Two-dimensional Bose gases in arbitrary-shaped potentials

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LPNHE, June 2017

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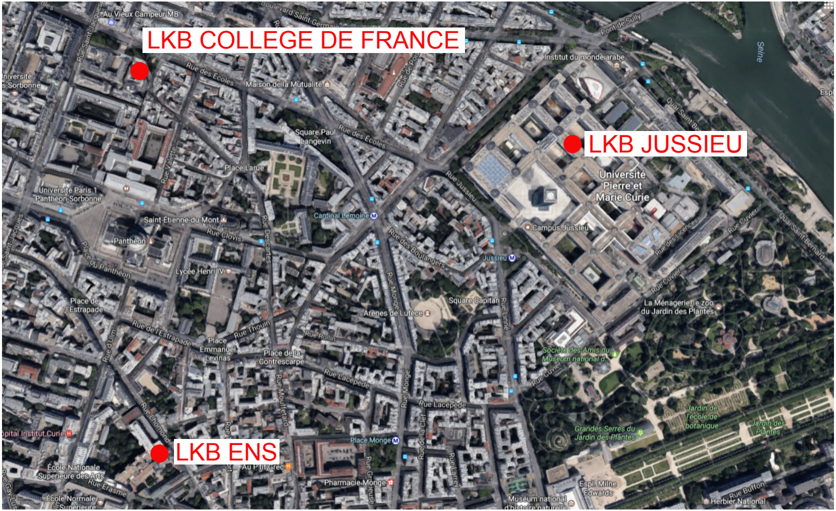

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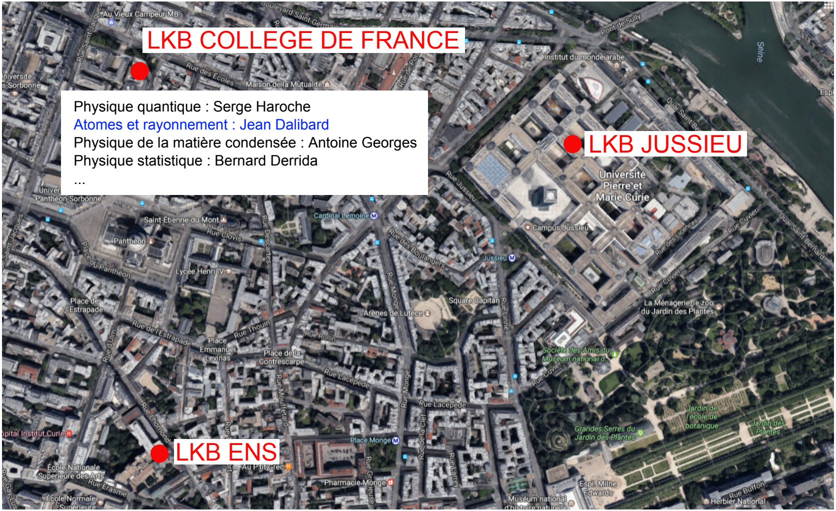

Outline

- Physics in 2D dimensions
- Quantum gases
- Our setup
- Out-of-equilibrium dynamics
- Light scattering

Physics in 2D dimensions

No long-range order in 1D or 2D.

Increased role of thermal and quantum fluctuations

Peierls (1935), Mermim & Wagner (1966), Hohenberg (1967)

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Topological matter is mainly 2D (quantum Hall effect, anyonic statistics, ...). Strongly interacting phases.

Bose-Einstein condensation (BEC) in 2D

BEC=macroscopic occupation of the single-particle ground state.

Uniform ideal 3D gas at temperature T and 3D density n.

$$\text{Set } \lambda_T = \frac{h}{\sqrt{2\pi m k_B T}}$$

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BEC can be recovered for a trapped/finite-size system

BKT phase transition

Berezinskii-Kosterlitz-Thouless prediction for an interacting gas: Transition from a normal to a superfluid state below a critical temperature T_c.

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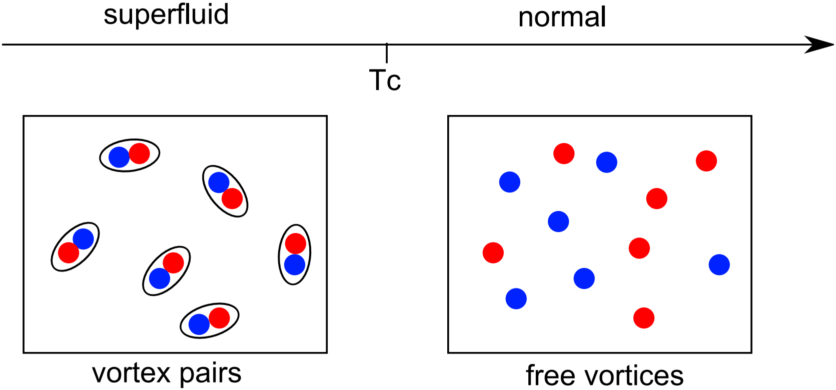

In the superfluid phase: quasi long-range order

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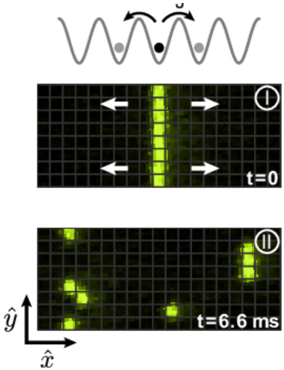
Optical measurement of density and momentum distribution

Quantum gases: some highlights

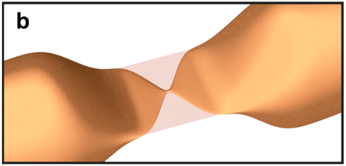
Single atoms in a lattice: quantum random walk via tunneling

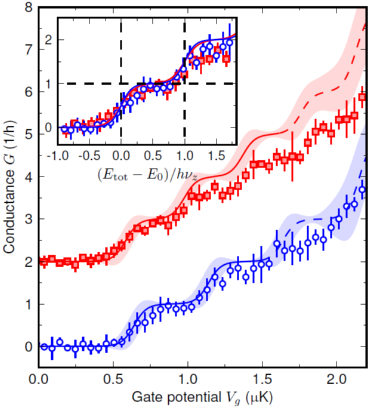


Greiner's group (MIT)

Quantum gases: some highlights

Fermion transport through a single channel: quantification of conductance





Esslinger's group (ETH Zurich)

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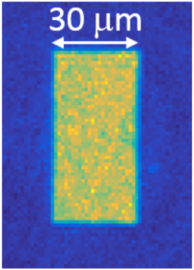

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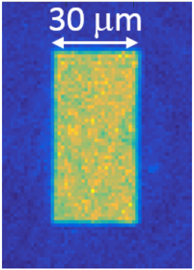

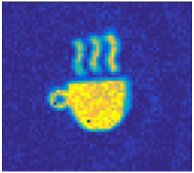

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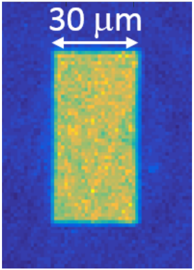
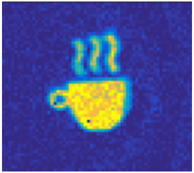
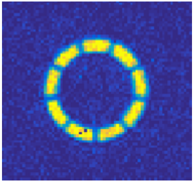
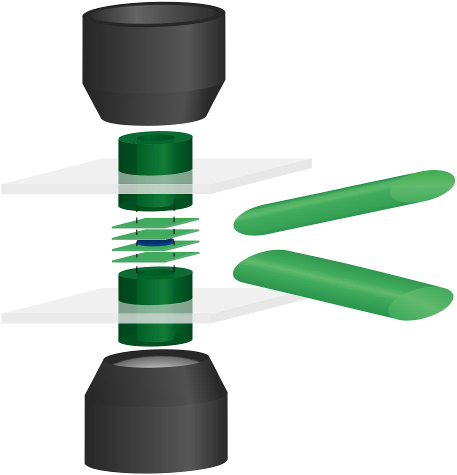






A single layer of ultracold atoms



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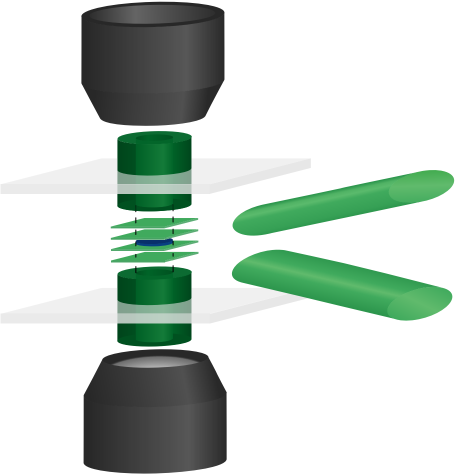

- $\omega_z = 2\pi \times 1.6$ kHz ($\Rightarrow \Delta z \approx 300\,$nm)
- $T \approx 10\,$nK
- $n_{2\mathrm{D}} \approx 30\,\mu\mathrm{m}^{-2}$
- Atom number $\approx 10^5$
- Spatial light modulator (DMD) to shape the potential.
  (10 kHz refresh rate)

More details on the optical accordion: Ville et al. PRA **95**, 013632 (2017)

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Kibble-Zurek mechanism

Kibble-Zurek mechanism predicts the formation of topological defects when quench cooling across a phase transition.

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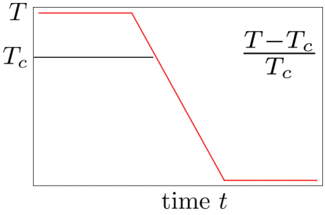

$$\frac{T-T_c}{T_c} \propto t/\tau_{\text{quench}}$$

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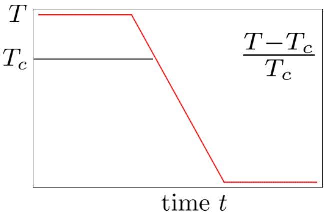
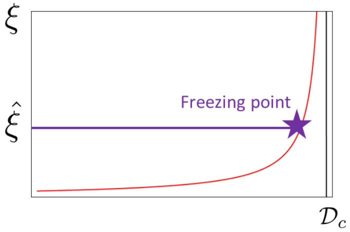


$$\frac{T-T_c}{T_c} \propto t/\tau_{\mathrm{quench}}$$

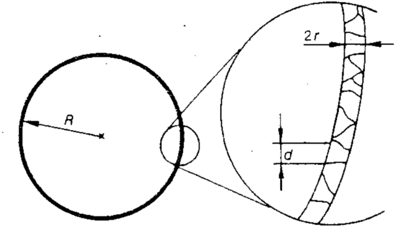
Thermalization time diverges around T_c
$\rightarrow$ out-of-equilibrium situation
$\rightarrow$ frozen dynamics
$\rightarrow$ formation of independent domains



Kibble-Zurek mechanism

Zurek's gedanken experiment:

Zurek Nature **307**, 505 (1985)



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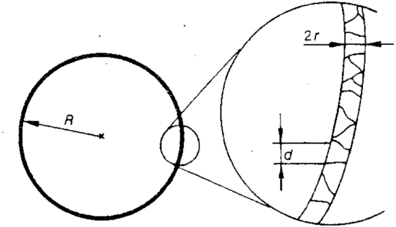


Domain size:

$$d \propto \tau_Q^{\nu/(1+\nu z)}$$

ν: correlation length critical exponent
z: relaxation time critical exponent

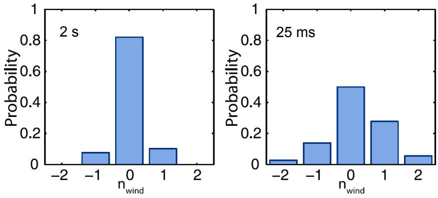
Winding number:

$$\langle n_w^2 \rangle \propto d^\alpha$$

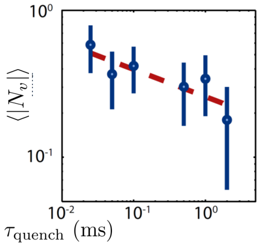
$\alpha = -1$ for a ring (depends on dimensionality).

KZM in an atomic ring

Winding number distribution for different quench times



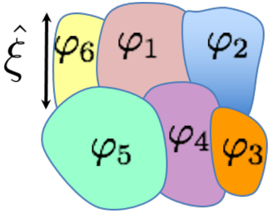
Average absolute winding number



Corman et al. PRL **113**, 135302 (2014)

KZM in a bulk 2D geometry

Form domains with independent phases



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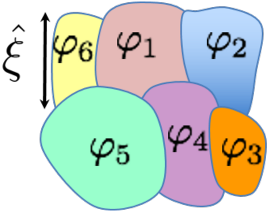
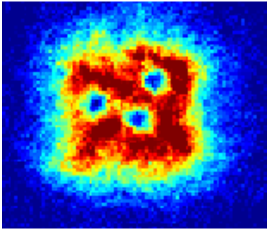


After relaxation generation of bulk vortices



Chomaz et al. Nat. Commun. **6**, 6162 (2015)

Merging dynamics

Full control of KZ mechanism relies on a good understanding of the relaxation dynamics
Crucial to be able to extract accurately critical exponents

- How does the phase homogenize ?
- How much time does it take to uniformize the phase ?
- Are the defects stable ?
- What are the underlying microscopic mechanisms ?

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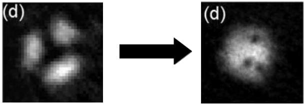
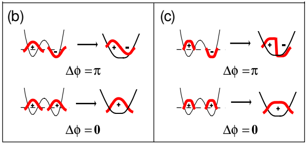
Merging N condensates with independent phases in a ring geometry and monitor relaxation

Related works

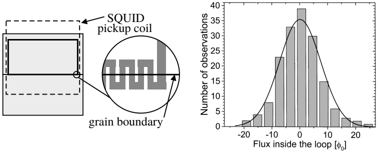
- Merging 3 BECs $\to$ vortices (Scherer et al. PRL **98**, 110402 (2007))



- Merging 2 BECs $\to$ heating (Jo et al. PRL **98** 180401 (2007))



- Connecting Josephson junctions (Carmi et al. PRL **84**, 4966 (2000))



Preparing independent BECs

We load a hot cloud in a N-segment configuration and perform evaporative cooling down to $T \approx 10\,\mathrm{nK}$.

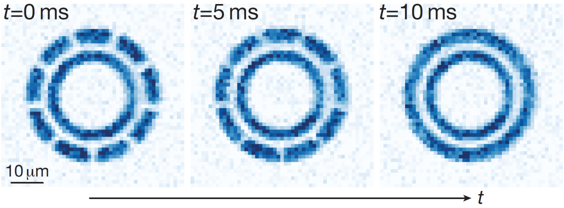
$N = 1$ $N = 3$ $N = 6$ $N = 9$

We checked that:

- The two rings have independent phases
- Our results are independent of the separation between domains in the range 2-3 μm. (Here 2.5 μm)

Merging

We merge the BECs by decreasing the barrier width in 10 ms.



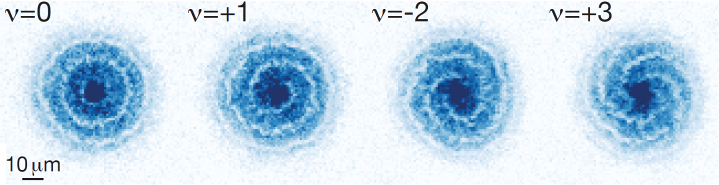
We empirically chose 10 ms because

- Faster merging leads to additional excitations.
- Slower merging leads to asynchronous merging.

We wait for 500 ms to let the phase homogenize.

Detection

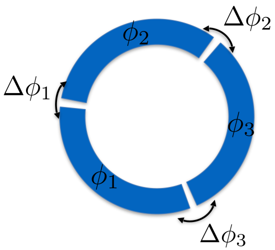
We perform matter-wave interference between the two rings

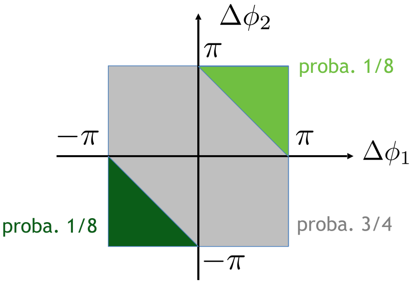


The number of spiral arms gives the winding number in the outer ring

see also Eckel et al. PRX **4** 031052 (2014) and Corman et al. PRL **113** 135302 (2014)

The 3-segment case





$\Delta\phi_1$, $\Delta\phi_2 \in (-\pi, \pi]$

- $\nu = +1$ if $\Delta\phi_1 + \Delta\phi_2 > \pi$
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- $\nu = 0$ otherwise

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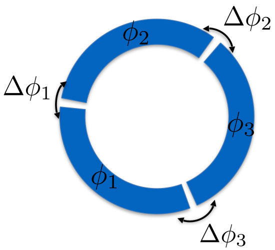

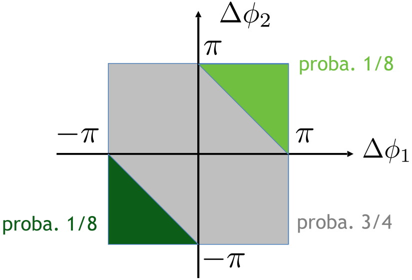

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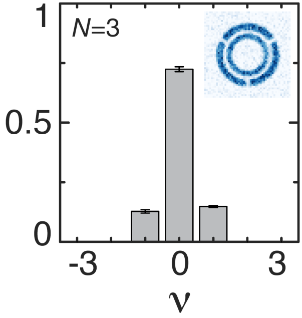
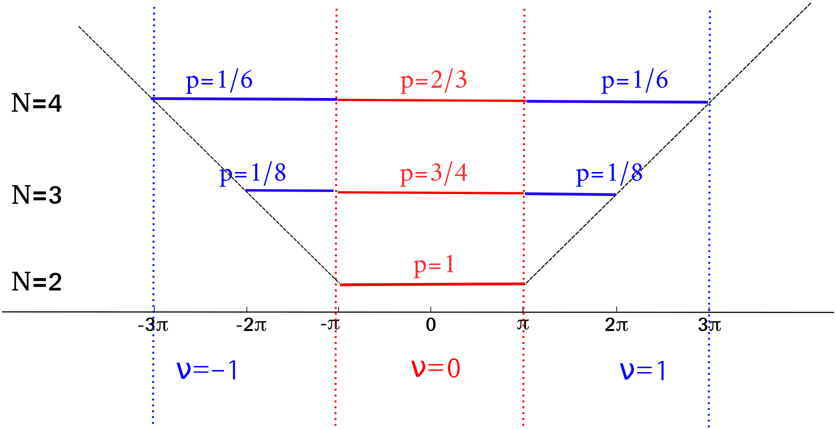
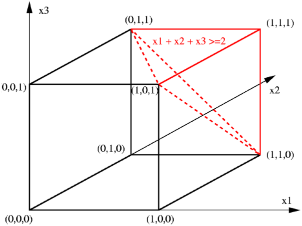


Varying the number of segments



Varying the number of segments

Compute hypervolumes of an hypercube



Already done by mathematicians !
Euler-Frobenius distribution gives:

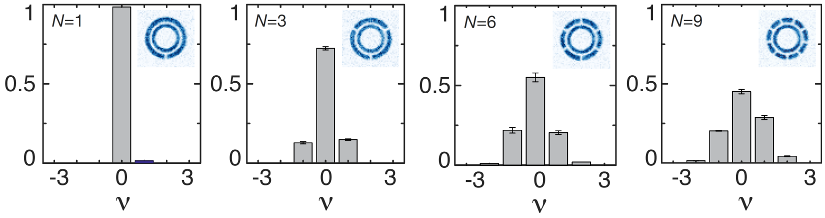
$$\boxed{\nu_{\rm rms} = \frac{\sqrt{N}}{2\sqrt{3}} \text{ for } N \geq 3}$$

with $\nu_{\rm rms}$ the rms width of the distribution.

S. Jansen, Online J. Anal. Comb. **8** (2013)

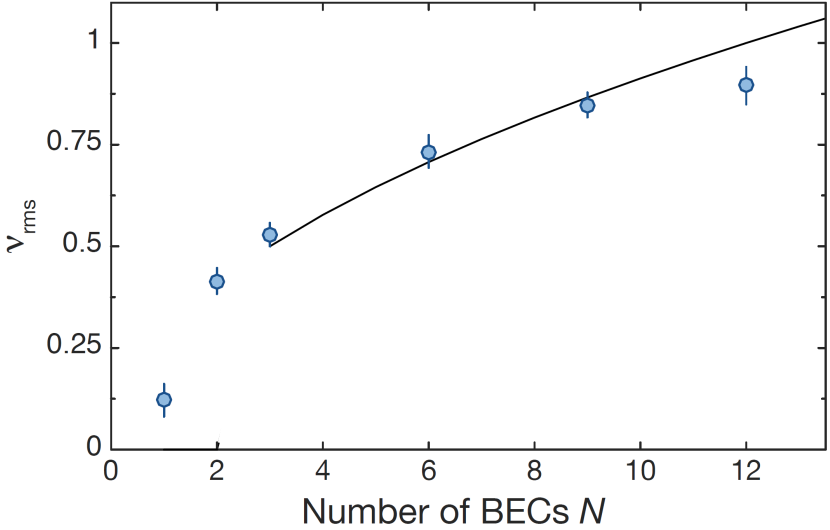
Results N segments

Vary number of segments N from 1 to 12.



The distribution broadens for increasing N

Results for N segments



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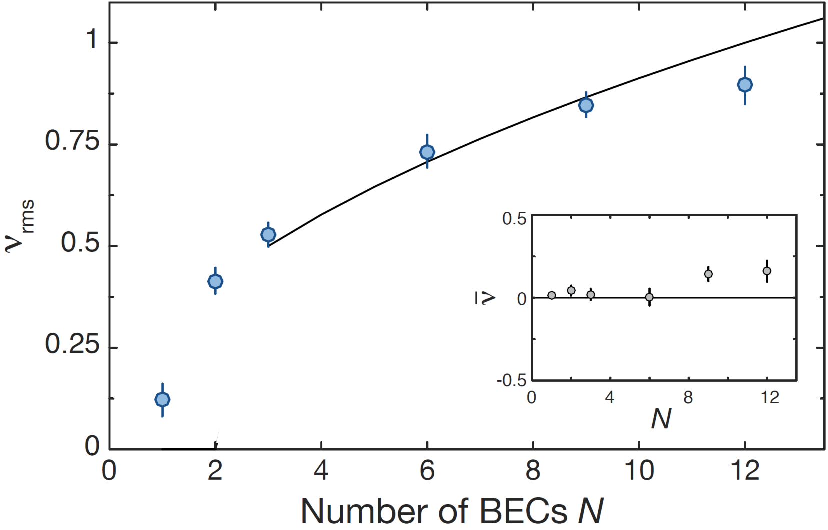
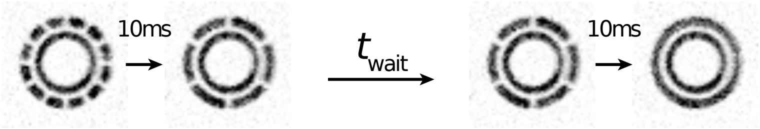


Timescales

Merging $<$ Sound round-trip $<$ Waiting $<$ Lifetime

$10\,\mathrm{ms} \quad < \quad 100\,\mathrm{ms} \quad < \quad 500\,\mathrm{ms} \quad < \quad 20\,\mathrm{s}$

Two-step merging



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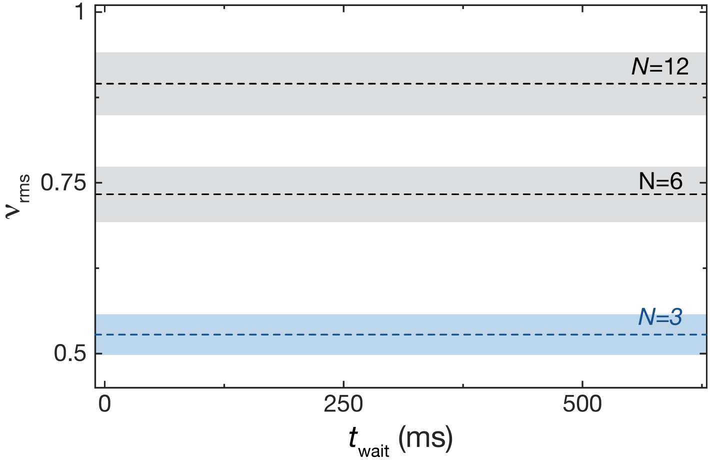

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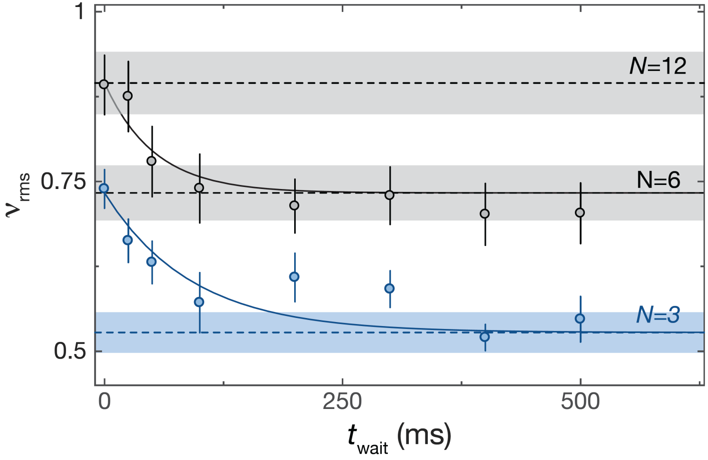

Exponential fits : $\tau_{12} = 52(17)$ ms, $\tau_6 = 90(30)$ ms
Shorter segments homogenize faster. Microscopic mechanism ?

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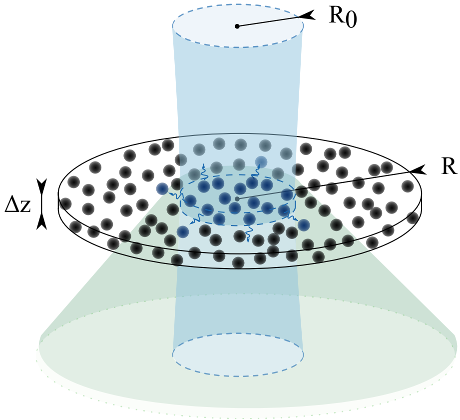
Light transport



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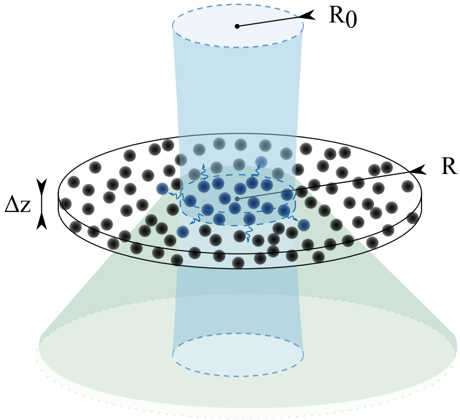
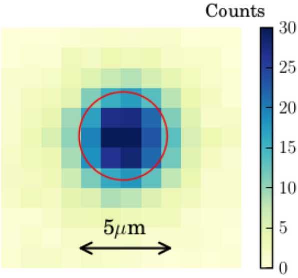


Dense clouds. Many atoms on the scale λ_{opt}.
Multiple scattering regime. Many-body physics

Fluorescence: experiment

Fluorescence signal



Local excitation:
disk diameter$= 5\,\mu$m
Measure fluorescence
(outside excitation region)
Light pulse:
duration$=10\,\mu$s, $I \approx 10 I_{\mathrm{sat}}$

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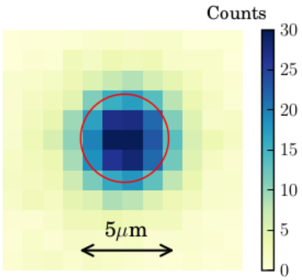

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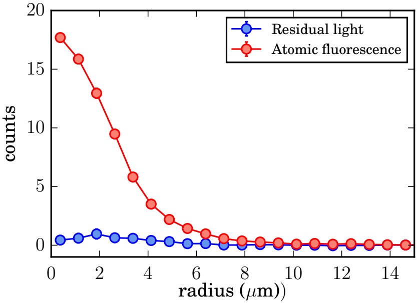
Radially averaged profile



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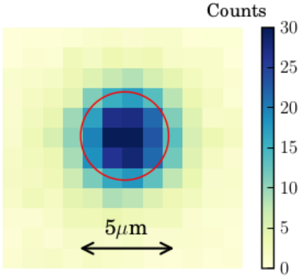

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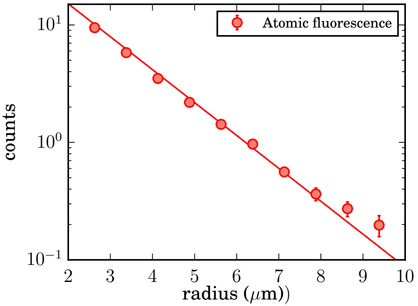
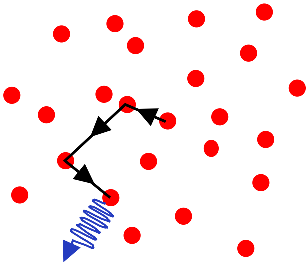


Get decay length from exponential fit,

$\approx 1 - 2\,\mu$m

Fluorescence: ballistic simulations

Simulations principle

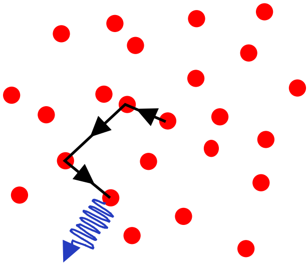


Photons are emitted by a random direction and diffuse on the first atom met.

Process is repeated until they leave the cloud.

Fluorescence: ballistic simulations

Simulations principle



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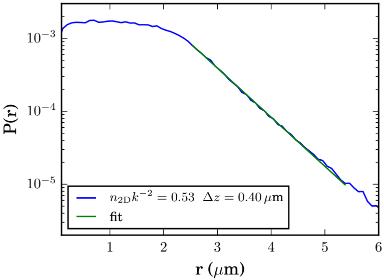
Probability distribution

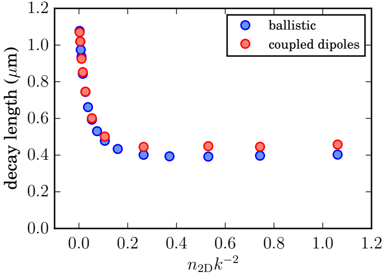


- Exponential decay

always the case for zero thickness and only for large enough OD otherwise

Fluorescence: influence of density

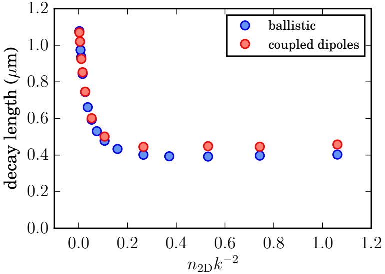
Simulations



- larger decay length at low densities
- plateau at large densities
- Comparable results with a more complete model (coupled dipoles)

Fluorescence: influence of density

Simulations



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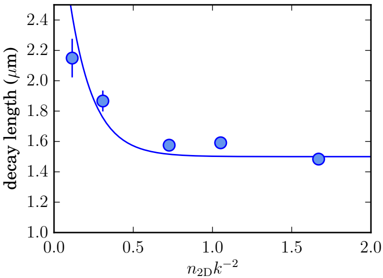
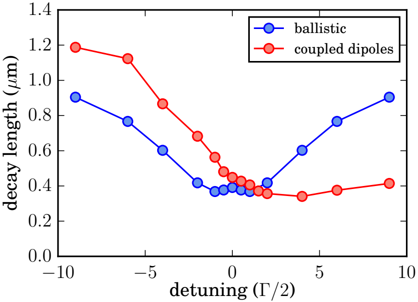
Experiments



- qualitative agreement
- limited optical resolution

Fluorescence: influence of detuning

Simulations



- classical model is symmetric
- clear asymmetry with quantum model

Fluorescence: influence of detuning

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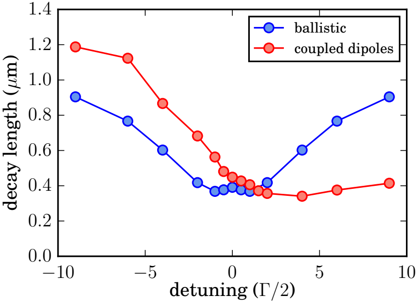

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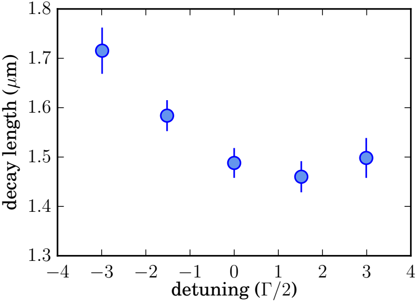
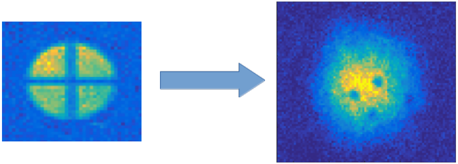


- asymmetric behavior with detuning
- in-plane guiding effect
(index of refraction gradient)

Guiding effects can be included in a modified ballistic model

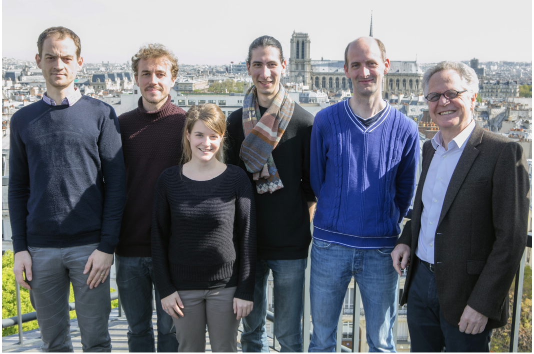
Perspectives

- Investigate different geometries for merging



- Study quench dynamics through BKT phase transition (infinite order)
- ...

The team



From left to right:

Sylvain Nascimbene

Jean-Loup Ville (PhD)

Monika Aidelsburger (Postdoc)

Raphaël Saint-Jalm(PhD)

Jérôme Beugnon

Jean Dalibard

+ Contributing former members (L. Chomaz, L. Corman, T. Bienaimé)

Funding:

Two-dimensional Bose gases in custom-shaped potentials

Jérôme Beugnon

LPNHE, June 2017

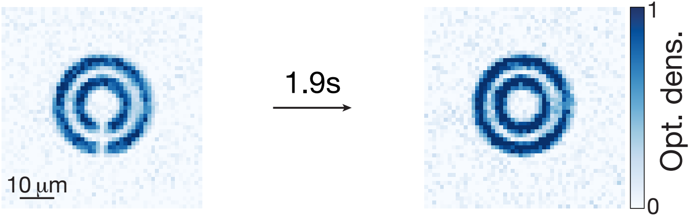
Laboratoire Kastler Brossel
Collège de France, ENS-PSL Research University, CNRS,
UPMC-Sorbonnes Universités
Paris, France

Mermin-Wagner-Hohenberg

For a system in dimension lower or equal to 2 and with short-range interactions, there cannot be a spontaneous breaking of a continuous symmetry at non-zero temperature.

Phase reference

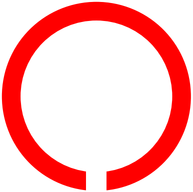
Check that the inner ring as no phase winding



- Cut the rings during evaporative cooling
- Close very slowly the rings

We detected 0 spiral pattern over 159 shots.

Special cases $N = 1$ and $N = 2$



No phase winding expected at zero temperature.

We find :
$P(0) = 98\%$ $P(\pm 1) = 2\%$

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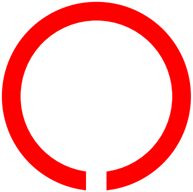

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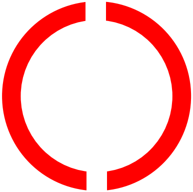
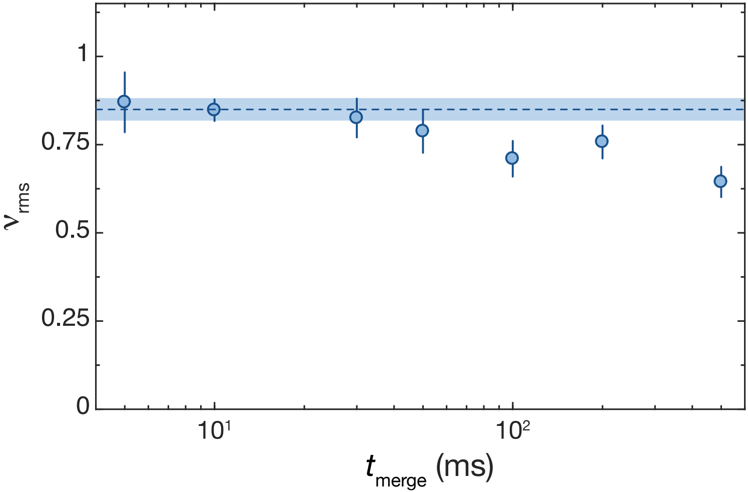


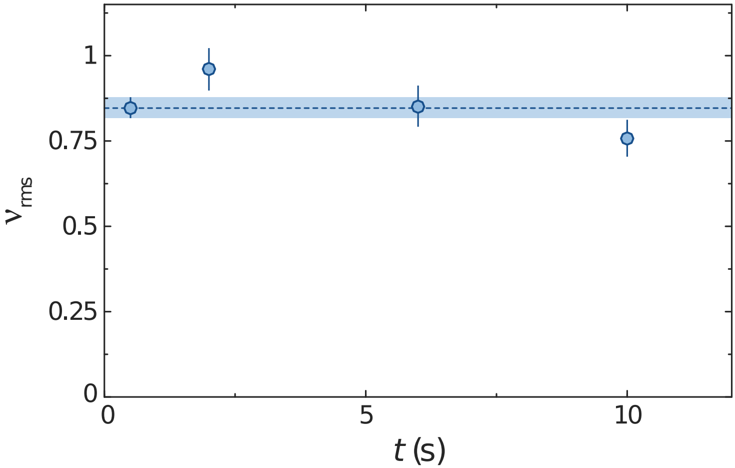
Marginal situation at zero temperature
Phase winding if $\Delta\phi = \pi$

We find :
$P(0) = 84\%$ $P(\pm 1) = 8\%$

Influence of the merging time



Lifetime



Superfluid current lifetime is very long ($>$10 s) and larger than the atomic lifetime.

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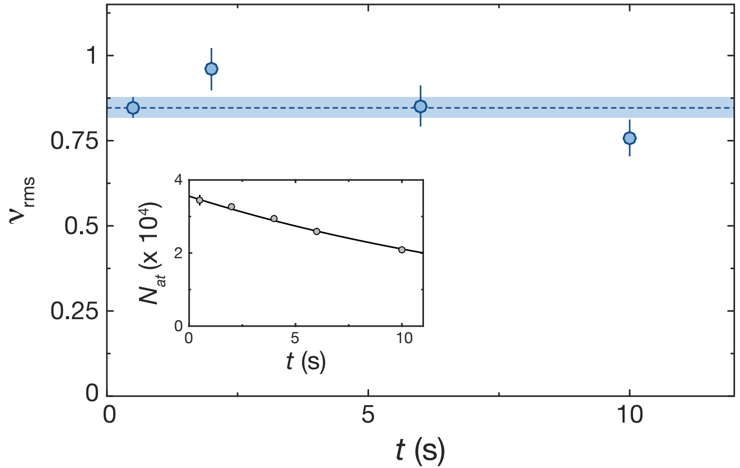

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Clear illustration of topological protection !