Driven-dissipative polariton quantum fluids in and out of equilibrium

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Designer Quantum Systems Out of Equilibrium
KITP, November 2016

Acknowledgements

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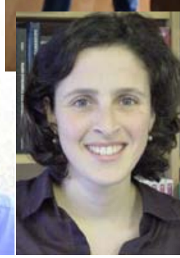

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I. Carusotto

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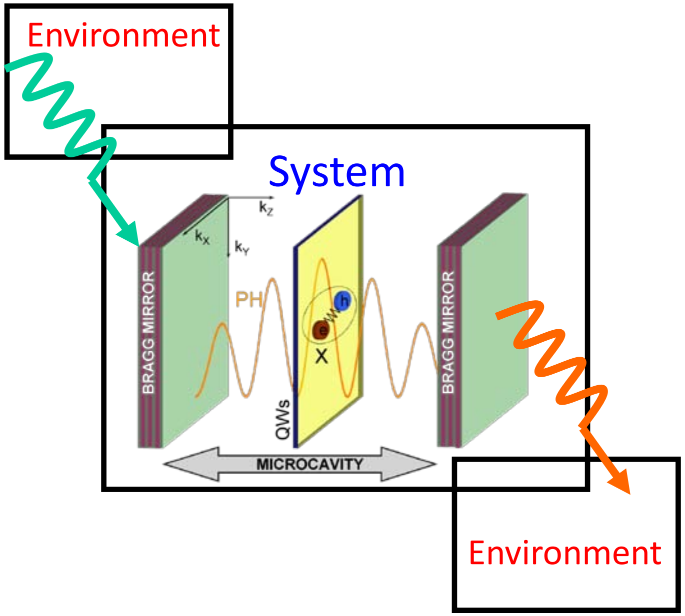
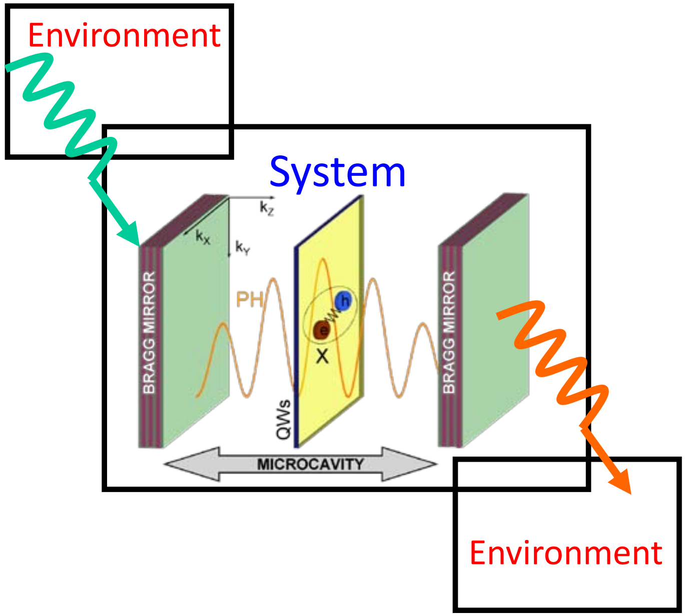
Driven-dissipative Condensates



2D Light-matter condensates with drive and decay

Polaritons
Photon BEC
Circuit QED systems
Atoms in cavities
....

Driven-dissipative Condensates



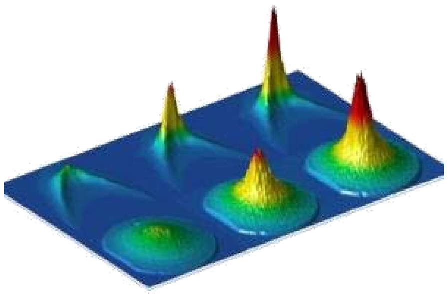
2D Light-matter condensates with drive and decay

Can thermal equilibrium be achieved?

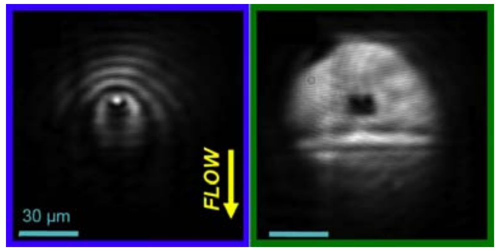
Can non-equilibrium but non-trivial phases be engineered?

State of the art: experiments

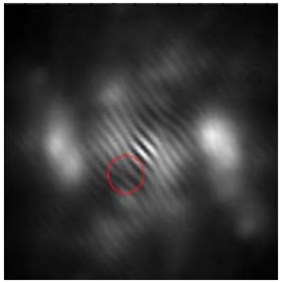
✧ Condensation, superfluidity and vortices



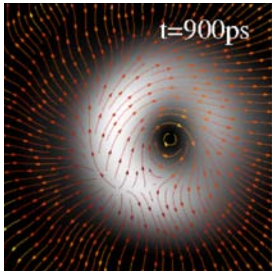
[Kasprzak et al., *Nature* 2006]



[Amo *et al. Nature Phys.* 2009]



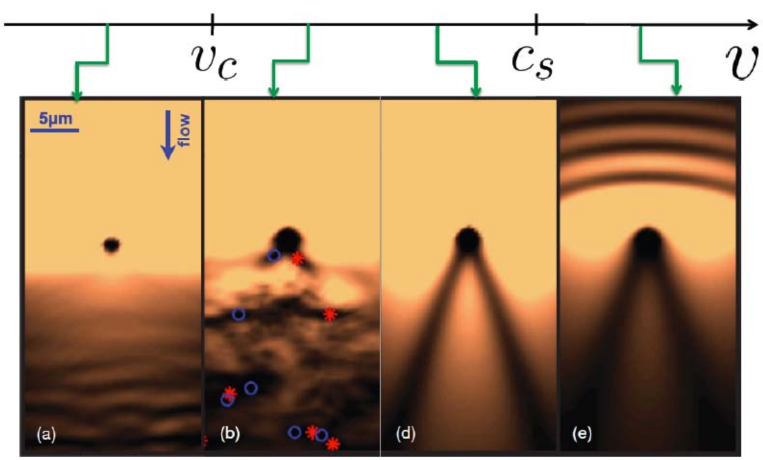
[K. G. Lagoudakis et al, *Nature Physics* 2008]



[Sanvitto et al., *Nature Phys.* 2010]

✧ Hydrodynamics (nucleation of V-AV pairs, solitons in the wake of an obstacle), quantum turbulence, pattern formation

Superfluidity vortices and solitons Cherenkov waves

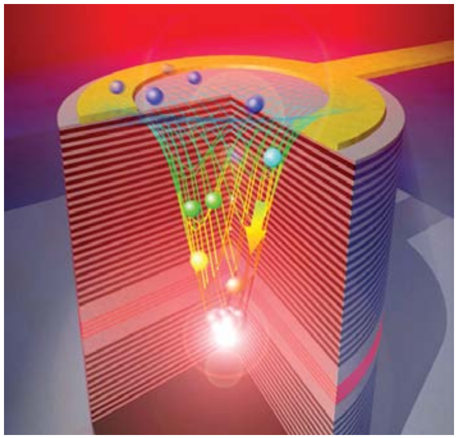


[Pigeon et al., PRB (2011)]

[Nardin et al., *Nature Phys*. 2011]
[Sanvitto et al., *Nature Photonics* 2011]
[Grosso et al., *PRL* 2011]
[Amo et al., *Science* 2011, *Nature* 2009]
[Wertz et al., *Nature Phys*. 2010]

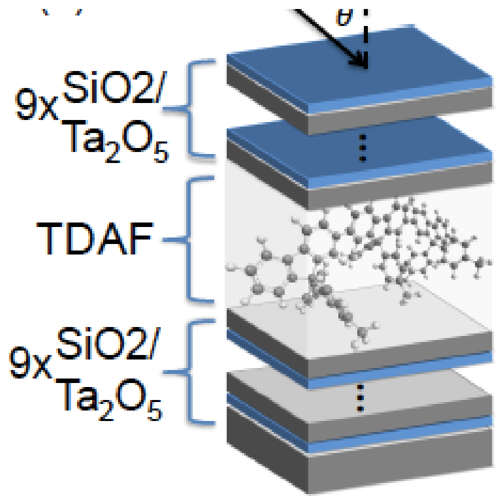
State of the art: towards applications

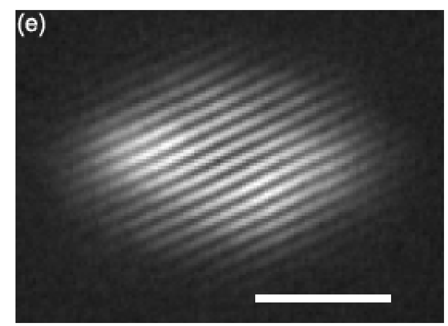
✧ Electrically pumped polariton laser



[Schneider et al., *Nature* 2013]

✧ Room temperature condensation and superfludity in organics

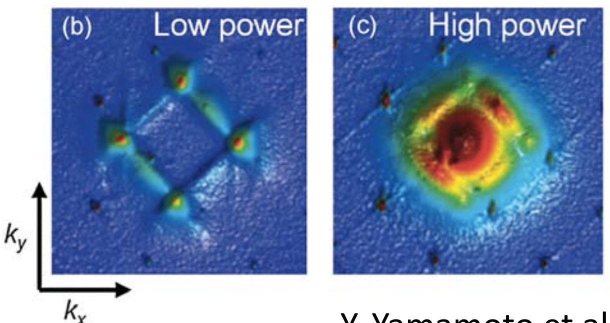




Kena-Cohen’s group 2015

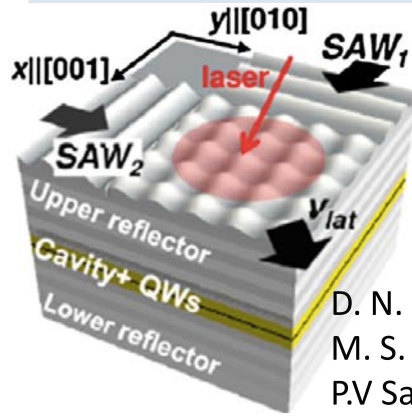
State of the art: lattices

Gold deposition



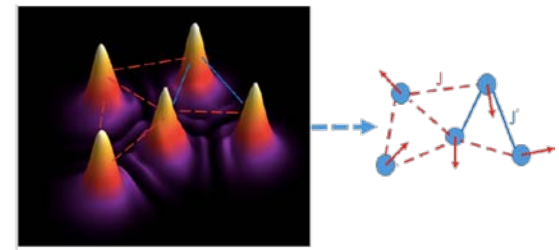
Y. Yamamoto et al.

Surface acoustic waves



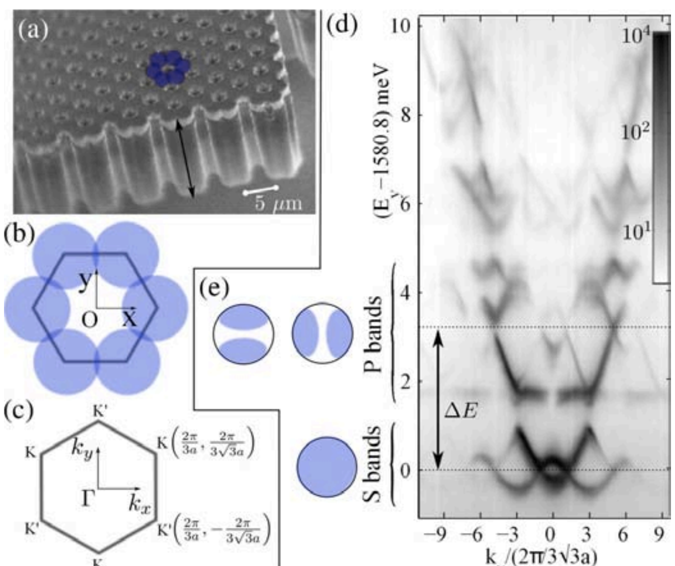
D. N. Krizhanovskii,
M. S. Skolnick,
P.V Santos et al.

Pump modulation



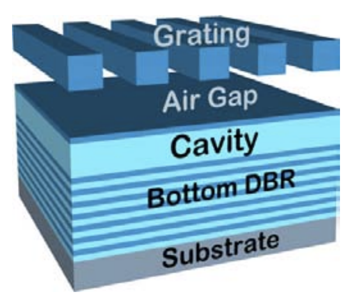
P. G. Lagoudakis
N. Berloff

Micropillars



A. Amo, J. Bloch et al.

Sub-wavelength Gratings



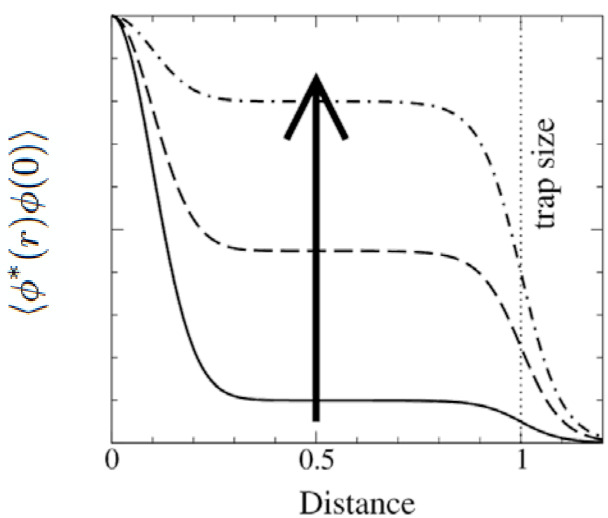
H. Deng et al.

Observed

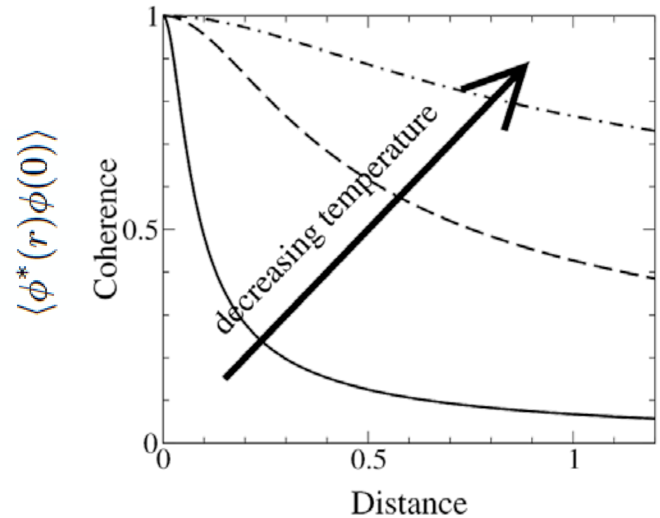
- Edge states
- Spin-orbit coupling
- Dirac cones
- Magnetic monopoles
- Condensation in flat band
- BH model
- XY Hamiltonian
- …

What Type of "Condensate"?

Finite-size BEC

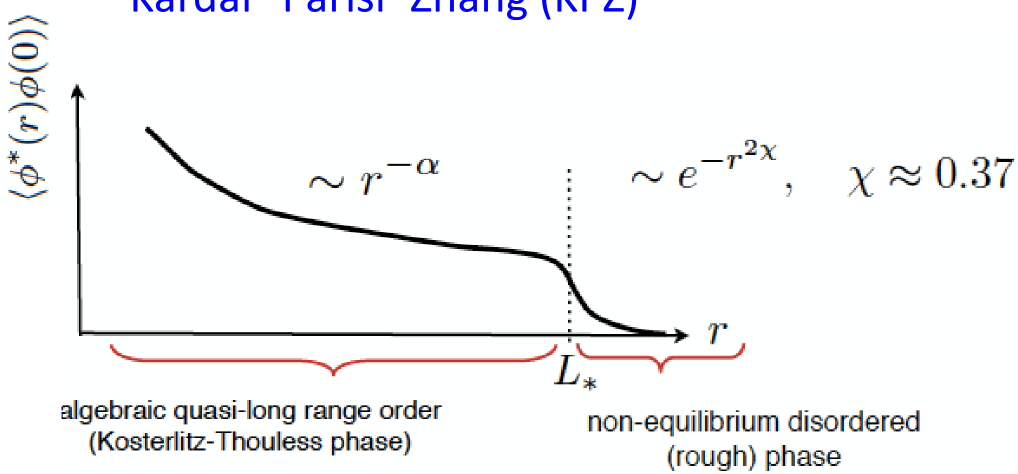


BKT

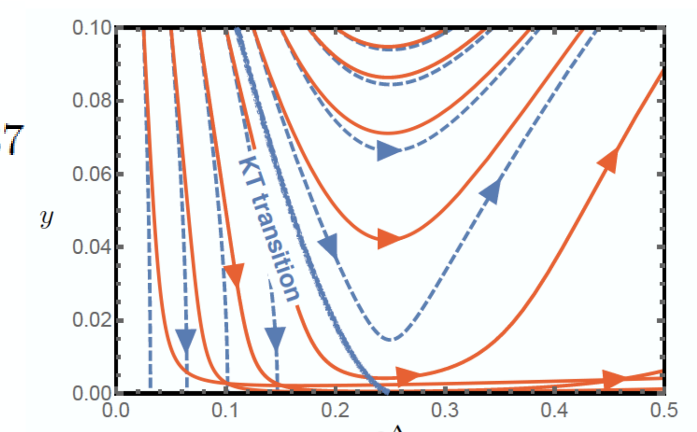


?

Kardar–Parisi–Zhang (KPZ)



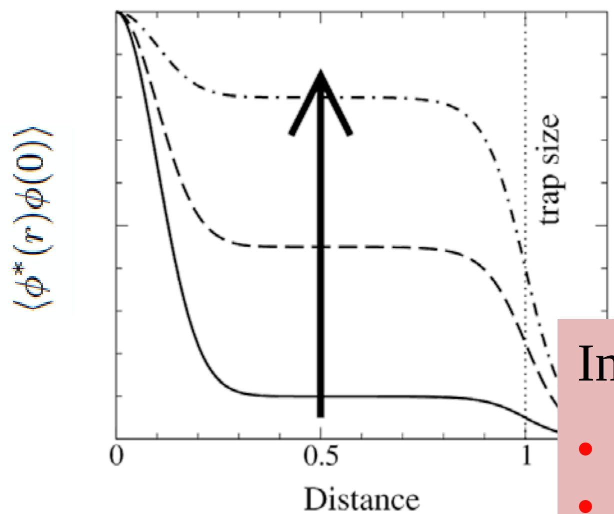
Disordered Phase



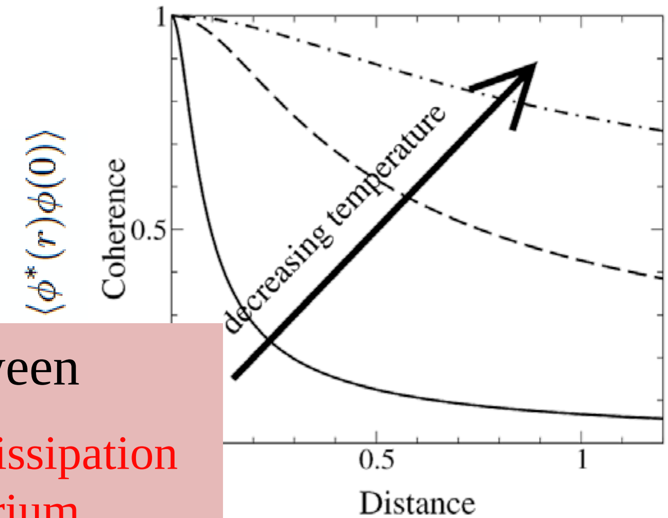
Sebastian Diehl's talk

What Type of “Condensate”?

Finite-size BEC



BKT

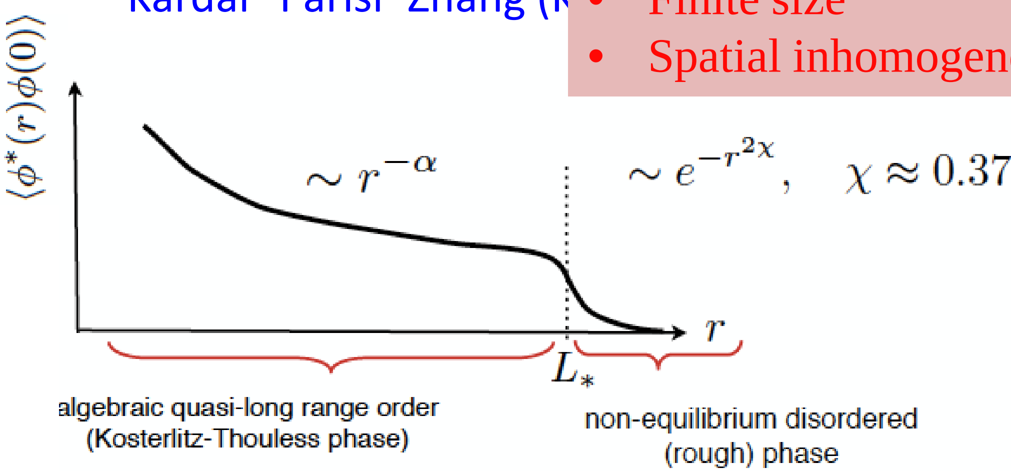


Interplay between

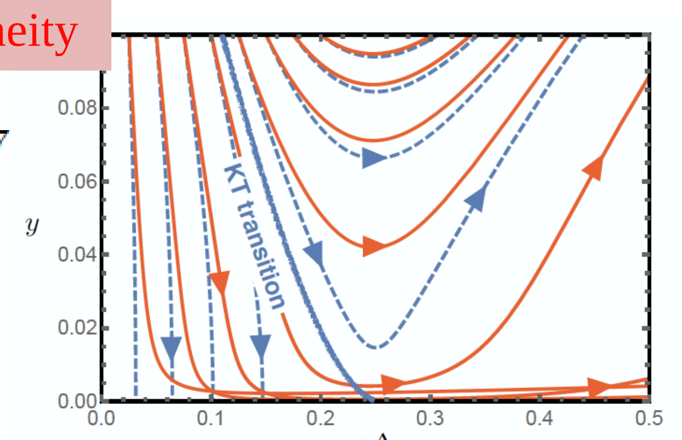
- Drive and Dissipation
- Non-equilibrium

- Finite size
- Spatial inhomogeneity

Kardar–Parisi–Zhang (K



Disordered Phase

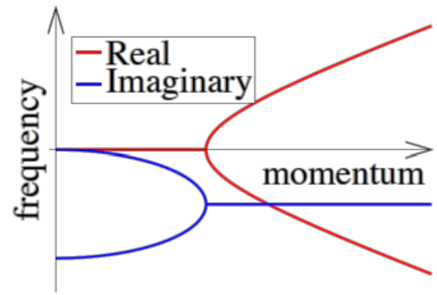


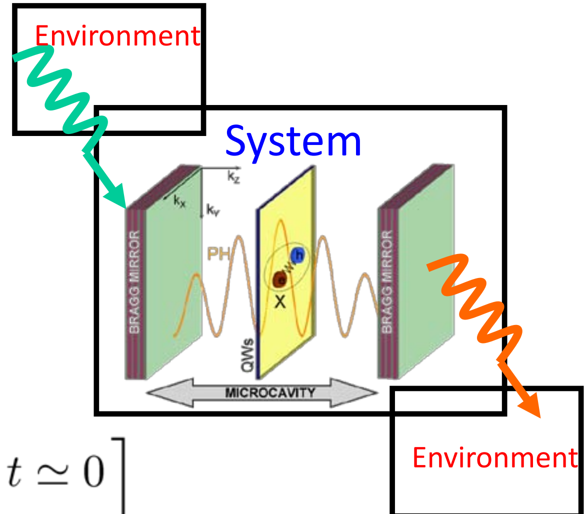
Sebastian Diehl’s talk

Spatial and Temporal Coherence

Driven-dissipative System

- ✧ Dimensionality: 2D
- ✧ Modes: diffusive
- ✧ Occupation: non-thermal





From Keldysh field theory

$$\langle \psi^\dagger(\mathbf{r},t)\psi(0,0)\rangle \simeq |\psi_0|^2 \exp\left[-\alpha \begin{cases} \ln(r/r_0) & r\to\infty, t\simeq 0 \\ \frac{1}{2}\ln(c^2 t/\gamma_{\rm tot} r_0^2) & r\simeq 0, t\to\infty \end{cases}\right]$$

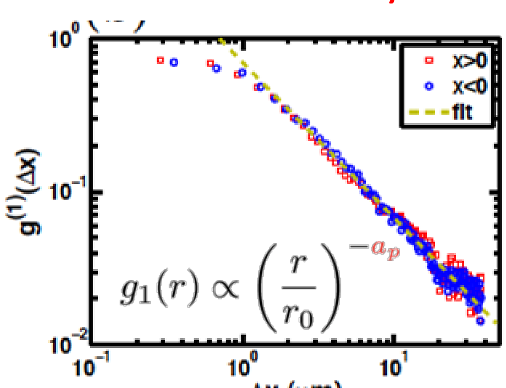
$\alpha(\text{pump}, \text{decay}, \text{density})$

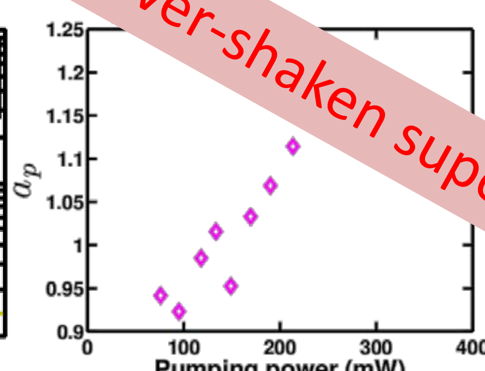
[Szymańska et al., *PRL* 2006; *PRB* 2007]

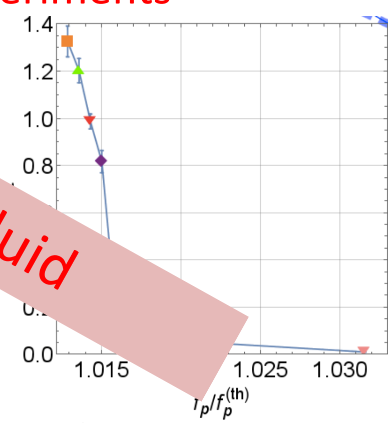
$$\alpha_t = 1/2\alpha_s$$

From stochastic dynamics ... BKT and early experiments

Over-shaken superfluid







Faster decay possible then equilibrium upper limit

PNAS (2012),

Spatial and Temporal Coherence

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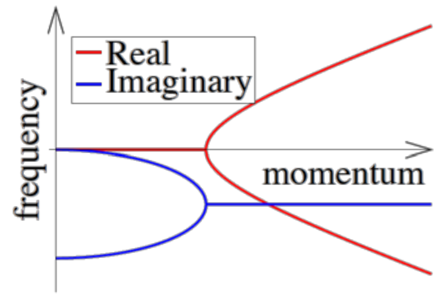

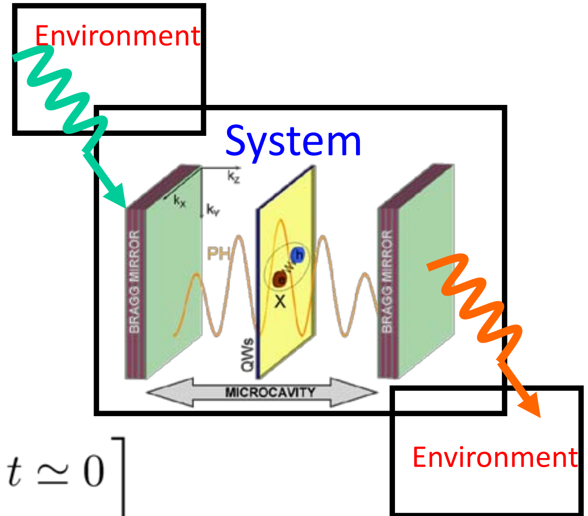

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$\alpha(\mathrm{pump}, \mathrm{decay}, \mathrm{density})$

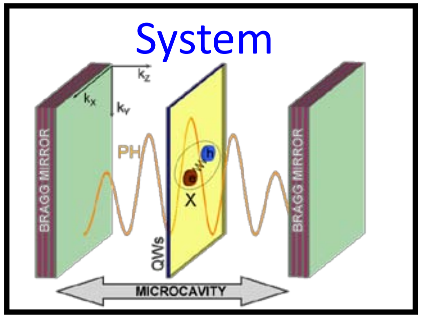
[Szymańska et al., *PRL* 2006; *PRB* 2007]

$$\alpha_t = 1/2\alpha_s$$

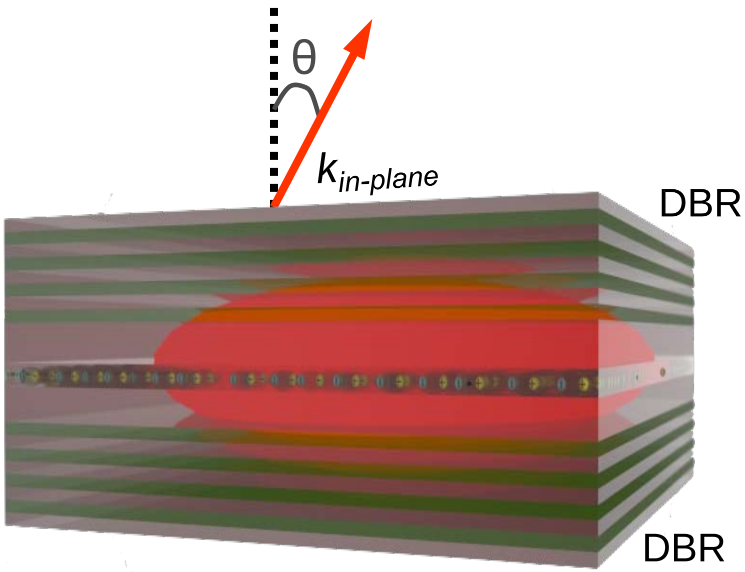
Closed System

- ✧ Dimensionality: 2D
- ✧ Modes: linear
- ✧ Occupation: thermal

$$\alpha_{s,t} = k_B T/n_s < 1/4$$



Long Lifetime Microcavity



K. West, L. N. Pfeifer
Studied in Snoke's and Sanvitto's groups

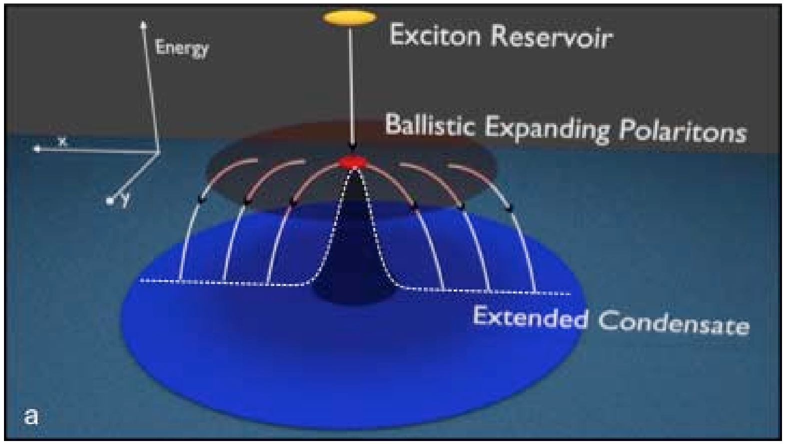
12 QWs

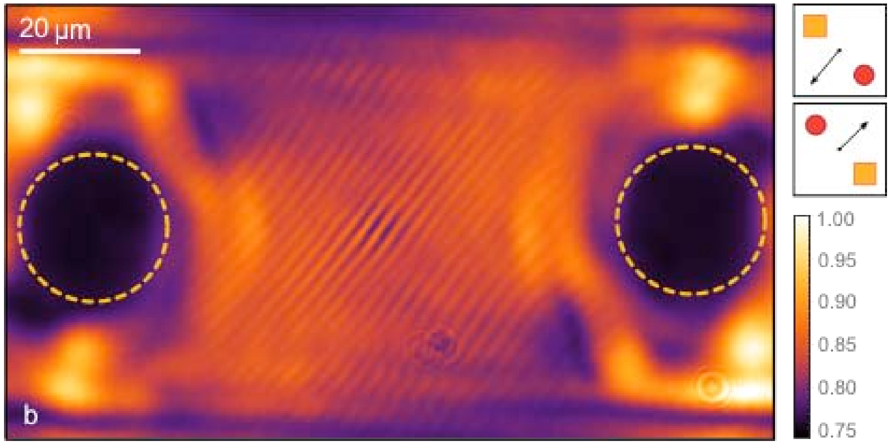
Rabi: 16 meV

t_p : 100 ps

Q > 100.000

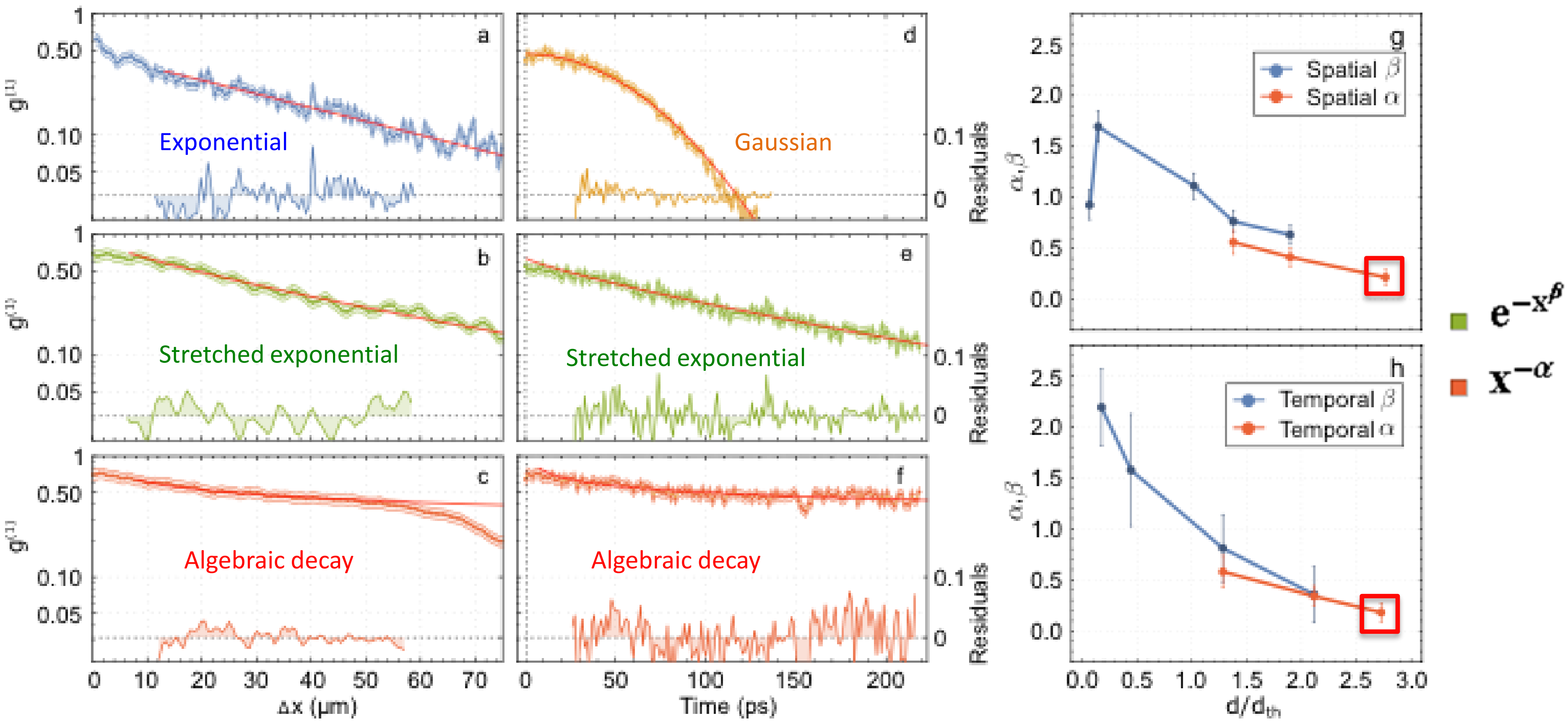
Spatially homogeneous





D. Caputo, et al. arXiv:1609.7603 (2016)

Spatial and Temporal Coherence - Experiment



$$\alpha_s = \alpha_t < 1/4$$

Crossover from exponential to algebraic decay of coherence with equilibrium exponents

D. Caputo, et al. arXiv:1609.7603 (2016)

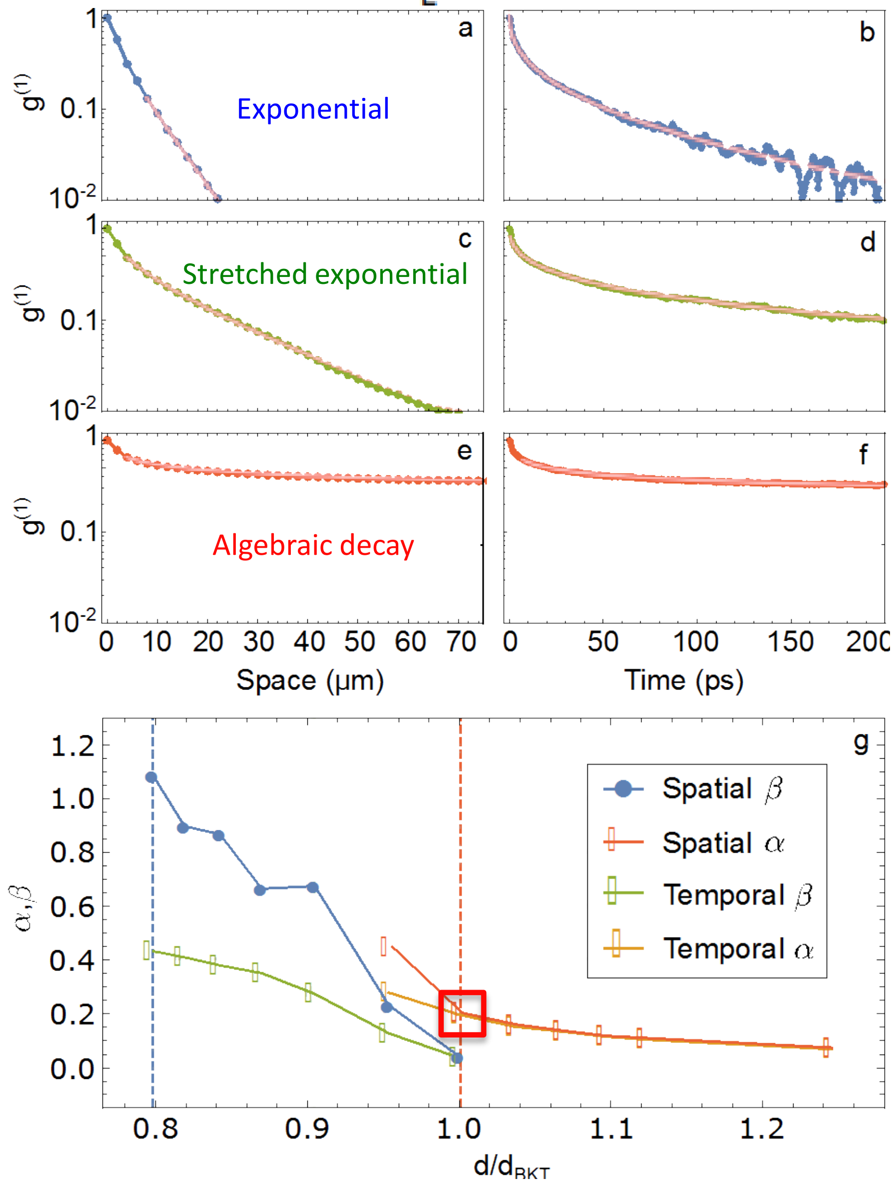
Spatial and Temporal Coherence - Theory

$$id\psi(\mathbf{r},t) = \left[-\frac{\nabla^2}{2m} + g|\psi(\mathbf{r},t)|_-^2 + i(\gamma - \kappa - \Gamma|\psi(\mathbf{r},t)|_-^2)\right]\psi(\mathbf{r},t)dt + dW$$

See Sebastian Diehl's talk

$$\frac{\gamma}{1+\frac{|\psi(\mathbf{r},t)|_-^2}{n_s}}$$

more non-linear drive



$$\langle dW^*(\mathbf{r}',t)dW(\mathbf{r},t)\rangle = \frac{\gamma + \kappa + \Gamma|\psi(\mathbf{r},t)|_-^2}{dV}\delta_{\mathbf{r},\mathbf{r}'}dt$$

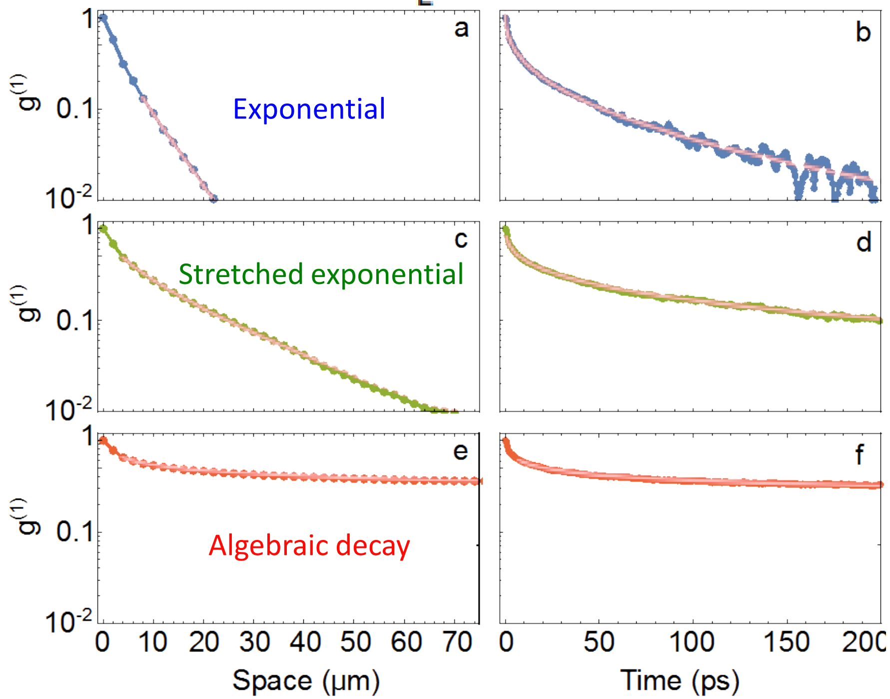
$$\frac{\gamma}{1+\frac{|\psi(\mathbf{r},t)|_-^2}{n_s}} + \kappa$$

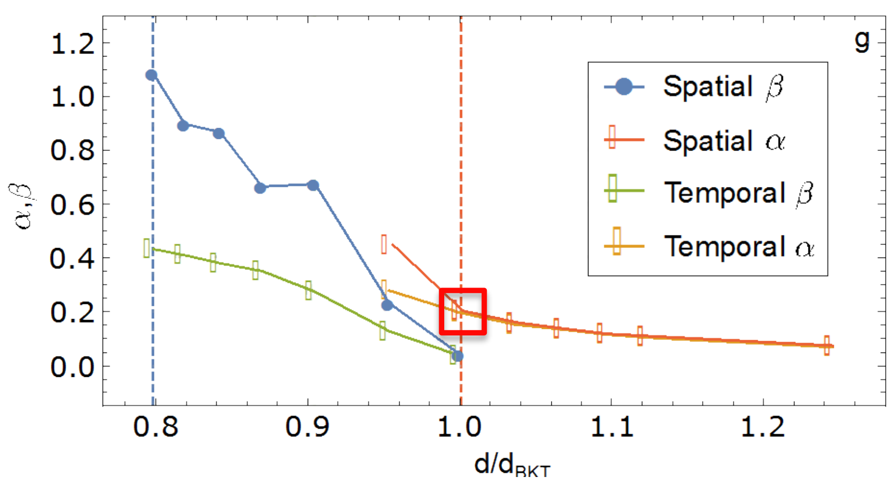
For experimental parameters

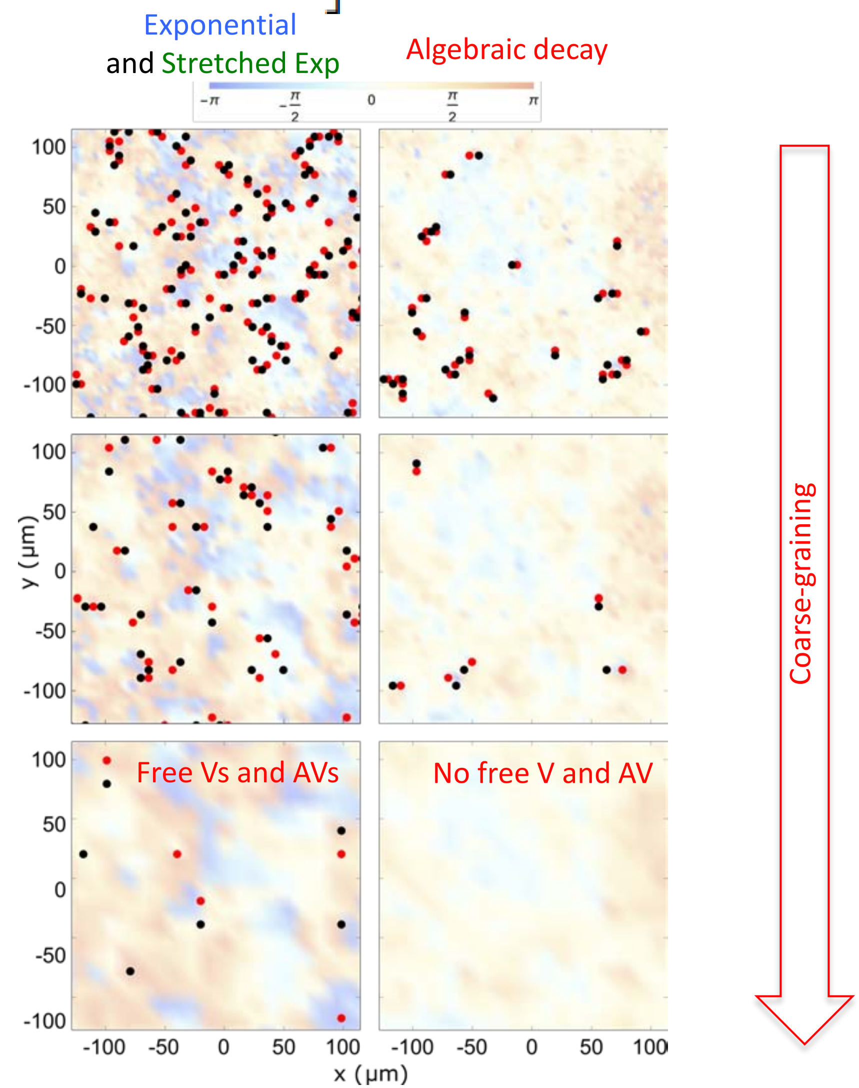
$$\alpha_s = \alpha_t < 1/4$$

Spatial and Temporal Coherence - Theory

$$i d\psi(\mathbf{r},t) = \left[-\frac{\nabla^2}{2m} + g|\psi(\mathbf{r},t)|^2_- + i(\gamma - \kappa - \Gamma|\psi(\mathbf{r},t)|^2_-)\right]\psi(\mathbf{r},t)dt + dW$$





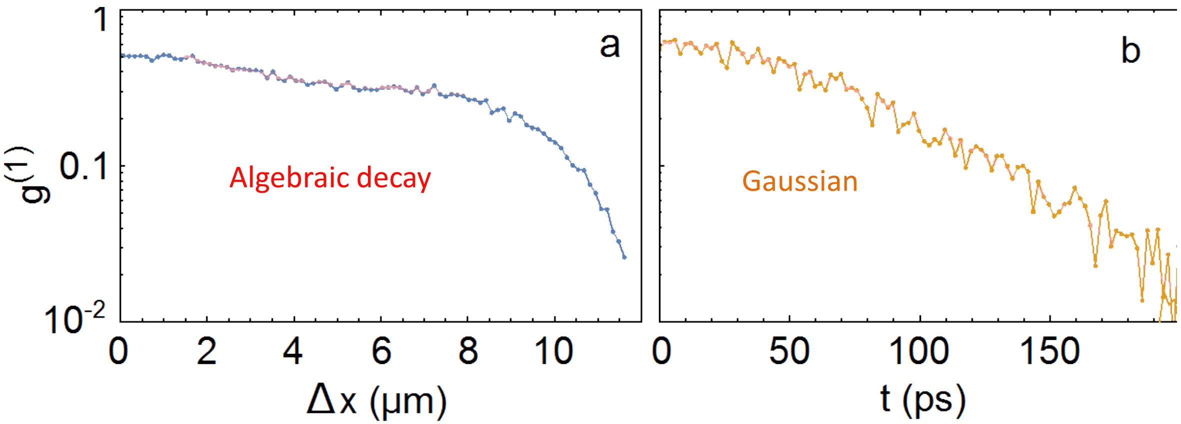


BKT crossover

Spatial and Temporal Coherence – Photon Laser

Measurements in a bad cavity (short lifetime) sample
in a weak coupling regime

In a lasing VCSEL coherence shows power law decay in space but Gaussian in time



Importance of consistent picture in space and
time correlations

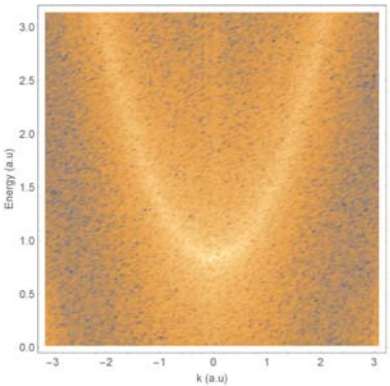
Spectrum of Excitations

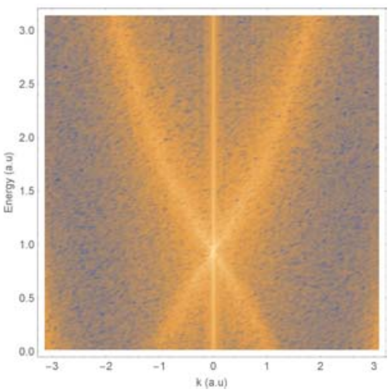
$$E(\omega) = -i\gamma \pm \sqrt{\omega_k(\omega_k + 2u) - \gamma^2}$$

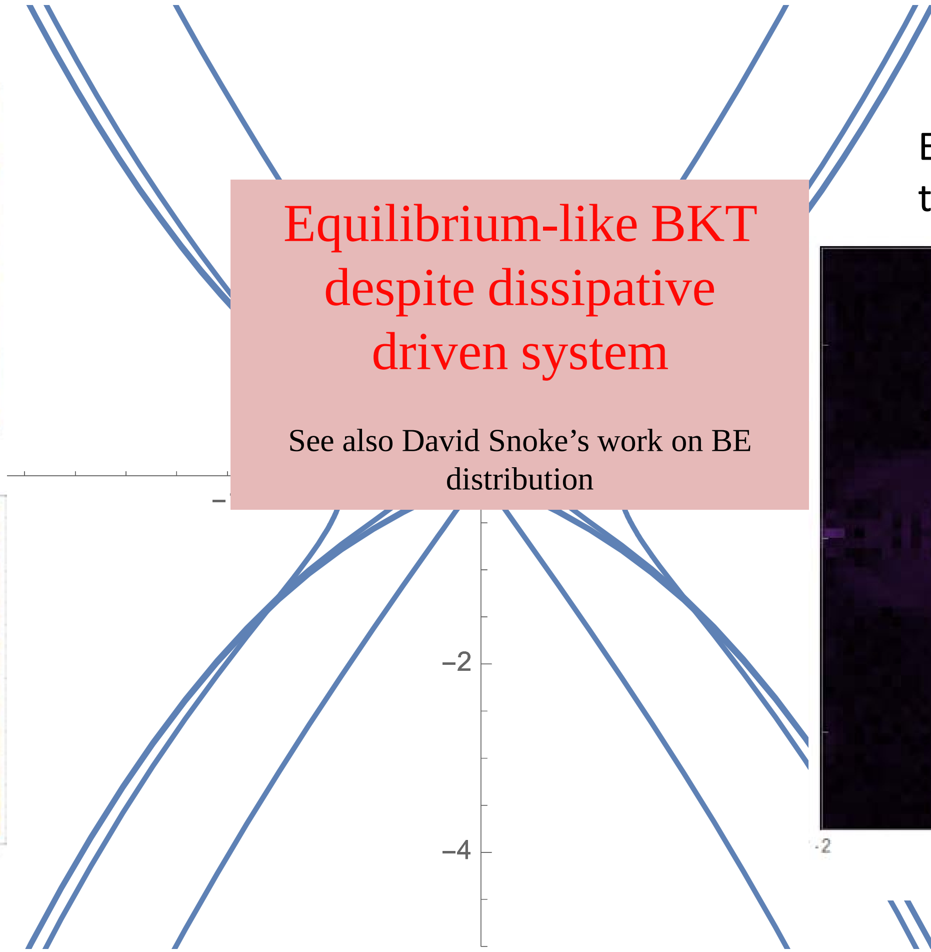
γ = 0.01

u = 5

Theoretical Fourier transform of $g^1(r,t)$



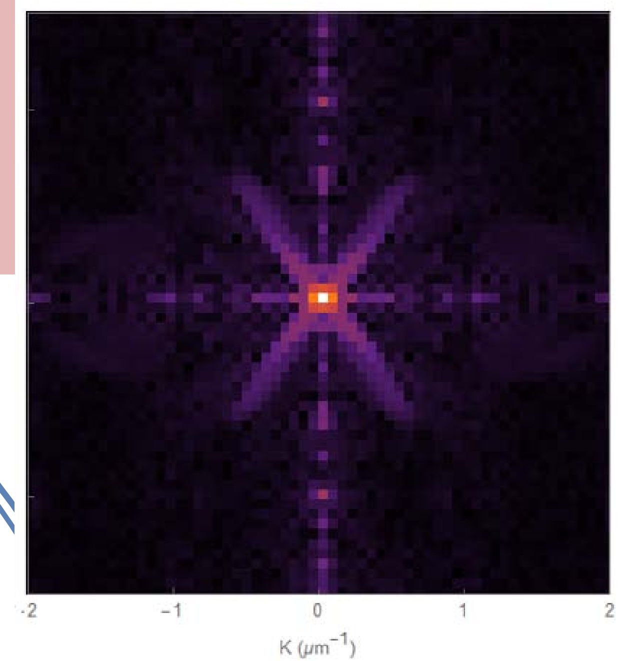




Equilibrium-like BKT despite dissipative driven system

See also David Snoke's work on BE distribution

Experimental Fourier transform of $g^1(r,t)$



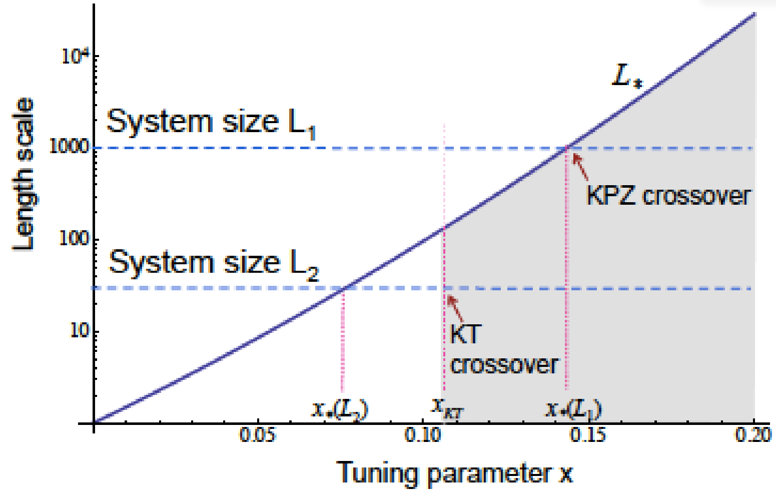
Kardar–Parisi–Zhang (KPZ) Theory

[Altman et al, *PRX* 2015]

$$\partial_t \theta = D_x \partial_x^2 \theta + D_y \partial_y^2 \theta + \frac{\lambda_x}{2}(\partial_x \theta)^2 + \frac{\lambda_y}{2}(\partial_y \theta)^2 + \bar{\zeta}(\mathbf{x}, t)$$

KPZ non-linearity

See Sebastian Diehl's talk

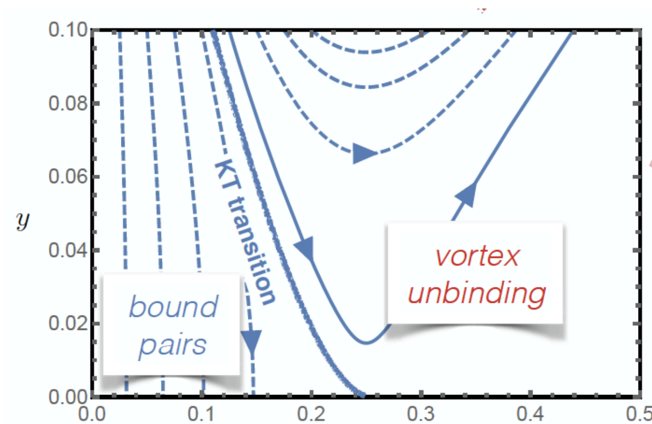


At large distances

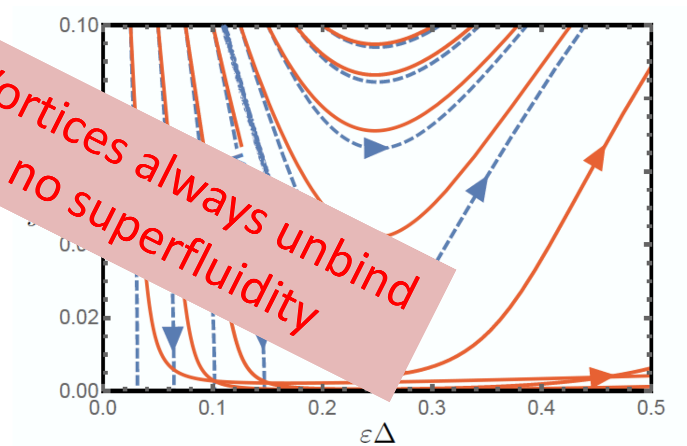
$$\langle \phi^*(r)\phi(0)\rangle \sim e^{-r^{2\chi}}, \quad \chi \approx 0.37$$

Stretched exponential (faster then algebraic) decay of coherence but superfluidity survives

Adding vortices



[S. Diehl KITP talk (2016)] $\varepsilon\Delta$



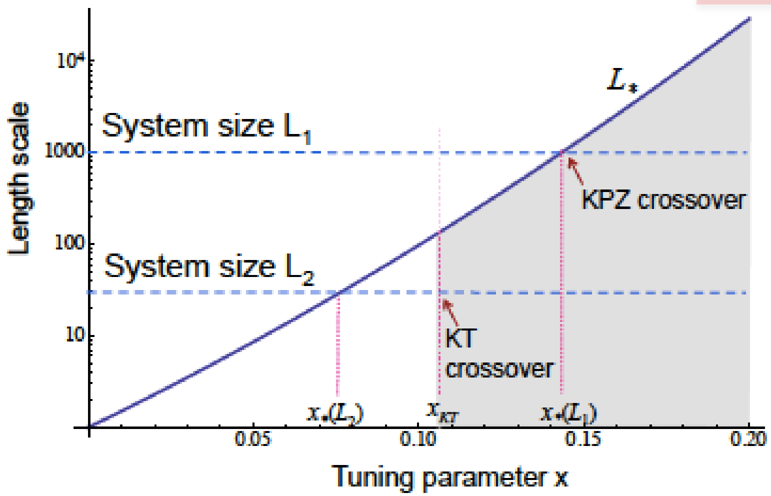
Vortices always unbind
no superfluidity

Kardar–Parisi–Zhang (KPZ) Theory

[Altman et al, *PRX* 2015]

$$\partial_t \theta = D_x \partial_x^2 \theta + D_y \partial_y^2 \theta + \frac{\lambda_x}{2}(\partial_x \theta)^2 + \frac{\lambda_y}{2}(\partial_y \theta)^2 + \bar{\zeta}(\mathbf{x}, t)$$

KPZ non-linearity



At large distances

$$\langle \phi^*(r)\phi(0)\rangle \sim e^{-r^{2\chi}}, \quad \chi \approx 0.37$$

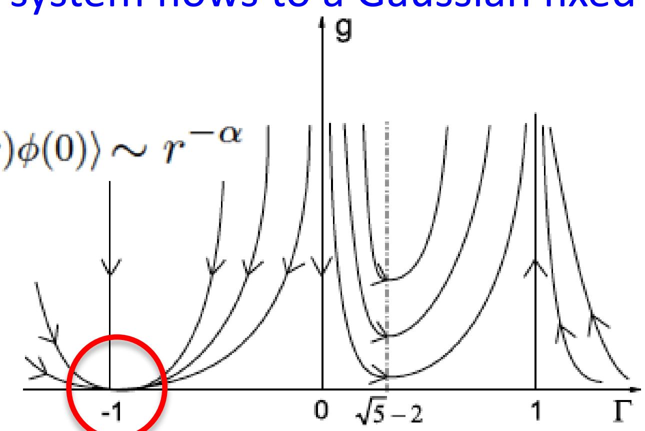
Stretched exponential (faster then algebraic) decay of coherence but superfluidity survives

However, anisotropic system flows to a Gaussian fixed point power-law at any scale

$$\langle \phi^*(r)\phi(0)\rangle \sim r^{-\alpha}$$

$$\Gamma = \frac{\lambda_y D_x}{\lambda_x D_y}$$

$$g = \frac{\lambda_x^2 \Delta}{D_x^2 \sqrt{D_x D_y}}$$



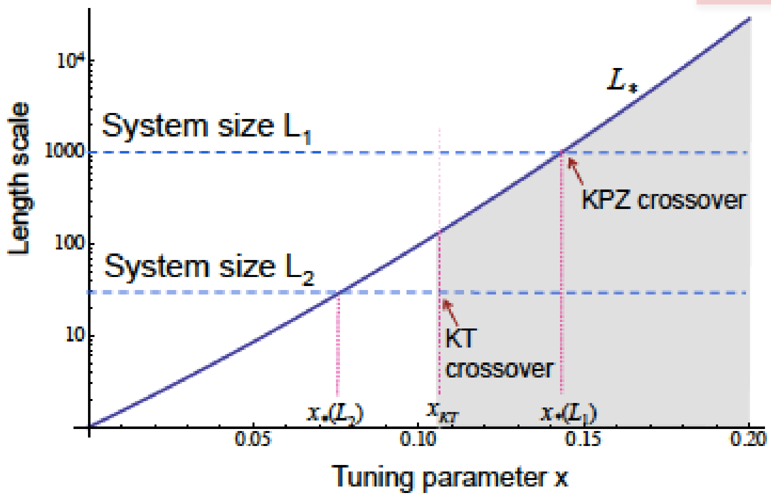
How to realise in experiment?

Kardar–Parisi–Zhang (KPZ) Theory

[Altman et al, *PRX* 2015]

$$\partial_t\theta = D_x\partial_x^2\theta + D_y\partial_y^2\theta + \frac{\lambda_x}{2}(\partial_x\theta)^2 + \frac{\lambda_y}{2}(\partial_y\theta)^2 + \bar\zeta(\mathbf{x},t)$$

KPZ non-linearity



At large distances

$$\langle\phi^*(r)\phi(0)\rangle \sim e^{-r^{2\chi}}, \quad \chi \approx 0.37$$

Stret

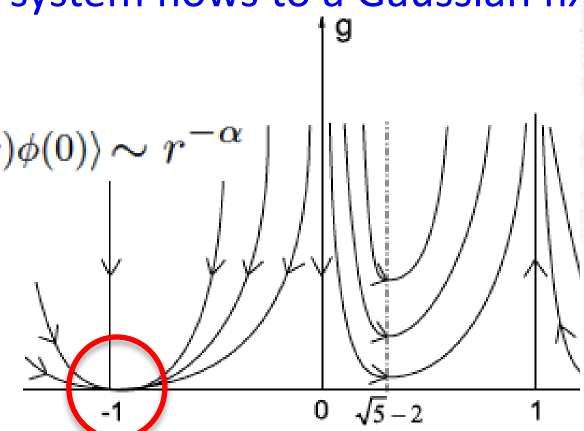
deca

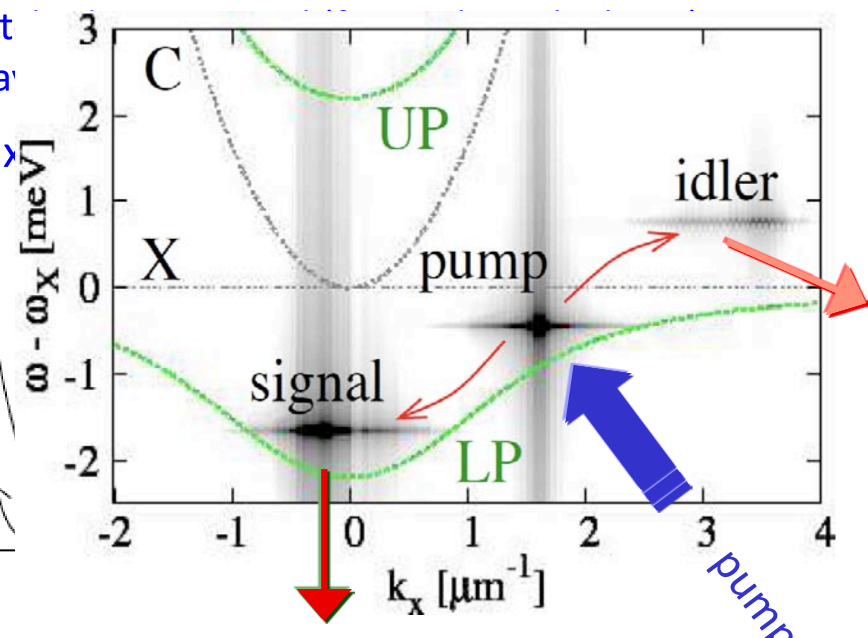
However, anisotropic system flows to a Gaussian fix

$$\langle\phi^*(r)\phi(0)\rangle \sim r^{-\alpha}$$

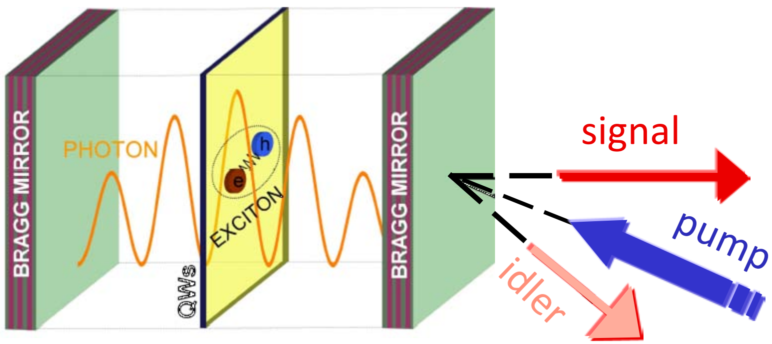
$$\Gamma = \frac{\lambda_y D_x}{\lambda_x D_y}$$

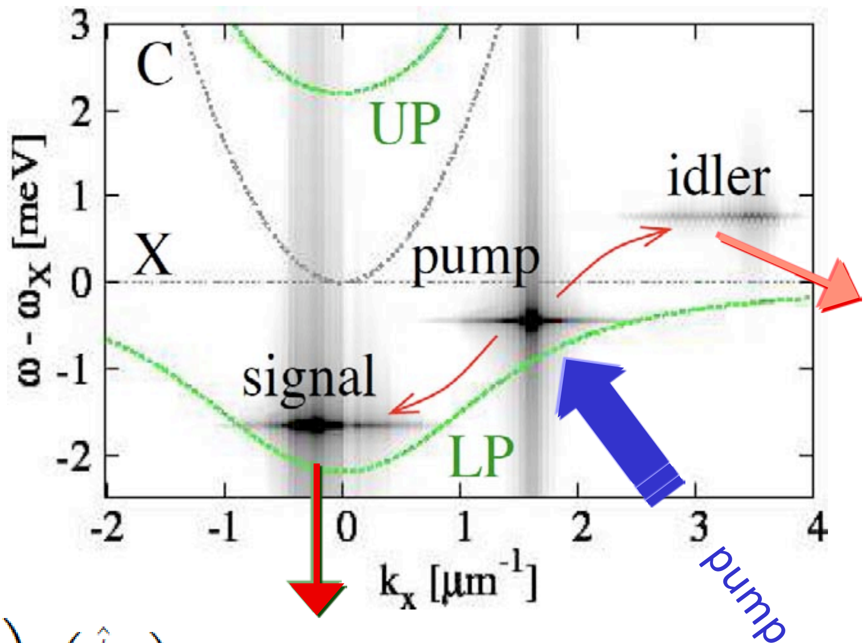
$$g = \frac{\lambda_x^2\Delta}{D_x^2\sqrt{D_x D_y}}$$





Playing with Spatial Anisotropy: OPO





$$\hat{H}_S = \int d\mathbf{r} \, (\hat{\psi}_X^\dagger \;\; \hat{\psi}_C^\dagger) \begin{pmatrix} \frac{-\nabla^2}{2m_X} + \frac{g_X}{2}|\hat{\psi}_X|^2 & \frac{\Omega_R}{2} \\ \frac{\Omega_R}{2} & \frac{-\nabla^2}{2m_C} \end{pmatrix} \begin{pmatrix} \hat{\psi}_X \\ \hat{\psi}_C \end{pmatrix}$$

$$\hat{H}_{SB} = \int d\mathbf{r} \left[F(\mathbf{r},t)\hat{\psi}_C^\dagger(\mathbf{r},t) + \mathrm{H.c.} \right]$$
$$+ \sum_{\mathbf{k}} \sum_{l=X,C} \left\{ \zeta_{\mathbf{k}}^l \left[\hat{\psi}_{l,\mathbf{k}}^\dagger(t) \hat{B}_{l,\mathbf{k}} + \mathrm{H.c.} \right] + \omega_{l,\mathbf{k}} \hat{B}_{l,\mathbf{k}}^\dagger \hat{B}_{l,\mathbf{k}} \right\}$$

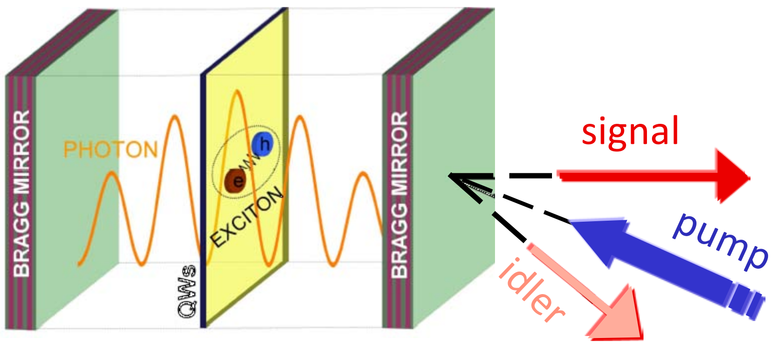
✧ Non-thermal occupation

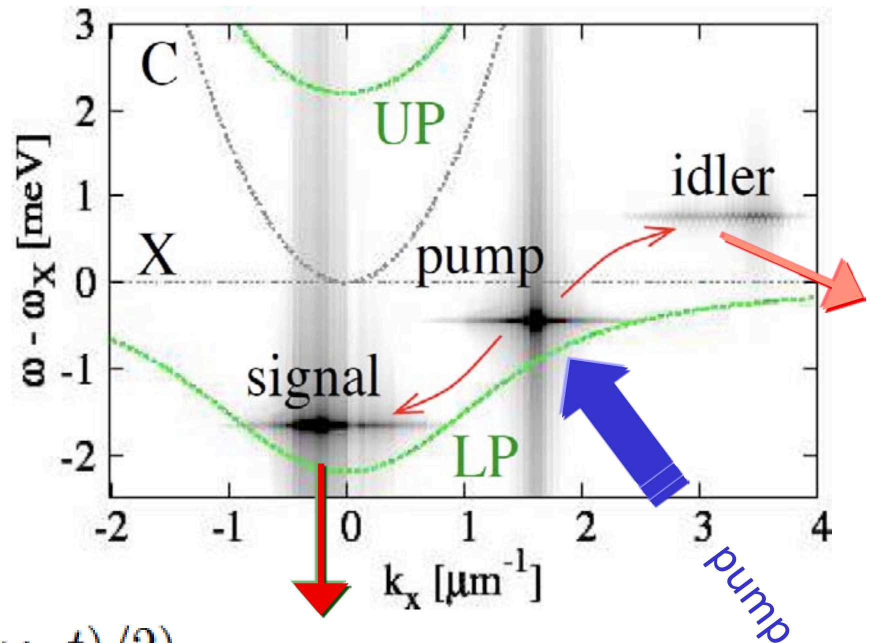
✧ Signal phase is completely free and idler phase locked to signal via pump

$$2\varphi_p = \varphi_s + \varphi_i$$

✧ Spontaneous U(1) symmetry breaking
gapless and diffusive Goldstone mode

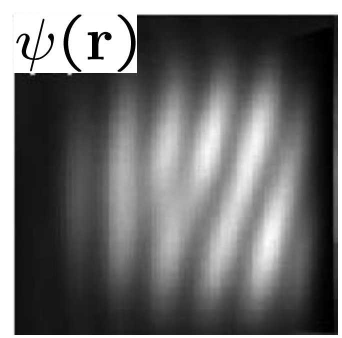
Playing with Spatial Anisotropy: OPO

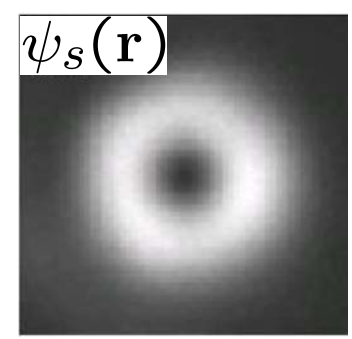




$$|\psi_{\rm LP}(\mathbf{r},t)|^2 = \sum_j \rho_j^2$$
$$+\,2\left(\sqrt{\rho_s\rho_p}\cos(\phi_s-\phi_p+(\mathbf{k}_{si}\cdot\mathbf{r}-\omega_{si}t)/2)\right.$$
$$+\sqrt{\rho_p\rho_i}\cos(\phi_i-\phi_p-(\mathbf{k}_{si}\cdot\mathbf{r}-\omega_{si}t)/2)$$
$$\left.+\sqrt{\rho_s\rho_i}\cos(\phi_s-\phi_i+\mathbf{k}_{si}\cdot\mathbf{r}-\omega_{si}t)\right)$$

- ✧ Time crystal
- ✧ Vortices: dislocations in density wave and time crystal
- ✧ After filtering in momentum: usual vortices





Stochastic Description

✧ From Keldysh action by ignoring the RG irrelevant terms (quantum fluctuations of order higher then second) and using MSR formalism

[Sieberer at al PRL (2013)]

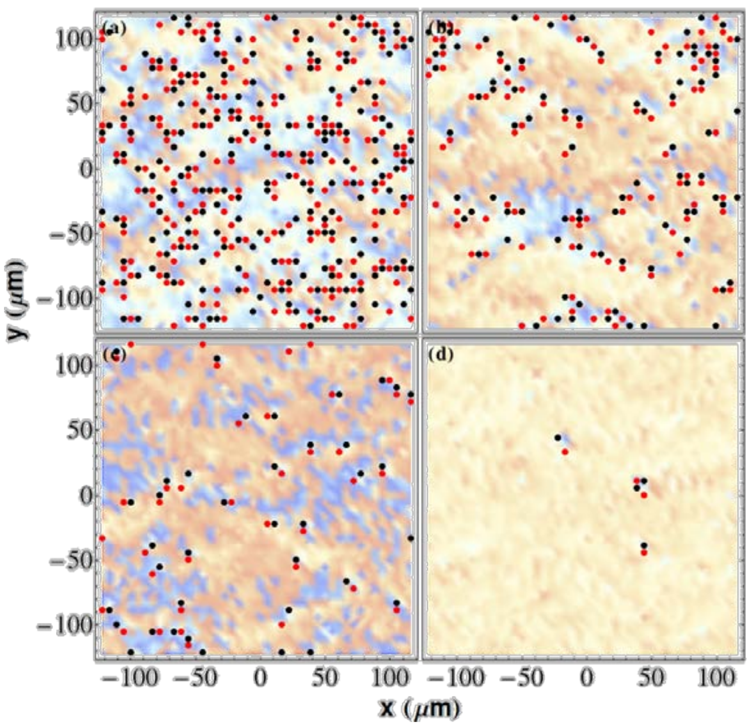
$$i\begin{pmatrix} d\psi_X \\ d\psi_C \end{pmatrix} = \left\{ \begin{pmatrix} \omega_X - i\kappa_X + g_X(|\psi_X|^2 - \frac{1}{\Delta V}) & \Omega_R/2 \\ \Omega_R/2 & \frac{\nabla^2}{2m_c} - i\kappa_C \end{pmatrix} \begin{pmatrix} \psi_X \\ \psi_C \end{pmatrix} + \begin{pmatrix} 0 \\ F_p \end{pmatrix} \right\} dt + \begin{pmatrix} \sqrt{\kappa_X} dW_X \\ \sqrt{\kappa_C} dW_C \end{pmatrix}$$

$$F_p(\mathbf{r}, t) = \mathcal{F}_p(\mathbf{r}) e^{i(\mathbf{k}_p \cdot \mathbf{r} - \omega_p t)}$$

dW - Wienner noise delta correlated in space and time

Observables: MC averages over noise

Exact numerical solution



Low density:

Vortex/antivortex proliferation

Medium density:

V/AV pairing

High density:

V/AV annihilation, no vortices

[G. Dagvadorj at al, PRX (2015)]

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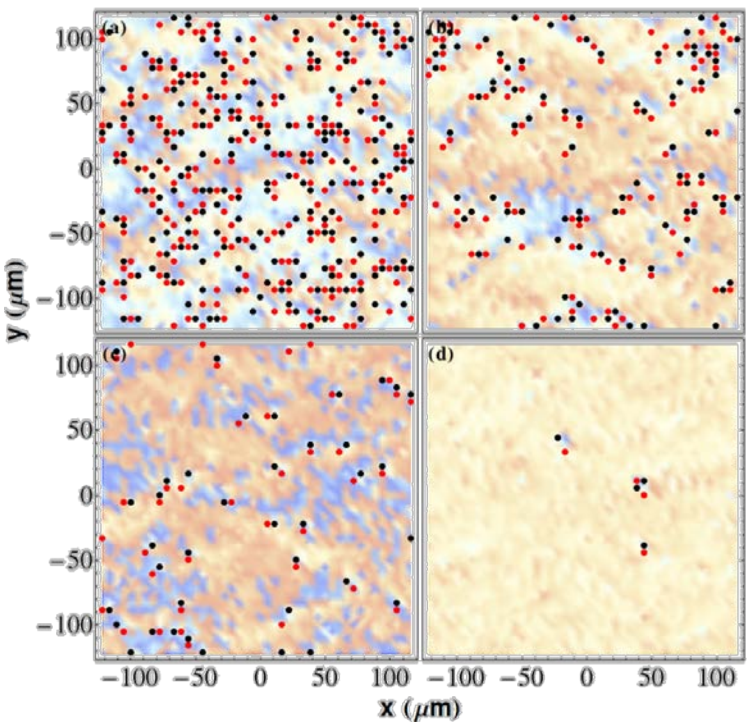
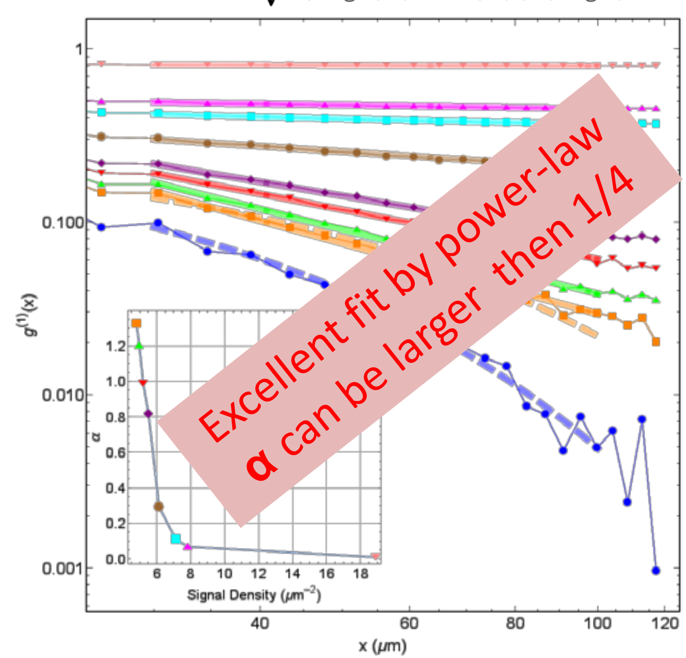


$$g_s^{(1)}(\mathbf{r}) = \frac{\langle \psi_s^*(\mathbf{r}+\mathbf{R})\psi_s(\mathbf{R})\rangle}{\sqrt{\langle \psi_s^*(\mathbf{r})\psi_s(\mathbf{r})\rangle \langle \psi_s^*(\mathbf{r}+\mathbf{R})\psi_s(\mathbf{r}+\mathbf{R})\rangle}}$$



[G. Dagvadorj at al, PRX (2015)]

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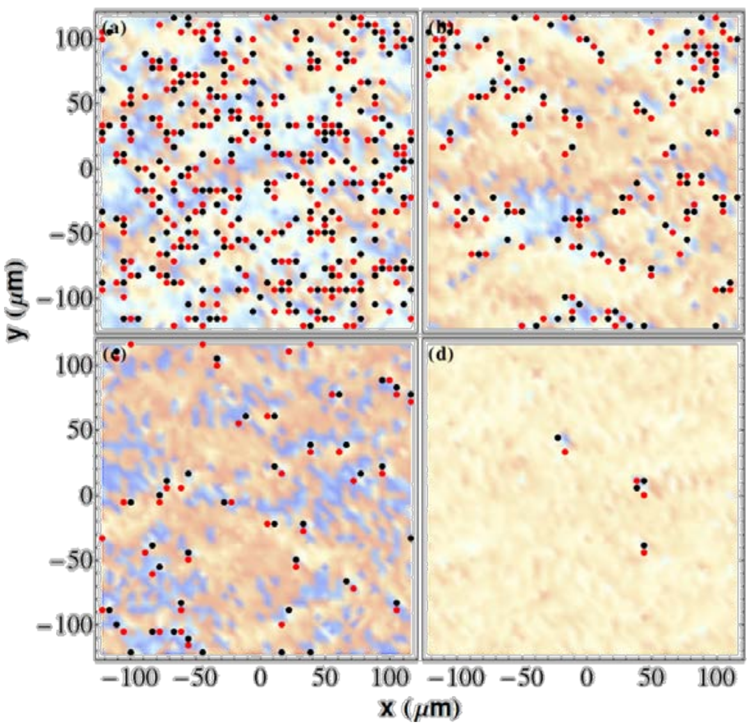

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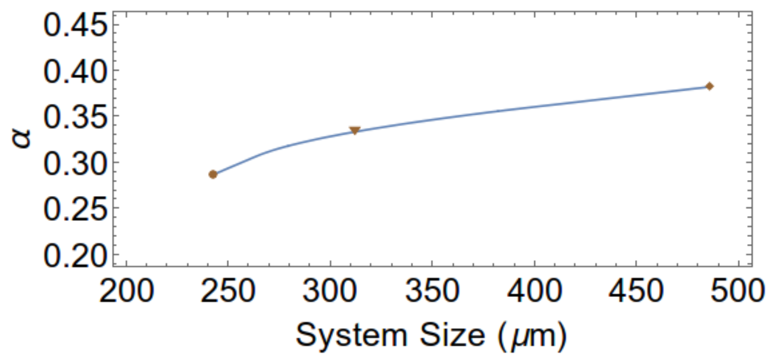


Excellent fit by power-law
α can be larger then 1/4

[G. Dagvadorj at al, PRX (2015)]

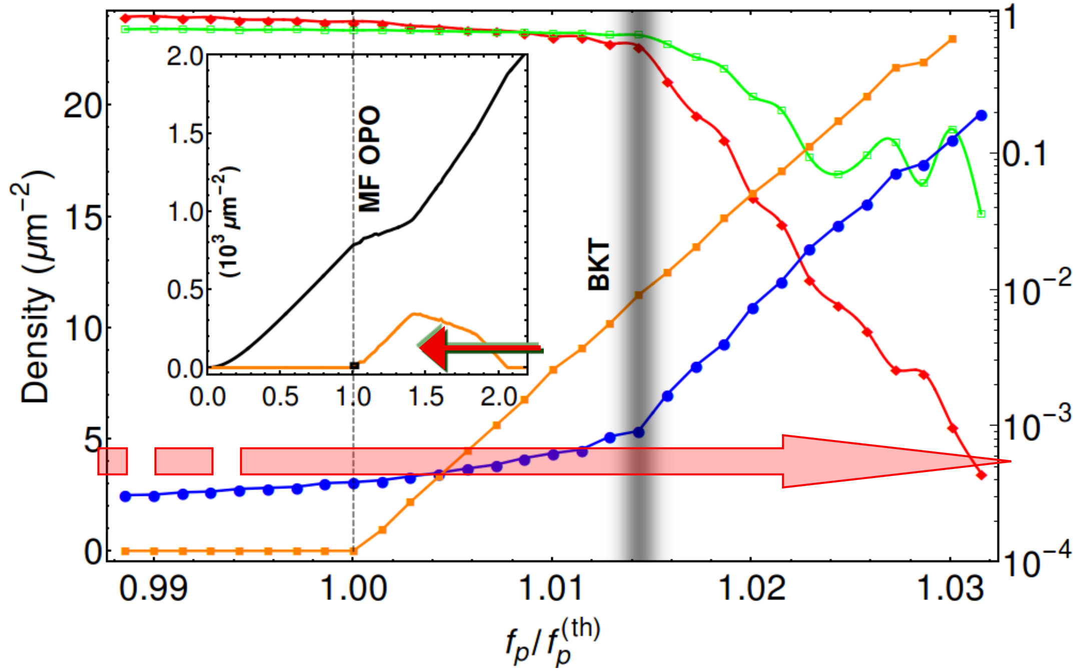
Quench Dynamics

[P. Comaron, G. Dagvadorj, A. Zamora, et al, in preparation]

Dynamics after infinitely fast quench

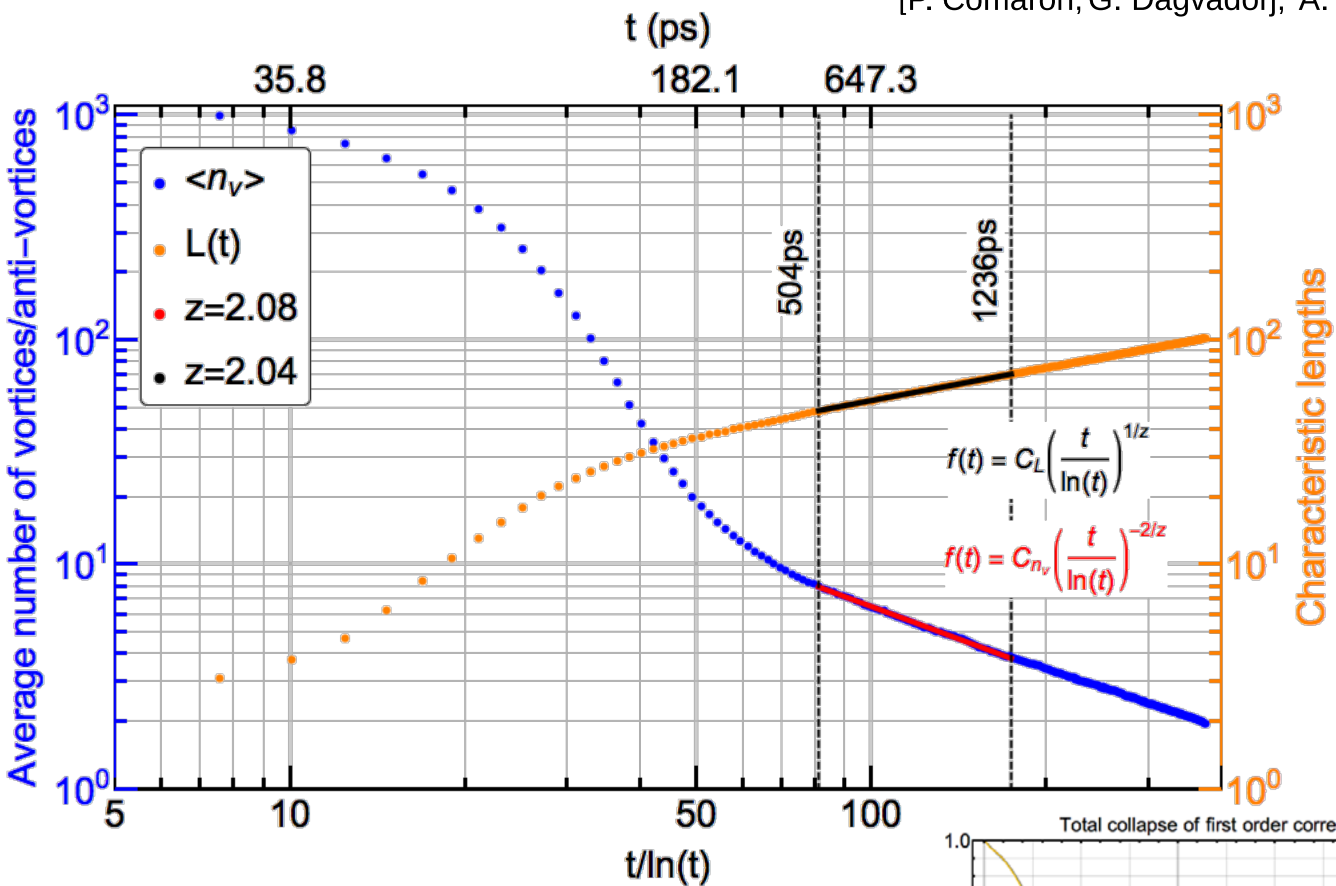
if universal can reveal the critical exponents of the transition

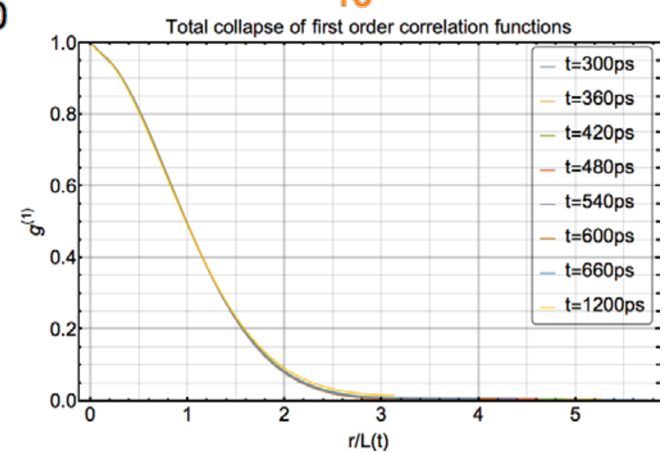
Fast change of pump strength



Dynamical Critical Exponents

[P. Comaron, G. Dagvadorj, A. Zamora, et al, in preparation]

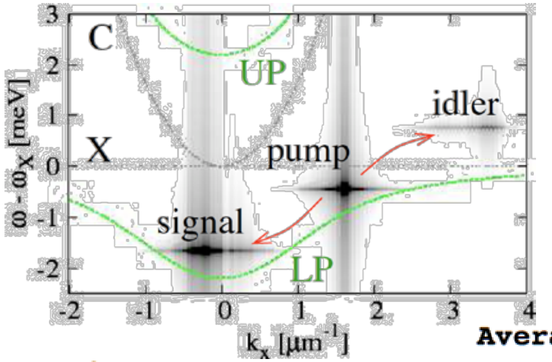




Critical exponent z=2

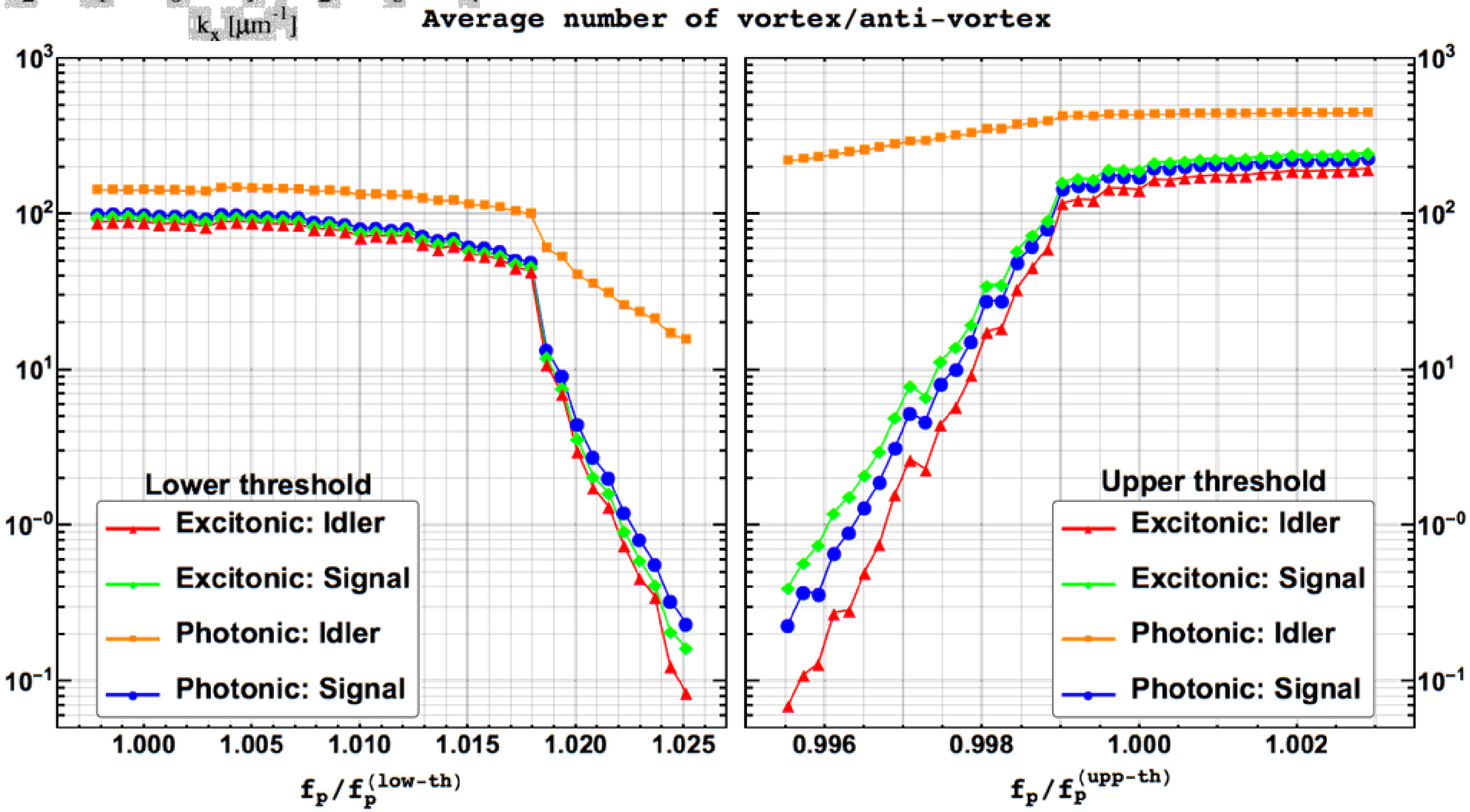
as in equilibrium XY model
i.e. equilibrium BKT

Multicomponent Condensate



Four coupled fields:

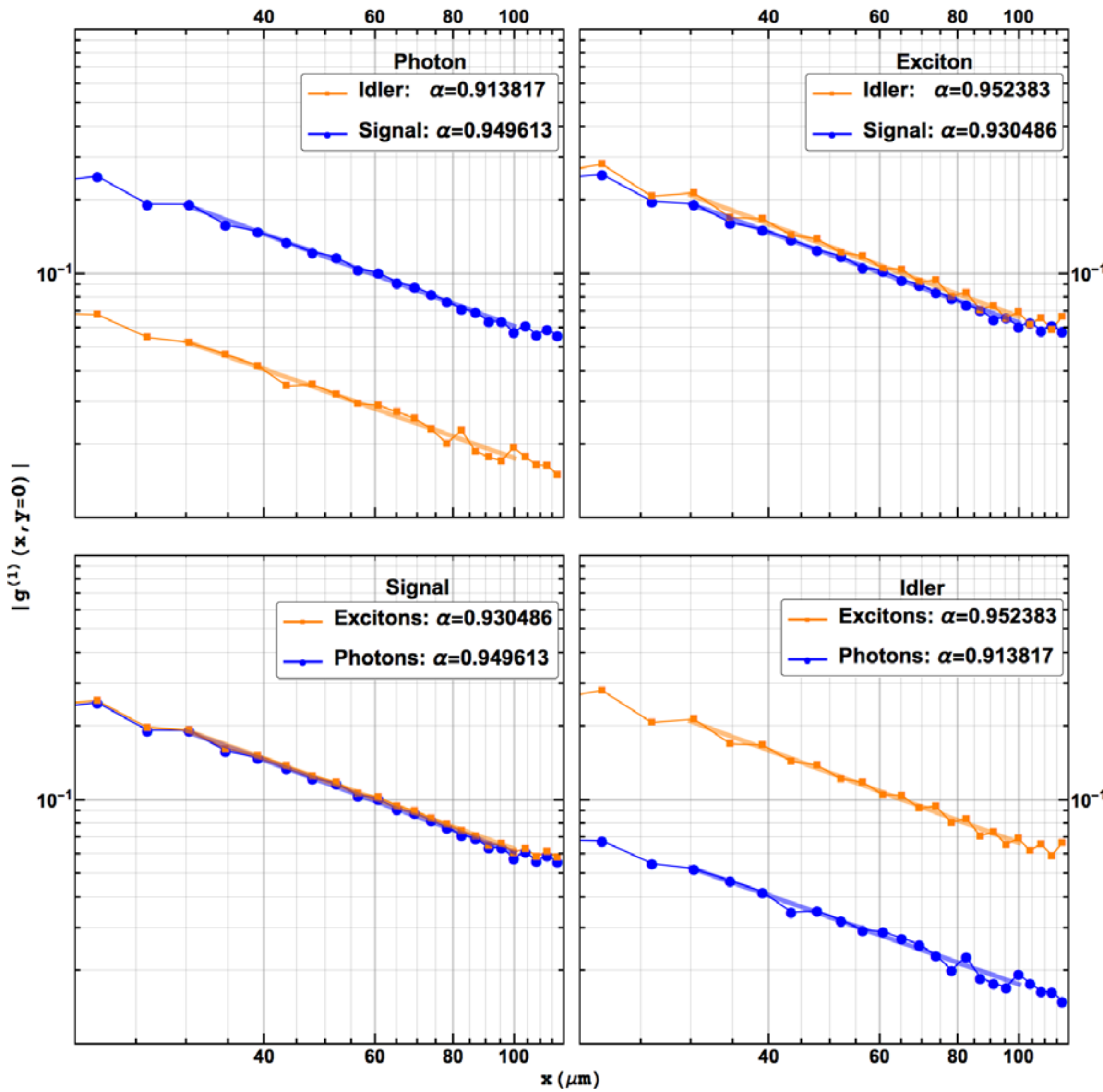
excitons, photons, signal, idler



Phase transition at the same point for all fields

despite much lower density for photonic idler

Spatial Coherence for All Components



The same exponent of the power-law decay of g1(r)

despite much lower density for photonic idler

Spinor Case and Fractional Vortices

- ✧ Polariton system is spinor: excitons +1 and -1, two polarisations of light

TE-TM splitting

$$i\frac{\partial\psi_\pm}{\partial t} = \left(-\frac{\nabla^2}{2m_\phi} - i\kappa_C\right)\psi_\pm + \frac{\Omega_R}{2}\phi_\pm + \chi\left(\frac{\partial}{\partial x} \mp i\frac{\partial}{\partial y}\right)^2\psi_\mp + \frac{1}{2}\chi_0\psi_\mp + F_\pm + \sqrt{\kappa_C}\,dW_{C,\pm}$$

Anisotropy splitting

$$i\frac{\partial\phi_\pm}{\partial t} = \left(-\frac{\nabla^2}{2m_\psi} - i\kappa_X\right)\phi_\pm + \frac{\Omega_R}{2}\psi_\pm + \alpha_1|\phi_\pm|^2\phi_\pm + \alpha_2|\phi_\mp|^2\phi_\pm + \sqrt{\kappa_X}\,dW_{X,\pm}$$

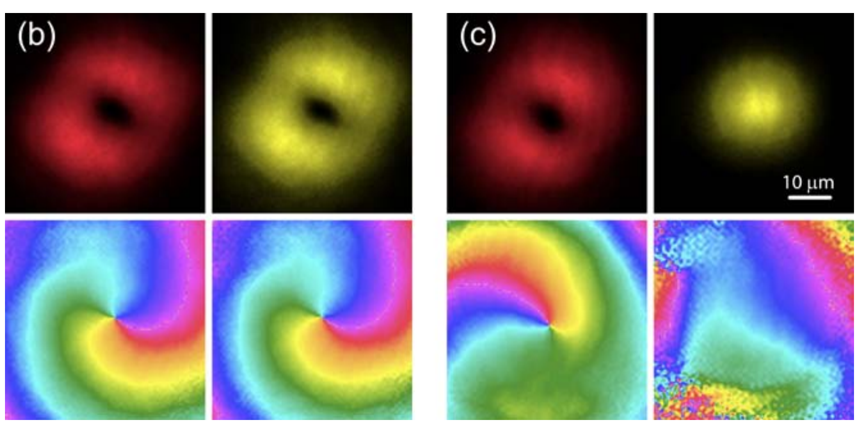
Interactions between different spins

- ✧ Full vortices and fractional vortices present

Vortex in both polarisations — Vortex in one polarisation

Density

Phase



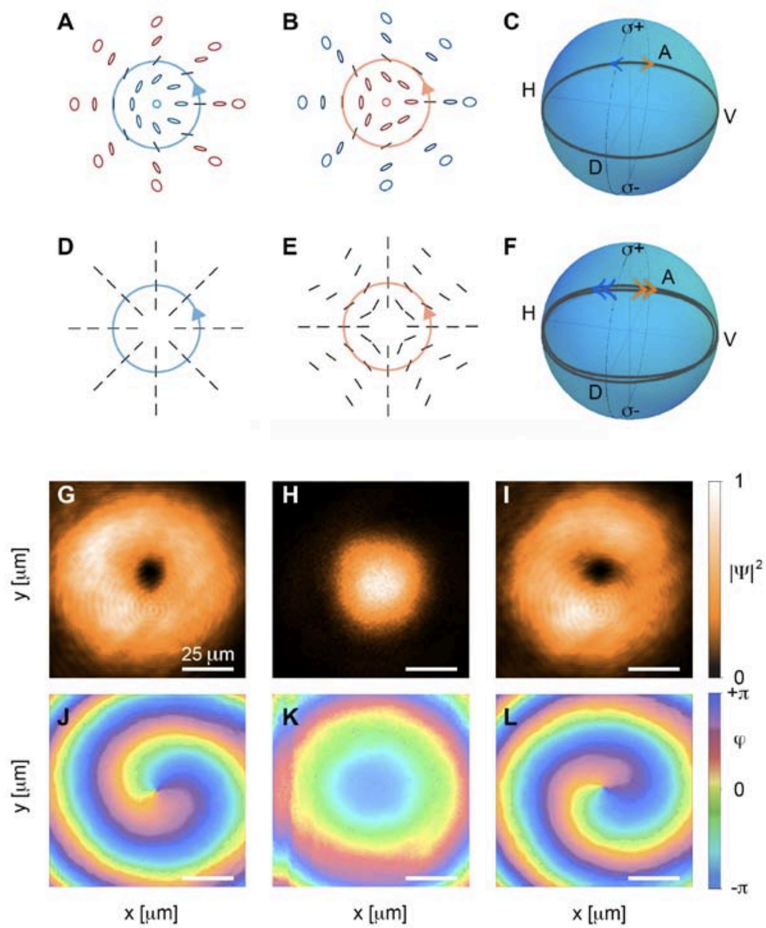
"Full" vortex — "Half" vortex

Dominici at al, Science Advances (2015)

Skyrmions and Spin Vortices

[Donati et al. to appear in PNAS]

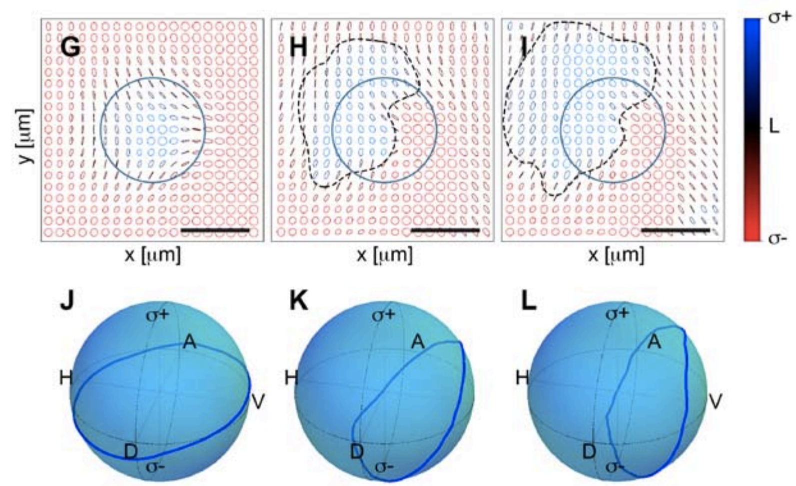
Spin and orbital angular momentum
are both quantized and mixed



σ- / σ +	LG_{0+1}	LG_{00}	LG_{0-1}
LG_{0+1}	Phase	Lemon	Hed
LG_{00}	Star	Gaussian	Lemon
LG_{0-1}	Hyp	Star	Phase

Polarization anisotropy leads to complex dynamics

$$i\frac{\partial\psi_\pm}{\partial t} = \left(-\frac{\nabla^2}{2m_\phi} - i\kappa_C\right)\psi_\pm + \frac{\Omega_R}{2}\phi_\pm + \chi\left(\frac{\partial}{\partial x} \mp i\frac{\partial}{\partial y}\right)^2\psi_\mp + \frac{1}{2}\chi_0\psi_\mp + F_\pm$$



Keldysh Action for OPO

Projected into LP sub-space and limited to three modes

$$\psi_{lp}(\mathbf{r},t) = \psi_s e^{i(\mathbf{k}_s\mathbf{r}-\omega_s t)} + \psi_i e^{i(\mathbf{k}_i\mathbf{r}-\omega_i t)} + \psi_p e^{i(\mathbf{k}_p\mathbf{r}-\omega_p t)}$$

Keldysh Action

$$S_C = \int dt d^2\mathbf{r} \Big\{ -(F_p^* \psi_p^Q + F_p \bar{\psi}_p^Q) + \sum_{j=s,p,i} \Big[\frac{1}{X_j^2} (\bar{\psi}_j^C \bar{\psi}_j^Q) \begin{pmatrix} 0 & [D_0^A]_j^{-1} \\ [D_0^R]_j^{-1} & [D_0^{-1}]_j^K \end{pmatrix} \begin{pmatrix} \psi_j^C \\ \psi_j^Q \end{pmatrix} - g_x \left(\left(2(|\psi_s^C|^2 + |\psi_i^C|^2 + |\psi_p^C|^2) - |\psi_j^C|^2\right) \psi_j^C \bar{\psi}_j^Q + \text{c.c.} \right) \Big] - g_x \left(2\psi_s^C \psi_i^C \bar{\psi}_p^C \bar{\psi}_p^Q + (\psi_p^C)^2 (\bar{\psi}_i^C \bar{\psi}_s^Q + \bar{\psi}_s^C \bar{\psi}_i^Q) + \text{c.c.} \right) \Big\},$$

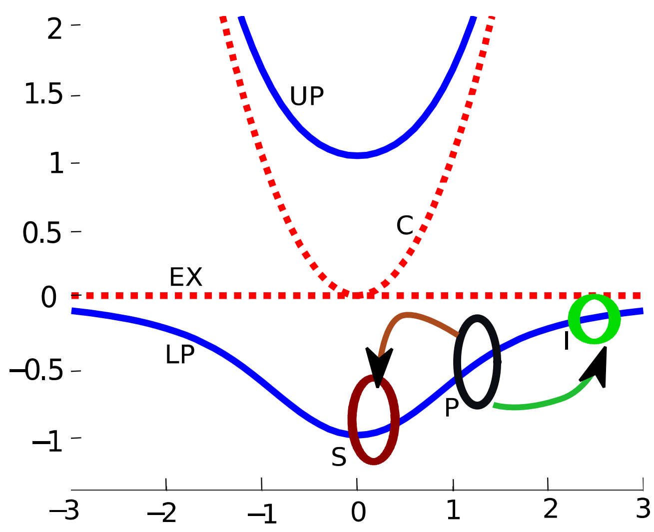
$$F_p(\mathbf{r},t) = \mathcal{F}_p(\mathrm{r}) e^{i(\mathbf{k}_p\cdot\mathbf{r}-\omega_p t)}$$

Polariton dispersion: non-quadratic and anisotropic

$$[D_0^A]_j^{-1} = i\partial_t - \omega_{lp}(\mathbf{k}_j - i\nabla) - i\gamma_j$$

$$\omega_{lp}(\mathbf{q}) = \frac{1}{2}\left(q^2 + \delta_{CX} - \sqrt{(q^2+\delta_{CX})^2 + 4}\right)$$

$$\delta_{CX} \equiv \omega_C(0) - \omega_X$$



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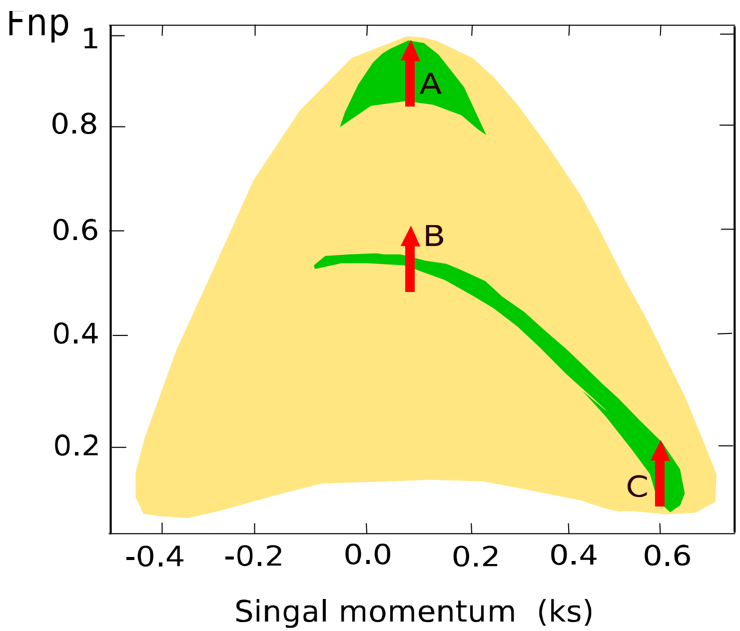


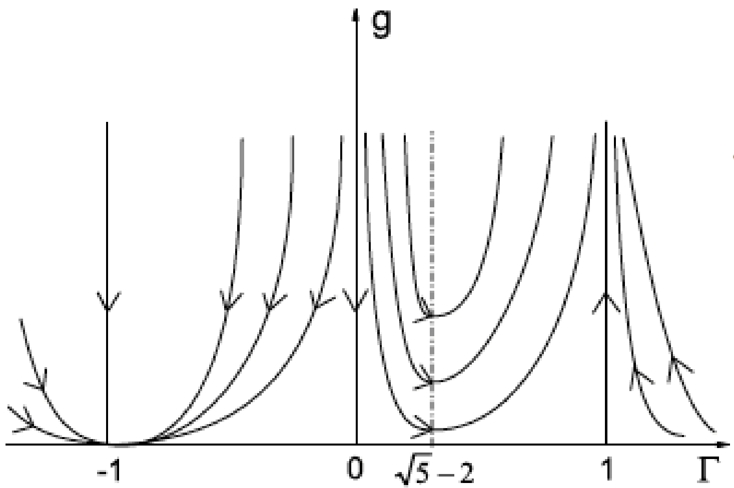
KPZ for OPO – Drift Term

$$\partial_t\theta = D_x\partial_x^2\theta + D_y\partial_y^2\theta + \frac{\lambda_x}{2}(\partial_x\theta)^2 + \frac{\lambda_y}{2}(\partial_y\theta)^2 + B_x\partial_x\theta + B_y\partial_y\theta + \bar{\xi}$$

[A. Zamora, L. Sieberer, S. Diehl, et al. in preparation]

The drift term can be eliminated with Galilean boost.

In the moving frame standard KPZ with RG flow:



$$g \equiv \lambda_x^2\Delta/(Dx^2\sqrt{DxDy})$$

$$\Gamma = \frac{\lambda_y D_x}{\lambda_x D_y}$$

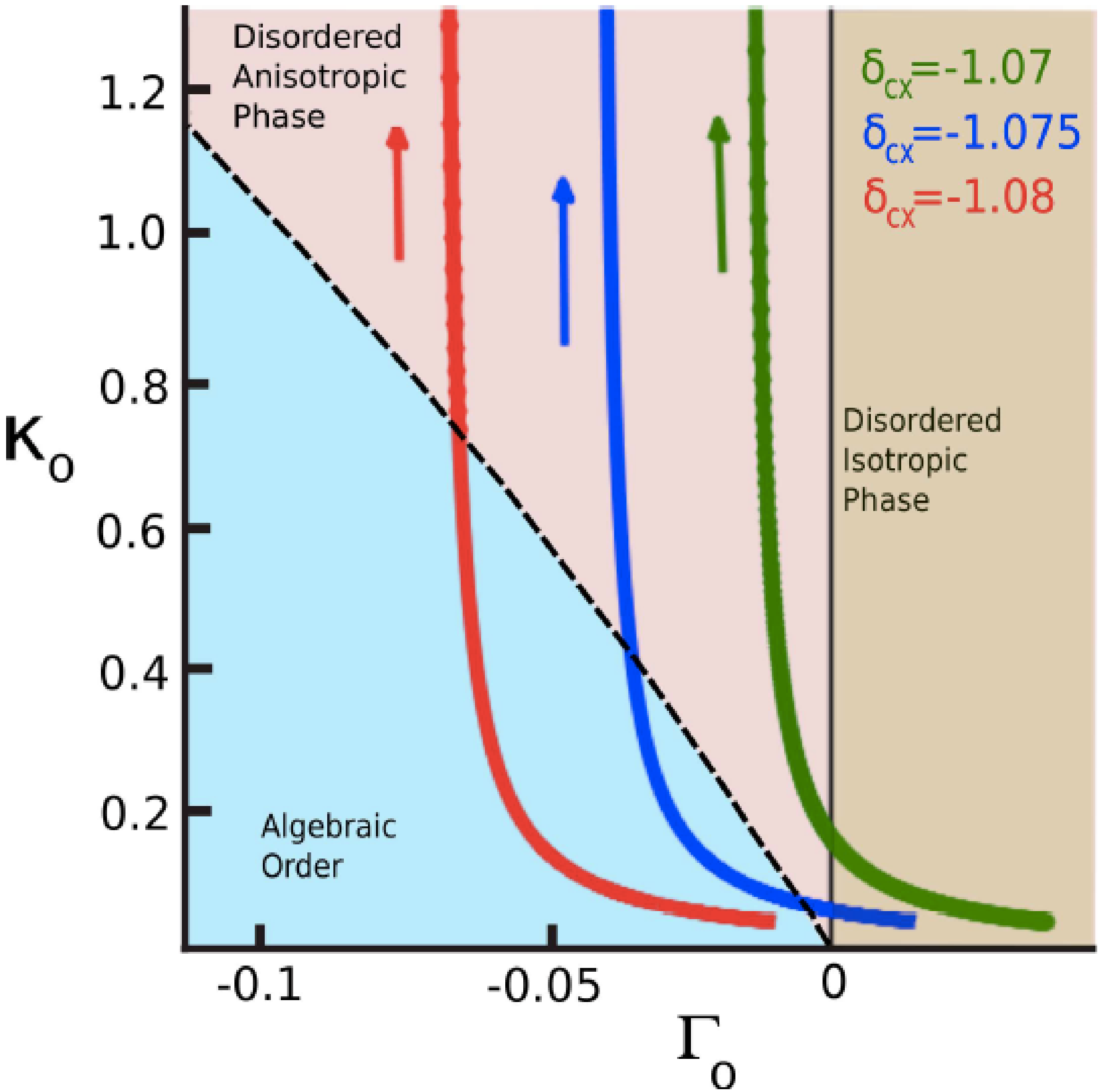
There is some influence on g1(t) = exp[-C/2]

$$C(0,t) \to (Bt)^{2\chi} F\left(\frac{t}{(Bt)^{z'}}\right) \to \begin{cases} t^{2\chi/z'} & \text{if } t \ll B^{z'/(1-z')} \\ t^{2\chi} & \text{if } t \gg B^{z'/(1-z')} \end{cases}$$

Faster temporal decay at long times

Infinite System – Driving Across Universalities

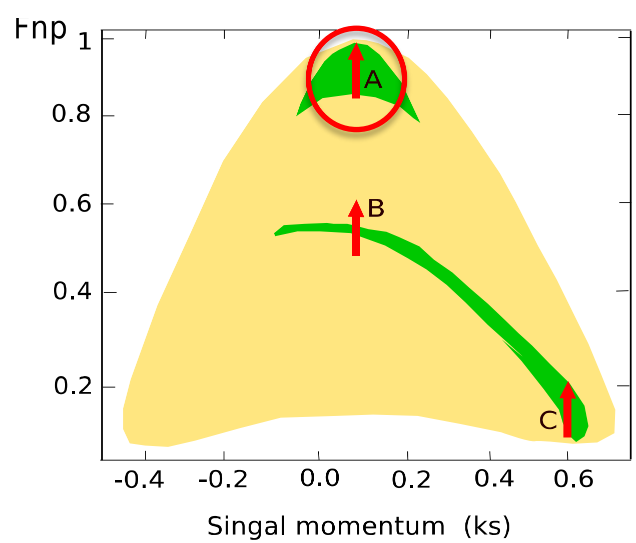
[A. Zamora, L. Sieberer, S. Diehl, et al. in preparation]



Negative detuning

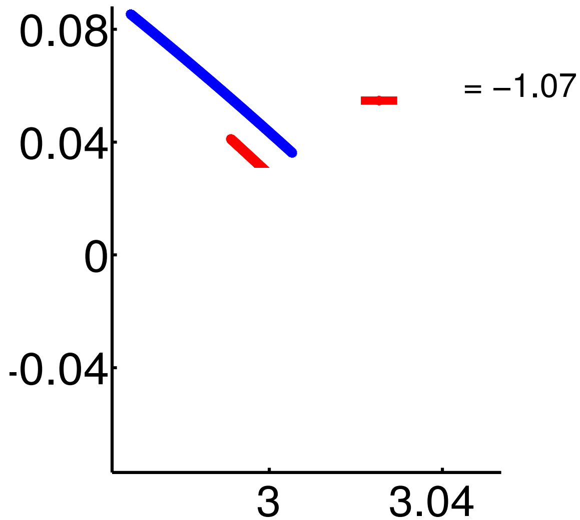
By increasing drive we move from non-equilibrium to equilibrium fixed point

Two different universality classes as the drive is increased

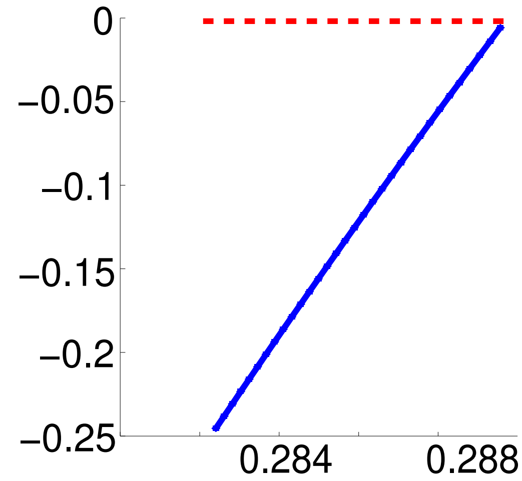


How to Achieve Large Anisotropy?

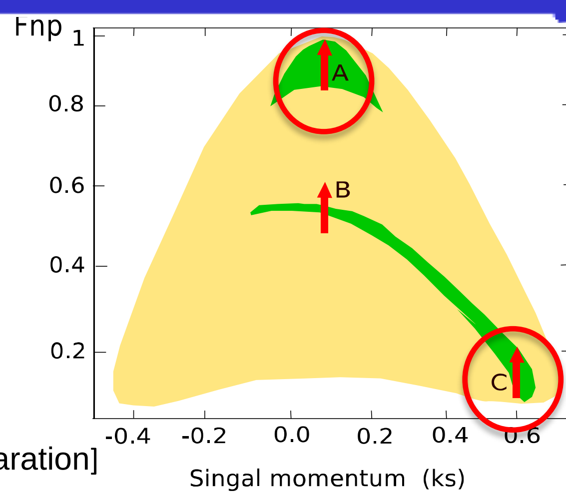
Small ks but Increasing detuning



At zero detuning by increasing ks



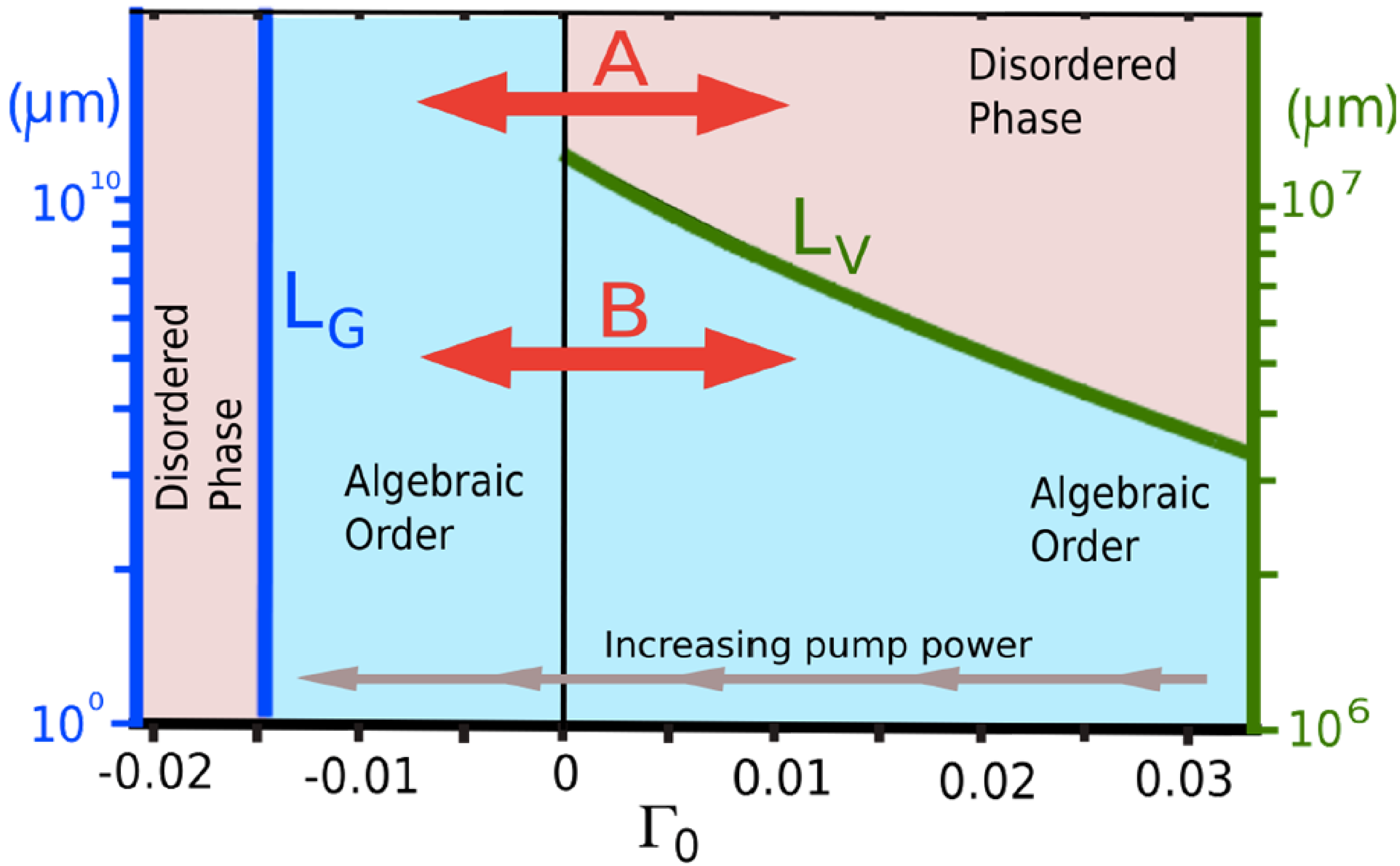
Increasing pump power



[A. Zamora, L. Sieberer, S. Diehl, et al. in preparation]

Driving Across Universalities in a Finite System

[A. Zamora, L. Sieberer, S. Diehl, et al. in preparation]

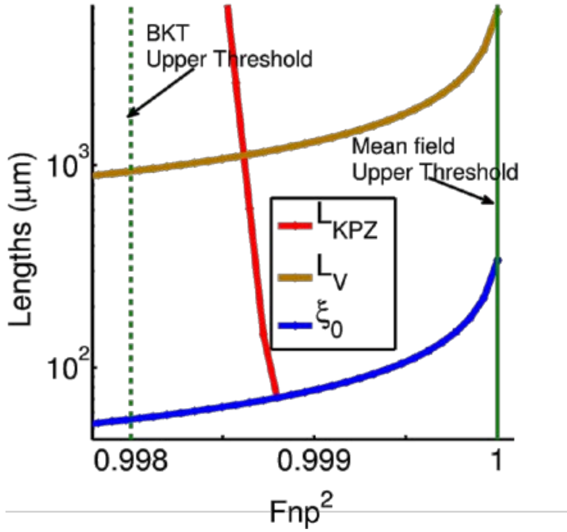


Equilibrium physics dominates: transition between algebraic order and exponential decay of coherence (disorder) BKT-like in systems up to meters

Worst quality samples needed for the transition A

Searching for the KPZ Phase

[A. Zamora, L. Sieberer, S. Diehl, et al. in preparation]



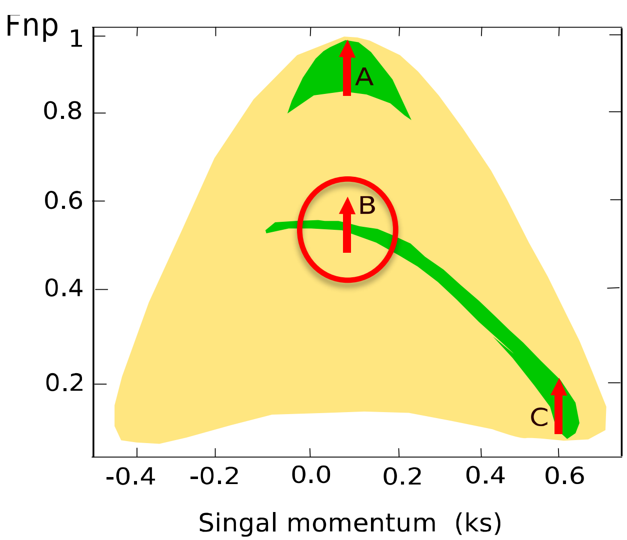
Away from threshold:

L_{KPZ} astronomical

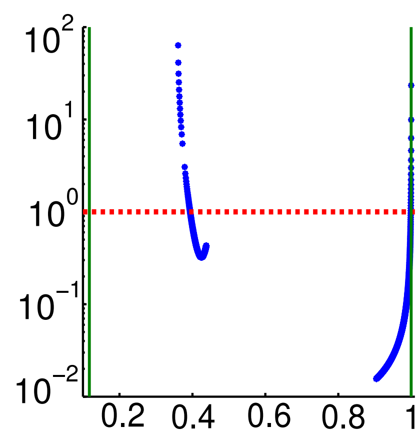
Very close to threshold

L_{KPZ} reasonable and $L_{KPZ} < L_V$ only extremely close to threshold i.e. below BKT transition

Note: analytics not valid in this regime



Middle of the OPO regime

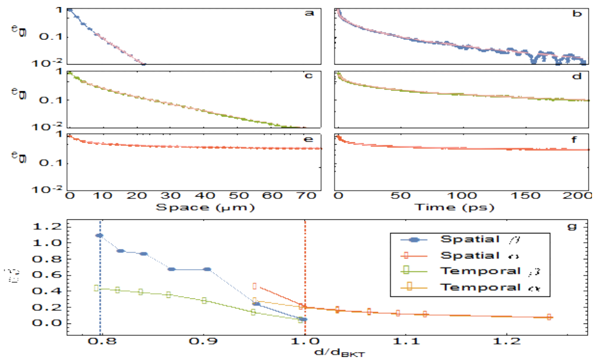


Large g, even > 1

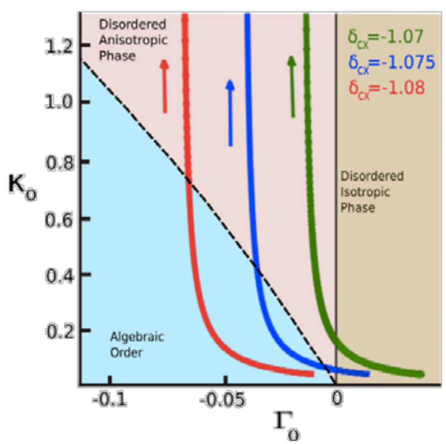
KPZ at all length-scales?

Conclusions

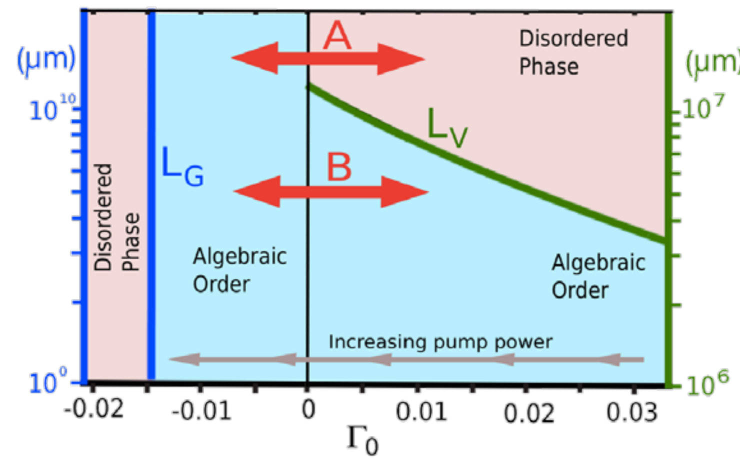
✧ Best microcavities indistinguishable from closed systems in equilibrium



✧ Anisotropy and dissipation – as in OPO – different phases possible



✧ Current microcavities "too good" for their size: equilibrium-like physics dominates



✧ But OPO shows a regime of strong KPZ non-linearity i.e. KPZ order at all length-scales?