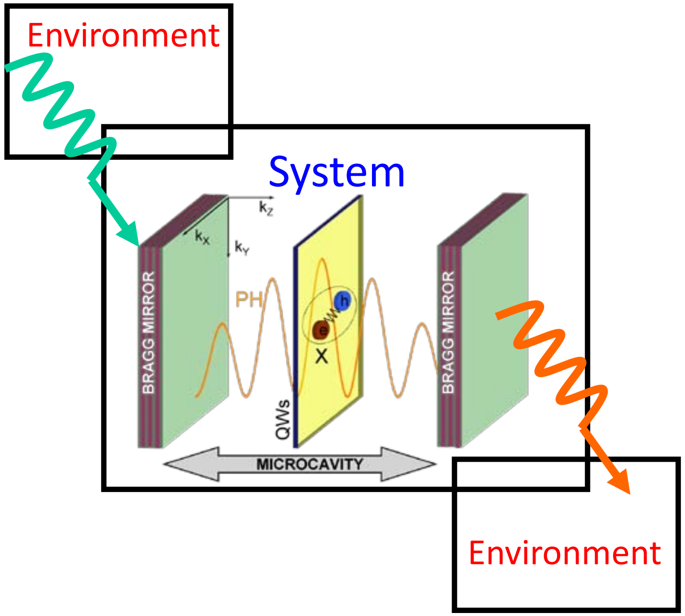
Driven-dissipative quantum fluids of light

Marzena Szymańska

KITP, April 2019

Photonic Platforms: Driven-dissipative Condensates



2D Light-matter condensates with drive and decay

Polaritons

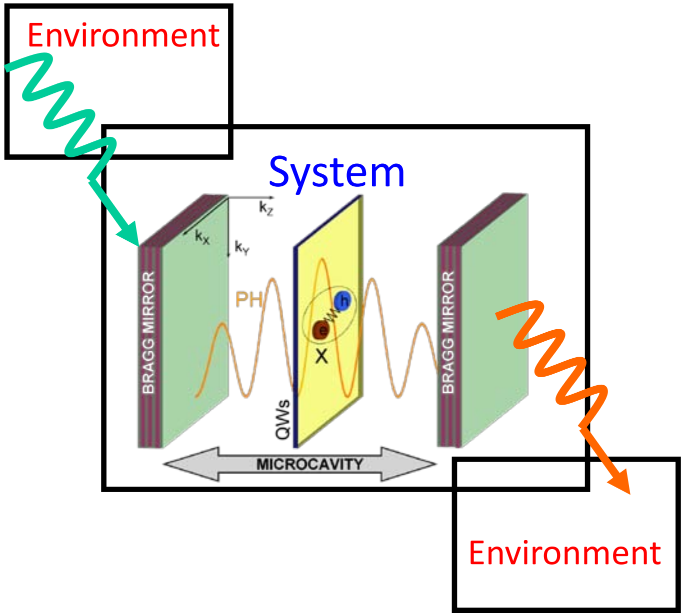
Photon BEC

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?

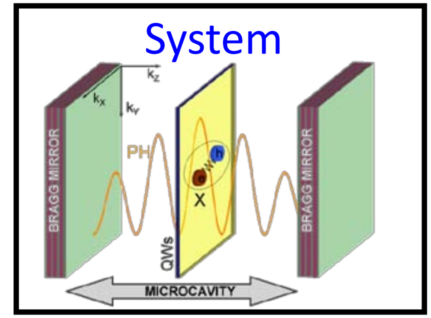
Spatial and Temporal Coherence for 2D Condensate

Closed System

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

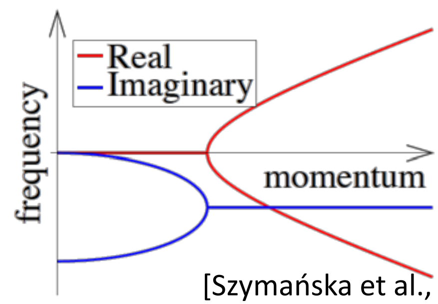
$$|g^{(1)}(x,-x)| = A|2x|^{-\alpha}$$

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

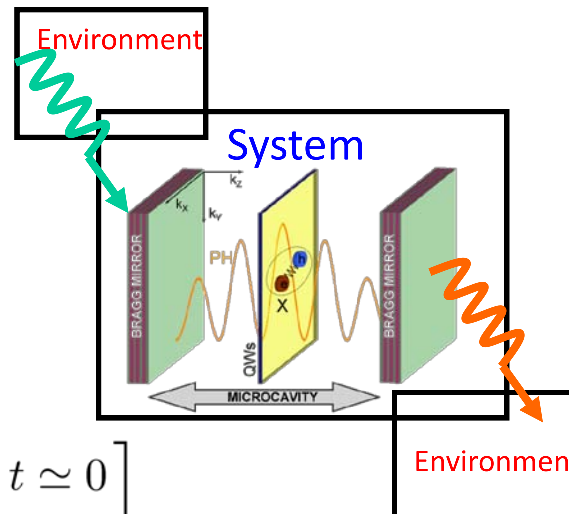


Driven-dissipative System

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



[Szymańska et al., *PRL* 2006
Wouters & Carusotto *PRA* 2007]



From Keldysh field theory

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

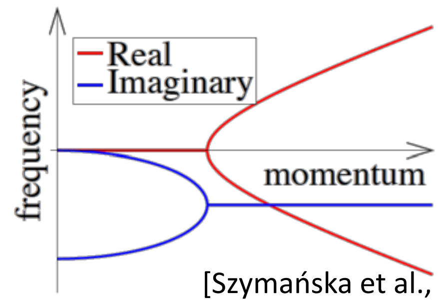
$$\alpha(\text{pump}, \text{decay}, \text{density})$$

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

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

Spatial and Temporal Coherence

Driven-dissipative System



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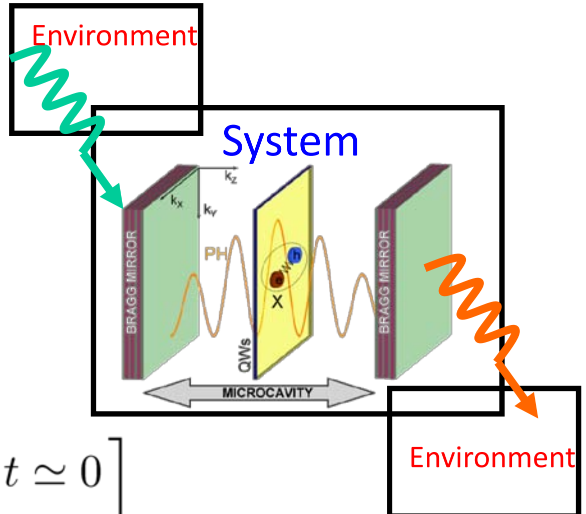

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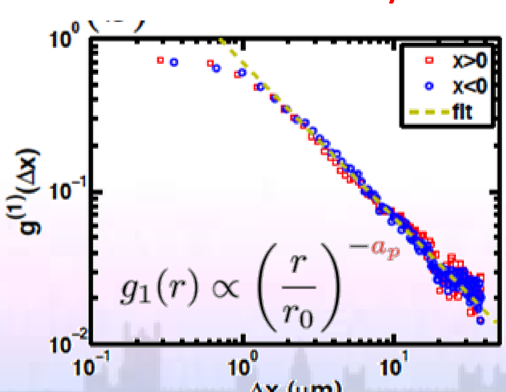
$\alpha(\text{pump}, \text{decay}, \text{density})$

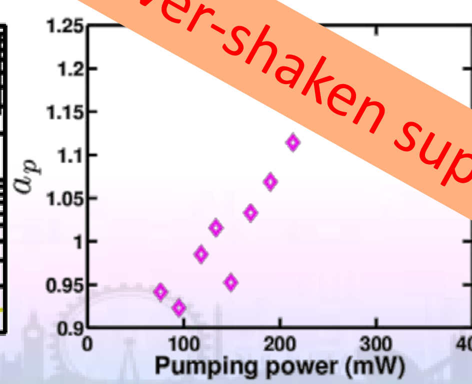
$$\alpha_t = 1/2\alpha_s$$

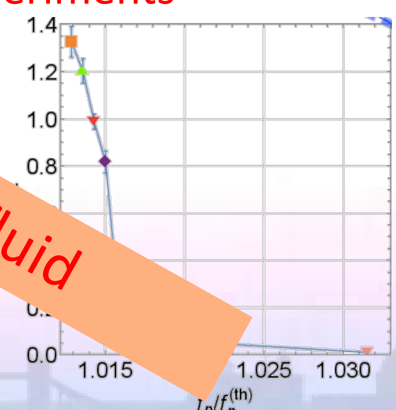
[Szymańska et al., *PRL* 2006; *PRB* 2007]

Over-shaken superfluid

From stochastic dynamics ... BKT and early experiments



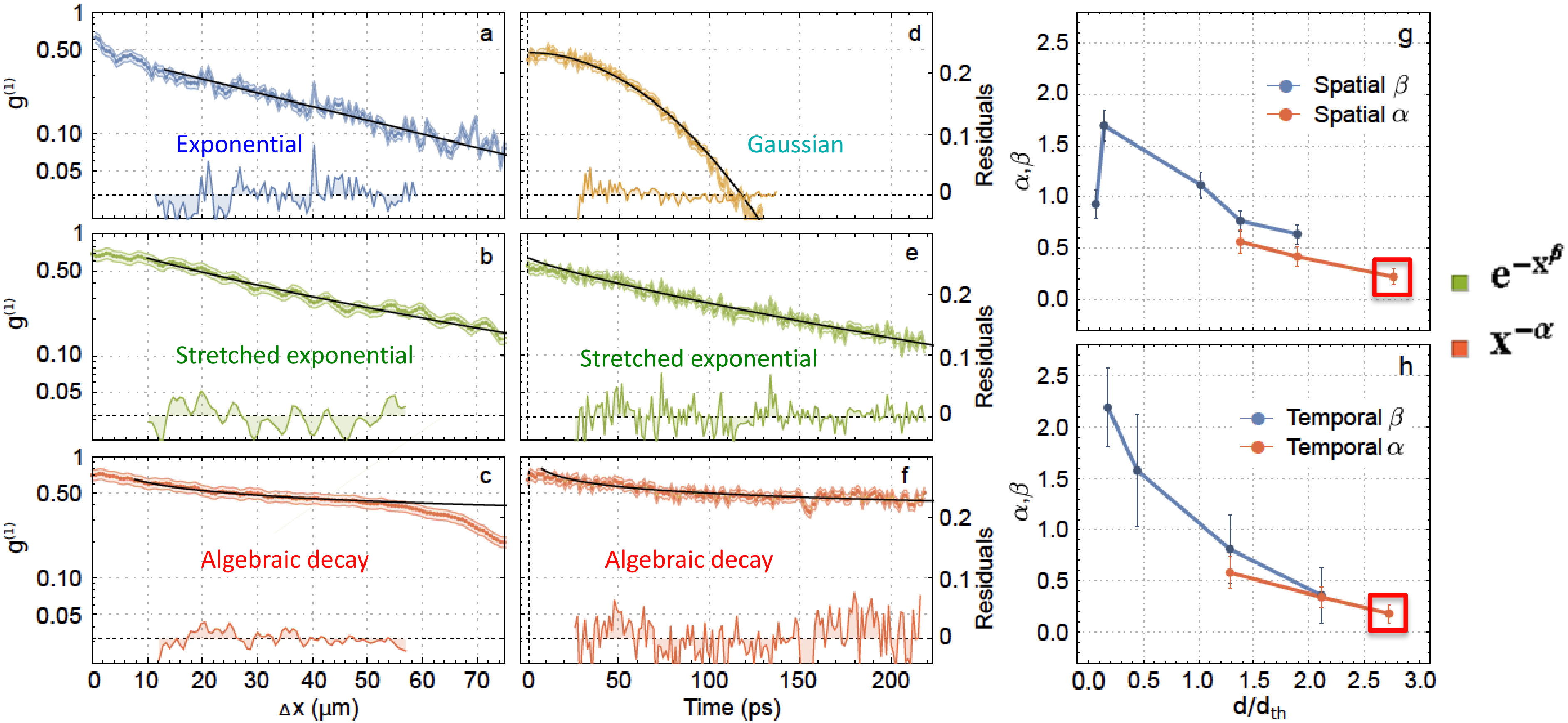




Faster decay possible then equilibrium upper limit

[*PNAS* (2012), *PRX* (2015)]

Spatial and Temporal Coherence - Experiment



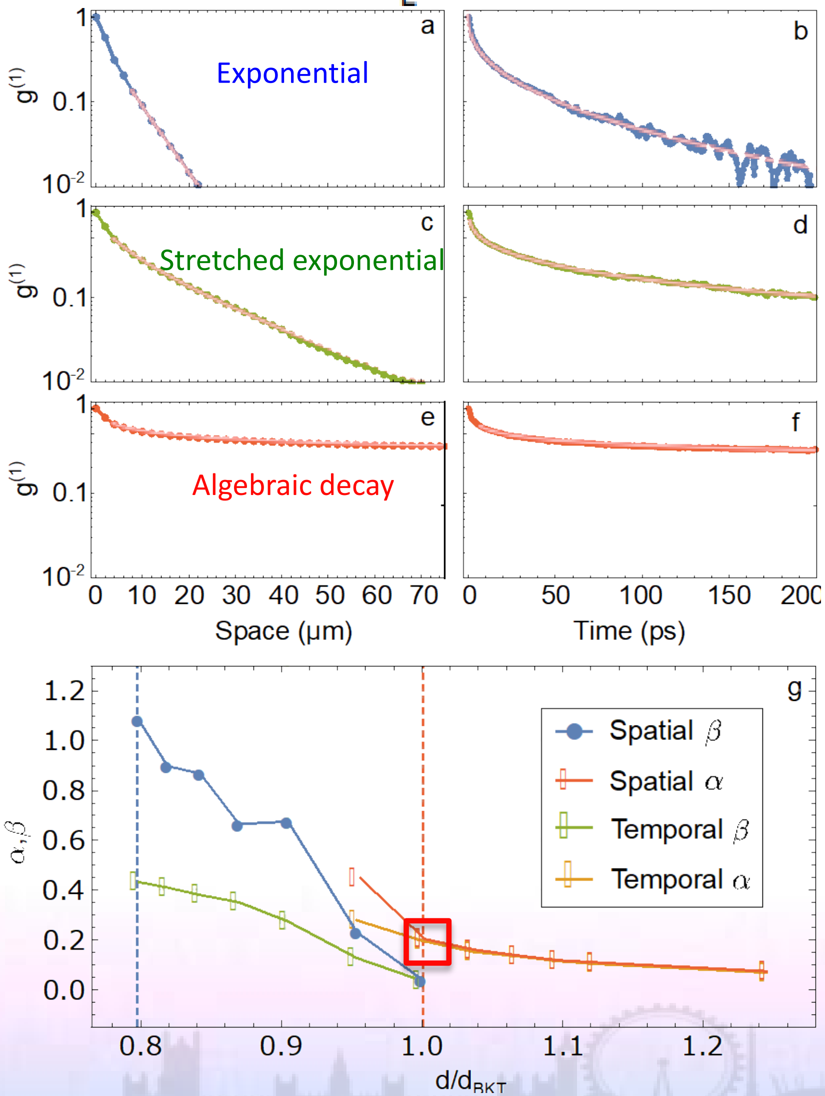
$$\alpha_s = \alpha_t < 1/4$$

Crossover from exponential to algebraic decay of coherence with equilibrium exponents

[D. Caputo, Nature Materials (2017)]

Spatial and Temporal Coherence - Theory

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



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

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

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

[D. Caputo, Nature Materials (2017)]

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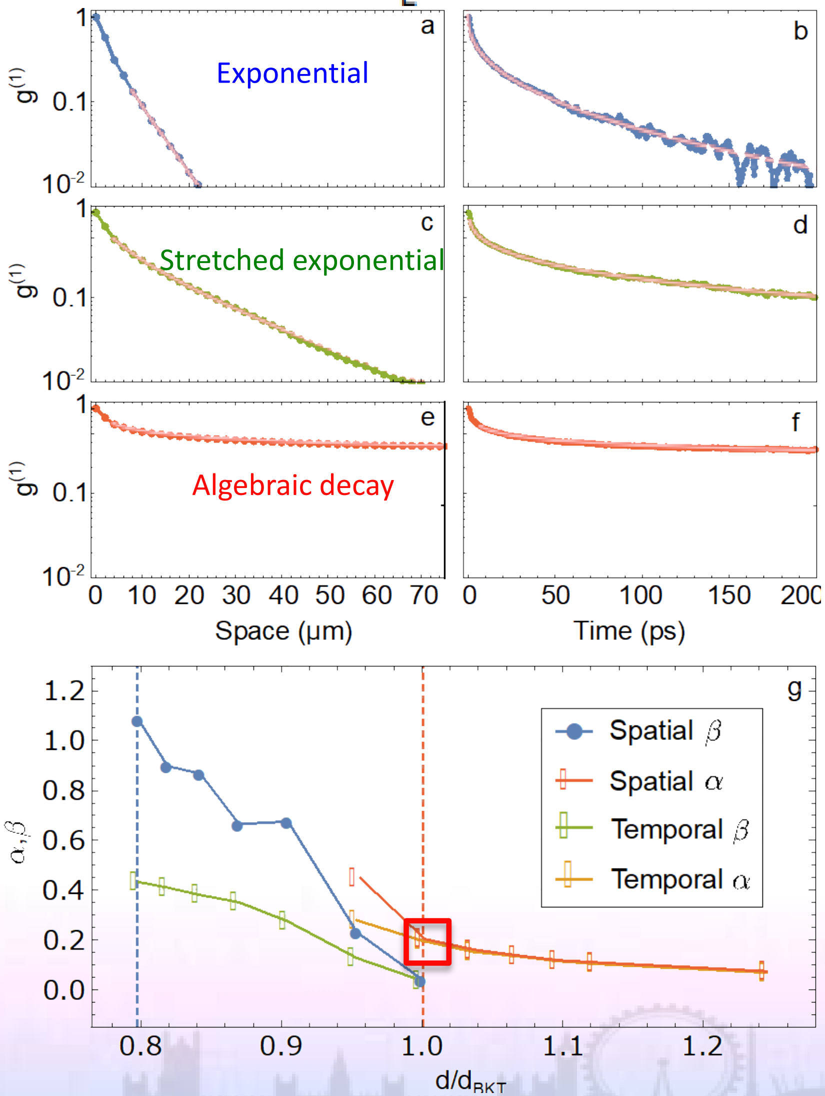
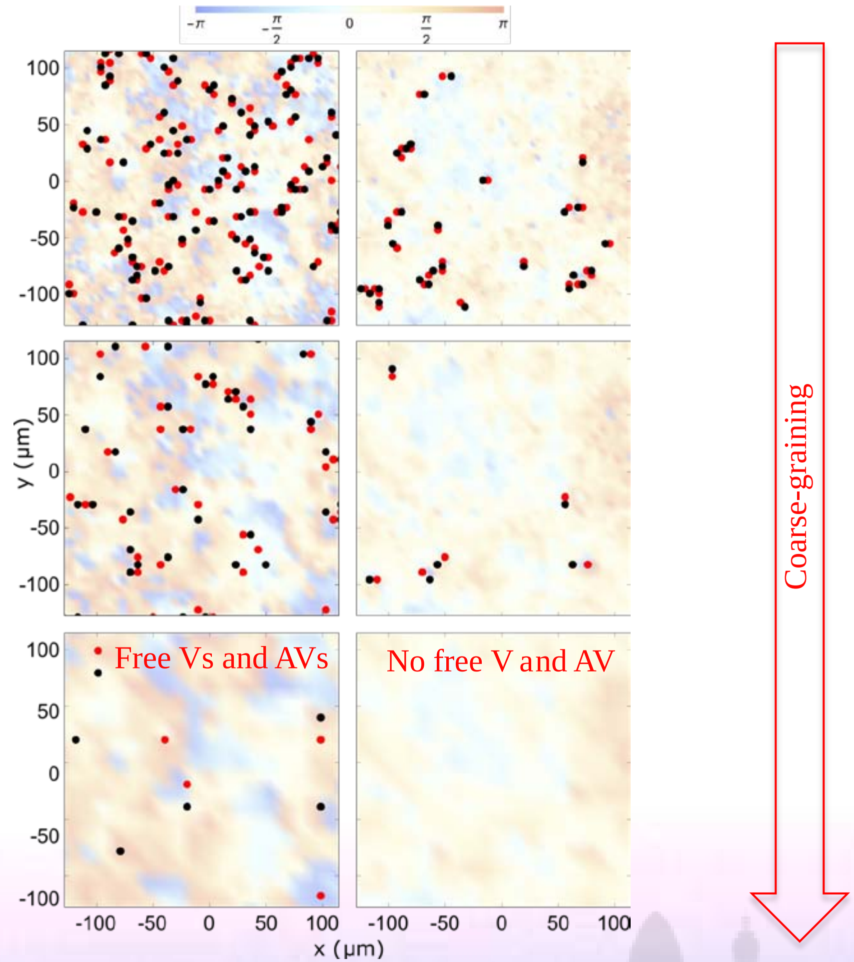
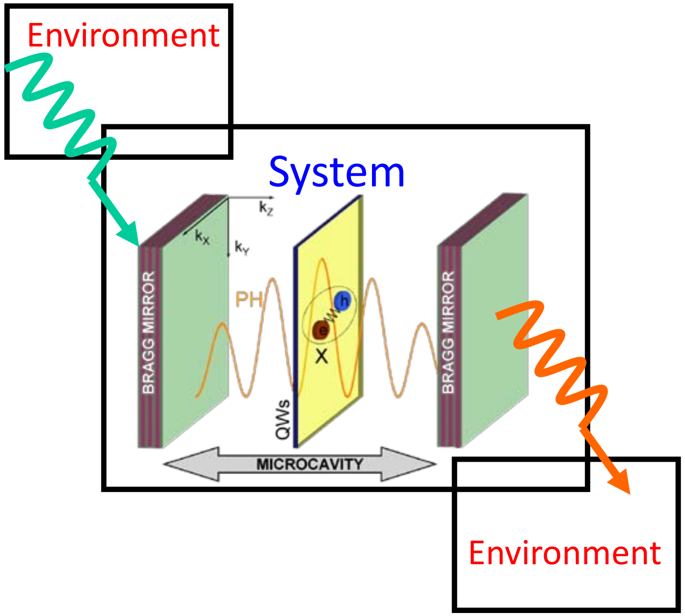




BKT crossover

[D. Caputo, Nature Materials (2017)]

Driven-dissipative Condensates



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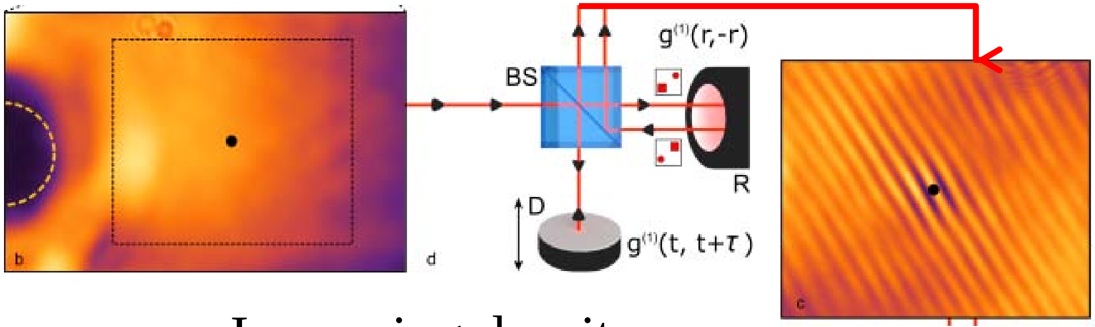
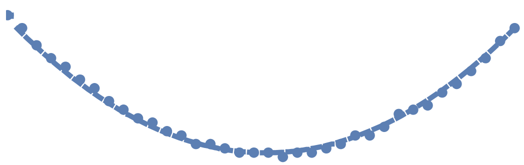
Can thermal equ[YES] be achieved?

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

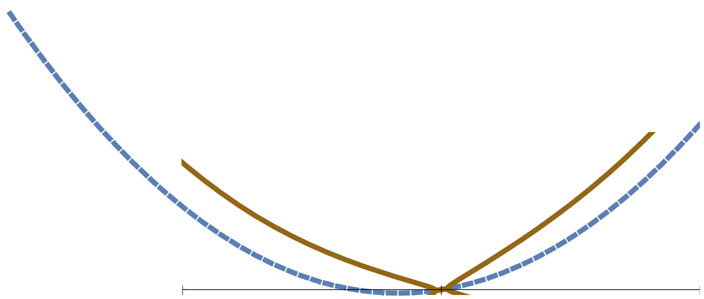
Fourier Transform of 2D Spatio-Temporal Coherence



Increasing density



$$\omega_{bog} = -i\Gamma/2 \pm \sqrt{\frac{k^2}{2M}\left(\frac{k^2}{2M} + 2g - \frac{\Gamma^2}{4}\right)}$$



$$\omega_{offset} = v_c * k_c$$

$$\omega_{doppler} = (k - k_c) * v_c$$

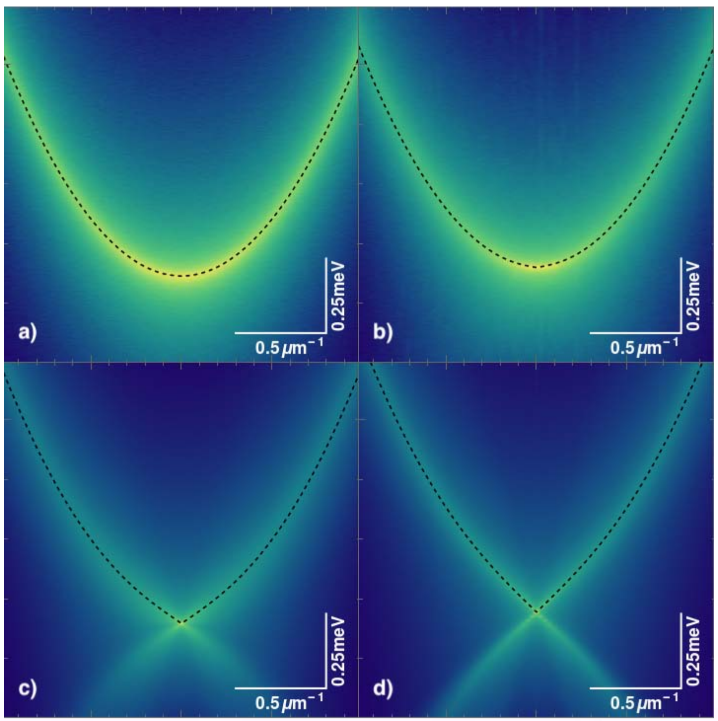
[Ballarini et all. 2019]

Luminescence Spectrum in Homogeneous System

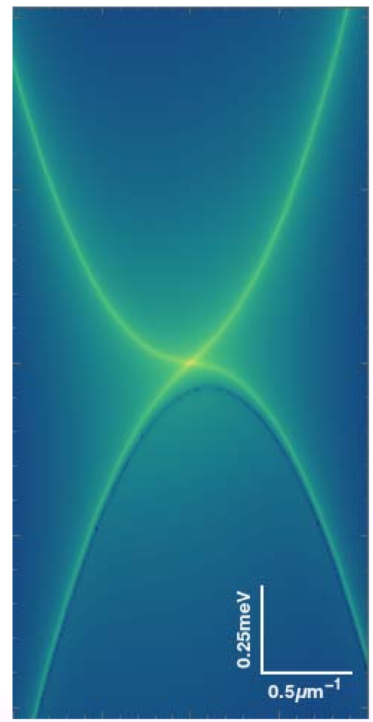
Theoretical Spectrum from

$$i\hbar\frac{\partial\psi(\mathbf{r},t)}{\partial t} = \left[-\frac{\hbar^2\nabla^2}{2m} + i\frac{\hbar}{2}\left(\frac{\gamma(\mathbf{r})}{1+\frac{|\psi(\mathbf{r},t)|^2}{n_s}} - \kappa\right) + g|\psi(\mathbf{r},t)|^2 + V(\mathbf{r})\right]\psi(\mathbf{r},t)$$

$k_c=0$



k_c finite

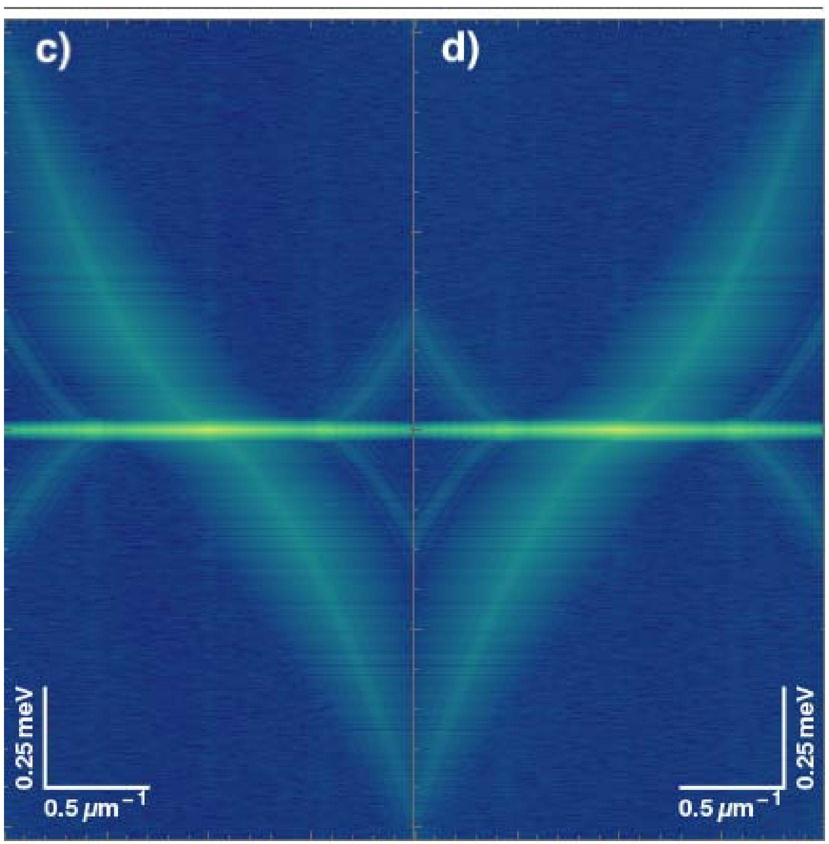


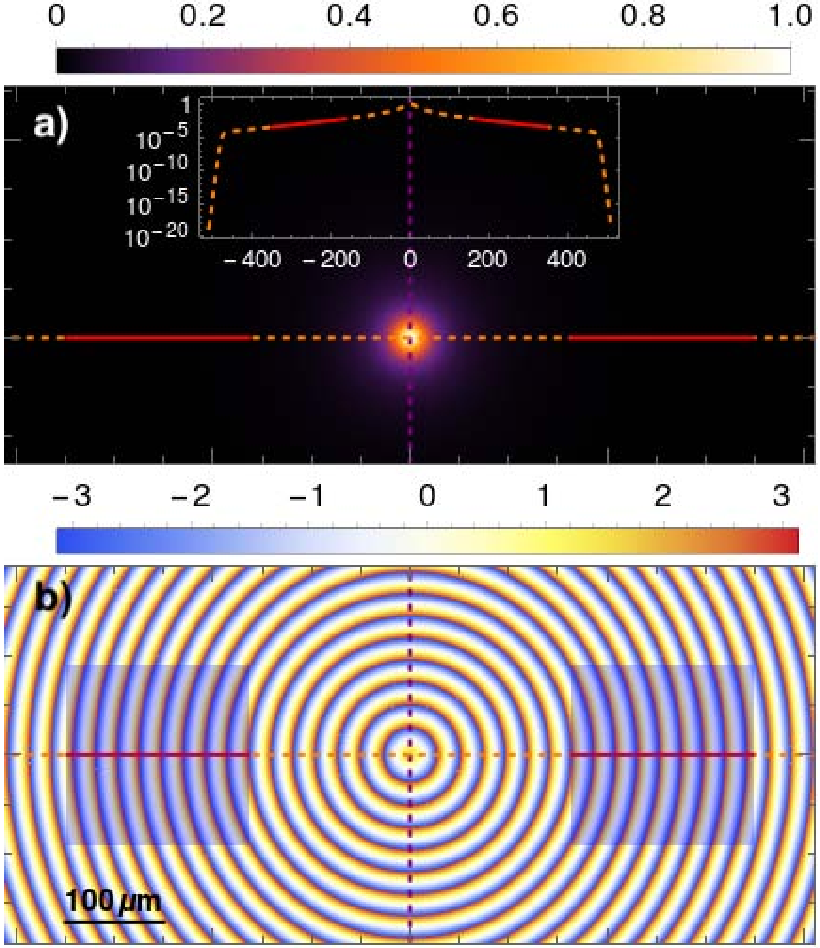
From Truncated Wigner and Keldysh Field theory

[Ballarini et all. 2019]

Luminescence Spectrum in Inhomogeneous System

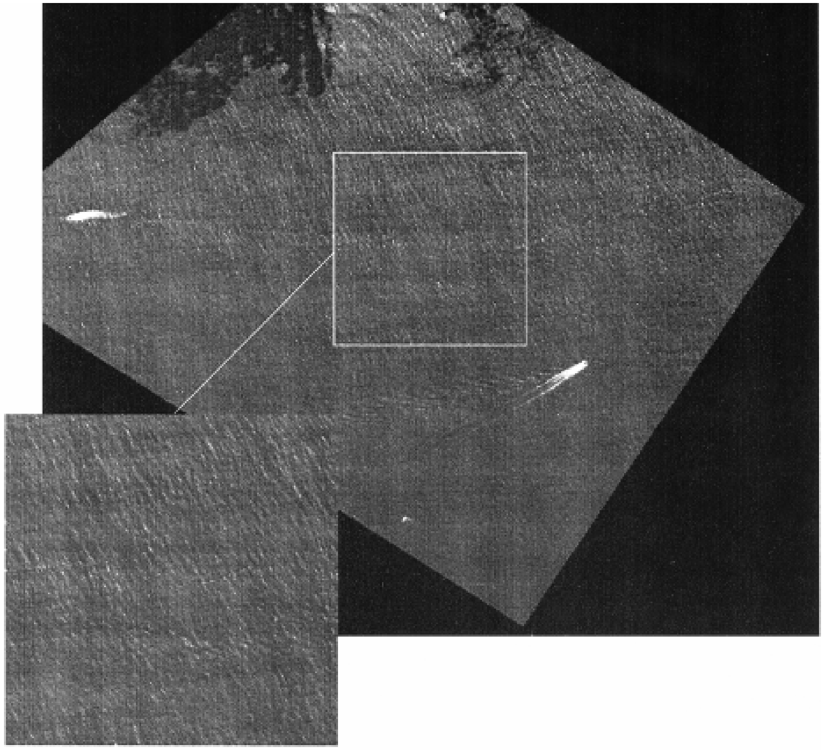
Theoretical Spectrum

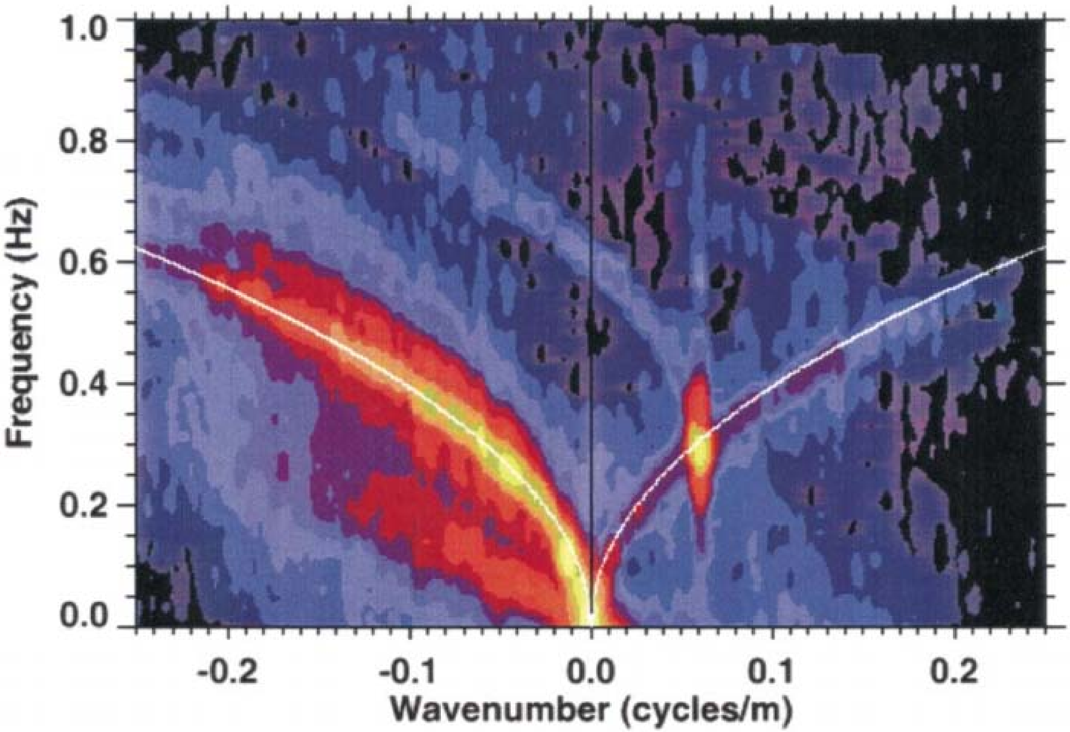




[Ballarini et all. 2019]

“Wind” Effect of the Asymmetric Reservoir





Airborne optical measurements of surface gravity wave dispersion

[J. P. Dugan, et al., Journal of Geophysical Research (2001)]

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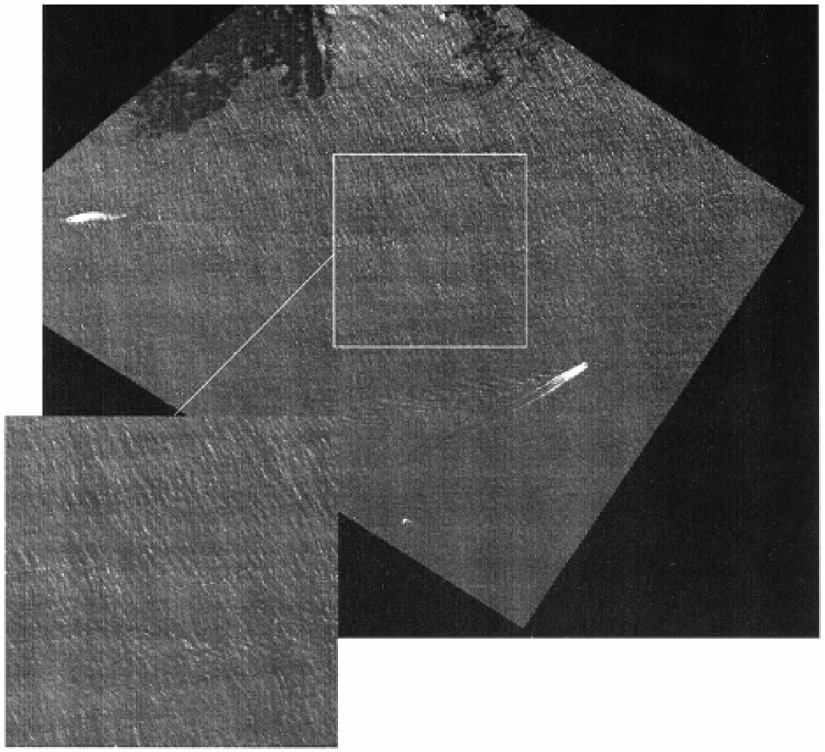

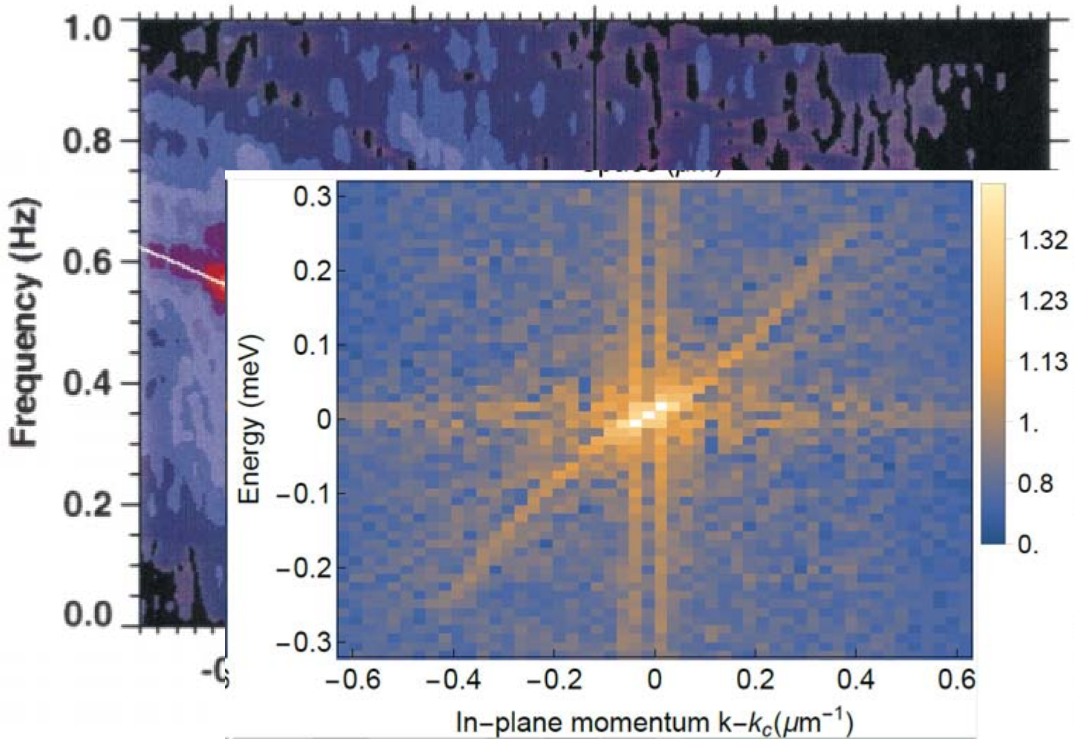

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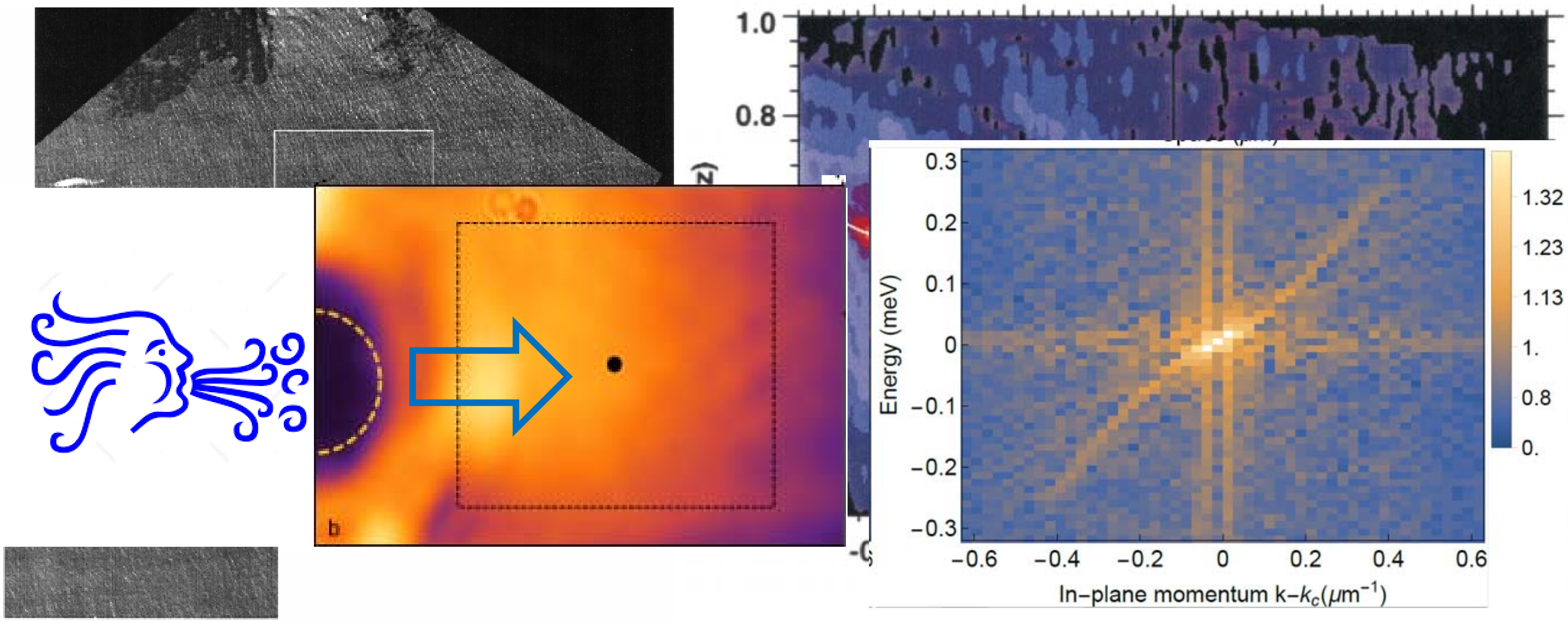


Airborne optical measurements of surface gravity wave dispersion

[J. P. Dugan, et al., Journal of Geophysical Research (2001)]

Kardar-Parisi-Zhang (KPZ) Theory

Treating phase fluctuations exactly

[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

Incoherently pumped microcavity:

L_1 unrealistically large away from BKT

KPZ order

killed by vortices → exponential decay of correlations

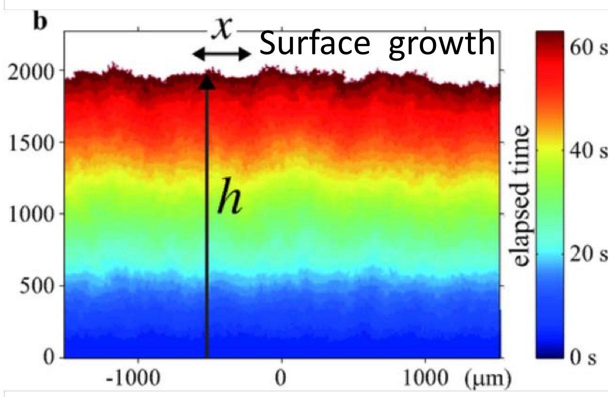
or shows up on too large lengthscales → power-law decay of correlations within system size

KPZ – why interesting?

Solving KPZ equation   Martin Hairer, Warwick

2014 Fields Medal

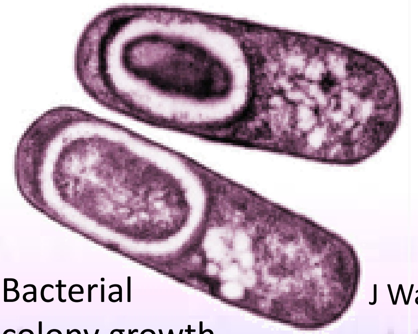
Universality class for a wide range of non-equilibrium phenomena in 1D



Takeuchi et al, 2011

Burning paper

J Maunuksela et al, PRL,1997

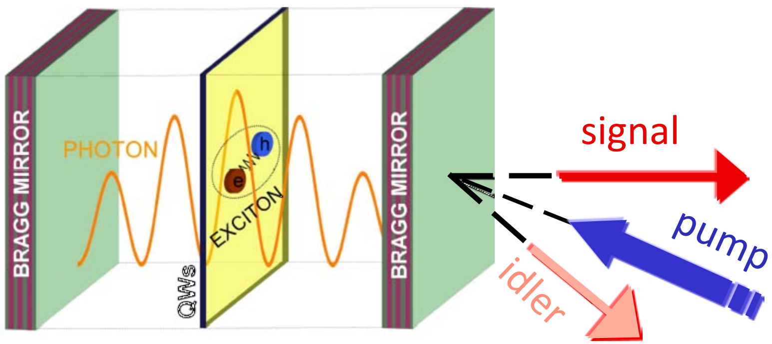


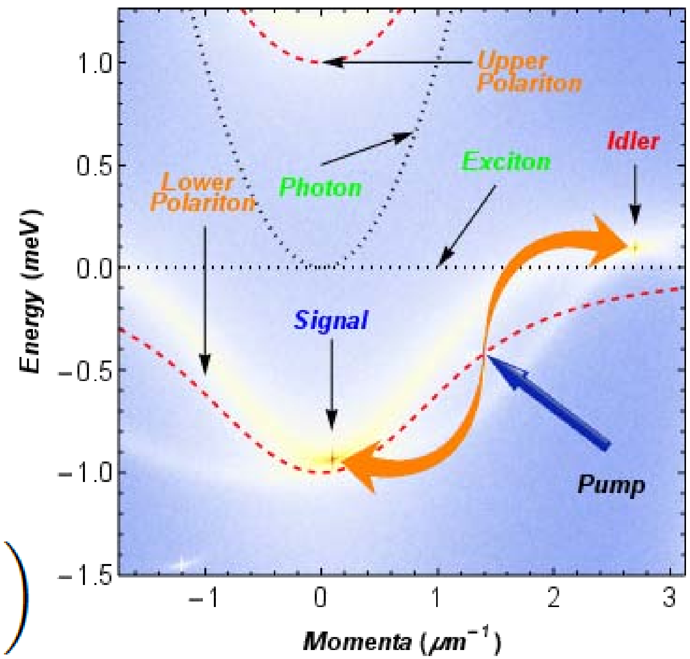
Bacterial colony growth

J Wakita et al, 1997

To date no experimental realisation of KPZ in 2D

Playing with Spatial Anisotropy: OPO





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

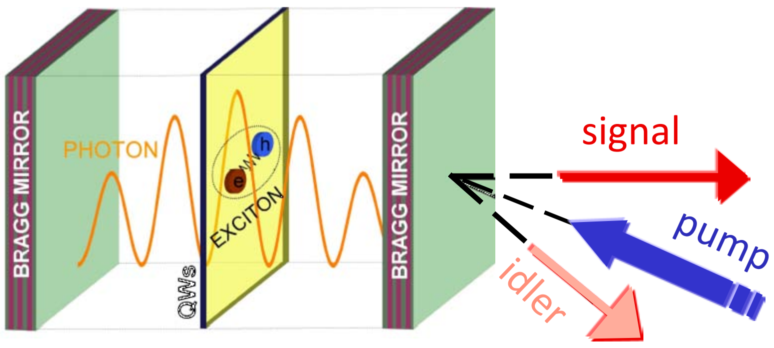
$$\hat{H}_{SB} = \int d\mathbf{r} \left[F(\mathbf{r},t)\hat{\psi}_C^\dagger(\mathbf{r},t) + \text{H.c.}\right]$$
$$+\sum_{\mathbf{k}} \sum_{l=X,C} \left\{\zeta_{\mathbf{k}}^l \left[\hat{\psi}_{l,\mathbf{k}}^\dagger(t)\hat{B}_{l,\mathbf{k}} + \text{H.c.}\right] + \omega_{l,\mathbf{k}}\hat{B}_{l,\mathbf{k}}^\dagger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

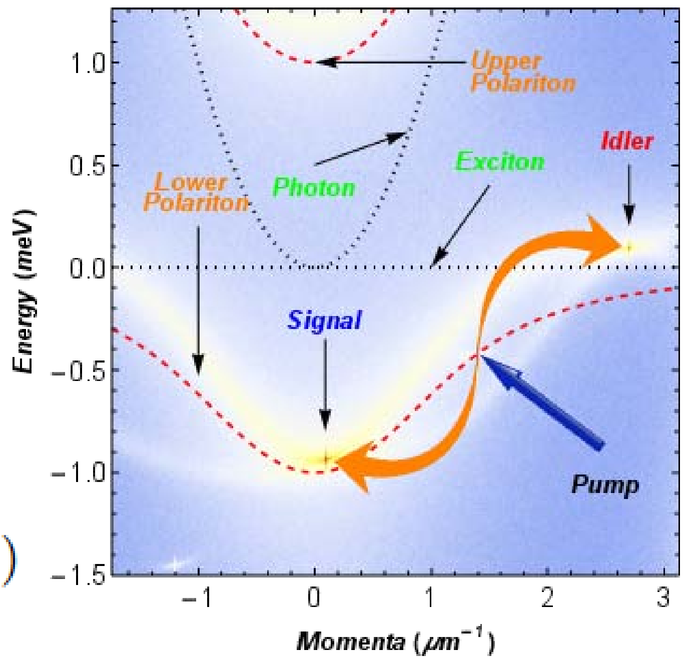
- ✧ Non-thermal occupation
- ✧ Signal phase is completely free and idler phase locked to signal via pump

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

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

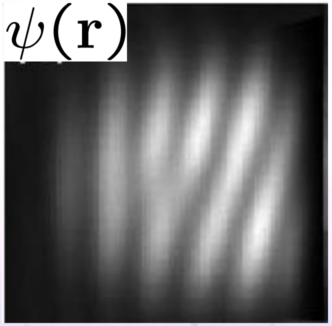
Playing with Spatial Anisotropy: OPO

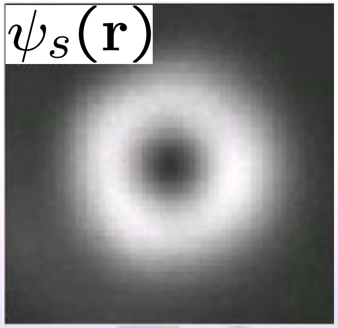




$$|\psi_{\rm LP}(\mathbf{r},t)|^2 = \sum_j \rho_j^2$$
$$+ 2\left(\sqrt{\rho_s\rho_p}\cos(\phi_s - \phi_p + (\mathbf{k}_{si}\cdot\mathbf{r} - \omega_{si}t)/2)\right.$$
$$+ \sqrt{\rho_p\rho_i}\cos(\phi_i - \phi_p - (\mathbf{k}_{si}\cdot\mathbf{r} - \omega_{si}t)/2)$$
$$\left.+\sqrt{\rho_s\rho_i}\cos(\phi_s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

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

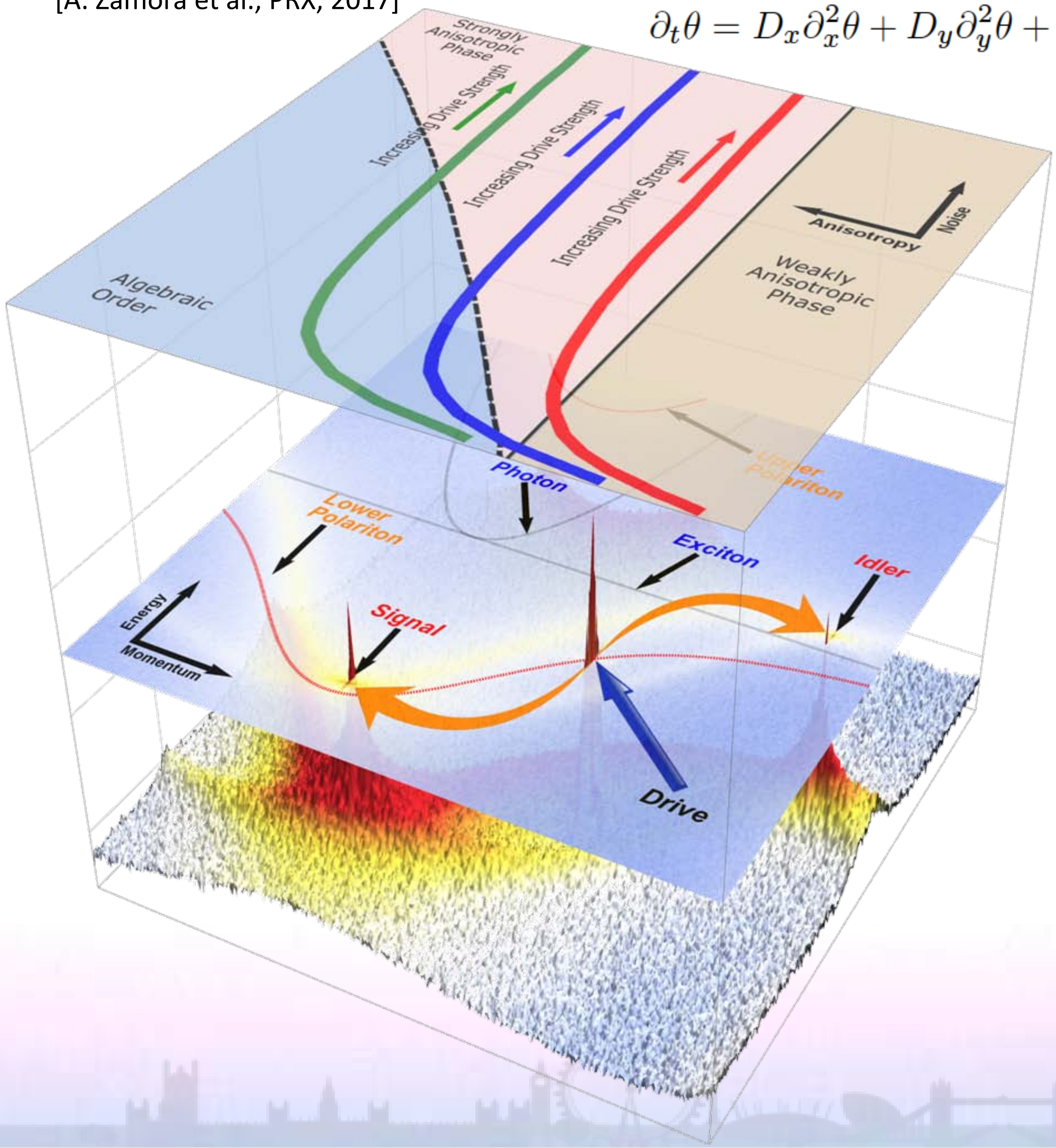




Tunning Across Universalities with OPO

[A. Zamora et al., PRX, 2017]

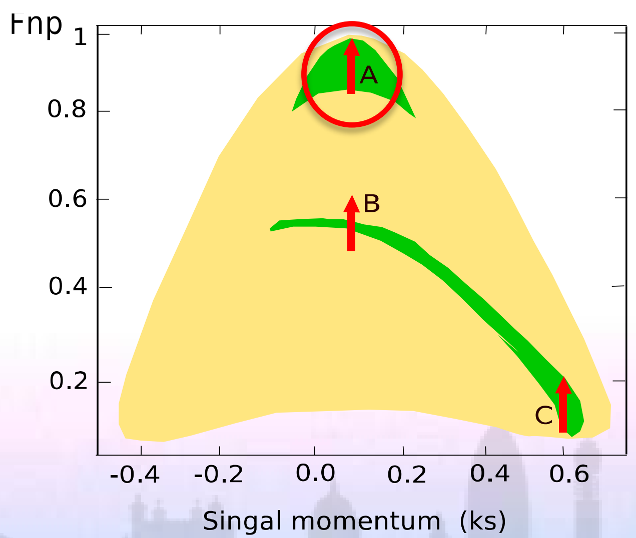
$$\partial_t \theta = D_x \partial_x^2 \theta + D_y \partial_y^2 \theta + \frac{\lambda_x}{2}(\partial_x \theta)^2 + \frac{\lambda_y}{2}(\partial_y \theta)^2 + \bar{\zeta}(\mathbf{x}, t)$$



Negative detuning

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

Two different universality classes as the drive is increased



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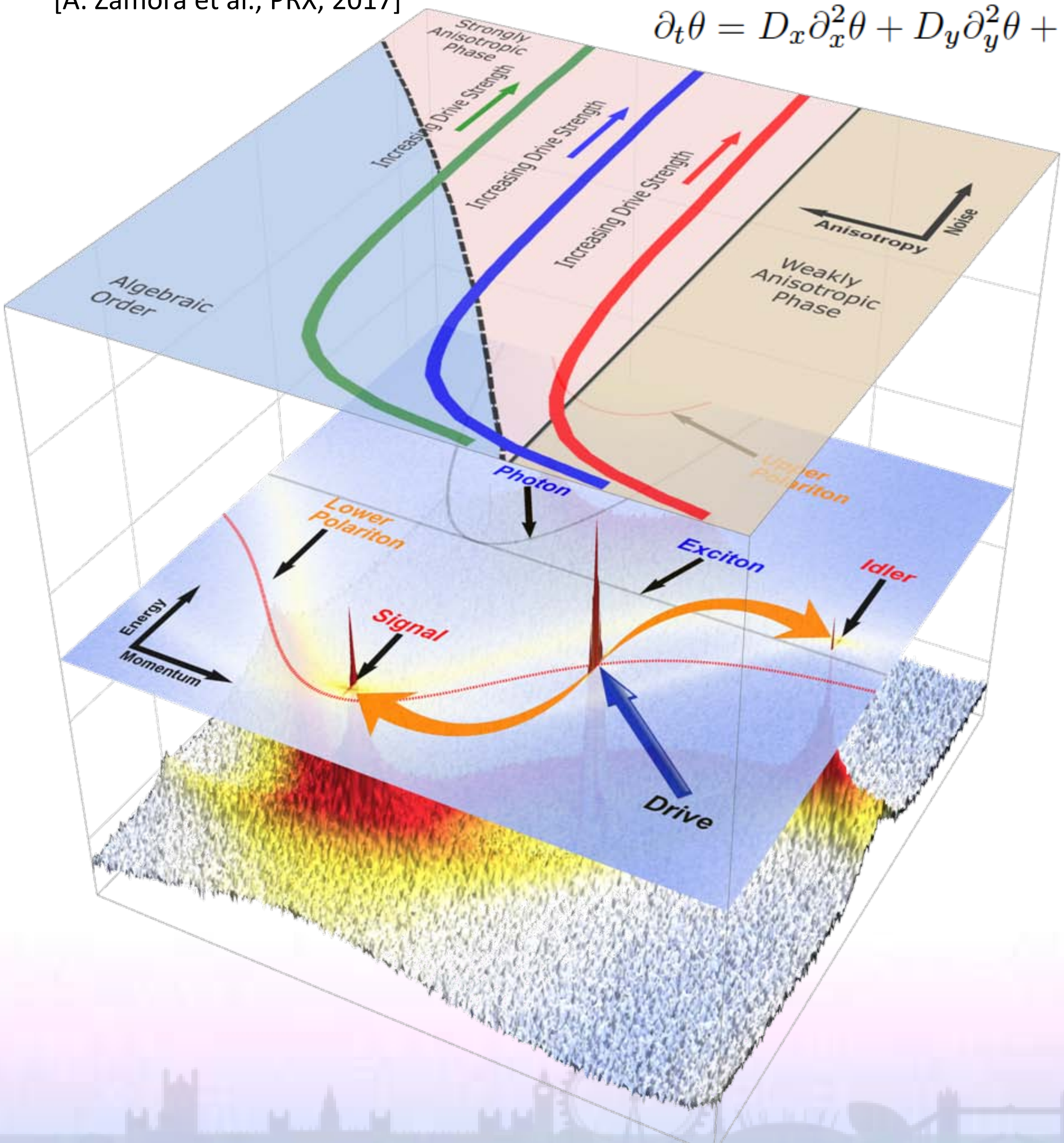

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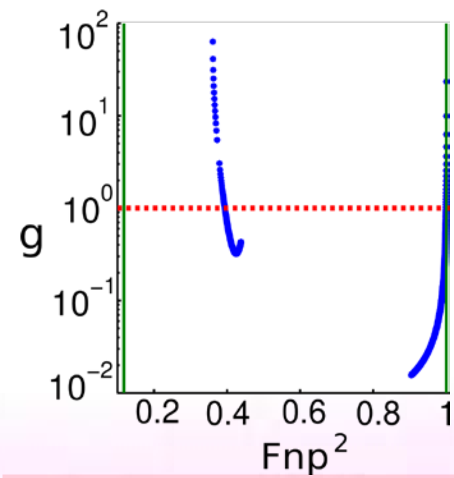


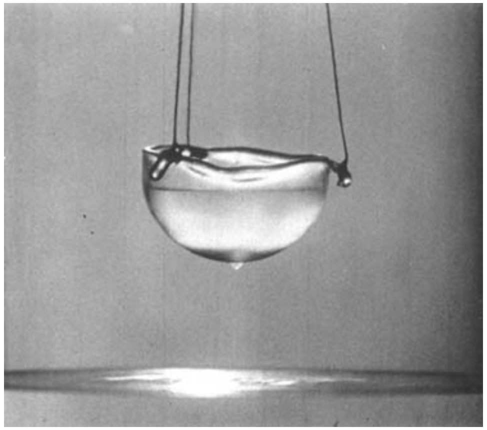
KPZ at all length-scales?

Flow Properties of Driven Quantum Fluids

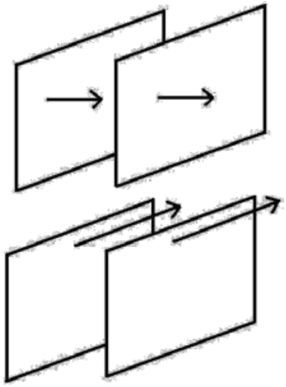
What is a superfluid?

Defined by flow properties:

- No viscosity
- No transverse response
- Quantised vortices
- Metastable persistent flow



Current-current response function: $\delta j_i(\boldsymbol{q}) = \chi_{ij}(\boldsymbol{q})\delta f_j(\boldsymbol{q})$



Long wavelength limit:

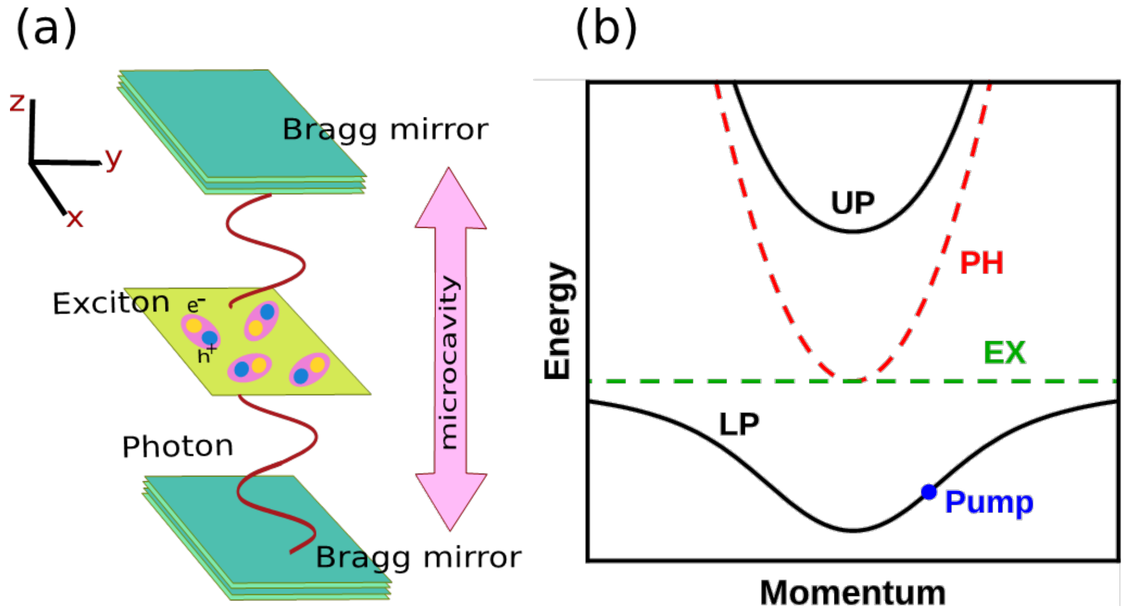
- Transverse direction first: longitudinal response
- Longitudinal direction first: transverse response

Superfluid component responds to longitudinal but not transverse perturbations

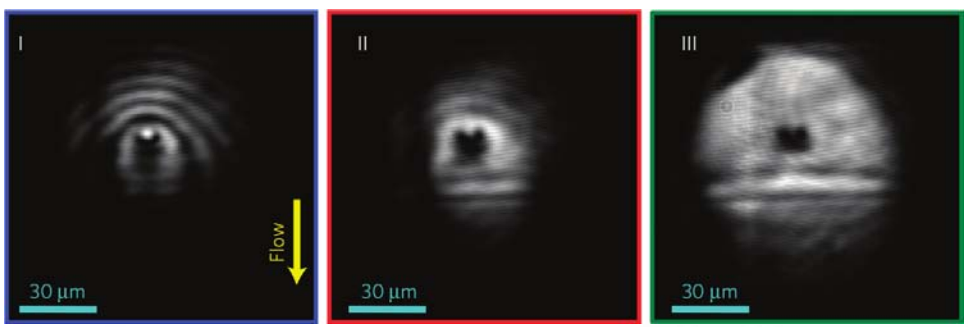
Superfluid density:

$$\rho_S = m \lim_{\boldsymbol{q}\to 0} \left(\chi_L(\boldsymbol{q}) - \chi_T(\boldsymbol{q})\right)$$

Coherently Driven Polaritons



Nearly dissipationless flow observed



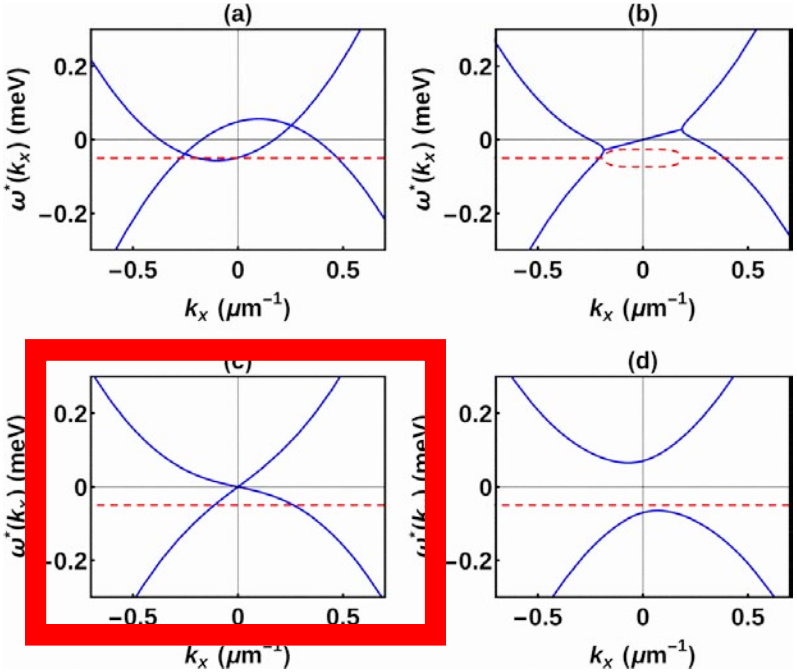
Amo et al. Nature Phys. 5 (2009)

Increasing Drive

Coherently Driven Polaritons

$$\hat{H} = \sum_{k} \epsilon_k \hat{a}^\dagger_k \hat{a}_k + \frac{F_p}{\sqrt{2}}(\hat{a}^\dagger_0 + \hat{a}_0) + \frac{V}{2}\sum_{k,k',q} \hat{a}^\dagger_{k-q}\hat{a}^\dagger_{k'+q}\hat{a}_k\hat{a}_{k'} + \sum_p \omega^A_p \hat{A}^\dagger_p \hat{A}_p + \sum_{k,p} \zeta_{k,p}(\hat{a}^\dagger_k \hat{A}_p + \hat{A}^\dagger_p \hat{a}_k)$$

$$\omega^{*,\pm}_k = \frac{\alpha^+_k - \alpha^-_k}{2} - i\kappa \pm \frac{1}{2}\sqrt{(\alpha^+_k + \alpha^-_k)^2 - 4V^2|\psi_0|^4}$$



- Phase fixed by the pump so

  spectrum always gapped

- Blue detuning $\Delta = V|\psi_0|^2 \rightarrow$ Landau criterion fulfilled in real part (c)

Coherently Driven Polaritons

[R. Juggins et al., Nature Comm. 2018]

Superfluid density from Keldysh: $\rho_S = m \lim_{\boldsymbol{q}\to\boldsymbol{0}} (\chi_L(\boldsymbol{q}) - \chi_T(\boldsymbol{q}))$ = 0

Coherently pumped polaritons are not superfluid

but …

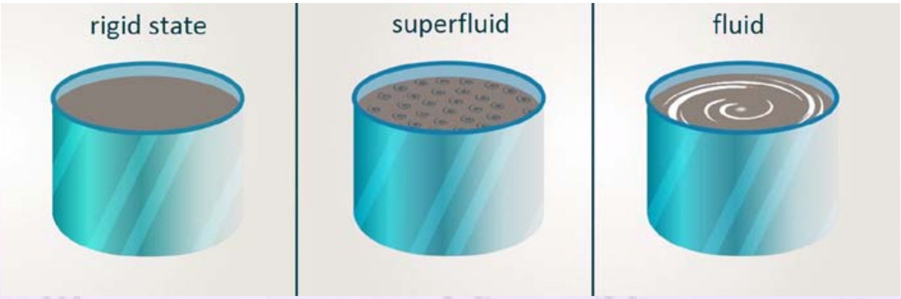
New quantum state

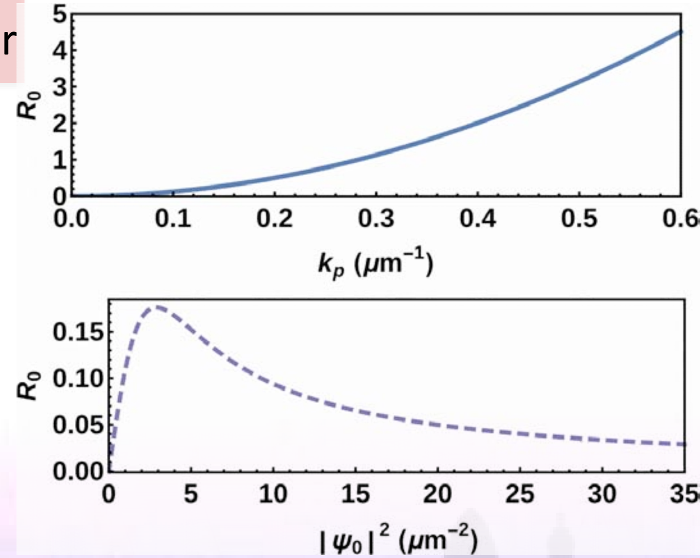
- Most of the system does not respond to neither longitudinal nor transverse forces

no superfluid but no normal fluid either

- Rigid state fixed by the external pump $\boldsymbol{k}_p$
- Some normal response dependent on pump vector

Rigid state fits well with inability to form vortices and solitons



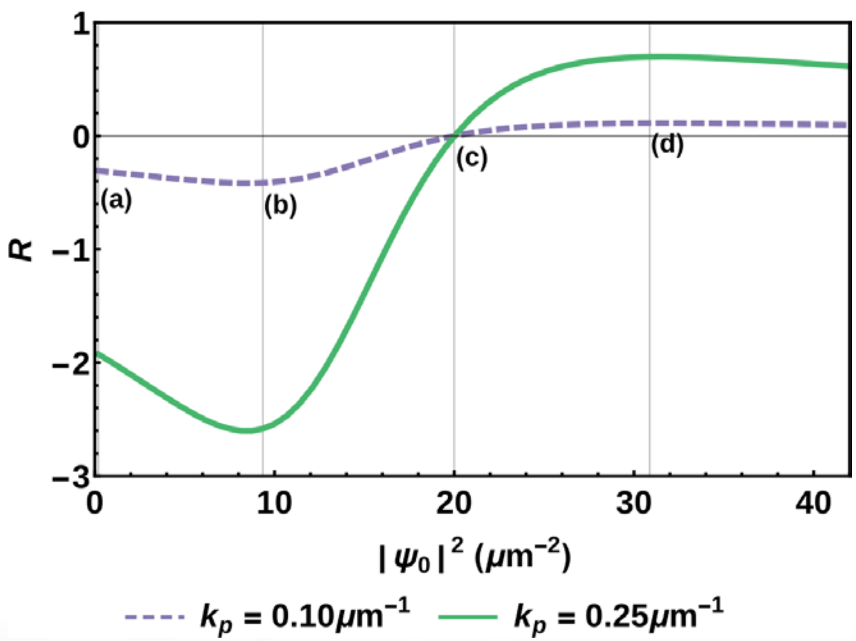


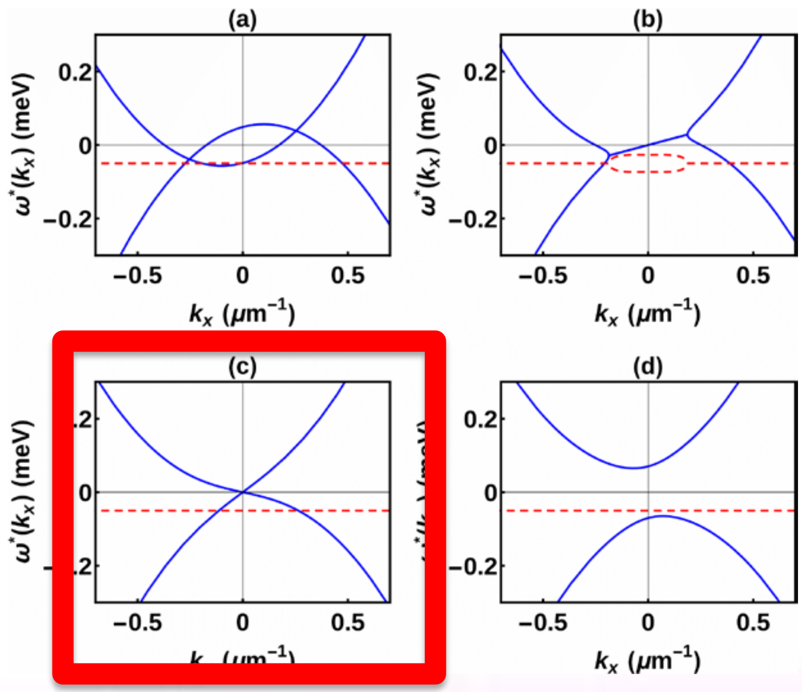
Reconciling with the Experiment

Detuning and the response function

[R. Juggins et al., Nature Comm. 2018]

- Vary pump strength for a given detuning
- Normal response goes to zero when the real spectrum fulfils the Landau criterion





Experiment records the non-fluid rather then superfluid state

Reconciling with the Experiment

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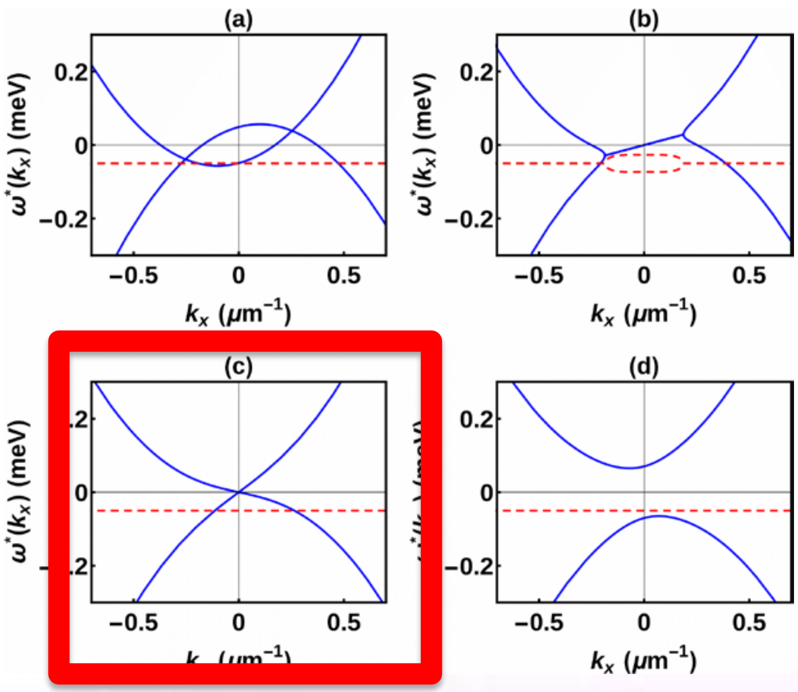
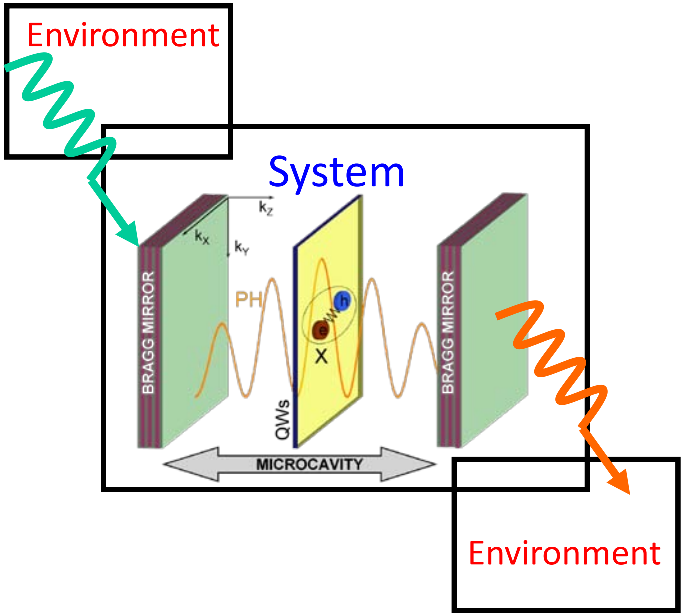


Experiment records the non-fluid rather then superfluid state

Driven-dissipative Condensates



2D Light-matter condensates with drive and decay

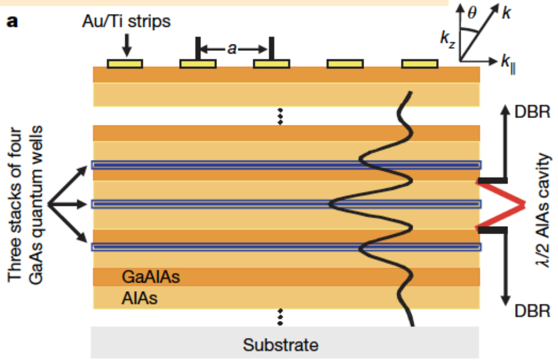
Can thermal equilibrium be achieved?

YES

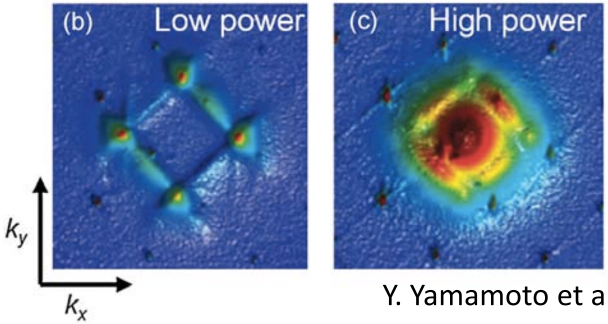
Can non-equilibrium but non-trivial phases be engineered?

Perspectives: Building Solids

Gold deposition



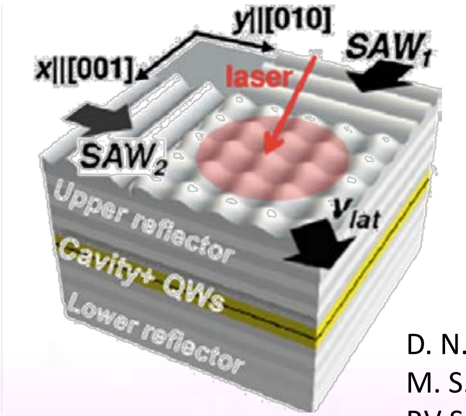
Energy of photons spatially modulated



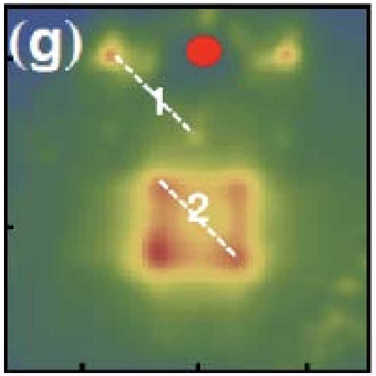
Y. Yamamoto et al.

Polaritons in a weak periodic potential

Surface acoustic waves



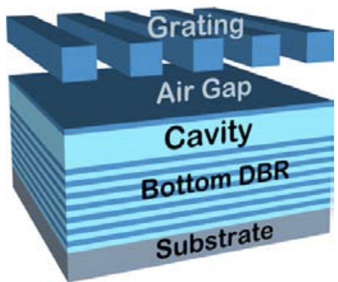
D. N. Krizhanovskii,
M. S. Skolnick,
P.V Santos et al.



Polaritons in a weak periodic moving potential

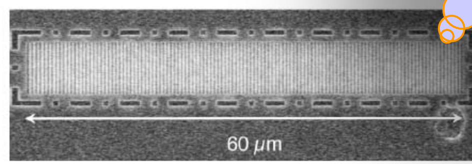
Building Solids

Sub-wavelength gratings

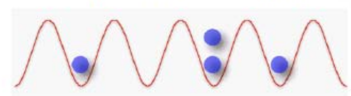


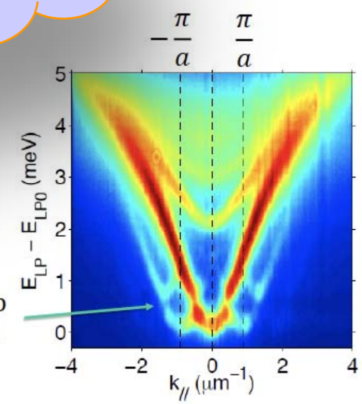
H. Deng et al.

Towards Bose-Hubbard model

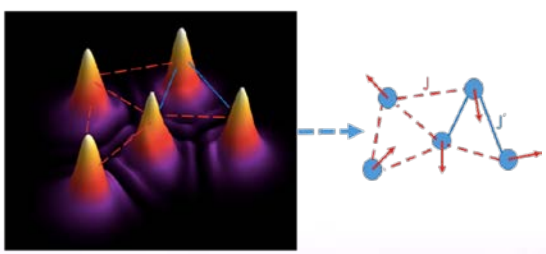


Polaritons modulated by periodic potentials
(period a = 7 μm)



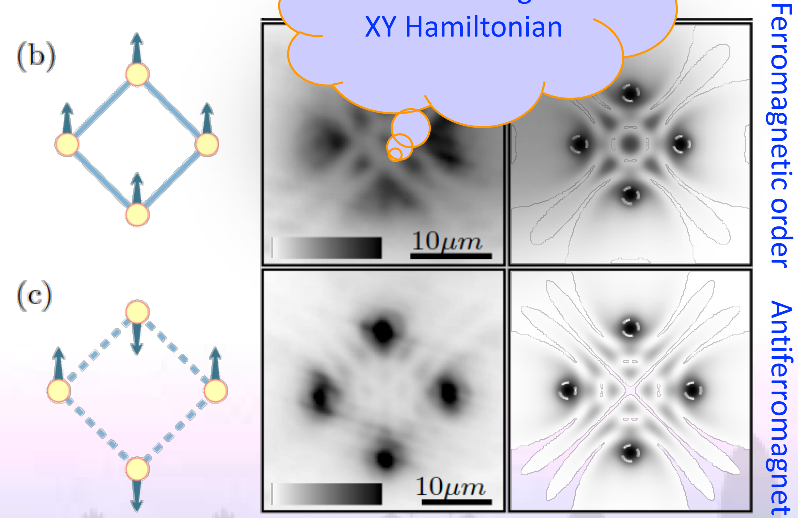


Pump modulation



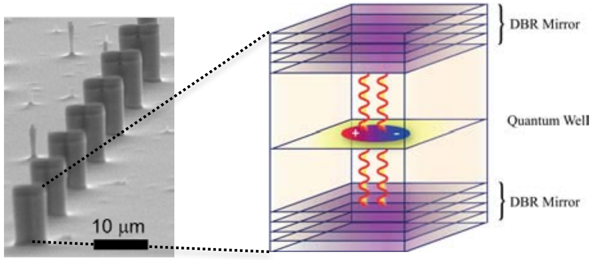
P. G. Lagoudakis
N. Berloff

Simulating XY Hamiltonian

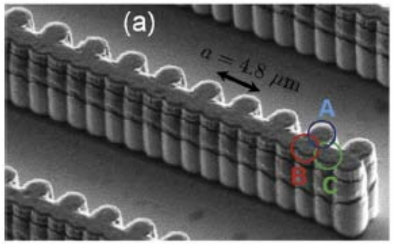


Building Solids

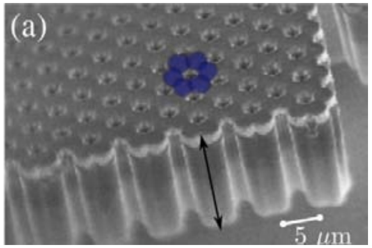
Micropillars



1D lattices

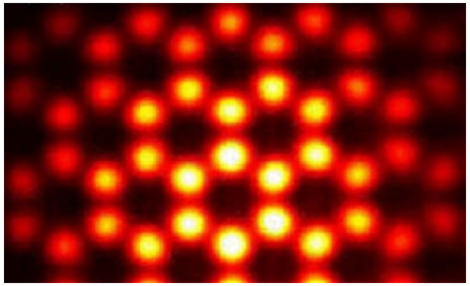


2D lattices



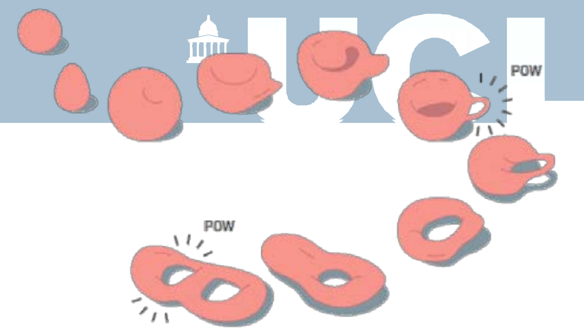
A. Amo, J. Bloch et al.

Honeycomb lattices (like in Graphene)

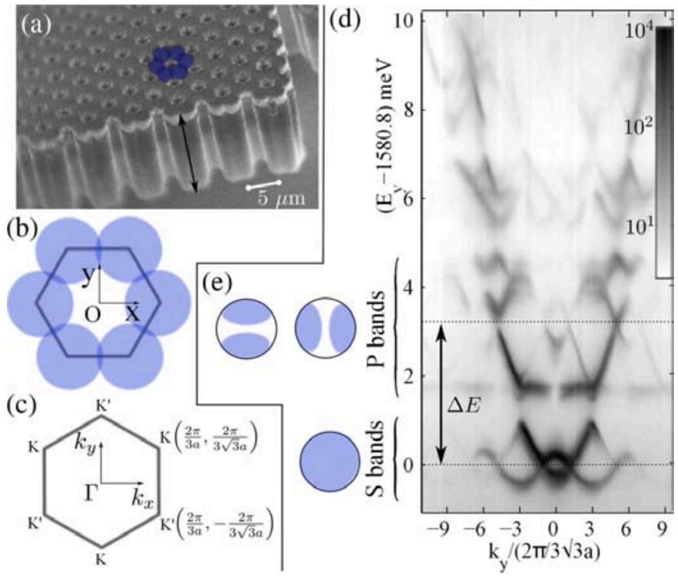


A. Amo, J. Bloch et al.

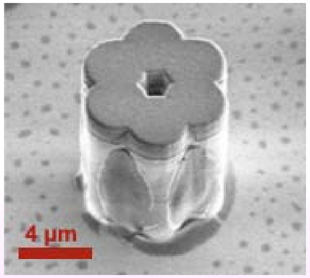
Topological Photons?



Building "photonic graphene" – Dirac cones

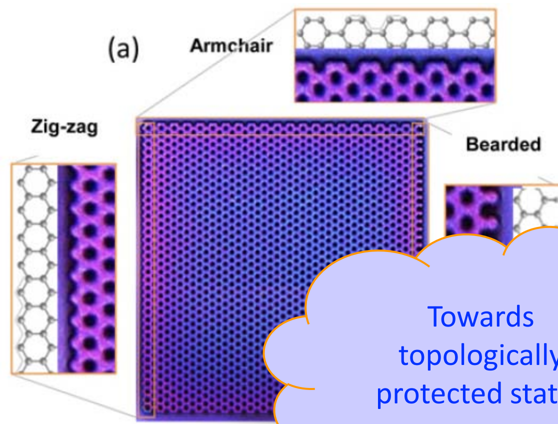


Spin-orbit coupling for photons

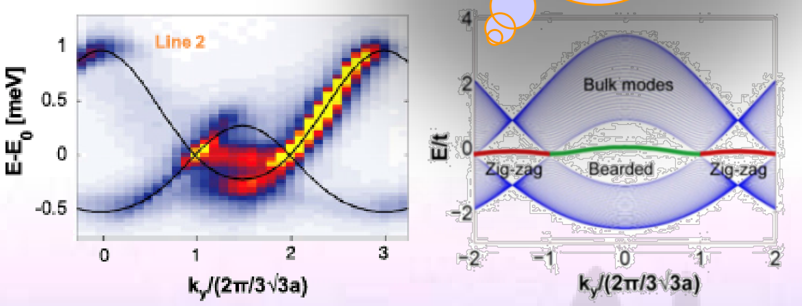


polarization-dependent confinement and tunneling of photons between adjacent micropillars

Edge states



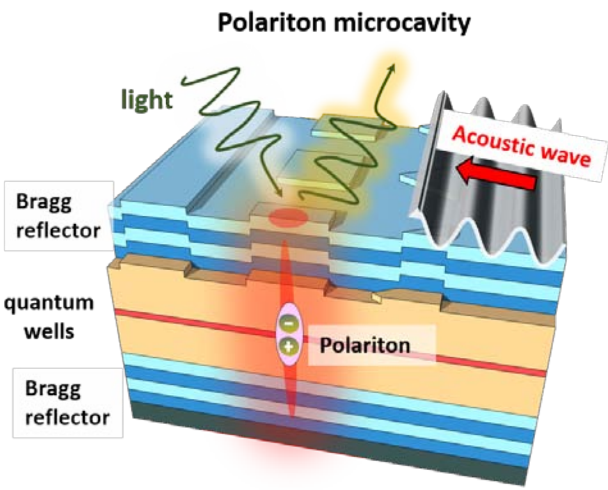
Towards topologically protected states

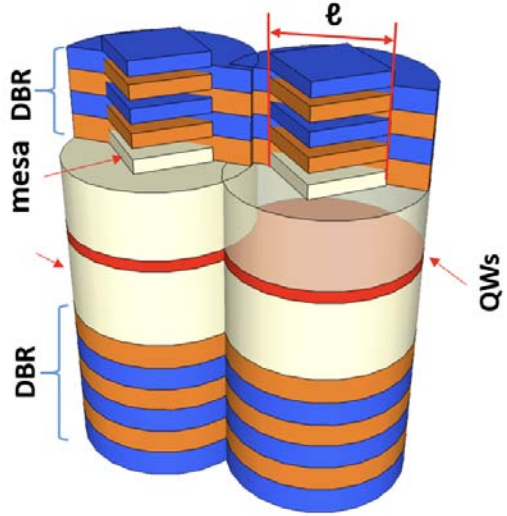


A. Amo, J. Bloch et al.

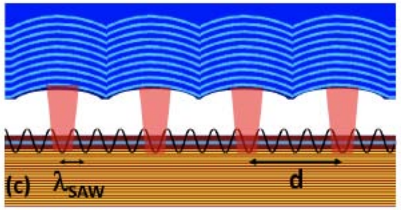
New directions – Strong Interactions

Optimising confinement



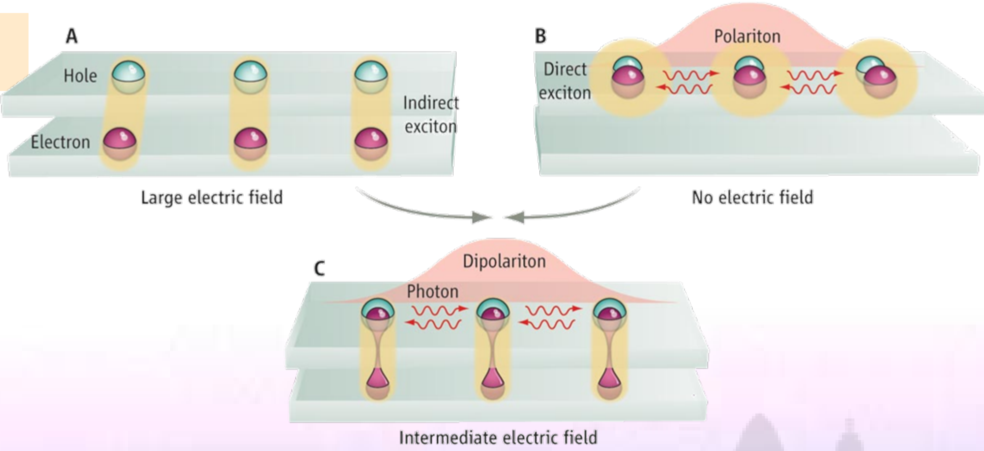


Quantera Interpol consortium
https://interpol-quantera.org



Increasing exciton-exciton interactions

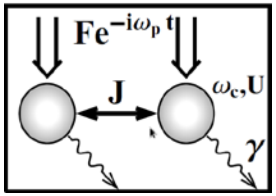
- Dipolar polartions but in lattice potentials
- Exciton Feschbach resonance



Bose-Hubbard Dimer with Non-Local Dissipation

$$\hat{H} = \sum_{i=1,2} (-\Delta \hat{a}_i^\dagger \hat{a}_i + U \hat{a}_i^\dagger \hat{a}_i^\dagger \hat{a}_i \hat{a}_i + F(\hat{a}_i^\dagger + \hat{a}_i)) - J(\hat{a}_1^\dagger \hat{a}_2 + \hat{a}_1 \hat{a}_2^\dagger)$$

$$\partial_t \hat{\rho} = -i[\hat{H}, \hat{\rho}] + D(\rho)$$



✧ Local:

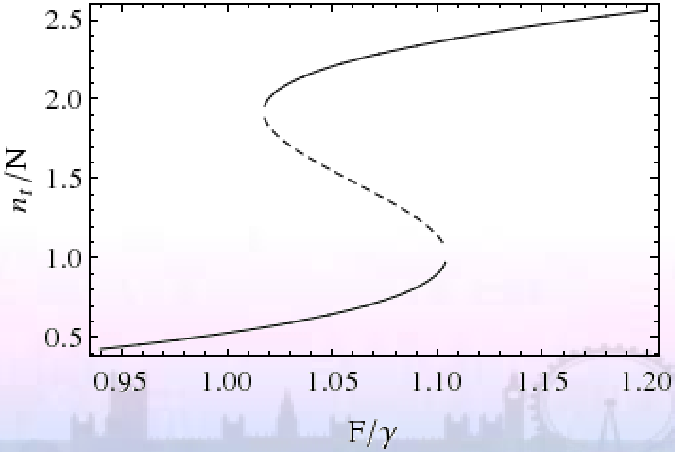
$$\frac{\gamma}{2} \sum_{i=1,2} 2\hat{a}_i \hat{\rho} \hat{a}_i^\dagger - \{\hat{a}_i^\dagger \hat{a}_i, \hat{\rho}\}$$

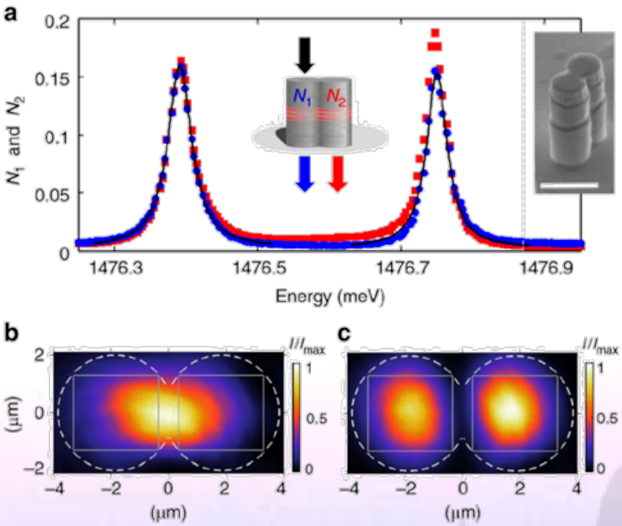
✧ Non-local:

$$\frac{\gamma}{2} \left(2(\hat{a}_1 + \hat{a}_2) \rho (\hat{a}_1^\dagger + \hat{a}_2^\dagger) - \{(\hat{a}_1^\dagger + \hat{a}_2^\dagger)(\hat{a}_1 + \hat{a}_2), \hat{\rho}\} \right)$$

✧ Semi-classical regime:

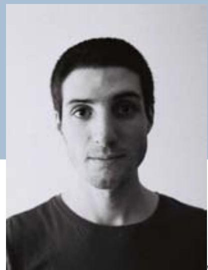
Bistability

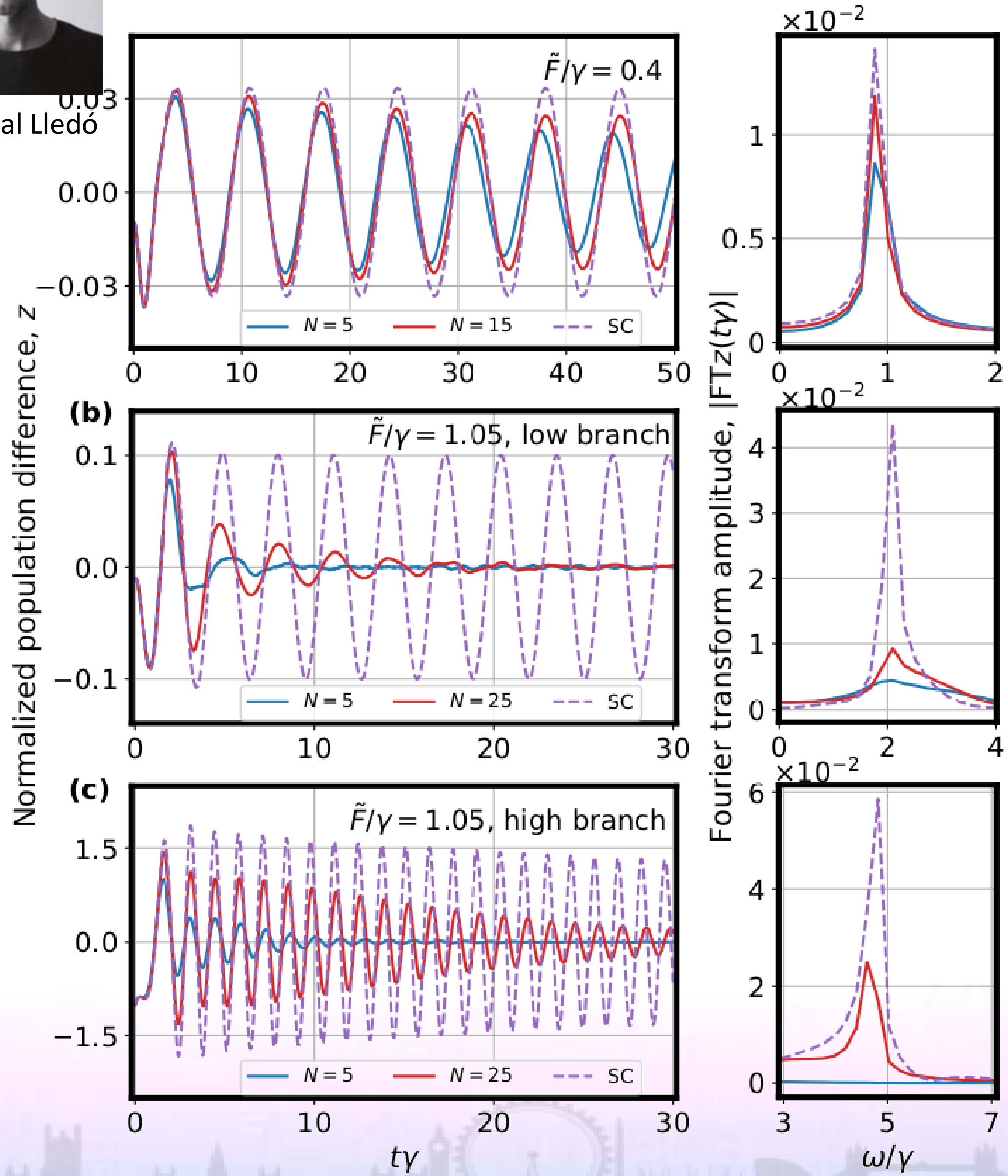




[Rodriguez *et al*. Nat. Comm. (2016)]

Bistable Time-Crystal


Cristóbal Lledó



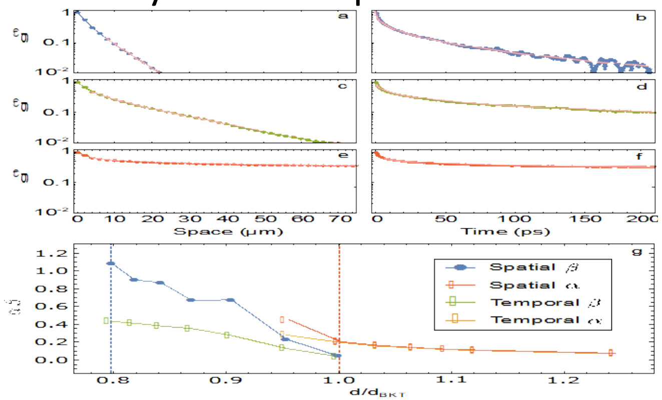
✧ Non-local dissipation leads to oscillatory solutions – bistable in bistability window

✧ Frequency of oscillations robust even for finite system and in the presence of perturbations

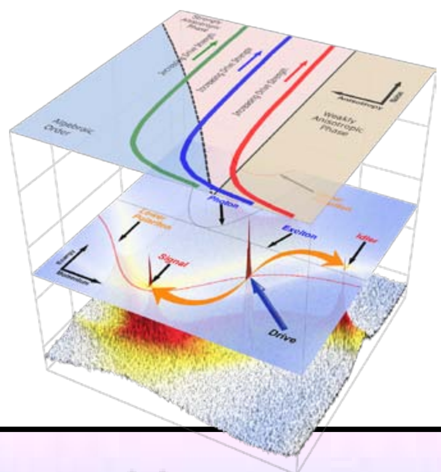
[Lledo et al. arXiv:1901.04438 (2019)]

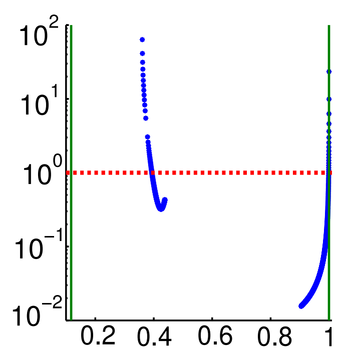
Conclusions

- Best microcavities indistinguishable from closed systems in equilibrium

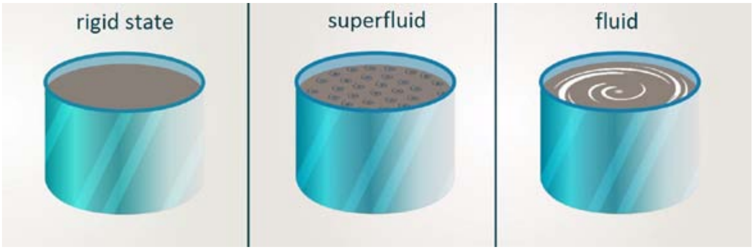


- Anisotropy and dissipation – as in OPO – different phases, KPZ order at all lengthscales?

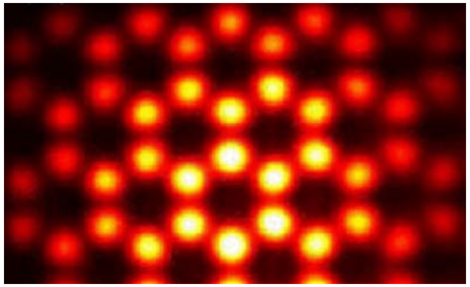




- Coherent drive – new quantum state with novel flow properties



- Lattice systems: correlated and topological states



Acknowledgements

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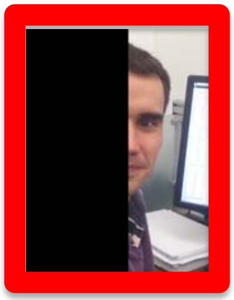

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QUANTERA