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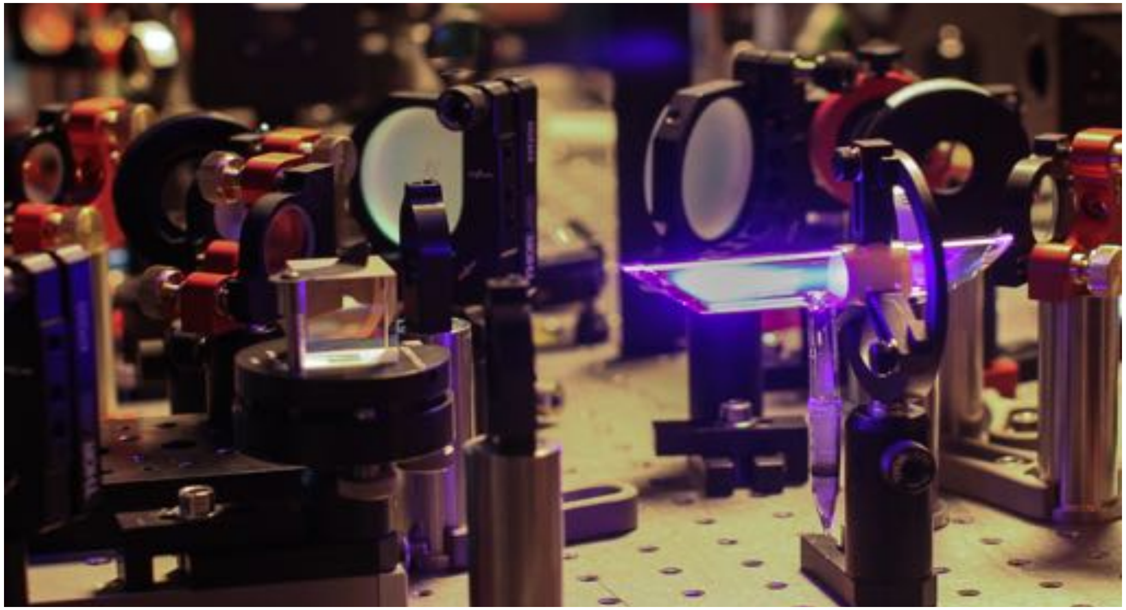


GdR Complexe, 08 December 2022

PRETHERMAL RELAXATION AND CORRELATED QUANTUM FLUCTUATIONS IN A QUENCHED FLUID OF LIGHT

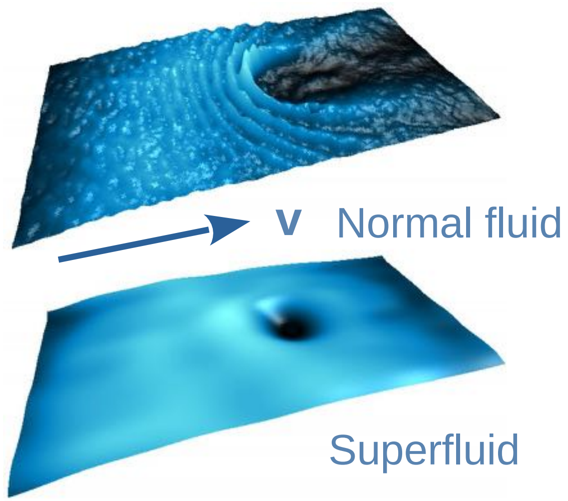
MURAD ABUZARLI

Supervised by Dr. QUENTIN GLORIEUX

PhoQuS
Photons for Quantum Simulation

Fluids of light

Can light behave as a quantum fluid?



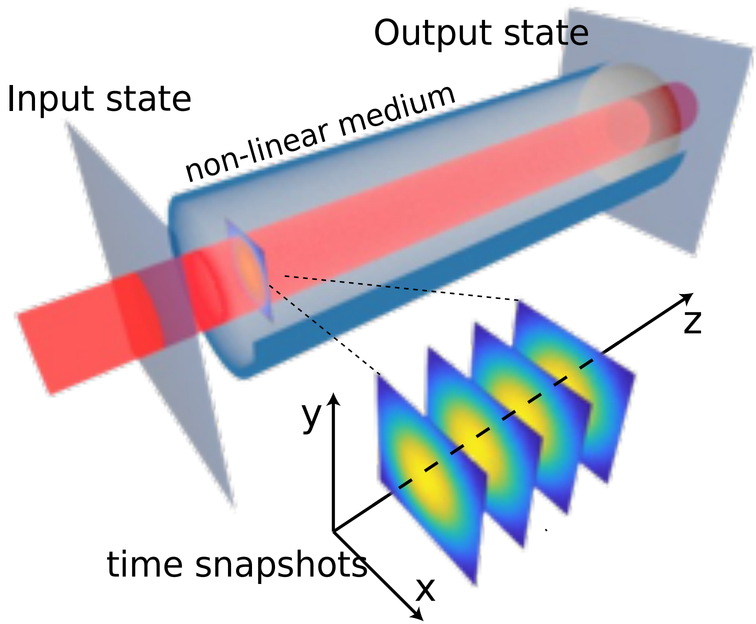
Gross Pitaevskii equation

$$i\hbar\frac{\partial\psi}{\partial t} = \left(-\frac{\hbar^2}{2m}\nabla^2 + V + g|\psi|^2\right)\psi$$

Kinetic energy, atomic **mass** m

External potential

Mean field **contact interaction**



Non-Linear Schrödinger equation:

$$i\frac{\partial\mathcal{E}}{\partial z} = \left(-\frac{1}{2k_0}\nabla_\perp^2 + \frac{k_0\delta\chi^{(1)}(\mathbf{r})}{2} + \frac{k_0\chi^{(3)}}{2}|\mathcal{E}|^2 - \frac{i\alpha}{2}\right)\mathcal{E}$$

Diffraction, laser **wavevector** k_0

Losses (absorption)

Transverse refractive index variation

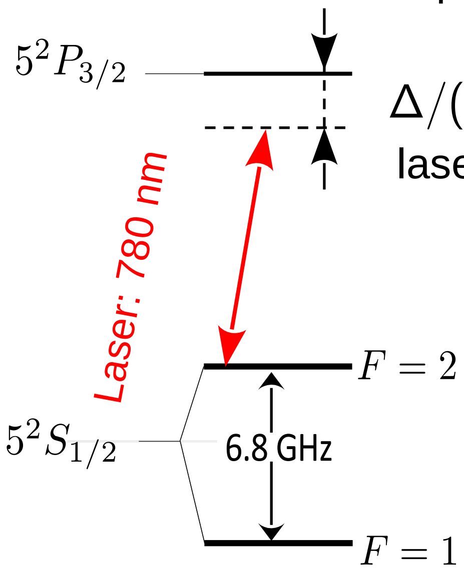
Non-linear refraction (Kerr effect) $\frac{k_0\chi^{(3)}}{2}|\mathcal{E}|^2 = -k_0 n_2 I$

The propagation direction plays the role of time, the “fluid” is 2D

Controlling Kerr effect

Why hot Rubidium vapor cells

Rubidium atom: simple picture

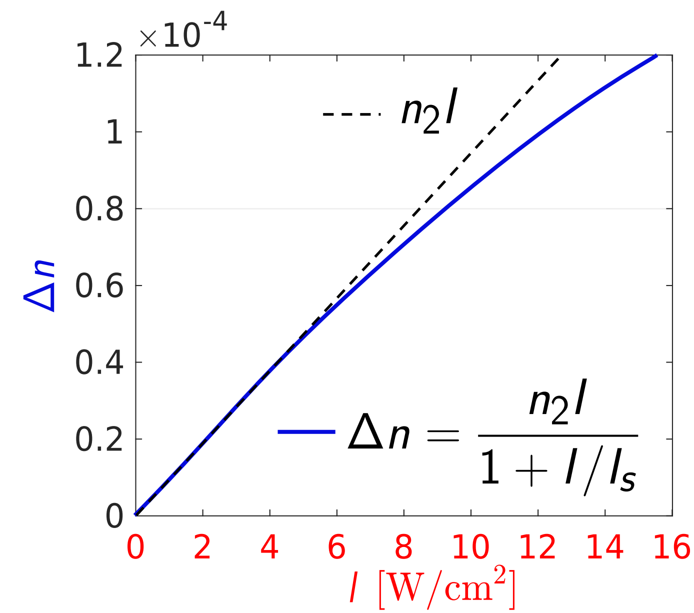


$\Delta/(2\pi) \simeq -2GHz$
laser detuning

Refractive index:

$$n = 1 + \frac{1}{2}\frac{\mathrm{Re}\left[\chi^{(1)}\right]}{1 + I/I_s}$$
$$= n^{(1)} + \Delta n(I)$$

Resonant Kerr non-linearity from saturation

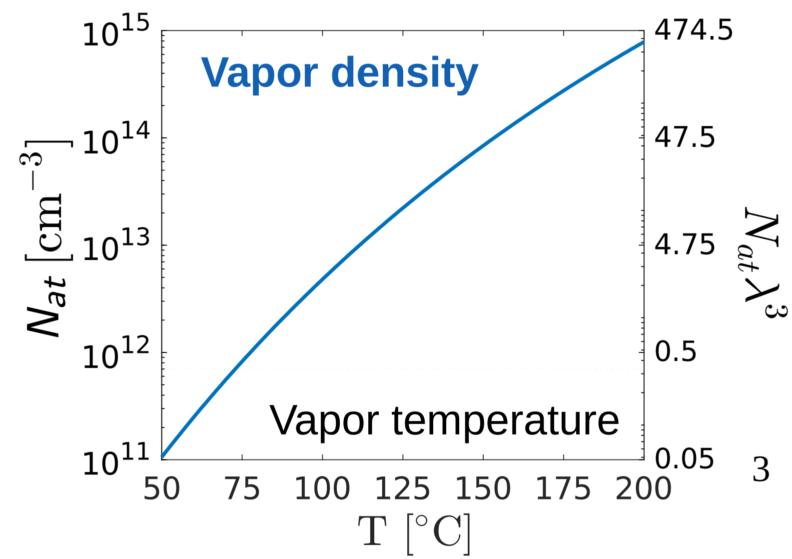


The Kerr index: interaction constant

$$n_2 = \frac{\mathrm{Re}\left[\chi^{(1)}\right]}{2I_s} \propto \frac{N_{at}}{\Delta^3}$$

Two control knobs for the interactions

- N_{at} atomic density (controlled by the temperature)
- Δ detuning (controlled by the laser frequency)

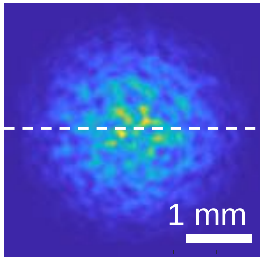


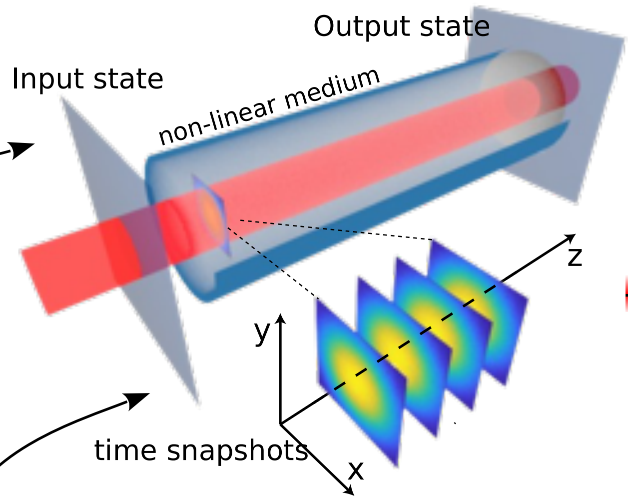
Nonequilibrium fluid of light

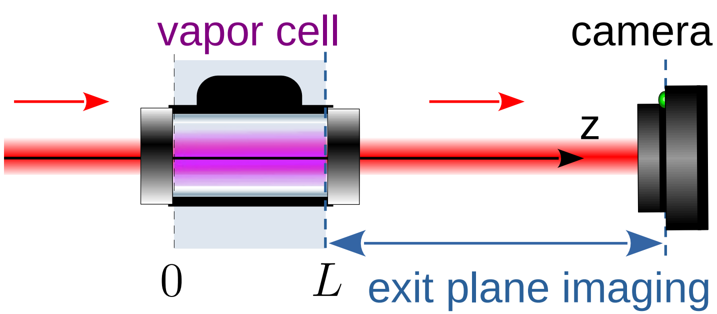
Paraxial fluids of light: naturally out of equilibrium

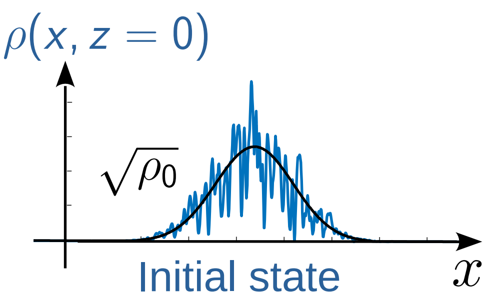
Nonequilibrium initial state:
Controllable way to drive the system out of equilibrium

Readout at fixed time:
Access to the system's non-steady dynamics









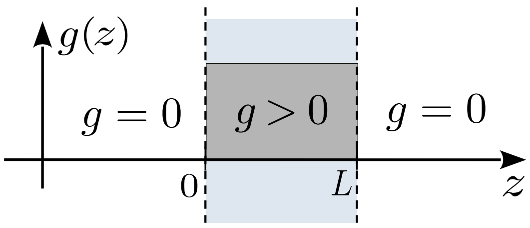
$$\mathcal{E}(\mathbf{r}, z) = \sqrt{\rho_0} + \delta\mathcal{E}(\mathbf{r}, z)$$

Background + fluctuations:

classical (wavefront shaping)

quantum (shot noise)

$$g \propto -n_2$$



Interaction quench:
sudden variation of a system parameter induces the system's nonequilibrium evolution

Two experiments

Prethermal relaxation

Probing the fluid’s relaxation after the onset of interactions

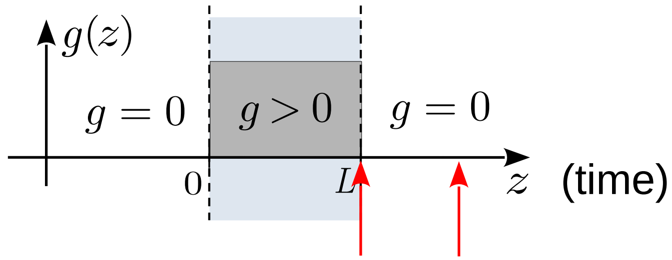
Spatial coherence

$$g^{(1)}(\Delta r = 2r, z) = \langle \mathcal{E}^*(-\mathbf{r}, z)\mathcal{E}(\mathbf{r}, z)\rangle$$

Evolution of the stimulated (classical) fluctuations

M. Abuzarli, N. Cherroret, T. Bienaimé, Q. Glorieux,
PRL. 129, 100602 (2022)

Interaction strength



Observation time

Correlated quantum fluctuations

Probing the fluid’s response after two interaction quenches

Static structure factor of the spatial intensity fluctuations

$$S(\mathbf{q}, z) \propto \langle |\delta\rho(\mathbf{q}, z)|^2\rangle$$

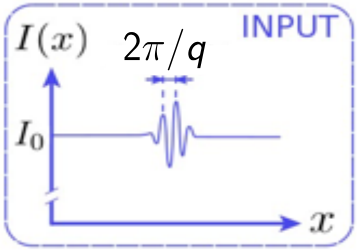
Evolution of the intrinsic spatial shot noise fluctuations

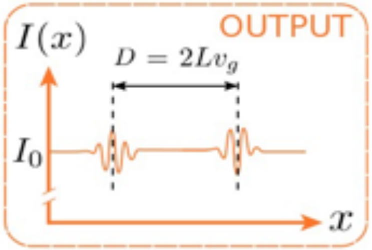
J. Steinhauer, M. Abuzarli, T. Aladjidi, T. Bienaimé, C. Piekarski, W. Liu, Elisabeth Giacobino, Alberto Bramati, Quentin Glorieux, Nat Commun 13, 2890 (2022)

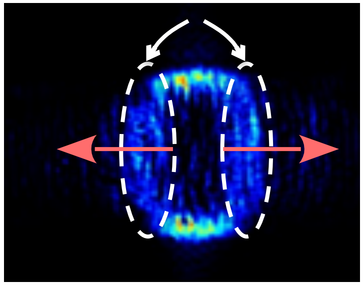
State of the art: Bogoliubov dispersion

Dispersion of weak intensity perturbations

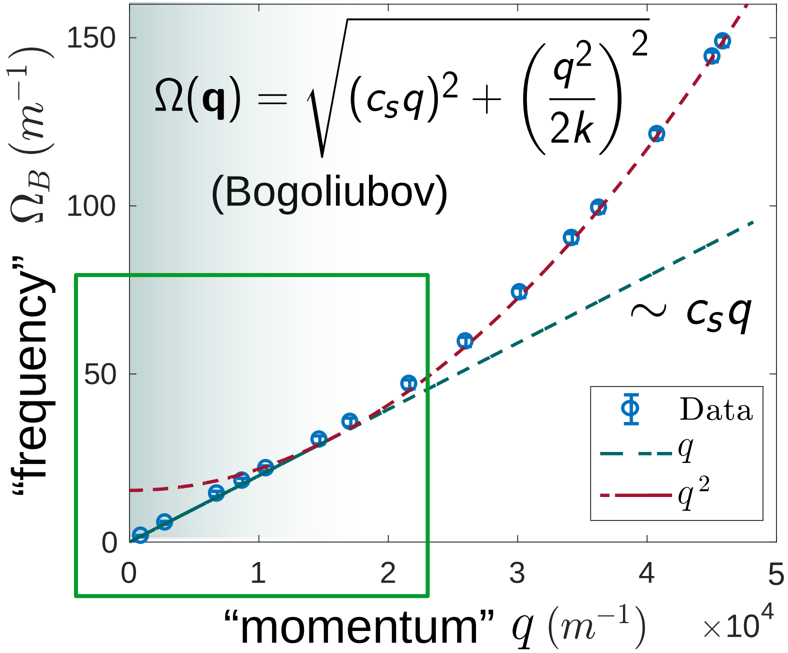
Background fluid at equilibrium

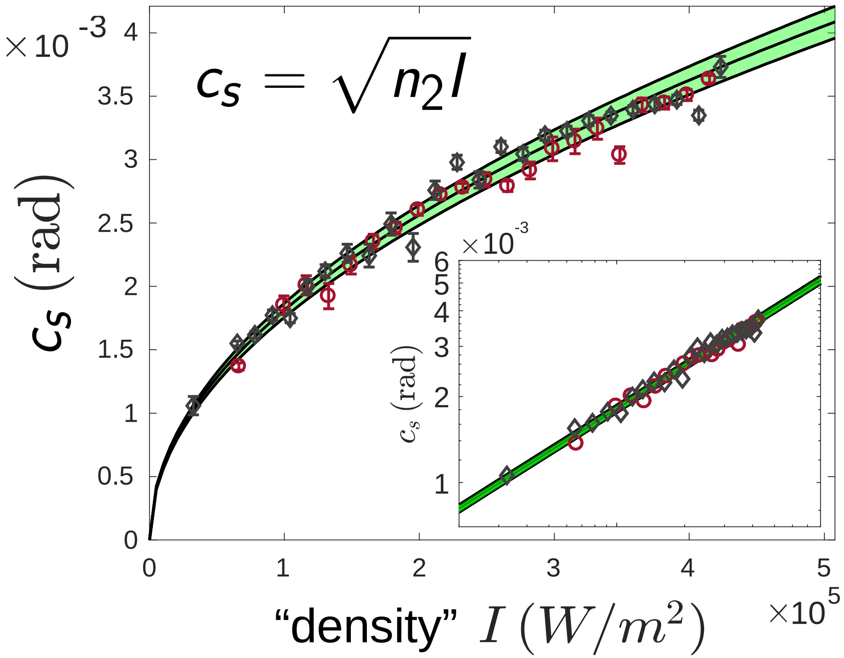






Perturbation image (output)



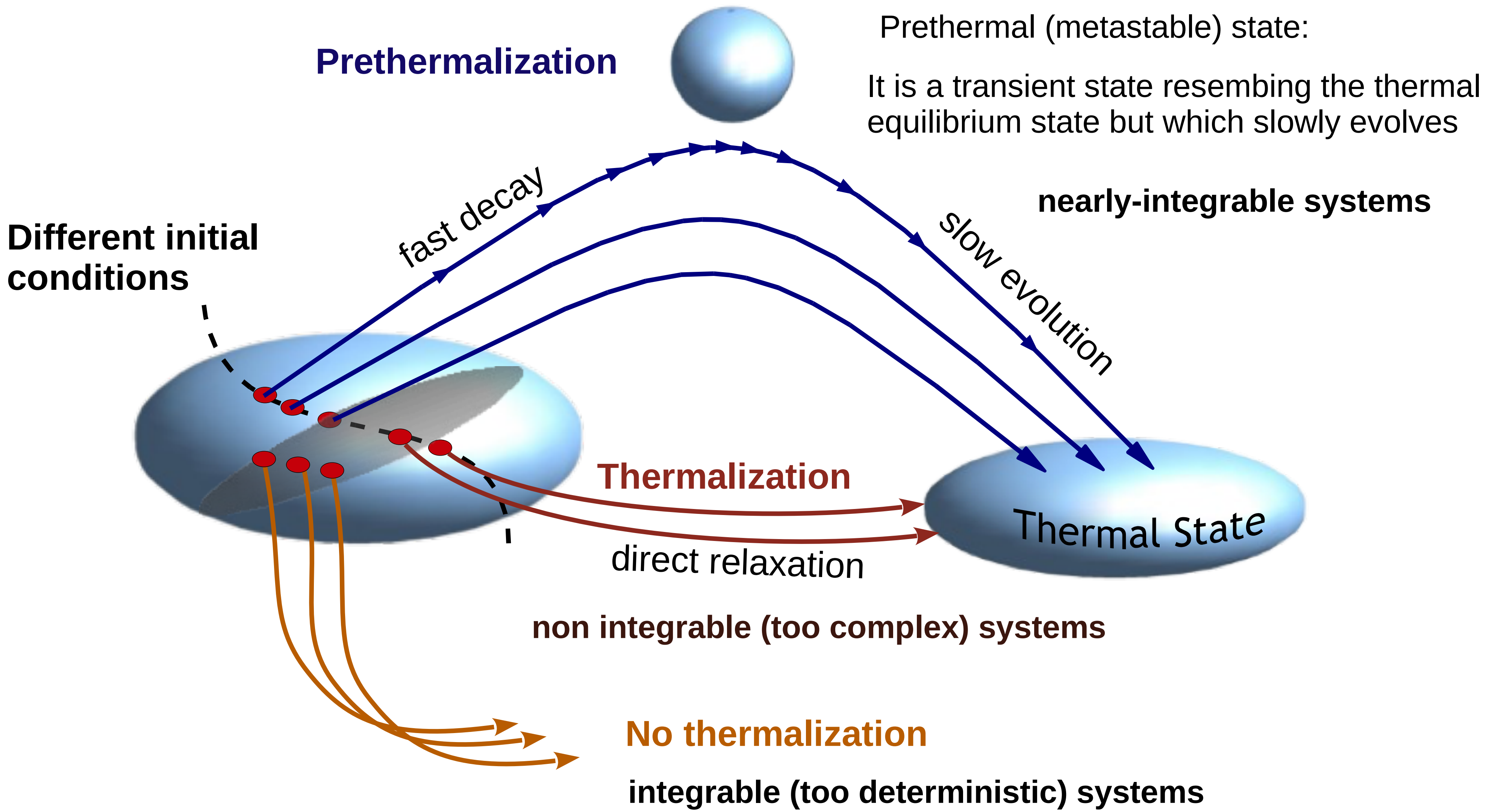


Low momentum density perturbations behave as sound waves

Q.Fontaine, T. Bienaimé, S. Pigeon, E. Giacobino, A. Bramati, and Q. Glorieux, PRL121:183604, 2018

Prethermal relaxation of a fluid of light

Can an isolated quantum system thermalize?



Tim Langen et al J. Stat. Mech. (2016) 064009; 1D Bose gas: Schmiedmayer group Vienna (2012)

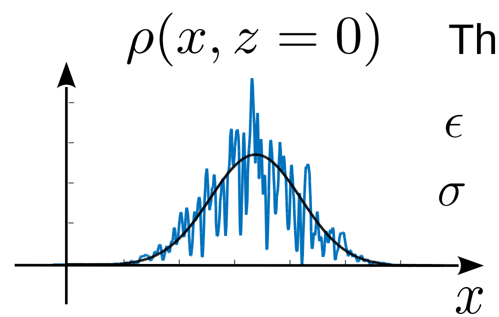
Prethermal relaxation of a fluid of light

Dynamics of a paraxial fluid of light driven out of equilibrium

Initial state:

$$\mathcal{E}(\mathbf{r}, z=0) = \sqrt{\rho(\mathbf{r})}\,[1 + \epsilon\psi_s(\mathbf{r})]$$

Background — weak fluctuations (speckle)

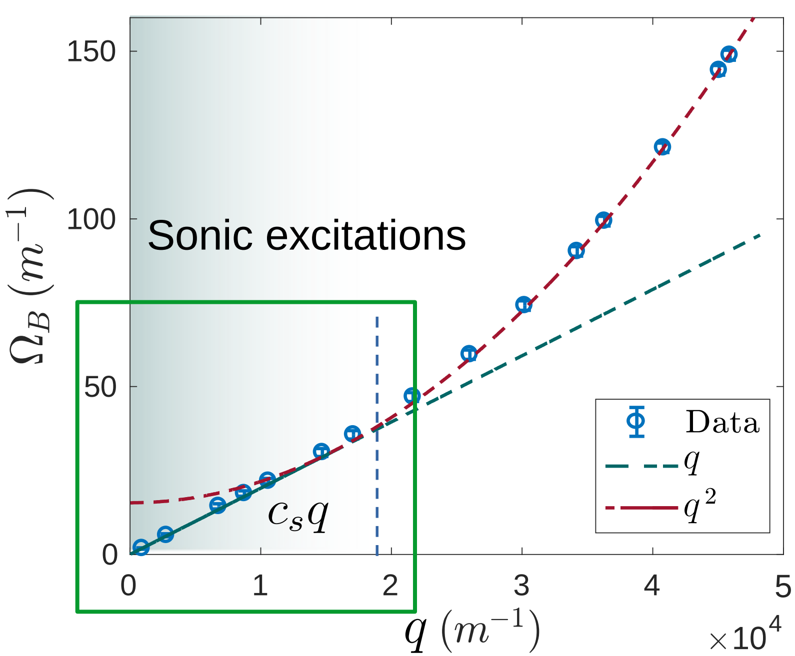


The initial state characterized by:

- ϵ Fluctuation strength
- σ Fluctuation's correlation length

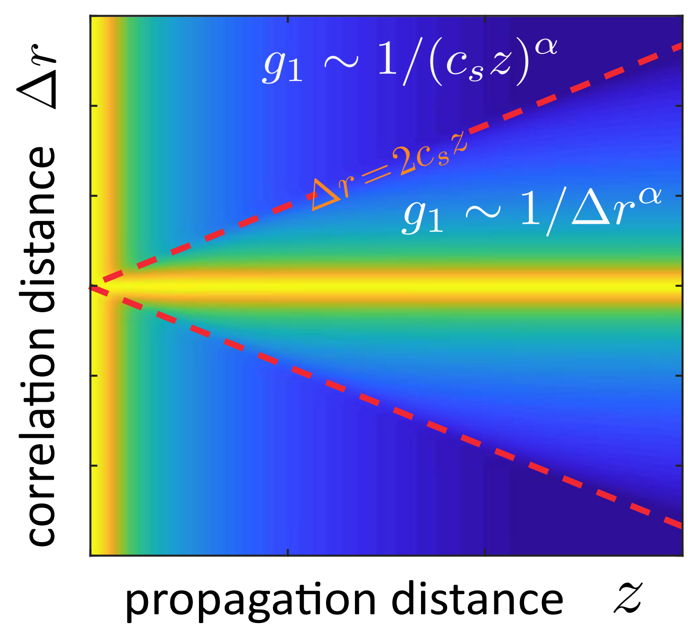
Characterization: spatial coherence

$$g^{(1)}(\Delta\mathbf{r}, z) = \langle \mathcal{E}^*(\mathbf{r}, z)\mathcal{E}(\mathbf{r} + \Delta\mathbf{r}, z)\rangle$$



Non-equilibrium evolution:

Light-cone type spreading correlations



Tamara Bardon-brun, Simon Pigeon, and Nicolas Cherroret, PRR 2, 013297, (2020)

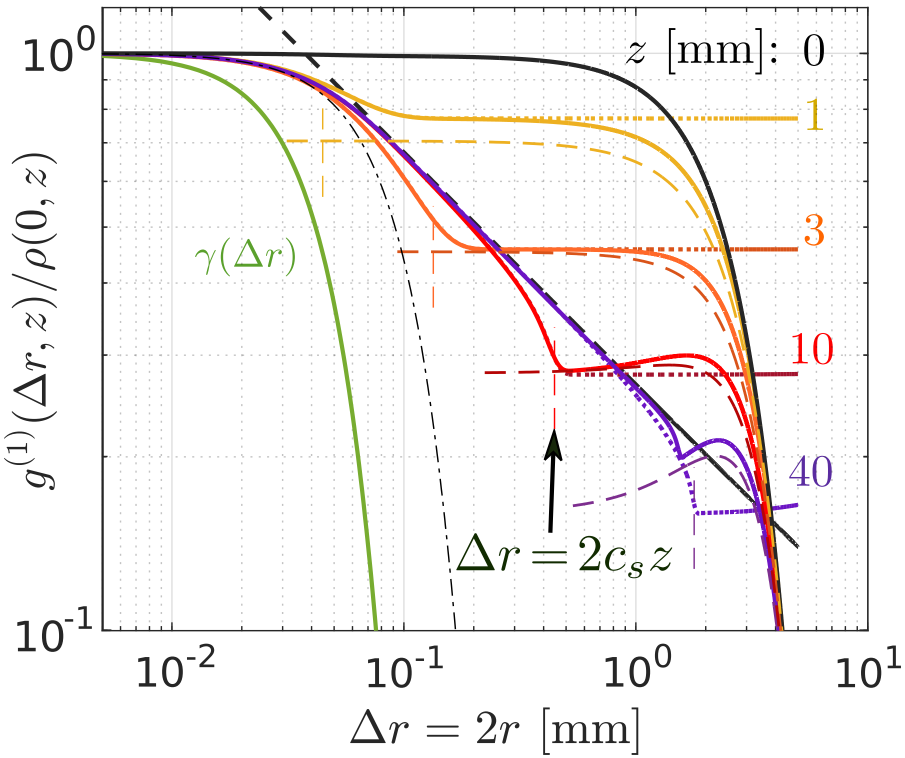
Prethermal relaxation of a fluid of light

Spatial coherence as a witness of prethermalization

Analytical result:

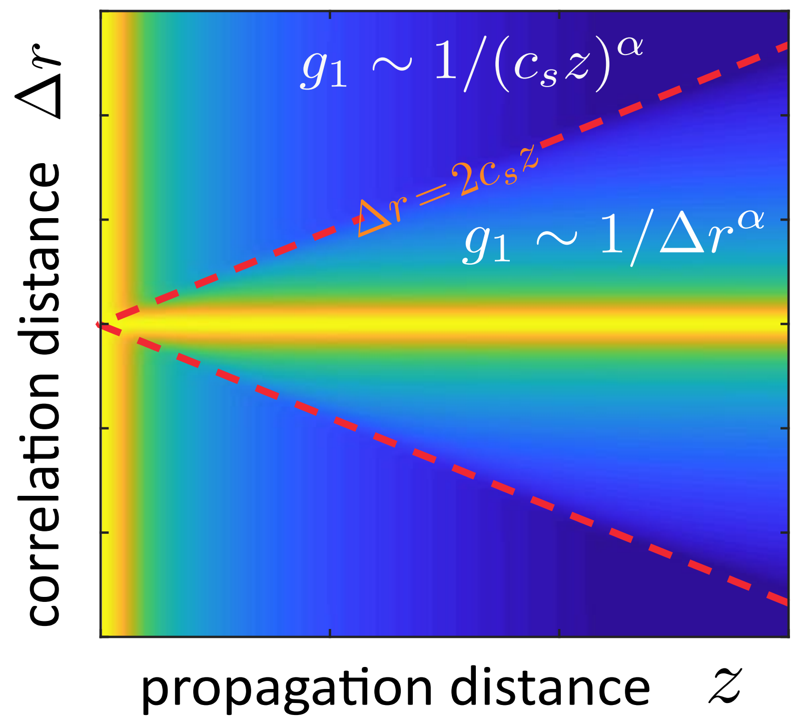
$$g^{(1)}(\Delta r, z) \propto \rho(r) \times \begin{cases} (4\sigma/\Delta r)^{\alpha} & \text{for} \quad \Delta r < 2c_s z \\ \text{const} & \text{for} \quad \Delta r > 2c_s z \end{cases}$$

Algebraic decay and plateau:



Inside the light cone: $\Delta r < 2c_s z$

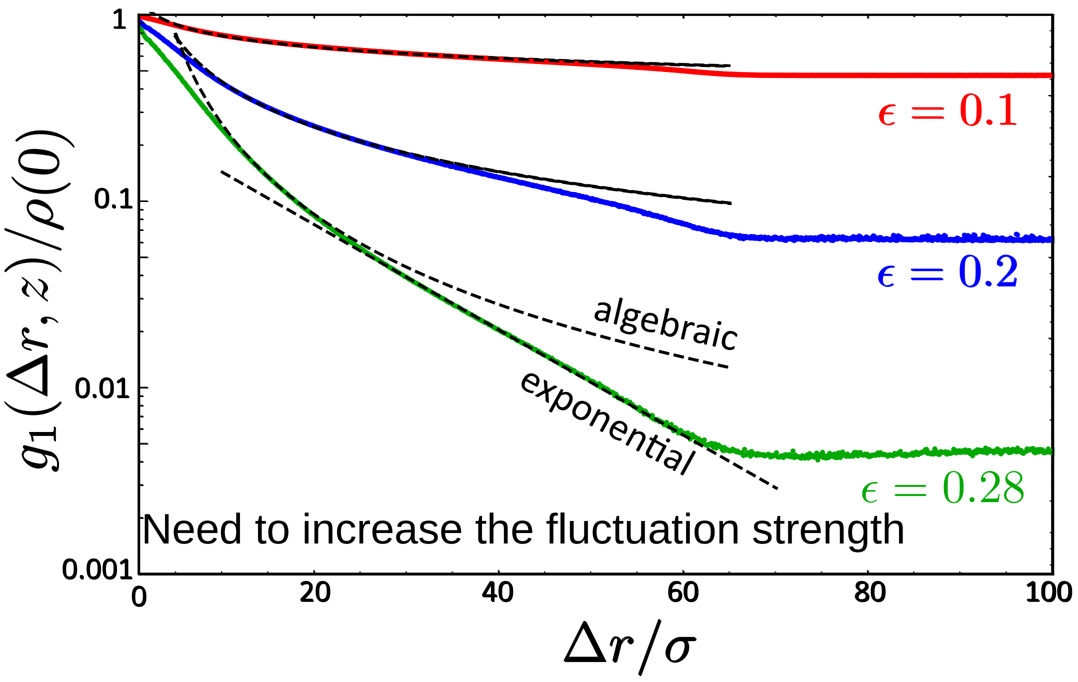
- Pre-thermal state
- Resemblance with an equilibrium state
- Further evolution due to phononic interactions



Tamara Bardon-brun, Simon Pigeon, and Nicolas Cherroret, PRR 2, 013297, (2020)

Prethermal relaxation of a fluid of light

Power law exponent and transition to exponential decay



Power-law exponent:

$$\alpha \propto \varepsilon^2 \sigma^2 c_s^2$$

Increases proportionally to the:

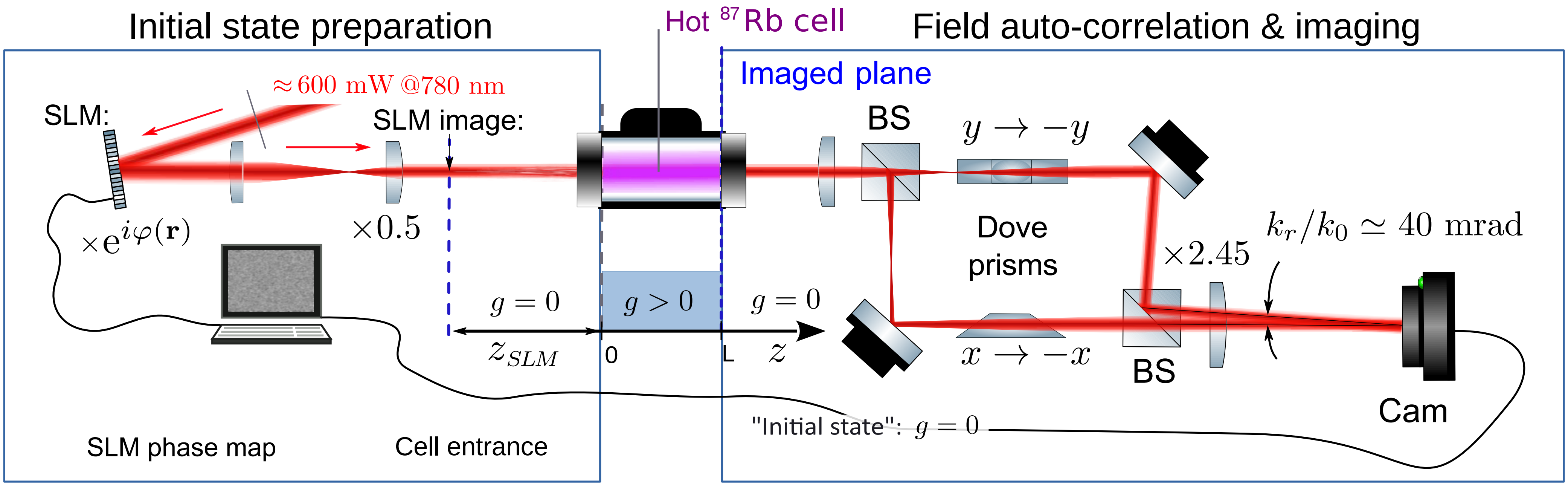
- interaction strength
- (fluctuation strength)²
- (speckle grain size)²

Transition from algebraic to exponential decay:
Reminescence of the equilibrium BKT (“superfluid” to “normal fluid”) transition?

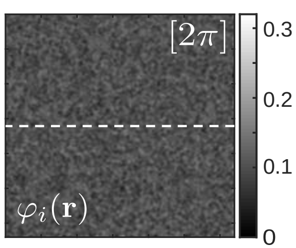
Tamara Bardon-brun, Simon Pigeon, and Nicolas Cherroret, PRR 2, 013297, (2020)

Prethermal relaxation of a fluid of light

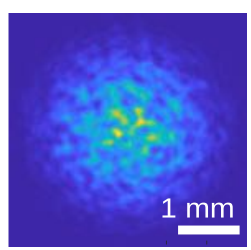
Experimental methods



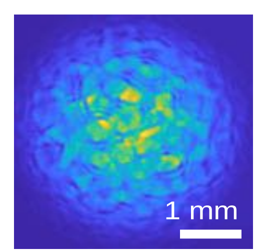
SLM phase map



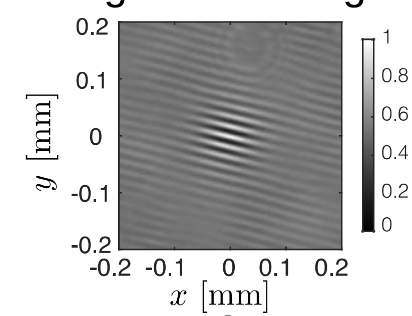
Initial state



final state



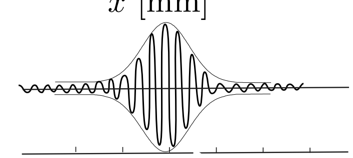
averaged interferogramm



Multiple disorder realizations

Evolution

Interference contrast



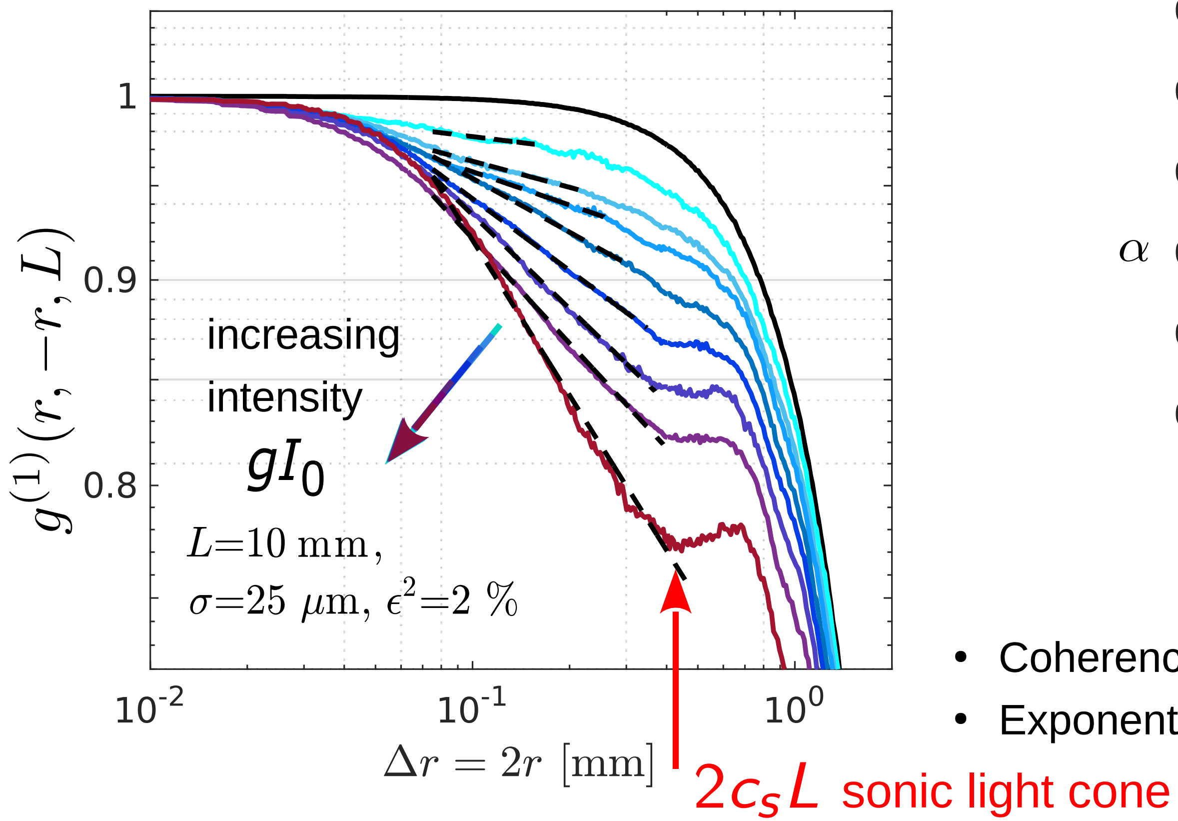
Murad Abuzarli, Nicolas Cherroret, Tom Bienaimé, Quentin Glorieux, PRL. 129, 100602 (2022)

Prethermal relaxation of a fluid of light

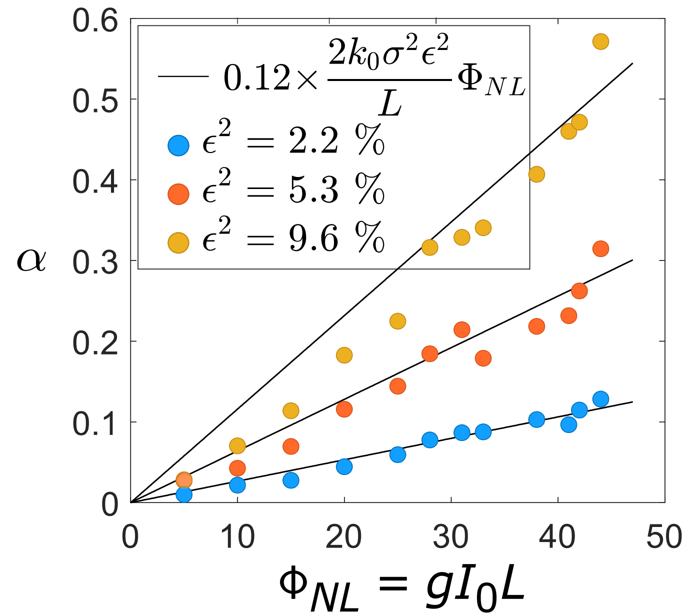
Experimental results

Increasing the interaction strength (weak fluctuations)

Radial coherence profiles



Fitted power law exponents



- Coherence decays algebraically (within the light cone)
- Exponent increases linearly with interaction strength

Murad Abuzarli, Nicolas Cherroret, Tom Bienaimé, Quentin Glorieux, PRL. 129, 100602 (2022)

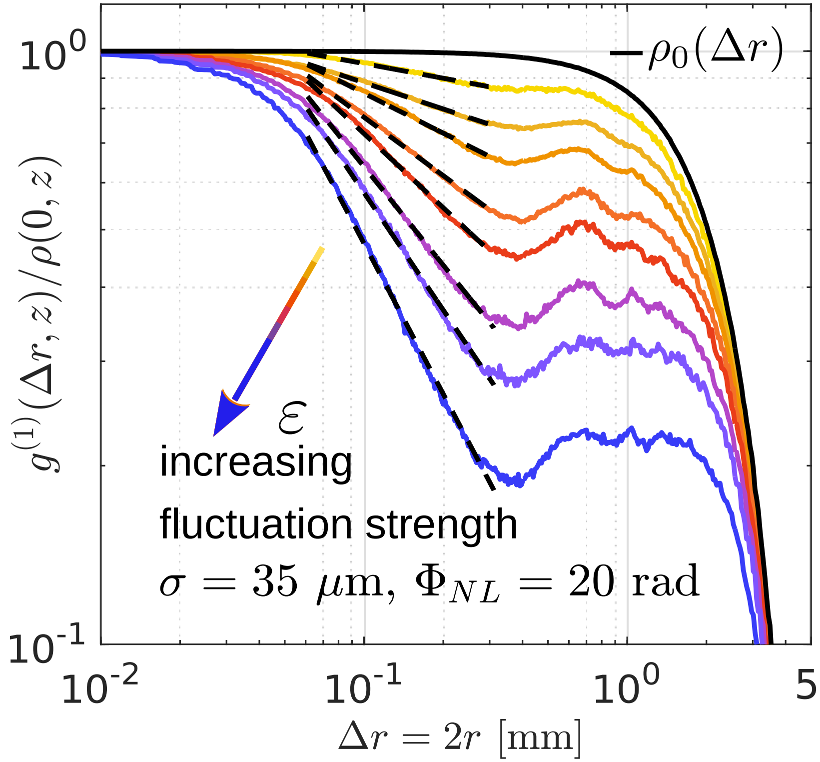
Algebraic coherence and the phononic light cone observed

Prethermal relaxation of a fluid of light

Experimental results

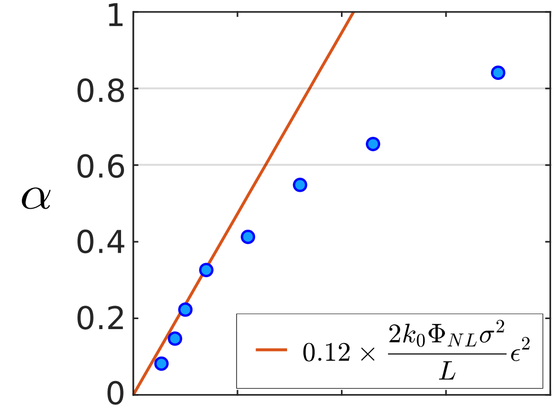
Increasing the fluctuation strength (moderate interactions)

Radial coherence profiles

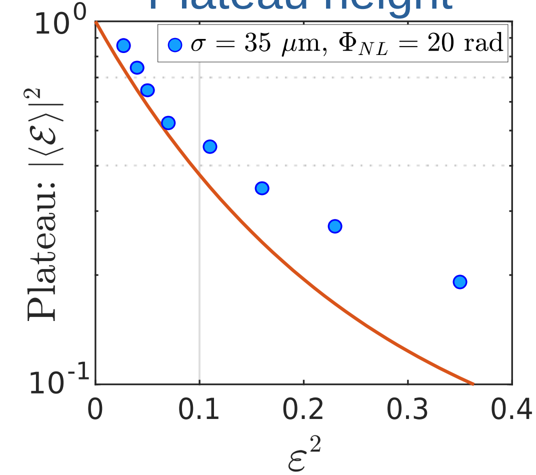


Faster decay with larger fluctuation strength

Fitted power law exponents



Plateau height

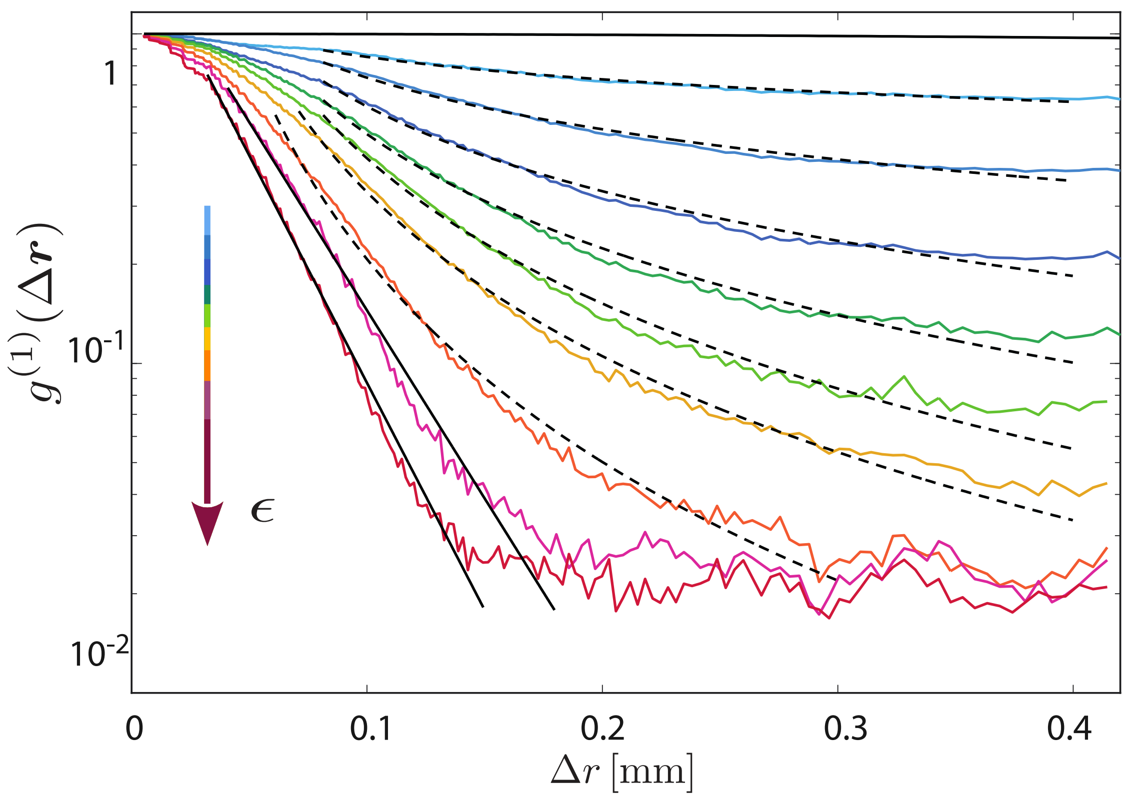


Algebraic exponent increases with the fluctuation strength

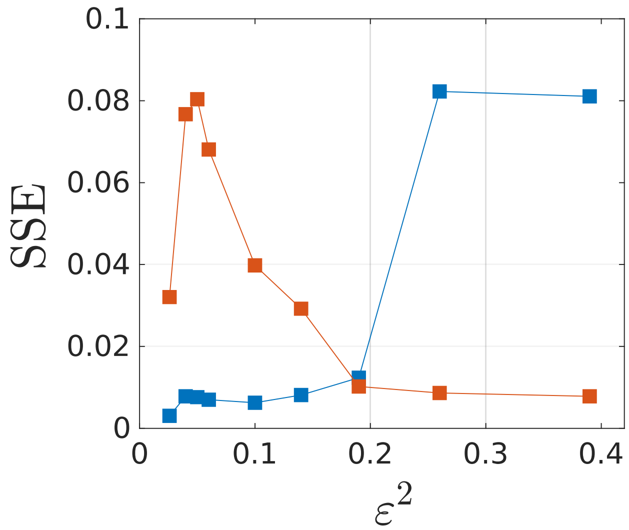
Prethermal relaxation of a fluid of light

Experimental results

Increasing the fluctuation strength (strong interactions)



Fit comparison: Power law Exponential



SSE: sum of squared errors

Non-equilibrium counterpart of the 2D BKT transition

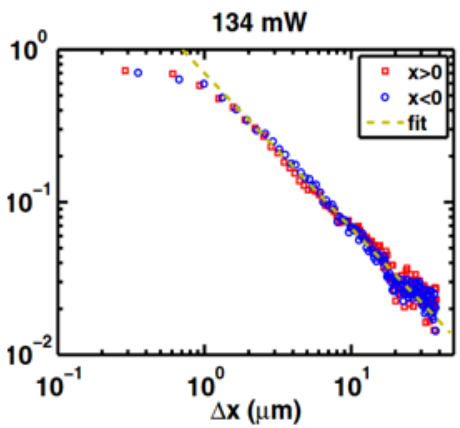
Murad Abuzarli, Nicolas Cherroret, Tom Bienaimé, Quentin Glorieux, PRL. 129, 100602 (2022)

Non-equilibrium transition from long-range to short-range correlations

Prethermal relaxation of a fluid of light

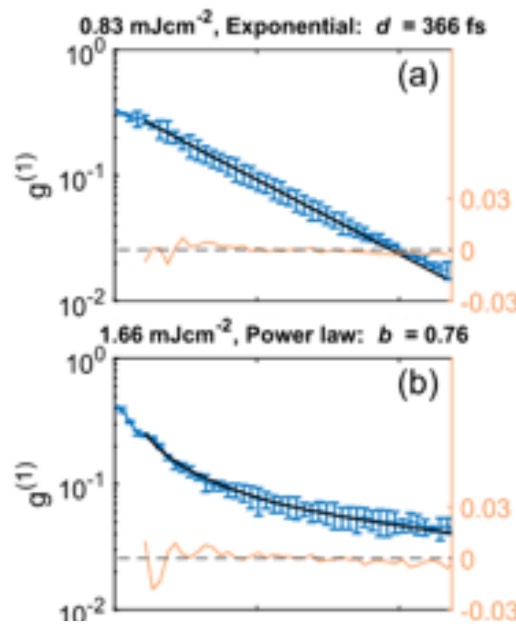
Similar results in other experimental platforms

State of the art: equilibrium or steady state 2D systems



Exciton polariton condensate
(steady state)

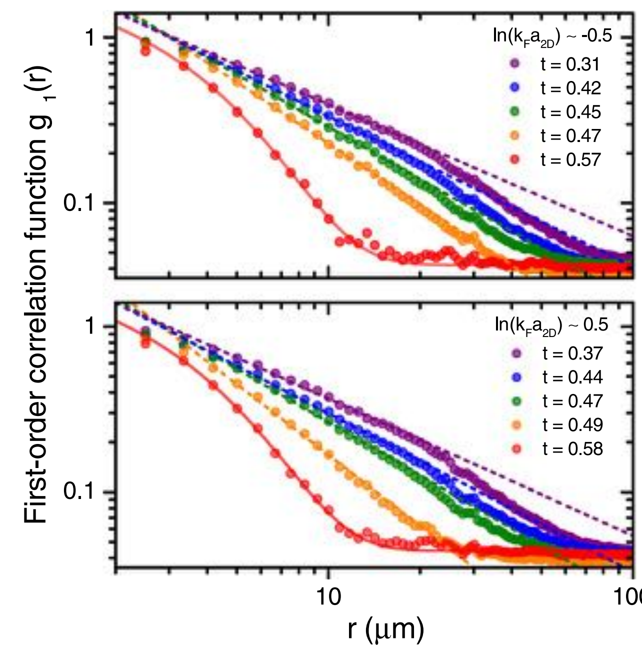
Yamamoto group Japan:
PNAS 109 (17) 6467-6472 (2012)



Plasmon BEC (steady state)

Antti J. Moilanen, Konstantinos S. Daskalakis, Jani M. Taskinen, and Päivi Törmä, PRL. 127, 255301 (2021)

Bosonic limit



Fermionic limit

Ultracold atoms (equilibrium)

P. A. Murthy et al., PRL115, 010401

In our system the time snapshot configuration allows observing the system's non-steady behavior

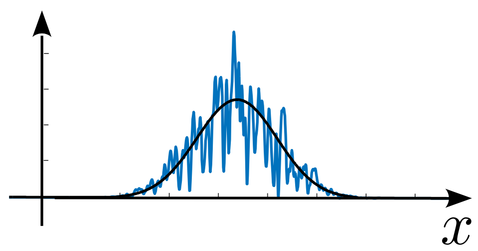
Non-equilibrium transition from long-range to short-range correlations

Correlated quantum fluctuations

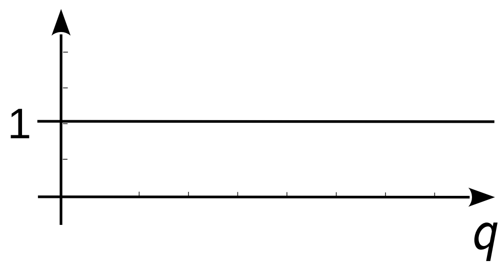
Fluid of light's quantum fluctuations and interaction quenches

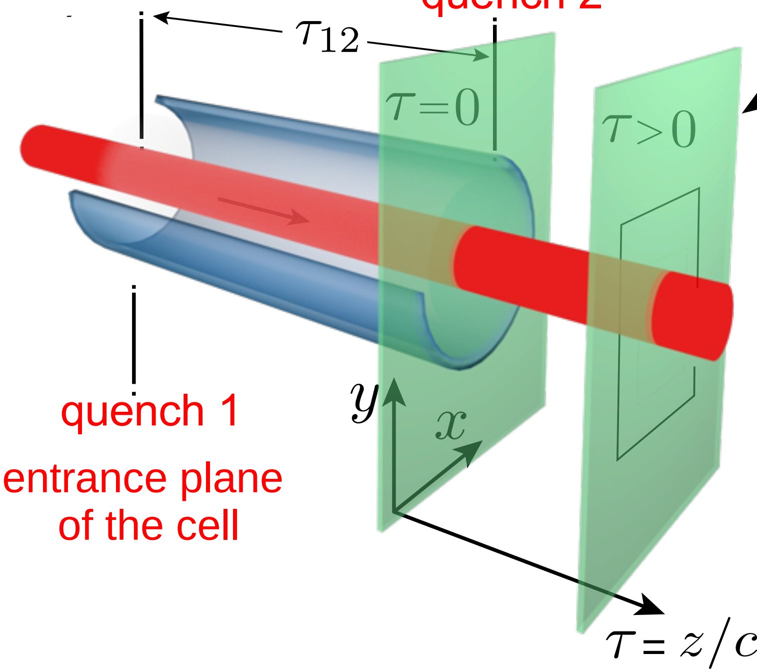
Spatial fluctuations due to shot noise:
fluid's intrinsic fluctuations

Initial state



Power spectrum



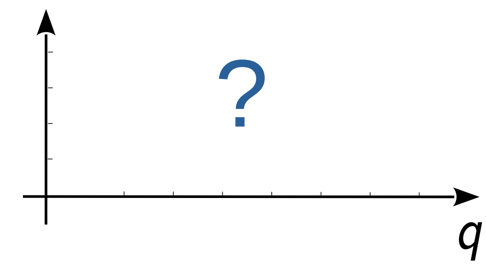


Final state

observation "time"

$$S(\mathbf{q}, z) = \frac{\langle|\delta I(\mathbf{q}, z)|^2\rangle}{N_p}$$

Power spectrum



* "peculiar features are predicted for the statistical properties of the light emerging from the nonlinear medium"

* Pierre-Élie Larré and Iacopo Carusotto, PRA 92, 043802 (2015)

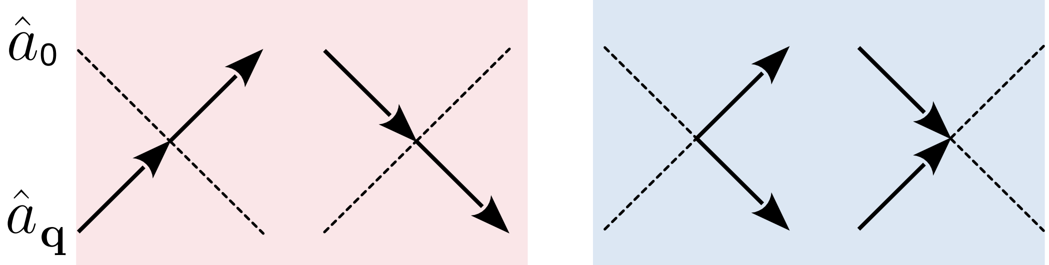
Correlated quantum fluctuations

Intensity power spectrum (static structure factor)

$$S(\mathbf{q}) = \frac{1}{N_p} \sum_{\mathbf{k},\mathbf{k}'} \langle \hat{a}^\dagger_{\mathbf{k}-\mathbf{q}} \hat{a}_{\mathbf{k}} \hat{a}^\dagger_{\mathbf{k}'+\mathbf{q}} \hat{a}_{\mathbf{k}'} \rangle$$

Bogoliubov approximation (weak interactions & fluctuations): most photons in the “0” mode

$$S(\mathbf{q}) \simeq \langle \hat{a}_{\mathbf{q}} \hat{a}^\dagger_{\mathbf{q}} \rangle + \langle \hat{a}^\dagger_{-\mathbf{q}} \hat{a}_{-\mathbf{q}} \rangle + \langle \hat{a}^\dagger_{\mathbf{q}} \hat{a}^\dagger_{-\mathbf{q}} \rangle + \langle \hat{a}_{\mathbf{q}} \hat{a}_{-\mathbf{q}} \rangle$$



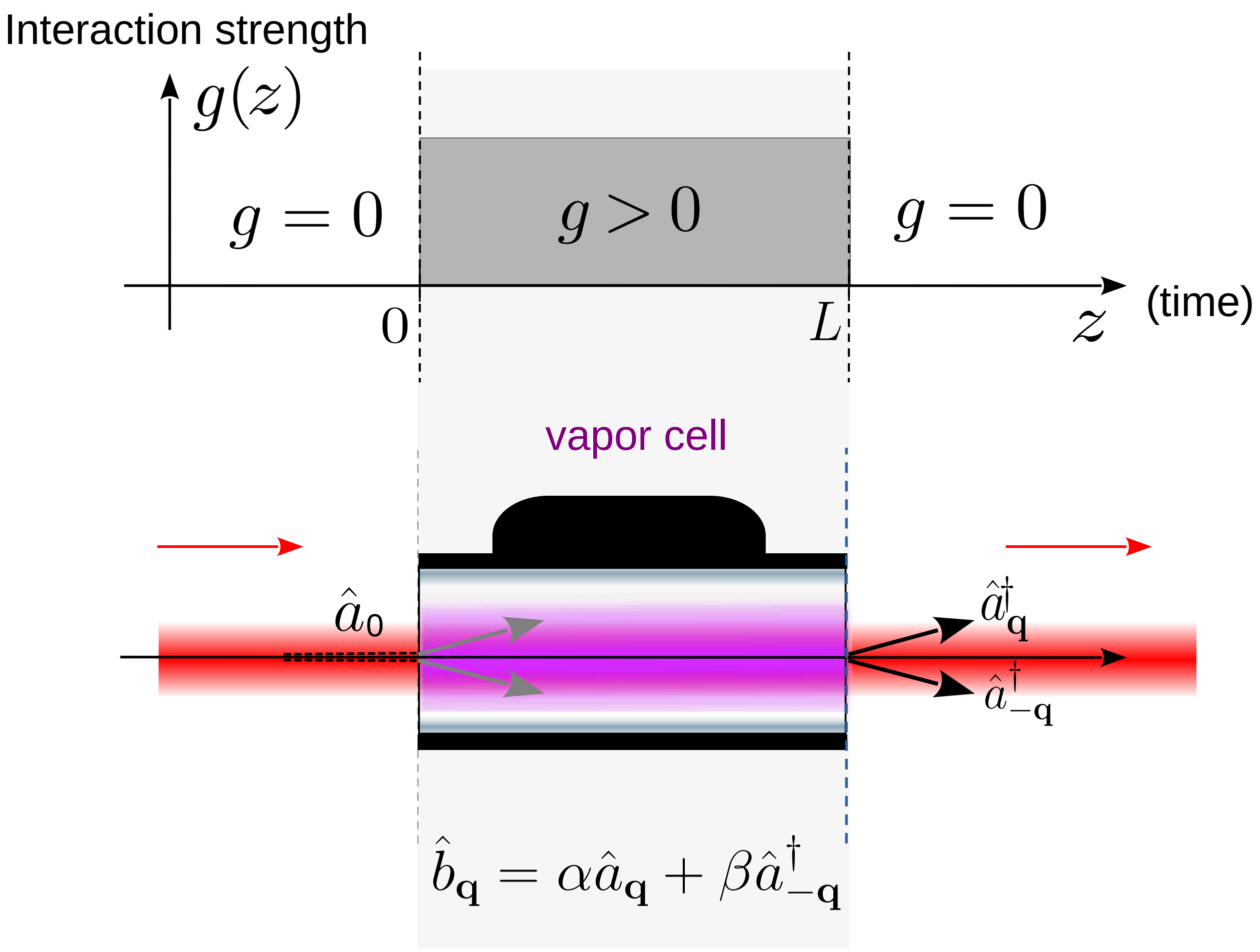
$1 + 2N$ — populations

$2\,\mathrm{Re}\left(C e^{-i2\omega_{\mathbf{q}}\tau}\right)$ — correlations

$$S(\mathbf{q}) = 1 + 2N + 2\,\mathrm{Re}\left(C e^{-i2\omega_{\mathbf{q}}\tau}\right)$$

Correlated quantum fluctuations

Pair creation during the interaction quenches

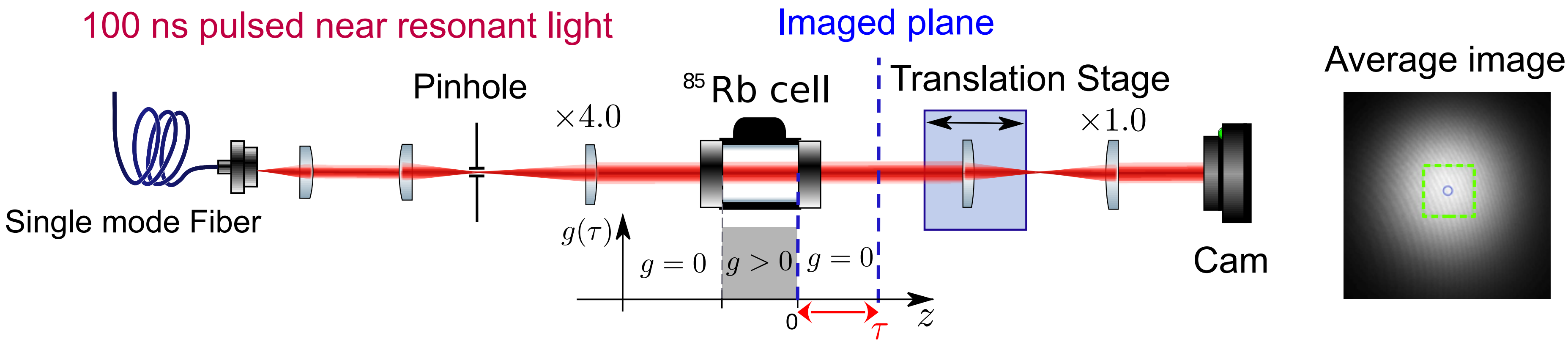


Quasiparticle populations $N^b_{\mathbf{q}} = \beta^2_{\mathbf{q}} + N^a_{\mathbf{q}}(\alpha^2_{\mathbf{q}} + \beta^2_{\mathbf{q}}) + 2\alpha_{\mathbf{q}}\beta_{\mathbf{q}}\ \mathrm{Re}(C^a_{\mathbf{q}})$

Quasiparticle correlations $C^b_{\mathbf{q}} = \alpha_{\mathbf{q}}\beta_{\mathbf{q}}(1 + 2N^a_{\mathbf{q}}) + \alpha^2_{\mathbf{q}} C^a_{\mathbf{q}} + \beta^2_{\mathbf{q}} C^{a*}_{\mathbf{q}}$

Correlated quantum fluctuations

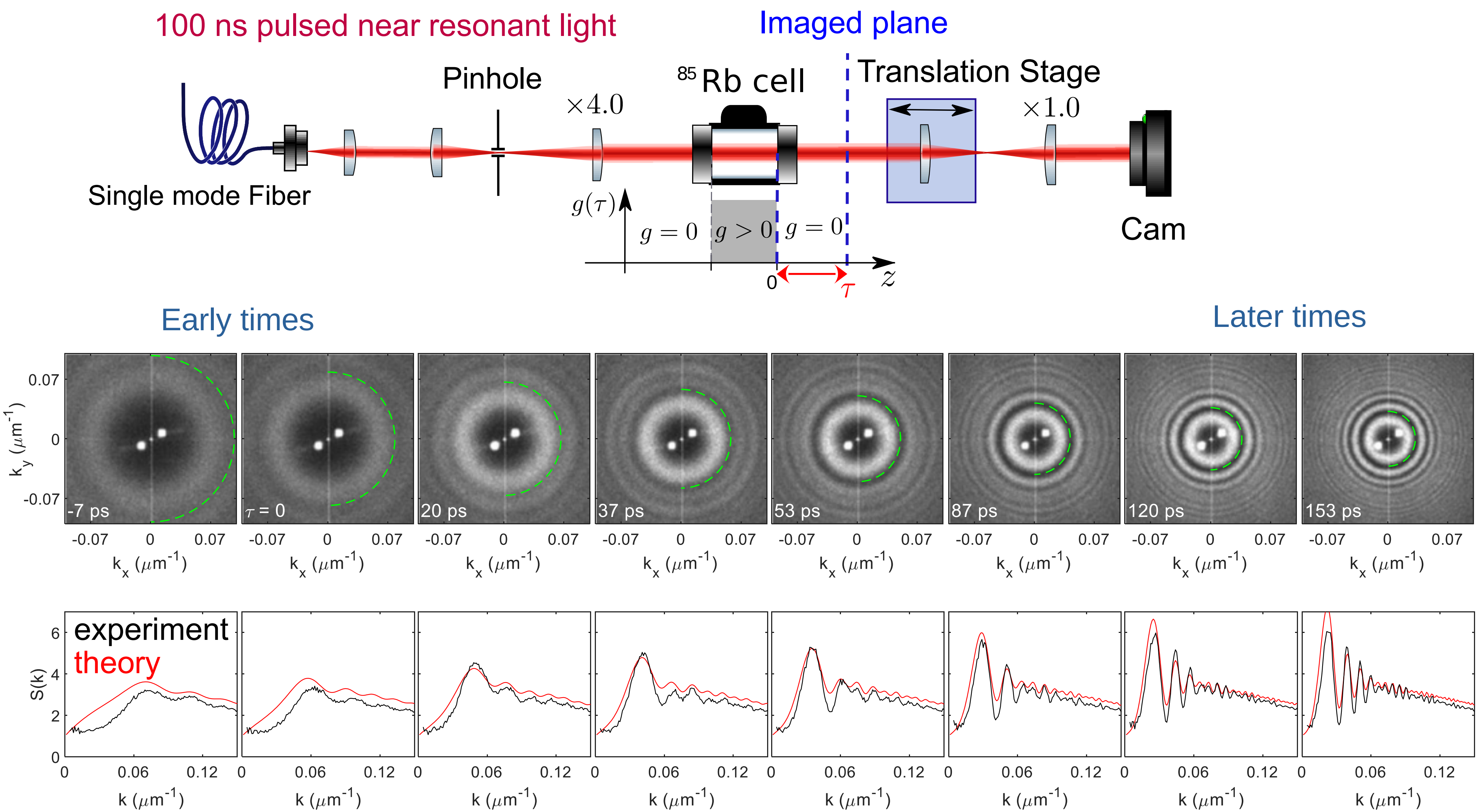
Probing quantum correlations in a paraxial fluid of light



Jeff Steinhauer, Murad Abuzarli, Tangui Aladjidi, Tom Bienaimé, Clara Piekarski, Wei Liu, Elisabeth Giacobino, Alberto Bramati, Quentin Glorieux, Nat Commun 13, 2890 (2022)

Correlated quantum fluctuations

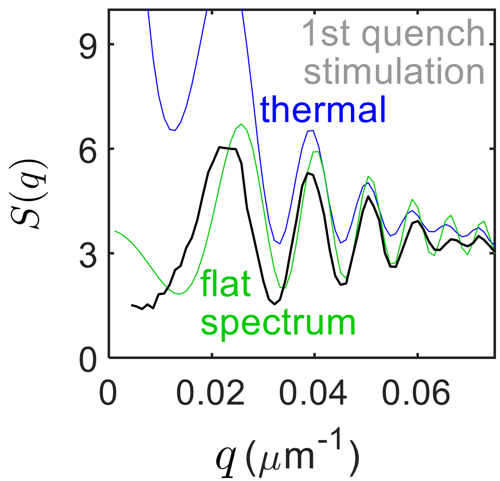
Probing quantum correlations in a paraxial fluid of light

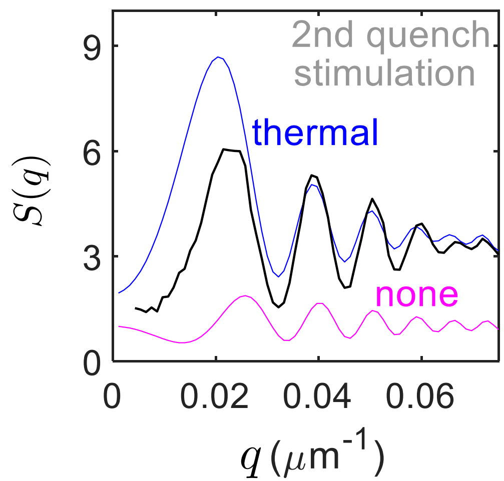


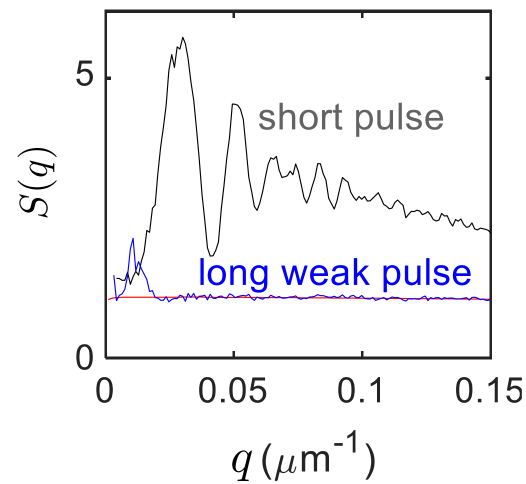
Jeff Steinhauer, Murad Abuzarli, Tangui Aladjidi, Tom Bienaimé, Clara Piekarski, Wei Liu, Elisabeth Giacobino, Alberto Bramati, Quentin Glorieux, Nat Commun 13, 2890 (2022)

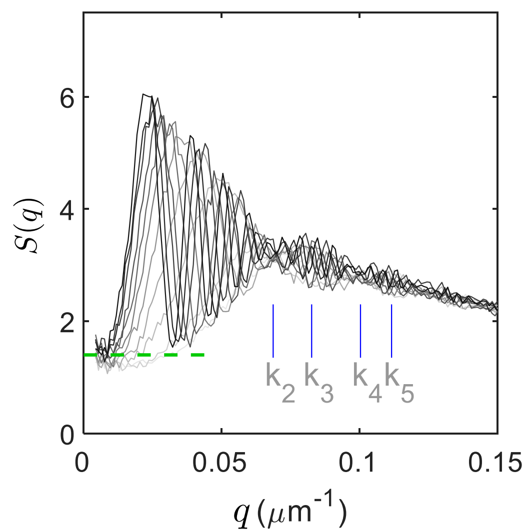
Correlated quantum fluctuations

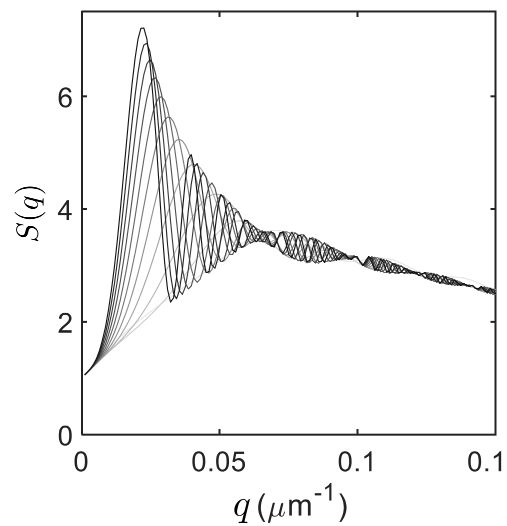
Spontaneous vs stimulated pair production and the first quench







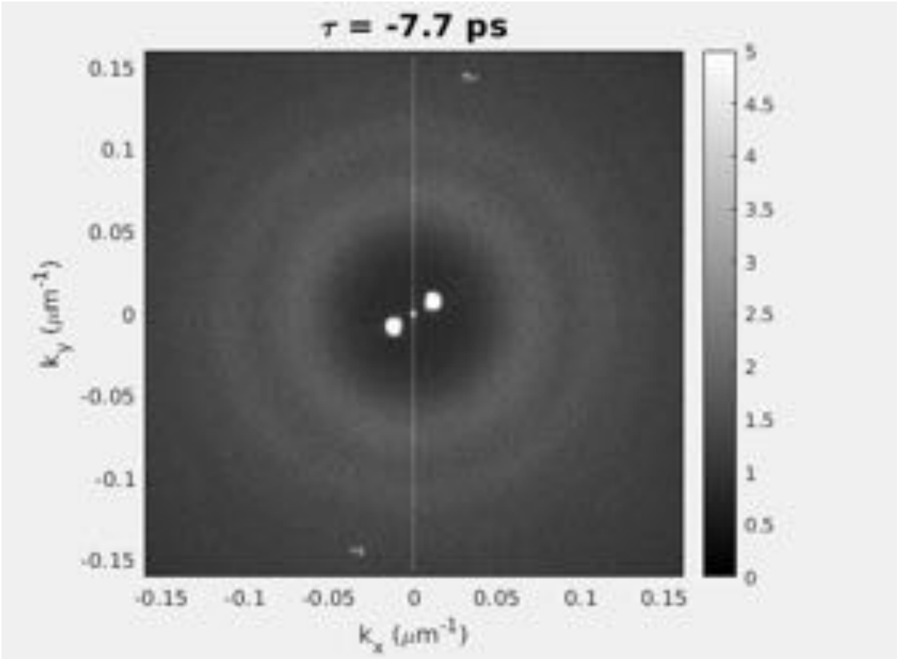


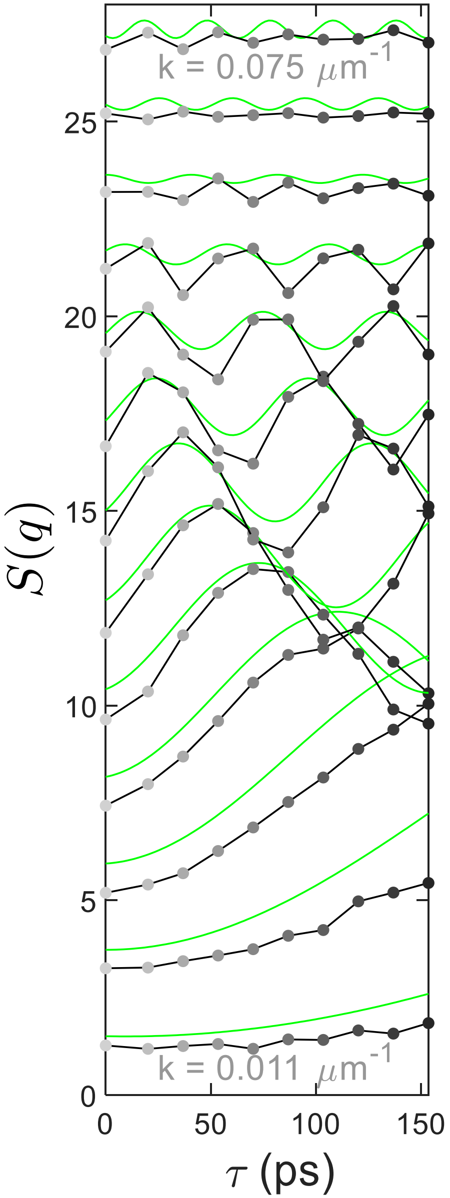


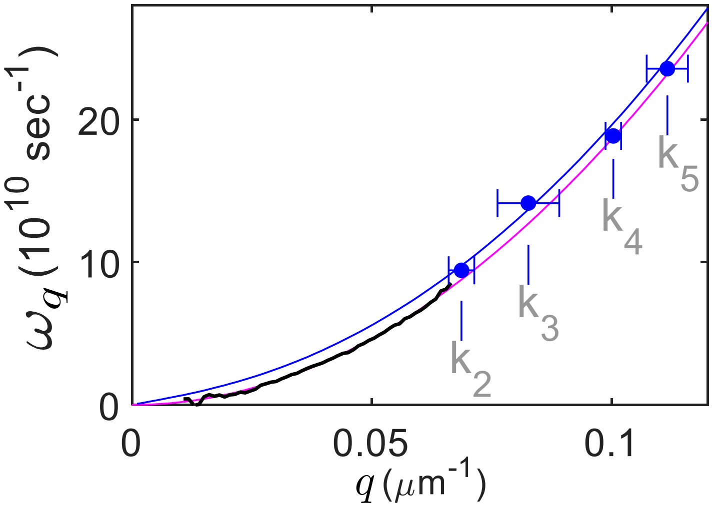
Jeff Steinhauer, Murad Abuzarli, Tangui Aladjidi, Tom Bienaimé, Clara Piekarski, Wei Liu, Elisabeth Giacobino, Alberto Bramati, Quentin Glorieux, Nat Commun 13, 2890 (2022)

Correlated quantum fluctuations

Time dynamics of separate modes

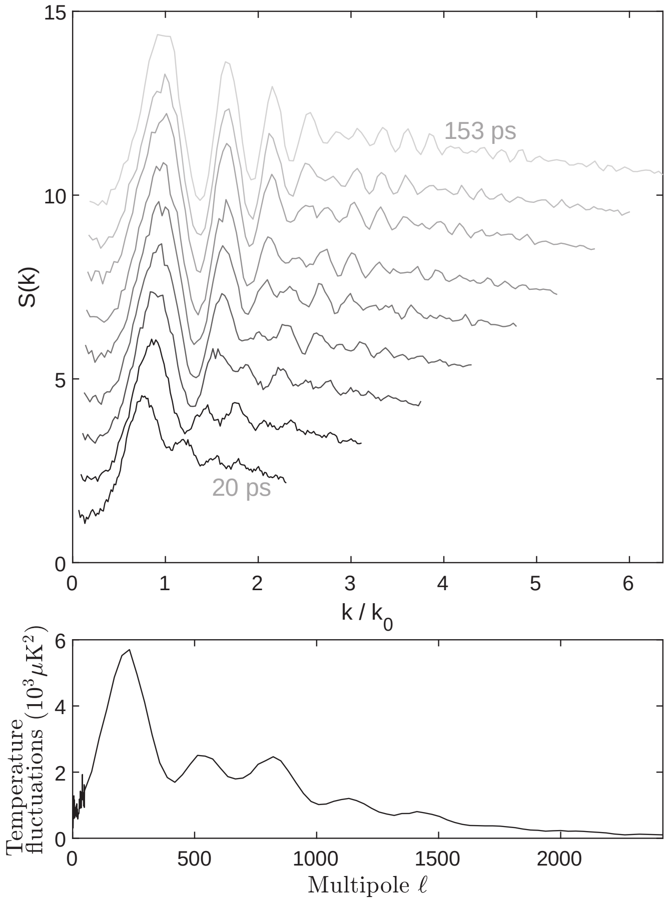






Correlated quantum fluctuations

Analogy with the acoustic peaks in the CMB



Albrecht, A., Coulson, D., Ferreira, P. & Magueijo, J. Causality, randomness, and the microwave background. Phys. Rev. Lett. 76, 1413–1416 (1996)

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The team

Thank you!

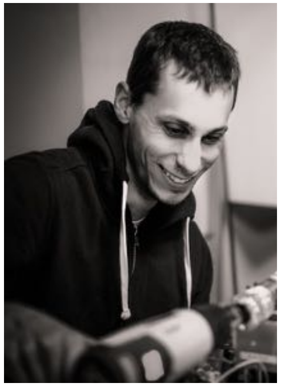
Nicolas Cherroret

Tamara Bardon-brun

Tom Bienaimé

Jeff Steinhauer

Quentin Fontaine



The Rubidium team:

PI-s: Dr. Quentin Glorieux, Prof. Alberto Bramati, Prof. Elisabeth Giacobino
Visiting professor (2020): Dr. Jeff Steinhauer from Technion-Haifa, Israel
PhD students: Tangui Aladjidi, Wei Liu, Myrann Abobaker, Clara Piekarski
Postdocs: Dr. Tom Bienaimé (now in Strassbourg)
Theory collab: Dr. Tamara Bardon-Brun, Dr. Thibault Scoquart, Dr. Nicolas Cherroret

Conclusion

Prethermal relaxation

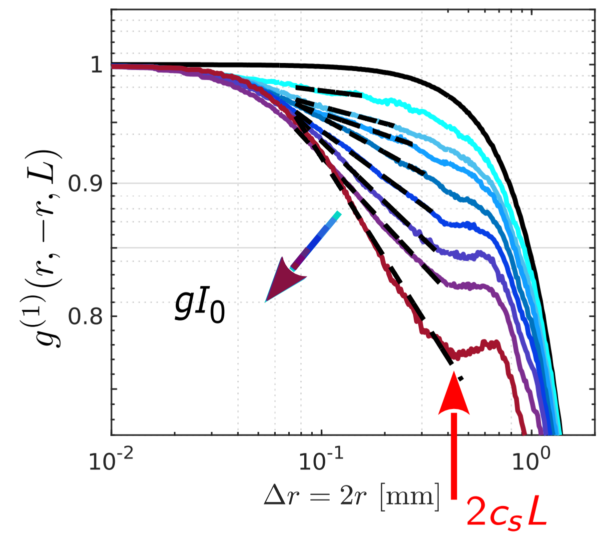
Probing the fluid's relaxation after the onset of interactions

Spatial coherence

$$g^{(1)}(\Delta r = 2r, z) = \langle \mathcal{E}^*(-\mathbf{r}, z)\mathcal{E}(\mathbf{r}, z)\rangle$$

Evolution of the stimulated (classical) fluctuations

M. Abuzarli, N. Cherroret, T. Bienaimé, Q. Glorieux,
PRL. 129, 100602 (2022)



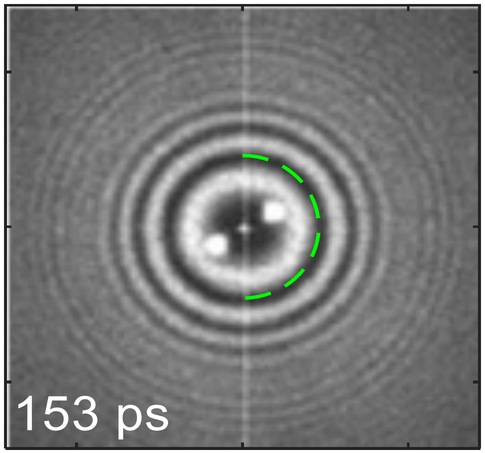
Correlated quantum fluctuations

Probing the fluid's response after two interaction quenches

Static structure factor of the spatial intensity fluctuations

$$S(\mathbf{q}, z) \propto \langle|\delta\rho(\mathbf{q}, z)|^2\rangle$$

Evolution of the intrinsic spatial shot noise fluctuations



J. Steinhauer, M. Abuzarli, T. Aladjidi, T. Bienaimé, C. Piekarski, W. Liu, Elisabeth Giacobino, Alberto Bramati, Quentin Glorieux, Nat Commun 13, 2890 (2022)