Spatial correlation functions & topological defects in polariton condensates

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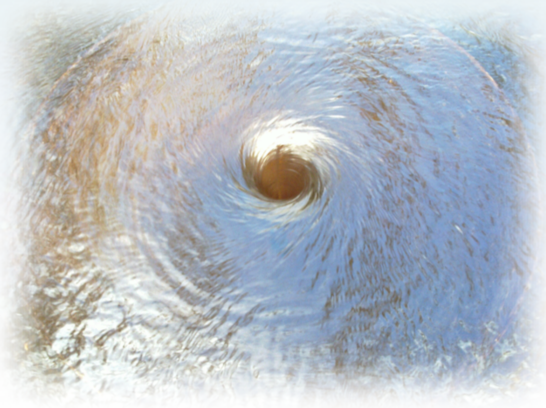
Phase Coherence and Topological Defects

Phase coherence and topological defects determine properties of quantum fluids



Quantum coherence and phases of matter

- 3D Bose-Einstein condensate

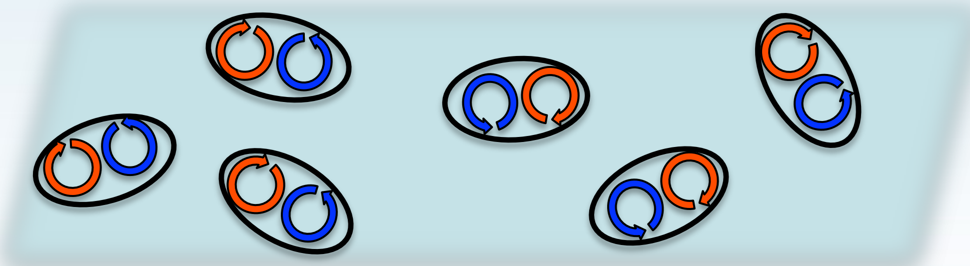
$$g_1(r,t) = \langle \psi^\dagger(\mathbf{r},t)\psi(0,0)\rangle \overset{r\to\infty}{\longrightarrow} |\psi_0|^2$$

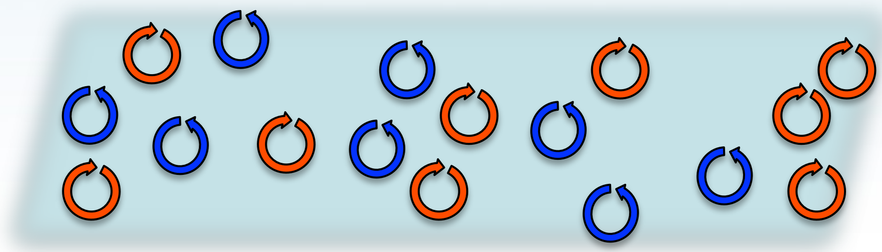
- 2D superfluid below the BKT transition

$$g_1(r,t) = \langle \psi^\dagger(\mathbf{r},t)\psi(0,0)\rangle \overset{r\to\infty}{\longrightarrow} 0$$ but slowly …

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

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





- Normal state in any dimension

$$g_1(r,t) = \langle \psi^\dagger(\mathbf{r},t)\psi(0,0)\rangle \overset{r\to\infty}{\longrightarrow} 0$$

fast exponential decay in r

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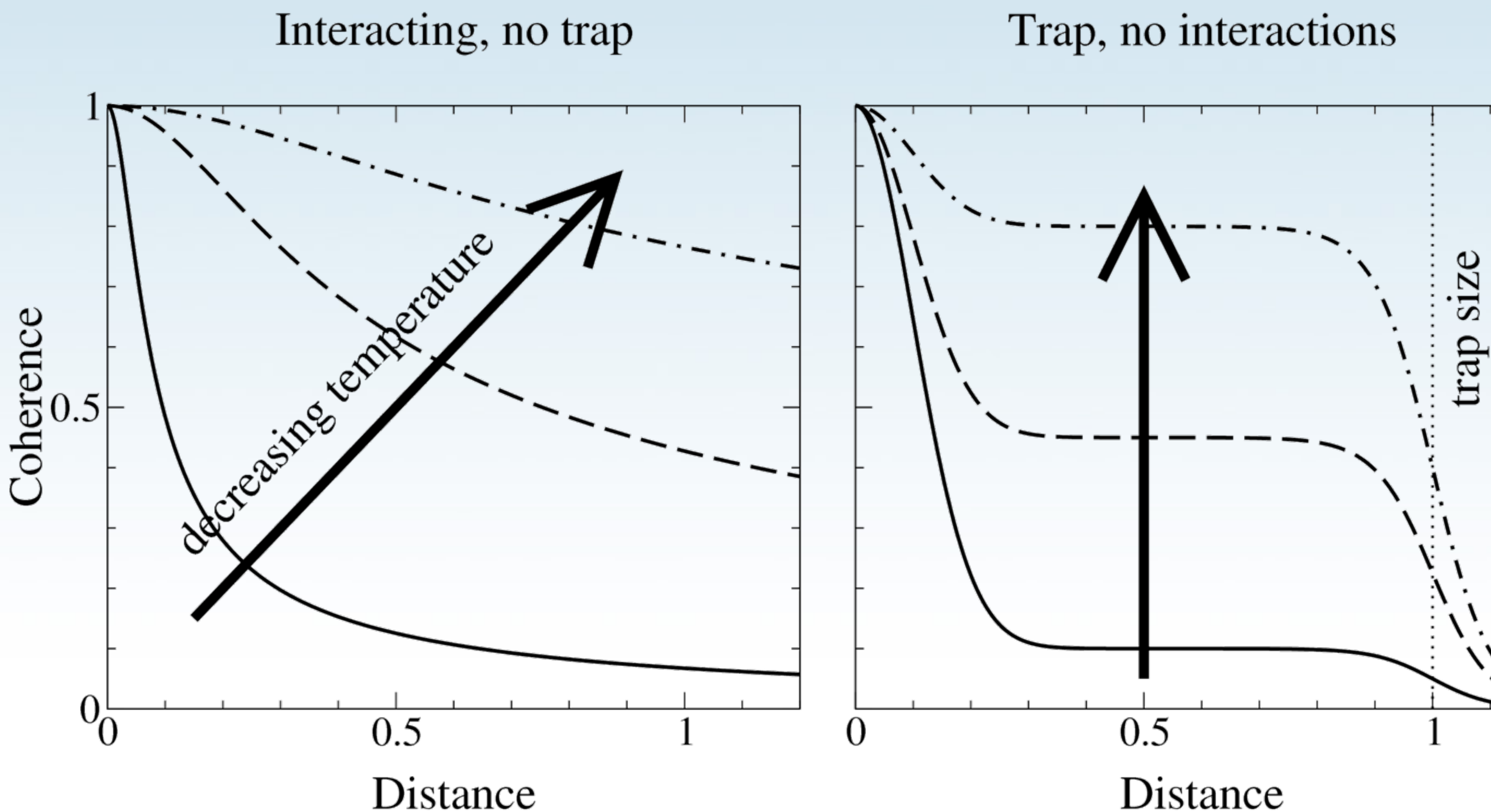
Spatial coherence in a finite 2D system

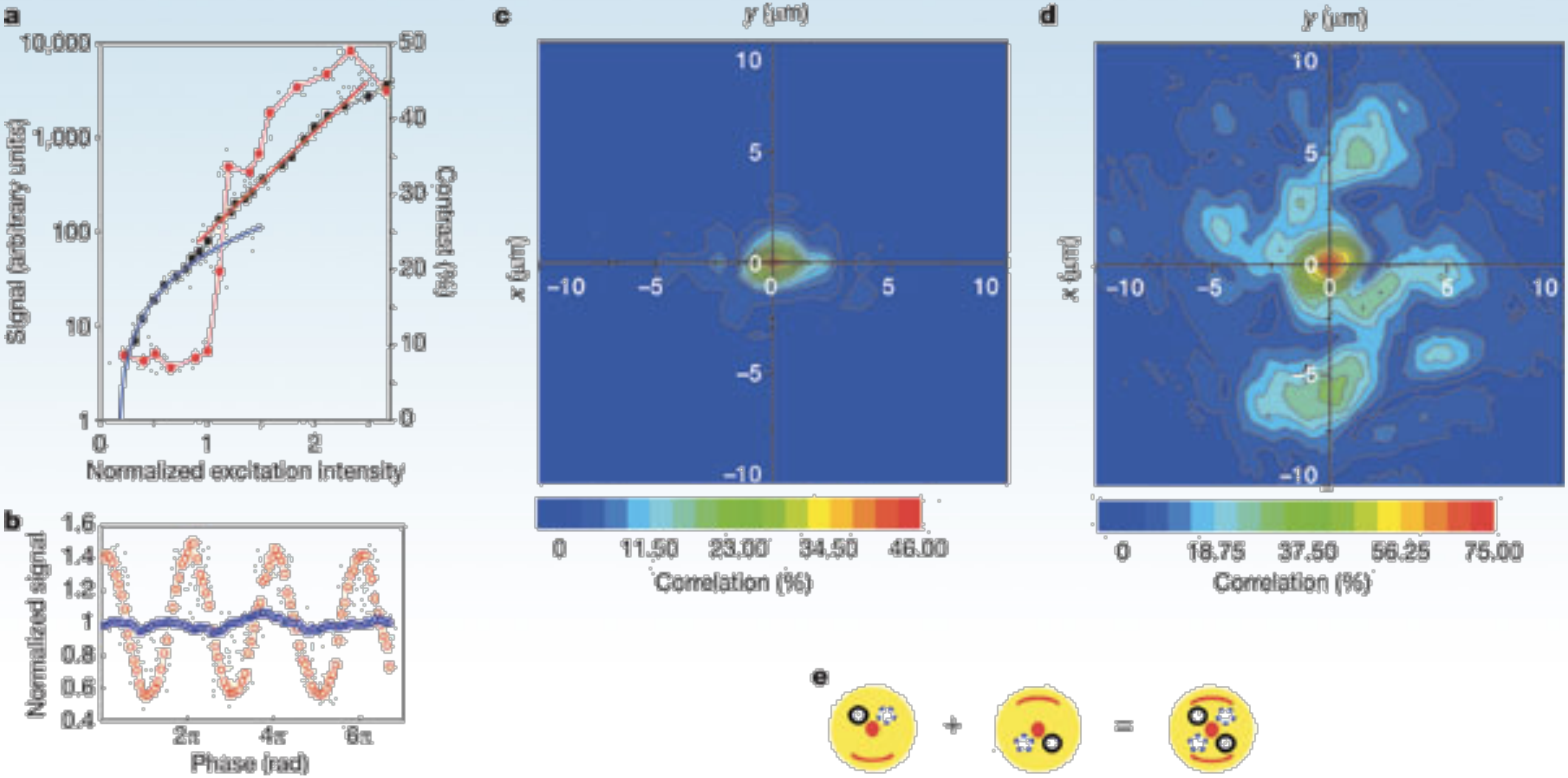
$$g_1(\mathbf{r}, -\mathbf{r}; \Delta t = 0)$$



Keeling et al. Semicond. Sci. Technol. '07

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

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Decay of coherence in general

- Fluctuations: amplitude to second, phase to all orders

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

$$D^<_{\phi\phi} = D^K_{\phi\phi} - D^R_{\phi\phi} + D^A_{\phi\phi}$$

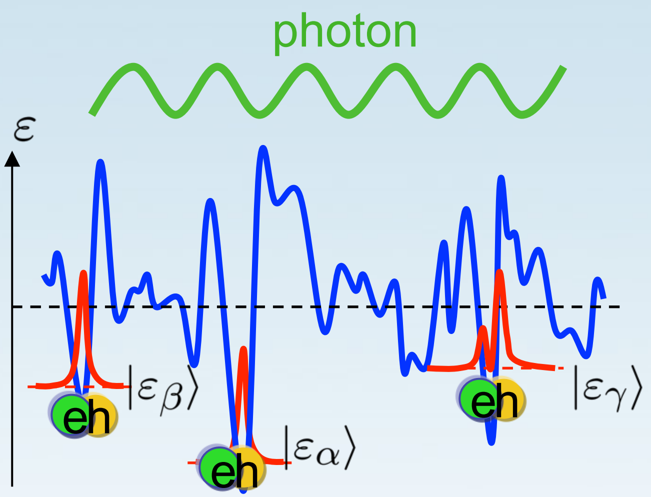
- translationally invariant 2D system

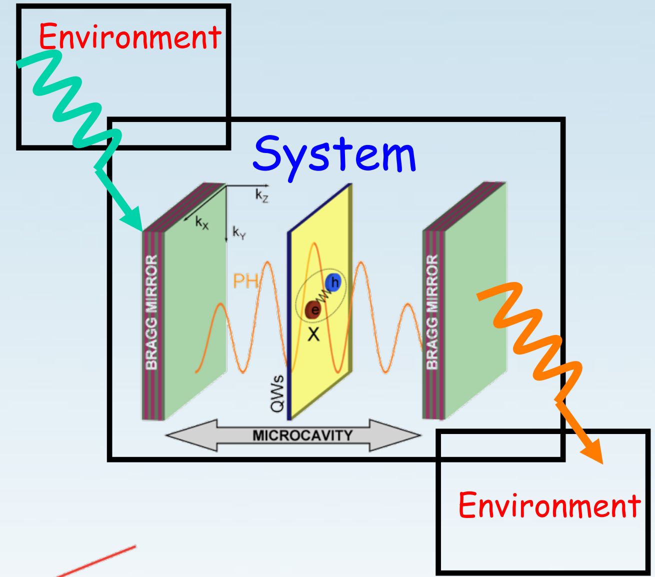
$$g_1(r,t) = |\psi_0|^2 \exp\left\{-\int \frac{kdk}{2\pi}\left[1 - J_0(kr)\right] f(k,t)\right\}$$

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

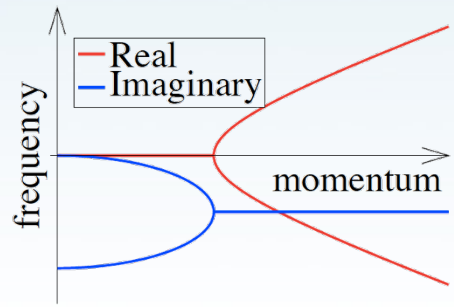
- Decay of coherence depends on
  - Dimensionality
  - Form of the excitation spectra (via D)
  - Occupation of excitations (via D^K)

Non-equilibrium polaritons





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



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

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

Szymańska et al. PRL ’06; PRB ’07

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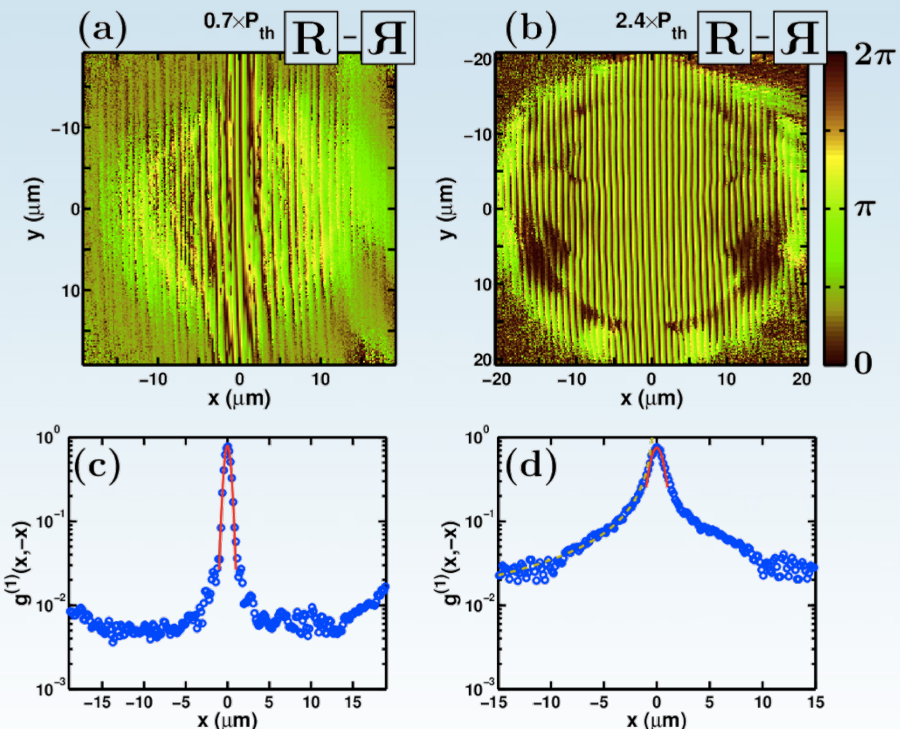
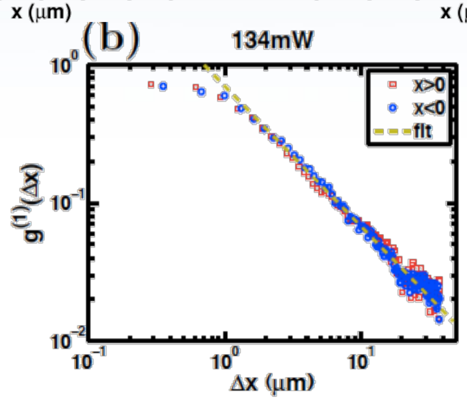
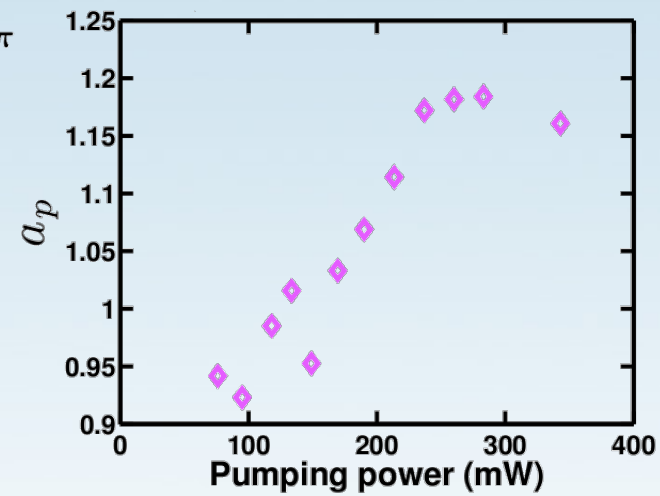
Experimental observation of power law decay







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

Roumpos et al, accepted to *PNAS* (2012)

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The simplest model

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

$$D^<_{\phi\phi} = D^K_{\phi\phi} - D^R_{\phi\phi} + D^A_{\phi\phi}$$

- Polariton Gross-Pitaevskii equation with pump and decay

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

- The spectra

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

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

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

- Phase-phase component

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

$$n_S = |\psi_0|$$

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Thermal distribution

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

$$D^<_{\phi\phi} = D^K_{\phi\phi} - D^R_{\phi\phi} + D^A_{\phi\phi}$$

- Dependent on occupation

$$[D^{-1}]^K = 2i\gamma_{\mathrm{net}} \coth(\beta\omega/2)\begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

- With thermal distribution the influence of diffusive spectra cancels!

$$\int \frac{d\omega}{2\pi} iD^<_{\phi\phi} \simeq \frac{\mu k_B T}{n_S \xi_k^2} \simeq \frac{m k_B T}{n_s \hbar^2 k^2}$$

as in equilibrium closed system

$$g_1(r) \propto \exp(-a_p \ln(r))$$

$$a_p = \frac{m k_B T}{2\pi\hbar^2 n_S}$$

Far from equilibrium flat distribution

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

$$D^<_{\phi\phi} = D^K_{\phi\phi} - D^R_{\phi\phi} + D^A_{\phi\phi}$$

- Dependent on occupation

$$[D^{-1}]^K = 2i\zeta \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$$

Before:

$$iD^<_{\phi\phi} \simeq \frac{4\gamma_{\rm net}\mu k_B T}{n_S|\omega^2 + 2i\gamma_{\rm net}\omega - \xi_k^2|^2}$$

Now:

$$iD^<_{\phi\phi} \simeq \frac{2\zeta(\mu^2 + {\gamma_{\rm net}}^2)}{n_S|\omega^2 + 2i\gamma_{\rm net}\omega - \xi_k^2|^2}$$

$$k_B T \quad \rightarrow \quad \zeta \frac{\mu^2 + {\gamma_{\rm net}}^2}{2\mu\gamma_{\rm net}}$$

- Power-law

$$g_1(r) \propto \exp(-a_p \ln(r))$$

$$a_p = \frac{\mu^2 + {\gamma_{\rm net}}^2}{2\mu\gamma_{\rm net}} m\zeta/2\pi n_s \hbar^2$$

$$\mu = \gamma_{\rm net} U/\Gamma$$

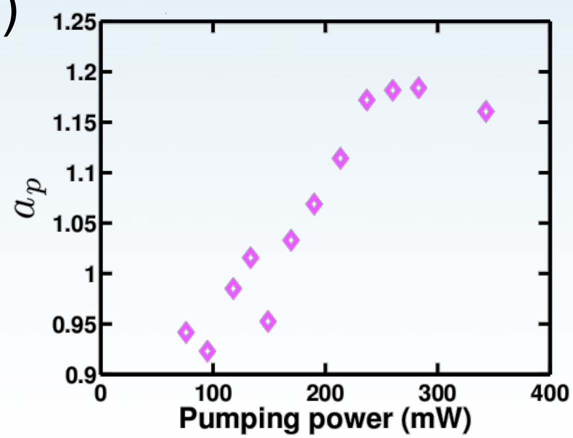
$$a_p \propto \frac{\zeta}{n_s} = \frac{\text{pumping noise}}{n_s}$$

Recap

2D condensate (with real pole) power-law decay of spatial coherence

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

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

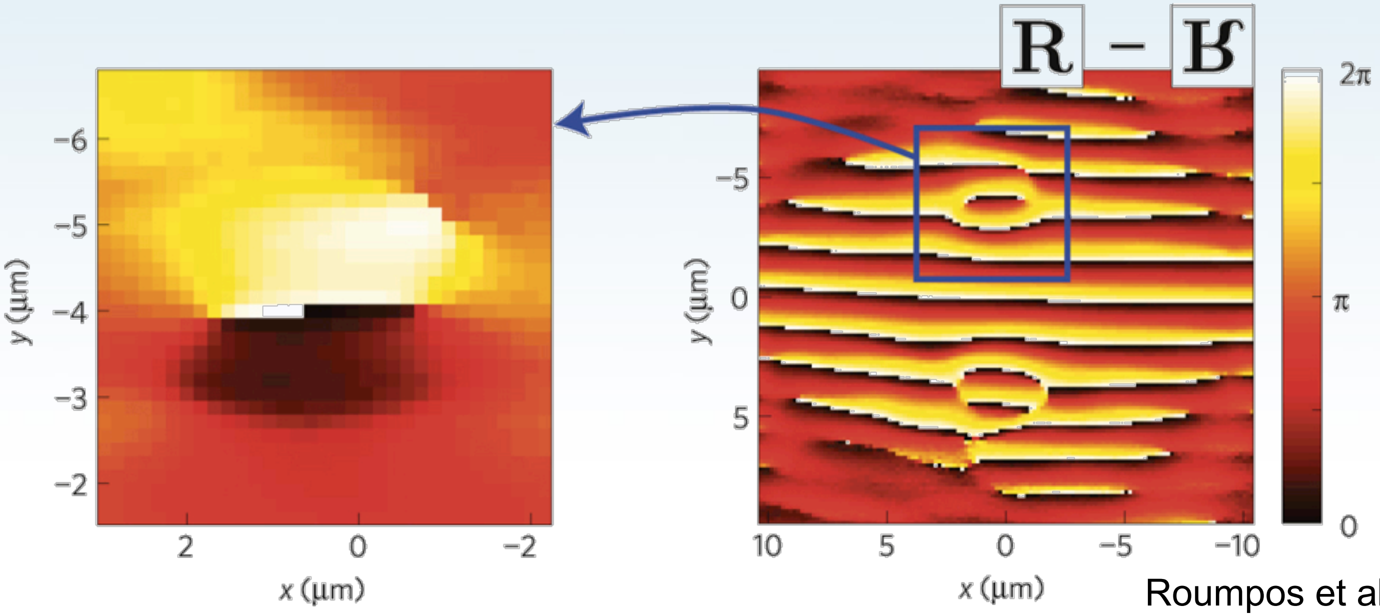


- Decay of spatial coherence measure of distribution
- BKT transition more robust then in equilibrium

Faster decay possible before vortices proliferate

Vortex-antivortex 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

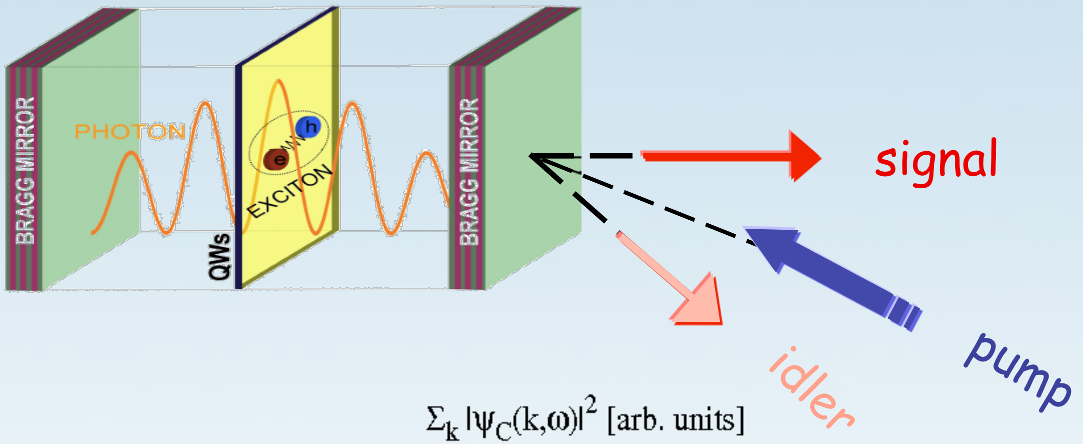


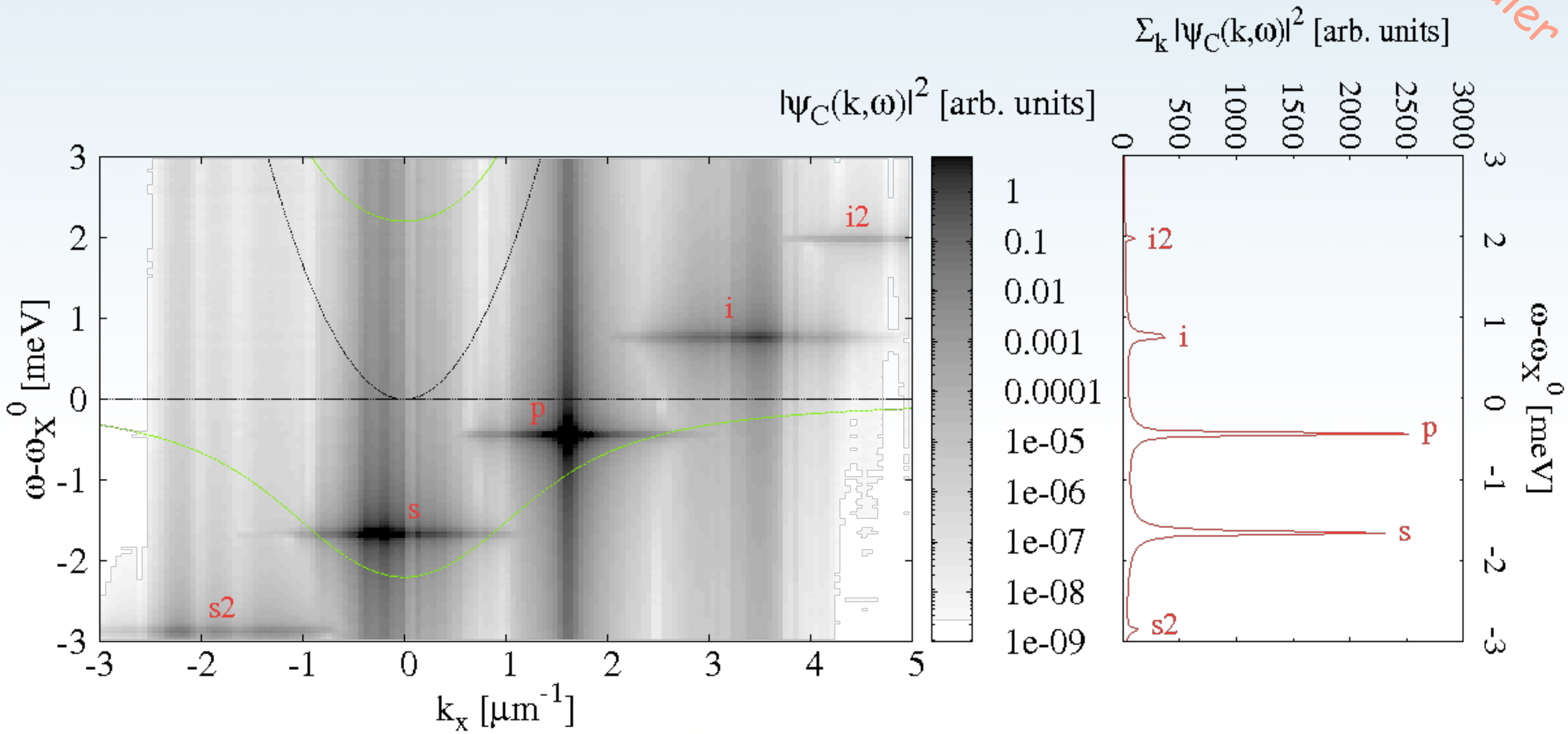
Roumpos et al, Nature Physics (2010)

… not exactly what we are looking for but maybe related

What about OPO condensate?

- Dimensionality: 2D
- Occupation: non-thermal





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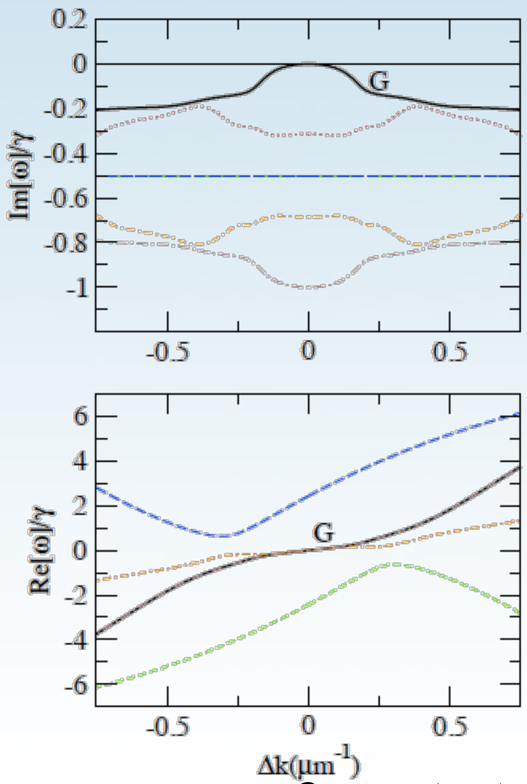
What about OPO condensate?

- Dimensionality: 2D
- Occupation: non-thermal
- Modes: diffusive but real pole at k=0 ω=0

we expect power-law with coefficient set by decay noise and non-thermal occupation



Carussoto et al (2006)

What about OPO condensate?

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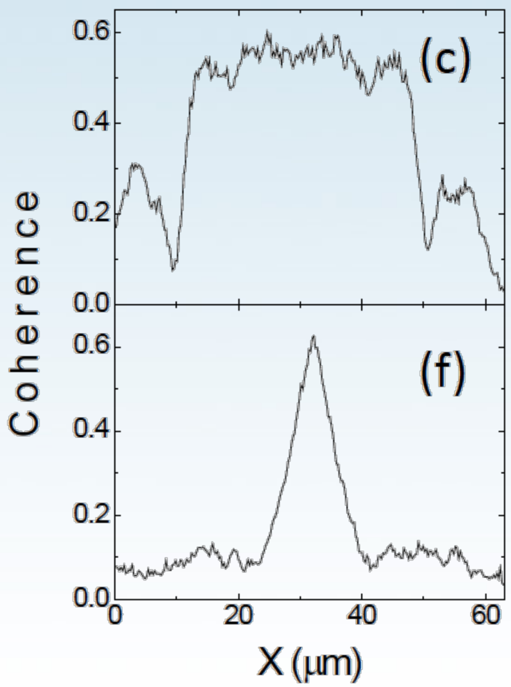
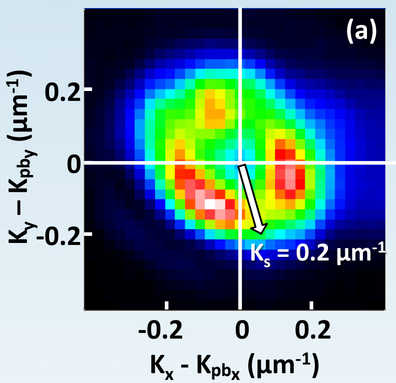


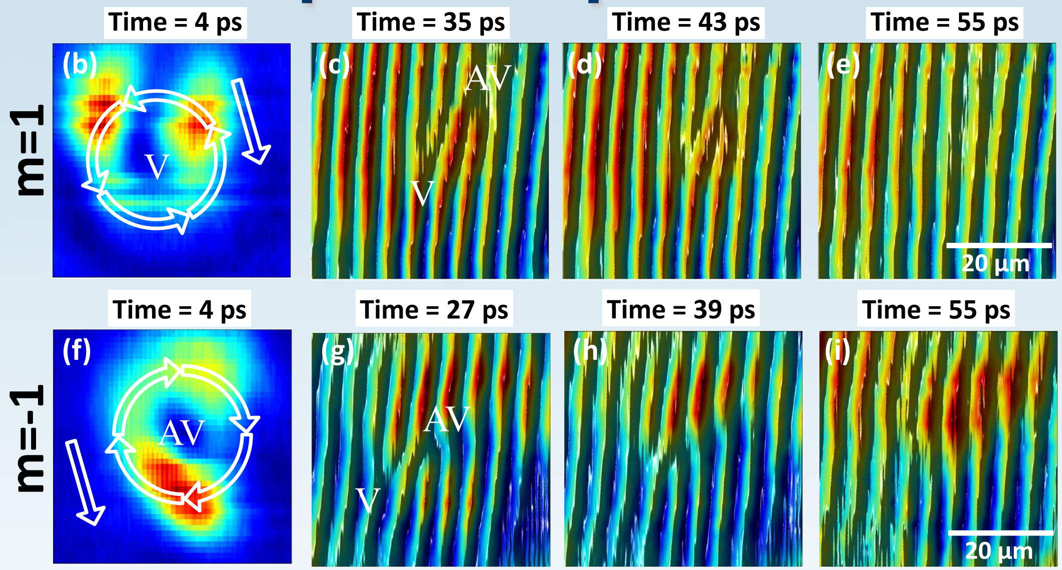
R. Spano et al (2011)

- In experiment so far roughly constant g1

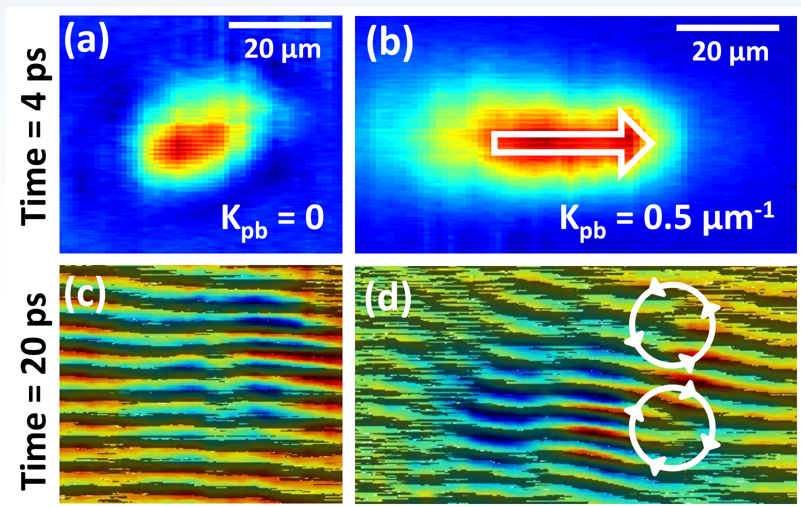
why? too small system, too far from the phase transition

Vortex-antivortex pairs in polariton OPO



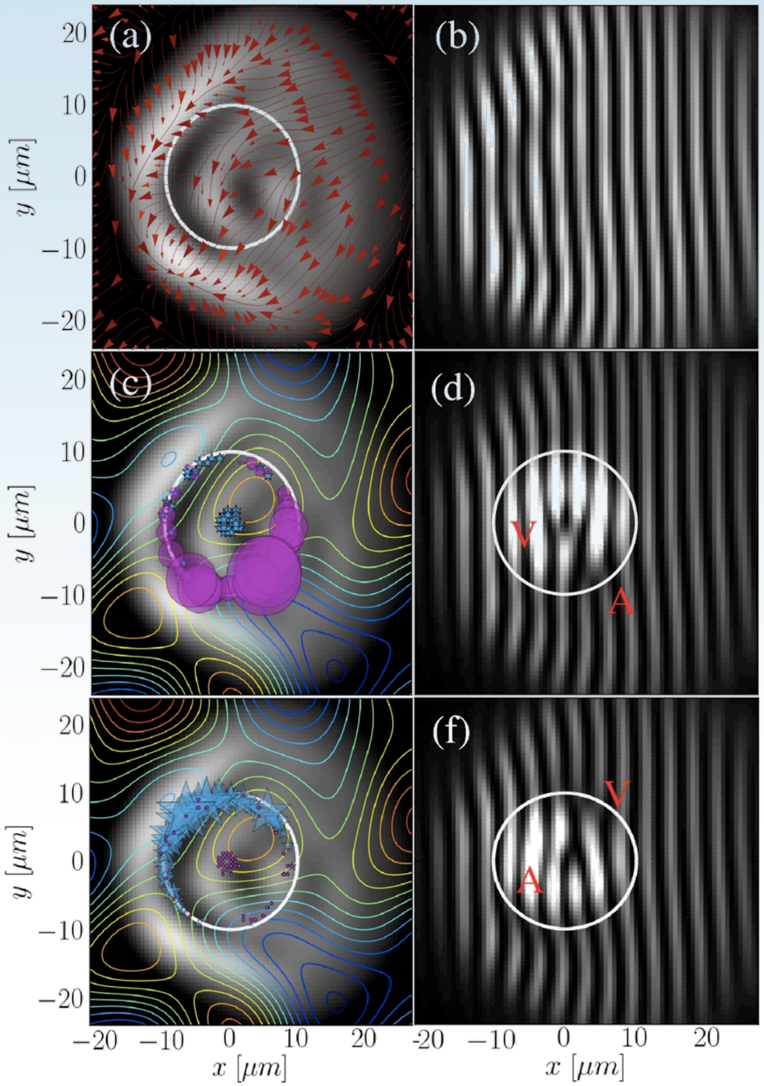


- Probe with a finite momentum (with respect to OPO signal) triggers V-AV pairs



Tosi at al, PRL (2011)

Vortex-antivortex pairs in polariton OPO

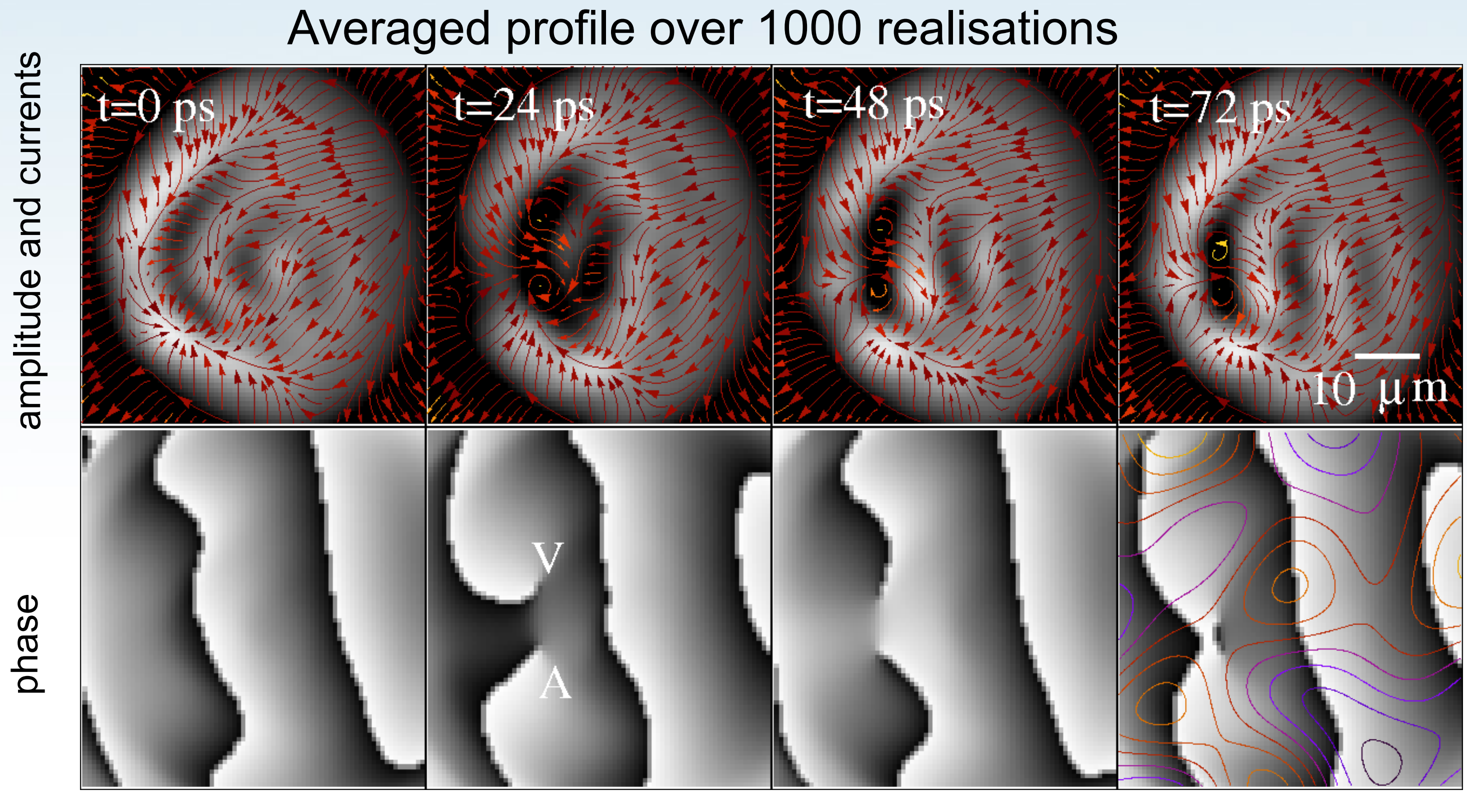


- OPO intensity & currents, phase
- 1000 realisations of a random phase between pump and probe
- Triggered vortex, antivortex appears at the edge of the probe

Tosi at al, PRL (2011)

Vortex-antivortex pairs in polariton OPO

- Multishot average shows V-AV pairs in density & phase profiles
- Deterministic dynamics governed by the OPO steady state supercurrents



Conclusions

- 2D condensate (real pole in the spectra)
  g1(r) power-law decay in equilibrium or not
- Coefficient of power-law set by occupation of excitations (pumping and decay noise)

  Observed in incoherently pumped not yet in OPO

- In 2D at equilibrium BKT transition
  - below: V-AV bound pairs
  - above: V-AV pairs unbind, free vortices

  V-AV pairs observed in incoherently pumped and OPO but …

  - not from thermal noise, triggered by external source of noise or perturbation
  - due to the supercurents deterministic dynamics & possibility to observe