Complex behavior of topological excitations in polariton quantum fluids

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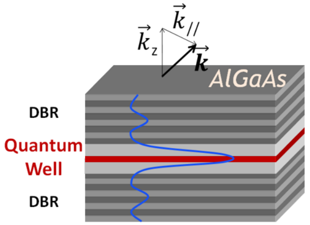
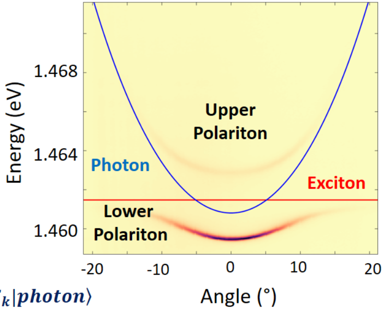
Plan of talk

- Cavity polaritons
- Solitons and vortex streets in resonantly pumped polariton quantum fluid
  - The story of domain wall propagation in bistable regime
  - Solitons stability and vortex street formation
  - Preliminary experimental results
- 2D Quantum turbulence in polariton condensates
  - Incompressible kinetic energy spectrum
  - Fractal properties of quantum vortex clusters

Exciton-polaritons - particles of fluid light





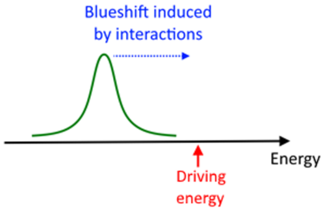
$$|polariton\rangle = X_k|exciton\rangle + C_k|photon\rangle$$

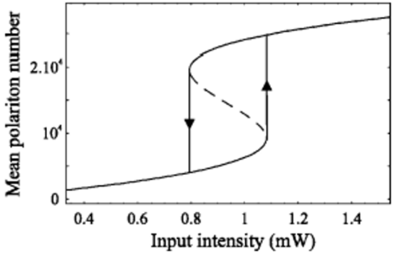
Exciton-exciton non-linear repulsive interaction
Due to photon component: excitation by laser (including SLM) and luminescence detection

Non-linear Schrodinger equation (Gross-Pitaevskii Equation, GPE):

$$i\hbar\frac{d\psi}{dt} = -\frac{\hbar^2}{2m}\Delta\psi + \underbrace{g|\psi|^2\psi}_{\text{Repulsion}} - \underbrace{i\Gamma_0\psi}_{\text{Losses}} + \underbrace{S\cdot\exp(-i\omega_p t)}_{\text{Laser Pump}}$$

Bistability in driven-dissipative GPE



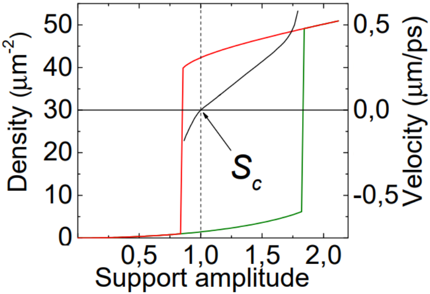


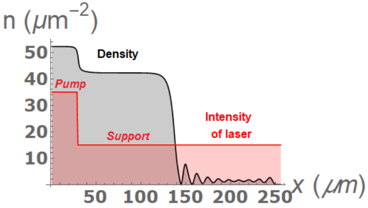
$$i\hbar \frac{d\psi}{dt} = -\frac{\hbar^2}{2m}\Delta\psi + \underbrace{g|\psi|^2\psi}_{\text{Repulsion}} - \underbrace{i\Gamma_0\psi}_{\text{Losses}} + \underbrace{S \cdot \exp(-i\omega_p t)}_{\text{Laser Pump}}$$

- Repulsion results in blueshift
- At upper bistability branch polaritons are in phase with Laser
- At lower branch polaritons have $\approx \pi$ phase shift

Solitons in the corridor with pump walls

Domain wall propagation in free space





Critical support:

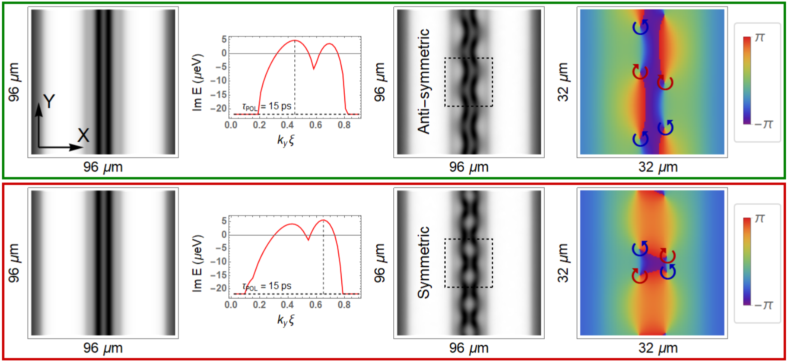
$$\boxed{S_c = \frac{2(\hbar\omega_p)^{3/2}}{3\sqrt{3}g^{1/2}}}$$

The domain wall **velocity** can be found as

$$v = \frac{\partial n}{\partial t}\frac{\Delta x}{\Delta n} \quad \text{and} \quad \frac{\partial \psi}{\partial t} = \frac{S - S_c}{i\hbar} \quad \rightarrow \quad \boxed{v \approx \sqrt{n_0}\frac{S - S_c}{\hbar}\frac{\xi}{n_0}}$$

Domain wall moves left ($S < S_c$) or right ($S > S_c$) depending on the value of the **support** S.

Development of snake instability

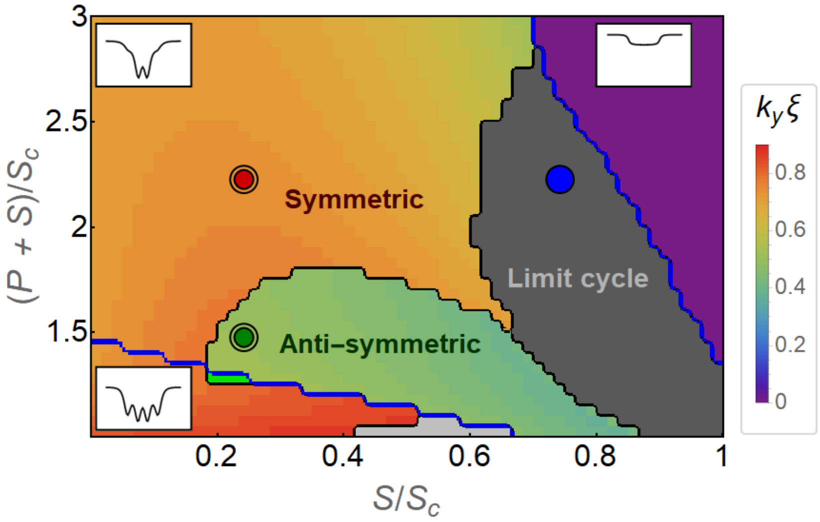


- The dispersion $\mathrm{Im}\{E(k_y)\}$ defines the intervortex distance:

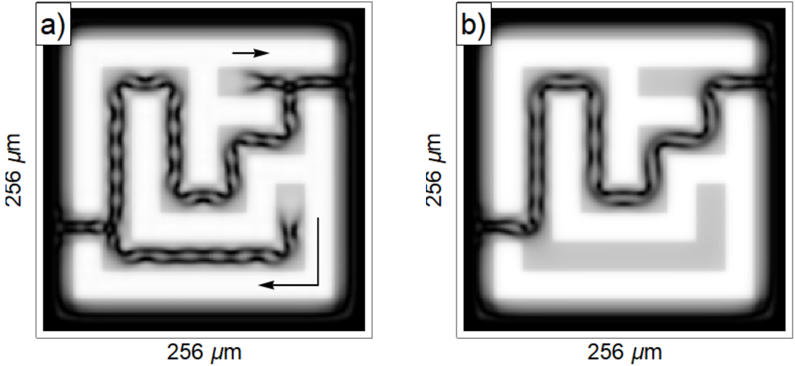
$$\frac{\pi}{D_{\mathrm{intervortex.}}} = k_y^{\mathbf{max}}$$

- Number of unperturbed solitons = number of peaks in dispersion
- Bonding and anti-bonding "orbitals" in bogolon "molecules"

Phase diagram Pump/Support

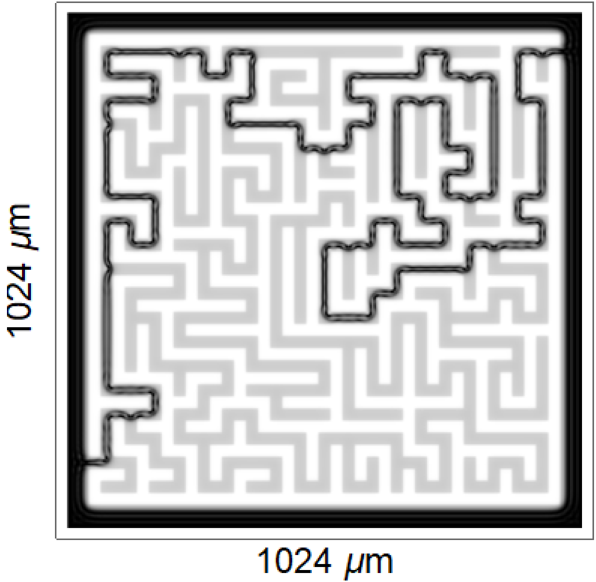


The solitons can be used to solve the maze

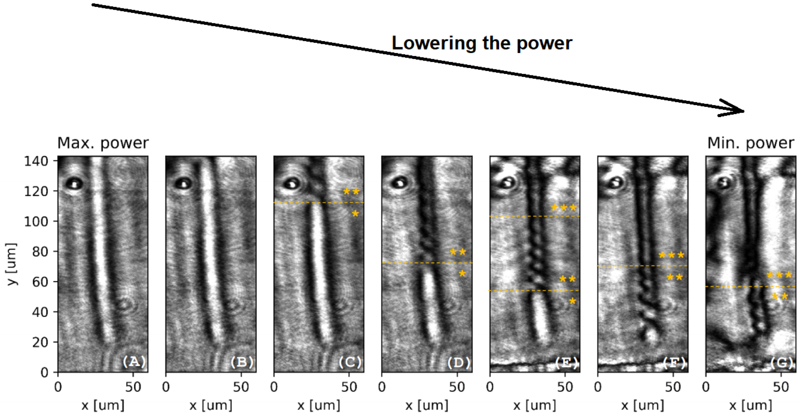


- Soliton goes out of a dead-end. This is also domain wall motion but along "**Y direction**"
- One sees the periodical pattern along the solitons in long corridors. This is again a **modulation instability**
- Oscillations are stabilized by already developed instability

... the really big maze



Vortex streets guided by dislocations



$\star$ - High dens. $\star\star$ - Bist. loop $\star\star\star$ - Linear

Preliminary experimental data by LKB, Sorbonne Universite, CNRS

2D quantum turbulence

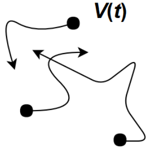
Main issues of 2D quantum turbulence

- In classical 3D turbulence the direct energy cascade exists and Incompressible Kinetic Energy (IKE) spectrum $E(k) \propto k^{-5/3}$ (Kolmogorov exponent)
- In 2D quantum turbulence existence and direction of the cascade are not a closed questions
- Are cavity polaritons suitable quantum fluid system to experimentally study the energy cascade?
- Their favorable features are control of wave function by SLM and possibility to fully reconstruct phase and amplitude of wave function

Here we study **conservative** case (no Γ term in GPE) to trace long-time evolution inaccessible at present level:

$$i\hbar \frac{\partial \psi}{\partial t} = \left[-\frac{\hbar^2 \Delta}{2m} + V(t) + g\,|\psi|^2 \right] \psi$$

Stirring by moving potential $V(t)$

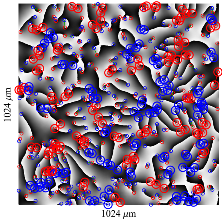


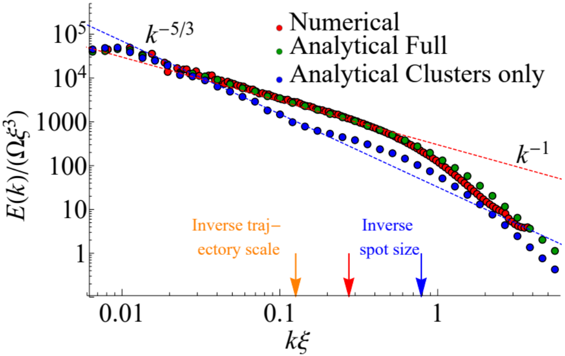
Size: 1024 um x 1024 um

Mesh: 1024 x 1024

Density: ~200 um^{-2}

Interaction strength *g*: 0.005 meV um^{2}



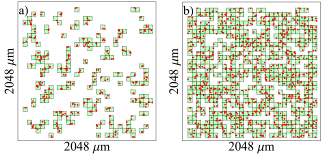


IKE spectra for all vortices and for **clustered vortices**

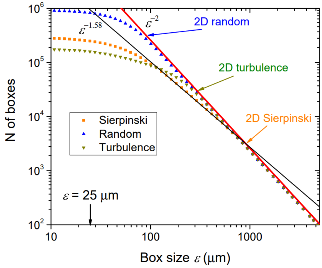
k^{-1} is for single vortex spectrum

$k^{-5/3}$ is seen for clustered vortices

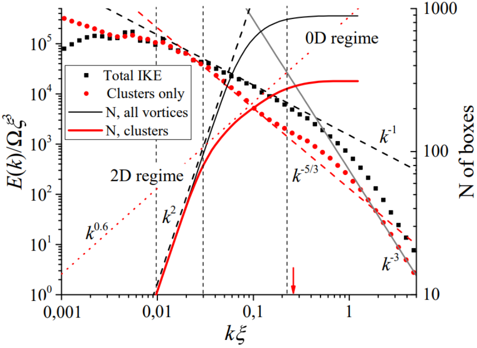
Fractal nature of vortex clusters



Example of box counting for clustered vortices a) and all vortices b)



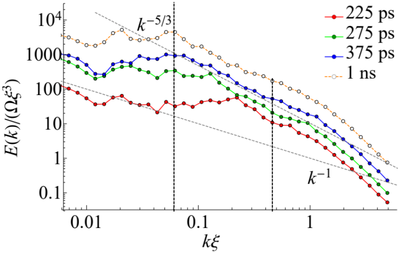
Fractional Minkowski dimension $\frac{\ln N(\varepsilon)}{\ln(1/\varepsilon)}$



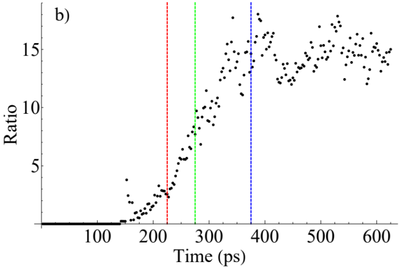
Box count N vs IKE spectrum $E(k)$

The region of **fractional dimension** matches with region **-5/3 exponent** in IKE spectrum

Time dynamics of IKE spectrum formation



IKE spectra at various time moments



Ratio of energy stored at long wavelengths and short wavelengths

Thanks for your attention!