Cosmology and quantum simulation

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

Victor Gondret, Charlie Leprince, Quentin Marolleau, Denis Boiron & Chris Westbrook

EDOM Days

ÉCOLE DOCTORALE
Ondes
et matière
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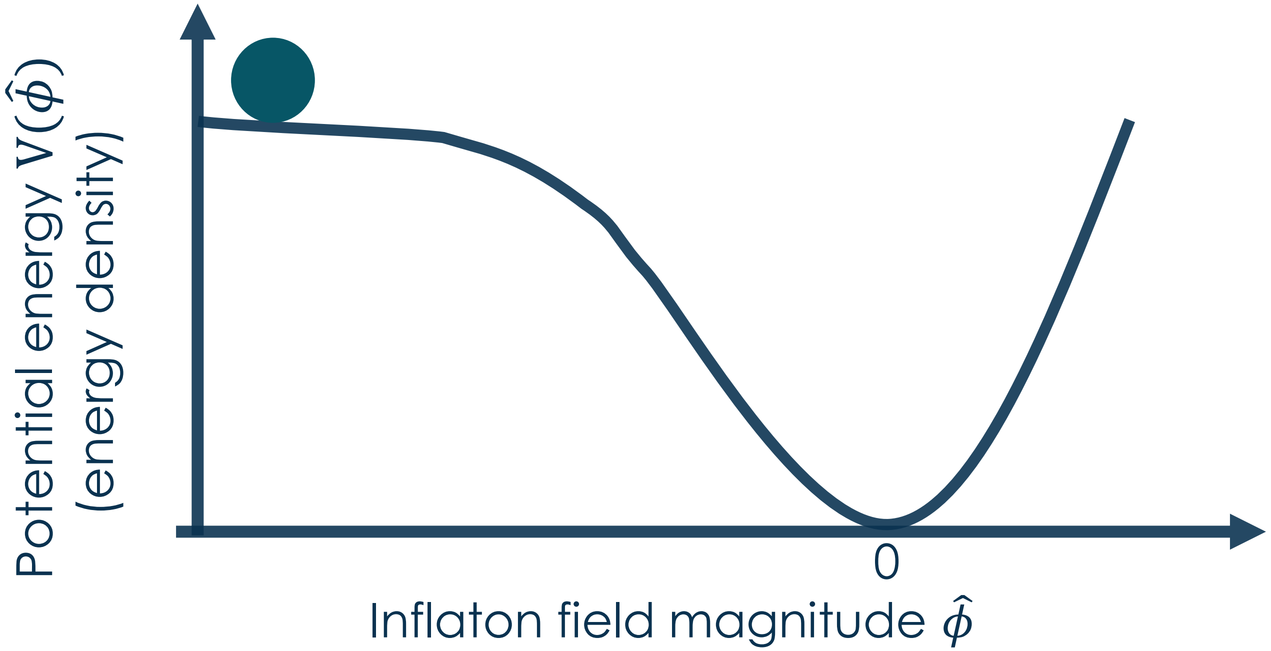
Theory of Inflation

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

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



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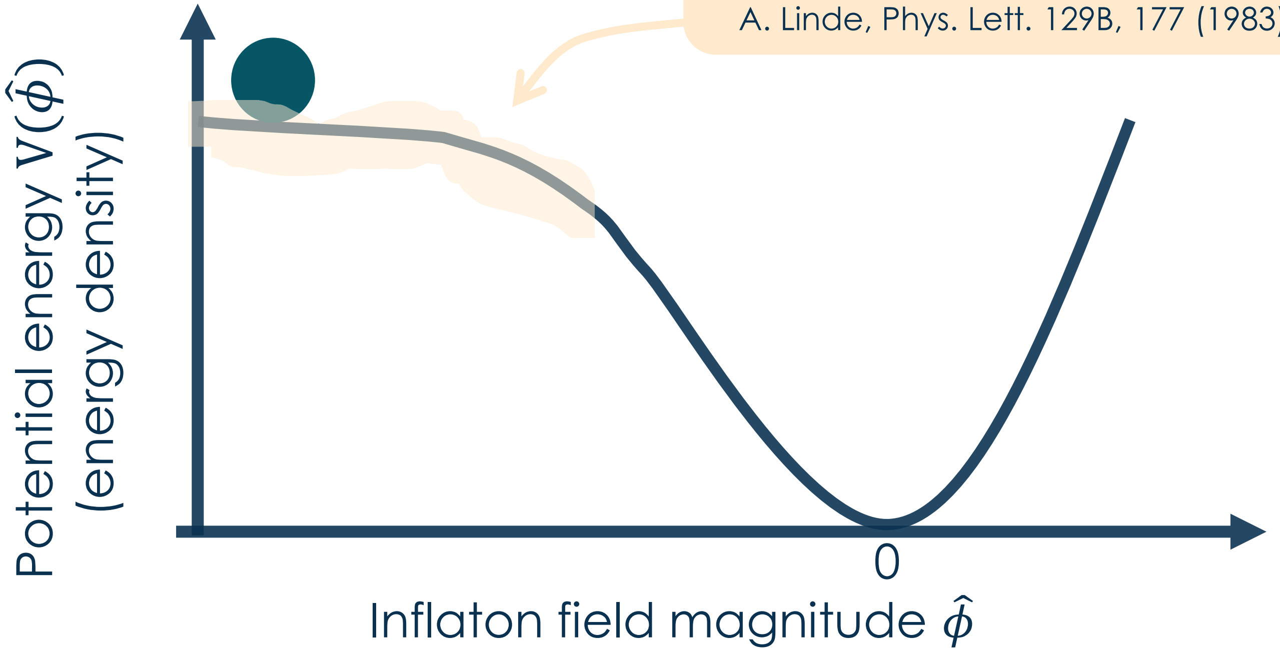

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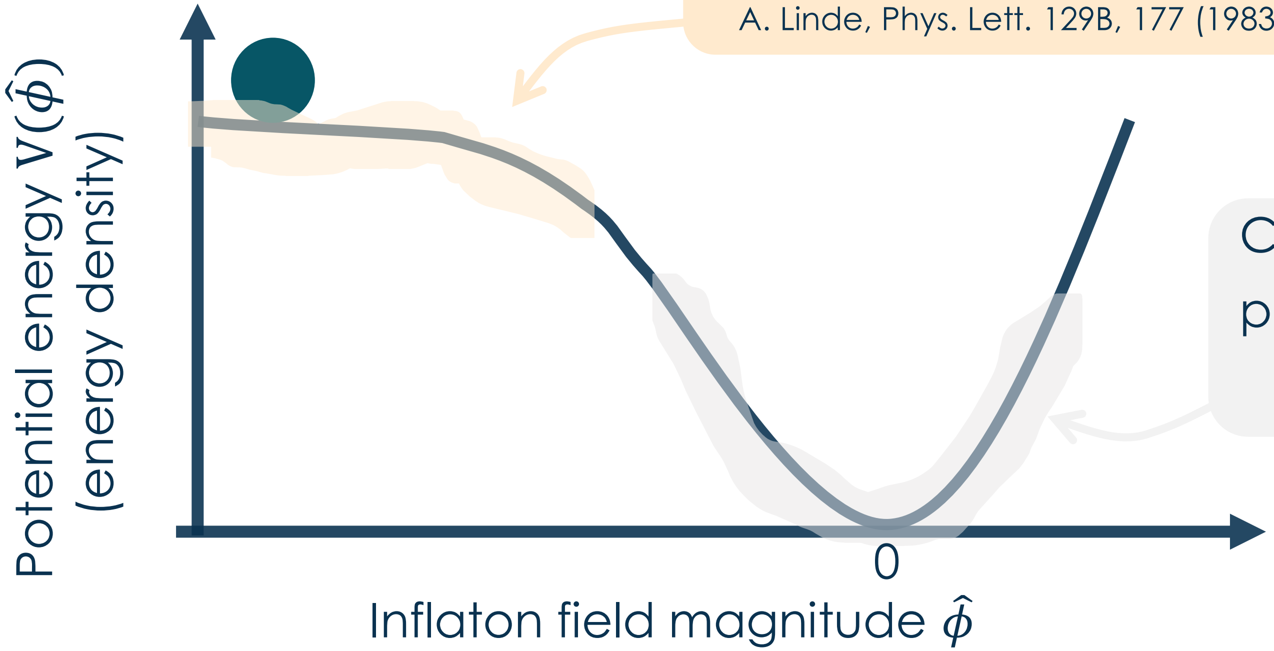

Creation of particles through parametric resonance.
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Only a few oscillations are needed !

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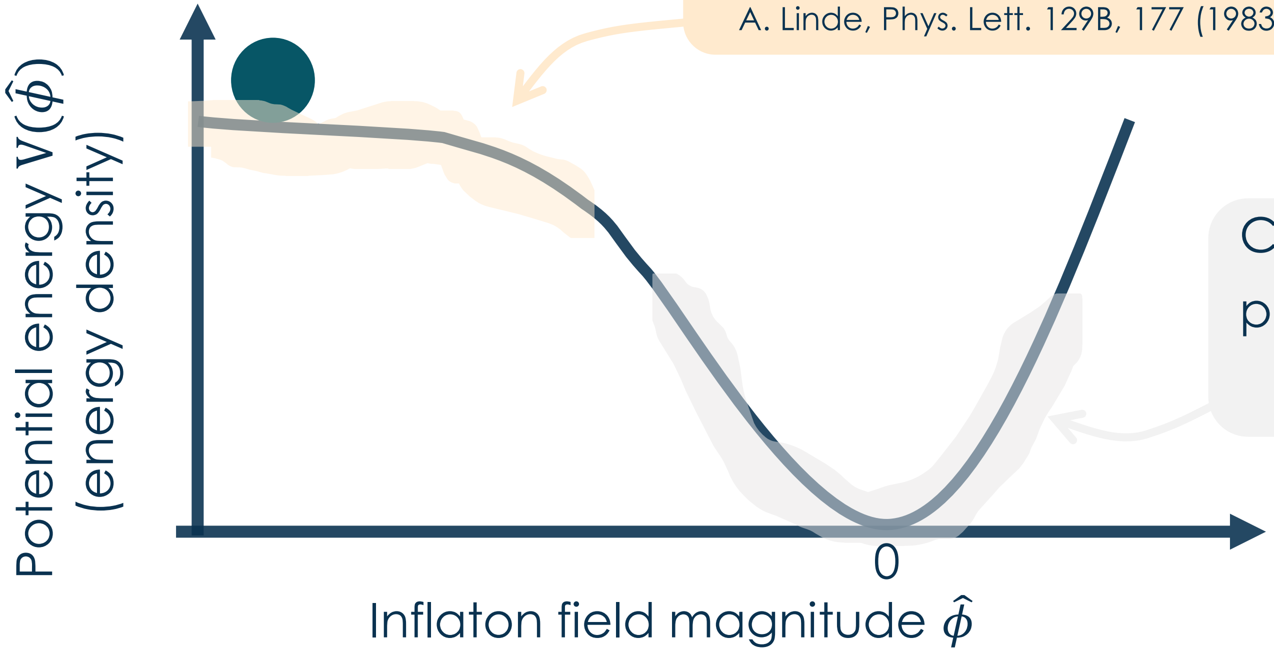

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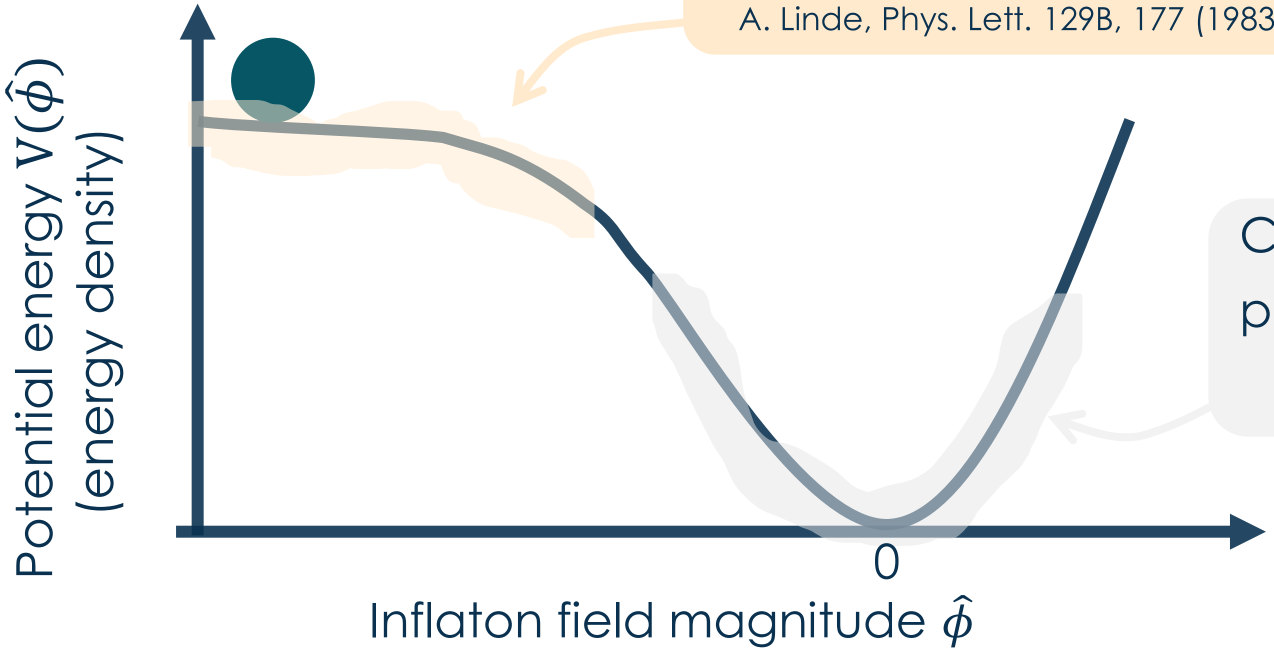

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Not experimentally accessible :
need for analogous phenomena

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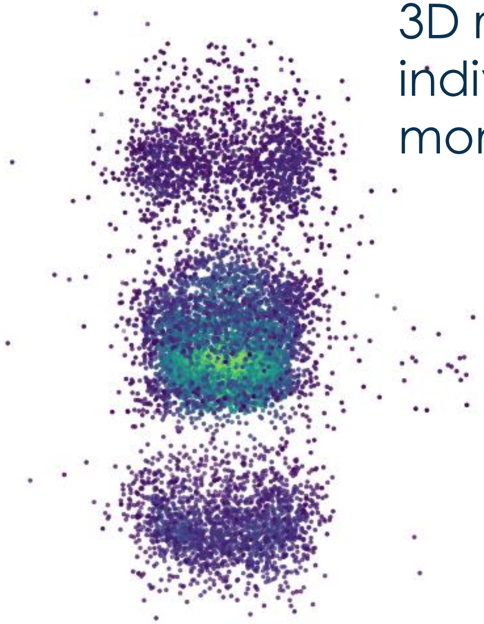
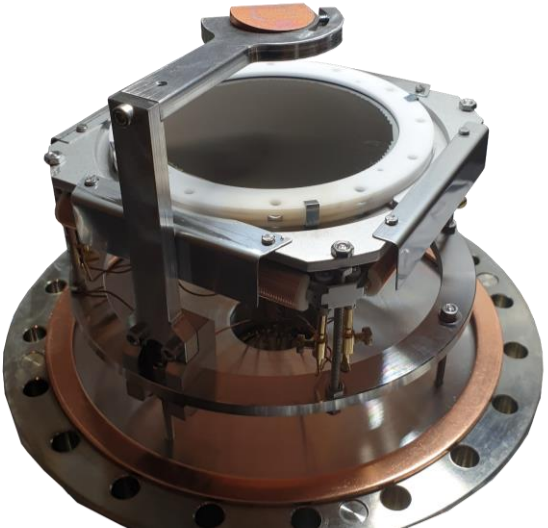
Detection of BEC of metastable helium atoms

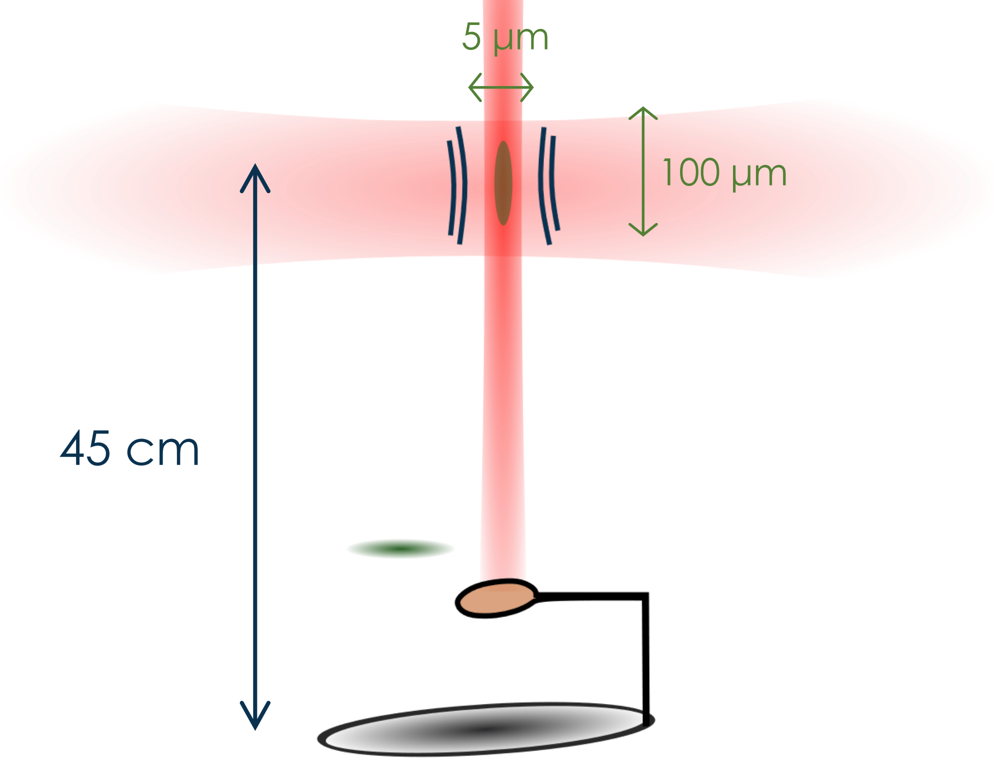


3D reconstruction of individual atoms momentum



Cigar shape BEC in a crossed dipole trap

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



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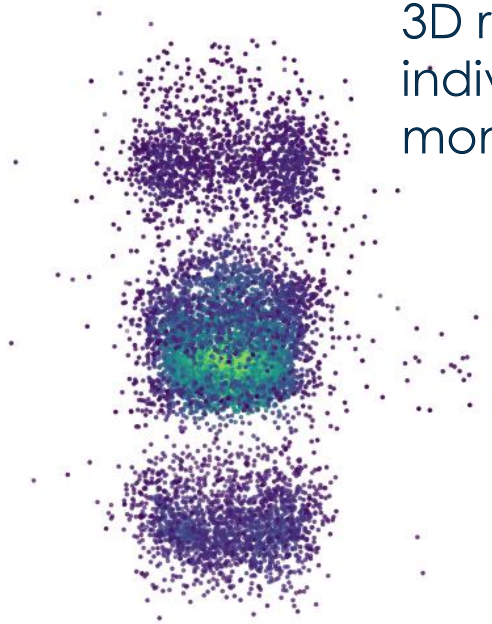

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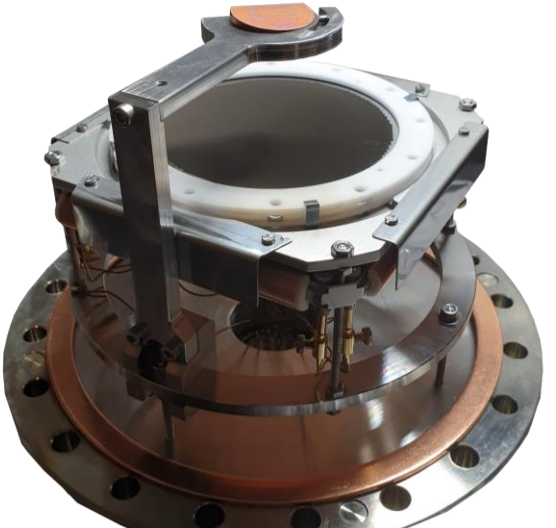

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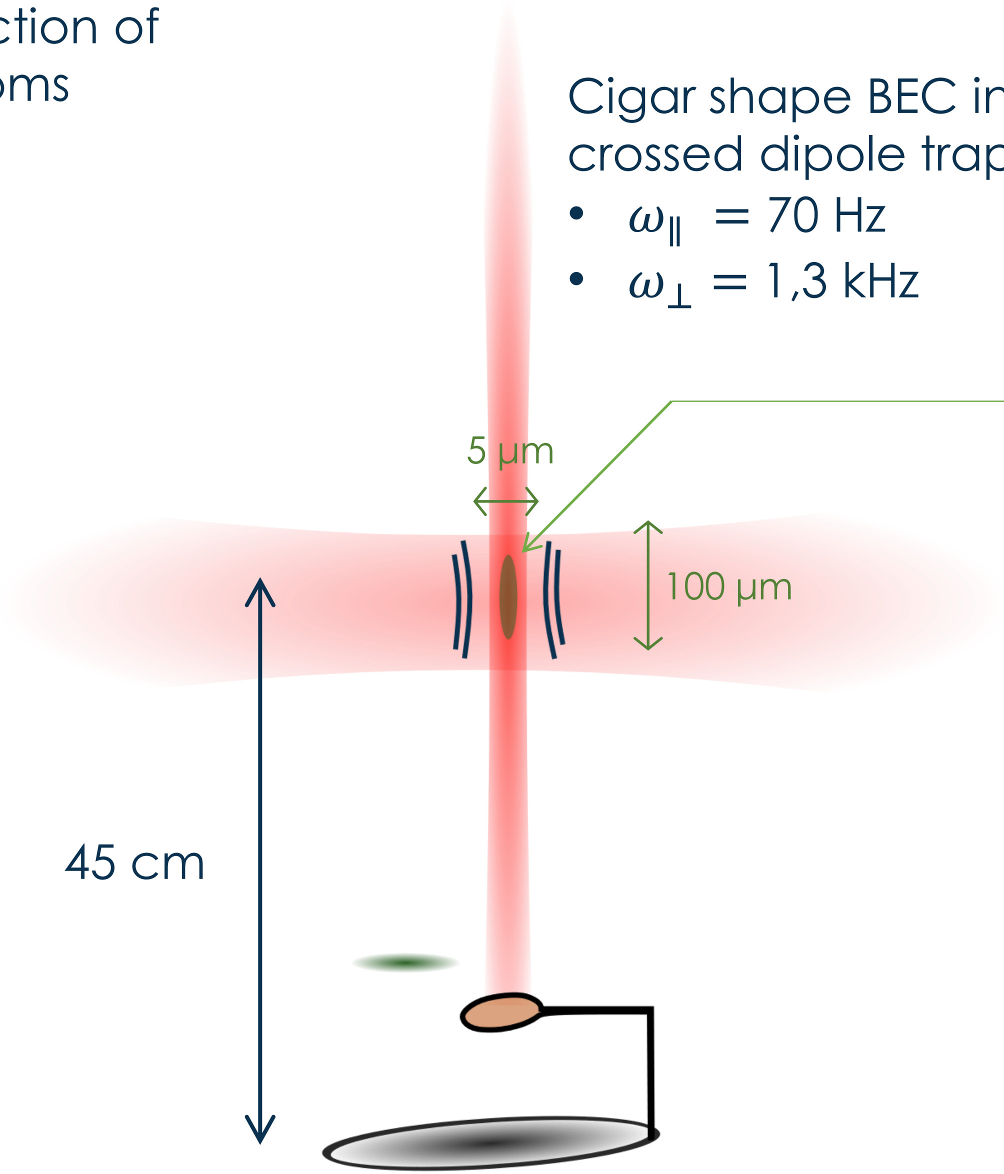
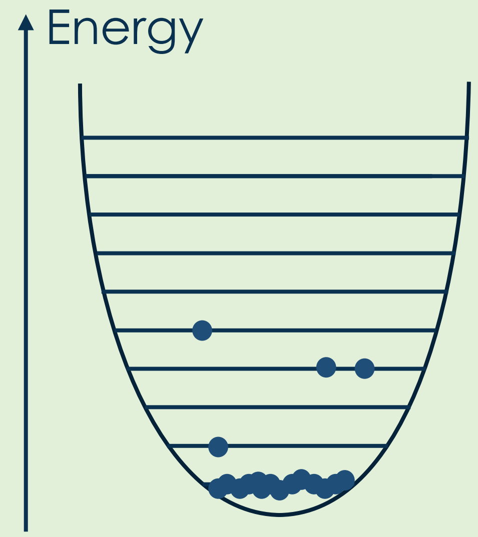


BEC is a macroscopic state at k=0



BEC for analog inflation

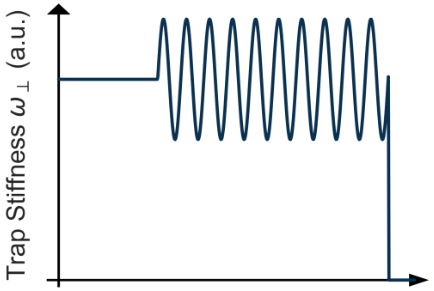
INFLATION MODEL

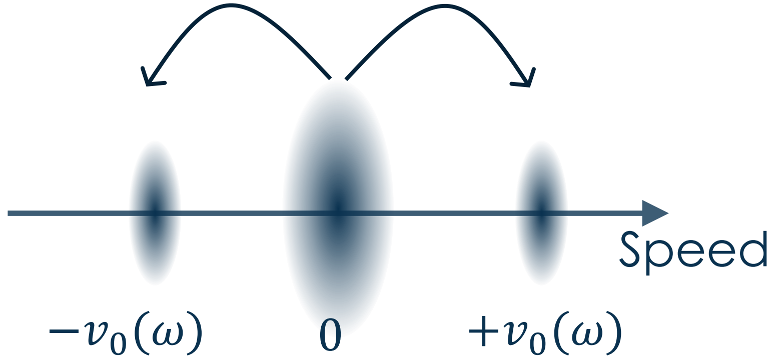
Oscillation of the inflaton ⇨ Creation of entangled particles pairs with opposite momenta ⇨ Interaction between particles, decoherence, thermalization

Preheating   Reheating

LAB SIMULATION

Oscillation of the BEC density ⇨ Creation of entangled phonons pairs with opposite momenta ⇨ Interaction between phonons, decoherence, thermalization





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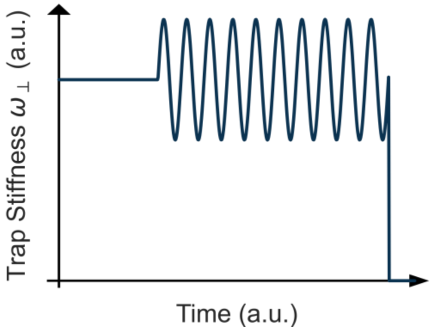
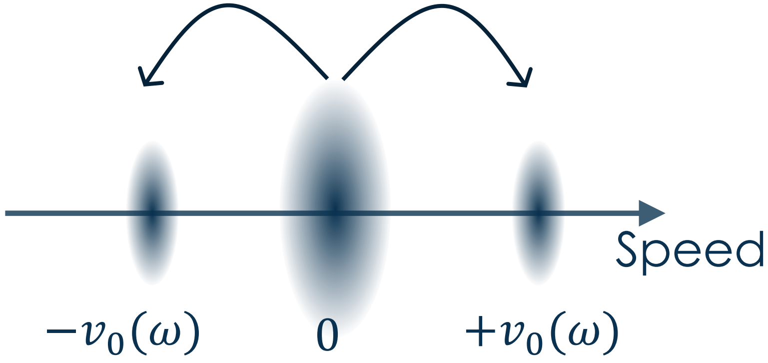
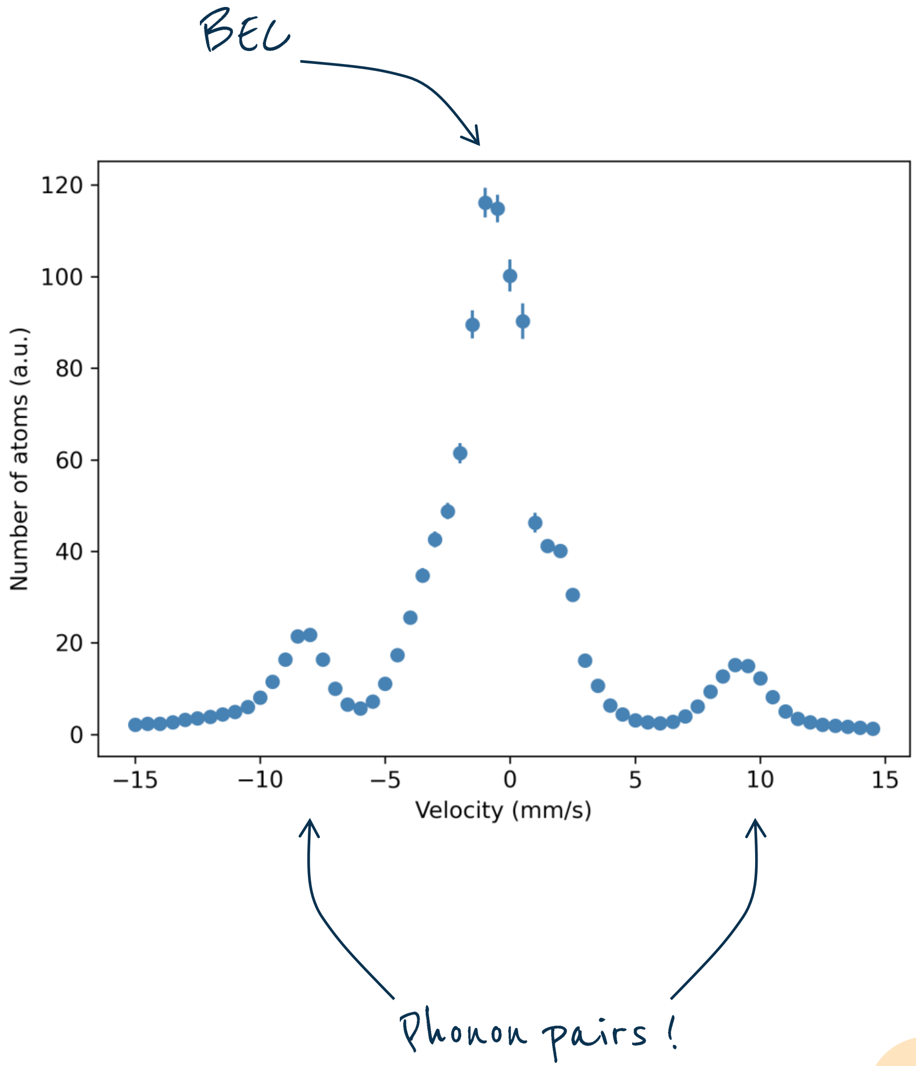






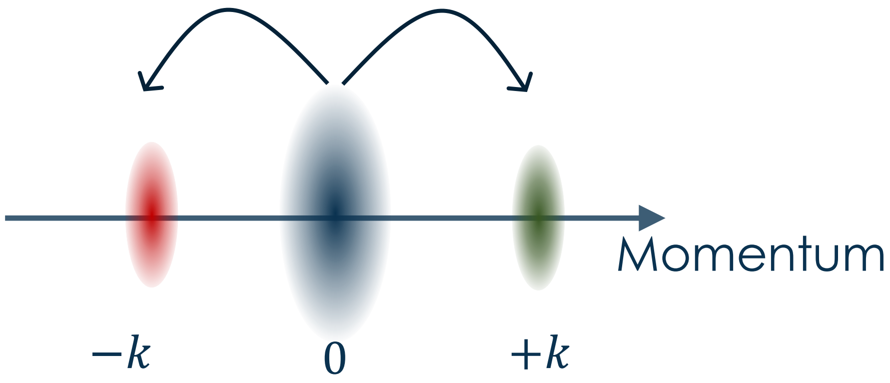
Probing correlations

Second order correlation function :

⟨...⟩ : average over experimental realizations

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

$g^{(2)}(k,-k) > 2$ is *a priori* needed to claim for entenglement



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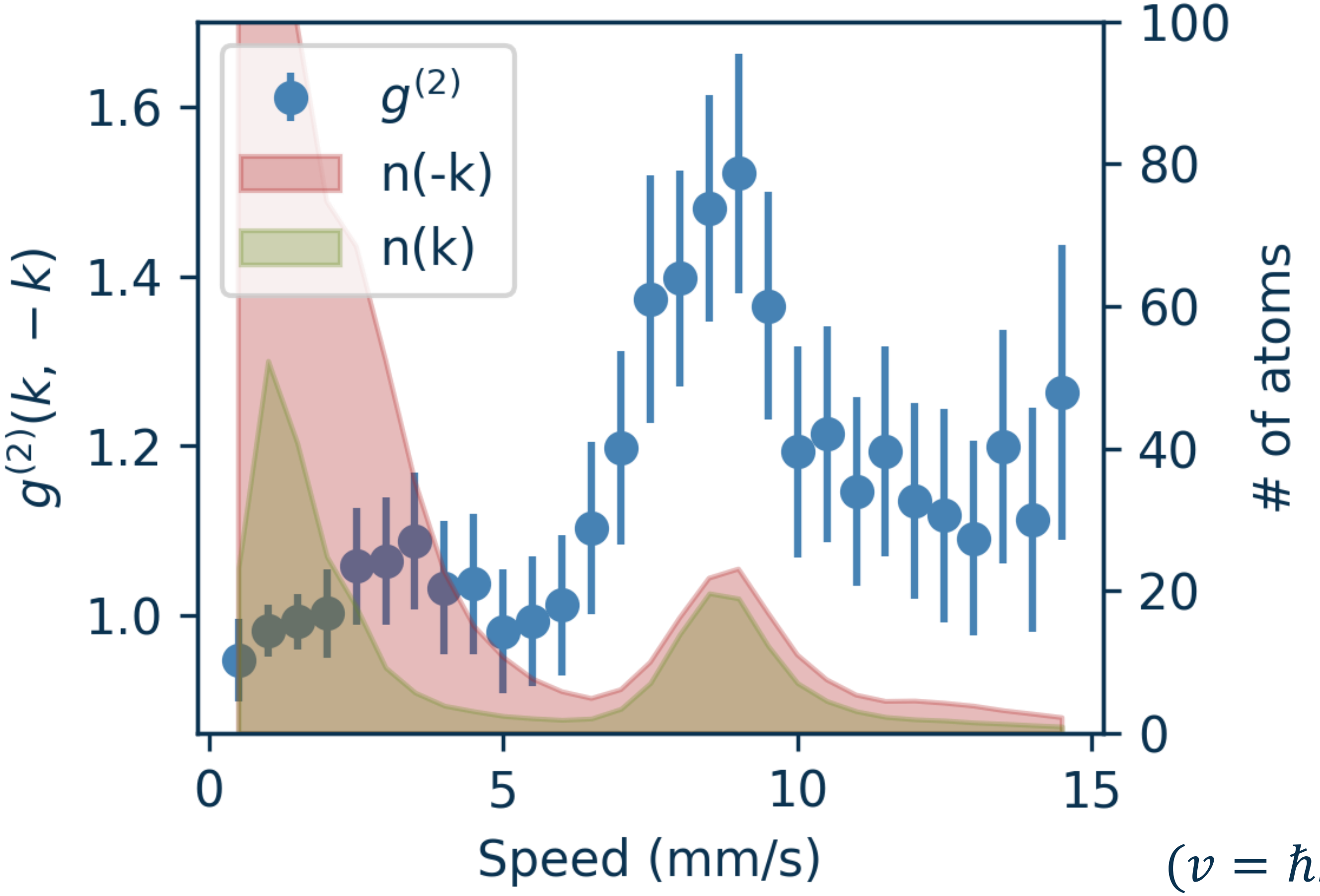
- Clear correlations between opposite momenta particles,
- But $g^{(2)}$ still under 2



$(v = \hbar k)$

Probing correlations

Second order correlation function :

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- Clear correlations between opposite momenta particles,
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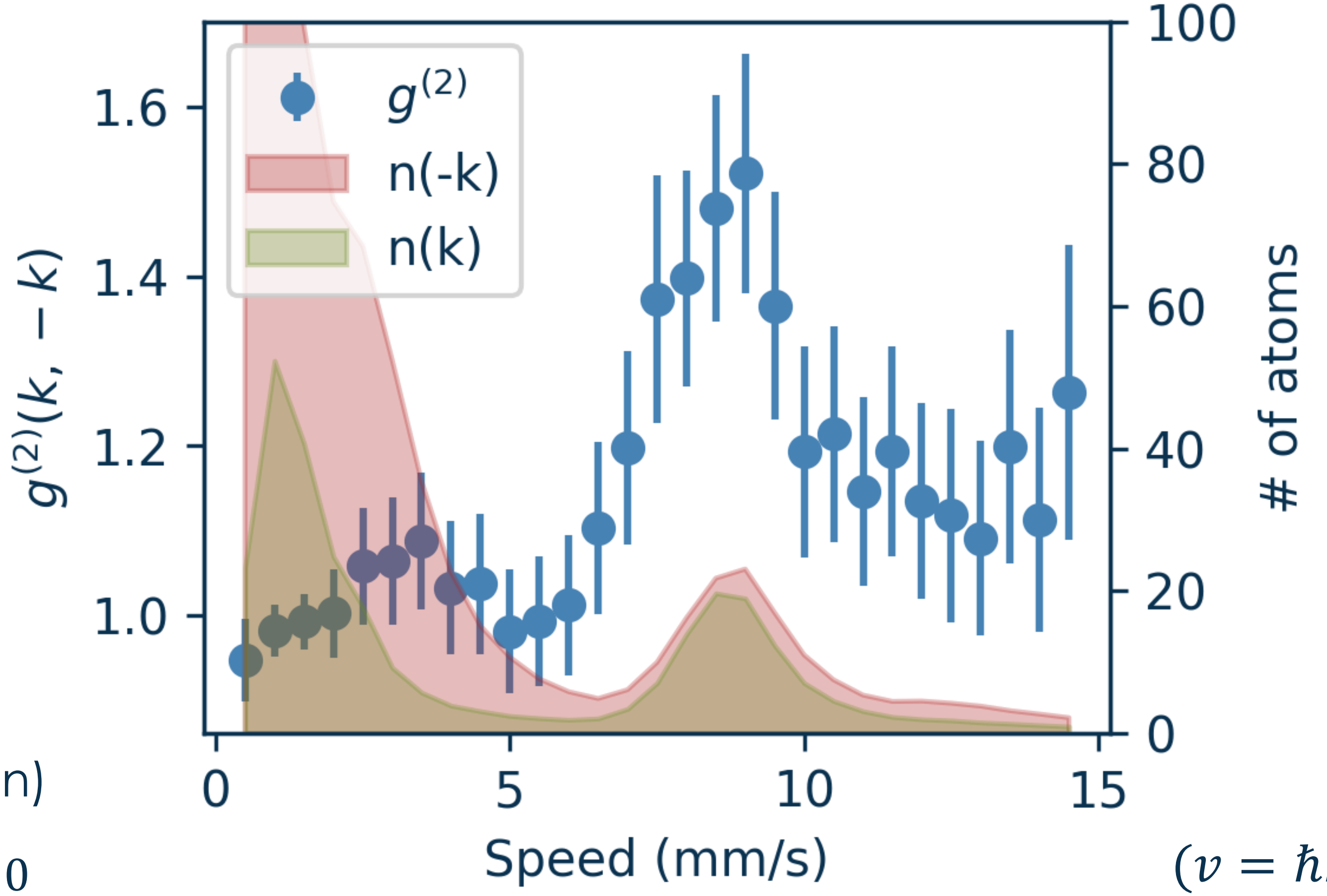
Perspectives

- 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



$(v = \hbar k)$

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

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université PARIS-SACLAY

Fundings

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QUANTUM FLAGSHIP

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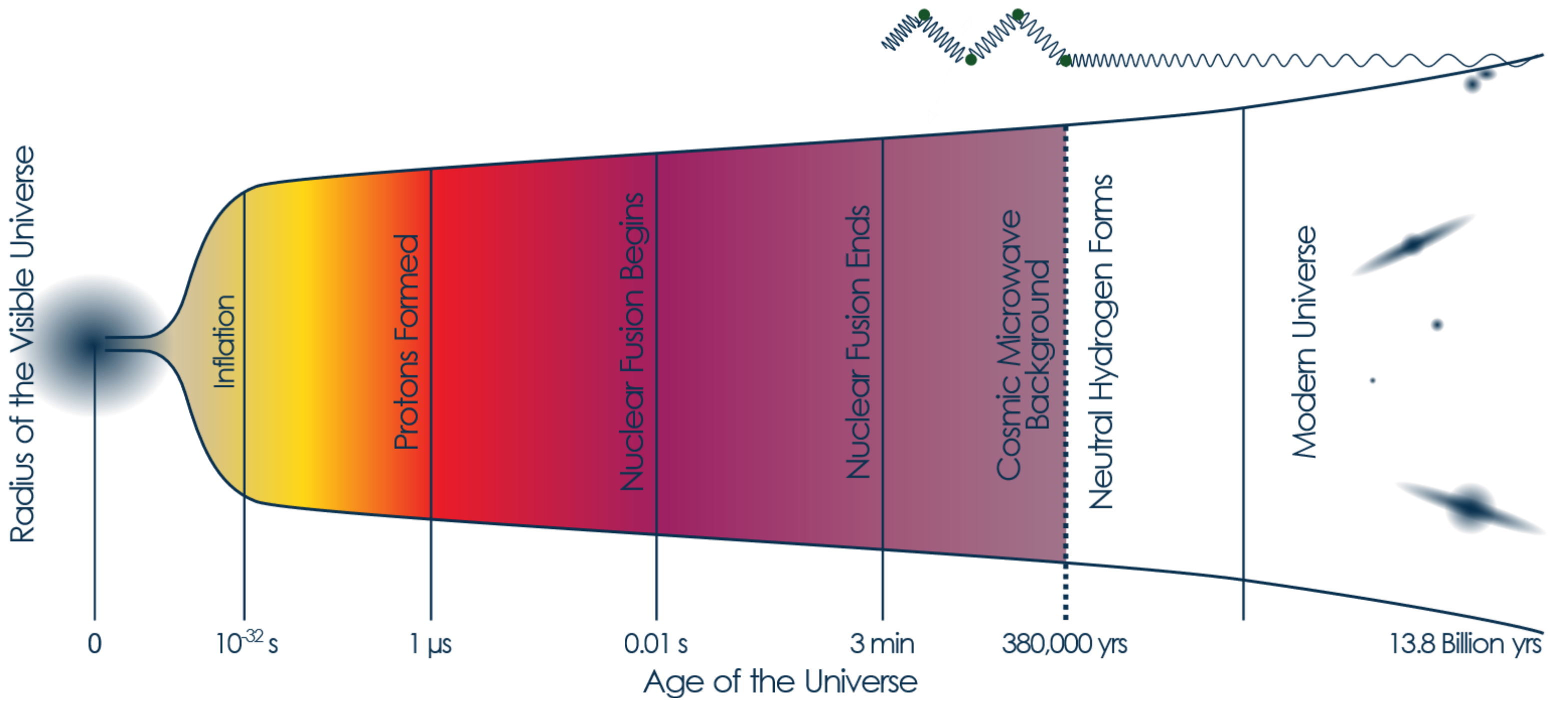
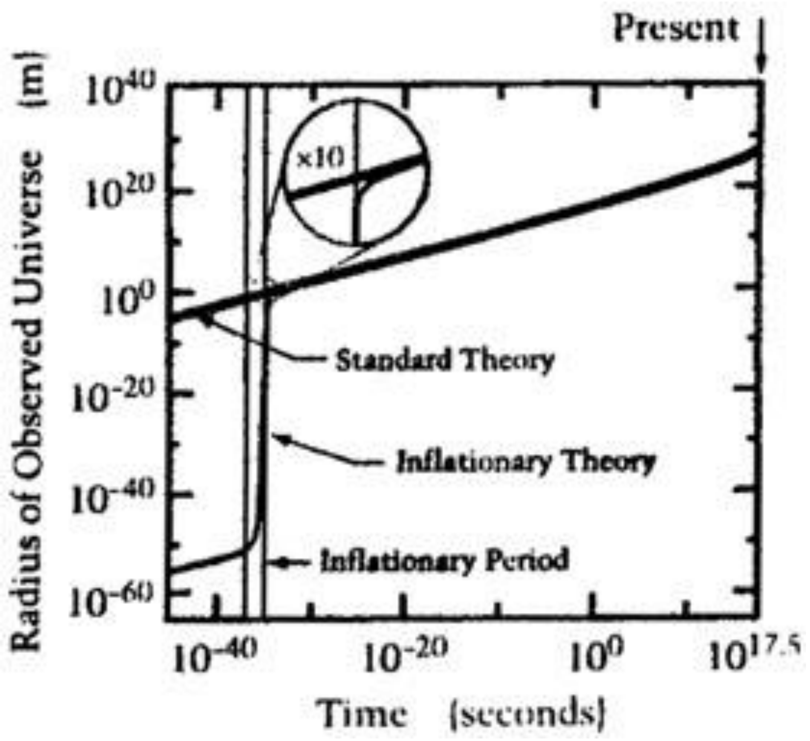
Theory of Inflation





Large scale homogeneity of the universe is not explained by the standard model of cosmology.

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
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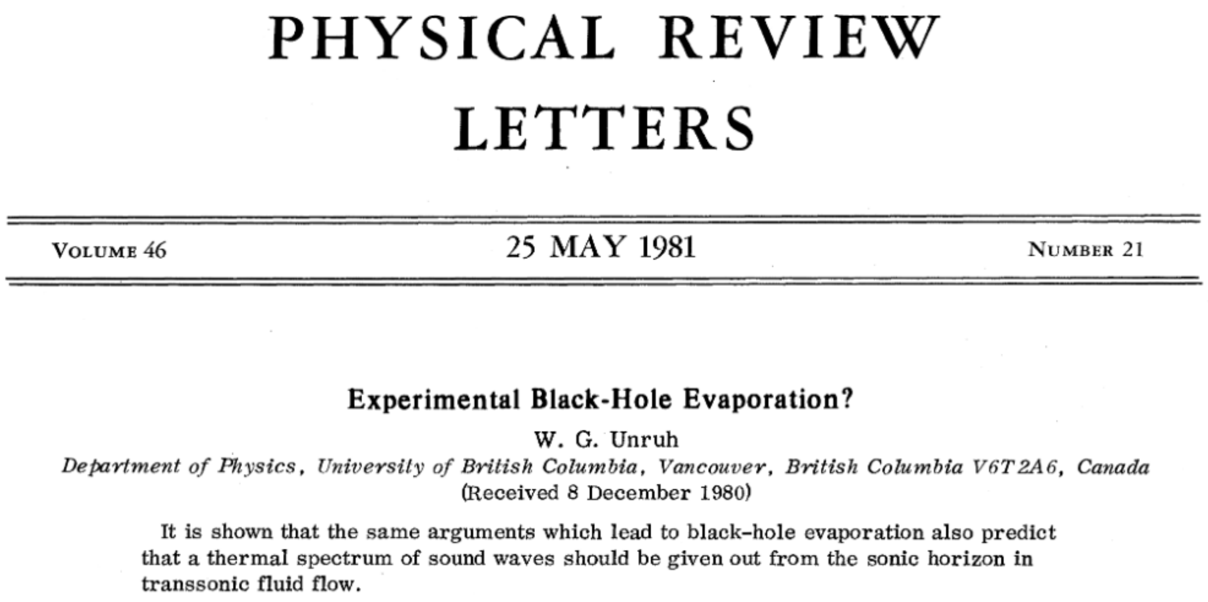
Analog gravity



PHYSICAL REVIEW LETTERS

VOLUME 46 | 25 MAY 1981 | NUMBER 21

Experimental Black-Hole Evaporation?

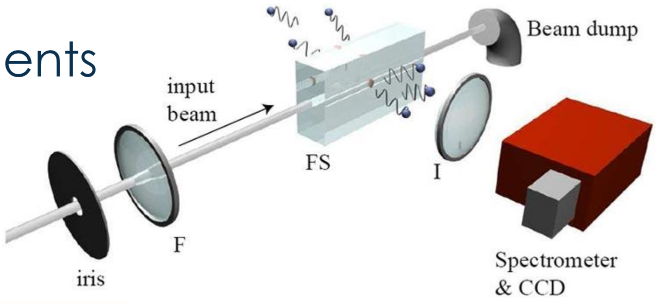
W. G. Unruh

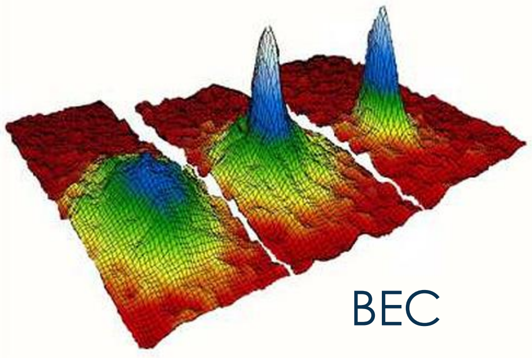
Department of Physics, University of British Columbia, Vancouver, British Columbia V6T 2A6, Canada

(Received 8 December 1980)

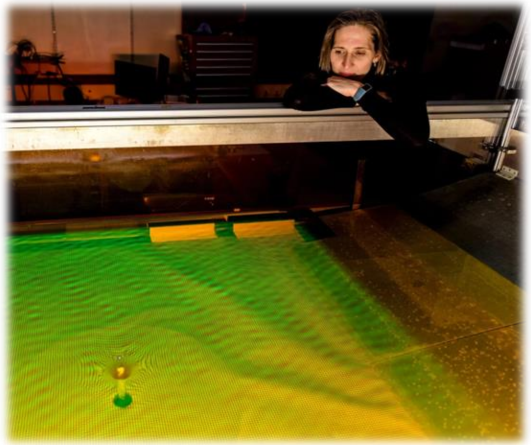
It is shown that the same arguments which lead to black-hole evaporation also predict that a thermal spectrum of sound waves should be given out from the sonic horizon in transsonic fluid flow.

Ultrashort laser pulse filaments

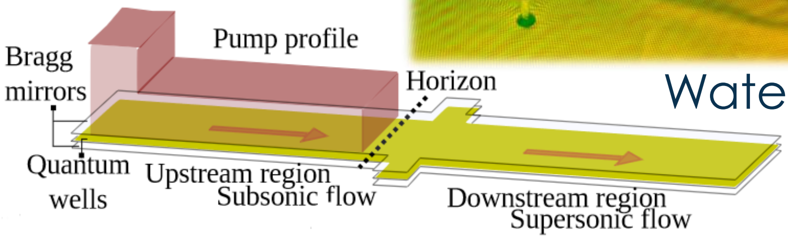




BEC



Water tank



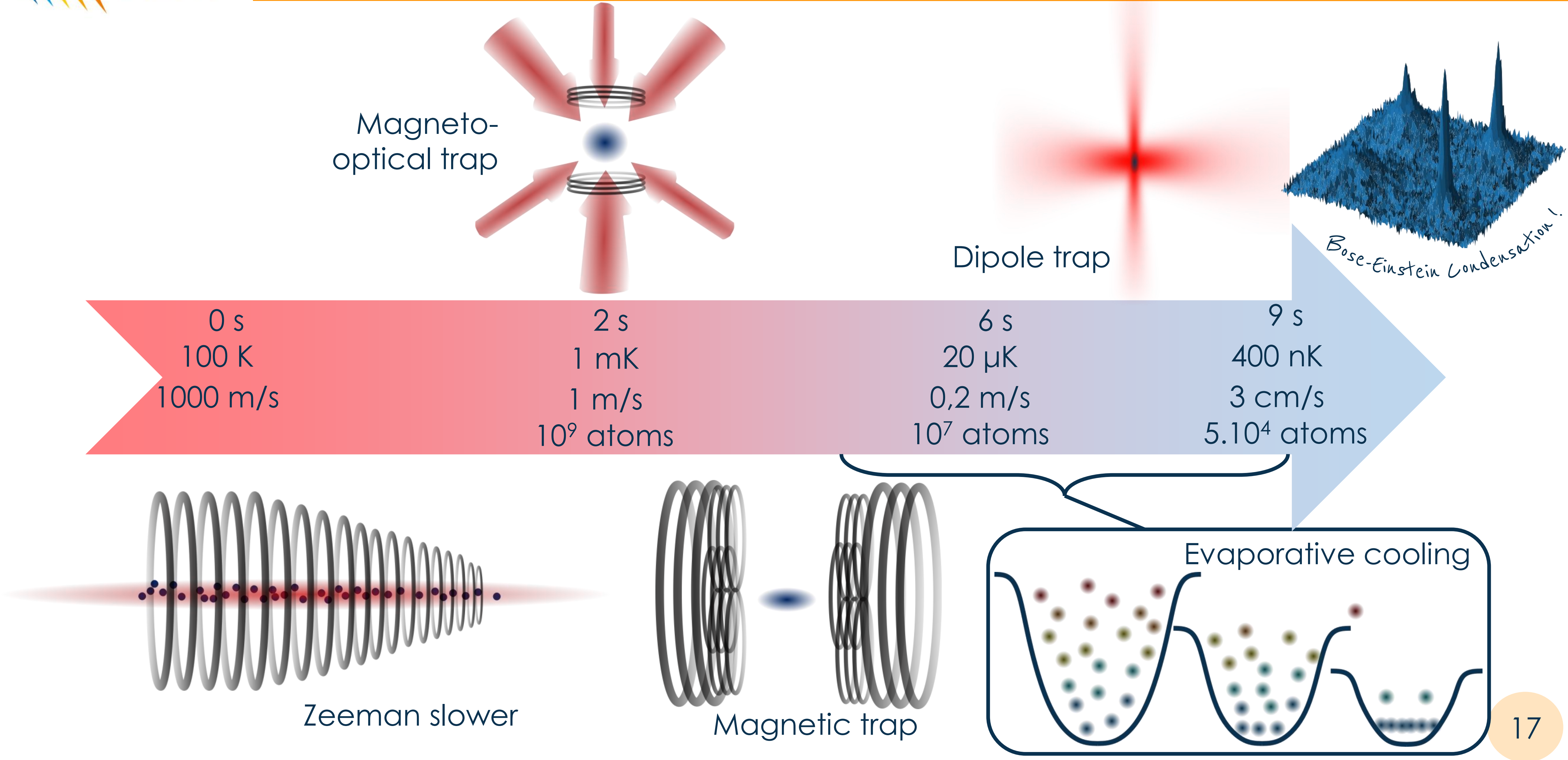
Polariton superfluid

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

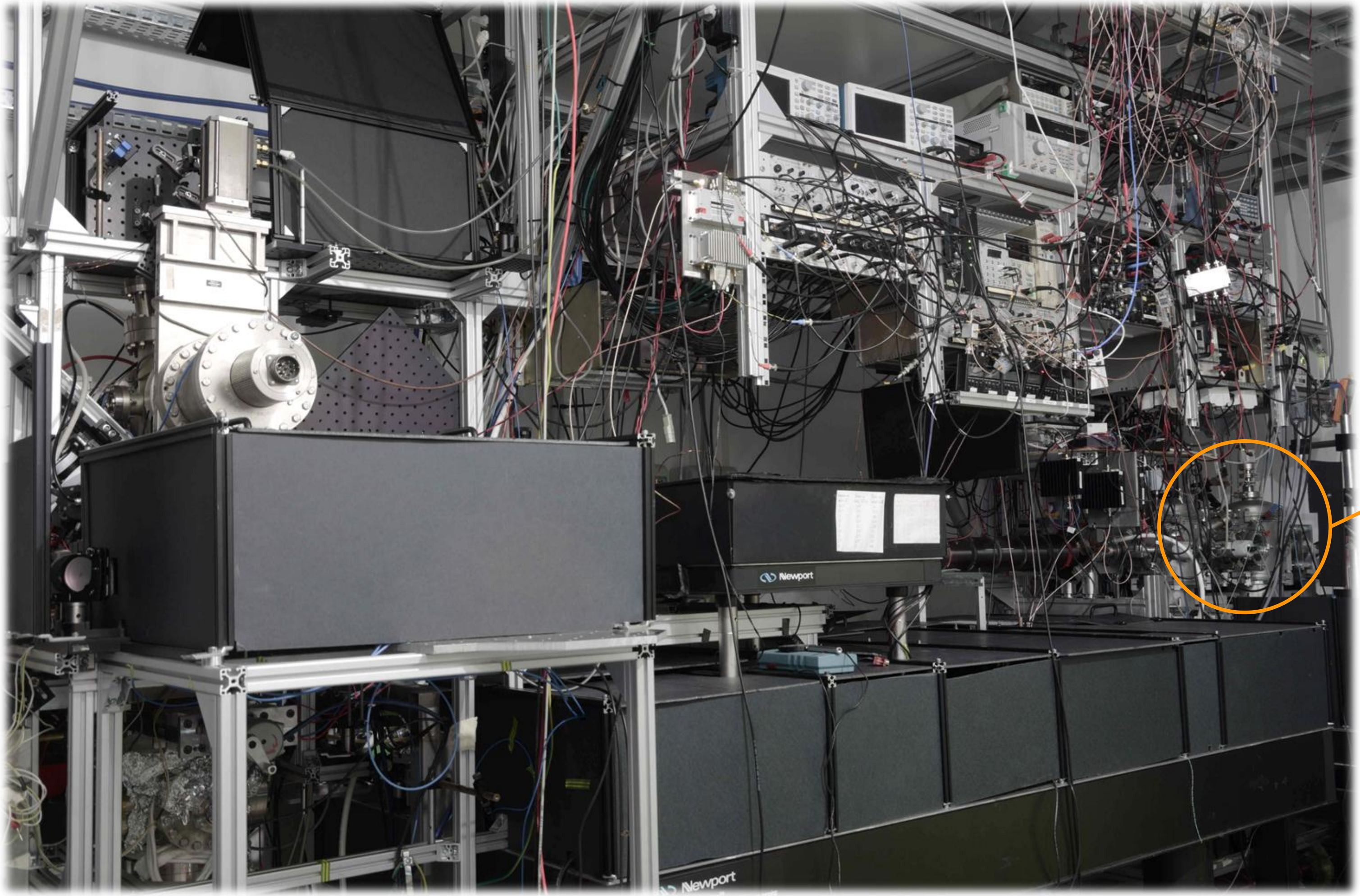
M. Jacquet *et al.*, Eur. Phys. J. D **76**, 152 (2022).

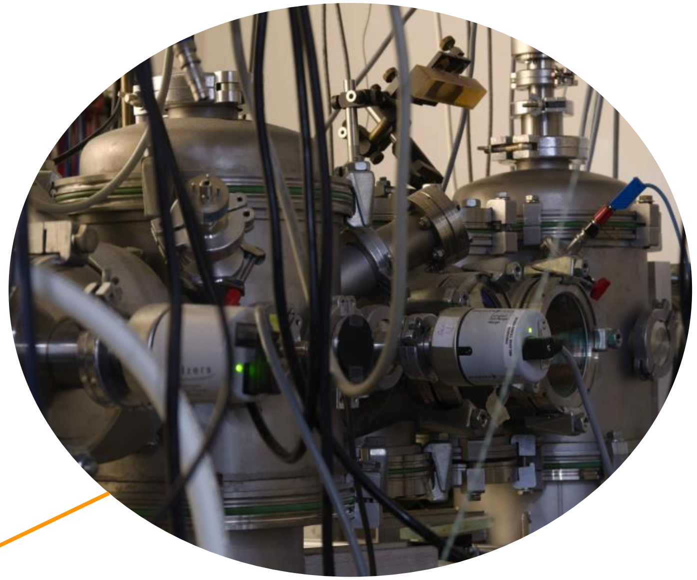
S. Weinfurtner *et al.*, Phys. Rev. Lett. **106**, 021302 (2011).

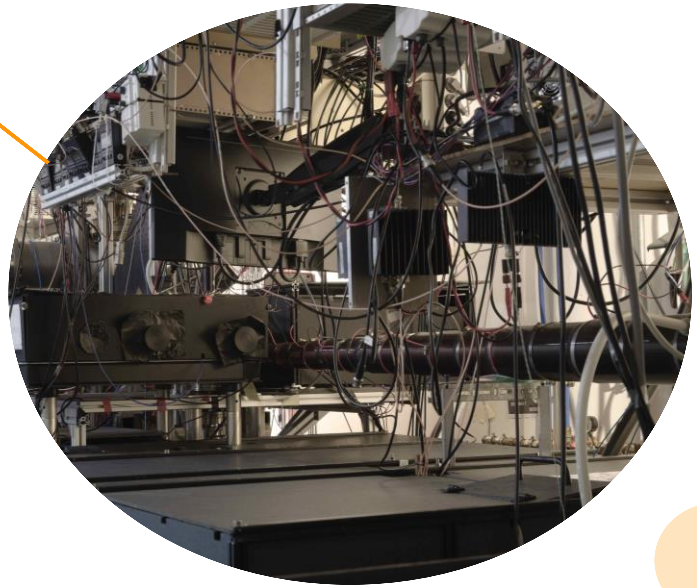
An experimental cycle



Experimental setup







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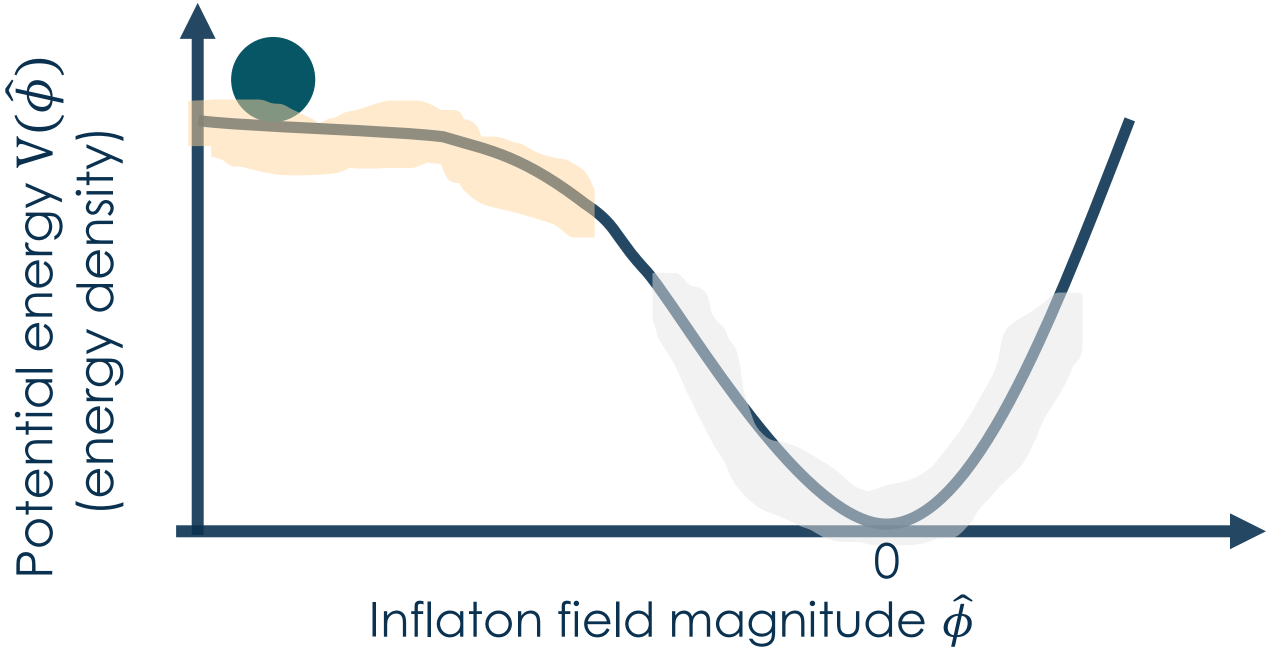

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The inflaton *slowly rolls* from its initial state. Its almost constant potential energy drives the inflation.

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

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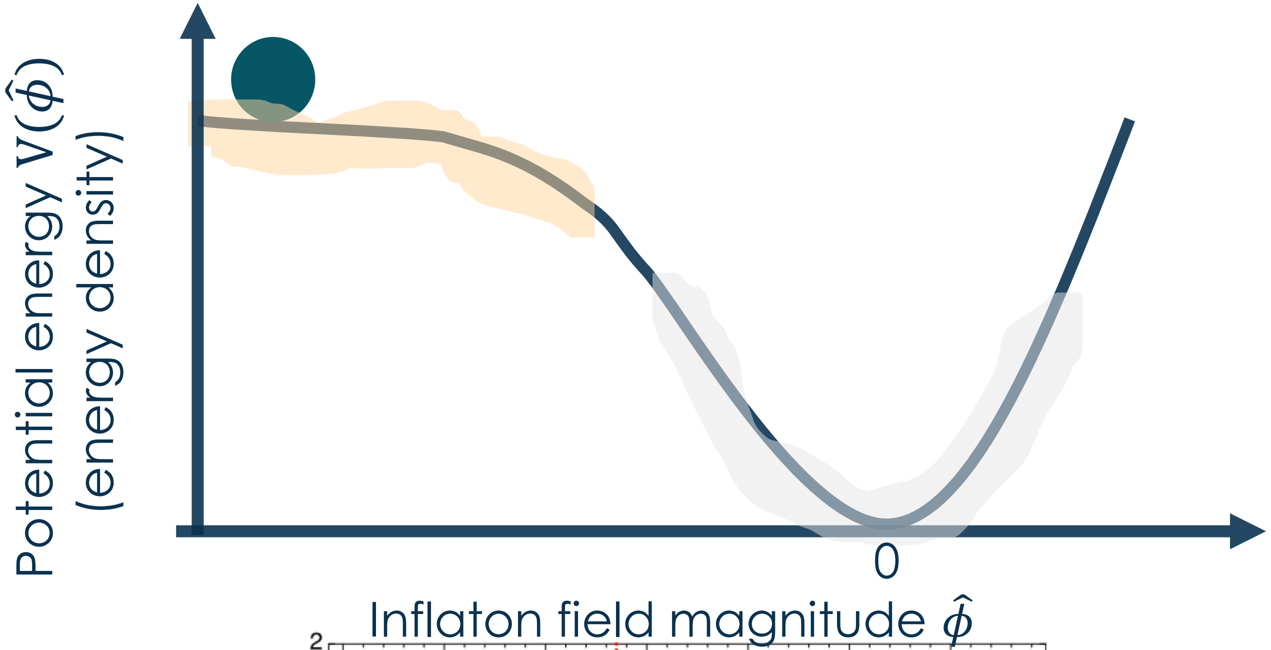

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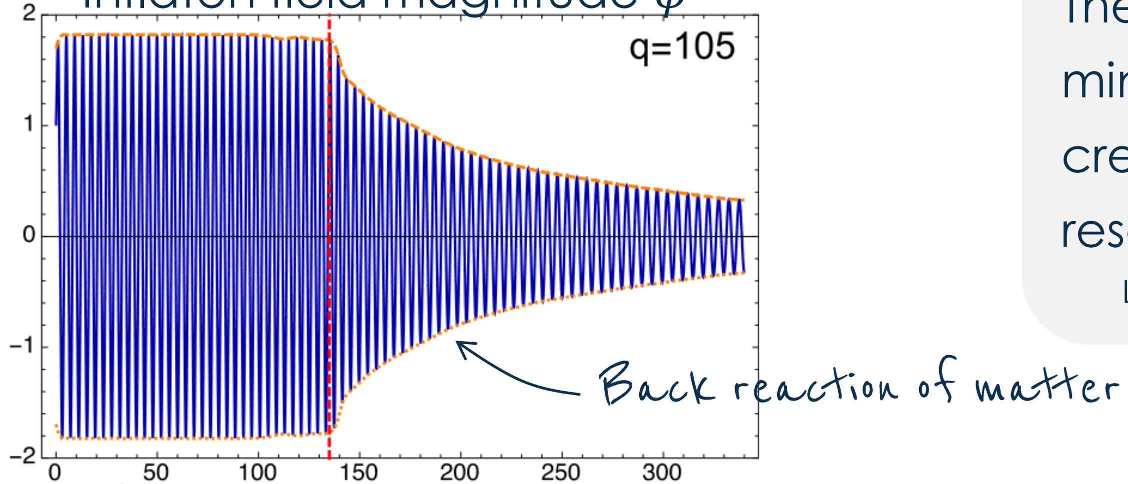
Decay of the inflaton field into particles



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

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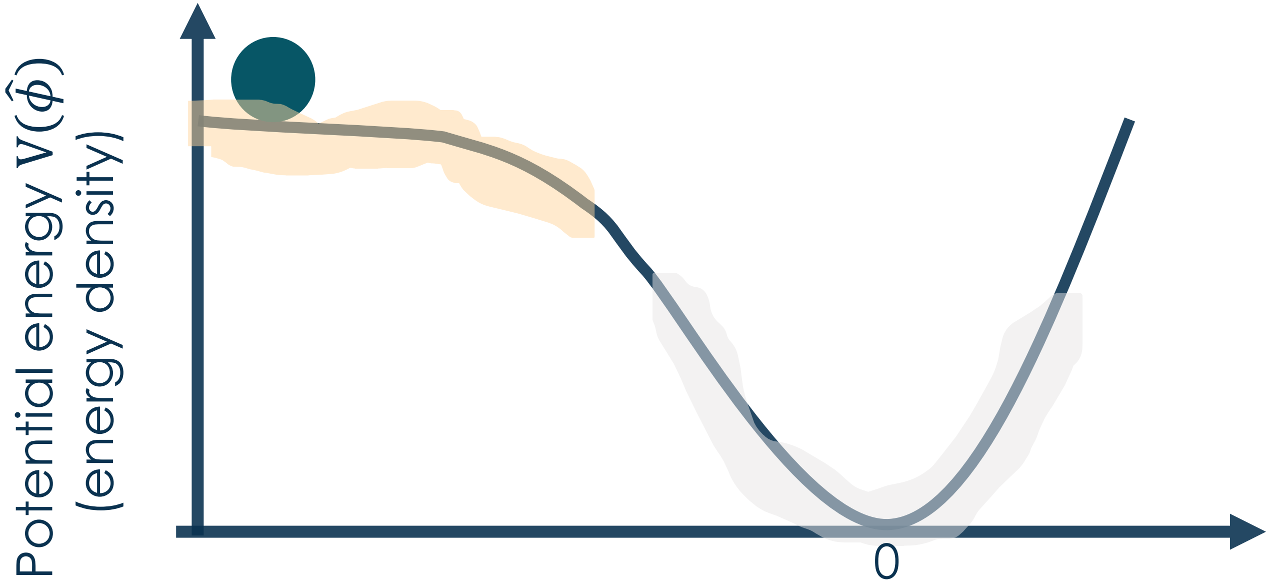

$V(\phi) = \lambda(\phi^2 - M^2)^2$ Higgs potential

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

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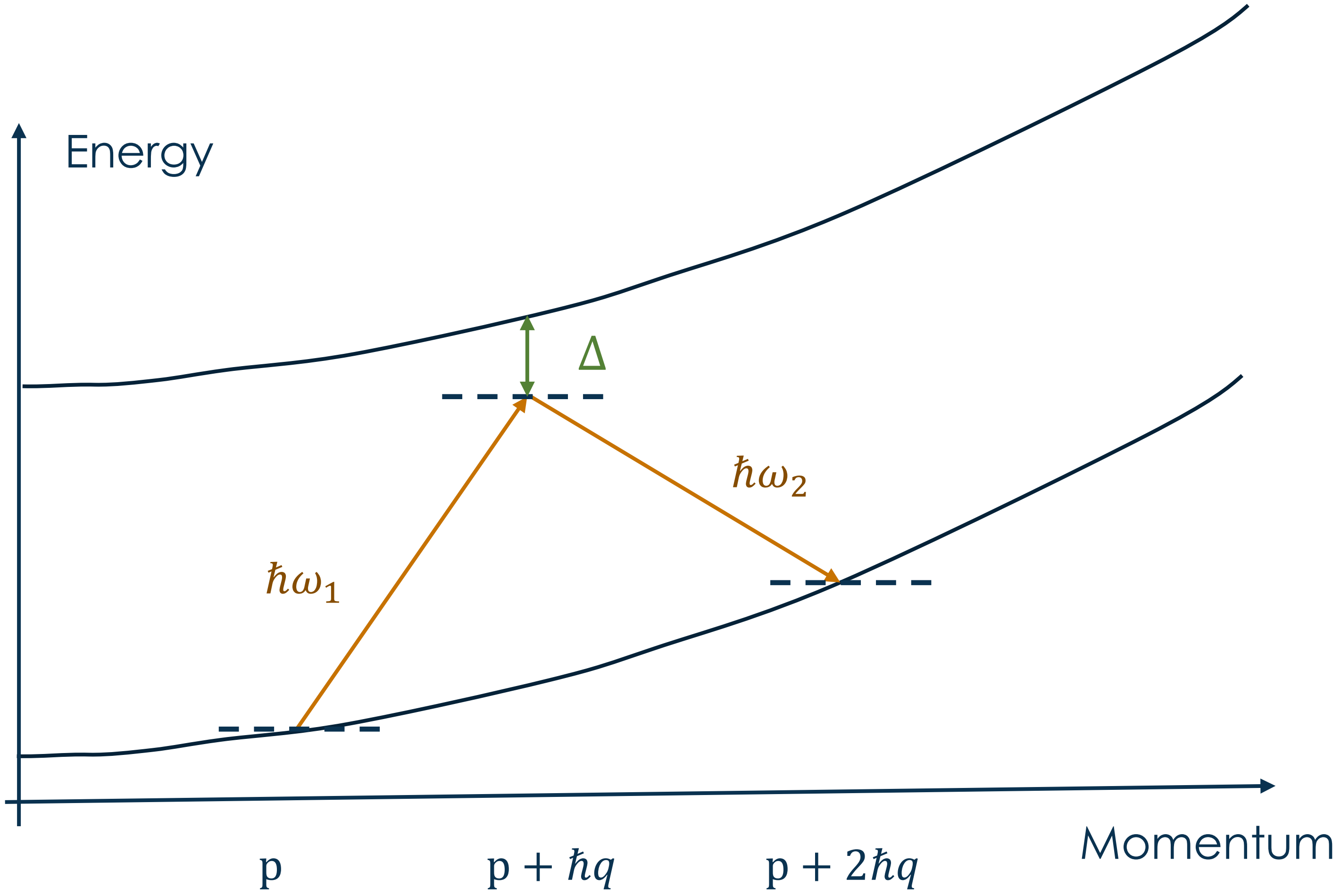
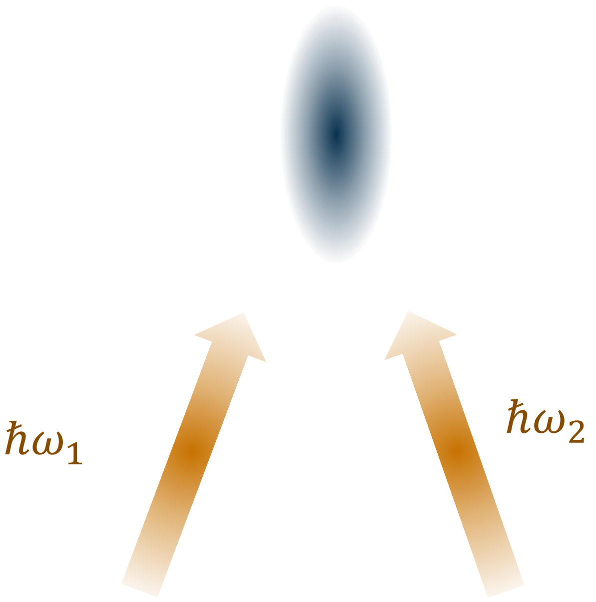
Supplement : Bragg diffraction for atomic mirrors



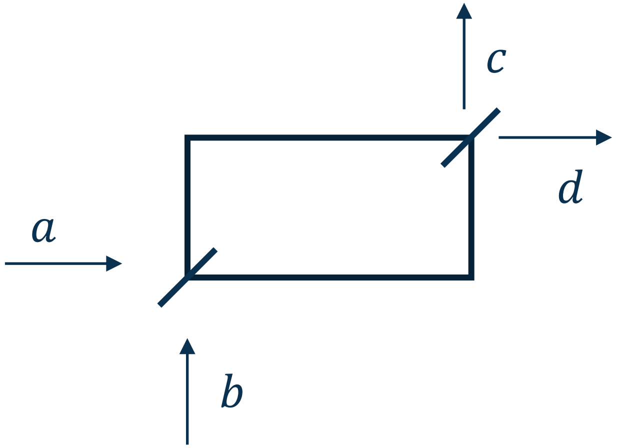


$$q = \frac{2\pi}{\lambda} \sin\theta$$

Supplement : checking the non-separability criteria

$$\langle \hat{n}_k \hat{n}_{-k} \rangle = \langle \hat{b}_k^\dagger \hat{b}_{-k}^\dagger \hat{b}_k \hat{b}_{-k} \rangle = n_k n_{-k} + \underbrace{\left|\langle \hat{b}_k \hat{b}_{-k} \rangle\right|^2}_{\le n_k n_{-k}} + \underbrace{\left|\langle \hat{b}_k^\dagger \hat{b}_{-k} \rangle\right|^2}_{0\ ????}$$

if the state is separable :



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

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

→ Check that this term is zero.

Supplement : inflation scenario

time

1,3×10¹⁰ years — Dark-matter dominated era

$a \propto e^{H_0 t}$

9,8×10⁹ years — Matter dominated era

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

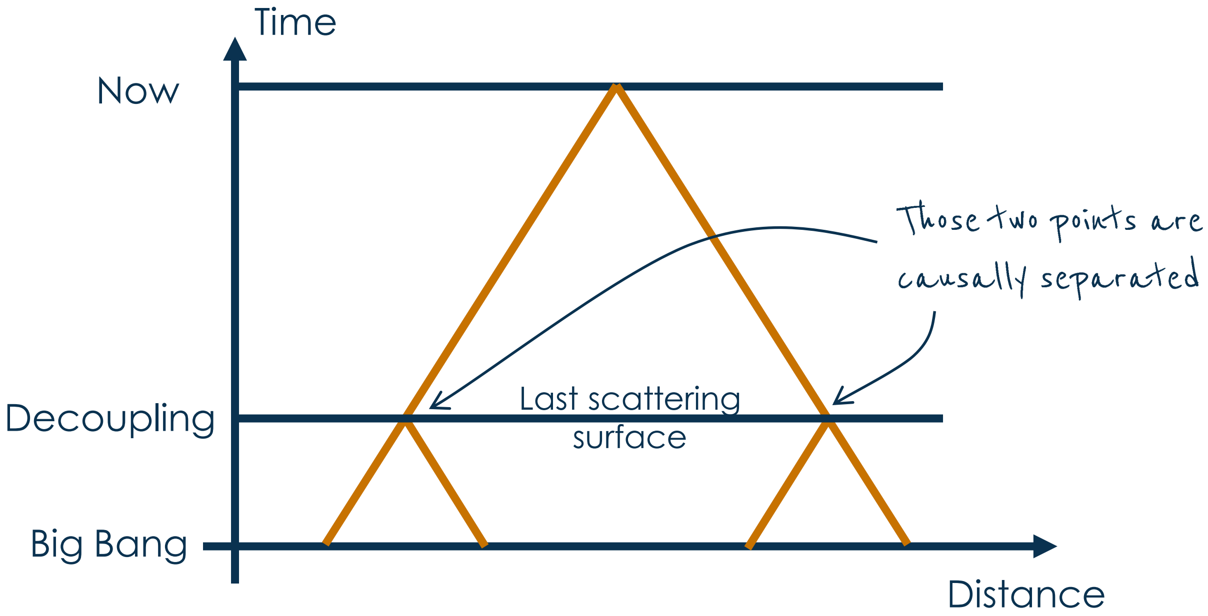
3,8×10⁵ years — Decoupling : CMB observed region

4,7×10⁴ years — Radiation dominated era

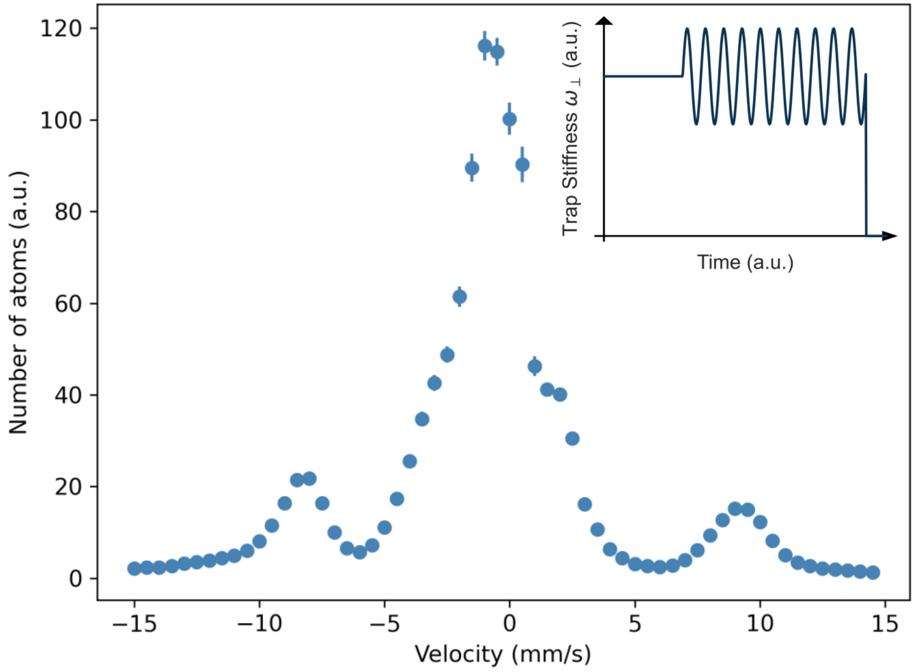
$a \propto t^{1/2}$

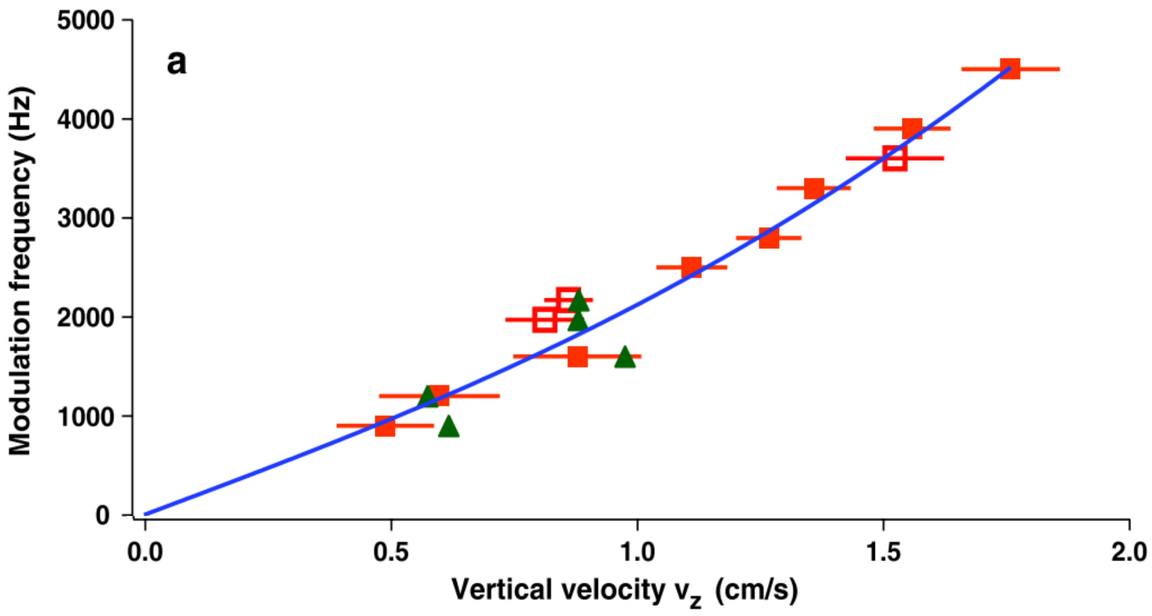
$a \propto e^{Ht}$ — Inflation

Big Bang



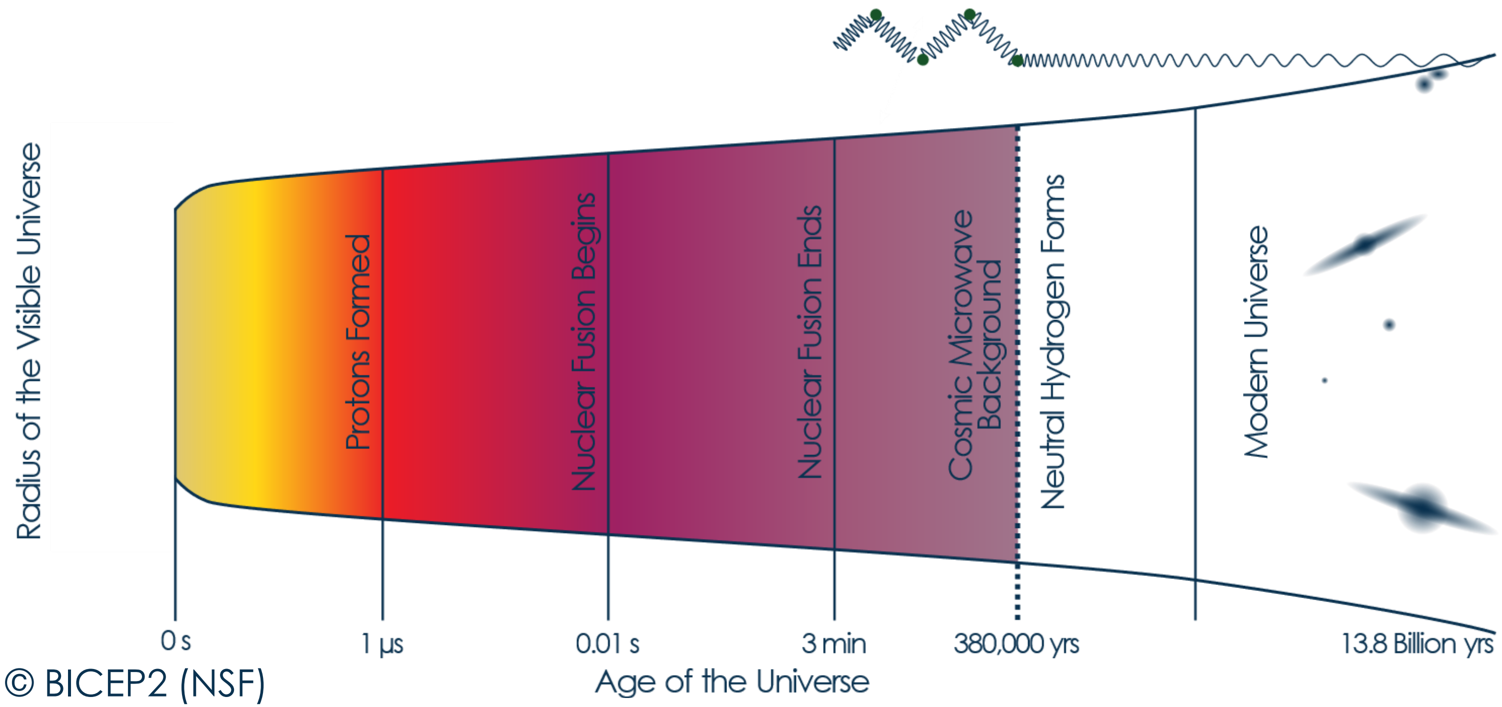
Supplement : excitation spectrum of quasi-particles





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

The Standard Model



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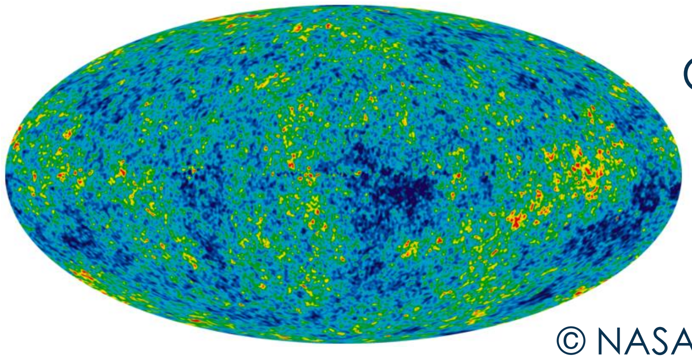


Cosmic microwave background at 2.7254 (6) K.

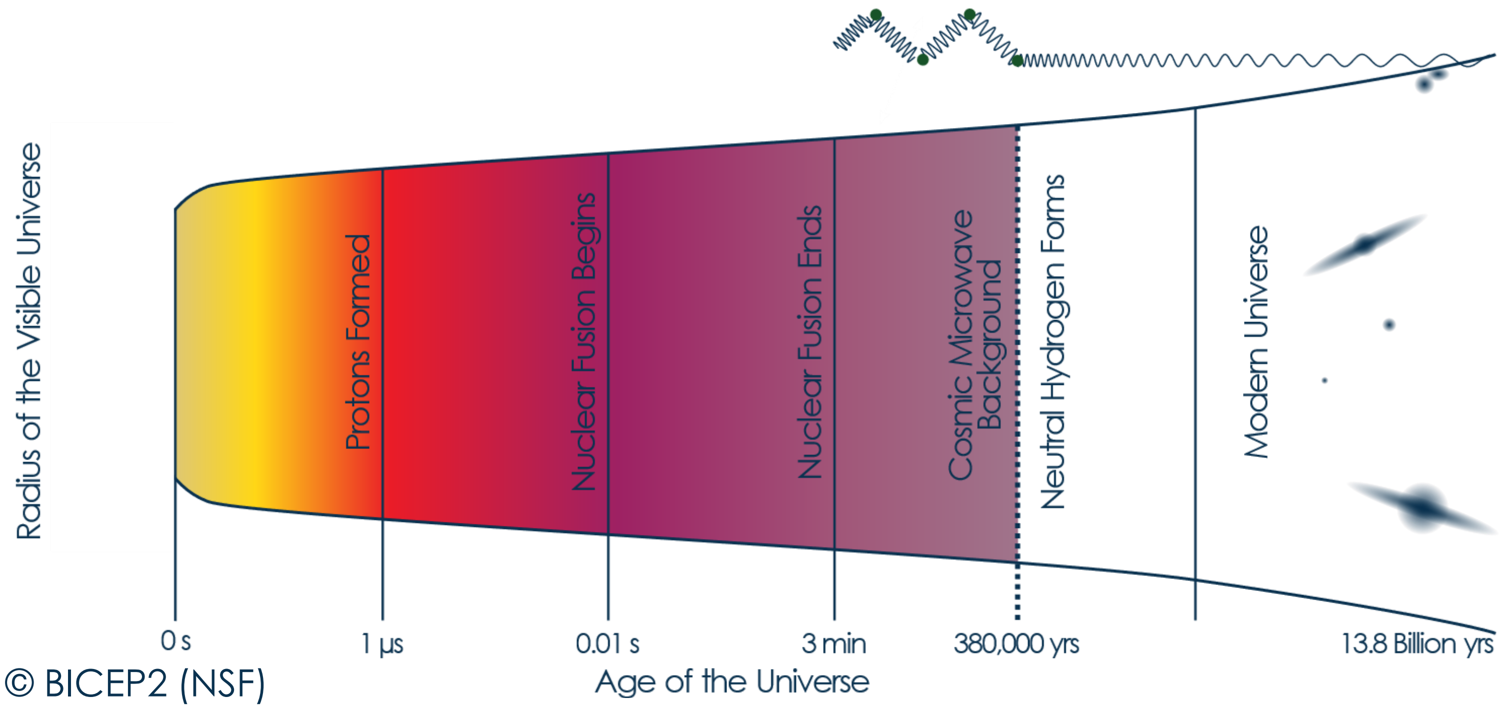
© NASA

Successes of the Standard Model of Cosmology

- 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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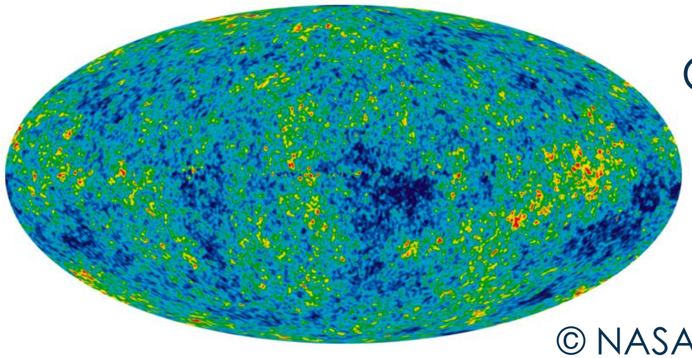
Failures of the Standard Model of Cosmology

- The horizon problem
- The flatness problem
- …



Cosmic microwave background at 2.7254 (6) K.

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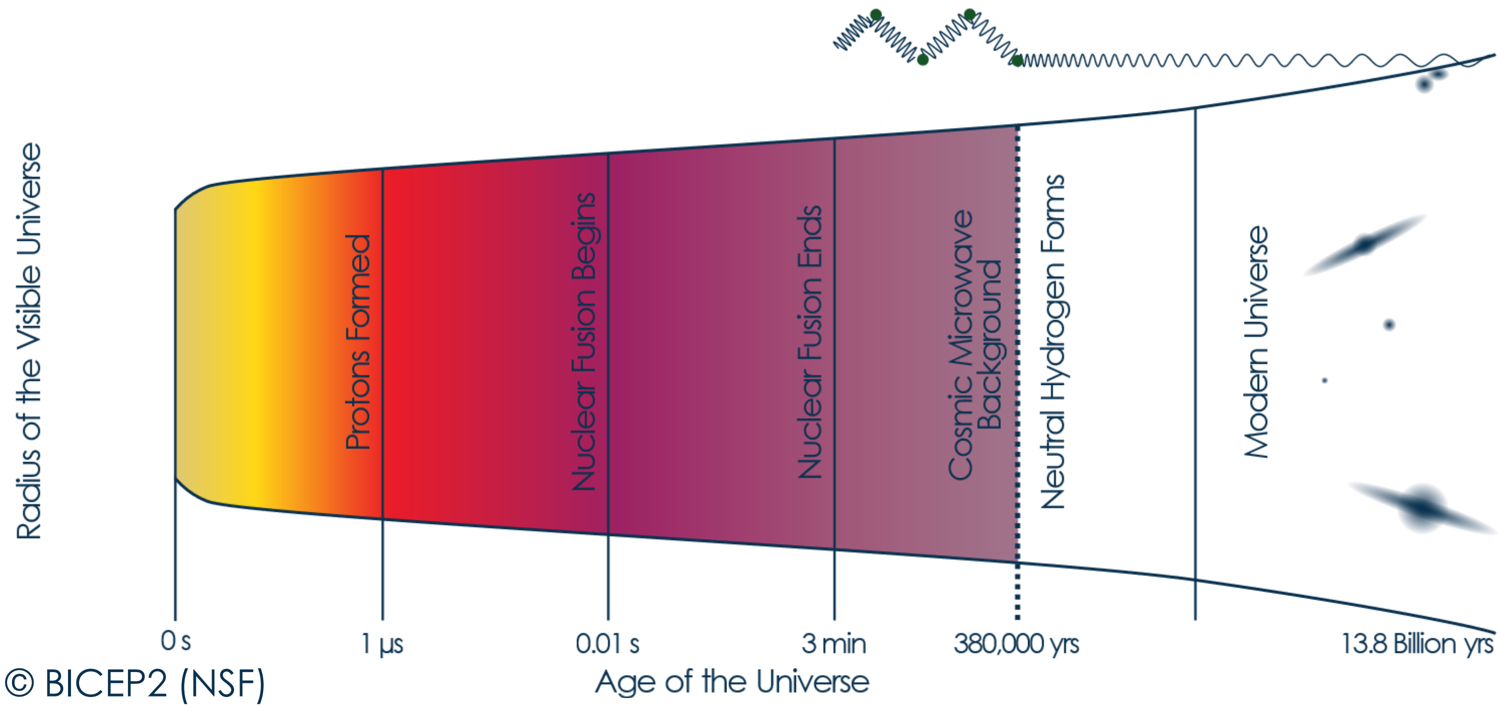
Horizon problem

Homogeneity of causally disconnected regions of space

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

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

The Standard Model



Failures of the Standard Model of Cosmology

- The horizon problem
- The flatness problem
- …

Flatness problem

Energy density

REALLY equal to one

$$\frac{\rho}{\rho_C} = 1$$

Critical energy density

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*

Detection of unique metastable helium atoms

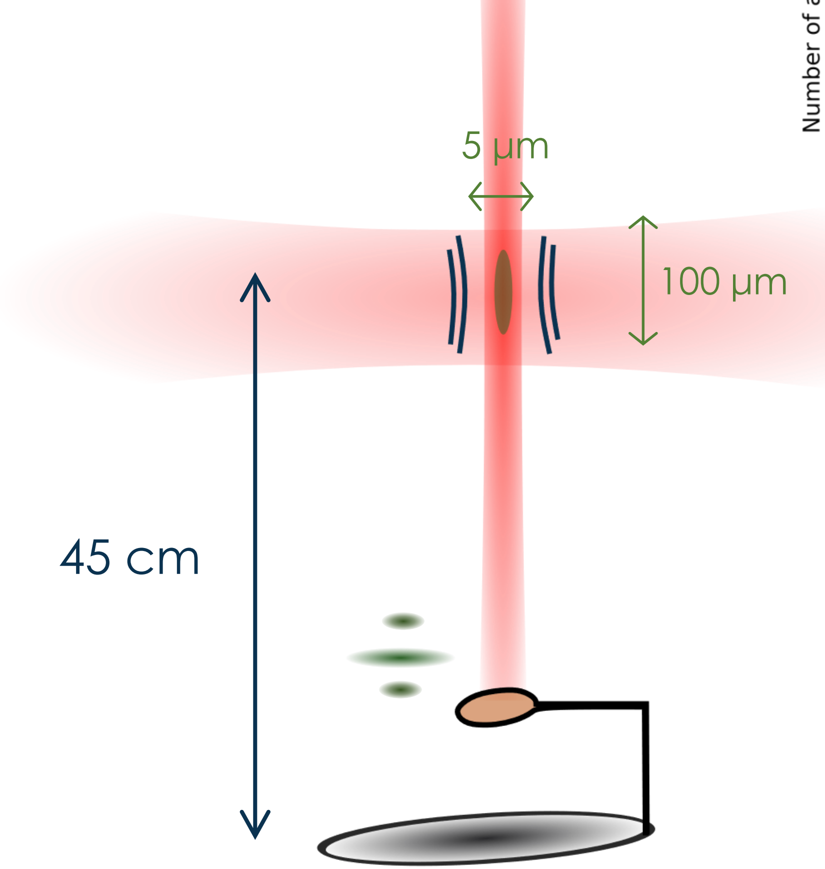
He*

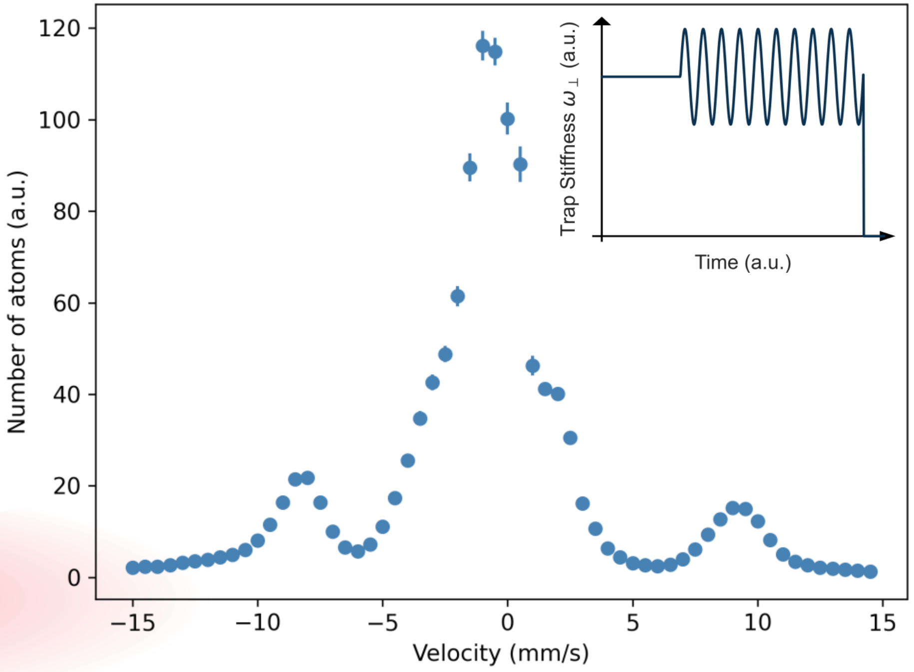
Metastable Helium 4

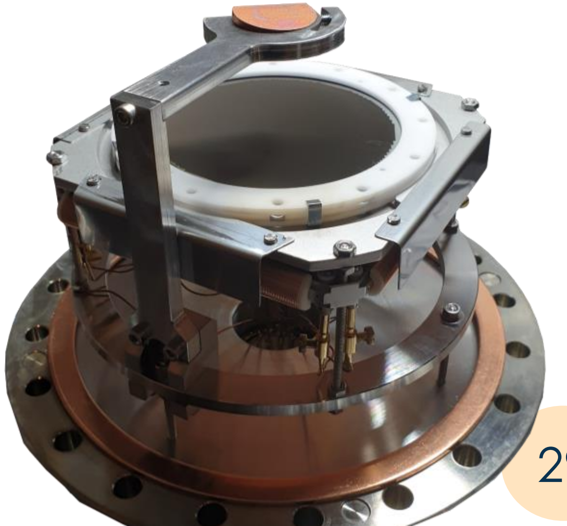
- Simple atomic structure
- No hyperfine structure
- Internal energy of 20 eV
- Recoil speed of 9 cm/s at 1083 nm

Cigar shape BEC in a crossed dipole trap

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

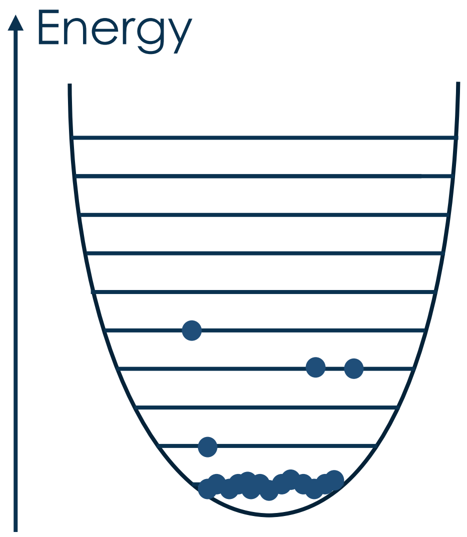






BEC for analog inflation

BEC is a macroscopic state at k=0



J.-C. Jaskula *et al.*, Phys. Rev. Lett. **109**, 220401 (2012).
X. Busch and R. Parentani, Phys. Rev. D **88**, 045023 (2013).
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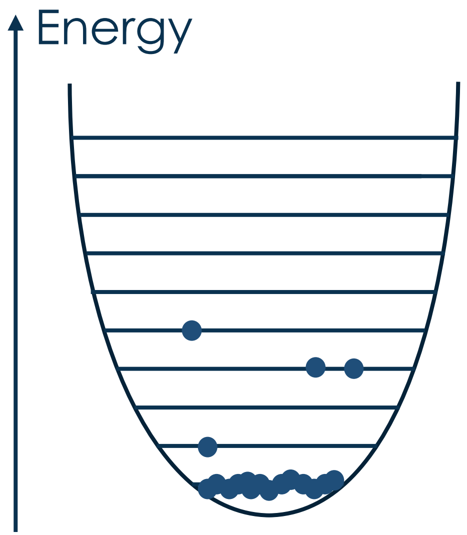

INFLATION MODEL

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

Preheating

Reheating

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BEC for analog inflation

INFLATION MODEL

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

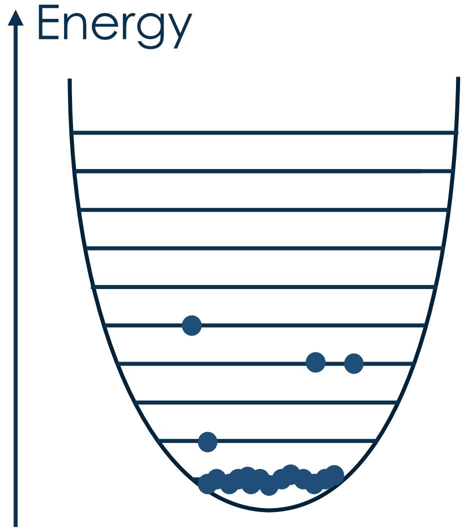
Preheating

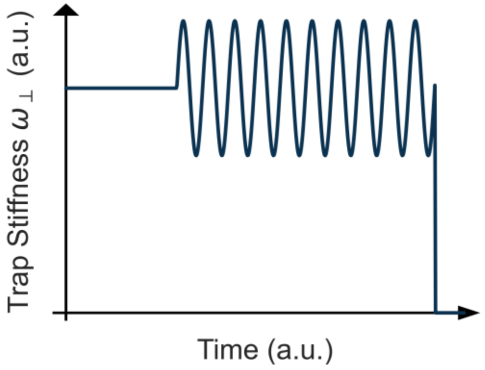
Reheating

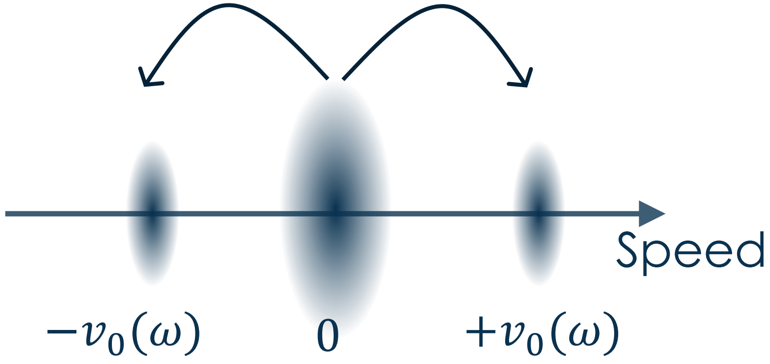
LAB SIMULATION

Oscillation of the BEC density ⇨ Creation of entangled phonons pairs with opposite momenta ⇨ Interaction between phonons, decoherence, thermalization

BEC is a macroscopic state at k=0







ω : excitation frequency

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