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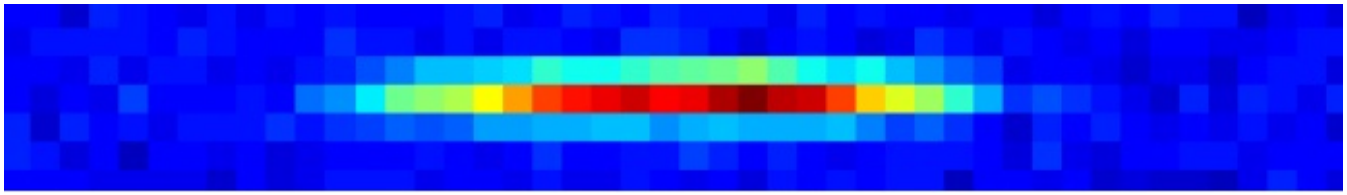
ing correlations in a 1D Bose gas on an atom chip

Mesures de corrélations dans un gaz de Bose 1D

Thibaut Jacqmin

Laboratoire Charles Fabry
Groupe d'optique atomique



November, 22nd 2012
PhD defense

UNIVERSITÉ PARIS SUD

INSTITUT d'OPTIQUE GRADUATE SCHOOL

The influence of dimensionality

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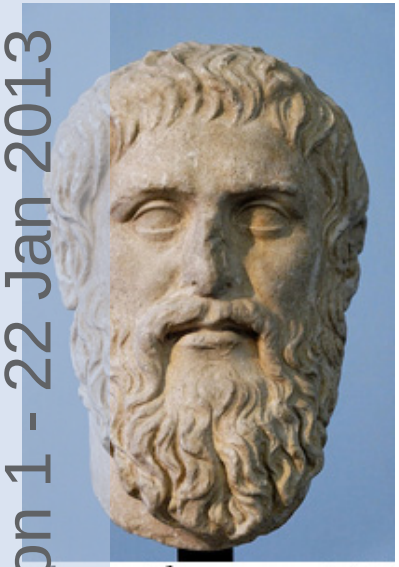
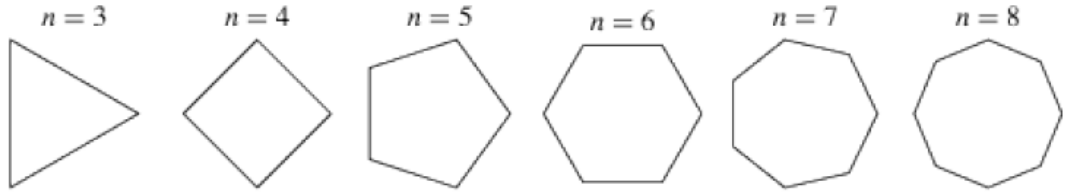
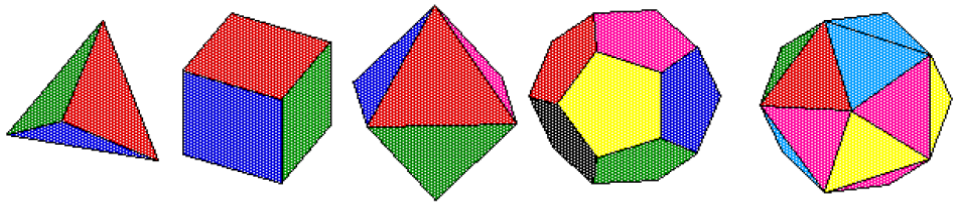


Plato 4th century BC

2D



3D



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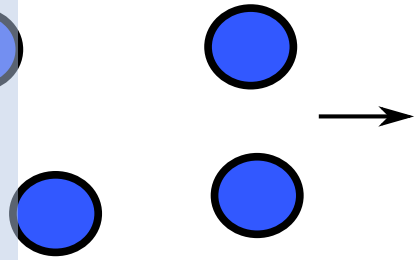
Example of a neuronal network



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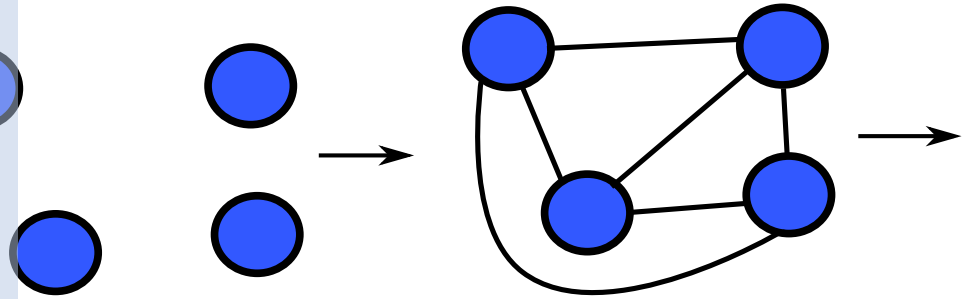

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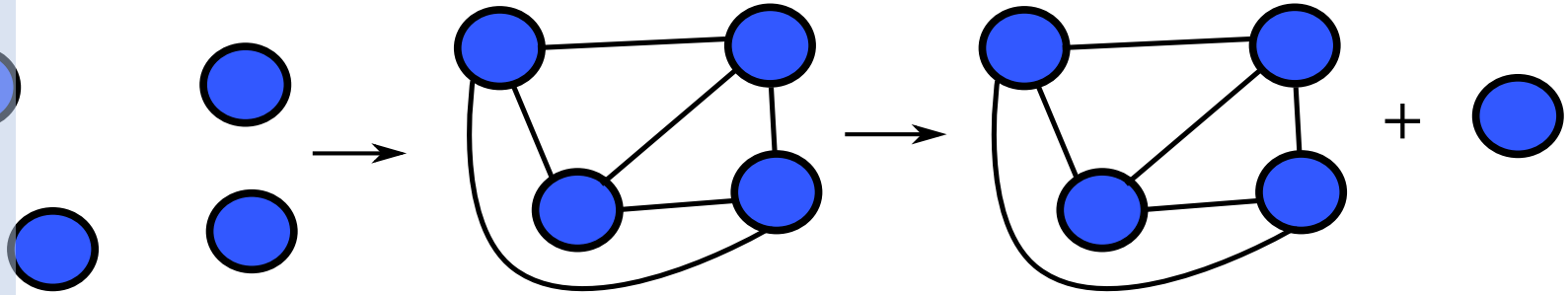

The influence of dimensionality

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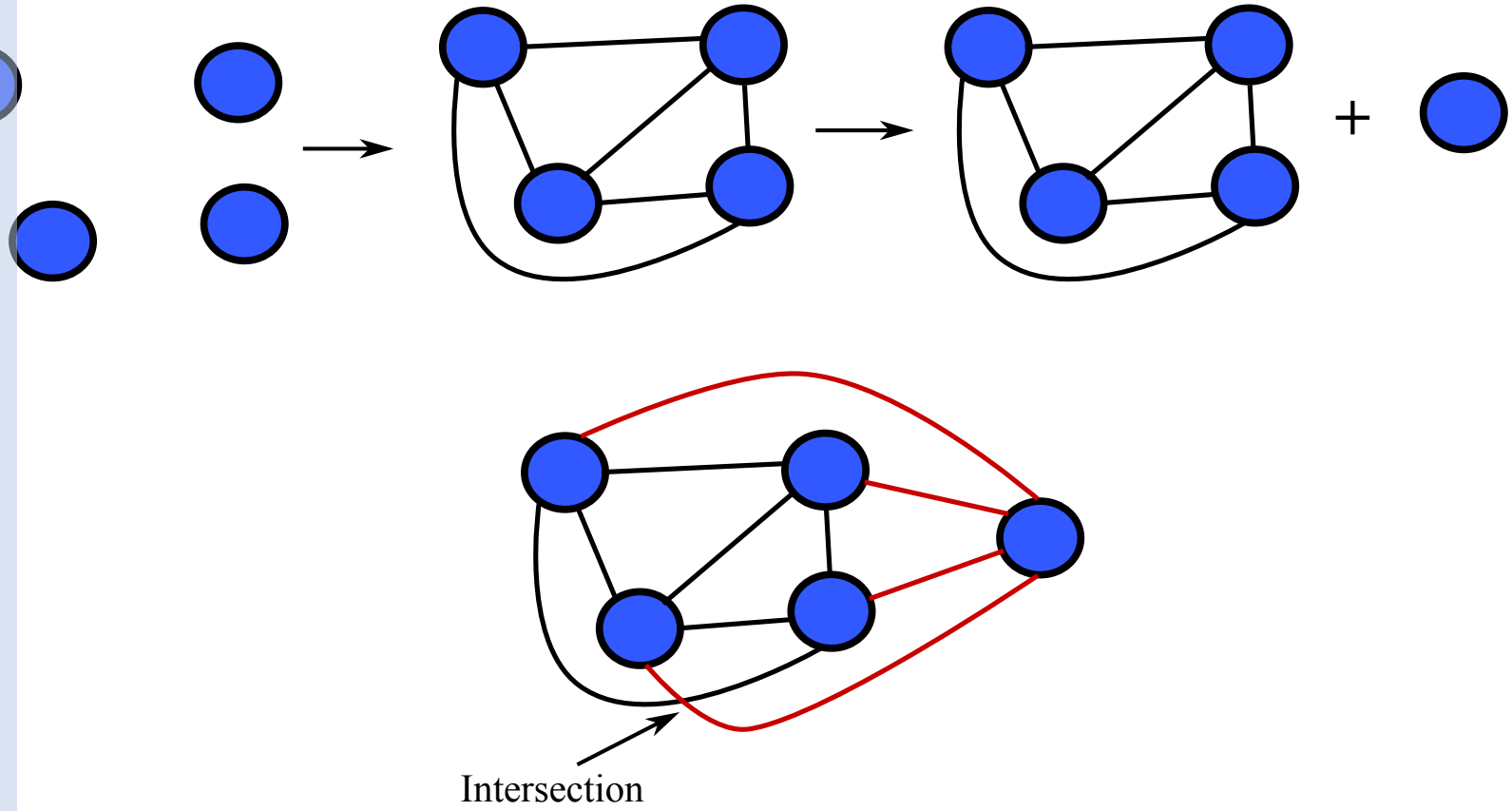
Example of a neuronal network



Impossibility to interconnect more than 4 neurones in 2D.

Why studying systems in dimensions lower than 3 ?

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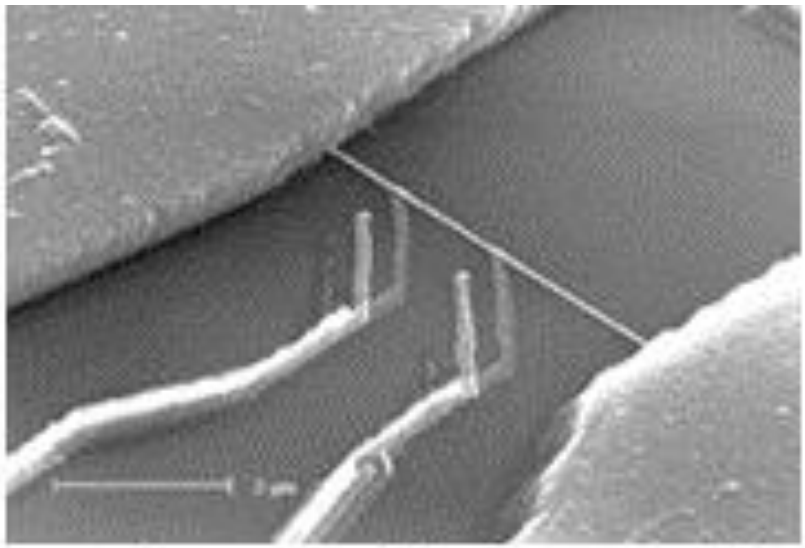
- Effect of interactions enhanced
- A whole bunch of new effects appear
- In quantum physics, thanks to confinement-induced quantization : very good quasi-low dimensional systems



Transport in a 50 nm nanowire (CEA)

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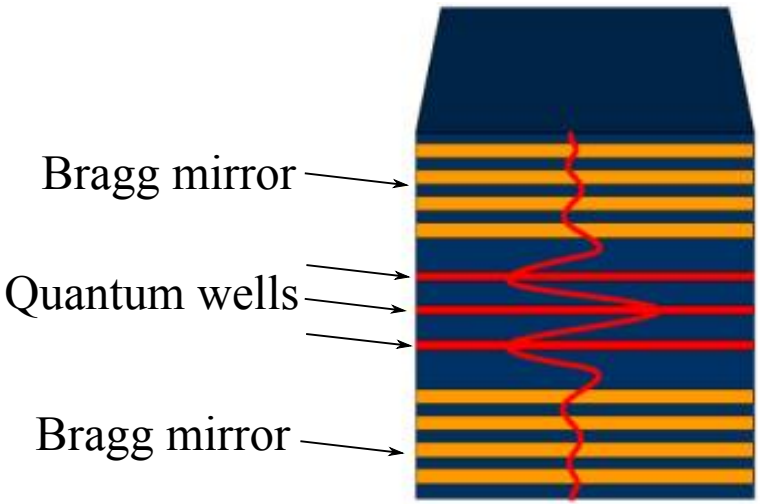

Image : University of Sheffield

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

Why studying 1D systems ?

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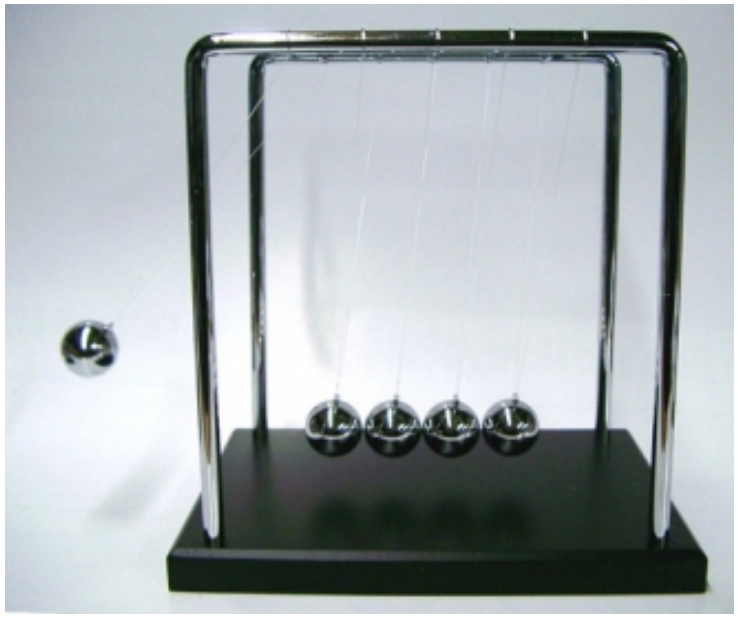
Very interesting from the theoretical point of view because :

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



Newton's cradle

Low dimensional gases of ultra-cold atoms

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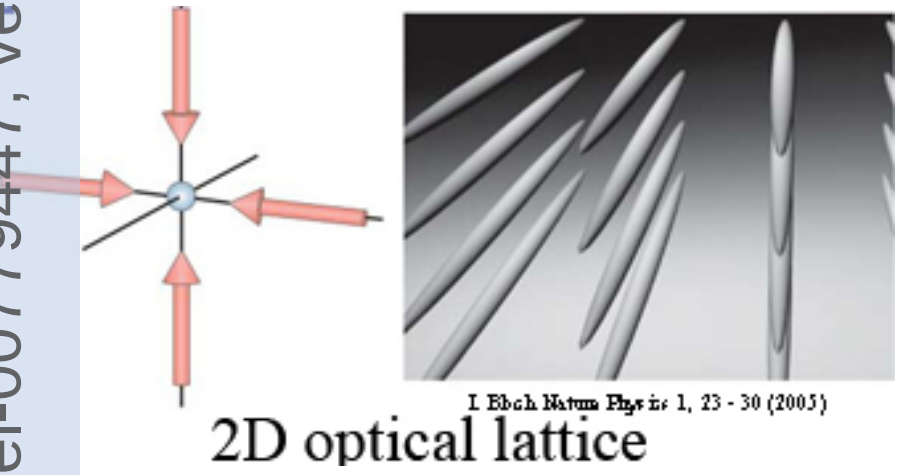
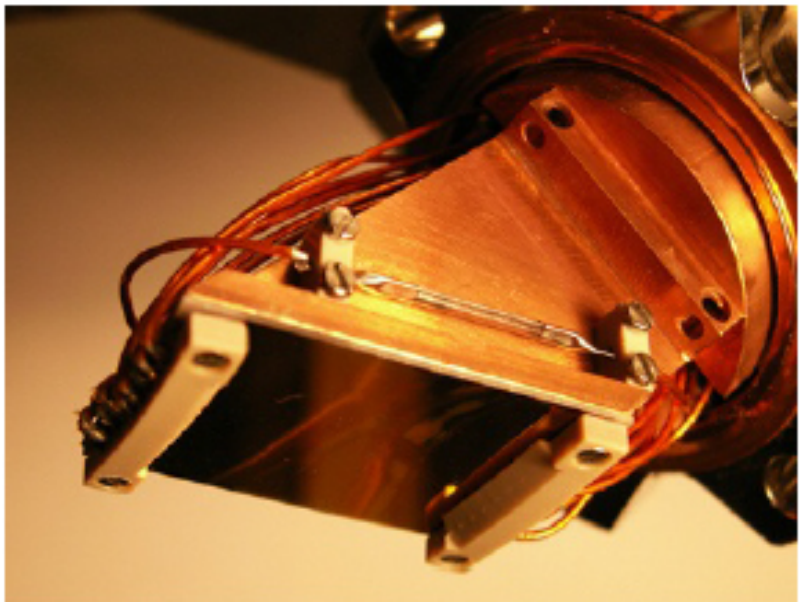
Cold atoms are suitable systems to study this Physics because

- 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

General framework : Quantum simulation

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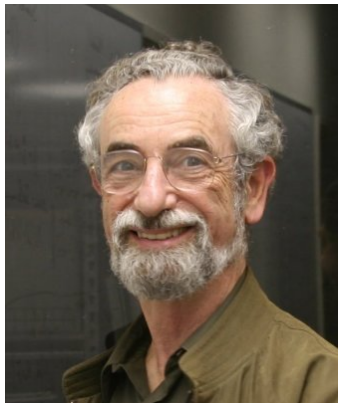
In general cold atoms can be used to simulate a lot of models :

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

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



Elliott H. Lieb

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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

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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

1D criterion

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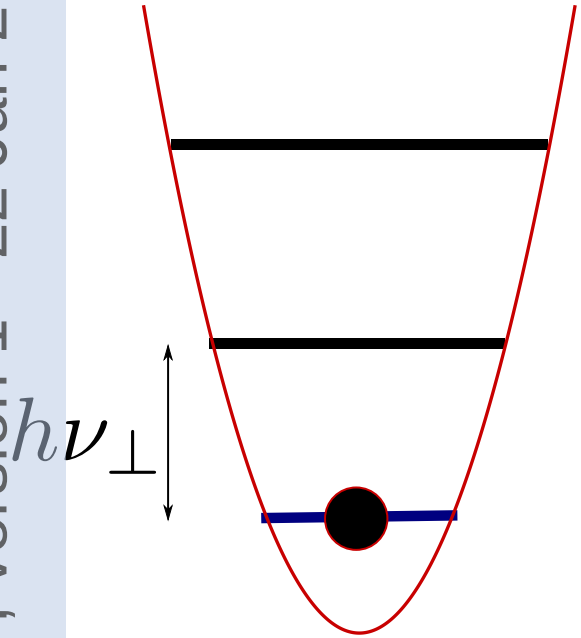

Transverse harmonic potential

- 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

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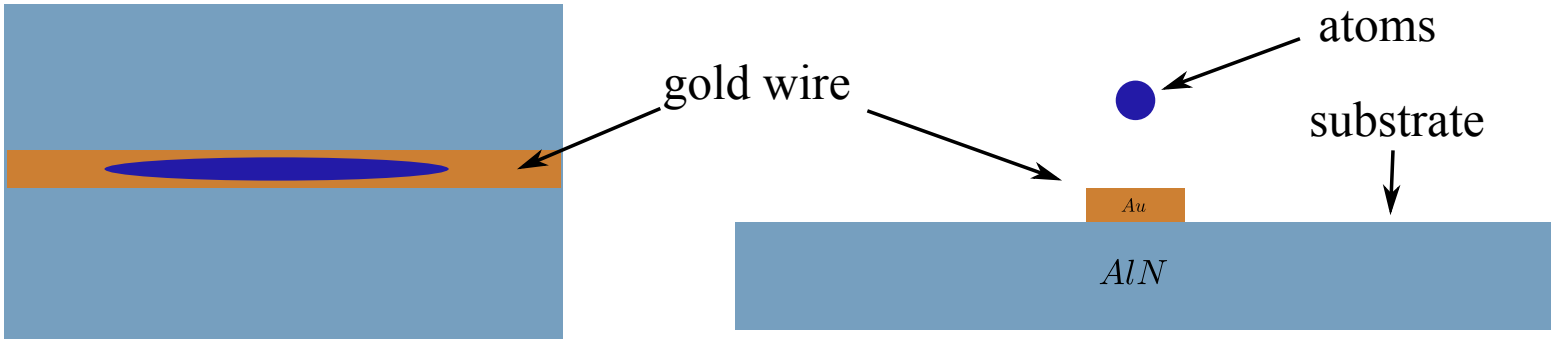
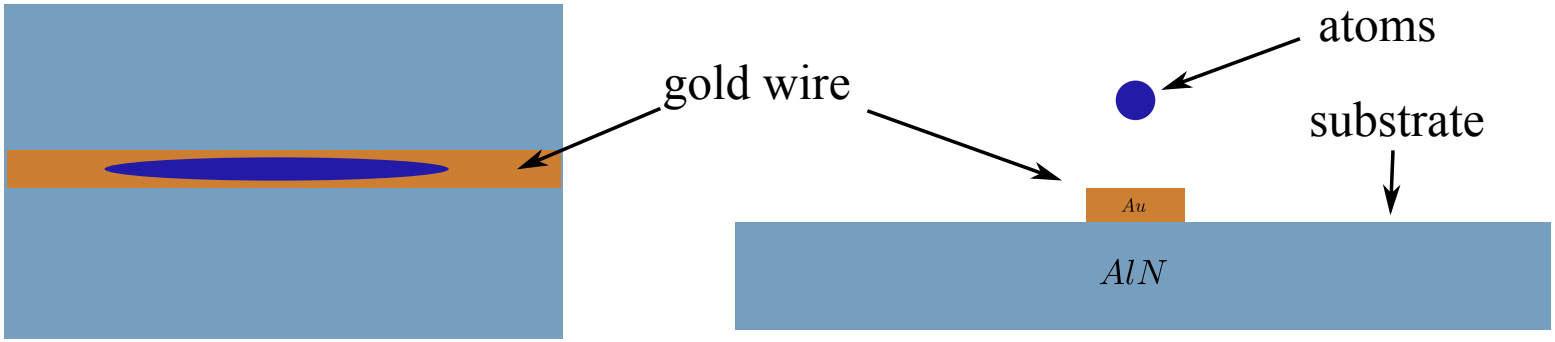
- The chip



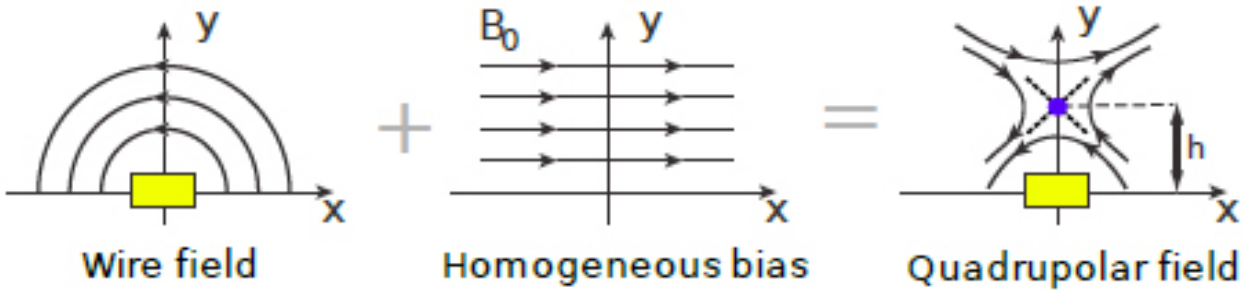
Transverse trapping with microwires

- The chip



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

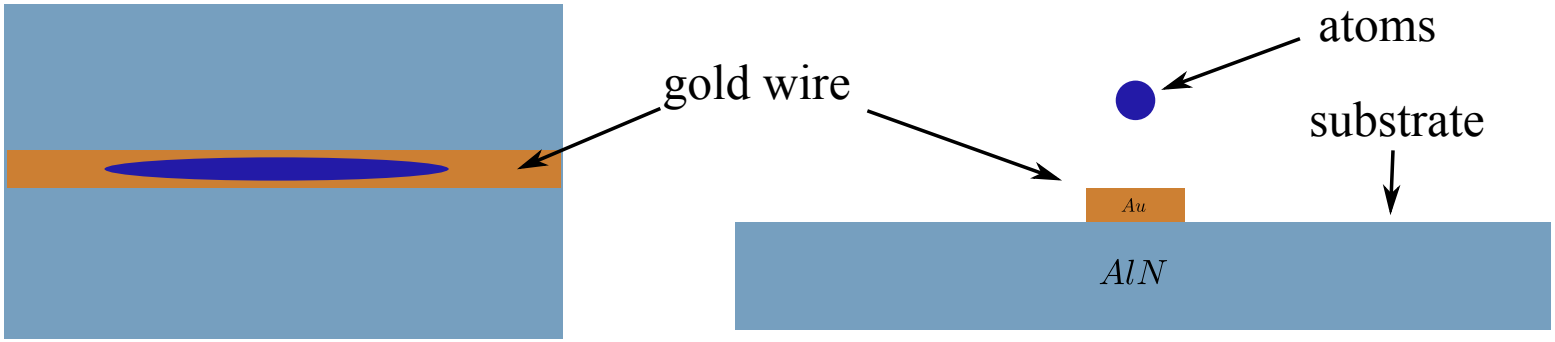
Magnetic potential $\boxed{V = -\mu_B |\vec{B}|}$



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

Transverse trapping with microwires

- The chip



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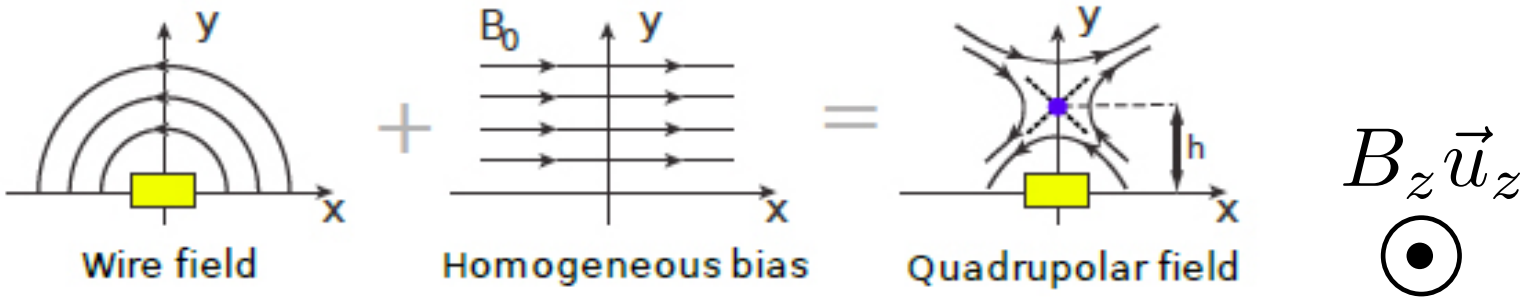

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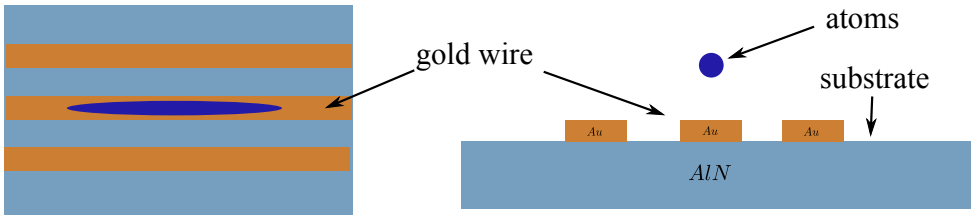
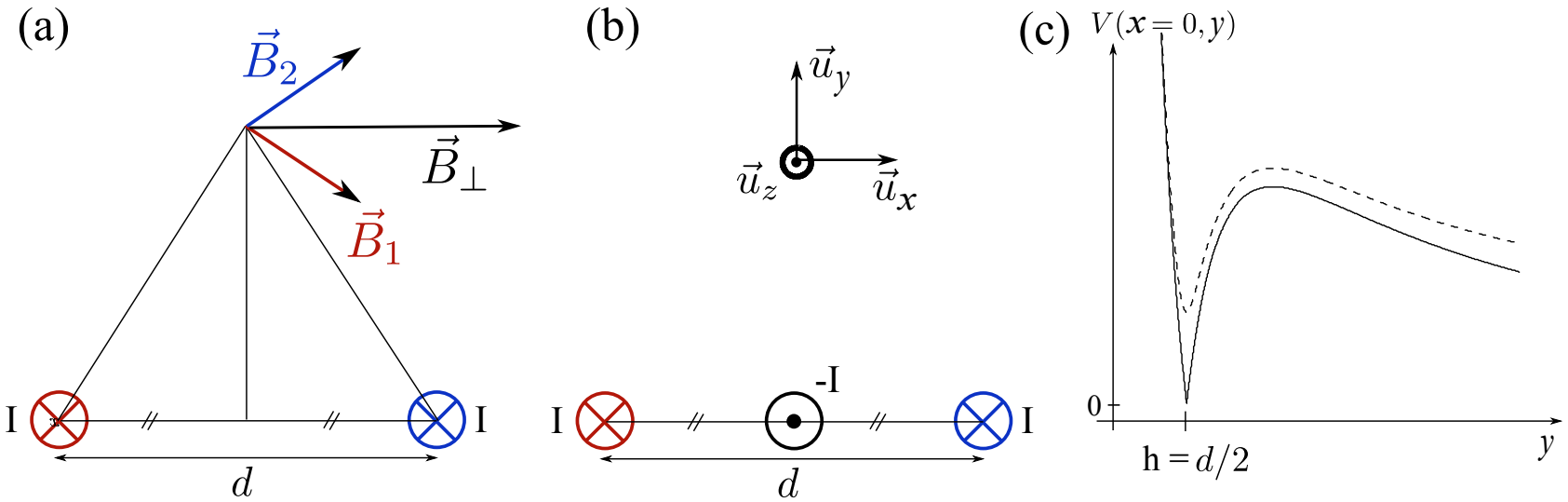
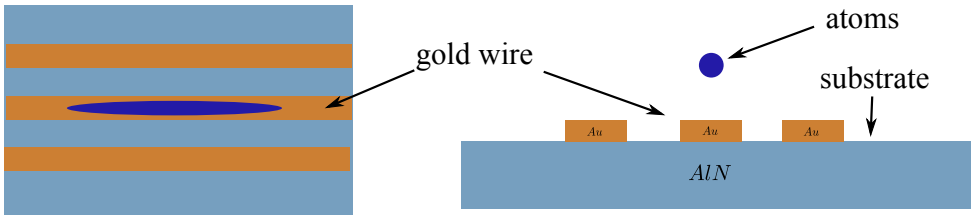
- Trapping in two directions with three parallel wires

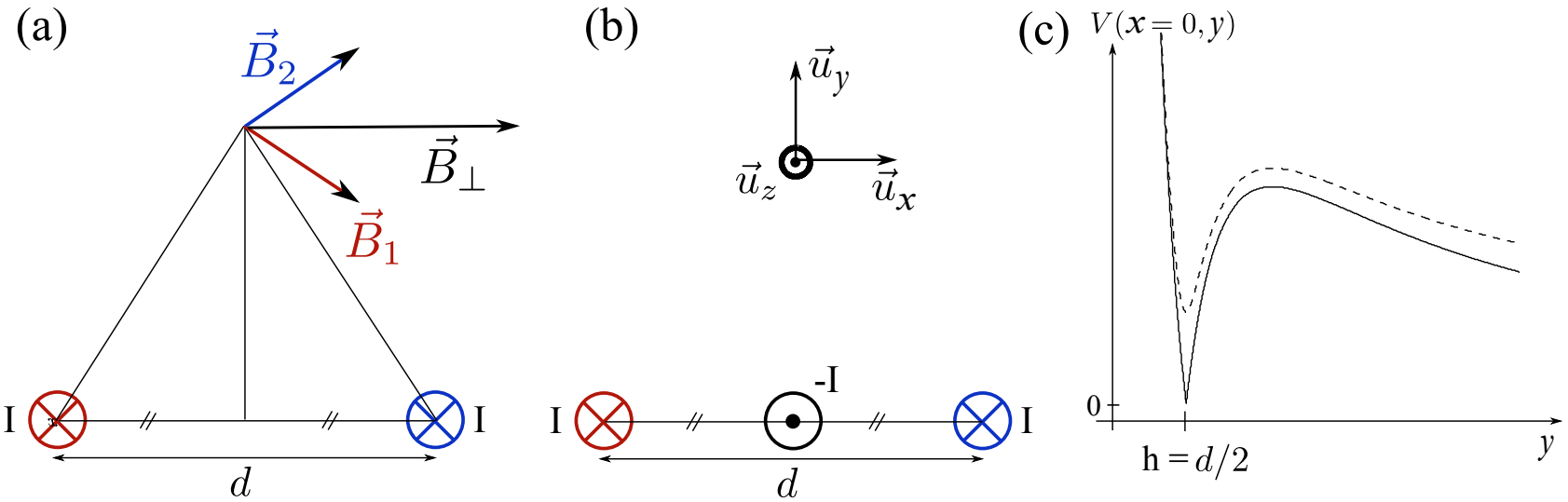




Transverse trapping with microwires

- Trapping in two directions with three parallel wires

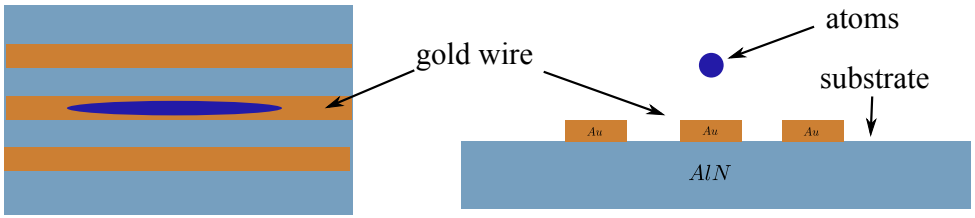


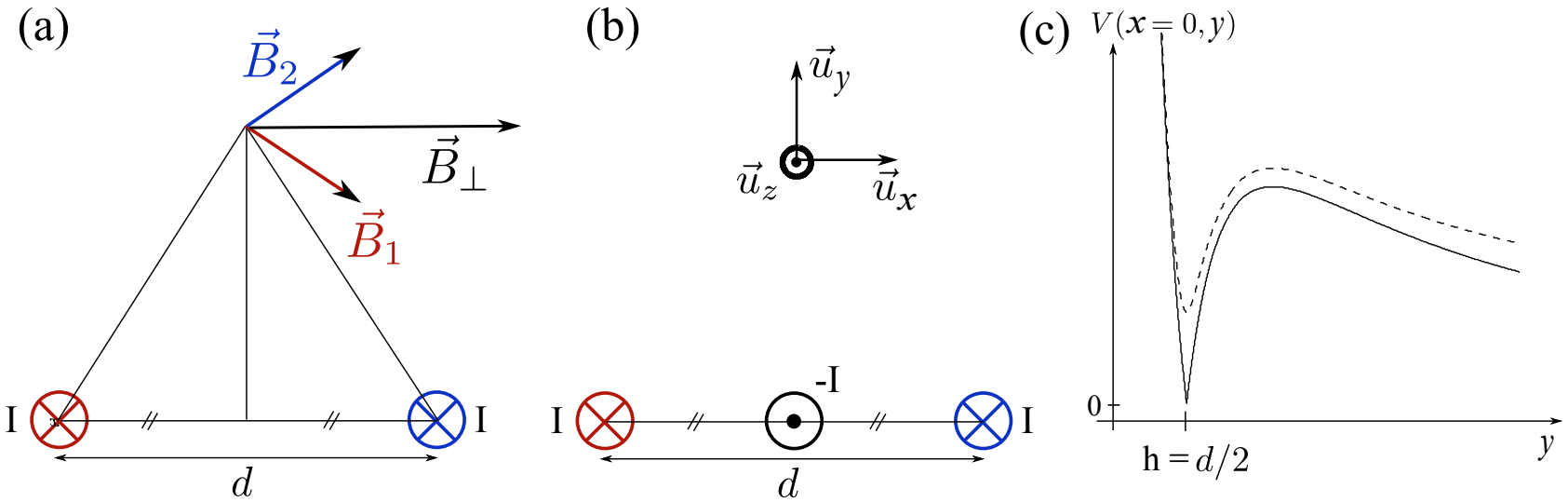


- If h is too small : longitudinal roughness of the potential

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

Transverse trapping with microwires

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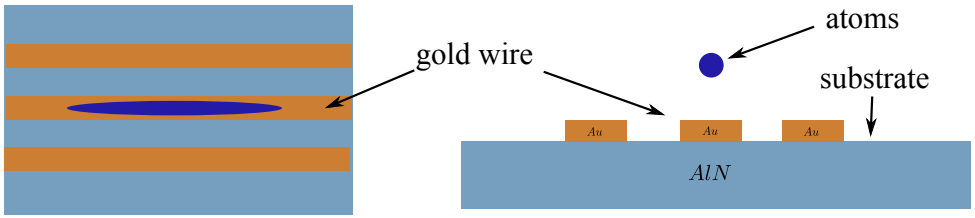

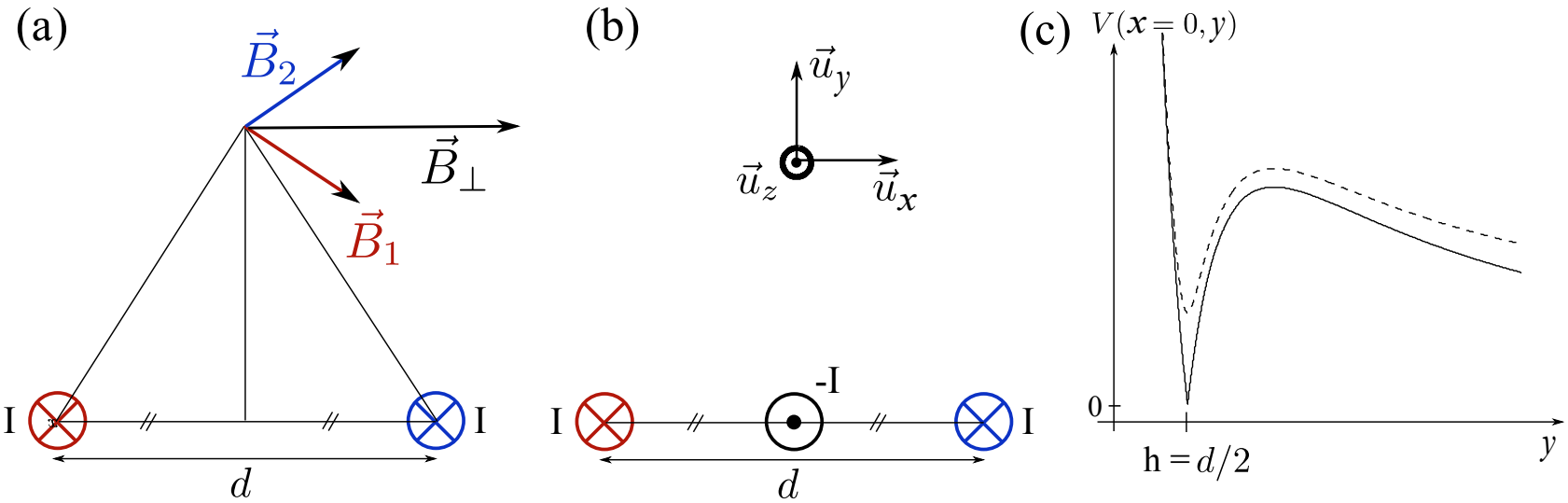

- If h is too small : longitudinal roughness of the potential
- Solution : current modulation
- for $h = 15$ μm and $I \leq 1$ A, $\omega_\perp/2\pi =$ [0.1, 80] kHz

Longitudinal trapping

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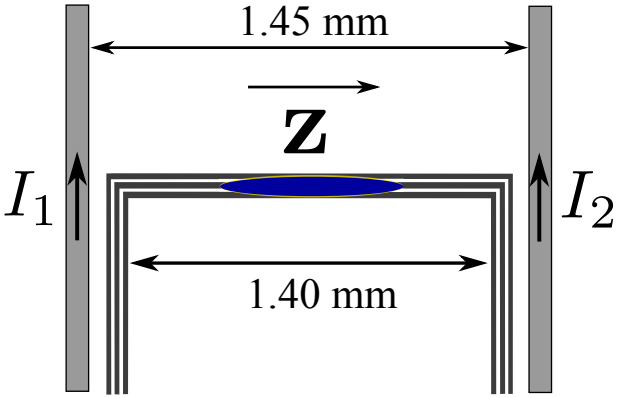
- Harmonic longitudinal trapping



Typical trapping frequencies :

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

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

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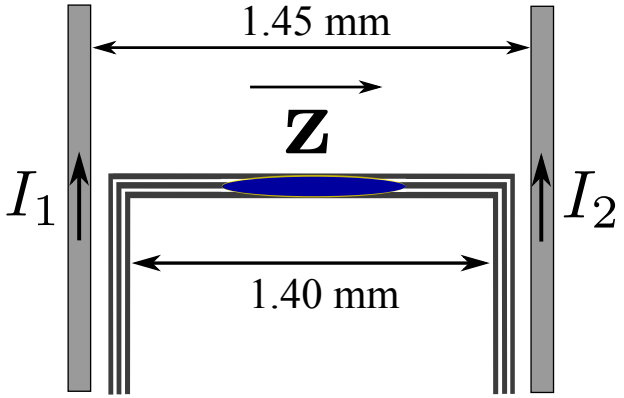

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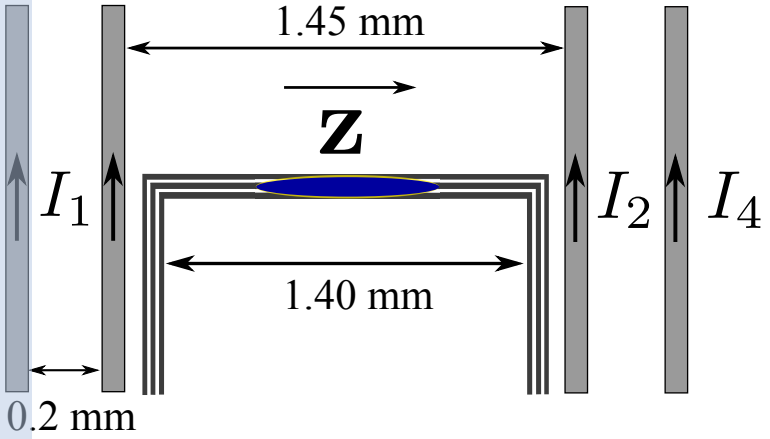
- Other longitudinal geometries



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

Longitudinal trapping

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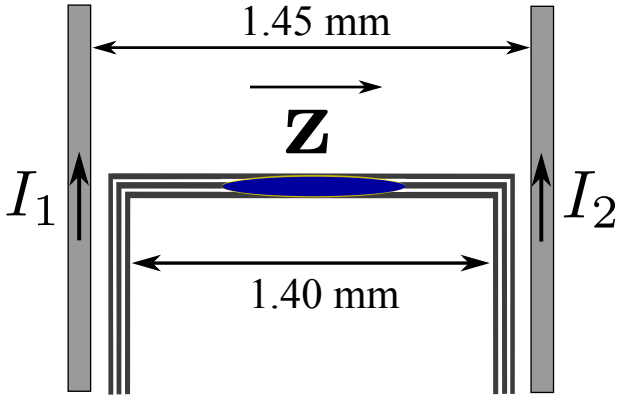

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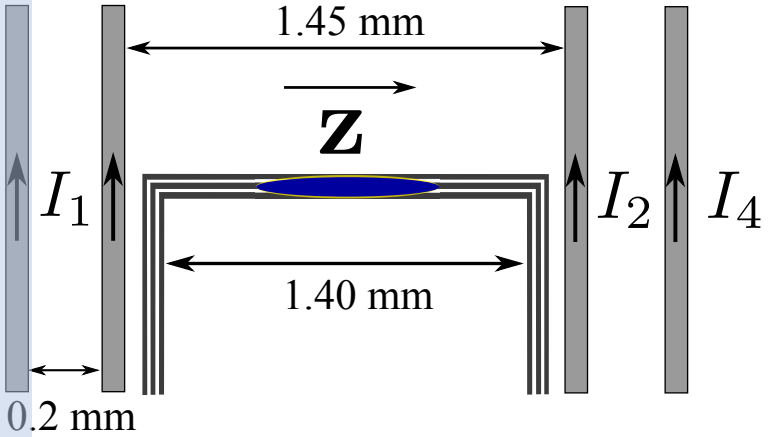

- Quartic trap
- Double well trap
- Fine tuning of anharmonicity

- Longitudinal and transverse traps totally decoupled

How do we observe the cloud ?

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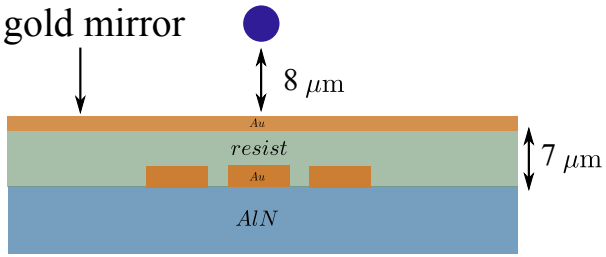
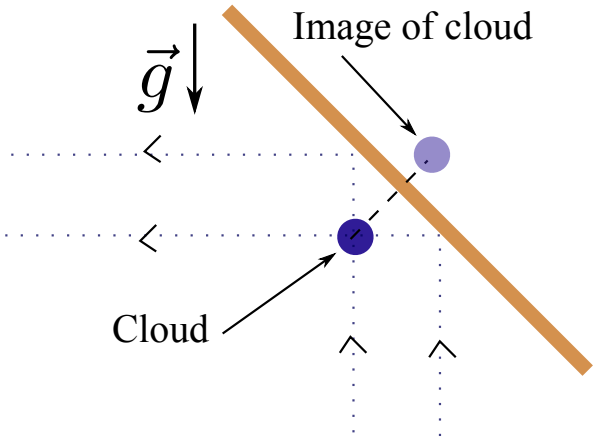
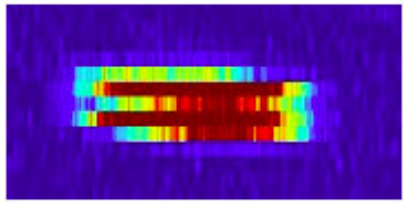
- Mirror on chip







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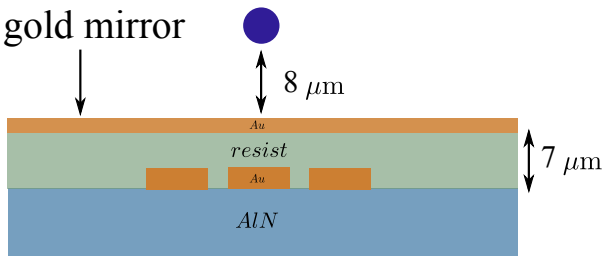
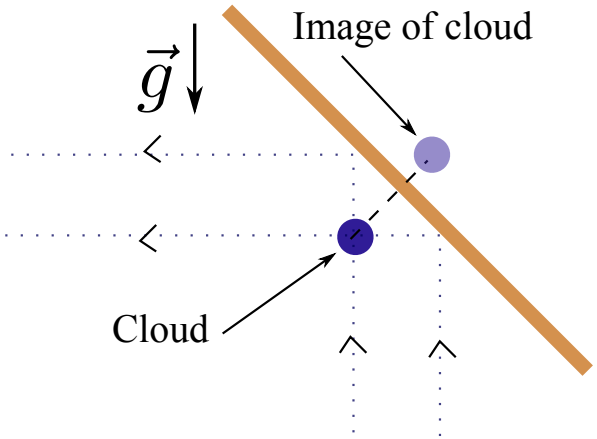
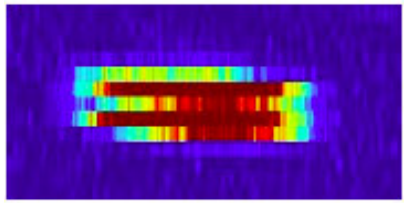
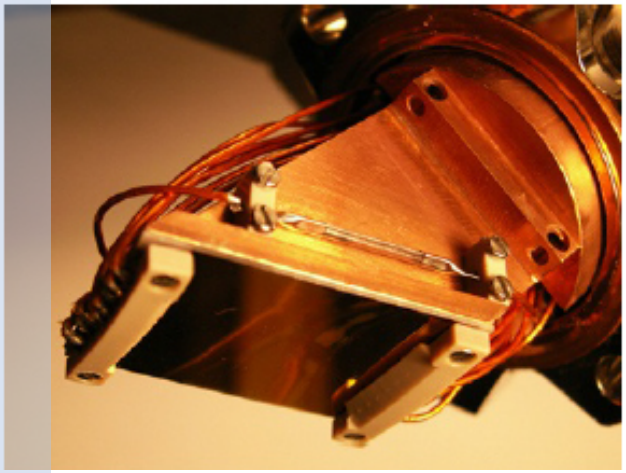
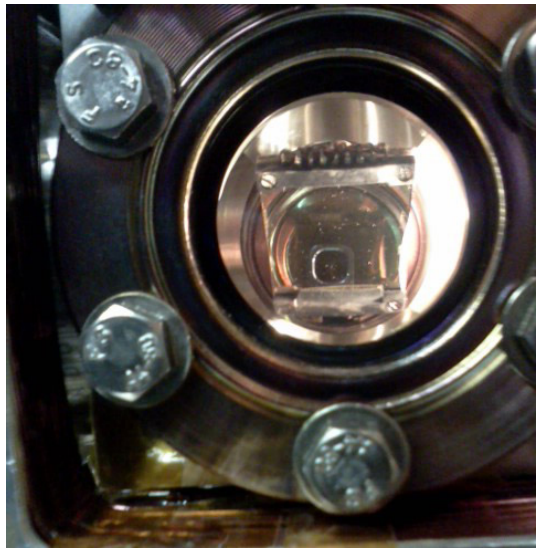








Chip on copper mount



Chip inside vacuum

How do we observe the cloud ?

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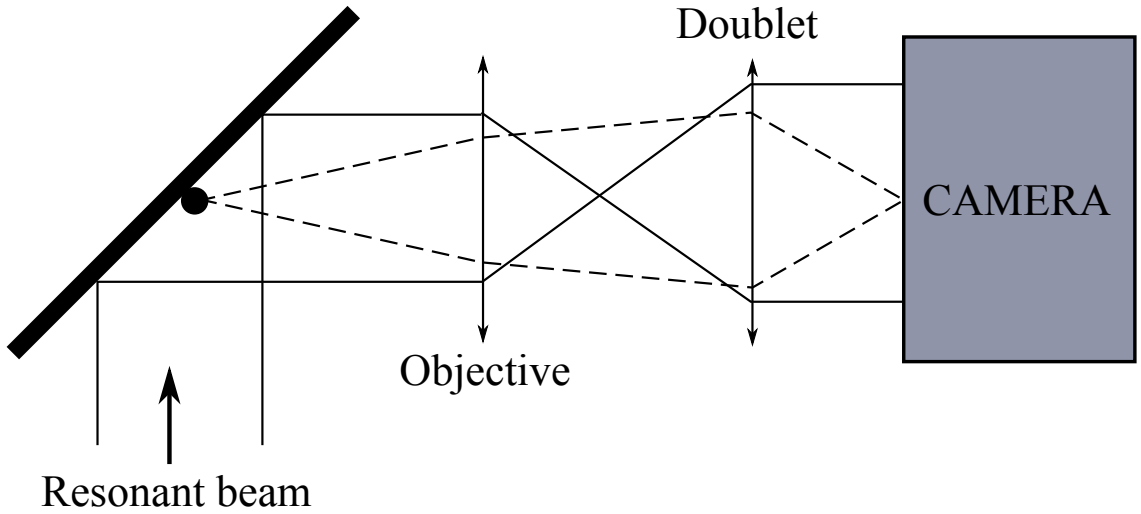
- Absorption imaging : a resonant laser illuminates the cloud, which is imaged on a CCD camera



- The Beer-Lambert law gives the atomic density ρ

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

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

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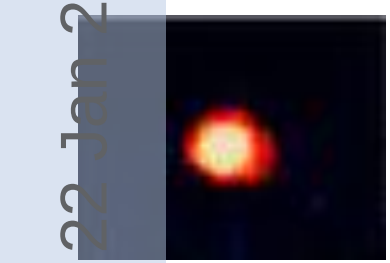
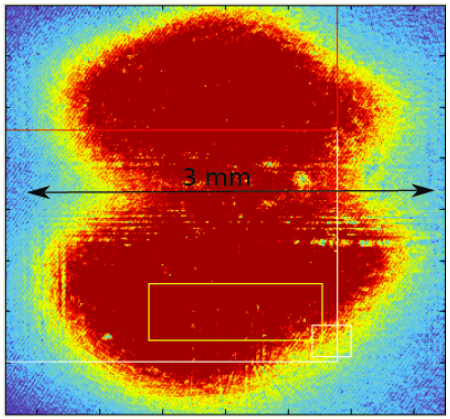


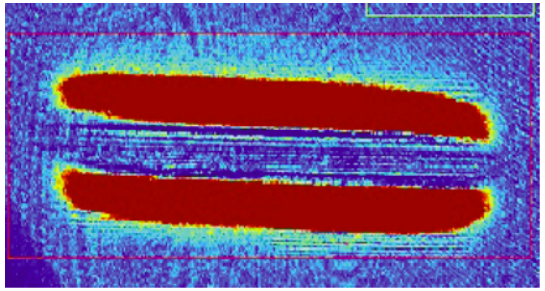
Laser cooling

MOT 1×10^8 at.
$\simeq 200\mu\ K$



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

Optical pumping in the trapped Zeeman sublevel



Magnetic trap
5×10^6 at.

Typical experimental sequence

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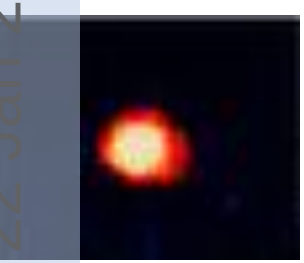
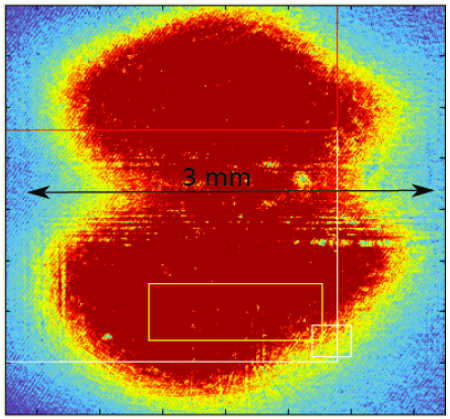


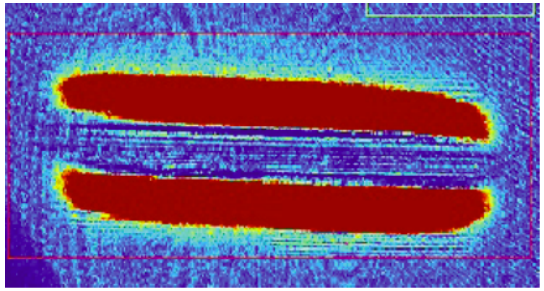
Laser cooling

MOT 1×10^8 at.
$\simeq 200\mu\ K$

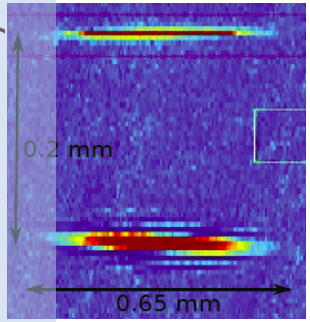


Optical mollases
5×10^7 at. $T \simeq 10\ \mu K$

Optical pumping in the trapped Zeeman sublevel

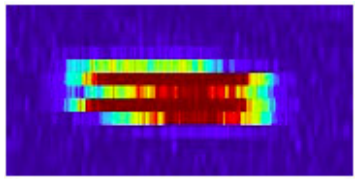


Magnetic trap
5×10^6 at.



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

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



AC Magnetic trap
8×10^4 at.

Final evaporation for about 1 s to the wanted temperature

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

Typical sequence

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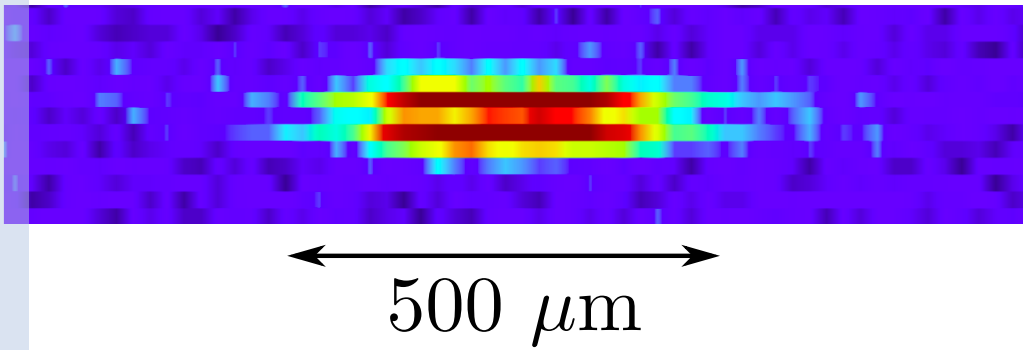
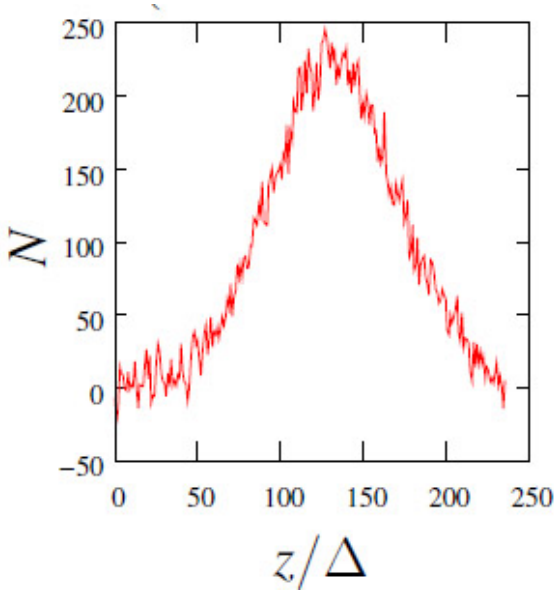
- Last step : take a picture
- Compute the longitudinal profile





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

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Outline

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- 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)

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- 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

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

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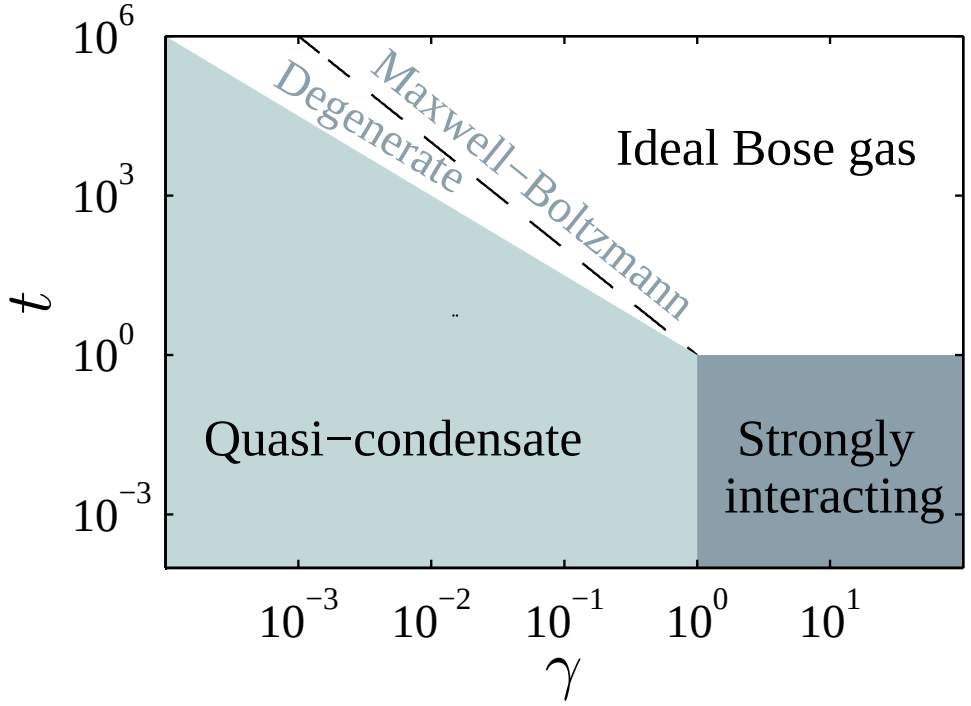
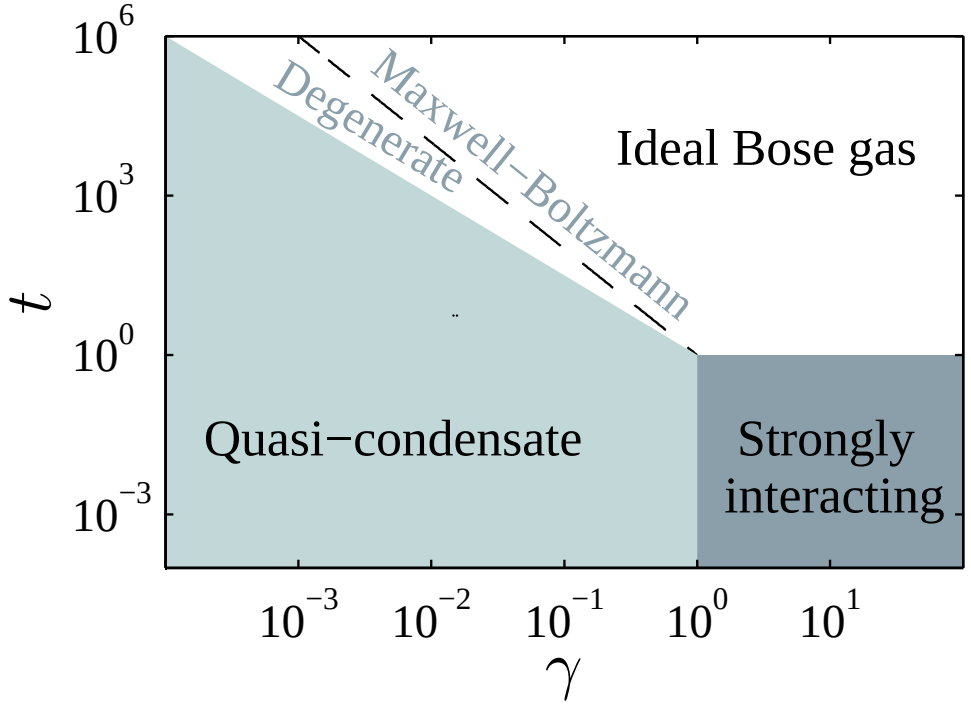


- Negligible interactions : Ideal Bose gas regime $g^{(2)}(0) = 2$

The 1D Bose gas at thermal equilibrium : Phase diagram



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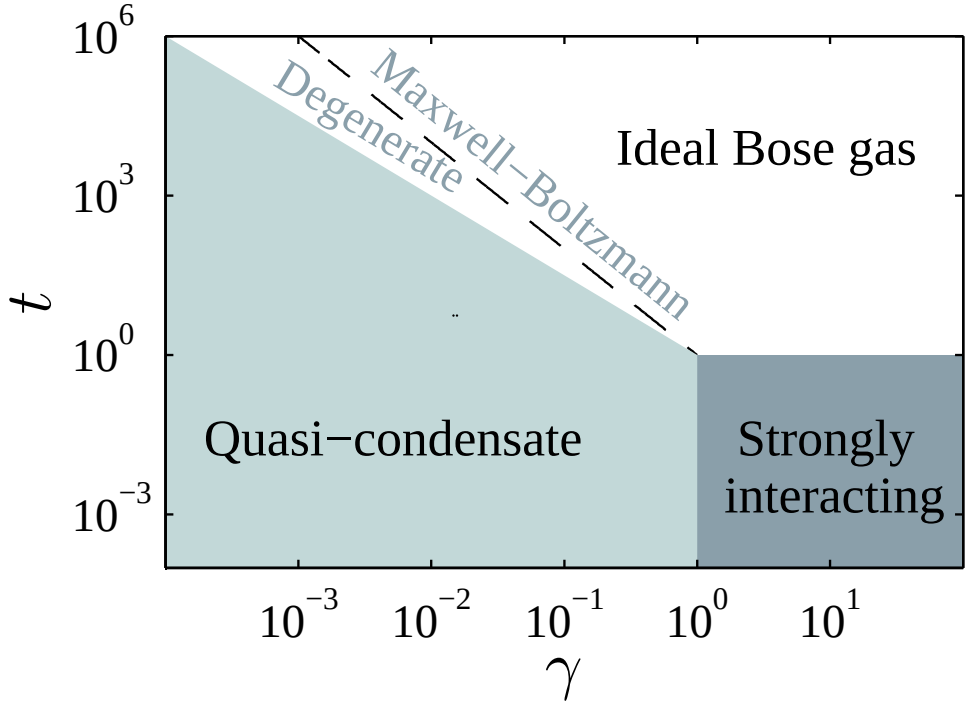

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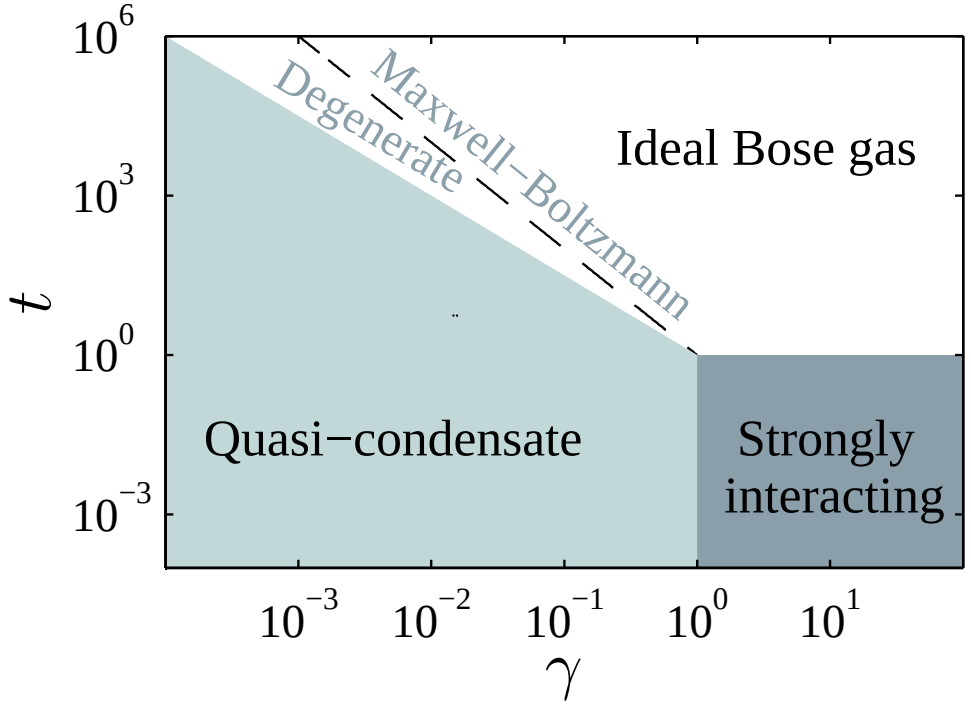

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- Density fluctuations reduced because of interactions : Quasi-condensate regime $g^{(2)}(0) \simeq 1$
- Interactions mimicking the Pauli principle for fermions : Strongly interacting regime $g^{(2)}(0) \ll 1$
- No phase transition in only smooth crossovers

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In situ density fluctuations measurements

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

Δ : pixel size

l_c : correlation length

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

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$\rightarrow$ Fluctuations-dissipation theorem :

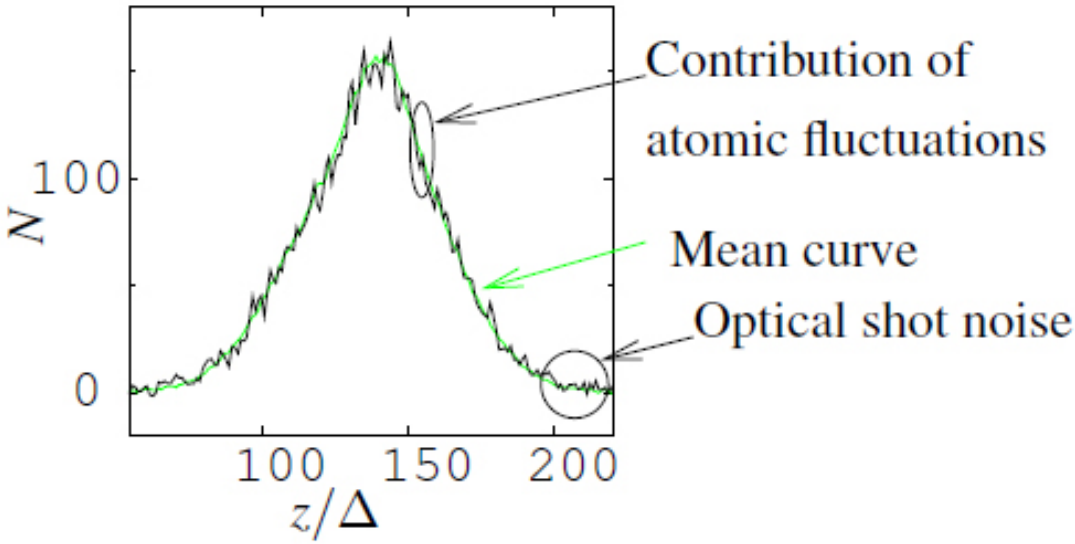
$$\boxed{\langle \delta N^2\rangle = \Delta k_B T \frac{\partial\rho}{\partial\mu}}$$

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

In situ density fluctuations measurements

tel-00779447, version 1 - 22 Jan 2013

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



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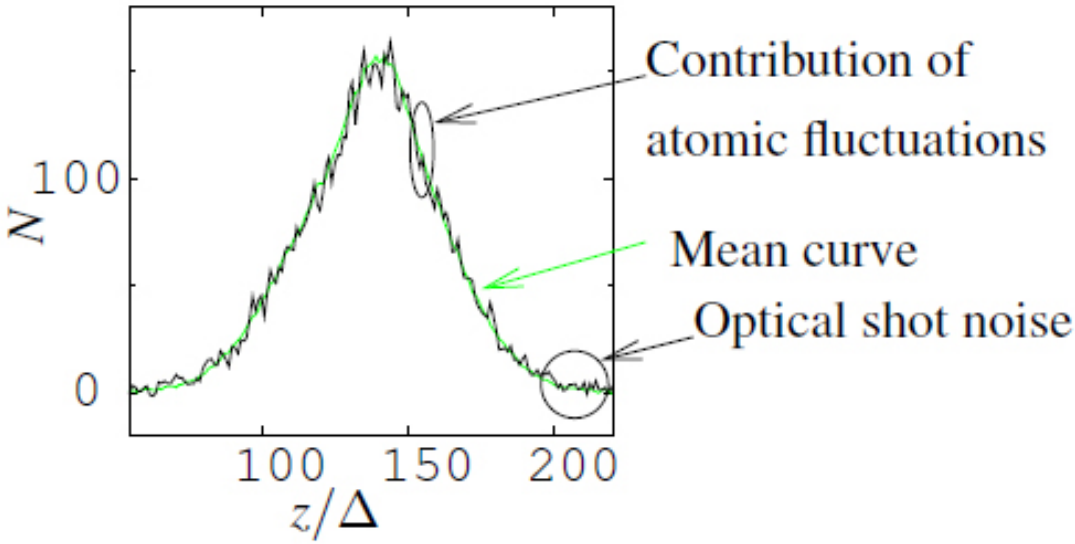

- We plot $\langle \delta N^2 \rangle$ as a function of $\langle N \rangle$
- Contribution of optical shot noise subtracted

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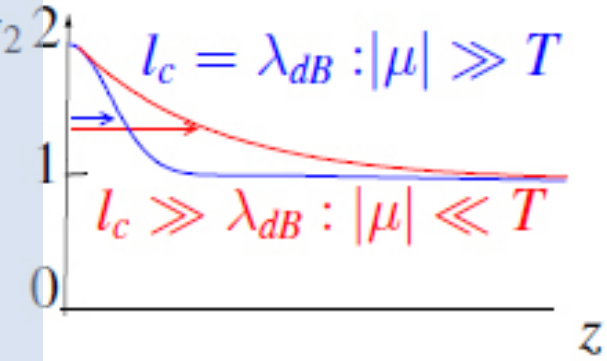
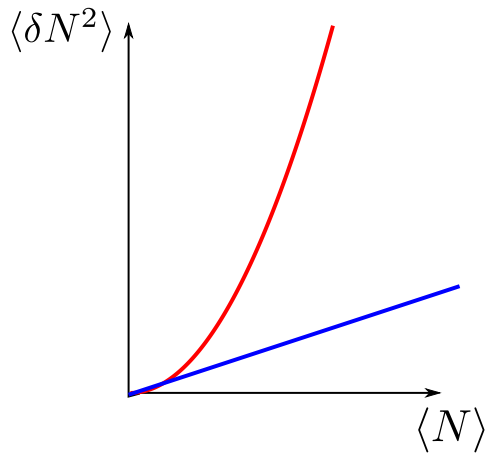
- Ideal Bose gas regime

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



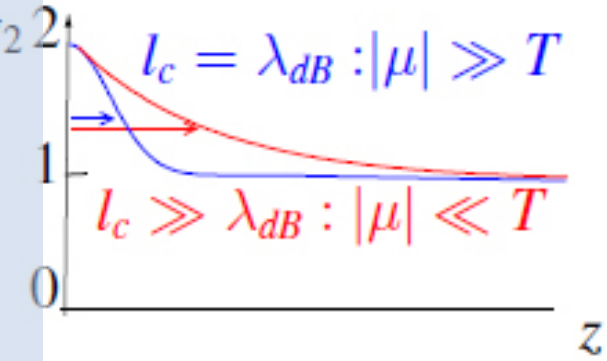
- Classical gas
  $\rho l_c \ll 1 \rightarrow \langle \delta N^2 \rangle \simeq \langle N \rangle$
- Degenerate gas
  $\rho l_c \gg 1 \rightarrow \langle \delta N^2 \rangle \simeq \langle N \rangle^2 l_c / \Delta$



Expected behaviour in different regimes

- Ideal Bose gas regime

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



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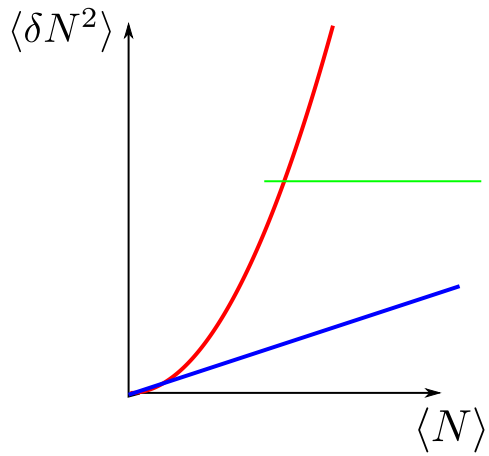

- Quasi-condensate :
  EOS : $\mu \simeq g\rho$
  $\langle \delta N^2 \rangle \simeq \Delta k_B T / g$

Experimental results in the quasi-condensate regime

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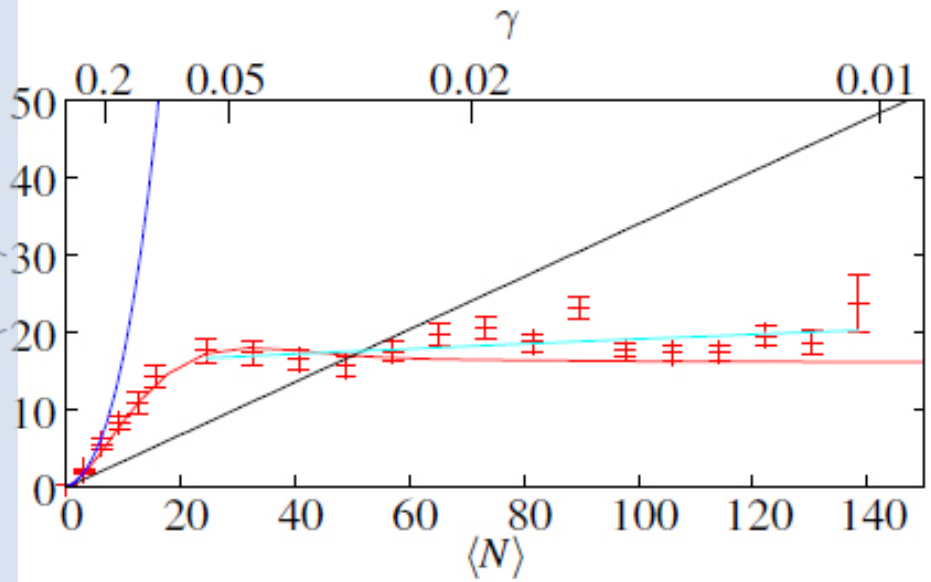
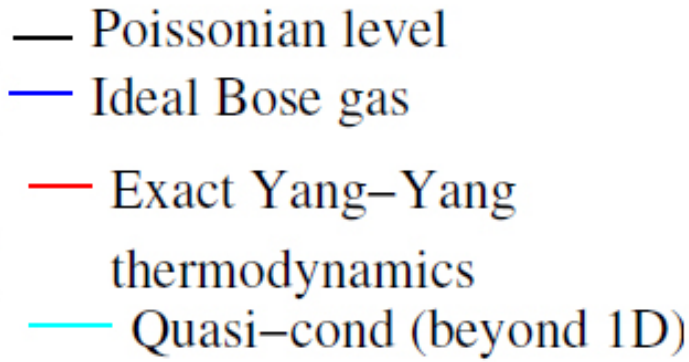
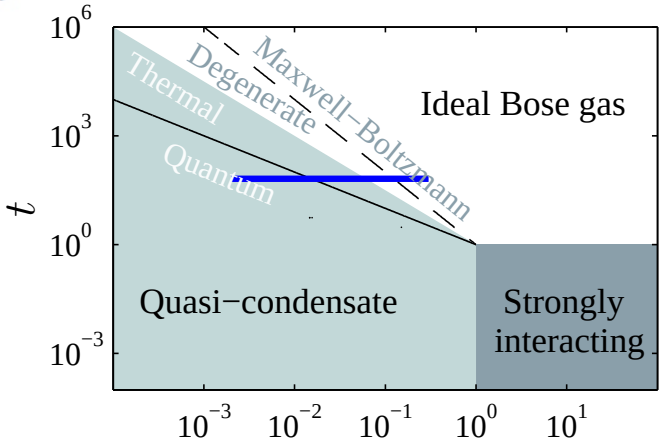
- Bosonic bunching at low densities $\rightarrow$ super-Poissonian fluctuations





- T $\simeq$ 15 nK
- $k_B T/\hbar\omega_\perp \simeq 0.1$
- $\mu \simeq 30nK$
- $\mu/\hbar\omega_\perp \simeq 0.2$

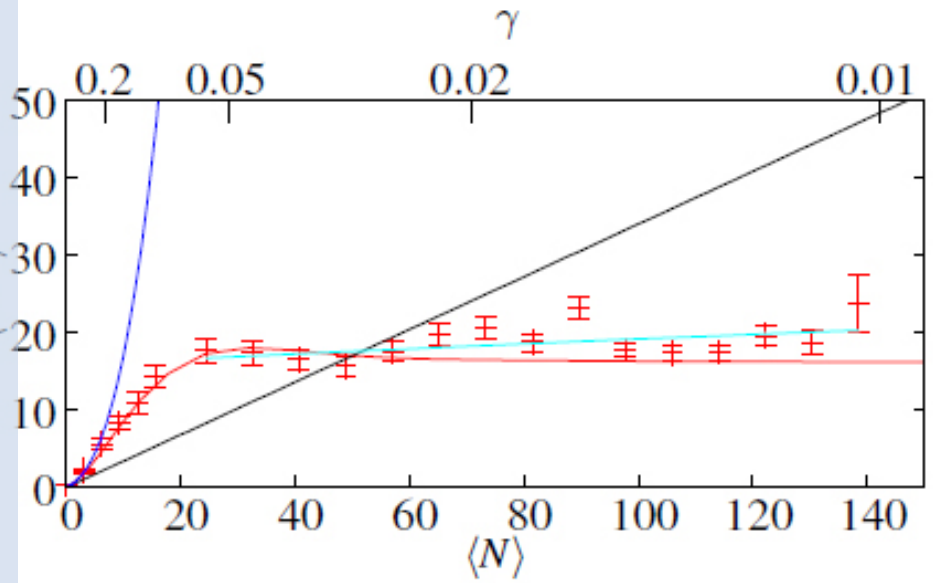


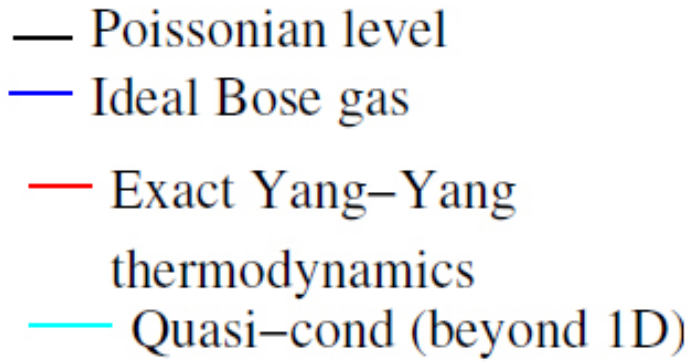
PRL **106**, 230405 (2011)

Experimental results in the quasi-condensate regime

tel-00779447, version 1 - 22 Jan 2013

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





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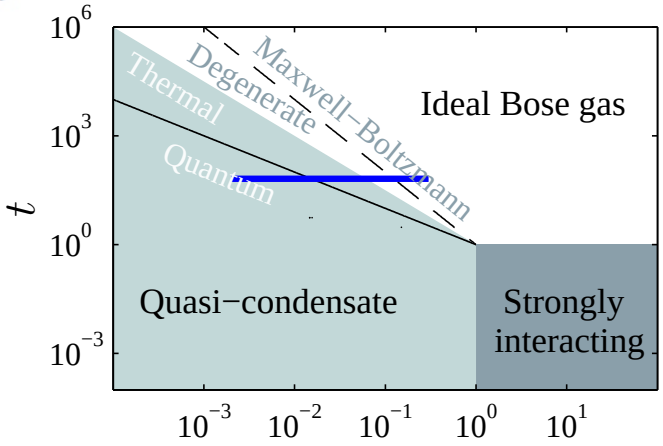

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Experimental results in the quasi-condensate regime

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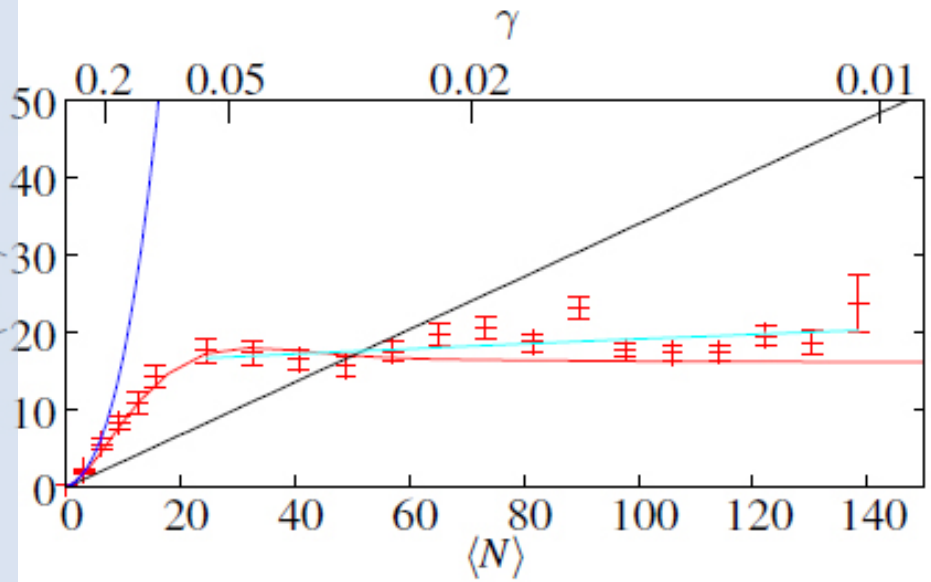
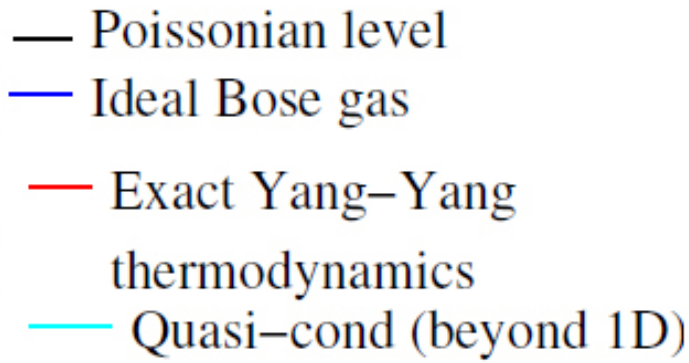
- Bosonic bunching at low densities $\rightarrow$ super-Poissonian fluctuations
- Saturation of the density fluctuations in the QBEC regime
- In the QBEC regime : super and sub-Poissonian fluctuations





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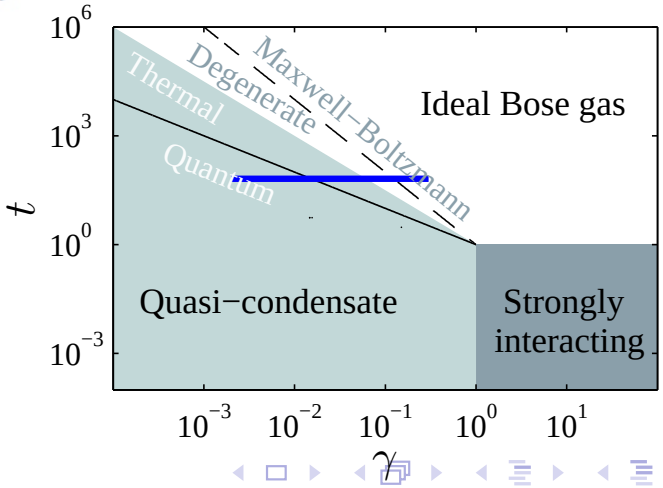

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First observation of the quantum quasi-condensate regime

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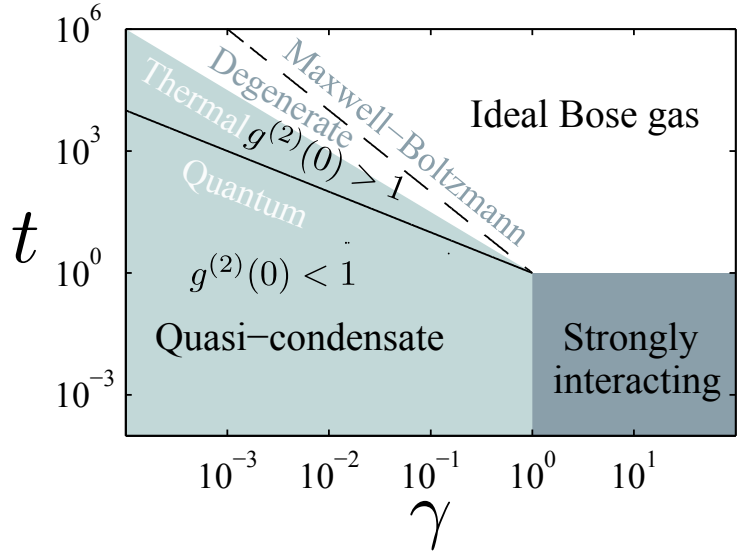
- $\langle \delta N^2 \rangle < \langle N \rangle$ and $\langle \delta N^2 \rangle = \langle N \rangle + \langle N \rangle \rho \int [g^{(2)}(z) - 1] dz$

$\rightarrow g^{(2)} < 1 \rightarrow g^{(2)}(0)$ dominated by quantum fluctuations.



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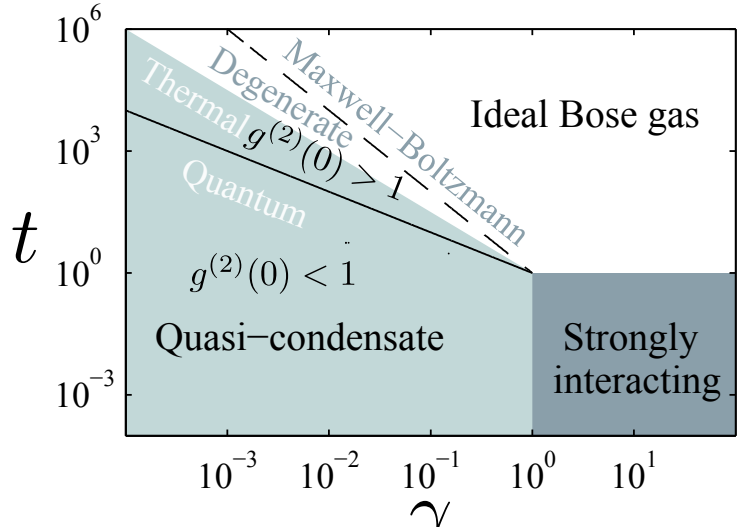
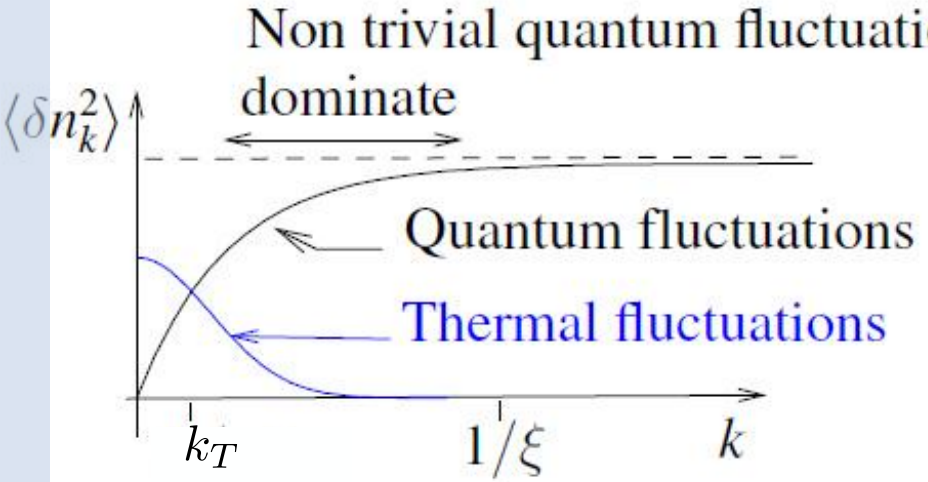


- However we still measure thermal fluctuations.



Thermal phonons :

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

$$\hbar\omega(k_T) = k_B T$$

$$k_T = \frac{k_B T}{\mu \xi} \gg \frac{1}{\Delta}$$

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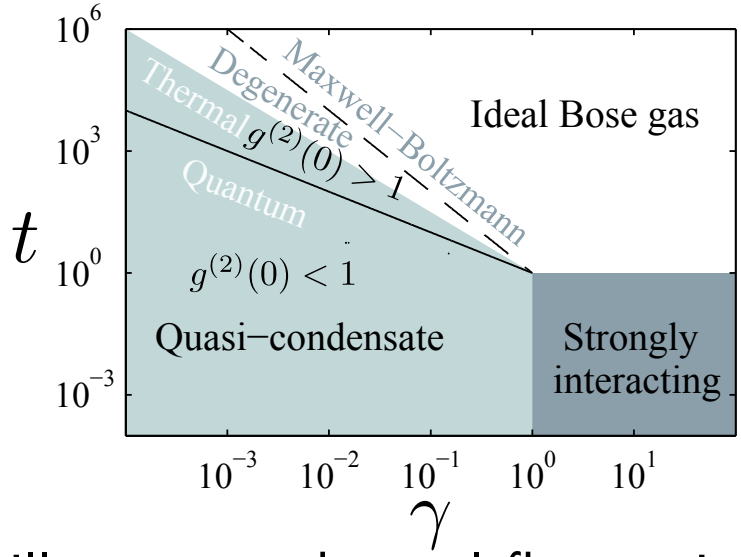

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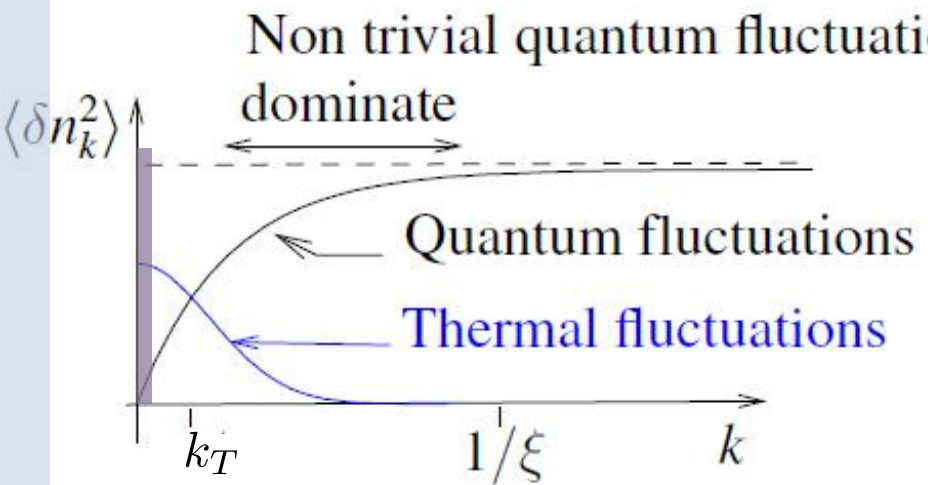

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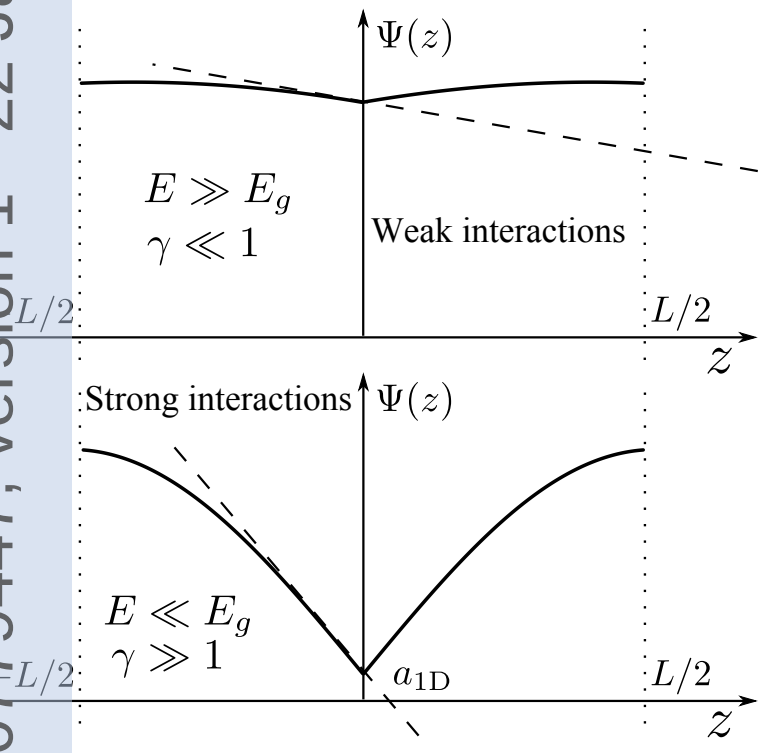
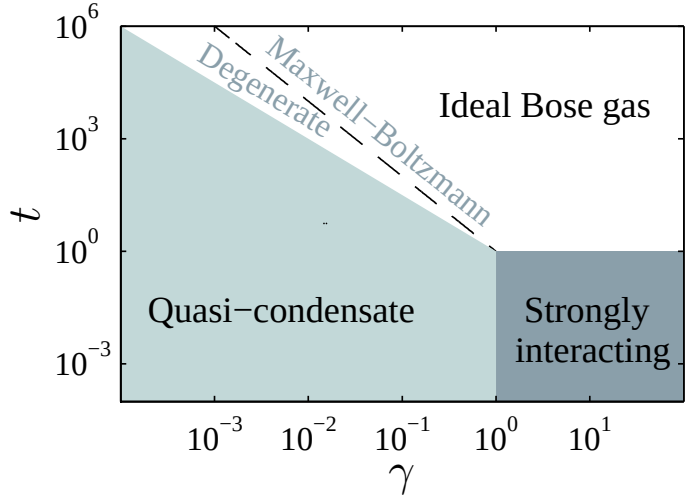
The strongly interacting regime

tel-00779447, version 1 - 22 Jan 2013

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



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



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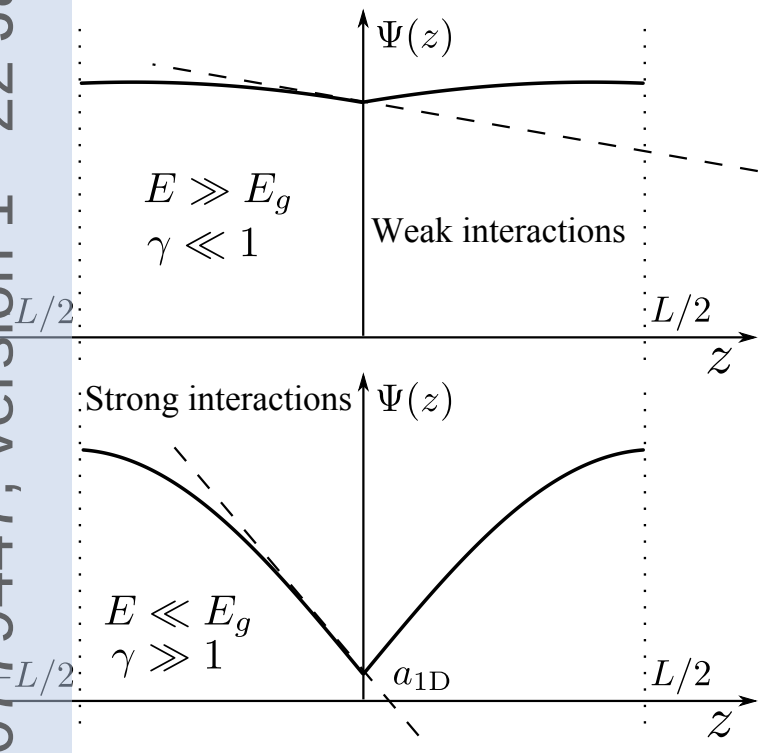

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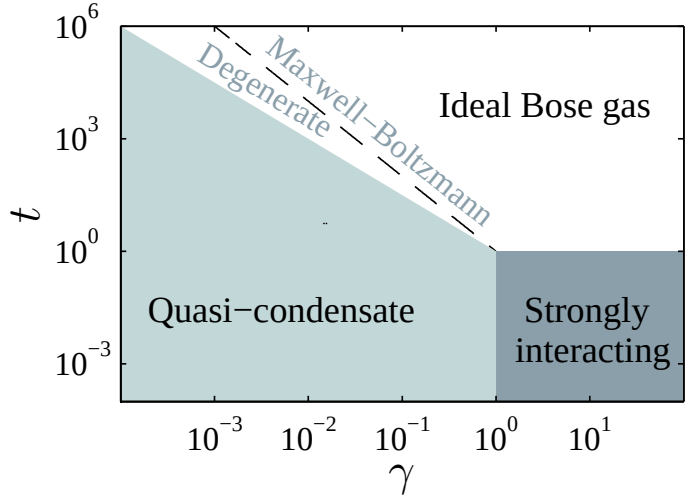
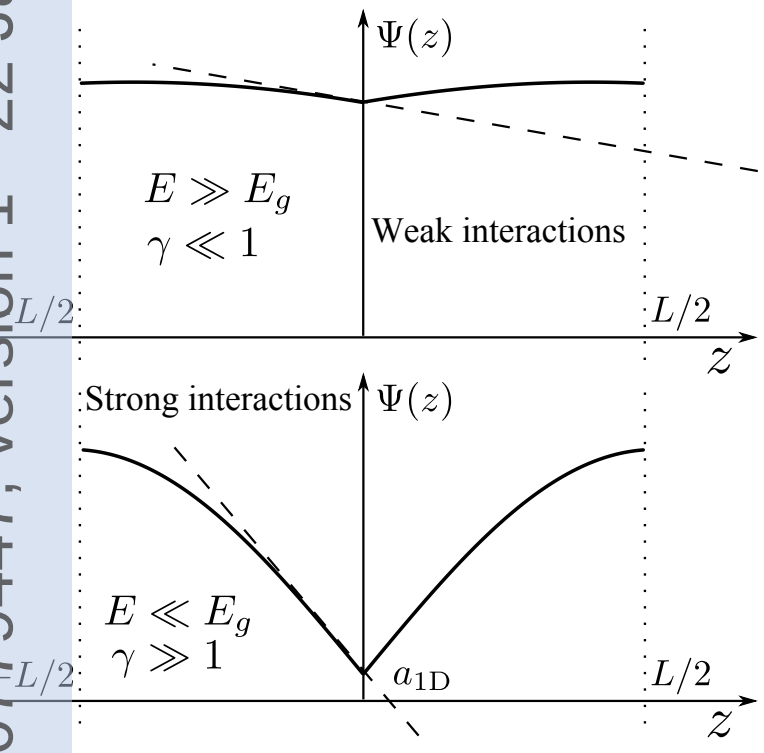


- Bose-Fermi mapping
  $\Psi_B(z_1, ..., z_N) = \mathcal{S}[\Psi_F(z_1, ..., z_N)]$

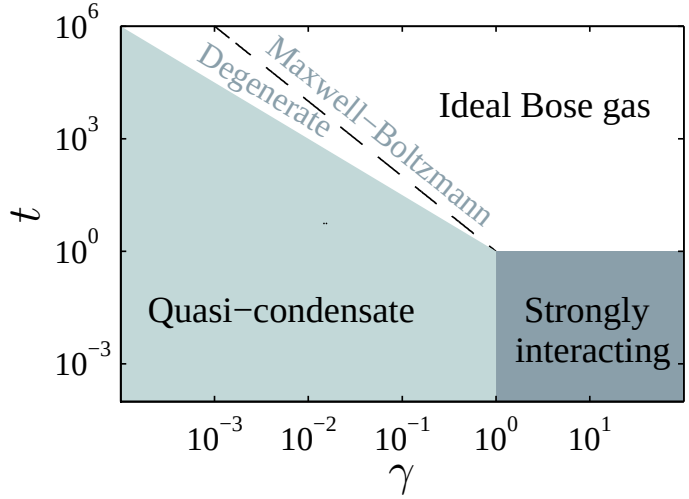
The strongly interacting regime

tel-00779447, version 1 - 22 Jan 2013

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



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



- Bose-Fermi mapping
  $\Psi_B(z_1, ..., z_N) = \mathcal{S}[\Psi_F(z_1, ..., z_N)]$

- 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

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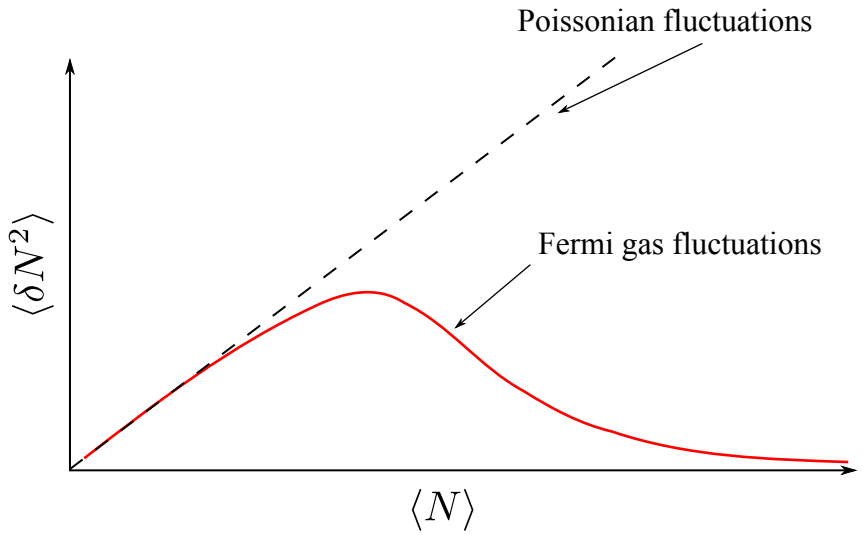

- Poissonian at low densities
- Sub-Poissonian at intermediate densities
- Zero at high densities

Experimental results in the strongly interacting regime

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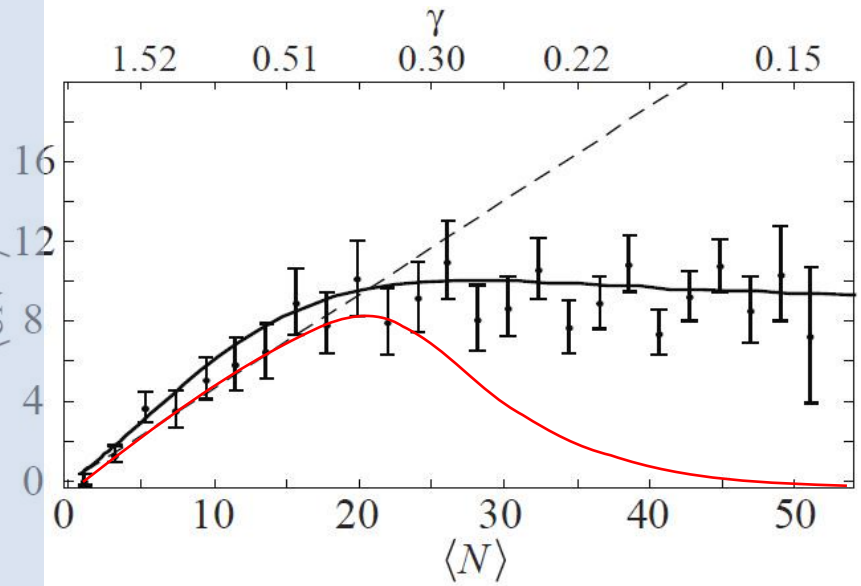
- t = 5.4 with $\nu_\perp \simeq 20$ *kHz*
- Absence of super-Poissonian density fluctuations
- Sub-Poissonian density fluctuations at any density

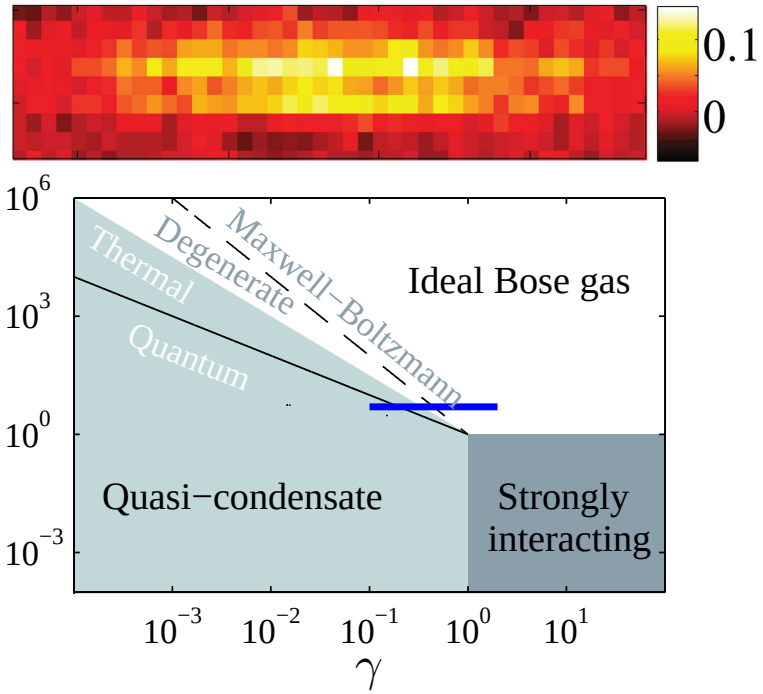


Solid line : Yang-Yang

Dashed line : Poissonian fluctuation

Red line : $t \ll 1$ limit

Typical image



PRL **106**, 230405 (2011)

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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

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- 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 $\hbar k$.
- **Conclusion** : 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)

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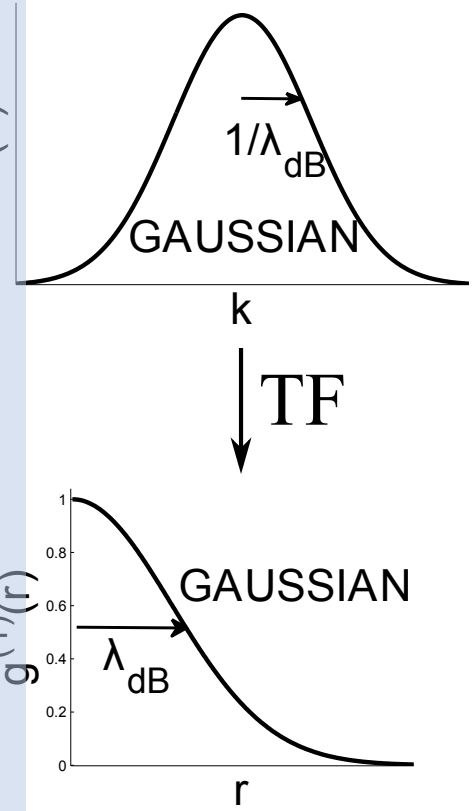
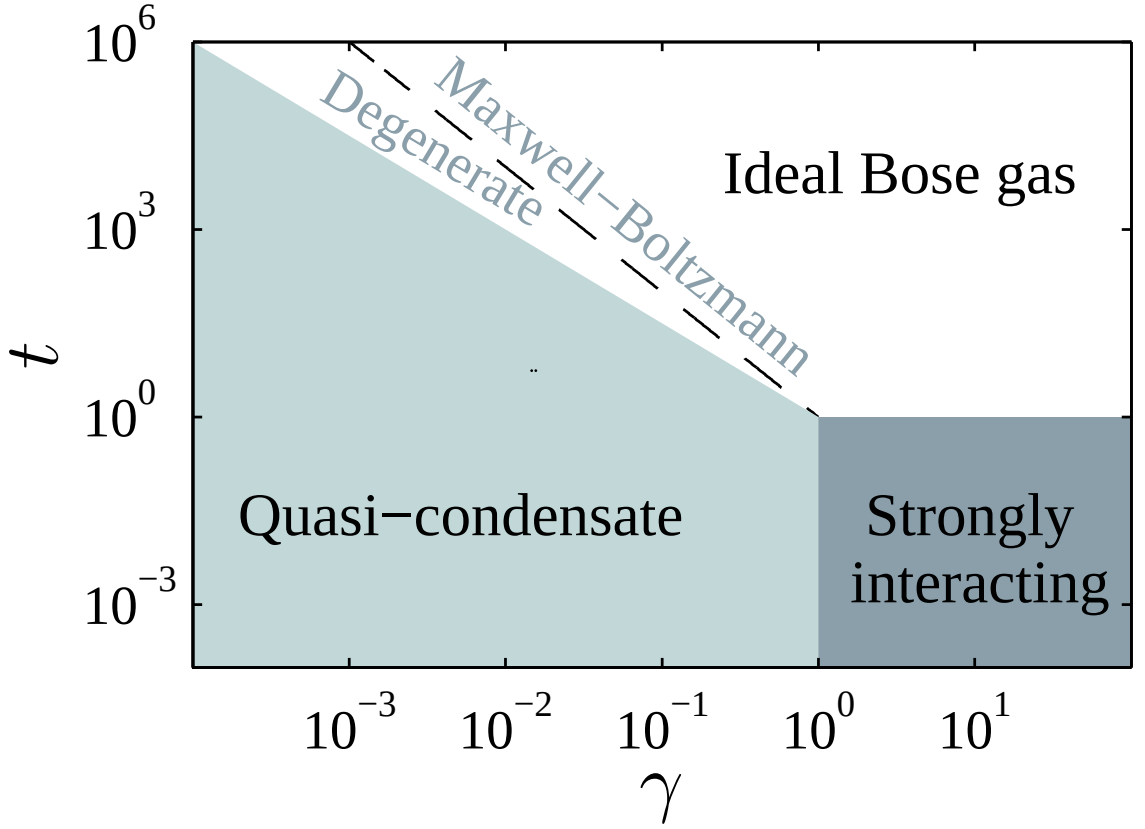
- Maxwell-Boltzmann gas





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

Degenerate Bose gas

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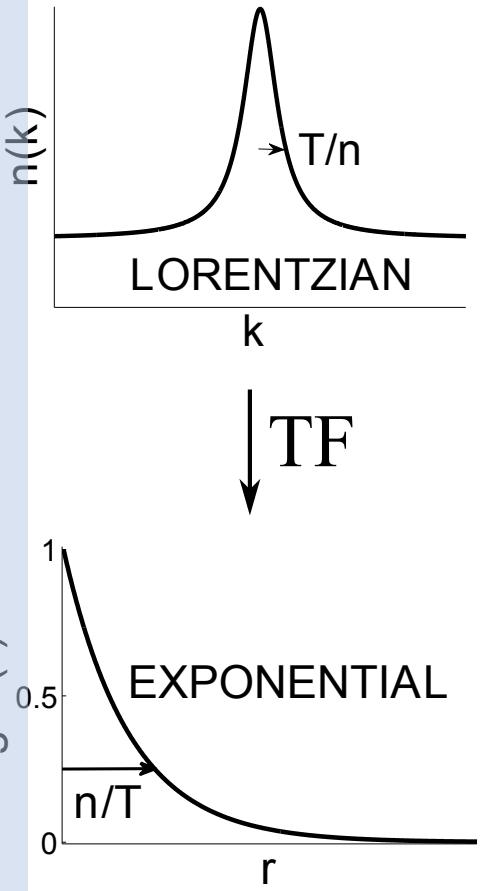

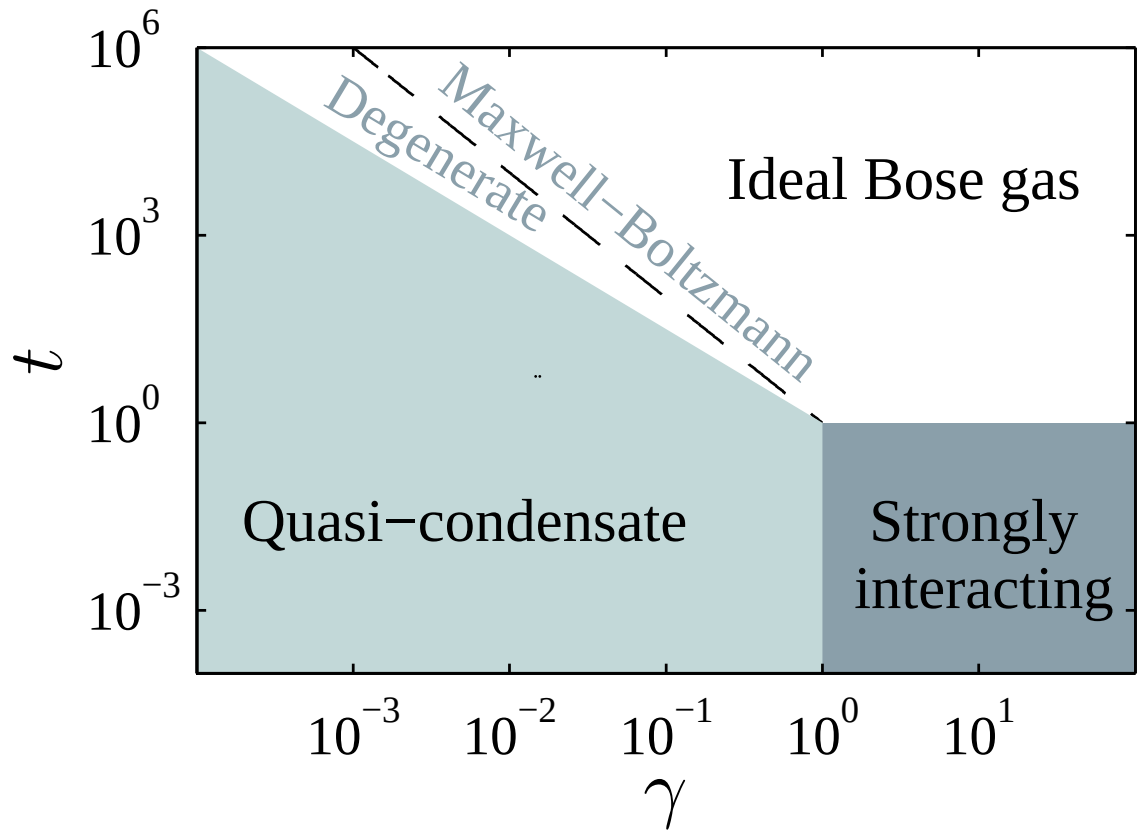

$k_B T \ll |\mu|$ Bose law limit : $\langle n_k \rangle \propto \frac{k_B T}{\epsilon_k - \mu}$, with $\epsilon_k = \frac{\hbar^2 k^2}{2m}$

Quasi-condensate

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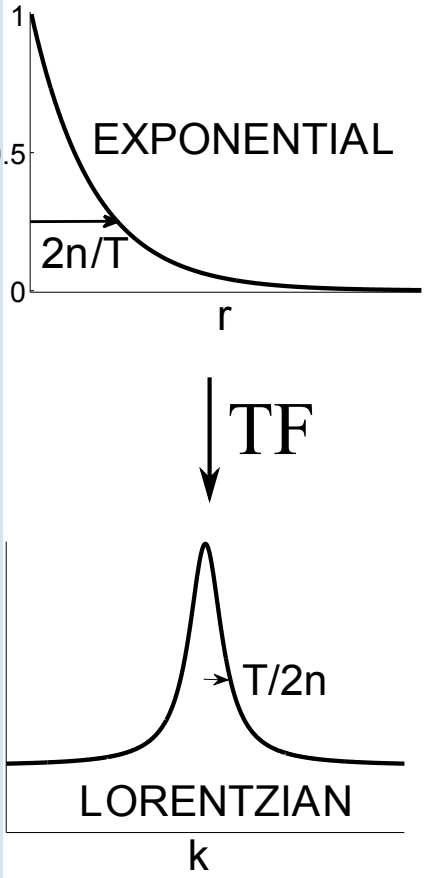

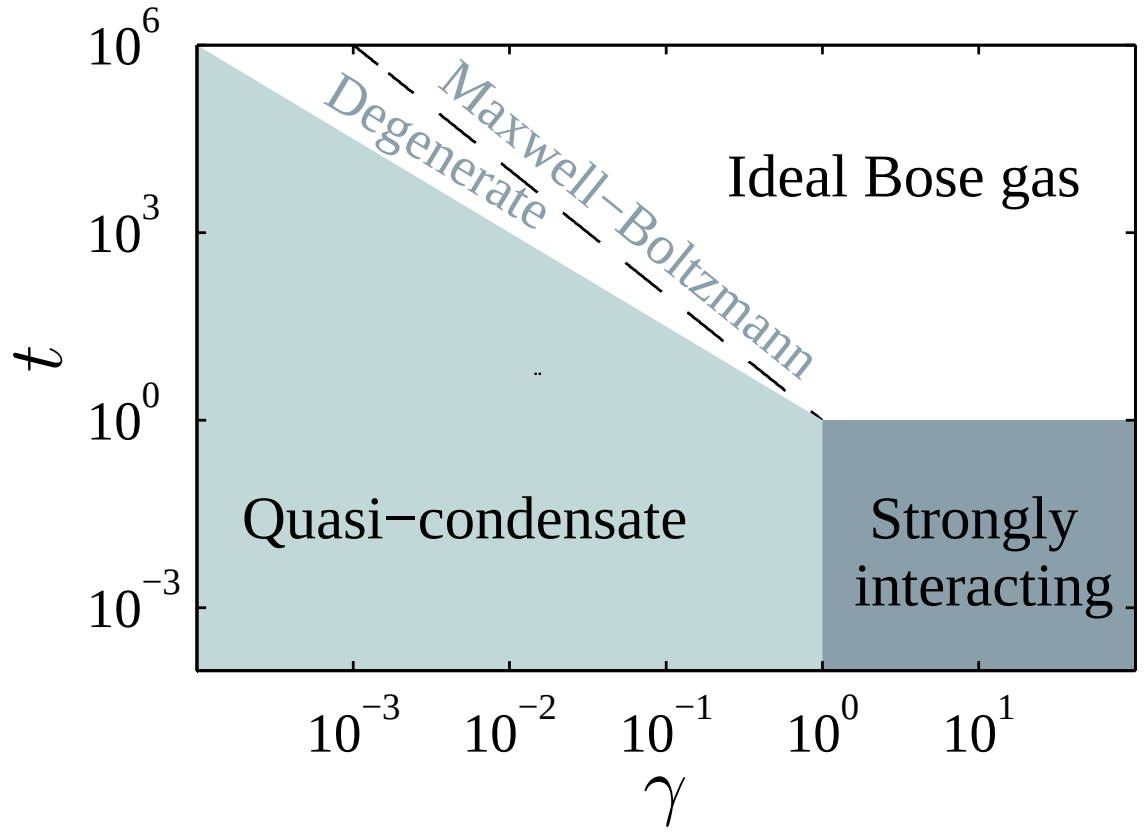

- Contribution of phonons give $g^{(1)}(r) = e^{-Tz/2n}$
- $n(k)$ is Lorentzian in ideal Bose gas degenerate regime and quasi condensate regime. The width differs by a factor 2.

$1/p^4$ tails and kinetic energy

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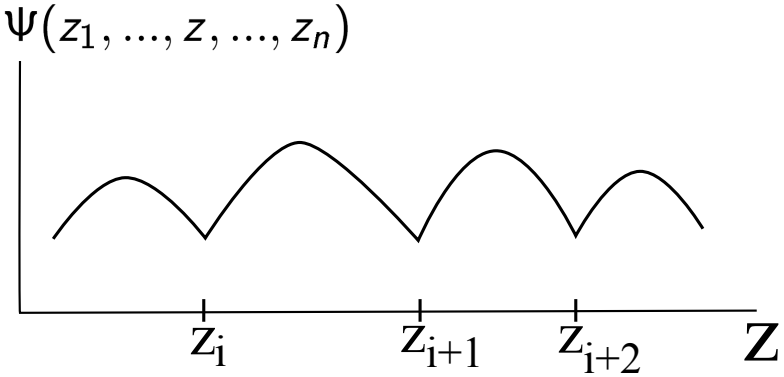
- Short distance correlation ("contact") properties of the Lieb-Liniger model :



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

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

Conclusion : E_K is a thermodynamic quantity

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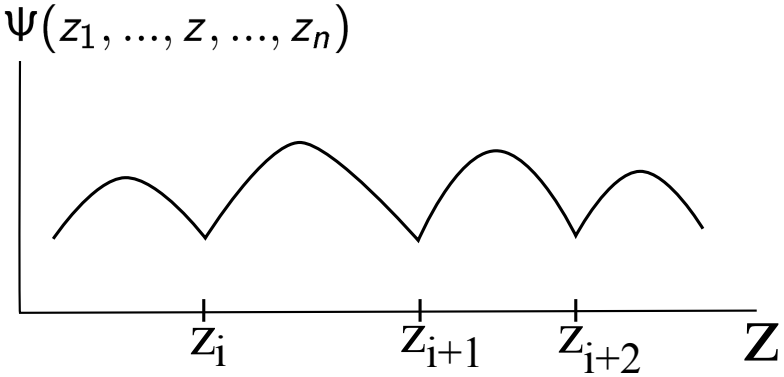

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And E_K is the RMS width of the momentum distribution :

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

State of the art

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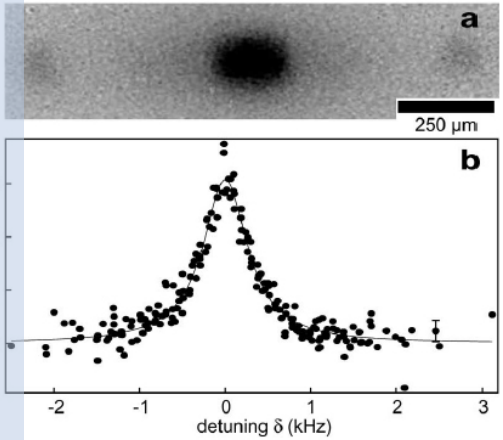
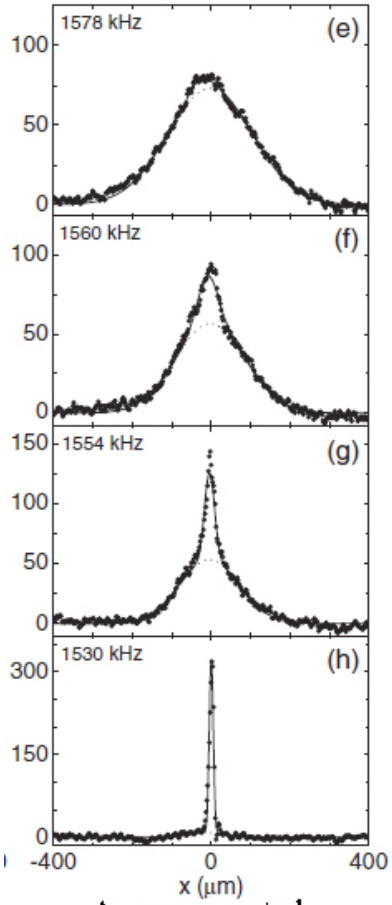
Elongated BEC, Bragg spectrocsopy



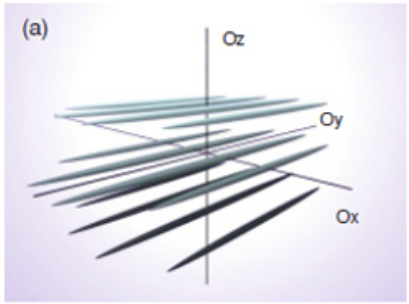
Richard et al. PRL **91**, 4 (2003)

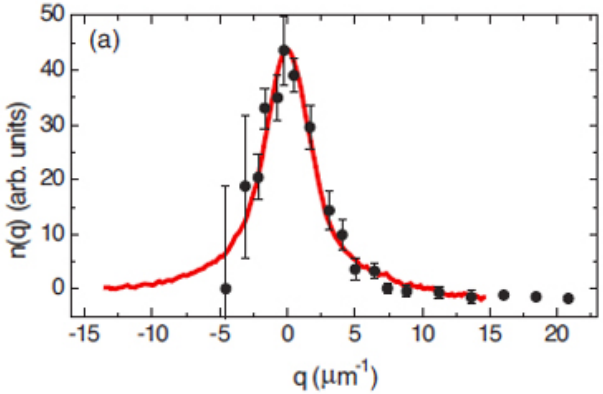
Quasi-1D quasi-condensate
Magnetic focusing



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

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- 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

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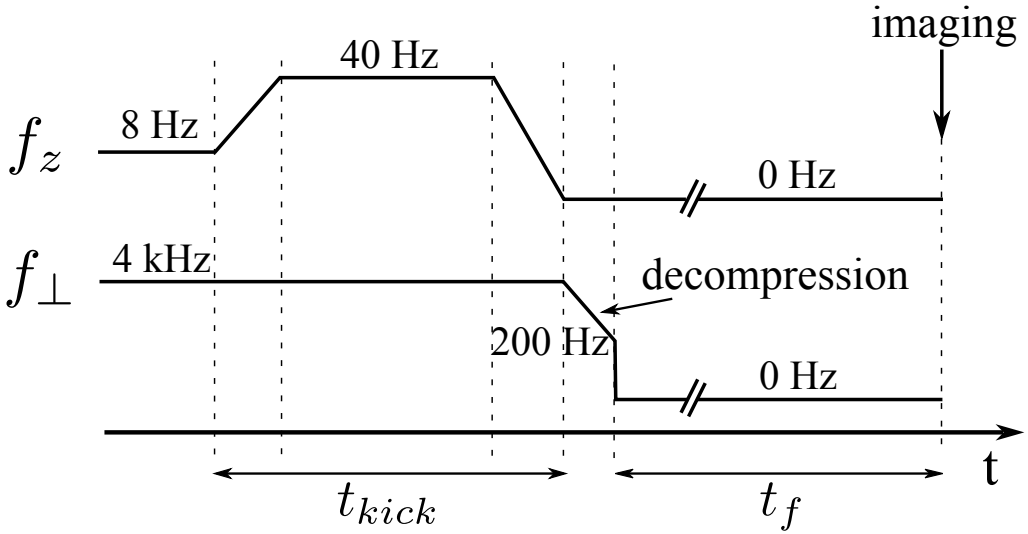
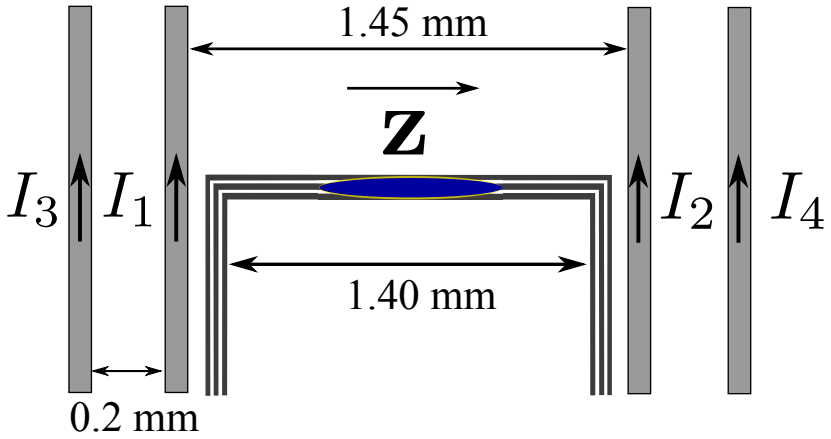


- Transverse decompression step to avoid too huge transverse expansion



- 4 wire configuration = very harmonic focusing pulse

Results : quasi-condensate regime

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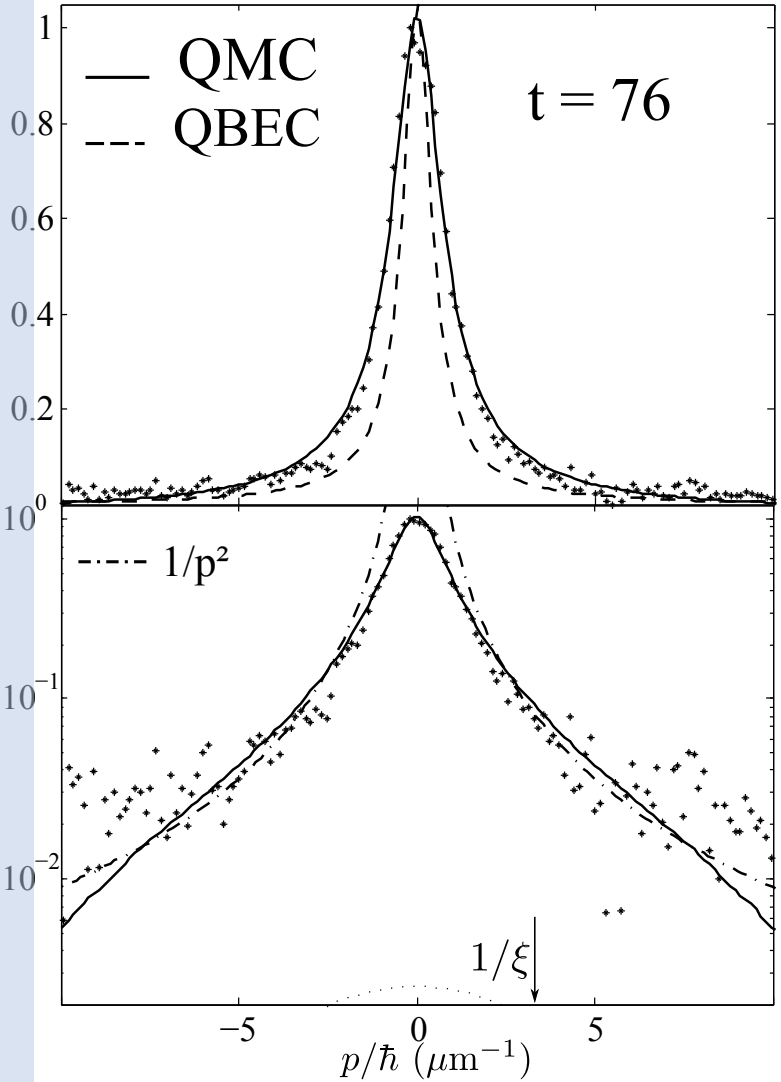

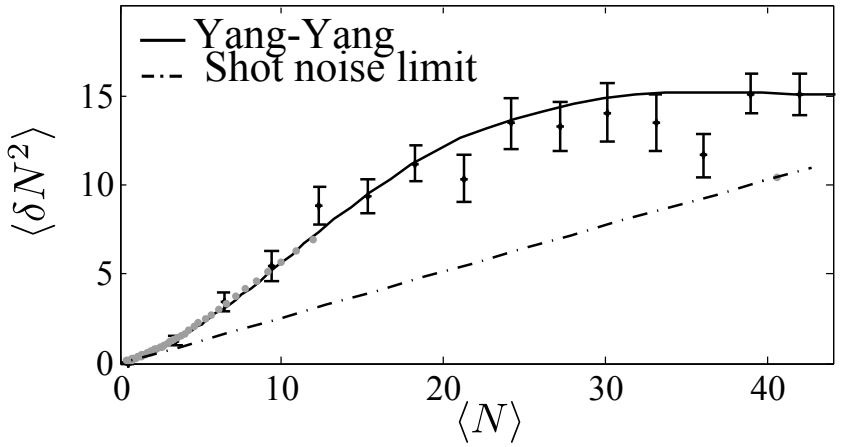

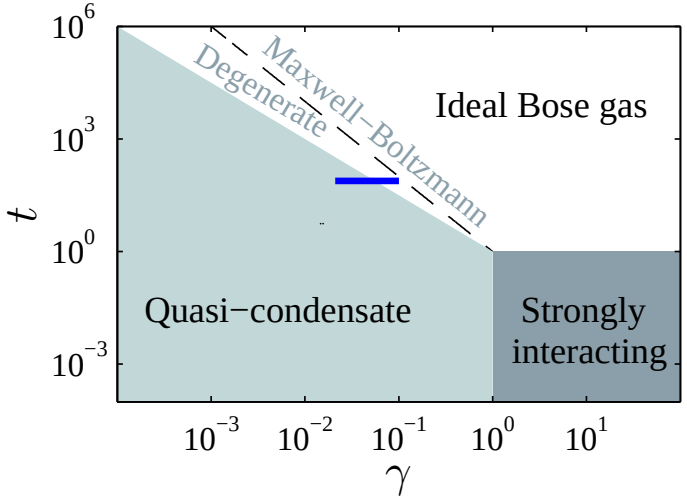

PRA **86**, 043626 (2012)

Results : degenerate ideal Bose gas

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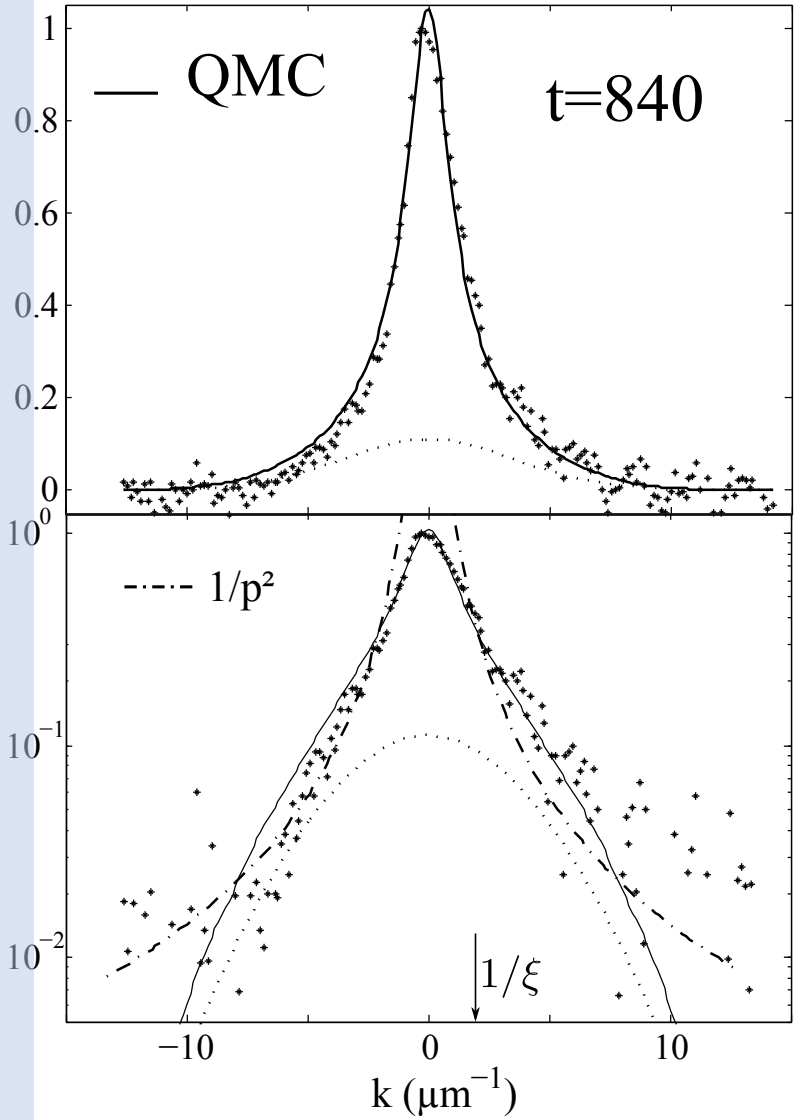

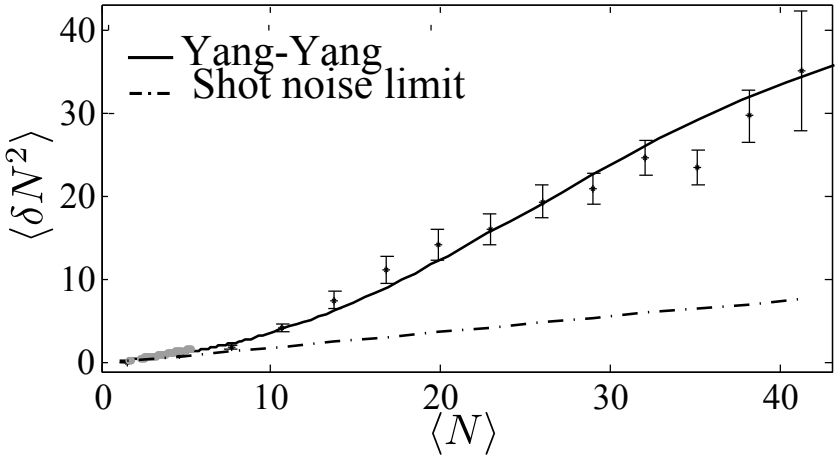

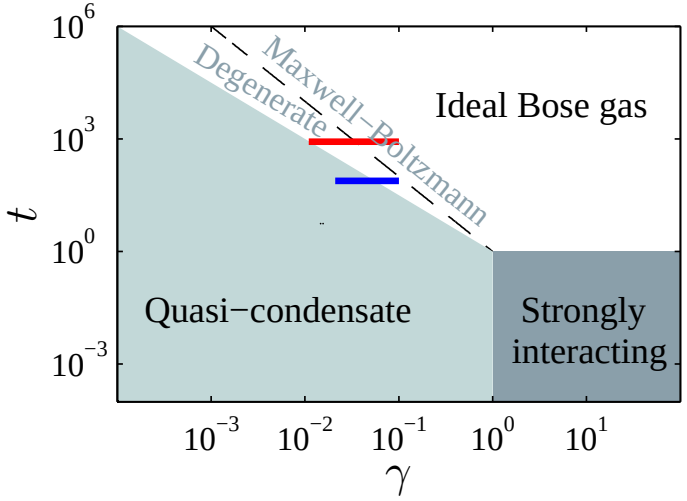

PRA **86**, 043626 (2012)

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tel-00779447, version 1 - 22 Jan 2013

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Prospects

tel-00779447, version 1 - 22 Jan 2013

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Remerciements

tel-00779447, version 1 - 22 Jan 2013

- **Atom Ship team**
  Isabelle Bouchoule
  Bess Fang
  Tarik Berrada
  Aisling Johnson
  Indranil Dutta
  Eugenio Cocchi
  Nicolas Tancogne
- **LPN (fabrication)**
  Sophie Bouchoule
  Sandy Phommaly
- **Atelier mécanique**
  André Guilbaud
  Patrick Roth
- **Ingénieurs électroniciens**
  André Villing
  Frédéric Moron
- **Collaborations théorie**
  Karen Kheruntsyan (YY)
  Tommaso Roscilde (QMC)
- **Directeurs**
  Chris Westbrook
  Christian Chardonnet
  Pierre Chavel
  Bernard Bourguignon
  Alain Aspect
- **Spécialistes du vide**
  Antoine Browaeys
  Alexei Ourjoumtsev

Remerciements

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- **Spécialiste d'Oslo**
  Yvan Sortais
- **Enseignement**
  Lionel Jacubowietz
  Fabienne Bernard
  Sylvain Perrot
  Julien Moreau
  Mathieu Hébert
  Gaëlle Lucas-Leclin
  Sylvie Lebrun
  Thierry Avignon
  Cédric Lejeune
  ...
- **Groupe d'optique atomique**