Driven-dissipative vs. unitary quantum dynamics in fluids of light:
integer quantum Hall effects and quantum quenches

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Standing on the shoulders of giants

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.

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.

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 vorticité dans les ondes électromagnétiques.

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]

<u>And of course many others:</u>

Coullet, Gil, Rocca,
Brambilla, Lugiato...

Part I:

Exploiting driving & dissipation to generate and characterize strongly correlated many-photon states

- **How to address a single many body state**
- **How to homogeneously populate a full band**

Coherent pumping schemes:
IC, D. Gerace, H. E. Türeci, S. De Liberato, C. Ciuti, A. Imamoglu, PRL **103**, 033601 (2009)
R. O. Umucalilar and IC, PRL **108**, 206809 (2012)

Other schemes proposed by Hafezi-Taylor group and Trento group.

Part I-a:

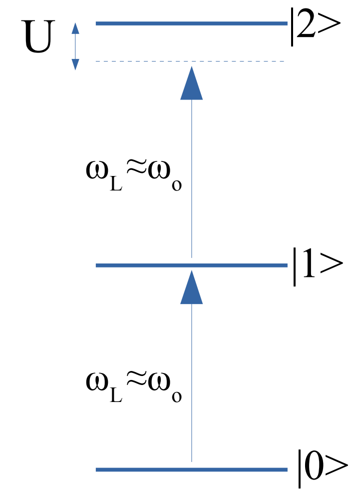
How to address a single many body state: Tonks-Girardeau gas and fractional quantum Hall effect for light

Photon blockade

Cavity array + strong nonlinearity, e.g. via Rydberg atoms

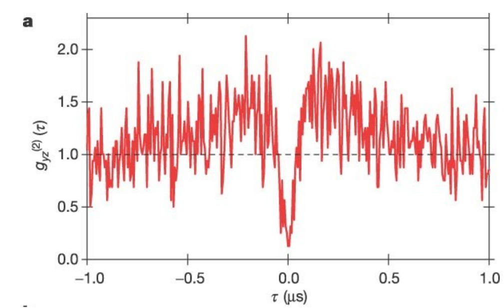
Bose-Hubbard model:

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



- single-mode cavities at ω_o. Tunneling coupling J. On-site repulsion U
- If U >> γ,J coher. pump resonant with 0→1 but not 1→2 transition.

Photon blockade → Effectively impenetrable photons



Birnbaum et al., Nature 436, 87 (2005)

Formally:

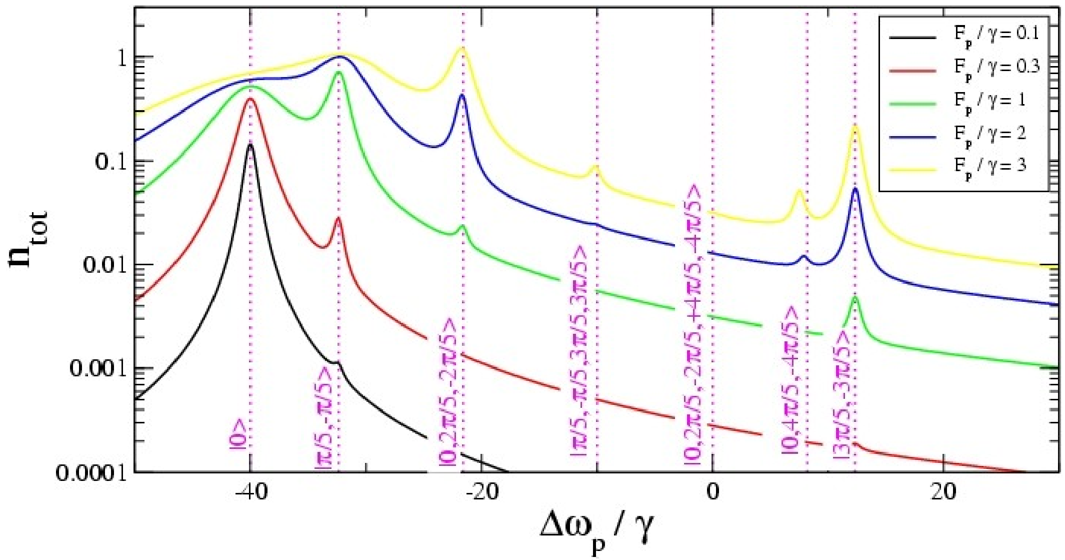
- Incident laser: coherent external driving $H_d = \sum_i F_i(t)\, \hat{b}_i + h.c.$
- Losses: Lindblad terms in master equation $\frac{d\rho}{dt} = \frac{1}{i\hbar}[H_0 + H_d, \rho] + L(\rho)$

→ Non-unitary evolution determines 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



N-particle state excited by N photon transition:

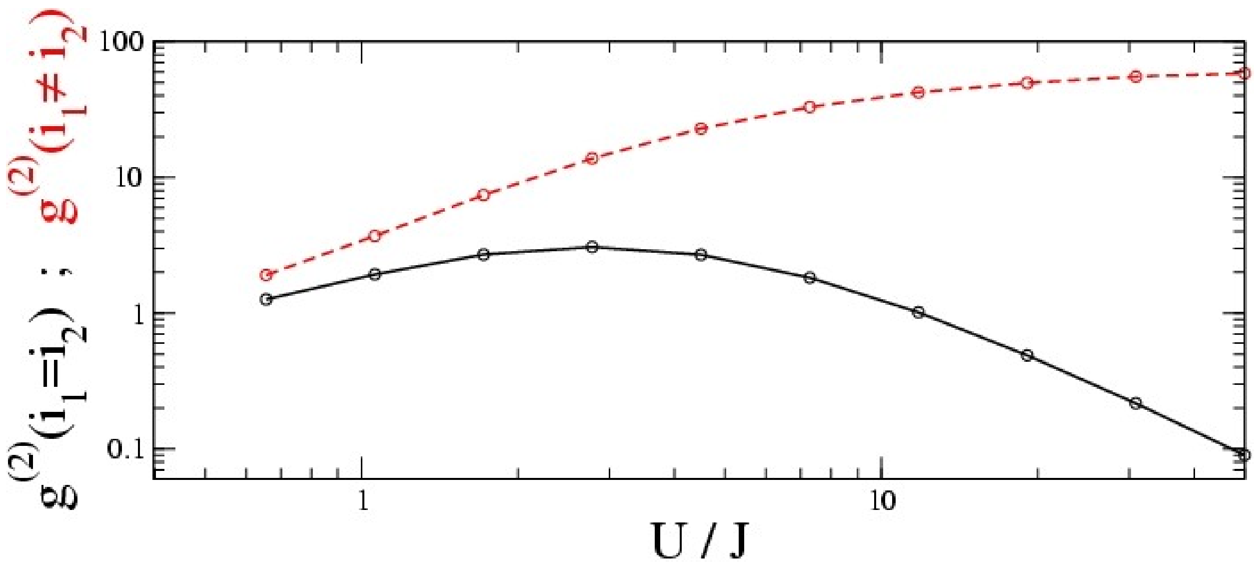
- Plane wave pump with k_p=0: selects states of total momentum P=0
- Monochromatic pump at ω_p: resonantly excites states of many-body energy E such that ω_p= E / N
- Of course, energy selectivity only efficient in mesoscopic limit of small N

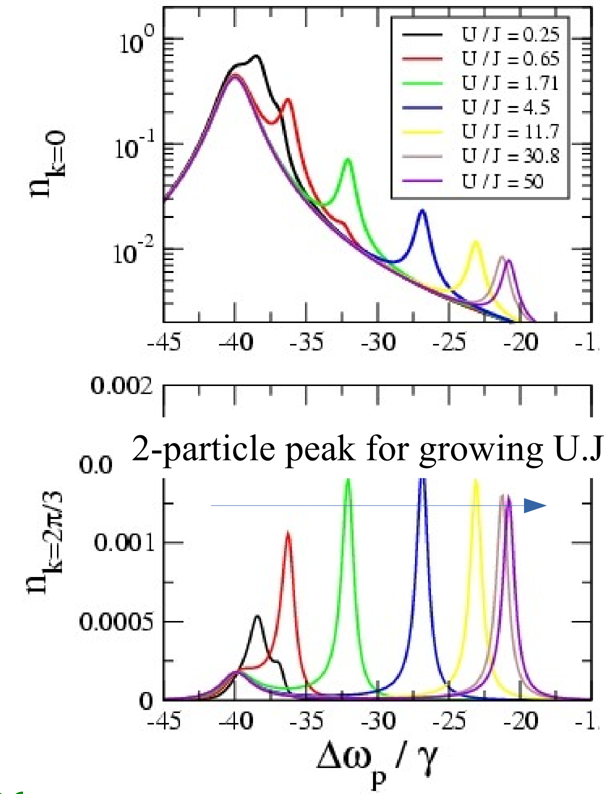
Transmission spectrum as a function pump frequency for fixed pump intensity:

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

IC, D. Gerace, H. E. Türeci, S. De Liberato, C. Ciuti, A. Imamoglu, PRL **103**, 033601 (2009)

State tomography from emission statistics





Finite U/J, pump laser tuned on two-photon resonance

- intensity correlation between the emission from cavities i_1, i_2
- at large U/γ, larger probability of having N=0 or 2 photons than N=1
  - low U<<J: bunched emission for all pairs of i_1, i_2
  - large U>>J: antibunched emission from a single site
    positive correlations between different sites
- Idea straightforwardly extends to more complex many-body states.

Photon blockade + synthetic gauge field = QHE for light

Bose-Hubbard model:

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

gauge field gives phase in hopping terms

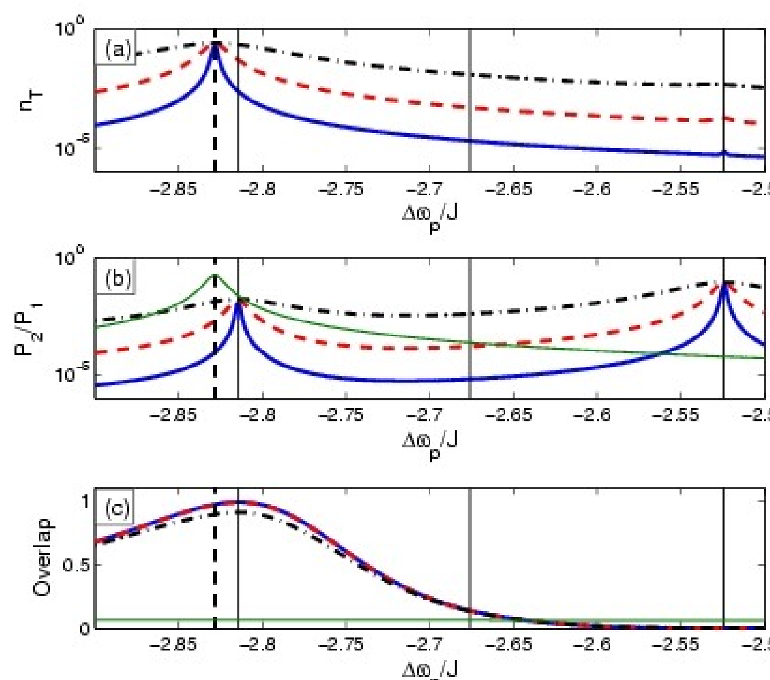
with usual coherent drive and dissipation → look for non-equil. steady state

Transmission spectra:

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

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

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



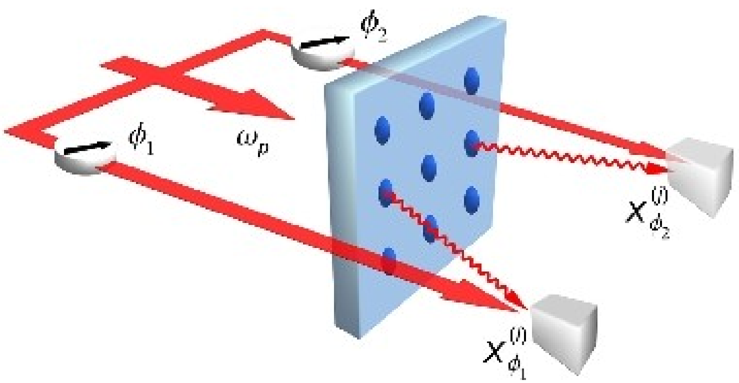
R. O. Umucalilar and IC, *Fractional quantum Hall states of photons in an array of dissipative coupled cavities*, PRL 108, 206809 (2012)

Tomography of FQH states

Homodyne detection of secondary emission

→ info on many-body wavefunction

$$\langle \hat{b}_i \hat{b}_j \rangle = \langle X_0^{(i)} X_0^{(j)} \rangle - \langle X_{\pi/2}^{(i)} X_{\pi/2}^{(j)} \rangle + i \langle X_0^{(i)} X_{\pi/2}^{(j)} \rangle + i \langle X_{\pi/2}^{(i)} X_0^{(j)} \rangle$$

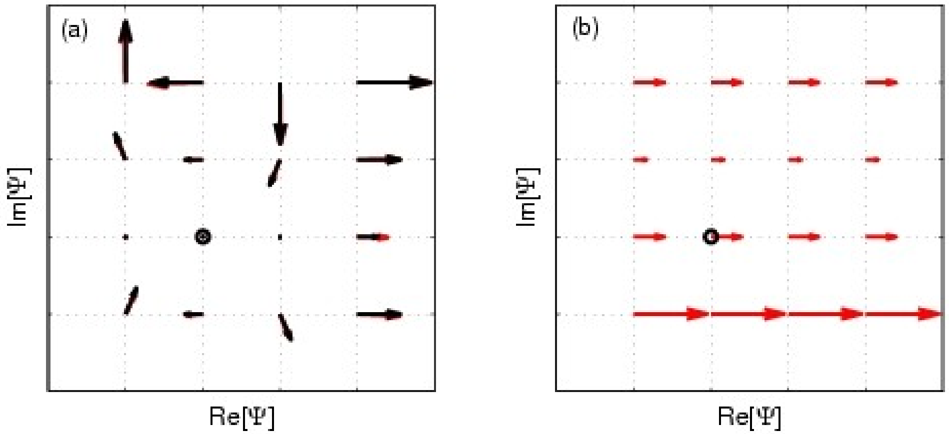


Note: optical signal gauge dependent,

optical phase matters !

Non-trivial structure of Laughlin state

compared to non-interacting photons



R. O. Umucalilar and IC, *Fractional quantum Hall states of photons in an array of dissipative coupled cavities*, PRL 108, 206809 (2012)

Part I-b:

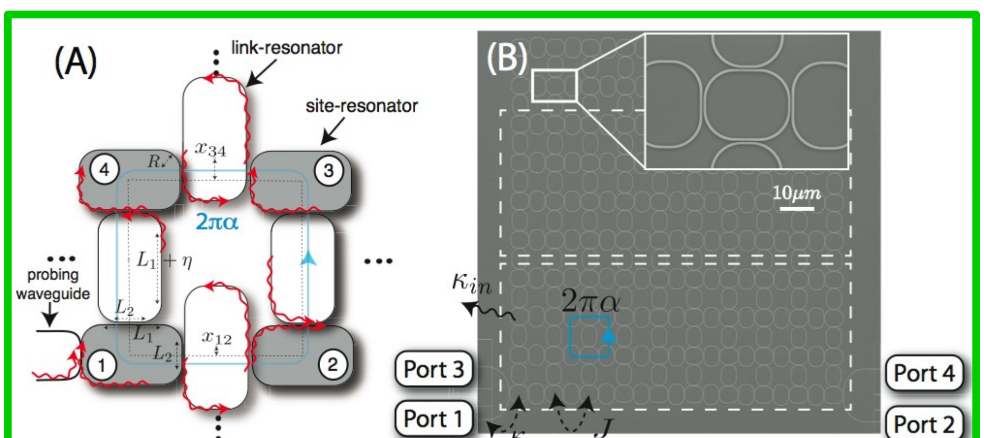
How to homogeneously populate a full band: an integer quantum Hall effect for light

Driven-dissipative photonic Hofstadter model (et similia)

2D lattice of coupled cavities with tunneling phase, coherent drive and dissipation

$$H = \sum_i \hbar\omega_\circ \hat{a}_i^\dagger \hat{a}_i - \hbar J \sum_{\langle i,j\rangle} \hat{a}_i^\dagger \hat{a}_j e^{i\phi_{ij}} + \sum_i \left[\hbar F_i(t)\, \hat{a}_i^\dagger + \text{h.c.}\right]$$

- silicon ring cavities → Hafezi/Taylor (JQI)
- electronic circuits with lumped elements → J. Simon (Chicago)
- related: honeycomb potential for polaritons → A. Amo/J.Bloch (LPN)

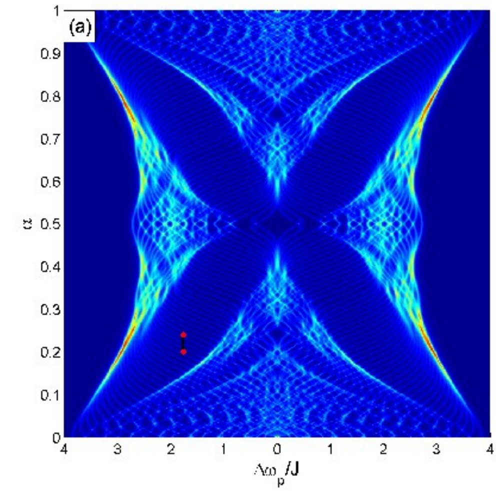


Hafezi et al.,Nat. Phot. **7**, 1001 (2013)

Topological properties of states

2D square lattice at large synthetic magnetic flux

- eigenstates organize in bulk Hofstadter bands
- Berry connection in k-space:



Geometrical and topological properties of bulk bands:

Berry connection $A_{n,k} = i\langle u_{n,k} | \nabla_k u_{n,k}\rangle$

Berry curvature $\Omega = curl\ A_{n,k}$

Topological invariant: Chern number → IQHE

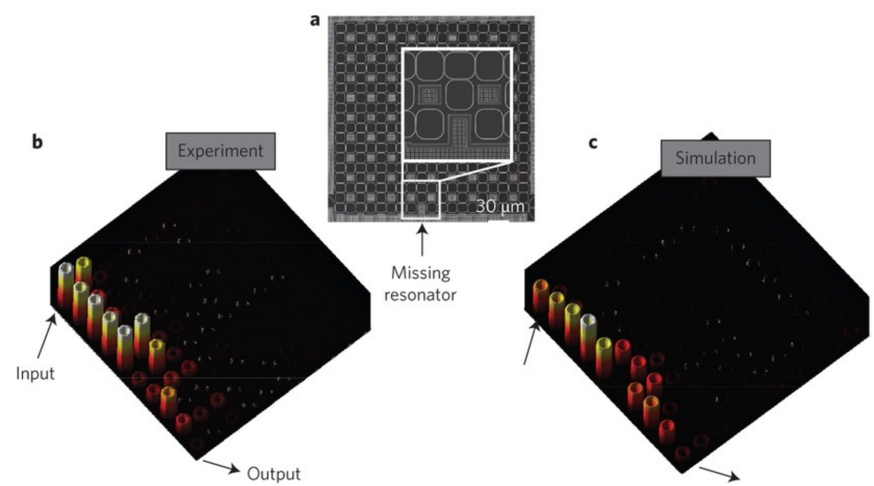
$$j^y = \frac{E_x}{(2\pi)^2} \int_{T^2} \Omega\, d^2 k = \frac{\nu_1}{2\pi} E_x$$

Bulk-edge correspondance:

- Non-zero ν_1 → chiral edge states within gaps
- unidirectional propagation, (almost) immune to scattering by defects

How to directly observe bulk ν_1 in optics ?

- Requires uniform population of band



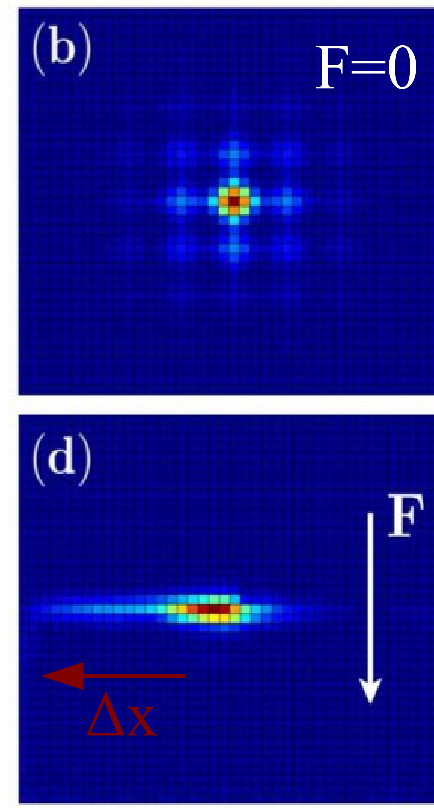
Hafezi et al.,Nat. Phot. **7**, 1001 (2013)

Photonic system

Coherent pumping $H_d = \sum_i F_i(t)\, \hat{b}_i + F_i^*(t)\, \hat{b}_i^\dagger$ + losses at rate γ

Pump spatially localized on one site only:

- couples to all k's within Brillouin zone
- resonance condition selects specific states



In the presence of force F:

motion in BZ → lateral drift in real space by Berry curvature

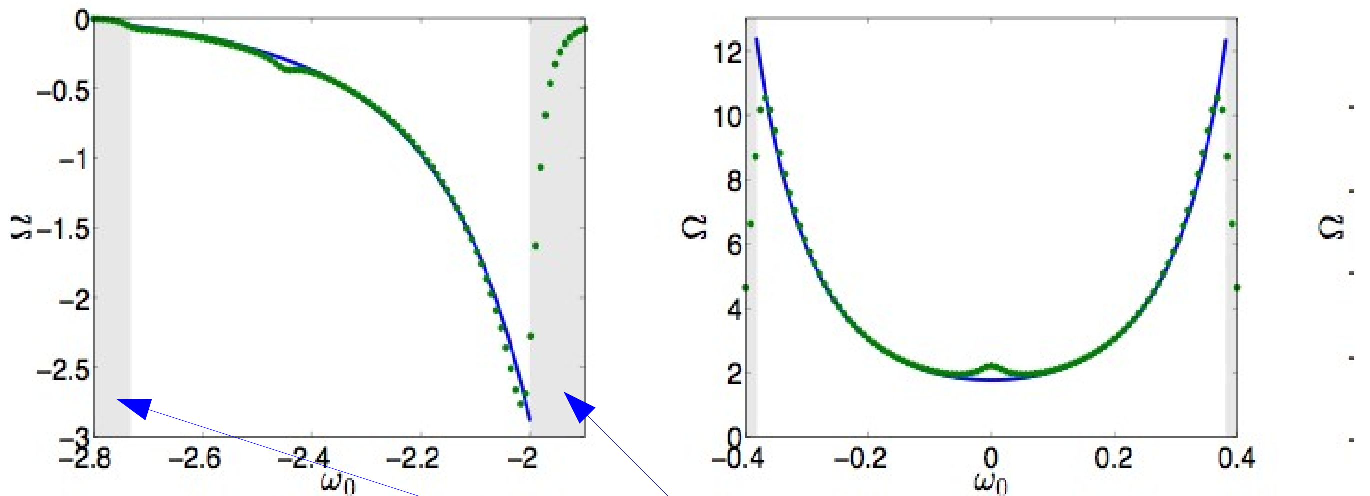
$$\hbar \dot{\mathbf{k}}_c(t) = e\mathbf{E}\,,$$
$$\hbar \dot{\mathbf{r}}_c(t) = \nabla_{\mathbf{k}} \mathcal{E}_{n,\mathbf{k}} - e\mathbf{E} \times \mathbf{\Omega}_n(\mathbf{k})$$

Detectable as lateral shift of intensity distribution by Δx perpendicular to F

T. Ozawa and IC, *Anomalous and Quantum Hall Effects in Lossy Photonic Lattices*, PRL (2014)

More quantitatively

		1st	2nd	3rd	4th	5th	6th
$\alpha = \frac{1}{3}$	$\mathcal{C}$	-1	$+2$	-1			
	$\mathcal{C}_n$	-0.91	-	-0.91			
$\alpha = \frac{1}{5}$	$\mathcal{C}$	-1	-1	$+4$	-1	-1	
	$\mathcal{C}_n$	-0.97	-0.66^*	-	-0.66^*	-0.97	
$\alpha = \frac{1}{6}$	$\mathcal{C}$	-1	-1	$+2$	$+2$	-1	-1
	$\mathcal{C}_n$	-0.96	-1.06	-	-	-1.06	-0.96
$\alpha = \frac{3}{7}$	$\mathcal{C}$	$+2$	-5	$+2$	$+2$	$+2$	-5
	$\mathcal{C}_n$	2.05	-	-	2.01	-	-
$\alpha = \frac{4}{9}$	$\mathcal{C}$	$+2$	$+2$	-7	$+2$	$+2$	$+2$
	$\mathcal{C}_n$	1.96	-	-	2.02	1.92	2.02
$\alpha = \frac{5}{11}$	$\mathcal{C}$	$+2$	$+2$	-9	$+2$	$+2$	$+2$
	$\mathcal{C}_n$	1.92	1.88	-	-	2.06	1.91



(a) Lowest band of $\alpha = 1/3$

(b) Middle band of $\alpha = 1/5$

band gaps

Low loss (γ < bandwidth) → excited modes are energy-selected

$\Delta x = F\,\Omega(k_0)/2\gamma$ (anomalous Hall eff.)

Large loss (bandwidth < γ < bandgap) → all states in the band equally excited

$\Delta x = q\,\text{Chern} / 2\pi\gamma$ (integer-QH)

Integer quantum Hall effect for photons (in spite of no Fermi level)

Photon phase observable => expts "sensitive to gauge-variant quantities"!!

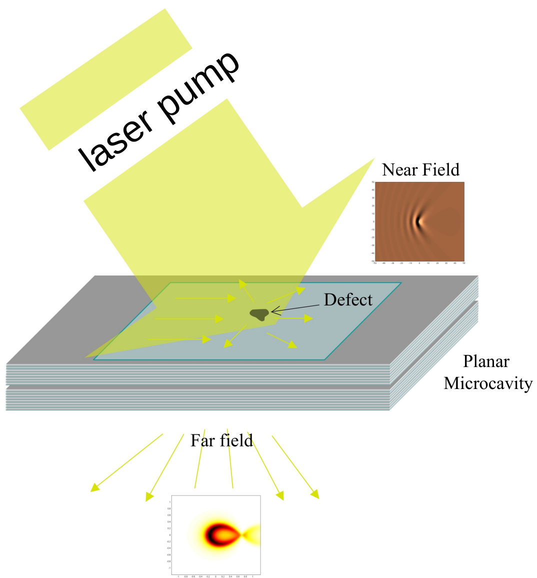
T. Ozawa and IC, *Anomalous and Quantum Hall Effects in Lossy Photonic Lattices*, PRL (2014)

Part II:

Quantum fluids of light with a *unitary* dynamics

Field equation of motion

Planar microcavities & cavity arrays



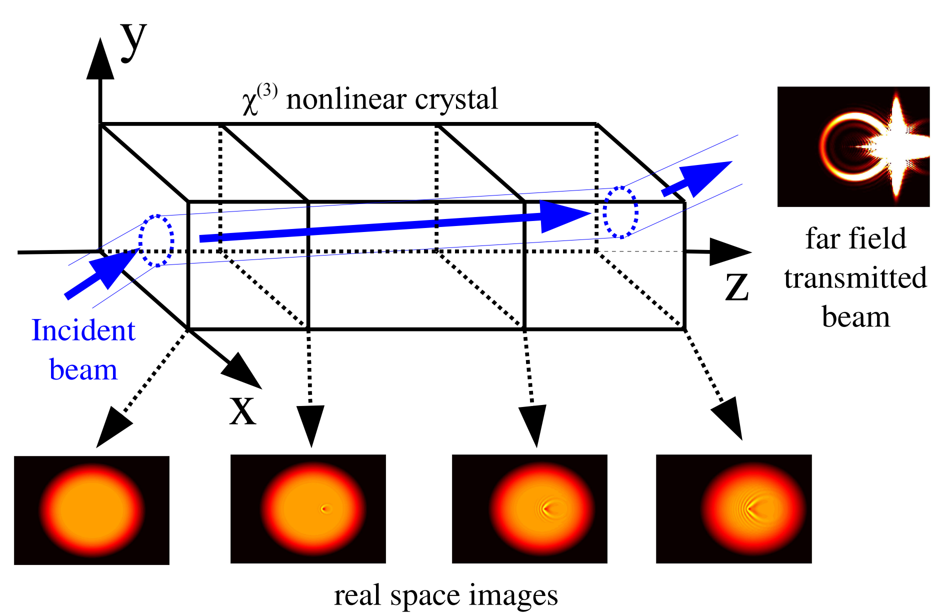
Pump needed to compensate losses:
driven-dissipative dynamics in real time
stationary state ≠ thermodyn. equilibrium

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



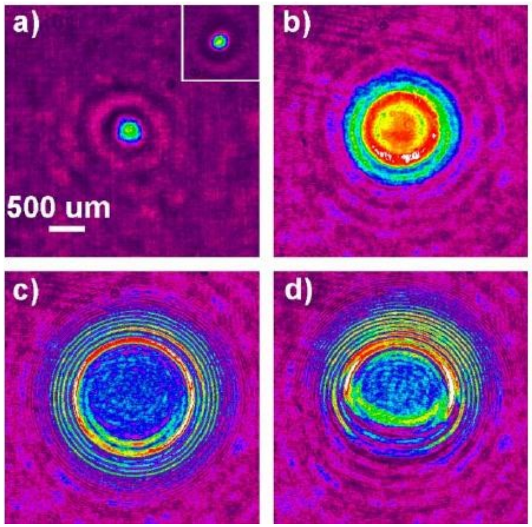
Monochromatic beam
Incident beam sets initial condition @ z=0
MF → Conserv. paraxial propag. → GPE

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

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

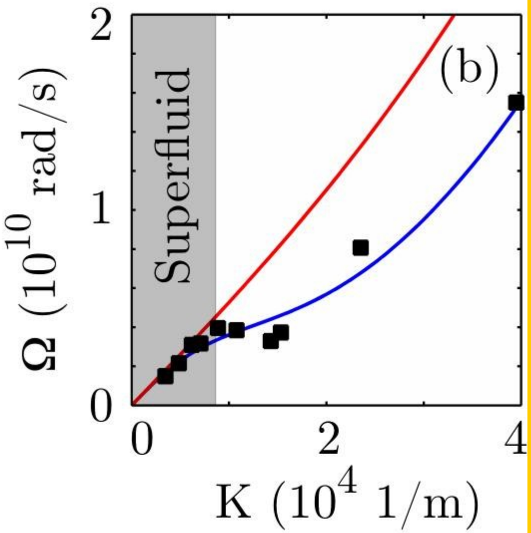
A few remarkable recent experiments

Dispersive superfluid-like shock waves



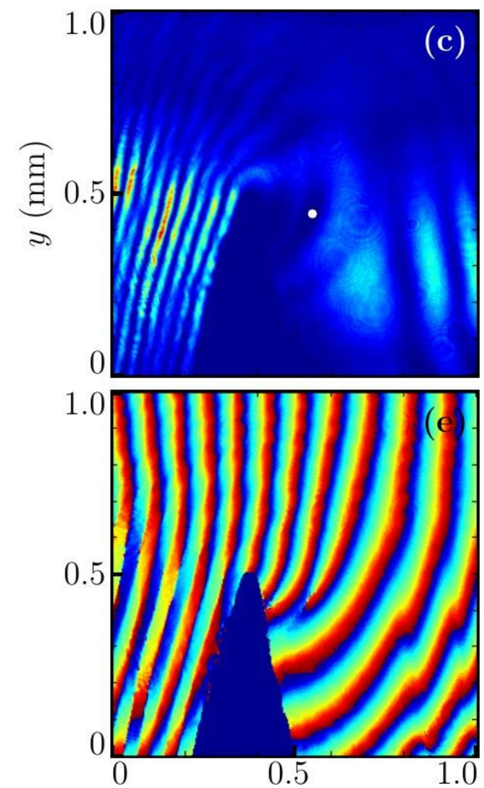
Wan et al., Nat. Phys. 3, 46 (2007)

Bogoliubov dispersion of collective excitations



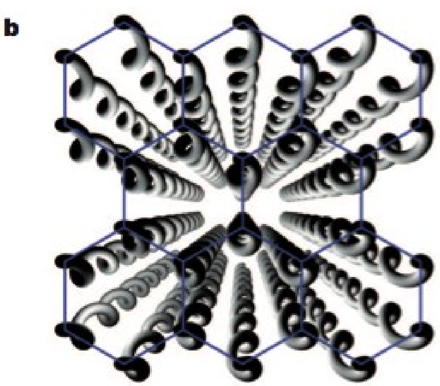
D. Vocke et al. Optica (2015)

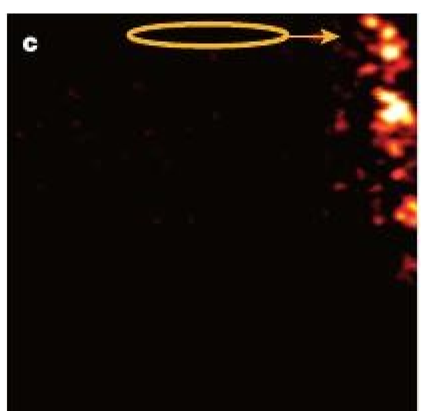
Hydrodynamic nucleation of quantized vortices



D. Vocke et al.,
in preparation (2015)

Chiral edge states in (photonic) Floquet topological insulator





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

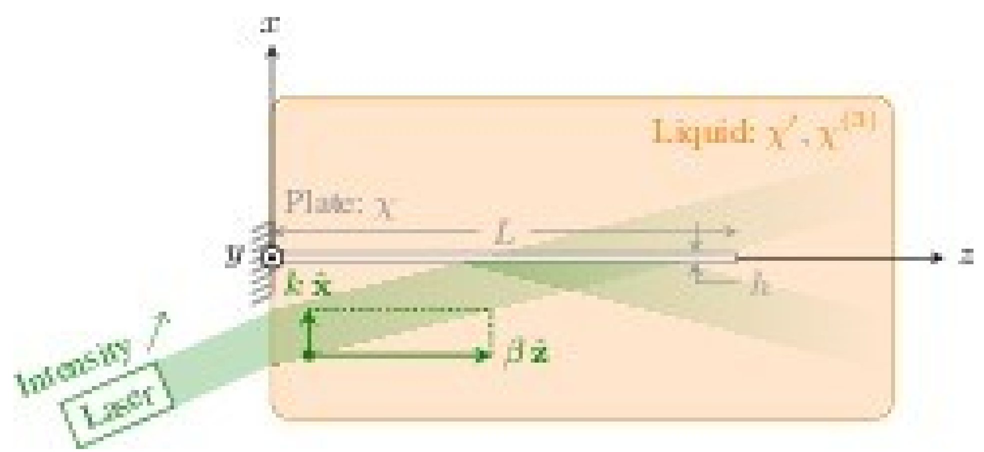
Frictionless flow of superfluid light (I)

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



P.-E. Larré and IC, arXiv:1405.2275, in the press on PRA (2015)

Frictionless flow of superfluid light (II)

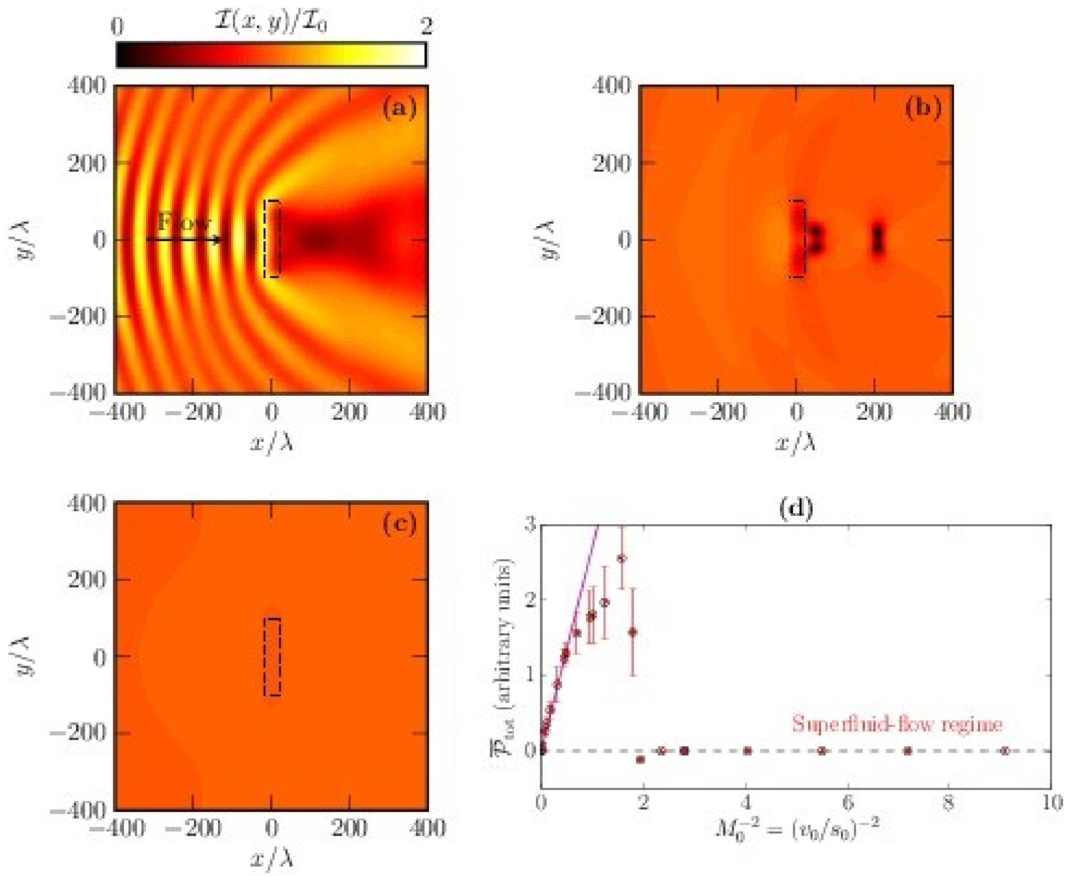
Numerics for propagation GPE of monochromatic laser:

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

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

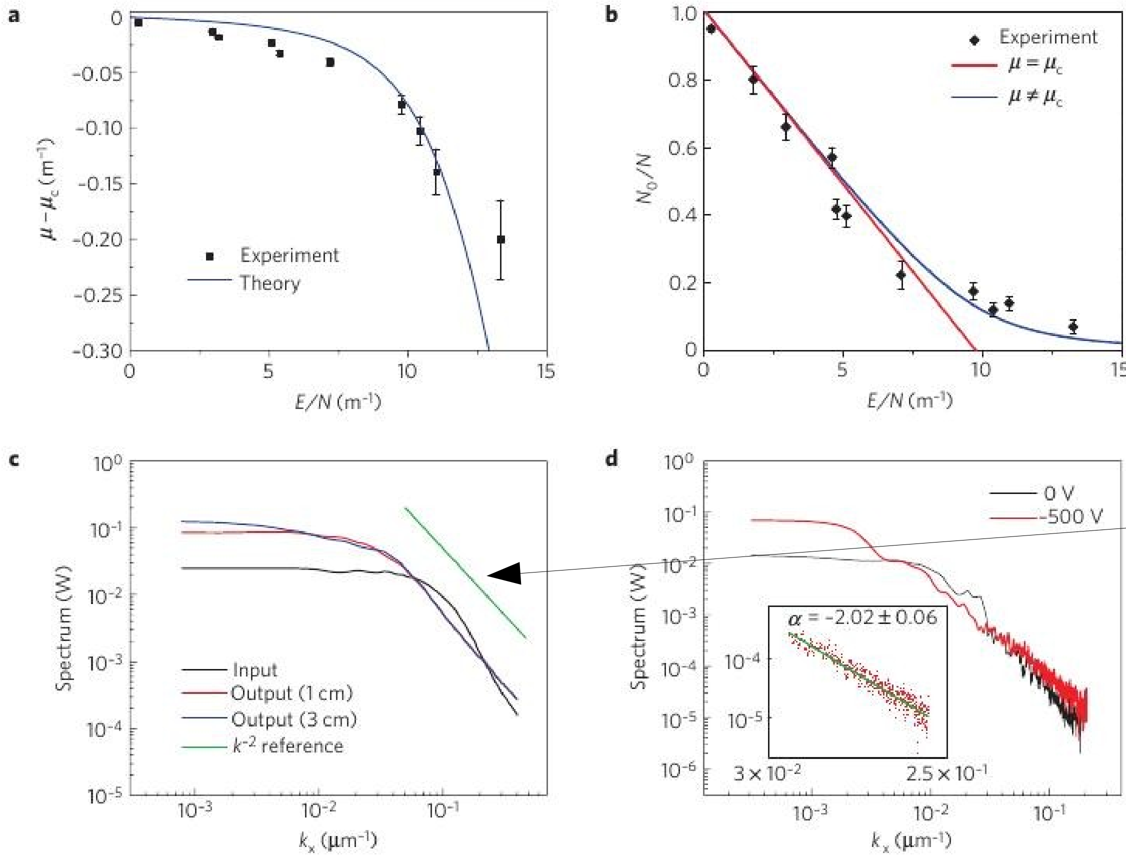


<u>Fused silica slab:</u>
deformation almost in the µm range

P.-E. Larré and IC, PRA (2015)

Condensation of classical waves

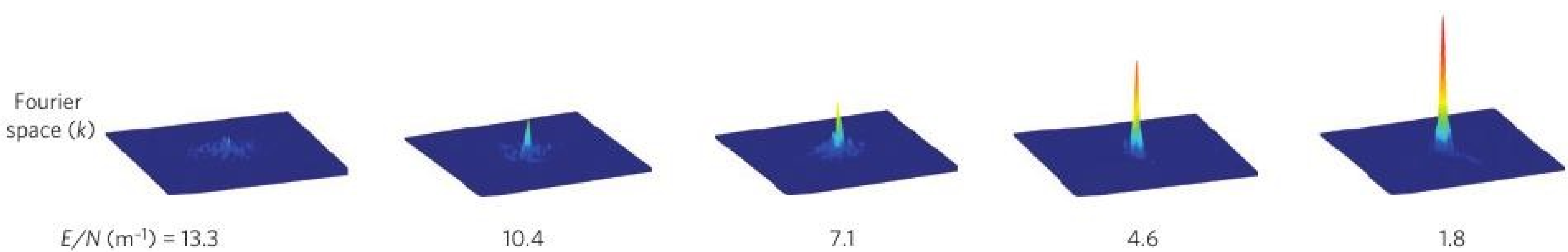
Monochromatic beam
but spatially noisy profile



Evolution during propagation
→ classical GPE
Slow nonlinearity
→ remains monochromatic

Thermalizes to condensate
plus thermal cloud
with Rayleigh-Jeans
1/k² high-momentum tail

- What about quantum effects?
- How to recover Planckian?



Sun et al., Nature Physics 8, 470 (2012)

How to include quantum fluctuations beyond MF

Requires going beyond monochromatic beam and explicitly including physical time

Gross-Pitaevskii-like eq. for propagation of quasi-monochromatic field

$$i\frac{\partial E}{\partial z}=-\frac{1}{2\beta_0}\left(\frac{\partial^2 E}{\partial x^2}+\frac{\partial^2 E}{\partial y^2}\right)-\frac{1}{2D_0}\frac{\partial^2 E}{\partial t^2}+V(r)E+g|E|^2E$$

Propagation coordinate z → time

Physical time → extra spatial variable, dispersion D_0 → temporal mass

Upon quantization → conservative many-body evolution in z: $i\frac{d}{dz}|\psi\rangle=H|\psi\rangle$

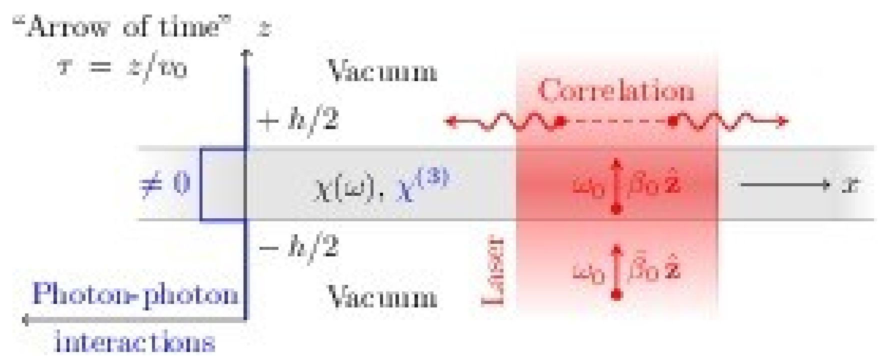
with $H=N\iiint dx\,dy\,dt\left[\frac{1}{2\beta_0}\nabla\hat{E}^\dagger\nabla\hat{E}-\frac{D_0}{2}\frac{\partial\hat{E}^\dagger}{\partial t}\frac{\partial\hat{E}}{\partial t}+V\hat{E}^\dagger\hat{E}+\hat{E}^\dagger\hat{E}^\dagger\hat{E}\hat{E}\right]$

Same z commutator $\left[\hat{E}(x.y,t,z),\hat{E}^+(x',y',t',z)\right]=\frac{c\hbar\omega_0 v_0}{\epsilon}\delta(x-x')\,\delta(y-y')\,\delta(t-t')$

P.-E. Larré and IC, arXiv:1412.5405, to appear on PRA. See also old work by Lai and Haus, PRA 1989

Dynamical Casimir emission at quantum quench (I)

Monochromatic wave @ normal incidence
Weakly nonlinear medium
→ Weakly interacting Bose gas at rest



Air / nonlinear medium interface

→ sudden jump in interaction constant when moving along *z*

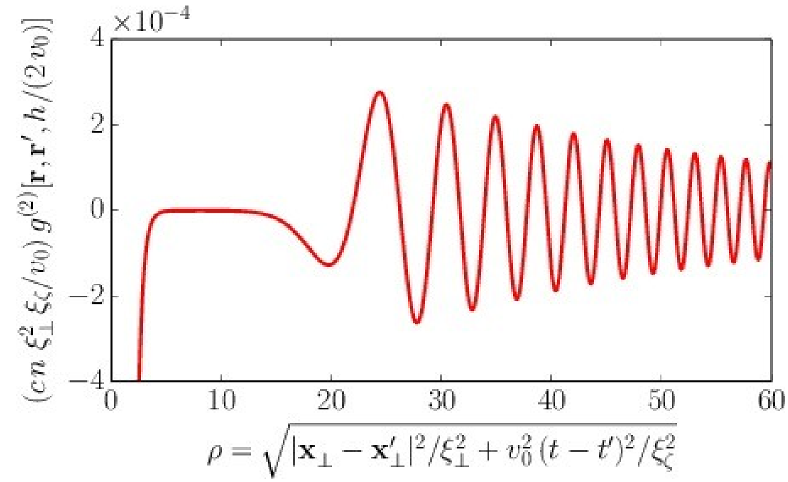
Mismatch of Bogoliubov ground state in air and in nonlinear medium
→ emission of phonon pairs at opposite k on top of fluid of light

Propagation along *z*
→ conservative quantum dynamics

<u>Important question:</u> what is quantum evolution at late times? Thermalization?

P.-E. Larré and IC, arXiv:1412.5405, to appear on PRA

Dynamical Casimir emission at quantum quench (II)



Observables:

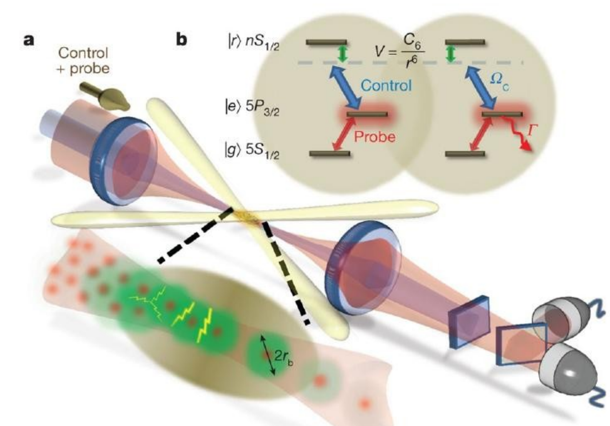
- Far-field → correlated pairs of photons at opposite angles
- Near-field → peculiar pattern of intensity noise correl.

First peak propagates at the speed of sound c_s

May simulate dynamical Casimir effect & fluctuations in early universe

Pimp & probe expt for speed of sound c_s in spatial (xy) and temporal (t) directions:

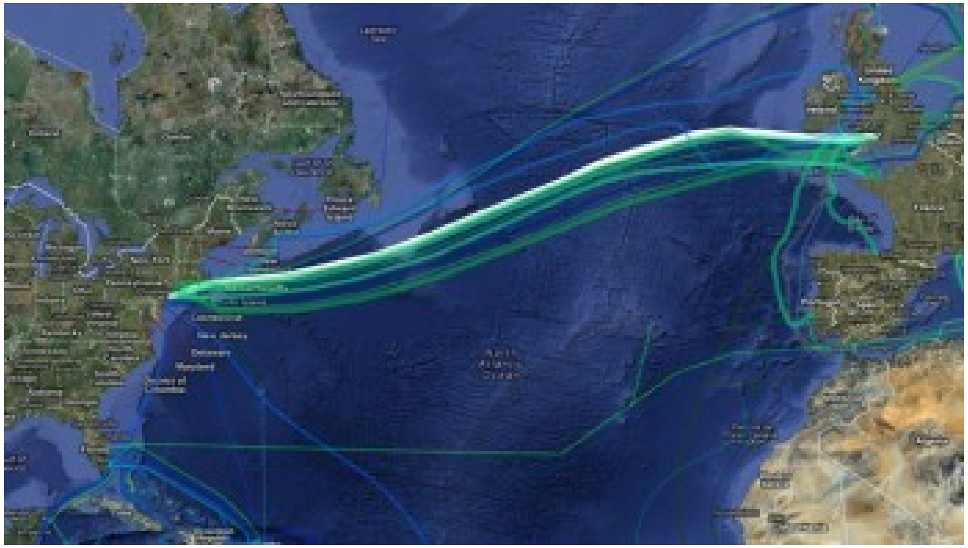
- c_s^{xy} (Heriot-Watt – Vocke et al. Optica '15)
- c_s^{t} (Trento, in progress)



Quantum dynamics most interesting in strongly nonlinear media, e.g. Rydberg polaritons

P.-E. Larré and IC, arXiv:1412.5405, to appear on PRA

A potentially important technological issue...



Long-distance fiber-optic set-ups
→ telecom over distances ~10^4 km

Can optical coherence be preserved?

Several disturbing effects:

- (extrinsic) fluctuations of fiber temperature, length, etc.
- (intrinsic) Fiber material has some (typically weak) $\chi^{(3)}$
  Shot noise on photon number gives fluctuations of $n_{refr} \sim n_0 + \chi^{(3)} I$

  Statistical mechanics suggests that phase fluctuations destroy 1D BEC

  → light at the end of fiber has lost its (temporal) phase coherence

Is this intuitive picture correct? How to tame phase decoherence?

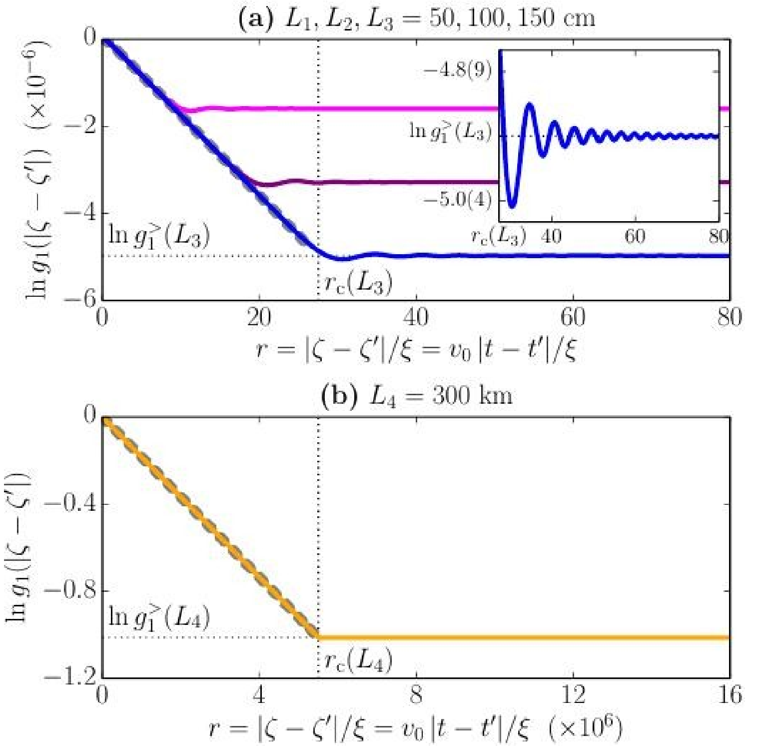
"Pre-thermalized" 1D photon gas

Perfectly coherent light injected into 1D optical fiber:

- quantum quench of interactions ~ $\chi^{(3)}$
- pairs of Bogoliubov excitations generated

Resulting phase decoherence in $g^{(1)}(t-t')$:

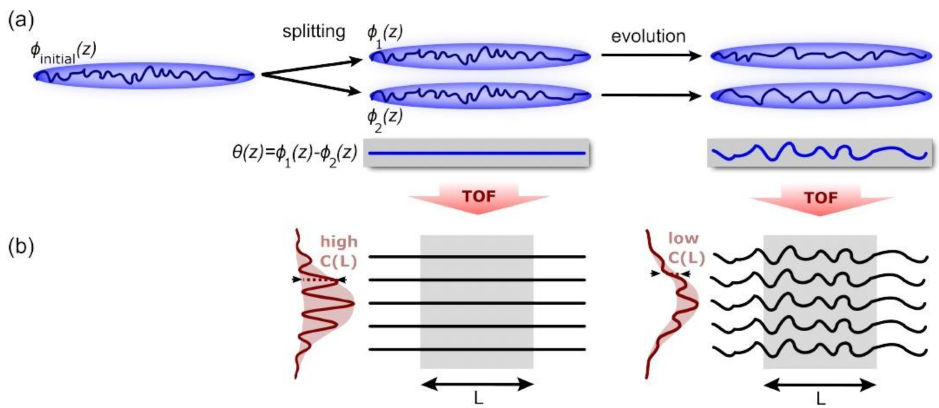
- Exponential decay at short $|t-t'| < 2z / c_s$
  (c_s = speed of Bogol. sound)
- Plateau at long $|t-t'| > 2z / c_s$
- Low-k modes eventually tends to thermal $T_{eff} = \mu / 2$
- Hohenberg-Mermin-Wagner theorem prevents long-range order in 1D quasi-condensates at finite T



Effect small for typical Si fibers, still potentially harmful on long distances
Decoherence slower if tapering used to "adiabatically" inject light into fiber

As in cold atom expts by J. Schmiedmayer when 1D quasi-BEC suddently split in two

Nature Physics 9, 640–643 (2013)



P.-E. Larré and IC, arXiv:1510.05558

A quite generic *quantum simulator*

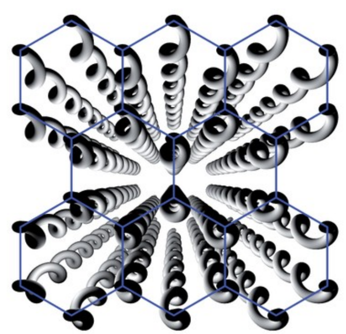
Quantum many-body evolution in *z:*

$$i \frac{d}{dz} |\psi> = H |\psi> \quad \text{with:} \quad H = N \iiint dx\, dy\, dt \left[\frac{1}{2\beta_0} \nabla \hat{E}^\dagger \nabla \hat{E} - \frac{D_0}{2} \frac{\partial \hat{E}^\dagger}{\partial t} \frac{\partial \hat{E}}{\partial t} + V \hat{E}^\dagger \hat{E} + \hat{E}^\dagger \hat{E}^\dagger \hat{E} \hat{E} \right]$$

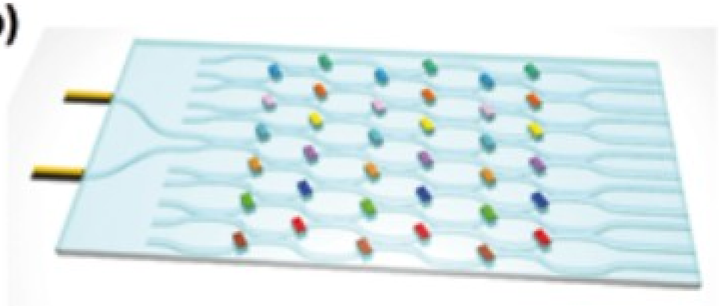
- Physical time t plays role of extra spatial coordinate
- Same z commutator: $\left[\hat{E}(x.y,t,z), \hat{E}^+(x',y',t',z)\right] = \frac{c \hbar \omega_0 v_0}{\epsilon} \delta(x-x') \delta(y-y') \delta(t-t')$

Clever design of V(x,y,z) → simulate wide variety of physical systems:

- Floquet topological insulators
- Arbitrary splitting/recombination of waveguides → quench of tunneling
- In addition to photonic circuit → many-body due to photon-photon interactions
- On top of moving fluid of light → simulate general relativistic QFT

b


Rechtsman et al., Nature 2012

(b)


P.-E. Larré and IC, arXiv:1412.5405

Conclusions and perspectives

Dilute photon gas
GP-like equation

- 2000-6 → BEC in exciton-polaritons gas in semiconductor microcav.
- 2008-10 → superfluid hydrodynamics effects observed
- 2009-13 → synthetic gauge field for photons and topologically protected edge states observed
- 2014- → revival of paraxial nonlinear optics in the new perspective of *propagating fluids of light*

- Optical microcavity systems are unavoidably lossy → driven-dissipative, non-equilibrium dynamics
  not always a hindrance for many-body physics, but can be turned into great advantage!
- Bulk cavityless geometries: paraxial propagation → conservative dynamics
  time plays role of third dimension; useful to study quantum quenches, thermalization, etc.

Many questions still open:

- high-dimensional photonics: new topological effects & device applications
- generate strongly correlated photon gases → Tonks-Girardeau gas in 1D necklace of cavities and Laughlin states in 2D arrays w/ synthetic gauge field

- Photons with unitary dynamics → many possible applications:
  - Thermalization past quantum quench
  - Onset of long-range coherence: coarsening, (quantum) aging, etc.
  - Main requirement: clean medium with large and fast and local $\chi^{(3)}$

If you wish to know more...

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

Quantum fluids of light

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I. Carusotto and C. Ciuti, Reviews of Modern Physics **85**, 299 (2013)


CIRCUMNAVIGATING AN OCEAN OF INCOMPRESSIBLE LIGHT
A JOURNEY ACROSS THE EXCITING PERSPECTIVES OF QUANTUM FLUIDS OF LIGHT
IACOPO CARUSOTTO
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I. Carusotto, Il Nuovo Saggiatore – SIF magazine (2013)

Or, even better, visit us in Trento!!
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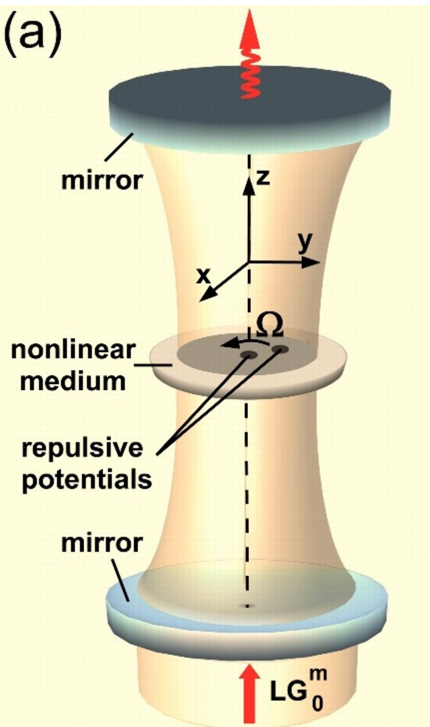
Save the date: May 8th-12th, 2017
2nd Workshop on Strongly Correlated Fluids of Light and Matter
Cargese, Corse

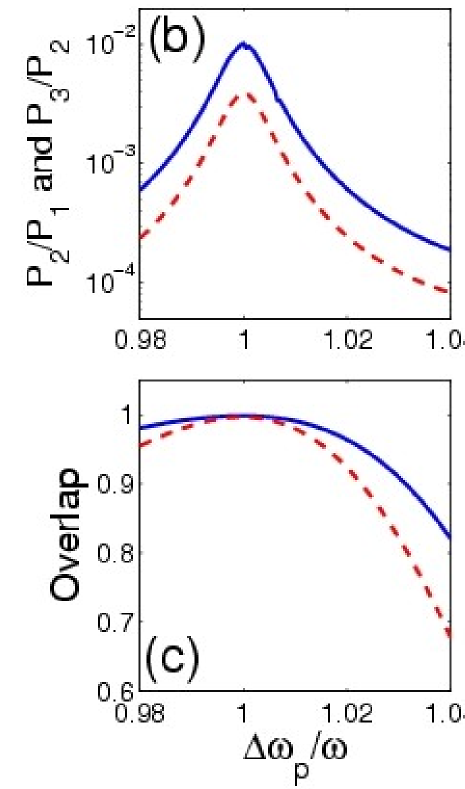
A simpler design: rotating photon fluids

Rotating system at angular speed Ω. No need for cavity array



same form → Coriolis $F_c = -2m\Omega \times v$

same form → Lorentz $F_L = e\, v \times B$



Rotating photon gas injected by LG pump

with finite orbital angular momentum

Strong repuls. interact., e.g. layer of Rydberg atoms

Resonant peak in transmission due to Laughlin state:

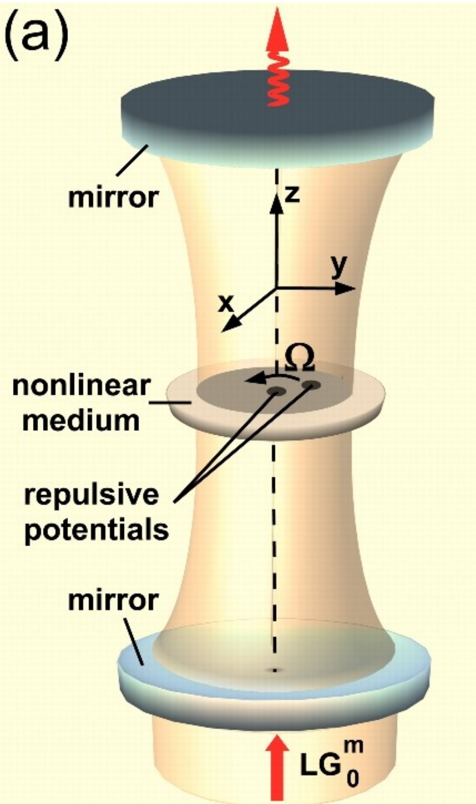
$$\psi(z_1,\ldots,z_N) = e^{-\sum_i |z_i|^2/2} \prod_{i<j} (z_i - z_j)^2$$

Overlap measured from quadrature noise of transmitted light

$$\langle \hat{b}_i \hat{b}_j \rangle = \langle X_0^{(i)} X_0^{(j)} \rangle - \langle X_{\pi/2}^{(i)} X_{\pi/2}^{(j)} \rangle + i\langle X_0^{(i)} X_{\pi/2}^{(j)} \rangle + i\langle X_{\pi/2}^{(i)} X_0^{(j)} \rangle$$

R. O. Umucalilar and IC, *Anyonic braiding phases in a rotating strongly correlated photon gas*, arXiv:1210.3070

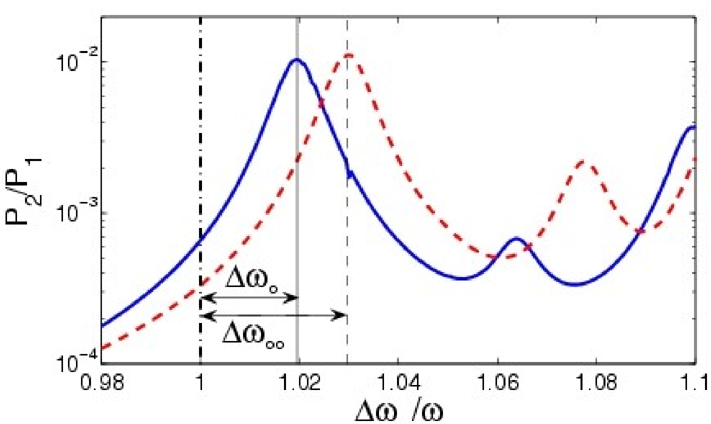
Anyonic braiding phase

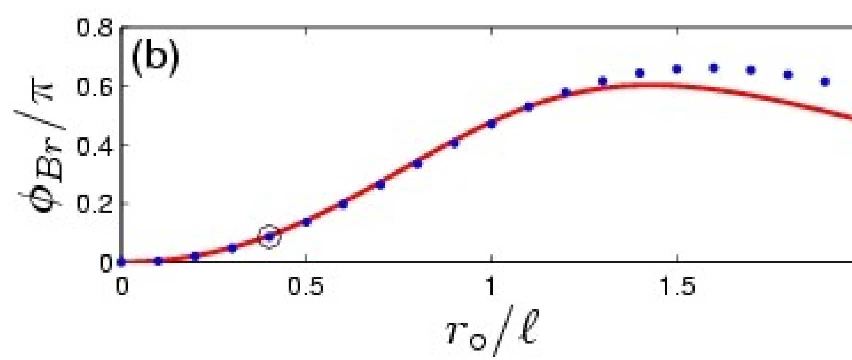


- LG pump to create and maintain quantum Hall liquid
- Localized repulsive potentials in trap:
  → create quasi-hole excitation in quantum Hall liquid
  → position of holes adiabatically braided in space
- Anyonic statistics of quasi-hole: many-body Berry phase ϕ_{Br}
  when positions swapped during braiding
- Berry phase extracted from shift of transmission resonance
  while repulsive potential moved with period T_{rot} along circle

$$\phi_{Br} \equiv (\Delta\omega_{oo} - \Delta\omega_{o})\, T_{rot} \quad [2\,\pi]$$

- so far, method restricted to low particle number





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