Phase diagram of a one-dimensional exciton-polariton condensate

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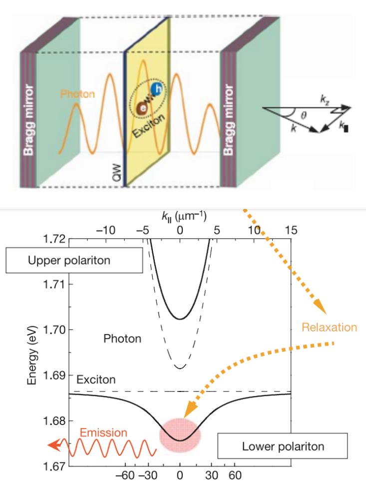
Exciton-polaritons



Strong coupling hamiltonian

$$\hat{H} = \sum_{\mathbf{k}} \{ E_{X,\mathbf{k}} \hat{a}^{\dagger}_{X,\mathbf{k}} \hat{a}_{X,\mathbf{k}} + E_{C,\mathbf{k}} \hat{a}^{\dagger}_{C,\mathbf{k}} \hat{a}_{C,\mathbf{k}} +$$

$$+ \hbar\Omega_R \left(\hat{a}^{\dagger}_{C,\mathbf{k}} \hat{a}_{X,\mathbf{k}} + \hat{a}^{\dagger}_{X,\mathbf{k}} \hat{a}_{C,\mathbf{k}} \right) \}$$

- cavity photons $\hat{a}_C$
- excitons in quantum well $\hat{a}_X$
- coupling rate Ω_R

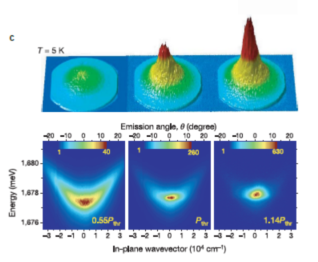
$\Rightarrow$ **Exciton-polaritons**

$$E_{UP/LP} = \frac{E_X + E_C}{2} \pm \sqrt{(\hbar\Omega_R)^2 + \left(\frac{E_X - E_C}{2}\right)^2}$$

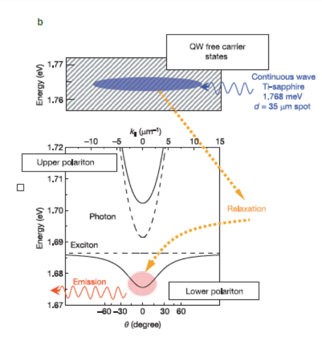
Exciton-polaritons condensation

Driven dissipative steady-state

- losses of photons
  $\Rightarrow$ finite lifetime of polaritons
- external laser driving (incoherent pumping)
  $\Rightarrow$ driven-dissipative steady state



Kasprzak et al, 2006. Nature, 443(7110)



Non equilibrium phase transition

- external laser driving > threshold
  $\Rightarrow$ Bose-Einstein Condensation
- Dynamics and statistical properties
  $\neq$ equilibrium BEC

Model for non equilibrium condensate

Mean-field dynamics of the condensate described by generalized **Gross-Pitaevskii equation**:

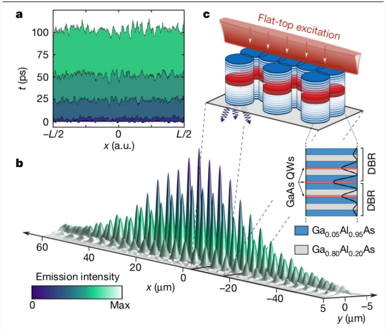
$$i\hbar\partial_t\psi = \left[\left(E_{EP}(\hat{k}) - \frac{i\hbar}{2}\gamma_{EP}(\hat{k})\right) + g|\psi|^2 + 2g_R n_R + \frac{i\hbar}{2}Rn_R\right]\psi + \hbar\xi$$

$$\partial_t n_R = P - \left(\gamma_R + R|\psi|^2\right) n_R$$

- Kinetic + 2 body interactions (equilibrium BEC)
- **losses** $\gamma_{EP}(\hat{k})$ + **driving** Rn_R
- **fluctuations** $\xi(t,x)$, white noise with amplitude $\sigma = Rn_R$:

$$\langle\xi(t,x)\rangle = 0$$

$$\langle\xi^*(t,x)\xi(t',x')\rangle = 2\sigma\delta(x-x')\delta(t-t')$$

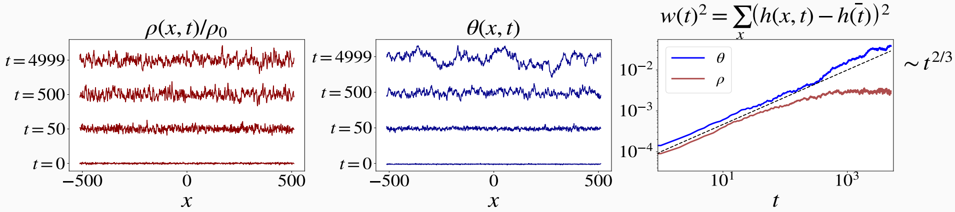


Q. Fontaine et al., Nature 608, 687 (2022)

Non-equilibrium condensate: KPZ dynamics of the phase

Density-phase decomposition $\psi = \sqrt{\rho}\, e^{i\theta}$
The dynamics of the phase $\theta = \mathrm{Arg}(\psi)$ is mapped to the **Kardar-Parisi-Zhang equation**:

$$\partial_t \theta = \nu \partial_x^2 \theta + \frac{\lambda}{2} (\partial_x \theta)^2 + \sqrt{D}\eta$$



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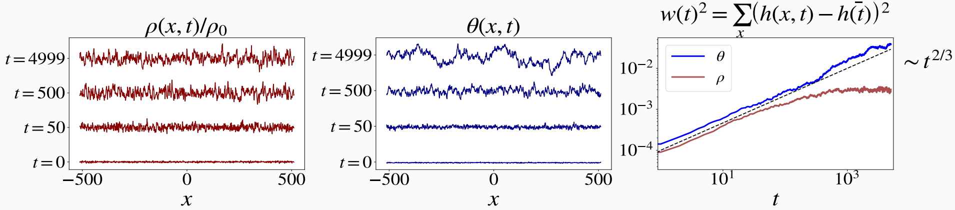
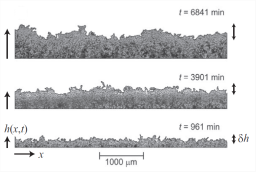
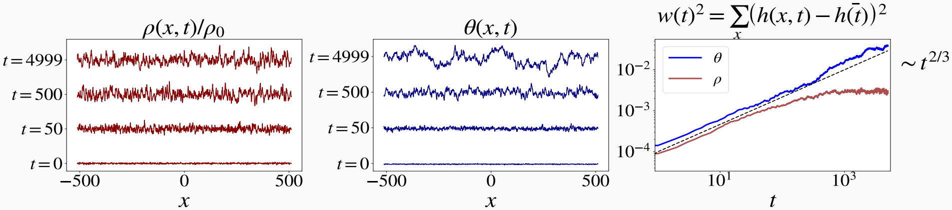


The **Kardar-Parisi-Zhang universality class** (non-equilibrium rough interfaces, randomly stirred fluids, ...)

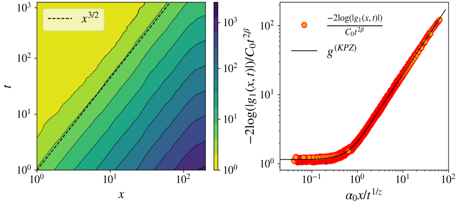


Non-equilibrium condensate: KPZ dynamics of the phase



The decay of **coherence** displays the **universal scaling behaviour** of KPZ

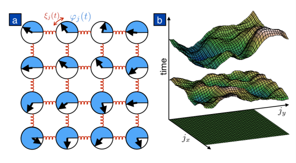
- $g^{(1)}(x,t) = \frac{\langle \psi^*(x_0,t_0)\psi(x_0+x,t_0+t)\rangle}{\sqrt{\langle|\psi(x_0,t_0)|^2\rangle\langle|\psi(x_0+x,t_0+t)|^2\rangle}}$
- $|g^{(1)}(x,t)| \simeq e^{-\frac{1}{2}C_\theta(x,t)}$
- $C_\theta(x,t) = C_0 t^{2\beta} g^{(KPZ)}(\alpha_0 \frac{x}{t^{1/z}})$
- $\beta = 1/3$, $z = 3/2$ **KPZ exponents (1d)**



Experiment → see talk of J.Bloch

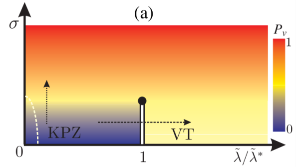
More non-equilibrium behaviours of exciton-polaritons

- Compact KPZ for discrete systems ⇒ de-synchronisation instability: **space-time vortices**



Arrays of coupled oscillators (in 1d and 2d)

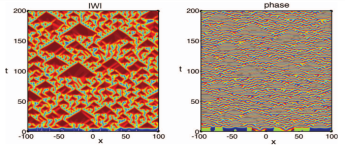
R. Lauter, A. Mitra, and F. Marquardt, Physical Review E 96, (2017)



Space-time vortices in neq condensates

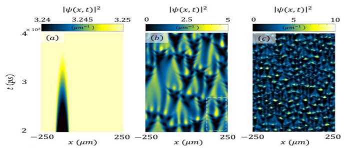
L. He, L. M. Sieberer, and S. Diehl, Physical Review Letters 118, (2017)

- **Instability** and **pattern-formation** $\Longleftrightarrow$ Complex Ginzburg-Landau Equation



Spatio-temporal chaos in CGLE

V. García-Morales and K. Krischer, Contemporary Physics 53, 79 (2012)



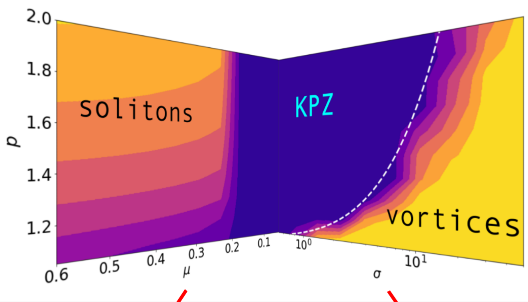
Space-time patterns in gGPE

N. Bobrovska et al., Physical Review B 99, (2019).

Study of the phase diagram of one-dimensional EP condensate

Laser pump

$$p = \frac{P}{P_{th}}$$



Interaction energy

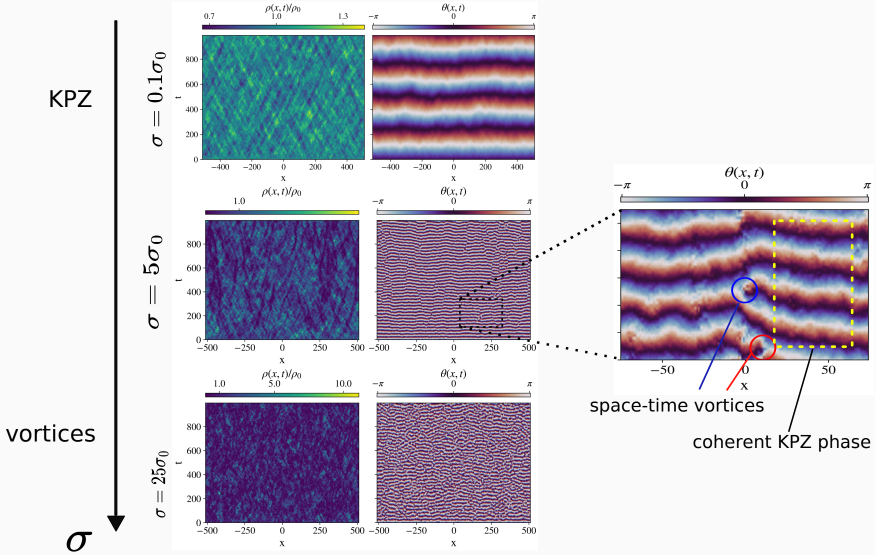
$$\mu = 2 g_R n_R$$

Noise strength

$$\frac{\sigma}{\sigma_0}$$

F.V. et al, in preparation (2023)

Effect of the noise: space-time vortex activation



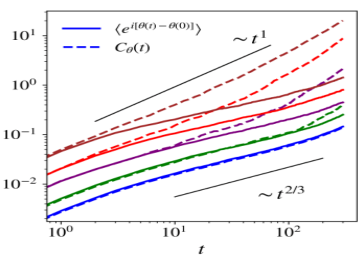
Defects vs KPZ

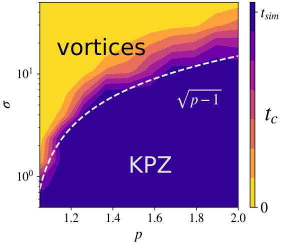
- With defects, the interface $\mathrm{Arg}(\psi) = \theta(x,t) + 2\pi N$ has singularities but is **KPZ piecewise**.
- The temporal coherence is not affected by random phase slips:

$$g^{(1)}(t) = \frac{\langle \psi^*(t_0)\psi(t+t_0)\rangle}{\langle |\psi|^2\rangle} \simeq \langle\, e^{i[\theta(t_0+t)-\theta(t_0)]}\rangle = g_0\, e^{-\alpha t^{2/3}}$$

- While the time-unwrapped phase $\theta^{(UW)}(x_0,t)$ is:

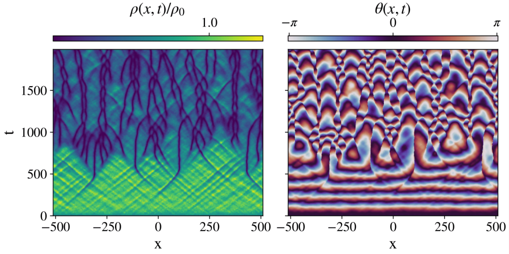
$$C_\theta^{(UW)}(t) = \langle \left[\theta^{(UW)}(t_0+t) - \theta^{(UW)}(t_0)\right]^2 \rangle \sim t^1$$



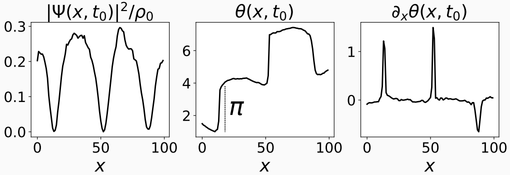


Solitons: pattern formation from instability

Spatio-temporal dynamics of $\psi = \sqrt{\rho}\, e^{i\theta}$

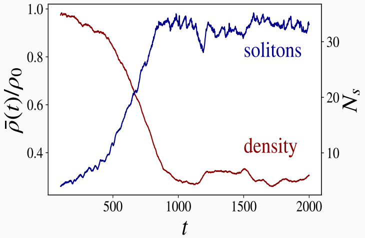


Soliton-like defects:



Characterisation of the transition:

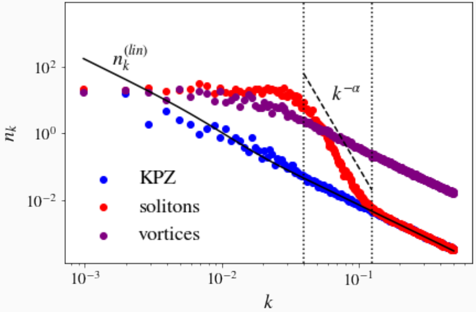
- Number of solitons:
  $N_s \simeq \frac{1}{\pi}\int_x |\partial_x\theta| dx$
- Average density:
  $\bar{\rho} = \frac{1}{L}\int_x |\psi|^2 dx$



$\Rightarrow (\mu, p)$ section of phase diagram

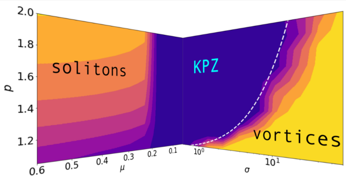
Signature of solitons: momentum distribution

Momentum distribution $n_k = \langle|\psi(k)|^2\rangle$



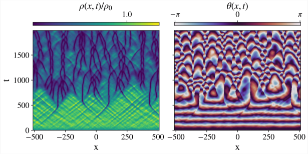
- KPZ: bogoliubov quasi-particles
- solitons: non-trivial behaviour $n_k \sim k^{-\alpha}$ ($\alpha = 6 \div 7$) at intermediate k
- vortices: spectral broadening for low k, but unclear signature

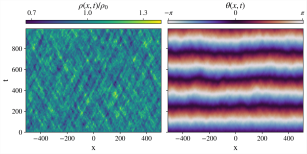
Summary

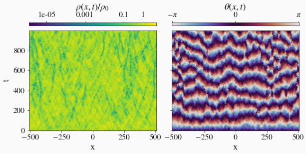


Non-equilibrium condensate of exciton-polaritons:

- Universal critical behaviour (KPZ)
- Rich phase diagram







- Long-lived soliton defects
- Short coherence
- Density-phase coupled dynamics

- No density dynamics
- Large coherence
- KPZ universality of the phase

- Random localized defects
- Piece-wise coherence
- Resilient KPZ scaling of the coherence

Outlook

- Understand modifications to the phase diagram due to **finite size** for experiments
- Extend analysis to understand the phase diagram of EP in two dimensions
- Accessing with EP the regimes of one-dimensional KPZ equation: new **inviscid fixed point** with dynamic scaling exponent $z = 1$ ($\rightarrow$ see talk of L.Canet)

Thank you

Thanks for the attention!

Collaborators:

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C2N

Jacqueline Bloch
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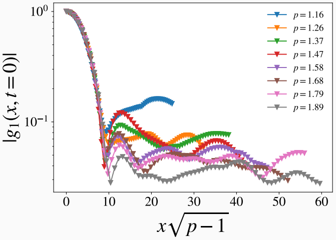
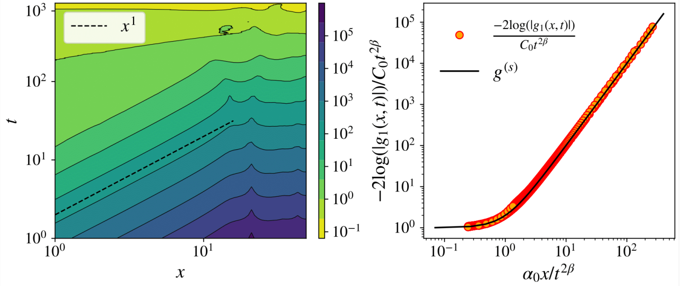
Extra: coherence in the soliton regime



Coherence in the soliton regime



Extra: Pump confinement

Trapping of single solitons with pump spatial profile