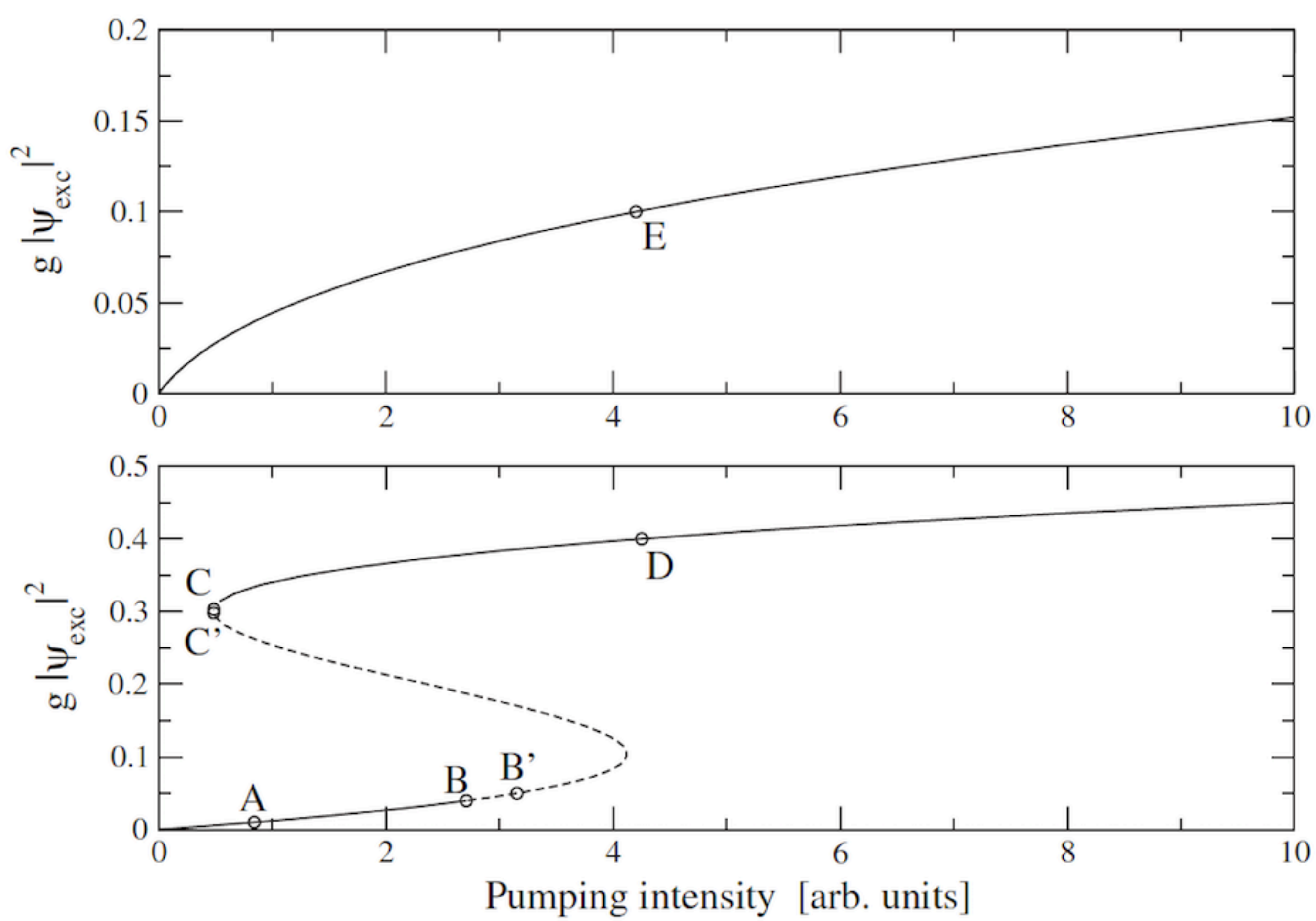
We arrive to the equation of state for the BEC density.

$$n_0 = |\Psi^0_{\mathrm{LP}}|^2$$



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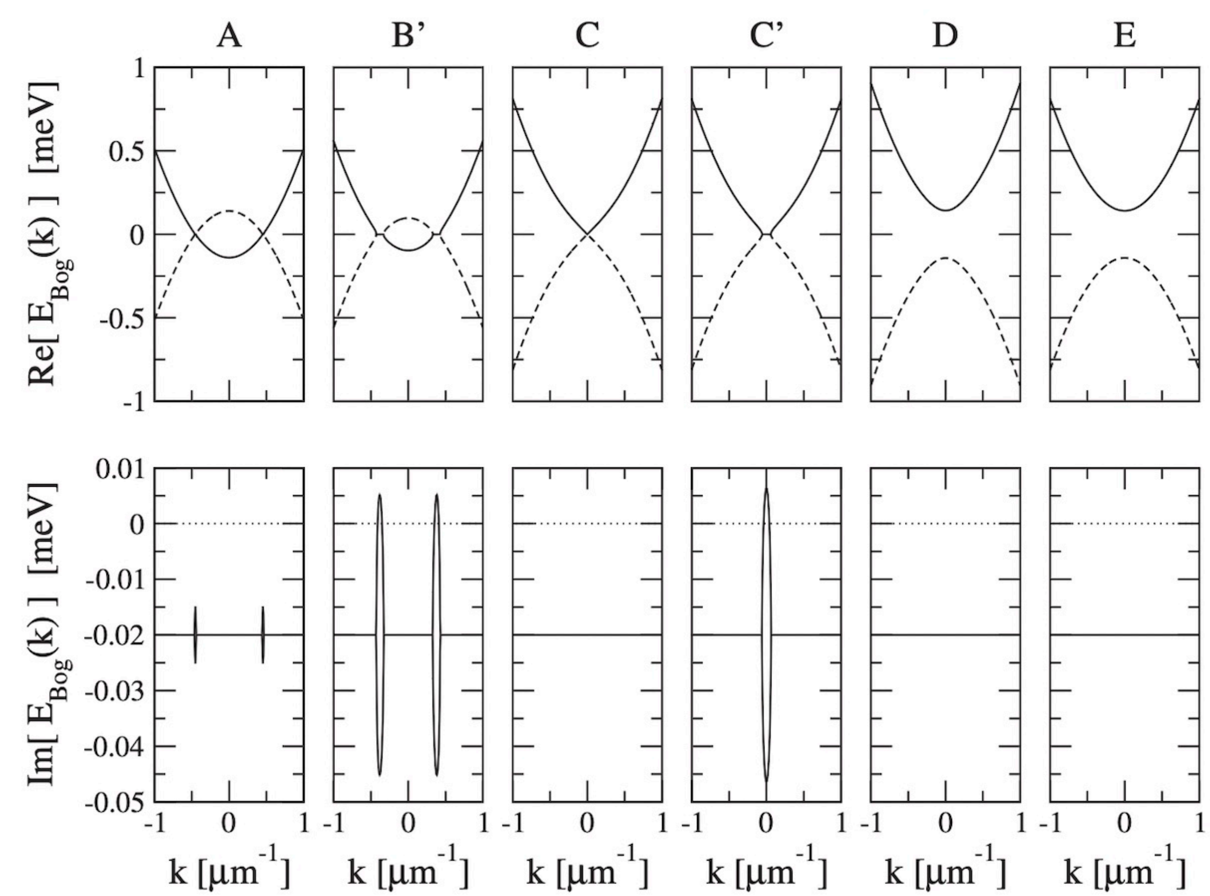

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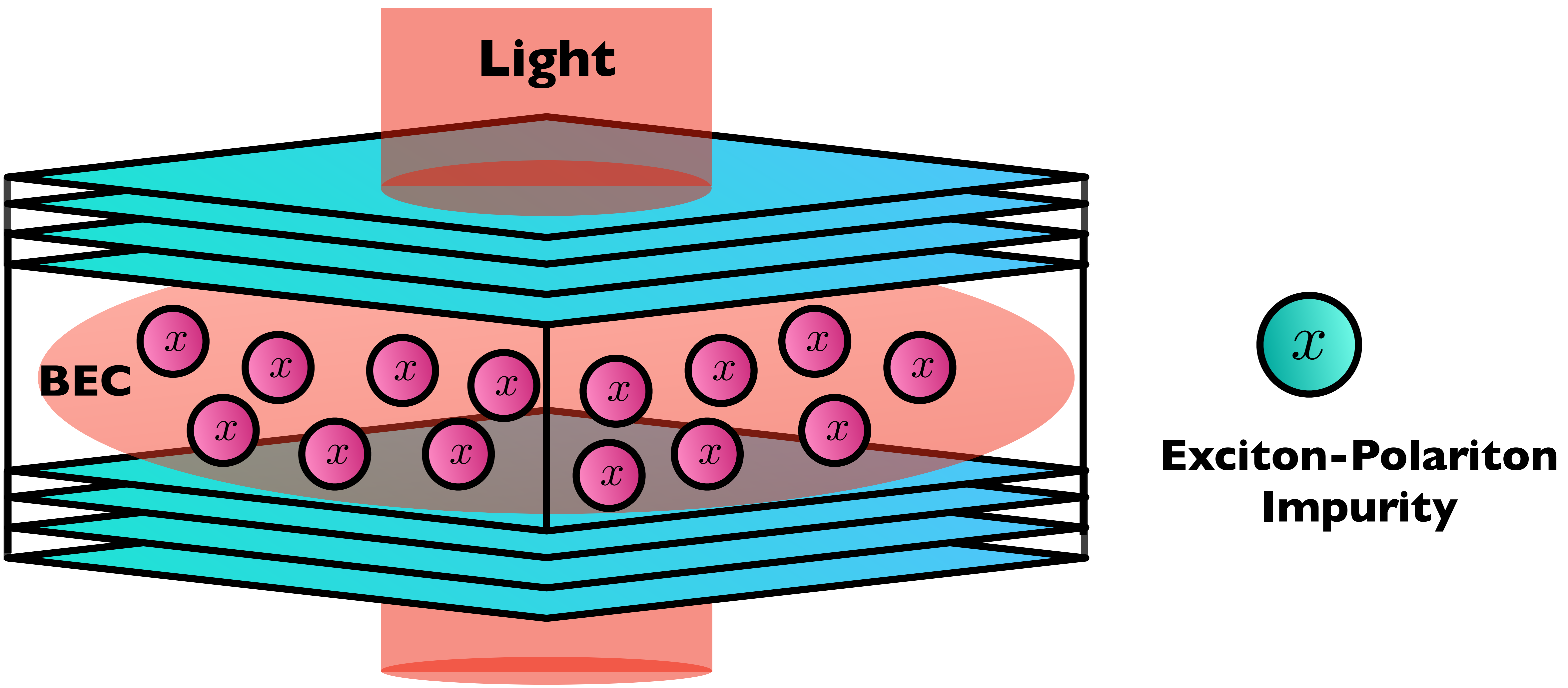
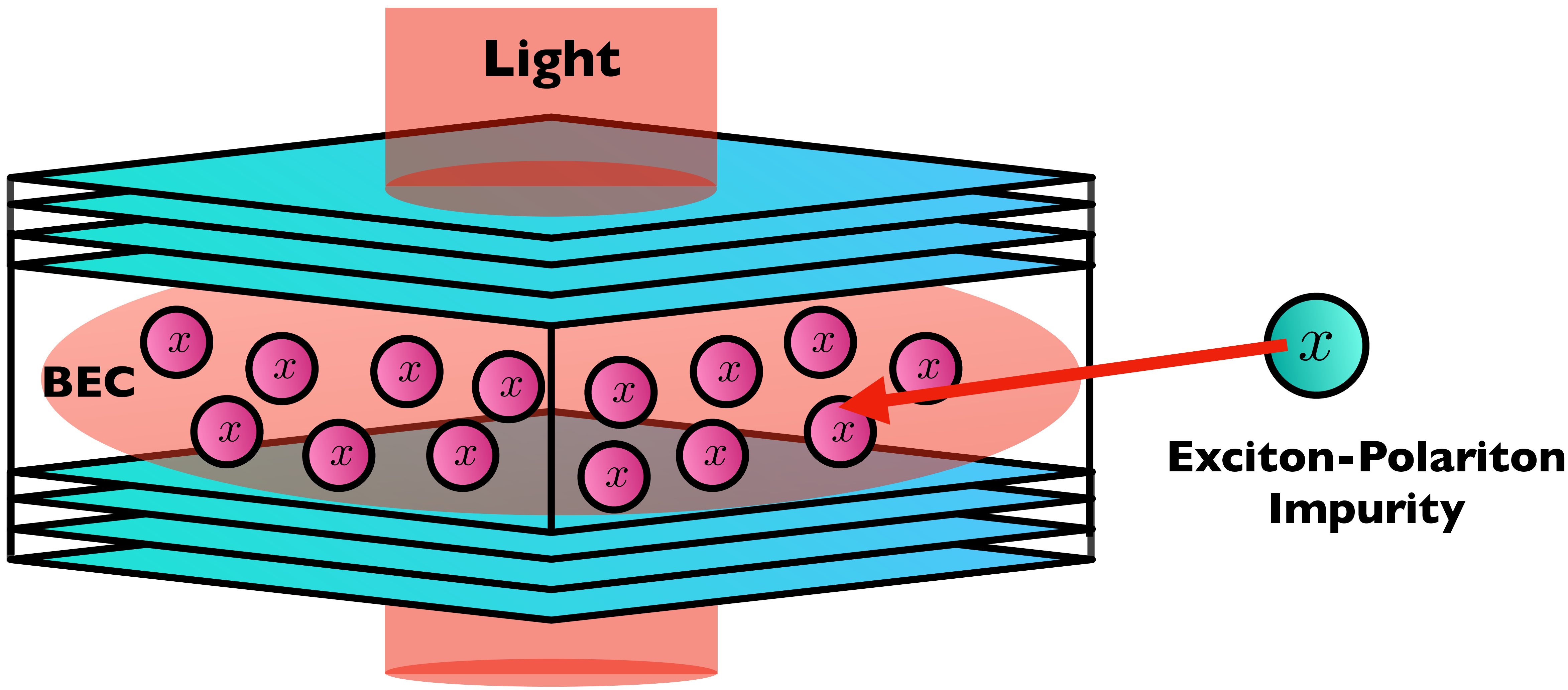
EXCITON-POLARITON INTERACTING WITH A MEDIUM



EXCITON-POLARITON INTERACTING WITH A MEDIUM



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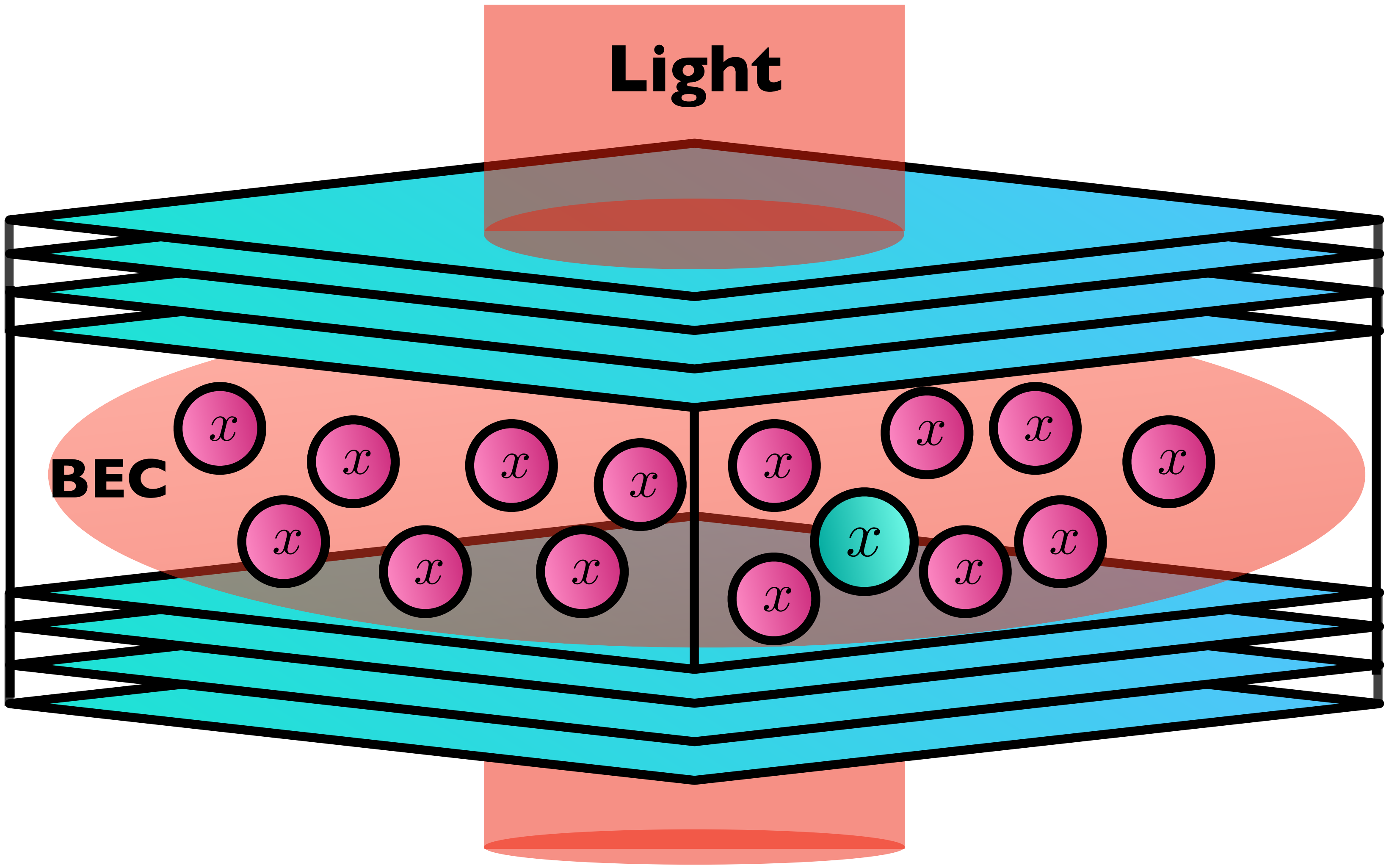
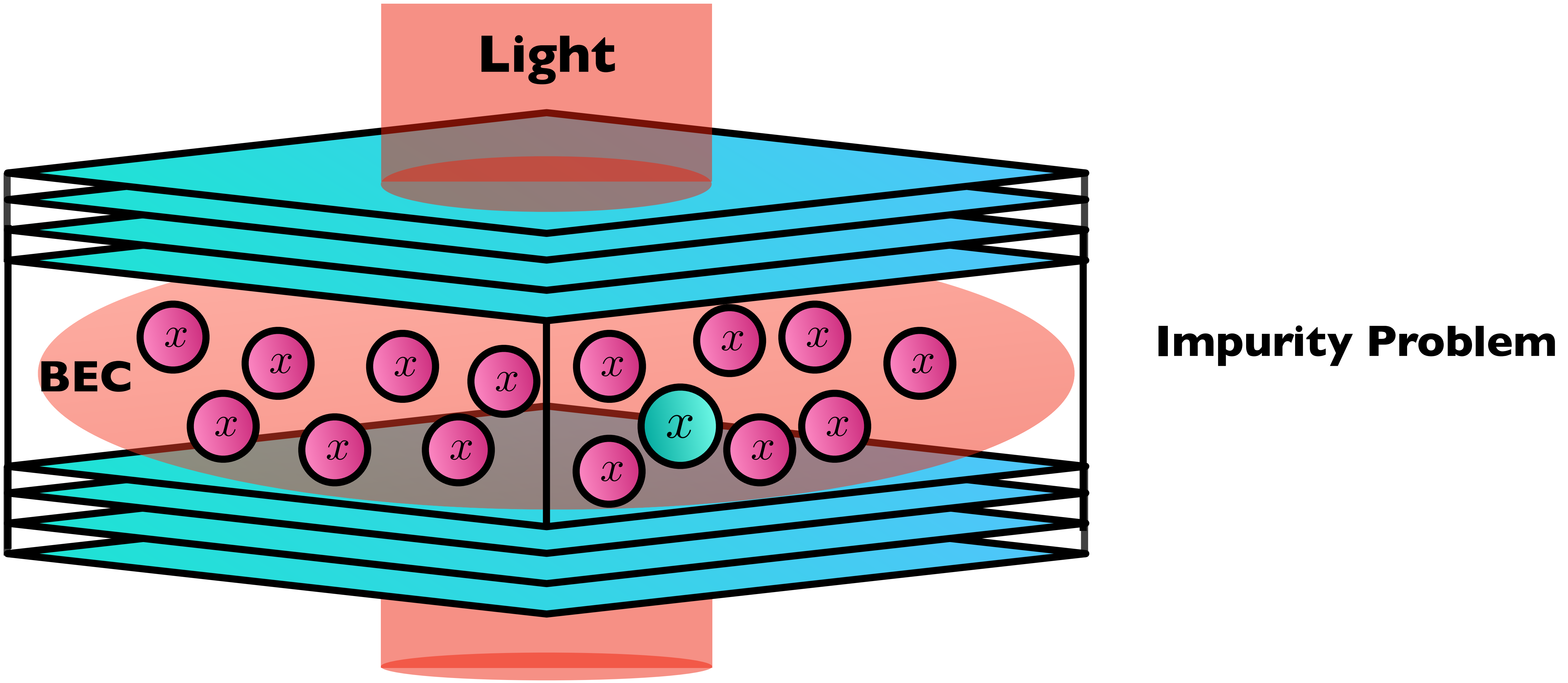


EXCITON-POLARITON INTERACTING WITH A MEDIUM



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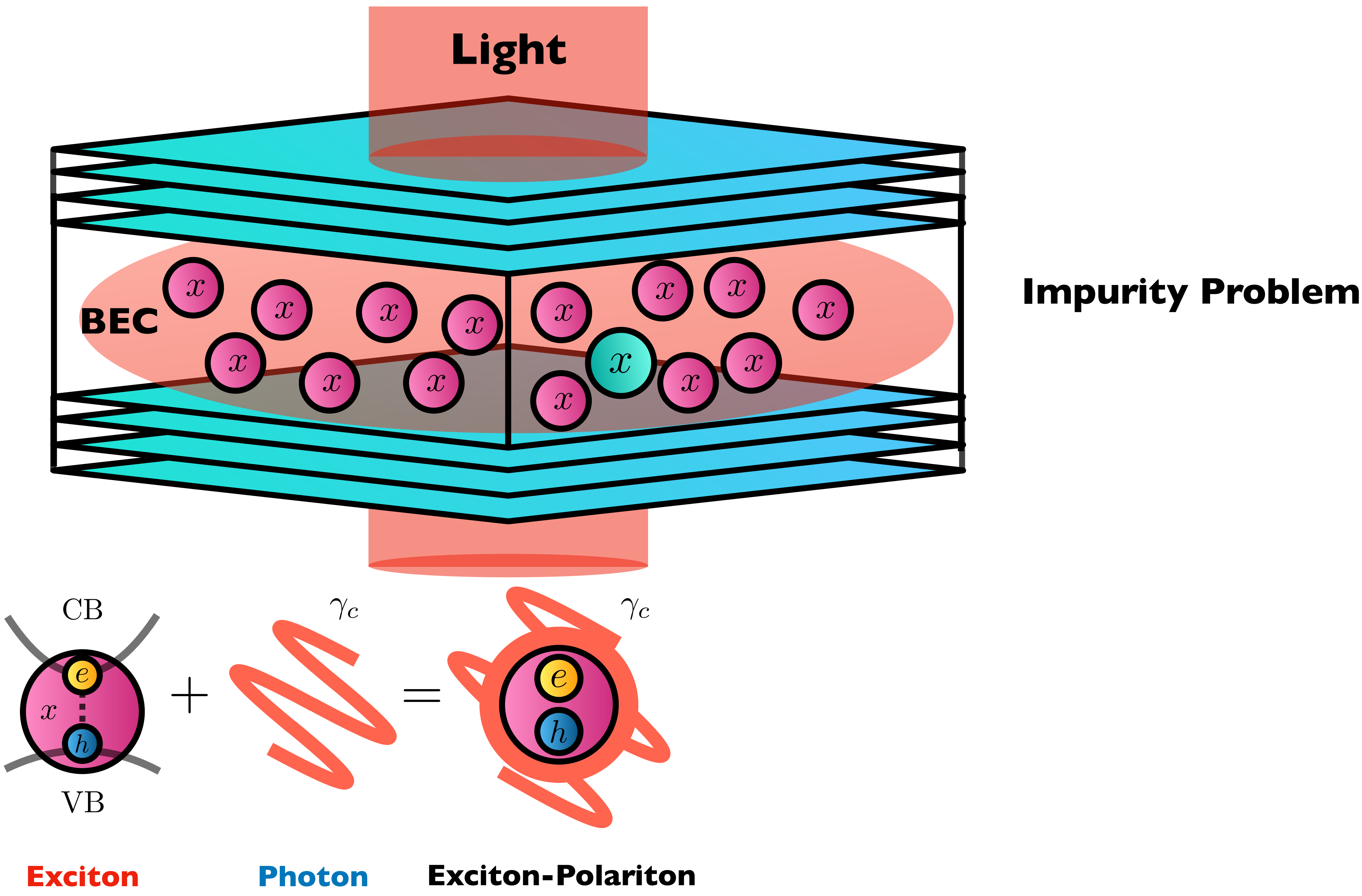

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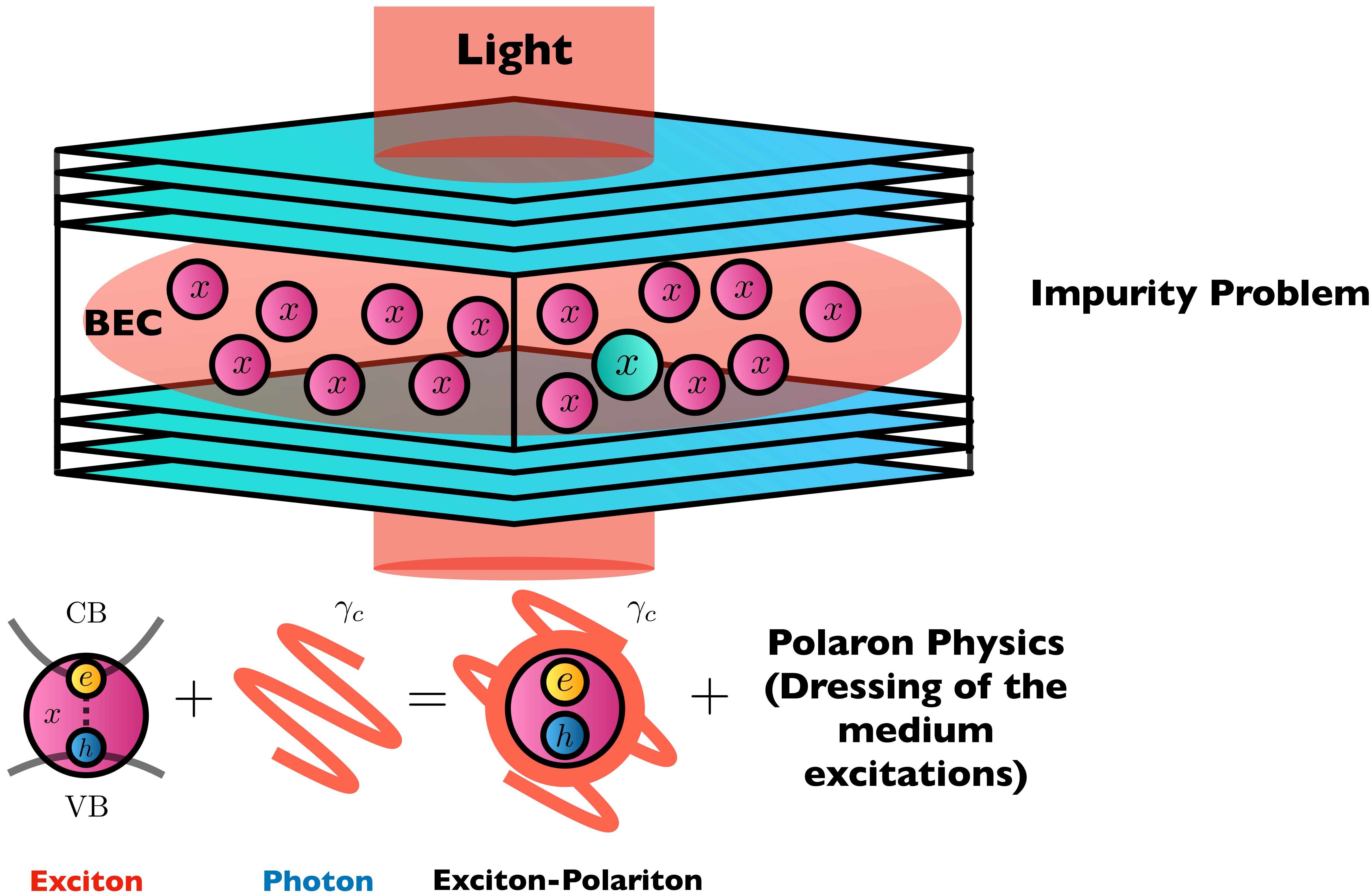
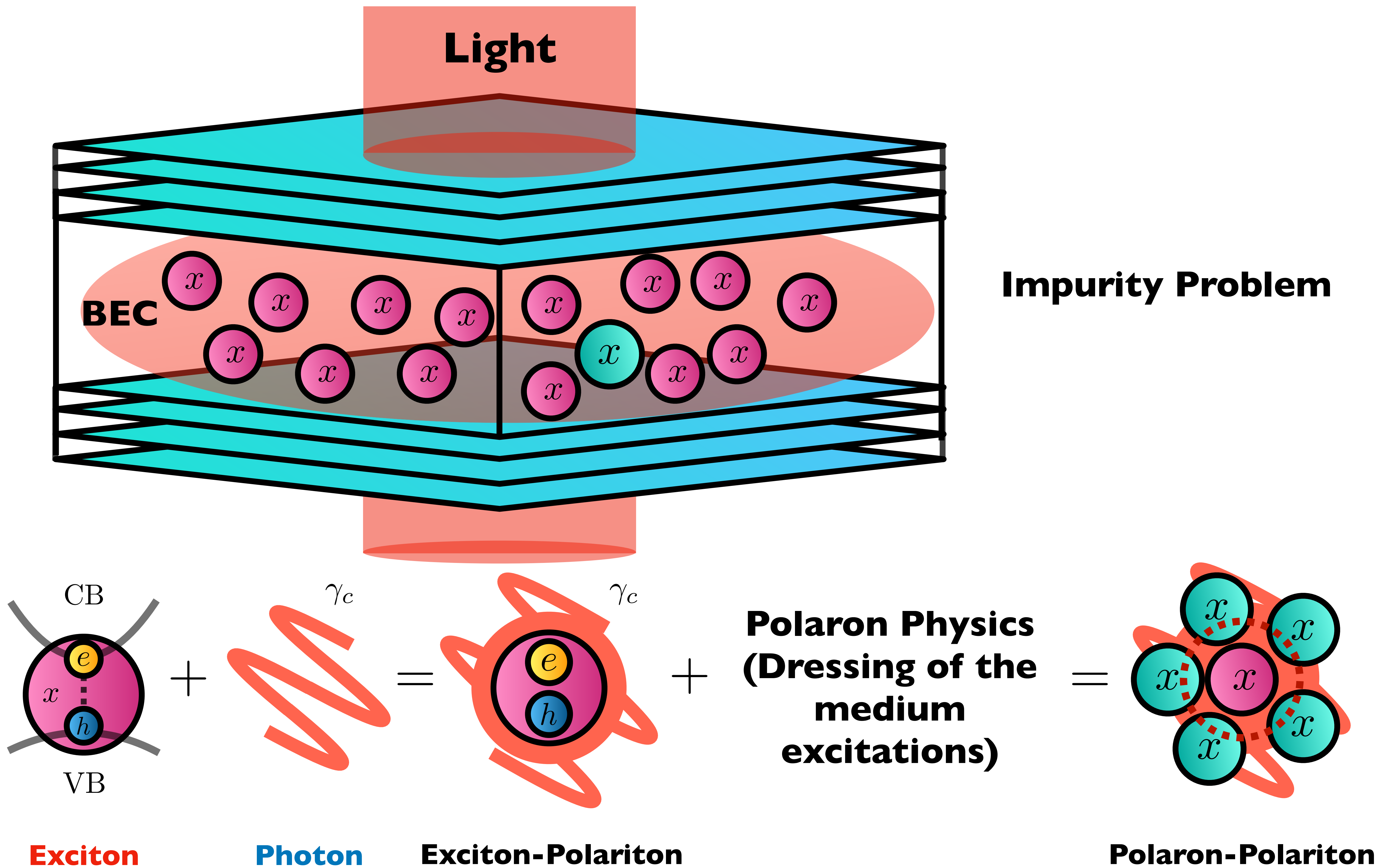
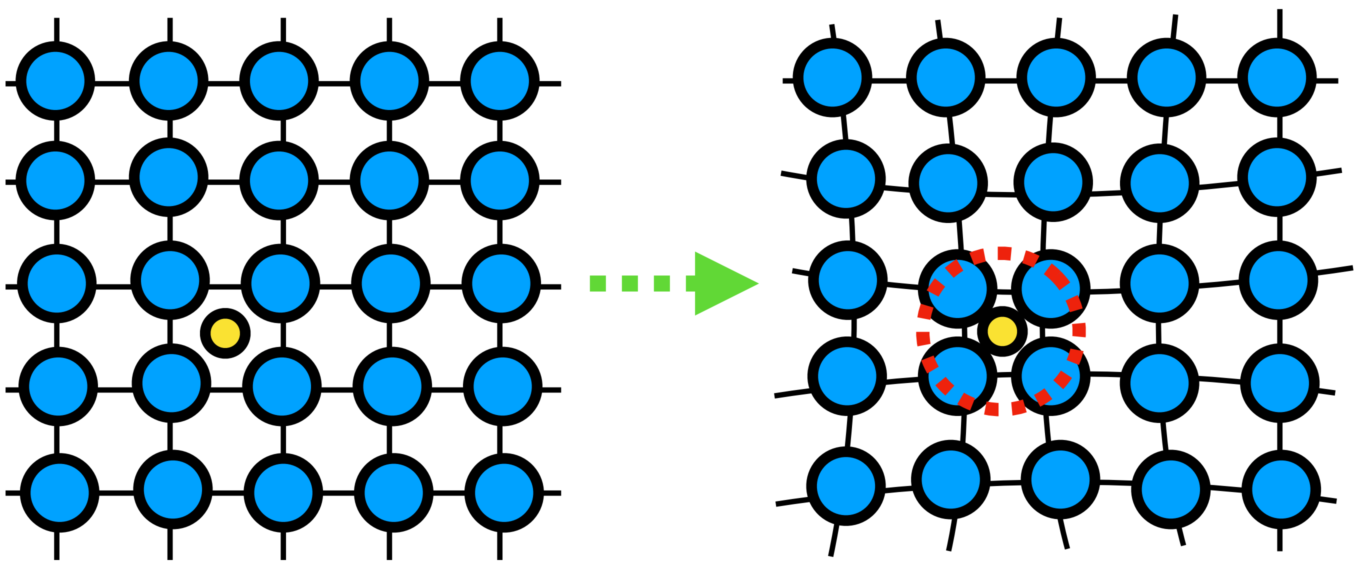


EXCITON-POLARITON INTERACTING WITH A MEDIUM

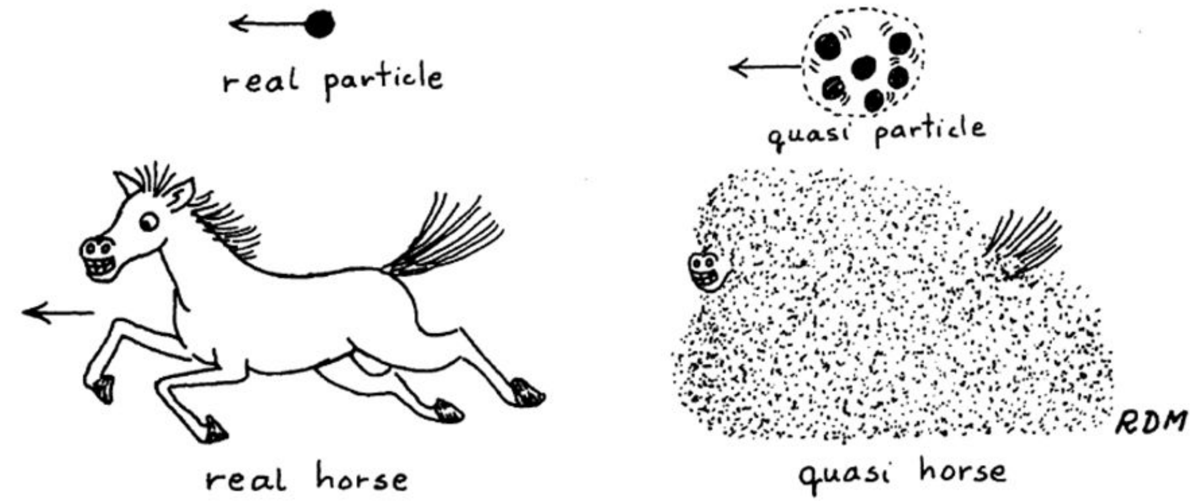


POLARONS

The polaron is a quasiparticle. When an electron moves in a crystal produces a deformation in the crystalline network when it interacts with nearby atoms.



L. D. Landau, Phys. Z. Sowjetunion 3, 644 (1933).



R. D. Mattuck, A Guide to Feynman Diagrams in the Many-Body Problem (Dover, New York, 1992)

POLARONS

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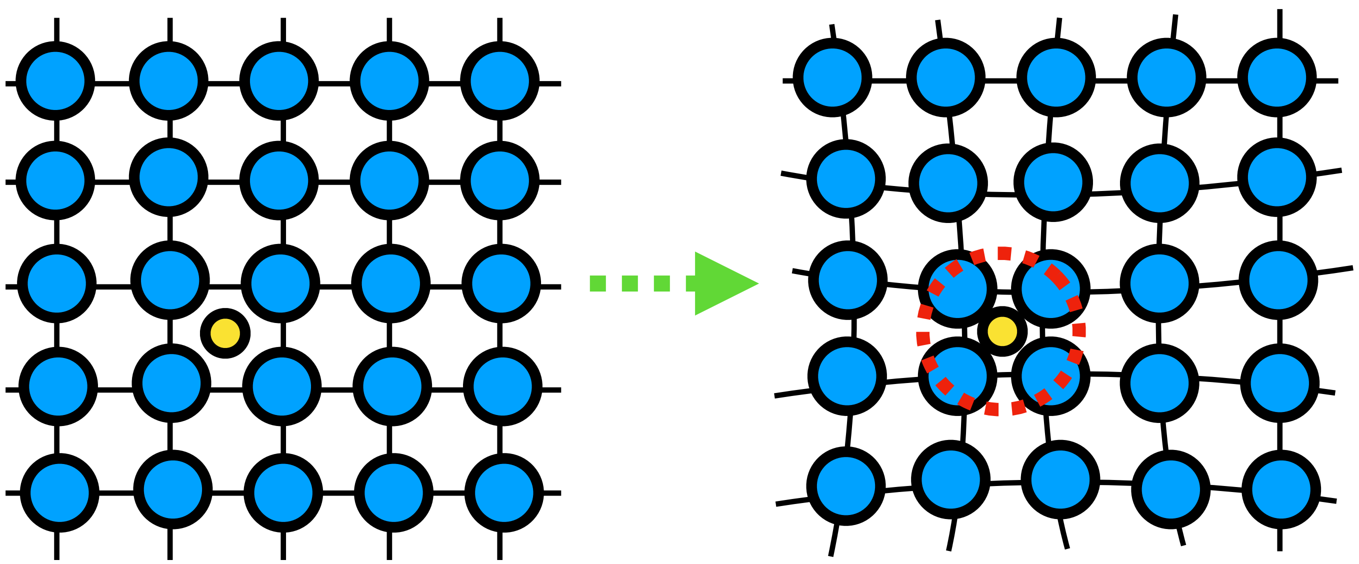

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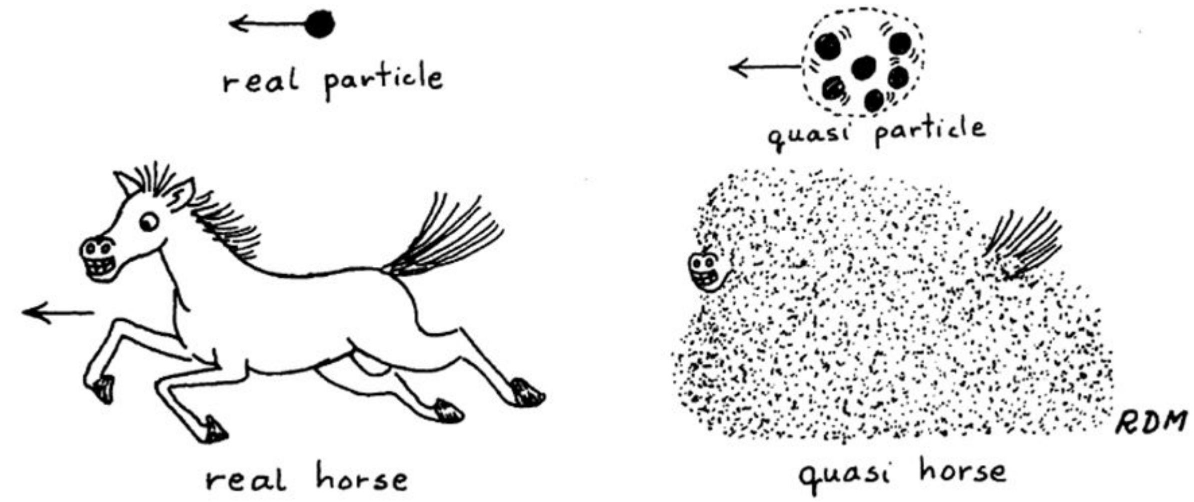
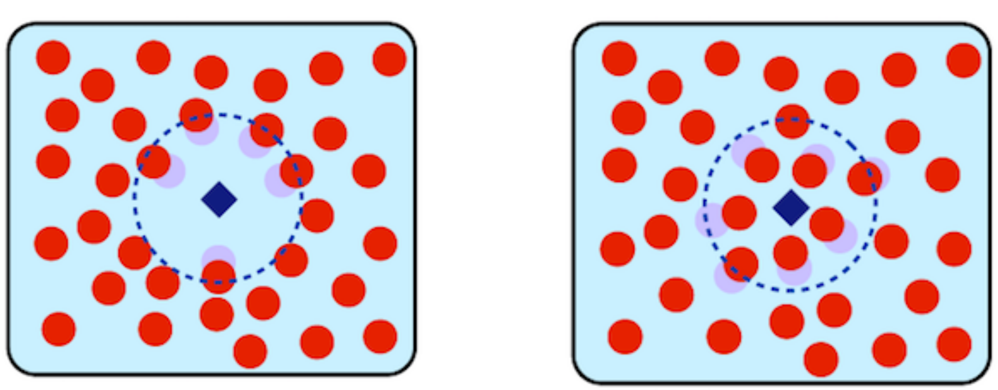


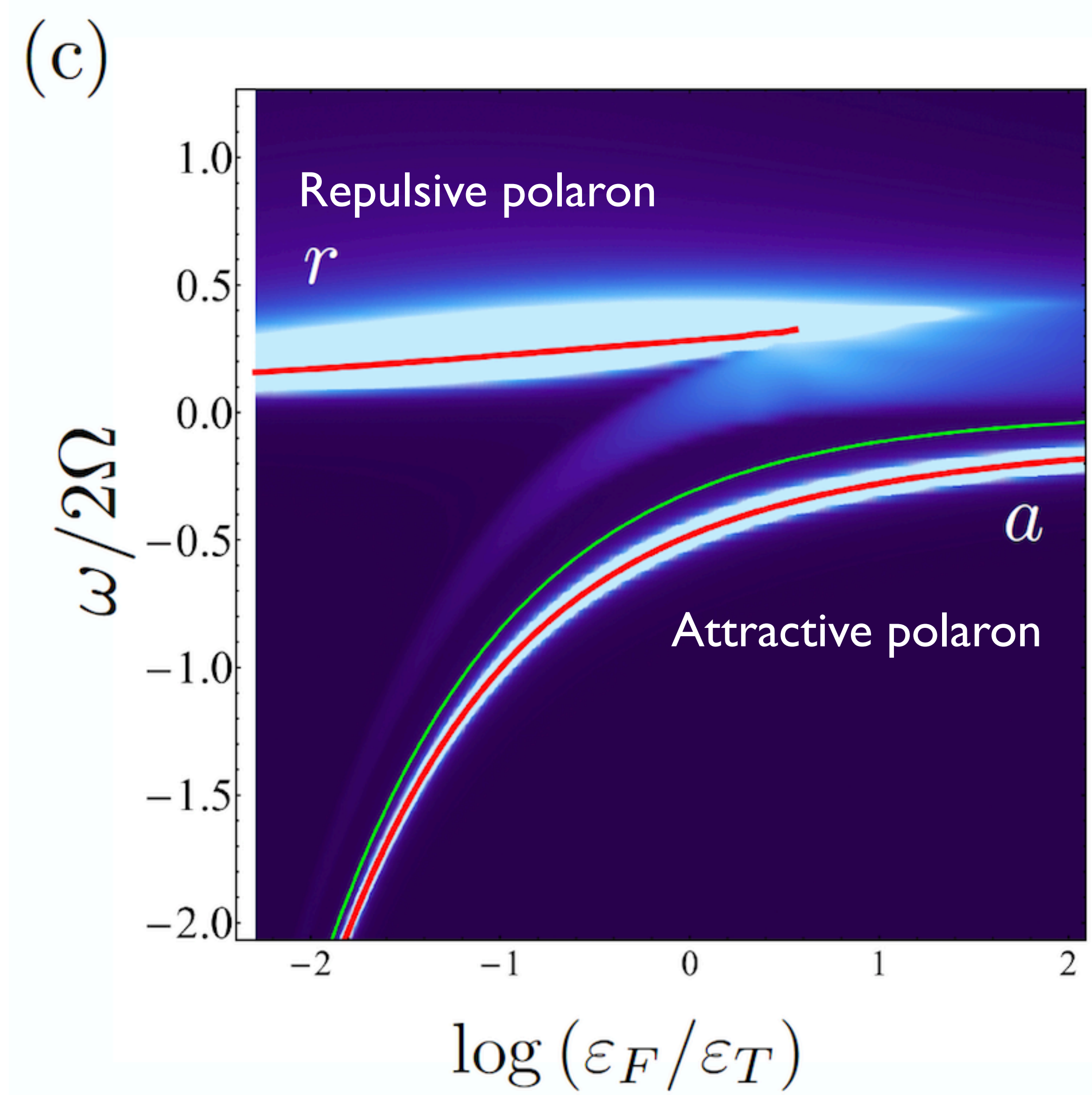
R. D. Mattuck, A Guide to Feynman Diagrams in the Many-Body Problem (Dover, New York, 1992)

The theory of the polaron has been applied before to atomic physics.



repulsive polaron attractive polaron

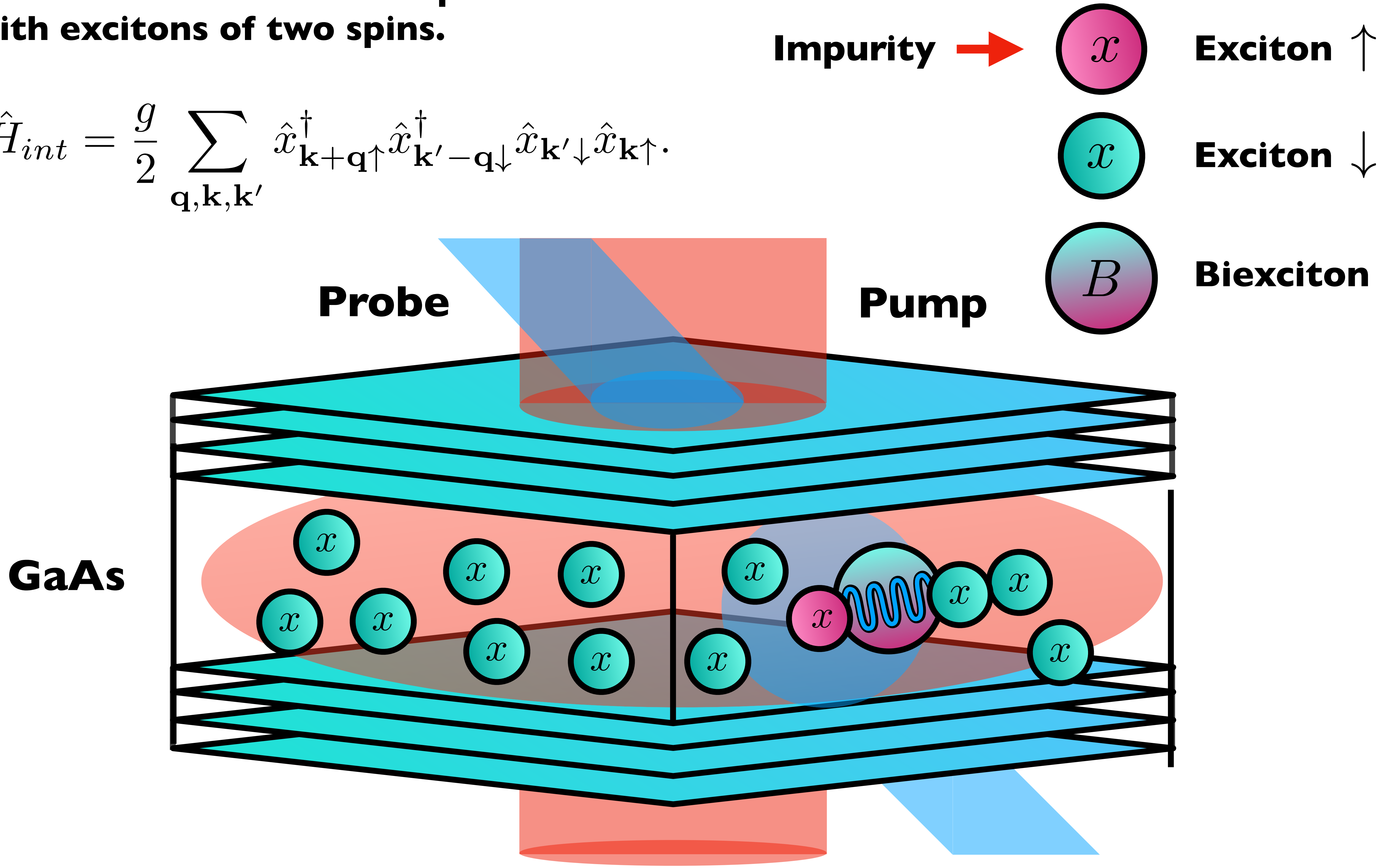
P. Massignan, et al., Rep. on Prog. in Phys. 2014, 77, 034401.



BOSE-POLARON-POLARITON

Let's consider a GaAs quantum well with excitons of two spins.

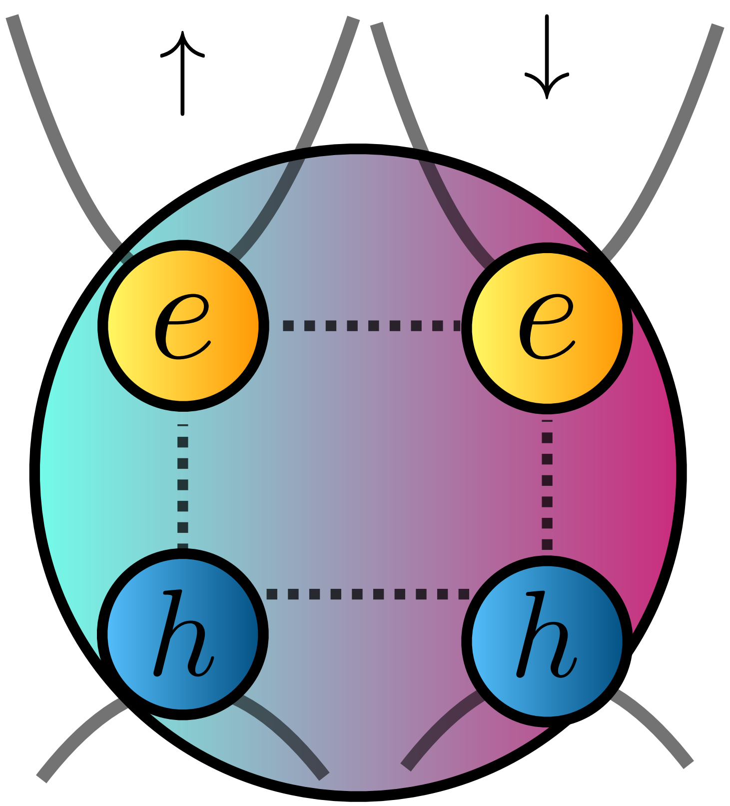
$$\hat{H}_{int} = \frac{g}{2}\sum_{\mathbf{q},\mathbf{k},\mathbf{k}'} \hat{x}^\dagger_{\mathbf{k}+\mathbf{q}\uparrow}\hat{x}^\dagger_{\mathbf{k}'-\mathbf{q}\downarrow}\hat{x}_{\mathbf{k}'\downarrow}\hat{x}_{\mathbf{k}\uparrow}.$$



MABM, A. Camacho-Guardian, and G. M. Bruun, PRB 100, 195301 (2019).

BIEXCITON

$$\hat{H}_{int} = \frac{g}{2} \sum_{\mathbf{q},\mathbf{k},\mathbf{k}'} \hat{x}^\dagger_{\mathbf{k}+\mathbf{q}\uparrow} \hat{x}^\dagger_{\mathbf{k}'-\mathbf{q}\downarrow} \hat{x}_{\mathbf{k}'\downarrow} \hat{x}_{\mathbf{k}\uparrow}.$$

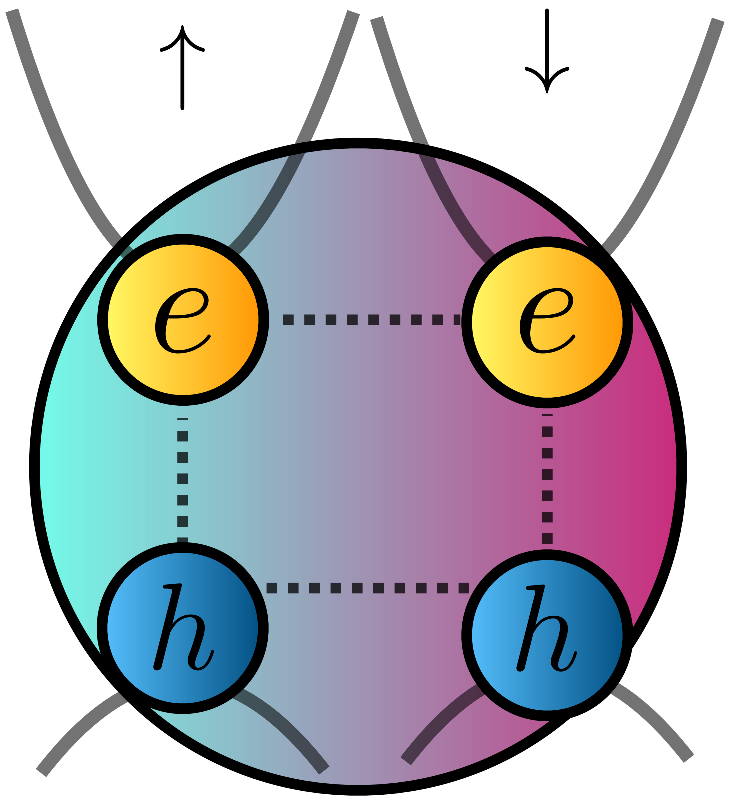


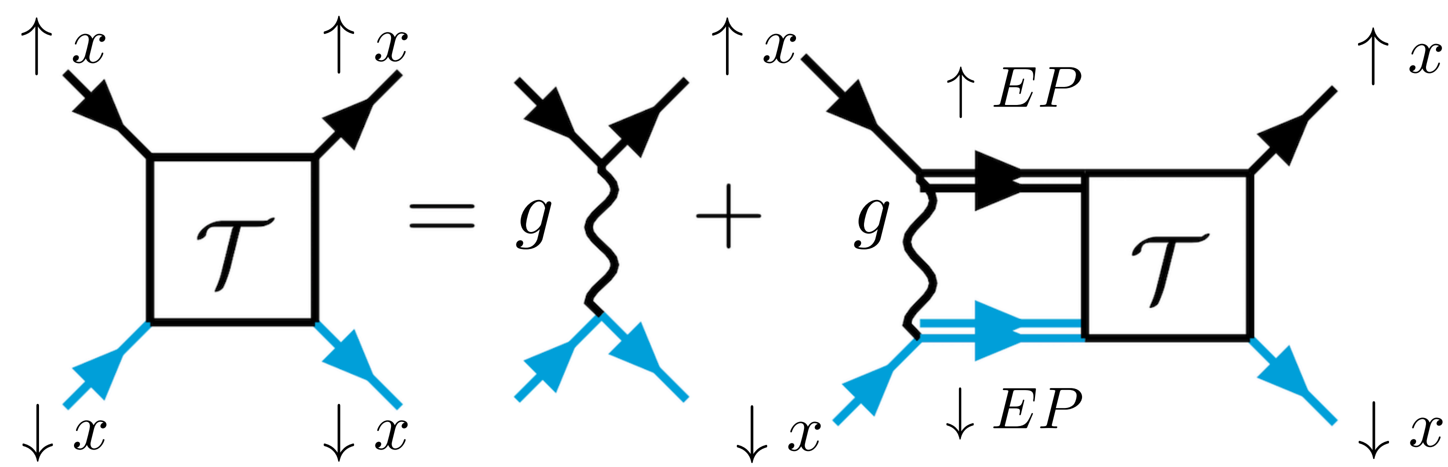
There is always a bound-state in 2D.

$$g^{-1} = \mathrm{Re}\Pi^V(E_B).$$

BIEXCITON

$$\hat{H}_{int} = \frac{g}{2}\sum_{\mathbf{q},\mathbf{k},\mathbf{k}'} \hat{x}^\dagger_{\mathbf{k}+\mathbf{q}\uparrow}\hat{x}^\dagger_{\mathbf{k}'-\mathbf{q}\downarrow}\hat{x}_{\mathbf{k}'\downarrow}\hat{x}_{\mathbf{k}\uparrow}.$$

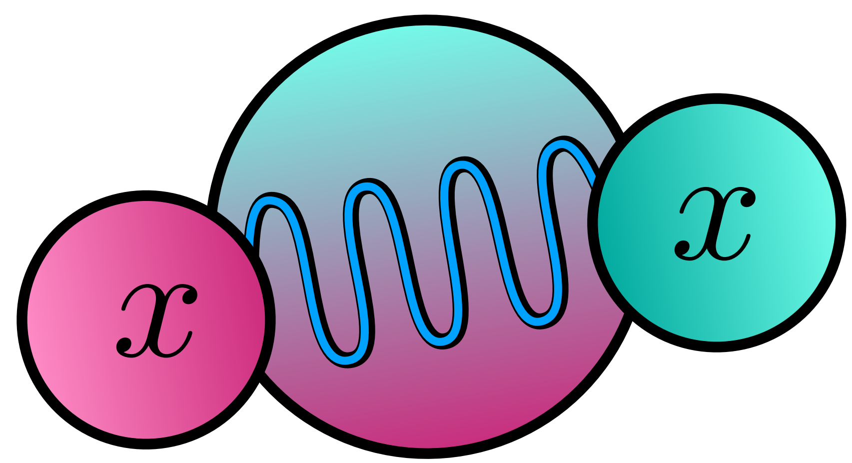




Repeated Scattering

There is always a bound-state in 2D.

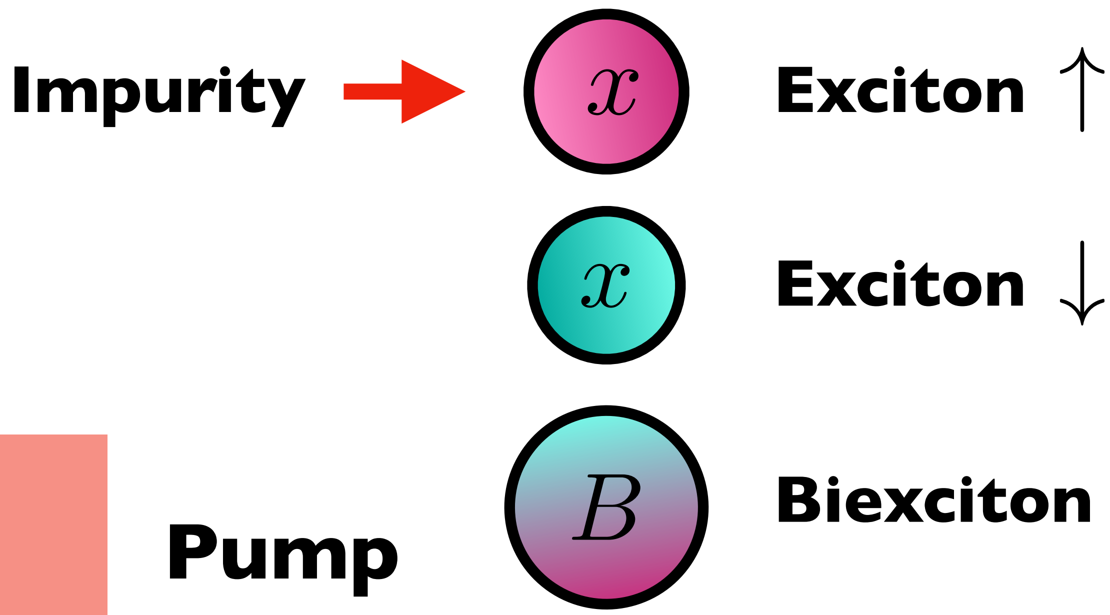
$$g^{-1} = \mathrm{Re}\Pi^V(E_B).$$



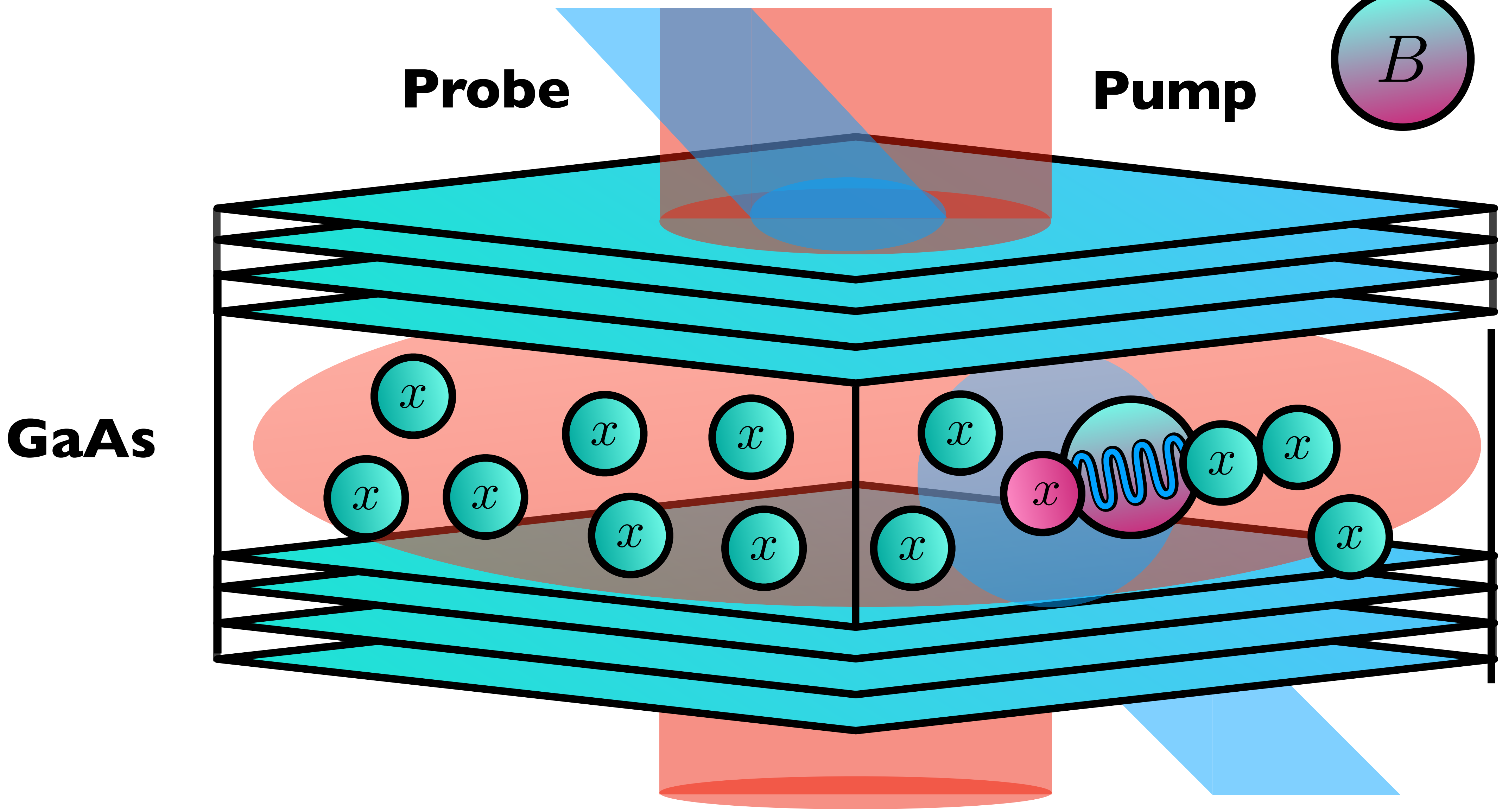
It results in strong interactions (Feshbach physics).

BOSE-POLARON-POLARITON

Let's consider a GaAs quantum well with excitons of two spins.

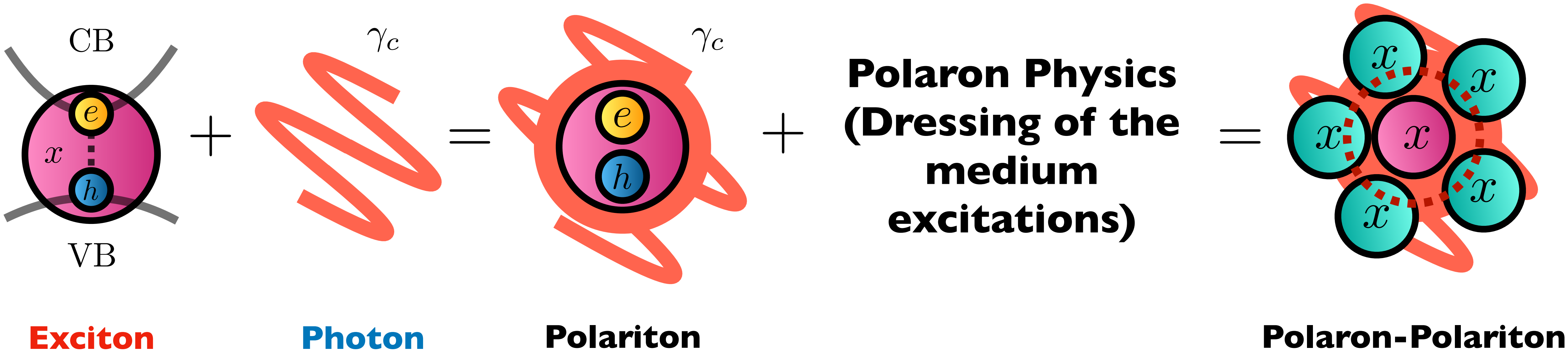


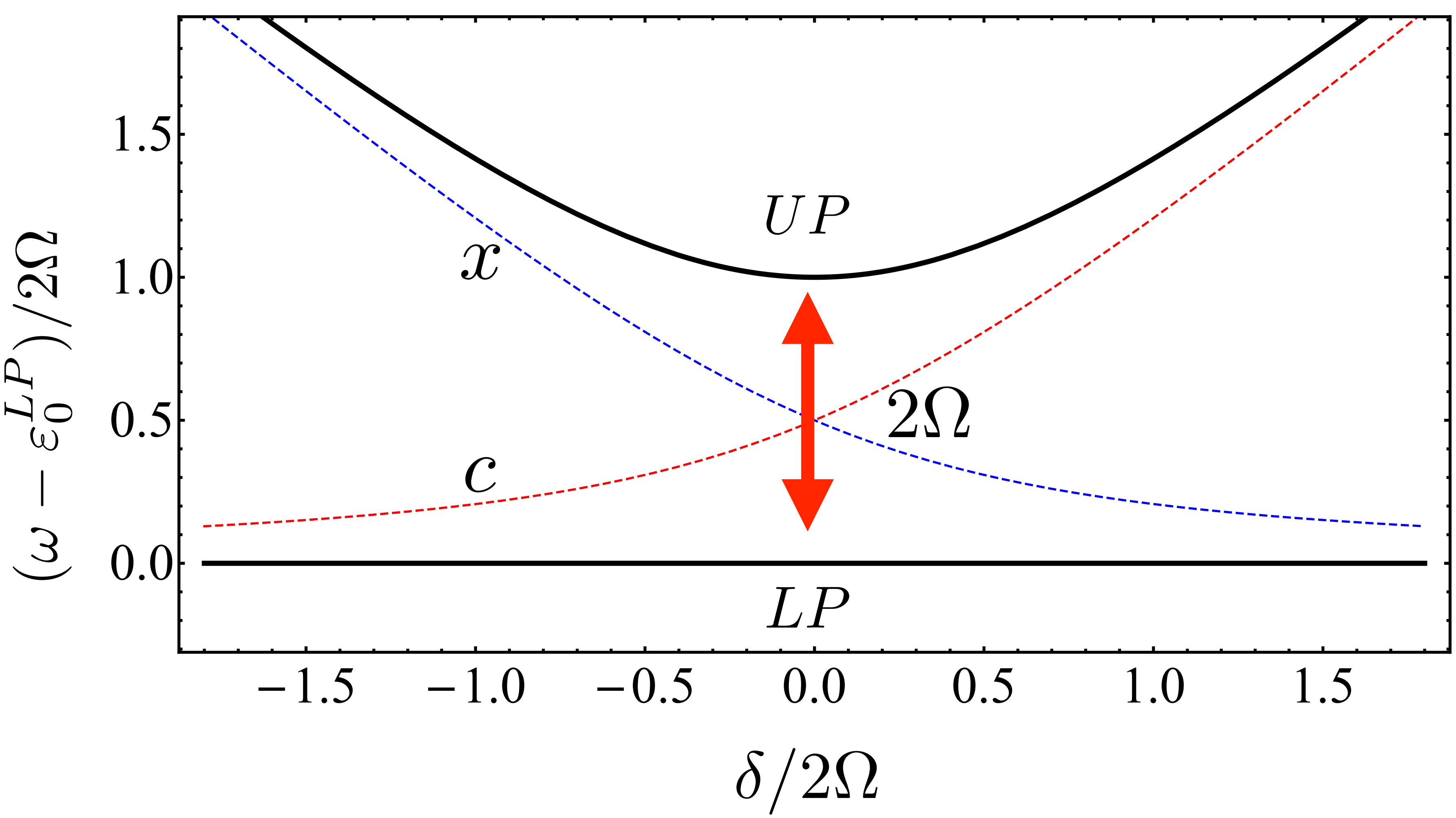
$$\hat{H}_{int} = \frac{g}{2} \sum_{\mathbf{q},\mathbf{k},\mathbf{k}'} \hat{x}^{\dagger}_{\mathbf{k}+\mathbf{q}\uparrow} \hat{x}^{\dagger}_{\mathbf{k}'-\mathbf{q}\downarrow} \hat{x}_{\mathbf{k}'\downarrow} \hat{x}_{\mathbf{k}\uparrow}.$$



MABM, A. Camacho-Guardian, and G. M. Bruun, PRB 100, 195301 (2019).

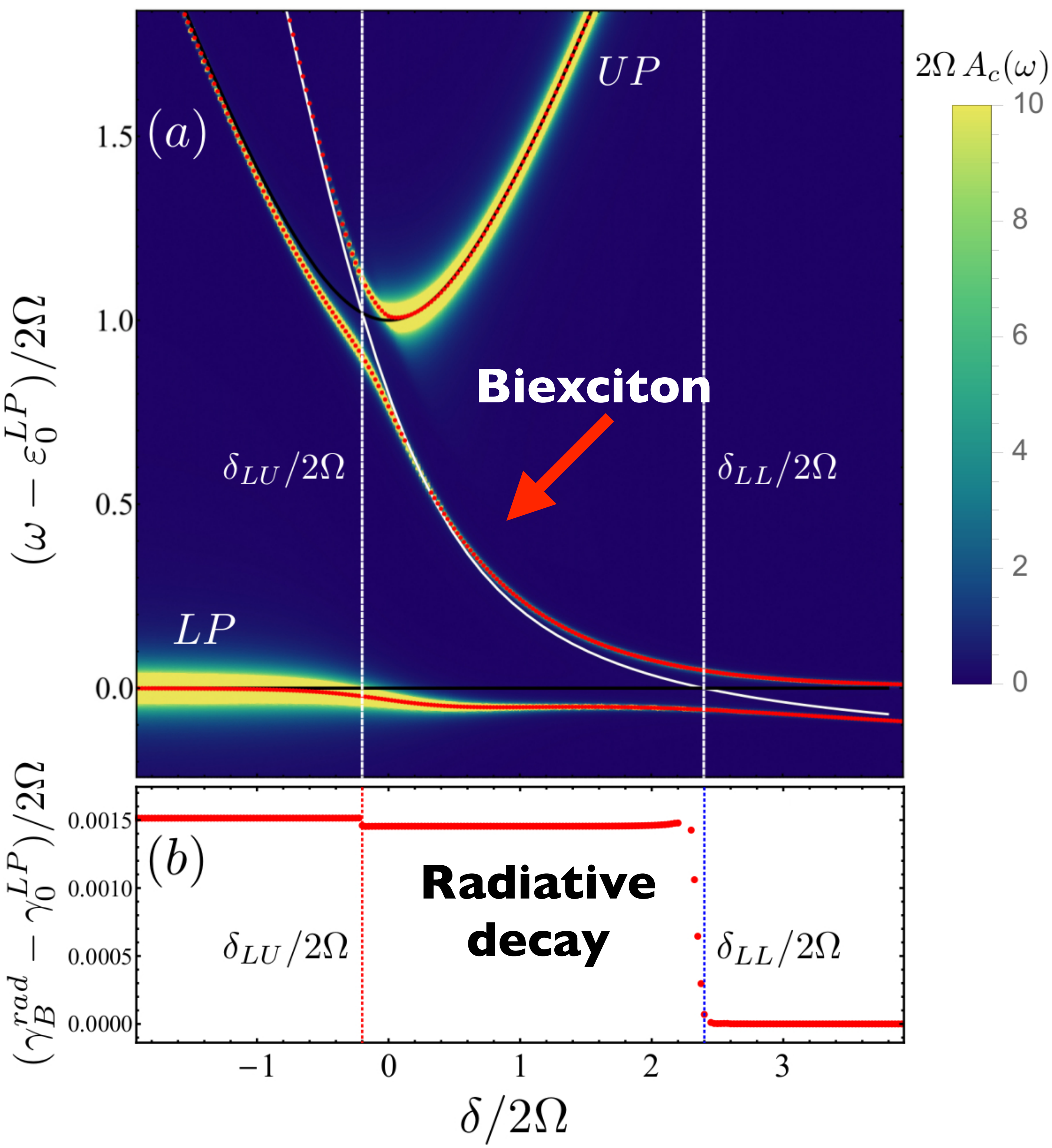
POLARON-EXCITON-POLARITON

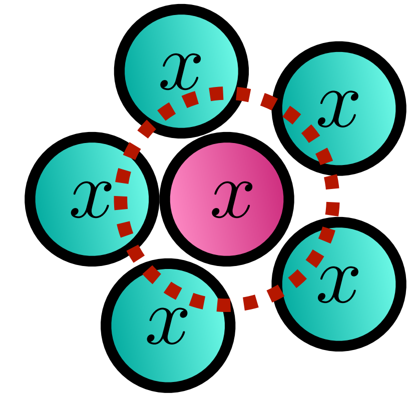




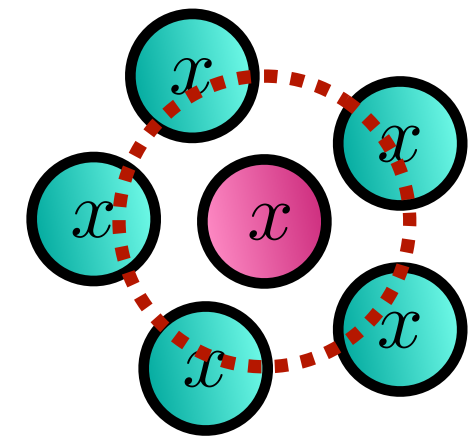
BOSE-POLARON-POLARITON

$$\mathcal{G}_{\downarrow}(\mathbf{k},\tau) = -\langle T_\tau\{\hat{\Psi}_{\mathbf{k}}(\tau)\hat{\Psi}^{\dagger}_{\mathbf{k}}(0)\}\rangle. \qquad A_c(\omega) = -2\mathrm{Im}\left[G_{cc}(\mathbf{k}=0,\omega)\right].$$





Attractive polaron



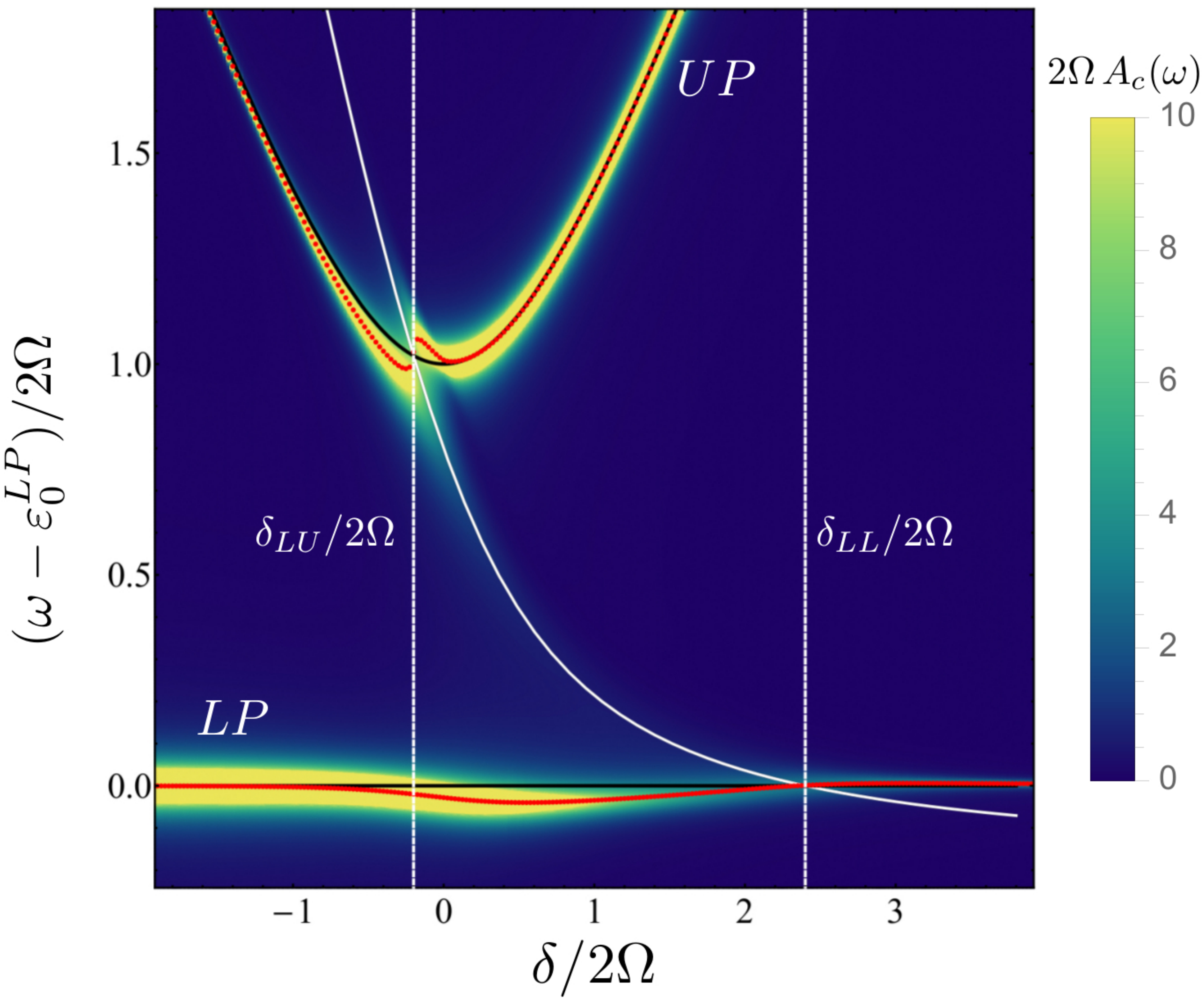
Repulsive polaron

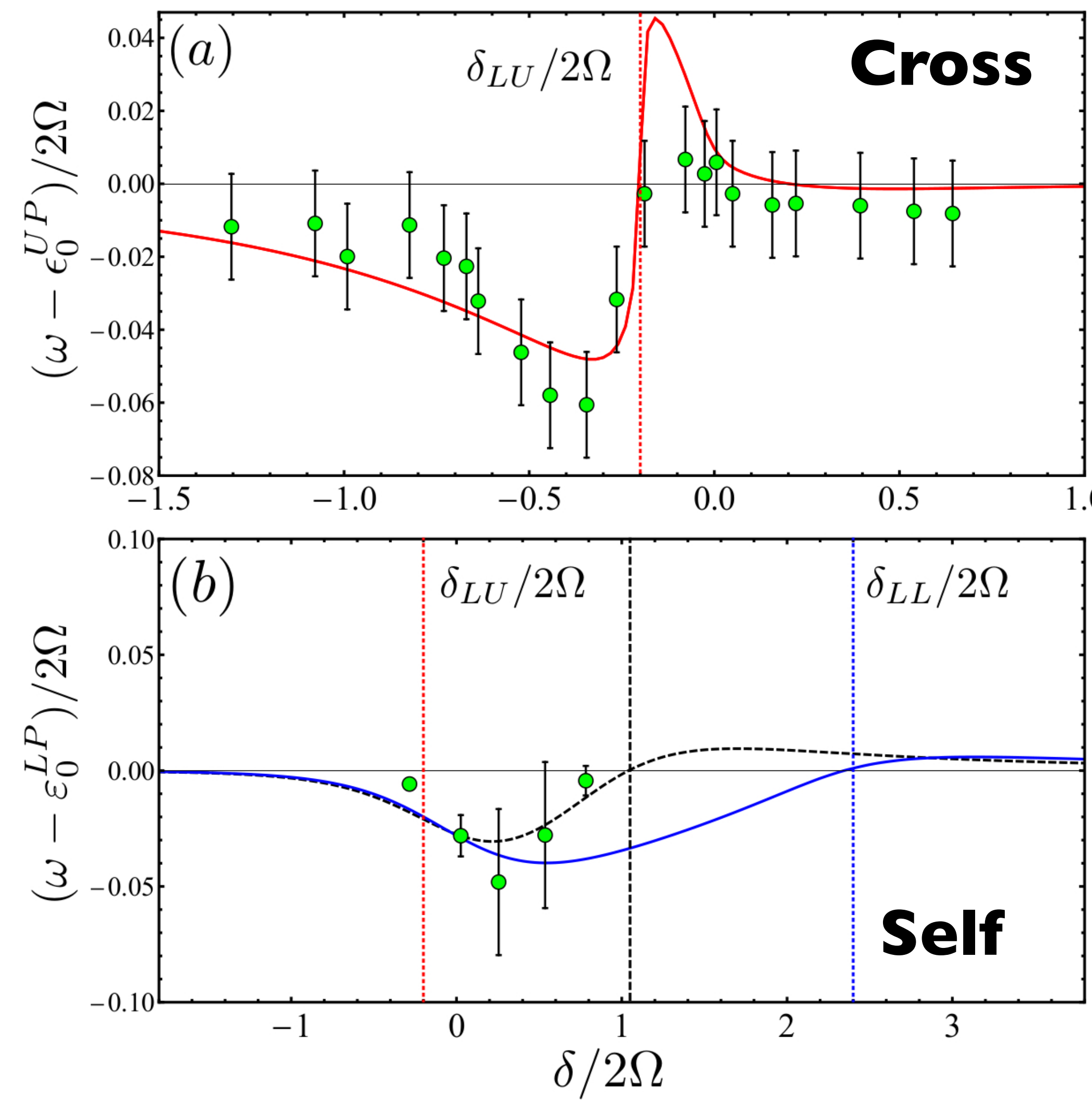
Light couples to the two states resulting in three branches.

MABM, A. Camacho-Guardian, and G. M. Bruun, PRB 100, 195301 (2019).

“POLARITONIC FESHBACH RESONANCE”

We obtain Feshbach physics due to the formation of a biexciton.





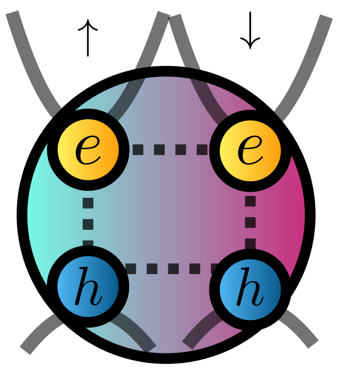
M. Navadeh-Toupchi, et al., PRL 122, 047402 (2019).

MABM, A. Camacho-Guardian, and G. M. Bruun, PRB 100, 195301 (2019).

POLARITONIC INTERACTIONS

By menas of a diagrammatic many-body theory to describe strong interacting effects between exciton-polaritones, i.e., **strong interactions between dressed photons.**

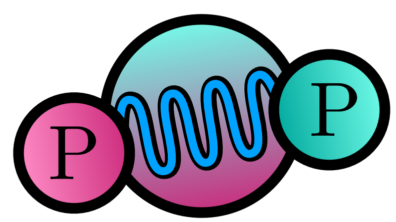
Bose polaron-polaritons

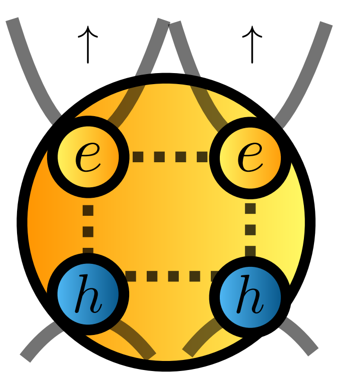


Biexciton (different spin)

Polaritonic Feshbach resonances: due to the presence of biexcitons formed between polaritons with different spin inside a BEC or polaritons.

MABM, A. Camacho-Guardian, and G. M. Bruun, PRB 100, 195301 (2019).

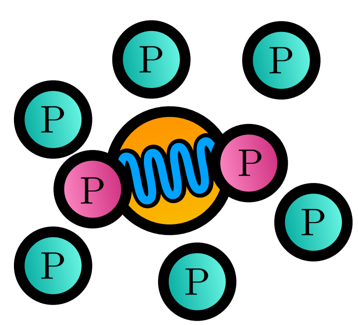




Biexciton (same spin)

Many-body bipolaritons: resulting from the exchange of sound waves in the polarity BEC thanks to the Feshbach resonance.

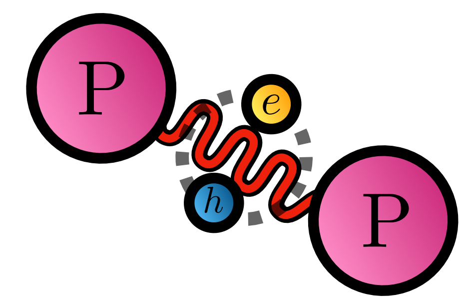
MABM, A. Camacho-Guardian, and G. M. Bruun, PRL 126, 017401 (2021).



Fermi polaron-polaritons

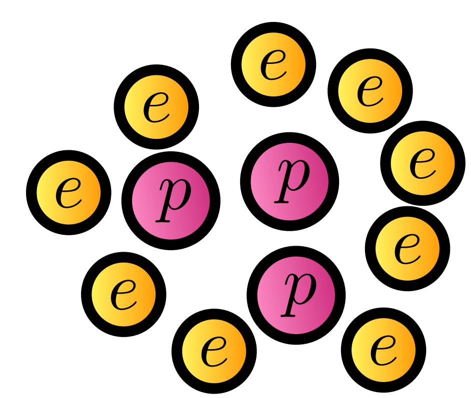
Strong polarizan interactions: mediated by a bidimensional gas of electrons and resulting from the presence of a trio resonance.

A. Camacho-Guardian, MABM, and G. M. Bruun, PRL, 126, 127405 (2021).



Polaron-polariton BEC: the properties of a condensate of exciton-polaritons is modified by the presence of a 2D electron gas.

A Julku, MABM, A Camacho-Guardian, GM Bruun PRB 104 (16), L161301 (2021).



CHAOS IN POLARITON FLUIDS

Recently, it has been pointed out that exciton-polariton systems have broad applications in the field of chaos.

Two species of exciton-polariton fluids with different spins can be employed to produce tunable **(classical) chaotic dynamics**.

PHYSICAL REVIEW B **101**, 155305 (2020)

Autonomous chaos of exciton-polariton condensates

R. Ruiz-Sánchez, R. Rechtman, and Y. G. Rubo*
Instituto de Energías Renovables, Universidad Nacional Autónoma de México, Temixco, Morelos 62580, Mexico

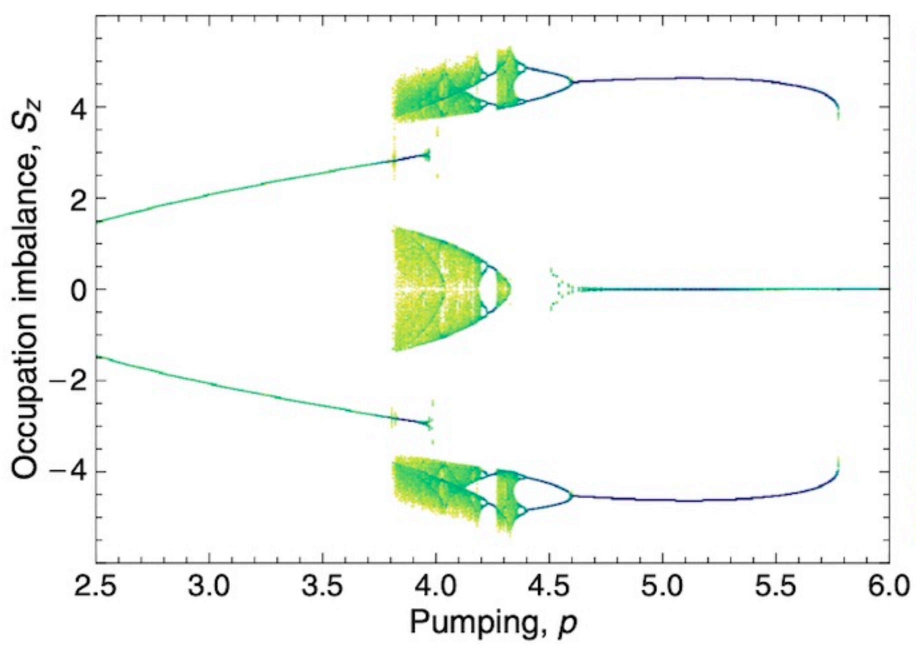


FIG. 1. Showing the imbalance of two condensate occupations S_z at the return points of the spin trajectory (points with $dS_z/dt = 0$, see text for details). The plot has been obtained by collecting the return points for eight trajectories with random initial conditions at the final stage of evolution between $t = 400$ and $t = 500$, and for the parameters $\gamma = 0.5$, $\varepsilon = 2$, $\alpha = 0.75$. All parameters are in the units of dissipation rate Γ.

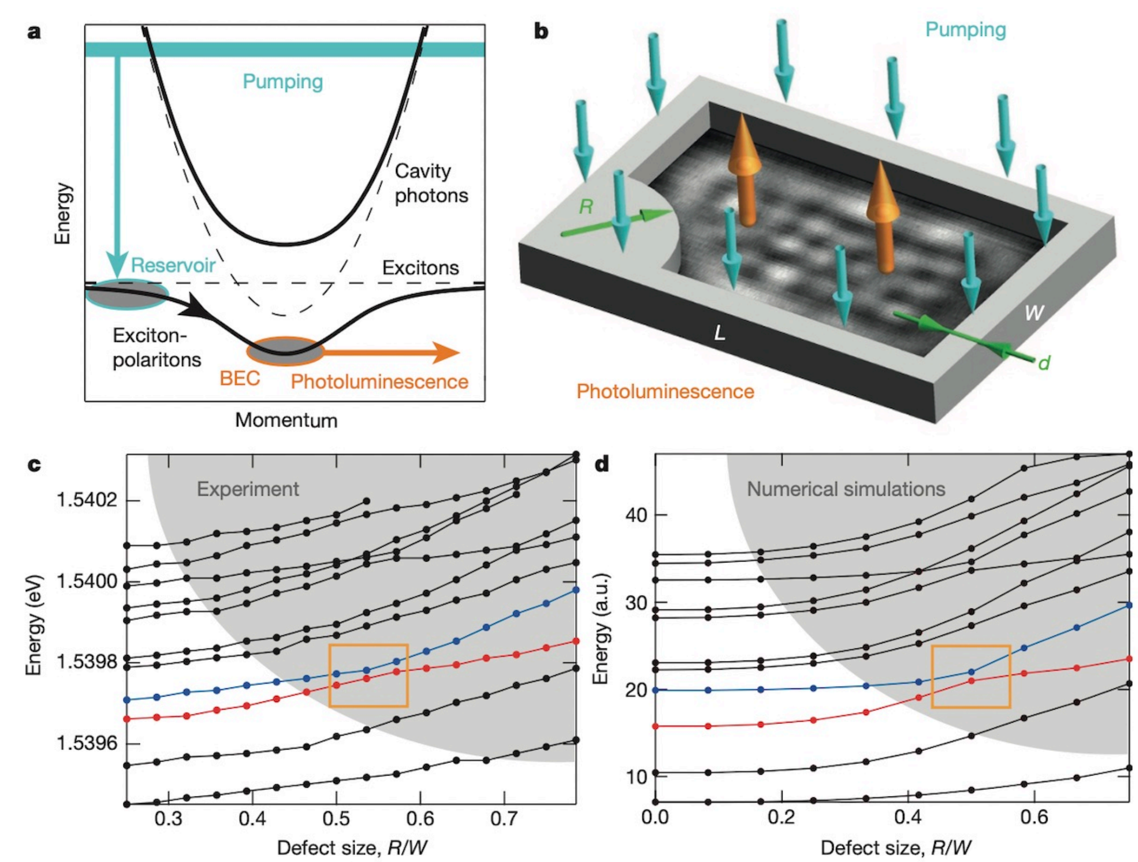
The microcavity polaritons can be used to study **quantum chaos,** for example as a setup to create quantum soft billiards with tunable geometric and physical properties.

LETTER

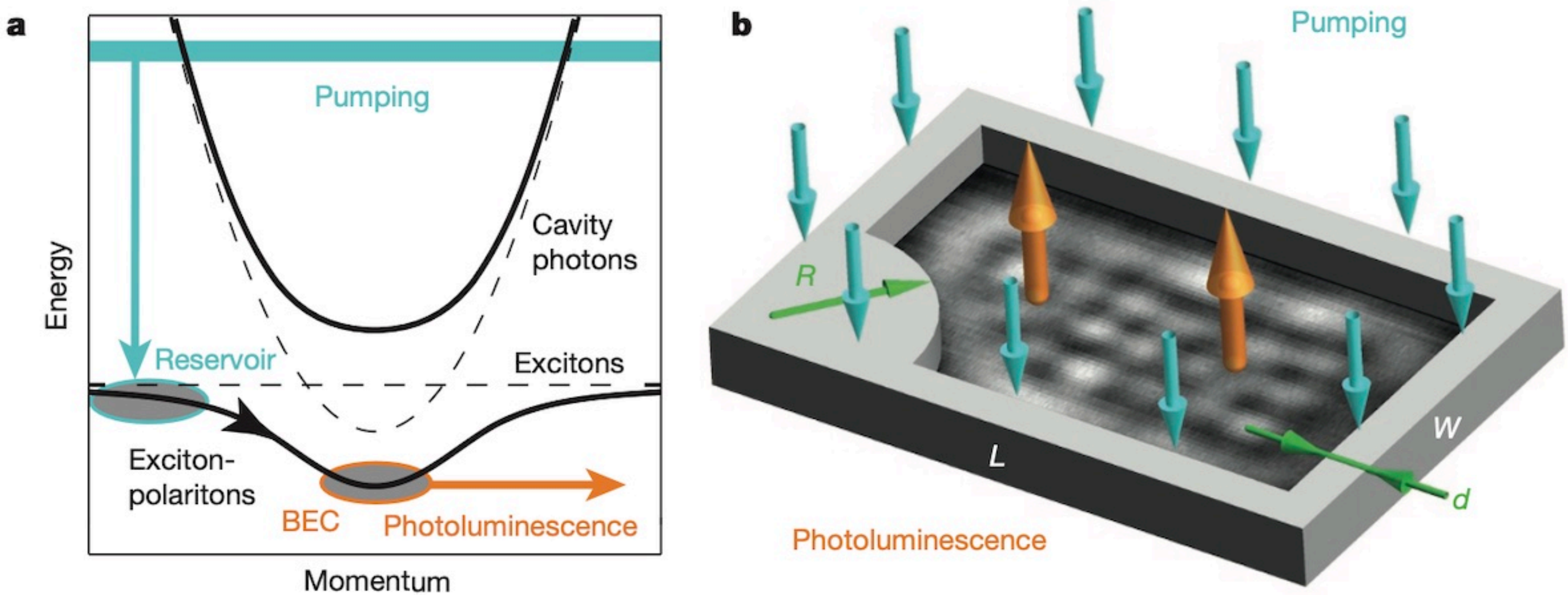
doi:10.1038/nature15522

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

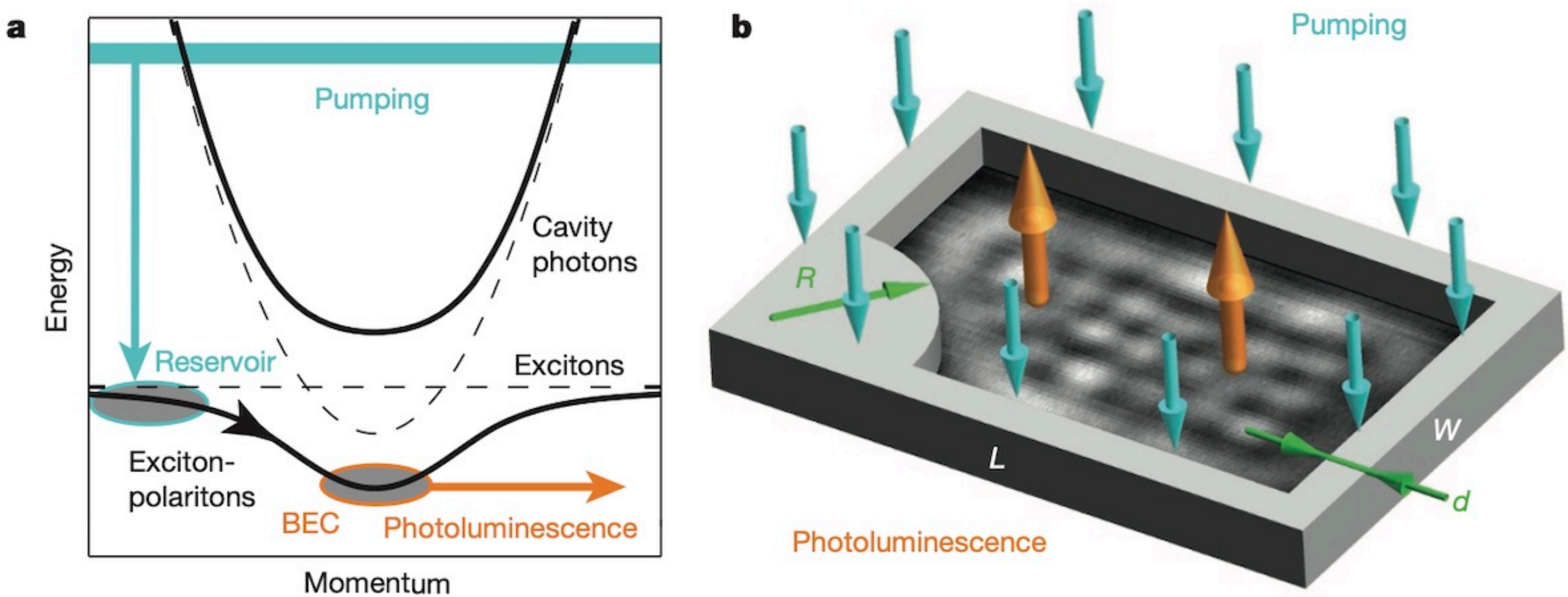
T. Gao[1], E. Estrecho[1], K. Y. Bliokh[1,2], T. C. H. Liew[3], M. D. Fraser[2], S. Brodbeck[4], M. Kamp[4], C. Schneider[4], S. Höfling[4,5], Y. Yamamoto[6,7], F. Nori[2,8], Y. S. Kivshar[1], A. G. Truscott[1], R. G. Dall[1] & E. A. Ostrovskaya[1]



CHAOS IN POLARITON FLUIDS



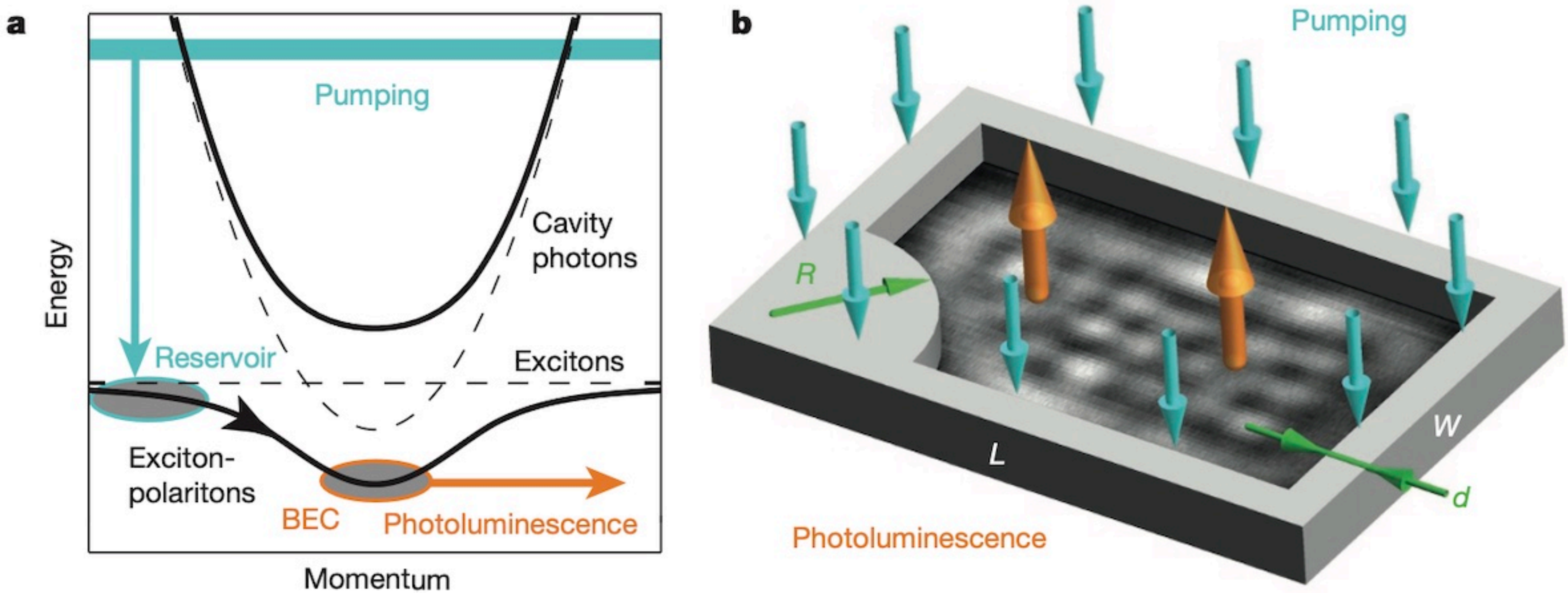
CHAOS IN POLARITON FLUIDS



Although this is a quantum system, it opens many questions about non-hermitian billiards and how they are quantized.

To this end, we are exploring the behavior of **classical soft billiards**.

CHAOS IN POLARITON FLUIDS



Although this is a quantum system, it opens many questions about non-hermitian billiards and how they are quantized.

To this end, we are exploring the behavior of **classical soft billiards**.

See Adan González presentation:
Tuesday 25th 13:00 – 13: 20
Caos en billares de paredes suaves

¡MUCHAS GRACIAS!

DIAGRAMMATIC APPROACH

We employ a finite temperature quantum field theory Empleamosto investigate the strong interactions and Feshbach physics.

We consider the problem of the exciton as that of a mobile impurity.

$$\mathcal{G}_{\downarrow}(\mathbf{k},\tau) = -\langle T_\tau\{\hat{\Psi}_{\mathbf{k}}(\tau)\hat{\Psi}^{\dagger}_{\mathbf{k}}(0)\}\rangle.$$

Finite temperature Green's function

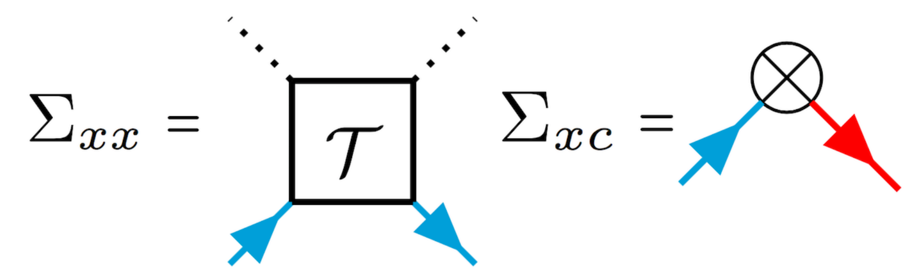
$$\mathcal{G}^{-1}_{\downarrow}(\mathbf{k},i\omega_n) = \begin{bmatrix} i\omega_n - \varepsilon^x_{\mathbf{k}} & \\ 0 & i\omega_n - \varepsilon^c_{\mathbf{k}} \end{bmatrix} - \begin{bmatrix} \Sigma(\mathbf{k},i\omega_n) & \Omega \\ \Omega^* & 0 \end{bmatrix}.$$

Frequency momentum space

Free propagation **Self-energy**

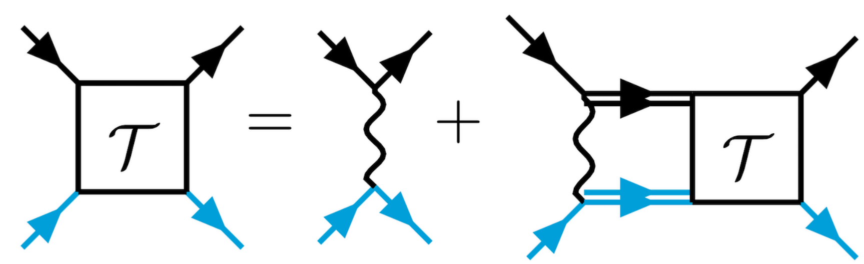
$$\Sigma(\mathbf{k},i\omega_n) = n_{x\uparrow}\mathcal{T}(\mathbf{k},i\omega_n).$$

Self-energy



$$[\mathcal{T}(\mathbf{k},i\omega_n)]^{-1} = \mathrm{Re}\Pi_V(E_B) - \Pi(\mathbf{k},i\omega_n) + i\gamma.$$

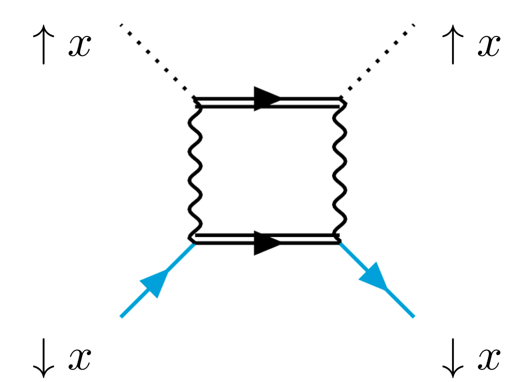
T-matrix



$$g^{-1} = \mathrm{Re}\Pi^V(E_B).$$ **Normalization**

$$\Pi(q) = -T\sum_q \mathcal{G}^{\downarrow}_x(q+k)\mathcal{G}^{\uparrow}_x(-q).$$

Pair propagator



$$\mathcal{G}^{\downarrow}_x(\mathbf{k},i\omega_n) = \frac{\mathcal{C}^2_{\mathbf{k}}}{i\omega_n - \varepsilon^{LP}_{\mathbf{k}\downarrow}} + \frac{\mathcal{S}^2_{\mathbf{k}}}{i\omega_n - \varepsilon^{UP}_{\mathbf{k}\downarrow}}.$$