# …ing correlations in a 1D Bose gas on an atom chip
## *Mesures de corrélations dans un gaz de Bose 1D*

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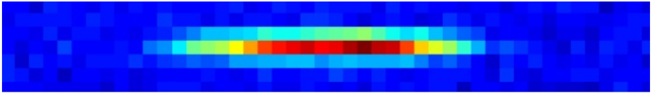
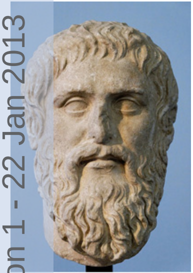
Groupe d'optique atomique

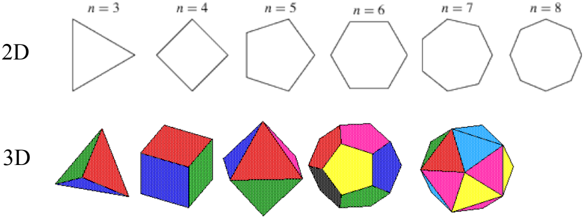


November, 22nd 2012
PhD defense

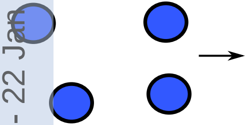
# The influence of dimensionality



Plato 4th century BC



Example of a neuronal network



# The influence of dimensionality

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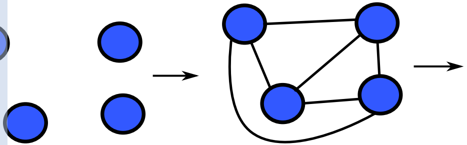

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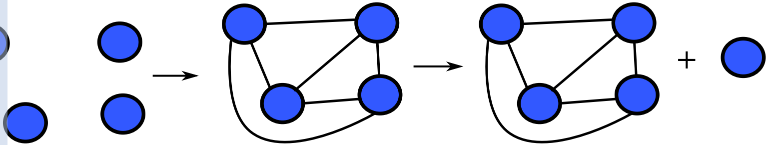

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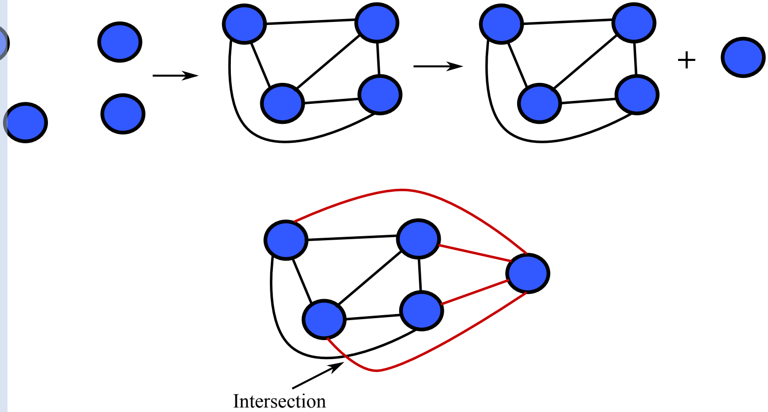
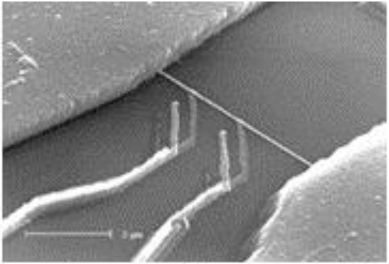



Impossibility to interconnect more than 4 neurones in 2D.

# Why studying systems in dimensions lower than 3 ?

- Effect of interactions enhanced
- A whole bunch of new effects appear
- In quantum physics, thanks to confinement-induced quantization : very good quasi-low dimensional systems



Transport in a 50 nm nanowire (CEA)

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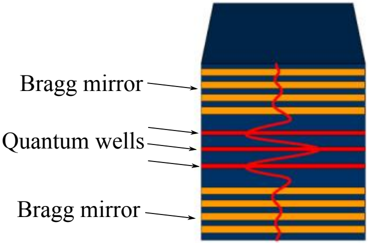
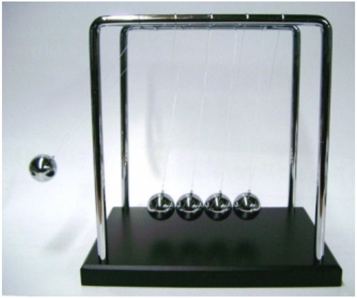


*Image : University of Sheffield*

2D electron gas in 1D quantum wells
Density of states modified, more gain
Example : laser diodes

Very interesting from the theoretical point of view because :

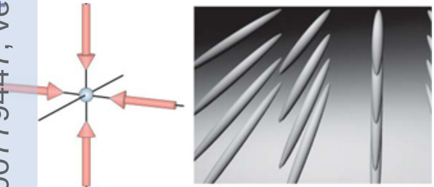
- Most "simple" strongly correlated many-body system
- There exists powerful theoretical methods
- There are exact results



Newton's cradle

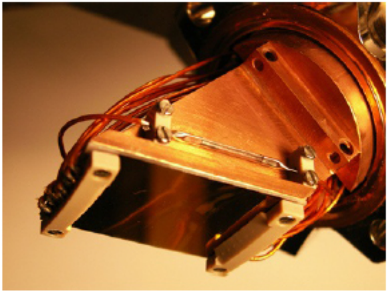
Cold atoms are suitable systems to study this Physics because

- possibility to get a 2D and 1D geometries
- isolated systems
- fine control of all parameters
- many observables



I. Bloch Nature Physics 1, 23 - 30 (2005)

2D optical lattice

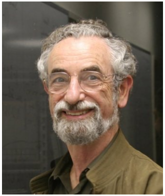


Atom chips

In general cold atoms can be used to simulate a lot of models :

- Bose-Hubbard
- Hawking radiation
- Anderson localization
- ...

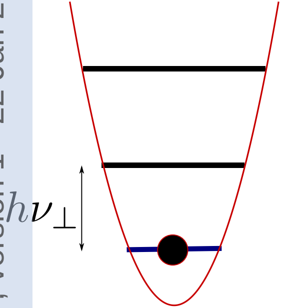
In this work → Lieb-Liniger model of 1D bosons with contact repulsive interactions.



Elliott H. Lieb

# Outline

1. Producing a 1D gas of bosons on an atom chip
2. Introduction to the physics of the 1D Bose gas
3. Density fluctuations in the quasi-condensate regime
4. Density fluctuations in the strongly interacting regime
5. Momentum distribution of 1D Bose gases

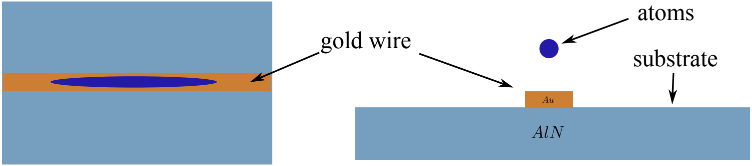



Transverse harmonic potential

- 1D criterion
  - $k_B T \ll h\nu_\perp$
  - $|\mu| \ll h\nu_\perp$

- Typically, for T$\simeq$ 40 nK it requires $\nu_\perp \gg 800$ Hz

- The chip



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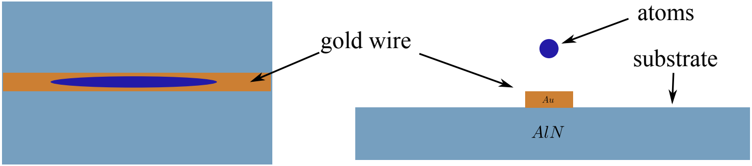
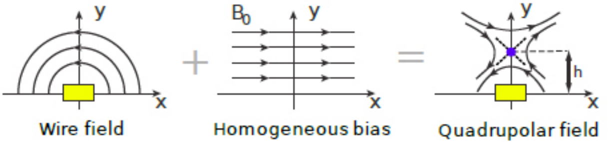


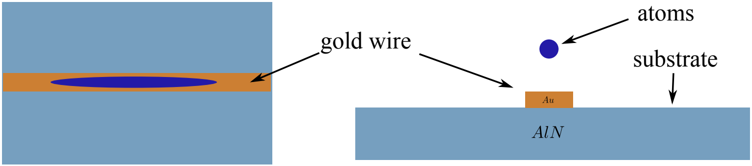

- Trapping in two directions with a wire and a homogeneous magnetic field

Magnetic potential $\boxed{V = -\mu_B|\vec{B}|}$




The transverse trapping frequency $\omega_\perp \propto 1/h^2$.

- The chip

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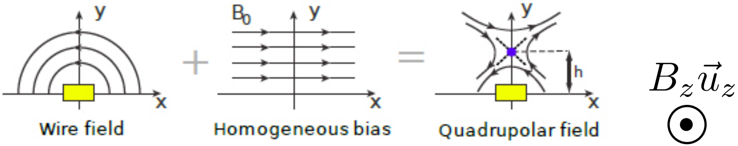


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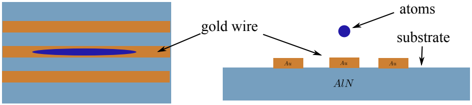
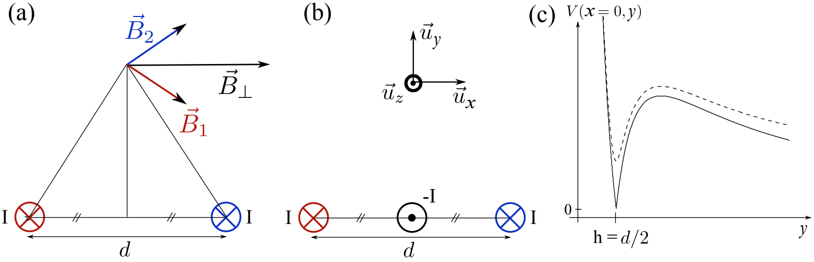
- Trapping in two directions with three parallel wires



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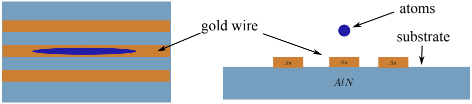
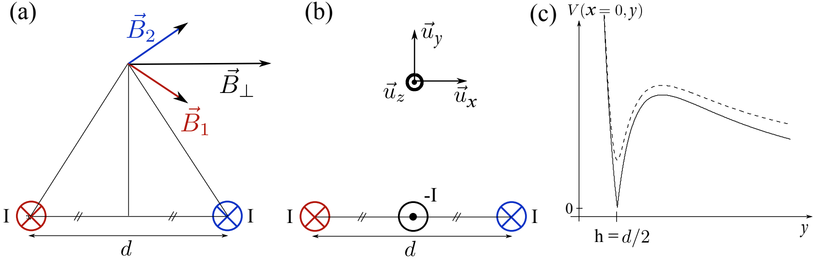


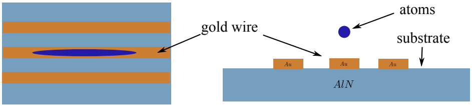



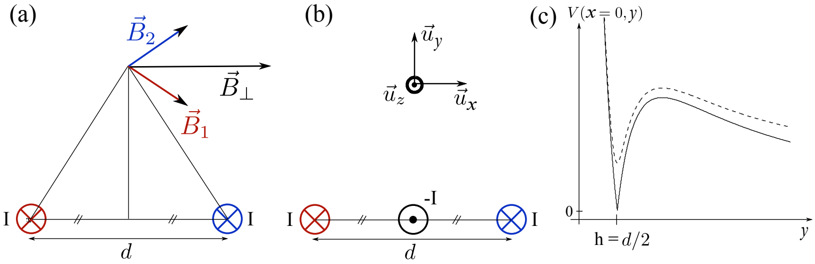

- If $h$ is too small : longitudinal roughness of the potential

# Transverse trapping with microwires



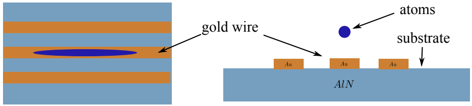
- Trapping in two directions with three parallel wires

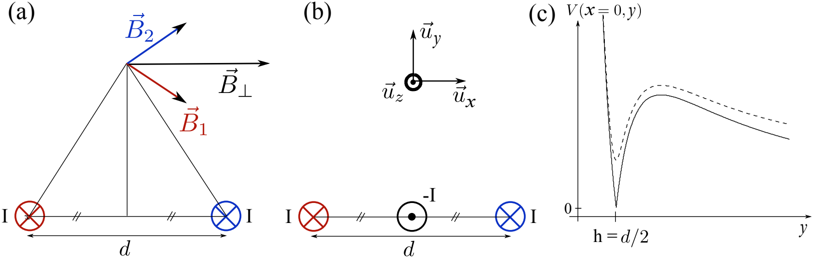



- If $h$ is too small : longitudinal roughness of the potential
- Solution : current modulation

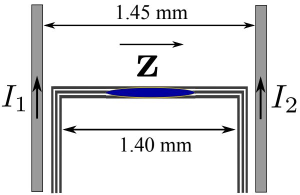
- Trapping in two directions with three parallel wires




- If $h$ is too small : longitudinal roughness of the potential
- Solution : current modulation
- for $h = 15\ \mu$m and $I \leq 1$ A, $\omega_\perp/2\pi = [0.1,\ 80]$ kHz

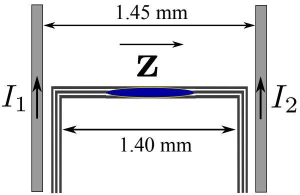
- Harmonic longitudinal trapping




Typical trapping frequencies :

$\omega_{\parallel}/2\pi = [3,\ 40]$ Hz
$\omega_{\perp}/2\pi = [0.1,\ 80]$ kHz

- Harmonic longitudinal trapping

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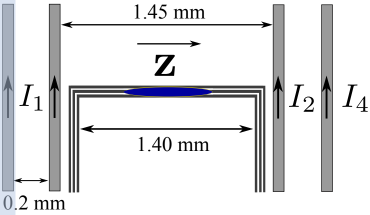
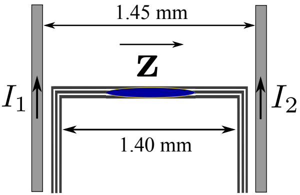
- Other longitudinal geometries




- Quartic trap
- Double well trap
- Fine tuning of anharmonicity

# Longitudinal trapping

- Harmonic longitudinal trapping

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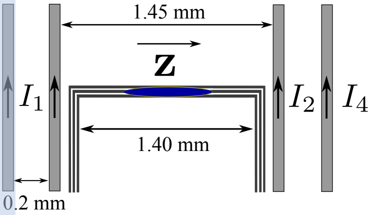
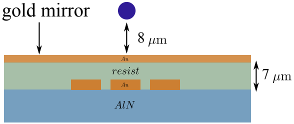


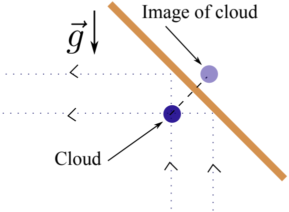

- Quartic trap
- Double well trap
- Fine tuning of anharmonicity

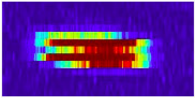
- Longitudinal and transverse traps totally decoupled

# How do we observe the cloud ?

- Mirror on chip



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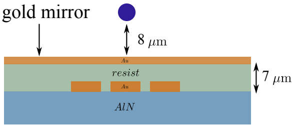
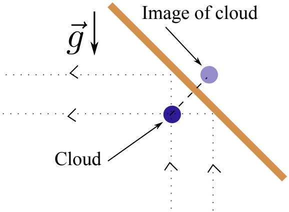
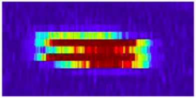
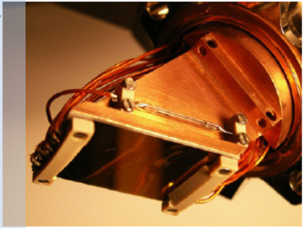


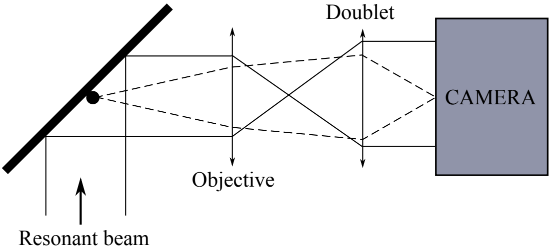





Chip on copper mount

Chip inside vacuum

- Absorption imaging : a resonant laser illuminates the cloud, which is imaged on a CCD camera




- The Beer-Lambert law gives the atomic density $\rho$

$$\rho \propto \ln \frac{I_2}{I_1}$$

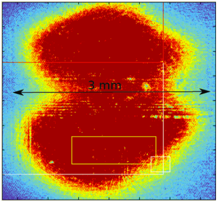
$I_2$ : intensity in absence of atoms
$I_1$ : intensity in presence of atoms

- Beer-Lambert $\rightarrow$ not always valid $\rightarrow$ more involved methods

# Typical experimental sequence

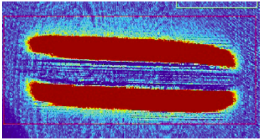
Laser cooling

MOT $1 \times 10^8$ at.
$T \simeq 200\mu\ K$




Optical mollases
$5 \times 10^7$ at. $T \simeq 10\ \mu K$

Optical pumping
in the trapped
Zeeman sublevel



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$5 \times 10^6$ at.

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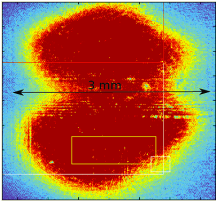


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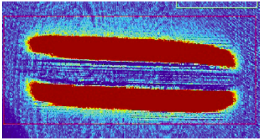

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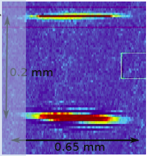
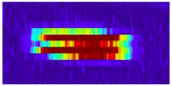



Evaporation for 2.5 s
$3 \times 10^5$ at. $T \simeq 1\mu K$

Transport towards AC trap position and transfer from DC trap to AC trap

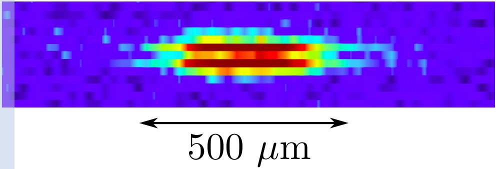


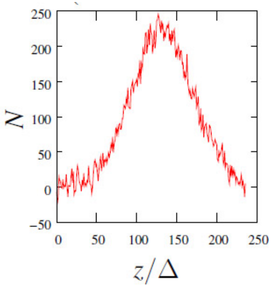
AC Magnetic trap
$8 \times 10^4$ at.

Final evaporation for about 1 s to the wanted temperature

$300 \rightarrow 10000$ at.
$T = 20 \rightarrow 120\ nK$

- Last step : take a picture
- Compute the longitudinal profile




- pixel size $\Delta = 4.5\ \mu$m
- Cycle time $\simeq 18$ s

# Outline

- No Bose-Einstein condensation in 1D
- No spontaneous continuous symetry breaking at finite $T$
- Lieb-Liniger Hamiltonian ($g > 0$) :

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

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- Two scales : $E_g = \frac{mg^2}{2\hbar^2}$ and $l_g = \frac{\hbar^2}{mg}$
- Thermal equilibrium defined by :
  - Temperature parameter : $t = \frac{k_B T}{E_g}$
  - Interaction parameter : $\gamma = \frac{1}{\rho l_g} = \frac{mg}{\hbar^2 \rho}$ Note that $\gamma \nearrow$ when $\rho \searrow$
- The equation of state can be computed exactly (Yang-Yang)

- 3D interactions are described by scattering length $a_{3D}$
- As long as $a_{3D} \ll l_{\perp} \rightarrow$ 3D interactions
- Effective 1D coupling constant $g = 2\hbar\omega_{\perp} a_{3D}$

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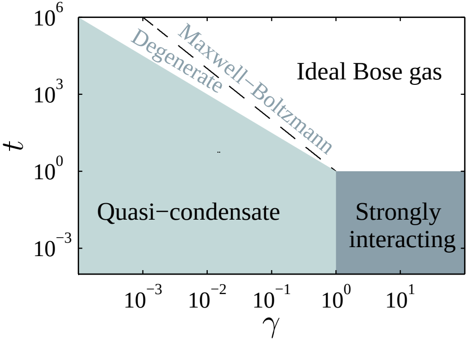
## Characterization of the system with correlation functions

- One-body correlation function $\rightarrow$ phase coherence

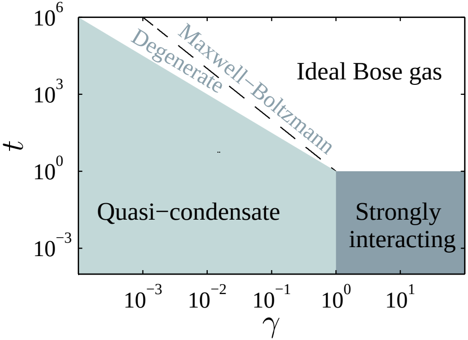
$$g^{(1)}(z) = \frac{\langle \hat{\Psi}^\dagger(z)\hat{\Psi}(0)\rangle}{\rho}$$

- Two-body correlation function $\rightarrow$ density fluctuations

$$g^{(2)}(z) = \frac{\langle \hat{\Psi}^\dagger(z)\hat{\Psi}^\dagger(0)\hat{\Psi}(0)\hat{\Psi}(z)\rangle}{\rho^2}$$



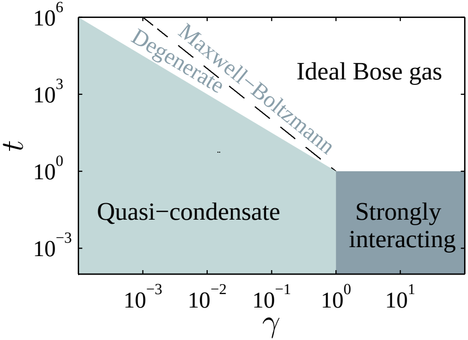

- Negligible interactions : Ideal Bose gas regime $g^{(2)}(0) = 2$




- Negligible interactions : Ideal Bose gas regime $g^{(2)}(0) = 2$
- Density fluctuations reduced because of interactions : Quasi-condensate regime $g^{(2)}(0) \simeq 1$

# The 1D Bose gas at thermal equilibrium : Phase diagram



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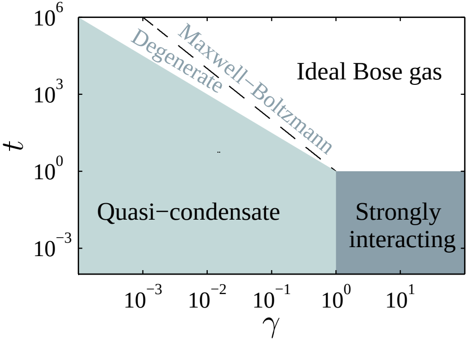


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- Interactions mimicking the Pauli principle for fermions : Strongly interacting regime $g^{(2)}(0) \ll 1$
- No phase transition in only smooth crossovers

# Outline

# *In situ* density fluctuations measurements



$\rightarrow \langle \delta\rho(z)\delta\rho(0)\rangle = \rho\delta(z) + \rho^2(g^{(2)}(z) - 1)$

$\Delta$ : pixel size

$l_c$ : correlation length

If $l_c \ll \Delta \rightarrow$ $\boxed{\langle \delta N^2\rangle = \langle N\rangle + \langle N\rangle\rho\int_{-\infty}^{+\infty}[g^{(2)}(z) - 1]dz}$

# *In situ* density fluctuations measurements

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If $l_c \ll \Delta \rightarrow$ $\boxed{\langle \delta N^2 \rangle = \langle N \rangle + \langle N \rangle \rho \int_{-\infty}^{+\infty} [g^{(2)}(z) - 1] dz}$

$\rightarrow$ Fluctuations-dissipation theorem :

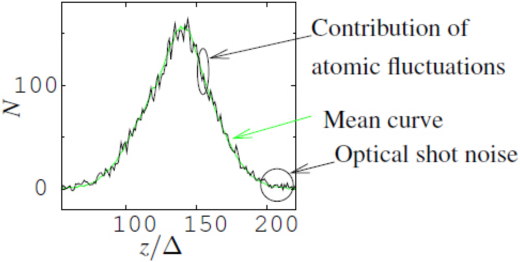
$$\boxed{\langle \delta N^2 \rangle = \Delta k_B T \frac{\partial \rho}{\partial \mu}}$$

- $\langle \delta N^2 \rangle \rightarrow$ Yang-Yang thermodynamics

# *In situ* density fluctuations measurements



- Statistical analysis over hundreds of images
- $\delta N$ binned according to $\langle N \rangle$
- Local density approximation
  - homogeneous system
  - $z$ is not relevant



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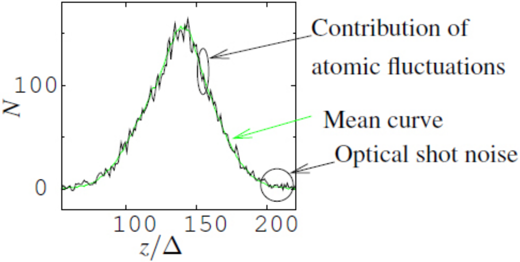


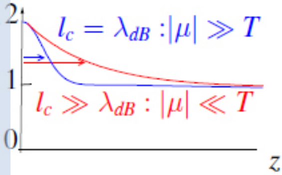

- We plot $\langle \delta N^2 \rangle$ as a function of $\langle N \rangle$
- Contribution of optical shot noise subtracted

# Expected behaviour in different regimes

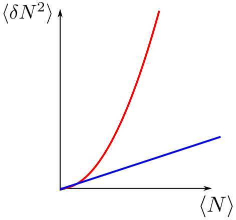


- Ideal Bose gas regime

$$\langle \delta N^2 \rangle = \langle N \rangle + \langle N \rangle \rho \underbrace{\int [g^{(2)}(z) - 1] dz}_{l_c}$$




- Classical gas
  $\rho l_c \ll 1 \rightarrow \langle \delta N^2 \rangle \simeq \langle N \rangle$
- Degenerate gas
  $\rho l_c \gg 1 \rightarrow \langle \delta N^2 \rangle \simeq \langle N \rangle^2 l_c / \Delta$



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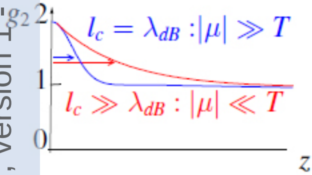


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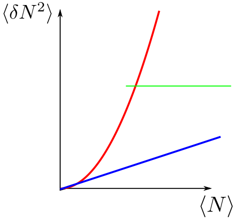
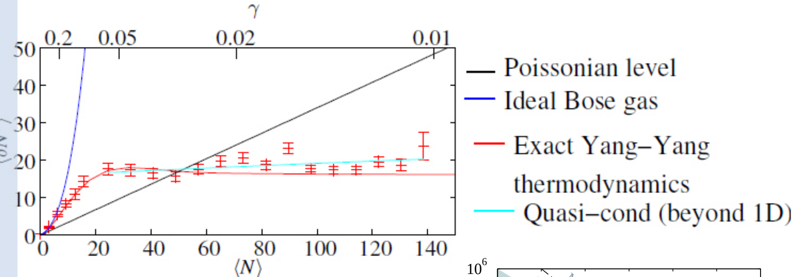



- Quasi-condensate :
  EOS : $\mu \simeq g\rho$
  $\langle \delta N^2 \rangle \simeq \Delta k_B T / g$

# Experimental results in the quasi-condensate regime

- Bosonic bunching at low densities → super-Poissonian fluctuations




- T $\simeq$ 15 nK
- $k_B T/\hbar\omega_\perp \simeq 0.1$
- $\mu \simeq 30nK$
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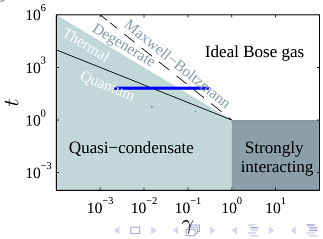
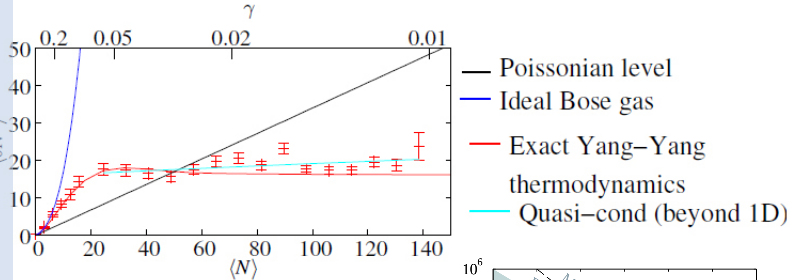



PRL **106**, 230405 (2011)

- Bosonic bunching at low densities $\rightarrow$ super-Poissonian fluctuations
- Saturation of the density fluctuations in the QBEC regime

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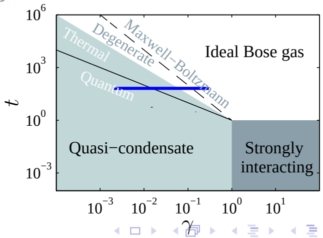
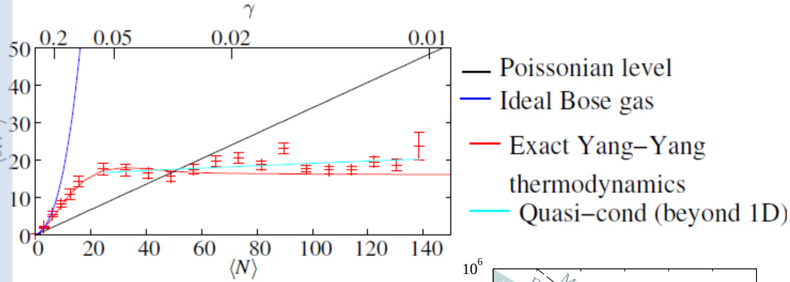



PRL **106**, 230405 (2011)

# Experimental results in the quasi-condensate regime



- Bosonic bunching at low densities $\rightarrow$ super-Poissonian fluctuations
- Saturation of the density fluctuations in the QBEC regime
- In the QBEC regime : super and sub-Poissonian fluctuations

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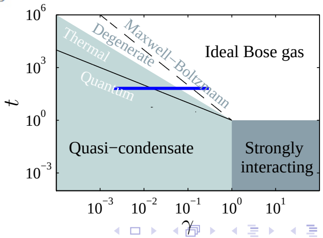


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# First observation of the quantum quasi-condensate regime

- $\langle \delta N^2 \rangle < \langle N \rangle$ and $\langle \delta N^2 \rangle = \langle N \rangle + \langle N \rangle \rho \int [g^{(2)}(z) - 1] dz$
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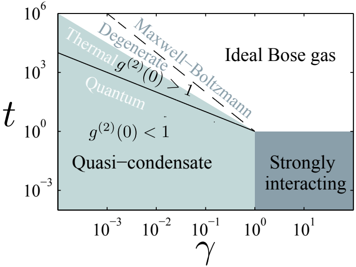

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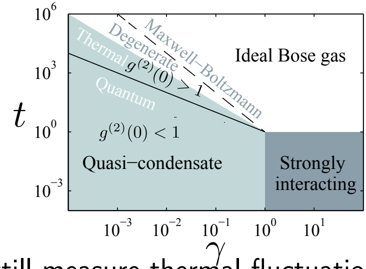
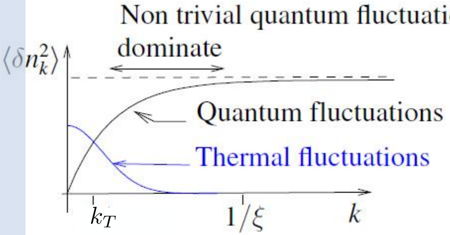



- <u>However we still measure thermal fluctuations</u>.




Thermal phonons :

$$\hbar\omega(k) \ll k_B T \rightarrow k \ll k_T$$

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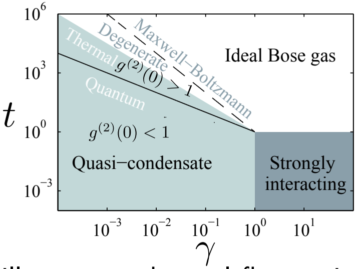


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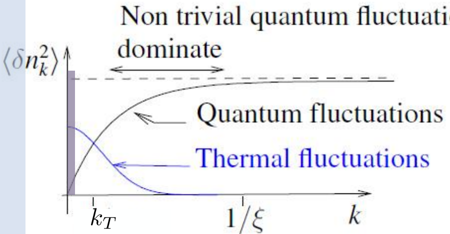


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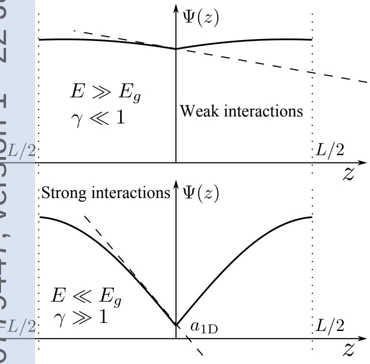
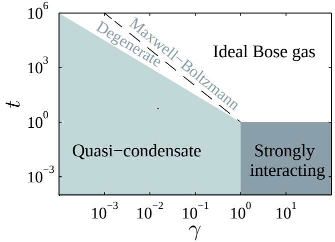
# Outline

Relative wavefunction of two bosons in a box at $T = 0$ :




- At finite T, strong interactions if $k_B T \ll E_g \to t \ll 1$



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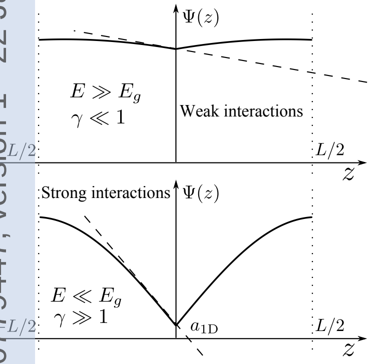


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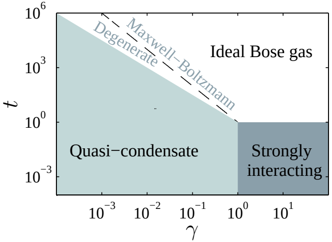


- Bose-Fermi mapping
  $\Psi_\mathrm{B}(z_1, ..., z_N) = \mathcal{S}[\Psi_\mathrm{F}(z_1, ..., z_N)]$

# The strongly interacting regime

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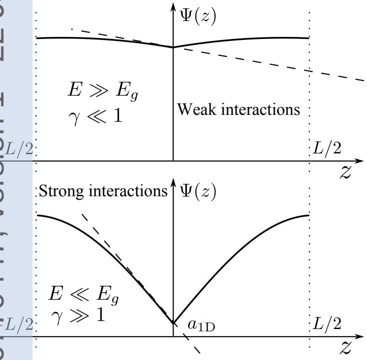


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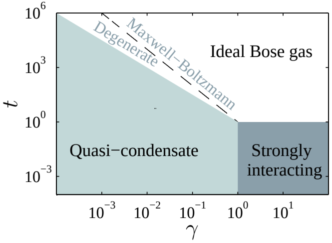
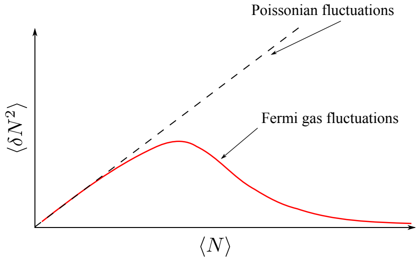



- Bose-Fermi mapping $\Psi_{\mathrm{B}}(z_1, \ldots, z_N) = \mathcal{S}[\Psi_{\mathrm{F}}(z_1, \ldots, z_N)]$

- Observed in many groups since 2004 in 2D optical lattices
  - Inhomogeneity of atom number, temperature, trapping frequency
  - Only global quantities are accessible
  - No thermometry available

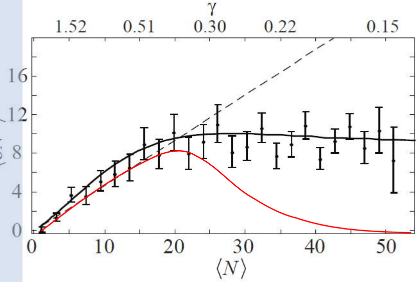
# Density fluctuations in a Fermi gas



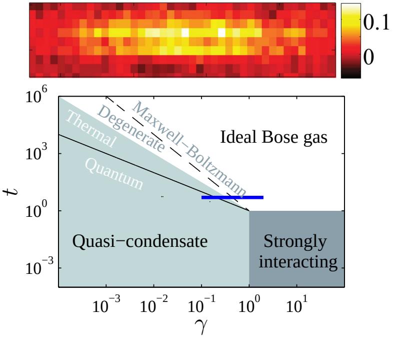



- Poissonian at low densities
- Sub-Poissonian at intermediate densities
- Zero at high densities

- t = 5.4 with $\nu_\perp \simeq 20\ kHz$
- Absence of super-Poissonian density fluctuations
- Sub-Poissonian density fluctuations at any density




Typical image




Solid line : Yang-Yang

Dashed line : Poissonian fluctuation

Red line : $t \ll 1$ limit

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# Outline

- Phase coherence is described by the one body correlation function

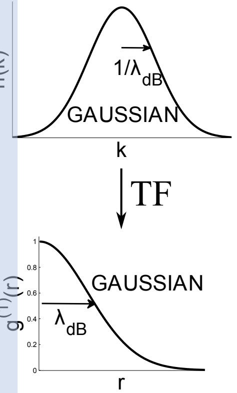
$$g^{(1)}(r) = \frac{\langle \Psi^\dagger(r)\Psi(0)\rangle}{\rho}$$

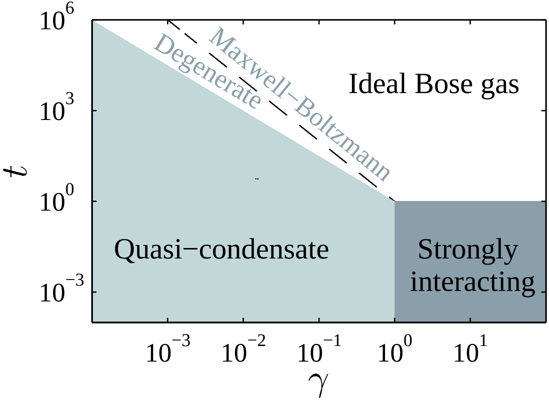
- $\boxed{g^{(1)}(r) = \frac{1}{\rho}\int \langle n_k\rangle e^{-ikr}\frac{dk}{2\pi}}$ $\langle n_k\rangle$ : population of momentum $\hbar k$.

- <u>**Conclusion**</u> : measuring $\langle n_k\rangle$ is equivalent to probing $g^{(1)}(r)$.

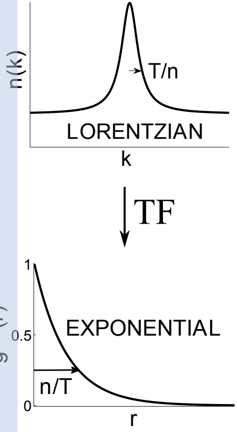
- $g^{(1)}(r)$ unknown in general $\rightarrow$ Quantum Monte Carlo calculations (Tommaso Roscilde, ENS Lyon)

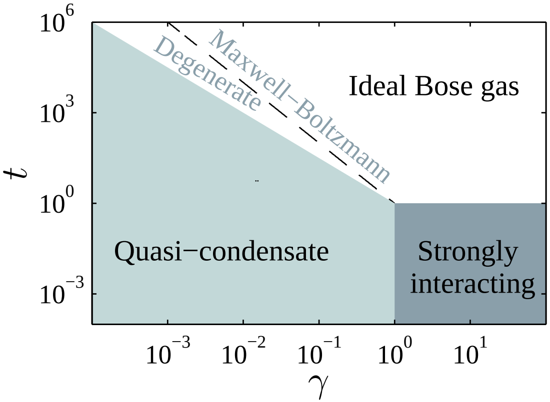
- Maxwell-Boltzmann gas




$k_B T \gg |\mu|$ Bose law limit : $\langle n_k \rangle \propto e^{-\frac{\epsilon_k}{k_B T}}$, with $\epsilon_k = \frac{\hbar^2 k^2}{2m}$

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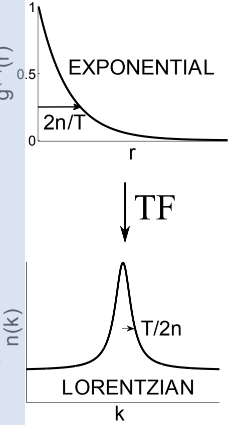
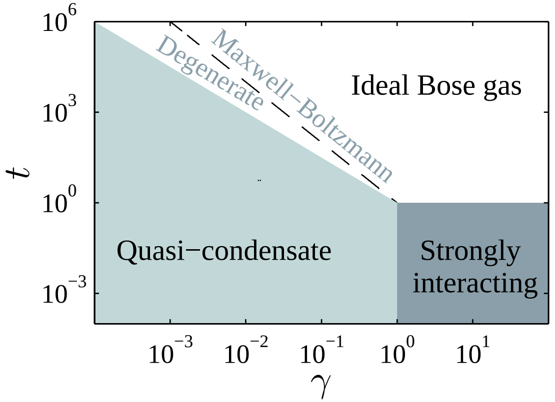
# Quasi-condensate

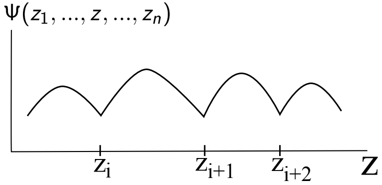





- Contribution of phonons give $g^{(1)}(r) = e^{-Tz/2n}$
- $n(k)$ is Lorentzian in ideal Bose gas degenerate regime and quasi condensate regime. The width differs by a factor 2.

- Short distance correlation ("contact") properties of the Lieb-Liniger model :




$\boxed{n(k) \propto \frac{1}{k^4}}$ for large k's

- $E = E_K + E_{int} \rightarrow$ Yang/Yang
  $E_{int} = \frac{1}{2} Ngng^{(2)}(0)$
  $g^{(2)}(0) \propto \partial E/\partial g \rightarrow$ Hellman-Feynman theorem

<u>**Conclusion**</u> : $E_K$ is a thermodynamic quantity

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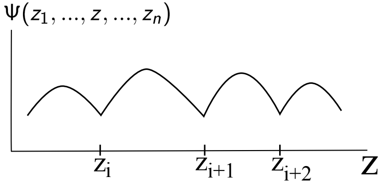


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  <u>**Conclusion**</u> : $E_K$ is a thermodynamic quantity

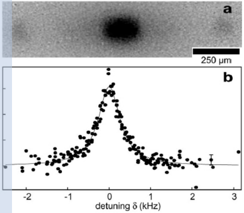
<u>**And**</u> $E_K$ is the RMS width of the momentum distribution :

$$E_K = \frac{\hbar^2}{2m} \int dk \; k^2 n(k) \to \textbf{thermometry}$$

# State of the art

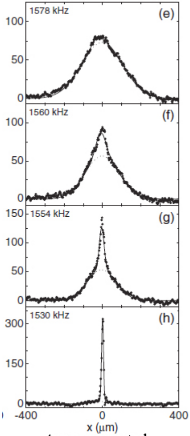


Elongated BEC, Bragg spectrocsopy



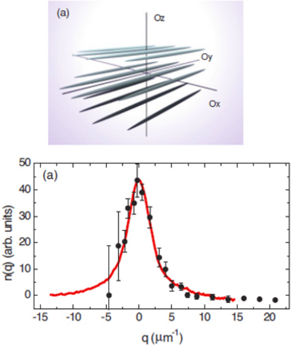

Richard et al. PRL **91**, 4 (2003)

Quasi-1D quasi-condensate
Magnetic focusing




Amerongen et al.
PRL **100**, 090402 (2008)

Array of purely 1D gases
Strongly interacting
Bragg spectroscopy




Fabbri et al. PRA **83**, 031604 (2011)

# Focusing method



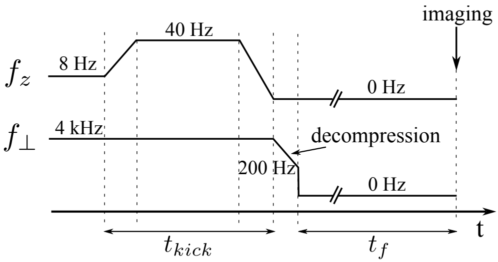
- In optics : Fourier transform of a field $\rightarrow$ Fourier plane of a lens
- Multiply by quadratic phase and propagate

*Adapted from Amerongen's thesis*

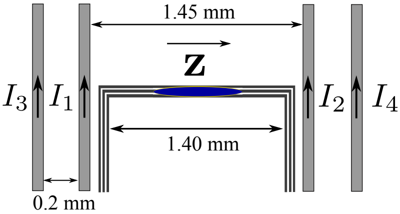
- Quadratic phase $\rightarrow$ longitudinal harmonic kick potential
- Propagation $\rightarrow$ time of flight
- Typical parameters :
  $f_{kick} = 40\ Hz$, $t_{kick} = 0.7\ ms$ and $TOF = 27ms$

# Focusing sequence





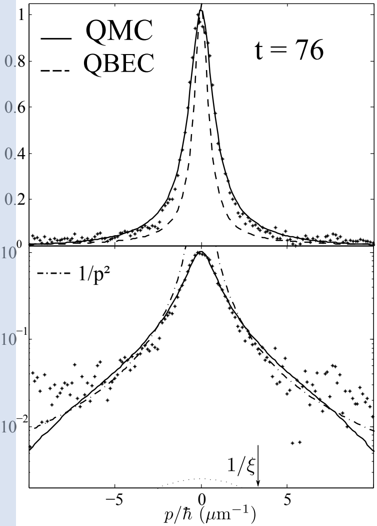

Transverse decompression step to avoid too huge transverse expansion

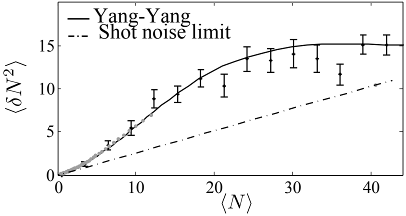


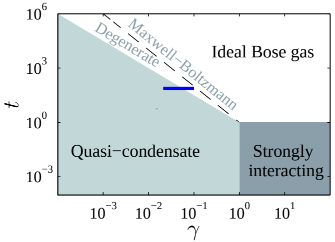

4 wire configuration = very harmonic focusing pulse

# Results : quasi-condensate regime





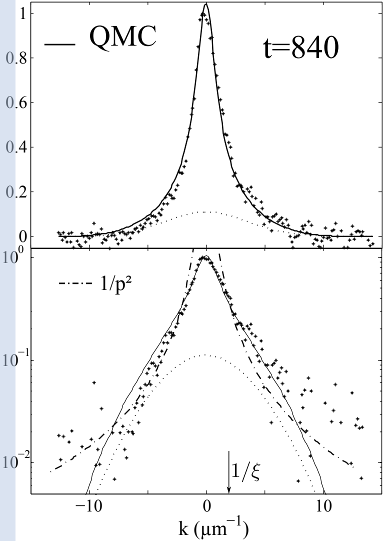



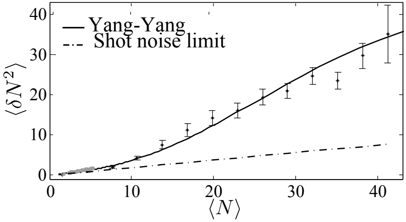



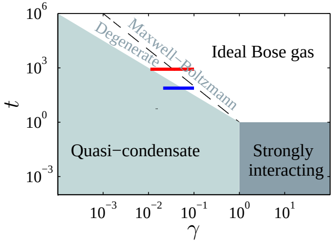

PRA **86**, 043626 (2012)

# Results : degenerate ideal Bose gas






PRA **86**, 043626 (2012)

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# Prospects



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