Inverse energy cascade in two-dimensional dissipative quantum turbulence

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The experimental investigation of quantum fluid dynamics, started in criogenic helium, has recently received a new boost thanks to the ability to create $3D$ or quasi-$2D$ Bose Einstein condensates in chaotic regimes [1,2]. In the $2D$ case, the theoretical framework of classical turbulence prescribes a mean energy transfer from small to larger scales, and a universal Kolmogorov-like $-5/3$ power law scaling of the kinetic energy spectrum. We experimentally demonstrate the existence of a turbulent inverse cascade in 2D quantum fluids of exciton-polaritons, hybrid light-matter quasiparticles with a finite lifetime. Thanks to optical measurements of the velocity field with an unprecedented control over the vortex dynamics, we are able to obtain a direct measure of the spectrum of the incompressible kinetic energy of the quantum fluid[3]. This exhibits a clear $-5/3$ scaling in a range of scales limited by the trap dimension and the healing length of the system. We relate the inverse energy cascade to the onset of vortex clustering in the quantum fluid. We demonstrate that the formation of clusters of quantum vortices is triggered by the increase of the incompressible kinetic energy per vortex, showing the tendency of the vortex gas towards highly excited states despite the dissipative nature of our system. These results pave the way for the study of turbulence in two-dimensional quantum fluids and enable future experiments of out-of-equilibrium regimes in nonlinear optical systems.

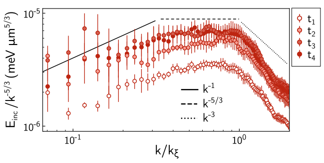

Figure 1: Time evolution of the compensated spectrum of the incompressible kinetic energy showing the buildup of the inverse cascade, in the initial stage of the experiment (t1 and t2), and in the fully turbulent stage (t3 and t4). The largest- and smallest-scale ranges behave according to the theoretical predictions $\propto k^{-1}$ and $\propto k^{-3}$, due to a collection of vortices in the far-field, and the internal structure of a vortex, respectively. The wavenumber in the horizontal axis is normalised to the wave-number at the healing length ξ, i.e. $k_\xi = 2\pi/\xi$.

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[1] White, Anderson, and Bagnato, *PNAS* **111**, 4719–26 (2014).
[2] Gauthier *et al.*, *Science*, **364**, 1264 (2019); Johnstone *et al.*, *Science*, **364**, 1267 (2019).
[3] Panico *et al.*, *Nat. Phot.* to appear (2023).