Excitations and dynamics of fractional quantum Hall fluids of light (and of atoms)

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Photons for Quantum Simulation
MIR-BOSE

Why not hydrodynamics of light ?

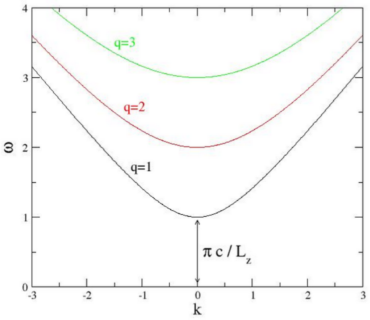
Light field/beam composed by a huge number of photons

- in vacuo photons travel along straight line at *c*
- (practically) do not interact with each other
- in standard cavity, thermalization via walls and absorption/emission

→ optics in vacuo typically dominated by single-particle physics

In suitable photonic structures:

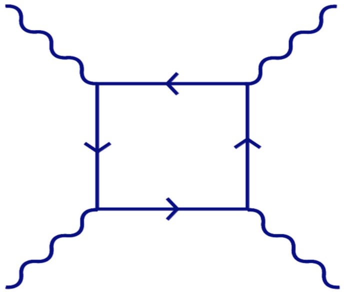
- spatial confinement → effective photon mass
- $\chi^{(3)}$ nonlinearity → photon-photon interactions



Collective behaviour of *quantum fluid of light*

Dilute-fluid physics well explored (BEC, superfluidity, etc.)
Now it is time for strongly correlated states of matter

IC-Ciuti, *Quantum Fluids of Light*, RMP **85**, 299 (2013)



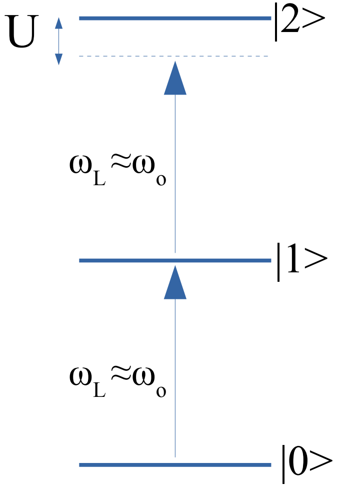
Photon blockade

- Single-mode cavity at ω_o , losses γ
- Photon-photon interaction due to optical nonlinearity → frequency shift ~ U n (n-1)
- If $U >> \gamma$, coherent pump $\omega_L \sim \omega_o$ resonant with 0→1, but not with 1→2.

Photon blockade (Imamoglu et al., PRL 1997) → Effectively impenetrable photons

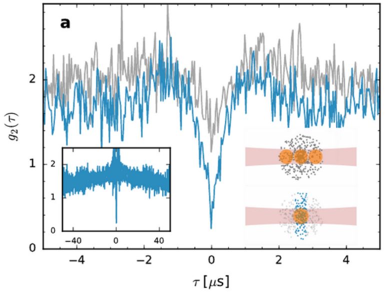
Opposite regime than non-interacting photons of Maxwell's eqs.

Single-cavity blockade observed in many platforms since the 2000s



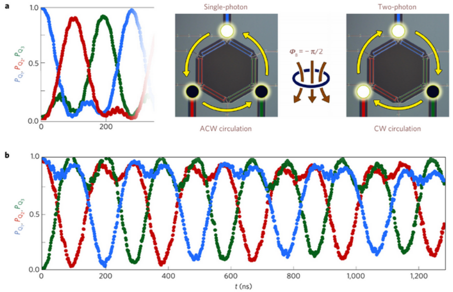
Many-cavities with tunneling J → driven-dissipative Bose-Hubbard / interacting Harper-Hofstadter model

→ many-body physics: Mott insulators, Fractional Quantum Hall fluids

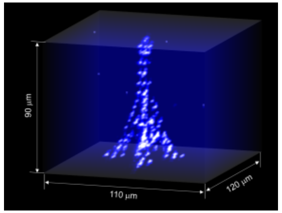


Polariton blockade via Rydberg-EIT (@ Chicago)

Circuit QED device (@GoogleLabs)



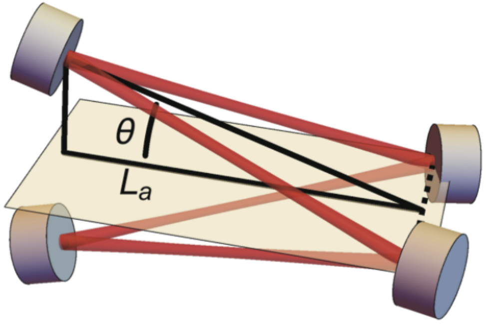
Fluid of spin excitations in lattice of Rydberg atoms.

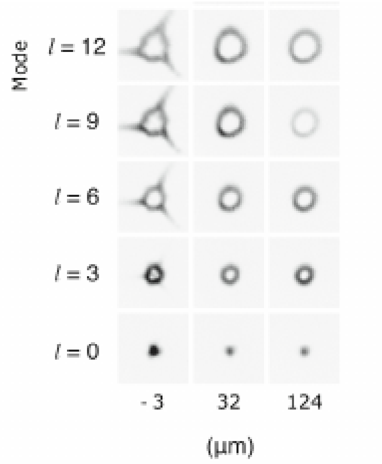


Quantum Hall fluid of light: Experiment @ Chicago

Non-planar ring cavity:

- Parallel transport→ synthetic B via periscope effect
- Landau levels for photons observed



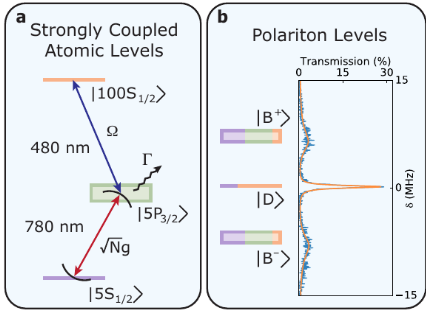


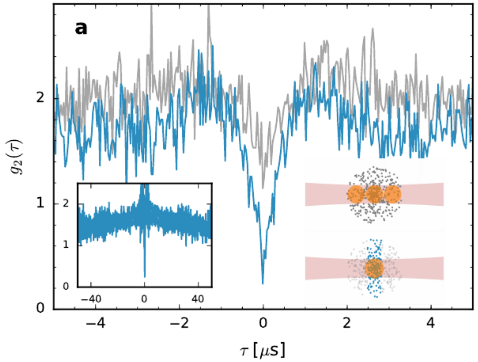
Crucial advantages:

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

Polariton blockade on lowest (0,0) mode

- Equivalent to $\Delta_{\text{Laughlin}} > \gamma$

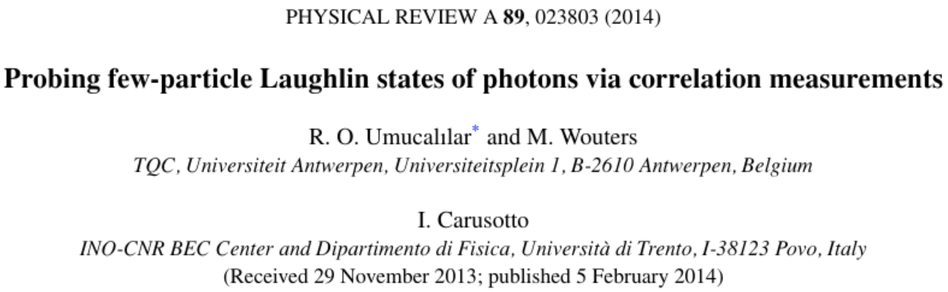




2-photon baby Laughlin state realized (Clark et al., Nature 2020)

Figures from Schine et al., Nature 2016; Jia et al. 1705.07475

Quantum Hall fluid of light: Experiment @ Chicago (II)



PHYSICAL REVIEW A **89**, 023803 (2014)

Probing few-particle Laughlin states of photons via correlation measurements

R. O. Umucalılar* and M. Wouters
TQC, Universiteit Antwerpen, Universiteitsplein 1, B-2610 Antwerpen, Belgium

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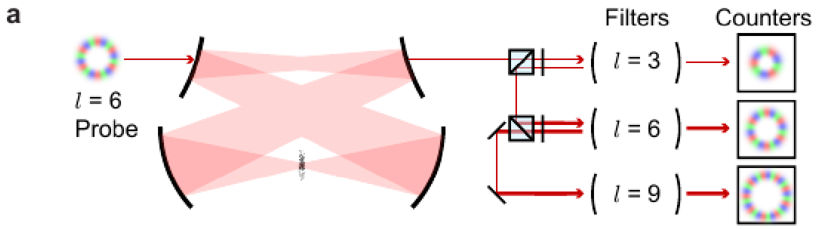
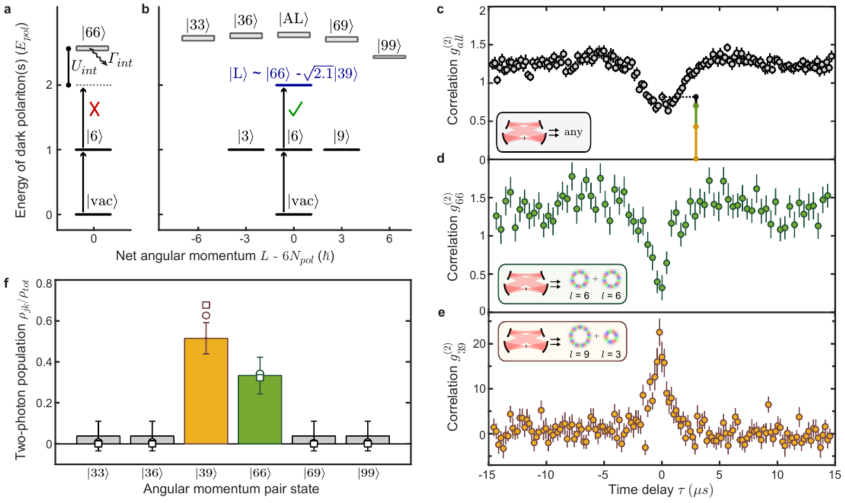
(Received 29 November 2013; published 5 February 2014)



Quantum optical tools to generate two-photon Laughlin state:

- Coherent pumping→ multi-photon peaks to many-body states
  Frequency selectivity isolates Laughlin state
  (Umucalilar-IC, PRL 2012)
- Probing → quantum correlations in emission of orbital modes
  (Umucalilar-Wouters-IC, PRA 2014)



Challenge: scale up to larger number of particles

Coherent pump scheme scales
very bad with N for topological states

L. W. Clark, N. Schine, C. Baum, N. Jia, J. Simon, *Observation of Laughlin states made of light*, Nature 2020

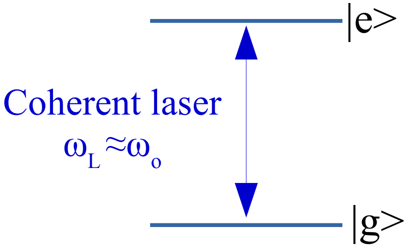
The next challenge:

Macroscopic FQH liquids of light

How to exploit non-Markovian drive & dissipation to stabilize a desired many-body state

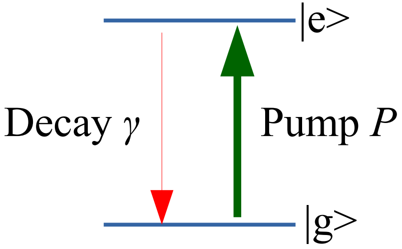
A recap on light-atom interaction

Coherent pump

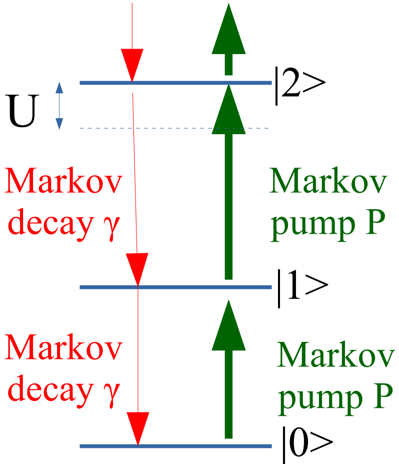


- Coherent laser drives absorption and stimulated emission
- |e> population saturates to ½ under CW strong pumping
- Population inversion requires e.g. pulsed excitation

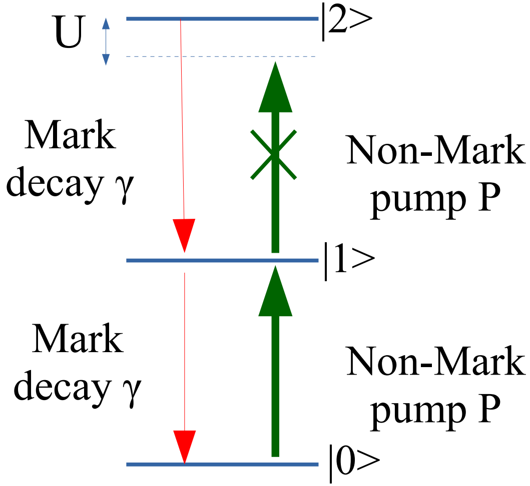
Standard (Markovian) incoherent pump



- For $P >> \gamma$ atom pumped in |e>
- Markovian pump energy-insensitive, keeps exciting to higher states



Frequency-dependent (i.e. non-Markovian) incoherent pump

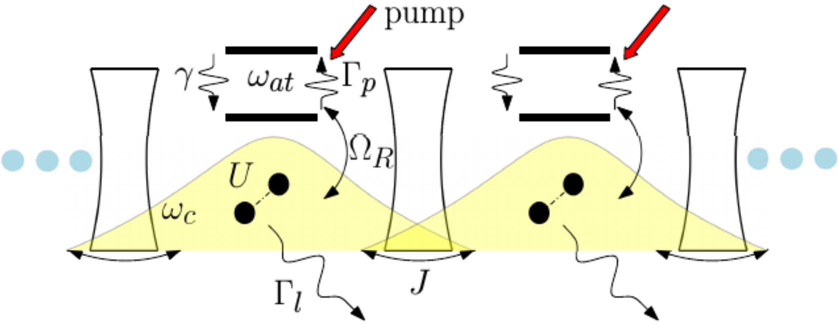


- Transition to |2> detuned → forbidden by freq-depend.
- For $P >> \gamma$ population accumulates into state |1>
- Naturally obtained via frequency-dependent gain, e.g. population-inverted emitters

Many-cavity system

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

José’s thm: for Markov pump → trivial T=∞ state for each N

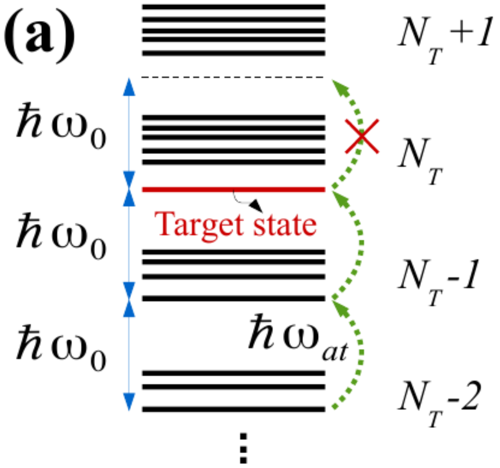


Non-Markovian pump:

- Inverted emitters → Lorentzian emission line around ω_{at}
- Photon injection only active if many-body transition is near resonance, otherwise losses dominate
- For $P >> \gamma$ photons injected until band is full (MI) or many-body gap develops (FQH)
- Many-body gap blocks excitation to higher states and larger N

→ desired correlated state gets stabilized !

(a)



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

Umucalilar-IC, PRA 2017
Lebreuilly, Biella et al., PRA 2017

Mott insulators of light

- Most naive non-Markovian master equation:
  frequency-dependent emission → rescaled jump operators

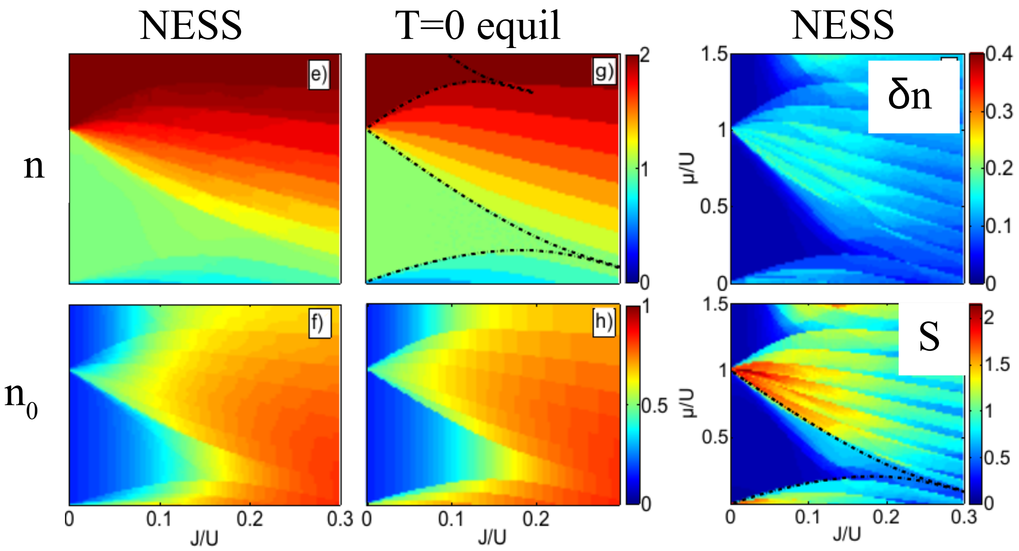
$$\bar{\mathcal{L}}_{\mathrm{em}}(\rho_{\mathrm{ph}}) = \frac{\Gamma_{\mathrm{em}}}{2}\sum_{i=1}^{k}\left[2\bar{a}_i^\dagger \rho_{\mathrm{ph}}\bar{a}_i - \bar{a}_i\bar{a}_i^\dagger \rho_{\mathrm{ph}} - \rho_{\mathrm{ph}}\bar{a}_i\bar{a}_i^\dagger\right]$$

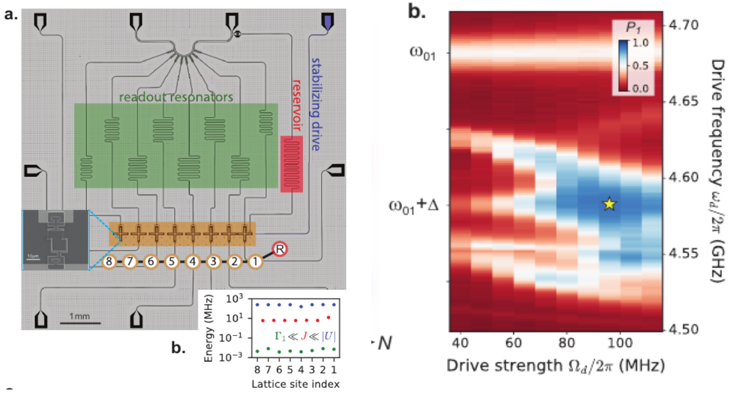
$$\langle f'|\bar{a}_i^\dagger|f\rangle = \frac{\Gamma_{\mathrm{pump}}/2}{\sqrt{(\omega_{\mathrm{at}}-\omega_{f',f})^2+(\Gamma_{\mathrm{pump}}/2)^2}}\langle f'|a_i^\dagger|f\rangle$$

- driven-dissipative steady state stabilizes
  strongly correlated many-body states
  e.g. Mott-insulator, FQH…

- resembles low-T equilibrium

- (in principle) no restriction to small N_{ph}
  only requirement → many-body energy gap

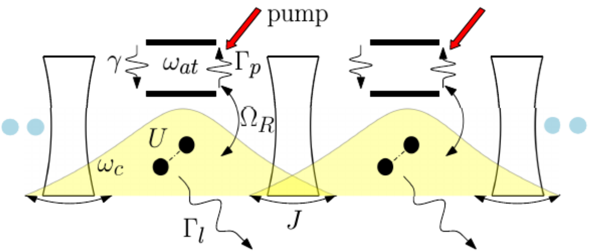


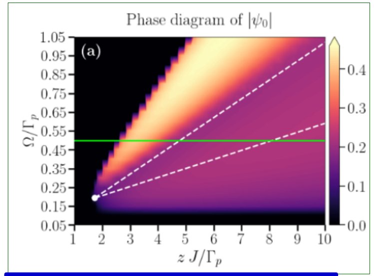


First expt: Ma *et al.* Nature 2019

Lebreuilly, Biella et al., 1704.01106 & 1704.08978
Related work in Kapit, Hafezi, Simon, PRX 2014

Mott insulators of light (II)



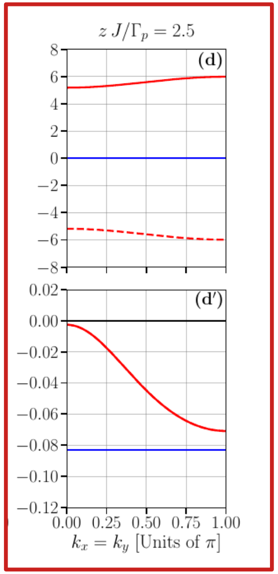


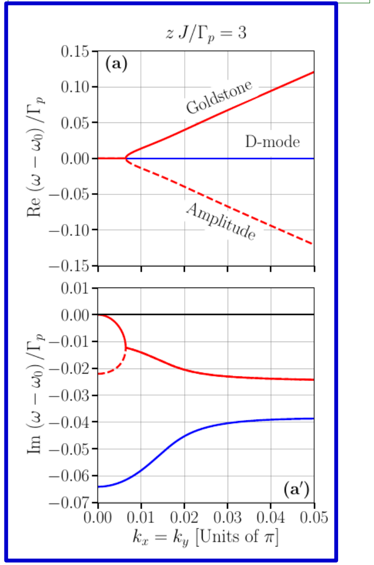
Exact description of non-Markovianity of emitter

→ explicit inclusion of two-level emitters:

- Markovian incoherent pump Γ_P
- Coupling to cavity mode Ω_R → emission irreversible via Γ's
- Frequency-dependent emission of linewidth Γ_P

Biella, Lebreully et al., 1704.08978



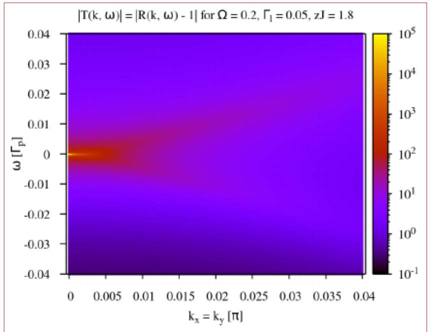


Superfluid-insulator non-equilibrium phase transition

Interesting behaviour of collective excitation modes across transition:

- Linearized Gutzwiller approach; observation in transmission/reflection/FWM
- Gap closes in Mott insulating phase approaching critical point
- Diffusive Goldstone mode in superfluid
- Similar physics as in polariton BECs (Wouters, Szymanska/Keeling, Diehl, expt: Bramati)

Fabio Caleffi, PhD thesis @ SISSA (to be submitted)



What about large FQH fluids?

Coherent pump:

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

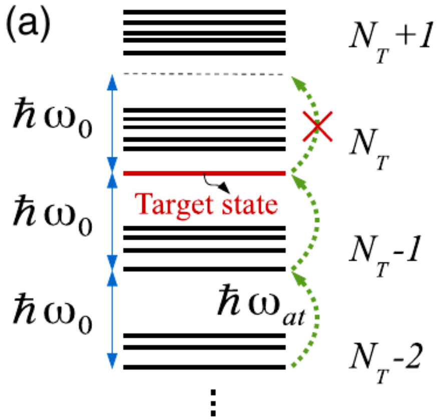
Frequency-dependent incoherent pump:

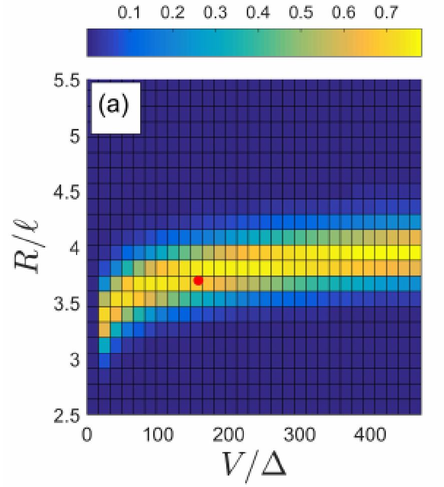
- Interactions → many-body gap Δ
- Edge excitations not gapped. Hard-wall confinement gives small δ
- Non-Markovianity blocks excitation to higher states

Calculations only possible for small systems:

- Large overlap with Laughlin states
- Residual excitations localized mostly on edge

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



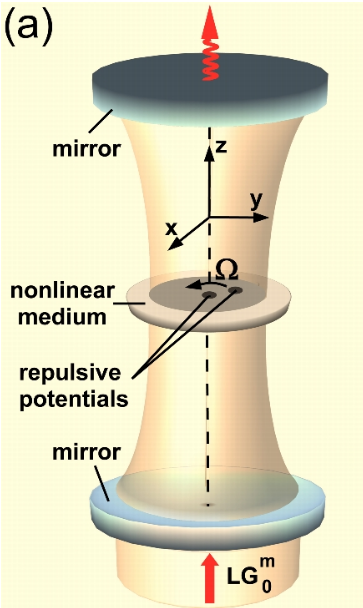


- R. O. Umucalilar, IC, *Generation and spectroscopic signatures of a fractional quantum Hall liquid of photons in an incoherently pumped optical cavity*, PRA 2017.
- R. O Umucalilar, J. Simon, IC, *Autonomous stabilization of photonic Laughlin states through angular momentum potentials*, PRA 2022
- Interesting subtleties: Kurilovich et al., *Stabilizing the Laughlin state of light: dynamics of hole fractionalization*, arXiv:2111.01157

How to probe the many-body state?

Probing anyonic statistics of quasi-holes in the bulk

Optical signatures of the anyonic braiding phase



Anyonic statistics of quasi-holes: Berry phase ϕ_{Br} when adiabatically moved around each other

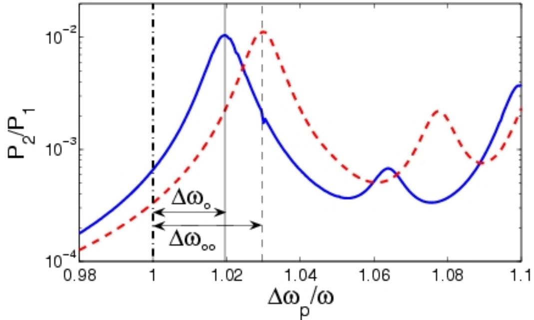
- Berry phase encoded in global phase of many-body wavefunction
- requires interference process to be revealed [Grusdt et al., Nat. Comm. (2016)]

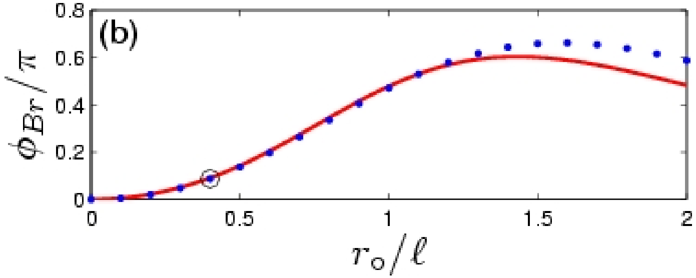
Naturally provided in optics:

- FQH fluid + localized potentials:→ create & braid QH in FQH fluid
- 0-photon state unaffected; phase-shift of N-body wavefunctio of FQH state
- Berry phase extracted from shift of transmission resonance |0> → |N>
  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





Quantum mechanics of anyons (I) – single particle

Laughlin wavefunction of Fractional Quantum Hall:

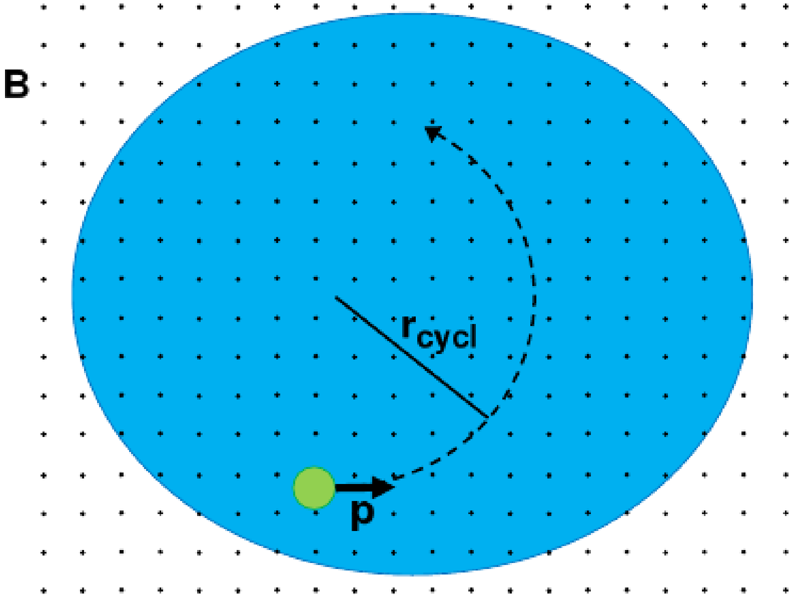
- quasi-holes → no E_{kin}, no independent life
- dressed by heavy impurity → anyonic molecule
- full-fledged quantum mechanical degree of freedom

Born-Oppenheimer approx:

- Heavy impurity→ slow Degree of Freedom
- Light FQH particles → fast DoF

$$H_{\mathrm{eff}} = \frac{\left[-i\nabla_{\mathbf{R}} - (Q - \nu q)\,\mathbf{A}(\mathbf{R})\right]^2}{2\mathcal{M}}$$

- Mass M → M (impurity) + QH dragging effect
- Impurity & FQH particles feel (Synth-)B,
  so synth-Charge → Q (impurity) – ν q (QH)



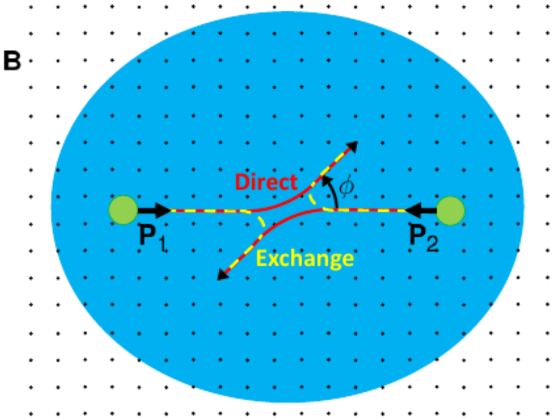
Cyclotron orbit → fractional charge and BO mass correction

A. Muñoz de las Heras, E. Macaluso, IC, PRX 2020

Quantum mechanics of anyons (II) – two particles

Each particle → attached flux

$$\mathcal{A}_j(\mathbf{R}) = \mathcal{A}_{\mathrm{q}}(\mathbf{R}_j) + \mathcal{A}_{\mathrm{stat},j}(\mathbf{R}) = \frac{\mathcal{B}_{\mathrm{q}}}{2}\mathbf{u}_{\mathrm{z}} \times \mathbf{R}_j + (-1)^j \frac{\nu}{R_{\mathrm{rel}}^2}\mathbf{u}_{\mathrm{z}} \times \mathbf{R}_{\mathrm{rel}}$$



Relative motion:

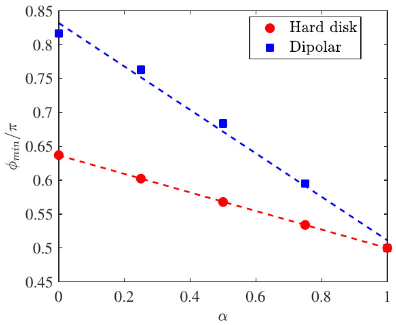
- inter-particle potential
- statistical A_{rel} due to attached flux

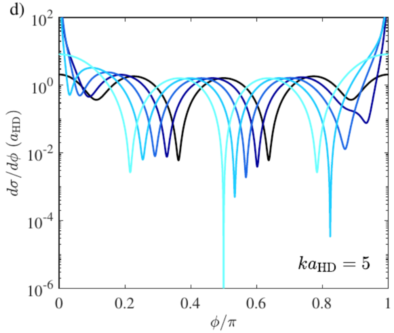
$$H_{\mathrm{rel}} = \frac{[\mathbf{P}_{\mathrm{rel}} + \mathbf{A}_{\mathrm{rel}}(\mathbf{R}_{\mathrm{rel}})]^2}{2\mathcal{M}_{\mathrm{rel}}} + V_{\mathrm{ii}}(R_{\mathrm{rel}})$$

2-body scattering: interference of direct & exchange

- fringes in differential cross section
- fringe position depends on attached flux, i.e. measure fractional statistics

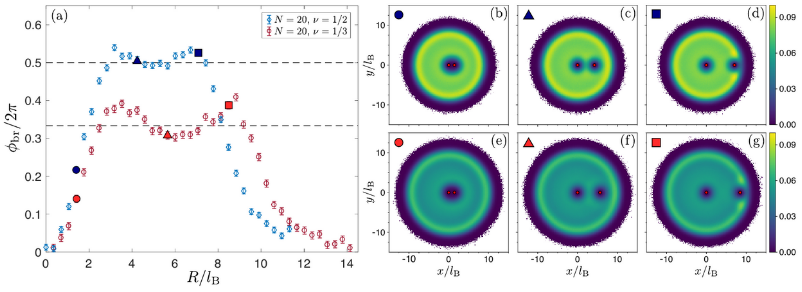
- ➢ Scheme works with polar molecules (heavy + long-range interactions) in atoms (light FQH gas)
- ➢ What about Rydberg polaritons?





A. Muñoz de las Heras, E. Macaluso, IC,
PRX 2020

A simpler strategy: observing anyonic statistics in ToF measurements



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

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

Braiding operation generated by rotations, braiding phase related to L_z

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

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

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

Can be applied to both cold atoms or to fluids of light looking at far-field emission pattern
Difficulty → small angular momentum difference of QH compared to total L_z

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

Connection to spin/statistics of anyons: Comparin, Opler, Macaluso, Biella, Polychronakos, Mazza,
Measurable fractional spin for quantum Hall quasiparticles on the disk, PRB 2022

Quasi-Hole structure vs. anyon statistics (I)

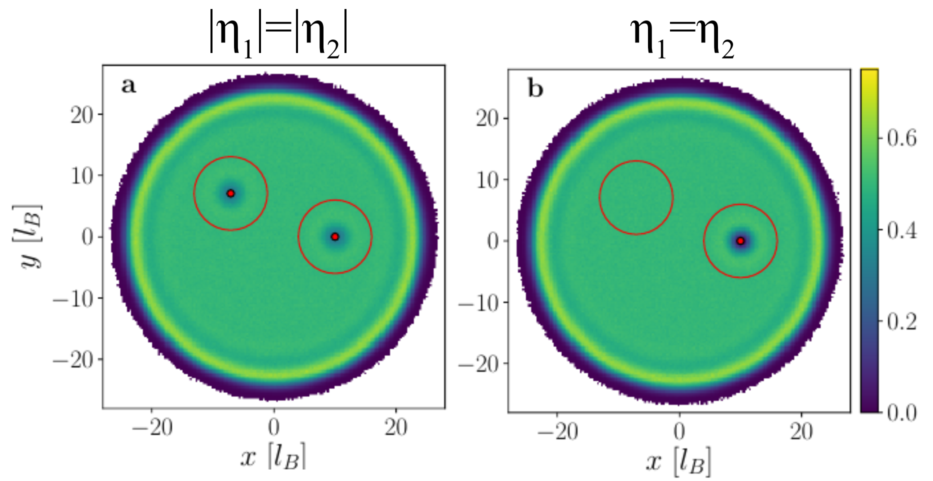
- Compare (two) single quasi-holes and
  overlapping pair of quasi-holes:

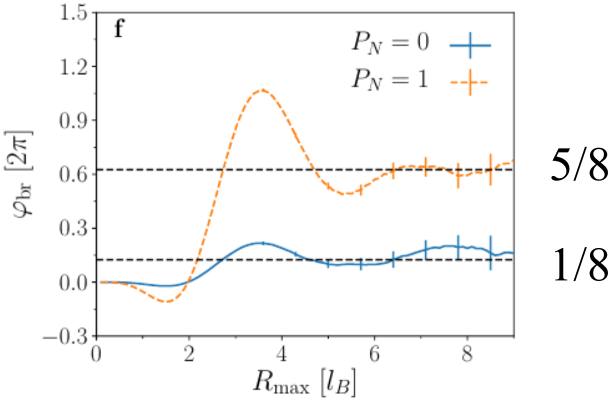
$$\frac{\varphi_{\rm br}}{2\pi} = \frac{1}{\hbar}\left[\langle \hat{L}_z\rangle_{|\eta_1|=|\eta_2|} - \langle \hat{L}_z\rangle_{\eta_1=\eta_2}\right].$$

- 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
- Statistics inferred from local density difference around QH core, i.e. spatial variance of density depletion
- To be distinguished from fractional charge inferred from missing charge
- Insensitive to spurious excitation of (ungapped) edge states
- Numerical calculation using Moore-Read wavefunction allows to distinguish fusion channels of even/odd total particle number

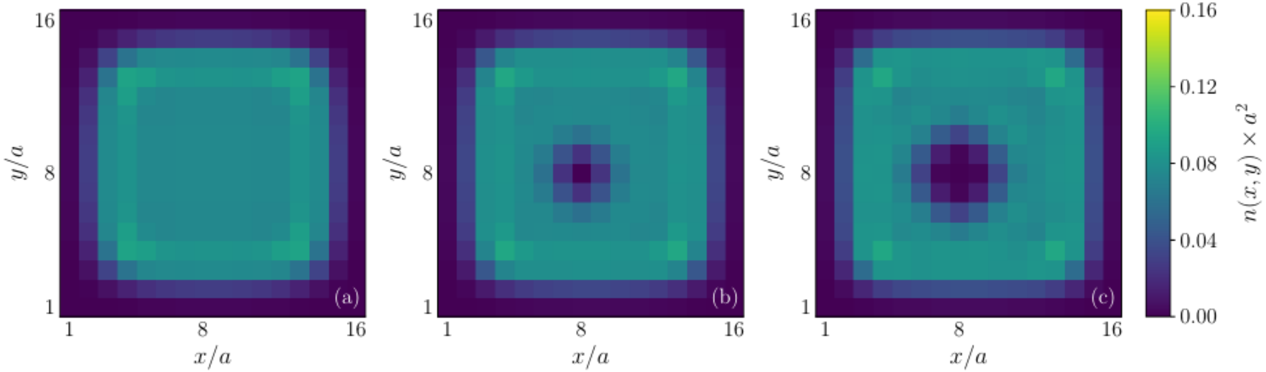


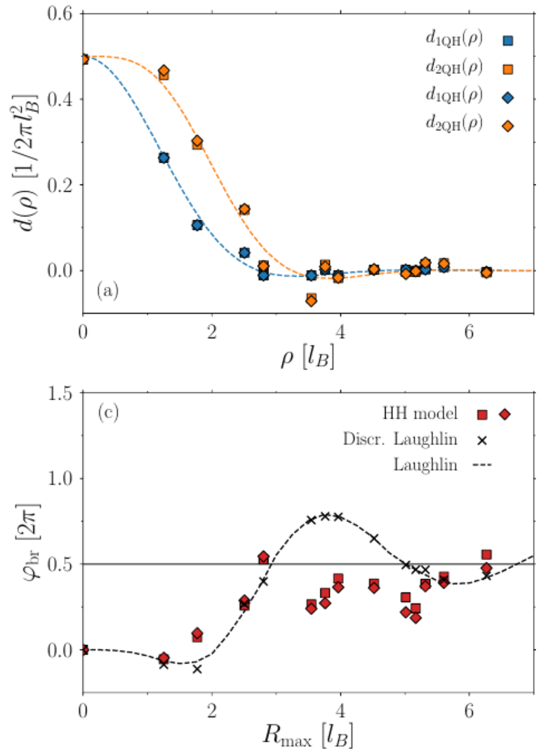


E. Macaluso, T. Comparin, L. Mazza, IC, *Fusion channels of non-Abelian anyons from angular-momentum and density-profile measurements*, PRL 2019

Connection to spin/statistics of anyons: Comparin, Opler, Macaluso, Biella, Polychronakos, Mazza, *Measurable fractional spin for quantum Hall quasiparticles on the disk*, PRB 2022

Quasi-Hole structure vs. anyon statistics (II)





Discrete lattice model → Harper-Hofstadter-Bose-Hubbard

Ground state using Tree-Tensor-Network ansatz

- experimentally realistic "large" system
- open boundary conditions with harmonic trap
- repulsive potentials to pin quasi-holes

Apply discretized version of braiding phase formula

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

to physical ground state wavefunction

→ Accurate reconstruction of anyonic statistics

→ Experiment accessible in state-of-the-art circuit-QED systems

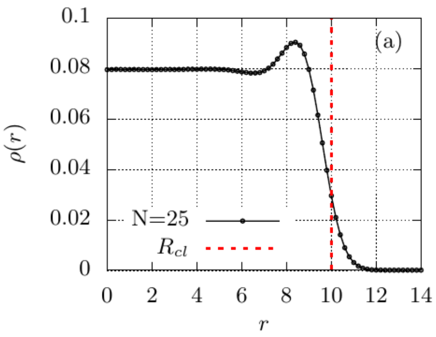
E. Macaluso *et al.*, *Charge and statistics of lattice quasiholes from density measurements: a Tree Tensor Network study,* Phys. Rev. Research (2020)

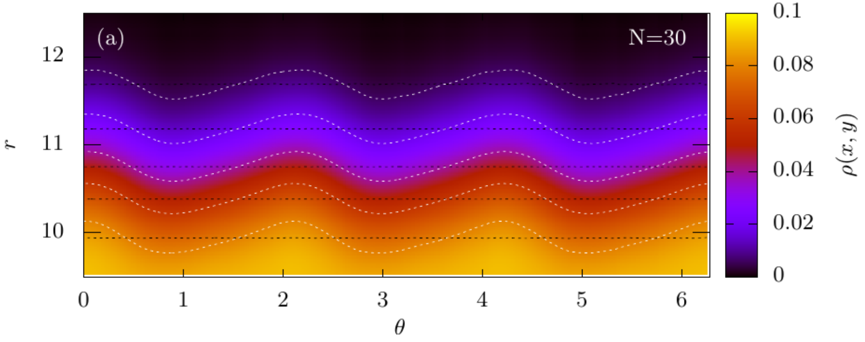
On-going work:

Linear and nonlinear edge dynamics of FQH clouds

Towards quantum optics of chiral Luttinger liquids

Response of trapped FQH cloud to external potential (I)





Trapping potential $V_{conf}(r) = \lambda r^\delta$

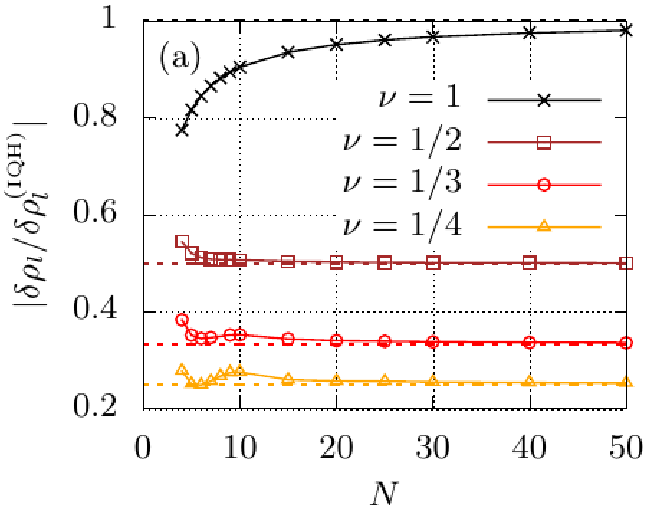
Ab initio ED calculations by MC evaluation of matrix elements of H via Metropolis (upto ~50 particles)

Time-dependent perturbation $U(r,\theta;t)$ running around edge:

- generates oscillatory perturbation on edge

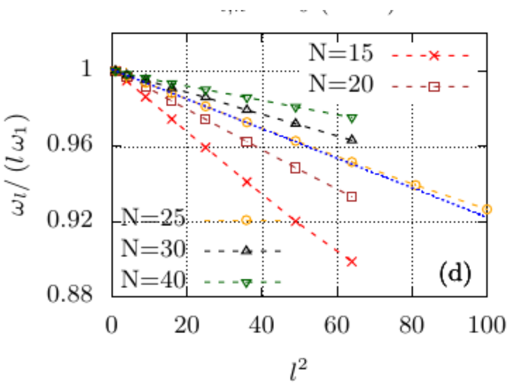
Weak perturbation → chiral Luttinger liquid behaviour

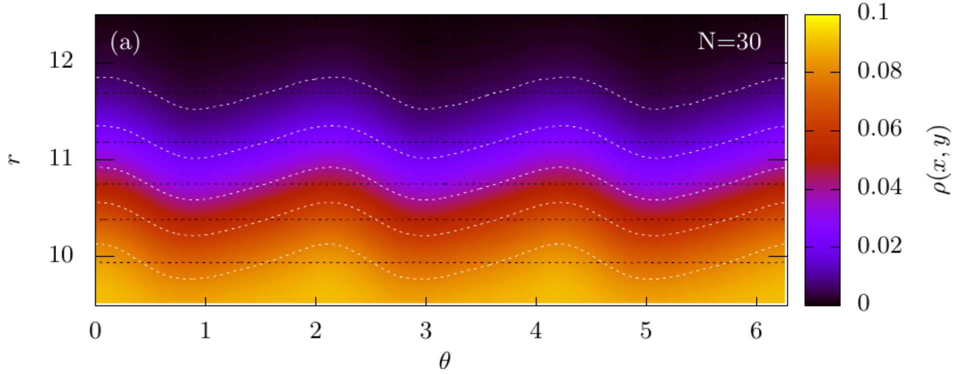
- linear response proportional to filling ν
- related to quantized transverse conductivity of FQH
- matches with numerics for long wavelength excitations…



A. Nardin, IC, *Linear and nonlinear edge dynamics of trapped fractional quantum Hall droplets beyond the chiral Luttinger liquid paradigm*, arXiv:2203.02539

Response of trapped FQH cloud to external potential (II)





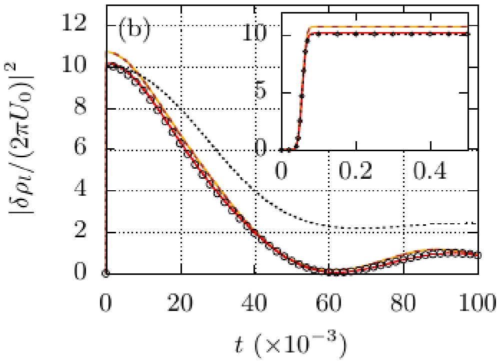
Linear response matches χLL… but much more physics hidden in edge perturbation σ(z,t) :

- free oscillation frequency shift ~ k^3 → group velocity dispersion
- nonlinear effects → frequency shift proportional to amplitude σ due to radially increasing trapping force (different functional form compared to FQH literature)

Well captured by classical evolution eq: driven Korteweg-de Vries

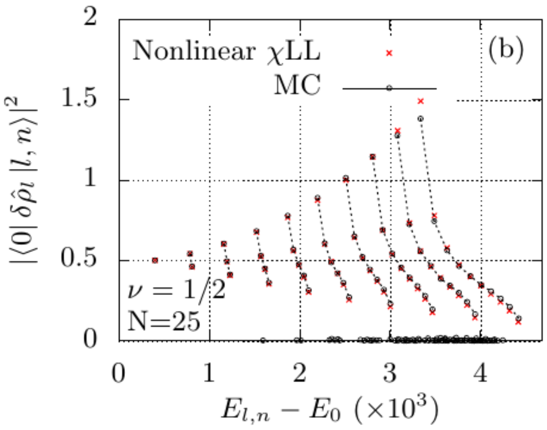
$$\frac{\partial \sigma}{\partial t} = -\left[v_0 + \frac{2\pi\tilde{c}_0}{\nu}\sigma\right]\frac{\partial \sigma}{\partial \zeta} - \beta_m \tilde{c}_0 \frac{\partial^3 \sigma}{\partial \zeta^3} - \frac{\nu}{2\pi}\frac{\partial U}{\partial \zeta}$$

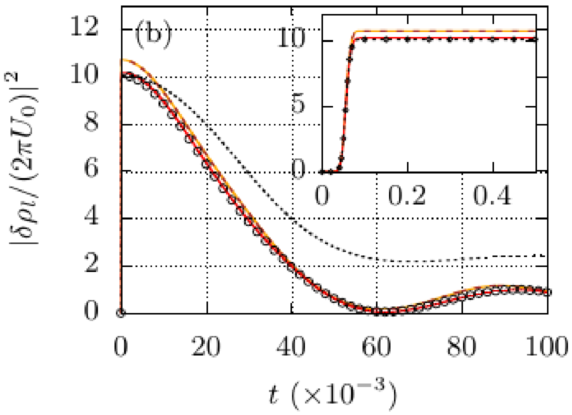
- but also shows temporal decay of oscillation… which requires further refinements...

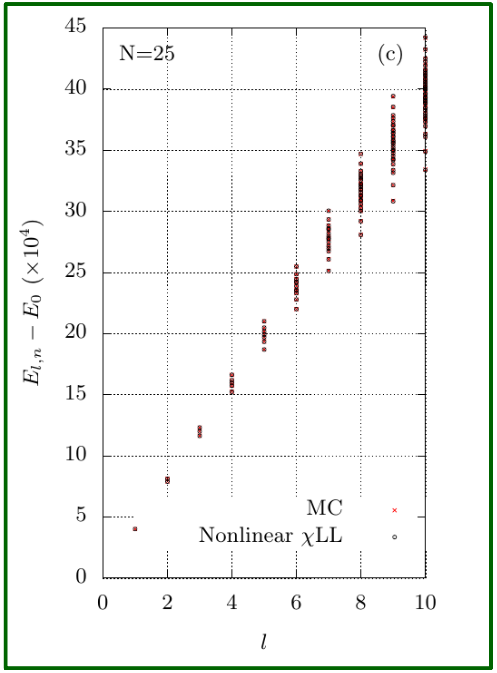


A. Nardin, IC, *Linear and nonlinear edge dynamics of trapped fractional quantum Hall droplets beyond the chiral Luttinger liquid paradigm*, arXiv:2203.02539

Response of trapped FQH cloud to external potential (III)







Broadening associated to damping well captured by quantum-χLL

$$\hat{H}^{NL}_{\chi\mathrm{LL}} = \int d\zeta \left[\frac{\pi\, v_0}{\nu}\,\hat\sigma^2 - \frac{\pi\,\beta_m\tilde{c}_0}{\nu}\left(\frac{\partial\hat\sigma}{\partial\zeta}\right)^2 + \frac{2\pi^2\tilde{c}_0}{3\nu^2}\hat\sigma^3 + U(\zeta,t)\,\hat\sigma\right]$$

with $[\hat\sigma(\zeta),\hat\sigma(\zeta')] = -i\,\frac{\nu}{2\pi}\,\partial_\zeta\delta(\zeta-\zeta').$

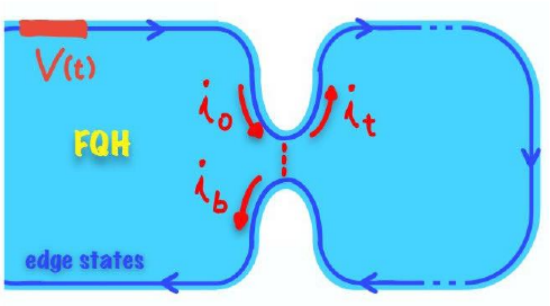
Quantum-χLL eigenstates well match ED results, as well as temporal evolution of observables

Dynamic structure factor → going to be explained in terms of refermionization of LL

A. Nardin, IC, *Linear and nonlinear edge dynamics of trapped fractional quantum Hall droplets beyond the chiral Luttinger liquid paradigm*, arXiv:2203.02539

Nonlinear optics of edge excitations at constriction (I)

Chern-Simons view: Linear χLL dynamics of edge + intrinsic nonlinearity at junction
(see D. Tong lectures on QH physics, 1606.06687)



$$H = \boxed{\frac{v_F}{4\pi}\int dx\,(\partial_x\phi)^2} + \boxed{\Gamma\cos[\phi(x_2)-\phi(x_1)]}$$

Edge mode propagation — Quasi-particle tunneling @ junction

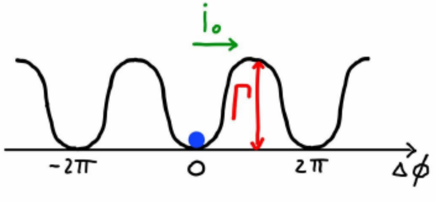
Charge density $\rho = \frac{1}{2\pi}\partial_x\phi$ $\qquad [\phi(x),\rho(y)] = \frac{i}{m}\delta(x-y)$ $\qquad$ QP operator $\Psi_{qp} = :e^{i\phi}:$ displaces 1/m charge

Semiclassical dynamics for Δφ = phase across junction = (2 π) transmitted charge

$$\partial_t\,\Delta\phi = -\Gamma\sin(\Delta\phi) + 2\pi\, I_0(t)$$

Backscattered current $I_B(t) = \frac{\Gamma}{2\pi}\sin(\Delta\phi)$

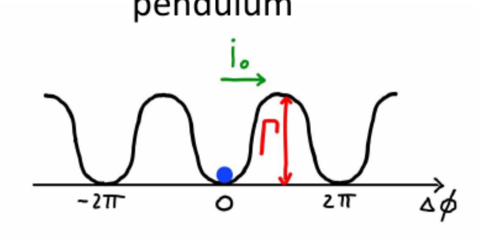
Overdamped pendulum



Z. Bacciconi, *Fractional quantum Hall edge dynamics from a quantum optics perspective*, MSc thesis at UniTrento (2021); arXiv:2111.05858
Z. Bacciconi, A. Nardin, IC, in preparation (2022)

Nonlinear optics of edge excitations at constriction (II)

Overdamped pendulum

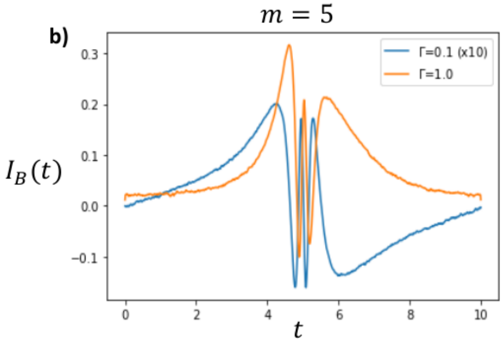


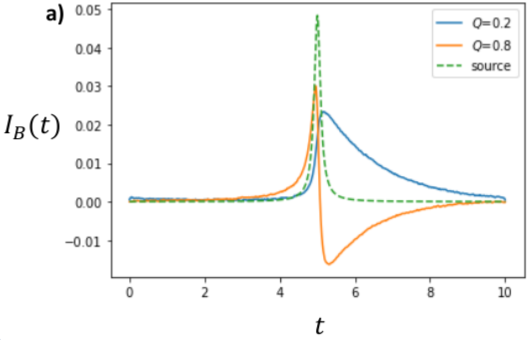
$$\partial_t\,\Delta\phi = -\Gamma\sin(\Delta\phi) + 2\pi\, I_0(t)$$

$$I_B(t) = \frac{\Gamma}{2\pi}\sin(\Delta\phi)$$

Crystallization effect

Incident pulse of integer total Q=3 → oscillating back-scattered current





Commensurability effect:

Incident pulse of generic total Q → relaxes to nearest integer

Coherent semiclassical dynamics robust against quantum fluctuations for sufficiently large m

(no such effects for integer QH state @ m=1 → free fermion propagation along edge)

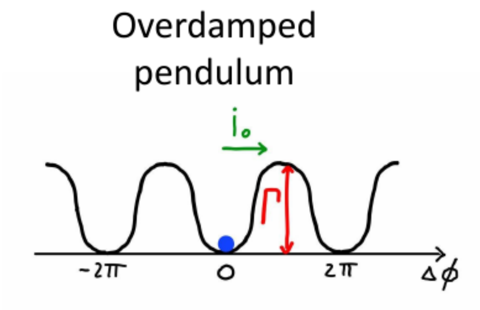
Z. Bacciconi, *Fractional quantum Hall edge dynamics from a quantum optics perspective*, MSc thesis at UniTrento (2021); arXiv:2111.05858

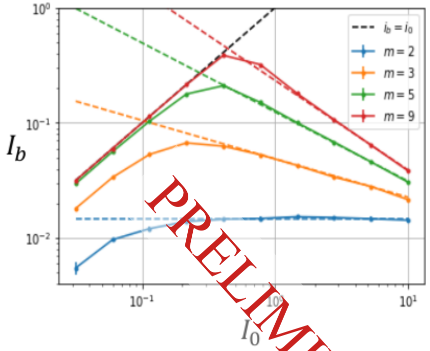
On-going: *Quantum* optics of edge excitations at constriction

Truncated-Wigner description of bosonic χLL: classical noise describes quantum statistics

$$\rho_s(x,t=0)=\sum_{k>0} r_k \alpha_k e^{ikx}+h.c. \qquad I(x,t)=v_F \rho_s(x,t)$$

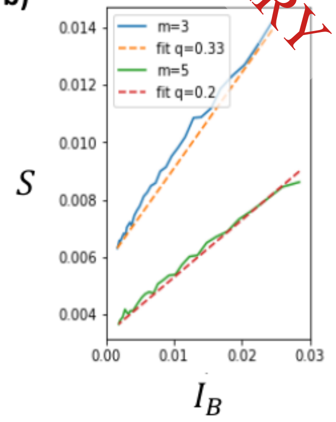
$$\langle \rho_s(0^-,0)\,\rho_s(0^-,t)\rangle \propto -\frac{1}{m t^2}$$





- For weak junction: drift across washboard potential dominates restoring force
    - Back-scattered current $I_B \sim I_0^{-(m-2)/m}$ in agreement with χLL prediction
    - Shot noise S ~ 1 / m fractional charge
    - …
- TWA calculation most accurate for weak junction and large *m*

b)



Quite surprising (at a first thought) that a semiclassical treatment of quantum fluctuations can capture reduced shot-noise due to fractional charges !

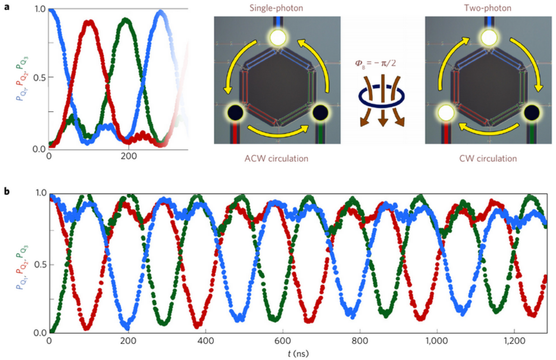
Z. Bacciconi, *Fractional quantum Hall edge dynamics from a quantum optics perspective*, MSc thesis at UniTrento (2021); arXiv:2111.05858

Experimental implementations

Superconductor-based circuit-QED platform

- Time-modulated couplings → synthetic B
- Long-lifetime → lossless coherent evolution
- Independently initialize sites, then follow unitary evolution

Multi-body effect: one-/two-photon state
→ opposite rotation direction

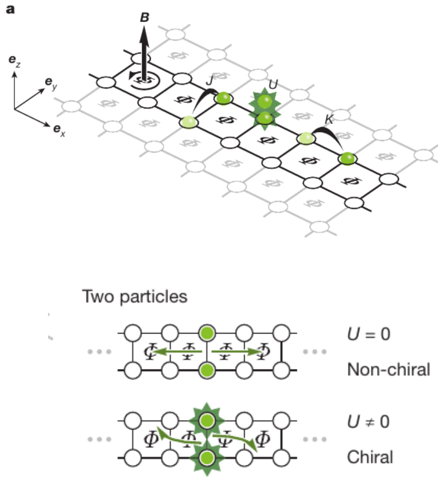


Roushan et al., Nat. Phys. 2016

Ultracold atoms in optical lattice

- Raman-assisted tunneling → synth-B
- Initialize atoms, then unitary dynamics

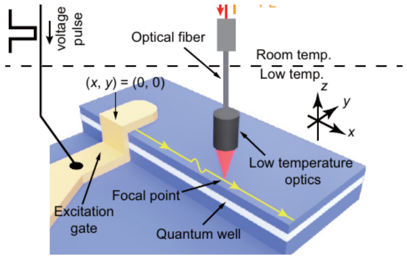
Chiral motion of interacting 2-body state

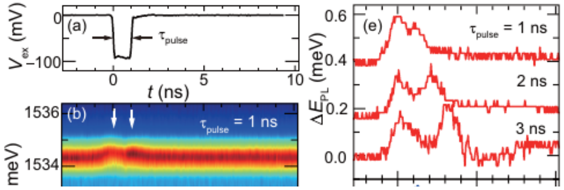


Tai et al., Nature 2017
See also previous talk by Leonard

But also electronic FQH fluids

- Electric injection of edge waves
- Optical detection of edge wave via shift of PL emission





Kamiyama et al.
Phys. Rev. Research (2022)

Other systems, e.g. Rydbergs in twisted cavities → new physics from driving and dissipation → to be explored !

Outlook

Non-equilibrium nature of quantum fluids of light may seem serious hindrance:

- Particle losses → difficult to adiabatically follow ground state
- Steady-state under driving + dissipation ≠ thermal equilibrium state

Taylor non-eq dynamics to reach desired many-body state

- No need for cooling, long-time kinetics does the job
- Wide artillery naturally available in optical systems
  → non-Markovian emitters stabilize MI and FQH fluids

New physics and new questions:

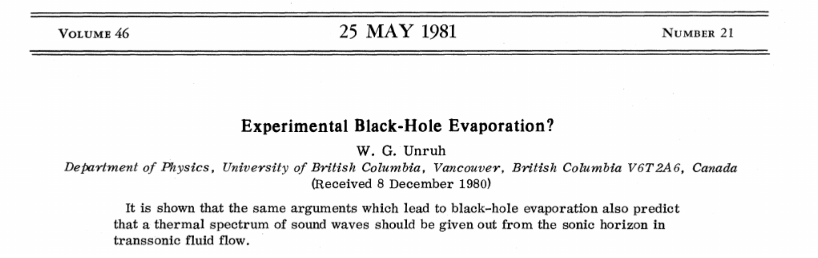
- Coherence of laser/non-eq BEC → KPZ class
  (first expts in J. Bloch's talk)
- Subtle definition of superfluidity

- What are ultimate limits of driven-dissipative schemes?
- Can topological quantum info be robust against losses/pumping?
- Extend nonlinear quantum optics of photons to edge waves of FQH fluid:
  new effects from underlying anyonic statistics?

Extend *quantum simulation* concept

- Focus on physical effects more than on precise mathematical equivalence
- Adding new ingredients facilitates observing and understanding desired physics
- Opens the way to new exciting physics
- Concept of "analogy" goes further and deeper than "simulation":
  bidirectional transfer same physical concepts to different contexts !

Analog models ~ quantum simulators of curved space-time QFTs



VOLUME 46 25 MAY 1981 NUMBER 21

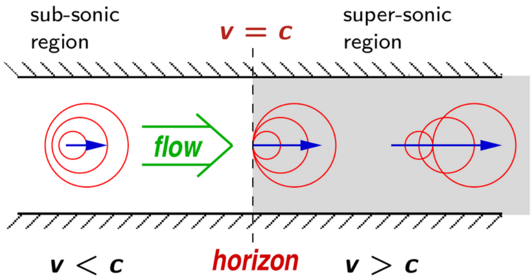
Experimental Black-Hole Evaporation?

W. G. Unruh

Department of Physics, University of British Columbia, Vancouver, British Columbia V6T 2A6, Canada

(Received 8 December 1980)

It is shown that the same arguments which lead to black-hole evaporation also predict that a thermal spectrum of sound waves should be given out from the sonic horizon in transsonic fluid flow.



Propagation of low-k sound waves in BECs equivalent to curved space-time KG eq.

$$\frac{1}{\sqrt{-G}}\,\partial_\mu\left[\sqrt{-G}\,G^{\mu\nu}\partial_\nu\right]\phi(x,t)=0$$

With exciting additional physics:

- superluminal corrections,
- wide variety of space-time metrics, ...

Stimulating bidirectional exchange of ideas and results between gravitation and cond-mat physics

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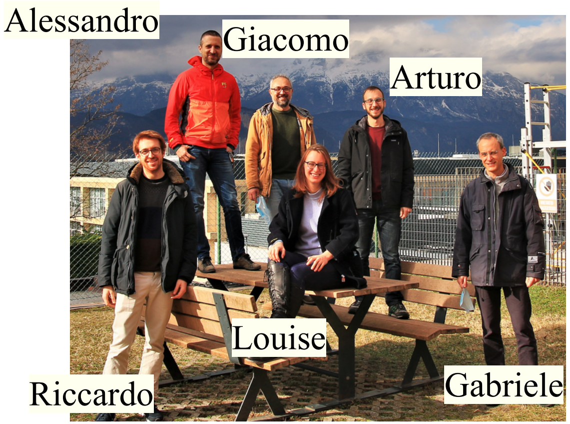
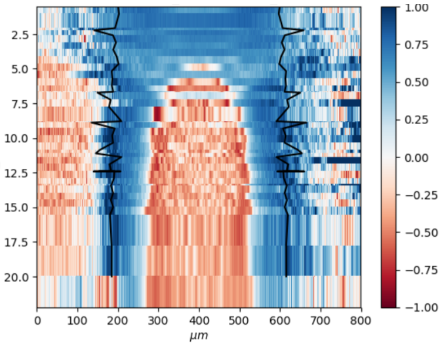
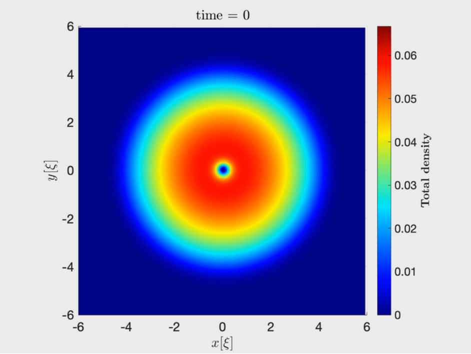
Trento experimental team

→ spin waves in 2-component BECs





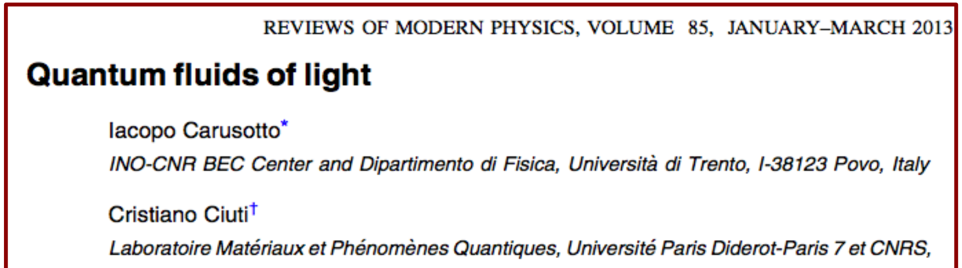
On-going work: bubble-mediated decay of metastable state @ 1st order phase trans.
→ false vacuum decay in cosmology



Next challenge: q=1-spin-vortex unstable
→ ergoregion instability of massive star
(A. Berti-IC, in preparation)

If you wish to know more...

BOSE EINSTEIN CONDENSATION


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

Quantum fluids of light

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INO-CNR BEC Center and Dipartimento di Fisica, Università di Trento, I-38123 Povo, Italy

Cristiano Ciuti†
Laboratoire Matériaux et Phénomènes Quantiques, Université Paris Diderot-Paris 7 et CNRS,

I. Carusotto, C. Ciuti, Rev. Mod. Phys. **85**, 299 (2013)


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PhD positions available

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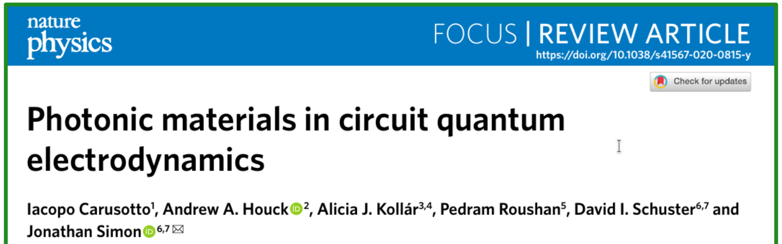
nature physics

FOCUS | REVIEW ARTICLE
https://doi.org/10.1038/s41567-020-0815-y

Check for updates

Photonic materials in circuit quantum electrodynamics

Iacopo Carusotto[1], Andrew A. Houck[2], Alicia J. Kollár[3,4], Pedram Roushan[5], David I. Schuster[6,7] and Jonathan Simon[6,7]

Review article on Nature Physics (2020)


REVIEWS OF MODERN PHYSICS, VOLUME 91

Topological photonics

Ozawa, Price, Amo, Goldman, Hafezi, Lu, Rechtsman, Schuster, Simon, Zilberberg, IC, RMP **91**, 015006 (2019)

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PhoQuS
Photons for Quantum Simulation


Non-equilibrium Bose–Einstein condensation in photonic systems

Jacqueline Bloch[1], Iacopo Carusotto[2] and Michiel Wouters[3]

Review article on Nat. Rev. Phys. (2022)