Condensation, coherence & superfluidity in non-equilibrium light-matter systems

Marzena Szymańska

CMP in the City, June 2013

WARWICK

Acknowledgements

People:

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EPSRC

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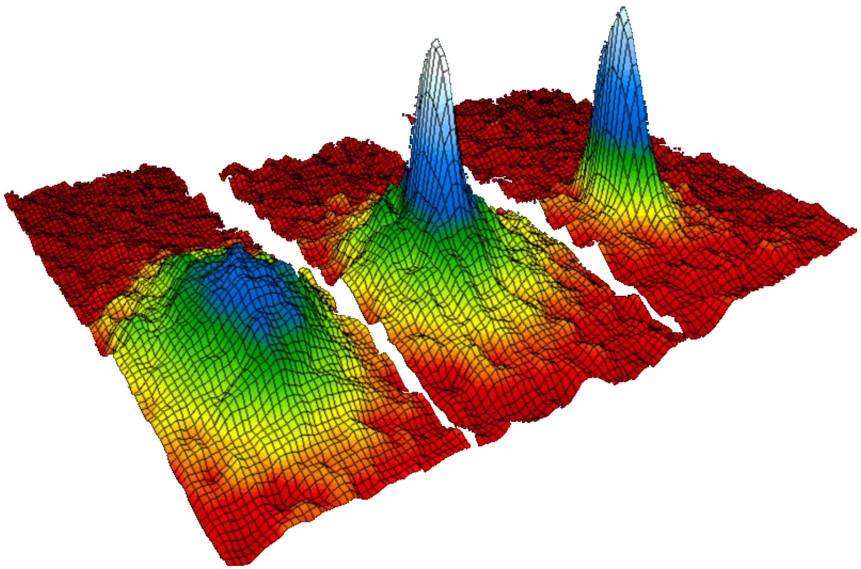
Research Council

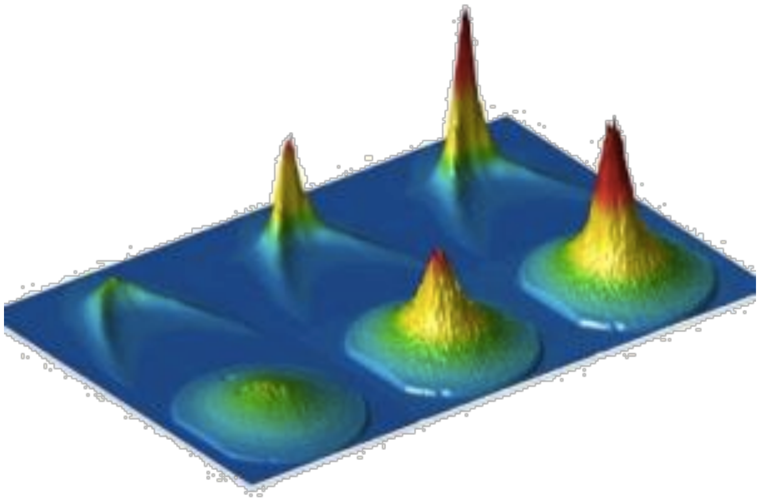
Bose-Einstein Condensation

Atoms 10^{-7}K



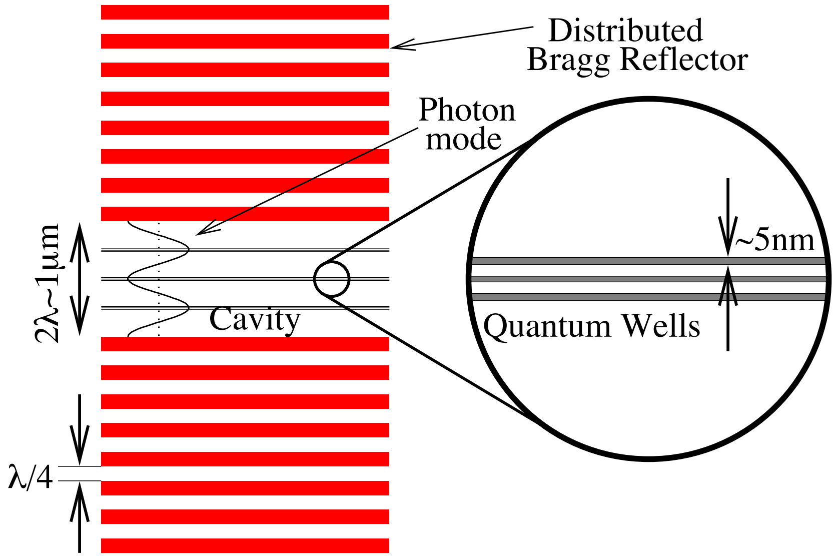
[Anderson et al., *Science* 1995]

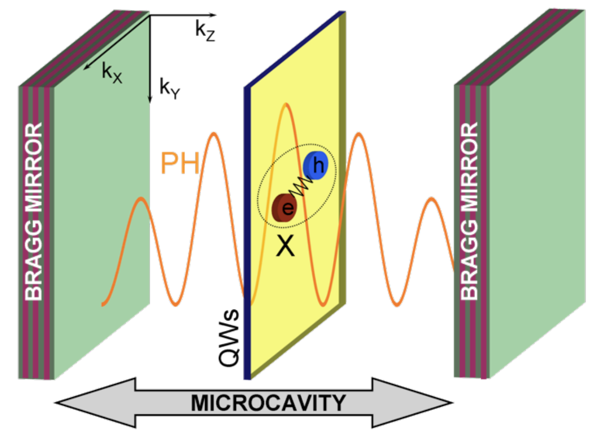
Polaritons 20K

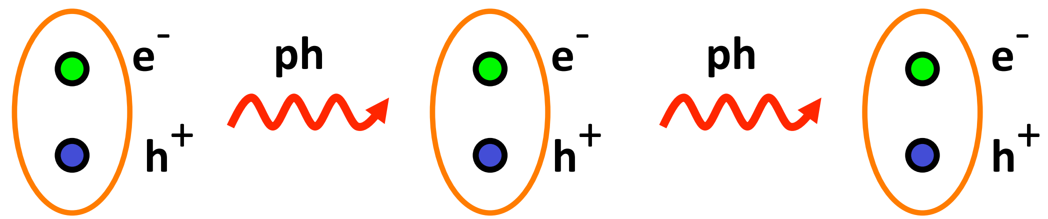


[Kasprzak et al., *Nature* 2006]

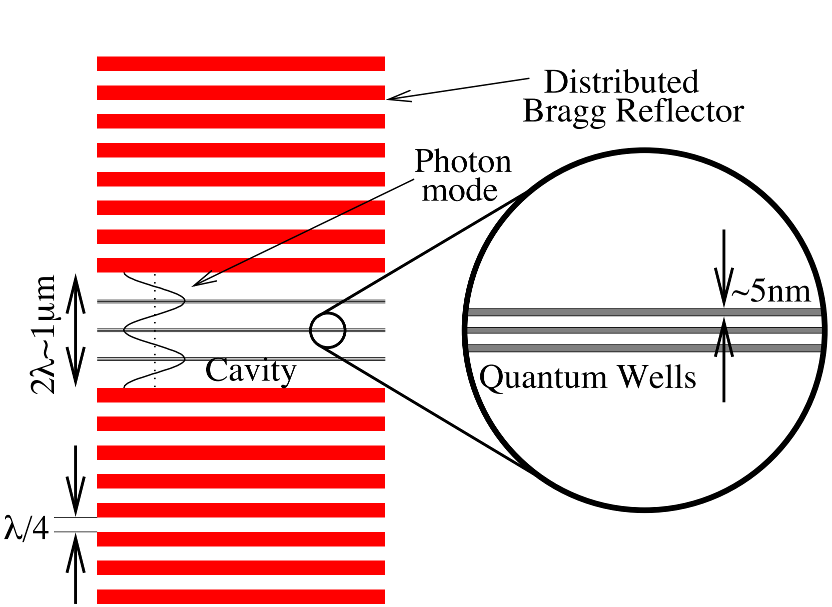
Microcavities and Polaritons

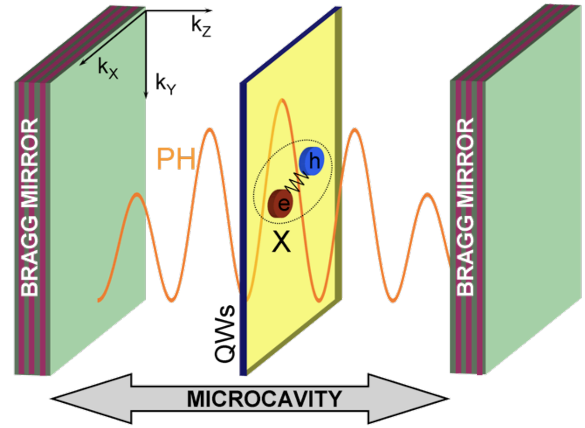


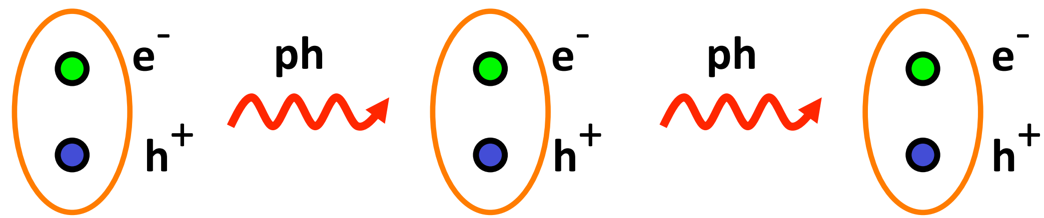


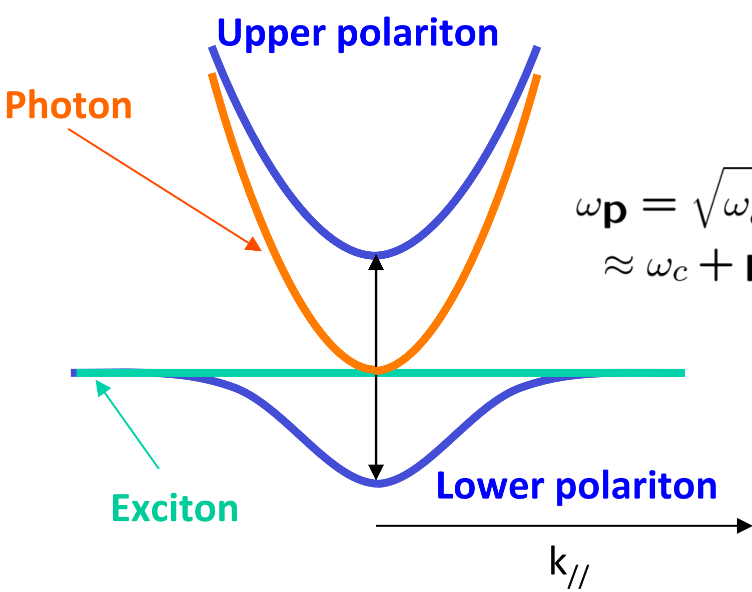


Microcavities and Polaritons









$$\omega_{\mathbf{p}} = \sqrt{\omega_c^2 + c^2 \mathbf{p}^2} \approx \omega_c + \mathbf{p}^2 / 2m_{\text{ph}}$$

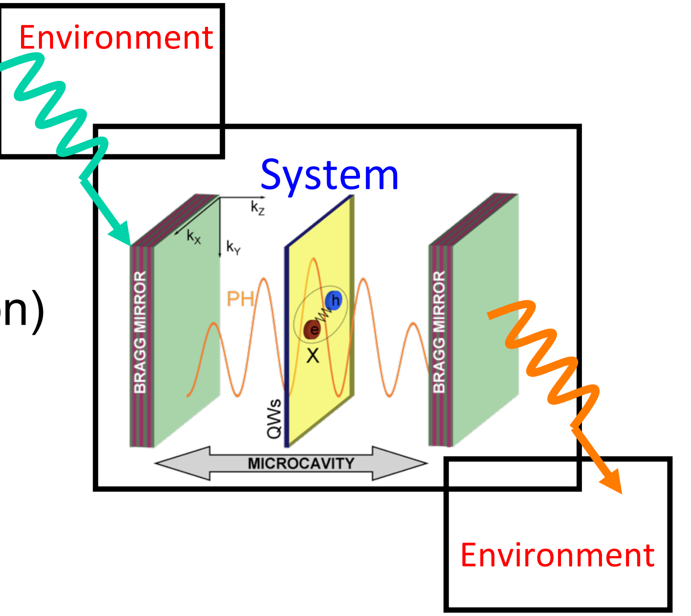
Polariton mass = 10^{-9} mass of Rubidium atom

Polaritons vs Cold Atoms

	atoms	polaritons
mass	$10^4 m_e$	$10^{-4} m_e$
T	10^{-7}K	10K
density	10^{14}cm^{-3}	10^{9}cm^{-2}
average spacing	10^{-5}cm	10^{-5}cm
thermalisation	1ms	0.5ps
lifetime	1s	10ps

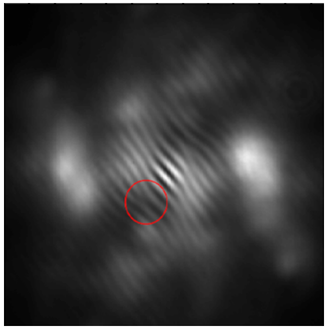
- ✧ 2D
- ✧ internal structure (X+C)
- ✧ stronger interaction(Coulomb & saturation)
- ✧ photonic and excitonic disorder

✧ Non-equilibrium

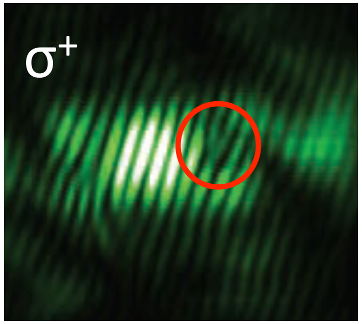


State of the art: experiments

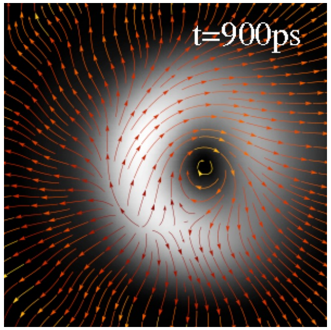
✧ Vortices, half vortices and persistent currents



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

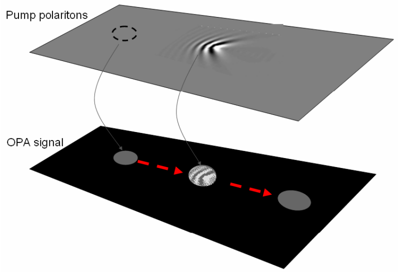


[K. G. Lagoudakis et al, *Science* 2009]

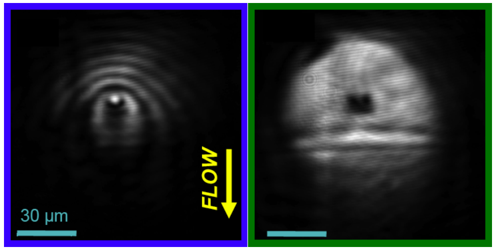


[Sanvitto et al., *Nature Phys.* 2010]

✧ Frictionless Propagation and Flow via obstacle

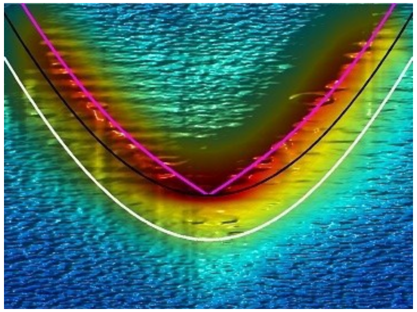


[Amo et al, *Nature* 2009]



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

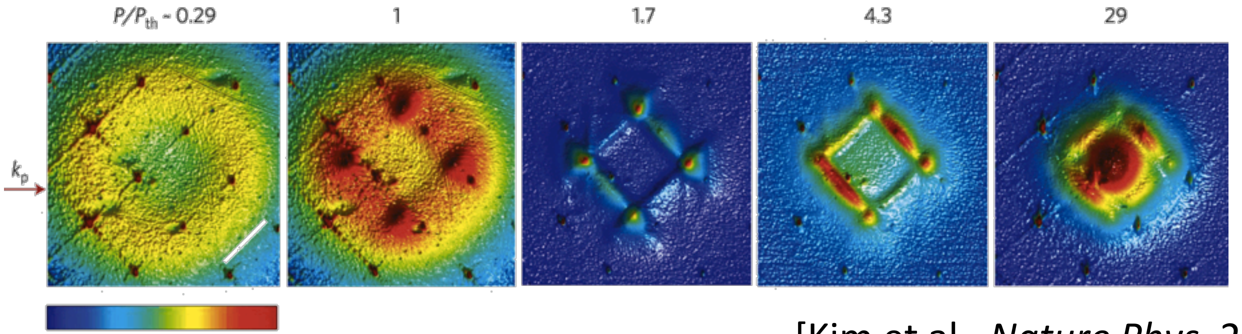
✧ Bogoliubov Excitation Spectrum



[S. Utsunomiya et al, *Nature Physics* 2008]

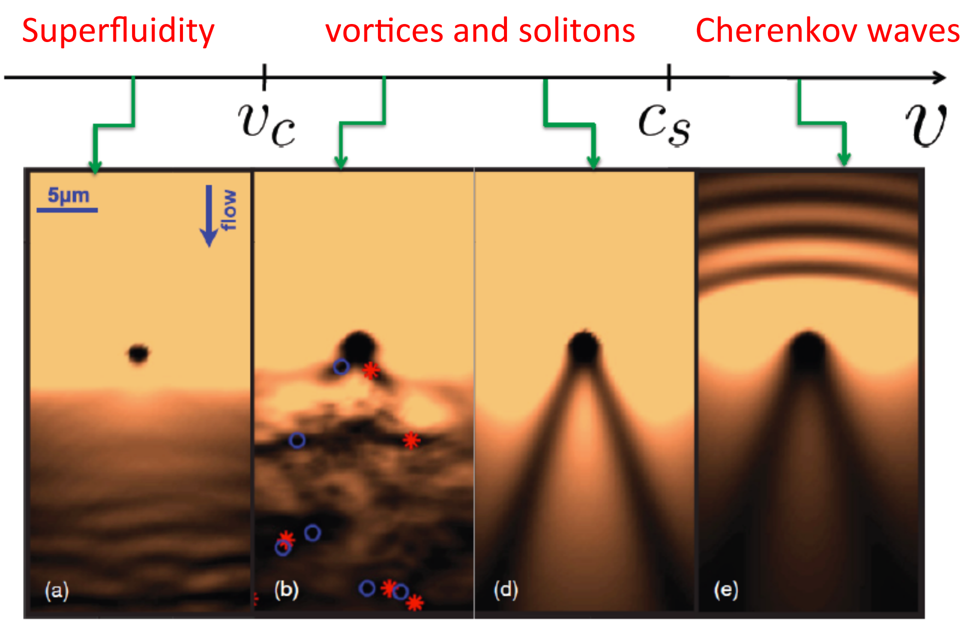
State of the art: experiments

✧ Lattices



[Kim et al., *Nature Phys*. 2011]

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



[Pigeon et al., PRB (2011)]

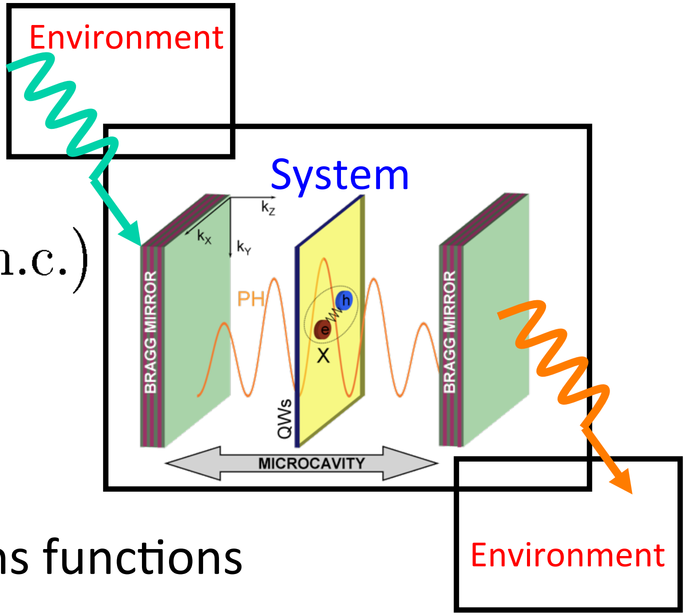
[Nardin et al., *Nature Phys*. 2011]
[Sanvitto et al., *Nature Photonics* 2011]
[Grosso et al., *PRL* 2011]
[Amo et al., *Science* 2011, *Nature* 2009]
[Wertz et al., *Nature Phys*. 2010]

Non-equilibrium Condensation

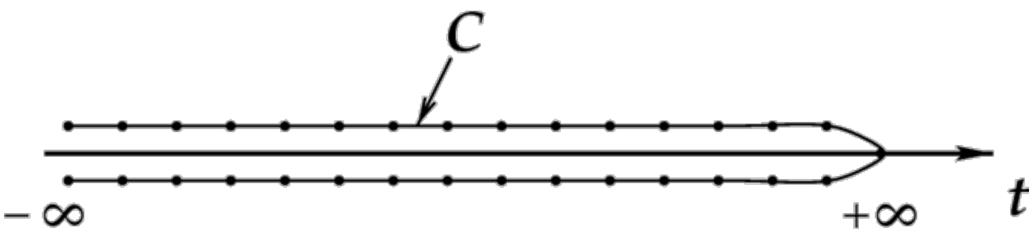
Hamiltonian

$$H = H_{\text{sys}} + H_{\text{sys,bath}} + H_{\text{bath}}$$

$$H_{\text{sys}} = \sum_{\mathbf{p}} \omega_{\mathbf{p}} \psi^\dagger_{\mathbf{p}} \psi_{\mathbf{p}} + \sum_{\alpha,\mathbf{p}} \left(g_{\alpha,\mathbf{p}} \psi_{\mathbf{p}} \phi^\dagger_\alpha + \text{h.c.} \right) + H_{\text{exc}}[\phi_\alpha, \phi^\dagger_\alpha]$$



Method: Non-equilibrium path integrals and Greens functions



Steady state $\quad \psi(t) = \psi e^{-i\mu_S t}$

Fluctuations

$$[D^R - D^A](t,t') = -i \left\langle \left[\psi(t), \psi^\dagger(t') \right]_- \right\rangle$$

$$D^K(t,t') = -i \left\langle \left[\psi(t), \psi^\dagger(t') \right]_+ \right\rangle$$

$$[D^R - D^A](\omega) = \text{DoS}(\omega)$$

$$D^K(\omega) = (2n(\omega) + 1)\text{DoS}(\omega)$$

Mean Field

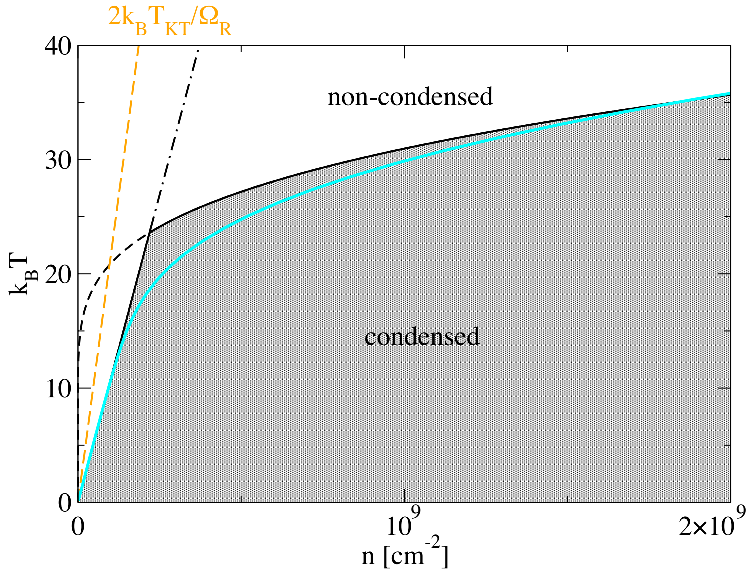
Non-equilibrium generalisation of Gross-Pitaevskii in BEC and gap equation in BCS regimes (note: now it is complex)

$$\left(i\partial_t + \frac{\nabla^2}{2m} - V(r) - i\kappa\right)\psi(r,t) = \chi[\psi(r,t)]\psi(r,t)$$

model that can show lasing and condensation

$$H_{\rm sys} = \sum_{\mathbf{p}} \omega_{\mathbf{p}} \psi^\dagger_{\mathbf{p}} \psi_{\mathbf{p}} + \sum_{\alpha} \left[\epsilon_\alpha S^z_\alpha + g_{\alpha,\mathbf{p}} \psi_{\mathbf{p}} S^+_\alpha + \text{h.c.}\right]$$

Equilibrium phase diagram BCS-BEC crossover



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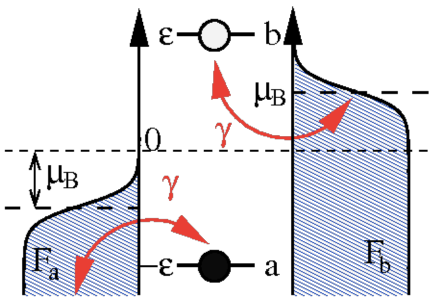
External drive



no trap V(r)=0 steady-state $\psi(t) = \psi e^{-i\mu_S t}$

$$(i\partial_t - \omega_c - i\kappa)\,\psi = \chi(\psi)\psi$$

$$\chi(\psi,\mu_S) = -g^2\gamma \sum_{\text{excitons}} \int \frac{d\nu}{2\pi} \frac{(F_a+F_b)\nu + (F_b - F_a)(i\gamma + \epsilon_\alpha - \frac{1}{2}\mu_S)}{[(\nu - E_\alpha)^2+\gamma^2][(\nu+E_\alpha)^2+\gamma^2]}$$

$$E^2_\alpha = (\epsilon_\alpha - \frac{1}{2}\mu_S)^2 + g^2|\psi|^2$$

Unifying Condensates and Lasers

Mean-field equations

$$\mu_s - \omega_c + i\kappa = -g^2\gamma \sum_{\text{excitons}} \int \frac{d\nu}{2\pi} \frac{(F_a + F_b)\nu + (F_b - F_a)(i\gamma + \epsilon_\alpha - \frac{1}{2}\mu_S)}{[(\nu - E_\alpha)^2 + \gamma^2][(\nu + E_\alpha)^2 + \gamma^2]}$$

$$E_\alpha^2 = (\epsilon_\alpha - \frac{1}{2}\mu_S)^2 + g^2|\psi|^2$$

[Szymanska et al., *PRL* 2006, *PRB* 2007; chapter, ICP (2012); Keeling et al., chapter, Springer (2010)]

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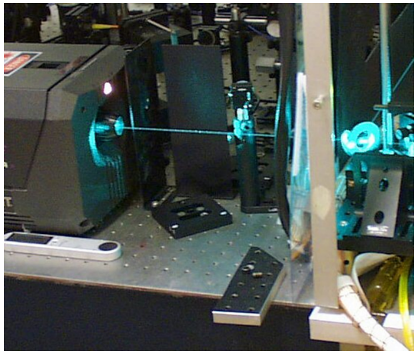
✧ Large temperature T: laser limit, only imaginary part, gain balances loss

$$\kappa = -g^2\gamma \sum_{\text{excitons}} \frac{F_b - F_a}{4E_\alpha^2 + 4\gamma^2} \rightarrow \frac{g^2}{2\gamma} \times \text{Inversion}$$



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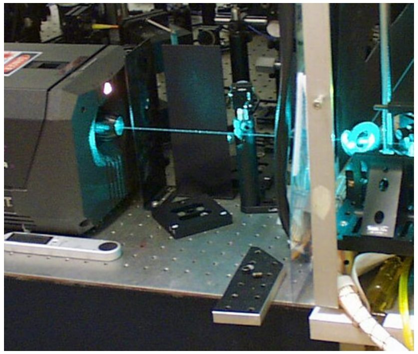


✧ Equilibrium limit $\kappa, \gamma \rightarrow 0$ known gap equation

$$\omega_c - \mu_s = \sum_{\text{excitons}} \frac{g^2}{2E_\alpha} \tanh\left(\frac{\beta E_\alpha}{2}\right)$$

[Szymanska et al., *PRL* 2006, *PRB* 2007; chapter, ICP (2012); Keeling et al., chapter, Springer (2010)]

Low density limit – complex GPE

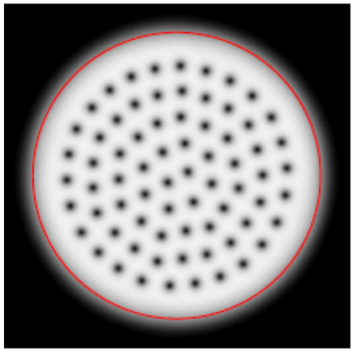
Mean-field equation

$$\left(i\partial_t + \frac{\nabla^2}{2m} - V(r) - i\kappa\right)\psi = \chi[\psi]\psi$$

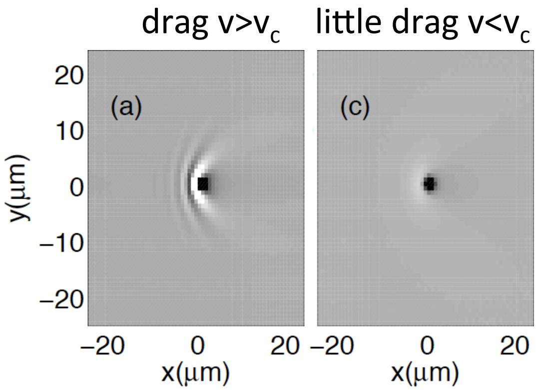
At low density the nonlinear, complex susceptibility can be simplified: Complex Gross-Pitaevskii equation

$$i\partial_t\psi = \left[-\frac{\nabla^2}{2m} + V(r) + U|\psi|^2 + i\left(\gamma_{\text{eff}} - \kappa - \Gamma|\psi|^2\right)\right]\psi$$

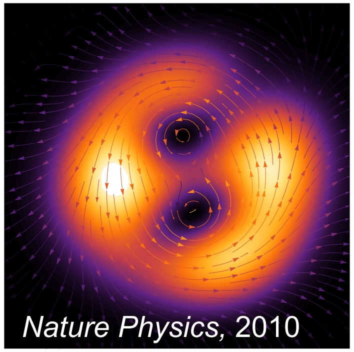
Rich phenomenology:



Vortex lattices
[Keeling et al., *PRL* 2008]



Flow via obstacles
[Carusotto et al., *PRL* 2006]



Persistent currents and vortices in OPO
[D. Sanvitto et al., Nature Phys. 2010
F. M. Marchetti et al., PRL 2010
M. H. Szymanska et al, PRL 2010]

Fluctuations: Phase Transition

$$\mathcal{L} = \langle \psi^\dagger \psi \rangle = n(\omega)\mathrm{DoS}(\omega)$$

$$[D^R]^{-1} = A(\omega) + iB(\omega)$$

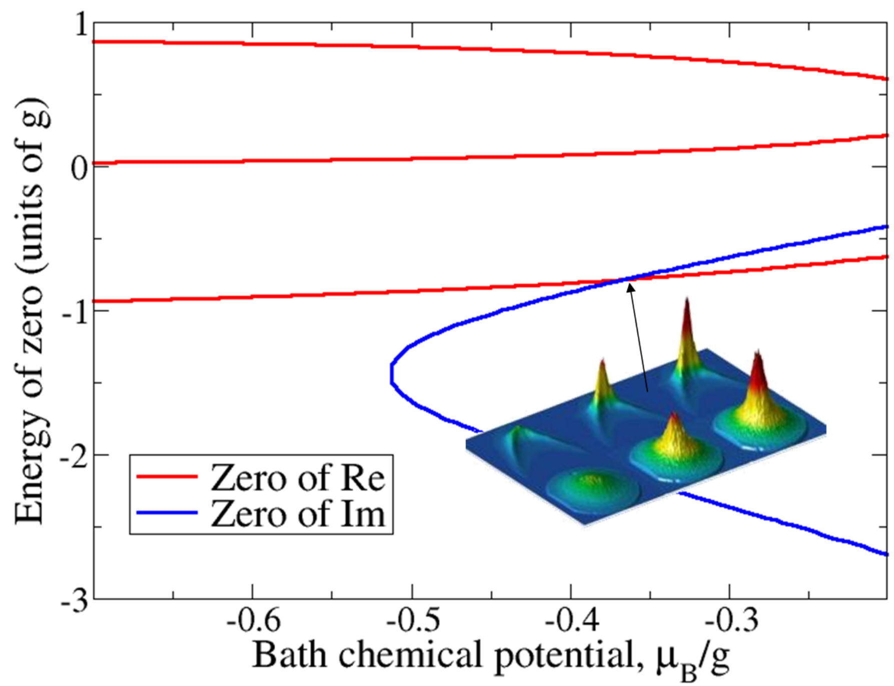
$$\mathrm{DoS}(\omega) = \frac{2B(\omega)}{B(\omega)^2 + A(\omega)^2}$$

$$n(\omega) = \frac{C(\omega)}{4B(\omega)}$$

$A(\omega_{\mathbf{p}}^*) = 0$ $\omega_{\mathbf{p}}^*$ normal modes

$B(\mu_{\mathrm{eff}}) = 0$ $n(\mu_{\mathrm{eff}})$ diverges

Non-equilibrium BEC



The same as in equilibrium: distribution far from thermal but it diverges at μ_{eff}

No need for BE distribution for BEC

[Szymanska et al., *PRL* 2006, *PRB* 2007; chapter, ICP (2012); Keeling et al., chapter, Springer (2010)]

Laser Limit

Maxwell-Bloch equations $P = -in\langle S^- \rangle, N = n\langle S^z \rangle$

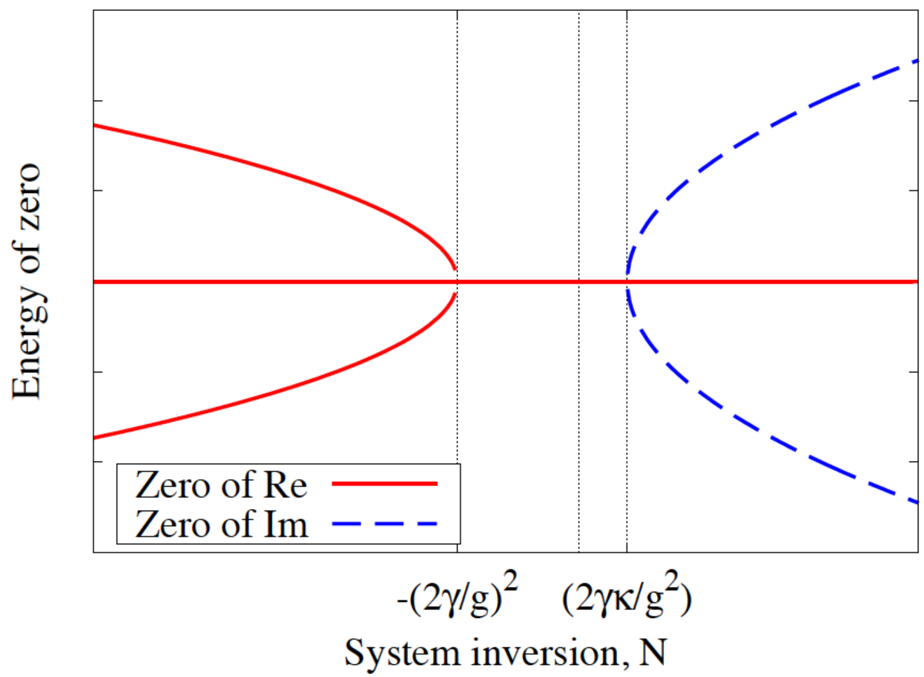
$$\partial_t \psi = (-i\omega_c - \kappa)\psi + gP$$
$$\partial_t P = (-2i\epsilon - 2\gamma)P + g\psi N$$
$$\partial_t N = 2\gamma(N_0 - N) - 2g(\psi^* P + P^* \psi)$$

Green's function

$$\psi = iD^R(\omega)Fe^{-i\omega t}$$

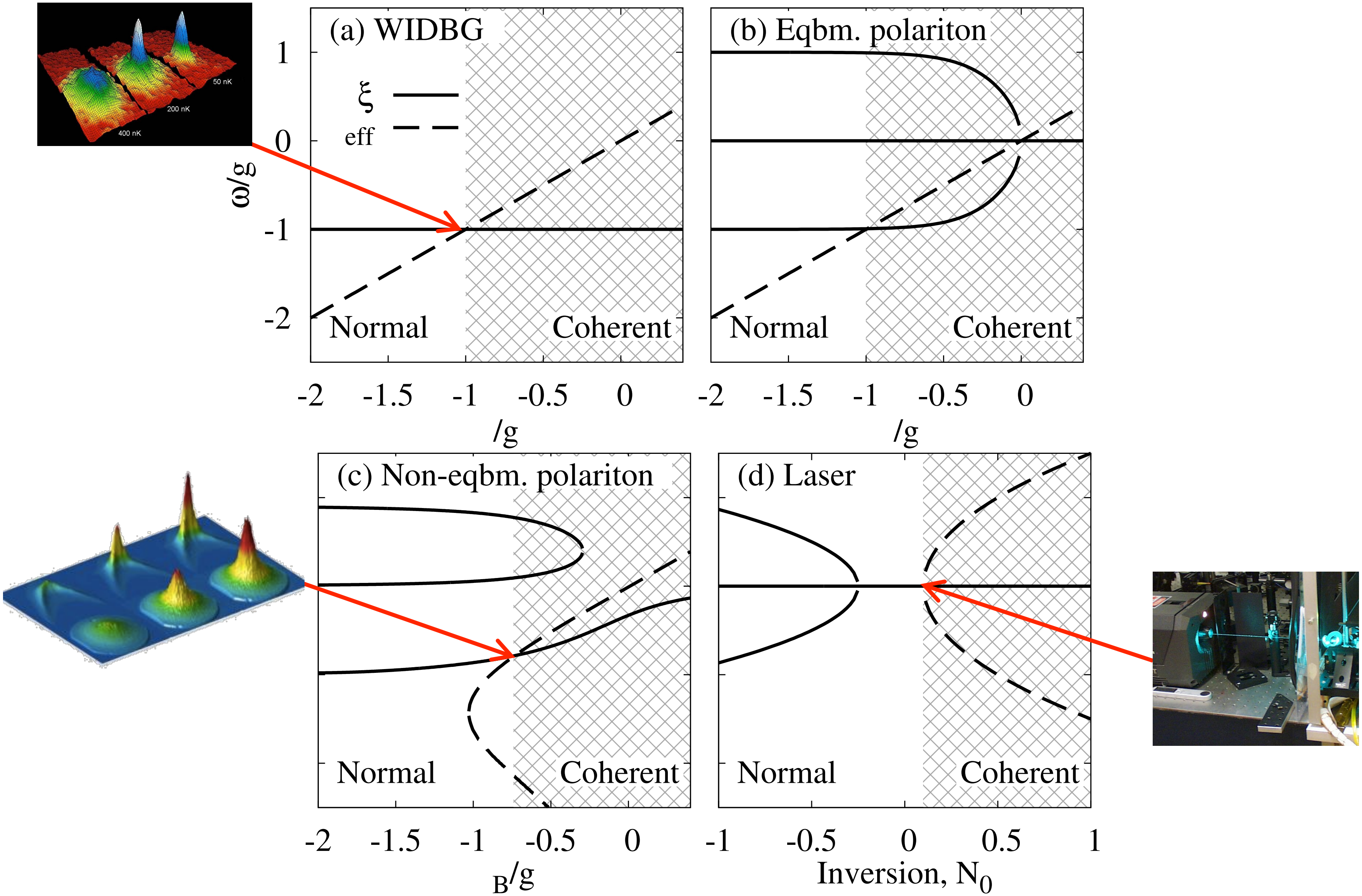
thus

$$[D^R]^{-1} = A(\omega) + iB(\omega) = \omega - \omega_c + i\kappa + \frac{g^2 N_0}{\omega - 2\epsilon + i2\gamma}$$



[Keeling et al., chapter Springer (2010); Szymanska et al., chapter ICP (2012)]

Unifying Condensates and Lasers



[Szymanska et al., chapter ICP (2012)]

Collective modes

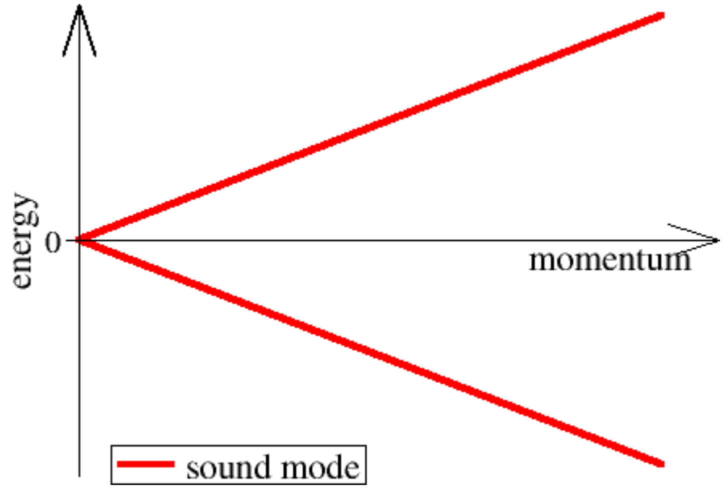
Collective modes

when condensed

$$\text{Det}\left[D_R^{-1}(\omega,\mathbf{p})\right] = \omega^2 - c^2\mathbf{p}^2$$

poles

$$\omega^* = c|\mathbf{p}|$$



Collective modes

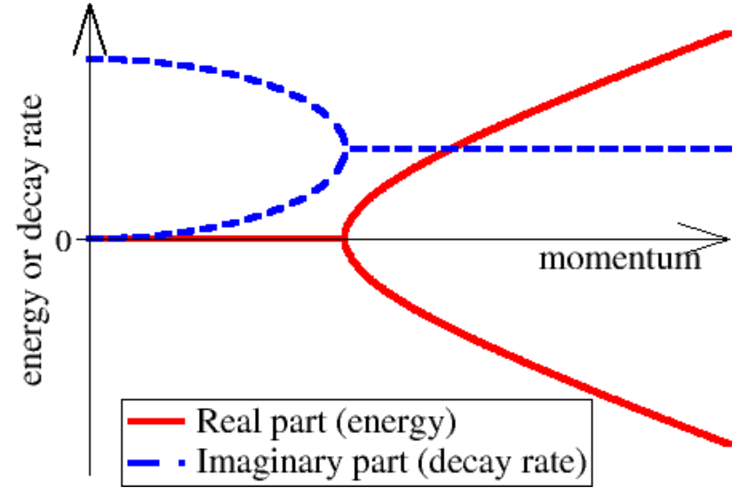
Collective modes

when condensed

$$\mathrm{Det}\left[D_R^{-1}(\omega,\mathbf{p})\right] = (\omega + ix)^2 + x^2 - c^2\mathbf{p}^2$$

poles

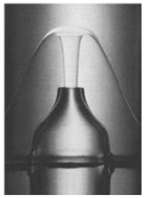
$$\omega^* = -ix \pm \sqrt{c^2\mathbf{p}^2 - x^2}$$



[Szymanska et al., *PRL* 2006, *PRB* 2007]

Landau criterion? Superfluidity?

$$v_c = \min_{\mathbf{p}} \frac{\omega(\mathbf{p})}{\mathbf{p}}$$

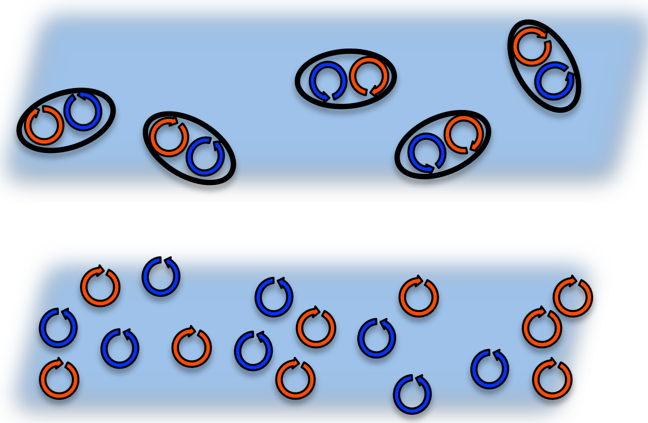


[Keeling et al, *Nature* 2009]

Table 1 | Superfluidity checklist

	Quantized vortices	Landau critical velocity	Metastable persistent flow	Two-fluid hydro-dynamics	Local thermal equilibrium	Solitary waves
Superfluid ^{4}He/cold atom Bose-Einstein condensate	✓	✓	✓	✓	✓	✓
Non-interacting Bose-Einstein condensate	✓	X	X	X	✓	X
Classical irrotational fluid	X	✓	X	✓	✓	✓
Incoherently pumped polariton condensates	✓	X	?	?	X	?
Parametrically pumped polariton condensates	?	✓	?	?	X	✓

Quasi Long Range Order?

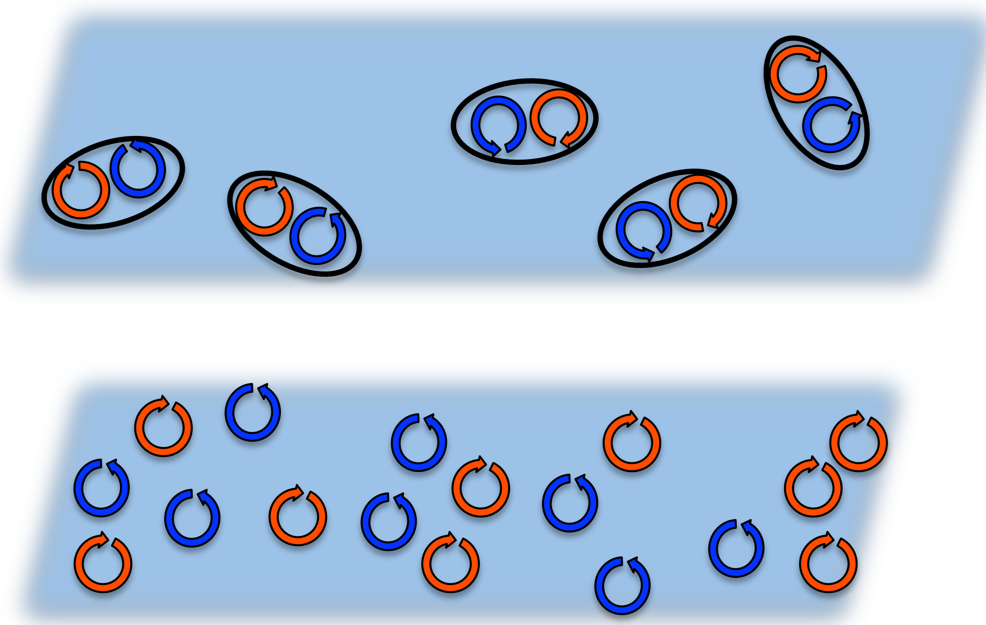


Quasi-Long Range Order

2D equilibrium superfluid below the BKT transition

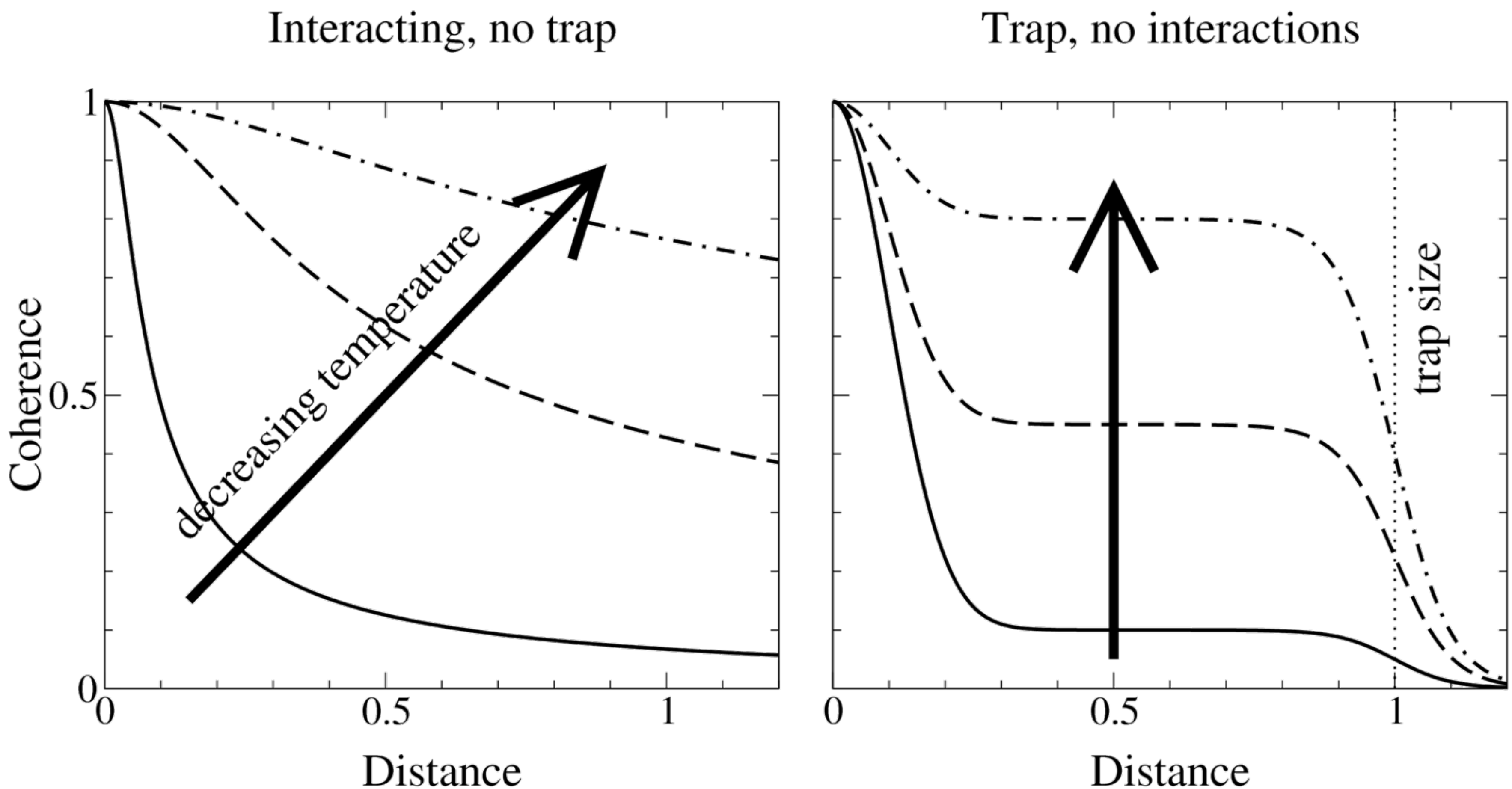
$$g_1(r) = \langle \psi^\dagger(\mathbf{r})\psi(0)\rangle \propto \left(\frac{r}{r_0}\right)^{-a_p}$$

$$a_p = \frac{mk_BT}{2\pi\hbar^2 n_S} < \frac{1}{4}$$



Spatial coherence in a finite 2D gas

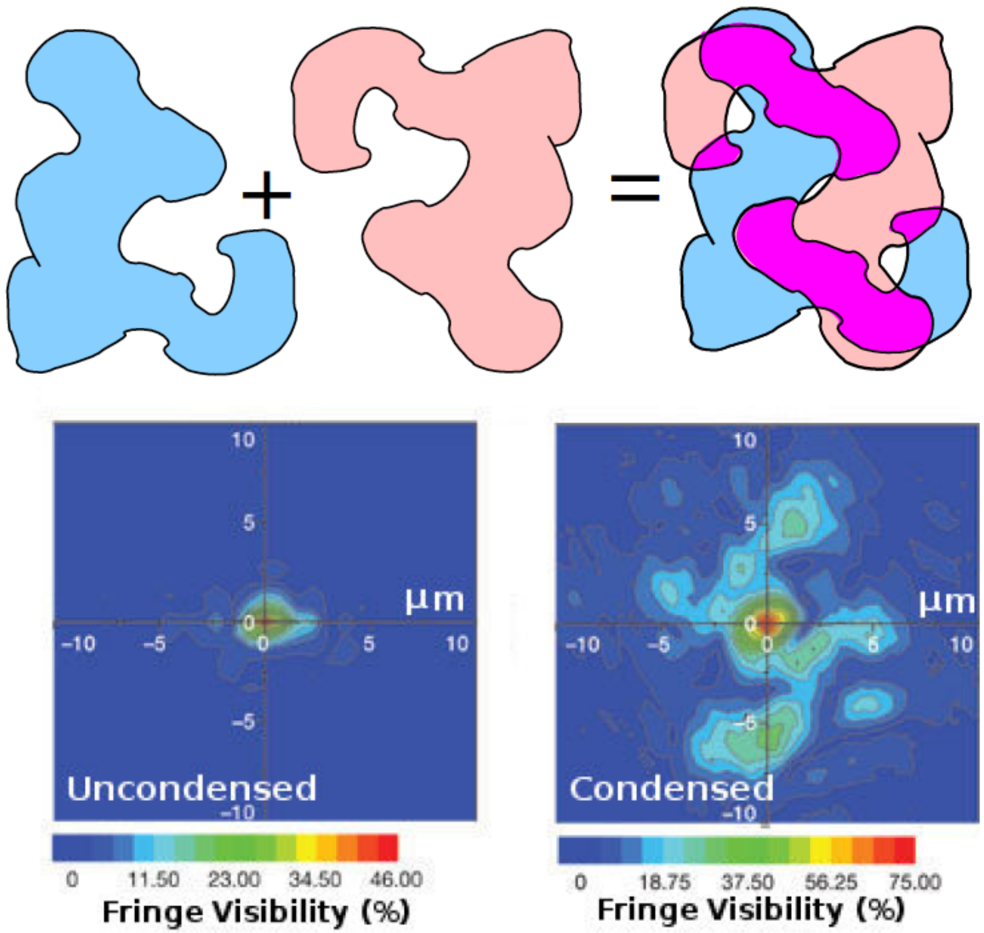
$$g_1(\mathbf{r}, -\mathbf{r}; \Delta t = 0)$$



[Keeling et al., *Semicond. Sci. Technol.* 2007]

First Experiments

$$g_1(\mathbf{r}, -\mathbf{r}; \Delta t = 0)$$



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

Contrast: up to 5% - below threshold, up to 45% - above

Decay of coherence in general

- **Fluctuations:** amplitude to second, phase to all orders

$$g_1(\mathbf{r},\mathbf{r}',\mathbf{t}) = \langle \psi^\dagger(\mathbf{r},t)\psi(\mathbf{r}',0)\rangle \simeq |\psi_0|^2 \exp\left[-D^<_{\phi\phi}(t,\mathbf{r},\mathbf{r}')\right]$$

$$D^< = D^K - D^R + D^A$$

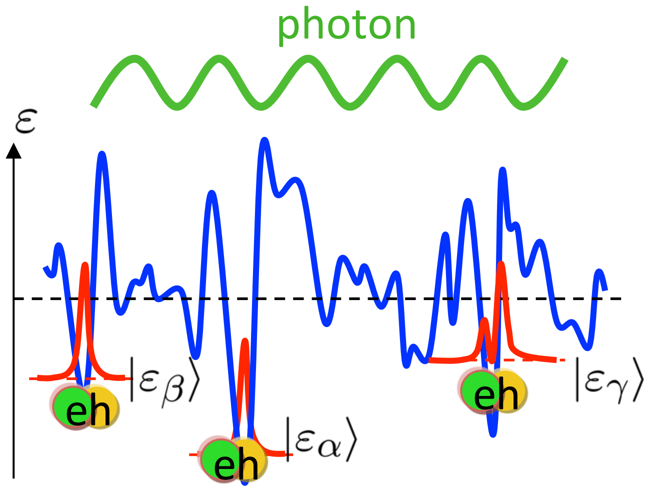
- Translationally invariant 2D system

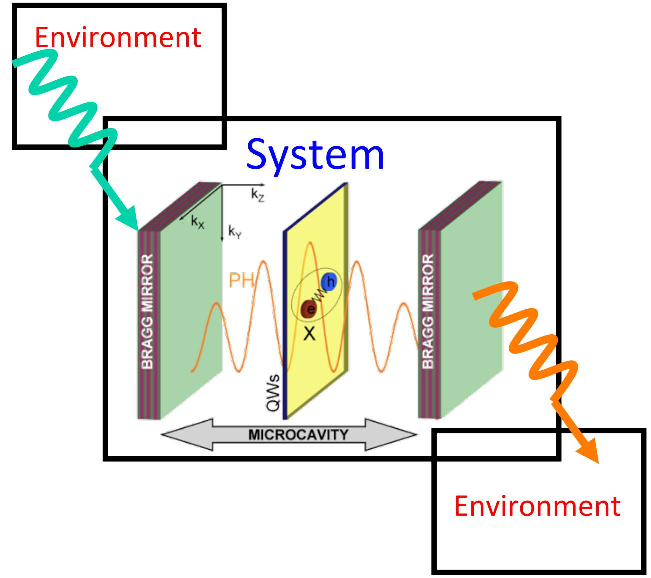
$$g_1(r,t) = |\psi_0|^2 \exp\left\{-\int \frac{kdk}{2\pi}\left[1 - J_0(kr)\right] f(k,t)\right\}$$

$$f(k) = \int (d\omega/2\pi)\, iD^<_{\phi\phi}(k,\omega)$$

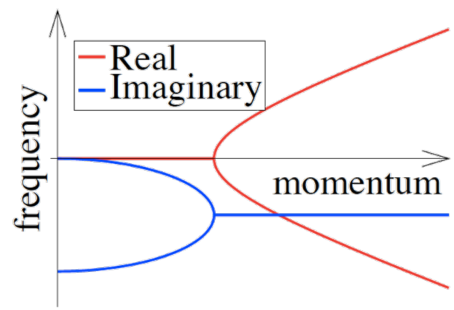
- Decay of coherence depends on
  - Dimensionality
  - Form of the excitation spectra (via D)
  - Occupation of excitations (via D^K)

Non-equilibrium polaritons





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

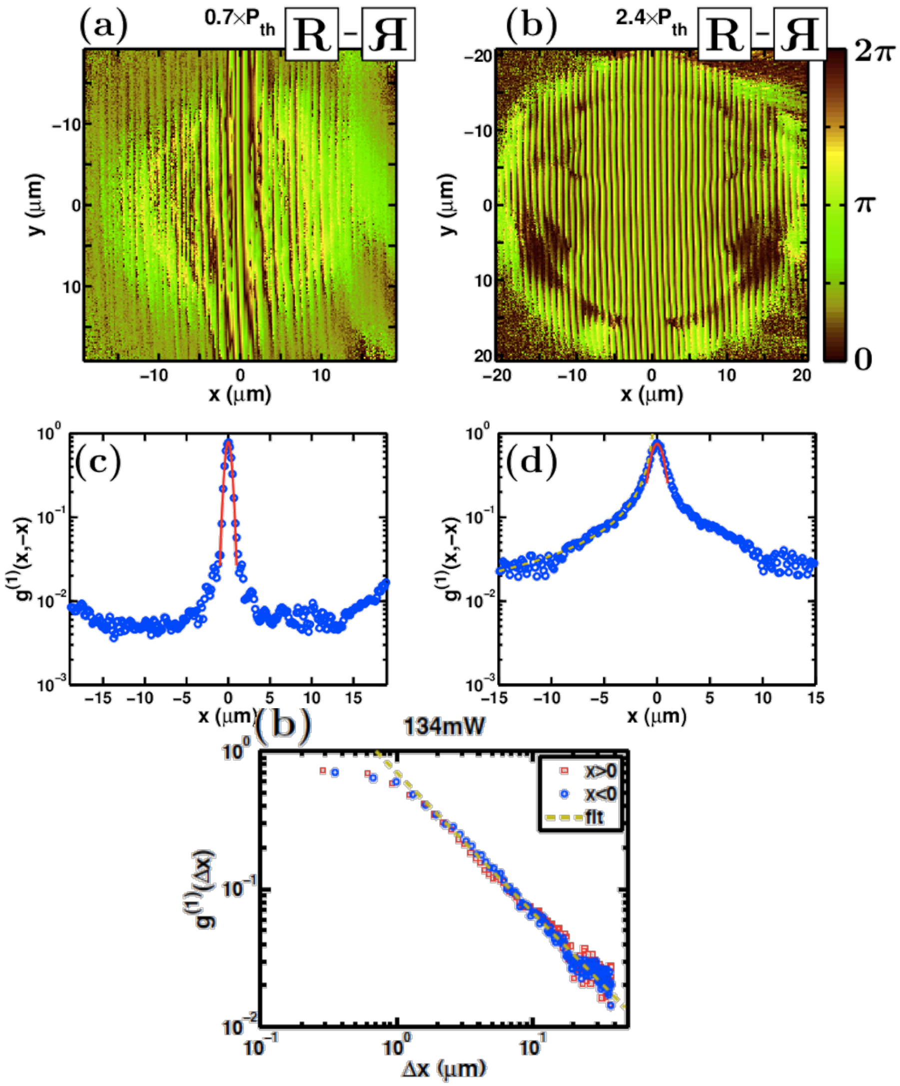


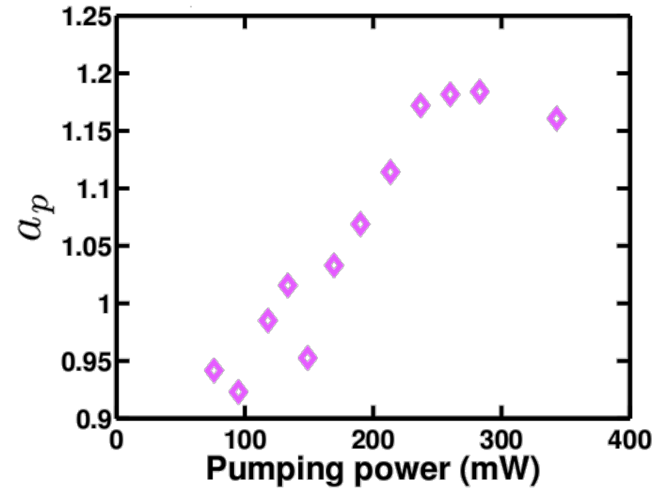
$$\langle \psi^\dagger(\mathbf{r},t)\psi(0,0)\rangle \simeq |\psi_0|^2 \exp\left[-a_p \begin{cases} \ln(r/r_0) & r\to\infty, t\simeq 0 \\ \frac{1}{2}\ln(c^2 t/\gamma_{\mathrm{tot}} r_0^2) & r\simeq 0, t\to\infty \end{cases}\right]$$

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

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

Experimental observation of power law decay





$$g_1(r) \propto \left(\frac{r}{r_0}\right)^{-a_p}$$

[Roumpos et al, *PNAS* 2012]

The simplest model

$$g_1(\mathbf{r},\mathbf{r}',\mathbf{t}) = \langle \psi^\dagger(\mathbf{r},t)\psi(\mathbf{r}',0)\rangle \simeq |\psi_0|^2 \exp\left[-D^<_{\phi\phi}(t,\mathbf{r},\mathbf{r}')\right]$$

$$D^< = D^K - D^R + D^A$$

- Polariton complex Gross-Pitaevskii equation with pump and decay

$$i\partial_t\psi = \left[-\frac{\nabla^2}{2m} + U|\psi|^2 + i\left(\gamma_{\rm net} - \Gamma|\psi|^2\right)\right]\psi$$

- The spectra

$$D^R = \frac{1}{\omega^2 + 2i\gamma_{\rm net}\omega - \xi_k^2}\begin{pmatrix} \mu + \epsilon_k + \omega + i\gamma_{\rm net} & -\mu + i\gamma_{\rm net} \\ -\mu - i\gamma_{\rm net} & \mu + \epsilon_k - \omega - i\gamma_{\rm net} \end{pmatrix}$$

$$\epsilon_k = k^2/2m$$

$$\xi_k = \sqrt{\epsilon_k(\epsilon_k + 2\mu)}$$

- Phase-phase component

$$iD_{\phi\phi} = \frac{i}{8n_S}(1 \quad -1)D\begin{pmatrix} 1 \\ -1 \end{pmatrix}$$

$$n_S = |\psi_0|$$

The simplest model

$$g_1(\mathbf{r},\mathbf{r}',\mathbf{t}) = \langle \psi^\dagger(\mathbf{r},t)\psi(\mathbf{r}',0)\rangle \simeq |\psi_0|^2 \exp\left[-D^<_{\phi\phi}(t,\mathbf{r},\mathbf{r}')\right]$$

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$$i\partial_t\psi = \left[-\frac{\nabla^2}{2m} + U|\psi|^2 + i\left(\gamma_{\text{net}} - \Gamma|\psi|^2\right)\right]\psi + \text{noise}$$

✧ The spectra

$$D^R = \frac{1}{\omega^2 + 2i\gamma_{\text{net}}\omega - \xi_k^2}\begin{pmatrix} \mu + \epsilon_k + \omega + i\gamma_{\text{net}} & -\mu + i\gamma_{\text{net}} \\ -\mu - i\gamma_{\text{net}} & \mu + \epsilon_k - \omega - i\gamma_{\text{net}} \end{pmatrix}$$

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✧ Phase-phase component

$$iD_{\phi\phi} = \frac{i}{8n_S}(1 \quad -1)D\begin{pmatrix} 1 \\ -1 \end{pmatrix}$$

$$n_S = |\psi_0|$$

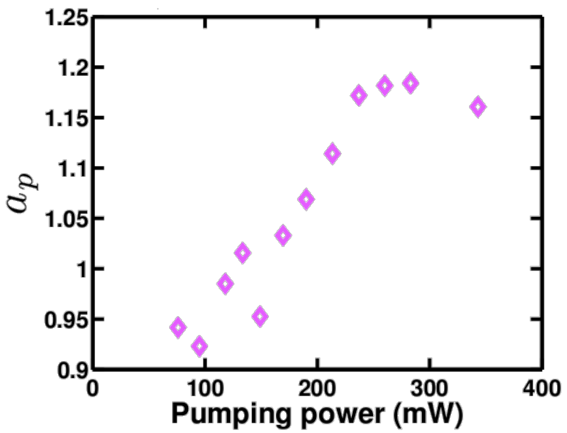
✧ Occupation

$$D^K = -D^R[D^{-1}]^K D^A$$
$$= (2n+1)(D^R - D^A)$$

Exponent in a non-equilibrium 2D gas

$$g_1(r) \propto \left(\frac{r}{r_0}\right)^{-a_p}$$

- ✧ Equilibrium closed system $a_p = \frac{mk_BT}{2\pi\hbar^2 n_S} < \frac{1}{4}$
- ✧ Non-equilibrium driven system (diffusive modes)
  - ➢ thermalised $a_p = \frac{mk_BT}{2\pi\hbar^2 n_S}$
  - ➢ non-thermalised $a_p \propto \frac{\text{pumping noise}}{n_s}$
- ✧ Experiment $a_p \simeq 1.2$



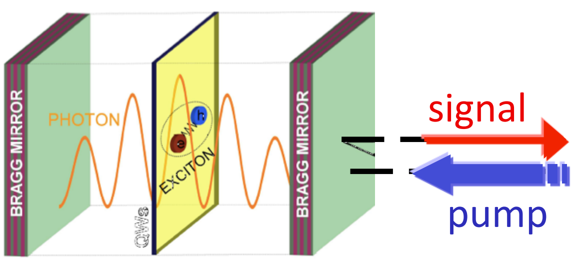
- ✧ Decay of spatial coherence measure of distribution
- ✧ BKT order more robust then in equilibrium

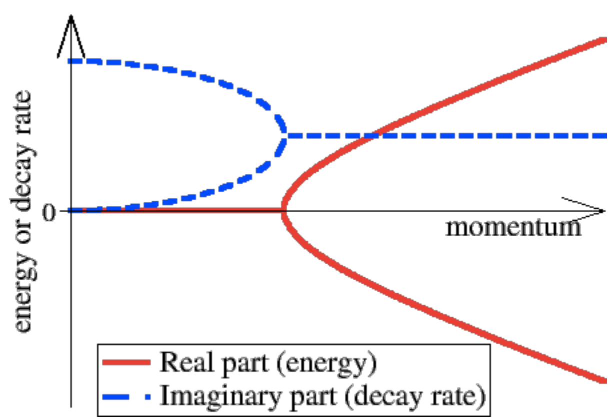
Faster decay possible before vortices proliferate

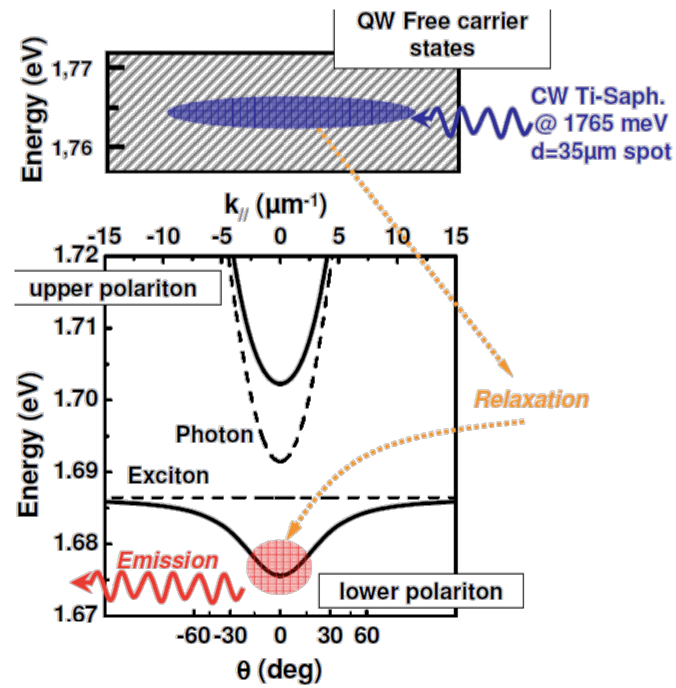
Polariton Superfluids

SUPERFLUID CHECKLIST

	Spontaneous symm. breaking	Landau criterion	frictionless flow	quantised vortices	metastable persistent flow
^{4}He/cold atoms BEC	✓	✓	✓	✓	✓
polariton condensates (incoherent pump)	✓	✗	?	✓	?
polariton condensates (parametric pump)	✓	✗	✓	✓	✓
polariton condensates (coherent pump)	✗	✓	✓	✗	?







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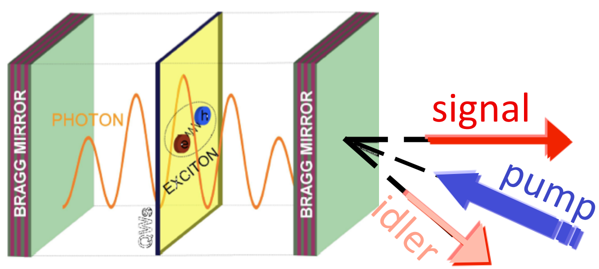
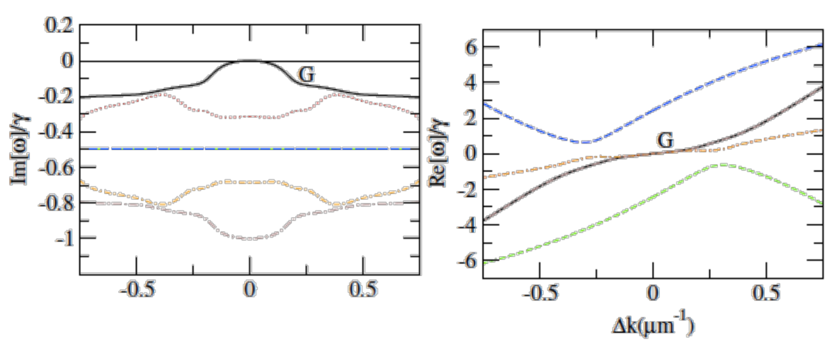
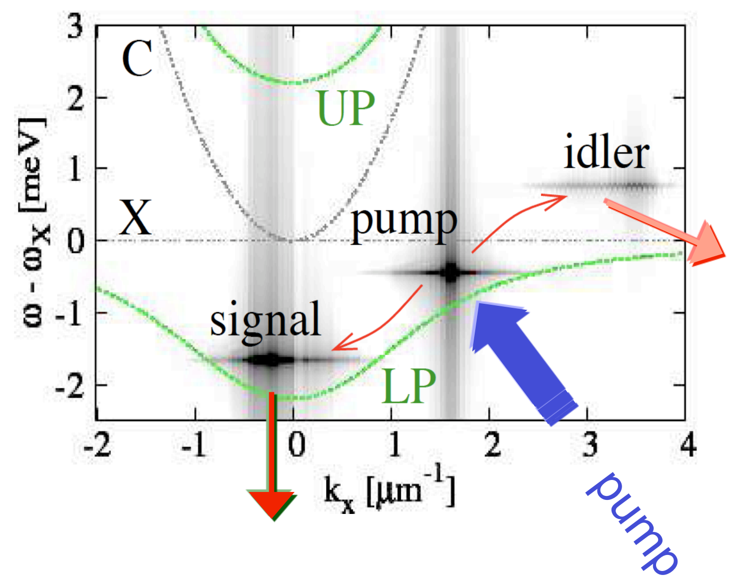
polariton condensates (coherent pump)	✗	✓	✓	✗	?





[Carussotto et al, *PRL* 2007]



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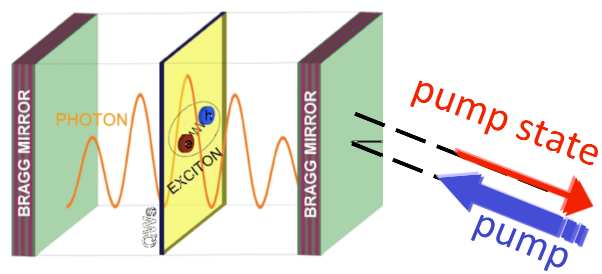
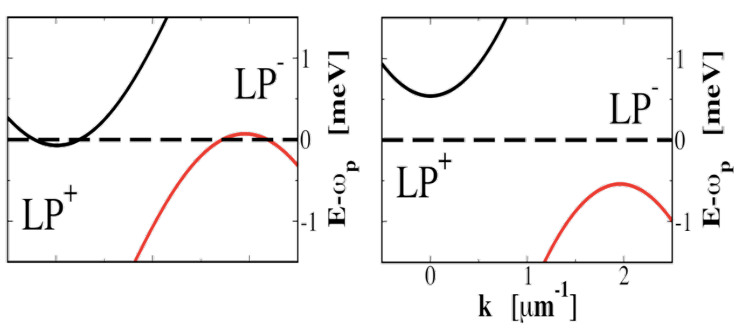
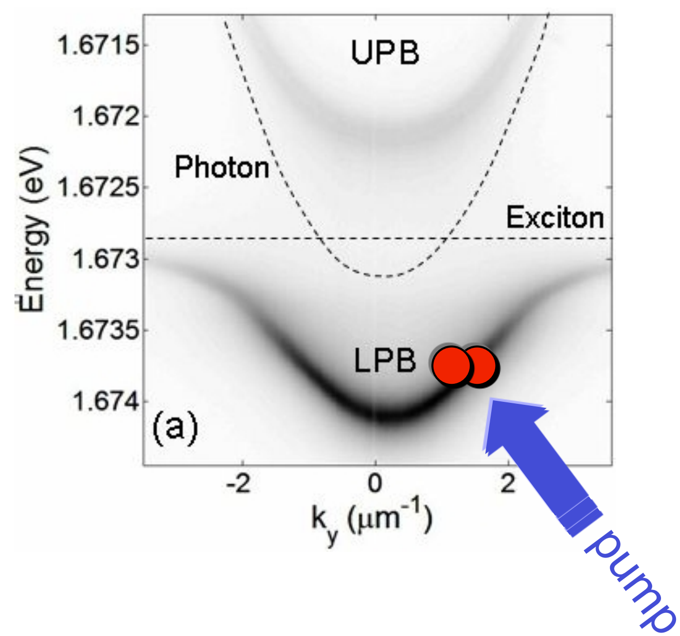
polariton condensates (coherent pump)	✗	✓	✓	✗	?



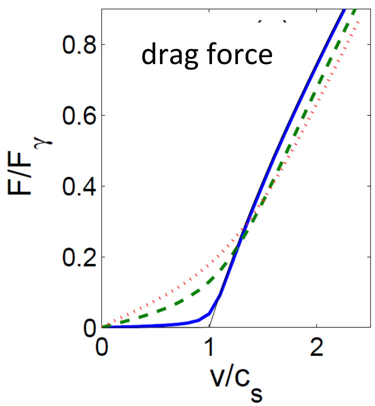


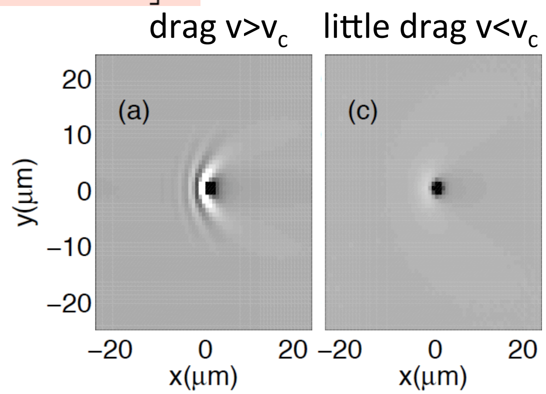


Frictionless Flow?

$$\mathbf{F} = -\frac{1}{\int |\psi_C(\mathbf{r})|^2 \, d^3x} \int |\psi_C(\mathbf{r})|^2 \, \vec{\nabla} \left[V(\mathbf{r}) \right] d^3x$$

$$i\partial_t \psi = \left[-\frac{\nabla^2}{2m} + U|\psi|^2 + i\left(\gamma_{\rm net} - \Gamma|\psi|^2 \right) \right] \psi$$



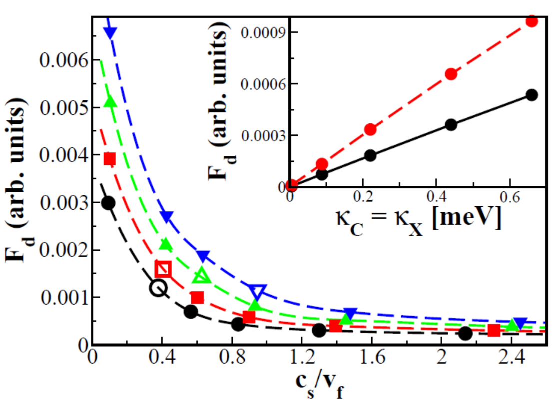


[Wouters & Carussotto, *PRL* (2010)]

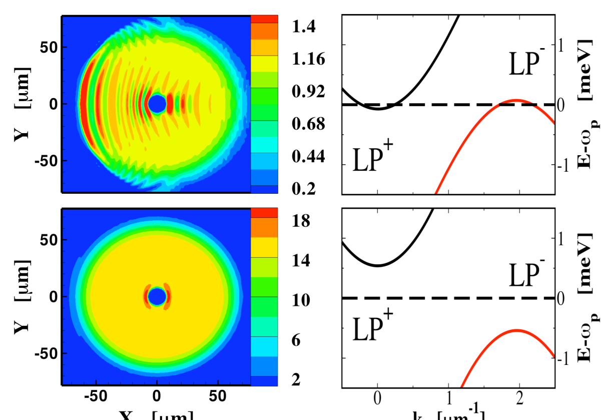
Crossover:
for v<vc excitations local to defect and decaying

$$i\partial_t \begin{pmatrix} \psi_X \\ \psi_C \end{pmatrix} = \begin{pmatrix} \omega_X - i\kappa_X + g_X|\psi_X|^2 & \Omega_R/2 \\ \Omega_R/2 & \omega_C - i\kappa_C \end{pmatrix} \begin{pmatrix} \psi_X \\ \psi_C \end{pmatrix} + \begin{pmatrix} 0 \\ F_p \end{pmatrix}$$

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



[Cancellieri et al., *PRB* 2010]

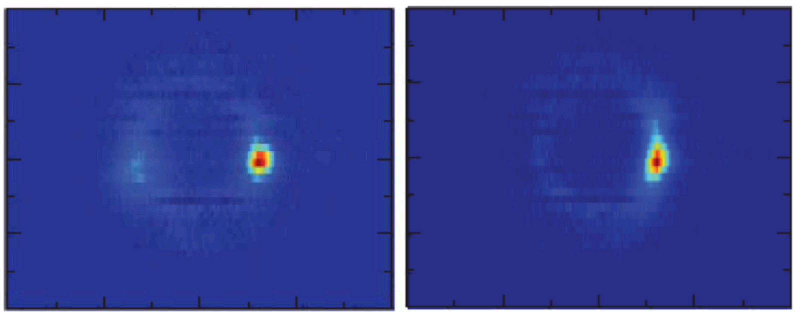


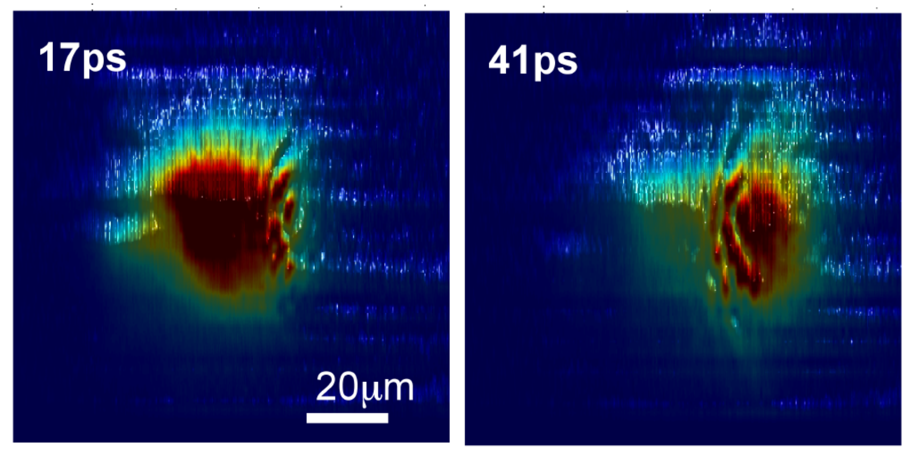
Also crossover:
despite energy gap there is broadening due to imaginary part

Frictionless Flow - Experiments

Above OPO threshold: TOPO pulse

Frictionless flow
(no scattering in momentum)

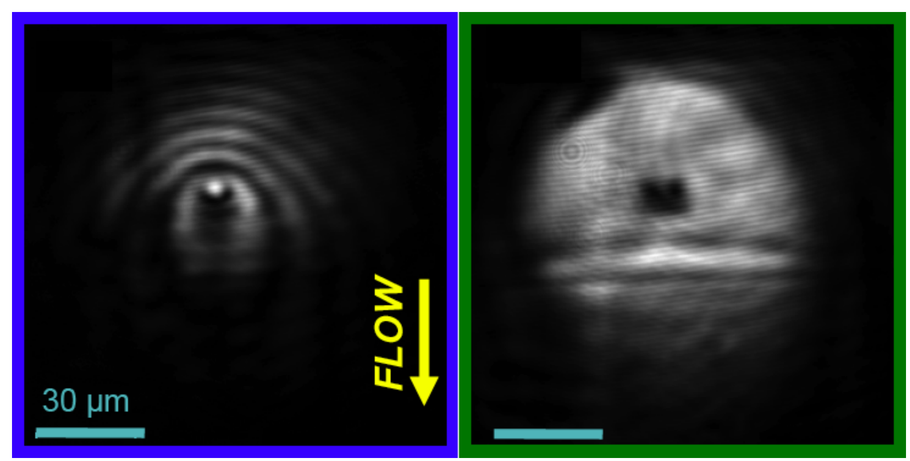




[Amo *et al.*, *Nature* 2009]

Below OPO threshold: pump only state

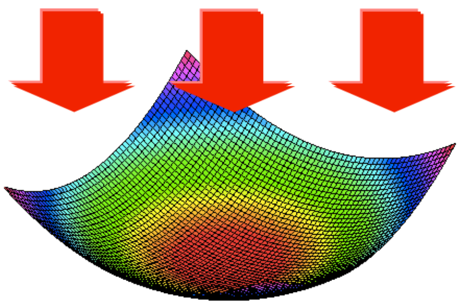
- ✧ Frictionless flow below critical flow velocity
- ✧ Phase fixed by the pump thus no vortices

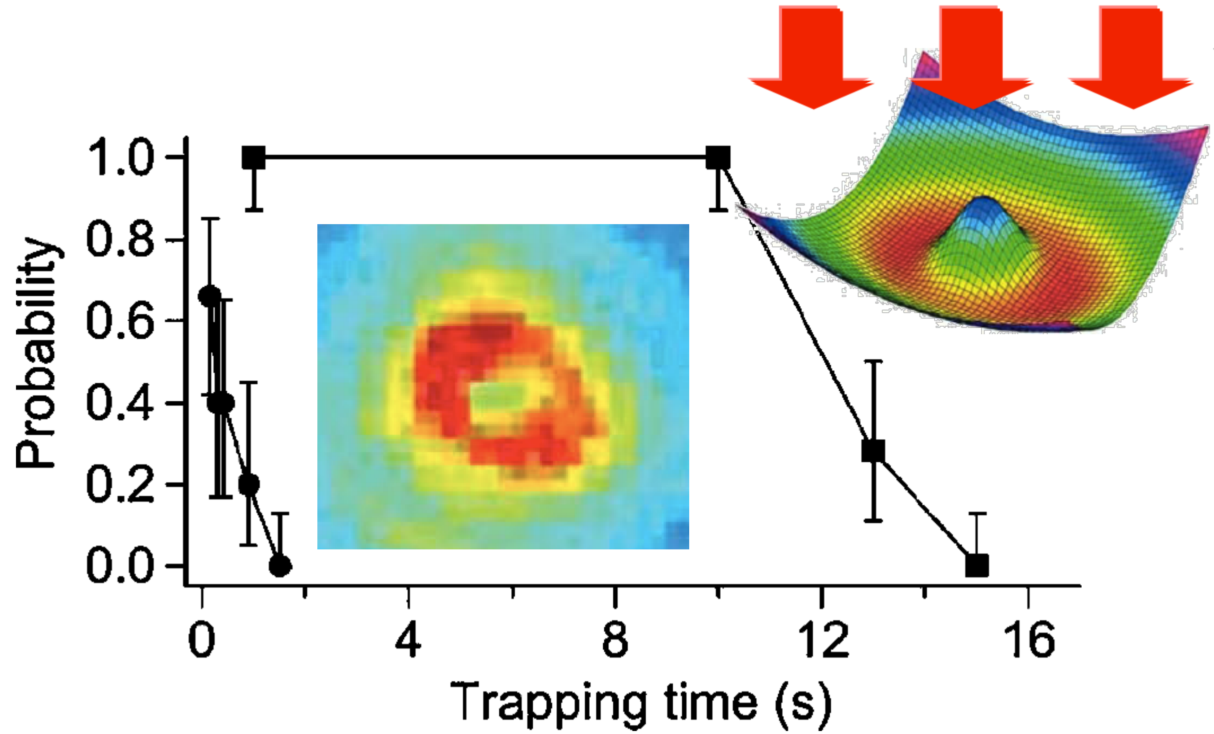


[Amo *et al.*, *Nature Phys* 2009]

Metastable persistent flow - equilibrium

Gauss-Laguerre beam
rotating drive





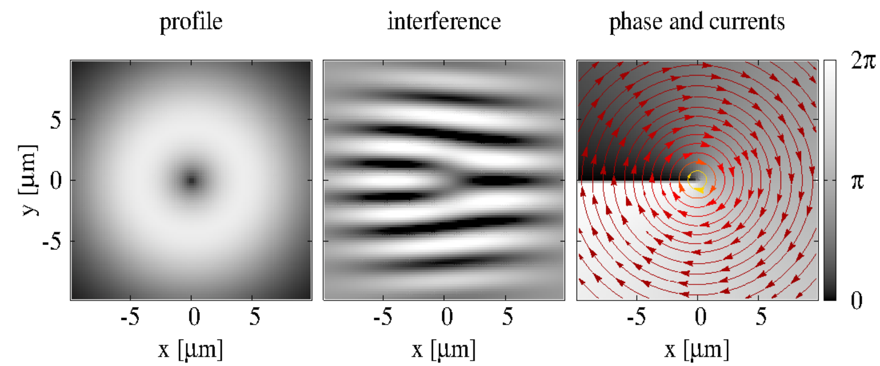
[Ryu *et al. PRL* 2007]

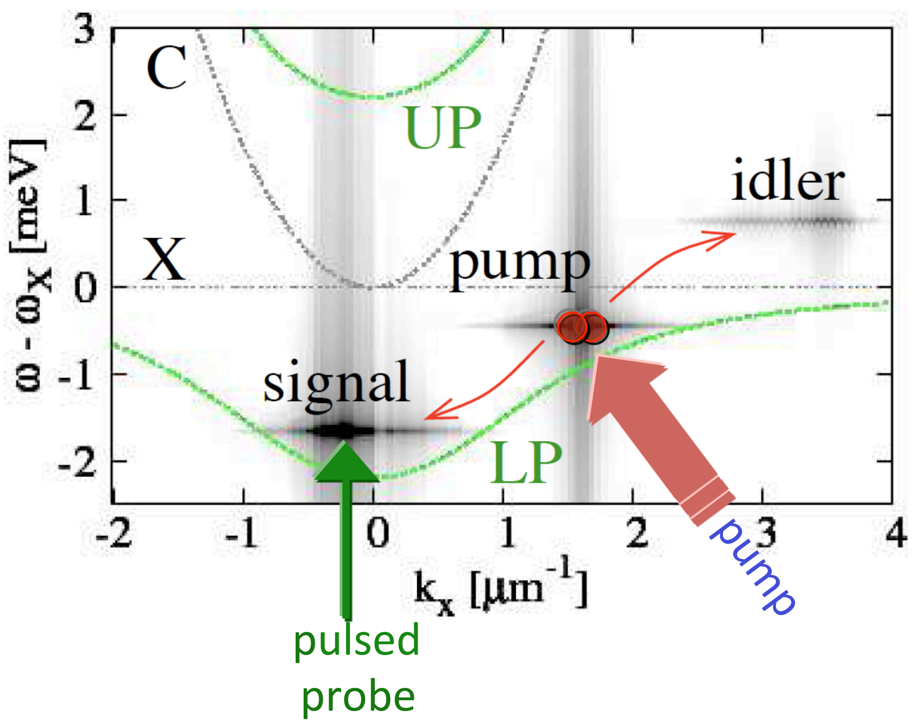
Equilibrium superfluids: a multiply connected geometry essential for stability of the flow

Persistent flow after a "stirring" pulse?

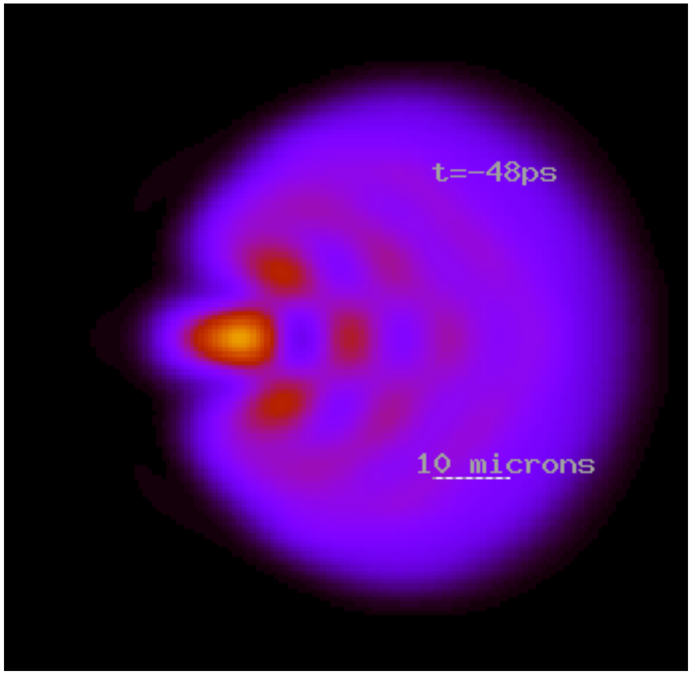
Gauss-Laguerre pulse (2ps)

$$F_{pb}(\mathbf{r},t) = \mathcal{F}_{pb}(\mathbf{r})e^{i\varphi(\mathbf{r})}e^{-\frac{t^2}{2\sigma_t^2}}e^{i(\mathbf{k}_s\cdot\mathbf{r}-\omega_s t)}$$



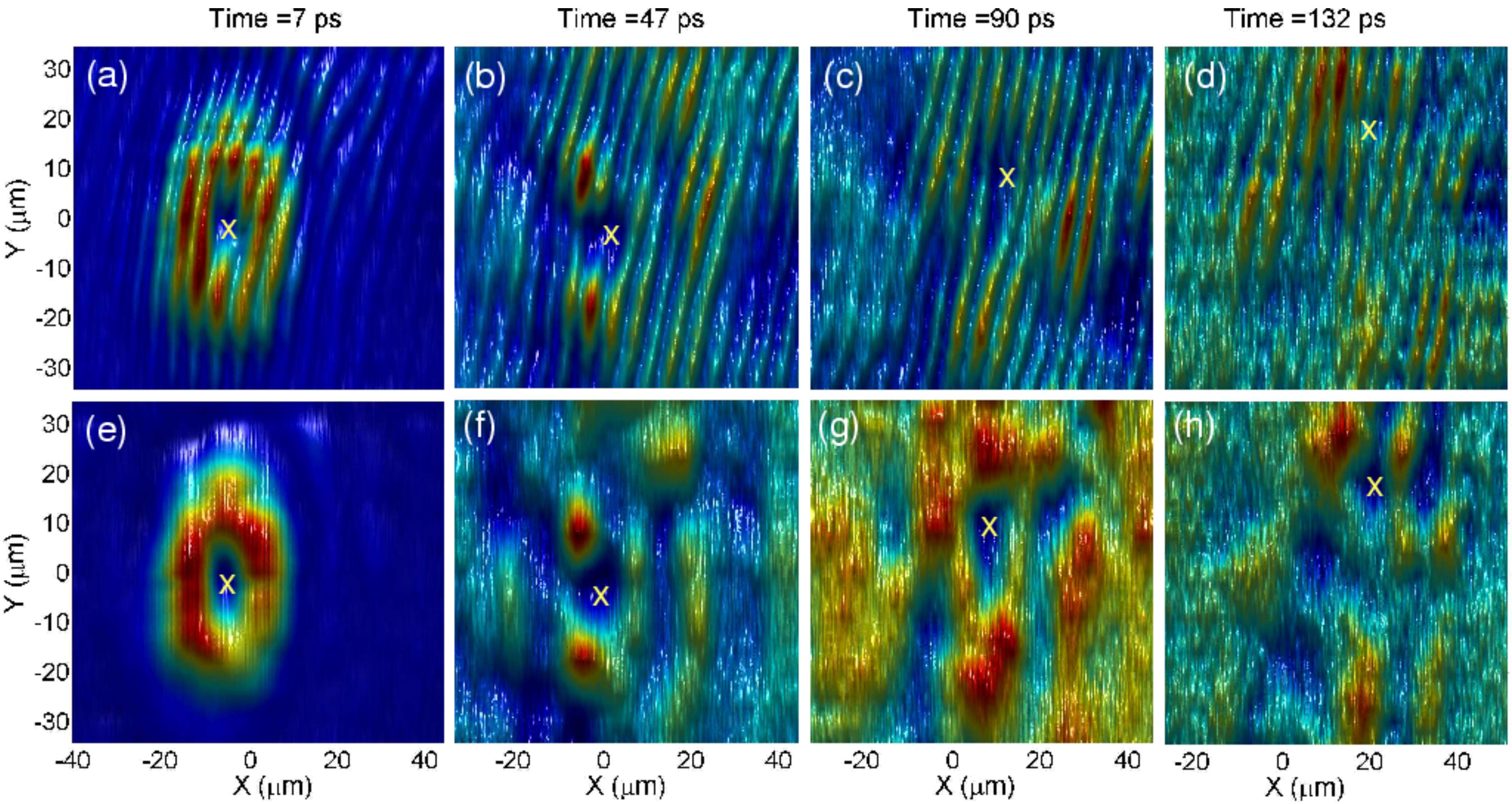


Steady-state persistent flow



[Sanvitto *et al., Nature Phys*. 2010; Marchetti et al., *PRL* 2010; Szymanska *et al*. *PRL* 2010]

Metastable persistent flow: experiment

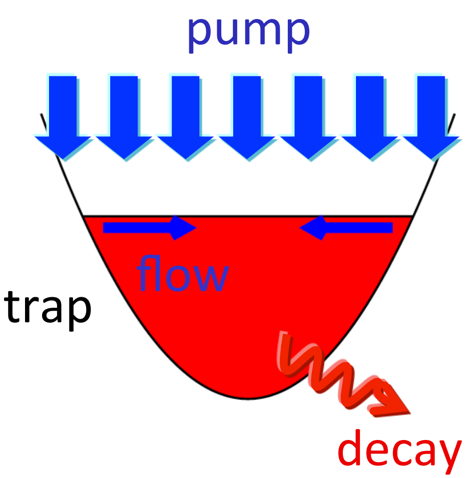


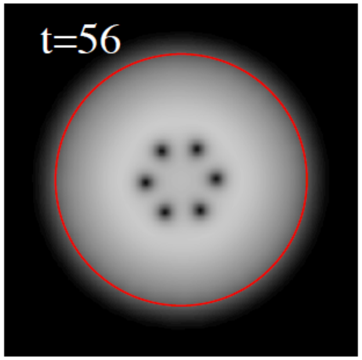
[Sanvitto et al., Nature Phys. 2010]

Vortices

Ground state is not flowless: spontaneous vortices

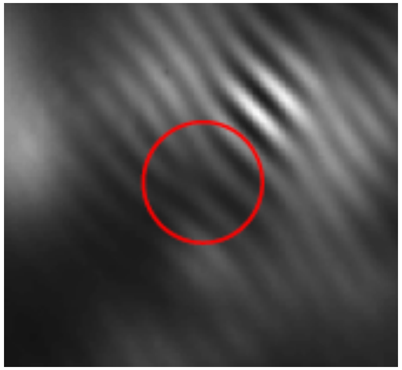
Incoherent pumping + trap





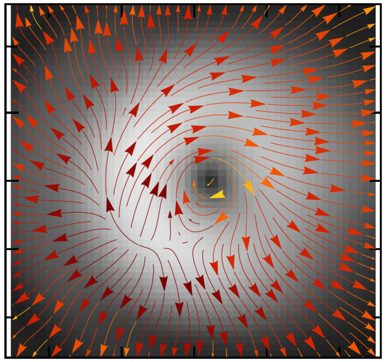
[Keeling et al., *PRL* (2008)]

Ground state with a vortex pined by disorder

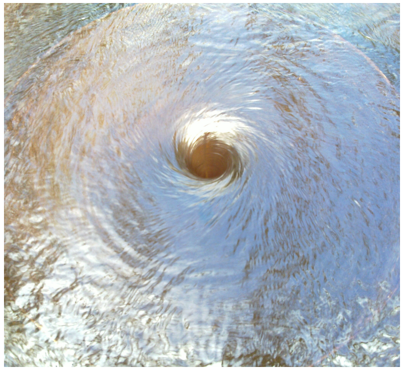


[Lagoudakis *et al.* *Nature Phys.* 2008]

OPO & no trap



[Marchetti et al., *PRL* 2010]



Windsor Savill Gardens

Vortex healing length in OPO

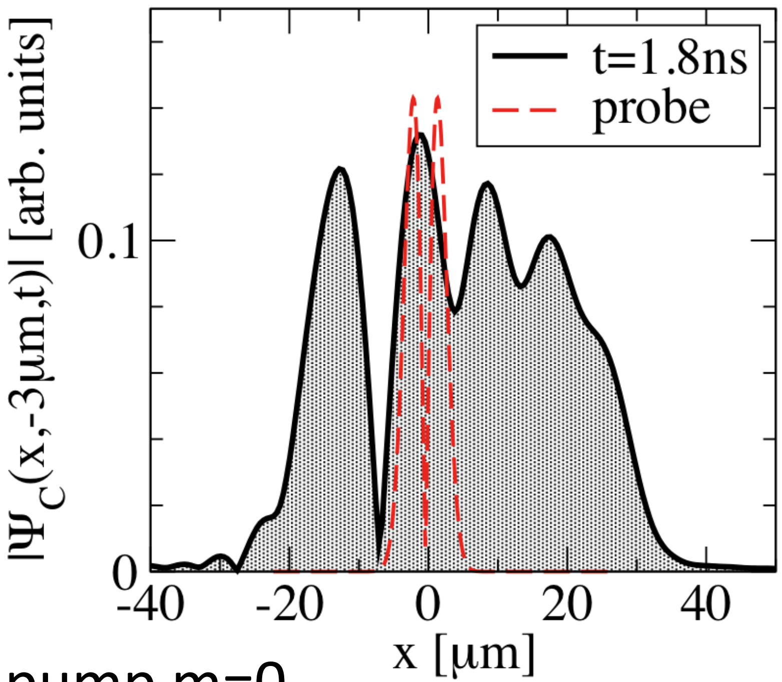
Only signal & idler carry a vortex

$$2\varphi_p = \varphi_s + \varphi_i$$
$$0 = +1 - 1$$

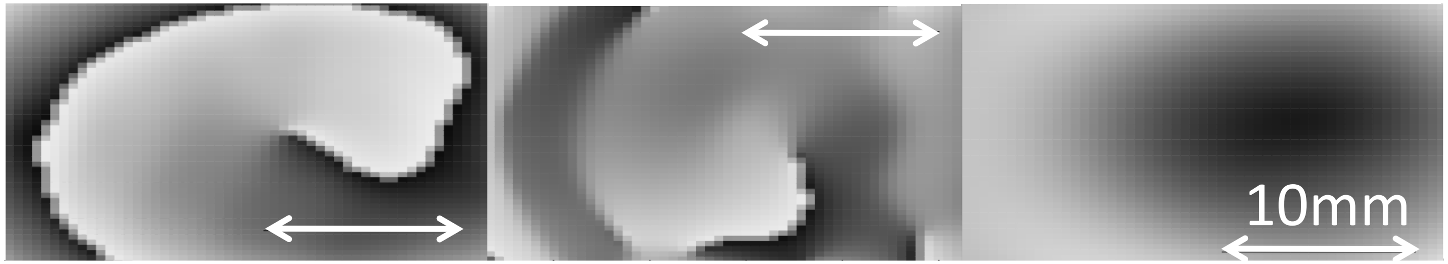
Independent on probe, but on OPO only

$$\xi \propto \left(m_C g_X \sqrt{n_s n_i}\right)^{-1/2}$$

[Marchetti *et al.*, *PRL* (2010)]



signal m=-1 idler m=+1 pump m=0



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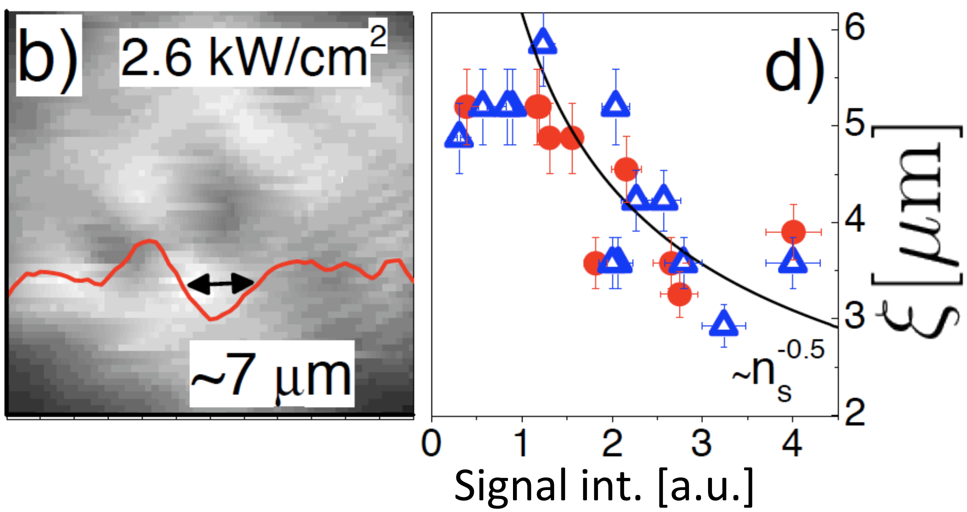
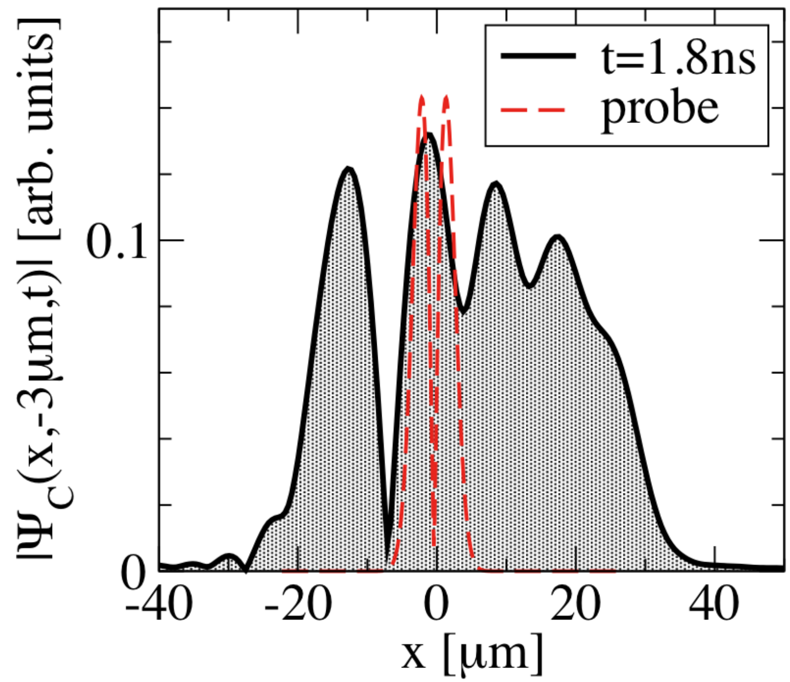


[Krizhanovskii *et al. PRL* 2010]

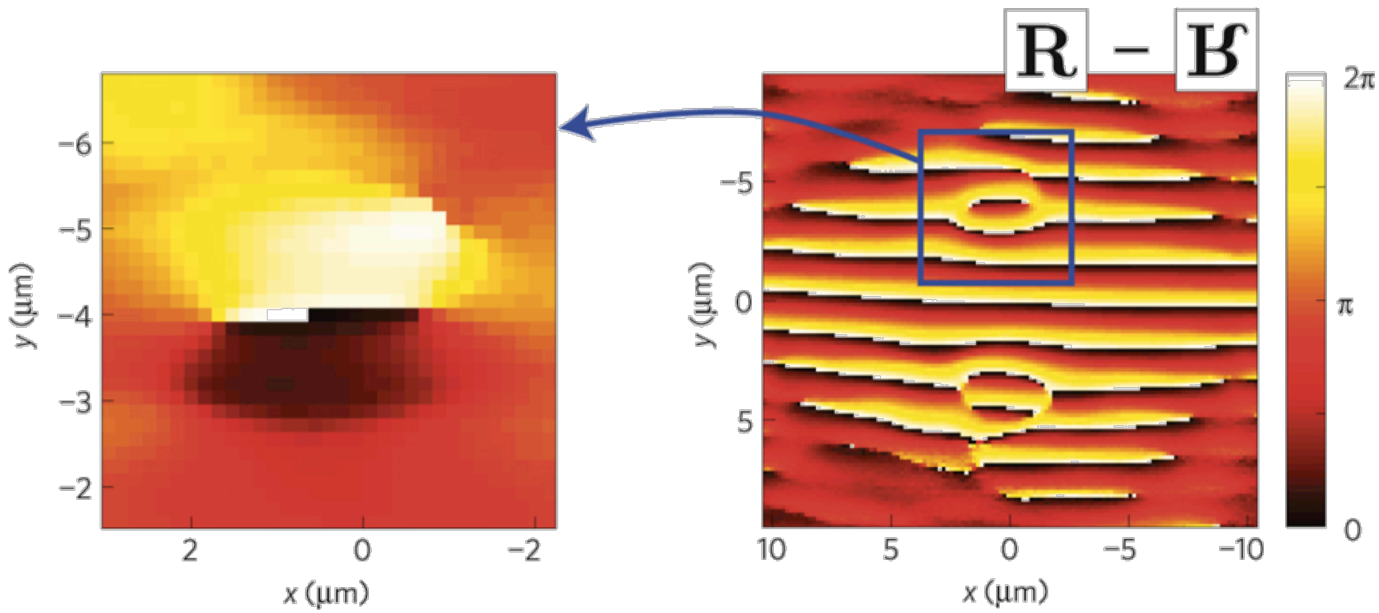
[Marchetti *et al.*, *PRL* (2010)]



checked by weak continuous-wave imprinting beam

Vortex anti-vortex pairs

- ✧ Below BKT transition: bound vortex-antivortex pairs
- ✧ Above BKT transition: pairs unbind, single vortices
- ✧ Experiment: V-AV pairs generated by intensity fluctuations of pump and inhomogeneous spot, finite lifetime

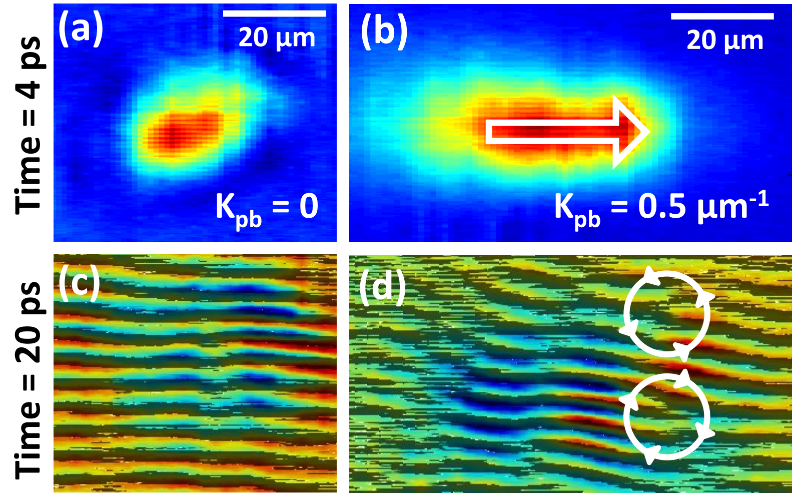


[Roumpos et al, *Nature Physics* 2010]

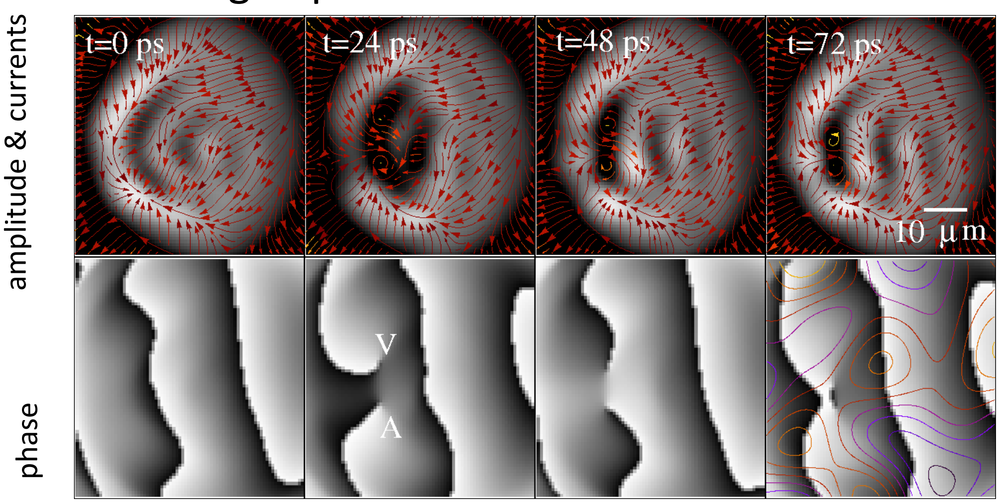
… not exactly what we are looking for but maybe related

Vortex anti-vortex pairs in polariton OPO

Probe with a finite momentum (with respect to OPO signal) triggers V-AV pairs



Averaged profile over 1000 realisations



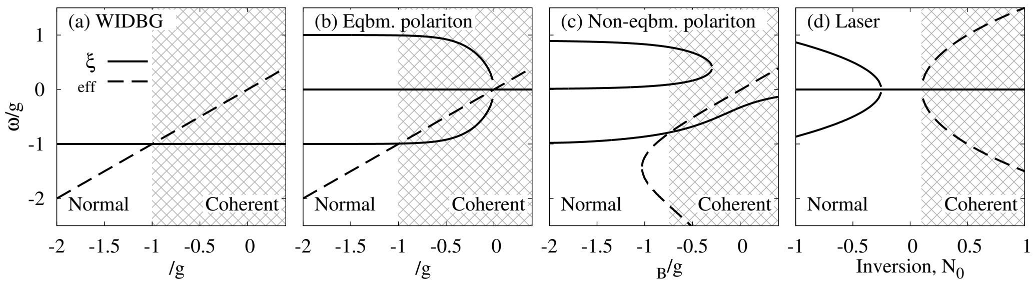
Multishot average shows V-AV pairs in density & phase

Deterministic dynamics governed by OPO steady state supercurrents

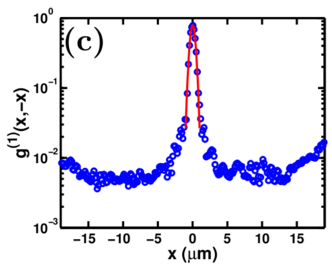
[Tosi at al, *PRL* 2011]

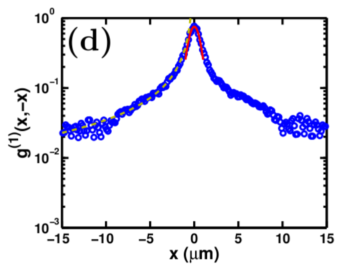
Conclusions

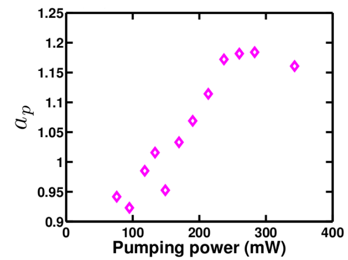
✧ Equilibirium, non-equilibirum condensation vs lasing



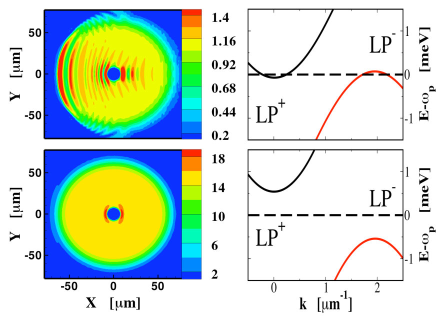
✧ Power law decay of correlations

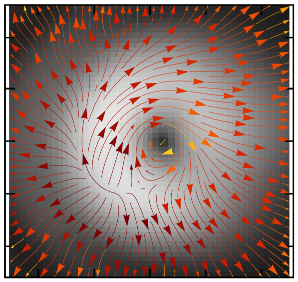


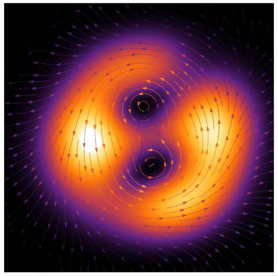




✧ Superfluid properties







Conclusions

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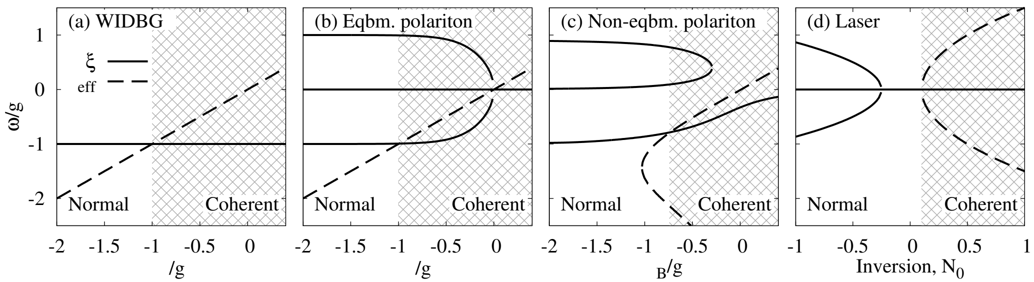

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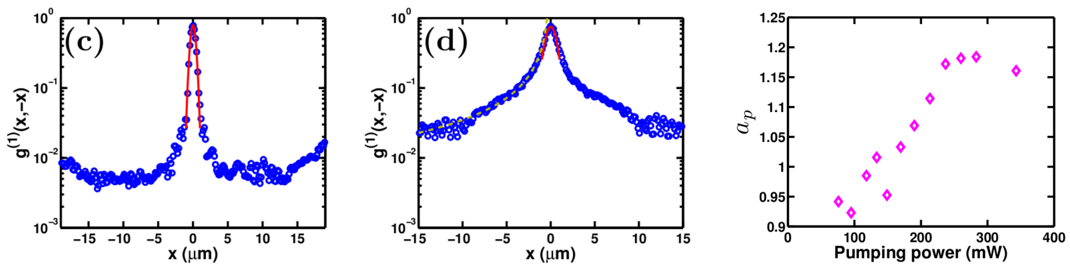

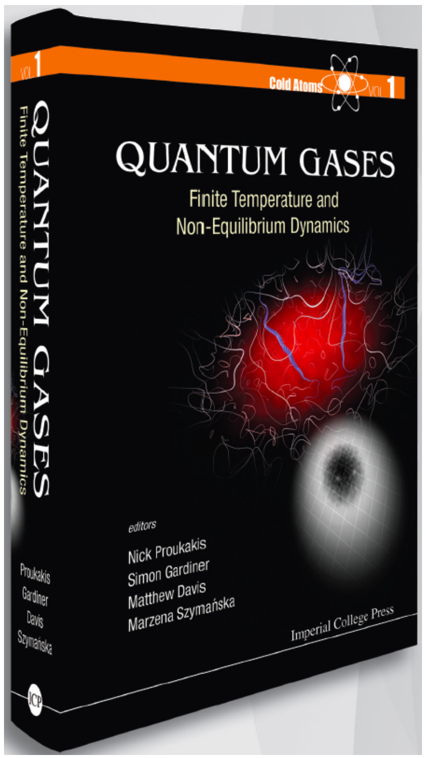

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