BEC
BOSE EINSTEIN CONDENSATION

Quantum fluids of light as a platform for non-equilibrium statistical mechanics

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Why is light different from matter ?

Matter is composed by a huge number of atoms

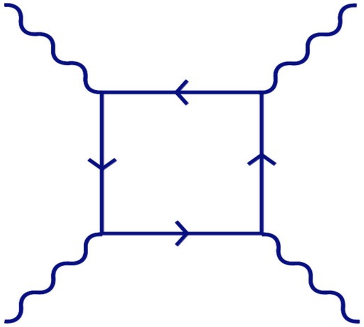
Light beam composed by a huge number of photons

- 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

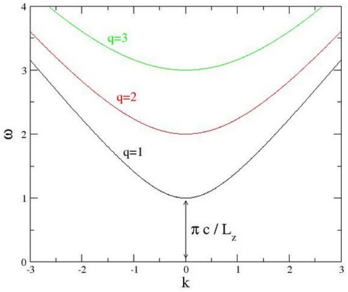
optics in vacuo typically dominated by single-particle physics

In suitable photonic structures:

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



Collective behaviour of *quantum fluid of light*

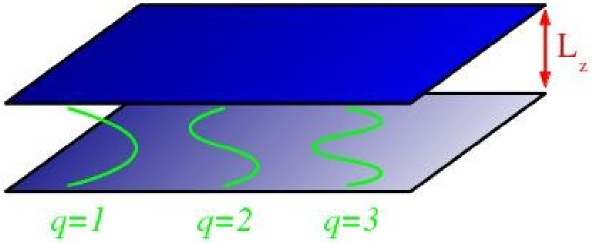


IC-Ciuti, *Quantum Fluids of Light*, RMP **85**, 299 (2013)

What about mass?

In vacuo: photons massless, dispersion $\omega = c\,|k|$

In planar cavity → confinement along *z*, free propagation along *x,y*



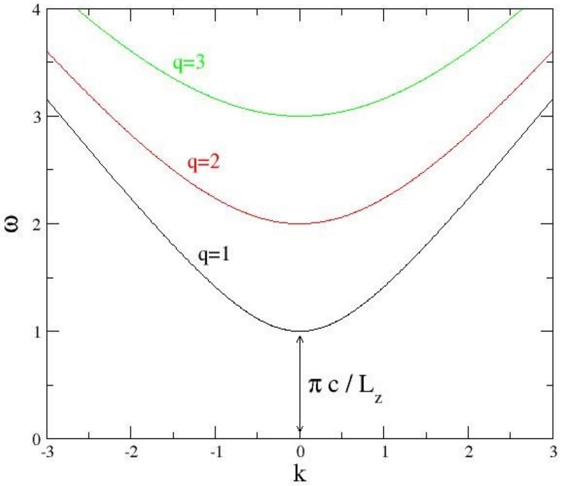
Quantization along *z*: $k_z^{(q)} = q\,\pi / L_z$

Massive dispersion along *x,y*:

$$\omega^{(q)}(\mathbf{k}_\parallel) = c\sqrt{[k_z^{(q)}]^2 + \mathbf{k}_\parallel^2} = c\sqrt{\left(\frac{q\pi}{L_z}\right)^2 + \mathbf{k}_\parallel^2} \simeq ck_z^{(q)} + \frac{c}{2k_z^{(q)}}\mathbf{k}_\parallel^2$$

Confinement gives effective photon mass $m_{ph}c^2 = \hbar c k_z^o$

- Rest mass → cut-off in the dispersion
- Inertial mass → curvature of dispersion



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

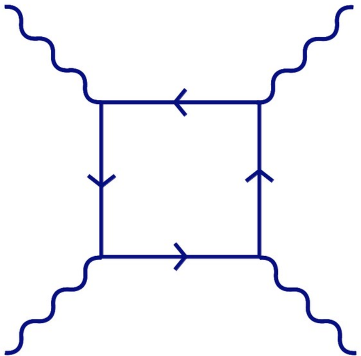
What about interactions?

Photon-photon interactions exist in QED:

Heisenberg-Euler processes via electron-positron exchange

… but cross section ridiculously small for visible light

(recent experiment in accelerator → Nat. Phys. 2017)



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

Compton λ → pm range

How to enhance it ?

Replace electron-positron pair (E ~ 1 MeV) with

electron-hole pair (E ~ 1 eV) → huge gain factor $(10^6)^6 = 10^{36}$!!

In optical language:

- $\chi^{(3)}$ nonlinearity ↔ local photon-photon interactions
- typical material → spatially local (or quasi-local) $\chi^{(3)}$

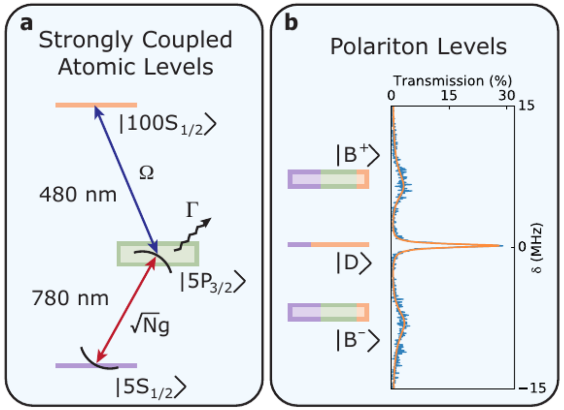
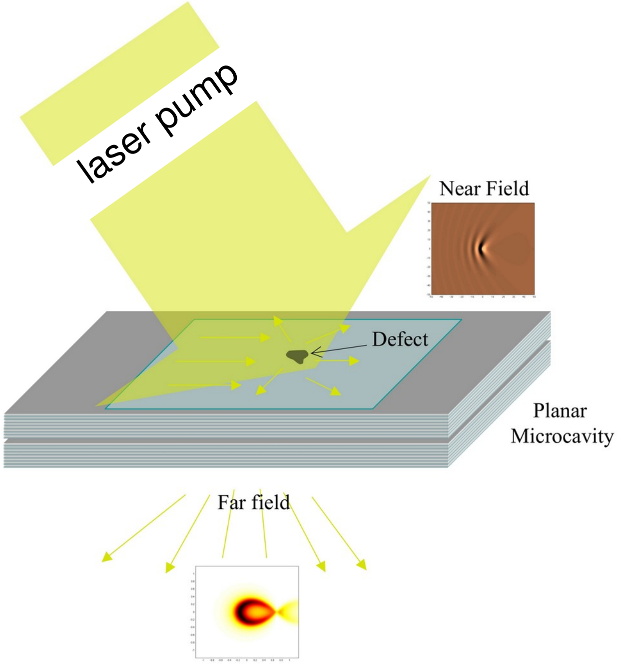


Figure: J. Simon's group @ U. Chicago

Modern exceptional media:

- Rydberg atoms
  - Ultra-large, long-range nonlinearity in Rydberg-EIT config.
- Superconducting circuits
  - Strong coupling to macroscopic oscillation mode of superconductor device

How to create and detect the photon gas?



Pump needed to compensate losses due to finite photon lifetime:
stationary state is NOT thermodynamical equilibrium

Turn a bug into a feature → Many different pumping schemes available:

- Coherent laser pump: directly injects photon BEC in cavity
- Incoherent (optical or electric) pump: BEC transition similar to laser threshold
- Exotic frequency-dependent incoherent pump → strongly correlated states

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

Mean-field theory: generalized GPE

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

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

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

→ a sort of Complex Landau-Ginzburg equation

To go beyond mean-field theory:

- Exact diagonalization, Wigner representation, Keldysh diagrams, ...

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

Part 1:

Non-Equilibrium condensation

2006 - Non-equilibrium Bose-Einstein condensation

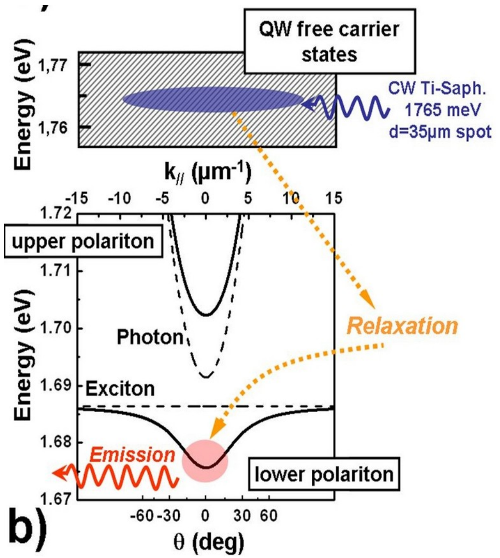
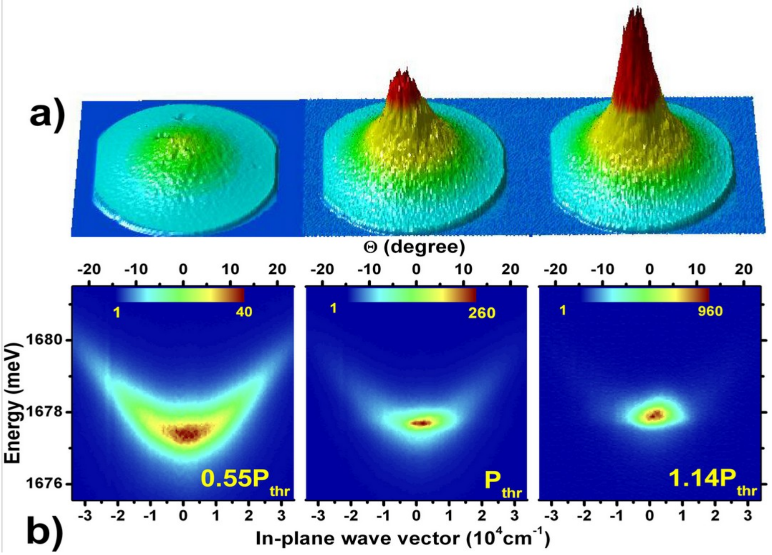
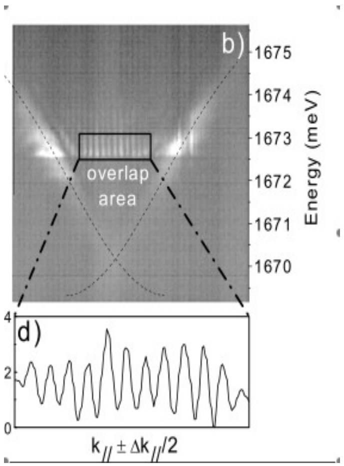


Figure from Kasprzak et al., Nature 2006



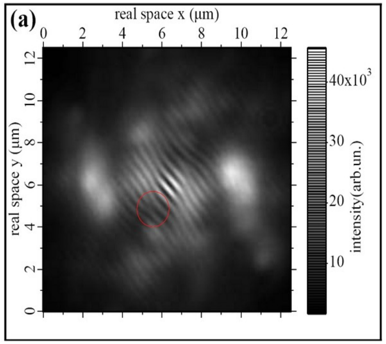
Momentum distribution

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



Interference

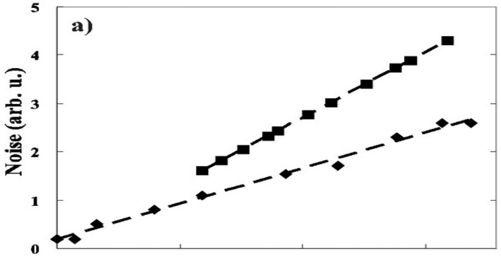
Richard et al., PRL **94**, 187401 (2005)



Quantized vortices

K. Lagoudakis *et al.*

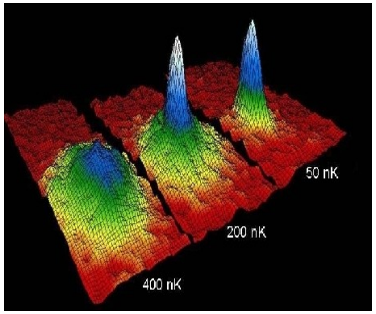
Nature Physics 4, 706 (2008).



Suppressed fluctuations

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

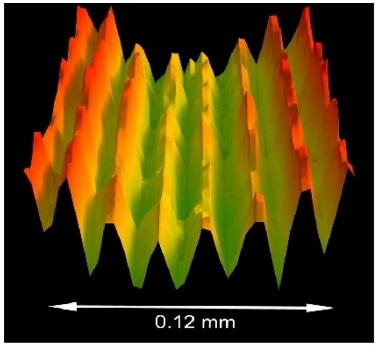
Many features very similar to atomic BEC



The first atomic BEC

M. H. Anderson et al.

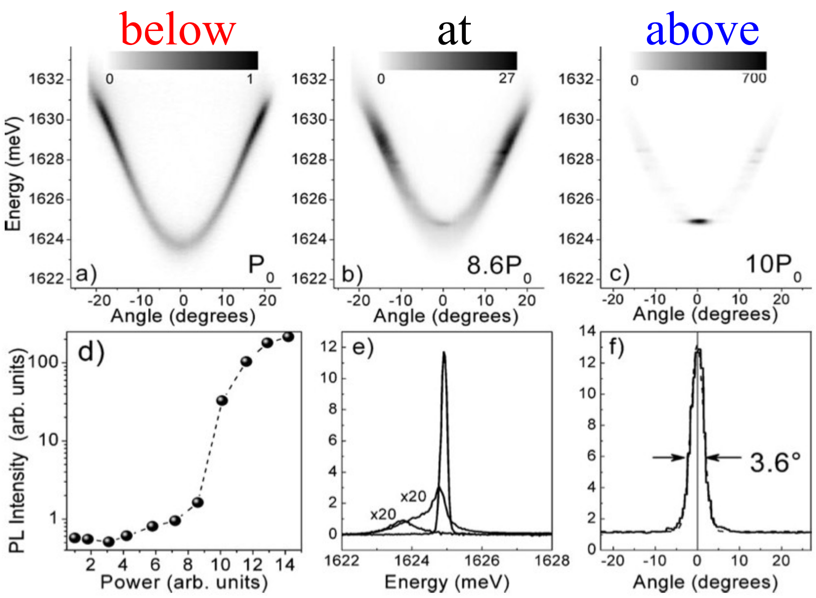
Science **269**, 198 (1995)



Interference pattern of two expanding atomic BECs

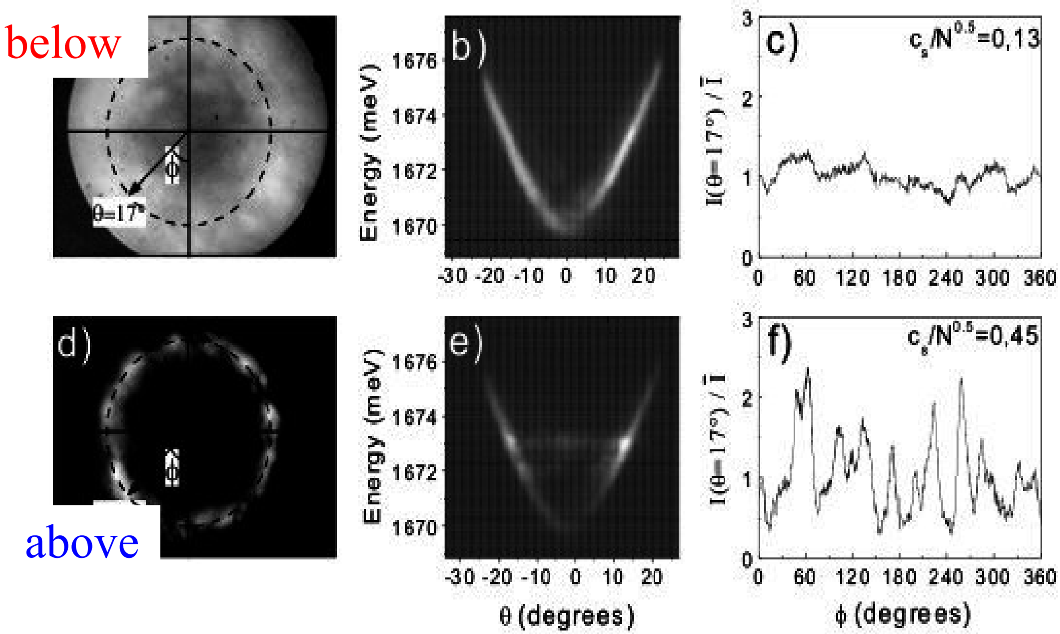
M. R. Andrews, Science **275**, 637 (1995)

~~The devil~~ The physicist is in the details: the shape of a non-equilibrium condensate



wide pump spot: 20 µm

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



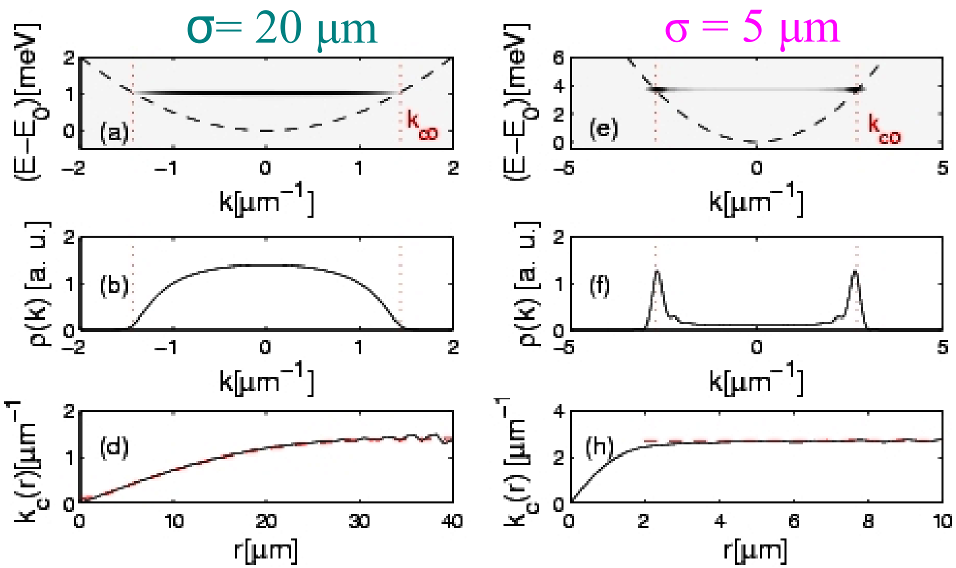
narrow pump spot: 3 µm

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

Experimental observations under non-resonant pump:

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

Physical interpretation of condensation at k≠0



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

Repulsive interactions

- outward radial acceleration
- energy conservation

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

→ radially increasing flow velocity

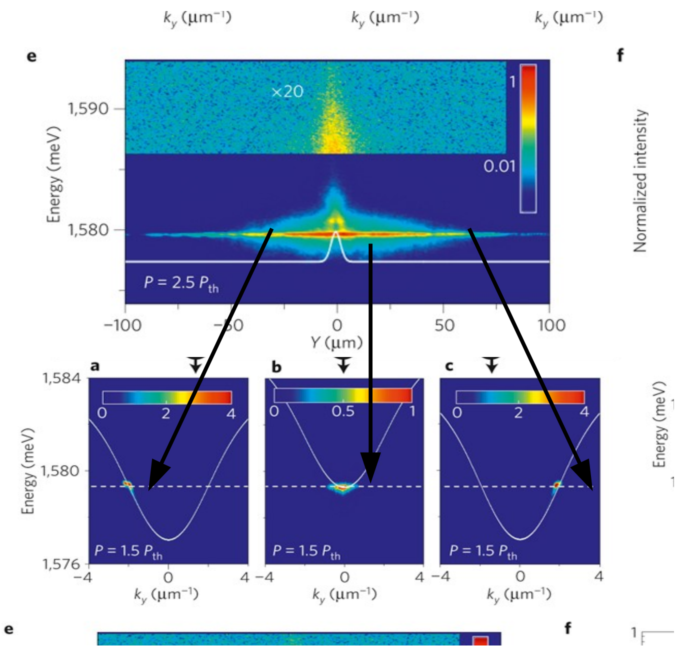
→ coherent ballistic flow

Narrow spot:

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

Later expts confirm mechanism →

(J. Bloch's group @ LPN in 1D)



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

T-reversal breaking:

- allowed by non-equilibrium
- allows for non-zero current
- also visible as n(k) ≠ n(-k)

Low-d effects: quasi-BEC → Jacqueline's talk

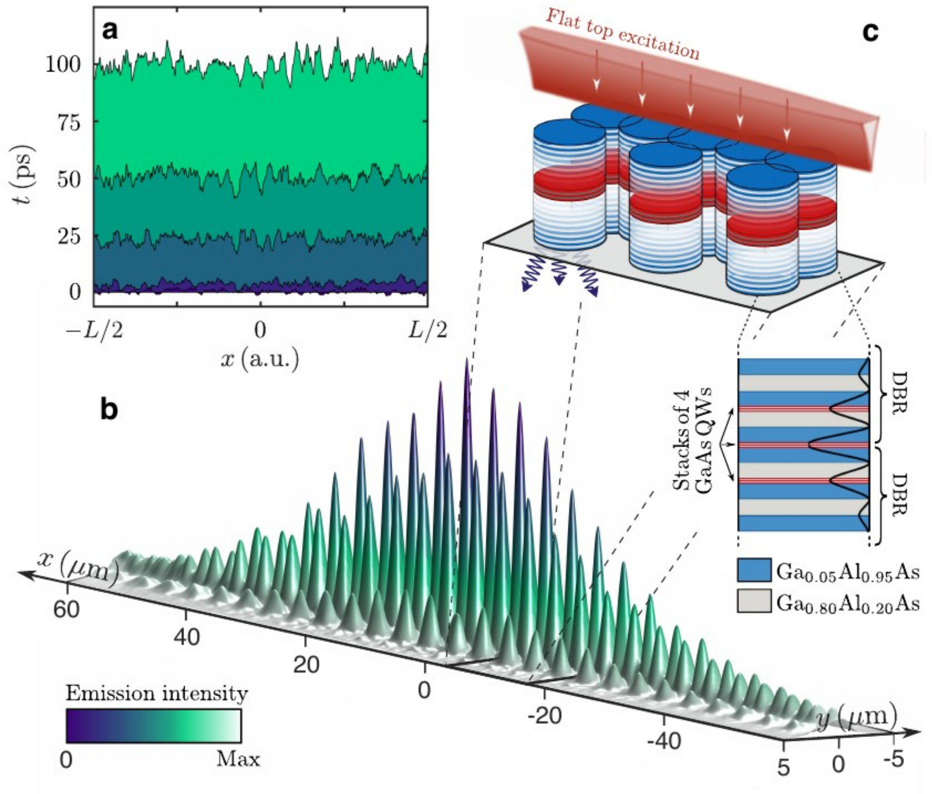
Quasi-condensation features:

Hohenberg-Mermin-Wagner theorem:

- at equilibrium, no BEC in d<3

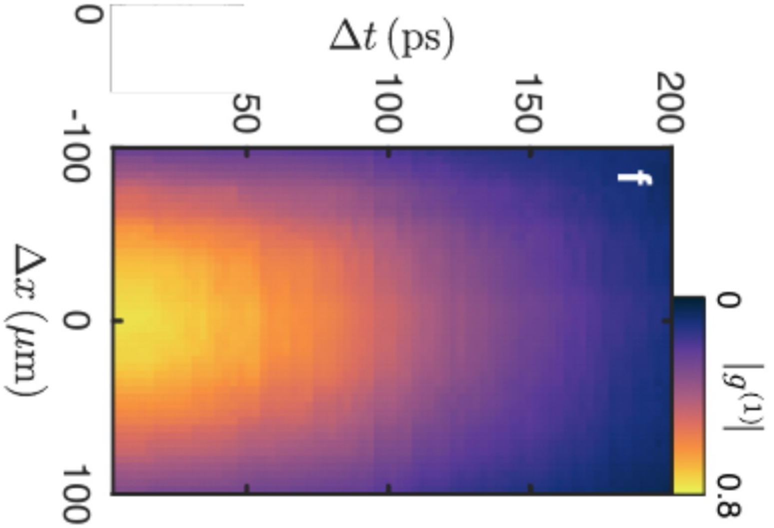
Non-equilibrium condensation or lasing:

- no BEC in 1D: exponential decay of $g^{(1)}(x)$
  (Graham-Haken, 1970; Wouters-IC, PRB 2006)
- debate in 2D: KPZ nonlin. destroy BKT phase?
  (Dagvadorj et al., PRX 2015; Altman et al., PRX 2015;
  Zamora et al., PRX 2017)



Experiment @ C2N Palaiseau:

- 1D lattice with array of semiconductor micropillars
- measure space-time coherence function $g^{(1)}(\Delta x,\Delta t)$
- Coherence only in limited space/time,
  then smoothly decays → quasi-BEC effect



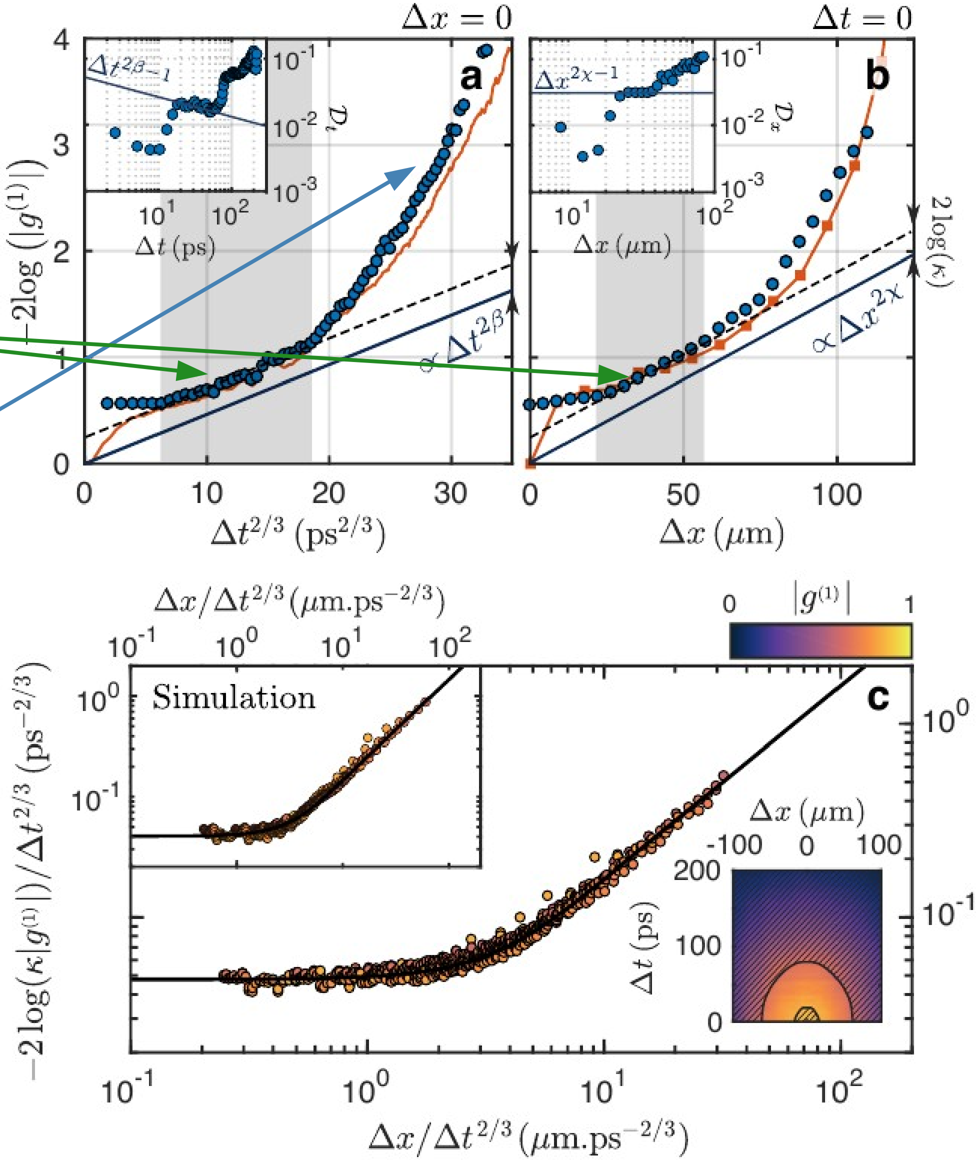
Fontaine, Squizzato, Baboux, Amelio, Lemaître, Morassi, Sagnes,
Le Gratiet, Harouri, Wouters, IC, Amo, Richard, Minguzzi, Canet,
Ravets, Bloch, *Observation of KPZ universal scaling in a*
1D polariton condensate, Nature 2022

KPZ universality features

Power laws in the decay of $g^{(1)}(\Delta x,\Delta t)$

KPZ exponent

Schawlow-Townes-like decay



Collapse of cuts of $g^{(1)}(\Delta x,\Delta t)$
on Kardar-Parisi-Zhang universal curve

→ Quasi-BEC dynamics involves non-equilibrium effects &
interactions between Bogoliubov excitations

Fontaine et al., *Observation of KPZ universal scaling in a 1D polariton condensate*, Nature 2022

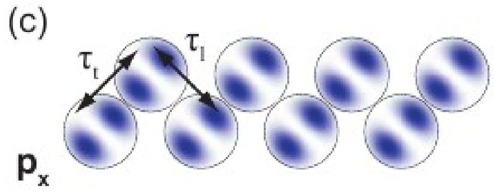
Part 1bis:

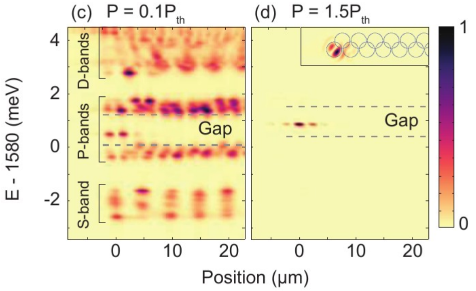
Condensation + Topology = ?

2017 - Topological lasing

a.k.a. non-equilibrium BEC in a topological edge state

In other words: what happens if gain added to topological photonics model ?



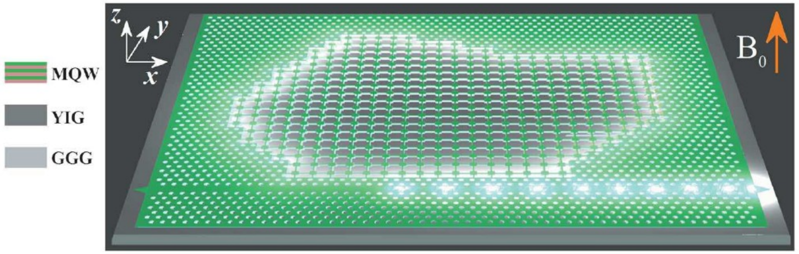


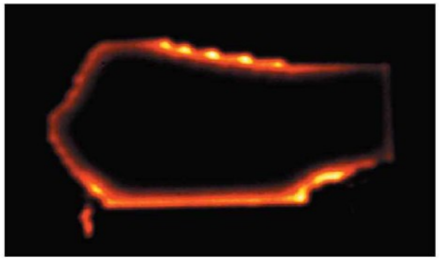
St. Jean, et al., Nat. Phot. '17

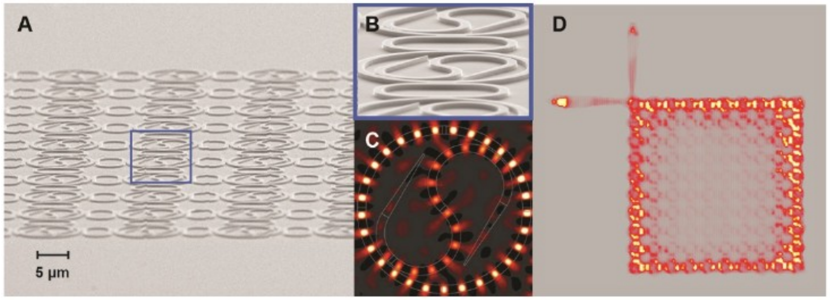
System: 1D SSH array of micropillar cavities for exciton-polaritons under incoherent pump

Bahari et al., Science 2017

System: 2D photonic crystal slab, amplification by QWs, magnetic field to break T







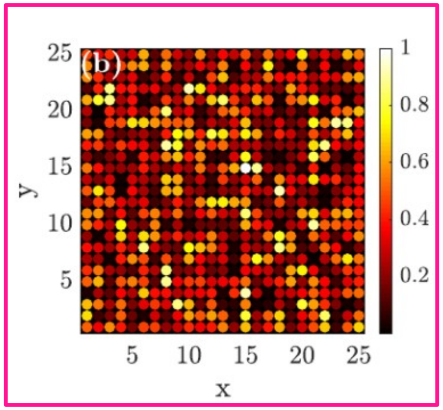
Bandres et al., Science 2018

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

Early theoretical work by Conti & Pilozzi, Solnyshkov, Nalitov & Malpuech...
Other expts: Khajavikhan's group, PRL 2018; Klembt et al., Nature 2018; Dikopoltsev et al. Science 2021,…

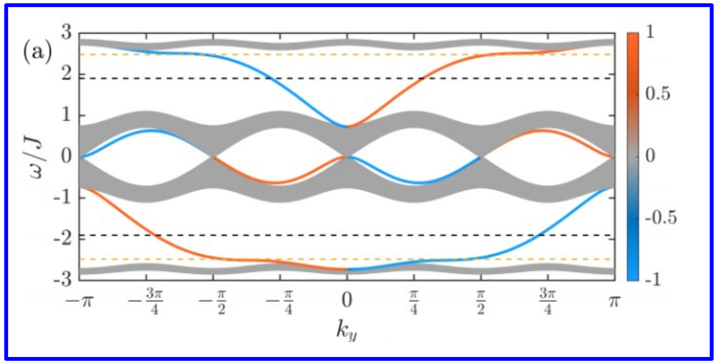
What new physics in these systems? What technological applications?

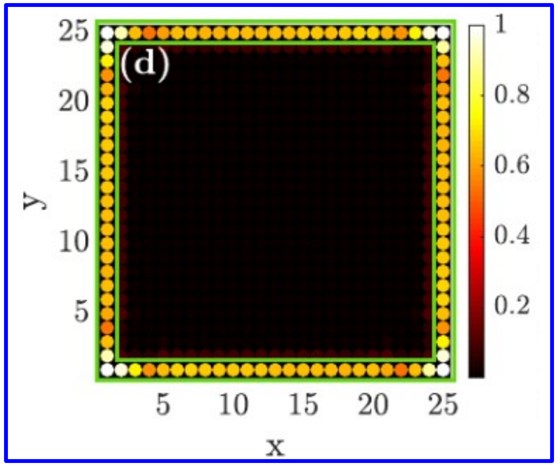
Topological lasing in 2D models: why interesting?



Topologically trivial system:

- pumping many cavities gives complicate many-mode emission because of unavoidable fabrication disorder
- hard to preserve coherence and fully exploit gain
- serious technological problem for high-power semiconductor laser applications





Topological system:

- Non-trivial band topology
  → chiral edge states, unidirectionally propagating around (finite) system
- 2D Topolaser operation into edge mode when edge only is pumped (WEG)
- Chiral motion → phase locks many sites

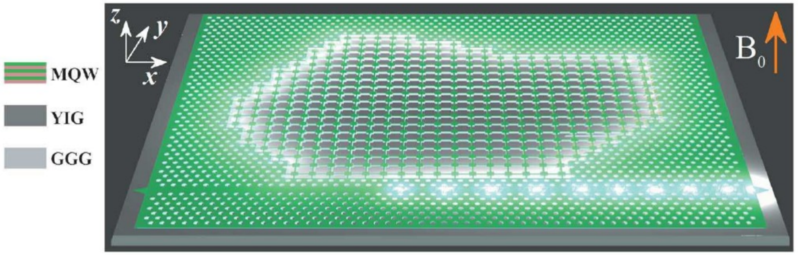
First proposal of topological photonics: Haldane & Raghu, 2006.
First expt: Wang et al., Nature 2009 (Soljacic's group @ MIT)

Figures from M. Seclì's Msc thesis @ UniTN, 2017 and Seclì *et al.*, Phys. Rev. Research 2019
See also: Harari et al., Science 2018.

Coherence of topolaser emission (I)

Important fundamental & applied questions:

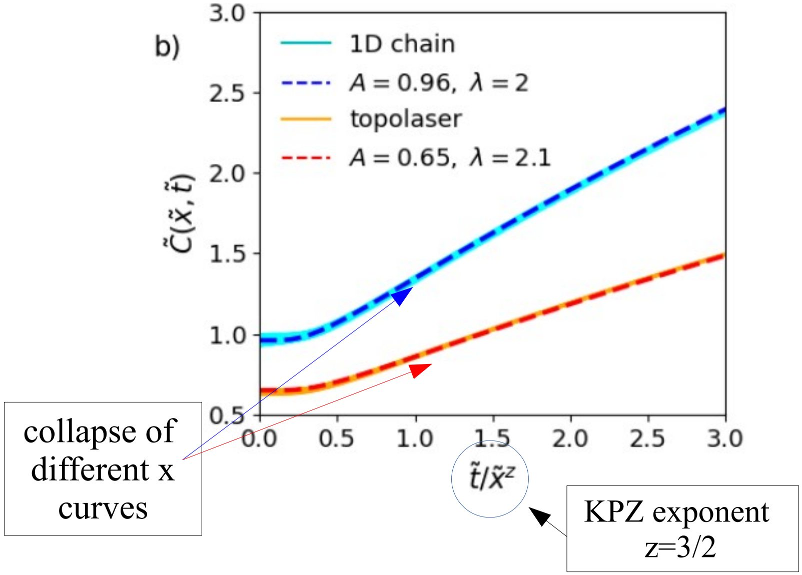
- What are ultimate limitations of coherence?
- How robust is coherence to disorder?
- What advantage over standard lasers?



Laser operation in spatially extended system:

- Linearized theory not enough, crucial role of nonlinearities
- Kardar-Parisi-Zhang model of non-equilibrium stat mech
  (Canet/Minguzzi, Altman/Diehl, Gladilin/Wouters)
- spatio-temporal scaling properties of phase-coherence

$$\tilde{C}(\tilde{t}, \tilde{x}^z) \equiv -2(\phi^*)^{-2}\tilde{x}^{-2\chi}\log g^{(1)}_{\mathrm{CM}}(\tilde{x},\tilde{t})$$



collapse of different x curves

KPZ exponent z=3/2

Topological laser:

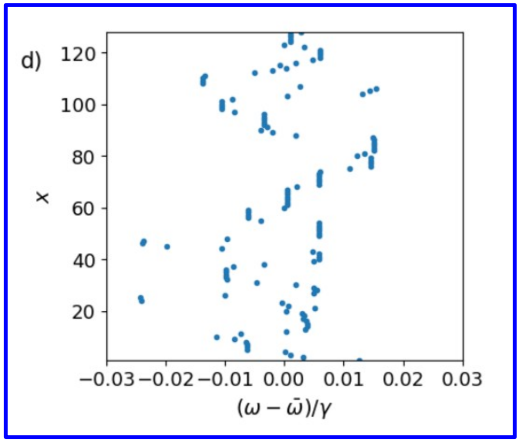
- One-dimensional edge state gives effective 1D dynamics
- KPZ spatio-temporal scaling of $g^{(1)}(x,t)$
- Most promising for experiments → periodic boundary conditions

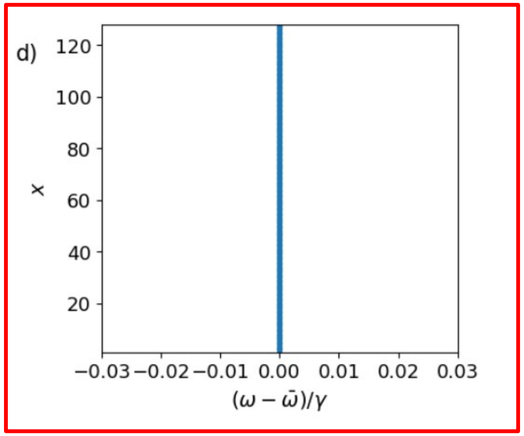
Closely related to polariton quasi-BECs @ C2N

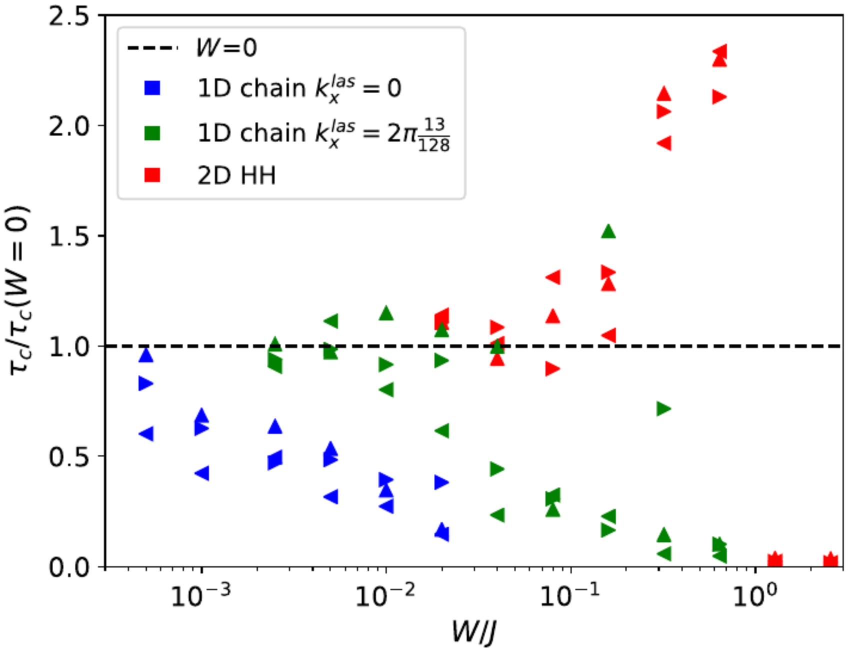
Q. Fontaine et al., Nature 2022

I. Amelio and IC, PRX 10, 041060 (2020)

Coherence of topolaser emission (II)







In the presence of static disorder:

- Non-Topological: weak disorder suppresses temporal coherence (mode fragmentation, multimode emission, localization, etc.)
- Topological: robust spatio-temporal coherence, chiral propagation travels through/around defects without backscattering.

Technologically important in (semiconductor) laser technology:

Allows to phase lock many individual lasers → strong intensity and high coherence

Next steps: extend theory to Class-B lasers. Control instabilities and maintain single-mode emission

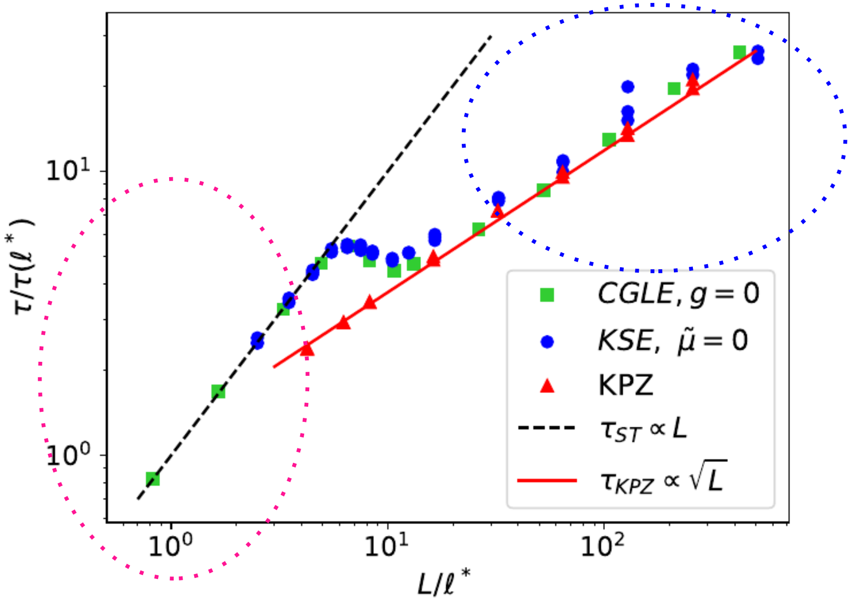
Fundamental question → effect of convective/absolute instability on coherence properties

I. Amelio and IC, *Theory of the coherence of topological lasers*, PRX 10, 041060 (2020)

Beyond Schawlow-Townes linewidth

Basic laser theory:

- single mode approximation → phase diffusion
- diffusion rate ~ 1/N$_{\text{phot}}$
  → Schawlow-Townes linewidth (with Henry factor)



Spatially extended, yet small device:

- many modes available for fluctuation dynamics
- linear Bogoliubov regime
  → fluctuation modes decoupled from each other
- only global phase matters → ST linewidth ~N$_{\text{phot}}$

Spatially large device:

- Fluctuations grow large in IR sector (smaller restoring force)
- Fluctuation modes coupled by KPZ-nonlinear terms

$$\partial_t\phi = \frac{1}{2m}\left[-\frac{\Gamma^{-1}}{2m}\partial_x^4\phi + \alpha\partial_x^2\phi - (\partial_x\phi)^2\right] + \sqrt{\frac{D(1+\alpha^2)}{n_0}}\xi_1$$

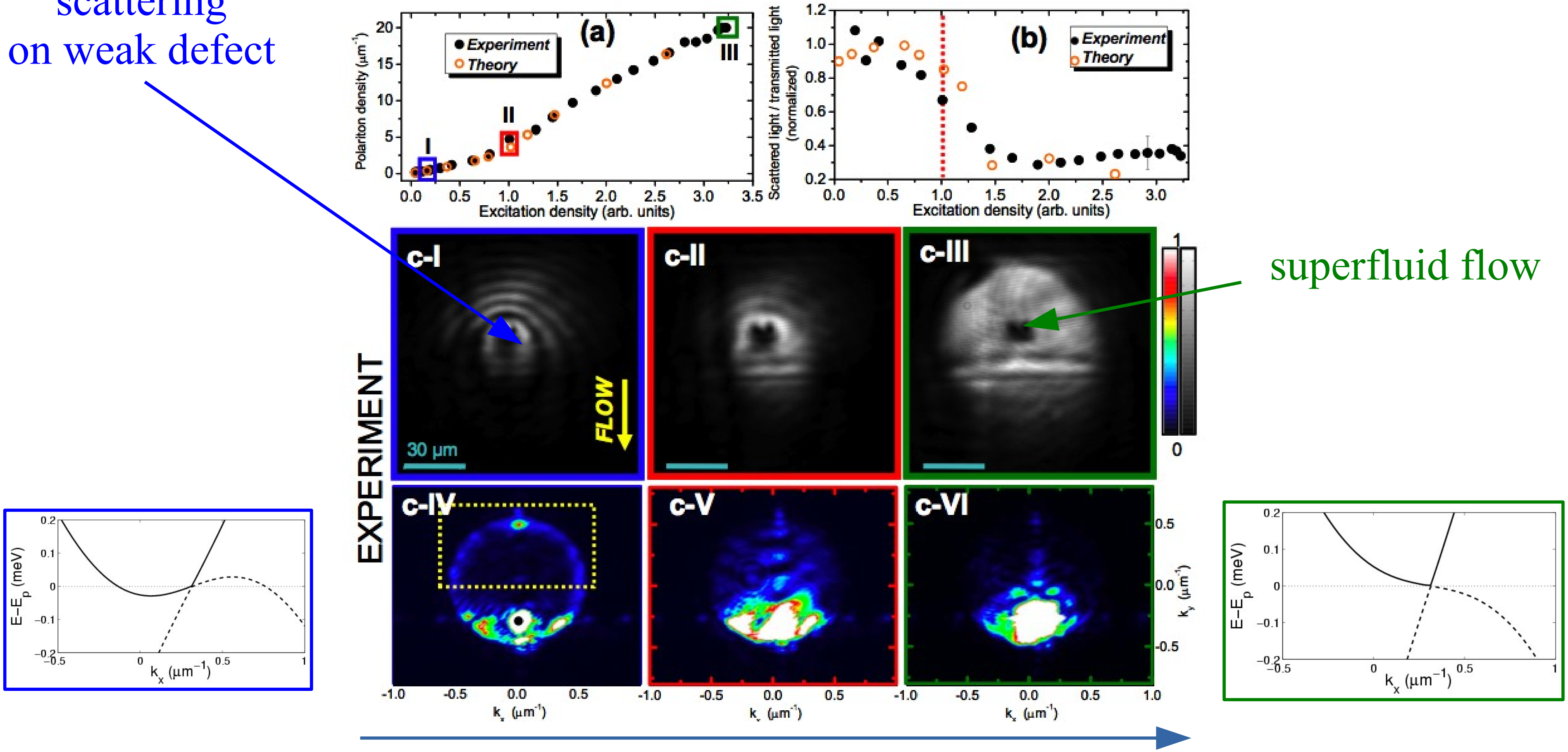
- Bogoliubov modes renormalized → different scaling of linewidth ~(N$_{\text{phot}}$)$^{1/2}$

I. Amelio, A. Chiocchetta, IC, *Kardar-Parisi-Zhang universality in the linewidth of non-equilibrium 1D Quasi-condensates*, PRE (2023)

Part 2:

Superfluidity & collective excitation modes

2008 - Superfluid light (under coherent pump)



scattering
on weak defect

superfluid flow

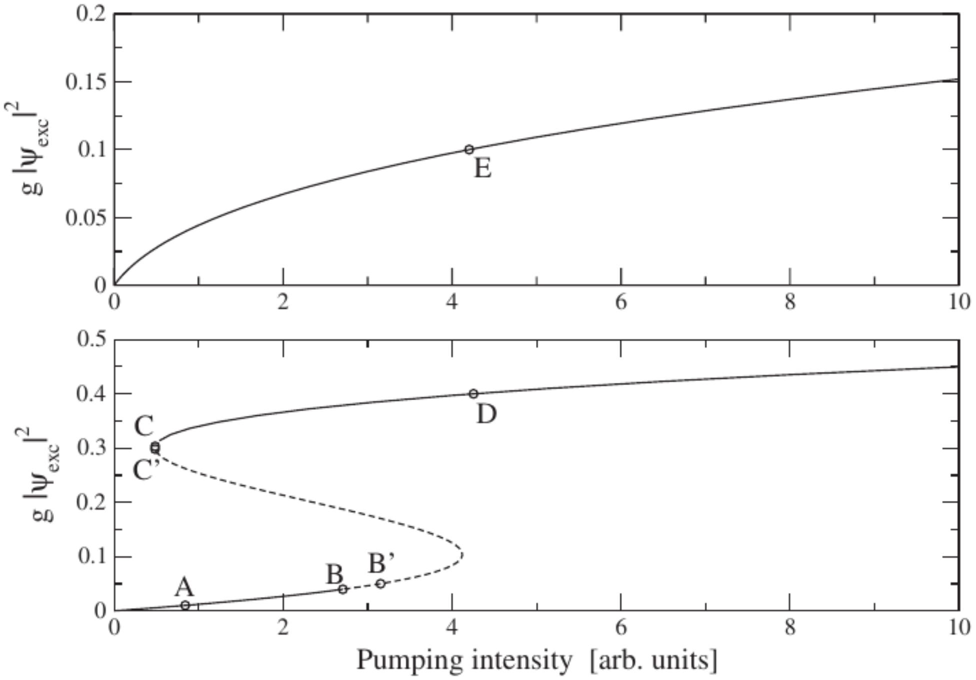
increase polariton density

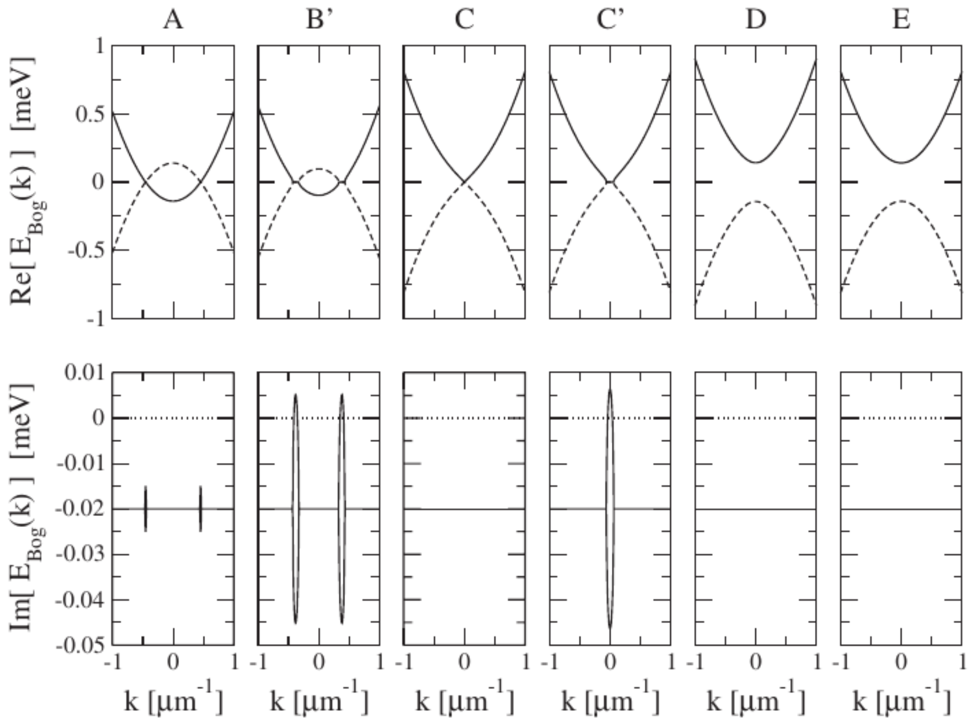
Figure from LKB-P6 group:
A.Amo, J. Lefrère, S.Pigeon, C.Adrados, C.Ciuti, IC, R. Houdré, E.Giacobino, A.Bramati, *Observation of Superfluidity of Polaritons in Semiconductor Microcavities*, Nature Phys. **5**, 805 (2009)

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

Very non-trivial collective excitation modes - theory

Under a coherent pump:





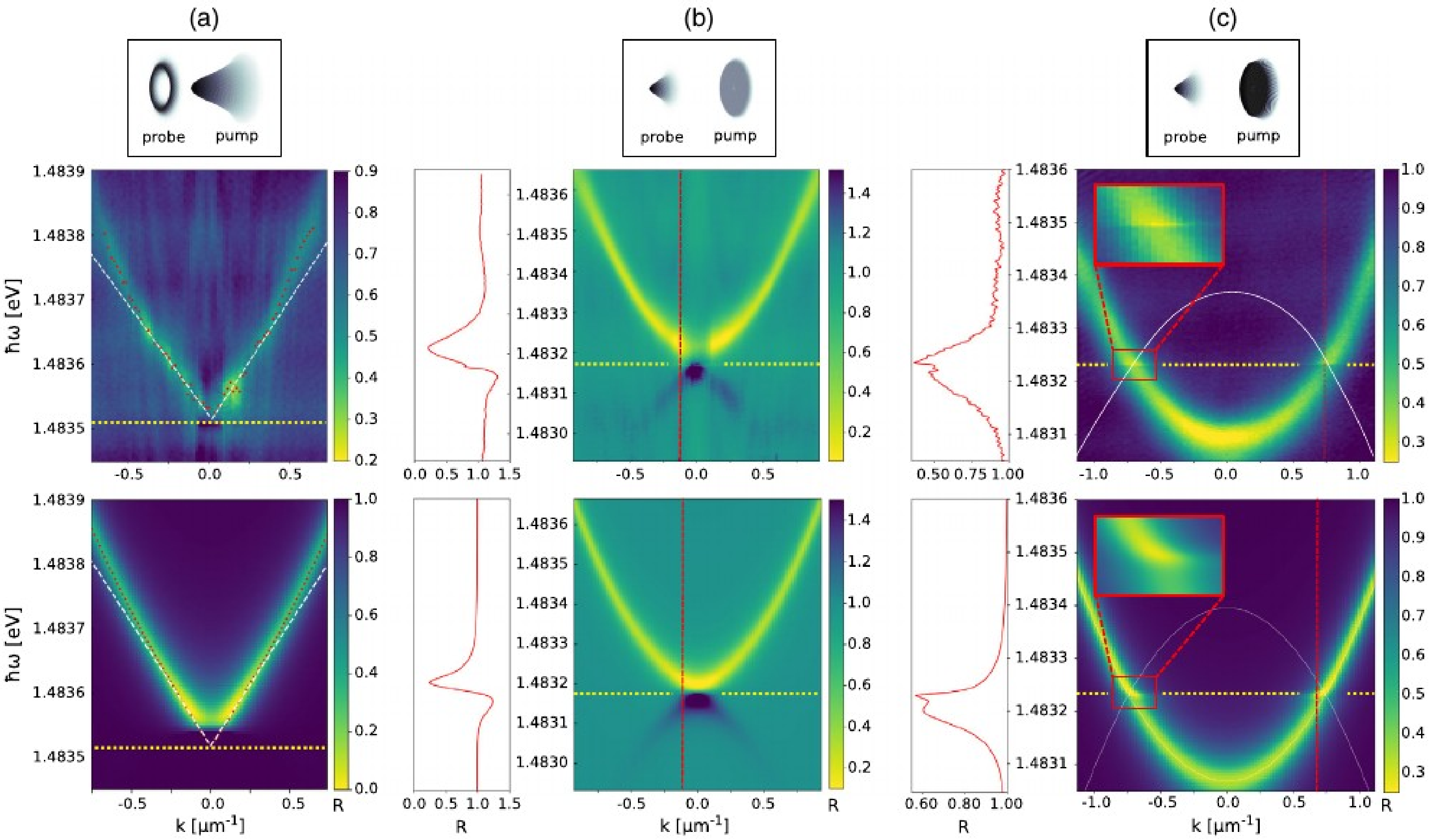
Depending on detuning / interaction energy, different regimes: gapless, gapped, dynamically unstable…

Physically: in contrast to equilibrium, GPE oscillation frequency fixed by pump, not by interaction energy

$$i\frac{d\,\psi}{dt}=\left\{\omega_o-\frac{\hbar\nabla^2}{2m}+V_{ext}+g\,|\psi|^2\right\}\psi+F_{ext}\,e^{-i\,\omega_p t}$$

IC and C. Ciuti, PRL **93**, 166401 (2004); RMP **85**, 299 (2013)

Experiment @ LKB under coherent pump



Sonic dispersion

Small gap + ghost branch

Precursor of instability

Collective excitation modes → peak in (k,ω) transmittivity of weak probe

Claude, Jacquet… IC … Glorieux, *High-Resolution Coherent Probe Spectroscopy of a Polariton Quantum Fluid,* PRL **129**, 103601 (2022)

Part 2bis:

Goldstone mode of a condensate

Sound in photon BECs: non-equilibrium effects

Polariton BEC regime under incoherent pump (i.e. polariton lasing)

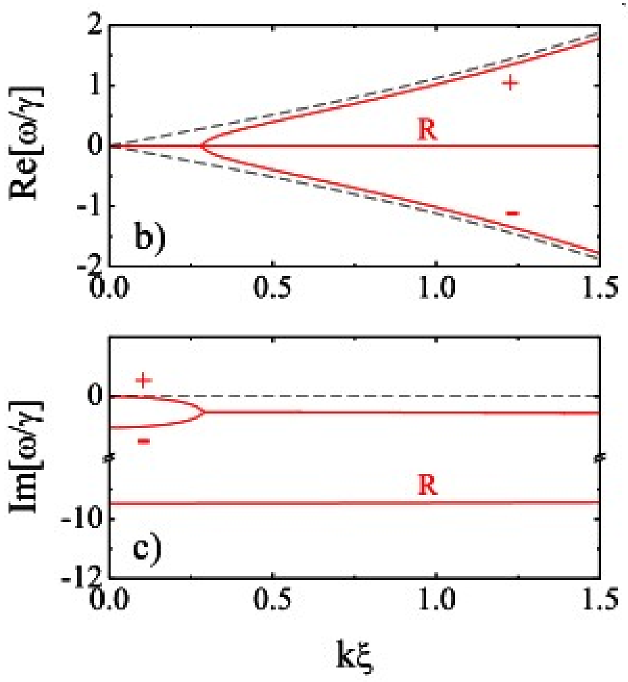
Linearize GPE around steady state

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

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

with:

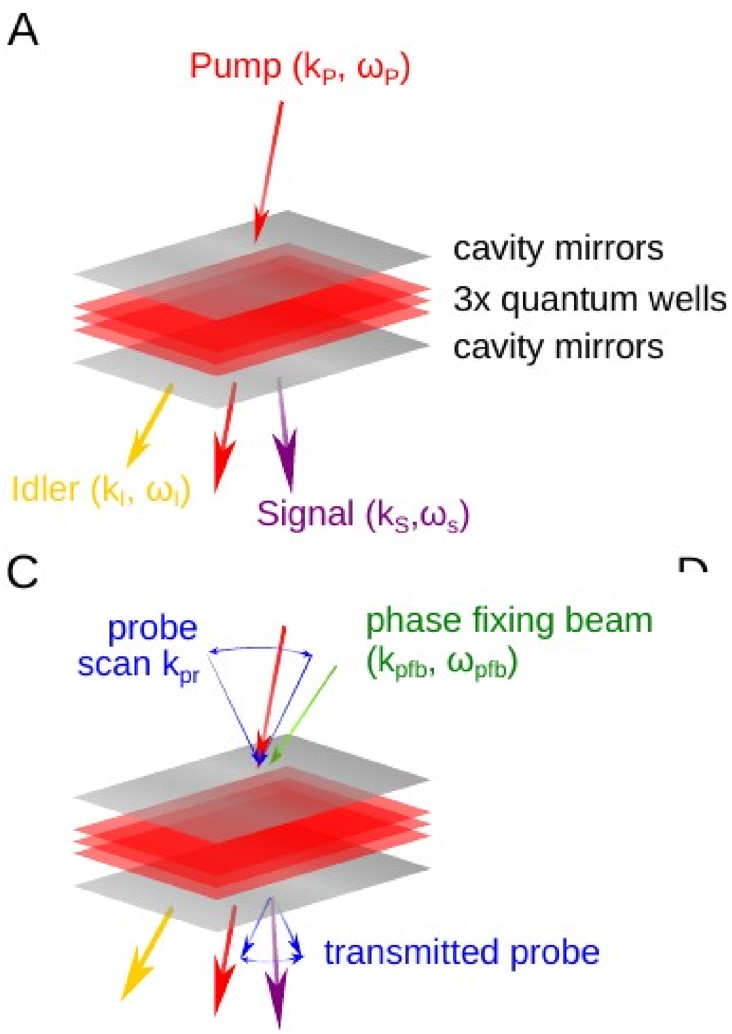
$$\omega_{Bog}(k) = \sqrt{\frac{\hbar k^2}{2m_{LP}}\left(\frac{\hbar k^2}{2m_{LP}} + 2\,\mu\right)}$$

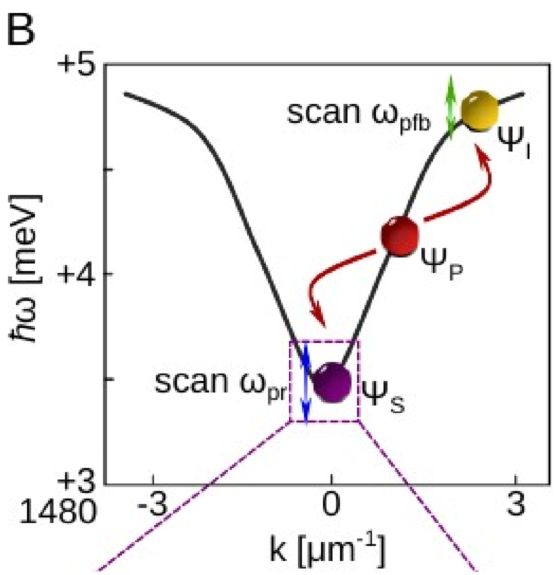


- density (-) and phase (+) oscillations decoupled around k=0
- Goldstone mode (+) associated to U(1) symmetry breaking is diffusive

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)
Experiment @ LKB: Claude, Jacquet… arXiv:2310.11903 (Bramati, Glorieux, Giacobino's group)

Experimental observation @ LKB (I)





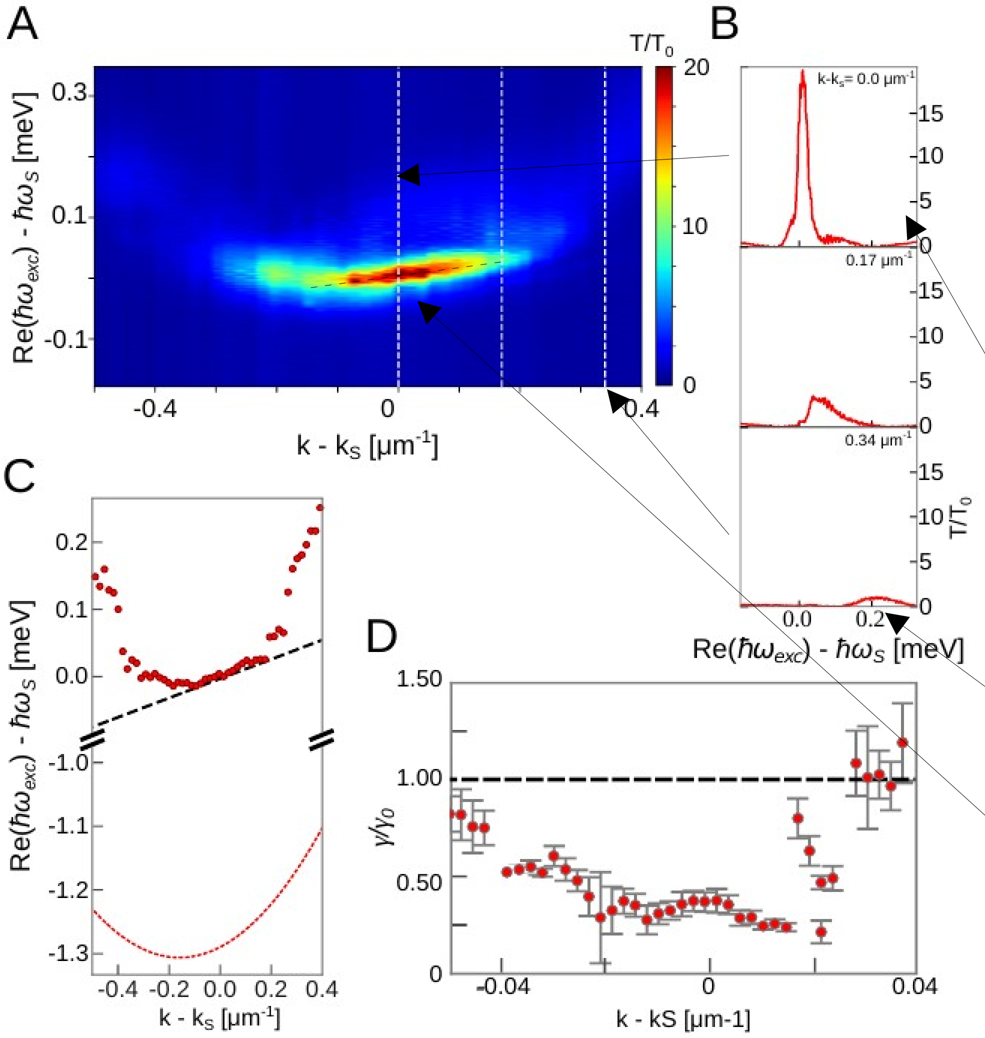
OPO (Optical Parametric Oscillator) condensation:

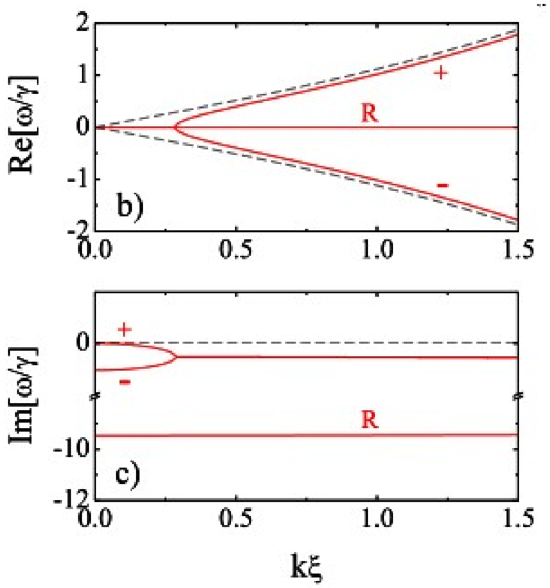
- Pair of pump photons scatter into signal/idler modes
- Above threshold: stimulated process,
  signal/idler get coherent
- Usual U(1) symmetry breaking

- Collective modes → peak in probe transmission
- Condensate phase locked with phase fixing beam
- Condensate @ finite v → easier spectroscopy

Claude et al. , *Observation of the diffusive Nambu-Goldstone mode of a non-equilibrium phase transition*, arXiv:2310.11903

Experimental observation @ LKB (II)



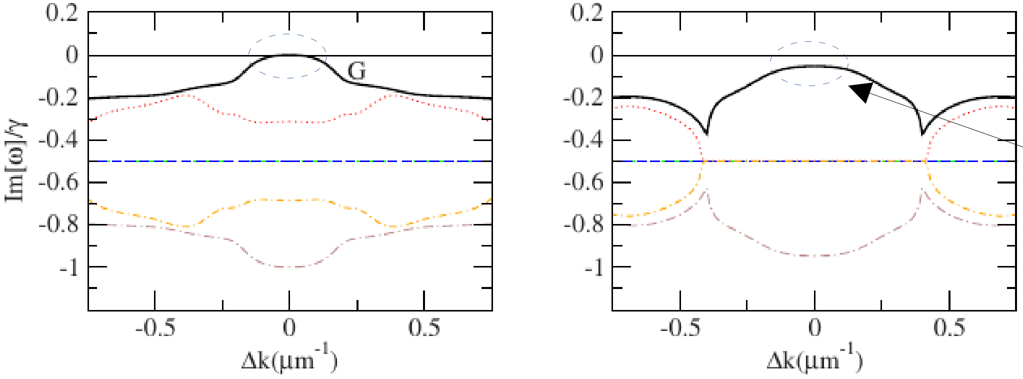


Probe transmission:

- Narrow peak for Goldstone mode @ small *k*
- Gets broader @ large *k*
- Plateau in dispersion,
  finite slope from finite condensate *v*

Claude et al. , *Observation of the diffusive Nambu-Goldstone mode of a non-equilibrium phase transition*, arXiv:2310.11903

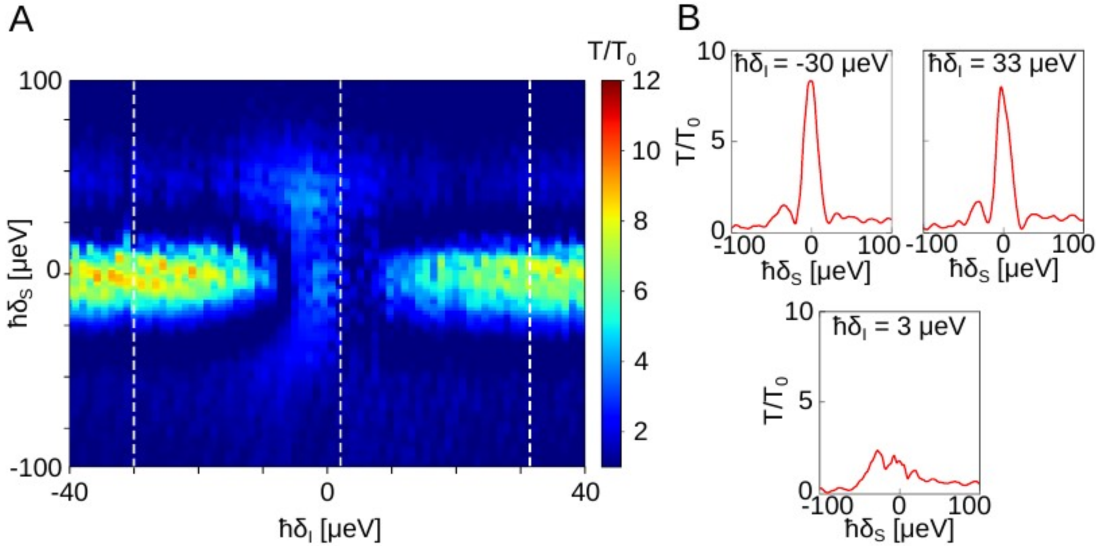
Experimental observation @ LKB (III)



Wouters, IC, PRA 2006

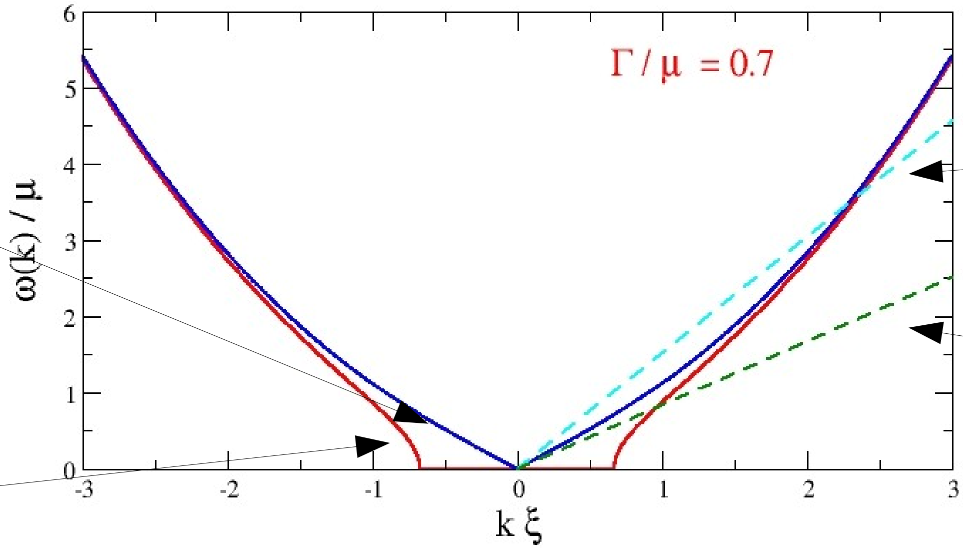
With phase fixing beam:

- U(1) symmetry explicitly broken
- Gapped dispersion
- Goldstone mode disappears, replaced by broad mode



Claude et al. , *Observation of the diffusive Nambu-Goldstone mode of a non-equilibrium phase transition*, arXiv:2310.11903

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

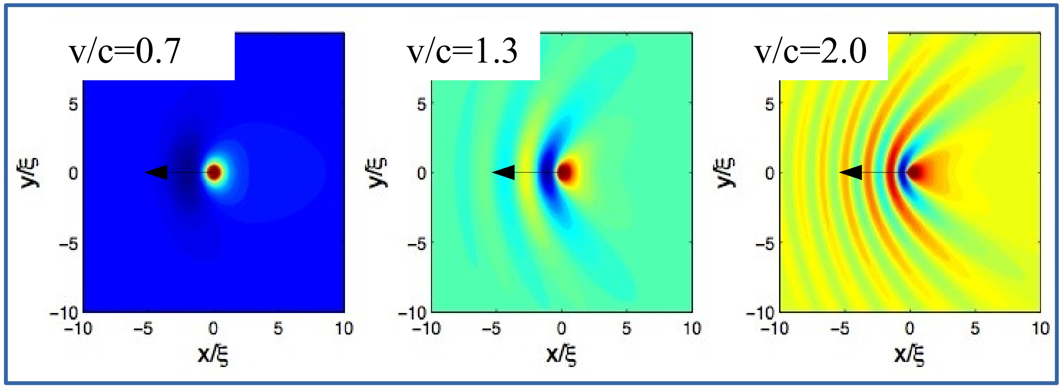
- Landau critical velocity $v_L = \min_k[\omega(k) / k] = 0$ at non-equilibrium BEC
- Any moving defect expected to emit phonons

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

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

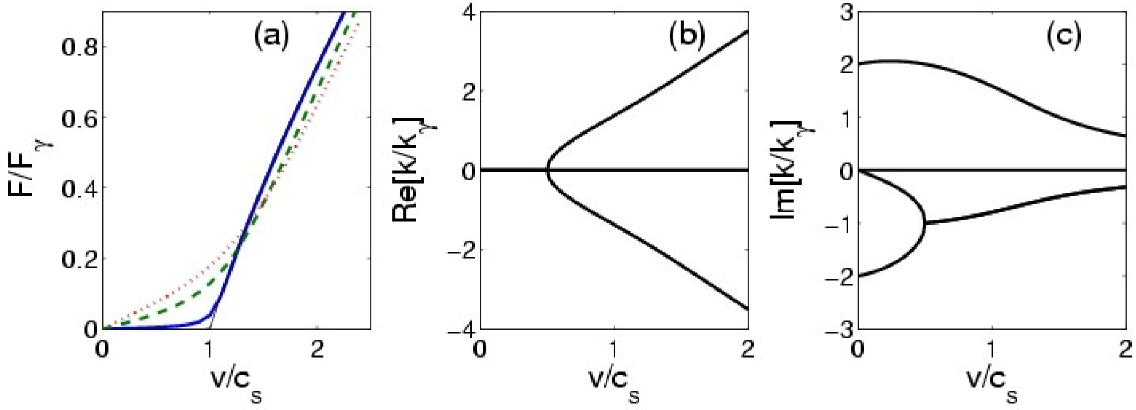


Low v :

- 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

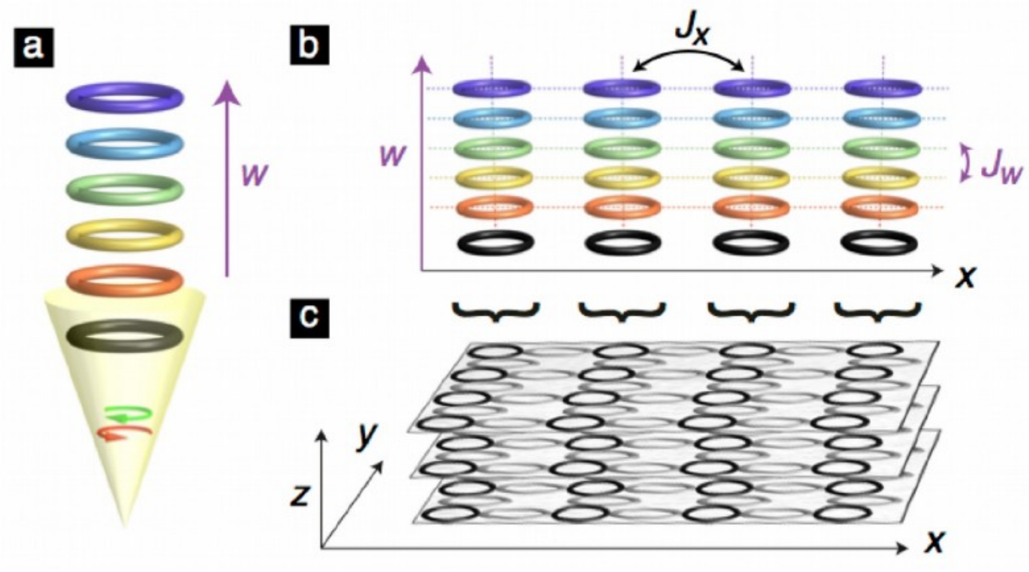
M. Wouters, IC, *Superfluidity and Critical Velocities in Nonequilibrium BECs*, PRL **105**, 020602 (2010).

Part 4:

The future:

High-dimensional
and/or
strongly interacting fluids of light

How to create synthetic dimensions for photons?



Different modes of ring resonators → synthetic dimension *w*

Tunneling along synthetic *w*:

- strong beam modulates resonator ε_{ij} at ω_{FSR} via optical $\chi^{(3)}$
- neighboring modes get linearly coupled
- phase of modulation → hopping phase along synthetic *w*

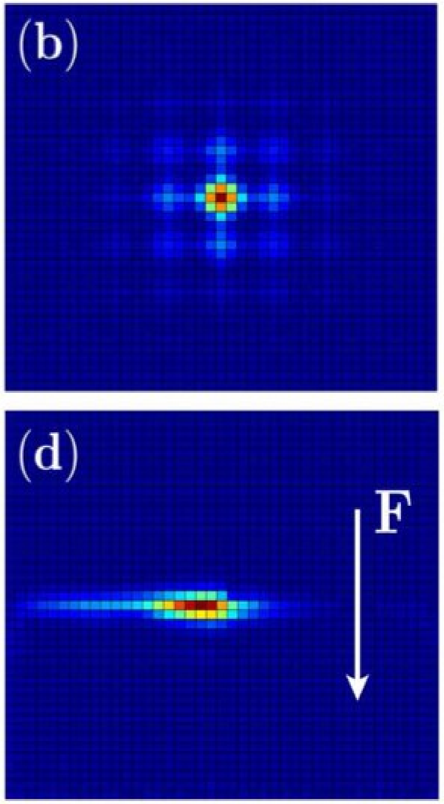
Extends Fan's idea
of synthetic gauge field via
time-dependent modulation
(Nat. Phys. 2008)

Theory: T. Ozawa, N. Goldman, O. Zilberberg, H. M. Price, and IC, *Synthetic Dimensions in Photonic Lattices: From Optical Isolation to 4D Quantum Hall Physics*, PRA (2016)
Many experimental realizations: Fan, St.-Jean, Cardano/Marrucci, ...

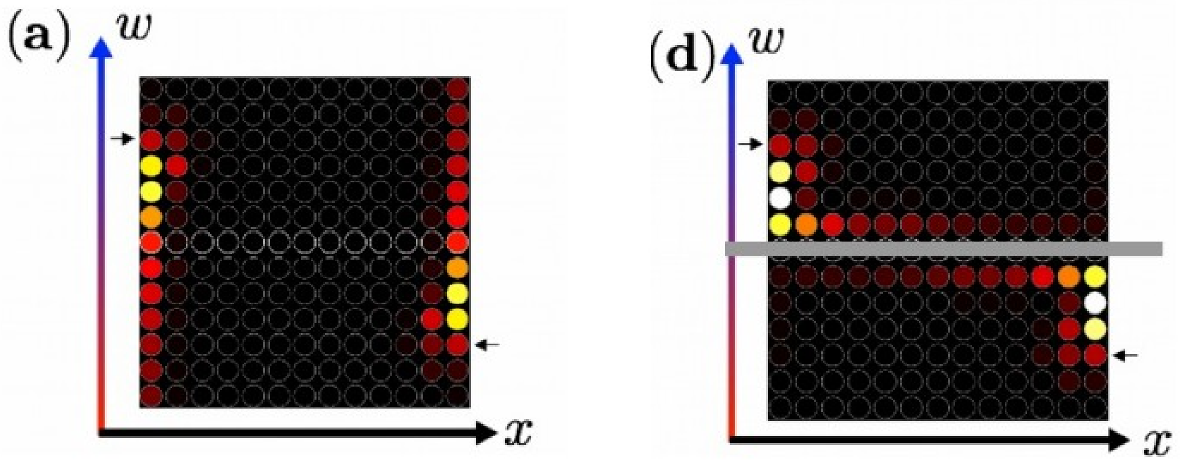
1+1 array: chiral edge states & optical isolation

1 (physical) + 1 (synthetic) dimensions: Hofstadter model

- Bulk topological invariant → Chern number
  - measured via Integer Quantum Hall effect



- Chiral states on edges:
  - Physical edges along x
  - Synthetic edges via design of ε(ω)
    (e.g. inserting absorbing impurities in chosen sites)
    → topologically protected optical isolator



Absorbing
row of sites

T. Ozawa, N. Goldman, O. Zilberberg, H. M. Price, and IC, *Synthetic Dimensions in Photonic Lattices: From Optical Isolation to 4D Quantum Hall Physics*, PRA 93, 043827 (2016)

3+1 array: 4D Quantum Hall physics

4D magneto-electric response

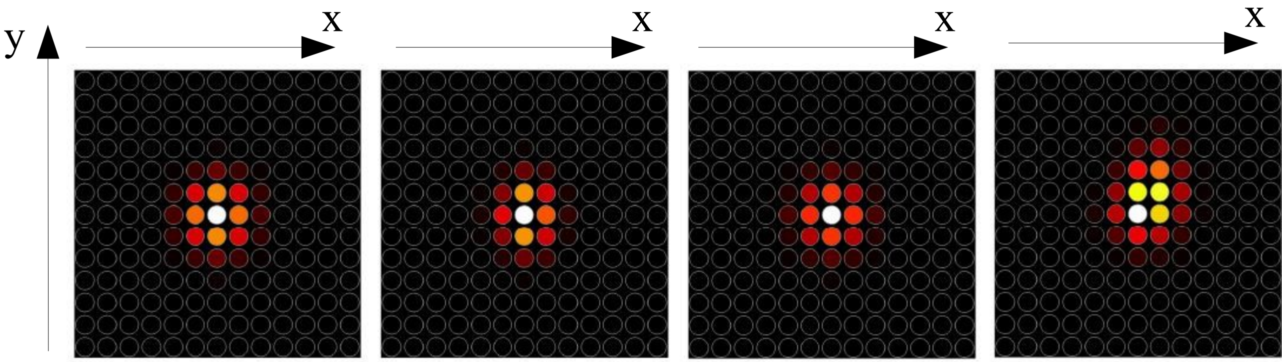
Nonlinear integer QH effect

Lateral shift of photon intensity distribution in response to external synth-E and synth-B:

- only present with both E & B
  - proportional to 2nd Chern

Natural question in this school:

- add gain to the model
- probe KPZ & roughening transition in high-d
- understand it in terms of mode-locked laser operation

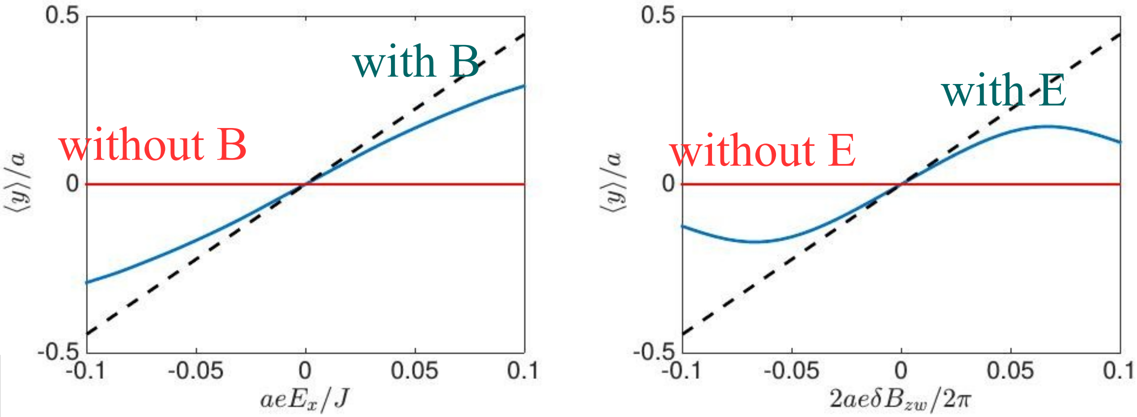


(a) $eE_xa, = 0$, $ea^2\delta B_{zw} = 0$

(b) $eE_xa = \frac{J}{10}$, $ea^2\delta B_{zw} = 0$

(c) $eE_xa = 0$, $ea^2\delta B_{zw} = \frac{2\pi}{10}$

(d) $eE_xa = \frac{J}{10}$, $ea^2\delta B_{zw} = \frac{2\pi}{10}$



$$j^\mu = E_\nu \frac{1}{(2\pi)^4}\int_{\mathbb{T}^4}\Omega^{\mu\nu}\mathrm{d}^4k + \frac{\nu_2}{4\pi^2}\varepsilon^{\mu\alpha\beta\nu}E_\nu B_{\alpha\beta}$$

$$\nu_2 = \frac{1}{4\pi^2}\int_{\mathbb{T}^4}\Omega^{xy}\Omega^{zw} + \Omega^{wx}\Omega^{yz} + \Omega^{zx}\Omega^{yw}\mathrm{d}^4k$$

T. Ozawa, N. Goldman, O. Zilberberg, H. M. Price, and IC, *Synthetic Dimensions in Photonic Lattices: From Optical Isolation to 4D Quantum Hall Physics*, PRA 93, 043827 (2016)

See also recent charge pumping experiments with atoms (Lohse et al. Nature ‘18) and light (Zilberberg et al. Nature ‘18)

Strong photon interactions: photon blockade

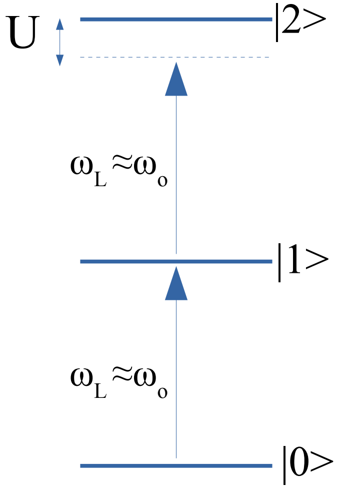
Driven-dissipative Bose-Hubbard model:

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

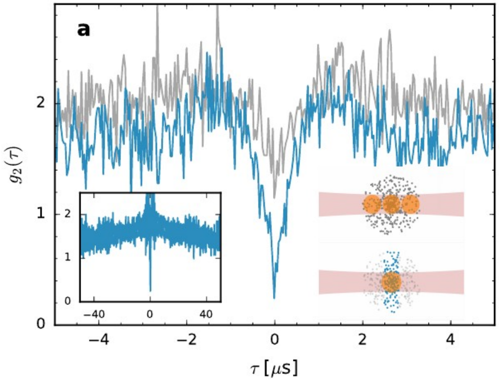
- Array of single-mode cavities at ω_o , tunnel coupling J , losses γ
- Polariton interactions: on-site interaction U due to optical nonlinearity
- If U >> γ & J, coherent pump resonant with 0→1, but not with 1→2.

Photon blockade → Effectively impenetrable photons

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

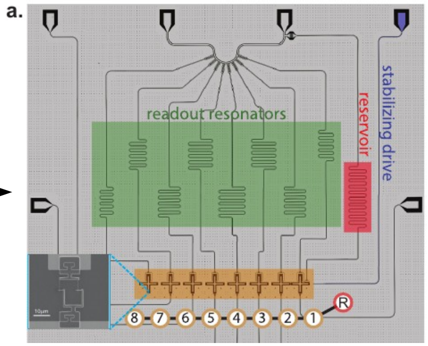


Single-cavity blockade observed in many platforms since the 2000s,

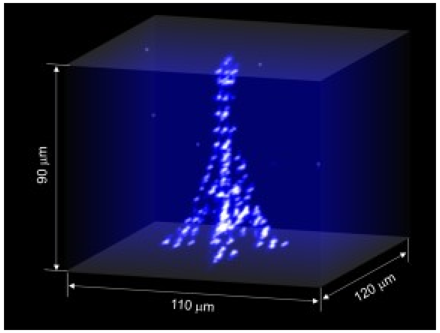


Polariton blockade via Rydberg-EIT

Circuit QED device



Fluid of spin excitations in lattice of Rydberg atoms. (Broways, Lukin,...)

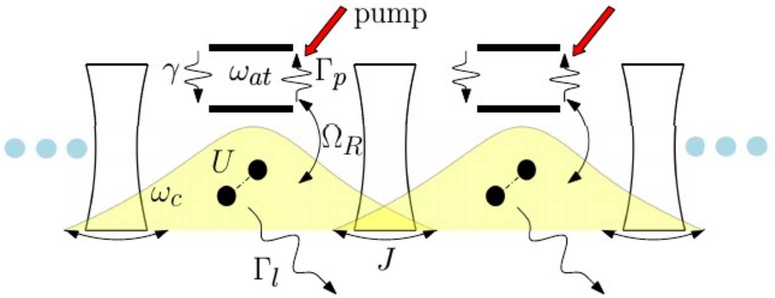


IC-Ciuti, *Quantum Fluids of Light*, RMP **85**, 299 (2013)

Many-cavity system

Scale up to large systems:

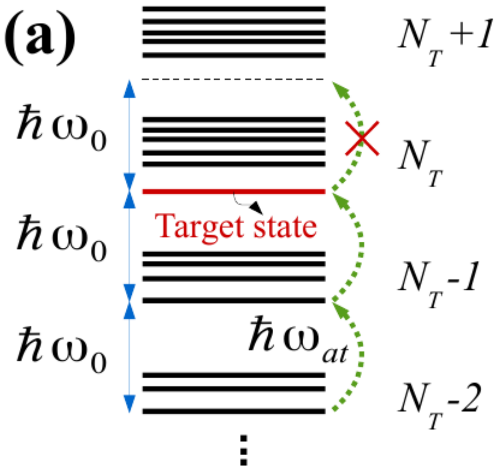
- Fabricate array of cavities with strong interactions
- Find a way to stabilize desired many-body state



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 >> γ 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 !



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

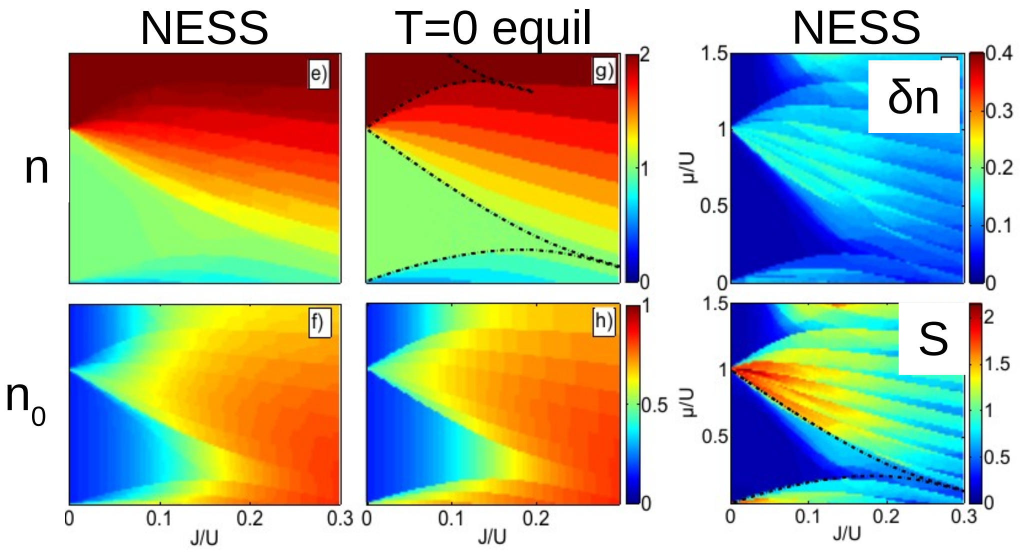
Umucalilar-IC, PRA 2017
Lebreuilly, Biella et al., PRA 2017

Mott insulator of light

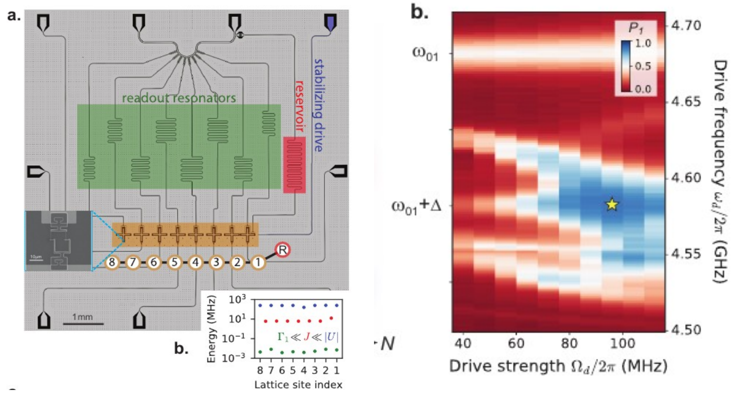
- Most naive non-Markovian master equation:
  frequency-dependent emission → rescaled jump operators
- driven-dissipative steady state stabilizes
  strongly correlated many-body states
  e.g. Mott-insulator, FQH…
- resembles low-T equilibrium
- (in principle) no restriction to small N_{ph}
  only requirement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

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

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



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



First expt: Ma *et al.* Nature 2019

First experimental observation of a Mott insulator state of impenetrable photons

Conclusions

Quantum fluids of light → ideal platform for non-equilibrium statistical mechanics

Non-equilibrium condensation (aka lasing):

- Peculiar shape of condensate under localized pump
- KPZ features in coherence function of emission
- Topological lasing → spatially homogeneous, periodic boundary conditions

Superfluid light:

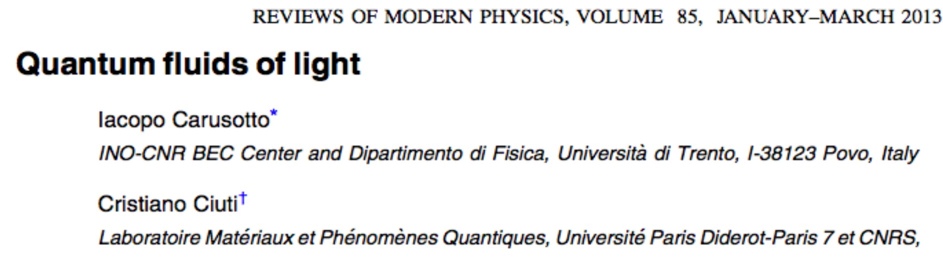
- Superfluid probed in frictionless flow past an obstacle
- Wide range of collective & hydrodynamic excitation modes
- Diffusive Goldstone mode of non-equilibrium condensate, gapped when symmetry explicitly broken

The future:

- Strongly interacting quantum fluids of light → quantum non-equilibrium statitsical mechanics
- High-dimensional systems beyond d=2 → promising platform for statistical models in high-d ?

If you wish to know more...

BEC
BOSE EINSTEIN CONDENSATION



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

Quantum fluids of light

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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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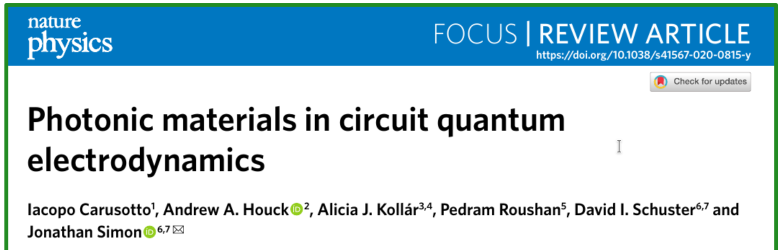

nature physics

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)

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)

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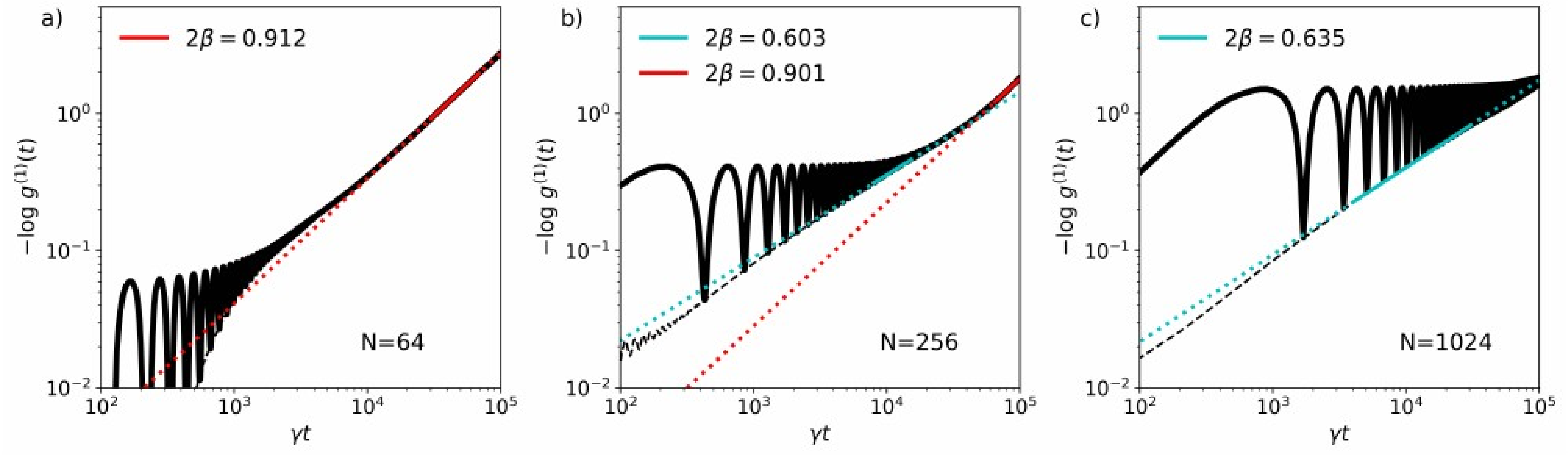
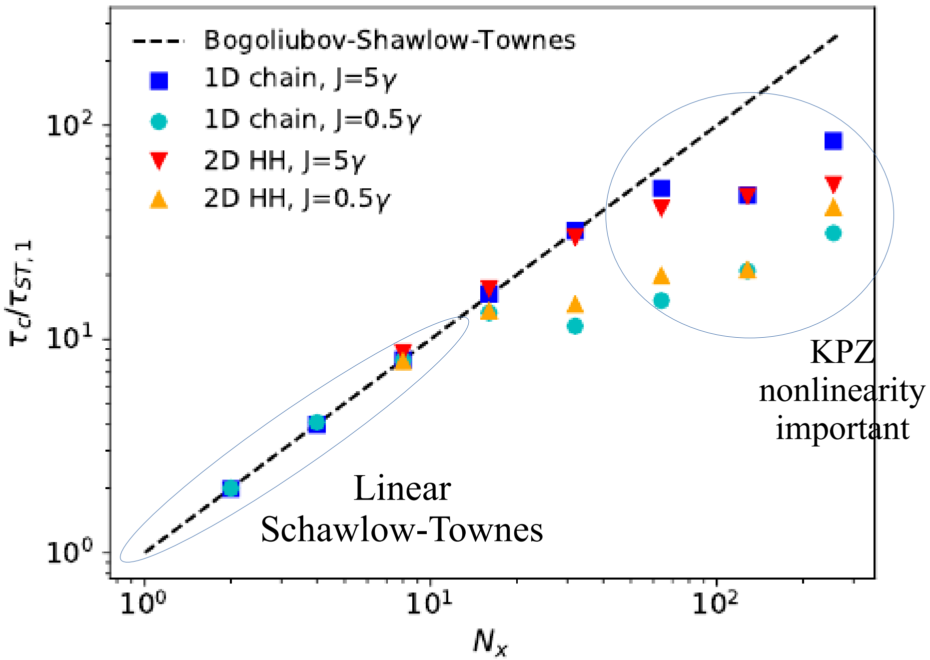
Coherence of topolaser emission (II)



Coherence of laser emission:

- Physical system necessarily finite
  → crossover from stretched-exp to exp decay
  at long times for given size N_x
- crossover from Schawlow-Townes τ_c to KPZ
  at long times for increasing size N_x
- imposes fundamental limitation to τ_c
- physics similar to non-topological 1D chains, but...

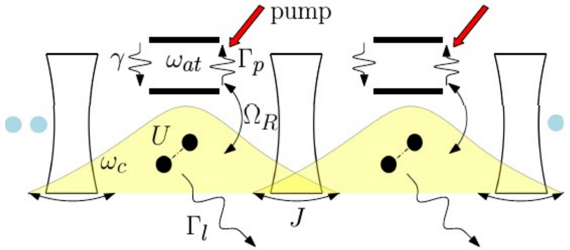


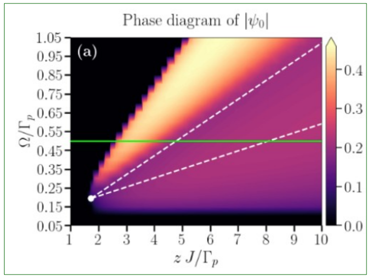
KPZ nonlinearity important

Linear Schawlow-Townes

I. Amelio and IC, *Theory of the coherence of topological lasers*, PRX 10, 041060 (2020)

Mott-superfluid phase transition: theory



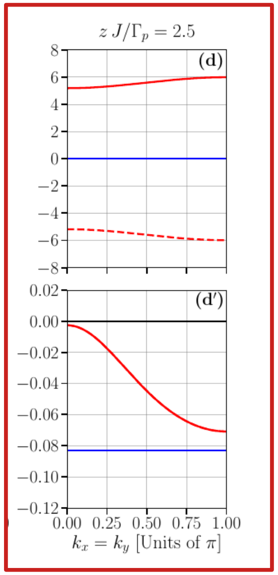


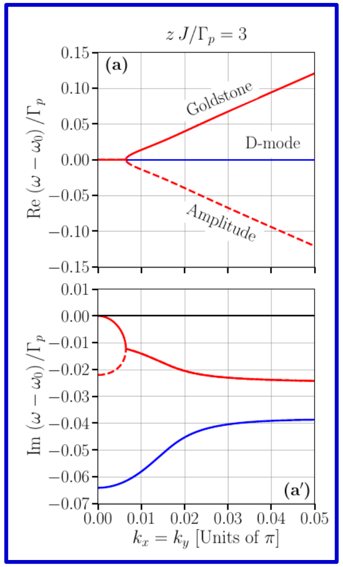
Exact description of non-Markovianity of emitter

→ 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

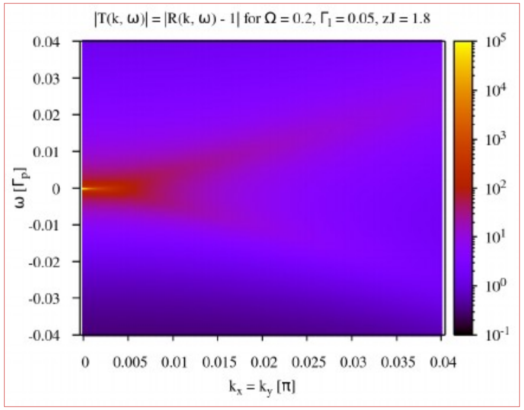




Superfluid-insulator non-equilibrium phase transition

Interesting behaviour of collective excitation modes across transition:

- Linearized Gutzwiller approach; visible 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)



F. Caleffi, M. Capone, IC, *Collective excitations of a strongly-correlated non-equilibrium photon fluid across the Mott/superfluid phase transition*, arXiv:2211.07246; Fabio Caleffi, PhD thesis @ SISSA (2022)