Kardar-Parisi-Zhang universality in 1D exciton-polaritons

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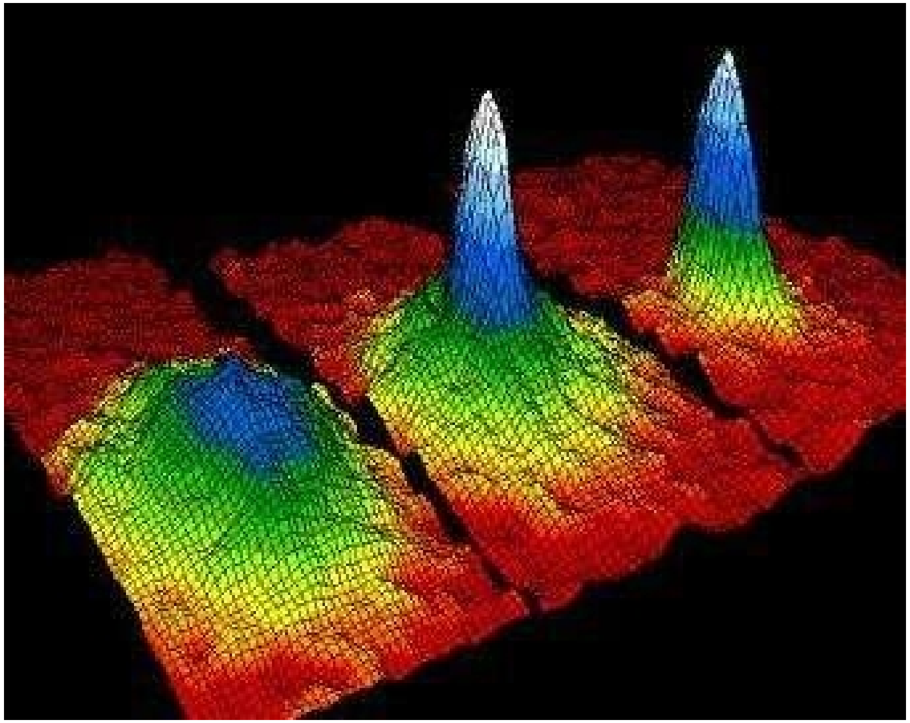
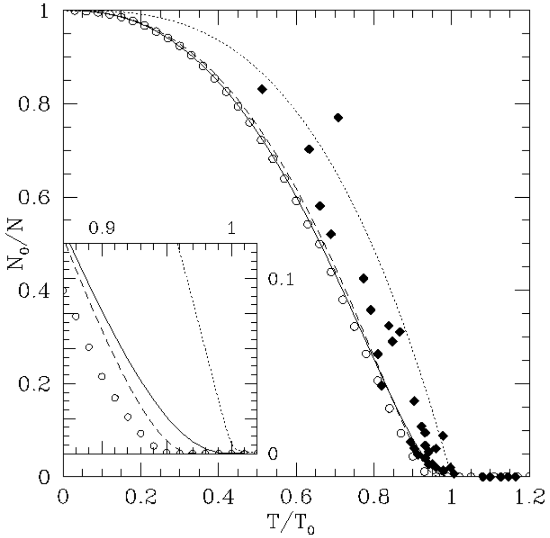
Equilibrium Bose-Einstein condensation



[Anderson et al 1995]

transition controlled by tuning the temperature

order parameter : condensate fraction



[Minguzzi, Conti, Tosi, 1997]

In the out-of-equilibrium realm

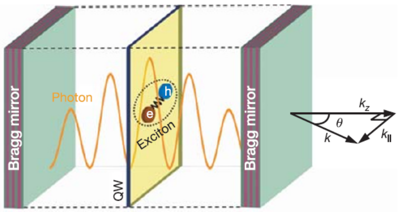
Bose-Einstein condensates out of equilibrium

- an open quantum system
- flow in energy/momentum space
- non-equilibrium phase transition
- non-equilibrium steady-state

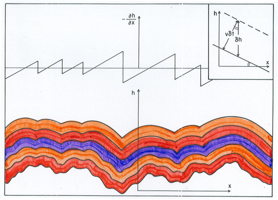
nature of the phase transition ?

properties of the state ?

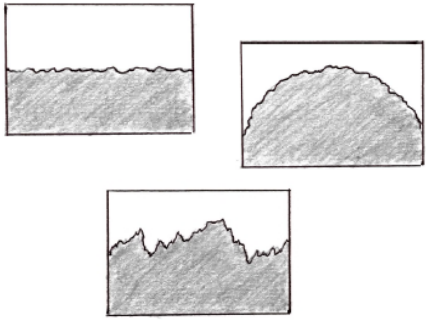
- Introduction I : Excitons-polaritons condensates



- Introduction II : The Kardar-Parisi-Zhang equation



- Emergence of KPZ universality in exciton-polaritons and its consequences : theory + experiment



- KPZ universality subclasses in 1D

- KPZ in 2D

[Squizzato, Canet and Minguzzi PRB 2018]

[Deligiannis, Squizzato, Minguzzi and Canet, EPL 2021]

[Fontaine et al, Nature 2022]

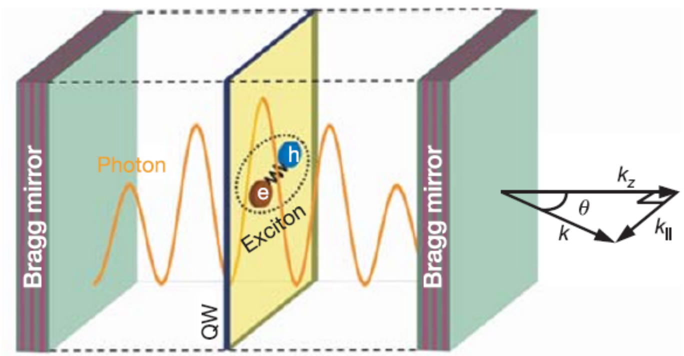
[Deligiannis et al Phys. Rev. Research 2022]

What is a polariton ?

- Exciton-polaritons : hybrid light-matter particles from strong coupling of excitons and cavity photons

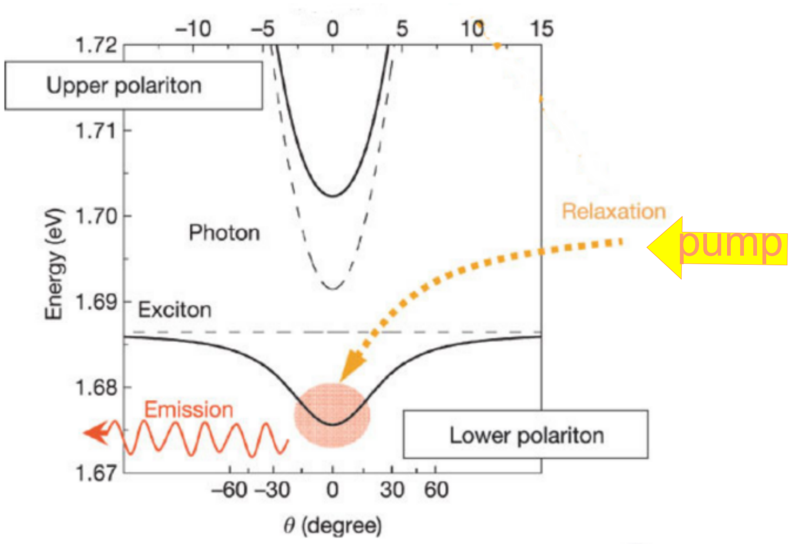
  Exciton : particle-hole bound state in a semiconductor

  Cavity photon : has quadratic dispersion at small k



[Kasprzak et al, Nat 443, 209 (2006)]

$$\mathcal{H}_{\rm exc} = \int \frac{d^2\mathbf{k}}{(2\pi)^2} \sum_{\sigma} \{\hbar\omega_{\rm exc}(\mathbf{k}) \hat{a}^{\dagger}_{X,\sigma}(\mathbf{k}) \hat{a}_{X,\sigma}(\mathbf{k}) + \hbar\Omega_R [\hat{a}^{\dagger}_{X,\sigma}(\mathbf{k}) \hat{a}_{C,\sigma}(\mathbf{k}) + \hat{a}^{\dagger}_{C,\sigma}(\mathbf{k}) \hat{a}_{X,\sigma}(\mathbf{k})]\}.$$



$$\mathcal{H}_{\rm cav} = \int \frac{d^2\mathbf{k}}{(2\pi)^2} \sum_{\sigma} \hbar\omega_{\rm cav}(\mathbf{k}) \hat{a}^{\dagger}_{C,\sigma}(\mathbf{k}) \hat{a}_{C,\sigma}(\mathbf{k})$$

$$\omega_{\rm cav}(k) = \frac{c}{n_0}\sqrt{q_z^2 + k^2} \simeq \omega^o_{\rm cav} + \frac{\hbar k^2}{2m_{\rm cav}}$$

$$q_z = \pi M/\ell_z, \quad m_{\rm cav} = \frac{\hbar n_0 q_z}{c} = \frac{\hbar\omega^o_{\rm cav}}{c^2/n_0^2}$$

[J. J. Hopfield Phys. Rev. 112, 1555 (1958)

I. Carusotto and C. Ciuti, Rev. Mod. Phys. 85, 300 (2013)]

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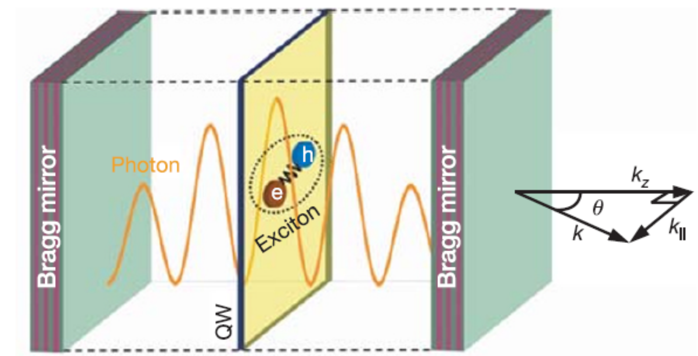
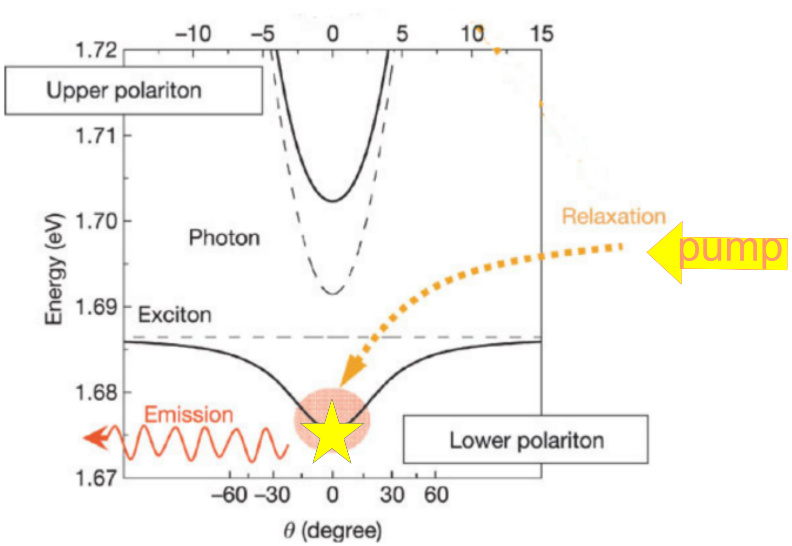


[Kasprzak et al, Nat 443, 209 (2006)]

$$\mathcal{H}_{\rm cav} + \mathcal{H}_{\rm exc} = \int \frac{d^2\mathbf{k}}{(2\pi)^2} \sum_{\sigma} [\hbar\omega_{{\rm LP},\sigma}(\mathbf{k}) \hat{a}^{\dagger}_{{\rm LP},\sigma}(\mathbf{k}) \hat{a}_{{\rm LP},\sigma}(\mathbf{k}) + \hbar\omega_{{\rm UP},\sigma}(\mathbf{k}) \hat{a}^{\dagger}_{{\rm UP},\sigma}(\mathbf{k}) \hat{a}_{{\rm UP},\sigma}(\mathbf{k})]$$



polariton are bosons...

Bose-Einstein condensation !

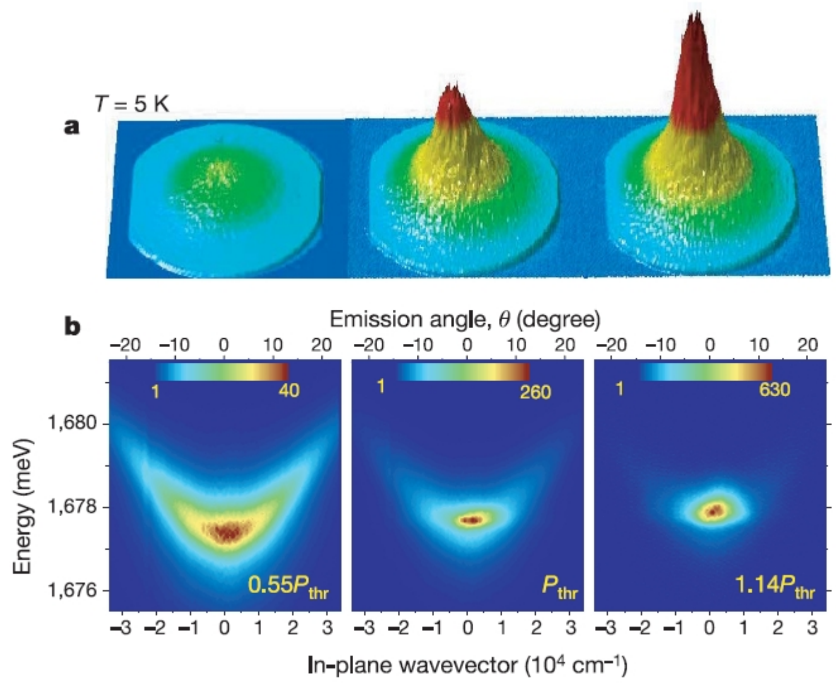
incoherent pump : the phase of the condensate is chosen spontaneously

[J. J. Hopfield Phys. Rev. 112, 1555 (1958)

I. Carusotto and C. Ciuti, Rev. Mod. Phys. 85, 300 (2013)]

Polariton condensation

- Bose-Einstein Condensation observed in experiments



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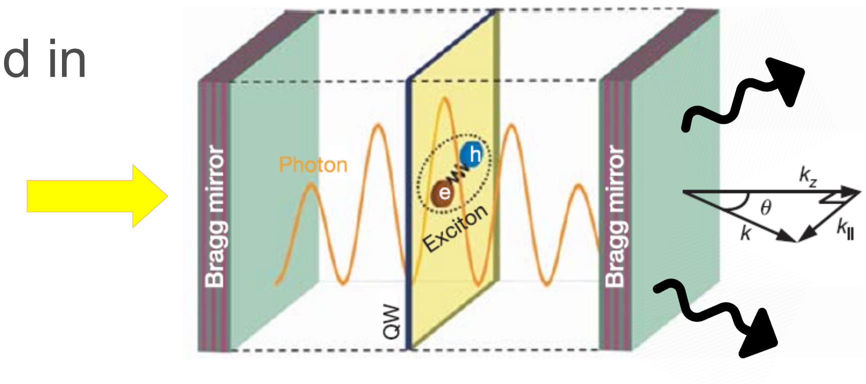


Non-equilibrium driven-dissipative conditions : laser pump compensates losses from mirrors

Control knob : the laser pump intensity

Condensation for $P > P_{th}$

→ Non-equilibrium phase transition

Exciton polariton condensates : the model

- Driven-dissipative stochastic Gross-Pitaevskii equation for the condensate wavefunction *[Carusotto, Ciuti RMP 2013]*

$$i\hbar\frac{\partial}{\partial t}\psi = \left[E(\hat{k}) - \frac{i\hbar}{2}\gamma(\hat{k}) + g|\psi|^2 + 2g_R n_R + \frac{i\hbar}{2}R n_R\right]\psi + \xi$$

polariton single-particle dispersion

condensate lifetime

condensate interactions

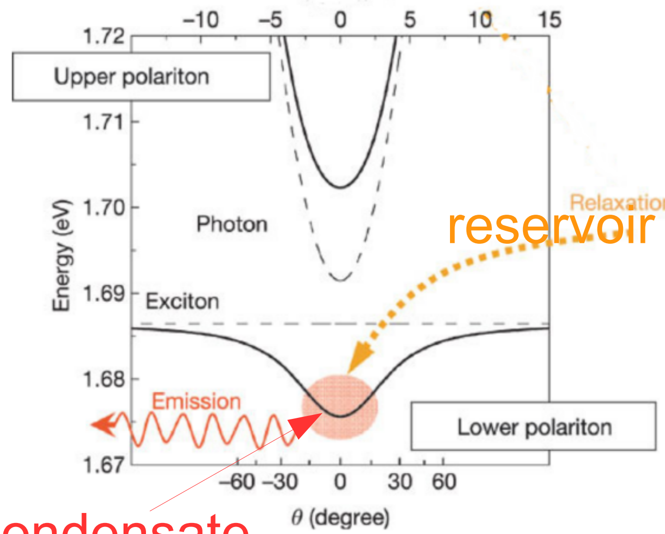
interactions with reservoir

relaxation from reservoir to condensate

noise from pump/losses

$$\langle \xi(x,t)\xi^*(x',t')\rangle = 2\xi_0\delta(x-x')\delta(t-t')$$

- Equation for the excitonic reservoir density, pumped by laser. It fills the condensate by collisions



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

pump

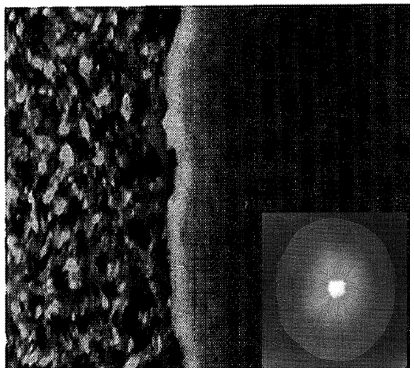
resevoir lifetime

reservoir-condensate relaxation

A famous statistical physics model

- The Kardar-Parisi-Zhang equation describes the kinetic roughening during stochastic interface growth

Frost on a window



Bacteria growth

Combustion front

Lichen on a rock

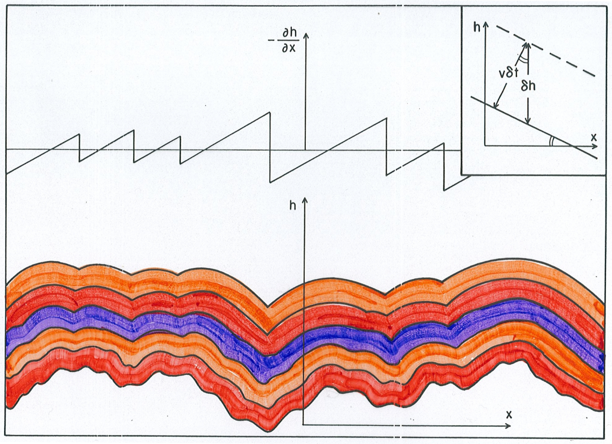
The Kardar-Parisi-Zhang equation

- Describing the growth of a classical interface
  [Kardar, Parisi, Zhang PRL 1986]

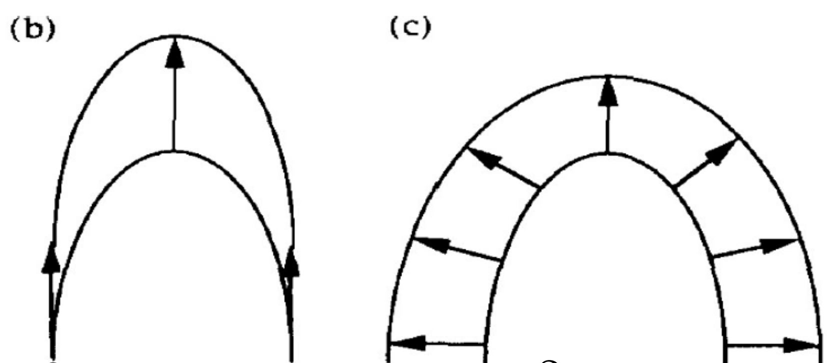
$$\partial_t h = \nu \nabla^2 h + \frac{\lambda}{2} (\nabla h)^2 + \eta$$

with random white noise

$$\langle \eta(x,t) \eta(x',t') \rangle = 2D \delta(x-x') \delta(t-t')$$



competition of *smoothening* from surface tension (diffusion term) and *roughening* due nonlinear growth normal to the interface



$\nu \nabla^2 h$ $\lambda (\nabla h)^2 / 2$

Universal scaling properties of the KPZ phase

Self-organized criticality : the whole parameter region is critical

- Scaling properties : power law increase of fluctuations of the height field

$$\langle |h(x,t)-h(x',t')|^2\rangle \sim |x-x'|^{2\chi} \quad \text{for} \quad |t-t'|=0$$

$$\langle |h(x,t)-h(x',t')|^2\rangle \sim |t-t'|^{2\beta} \quad \text{for} \quad |x-x'|=0$$

critical exponents :
saturation exponent χ
roughness exponent β
dynamical exponent $z=\chi/\beta$

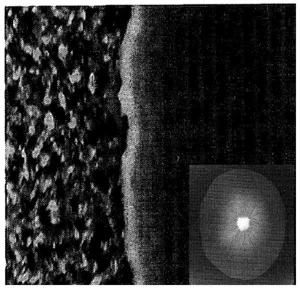
in 1D :
$\chi = 1/2 \quad \beta = 1/3$

in 2D :
$\chi \simeq 0.38 \quad \beta \simeq 0.24$

- Space-time scaling : collapse on a single scaling function

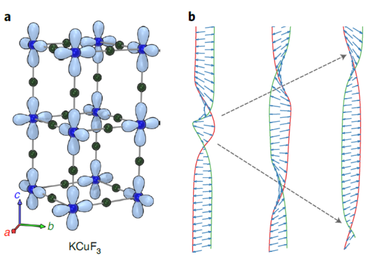
$$\langle |h(x,t)-h(x',t')|^2\rangle \sim |x-x'|^{2\chi} f\left(|t-t'|/|x-x'|^{z}\right)$$

An emergent statistical physics model



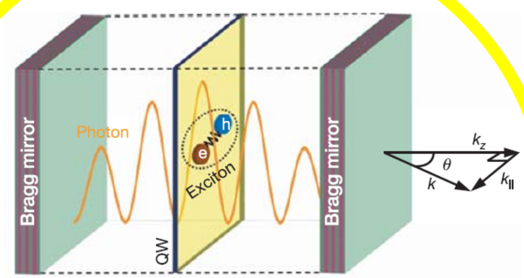
……

...but also KPZ in quantum systems !



Heisenberg chains
[Ljuobotina et al Nat Phys 2017]

- 1D antiferromagnets ($KCuF_3$)
  [Schele et al Nat Phys 2021]
- Ultracold bosons in optical lattices
  [Wei el al Science 2022]
- Strongly repulsive fermions in trap
  [Pecci et al PRR 2022]



- Excitons polaritons in semiconductors

- Which interface ?
- Conditions and parameters for KPZ ?
- Observables ?
- Is it *really* the same physics?

Polariton phase dynamics : emergence of KPZ

- Using the Gross-Pitaevskii equation for the condensate wavefunction, $\psi = \sqrt{\rho} e^{i\theta}$

  $\rightarrow$ KPZ equation for the condensate phase *[Altman et al, PRX 2015]*

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

with $\langle \eta(x,t) \eta(x',t') \rangle = 2D \delta(x-x') \delta(t-t')$

ν, λ, D related to to the parameters of the Gross-Pitaevskii equation

- Observable in experiments via the first-order correlation function of the condensate

$$g^{(1)}(\Delta x, \Delta t) = \frac{\langle \psi^*(x,t) \psi(x',t') \rangle}{\sqrt{\langle \rho(x,t) \rangle \langle \rho(x',t') \rangle}}$$

$$|g^{(1)}(\Delta x, \Delta t)|^2 \simeq \exp(-\langle \mathrm{Var}[\theta(x,t) - \theta(x',t')] \rangle)$$

- at difference from an interface, the phase is a compact variable
  $\rightarrow$ we unwind the phase trajectories
  $\rightarrow$ some differences may occur...

Signatures of KPZ in polaritons : theory

- Early theoretical works predicted emergence of KPZ in polaritons, but in a too large system (not realistic parameter conditions)

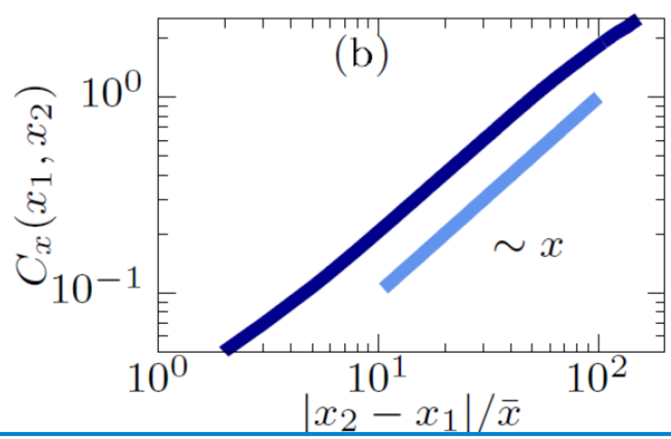
[He, Sieberer, Altman, Diehl PRB 2015]

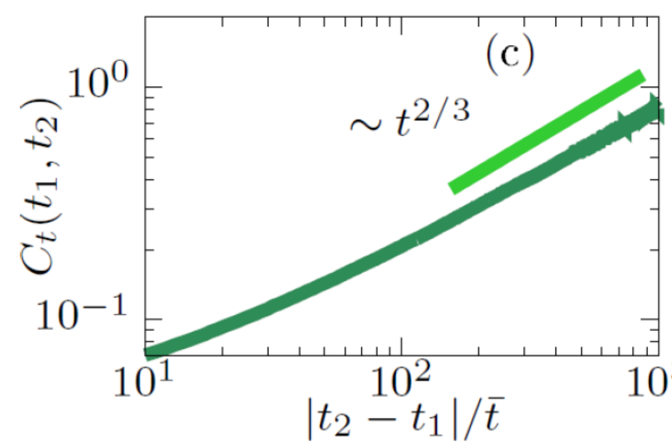
- Our work : momentum-dependent condensate lifetime, experimentally relevant, stabilizes the KPZ phase within experimentally accessible parameters !

[Squizzato, Canet and Minguzzi PRB 2018]

Our theoretical predictions of KPZ scaling in polaritons :

$$C(\Delta x, \Delta t) = -2\log(|g^{(1)}(\Delta x, \Delta t)|) \qquad |g^{(1)}(\Delta x, \Delta t)|^2 \simeq \exp(-\langle \mathrm{Var}[\theta(x,t) - \theta(x',t')]\rangle)$$





KPZ scalings :

$$\langle \mathrm{Var}[\theta(x, t_0) - \theta(x', t_0)]\rangle \sim |x - x'|^{2\chi}$$

$$\langle \mathrm{Var}[\theta(x_0, t) - \theta(x_0, t')]\rangle \sim |t - t'|^{2\beta}$$

Implications of KPZ behaviour: the Penrose-Onsager criterion

- Bose-Einstein condensation : condensate density n_0 from the off-diagonal long range order (ODRLO) of the one-body density matrix *[Penrose, Onsager PR 104, 576 (1956)]*

$$\langle \psi^*(x)\psi(x')\rangle \to n_0 \quad \text{for} \quad |x-x'| \to \infty$$

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  [Penrose, Onsager PR 104, 576 (1956)]

$$\langle \psi^*(x)\psi(x')\rangle \to n_0 \quad \text{for} \quad |x-x'| \to \infty$$

- KPZ correlations of the phase-phase correlations imply that driven-dissipative polariton condensates are not true Bose-Einstein condensates !

$$|g^{(1)}(\Delta x, \Delta t)|^2 = \frac{\langle \psi^*(x,t)\psi(x',t')\rangle}{\sqrt{\langle \rho(x,t)\rangle\langle \rho(x',t')\rangle}} \simeq \exp(-\langle \mathrm{Var}[\theta(x,t)-\theta(x',t')]\rangle)$$

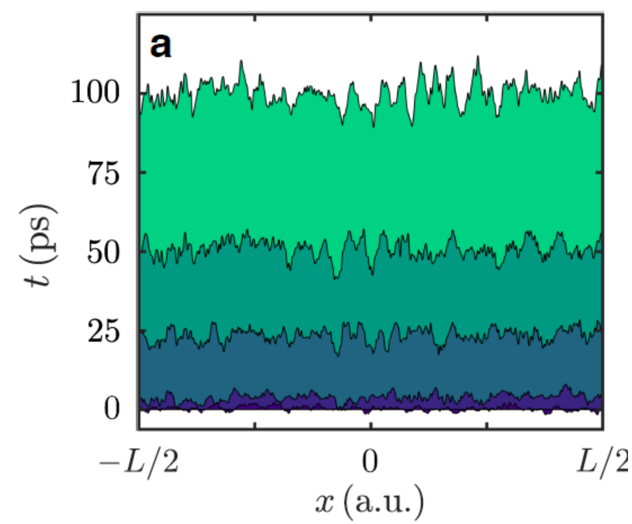
KPZ : $\left\langle |\theta(x,t)-\theta(x',t')|^2 \right\rangle \sim |x-x'|^{2\chi} f\left(|t-t'|/|x-x'|^{z}\right.$

$\to$ growing phase fluctuations destroy ODRLO

$\to$ the polariton condensates belong to a different universality class than equilibrium ones

$\to$ fundamental limit on the coherence of open quantum systems

phase profiles



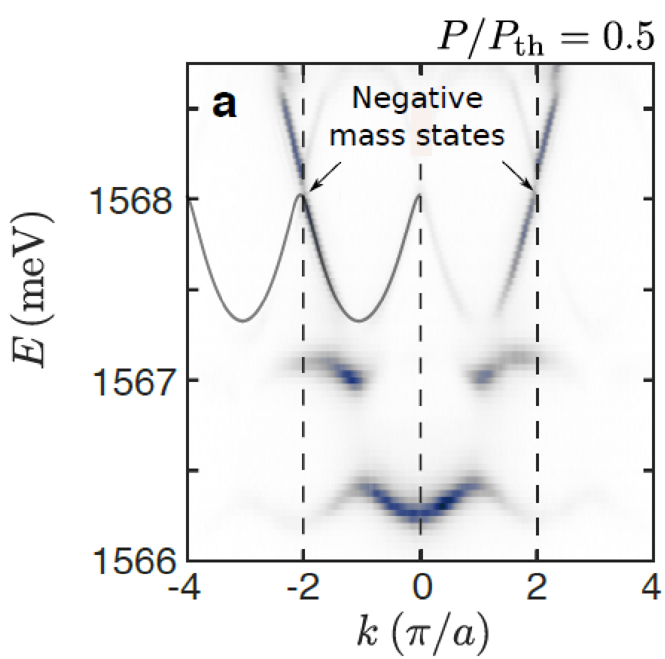
[Fontaine et al, Nature 2022]

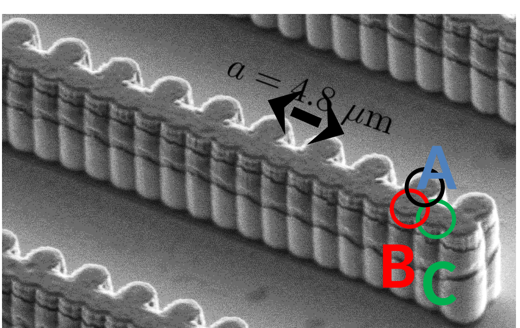
The quest for experimental observation

- Jacqueline Bloch team @CN2, Palaiseau : control over decoherence and instability effects by band engineering in a lattice : condensates with negative mass

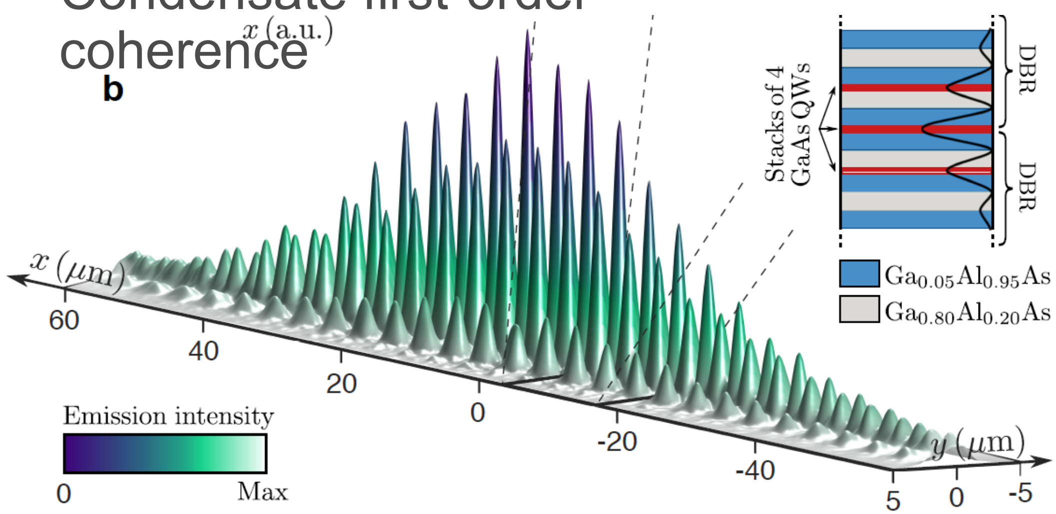
[Baboux et al, Optica 2018]

Band dispersion





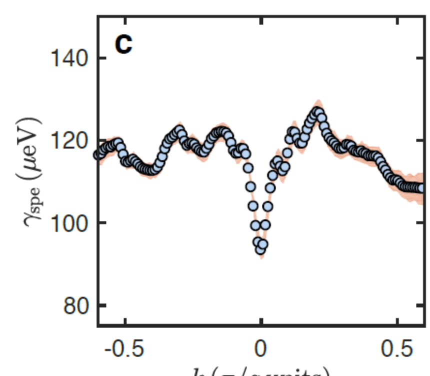
Condensate first-order coherence



Effective interaction strength

$$g_{eff} = g - 2g_R \frac{\gamma_0}{\gamma_R} \frac{P}{P_{th}}$$

Momentum-dependent lifetime

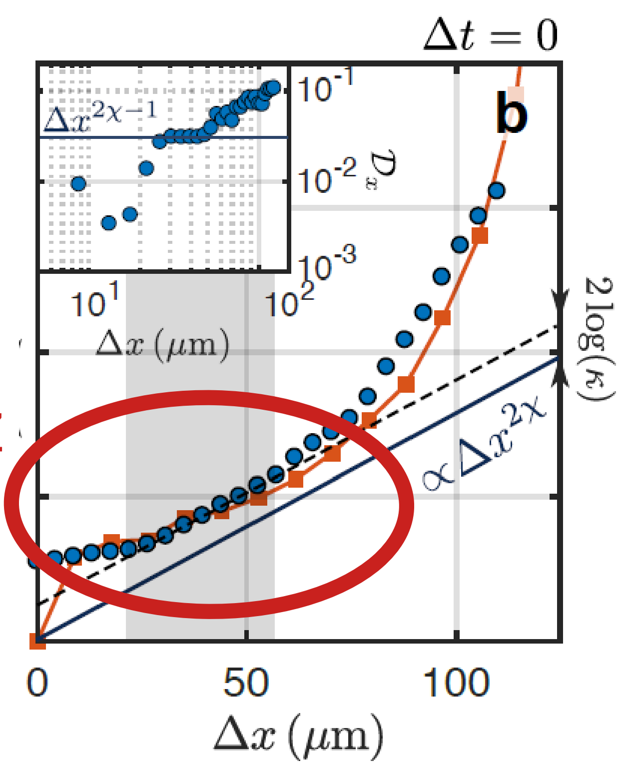


KPZ evidence : space and time correlations

$$g^{(1)}(\Delta x, \Delta t) = \frac{\langle \psi^*(x,t_0)\psi(-x,t_0+\Delta t)\rangle}{\sqrt{\langle|\psi(x,t_0)|^2\rangle}\sqrt{\langle|\psi(-x,t_0+\Delta t)|^2\rangle}}$$

from Michelson interferometry

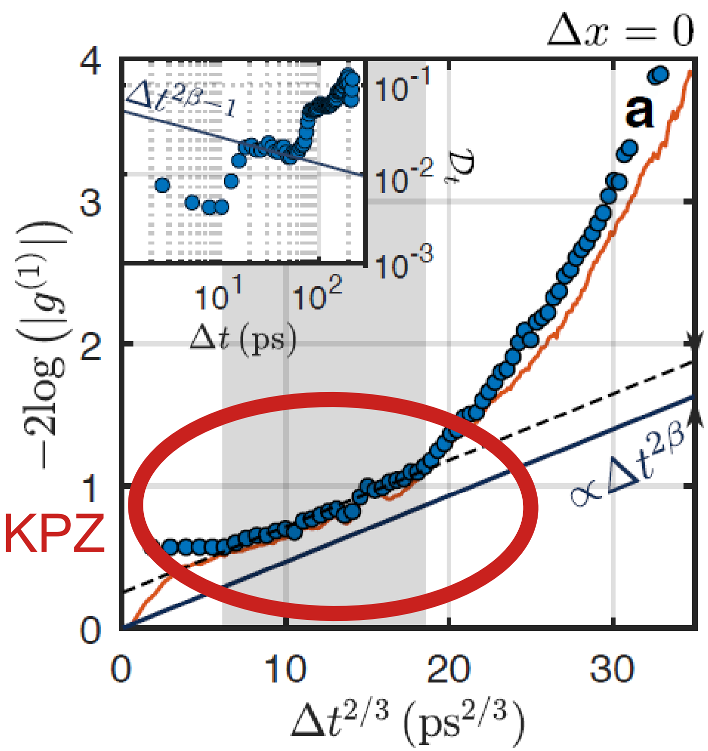
- Spatial correlations



KPZ

o Experiment
– Simulation

- Temporal correlations



KPZ

- Evidence for KPZ window both in space and time
- Extracted critical exponents $\chi = 0.51 \pm 0.08$ $\beta = 0.35 \pm 0.02$

[Fontaine et al, Nature 2022]

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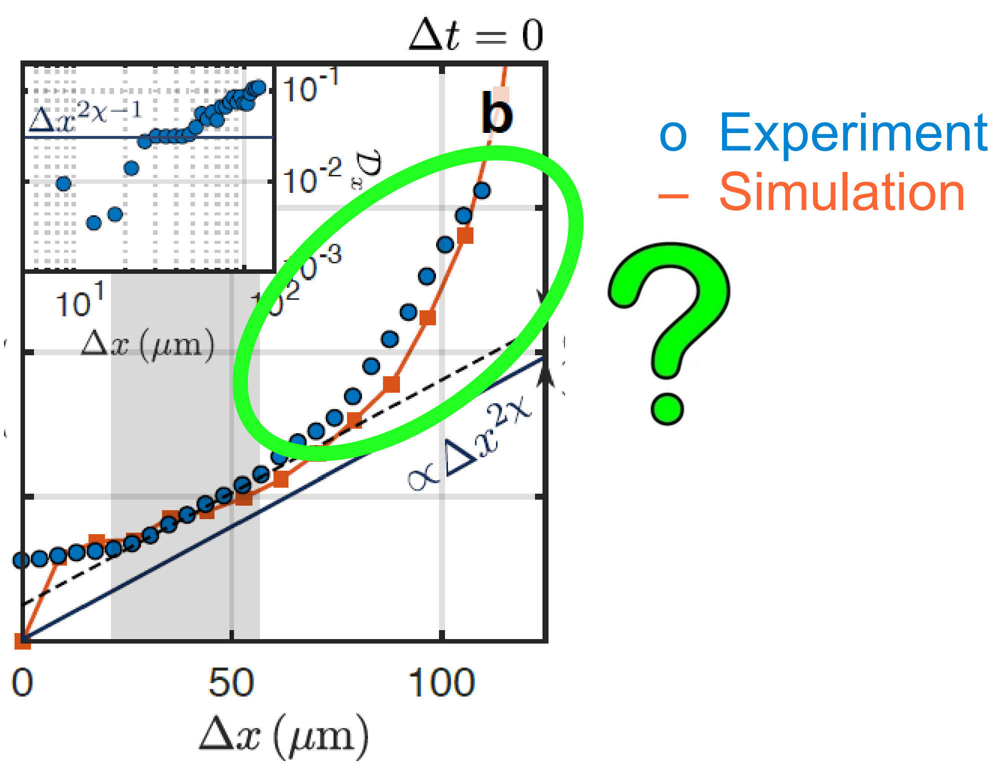
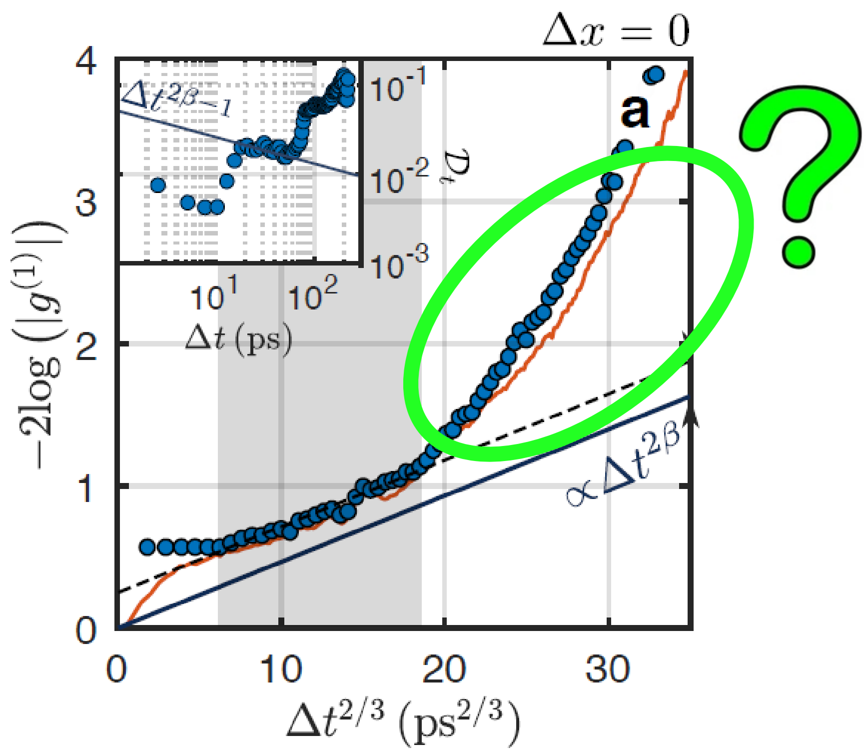


- Temporal correlations



- Deviation from KPZ behaviour at large time and space

[Fontaine et al, Nature 2022]

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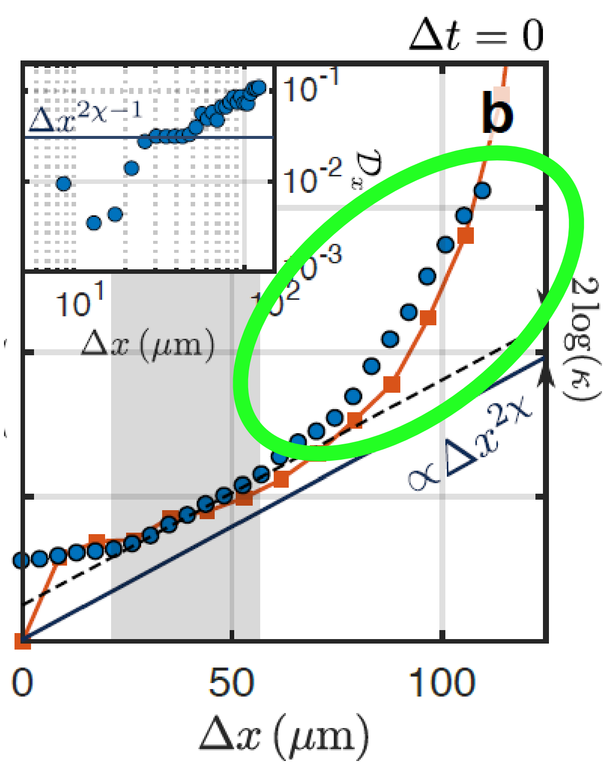
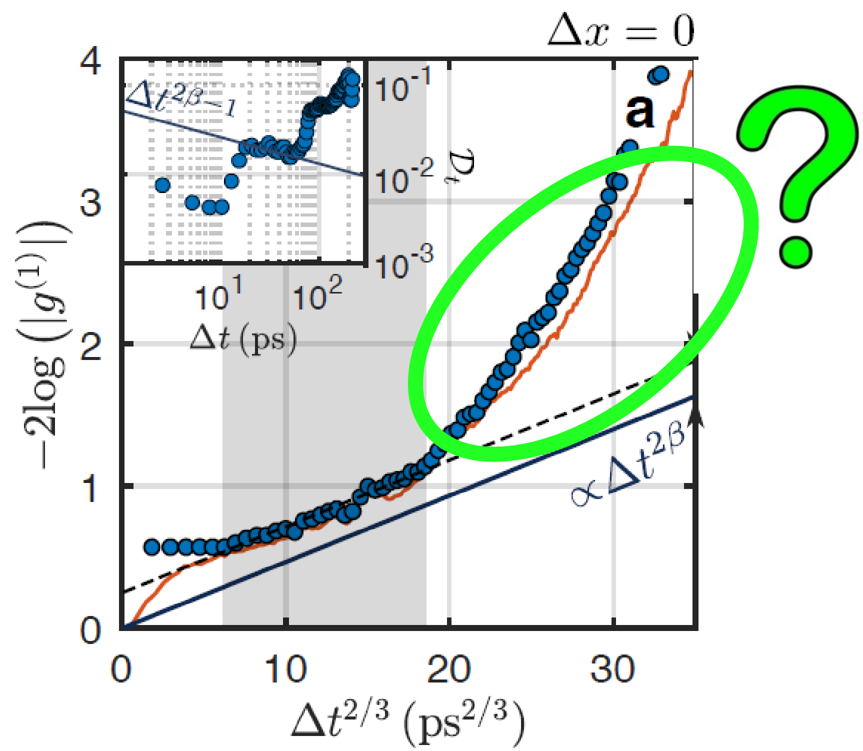
from Michelson interferometry

- Spatial correlations
- Temporal correlations





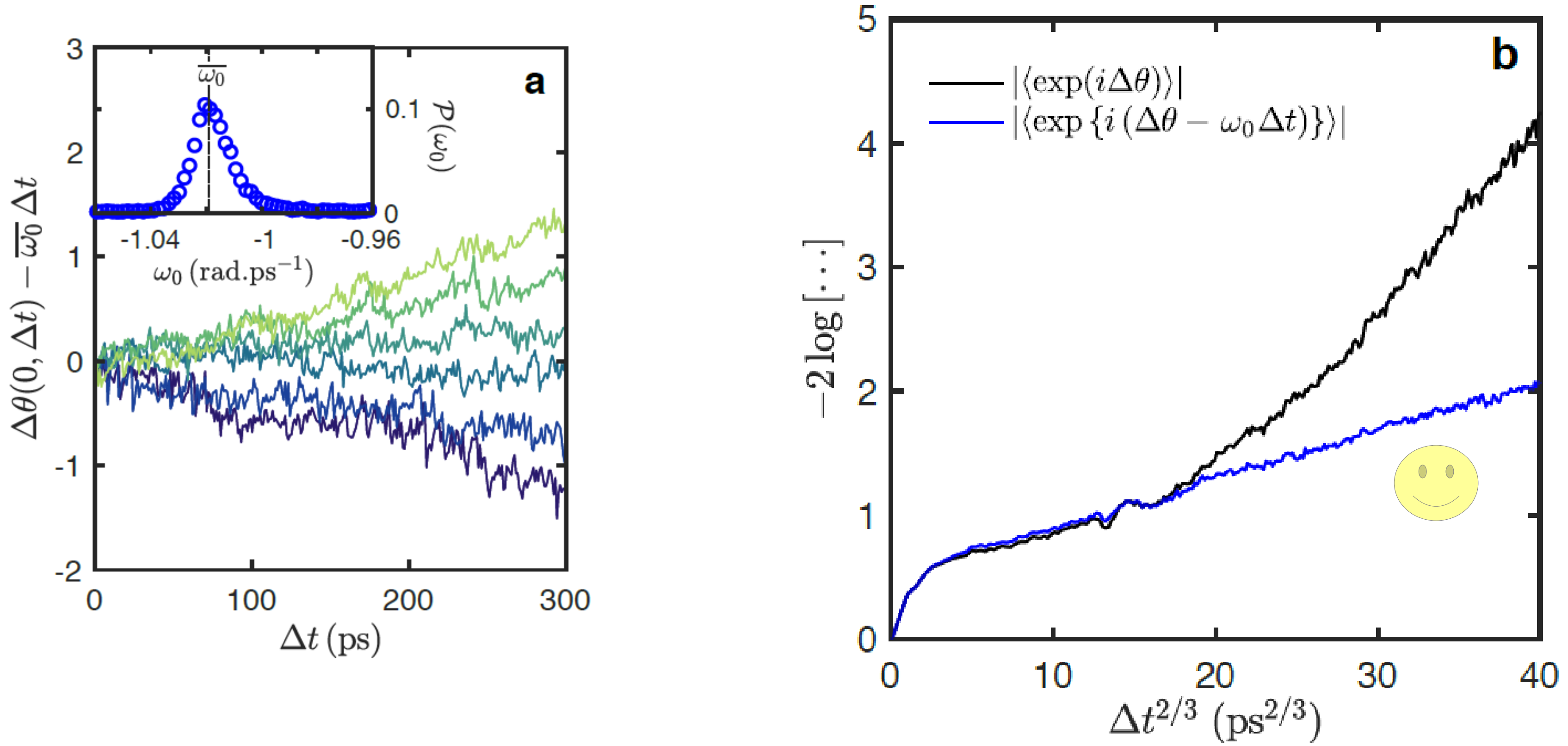
- Deviation from KPZ behaviour at large time and space

[Fontaine et al, Nature 2022]

Deviation from KPZ scaling at large times

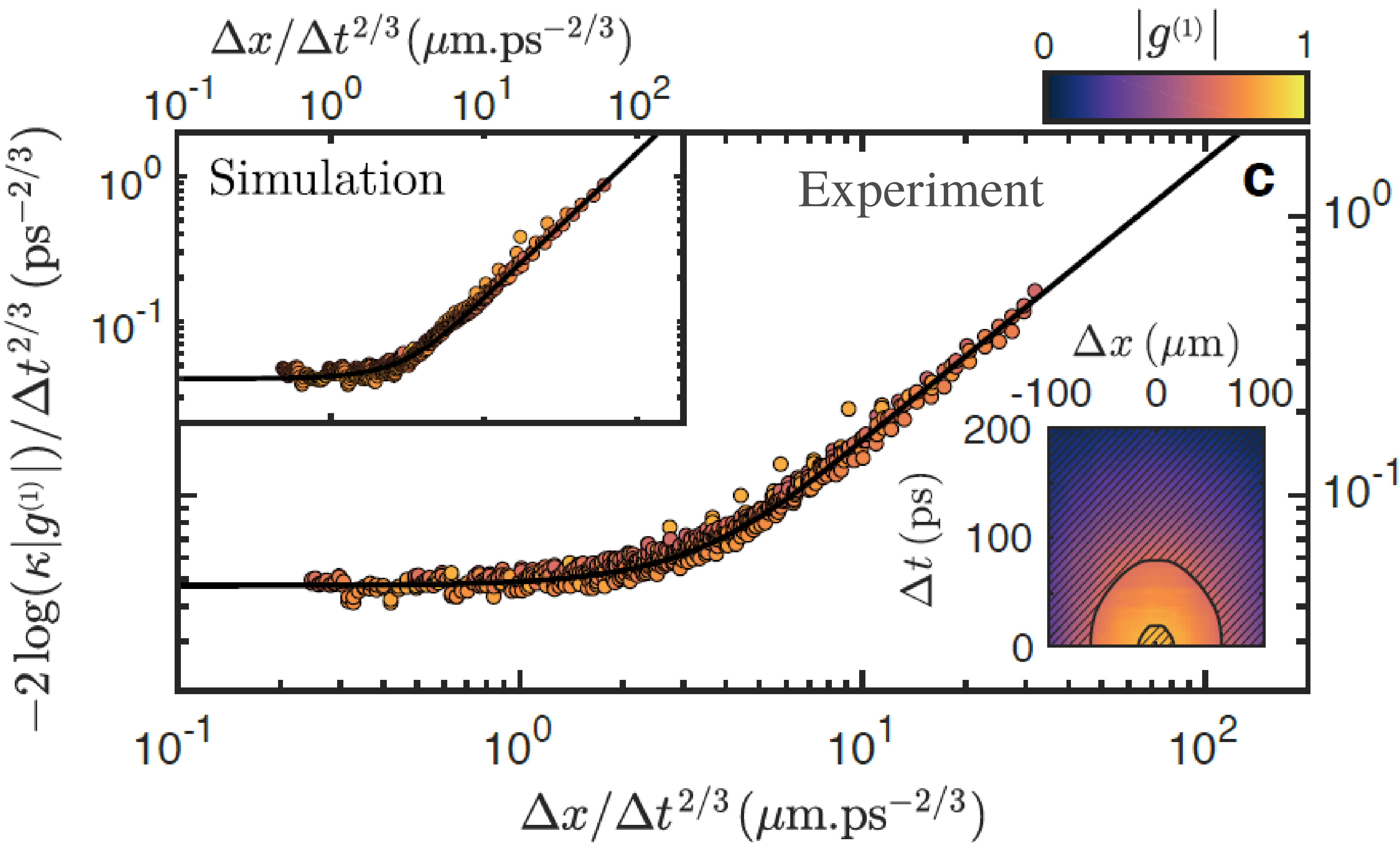
- Observed spread of slopes for the phase trajectories

$$\Delta\theta(t_0, \Delta t) \equiv \theta(t_0 + \Delta t) - \theta(t_0) \sim \boxed{\omega_0}\Delta t + (|\Gamma|\Delta t)^{\chi/z}\,\tilde{\theta}(\Delta t)$$



- The observed disruption of KPZ scaling at large time differences is due to the spread of slopes, ie an inhomogeneous broadening

KPZ evidence : scaling function and data collapse

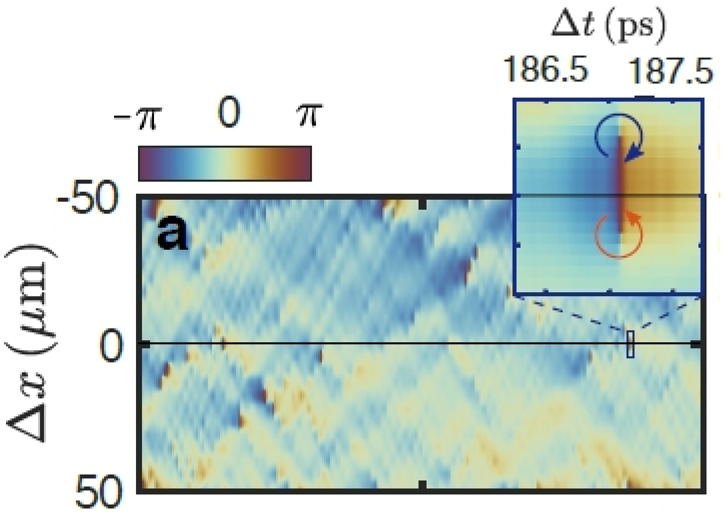


- Excellent agreement with the theoretical KPZ scaling function
- Normalization non-universal parameters are very close to microscopic ones

[Fontaine et al, Nature 2022]

Robustness to phase slips

- simulations show phase slips corresponding to *vortices in space time*



Vortex-antivortex pairs perturb only locally the phase map

→ first order correlation robust to few phase slips :
jumps close to multiples of 2π
they do not affect it !

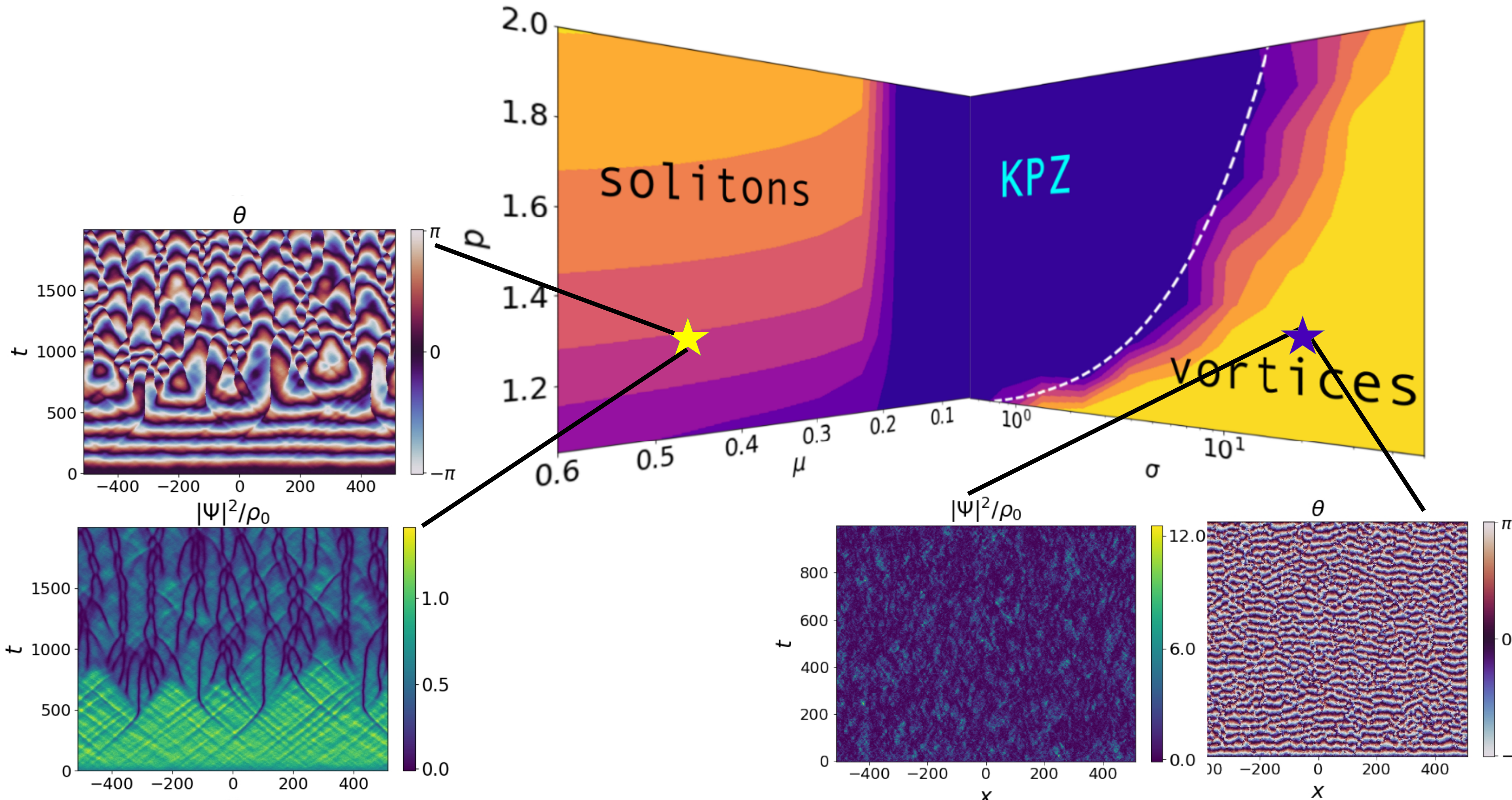
$$g^{(1)}(\Delta x, \Delta t) \sim \langle e^{i(\theta(x,t)-\theta(x',t'))} \rangle$$

theoretical analysis full supports observation of KPZ scaling

[Fontaine et al, Nature 2022]

Full non-equilibrium phase diagram

- By increasing noise, pump or interactions, three main phases

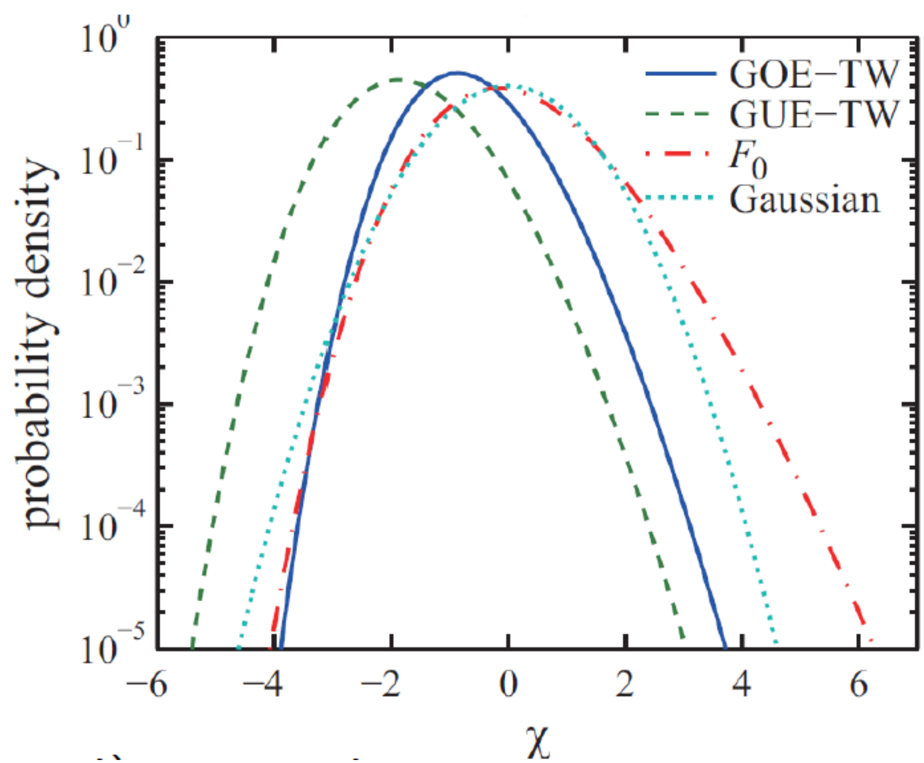


[Vercesi et al, in preparation]

Beyond scaling : KPZ probability distribution of height fluctuations

- In KPZ universality class : non-Gaussian probability distribution for height fluctuations *[Corwin, Rand. Mat. 2012]*

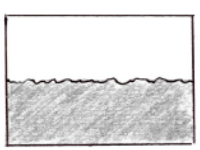
$$h(x,t) \sim v_\infty t + (\Gamma t)^{1/3}\chi(x,t)$$



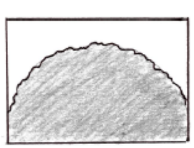
[Prahofer and Spohn, PRL 2004]

- various universality *subclasses* (all with the same critical exponents)

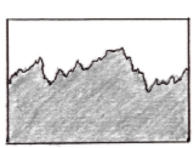
→ depending on the initial conditions for the interface, different shapes of the distribution



Flat : Tracy-Widom GOE



Curved : Tracy-Widom GUE

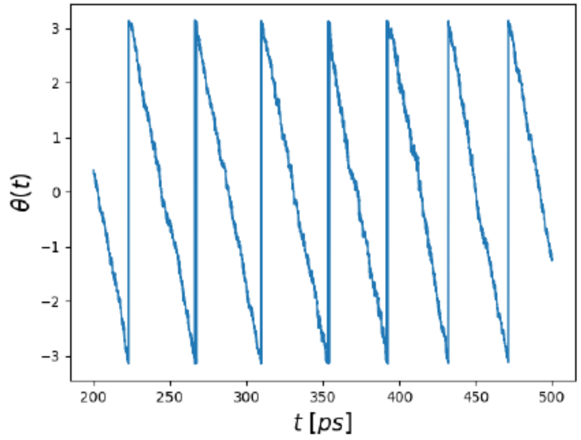


Disordered : Baik-Rains

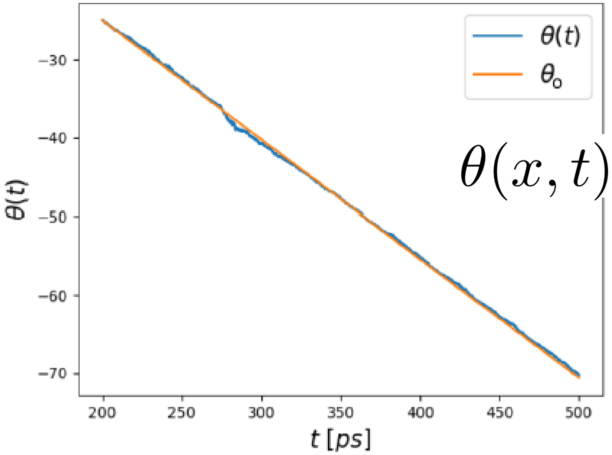
Beyond scaling : probability distribution of the condensate phase fluctuations

- Distribution of the rescaled phase of a polariton condensate – from numerical simulations of the stochastic generalized Gross-Pitaevskii equation

temporal phase trajectory

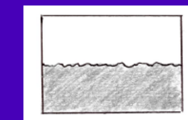


unwounded phase



$$\theta(x,t) \sim \omega_\infty t + (\Gamma t)^{1/3}\tilde{\theta}$$

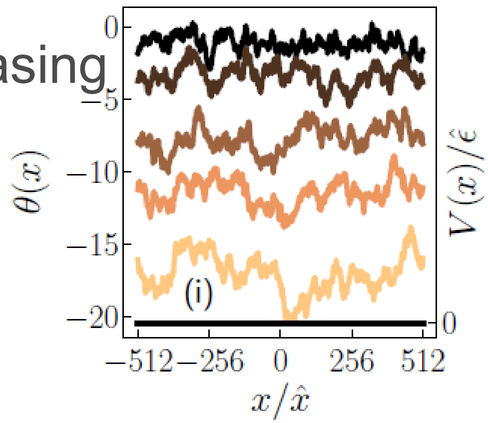
Probability distribution of the condensate phase fluctuations, flat case



- Excellent agreement with the theoretical prediction Tracy-Widom GOE $\rightarrow$ confirms KPZ universality in polaritons

spatial phase profiles

increasing time



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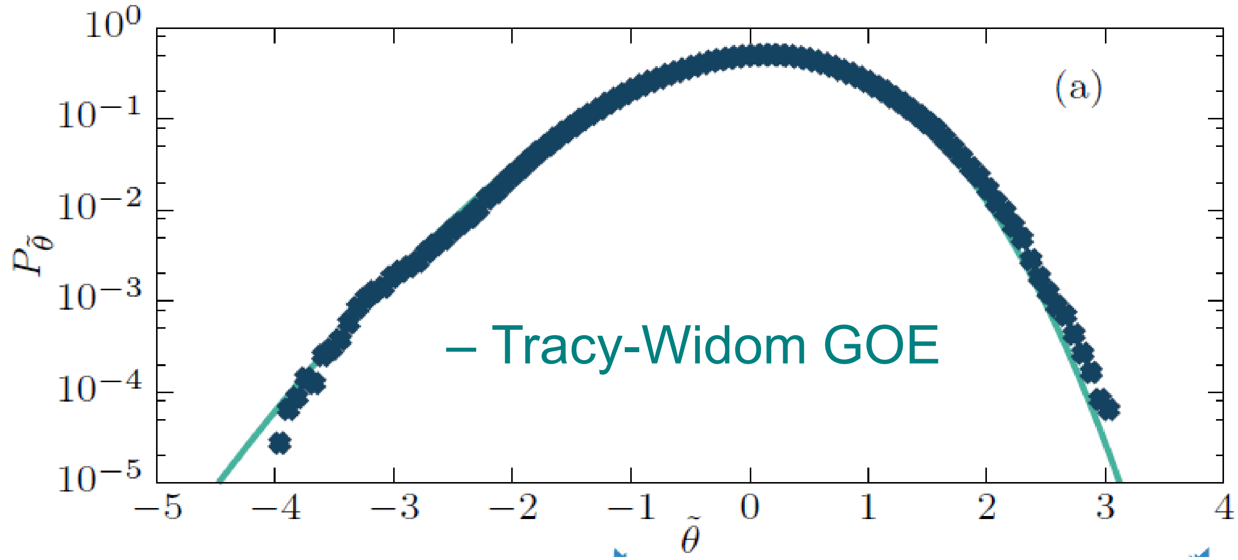
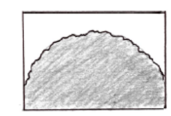


[Squizzato, Canet and Minguzzi PRB 2018]

Beyond scaling : probability distribution of the condensate phase, curved case



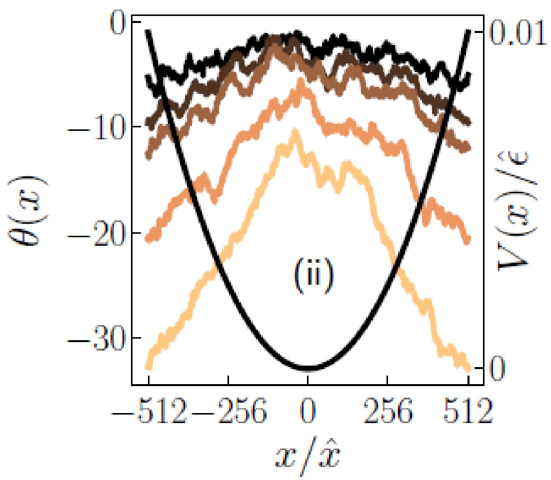
- Possibility to tune the universality subclass by an external confining potential : realization with polaritons of curved case, Tracy-Widom GUE !

$$V(x) = \frac{1}{2} m\omega^2 x^2$$

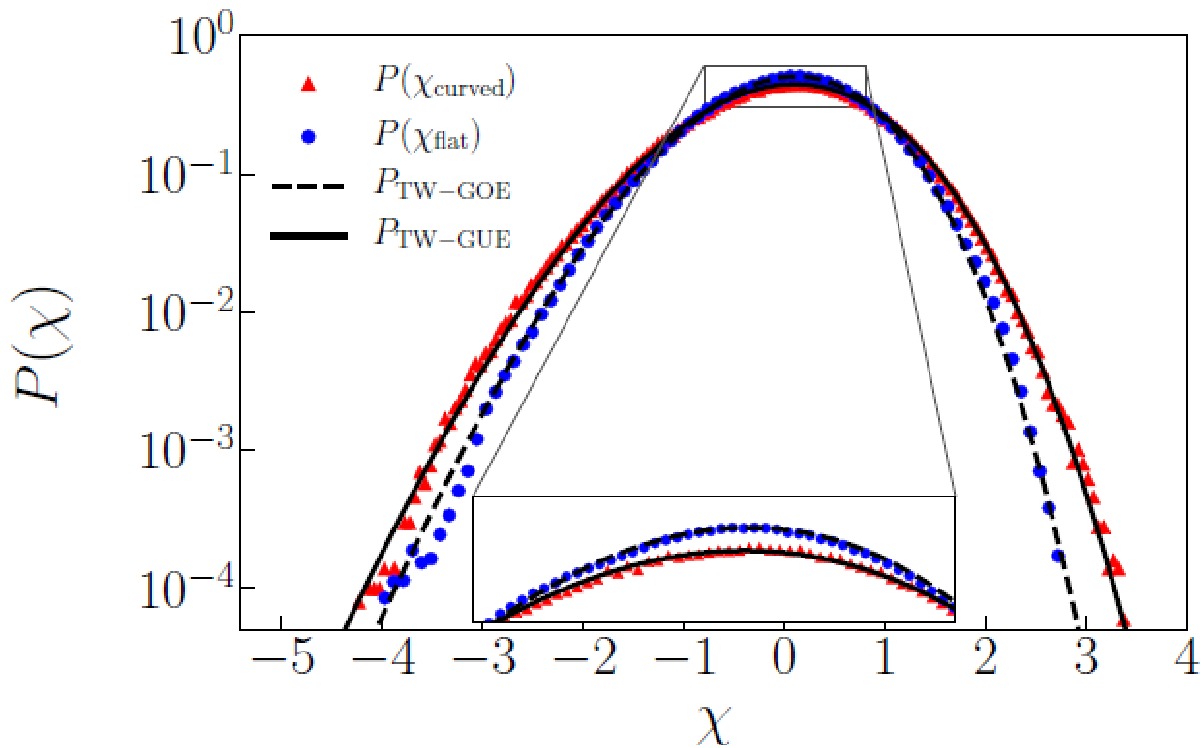
- KPZ mapping still holds

$$\theta(x,t) \sim \omega_\infty t + (\Gamma t)^{1/3}\chi$$

spatial phase profiles

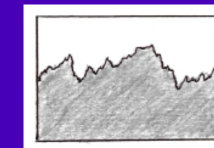


increasing time



[Deligiannis, Squizzato, Minguzzi and Canet EPL2021]

Beyond scaling : probability distribution of the condensate phase, disordered case



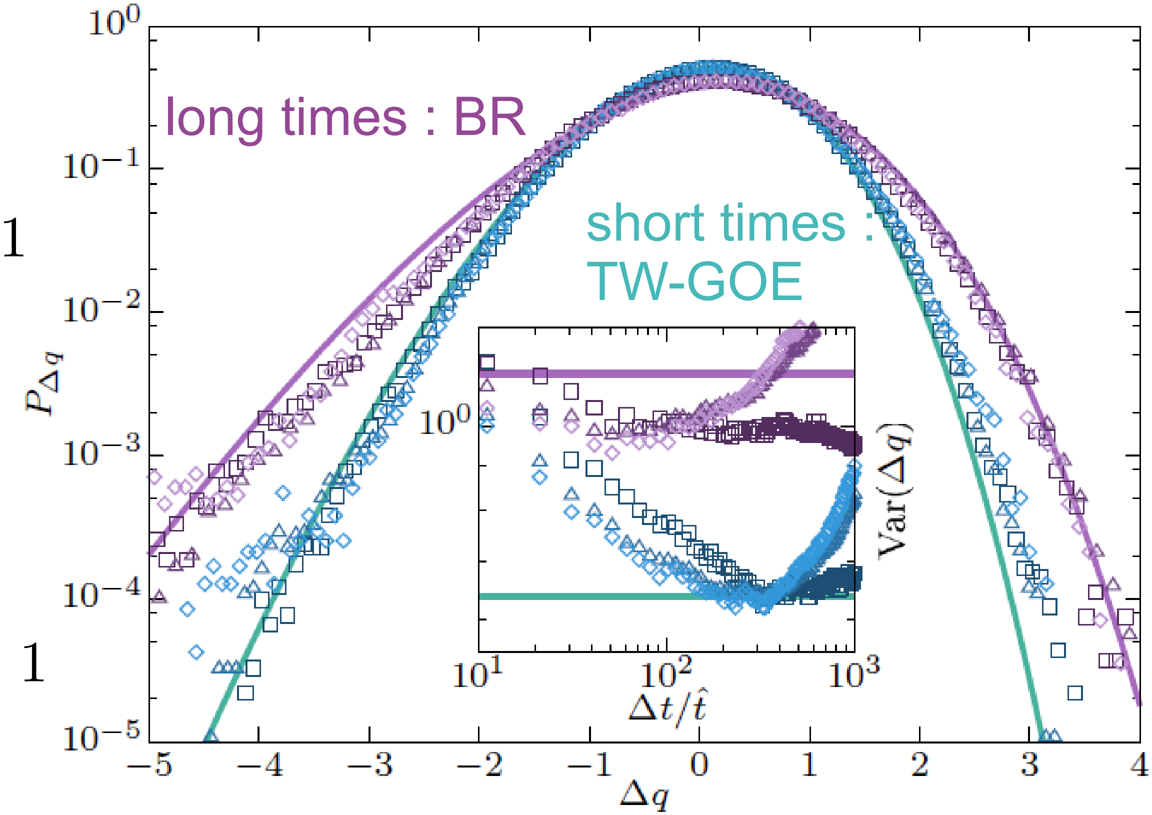
- KPZ : phase profile becomes more and more rough with time

$$\Delta q = [\delta\theta(x, t_0 + \Delta t) - \delta\theta(x, t_0)]/(\Gamma t)^{1/3}$$

Disordered subclass expected at long times : Baik-Rains distribution !

$t_0/\Delta t \gg 1$

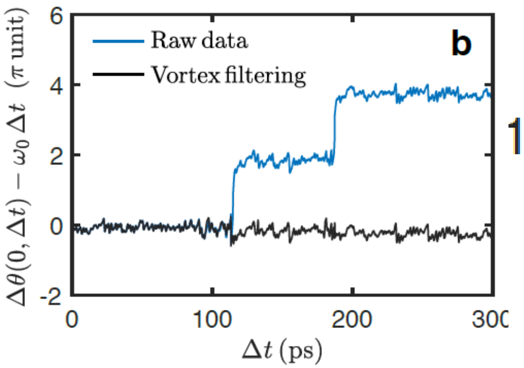
$t_0/\Delta t \ll 1$

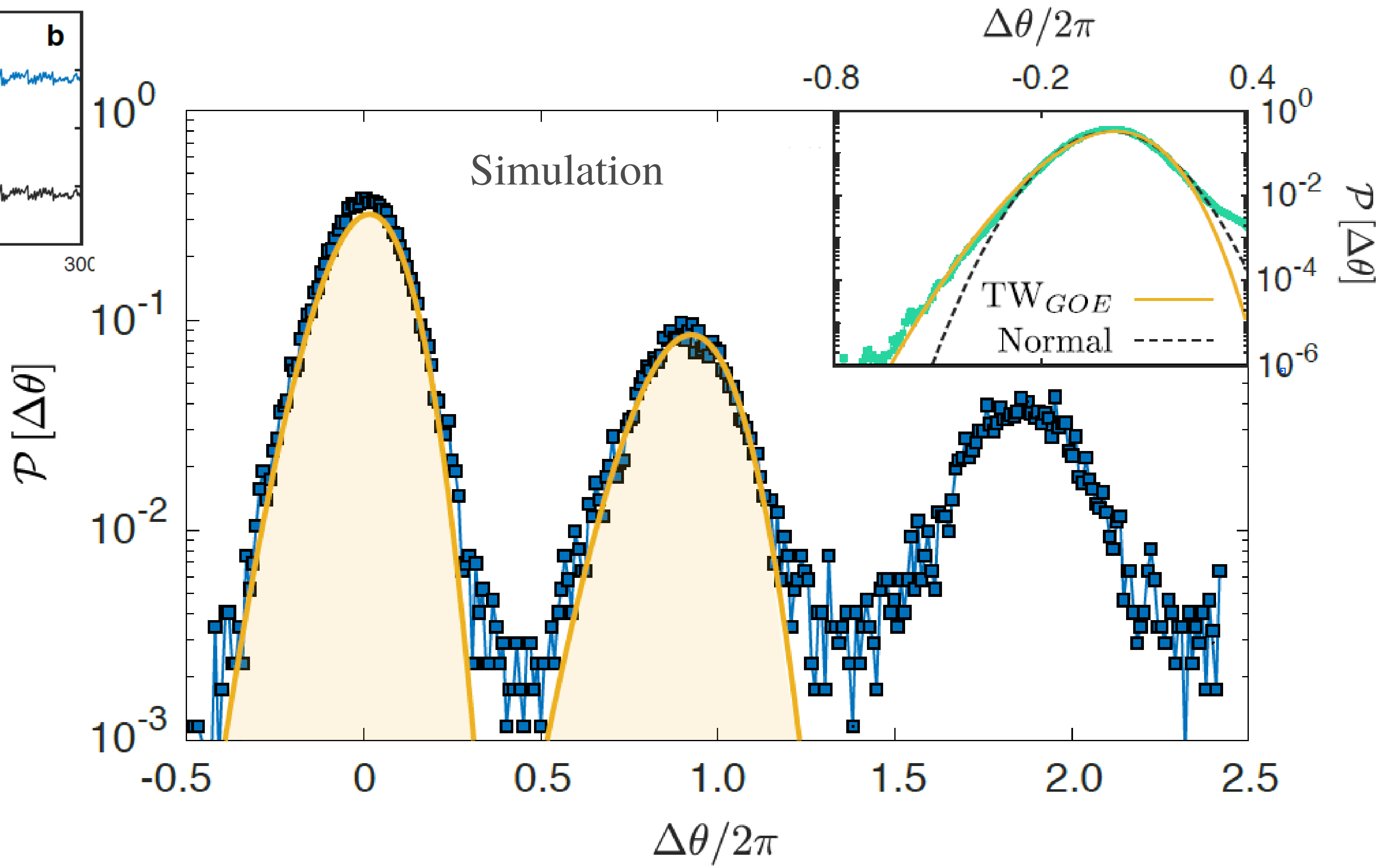


[Squizzato, Canet and Minguzzi PRB 2018]

Probability distribution of the condensate phase fluctations – experimental parameters

- *Phase slips* give rise to *copies* of the Tracy-Widom-GOE phase distribution





[Fontaine et al, Nature 2022]

Exciton-polaritons in 2D : KPZ ??

- 2D at equilibrium : BKT transition – vortex unbinding and proliferation

- In driven-dissipative condensates : spatial vortices may hinder KPZ

- Perturbative RG argument : always vortex unbinding at large distances

  [Altman et al PRX 1015]

- Power-law decay of correlations reported close to pump threshold with non-equilibrium power-law exponent   *[Comaron et al EPL 2021]*

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- Power-law decay of correlations reported close to pump threshold with non-equilibrium power-law exponent *[Comaron et al EPL 2021]*
- Numerical evidence of KPZ scaling with artificially low noise and very high pump

  $$P/P_{th} = 10$$

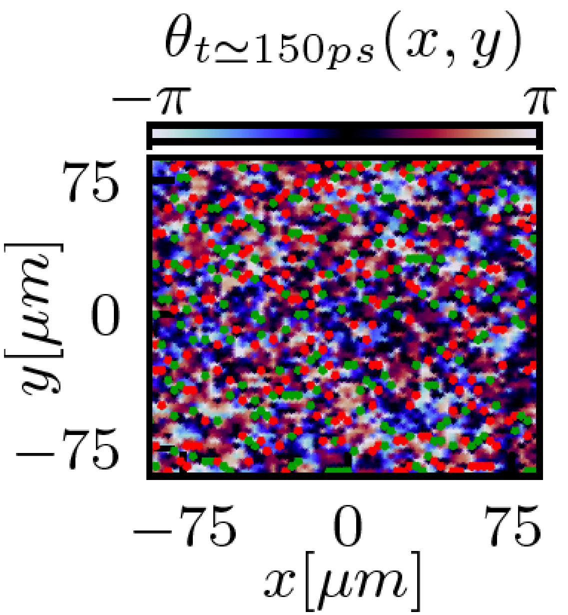
  [Mei, Ji, Wouters PRB 2021]
- Possibility to reach KPZ regime in OPO configuration

  [Zamora et al PRX 2017, Ferrier et al PRB 2022]

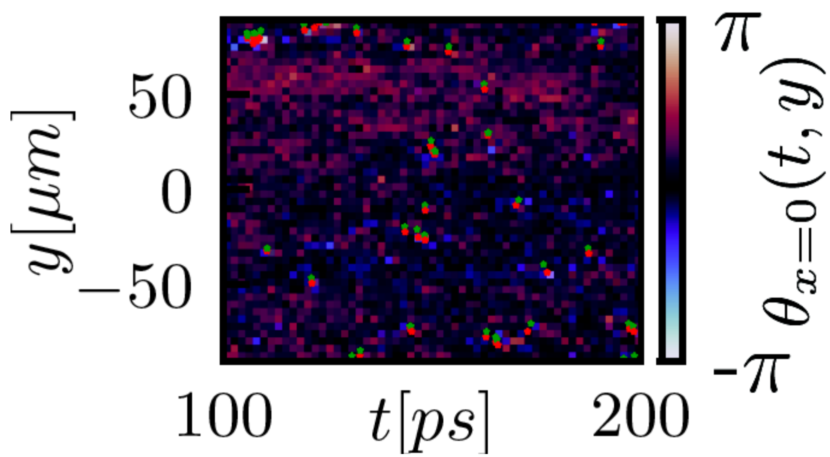
→ our work : lattice model, realistic parameters

Various topological defects...

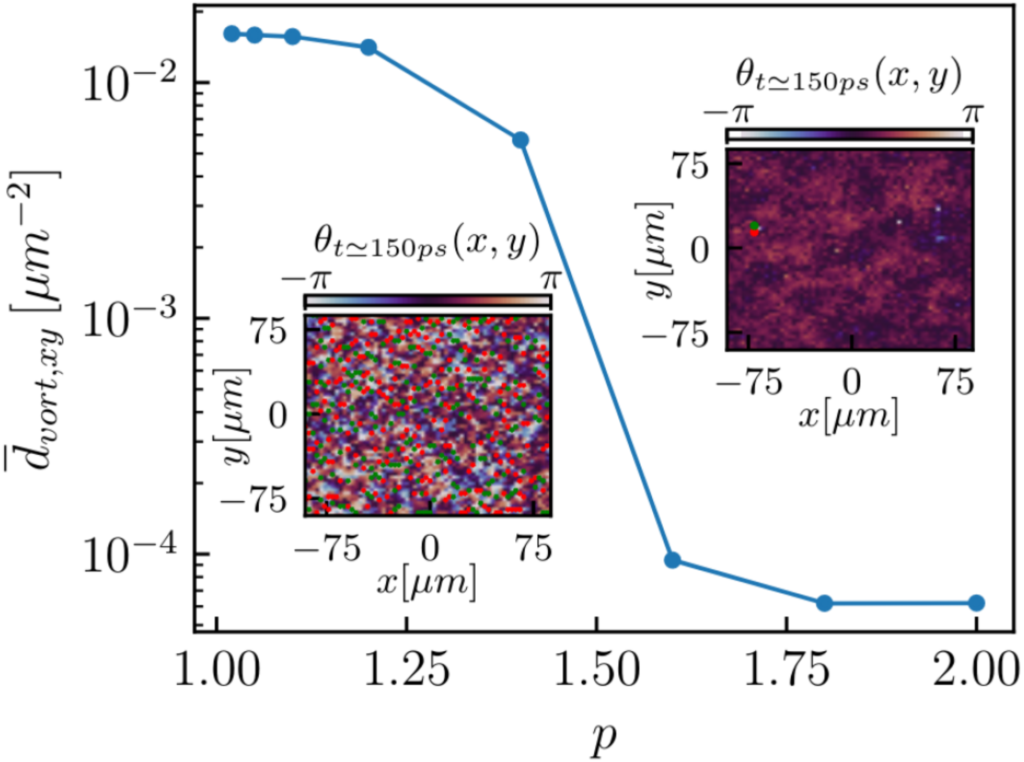
- Spatial vortices



- Space-time vortices

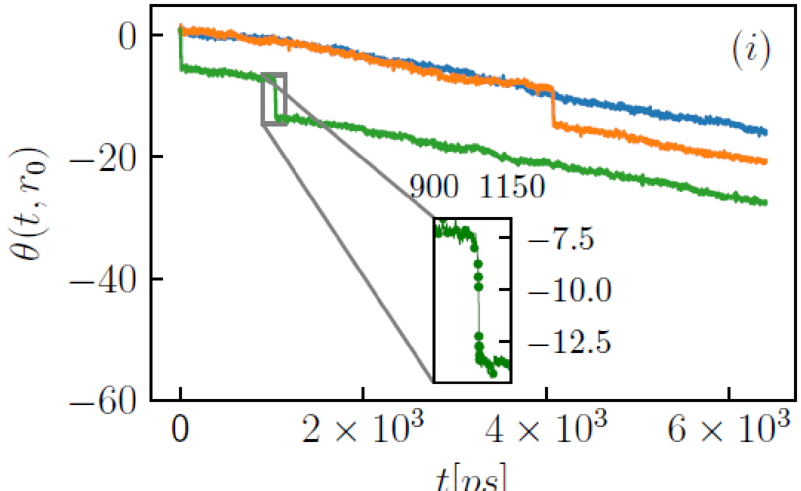


Control over topological defects



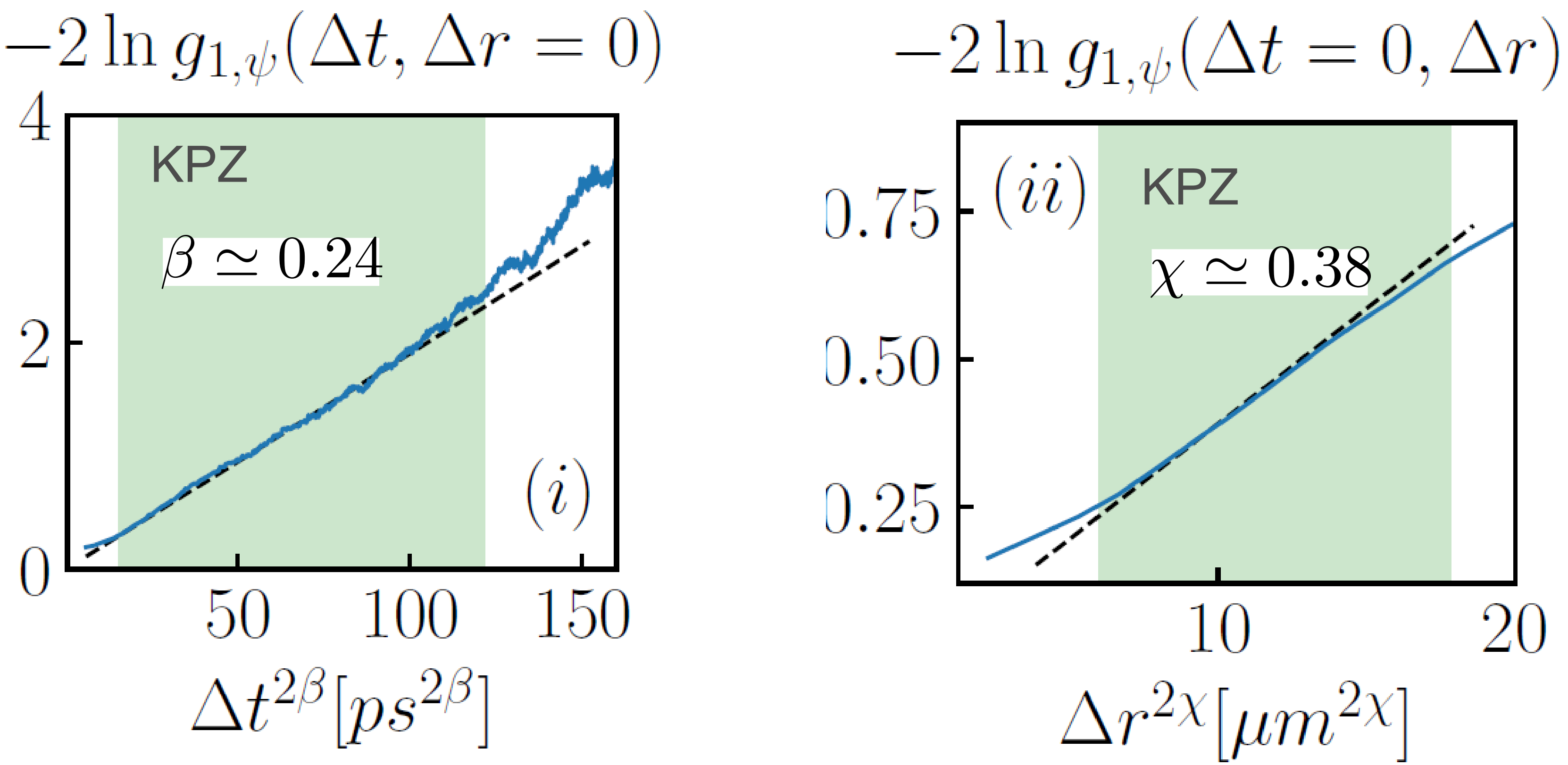
Spatial vortices decrease at increasing pump !

Space-time vortices are close to multiples of 2π
→ as in 1D, they should do not disrupt KPZ universality...



Evidence of KPZ universality in 2D polaritons !

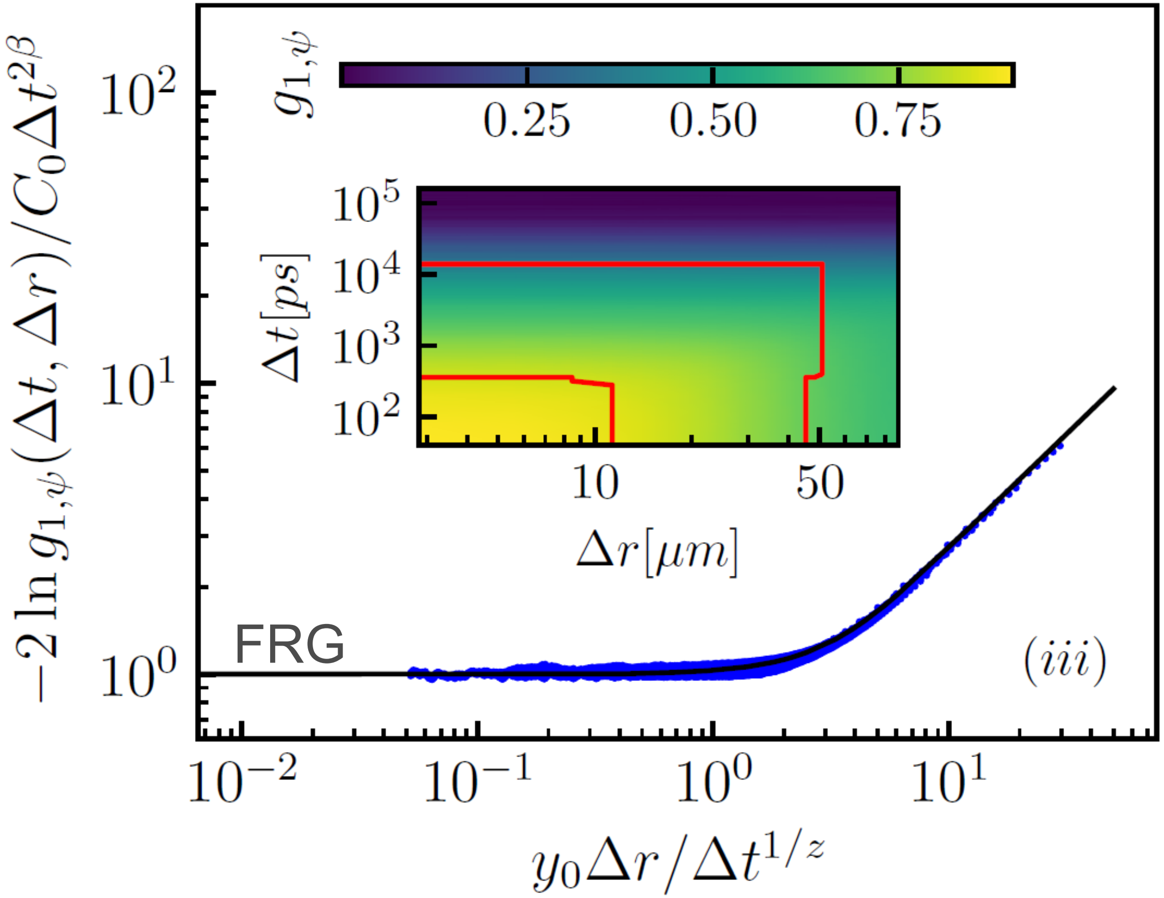
- Space-time scaling with KPZ critical exponents in 2D



[Deligiannis et al Phys. Rev. Research 2022]

Evidence of KPZ universality in 2D polaritons !

- Comparison to the theoretical KPZ scaling function obtained by Functional Renormalization Group *[Kloss et al PRE 2012]*



Space-time data collapse

Evidence for KPZ in 2D polaritons !

[Deligiannis et al Phys. Rev. Research 2022]

Probability distribution of phase fluctuations

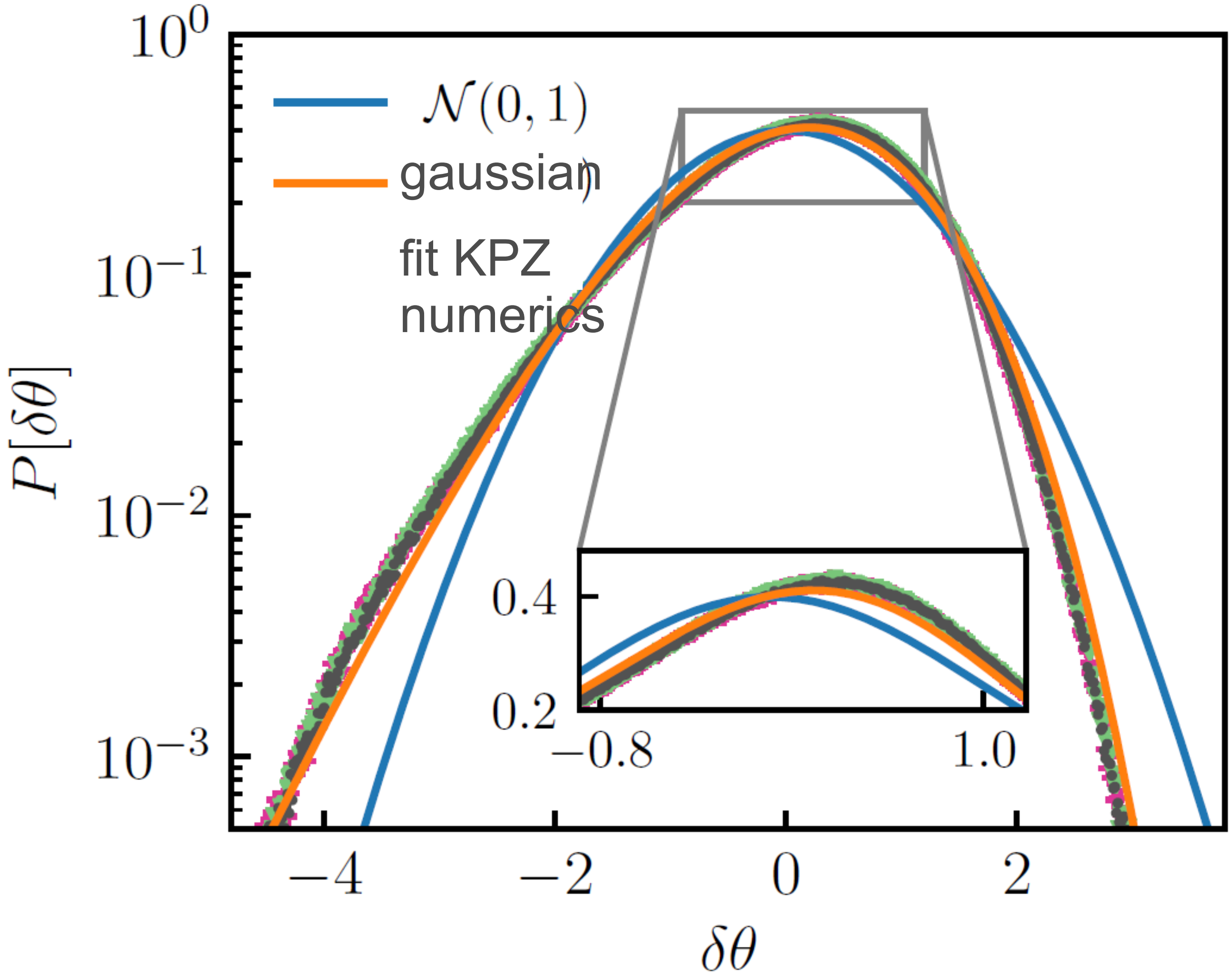
- No analytical prediction available for the KPZ distribution in 2D

Polaritons : from large-scale numerical simulations

- non-gaussian distribution of phase fluctuations
- good agreement with numerical data from KPZ simulations *[Oliveira et al PRE 2013]*

Further evidence of KPZ universality in 2D polaritons

A long-sought experimental platform for KPZ studies

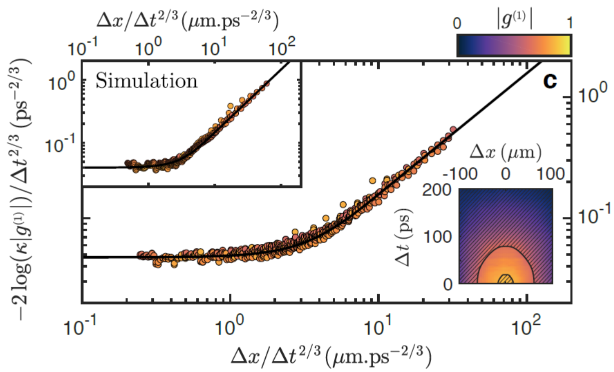


[Deligiannis et al Phys. Rev. Research 2022]

Conclusions & Outlook

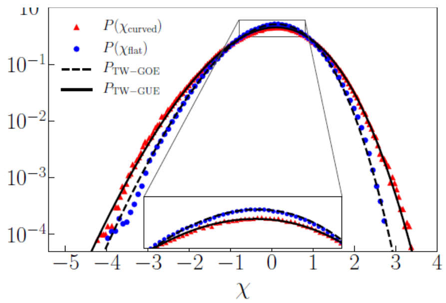
- Exciton-polaritons : driven-dissipative condensates, the phase dynamics belongs to the KPZ universality class → fundamental limit of coherence

- Experimental observation KPZ scaling function & critical exponents



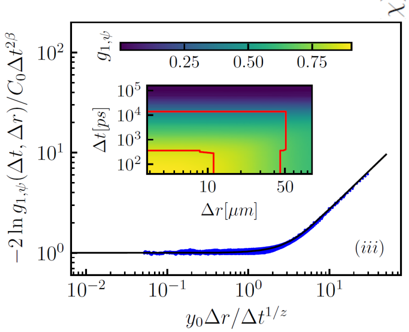
Effects of more phase slips ?

- Phase distributions in 1D



How to access to phase distributions ?

- KPZ in 2D



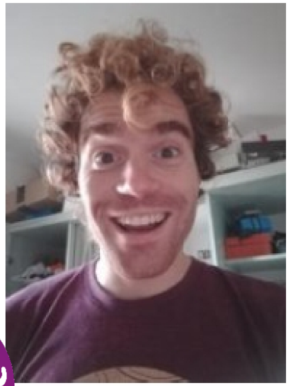
Experiment & full phase diagram in 2D ?

[Squizzato, Canet and Minguzzi PRB 97, 195453 (2018)]
[Deligiannis, Squizzato, Minguzzi and Canet, EPL 132, 67004 (2021)]
[Fontaine et al, Nature 608, 687 (2022)]
[Deligiannis et al, PRR 4, 043207 (2022)]

A big thanks to :

Léonie Canet

Davide Squizzato



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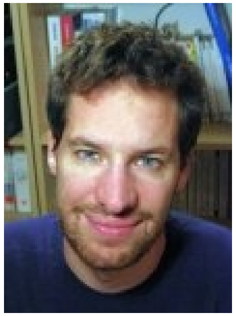
Michiel Wouters

Iacopo Carusotto

,
Quentin Fontaine



Florent Baboux

Alberto Amo

Jacqueline Bloch

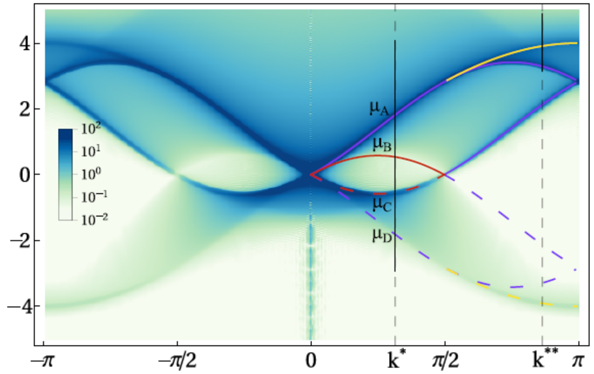
Sylvain Ravets

Ivan Amelio

Other recent results

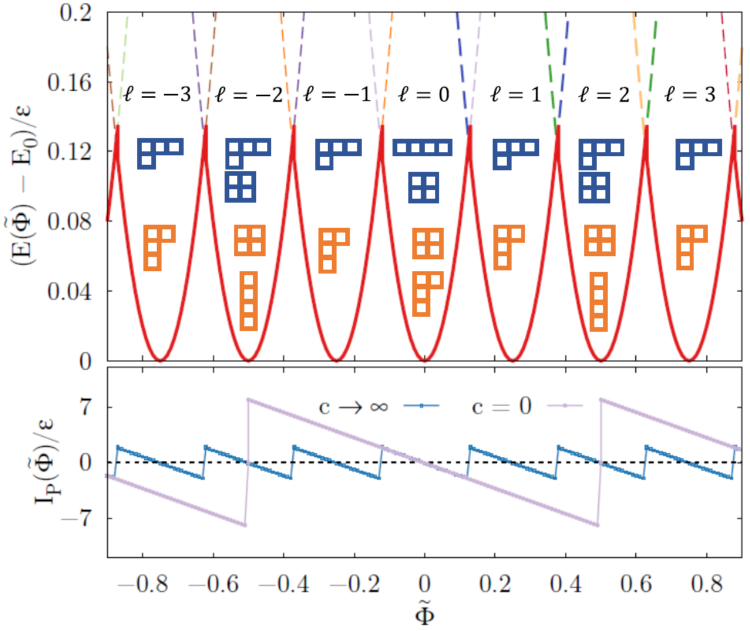
Exact spectral function of a Tonks-Girardeau gas on a lattice

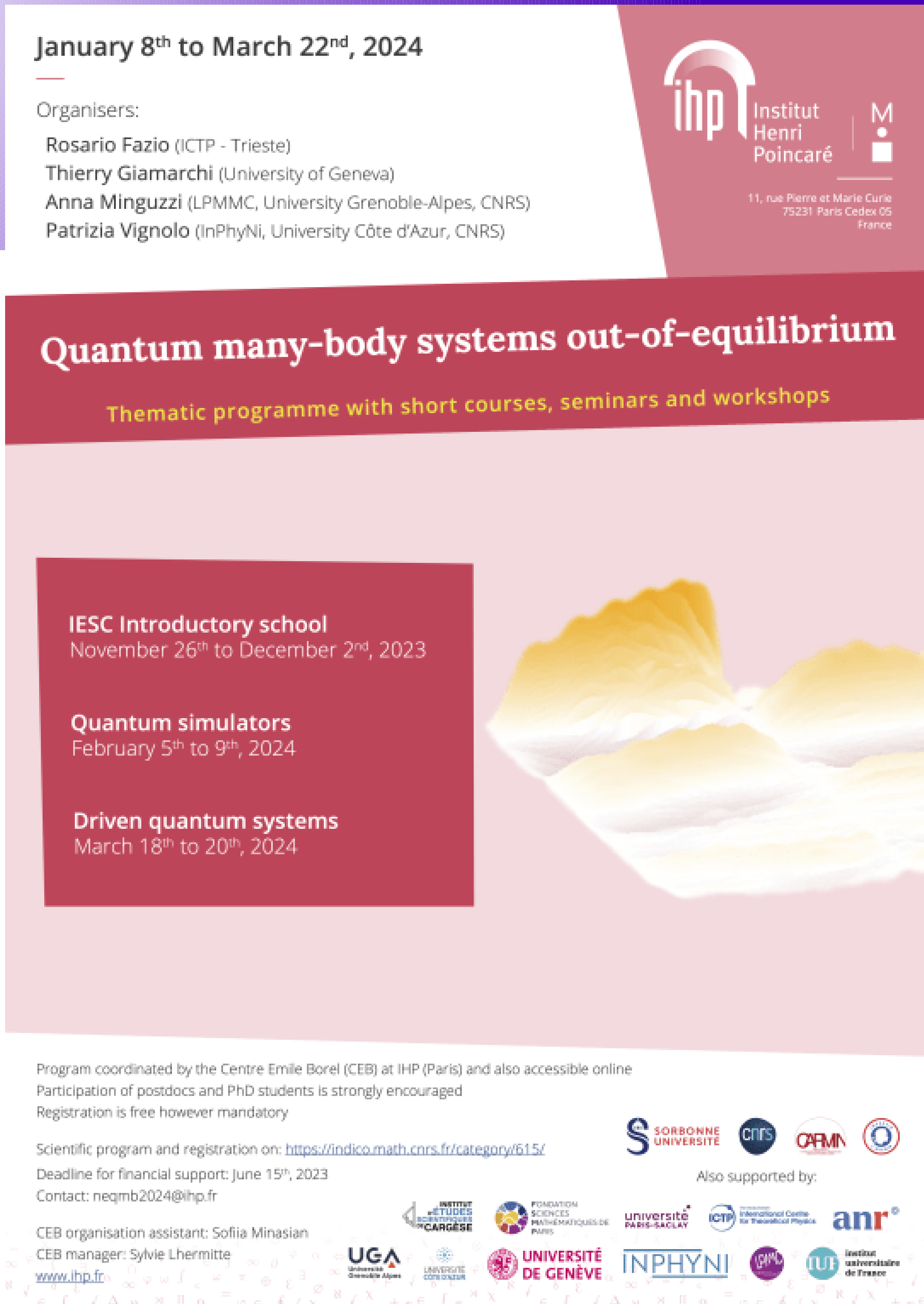
[Jacopo Settino, Nicola Lo Gullo, Francesco Plastina and Anna Minguzzi, PRL 126, 065301, 2021]



Persistent currents in a strongly interacting multicomponent Bose gas on a ring

[Giovanni Pecci, Gianni Aupetit-Diallo, Mathias Albert, Patrizia Vignolo and Anna Minguzzi, arXiv:2211.16194]





Deadline for participants application : June 15th

Thank you for your attention !

Is it really the KPZ phase-phase correlator ?

to read-out the KPZ phase-phase correlator

$$\left\langle |\theta(x,t) - \theta(x',t')|^2 \right\rangle \sim |x - x'|^{2\chi} f\left(|t - t'|/|x - x'|^z\right)$$

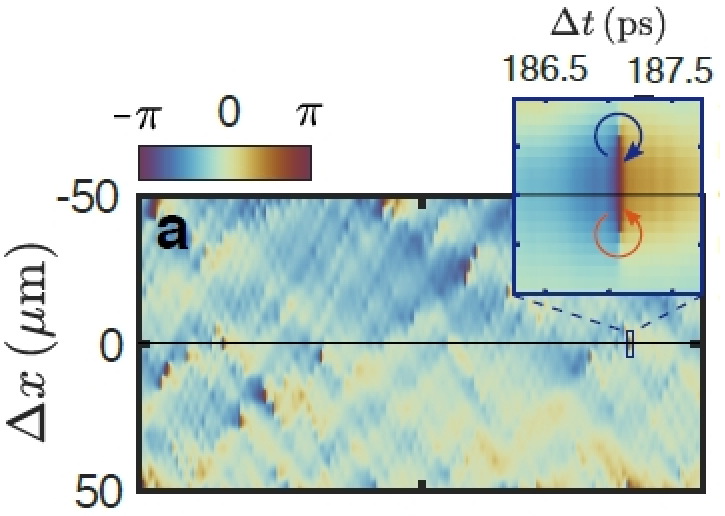
we assumed

$$|g^{(1)}(\Delta x, \Delta t)|^2 = \frac{\langle \psi^*(x,t)\psi(x',t')\rangle}{\sqrt{\langle \rho(x,t)\rangle \langle \rho(x',t')\rangle}} \simeq \exp(-\langle \mathrm{Var}[\theta(x,t) - \theta(x',t')]\rangle)$$

$\rightarrow$ check this hypothesis by numerical simulations

Role of compactness of the phase : space-time vortices

- simulations show phase slips corresponding to *vortices in space time*



[Fontaine et al, Nature 2022]

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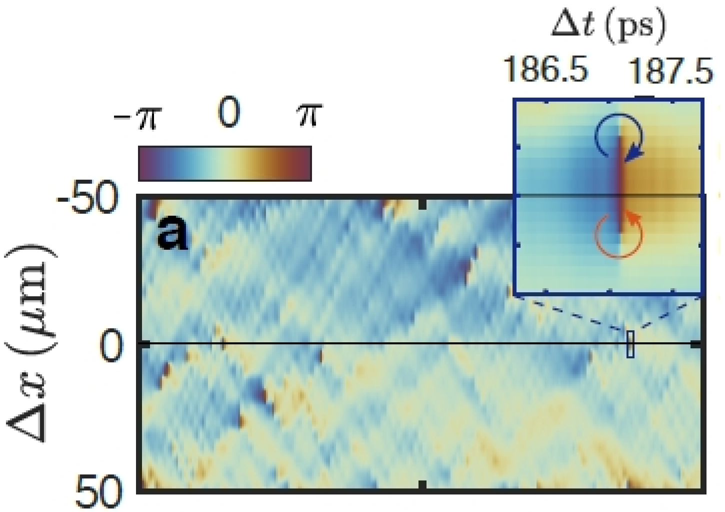
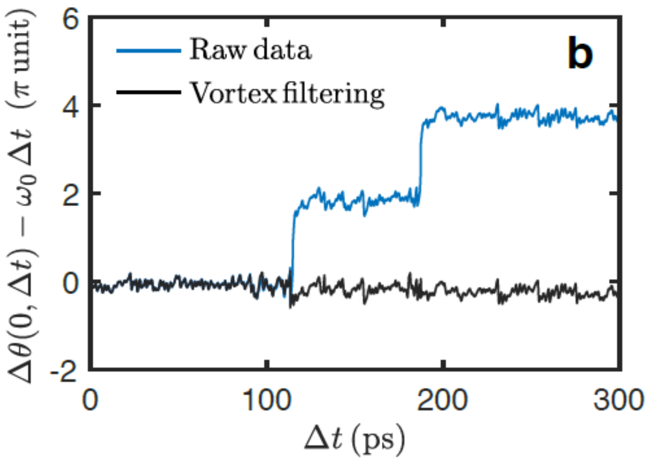


- vortex filtering by adding an antivortex



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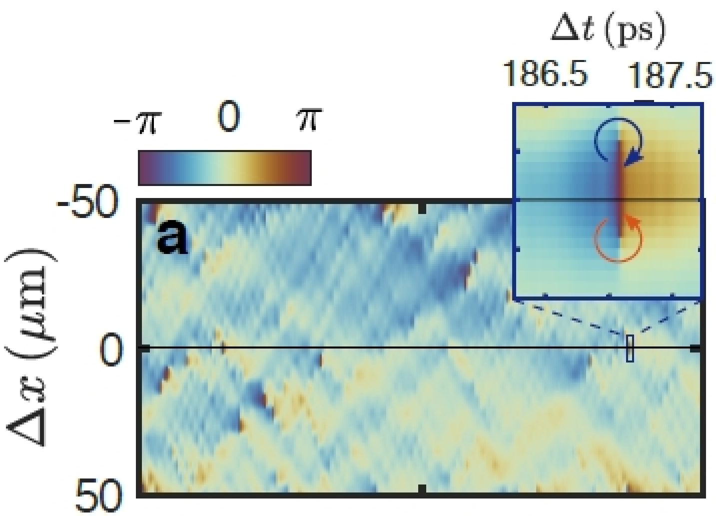

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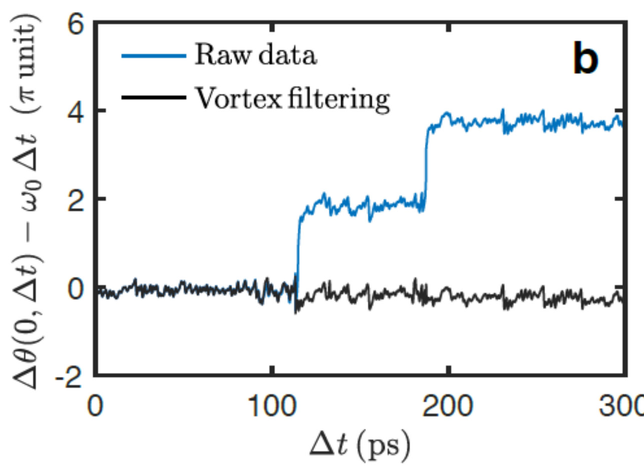
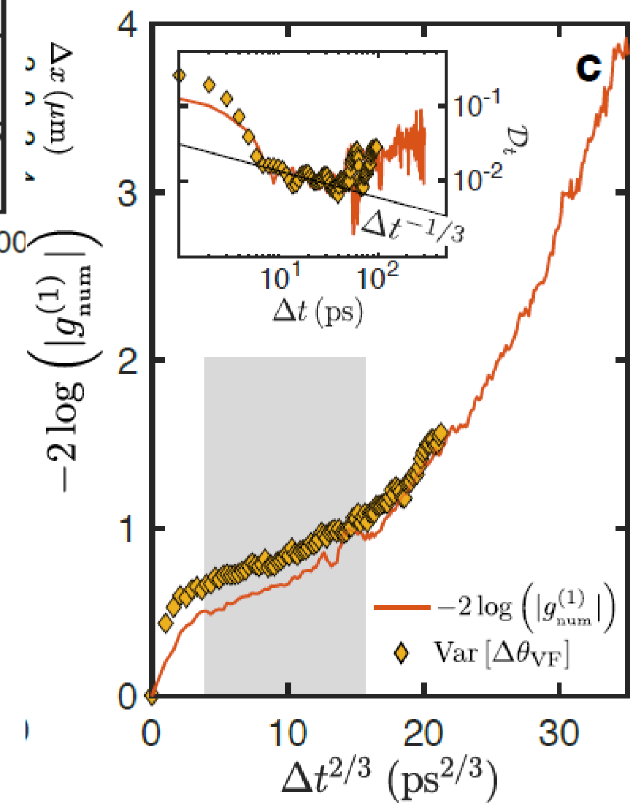


good agreement !

$$-2\log|g^{(1)}| \simeq \mathrm{Var}\Delta\theta$$

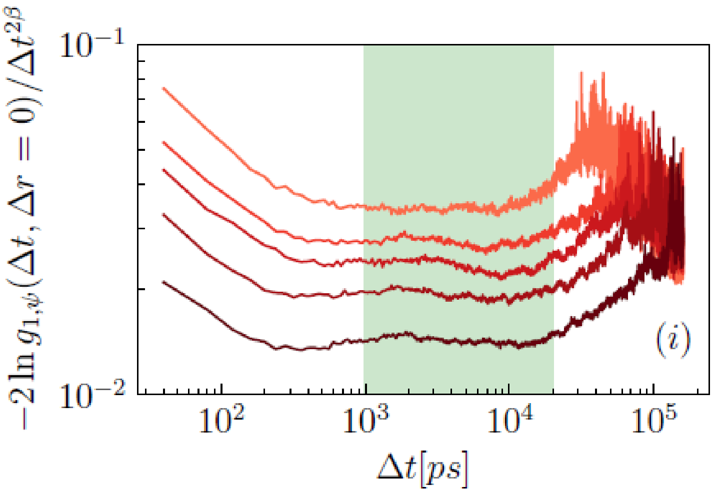


OK equivalence g1 – variance of the phase :
→ readout of KPZ phase correlations from g1

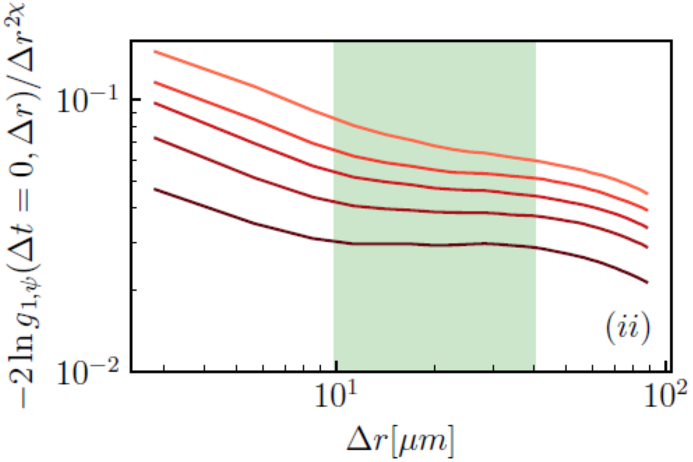
[Fontaine et al, Nature 2022]

Robustness of KPZ in 2D

- KPZ region at varying pump strength $P/P_{th} = 1.6...2.5$



increasing pump



increasing pump

[Deligiannis et al Phys. Rev. Research 2022]