Laboratoire Kastler Brossel
Physique quantique et applications

Superfluidity of a 2D Bose gas

(arXiv:1205.4536v1)

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Phase transitions in 2D

- Mermin-Wagner theorem: no long ranged order in low dimensions (no breaking of continuous symmetry). In particular no BEC at finite T in uniform system.
- But Berezinskii-Kosterlitz Thouless (BKT) transition to state with quasi-long-ranged order below T_{BKT} (algebraic decay of coherence).

$$\boxed{n_s = 4/\lambda^2}$$

$$g_1(|\vec{r} - \vec{r}'|) = \langle \psi^\dagger(\vec{r})\, \psi(\vec{r}') \rangle$$

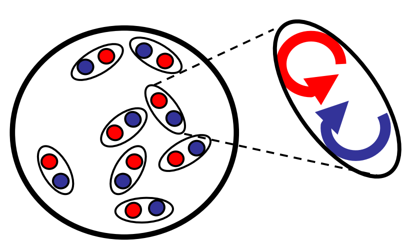
$$n_s = 0$$

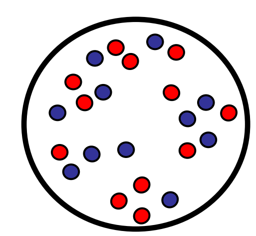
0 — T_{BKT} — T

superfluid state
algebraic decay of g_1

normal state
exponential decay of g_1

Bound vortex-antivortex pairs



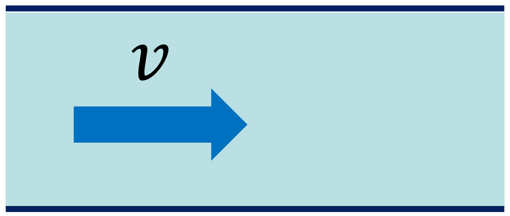


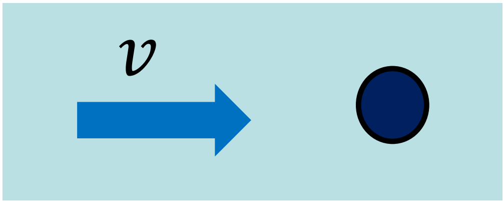
Proliferation of free vortices

- Coherence and microscopic nature of the transition were studied with cold atoms. But a direct proof of superfluidity is missing with these systems.

Hadzibabic et al., Nature **441**, 1118 (2006)
Cladé et al., PRL **102**, 170401 (2009)
Tung et al., PRL **105**, 230408 (2010)

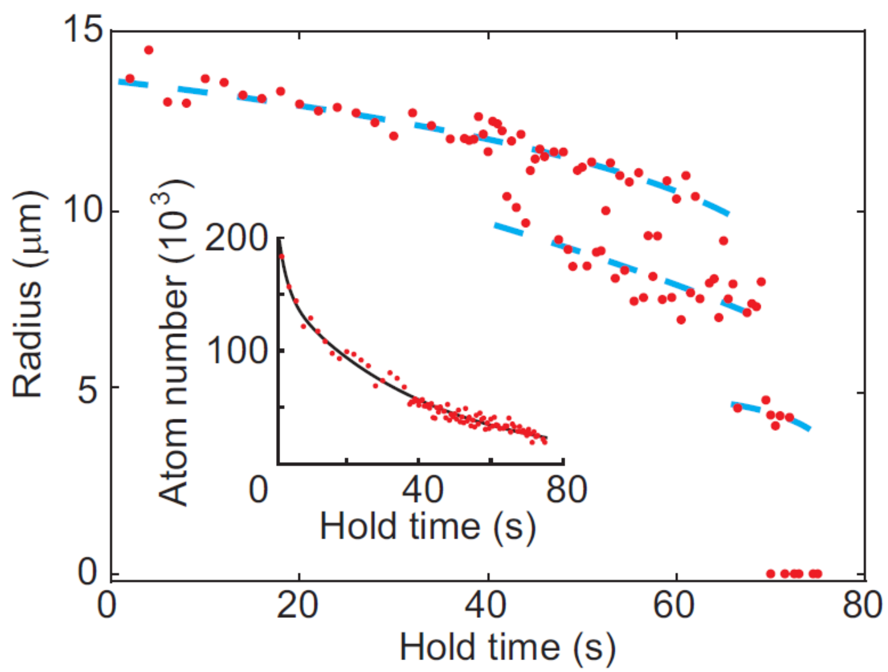
Superfluidity (in 2D and 3D)





Fluid flows with velocity v with respect to container walls or impurity

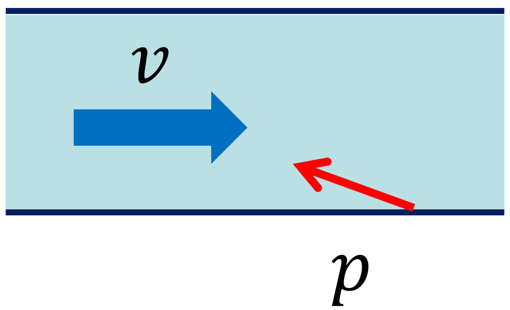
- Flow without friction, persistent current.
- Metastable state: equilibrium means fluid at rest ($v = 0$).
- Height of energy barrier depends on v and T and disappears at a critical velocity v_c.
- Decay time can be very long.
- Elementary excitations: phonons, vortices, rotons…

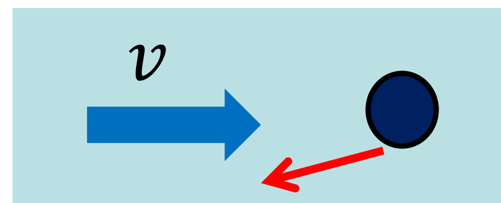


Persistent current in 3D toroidal trap
Moulder et al., arXiv:1112.0334 (2012)

Leggett, Quantum Liquids, Oxford Univ. Press (2006)
Pitaevskii and Stringari, Bose-Einstein Condensation, Oxford Science Publications (2003)

Landau criterion





An excitation with momentum p opposes the flow.

- Derived critical velocity for a dispersion relation $\epsilon(p)$ from consideration of transformation of energy and momentum.
- Excitation energy in rest frame of container $\epsilon(p) + p \cdot v$

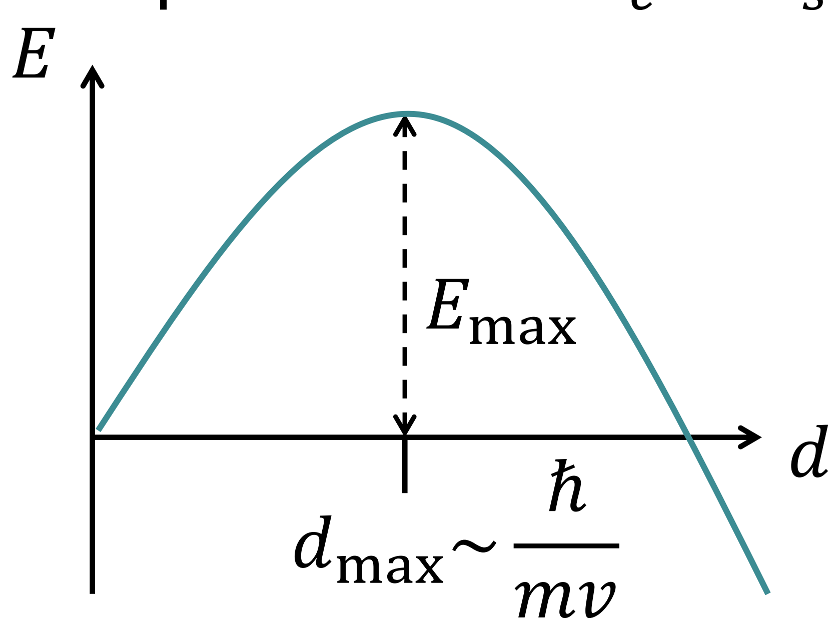
  Landau critical velocity $v_c = \min_p \frac{\epsilon(p)}{p}$
- For free particles $v_c = 0$
- For Bogoliubov spectrum $v_c = c_s$ (~ 1 mm/s for cold atoms)

Leggett, Quantum Liquids, Oxford Univ. Press (2006)
Pitaevskii and Stringari, Bose-Einstein Condensation, Oxford Science Publications (2003)

Stability of the superfluid flow

The flow can decay via vortex pairs (rings in 3D) that oppose the flow.

- Energy as function of vortex separation d has barrier $E_{\max}$
- Stability for $\gamma k_B \mathrm{T} \lesssim E_{\max} \;\Rightarrow v < v_c$
- Extended obstacle with diameter w: vortex pair created with $d \sim w$. If $w > d_{\max}$ (or $v > v_c = \hbar/mw$) the flow is unstable.
- Similar argument by Feynman for flow through channel to explain the low $v_c \ll c_s$ observed for liquid helium.



In 3D (vortex ring):

$$E_{\max} = \frac{\rho_s \hbar^3}{m^2 v}$$

$$v_c = \rho_s \frac{\hbar^3}{\gamma m^2 k_B \mathrm{T}}$$

In 2D (vortex pair):

$$E_{\max} \approx \frac{\rho_s^{(2D)} \hbar^2}{m} \ln \frac{\hbar}{m\xi v}$$

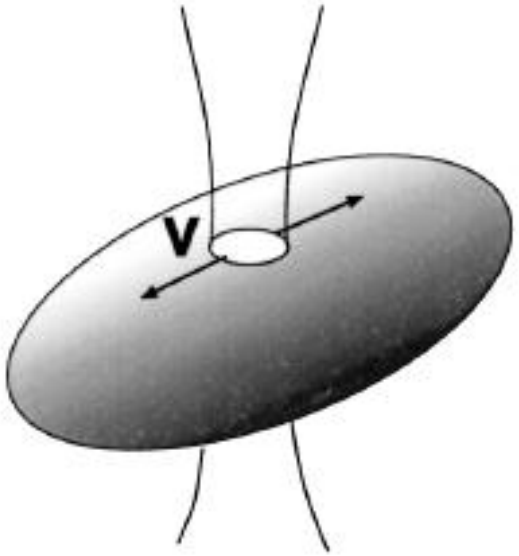
$$v_c = c\, e^{-\gamma / PSD}$$

Feynman (1955)
Ma (1985)
Langer and Fisher, PRL **19**, 560 (1967)
Stießberger and Zwerger , PRA **62**, 061601R (2000)

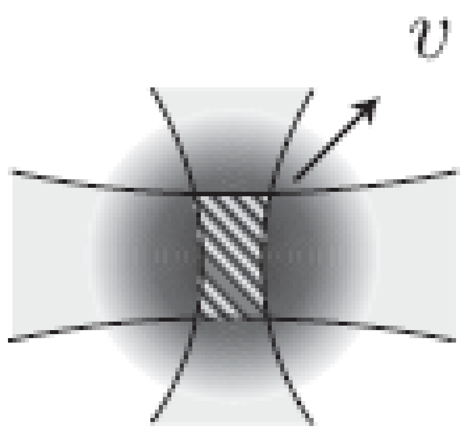
Stirring the superfluid

Experiments with cold atoms (3D systems)

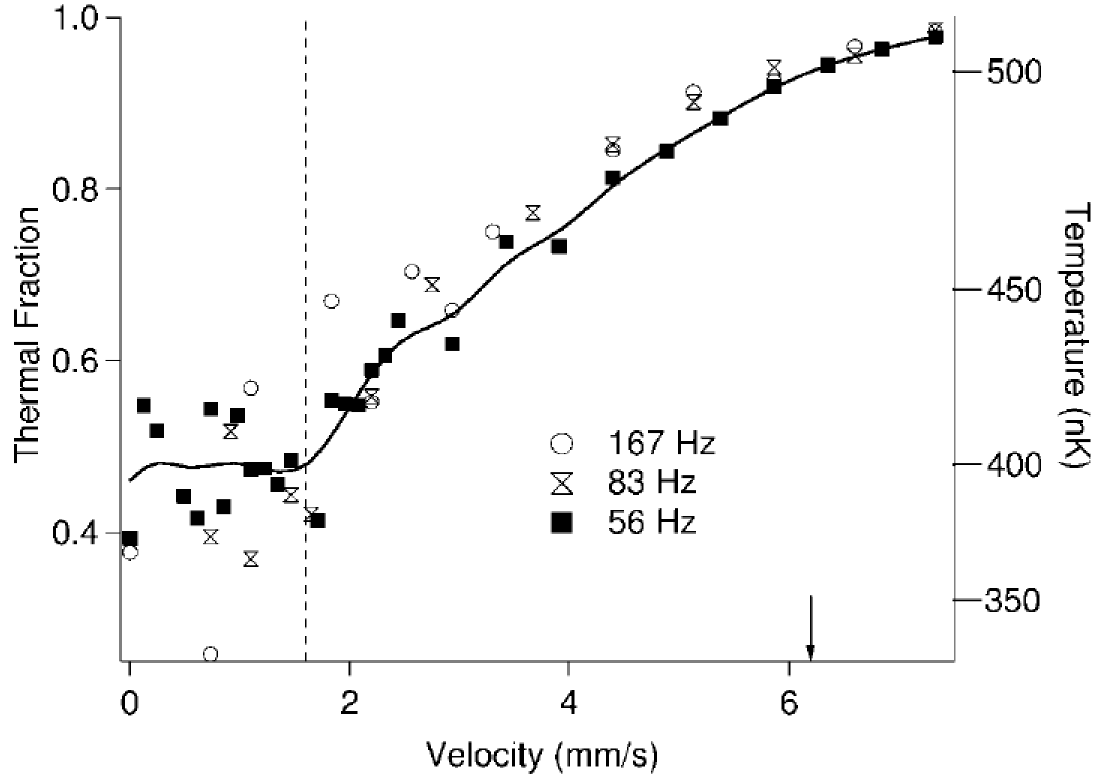
- move a small defect (laser beam or 1D lattice) through the cloud
- observe subsequent heating or excitations
- done for Bosonic and Fermionic systems



Moving laser beam



Moving optical lattice



Transpose technique to 2D system

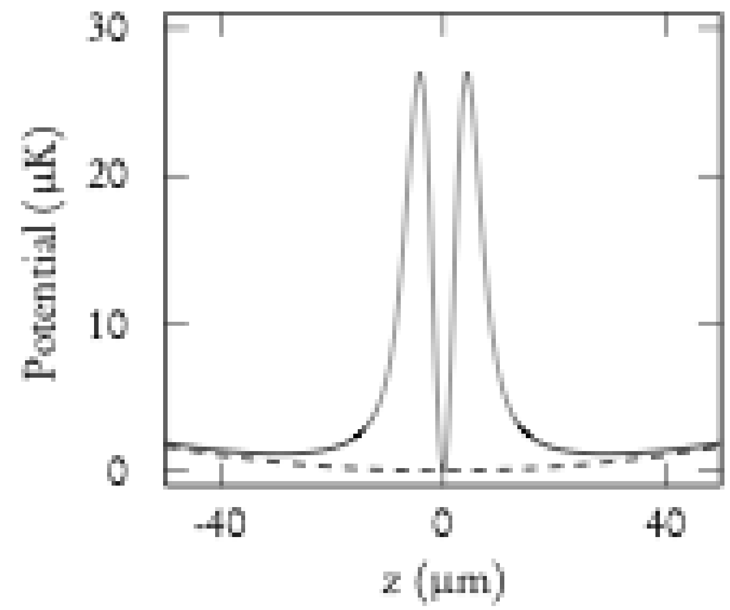
- Allows smaller defect (no divergence of laser beam inside cloud)
- Allows mesurements at fixed density by stirring in a circle

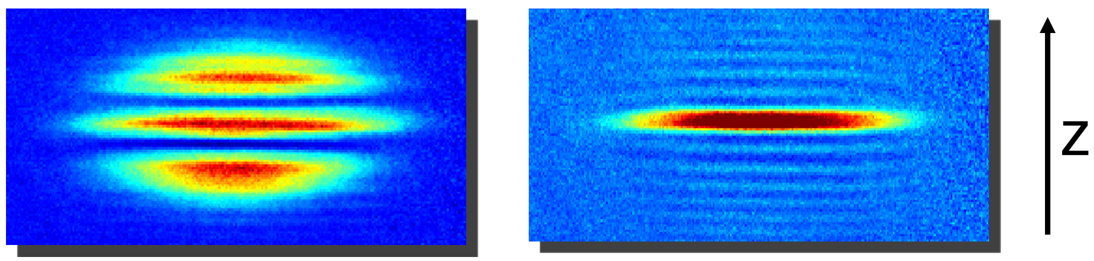
Raman et al., PRL **83**, 2502 (1999)
Raman et al., J. Low Temp. Phys. **122**, 99 (2001)
Neely et al., PRL **104**, 160401 (2010)
Onofrio et al., PRL **85**, 2228 (2000)
Engels and Atherton, PRL **99**, 160405 (2007)
Miller et al., PRL **99**, 070402 (2007)

Preparation of 2D Bose gases

- Superimpose a blue-detuned dipole potential to a degenerate 3D gas (^{87}Rb) in a magnetic TOP trap
- Depump atoms in the side wells with resonant light
- Evaporate with RF to reach degeneracy

magnetic TOP trap
+
optical confinement



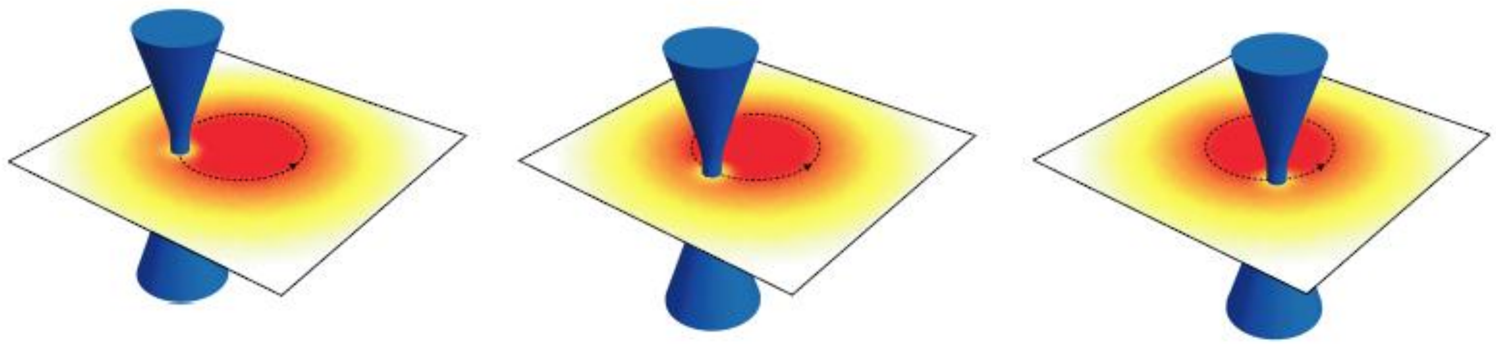


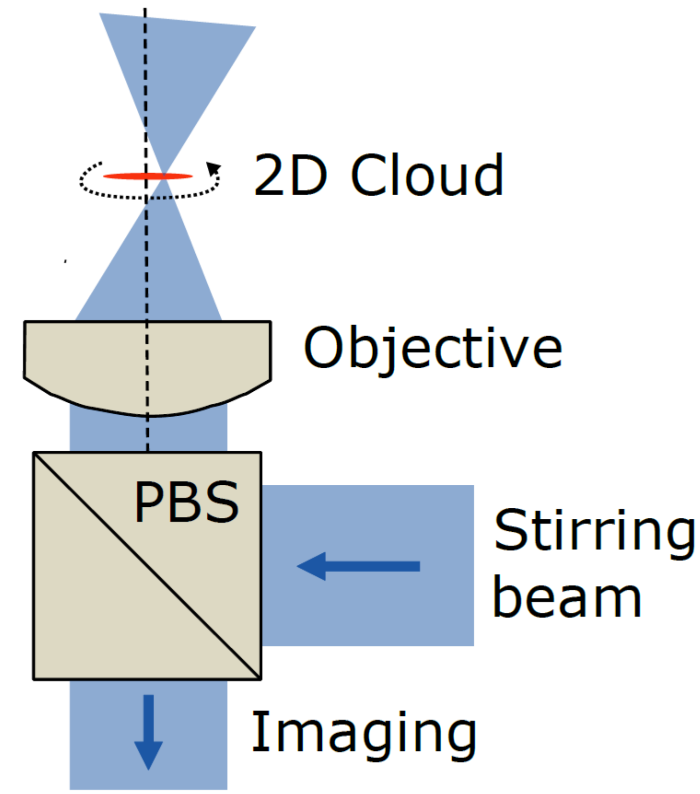
Typical cloud :

$T = 65 - 120$ nK
$N = 3 - 9 \cdot 10^4$
$\mu = k_B \cdot 35 - 60$ nK
$\omega_r = 2\pi \cdot 25$ Hz
$\omega_z = 2\pi \cdot 1.4$ kHz
$\tilde{g} = \sqrt{8\pi}\, a/l_z = 0.093$
$\xi \sim 0.5$ μm

Quasi 2D regime:
$\hbar\omega_z = k_B \times 70$ nK comparable to $k_B T$ and $U_{\mathrm{int}} \sim k_B \times 40$ nK.

Stirring the cloud

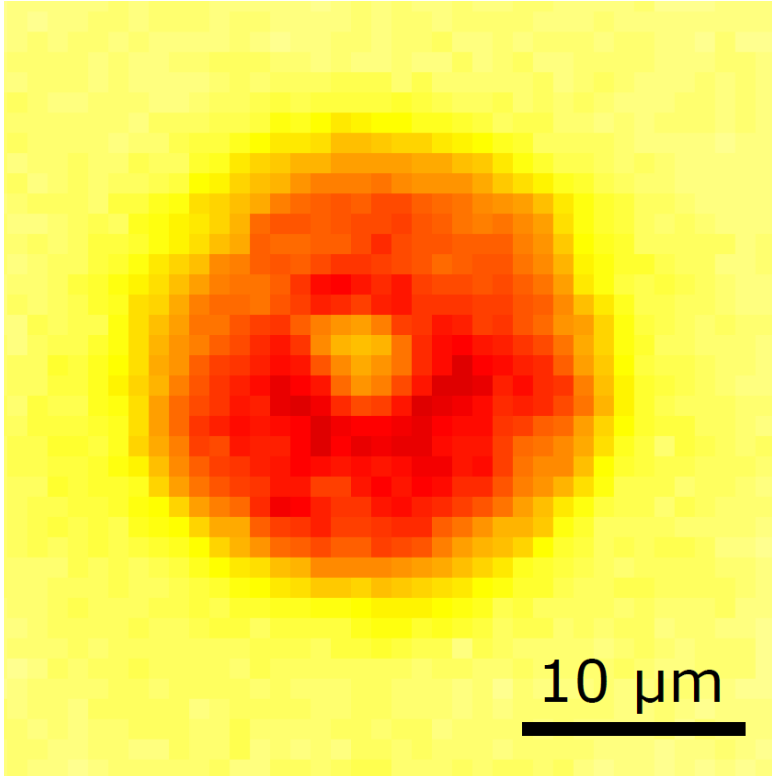




- Use the imaging microscope objective to focus a blue-detuned laser beam (waist $w_0 = 2$ µm, trap depth $V = k_B \times 80\,\mathrm{nK}$)

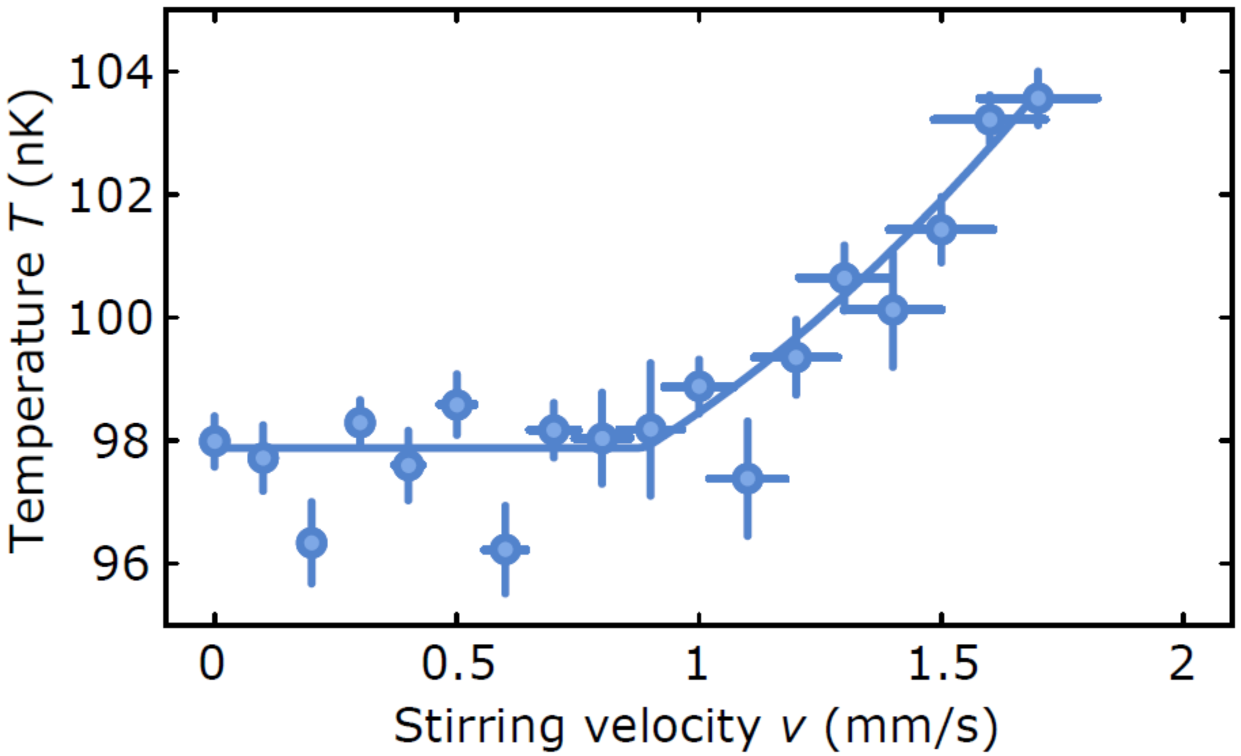
- Stir in circles at constant velocity v for $t_{\mathrm{stir}} = 200$ ms.

- Let the cloud equilibrate and measure temperature T (average over 10 shots).

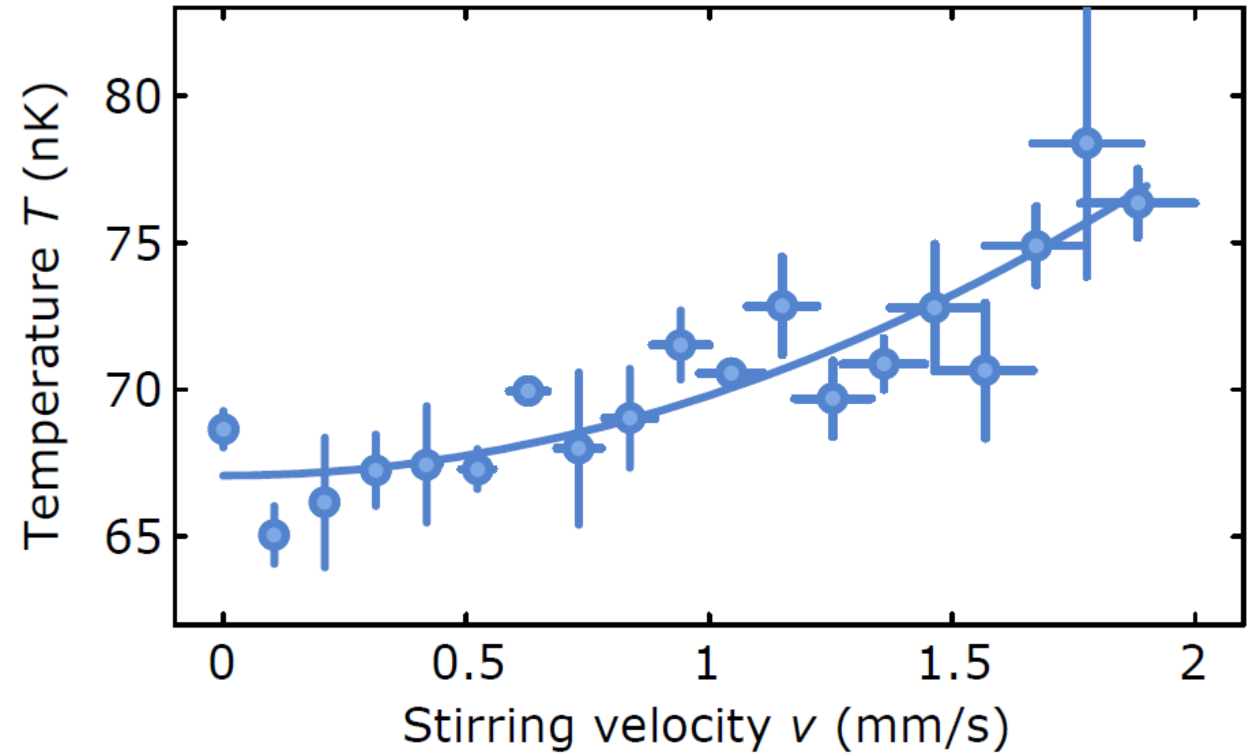


Evidence for a critical velocity

In the core



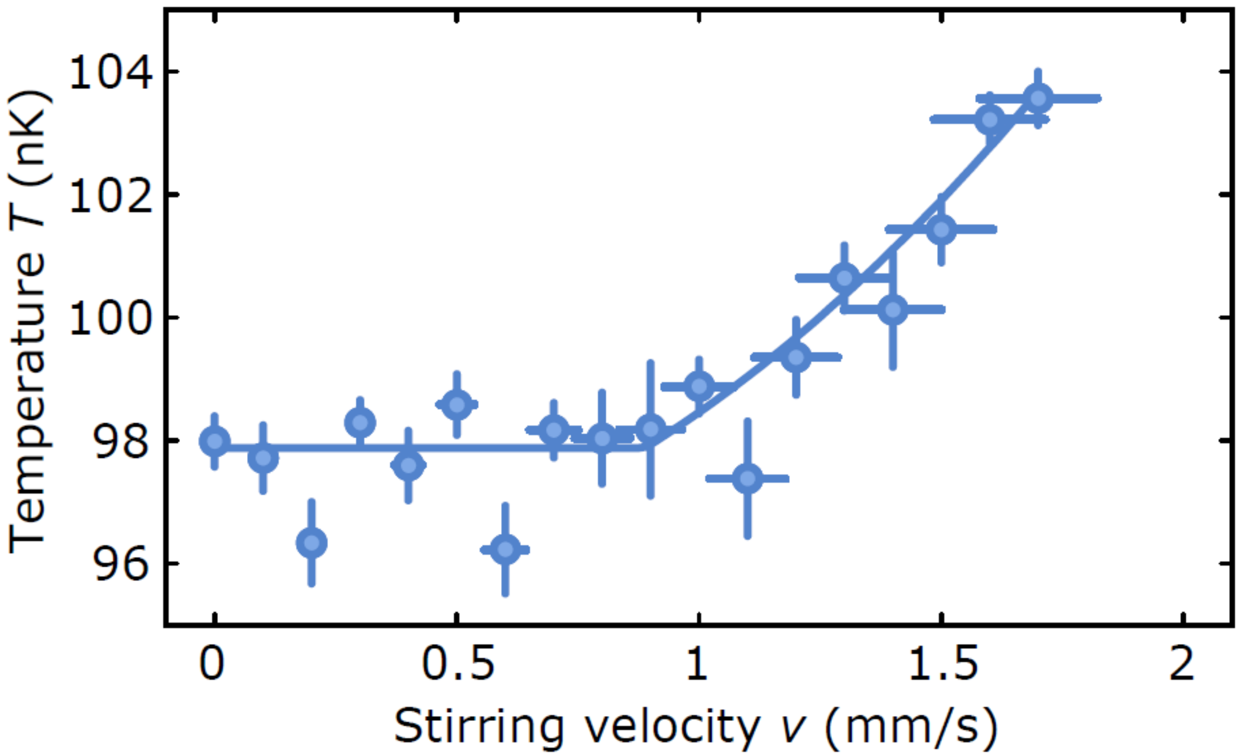
In the wings

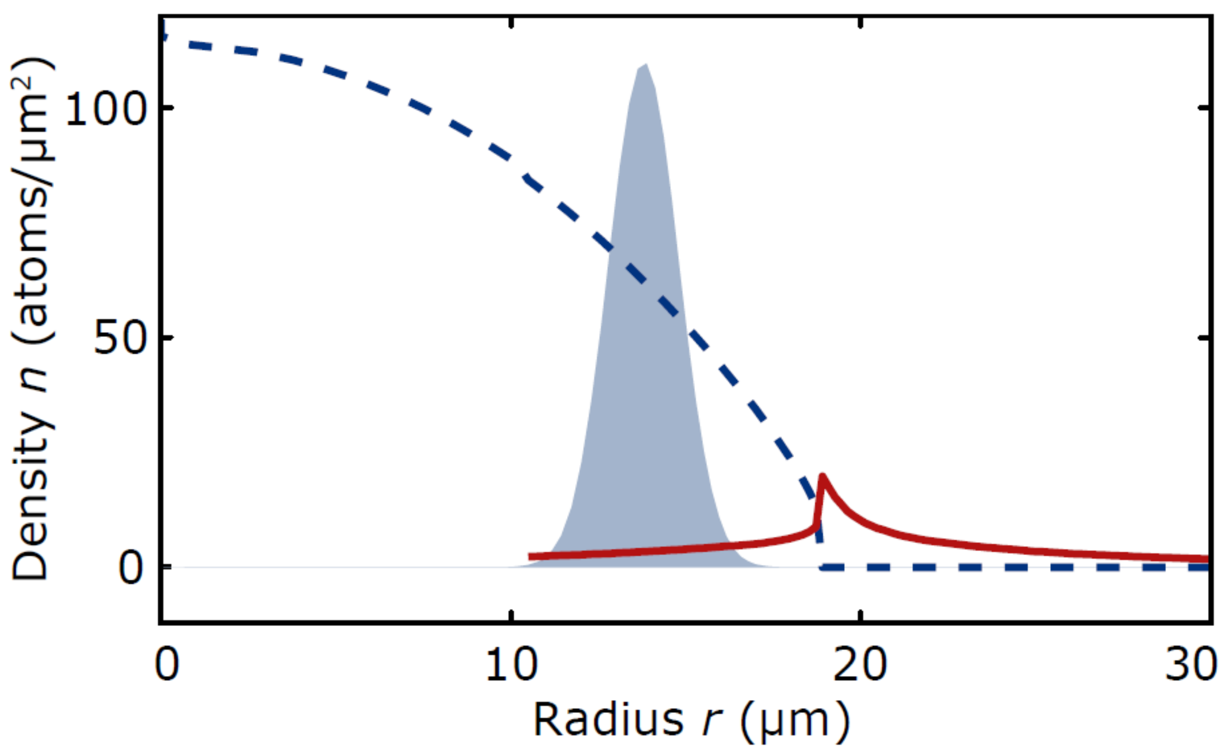


- In the core (superfluid state): clear threshold behaviour with no discernable dissipation below a critical velocity.
- In the wings (normal state): quadratic heating without threshold. Due to linear scaling of the drag force.
- Model with fit function : $T = T_{v=0} + \kappa \cdot t_{\mathrm{stir}} \cdot \max[v^2 - {v_c}^2, 0]$
- Record the fit parameters κ and v_c for a given experimental configuration (N, T, r)

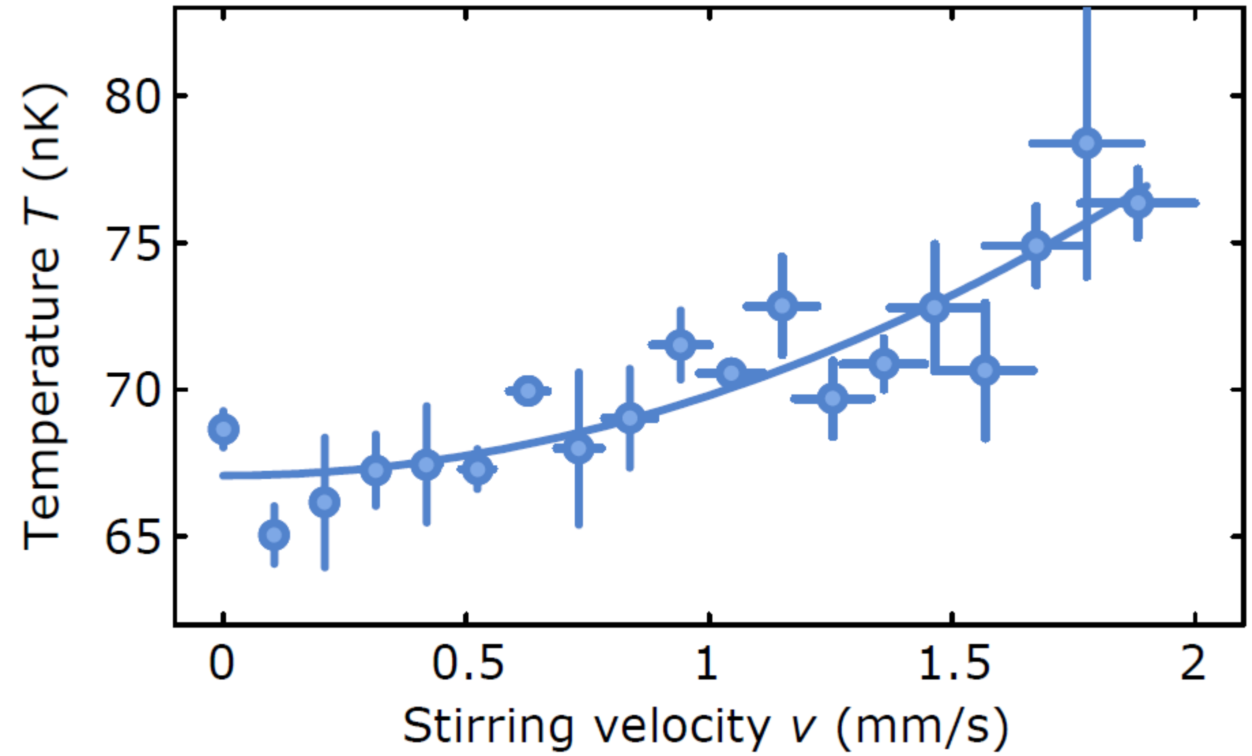
Evidence for a critical velocity

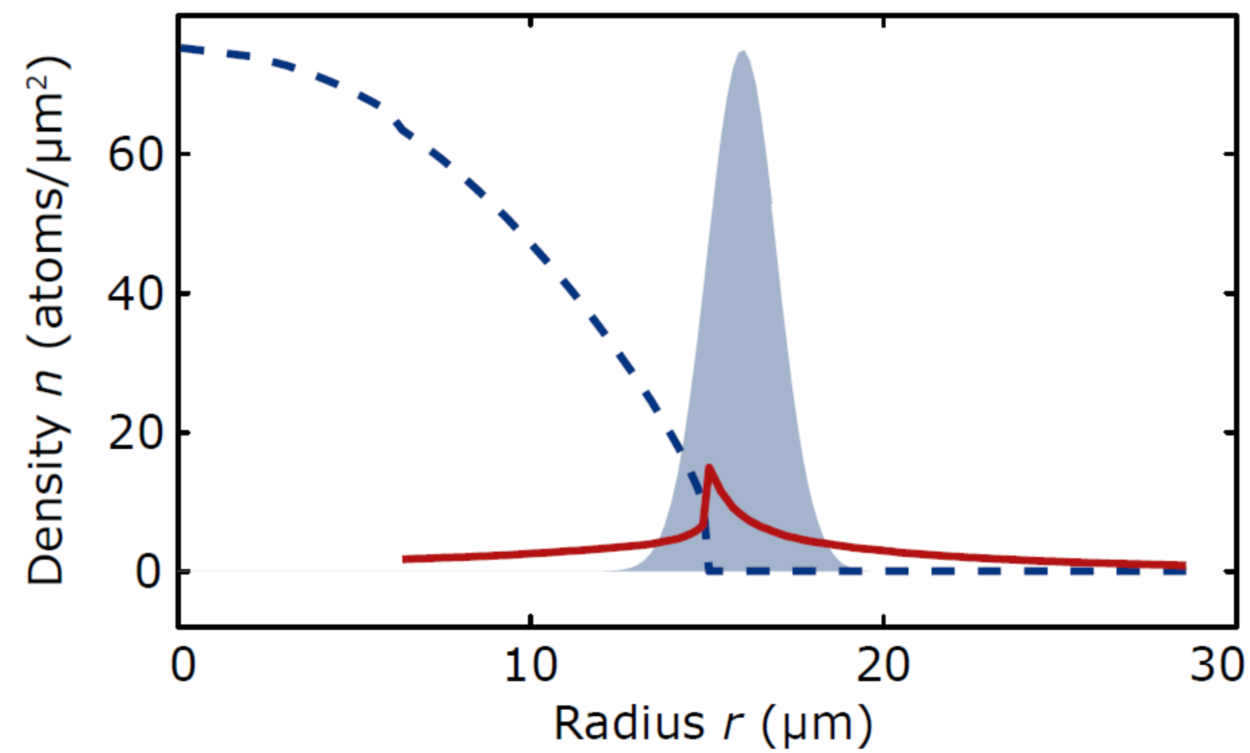
In the core





In the wings





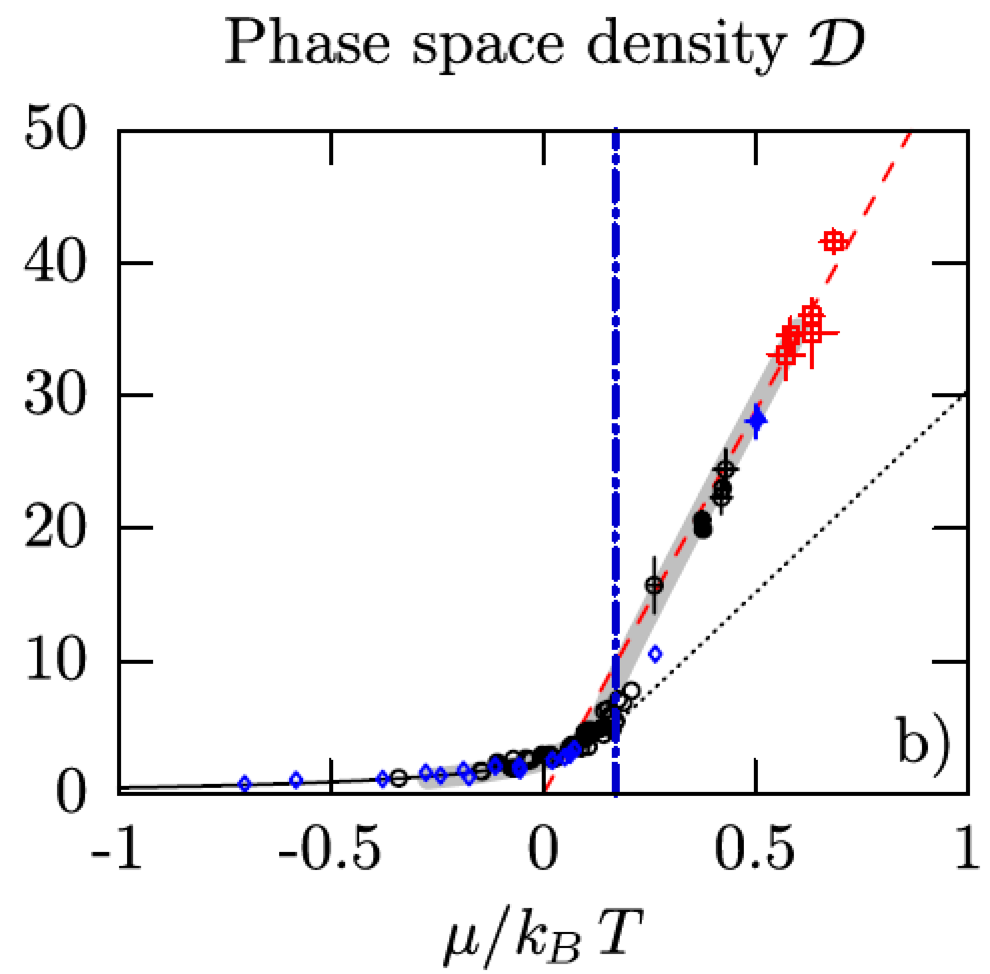
The trapped 2D Bose gas

Local Density Approximation (LDA):

- For each configuration (N, T, r), apply LDA to determine $\mu_{\text{loc}}(r) = \mu_0 - V(r)$
- relate to the uniform gas with T and μ_{loc}

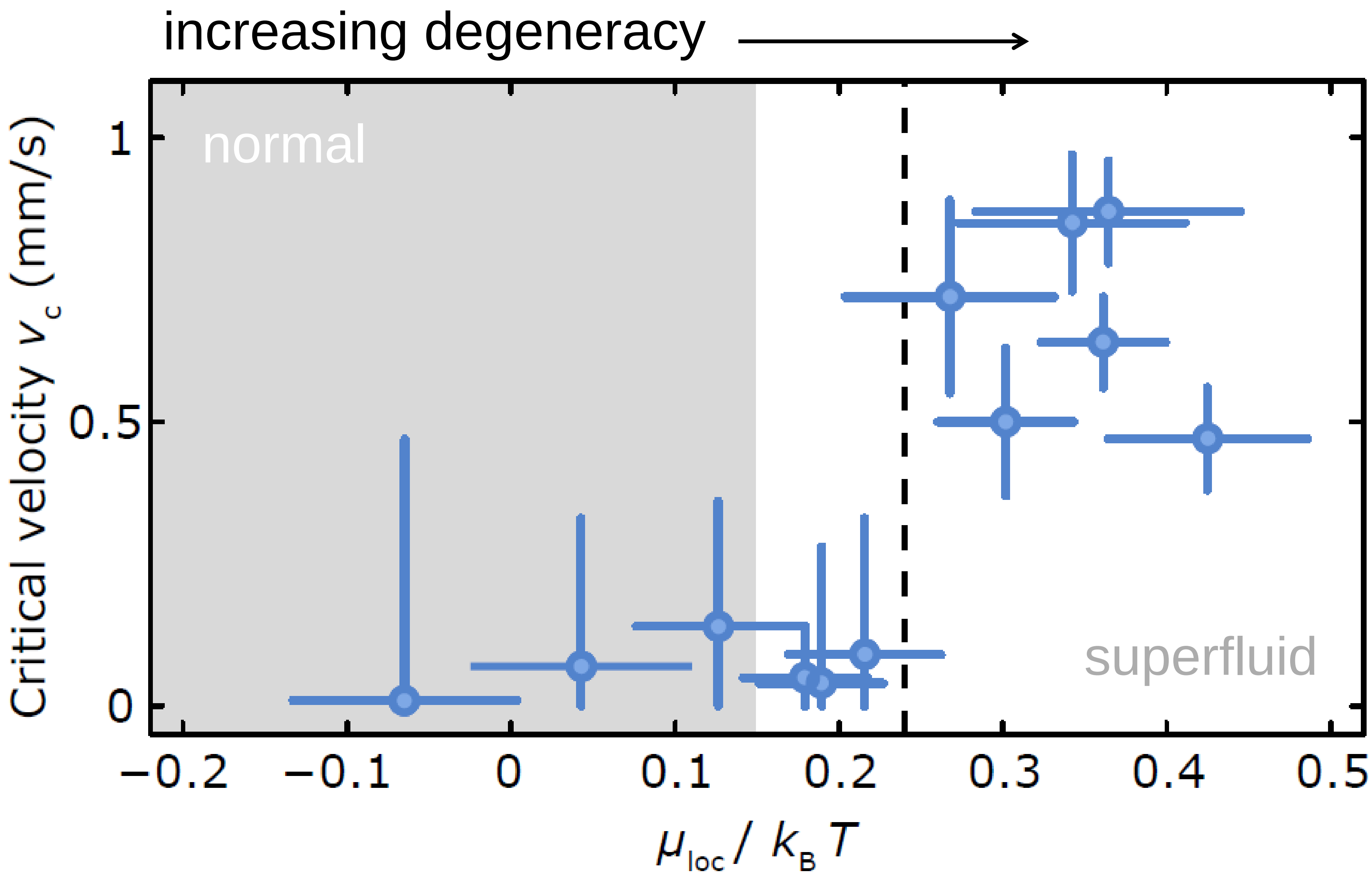
Scale invariance:

- Plot v_c against $\mu_{\text{loc}}/\mathrm{k}_B T$.
- Due to the scale invariance of the 2D Bose gas, dimensionless quantities depend only on this ratio.
- It is univocally related to PSD and characterizes the degree of degeneracy of the cloud.



Hung et al., Nature **470**, 236 (2011)
Yefsah et al., PRL **107**, 130401 (2011)

Across the BKT transition



- Two regimes: $v_c = 0$ and $v_c > 0$
- x error bars represent the finite beam size and the “background heating”
- BKT transition expected at $\mu_{\text{loc}}/k_{\text{B}}\text{T} = 0.15$ (for homogeneous system and $\tilde{g} = 0.093$) but shifted to 0.24, possibly due to the size of the beam.

Prokoveff and Svistunov, PRA **66**, 043608 (2002)

Dissipation mechanisms

obstacle size / healing length

0 — 1 — w_0/ξ

Phonons
$v_c = c_s \sim$ 1.6 mm/s

Vortex pairs
$v_c \sim ?$

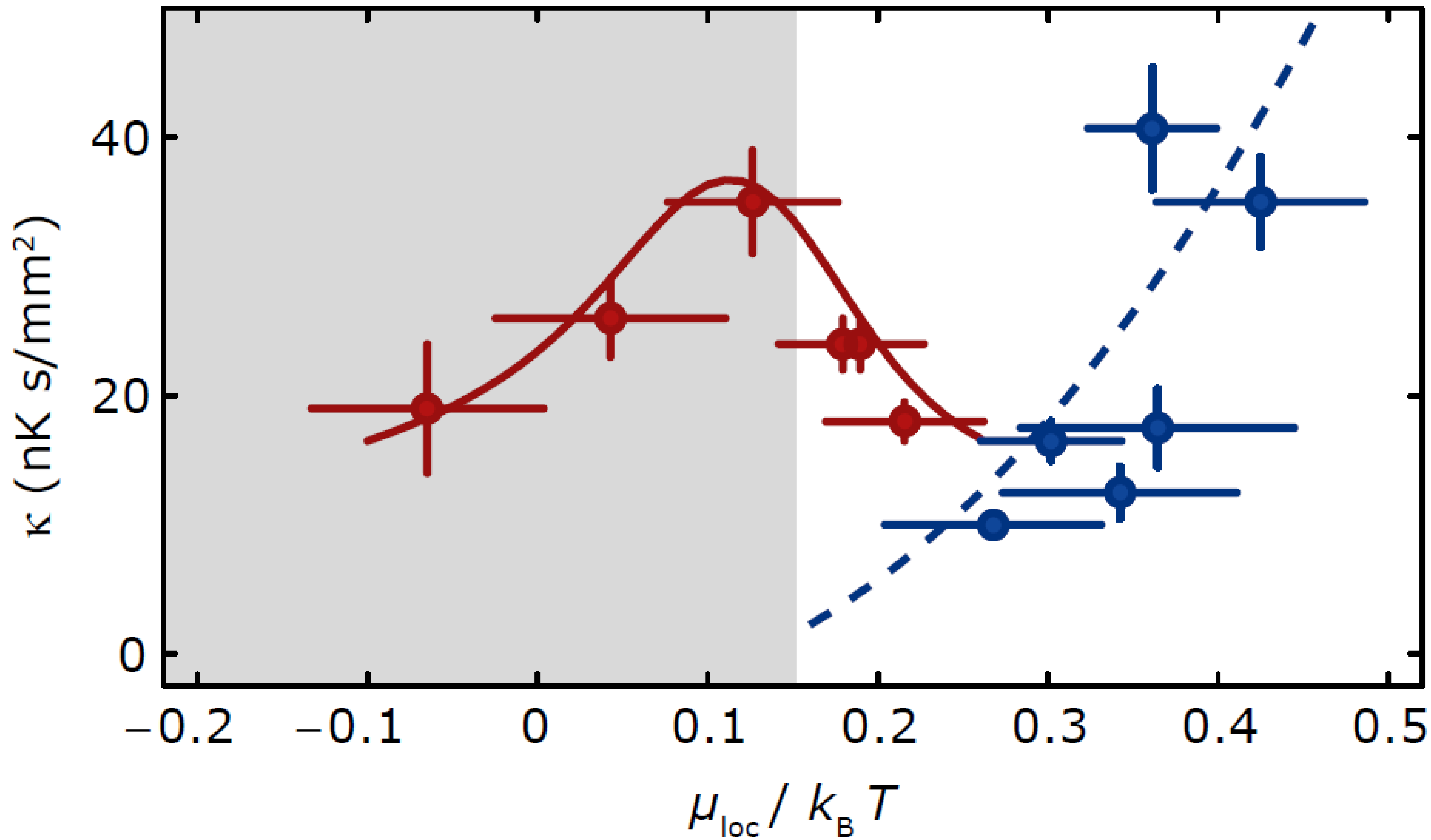
Vortex pairs
$v_c \sim \frac{\hbar}{m w_0} \sim 0.3$ mm/s

- What can we tell from the value of the critical velocity?
  We find $v_c = 0.5 - 1.0$ mm/s.
- This means $v_c/c_s = 0.3 - 0.7$ (compare to 0.1 in 3D experiments)
- We are in intermediate regime, cannot determine dominant mechanism from value of v_c.
- Simulations for similar systems suggest vortices
  (one should observe vortices directly)

Langer and Fischer, PRL **19**, 560 (1967)
Frisch, Pomeau, Rica, PRL **69**, 1644 (1992)
Winiecki, McCann, Adams, PRL **82**, 5186 (1999)
Stießberger and Zwerger, PRA **62**, 061601R (2000)
Crescimanno et al., PRA **62**, 063612 (2000)

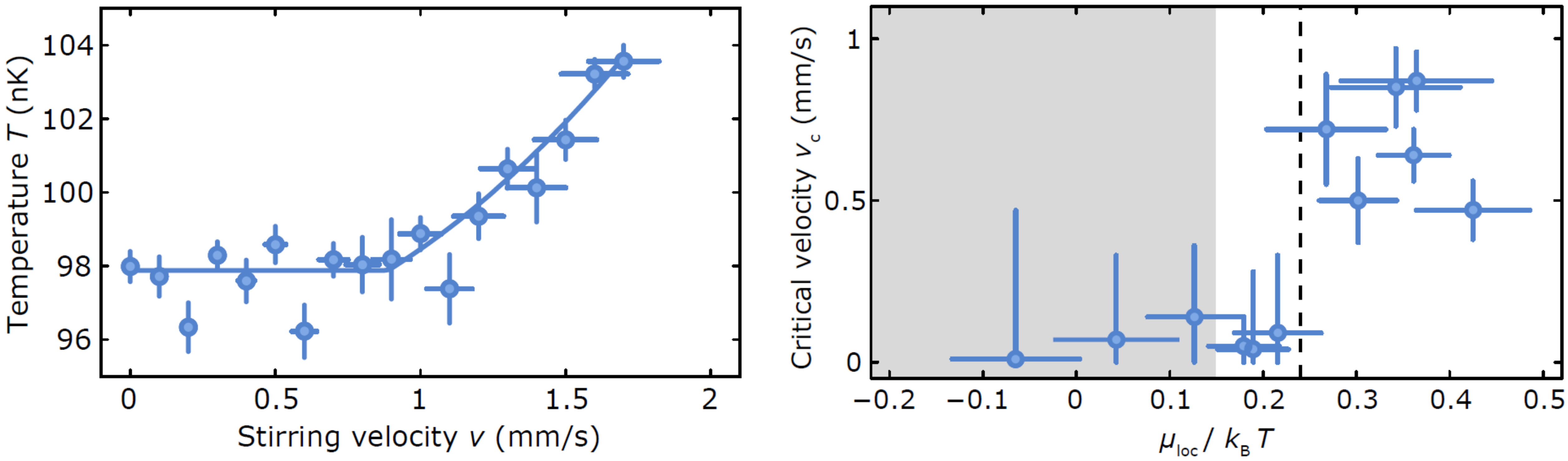
$c_s = \hbar/m\sqrt{\tilde{g}n}$ (for uniform gas, $T = 0$)
$c_s \sim$1.6 mm/s (for $n = 50$ atoms/μm^2)

Heating coefficient



- Normal region (red): heating coefficient scales linear with the normal density (averaged over the beam size).
- Maximum of normal density around the expected superfluid transition.
- Compatible with model of single-particles colliding with beam.
- Superfluid region (blue): stronger scaling with density (here quadratic).

Summary

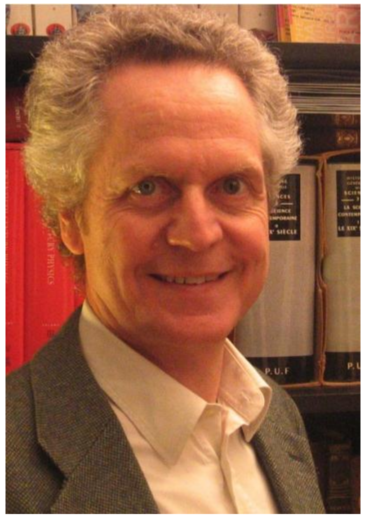


- We measured the superfluid behaviour of a 2D Bose gas via the dissipationless response to a moving obstacle.

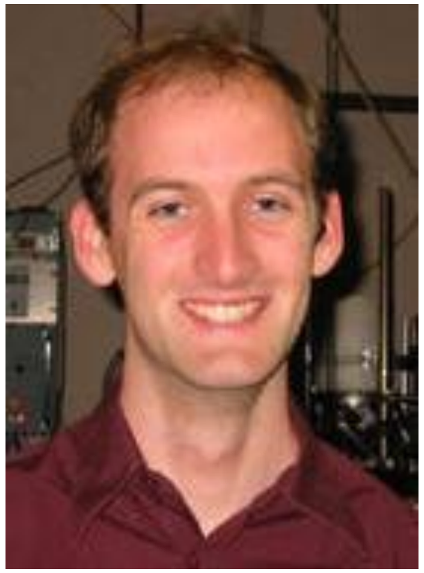
- We probed a trapped system at fixed density, and directly observed the transition between the normal and the superfluid phase.

Desbuquois et al., arXiv:1205.4536v1 (2012), to appear in Nature Physics

The Team at LKB



Jean Dalibard



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