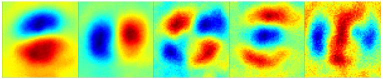
Imaging the collective excitations of a quantum gas using statistical correlations



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Atomtronics, Benasque, May 6, 2015

Introduction

- Following the dynamics of a quantum gas is relevant for many problems: superfluid behaviour (superfluid fraction [Grimm,Stringari], symmetry breaking (e.g. in 2D) . . .), atomtronics, Kibble-Zurek mechanisms, transport, etc.
- Superfluidity in particular is a dynamical property, characterised by collective modes, vortices, critical velocity, persistent flow . . .
- Tracking the excitations is also a relevant diagnostic, for atomtronics (performance of waveguides, critical velocity through a rotating barrier. . .) or to study quantum turbulence [Tsubota, B. Anderson, Gasenzer, D. Hall, Bagnato. . .]
- This requires new analysis capabilities (e.g.: analysing movies)

Introduction

Improving imaging and image analysis

- Impressive improvement in imaging techniques [Greiner,Bloch]
- Time-resolved multiple detection of the same sample possible in some cases (phase contrast imaging)

$\Rightarrow$ image analysis also must be improved when many pictures are taken, noise must be eliminated

Statistical tools are relevant to extract the maximum information from a complex system or a noisy environment.

Introduction
Statistical image analysis

- Statistical data analysis is widely used in astronomy or biology (low signal, noisy environment)
- Recently applied to cold atoms to perform noise filtering (e.g. in interferometry [Dana Anderson2010,Kasevich2011]) or noise analysis, when taking many pictures in the same conditions [Farkas et al. 2015]
- Principal component analysis is a powerful tool, more robust than FFT

In this talk, application of principal component analysis to a series of absorption images to identify the amplitudes of the true collective excitations of a real (not idealised) 2D gas in a harmonic trap.

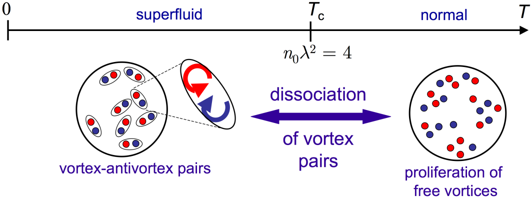
Outline

1. Collective modes in two dimensions
   - The 2D Bose gas
   - Excitation spectrum and critical velocity
   - A very smooth trap for the study of collective modes
   - The monopole mode
   - The scissors mode
2. Imaging the collective modes with PCA
   - Excitation of the 2D gas
   - Applying PCA
   - Identification of the collective modes
   - Comparison with numerical simulations
3. Outlook

The two-dimensional Bose gas
2D: A marginal dimension

2D is a very special case! In contrast with 3D, superfluidity doesn't appear together with BEC [bosons: ENS, Chicago, Palaiseau, Seoul...]

- homogeneous case: Berezinslii-Kosterlitz-Thouless transition: a **superfluid transition** relying on vortex-antivortex pairing, but not BEC fraction.



[ENS 2006]
[Seoul 2013]

- BEC recovered in a trap. Summary:

	ideal	interacting
homogeneous	no BEC, no SF	BKT SF
trapped	BEC, no SF	BKT+BEC

The two-dimensional Bose gas
Scaling symmetry

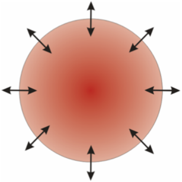
2D is a very special case!

- scaling invariance $r \to \lambda r$: $E_K \to \frac{1}{\lambda^2} E_K$, $E_{\text{int}} \to \frac{1}{\lambda^2} E_{\text{int}}$
- no length scale: dimensionless interaction strength $\tilde{g}$

$$g = \frac{\hbar^2}{M} \tilde{g}$$

cf EOS($\mu / k_B T$) work at ENS / Chicago

- Pitaevskii-Rosch monopole mode **in an isotropic trap**:



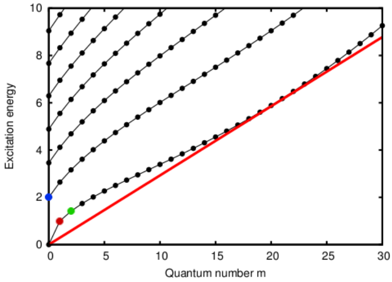
- no damping [ENS 2002, in a cigar]
- $\Omega_M = 2\omega$ for all amplitudes
- linked to scaling symmetry

Superfluid two-dimensional quantum gas

Low energy collective modes in a trap

Low energy modes of a **trapped 2D superfluid**

Excitation spectrum in a trap:



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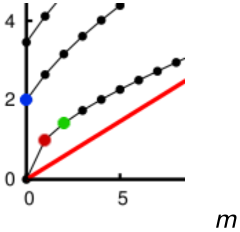

- dipole mode ($m = 1$), both superfluid and thermal: centre of mass oscillation

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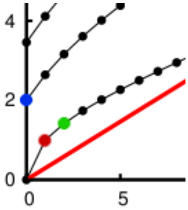
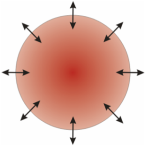


m

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

- monopole ($m = 0$): superfluid and thermal **signature of the EOS**



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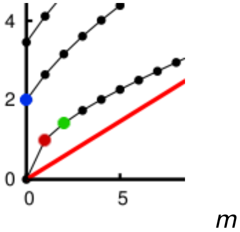

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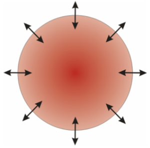

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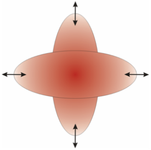

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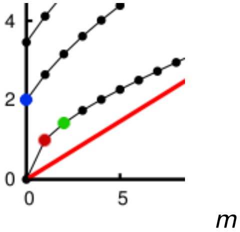

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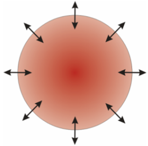

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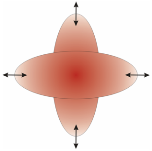
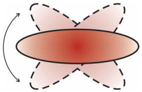


- **scissors** for $\omega_x \neq \omega_y$ **superfluid only**



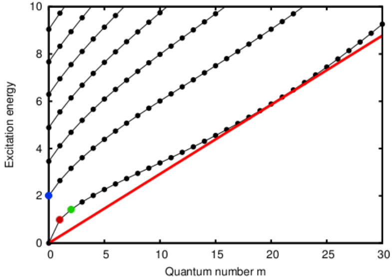
[N.B.: thermal gas always in the collisionless regime]

Superfluid two-dimensional quantum gas

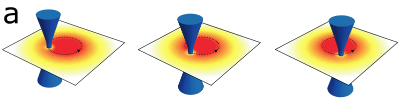
Measuring the critical superfluid velocity

Low energy modes of a **trapped 2D superfluid**

Excitation spectrum in a trap:



red line: gives the critical velocity, related to surface modes [Anglin2001]. Can be measured (in principle) with a rotating defect, see [Desbuquois2012].



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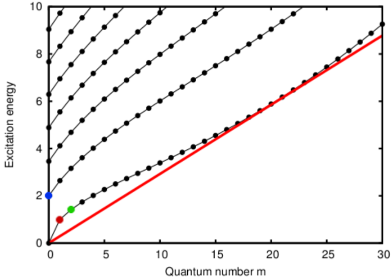

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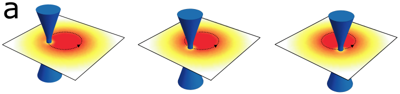


Global measurement: A heating is measured as the laser is stirred. But the (first) excited modes have not been identified.
⇒ a way to identify multiple excited modes is missing!

Two examples of collective modes

Monopole vs scissors

We study experimentally two low energy collective modes:

- The monopole mode probes the equation of states.
- The scissors mode probes superfluidity.

Experimental constraints:

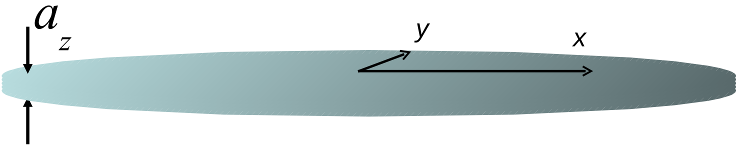
- The gas is confined to 2D . . .
- in a very smooth harmonic potential.

First approach: 'top-down', or fit with an expected mode shape.

Confining a gas to two dimensions

A very anisotropic trap

- very anisotropic harmonic trap $\omega_z \gg \omega_x, \omega_y$
- z degree of freedom is frozen if $\mu, k_B T < \hbar\omega_z$
- confinement size $a_z = \sqrt{\frac{\hbar}{M\omega_z}}$



Dimensionless coupling constant depends on confinement:

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

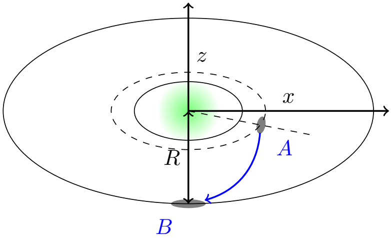
Study of collective modes: need a smooth horizontal potential.

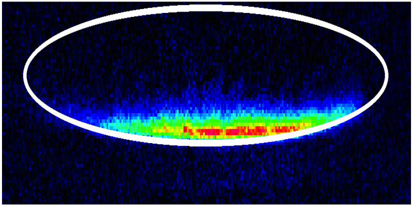
rf-induced adiabatic potentials

The dressed quadrupole trap

Adiabatic potentials for rf-dressed atoms:
the dressed quadrupole trap

- smooth potentials (magnetic fields with large coils)
- naturally very anistropic
- geometry can be modified dynamically



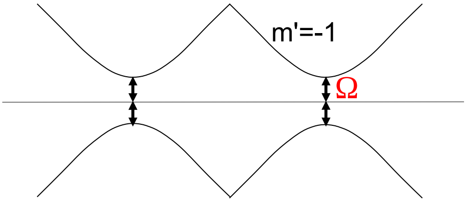


Atoms are confined to the isopotentials of a quadrupole field.

rf-induced adiabatic potentials

rf-induced adiabatic potentials

isomagnetic surfaces: ellipsoids with $r_0 \propto \frac{\omega_{\text{rf}}}{b'}$



$$\omega_z \propto \frac{b'}{\sqrt{\Omega}} \sim \text{1-2 kHz} \qquad \omega_x, \omega_y \propto \sqrt{\frac{g}{r_0}} \sim \text{20-50 Hz}$$

anisotropy $\eta = \frac{\omega_x}{\omega_y}$ controlled through rf polarisation

NB: $\eta = 1$ with a circular rf polarisation

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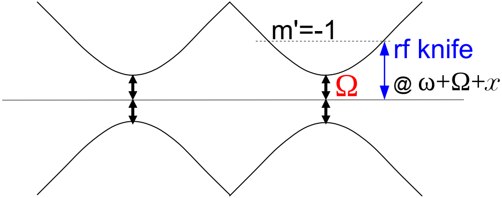

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temperature T controlled with a rf knife at $\omega_{\rm rf} + \Omega + \nu_{\rm cut}$

The monopole mode in an isotropic harmonic trap

A way to study the Equation Of State

isotropic harmonic 2D trap, frequency ω

- monopole probes the compressibility $\Rightarrow \Omega_M$ is related to the 2D EOS $\mu(n)$:

$$\Omega_M = \sqrt{2(2+\epsilon)}\,\omega \quad \text{with} \quad \epsilon = \frac{n\mu''(n)}{\mu'(n)}$$

  cf Rudi Grimm's expt with fermions [Altmeyer 2006]

- Ex: 2D weakly interacting gas: $\mu(n) = gn \Rightarrow \Omega_M = 2\omega$

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- Ex: flat, but 3D gas: $\mu(n) \propto n^{2/3} \Rightarrow \Omega_M = \sqrt{10/3}\,\omega$

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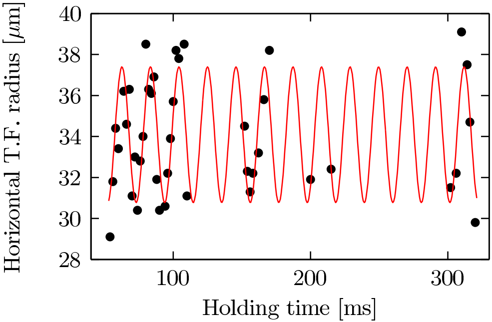
- Ex: flat, but 3D gas: $\mu(n) \propto n^{2/3} \Rightarrow \Omega_M = \sqrt{10/3}\,\omega$
- we probe the intermediate case: for non negligible interactions is there a shift as a function of $\alpha = \dfrac{\mu}{2\hbar\omega_z}$? [Merloti 2013]

Observation of the monopole mode

Isotropic trap

Circular rf polarisation ⇒ isotropic 2D trap
Excitation through a sudden change in ω
Very low T (no thermal fraction)

• experimental data:
fit of TF radius after a tof
—— sinusoidal fit
[Merloti NJP2013]

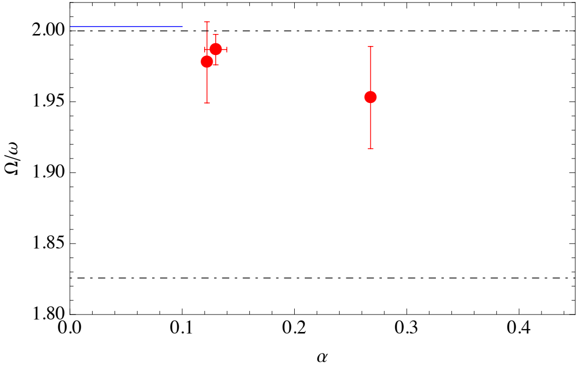


typical data: Ω_M close to 2ω; no measurable damping

Results: shift of the monopole mode

A modified EOS

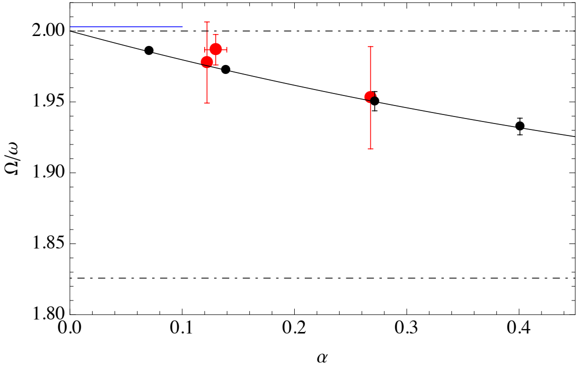
We observe a small negative shift as a function of α [Merloti PRA2013]:



The finite z frequency implies a **modified EOS**.

Results: shift of the monopole mode
A modified EOS

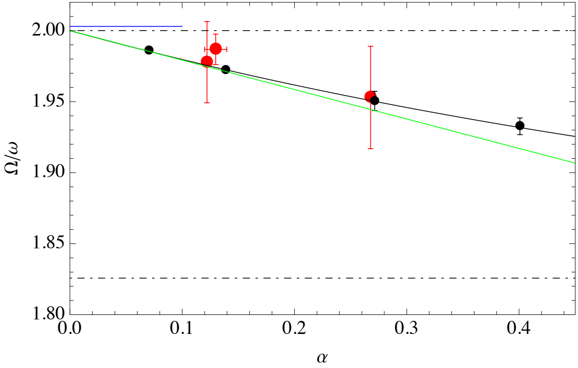
Comparison with a **3D** GPE simulation:



The in-plane EOS is indeed impacted by the **third dimension**, even at $\alpha = 0.1$.

Results: shift of the monopole mode
A modified EOS

Comparison with a perturbation theory:



Recover the observed behaviour at first order.
Merloti et al., PRA 88, 061603(R) 2013.

The scissors mode

A signature of superfluidity

Scissors mode: anisotropic harmonic trap, frequencies $\omega_x \neq \omega_y$, anisotropy $\eta = \omega_y/\omega_x \sim 1.3$, mean frequency $\omega_0 = \sqrt{\omega_x \omega_y}$

- no scissors mode in the thermal phase, only harmonic modes $\omega_x \pm \omega_y$

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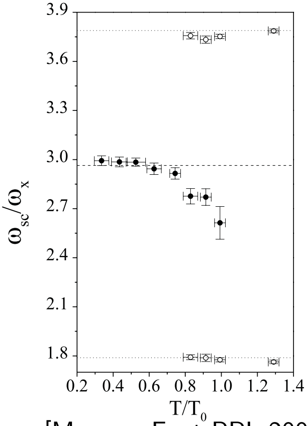
- scissors mode expected at $\omega_{sc} = \sqrt{\omega_x^2 + \omega_y^2}$ for a **superfluid**
- damping when T increases
- different behaviour in 3D and 2D expected

$\Rightarrow$ Use the scissors mode as a signature of superfluidity across the BKT transition!

The scissors mode

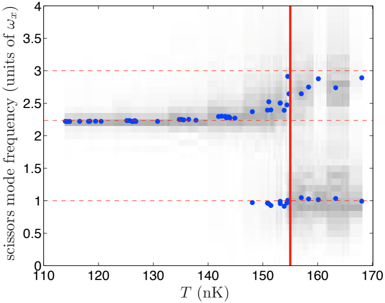
3D vs 2D as a function of temperature

3D: observed negative shift



exp: [Marago, Foot PRL 2001]

2D: positive shift expected

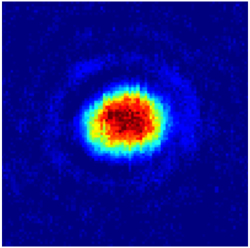


numerics: [Simula, PRA 2008]

The scissors mode
Experiments at LPL

Excitation method:

- Prepare a 2D gas in an anisotropic trap



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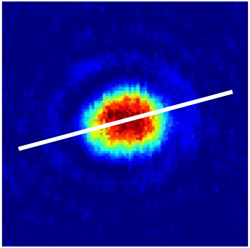

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Experiments at LPL

Excitation method:

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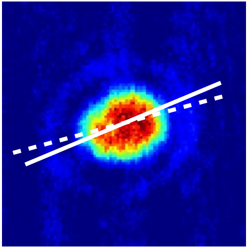
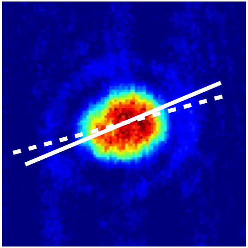


The scissors mode
Experiments at LPL

Excitation method:

- Prepare a 2D gas in an anisotropic trap
- Sudden change of the eigenaxes with rf polarisation
- Record the cloud axis angle with an *in situ* image



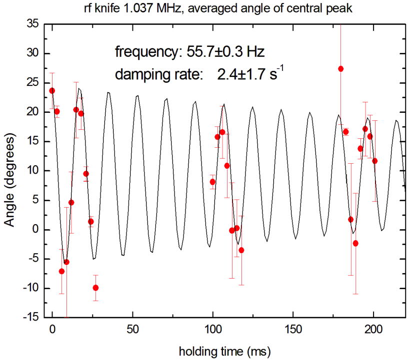
The scissors mode

Time evolution of the fitted axis angle

Dressing frequency 1 MHz, Rabi frequency 30 kHz.

Fit 1 or 2 angles with a TF profile or TF + Gaussian

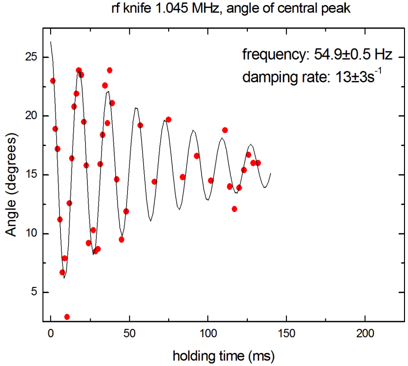
low temperature



rf knife @ 1.037 MHz

$= \nu_{\rm rf} + \Omega_{\rm rf} + 7$ kHz

higher temperature



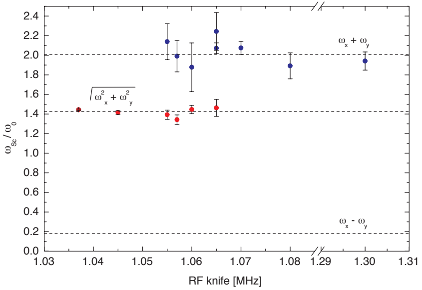
rf knife @ 1.045 MHz

$= \nu_{\rm rf} + \Omega_{\rm rf} + 15$ kHz

Results with a model fit

Frequency vs temperature

superfluid / thermal



Thermal gas: the slow oscillation expected at $\omega_y - \omega_x$ (10 Hz) is not observed: is it really there, hidden by damping or noise?

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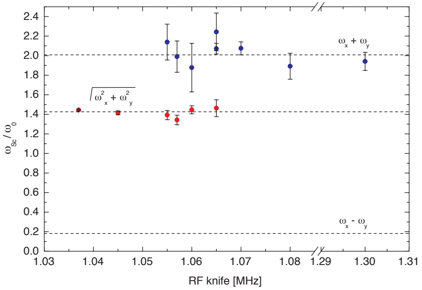

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How can we extract more information with less assumptions?

Statistical analysis applied to quantum gases

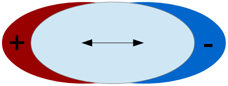
What are the experimental imaging conditions?

- Dynamical system, evolving with time
- Snapshots taken after various times, not necessarily evenly spaced
- Technical noise (fringes, etc.)
- Trap imperfections lead to errors in the predicted shape of collective modes
- Fits made difficult when many parameters are to be fitted
- Excitation procedure, though well controlled, can excited several modes

$\Rightarrow$ we need a method for extracting data with a minimum input.

Principal component analysis

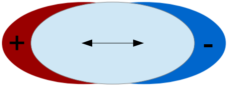
- Main idea: extract correlations between images from a given series.



Example: if the left-right dipole mode is excited, there will be a positive correlation between the left pixels in the series, even for irregular sampling. The right pixels will also be correlated, with an opposite phase.

Principal component analysis

- Main idea: extract correlations between images from a given series.



Example: if the left-right dipole mode is excited, there will be a positive correlation between the left pixels in the series, even for irregular sampling. The right pixels will also be correlated, with an opposite phase.

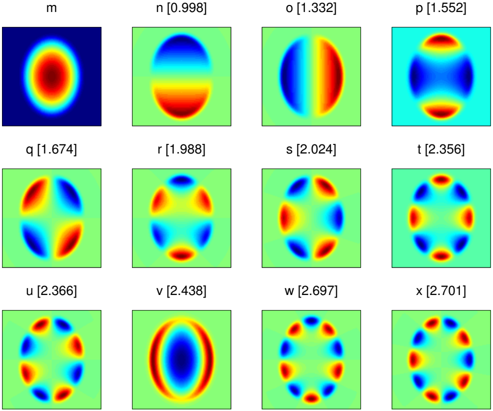
- Method:
  1. prepare an excited 2D gas
  2. take successive in situ images
  3. compute and diagonalize the covariance matrix (quite fast!)
  4. identify the excited modes and filter noise.

See R. Dubessy et al., Fast Track Comm. of New J. Phys. **16**, 122001 (2014) + video abstract.

Expected collective modes

From Bogolubov diagonalisation of an idealised case

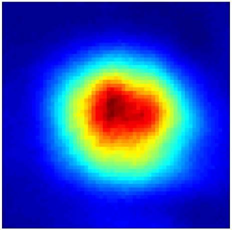
Bogolubov modes computed numerically for the 2D gas in a harmonic anisotropic trap ω_x, ω_y:



2 dipoles (ω_x, ω_y), quadrupole-like (ω_Q), scissors $(\omega_S = \sqrt{\omega_x^2 + \omega_y^2})$, 4 more modes of higher order symmetry and then monopole-like (ω_M)

Exciting the atomic cloud

A BEC prepared in a plugged quadrupole trap is transferred too fast into the 2D rf-dressed quadrupole trap, whose axes are also suddenly rotated. Several modes are excited during this process.



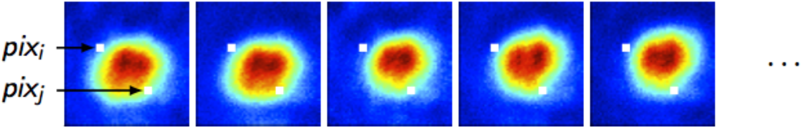
excited cloud

2D trap frequencies:
$\omega_x = 2\pi \times 33$ Hz,
$\omega_y = 2\pi \times 44$ Hz

133 images
taken during 100 ms, after various holding times.

Applying principal component analysis

N images, N_p pixels labeled by an index i: pix_1, $\mathrm{pix}_2, \ldots \mathrm{pix}_i \ldots$



Element (i, j) of the covariance matrix:

$$S_{i,j} = \langle \mathrm{pix}_i \mathrm{pix}_j \rangle - \langle \mathrm{pix}_i \rangle \langle \mathrm{pix}_j \rangle$$

Diagonalization: S has a huge size $N_p \times N_p$ but its eigenvalues are the same than the covariance of the image series, with a size $N \times N$ (much smaller).

Applying principal component analysis

Diagonalization gives the eigenvariances and the eigenimages or principal components.

Diagonal matrix:
$$\begin{pmatrix} 0.41 & 0 & \cdots & 0 \\ 0 & 0.33 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & 0 \end{pmatrix}$$

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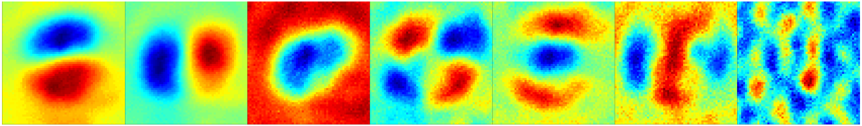
PC1 PC2 PC3 **PC4** PC5 PC6 PC7...



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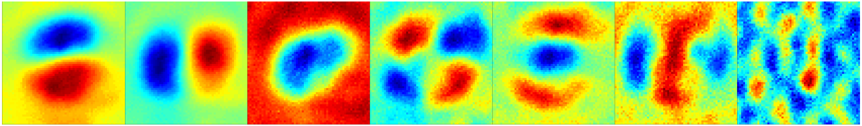
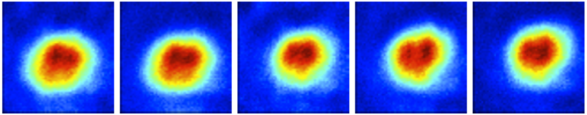


dipole y? dipole x? **scissors**? monopole? quadrupole?

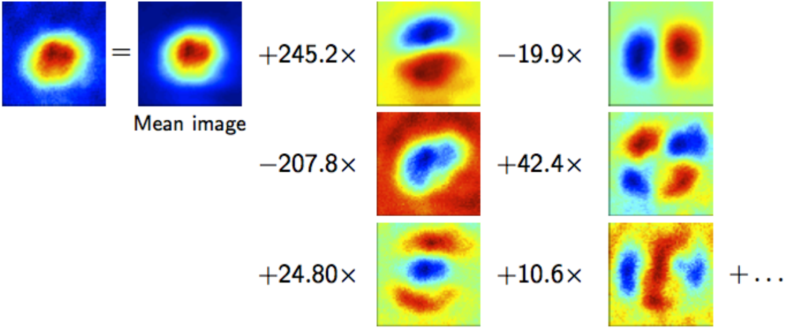
N_{at} fluctuations? noise?

Decomposition onto the components



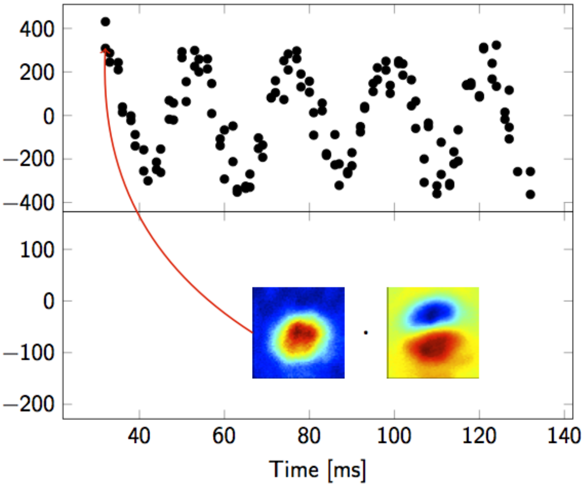
. . .

Each image from the original series can be decomposed onto the various PC's:



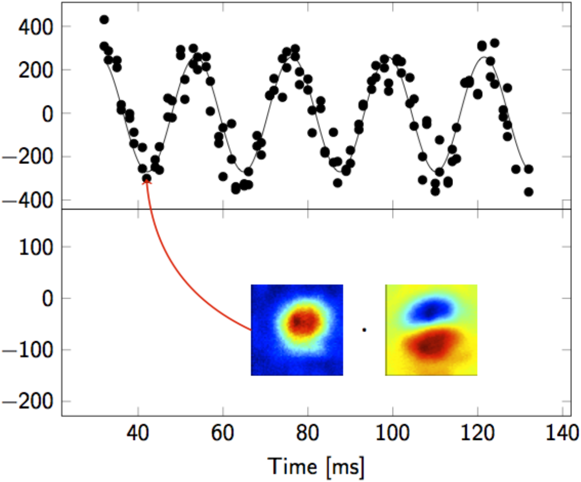
Recovering the modes
Dipole mode

Weight onto PC1 as a function of time: oscillation at 44 Hz (ω_y).



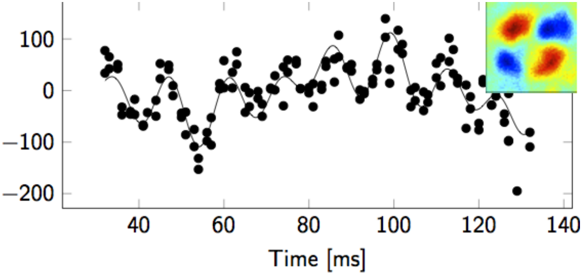
Recovering the modes
Dipole mode

Weight onto PC1 as a function of time: oscillation at 44 Hz (ω_y).
We can identify the dipole mode along y.



Recovering the modes
Scissors mode

Back to the scissors mode: weight onto PC4.



Fit with 3 frequencies: 12 Hz, 55 Hz, 77 Hz.
Now we can identify the 3 frequencies at which the scissors component $\langle x^2 - y^2 \rangle$ oscillates: $\omega_y - \omega_x$ becomes visible.
The three frequencies can thus coexist also in 2D.

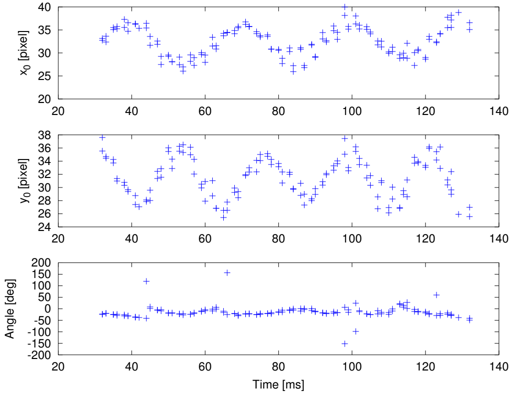
Comparison with a Thomas-Fermi fit

A Thomas-Fermi fit of the density profile with the same data set is able to recover the dipole oscillation, but not the scissors mode:

x coordinate
33 Hz

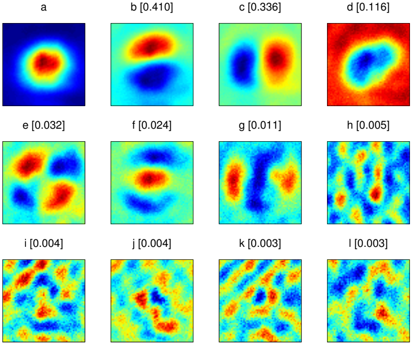
y coordinate
44 Hz

fitted angle

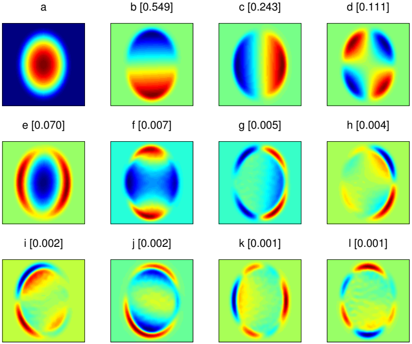


Simulation of GPE vs experiment

PCA applied to a simulation of GPE in the experimental conditions vs PCA applied to the experiment:



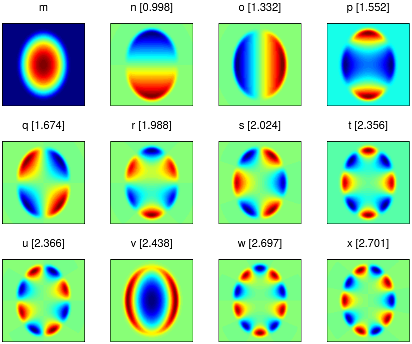
PCA applied to experiment



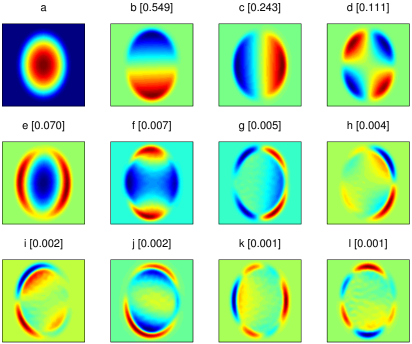
PCA applied to simulation

Simulation of GPE vs Bogoliubov diagonalization

PCA applied to simulation vs the Bogolubov diagonalisation: the mode amplitudes, with their sign, are clearly captured



Bogolubov modes



PCA applied to simulation

Mode frequencies

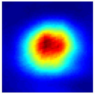
- PCA correctly identifies the modes, with the expected frequency (in units of ω_x):

mode	$\omega_{\rm pca}$	$\omega_{\rm diag}$	$\omega_{\rm th}$
dipole (x)	0.999	0.998	1
dipole (y)	1.332	1.332	1.334
quadrupole-like	1.547	1.552	1.548
scissors	1.674	1.674	1.667
monopole-like	2.441	2.438	2.438

- PCA gives access to the true modes when the potential differs from the model harmonic potential.
- It is not sensitive to aliasing (like FFT), and also works for not evenly spaced sampling times.

Summary

- A 2D Bose gas in a very smooth trap with a tunable geometry



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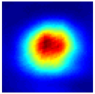
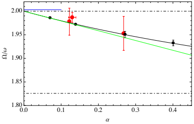


- monopole (EOS) and scissors (superfluidity) modes observed



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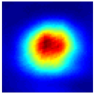

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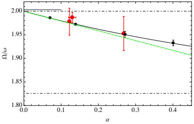
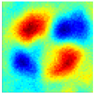


- principal component analysis identifies the mode shapes and frequencies



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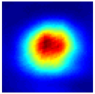

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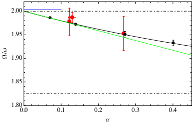

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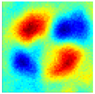
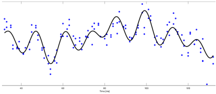


- The low frequency $\omega_y - \omega_x$ component recovered, all 3 frequencies present in 2D

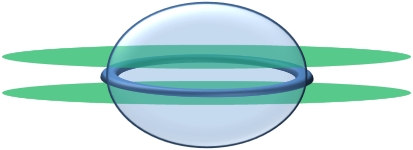


Outlook: Application to an annular superfluid

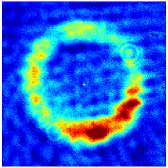
Superfluid in a ring trap

What do we expect in a ring?

Yet another ring trap, well adapted to 2D Bose gases [Morizot et al. PRA 2006, also Foot 2008]:



rf bubble + light potential



LPL 2015

Very anisotropic trap with independent frequencies (vertical frequency 1-10 kHz, radial 300 Hz - 1 kHz), with dynamically adjustable radius, anisotropy, frequency, etc

⇒ probe 2D superfluidity

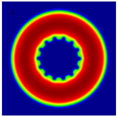
Critical velocity of an annular superfluid

The role of edge modes

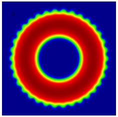
[Dubessy et al., PRA 2012]

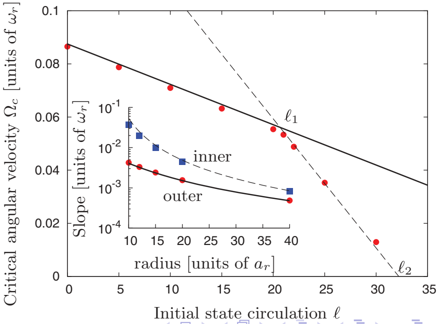
- 2D/3D rings: The Bologlubov spectrum gives access to the critical angular velocity and to the energy stability, evidencing the role of surface modes.
- Due to the way a superfluid rotates, the two edges don't play the same role, in contrast with a superfluid flowing in a straight tube.

inner surface mode



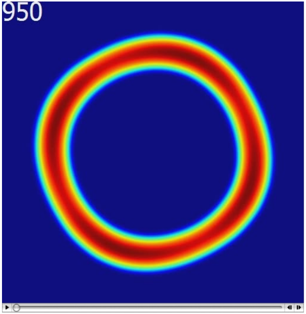
outer surface mode



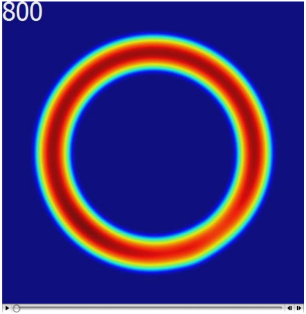


Simulation of the dynamics of stirring

Excitation rotating at an increasing frequency Ω



$\ell = 4$ excitation



rotating barrier

Simulations by Thomas Liennard in his PhD thesis (Paris 13, 2011). See also recent work by Yakimenko et al.
Next step: use PCA to identify the excitations triggering the critical velocity or responsible for phase slips!

Acknowledgments

T. Badr R. Dubessy D. Ben Ali A. Perrin
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K. Merloti

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B. Garraway

P. Pedri

www-lpl.univ-paris13.fr/bec