Polariton Condensation in Photonic Crystals with High Molecular Orientation

Coherence in 2D polaritons BEC in semiconductor microcavity at finite temperature

Karpov Denis

ITMO university, Russia

Outline

Polaritons in photonic crystals with organic active medium

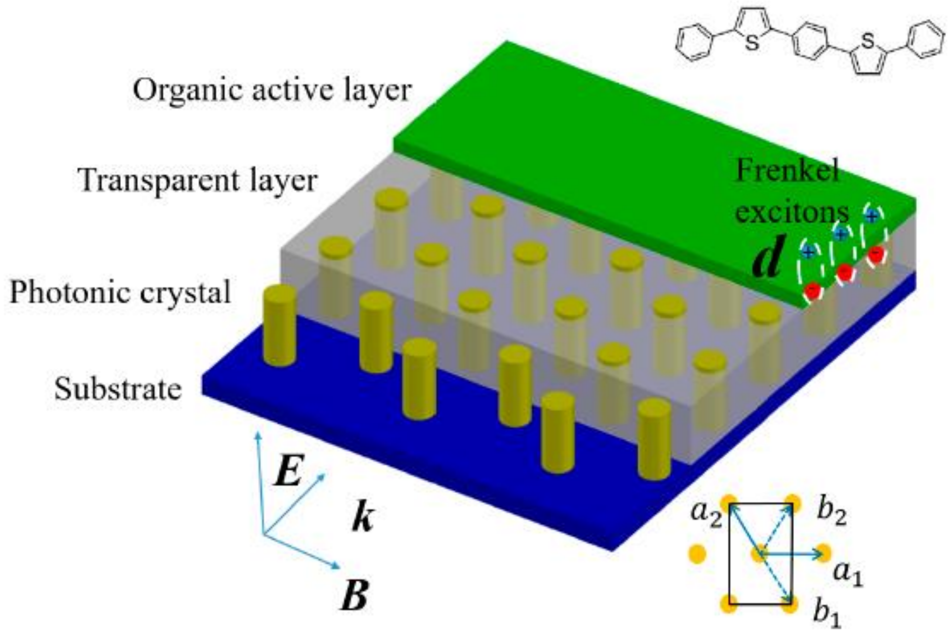
- Photonic bands calculation
- Photons lifetime
- Condensation diagram in momentum space
- Condensation threshold

Coherence of 2D polaritons BEC in GaAs microcavity at finite temperature

- Stochastic Gross-Pitaevskii equation with phonons
- Condensation threshold at finite tempratures
- First order correlation function
- Second order correlation function

Organic polaritons in photonic crystals

1,4-bis(5-phenyl thiophen-2yl)benzene



The structure consists of aluminum nitride (AlN) pillars of radius 450 nm forming the photonic crystal, with a lattice constant of 1 μm and a refractive index (n) of 2.15

Dispersion relation

TM polarization

$$\mathbf{E}(\mathbf{r}) = (0, 0, E_z(\mathbf{r})),$$
$$\mathbf{H}(\mathbf{r}) = (H_x(\mathbf{r}), H_y(\mathbf{r}), 0).$$

$$\frac{1}{\epsilon(\mathbf{r})}\frac{\partial^2 E_z(\mathbf{r})}{\partial^2 x} + \frac{1}{\epsilon(\mathbf{r})}\frac{\partial^2 E_z(\mathbf{r})}{\partial^2 y} + \frac{\omega^2}{c^2}E_z(\mathbf{r}) = 0,$$

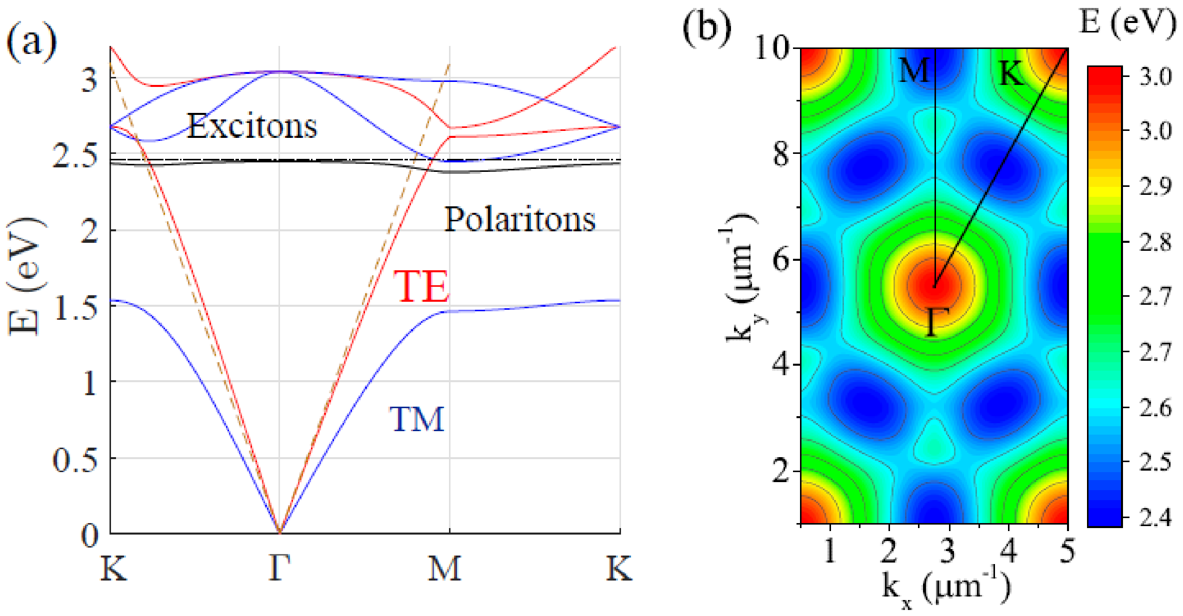
and by substituting the ansatz

$$E_z(\mathbf{r}) = \sum_G B_G(k) e^{-i(\mathbf{k}\cdot\mathbf{r}+\mathbf{G}\cdot\mathbf{r})}$$

we arrive at the eigenvalue problem:

$$\sum_{G'} \epsilon^{-1}_{G,G'}(\mathbf{k}+\mathbf{G}')^2 \mathbf{B}_G = \frac{\omega^2}{c^2}\mathbf{B}_G.$$

M. Plihal and A. A. Maradudin, PHYSICAL REVIEW B 44(1), 1993



(a) Band structure of the 2D photonic crystal consisting of a pillar triangular lattice (b) 2D photon dispersion for the TM-mode which is coupled to excitons

$$\omega_{LP}(k) = \frac{\omega^C + \omega_k^X}{2} - \frac{\sqrt{(\omega_k^C - \omega^X)^2 + \Omega_R^2}}{2}$$

$$\hbar\Omega_R = \sqrt{\frac{2|\mu|^2\hbar\omega_C(N/V)}{\epsilon}},$$

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Quality factor and lifetime

$$Q^{-1} = Q_v^{-1} + Q_l^{-1}$$

$$Q_v^{-1} = -\omega_{real}/2\omega_{im}$$

$$Q_l = \frac{\pi}{1 - R(\lambda_0)} \left[\frac{2cL^2}{\lambda_0 \alpha} \frac{1}{p\pi - \phi_r} - \frac{\lambda_0}{\pi} \frac{d\phi_r}{d\lambda}\bigg|_{\lambda_0} \right]$$

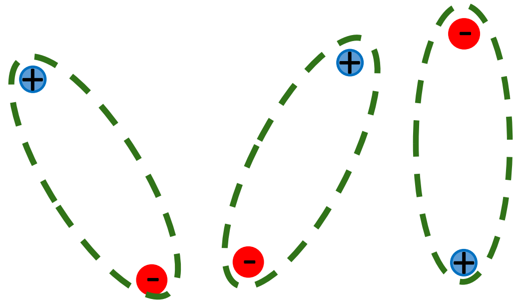
$$\tau_p \approx 5 \text{ ps}$$

$\hbar\Omega_R$ = 100 - 800 meV

Kinetics

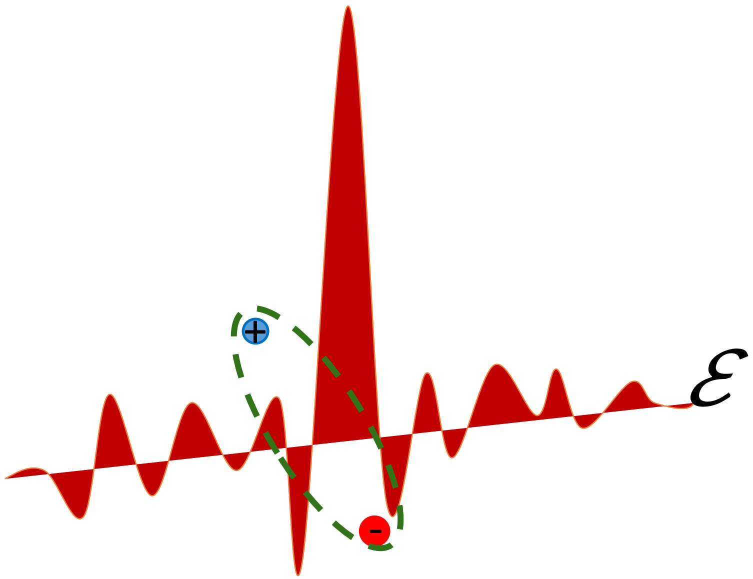
Boltzmann equation (exciton transport)

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

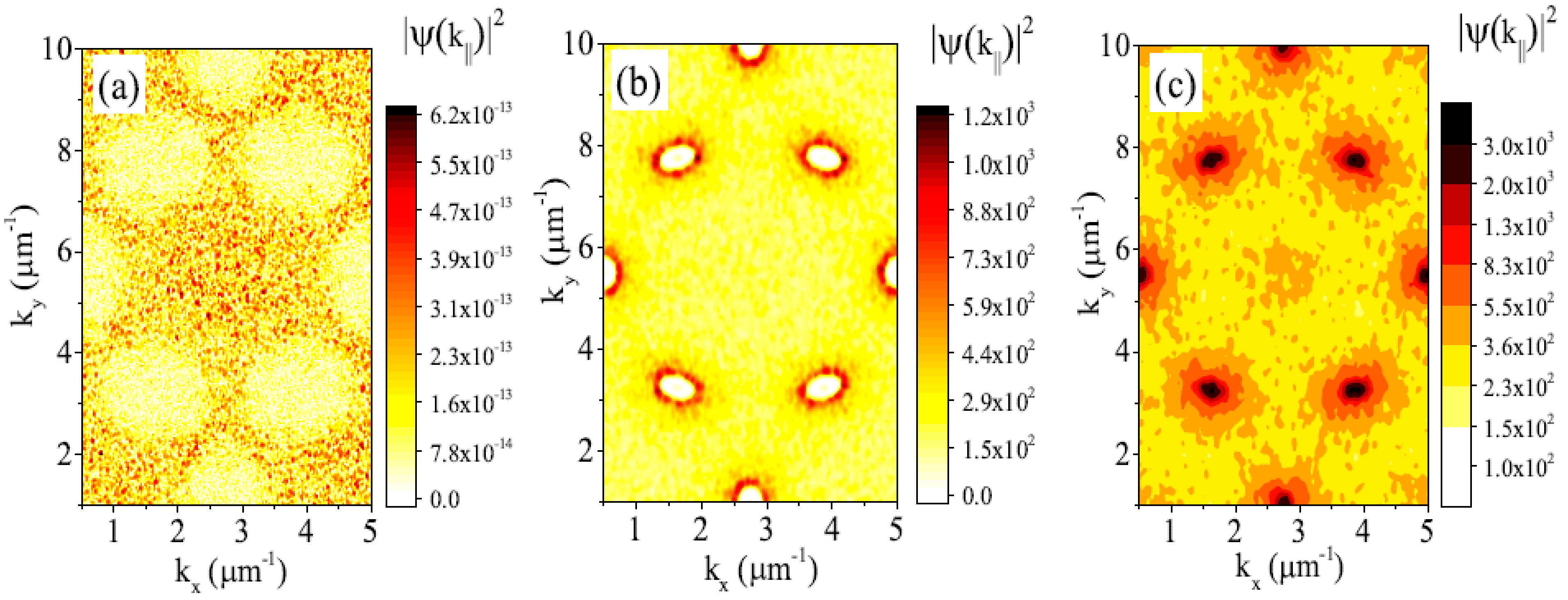


2D Gross-Pitaevskii equation (polariton transport)

$$i\hbar\frac{\partial}{\partial t}\psi = \left[E_{LP}(k) + i\frac{\hbar}{2}(Rn_R + \gamma_c) + g|\psi|^2\right]\psi$$

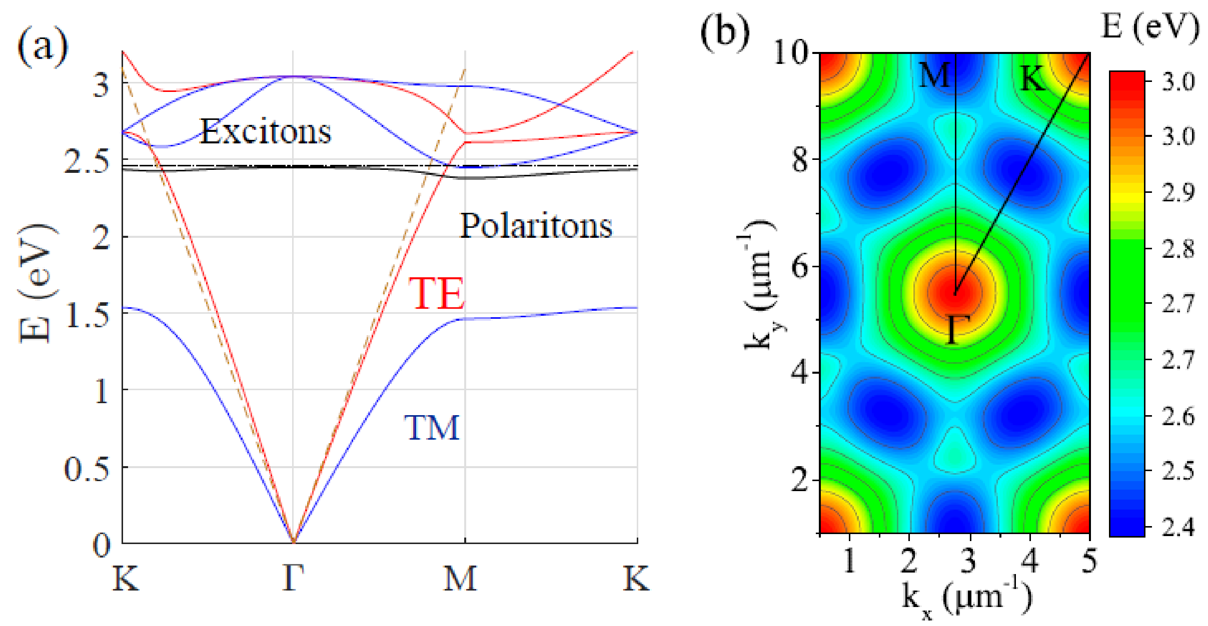


Condensation diagram in momentum space

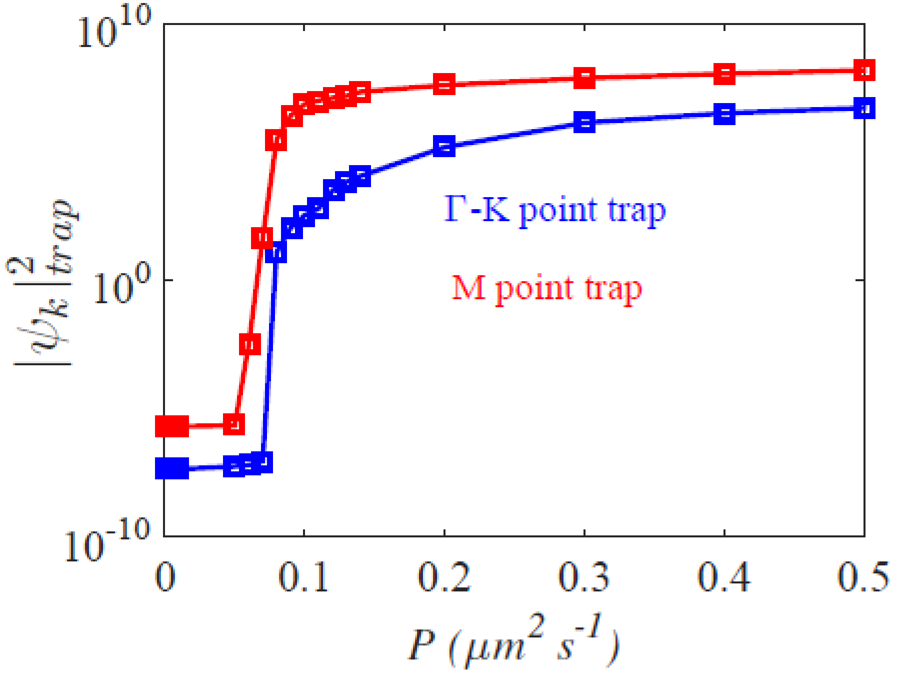


Polaritons distribution in momentum space for different pumping powers

Threshold characteristics



(a) Band structure of the 2D photonic crystal consisting of a pillar triangular lattice (b) 2D photon dispersion for the TM-mode which is coupled to excitons



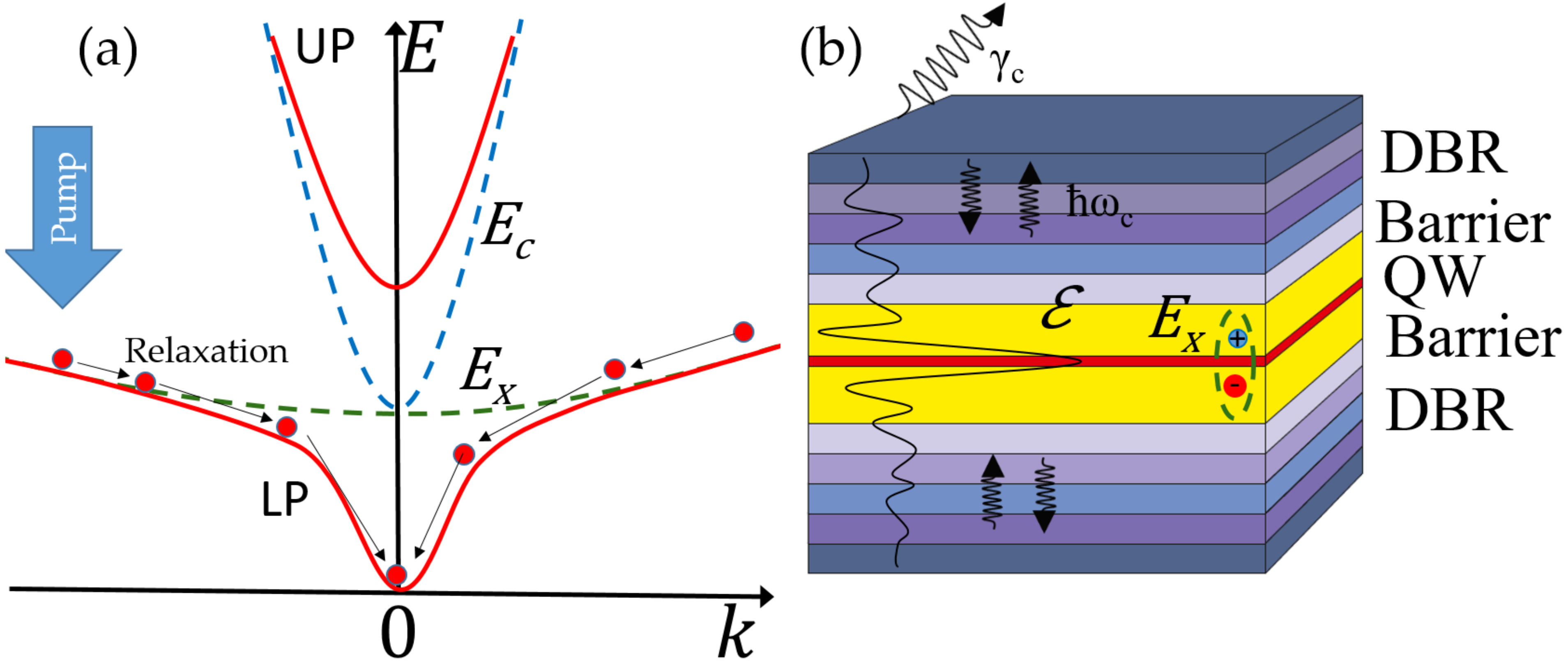
Polartion density at the bottom of the trap as function of reservoir pumping.

Conclusion

- PCs can be employed to achieve polariton condensation at non-zero momenta

- organic materials with high molecular orientation provide selective coupling with TM-modes (in contrast to Bose-Einstein condensation in conventional quantum wells)

Coherence of 2D polaritons BEC in GaAs microcavity at finite temperature



Stochastic Gross-Pitaevskii equation

$$\hat{\mathcal{H}}_1 = \sum_k E_k \hat{a}_k^\dagger \hat{a}_k + \sum_x \left(V_x \hat{\Psi}_x^\dagger \hat{\Psi}_x + \alpha \hat{\Psi}_x^\dagger \hat{\Psi}_x^\dagger \hat{\Psi}_x \hat{\Psi}_x \right)$$

$$\hat{\mathcal{H}}_2 = \sum_{\vec{q}} \hbar \omega_{\vec{q}} \hat{b}_{\vec{q}}^\dagger \hat{b}_{\vec{q}} + \sum_{\vec{q},k} G_{\vec{q}} \hat{b}_{\vec{q}} \hat{a}_{k+q_x}^\dagger \hat{a}_k + G_{\vec{q}}^* \hat{b}_{\vec{q}}^\dagger \hat{a}_{k+q_x} \hat{a}_k^\dagger,$$

Polariton field dynamic: $$\frac{d\hat{\Psi}_x}{dt} = \frac{i}{\hbar}\left[\hat{\mathcal{H}}_1 + \hat{\mathcal{H}}_2, \hat{\Psi}_x\right],$$

Phonon field: $$\hat{b}_{\vec{q}}(t) = \hat{b}_{\vec{q}}(0) e^{-i\omega_{\vec{q}} t} - \frac{i}{\hbar}\int_0^t G_{\vec{q}}^* \sum_k \hat{a}_{k+q_x}^\dagger(t') \hat{a}_k(t') e^{-i\omega_{\vec{q}}(t-t')} dt'.$$

Phonons represent an incoherent thermal reservoir ->Markov approximation (randomly varying phase) - > Stochastic classical variable:

$$\langle b_{\vec{q}}^*(t) b_{\vec{q}'}(t')\rangle = n_{\vec{q}} \delta_{\vec{q}\vec{q}'} \delta(t-t'),$$

$$\langle b_{\vec{q}}(t) b_{\vec{q}'}(t')\rangle = \langle b_{\vec{q}}^*(t) b_{\vec{q}'}^*(t')\rangle = 0,$$

In Mean field approximation, turn to classical variable: $$\psi_x = \langle \hat{\Psi}_x \rangle$$

Polariton BEC

Free dispersion

emission of phonons by condensate

reservoir-system excitations exchange rate

Exciton-phonon interaction

$$i\hbar\frac{d\psi(\mathbf{r},t)}{dt}=F^{-1}\left[E_{\mathbf{k}_{\parallel}}\psi_{\mathbf{k}_{\parallel}}(t)+S_{\mathbf{k}_{\parallel}}(t)\right]+\left[i\frac{\hbar}{2}Rn_R-i\frac{\hbar\gamma}{2}+\alpha\left|\psi(\mathbf{r},t)\right|^2\right]\psi(\mathbf{r},t)+\sum_{\mathbf{k}_{\parallel}}\left\{T_{-\mathbf{k}_{\parallel}}(t)+T^{*}_{\mathbf{k}_{\parallel}}(t)\right\}e^{-i\mathbf{k}_{\parallel}\cdot\mathbf{r}}\psi(\mathbf{r},t)$$

Polariton lifetime

Reservoir

Reservoir lifetime

Incoherent pulsed pumping

$$\frac{\partial n_R}{\partial t}=-\left(\gamma_R+R|\psi|^2\right)n_R+P_i$$

Exciton-phonon interaction

Phonon dispersion: $\hbar\omega_{\vec{q}} = \hbar u\sqrt{q_x^2 + q_y^2 + q_z^2}$

$$\mathcal{S}_k(t) = \sum_{q_x} \psi_{k+q_x}(t)\left(\int_0^t \mathcal{A}_{q_x}(t')\mathcal{K}_{q_x}(t-t')dt'\right), \quad \text{where } \mathcal{A}_{q_x}(t) = \sum_{k'} \psi^*_{k'+q_x}(t)\psi_{k'}(t).$$

$$\mathcal{K}_{q_x}(t) = -\sum_{q_u, q_z} |G_{\vec{q}}|^2 (e^{-i\omega_{\vec{q}}t} - e^{i\omega_{\vec{q}}t}) \quad \rightarrow 2i\frac{L_z}{2\pi}\frac{a_B}{2\pi}\iint |G(\vec{q})|^2 \sin[\omega(\vec{q})t] dq_y dq_z$$

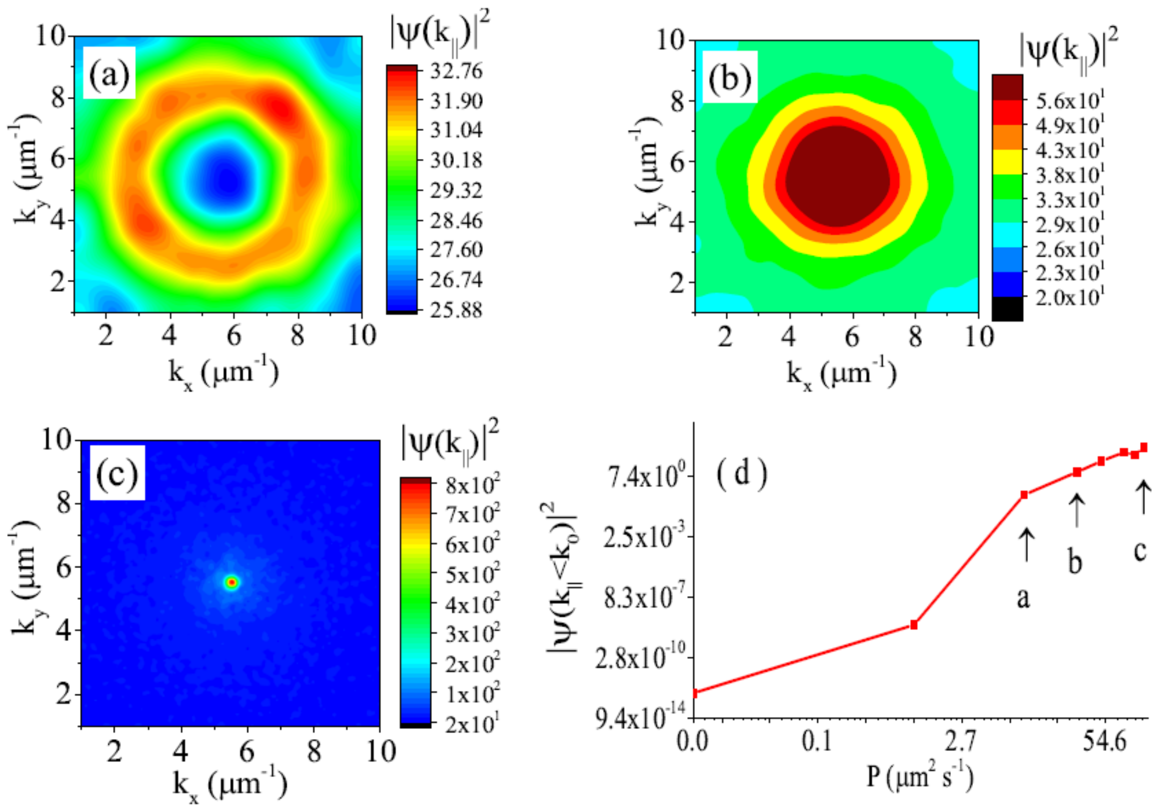
$$\left\langle \mathcal{T}^*_{\mathbf{q}_\parallel}(t)\mathcal{T}_{\mathbf{q}'_\parallel}(t')\right\rangle = \sum_{q_z} \left|G_{\mathbf{q}_\parallel, q_z}\right|^2 n_{\mathbf{q}_\parallel, q_z}\delta_{\mathbf{q}_\parallel, \mathbf{q}'_\parallel}\delta(t-t')$$

$$\left\langle \mathcal{T}_{\mathbf{q}_\parallel}(t)\mathcal{T}_{\mathbf{q}'_\parallel}(t')\right\rangle = \left\langle \mathcal{T}^*_{\mathbf{q}_\parallel}(t)\mathcal{T}^*_{\mathbf{q}'_\parallel}(t')\right\rangle = 0.$$

I. G. Savenko, T. C. H. Liew, and I. A. Shelykh, PRL110, 127402 (2013).

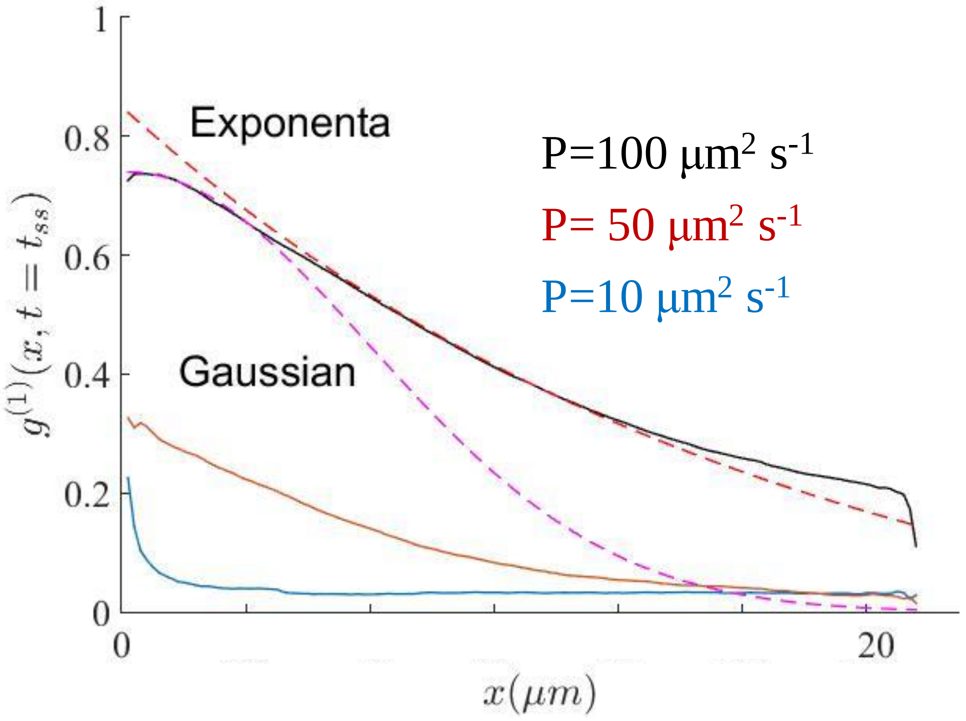
Condensation threshold

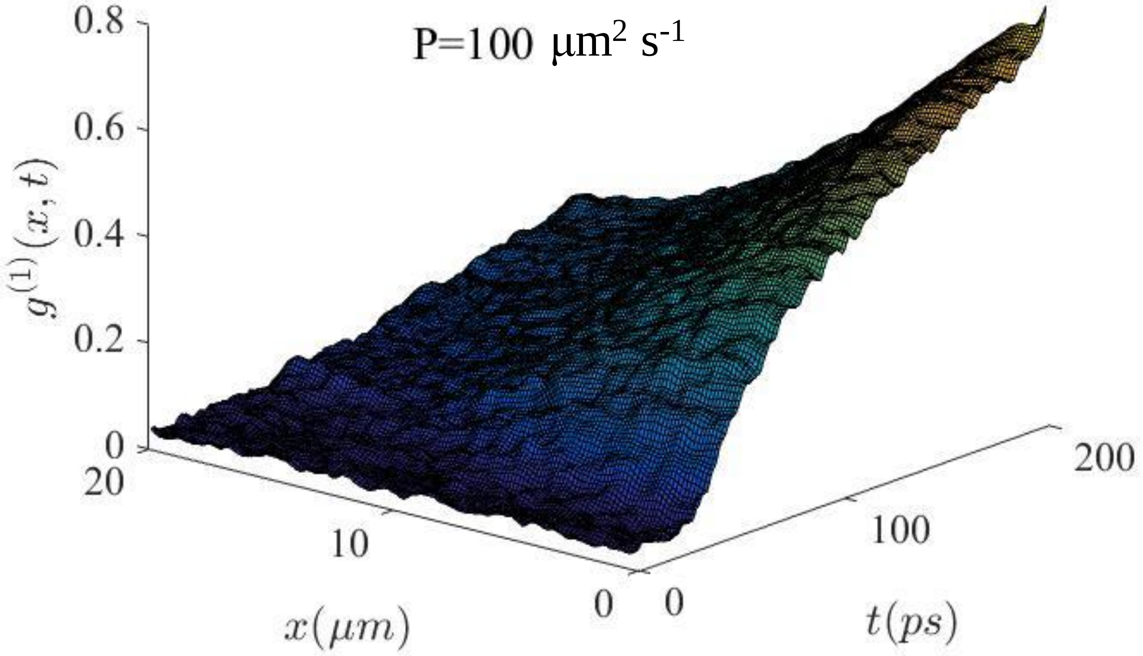
T= 10 K



First order correlation function

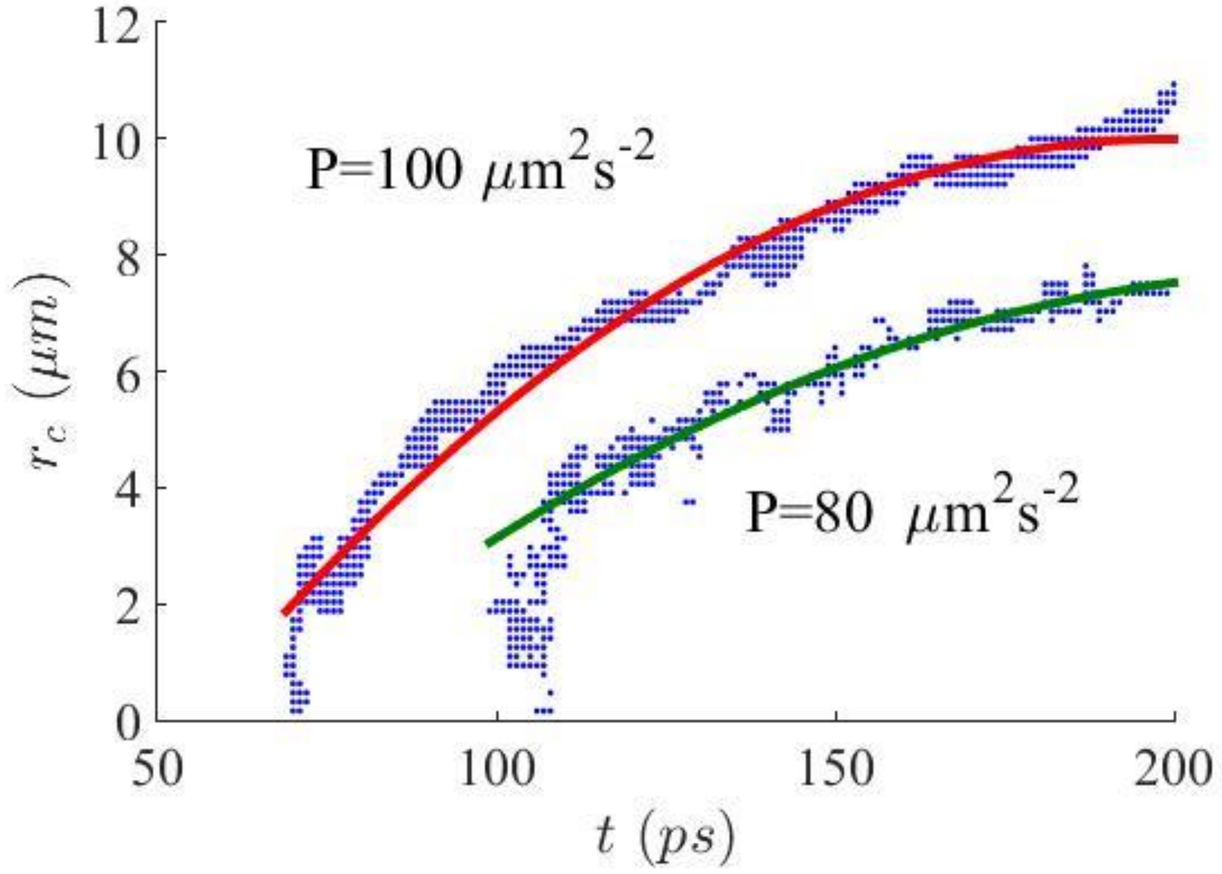
$$g^{(1)}(\mathbf{r}_\parallel) = \frac{\langle \psi^*(0, t_{ss})\psi(r_\parallel, t_{ss})\rangle}{\sqrt{\langle|\psi(r_\parallel, t_{ss})|^2\rangle\langle|\psi(0, t_{ss})|^2\rangle}}$$





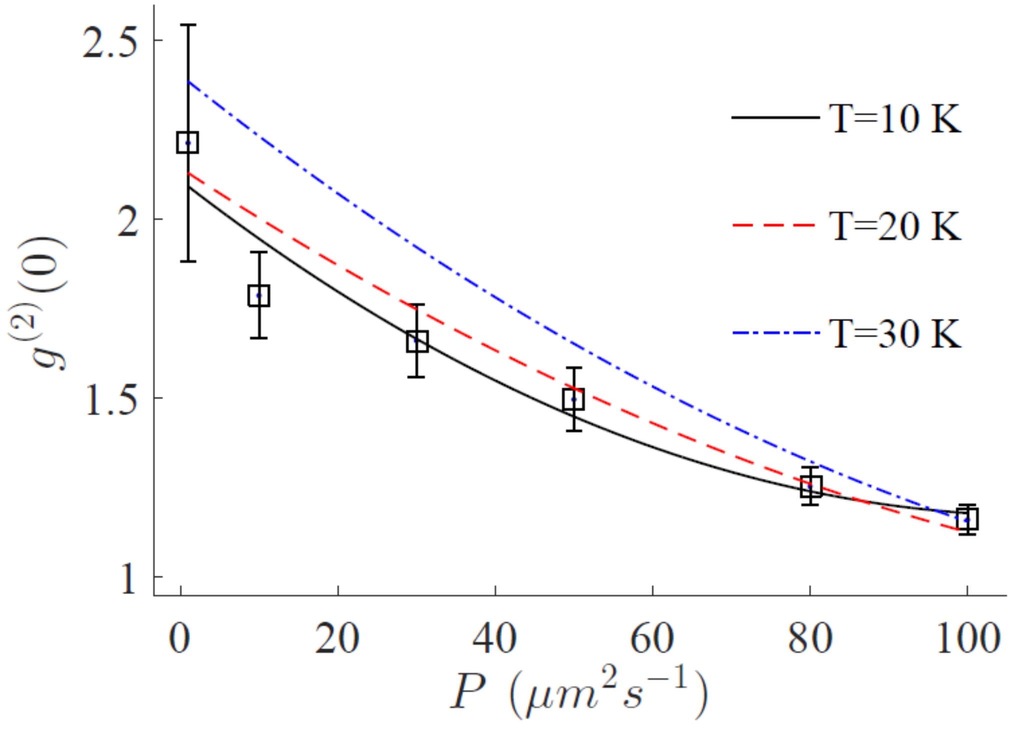
Correlation radius

$$g^{(1)}(r_c) = e^{-1}$$



Second order correlation function

$$g^{(2)}(t) = \frac{\langle \psi^*(0, t_{ss}) \psi^*(0, t) \psi(0, t_{ss}) \psi(0, t) \rangle}{\langle |\psi(0, t_{ss})|^2 \rangle \langle |\psi(0, t)|^2 \rangle}$$



Conclusion

- We derived a two-dimensional stochastic Gross-Pitaevskii equation, where the energy relaxation of bosons is provided by coupling to an incoherent field, treated as stochastic variable.

- We derived stochastic noise from first principles based on exciton-phonon equation

- Correlation analysis was employed to demonstrate opportunity of this approach

Thank you!