Blueshift corrections of a 1D exciton-polariton condensate

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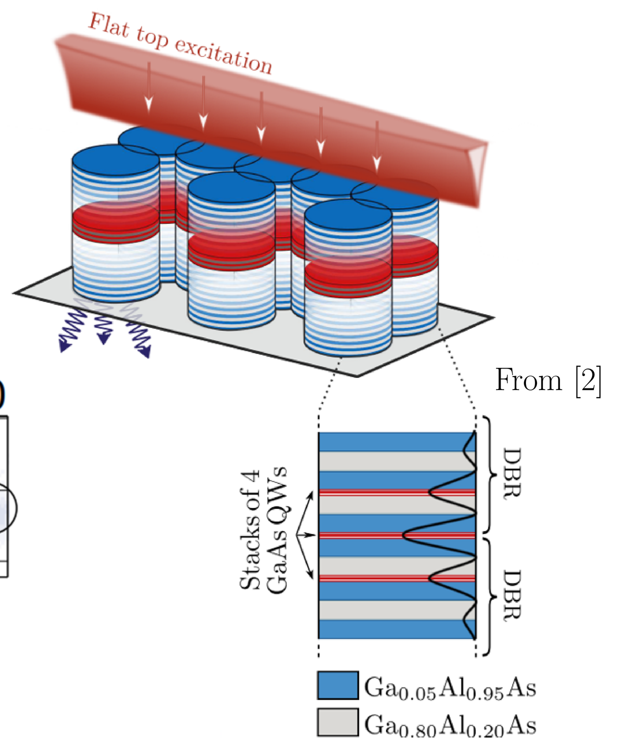
Introduction

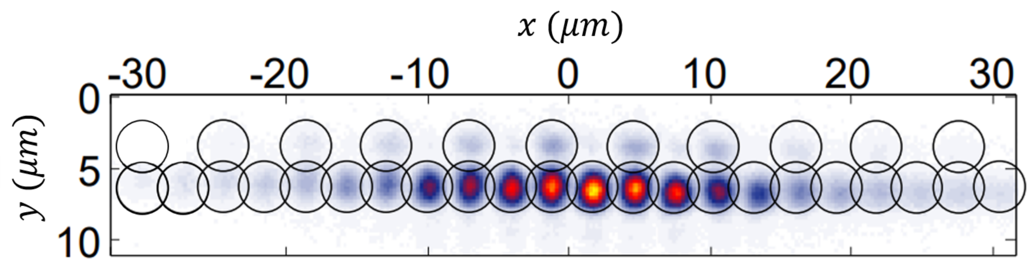
Exciton-polariton are bosonic quasi-particles that arise from the strong coupling between light and matter. They are typically formed in a quantum well embedded in an optical microcavity, from the interaction between quantum well excitons and cavity photons. Under non-resonant pumping, it is shown that exciton-polariton can form a Bose-Einstein condensate (BEC). This out of equilibrium BEC is sustained in a stationary state by the competition between continuous laser driving and losses coming from the leakage of cavity photons. Recent studies focused on the coherence properties of such driven-dissipative condensates and established connections with the Kardar-Parisi-Zhang (KPZ) universality class [1]. In particular, it is now known that the variance of the phase of one-dimensional polariton condensates follows the KPZ scaling in space and in time [2]. In the defect-free KPZ phase [4] of a 1D polariton BEC, we investigate the parameter dependence of blueshift stochastic fluctuations and propose a parallel with chemical potential quantum corrections. Chemical potential corrections are extensively studied for equilibrium BECs [3], but their description is still lacking in driven-dissipative condensates.

Driven-dissipative polariton BEC

Polariton: Eigenstates of a strongly interacting exciton-photon system
$\rightarrow$ **out of equilibrium** BEC above a pump threshold



From [3]



Negative effective mass polariton [5]: stable BEC of repulsive effective polariton coupling

Constitutive equation

- ψ BEC wavefunction: **non-linear stochastic Schrödinger equation**
- n_R exciton reservoir density: **rate equation**

$$i\hbar\partial_t\psi = \left[-\frac{\hbar^2}{2m}\partial_x^2 - \frac{i\hbar\gamma\left(\partial_x^2\right)}{2} + g|\psi|^2 + 2g_R n_R + \frac{i\hbar R}{2}n_R\right]\psi + \hbar\sqrt{\sigma}\xi$$

k-dependent dissipation: $\mathcal{F}\left[\gamma\left(\partial_x^2\right)\right]\ \gamma_o+\gamma_2 k^2$; polariton interactions; polariton-exciton interaction; Gaussian noise

$$\partial_t n_R = P_{th}p - \left(\gamma_R + R|\psi|^2\right)n_R$$

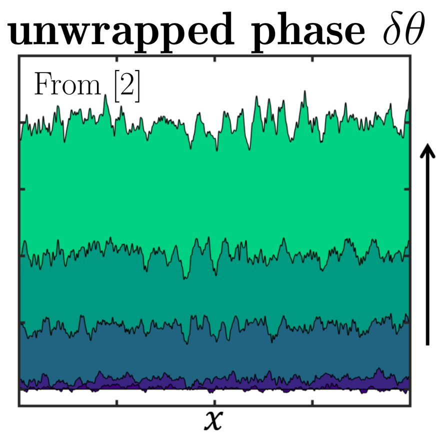
incoherent pump; dissipation; exciton-polariton scattering

Link to KPZ universality class

$$\psi = \sqrt{\rho}e^{i\theta} \text{ and expand } \begin{cases} \rho(x,t) = \rho_o + \delta\rho(x,t) \\ \theta(x,t) = \theta_o(t) + \delta\theta(x,t) \\ n_R(x,t) = n_{Ro} + \delta n_R(x,t) \end{cases} \quad \text{with } \theta_o(t) = -\overbrace{(g\rho_o + 2g_R n_{Ro})}^{\Omega_o} t$$

$\downarrow\ \partial_{x,t}\delta\rho \approx 0,\ \partial_{x,t}\delta n_R \approx 0$

Kinetically roughening of unwrapped phase $\delta\theta$



KPZ equation for the phase fluctuations [1]: $\partial_t\delta\theta = \nu\partial_x^2\delta\theta + \frac{\lambda}{2}(\partial_x\delta\theta)^2 + \sqrt{D}\eta$,
$\langle\eta\rangle = 0$ and $\langle\eta(x,t)\eta(x',t')\rangle = 2\delta(x-x')\delta(t-t')$

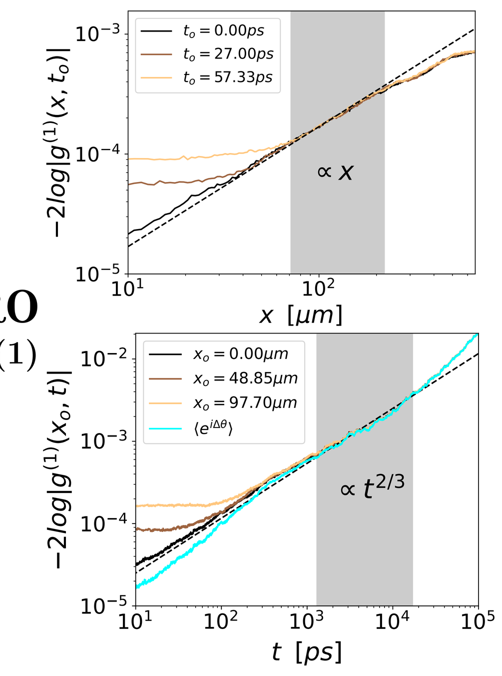
$\Longrightarrow\ \delta\theta \underset{t\to+\infty}{\sim} -\Omega_\infty t + (\Gamma t)^{1/3}\chi$, with $\Omega_\infty = \lim_{t\to+\infty} -\langle\partial_t\delta\theta\rangle$, **KPZ long time behaviour**

Coherence properties

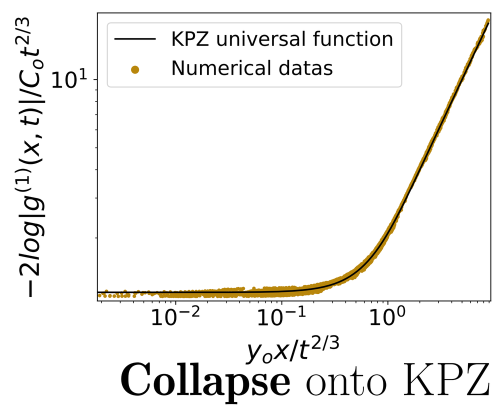
$$g^{(1)}(x,t) = \frac{\langle\psi^*(x,t)\psi(0,0)\rangle}{\sqrt{\langle\rho(x,t)\rangle\langle\rho(0,0)\rangle}} \approx \exp\left(-\frac{1}{2}\text{Var}\left[\delta\theta(x,t)\right]\right)$$

KPZ scaling $\text{Var}[\delta\theta(x,t_o)] \sim x^{2\alpha}$, $\text{Var}[\delta\theta(x_o,t)] \sim t^{2\beta}$, $\alpha = 1/2$, $\beta = 1/3$

No ODLRO for $g^{(1)}$



$\longrightarrow$



Collapse onto KPZ universal function

Blueshift fluctuations

- Equilibrium BEC: $\psi(x,t) = \sqrt{\rho(x)}e^{i\theta(t)}$ with $\theta(t) = -(\mu_{MF} + \mu_{QD})t$
- Driven-dissipative BEC: small fluctuations $\rho(x,t) \approx \rho(x)$

$$\theta(t) = -\underbrace{(\Omega_o + \Omega_\infty)}_{\substack{\text{MF chem. pot.} \\ +\text{ fluctuations}}} t + (\Gamma t)^{1/3}\chi$$

Adiabatic **Bogoliubov's theory**

$$\langle\xi_i\rangle = 0,\ \langle\xi_1\xi_2\rangle = 0$$

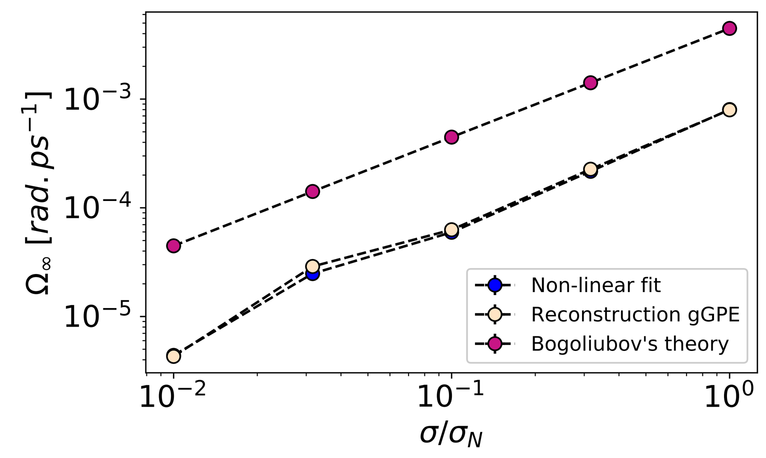
$$(\partial_t - \mathcal{L}_k)\begin{pmatrix}\delta\theta \\ \delta\rho/\rho_o\end{pmatrix} = \begin{pmatrix}\xi_1 \\ \xi_2\end{pmatrix},\ \langle\xi_i(x,t)\xi_i(x',t')\rangle = \frac{\sigma}{\rho_o}\left(1 + 3\delta_{i,2}\right)\delta(x-x')\delta(t-t')$$

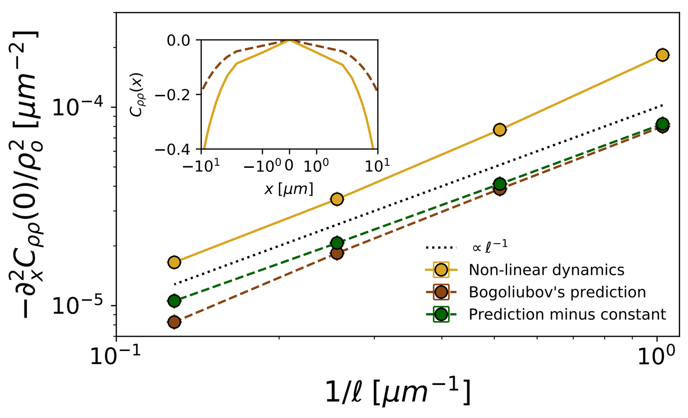
$$\mathcal{L}_k = \begin{pmatrix} -\frac{\gamma_2}{2}k^2 & -\frac{1}{2}\varepsilon_k - g_{eff}\rho_o \\ 2\varepsilon_k & -\frac{\gamma_2}{2}k^2 - \gamma_o \end{pmatrix},\ \text{effective coupling } g_{eff} = g - 2\frac{g_R\gamma_o}{\gamma_R p} \text{ and } \varepsilon_k = \frac{\hbar}{2m}k^2$$

Results

Slope fluctuation computed from equal-time **correlation functions** [6]

$$\Omega_\infty = \frac{\hbar}{2m}\left\langle \frac{1}{2\rho}\partial_x^2\delta\rho - \frac{1}{4}\left(\frac{\partial_x\delta\rho}{\rho}\right)^2 - (\partial_x\delta\theta)^2 \right\rangle + \frac{\gamma_2}{2}\left\langle \frac{\partial_x\delta\rho\partial_x\delta\theta}{\rho} + \partial_x^2\delta\theta \right\rangle - \langle g\delta\rho + 2g_R\delta n_R\rangle$$





$\Omega_\infty \propto \sigma$ non-universal
Ω_∞ doesn't vanish when $\lambda(g) = 0$
low-D BEC $\rightarrow$ depend on lattice parameter ℓ [7]
In typical defect-free conditions, $|\Omega_\infty| \approx 0.5\mu$eV $\sim 5\times10^{-3}|\Omega_o|$

References

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Conclusions

- Ω_∞ is extracted from numerical simulations in the defect-free KPZ phase of a 1D polariton BEC
- Bogoliubov's theory accurately predicts the dependence on σ and on the lattice parameter ℓ.
- Contrary to its equilibrium counterparts, the blueshift of a 1D polariton BEC still depend on the lattice parameter ℓ.
- Blueshift corrections remain in the Edward-Wilkinson regime ($\lambda = 0$), highlighting non-negligible density corrections to the KPZ phase dynamics.

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