Bose-Einstein condensate in a dressed trap: collective modes in a two-dimensional superfluid

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December 11, 2013

Outline

LPL Laboratoire de physique des lasers

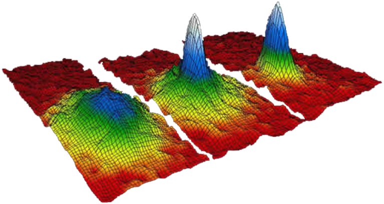
Outline

Bose-Einstein condensation

Degenerate quantum gases ⇒ Bose-Einstein condensate (BEC)

- Thermodynamic phenomenon
- Macroscopic occupation of a single state, due to a saturation of the excited states
- Phase coherence over the sample

- 1924/25 : prediction, Albert Einstein
- 1995 : first realization, Eric Cornell and Carl Wieman

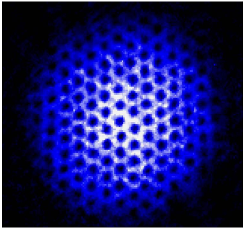


[E. A. Cornell *et al.*, Science **269**, 198 (1995)]

Bose-Einstein condensation

1995 → 2013 : a lot of achievements !

Superfluidity

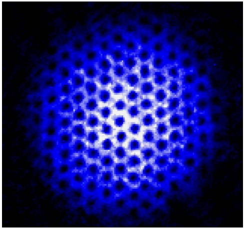


[JILA]

Bose-Einstein condensation

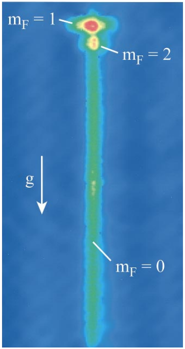
1995 $\rightarrow$ 2013 : a lot of achievements !

Superfluidity



[JILA]

Atom laser



[Munich]

Bose-Einstein condensation

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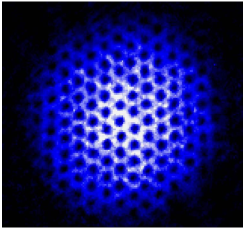
Superfluidity



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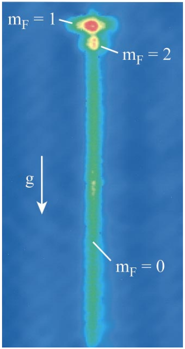
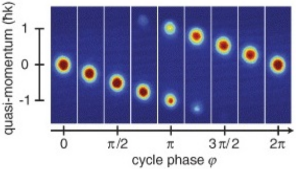


[Munich]

Metrology...



[Innsbruck]

Quantum gases as a model system

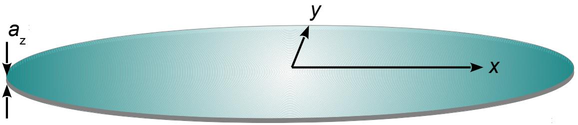
Quantum gases are tunable quantum systems :

- Control of the temperature in the range 10 nK – 1 μK
- Possible control of the interaction strength : scattering length a
- Dynamical control of the confinement geometry
- Periodic potentials (optical lattices)
- Low dimensional systems accessible (1D, 2D)
- Several internal states or species available
- Easy optical detection

Toward the realization of quantum simulators

Confining a gas to two dimensions

- Very anisotropic harmonic trap $\omega_z \gg \omega_x, \omega_y$
- Quasi-2D regime : $\mu, k_B T \ll \hbar\omega_z$
- Fundamental state size along z : $a_z = \sqrt{\hbar/M\omega_z}$



- Dimensionless coupling constant (no length scale) :

$$\tilde{g} = \sqrt{8\pi}\frac{a}{a_z}$$

- Scaling invariance : dimensionless thermodynamic properties depend on $\mu/(k_B T)$ and $\tilde{g}$

The two-dimensional Bose gas

2D is a very special case!

	ideal	interacting
homogeneous	-	BKT
trapped	BEC	BEC,BKT

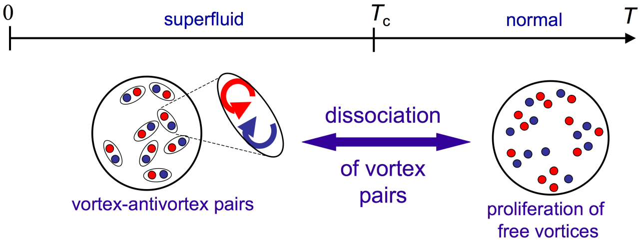
- No BEC for a homogeneous ideal 2D gas!
- Berezinskii-Kosterlitz-Thouless transition (BKT) : a superfluid transition for a homogeneous 2D gas with repulsive interaction
- The harmonic trapped ideal gas (frequency ω) :

$$k_B T_c \simeq \hbar\omega N^{1/2}$$

- Superfluidity $\neq$ BEC

Berezinskii-Kosterlitz-Thouless transition

- Superfluidity present in the homogeneous interacting 2D gas below T_{BKT}
- 1972/73 : Description of the microscopic mechanism independently by Berenzinskii and Kosterlitz & Thouless
- The transition relies on vortex-antivortex pairing

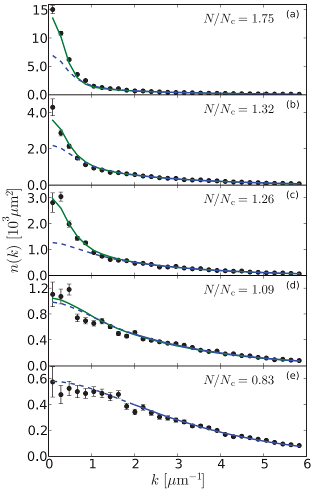


- 2006 : first experimental evidence for the microscopic mechanism [Z. Hadzibabic *et al.*, Nature **441**, 1118 (2006)]

Berezinskii-Kosterlitz-Thouless transition

- Increase of the range of coherence around BKT transition
- Peak in the momentum distribution before the BKT transition

[T. Plisson *et al.*, PRA **84**, 061606 (2011)]



Superfluidity and Landau criterion

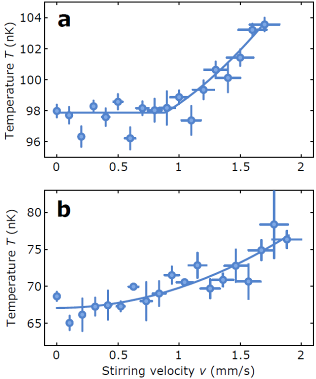
- Dynamic property depending on the excitation spectrum
- No excitation for $v < v_c$
- Landau criterion for the critical velocity :

$$v_c = \text{Min}\left(\frac{E(p)}{p}\right)$$

$v_c > 0$ for a spectrum linear around $p = 0$

- Hydrodynamic behaviour
- Vortices in a rotating gas
- Specific collective modes in a trap

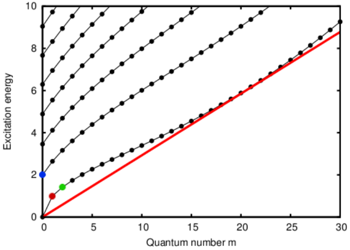
- Direct observation of the superfluid character of a 2D Bose gas



[R. Desbuquois *et al.*, Nat. Phys. **8**, 645 (2012)]

Low energy collective modes of a superfluid

Excitation spectrum in a 2D isotropic trap :



- dipole mode ($m = 1$), both superfluid and thermal : centre of mass oscillation

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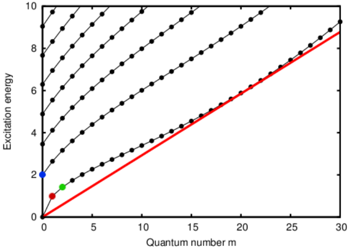
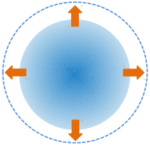


- monopole ($m = 0$) : superfluid and thermal



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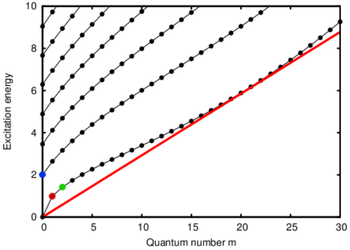

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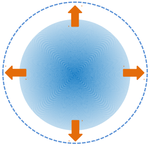
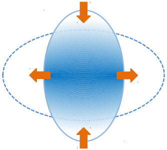


- quadrupole ($m = 2$) **superfluid only**



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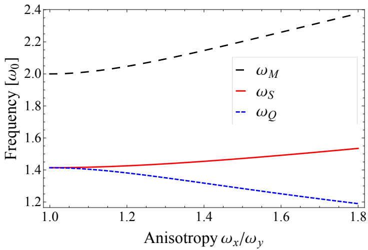

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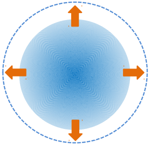
- monopole ($m = 0$) : superfluid and thermal



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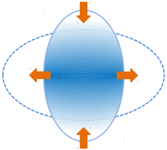
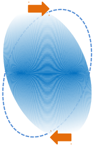


- scissors for $\omega_x \neq \omega_y$ **superfluid only**



My thesis

1. Production of a ^{87}Rb Bose-Einstein condensate in a optically plugged quadrupole trap
   - Trap characterization
   - Majorana losses
2. Transfer of the condensate into a quadrupole dressed trap
   - Trap characterization
   - Landau-Zener transitions
   - Trap tuning and quasi-2D regime
   - Degenerate gas with a superfluid fraction
3. Study of low energy collective modes
   - Excitation of collective modes by controlling the radiofrequency field
   - Monopole : dimensionality and third dimension effect
   - Quadrupole and scissors mode : superfluidity

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Outline

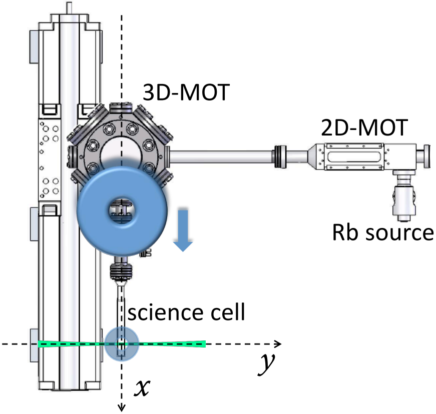
Experimental sketch

^{87}Rb, $|F = 1, m_F = -1\rangle$ state

Experimental sequence :

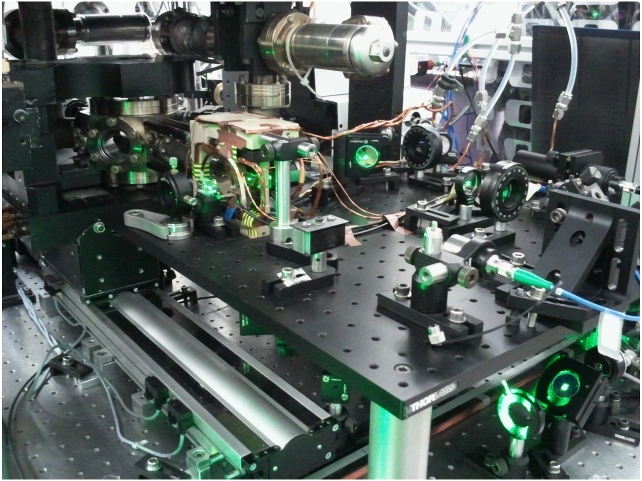
1. Loading the 3D magneto-optical trap
2. Transfer to a magnetic trap
3. Magnetic transport
4. Transfer to a quadrupole optically plugged trap
5. Evaporative cooling to quantum degeneracy
6. Absorption imaging of the atoms

Sketch of the vacuum chamber and magnetic coils :



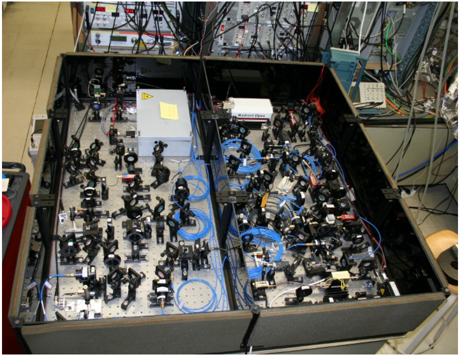
In real life

Vacuum chamber and magnetic coils :

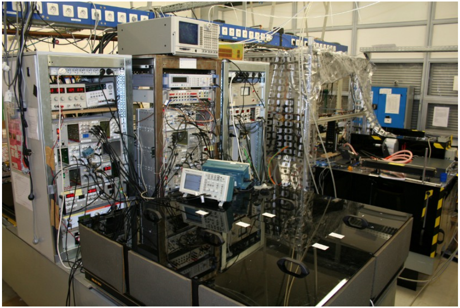


In real life

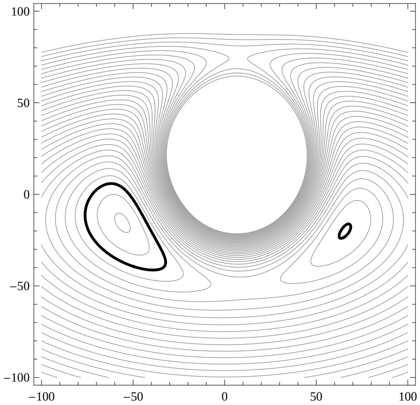
Laser source :



Overview :

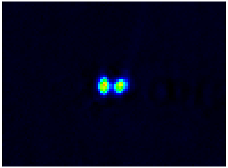


Optically plugged quadrupole trap



Misaligned laser beam ⇒ 2 asymmetric minima

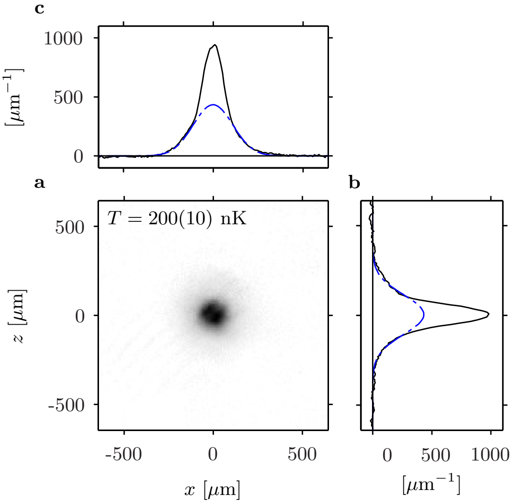
Absorption imaging :



Evaporative cooling

- BEC every 45 s
- $\sim 2 \times 10^5$ atomes à 140 nK
- Trap bottom : ~ 300 kHz
- Lifetime : 20 ± 2 s

[R. Dubessy, K. Merloti *et al.*, PRA **85**, 013643 (2012)]



Outline

Dressed quadrupole trap

The atoms are transferred to a dressed quadrupole trap

- Zeeman states coupled through a radiofrequency field ω_{rf}
- Naturally very anisotropic
- Smooth adiabatic potentials
- Excellent lifetime
- Geometry can be modified dynamically $\Rightarrow$ collective modes

Principle of rf-induced adiabatic potentials

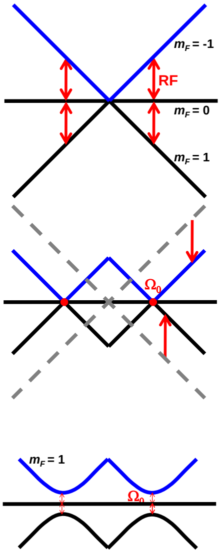
- 2001 : First proposal with rf fields
  [O. Zobay and B. Garraway, PRL **86**, 1195 (2001)] :

$$\mathbf{B}(\mathbf{r}) + \mathbf{B}_{rf} \cos(\omega_{rf} t)$$

  inhomogeneous magnetic field + rf field

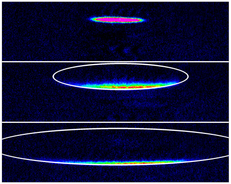
- Strong coupling regime (large $\Omega_0 \propto B_{rf}$)
  $\Rightarrow$ avoided crossing at the resonance points
- Atoms trapped at the isomagnetic surface of an inhomogeneous magnetic field set by ω_{rf} :

$$\text{surface} \quad B(\mathbf{r}) = \frac{\hbar}{|g_F|\mu_B}\,\omega_{rf}$$



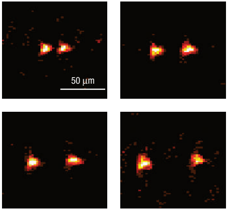
Rf-induced adiabatic potentials

2003 : First experimental realization with a rf field



[Y. Colombe *et al.*, Europhys. Lett. **67**, 593 (2004)]

Several trap geometries : bubble, double well (atom chip), ring and lattice

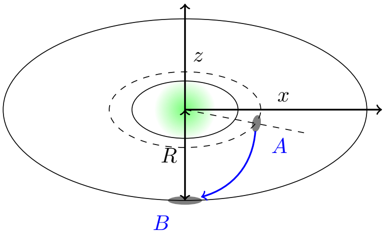


[T. Schumm *et al.*, Nat. Phys. **1** 57, (2005)]

Rf dressed atom in a quadrupole field

- Atoms trapped at the isomagnetic surface :
  $\Rightarrow$ Ellipsoid with radius

$$R \propto \frac{\omega_{rf}}{b'}$$



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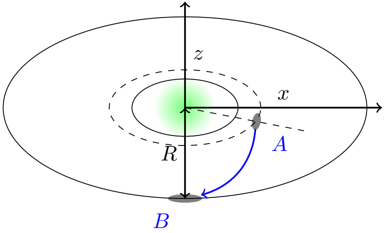
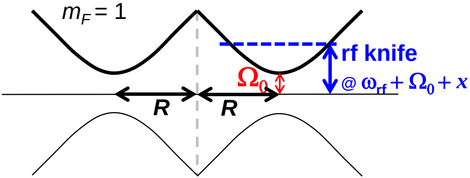
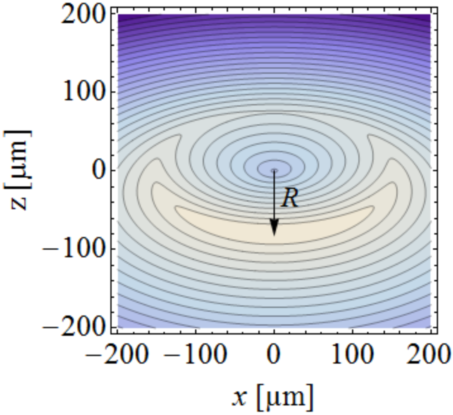


- Control of the temperature :
  rf knife at $\omega_{rf} + \Omega_0 + x$



Trap potential

Taking account of gravity :



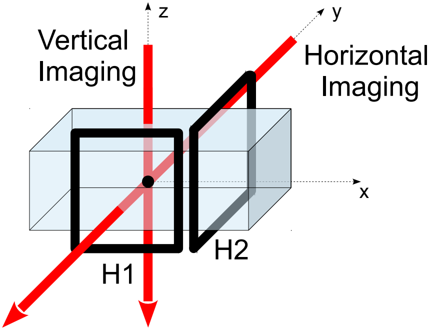
- Trap position :
  $R \propto \frac{\omega_{rf}}{b'}$
- Frequencies :
  $\omega_z \propto \frac{b'}{\sqrt{\Omega_0}} \sim 400\,\text{Hz}-2\,\text{kHz}$
  $\omega_{x,y} \propto \sqrt{\frac{g}{R}} \sim 20 - 50\,\text{Hz}$
- Anisotropy $\frac{\omega_x}{\omega_y}$:
  depends on polarization

[K. Merloti *et al.*, NJP **15**, 033007 (2013)]

Rf antennas

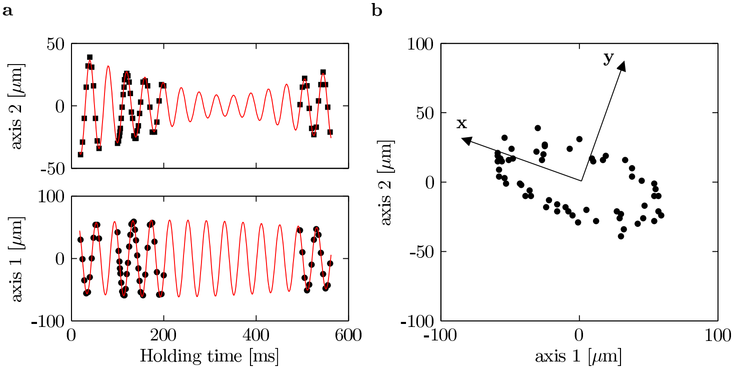
- Two squared antennas
- Linear polarization
  - In phase signal
  - Anisotropic trap, $\omega_x \neq \omega_y$
  - The trap axis can be controlled
- Circular polarization
  - Signal in quadrature
  - Equal amplitudes
  - Isotropic trap, $\omega_x = \omega_y$

⇒ Fine control of the trap geometry



Trap potential

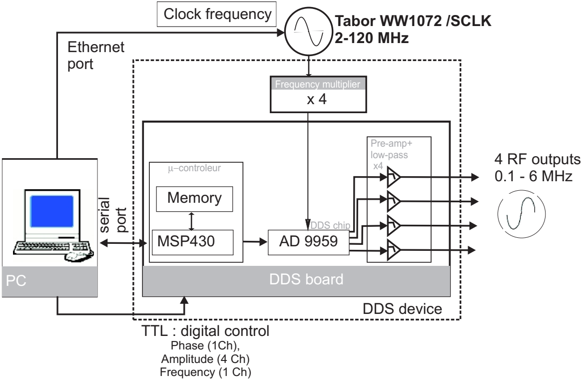
Very smooth trap : no damping of the dipole modes in the *xy* plan !



Oscillation frequencies :

$$\omega_x = 24,7 \pm 0,1\,\text{Hz} \qquad \omega_y = 25,3 \pm 0,1\,\text{Hz}$$

Home-made synthesizer



[Paul-Éric Pottie, Fabrice Wiotte]

- Supplies two rf antennas with the same frequency
- Independent amplitude and phase
- Linear ramps for frequency, amplitude and phase

Quasi-2D regime

$\mu, k_B T \ll \hbar\omega_z$

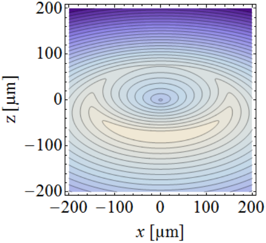
- Temperature : controlled by rf knife
- Chemical potential :

$$\frac{\mu_{3D}}{\hbar\omega_z} \propto \left(\frac{\omega_x^2\omega_y^2}{\omega_z^3}\right)^{\frac{1}{5}} \propto \left(\frac{\Omega_0^{3/2}}{\omega_{rf}^2 b'}\right)^{\frac{1}{5}}$$

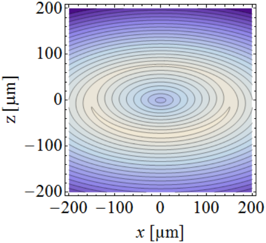
(Thomas-Fermi approximation)

- $\omega_z \gg \omega_x, \omega_y$
- $\downarrow \Omega_0, \uparrow \omega_{rf}, \uparrow b'$

$b' = 55,4\,\text{G}\cdot\text{cm}^{-1}$, $\omega_{rf} = 600\,\text{kHz}$

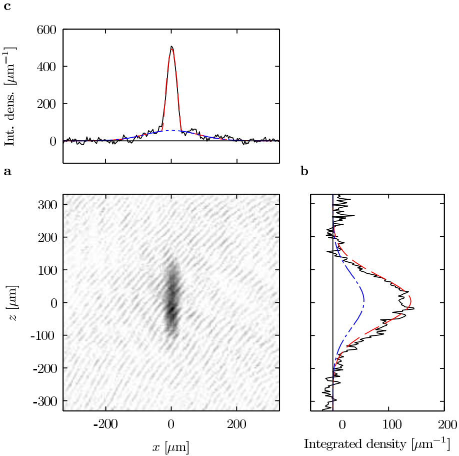


$b' = 216\,\text{G}\cdot\text{cm}^{-1}$, $\omega_{rf} = 2336\,\text{kHz}$



Quasi-2D regime

Image after time-of-flight (25 ms)



- First 2D magnetic trap !
- Oscillation frequencies :

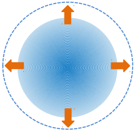
$$\omega_r = 27\,\text{Hz}$$
$$\omega_z = 1,93 \pm 0,01\,\text{kHz}$$

- Chemical potential, temperature

$$\mu_{2D} = 0,37\hbar\omega_z$$
$$k_B T = 1,2\hbar\omega_z$$

Outline

Monopole mode : a probe of dimensionality



- In phase oscillation of the radii
- Compression mode
  $\Rightarrow \omega_M$ related to the equation of state $\mu(n)$

- **Anisotropic 3D condensate** $(\omega_r \ll \omega_z)$:

$$\omega_M^{3D} = \sqrt{\frac{10}{3}}\omega_r$$

- **Isotropic 2D gas** :

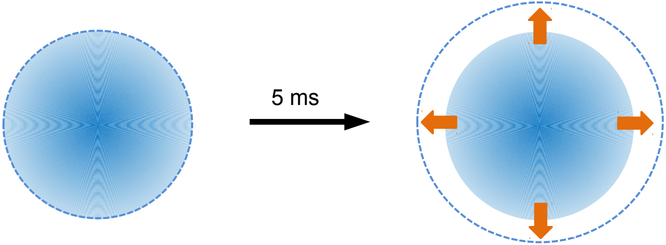
$$\omega_M^{2D} = 2\omega_r$$

  - No damping
  - Linked to scaling invariance
  - Quantum anomaly : $0,2\%$ positive shift of ω_M
    $\Rightarrow$ too small to be detected

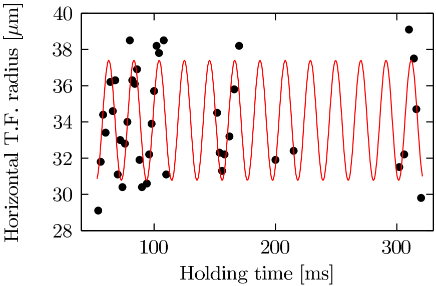
Excitation of the monopole

- **Circular** polarization $\Rightarrow$ 2D isotropic trap, frequency ω_r
- Very low temperature (no thermal fraction)

- Excitation :
  - Sudden increase of ω_{rf} $\Rightarrow$ decrease of ω_r ($\sim$ 15%)



Observation of the monopole mode



$\omega_r = 2\pi \times (24,21 \pm 0,03)$ Hz

$\omega_M/2\pi = (48,1 \pm 0,2)$ Hz

Prediction for a **2D gas** :

$\omega_M^{2D}/2\pi = (48,42 \pm 0,06)$ Hz

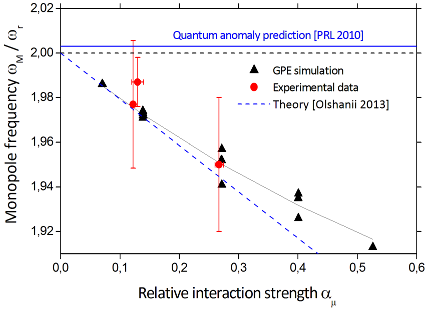
Prediction for a **3D condensate** :

$\omega_M^{3D}/2\pi = (44,20 \pm 0,05)$ Hz

- ω_M close to $2\omega_r \Rightarrow$ **2D gas**
- No measurable damping $\Rightarrow$ quality factor > 150

Breakdown of scale invariance

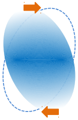
- Finite frequency $\omega_z \Rightarrow$ modified equation of state
- Monopole frequency versus $\alpha_\mu = \frac{\mu}{2\hbar\omega_z}$



- **Negative shift** of ω_M, in fair agreement with the prediction

[K. Merloti *et al.*, PRA submitted, arxiv :1311.1028, (2013)]

Scissors mode : a probe of superfluidity



Oscillation of the anisotropic cloud axis
Mean frequency : $\omega_0 = \sqrt{\omega_x \omega_y}$

- **Superfluid** :

$$\omega_S = \sqrt{\omega_x^2 + \omega_y^2}$$

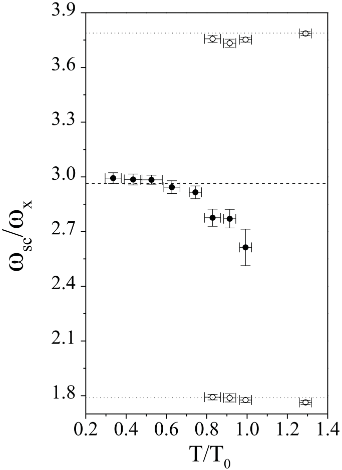
- **Classical gas** :
  Harmonic modes similar to scissors mode (collisionless regime) :

$$\begin{aligned} \omega_{S1} &= \omega_x + \omega_y, \\ \omega_{S2} &= |\omega_x - \omega_y| \end{aligned}$$

- Use the scissors mode as a signature of superfluidity across the BKT transition

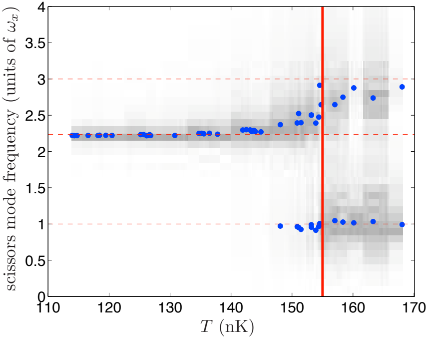
Scissors mode versus temperature : state of the art

3D : observed negative shift



[Marago, PRL **86**, 3938 (2001)]

2D : positive shift expected

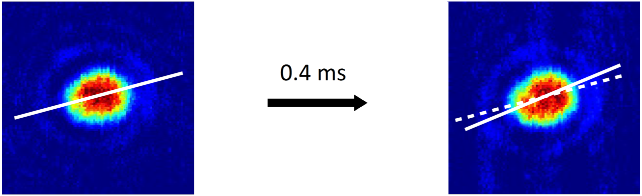


[Simula, PRA **77**, 023618 (2008)]

Exciting the scissors mode

- **Linear** polarization $\Rightarrow \omega_x \neq \omega_y$
- **Anisotropy** $\omega_x/\omega_y = 1,28 \pm 0,04$
- Control of the eigenaxes through the two rf antenna amplitudes
- Control of the temperature through rf knife

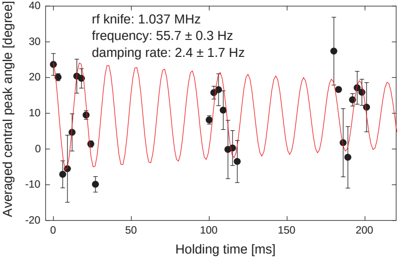
- Excitation :
  - We exchange the rf amplitudes $\Rightarrow$ sudden rotation of the trap (10° in $0.4\,\text{ms}$)



Observation of the scissors mode

Dressing frequency 1 MHz, Rabi frequency 31,5 kHz

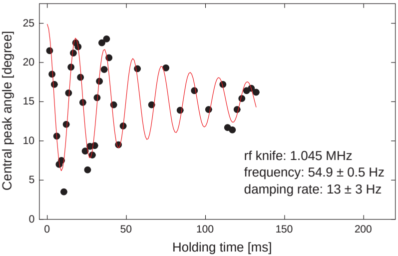
Low temperature :



Rf knife @1.037 MHz

$= \omega_{rf} + \Omega_0 + 2\pi \times 5,5\,\mathrm{kHz}$

Higher temperature



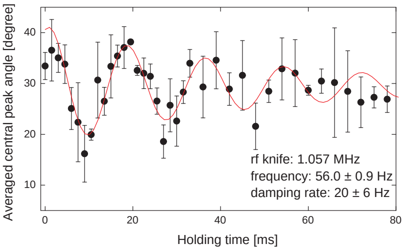
Rf knife @1.045 MHz

$= \omega_{rf} + \Omega_0 + 2\pi \times 13,5\,\mathrm{kHz}$

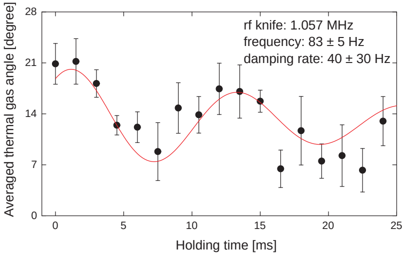
Superfluid and thermal gas

Rf knife @1.057 MHz $= \omega_{rf} + \Omega_0 + 2\pi \times 25,5\,\text{kHz}$

Superfluid :

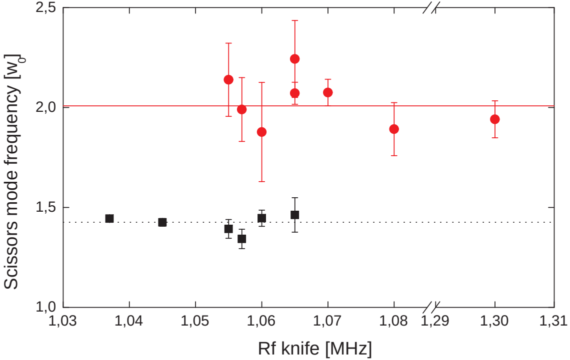


Thermal gas :



Scissors mode versus temperature

Superfluid / Thermal gas

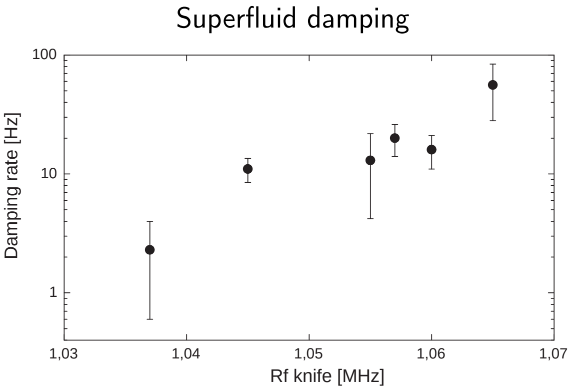


NB : The slow oscillation of the thermal gas is not observable

$$\frac{|\omega_x - \omega_y|}{2\pi} \sim 10\,\mathrm{Hz}$$

[Article in preparation]

Damping of the scissors mode

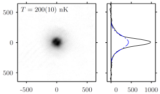


- Increase in the damping rate with temperature
- Qualitative understanding (Landau damping)
- No quantitative interpretation

Outline

Conclusions

- Fast production of a Bose-Einstein condensate in a optically plugged quadrupole trap
  [R. Dubessy, K. Merloti *et al.*, PRA **85**, 013643 (2012)]



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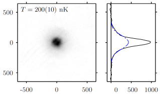
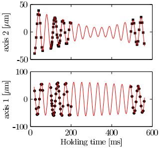


- Production of a degenerate quasi-2D Bose gas presenting a superfluid phase in a rf dressed trap : tunable geometry and smooth traps for the study of low energy collective modes
  [K. Merloti *et al.*, NJP **15**, 033007 (2013)]



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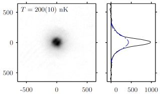

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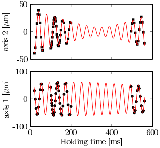

- Breakdown of scale invariance in a quasi-2D gas due to the third dimension on the monopole mode
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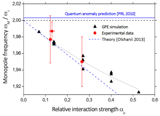

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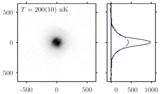

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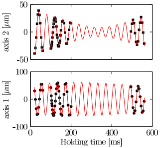

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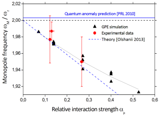
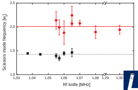


- Scissors mode as a signature of superfluidity ; damping induced by temperature



Prospects

- Detection of the quantum anomaly effect in the monopole mode

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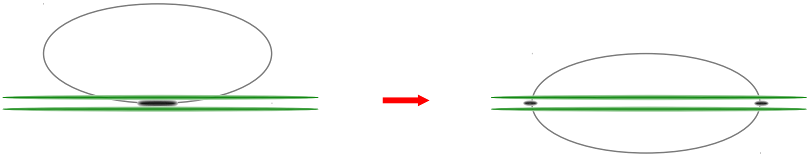
- Detection of the quantum anomaly effect in the monopole mode
- BKT transition : superfluid to normal transition through scissors mode
  - Measure of the temperature by analyzing *in situ* images
- New panorama : quasi-2D gas in ring traps
  - Persistent currents
  - Superfluid properties according to dimensionality

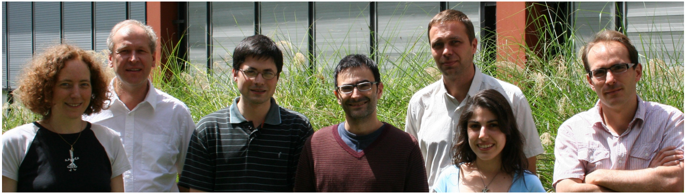


Vertical optical confinement produced with a phase plate

Translation of the « bubble » with a magnetic offset

Acknowledgments

www-lpl.univ-paris13.fr/bec



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V. Lorent L. Longchambon K. Merloti

T. Badr

Technical and administrative staff

Albert Kaladjian

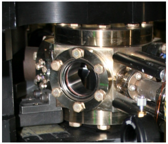
Fabrice Wiotte

Best wishes to Camilla de Rossi and Dany Ben Ali

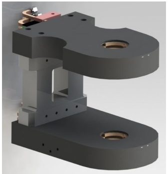
⋆ now at LNE-SYRTE, Paris

Characteristics

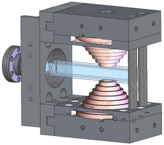
3D magneto-optical trap
$\sim 10^9$ ^{87}Rb atoms



Magnetic transport
Gradient radial : $b' = 74\,\mathrm{G{\cdot}cm^{-1}}$
Distance : $28\,\mathrm{cm}$
Duration : $1,05\,\mathrm{s}$



Optically plugged trap
Radial gradient : $b' = 216\,\mathrm{G{\cdot}cm^{-1}}$
$\sim 2 \times 10^8$ atoms in the $|F = 1, m_F = -1\rangle$ state



Majorana losses in quadrupole trap

Model :

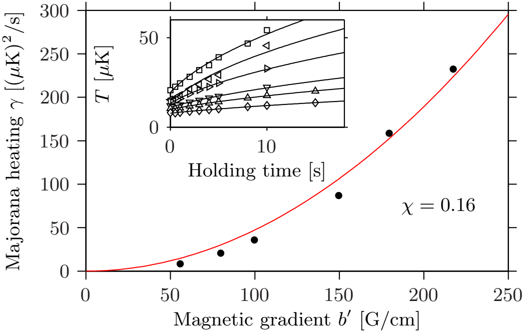
$$N(t) = N_0 \frac{e^{-\Gamma_b t}}{\left(1+\frac{\gamma t}{T_0^2}\right)^{\frac{9}{8}}}$$

$$T(t) = \sqrt{T_0^2 + \gamma t}$$

Majorana heating γ :

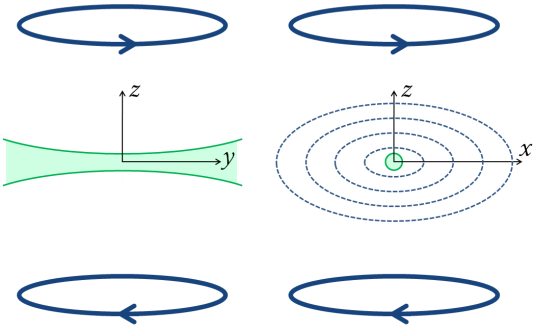
$$\gamma = \frac{8}{9}\chi\frac{\hbar}{M}\left(\frac{2\mu_m b'}{k_B}\right)^2$$

- Spin flips near $\mathbf{B} = \mathbf{0}$



- Trap decompression essential for BEC !

Optically plugged quadrupole trap



Plug :

- Laser beam focused near $\vec{B} = \vec{0}$
- 532 nm (blue-detuned, transition at 780 nm)
- Waist : 46 μm
- Power : 6 W