Cosmology and quantum simulation

Non separability of phonon pairs in a time-modulated BEC linked to inflationary scenarii

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

Equipe Optique Atomique Quantique

Outline

① Inflation in cosmology

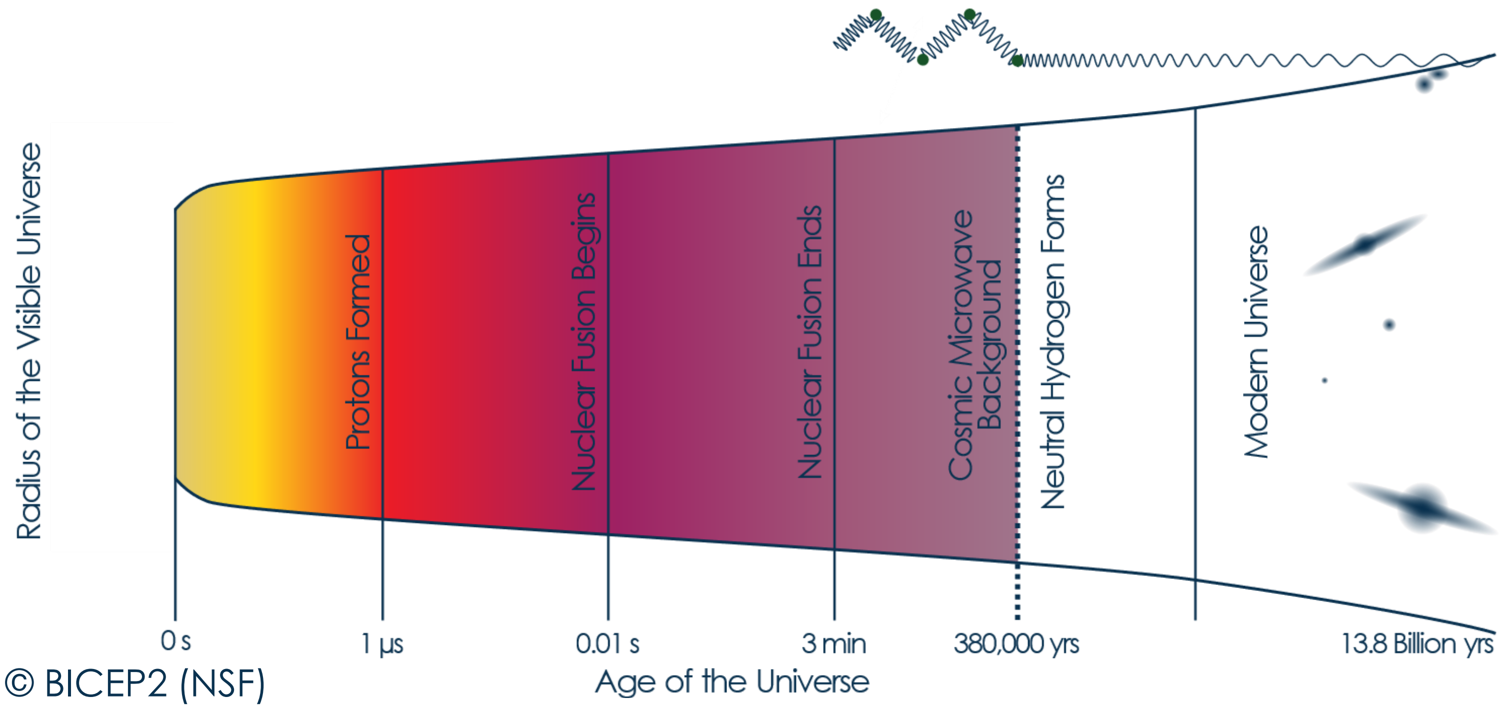
② Analog gravity and Bose-Einstein Condensates

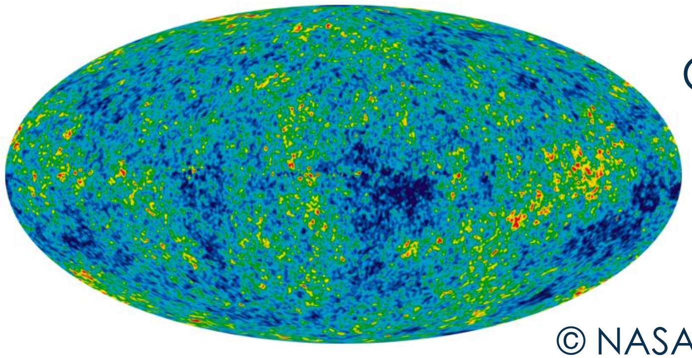
③ Work in progress @LCF

LABORATOIRE CHARLES FABRY

① Inflation in cosmology

The Standard Model





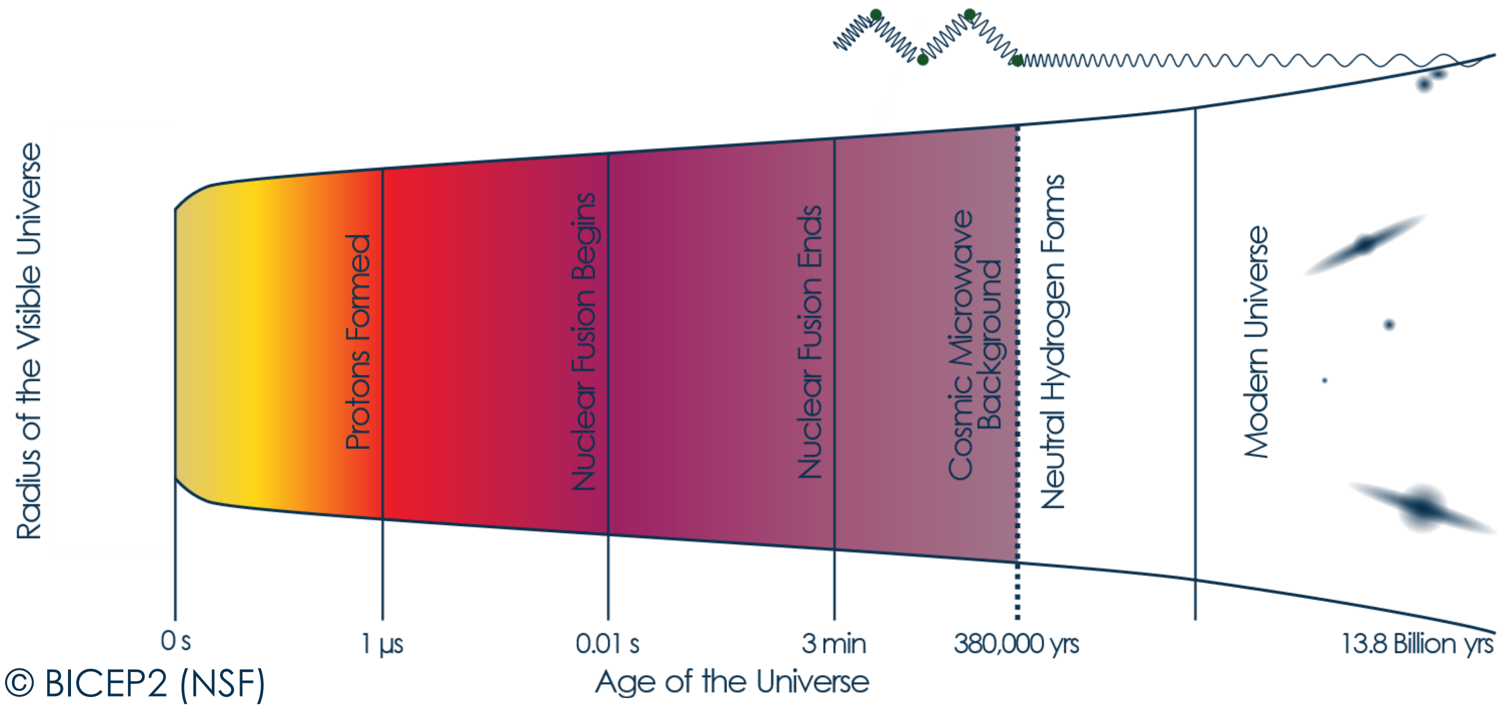
Cosmic microwave background at 2.7254 (6) K.

Successes of the Standard Model

- Successful account for nucleosynthesis and the relative abundance of light elements,
- Predicts the fact that universe is expanding (Hubble law)
- Right prediction of the Cosmic Background Radiation temperature

A.H. Guth, Beem Line 27(3), 1997
S. Watson, *An Exposition on Inflationary Cosmology, 2000*

The Standard Model



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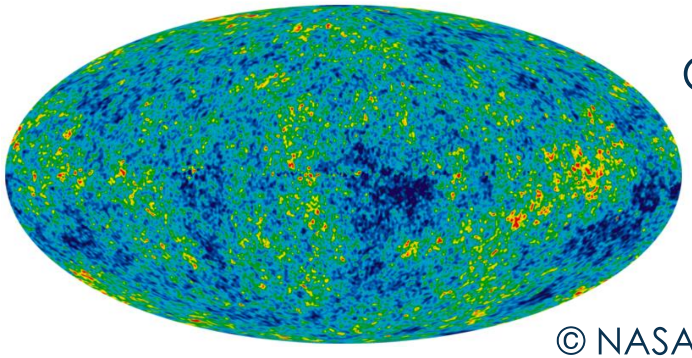
Failures of the Standard Model

- The horizon problem
- The flatness problem
- …



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Cosmic microwave background at 2.7254 (6) K.

Horizon problem

Homogeneity of causally disconnected regions of space

A.H. Guth, Beem Line 27(3), 1997
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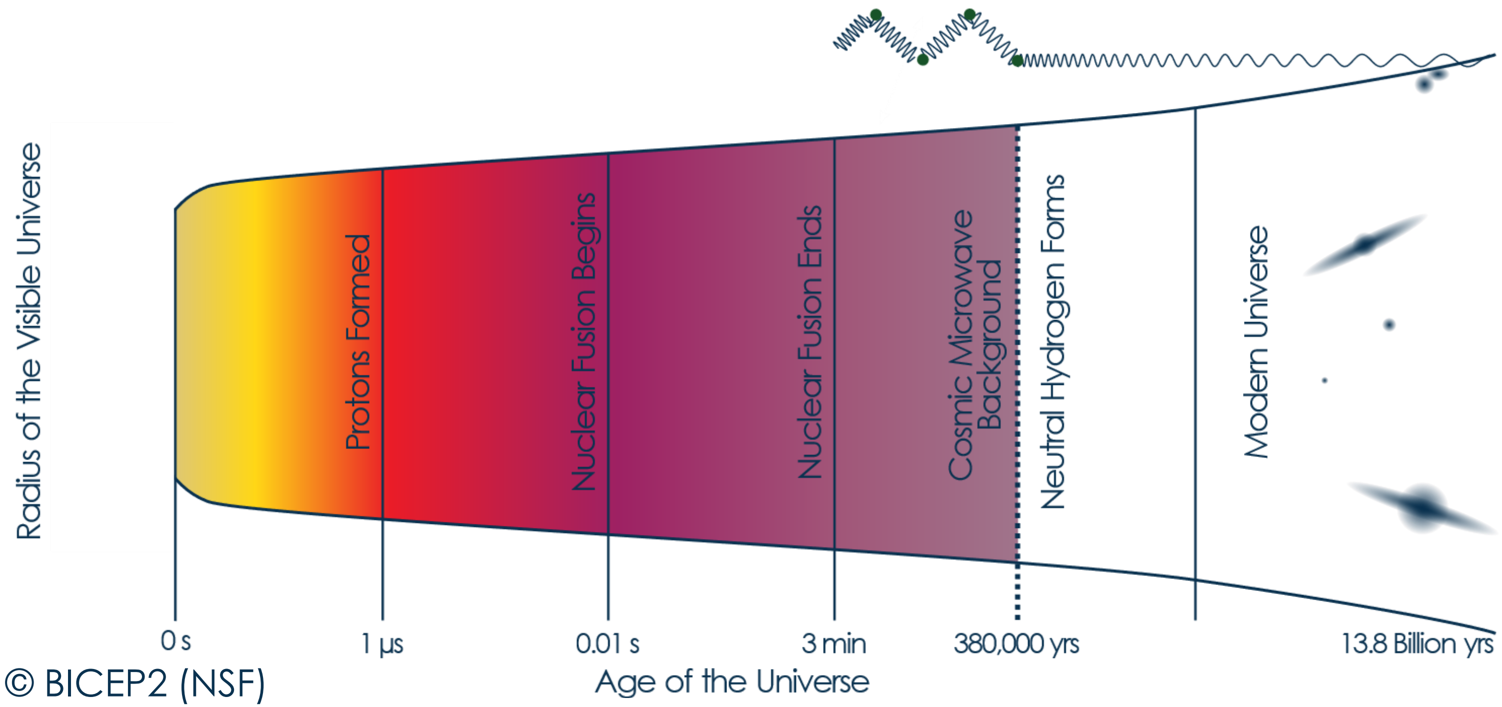
The Standard Model



Failures of the Standard Model

- The horizon problem
- The flatness problem
- …

Flatness problem

Energy density → $\frac{\rho}{\rho_c} = 1$ ← REALLY equal to one

Critical energy density → ρ_c

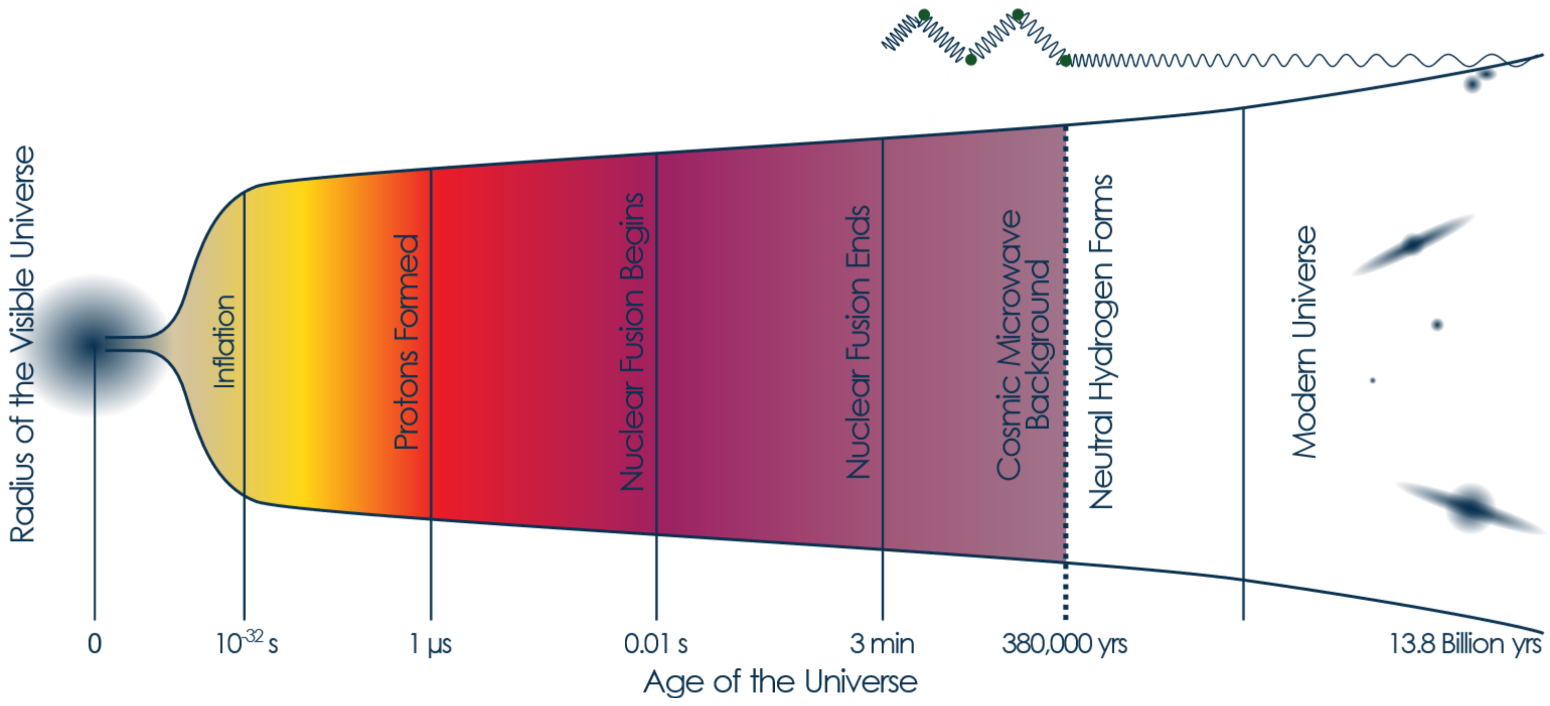
1,02±0,02 now

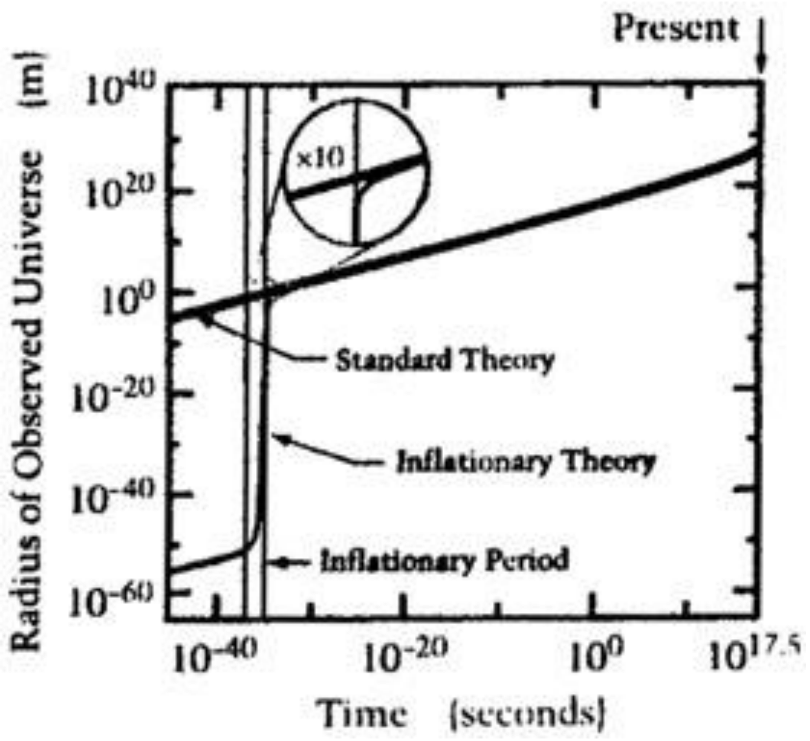
Horizon problem

Homogeneity of causally disconnected regions of space

A.H. Guth, Beem Line 27(3), 1997
S. Watson, *An Exposition on Inflationary Cosmology, 2000*

Theory of Inflation





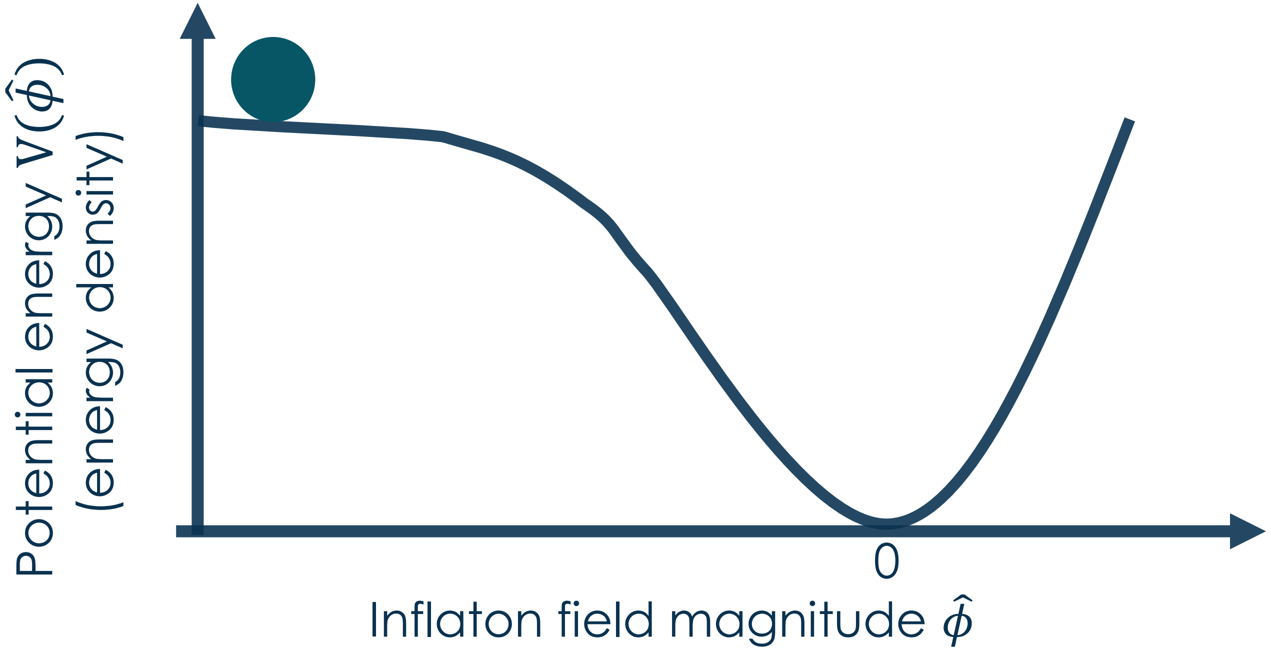
- Horizon problem : regions are no more causally connected & the inflation washes out inhomogeneities
- Flatness problem : no matter initial conditions, inflation drives ρ/ρ_C to 1.

Guth, A.H., 1981. *Inflationary universe: A possible solution to the horizon and flatness problems*. Phys. Rev. D 23, 347–356.

A.H. Guth, Beem Line 27(3), 1997

S. Watson, *An Exposition on Inflationary Cosmology, 2000*

Theory of Inflation



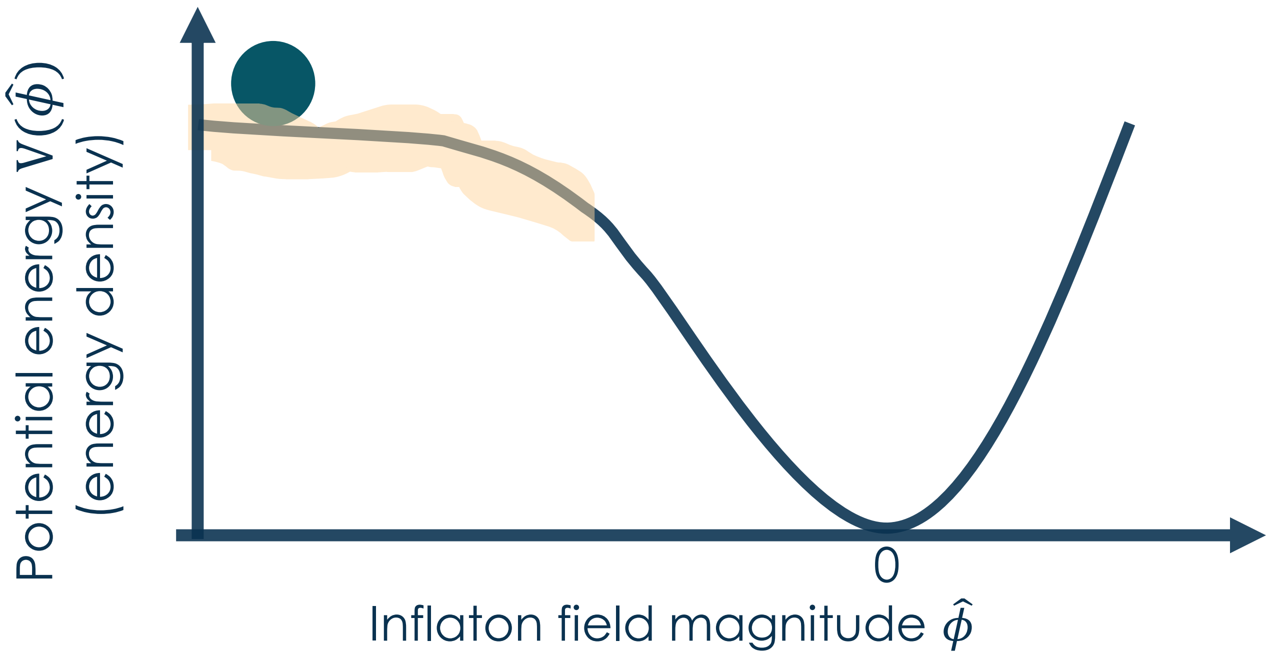
Add a new field $\hat{\phi}$ called *inflaton*

A. H. Guth, Phys. Rev. D23, 347 (1981)

A.H. Guth, Beem Line 27(3), 1997

S. Watson, *An Exposition on Inflationary Cosmology, 2000*

Theory of Inflation



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The inflaton *slowly rolls* from its initial state. Its almost constant potential energy drives the inflation.

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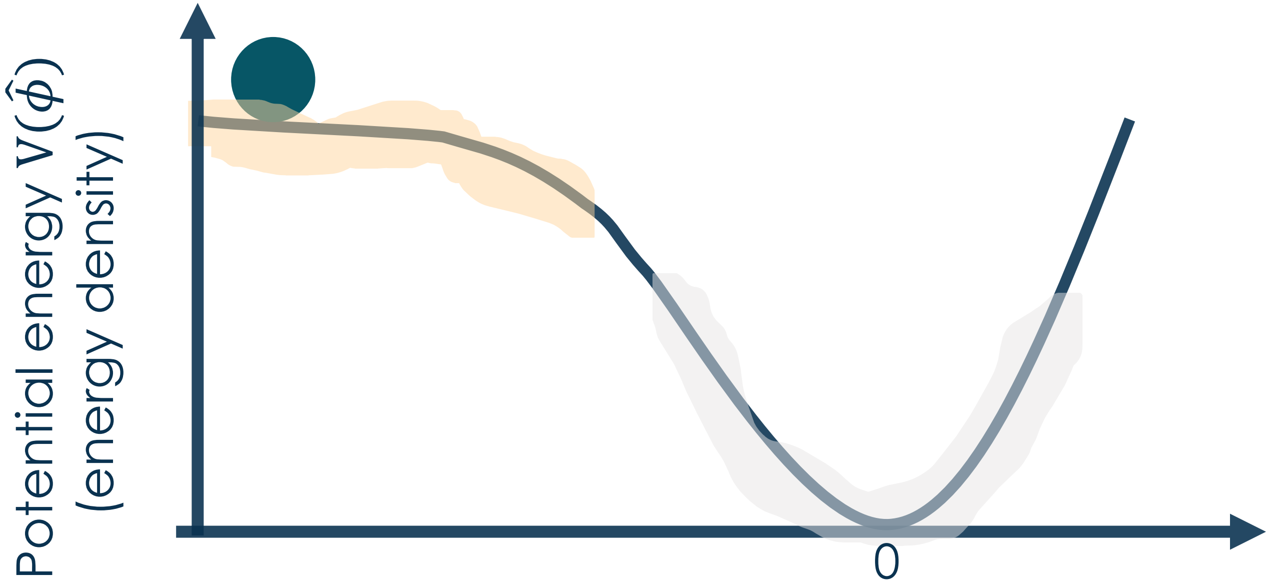

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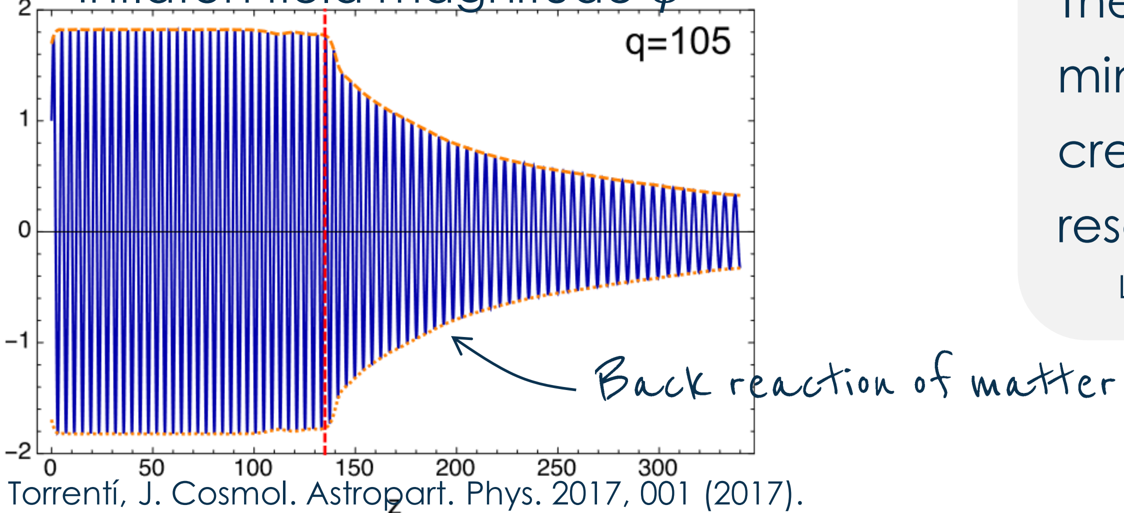
A. Linde, Phys. Lett. 129B, 177 (1983).

The inflaton starts to oscillate around its minimum and, coupled to matter fields, it creates particles through parametric resonance.

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

Decay of the inflaton field into particles



D. G. Figueroa and F. Torrentí, J. Cosmol. Astropart. Phys. 2017, 001 (2017).

A.H. Guth, Beem Line 27(3), 1997

S. Watson, *An Exposition on Inflationary Cosmology, 2000*

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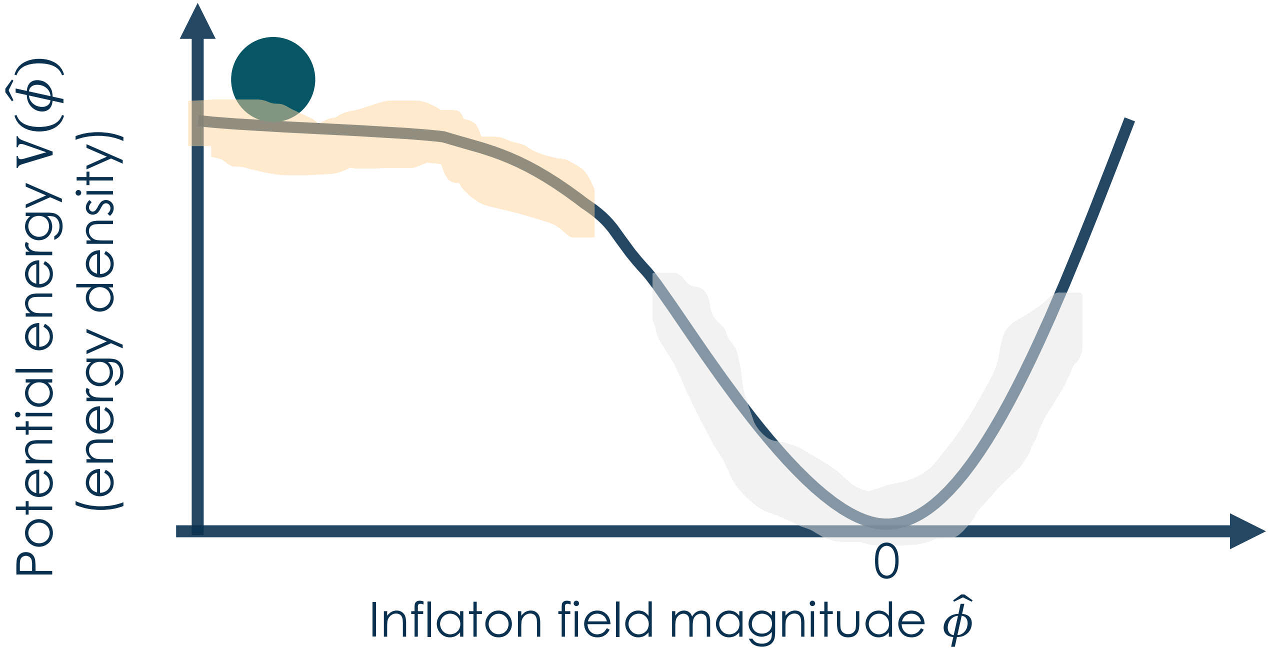

$V(\phi) = \lambda(\phi^2 - M^2)^2$ Higgs potential

$V(\phi) = \frac{1}{2}m^2\phi^2$ Massive scalar field

$V(\phi) = \lambda\phi^4$ Self interacting scalar field

$V(\phi) = 2H_i^2\left(3 - \frac{1}{s}\right)e^{-\phi/\sqrt{s}}$ String theory

Add a new field $\hat{\phi}$ called *inflaton*

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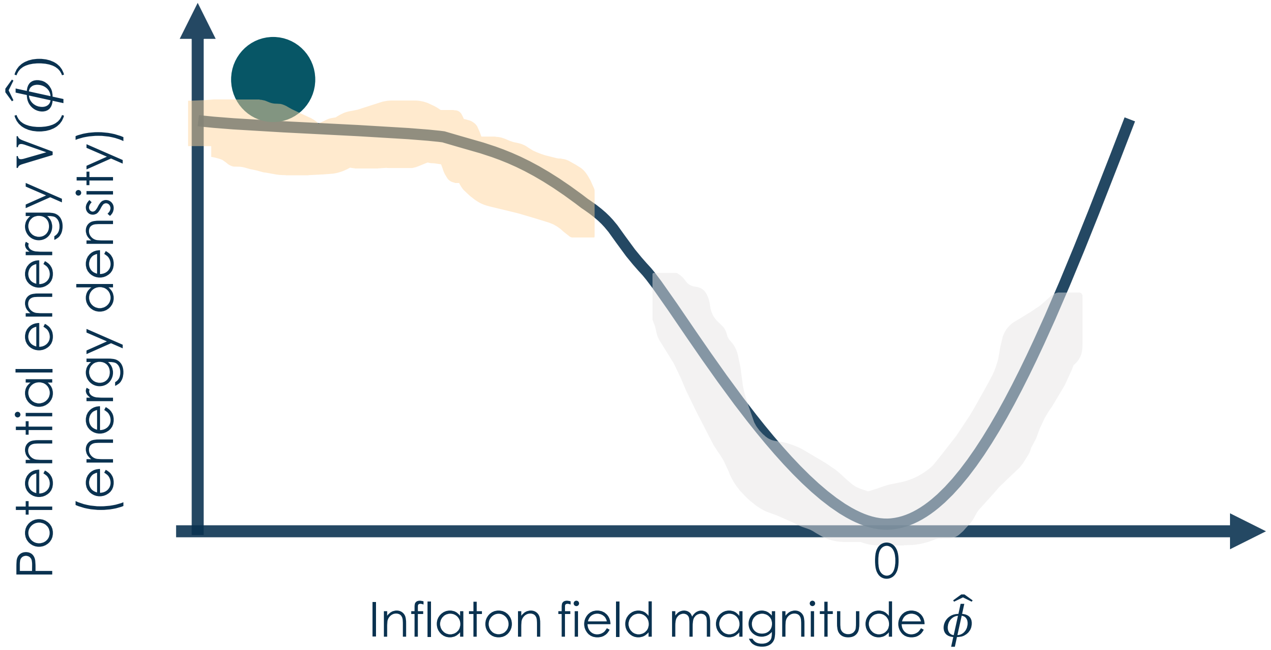

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L. Kofman, A. Linde & A. Starobinsky, Phys. Rev. D 56, (1997).

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

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

A.H. Guth, Beem Line 27(3), 1997

S. Watson, *An Exposition on Inflationary Cosmology, 2000*

② Analog gravity and Bose-Einstein Condensates

Analog gravity

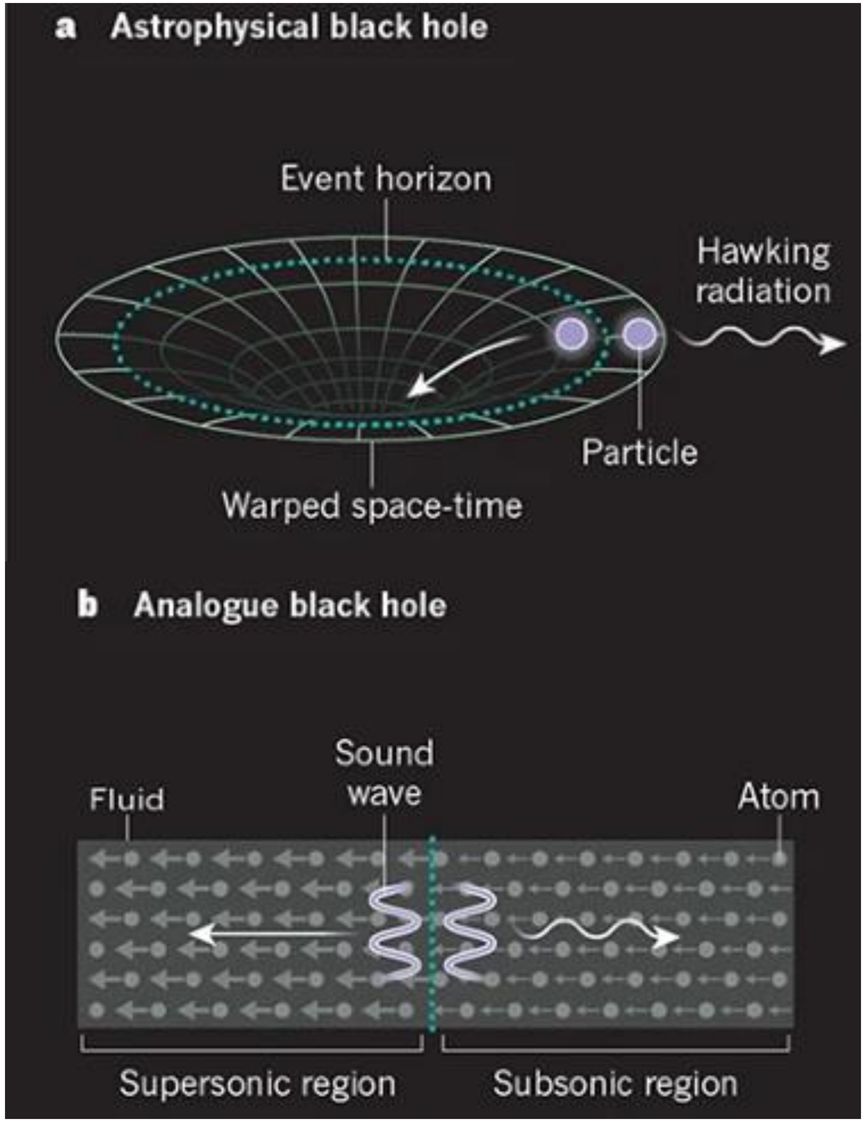
PHYSICAL REVIEW LETTERS

VOLUME 46 | 25 MAY 1981 | NUMBER 21

Experimental Black-Hole Evaporation?

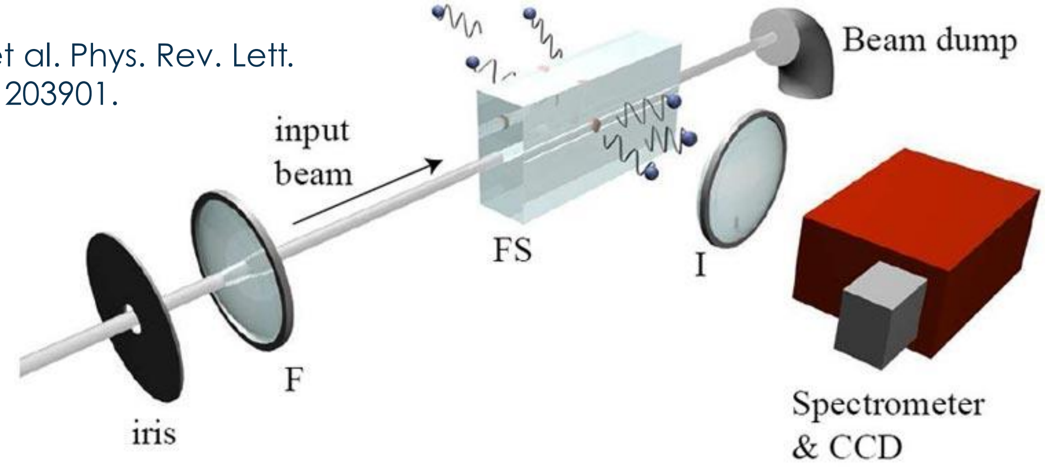
W. G. Unruh
Department of Physics, University of British Columbia, Vancouver, British Columbia V6T 2A6, Canada
(Received 8 December 1980)

It is shown that the same arguments which lead to black-hole evaporation also predict that a thermal spectrum of sound waves should be given out from the sonic horizon in transsonic fluid flow.



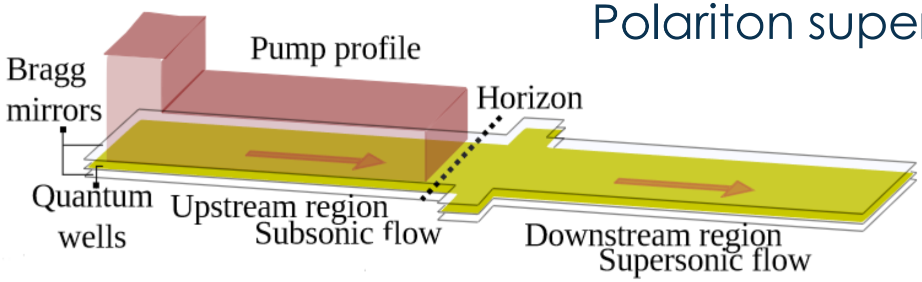
Analog gravity setups

F. Belgiorno, et al. Phys. Rev. Lett. 105.20 (2010): 203901.



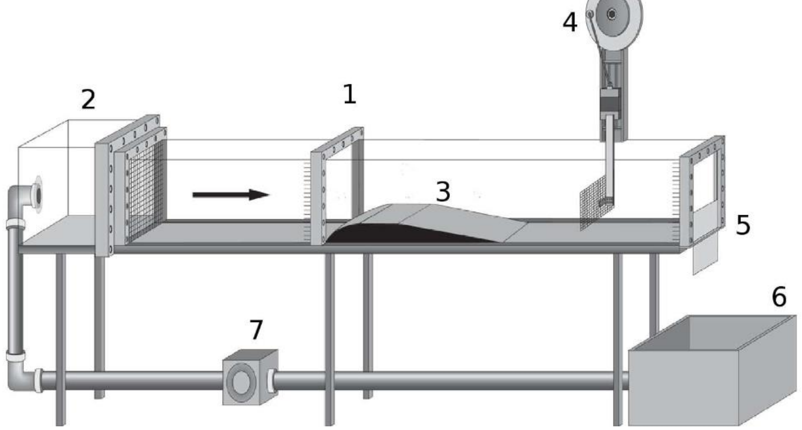
Ultrashort laser pulse filaments

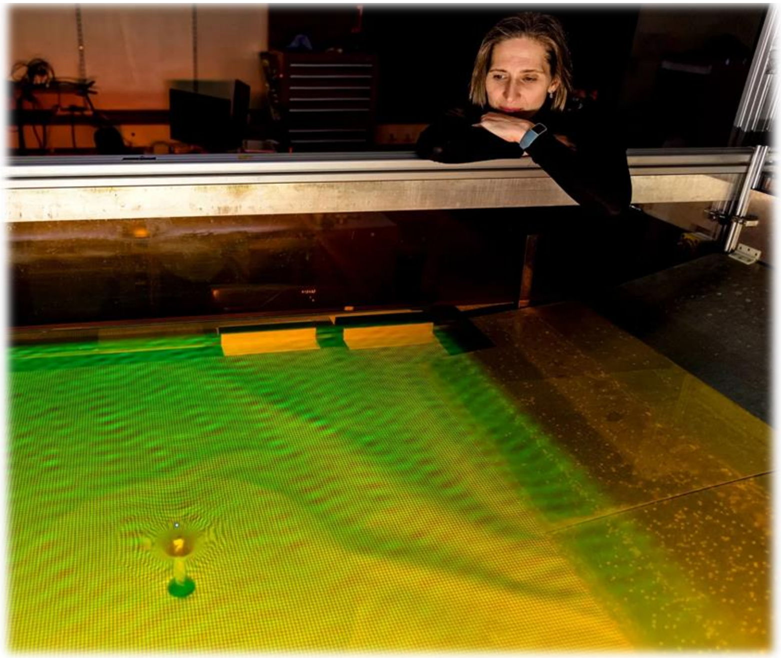
Polariton superfluid



M. J. Jacquet *et al.*, Eur. Phys. J. D **76**, 152 (2022).

Water tank



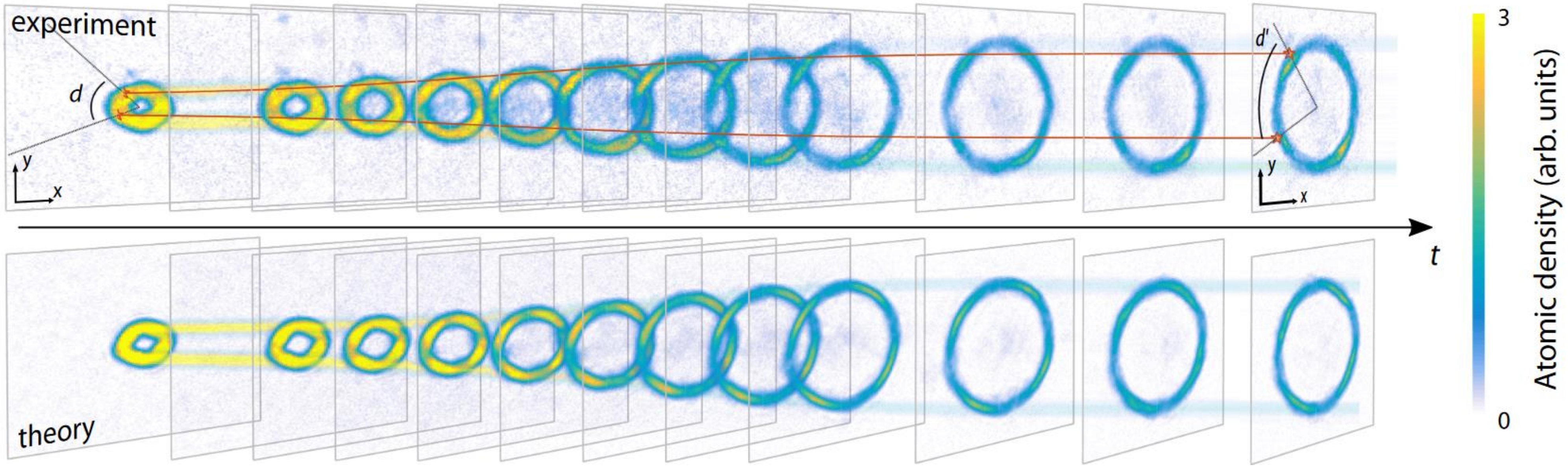


(…)

S. Weinfurtner *et al.*, Phys. Rev. Lett. **106**, 021302 (2011).

→ M. J. Jacquet, S. Weinfurtner, and F. König, *The next Generation of Analogue Gravity Experiments*, Phil. Trans. R. Soc. A. **378**, 20190239 (2020).

BEC for analog inflation

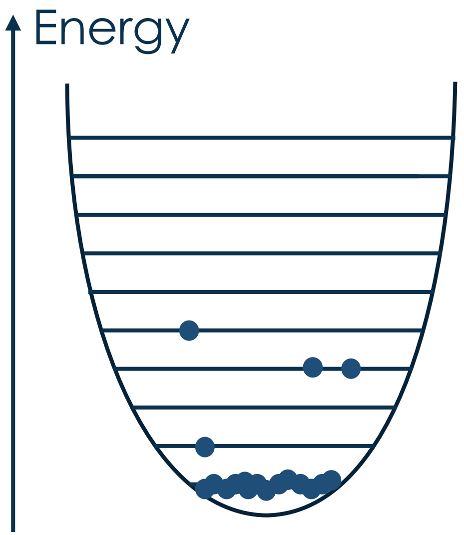


Experiment at Maryland, USA : a ring BEC is expanded at supersonic speed [1].

[1] S. Eckel et al., *A Rapidly Expanding Bose-Einstein Condensate: An Expanding Universe in the Lab*, Phys. Rev. X **8**, 021021 (2018).
[2] A. Chatrchyan et al., *Analog Cosmological Reheating in an Ultracold Bose Gas*, Phys. Rev. A **104**, 023302 (2021).
[3] C. Viermann et al., *Quantum Field Simulator for Dynamics in Curved Spacetime*, Nature **611**, 260 (2022).

BEC for analog inflation

BEC is a macroscopic
state at k=0



S. Robertson, F. Michel, and R. Parentani, Phys. Rev. D **95**, 065020 (2017).
X. Busch and R. Parentani, Phys. Rev. D **88**, 045023 (2013).

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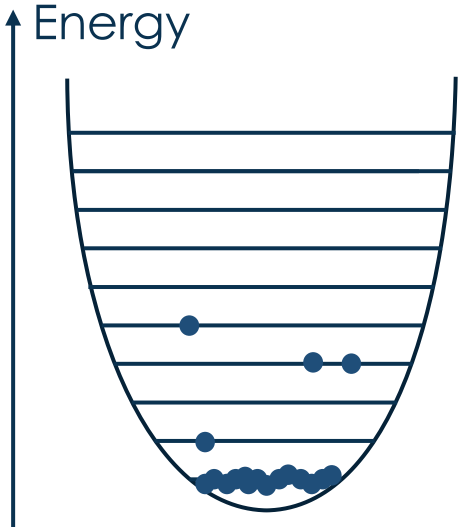

INFLATION MODEL

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

Preheating

Reheating

S. Robertson, F. Michel, and R. Parentani, Phys. Rev. D **95**, 065020 (2017).
X. Busch and R. Parentani, Phys. Rev. D **88**, 045023 (2013).

BEC for analog inflation

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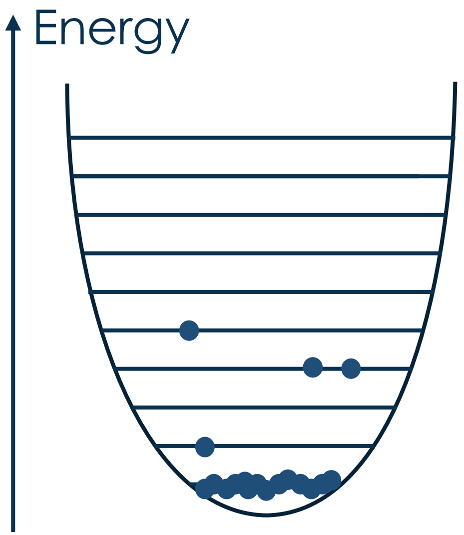
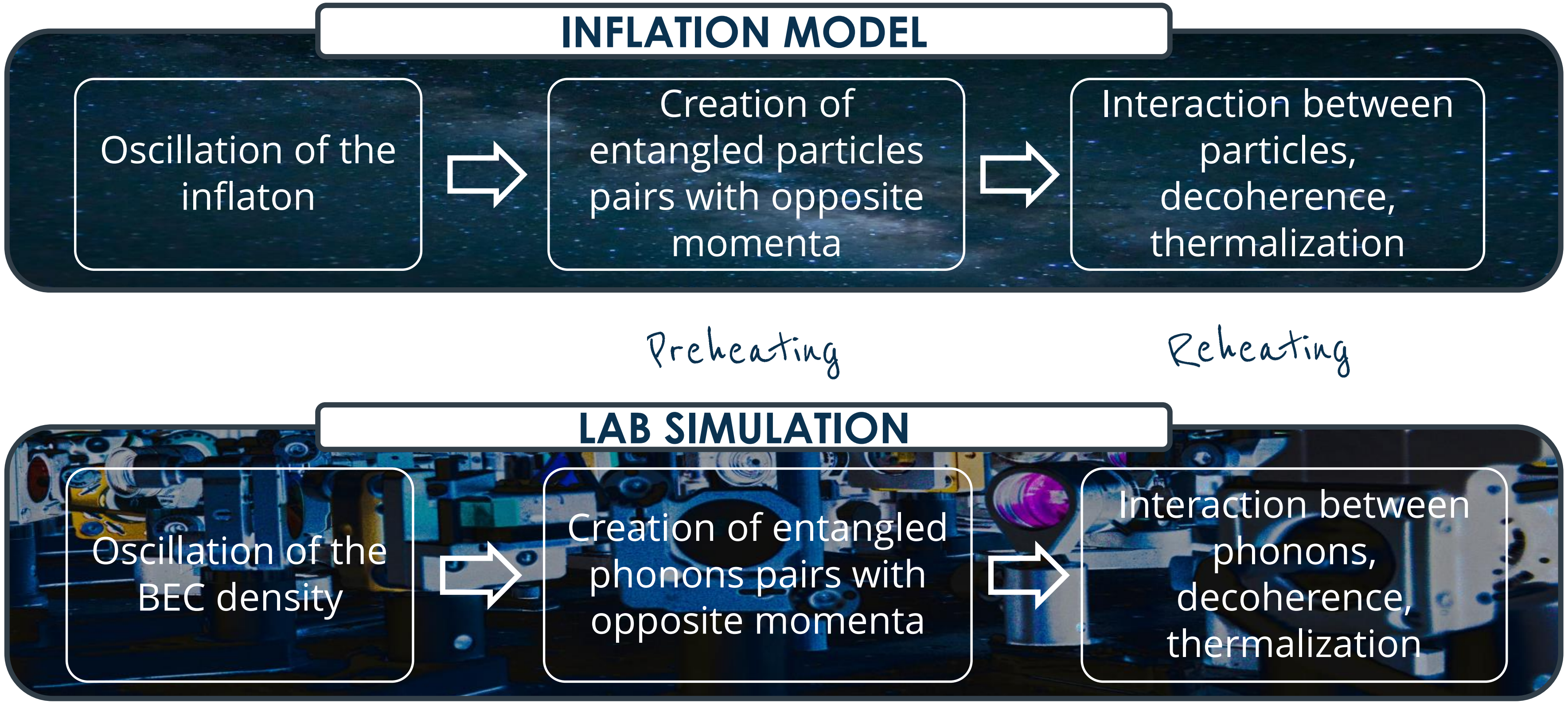
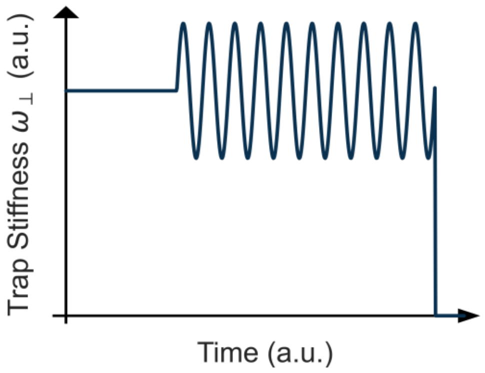
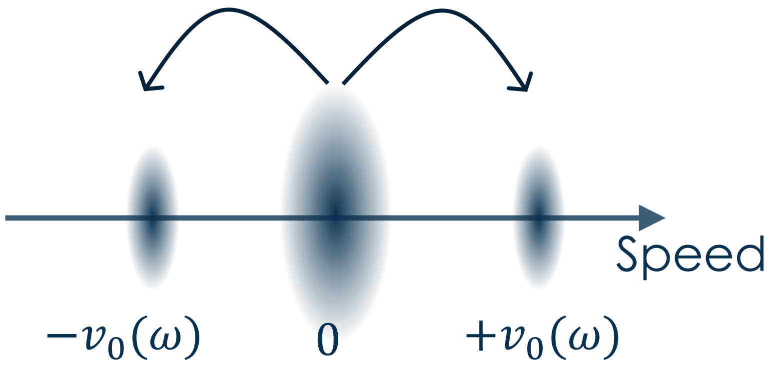




ω : excitation frequency





S. Robertson, F. Michel, and R. Parentani, Phys. Rev. D **95**, 065020 (2017).
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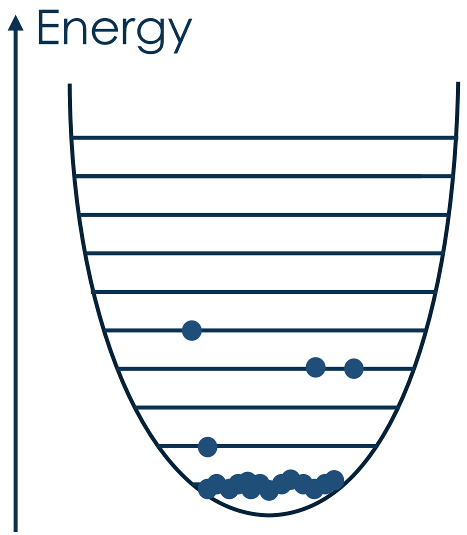


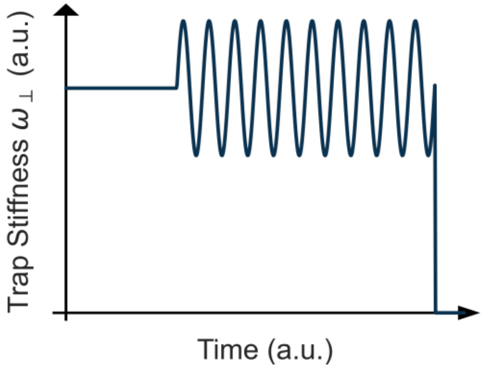
ω : excitation frequency

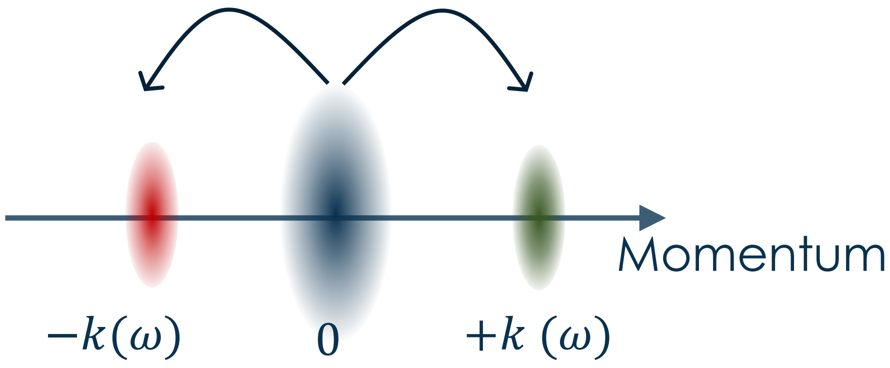
Probing entenglement

Second order correlation function : $g^{(2)}(k_1, k_2) = \frac{\langle n_{k1} n_{k2} \rangle}{\langle n_{k1} \rangle \langle n_{k2} \rangle}$ ← ⟨…⟩ : average over experimental realizations

- $g^{(2)}(k,-k) > 2$
- $\hat{a}_k \hat{a}^\dagger_{-k} = 0$

for entangled (quasi) particles with momentum k





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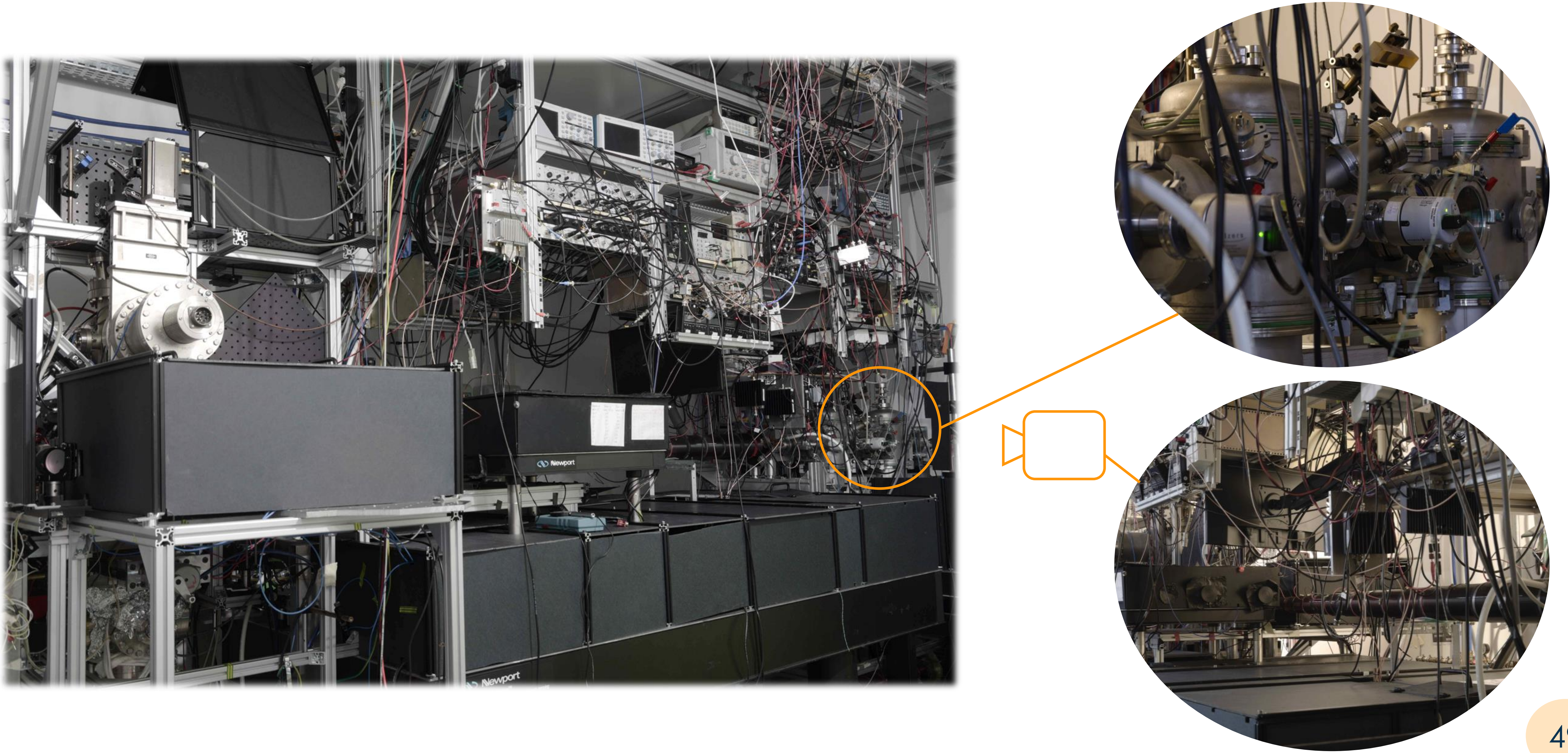
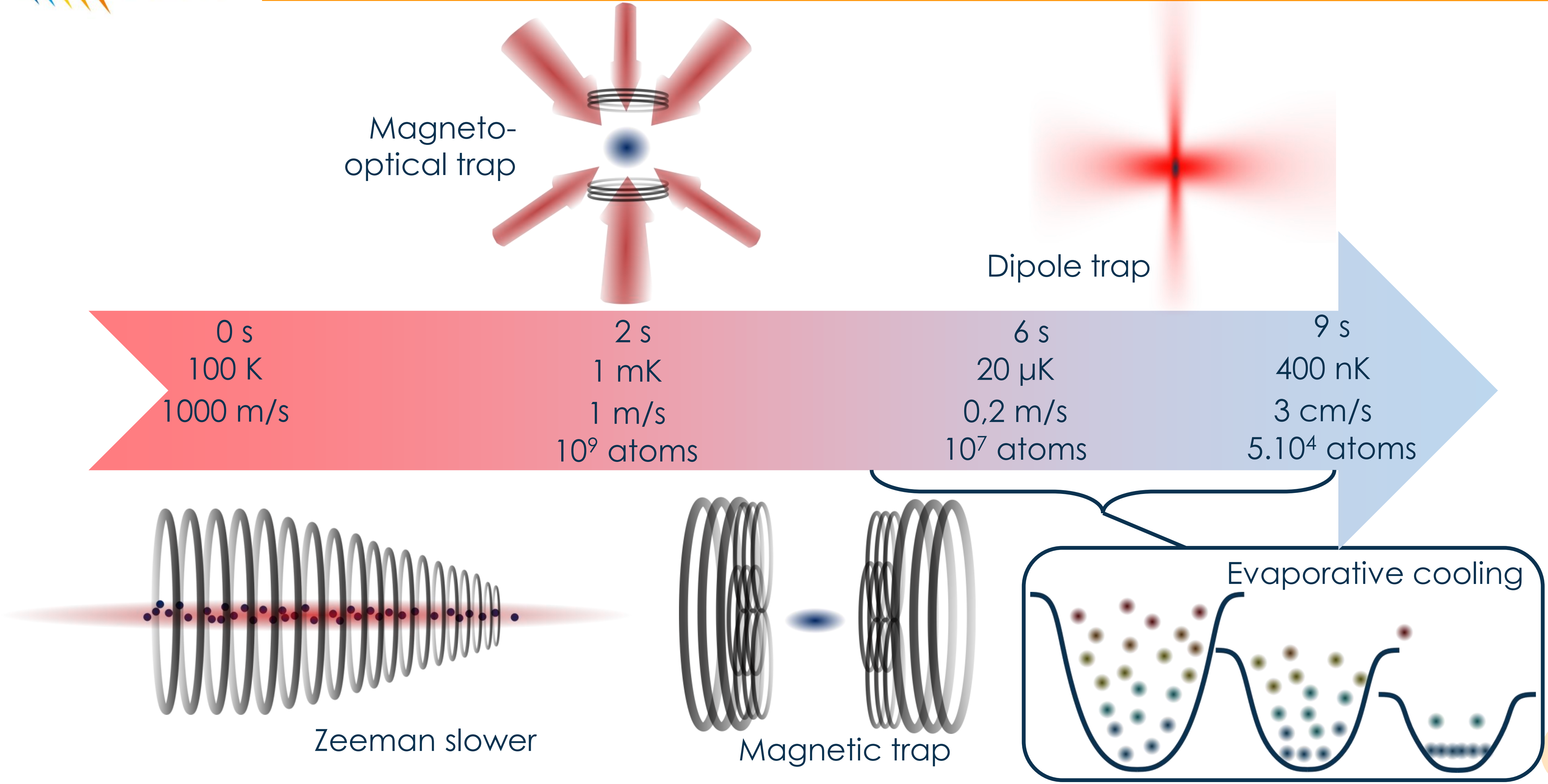
LABORATOIRE CHARLES FABRY

③ Work in progress @LCF

Experimental setup



An experimental cycle



Detection of unique metastable helium atoms

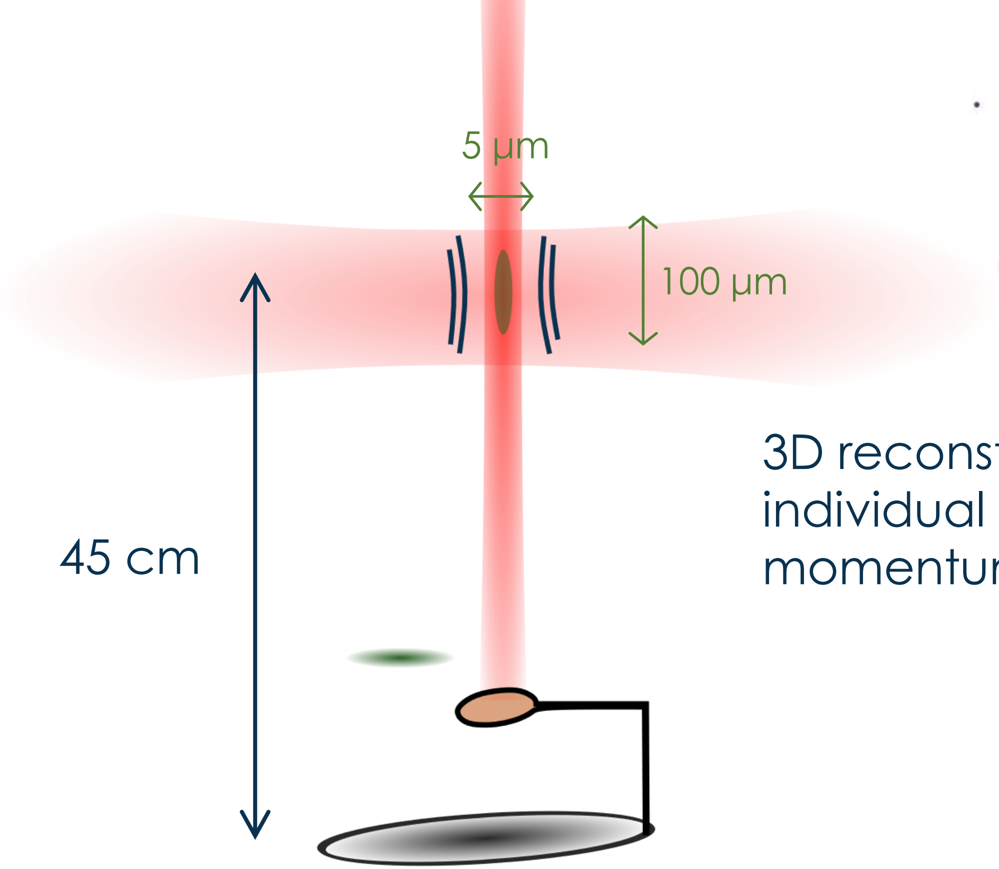
He*

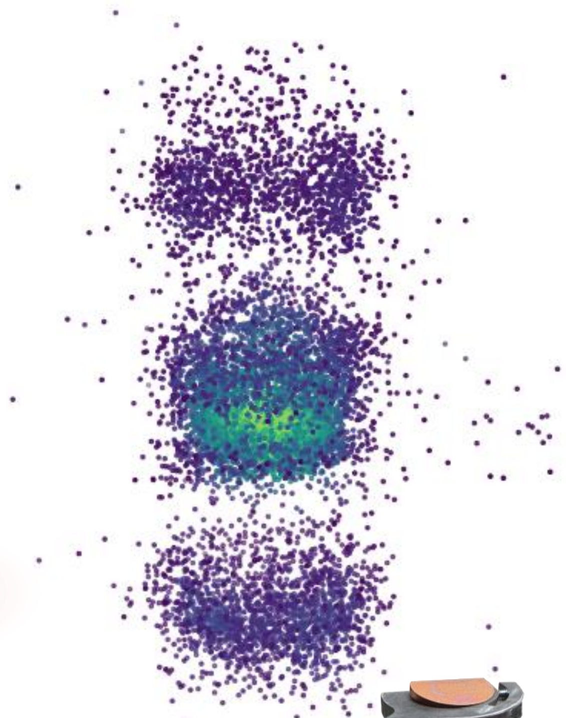
Metastable Helium 4

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

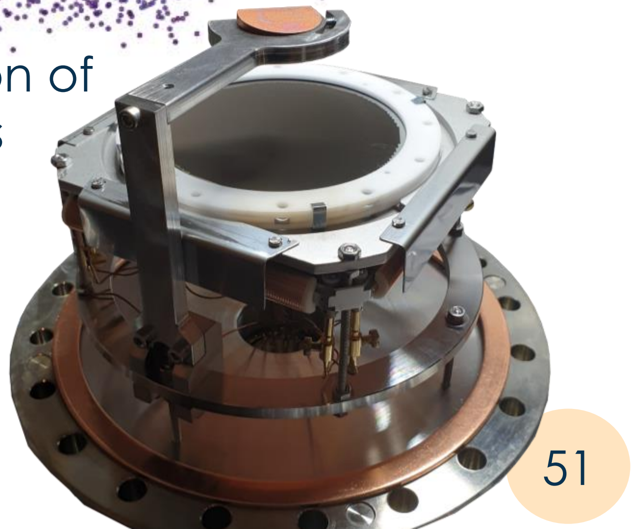
Cigar shape BEC in a crossed dipole trap

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





3D reconstruction of individual atoms momentum



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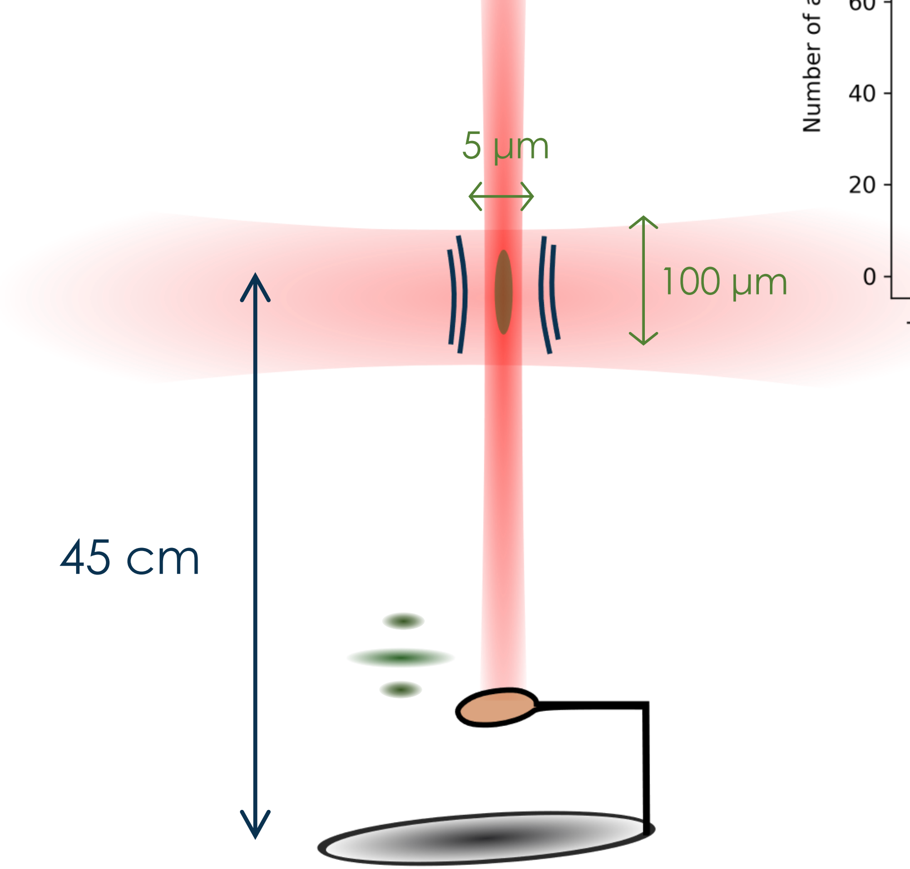
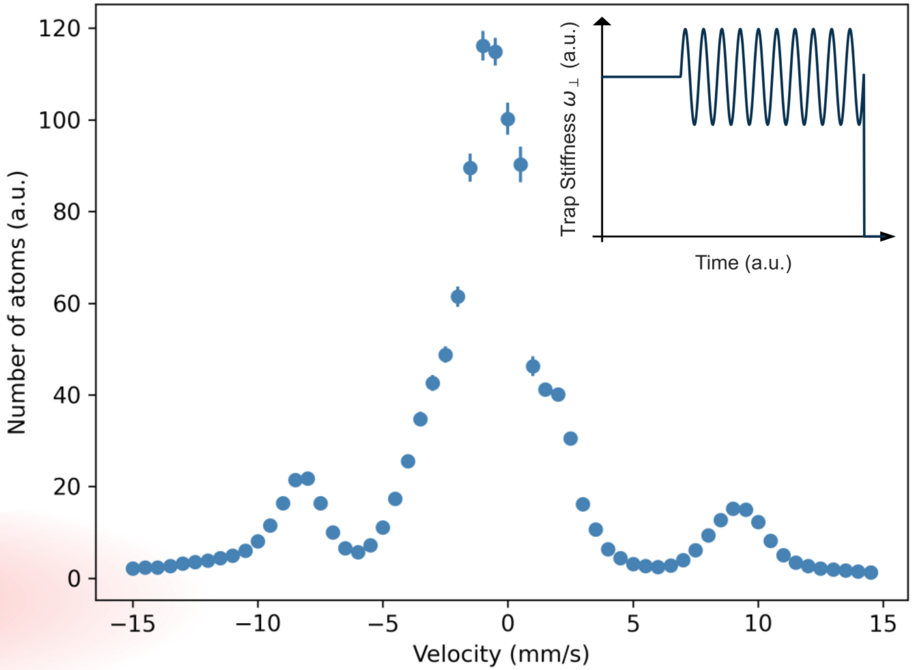




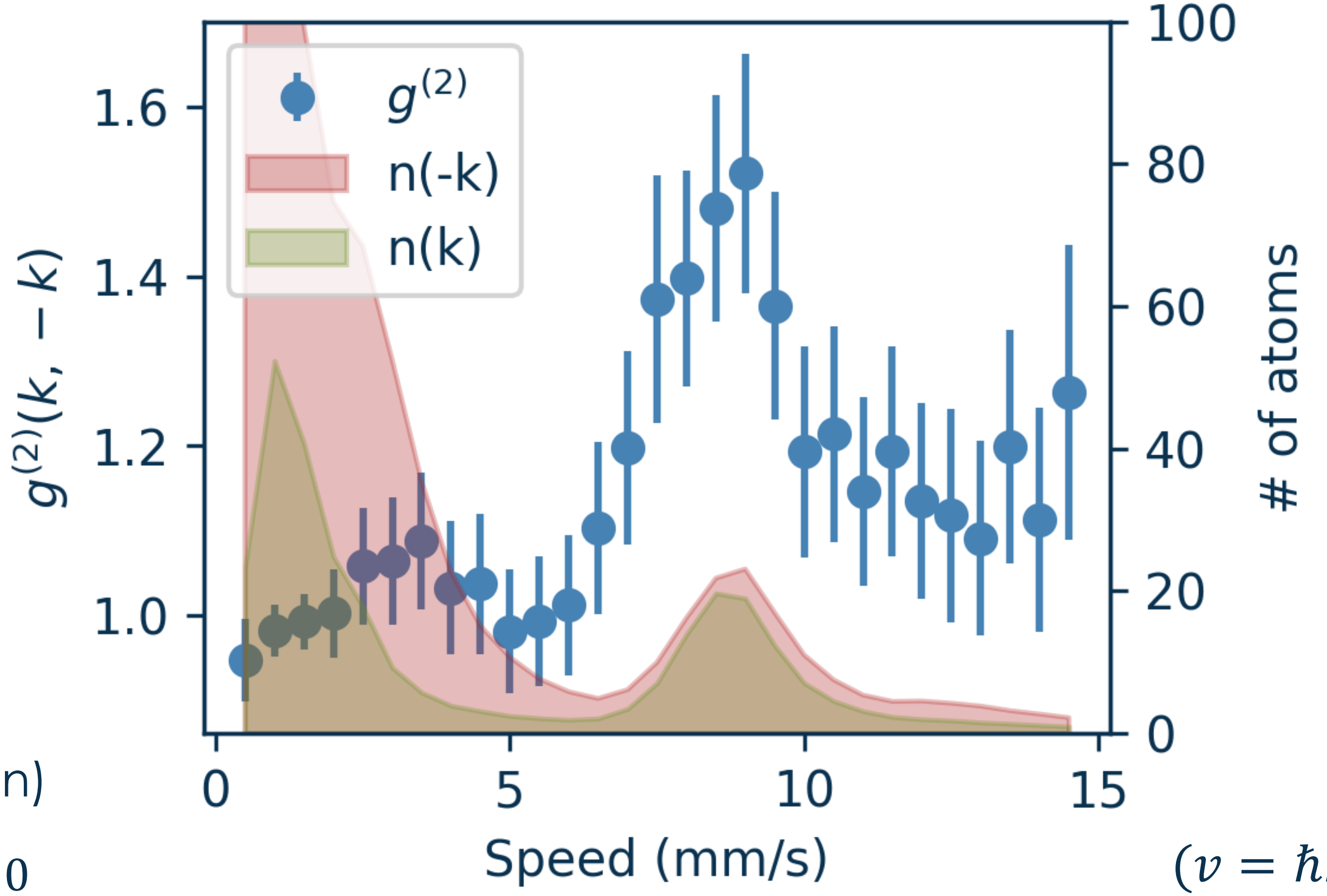
Probing correlations

Second order correlation function :

$$g^{(2)}(-k,k) = \frac{\langle n_{-k} n_k \rangle}{\langle n_{-k}\rangle\langle n_k \rangle}$$

$\langle \dots \rangle$: average over experimental realizations

- Clear correlations between opposite momenta particles,
- But $g^{(2)}$ still under 2



$(v = \hbar k)$

Perspectives

- Decrease the temperature
- Decrease the # of oscillations (↓ population)
- Check $g^{(2)} > 2 \leftrightarrow$ entanglement : $\hat{a}_k \hat{a}^\dagger_{-k} = 0$
- Study the thermalization

J.-C. Jaskula *et al.*, Phys. Rev. Lett. **109**, 220401 (2012).

Thank you for your time !

Some lecture

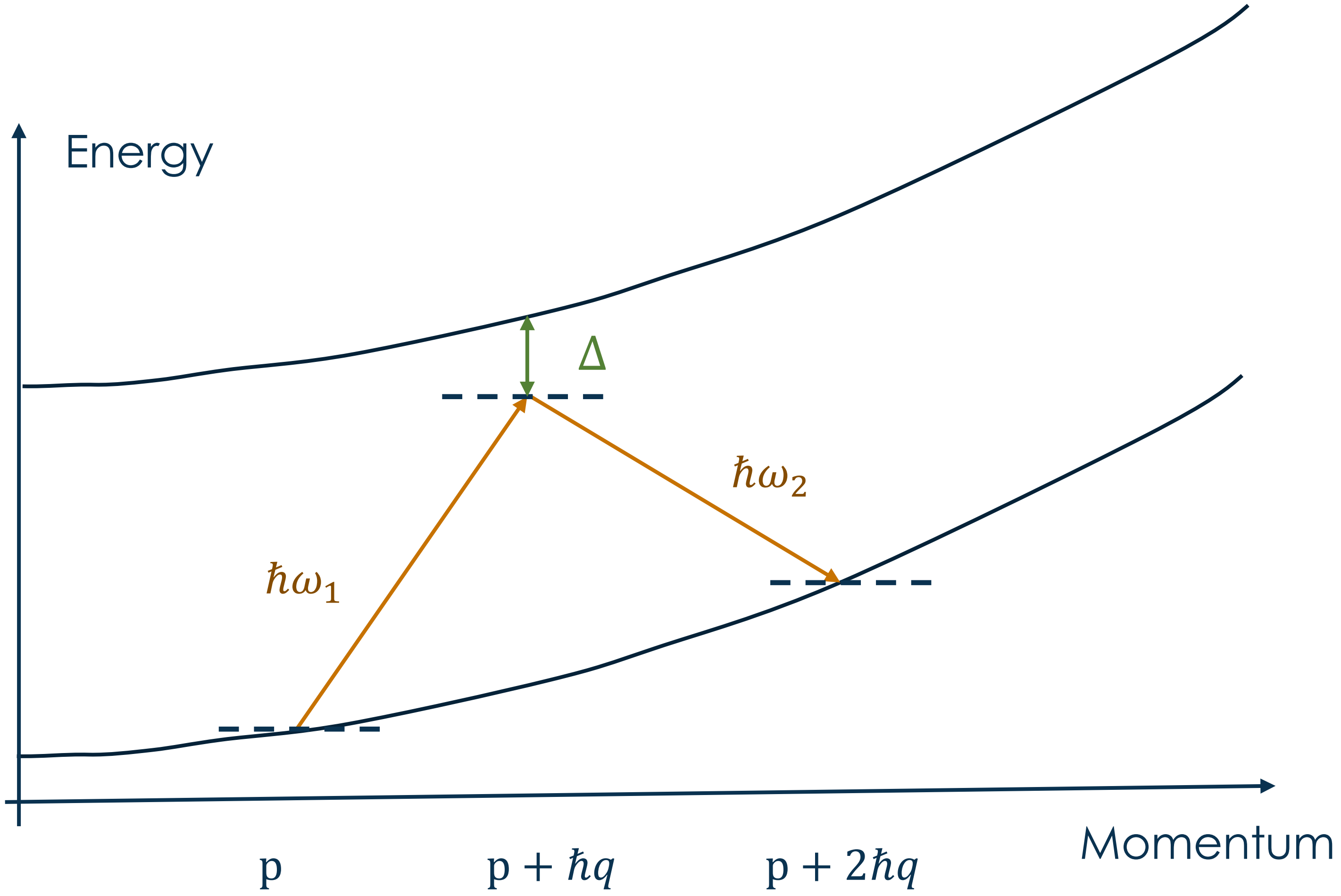
- S. Watson, *An Exposition on Inflationary Cosmology, 2000*
- J.-C. Jaskula *et al.*, Phys. Rev. Lett. **109**, 220401 (2012).
- S. Robertson, F. Michel, and R. Parentani, Phys. Rev. D **95**, 065020 (2017).
- A. Micheli and S. Robertson, Phys. Rev. B **106**, 214528 (2022).

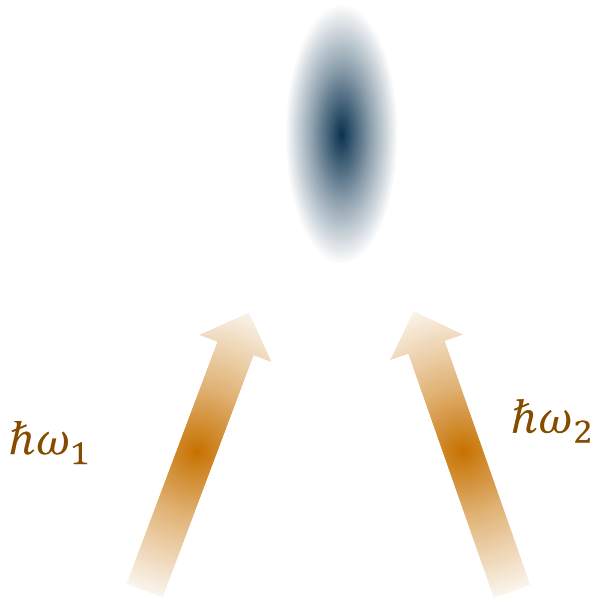
On the experimental side

On the theory side

Fundings

Supplement : Bragg diffraction for atomic mirrors



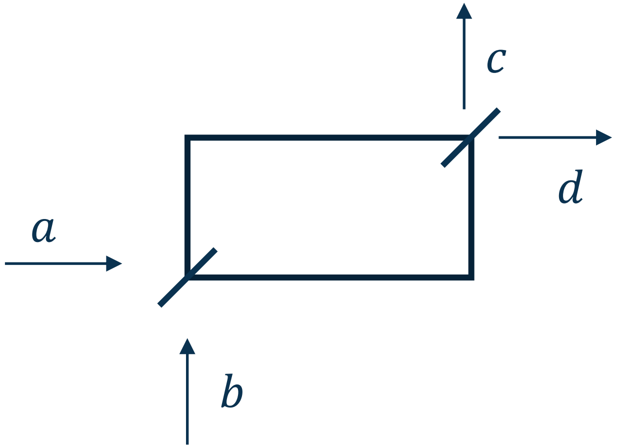


$$q = \frac{2\pi}{\lambda} \sin\theta$$

Supplement : checking the non-separability criteria

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

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



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

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

→ Check that this term is zero.

Supplement : inflation scenario

time

1,3×10^{10} years — Dark-matter dominated era

$a \propto e^{H_0 t}$

9,8×10^{9} years

Matter dominated era

$a \propto t^{2/3}$

3,8×10^{5} years — Decoupling : CMB observed region

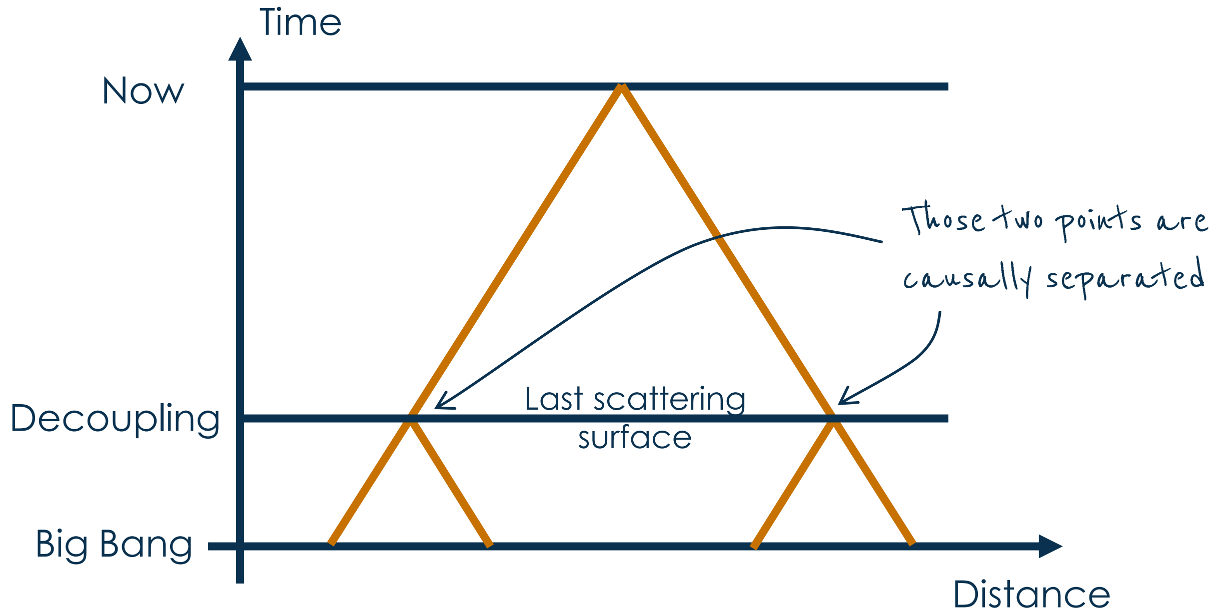
4,7×10^{4} years

Radiation dominated era

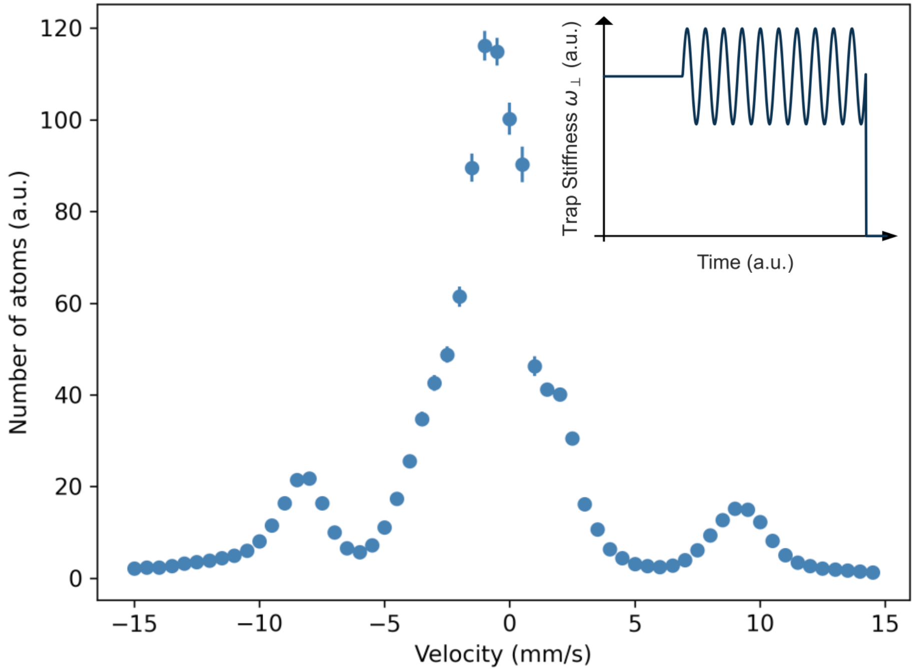
$a \propto t^{1/2}$

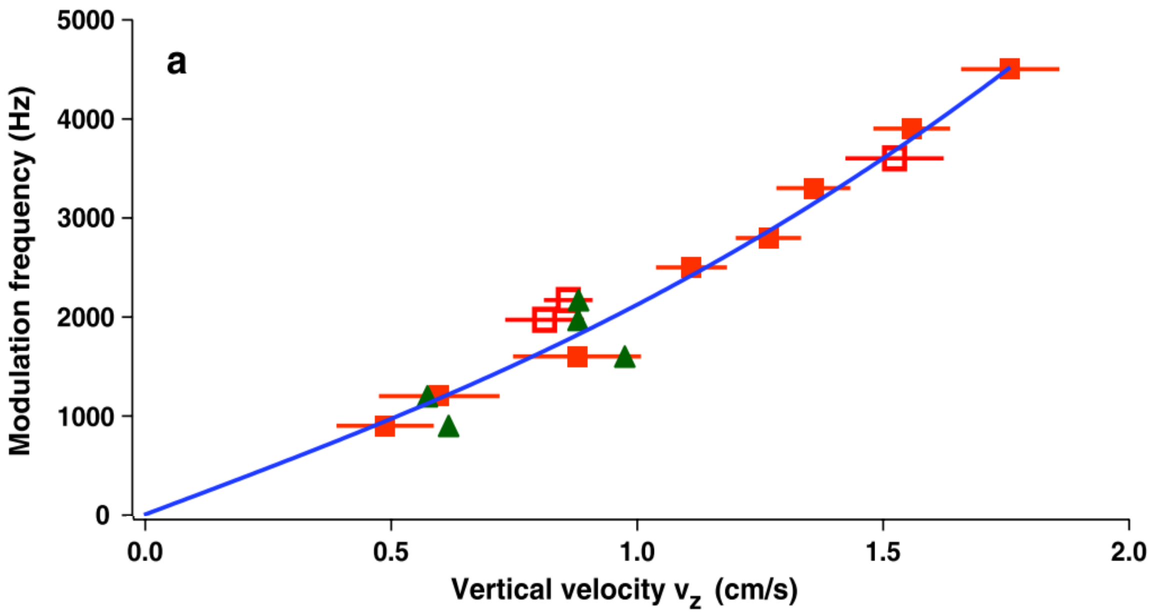
$a \propto e^{Ht}$ — Inflation

Big Bang



Supplement : excitation spectrum of quasi-particles





J.-C. Jaskula *et al.*, Phys. Rev. Lett. **109**, 220401 (2012).