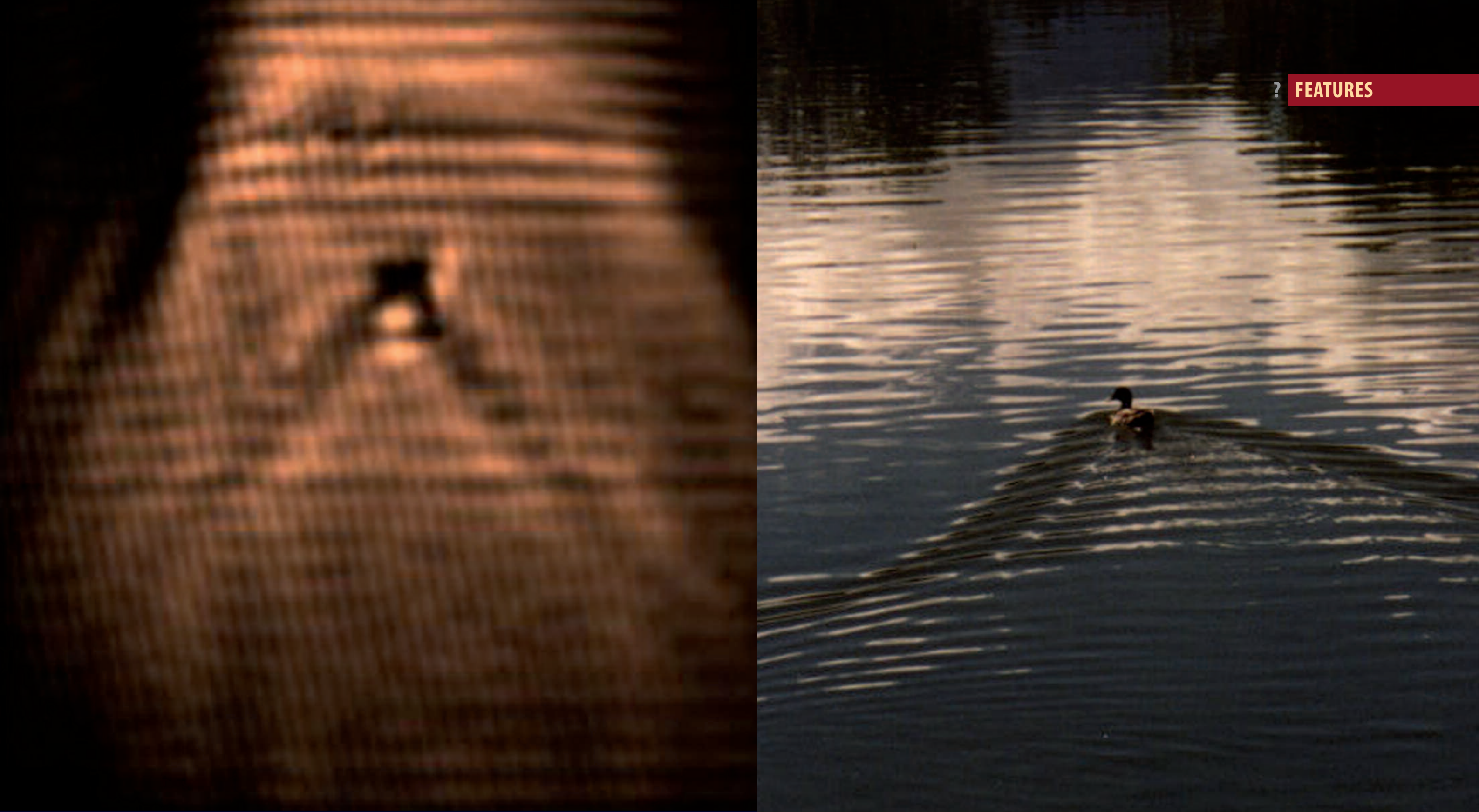

SWIMMING IN A SEA OF SUPERFLUID LIGHT

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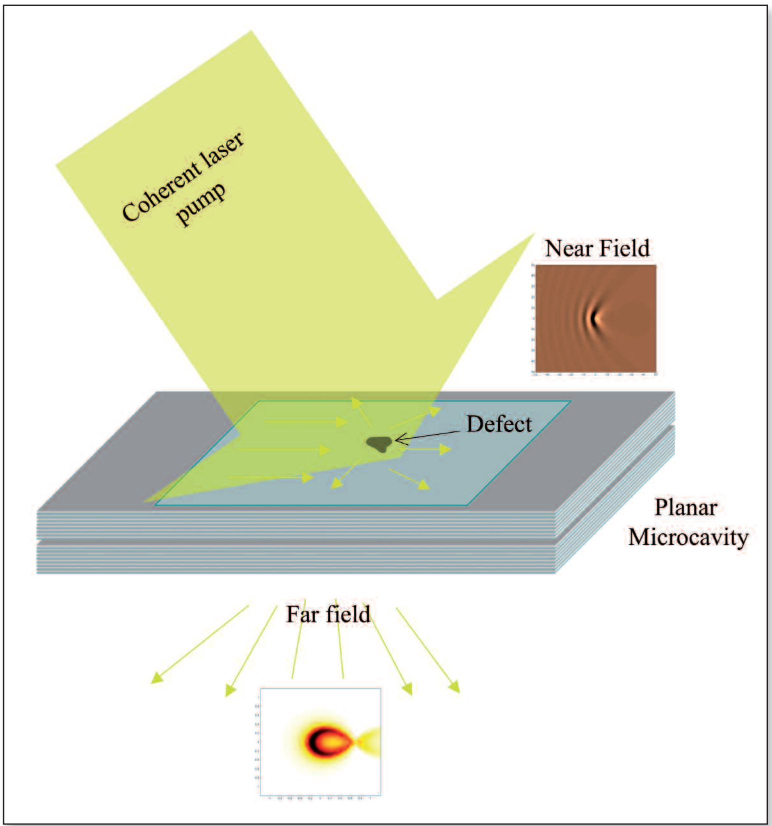
An implicit assumption of Newton's corpuscular theory is that the basic constituents of light do not mutually interact. Once they have been emitted by the source, they travel through homogeneous media along straight lines until they get reflected, refracted or absorbed. What would have happened had Newton foreseen the possibility of efficient collisions between these corpuscles? Would he have imagined the possibility of having a kind of luminous liquid of such particles?

▲ **FIG. 1:** Left hand panel. Experimental image of the Cherenkov-like wake pattern created by a defect in a flowing photon fluid (courtesy of A. Amo *et al.*, Laboratoire Kastler-Brossel, Université Paris 6 and CNRS, France). Right hand panel: wake pattern behind a swimming duck (photograph courtesy of Fabrice Neyret, ARTIS-CNRS, France).

To the best of our knowledge, it is not clear whether such questions ever crossed Newton's thoughts. In the following decades, the rising success of Huygens' wave theory of light completely deflected the interest of the physics community from these speculations. Even though the corpuscular theory of light had a sudden revival at the beginning of the twentieth century when Einstein put forward his theory of the photo-electric effect, the idea of observing collective hydrodynamic behaviour in a fluid of interacting photons had to wait another few decades until the very recent spectacular observations of superfluidity of light.

Light and quantum gases: historical developments

The first evidence of interactions between light waves was reported in the early 1960's, soon after the first demonstration of laser operation, inaugurating the novel field of nonlinear optics. So far, most textbook presentations of non-linear optics are based on a purely wave picture of light based on Maxwell's equations including a nonlinear polarization term. Given the weak value of the nonlinear susceptibility of most optical media, nonlinear optical experiments require in fact the use of strong fields containing a huge number of photons. In this regime, the coherent field approximation underlying



▲ **FIG. 2: Sketch of a planar microcavity system resonantly excited by a coherent laser field. The continuous-wave laser beam injects photons, which propagate along the cavity plane. The photon density is controlled by the laser intensity; the excited cavity photon field oscillates at the same frequency as the incident laser; the cavity photon flow velocity is tuned by changing the laser incidence angle. Near-field microscopy of the emitted light gives direct access to the real-space photon density profile, while far-field angle-resolved measurements provide the momentum distribution. Scattering of the flowing photons occurs on either natural or artificial defects. The injected photons can display a collective fluid behavior as soon as the microcavity embeds a material with a sizable optical nonlinearity.**

Maxwell's equations provides an extremely accurate picture of most nonlinear optical phenomena. The small quantum corrections due to the corpuscular nature of light are generally described in terms of the so-called quantum fluctuations around the classical field. In practice, including these corrections is necessary only when shot noise becomes an issue or the device is specifically designed to highlight some quantum features.

The historical evolution of our understanding of gases has followed a specular path: since Demokritus' atomistic hypothesis, the picture that one learns at school involves an assembly of point-like material objects flying across the container and interacting with each other via frequent binary collisions. These collisions guarantee that the gas is able to locally relax to a thermal equilibrium state, which in turn allows for a hydrodynamic description of the system. This purely corpuscular description is accurate as long as the thermal de Broglie wavelength $\lambda_{dB} = (h^2/2\pi m k_B T)^{1/2}$ of the particles is much shorter than the mean inter-particle distance. The situation changes drastically at lower temperatures, when the wave nature of the indistinguishable particles starts playing a crucial role as well as their Bose (or Fermi) statistics.

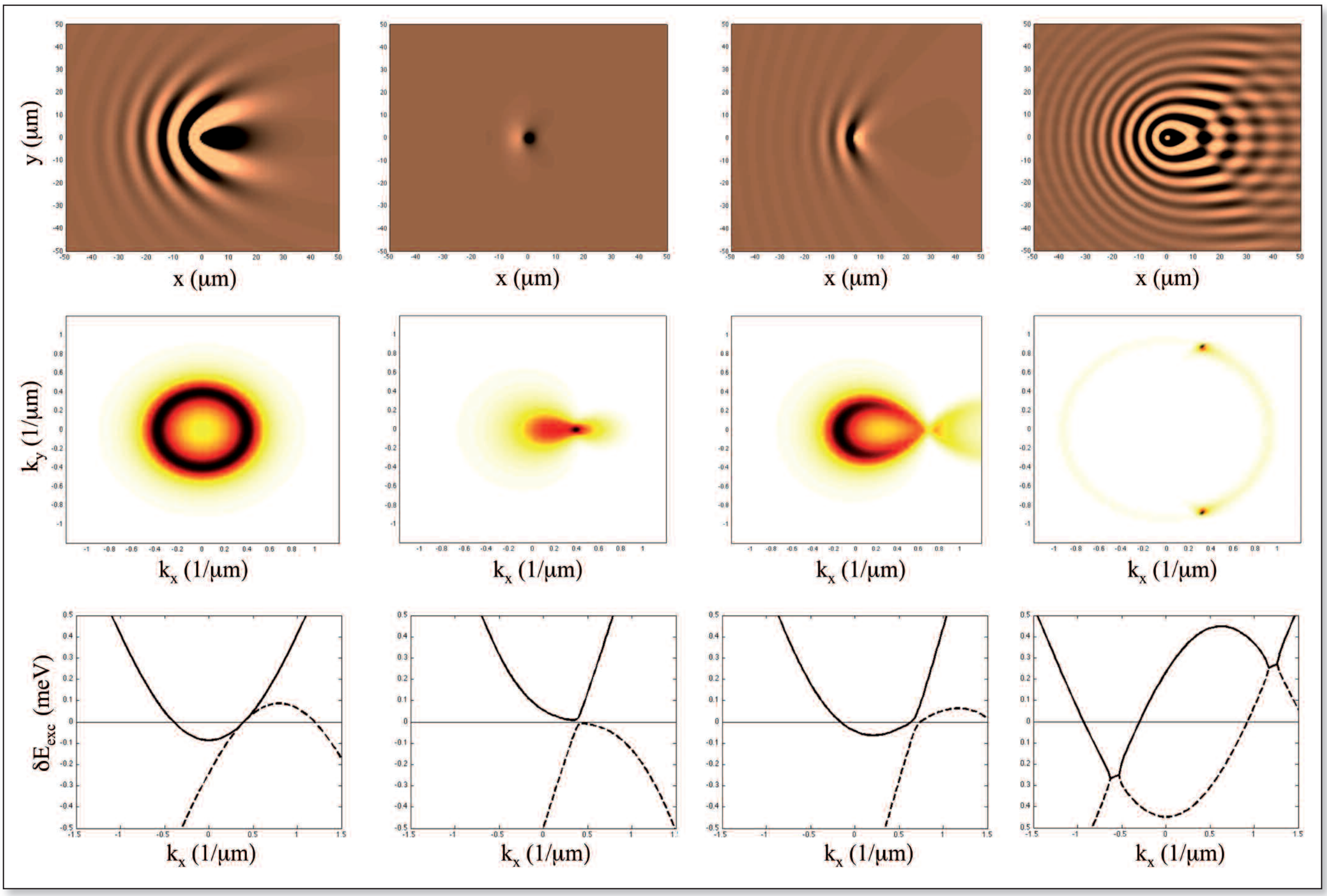
Bose-Einstein condensation is among the most dramatic consequences of quantum statistics. The ground state of a weakly interacting gas of integer-spin Bose particles sees most of the constituent bosons being piled up into a single quantum state and sharing the same one-particle wave function. The evolution of such a Bose-Einstein condensate can then be described in terms of a complex-valued classical matter field that evolves according to a nonlinear Schroedinger equation for the macroscopic wave function, the so-called Gross-Pitaevskii equation. In a nutshell, the material particles are losing memory of their corpuscular nature, which is taken over by their wave character.

Quantum hydrodynamics of a Bose-Einstein condensate then shares many analogies with nonlinear optics. The Gross-Pitaevskii equation for the Bose-condensed atomic matter field plays the same role as Maxwell's equation for the electromagnetic field in a nonlinear optical medium. The nonlinear term describing binary atom-atom interactions corresponds to the nonlinear polarization contribution. Since its original proposal in the early 1960's, the Gross-Pitaevskii equation has turned out to be an extremely useful tool to describe the peculiar quantum hydrodynamic properties of superfluids, *e.g.*, their ability to flow without any apparent dissipation along a pipe even in the presence of some wall roughness.

Collective effects in photon hydrodynamics

Stimulated by the striking success of the description of a Bose-condensed gas of material particles in terms of a coherent matter wave, in the late '80s researchers started undertaking the opposite path, trying to transpose ideas from quantum hydrodynamics to the emerging field of nonlinear optics. Specific attention was paid to collective behaviour. Among the first developments in this direction, pioneering studies of quantized vortices in laser devices unveiled a fascinating description of the field dynamics in terms of superfluid hydrodynamics of an optical fluid [1]. In particular, it was soon realized that two-dimensional planar microcavity geometries such as the one sketched in Fig.2 can offer interesting advantages in view of the experimental manipulation and diagnostics of the fluid via the incident and the emitted light, respectively [2]. This development immediately pinpointed a most significant difference between optical fluids and traditional, condensed-matter ones. While the basic constituents of matter (e.g. Helium atoms) are stable particles for cosmologically long times, photons have a finite and short lifetime (of the order of picoseconds in typical semiconductor microcavity systems). To maintain a stationary state, the light fluid then needs to be continuously replenished by some pumping mechanism and its non-equilibrium stationary state arises from a dynamical balance between pumping and losses rather than from a true thermal equilibrium state. The first theoretical studies of quantum fluid effects in optical systems were presented and discussed in Ref. [3]. The fundamental analogies and differences between a standard close-to-equilibrium Bose fluid and the non-equilibrium photon fluid were later explored in Ref. [4]. In particular, it was shown how the scattering from defects in the microcavity can be efficiently suppressed by judiciously choosing the driving laser parameters. This regime of photon superfluidity is illustrated in the second column of Fig.3. Note in particular the disappearance of the resonant Rayleigh scattering ring from the momentum distribution. Correspondingly, the real-space density perturbation remains localized in the vicinity of the defect. The underlying mechanism can be understood in terms of a direct generalization of the usual Landau criterion: superfluidity is observed whenever energy conservation prevents elementary excitations from being created in the moving fluid. Remarkably, the suppression of scattering by defects critically depends on the collective nature of its elementary excitations and cannot be explained in a standard single-particle picture of independent photons. In a standard dilute Bose condensate at equilibrium, *e.g.* of ultracold atoms, this condition is verified as long as the fluid is flowing at speeds slower than the speed of sound. With a suitable choice of the laser intensity (controlling the photon density), of the laser frequency (imposing the photon field oscillation frequency) and of the incidence angle (determining the in-plane photon flow velocity), a different regime of super-sonic flow can be accessed. This regime is illustrated in the third column of Fig.3: as the flow speed is faster than the sound velocity, elementary excitations are now efficiently created by the defect into the fluid. As a direct consequence of their linear energy-momentum dispersion, the density perturbation pattern has a Cherenkov-like conical shape in the wake of the defect. In addition, a series of parabolic precursors appears upstream of the defect. In addition to these quite standard behaviours, recently observed also in atomic systems [6], the non-equilibrium nature of the photon fluid allows for a much richer variety of collective ▮▮▮

▼ **FIG. 3: Theoretical patterns describing the interaction of an otherwise spatially homogeneous photon flow with a point-like defect in the cavity. Top row: real-space images of the photon density profile. The defect is located in the center. Middle row: corresponding momentum distributions. Bottom row: energy-momentum dispersion of the collective elementary excitations in the photon fluid; solid lines correspond to the physical, positive-norm modes, dashed lines to the negative-norm "ghost" ones. First column from left: the low-density regime of non-interacting photons. Second column: superfluid regime of sub-sonic flow. Third column: Cherenkov regime of super-sonic flow. Fourth column: anomalous «Zebra-Cherenkov» pattern in the vicinity of a parametric instability in the flow. Parameters can be found in Refs. [4]. Spectacular experimental results confirming these theoretical predictions have been recently published in Ref. [5]. An example is shown as a background image under the title. Comparison of experimental and theoretical images can be freely downloaded at the page: www.nature.com/nphys/journal/v5/n11/suppinfo/nphys1364_S1.html**



features. While in equilibrium systems the particle density and the chemical potential are fundamentally related by the so-called equation of state, in the non-equilibrium case the analogous quantities (photon density and field oscillation frequency) can in fact be independently tuned by controlling the external driving laser. This remarkable fact leads to exotic propagation features with no analog in close-to-equilibrium quantum fluids. As a most striking example, we have illustrated in the rightmost panels of Fig.3 the «zebra-Cherenkov» pattern that is created by the defect when the photon fluid is not far from a parametric instability.

The recent experiments

Following these theoretical predictions, the experimental quest for a photonic superfluid was quickly launched. So far, this challenge has been carried out mostly in planar semiconductor microcavities in the so-called strong light-matter coupling regime [2]. In these systems, the elementary excitations consist of a superposition of a cavity-photon and a quantum well exciton, the so-called polaritons. These bosonic particles combine the advantages in manipulation and detection that are provided by their photonic component with the strong binary interactions that instead originate from the excitonic one. Furthermore, the advances in the growth techniques are now able to fabricate planar semiconductor microcavities with weak structural disorder and therefore perfectly suitable for studies of polariton hydrodynamics.

Bose-Einstein condensation of polaritons was firmly demonstrated for the first time by a Grenoble-Lausanne collaboration, which immediately triggered investigations of the superfluidity properties of the polariton condensate. The first experimental studies by the UAM group addressed quantum fluid effects in wave packet propagation [7] and later the metastability of supercurrents in vortex geometries [8]. Meanwhile, experiments performed by the group of A. Bramati and E. Giacobino at Laboratoire Kastler Brossel in Paris have shown spectacular evidence of photon superfluidity in the sense of the Landau criterion [5]. In contrast to other configurations, the resonant coherent pumping allows in fact for a quantitative theoretical modeling of the experiment in terms of a nonlinear differential equation that generalizes the Gross-Pitaevskii equation to the non-equilibrium context. The agreement of the experimental observations with the theoretical predictions of Ref. [4] turns out to be very good. Even if coherence is imposed to the fluid from the outset, typical signatures of superfluidity are apparent: suppression of scattering on a defect for low enough flow speeds and the appearance of a Cerenkov-like pattern in the case of a supersonic flow. A typical experimental pattern in the Cherenkov regime is reproduced in the background image under the title of the present paper.

The future: strongly correlated photon gases

While the peculiar superfluidity properties of non-equilibrium condensates under different pumping configurations are still raising interesting conceptual questions [9,10], a new research direction on strongly correlated photon gases has recently moved its first steps with a few preliminary theoretical investigations. The first proposals have addressed the possibility of observing the transition from a superfluid to a Mott insulator state in a photon gas confined in an array of cavities [11]. Unfortunately, an experimental realization of this physics is likely to be severely disturbed by the finite lifetime of the photon. Other predictions of this same Bose-Hubbard model look instead more robust, and may even take advantage of the non-equilibrium nature of the photon gas to produce novel states of matter. As a simplest example, the possibility of creating a gas of impenetrable polaritons in a one-dimensional geometry has been predicted [12]. Unambiguous signatures of the strongly correlated nature of such Tonks-Girardeau gas have been predicted to appear in quantities as simple as the absorption spectrum. From this perspective, the presence of a radiative decay channel is more an advantage than a hindrance, as it allows to extract information on the quantum many-body state of the gas from the statistical properties of the emitted light.

At the present stage of the experimental research in this direction, the most demanding step appears to be the identification of a nonlinear optical medium with a strong enough nonlinearity to enter the so-called photon (or polariton) blockade regime. In this regime, the presence of a single photon (or polariton) is able to detune the cavity resonance of a large enough frequency to prevent a second resonant photon (or polariton) from entering. Once again, a promising possible solution to this problem is suggested by the analogy with atomic gases: the photon-photon collision amplitude has been anticipated to be dramatically enhanced at Feshbach resonance on an intermediate biexciton state [13]. Other schemes to enhance the effective strength of photon-photon interactions taking advantage of the strong dissipative nonlinearities of coherently driven atomic media or of quantum interference effects in suitably designed geometries have also been recently proposed [14].

It is therefore legitimate to believe that the quantum physics of strongly correlated photon fluids has all the potential for a very bright future! ■

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Cristiano Ciuti studied physics at Scuola Normale Superiore in Pisa. He received his PhD from EPFL, Switzerland in 2001. After a post-doc at UC San Diego, in 2003 he obtained a lecturer position at École Normale Supérieure in Paris. Since 2006, he is professor at Université Paris Diderot-Paris 7.

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