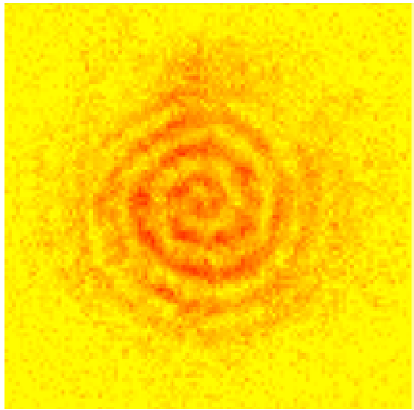
Laboratoire Kastler Brossel
Physique quantique et applications

Out-of-equilibrium physics with Bose gases in 2D geometries

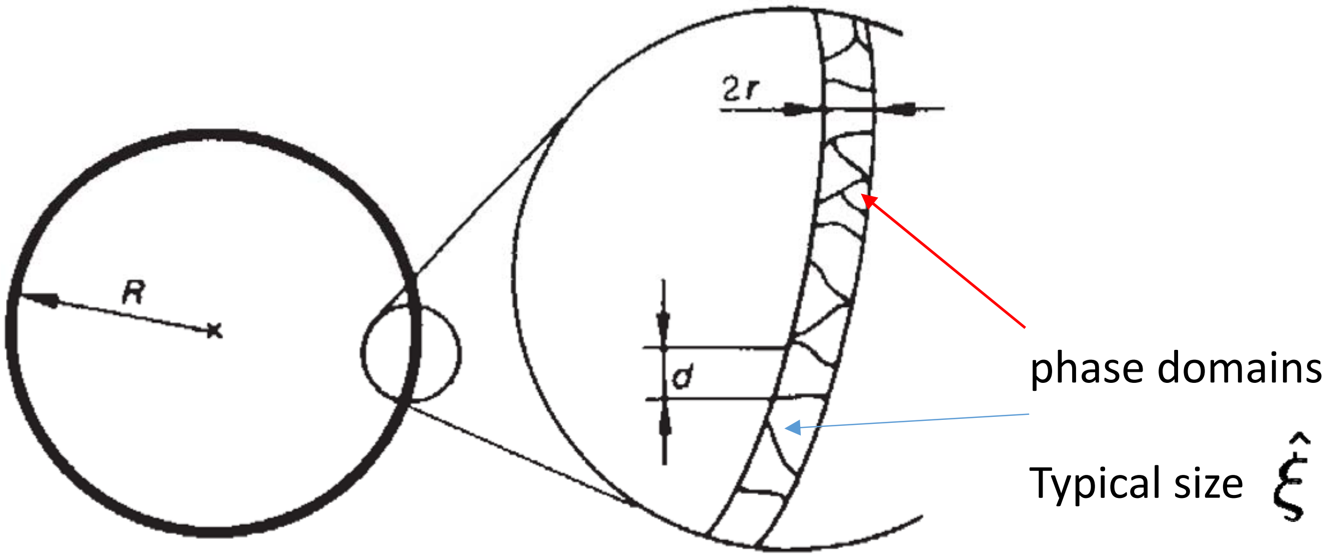


current members: Lauriane Chomaz, Laura Corman, Tom Bienaimé, Jean-Loup Ville, Raphaël de Saint-Jalm
former members: R. Desbuquois, C. Weitenberg, D. Perconte, K. Kleinklein, A. Invernizzi
permanent members: Sylvain Nascimbene, Jérôme Beugnon, Jean Dalibard

References : Phys. Rev. Lett. **103**:135302 (2014) & Nat. Comm. **6**:6162 (2015)

Zurek's experiment

★ Quench cooling of helium confined in a ring should lead to the creation of superfluid currents



Zurek Nature **317**, 505 – 508 (1985)

KZ mechanism is used to described many different experiments :
Cosmology, liquid helium, squids, ferroelectrics, liquid crystals, ion chains, quantum gases, ….

See del Campo, A. & Zurek, W. H. Int. J. Mod. Phys. A 29, 1430018 (2014)) Kibble, T. Physics Today 60(9), 47 (2007)

Zurek's experiment

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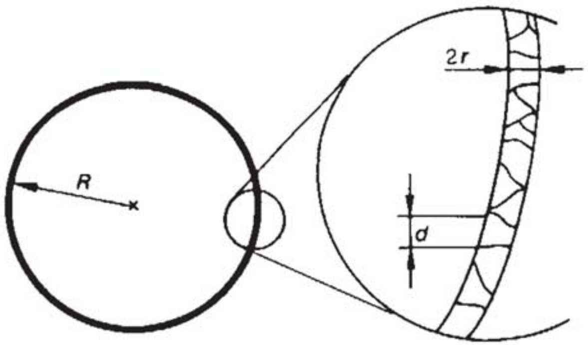
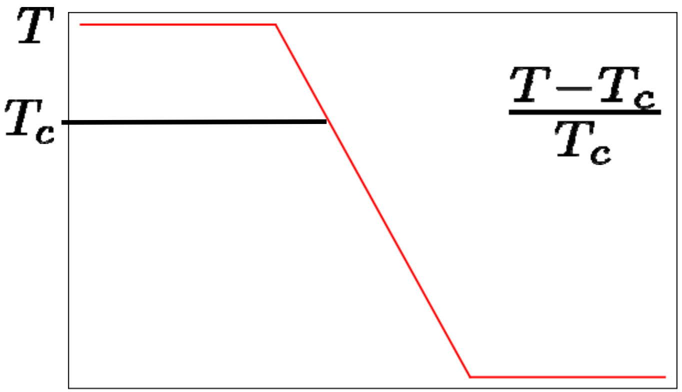


Zurek *Nature* **317**, 505 – 508 (1985)



$$\frac{T-T_c}{T_c} \propto t/\tau_{\text{quench}}$$

Kibble-Zurek mechanism predicts :

$$\hat{\xi} \propto \left(\tau_{\text{quench}}\right)^{\frac{\nu}{1+\nu z}}$$

Experiments in the Cambridge team 3D BEC :
Navon et al. Science **347**, 167 (2015)

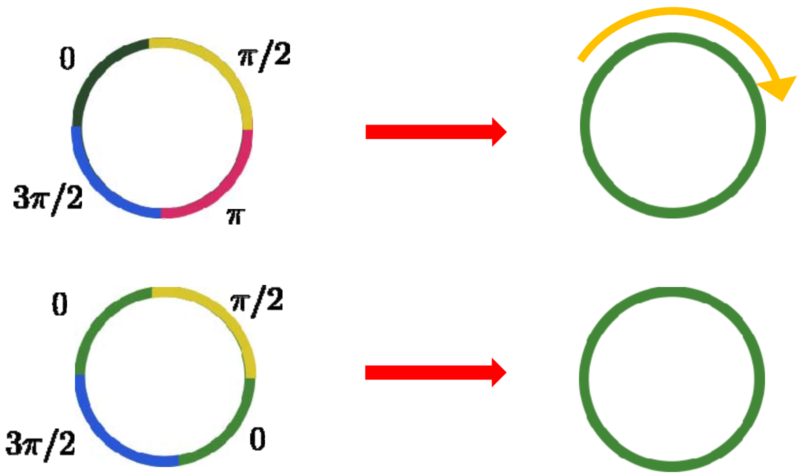
Correlation length $\xi \propto \left(\frac{T-T_c}{T_c}\right)^{-\nu}$ Thermalization time $\tau \propto \xi^z$

Zurek's experiment

Superfluid current are generated stochastically during the merging of the phase domains

$$\hat{\xi} \propto (\tau_{\text{quench}})^{\frac{\nu}{1+\nu z}}$$

Number of phase domains $N_\phi \propto L/\hat{\xi}$ L : Ring perimeter



2π Phase winding

0π Phase winding

Examples :

$N_\phi = 3 \rightarrow \langle |W| \rangle = 0.25$

$N_\phi = 20 \rightarrow \langle |W| \rangle \approx 1$

average absolute winding number $\langle |W| \rangle \approx \sqrt{\langle W^2 \rangle} \propto \sqrt{N_\phi}$ $\langle |W| \rangle \propto \tau_{\text{quench}}^{-\frac{\nu}{2(1+\nu z)}}$

but if $N_\phi \ll 1$ then $\langle |W| \rangle \propto N_\phi^2$ and $\langle |W| \rangle \propto \tau_{\text{quench}}^{-\frac{2\nu}{(1+\nu z)}}$

Zurek J. Phys.: Condens. Matter **25**, 404209 (2013)

How to trap an ultracold gas in a ring ?

How to detect the superfluid current ?

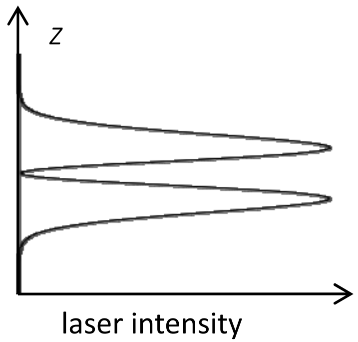
Which phase transition are we crossing ?

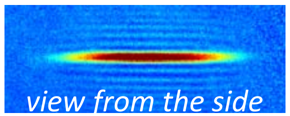
How to trap an ultracold gas in a ring ?

★ Start from a standard 3D ^{87}Rb cloud

★ Vertical confinement ⟶ 2D cloud

Single blue detuned laser beam
with a central node (Hermite-Gauss)





$$\frac{\omega_z}{2\pi} = 350 - 1500\,\mathrm{Hz}$$

10^4 to 10^5 atoms

Temperature controlled by
evaporation: 10 to 250 nK

$$\frac{k_B T}{\hbar \omega_z} = 0.1 - 10$$

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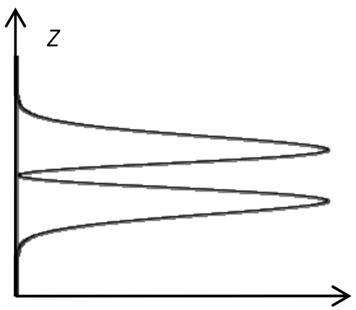

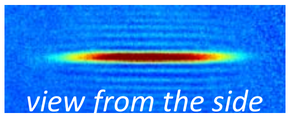

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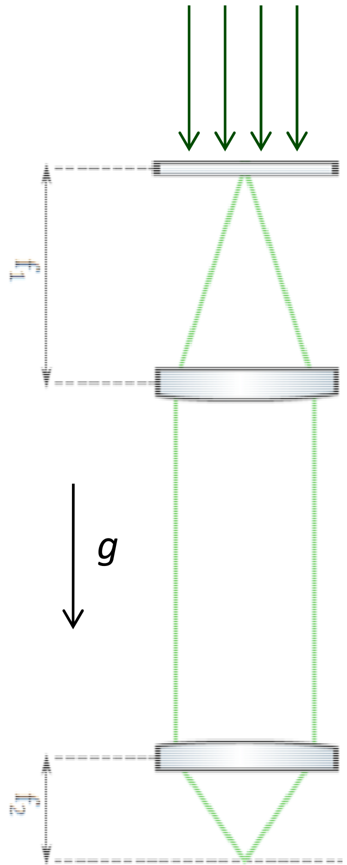
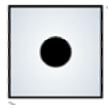
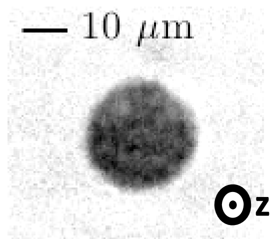
★ Horizontal confinement ⟶ flat-bottom

Image a mask on the atom plane

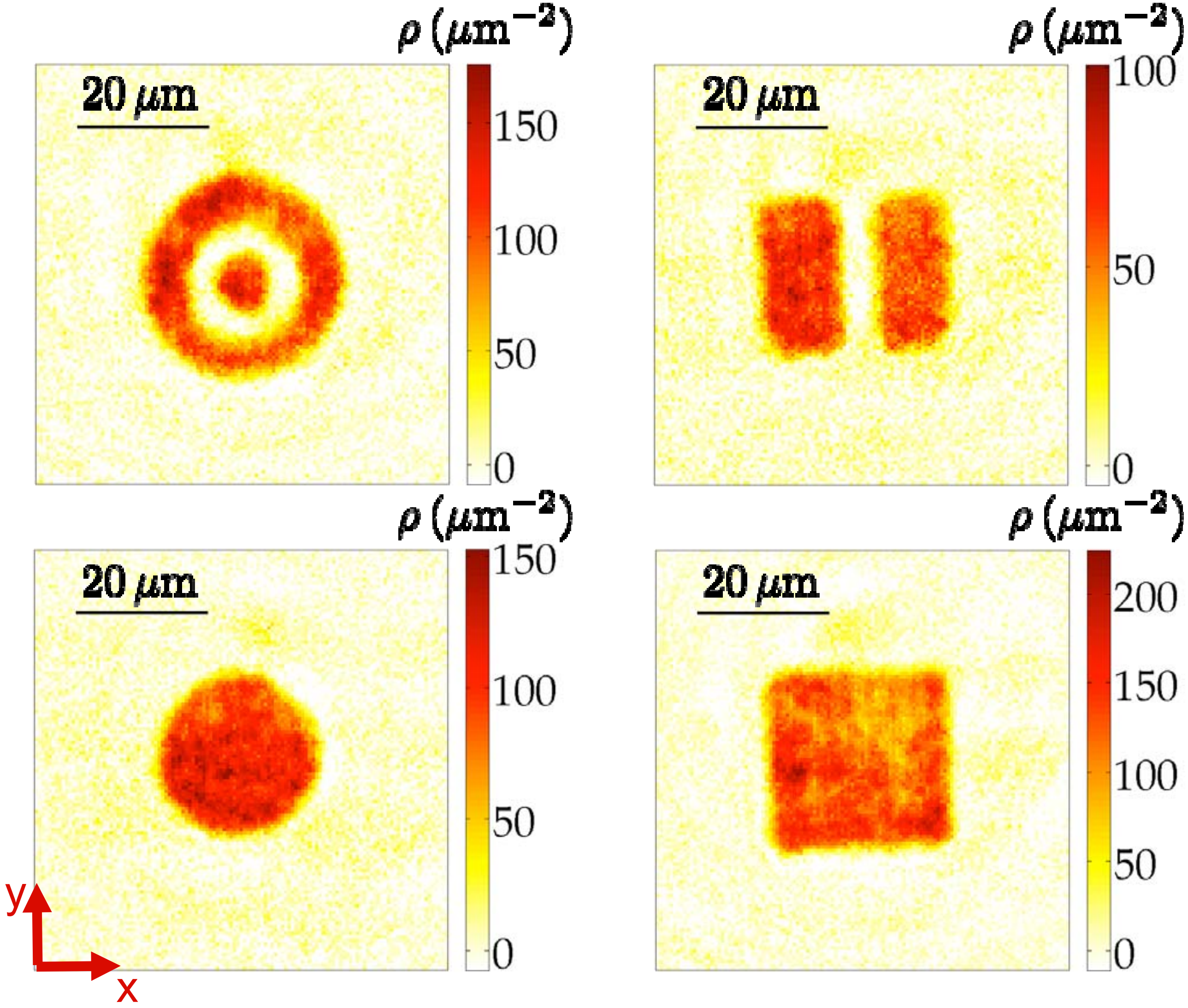






View from above

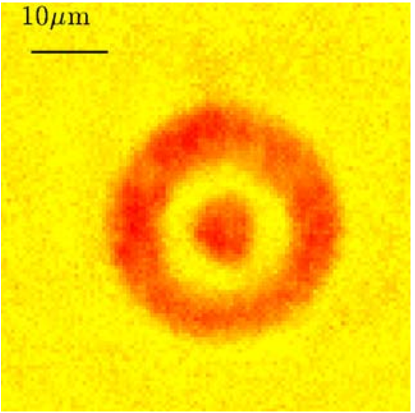
How to trap an ultracold gas in a ring …



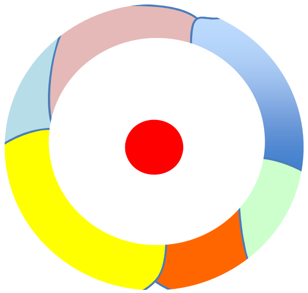
… or anything else

How to detect superfluid currents ?

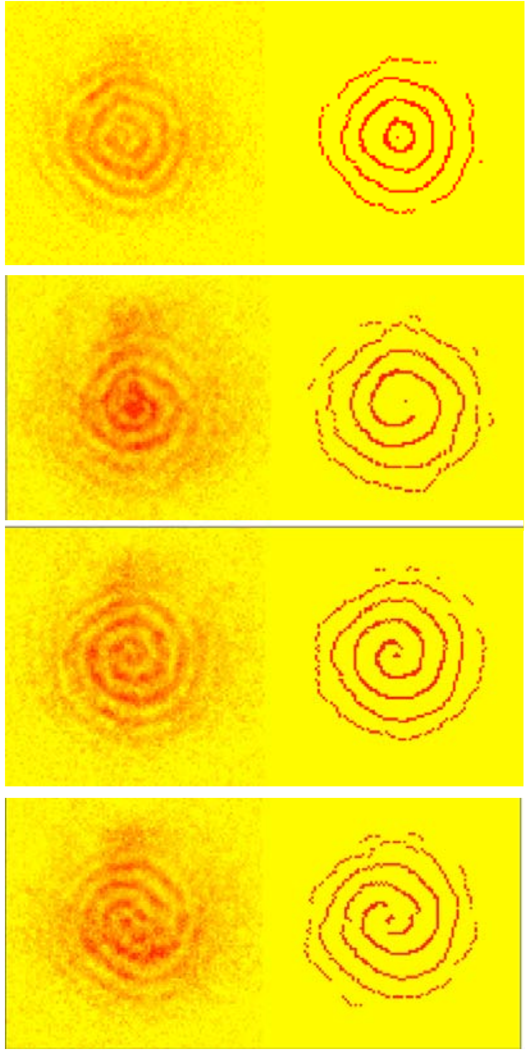
★ Rapid cooling (~ 50 ms→ 2s) via lowering the trap depth
★ Hold time (500 ms → 2s)
★ 2D expansion in plane (7 ms)



In situ



Phase patterns



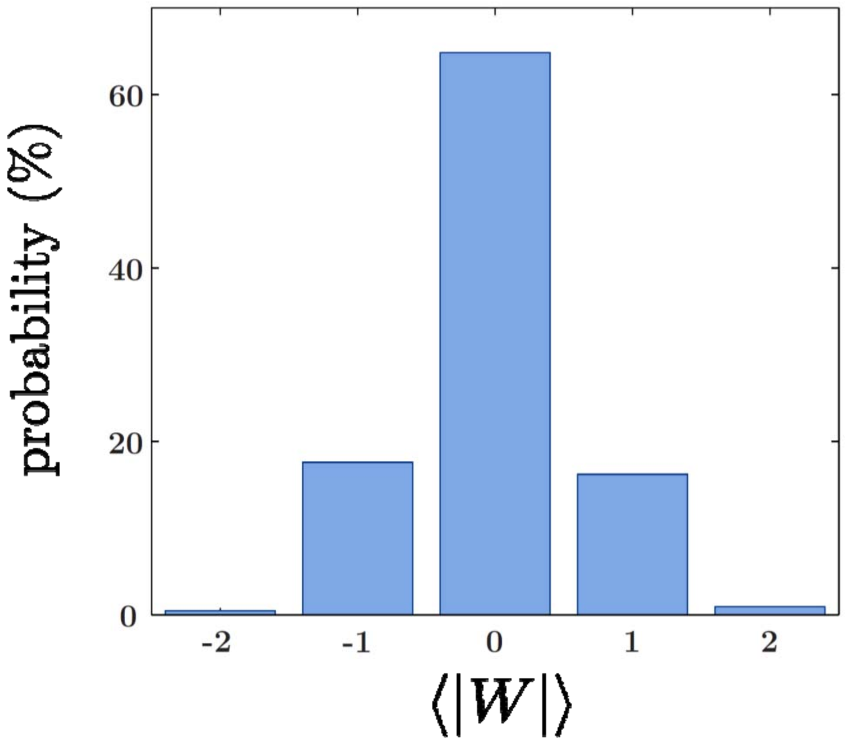
After expansion

Quantized circulation of superfluid currents

Similar experiments at NIST *Eckel et al. Phys. Rev. X 4, 031052 (2014)*

How to detect superfluid currents ?

Stochatisc origine :



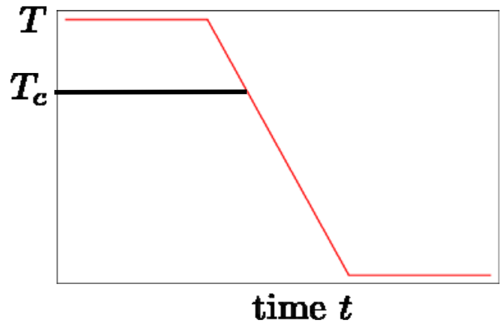
No imbalance between positive and negative winding

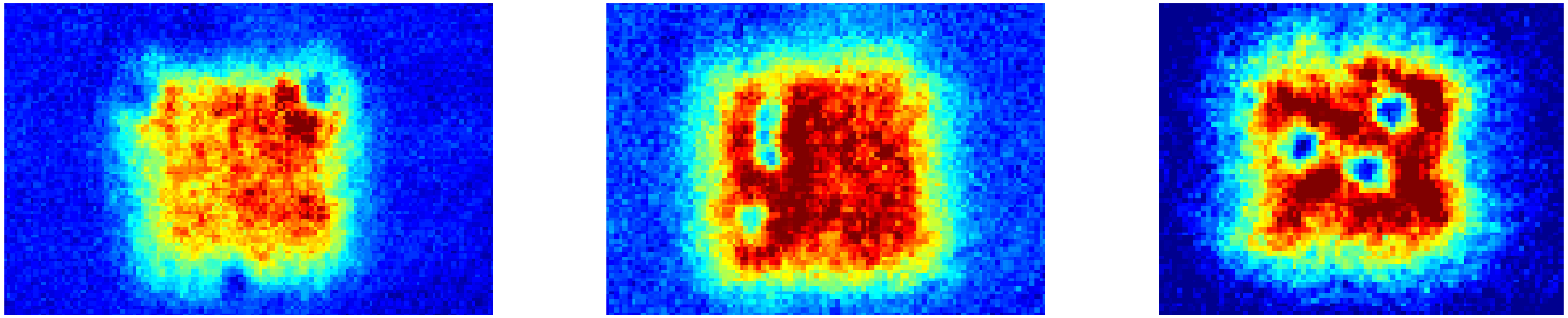
P_1/P_0 Incompatible with thermal excitation

Typical lifetime : 7s : comparable with the sample lifetime.

Bulk vortices in a square trap

★ Rapid cooling (~ 50 ms➞ 2s) via lowering the trap depth
★ Hold time (500 ms ➞ 2s)
★ Short 3D time-of-flight (4 ms)





Clear signature of high contrast quantum vortices

Related work in Trento (solitonic vortices in a 3D harmonic trap):

Lamporesi et al. Nature Physics **9**,656–660 (2013)
Donadello et al. Phys. Rev. Lett. **113**, 065302 (2014)

Which phase transition are we crossing ?

★ For an ideal **infinite** uniform system no Bose-Einstein condensation at non zero temperature

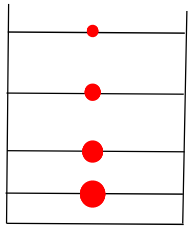
★ For a ideal **finite** system Bose-Einstein condensation is possible for $\mathcal{D}^{(2D)} \approx \ln(S/\lambda_{\mathrm{dB}}^2)$

★ For an interacting Bose gas a superfluid (BKT) phase appears a low temperature

For our parameters, BEC and BKT appears for a 2D phase-space density $\mathcal{D}^{(2D)} \approx 8$

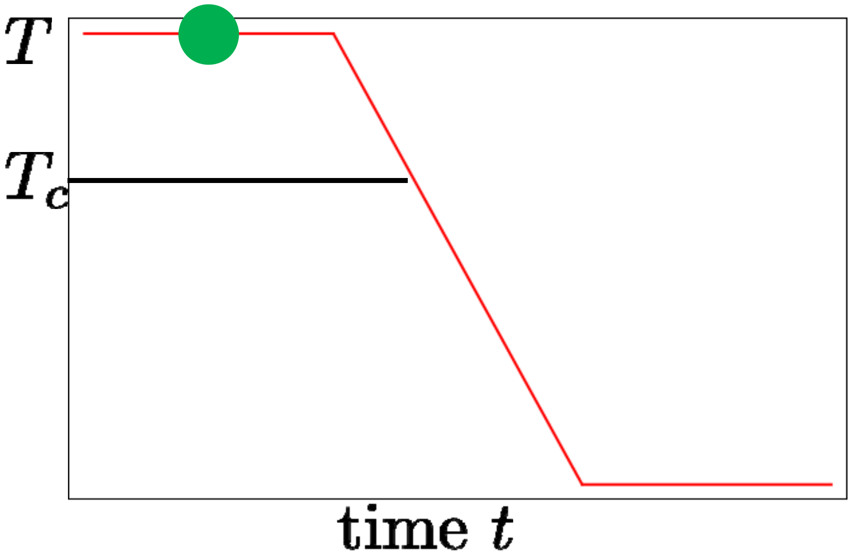
2D phase diagram

Which phase transition are we crossing ?



Vertical confinement

non degenerate 3D cloud



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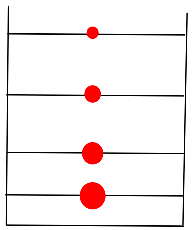

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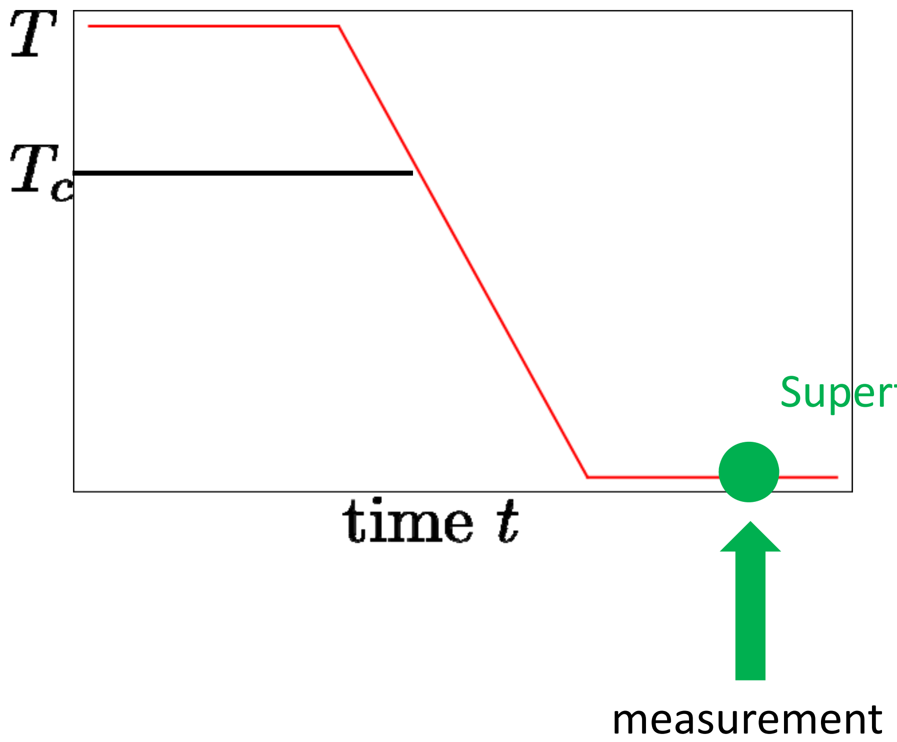

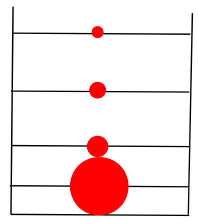

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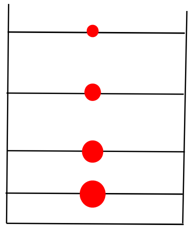

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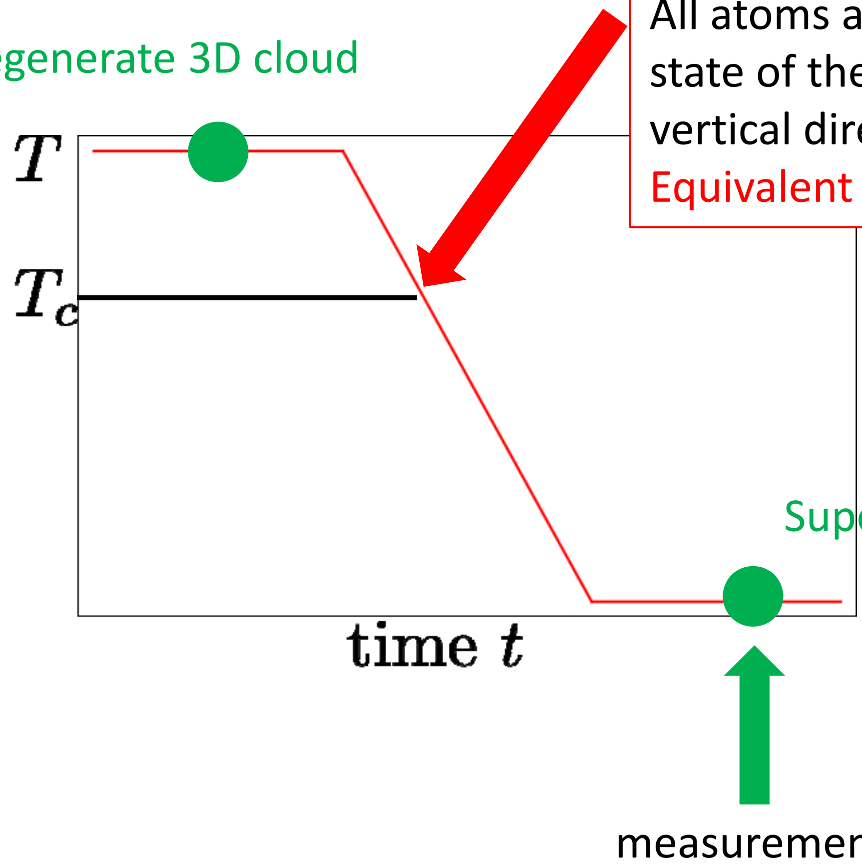
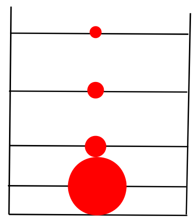


Transverse condensation :
All atoms accumulate in the ground state of the motion along the vertical direction : fast increase of ξ
Equivalent to 3D BEC transition

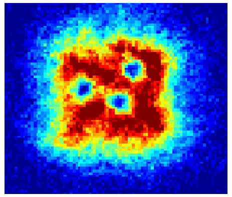
Superfluid 2D cloud

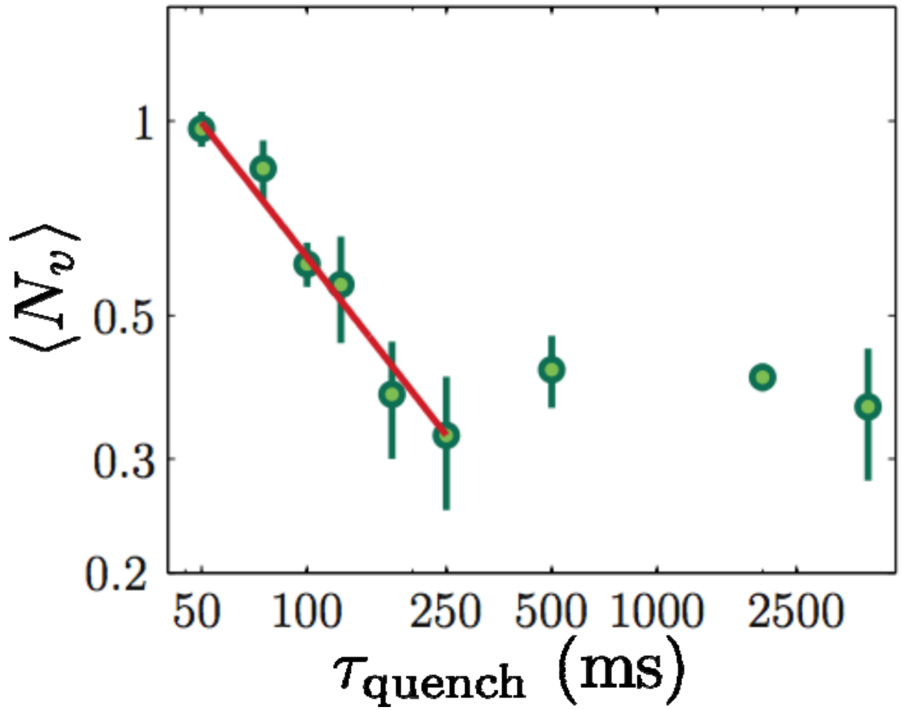


2D phase diagram

Results

★ Square box





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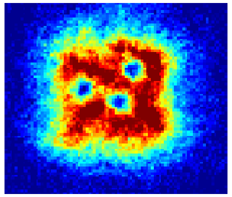
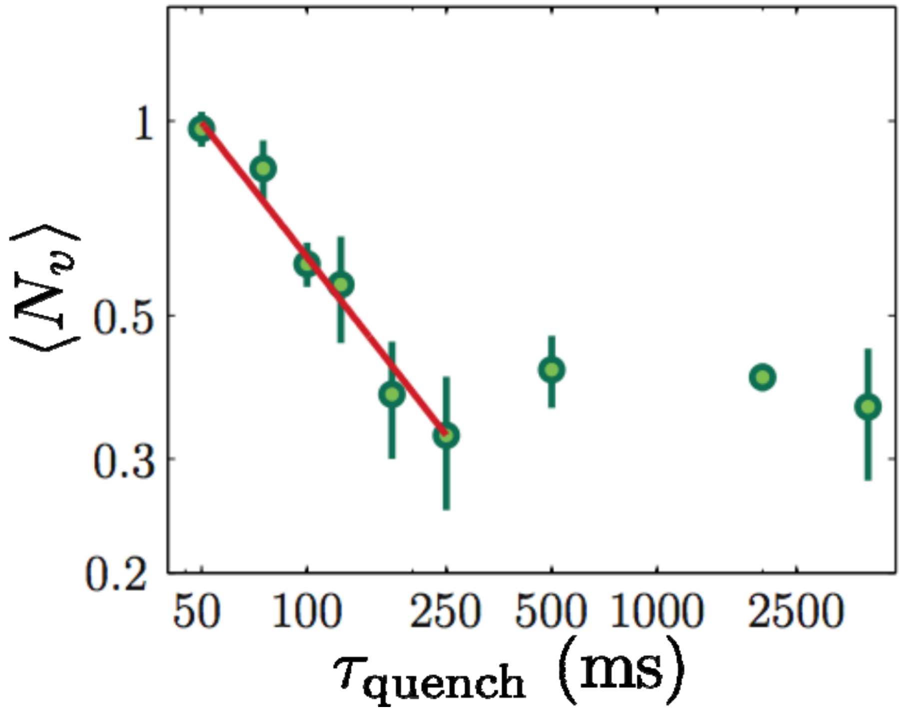
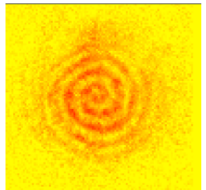
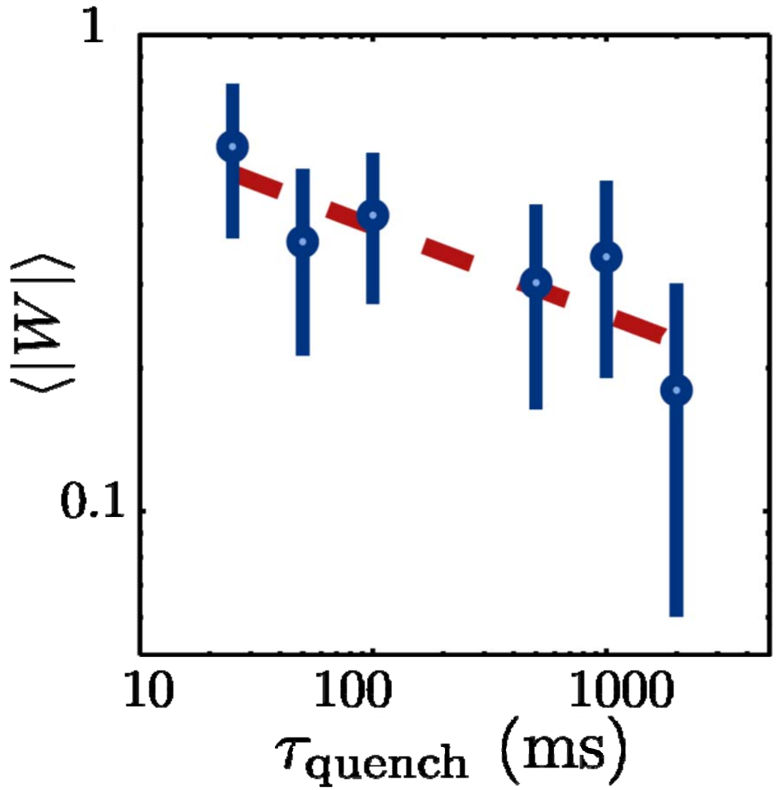




★ Annulus





Comparison with Kibble-Zurek prediction

★Theory

$$\hat{\xi} = (\tau_{\text{quench}})^{\frac{\nu}{1+\nu z}}$$

model	ν	z	$\frac{\nu}{1+\nu z}$
mean-field	1/2	2	0.25
F-model	2/3	3/2	0.33

$$\xi \propto \left(\frac{T - T_c}{T_c}\right)^{-\nu}$$ Correlation length

$$\tau \propto \xi^z$$ Thermalization time

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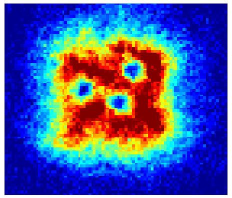
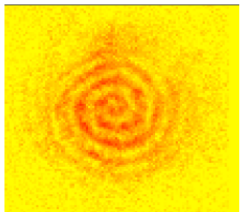


$$\frac{\nu}{1+\nu z} = 0.35(9)$$



$$\frac{\nu}{1+\nu z} = 0.25(8)$$ (Corrected slope for small number of vortices)

Comparison with Kibble-Zurek prediction

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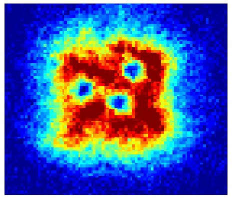

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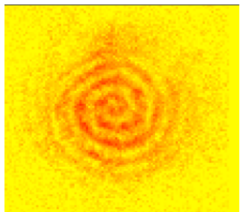


$$\frac{\nu}{1+\nu z} = 0.25(8)$$

Difficulties :

- Few defects (large statistics required)
- Limited range for quench time
- Small value for the exponent
- Complex behaviour after the quench

Transverse condensation

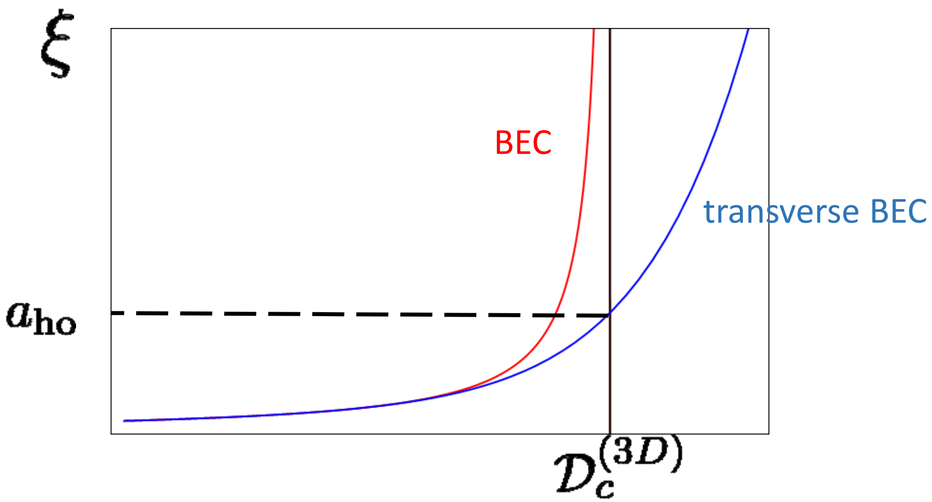
★ For an anisotropic system : two-step condensation is possible :

- condense in the vertical direction to get a 2D system
- fully condense in 3D

already observed in 1D systems : Phys. Rev. Lett. 111, 093601 (2013)
Phys. Rev. A 83 (2), 021605 (2011)

★ Surface density in the transverse excited states is bounded : $n^{(2D)}_{\text{excited}}\lambda^2_{\text{dB}} < 1.6\frac{k_BT}{\hbar\omega_z}$

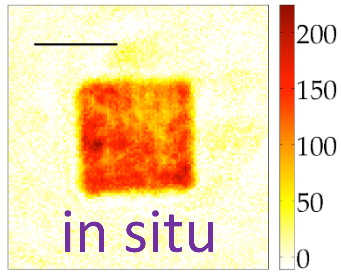
★ At this point coherence is created in plane : $\xi \approx a_{\text{ho}} \gg \lambda_{\text{dB}}$ with $a_{\text{ho}} = \sqrt{\frac{\hbar}{m\omega_z}}$



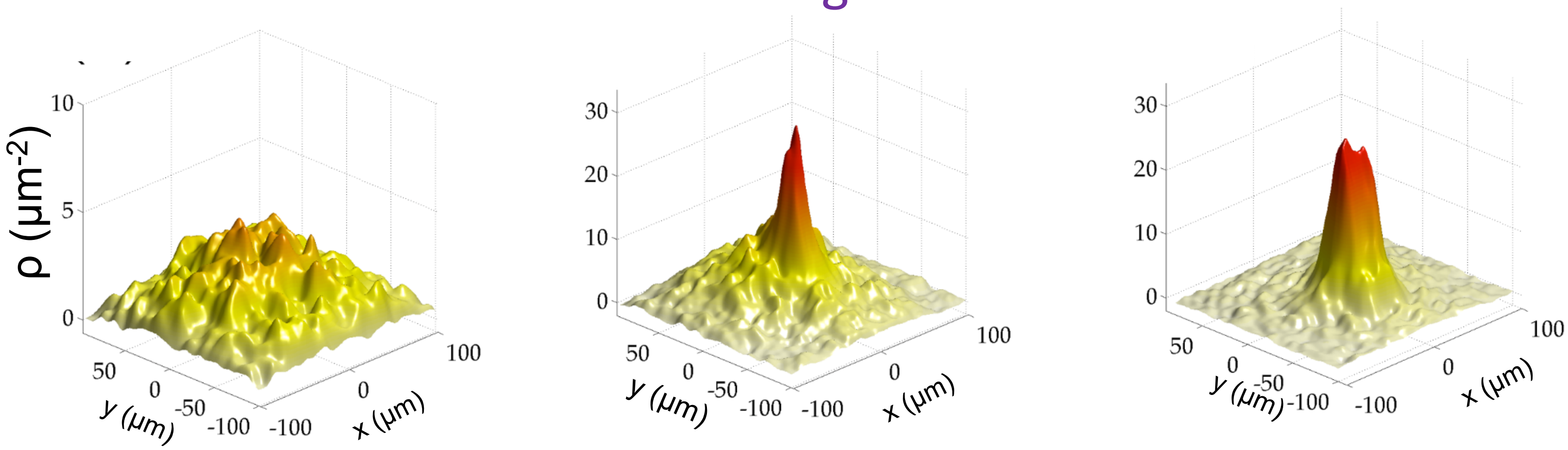
Emergence of coherence

★ Study the coherence of the gas at equilibrium around the transverse condensation crossover

★ momentum distribution via Time-of-flight measurements



time-of-flight



low $\mathcal{D}$ → high $\mathcal{D}$

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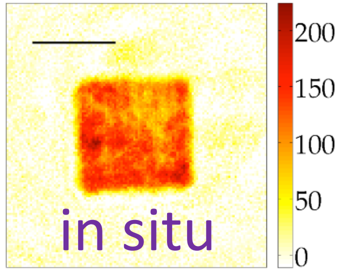
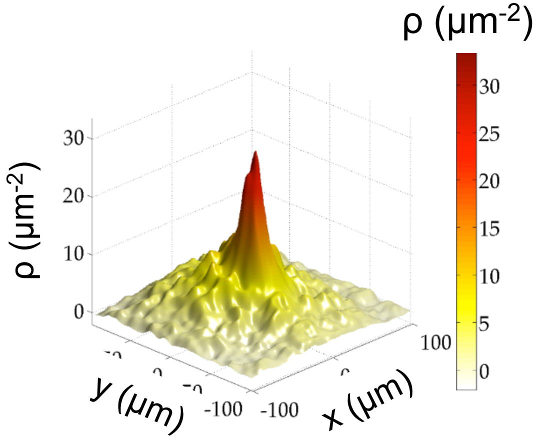
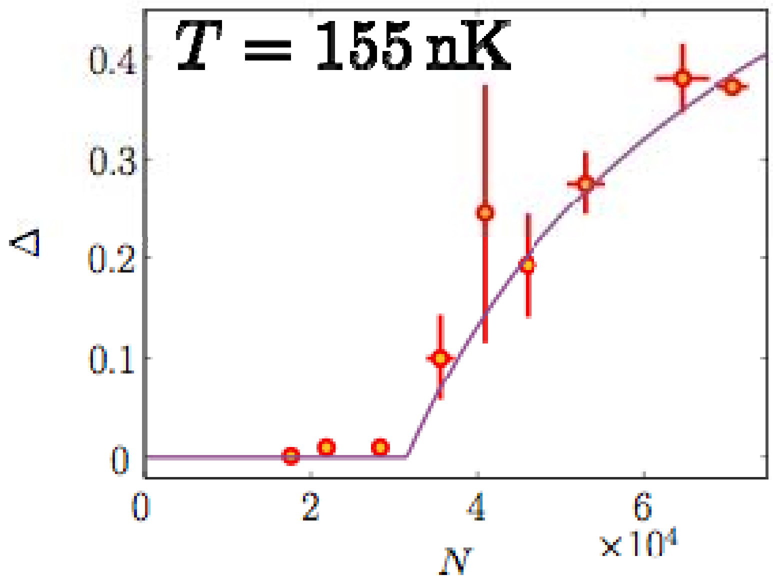
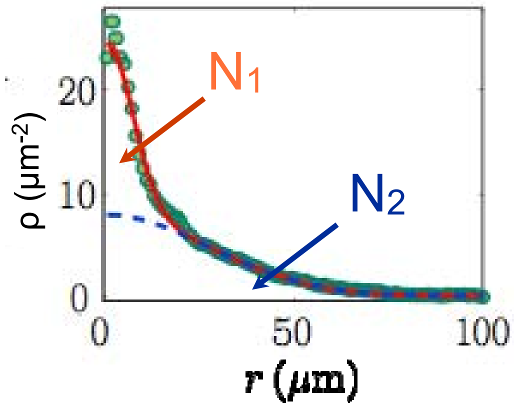






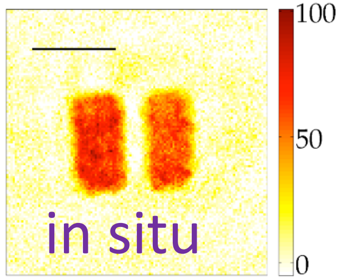


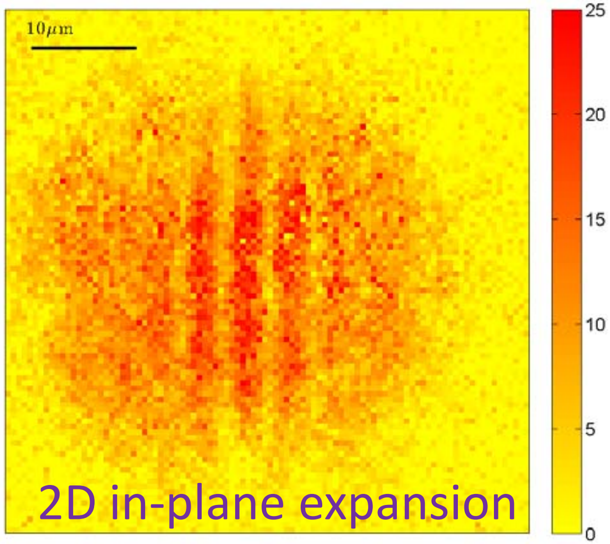
bimodality parameter : $\Delta = \dfrac{N_1}{N_1 + N_2}$

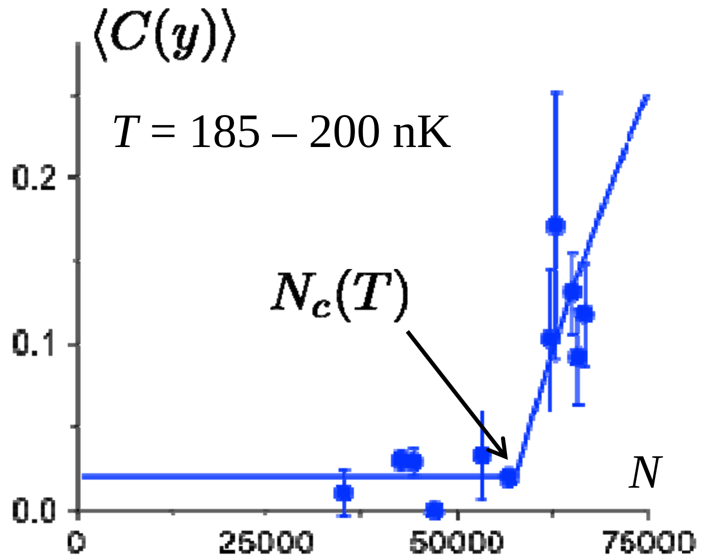
Emergence of coherence

★ Study the coherence of the gas at equilibrium around the transverse condensation crossover

★ momentum distribution via interference measurements
after in plane expansion (16ms)







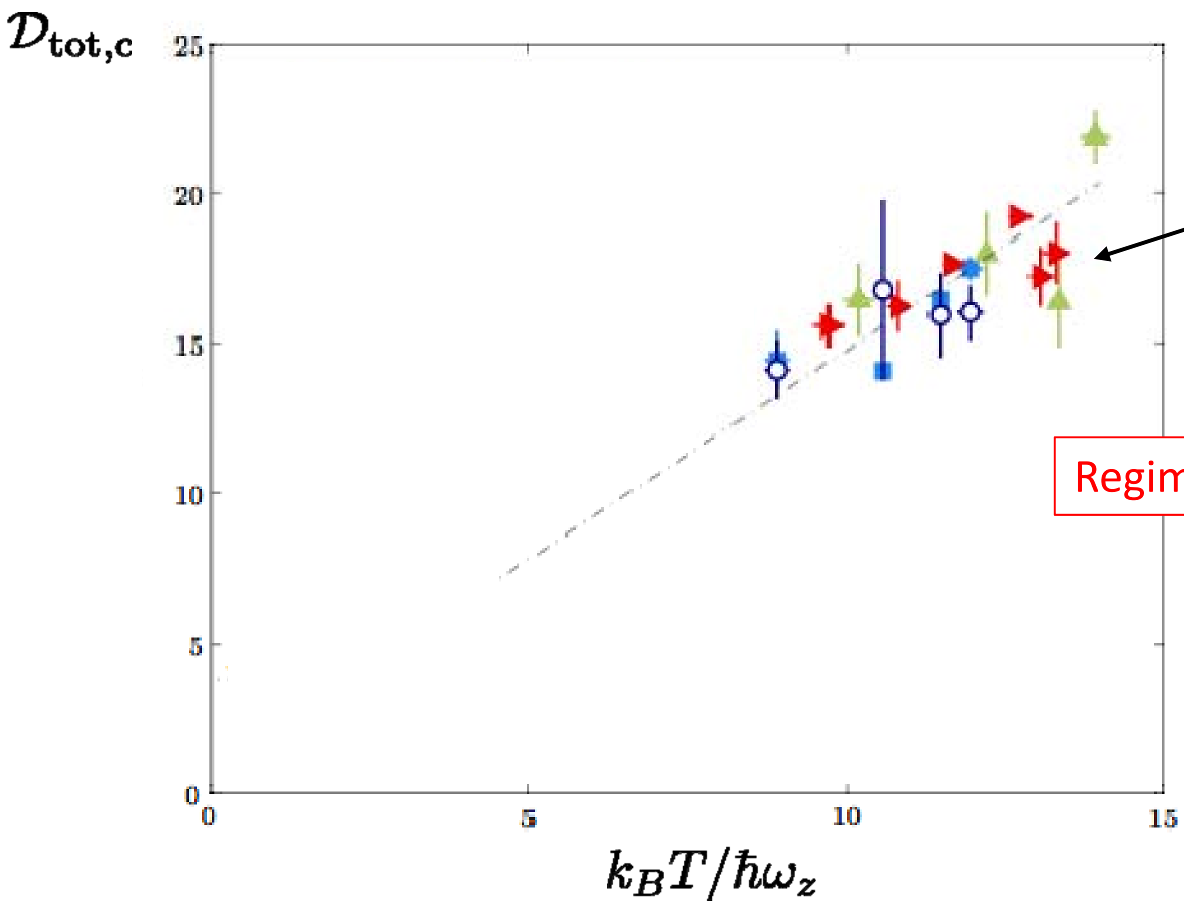
Fit along a horizontal line by :

$$C(y)e^{ikx} + c.c. + \text{constant}$$

$\langle C(y) \rangle$ is a good signature for the emergence of coherence

Mapping the transition

★ Critical point for the emergence of coherence $\mathcal{D}_{\mathrm{tot,c}} = n_{\mathrm{c}}^{(2D)} \lambda_{\mathrm{dB}}^2 = 1.6 \frac{k_B T}{\hbar \omega_z}$



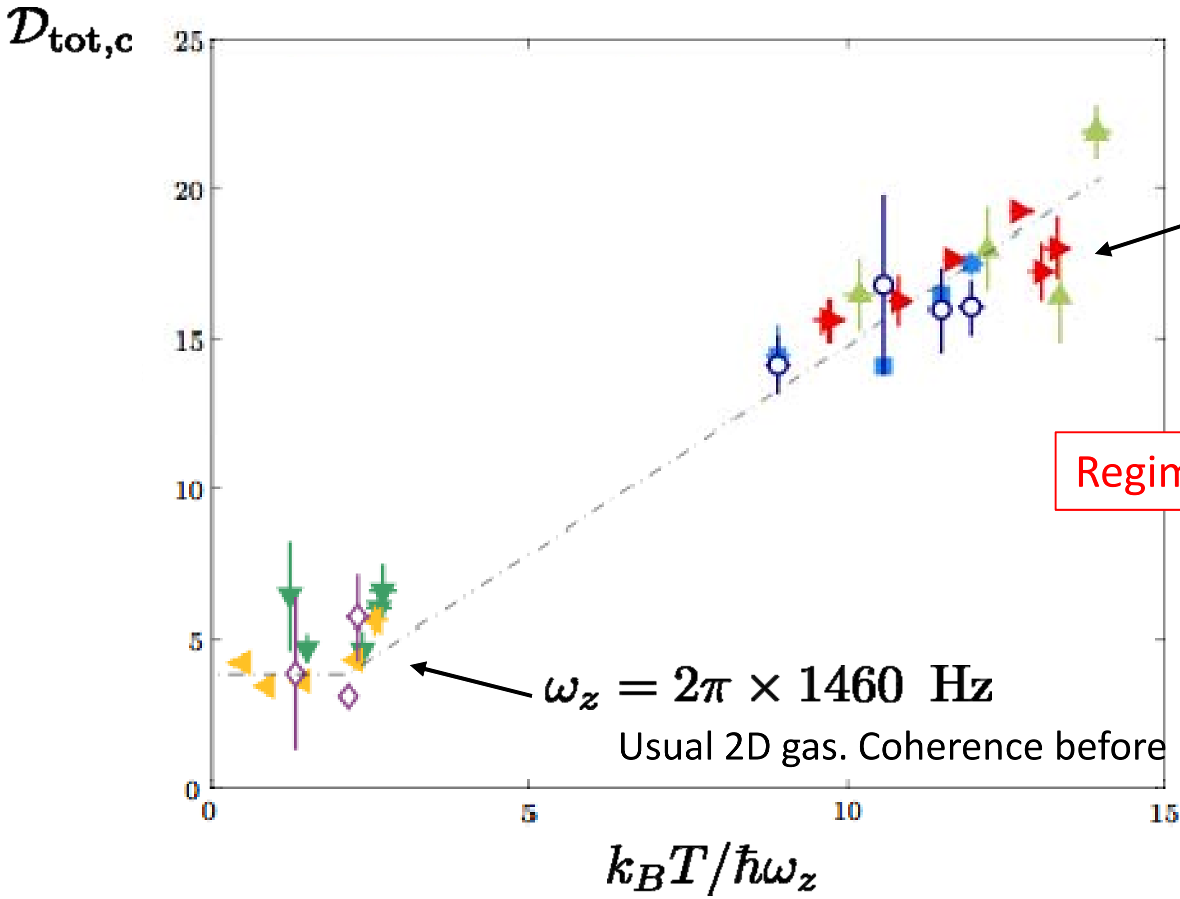
$\omega_z = 2\pi \times 365\ \mathrm{Hz}$

Slope =1.4 (3)

Regime for the quench experiments

Mapping the transition

★ critical point for the emergence of coherence $\mathcal{D}_{\mathrm{tot,c}} = n_{\mathrm{c}}^{(2D)} \lambda_{\mathrm{dB}}^2 = 1.6 \frac{k_B T}{\hbar \omega_z}$



Slope =1.4 (3)

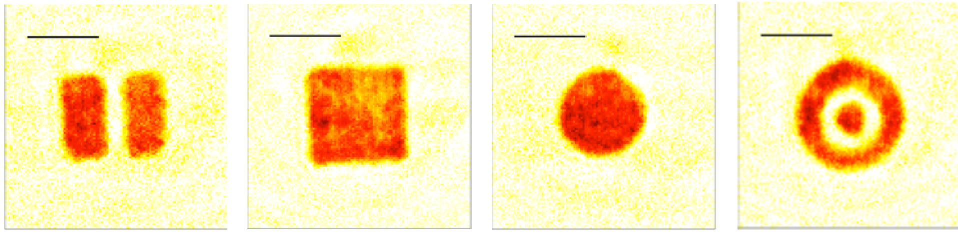
Regime for the quench experiments

Usual 2D gas. Coherence before BKT/BEC transition : Quasi-condensate

Results summary and outlook

★ flat bottom potentials with various shapes

future : Spatial light modulator

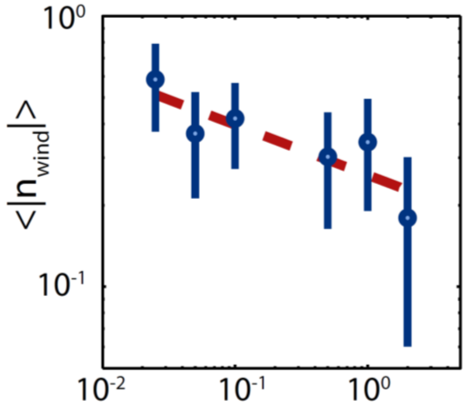


★ Measurements of critical exponents

future : improved statistics,

coarse graining dynamics after the quench,

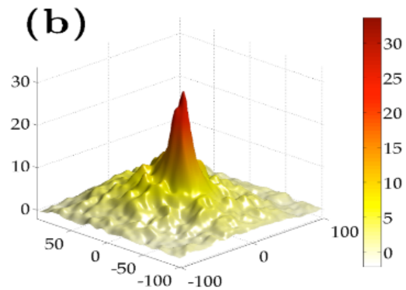
quench through BKT transition



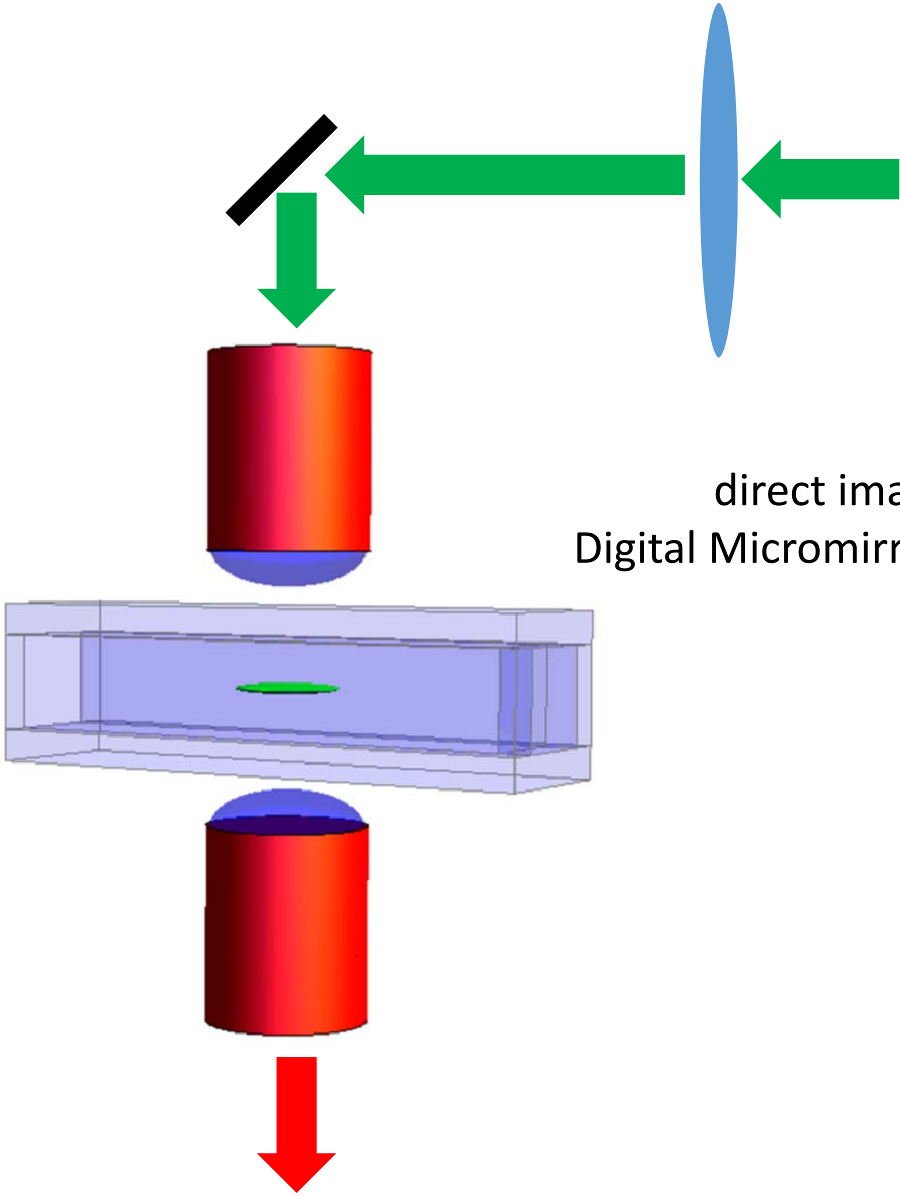
★ Characterization of the coherence in quasi 2D geometry

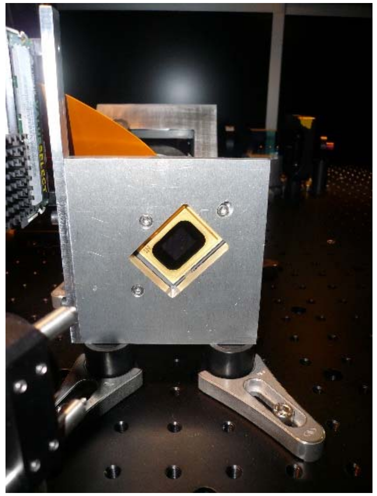
future : direct measurements of correlation

functions in BEC, BKT phases.



New experiment





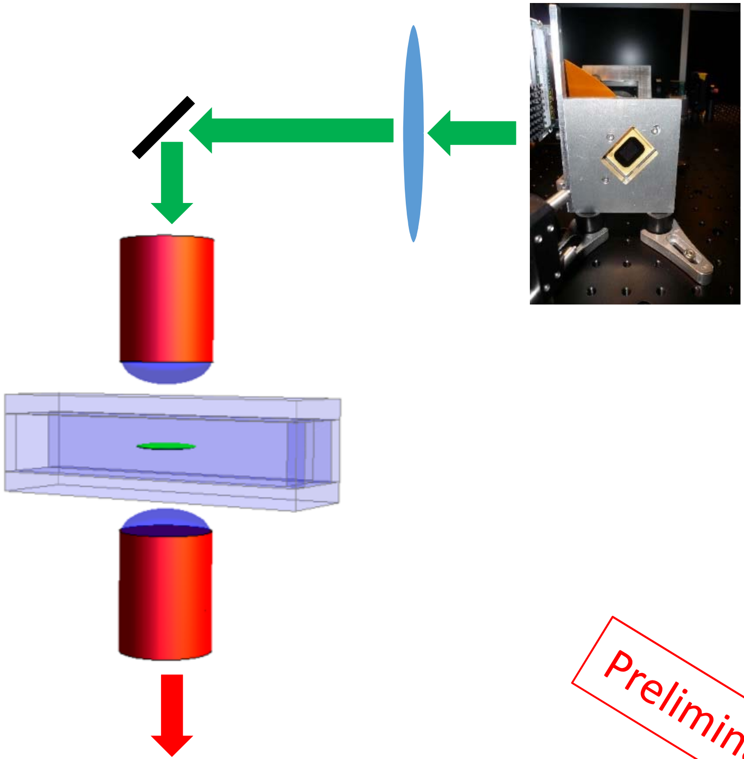
direct imaging of a
Digital Micromirror Device (DMD)

2 microscope objectives
with NA=0.45

Resolution ~ 1 µm

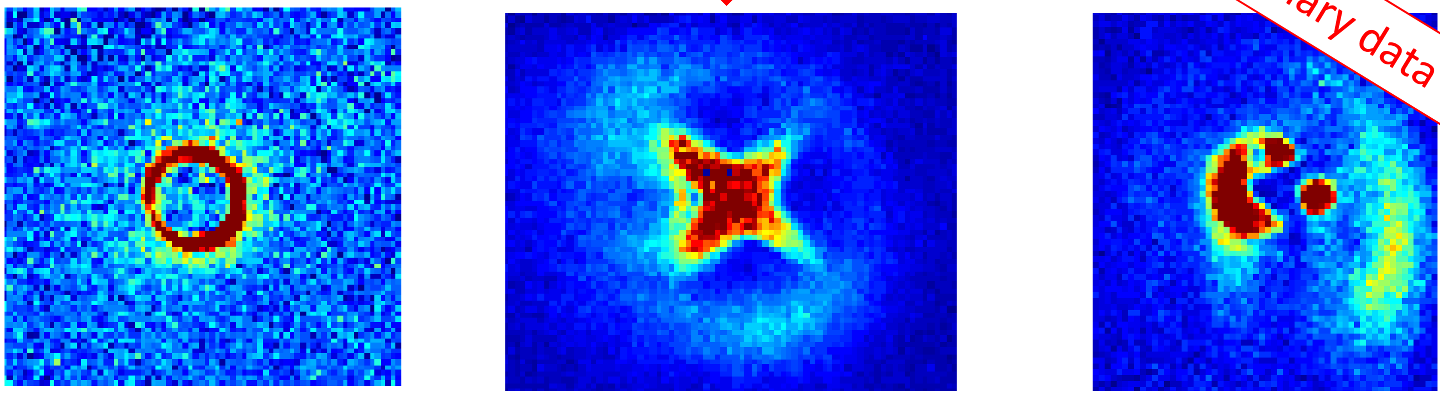
atomic cloud imaging

New experiment



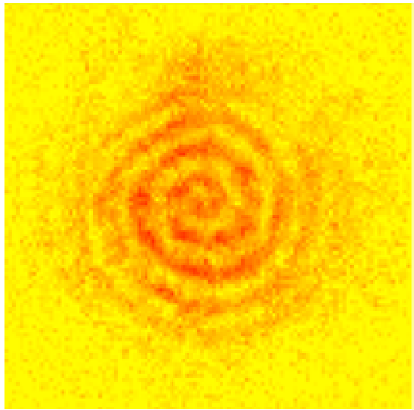
Resolution ~ 1 μm

Preliminary data (June 2015)



Atomic clouds in custom flat-bottom potentials

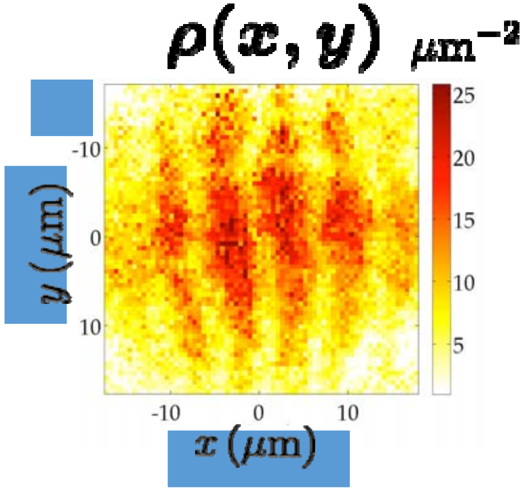
Out-of-equilibrium physics with Bose gases in 2D geometries



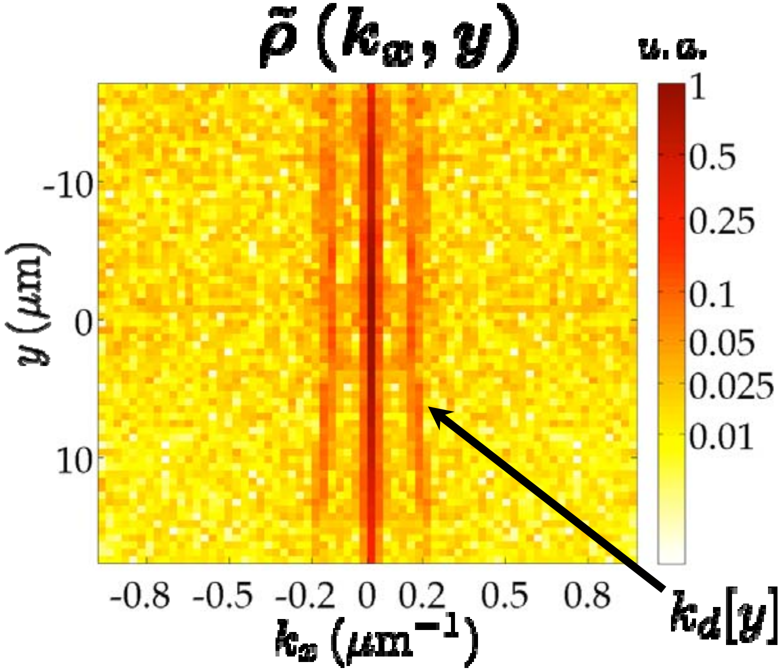
current members: Lauriane Chomaz, Laura Corman, Tom Bienaimé, Jean-Loup Ville, Raphaël de Saint-Jalm
former members: R. Desbuquois, C. Weitenberg, D. Perconte, K. Kleinklein, A. Invernizzi
permanent members: Sylvain Nascimbène, Jérôme Beugnon, Jean Dalibard

References : Phys. Rev. Lett. **103**:135302 (2014) & Nat. Comm. **6**:6162 (2015)

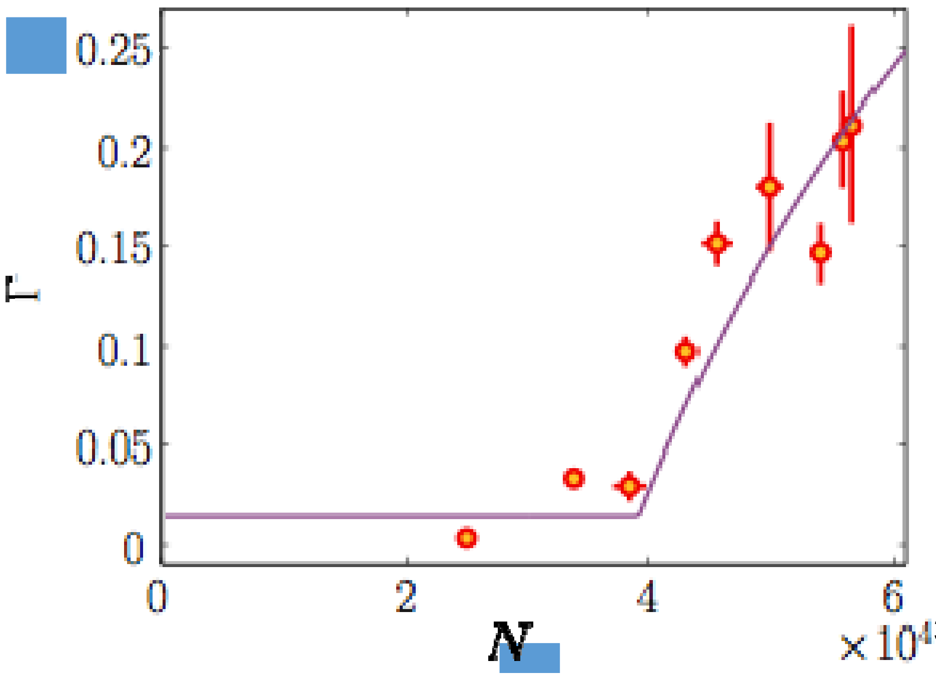
Characterizing the fringe contrast



1D Fourier transform



$$\Gamma = b + a\left(1-(N_c/N)^{0.6}\right)\Theta(N > N_c)$$



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✤1-Body corr. on complex fringe contrast:

$$\gamma(d) = \left|\langle\, \tilde{\rho}[k_p(y), y]\; \tilde{\rho}^*[k_p(y+d), y+d]\,\rangle\right|$$

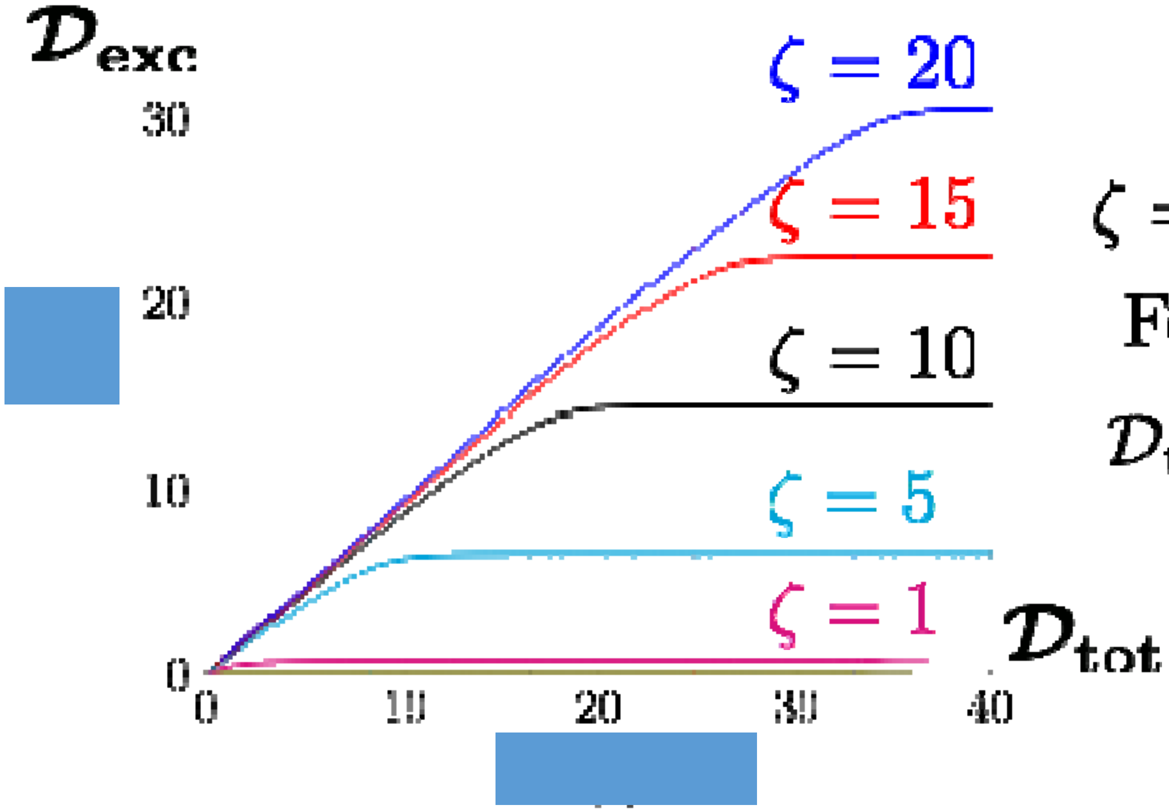
∞ 1D gases: $\gamma(d) = |G_1(d)|^2$

✤Look for extended coherence:

$$\Gamma = \langle \gamma(d) \rangle_{2\,\mu m < d < 5\,\mu m}$$

[sup $(\lambda_T) < 2\mu m$]

Transverse condensation

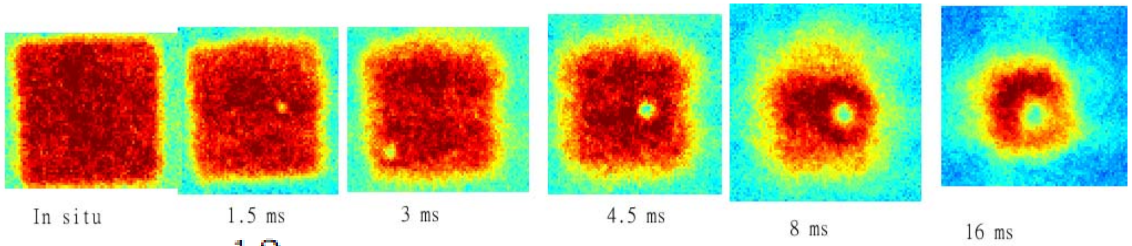


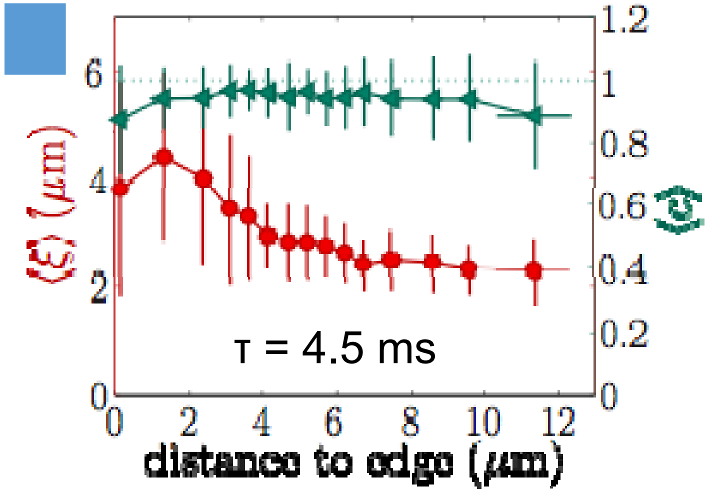
$$\zeta = k_{\mathrm{B}}T/\hbar\omega_z$$

For $\zeta \gg 1$:

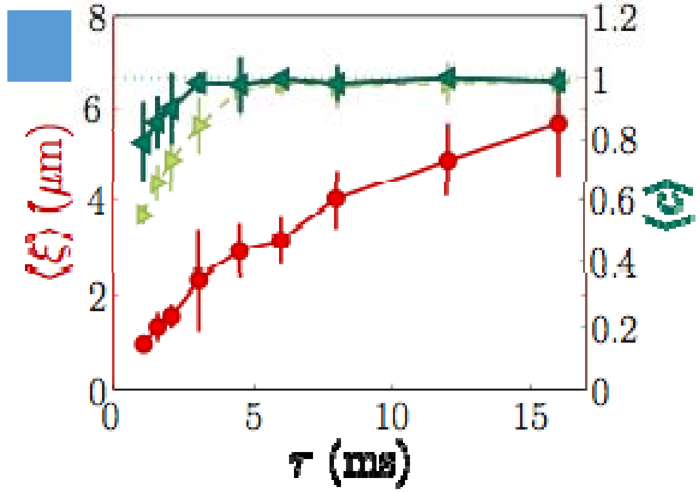
$$\mathcal{D}_{\mathrm{tot,c}} = \frac{\pi^2}{6}\zeta$$

Vortices





similar properties at a given τ
+ high contrast



constant contrast and
increasing size with τ

Hole Nature:

= single vortices

≠ phonons

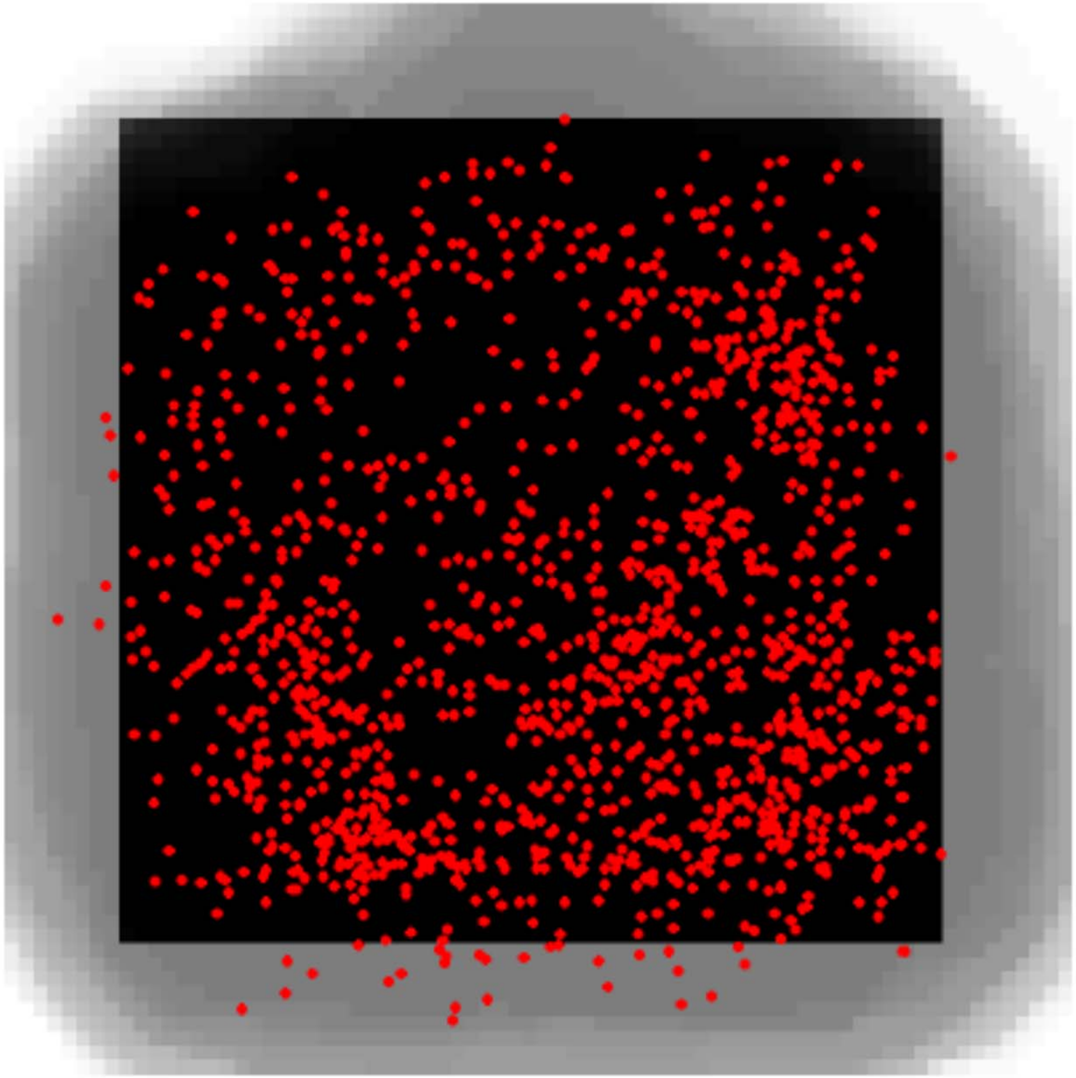
≠ pairs of vortices

Dynamical orgin:

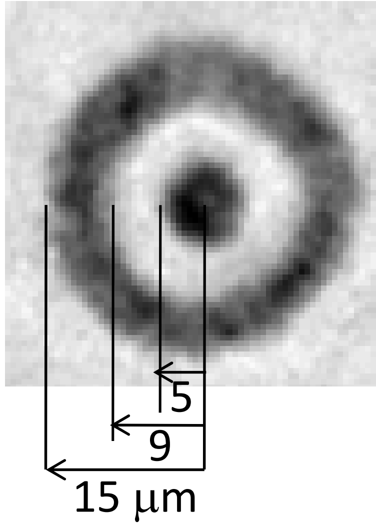
✤ Equilibrium expectation at final PSD (>100) = vanishingly small mean vortex number N_v. Experimentally $N_v \approx 0.6$

✤ BKT theory at final PSD = vortices must be tightly paired.

✤ Dissipative dynamic (variation of N_v) with a varying hold time ≠ equilibrium.



Where is the vortex located?



Experimental observation: we never observe a density hole in the small central disk, even after 3D time-of-flight

Energetic argument: what is the energy required for creating a vortex in one of the two parts of the "target"?

$\xi \sim 1\,\mu m$

The energy of a vortex is essentially kinetic

$$E_K = \frac{1}{2} m \rho_s \int v^2(r)\, \mathrm{d}^2 r$$
$$v = \frac{\hbar}{mr}$$

$$\longrightarrow \quad E_K = \frac{\pi \hbar^2 \rho_s}{m} \int \frac{1}{r}\, \mathrm{d}r$$

vortex in the outer ring | **vortex in the inner disk**

$$E_K = \frac{\pi \hbar^2 \rho_s}{m} \ln(R_{\mathrm{max}}/R_{\mathrm{min}}) \quad < \quad E_K = \frac{\pi \hbar^2 \rho_s}{m} \ln(R_{\mathrm{disk}}/\xi)$$

energetically favoured