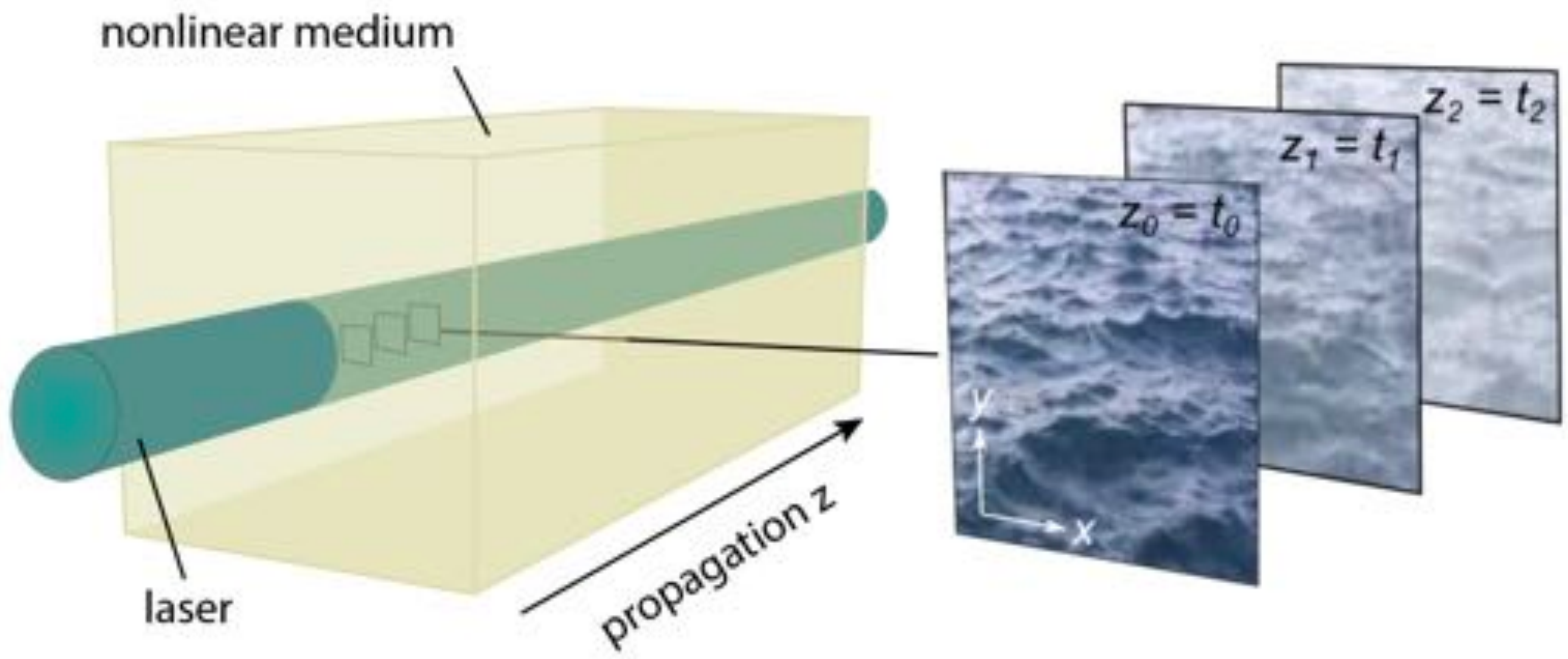
OBSERVATION OF VORTEX DYNAMICS IN A FLUID OF LIGHT

Matthieu Bellec

Institut de Physique de Nice — Université Côte d'Azur, CNRS



GDR COMPLEX, Annual workshop – Paris, December 7-9, 2022

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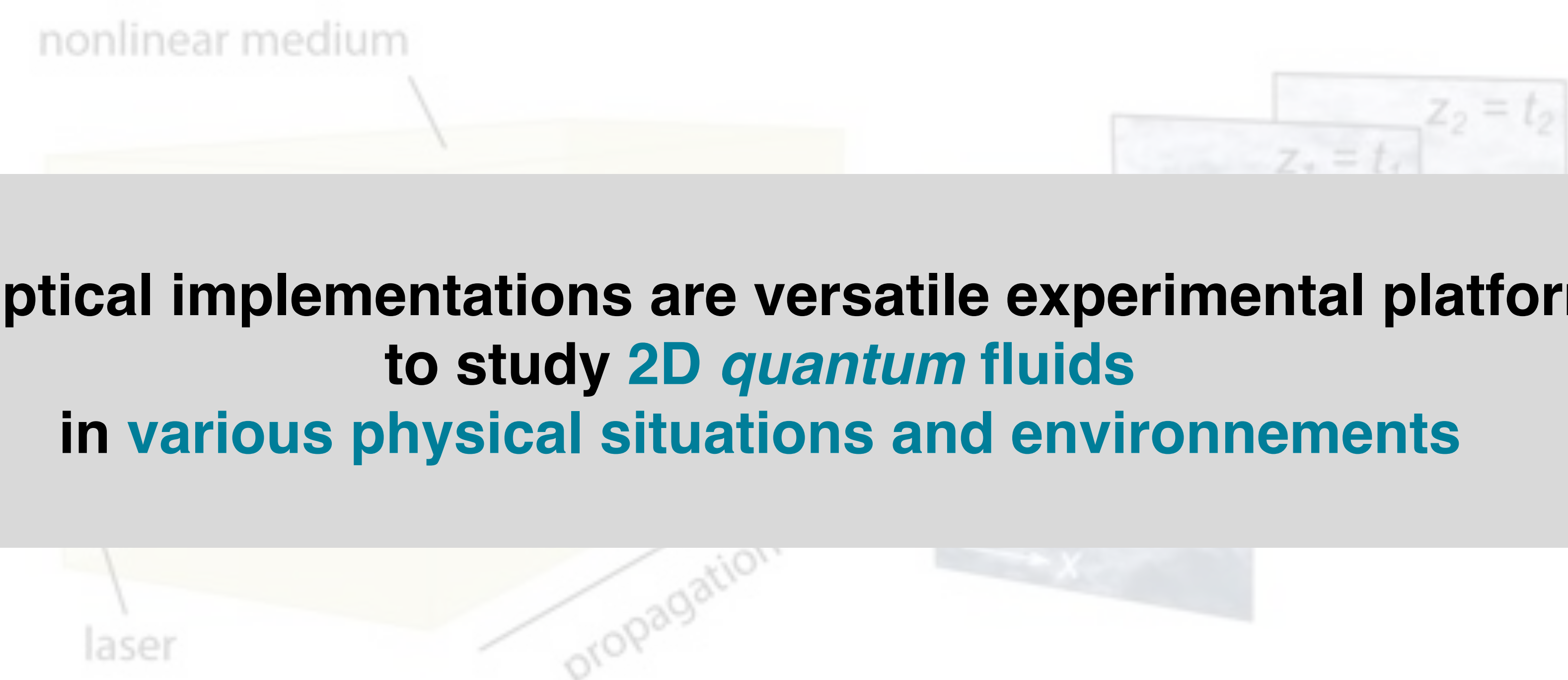

All-optical implementations are versatile experimental platforms to study 2D *quantum* fluids in various physical situations and environnements

GDR COMPLEX, Annual workshop – Paris, December 7-9, 2022

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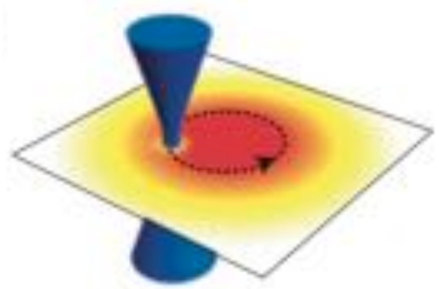
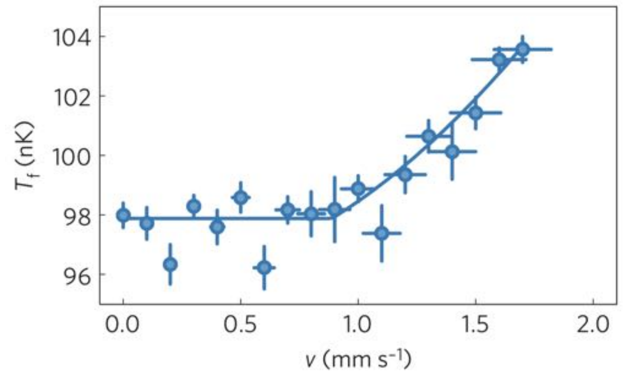
cnrs

21st century superfluidity

- with **matter**

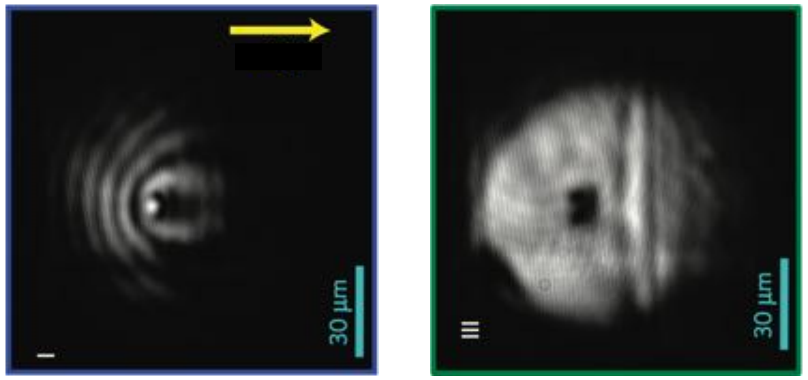




Evidence for a critical velocity in a stirred 2D Bose gaz

R. Desbuquois et al., Nature Phys. **8**, 645 (2012)

- with **polaritons** in cavity

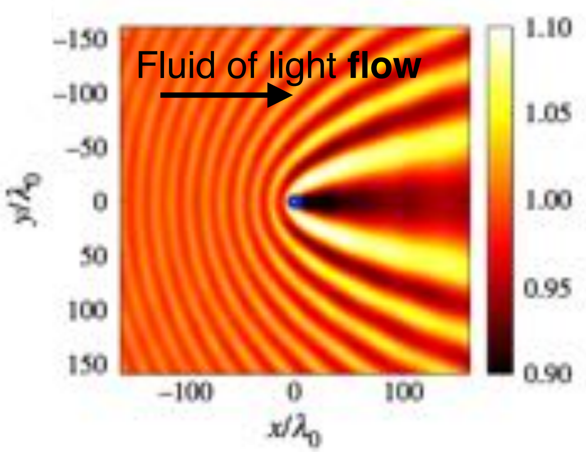


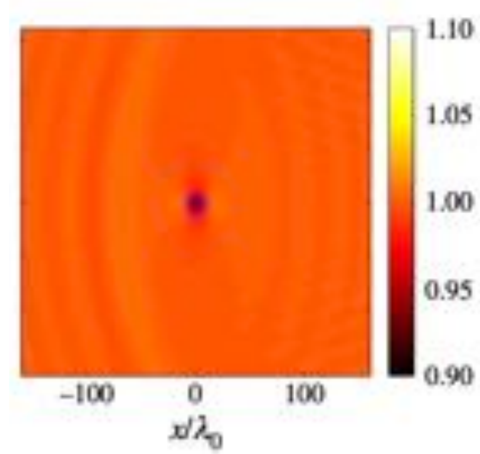
Superfluid polariton flow past an obstacle

A. Amo et al., Nature Phys. **5**, 805 (2009)

- with **light** in propagating geometry

Normal
(dissipative)
regime





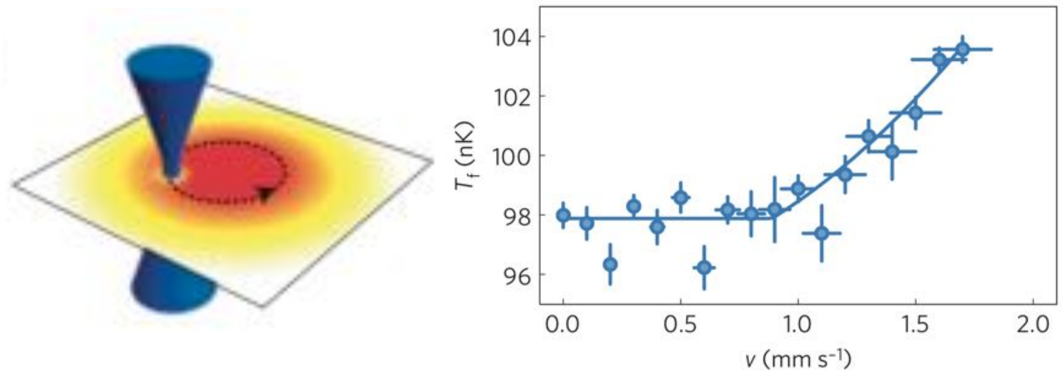
Superfluid
regime

Simulations of laser intensity at the output of a nonlinear medium with a weak defect

T. Frisch et al., Phys. Rev. Lett. 69, 11 (1992)
I. Carusotto, Proc. R. Soc. A 470, 0320 (2014)

21st century superfluidity

- with **matter**



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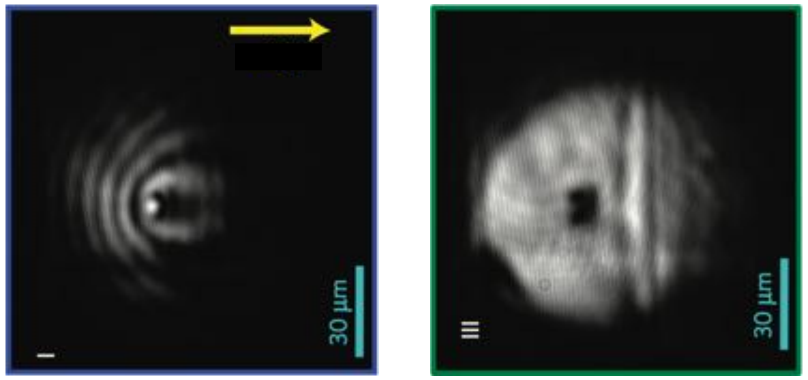


Superfluid polariton flow past an obstacle

A. Amo et al., Nature Phys. **5**, 805 (2009)

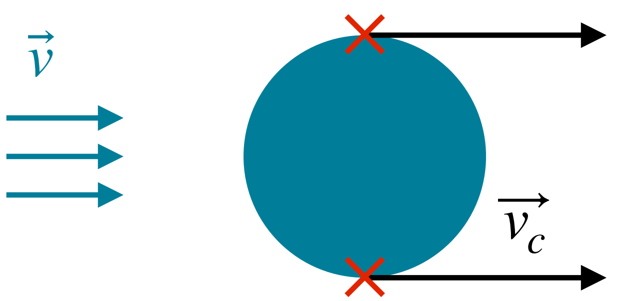
- with **light** in propagating geometry

Few **experimental** platforms

R. Kaiser (INPHYNI) – *hot atomic vapors*
Q. Glorieux (LKB) – *hot atomic vapors*
T. Bienaimé (Strasbourg Univ.) – *ultracold atoms*
D. Faccio (Glasgow Univ.) – *thermal liquids*
J. Fleischer (Princeton Univ.) – *photorefractive crystals*
M. Bellec, C. Michel (INPHYNI) – *photorefractive crystals*
A. Guerreiro, N.A. Silva (Univ. Porto) – *photorefractive crystals*

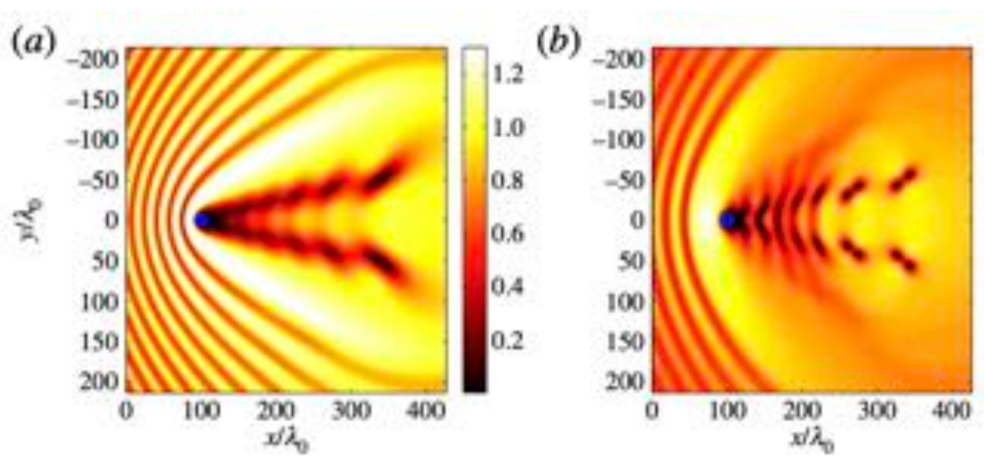
Quantized vortices in superfluids of light

- Turbulent regime expected for strong/large obstacles



Dissipation occurs locally via nonlinear excitations

- Rich dynamics – vortices nucleation (w/ quantized circulation), instabilities, dark solitons



Simulations of laser intensity at the output of a nonlinear medium with an strong defect

T. Frisch et al., Phys. Rev. Lett. 69, 11 (1992)
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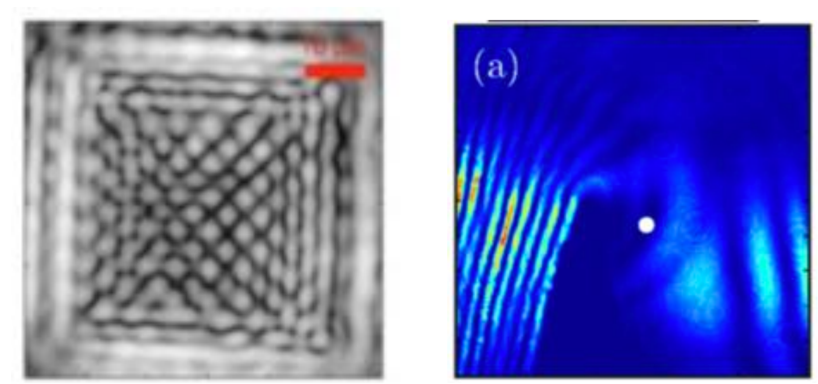


Observation of quantized vortices in polaritonic micro-cavities and thermal fluids

T. Boulier et al. C. R. Phys 17, 893 (2016)
D. Vocke et al, Phys. Rev. A 94, 013849 (2016)

Fluids of light

Collective behaviour of *massive* **photons** in effective *interaction*

- **Propagation** of a monochromatic laser beam in a nonlinear medium

$$i\partial_z E = -\frac{1}{2k_0}\nabla^2 E - k_0\,\Delta n(I)\,E - k_0 \delta n E$$

"time" evolution

"mass" term

"interaction" term

external potential

E: slowly variable envelope of the optical field, $I = |E|^2$

n_0: refractive index of the material with $k_0 = 2\pi n_0/\lambda$

$\Delta n(I)$: nonlinear index variation

δn: refractive index modification

Hydrodynamical description

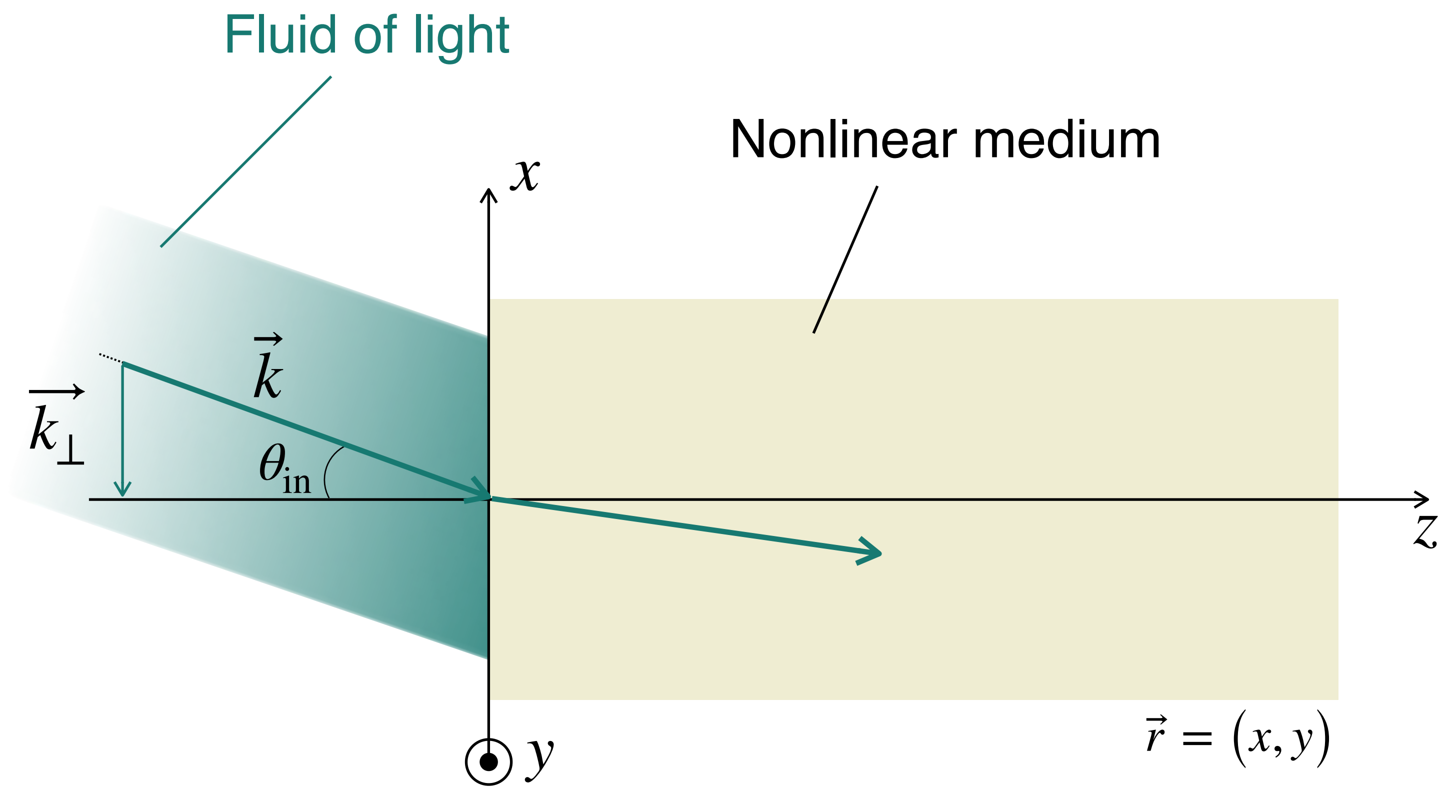
- **Hydrodynamical** description — Madelung transformation, $E = \sqrt{\rho}\,\exp(i\phi)$

⟶ **Euler** equations with

$\rho = |E|^2$: fluid of light **density**

$\boldsymbol{v} = (1/k_0)\nabla\phi$: transversal fluid of light **velocity**

Plane wave: $e^{i(\overrightarrow{k_\perp}\cdot\vec{r}+k_z z)}$



Phase in the transverse plane: $\phi = \overrightarrow{k_\perp}\cdot\vec{r}$

Transverse fluid velocity: $v = (1/k_0)\nabla\left(\overrightarrow{k_\perp}\cdot\vec{r}\right) = \frac{\sin\theta_{in}}{n_0} \simeq \theta_{in}/n_0$

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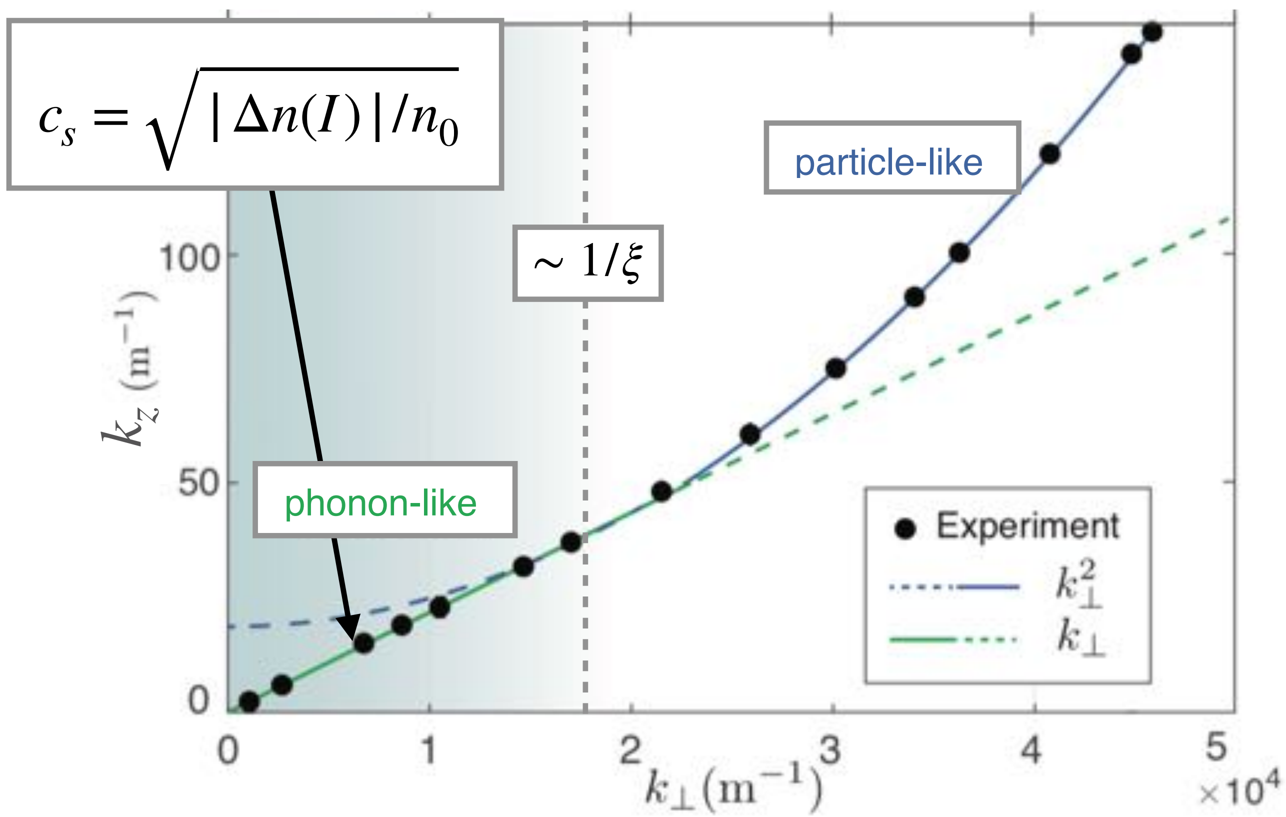

Bogoliubov dispersion relation measured in a hot atomic vapour

Q. Fontaine et al., PRL 121, 183604 (2018)

Characteristic **healing length**

$$\xi = \sqrt{\frac{n_0}{k_0^2\,|\Delta n(I)|}}$$

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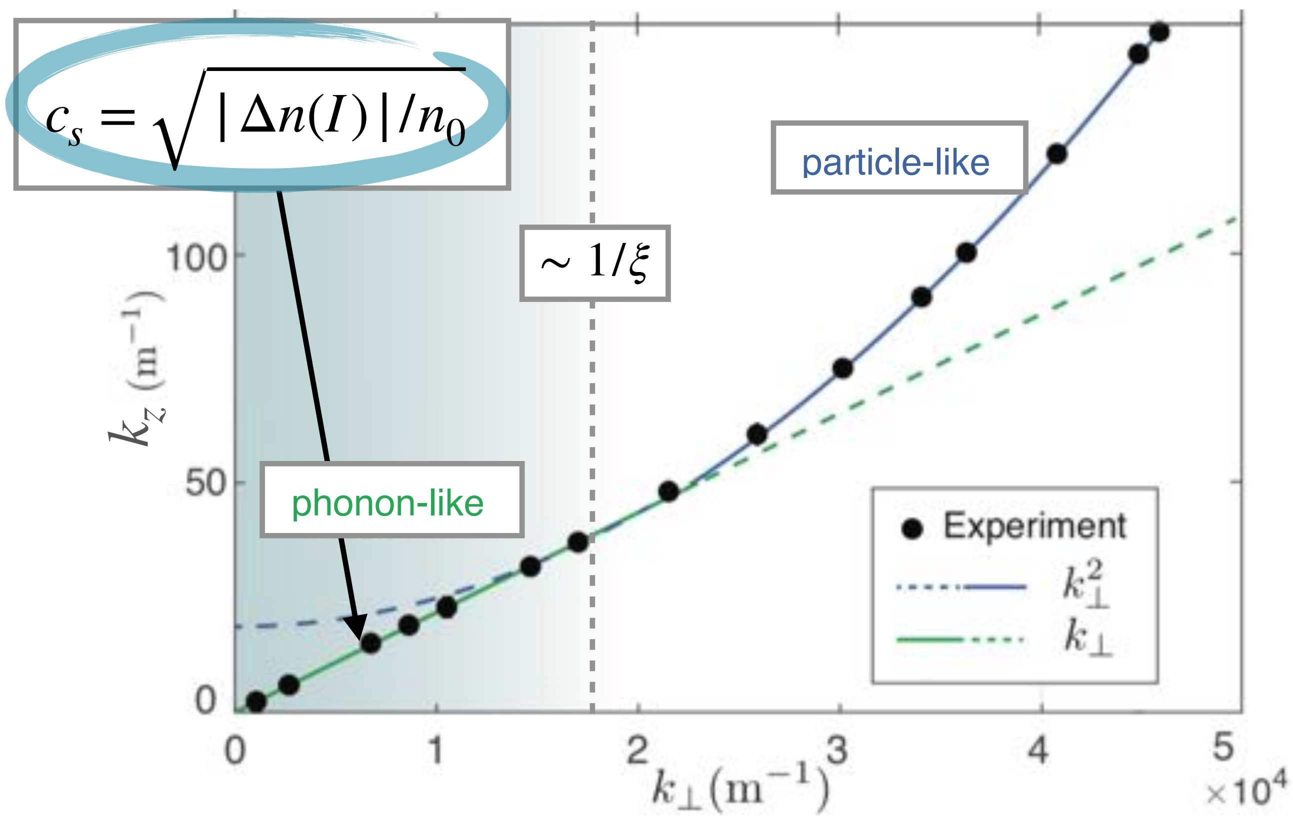

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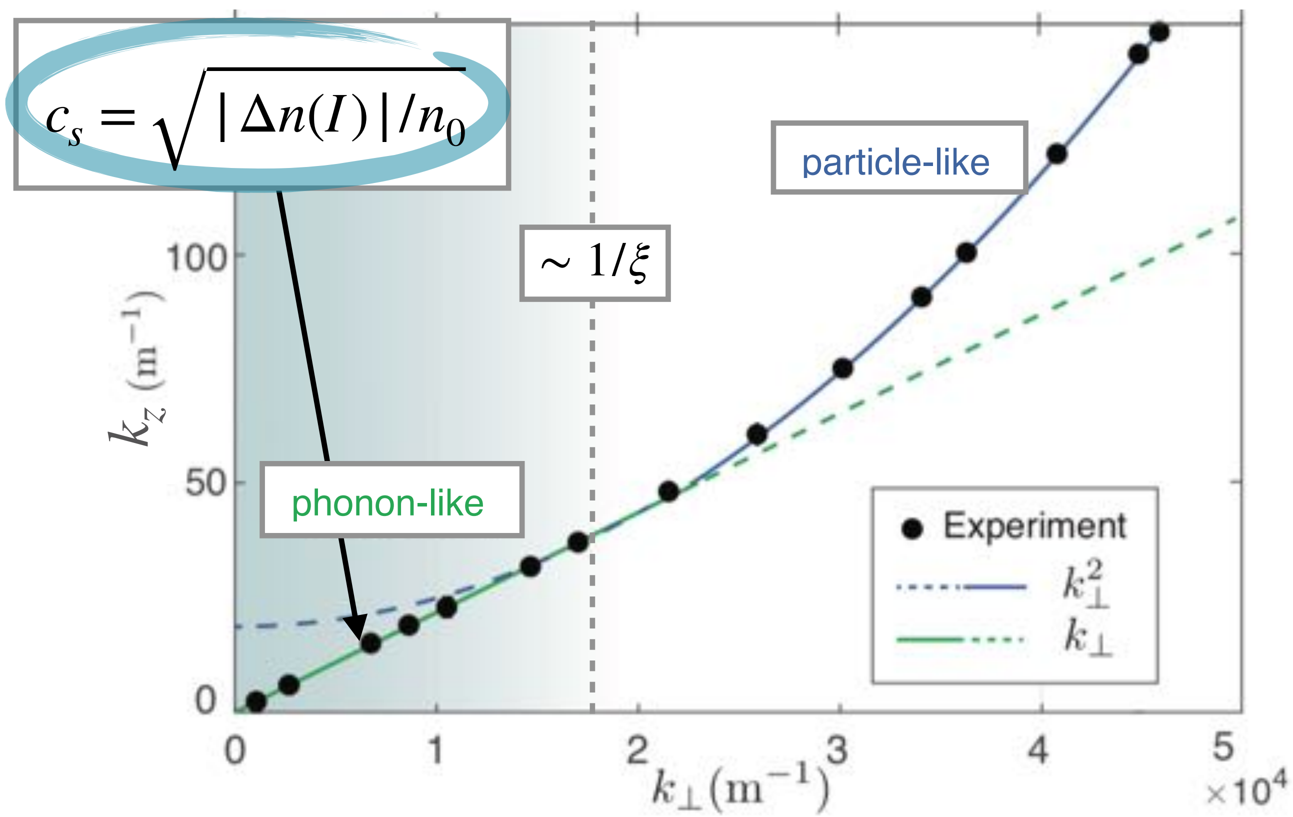

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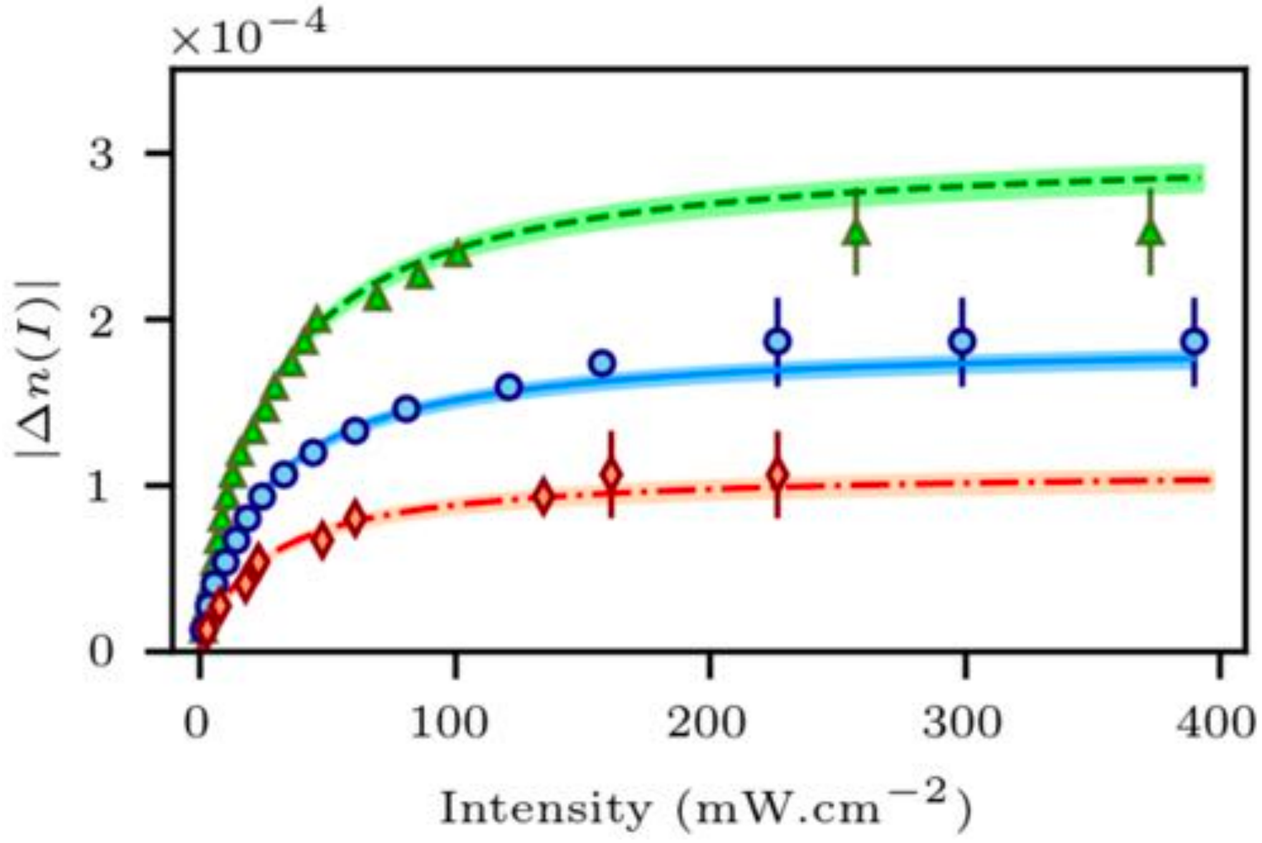
Landau criterion for **superfluidity**
no excitations for $v < \min k_z/k_\perp = c_s$

Photorefractive nonlinear index variation

$$|\Delta n(I)| = |\Delta n_{\max}| \frac{I/I_{\mathrm{sat}}}{1 + I/I_{\mathrm{sat}}} \propto E_{\mathrm{ext}} \frac{I/I_{\mathrm{sat}}}{1 + I/I_{\mathrm{sat}}}$$

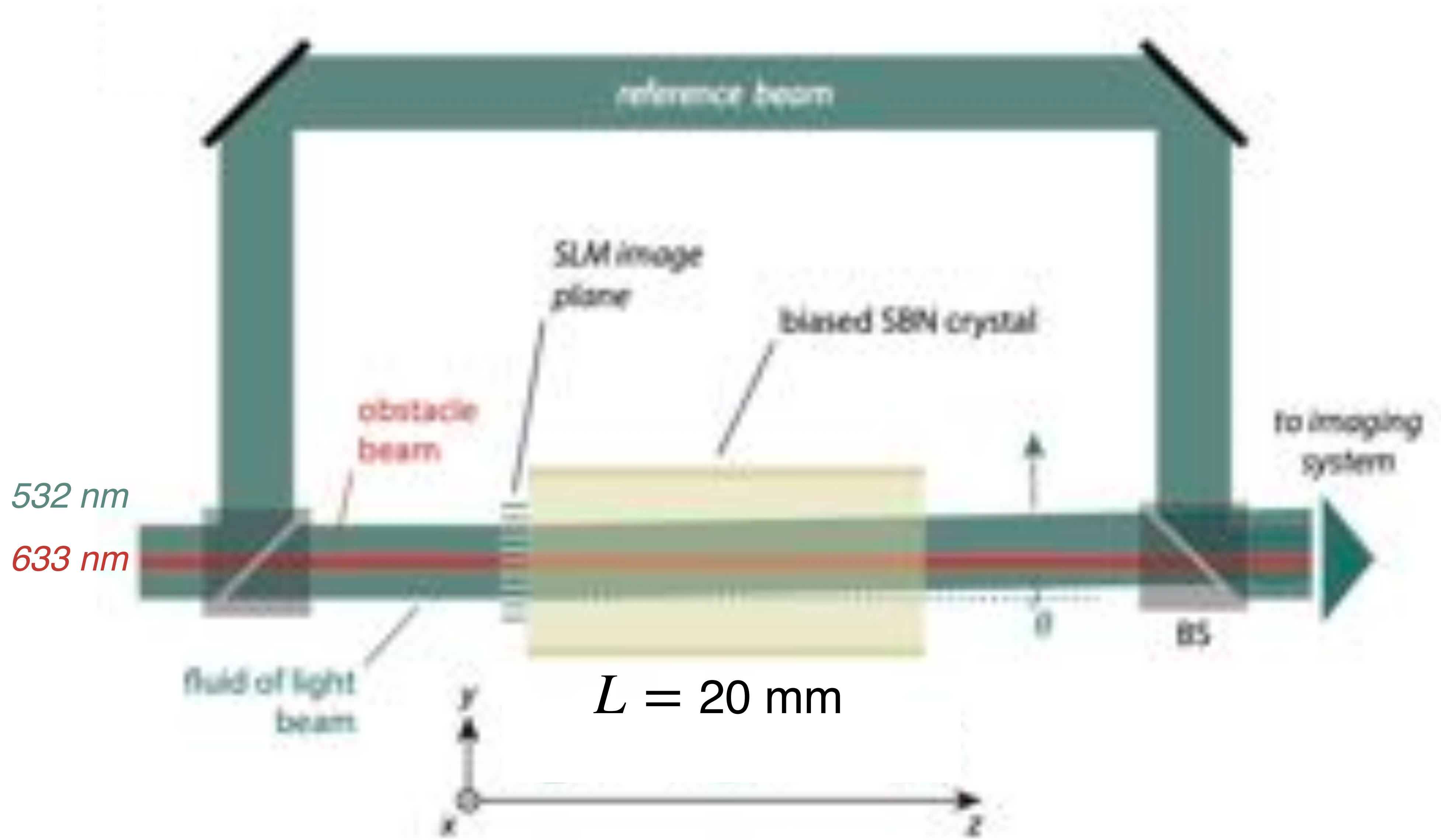
Response of a biased SBN crystal at fixed I_{sat} with varying E_{ext} at 630 nm



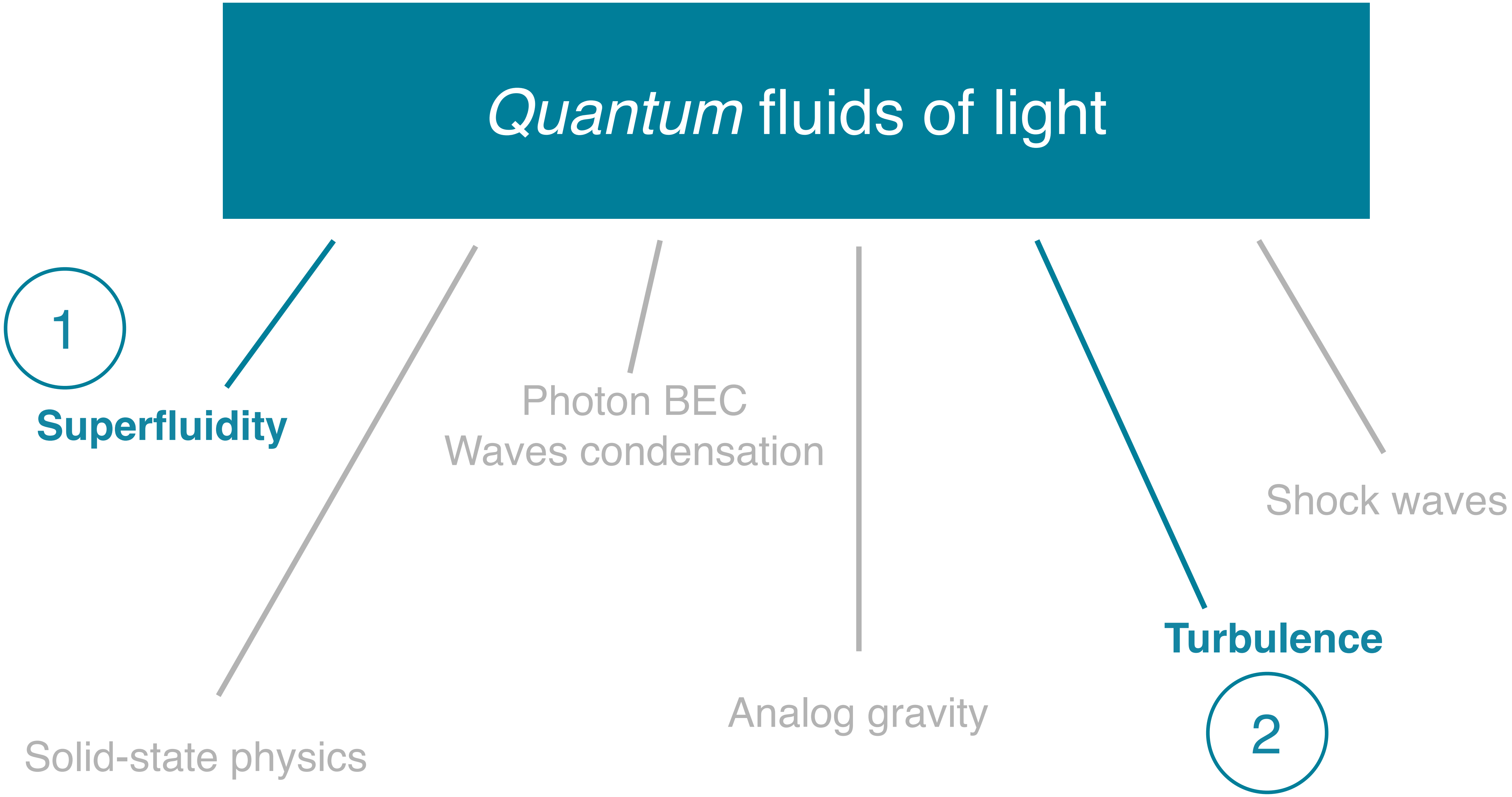
- Healing length $\xi \sim 10\ \mu m$
- v/c_s ranging from 0 to 3

O. Boughdad *et al.*, Opt. Exp. **27**, 21 (2019)

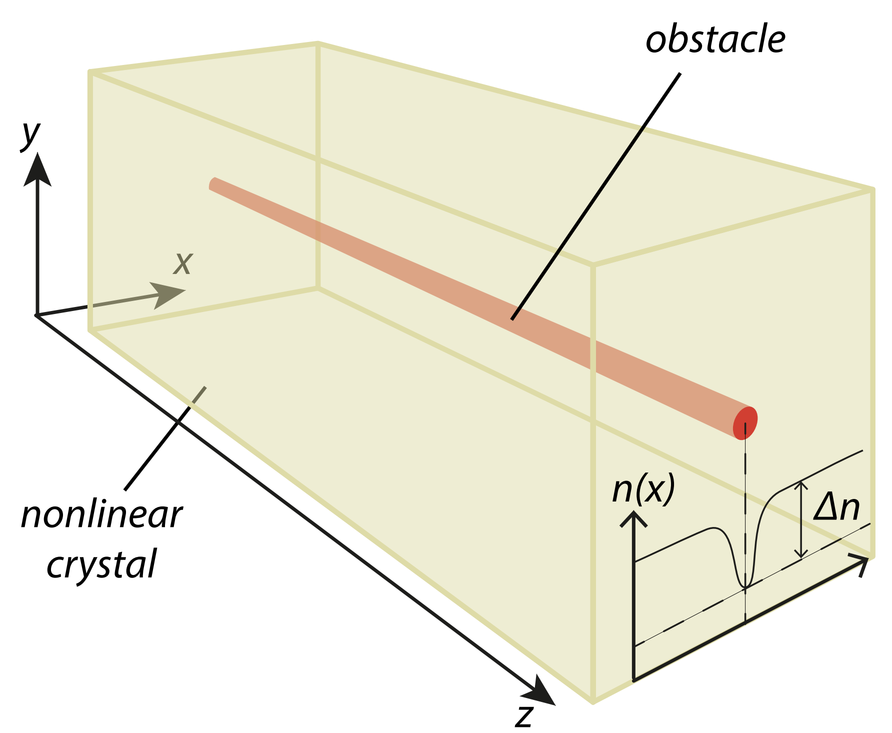
An all-optical implementation



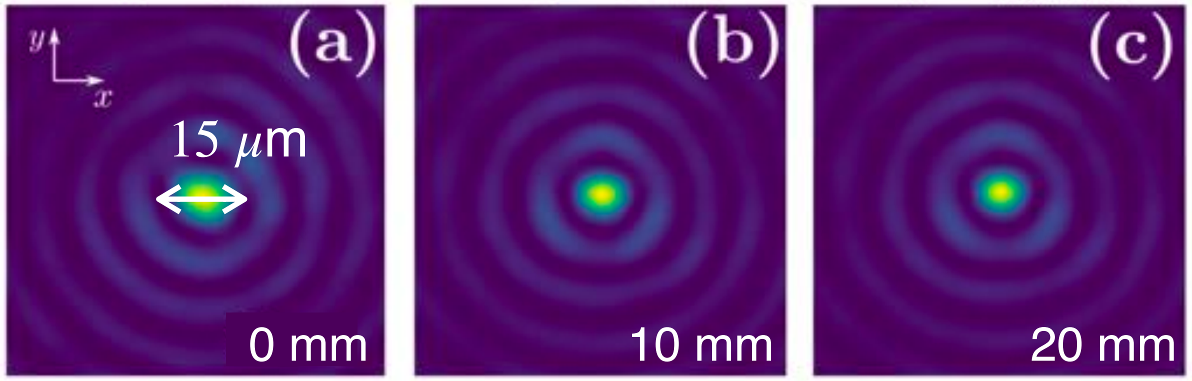
- Control of the fluid of light initial conditions and environnement
- Measurement of the output fluid of light density and velocity field


Quantum fluids of light
1
Superfluidity
Solid-state physics
Photon BEC
Waves condensation
Analog gravity
Turbulence
2
Shock waves

Scattering on a localized defect

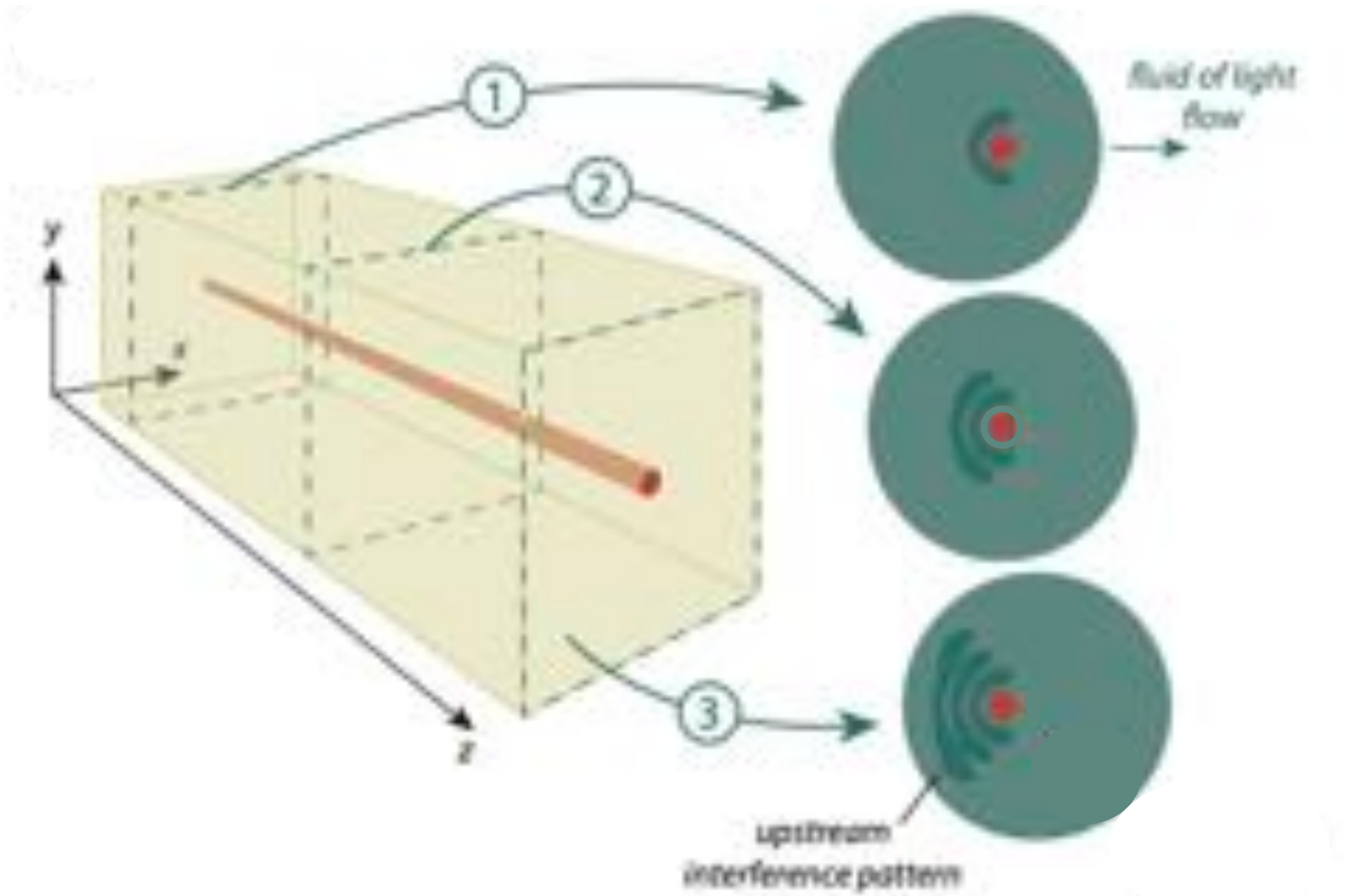


Obstacle = non-diffracting Bessel beam



- **Photo-induced** obstacle through **photorefractive effect**
- **Weakly** perturbing point-like obstacle $\leftrightarrow$ $\Delta n(I_{\rm ob})$ weak, $\varnothing \simeq \xi$

Scattering on a localized defect



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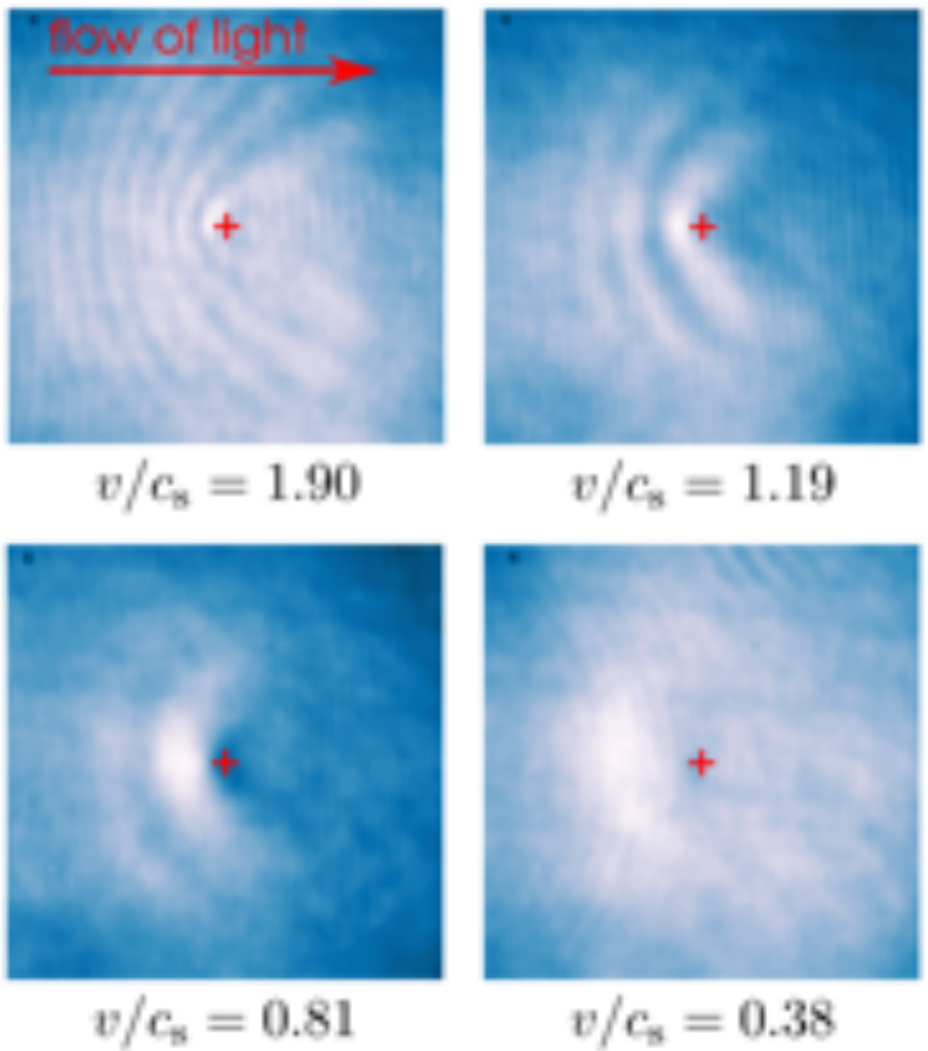
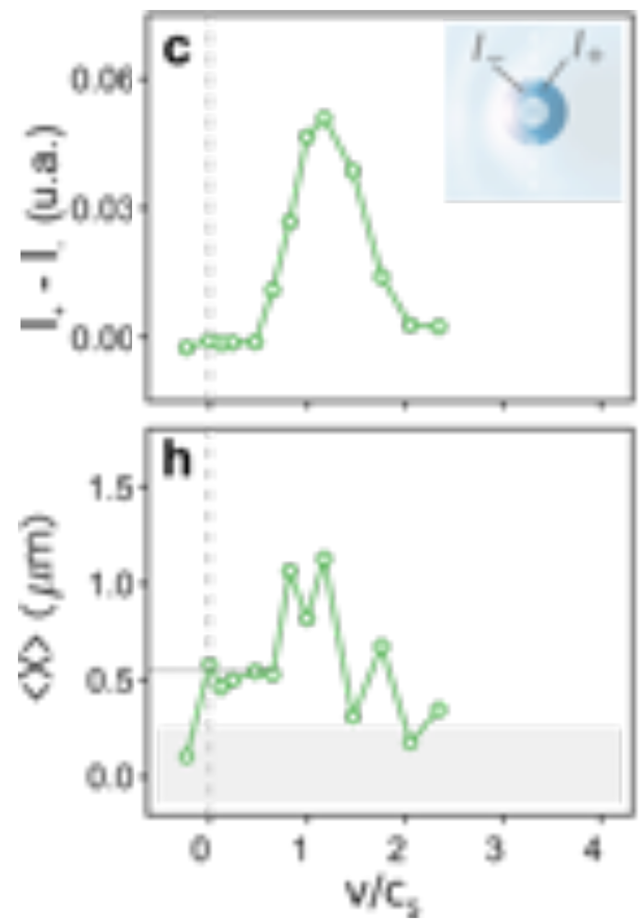
Near-field intensity

Fixed intensity ⟶ **Fixed c_s**

θ_{in} ⟶ **Variation of v**





Optical analog of the **drag-force** experienced by the obstacle

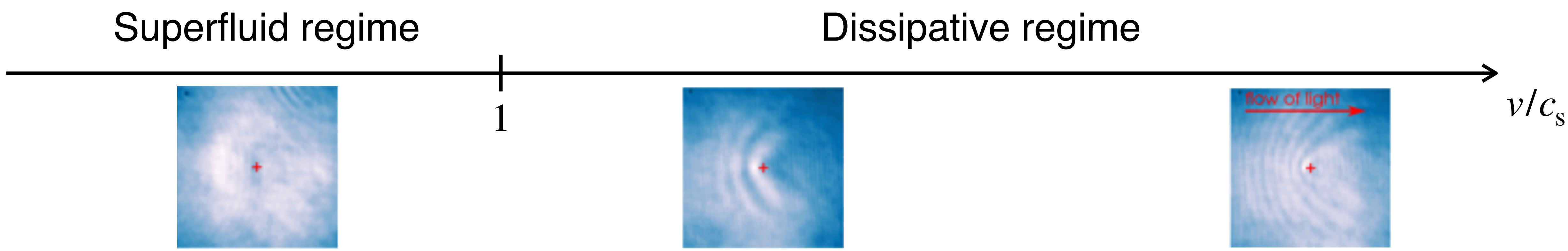
Transverse displacement of the obstacle due to the drag-force

→ Observation of the **superfluid transition** from the **intensity** and the **drag-force cancellation**

C. Michel et al., Nat. Commun. 9, 2108 (2018)

Towards a turbulent regime

Perturbative obstacle $\sim \xi$

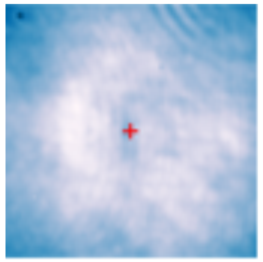


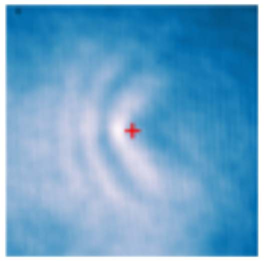
Towards a turbulent regime

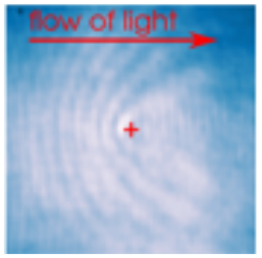
Perturbative obstacle $\sim \xi$

Superfluid regime | Dissipative regime

1   v/c_s







Larger and **stronger** obstacle

Superfluid regime | **Turbulent regime** | Dissipative regime

v/c_s

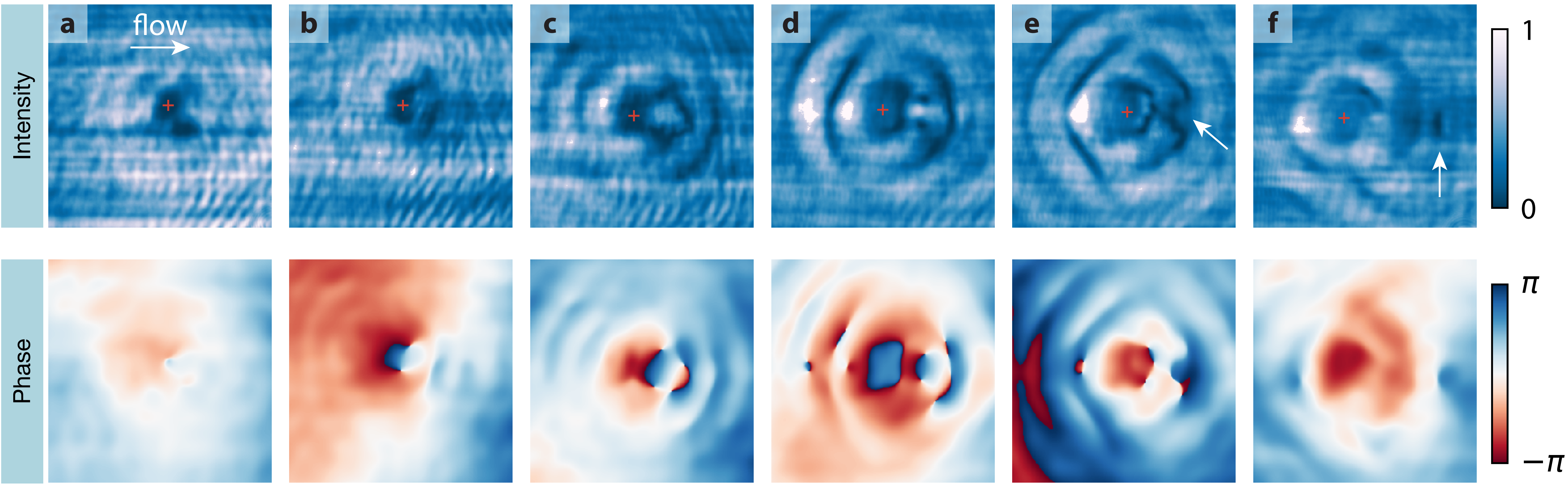
Instabilities

Vortex

Solitons

Coherent structures in the turbulent regime

Large obstacles $\sim 5 - 10 \times \xi$



Observation of **dark solitons** that bend due to **instability** before decaying into **vortices**

A. Eloy et al. Eur. Phys. Lett. 134, 26001 (2021)

Coherent structures in the turbulent regime

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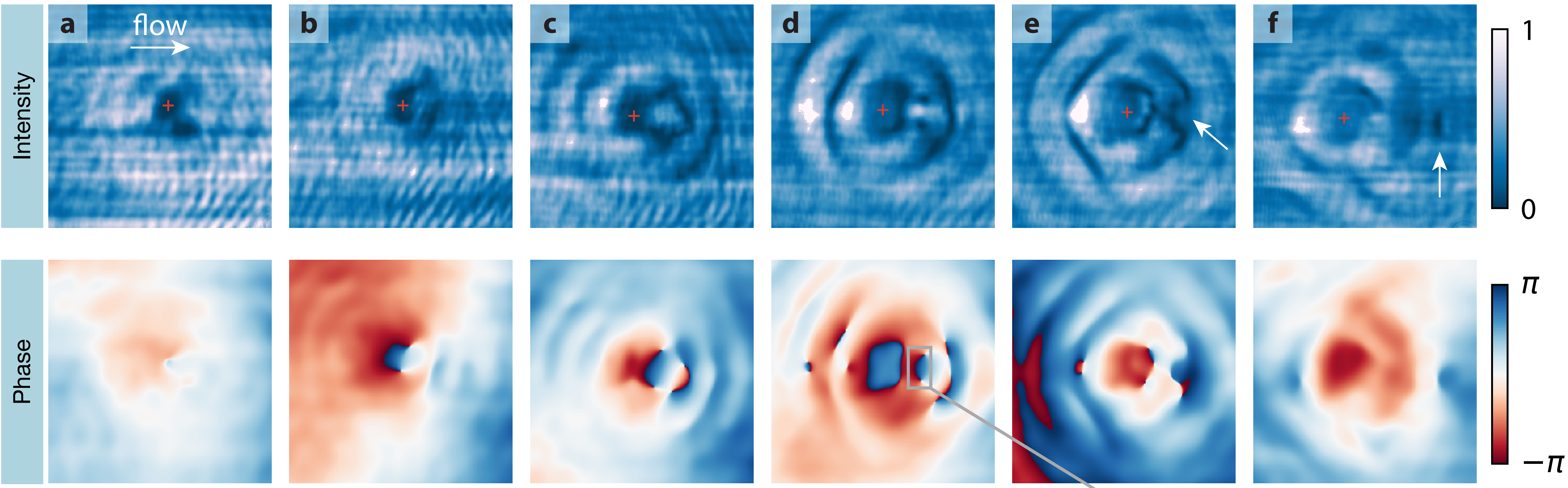
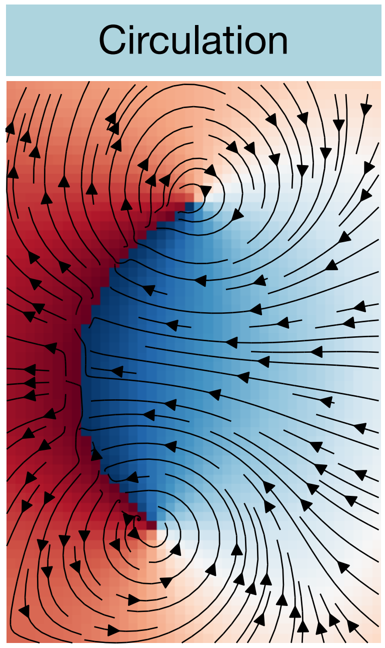


→ Pairs of **vortices** with **opposite** 2π **circulation**



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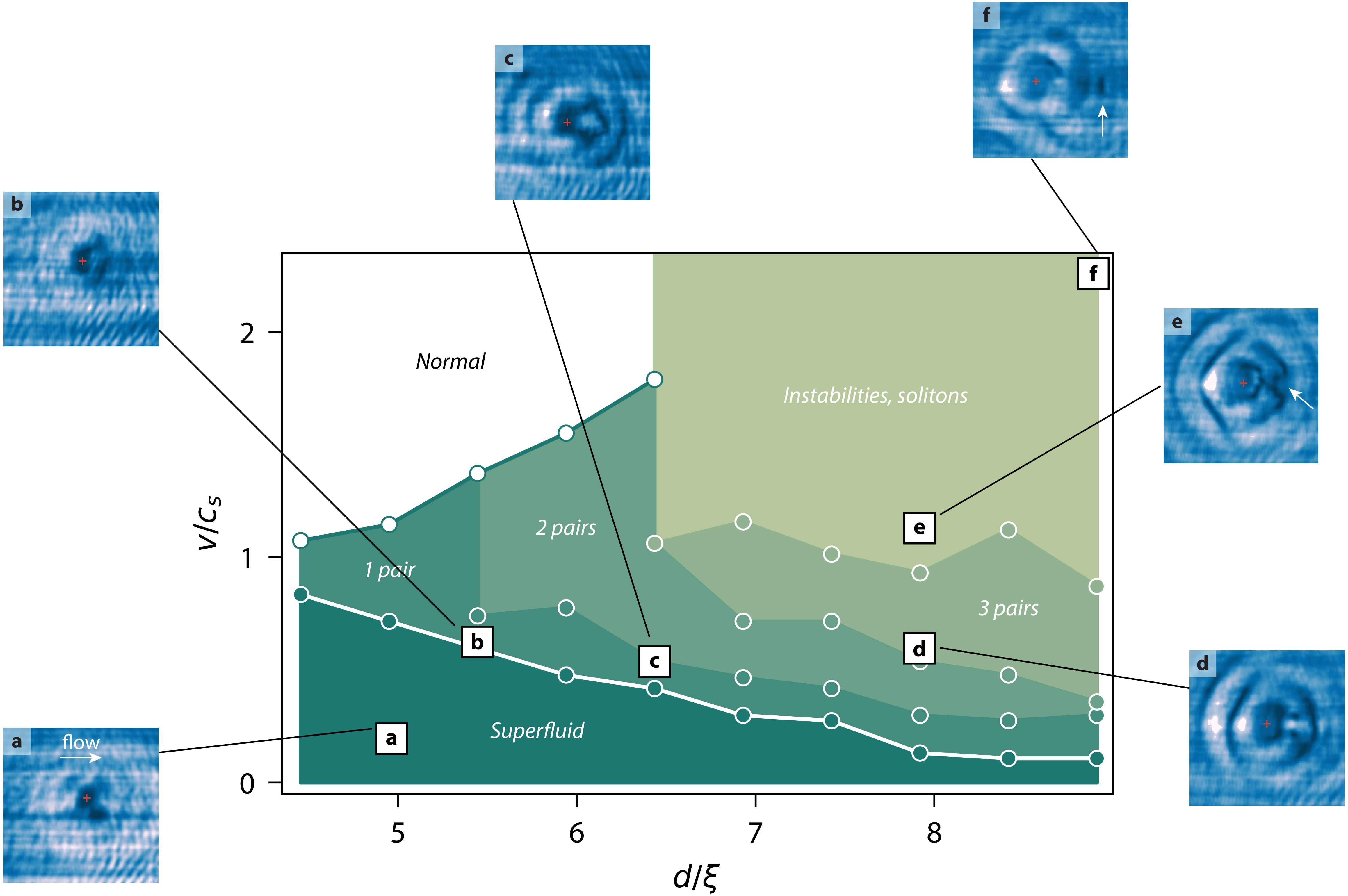
Phase diagram of nonlinear coherent structures



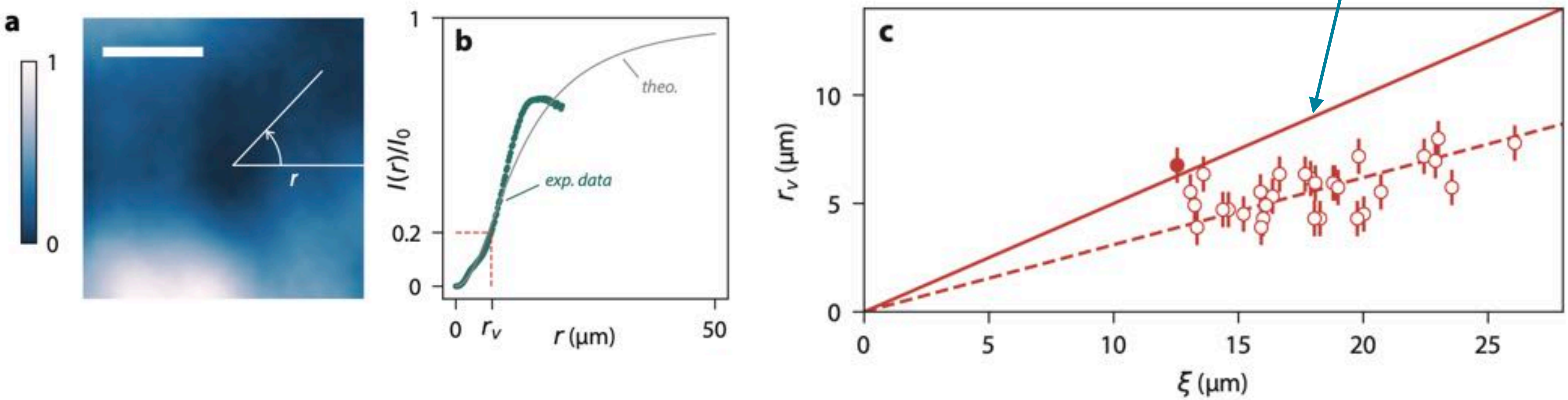
A. Eloy et al. Eur. Phys. Lett. 134, 26001 (2021)

Analysis of an *isolated* vortex

Profile of an isolated vortex: $I_v(r) = I_0 \frac{(r/\xi)^2}{1+(r/\xi)^2}$

Radius of a vortex: $r_v(s) = \sqrt{\frac{s}{1-s}}\xi$ with $I_v(r_v)/I_0 = s$

Prediction for $s = 0.2$

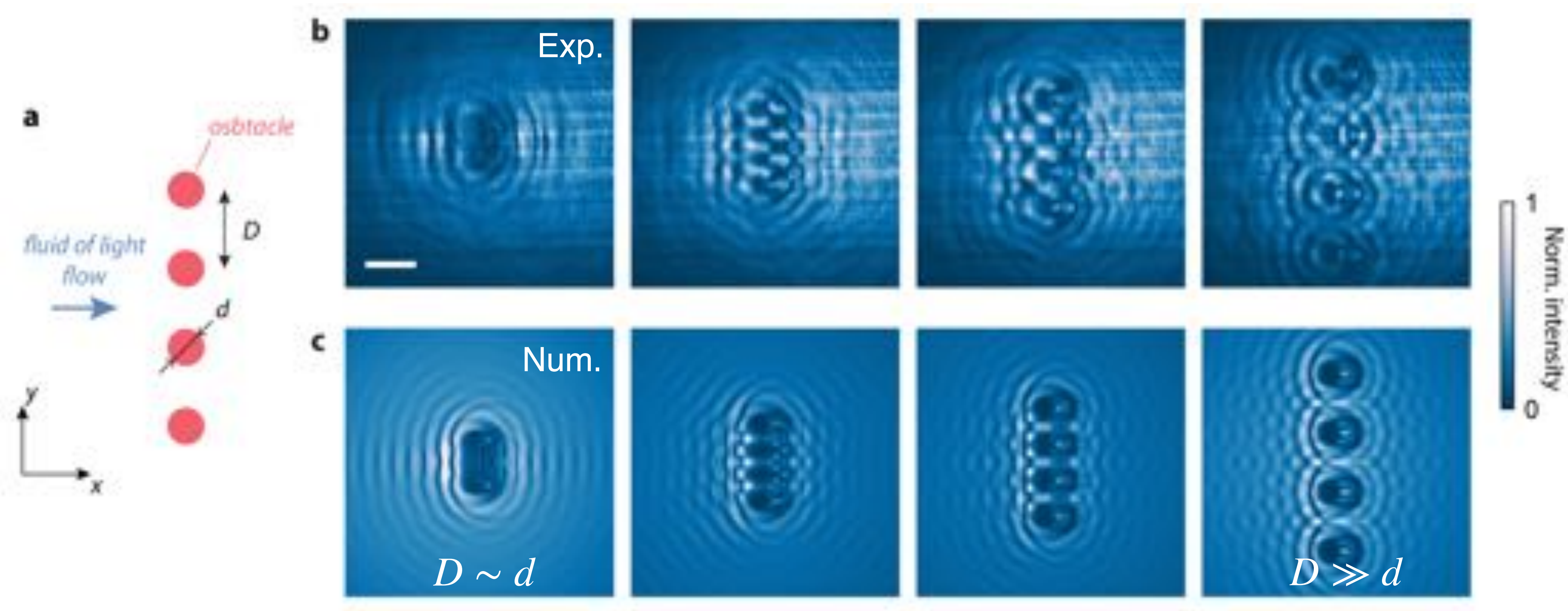


- The close environnement of the vortices modifies their profiles
- Experimental configurations (obstacle diameter/strength or initial velocity) do not strongly influence the size of the vortex core

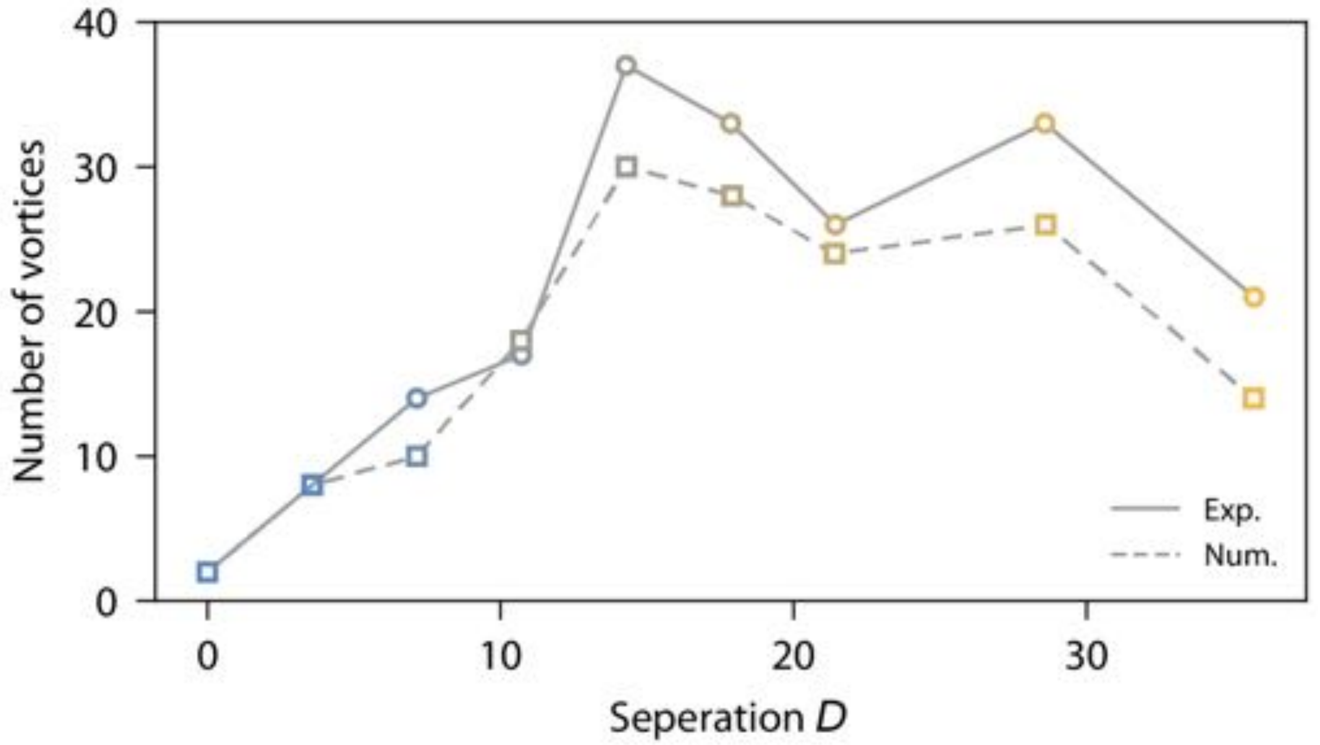
A. Eloy et al. Eur. Phys. Lett. 134, 26001 (2021)

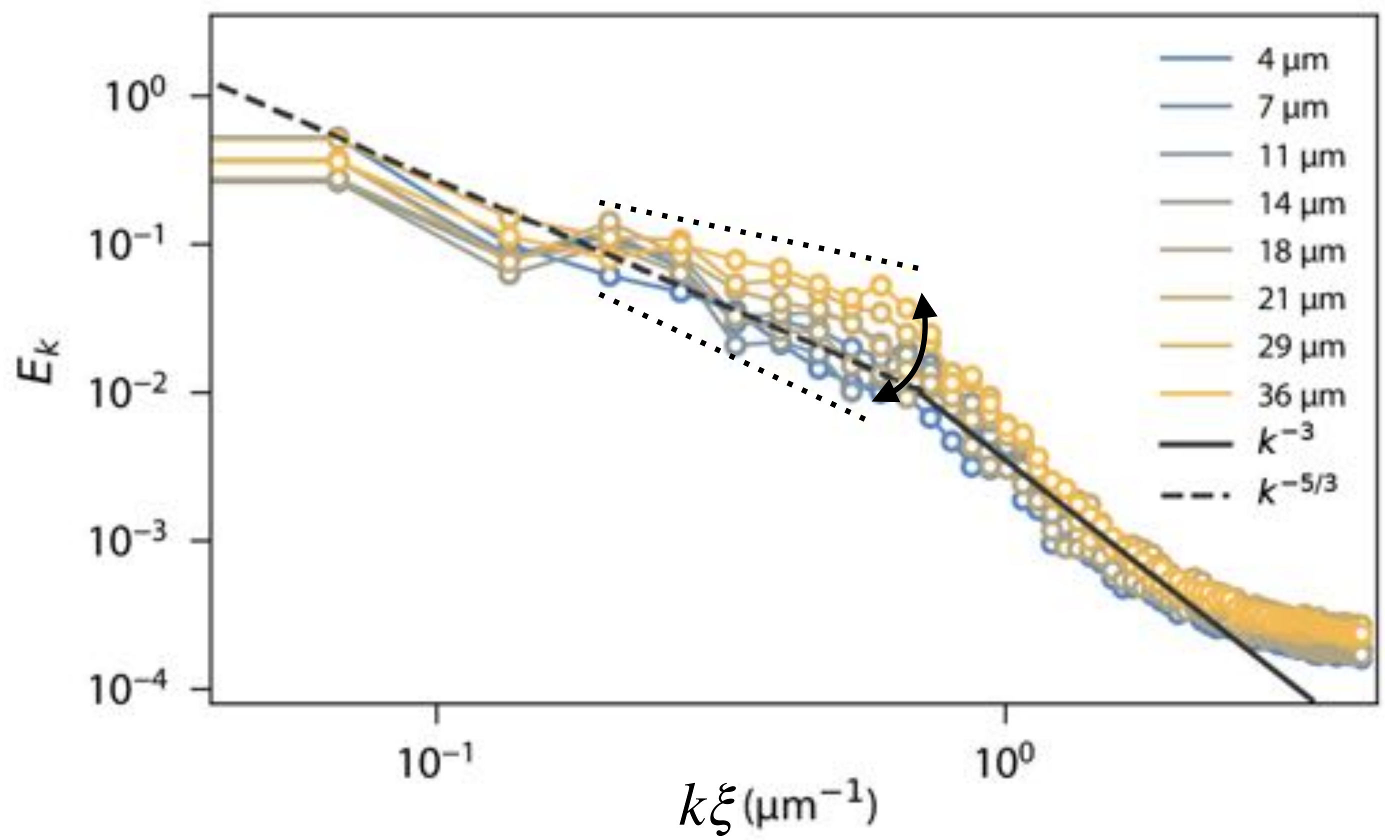
Fluids of light on a line grid

Vertical line grid with four obstacles of diameter d separated by D



Vortices and kinetic-energy spectra



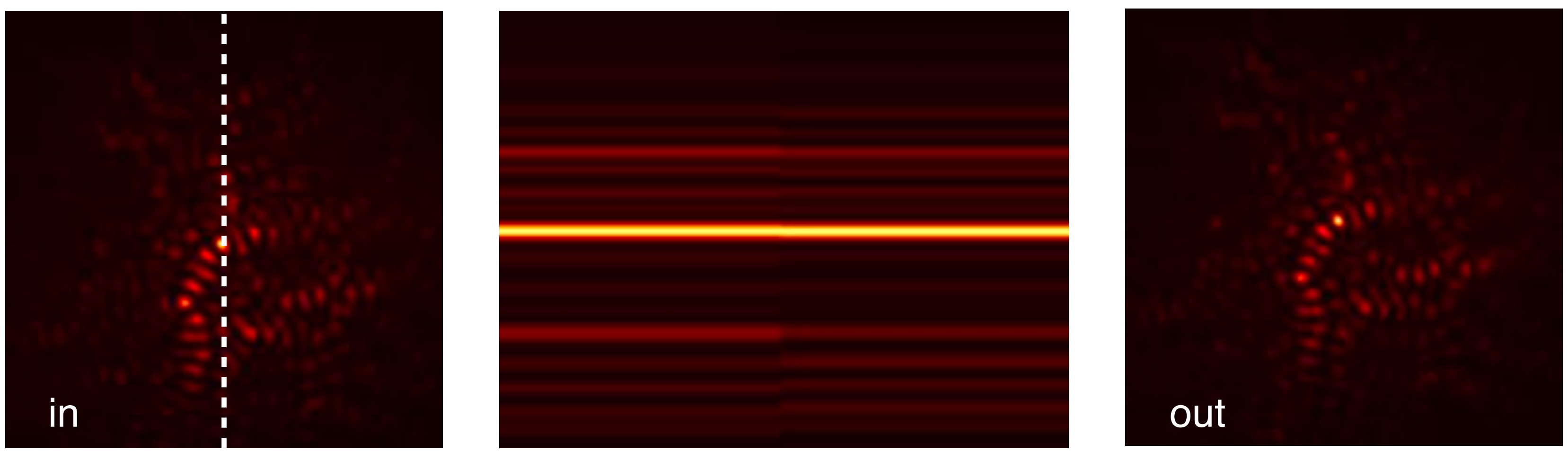


- For $k > 1/\xi \ \rightarrow k^{-3}$ single-vortex contributions
- For $k < 1/\xi$: contribution that depends on the configuration of vortices within the fluid

Bradley et al. Phys. Rev. X 2, 041001 (2012)
M. Abobaker et al. arXiv:2211.08441 (2022)

Near-future topics

Superfluid and turbulent light in complex media



Photoinduced non-diffracting disorder in a 2cm long crystal

anr® – *STLight project*

C. Michel, C. Keyrouz (PhD)

3D fluids of light

Temporal dimension — combine slow (photorefractive) and fast (Kerr) nonlinear responses

Conclusion

Fluids of light in photorefractive crystals

A versatile photonic platform to study
quantum hydrodynamical phenomena in *complex landscapes*

Collaborations

Claire Michel
Mathias Albert
Pierre-Elie Larré
Fabrice Mortessagne
Sergey Nazarenko

Carelle Keyrouz (PhD, 2022-2025)
Juliette Huynh (PhD, 2021-2024)
Adam Griffin (post-doc, 2021)
Aurélien Eloy (post-doc, 2019-2021)
Omar Boughdad (PhD, 2016-2020)

Anthony Guiri, Maïlys Guérault,
Loïc Barbaro, Milino Kerowgodage

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European Commission
PhoQuS
Project #820392

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Waves in complex systems @ INPHYNI

Wavefront shaping in microwave waveguide

Chaotic reverberation chamber

Correlated disorder and wave transport → *Poster A. Razo Lopez*

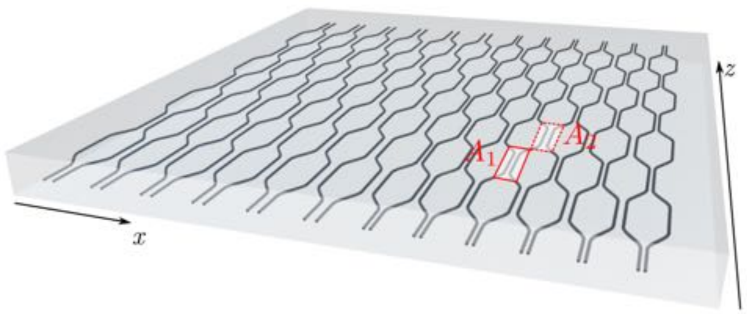
Optical wave turbulence/fluids of light → *Poster L. Zanaglia*

Topological photonics → *Talk M. Reisner*

Direct-laser-writing of complex structures

Direct-laser-writing in glass chips and optical fibers

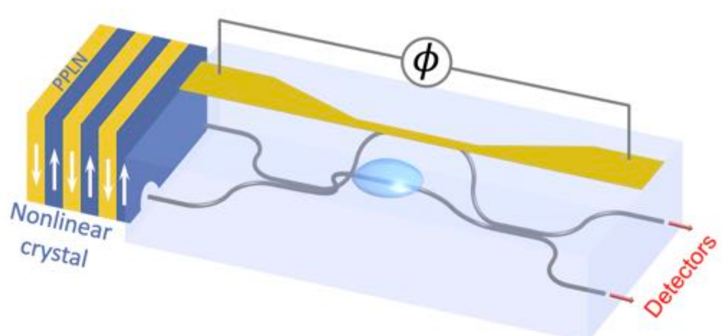
Fabrication of complex 3D photonic nano/microstructures



Topological photonics

U. Kuhl, C. Michel,
F. Mortessagne (INPHYNI)
P. Delplace (ENS Lyon)
S. Tzortzakis (IESL, Greece)

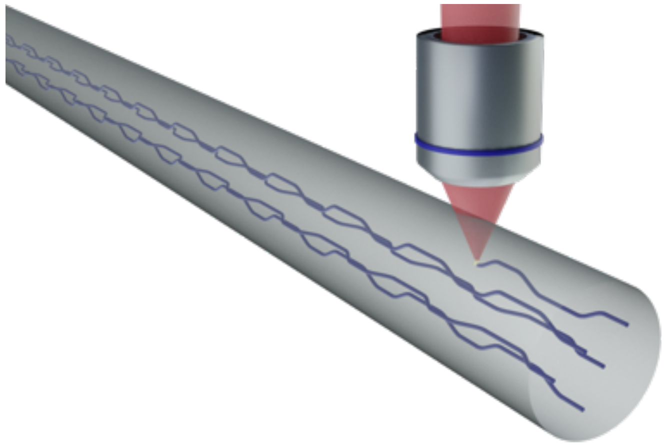
Bellec et al., Eur. Phys. Lett. 119, 14003 (2017)



Quantum biosensors

L. Labonté, A. Haykal (INPHYNI)

Postdoc position opening early 2023



DLW in optical fibers

L. Colliard, G. Aubry, W. Blanc (INPHYNI)
M. Bernier, R. Vallée (COPL, Québec)

Colliard et al., Opt. Lett. 47, 6253 (2022)