Berezinskii-Kosterlitz-Thouless physics with atomic gases

Harmonically trapped vs. uniform systems

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BKT transition with dilute Bose gases

J.M. Kosterlitz

D.J. Thouless

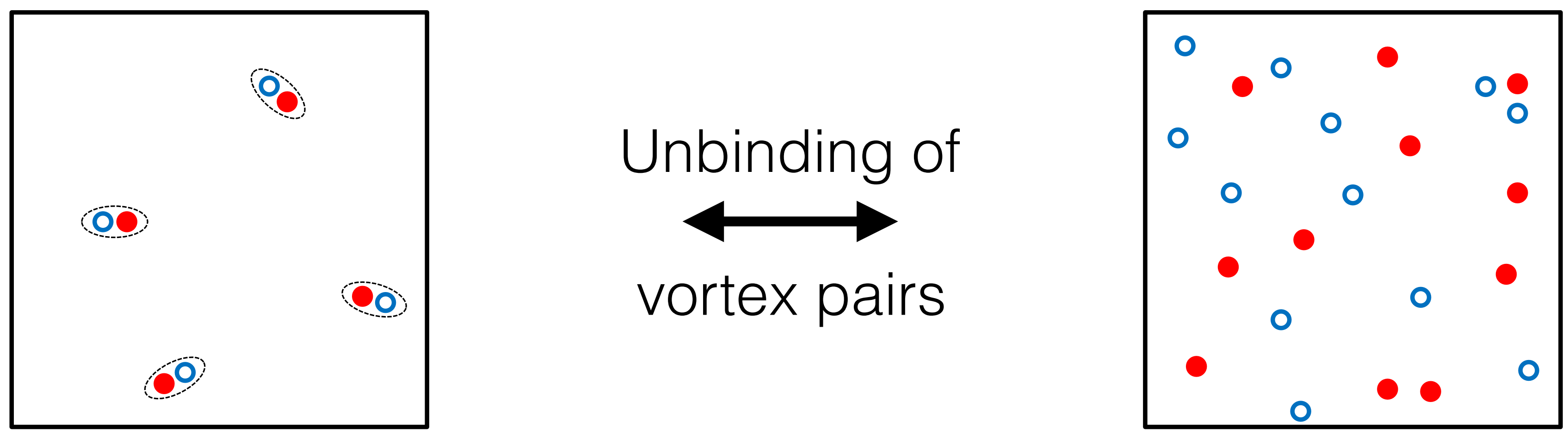
1971-73: In spite of Mermin-Wagner theorem, a phase transition can occur at $T \neq 0$ between a normal and a superfluid state

Topological phase transitions:
Not in the usual Landau classification, i.e., no breaking of a « standard » symmetry

BKT transition with dilute Bose gases

Feature 1: The decay of the one-body correlation function $G_1(r) = \langle \psi^\dagger(\boldsymbol{r})\psi(0)\rangle$.

Infinite order phase transition between two different <u>disordered</u> phases



The two phases correspond to a different decay of $G_1(r)$

Superfluid state **Normal state** Temperature

0 T_c

$G_1(r) \propto 1/r^\alpha$

$\alpha = 1/\rho_s\lambda^2$

ρ_s : superfluid density

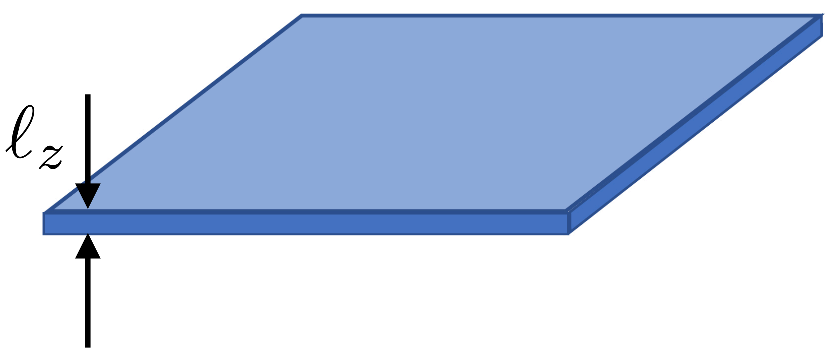
$G_1(r) \propto \mathrm{e}^{-r/\ell}$

BKT transition with dilute Bose gases

Feature 2: Classical field analysis and scale invariance

Description of the state of the gas by a classical field $\psi(\boldsymbol{r})$

Interaction between atoms represented by a contact potential $V(\boldsymbol{r}) = \dfrac{\hbar^2}{m}\,\tilde{g}\,\delta^{(2)}(\boldsymbol{r})$



$$\tilde{g} \propto \frac{a_{\mathrm{s}}^{(3\mathrm{D})}}{\ell_z}$$

Dimensionless parameter

Typically $\tilde{g} \sim 0.1 - 0.3$

Energy functional: $E[\psi] = \dfrac{\hbar^2}{2m}\left(\int |\boldsymbol{\nabla}\psi|^2 + \tilde{g}\int |\psi|^4\right)$

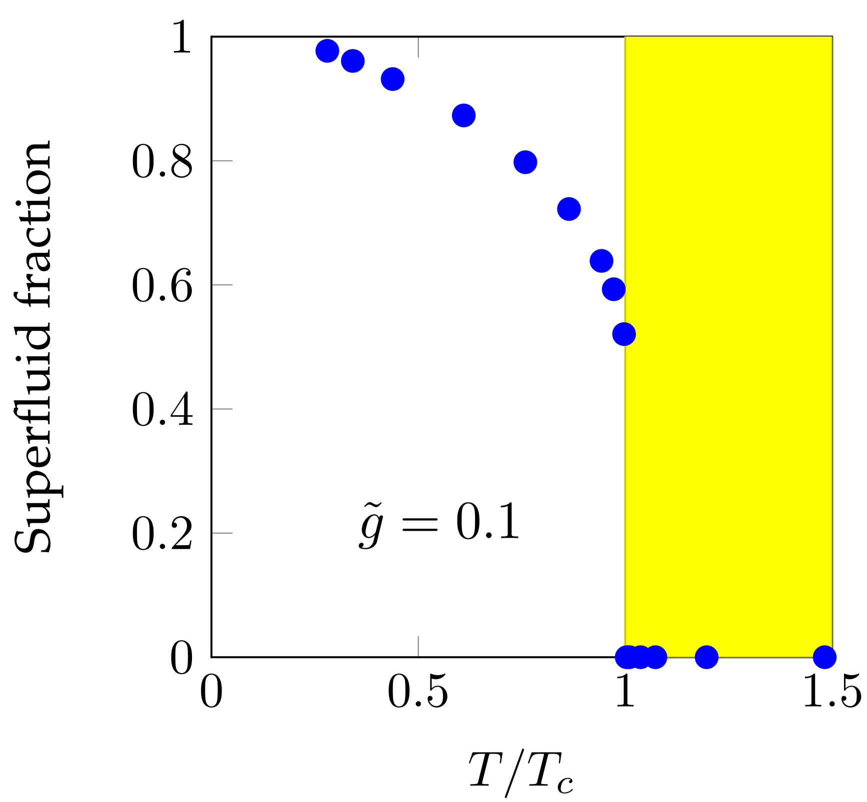
Scale invariance for a weakly interacting 2D Bose gas:
Thermodynamic functions depend only on $\tilde{g}$ and the ratio $\dfrac{\mu}{k_{\mathrm{B}}T}$

BKT transition with dilute Bose gases

Feature 3 : The ``universal jump''

Infinite order transition: All thermodynamic functions (Pressure, density, entropy) are continuous at the transition point but the superfluid density is discontinuous!

Universal jump $\Delta(\rho_s \lambda^2) = 4$ at the transition: Independent of interaction strength



Data from a classical field simulation by Prokof'ev & Svistunov

at $T_c^{(-)}$: $\rho_s \approx \rho_n$ for $\tilde{g} \sim 0.1$

$\tilde{g}$: dimensionless parameter describing the interaction strength in 2D

Experiments on BKT physics with atomic or polariton gases

Existence of a critical point

Rapid change of $G_1(r) = \langle \psi^\dagger(\boldsymbol{r})\psi(0)\rangle$ or the momentum distribution

Boulder, NIST-Gaithersburg, MIT, Chicago, Cambridge, Palaiseau, Paris

Observation of vortices Boulder, Seoul, Amherst, Paris

Superfluid behavior Hamburg, Seoul, Villetaneuse, Paris

Evidence for algebraic decay $G_1(r) \propto 1/r^\alpha$

Measured α's are often larger than the theoretical upper bound (α_{max}=1/4)

NIST-Gaithersburg, Heidelberg, Seoul, Tokyo-Stanford, Paris

Scale invariance and universality Chicago, Paris

Influence of disorder Palaiseau

Outline of this talk

Explore the vicinity of the critical point and the possible observation of the universal jump $\Delta(\rho_s \lambda^2) = 4$

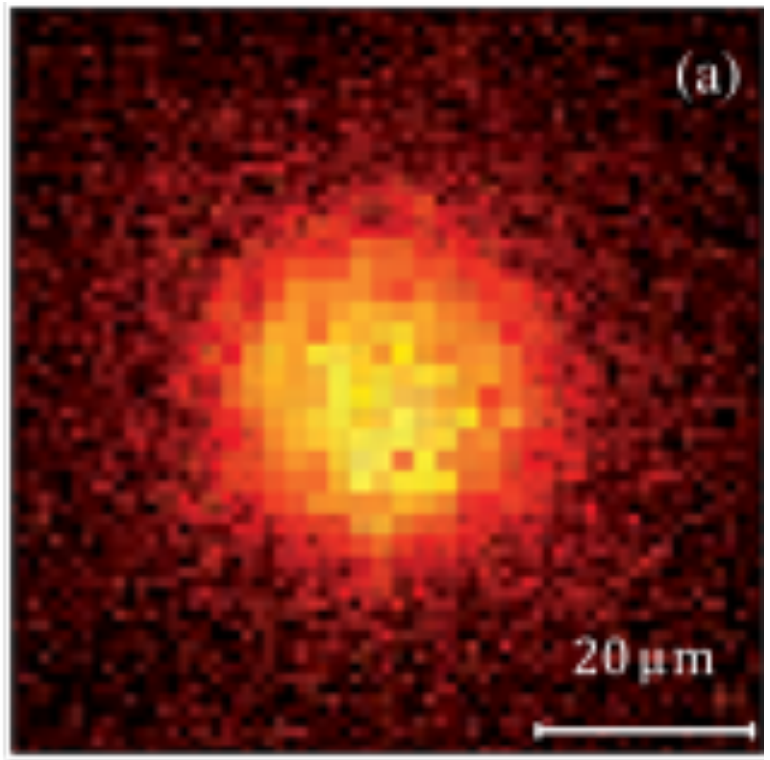
1. Friction-less motion of an impurity

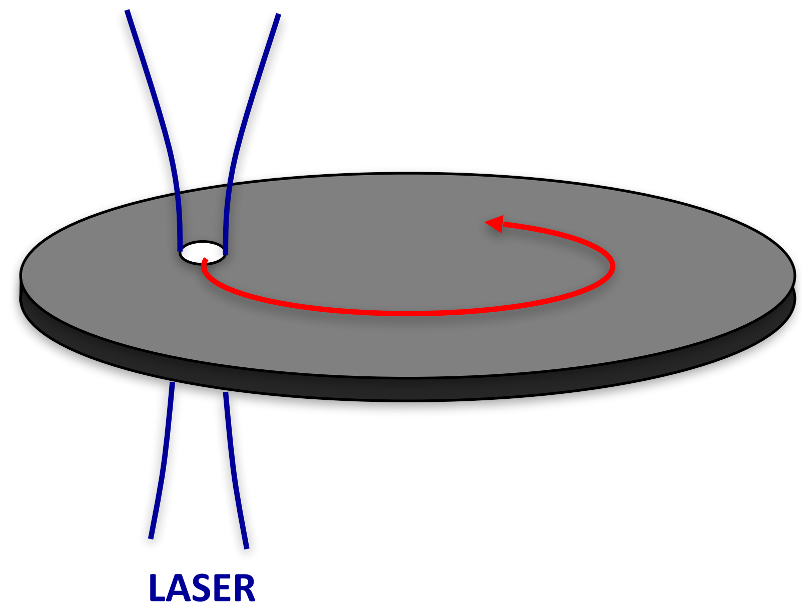
Collaboration with Vijay Pal Singh and Ludwig Mathey (Hamburg)

2. Sound propagation in the fluid

Testing superfluidity with atomic gases

Rb quasi2D gas in a harmonic trap: Central superfluid core, outer normal region



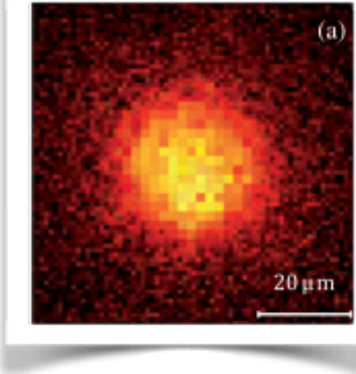


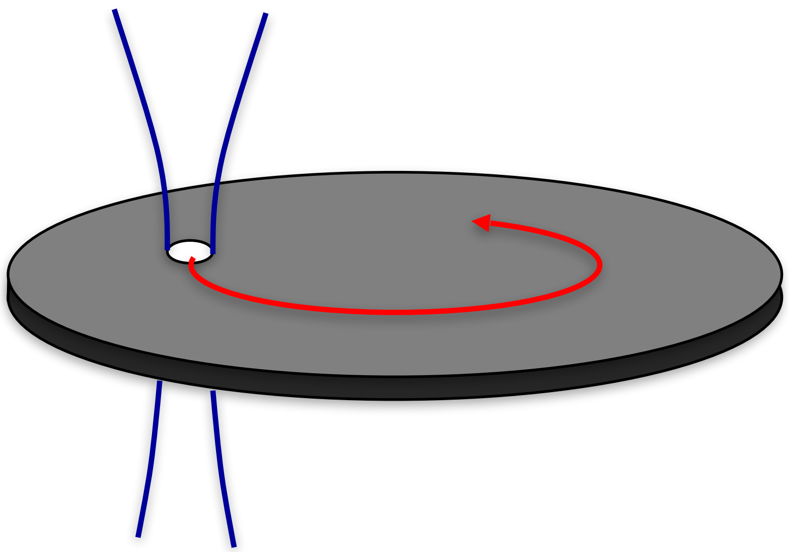
Does a moving impurity “heat” the sample?

Impurity: focused laser beam that repels the atoms

(3D version implemented much earlier at MIT)

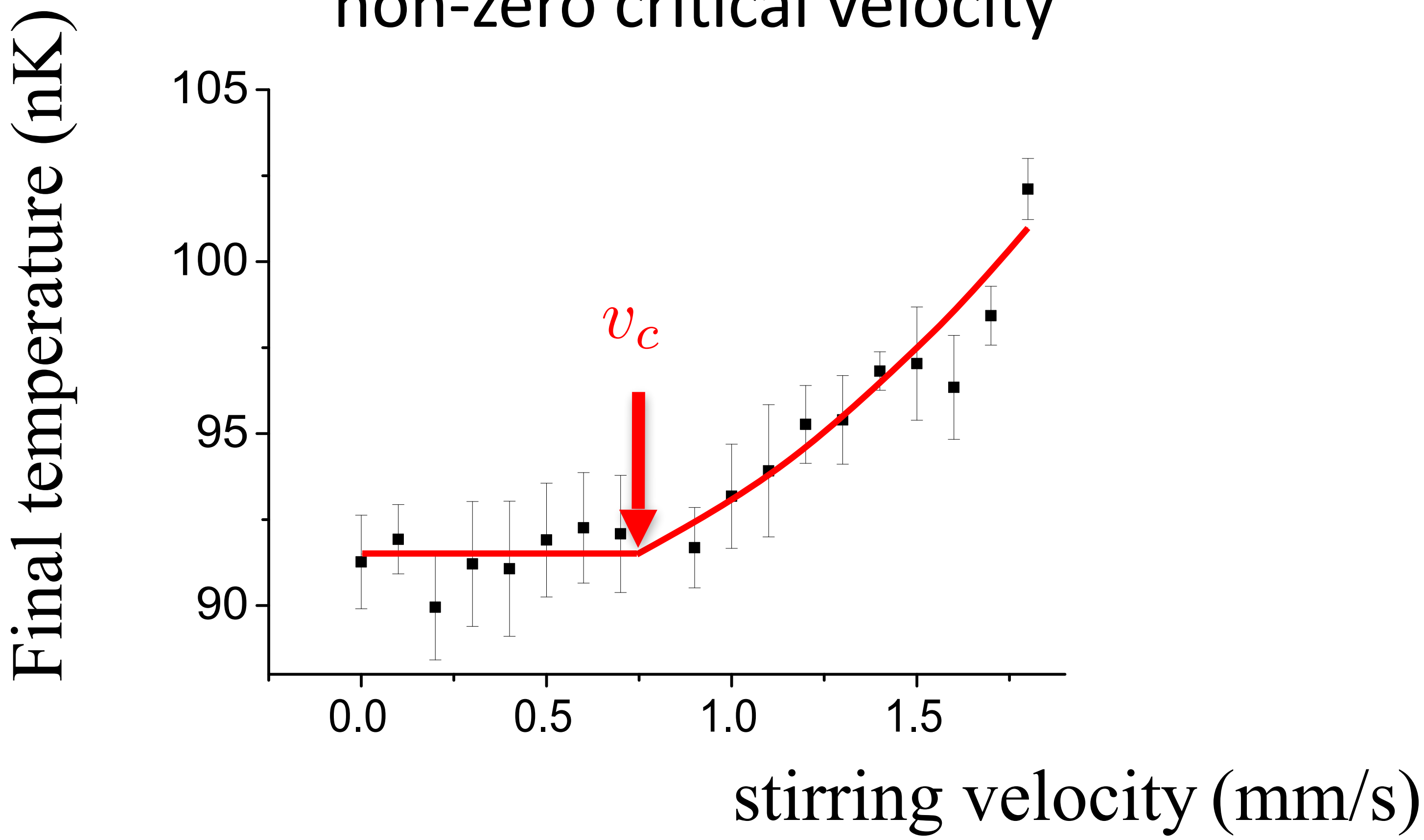
Testing superfluidity with atomic gases





For given μ, T, we stir for 200 ms, wait for 100 ms for thermalization and measure the increase of temperature

Stirring in the superfluid core:
non-zero critical velocity

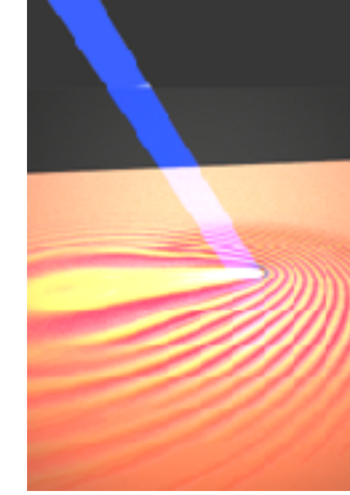


R. Desbuquois, L. Chomaz,
T. Yefsah, J. Leonard,
J. Beugnon, C. Weitenberg,
J. Dalibard

Nature Physics **8,** 645

Related experiments in Seoul
and in Hamburg
Shin and Moritz groups

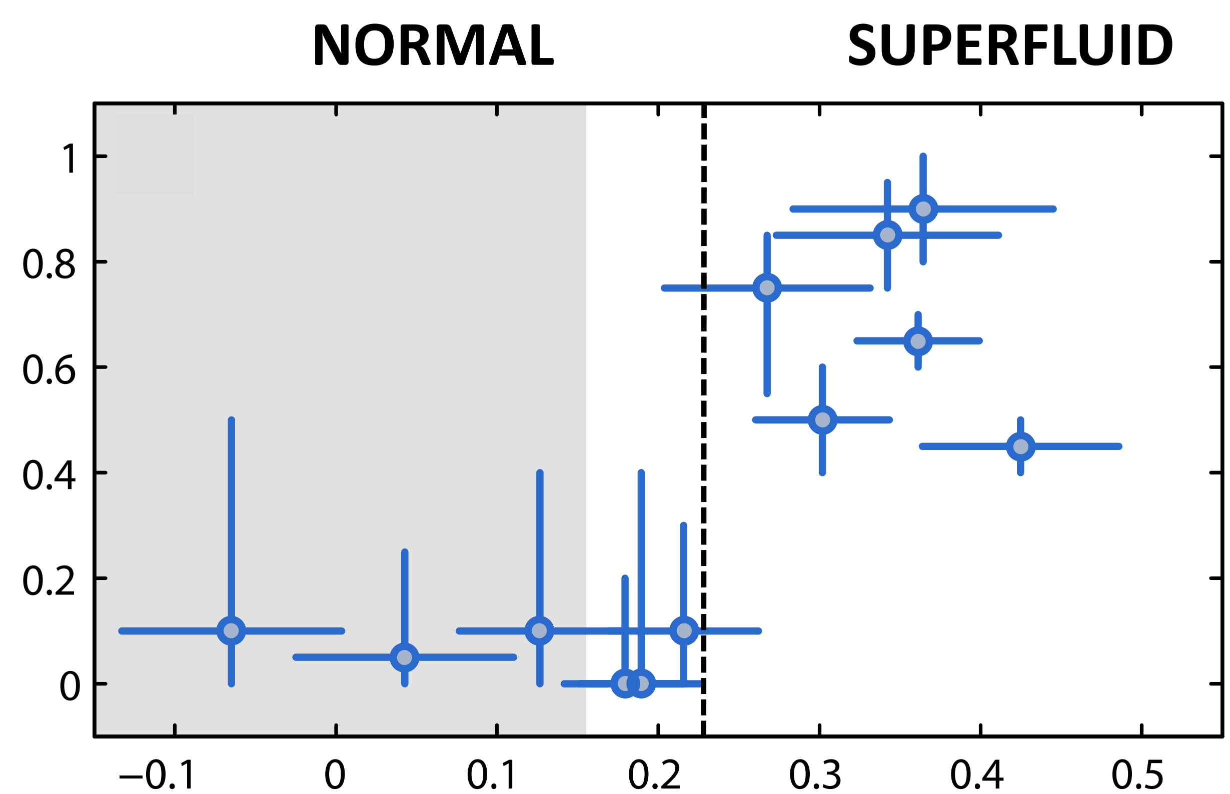
The critical velocity in 2D



Critical velocity measured for various $\mu, \ T$

R. Desbuquois *et al.*
Nature Physics **8,** 645

critical velocity
v_c [mm/s]



$\mu/k_{\mathrm{B}}T$

$v_c \approx 0.3 \text{ to } 0.6 \ c_s$

c_s : sound velocity

How to explain the observed critical velocity in the superfluid regime?

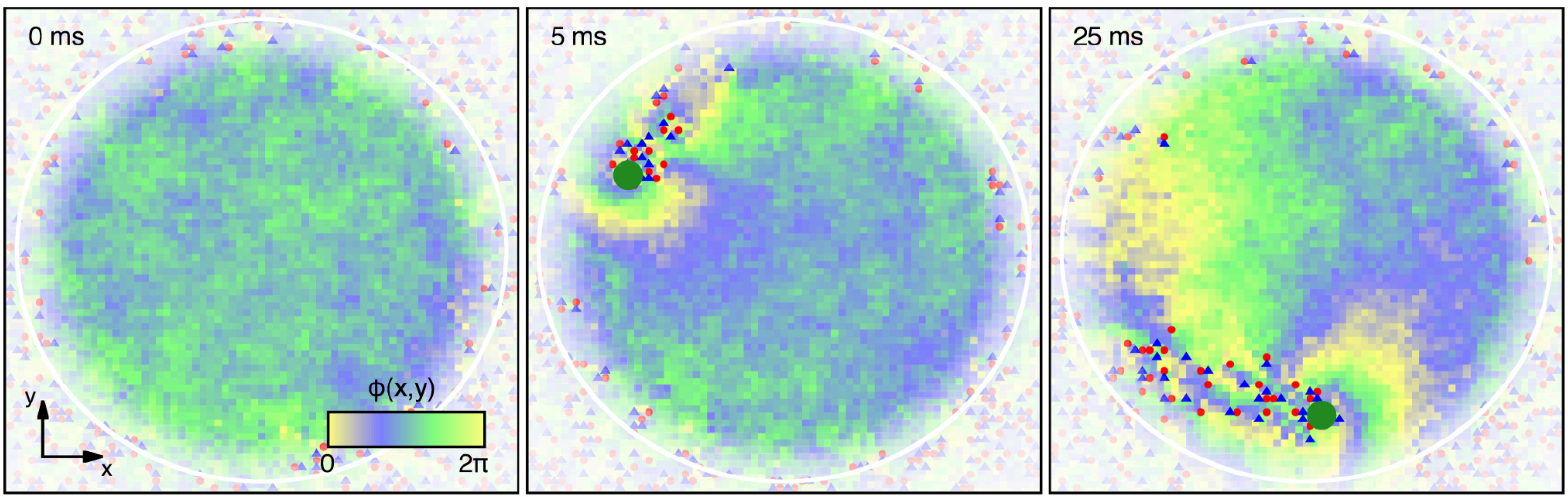
Why is there a small shift in the position of the critical point?

Classical field analysis of the stirring (1)

V. P. Singh, C. Weitenberg, J. Dalibard, L. Mathey, Phys. Rev. A **95**, 043631 (2017)

Creation of pairs of vortices in the wake of the impurity:

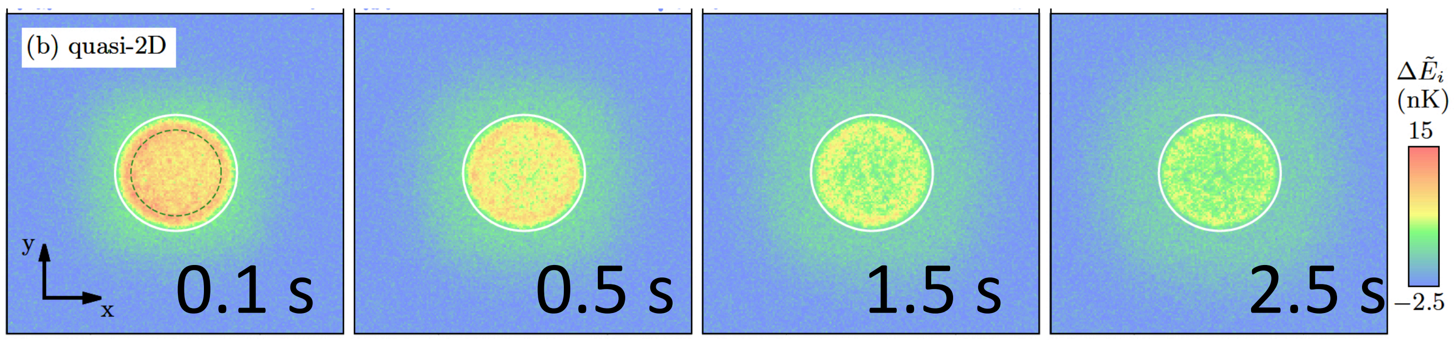
Explain the measured value of v_c (notably below the speed of sound)



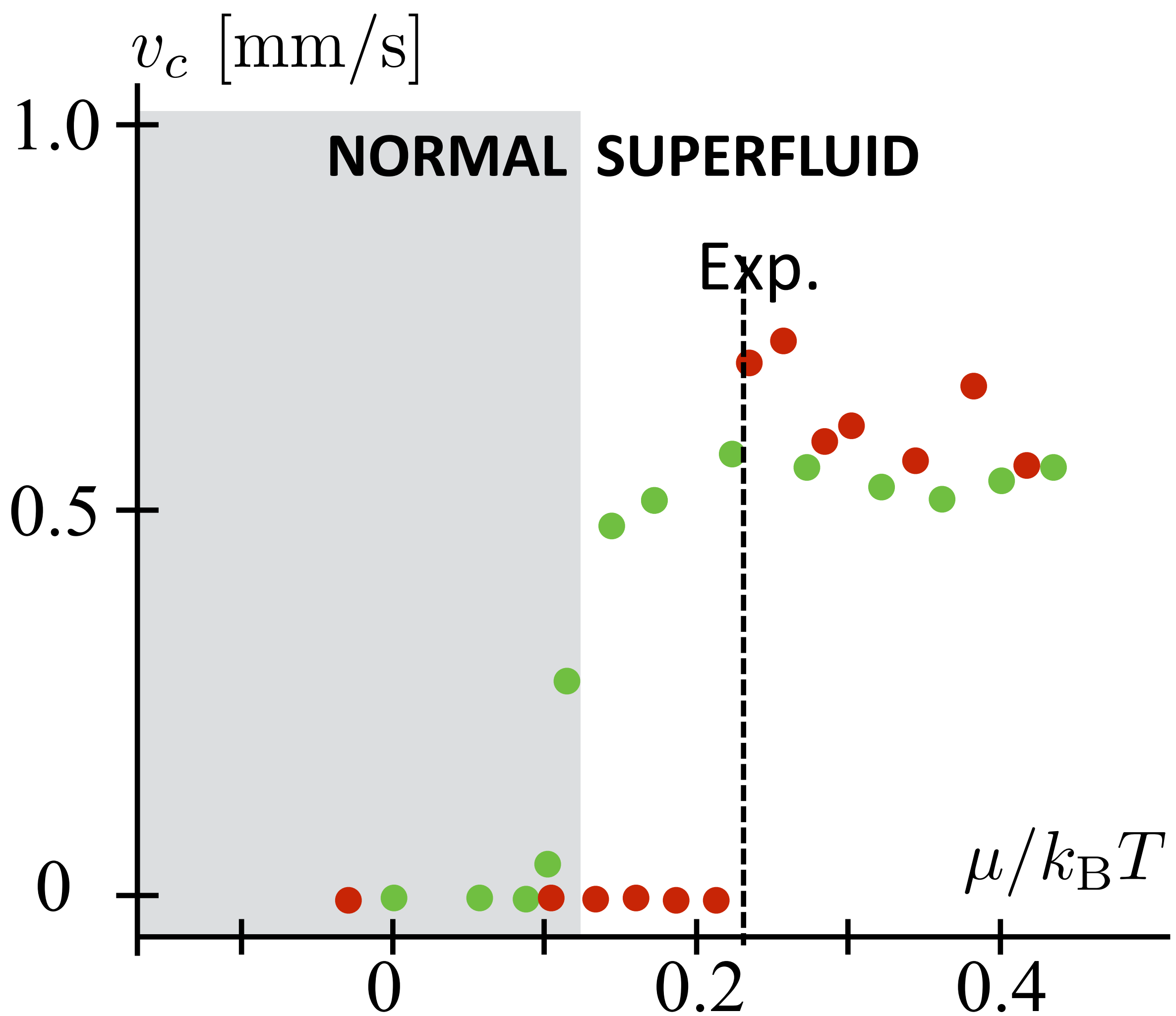
Classical field analysis of the stirring (2)

V. P. Singh, C. Weitenberg, J. Dalibard, L. Mathey Phys. Rev. A **95**, 043631 (2017)

The transfer of energy between the external normal region and the central superfluid region is very slow (at least 2 seconds)



varying the thermalization time



- Theory with full thermalization
- Theory with thermalization of 0.1 s

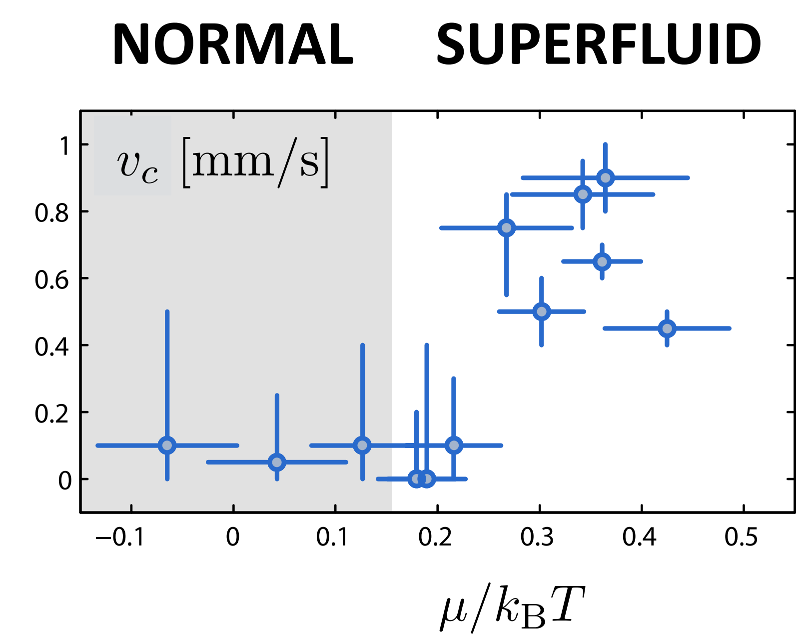
For technical reasons, experimental measurements were taken after a thermalization time of only 0.1 s.

Summary of the first part

1. Friction-less motion of an impurity

The experiment reveals the existence
of the superfluid transition

The critical velocity in the superfluid regime
is well accounted for by a classical field analysis
as well as the position of the transition point



2. (Second) sound propagation in the fluid

Not yet published data: J.-L. Ville, R. Saint-Jalm, M. Aidelsburger,
E. LeCerf, M. Villiers, S. Nascimbene, J. Beugnon, J. Dalibard

Inspired by Tomoki Ozawa and Sandro Stringari,
many discussions with the Trento group and N. Proukakis

Sound in a superfluid

Propagation of a weak perturbation with a wavelength much larger than the mean-free path of elementary excitations

Landau approach based on the two-fluid model

$$\rho = \rho_s + \rho_n$$
$$\boldsymbol{j} = \rho_s \boldsymbol{v}_s + \rho_n \boldsymbol{v}_n$$

Superfluid hydrodynamics leading to two wave equations

$$\frac{\partial^2 \rho}{\partial t^2} = \nabla^2 P \qquad \frac{\partial^2 \tilde{s}}{\partial t^2} = \frac{\rho_s}{\rho_n} \tilde{s}^2 \nabla^2 T$$

P : pressure

$\tilde{s}$: entropy/unit mass

Bi-square equation for the speed of sound: $c^4 - \alpha c^2 + \beta = 0$

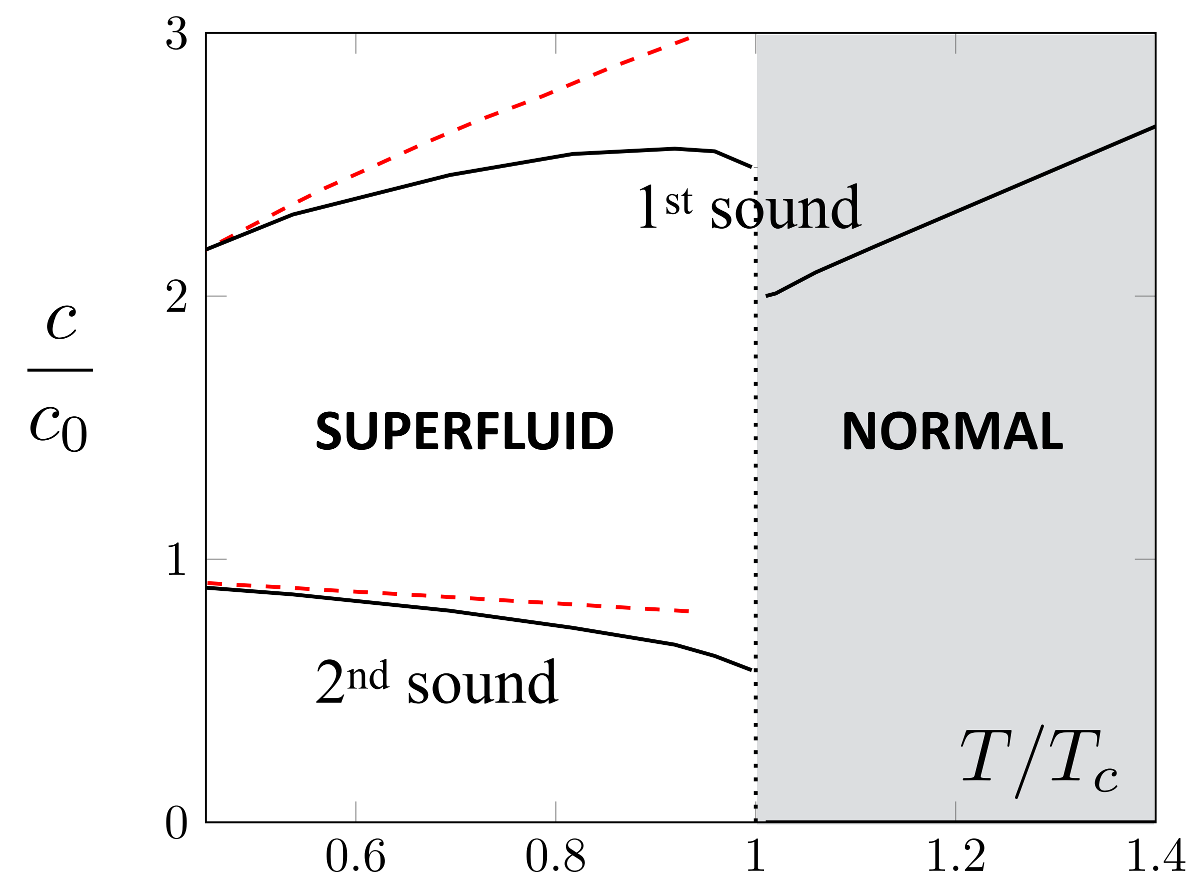
α, β : functions of ρ_s/ρ_n and of thermodynamic quantities

First and second sound in a dilute 2D Bose gas

Ozawa & Stringari, PRL **112** 025302 (2014)

c_0 : Bogoliubov speed

Dashed: prediction from Bogoliubov modes



Superfluid region: 1st and 2nd sound

1st sound: oscillation involving mainly the normal component

2nd sound: superfluid is moving, normal part practically at rest

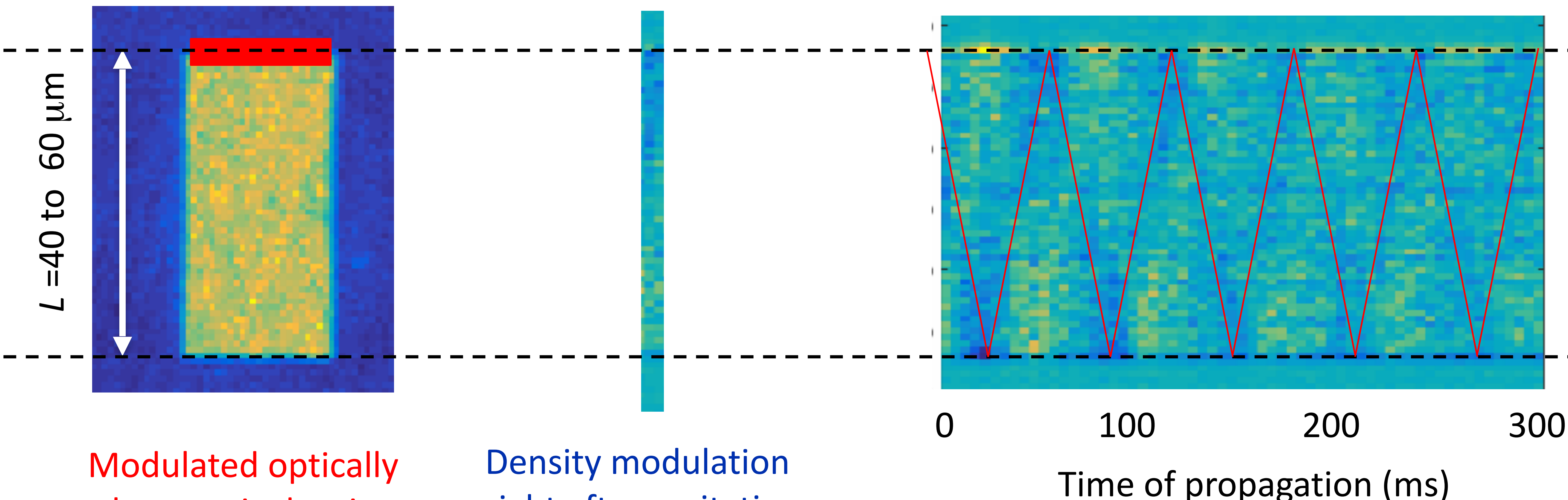
Remark 1: Both velocities jump at T_c reflecting the jump of the superfluid density

Remark 2: Only 2nd sound is excited by a density perturbation in the SF region

Our experimental scheme

Rb gas strongly confined along z ($\nu_z = 4.6\,\mathrm{kHz}$)

Rectangle box potential in the xy plane (image of a mask)



Modulated optically the atomic density for a short time (20ms) on the upper side

Density modulation right after excitation

Multiple bounces of the wave-packet

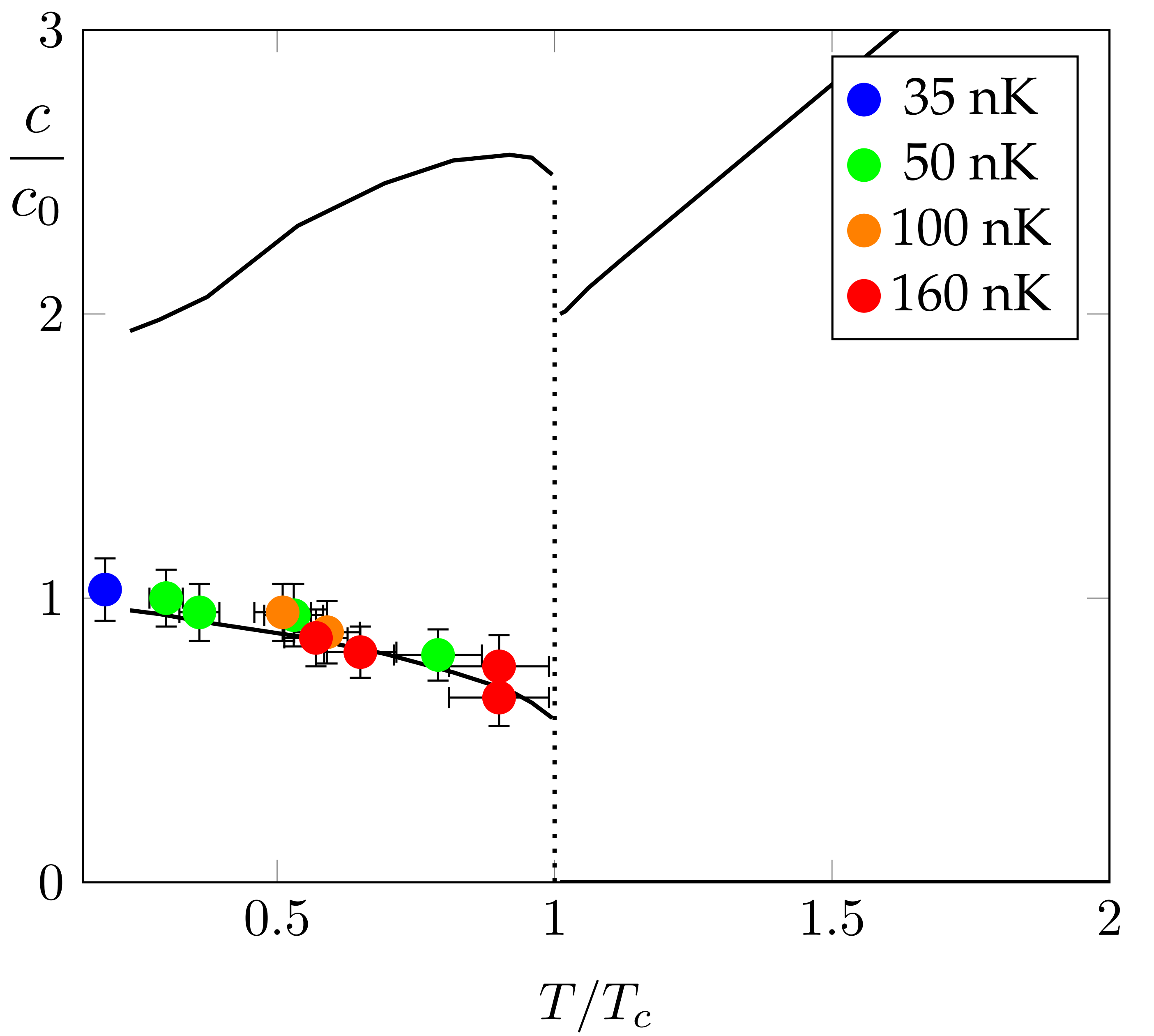
Precise determination of the sound velocity via the center-of-mass oscillation

Lowest mode, wavelength $\lambda = 2L$

Similar experiment in a 3D Fermi gas at MIT: M. Zwierlein's talk

Sound velocity measurements

c_0 : Expected Bogoliubov speed for the measured density

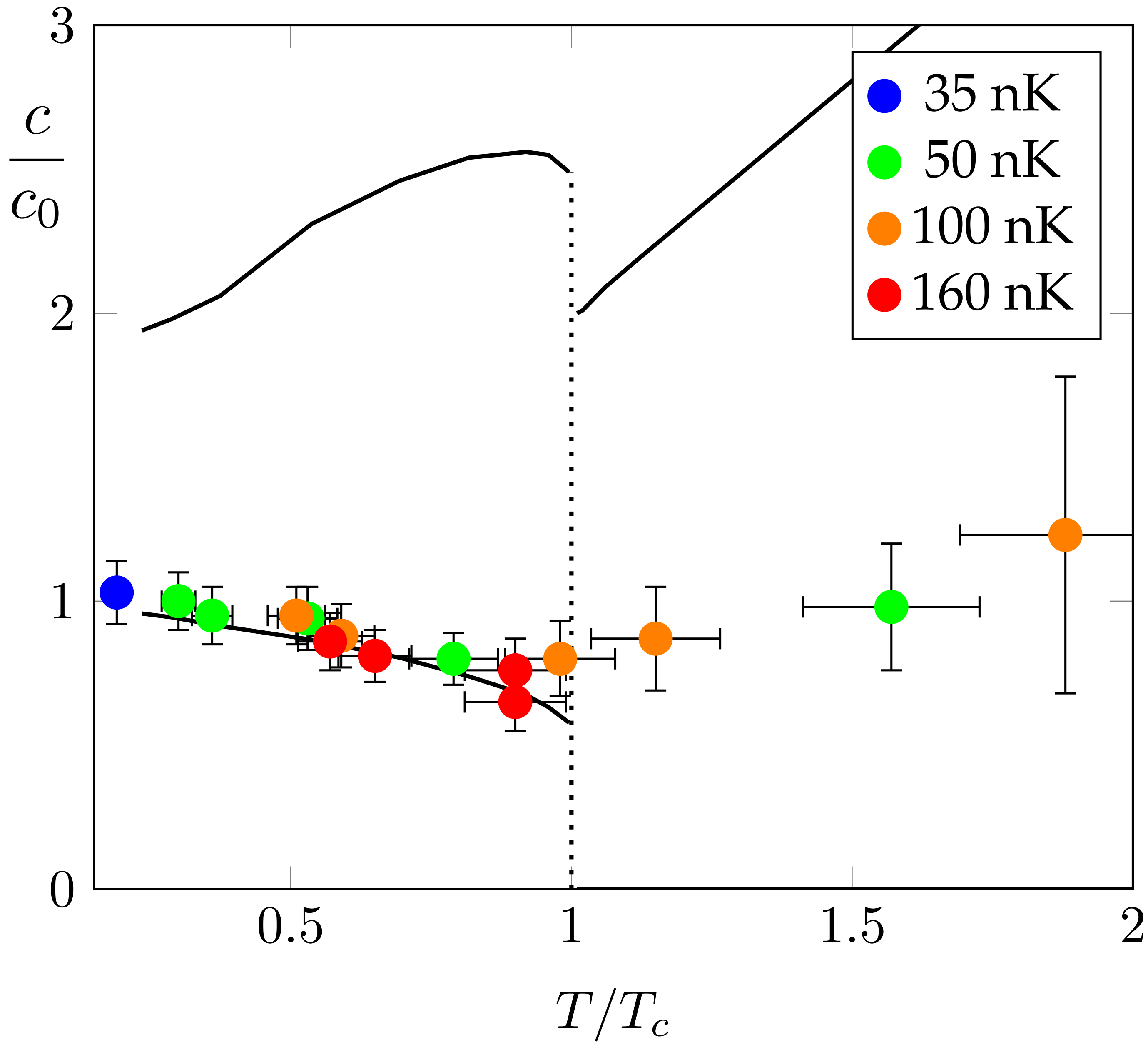


No evidence for 1st sound (as expected)

Observation of the second sound in a 2D superfluid!

- Good agreement with theory
- By contrast to 3D, the 2nd sound velocity does not tend to 0 at T_c

Sound velocity measurements (2)



Above Tc, we do not recover the prediction for the first sound

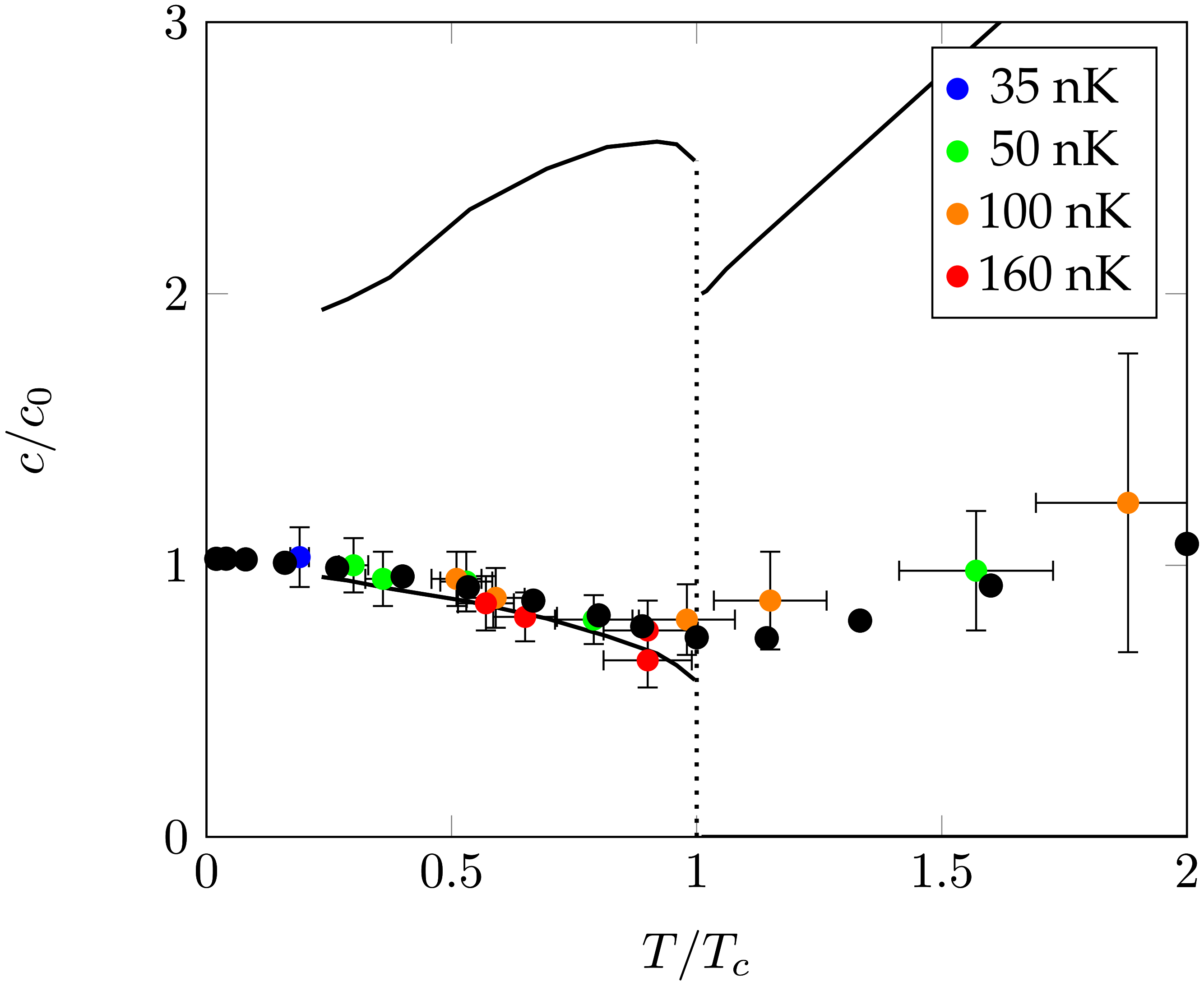
In the normal region, the mean-free path is comparable to the size of the box

→ ***The thermal gas is not in the hydrodynamic regime***

Also the sound wave is strongly damped in the thermal regime:

Damping over a propagation length comparable to the wavelength of the phonon

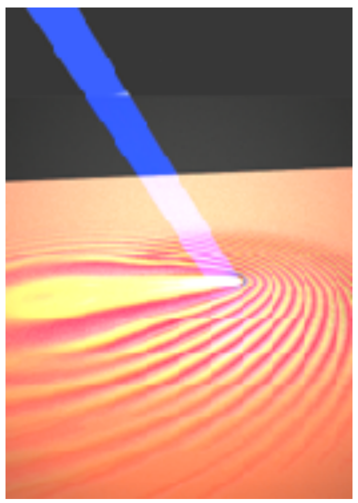
Classical field simulations



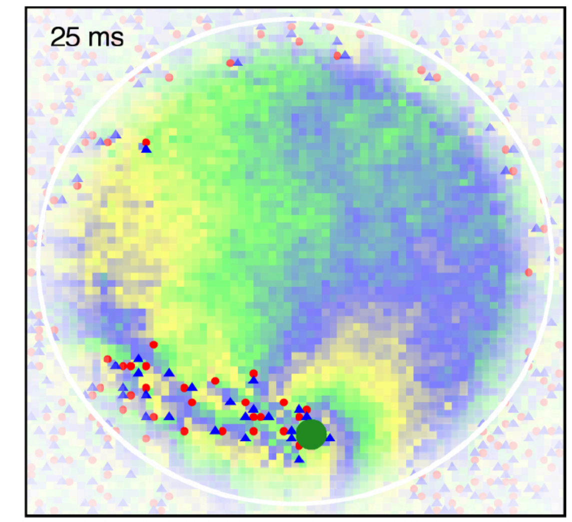
Again an excellent agreement with experimental data in this parameter regime

Summary

Frictionless motion of an « impurity »



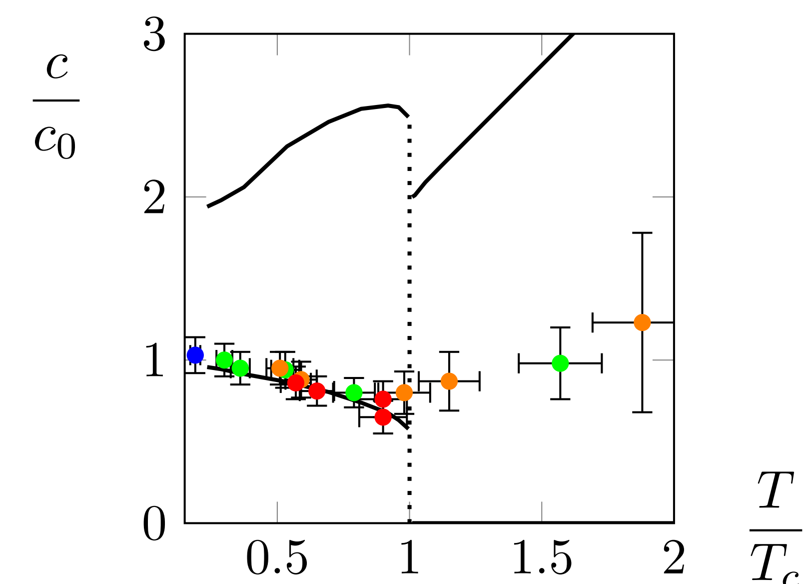
Reveals the superfluid transition at the position and the critical velocity predicted by BKT theory, once subtleties in thermalization processes are taken into account



Long wavelength excitations and sound propagation

Existence of a 2nd sound that connects to Bogoliubov sound at T=0 and survive up to the critical point

In the thermal regime, the small collision rate makes it difficult to reach the hydrodynamic regime:



mean free path $\cancel{\ll}$ largest possible phononwavelength $\approx$ box size

The LKB-College de France team

From left to right:

Sylvain Nascimbène
Jean-Loup Ville
Monika Aidelsburger
Raphaël Saint-Jalm
Jérôme Beugnon
Jean Dalibard

Interns:
- Edouard LeCerf
- Marius Villiers