On the theory of

Quantum Fluids of Light

Part 2/3

Iacopo Carusotto

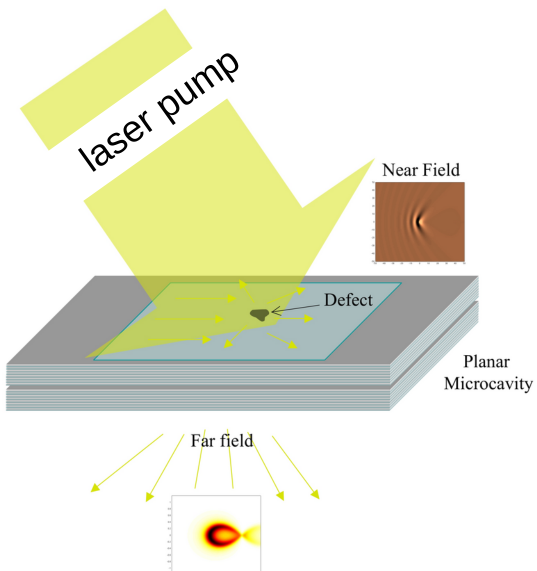
INO-CNR BEC Center and Università di Trento, Italy

Part 3:

Quantum fluids of light with a unitary dynamics

Field equation of motion

Planar microcavities & cavity arrays



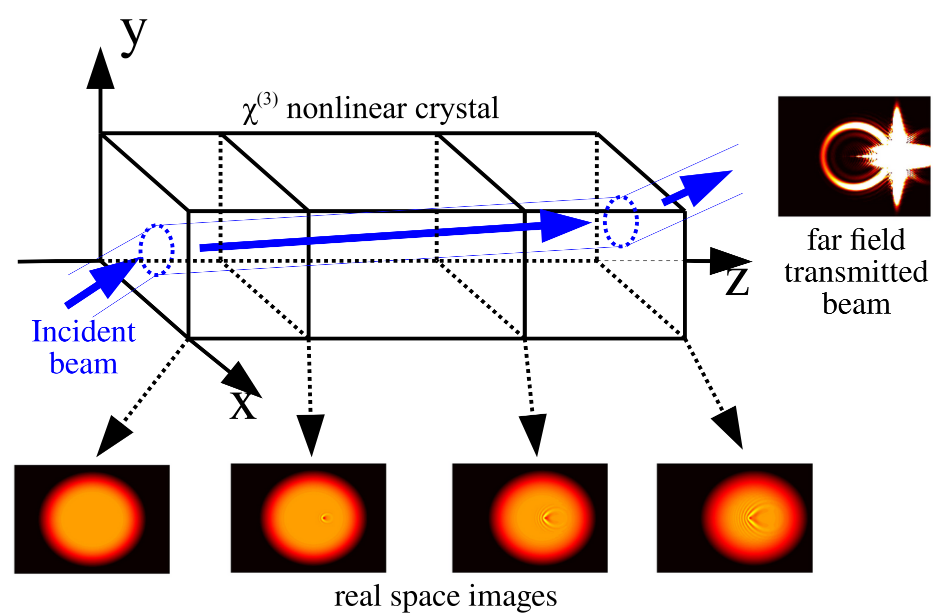
Pump needed to compensate losses:
driven-dissipative dynamics in real time
stationary state ≠ thermodyn. equilibrium

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



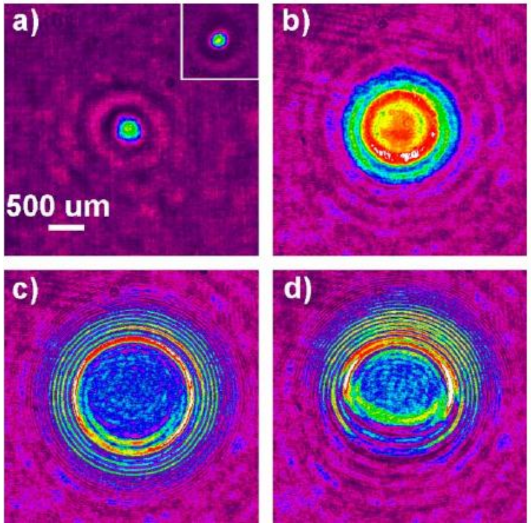
Monochromatic beam
Incident beam sets initial condition @ z=0
MF → Conserv. paraxial propag. → GPE

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

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

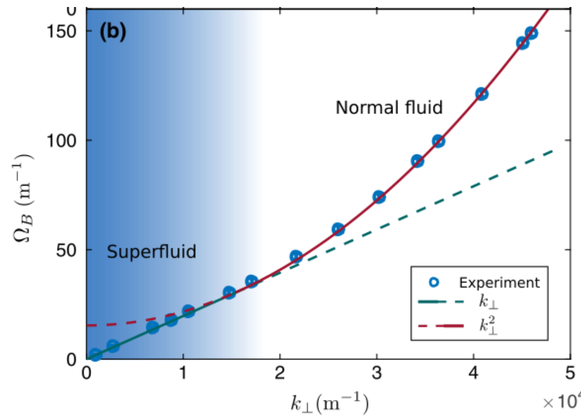
A few landmark experiments (among many)

Dispersive superfluid-like shock waves



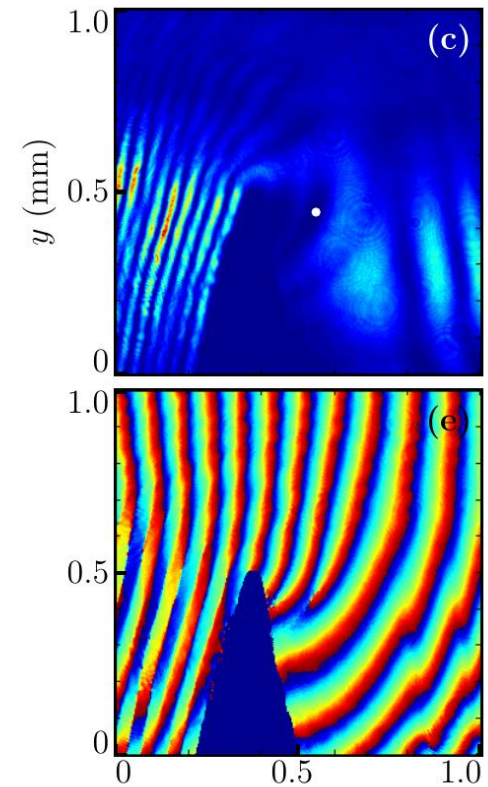
Wan et al., Nat. Phys. 3, 46 (2007)

Bogoliubov dispersion of collective excitations



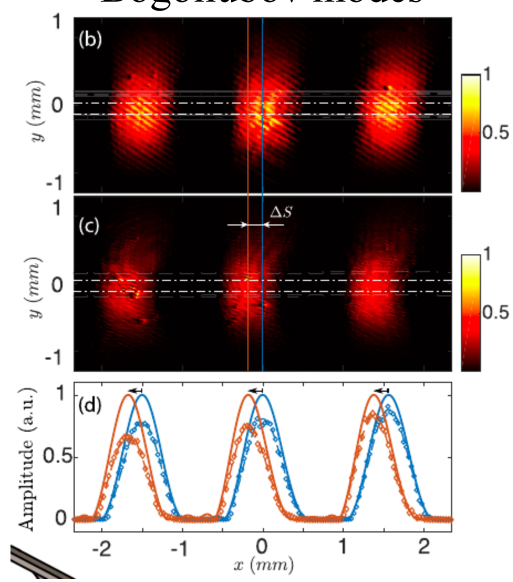
Q. Fontaine et al., PRL 2018

Hydrodynamic nucleation of quantized vortices



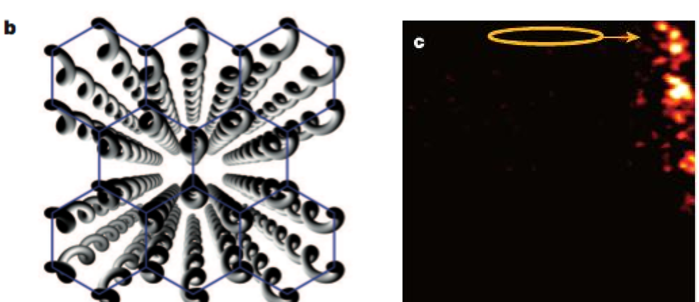
D. Vocke et al., PRA (2016)

Microscopic structure of Bogoliubov modes



Q. Fontaine et al., Phys. Rev. Res. (2020)

Chiral edge states in (photonic) Floquet topological insulator



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

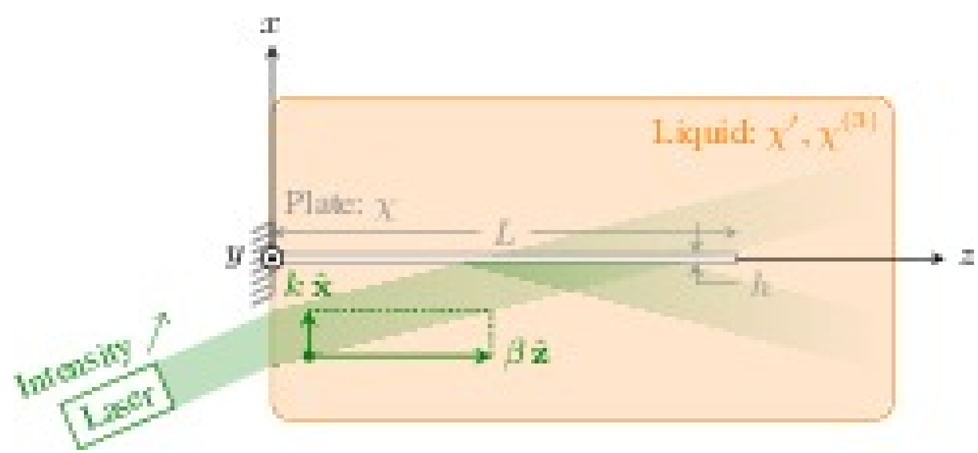
Frictionless flow of superfluid light (I)

All superfluid light experiments so far:

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

Propagating geometry more flexible:

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



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

Frictionless flow of superfluid light (II)

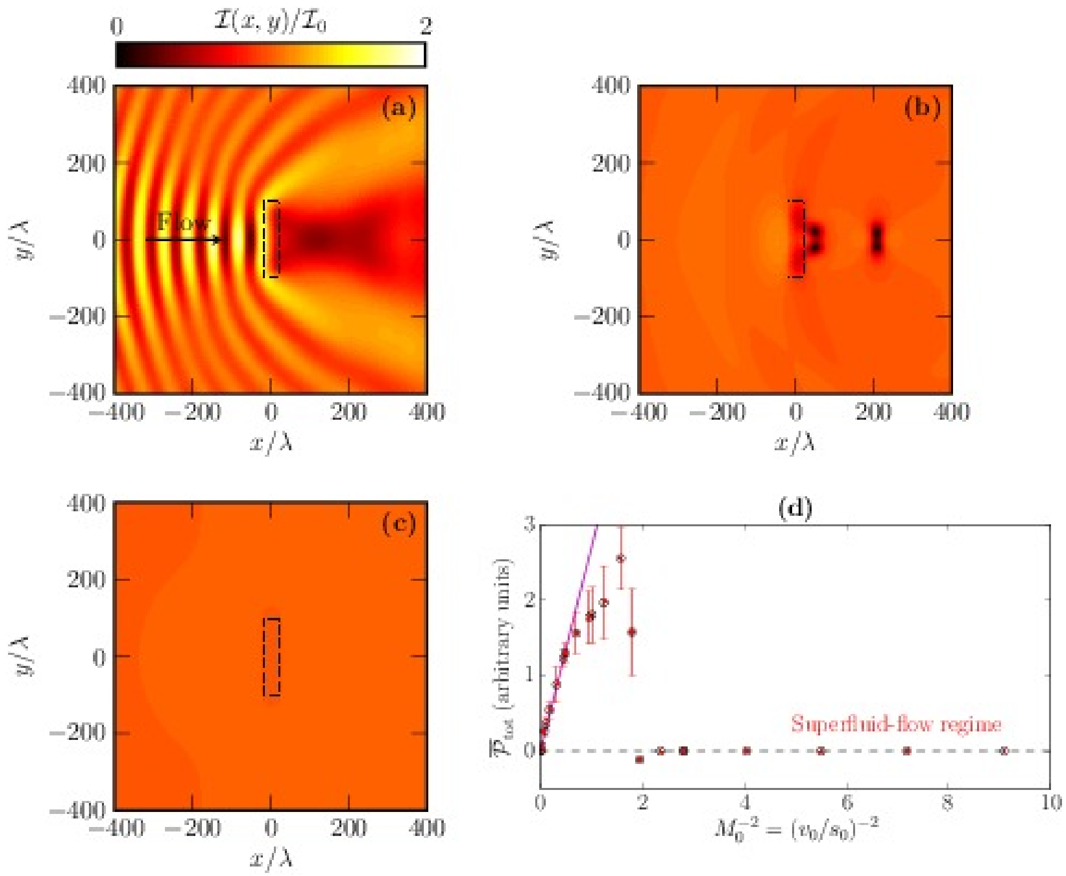
Numerics for propagation GPE of monochromatic laser:

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

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:

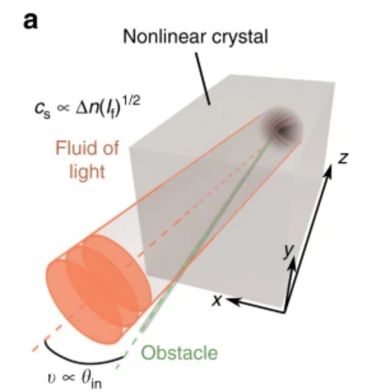
- Intensity modulation disappears
- Suppression of opto-mechanical force



Fused silica slab:
deformation almost in the µm range

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

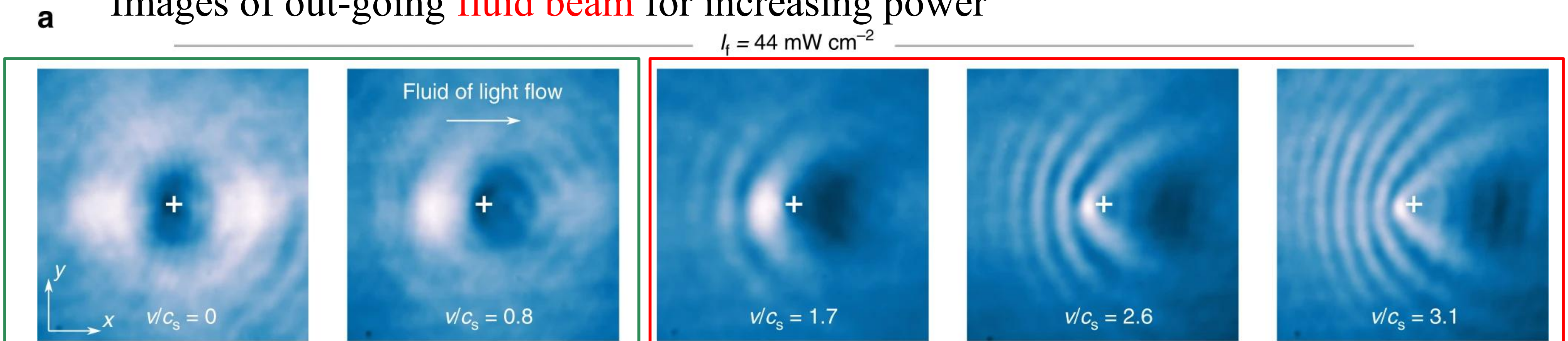
Frictionless flow of superfluid light (III)



Smarter all-optical design:

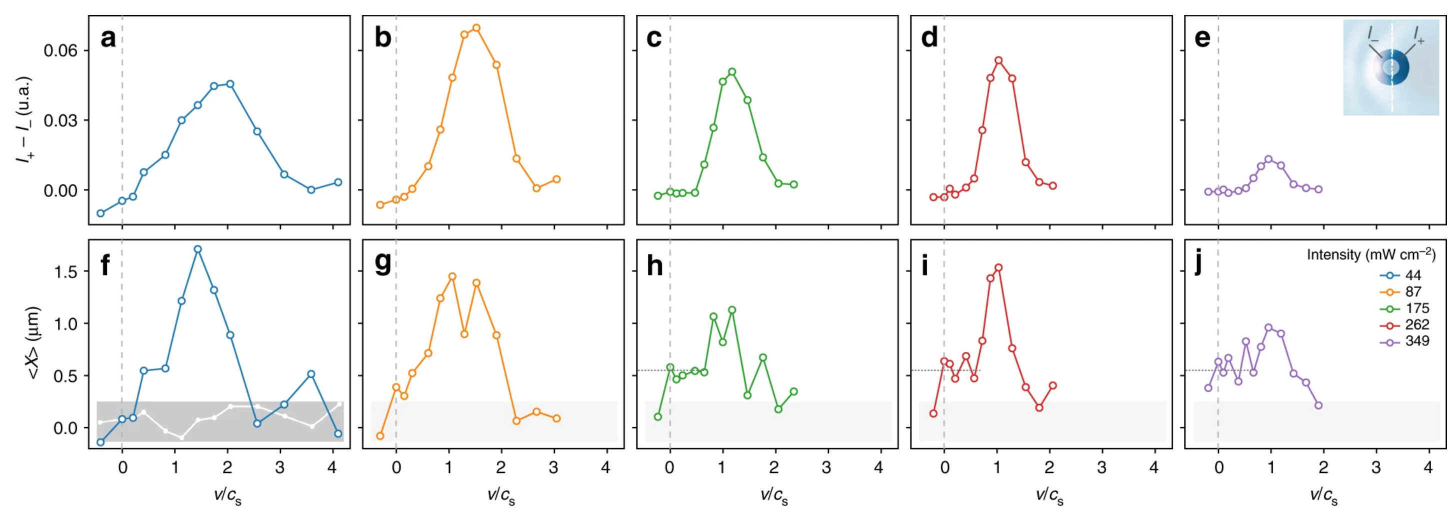
- defect → static Δn by additional beam
- friction force measured by displacement of defect beam

Images of out-going fluid beam for increasing power



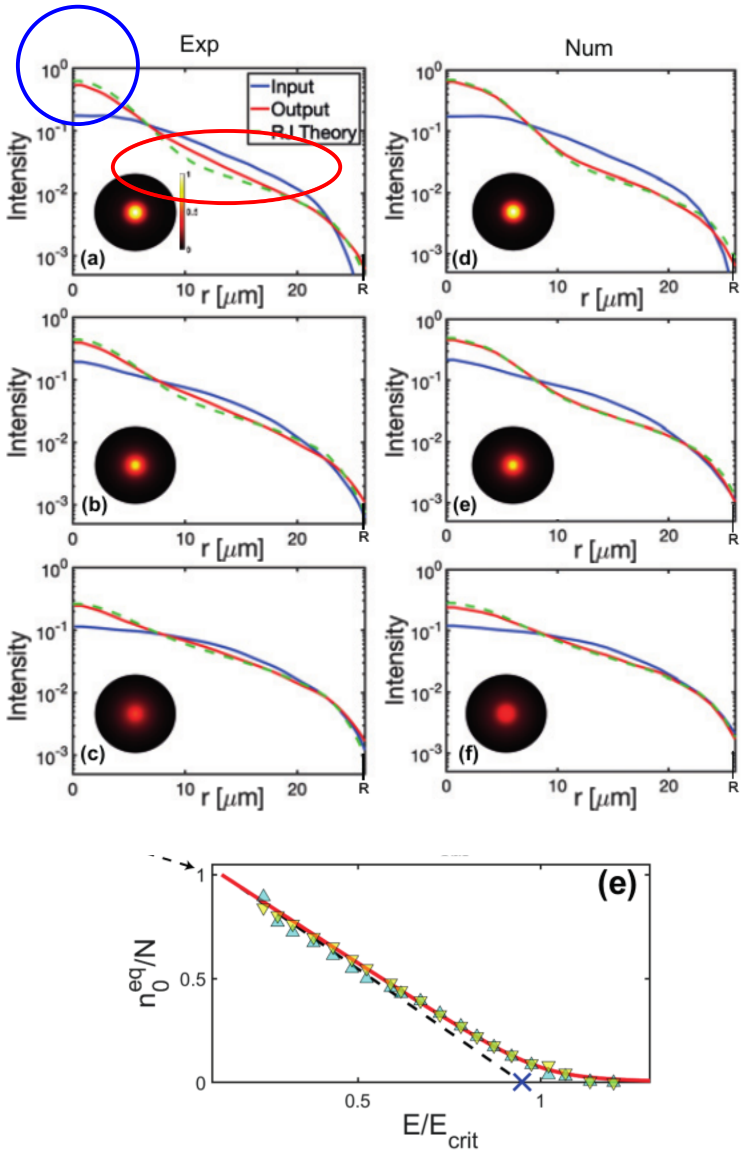
superfluid regime → no fringes

fringes → friction



Figures from:
C. Michel et al.,
Nat. Comm. 2018

Condensation of classical waves



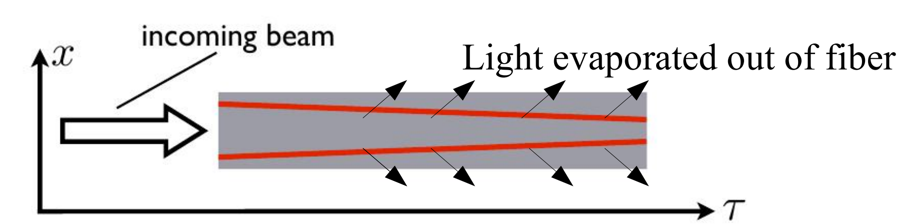
Monochromatic beam
with noisy spatial profile
injected into multi-mode fiber

Classical nonlinearity → stays monochromatic
GPE evolution during propagation

Thermalizes to:

- classical condensate
- thermal cloud with
  Rayleigh-Jeans $1/k^2$ high-k tail

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



Expts in progress in Picozzi's lab @ Dijon

Images from Baudin PRL (2020) + EPL (2020)
Earlier expts in Sun et al., Nature Physics 8, 470 (2012)
Other works by Krupa, Wabnitz, etc.

More sophisticated theory: Chiocchetta et al., EPL 2016

How to include quantum fluctuations beyond MF

Requires going beyond monochromatic beam and explicitly including physical time

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

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

Propagation coordinate z $\rightarrow$ time

Physical time $\rightarrow$ extra spatial variable, dispersion D_0 $\rightarrow$ temporal mass

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

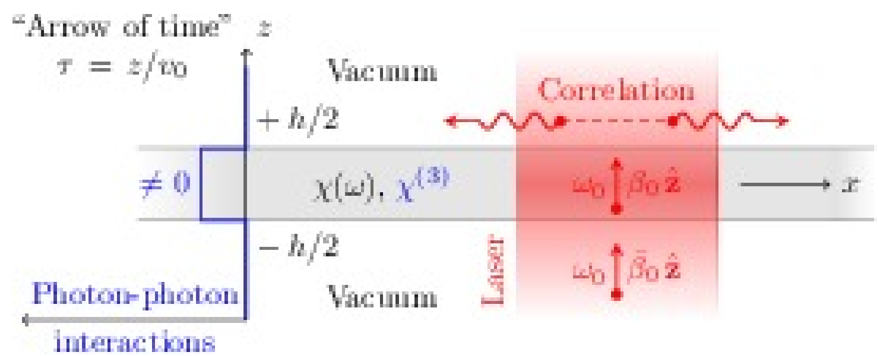
with $$H=N\iiint dx\, dy\, dt\left[\frac{1}{2\beta_0}\nabla\hat{E}^\dagger\nabla\hat{E}-\frac{D_0}{2}\frac{\partial\hat{E}^\dagger}{\partial t}\frac{\partial\hat{E}}{\partial t}+V\hat{E}^\dagger\hat{E}+\hat{E}^\dagger\hat{E}^\dagger\hat{E}\hat{E}\right]$$

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

P.-E. Larré, 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

Dynamical Casimir emission at quantum quench (I)



Monochromatic wave @ normal incidence

Slab of weakly nonlinear medium

→ Weakly interacting Bose gas at rest

Air / nonlinear medium interface

→ sudden jump in interaction constant when moving along z

Mismatch of Bogoliubov ground state in air and in nonlinear medium

→ emission of phonon pairs at opposite k on top of fluid of light

Propagation along z

→ conservative quantum dynamics

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

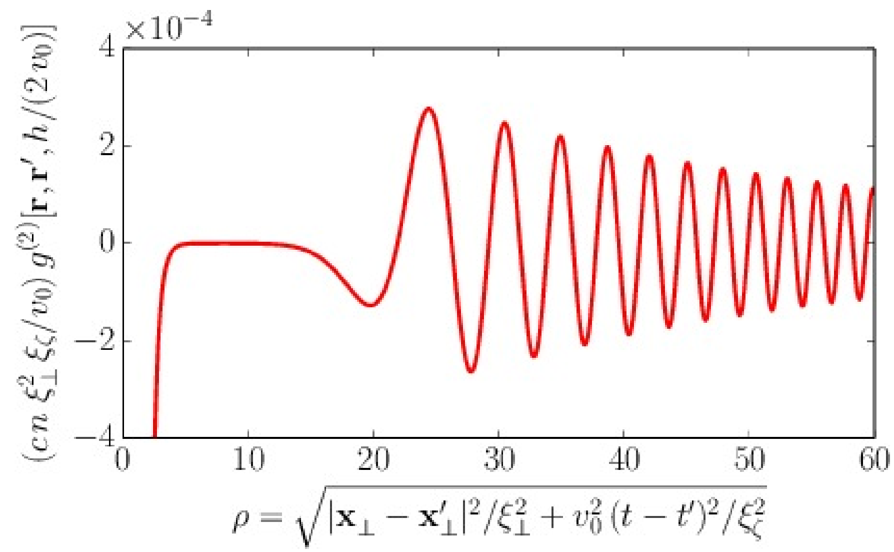
P.-E. Larré and IC, PRA **92**, 043802 (2015)

Dynamical Casimir emission at quantum quench (II)

Observables:

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

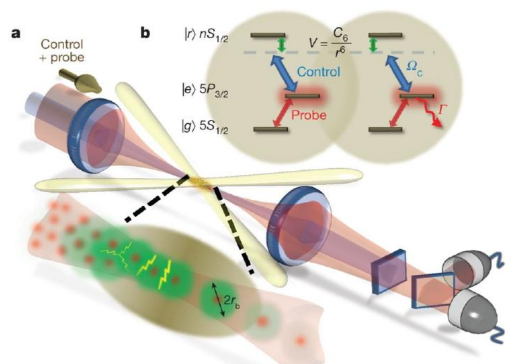
First peak propagates at the speed of sound c_s



quantum simulation of fluctuations in early universe

:

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

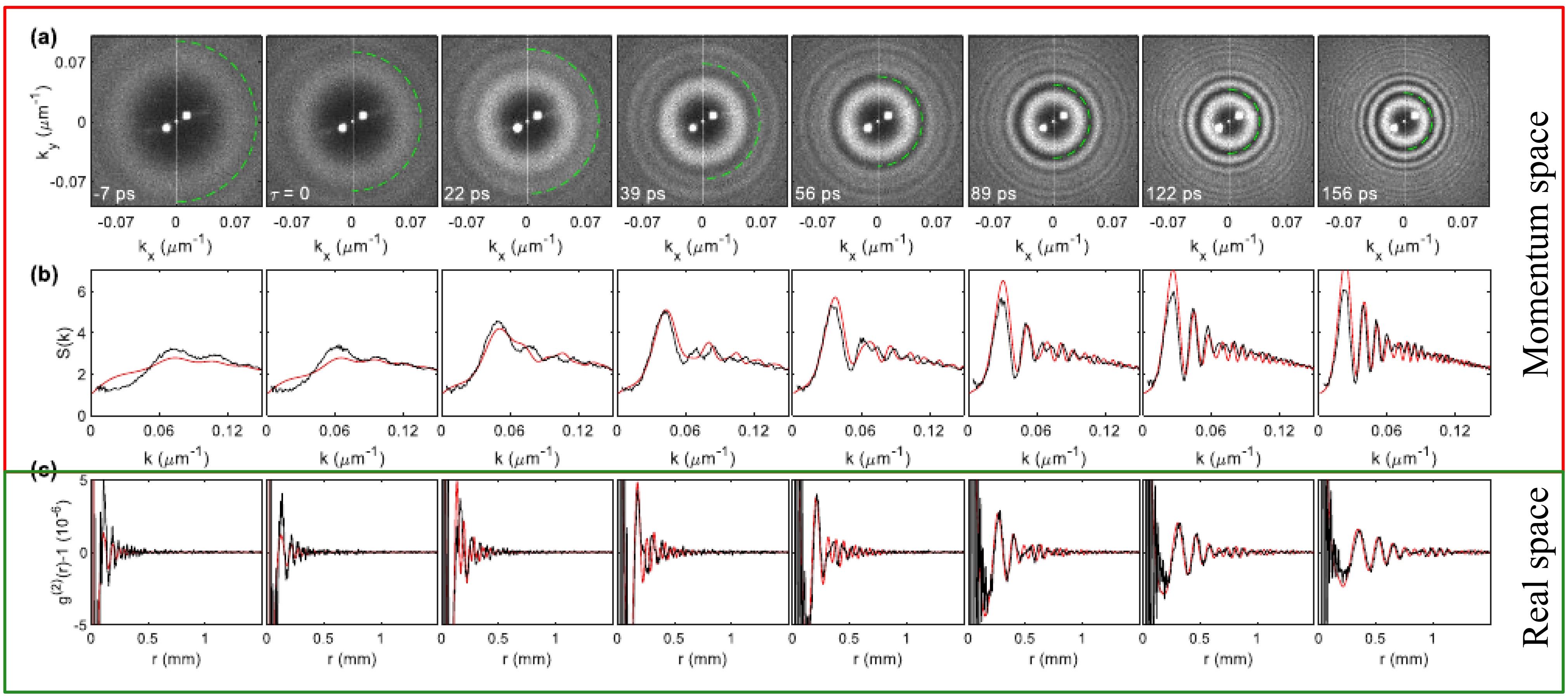


P.-E. Larré and IC, PRA **92**, 043802 (2015)

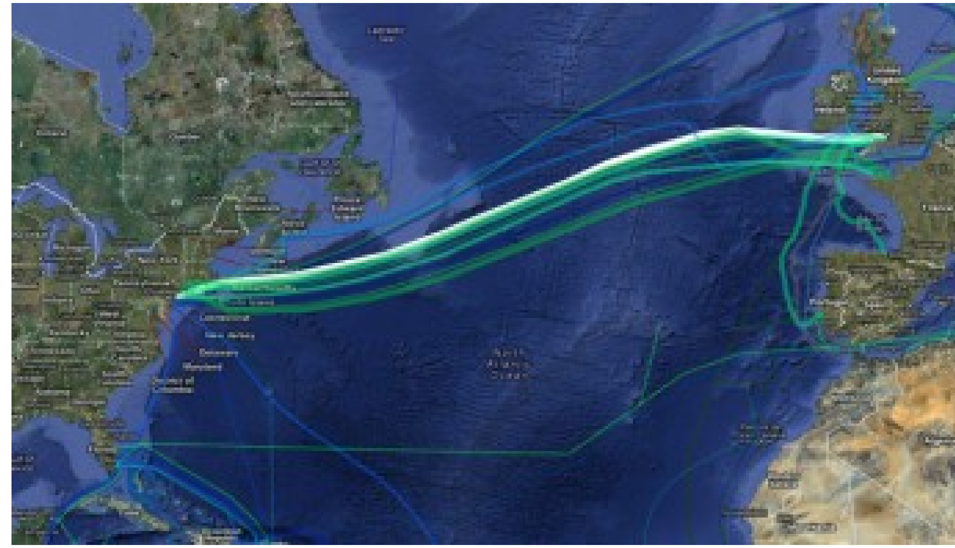
Dynamical Casimir emission at quantum quench (III)

Experimental data from: Steinhauer, Abuzarli, Bienaimé, Piekarski, Liu, Aladjidi, Giacobino, Bramati, Glorieux (2021)
"Spontaneous and stimulated dynamical Casimir effects in a quantum fluid of light"

Experimental correlation pattern in outgoing beam



A potentially important technological issue...



Long-distance fiber-optic set-ups
→ telecom over distances $\sim 10^4$ km

Can optical coherence be preserved?

Several disturbing effects:

- (extrinsic) fluctuations of fiber temperature, length, etc.

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

  Statistical mechanics suggests that phase fluctuations destroy 1D BEC

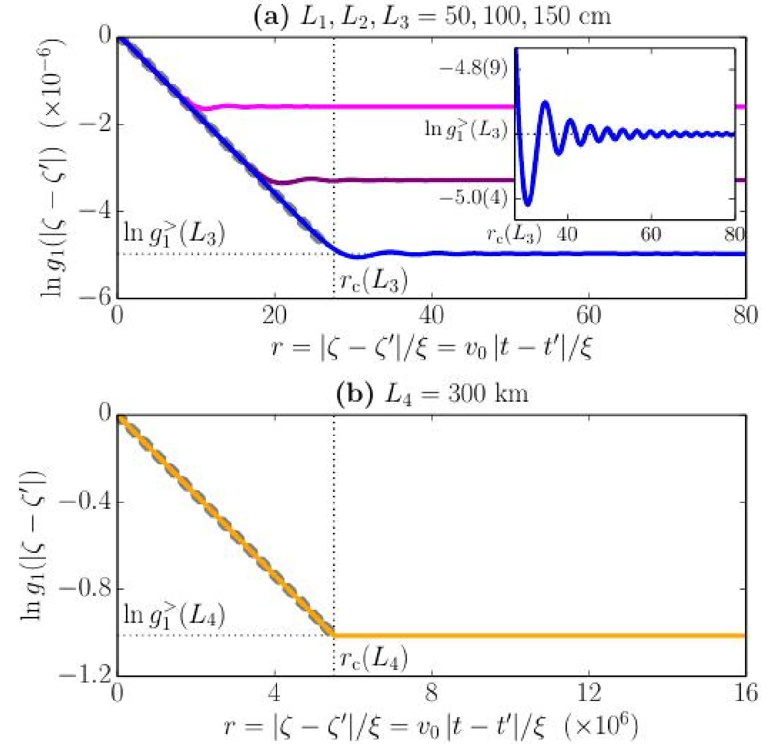
  → light at the end of fiber has lost its (temporal) phase coherence

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

“Pre-thermalized” 1D photon gas

Perfectly coherent light injected into 1D optical fiber:

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



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

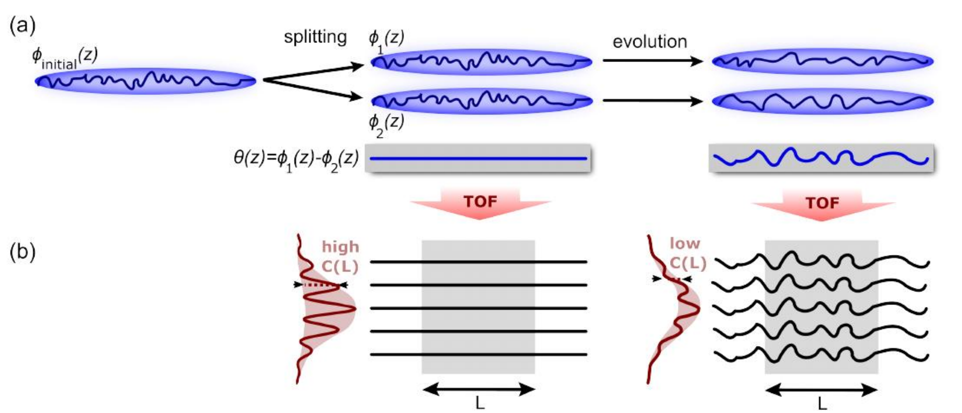
- Exponential decay at short $|t-t'| < 2z / c_s$
  (c_s = speed of Bogol. sound)
- Plateau at long $|t-t'| > 2z / c_s$
- Low-k modes eventually tends to thermal $T_{eff} = \mu / 2$
- Hohenberg-Mermin-Wagner theorem prevents long-range order in 1D quasi-condensates at finite T

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

Decoherence slower if tapering used to “adiabatically” inject light into fiber

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*, arXiv:1510.05558

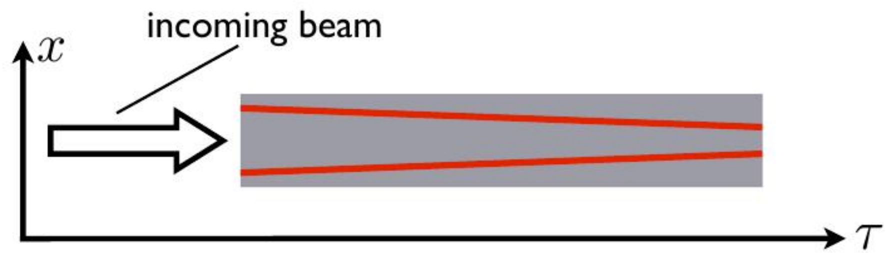
Application: evaporative cooling of light

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

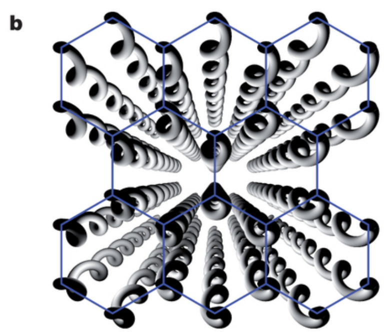
A. Chiocchetta, P.-É. Larré, IC, EPL (2017)

A quite generic *quantum simulator*

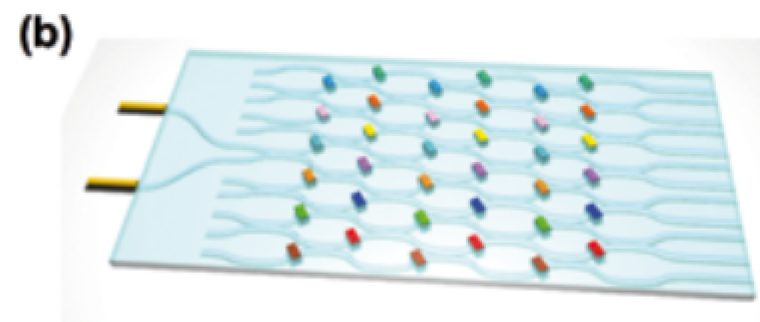
Quantum many-body evolution in *z:*

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

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



Rechtsman et al., Nature 2012



Clever design of V(x,y,z) → 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
- On top of moving fluid of light → simulate general relativistic QFT

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

If you wish to know more...

BEC

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

Quantum fluids of light

Iacopo Carusotto*
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, Bâtiment Condorcet, 10 rue Alice Domon et Léonie Duquet, 75205 Paris Cedex 13, France

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

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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

Review article arXiv:1802.04173 by Ozawa, Price, Amo, Goldman, Hafezi, Lu, Rechtsman, Schuster, Simon, Zilberberg, <u>IC</u>, RMP **91**, 015006 (2019)

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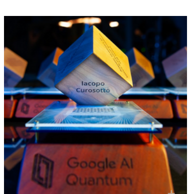
Non-equilibrium Bose–Einstein condensation in photonic systems

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

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



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PhoQuS Photons for Quantum Simulation

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