Exotic opportunities in cryogenic helium

Flow of normal and superfluid helium due to submerged oscillating objects

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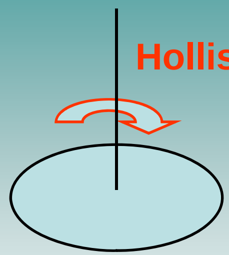
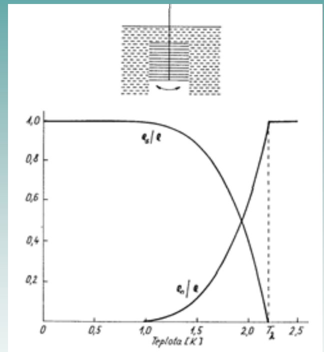
EUTUCHE Meeting, CERN, 2007

Oscillating objects used in experiments in He II and in ^{3}He

Discs and piles of discs

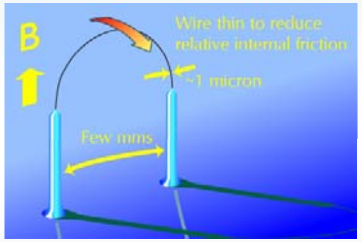


Hollis-Hallett

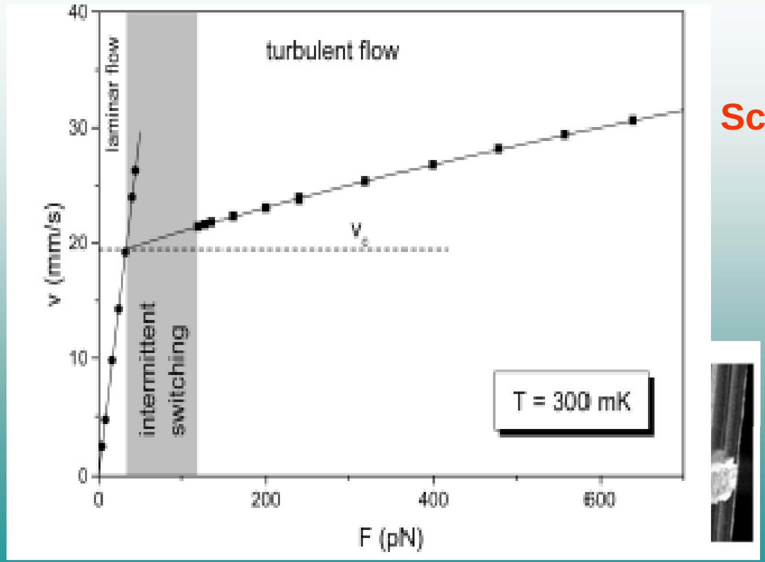


Andronikashvili

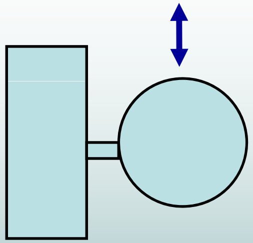
Wires
He II and 3He



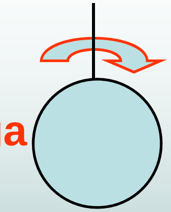
Many authors – vibrating wire viscometers
Vinen
Morishita, Kuroda, Sawada, Satoh, JLTP 76, 387 (1989)
Lancaster – Pickett's group, Osaka – Yano et al.,
Kosice Skyba et al., Moscow Dmitriev et al.,
Helsinki- YKI group…, Grenoble Bunkov et al., …



Schoepe et al



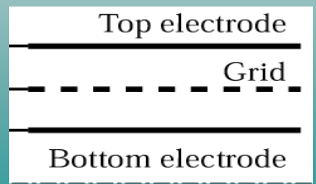
Luzuriaga

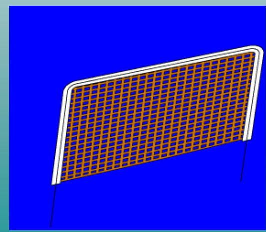


Hollis-Hallett

Lancaster – P. McClintock's group

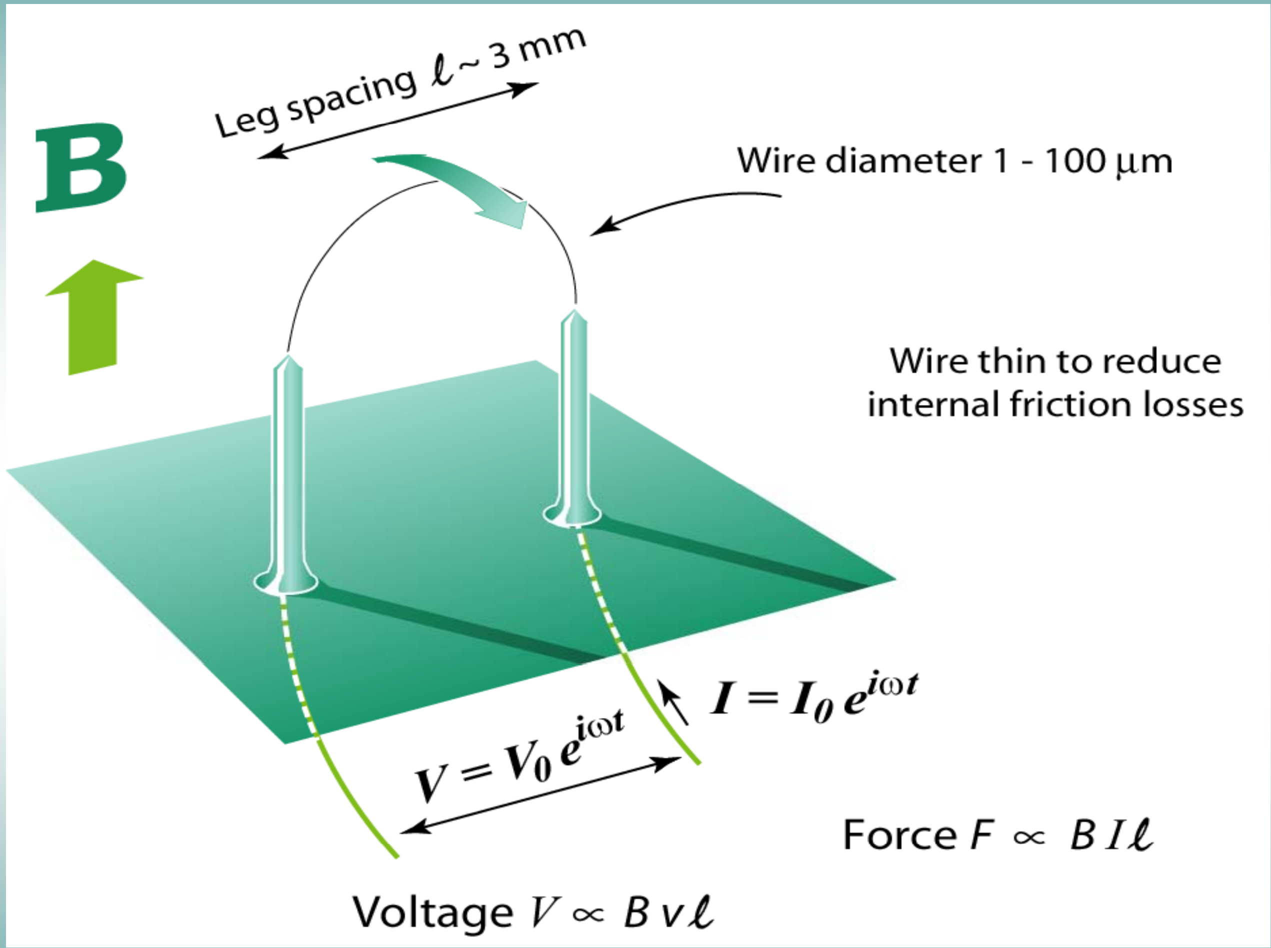
Lancaster – G. Pickett's group



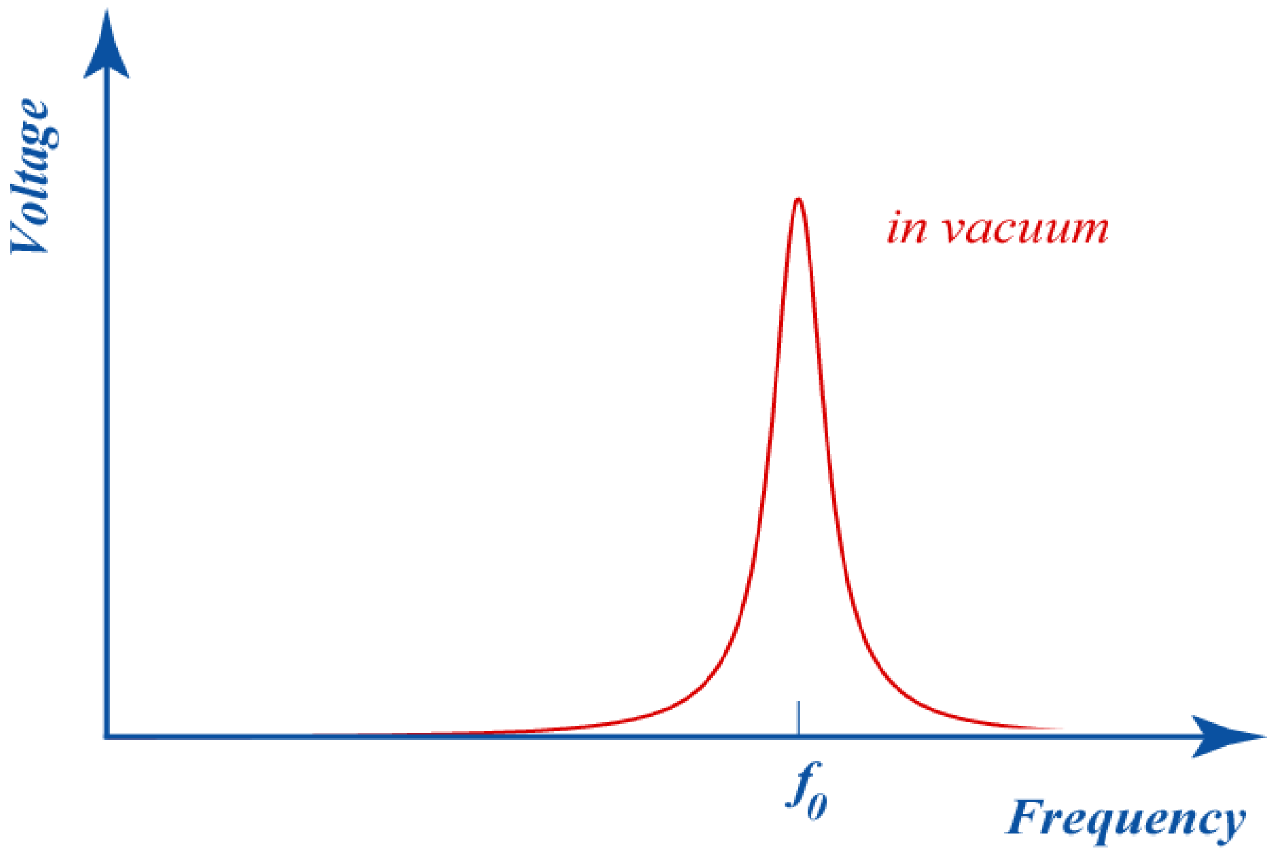


Vibrating wires Lancaster, Helsinki, Kosice, Osaka, Grenoble….

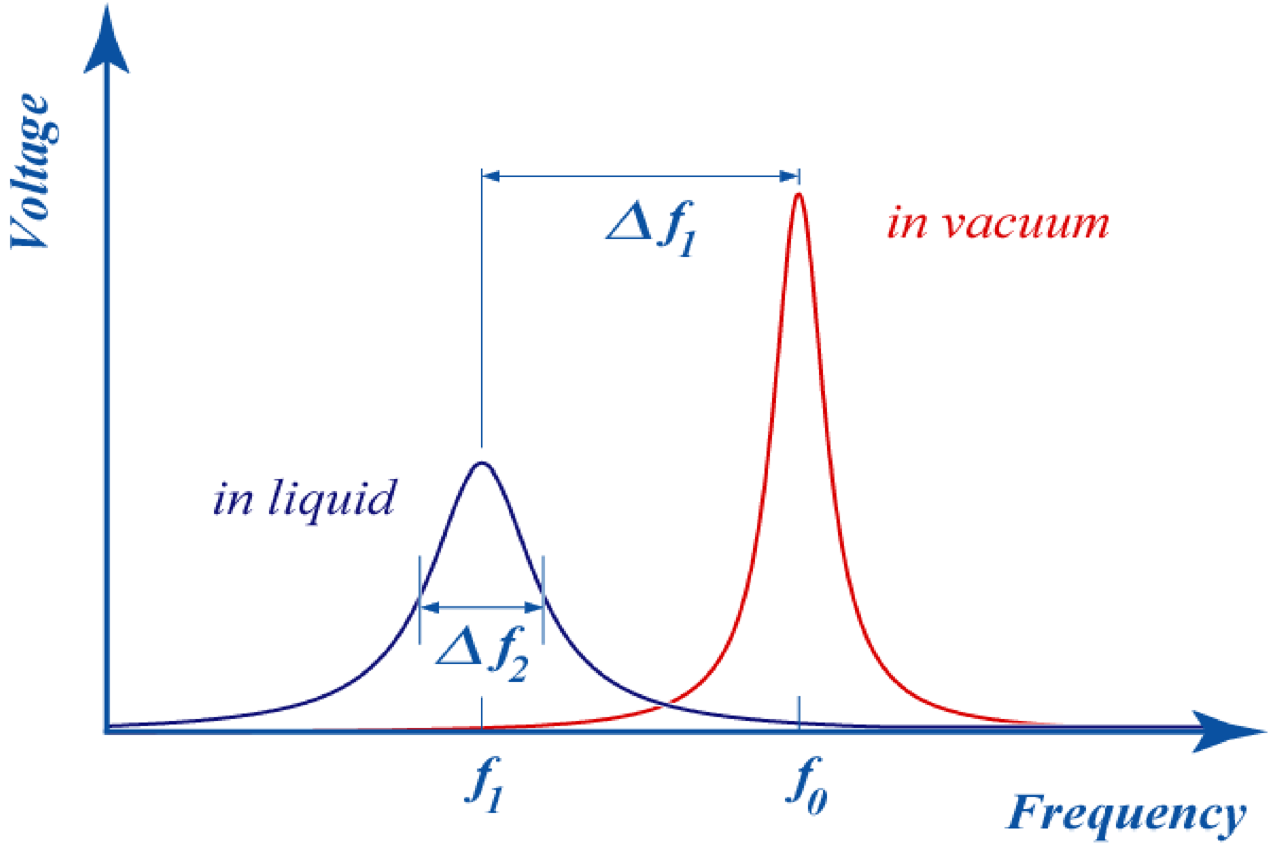
Both in He II and 3He, in mixtures



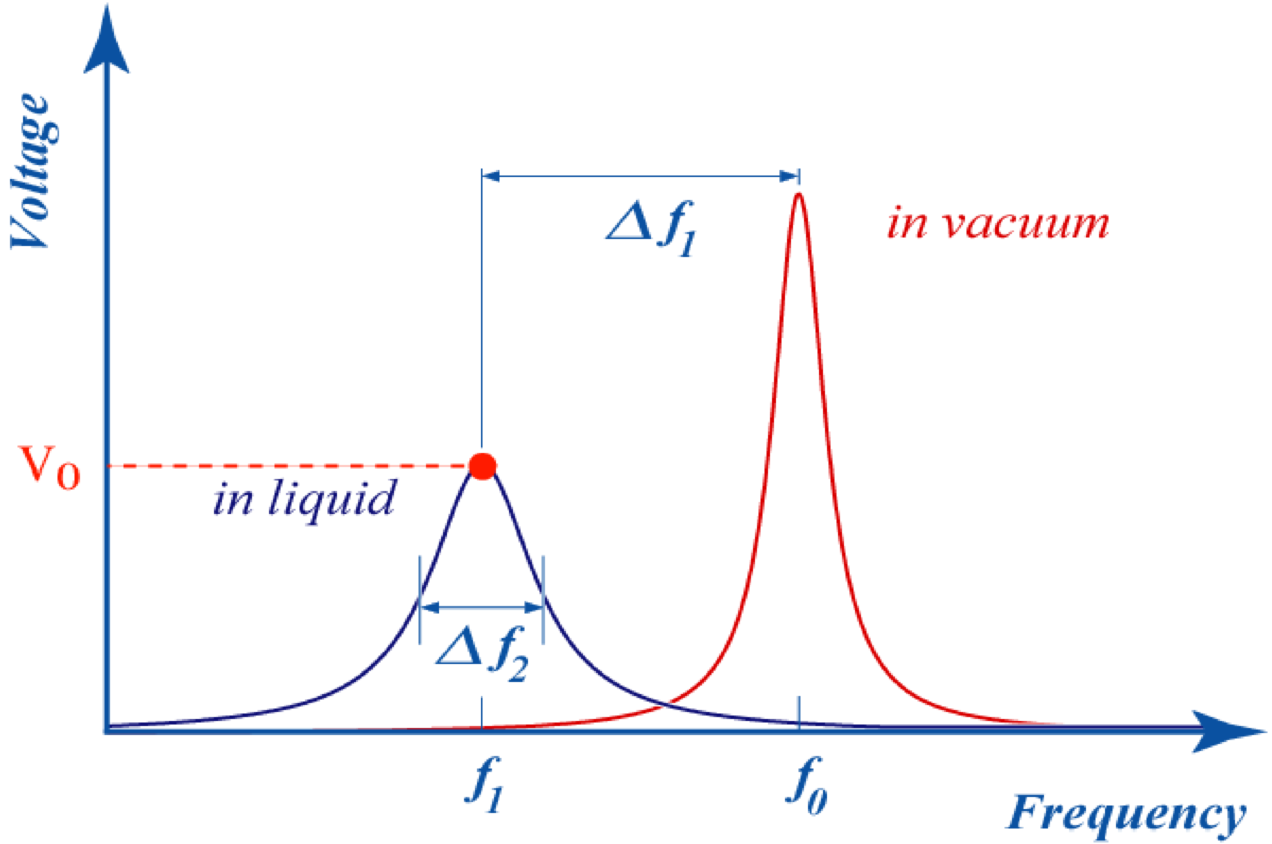
Note: care must be taken in order to distinguish between "superfluid" and "superconducting" effects, as applied magnetic field is usually of order of Bc1 of the superconducting wire !



Voltage
in vacuum
f_0
Frequency

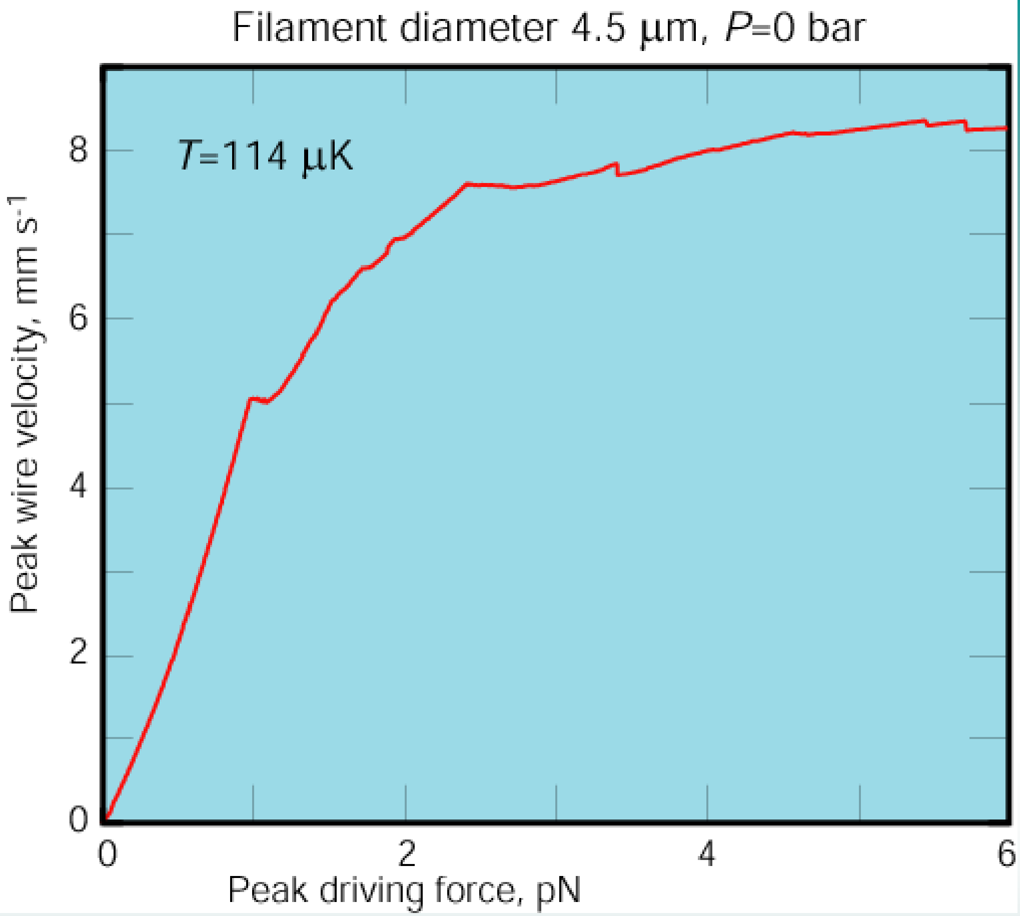


Voltage
Δf1
in vacuum
in liquid
Δf2
f1
f0
Frequency



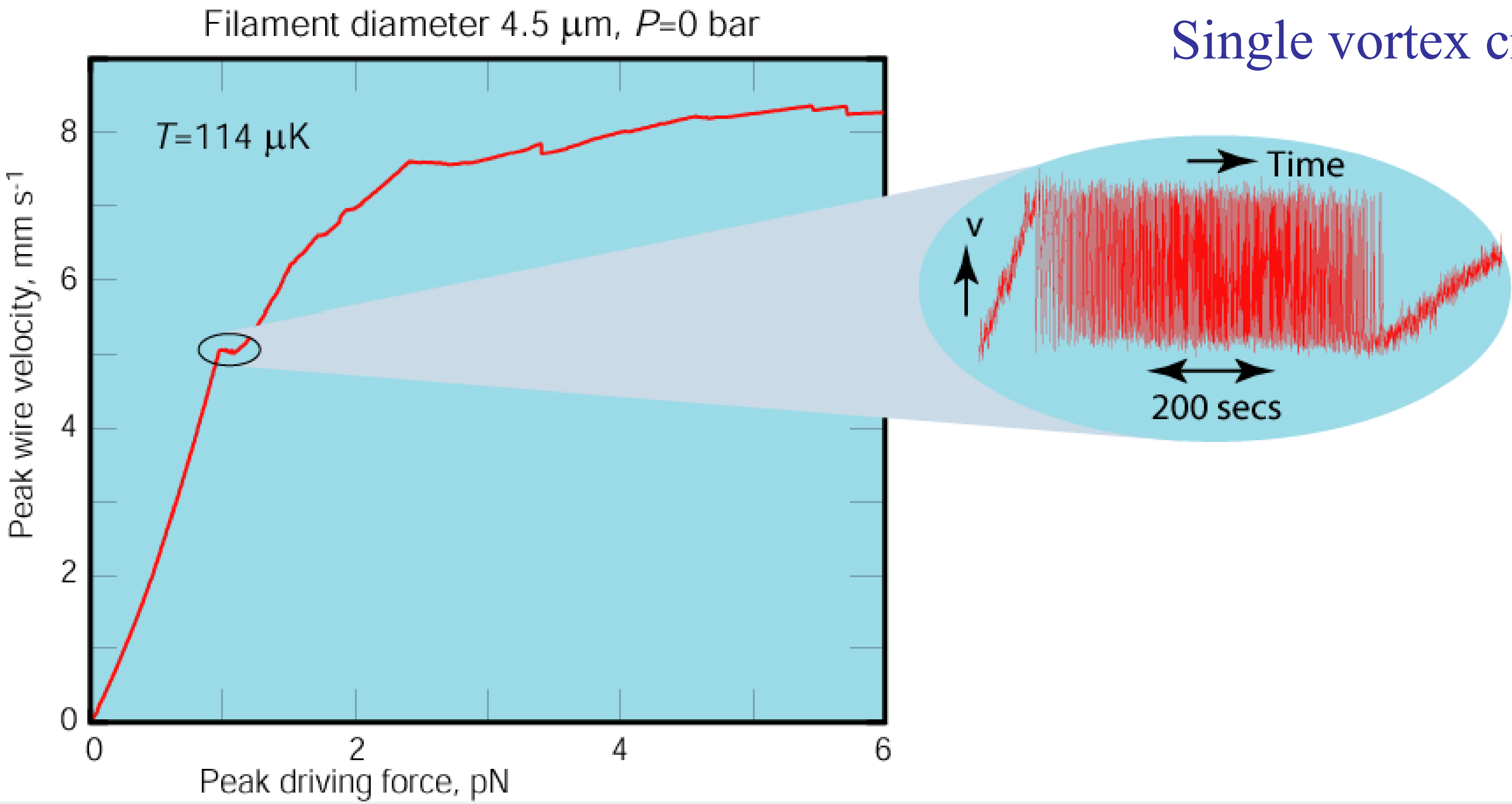
Resonant Signal Voltage, $V_0 \sim 1/\Delta f_2$

Single vortex creation

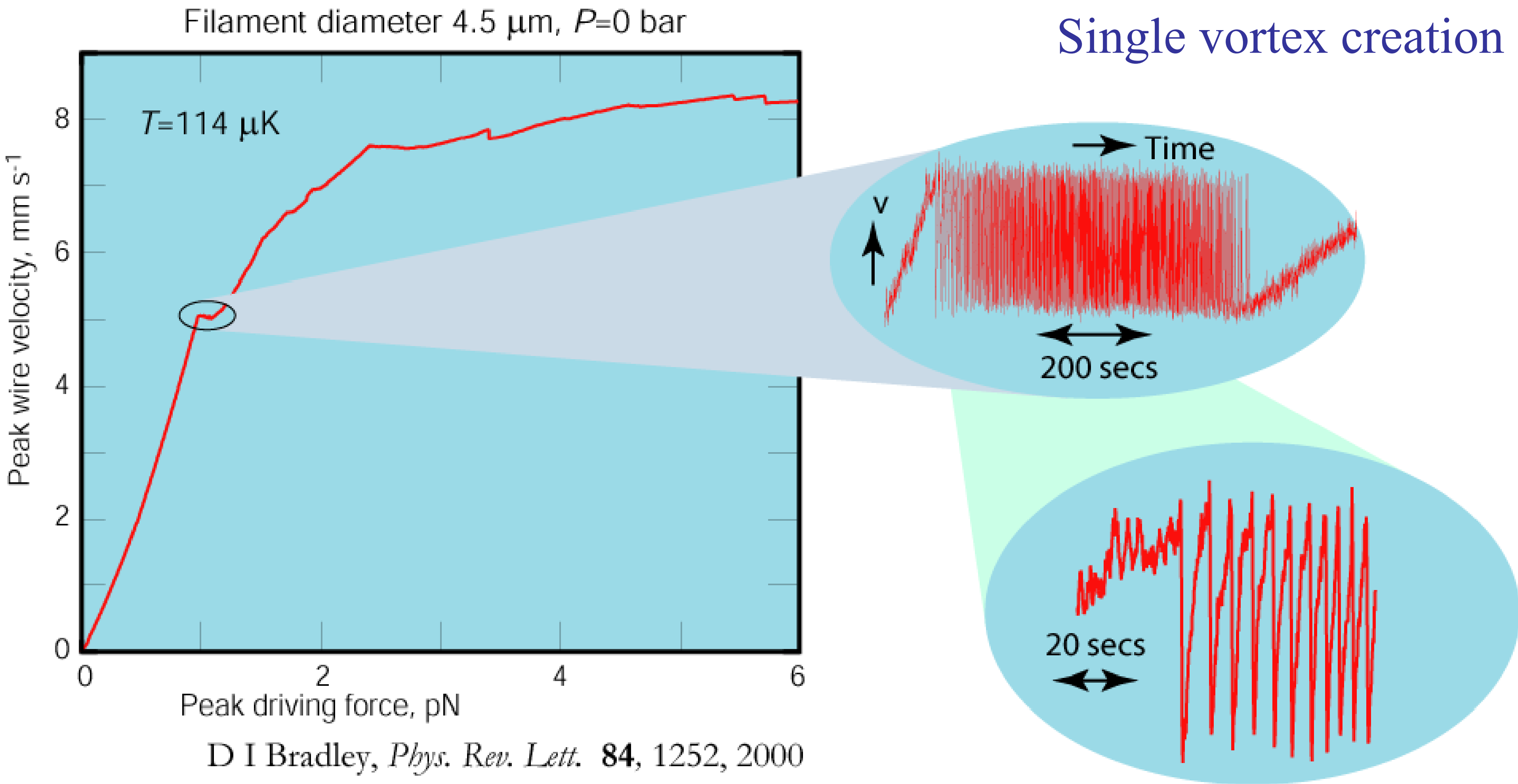


Superfluid 3He B-phase
***P*= 0 bar**
T~110 – 300 mK

Single vortex creation

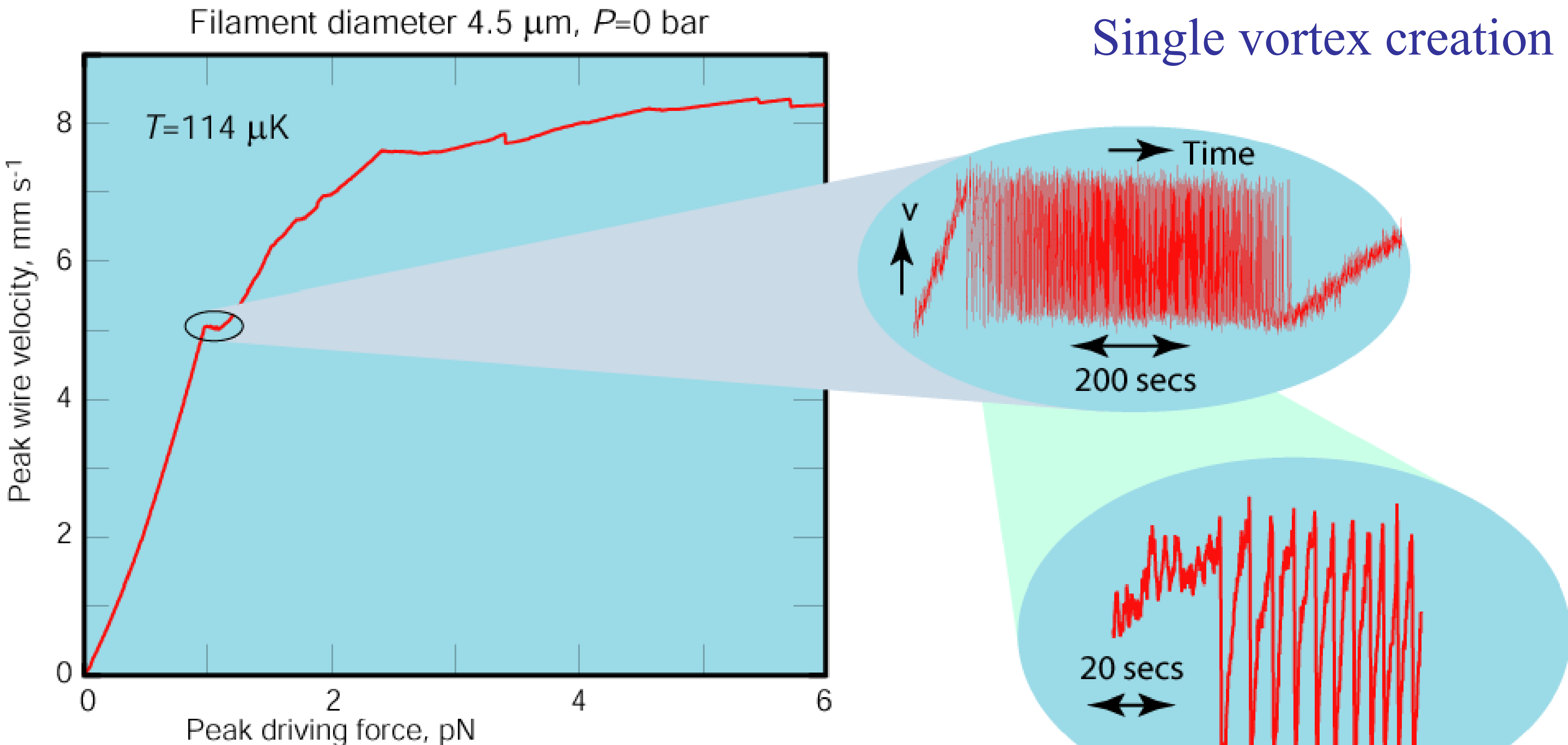


Single vortex creation

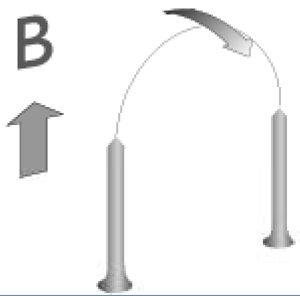


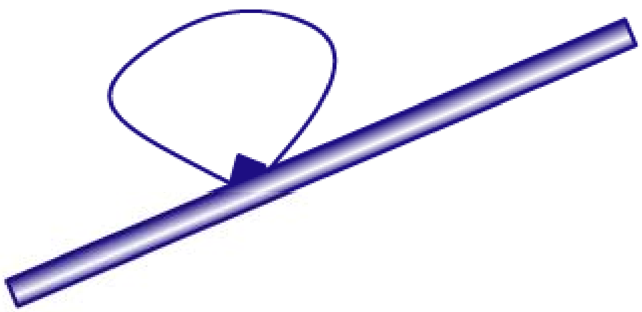
D I Bradley, *Phys. Rev. Lett.* **84**, 1252, 2000

Single vortex creation

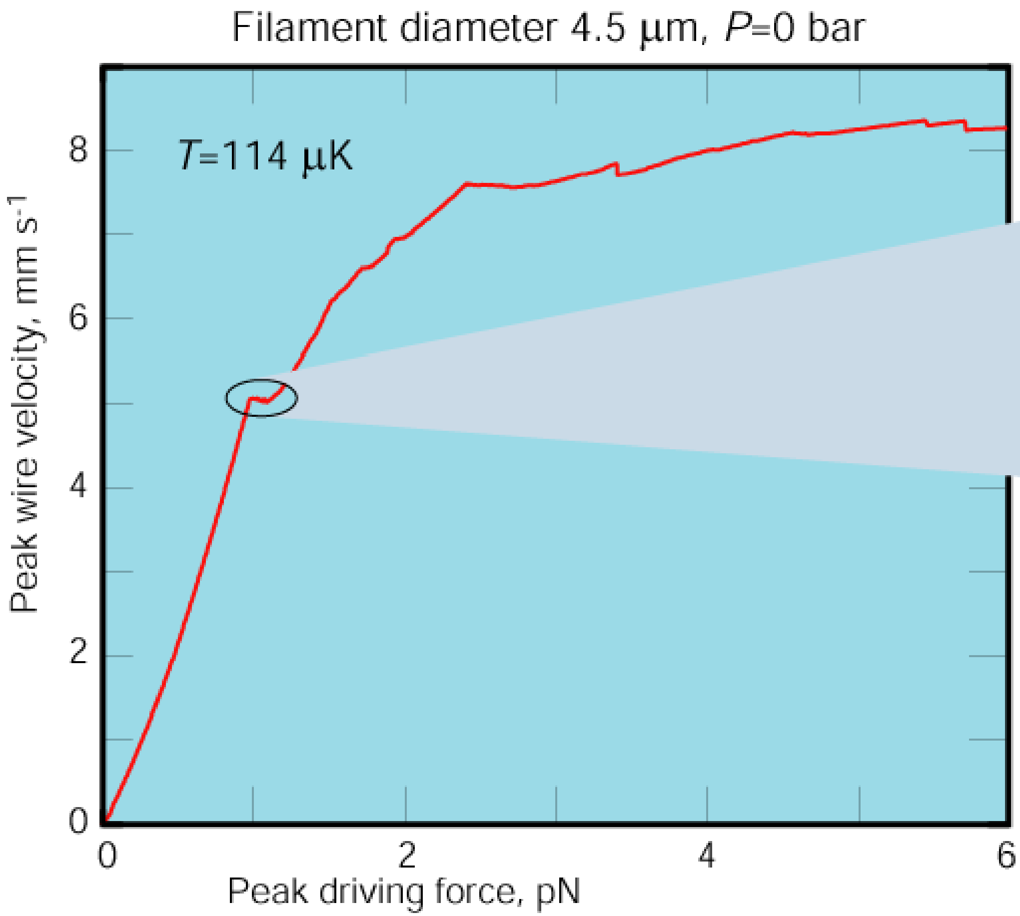


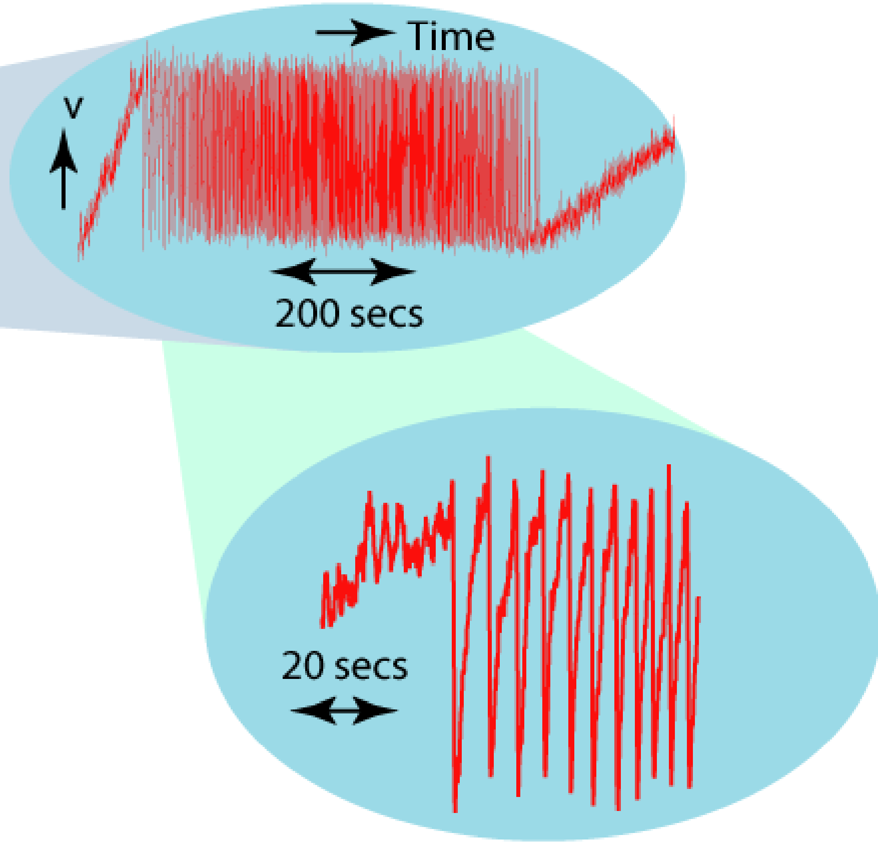
D I Bradley, *Phys. Rev. Lett.* **84**, 1252, 2000



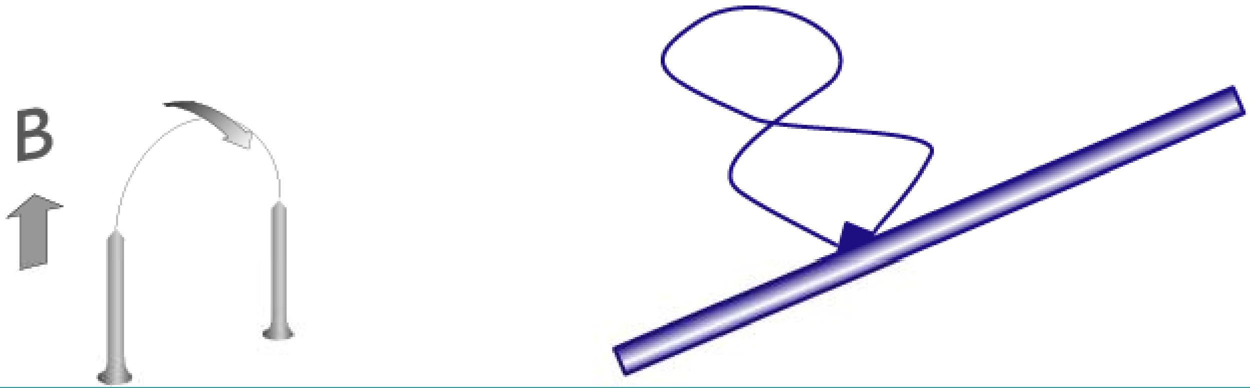


Single vortex creation

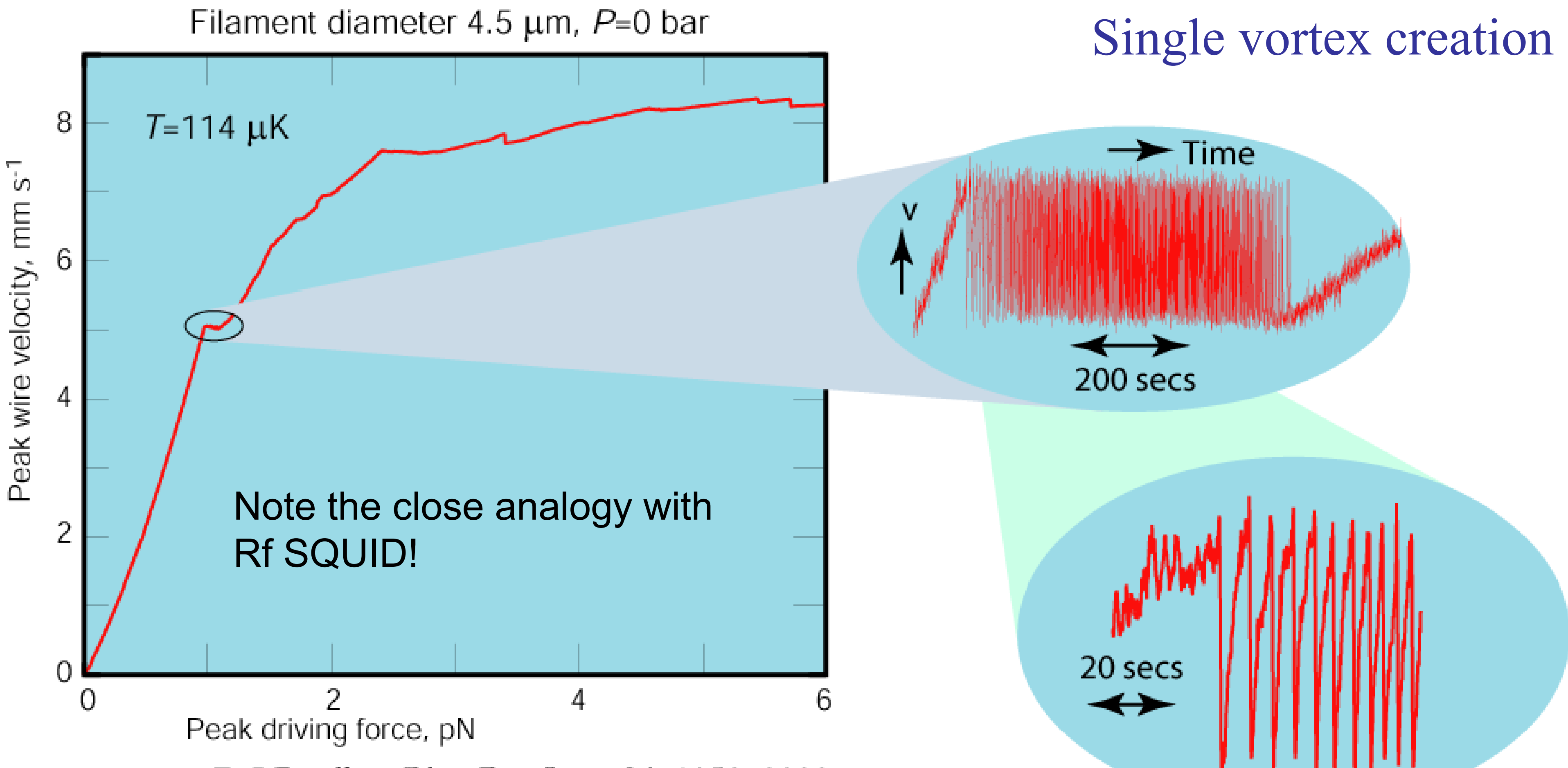




D I Bradley, *Phys. Rev. Lett.* **84**, 1252, 2000



Single vortex creation



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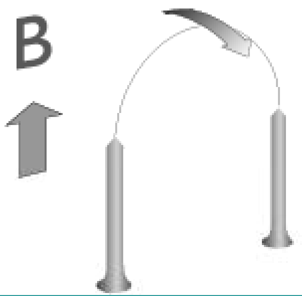
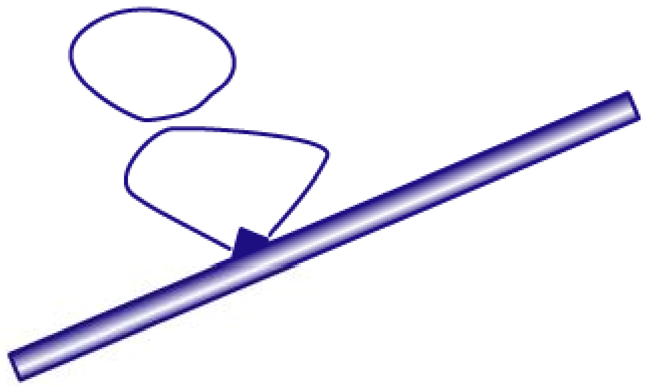
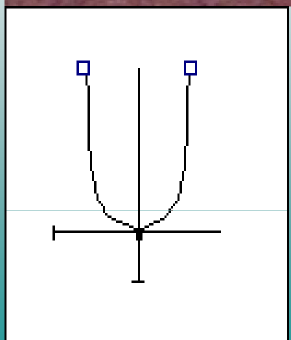
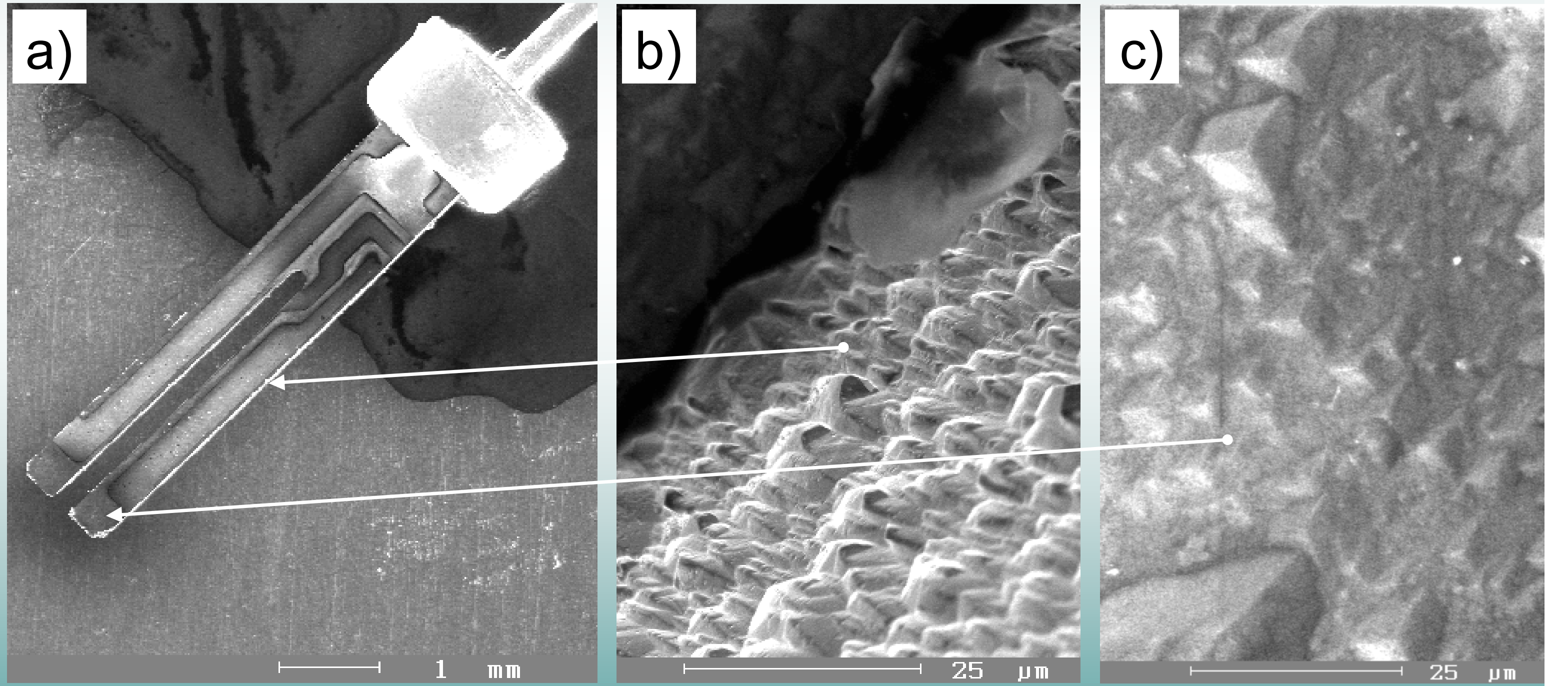




Quartz tuning forks –

- Commercially produced piezoelectric oscillators, used as frequency standards in watches (2^{15} Hz = 32 768 Hz at room temperature)
- New addition to a family of oscillating objects, a probe to investigate physical properties of cryogenic fluids, especially gaseous He, He I, He II and ^{3}He-B
- Cheap, robust, widely available, easy to install and use, extremely sensitive ($Q \approx 10^5 – 10^6$ in vacuum at low T)





An electron micrograph of the quartz tuning fork (a) and details of its side (b) and top (c) quartz surface.

Oscillations of a submerged body in a viscous fluid

Simple harmonic oscillator:

$$m\ddot{x} + F_{damp} + kx = F_0\cos(\omega t)$$ ← harmonic drive

↑ damping

Damping in a Newtonian viscous fluid:

$$F_{damp} = \Delta m\,\ddot{x} + \gamma\,\dot{x}$$ ← viscous drag

↑ hydrodynamic mass enhancement

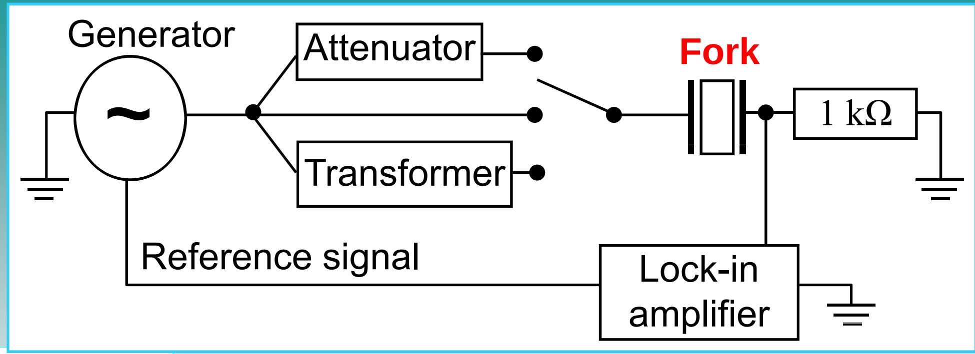
These depend on liquid density and viscosity.

! F_{damp} is phase-shifted relative to velocity

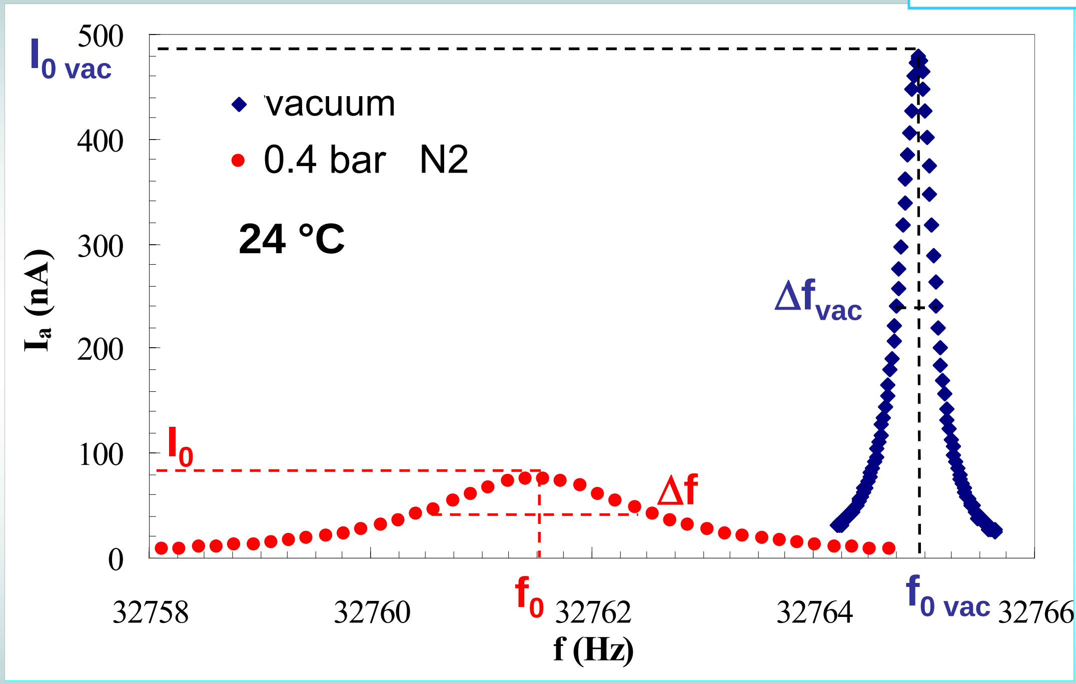
Equation of motion: $$m_{eff}\,\ddot{x} + \gamma\,\dot{x} + k\,x = F_0\cos(\omega t)$$

Forks are easy to use

Connection diagram



Hydrodynamic mass enhancement



Δf, f_0, I_0

↓

ρ, η, v_0

$$\left(\frac{f_{0vac}}{f_0}\right)^2 = 1+\frac{\rho}{\rho_f}\left(\beta + B\frac{S}{V}\sqrt{\frac{\eta}{\pi\rho f_0}}\right)$$

$$\Delta f - \Delta f_{vac} = \frac{1}{2}\sqrt{\frac{\rho\eta f_0}{\pi}}\,\frac{CS}{m_{vac}}\left(\frac{f_0}{f_{0vac}}\right)^2$$

ρ_f Fork's density

ρ Density of the working fluid

η Dynamic viscosity

S Surface of the oscillating body

V Volume of the oscillating body

β, **B, C** numerical constants ~ geometry

β, B, C – fitting parameters, characterize determined fork

Working fluids

1) gaseous N_2, room temperature, up to 30 bar

2) gaseous He, room temperature, up to 30 bar

78 K, up to 30 bar

3) normal liquid He (2.17 K; 4.2 K), up to 30 bar

4) superfluid liquid He (1.3 K; 2.17 K), SVP

Playground:

Kinematic viscosity: **(1**$\cdot 10^{-4}$ **- 0.15)** cm^2/s

Dynamical response over 7 orders of magnitude of drive

Quartz Tuning Fork: Thermometer, Pressure- and Viscometer for Helium Liquids*

JLTP, 2007

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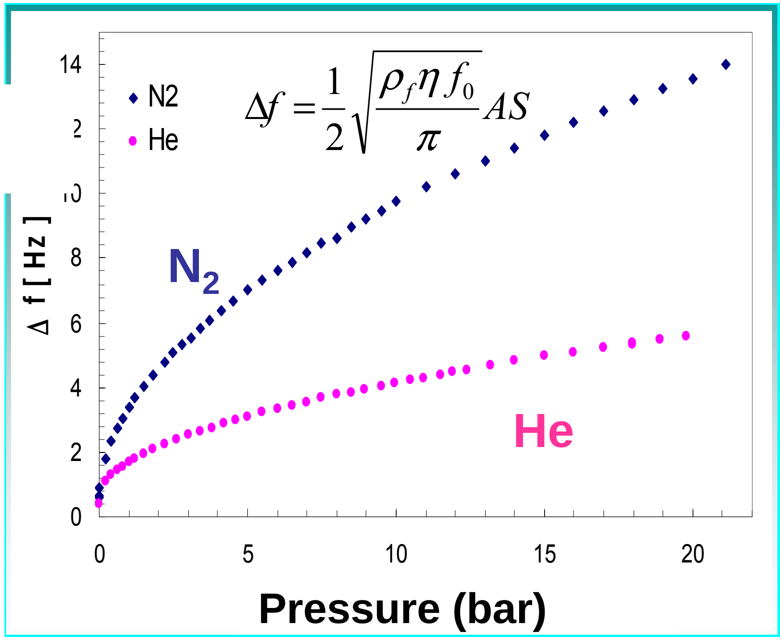
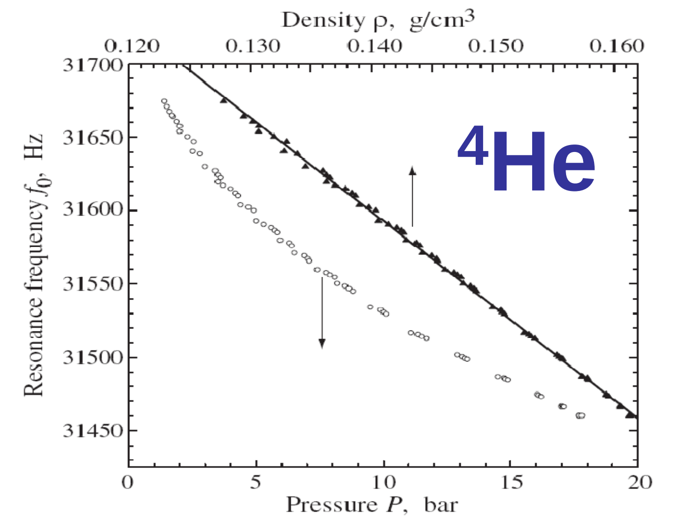
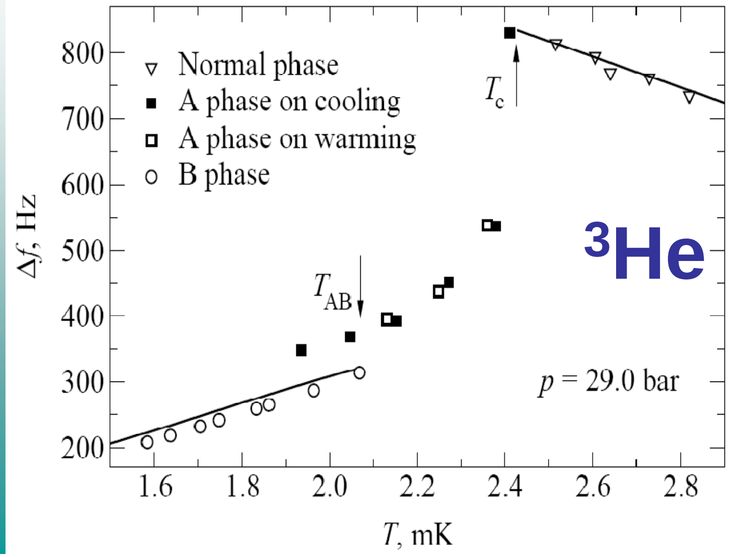
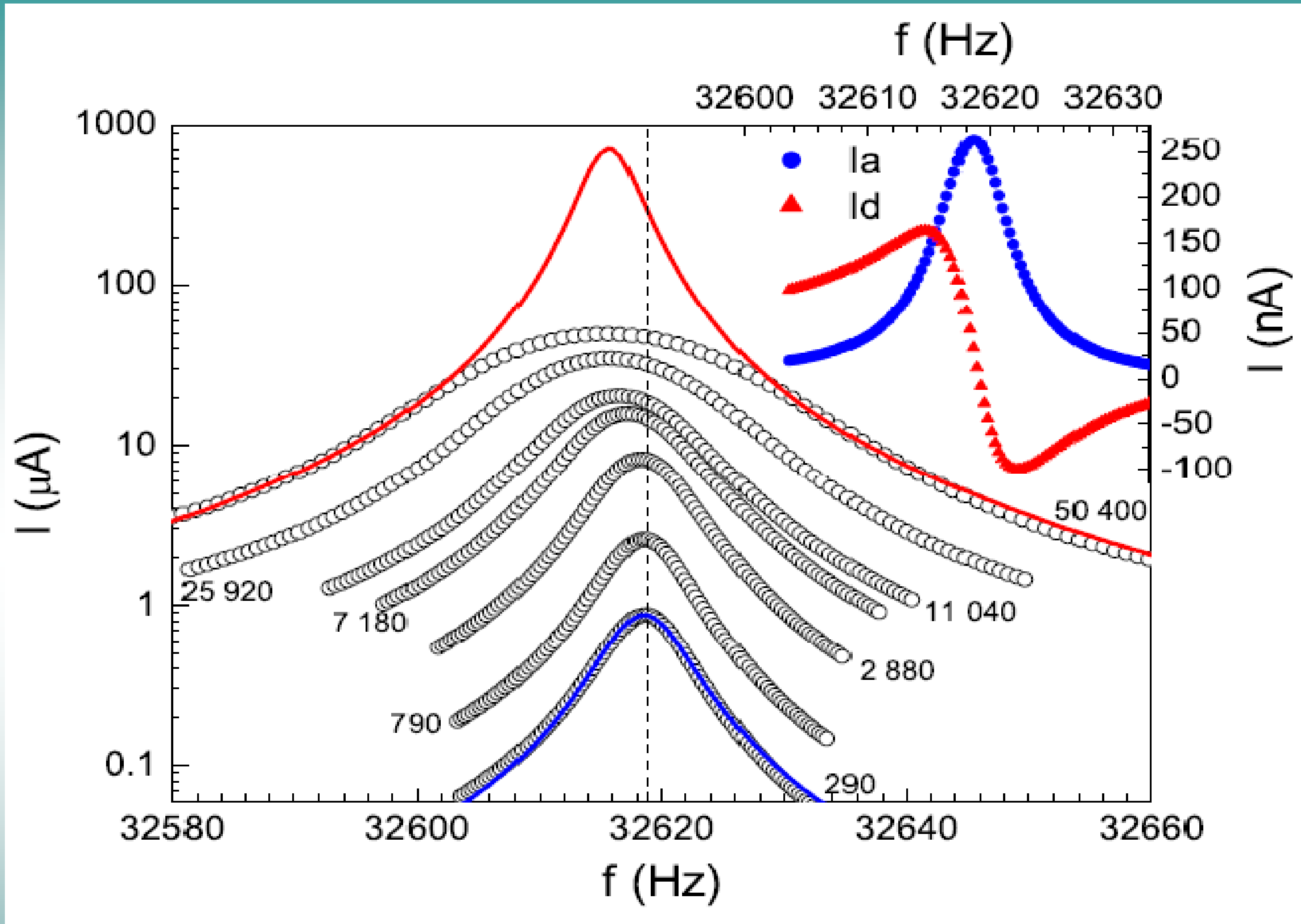






$$\left(\frac{f_{0vac}}{f_0}\right)^2 = 1 + \frac{\rho}{\rho_f}\left(\beta + B\frac{S}{V}\sqrt{\frac{\eta}{\pi\rho\ f_0}}\right) + ???$$

Quartz fork as a generator and detector of turbulence



The in-phase resonant response of the driven quartz fork versus applied frequency measured for various drive voltage levels (in mV_{rms}) as indicated. The solid curves are Lorentzian fits to the data.

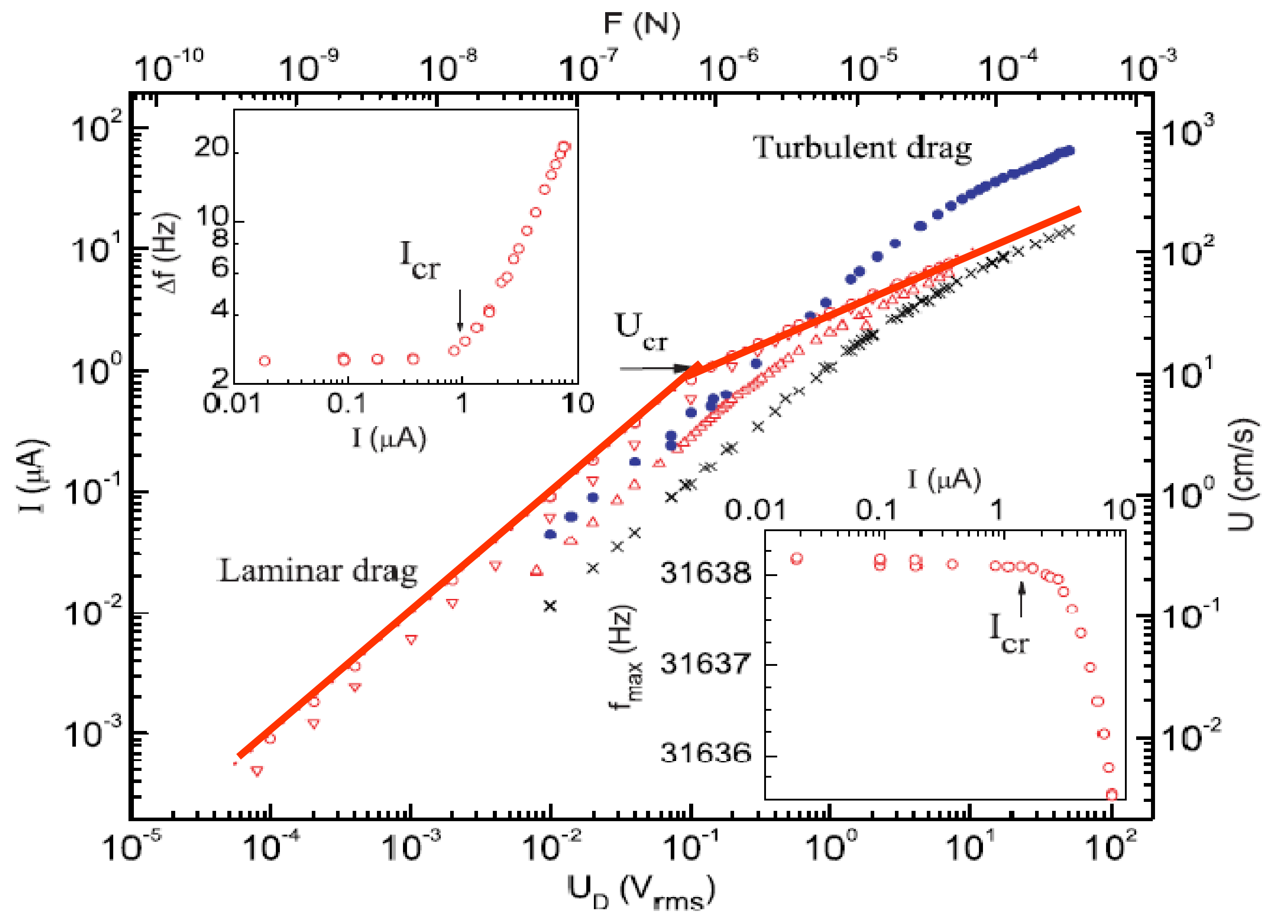


FIG. 2: Transition from laminar to turbulent drag regime as detected by the vibrating quartz fork A2 in He I at 4.2 K and 18.6 bar (×), in He II at SVP at 1.37 K (○), 1.61 K (▽), 2.06 K (△) and in gaseous helium at 78 K and 10.05 bar (•). For conversion of measured electrical quantities U_D and I to F and U, see [1]. The insets show the width Δf of the in-phase resonance response (top) and the frequency of maximum response f_{max} (bottom) versus measured current; both being constant in a linear regime. Increase of Δf and decrease of f_{max} indicate an onset of the turbulent drag regime.

Quartz fork - a generator and detector of turbulence

Transition from laminar to turbulent drag in ^4He

Measured in: (i) He gas at 78 K and ambient and elevated pressure up to 30 bar
(ii) He I at 4.2 K and various pressures and down to Tλ at SVP
(iii) He II down to 1.3 K at saturated vapour pressure (SVP)

All these experiments (with three tuning forks A1, A2, B1) were performed in the **same experimental pressure cell** using the **same sample of He** throughout, starting with the highest density which was gradually released in order to prevent gathering of any solid particles on the fork's surface

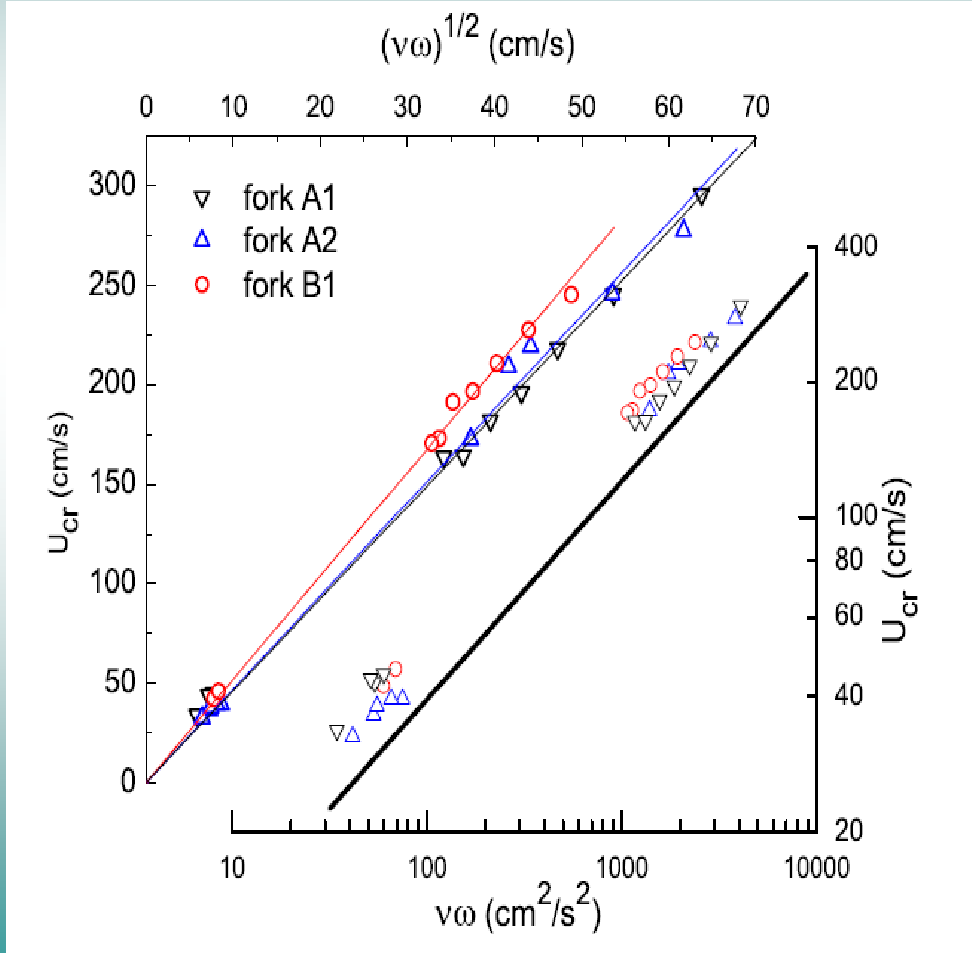
^{4}He properties are very well known and tabulated:

R. J. Donnelly and C. F. Barenghi, J. Phys. Chem. Data **27** (1998) 1217.
R.D. McCarty, *Technical Note* 631, National Bureau of Standards, Gaithersburg, Maryland (1972);
V.D. Arp, R.D. McCarty, *The properties of Critical Helium Gas*, Technical Report, Univ. Oregon (1998)

Critical velocities (classical fluids)

Critical velocity scaling:

$$U_C \approx \sqrt{\nu\omega}$$

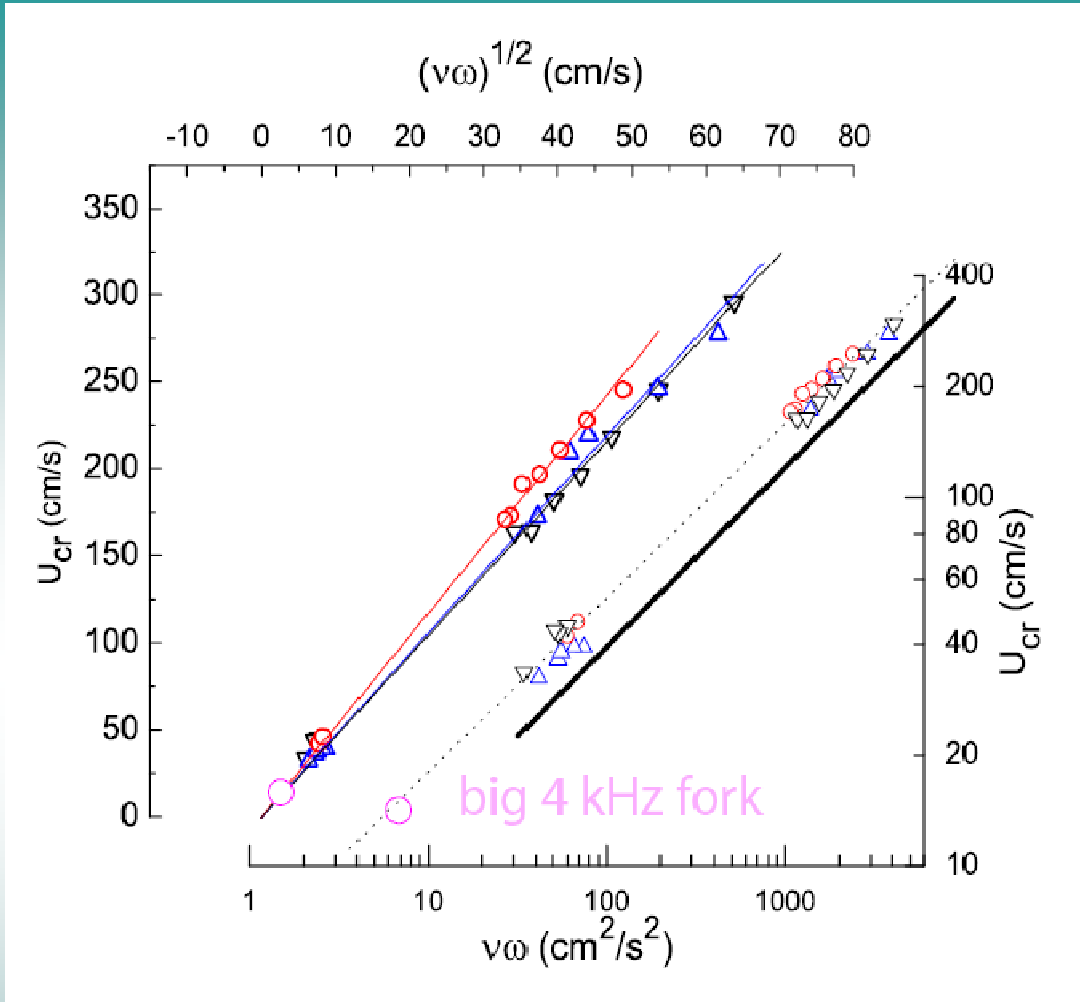


We experimentally verify (using He I at SVP and elevated pressures and He gas at nitrogen temperature as working fluids) that this scaling indeed holds.

The logarithmic graph gives a gradient 0.48 ± 0.04

M. Blažková, D. Schmoranzer, L. Skrbek,

Phys. Rev. E75, 025302R (2007)



Steady viscous flows - transition from laminar to turbulent drag regime
is characterized

$$\mathrm{Re}_c = \frac{U_c D}{\nu}$$

Flow due to an oscillating object : another length scale:

$$\delta = \sqrt{2\nu / \omega}$$

$$\mathrm{Re}_c^{\delta} = \frac{U_c \delta}{\nu}$$

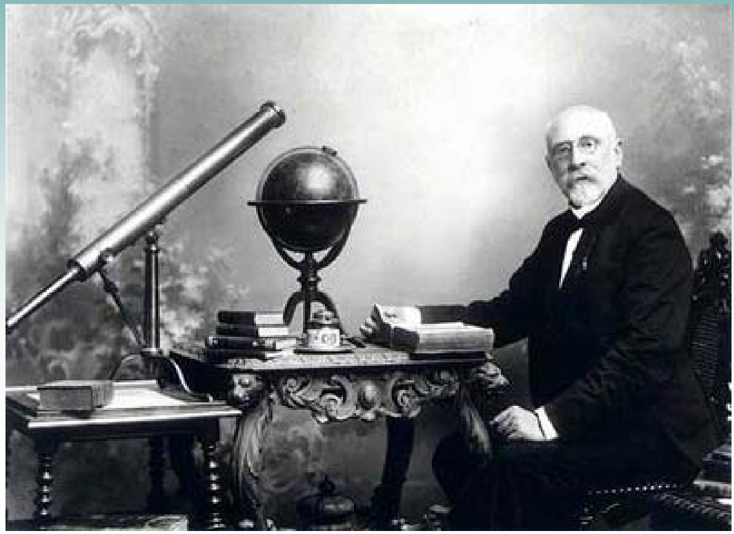
The critical velocity is independent of the object size if $\delta << D$

$$U_C \approx \sqrt{\nu\omega}$$

To describe an oscillatory boundary layer flow,

Reynolds AND Strouhal numbers needed:

$$\mathrm{Re} = \frac{UD}{\nu} \qquad S = \frac{U\tau}{D}$$



Professor Čeněk Strouhal

However for the oscillating

fork we assume:

Characteristic length scale –

NOT fork dimension *D*, but

viscous penetration depth δ!!!

$$\delta = \sqrt{\frac{2\nu}{\omega}} \approx 0.5\mu m << D \approx 100\mu m$$

Replacing *D* by δ in both *Re* and *S* we get:

$$S \propto Re \propto \frac{U}{\sqrt{\nu\omega}}$$

•The transition to turbulence can be thus described by the Reynolds (Strouhal) number alone

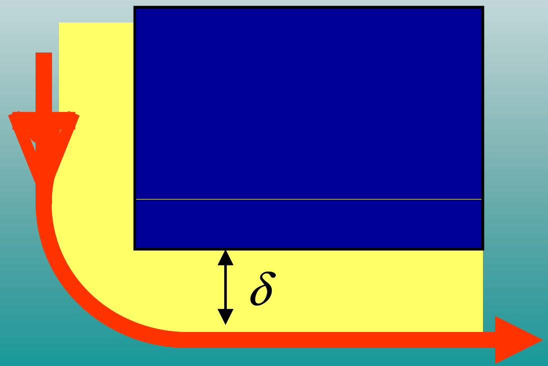
Exactly soluble example – an oscillating sphere in a limit $R >> \delta = \sqrt{2\nu / \omega}$

Laminar drag force $F_{lam} = \lambda U = 6\pi\eta \mathrm{RU} \left(1 + \frac{\mathrm{R}}{\delta}\right)\Big|_{R>>\delta} \approx 6\pi\eta \mathrm{R} \frac{\mathrm{R}}{\delta} \mathrm{U}$

Turbulent drag force $F_{turb} = \gamma U^2 = 0.5\, \mathrm{C_D} \pi\rho \mathrm{R}^2 U^2$

Crossover $U_C = \frac{\lambda}{\gamma} = \frac{6}{C_D}\sqrt{2\nu\omega} \approx 21\sqrt{\nu\omega}$

This gives about 1.3 m/s for a sphere of any size, oscillating at 32 kHz in He I at SVP right above the superfluid transition
(factor of 4 higher than what is observed for our forks)

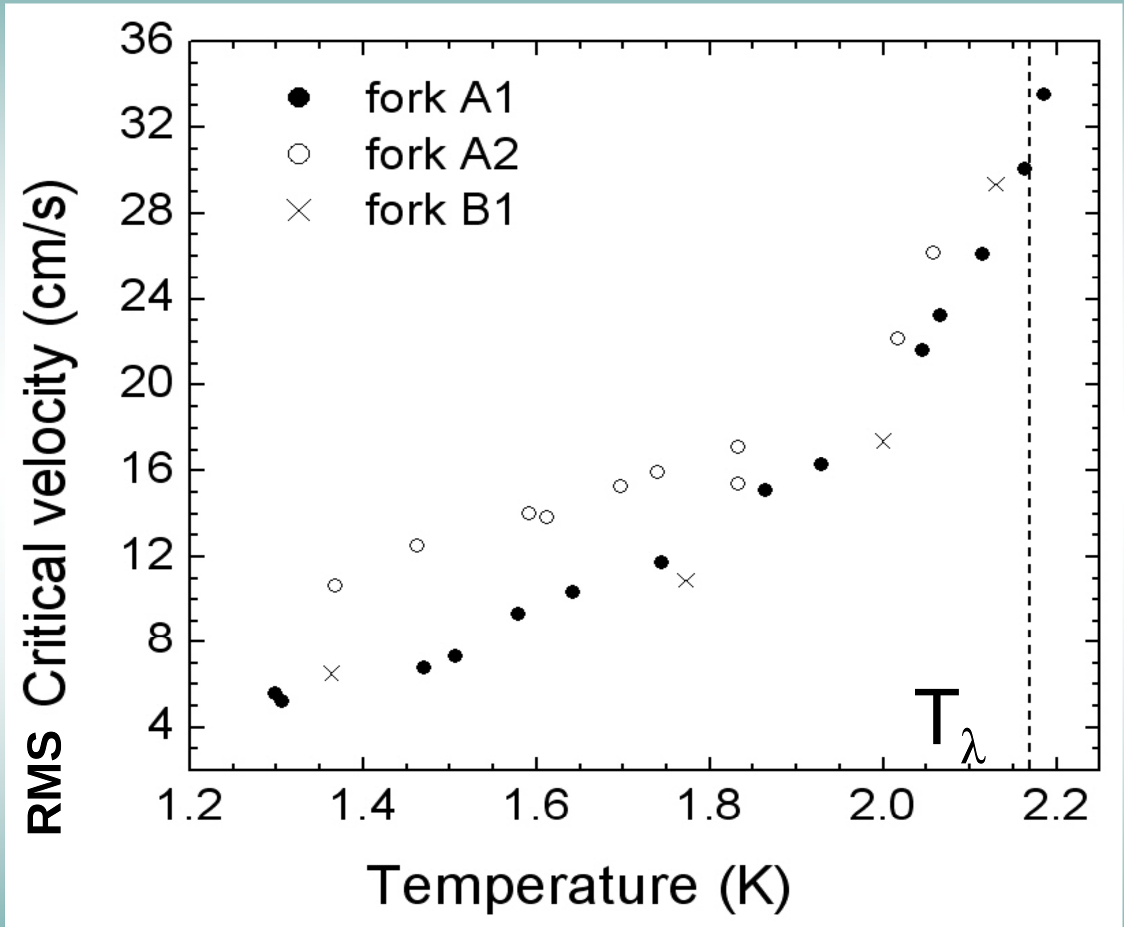


velocity enhancement at the corner

$$U_{enh} \approx \left(d / r\right)^{1/3} U \approx 5\ U$$

gives even better agreement with the experiment

Results in He II



The observed critical velocity at which transition from laminar to turbulent drag regime occurs for three forks marked A1, A2 and B1.

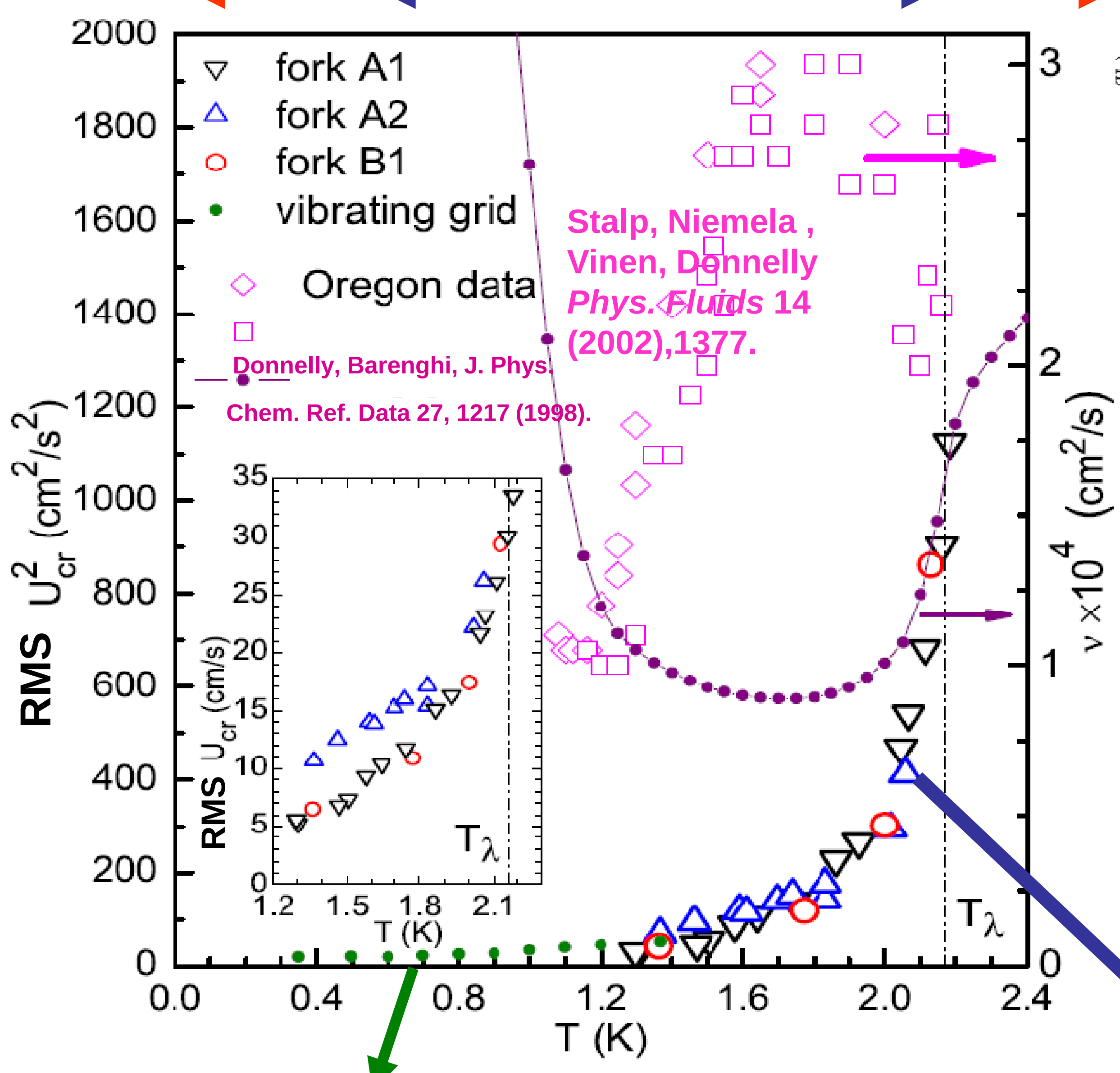
These data allow extracting the T-dependence of the effective kinematic viscosity, using the scaling:

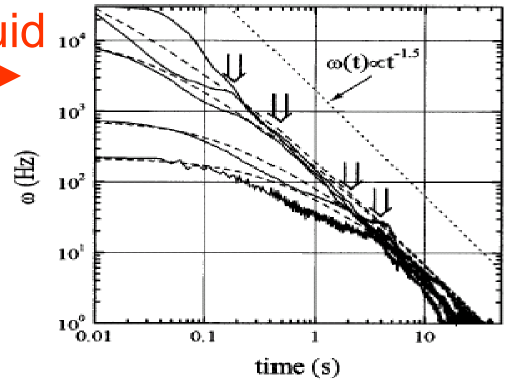
$$U_C \approx \sqrt{\nu\omega}$$

verified for classical viscous fluids, **if** **He II is treated as a single-component quasiclassical fluid.**

The unknown multiplicative constant is best determined by matching the data at T_λ.

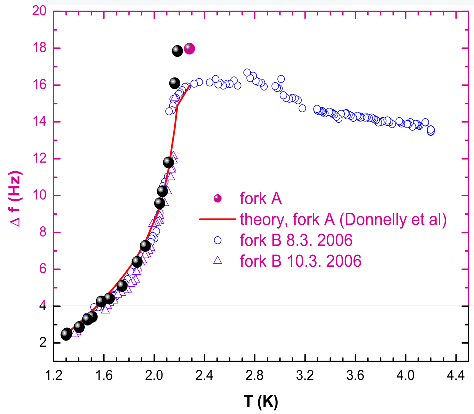
Pure superfluid — Two-fluid model — Classical fluid





Stalp, Skrbek, Donnelly: Phys.Rev.Lett. 82 (1999) 4831

$$L(t) = \frac{D(3C)^{3/2}}{2\pi\kappa\sqrt{\nu_{eff}}}(t+t^*)^{-3/2}$$

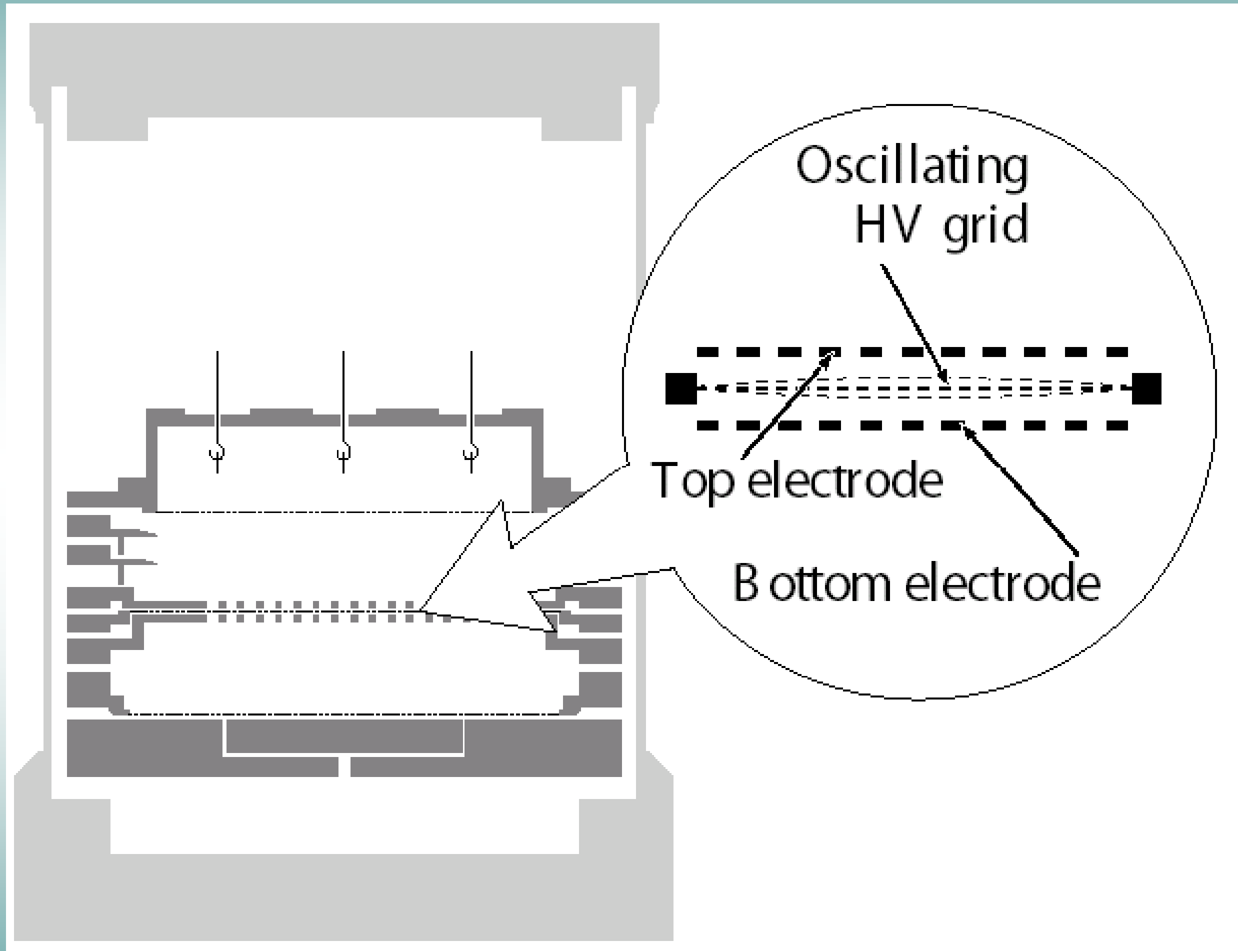


Our data, obtained via scaling

$$\sqrt{\nu_{eff}^{fork}(T)\omega}$$

D. Charalambous, L. Skrbek, P.C. Hendry, P.V.E. McClintock, W.F. Vinen, Phys. Rev.E 74, 036307 (2006)

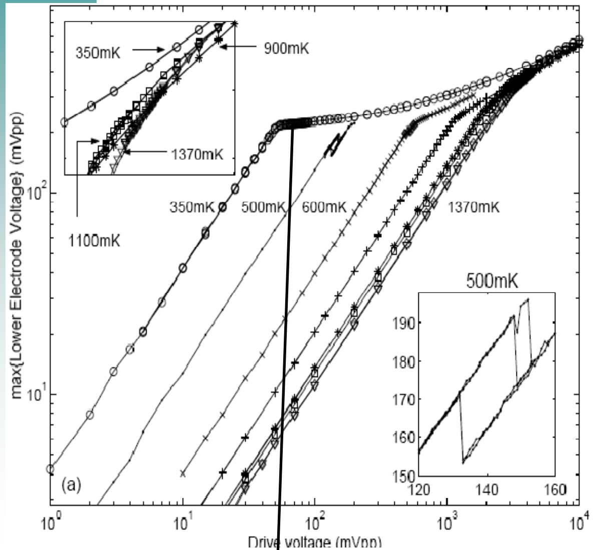
Experimental cell containing 1.5 litre of spectrally pure He-4, attached to the dilution refrigerator (base T about 10 mK)

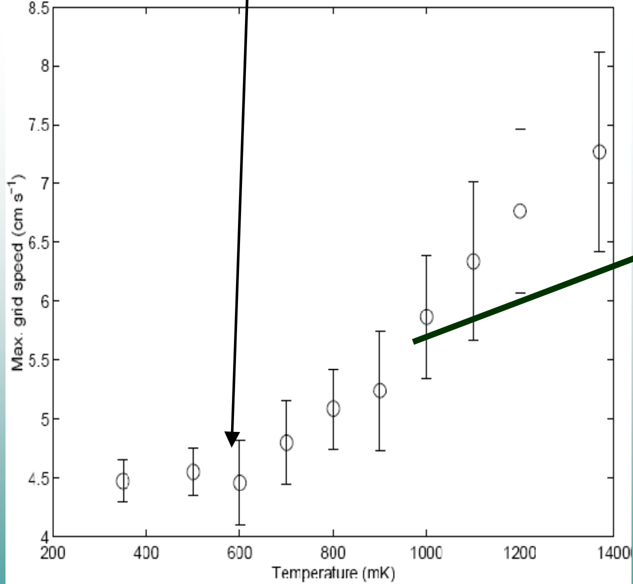


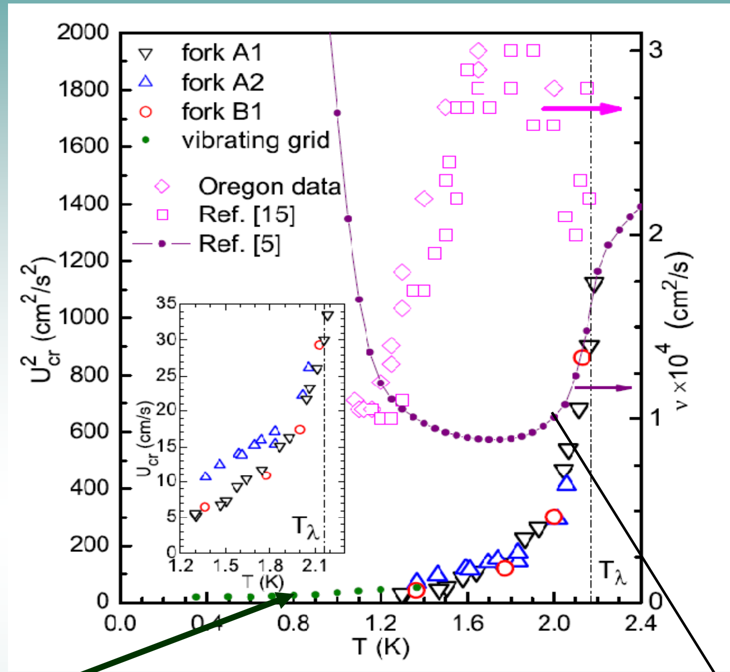
T < 130 mK
0 < p < 25 bar

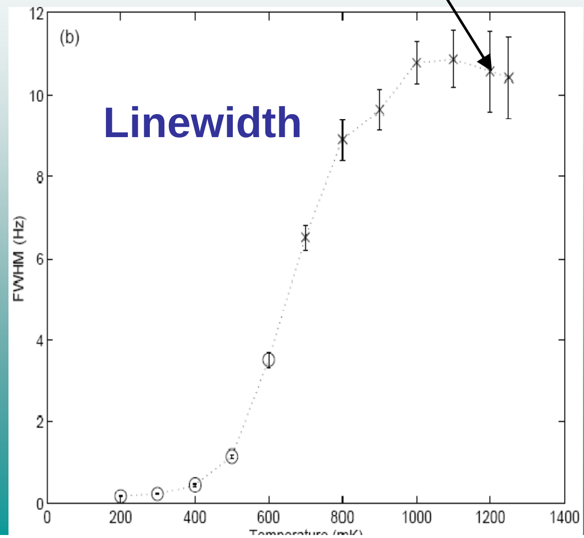
Experimental Investigation of the Dynamics of a Vibrating Grid in Superfluid ^{4}He over a Range of Temperatures and Pressures

D. Charalambous,[1,2,*] L. Skrbek,[3] P.C. Hendry,[1] P.V.E. McClintock,[1] and W.F. Vinen[4]



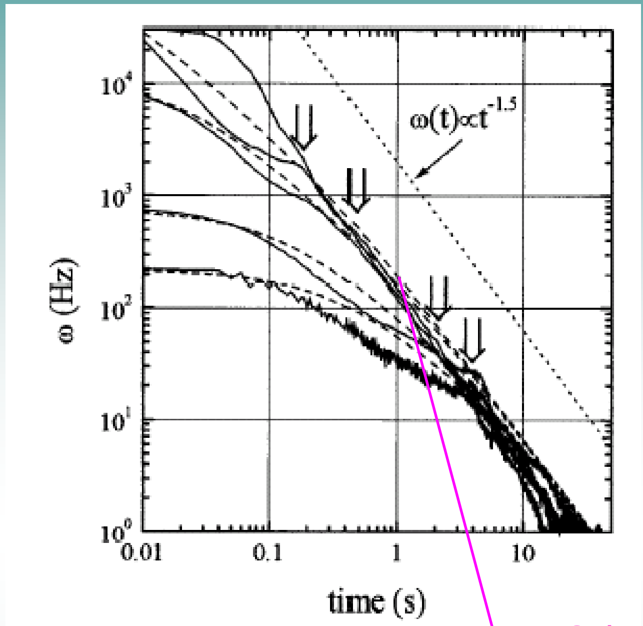






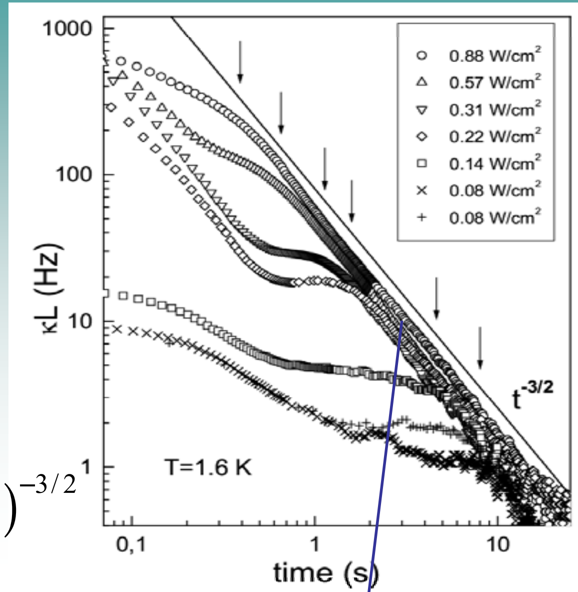
Decay of towed grid turbulence in He II above 1K

Stalp, Skrbek, Donnelly: PRL **82** (1999) 4831



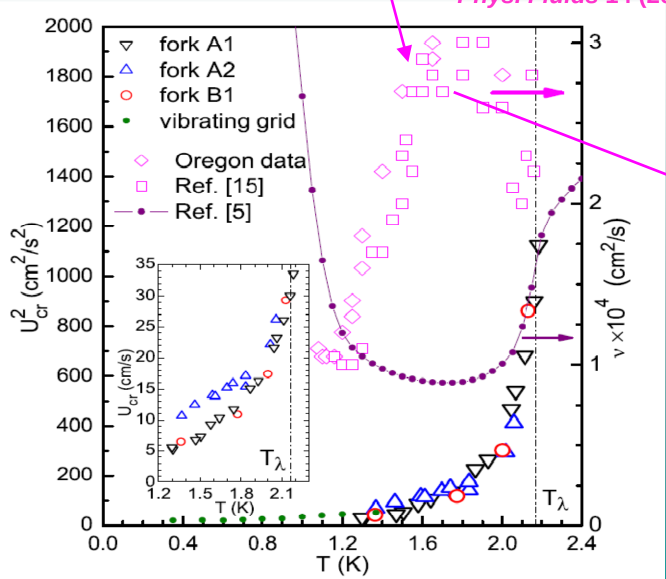
counterflow turbulence

Skrbek, Gordeev, Soukup: PRE **67**, 047302 (2003)



$$L(t) = \frac{D(3C)^{3/2}}{2\pi\kappa\sqrt{\nu_{eff}}}(t+t^*)^{-3/2}$$

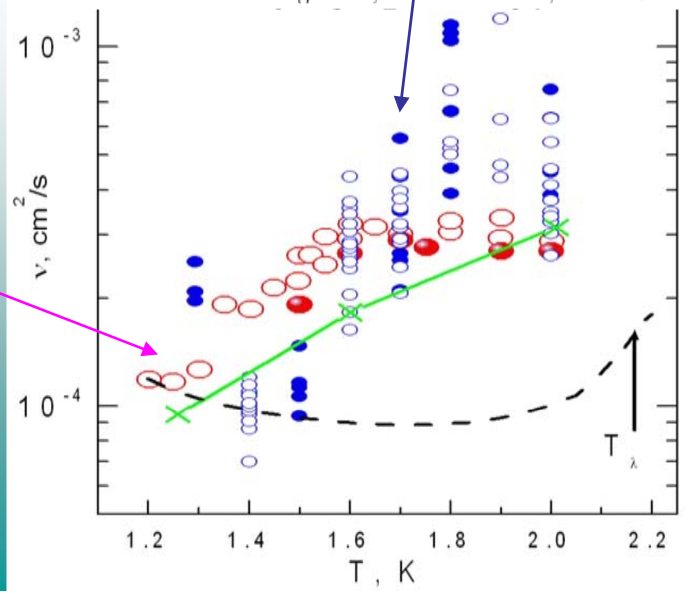
Stalp, Niemela , Vinen, Donnelly
Phys. Fluids 14 (2002),1377.



Effective Kinematic Viscosity of Turbulent He II

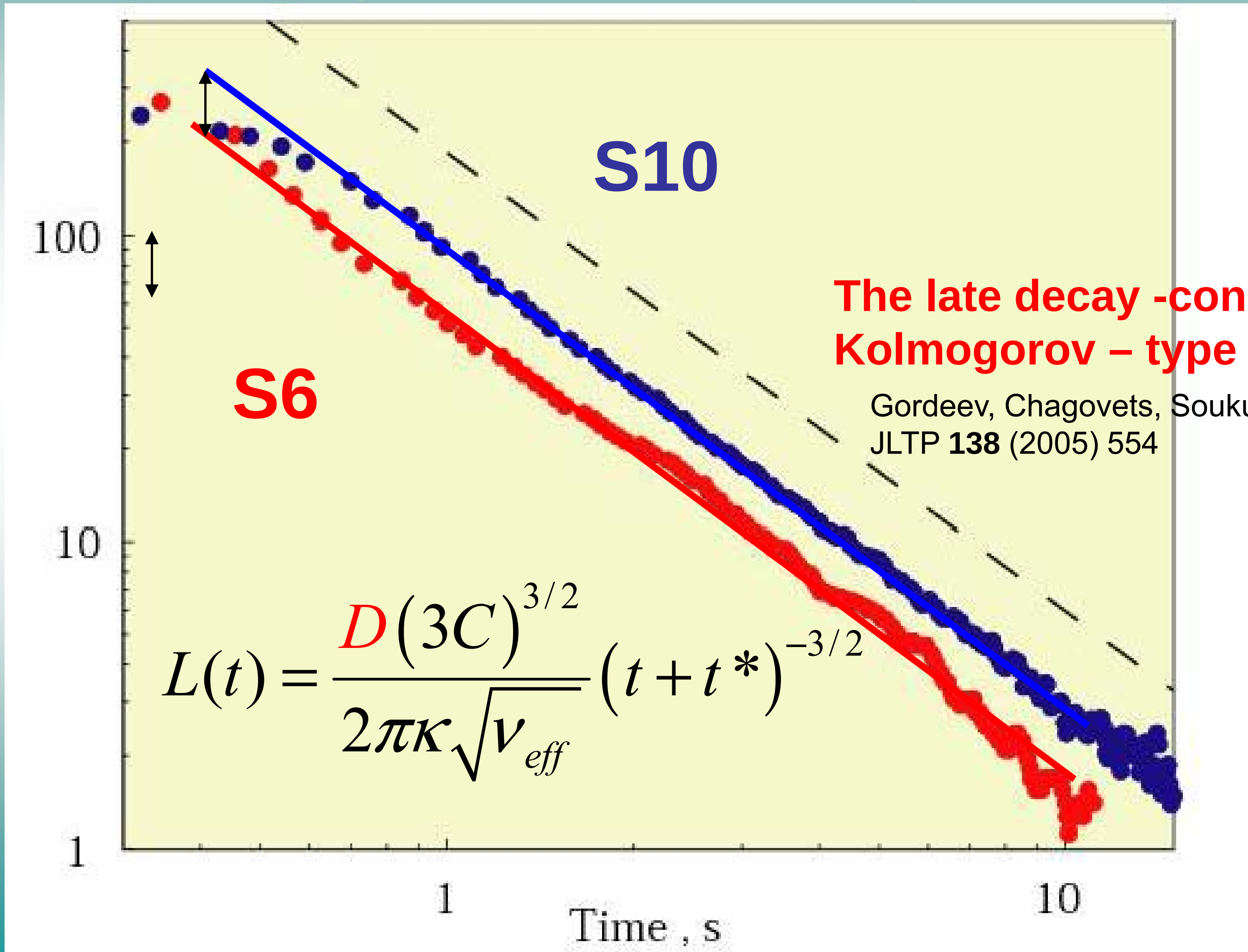
Subm. to PRE

T.V. Chagovets[1], A.V. Gordeev[1], L. Skrbek[2]



After saturation of the energy-containing length scale – universal decay law

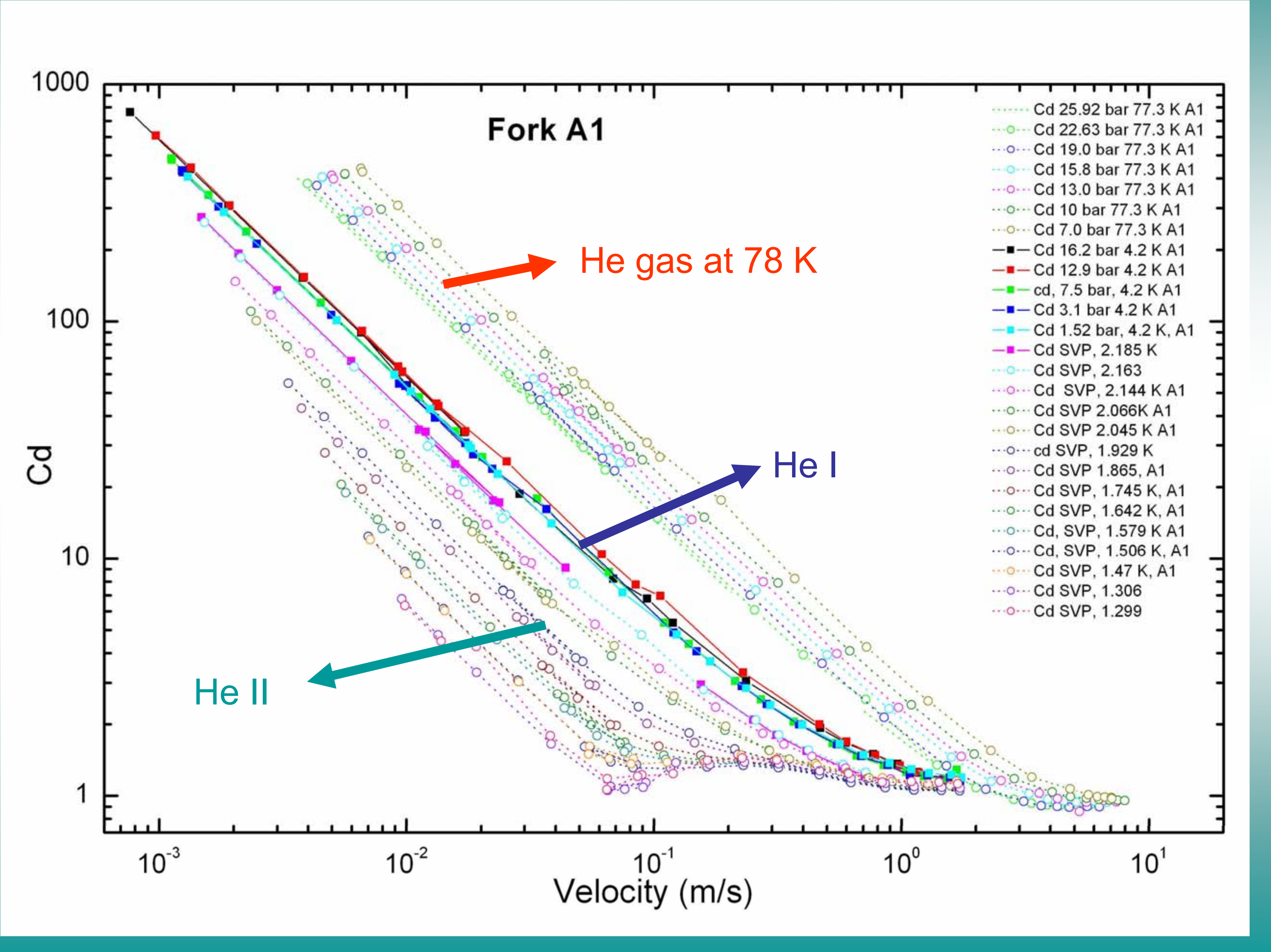
Dependence on the channel size experimentally confirmed for the first time (even for classical turbulence)



The late decay -consistent with Kolmogorov – type turbulence

Gordeev, Chagovets, Soukup, Skrbek, JLTP **138** (2005) 554

Drag coefficient versus velocity in helium gas, He I and He II



Second approach – normal fluid and superfluid are fully independent

The fitting function for the normal phase is obtained simply by adding the drag coefficient appropriate to the laminar regime to that appropriate to the fully turbulent regime - the drag at all velocities is the sum of the laminar drag and the turbulent drag, both terms being present at all velocities, the dominant term being simply the larger one.

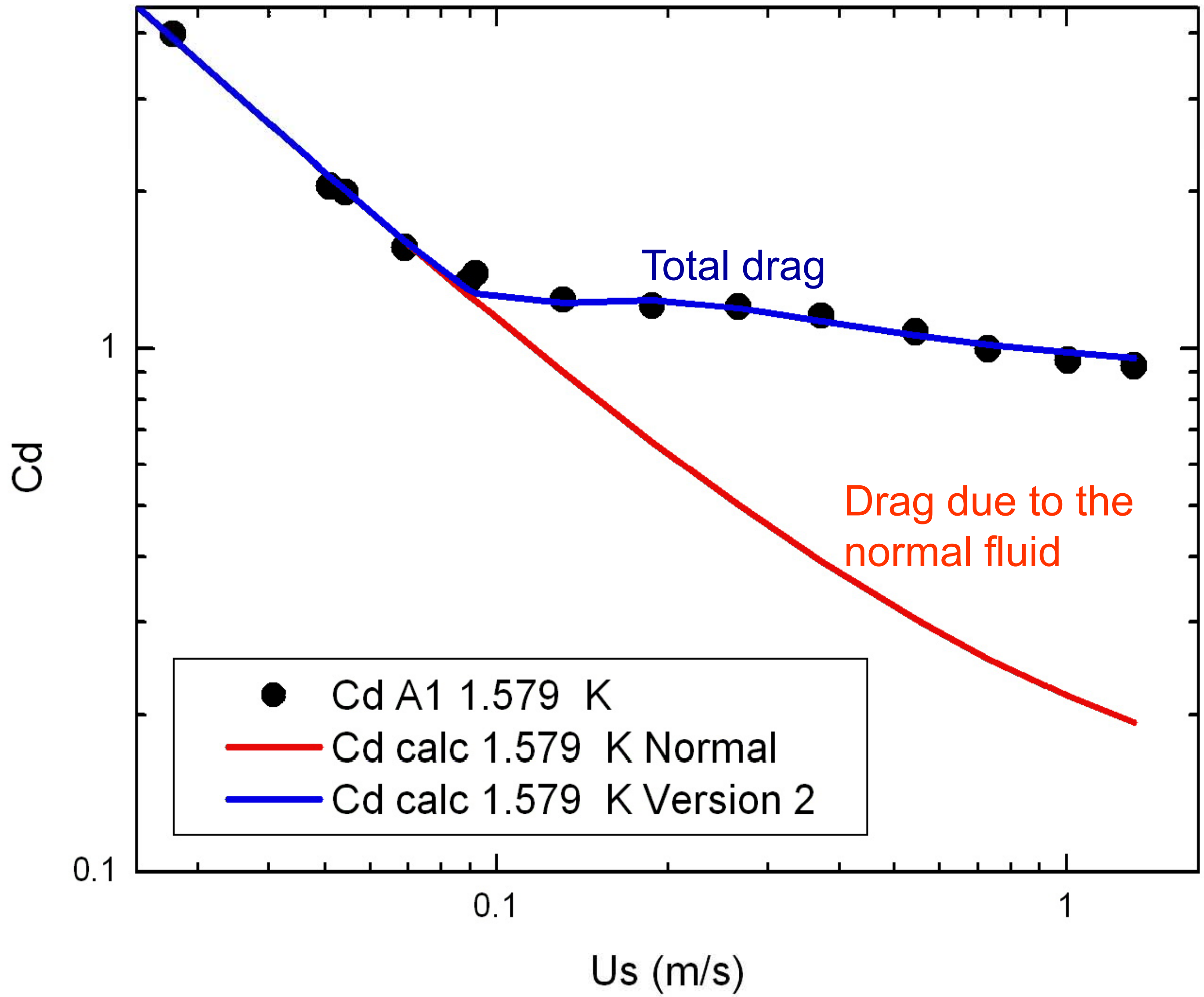
N laminar N turbulent (const) SF turbulent

$$Cd(U, \frac{\rho_n}{\rho}, \nu) = \frac{\alpha' \, 2 \, S/A \sqrt{2\pi f_0 \, \frac{\rho_n}{\rho} \, \nu}}{U} + \beta \frac{\rho_n}{\rho} + \gamma \left(1 - \frac{\rho_n}{\rho}\right) \Phi(U - U_c) \left[\frac{(U - U_c)^2}{\epsilon + (U - U_c)^2}\right]$$

Step function

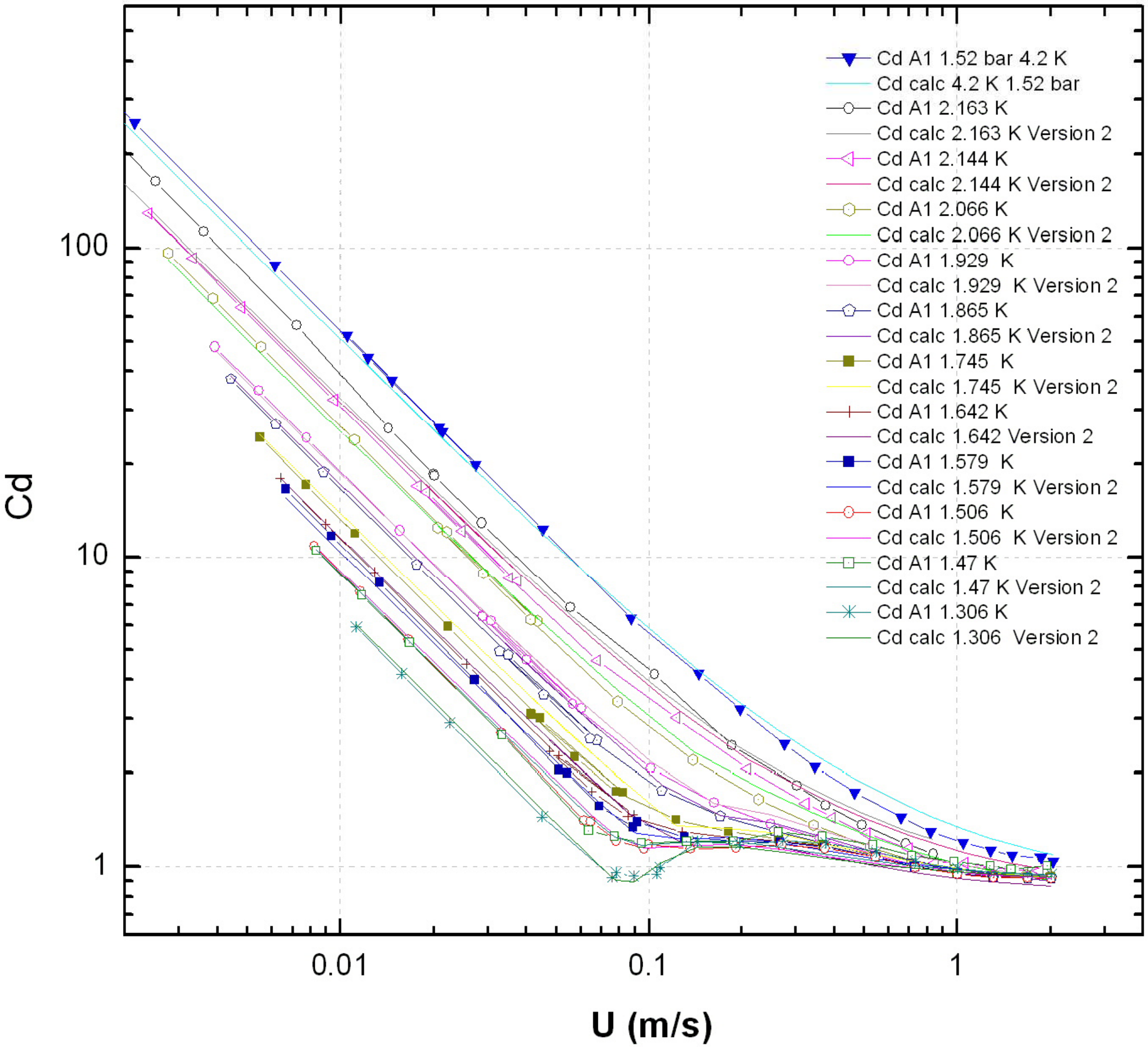
Uc is the sharp critical velocity for onset of turbulence in the superfluid component.

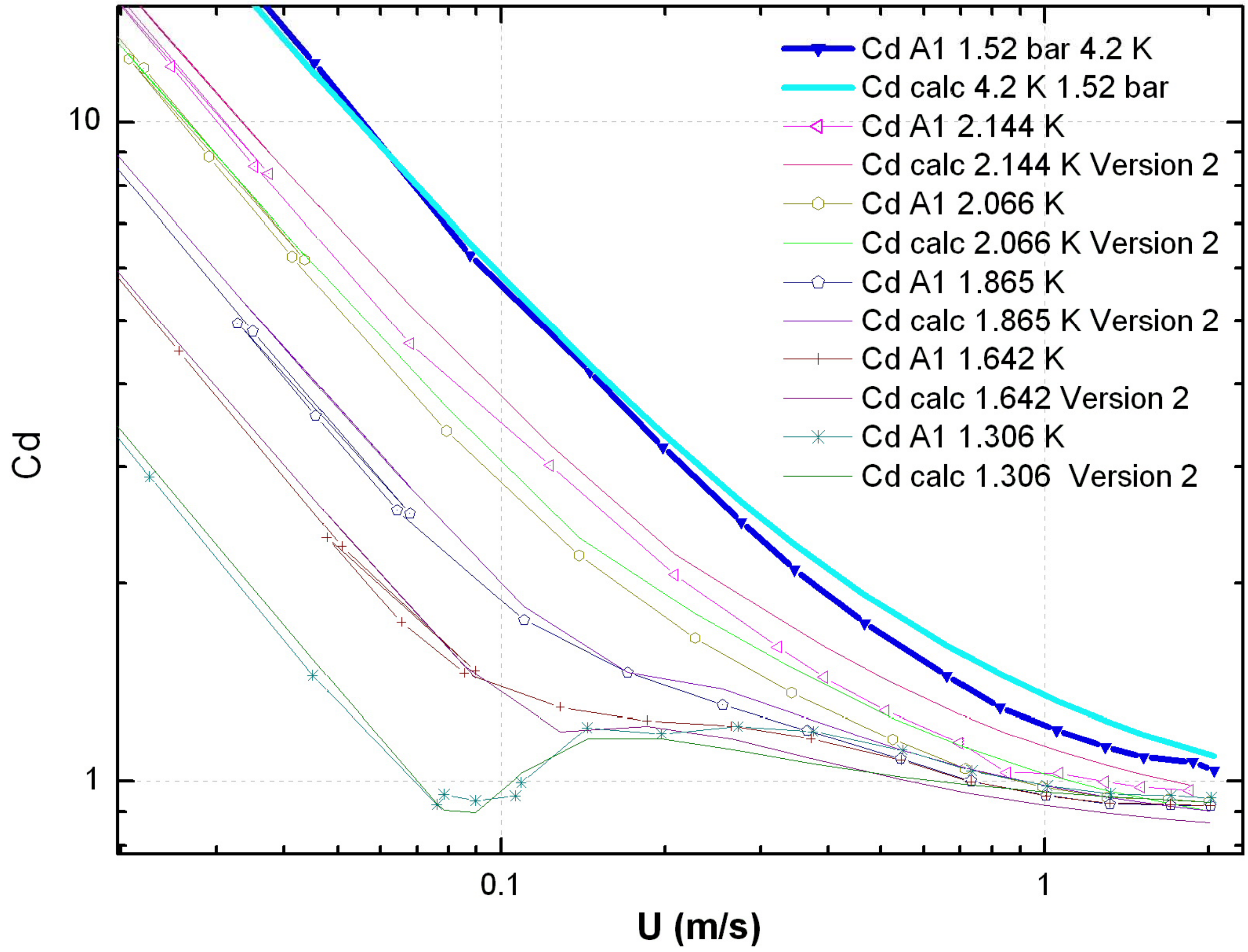
Does this functional dependence fit the experimental data?

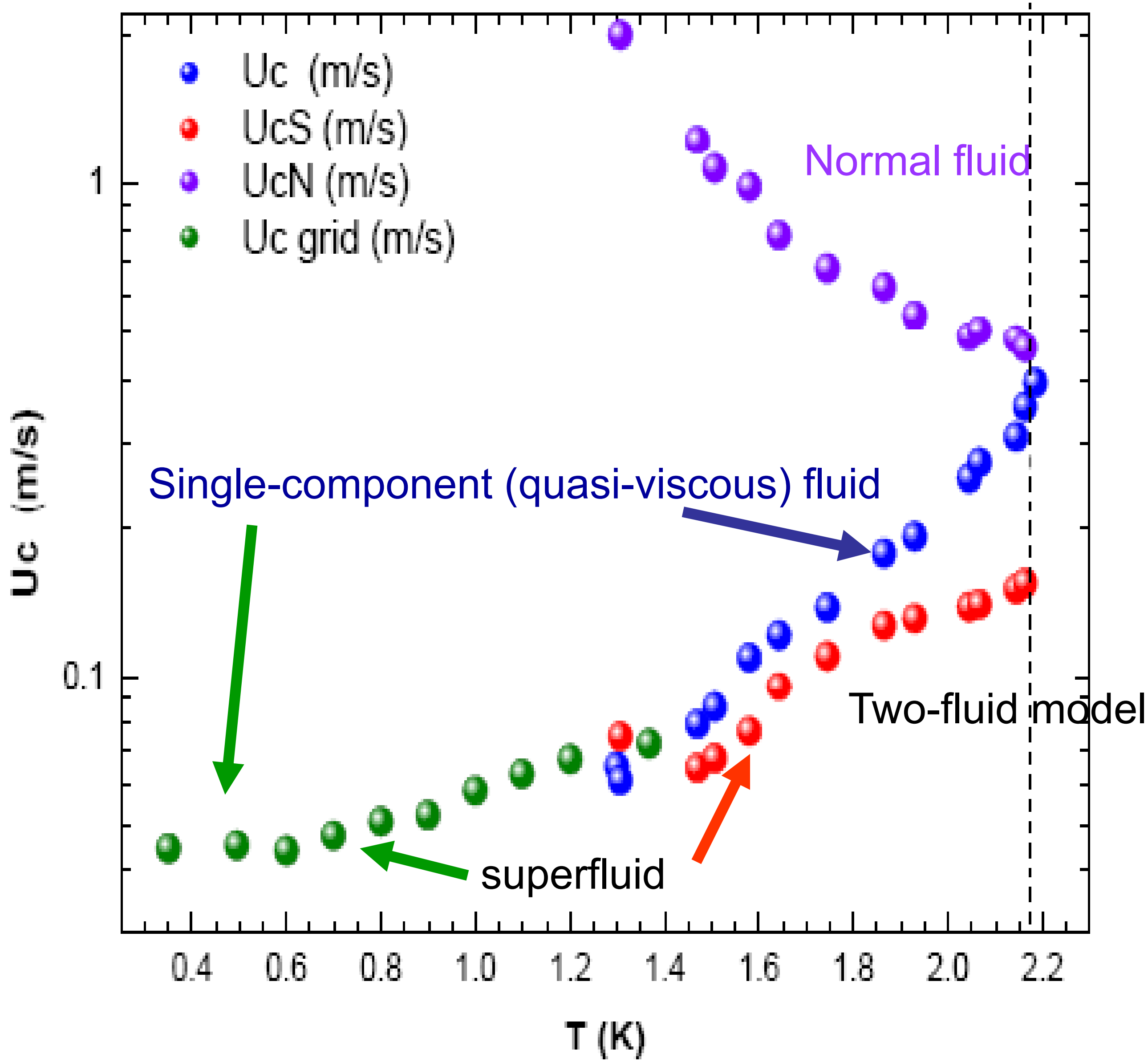


Total drag
Drag due to the
normal fluid
Cd A1 1.579 K
Cd calc 1.579 K Normal
Cd calc 1.579 K Version 2
Cd
1
0.1
0.1
1
Us (m/s)

$$Cd(U, \frac{\rho_n}{\rho}, \nu) = \frac{\alpha' \, 2 \, S/A \sqrt{2\pi f_0 \, \frac{\rho_n}{\rho} \, \nu}}{U} + \beta \frac{\rho_n}{\rho} + \gamma \left(1 - \frac{\rho_n}{\rho}\right) \Phi(U - U_c) \left[\frac{(U - U_c)^2}{\epsilon + (U - U_c)^2}\right]$$

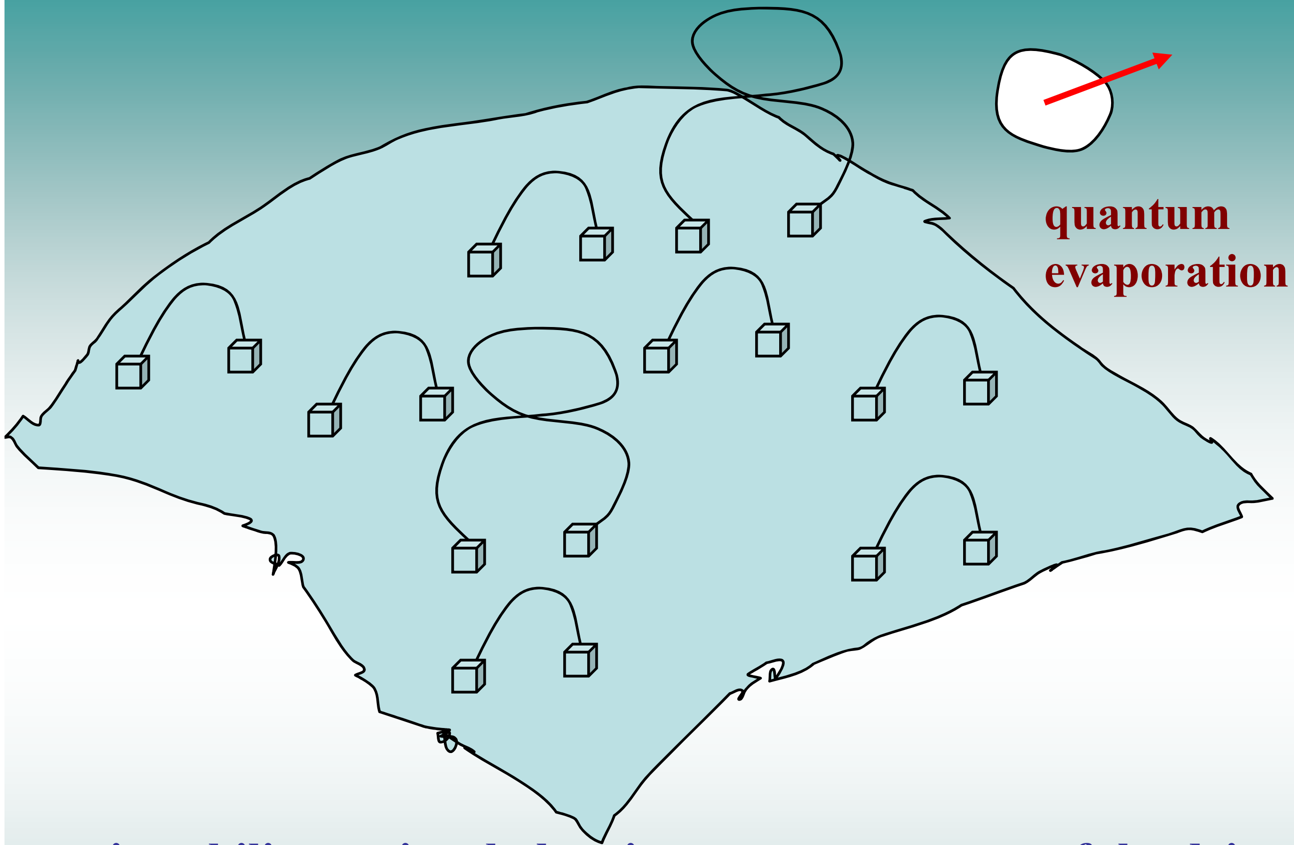


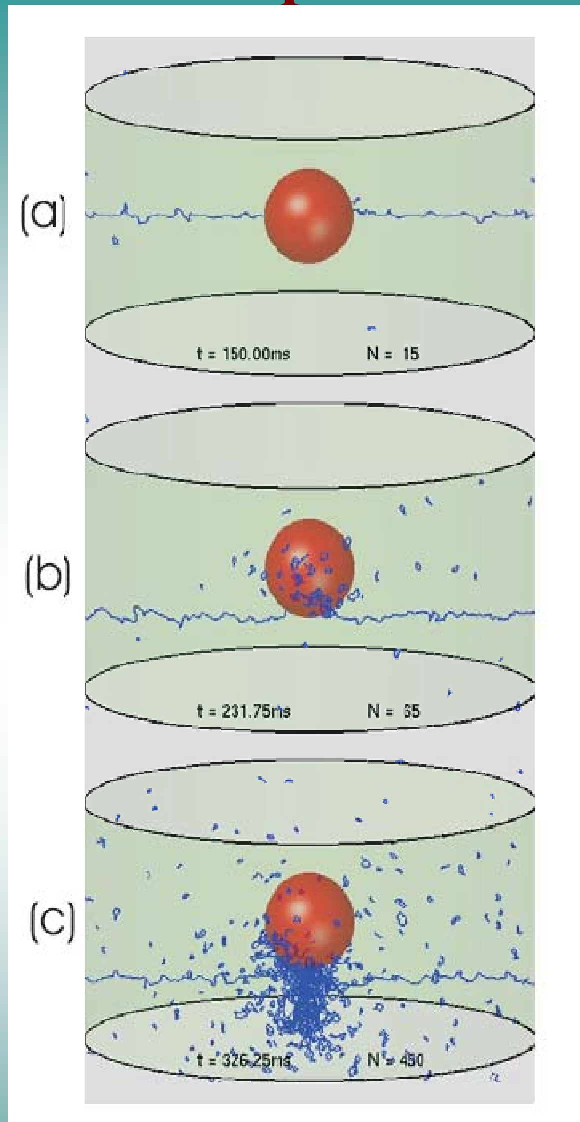

Cd A1 1.52 bar 4.2 K
Cd calc 4.2 K 1.52 bar
Cd A1 2.144 K
Cd calc 2.144 K Version 2
Cd A1 2.066 K
Cd calc 2.066 K Version 2
Cd A1 1.865 K
Cd calc 1.865 K Version 2
Cd A1 1.642 K
Cd calc 1.642 Version 2
Cd A1 1.306 K
Cd calc 1.306 Version 2
10
1
Cd
0.1
1
U (m/s)



Uc (m/s)
UcS (m/s)
UcN (m/s)
Uc grid (m/s)
Normal fluid
Single-component (quasi-viscous) fluid
Two-fluid model
superfluid
1
0.1
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
T (K)
Uc (m/s)

Effective boundary layer constituent of vortex loops



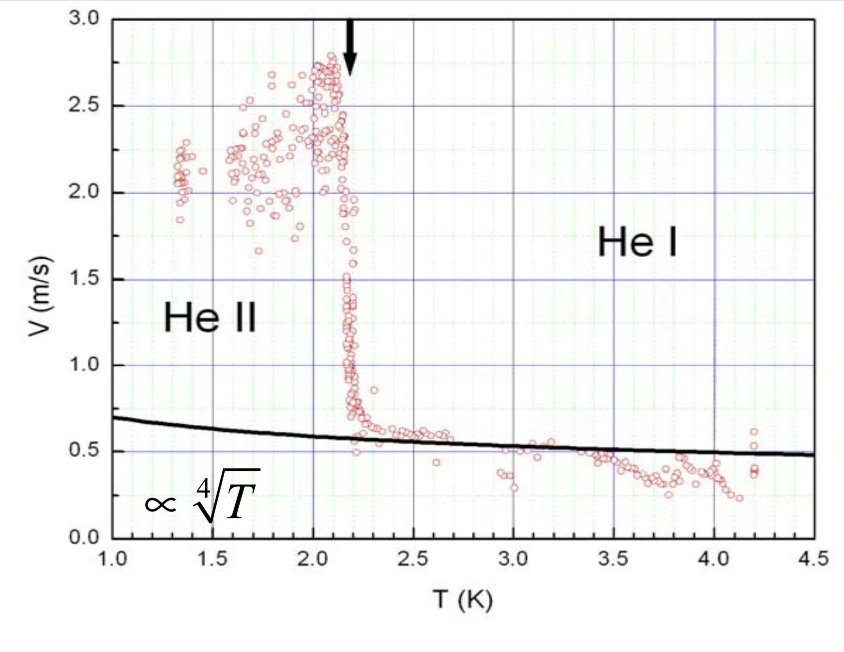


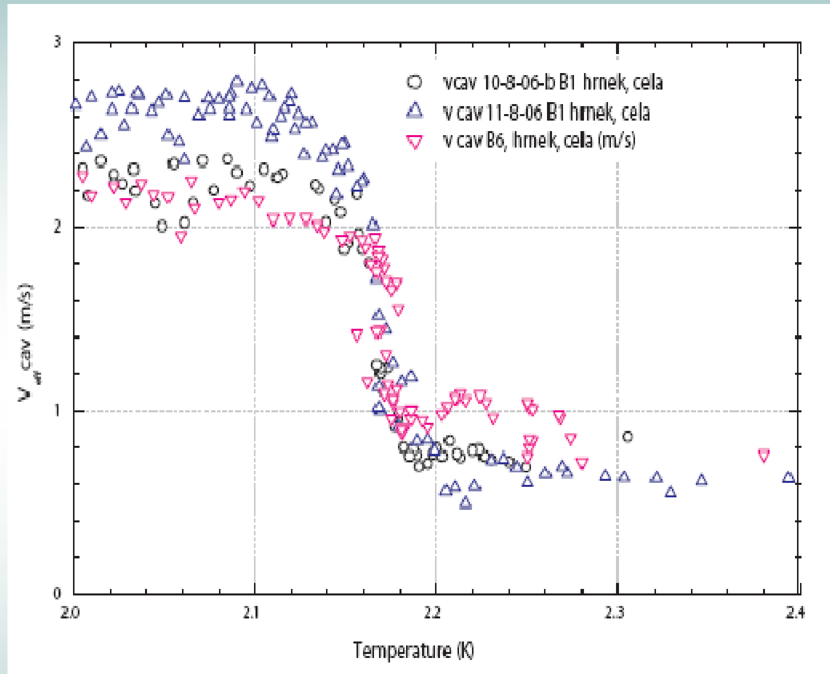
– instability against balooning out, vortex wave of the drive frequency becomes excited, the loop twists, reconnects and the free vortex ring flies away – dissipation

Dissipation can occur without reconnections

- According to Schwarz [PRL 57(1996)1448], even at zero temperature, dissipation occurs – by ends of vortex loops sliding the rough surface
- Dissipation due to sound emission – Kolmogorov cascade on the long enough vortex loop
- At finite T, mutual friction

Cavitation (boiling?) in LHe – Fork Results



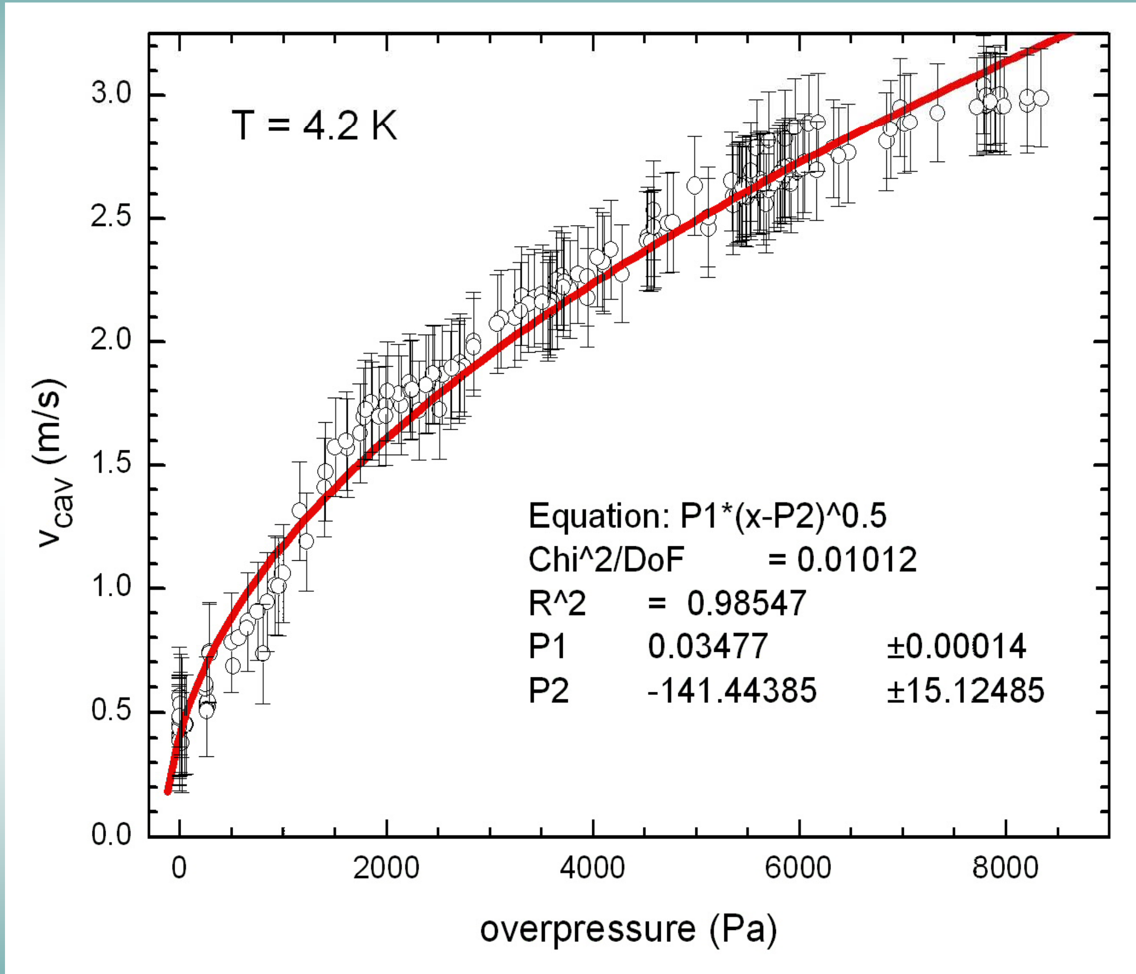


Standard nucleation theory does not explain the steep increase when crossing the superfluid transition

Explanation ????

Bernoulli equation

$$p + \rho \frac{v^2}{2} = const.$$



Conclusions

•Torsionally oscillating and vibrating submerged objects prove to be very useful tools to study classical fluid dynamics and superfluid hydrodynamics.

•Cryogenic helium offers an unprecedented range of easily tunable (p, T) flow properties, where response of these mechanical oscillators to an external drive of an externally applied flow can be monitored over many (8 ???) orders of magnitude.

•They can generate and detect turbulence (and transition to turbulence in particular) in gaseous helium, He I and He II as well as in 3He.

•Furthermore, vibrating quartz forks can be used to give us information about cavitation phenomena in He I and He II (quantum cavitation).