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PROVINCIA AUTONOMA DI TRENTO
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European Commission
Horizon 2020
European Union funding
for Research & Innovation
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Photons for Quantum Simulation

Quantum Optical Tools for Generation, Manipulation, and Diagnostic of Driven-Dissipative Many-Body States of Light

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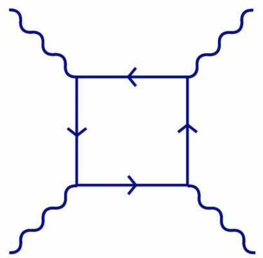
- P. Comaron, N. Proukakis (Newcastle)
- M. Wimmer, U. Peschel (Jena)

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



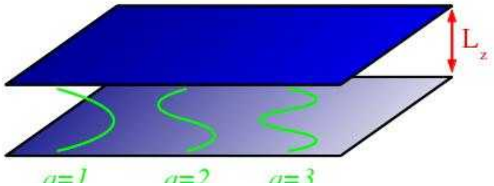
=> **optics typically dominated by single-particle physics**

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

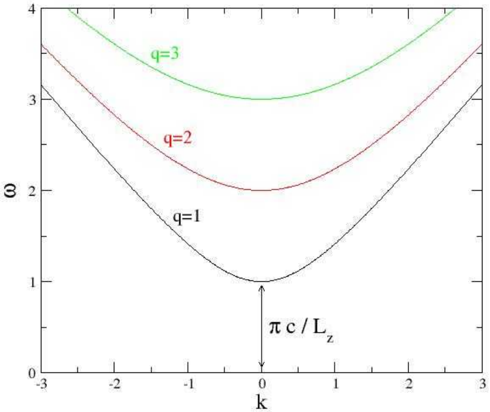
In photonic structure:

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

Spatial confinement → effective photon mass



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



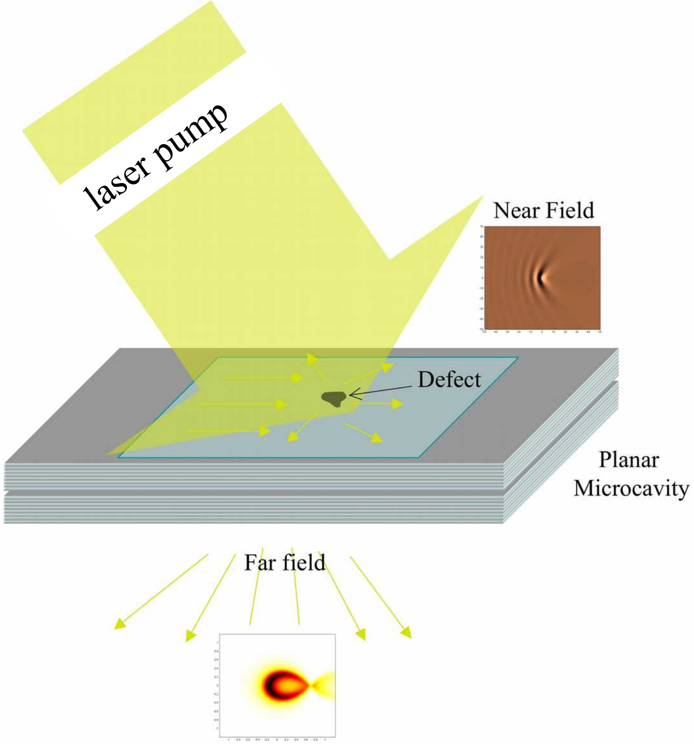
Many experiments and many intriguing effects

In this talk:

A few selected topics related to open quantum systems

How to exploit driven-dissipative condition to generate/manipulate/diagnostic quantum many-body states?

How to create and detect the photon gas?



Photon fluid consists of excitations on top of ground state:

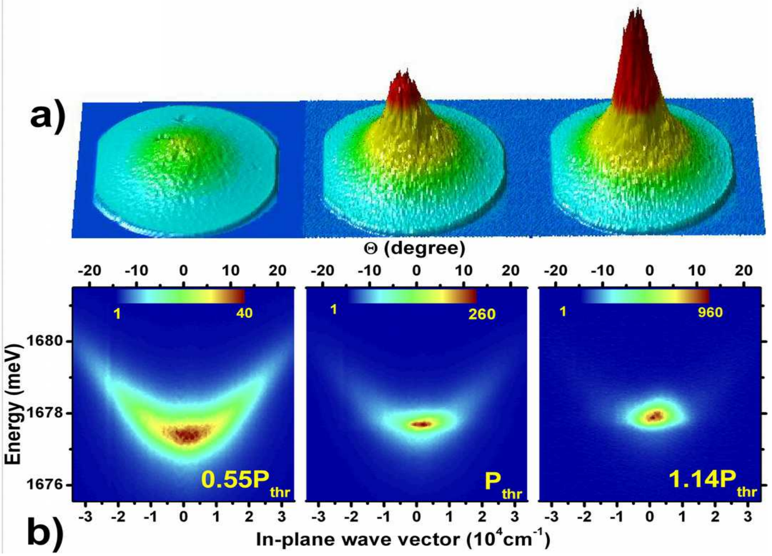
- Radiative and non-radiative losses intrinsic to optical systems
- Pump needed to compensate losses: stationary state is NOT thermodynamical equilibrium
  - Coherent laser pump: directly injects photon BEC in cavity, may lock BEC phase
  - Incoherent (optical or electric) pump: BEC transition similar to laser threshold
    spontaneous breaking of U(1) symmetry
- Classical and quantum correlations of in-plane field directly transfer to emitted radiation

Part 1:

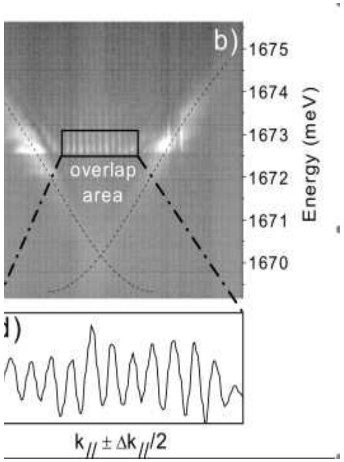
Open system features in weakly-interacting photon fluids

non-equilibrium Bose-Einstein condensation
& non-equilibrium superfluidity

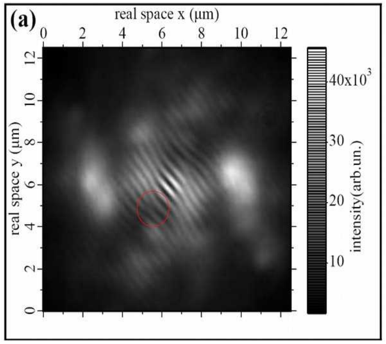
2006 - Photon/polariton Bose-Einstein condensation



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

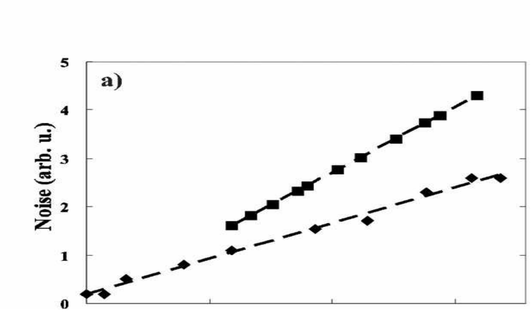


Interference
Richard et al., PRL **94**, 187401 (2005)



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

Many features very similar to atomic BEC

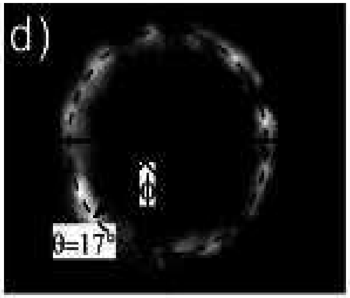


Suppressed fluctuations
A. Baas et al., PRL **96**, 176401 (2006)

But also differences due to non-equilibrium:

- BEC @ k≠0 → volcano effect
- T-reversal broken → n(k)≠n(-k)
- interesting questions about thermalization

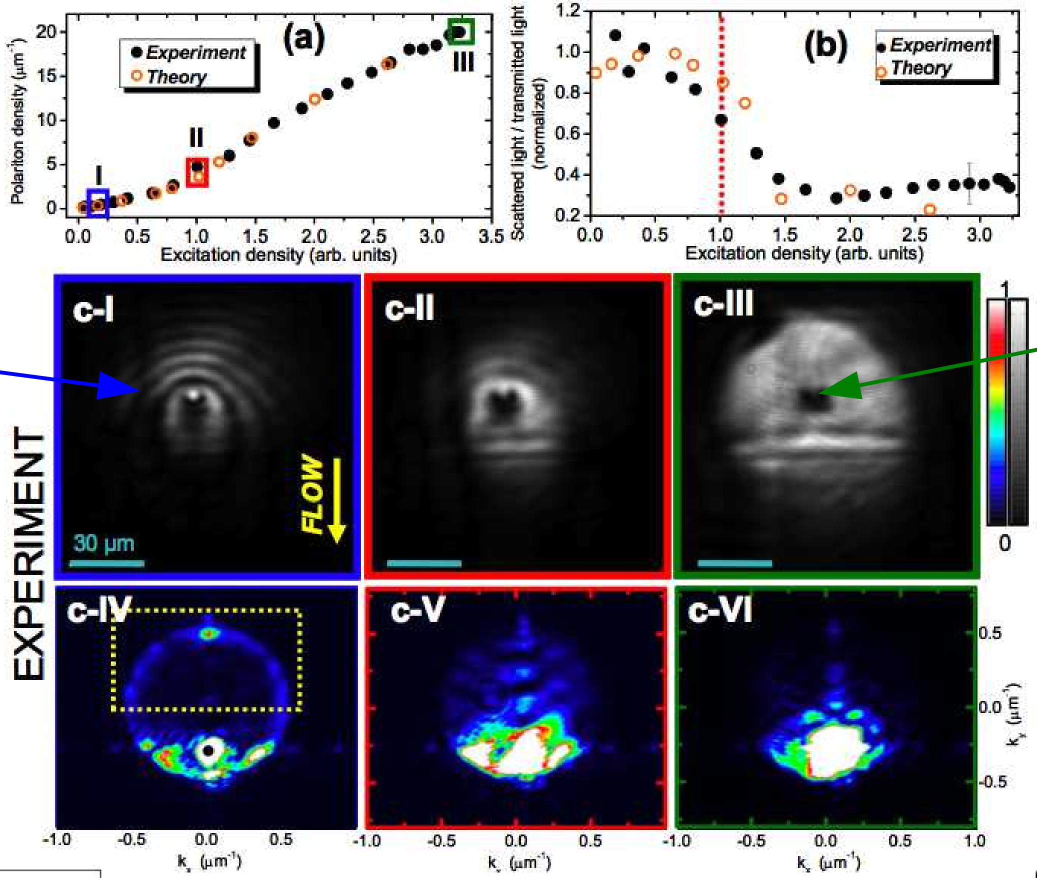
Photon/polariton BEC closely related to laser operation in VCSELs



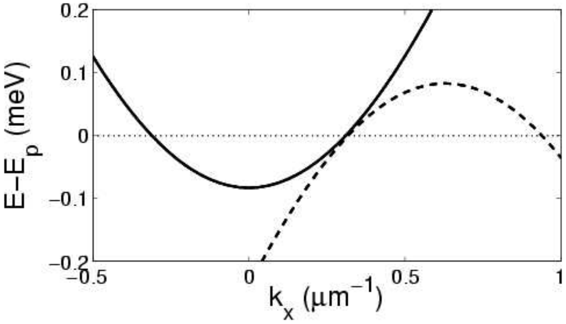
BEC on k-space ring
M. Richard et al.,
PRL **94**, 187401 (2005)

2008 - Superfluid light (under coherent pump)

scattering
on weak defect



superfluid flow



increase polariton density

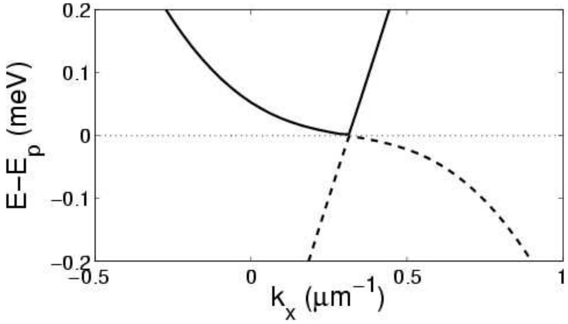


Figure from LKB-P6 group: A.Amo, J.Lefrère, S.Pigeon, C.Adrados, C.Ciuti, IC, R. Houdré, E.Giacobino, A.Bramati, *Observation of Superfluidity of Polaritons in Semiconductor Microcavities*, Nature Phys. **5**, 805 (2009)
Theory: IC and C. Ciuti, PRL **93**, 166401 (2004)

Are non-equilibrium BECs superfluid?

Polariton superfluidity expts under coherent pump → explicitly broken U(1)

(non-equilibrium) BEC phase transition → spontaneous breaking of U(1),

e.g. under incoherent pump (or polariton lasing)

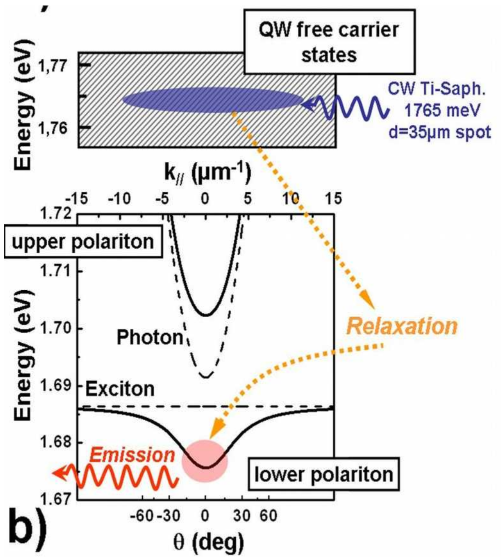


Figure from Kasprzak et al., Nature 2006

Driven-dissipative GPE

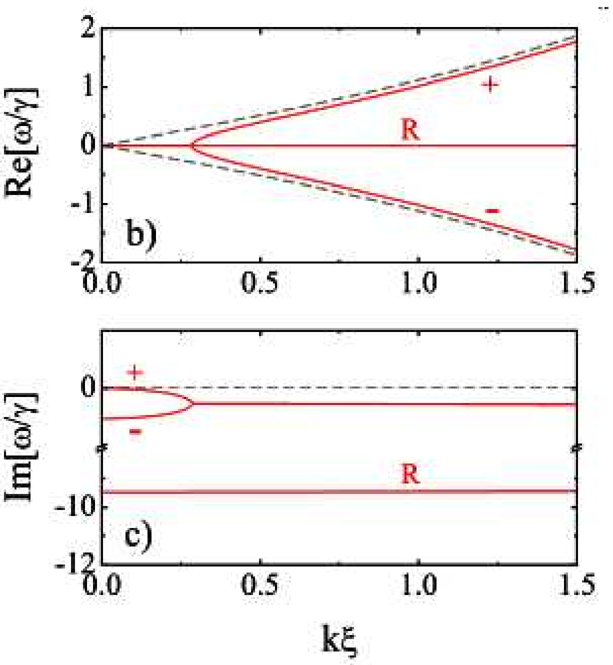
$$\begin{cases} i\frac{\partial\psi}{\partial t} = \left\{-\frac{\hbar\nabla^2}{2m_{\mathrm{LP}}} + \frac{i}{2}[R(n_R)-\gamma] + g|\psi|^2 + 2\tilde{g}n_R\right\}\psi. \\ \frac{\partial n_R}{\partial t} = P - \gamma_R n_R - R(n_R)|\psi(\mathbf{r})|^2 + D\nabla^2 n_R \end{cases}$$

Linearize GPE around steady state

- Reservoir R mode at -i γ_R + BEC density and phase modes at:

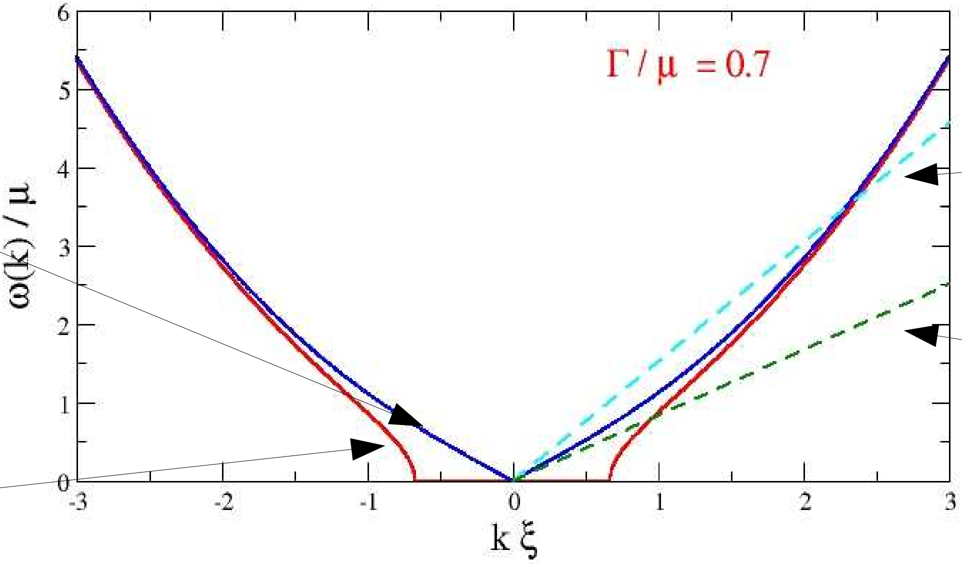
$$\omega_{\pm}(k) = -\frac{i\Gamma}{2} \pm \sqrt{[\omega_{Bog}(k)]^2 - \frac{\Gamma^2}{4}}$$

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



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)

Consequences on superfluidity



Equilibrium Bogoliubov dispersion

Non-equilibrium Bogoliubov dispersion

$v > c_s^{eq}$

$v < c_s^{eq}$

Long-range coherence → metastability of supercurrents (mode stability of ring lasers)

Interaction with defect: naïf Landau argument

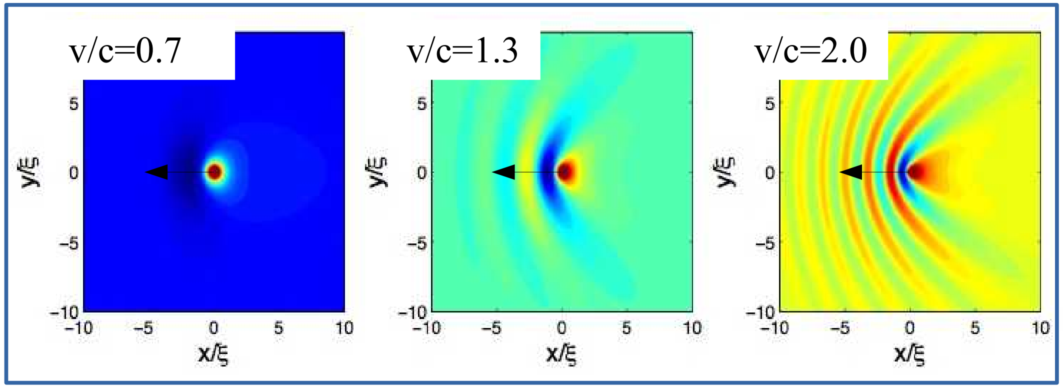
- Landau critical velocity $v_L = \min_k[\omega(k) / k] = 0$ at non-equilibrium BEC
- Any moving defect expected to emit phonons

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...

Steady-state → well defined ω
Defect → k not a good quantum number

(Complex) k vs.(real) ω dispersion

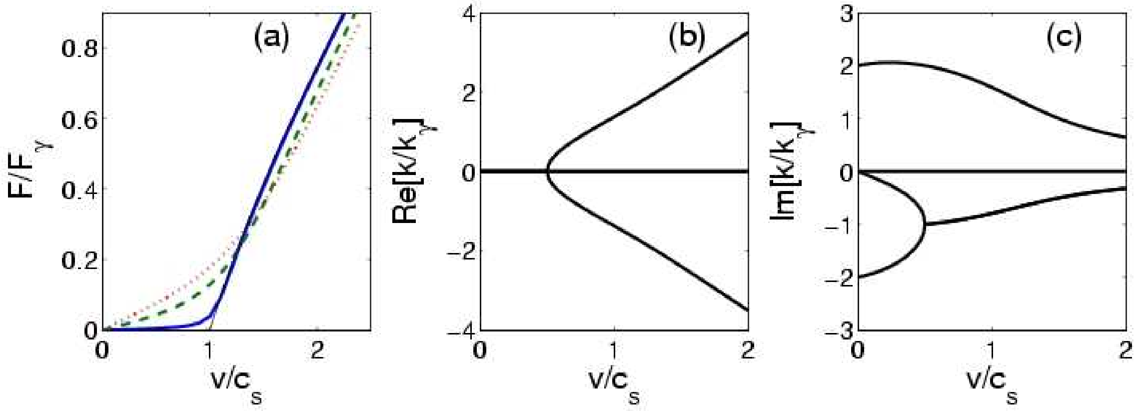


Low v :

- 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

M. Wouters, IC, *Superfluidity and Critical Velocities in Nonequilibrium BECs*, PRL **105**, 020602 (2010).

Part 2:

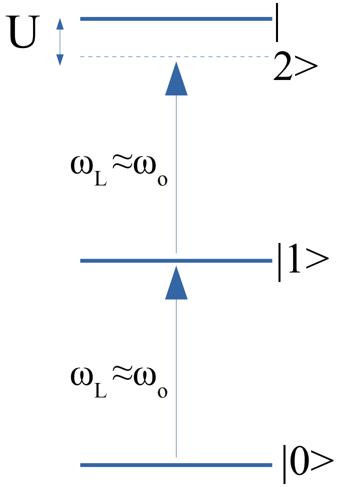
Strongly interacting photons

from Tonks-Girardeau gases
to Mott insulator states

Photon blockade

Driven-dissipative Bose-Hubbard model:

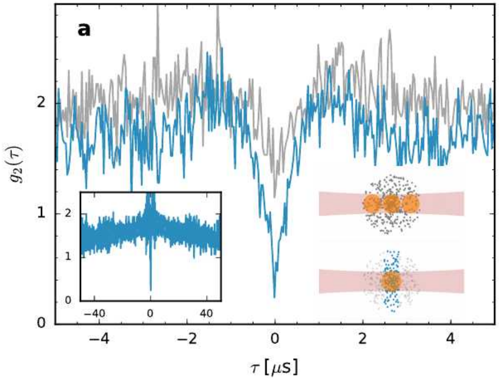
$$H_0 = \sum_i \hbar\omega_o \hat{b}_i^\dagger \hat{b}_i - \hbar J \sum_{\langle i,j\rangle} \hat{b}_i^\dagger \hat{b}_j + \hbar\frac{U}{2}\sum_i \hat{n}_i(\hat{n}_i - 1) + \sum_i F_i(t)\,\hat{b}_i + h.c.$$



- Array of single-mode cavities at ω_o , tunneling coupling J
- Losses γ → Lindblad terms in master eq.
- Polariton interactions: on-site interaction U due to optical nonlinearity
- If U >> γ , J, coherent pump resonant with 0→1 transition,
  but not with 1→2 transition.

Photon blockade → Effectively impenetrable photons

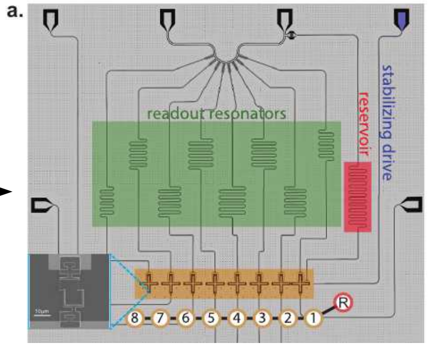
- Single-cavity blockade observed in many platforms since the 2000s,
  present challenge → scale up to many-cavity geometry

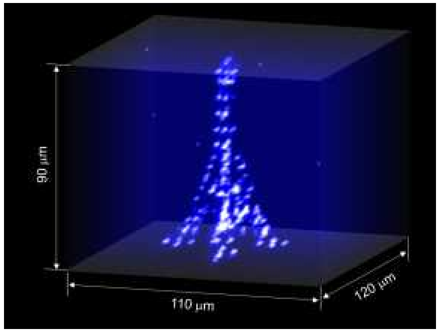


Polariton blockade
via Rydberg-EIT

Circuit QED device

More in next talk by Jon
(and in Pedram's one)



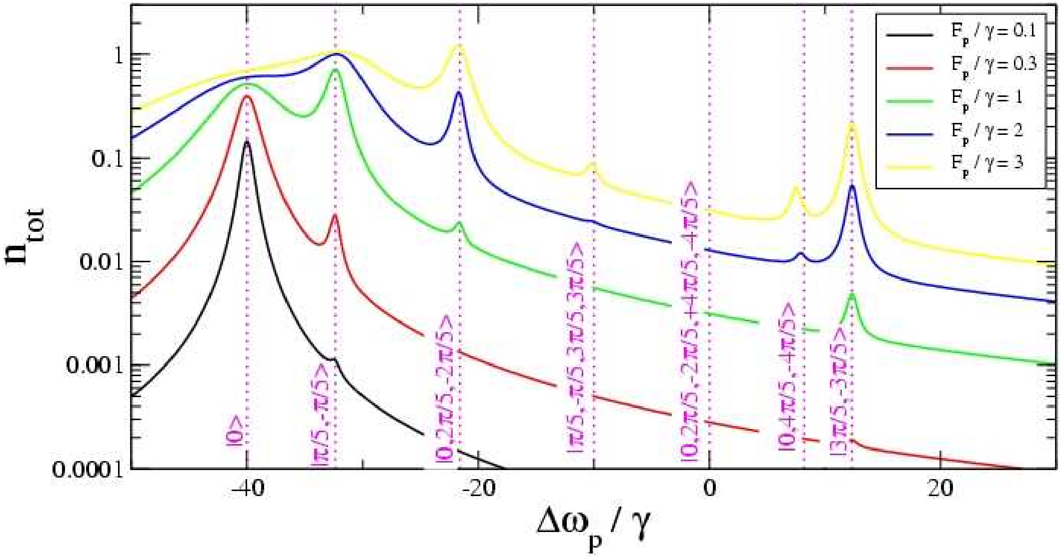


Fluid of spin excitations in
lattice of Rydberg atoms.
More in Antoine's talk
Similar expt by Lukin's group

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:

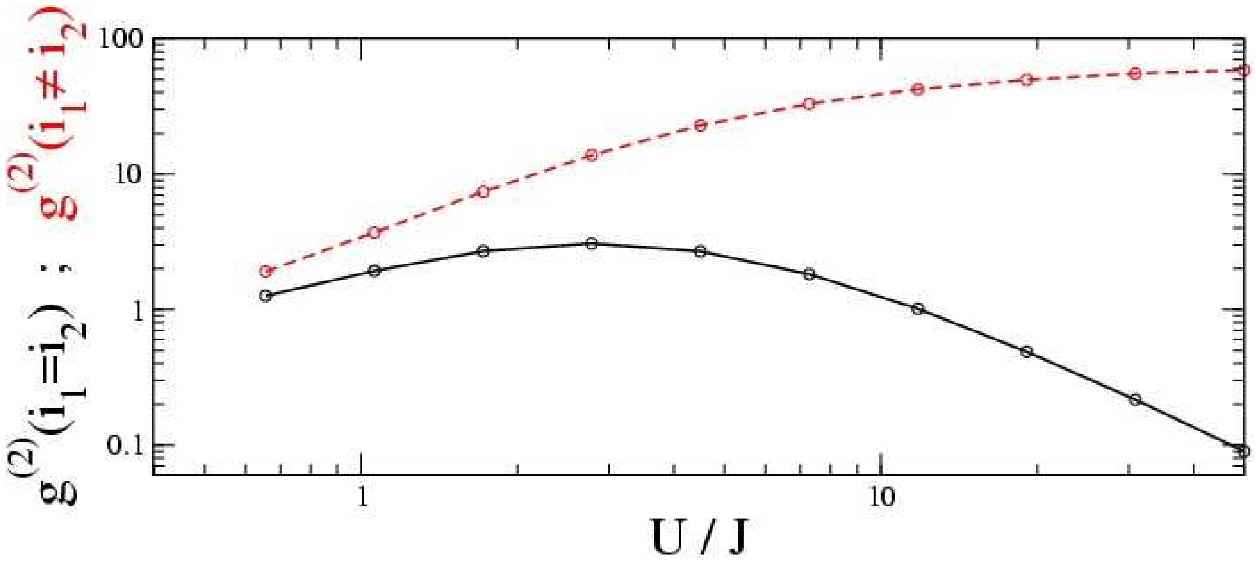
- each peak corresponds to a Tonks-Girardeau many-body state $|q_1,q_2,q_3\ldots>$
- q_i quantized according to PBC/anti-PBC depending on N=odd/even
- U/J >> 1: efficient photon blockade, impenetrable photons.

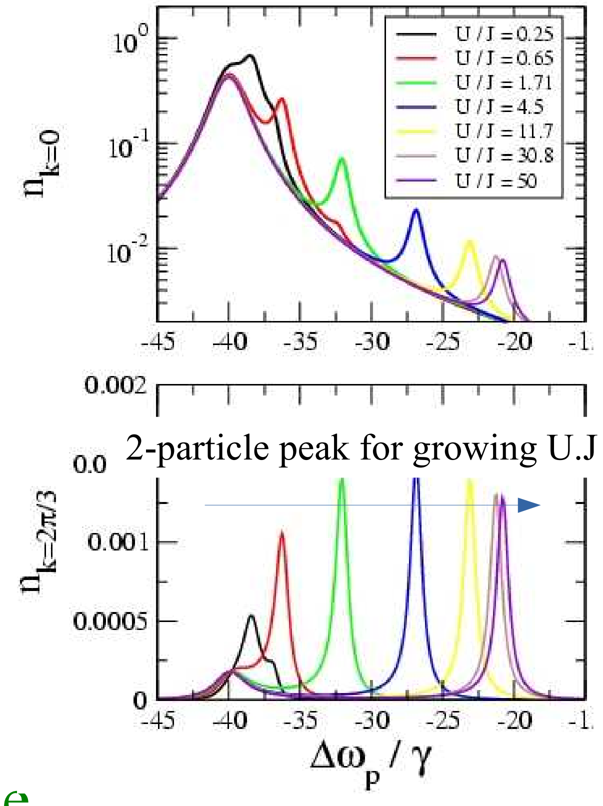
N-particle state excited by N photon transition:

- 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 $\omega_p = E / N$

IC, D. Gerace, H. E. Türeci, S. De Liberato, C. Ciuti, A. Imamoglu, PRL **103**, 033601 (2009)
See also related work D. E. Chang et al, Nature Physics (2008)

State tomography from emission statistics





2-particle peak for growing U.J

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

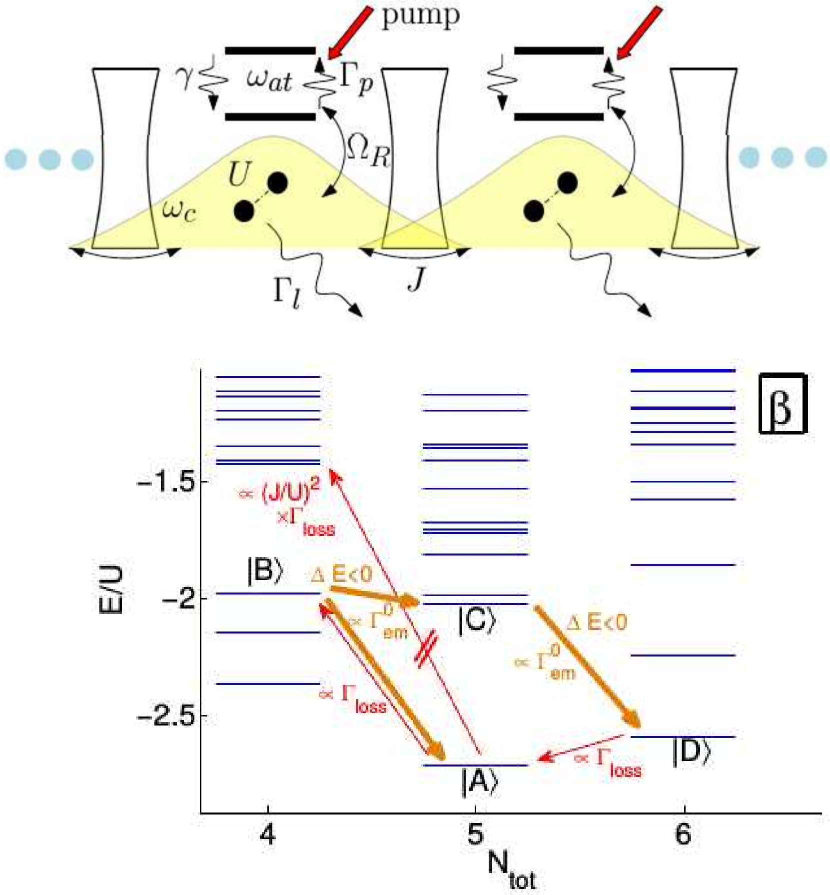
- intensity correlation between the emission from cavities i_1, i_2
- at large U/γ, larger probability of having N=0 or 2 photons than N=1
  - low U<<J: bunched emission for all pairs of i_1, i_2
  - large U>>J: antibunched emission from a single site
positive correlations between different sites
- Idea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

How to access larger particle numbers

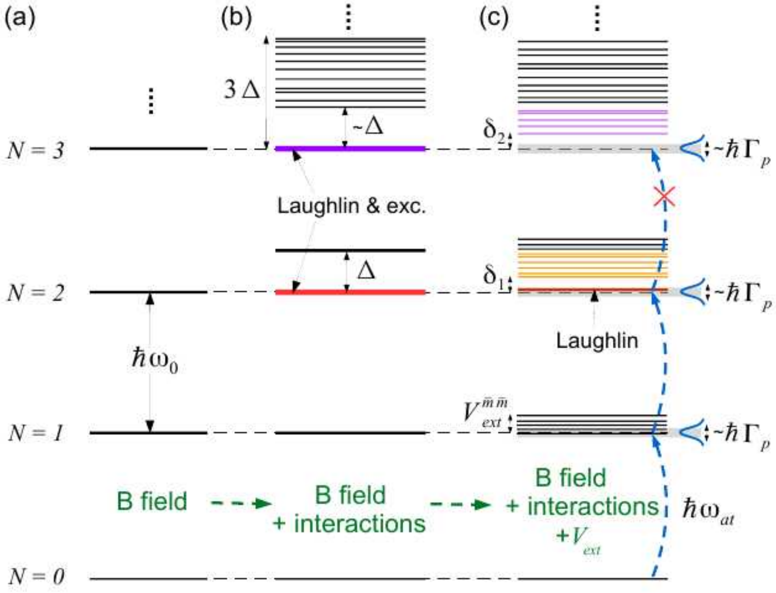
Coherent pump only able to selectively excite few-photon states

→ Frequency-dependent incoherent pumping, e.g. collection of inverted emitters

- Lorentzian emission line around ω_{at}
  sophisticated schemes → other spectral shapes
- Emission only active if many-body transition
  is near resonance
- Injects photons until band is full (MI) or
  many-body gap develops (FQH)
- Many-body gap blocks excitation of higher bands



Lebreuilly, Biella et al., PRA 2017



Umucalilar-IC, PRA 2017

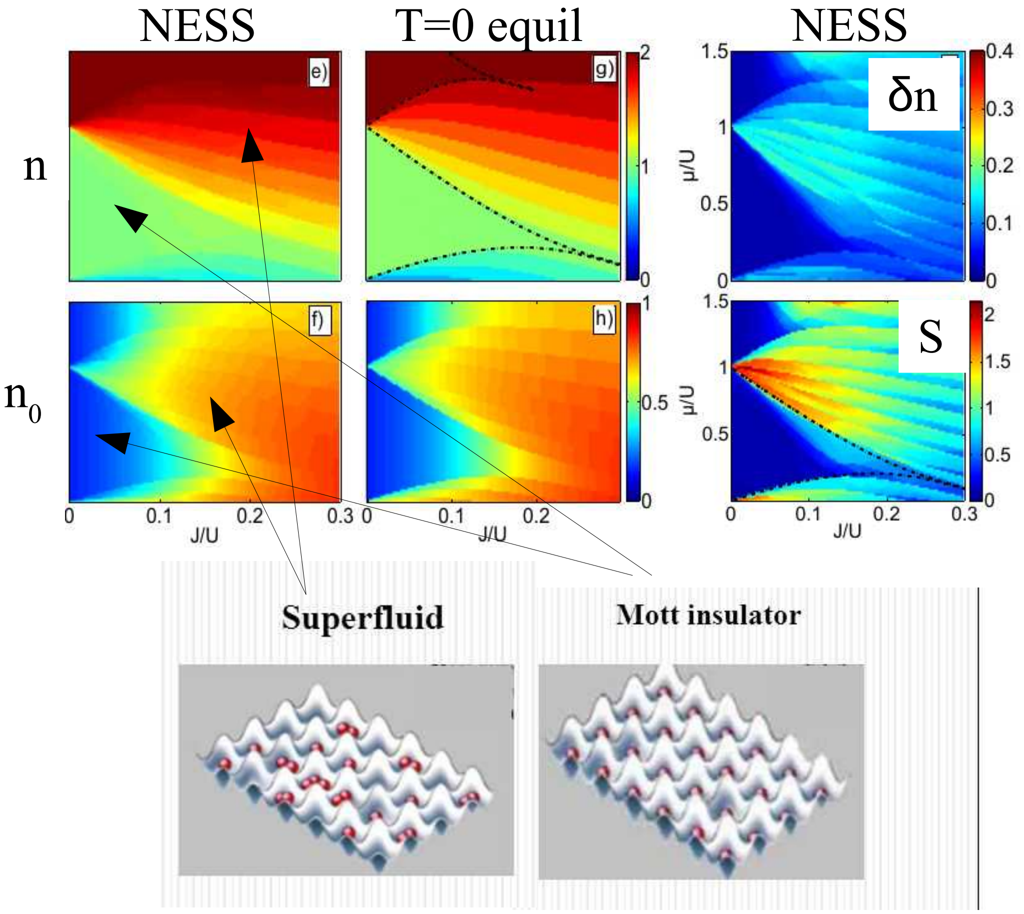
General idea: Lebreuilly et al. CRAS (2016)
and Kapit, Hafezi, Simon, PRX 2014

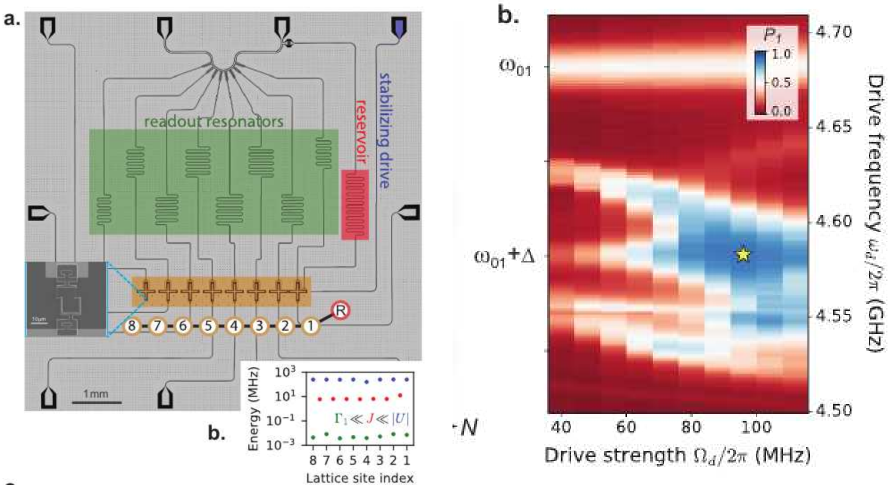
Numerical validation for MI & FQH

- non-Markovian master equation:
  frequency-dependent emission
  → rescaled jump operators
- driven-dissipative steady state stabilizes
  strongly correlated many-body states
  e.g. Mott-insulator, FQH…
- resembles low-T equilibrium
  (but interesting deviations in some cases)
- (in principle) no restriction to small N_{ph}

$$\bar{\mathcal{L}}_{\rm em}(\rho_{\rm ph}) = \frac{\Gamma_{\rm em}}{2}\sum_{i=1}^{k}\left[2\bar{a}_i^\dagger \rho_{\rm ph}\bar{a}_i - \bar{a}_i\bar{a}_i^\dagger \rho_{\rm ph} - \rho_{\rm ph}\bar{a}_i\bar{a}_i^\dagger\right]$$

$$\langle f'|\bar{a}_i^\dagger|f\rangle = \frac{\Gamma_{\rm pump}/2}{\sqrt{(\omega_{\rm at}-\omega_{f',f})^2+(\Gamma_{\rm pump}/2)^2}}\langle f'|a_i^\dagger|f\rangle$$





First expt: Ma *et al.* Nature 2019
All details in next talk by Jon!

Lebreuilly, Biella et al., 1704.01106 & 1704.08978
(published on PRA, 2017)

Related work in Kapit, Hafezi, Simon, PRX 2014

Part 3:

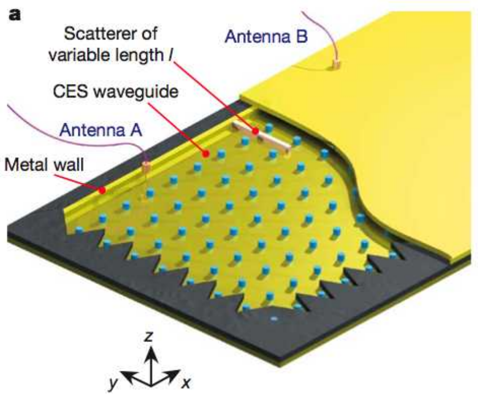
Topological photonics

from Chern insulators
towards Fractional Quantum Hall liquids

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

MIT '09, Soljacic group

Original proposal Haldane-Raghu, PRL 2008



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

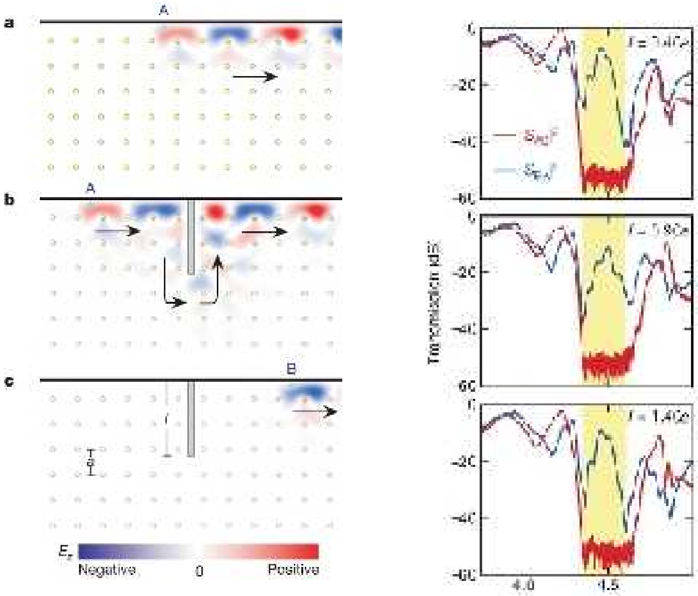
Magneto-optical photonic crystals for μ-waves

T-reversal broken by magnetic elements

Band wih 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)

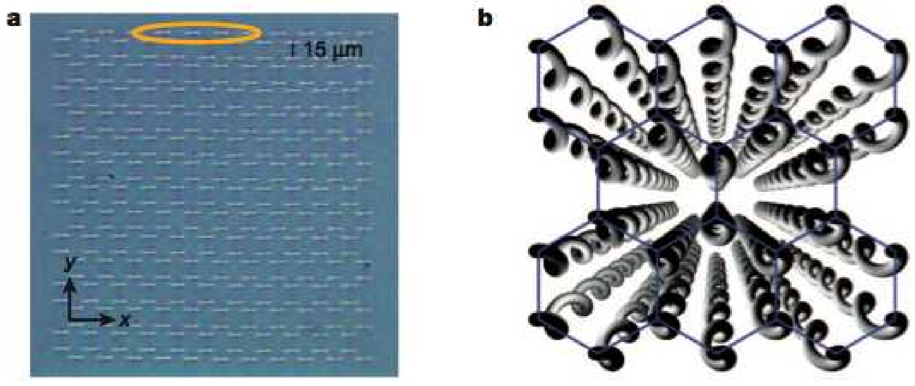
2013 - Harper-Hofstadter & Haldane models for visible photons

2D lattice of coupled cavities with tunneling phase

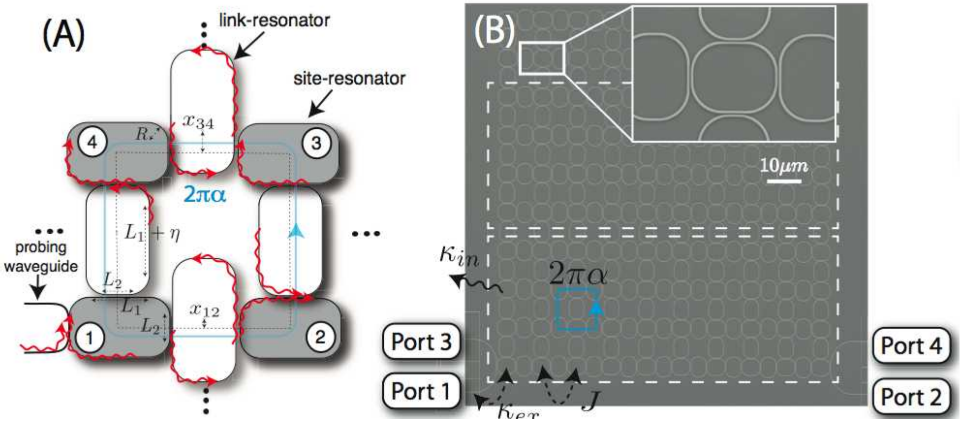
$$H = \sum_i \hbar\omega_\circ \hat{a}_i^\dagger \hat{a}_i - \hbar J \sum_{\langle i,j\rangle} \hat{a}_i^\dagger \hat{a}_j e^{i\phi_{ij}} + \sum_i \left[\hbar F_i(t)\, \hat{a}_i^\dagger + \text{h.c.}\right]$$

Experiments along these lines:

- Floquet bands in helically deformed honeycomb waveguide lattices → Rechtsman/Segev
- silicon ring cavities → Hafezi/Taylor (JQI)
- electronic circuits with lumped elements → J. Simon (Chicago)
- honeycomb lattice for polaritons → A. Amo/J.Bloch (C2N)



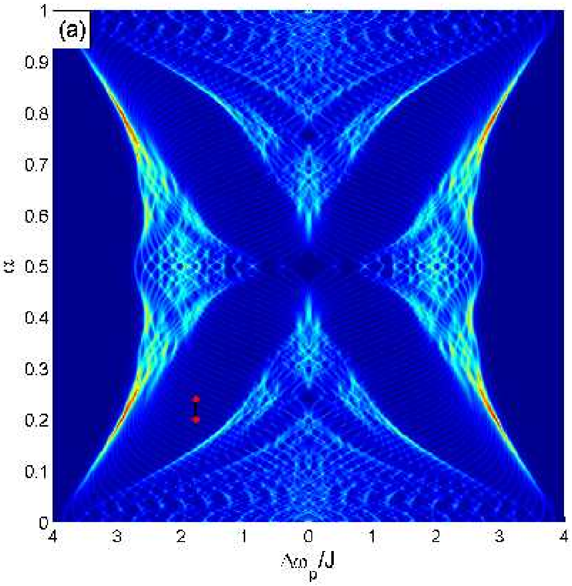
Rechtsman, Plotnik, et al., Nature 496, 196 (2013)



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

2013 - Imaging chiral edge states

2D square lattice of coupled cavities
at large magnetic flux



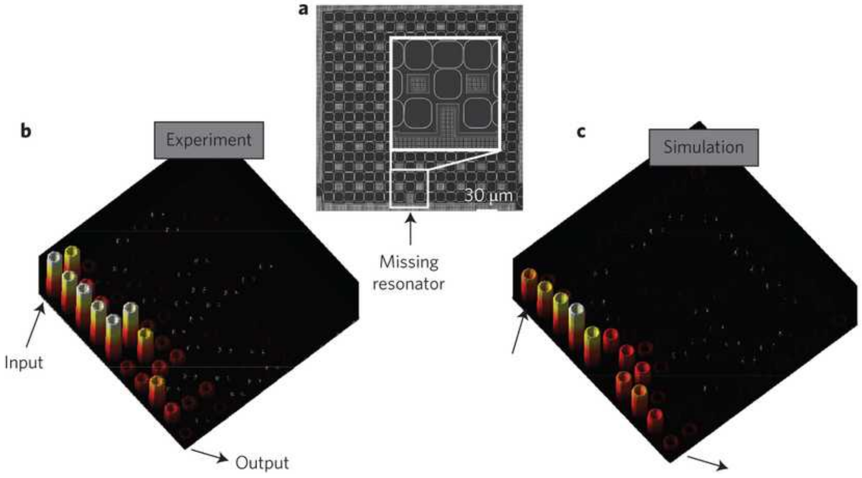
- eigenstates organize in bulk Hofstadter bands
- Berry connection in k-space: $A_{n,k} = i\langle u_{n,k}|\nabla_k u_{n,k}\rangle$

Bulk-edge correspondance:

$A_{n,k}$ has non-trivial Chern number

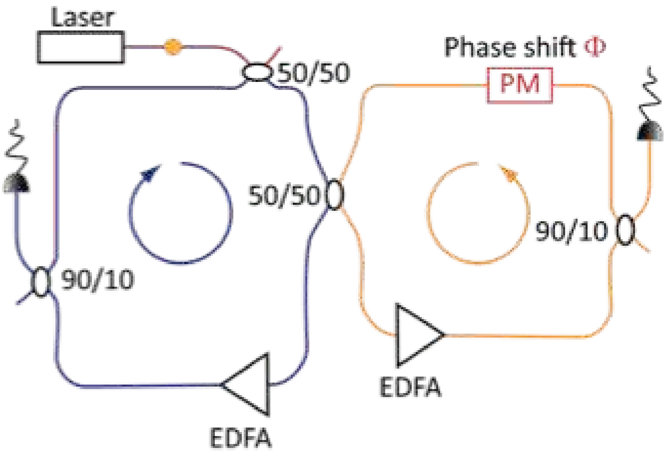
→ chiral edge states within gaps

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



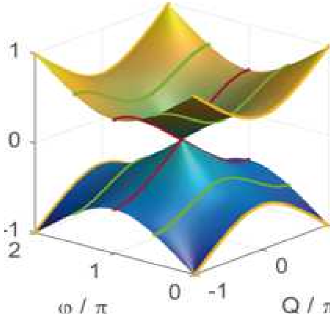
Hafezi et al.,Nat. Phot. **7**, 1001 (2013)

2016 - Experimental mapping of Berry curvature



Periodic temporal modulation of *Φ(m)*=±*φ*:

- 1D Floquet band structure *θ(Q,φ)*,
  φ considered as 2nd dim

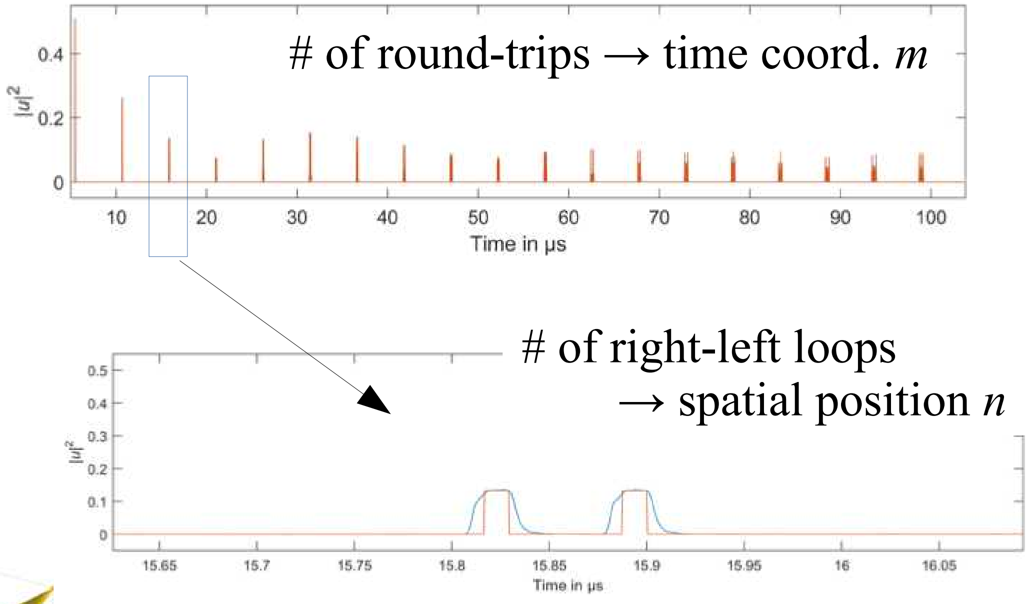


- Berry curvature

$$\Omega_j^{\varphi,Q} = \frac{\partial}{\partial\varphi}\langle\psi_j|i\frac{\partial}{\partial Q}|\psi_j\rangle - \frac{\partial}{\partial Q}\langle\psi_j|i\frac{\partial}{\partial\varphi}|\psi_j\rangle$$

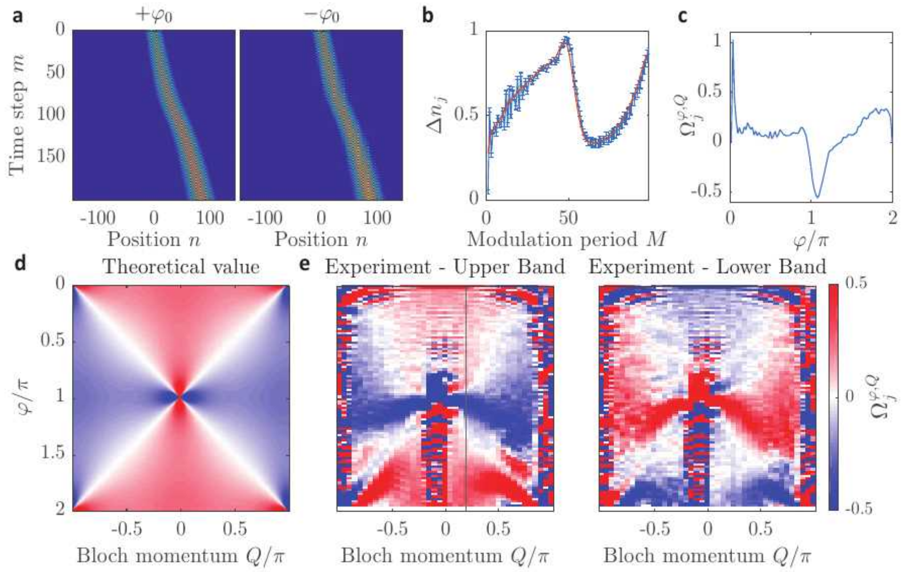
- Geometrical charge pumping if *φ* adiabatically varied
- Look at lateral displacement along *n* at all times *m*
  → reconstruct Berry curvature $\Omega_j^{(\varphi,Q)}$ in whole FBZ

Cold atoms → Berry phase reconstructed via state tomography
(Fläschner et al., Science '16)



# of round-trips → time coord. *m*

# of right-left loops
→ spatial position *n*



Wimmer, Price, IC, Peschel, Nat. Phys. 2017

Photon blockade + synthetic gauge field = FQHE 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

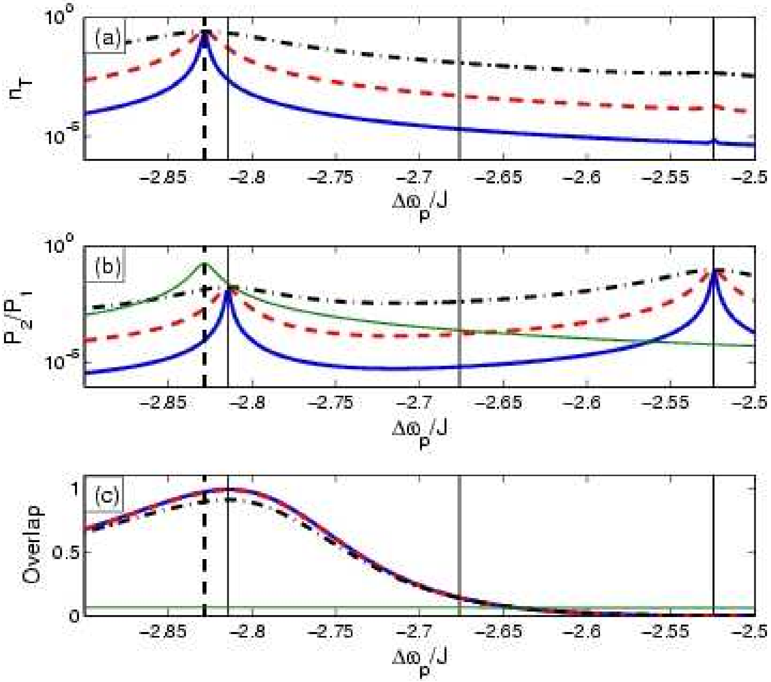
with usual coherent drive and dissipation → look for non-equil. steady state

Transmission spectra:

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

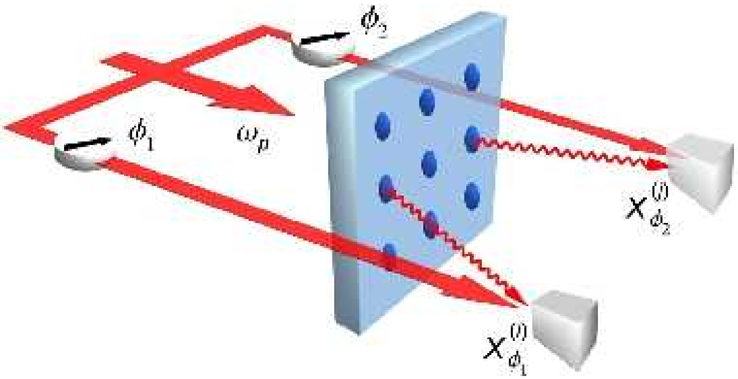
$$\psi_l(z_1, \ldots, z_N) = \mathcal{N}_L F_{\mathrm{CM}}^{(l)}(Z) e^{-\pi\alpha\sum_i y_i^2} \times \prod_{i<j}^{N} \left(\vartheta\left[\begin{smallmatrix}\frac{1}{2}\\ \frac{1}{2}\end{smallmatrix}\right]\left(\frac{z_i - z_j}{L}\middle| i\right)\right)^2$$

- 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)
See also related work by Cho, Angelakis, Bose, PRL 2008; Hafezi et al. NJP 2013; arXiv:1308.0225

Tomography of FQH states

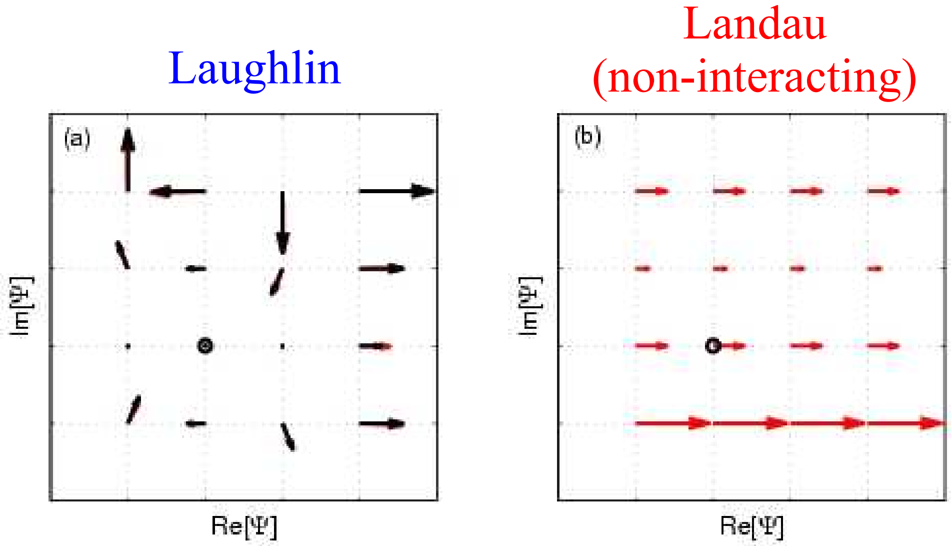


Homodyne detection of secondary emission

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

Non-trivial structure of Laughlin state

compared to non-interacting photons



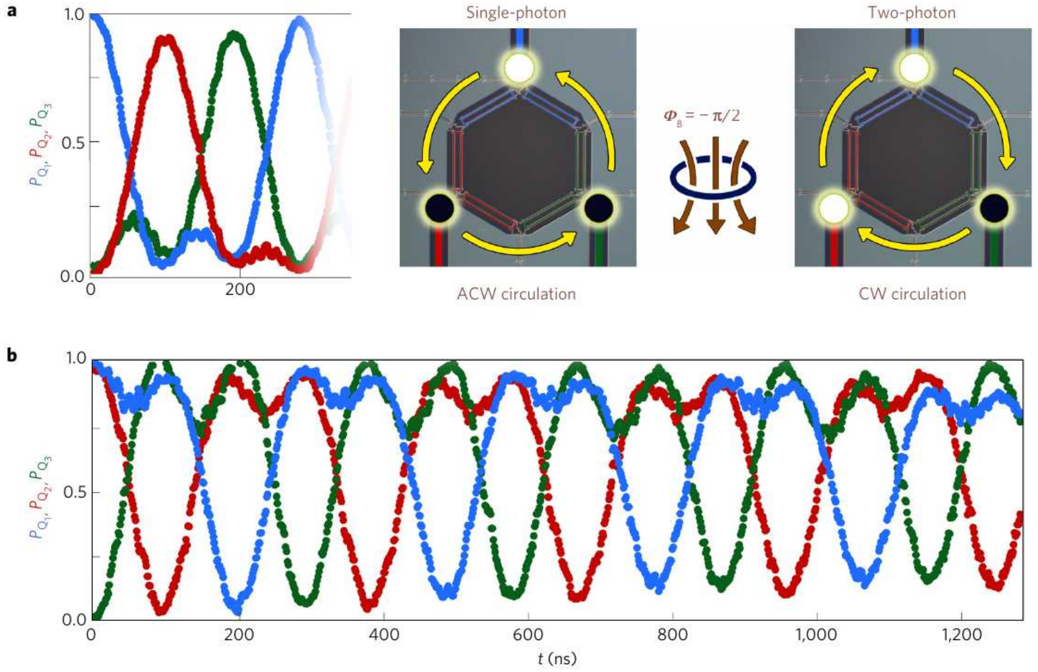
R. O. Umucalilar and IC, *Fractional quantum Hall states of photons in an array of dissipative coupled cavities*, PRL 108, 206809 (2012)

Circuit-QED experiment

Ring-shaped array of qubits

- Transmon qubit: two-level system
  → Impenetrable photons

- Time-modulation of couplings
  → synthetic gauge field



Roushan et al., Nat. Phys. 2016
More in Pedram’s talk on Wed.

Independently initialize sites

Follow unitary evolution until bosons lost

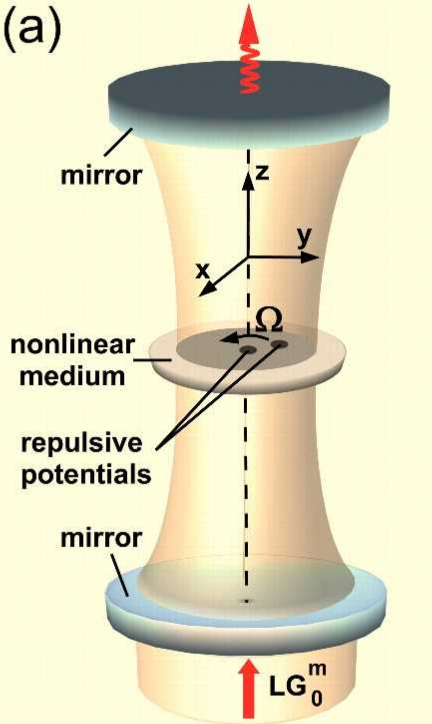
Monitor site occupation in time

<u>“Many”-body effect:</u>

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

Continuous space FQH physics

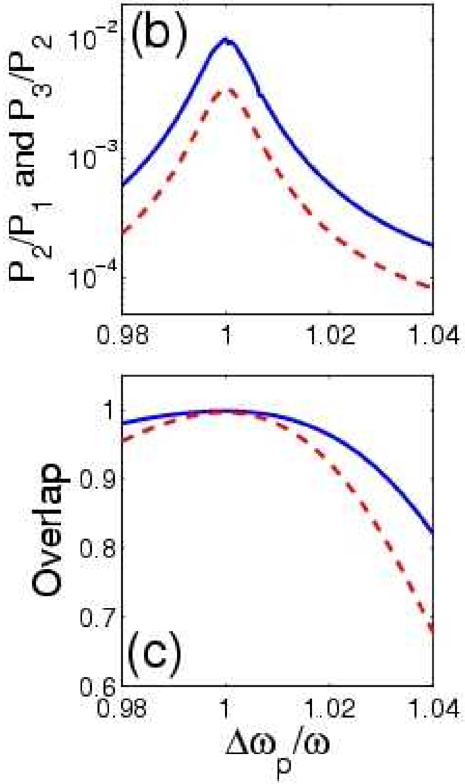
Single cylindrical cavity. No need for cavity array



same form

Coriolis $F_c = -2m\Omega \times v$

Lorentz $F_L = e v \times B$



Photon gas injected by Laguerre-Gauss pump

with finite orbital angular momentum

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

Resonant peak in transmission due to Laughlin state:

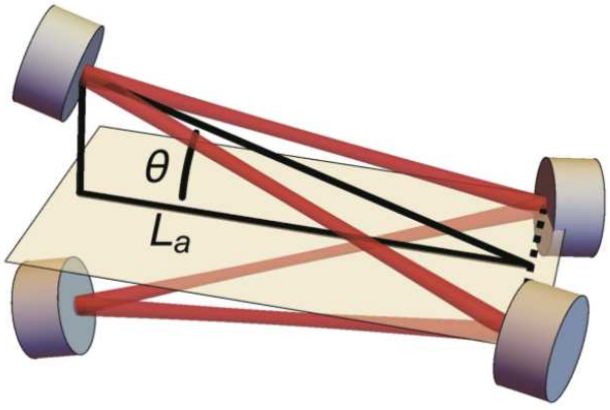
$$\psi(z_{1,}\dots,z_N)=e^{-\sum_i |z_i|^2/2}\prod_{i<j}(z_i-z_j)^2$$

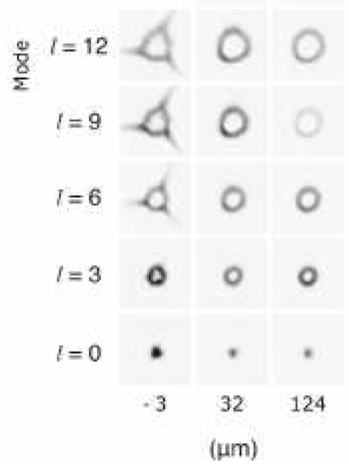
Overlap measured from quadrature noise of transmitted light

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

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

Experiment @ Chicago





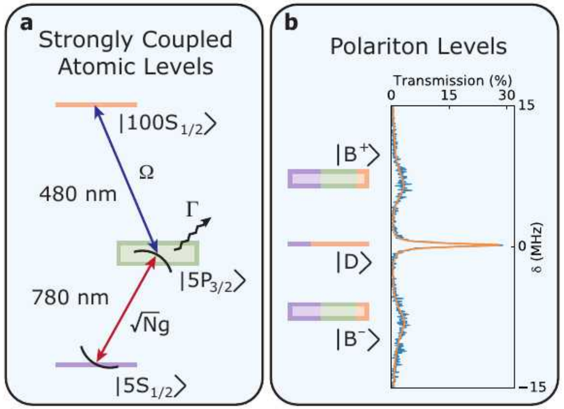
A far smarter design

Non-planar ring cavity:

- Parallel transport→ synthetic B
- Landau levels for photons observed

Crucial advantages:

- Narrow frequency range relevant
- Integrated with Rydberg-EIT reinforced nonlinearities



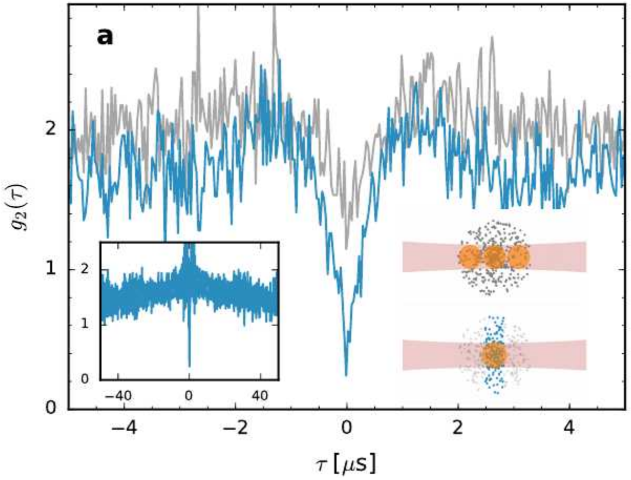
Polariton blockade on lowest (0,0) mode

- Equivalent to $\Delta_{\text{Laughlin}} > \gamma$: Laughlin physics coming soon!

Easiest strategy for Laughlin

- Coherent pumping→ multi-photon peaks to few-body states
- Laughlin state → quantum correlations between orbital modes

(Umucalilar-Wouters-IC, PRA 2014)



Figures from J. Simon's group @ U. Chicago
Schine et al., Nature 2016; Jia et al. 1705.07475

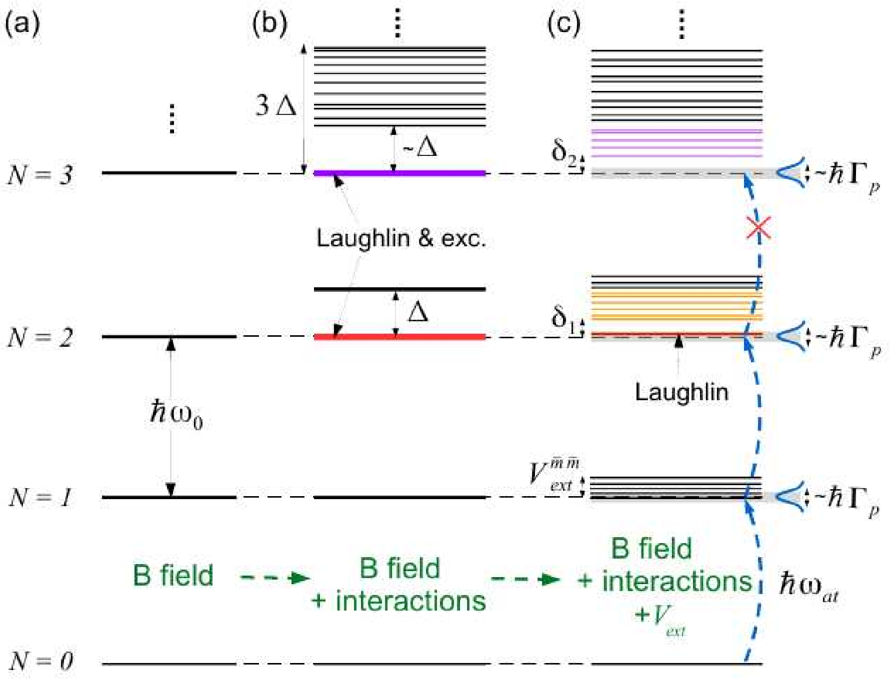
How to access larger fluids?

Coherent pump:

- Able to selectively generate few-body states
- Limited by (exponentially) decreasing matrix element for larger systems

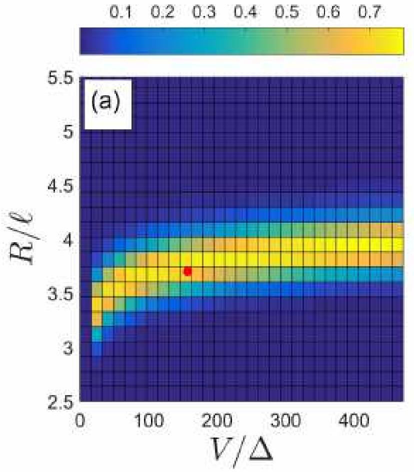
Frequency-dependent incoherent pump:

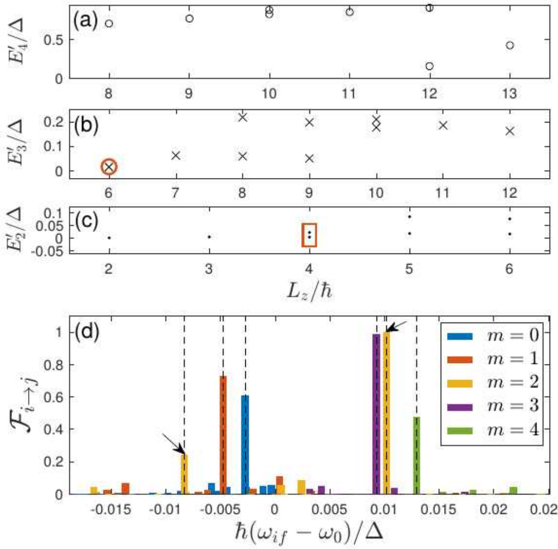
- Interactions → many-body gap Δ
- Edge excitations not gapped.
  Hard-wall confinement gives small δ
- Non-Markovianity blocks excitation to higher states



Calculations only possible for small systems:

- Overlap with Laughlin still large
- Spectroscopy of emitted light gives
  info on many-body states & excitations
- Excitations localized mostly on edge

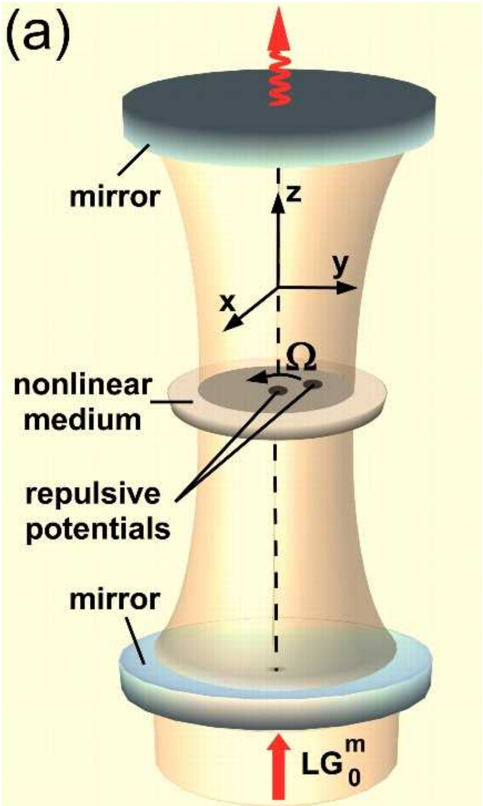




Open question: what are ultimate limitations of this pumping method?

R. O. Umucalilar and IC, *Generation and spectroscopic signatures of a fractional quantum Hall liquid of photons in an incoherently pumped optical cavity*, PRA 2017.

Theorists' speculations: anyonic braiding phase



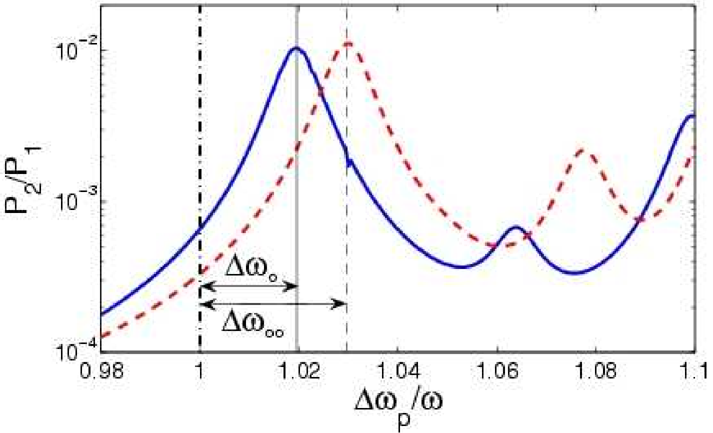
- LG pump to create and maintain quantum Hall liquid

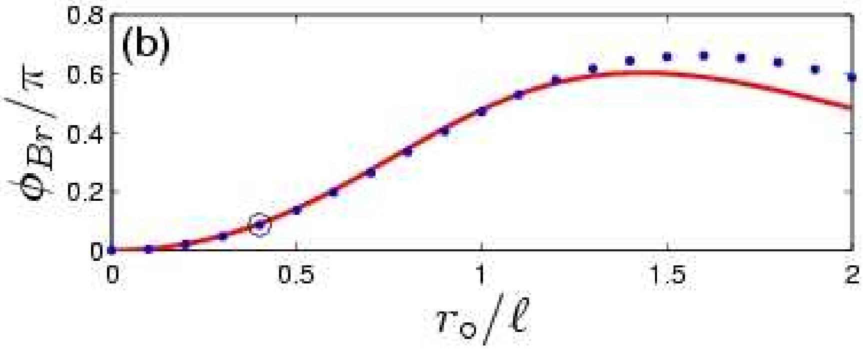
- Localized repulsive potentials in trap:
  → create quasi-hole excitation in quantum Hall liquid
  → position of holes adiabatically braided in space

- 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

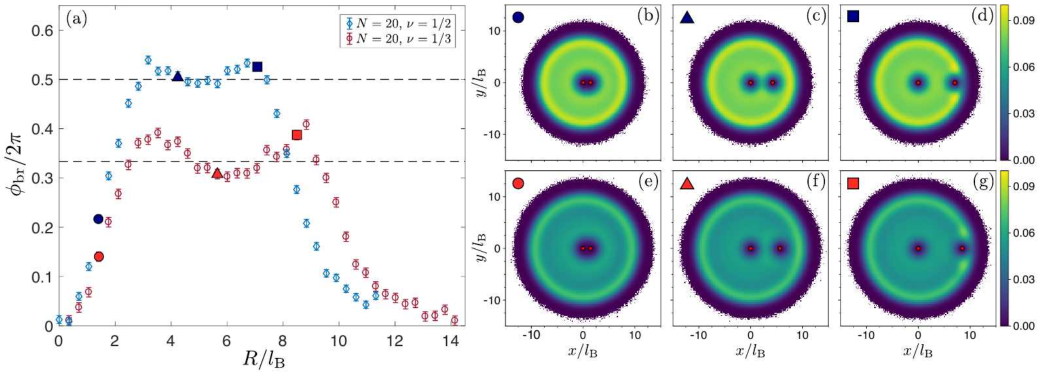
$$\phi_{Br} \equiv (\Delta\omega_{oo} - \Delta\omega_{o})\, T_{rot} \quad [2\,\pi]$$





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

Observing anyonic statistics via time-of-flight measurements



Braiding phase → Berry phase when two quasi-holes are moved around each other

$$\varphi_{\mathrm{B}}(R) = i \oint_R \langle \Psi(\theta) | \partial_\theta | \Psi(\theta) \rangle d\theta.$$

Braiding operation can be generated by rotations, so braiding phase related to L_z

$$\varphi_{\mathrm{B}}(R) = \frac{1}{\hbar} \oint_R \langle \Psi(\theta) | L_z | \Psi(\theta) \rangle d\theta = \frac{2\pi}{\hbar} \langle L_z \rangle$$

Self-similar expansion of lowest-Landau-levels → L_z can be measured in time-of-flight via size of the expanding cloud

$$\langle r^2 \rangle_{\mathrm{tof}} = \frac{1}{N} \left(\frac{\hbar t}{\sqrt{2} M l_B} \right)^2 \left(\frac{\langle L_z \rangle}{\hbar} + N \right) = \left(\frac{\hbar t}{2 M l_B^2} \right)^2 \langle r^2 \rangle$$

Can be applied to both cold atoms or to fluids of light looking at far-field emission pattern

Umucalilar, Macaluso et al., *Observing anyonic statistics via time-of-flight measurements*, PRL (2018)

Quasi-Hole structure vs. anyon statistics

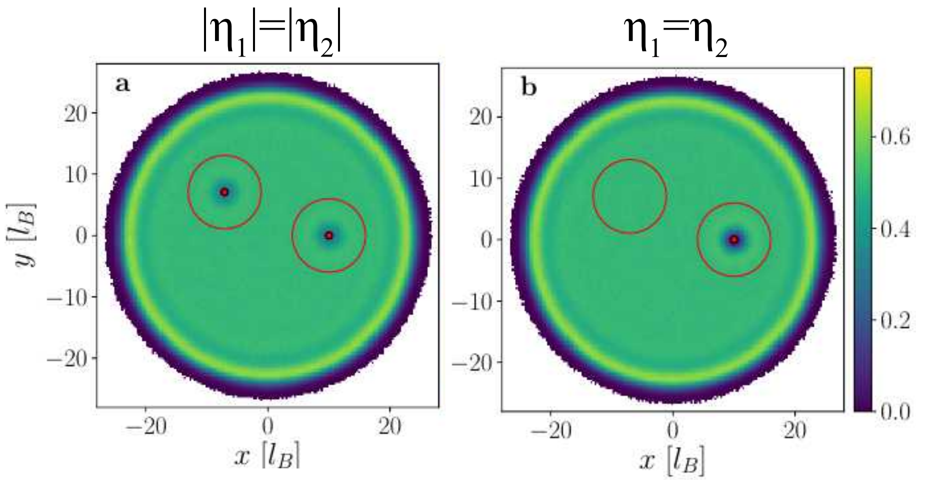
- Compare (two) single quasi-holes and overlapping pairs of quasi-holes:

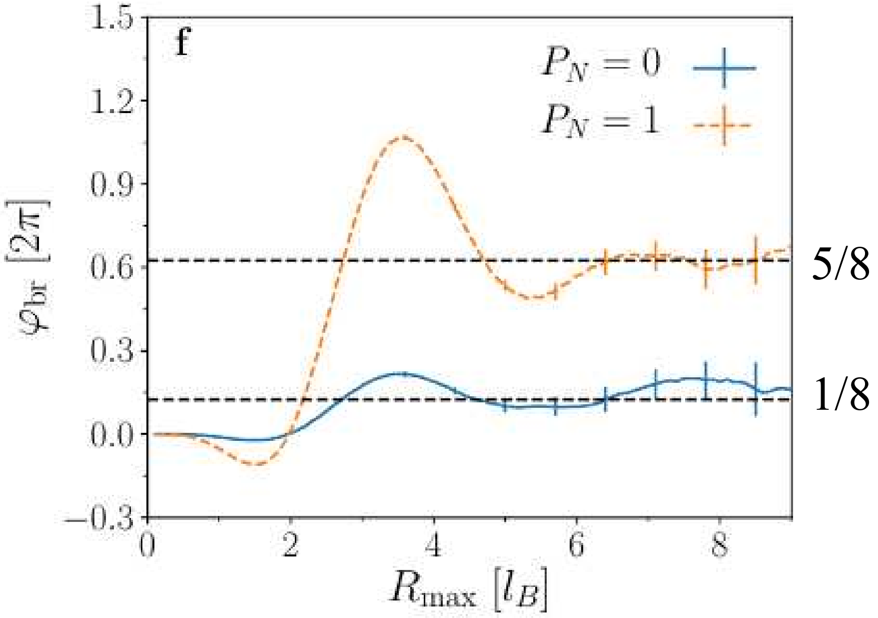
$$\frac{\varphi_{\rm br}}{2\pi} = \frac{1}{\hbar}\left[\langle \hat{L}_z\rangle_{|\eta_1|=|\eta_2|} - \langle \hat{L}_z\rangle_{\eta_1=\eta_2}\right].$$

- Relates to difference of density profiles:

$$\frac{\varphi_{\rm br}}{2\pi} = \frac{N}{2l_B^2}\left[\langle r^2\rangle_{|\eta_1|=|\eta_2|} - \langle r^2\rangle_{\eta_1=\eta_2}\right],$$

- Incompressibility → external region unaffected
- Reduces to local density difference around QH core, i.e. variance of density depletion
- Insensitive to spurious excitation of (ungapped) edge states
- Numerical calculation for Moore-Read states: allows to distinguish fusion channels of even/odd total particle number





E. Macaluso, T. Comparin, L. Mazza, IC, *Fusion channels of non-Abelian anyons from angular-momentum and density-profile measurements*, 1903.03011.
Lattice calculations in progress in collaboration with M. Rizzi & S. Montangero.

Conclusions and perspectives

Superfluid hydrodynamics in dilute fluid of light:

- Superfluid flow past an obstacle, nucleation of topological defects (2009-2011)
- Complex flows showing analog black hole horizons, on-going experimental quest for signatures of analog Hawking emission in two-point intensity correlations (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-)

First steps in strongly correlated many-body physics:

- Photon blockade in many platforms: CQED with atoms and solids, circuit-QED, Rydberg atoms,…
- Mott-insulator → recent experimental observation @ Chicago – listen at next talk!
- Chain of strongly interacting bosons in synthetic gauge field
  → recent experimental observation @ GoogleLabs!
- Few-body Laughlin states → don't get asleep!

Some open questions

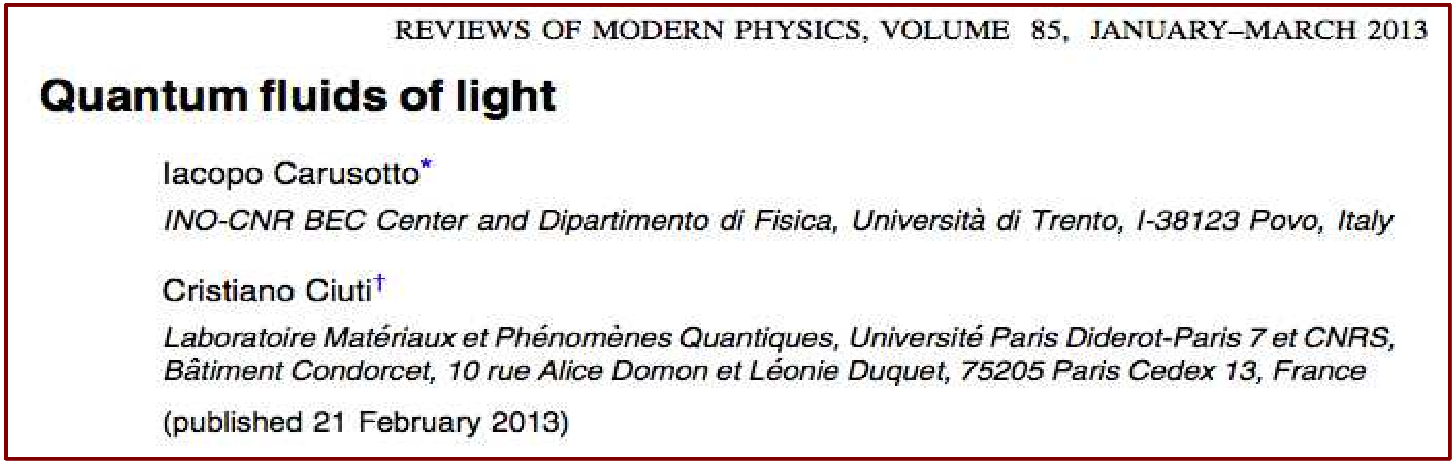
Topological states of matter:

- Meso- to macro-scopic number of photons typically required
  - Fabricate a large enough cavity or cavity array with low disorder: circuit-QED or Rydberg polaritons in optical cavities or Rydberg atoms
  - Create and stabilize desired many-photon state: what is best pumping scheme (coherent vs. frequency-dependent incoherent vs …) ?
  - How to theoretically guide experiment? Lindblad ME not enough, non-Markovianity needed, not clear how to combine with DMRG-like methods
- Probe topological nature of many-photon state
  - Edge spectroscopy: optical signatures of fractional charge / statistics? Anyon interference?
  - Non-Abelian anyons, schemes to probe topological degeneracy
- How stable is topological degeneracy against pumping/losses?
  - Losing one photon → multiple QHs created, still exchange needed to affect topological state.
  - Fine if immediately refilled. But what if some escape? What kinetics of creation and refilling?

New material platforms and spectral domains:

- Available platforms challenging to work with. Promising alternatives
  - Integrated solid-state devices in the visible/near-IR/telecom, to be included in photonic circuits
  - Mid- and Far-IR domains: huge dipoles of intersubband transitions, ultra-strong light-matter coupling, modified quantum vacuum state, integrable in quantum cascade structures

If you wish to know more...


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, 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

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, RMP **91**, 015006 (2019)

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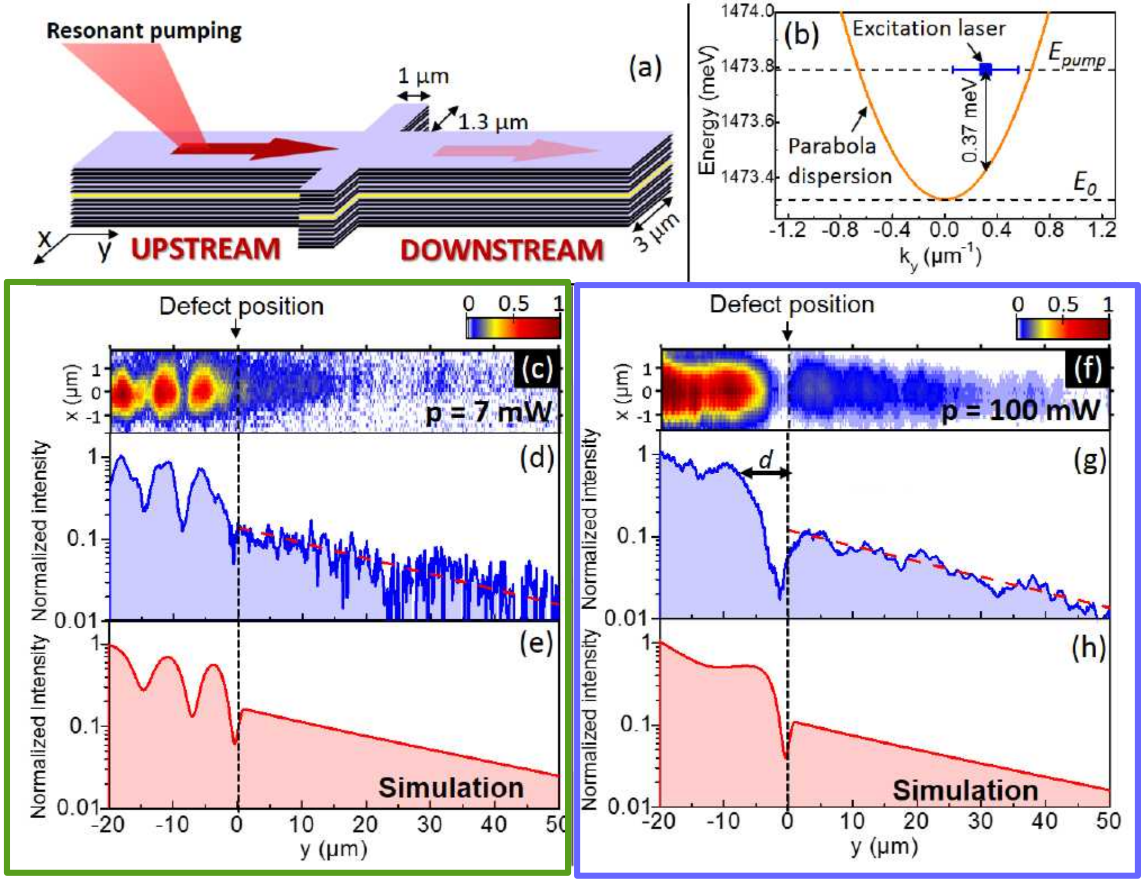
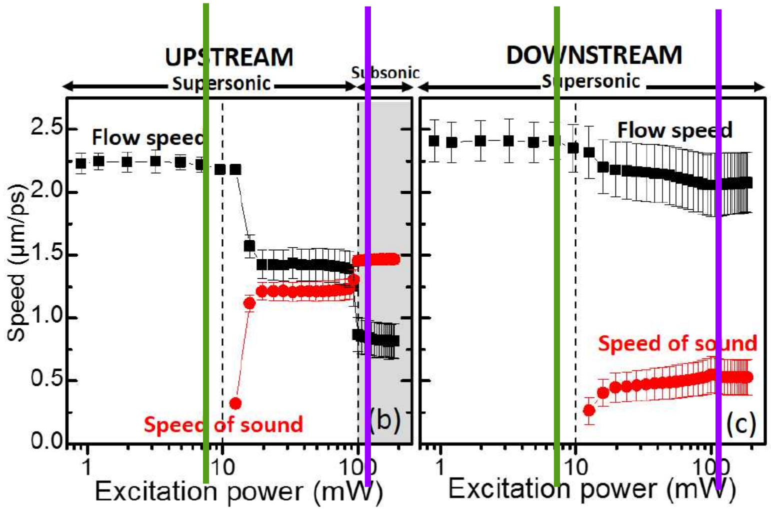
MIR-BOSE

2015 - Acoustic Black Hole in flowing fluid of light





BH created!

The hunt for
Hawking radiation
is now open!!

H.-S. Nguyen, Gerace, IC, *et al.,* PRL **114**, 036402 (2015)
Analogous (more advanced!) experiments with atoms: J. Steinhauer, Nat. Phys 2014 & 2016.

2017-8 - Topological lasing

What happens if one adds gain to a topological model ?

First experiments on topological lasing:

- St.Jean et al., Nat. Phot 2017 (1D-SSH model)
- A bit later: Khajavikhan's group, 2017 (1D-SSH); Bahari et al., Science 2017 (2D magnetic photonic crystal)

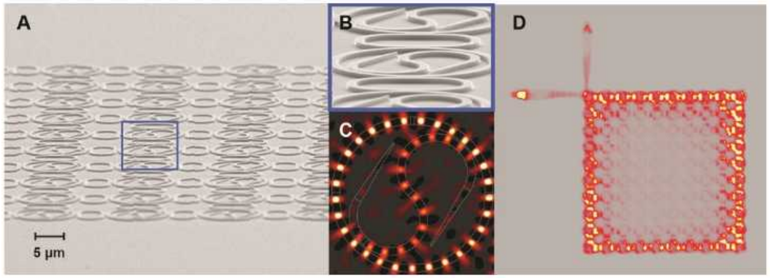
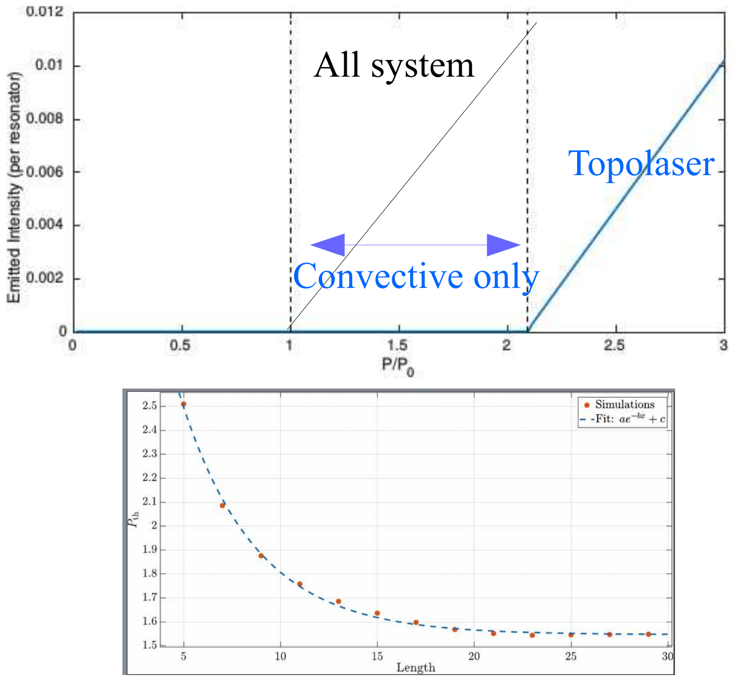


Figure from Bandres et al., Science 2018
Theory in Harari et al., Science 2018
System: array of Si-based ring resonators with optically pumped III-V amplifier layer.
Tai-Ji shape to break inversion symmetry

Pump position selects edge mode → unidirectional emission; robust to disorder; high slope efficiency, but:

- Convective vs. absolute instability:
  - different threshold of edge-mode lasing
  - unusual statistical properties in between
- Topological effects visible in lasing threshold for high number of pumped sites
- Topological robustness against mode jumps:
  - Random choice of lasing mode
  - Extra-slow relaxation of fluctuations
  - What consequences for quantum noise?



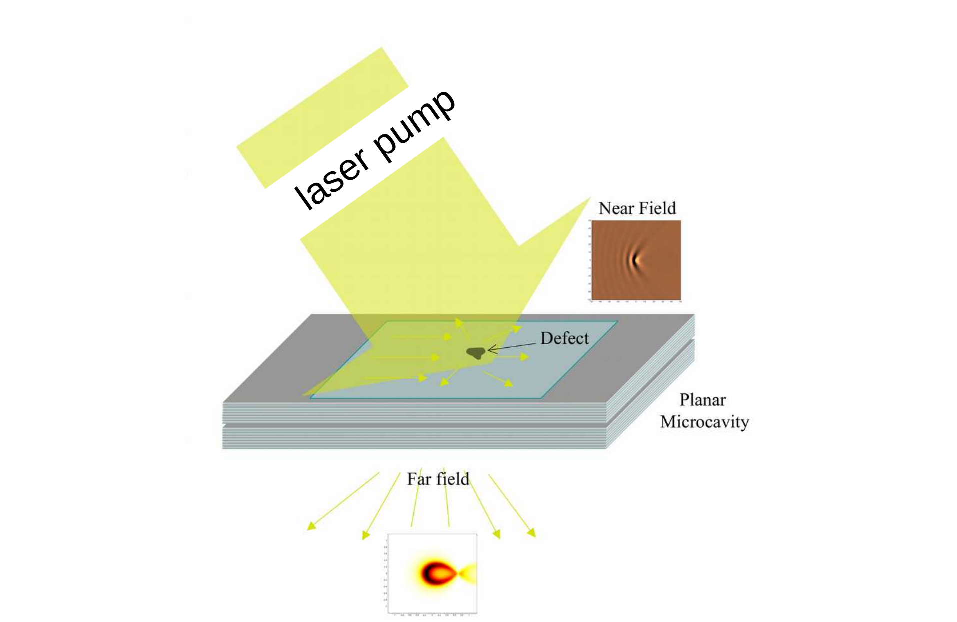
M. Seclì's MSc thesis, UniTN (Oct. 2017)

Part 2:

Quantum fluids of light with a *unitary* dynamics

Field equation of motion

Planar microcavities & cavity arrays



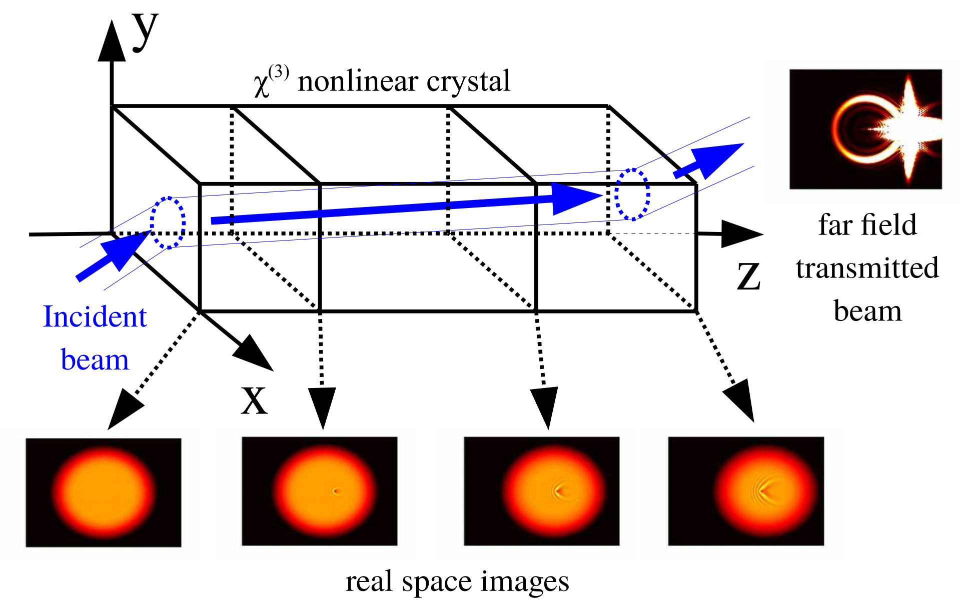
Pump needed to compensate losses:
driven-dissipative dynamics in real time
stationary state ≠ thermodyn. equilibrium

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



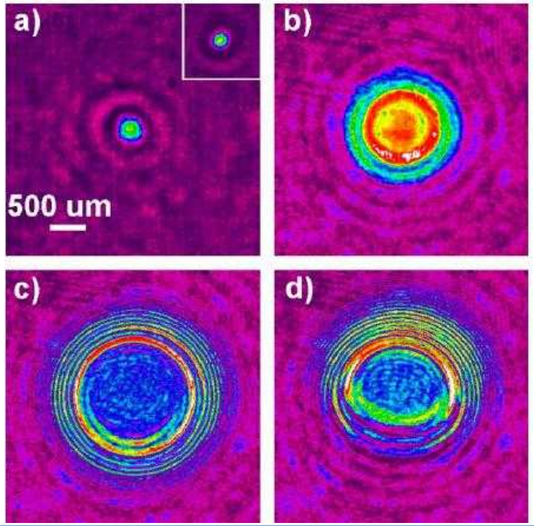
Monochromatic beam
Incident beam sets initial condition @ z=0
MF → Conserv. paraxial propag. → GPE

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

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

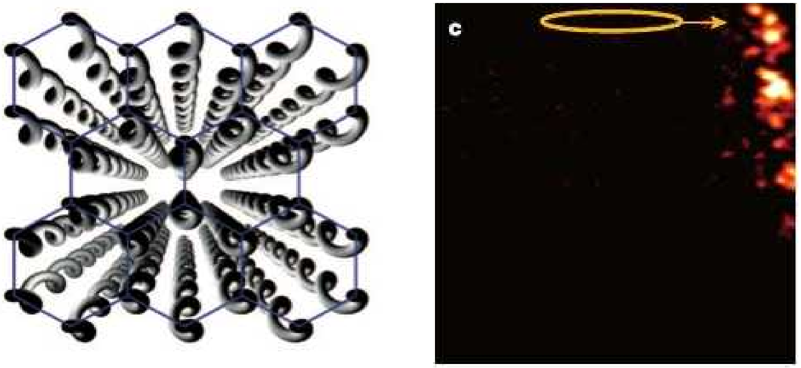
First expts with (almost) conservative QFL's

Dispersive superfluid-like shock waves



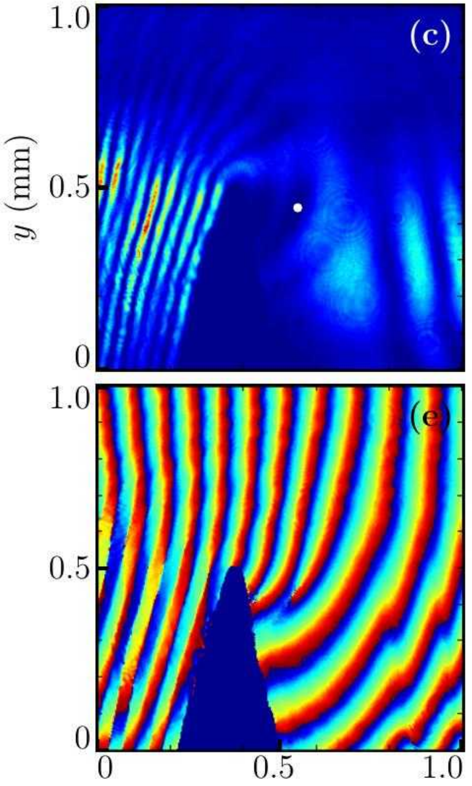
Wan et al., Nat. Phys. 3, 46 (2007)

Chiral edge states in (photonic) Floquet topological insulator

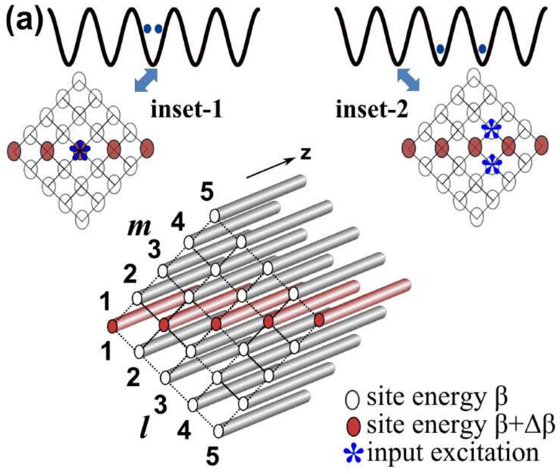


Rechtsman, et al., Nature 496, 196 (2013)

Hydrodynamic nucleation of quantized vortices

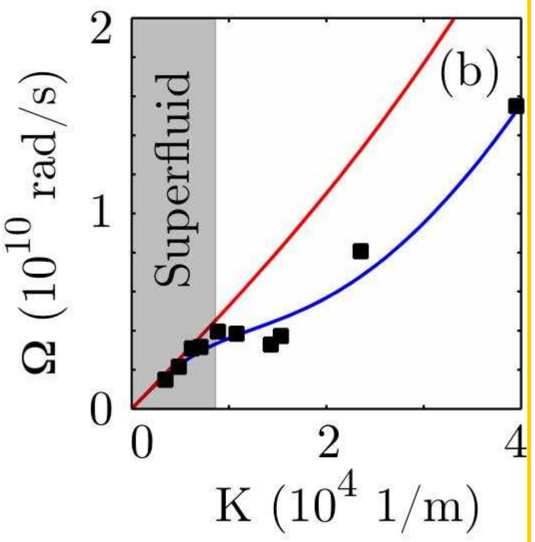


D. Vocke et al.,
arXiv:1511.06634



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

Bogoliubov dispersion of collective excitations



D. Vocke et al. Optica (2015)

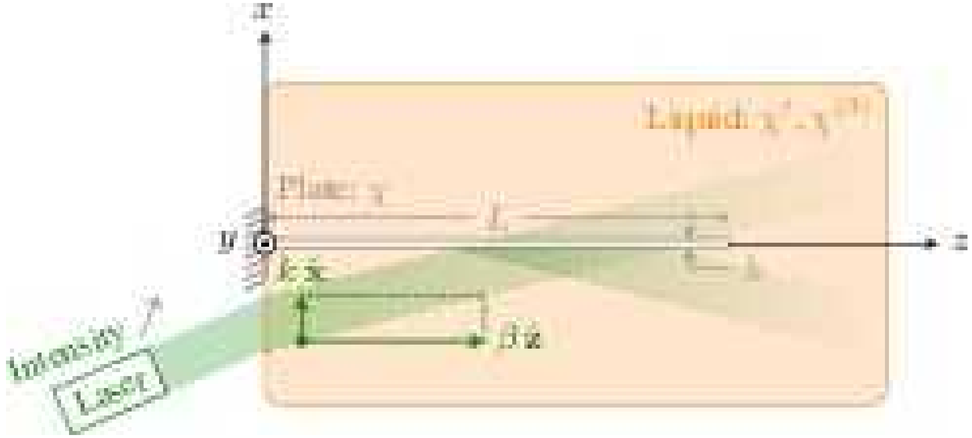
Frictionless flow of superfluid light (I)

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



P.-E. Larré, IC, *Optomechanical Signature of a Frictionless Flow of Superfluid Light*, Phys. Rev. A 91, 053809 (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

An intermediate powers:

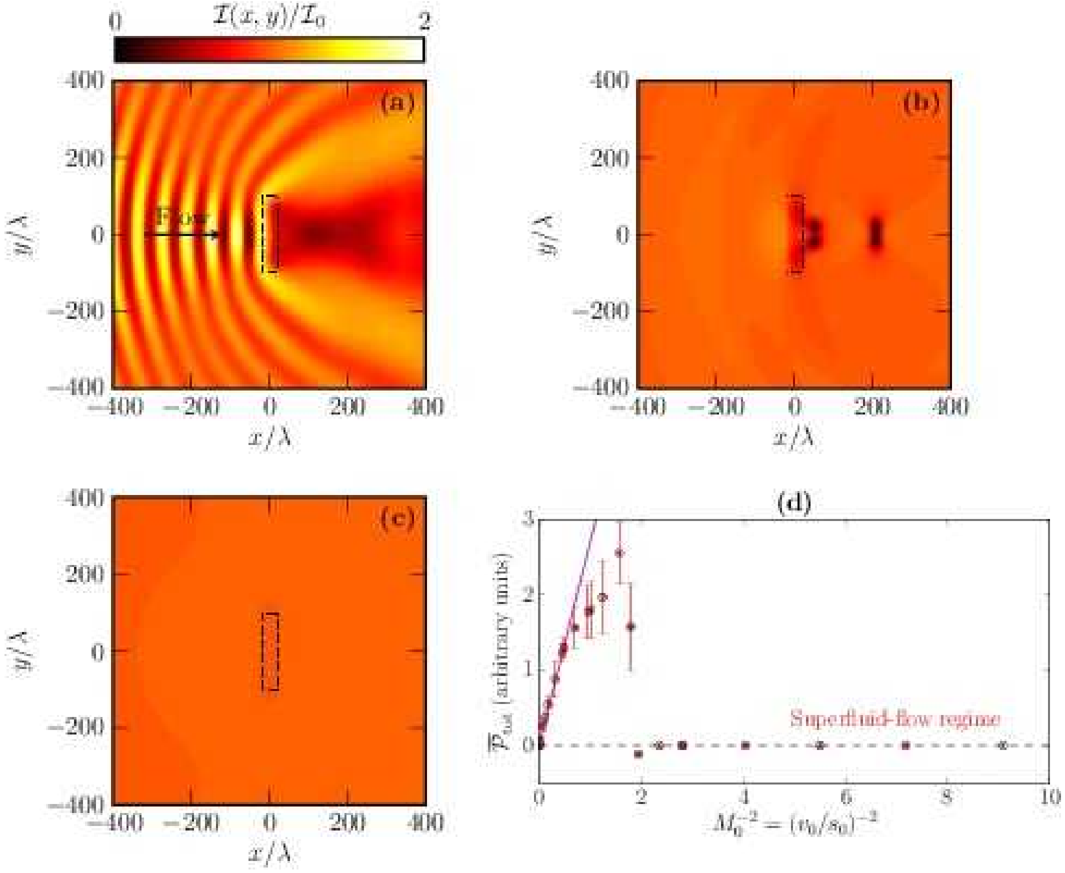
- Periodic nucleation of vortices
- Turbulent behaviours

Fused silica slab as obstacle

→ deformation almost in the μm range

Experiment in progress

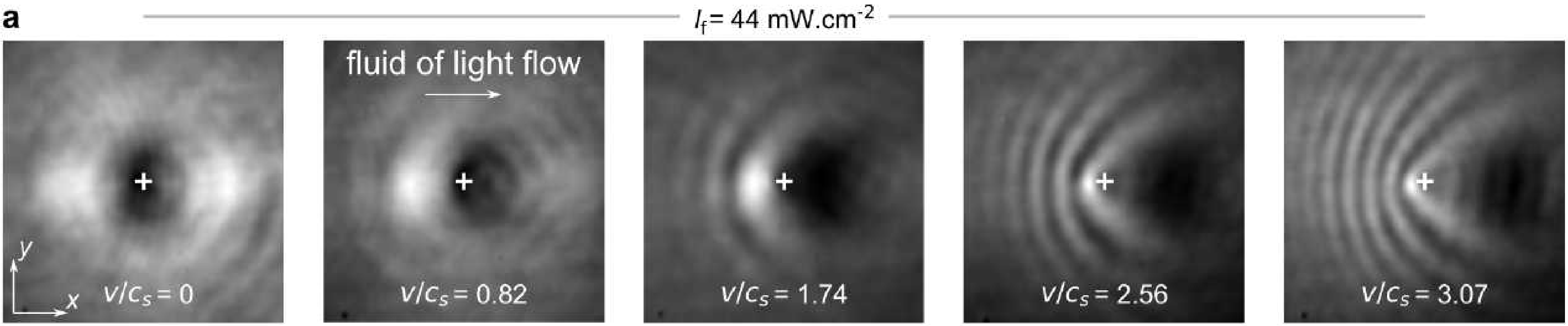
→ surrounding medium in fluid state
but local nonlinearity (e.g. atomic gas)



P.-E. Larré, IC, *Optomechanical Signature of a Frictionless Flow of Superfluid Light*, Phys. Rev. A 91, 053809 (2015).

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

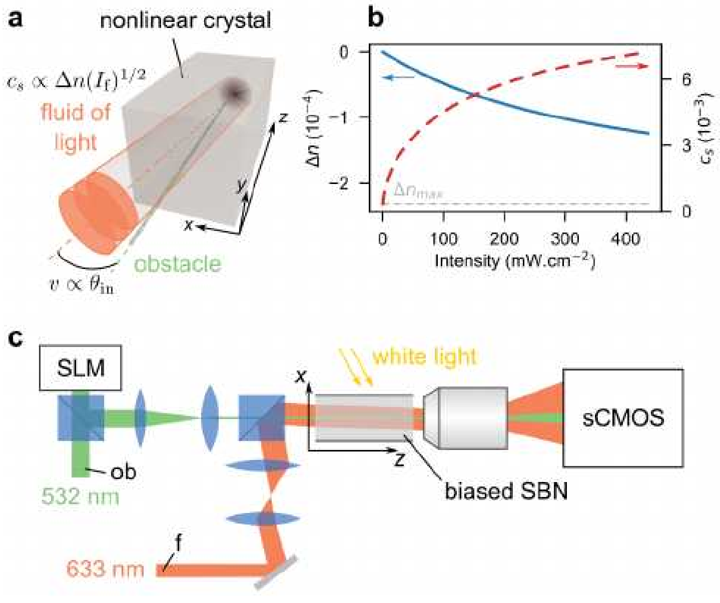
Increasing incidence angle, i.e. speed



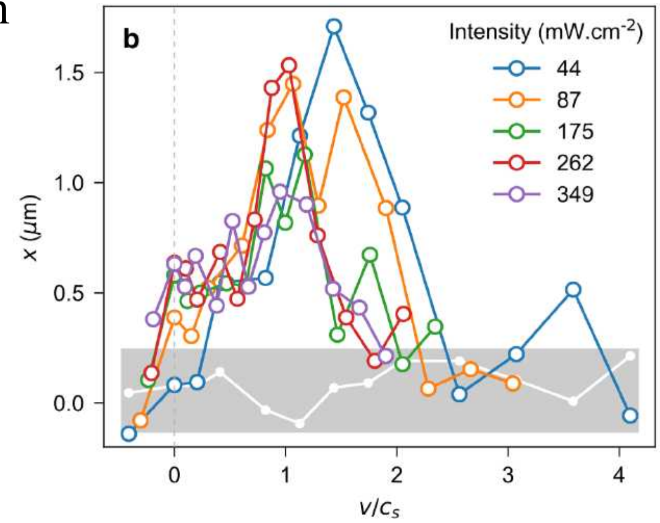
Superfluid

Cherenkov cone shrinks with v/c_s

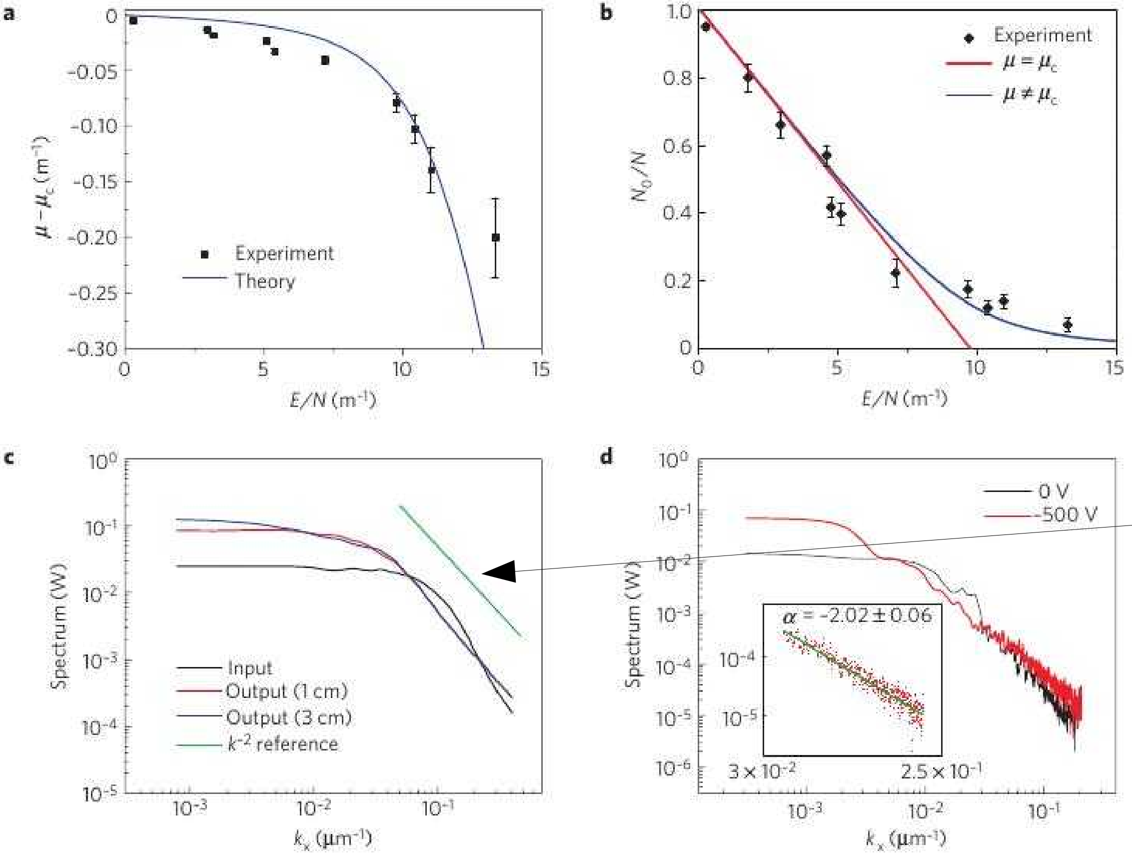
First attempt to measure absence of mechanical effect of superfluid light.

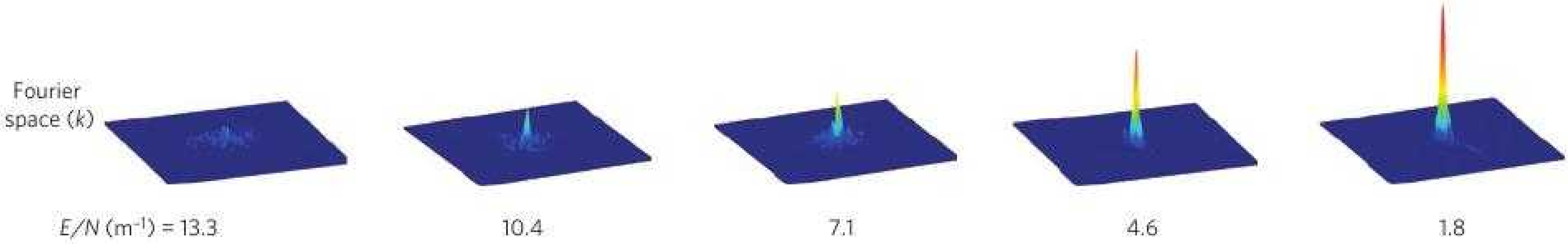


All-optical analog:
lateral shift of obstacle beam



Condensation of classical waves





Monochromatic beam
but spatially noisy profile

Slow nonlinearity
→ remains monochromatic
Evolution during propagation
→ classical GPE

Thermalizes to condensate plus thermal cloud with Rayleigh-Jeans $1/k^2$ high-k 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 with spatially local $\chi^{(3)}$

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

Propagation coordinate z → time

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

(similar to Michael's description of light propagation in EIT medium)

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

Difficulty for Rydberg-EIT: interactions non-local in *x*,*y*, and *z* → approximated as non-local in *t*

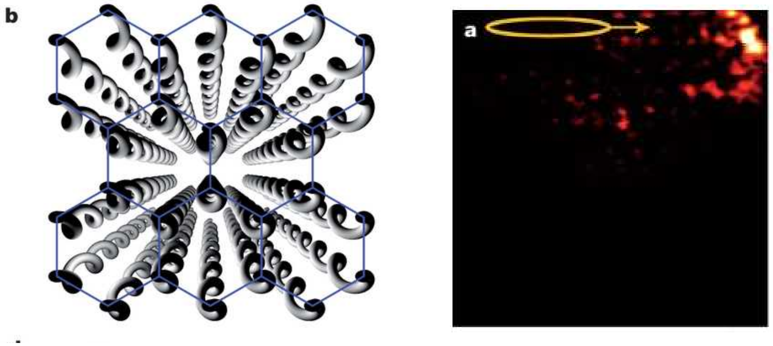
P.-E. Larré, IC, *Propagation of a quantum fluid of light in a cavityless nonlinear optical medium: General theory and response to quantum quenches,* PRA **92**, 043802 (2015)
See also old work by Lai and Haus, PRA 1989

A quite generic *quantum simulator*

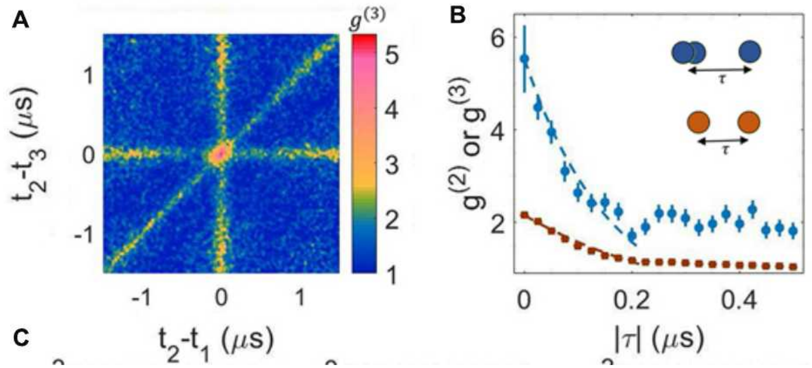
Quantum many-body evolution in *z:*

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

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



Rechtsman et al., Nature 2012



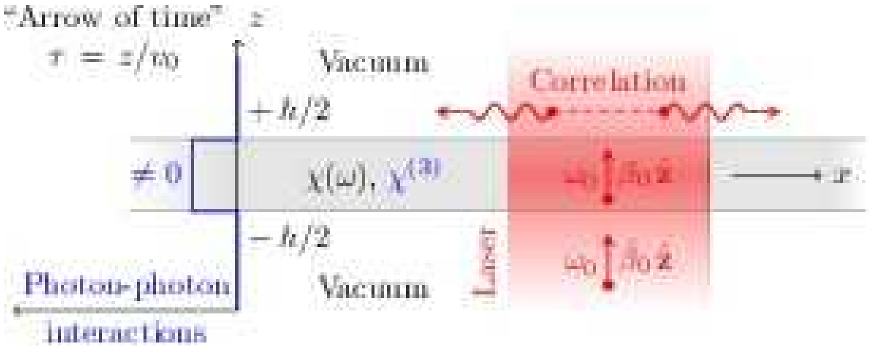
Qi-Yu Liang et al., Science 2018

Can realize (or quantum simulate) wide variety of physical systems:

- Arbitrary splitting/recombination of waveguides → quench of tunneling
- Modulation along *z* → Floquet topological insulators

- In addition to photonic circuit → many-body due to photon-photon interactions
- Pioneering experiments of few-body physics, e.g. two- and three-photon bound states

Dynamical Casimir emission at quantum quench (I)



Monochromatic wave @ normal incidence
into slab of weakly nonlinear medium
→ Weakly interacting Bose gas

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
(sort of Dynamical Casimir Effect for phonons)

Propagation along *z*
→ conservative quantum dynamics

Important question: what is quantum evolution at late times? Thermalization?

P.-E. Larré and IC, PRA **92**, 043802 (2015)

"Pre-thermalized" 1D photon gas

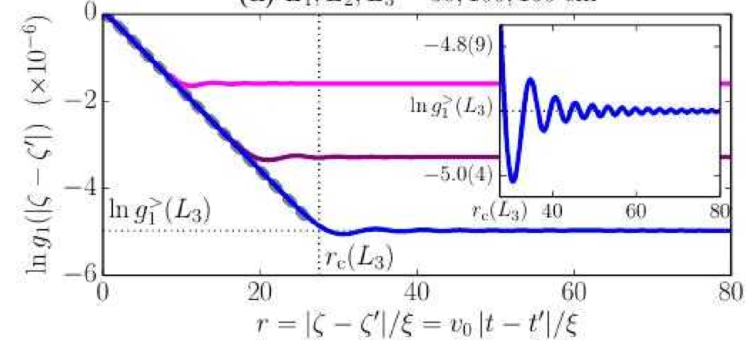
Perfectly coherent light injected into 1D optical fiber:

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

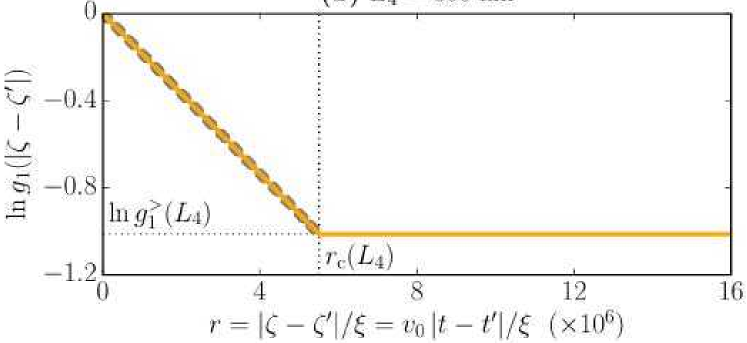
Resulting phase decoherence in $g^{(1)}(t-t')$:

- 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

(a) $L_1, L_2, L_3 = 50, 100, 150$ cm



(b) $L_4 = 300$ km

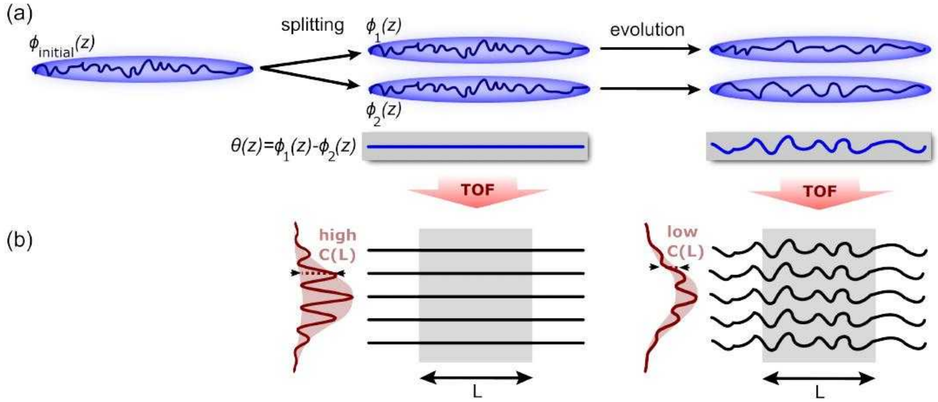


Effect small for typical Si fibers, still potentially harmful on long distances

Decoherence slower if tapering used to "adiabatically" inject light into fiber

Related 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, *Prethermalization in a quenched one-dimensional quantum fluid of light*, EPJD 2016

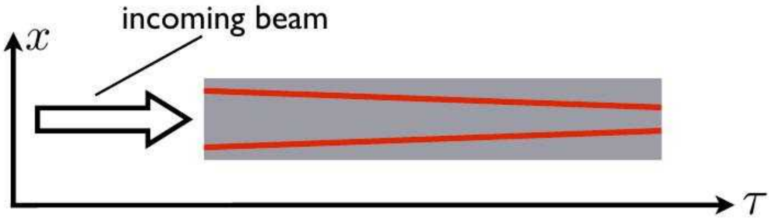
Evaporative cooling of light

Quantum Hamiltonian under space-z / time-t mapping:

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

In 3D bulk crystal after long propagation distances:

- equilibration in transverse k and frequency ω leads to Bose-Einstein distribution
- temperature and chemical potential fixed by incident distribution I(k,ω)



Harmonic trap in xy plane + selective absorption of most energetic particles:

- Energy redistributed by collisions; photon gas evaporatively cooled
- Incident incoherent (in both space and time) field eventually gets to BEC state
- NOTE: fast and coherent optical nonlinearity $\chi^{(3)}$ essential !!

Novel source of coherent light

A. Chiocchetta, P.-É. Larré, IC, EPL (2016).
Intriguing (and not yet fully understood) experiment, Krupa et al., Nat. Phot. 2017