Creation and non-separability of phonon pairs in a modulated BEC

Victor Gondret, Charlie Leprince, Quentin Marolleau, Marc Cheneau, Denis Boiron,
Chris Westbrook, Amaury Micheli and Scott Robertson

victor.gondret@institutoptique.fr

Optique Nice 2022

Société Française d'Optique

Summary

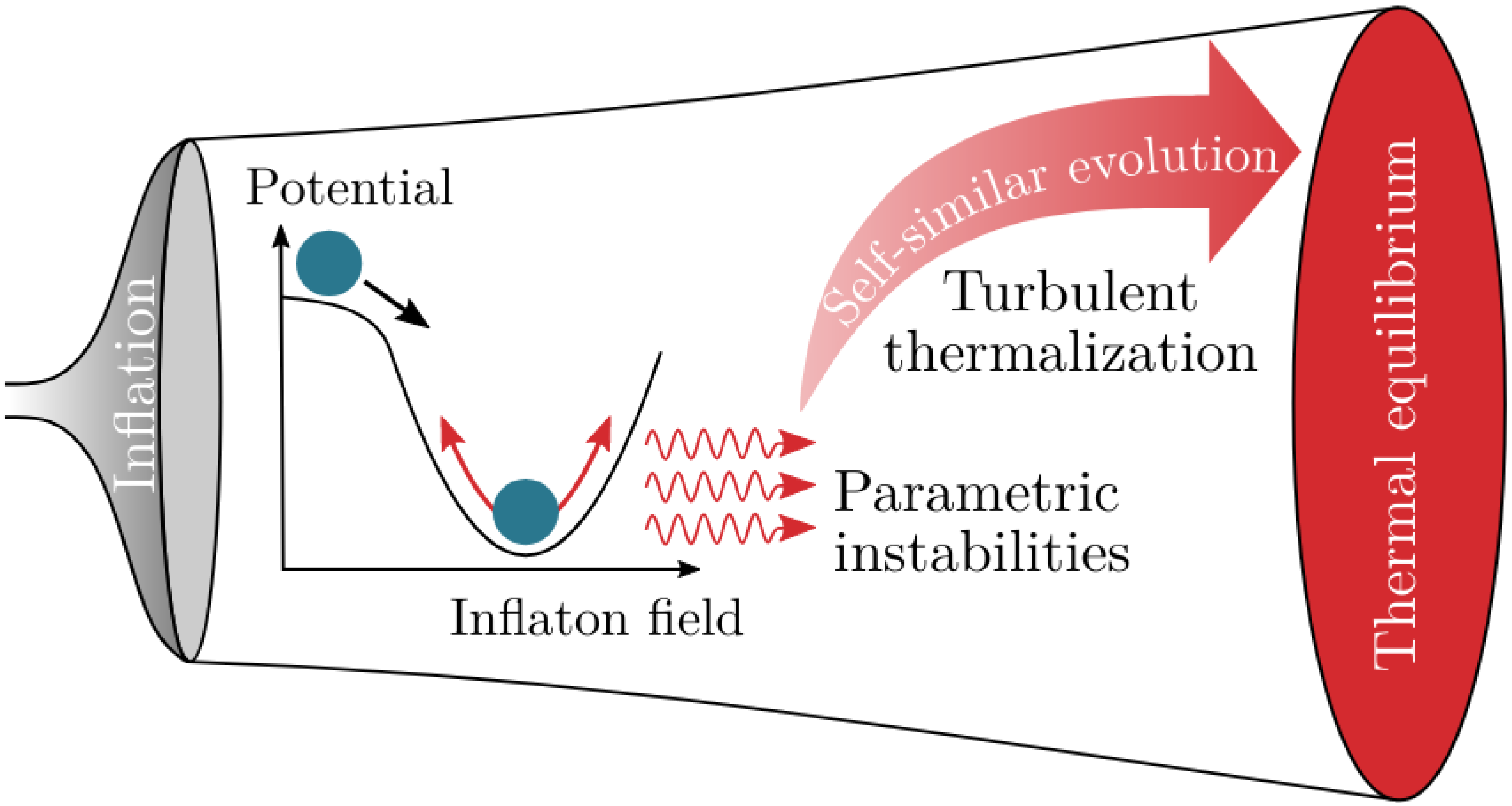
① Context

② Experimental setup

③ Phonon pair creation and non-separability of the phonon pair

④ First experimental result

The story of the universe in a nutshell



Inflation
⇩
Preheating
⇩
Re-heating

Chatrchyan *et al.*, (2021) Analog cosmological reheating in an ultracold Bose gas, Phys. Rev. A 104, 023302.

García–Bellido, J. (1999). The origin of matter and structure in the universe. *Philosophical Transactions of the Royal Society of London. Series A: Mathematical, Physical and Engineering Sciences* 357.1763 (1999): 3237-3257.

LABORATOIRE CHARLES FABRY

Analogy : simulating the early universe in our lab

COSMOLOGY STANDARD MODEL

Oscillation of the inflaton ⇨ Creation of entangled particles pairs with opposite momenta ⇨ Interaction between particles, decoherence, thermalization

Preheating

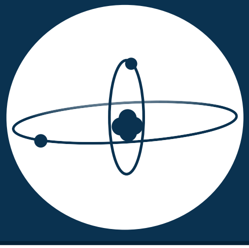
Re-heating

LAB SIMULATION

Oscillation of the speed of sound in a BEC ⇨ Creation of entangled phonons pairs with opposite momenta ⇨ Interaction between phonons, decoherence, thermalization

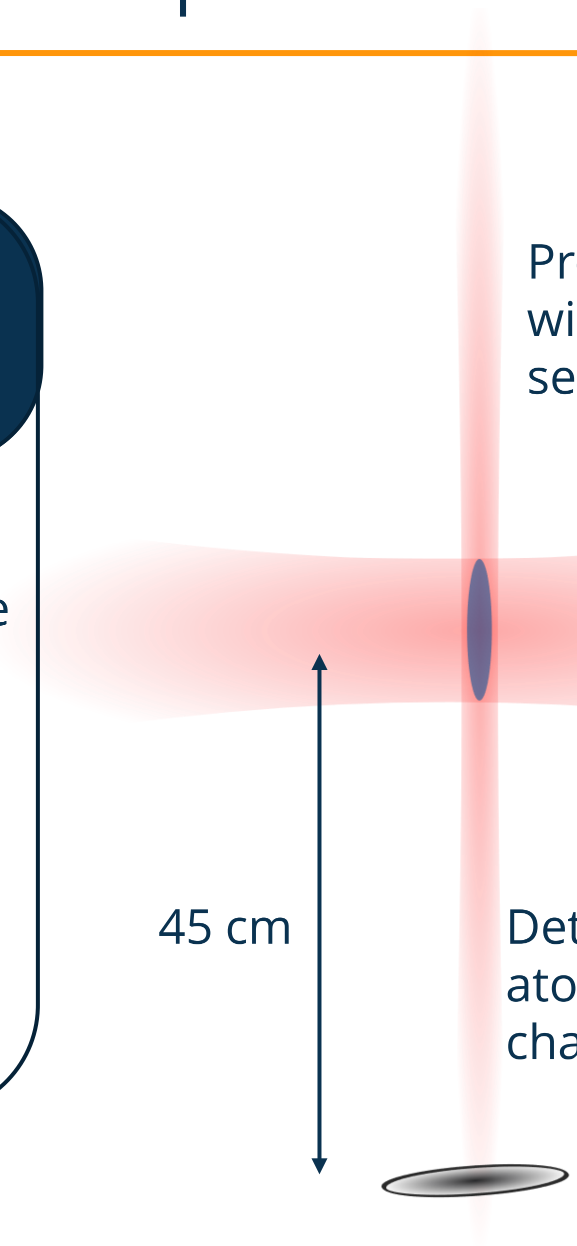
Experimental setup

He*



Metastable Helium 4

- Simple atomic structure
- No hyperfine structure
- Internal energy of 20 keV
- Recoil speed of 9 cm/s at 1083 nm

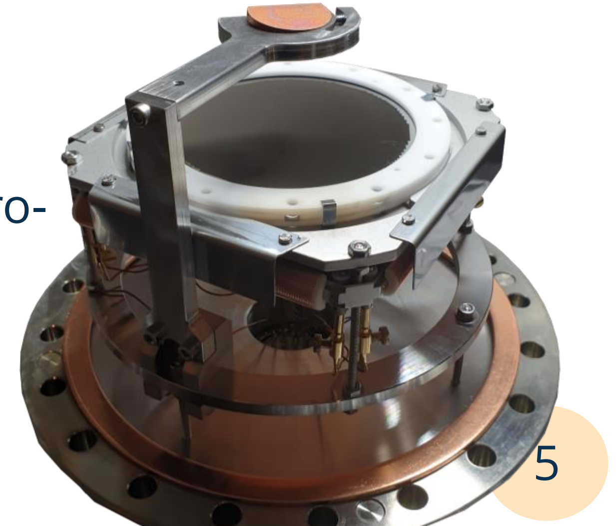


Production of a He* BEC with ~10^5 atoms every 10 seconds

Cigar shape BEC in a crossed dipole trap

- $\omega_{\parallel} = 70$ Hz
- $\omega_{\perp} = 1{,}3$ kHz

Detection of individual atoms using a MCP (micro-channel plate)



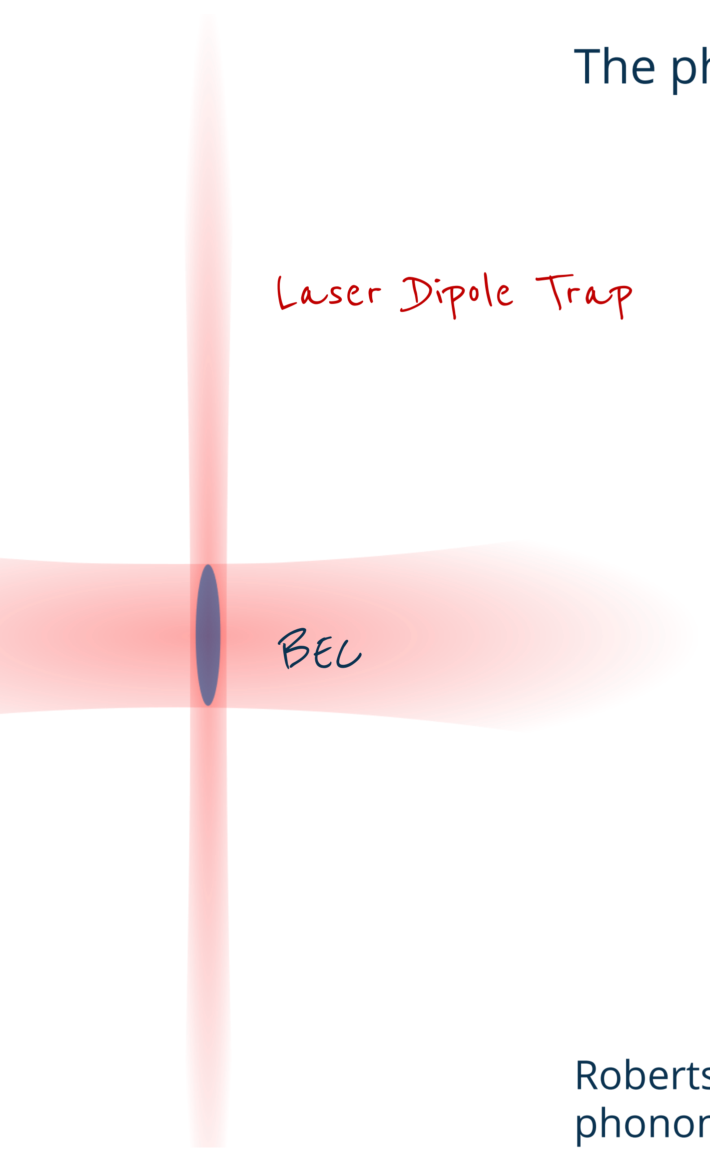
Phonon pair creation

The physics is 1D $\hat{\Phi} = \Phi_0(r,t) \times (1 + \hat{\phi}(z,t))$:

$$i\partial_t \hat{\phi} = -\frac{1}{2m}\partial_{zz}\hat{\phi} + g_1(t)\, n_1\, (\hat{\phi} + \hat{\phi}^\dagger)$$

1D density of the BEC
# of atoms / length

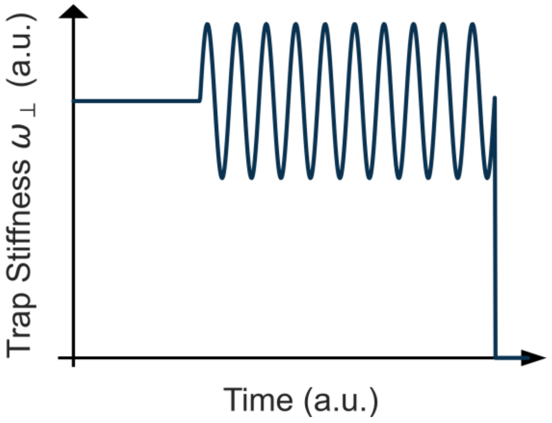
Effective 1D interaction strength



Oscillation of the transverse trap frequency

↓

Oscillation of the effective 1D interaction strength



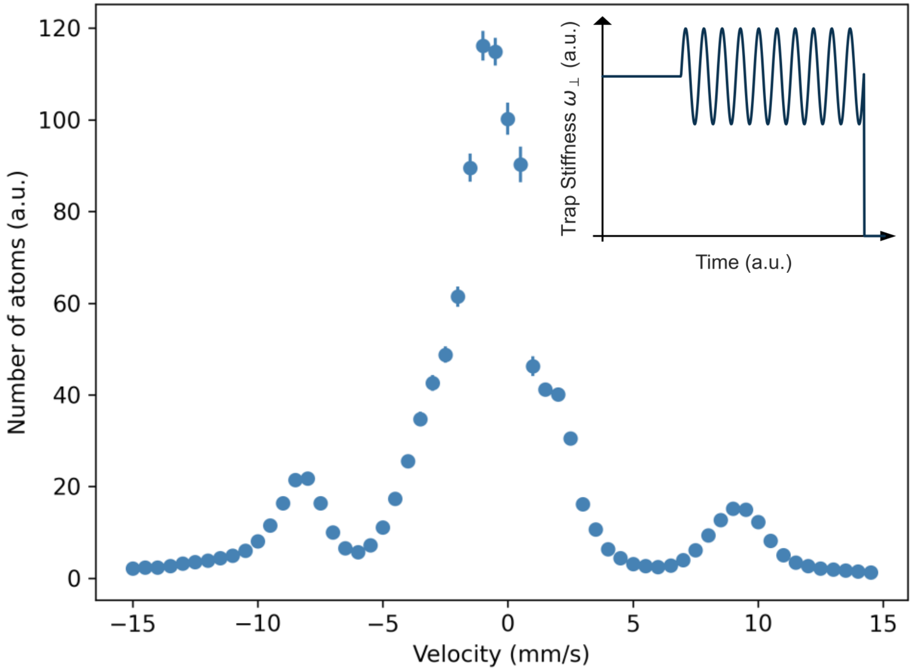
Robertson, S., Michel, F., Parentani, R., 2017. Controlling and observing nonseparability of phonons created in time-dependent 1D atomic Bose condensates. Phys. Rev. D 95, 065020.

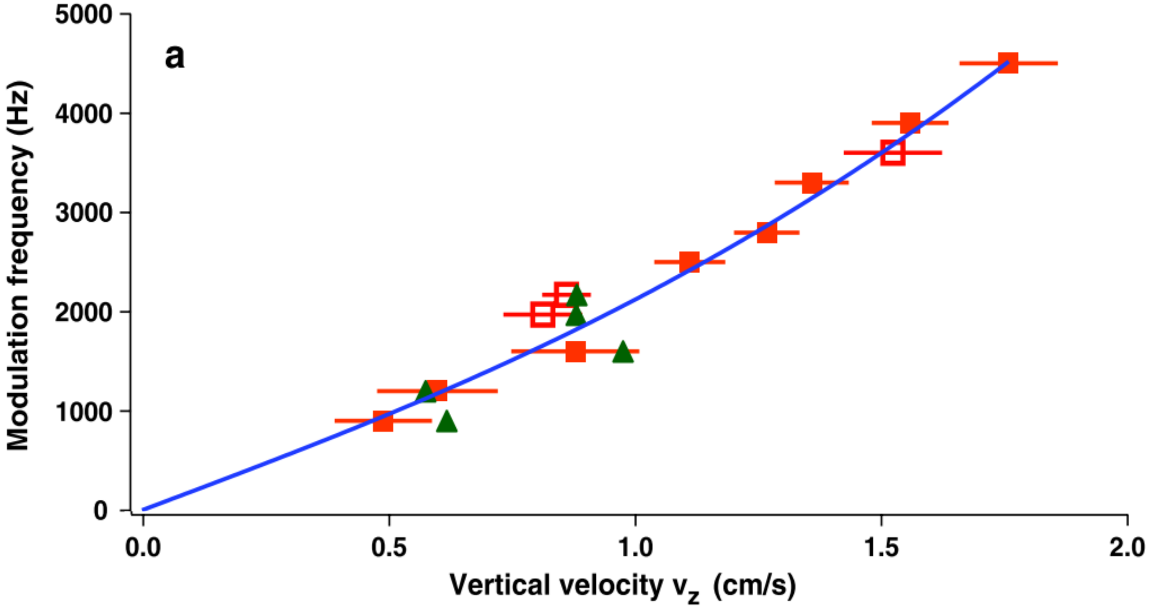
Phonon pair creation

$$i\partial_t \begin{pmatrix} \hat{a}_k \\ \hat{a}^\dagger_{-k} \end{pmatrix} = \begin{pmatrix} \Omega_k & -i\partial_t\Omega_k/2\Omega_k \\ -i\partial_t\Omega_k/2\Omega_k & -\Omega_k \end{pmatrix} \begin{pmatrix} \hat{a}_k \\ \hat{a}^\dagger_{-k} \end{pmatrix} \qquad \text{with} \quad \Omega_k^2 = \frac{g_1 n_1 k^2}{m} + \left(\frac{k^2}{2m}\right)^2$$

- $\hat{a}_k$ is the annihilation operator for collective excitations (phonons or quasi-particles)
- When $\partial_t\Omega_k = 0$: k and $-k$ modes evolve independently from each other
- When $\partial_t\Omega_k \neq 0$: mixing between k and $-k$ modes

Robertson *et al*, 2017.. Phys. Rev. D 95, 065020.





Jasukula *et al*., 2012. *Acoustic Analog to the Dynamical Casimir Effect in a Bose-Einstein Condensate*. Phys. Rev. Lett. 109, 220401.

Non-separability of the phonon pairs

In the experiment, we count the number of atoms arriving of the detector and compute

$$g^{(2)}(k,-k) = \langle : \hat{n}_k \hat{n}_{-k} : \rangle / \langle \hat{n}_k \rangle \langle \hat{n}_{-k} \rangle$$

Noting that $\hat{n}_k = \hat{a}_k^\dagger \hat{a}_k$ and using Wick contraction

$$\langle : \hat{n}_k \, \hat{n}_{-k} : \rangle = \left\langle : \hat{a}_k^\dagger \, \hat{a}_{-k}^\dagger \hat{a}_k \hat{a}_{-k} : \right\rangle = n_k n_{-k} + |\langle \hat{a}_k \hat{a}_{-k} \rangle|^2 + \left|\langle \hat{a}_k^\dagger \hat{a}_{-k} \rangle\right|^2$$

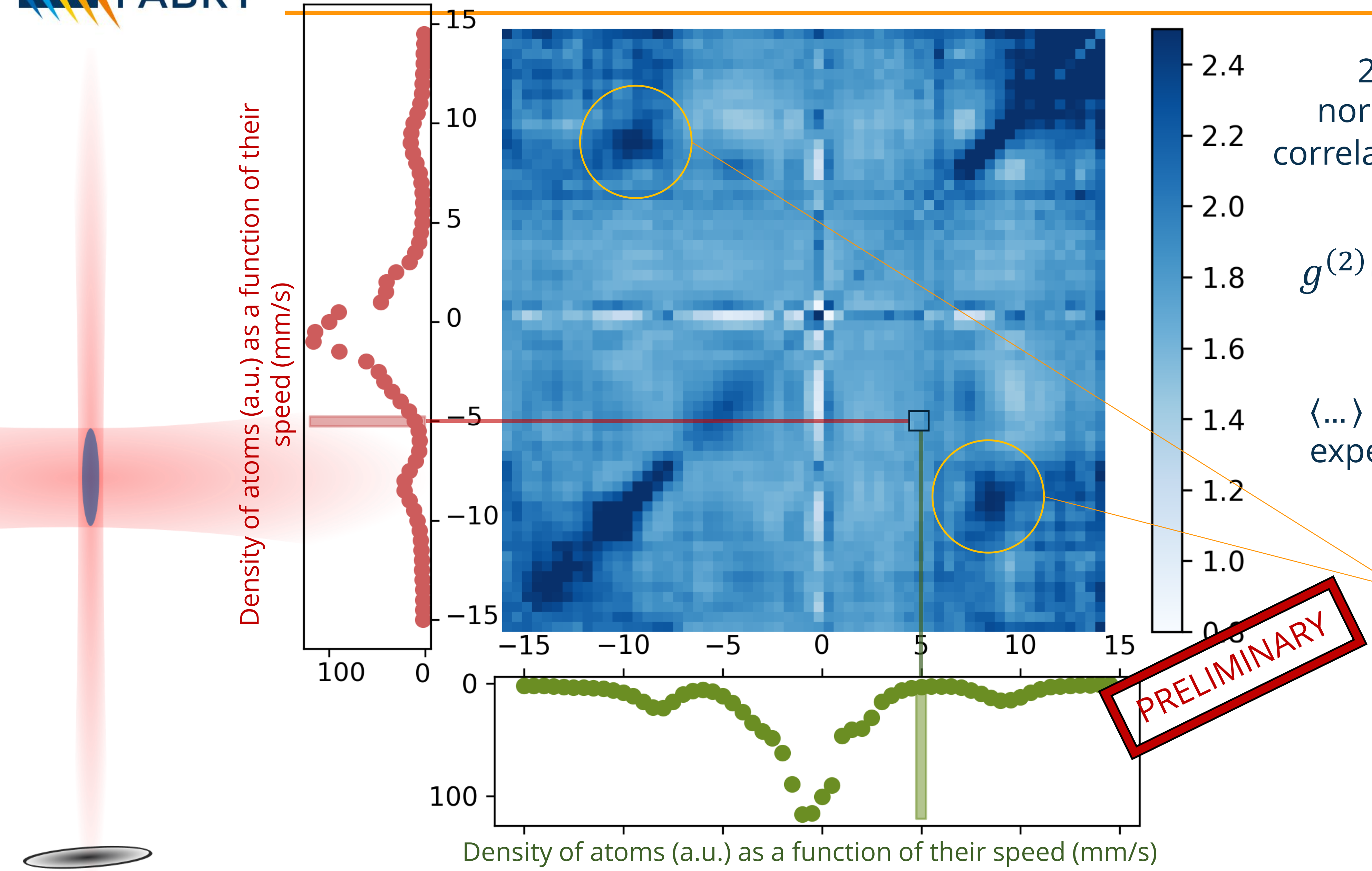
if the state is separable : $\overbrace{\leq n_k n_{-k}}$

Non separability criteria

$$g^{(2)}(k,-k) > 2$$

Busch, X., Parentani, R., 2013. Dynamical Casimir effect in dissipative media: When is the final state nonseparable? Phys. Rev. D 88, 045023.

First experimental result



2D color map of the normalized second order correlation function $g^{(2)}(k_1, k_2)$

$$g^{(2)}(k_1, k_2) = \frac{\langle n_{k1} n_{k2} \rangle}{\langle n_{k1} \rangle \langle n_{k2} \rangle}$$

$\langle \ldots \rangle$ = average over experimental realisations

Correlations !

Perspectives

- Longer acquisition
- Try to modulate the effective mass of the atoms using a lattice
- Study the creation dynamics of the phonon pairs
- Check the non-separability criteria assumptions : Bragg diffraction + interferometer
- Study the time evolution of the phonon pair correlations / entenglement, the time evolution of the re-thermalization

Thank you for your time !

On the theory side


Amaury Micheli and Scott Robertson

IJCLab Irène Joliot-Curie Laboratoire de Physique des 2 Infinis

université PARIS-SACLAY

Marc Cheneau, Alexandre Dareau, Denis Boiron

Charlie Leprince, V.G., Quentin Marolleau, Chris Westbrook

On the experimental side

Some lecture

- Jaskula *et al.*, 2012. *Acoustic Analog to the Dynamical Casimir Effect in a Bose-Einstein Condensate*. Phys. Rev. Lett. 109, 220401.
- Robertson, Michel & Parentani, 2017. *Controlling and observing nonseparability of phonons created in time-dependent 1D atomic Bose condensates*. Phys. Rev. D 95, 065020
- Robertson, Michel & Parentani 2018. *Nonlinearities induced by parametric resonance in effectively 1D atomic Bose condensates.* Phys. Rev. D 98, 056003.
- Micheli & Robertson, 2022. *Phonon decay in 1D atomic Bose quasicondensates via Beliaev-Landau damping*. ArXiv.

Fundings

QUANTUM FLAGSHIP

anr

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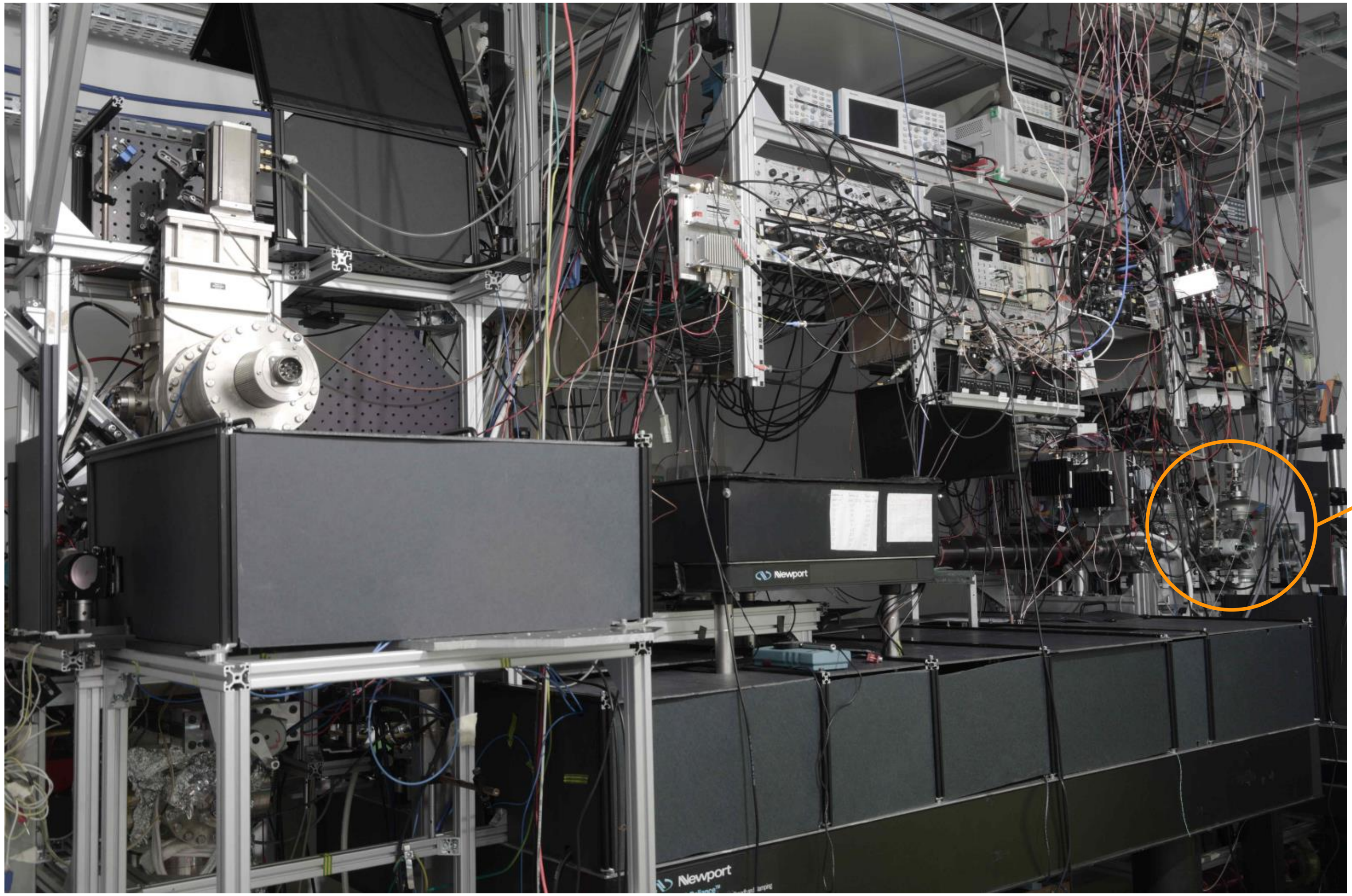
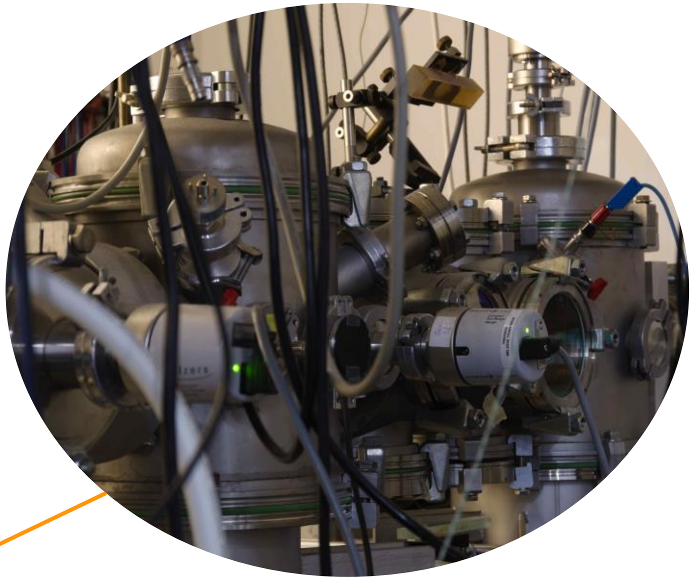
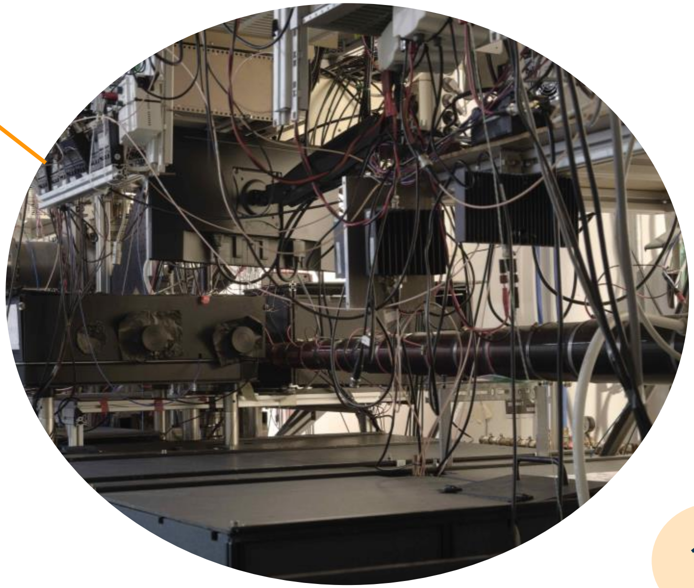
université PARIS-SACLAY

Experimental setup







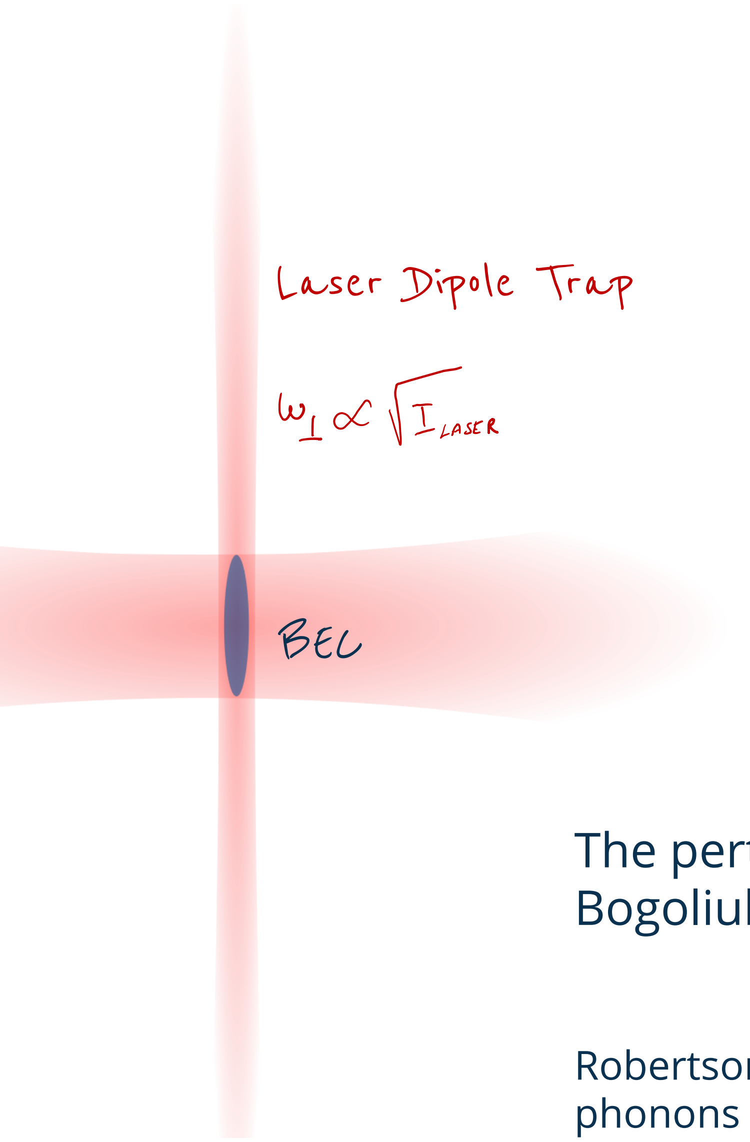
From the Gross-Pitaevski to Bogoliubov-de Gennes

Describe the BEC as $\hat{\Phi} = \Phi_0(1+\hat{\phi})$

Ansatz for the density : $|\Phi_0(r,t)|^2 \sim \frac{n_1}{\pi\sigma^2} e^{-r^2/\sigma^2}$

1D density of the BEC
# of atoms / length

Width of the BEC



Oscillation of the transverse trap frequency

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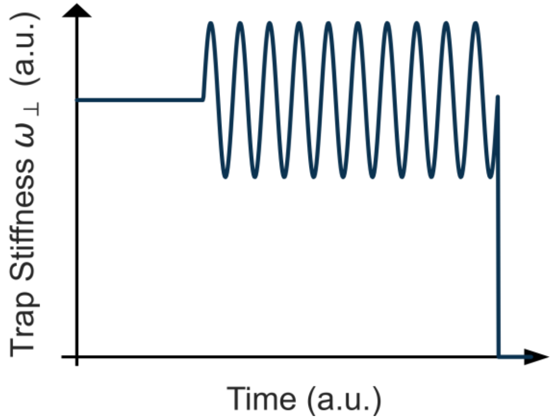
Oscillation of the BEC transverse width



The perturbative field follows the Bogoliubov – de Gennes equation

$$i\partial_t\hat{\phi} = -\frac{1}{2m}\partial_{zz}\hat{\phi} + g_1 n_1(\hat{\phi}+\hat{\phi}^\dagger)$$

$g_1(t) \sim 1/\sigma^2(t)$

Robertson, S., Michel, F., Parentani, R., 2017. Controlling and observing nonseparability of phonons created in time-dependent 1D atomic Bose condensates. Phys. Rev. D 95, 065020.

Phonon pair creation

$$i\partial_t\hat{\phi} = -\frac{1}{2m}\partial_{zz}\hat{\phi} + g_1(t)n_1(\hat{\phi} + \hat{\phi}^\dagger)$$

1. Fourier Transform
2. Bogliubov transformation

$$i\partial_t\begin{pmatrix}\hat{a}_k \\ \hat{a}^\dagger_{-k}\end{pmatrix} = \begin{pmatrix}\Omega_k & -i\partial_t\Omega_k/2\Omega_k \\ -i\partial_t\Omega_k/2\Omega_k & -\Omega_k\end{pmatrix}\begin{pmatrix}\hat{a}_k \\ \hat{a}^\dagger_{-k}\end{pmatrix} \qquad \text{with} \quad \Omega_k^2 = \frac{g_1 n_1 k^2}{m} + \left(\frac{k^2}{2m}\right)^2$$

- $\hat{a}_k$ is the annihilation operator for collective excitations (phonons or quasi-particles)
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Why do we **create phonons**?

Define the number of phonons with momentum k : $n_k \equiv \langle \hat{a}^\dagger_k \hat{a}_k \rangle$

$$\hat{a}_k(t) = \alpha(t) \times \hat{a}_k(0) \; + \; \underbrace{\beta(t)}_{\neq 0 \text{ if } \partial_t\Omega_k \neq 0} \times \hat{a}^\dagger_{-k}(0)$$

Phonon pair creation

$$i\partial_t \begin{pmatrix} \hat{a}_k \\ \hat{a}^\dagger_{-k} \end{pmatrix} = \begin{pmatrix} \Omega_k & -i\partial_t\Omega_k/2\Omega_k \\ -i\partial_t\Omega_k/2\Omega_k & -\Omega_k \end{pmatrix} \begin{pmatrix} \hat{a}_k \\ \hat{a}^\dagger_{-k} \end{pmatrix} \quad \text{with} \quad \Omega_k^2 = \frac{g_1 n_1 k^2}{m} + \left(\frac{k^2}{2m}\right)^2$$

- $\hat{a}_k$ is the annihilation operator for collective excitations (phonons)
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- When $\partial_t\Omega_k \neq 0$: mixing between k and $-k$ modes

Why do we create **pairs** of phonons ?

Define the number of phonons with momentum k : $n_k \equiv \langle \hat{a}_k^\dagger \hat{a}_k \rangle$

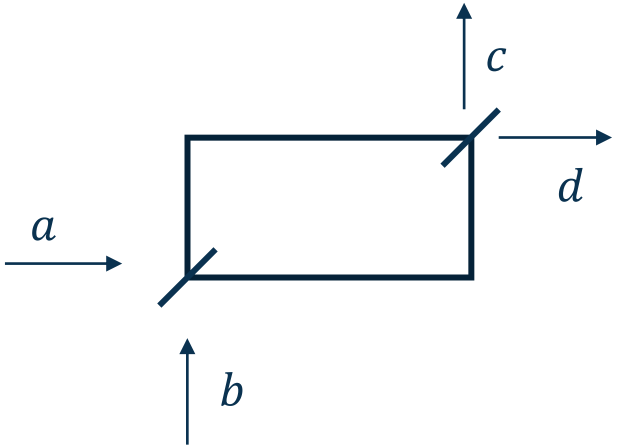
Show that

$$\partial_t(n_k - n_{-k}) = 0$$

Supplement : checking the non-separability criteria

$$\langle \hat{n}_k \hat{n}_{-k} \rangle = \langle \hat{b}_k^\dagger \hat{b}_{-k}^\dagger \hat{b}_k \hat{b}_{-k} \rangle = n_k n_{-k} + \left|\langle \hat{b}_k \hat{b}_{-k} \rangle\right|^2 + \left|\langle \hat{b}_k^\dagger \hat{b}_{-k} \rangle\right|^2$$

if the state is separable : $\leq n_k n_{-k}$ $\quad$ 0 ????



$$c = \cos(\phi)\, a + \sin(\phi)\, b$$

$$n_c = \langle c^\dagger c \rangle = \cos(\phi)^2\, a^\dagger a + \sin(\phi)^2\, b^\dagger b + \cos\phi \sin\phi\, (a^\dagger b + b^\dagger a)$$

→ Check that this term is zero.