Lecture 3: Superfluid dynamics at the bottom of a bubble trap

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Vortex Dynamics, Turbulence and Related Phenomena in Quantum Fluids — Natal, June 24-28, 2019

Outline of the course

- Lecture 1: Bose-Einstein condensation, superfluid hydrodynamics and collective modes
- Lecture 2: Adiabatic potentials for confining quantum gases
- Lecture 3: Superfluid dynamics at the bottom of a bubble trap

Tuning quantum gases

Quantum gases benefit from a wide range of tunable parameters:

- temperature in the range 10 nK – 1 μK
- 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

Collective modes as a probe of the system

This lecture: exploring the collective modes at the bottom of the bubble trap:

- support temperature in the range 10 nK – 1 μK
- interaction strength controlled by confinement
- 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

Outline of the course

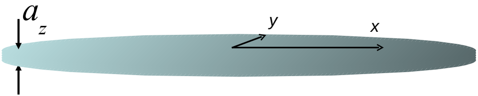
References for the lecture

1. F. Dalfovo, S. Giogini, L. Pitaevskii and S. Stringari, Rev. Mod. Phys. **71**, 463 (1999).
2. I. Bloch, J. Dalibard, W. Zwerger, Rev. Mod. Phys. **80**, 885 (2008)
3. R. Dubessy et al., New J. Phys. **16**, 122001 (2014)
4. M. Olshanii, H. Perrin, and V. Lorent, Phys. Rev. Lett. **105**, 095302 (2010)
5. D. Guéry-Odelin and S. Stringari, Phys. Rev. Lett. **83**, 4452 (1999)
6. K. Merloti et al., Phys. Rev. A **88**, 061603(R) (2013)
7. M. Holten et al., Phys. Rev. Lett. **121**, 120401 (2018)
8. C. De Rossi et al., New J. Phys. **18**, 062001 (2016)

Confining to two dimensions

Prepare a 2D Bose gas

- Harmonic trap $V_{\mathrm{ext}}(x,y,z) = \frac{1}{2}M\omega_x^2x^2 + \frac{1}{2}M\omega_y^2y^2 + \frac{1}{2}M\omega_z^2z^2$
- 2D gas: compress strongly the transverse direction (z)
  $\omega_z \gg \omega_{x,y}$ such that $\mu, k_BT \ll \hbar\omega_z$: frozen along z
- Ground state of size $a_z = \sqrt{\hbar/M\omega_z}$



Two cases depending of the ratio a/a_z where a is the 3D scattering length.

Case 1: The quasi two-dimensional Bose gas: $a_z > a$

Collisions remain 3D

- $\psi(\mathbf{r}) = \psi_\perp(\mathbf{r}_\perp)\phi_z(z)$ with $-\hbar^2\partial_z^2\phi + \frac{1}{2}m\omega_z^2 z^2\phi(z) = \frac{\hbar\omega_z}{2}\phi(z)$
- Plug into GPE:

$$\psi_\perp\left\{\mu\phi(z) - \left[-\frac{\hbar^2}{2M}\triangle_z\phi_z + \frac{1}{2}m\omega_z^2 z^2\phi_z(z)\right]\right\} =$$

$$\left[-\frac{\hbar^2}{2M}\triangle_\perp\psi_\perp + V(\mathbf{r}_\perp)\psi_\perp\right]\phi(z) + g|\psi_\perp|^2\psi_\perp|\phi(z)|^2\phi(z)$$

- Average over the z degree of freedom: $\int\phi(z)^* \times \ldots$

2D GPE $$\boxed{\mu_2\psi_\perp = -\frac{\hbar^2}{2M}\triangle_\perp\psi_\perp + V(\mathbf{r}_\perp)\psi_\perp + g_2|\psi_\perp|^2\psi_\perp}$$

where $\boxed{\mu_2 = \mu - \frac{1}{2}\hbar\omega_z}$ and $g_2 = g\int|\phi(z)|^4 dz = \frac{g}{\sqrt{2\pi}a_z}$

- Dimensionless interaction $g_2 = \frac{\hbar^2}{M}\tilde{g}$ with $\boxed{\tilde{g} = \sqrt{8\pi}\frac{a}{a_z}}$

Case 2: Exotic case: $a_z < a$

True 2D collisions

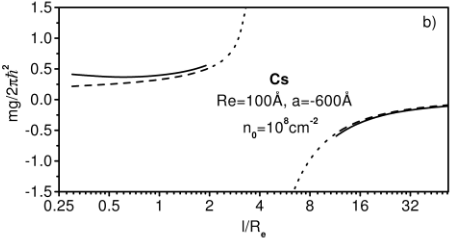
Collisions occur in 2D, scattering length $a_{2D} \simeq 2a_z e^{-\sqrt{\frac{\pi}{2}}\frac{a_z}{a}} \neq 0$

Renormalization of the interaction constant: $g_2 \times f\left(\frac{a}{a_z}, na_{2D}^2\right)$

- Coupling 'constant' depends on atomic density!
- Modified EOS: $\mu(n) \neq g_2 n \Rightarrow$ quantum anomaly
- $g_{2D} > 0$ possible for small a_z even if $a < 0$

confinement-induced resonance for $a < 0$

[Petrov, Holzmann, Shlyapnikov (2000)]



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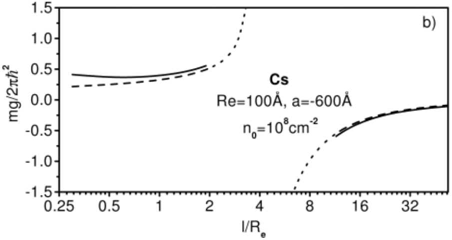


In the following we consider essentially **case 1** with $\tilde{g} = \sqrt{8\pi}a/a_z$.

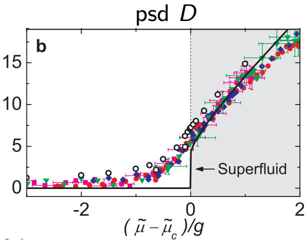
The two-dimensional Bose gas

2D: A marginal dimension

2D is a very special case! Logs and topological phase transitions

- **Scaling symmetry and universality**

- kinetic energy $\propto k^2$, interactions $\propto 1/r^2$, integrand $k\,dk \Rightarrow$ critical dimension with Log divergences
- no length scale: dimensionless interaction strength $g = \frac{\hbar^2}{M}\tilde{g}$
- EOS depends only on $\alpha = \mu/k_B T$: $D = f(\alpha, \tilde{g})$ [ENS,Chicago]



scaled μ: $(\alpha - \alpha_c)/\tilde{g}$

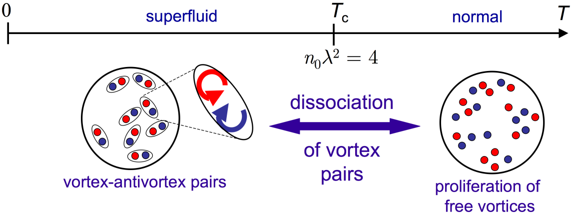
[Chin et al. 2011]

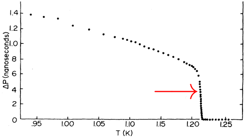
The two-dimensional Bose gas

2D: A marginal dimension

2D is a very special case! Logs and topological phase transitions

• **2D homogeneous case** No long range order/BEC (Hohenberg–Mermin–Wagner theorem), but a Kosterlitz–Thouless transition to a superfluid state below T_{BKT}, relying on vortex-antivortex pairing. Universal jump of the superfluid density.





Bishop and Reppy

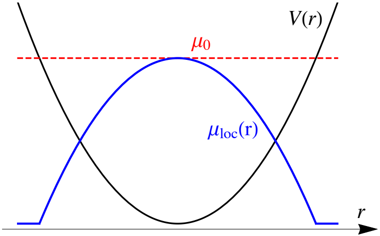
[ENS-CdF, NIST, Chicago, Palaiseau, Seoul, Cambridge...]

2016 Nobel prize in physics to Haldane, Kosterlitz and Thouless

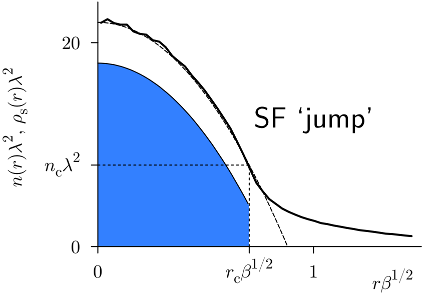
The two-dimensional Bose gas
2D: A marginal dimension

- **trapped gas** $V(\mathbf{r})$:
  - **BEC** recovered in a harmonic trap (finite size helps)
  - **BKT** still relevant within local density approximation (LDA). BEC-BKT interplay [Cambridge]

replace
μ by $\mu_{\rm loc}(\mathbf{r}) = \mu_0 - V(\mathbf{r})$,
α by $\alpha_{\rm loc}(\mathbf{r}) = \alpha_0 - V(\mathbf{r})/k_B T$



BKT superfluid phase within LDA



from Holzmann & Krauth, PRL 2008

The two-dimensional Bose gas

2D: A marginal dimension

2D is a very special case! Logs and topological phase transitions

Summary:

	ideal	interacting
homogeneous	no BEC, no SF	BKT SF [ENS-CdF]
trapped	BEC, no SF	BEC + BKT within LDA

The two-dimensional Bose gas

2D: A marginal dimension

2D is a very special case! Logs and topological phase transitions

Summary:

	ideal	interacting
homogeneous	no BEC, no SF	BKT SF [ENS-CdF]
trapped	BEC, no SF $\leftrightarrow$	BEC + BKT within LDA

BEC-BKT interplay [Cambridge]

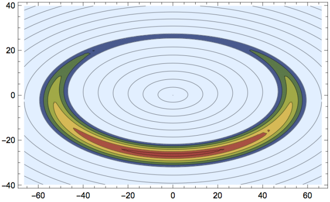
Experimental implementation

rf-induced adiabatic potentials – the dressed quadrupole trap

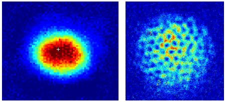
Adiabatic potentials for rf-dressed atoms: dressed quadrupole trap
[reviews Garraway/Perrin: JPB 2016 and Adv.At.Mol.Opt.Phys. 2017]
Atoms are confined to an isomagnetic surface of a quadrupole field.

- smooth potentials (magnetic fields with large coils)
- strong confinement to the surface: $\omega_\perp \sim 2\pi \times 1 - 2$ kHz
- geometry (r_0, xy-anisotropy) can be fine-tuned dynamically
- temperature adjusted with a (weak) rf knife (30 – 200 nK)

side view (isopotentials):

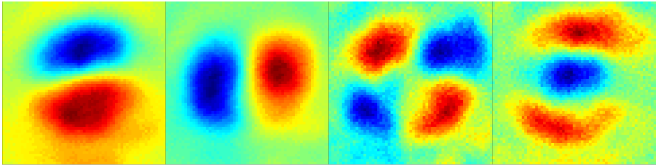


top-view:
a 2D quantum gas



Collective modes of the quasi-2D Bose gas

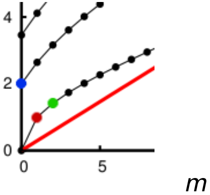
Overview of the collective modes



Reminder for a 2D trapped Bose gas

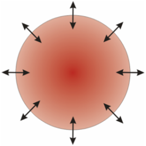
Excitation spectrum and collective modes

Collective modes for the isotropic 2D gas: n, m are good quantum numbers: $\omega(n,m) = \omega_0 \left[2n^2 + 2n|m| + 2n + |m|\right]^{1/2}$

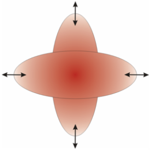


- dipole mode $n = 0, m = 1$, both superfluid and thermal: centre of mass oscillation: **clock**

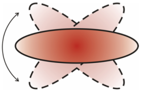
- monopole $n = 1, m = 0$: superfluid and thermal **signature of the EOS**



- quadrupole $n = 0, m = \pm 2$ **signature of superfluidity**



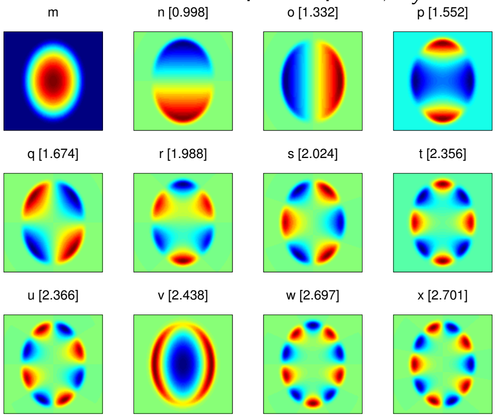
- **scissors** for $\omega_x \neq \omega_y$ **signature of superfluidity**



Expected collective modes in an anisotropic trap

From Bogolubov diagonalisation of an idealised case

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

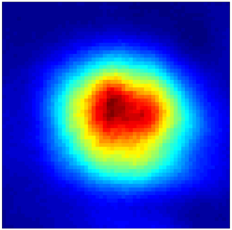


2 dipoles (ω_x, ω_y), quadrupole-like (ω_Q), scissors $(\omega_S = \sqrt{\omega_x^2 + \omega_y^2})$, 4 more modes of higher order symmetry and then monopole-like (ω_M)

Overview of low energy collective modes

Exciting low energy collective modes

A BEC prepared in 3D trap and transferred quickly into the 2D rf-dressed quadrupole trap, whose axes are also suddenly rotated. Several modes are excited during this process.



excited cloud

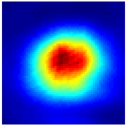
2D trap frequencies:
$\omega_x = 2\pi \times 33$ Hz,
$\omega_y = 2\pi \times 44$ Hz

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

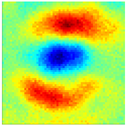
Overview of the Bogolubov modes

Principal component analysis

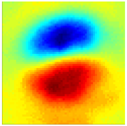
Analysis of the **correlations between pixels** allows to recover the collective modes.



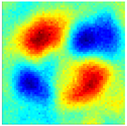
average picture



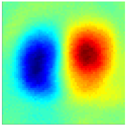
monopole-like



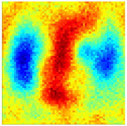
dipole mode x



scissors



dipole mode y



quadrupole-like

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

Overview of the Bogolubov modes

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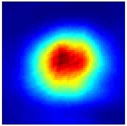
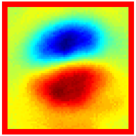


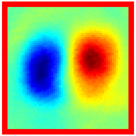
average picture



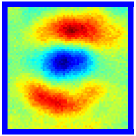
dipole mode x

serve as a clock

for ω_x, ω_y

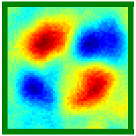


dipole mode y



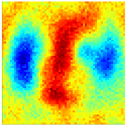
monopole-like

EOS



scissors

superfluidity



quadrupole-like

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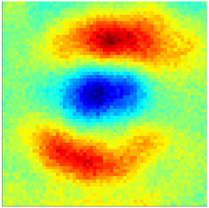
The monopole mode

Monopole mode and Equation of State



$$\mu(n) \propto n^{\gamma}, \gamma = ?$$

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: quantum anomaly due the beaking of scaling symmetry: $\tilde{g}/(16\pi)$ **positive shift** [Olshanii 2010]

The monopole mode in an isotropic harmonic trap

Quantum anomaly

Olshanii, Perrin, Lorent, PRL 2010

isotropic harmonic 2D trap, frequency ω

Pitaevskii-Rosch symmetry: Classical Field Theory (CFT) for 2D bosons in a harmonic trap

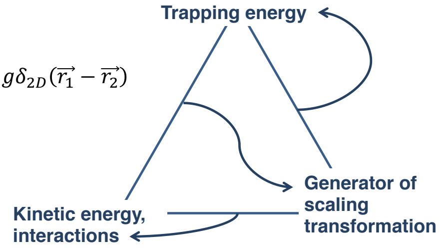
Scaling invariance in 2D in the CFT: $\hat{H}_0 = \hat{H}_K + \hat{H}_I$, $\hat{H}_{\rm trap}$, $\hat{Q}$ form a closed algebra SO(2,1)

Kinetics, interactions

$$\begin{cases} \dfrac{p^2}{2m} \xrightarrow{\vec{r}\to\lambda\vec{r}} \dfrac{1}{\lambda^2}\dfrac{p^2}{2m} \\ g\delta_{2D}(\vec{r_1}-\vec{r_2}) \xrightarrow{\vec{r}\to\lambda\vec{r}} \dfrac{1}{\lambda^2} g\delta_{2D}(\vec{r_1}-\vec{r_2}) \end{cases}$$

trap: $\frac{1}{2}M\omega^2 r^2 \xrightarrow{\vec{r}\to\lambda\vec{r}} \lambda^2 \frac{1}{2}M\omega^2 r^2$

generator of scaling transformations: $\frac{1}{2}(\mathbf{r}\cdot\mathbf{p}+\mathbf{p}\cdot\mathbf{r})$



closed algebra, SO(2,1)

The monopole mode in an isotropic harmonic trap

Quantum anomaly — Olshanii, Perrin, Lorent, PRL 2010

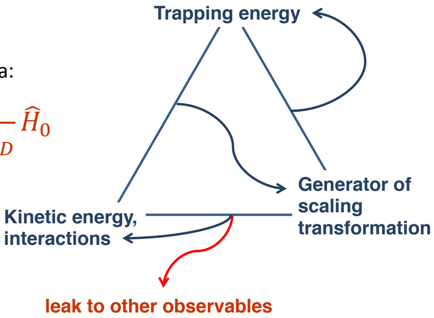
Petrov 2001: $a_{2D} = 1.48\ldots\ a_\perp \exp\left[-\frac{\sqrt{\pi}}{2}\frac{a_\perp}{a_{3D}}\right]$ a quantum length scale appears!

New equation of state: $\mu(n) = \frac{4\pi\hbar^2}{m} n\chi(\pi e^{2\gamma+1} n {a_{2D}}^2)$ (Popov 1983, Mora&Castin 2003)

where $\chi(x) = \frac{1}{-W_{-1}(-x)} \overset{x\to 0}{\approx} 1/\ln(1/x) + \mathcal{O}\left(\frac{\ln(\ln(1/x))}{\ln(1/x)^2}\right)$

Consequence: `leak' in the algebra:

$$[\hat{Q}, \hat{H}_0] = 2i\hat{H}_0 + i a_{2D}\frac{\partial}{\partial a_{2D}}\hat{H}_0$$



$\Rightarrow$ small shift of Ω_M

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A way to study the Equation Of State

isotropic harmonic 2D trap, frequency ω

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- Ex: quantum anomaly due the beaking of scaling symmetry: $\tilde{g}/(16\pi)$ **positive shift** [Olshanii 2010]
- Ex: flat, but 3D gas: $\mu(n) \propto n^{2/3} \Rightarrow \Omega_M = \sqrt{10/3}\,\omega$

The monopole mode in an isotropic harmonic trap
A way to study the Equation Of State

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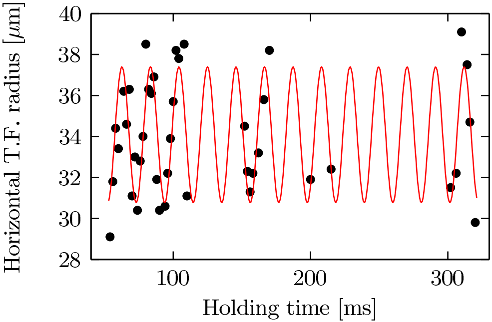
- Ex: flat, but 3D gas: $\mu(n) \propto n^{2/3} \Rightarrow \Omega_M = \sqrt{10/3}\,\omega$
- we probe the intermediate case: for non negligible interactions is there a shift a as function of $\dfrac{\mu}{2\hbar\omega_z}$? [Merloti 2013]

Observation of the monopole mode

Isotropic trap

Prepare a degenerate sample in an isotropic 2D trap
Excitation through a sudden change in ω
Very low T (no thermal fraction)

● experimental data
—— sinusoidal fit
[Merloti NJP2013]

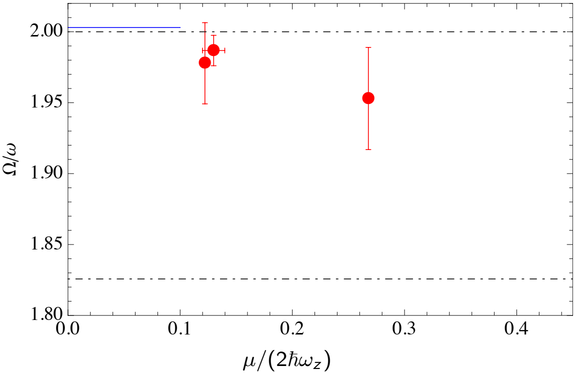


typical data: Ω_M close to 2ω; no measurable damping

Results: shift of the monopole mode

A modified EOS

We observe a small negative shift as a function of $\mu/(2\hbar\omega_z)$ [Merloti PRA2013]:



$\gamma = 1$

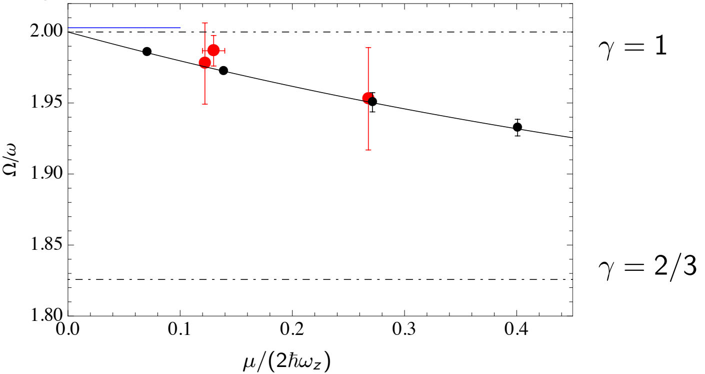
$\gamma = 2/3$

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

Typically 1% shift: $\gamma = 0.96$, $\mu \propto n^{0.96}$.

Results: shift of the monopole mode
A modified EOS

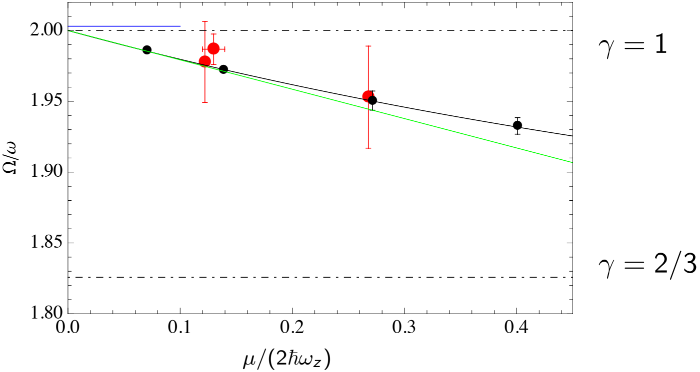
Comparison with a **3D** GPE simulation:



The in-plane EOS is indeed impacted by the **third dimension**.

Results: shift of the monopole mode
A modified EOS

Comparison with a **perturbative theory** (Olshanii): interactions deform the 1D ground state and shift μ.

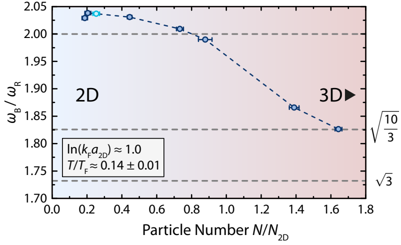


Recover the observed behaviour at first order.
Merloti et al., PRA **88**, 061603(R) 2013.

Observing the quantum anomaly?

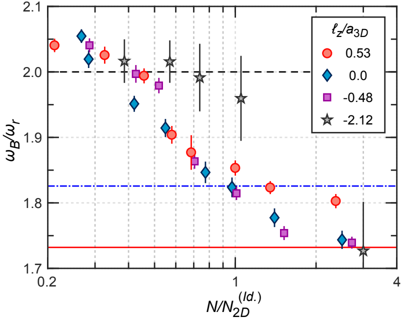
Recently observed with fermions, using a Feshbach resonance

S. Jochim, Heidelberg, ^{6}Li
(also uses PCA)



[PRL **121**, 120401 (2018)]

Chris Vale, Swinburne, ^{6}Li

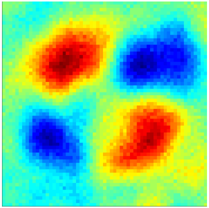


[PRL **121**, 120402 (2018)]

For bosons: yet to be done

The scissors mode

Scissors mode and superfluid transition

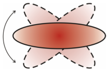


thermal or superfluid gas?

The scissors mode

A signature of superfluidity in a dilute 2D gas

Using the scissors mode to characterize a superfluid dilute gas [DGO Stringari 1999, Foot2000]



Scissors mode: oscillation of $\langle xy \rangle \propto \theta$ in an **anisotropic** harmonic trap, $\omega_x/\omega_y \sim 1.3$

The scissors mode

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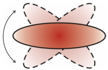

Scissors mode: oscillation of $\langle xy \rangle \propto \theta$ in an **anisotropic** harmonic trap, $\omega_x/\omega_y \sim 1.3$

- scissors mode expected at $\omega_{\mathrm{sc}} = \sqrt{\omega_x^2 + \omega_y^2}$ for a **superfluid**
- no scissors mode in the thermal phase in the **collisionless** regime, only beat notes of harmonic modes $\omega_\pm = \omega_x \pm \omega_y$

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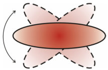

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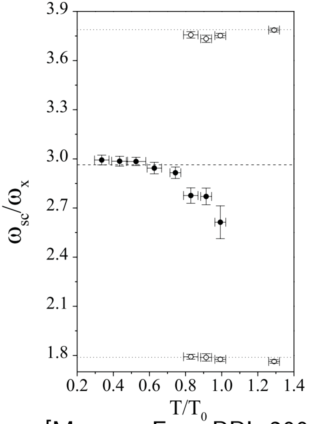
- no scissors mode in the thermal phase in the **collisionless** regime, only beat notes of harmonic modes $\omega_\pm = \omega_x \pm \omega_y$
- crossover between the two regimes when T increases?

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

The scissors mode: previous work and expectations

3D vs 2D as a function of temperature

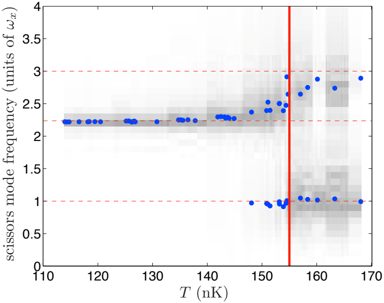
3D, bimodal fit of the angle(s): observed negative shift



exp: [Marago, Foot PRL 2001]

2D: positive shift expected

ω_{sc} connects to ω_+



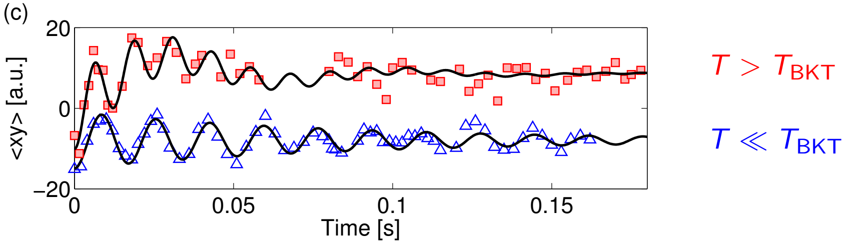
numerics: [Simula, PRA 2008]

compute $\langle xy \rangle$, FFT analysis

Exciting the scissors mode

Procedure:

- Anisotropic trap + sudden rotation of the trap axes.
- Compute $\langle xy \rangle$ and plot its time variation.
- Extract oscillation frequency ω and damping Γ.
- Repeat for various μ and T (i.e. $\alpha = \mu/k_B T$)

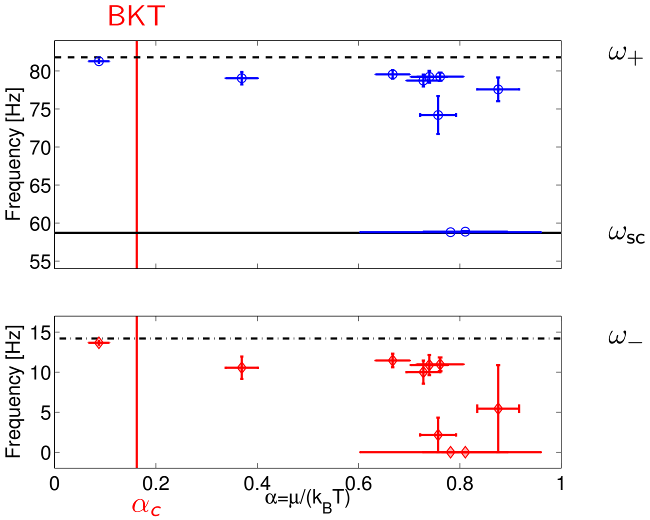


Results with a global analysis of $\langle xy \rangle$

Two frequency branches: upper branch from ω_+ to ω_{sc}, lower branch from ω_- to 0.

upper branch

lower branch



Results with a global analysis of $\langle xy \rangle$

Two frequency branches: upper branch from ω_+ to ω_{sc}, lower branch from ω_- to 0.

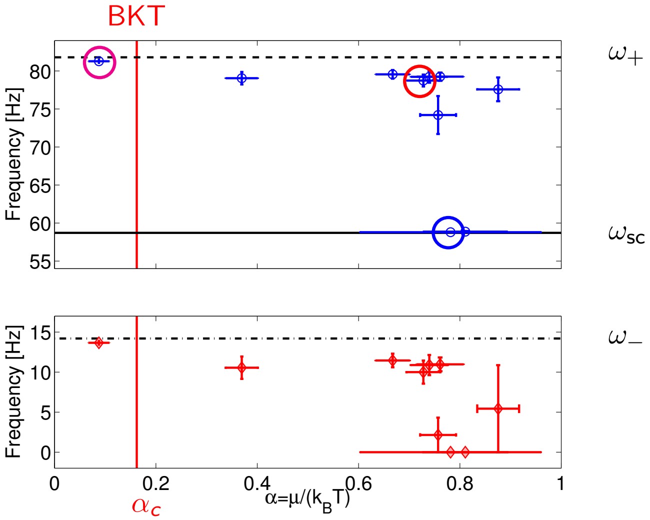
$\alpha \gg \alpha_c$

$\alpha > \alpha_c$

$\alpha < \alpha_c$

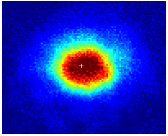
upper branch

lower branch



Going local

The frequencies $\omega_{\pm}$ are present in $\langle xy \rangle(t)$ even for $\alpha > \alpha_c$ (or $T < T_{\mathrm{BKT}}$), where a superfluid should be present.



The gas is inhomogeneous...

- Superfluid oscillation hidden by thermal contribution to $\langle xy \rangle$?
- Can we get **more local information**?
- Can we identify the superfluid phase in the inhomogeneous gas with purely dynamical criteria?

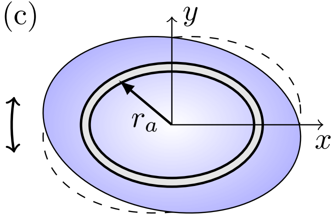
$\Rightarrow$ perform a local analysis of the dynamics

Analysing the local average

Local analysis: use the fact that the scissors oscillation is a surface mode

In the spirit of LDA, compute the $\langle xy \rangle_{r_a}$ average over an annulus, isopotential of **given average density**

rescaled radius r_a:
$\omega_x^2 x^2 + \omega_y^2 y^2 = \omega_0^2 r_a^2$



Extract the local values of ω and Γ

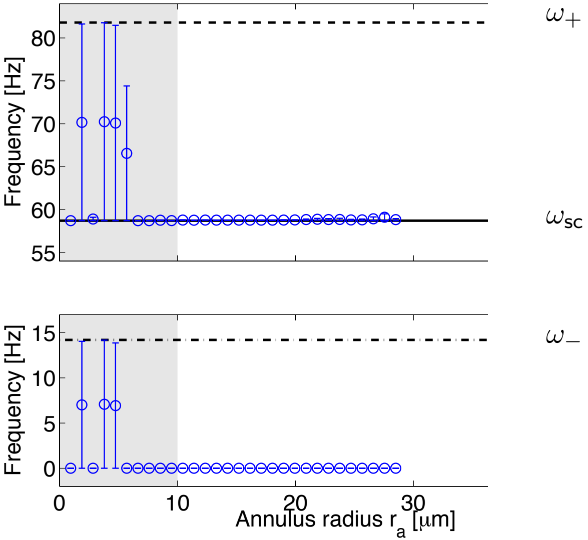
Three cases $\alpha \gg \alpha_c$, $\alpha > \alpha_c$, $\alpha < \alpha_c$

Analysing the local average

$\alpha \gg \alpha_c$

upper branch

lower branch



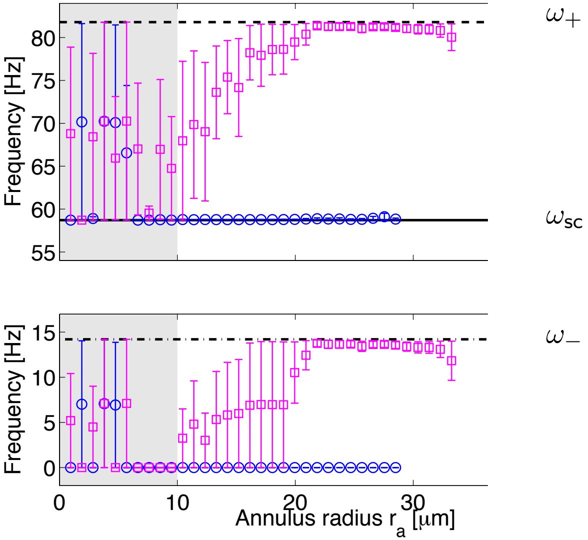
Analysing the local average

$\alpha \gg \alpha_c$

$\alpha < \alpha_c$

upper branch

lower branch



Analysing the local average

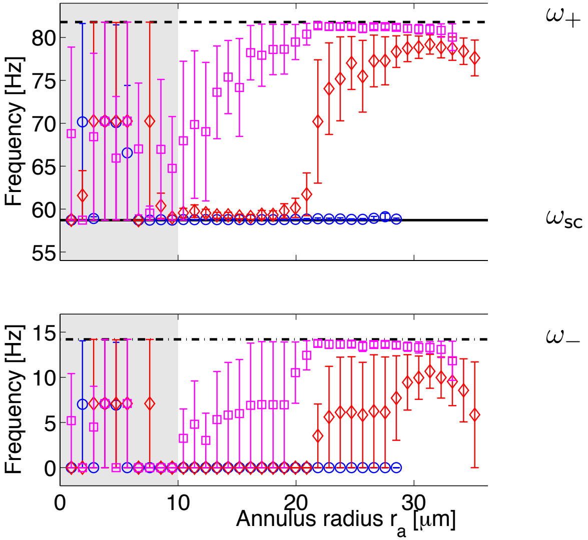
$\alpha \gg \alpha_c$

$\alpha > \alpha_c$

$\alpha < \alpha_c$

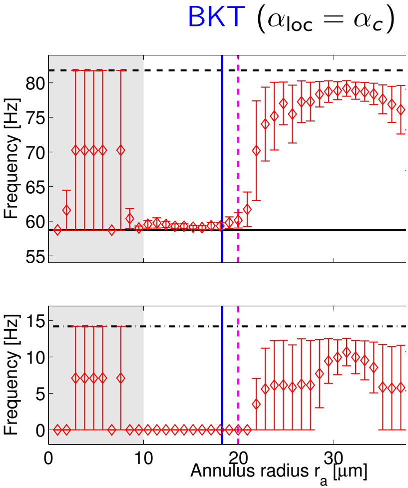
upper branch

lower branch



Comparison with BKT LDA threshold

Case $\alpha > \alpha_c$



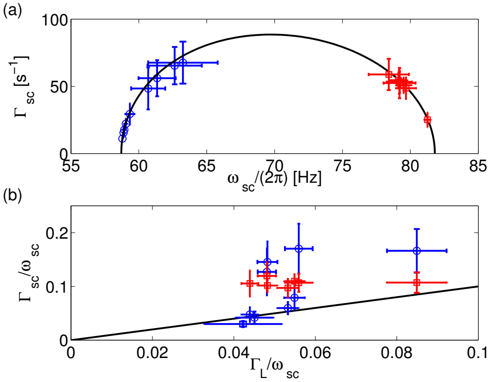
The equilibrium LDA threshold for BKT is in agreement with the local analysis of the dynamics.

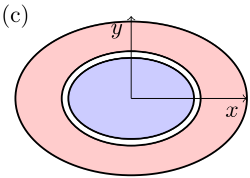
[De Rossi et al., NJP 2016]

Open question: can we use it to determine the SF fraction?

Superfluid - normal boundary

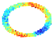
Conclusion: the superfluid-normal boundary is located with a purely dynamical criterion = frequency of the scissors mode. Damping analysis on each side of the boundary: larger than Laudau damping ⇒ SF to thermal gas coupling?

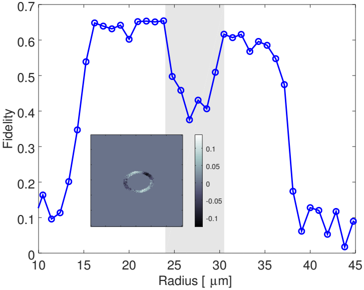


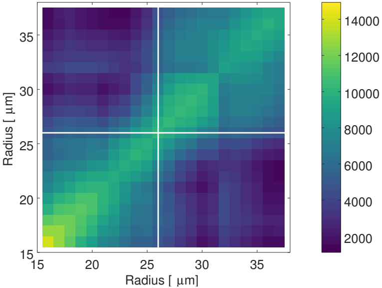


boundary determined with LAA

Bonus: Local PCA

PCA applied on an annulus also reveals the scissors mode 





boundary determined by comparison between PCA eigenvectors and the $\langle xy \rangle$ mode

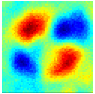
[Dubessy 2018]

correlations between two radii: qualitative agreement with a two-fluid model

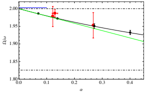
Summary & prospects

2D Bose gas: a very smooth and tunable trap to study the collective modes

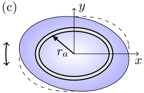
- Direct observation of the mode shapes



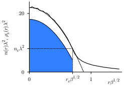
- A modified EOS evidenced with the monopole mode



- The scissors mode reveals normal-to-superfluid boundary with a local analysis of the dynamics.



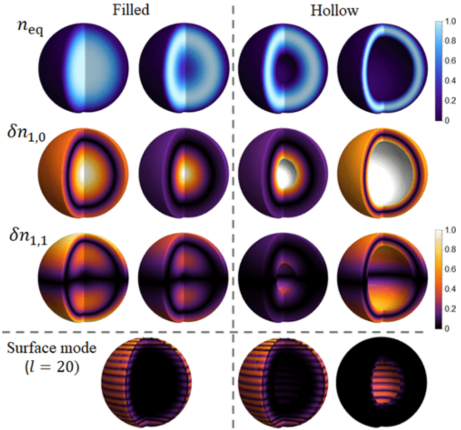
- Outlook: use this probe to access a sharp change in ρ_s at the boundary?



Summary & prospects

Beyond the bottom of the bubble:

- Looking for the collective modes of a shell (cf Natália's talk)

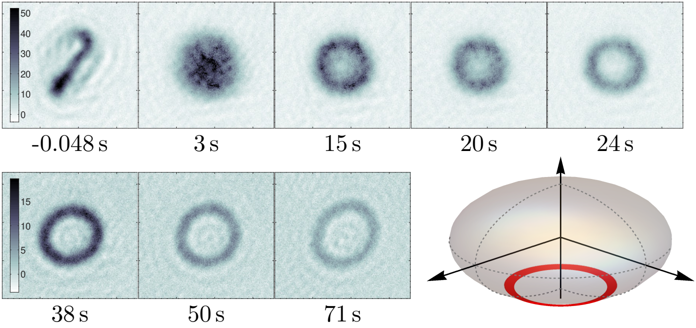


Sun et al., Phys. Rev. A **98**, 013609 (2018)]

Summary & prospects

Beyond the bottom of the bubble:

- Observation of the collective modes of a shell
- Fast rotation in the shell: superfluid supersonic flow



[Guo et al., submitted]

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M. Olshanii

B. Garraway

V. Bagnato

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