Phase relaxation in a superfluid atomic ring

arXiv:1705.02650

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Benasque, May 2017

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Our approach to atomtronics

Confine Bose gases in a single plane and design arbitrary optical potentials

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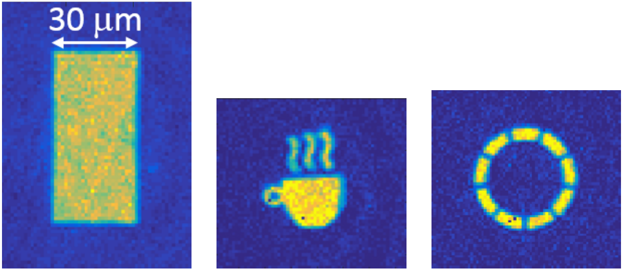


- Custom-shaped potentials
- Time-dependent potentials
- Coupling between clouds
- Manipulate spin degrees of freedom

Phase relaxation in atomtronics devices

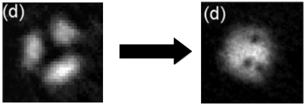
When coupling different subsystems, we usually consider the role of ΔT, $\Delta\mu$.

With superfluids, phase difference $\Delta\phi$ is crucial (Josephson physics).

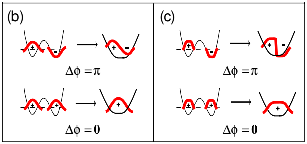
- What happen when connecting independent superfluids ?
- Does the phase homogenize ?
- How much time does it take to uniformize the phase ?
- What are the underlying microscopic mechanisms ?

Related works

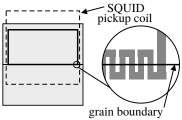
- Merging 3 BECs $\rightarrow$ vortices (Scherer et al. PRL **98**, 110402 (2007))

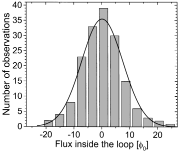


- Merging 2 BECs $\rightarrow$ heating (Jo et al. PRL **98** 180401 (2007))



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



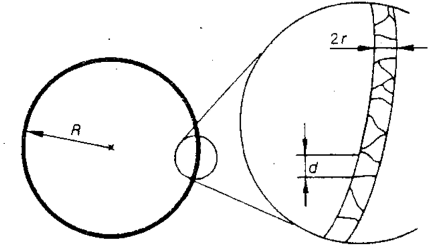


Link to Kibble-Zurek physics

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

Zurek's gedanken experiment:

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



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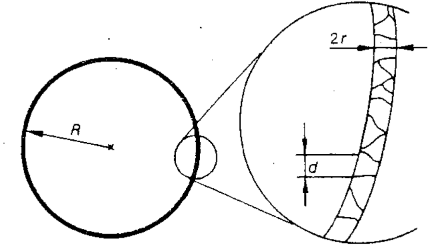

Independent phase domains form because of the divergence of the thermalization time around T_c.

Domain size:

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

ν, z: critical exponents

Winding number:

$$\langle n_w^2 \rangle \propto \hat{\xi}^{\alpha}$$

α depends on dimensionality.

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

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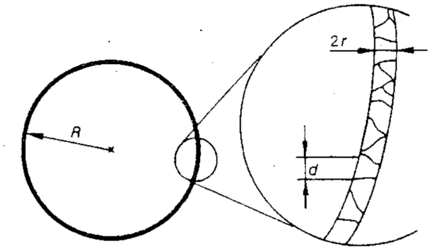

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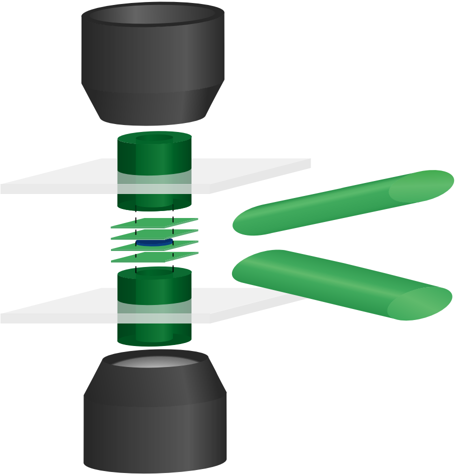
Zurek assumes a $\sqrt{N}$-scaling of $\sqrt{\langle n_w^2 \rangle}$. We can test it !

A single layer of ultracold atoms



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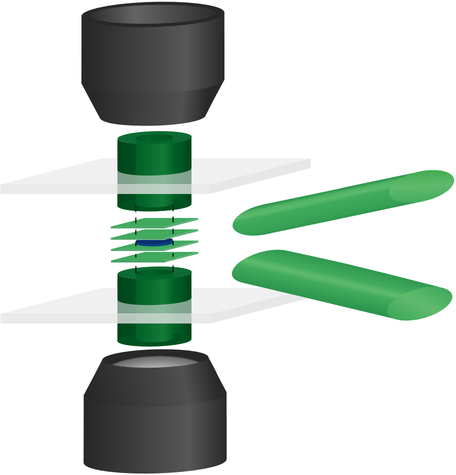
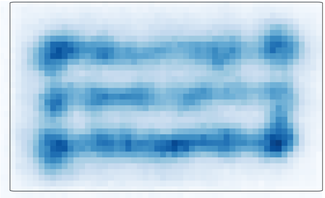


- $\omega_z = 2\pi \times 1.6$ kHz ($\Rightarrow \Delta z \approx 300\,$nm)
- $T \approx 10\,$nK
- $n_{2\mathrm{D}} \approx 30\,\mu\mathrm{m}^{-2}$
- Atom number $\approx 10^5$
- Spatial light modulator (DMD) to shape the potential.
  (10 kHz refresh rate)

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

Other physics to be explored

- Demixing dynamics in a two-component cloud



Non-miscible components evolve into well-defined patterns

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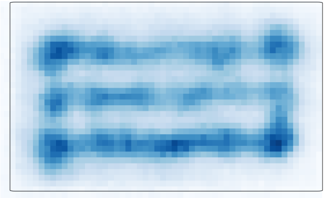
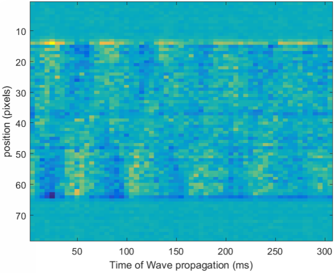


Non-miscible components evolve into well-defined patterns

- Sound wave propagations



Observation of traveling waves in a box

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

Preparing independent BECs

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

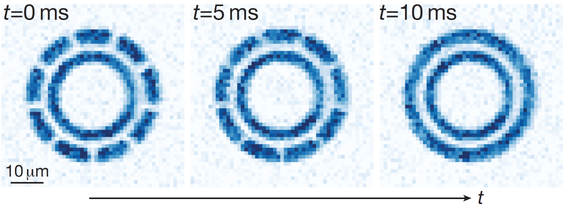
$N = 1$ $N = 3$ $N = 6$ $N = 9$

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.



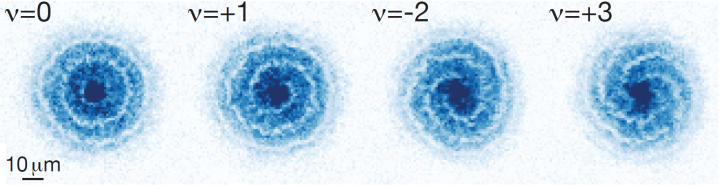
We empirically chose 10 ms because

- 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

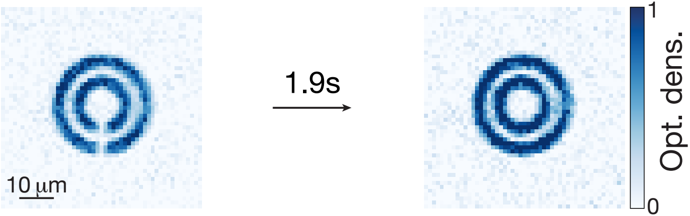


The number of spiral arms gives the winding number in the outer ring

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

Phase reference

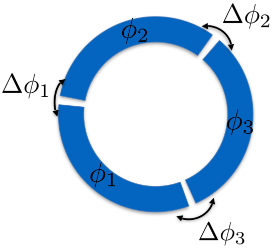
Check that the inner ring as no phase winding

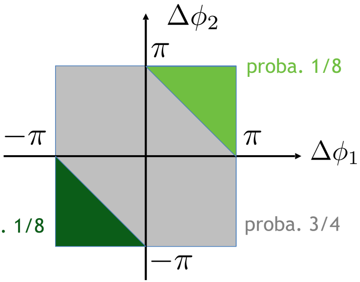


- Cut the rings during evaporative cooling
- Close very slowly the rings

We detected 0 spiral pattern over 159 shots.

The 3-segments case





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

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

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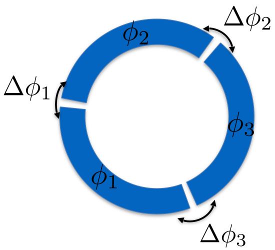

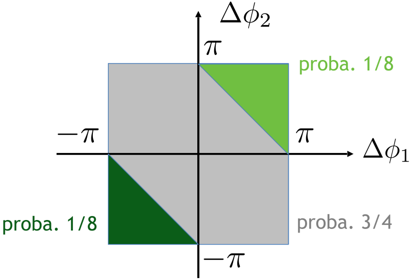

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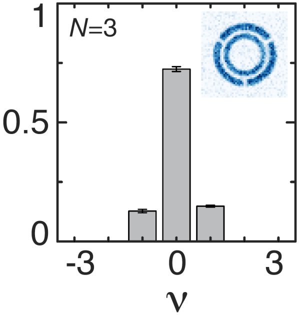
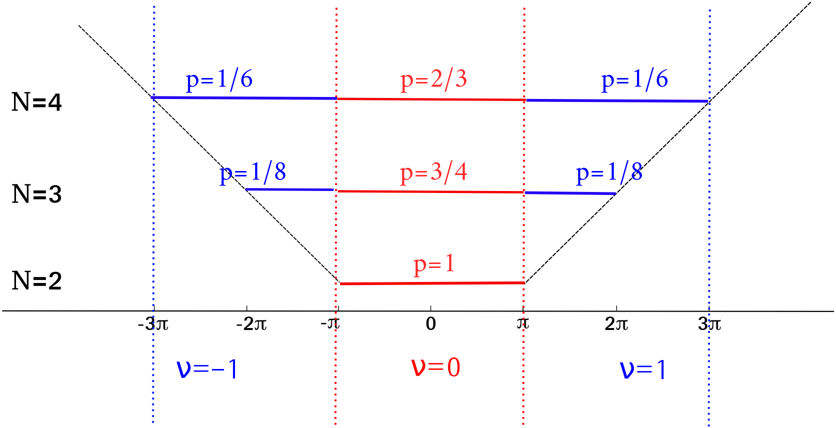
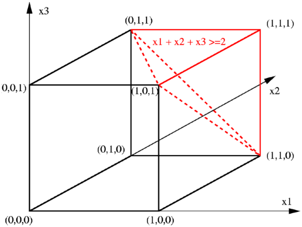


Varying the number of segments



Varying the number of segments

Compute hypervolumes of an hypercube



Already done by mathematicians !
Euler-Frobenius distribution gives:

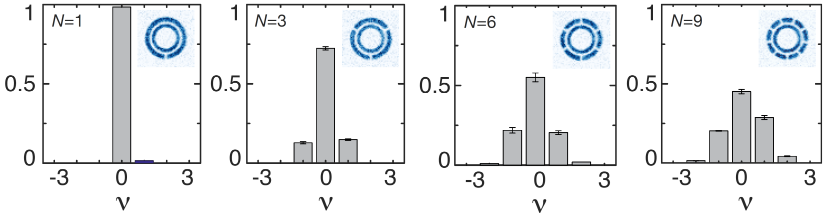
$$\boxed{\nu_{\mathrm{rms}} = \frac{\sqrt{N}}{2\sqrt{3}} \text{ for } N \geq 3}$$

with ν_{rms} the rms width of the distribution.

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

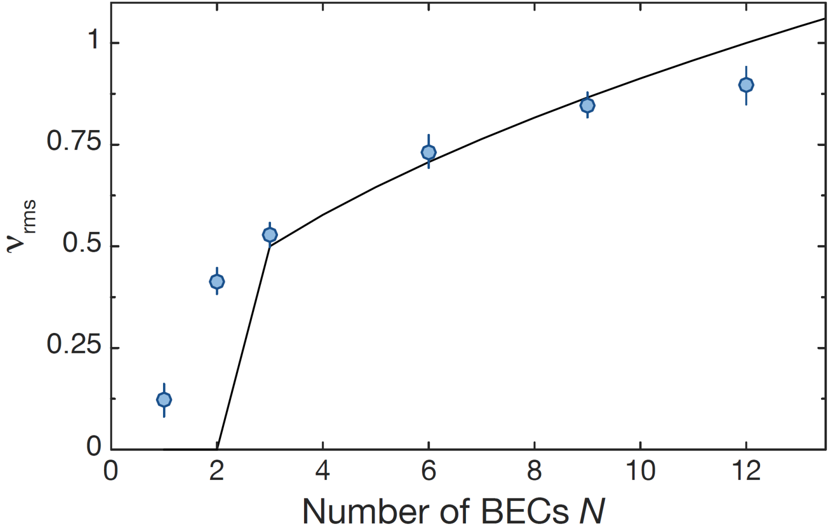
Results N segments

Vary number of segments N from 1 to 12.



The distribution broadens for increasing N

Results for *N* segments



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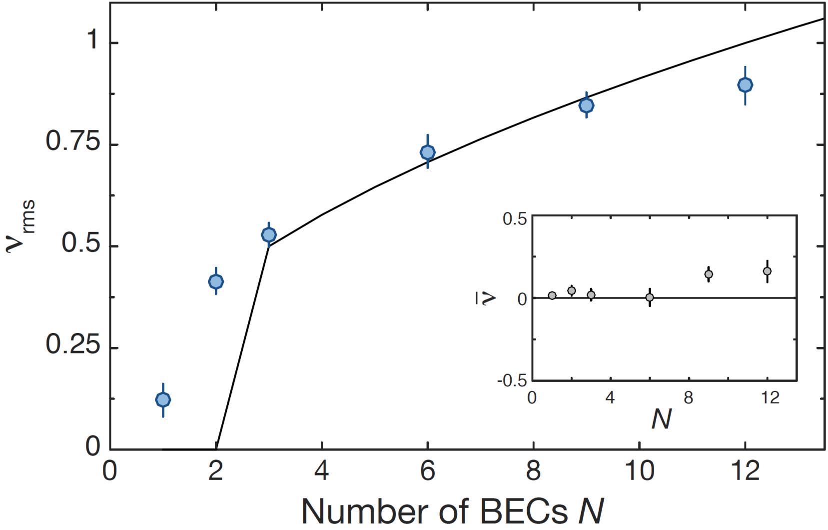
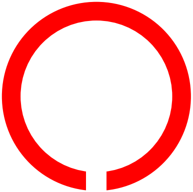


Special cases $N = 1$ and $N = 2$



No phase winding expected at zero temperature.

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

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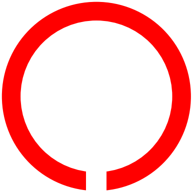

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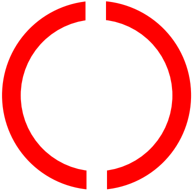


Marginal situation at zero temperature
Phase winding if $\Delta\phi = \pi$

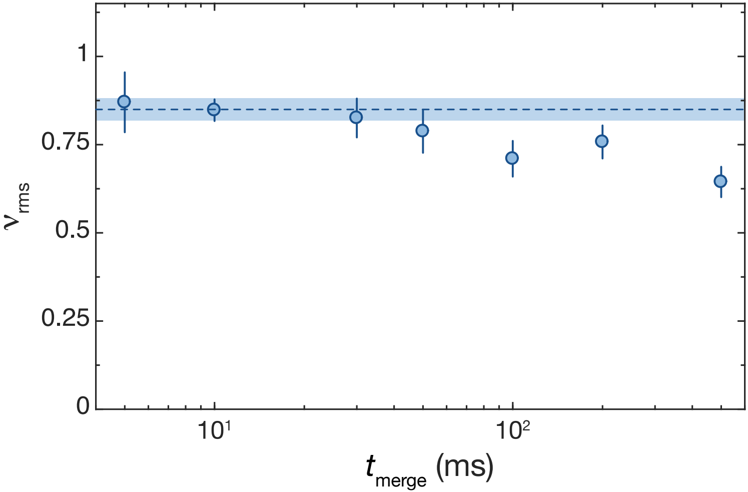
We find :
$P(0) = 84\%$ $P(\pm 1) = 8\%$

Timescales

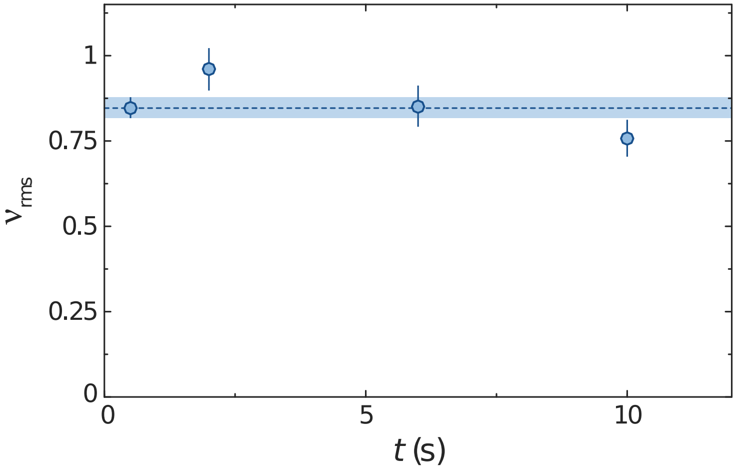
Merging $<$ Sound round-trip $<$ Relaxation $<$ Lifetime

10 ms $<$ 100 ms $<$ 500 ms $<$ 20 s

Influence of the merging time



Lifetime



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

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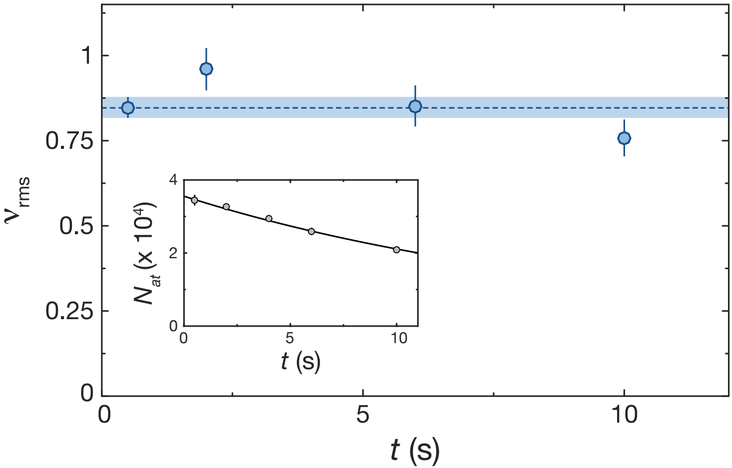

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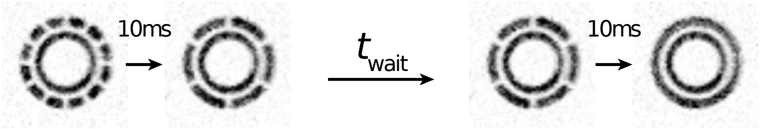
Clear illustration of topological protection !

Two-step merging



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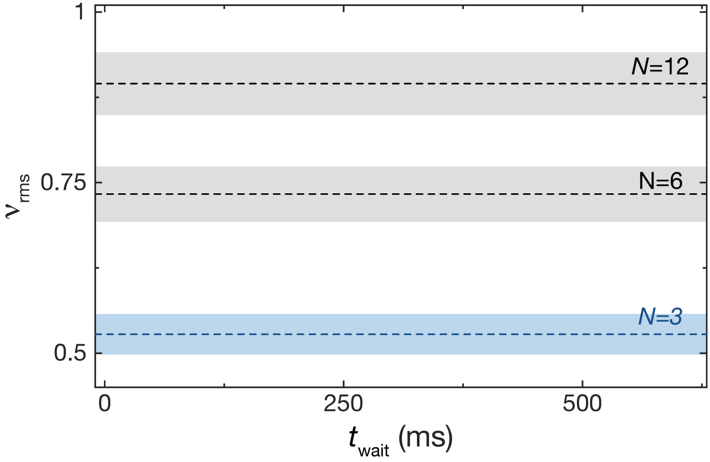

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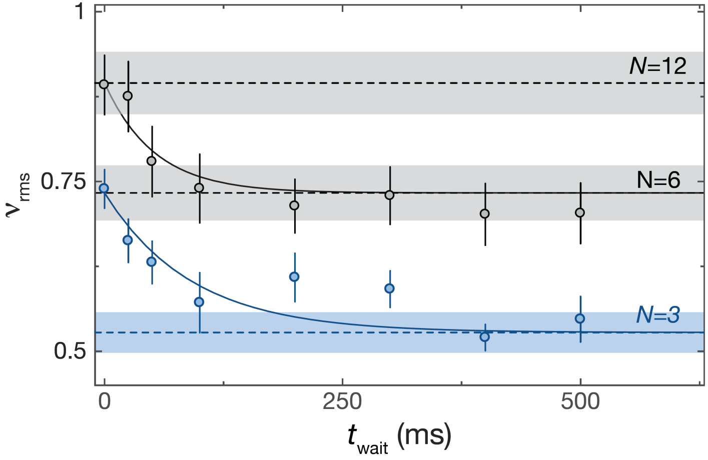


Exponential fits : $\tau_{12} = 52(17)$ ms, $\tau_6 = 90(30)$ ms

Shorter segments homogenize faster. Microscopic mechanism ?

The team

From left to right:

Sylvain Nascimbene

Jean-Loup Ville (PhD)

Monika Aidelsburger (Postdoc)

Raphaël Saint-Jalm(PhD)

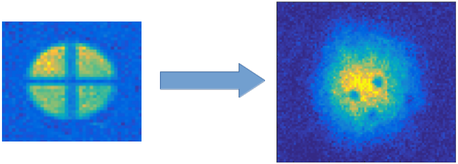
Jérôme Beugnon

Jean Dalibard

Funding:

Perspectives

- Investigate different geometries



- Control the relative phase
- Observe microscopic dynamics

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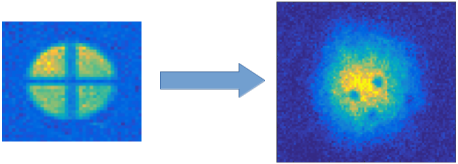

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¡ Post-doc position available !