Observation of entanglement between collective excitation in a quantum fluid: when Faraday waves grow from vacuum fluctuations

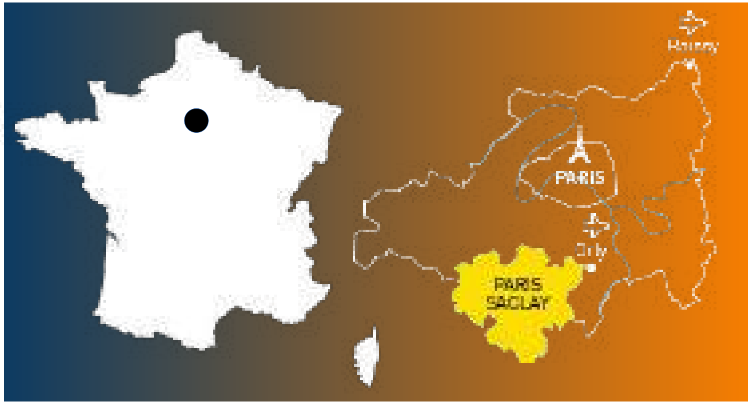
Victor Gondret,

13th of November, 2025

Concepción

Slides available at
www.normalesup.org/~gondret/talk.pdf

Paris-Saclay University



Paris-Saclay University

Do not be fooled, it is more Saclay, than Paris!

Institut d'Optique Graduate School

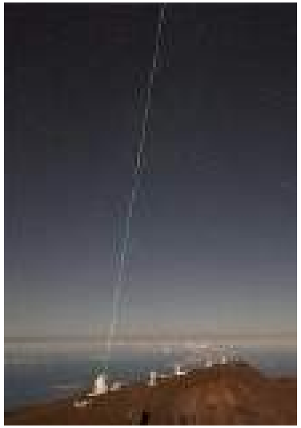
Is part of the university

LABORATOIRE CHARLES FABRY

The unique lab of the school

43 researchers/profs
75 PhDs/post-docs

Research @LCF



Adaptative optics

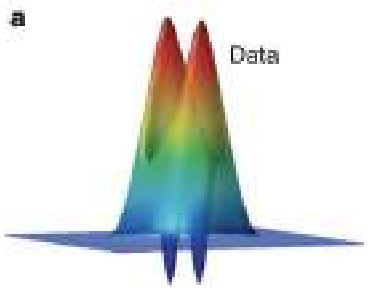
Nanophotonics

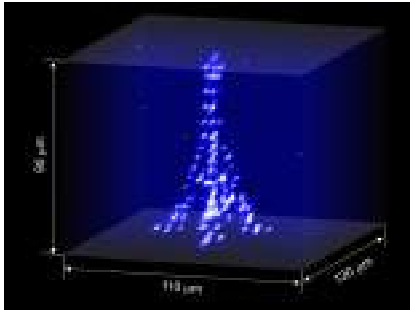
Biophotonics

Laser

Quantum optics

Photons → Atoms



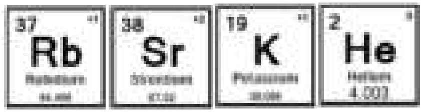


Quantum gases

Quantum gases at LCF

8 researchers/professors

6 experiments (from 1D to 3D)



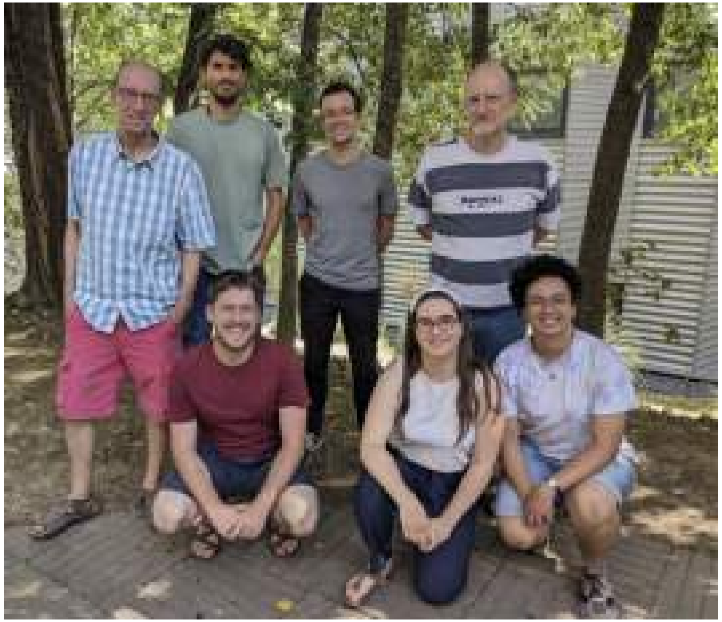
Optical lattice

3D Anderson localization

1D gases

Ultracold Fermions

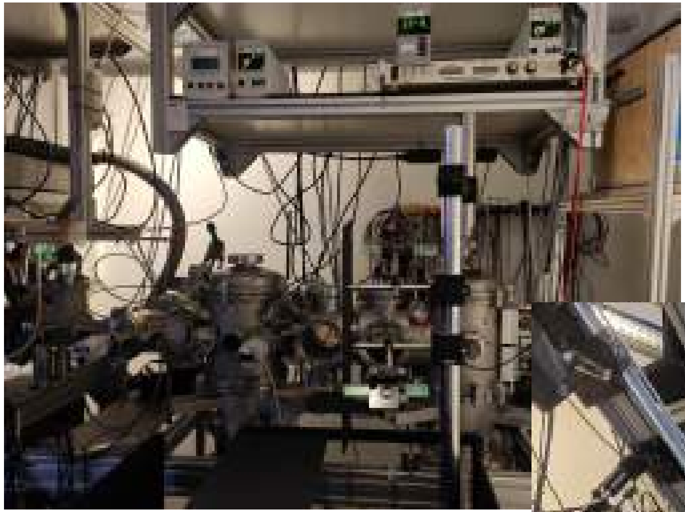
Quantum microscope

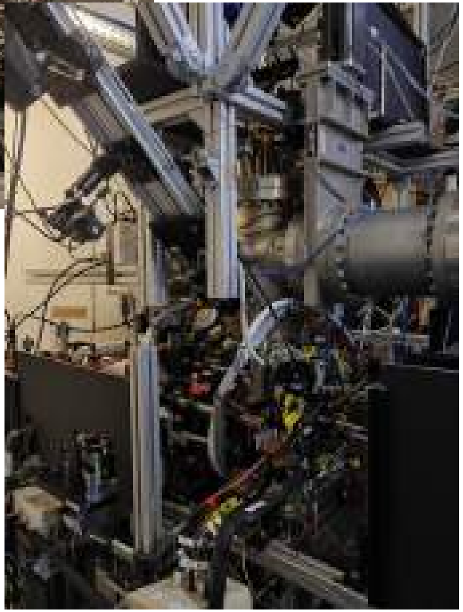


Exp: Chris Westbrook, Rui Dias, Charlie Leprince, Denis Boiron, Victor Gondret, Clothilde Lamirault, Léa Camier

Th: Amaury Micheli & Scott Robertson

Experimental setup





Experiment started in 1994: oldest BEC experiment in France (metastable Helium).

OUTLINE

I. Introduction

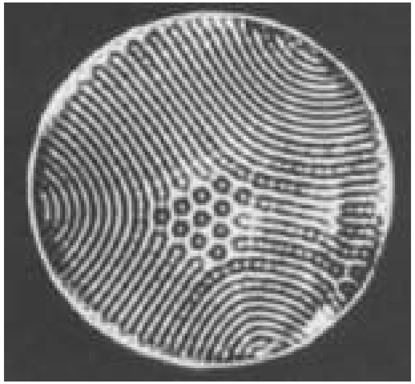
II. Model and setup

III. Growth and decay of quasiparticles

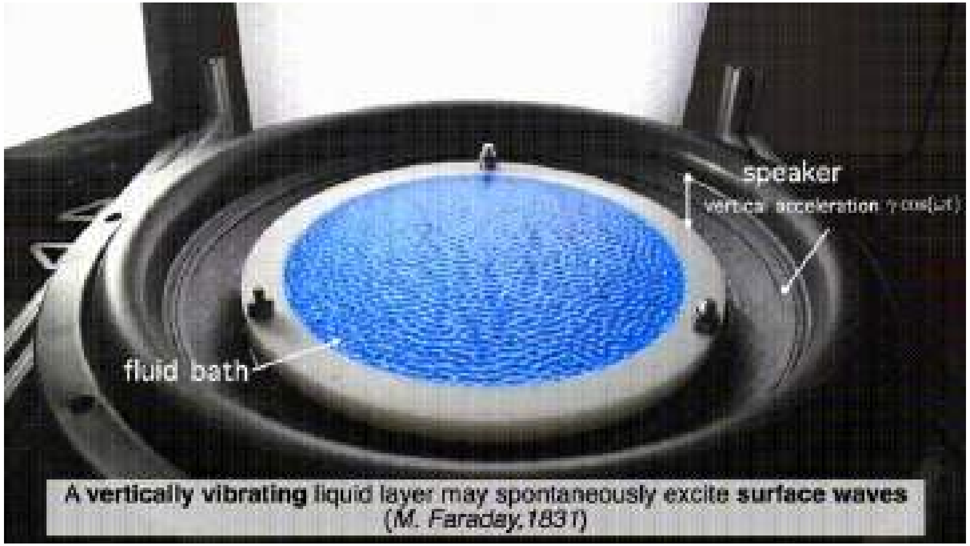
IV. Assessing entanglement of two-mode Gaussian states with many-body correlation function

V. Observation of entanglement

I. Introduction

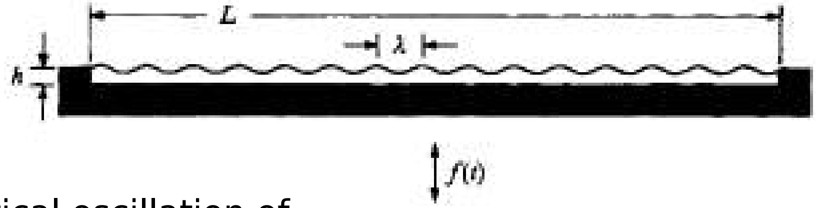


Faraday waves



Guan *et al.* PR Fluids (2023), Edwards & Fauve J. Fluid Mech. (1994)

Broughton Suspension Bridge collapsed in 1831



Vertical oscillation of the tank at Ω

$$\omega_k = \sqrt{\tanh(hk)[gk + \gamma k]} = \Omega/2$$

Modulation of the effective gravity

- g gravity
- γ surface tension

Parametric oscillation ≠ forced oscillation

Parametric oscillation	Forced oscillation
Ω/2	Ω
Variation of an internal parameter	External force

Parametric excitation & forced oscillation

Parametric oscillation ≠ forced oscillation

Parametric oscillation	Forced oscillation
$\Omega/2$	Ω
Variation of an internal parameter	External force

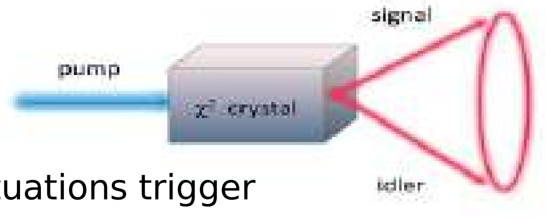
Parametric excitation & forced oscillation

Parametric oscillation ≠ forced oscillation	
$\Omega/2$	Ω
Variation of an internal parameter	External force
Growth triggered by fluctuations	Growth initialized by the force

- Experimental imperfection
- Thermal fluctuations,
- Quantum fluctuation

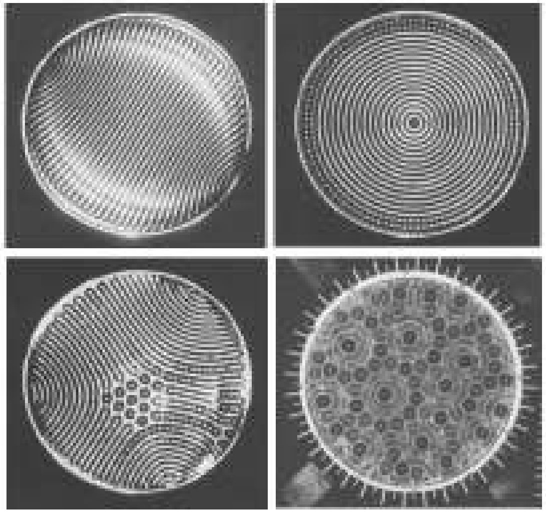
Parametric resonance at all scales

Photons



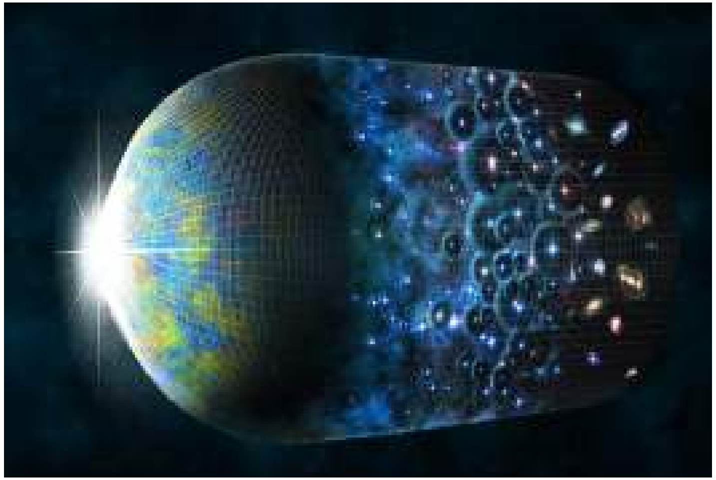
Vacuum fluctuations trigger amplification which leads to entanglement.

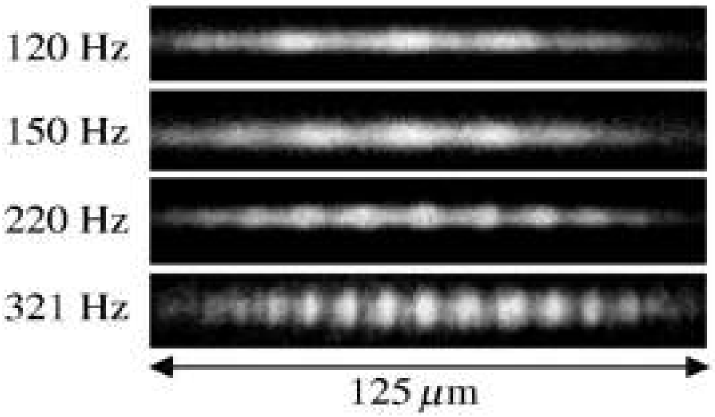
Fluid



Edwards & Fauve J. Fluid Mech. **278**, 123 (1994).

Early universe





Bose-Einstein condensates

Preheating in the early universe

The **inflaton** goes from its initial false vacuum state. Its almost constant potential energy **drives the inflation**.

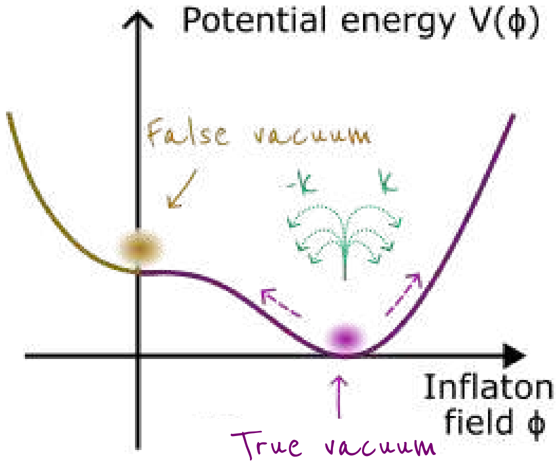
A. Linde, Phys. Lett. **129B**, 177 (1983).

It starts to oscillate around its minimum and, coupled to matter fields, it creates particles through broad **parametric resonance**.

L. Kofman, A. Linde & A. Starobinsky, Phys. Rev. D 56, (1997).

Particles are created in **pairs** with **opposite momenta from vacuum** in a highly entangled two modes squeezed state. Interactions lead to decoherence and thermalization.

D. Campo & R. Parentani, Phys. Rev. D **74**, 025001 (2006).



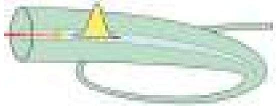
BUT NOT OBSERVABLE

Analog gravity

Use the tools of quantum field theory formalism to describe a condensed matter system,

Water

BEC



Optical fibers

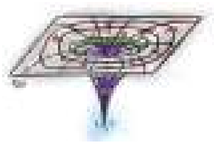
Polariton

Analog gravity

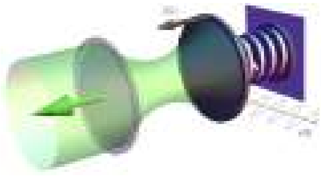
In the presence of a strong coherent background, the excitations of a fluid, or *quasi*particles, can be treated using the same formalism as particles in a curved spacetime.

Unruh, *Experimental black-hole evaporation?*
Phys. Rev. Lett. **46**, 1351 (1981)

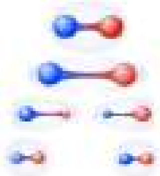
Shape the fluid to mimic famous effect of QFT.



Hawking Radiation

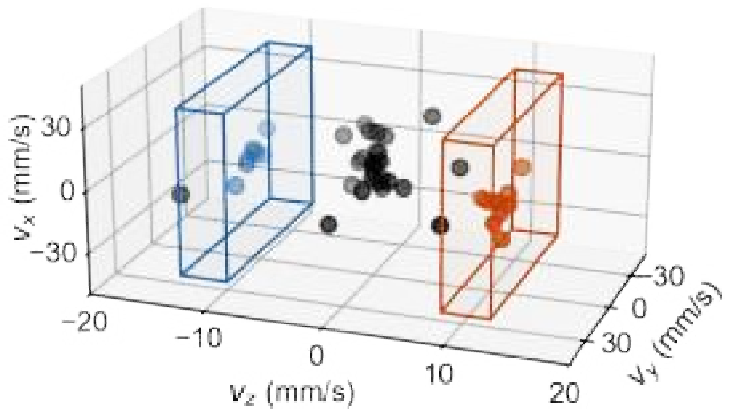


Dynamical Casimir Effect

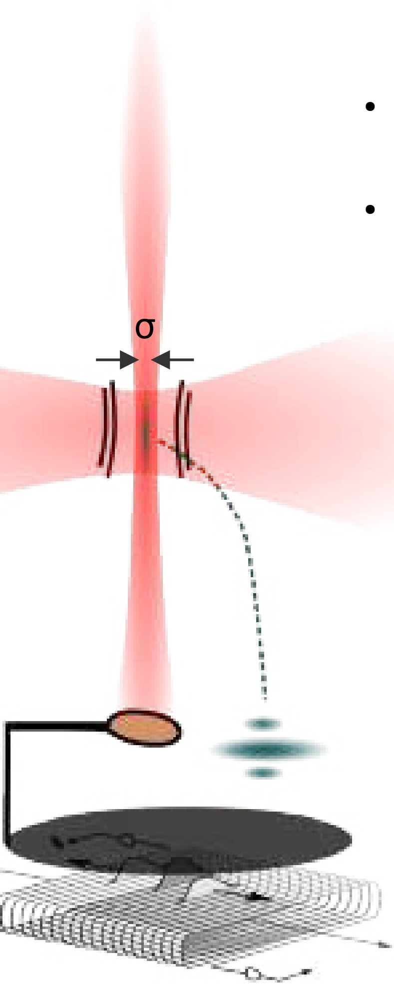


Schwinger effect

II. Model and setup



Collective excitations in a BEC



- BEC of He* in 10s with few thousands atoms at 25(5) nK.
- 1 kHz & 50 Hz: effective 1D dynamics

Bose gas with contact interaction

$$\hat{H} = \sum_k \epsilon_k \hat{a}_k^\dagger \hat{a}_k + \frac{g}{2V} \sum_{k_1,k_2,q} \hat{a}_{k_1+q}^\dagger \hat{a}_{k_2-q}^\dagger \hat{a}_{k_2} \hat{a}_{k_1}$$

with $\hat{a}_k$ the atomic annihilation operator.

How to change *gn* ?

- *g* with a Feshbach resonance (Chicago, Rice, Heidelberg)
- *n* with trap modulation (Mexico, NIST, Palaiseau, Trento, Utrecht)

Bogoliubov description:

We treat the BEC as a coherent state and quantized other modes k. Introduce the quasiparticle modes b_k which diagonalize the Hamiltonian.

$$\hat{a}_k = u_k \hat{b}_k + v_k \hat{b}_{-k}^\dagger$$

with u_k and v_k the Bogoliubov coefficients and

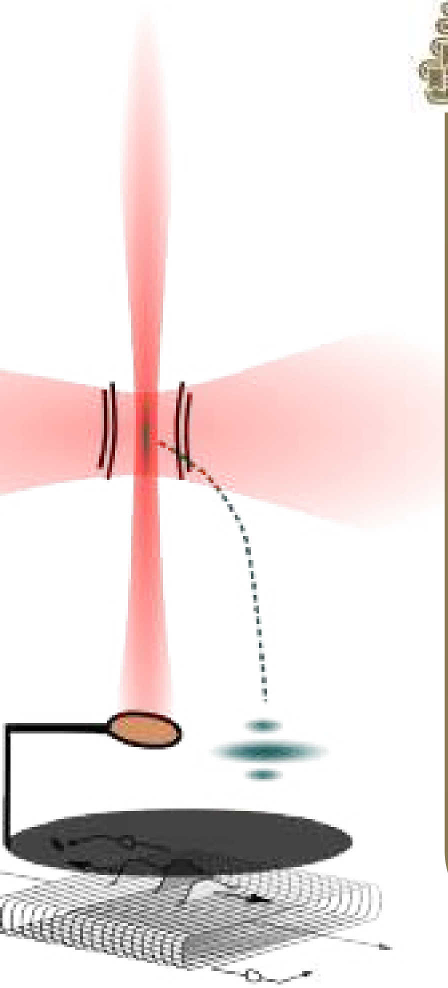
$$\omega_k = \sqrt{\frac{gn}{m}k^2 + \left(\frac{\hbar k^2}{2m}\right)^2}$$

Quasiparticle evolution

$$\partial_t \hat{b}_k = -i\omega_k \hat{b}_k + \frac{\dot{\omega}_k}{2\omega_k} \hat{b}_{-k}^\dagger$$

Busch *et al.* Phys. Rev. A **89** (2014)

Theoretical details



Theoretical cheatsheet

If non-zero temperature, both thermal and vacuum fluctuations trigger the exponential growth.

Amplification of vacuum fluctuation is witnessed by two-mode entanglement.

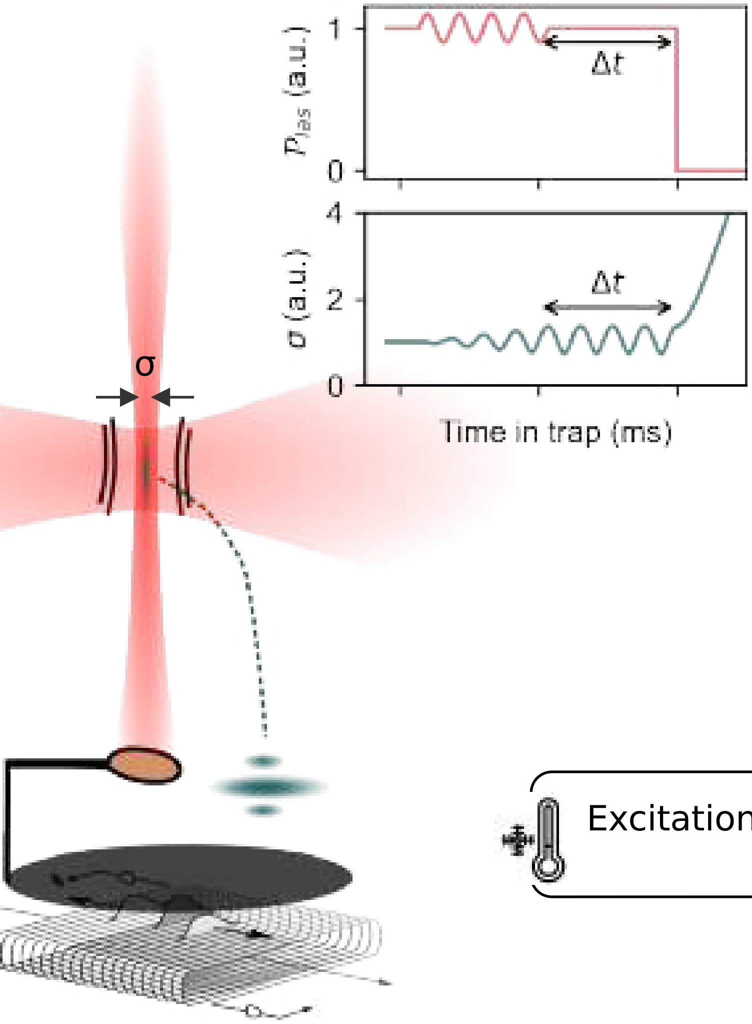
A large temperature prevent the appearance of entanglement.

Beyond Bogoliubov numerics: quasiparticle interactions further destroy entanglement.

Busch *et al.* Phys. Rev. A **89** (2014),
Robertson *et al.*, Phys. Rev. D **95**, 065020 (2017),
Robertson *et al.*, Phys. Rev. D **98**, 056003 (2018).

Two-mode squeezing model.

Faraday waves with quantum fluids



Protocol

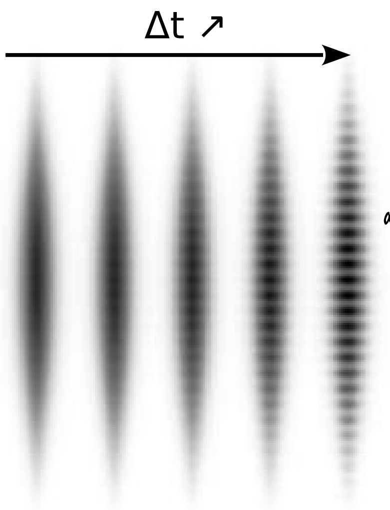
(1) Excite the transverse breathing mode of the BEC at Ω for 4 periods,

(2) Let it breath for Δt: longitudinal collective excitations with $\omega_k = \Omega/2$ are parametrically excited

$$\omega_k = \sqrt{\frac{gn}{m}k^2 + \left(\frac{\hbar k^2}{2m}\right)^2}$$

Modulation of interactions at Ω

- g effective interaction strength
- n density
- m atomic mass
- $\hbar$ reduced Planck cte



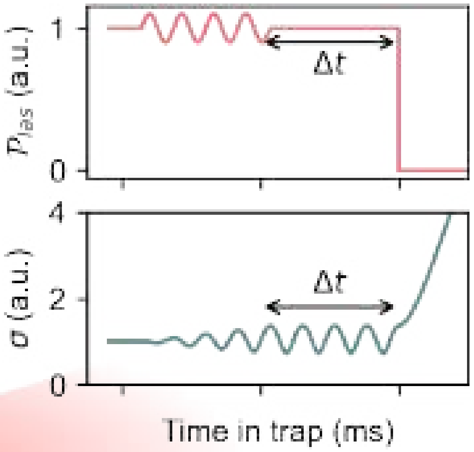
The pattern appears as Δt increases!

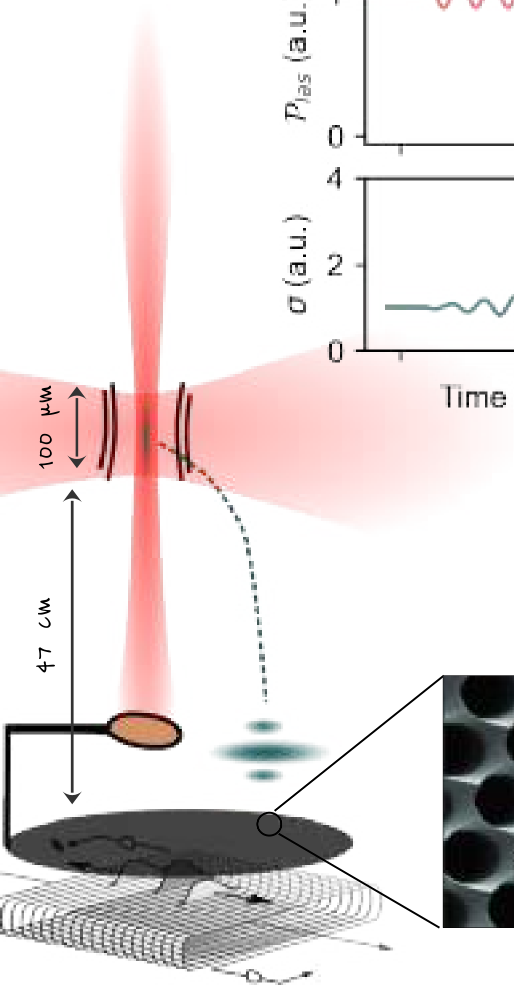
Excitation procedure does not heat the cloud.

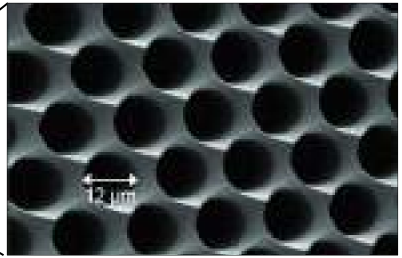
We can hope to get an entangled state!

Chevy et al., Phys. Rev. Lett. **88**, 250402 (2002)
Jackson and Zaremba Phys. Rev. Lett. **89**, 150402 (2002)

Faraday waves with quantum fluids







Protocol

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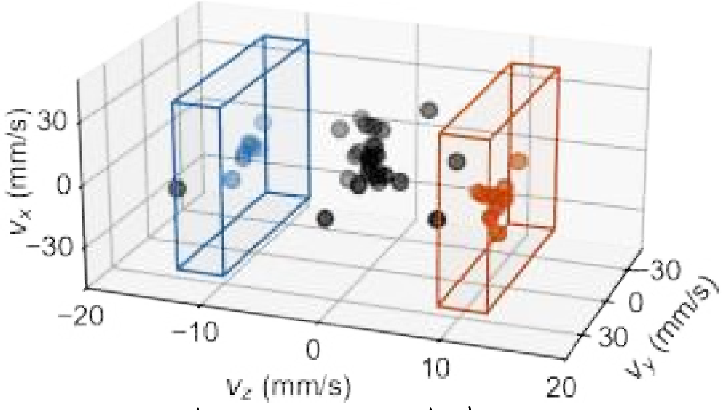
$$\omega_k = \sqrt{\frac{gn}{m}k^2 + \left(\frac{\hbar k^2}{2m}\right)^2}$$

(3) Switch off the trap: cloud expansion

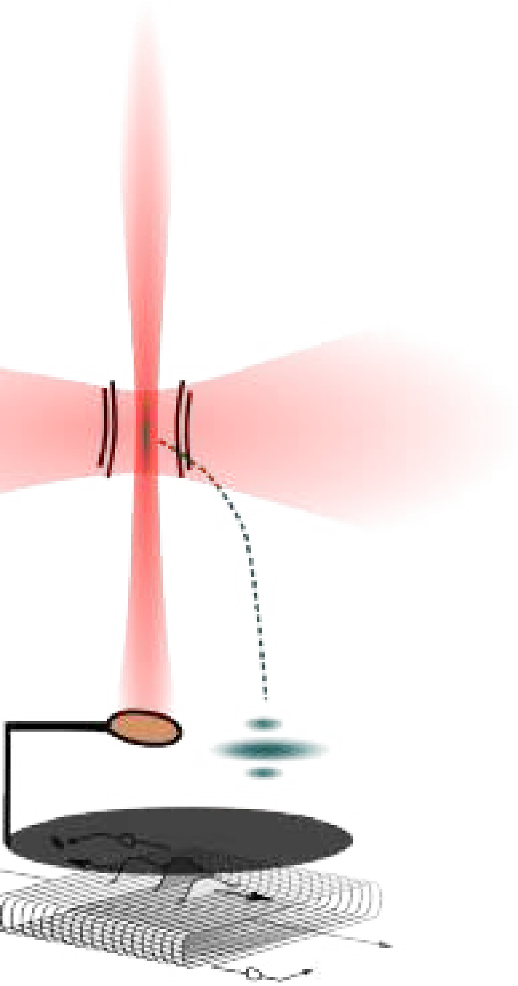
(4) Single particle detection after time of flight

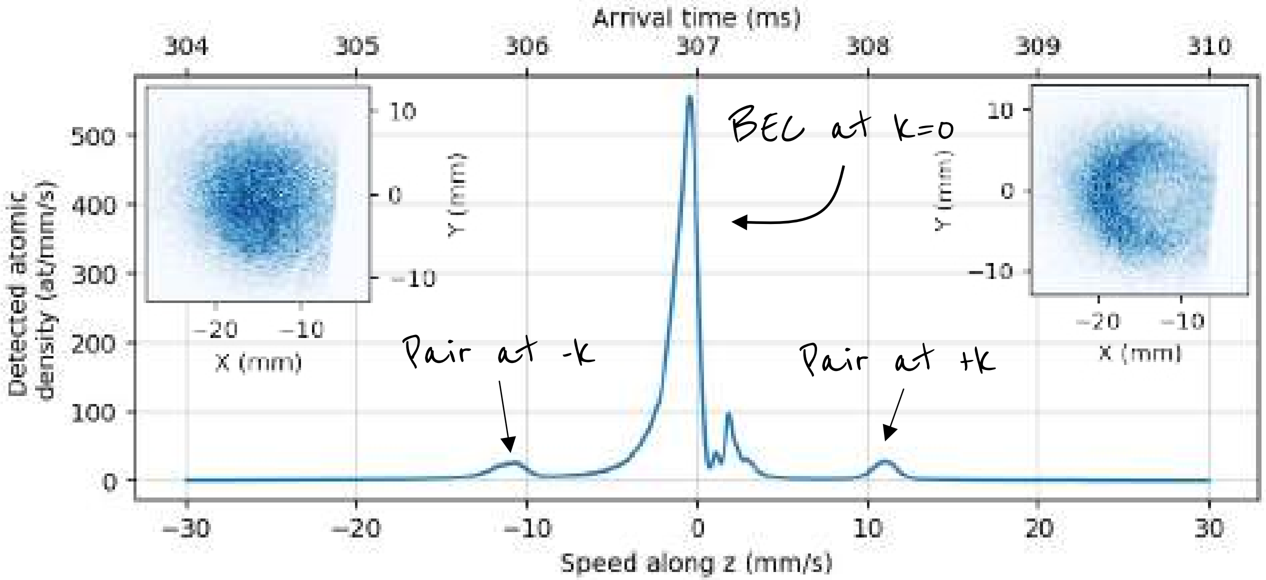
$(t,x,y) \leftrightarrow (v_Z, v_X, v_Y)$



Single shot "image", each dot is an atom. We count atoms in voxels which define the modes → measure the full particle number probability distribution

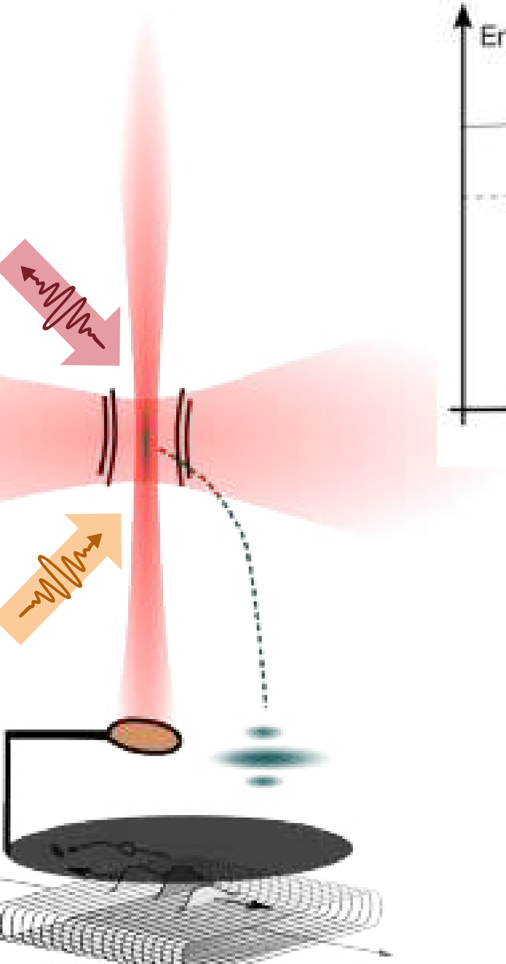
Saturation of the detector

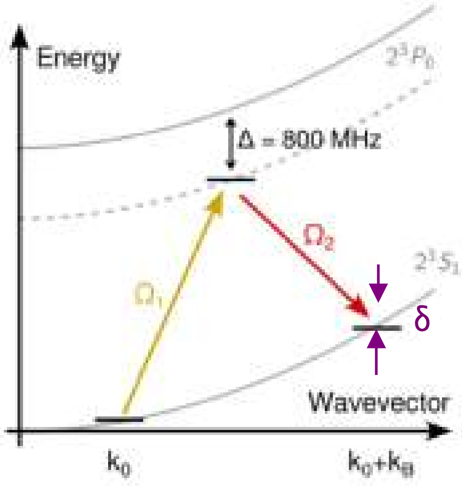




The BEC saturation affects the 2nd pair detectivity….

Use a velocity selective two-photon process to deflect only the BEC.





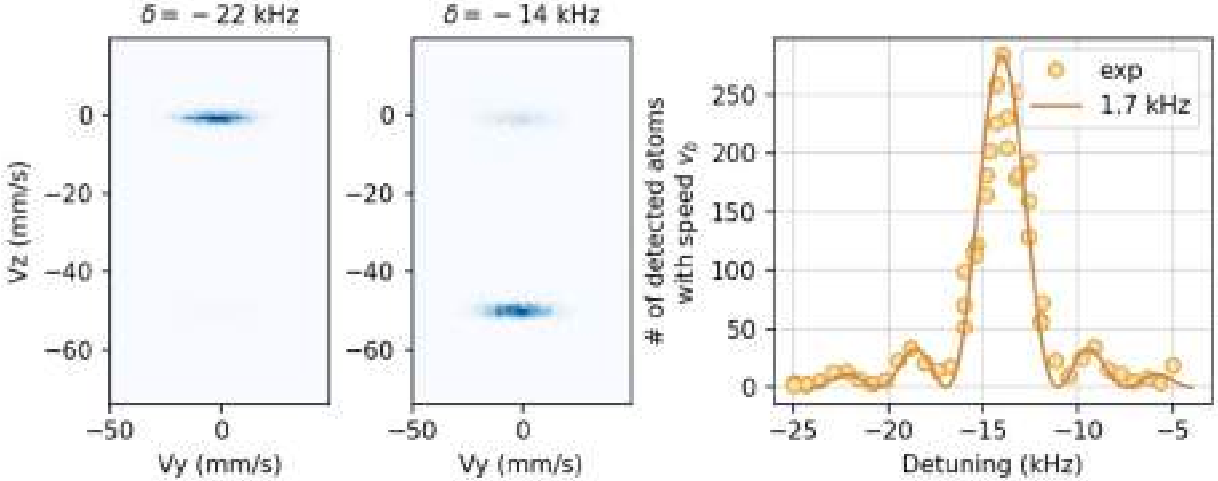
Use a velocity selective two-photon process to deflect only the BEC.

The two-photons Rabi frequency:

$$\Omega_R = \frac{\Omega_1 \Omega_2^*}{2\Delta}$$

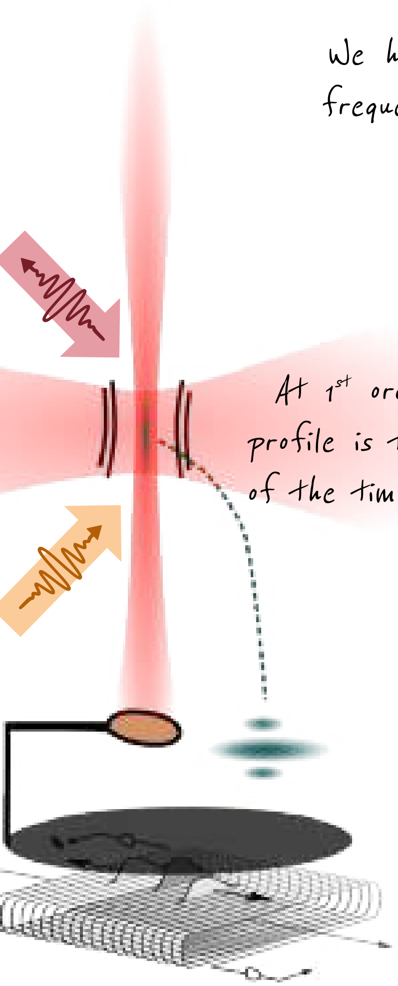
→ By changing the detuning δ between the two lasers, different velocity speeds can be addressed: $\delta \leftrightarrow v_{res}$.

The velocity kick is fixed by the angle between the two lasers



Leprince *et al* Phys. Rev. A **111**, 063304 (2025)

Bragg deflection of the BEC

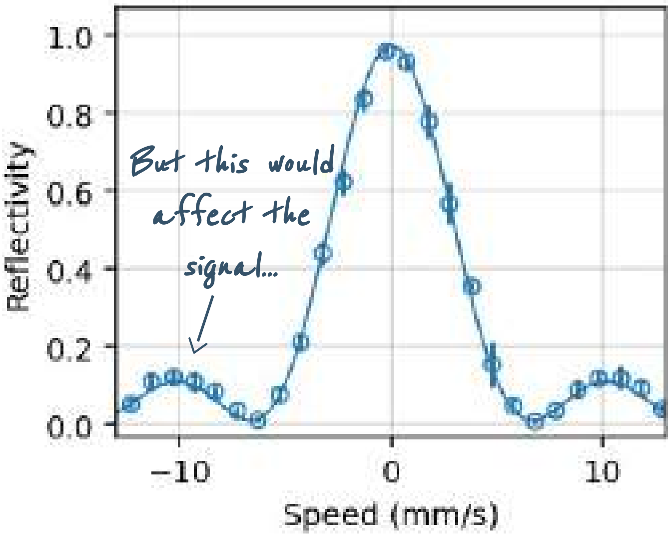


We have an equivalence
frequency momentum

At 1st order, the reflectivity profile is the Fourier transform of the time profile of the light pulse

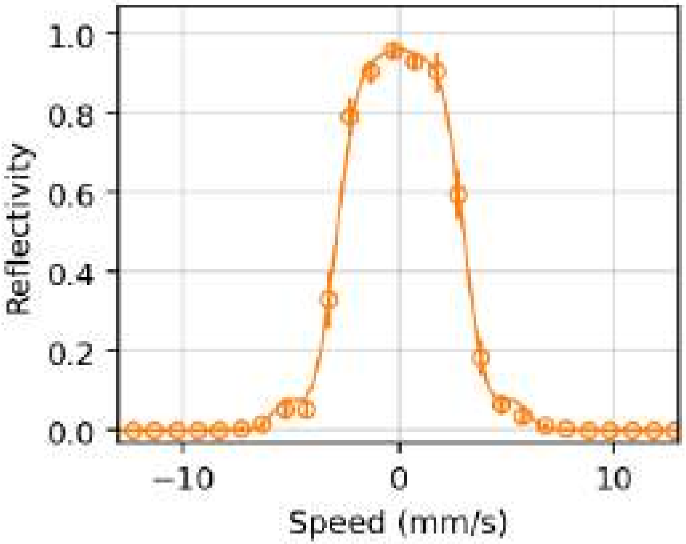
Use a velocity selective two-photon process to deflect only the BEC.

π pulse with constant Rabi frequency



(it looks like a |sinc|² function)

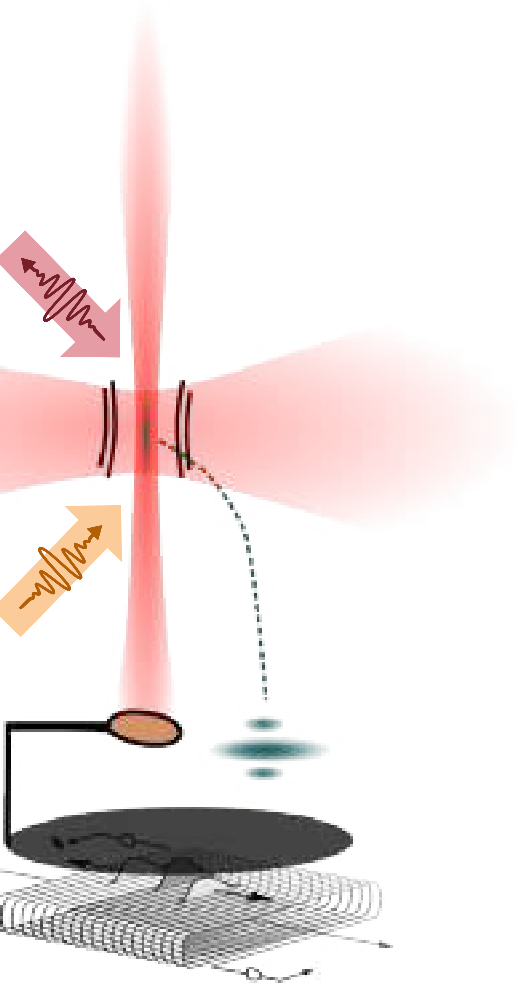
Time dependent Rabi freq as a sinc function



(it looks more like a square)

Leprince *et al* Phys. Rev. A **111**, 063304 (2025)

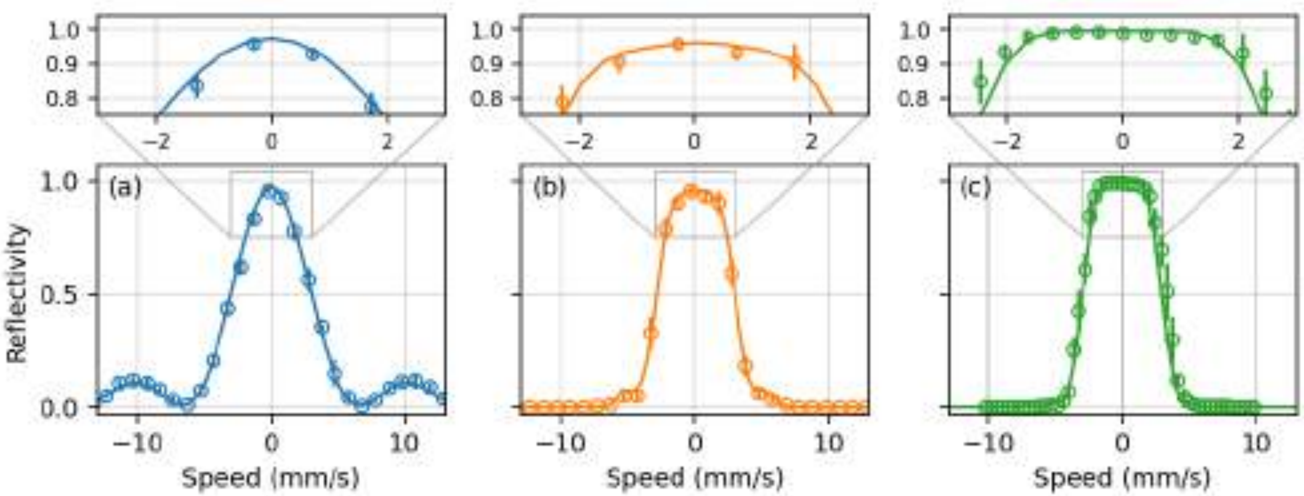
Summary



Constant pulse

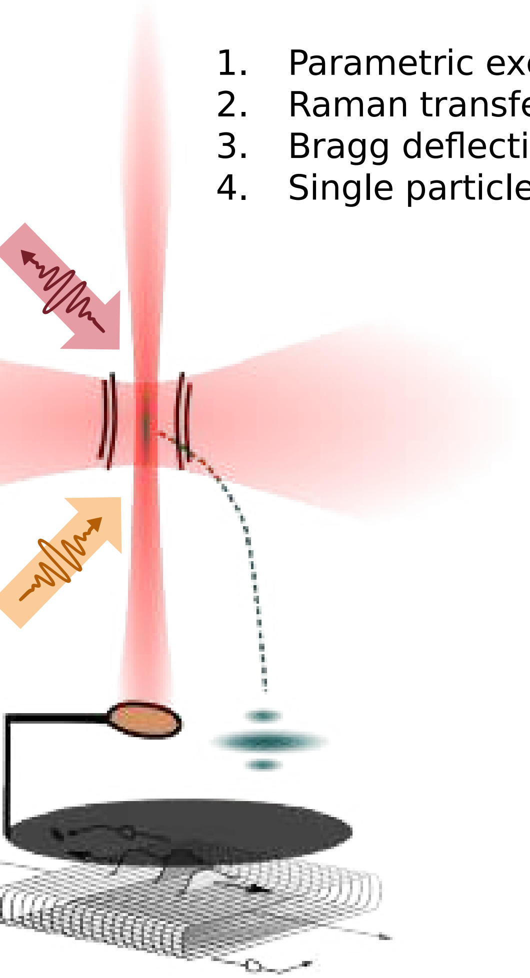
Sinc pulse

Optimized pulse
("Reburp")

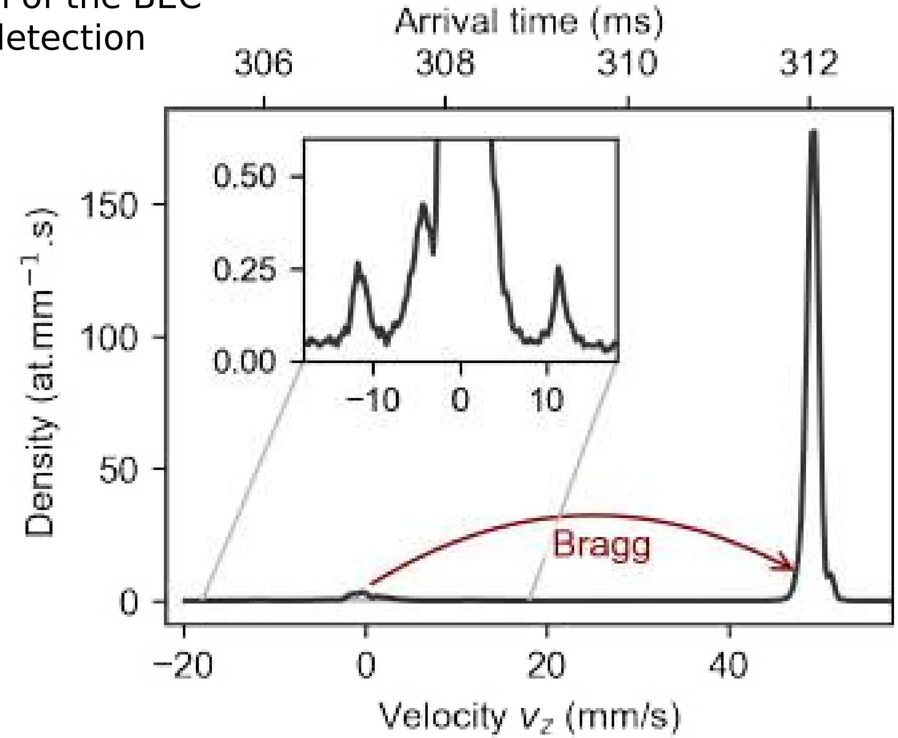


Leprince *et al* Phys. Rev. A **111**, 063304 (2025)

So does it work?



1. Parametric excitation
2. Raman transfer (+kick)
3. Bragg deflection of the BEC
4. Single particle detection



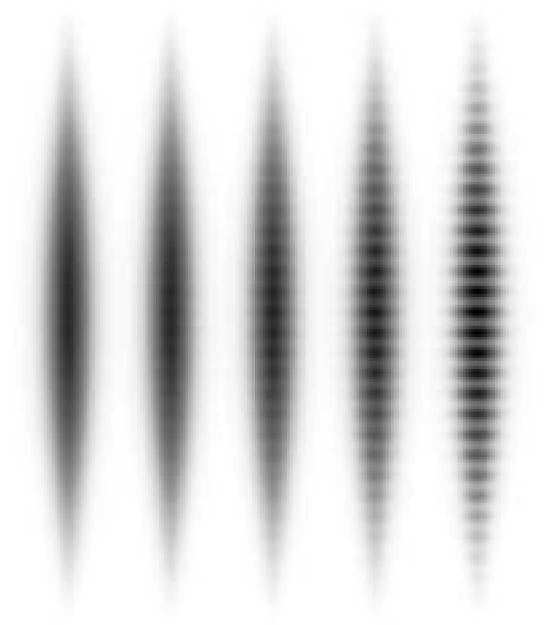
In the following, we use a pulse-shaped Bragg deflector

Leprince *et al* Phys. Rev. A **111**, 063304 (2025)

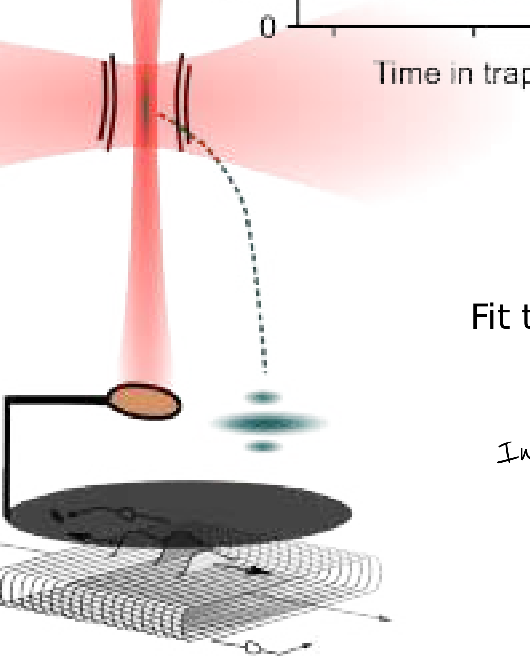
III. Growth and decay of quasiparticles

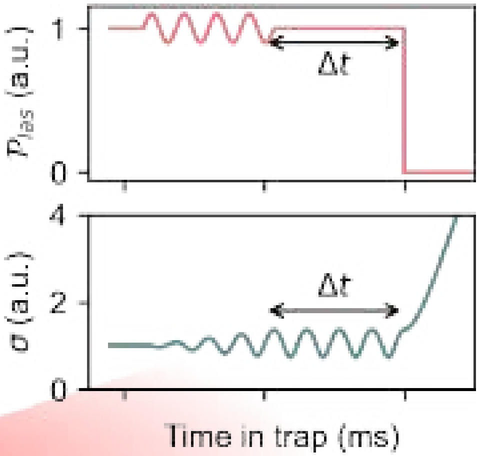
Gondret *et al.*, Parametric pair production of collective excitations in a Bose–Einstein condensate, Comptes Rendus. Physique **25**, 1 (2025).

So freeeesh: published last week!

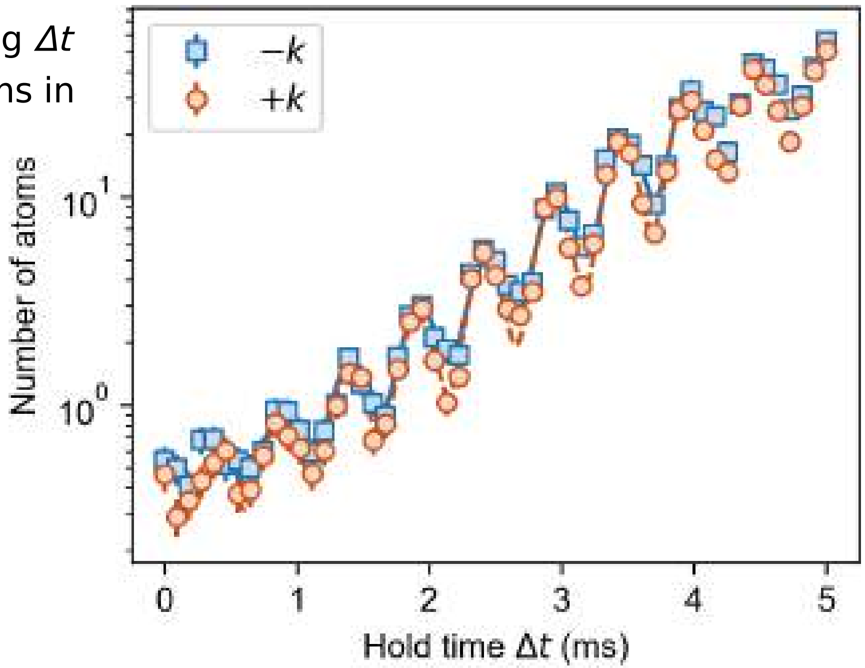


Growth of the (quasi)particle number





Repeat the experiment varying Δt and count the number of atoms in each mode



Apparent pairwise production

Exponential growth[1] as expected in parametric amplification

A large oscillation in the growth

Fit the data:

$$n_k(\Delta t) = n_0 + \Delta n\, e^{G_k \Delta t} \times [1 + A_k \cos(2\omega_k \Delta t + \varphi_k)]\,.$$

Exponential

Initial thermal population

Fluctuations that trigger the growth $\propto (n_k + n_{-k} + 1)$

Oscillation part

[1] Gondret *et al.*, Comptes Rendus. Physique **25**, 1 (2025).

Measuring the growth

Theory: assuming a sine modulation of *gn* with amplitude *a*

$$\omega_k = \sqrt{\frac{gn}{m}k^2 + \left(\frac{\hbar k^2}{2m}\right)^2}$$

The growth is analytical:

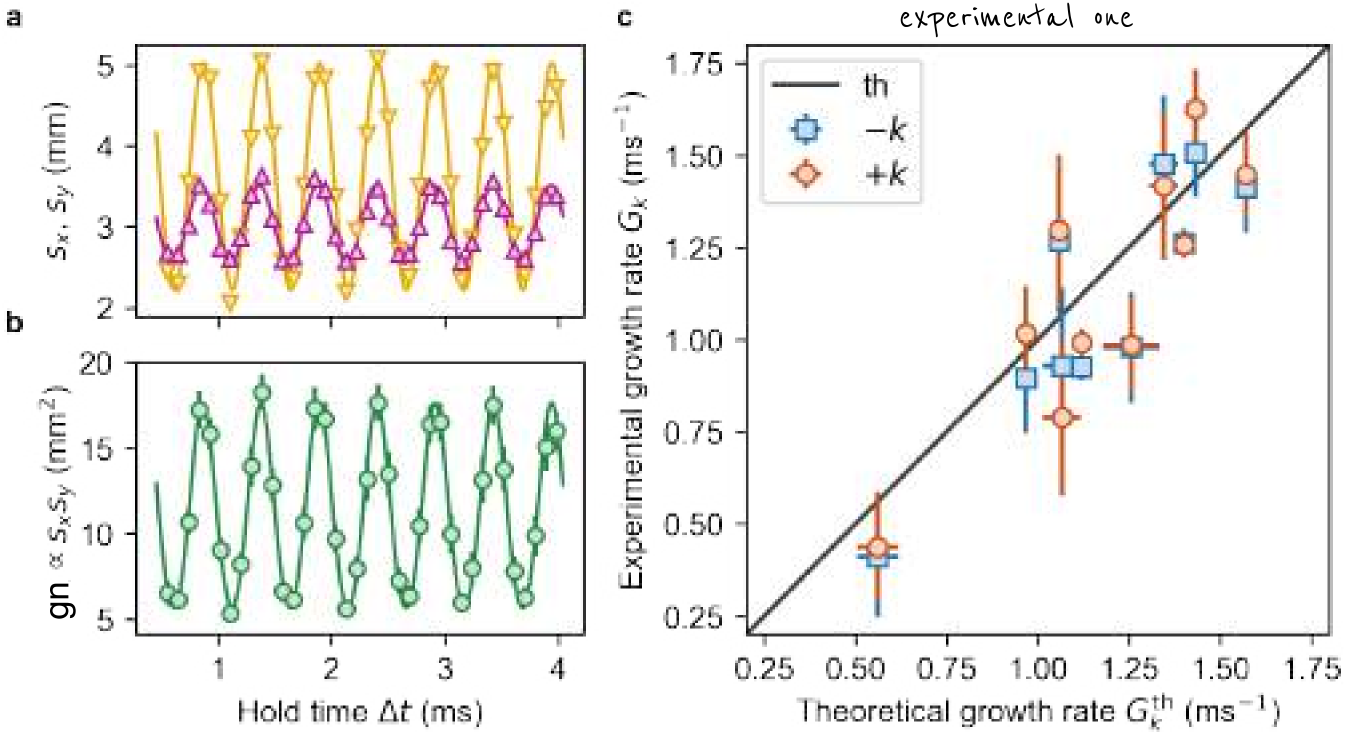
$$G_k^{th} = \frac{a}{2}\frac{\omega_k}{1 + k^2\xi^2/4}$$

BEC healing length

→ This model does not account for damping: the discrepancy between theory and experiment gives the value of the decay rate in the experiment.

We have access to the density modulation of the BEC

Comparison of the undamped theoretical growth rate to the experimental one

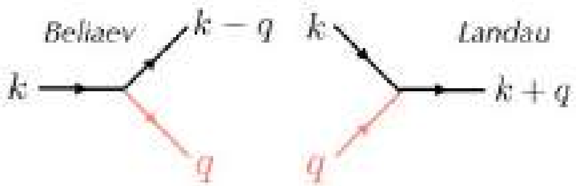


[1] Gondret *et al.*, Comptes Rendus. Physique **25**, 1 (2025).

Why measuring the decay is interesting?

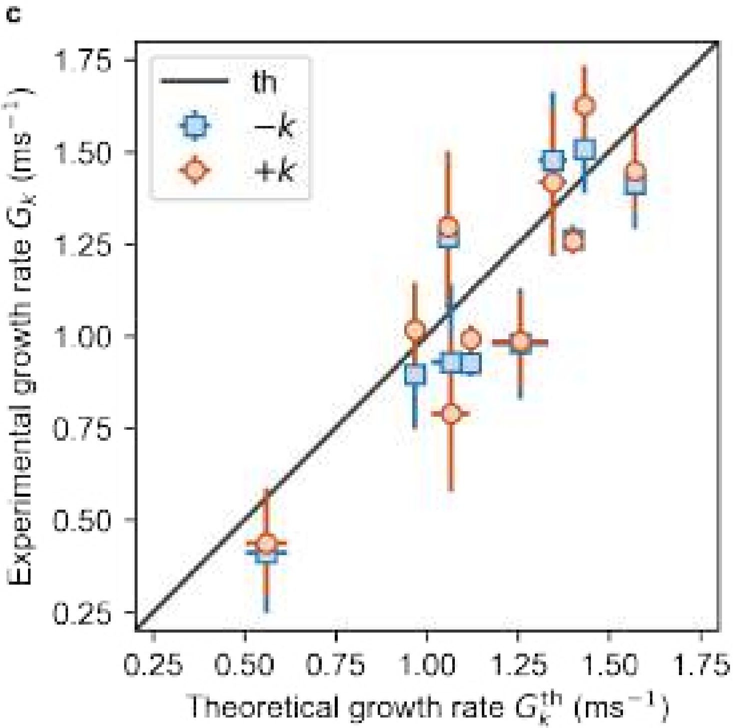
In a pure 1D gas, collective excitations do not decay because the system is **integrable** [1].

Recent prediction [2] derive an analytical formula for the decay of Bogoliubov quasiparticles in elongated Bose gases.



Although 3D, our cloud approach the 1D regime.

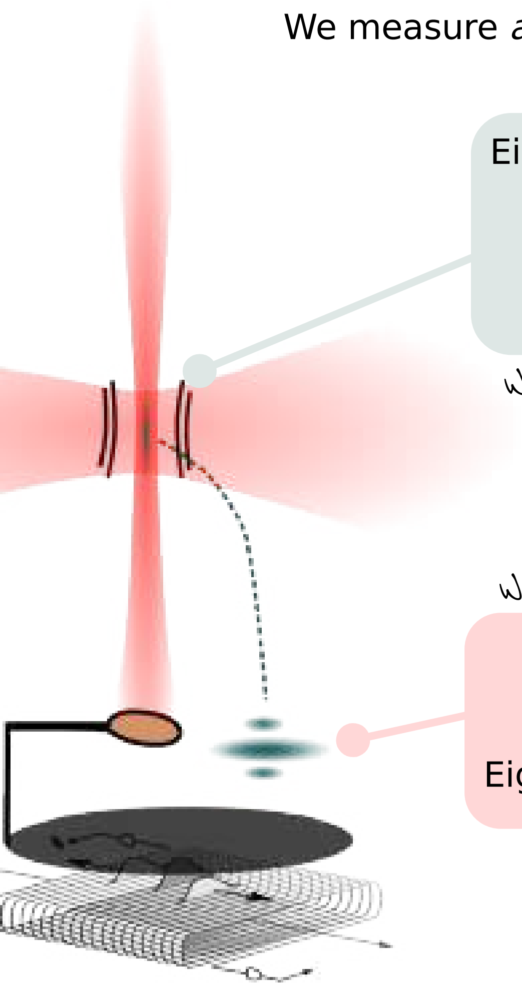
Can we check the validation of the prediction?



[1] Bouchoule *et al.,* Phys. Rev. Lett. **130**, 140401 (2023).
[2] Micheli & Robertson, Phys. Rev. B **106**, 214528 (2022).

Why this oscillation? Mapping the quasiparticles onto the particles

We measure *atoms* and not *quasiparticles*



Eigenbasis in an interacting gas

$$\omega_k = \sqrt{\frac{g_1 n_1}{m} k^2 + \left(\frac{\hbar k^2}{2m}\right)^2}$$

What we produce

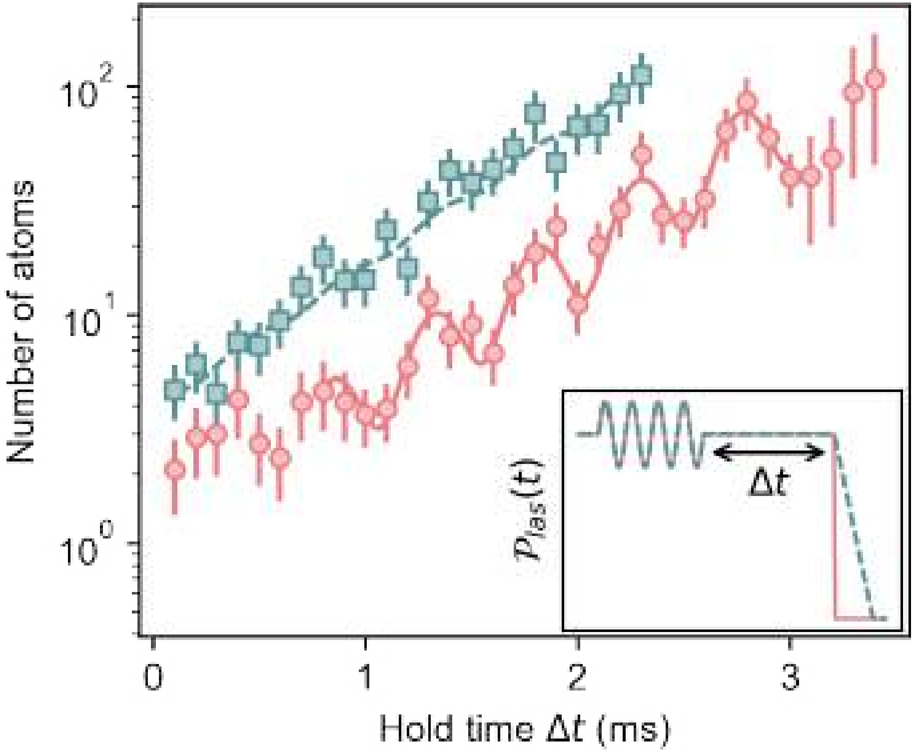
Equivalence if

$\partial_t \omega_k / \omega_k \ll \omega_k$

What we measure

$$\omega_k = \frac{\hbar k^2}{2m}$$

Eigenbasis for non-interacting atoms



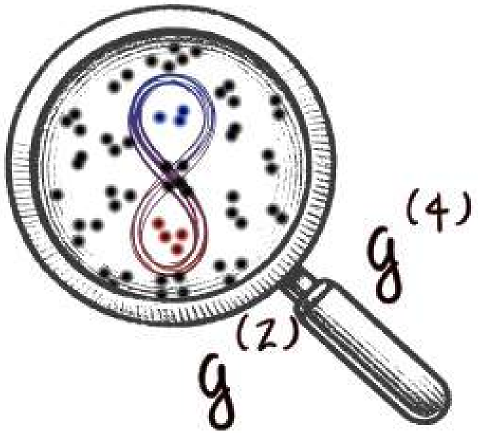
→ In the following, we slowly turn off interactions.

[1] Gondret *et al.*, Comptes Rendus. Physique **25**, 1 (2025).

We measure the full probability distribution of the quasiparticle number of a two-mode state.

→ How extract entanglement from it?

IV. Assessing entanglement of two-mode Gaussian states with many-body correlation function



Gondret *et al.*, Quantifying Two-Mode Entanglement of Bosonic Gaussian States from Their Full Counting Statistics, Phys. Rev. Lett. **135**, 100201 (2025).

What is entanglement

HOW?

Just violate a Bell inequality

Bell *Physics* (1964)
CHSH *Phys. Rev. Lett.* (1969)

Entanglement ⇔ Bell inequalities
⇔ Distillability
⇔ Teleportation

EQUIVALENCE ONLY FOR PURE STATES

Gisin, *Phys. Lett. A* (1991)
Gisin & Peres, *Phys. Lett. A* (1992)
Popescu & Rohrlich, *Phys. Lett. A* (1992)

WHAT ABOUT *MIXED* STATES?

Teleportation ⇏ Bell inequalities

Popescu Phys. Rev. Lett. (1994)

Define a partition 1-2 (two modes here). Any **separable** state can be written as

$$\rho = \sum_i \alpha_i \rho_{i,1} \otimes \rho_{i,2}$$

where $\alpha_i \geq 0$ are probabilities.

Other states are non-separable / entangled.

Werner *Phys. Rev. A* (1989)

How to assess entanglement?

SO HOW?

Many entanglement witnesses and criteria in the literature

PPT: $\hat{\rho}^{t_2} \geq 0$

Peres, *Phys. Rev. Lett.* (1996)

$$|\langle \hat{a}_1 \hat{a}_2 \rangle|^2 \leq n_1 n_2$$

Hillery & Zubairy *Phys. Rev. Lett.* (2006)

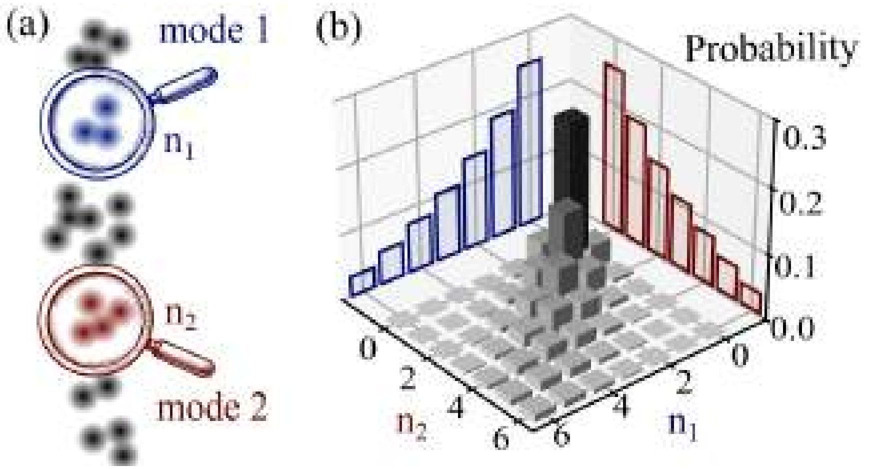
⋮

EXERIMENTAL TOOLS NEEDED

To measure the mean/variances of field operators, one needs homodyne-like detection schemes[1] or to reconstruct the state measuring non-commuting operators[2] (e.g. $\hat{x}$ and $\hat{p}$)

[1] Gross *et al.* Nature (2011)
[2] Bergschneider *et al.* Nat. Phys. (2019)

COULD WE USE THE FULL COUNTING STATISTICS?



Yields any order of *particle number* correlation function $G_{12}^{(m,p)} = \left\langle (\hat{a}_1^\dagger)^m (\hat{a}_2^\dagger)^p \hat{a}_1^m \hat{a}_2^p \right\rangle$

See also Barasiński *et al* PRL (2023)

Can we assess entanglement in general from the FCS?

Entanglement definition

A (k,-k) state is entangled if it is not separable i.e. it cannot be written as

$$\hat{\rho} = \sum_i \alpha_i \hat{\rho}_{i,k} \otimes \hat{\rho}_{i,-k}$$

with $\alpha_i \geq 0$.

Werner, Phys. Rev. A **40**, 4277 (1989)

Take a two-mode squeezed state

$$\hat{\rho}_{TMS} \propto \sum_{i,n} \kappa^i \kappa^n |i\rangle\langle i|_k \otimes |n\rangle\langle n|_{-k}$$

→ Can we prove it is entangled from its full counting statistics?

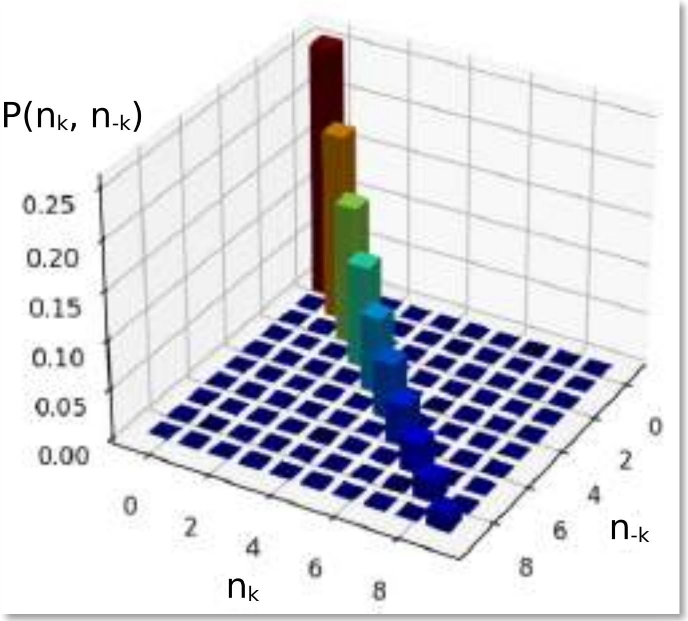


Fig: full counting statistics of a two-mode squeezed state

NO

(in general)

Ex: the following separable state has the same full counting statistics

$$\hat{\rho}_{separ} \propto \sum_i \kappa^i |i\rangle\langle i|_k \otimes |i\rangle\langle i|_{-k}$$

This state IS separable

Conclusion?

One cannot assess the entanglement of *any* quantum state from its full counting statistics.

It only measures the diagonal terms of the density matrix

So... thank you ??

Wait a minute... this is not true for *Gaussian* states!

Two-body correlation function to witness entanglement

DEFINITION

A Gaussian state is defined by its 1st and 2nd moments: it has vanishing cumulants of order > 2.

PROPERTIES

Any operator that involves more than 2 fields $\hat{a}^{(\dagger)}$ can be expressed with 1- and 2-field operators.

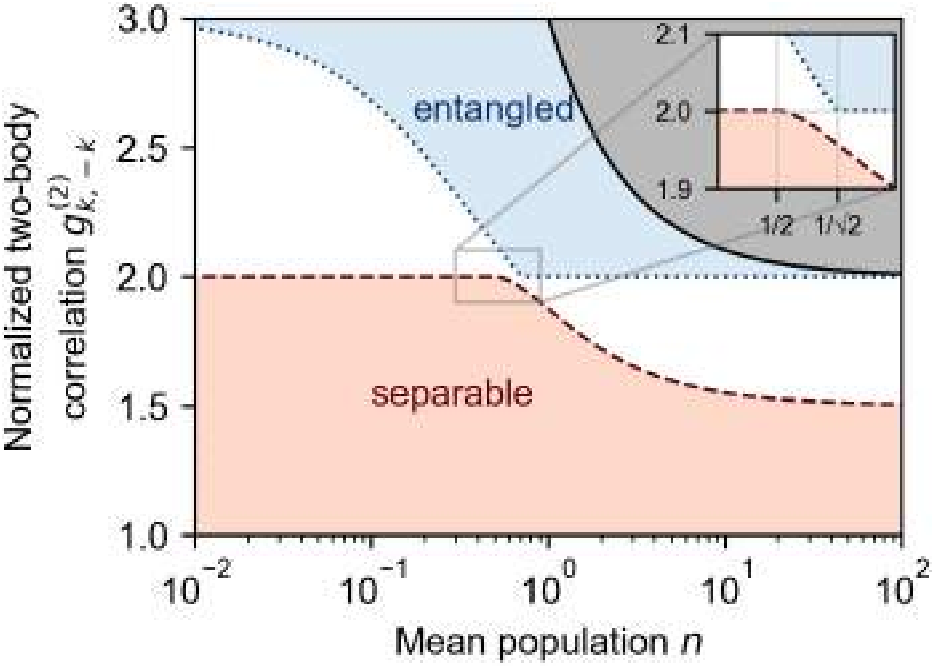
Ex: for zero mean Gaussian states,

$$G^{(2)}_{-k,k} = \langle \hat{a}^\dagger_k \hat{a}^\dagger_{-k} \hat{a}_k \hat{a}_{-k} \rangle = n_k n_{-k} + |\langle \hat{a}_k \hat{a}_{-k} \rangle|^2 + |\langle \hat{a}_k \hat{a}^\dagger_{-k} \rangle|^2$$

Populations

Entanglement is guaranteed when these quantities are sufficiently greater than the populations

If we assume that each mode exhibits a thermal probability distribution, $G^{(2)}$ is an entanglement witness[1]:



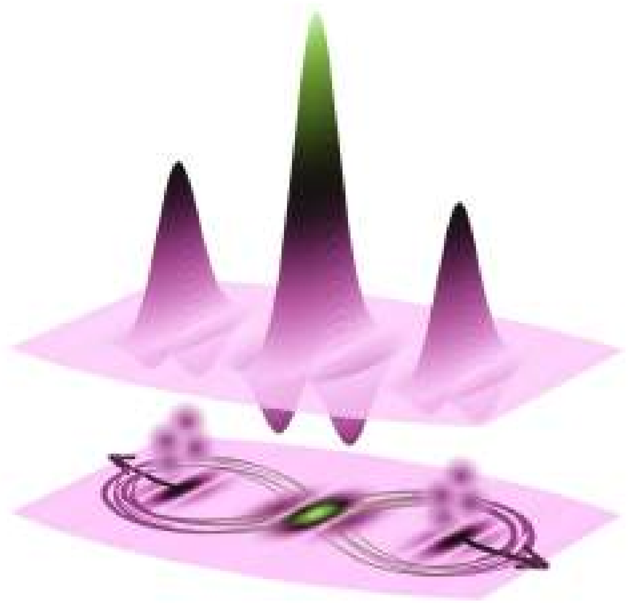
If we also measure the four-body correlation function, entanglement can be certified and quantified through logarithm negativity [1].

[1] Gondret *et al.*, Phys. Rev. Lett. **135**, 100201 (2025)

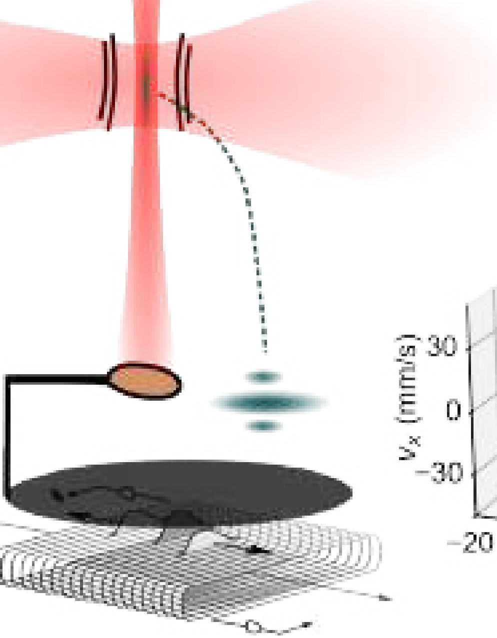
V. Observation of entanglement between collective excitations in a parametrically driven BEC

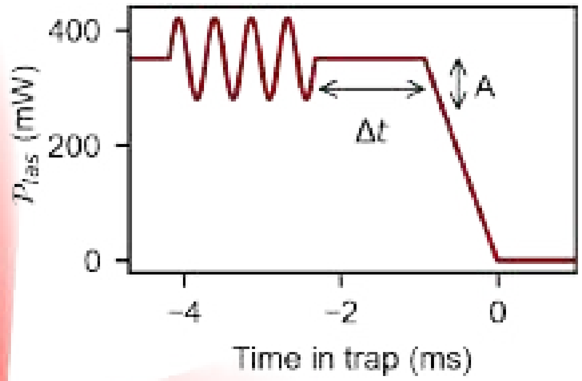
Gondret *et al.*, Observation of Entanglement in a Cold Atom Analog of Cosmological Preheating, arXiv 2506.22024 (2025)

Just accepted last week in PRL! Yippee!!!



Thermal single mode probability distribution



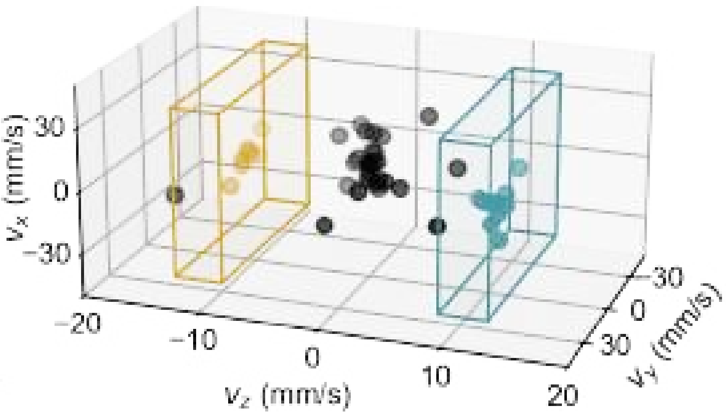


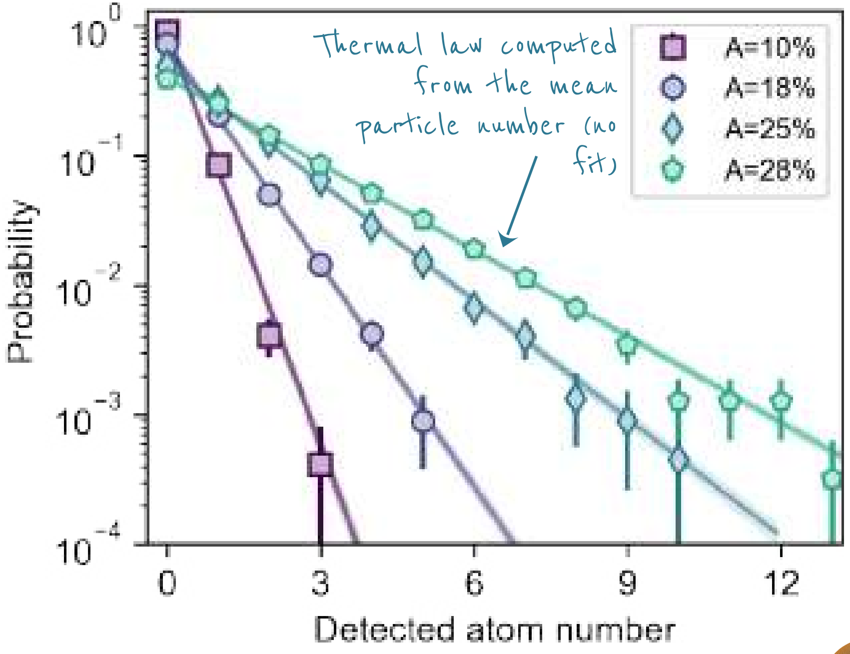
Protocol: We repeat the experiment varying the amplitude of the excitation A.

Few thousand repetitions per point, 3 weeks 24/7 in total

Measurement: probability distribution of each mode

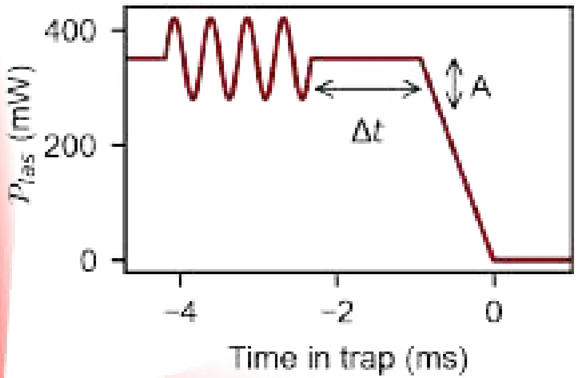
Result: thermal single mode probability distribution (i.e. bosonic bunching)

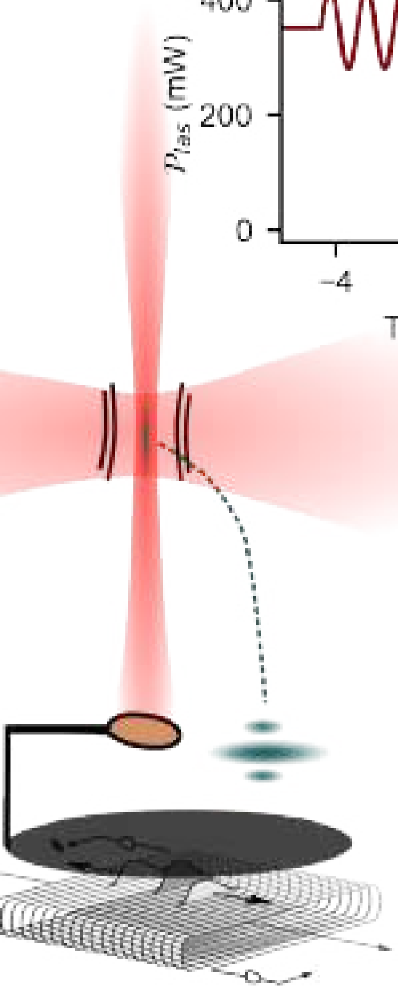




Gondret *et al.*, arXiv 2506.22024 (2025)

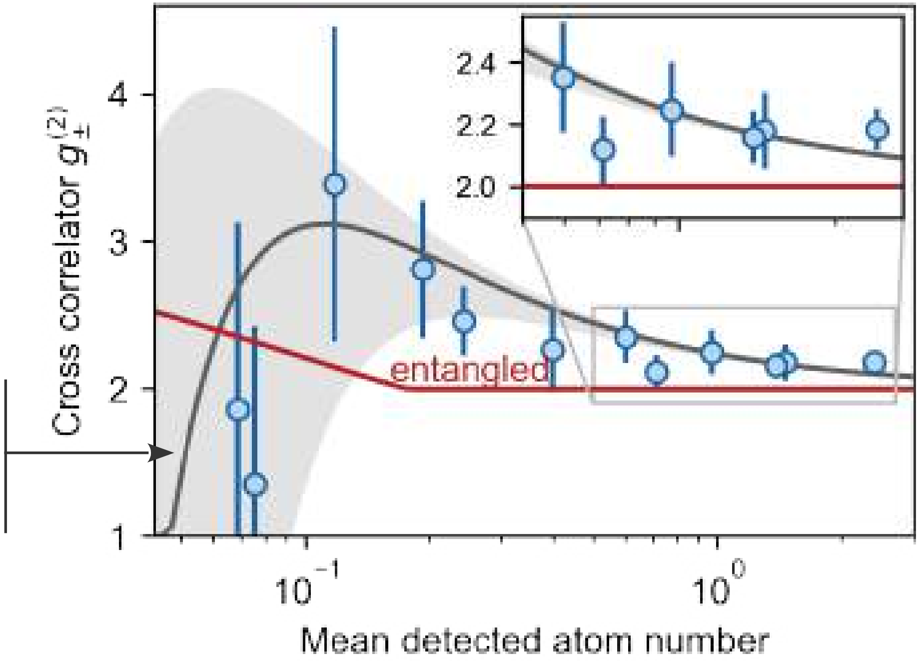
Thermal single mode probability distribution





Protocol: We repeat the experiment varying the amplitude of the excitation A.

Measurement: cross normalized two-body correlation function $g^{(2)}$



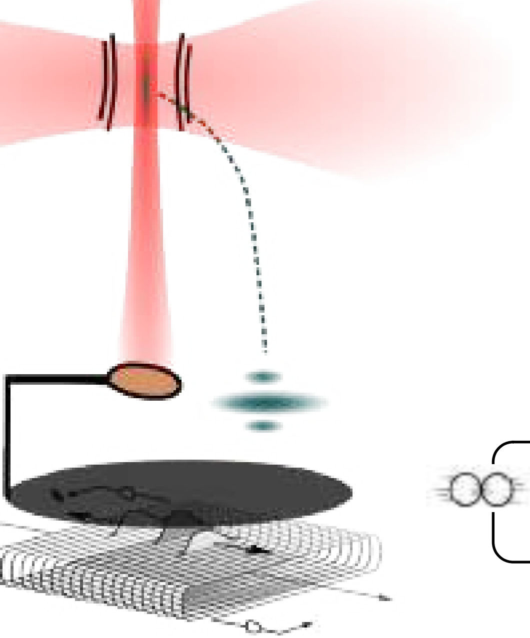
Result: assuming the two-mode state is Gaussian, it is entangled for sufficiently large excitation amplitude.

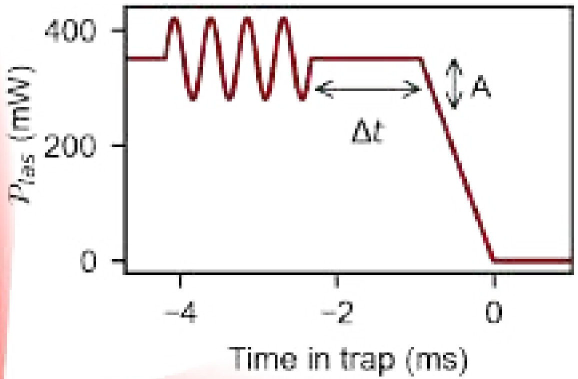
Model: two-mode squeezed thermal state without free parameter.

- 25(5)% detector efficiency,
- 25(5) nK temperature. Fluctuation of

0.5 + 0.18(8)

Vacuum ↗ ↖ Thermal





Protocol: vary the excitation duration Δt

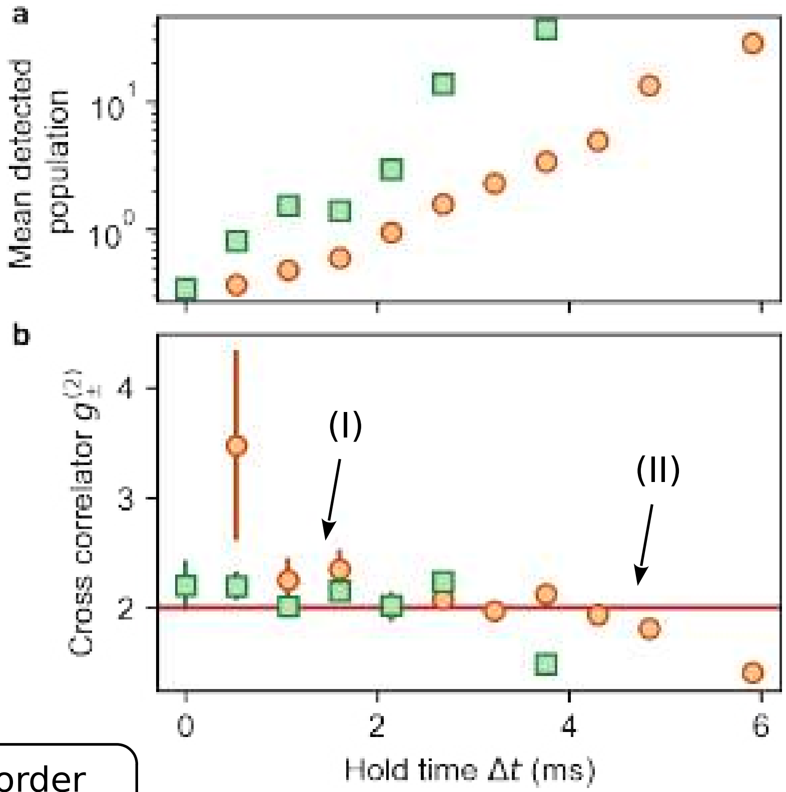
Results:

Expected in the two-mode squeezing model.

(I) $g^{(2)} \to 2$ as population grows

(II) At later time, $g^{(2)}$ drops below 2

Not expected



Onset of a late-time regime where higher order quasi-particle interactions become relevant.

Outlooks

Onset of a late-time regime where higher order quasi-particle interactions become relevant.

Towards the study of the much-less understood interaction-dominated regime:

- decoherence of the resonant modes,

  Robertson *et al.*, Phys. Rev. D **98**, 056003 (2018)

- loss of Gaussianity,

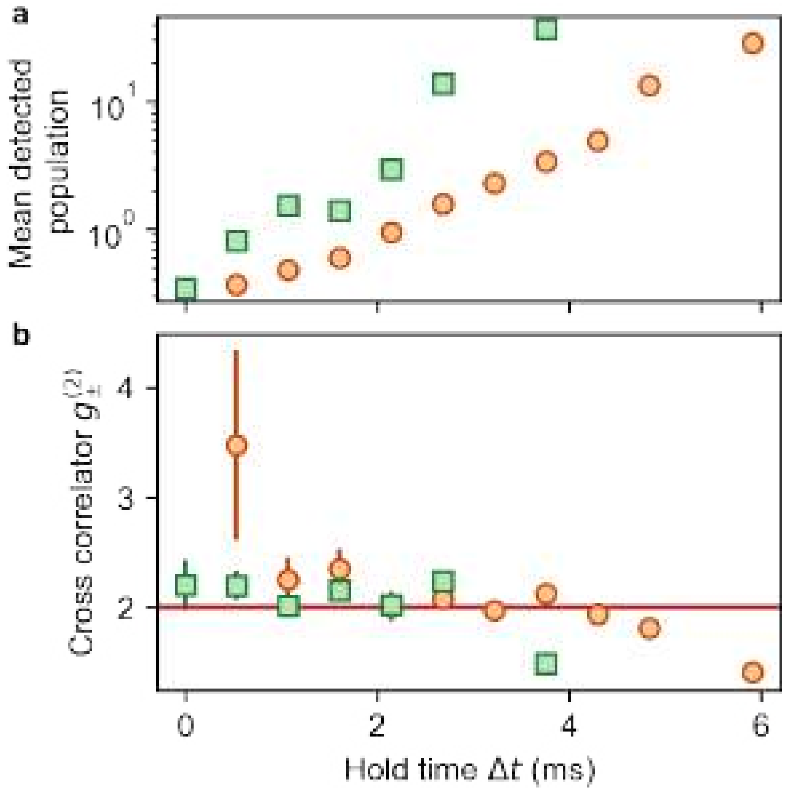
  Schweigler *et al.*, Nat. Phys. **17**, 559 (2021)
  Bureik *et al.*, Nat. Phys. **21**, 57 (2025)

- appearance of higher order peaks,

  Gregory *et al.*, arXiv:2410.08842 (2025)

- back-reaction of the quasiparticles on the BEC...

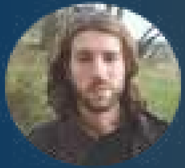
  Butera and I. Carusotto, Phys. Rev. Lett. **130**, 241501 (2023)

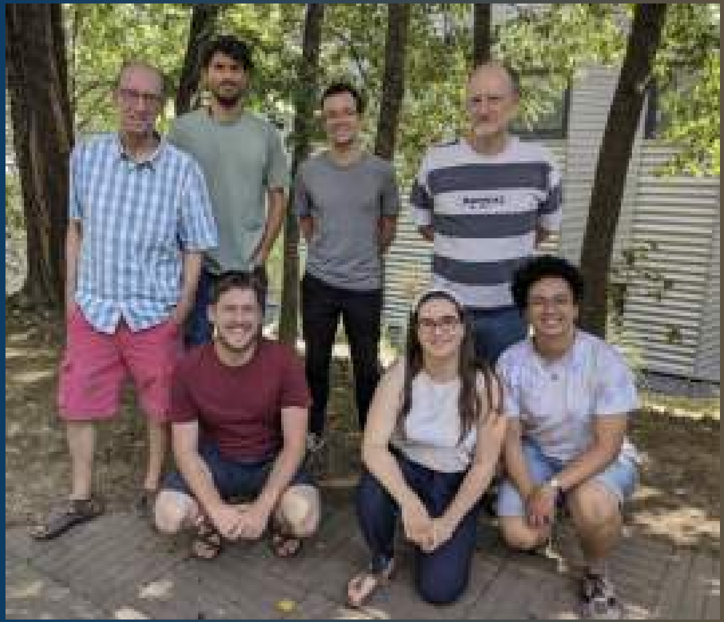


Take home message

- Analogy between quasiparticles in a fluid and particles in curved space time,
- Two-mode entanglement of Gaussian state can be assessed from particle number correlation,
- Observation of vacuum amplification through entanglement between quasiparticles in a BEC.

Thank you for your attention!





Refs

- arXiv 2411.09284
- arXiv 2503.09555
- arXiv 2506.22024
- arXiv 2508.01654

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