Kardar Parisi Zhang universal scaling in the coherent emission of polariton condensates

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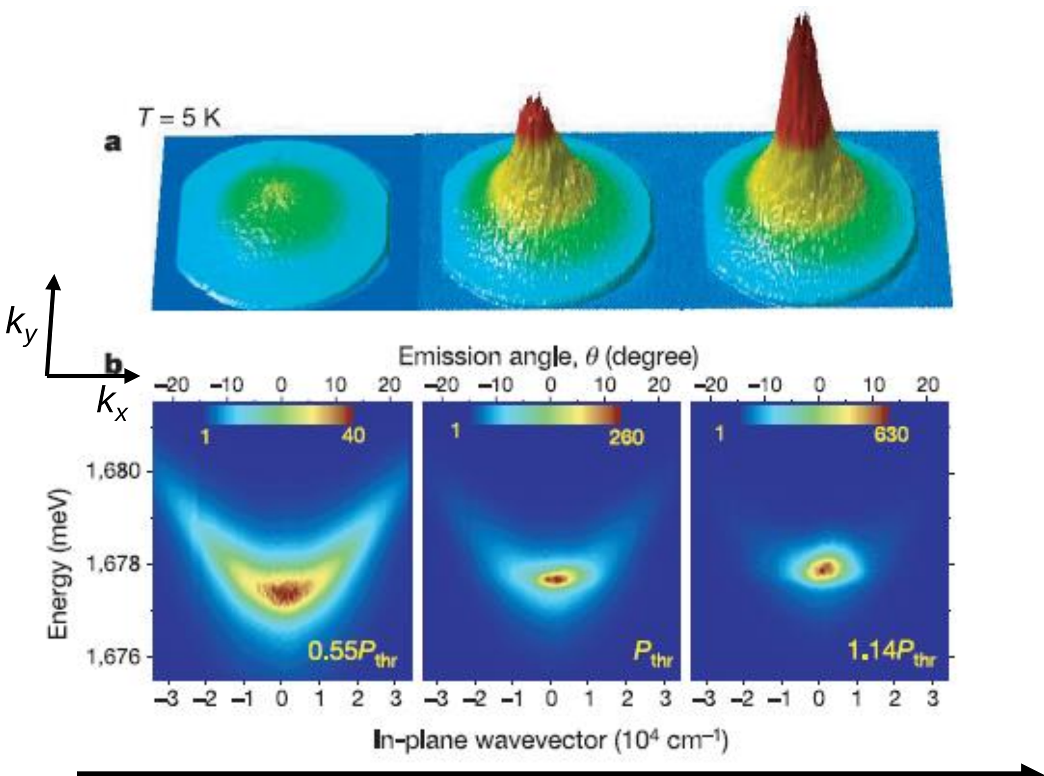
M. Wouters

Bose–Einstein condensation of exciton polaritons

J. Kasprzak[1], M. Richard[2], S. Kundermann[2], A. Baas[2], P. Jeambrun[2], J. M. J. Keeling[3], F. M. Marchetti[4], M. H. Szymańska[5], R. André[1], J. L. Staehli[2], V. Savona[2], P. B. Littlewood[4], B. Deveaud[2] & Le Si Dang[1]



Increase excitation power

Similarities with atomic BEC

BUT

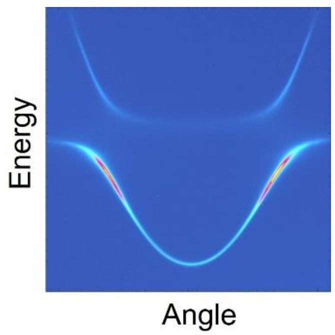
Driven dissipative system
Out of equilibrium

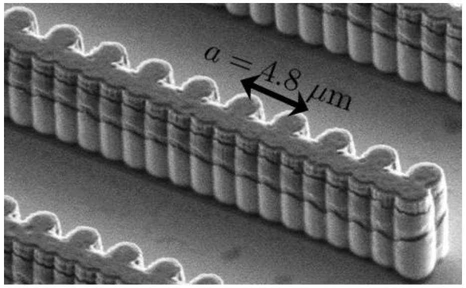
⇒ Different universality class than their equilibrium counterpart

Kasprzak *et al.* Nature, **443**, 409 (2006)
Also H. Deng et al. Science (2002), R. Balili et al., Science (2007),…..

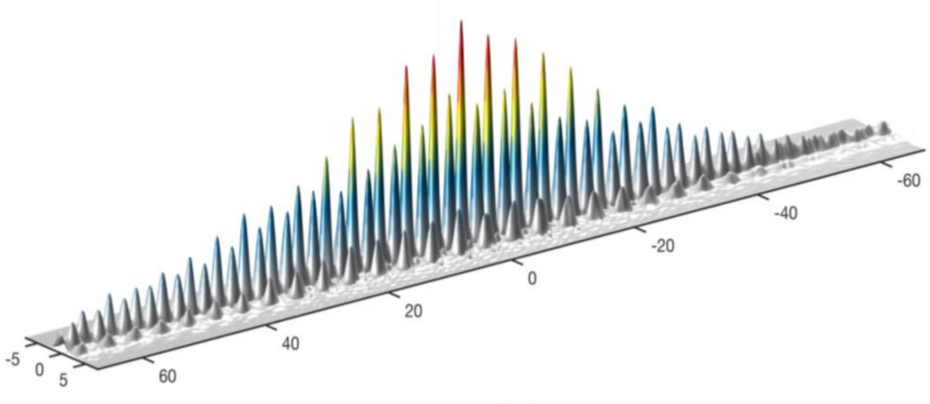
Outline of the talk

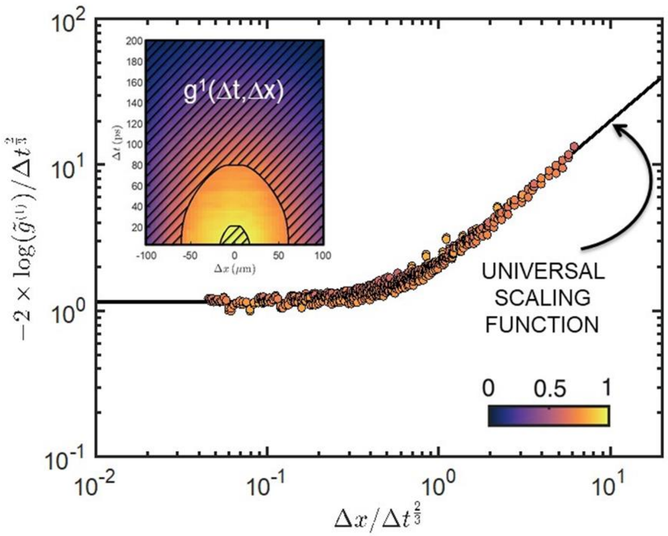
- Introduction : synthetic polariton matter



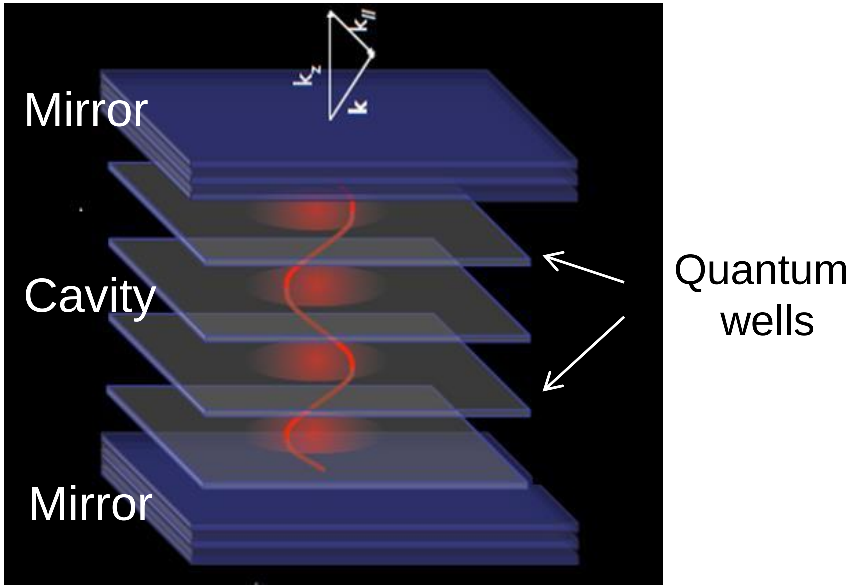


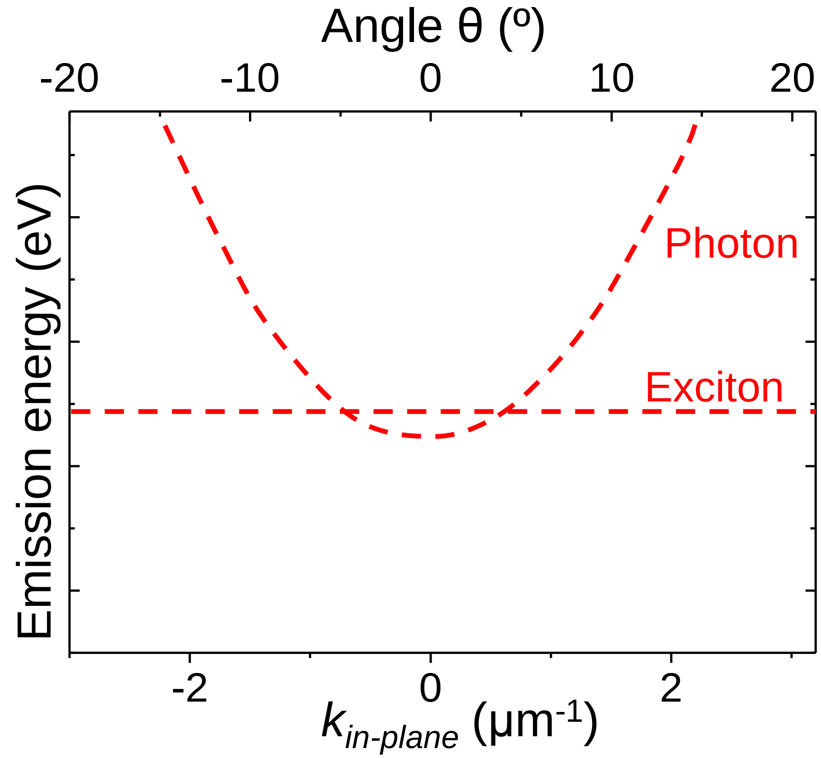
- Polariton condensates belong to the Kardar Parisi Zhang universality class



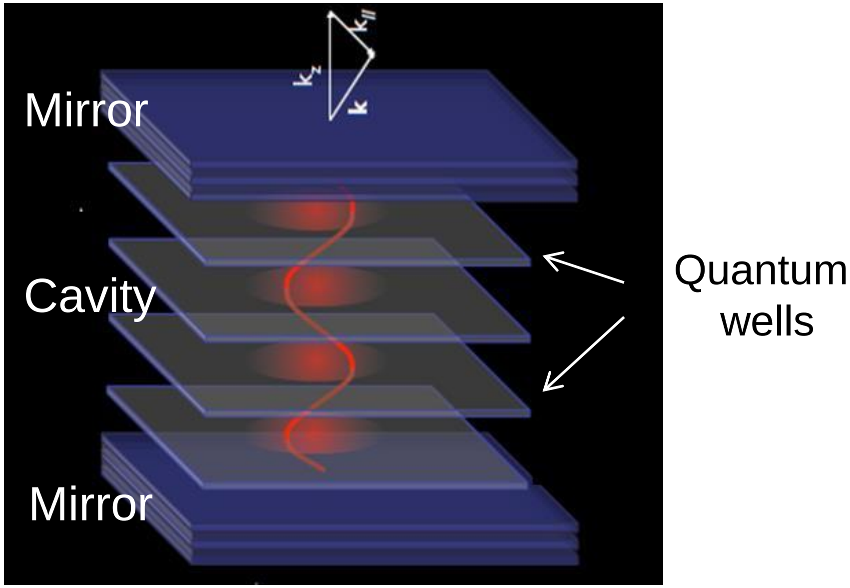


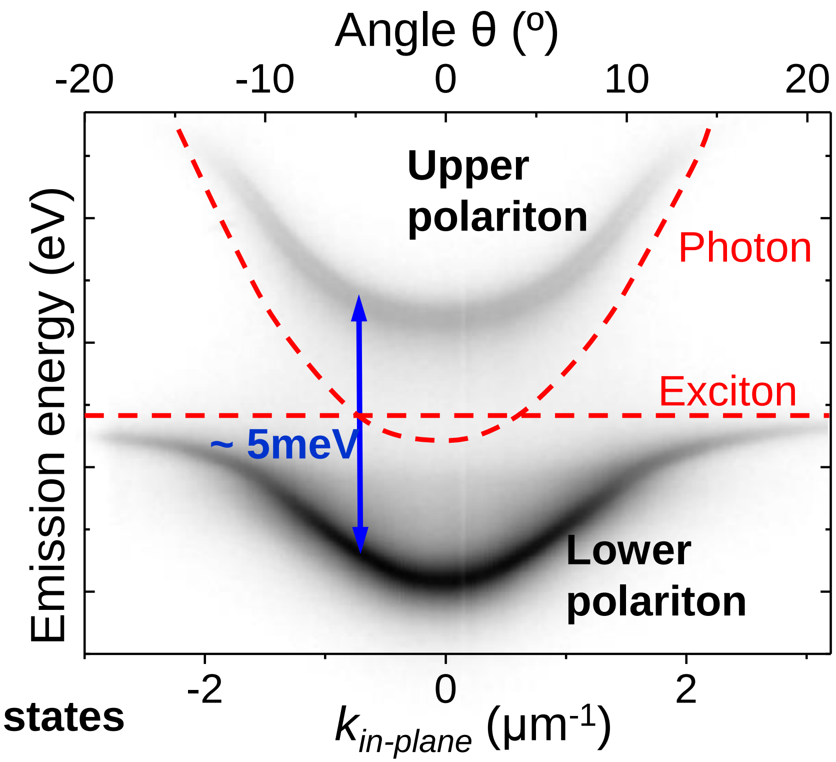
Microcavity polaritons



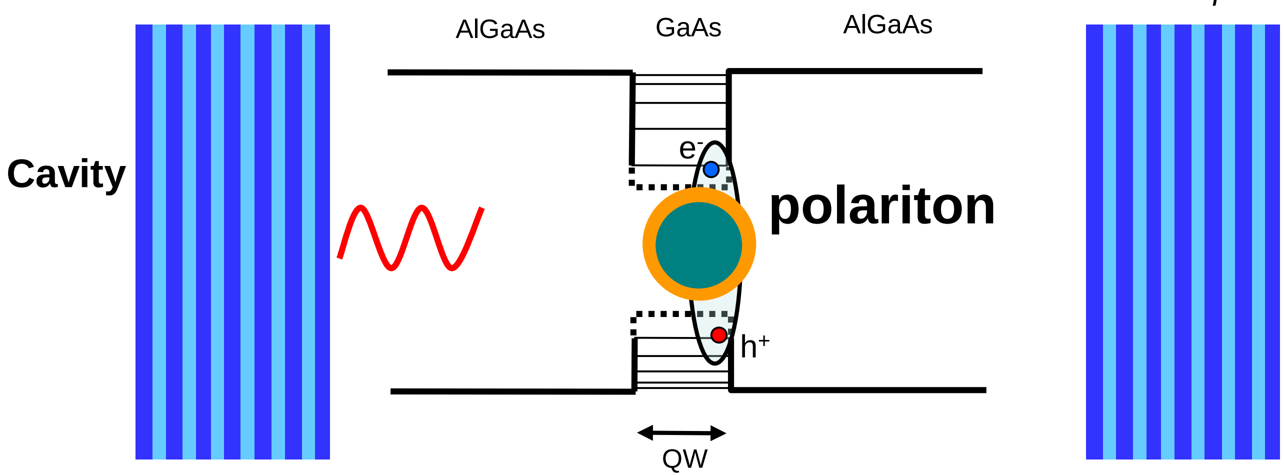


Microcavity polaritons





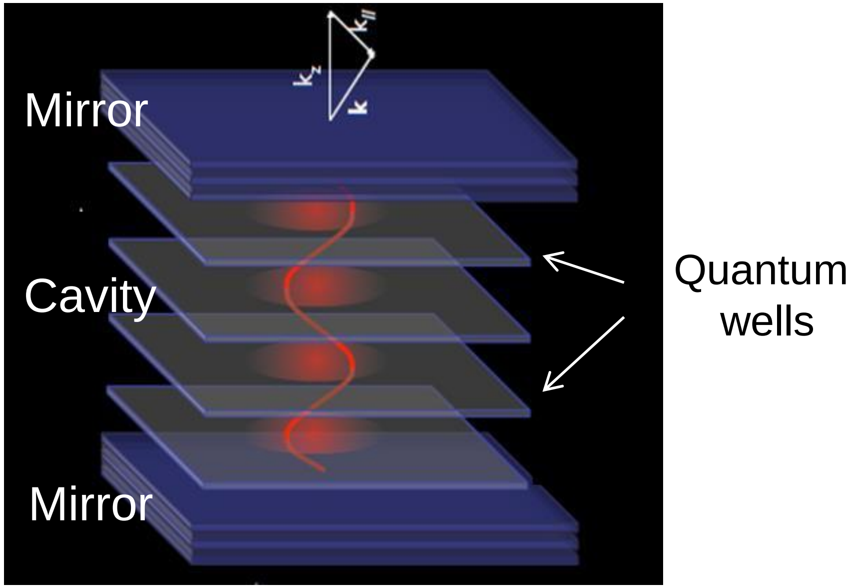
Microcavity polaritons : mixed exciton-photon states

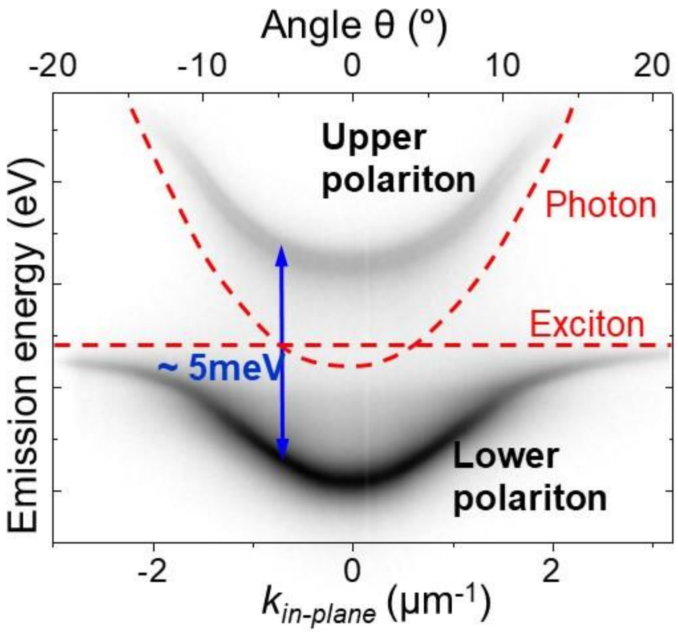


Courtesy D.Sanvitto

Claude Weisbuch
PRL **69**, 3314 (1992)

Microcavity polaritons





Microcavity polaritons : mixed exciton-photon states

Properties $$|1\mathrm{LP}_{\mathbf{k}}, 0_{\mathbf{k}}\rangle = (\cos\theta_{\mathbf{k}}\hat{a}^{\dagger}_{\mathbf{k}} + \sin\theta_{\mathbf{k}}\hat{b}^{\dagger}_{\mathbf{k}})\,|0_{\mathbf{k}}, 0_{\mathbf{k}}\rangle$$

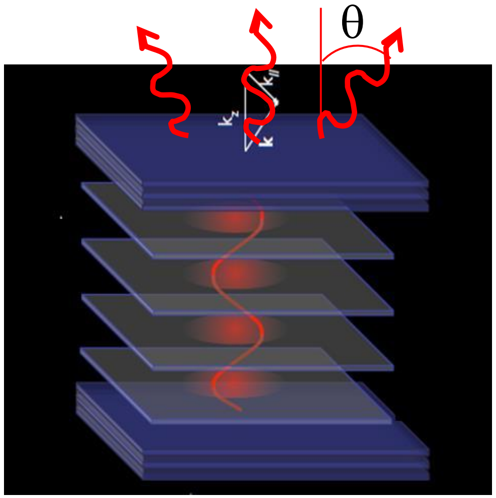
Photons — Excitons

- Photonic component ➡ Confinement in microstructures
  Dissipation
- Excitonic component ➡
  - Interactions - $\chi^{(3)}$ (dominated by exchange)
  - Gain (lasing)
  - Sensitivity to magnetic field

Claude Weisbuch PRL **69**, 3314 (1992)

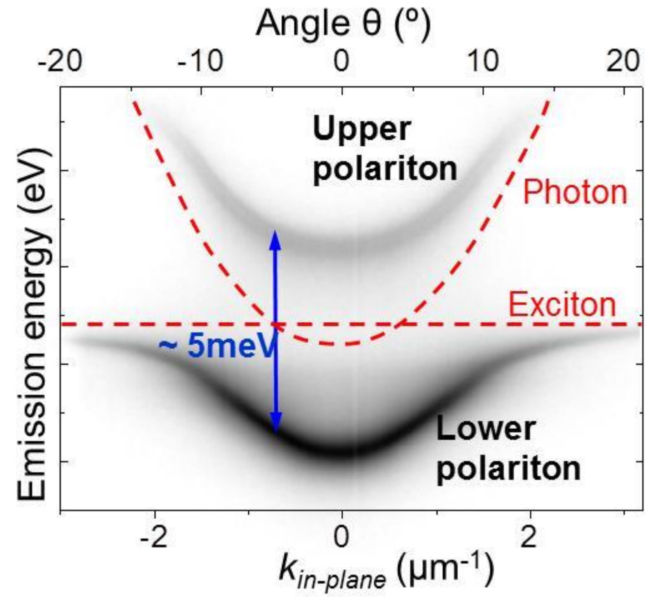
C. Ciuti & I. Carusotto, Rev. Mod. Phys. **85**, 299 (2013)

Probing polariton states

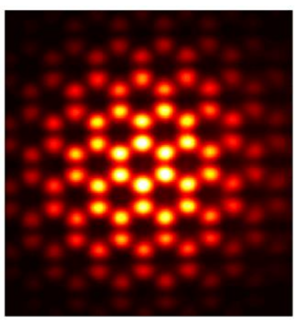


$k_{//} = \omega/c \sin(\theta)$

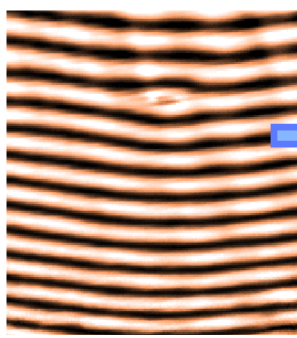
Imaging of k-space



Imaging of real space

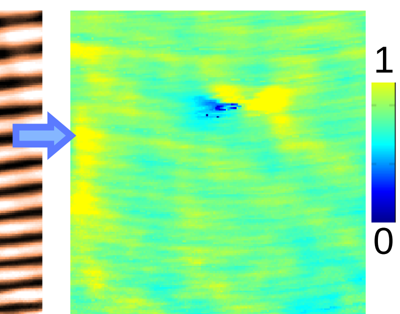


Density



Interferometry

- vortices
- solitons

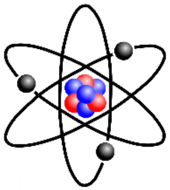


Coherence

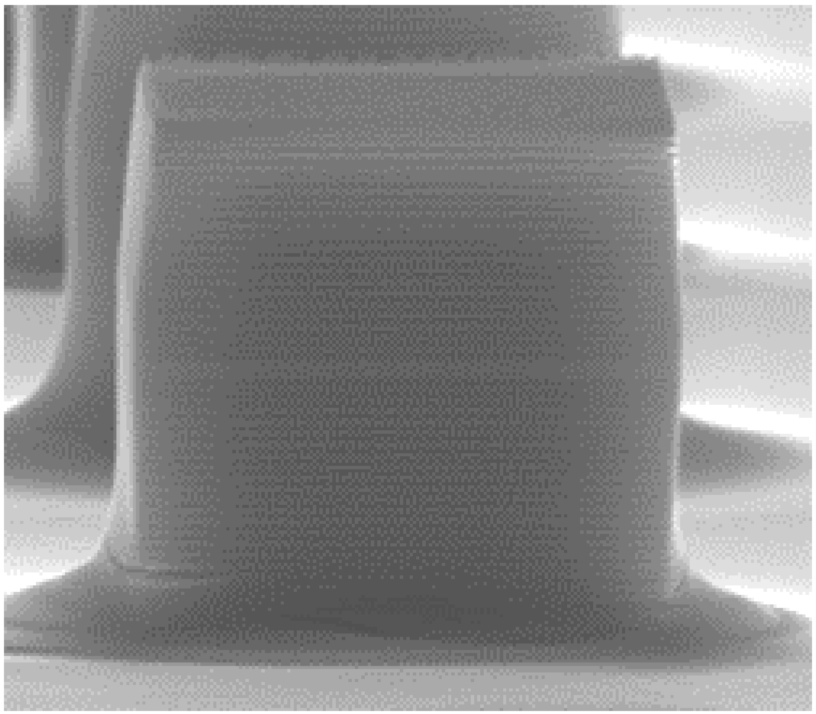
$g^{(1)}$

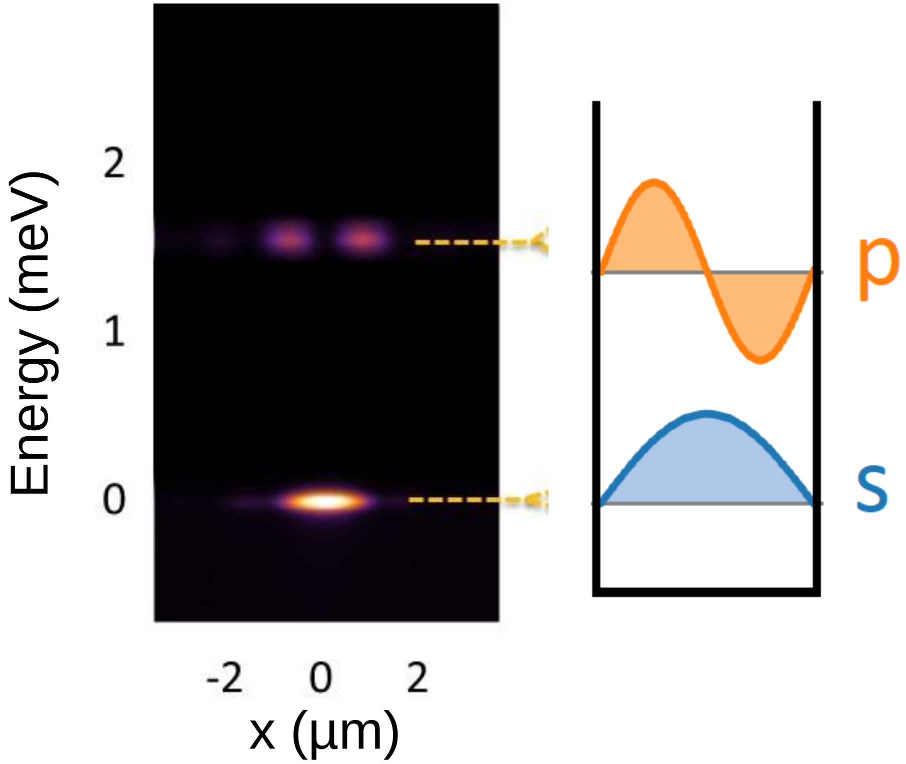
$g^{(2)}$

Lattices of coupled micropillars

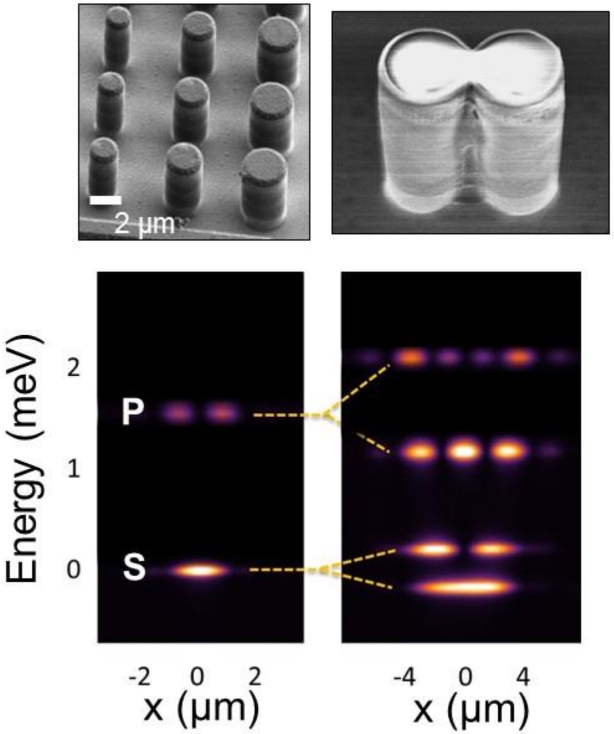


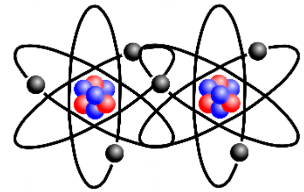
Building block



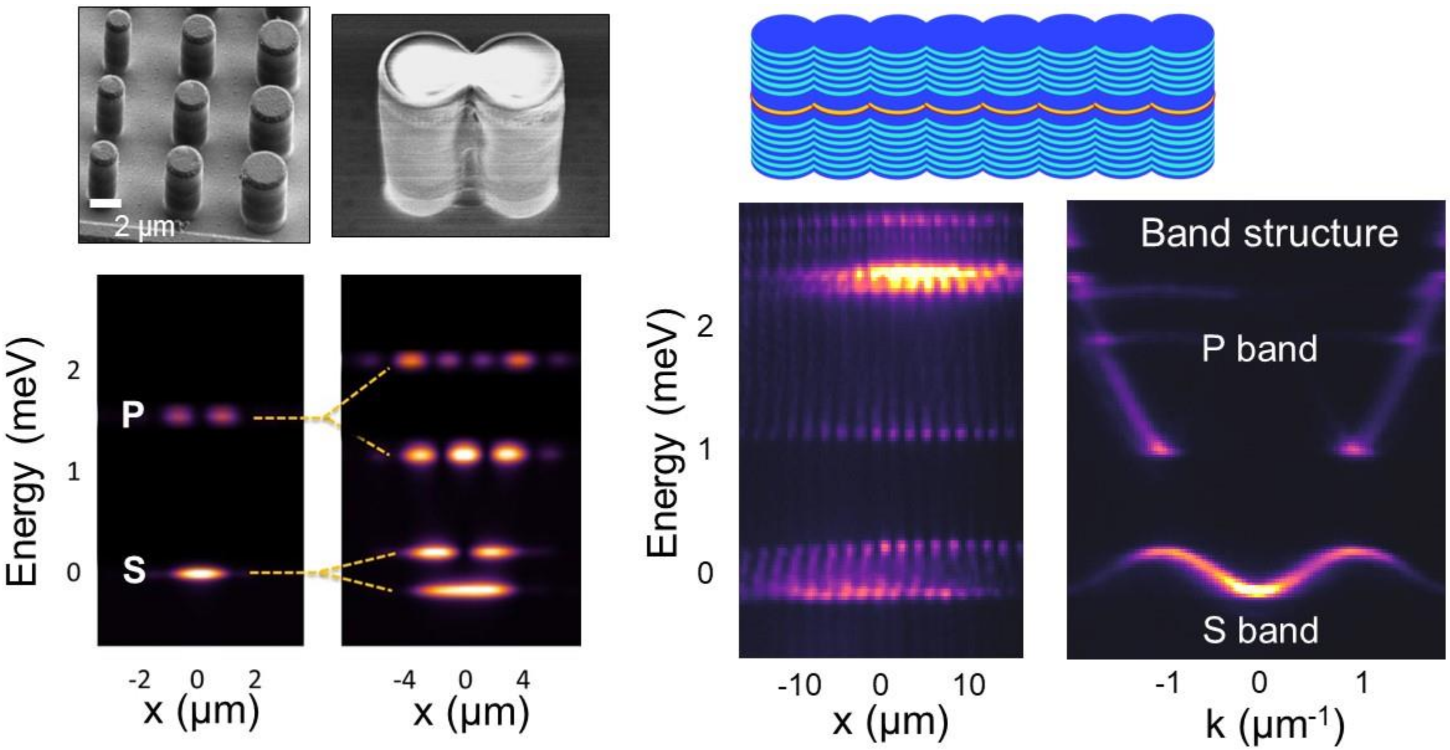


Lattices of coupled micropillars





Lattices of coupled micropillars



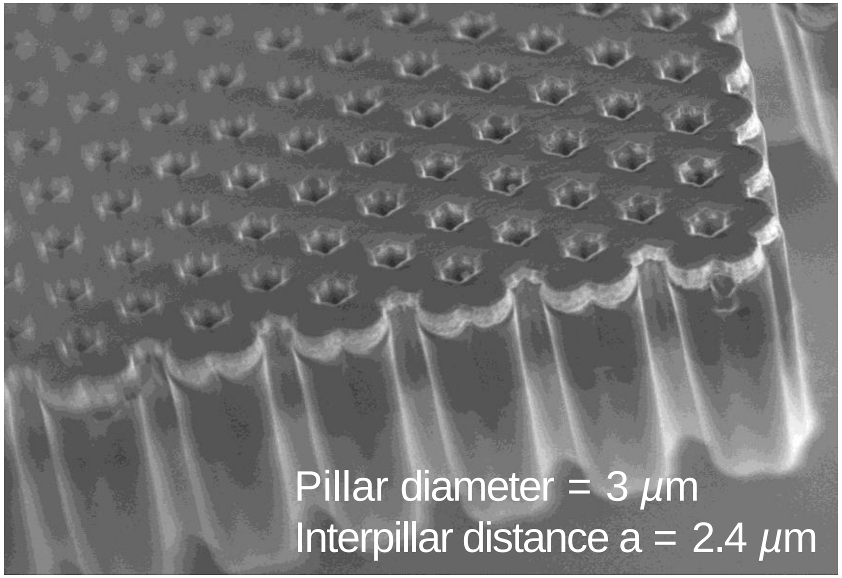
Correspondance : Wavefunction = electric field

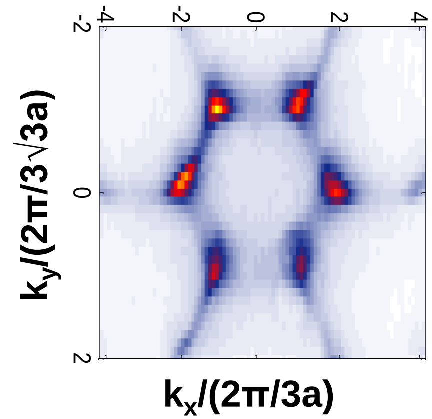
Spin = Polarisation

$$i\hbar\dot{\psi}_n = \left(\hbar\omega_n - i\frac{\gamma_n}{2}\right)\psi_n + U\left|\psi_n\right|^2\psi_n - J\psi_m + F_n e^{-i\omega t}$$

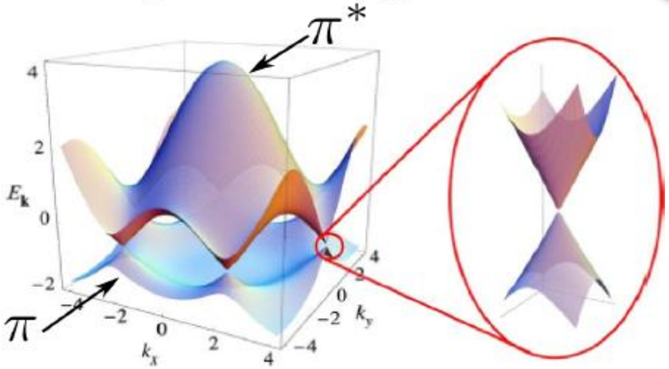
C. Ciuti & I. Carusotto, Rev. Mod. Phys. **85**, 299 (2013)
Compte Rendus Physique Vol. 17, Issue 8, Pages 805-956 (2016)
Physique des polaritons: Edité par A. Amo, J. Bloch and I. Carusotto

Polariton honeycomb lattice

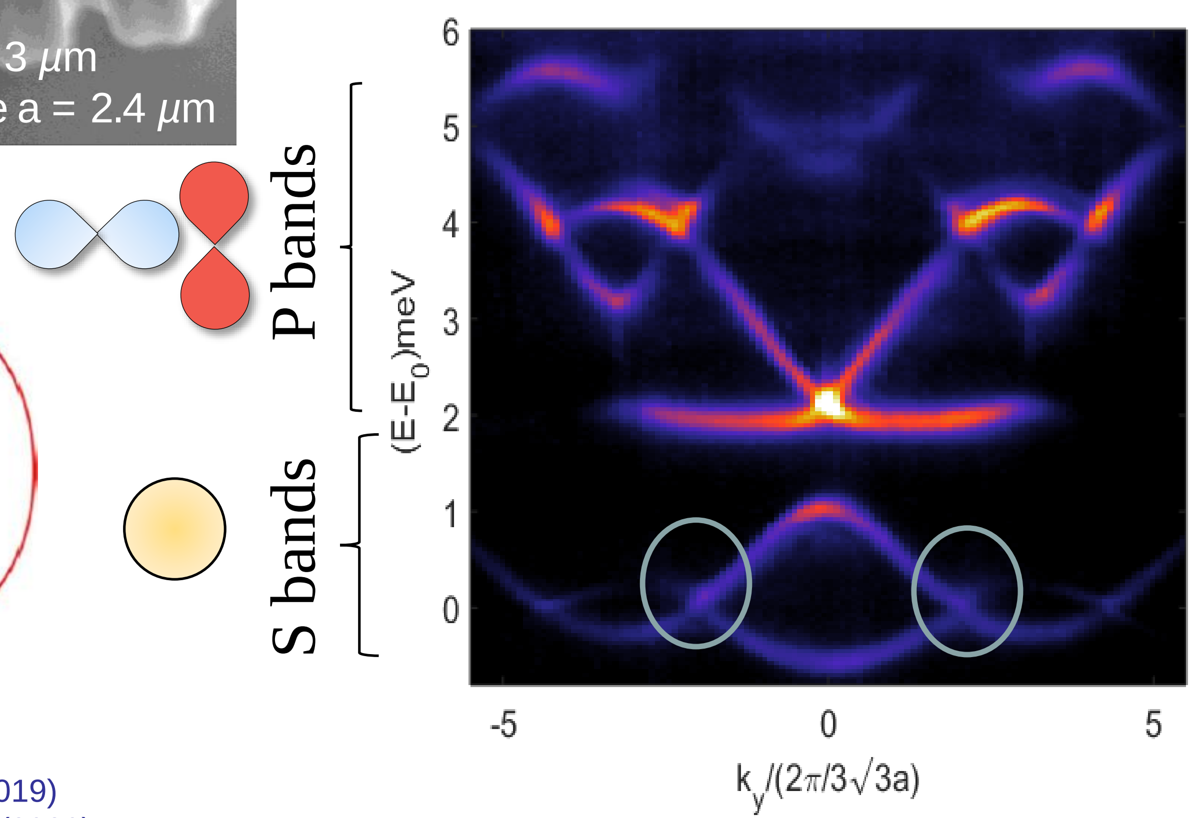




Graphene energy bands



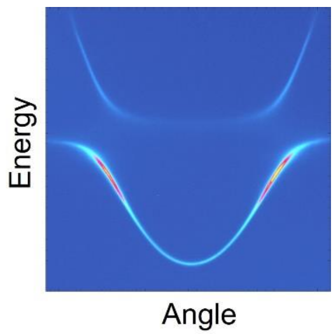
Castro Neto et al., Rev. Mod. Phys. 81 (2009)

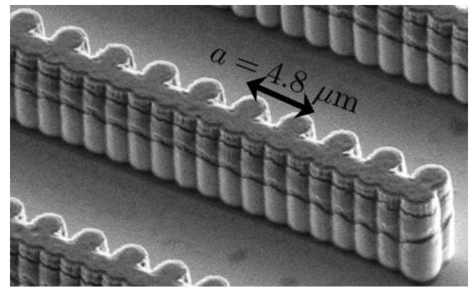


Jacqmin *et al.,* PRL **112,** 116402 (2014)
M. Milićević et al., Phys. Rev. X 9, 31010 (2019)
B. Real et al., Phys. Rev. Lett. 125, 186601 (2020)

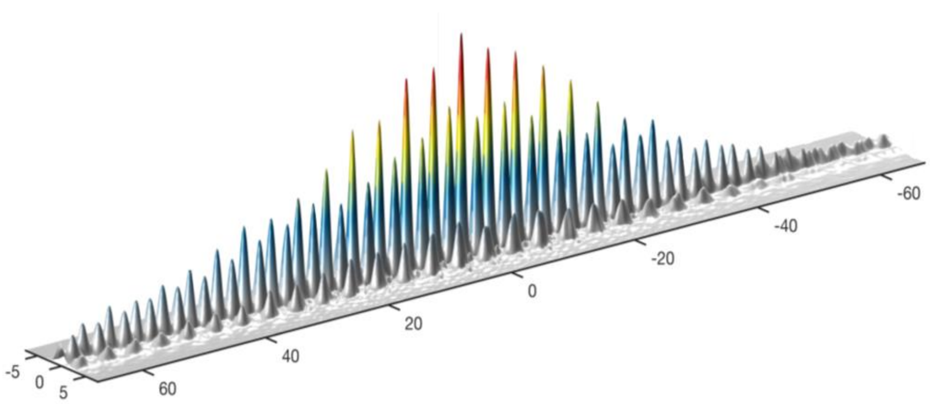
Outline of the talk

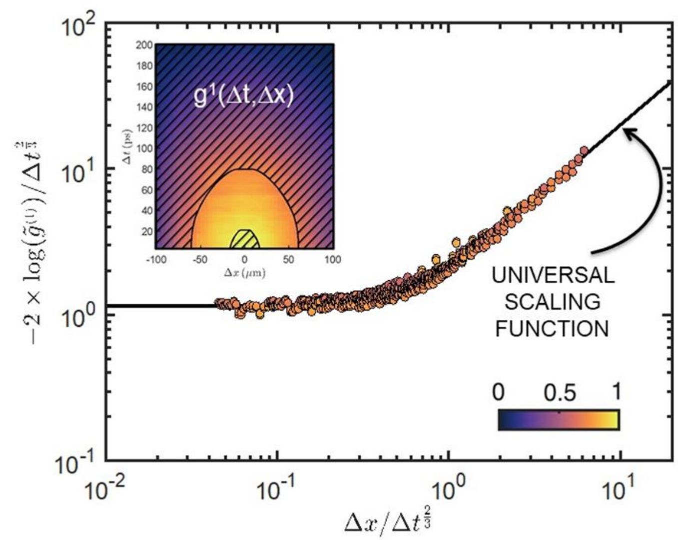
➢ Introduction : synthetic polariton matter



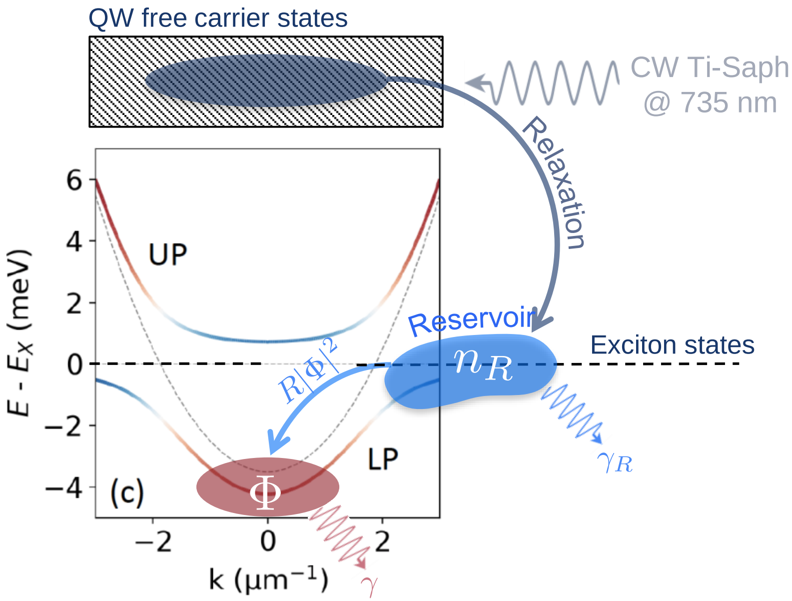


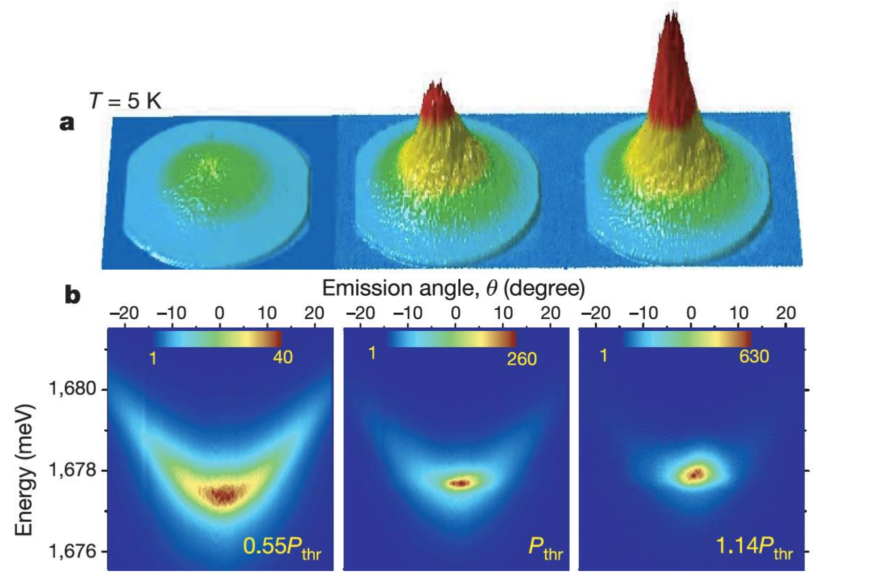
➢ Polariton condensate belong to the Kardar Parisi Zhang universality class





Polariton Bose Einstein condensation





Kasprzak *et al.* Nature, **443**, 409 (2006)

See also H. Deng et al. Science (2002), R. Balili et al., Science (2007)

J. Bloch, I. Carusotto and M. Wouters, *Spontaneous coherence in spatially extended photonic systems: Non-Equilibrium Bose-Einstein condensation, Nature Review Physics (2022) (https://doi.org/10.1038/s42254-022-00464-0)*

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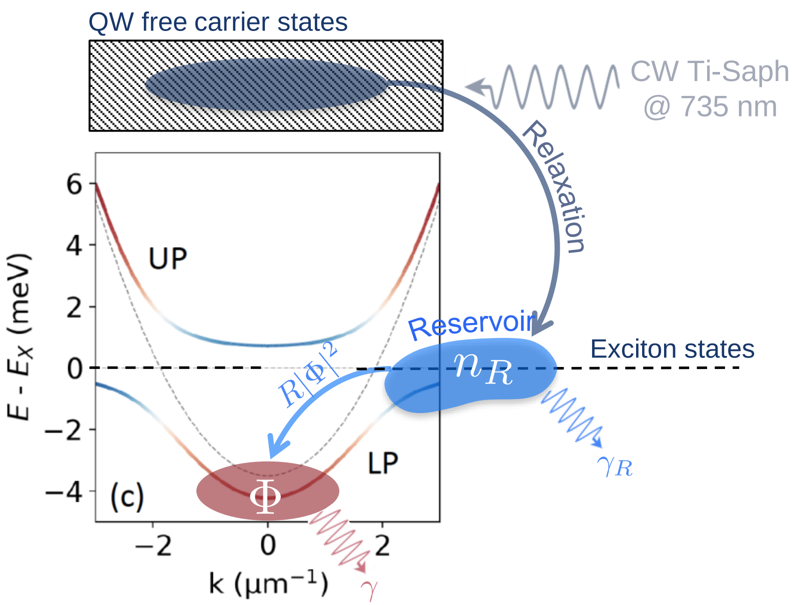
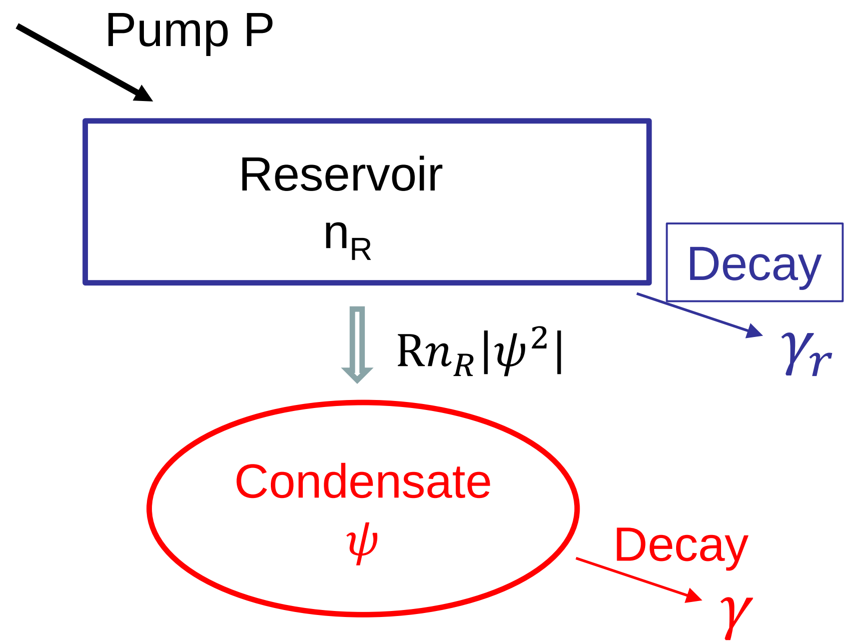




MEAN FIELD DESCRIPTION OF THE POLARITON FLUID

(Incoherent Pumping = GPE + Reservoir)

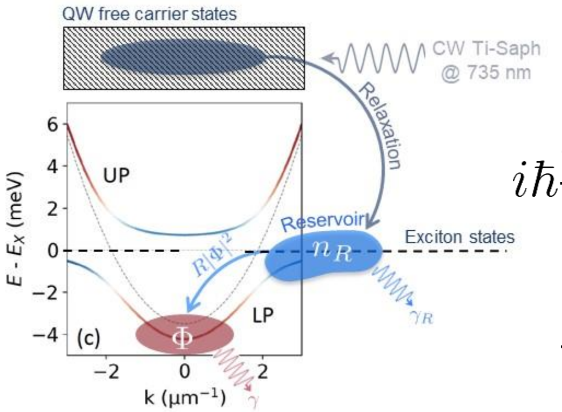
$$i\hbar\frac{\partial\psi}{\partial t} = \left[-\frac{\hbar^2}{2m^*}\nabla^2 + g\,|\psi|^2 + 2g_R n_R + i\frac{\hbar}{2}(Rn_R - \gamma(\mathbf{k}))\right]\psi + \xi$$

noise

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

J. Bloch, I. Carusotto and M. Wouters, *Spontaneous coherence in spatially extended photonic systems: Non-Equilibrium Bose-Einstein condensation, Nature Review Physics (2022) (https://doi.org/10.1038/s42254-022-00464-0)*

Phase coherence in a polariton condensates



E. Altman, S. Diehl, M. Wouters 2015

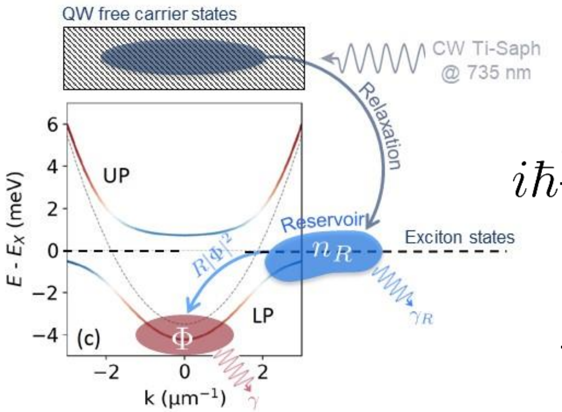
$$i\hbar\frac{\partial\psi}{\partial t} = \left[-\frac{\hbar^2}{2m^*}\nabla^2 + g\,|\psi|^2 + 2g_R n_R + i\frac{\hbar}{2}(Rn_R - \gamma(\mathbf{k}))\right]\psi + \xi$$

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

- Density-phase representation : $\psi(\mathbf{x},t) = \sqrt{\rho(\mathbf{x},t)}e^{-i\omega_0 t + i\theta(\mathbf{x},t)}$
- Assume different time scales for density and phase fluctuations :

E. Altman, *et al.*, PRX **5**, 011017 (2015)
K. Ji, *et al.*, PRB **91**, 045301 (2015)
L. He, et al., PRB **92**, 155307 (2015)

Phase coherence in a polariton condensates



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$$i\hbar\frac{\partial\psi}{\partial t} = \left[-\frac{\hbar^2}{2m^*}\nabla^2 + g\left|\psi\right|^2 + 2g_R n_R + i\frac{\hbar}{2}(Rn_R - \gamma(\mathbf{k}))\right]\psi + \xi$$

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- Density-phase representation : $\psi(\mathbf{x},t) = \sqrt{\rho(\mathbf{x},t)}e^{-i\omega_0 t + i\theta(\mathbf{x},t)}$
- Assume different time scales for density and phase fluctuations :

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

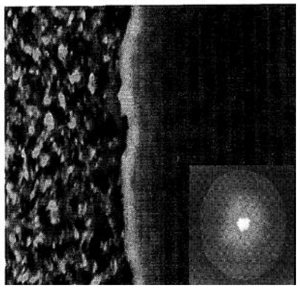
This is the famous Kardar Parisi Zhang equation!!

E. Altman, *et al.*, PRX **5**, 011017 (2015)
K. Ji, *et al.*, PRB **91**, 045301 (2015)
L. He, et al., PRB **92**, 155307 (2015)

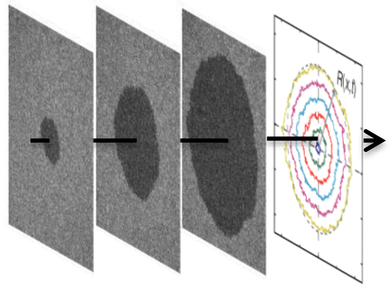
Kardar-Parisi-Zhang theory of interface stochastic growth

Kardar, Parisi and Zhang, *PRL* (1986)

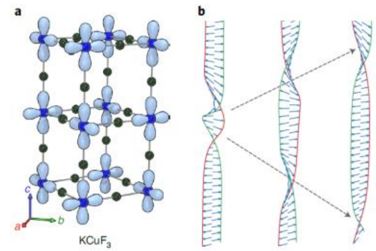
Frost on a window



Bacteria



Liquid crystals

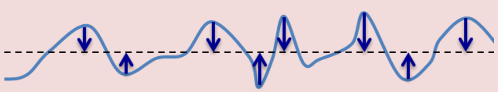


1D antiferromagnet (Nature Phys. 2021)
See also D. Wei, Science 376 716 (2022)

$$\frac{\partial h}{\partial t} = \nu \boldsymbol{\nabla}^2 h + \frac{\lambda}{2}(\boldsymbol{\nabla} h)^2 + \eta(\boldsymbol{x}, t)$$

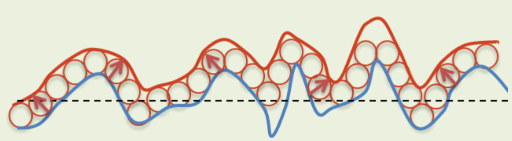
Diffusion term

- *smoothens the surface*



Growth term (nonlinear)

- *Orthogonal to the surface*
- *Non-equilibrium*



Stochastic term (fluctuations)

- *White Gaussian noise*

$$\langle \eta(\boldsymbol{x}, t) \rangle = 0$$

$$\langle \eta(\mathbf{x})\eta(\mathbf{x}') \rangle = \delta(\mathbf{x} - \mathbf{x}')$$

Landmark signatures of KPZ physics

Kardar, Parisi and Zhang, *PRL* (1986)

- Self-organized **scale invariance**

$\Longrightarrow$ Critical exponents (universal)

$$C(\mathbf{x},t) = \langle h(\mathbf{x},t)h(0,0)\rangle - \langle h(\mathbf{x},t)\rangle\langle h(0,0)\rangle \propto \begin{cases} t^{2\beta} & (\mathbf{x}=0) \\ x^{2\chi} & (t=0) \end{cases}$$

$$C(\mathbf{x},t) \propto t^{2\beta}\mathcal{F}_{\mathrm{KPZ}}\left(\kappa\frac{|\mathbf{x}|}{t^{1/\mathcal{Z}}}\right)$$

KPZ **universal scaling function** (tabulated)

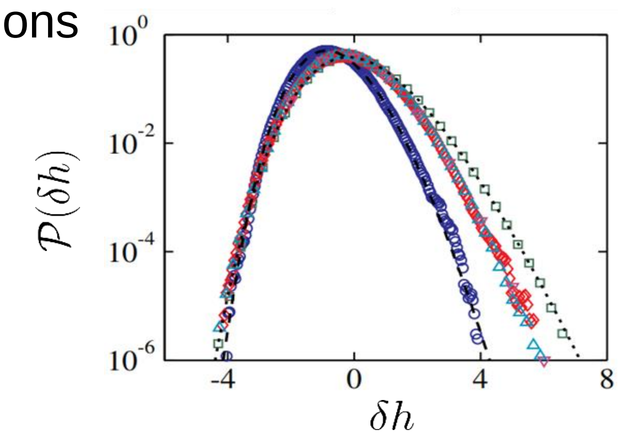
1D KPZ universality class

$\beta = 1/3 \qquad \chi = 1/2$

$\mathcal{Z} = \chi/\beta = 3/2$

- Non-Gaussian probability distribution of height fluctuations

$$\delta h(t) = \frac{h(\mathbf{x_0},t) - v_\infty t}{(\Gamma t)^{1/3}}$$

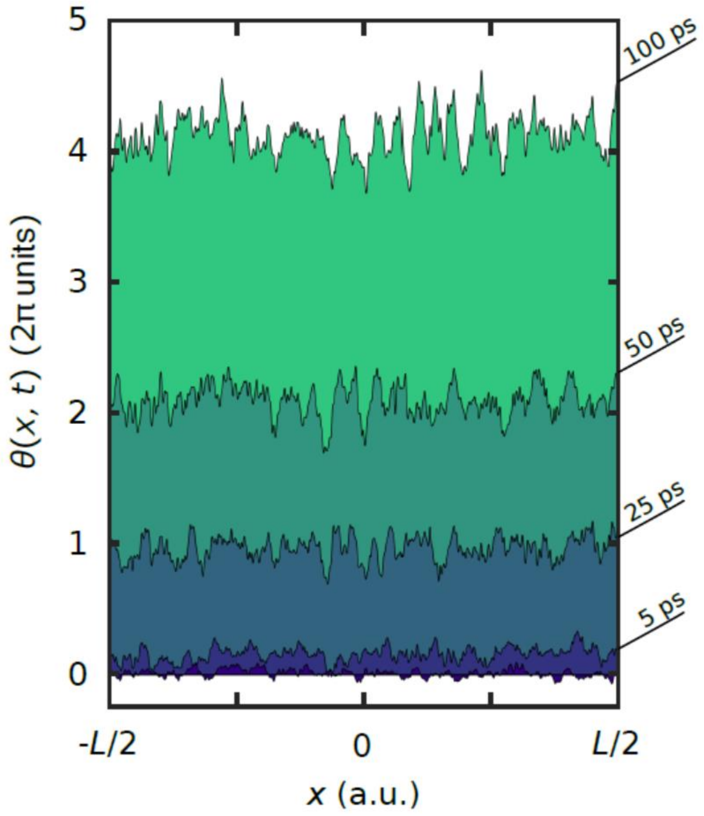


K. A. Takeuchi, PRL **110**, 210604 (2013)

T. Halpin-Healy, & Y.-C. Zhang, Phys. Rep. **254**, 215 (1995)
J. Krug, Adv. Phys. **46**, 139 (1997)
K. A. Takeuchi, Physica A **504**, 77 (2018)

Polariton condensates

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



- The phase front behaves as a growing interface

KPZ scaling expected in the spatio-temporal correlations of the phase

$$\mathrm{Var}\left[\Delta\theta(\Delta x, \Delta t)\right]$$

Instantaneous phase : difficult to access in the experiment …

How to probe KPZ scaling ???

E. Altman, *et al.*, PRX **5**, 011017 (2015)
K. Ji, *et al.*, PRB **91**, 045301 (2015)

L. He, et al., PRB **92**, 155307 (2015)

Polariton condensates

We can measure amplitude amplitude correlations of the field (first order coherence :

$$g^{(1)}(\Delta x, \Delta t) = \frac{\langle \psi^*(x, t_0)\psi(-x, t_0 + \Delta t)\rangle}{\sqrt{\langle \rho(x, t_0)\rangle}\sqrt{\langle \rho(-x, t_0 + \Delta t)\rangle}}$$

- If phase fluctuations are independent of density fluctuations and for small density fluctuations :

$$g^{(1)}(\Delta x, \Delta t) = \Big\langle \exp\left[i\Delta\theta(\Delta x, \Delta t)\right] \Big\rangle$$

See derivation in Q. Fontaine, *et al*, Nature 608, 687 (2022)

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- For small phase fluctuations :

$$|g^{(1)}(\Delta x, \Delta t)|^2 \simeq \exp(-\langle \Delta\theta(\Delta x, \Delta t)^2\rangle + \langle \Delta\theta(\Delta x, \Delta t)\rangle^2) \equiv \exp(-\mathrm{Var}\left[\Delta\theta(\Delta x, \Delta t)\right])$$

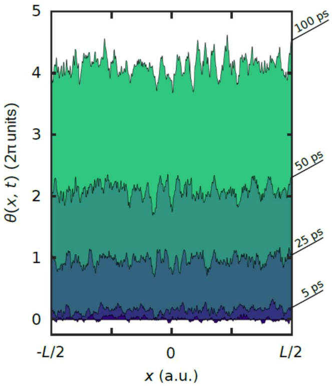
$$\boxed{\mathrm{Var}\left[\Delta\theta\right] \simeq -2\log\left(\left|g^{(1)}\right|\right)}$$

➢ In 1D: $$-2\log\left(\left|g^{(1)}(\Delta x, \Delta t)\right|\right) \sim \begin{cases} \Delta t^{2\beta} & (\Delta \mathrm{x} = 0) \\ \Delta x^{2\chi} & (\Delta \mathrm{t} = 0) \end{cases}$$

$\beta = 1/3$ $\chi = 1/2$

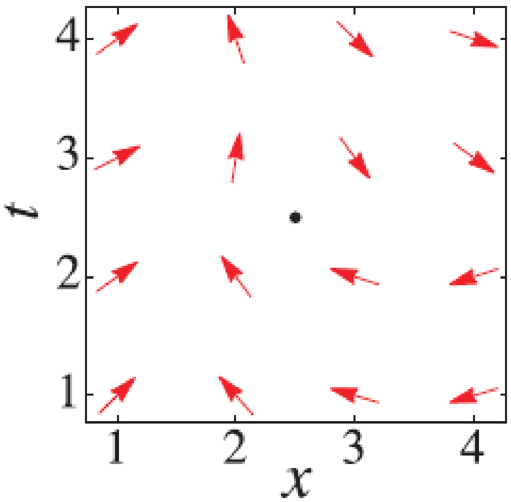
See derivation in Q. Fontaine, *et al*, Nature 608, 687 (2022)

KPZ physics in polariton condensates

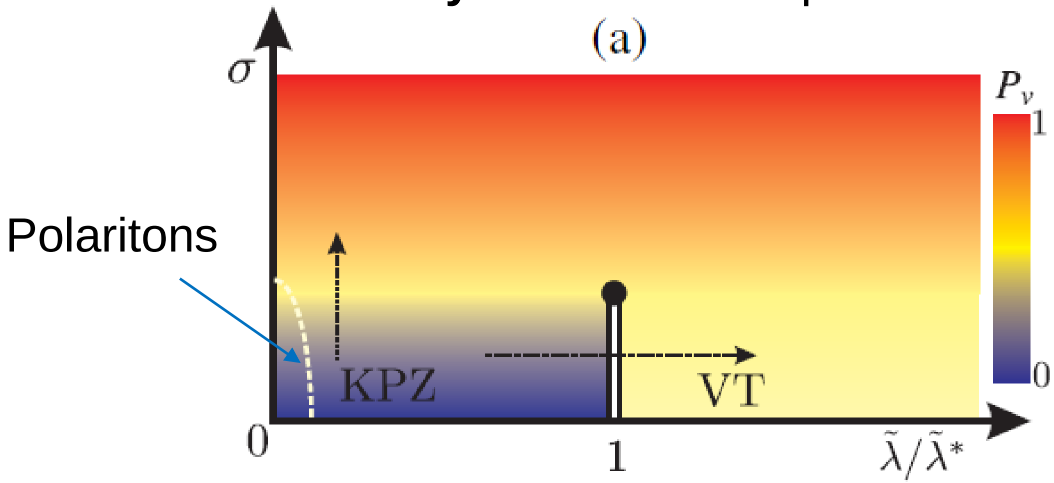


The phase is a compact variable : $\theta \epsilon [0, 2\pi]$

- Even **in 1D** : Space time vortex

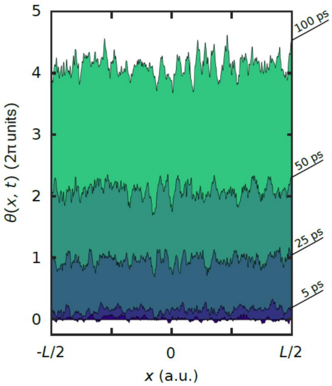


Effective 2D system: 1st order phase transition



L. He, L.M. Sieberer and S. Diehl, Phys. Rev. Lett. 118, 085301 (2017)

KPZ physics in polariton condensates



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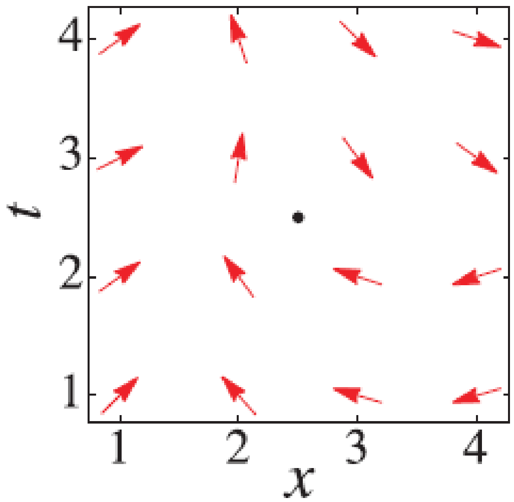

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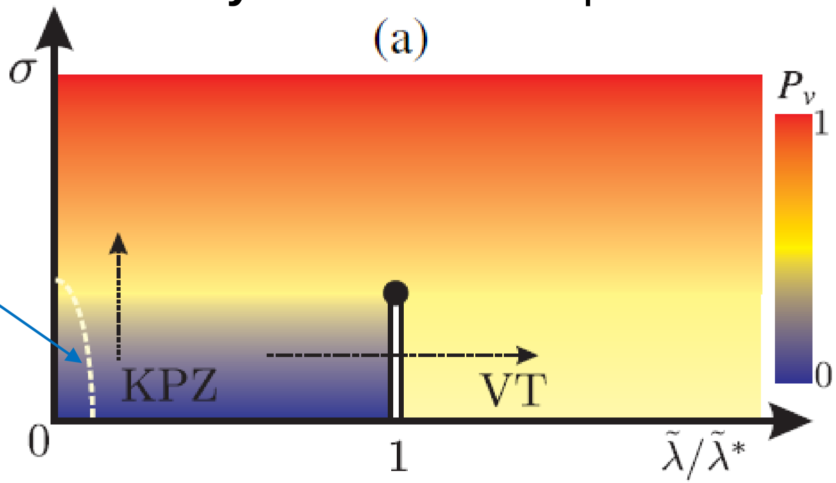


L. He, L.M. Sieberer and S. Diehl, Phys. Rev. Lett. 118, 085301 (2017)

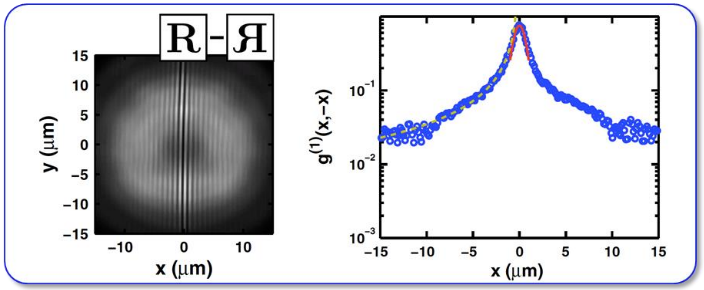
- **In 2D**: Space time AND spatial vortices

KPZ scaling in 2D open condensates? $\Longrightarrow$ Still actively debated

E. Altman, et al., PRX 5, 011017 (2015)
A. Zamora, et al., PRX 7, 041006 (2017)
Q. Mei, et al., PRB 103, 045302 (2021)
A. Ferrier, et al., PRB 105, 205301 (2022)

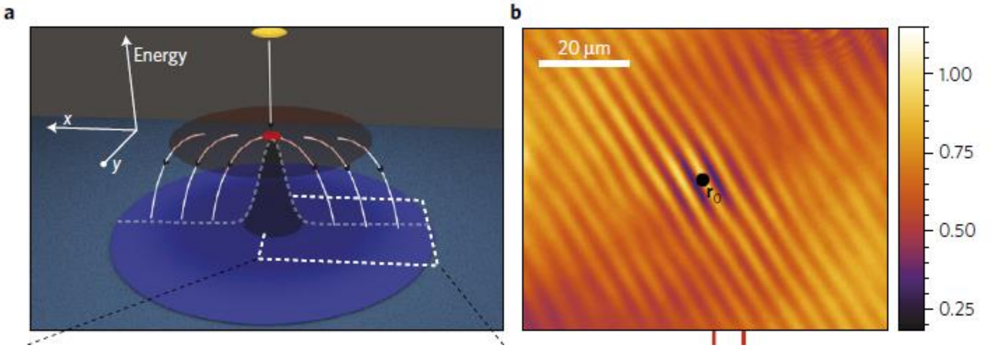
Experimental observation?

Small size effects



G. Roumpos et al., PNAS109 (17) 6467 (2011)
See also J. Fischer et al., Phys. Rev. Lett. 113, 203902 (2014)

Weak overlap with the reservoir



D. Caputo et al., Nature Materials 17, 145 (2018)
D. Ballarini et al, Phys. Rev. Lett. 118, 215301 (2017)

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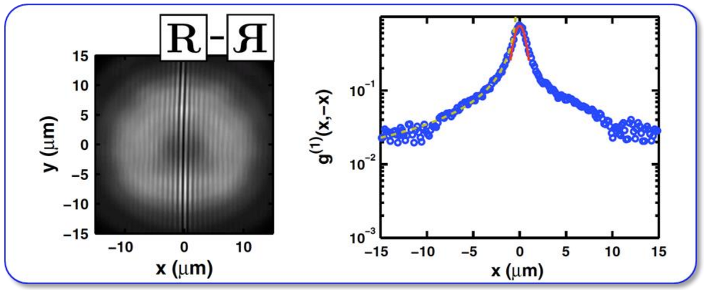

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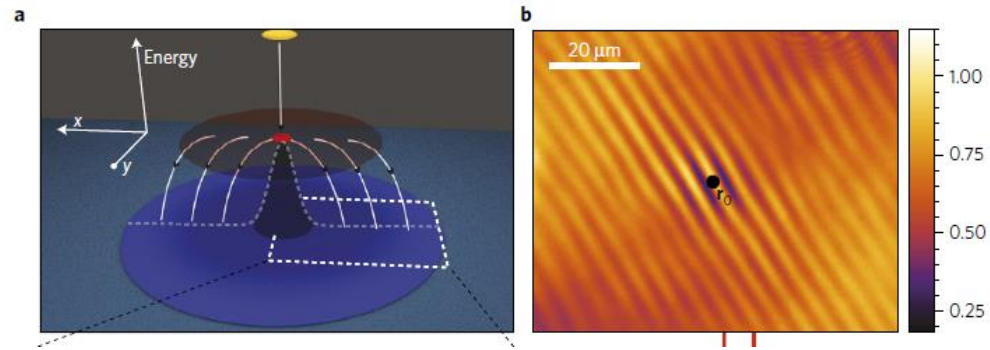

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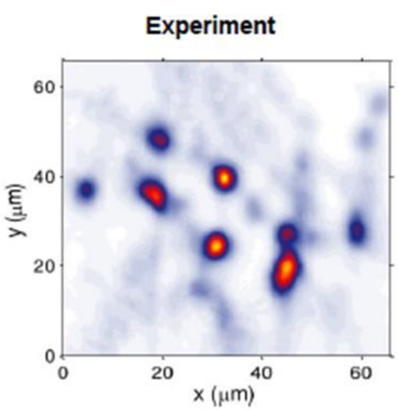
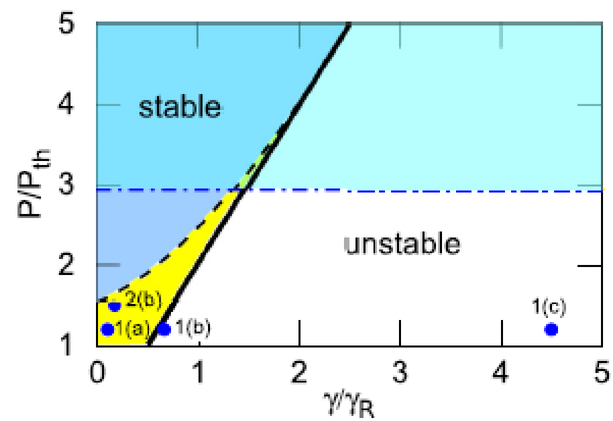
D. Ballarini et al, Phys. Rev. Lett. 118, 215301 (2017)

Condensation within an large excitation spot



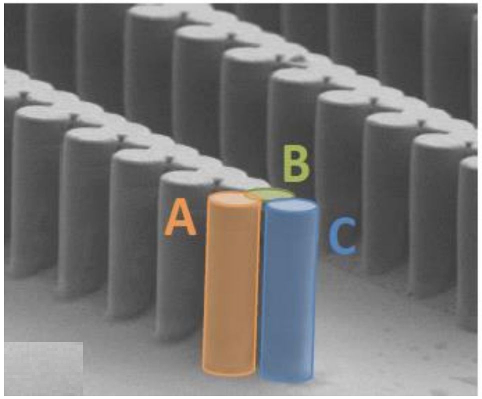
F. Baboux *et al.*, Optica **5**, 1163 (2018)

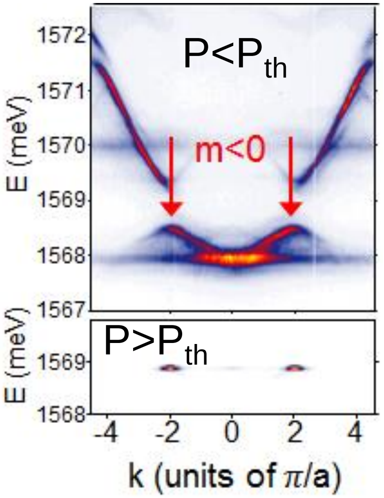
Modulation instability
☹ ☹



M. Wouters et al., Phys. Rev. B 77, 115340 (2008)
N. Bobroska et al., PRB 90, 205304 (2014),
N. Bobrovska and M. Matuszewski,PRB 92, 035311 (2015)

Taming the instability : condensation in a negative mass band





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Review on polariton lattice engineering: C. Schneider et al., Rep. Prog. Phys. 80, 16503 (2017)

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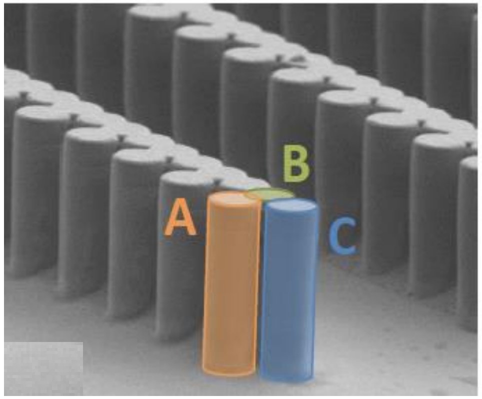

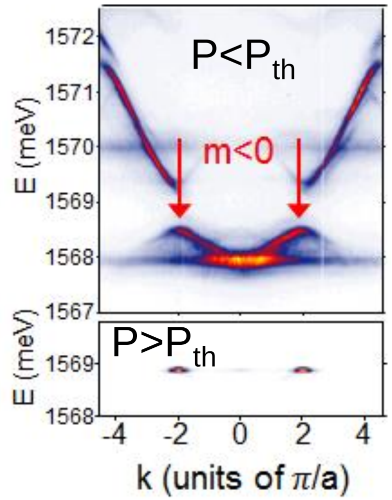

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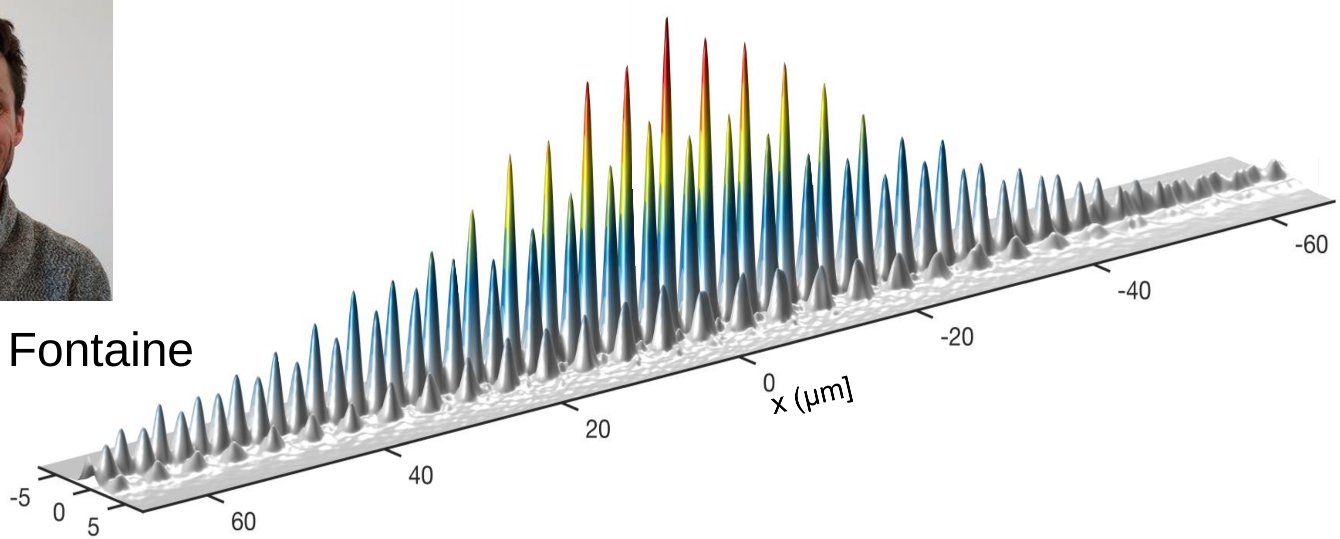
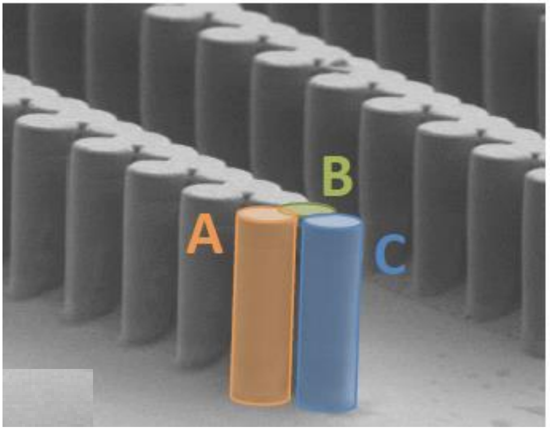
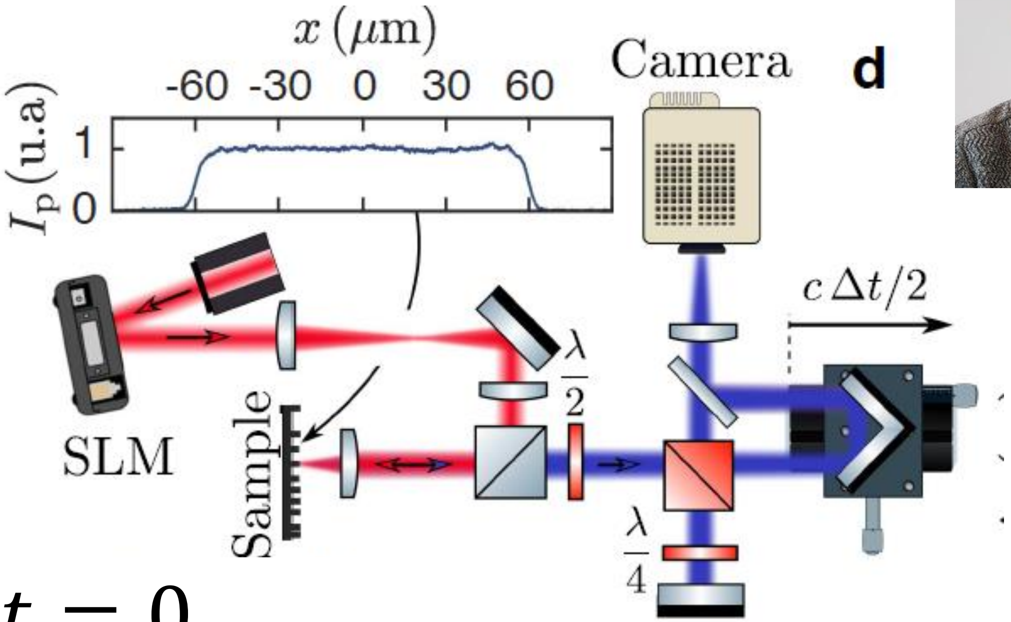
Quentin Fontaine



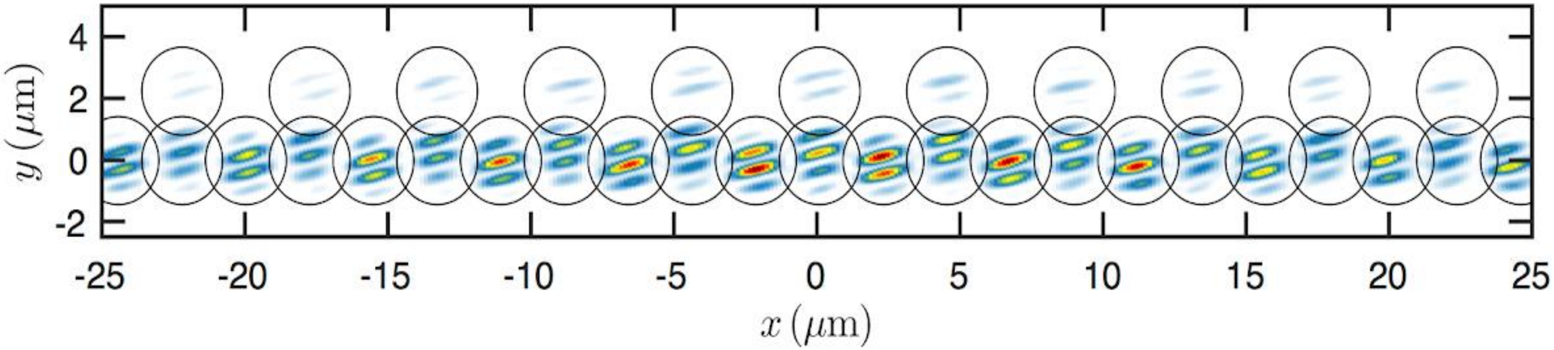
Q. Fontaine, *et al*, Nature 608, 687 (2022)

KPZ physics in 1D polariton condensates





$\Delta t = 0$



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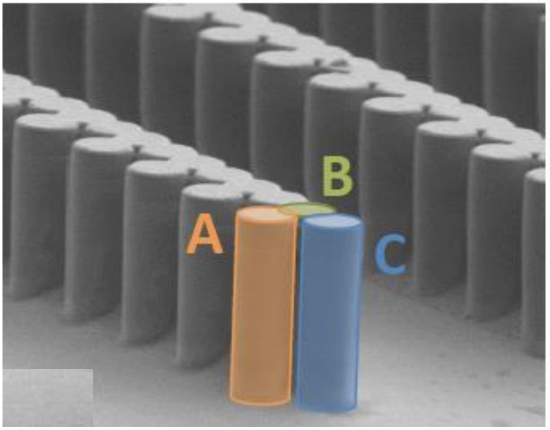

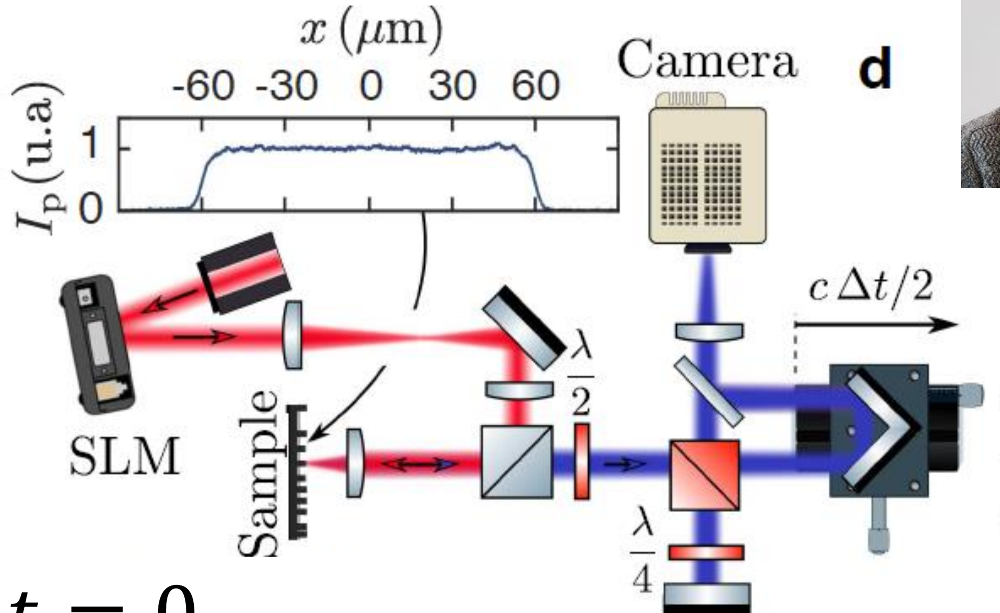

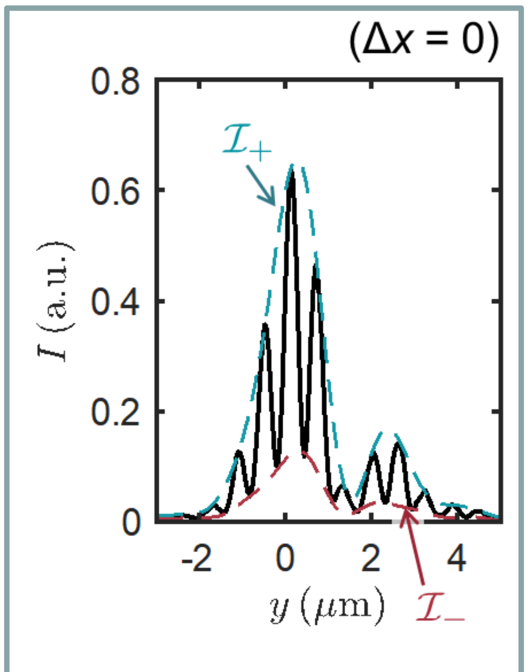

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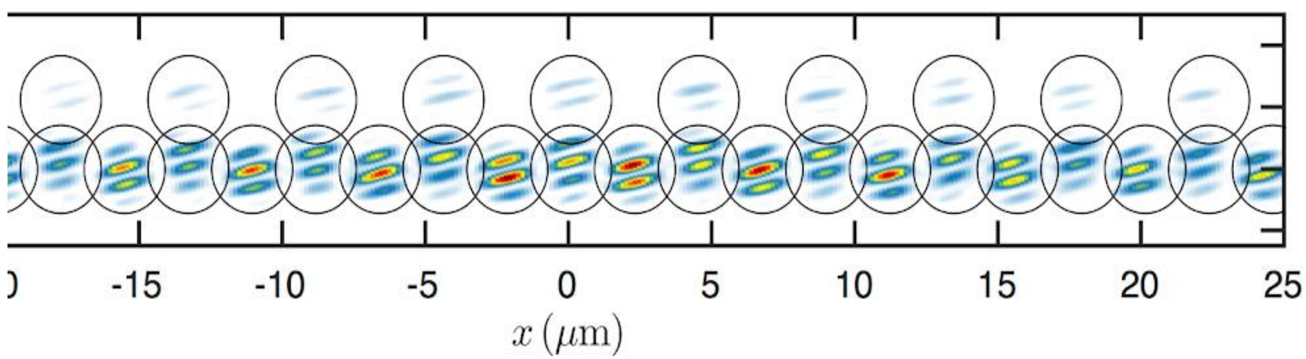
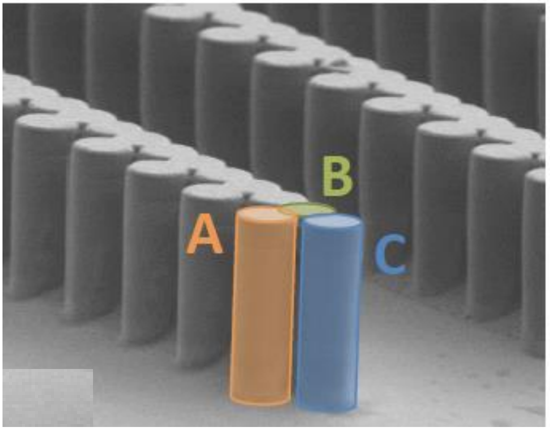
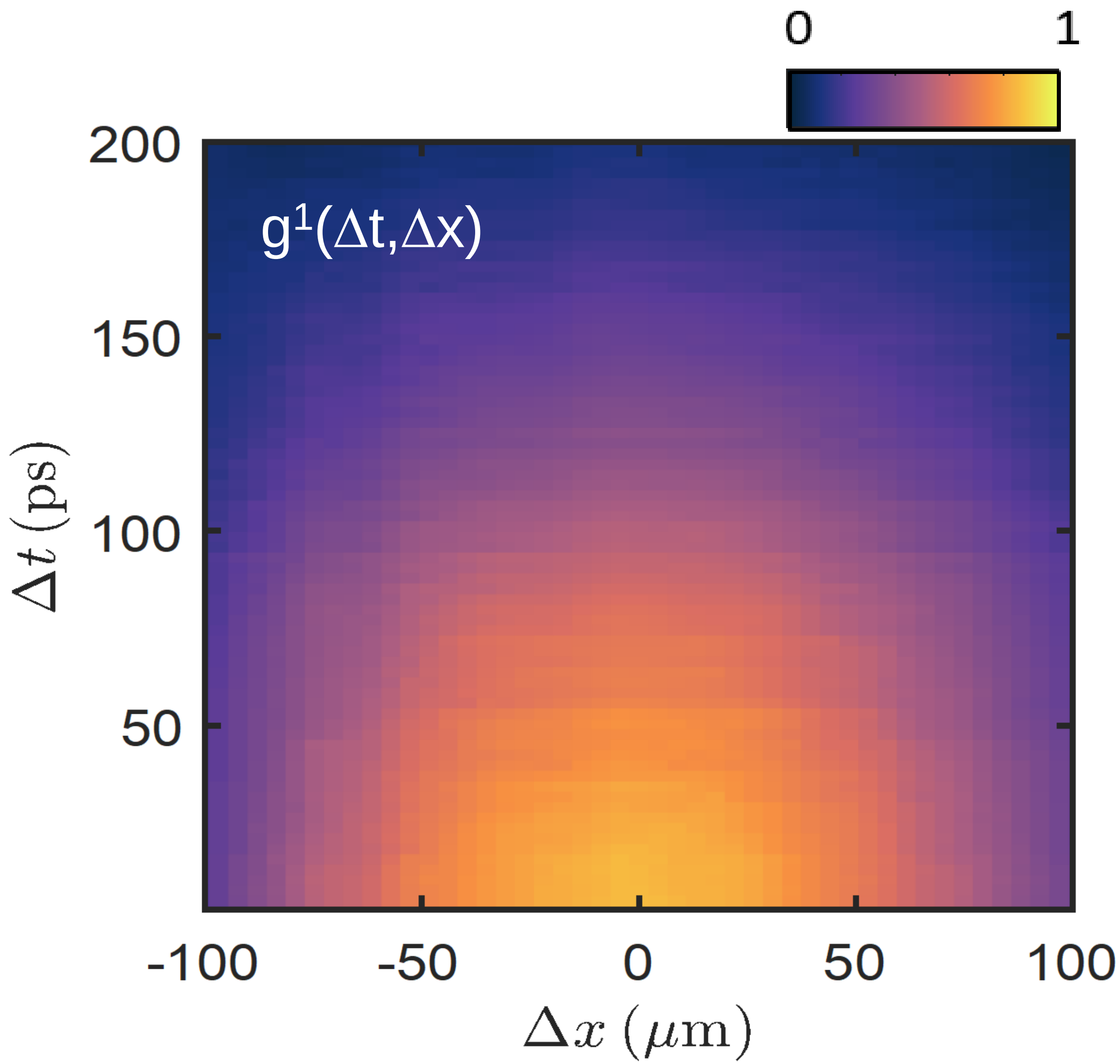


$$\frac{\mathcal{I}_+ - \mathcal{I}_-}{\mathcal{I}_+ + \mathcal{I}_-} = \frac{2\sqrt{\mathcal{I}(\boldsymbol{r})\,\mathcal{I}(-\boldsymbol{r})}}{\mathcal{I}(\boldsymbol{r}) + \mathcal{I}(-\boldsymbol{r})}\,|g^{(1)}(\boldsymbol{\Delta r}, \Delta t)|$$

KPZ physics in 1D polariton condensates

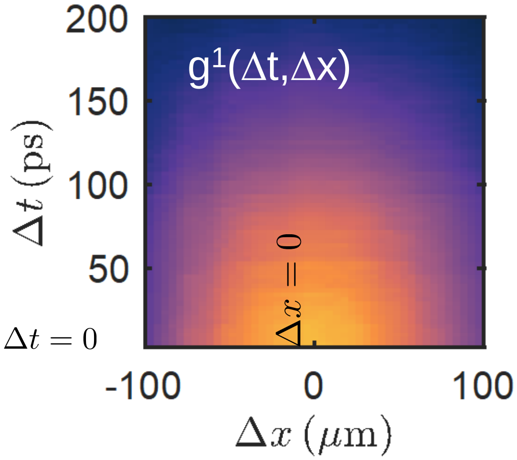




KPZ physics in 1D polariton condensates

- "SURFACE ROUGHNESS" ⟷ $$\mathrm{Var}\left[\Delta\theta\right] \simeq -2\log\left(g^{(1)}\right)$$
- WE EXPECT:

$$-2\ln\{g^{(1)}(\Delta x, \Delta t)\} \sim \begin{cases} \Delta t^{2\beta} & \text{for } \Delta x = 0 \quad \beta = 1/3 \\ \Delta x^{2\chi} & \text{for } \Delta t = 0 \quad \chi = 1/2 \end{cases}$$



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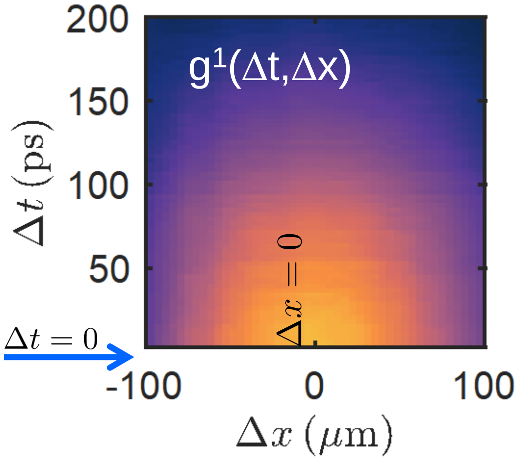

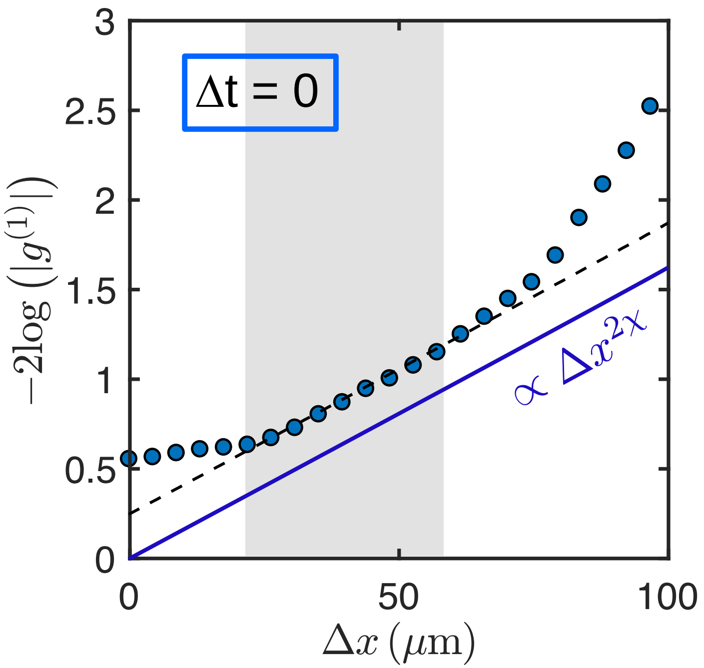

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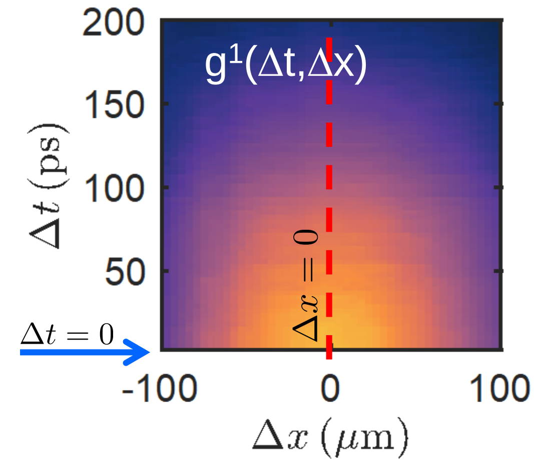

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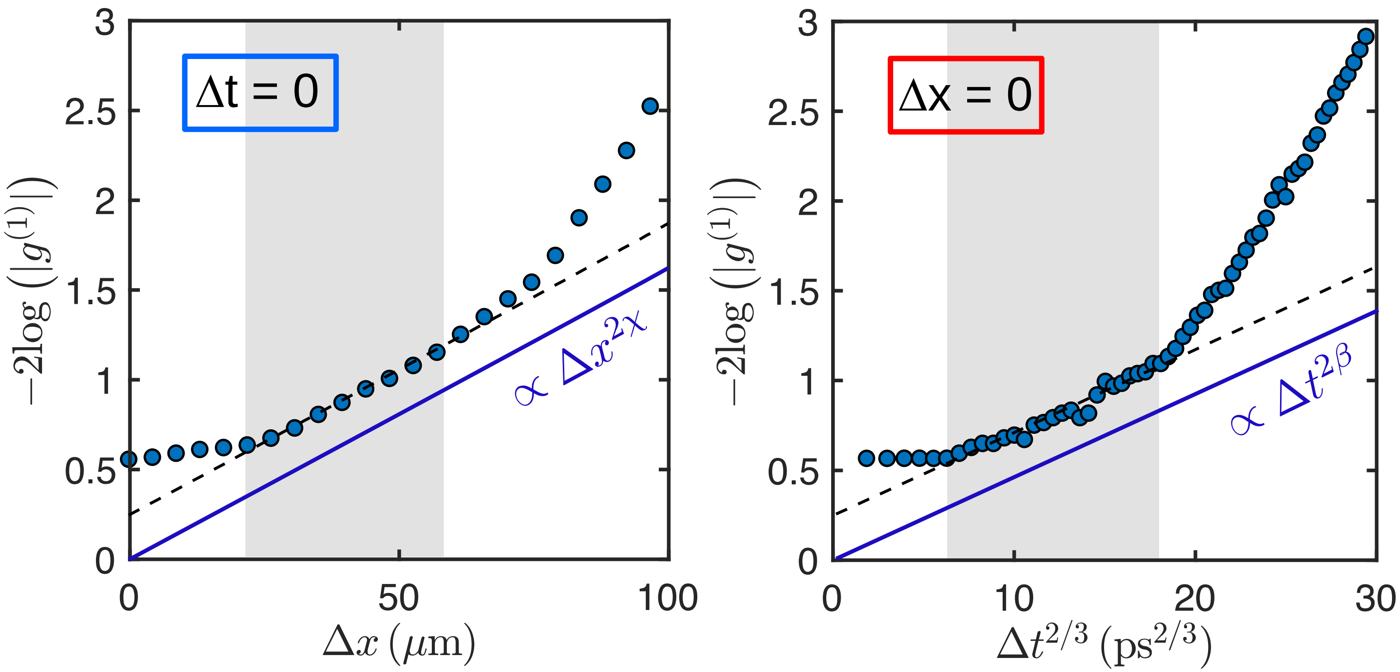
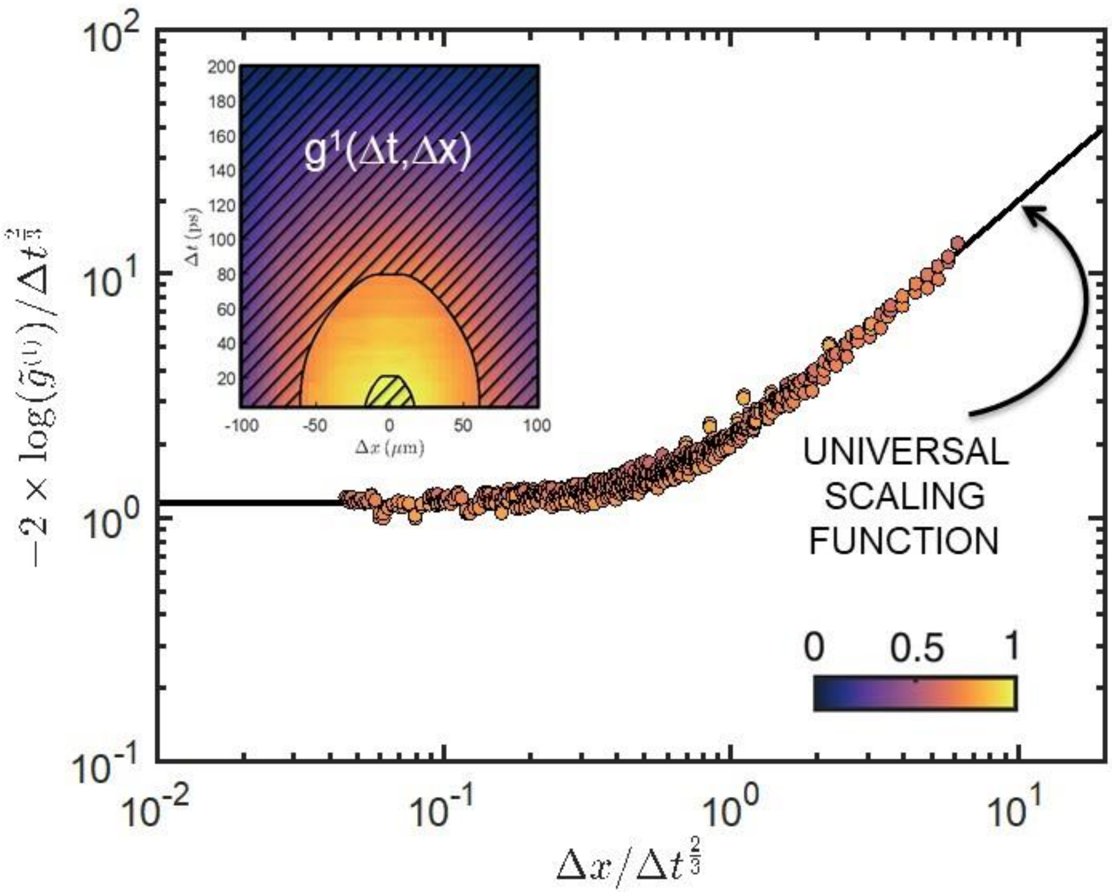


KPZ scaling laws in 1D polariton condensates

KPZ scaling $$-2\ln\{g^{(1)}(\Delta x, \Delta t)\} = A \times \Delta t^{2\beta}\,\mathcal{F}\left[B \times \frac{\Delta x}{\Delta t^{1/z}}\right]$$

where $$\mathcal{F}(y) = \begin{cases} c_0, & y \to 0 \\ y, & y \to \infty \end{cases}$$ is the UNIVERSAL KPZ SCALING FUNCTION.



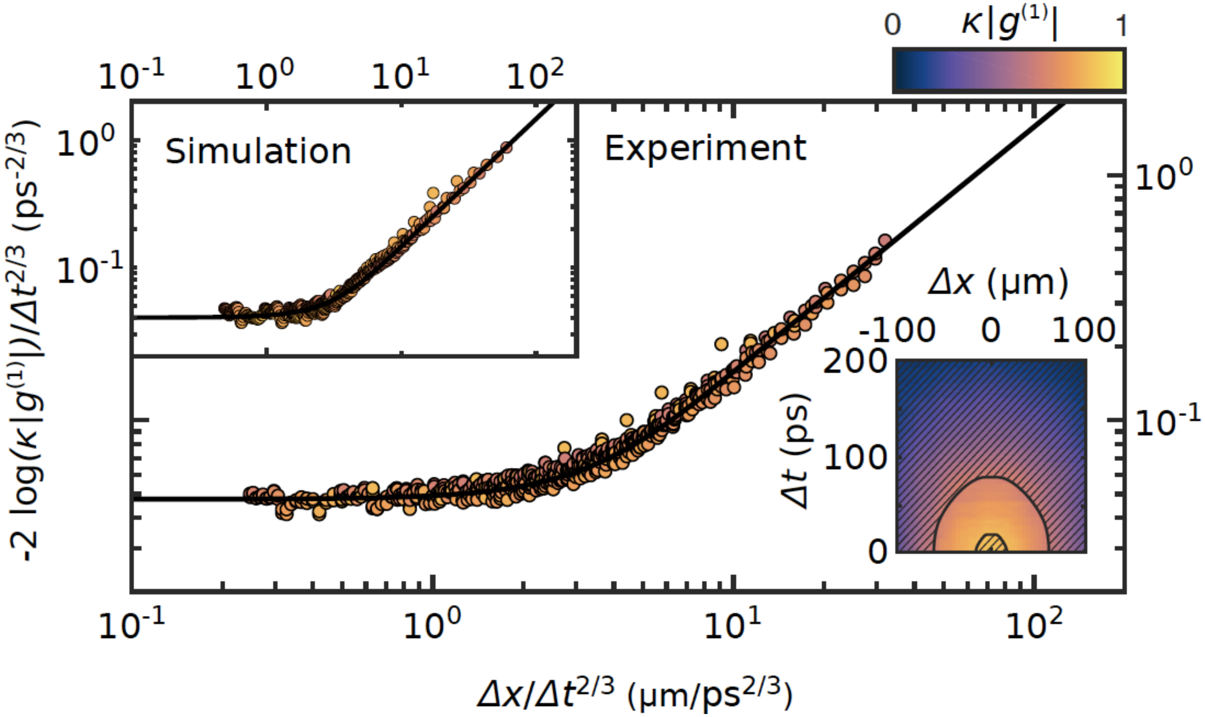
Q. Fontaine, *et al*, Nature 608, 687 (2022)

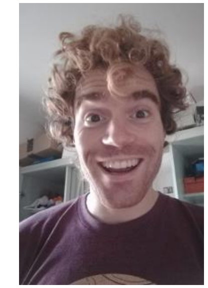
SIMULATIONS - COMPARISON WITH EXPERIMENTS

- Integrate numerically the two coupled equations model

$$i\hbar\frac{\partial\psi}{\partial t} = \left[-\frac{\hbar^2}{2m^*}\nabla^2 + g\,|\psi|^2 + 2g_R n_R + i\frac{\hbar}{2}(Rn_R - \gamma(\mathbf{k}))\right]\psi + \xi$$

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





D. Squizzato

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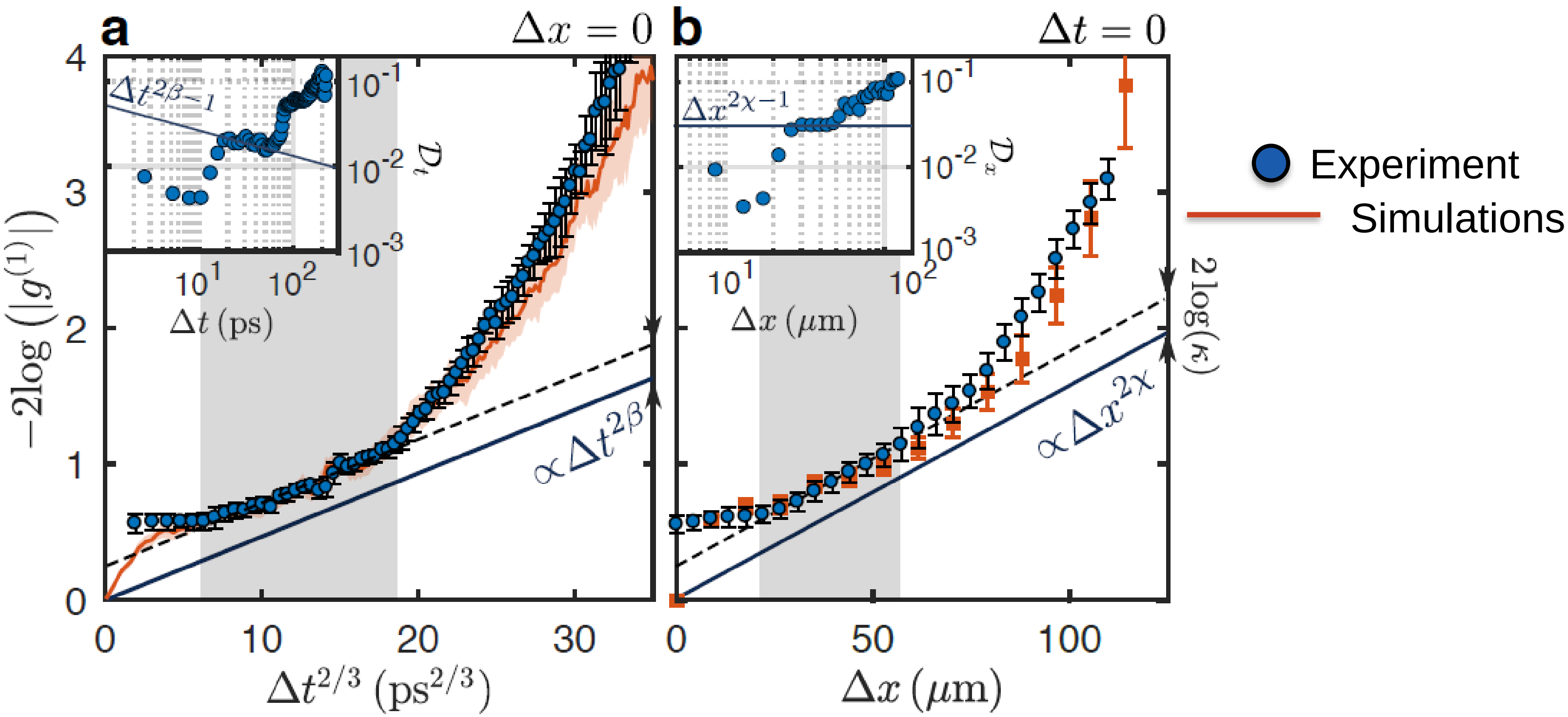

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$$\chi_{\rm exp} = 0.51 \pm 0.08$$
$$\beta_{\rm exp} = 0.36 \pm 0.11$$

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

Phase dynamics (simulations)

- Calculate total phase (unwrapped) difference for several noise realisations:

$$\Delta\varphi_{\text{tot}}(0, \Delta t) = \varphi_{\text{tot}}(0, \Delta t) - \varphi_{\text{tot}}(0, 0) = -\omega_0 \Delta t + \Delta\theta(0, \Delta t)$$

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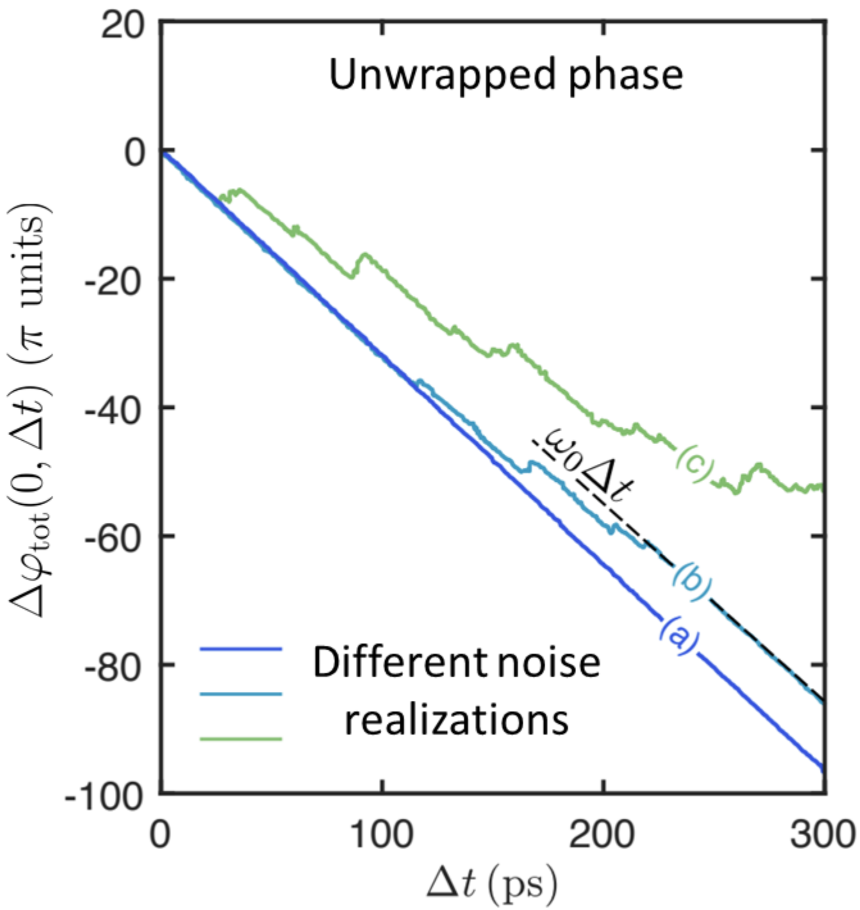

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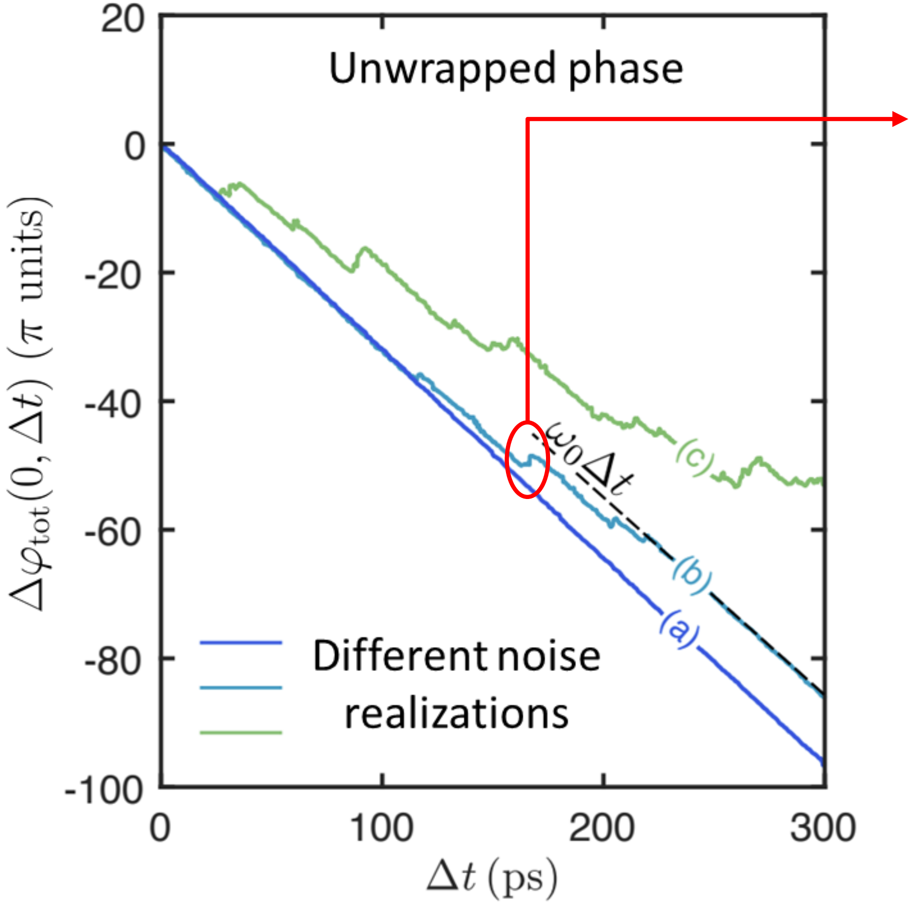

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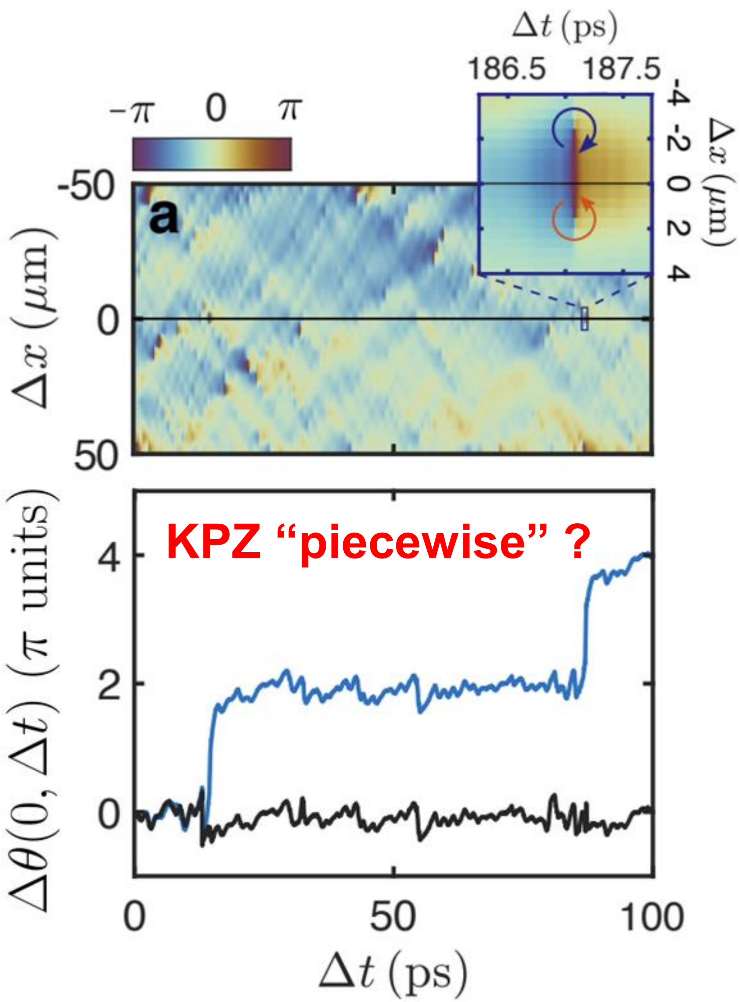


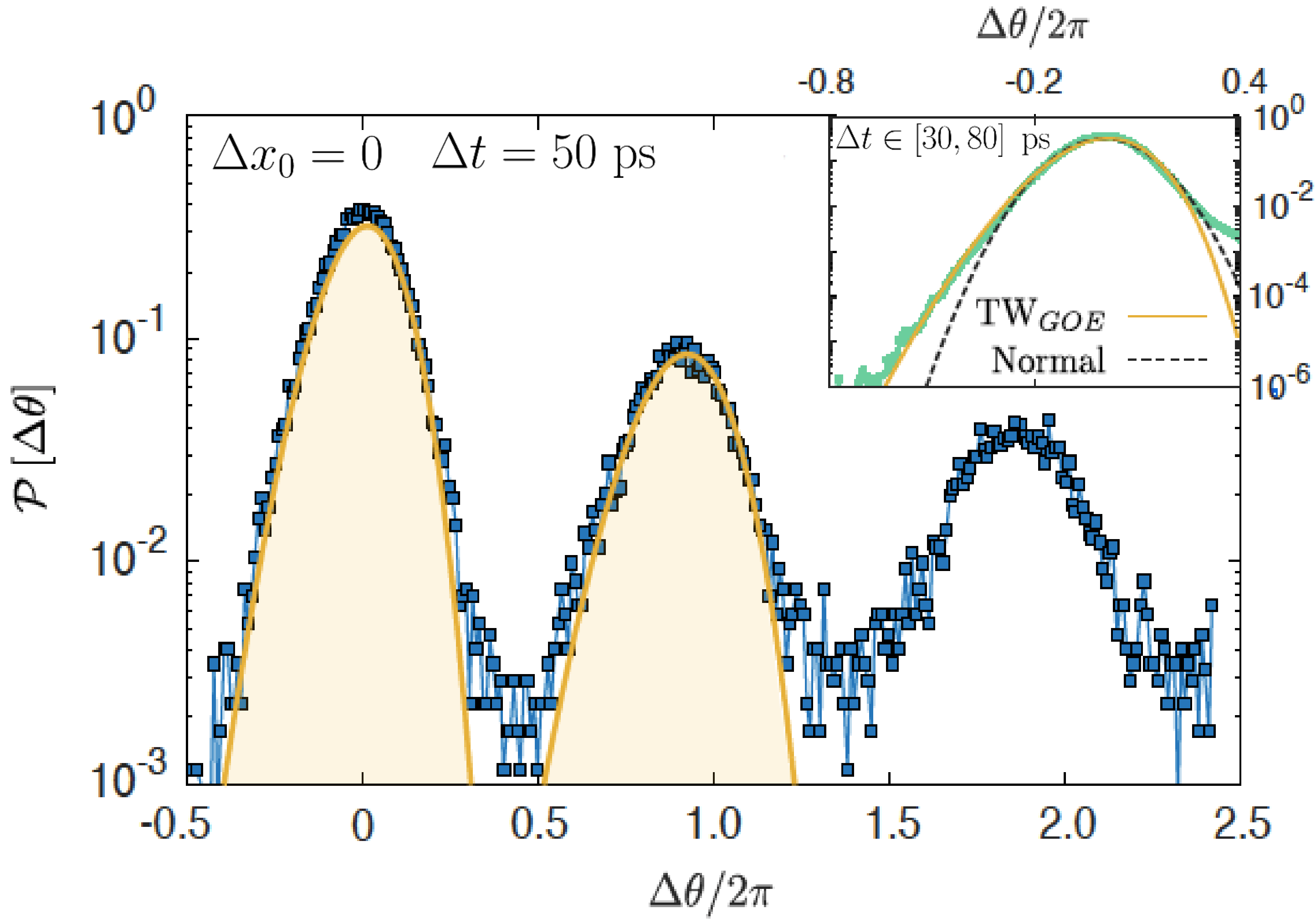
- Occasional 2π phase jumps.

- Pairs of vortex and antivortex appear in effective 2D space (Δx, Δt).

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

Amplitude distribution of phase fluctuations

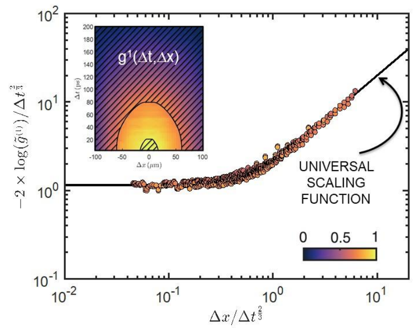
- For Δx and Δt within KPZ window $\Delta\theta(\Delta x_0, \Delta t)/(|\Gamma|\Delta t^{2/3})$ is a random variable expected to obey Tracy-Widom statistics (non-Gaussian).



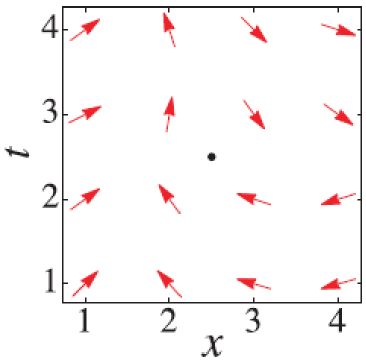
Q. Fontaine, *et al*, Nature 608, 687 (2022)

Conclusion and prospects

- 1D driven-dissipative condensates belong to the KPZ universality class



- Compact version of KPZ with a phase variable
  $\Longrightarrow$ topological defects



- KPZ scaling can be resilient to these defects

Turbulent phase for higher noise / pump power?

L. He, L. M. Sieberer, & S. Diehl, PPRL **118**, 085301 (2017)

Conclusion and prospects

- In 2D: Space time **AND** spatial vortices
Vortex proliferation kills KPZ correlations?

Debated topics!

E. Altman, *et al.*, PRX **5**, 011017 (2015)
A. Zamora, *et al.*, PRX **7**, 041006 (2017)
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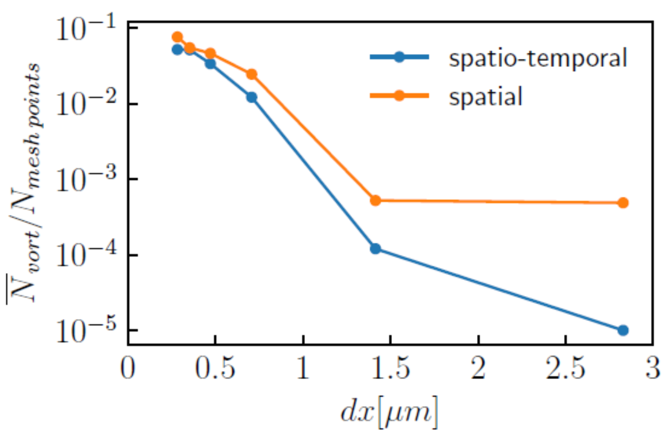
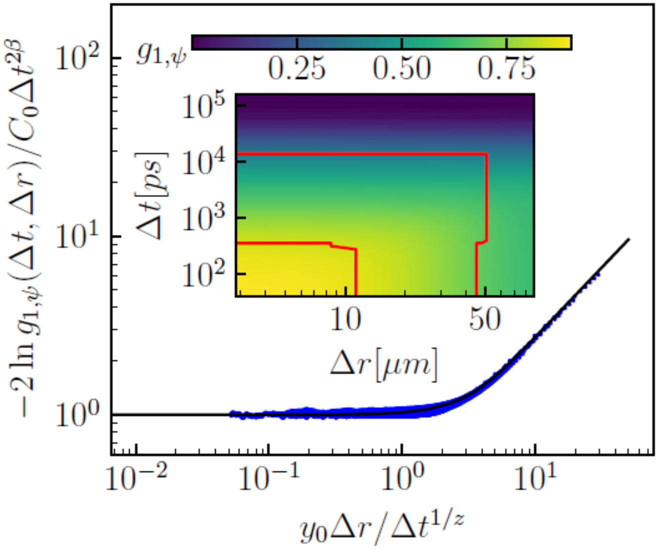
- KPZ predicted in recent simulations using 2D discrete (lattice) model

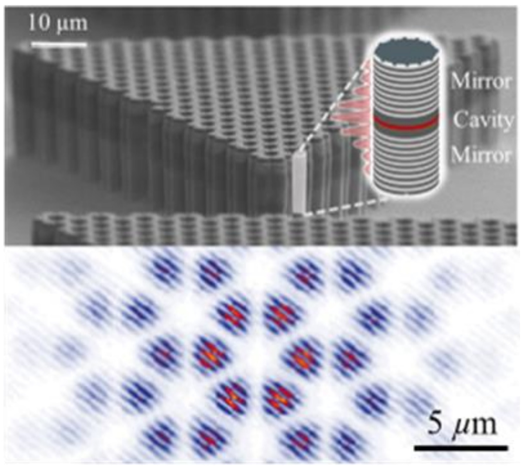




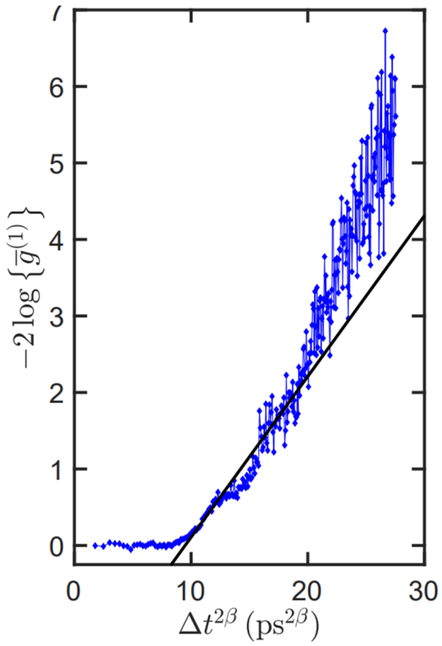
K. Deligiannis, *et al.*, Phys. Rev. Research 4, 043207 (2022)

Conclusion and prospects

Negative mass condensates in 2D



Preliminary results in 2D



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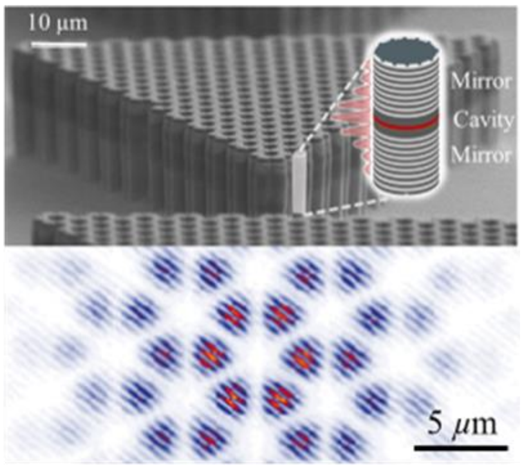
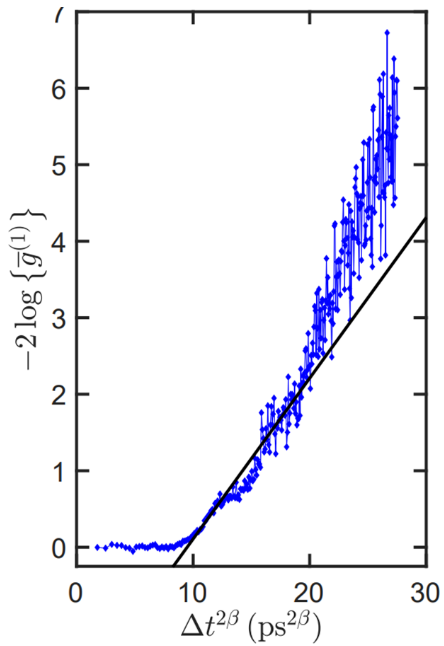
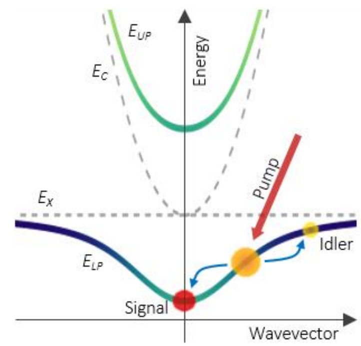
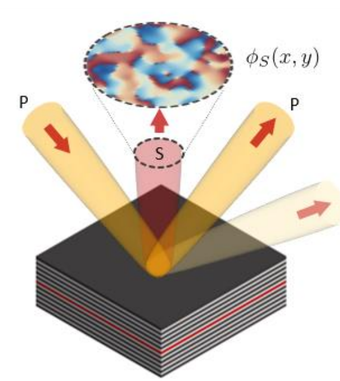




KPZ scaling predicted in the OPO regime





A. Zamora, *et al.*, PRX **7**, 041006 (2017)

Polariton lattices may provide the first experimental platform to probe KPZ physics in 2D