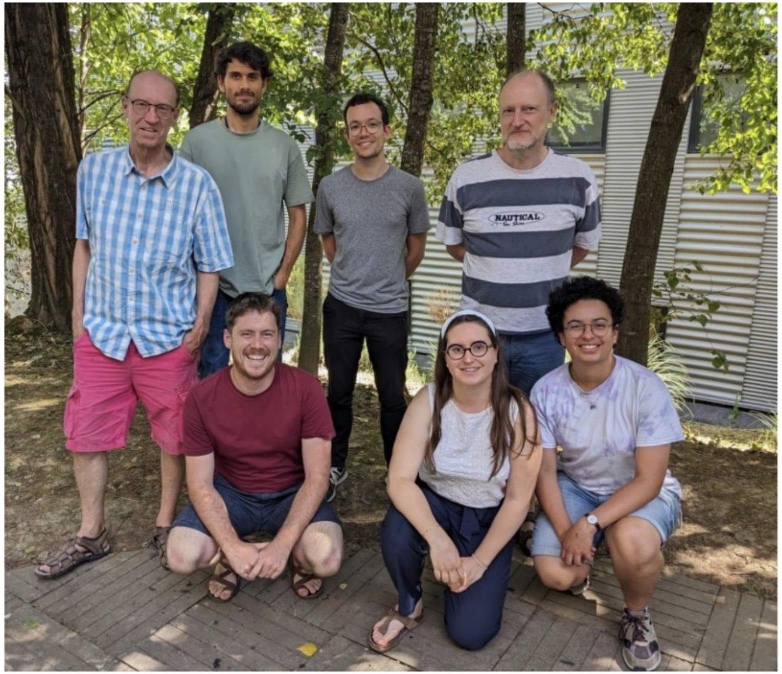
Observation of entanglement in a cold atom analog of cosmological preheating

Victor Gondret,

5-7 of November, 2025

QUOSTIX, Valparaiso



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

Th: Amaury Micheli & Scott Robertson

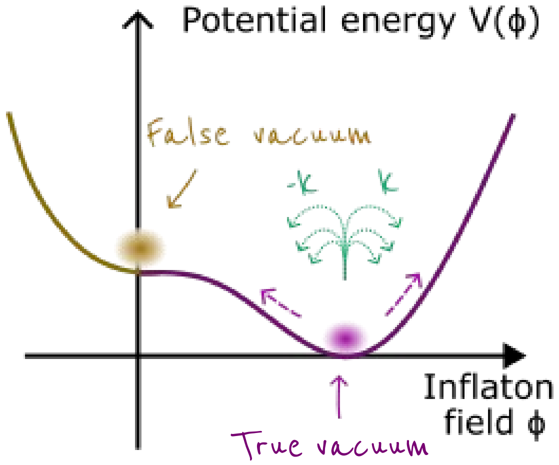
Slides available at
www.normalesup.org/~gondret/talk.pdf

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).

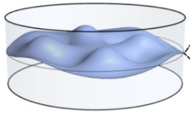
Particles are created in **pairs** with **opposite momenta from vacuum** in a highly entangled two modes squeezed state. Interactions lead to decoherence and thermalization.
D. Campo & R. Parentani, Phys. Rev. D **74**, 025001 (2006).



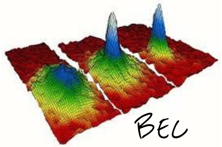
BUT NOT OBSERVABLE

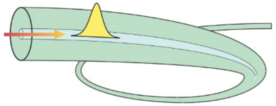
Analog gravity

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

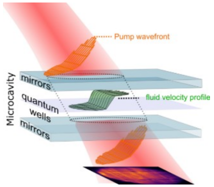


Water





Optical fibers



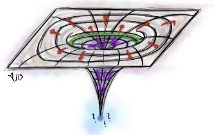
Polariton

Analog gravity

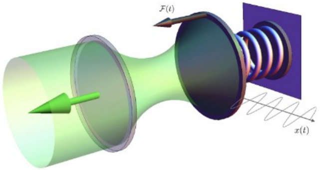
In the presence of a strong coherent background, the excitations of a fluid, or *quasi*particles, can be treated using the same formalism as particles in a curved spacetime.

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

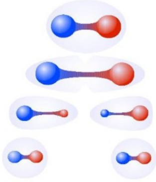
Shape the fluid to mimic famous effect of QFT.



Hawking Radiation



Dynamical Casimir Effect



Schwinger effect

A quantum version of Faraday waves

This work: parametric production of *quasi*particles in a non expanding background (i.e. cosmological toy-model).

Or simply the quantum version of Faraday's instability

Goal: observe the amplification of vacuum fluctuations which manifests through entanglement between opposite waves.

Faraday waves with BEC in Chicago, Heidelberg, Houston, Mexico, Trento, Utrecht, Washington.

Faraday waves

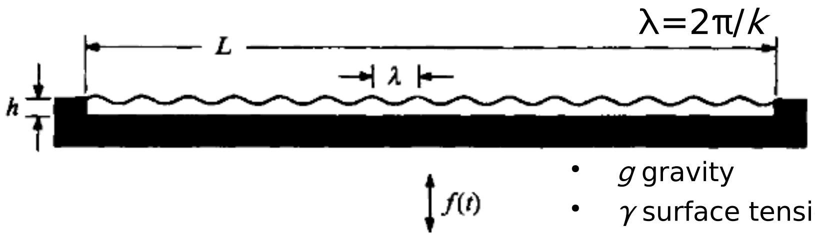
Vertical oscillation of the tank at Ω

→ Periodic modulation of the dispersion relation sets the excited mode

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

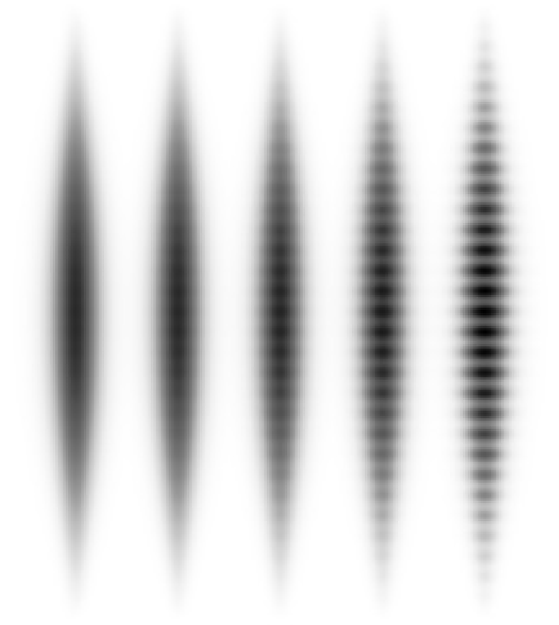
Modulation of the effective gravity

→ The growth of the pattern is triggered by **fluctuations** (e.g. thermal fluctuations)



- g gravity
- γ surface tension

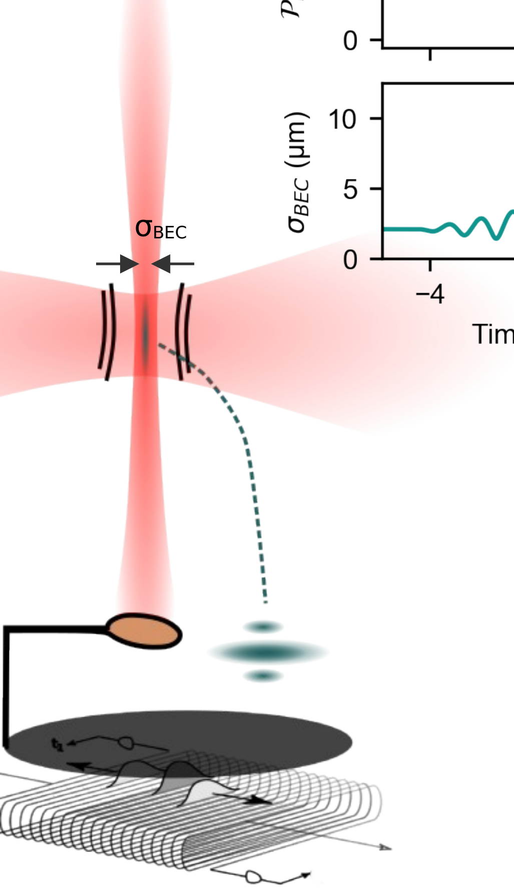
I. Parametric production of quasiparticles in a density-modulated BEC

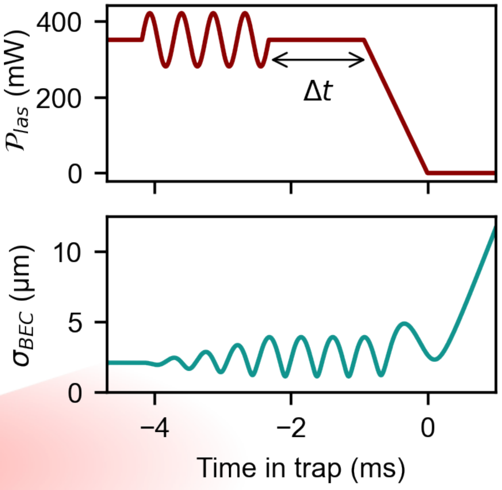


Gondret *et al.*, Parametric pair production of collective excitations in a Bose–Einstein condensate, Comptes Rendus. Physique **25**, 1 (2025).

Just published this Monday! Yippee!!!

→ Production of a cigar-shaped He* BEC each 10 s





Protocol

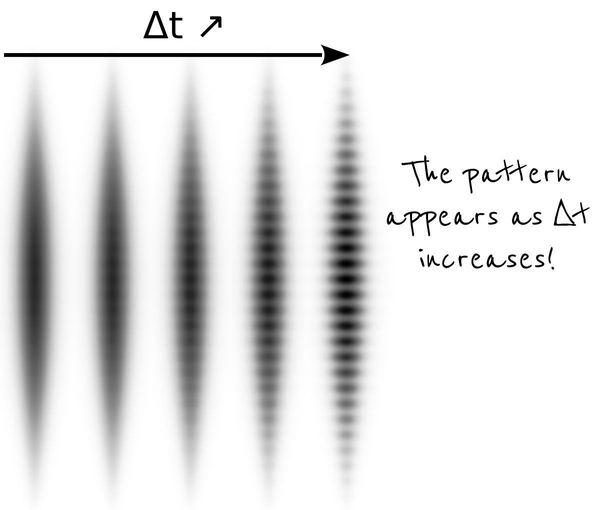
(1) Excite the transverse breathing mode of the BEC at Ω for 4 periods, |

(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

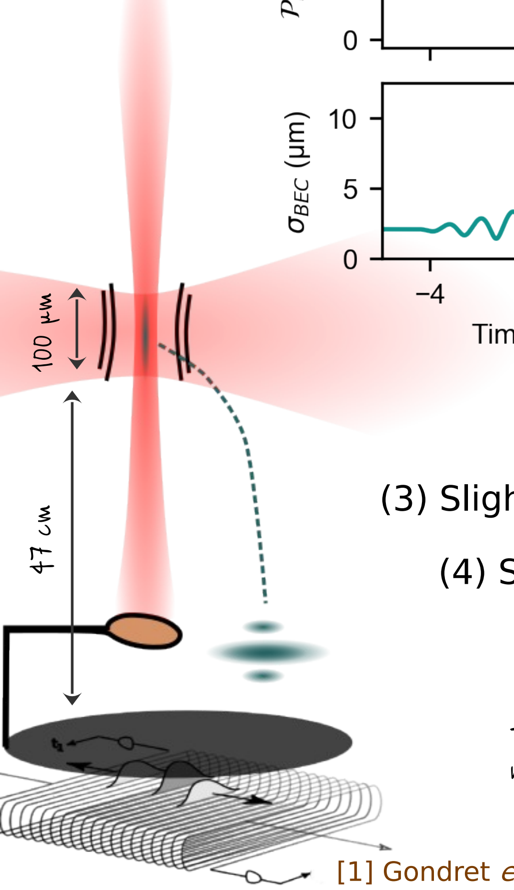
- g effective interaction strength
- n density
- m atomic mass
- $\hbar$ reduced Planck cte

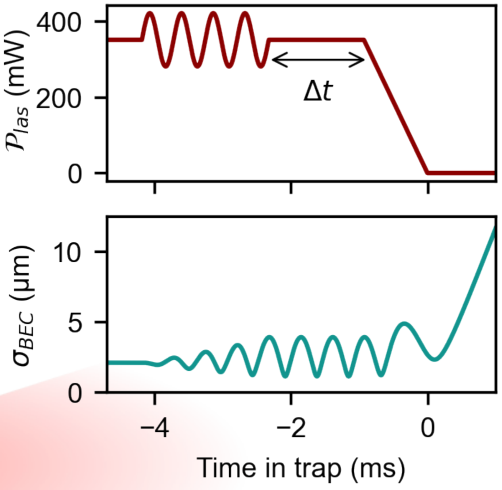


The pattern appears as Δt increases!

Faraday waves with quantum fluids

→ Production of a cigar-shaped He* BEC each 10 s





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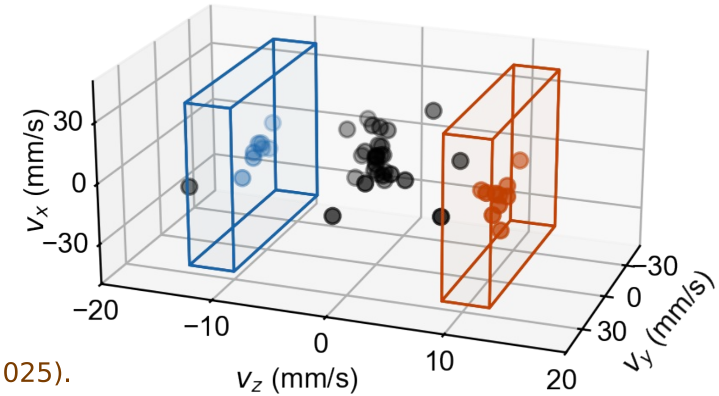
$$\omega_k = \sqrt{\frac{gn}{m}k^2 + \left(\frac{\hbar k^2}{2m}\right)^2}$$

(3) Slightly turn off interactions[1]

(4) Single particle detection after time of flight

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

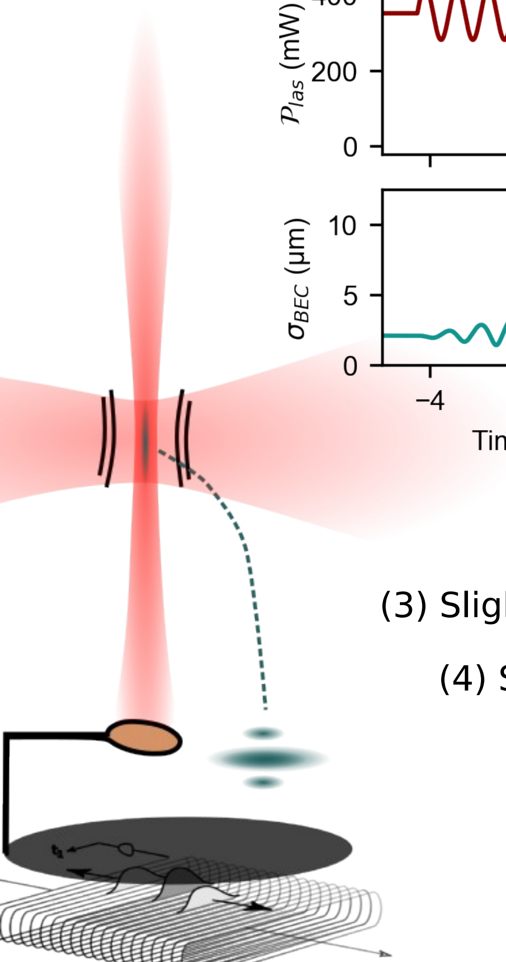
→ Measure the full particle number probability distribution

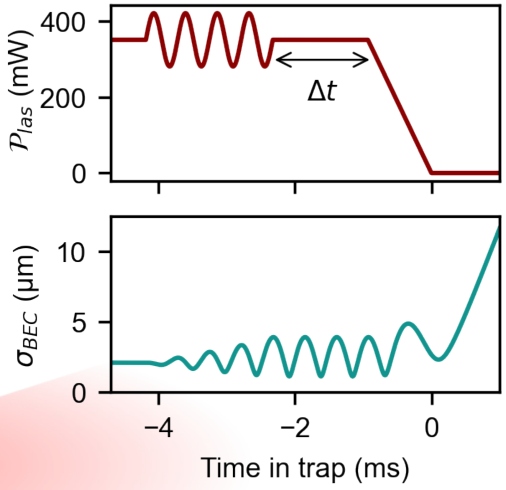


Single shot "image", each dot is an atom. The voxels define the mode

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

Faraday waves with quantum fluids





Protocol

Small depletion of the BEC: Bogoliubov approximation → Gaussian state

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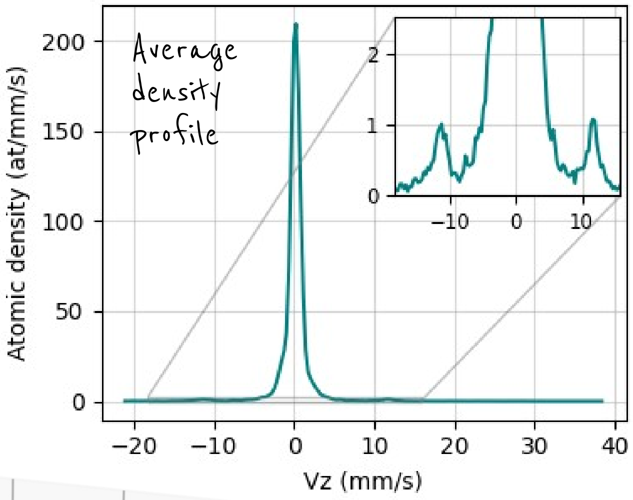

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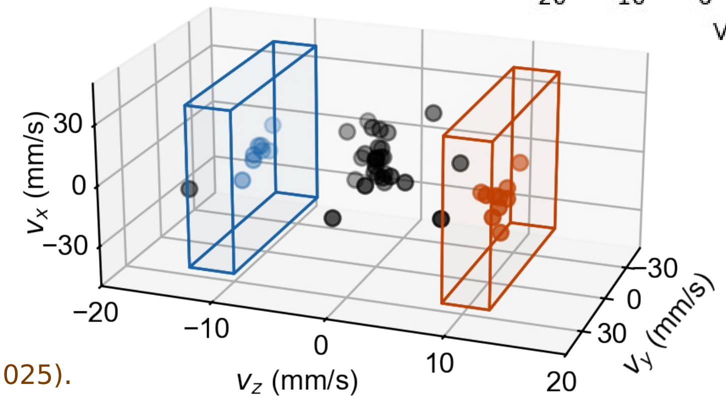

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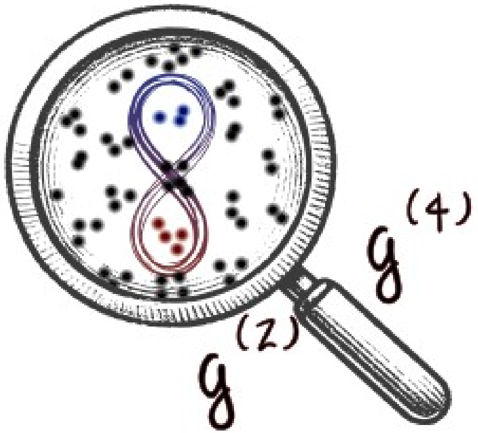
We measure the full probability distribution of the quasiparticle number of a two-mode state.

→ How extract entanglement from it?

II. 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).



Entanglement

For pure states

Entanglement $\Leftrightarrow$ violation of a Bell inequality

Gisin, Phys. Lett. A **154**, 201 (1991)

For mixed states

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)

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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?

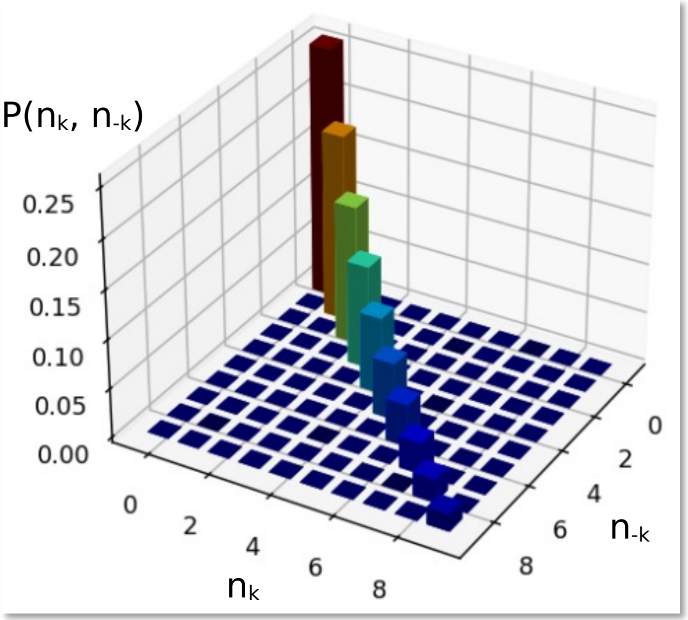

Fig: full counting statistics of a two-mode squeezed state

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

NO
(in general)

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

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

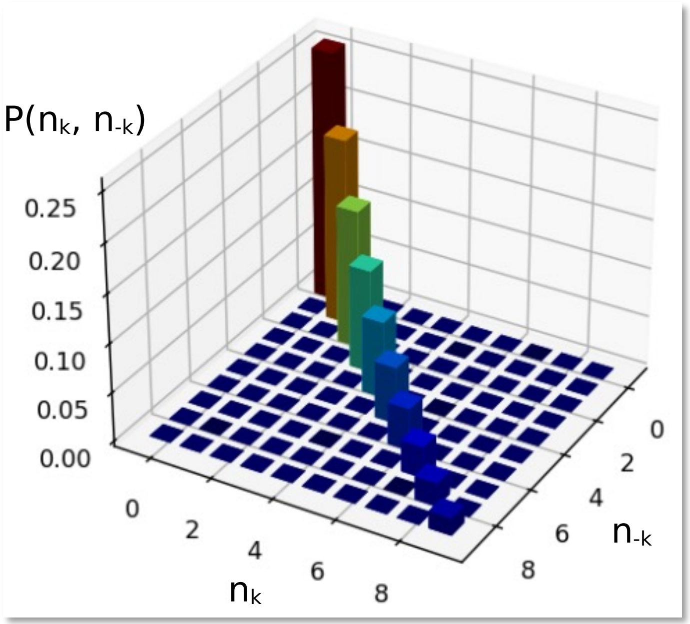

Fig: full counting statistics of a two-mode squeezed state

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 ??

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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 N>2 connected correlation functions

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

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Populations

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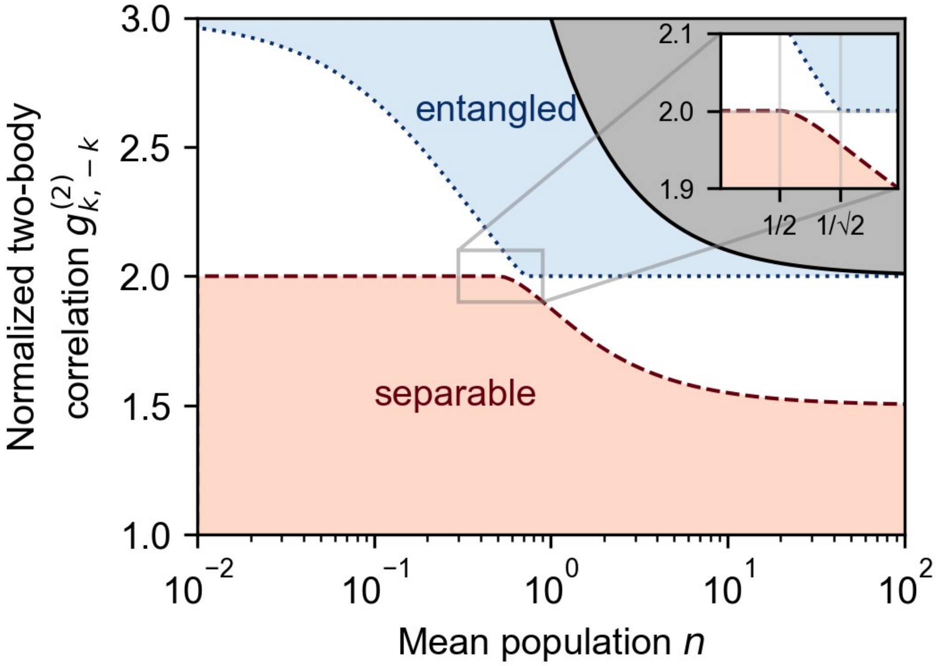
If we assume that each mode exhibits a thermal probability distribution, $G^{(2)}$ is an entanglement witness[1]:



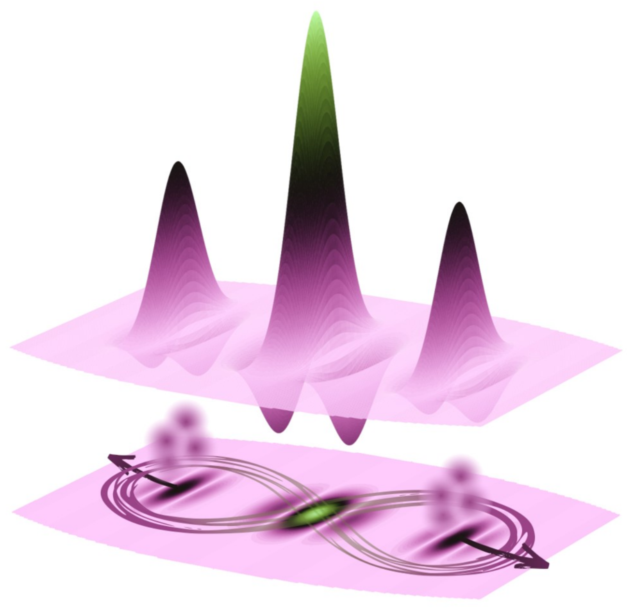
If we also measure the four-body correlation function, entanglement can be certified and quantified through logarithm negativity [1].

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

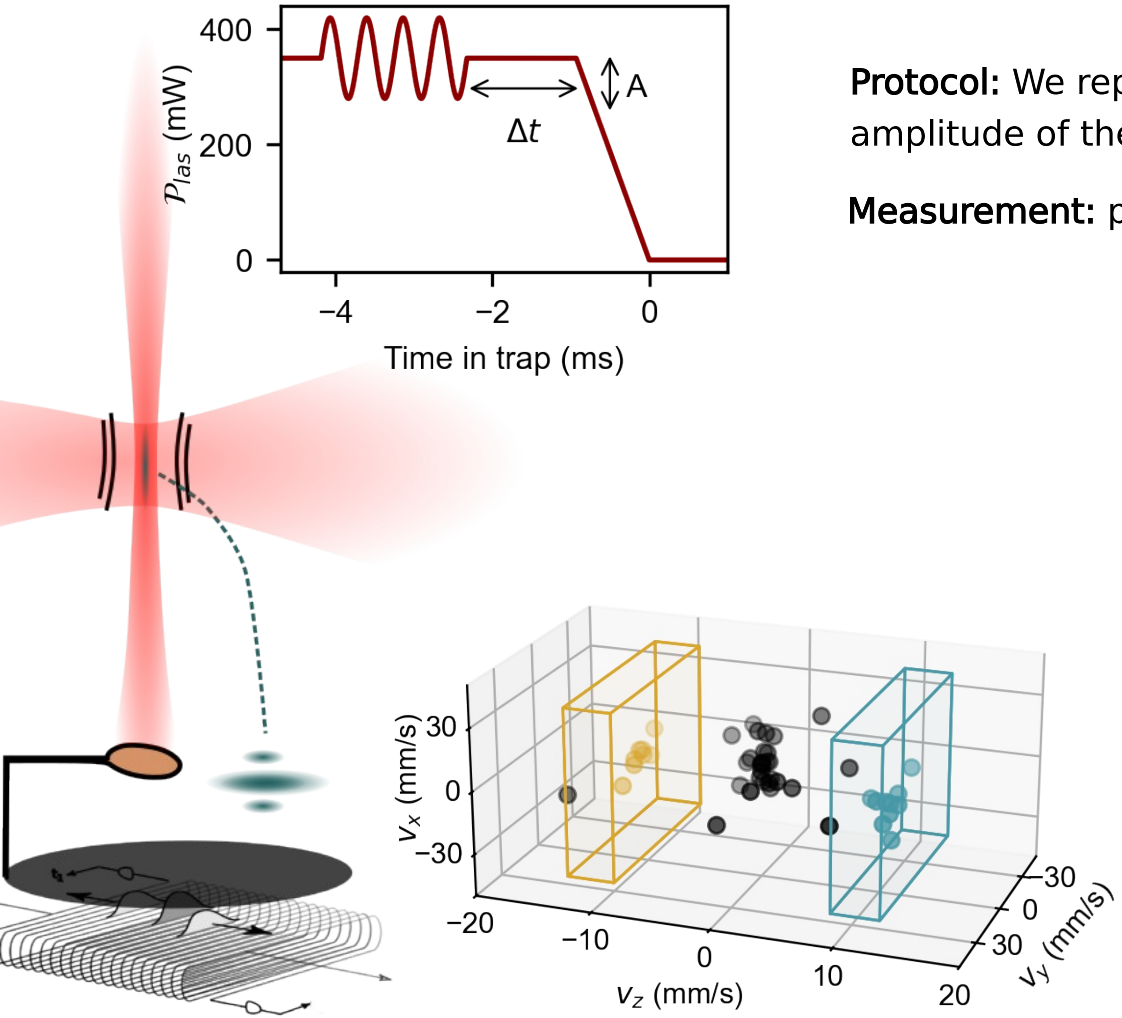
III. Observation of entanglement between collective excitations in a parametrically driven BEC

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

Just accepted yesterday
in PRL! Yippee!!!



Thermal single mode probability distribution



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

Measurement: probability distribution of each mode

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

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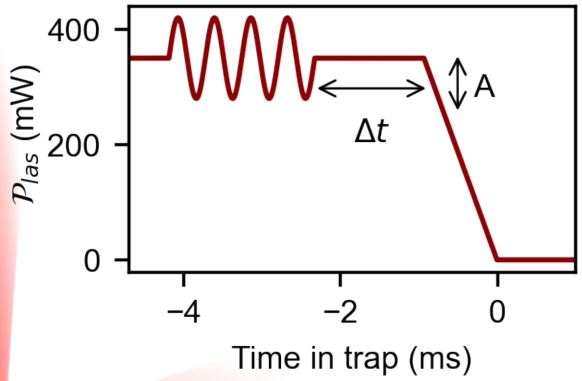

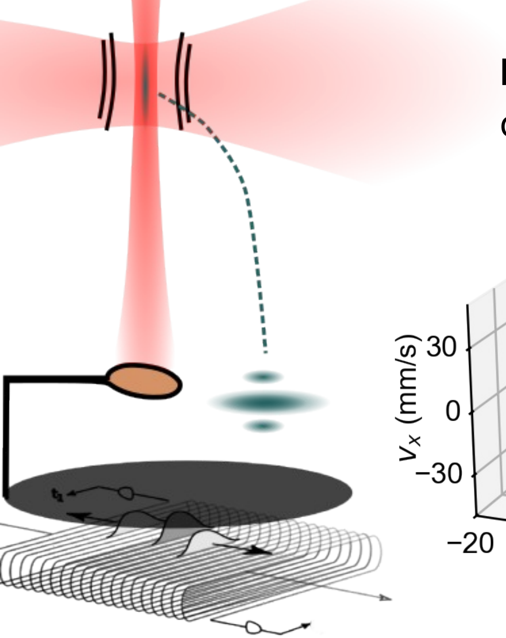

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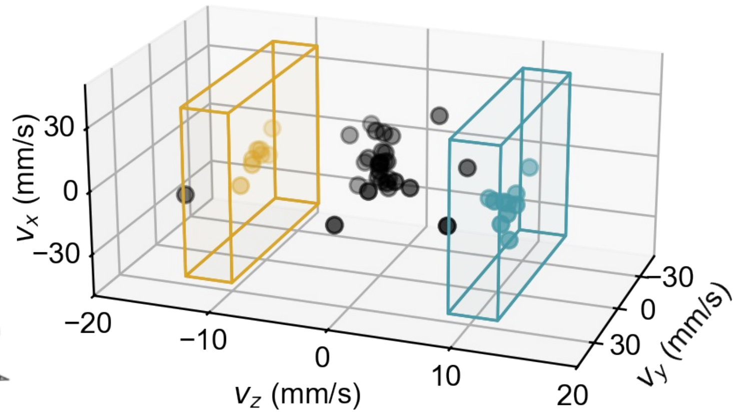
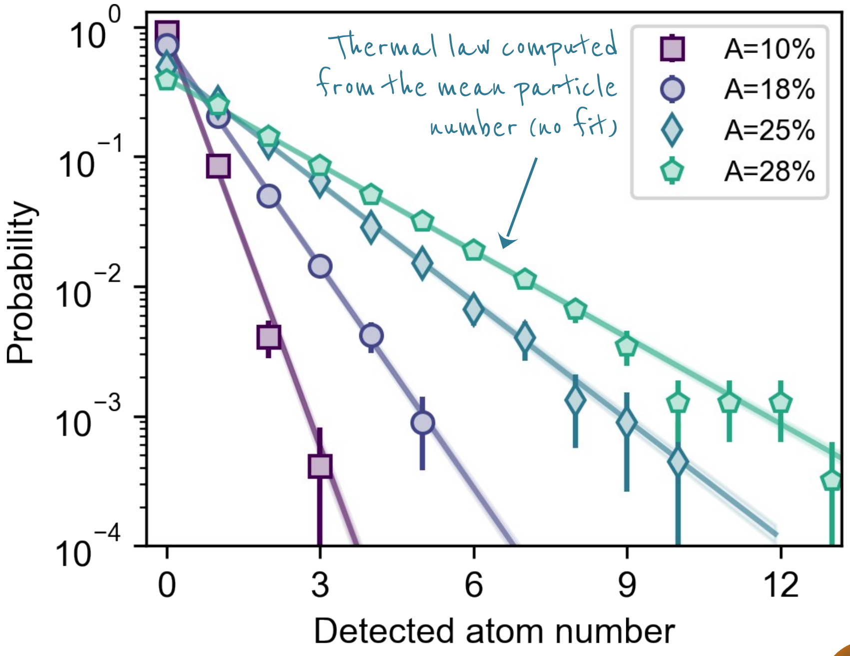
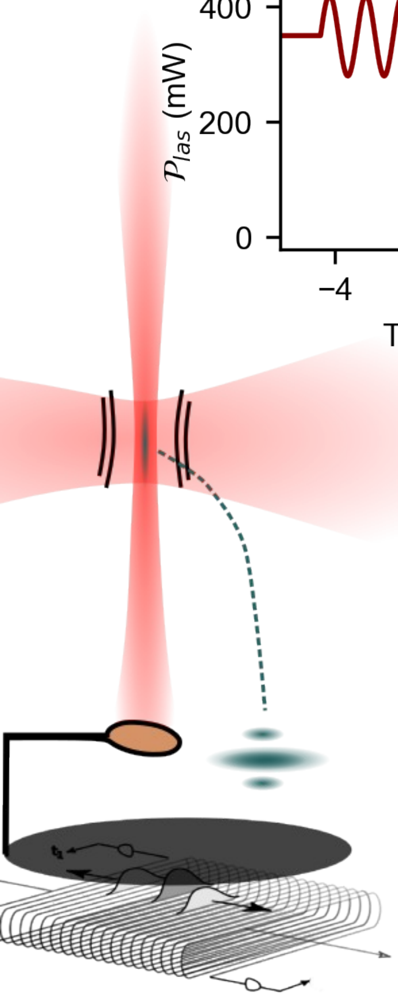
Measurement: probability distribution of each mode

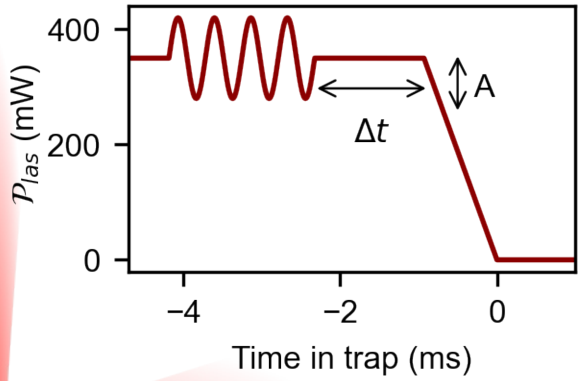
Result: thermal single mode probability distribution (i.e. bosonic bunching)





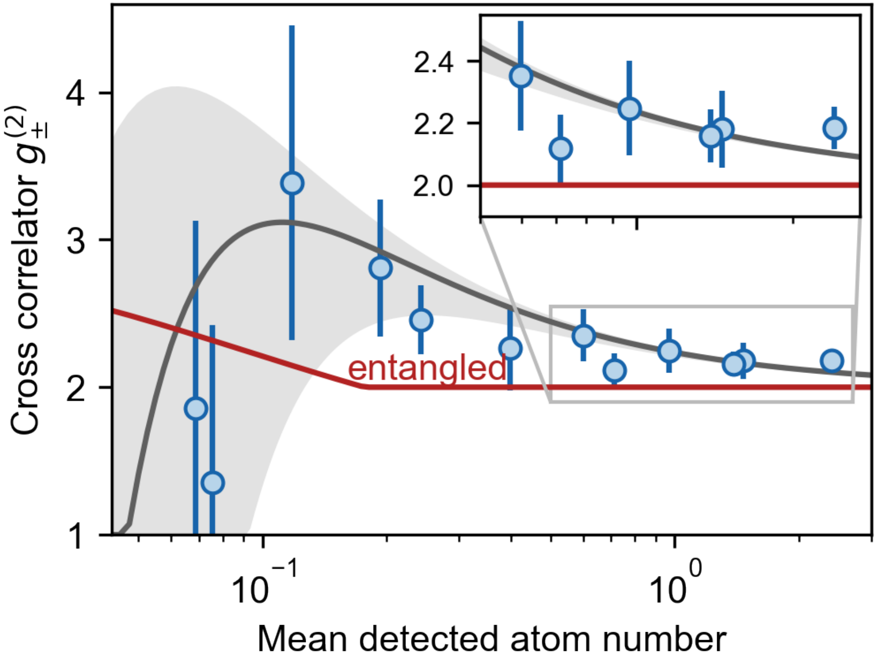
Thermal single mode probability distribution





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.

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

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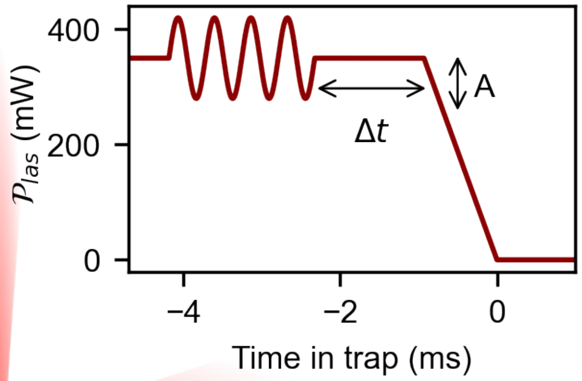

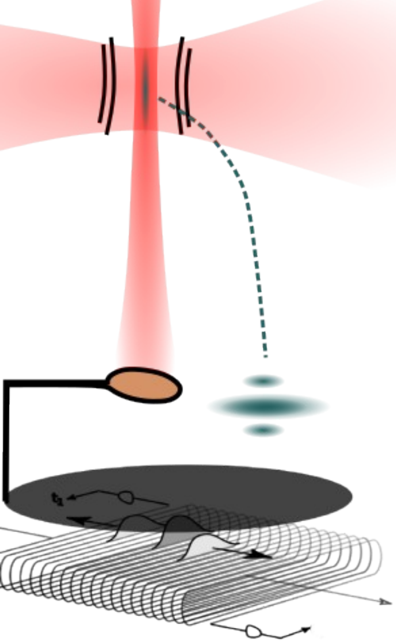

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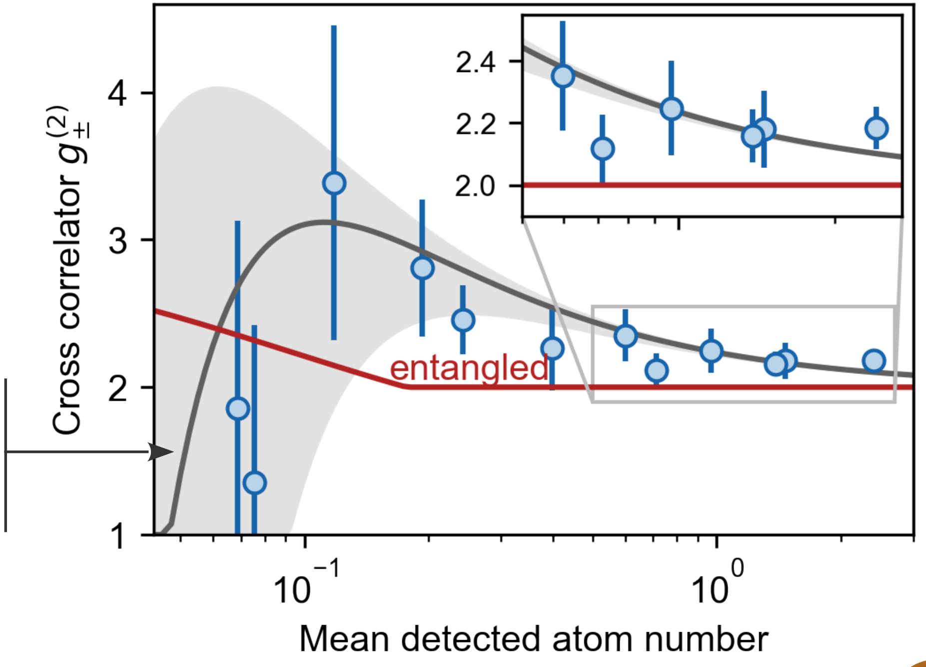


Result: assuming the two-mode state is Gaussian, it is entangled for sufficiently large excitation amplitude.

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

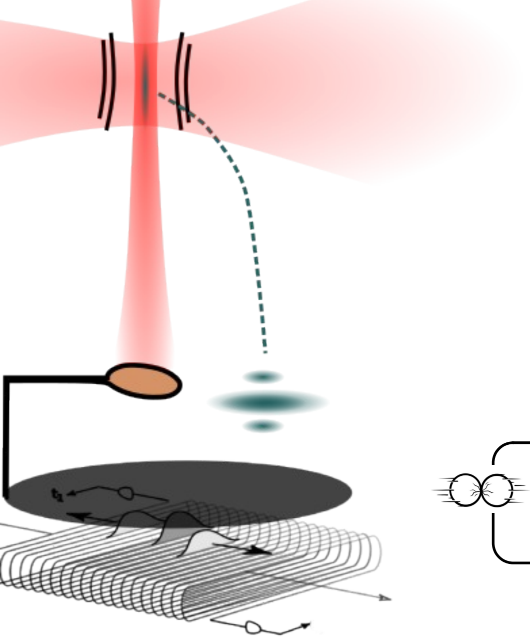
- 25(5)% detector efficiency,
- 25(5) nK temperature. Fluctuation of

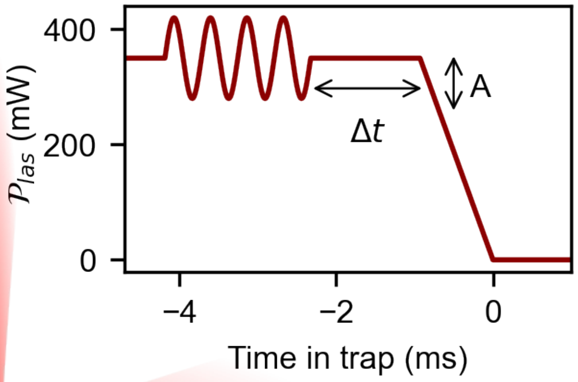
0.5 + 0.18(8)

Vacuum ↗ ↖ Thermal

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

Continuing the driving





Protocol: vary the excitation duration Δt

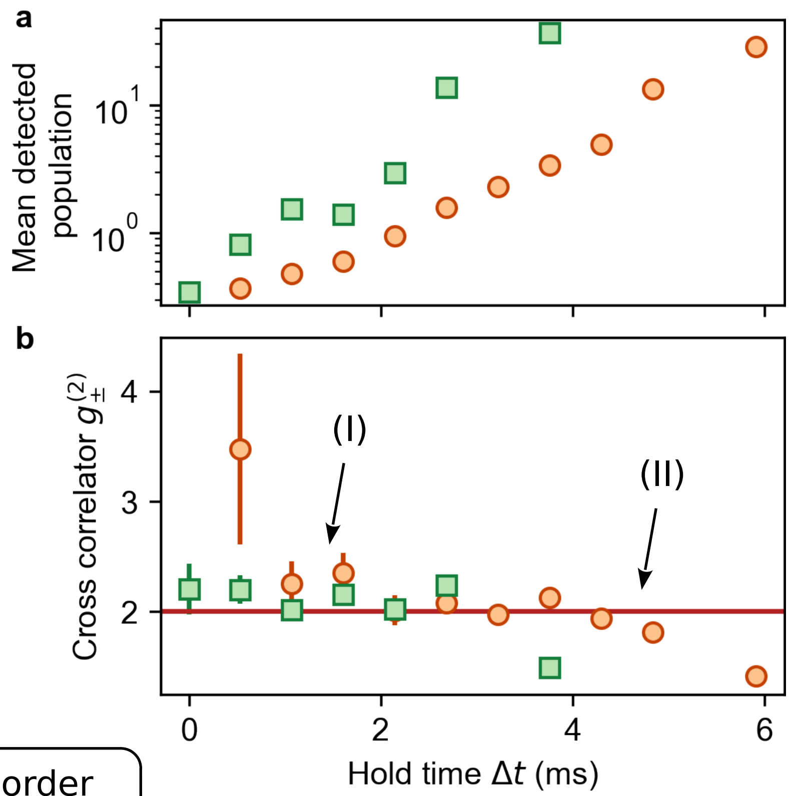
Expected in the two-mode squeezing model.

Results:

(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)

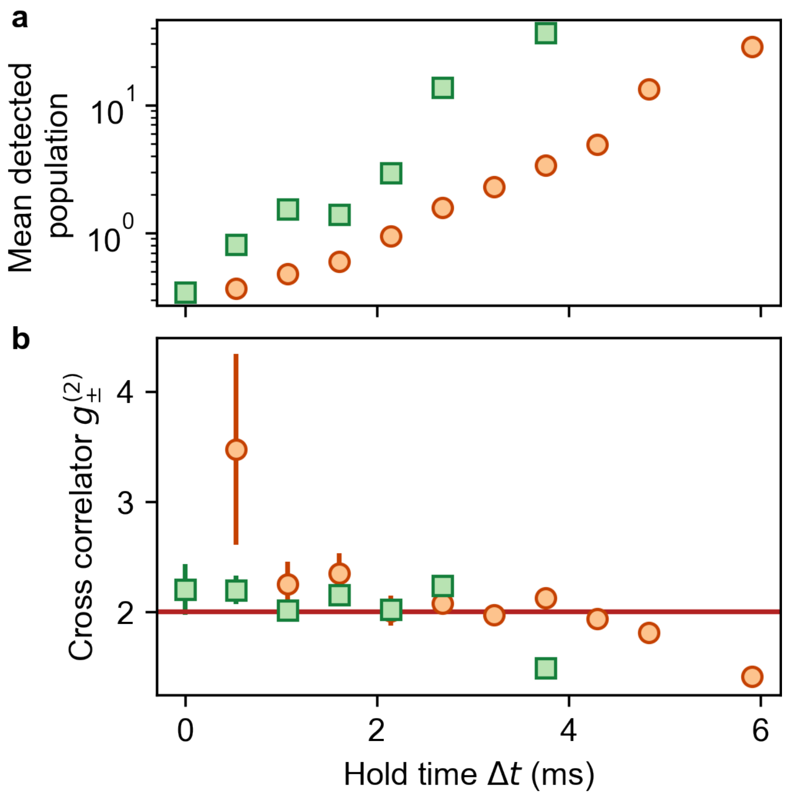
  Bureik *et al.*, Nat. Phys. **21**, 57 (2025)

- 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)



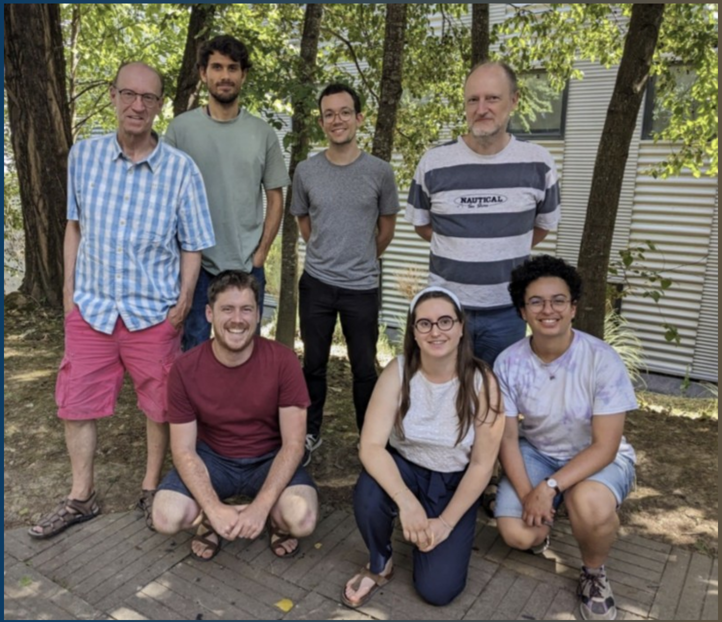
Take home message

- 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.

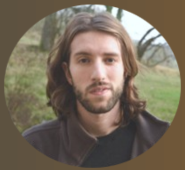
Refs

- arXiv 2503.09555
- arXiv 2506.22024
- arXiv 2508.01654

Thank you for your attention!



Th: Amaury Micheli & Scott Robertson



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

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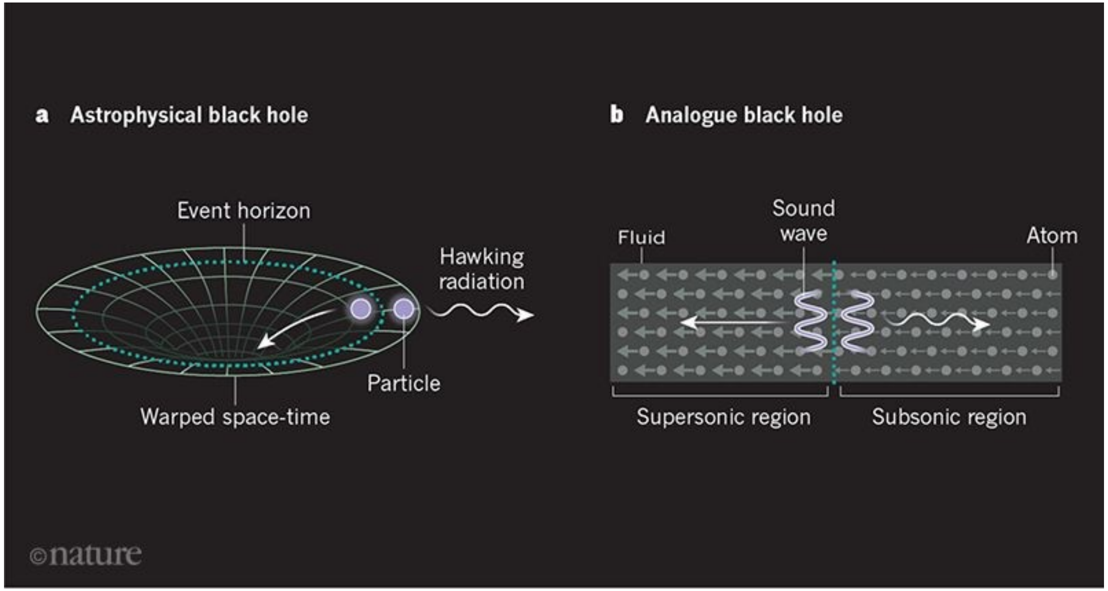
Analog gravity

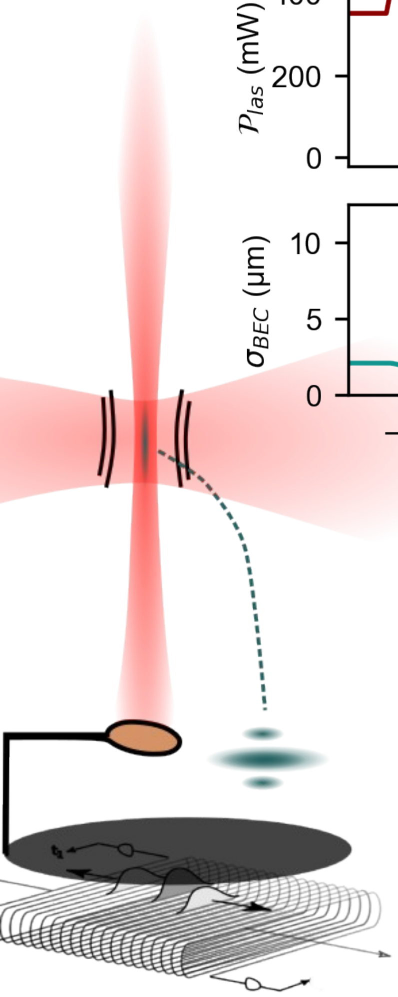
The equation for the dynamics of collective excitations, or *quasiparticles* on a strong coherent background is analog to that of particles in curved space-time.

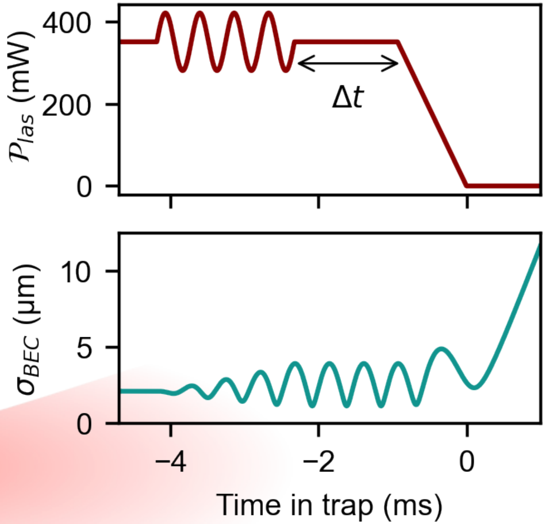
Unruh, *Experimental black-hole evaporation?*
Phys. Rev. Lett. **46**, 1351 (1981)



Weinfurtner, Nature **569**, 634-635 (2019)

Faraday waves with quantum fluids





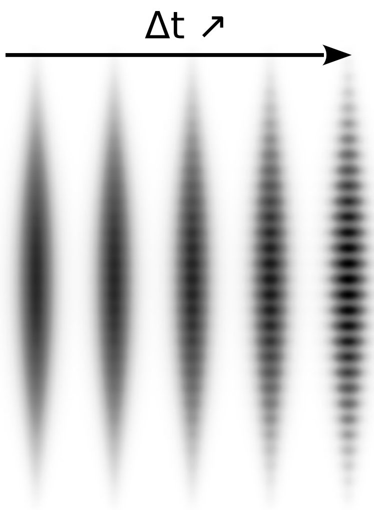
Protocol

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

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

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

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

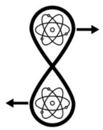


The pattern appears as Δt increases!

The time modulation of the dispersion relation squeezes $\pm k$ quasiparticle modes b_k

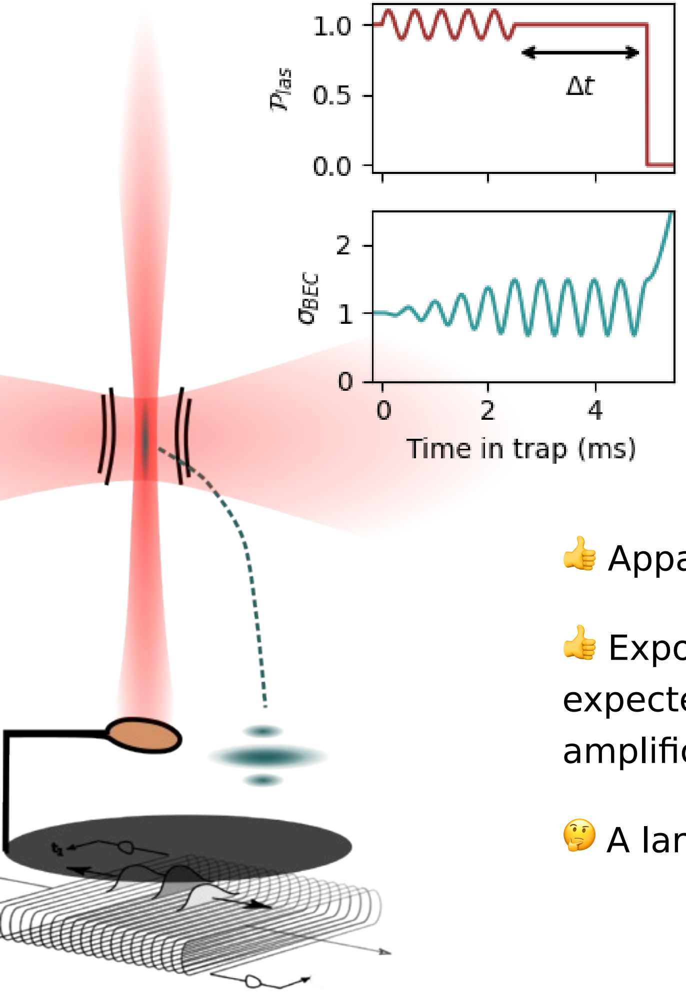
$$\partial_t \hat{b}_k = -i\omega_k \hat{b}_k + \frac{\dot{\omega}_k}{2\omega_k}\hat{b}^\dagger_{-k}$$

Exponential production for mode $\omega_k = \Omega/2$ triggered by both thermal and vacuum fluctuations

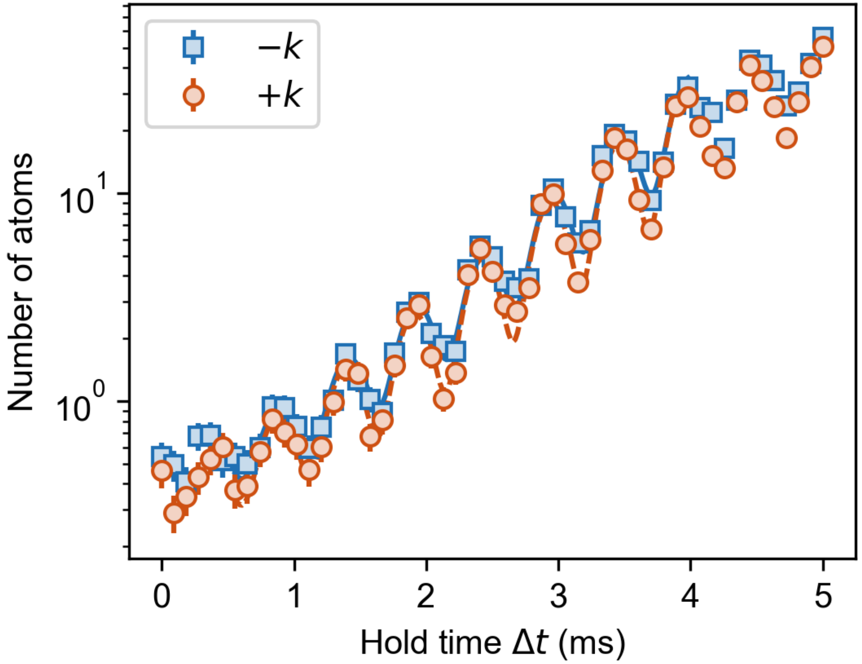


Two-mode entanglement reveals the role of vacuum in seeding the growth

Growth of the (quasi)particle number



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



👍 Apparent pairwise production

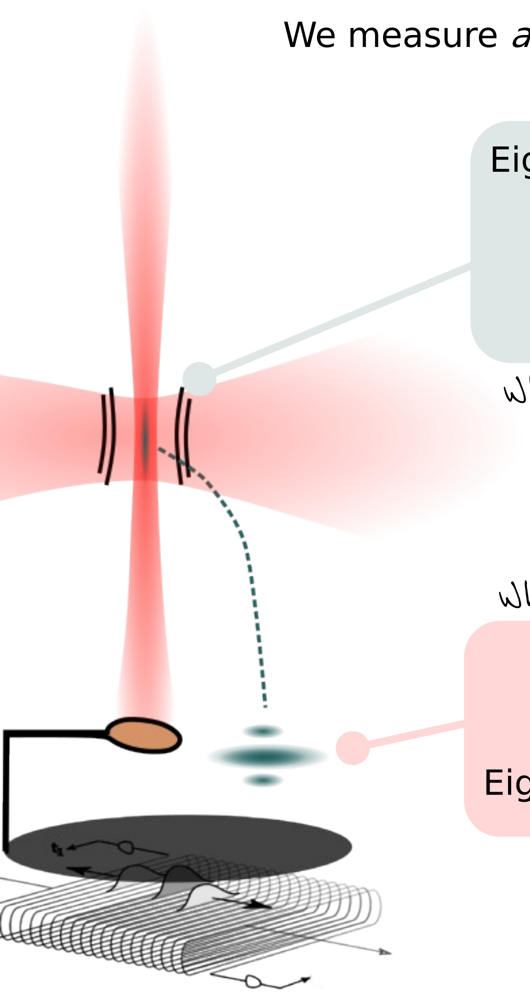
👍 Exponential growth[1] as expected in parametric amplification

🤔 A large oscillation in the growth

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

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

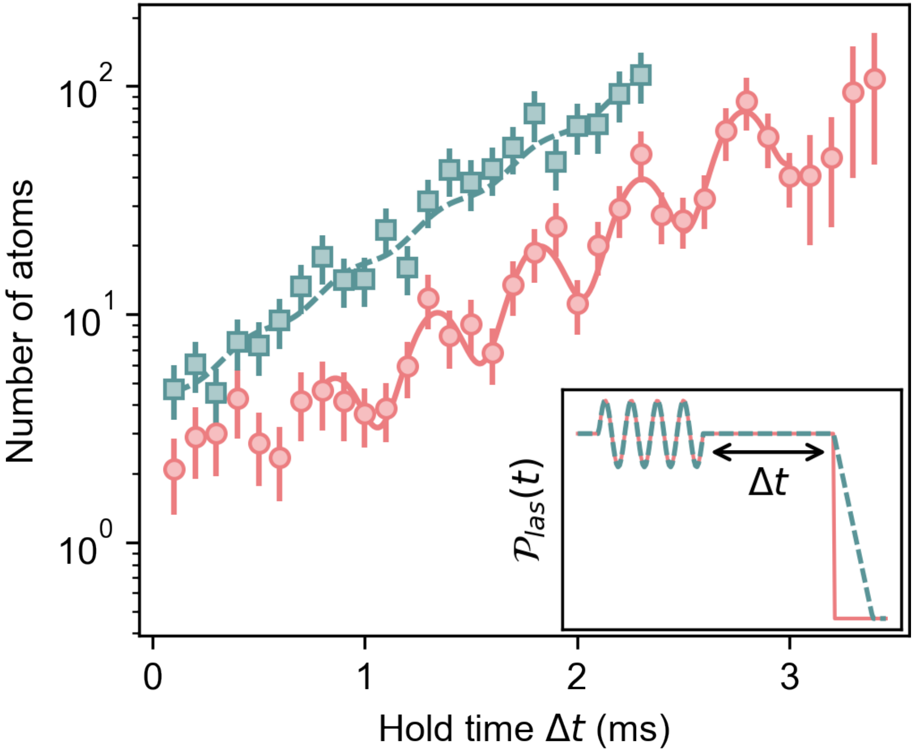
Equivalence if

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

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).