Universitas Carolina

Charles University in Prague

Recent Results on Quantum Turbulence in 4He Obtained Using Visualization, and Oscillating Objects in Prague

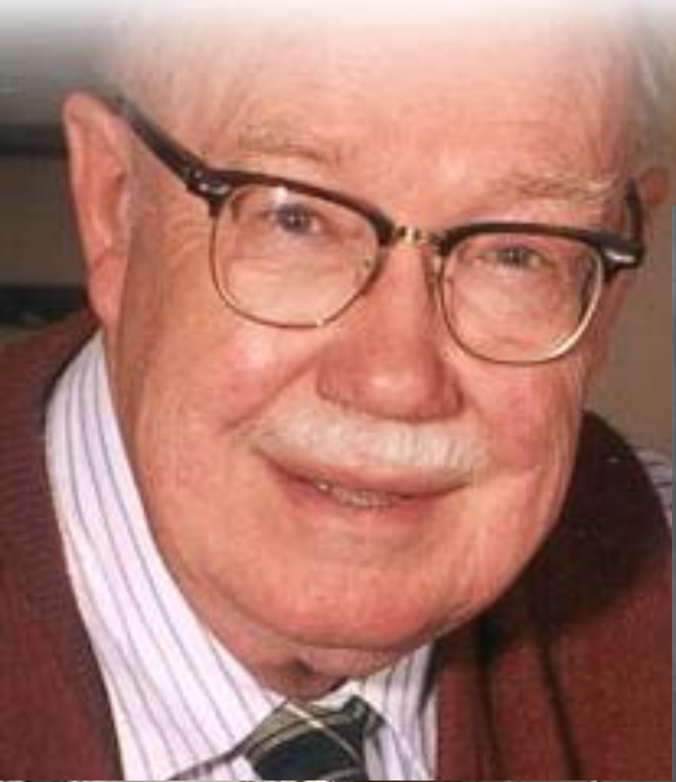
L. Skrbek, Faculty of Mathematics and Physics, Charles University in Prague

Prague group:
M. La Mantia, M. Jackson, D. Duda, E. Varga S. Babuin, M. Rotter, LS, D. Schmoranzer

Saclay, September 14-18, 2015

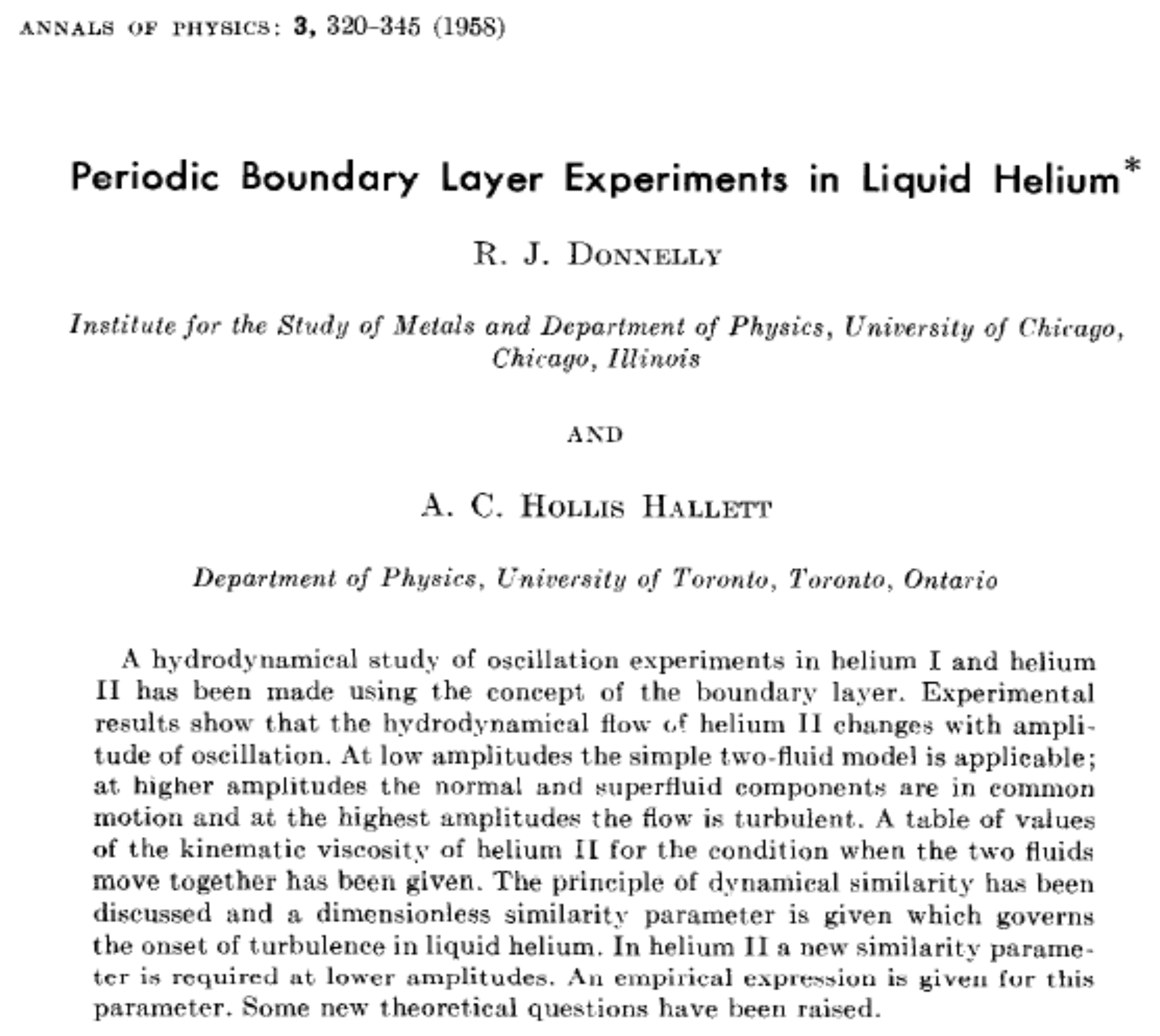
Russell J. Donnelly , Professor of Physics

University of Oregon



* April 16, 1930
† June 13, 2015

1958 - Periodic Boundary Layer Experiments in Liquid Helium



ANNALS OF PHYSICS: **3**, 320–345 (1958)

Periodic Boundary Layer Experiments in Liquid Helium*

R. J. DONNELLY

Institute for the Study of Metals and Department of Physics, University of Chicago, Chicago, Illinois

AND

A. C. HOLLIS HALLETT

Department of Physics, University of Toronto, Toronto, Ontario

A hydrodynamical study of oscillation experiments in helium I and helium II has been made using the concept of the boundary layer. Experimental results show that the hydrodynamical flow of helium II changes with amplitude of oscillation. At low amplitudes the simple two-fluid model is applicable; at higher amplitudes the normal and superfluid components are in common motion and at the highest amplitudes the flow is turbulent. A table of values of the kinematic viscosity of helium II for the condition when the two fluids move together has been given. The principle of dynamical similarity has been discussed and a dimensionless similarity parameter is given which governs the onset of turbulence in liquid helium. In helium II a new similarity parameter is required at lower amplitudes. An empirical expression is given for this parameter. Some new theoretical questions have been raised.

2015 – Repeat using modern technology, such as imaging and data processing and interpret using current knowledge

Recent Praque results on visualization of cryogenic helium flows

Marco La Mantia, Daniel Duda, Patrick Švančara, Miloš Rotter, LS
Numerics: **Emil Varga**
Coworkers: Carlo Barenghi, Yuri Sergeev

Investigated flows:

Thermal counterflow
Counterflow past a cylinder
Flows of normal and superfluid 4He due to oscillating objects

- M. La Mantia, T. V. Chagovets, M. Rotter and LS *Testing the performance of a cryogenic visualization system on thermal counterflow by using hydrogen and deuterium solid tracers.* **Rev. Sci. Instrum. 83, 055109 (2012)**

- M. La Mantia, D. Duda, M. Rotter and LS, *Lagrangian accelerations of particles in superfluid turbulence.* **JFM 717, R9 (2013)**

- M. La Mantia and L. Skrbek, *Quantum, or classical turbulence?* **EPL 105, 46002 (2014)**

- D. Duda, M. La Mantia, M. Rotter and LS, *On the visualization of thermal counterflow of He II past a circular cylinder.* **JLTP 175, 331-338 (2014)**

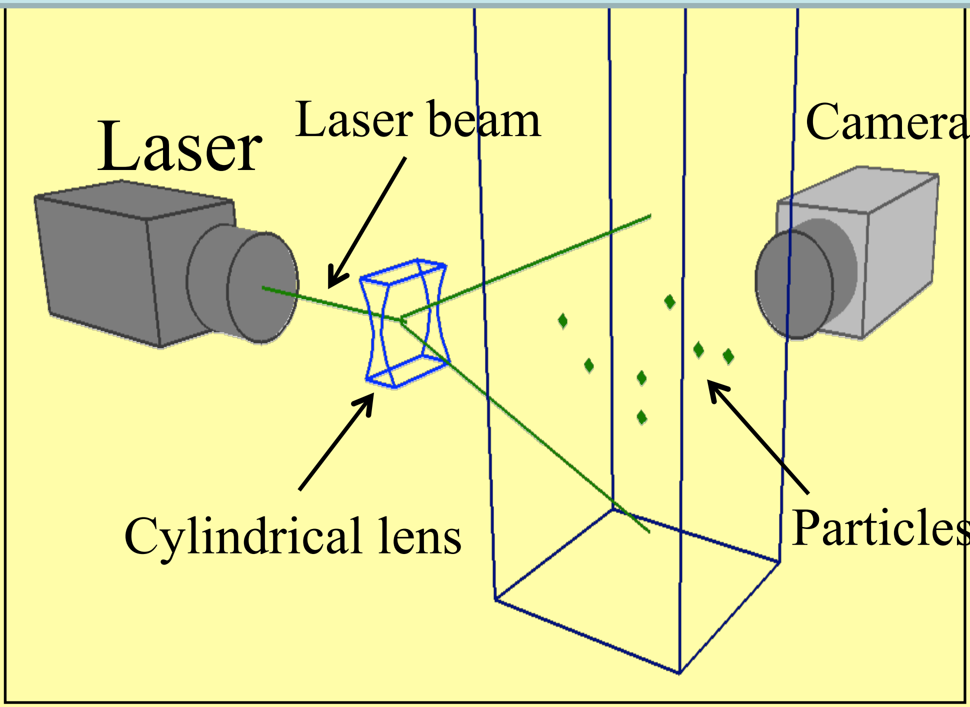
- W. Guo, M. La Mantia, D. P. Lathrop and S. W. Van Sciver, *Visualization of two-fluid flows of superfluid helium-4.* **PNAS 111, 4653-4658 (2014)**

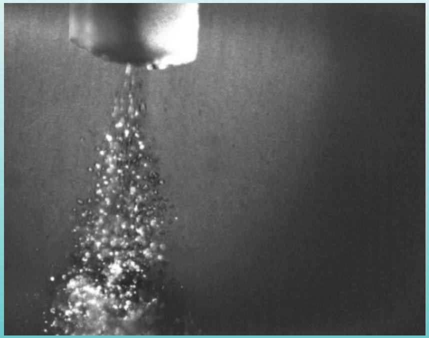
- M. La Mantia and LS, *Quantum turbulence visualized by particle dynamics.* **Phys. Rev. B 90, 014519 (2014)**

- D. Duda, P. Švančara, M. La Mantia, M. Rotter and LS, *Visualization of viscous and quantum flows of liquid 4He due to an oscillating cylinder of rectangular cross section.* **Phys. Rev. B, in print**

E. Varga, C. F. Barenghi, Y. A. Sergeev, LS *Backreaction of Tracer Particles on VortexTangle in Helium II Counterflow* **Submitted to JLTP –Proc. of QFS 2015**

Prague Visualization Laboratory





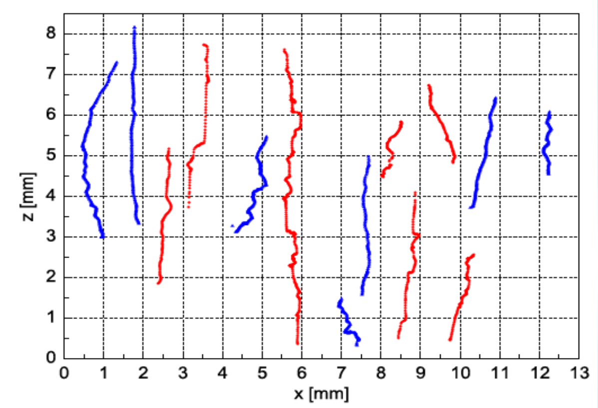
Micron-sized hydrogen/deuterium tracers

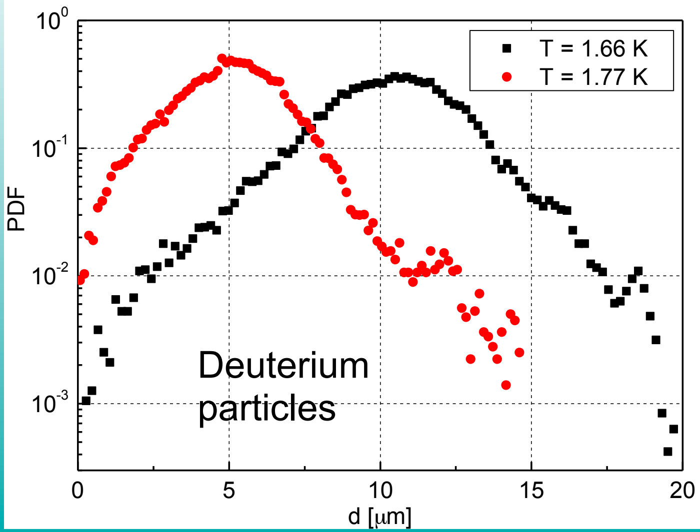
- Custom-built low-loss cryostat with five sets of windows that minimise heat input into the helium bath, enabling horizontal as well as vertical optical access
- Continuous wave solid state laser, fast digital camera and relevant hardware and software to implement the PIV and PTV techniques for cryogenic flows analysis

Experimental conditions

Thermal counterflow of superfluid ^{4}He
in a square channel
of 25 mm sides and 100 mm long
experimentally studied by visualization

Temperature: $1.3\ \mathrm{K} < T < 2.1\ \mathrm{K}$
Applied heat flux: $50\ \mathrm{W/m^2} < q < 500\ \mathrm{W/m^2}$
Counterflow velocity v_{ns} up to 10 mm/s



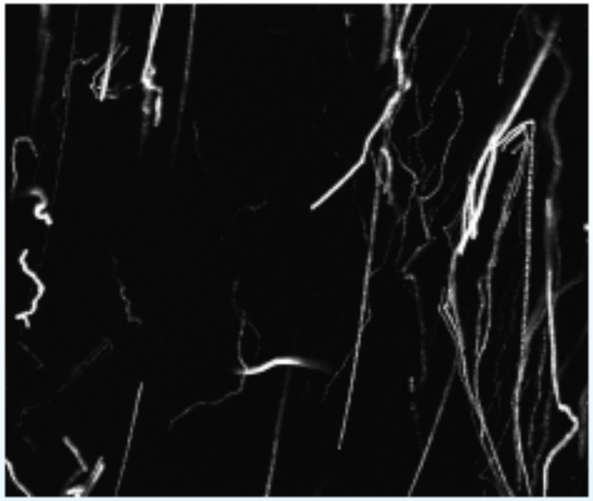


The particles' radii are calculated by assuming that the particles are spherical and that the buoyancy force is balanced by the Stokes drag,

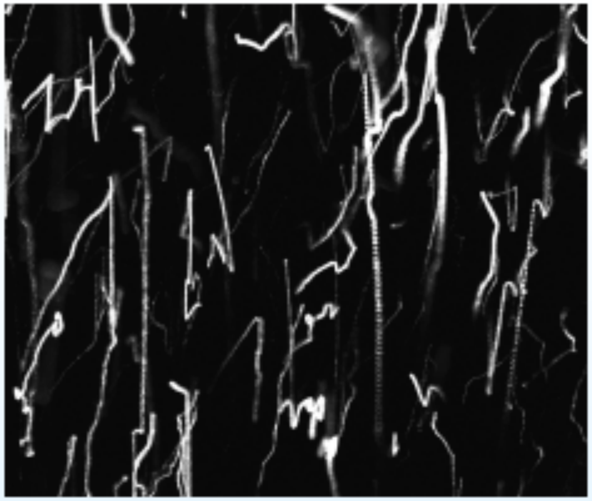
$$R_p = \sqrt{\frac{9\ \mu\ v_1}{2\ g\ (\rho - \rho_p)}}$$

Results

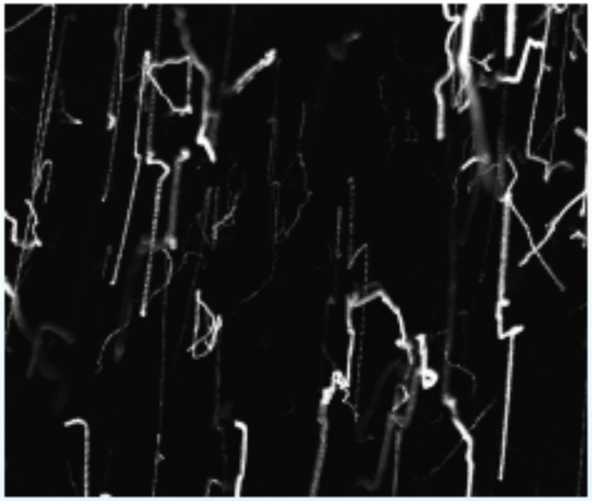
$T = 1.95$ K



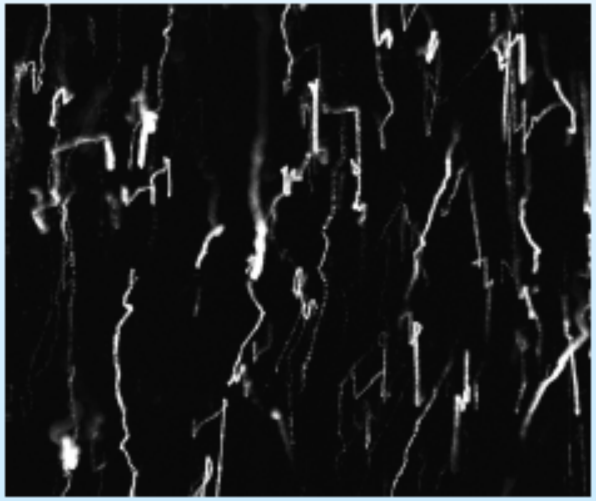
$q = 97$ W/m^2 ; $v_{ns} = 0.80$ mm/s



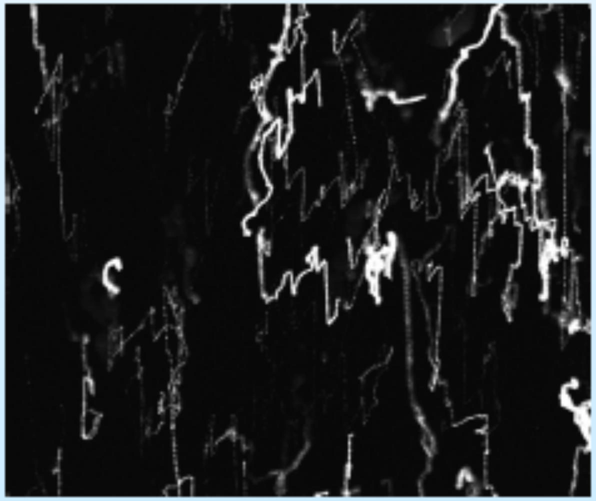
$q = 121$ W/m^2 ; $v_{ns} = 1.00$ mm/s



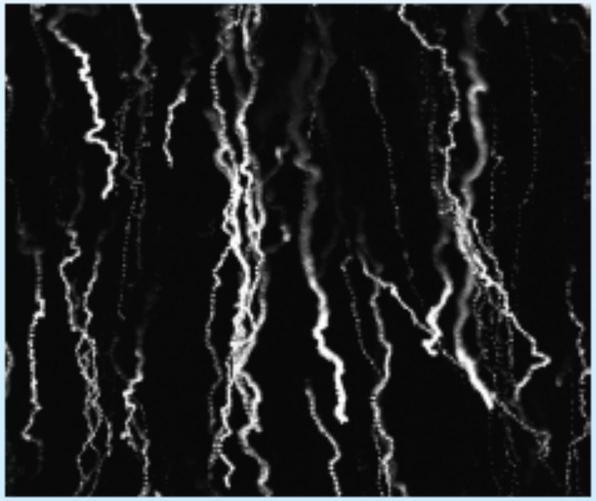
$q = 146$ W/m^2 ; $v_{ns} = 1.21$ mm/s



$q = 193$ W/m^2 ; $v_{ns} = 1.60$ mm/s



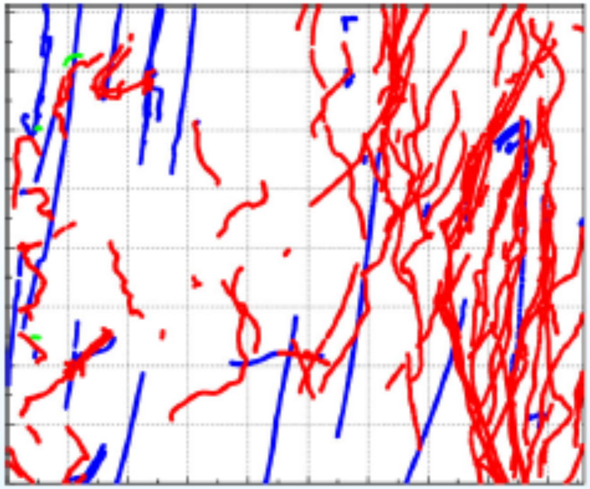
$q = 242$ W/m^2 ; $v_{ns} = 2.01$ mm/s



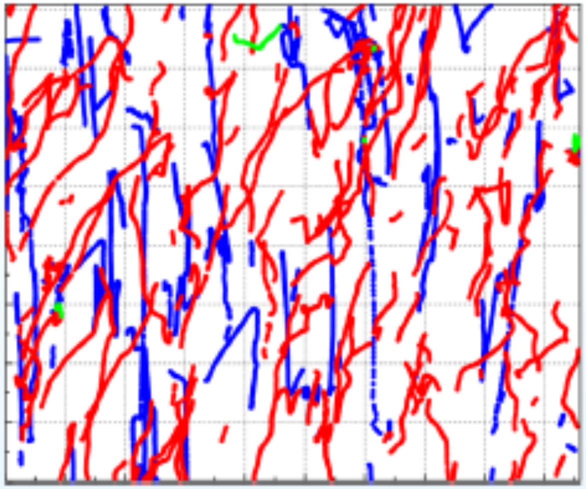
$q = 484$ W/m^2 ; $v_{ns} = 4.01$ mm/s

Results

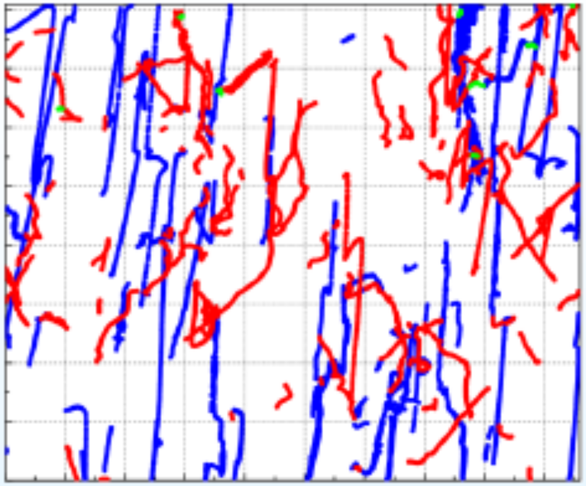
$T = 1.95$ K



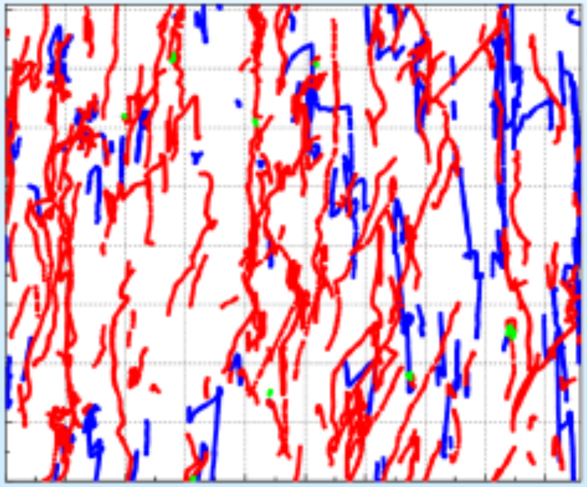
$q = 97$ W/m^2 ; $v_{ns} = 0.80$ mm/s



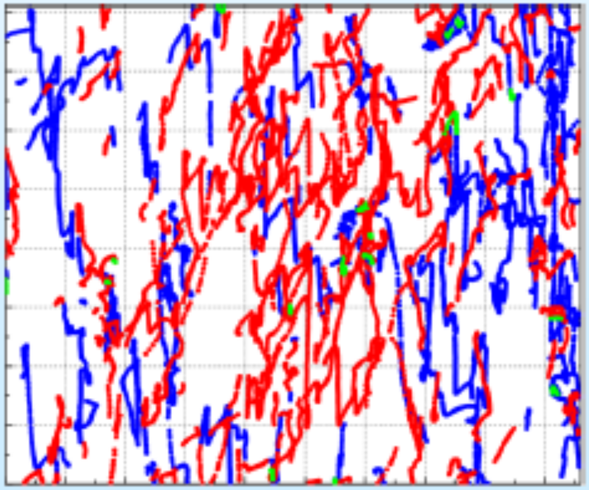
$q = 121$ W/m^2 ; $v_{ns} = 1.00$ mm/s



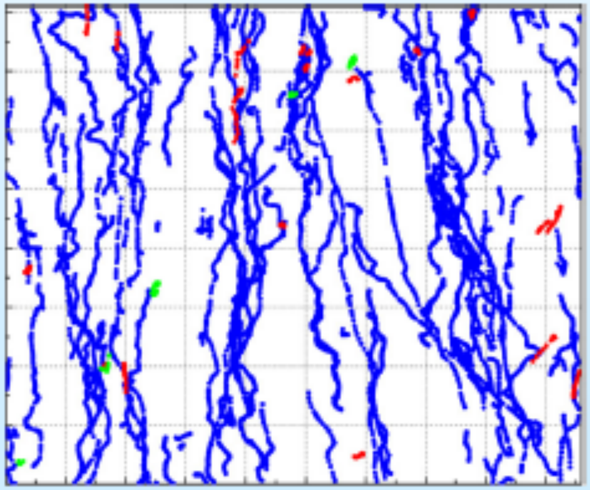
$q = 146$ W/m^2 ; $v_{ns} = 1.21$ mm/s



$q = 193$ W/m^2 ; $v_{ns} = 1.60$ mm/s

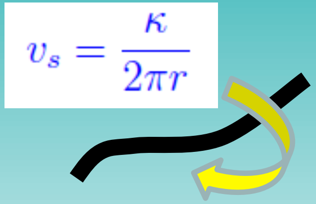


$q = 242$ W/m^2 ; $v_{ns} = 2.01$ mm/s

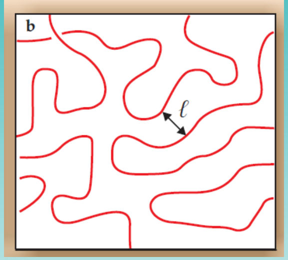


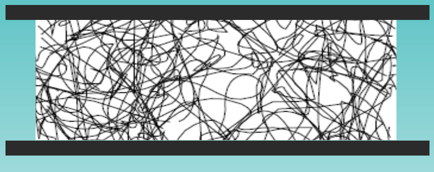
$q = 484$ W/m^2 ; $v_{ns} = 4.01$ mm/s

Characteristic length scales in 4He counterflow turbulence



$v_s = \frac{\kappa}{2\pi r}$





$\xi \approx 10^{-8}\ cm$

Vortex core size

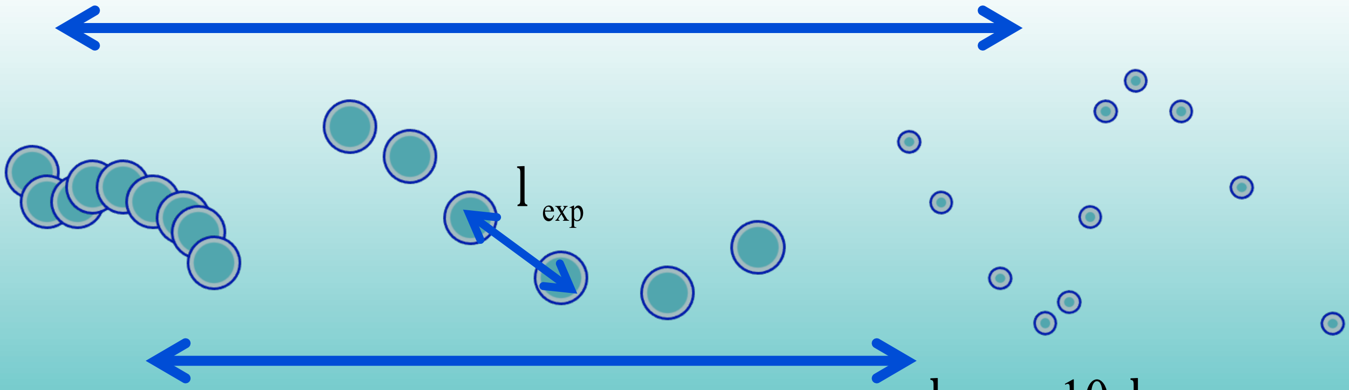
$l = 1/\sqrt{L} \approx 100\ \mu m = 10^{-2}\ cm$

Mean intervortex distance

$D \approx 1\ cm$

Outer scale

Scales experimentally accessible by particle tracking



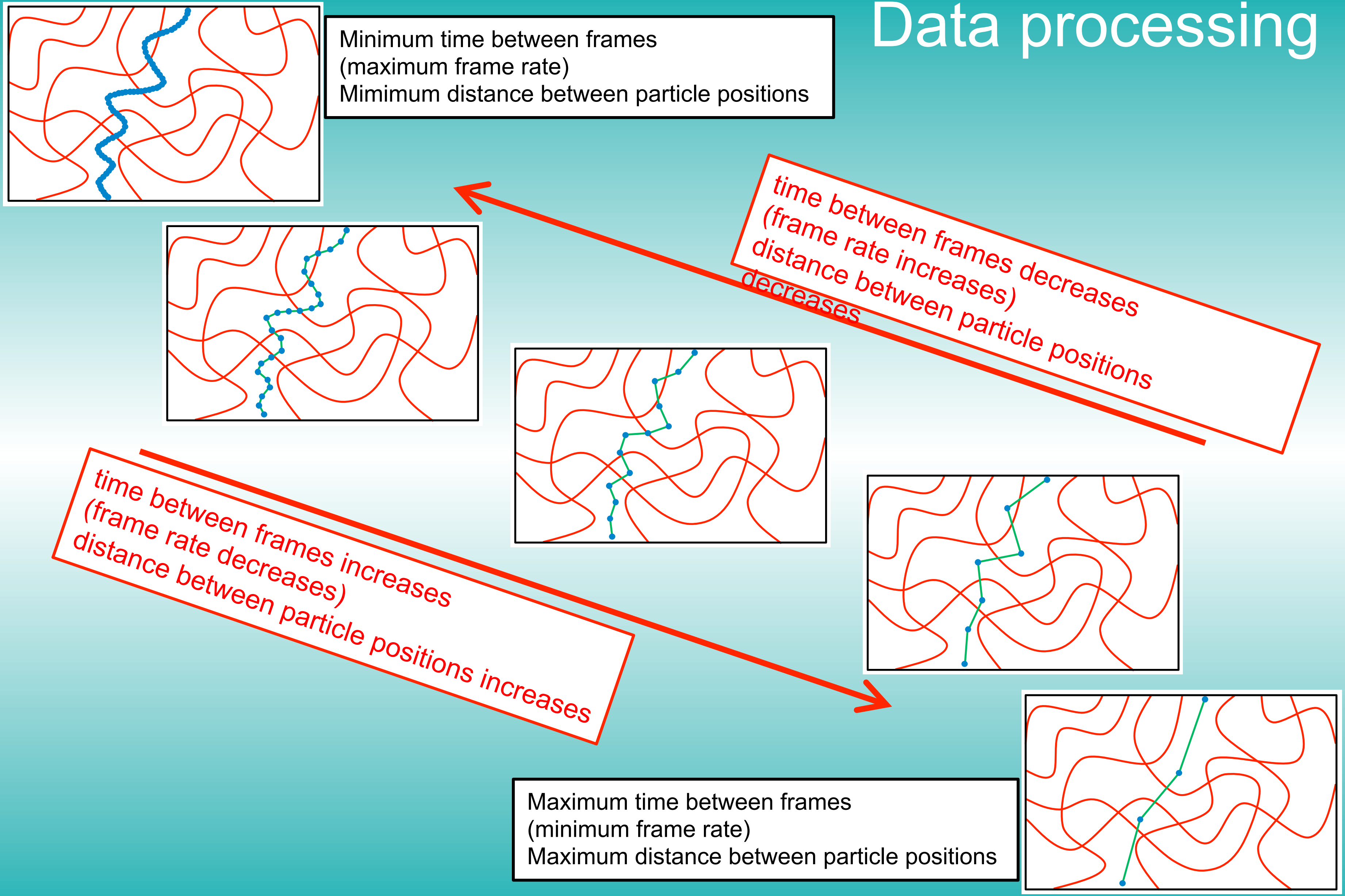
$l_{exp} \approx l/10$

$l_{exp} \approx 10\ l$

Vinen (ultraquantum) QT → crossover → Kolmogorov (quasiclassical) QT

???

Data processing



Minimum time between frames
(maximum frame rate)
Mimimum distance between particle positions

time between frames decreases
(frame rate increases)
distance between particle positions
decreases

time between frames increases
(frame rate decreases)
distance between particle positions increases

Maximum time between frames
(minimum frame rate)
Maximum distance between particle positions

Quantum signature: velocity and acceleration PDFs

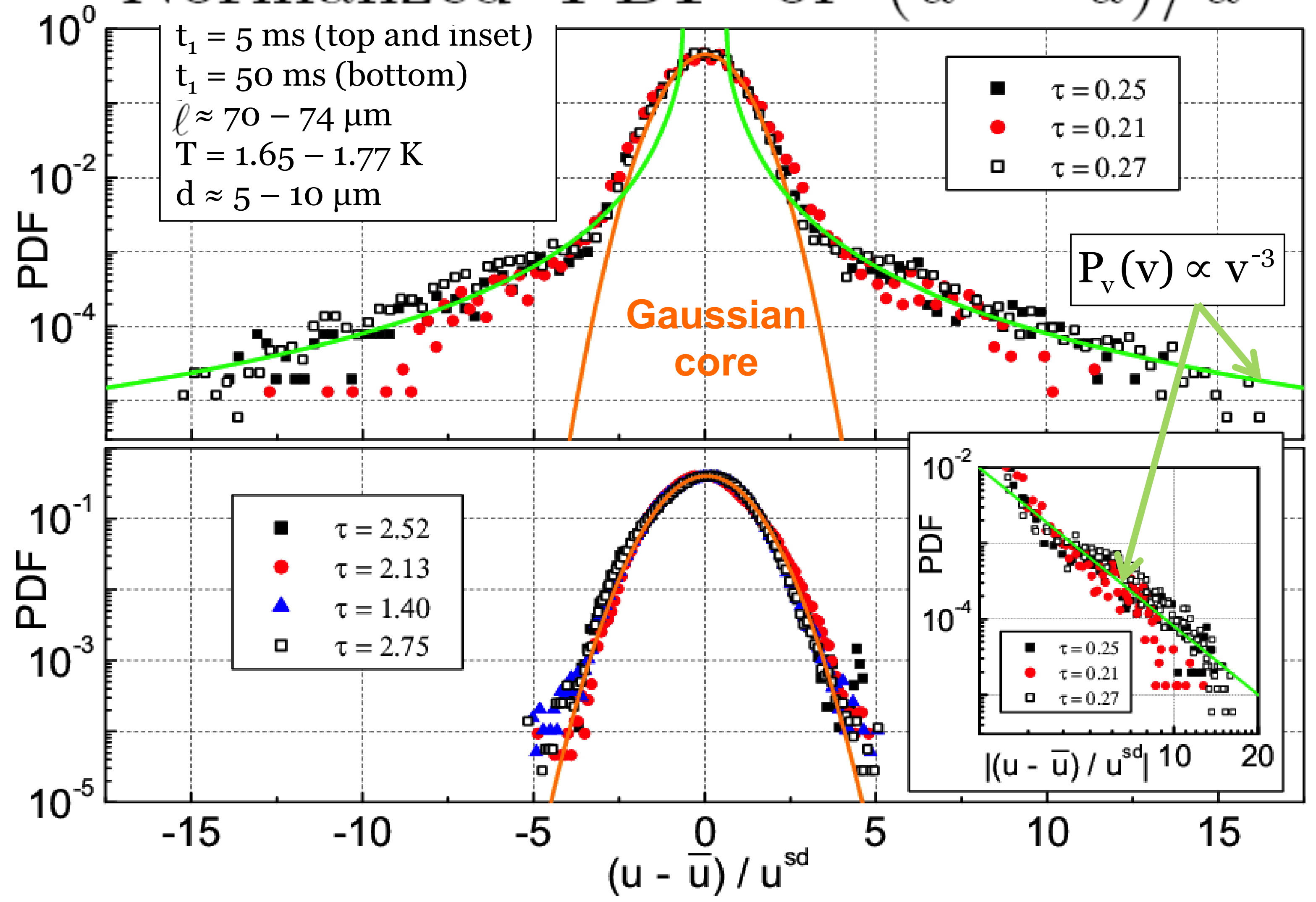
The probability of observing a velocity *V* in the proximity of a quantized vortex can be written as

$$P(V) \propto \int \delta(V - v_s)\, rdr = \int \delta\left(V - \frac{\kappa}{2\pi r}\right) rdr \propto V^{-3}$$

Similarly, the probability of observing an acceleration A in the proximity of a quantized vortex is obtained as

$$P(A) \propto \int \delta(A - a_s)\, rdr = \int \delta\left(A - \frac{v_s^2}{r}\right) rdr \propto A^{-5/3}$$

Normalized PDF of $(u - \overline{u})/u^{sd}$



t_1 = 5 ms (top and inset)
t_1 = 50 ms (bottom)
$\ell \approx 70 - 74$ µm
T = 1.65 – 1.77 K
d ≈ 5 – 10 µm

Gaussian core

$P_v(v) \propto v^{-3}$

Quantum, or classical turbulence?

EPL, **105** (2014) 46002
doi: 10.1209/0295-5075/105/46002

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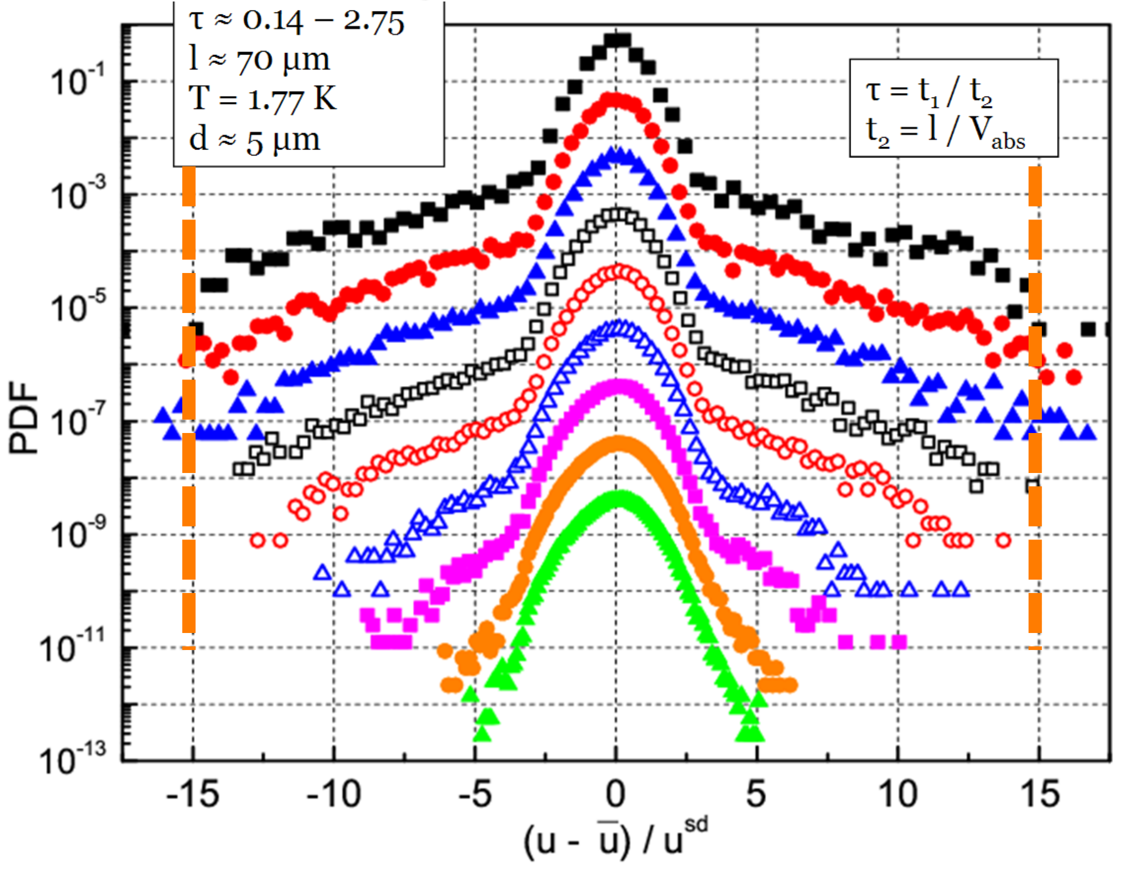
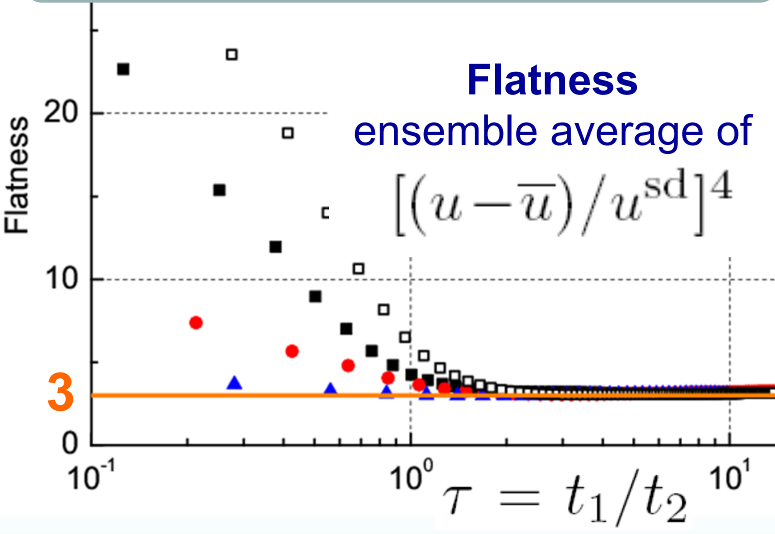
Crossover from Quantum to Classical Behavior



Quantitative confirmation



Flatness
ensemble average of
$[(u-\overline{u})/u^{\mathrm{sd}}]^4$

$\tau = t_1/t_2$

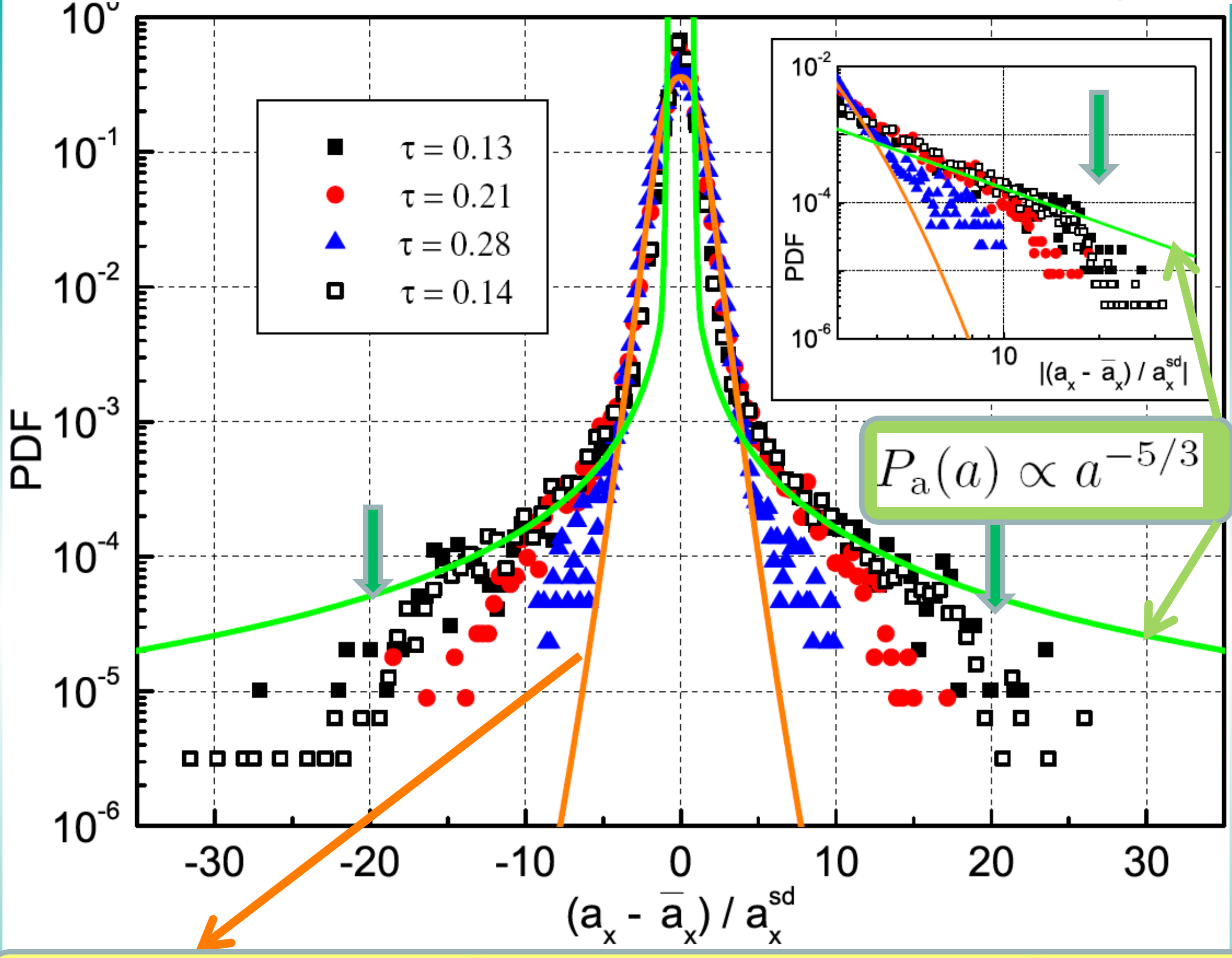
The flatness at $\tau < 1$ $(\ell_{\mathrm{exp}} < \ell)$ depends on the frame rate used to collect the images due to to the detection of less events of large magnitude

The width of the tails of the velocity PDF (**a quantum effect**) due to the finite size of the particles
The upper limit results from the assumption that the particle is subject to the tension of a quantized vortex line, which is balanced by the viscous Stokes drag, leading to a maximum velocity

$$v_{\max} = \frac{\rho_s \kappa^2}{6\pi^2 d\eta} \ln\left(\frac{d}{\xi}\right)$$

➡ $v_{\max} \approx 30\ \mathrm{mm/s}$ ➡ corresponds to about $15u^{\mathrm{sd}}$

PDF of the non-dimensional acceleration $(a_\mathrm{x} - \overline{a}_\mathrm{x})/a_\mathrm{x}^\mathrm{sd}$



$P_\mathrm{a}(a) \propto a^{-5/3}$

Prediction for the tails:

about $20|a_\mathrm{x}^\mathrm{sd}|$

corresponds to the acceleration of a few micrometer-sized particle touching a vortex core (note that the particle size *d has a large* influence on the acceleration magnitude as $a \propto d^{-3}$

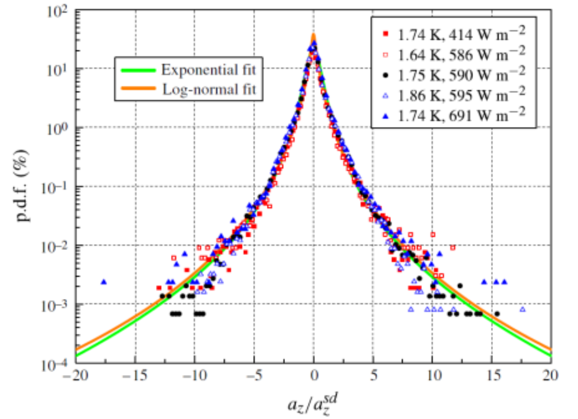
log-normal distribution of the acceleration magnitude of classical turbulent flows: Mordant,Crawford, Bodenschatz, PRL **93,** 214501 (2004); Qureshi et al PRL **99,** 184502 (2007); Eur. Phys. J. B **66,** 531 (2008)

$$\mathrm{PDF} = \frac{\exp(3s^2/2)}{4\sqrt{3}} \left[1 - \mathrm{erf}\left(\frac{\ln|a/\sqrt{3}| + 2s^2}{\sqrt{2}s} \right) \right]$$

s is a fitting parameter

$s = 0.4$

s = 1 – fluid particles, S < 1 - inertial particles



For l_{exp}; l the classical-like log-normal PDF shape is recovered La Mantia, Duda, Rotter, and LS, J. Fluid Mech. **717**, R9 (2013).

Summary: velocity and acceleration PDFs

Quantum turbulence, generated in thermal counterflow of superfluid ^{4}He, has been probed experimentally at length scales straddling about two orders of magnitude across the mean distance l between quantized vortices.

- Quantum signature is apparent from the velocity and cceleration distributions, at length scales smaller than l and from the temperature and velocity dependence of the acceleration magnitude, at length scales of the order of l

- Classical-like signature is found, from the velocity and acceleration distributions, at length scales larger than l

- Indirect evidence of macroscopic, classical-like vortical structures is obtained at length scales larger than l and smaller than the integral length scale

Results: added mass

inviscid fluid

$$\rho_p \frac{du_p}{dt} = \rho_f \frac{Du_f}{Dt} + C\rho_f\left(\frac{Du_f}{Dt} - \frac{du_p}{dt}\right) \Rightarrow \frac{du_p}{dt} = \frac{1+C}{\rho_p/\rho_f + C}\,\frac{Du_f}{Dt} = K_p \frac{Du_f}{Dt}$$

i) if $\rho_p = \rho_f$, $K_p = 1$, i.e., the particle has the same acceleration as the fluid

ii) if $\rho_p > \rho_f$, $K_p < 1$, i.e., the particle accelerates less than the fluid

iii) if $\rho_p >> \rho_f$, $K_p << 1$, i.e., the particle accelerates much less than the fluid

iv) if $\rho_p < \rho_f$, $K_p > 1$, i.e., the particle accelerates more than the fluid

v) if $\rho_p << \rho_f$, $K_p \approx (1+C)/C$, e.g., negative ion in He II

solid hydrogen, $\boldsymbol{\rho_H \approx 80}$ **kg m^{-3}** deuterium, $\boldsymbol{\rho_D \approx 200}$ **kg m^{-3}** helium $\boldsymbol{\rho_f = \rho_{He\,II} \approx 146}$ **kg m^{-3}**

$K_H \approx 1.36$ $K_D \approx 0.80$

$\boldsymbol{K_H / K_D \approx 1.70}$ **(sphere)** $K_H / K_D \approx 1.5 – 2$ (prolate spheroid)

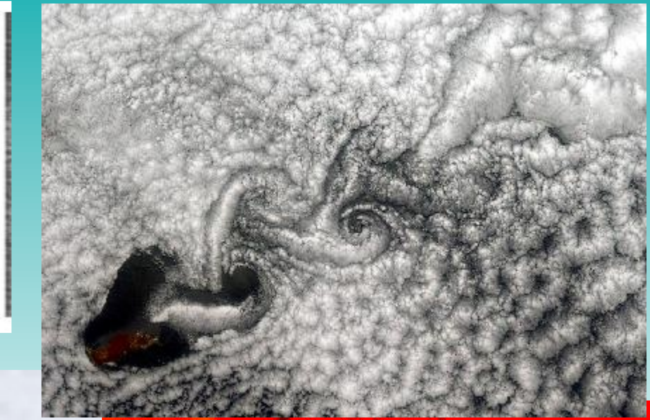
Prediction: hydrogen particles in He II are expected to accelerate roughly 1.5 to 2 times more rapidly than deuterium particles

This is in agreement with experimental observation

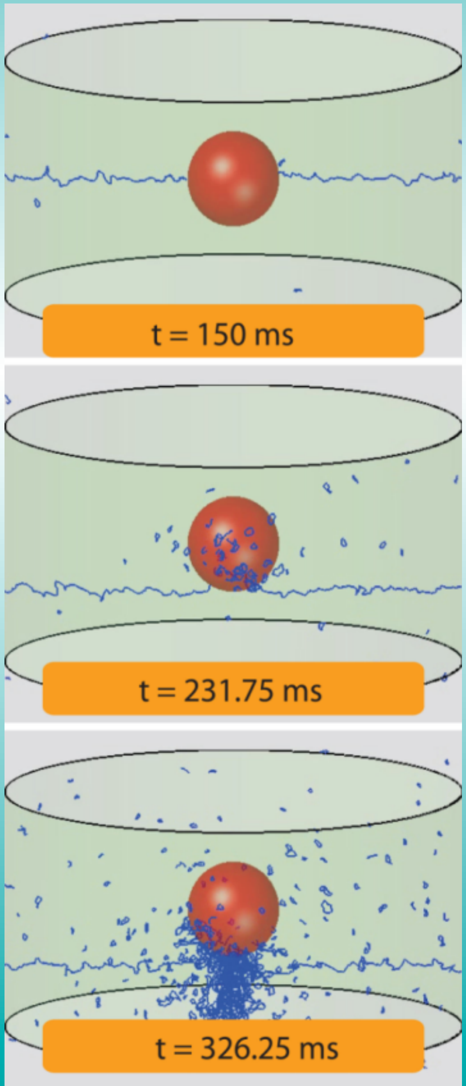
•M. La Mantia and LS *Dynamics of particles visualizing quantum turbulence*
Phys. Rev. **B 90**, 014519 (2014)

Large vortex structures exist is classical viscous flows

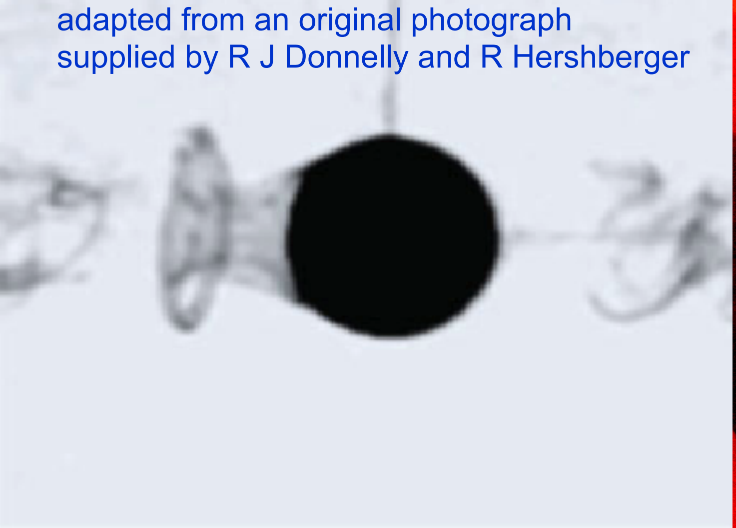
Picture from Van Dyke (1982)



Oscillating sphere in He II,
simulation adapted from original work by Hanninen R, Tsubota M, Vinen WF (2007) Phys Rev B 75:064502.



Oscillating sphere in water;
adapted from an original photograph supplied by R J Donnelly and R Hershberger



Baker technique, Prague, unpublished

Do large vortex structures exist in (various) quantum flows ???

Experiments

M. Murakami, M. Hanada, and T. Yamazaki, Jpn. J. Appl. Phys. Suppl.26-3, 107 (1987).

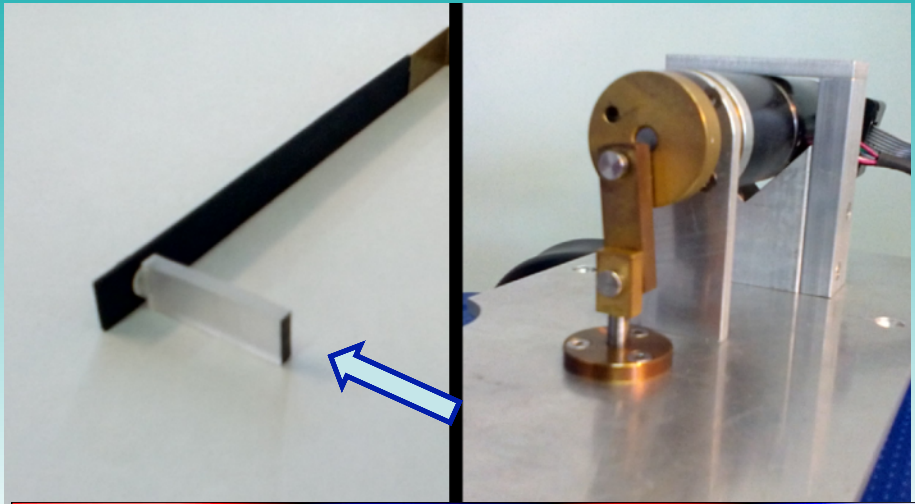
G. Stamm, F. Bielert, W. Fiszdon, and J. Piechna, Physica B 193, 188 (1994).

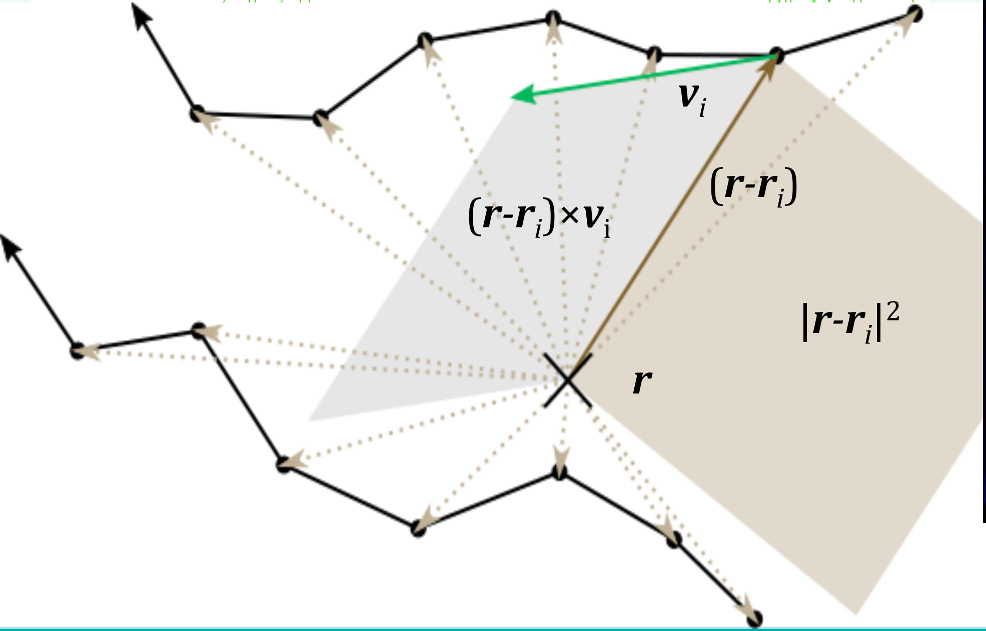
Oscillating cylinder of rectangular cross-section 3 x 10 mm

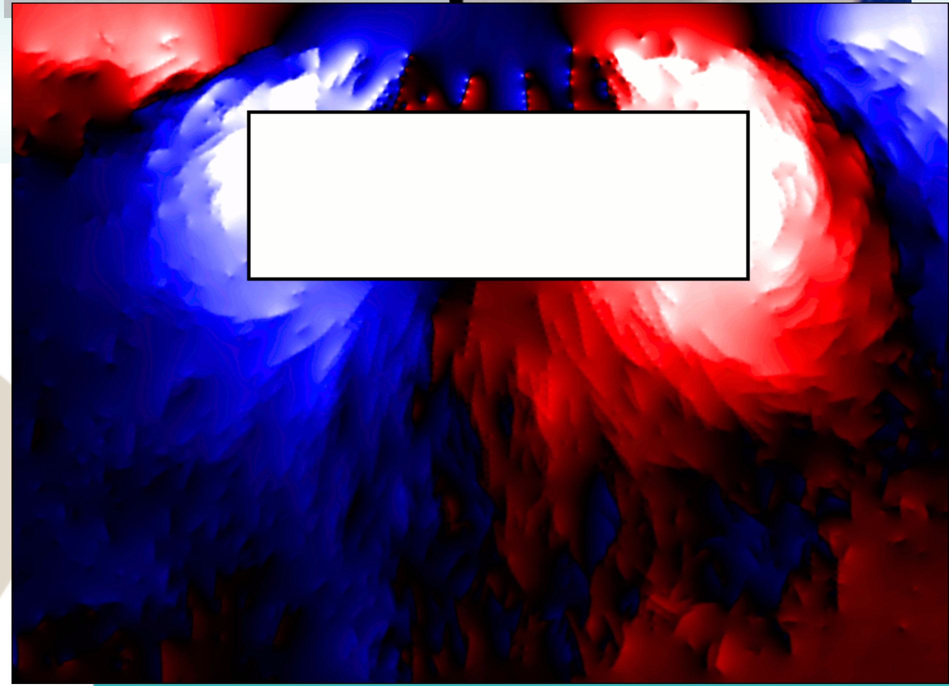
Oscillations:
frequency 0.5 Hz, amplitude 5 mm

20 s entire video,
camera frequency 100 Hz (exposition time 5 ms),
phase averaged,
trajectories of min 5 points shown ,
laser power 1.05 W

T=1.24 K

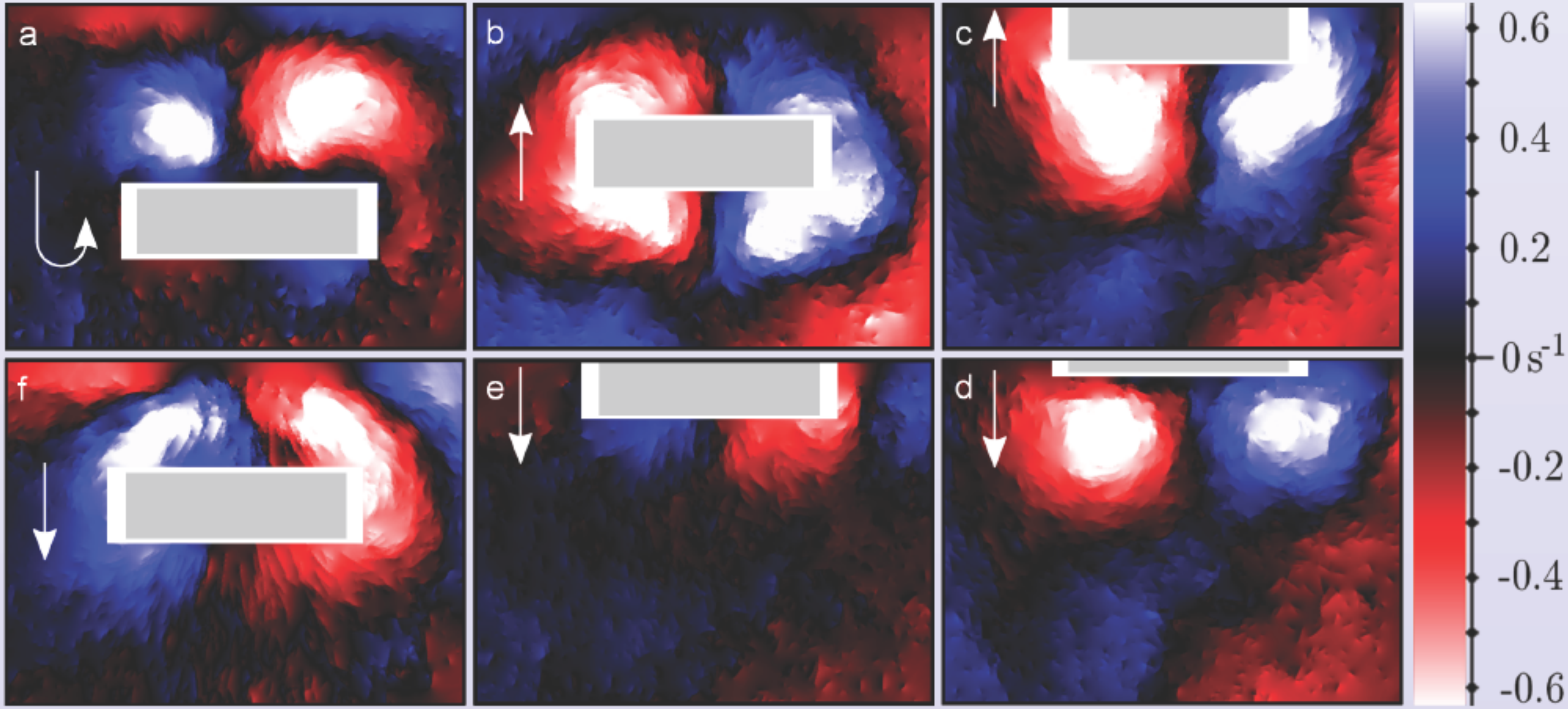




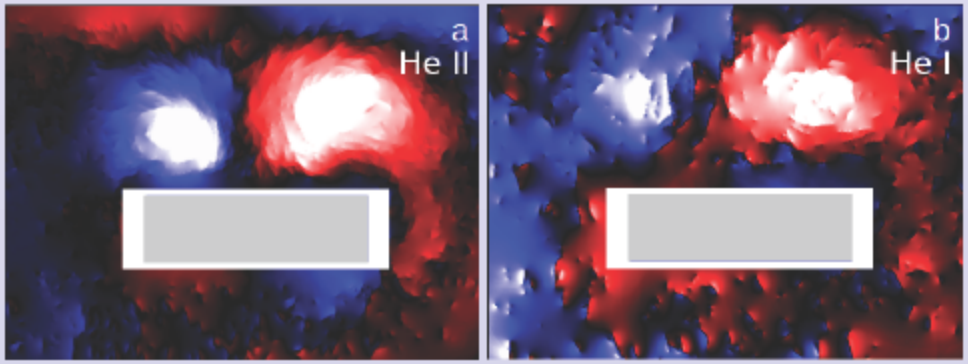


R_M – radius of region of interest
Φ – phase window half-width

During the cycle, two pairs of vortices of opposite direction are shed



$T = 1.24\,\mathrm{K},\ f = 0.5\,\mathrm{Hz},\ a = 5\,\mathrm{mm}$



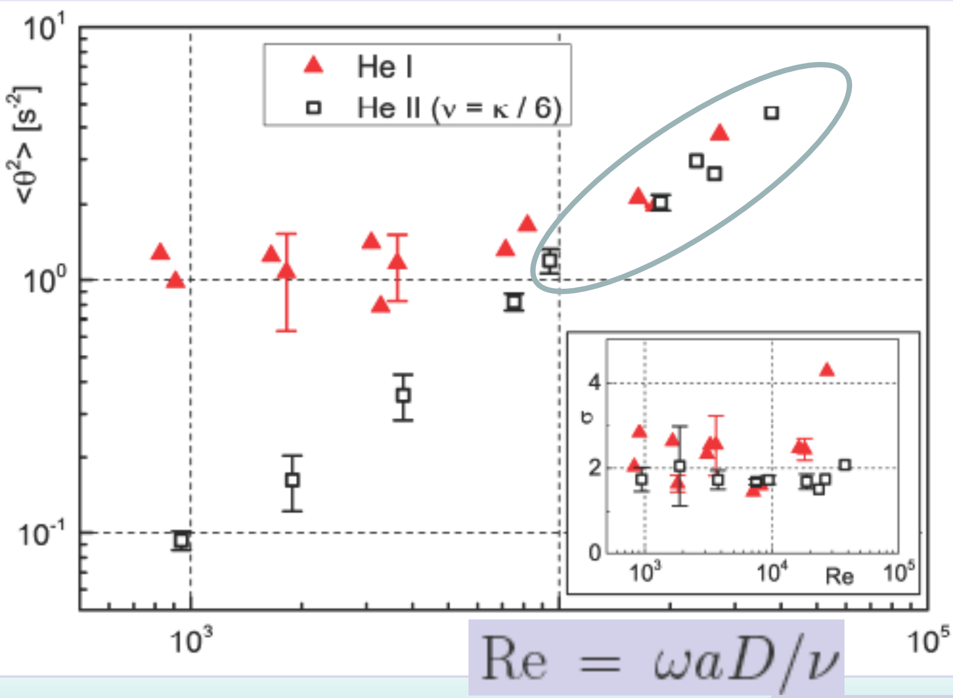
a: He II, T = 1:24 K, a = 5mm, f = 0:5 Hz
b: He I, T = 2:18 K, a = 5mm, f = 0:5 Hz

Vortices appear similar in He I and He II

$\langle\theta^2\rangle$: ensemble average of the θ^2 parameter

Kinematic viscosity:

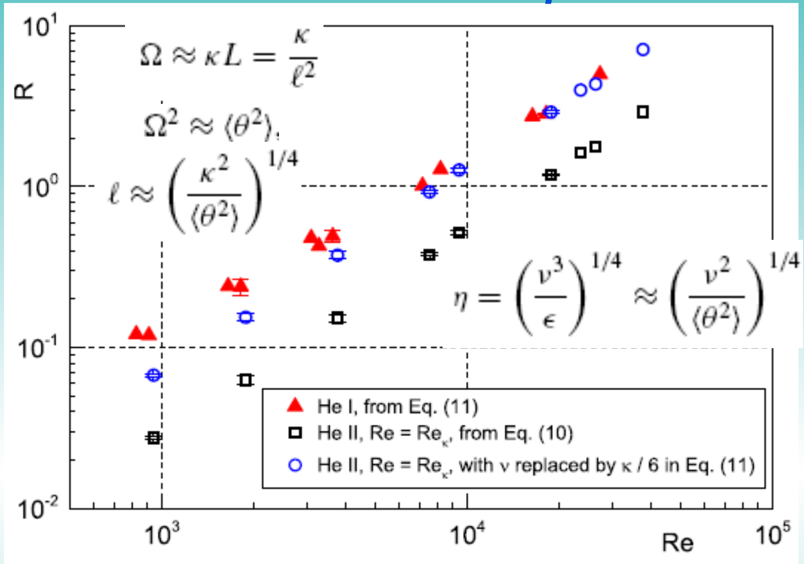
for He II, $\nu = \kappa/6$,



$$\mathrm{Re} = \omega a D/\nu$$

ω and a **angular frequency and amplitude** $D = 10\,\mathrm{mm}$

Ratio *R between the probed length scale and the flow scale plotted vs Re*



$$\Omega \approx \kappa L = \frac{\kappa}{\ell^2}$$

$$\Omega^2 \approx \langle\theta^2\rangle,$$

$$\ell \approx \left(\frac{\kappa^2}{\langle\theta^2\rangle}\right)^{1/4}$$

$$\eta = \left(\frac{\nu^3}{\epsilon}\right)^{1/4} \approx \left(\frac{\nu^2}{\langle\theta^2\rangle}\right)^{1/4}$$

Visualization of viscous and quantum flows of liquid 4He due to an oscillating cylinder of rectangular cross section D. Duda, P. Švančara, M. La Mantia, M. Rotter, LS **PRB, in print**

At large enough length scales (larger than Kolmogorov dissipation length and quantum length scale - average distance between quantized vortices) He I and II behave similarly.

Similarly to thermal counterflow, both viscous and quantum features can be observed in mechanically driven flows of He II, depending on the length scales at which the quantum flow is probed

Warning: particles can significantly affect both average tangle properties and also the statistics of particle motion; current PTV experiments, however, use safe, low numbers of particles.

Numerical study Backreaction of Tracer Particles on Vortex Tangle in Helium II Counterflow

By E. Varga, C. F. Barenghi Y. A. Sergeev, LS

Newcastle University

Recent Praque results on 4He quantum flows due to oscillating objects

David Schmoranzer, Martin Jackson, Tamara Skokankova, LS

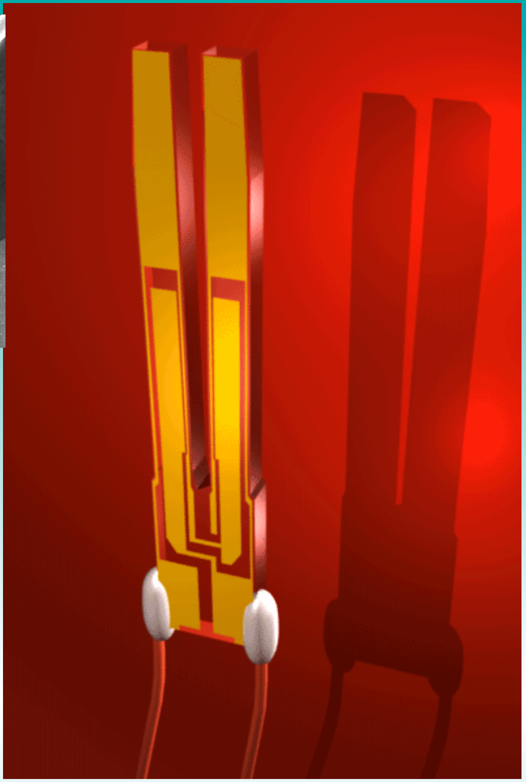
Coworkers: Joe Vinen, Viktor Tsepelin, Andrew Woods, Oleg Kolosov, Javier Luzuriaga, Eddy Collin

Quntum flows and sound emission due to :
- **Quartz tuning forks**
- **Microwires**
- **Double paddle oscillators**
- **Oscillating disc**

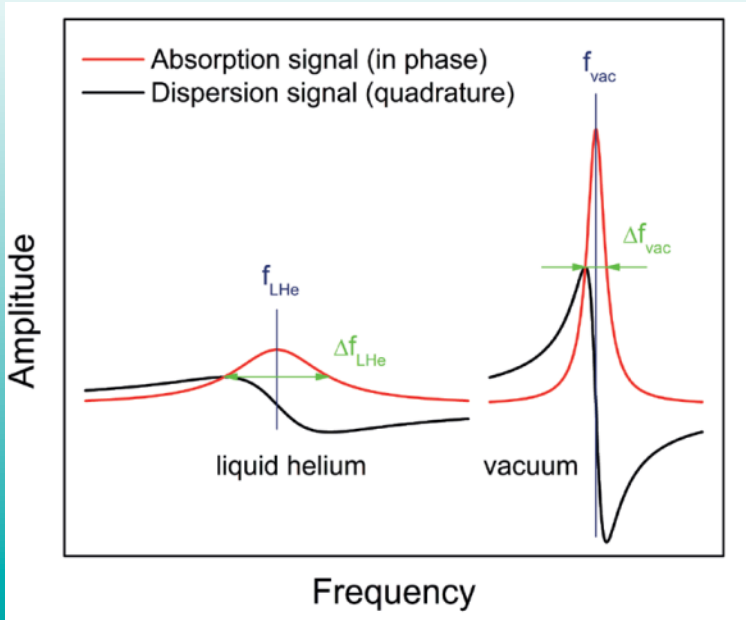
D. Schmoranzer, M.J. Jackson, LS, O. Kolosov, V. Tsepelin, A.J. Woods *Measurements of Vortex Line Density Generated by a Quartz Tuning Fork in Superfluid 4He*, **submitted to JLTP**

M.J. Jackson, D. Schmoranzer, LS, and A.J. Woods Turbulent Transition in Superfluid 4He due to Quartz Tuning Forks
In preparation

Quartz Tuning Forks



- Used as Time Standards
- Piezoelectric Oscillator - Oscillates with applied voltage
- Oscillation induces a current ∝ Velocity
- Damping governed by excitations
  - Thermometry
- Can create and detect turbulence



Classical Oscillatory Flow - High-Frequency Limit

Introduce the dimensionless quantities

$$u = U u' ,\ \nabla = 1/l\, \nabla' ,\ t = 1/\omega\, t' ,\ p = \rho U^2 p' ,$$

to yield the dimensionless Navier-Stokes Equation

$$l\omega/U\, \partial u'/\partial t' + u' \cdot \nabla' u' + \nabla' p' = \nu/Ul\, \Delta' u' .$$

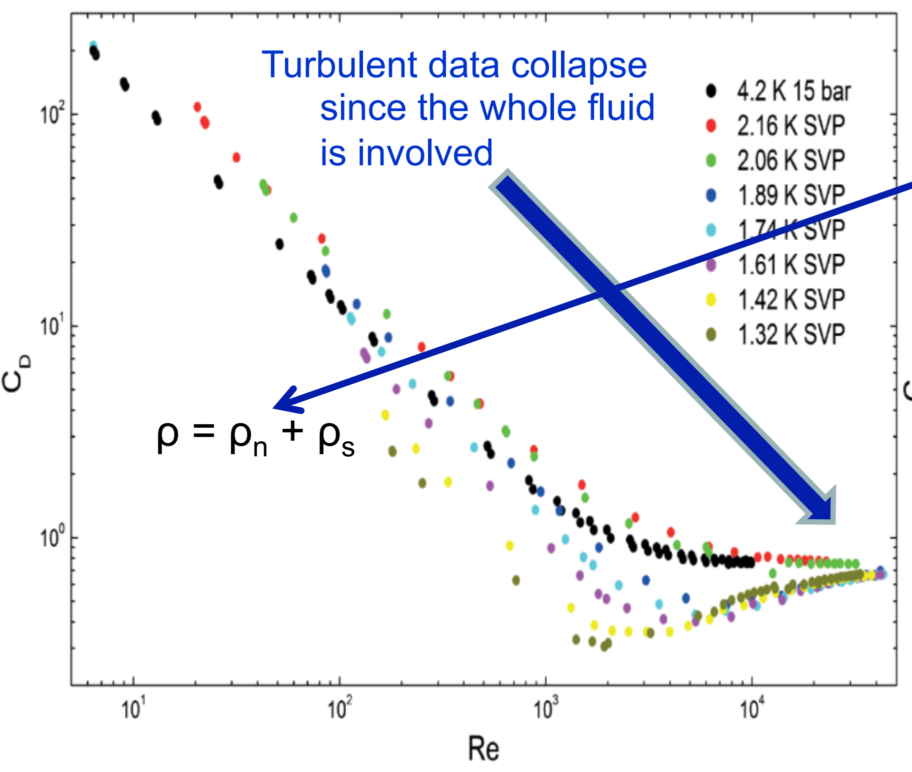
$2\square/Kc$

$1/Re$

- At high frequencies, velocity changes occur on the scale of the viscous penetration depth $\delta = \sqrt{2\nu/\omega}$.
- Thus $Kc/\pi = Re = U\delta/\nu$
- Therefore, one parameter is sufficient to characterise such flow, provided $\delta \ll D$ (We neglect surface roughness).

Measure damping force (F) against velocity (U) and convert to drag coefficient and Reynolds number

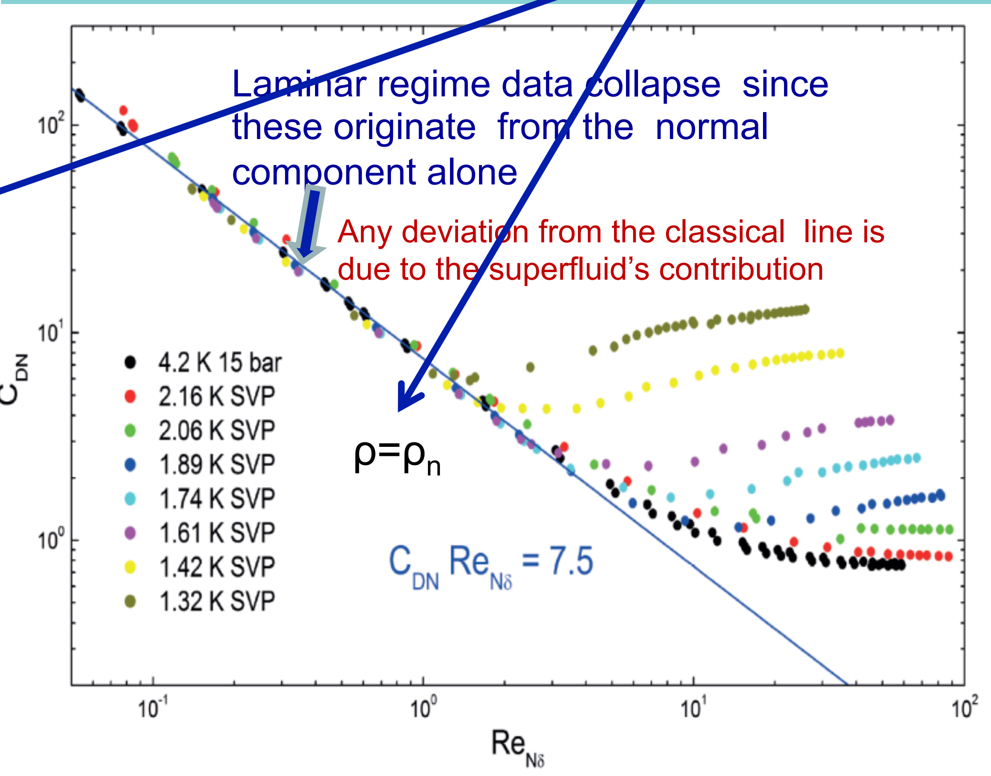
$$C_{Dx} = \frac{2F}{\rho_x A U^2}$$



Turbulent data collapse since the whole fluid is involved

$\rho = \rho_n + \rho_s$

based on the size of the fork, dynamic viscosity and total fluid density of He



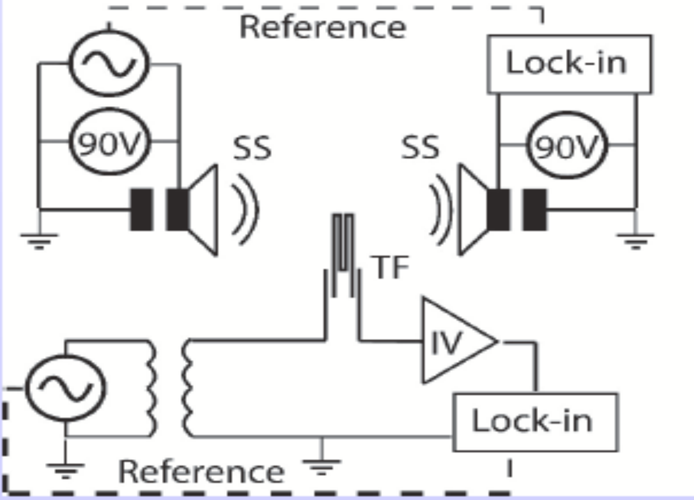
Laminar regime data collapse since these originate from the normal component alone

Any deviation from the classical line is due to the superfluid's contribution

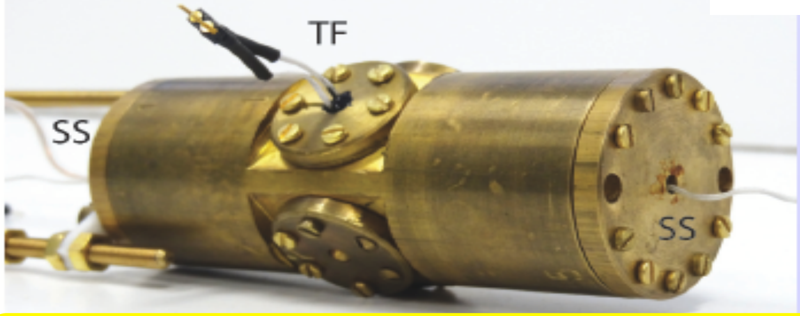
$\rho = \rho_n$

based not on the size of the fork, but on the viscous penetration depth in the normal fluid

Does the oscillating tuning fork produce quantized vortices ?

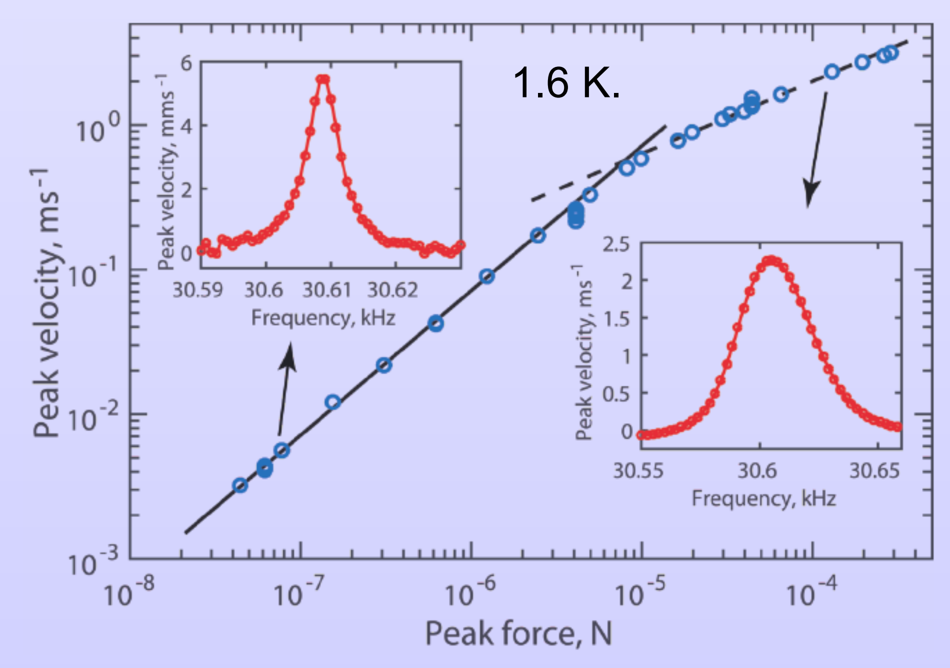


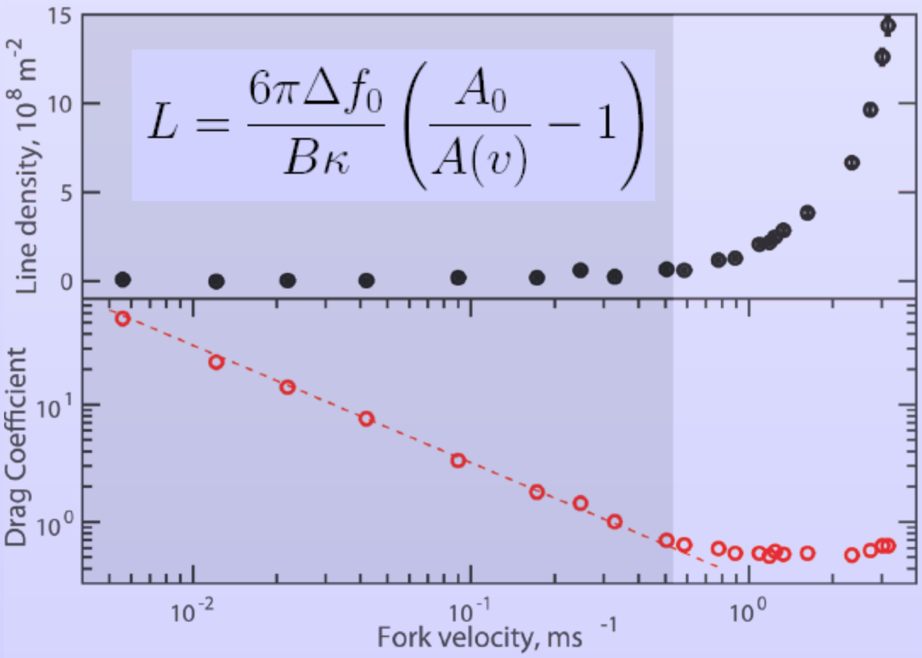
cylindrical second sound resonator



Measurements of Vortex Line Density Generated by a Quartz Tuning Fork in Superfluid 4He

D. Schmoranzer, M.J. Jackson, LS, O. Kolosov, V. Tsepelin, A.J. Woods



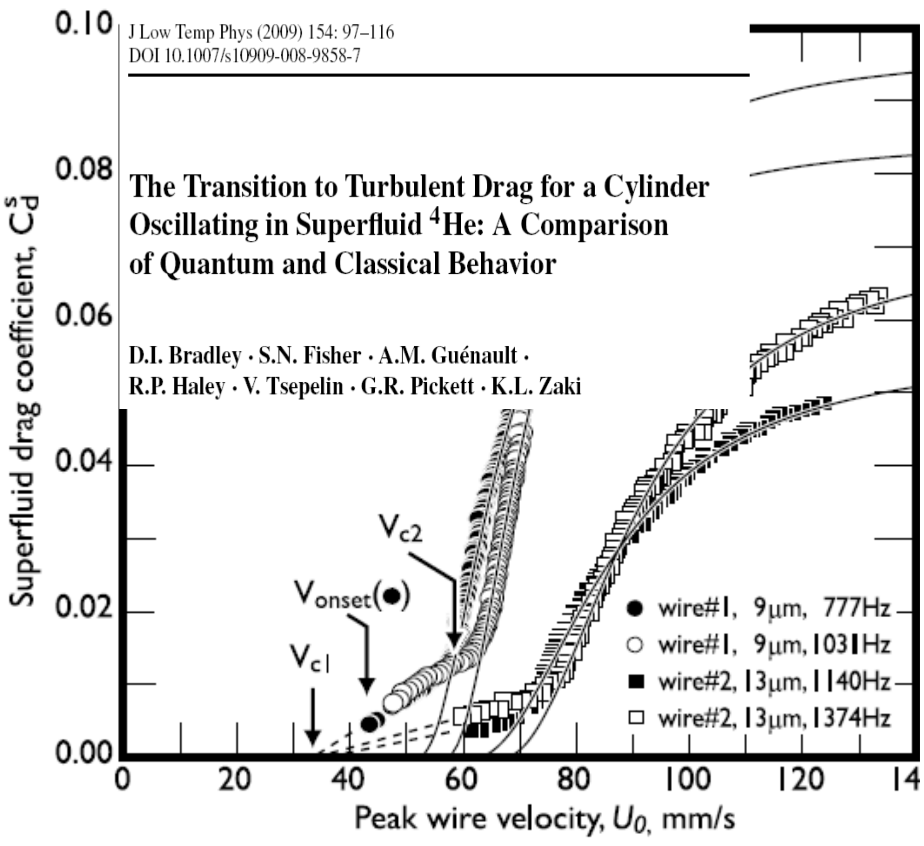


$$L = \frac{6\pi\Delta f_0}{B\kappa}\left(\frac{A_0}{A(v)} - 1\right)$$

Directly tested by second sound attenuation:

Production of quantized vortices is directly related to the onset of excess damping

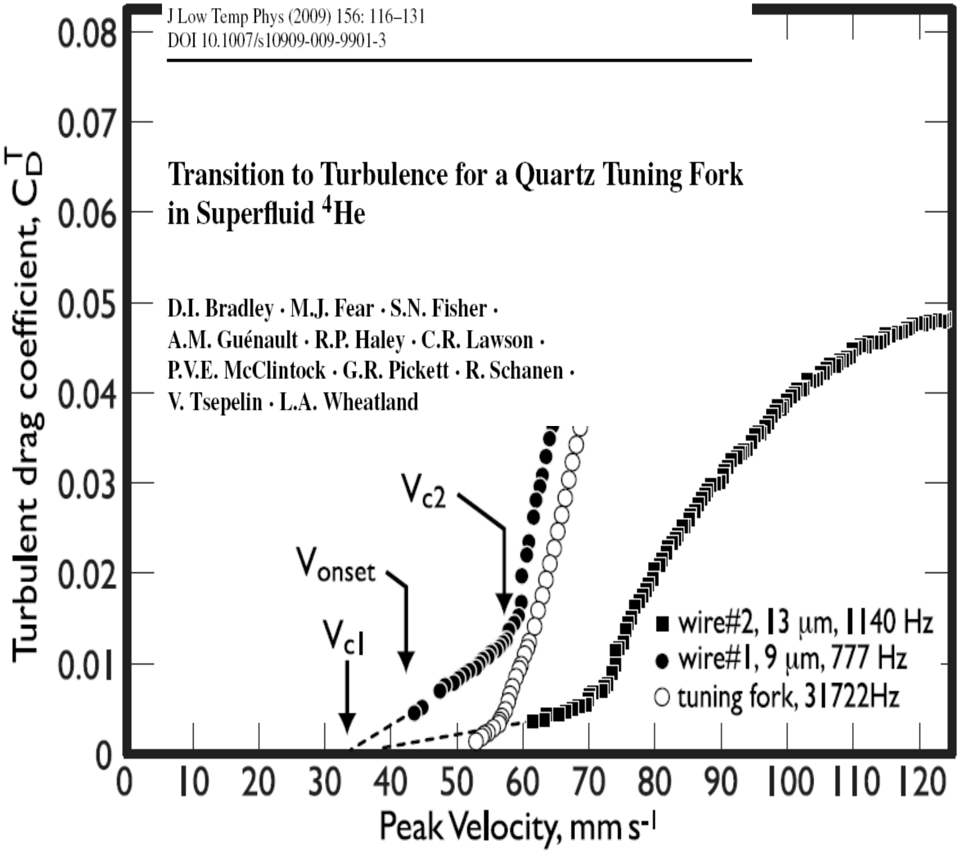
Two critical velocities?!?



J Low Temp Phys (2009) 154: 97–116
DOI 10.1007/s10909-008-9858-7

The Transition to Turbulent Drag for a Cylinder Oscillating in Superfluid ^{4}He: A Comparison of Quantum and Classical Behavior

D.I. Bradley · S.N. Fisher · A.M. Guénault ·
R.P. Haley · V. Tsepelin · G.R. Pickett · K.L. Zaki



J Low Temp Phys (2009) 156: 116–131
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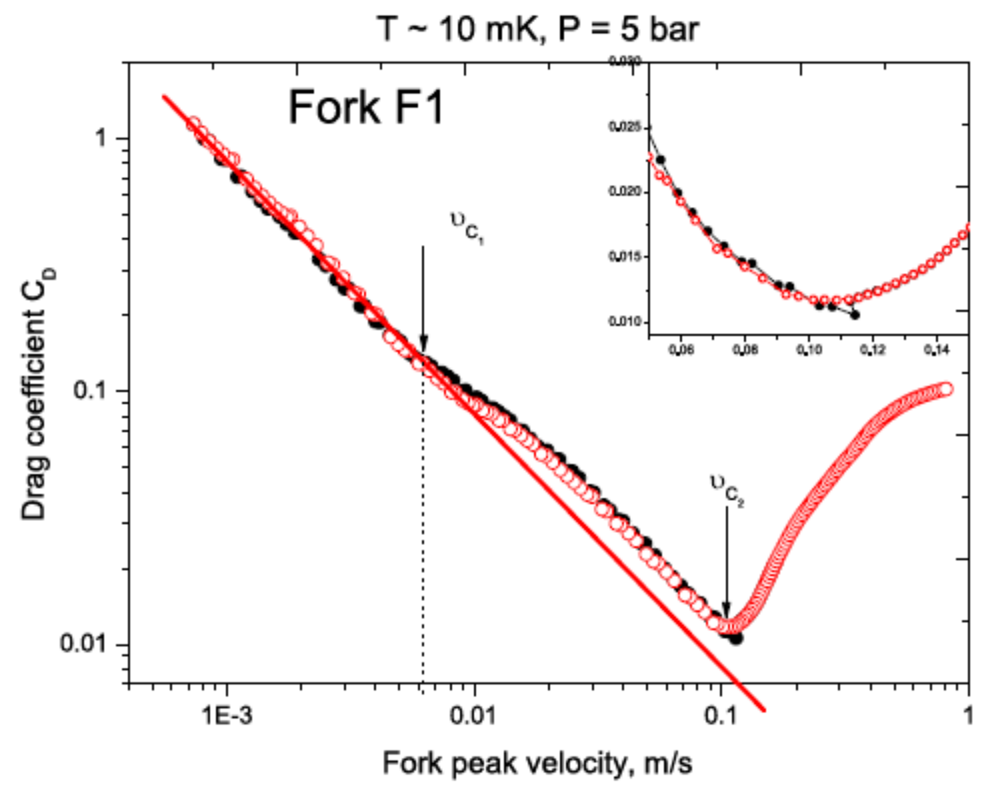
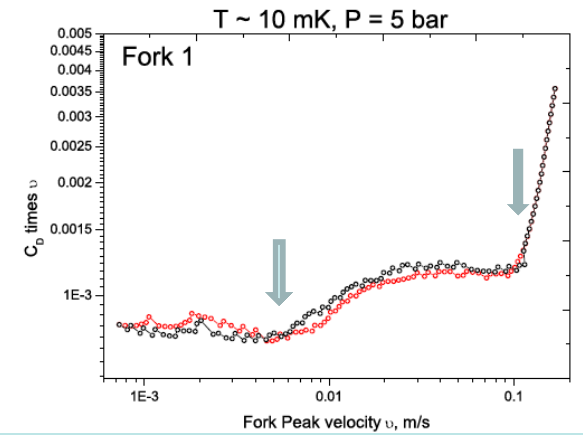
Transition to Turbulence for a Quartz Tuning Fork in Superfluid ^{4}He

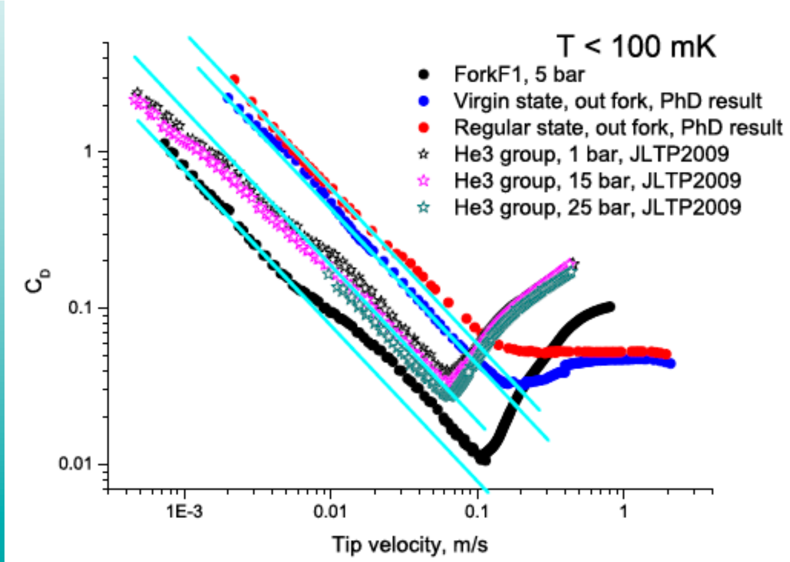
D.I. Bradley · M.J. Fear · S.N. Fisher ·
A.M. Guénault · R.P. Haley · C.R. Lawson ·
P.V.E. McClintock · G.R. Pickett · R. Schanen ·
V. Tsepelin · L.A. Wheatland

The superfluid drag coefficient as a function of peak velocity for the two wire resonators in superfluid 4He and comparison with the standard 32 kHz quartz tuning fork





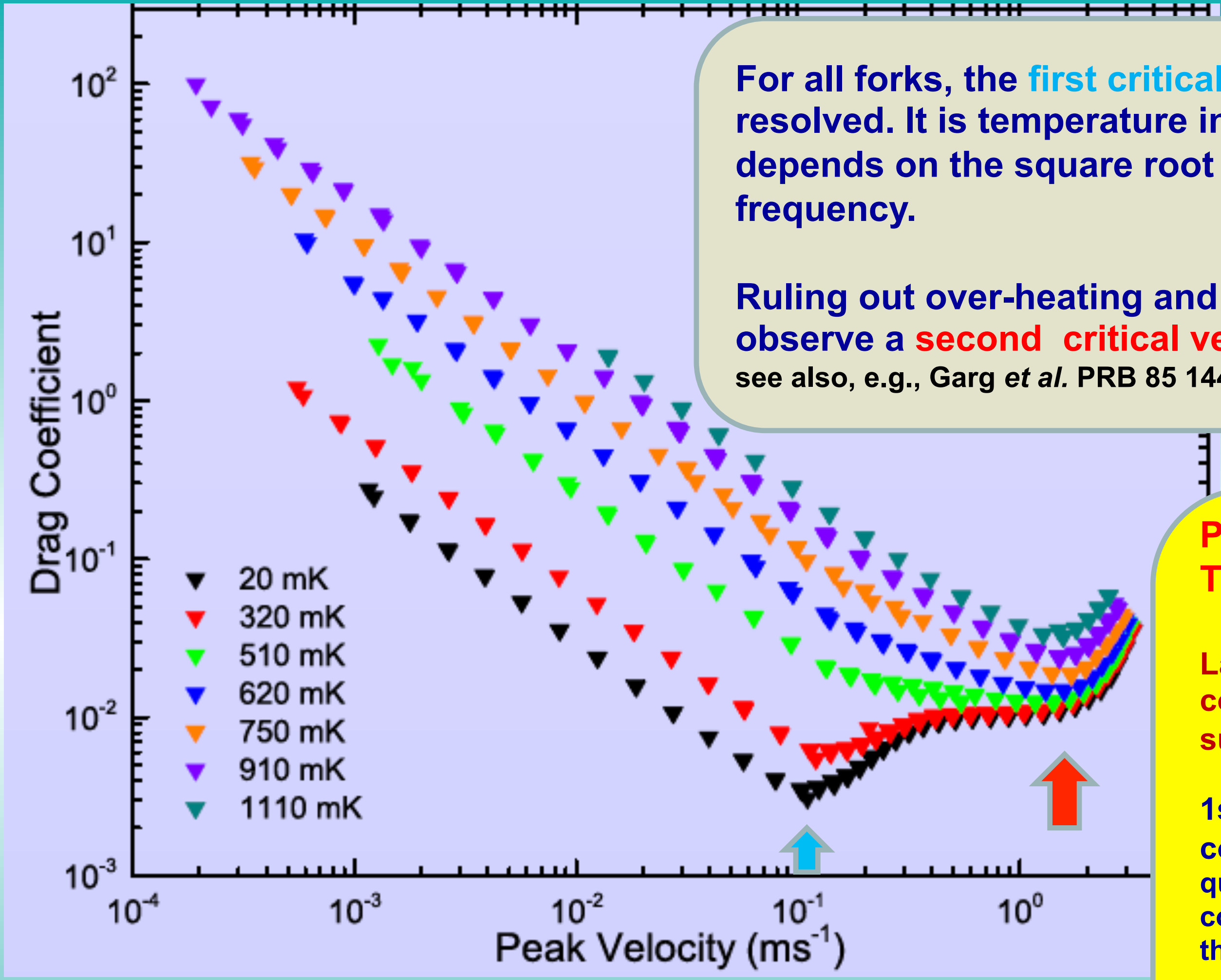
D. Garg, V. B. Efimov, M. Giltrow, P. V. E. McClintock LS and W. F. Vinen: **On Flow of Isotopically Pure 4He due to Vibrating Quartz Forks in the *T* → *0* Limit**
PHYSICAL REVIEW B **85, 144518 (2012)**



- **Two critical velocities are clearly observed**

- **The behaviour in the turbulent drag regime Is not always reproducible, at low T the drag coefficient does not approach the clasical value of order unity and is poorly understood**

Evidence for two critical velocities 6 kHz fork, first overtone at 40 kHz



For all forks, the first critical velocity is clearly resolved. It is temperature independent, but it depends on the square root of the oscillation frequency.

Ruling out over-heating and cavitation, we also observe a second critical velocity of order 1 m/s. -
see also, e.g., Garg *et al.* PRB 85 144518 (2012)

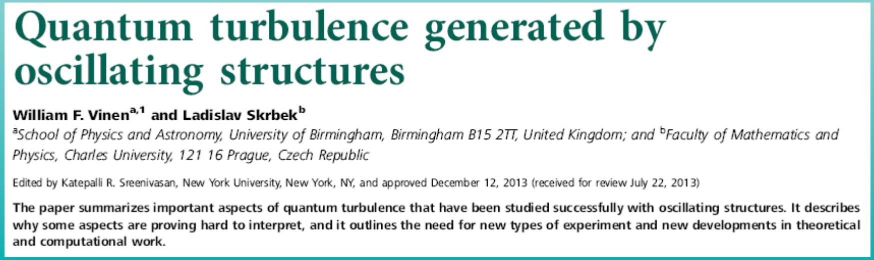
POSSIBLE SCENARIO OF THE TRANSITION

Laminar flow of the normal component, potential flow of the superfluid

1st instability (in the superfluid component) - nucleation of quantized vortices leads to coupling of the components through mutual friction force

Quasi-laminar flow of the coupled components

Further instabilities trigger classical-like transition to turbulence



Quantum turbulence generated by oscillating structures

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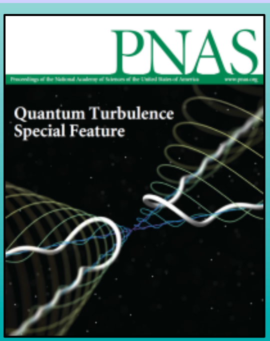
Edited by Katepalli R. Sreenivasan, New York University, New York, NY, and approved December 12, 2013 (received for review July 22, 2013)

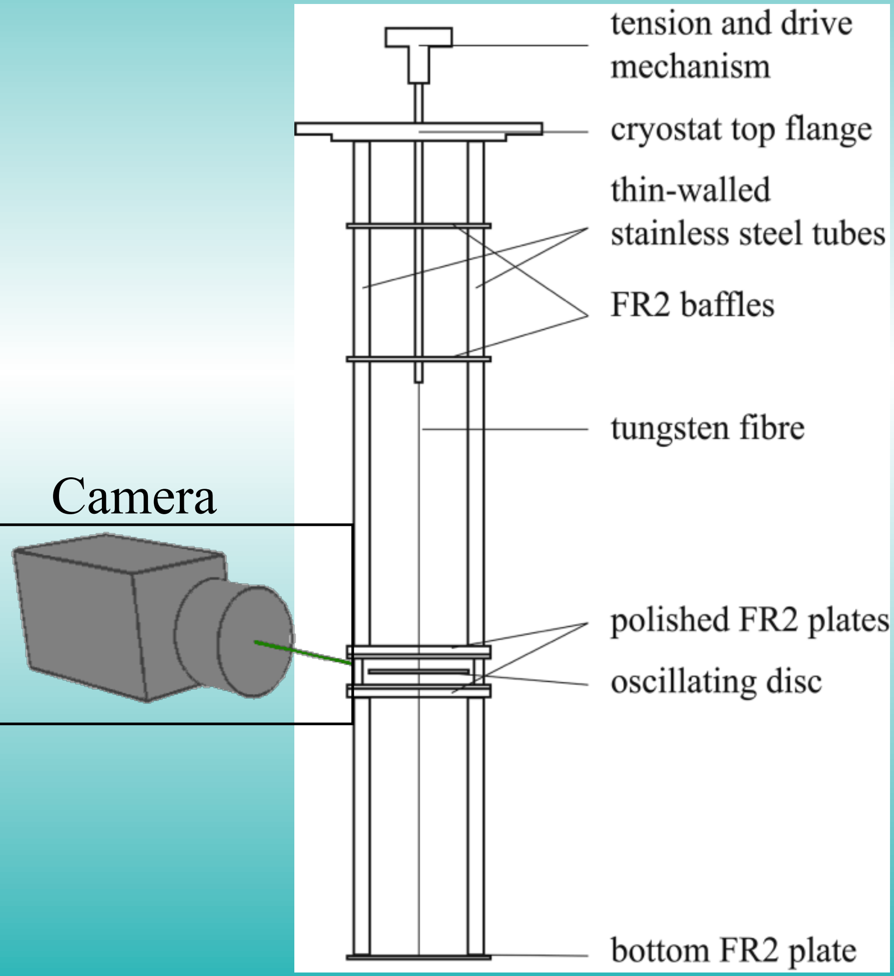
The paper summarizes important aspects of quantum turbulence that have been studied successfully with oscillating structures. It describes why some aspects are proving hard to interpret, and it outlines the need for new types of experiment and new developments in theoretical and computational work.

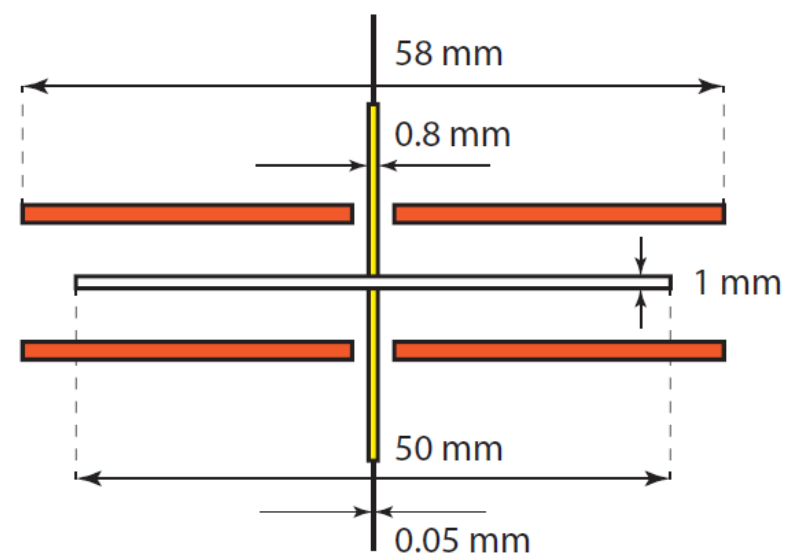


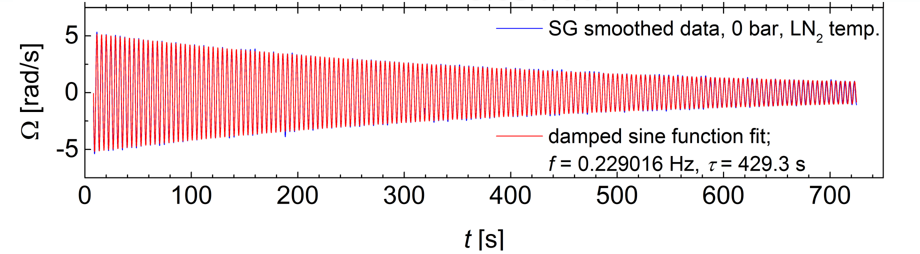
Torsionally oscillating disc experiment

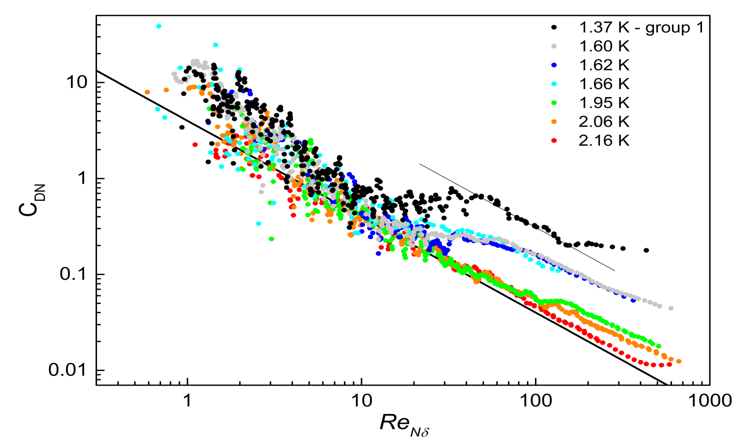
revisited in Prague

R.J. Donnelly, A.C. Hollis Hallett:
Annals of Physics 3 (1958) 320









Summary

- All forms of 4He - cryogenic helium gas, normal liquid He I and superfluid He II - serve as outstanding working fluids for **cryogenic fluid dynamics** and **quantum turbulence**

  - Extremely high Re and Ra flows can be studied under controlled laboratory conditions
  - **Quantum turbulence** has been investigated over 50 years -a lot is known about it, but it is still only partly understood
  - In the zero temperature limit QT represents the simplest prototype of turbulence
  - At finite temperature, in the wo-fluid regime, QT is more complex than classical turbulence, combining classical turbulencein the normal fluid with the dynamics of the vortex tangle in the superfluid, coupled by the mutual friction force

Does 4He, together with other quantum fluids, hold the key to unlocking the underlying physics of fluid turbulence?

Plenty of interesting physics to play with…