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Density fluctuations in a very elongated Bose gas : crossover from weakly to strongly interacting regimes and 1D-3D dimensionnal crossover

Isabelle Bouchoule, Julien Armijo, Thibaut Jacqmin and
Karen Kheruntsyan

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Grenoble, December 2010



Outline

- 1 Introduction
 - 1D interacting Bose gases
- 2 Density fluctuations in weakly interacting regimes
 - Experiment
 - Quasi-condensation
 - Quantum regime : sub-poissonian fluctuations
- 3 1D-3D Crossover
 - Quasi-bec
 - Quasi-bec transition in the dimensionnal crossover
- 4 Entering the strongly interacting regime

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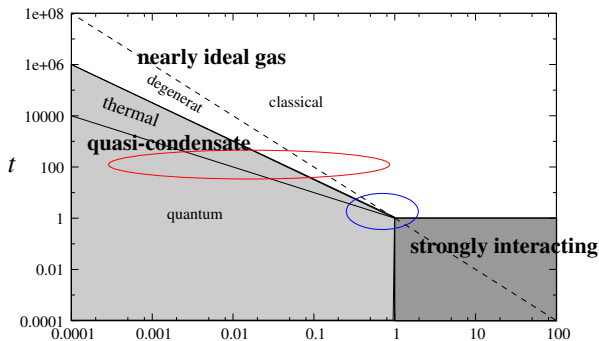
1D Bose gas with repulsive contact interaction

$$H = -\frac{\hbar^2}{2m} \int dz \psi^\dagger \frac{\partial^2}{\partial z^2} \psi + \frac{g}{2} \int dz \psi^\dagger \psi^\dagger \psi \psi,$$

Exact solution : Lieb-Liniger Thermodynamic : Yang-Yang (60') n, T

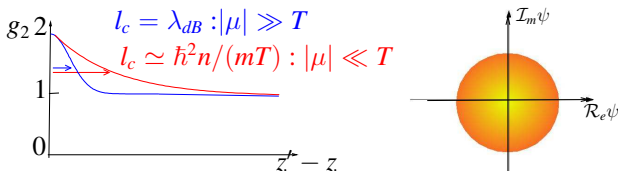
Length scale : $l_g = \hbar^2/mg$, Energy scale $E_g = g^2 m/2\hbar^2$

Parameters : $t = T/E_g$, $\gamma = 1/nl_g = mg/\hbar^2 n$



Nearly ideal gas regime : bunching phenomena

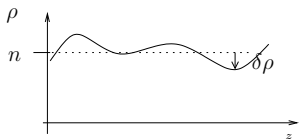
- Two-body correlation function $g_2(z) = \langle \psi_z^+ \psi_0^+ \psi_0 \psi_z \rangle / n^2$



- Bunching effect \rightarrow density fluctuations.
 $\langle \delta n(z) \delta n(z') \rangle = \langle n \rangle^2 (g_2(z' - z) - 1) + \langle n \rangle \delta(z - z')$
- Bunching : correlation between particles. Quantum statistic
- Field theory $\psi = \sum \psi_k e^{ikz}$, $n = |\psi|^2$: speckle phenomena

Transition towards quasi-condensate

- Repulsive Interactions \rightarrow Density fluctuations require energy



$$H_{int} = \frac{g}{2} \int dz \rho^2 \Rightarrow \delta H_{int} > 0$$

Reduction of density fluctuations at low temperature/high density

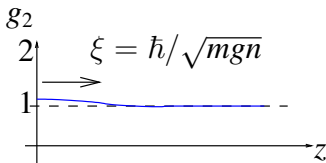
weakly interacting : $\gamma = mg/\hbar^2 n \ll 1$

Cross-over : $\frac{1}{N} H_{int} \propto gn \simeq |\mu|$

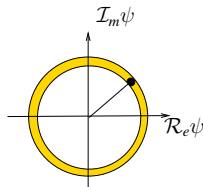
$$\mu = mT^2/2\hbar^2 n^2, \Rightarrow T_{c.o.} \simeq \frac{\hbar^2 n^2}{2m} \sqrt{\gamma}, \quad n_{c.o.} \propto T^{2/3}$$

Transition for a degenerate gas

- For $T \ll T_{c.o.}$: quasi-bec regime, $g^{(2)} \simeq 1$

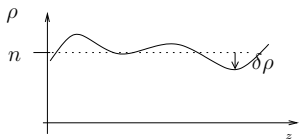


$$T > gn$$



Transition towards quasi-condensate

- Repulsive Interactions \rightarrow Density fluctuations require energy



$$H_{int} = \frac{g}{2} \int dz \rho^2 \Rightarrow \delta H_{int} > 0$$

Reduction of density fluctuations at low temperature/high density

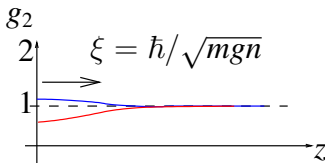
weakly interacting : $\gamma = mg/\hbar^2 n \ll 1$

Cross-over : $\frac{1}{N} H_{int} \propto gn \simeq |\mu|$

$$\mu = mT^2/2\hbar^2 n^2, \Rightarrow T_{c.o.} \simeq \frac{\hbar^2 n^2}{2m} \sqrt{\gamma}, \quad n_{c.o.} \propto T^{2/3}$$

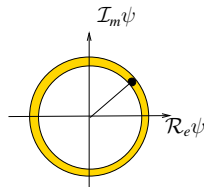
Transition for a degenerate gas

- For $T \ll T_{c.o.}$: quasi-bec regime, $g^{(2)} \simeq 1$

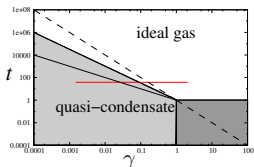


$$T > gn$$

$$T < gn$$



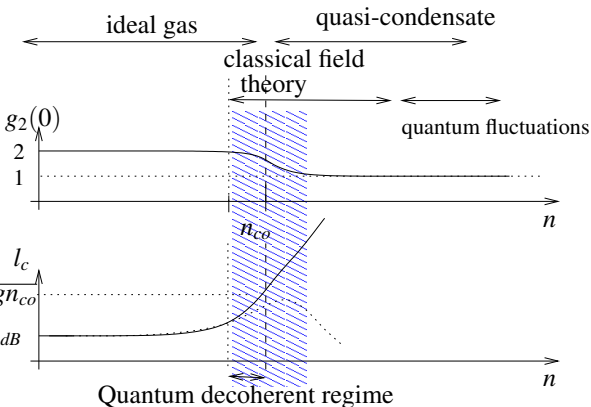
1D weakly interacting homogeneous Bose gas



$$t = 2\hbar^2 T / (mg^2)$$

$$n_{co} = \frac{1}{\lambda_{dB}} t^{1/6}$$

large transition
quantum decoherent
regime barely exists
for $t < 1000$



$$\mu < 0$$

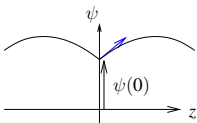
$$\mu \simeq gn > 0$$

Strongly interacting 1D Bose gas

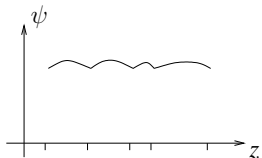
- Relative wave function

$$\text{If } E \gg E_g, |\psi(0)| \simeq 1$$

$$\text{If } E \ll E_g, |\psi(0)| \ll 1$$

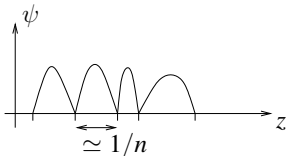


- Many body system



$$E = gn \gg E_g$$

$$\Rightarrow \gamma \ll 1$$



$$E = \hbar^2 n^2 / m \ll E_g$$

$$\Rightarrow \gamma \gg 1$$

$g^{(2)}(0) \simeq 0$
Fermionization

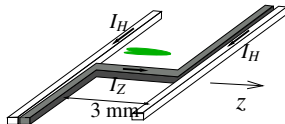
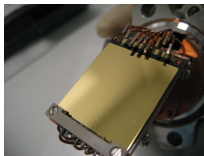
Strongly interacting regime : $\gamma \gg 1, t \ll 1$

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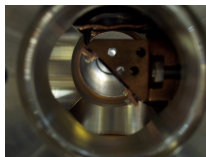
Realisation of very anisotropic traps on an atom chip

Magnetic confinement of ^{87}Rb by micro-wires
H-shape trap

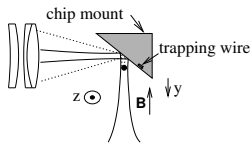


$$\begin{cases} \omega_{\perp}/2\pi = 3 - 4 \text{ kHz} \\ \omega_z/2\pi = 5 - 10 \text{ Hz} \end{cases}$$

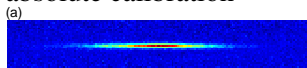
$$1\text{D} : T, \mu \ll \hbar\omega_{\perp} \\ g = 2\hbar\omega_{\perp}a$$



CCD camera



In-situ images
absolute calibration



$$T \simeq 400 - 15 \text{ nK} \\ \simeq 3.0 - 0.1 \hbar\omega_{\perp} \\ N \simeq 5000 - 1000.$$

$t \simeq 80 - 1000$
**Weakly interacting
gases**

Density fluctuation measurements

- Statistical analysis over hundreds of images

$$l_c \ll \Delta \ll L$$

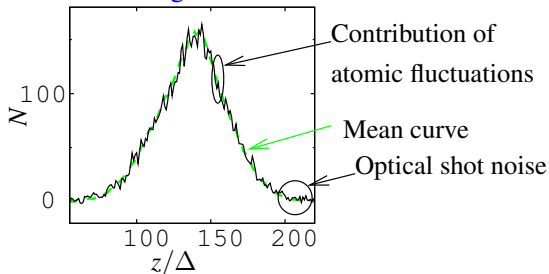
→ Local Density

Approximation valid

δN binned according to $\langle N \rangle$

$\langle \delta N^2 \rangle$ versus $n = \langle N \rangle / \Delta$

Optical shot noise
subtracted



→ Two-body correlation function integral

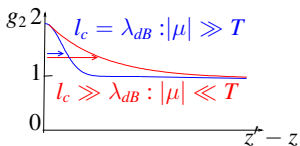
$$\langle \delta N^2 \rangle = \langle N \rangle + \langle N \rangle n \int dz (g_2(z) - 1)$$

→ Thermodynamic quantity

$$\langle \delta N^2 \rangle = k_B T \frac{\partial n}{\partial \mu}$$

Expected behavior in asymptotic regimes

• Ideal gas regime



• Quasi-bec regime

$$H_{k=0} = g\Delta\delta n_0^2/2$$

$$\text{Equipartition : } T/2 = H_k$$

$$\Rightarrow \langle \delta N^2 \rangle = \Delta T/g$$

$$\text{Thermodynamic : } \mu \simeq gn$$

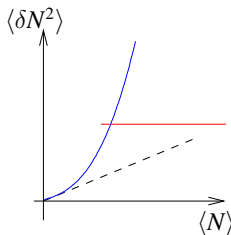
$$\langle \delta N^2 \rangle = \langle N \rangle + \underbrace{\langle N \rangle n \int dz (g_2(z) - 1)}_{l_c}$$

▷ Non degenerate gas : $nl_c \ll 1$

$$\langle \delta N^2 \rangle \simeq \langle N \rangle$$

▷ Degenerate gas : $nl_c \gg 1$

$$\langle \delta N^2 \rangle \simeq \langle N \rangle nl_c = \langle N \rangle^2 l_c / \Delta$$



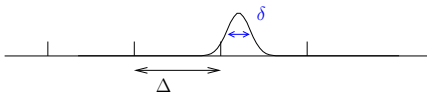
Effect of finite spatial resolution

- Absorption of an atom spreads on several pixels

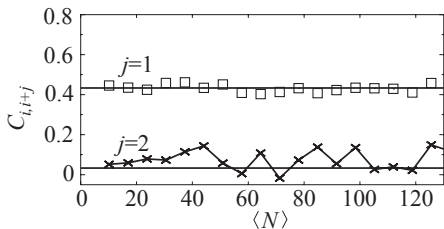
→ blurring of the image

Decrease of fluctuations :

$$\langle \delta N^2 \rangle = \kappa_2 \langle \delta N^2 \rangle_{\text{true}}$$



→ Correlation between pixels



δ deduced from measured correlations between adjacent pixels

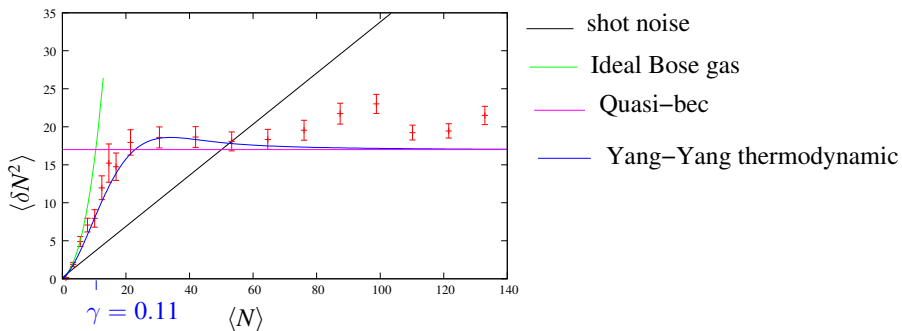
κ_2 deduced

Experimental results

$$T = 15 \text{ nK} \simeq \hbar\omega_{\perp}/10$$

$$t \simeq 80$$

$$\mu \simeq 30 \text{ nK} \simeq 0.2 \hbar\omega_{\perp}$$



- Strong bunching effect in the transition region
- Quasi-bec both in the thermal and quantum regime

Quasi-condensate in the quantum regime

We measure : $\langle \delta N^2 \rangle < \langle N \rangle$ (by more than a factor 2)

$$\langle \delta N^2 \rangle = \langle N \rangle + \langle N \rangle n \int dz (g_2(z) - 1)$$

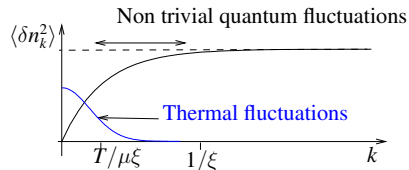
$\Rightarrow g^{(2)}$ function smaller than one \Rightarrow **Quantum regime**

$$\langle \delta N^2 \rangle = \Delta T / g \Rightarrow T < gn$$

- However we still measure thermal excitations

Low momentum phonons : high occupation number

Shot noise term, removed from the $g^{(2)}$ function, IS quantum.



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1D-3D Crossover in the quasi-bec regime

$\mu \ll \hbar\omega_{\perp}$ ($na \ll 1$) \rightarrow Pure 1D quasi-bec

$\mu \gtrsim \hbar\omega_{\perp}$: 1D \rightarrow 3D behavior

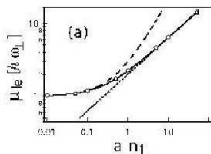
Transverse breathing associated with a longitudinal phonon has to be taken into account.

Thermodynamic argument : $\text{Var}(N) = k_B T \left(\frac{\partial N}{\partial \mu} \right)_T$

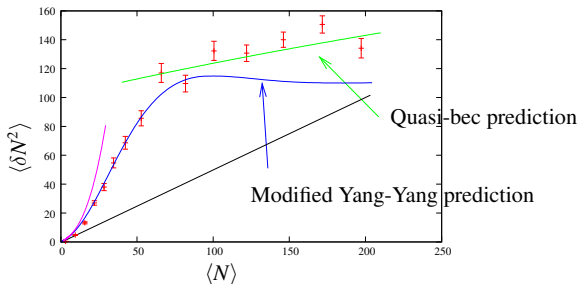
$$T = 96 \text{ nK} \simeq 0.5 \hbar\omega_{\perp}$$

Heuristic equation :

$$\mu = \hbar\omega_{\perp} \sqrt{1 + 4na}$$

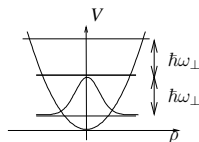
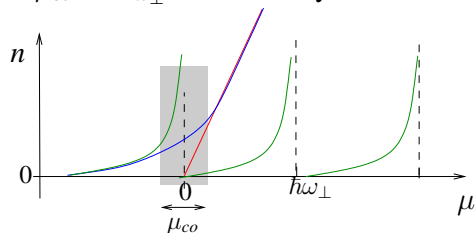


Efficient thermometry



Modified Yang-Yang model

If $\mu_{co} \ll \hbar\omega_{\perp}$, transversally excited states behave as ideal Bose gases.



$$\mu_{co} \simeq E_g^{1/3} T^{2/3} = (mg^2/\hbar^2)^{1/3} T^{2/3} \Rightarrow \mu_{co}/(\hbar\omega_{\perp}) \simeq \left(\frac{T}{\hbar\omega_{\perp}} \frac{a}{l_{\perp}} \right)^{2/3}$$

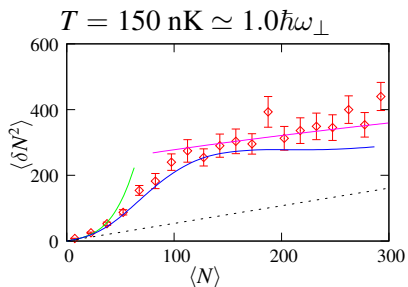
For our parameters : $a/l_{\perp} \simeq 0.025$

Modified Yang-Yang model :

- Transverse ground state : Yang-Yang thermodynamic
- Excited transverse states : ideal 1D Bose gases

First introduced by Van Druten and co-workers : Phys. Rev. Lett. 100, 090402 (2008)

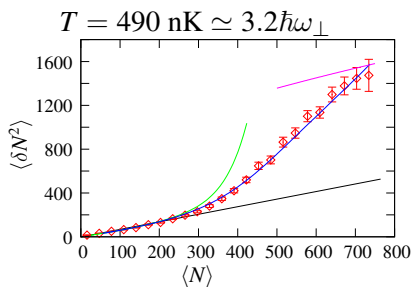
Modified Yang-Yang model



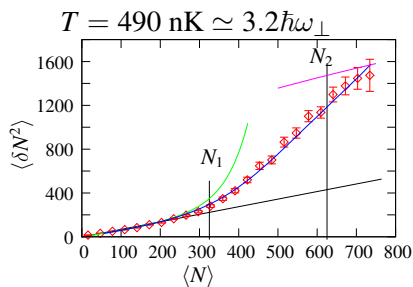
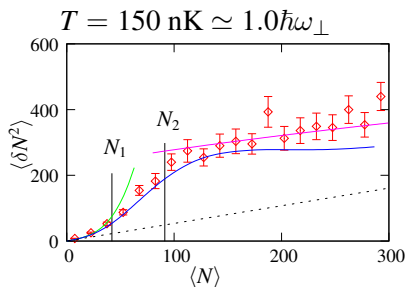
Very good agreement

N_1 (resp. N_2) :

deviation from the ideal gas (resp. quasi-bec) model by 20%



Modified Yang-Yang model

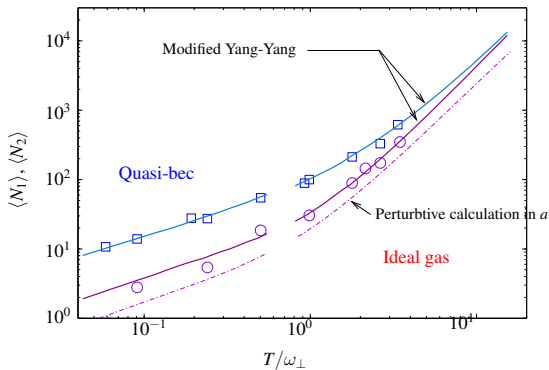


Very good agreement

N_1 (resp. N_2) :

deviation from the ideal gas (resp. quasi-bec) model by 20%

Quasi-bec transition in the 1D-3D crossover



Good agreement with MYY

Perturbation theory gives qualitative behavior for N_1

Weakly interacting Bose gases : 1D versus 3D behavior

1D physics

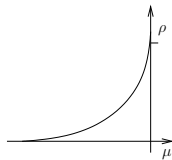
$$T \ll \hbar\omega_{\perp}$$

Weakly interacting gas :
Smooth transition
towards quasi-bec
driven by interactions

$$n_{co} \simeq (mT^2/(\hbar^2 g))^{1/3}$$

3D physics

$$T \gg \hbar\omega_{\perp}, \hbar\omega_{\perp} (a/l_{\perp})^{2/11}$$



Transverse BEC :

$$\rho \lambda_{dB}^3 = 2.612\dots$$

$$n_{c\perp} \propto T^{5/2}$$

If $n_{c\perp} \gg n_{co}$,

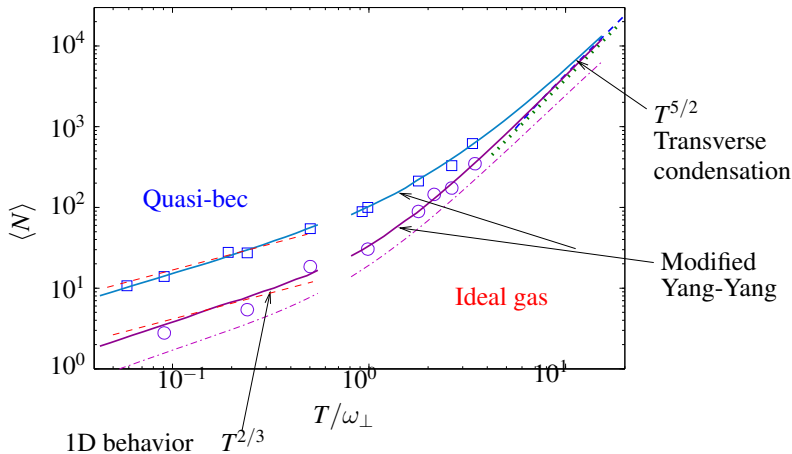
quasi-bec just after transverse BEC

$$n_{c\perp}/n_{co} \simeq ((T/\hbar\omega_{\perp}) \underbrace{(a/l_{\perp})^{2/11}}_{0.34})^{11/6}$$



dimensional crossover

Quasi-bec transition in the 1D-3D crossover



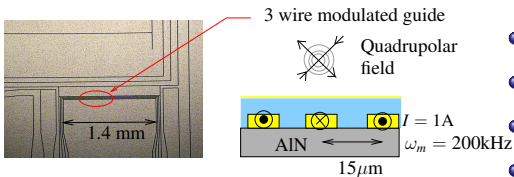
From a 1D behavior to 3D condensation phenomena

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Reaching strongly interacting gases on an atom-chip

- A new atom-guide



- Roughness free (modulation)
- Strong confinement : 1 – 150 kHz
- Diverse longitudinal potentials
- Dynamical change of g

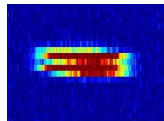
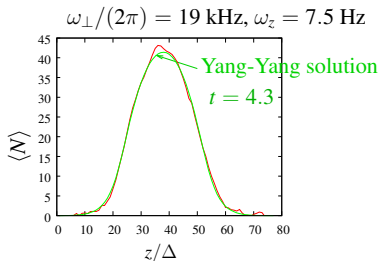
- Approaching strong interactions

Experimental sequence :

★ Cooling at moderate ω_{\perp}

★ Increase ω_{\perp}

Problem : excess of heating
(Entropy not preserved)

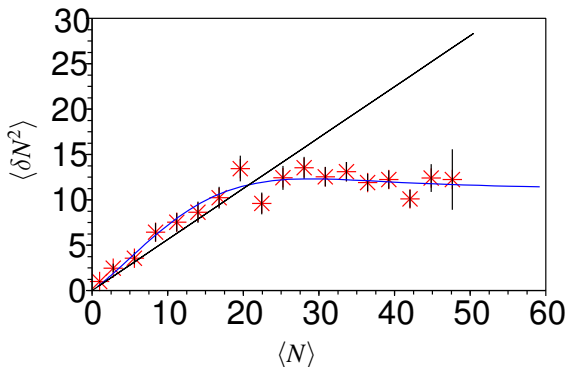


Density fluctuations close to the strongly interacting regime

$$T = 40 \text{ nK} \simeq \hbar\omega_{\perp}/20$$

$$t \simeq 4$$

$$\mu/T \simeq 1.9$$



Almost no bunching anymore. Behaviour close to that of a Fermi gas

Conclusion

Summary

- Investigation of the quasi-bec cross-over
- 1D-3D dimensionnal crossover
- 1D quasi-bec in the quantum fluctuations regime (subshotnoise)
- Non gaussian atom number distribution measured \rightarrow 3 body correlations
- Evidence for three-body effect (strong cooling in the strongly 1D regime)

Prospect

- Study of correlation length of density fluctuations in 1D gases.
- 1D strongly interacting regime
- Localisation in strongly interacting 1D gases : in periodic and random potentials
- Momentum distribution/correlations