Elongated BEC’s : experimental results and open questions

3rd Windsor Summer School on Condensed Matter Theory

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Phase fluctuations in a quasi 1D BEC

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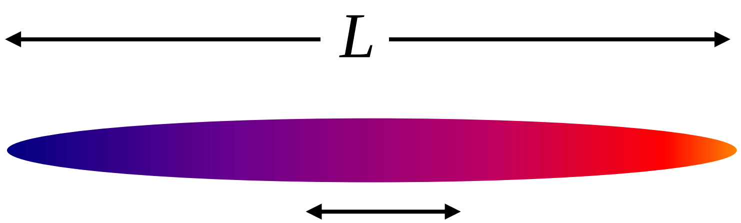
Theoretical prediction for an elongated condensate

D. Petrov, J. Walraven, G. Shlyapnikov, PRL **85**, 3545 (2000), **87**, 050404 (2001)

For

- density fluctuations suppressed
- axial phase fluctuations ⇒ $lc < L$



l_C : coherence length

$$T_\phi \approx \frac{\hbar^2 N_0}{M k_B L^2} \quad < T_c \text{ if } L \text{ large}$$

$$l_C = L\frac{T_\phi}{T} \quad < L$$

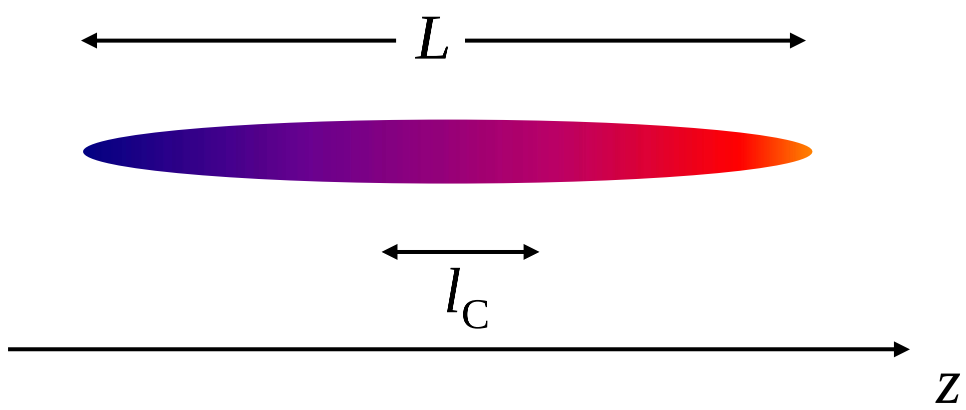
Reminiscence of no 1D homogeneous BEC

First experimental evidence (Hannover, 2001)

Density fluctuations after free expansion (phase fluctuations convert into density fluctuations in the far field diffraction pattern): not fully quantitative

Effect of phase fluctuations also observed in Amsterdam (« focusing », 2002)

Momentum distribution: a global way to measure the coherence length



Momentum distribution $P(p_z)$

= Fourier transform of the correlation function $C^{(1)}(\delta z)$

$$C^{(1)}(\delta z) = \int dz \left\langle \psi^*(z)\psi(z+\delta z)\right\rangle$$

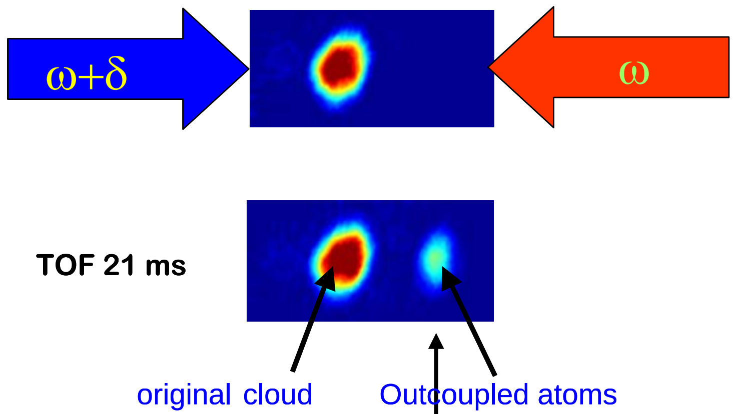
- Fully quantitative method (cf MIT: transverse coherence length = BEC size)
- Analogous to traditional (dispersion) spectroscopy – *i.e.* meas. of spectral distribution $I(\omega)$ – compared to Fourier transform spectroscopy – *i.e.* meas. of field correlation function $\Gamma(\tau)$.

If $l_C < L \ , \ \Delta p_z > \dfrac{\hbar}{L}$

Good for « broad spectrum », i. e. when $l_c << L \ \leftrightarrow \ T >> T_\phi$

Bragg spectroscopy of the momentum distribution: principle

cf MIT, NIST, Weizmann



Energy and momentum conservation (atom-photons interaction): resonant outcoupling of atoms of momentum p_z determined by the detuning δ

$$\delta = 2\frac{\hbar k_L^{\ 2}}{M} + 2k_L\frac{p_z}{M}$$

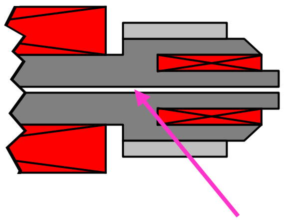
Number of extracted atoms reflects $\mathrm{P}(p_z)$

By scanning δ one can measure the momentum distribution $\mathrm{P}(p_z)$

Wave interpretation: resonant Bragg scattering of atomic matterwaves with a de Broglie wavelength matching the period of the thick grating sliding at velocity $\delta / 2k_{\mathrm{L}}$

Elongated ^{87}Rb BEC in an iron core electromagnet

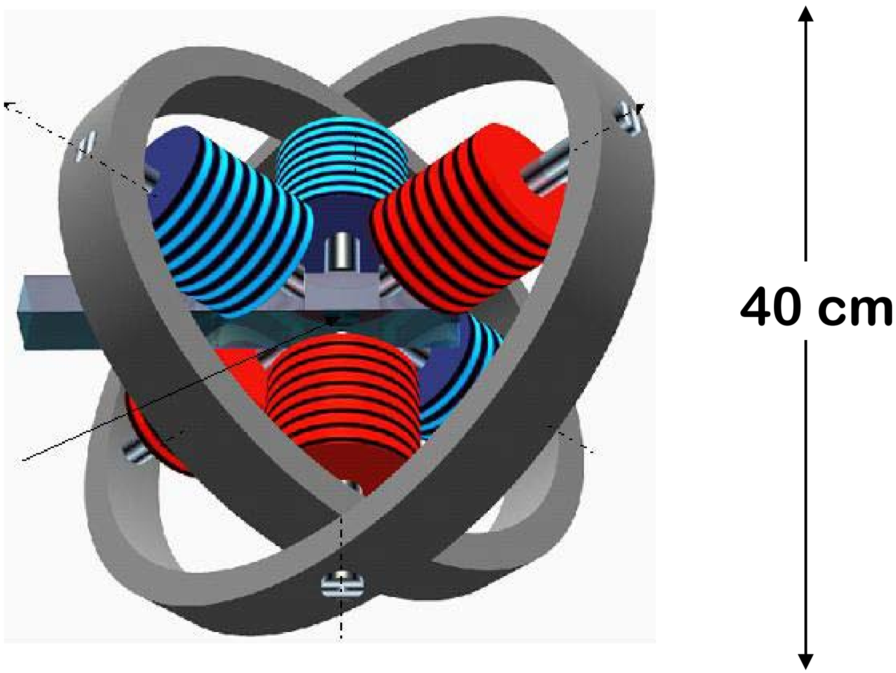
Strong quad. gradient (1.4 kG /cm) with moderate electric power



Compensated dipole: decoupling curvature from bias field

Excellent alignment of laser holes with long axis

Shielding of the ambient magnetic field by iron yoke



•B. Desruelle *et al.*, EPJD **1**, 255 (1998)
•B. Desruelle *et al.*, PRA **60**, R1759 (1999)

Large anisotropy ratio: 760 Hz / 5 Hz

Bragg spectroscopy along the axis of an elongated BEC: a challenge

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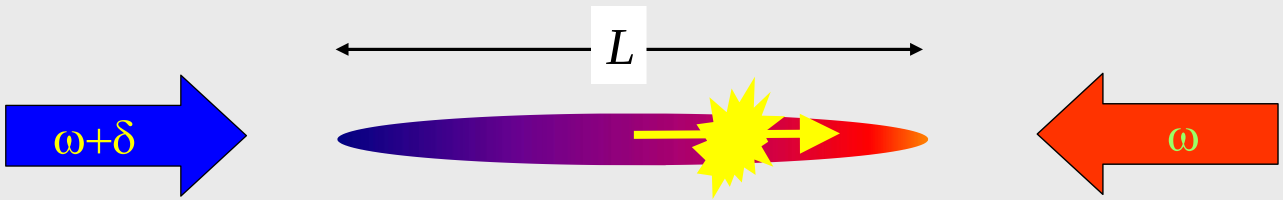
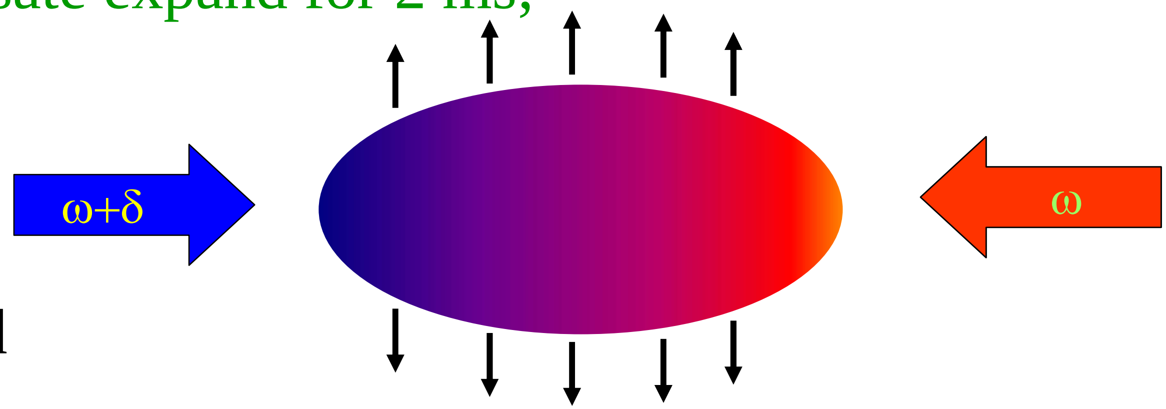
A major problem: collisions between the extracted atoms and the remaining condensate. Mean free path << L



Solution: let the (quasi) condensate expand for 2 ms;

- density drops by 10^{-2};
- expansion mostly radial;
- axial p_z distribution unaffected



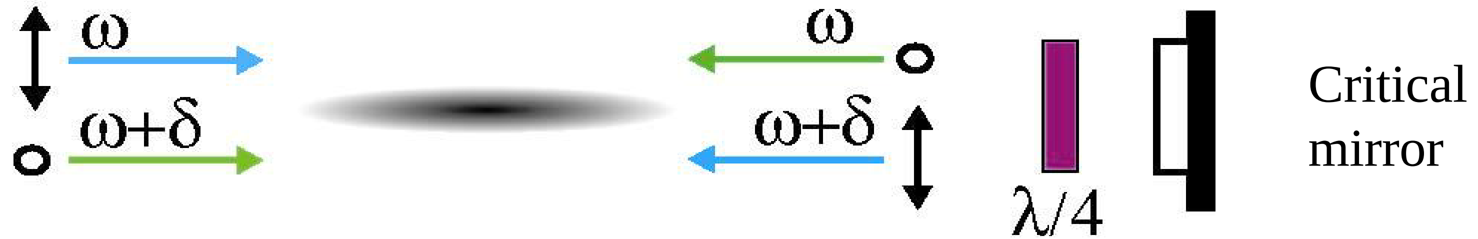
… then apply Bragg lasers

Laser beam must be perfectly orthogonal to expansion!

Bragg spectroscopy along the axis of an elongated BEC

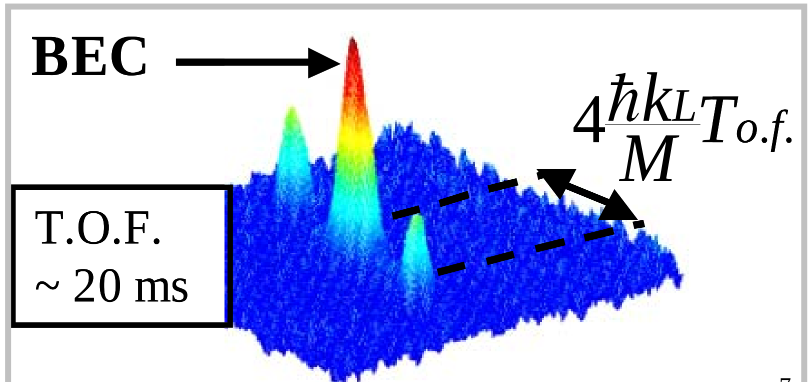
Frequency jitter between counterpropagating lasers as small as possible:

$$\frac{\Delta\delta}{2\pi} = 100\,\mathrm{Hz} \;\leftrightarrow\; \frac{\Delta p_z}{M} = 4\times10^{-6}\ \mathrm{m/s} \;\leftrightarrow\; l_c^{\max} = \frac{\hbar}{\Delta p_z} = 20\times10^{-6}\ \mathrm{m}$$



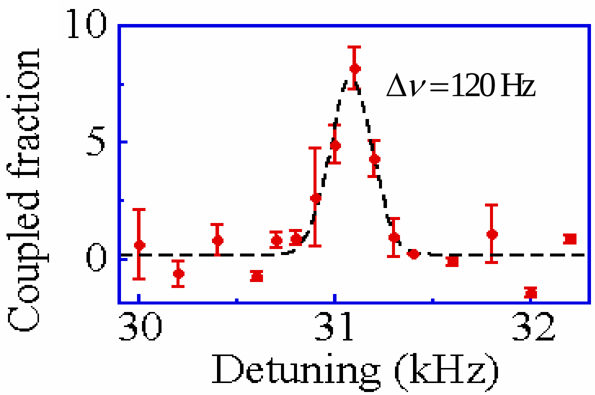
Overlapping laser beams with orthogonal polarisations, retroreflected

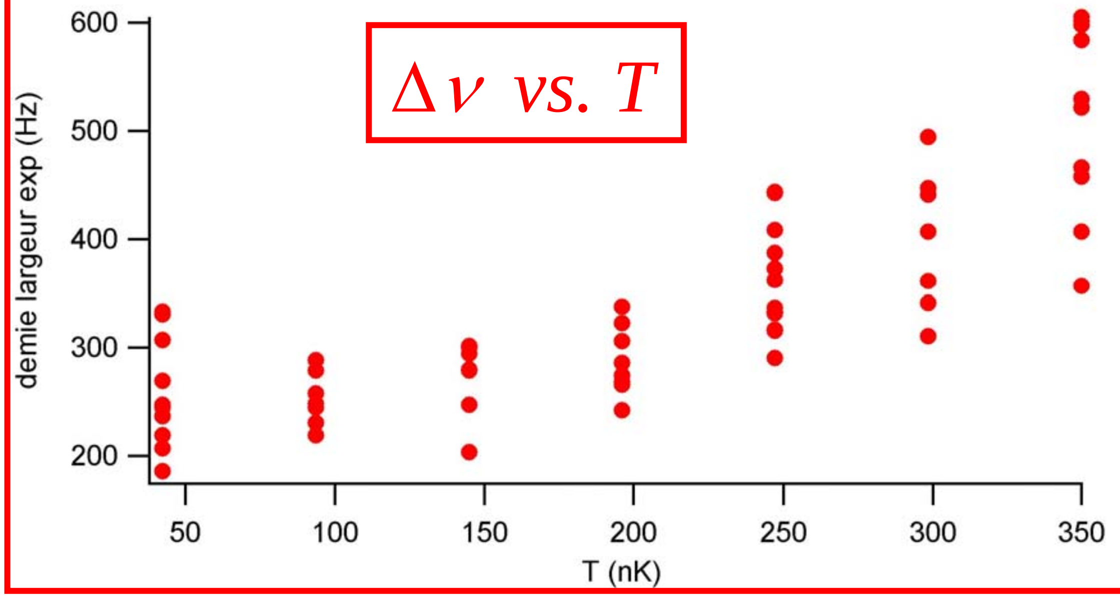
- Two counterpropagating lattices with orthogonal polarizations
- Extract $+\,p_z$ and $-\,p_z$ simultaneously
- 4 photons transition to increase separation



Bragg spectroscopy of the momentum distribution: results

Example of result





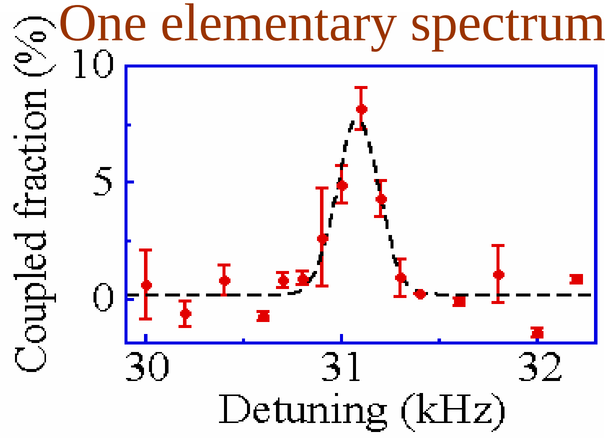
$\Delta\nu$ clearly increases with T, i.e. l_c decreases, as predicted by theory

But large dispersion of individual measurements. Quantitative comparison to theory?

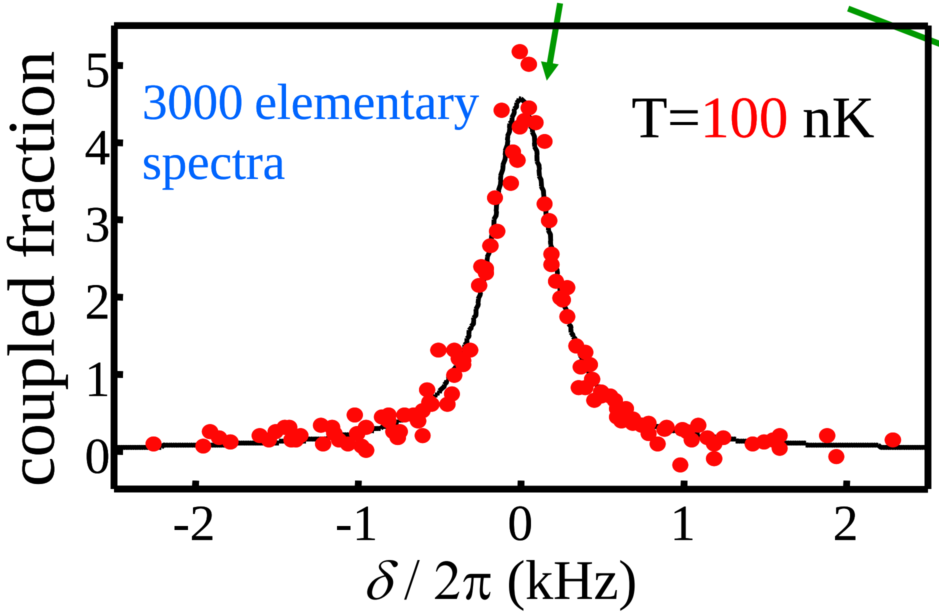
Averaging the momentum profiles

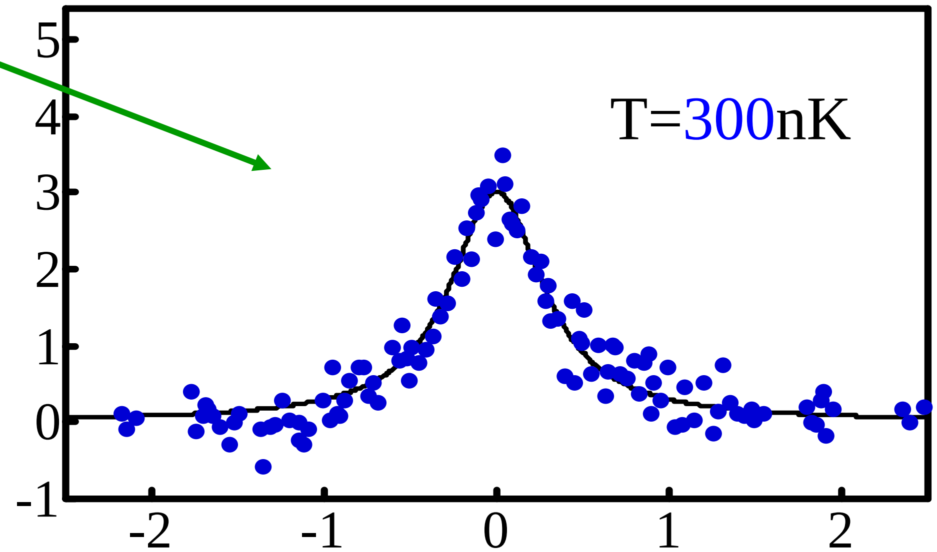
For a given condensate temperature (controlled within 20 nK), average many spectra, taken at different hold times after BEC (averaging over possible residual breathing oscillations)

One elementary spectrum



3000 elementary data



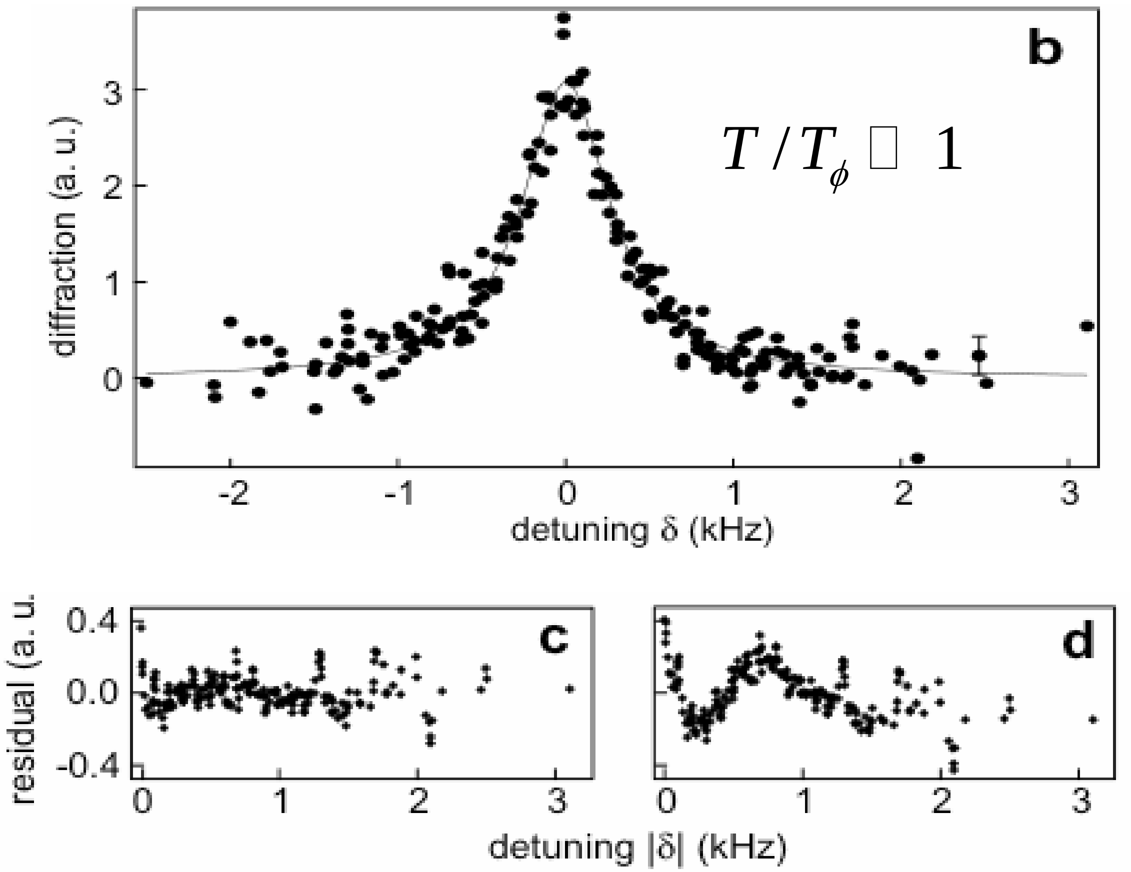


Quantitative comparison to theory becomes possible: shape, width

Shape of momentum distribution

$$\left(T / T_{\phi} \gg 1\right)$$

After averaging:
unambiguous discrimination between Gaussian and Lorentzian



Lorentzian residual Gaussian residual

For $T / T_{\phi} \gg 1$,
Lorentzian momentum profile:
exponential decrease of correlation function ($l_C << L$):
phase fluctuations dominate effect of density profile

Width of the momentum profile: theoretical predictions

Coherence length at the center of quasi condensate

1D density at center

$$2L_\phi = \frac{2\hbar^2 n_1(0)}{2Mk_B T} \Rightarrow \Delta p_\phi = \frac{\hbar}{2L_\phi}$$

$$\Rightarrow \quad \Delta p_\phi = \frac{\hbar}{L_\phi} \propto \frac{T}{n_1(0)}$$: convenient parameter

Momentum distribution width of a trapped quasicondensate

Averaging over the density profile $\Delta p = \alpha \, \Delta p_\phi$

$\alpha = 0.67$ for a Thomas Fermi profile

Width of the momentum profile: experimental strategy

Theoretical prediction (in experimentalist units)

$$\Delta\nu = \alpha\,\Delta\nu_\phi \quad \text{with} \quad \Delta\nu_\phi \propto \frac{n_1(0)}{T}$$

Experimental strategy

$\Rightarrow$ measure $\Delta\nu, n_1(0),$ and T and plot $\Delta\nu$ vs. $\Delta\nu_\phi$

$\Rightarrow$ deduce α and compare to theoretical value of 0.67

Deconvolution from the resolution function

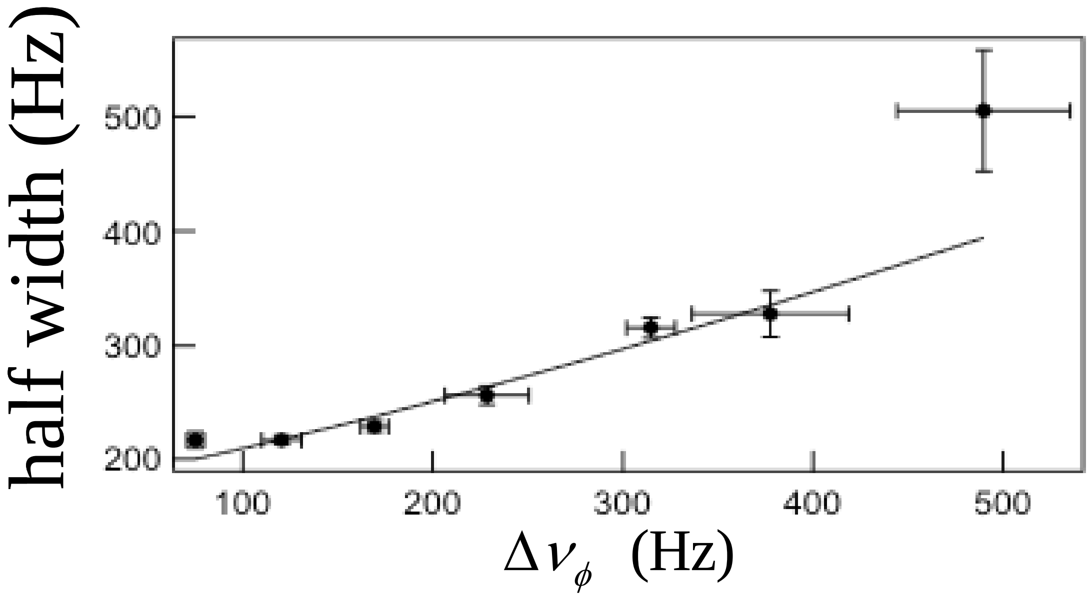
When the momentum width associated with phase fluctuations is not large compared to the experimental resolution function: fit by a Voigt profile (convolution of a Lorentzian by a Gaussian).

$$\Delta\nu_{\mathrm{exp}} = \frac{\alpha\Delta\nu_\phi}{2} + \sqrt{\left(\frac{\alpha\Delta\nu_\phi}{2}\right)^2 + (\Delta\nu_{\mathrm{res}})^2}$$

phase fluctuations → $\frac{\alpha\Delta\nu_\phi}{2}$; resolution → $\Delta\nu_{\mathrm{res}}$

Data ($\Delta\nu_{exp}$ and $\Delta\nu_\phi$) fitted with α and $\Delta\nu_{res}$ as free parameters

Momentum width: results



Fit to

$$\Delta\nu_{\rm exp} = \frac{\alpha\Delta\nu_\phi}{2} + \sqrt{\left(\frac{\alpha\Delta\nu_\phi}{2}\right)^2 + (\Delta\nu_{\rm res})^2}$$

α and $\Delta\nu_\phi$ free parameters

Result of fit

$\Delta\nu_{res} = 176(16)$ Hz

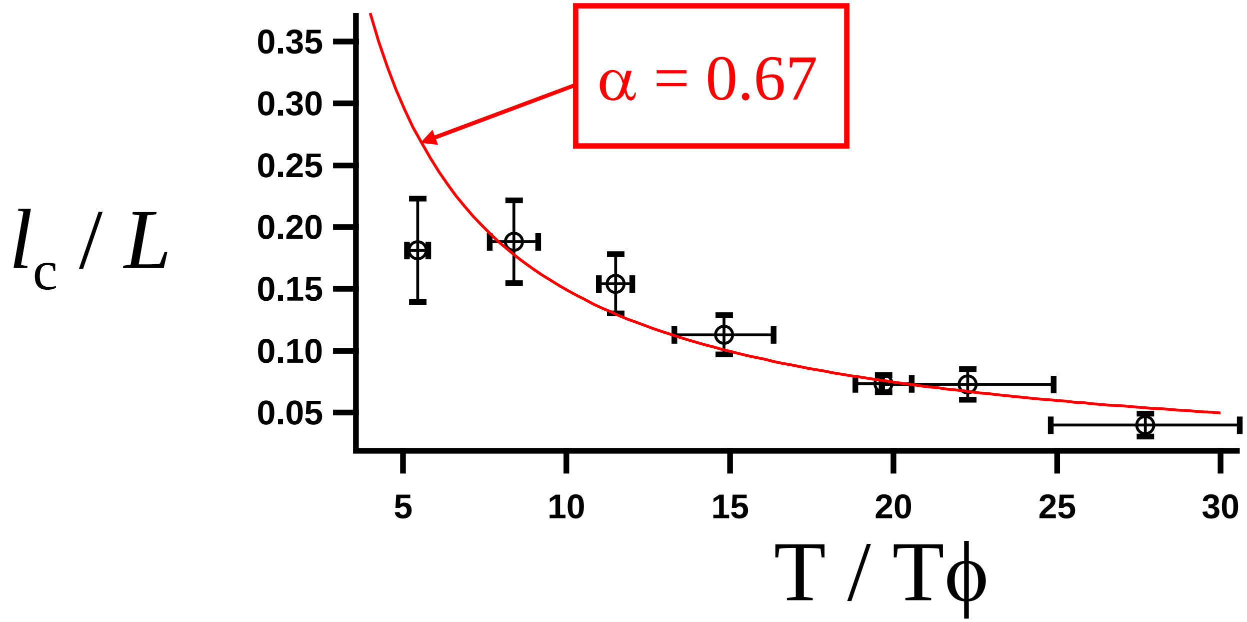
$\alpha = 0.64(5)(5)$

convincing deconvolution

Good agreement with theory : $a = 0.67$

Coherence length *vs.* temperature

$$l_C = \frac{\hbar}{\Delta p_z}$$



- Coherence length l_C definitely smaller than condensate size L for $T >> T_\phi$
- Good agreement with theory $\frac{l_C}{L} = \frac{T_\phi}{T}$
- Also checked: suppression of density fluctuations: $\langle n^2 \rangle = \langle n \rangle^2$ (5% accuracy)

How to investigate the situation $T / T_\phi \approx 1$? (Case of large coherence length)

How to measure the axial coherence length when $T \approx T_\phi \Rightarrow l_c \approx L$?

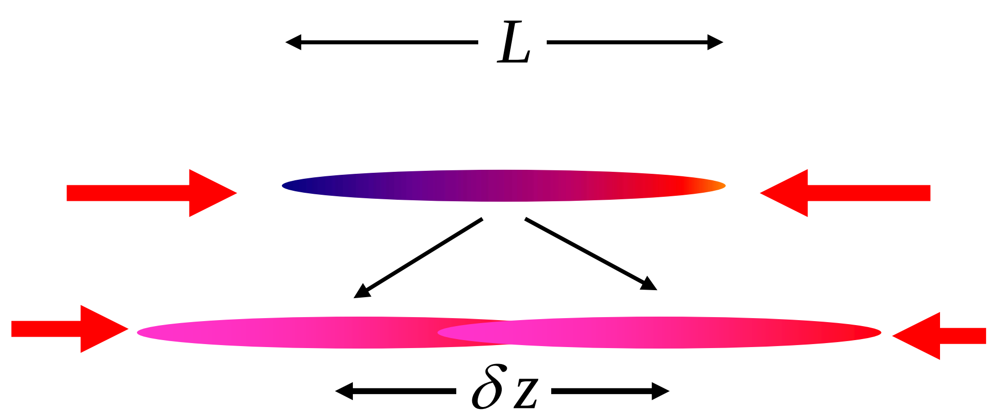
p_z resolution not good enough ($\Delta \nu_\phi$ too small)

Go to Fourier space (conjugate variable *z*): atom interferometry

Interference visibility *vs* separation δz :

direct measurement of the correlation function

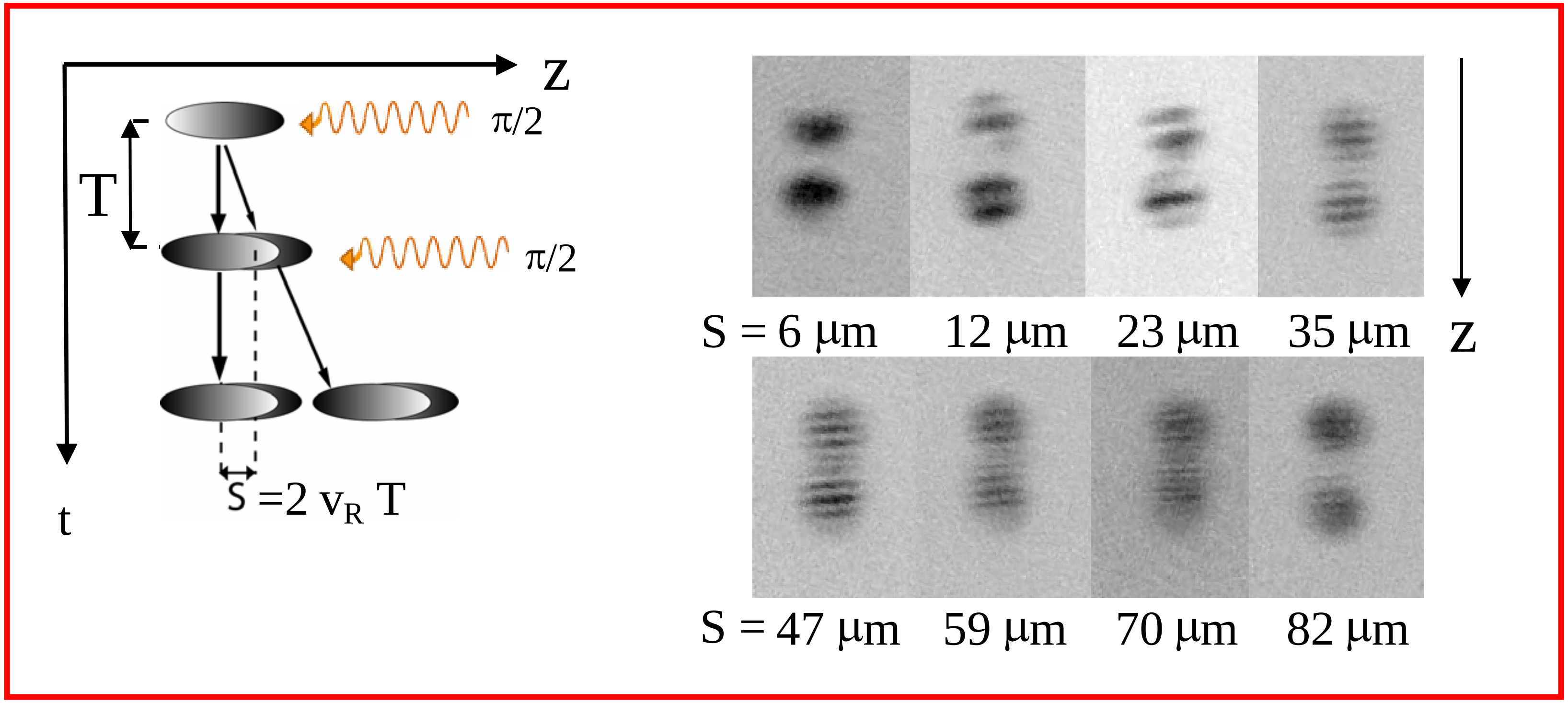
$$C^{(1)}(\delta z) = \int dz\, \psi^*(z - \frac{\delta z}{2})\psi(z + \frac{\delta z}{2})$$



cf coherence measurement of a 3D condensate (MIT, NIST, Munich): $l_c = L$

Method used in Hannover (2003) to explore the regime $l_c / L \ll 1$

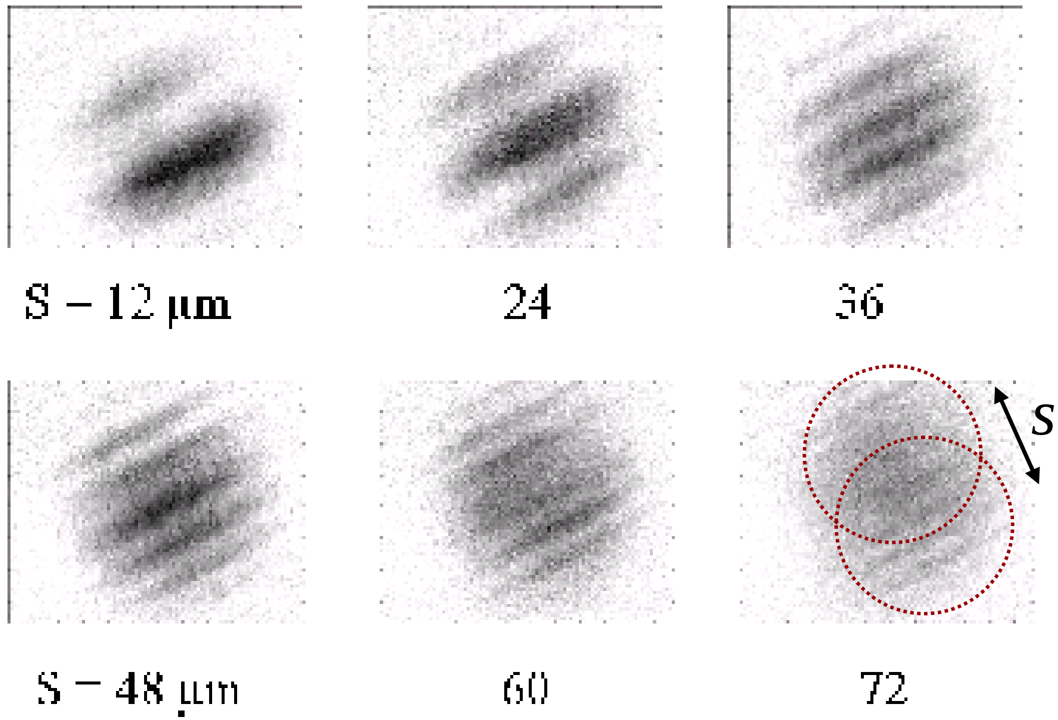
Interferometric measurement of the coherence length

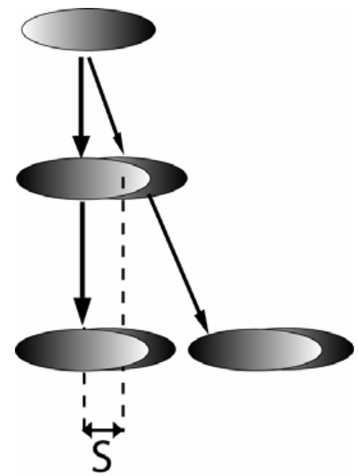


Encouraging results: fringe visibility decay length with separation s (coherence length) varies as expected as a function of $n_1(0)/T$ even at large separation

But…

Fringes that should not be there





There should be no fringes out of the overlap of the two condensate copies

How can I trust a measurement of visibility of fringes that I do not understand ?

Help appreciated!

How do quasi condensates grow?

Theory

- Kagan, Svistunov, Shlyapnikov (1992): BEC's grow in 2 stages
  1. Kinetic stage: macroscopic population builds in low levels; suppression of density fluctuations; phase fluctuations (quasi condensates, coherence length smaller than condensate size)
  2. Phase coherence development across the condensate
- Gardiner et al.: analytic expression for the growth of condensed fraction

Experiments

- Miesner et al. (1998)
- Köhl et al., (2002)
- Schvarchuk et al. (2001)

Condensed fraction grows in agreement with Gardiner's prediction

Delayed development of phase coherence? Still an open question

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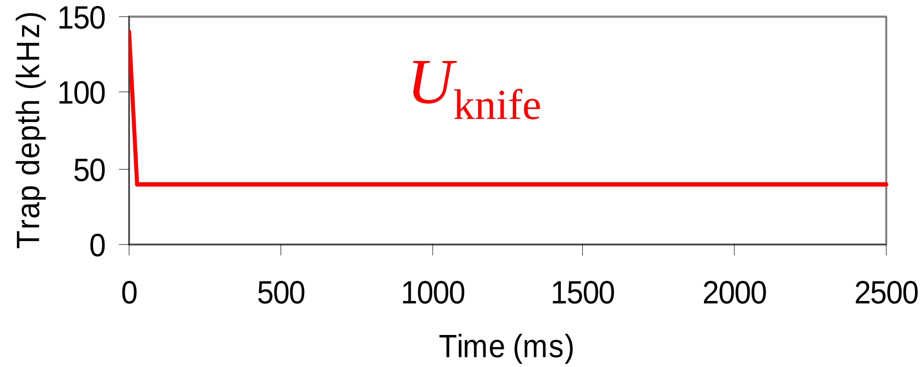
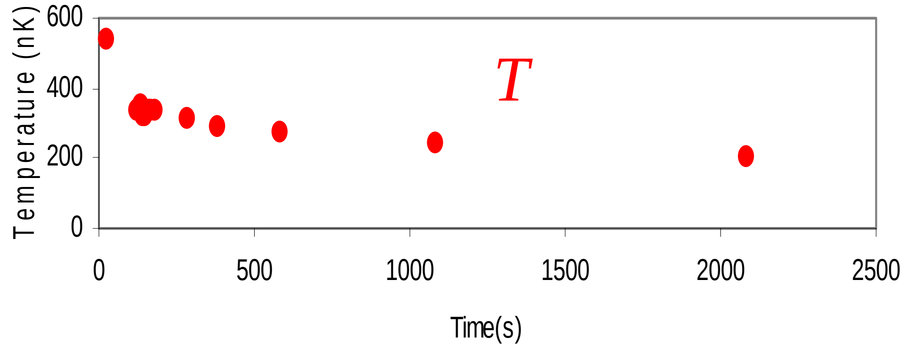
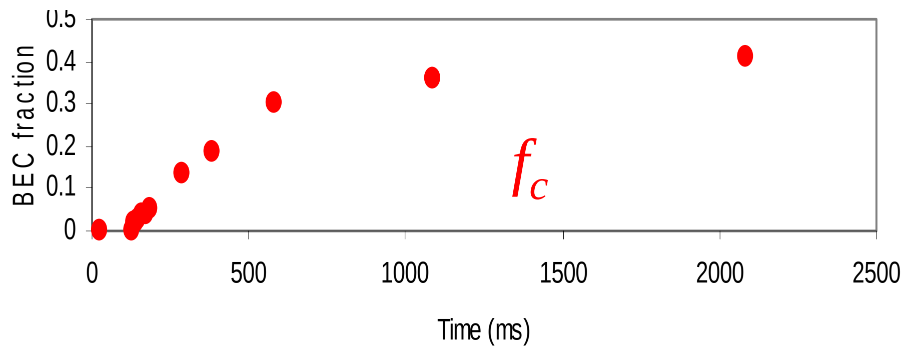
Condensate growth: our experimental strategy

- Start from thermal cloud just above T_c
- Sudden lowering of RF knife, kept at new position: Boltzmann distribution truncated at $\eta = U_{\mathrm{knife}} / k_{\mathrm{B}} T \simeq 3.3$
- Observe condensate growth
  - ✓ Condensed fraction
  - ✓ Momentum distribution width (phase coherence)

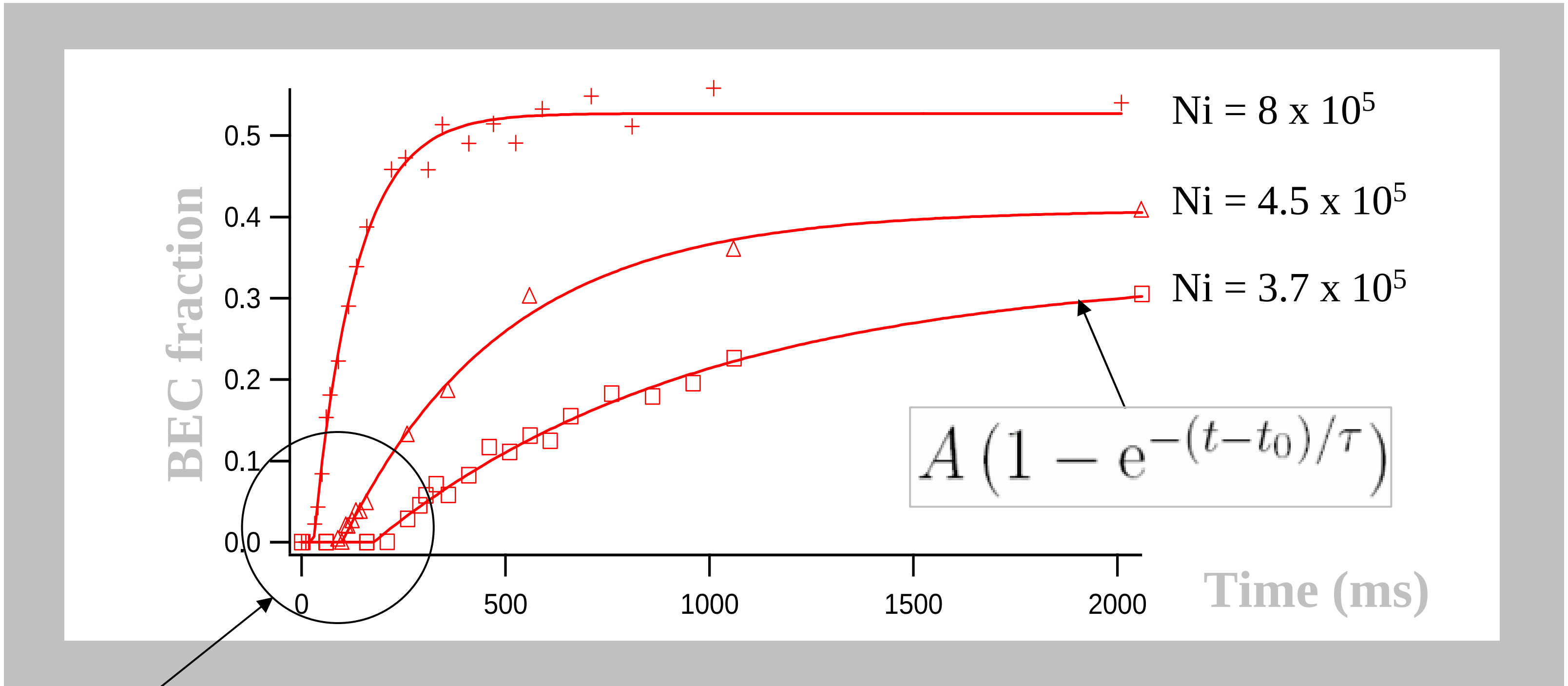
NB: study with elongated trap: anisotropy ratio of 100







Condensed fraction growth



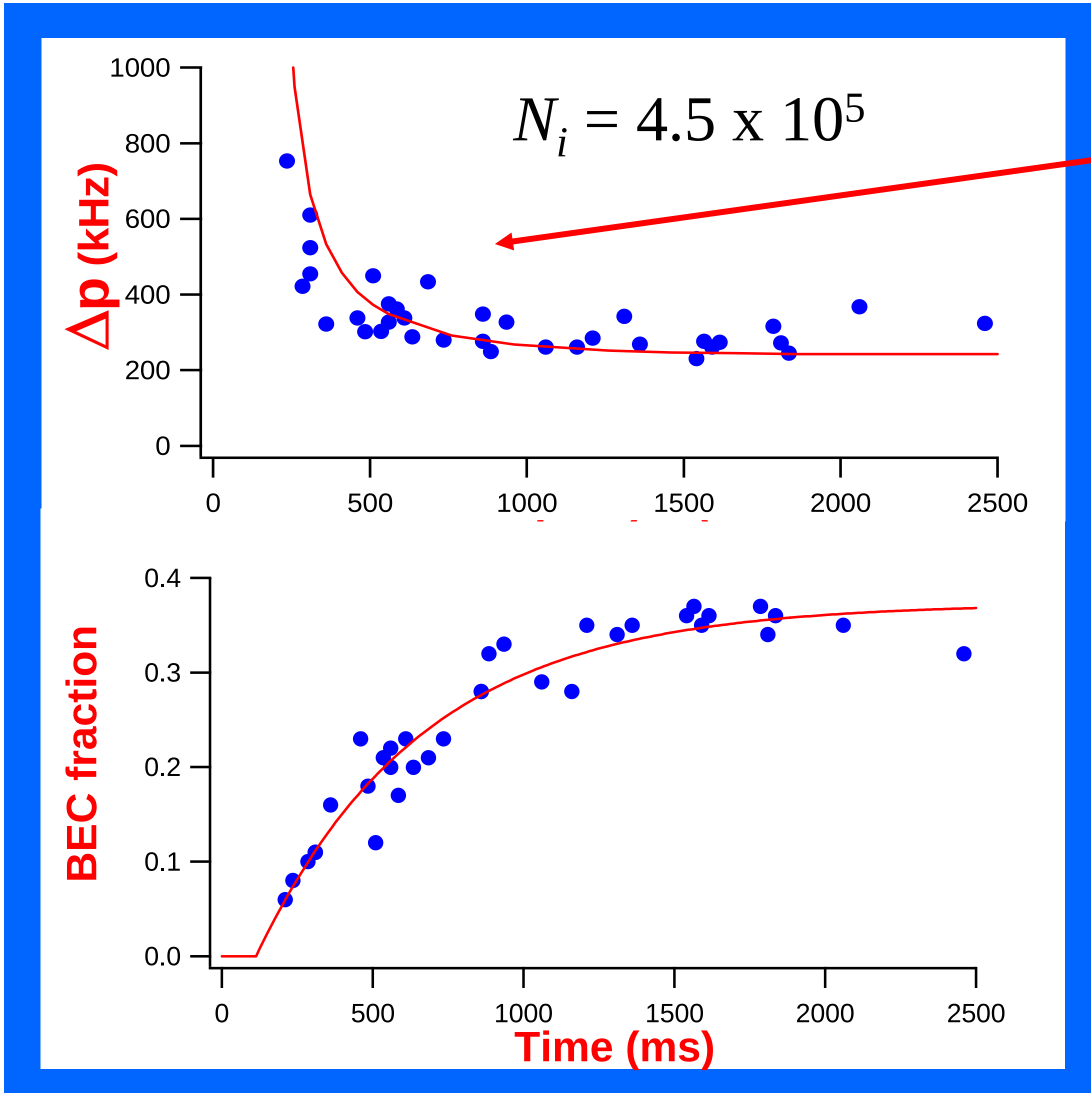
Delay time t_0 before onset of condensate growth: 30 – 180 ms

~ 15 → 40 τ_{coll}

Agreement (to be double checked) with Gardiner equation for delay and time constant

NB: At equilibrium: $T/T_\phi = 5 \rightarrow 10 \leftrightarrow$ quasi-condensate regime

Momentum width evolution (Bragg spectra width)



Δp decreases with time

$\rightarrow l_c$ increases

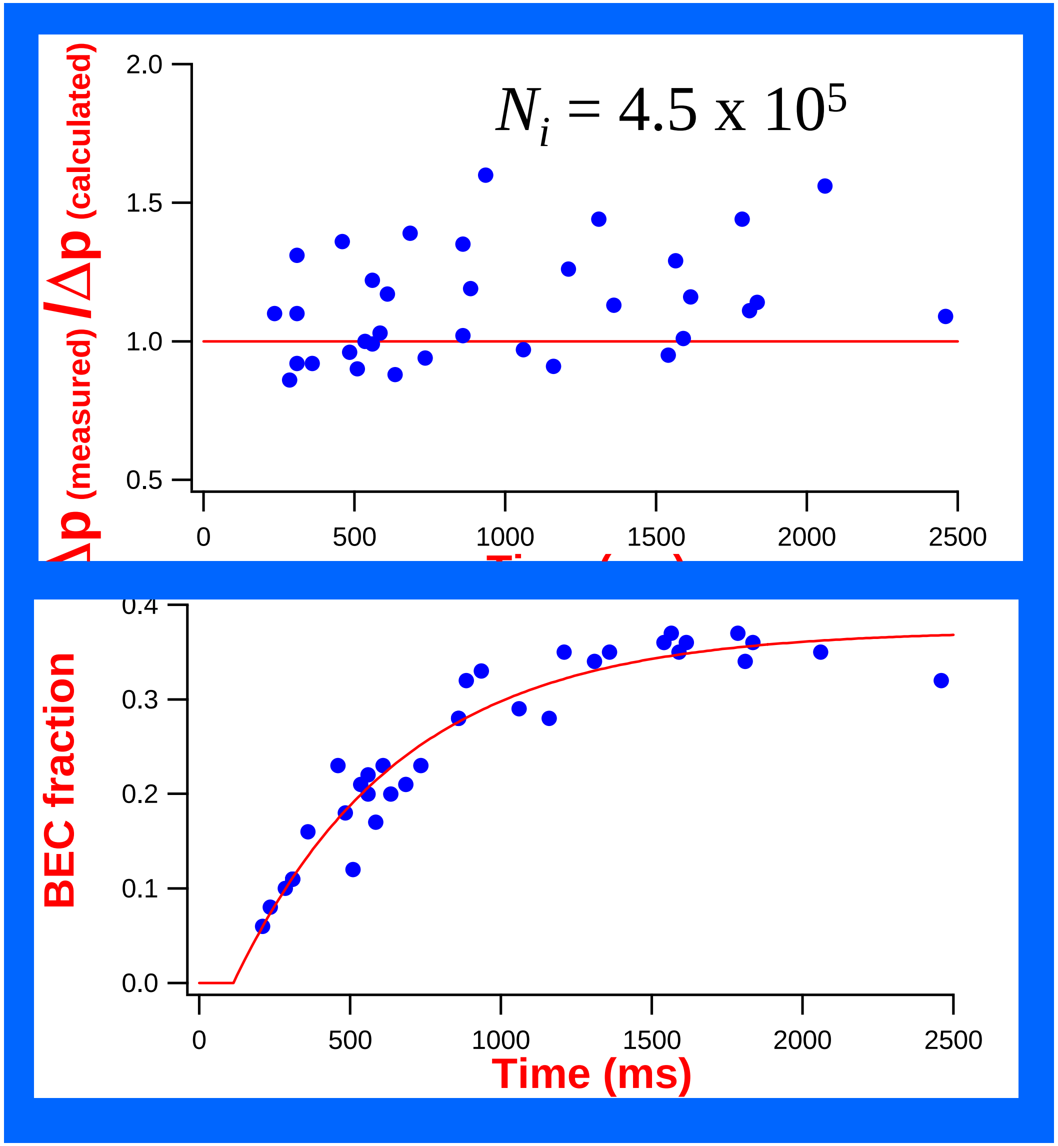
Phase coherence onset?

Need to compare to steady state value Δp_{th} (thermal equilibrium of elongated condensate)

$\Rightarrow$ Measure T and $n_1(0)$

$\Rightarrow$ Calculate Δp_{th}, and compare to Δp

Comparison to equilibrium condensate



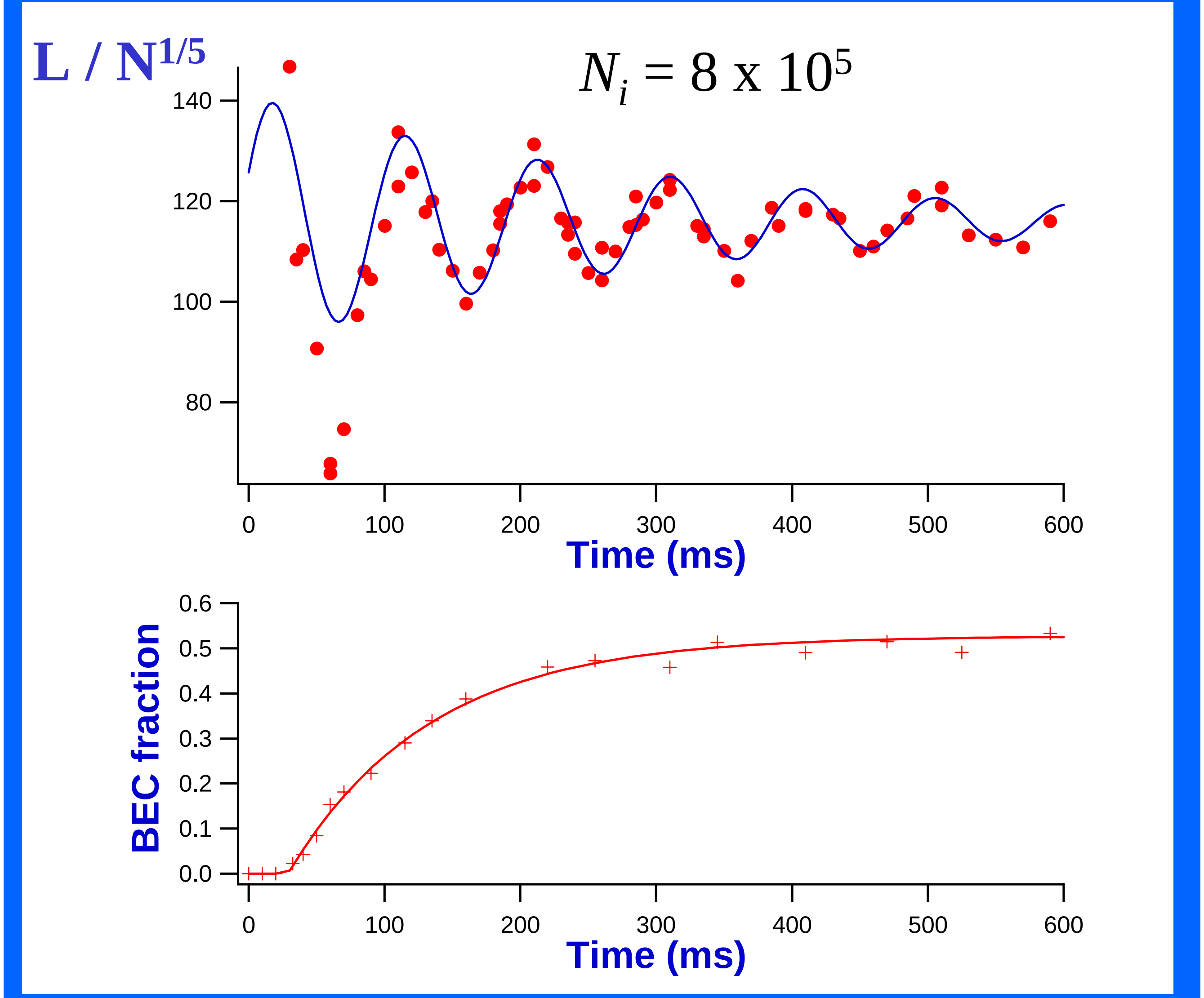
No time decrease of Δp_{meas} / Δp_{th}

Δp_{meas} seems to follow adiabatically the evolution of temperature and condensed fraction

Excess to 1 ???

Attributed to residual quadrupole oscillations

Quadrupole oscillations

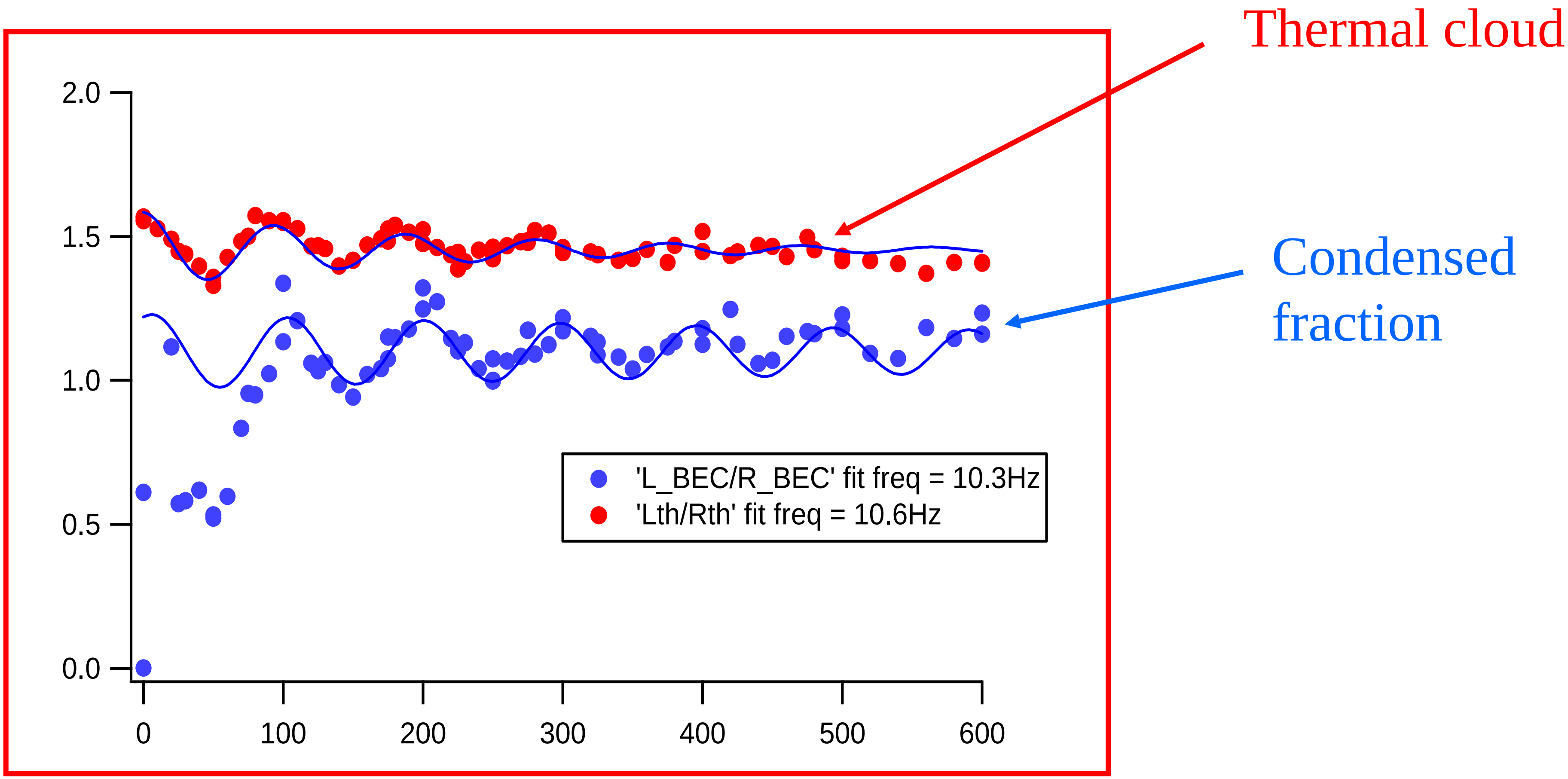


Regime of deep schock cooling (*cf.* Schvarchuk et *al.*, *PRL 2002*)

- axial hydrodynamic regime
- Initial cooling below local T_c all along the axis of the thermal cloud

Residual oscillations likely to exist even in the « soft » shock cooling: a serious experimental issue

Two components quadrupole oscillations



Any interest for theorists?

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Conclusion

A lot still to be done! Suggestions welcome

The people (elongated BEC team)

Fabrice Gerbier
Simon Richard
Joseph Thywissen

past team

Mathilde Hugbart
Andres Varon
Jocelyn Retter

present team

Philippe Bouyer

Ze boss

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Team with and without the boss