

Quantum Fluids of Light

from superfluid light towards fractional quantum Hall effects

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- A.Biella, D.Rossini (SNS), R. Fazio (ICTP)
- M. Wouters (Antwerp)

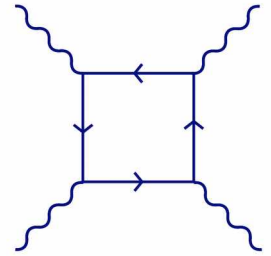
- M. Kroner, A. Imamoglu (ETHZ)
- N. Goldman (UL Brussels)
- O. Zilberberg (ETHZ)
- M. Wimmer, U. Peschel (Jena)

Why not hydrodynamics of light ?

Light field/beam composed by a huge number of photons

- in vacuo photons travel along straight line at c
- (practically) do not interact with each other
- in cavity, collisional thermalization slower than with walls and losses

=> **optics typically dominated by single-particle physics**

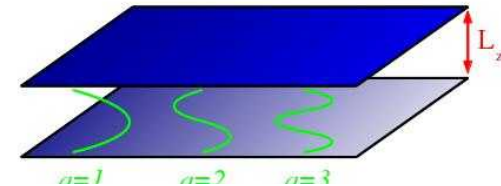


$$\sigma \sim \alpha^4 \frac{\hbar^2}{m^2 c^2} \left(\frac{\hbar \omega}{mc^2} \right)^6$$

In photonic structure:

$\chi^{(3)}$ nonlinearity → photon-photon interactions

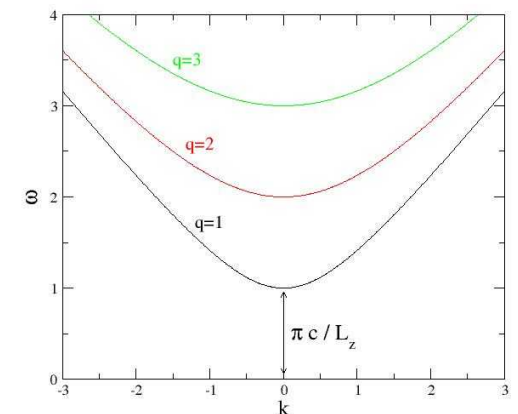
Spatial confinement → effective photon mass



=> **collective behaviour of a quantum fluid**

Many experiments so far

BEC, superfluidity, quantum hydrodynamics, analog gravity, strongly interacting gases, quantum Hall effects...



In this talk: a few selected topics to make the audience curious about this physics!

Standing on the shoulders of giants

Laserlight — First Example of a Second-Order Phase Transition Far Away from Thermal Equilibrium*

R. GRAHAM and H. HAKEN

I. Institut für theoretische Physik der Universität Stuttgart

Received April 23, 1970

We solve the functional Fokker-Planck equation established in a previous paper in the vicinity of laser threshold. The stationary solution is obtained explicitly in the form $P = N \exp [-\varphi(\{\bar{u}, \bar{u}^*\})]$. φ has exactly the same form as the Ginzburg-Landau expression for the free energy of a superconductor, if the pair wave function is replaced by the electromagnetic field amplitude \bar{u} . This gives us the key for a thermodynamic reinterpretation of all laser phenomena.

In particular the laser threshold appears as a second-order phase transition in all details. It is indicated that our theory provides a new formalism also for the Ginzburg-Landau theory.

VOLUME 67, NUMBER 27

PHYSICAL REVIEW LETTERS

30 DECEMBER 1991

Vortices and Defect Statistics in Two-Dimensional Optical Chaos

F. T. Arecchi,^(a) G. Giacomelli, P. L. Ramazza, and S. Residori

Istituto Nazionale di Ottica, Largo E. Fermi, 6, 50125 Firenze, Italy

(Received 1 April 1991)

We present the first direct experimental evidence of topological defects in nonlinear optics. For increasing Fresnel numbers F , the two-dimensional field is characterized by an increasing number of topological defects, from a single vortex, up to a large number of vortices with zero net topological charge. At variance with linear scattering from a fixed phase plate, here the defect pattern evolves in time according to the nonlinear dynamics. We assign the scaling exponents for the mean number of defects, their mean separation, and the charge unbalance as functions of F , as well as the correlation time of the defect pattern.

C. R. Acad. Sci. Paris, t. 317, Série II, p. 1287-1292, 1993

1287

Optique/Optics

Diffraction non linéaire

Yves POMEAU et Sergio RICA

Résumé — Une expérience classique en mécanique des fluides est la formation de structures vorticales à l'arrière d'un obstacle, comme par exemple l'écoulement de Bénard-von-Kármán. Est-il possible d'imaginer une expérience similaire en optique ? C'est-à-dire, en illuminant un obstacle pourrait-on engendrer des structures tourbillonnaires caractéristiques d'un régime pré-turbulent ? Cette Note est consacrée au problème de la génération de vorticit  dans les ondes  lectromagn tiques.

PHYSICAL REVIEW A

VOLUME 54, NUMBER 1

JULY 1996

Hydrodynamic phenomena in laser physics: Modes with flow and vortices behind an obstacle in an optical channel

M. Vaupel, K. Staliunas, and C. O. Weiss

Physikalisch-Technische Bundesanstalt, 38116 Braunschweig, Germany

(Received 16 February 1995; revised manuscript received 20 February 1996)

The transverse patterns of an active resonator with cylindrical optics are investigated. This resonator configuration corresponds to a "channel" form of the potential for the "photon fluid." Simultaneous emission of different transverse modes along the channel, periodic nucleation of vortices in the form of a vortex street (vortices of alternating senses of rotation appearing in a flow behind an obstacle), accelerated flow in a "tilted channel," and destabilization of the one-directional flow in the channel are demonstrated and interpreted in terms of tilted waves and beating of channel modes, as well as in fluid terms, illustrating the fluid dynamics correspondence of class-A lasers. [S1050-2947(96)02407-9]

And of course many others:

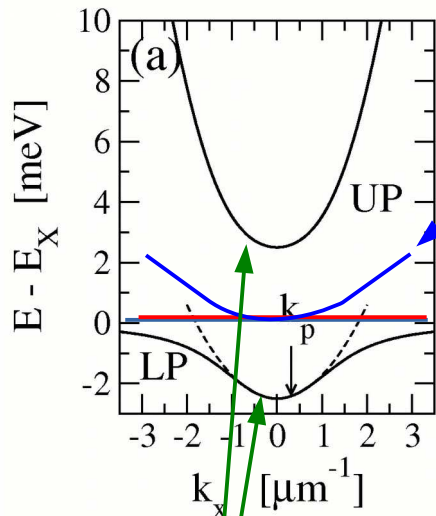
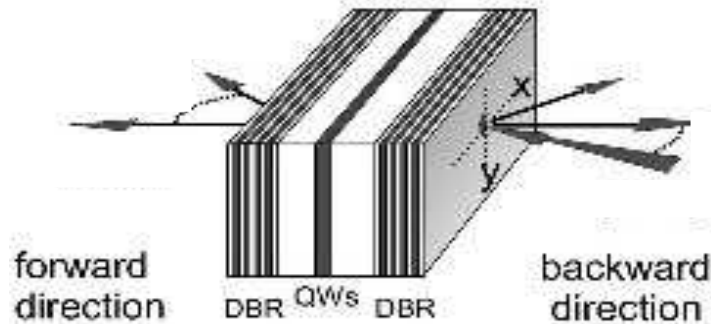
Coulet, Gil, Rocca,
Brambilla, Lugiato...

Part 1:

A primer to

semiconductor microcavities

Planar DBR microcavity with QWs



Photon

- **DBR**: stack $\lambda/4$ layers (e.g. GaAs/AlAs)
- Cavity layer \rightarrow **confined photonic mode**, **delocalized** along 2D plane:

$$\omega_c(\mathbf{k}) = \omega_c^0 \sqrt{1 + \mathbf{k}^2 / k_z^2}$$

Exciton

- e-h pair in QW: sort of H atom. **Exciton**
- **bosons** for $n_{\text{exc}} a_{\text{Bohr}}^2 \ll 1$
- Excitons **delocalized** along cavity plane.
Flat exciton dispersion $\omega_x(\mathbf{k}) \approx \omega_x$
- Optical $\chi^{(3)}$ from exciton collisions

Polaritons

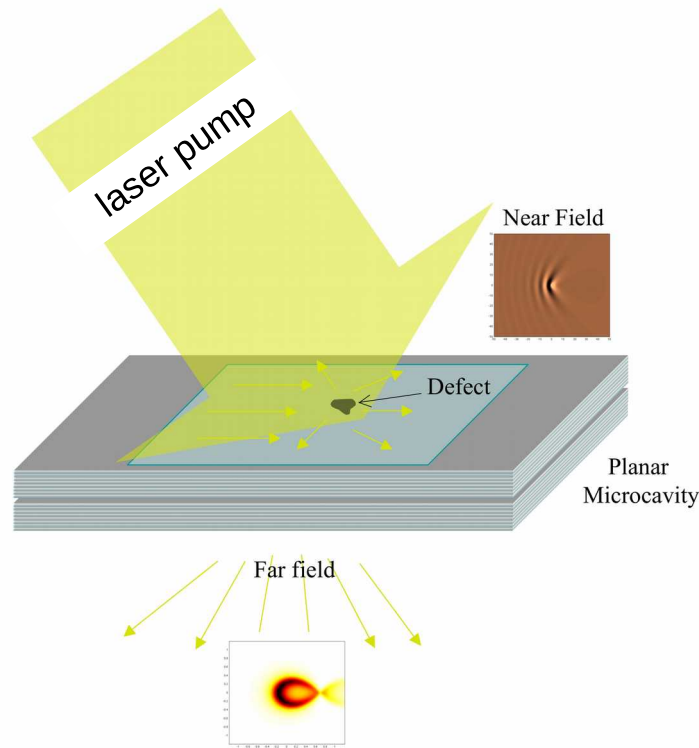
Exciton radiatively coupled to cavity photon **at same in-plane k**
Bosonic superpositions of **exciton** and **photon**, called **polaritons**

Two-dimensional gas of polaritons

Small effective mass $m_{\text{pol}} \approx 10^{-4} m_e \rightarrow$ originally promising for BEC studies

Exciton \rightarrow interactions. **Photons** \rightarrow radiative coupling to external world

How to create and detect the photon gas?



Pump needed to compensate losses: stationary state is NOT thermodynamical equilibrium

- Coherent laser pump: directly injects photon BEC in cavity, may lock BEC phase
- Incoherent (optical or electric) pump: BEC transition similar to laser threshold
spontaneous breaking of $U(1)$ symmetry

Classical and quantum correlations of in-plane field directly transfer to emitted radiation

Mean-field theory: generalized GPE

$$i \frac{d\psi}{dt} = \left[\omega_o - \frac{\hbar \nabla^2}{2m} + V_{ext} + g|\psi|^2 + \frac{i}{2} \left(\frac{P_0}{1 + \alpha|\psi|^2} - \gamma \right) \right] \psi + F_{ext}$$

Time-evolution of macroscopic wavefunction ψ of photon/polariton condensate

- standard terms: kinetic energy, external potential V_{ext} , interactions g , losses γ
- under coherent pump: forcing term
- under incoherent pump: polariton-polariton scattering from thermal component give saturable amplification term as in semiclassical theory of laser

=> a sort of Complex Landau-Ginzburg equation

To go beyond mean-field theory:

- Wigner representation (Paris 7, Antwerp); exact diagonalization
- Keldysh diagrams (Cambridge)

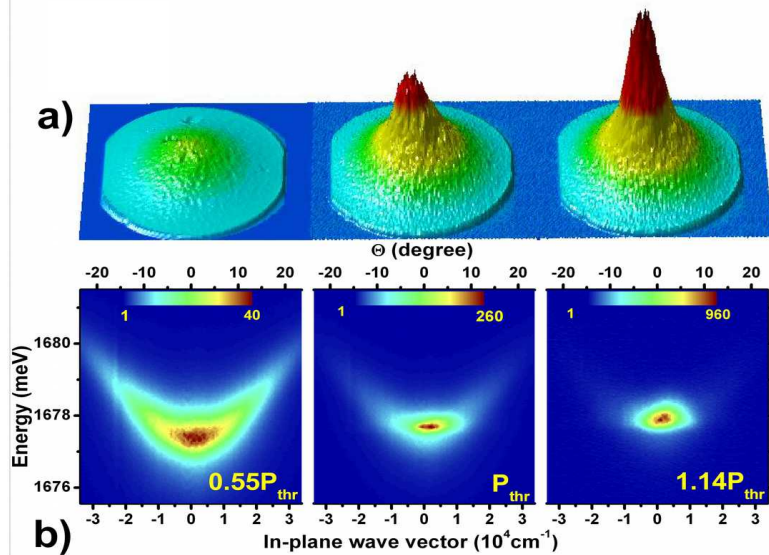
Exact value of interaction constant g :

- not known exactly from expts; no *ab initio* calculation available (only Born approximation)
- biexciton Feshbach resonance used to increase value, unfortunately more lossy than in atoms (Wouters, PRB '07; IC, Volz, Imamoglu, EPL '10; Takemura et al., Nat. Phys. '14)

Part 2:

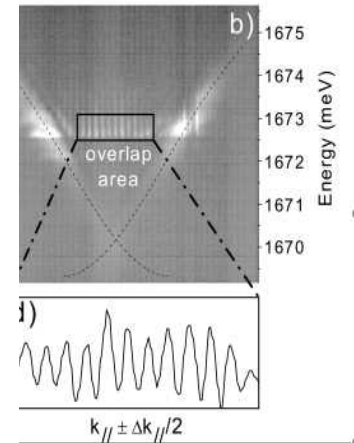
Polariton BEC

2006 - Photon/polariton Bose-Einstein condensation



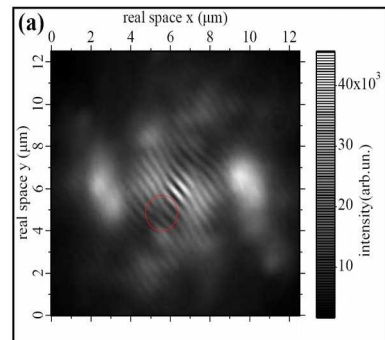
Momentum distribution

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



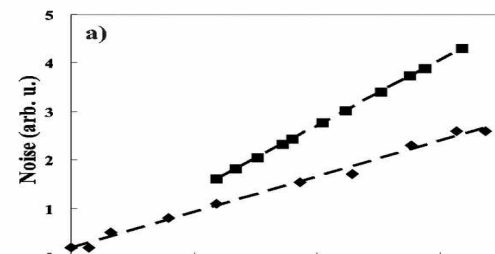
Interference

Richard et al., PRL **94**, 187401 (2005)



Quantized vortices

K. Lagoudakis *et al.*
Nature Physics **4**, 706 (2008).

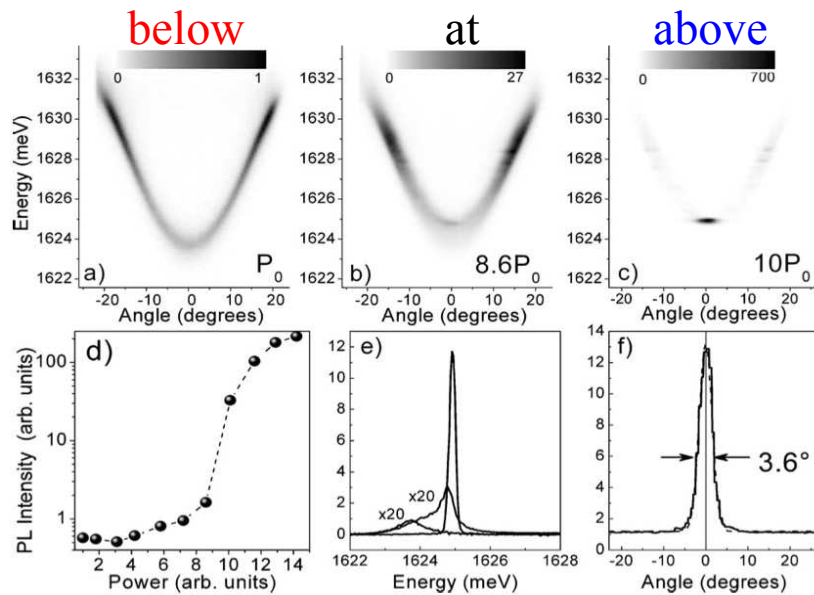


Suppressed fluctuations

A. Baas et al., PRL **96**, 176401 (2006)

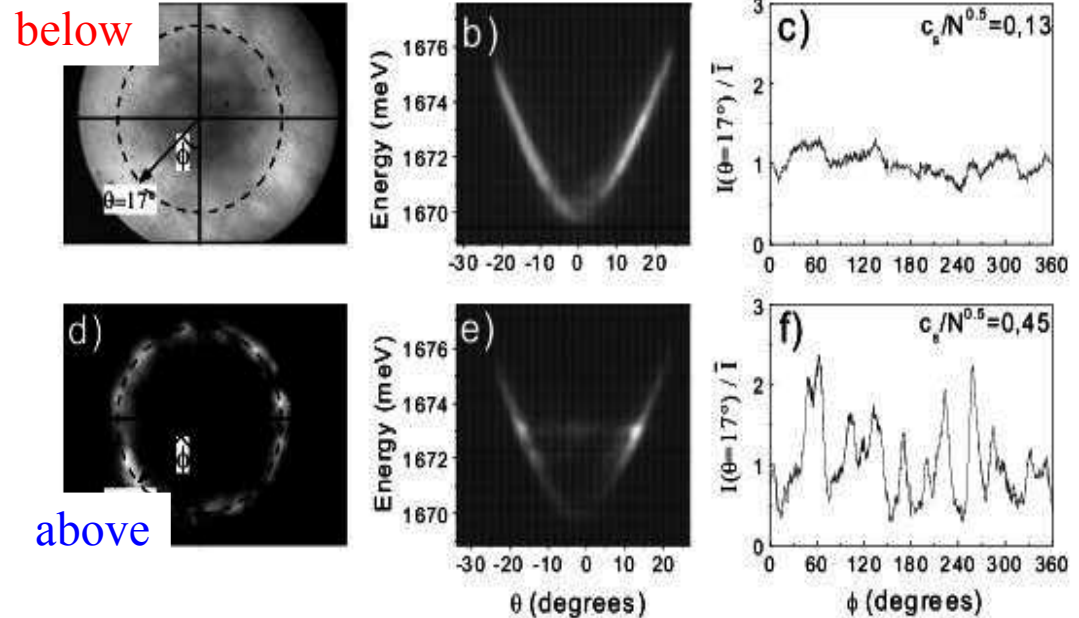
Many features very similar to atomic BEC

Intriguing experimental data for the BEC shape



wide pump spot: 20 μm

M. Richard et al., PRB **72**, 201301 (2005)



narrow pump spot: 3 μm

M. Richard et al., PRL **94**, 187401 (2005)

Experimental observations **under non-resonant pump**:

- condensate shape depends on **pump spot size**
 - wide pump spot**: condensation at $k=0$
 - narrow pump spot**: condensation on a **ring of modes** at finite $|k|$

Narrow pump spot experiments : fragmentation or BEC ?

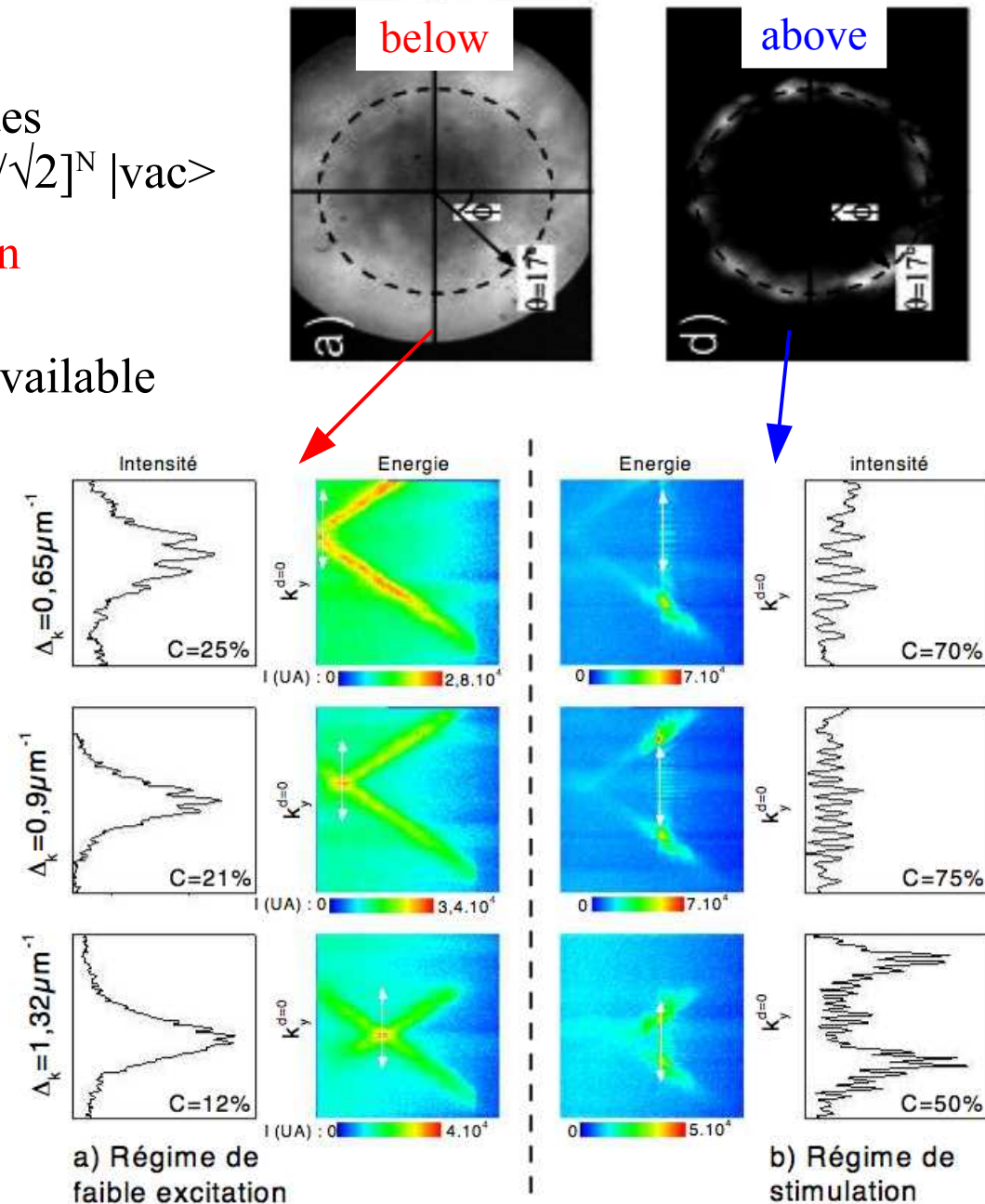
Fragmentation:

- incoherent superposition of different modes

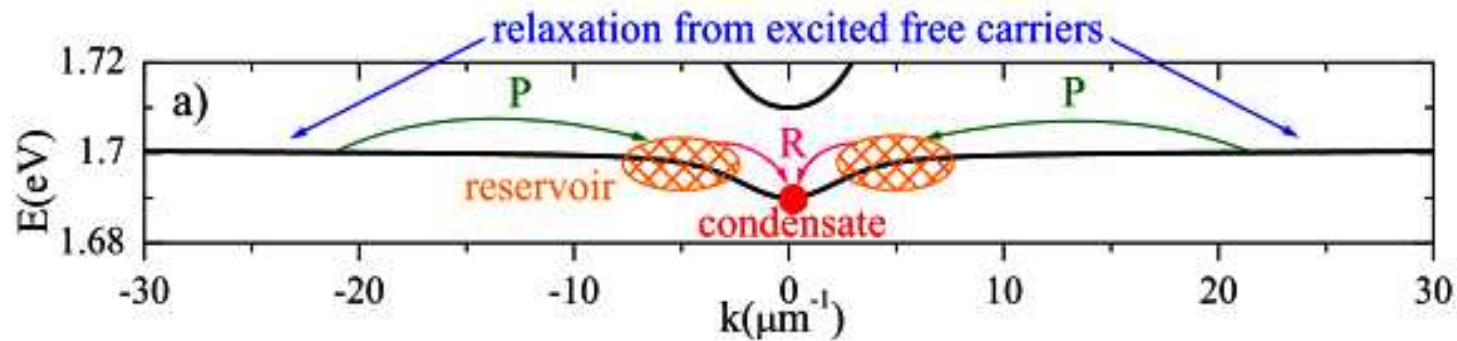
$$|\psi\rangle = a_1^{N/2} a_2^{N/2} |\text{vac}\rangle \neq [(a_1 + a_2)/\sqrt{2}]^N |\text{vac}\rangle$$
- at equilibrium: fragmented BEC **forbidden**
on energetic arguments
- non-equilibrium: no energetic argument available

Experimental evidence:

- momentum-space emission peaked on a **ring at finite $|k|$**
- coherence of $k \pm \Delta k$ emission measured by Billet interferometer:
 - **below threshold**: coherence quickly decays with Δk
 - **above threshold**: high coherence even at opposite points of the ring



A generalized GPE for non-resonantly pumped BECs



- **Condensate** : mean-field approx., GPE with losses / amplification

$$i \frac{\partial}{\partial t} \psi = \left[-\frac{\hbar^2 \nabla^2}{2m_{LP}} - i\gamma/2 + \frac{i}{2} R(n_B) + g|\psi|^2 + 2\tilde{g}n_B \right] \psi$$

macroscopic wavefunction $\psi(x)$, loss rate γ , amplification $R(n_B)$

- **Incoherent reservoir** : rate equation for density $n_B(x)$

$$\frac{\partial}{\partial t} n_B = P - \gamma_B \bar{n}_B - R(n_B) |\psi(x)|^2 + \frac{D}{2} \nabla^2 n_B$$

pumping rate P , spatial diffusion D , thermalization rate γ_B

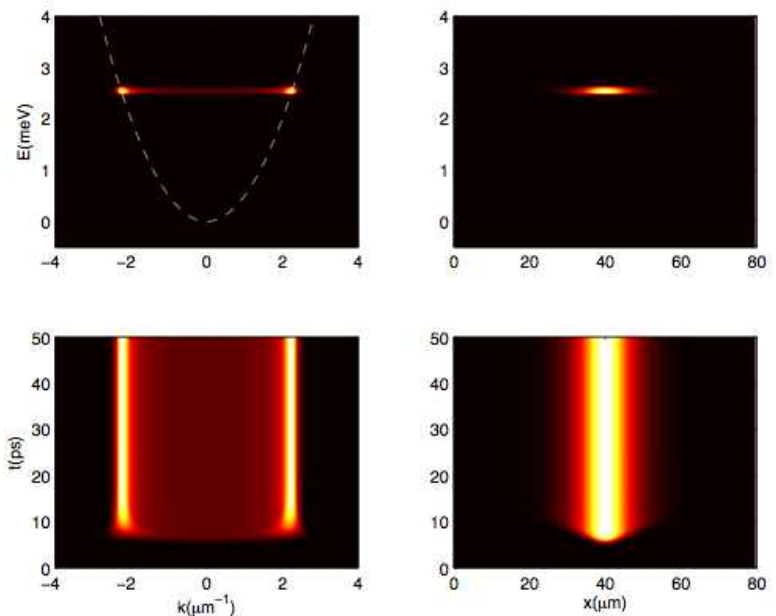
- **Fast reservoir limit**: reduces to a **Complex-Ginzburg Landau Equation**

$$i \frac{d\psi}{dt} = \left[\omega_o - \frac{\hbar \nabla^2}{2m} + V_{ext} + g|\psi|^2 + \frac{i}{2} \left(\frac{P_0}{1 + \alpha |\psi|^2} - \gamma \right) \right] \psi$$

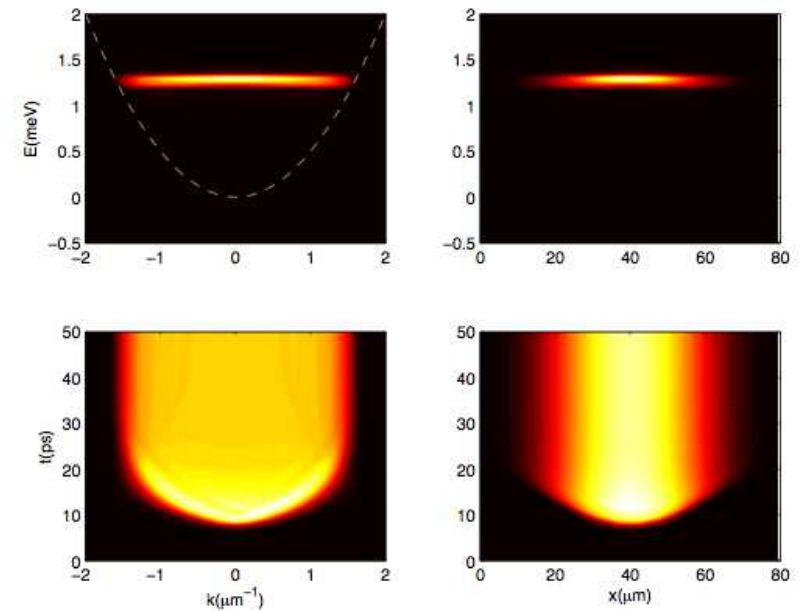
- **Beware**: fast reservoir approx sometimes inaccurate (Baboux et al. Optica '18; Stepanov, arXiv '18)

Numerical integration of non-equilibrium GPE

- Equilibrium, harmonic trap: Thomas-Fermi parabolic profile
- Non-equilibrium: dynamics affects shape. Stationary flow possible
related work on flow patterns : J. Keeling, N. G. Berloff, PRL **100**, 250401 (2008)



Narrow pump spot: $\sigma = 5 \mu\text{m}$
Emission on ring at finite k



Wide pump spot: $\sigma = 20 \mu\text{m}$
Broad emission centered at $k=0$

Good agreement with experiments !!

M. Wouters, IC, and C. Ciuti, *Spatial and spectral shape of inhomogeneous non-equilibrium exciton-polariton condensates*, PRB **77**, 115340 (2008)

Physical interpretation: Volcano effect

Repulsive interactions

- outward radial acceleration
- energy conservation

$$E = k^2/2m + U_{\text{int}}(r)$$

→ radially increasing

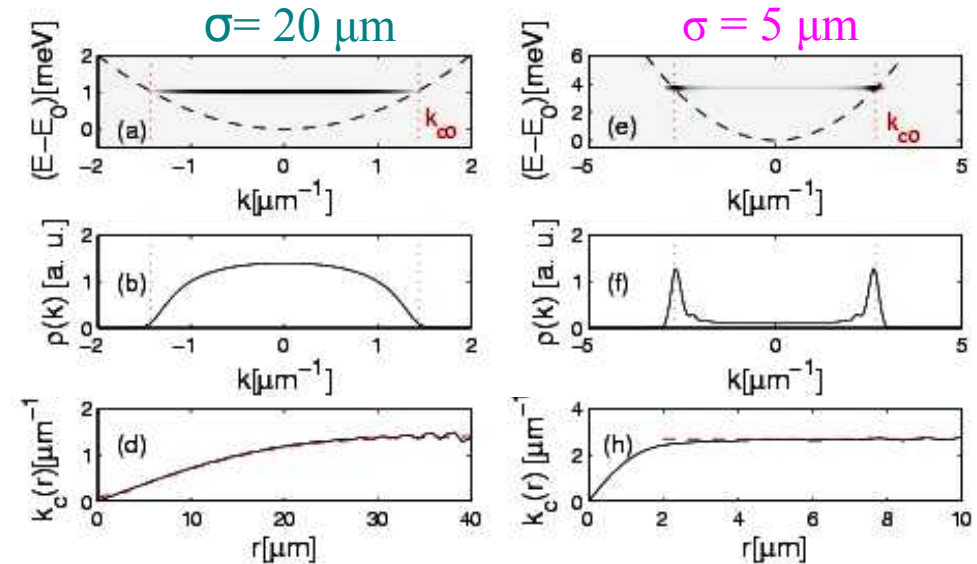
local flow velocity

→ coherent ballistic flow

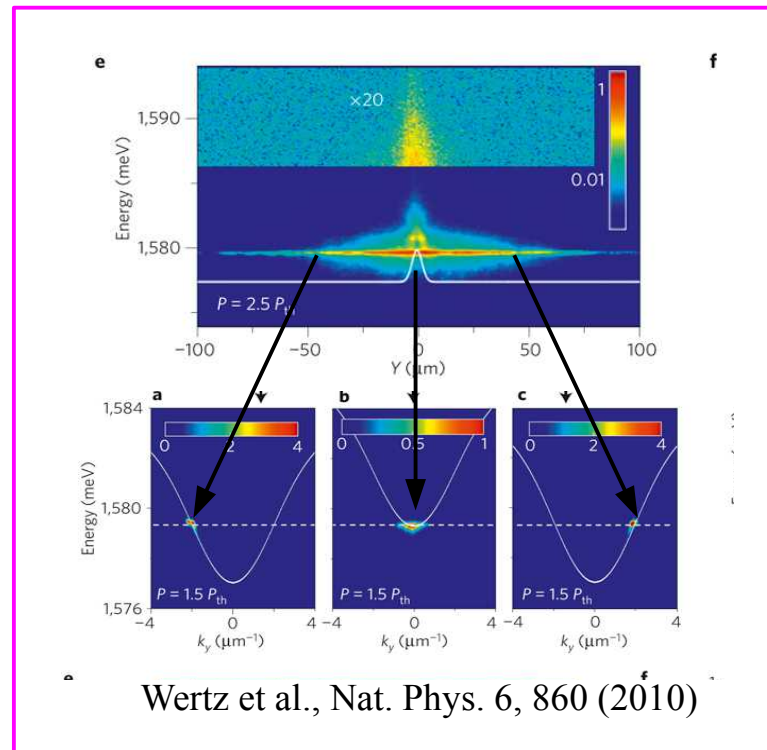
Narrow spot:

- ballistic free flight outside pump spot $U_{\text{int}}(r)=0$
- emission mostly on free particle dispersion

Later expts confirm mechanism



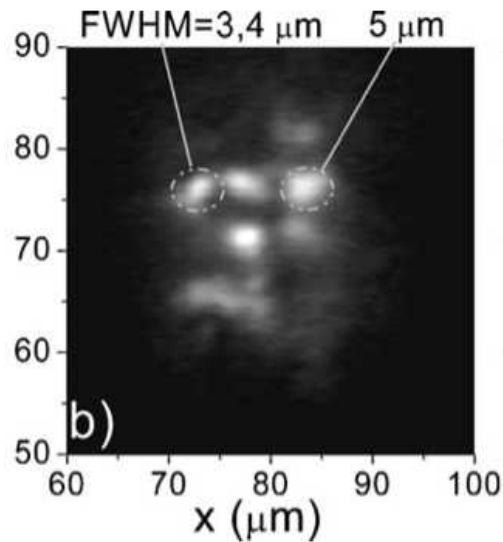
M. Wouters, IC, and C. Ciuti, PRB 77, 115340 (2008)



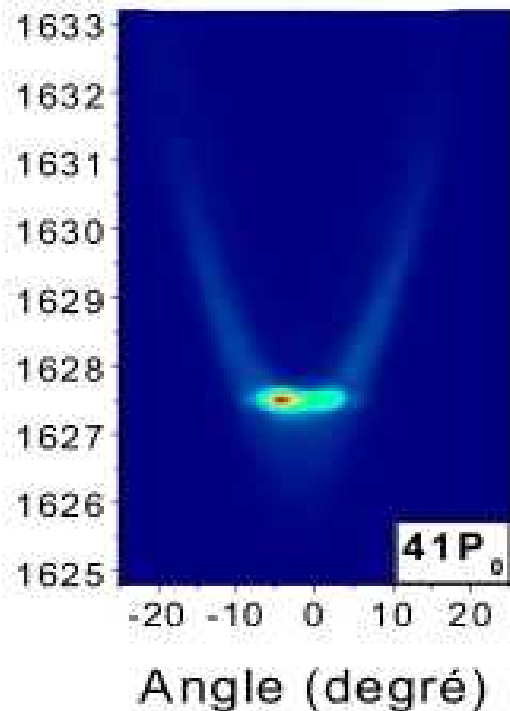
Wertz et al., Nat. Phys. 6, 860 (2010)

A closer look at experimental data: disorder effects

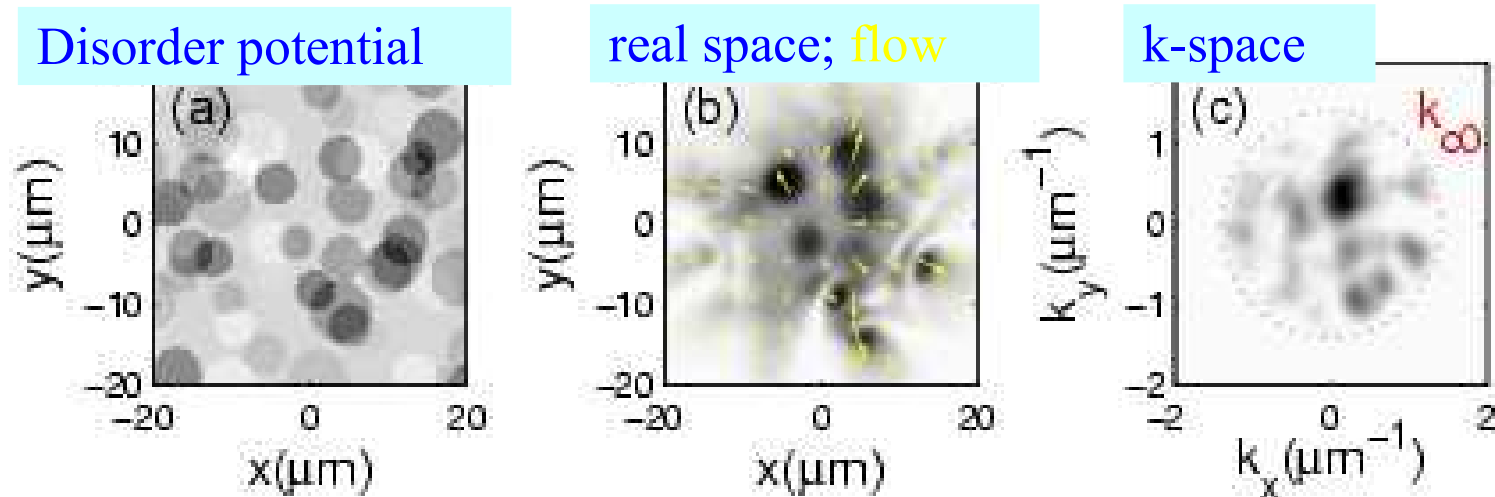
Expt with large pump spot



- random **disorder potential** in GPE
- **k-space**: **speckle modulation** over broad profile
 - peak at $k \neq 0$: signature of **non-equilibrium**
 - **T-reversal** symmetry violated $n(\mathbf{k}) \neq n(-\mathbf{k})$
- **real space**: **outward flow**, **modulation** roughly follows disorder potential



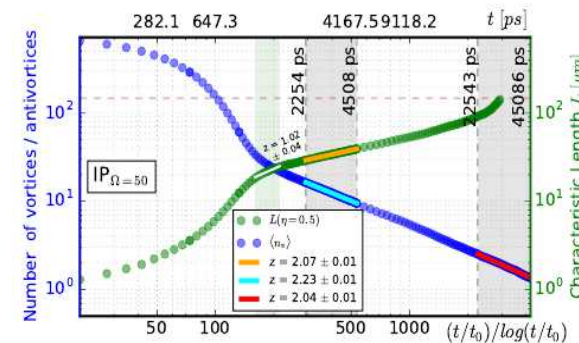
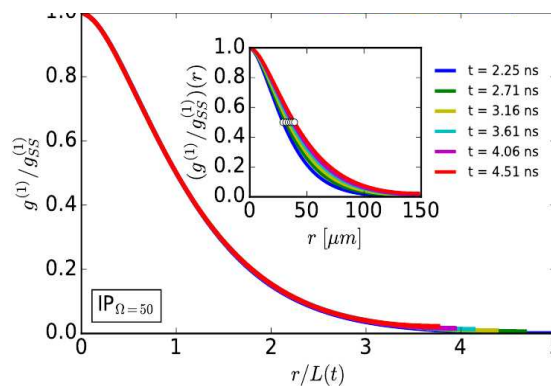
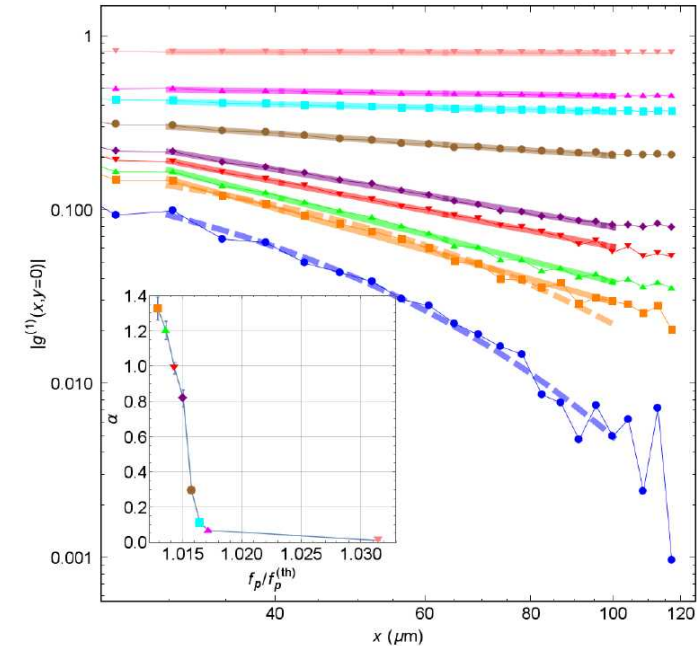
A new example of random laser !!



Recent theoretical advances and challenges

New features for 2D non-equilibrium BEC/superfluidity:

- BKT @ intermediate length: $g^{(1)}(r)$ power-law with $\alpha > 1/4$
- Very long distances: stretched exponential (Sieberer/Altman/Diehl/etc)
- Sudden quench to ordered phase: dynamical scaling, critical exponent $z \sim 2$ (plus log corrections), different from (many) conservative cold-atom systems

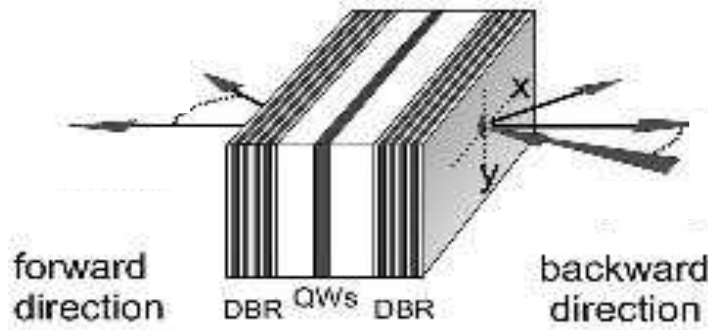


Comaron et al., arXiv:1708.09199. Newcastle/UCL/Trento collaboration

Part 3:

Polariton superfluidity

Simplest configuration: coherent, resonant pump



$$i \frac{d\psi}{dt} = \left(\omega_o - \frac{\hbar \nabla^2}{2m} + V_{ext} + g |\psi|^2 - \frac{i\gamma}{2} \right) \psi + F_{ext}$$

Direct injection of polaritons by resonant pump

- coherence inherited from pump
- condensate dynamics fully described by non-equilibrium GPE
 - no incoherent dynamics to be modeled, almost *ab initio* calculation
 - next order: Bogoliubov theory, interesting quantum fluctuation effects (quantum images, analog Hawking radiation...)
- resonant Rayleigh scattering on defect, suppressed when superfluid
- near- and far-field profiles observed in reflection and/or transmission

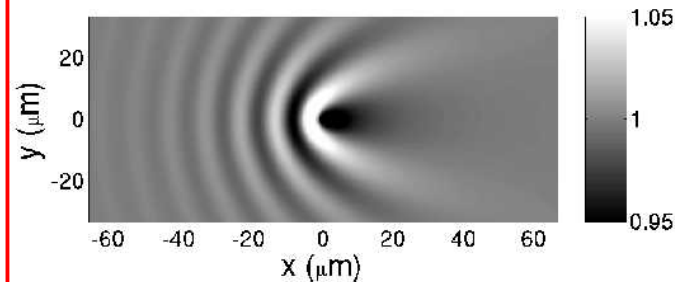
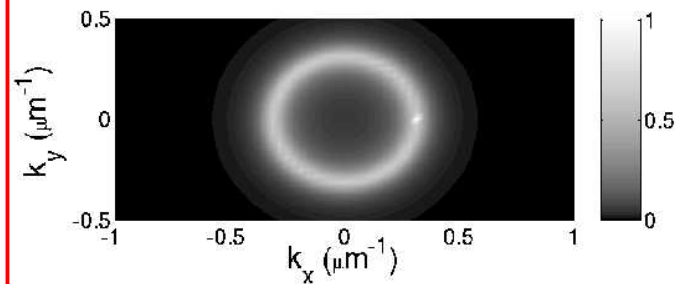
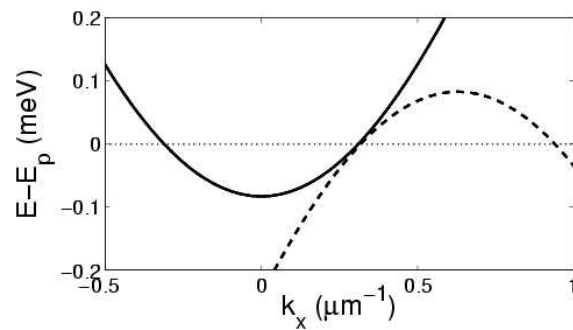
IC and C.Ciuti, PRL **93**, 166401 (2004)

Related proposals: Chiao, Boyce, PRA 60, 4114 (1999); Tanzini, Sorella, PLA 263, 43 (1999). Bolda, Chiao, Zurek, PRL 86, 416 (2001).

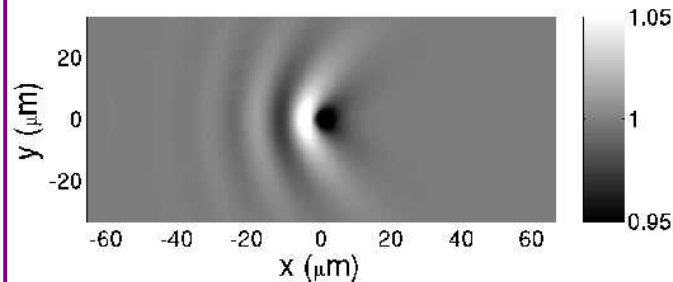
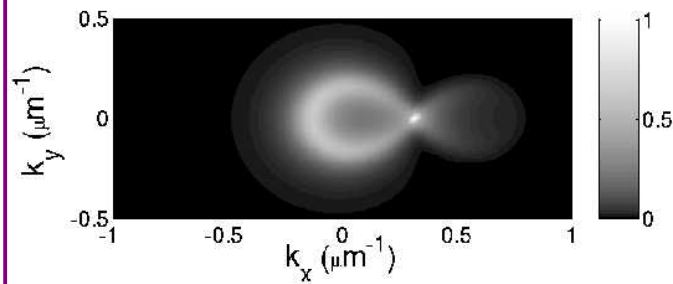
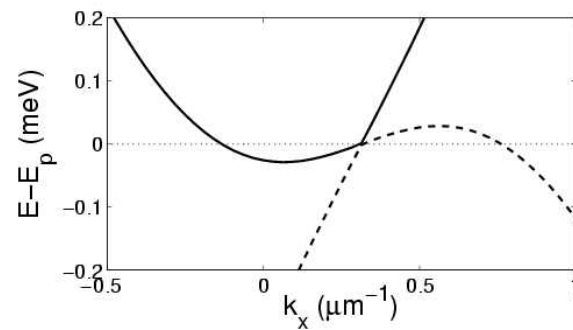
Collective modes and Landau criterion

Polaritons injected at finite k_p : flow towards right incident on defect

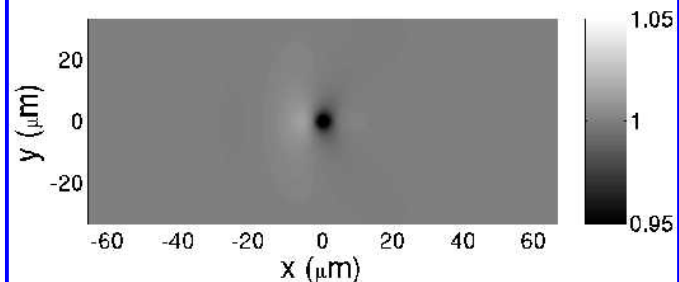
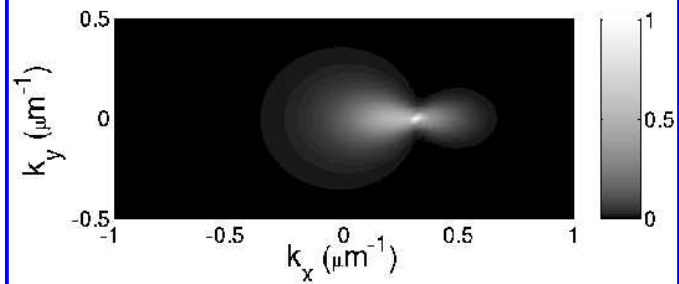
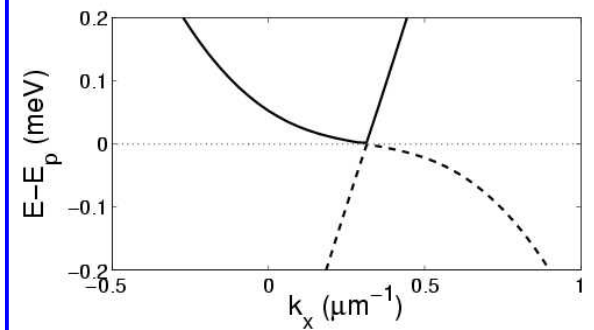
Non-interacting
polaritons



Non-superfluid
(a kind of $v_p > c_s$)



Superfluid
(a kind of $v_p < c_s$)



2008 - Superfluid light

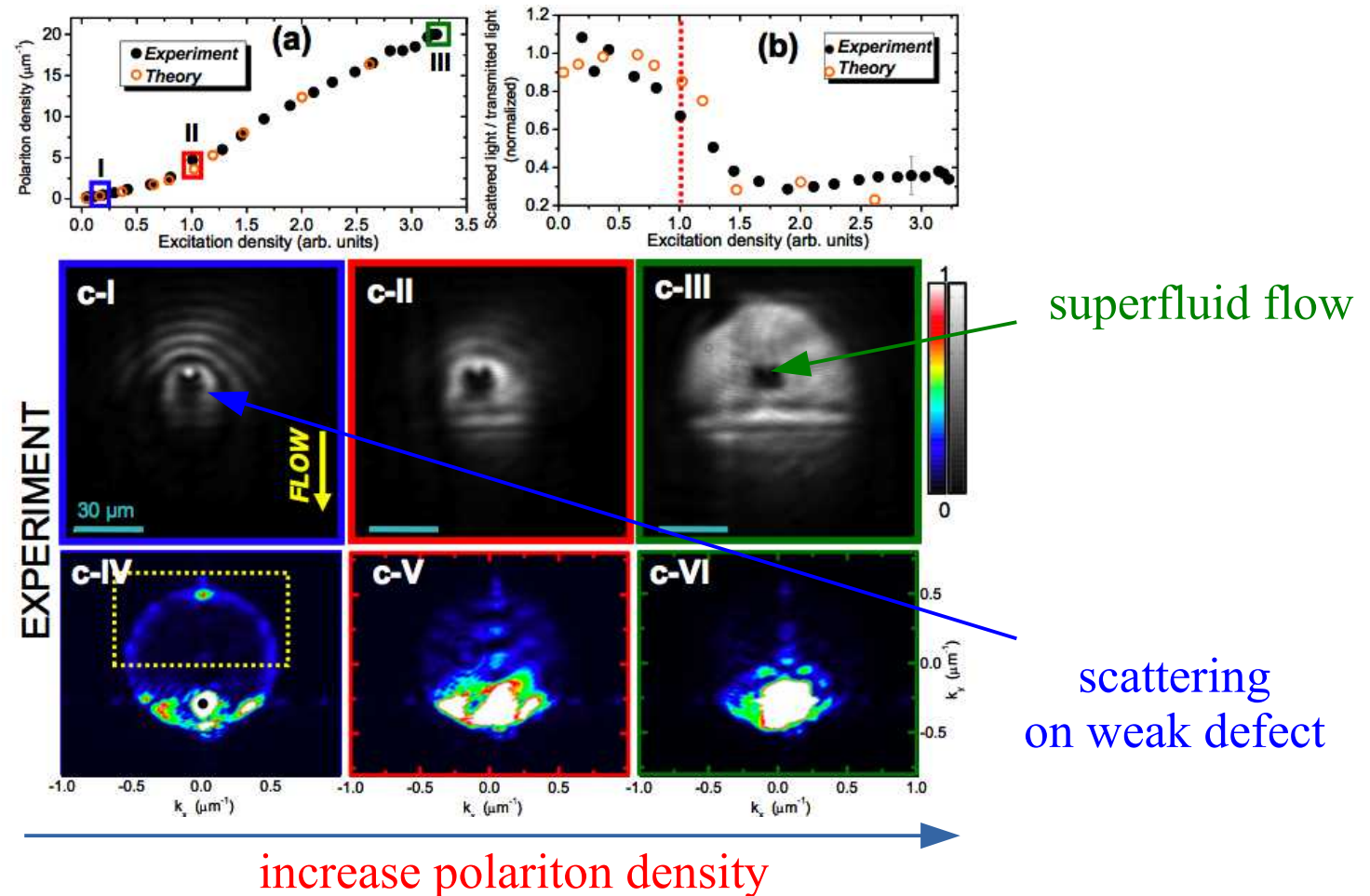


Figure from LKB-P6 group:

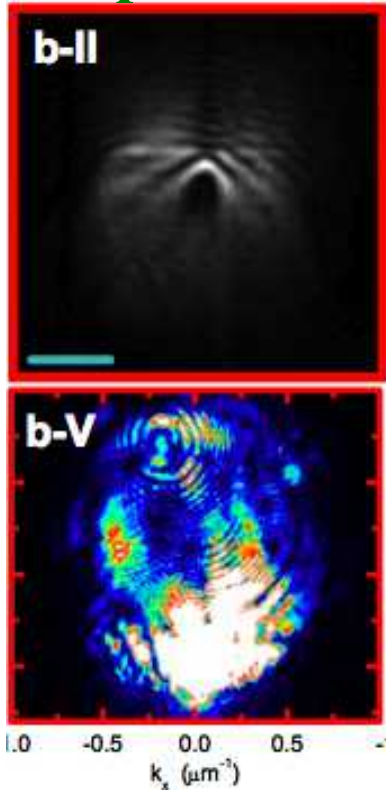
J.Lefrère, A.Amo, S.Pigeon, C.Adrados, C.Ciuti, IC, R. Houdré, E.Giacobino, A.Bramati, *Observation of Superfluidity of Polaritons in Semiconductor Microcavities*, Nature Phys. **5**, 805 (2009)

Theory: IC and C. Ciuti, PRL **93**, 166401 (2004)

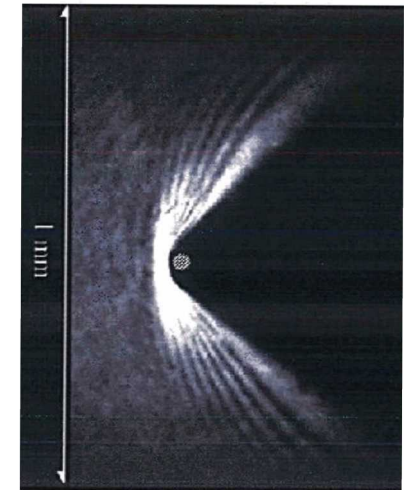
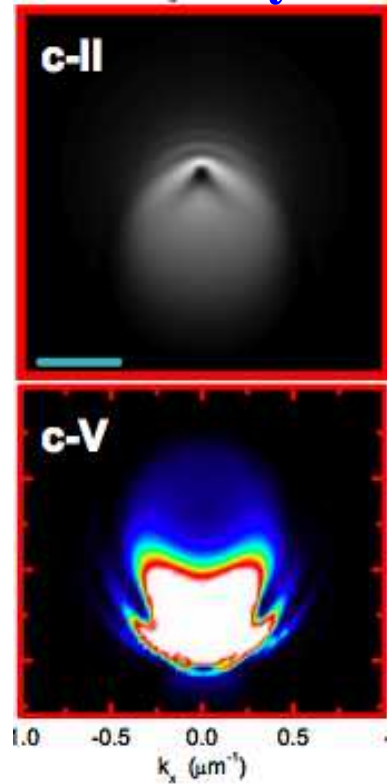
Similar experiments with atoms by H.Moritz and J. Dalibard's groups

More experimental data: Cerenkov wake

Experiment



Theory



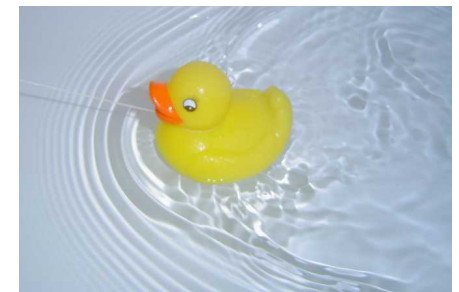
Expt with atomic BEC

Expt. image from JILA
(P. Engels, E. Cornell).

Theory IC, Hu, Collins, Smerzi,
PRL 97, 260403 (2006)

Super-sonic flow hitting a defect:

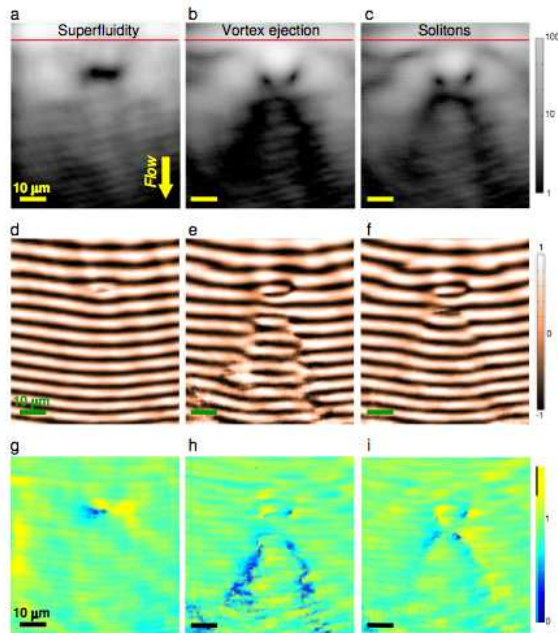
- Cerenkov conical wave, aperture $\cos(\varphi) = c_s / v$
- single-particle-like parabolic precursors



Expt with duck

2009-10 - Superfluid hydrodynamics

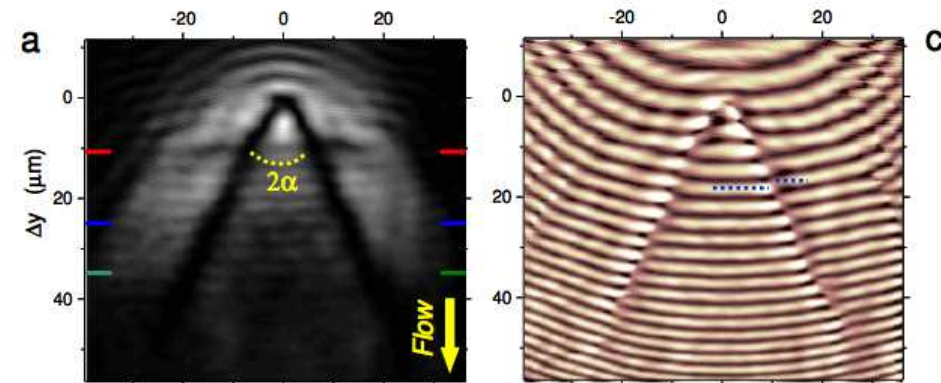
Oblique dark solitons →



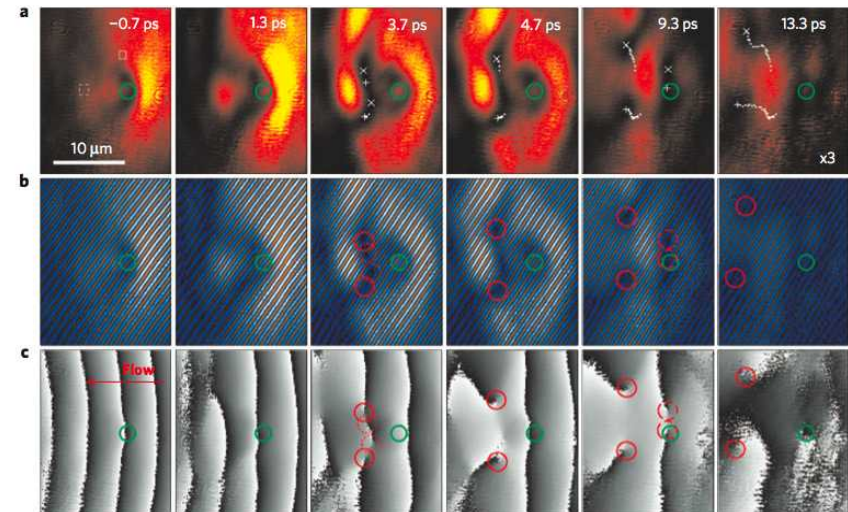
A. Amo, et al., Science **332**, 1167 (2011)

← Turbulent behaviours

Hydrodynamic
nucleation →
of vortices



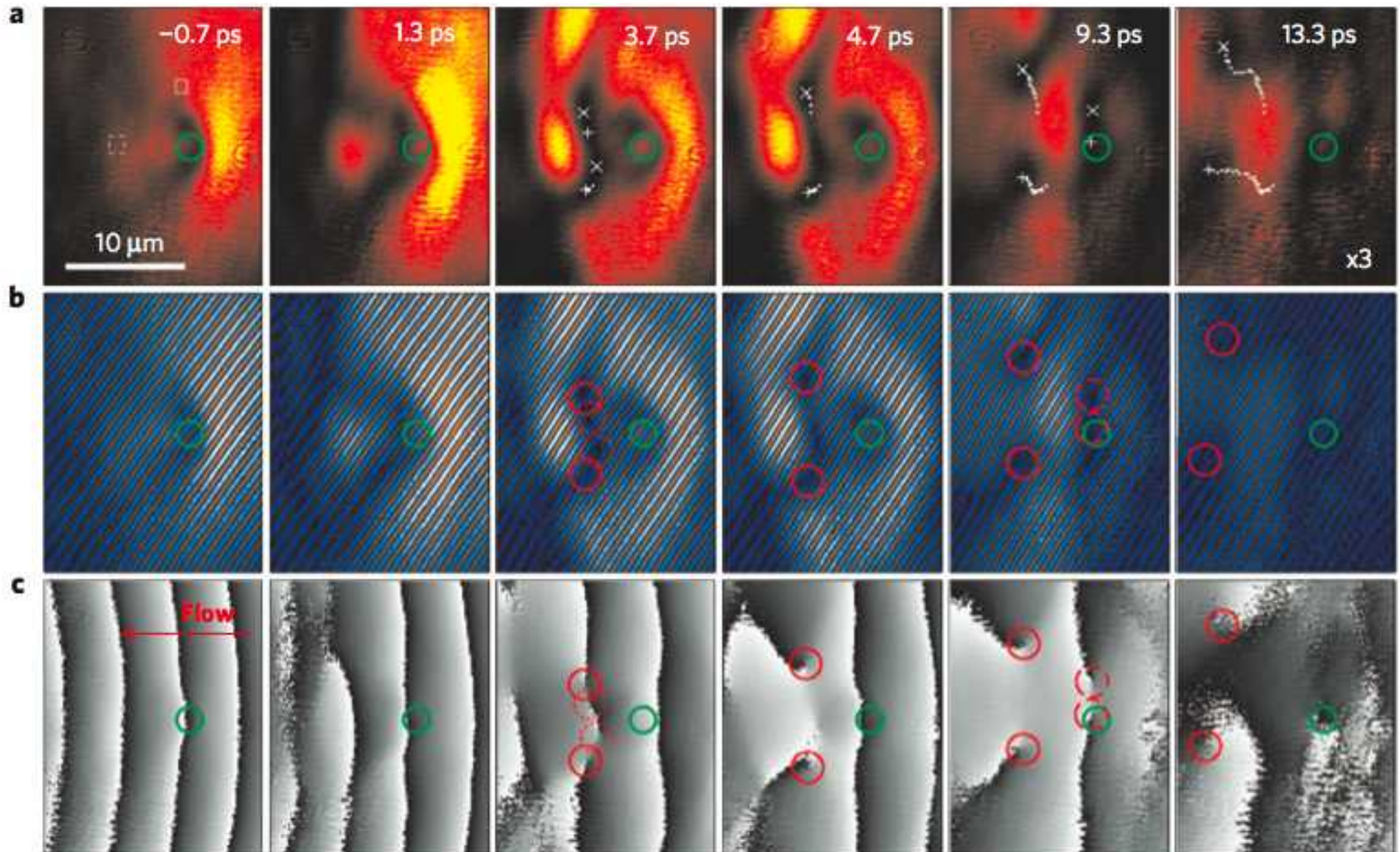
A. Amo, et al., Science **332**, 1167 (2011)



Nardin et al., Nat. Phys. **7**, 635 (2011)

Role of interactions crucial in determining regimes as a function of v/c_s

2010 – Hydrodynamics vortex nucleation



Open question: are non-equilibrium BECs superfluid?

Polariton superfluidity expts → so far with **explicitly broken U(1)**

BEC phase transition → spontaneous breaking of U(1),
e.g. under **incoherent pump** (or polariton lasing)

Driven-dissipative GPE

$$\begin{cases} i\frac{\partial\psi}{\partial t} = \left\{ -\frac{\hbar^2\nabla^2}{2m_{LP}} + \frac{i}{2}[R(n_R) - \gamma] + g|\psi|^2 + 2\tilde{g}n_R \right\} \psi. \\ \frac{\partial n_R}{\partial t} = P - \gamma_R n_R - R(n_R)|\psi(\mathbf{r})|^2 + D\nabla^2 n_R \end{cases}$$

Linearize GPE around **steady state**

→ **Reservoir R** mode at $-i\gamma_R$ + **BEC density** and **phase** modes at:

$$\omega_{\pm}(k) = -\frac{i\Gamma}{2} \pm \sqrt{[\omega_{Bog}(k)]^2 - \frac{\Gamma^2}{4}}$$

- **density (-)** and **phase (+)** oscillations **decoupled** around $k=0$
- **Goldstone phase (+)** mode is **diffusive**

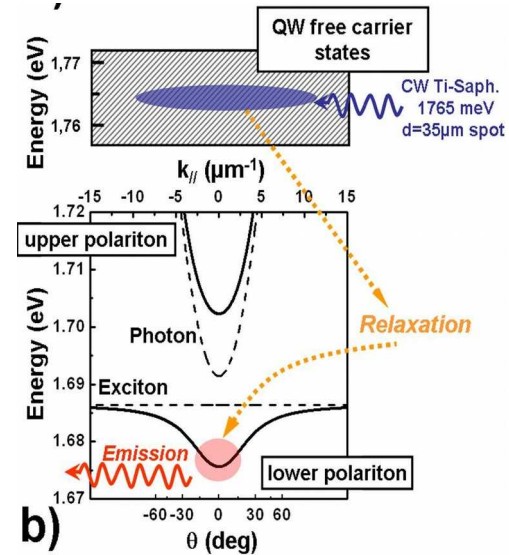
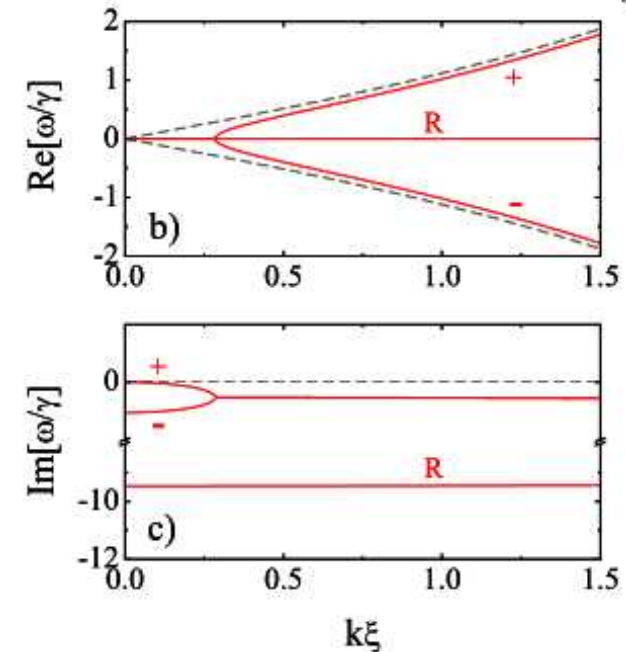


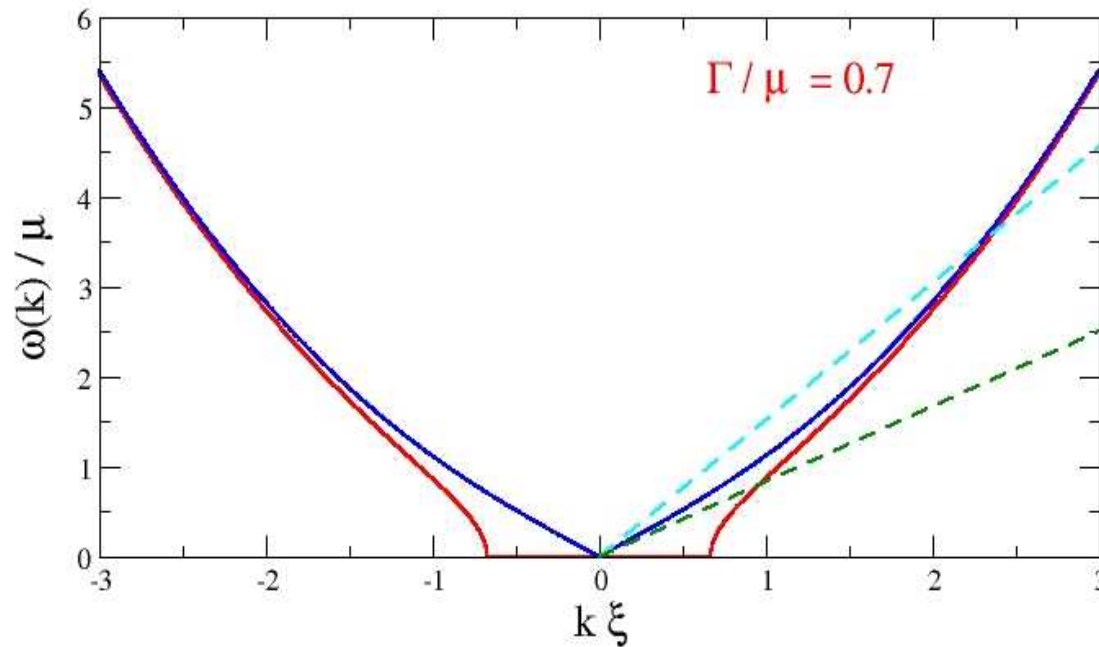
Figure from Kasprzak et al., Nature 2006



M. Wouters and IC, *Excitations in a non-equilibrium polariton BEC*, Phys. Rev. Lett. **99**, 140402 (2007)

Similar results in: M. H. Szymanska, J. Keeling, P. B. Littlewood, PRL **96**, 230602 (2006)

Naive Landau criterion



Naïf Landau argument:

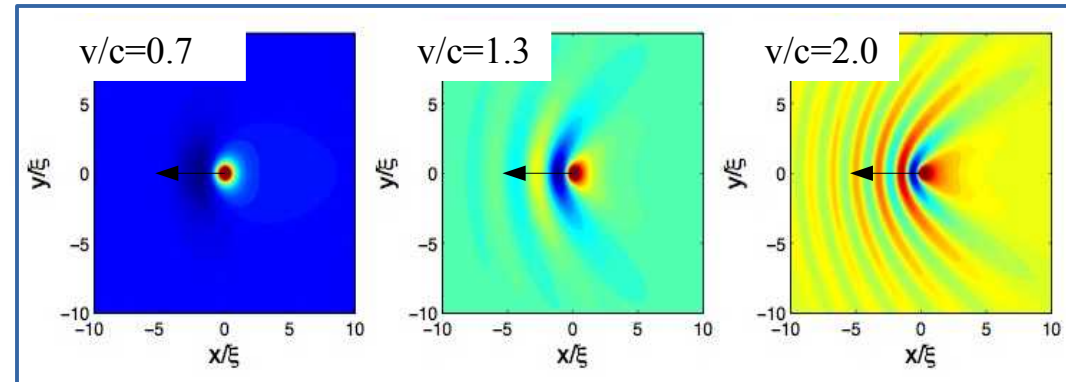
- Landau **critical velocity** $v_L = \min_k [\omega(k) / k] = 0$ at non-equilibrium BEC
- Any **moving defect** expected to **emit phonons**

M. Wouters and IC, *Excitations in a non-equilibrium polariton BEC*, Phys. Rev. Lett. **99**, 140402 (2007)
Similar results in: M. H. Szymanska, J. Keeling, P. B. Littlewood, PRL **96**, 230602 (2006)

But nature is always richer than expected...

Low v :

- emitted k_{\parallel} purely imaginary
- no real propagating phonons
- perturbation localized around defect

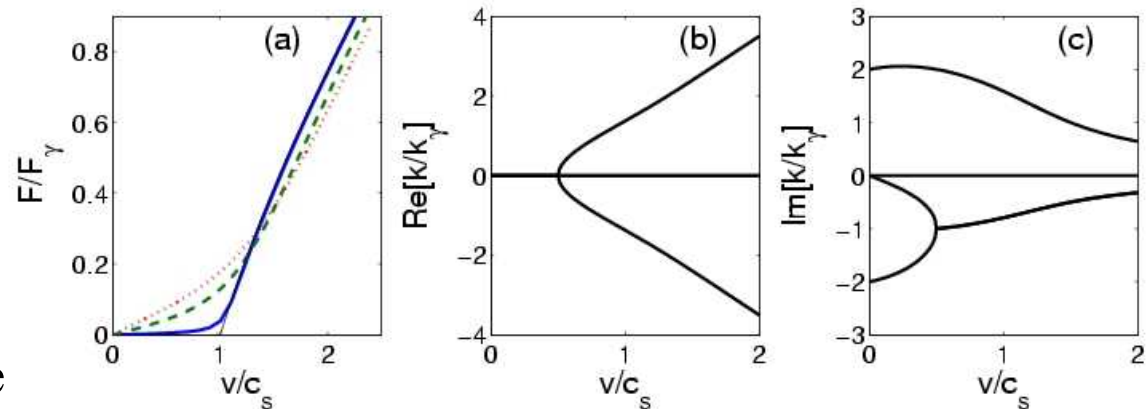


Critical velocity $v_c < c$:

- corresponds to bifurcation point
- decreases with Γ / μ

High v :

- emitted propagating phonons:
 - Cerenkov cone
 - parabolic precursors
- spatial damping of Cerenkov cone

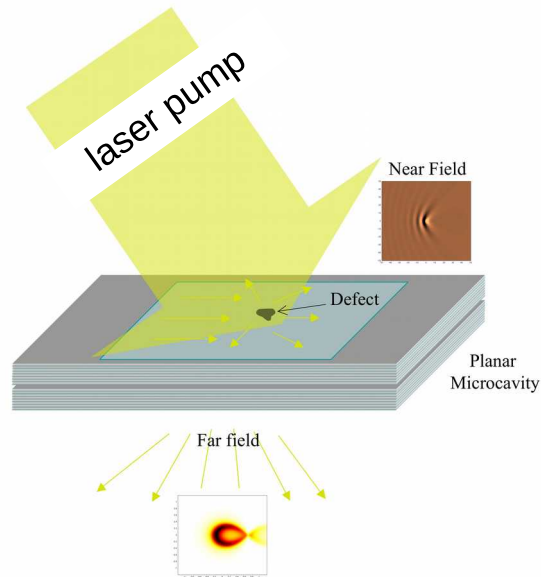


Interlude:

Quantum fluids of light
with a *unitary* dynamics

Field equation of motion

Planar microcavities & cavity arrays



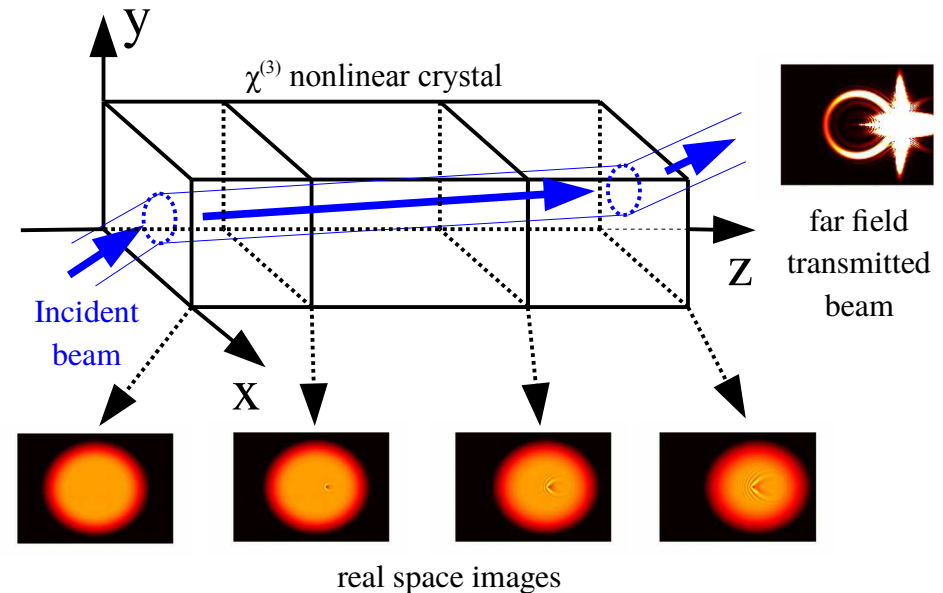
Pump needed to compensate losses:
driven-dissipative dynamics in real time
stationary state \neq thermodyn. equilibrium

Driven-dissipative CGLE evolution

$$i \frac{dE}{dt} = \left[\omega_o - \frac{\hbar \nabla^2}{2m} + V_{ext} + g|E|^2 + \frac{i}{2} \left(\frac{P_0}{1 + \alpha|E|^2} - \gamma \right) \right] E + F_{ext}$$

Quantum correl. sensitive to dissipation

Propagating geometry



Monochromatic beam

Incident beam sets initial condition @ $z=0$

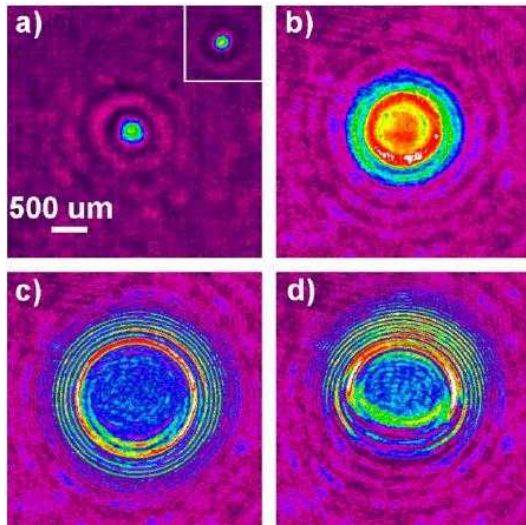
MF \rightarrow Conserv. paraxial prop. \rightarrow GPE

$$i \frac{dE}{dz} = \left[-\frac{\hbar \nabla_{xy}^2}{2\beta} + V_{ext} + g|E|^2 E \right] E$$

- V_{ext} , g proportional to $-(\epsilon(r)-1)$ and $\chi^{(3)}$
- Mass \rightarrow diffraction (xy)

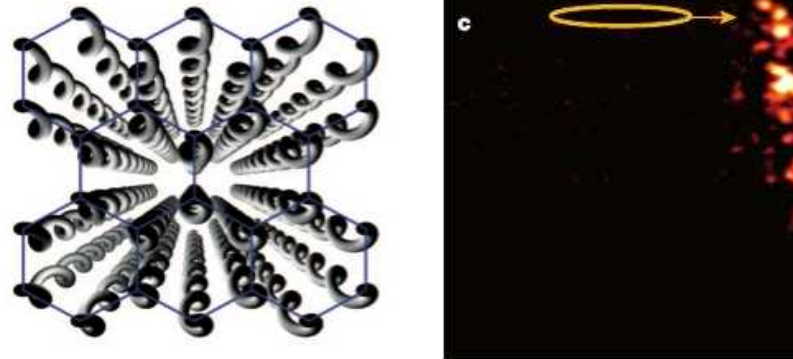
First expts with (almost) conservative QFL's

Dispersive superfluid-like shock waves



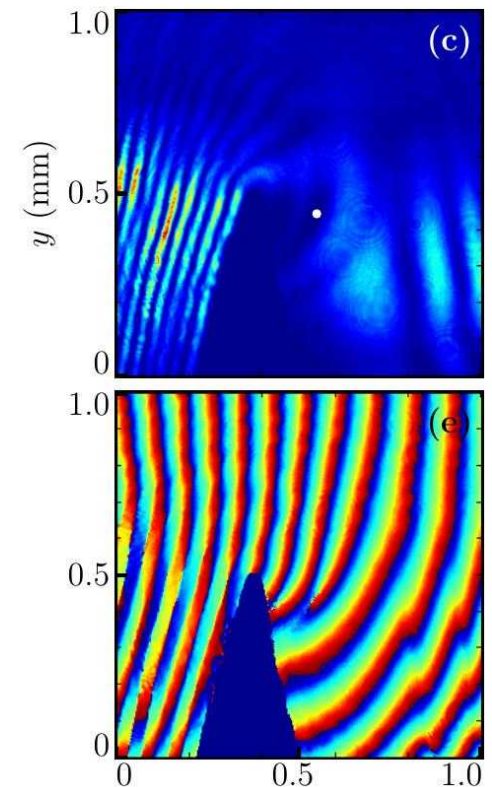
Wan et al., Nat. Phys. 3, 46 (2007)

Chiral edge states in (photonic) Floquet topological insulator

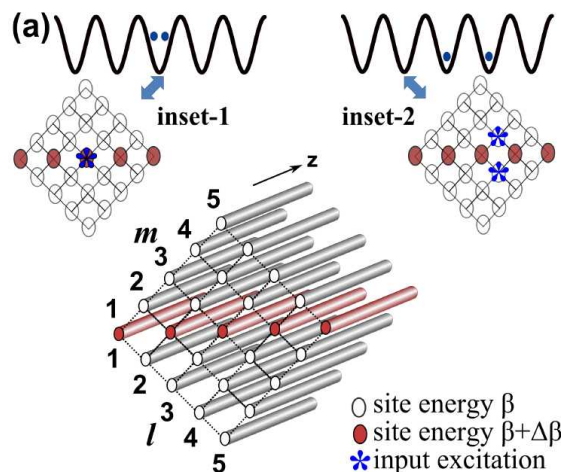


Rechtsman, et al., Nature 496, 196 (2013)

Hydrodynamic nucleation of quantized vortices

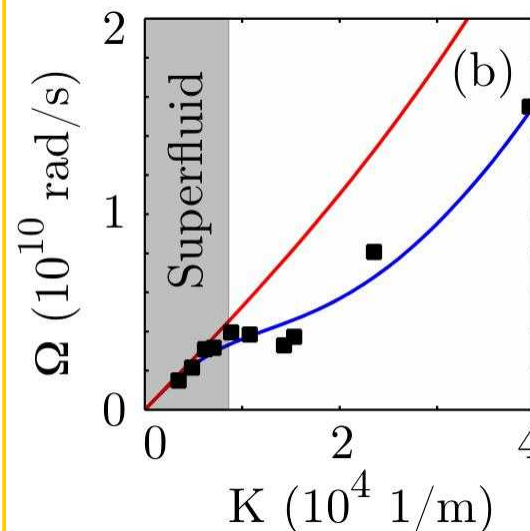


D. Vocke et al.,
arXiv:1511.06634



Quantum simul. of 2-body physics
Mukherjee et al., arXiv:1604.00689

Bogoliubov dispersion of collective excitations



D. Vocke et al. Optica (2015)

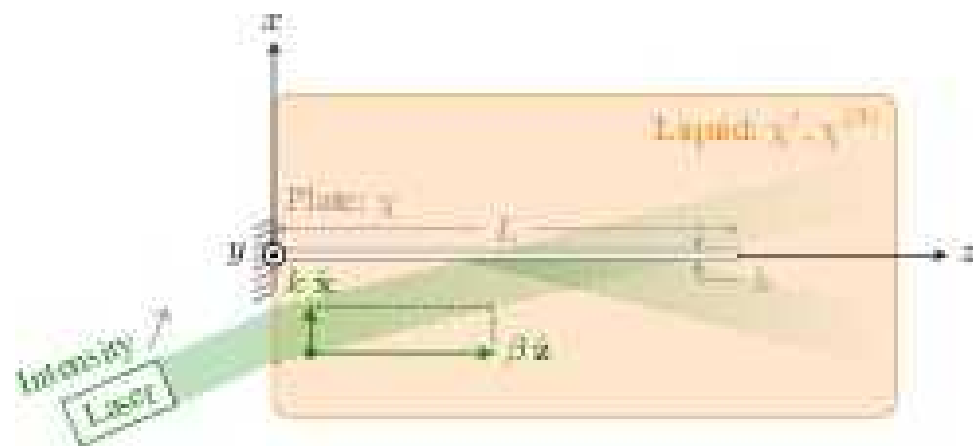
Frictionless flow of superfluid light (I)

All superfluid light experiments so far:

- Planar microcavity device with stationary obstacle in flowing light
- Measure response on the **fluid density/momentum pattern**
- Obstacle typically is defect **embedded in semiconductor material**
- **Impossible to measure mechanical friction force exerted onto obstacle**

Propagating geometry more flexible:

- Obstacle can be solid dielectric slab with different refractive index
- Immersed in **liquid nonlinear medium**, so can move and deform
- **Mechanical force measurable from magnitude of slab deformation**



Frictionless flow of superfluid light (II)

Numerics for **propagation GPE** of **monochromatic laser**:

$$i \partial_z E = -\frac{1}{2\beta} (\partial_{xx} + \partial_{yy}) E + V(r) E + g |E|^2 E$$

with $V(r) = -\beta \Delta \varepsilon(r) / (2\varepsilon)$ with rectangular cross section and $g = -\beta \chi^{(3)} / (2\varepsilon)$

For growing light power, **superfluidity** visible:

- Intensity modulation disappears
- Suppression of opto-mechanical force

An intermediate powers:

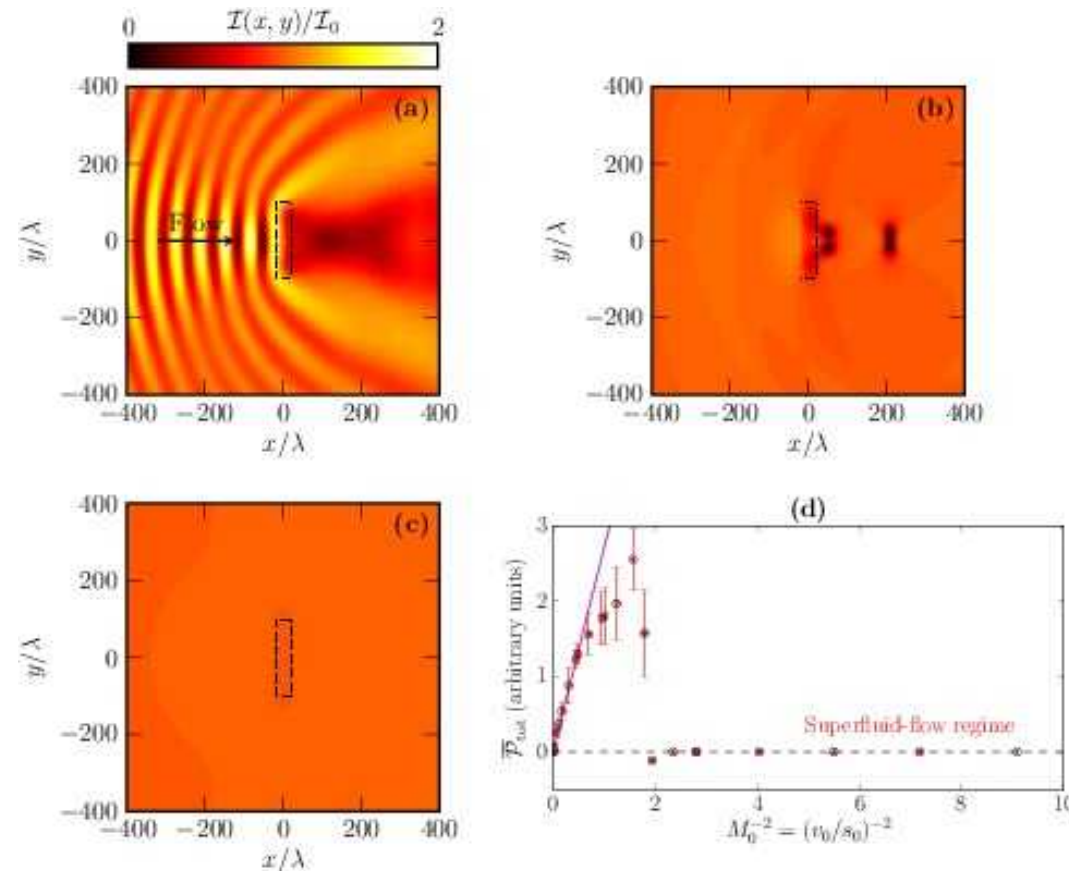
- Periodic nucleation of vortices
- **Turbulent** behaviours

Fused silica slab as obstacle

→ deformation almost in the μm range

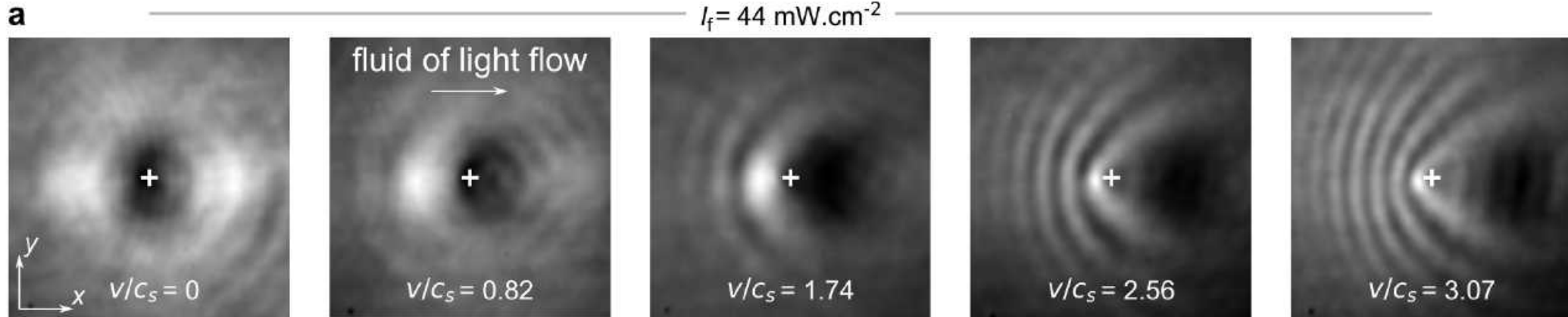
Experiment in progress

→ surrounding medium in fluid state
but local nonlinearity (e.g. atomic gas)



Nice experiments: Michel et al., Nat. Comm. 2018

Increasing incidence angle, i.e. speed

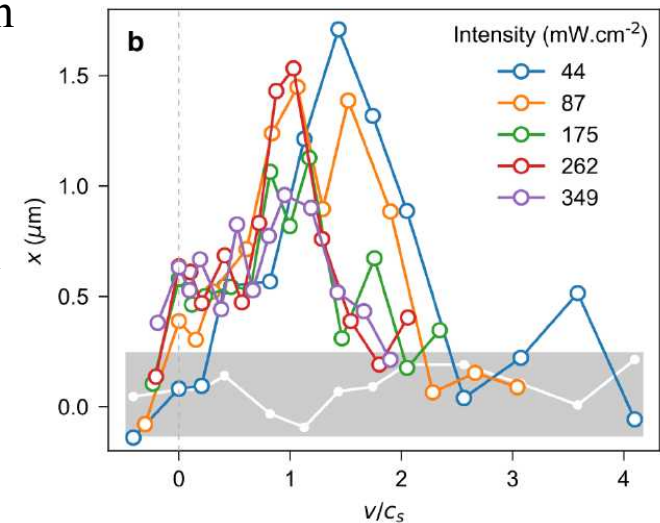
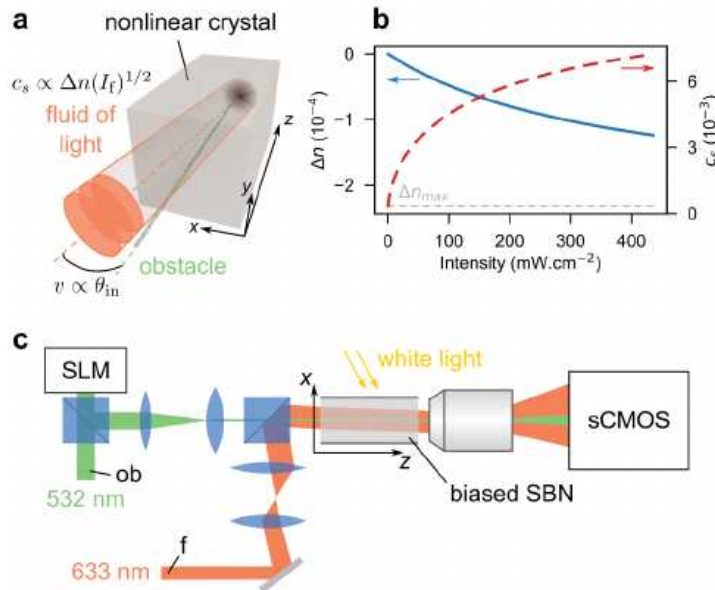


Superfluid

Cherenkov cone shrinks with v/c_s

First attempt to measure absence of mechanical effect of superfluid light.

All-optical analog:
lateral shift of obstacle beam



Part 4:

Topological effects in optics

2009 - the dawn of Topological Photonics: Photonic (Chern) topological insulator

MIT '09, Soljacic group

Original proposal Haldane-Raghu, PRL 2008

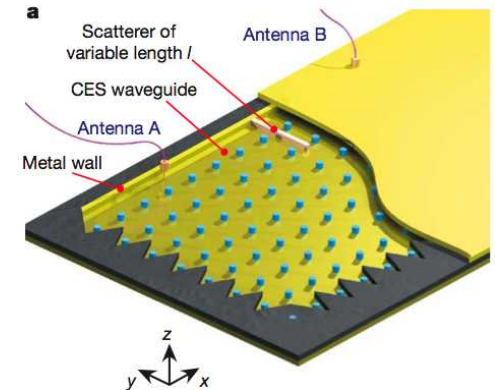
Magneto-optical photonic crystals for μ -waves

T-reversal broken by magnetic elements

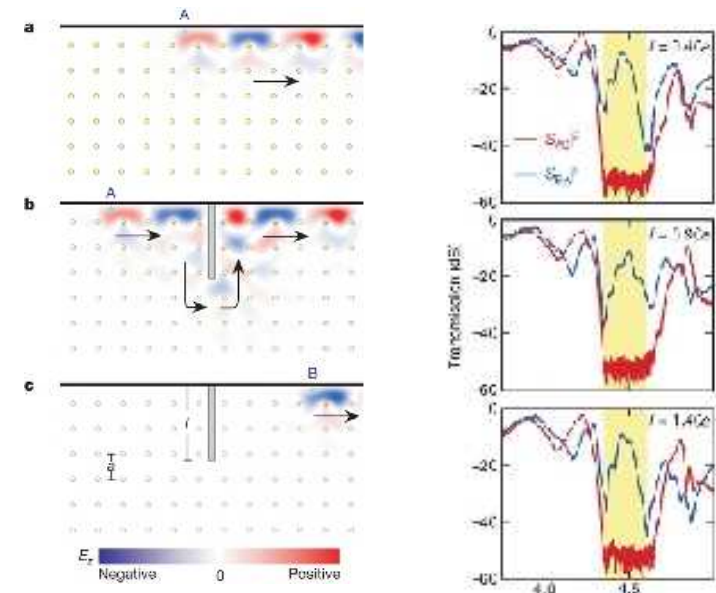
Band with non-trivial Chern number:
→ chiral edge states within gaps

Experiment:

- measure transmission from antenna to receiver
- only in one direction: unidirectional propagation
- immune to back-scattering by defects topologically protected



Wang et al., Nature 461, 772 (2009)

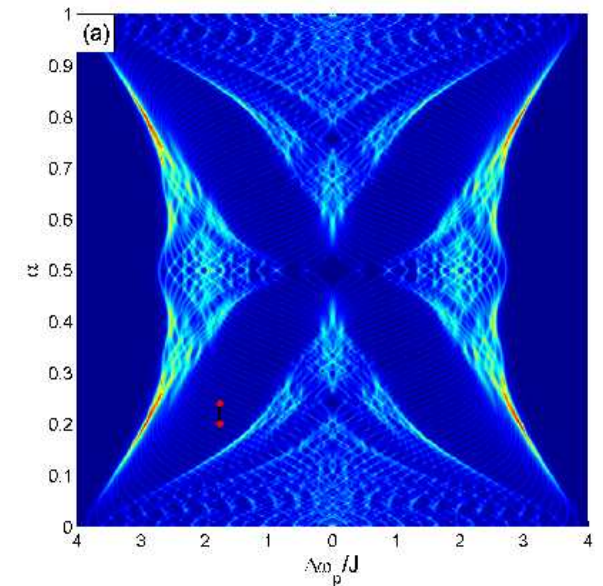


Wang et al., Nature 461, 772 (2009)

2013 - Imaging chiral edge states

2D square lattice of coupled cavities
at large magnetic flux

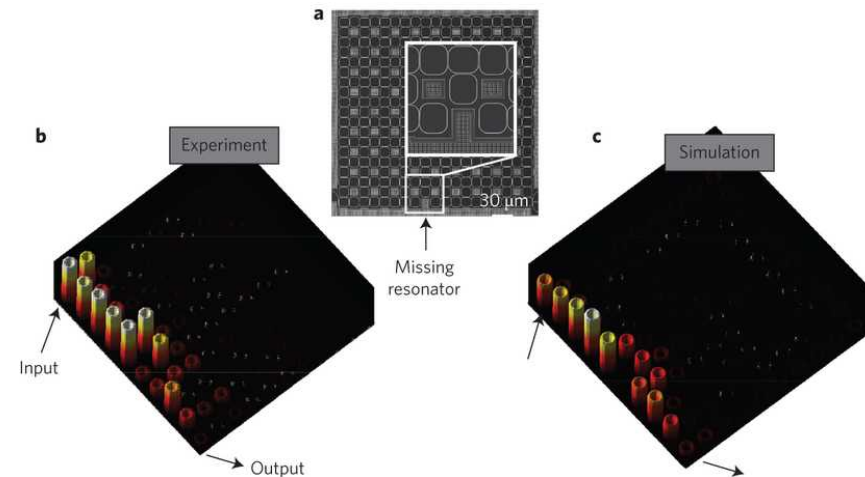
- eigenstates organize in **bulk Hofstadter bands**
- Berry connection in k-space:** $A_{n,k} = i \langle u_{n,k} | \nabla_k u_{n,k} \rangle$



Bulk-edge correspondance:

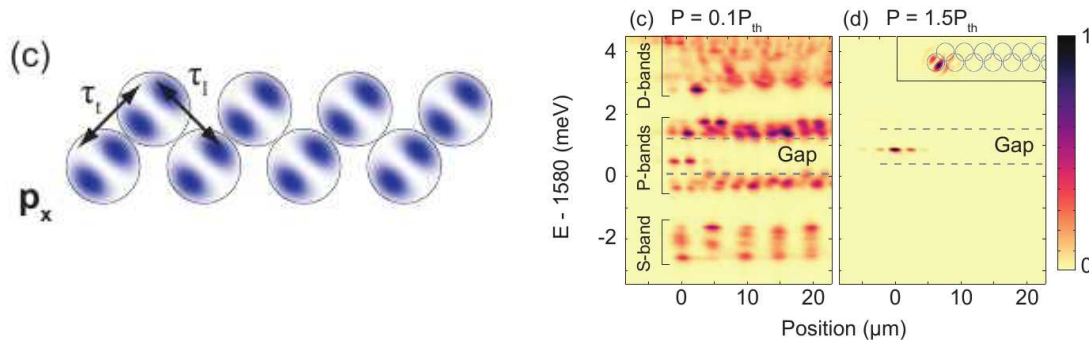
$A_{n,k}$ has non-trivial **Chern number**
→ **chiral edge states** within gaps

- unidirectional propagation
- (almost) immune to scattering by defects



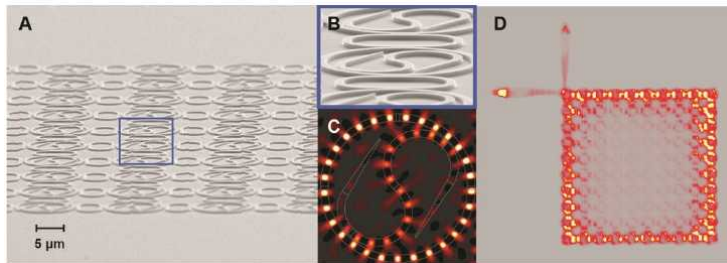
2017-8 – Topological lasing

What happens if one adds gain to a topological model ?



St. Jean, Ozawa, et al., Nat. Phot. '17

System: 1D SSH array of micropillars cavities
for exciton-polaritons under incoherent pump



Bandres et al., Science 2018

System: array of Si-based ring resonators with
optically pumped III-V amplifier layer.
Tai-Ji shape to break inversion symmetry

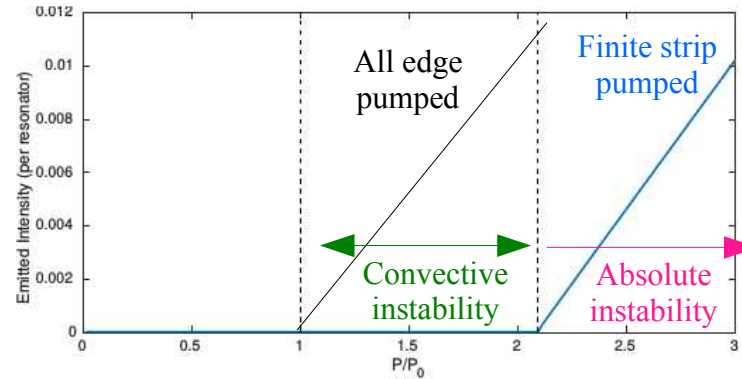
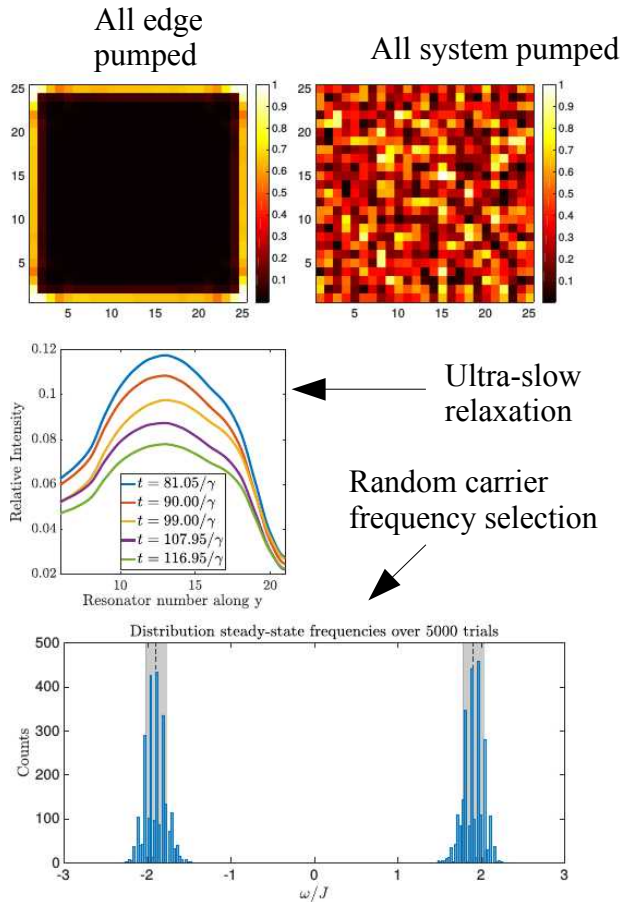
- Next days: Khajavikhan's group, PRL 2018; Kanté's group, Science 2017; Klembt et al., Nature 2018.

Topologically trivial system: pumping many cavities \rightarrow complicate many-mode emission

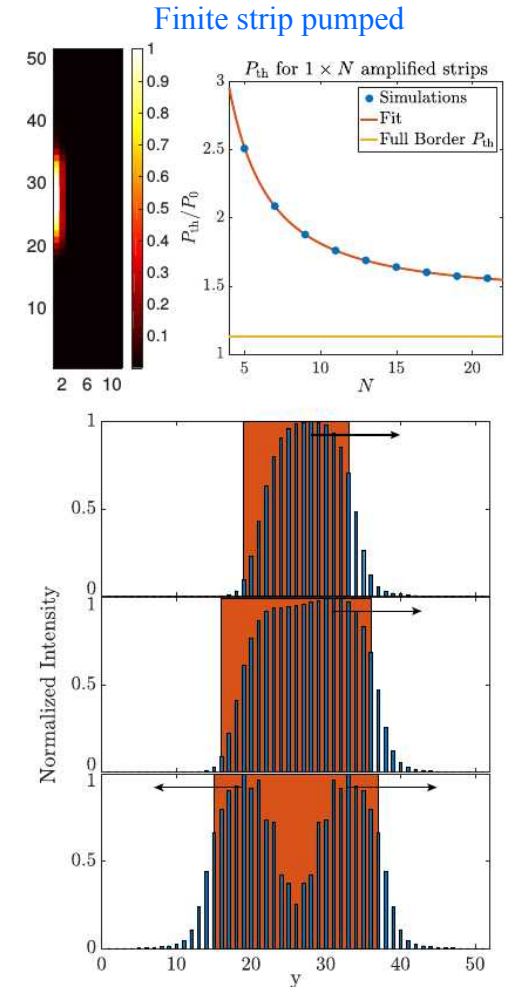
2D Topolaser operation into edge mode when many cavities pumped:

- Chiral propagation immune to disorder
 - Efficiently funnels pumped energy into single mode laser emission, high slope efficiency
- but....

A few intriguing surprises...



Figures from M. Secli, MSc thesis @ UniTN (10/17)
Secli-IC, in preparation



Large (finite) pump spot:
emission breaks into 2
modes with opposite
chirality

Convective vs. absolute instability → different threshold of edge-mode lasing

Topological effects visible in lasing threshold for high number of pumped sites

Topological protection:

- Random choice of lasing mode when all edge pumped, robust against mode jumps
- Large mass → Extra-slow relaxation → “lasing chiral Luttinger liquid” with short l_c
- Single mode recovered if pumping is spatially interrupted but fragmentation likely

Part 5:

Strongly interacting photons

*from Tonks-Girardeau gases
towards Fractional Quantum Hall states*

Photon blockade

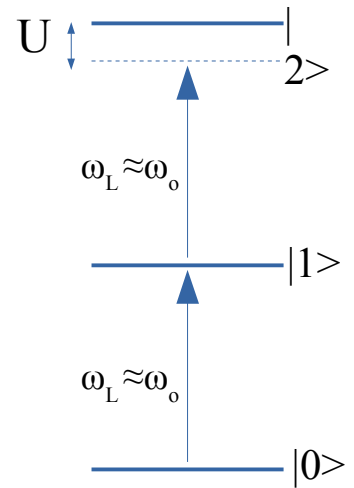
Bose-Hubbard model:

$$H_0 = \sum_i \hbar \omega_o \hat{b}_i^\dagger \hat{b}_i - \hbar J \sum_{\langle i,j \rangle} \hat{b}_i^\dagger \hat{b}_j + \hbar \frac{U}{2} \sum_i \hat{n}_i (\hat{n}_i - 1)$$

- single-mode cavities at ω_o . Tunneling coupling J
- Polariton interactions: on-site interaction U due to optical nonlinearity

If $U \gg \gamma, J$, coherent pump resonant with $0 \rightarrow 1$ transition, but not with $1 \rightarrow 2$ transition.

Photon blockade \rightarrow Effectively impenetrable photons



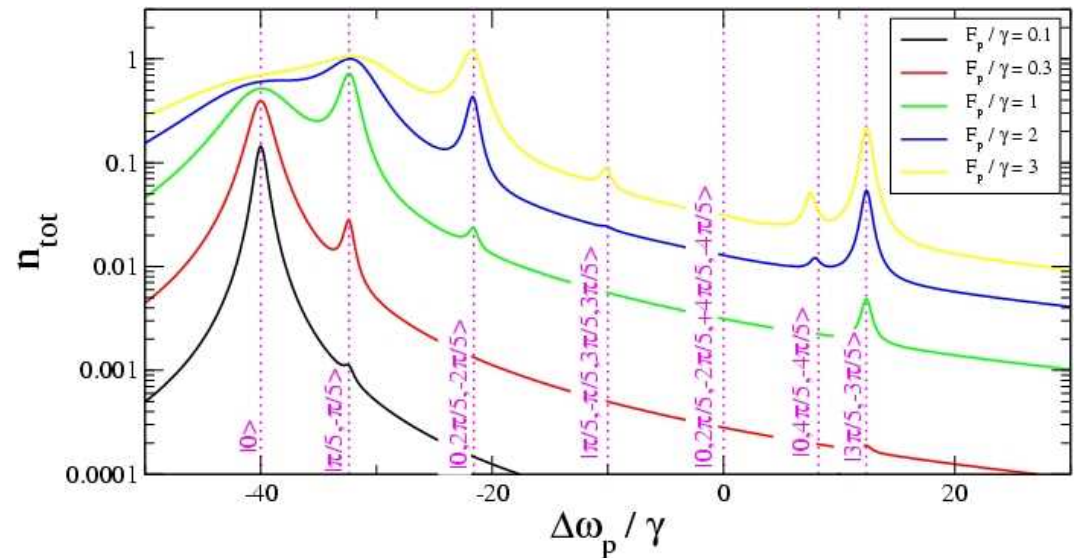
Need to add driving and dissipation:

- Incident laser: coherent external driving $H_d = \sum_i F_i(t) \hat{b}_i + h.c.$
- Weak losses $\gamma \ll J, U \rightarrow$ Lindblad terms in master eq. determine non-equilibrium steady-state

Impenetrable “fermionized” photons in 1D necklaces

Many-body eigenstates of
Tonks-Girardeau gas
of impenetrable photons

Coherent pump
selectively addresses
specific many-body states



Transmission spectrum as a function pump frequency for fixed pump intensity:

- each peak corresponds to a Tonks-Girardeau many-body state $|q_1, q_2, q_3, \dots\rangle$
- q_i quantized according to PBC/anti-PBC depending on $N=\text{odd/even}$
- $U/J \gg 1$: efficient photon blockade, impenetrable photons.

N-particle state excited by N photon transition:

- Plane wave pump with $k_p=0$: selects states of total momentum $P=0$
- Monochromatic pump at ω_p : resonantly excites states of many-body energy E such that $\omega_p = E / N$

Photon blockade + synthetic gauge field = FQHE for light

Bose-Hubbard model:

$$H_0 = \sum_i \hbar \omega_0 \hat{b}_i^\dagger \hat{b}_i - \hbar J \sum_{\langle i,j \rangle} \hat{b}_i^\dagger \hat{b}_j e^{i\varphi_{ij}} + \hbar \frac{U}{2} \sum_i \hat{n}_i (\hat{n}_i - 1)$$

gauge field gives phase in hopping terms

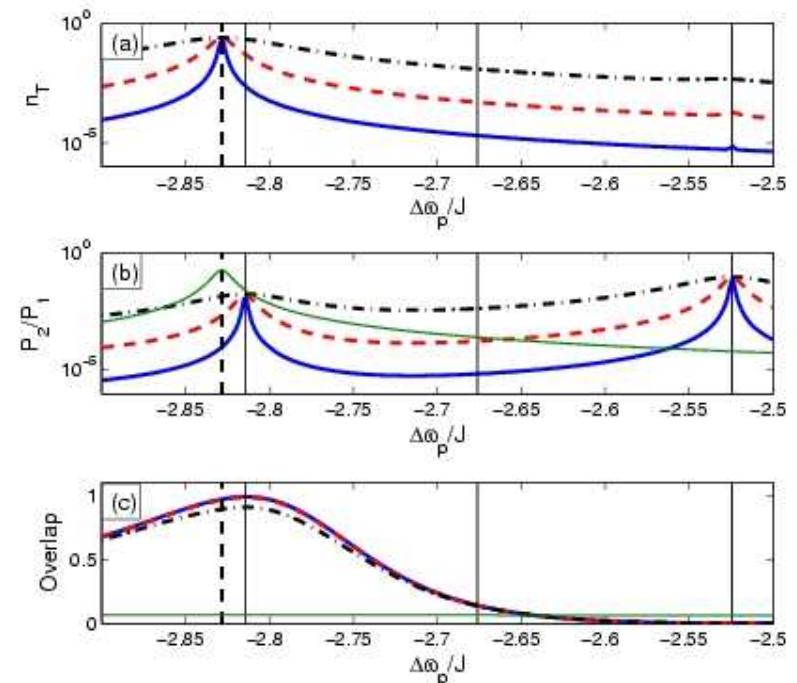
with usual coherent drive and dissipation → look for non-equil. steady state

Transmission spectra:

- peaks correspond to many-body states
- comparison with eigenstates of H_0
- good overlap with Laughlin wf (with PBC)

$$\psi_l(z_1, \dots, z_N) = \mathcal{N}_L F_{\text{CM}}^{(l)}(Z) e^{-\pi \alpha \sum_i y_i^2} \times \prod_{i < j}^N \left(\vartheta \left[\begin{matrix} \frac{1}{2} \\ \frac{1}{2} \end{matrix} \right] \left(\frac{z_i - z_j}{L} \middle| i \right) \right)^2$$

- no need for adiabatic following, etc....



Circuit-QED experiment

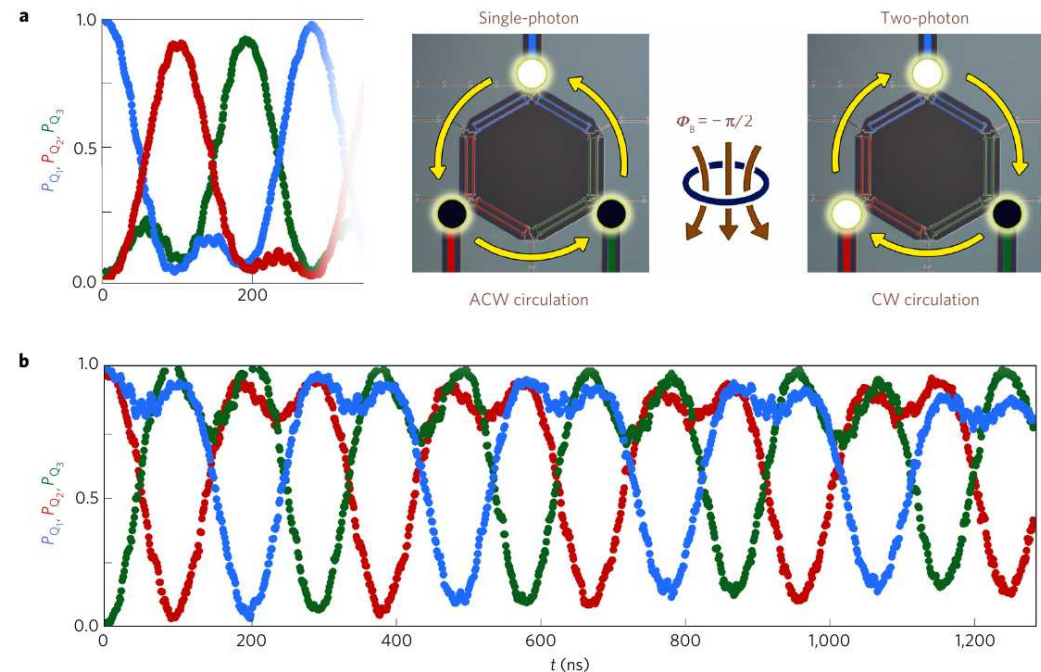
Ring-shaped array of qubits

- Transmon qubit: two-level system
→ Impenetrable photons
- Time-modulation of couplings
→ synthetic gauge field

Independently initialize sites

Follow unitary evolution until bosons lost

Monitor site occupation in time



J. Martinis group @ Google/UCSB
Roushan et al., Nat. Phys. 2016

“Many”-body effect:

two-photon state → opposite rotation compared to one-photon state
(similar to cold-atom experiment in Greiner’s lab: Tai et al., Nature 2017)

Conclusions and perspectives

Superfluid hydrodynamics in dilute fluid of light:

- Superfluid flow past an obstacle, nucleation of topological defects (2009-2011)
- Complex flows showing horizons (2015-)
- Mechanical effects of superfluid light (2017-)

1-body magnetic and topological effects for photons in synthetic gauge field:

- Unidirectional and topologically protected edge states (2009-)
- Geometrical properties of bulk & anomalous current (2016-)
- Landau levels in cylindrical trap; smart tricks to generate conical geometry (2016-)

Towards many-body physics:

- Many platforms for photon blockade: CQED with atoms and solids, circuit-QED,...
- Rydberg blockade easily integrated with synthetic-B in non-planar ring cavities
- Intersubband polaritons in FIR/MIR, large electric dipole moment, large coupling to phonons
- Propagating light in cavity-less media → unitary (conservative) many-body dynamics

Theoretical proposals:

- Mott-insulator (recent experiment report!), Laughlin states, etc. (expected to come soon!)
- Speculations: non-Abelian anyonic braiding; Dream: all-optical topological quantum operations

If you wish to know more...



Come and visit us in Trento!

REVIEWS OF MODERN PHYSICS, VOLUME 85, JANUARY–MARCH 2013

Quantum fluids of light

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(published 21 February 2013)

I. Carusotto and C. Ciuti, RMP **85**, 299 (2013)

CIRCUMNAVIGATING AN OCEAN OF INCOMPRESSIBLE LIGHT

A JOURNEY ACROSS THE EXCITING PERSPECTIVES OF
QUANTUM FLUIDS OF LIGHT

IACOPO CARUSOTTO

INO-CNR BEC Center and Dipartimento di Fisica, Università di Trento, Povo, Italy

I. Carusotto, Il Nuovo Saggiatore
SIF magazine (2013)

Topological Photonics

Review article arXiv:1802.04173 by Ozawa, Price, Amo, Goldman, Hafezi, Lu, Rechtsman, Schuster, Simon, Zilberberg, IC to appear on RMP (2019)

PhD and PostDoc positions
hopefully available soon.
Don't hesitate contacting me!
iacopo.carusotto@unitn.it

