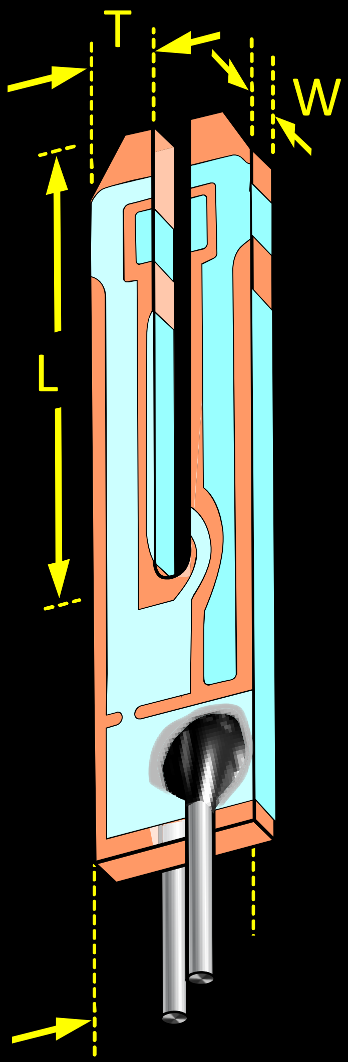

Physics | Lancaster University

Turbulent drag on quartz tuning forks in superfluid ^{4}He

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Saclay, 16th September 2015

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EPSRC Engineering and Physical Sciences Research Council

European Microkelvin Collaboration

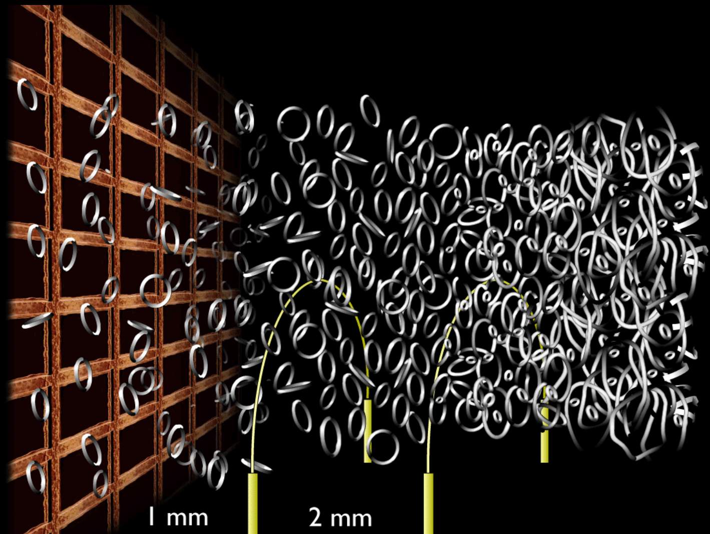
CAPACITIES

THE ROYAL SOCIETY

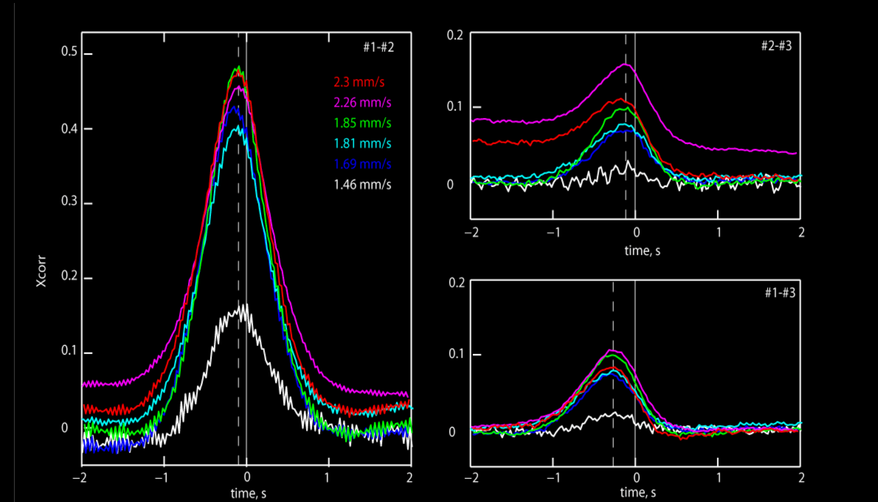
Turbulent drag on quartz tuning forks in superfluid ^{4}He

- Motivation
- Manufacturing and calibration TF
- Critical velocity for turbulence nucleation
- Frequency dependence of turbulent drag
- Acoustic emission

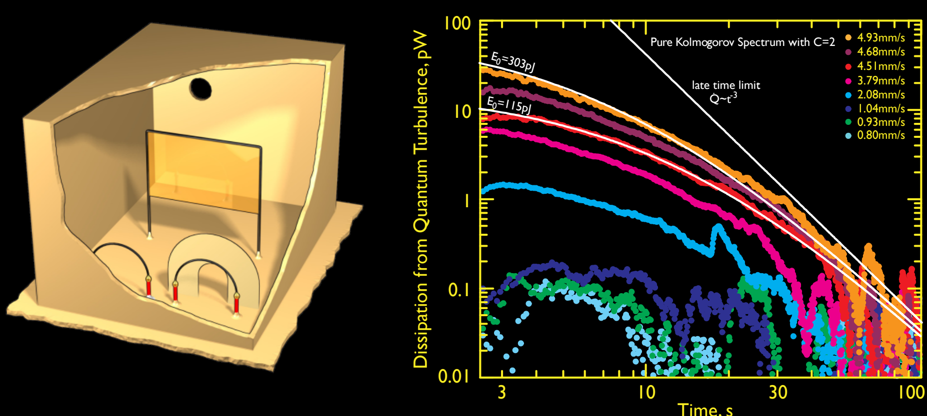
Pure quantum turbulence in superfluid ^{3}He-B



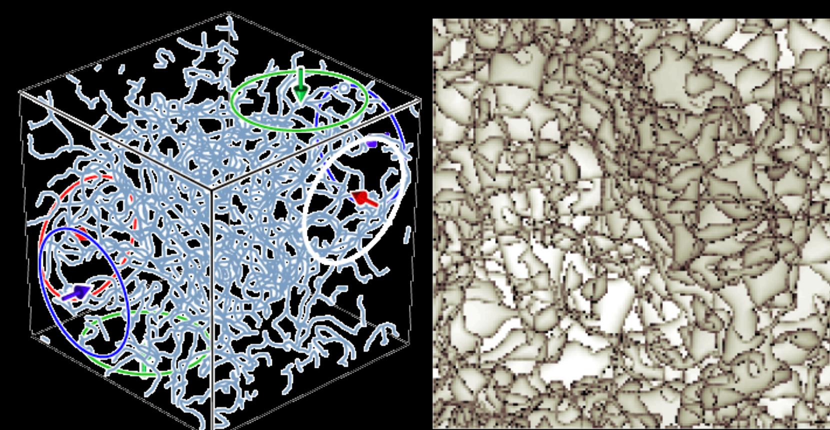
Tangle appears from rings,
PRL 96 (2006) 035301



QT has range of length scales,
PRL 101 (2008) 065302

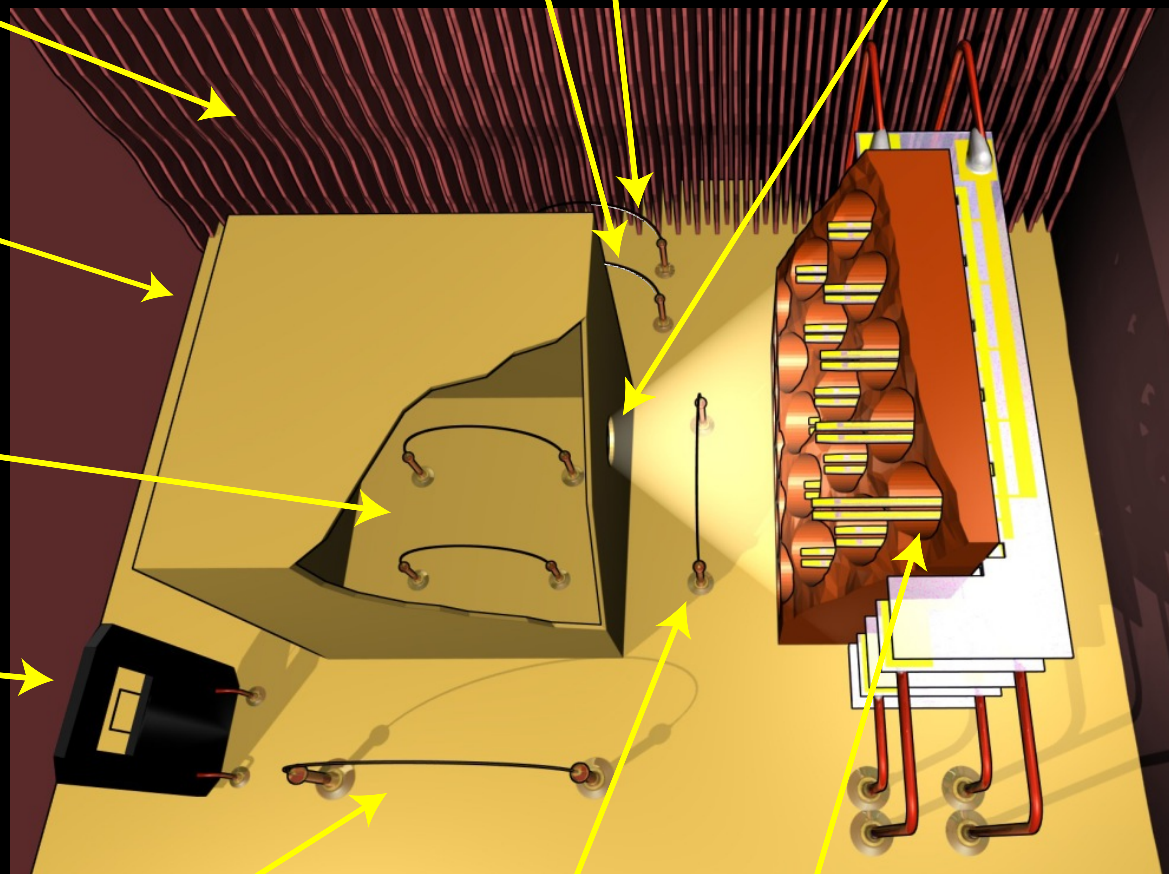


QT has Kolmogorov like energy spectrum,
Nature Physics 7 (2011)



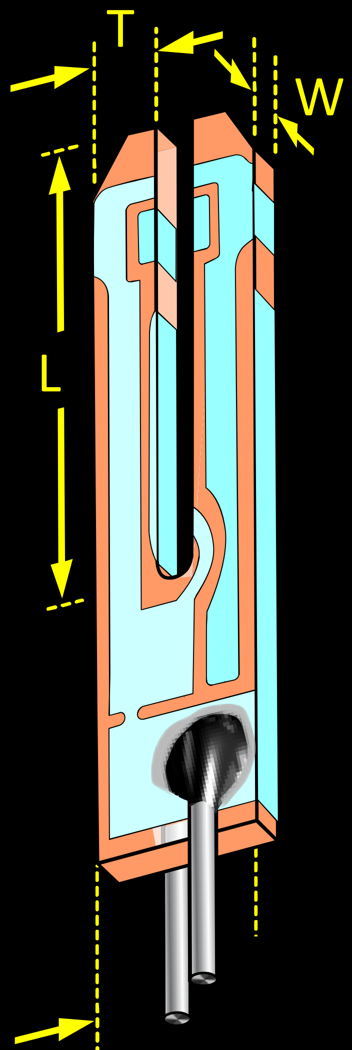
Correlation of Andreev reflection and VLD,
PRL 115 (2015) 015302

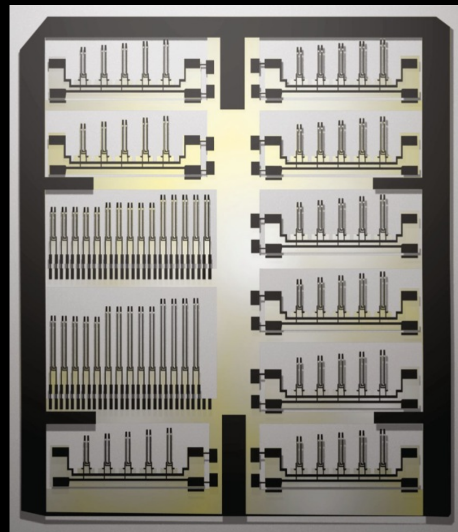
Quasiparticle Imaging Experimen



Manufacturing and Calibration

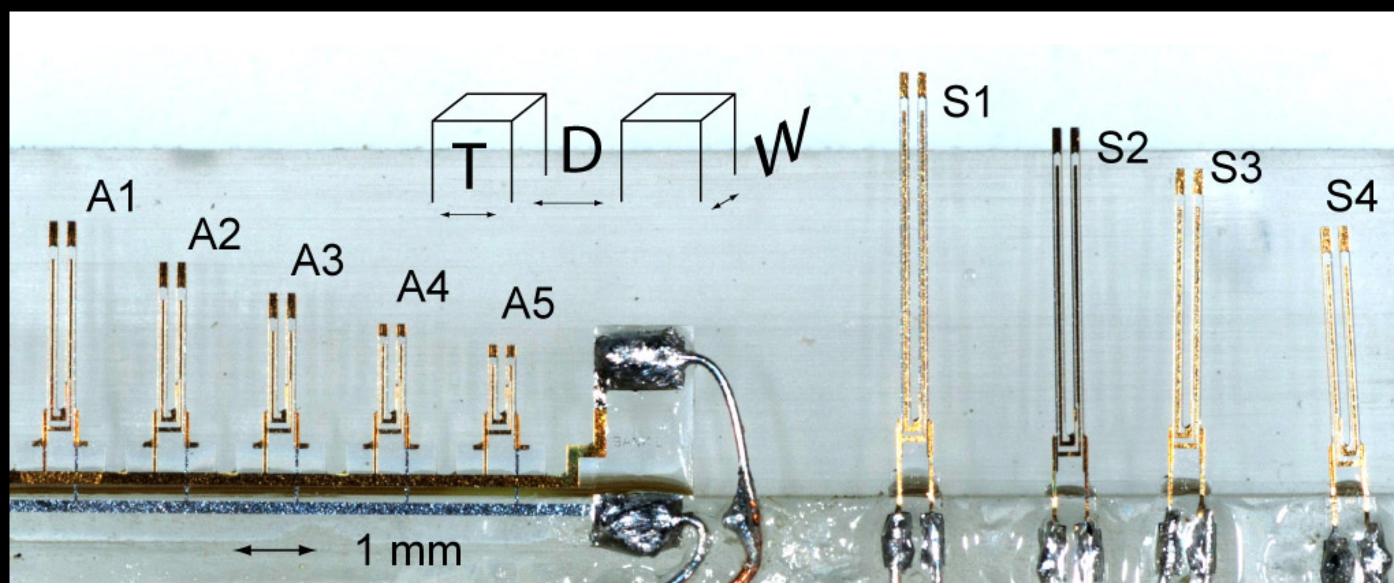
Quartz Tuning Forks: manufacturing





All forks are manufactured on a single quartz wafer and have identical width W = 50 or 75μm, tine size T = 90μm and distance between tines D = 90μm.

Frequency is varied by L = 700 - 3500μm

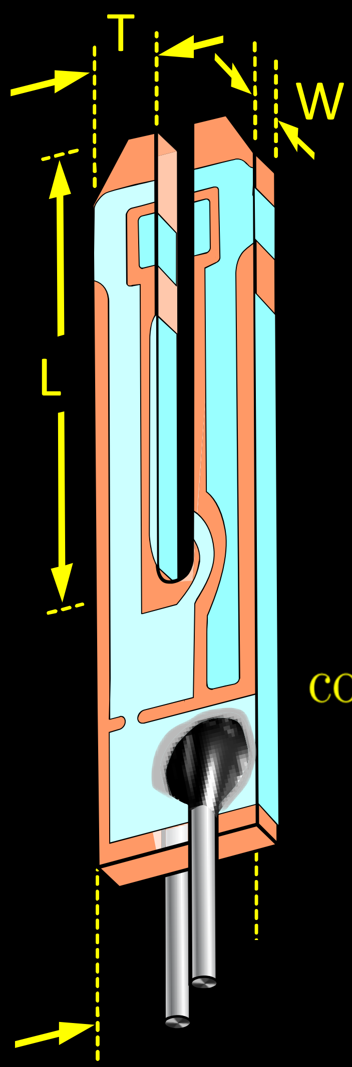


kHz ***21.9*** ***36.0*** ***54.2*** ***95.4*** ***155*** ***6.5*** ***8.3*** ***12.X*** ***16.3***

kHz

PRB 85, 014501 (2012), PRB 89, 014515 (2014

Fork (cantilever) flexure modes



$$\mu \frac{\partial^2 u(x,t)}{\partial t^2} + \frac{\partial^2}{\partial x^2}\left(EI \frac{\partial^2 u(x,t)}{\partial x^2} \right) = q_0 e^{i\omega t}$$

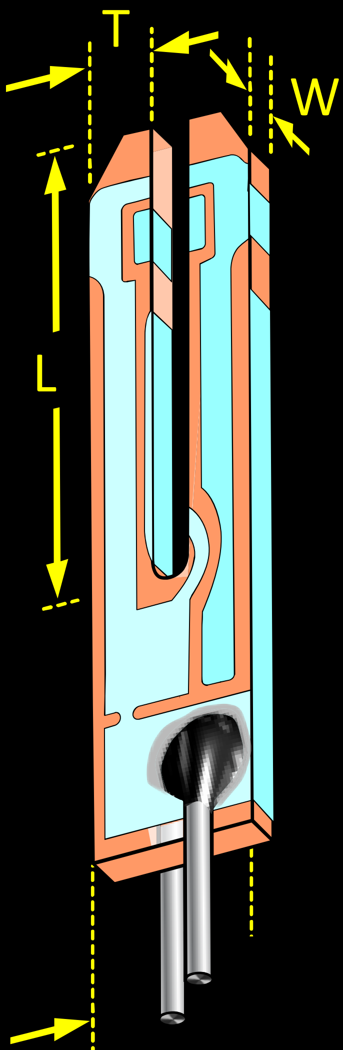
$$u(x,t) = X^n(x) e^{i\omega_n t} \qquad \omega_n = 2\pi f_n = \sqrt{\frac{ET^2}{12\rho}}\, b_n^2$$

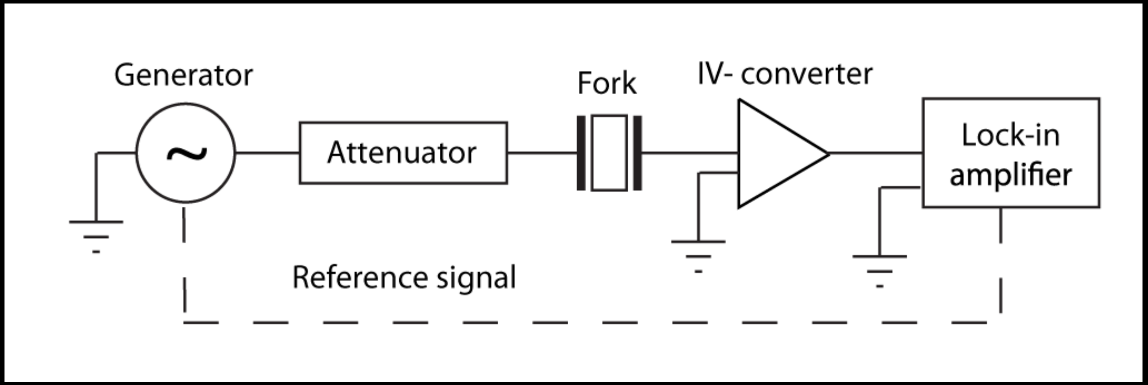
$$\cos(b_n L)\cosh(b_n L) + 1 = 0$$

$b_0 L = 1.87510$
$b_1 L = 4.694091$
$b_2 L = 7.854757$
$b_3 L = 10.9955407$

$f_1 / f_0 = 6.267$
$f_2 / f_0 = 17.54$
$f_3 / f_0 = 34.38$

Quartz Tuning Forks





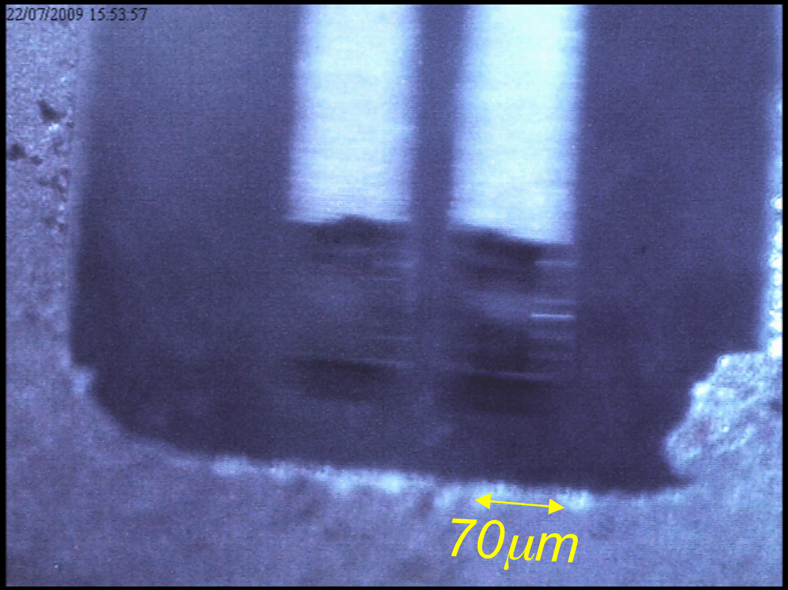
Driven by Piezoelectric Force from applied Voltage, Resulting Velocity produces a Current.

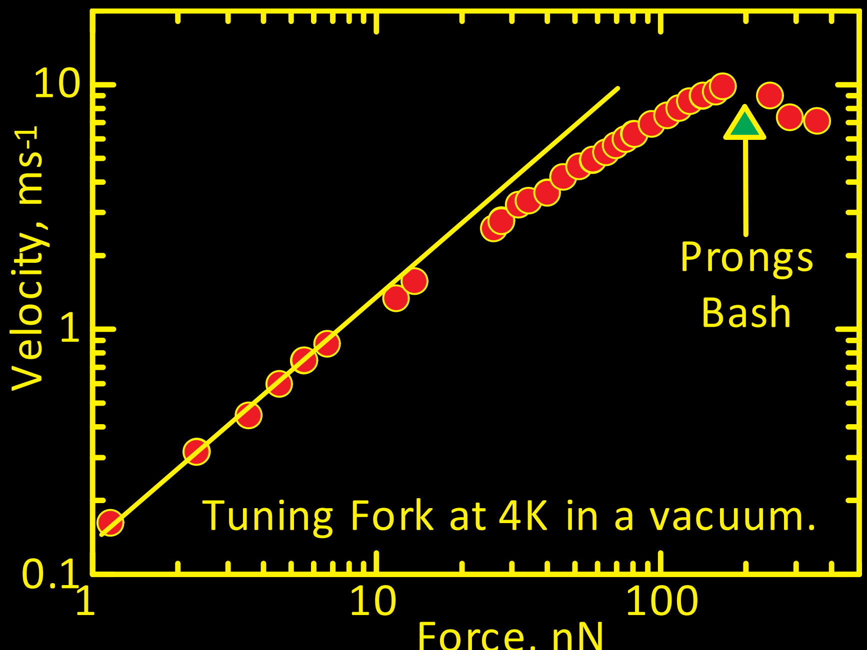
Driving Force F = a V/2 **Velocity** v = I / a

$$a = \sqrt{\frac{4\pi m_{\mathrm{eff}}\,\Delta f_2\, I}{V}} \qquad m_{\mathrm{eff}} = 0.25m$$

PHYSICAL REVIEW B 85, 014501 (2012)

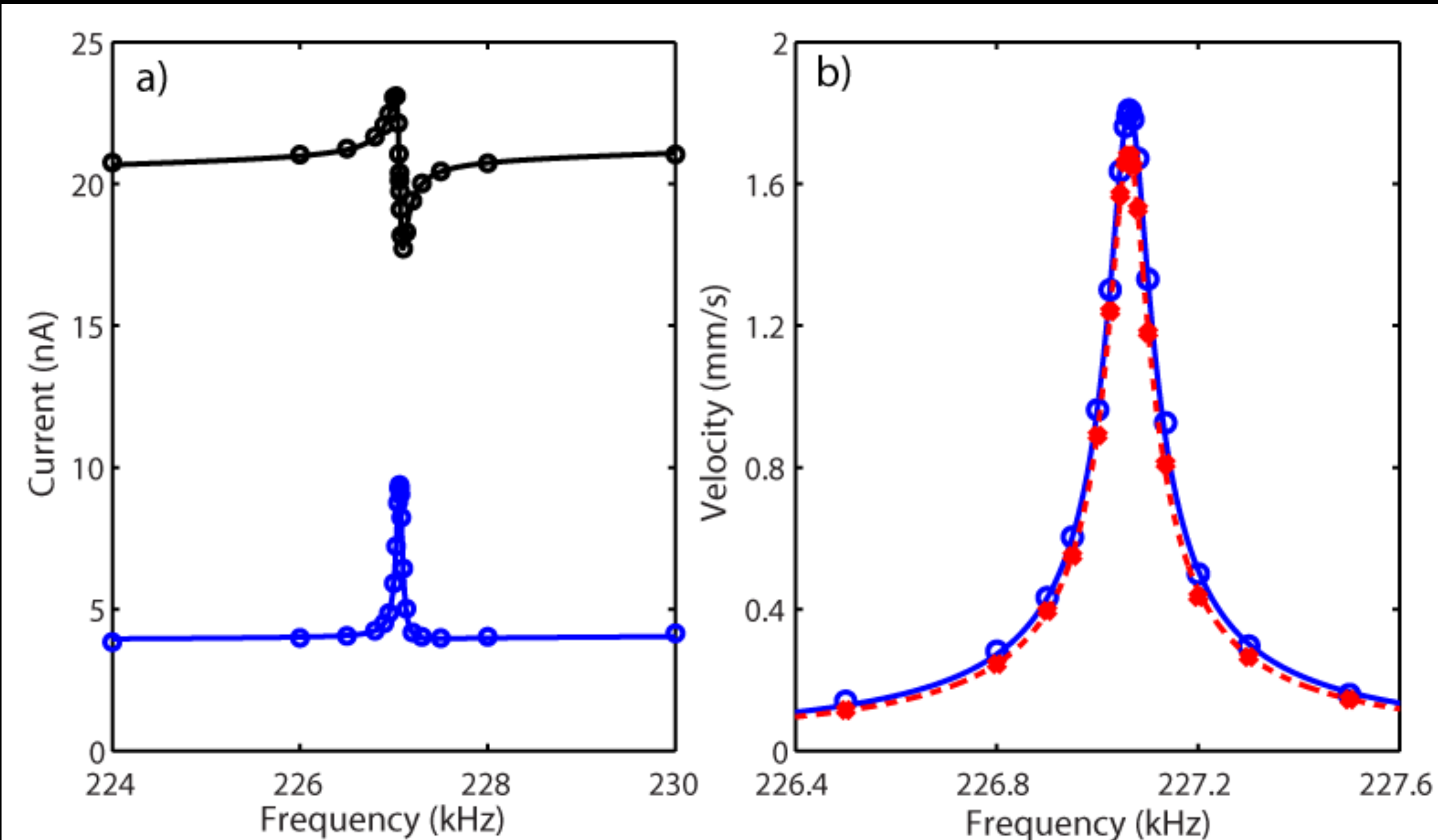
Optical Fork Calibration Technique



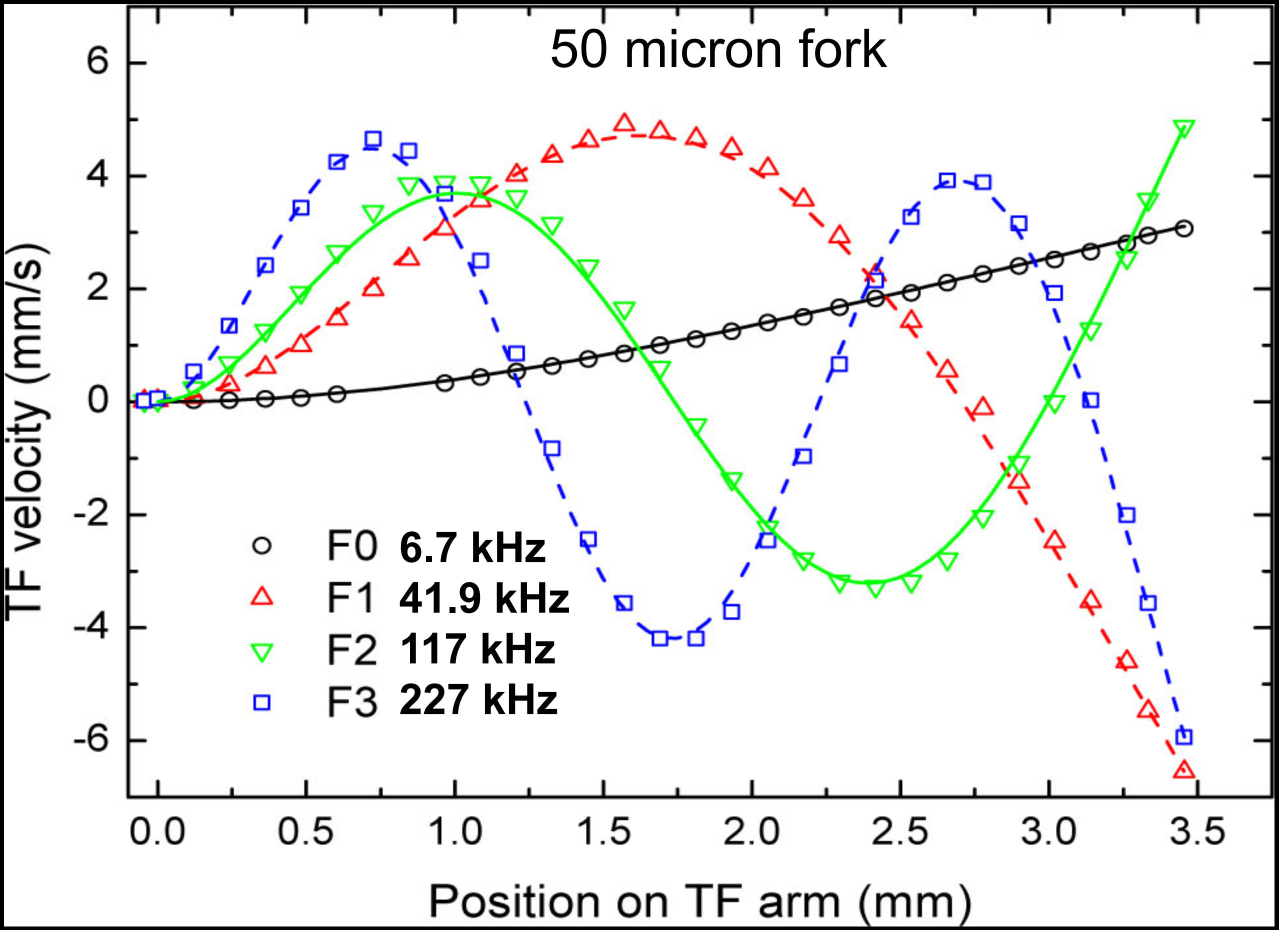


LANCASTER UNIVERSITY DEPARTMENT OF PHYSICS

Optical vs. electromechanical measurement of 6.5kHz fork



Optical measurements of prong velocity profile



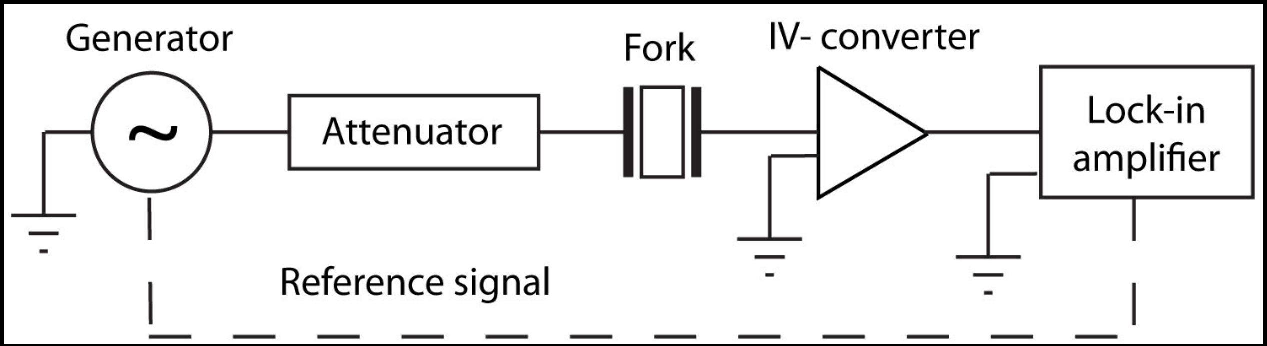
$$X^n(x) = X_r^n(x) X^n(L)$$

$$A = \frac{1}{2}\frac{\sin(b_n L)\sinh(b_n L)}{\cosh(b_n L) + \cos(b_n L)}$$

$$X_r^n(x) = A[\cosh(b_n x) - \cos(b_n x)] - B[\sinh(b_n x) - \sin(b_n x)]$$

$$B = \frac{1}{2}\frac{\cos(b_n L)\sinh(b_n L) + \sin(b_n L)\cosh(b_n L)}{\cosh(b_n L) + \cos(b_n L)}$$

Fork calibration

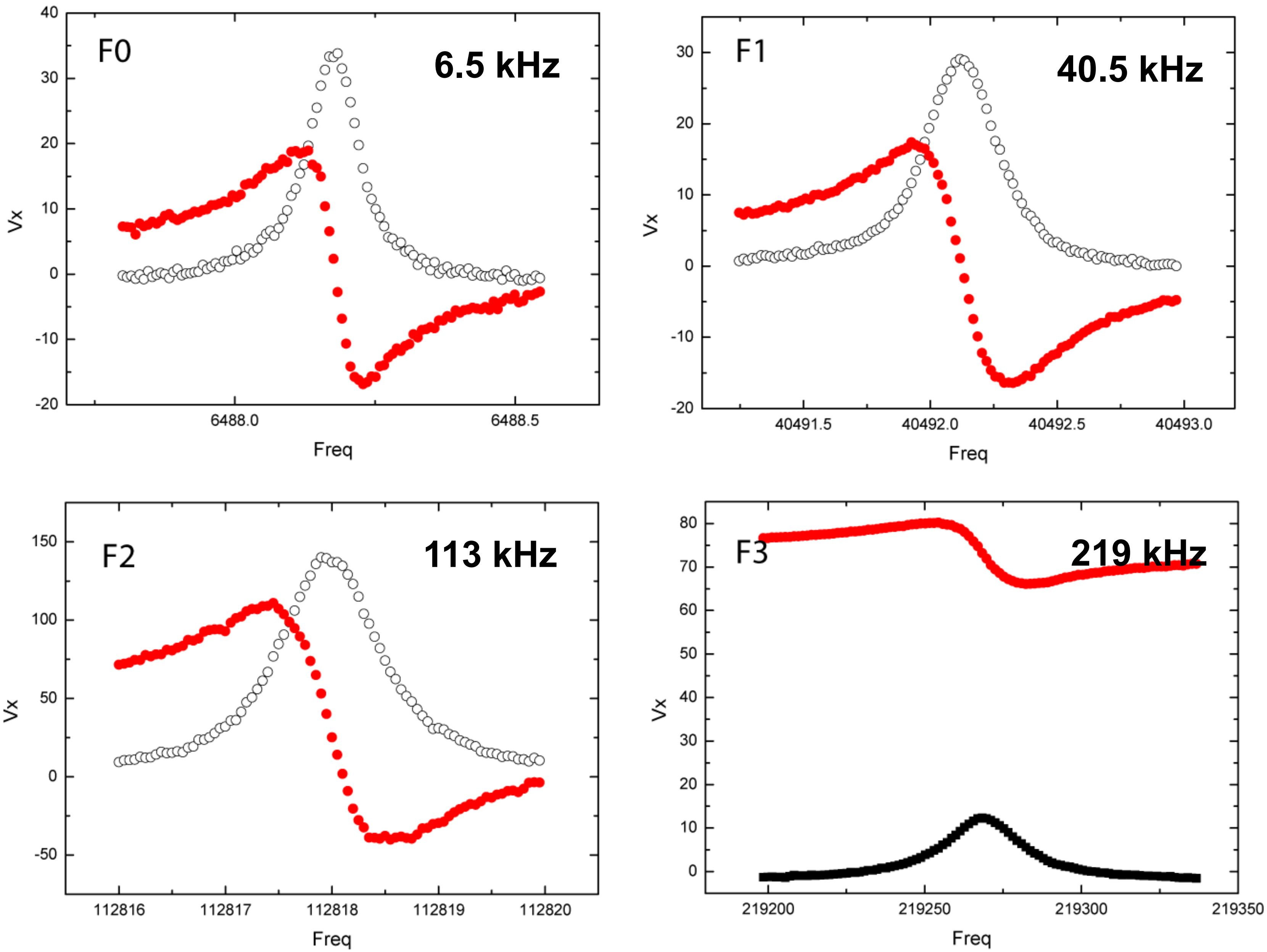


mode	f_0 Hz	Δf_2^{el} Hz	Δf_2^{opt} Hz	$a\times10^7$ Cm^{-1}	v_{el}^{max} $mm\,s^{-1}$	v_{opt}^{max} $mm\,s^{-1}$	ratio
S1F0	6708.4	7.7	8.2	3.80	2.39	2.24	1.07
S1F1	41932	14.9	14.9	14.7	4.76	4.85	0.98
S1F2	116801	24.1	23.3	18.2	3.65	3.66	1.00
S1F3	227063	80.5	77.7	30.1	1.81	1.69	1.07
S4F0	16934	10.4	10.7	5.65	4.15	3.89	1.04
S4F1	105460	22.9	22.3	22.1	7.43	7.12	1.04
S4F2	291568	42.5	44.0	19.5	3.54	2.89	1.23

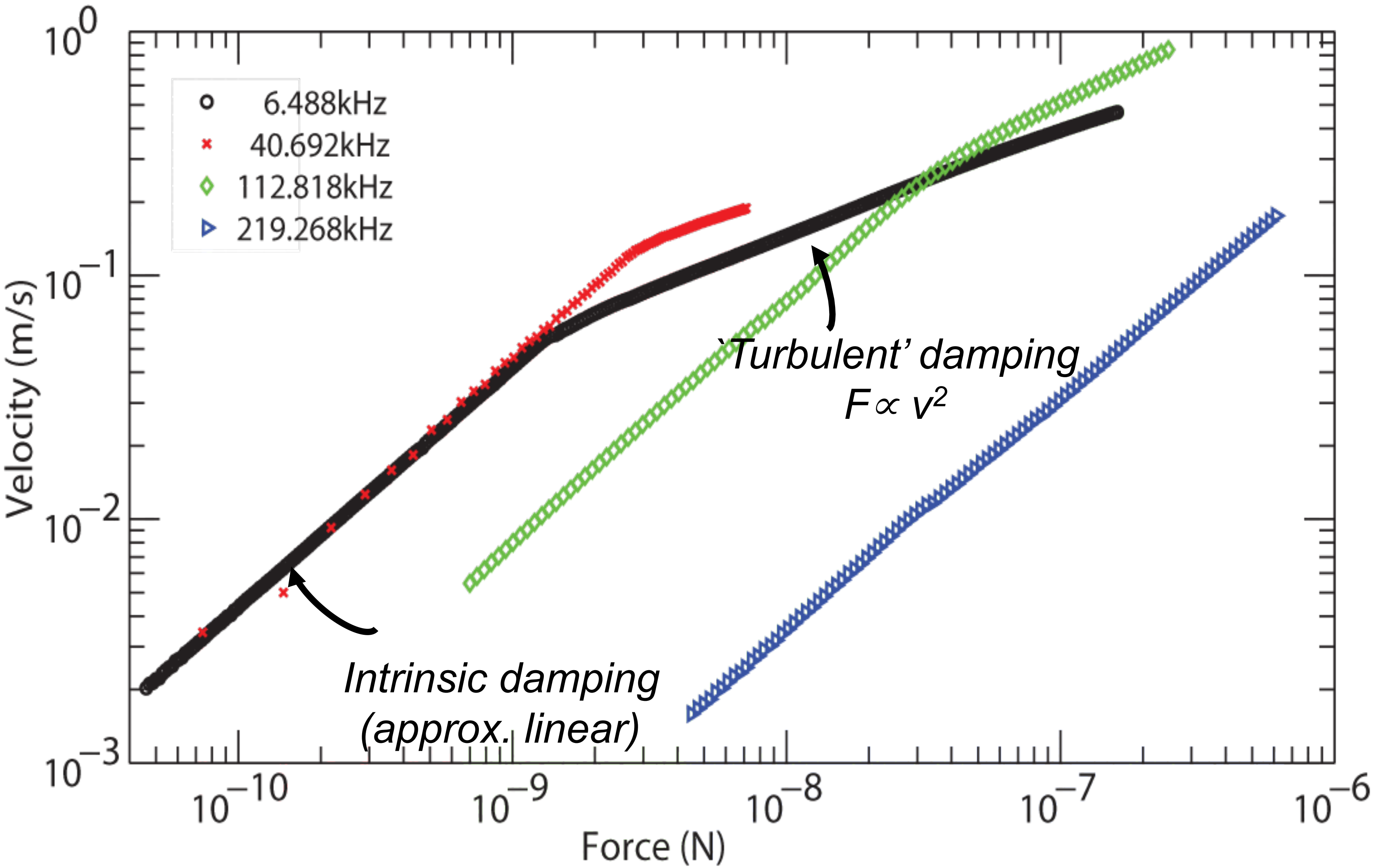
Optical and electromechanical detection agree within 10% for all modes

PRB 85, 014501 (2012), PRB 89, 014515 (2014

Frequency sweeps for 6.5kHz fork at 450mK in 4He

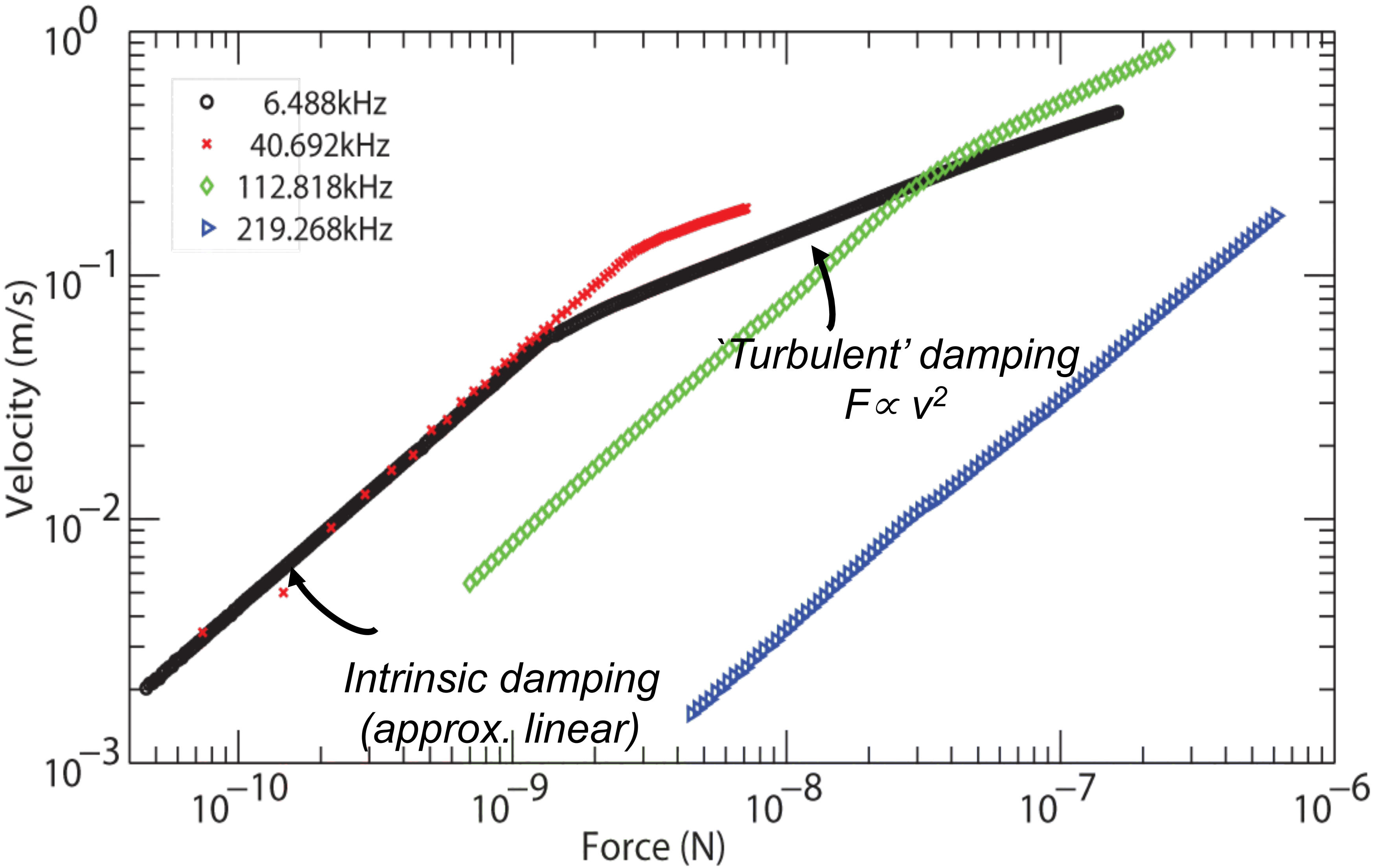


Amplitude sweeps for 6.5kHz fork at 450mK in 4He

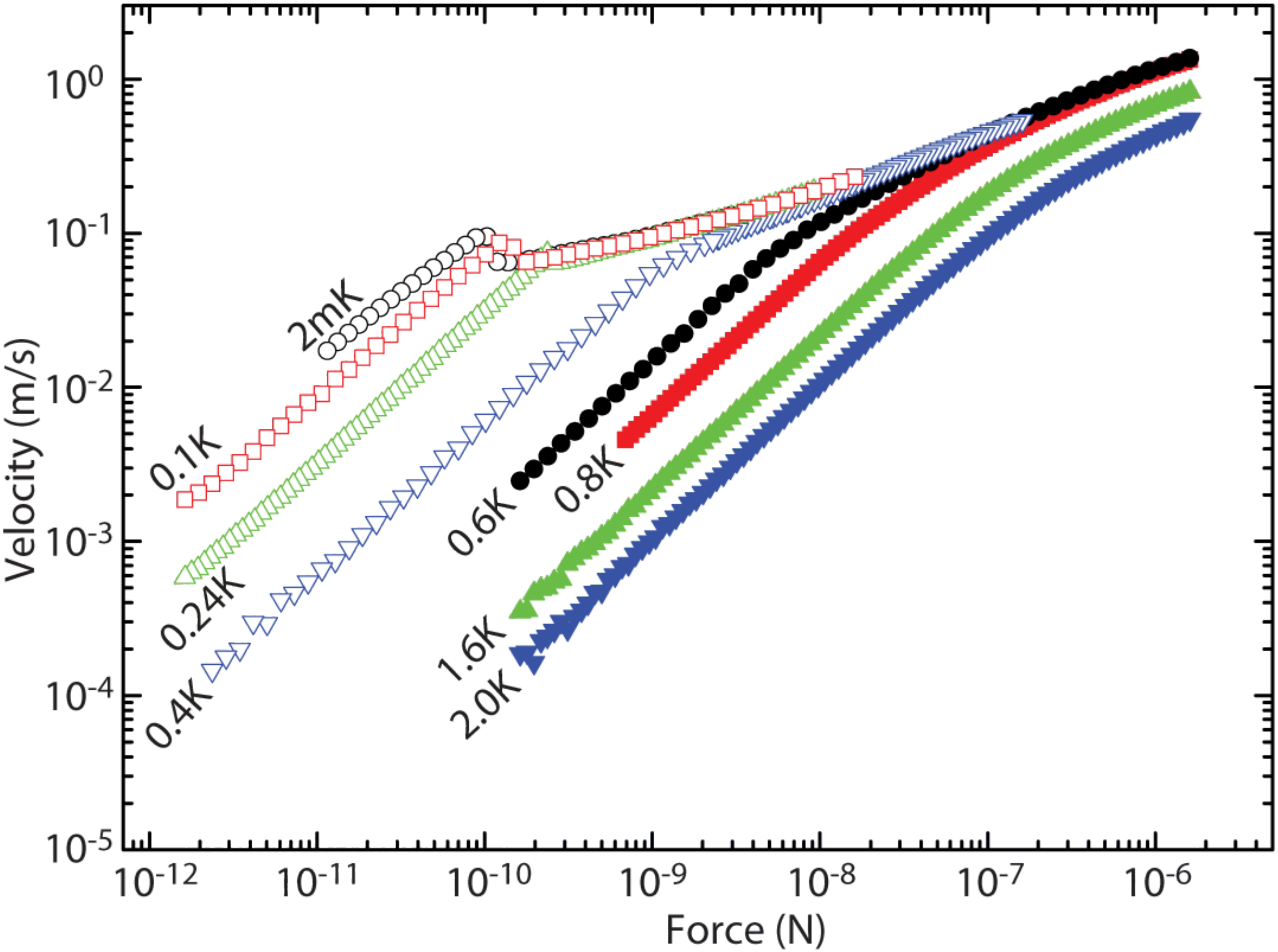


Temperature and frequency dependence of critical velocity

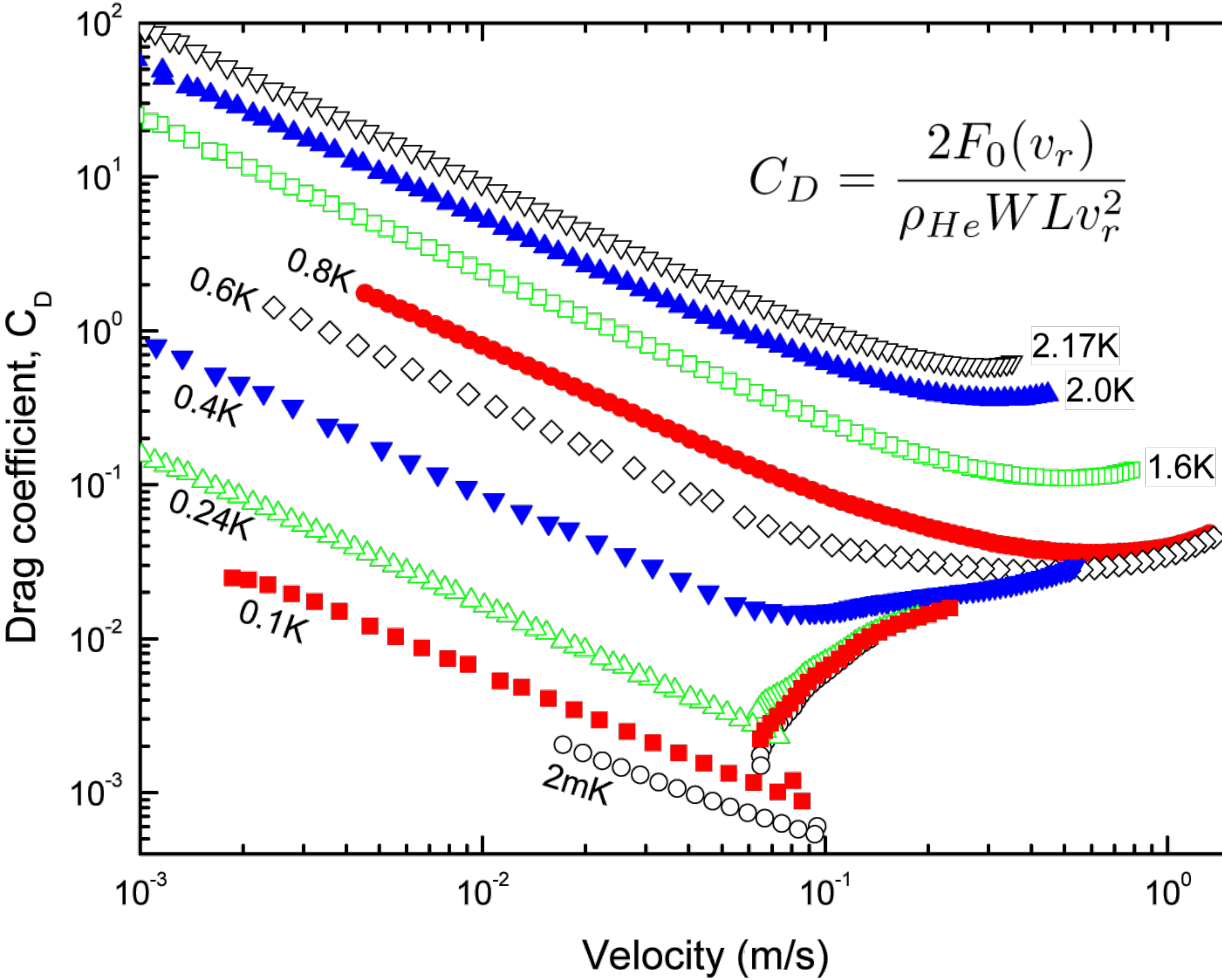
Amplitude sweeps for 6.5kHz fork at 450mK in 4He



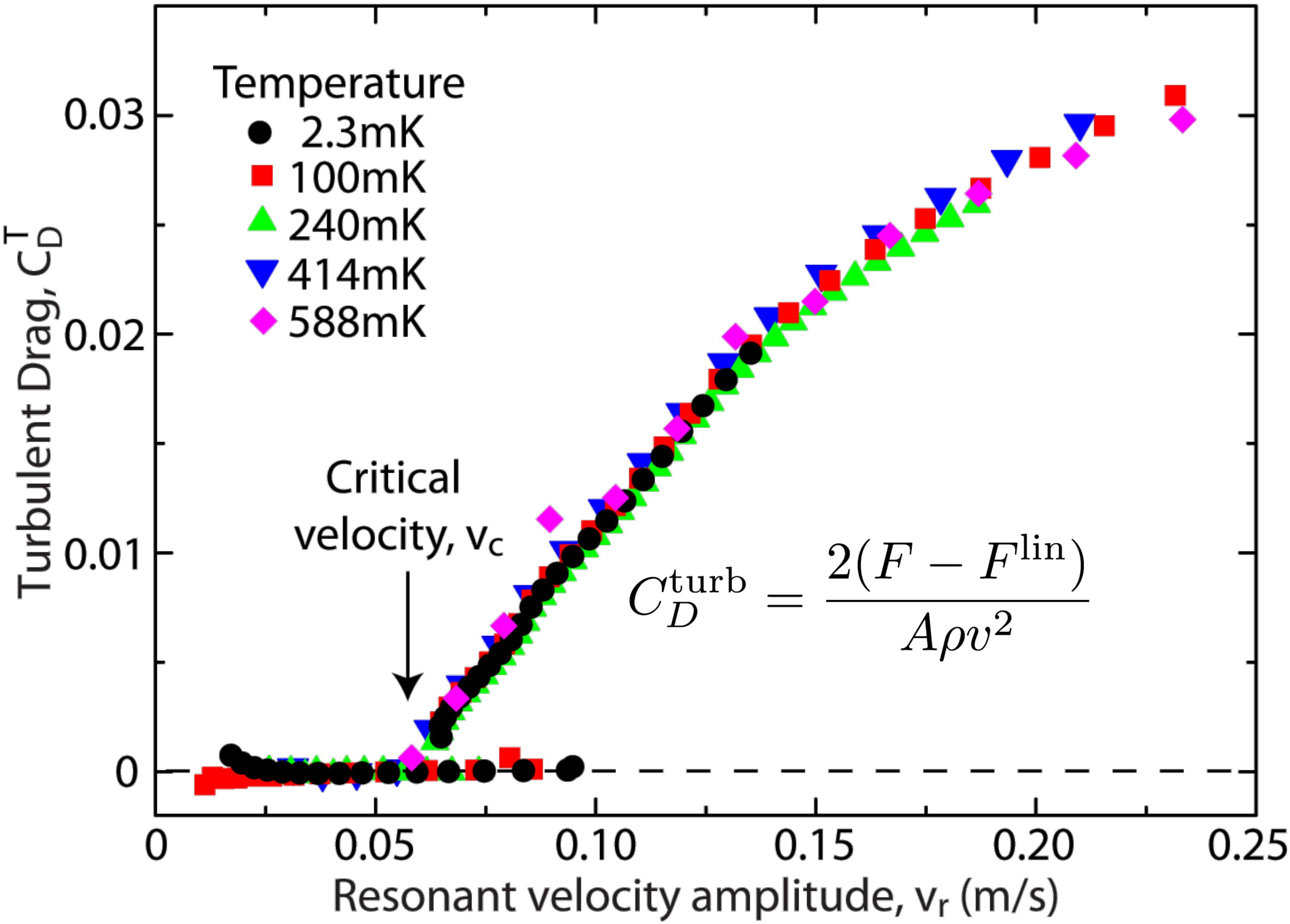
Amplitude sweeps for 6.5kHz fork



Drag coefficient 6.5kHz fork

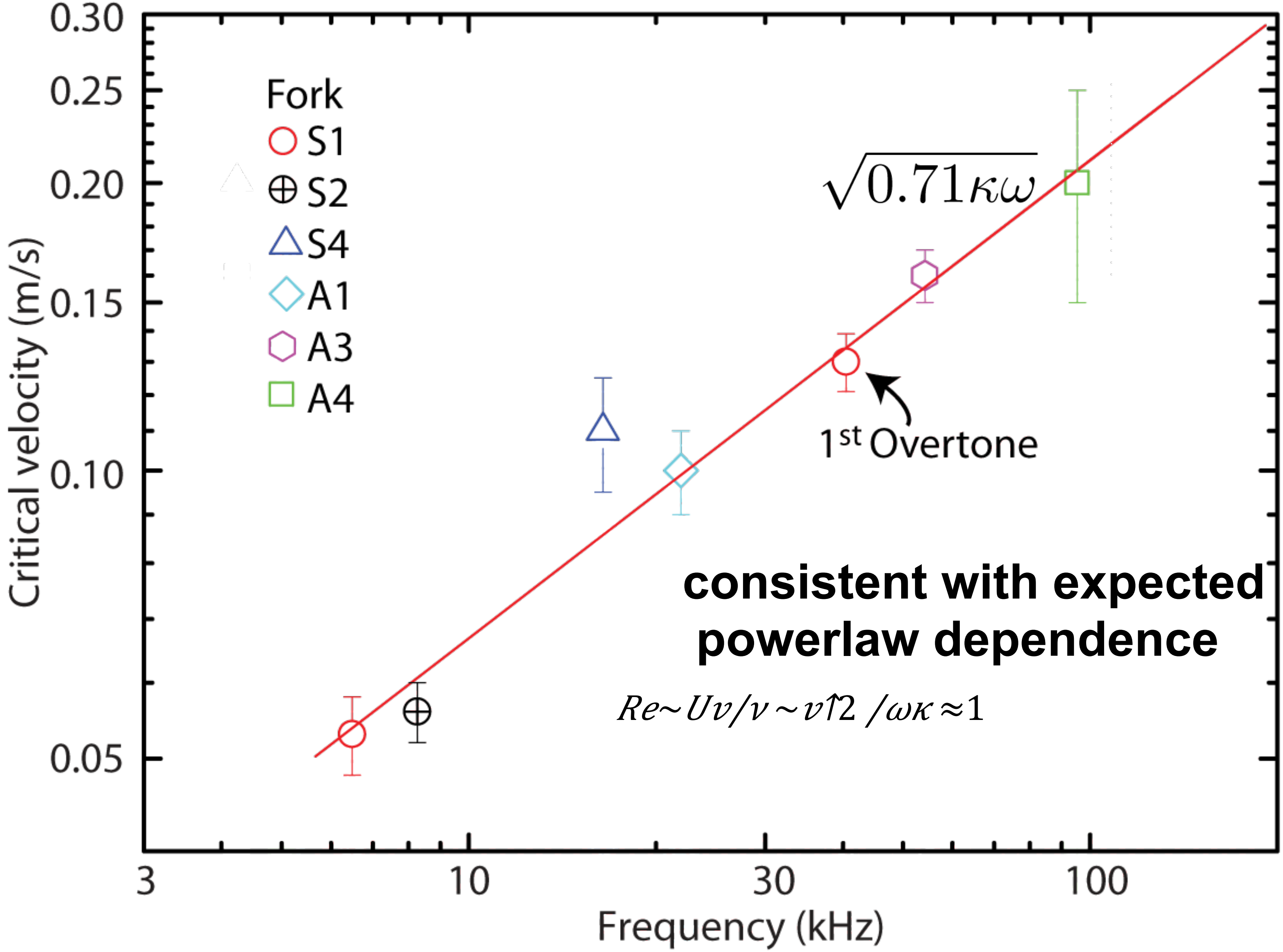


Turbulent drag for the fundamental mode of 6.5kHz fork

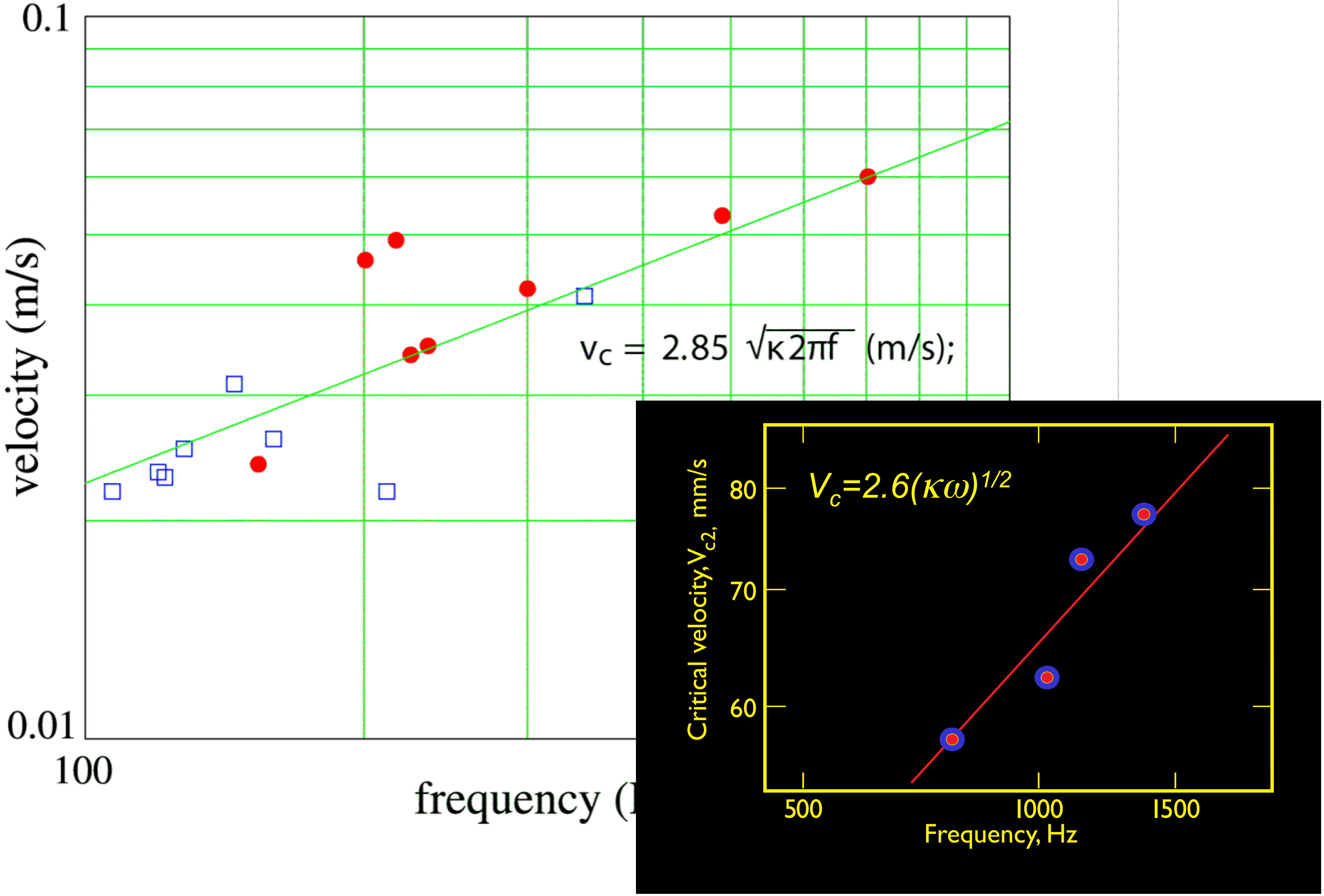


Critical velocity and superfluid turbulent drag are temperature independ

Frequency dependence of critical velocity



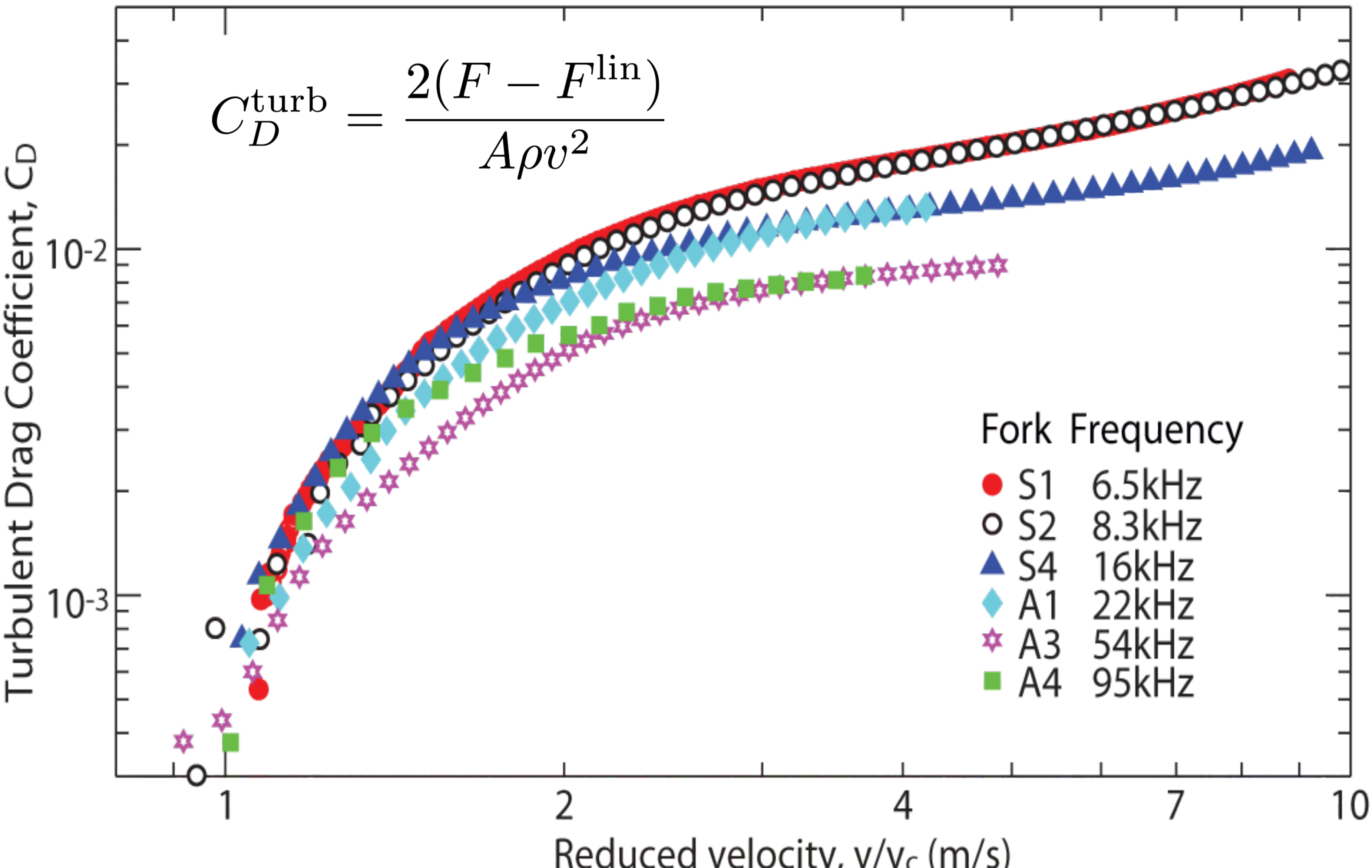
Frequency dependence of critical velocity



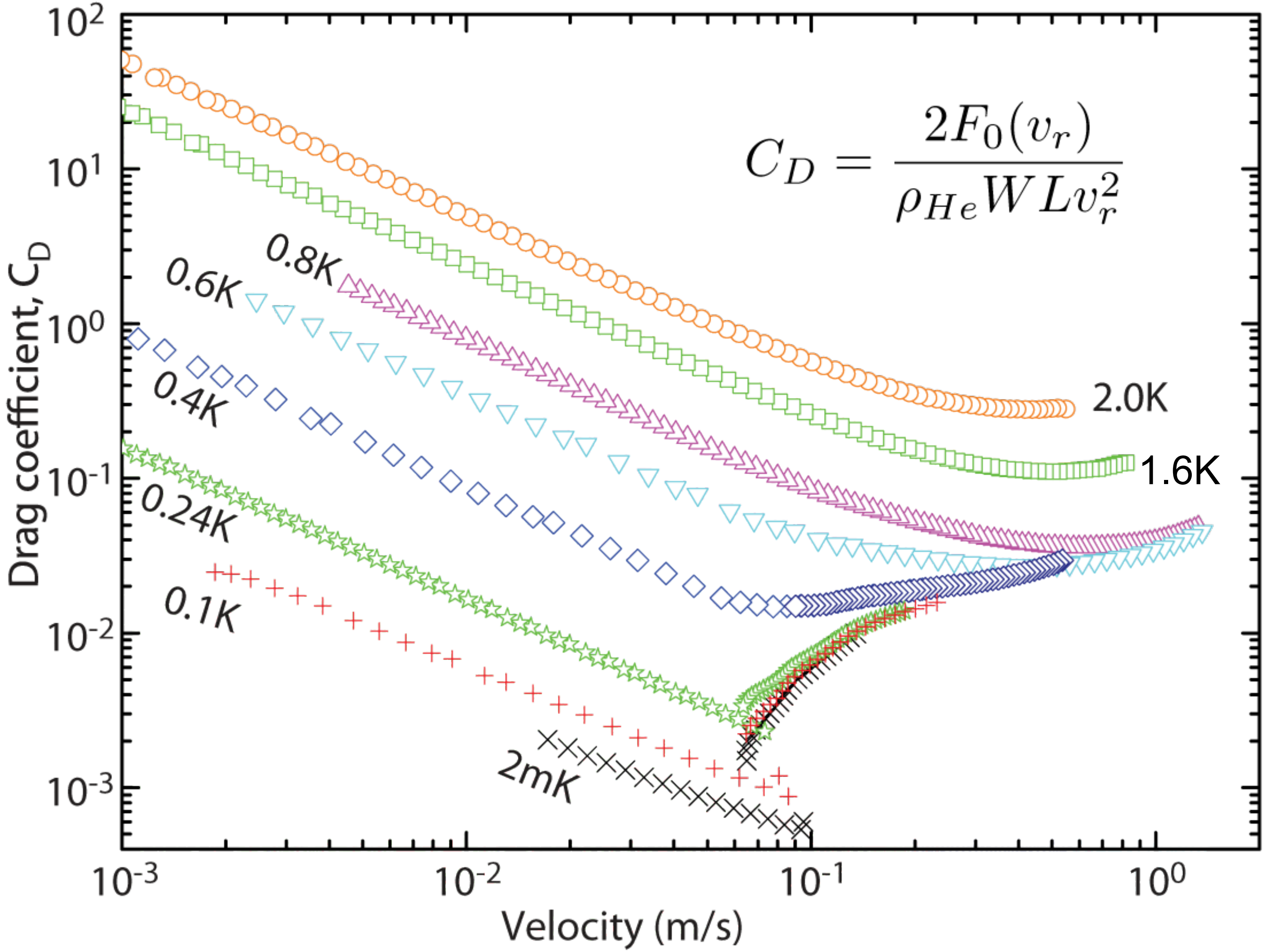
R. Hänninen et al. , J Low Temp Phys (2011) 164:1–4

Frequency and temperature dependencies of turbulent drag

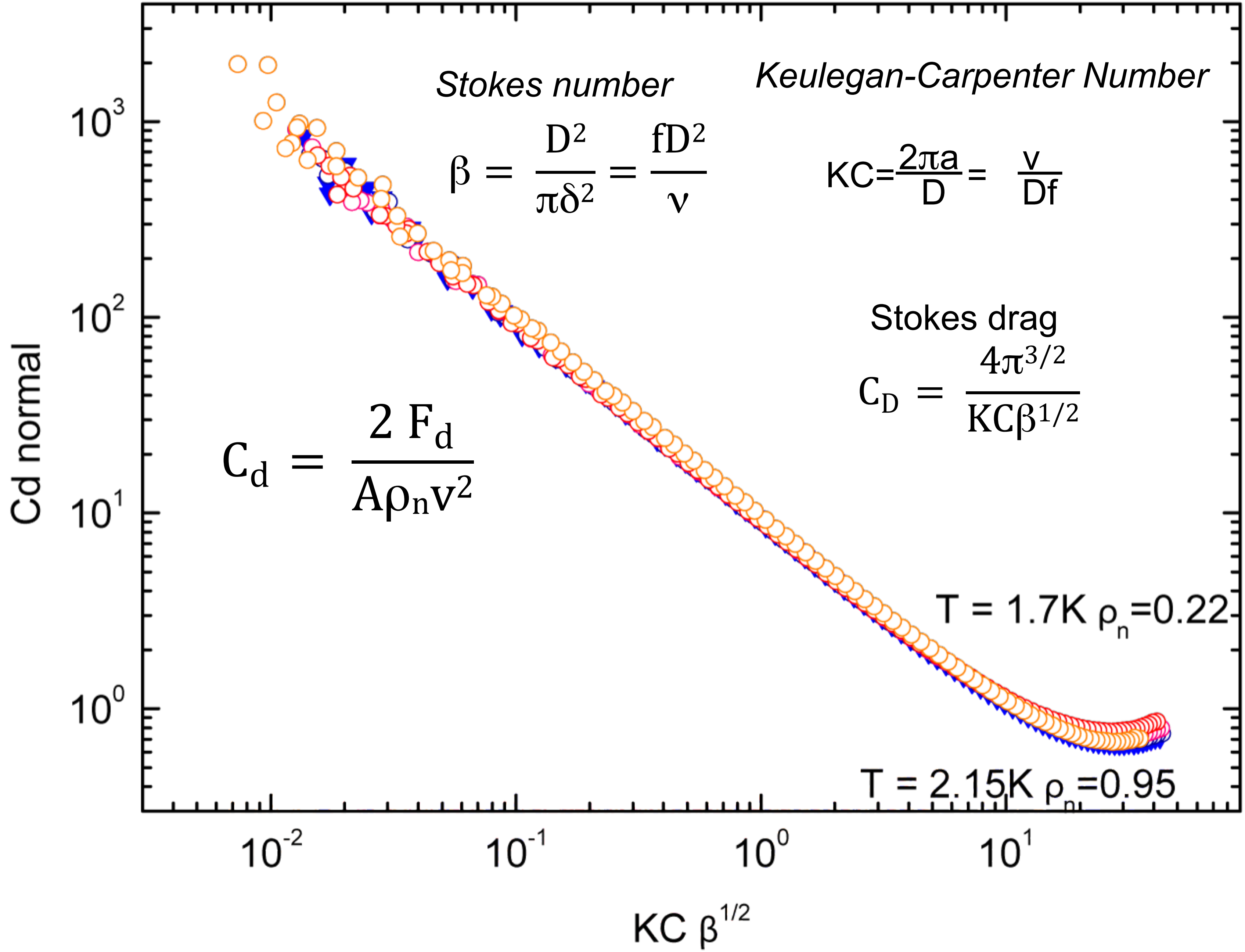
Turbulent drag for the fundamental mode of various forks



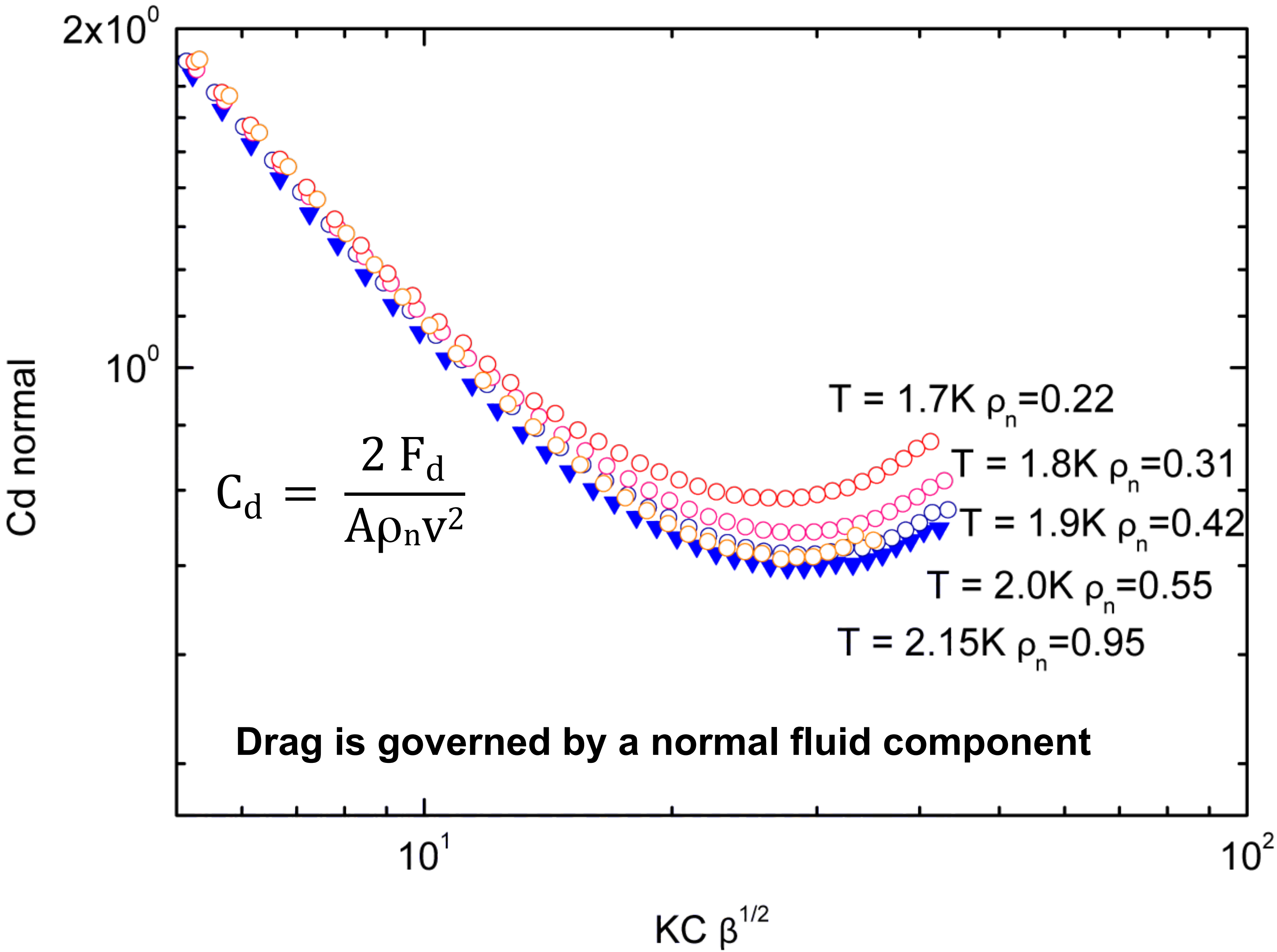
Drag coefficient 6.5kHz fork



Normal fluid Drag vs KC $\beta^{1/2}$



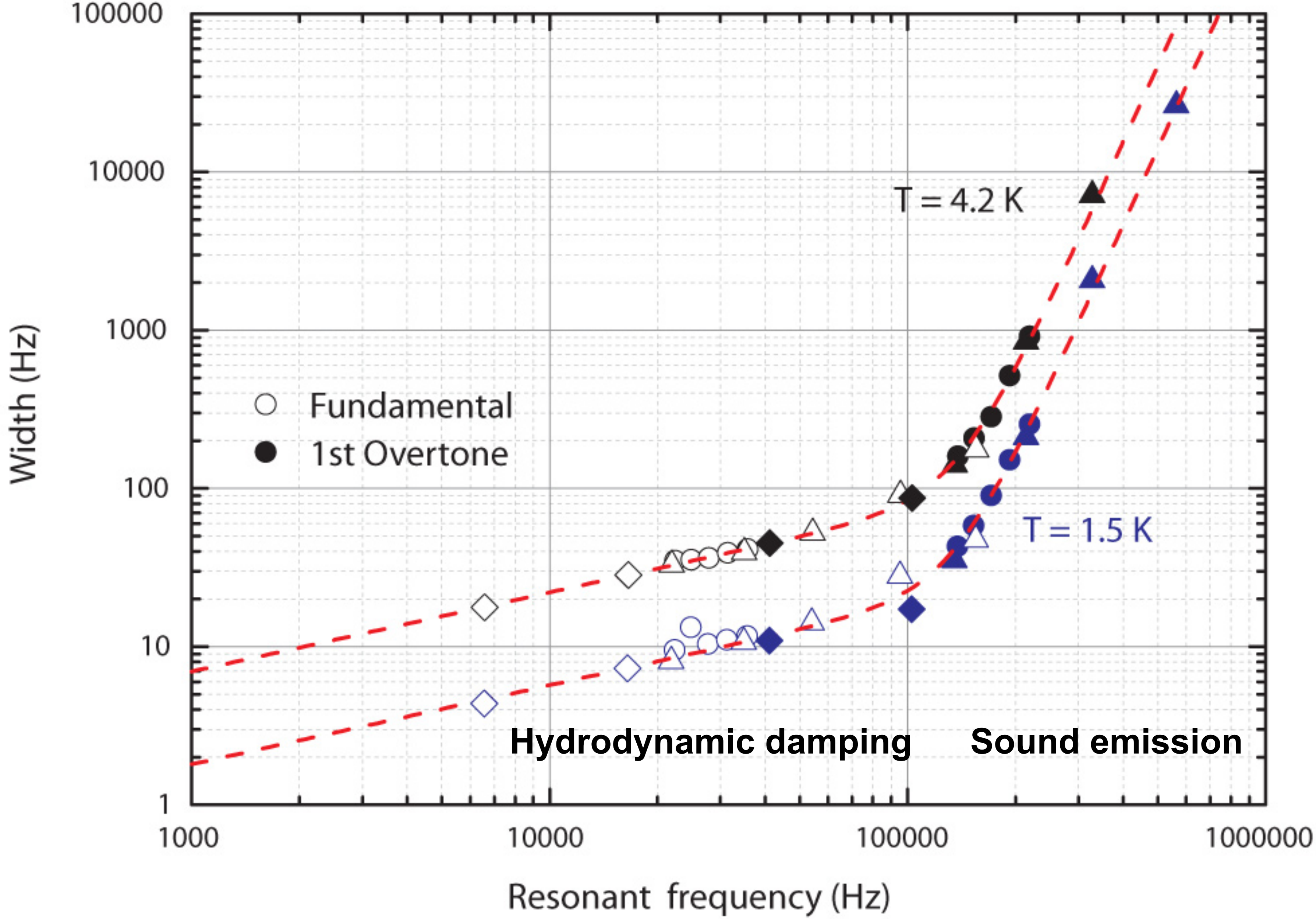
Normal fluid Drag vs KC $\beta^{1/2}$



Medium and high frequencies

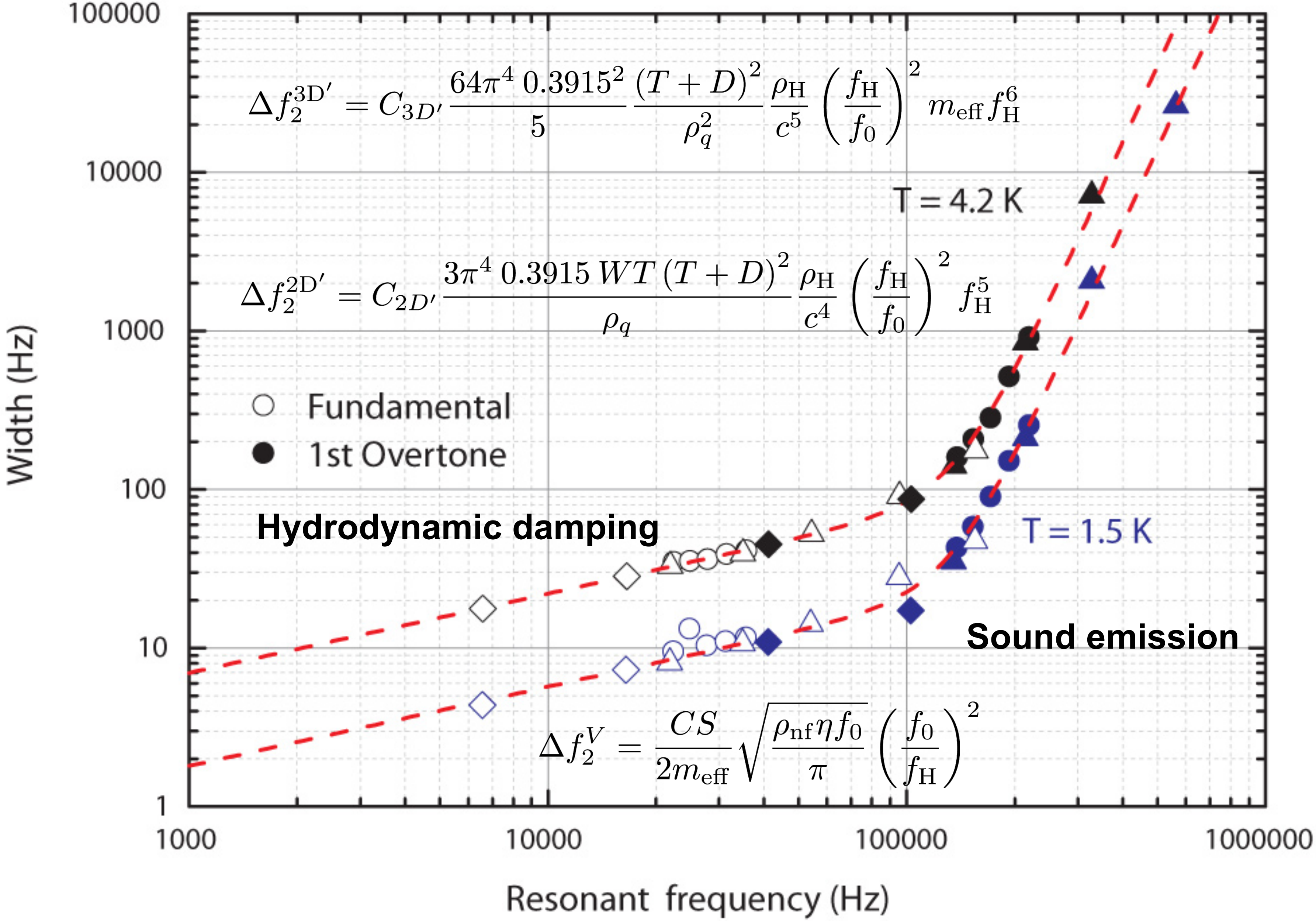
Sound emission

TF damping at 4.2K and 1.5K



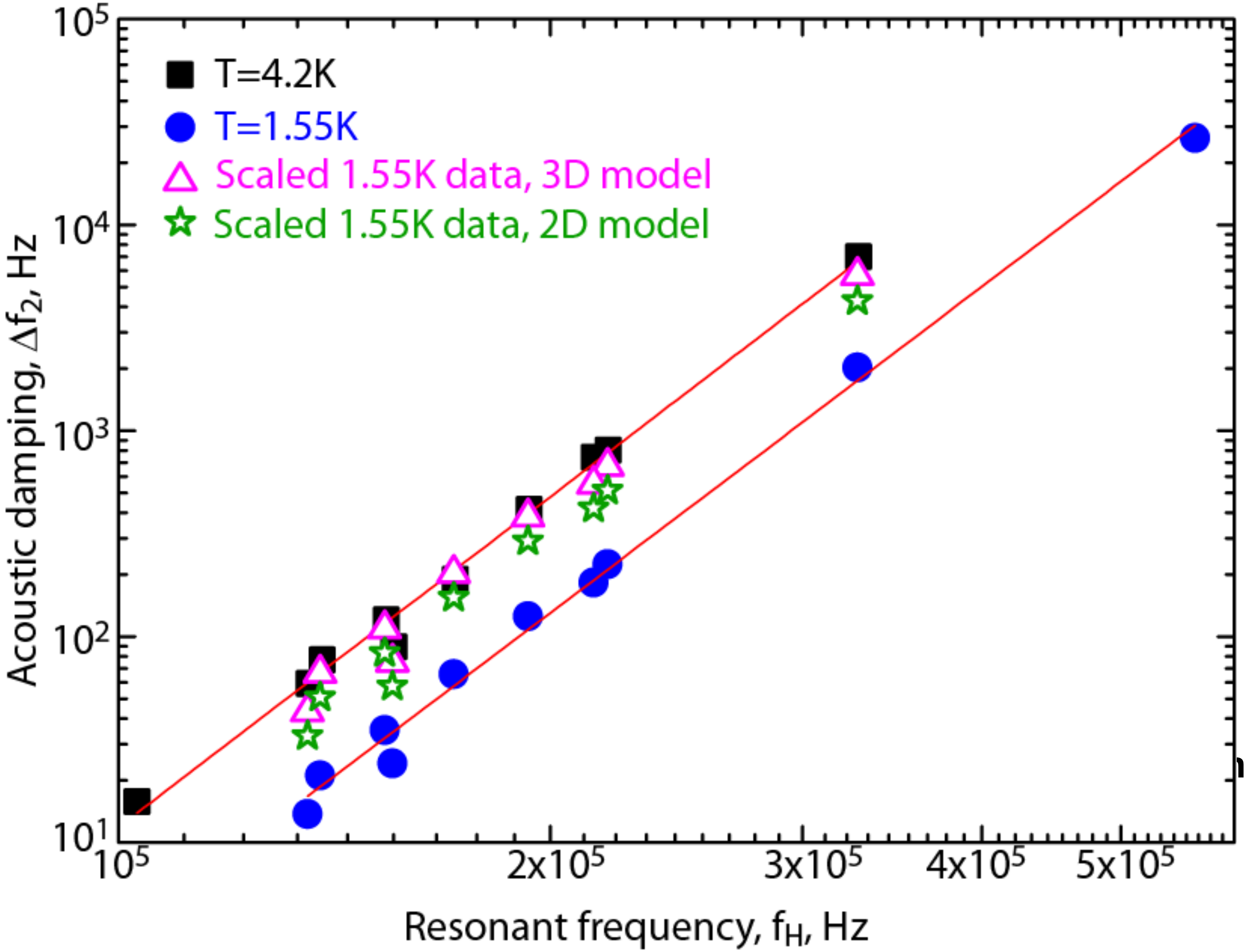
PHYSICAL REVIEW B 85, 014501 (2012)

TF damping at 4.2K and 1.5K



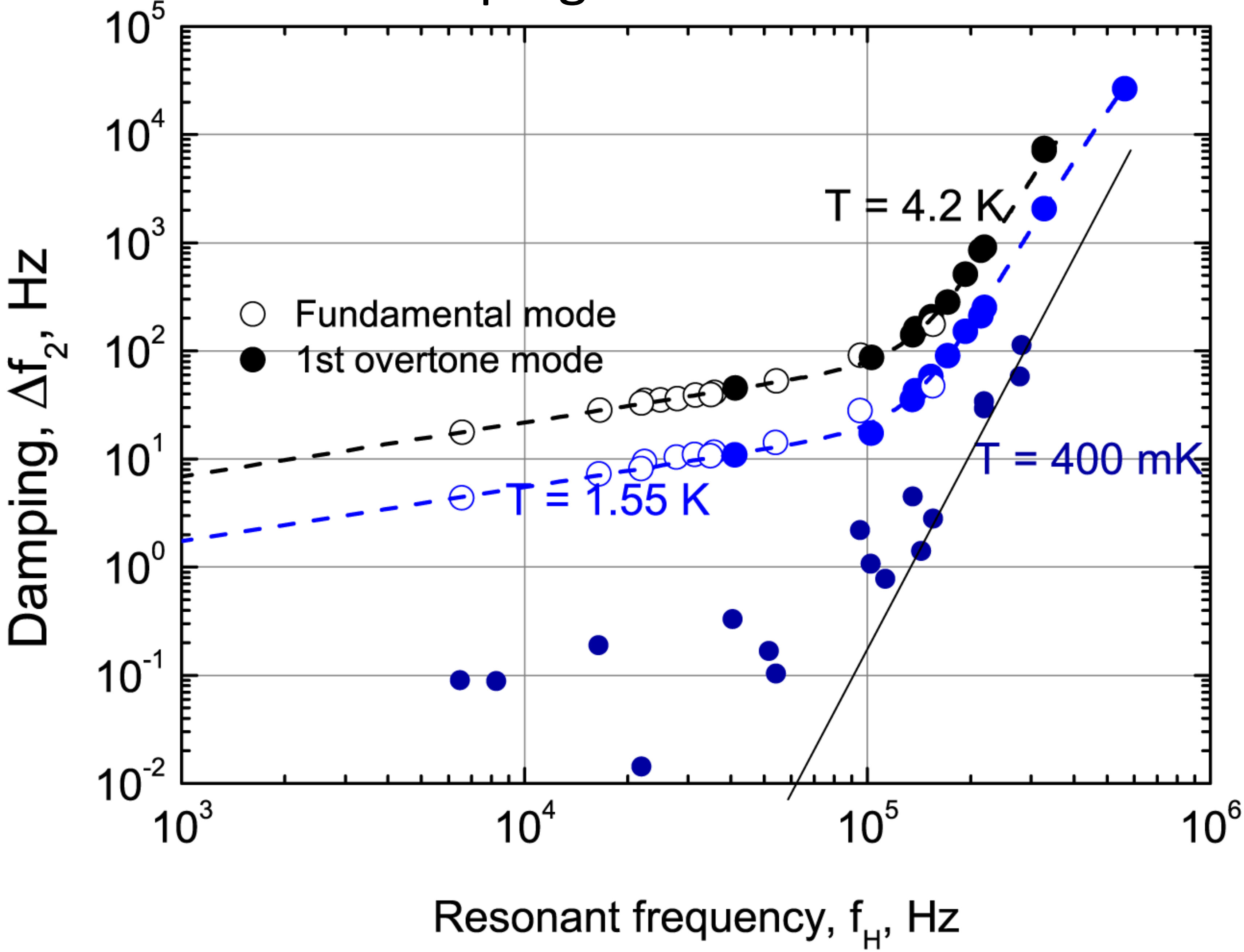
PHYSICAL REVIEW B 85, 014501 (2012)

TF acoustic damping at 4.2K and 1.5K

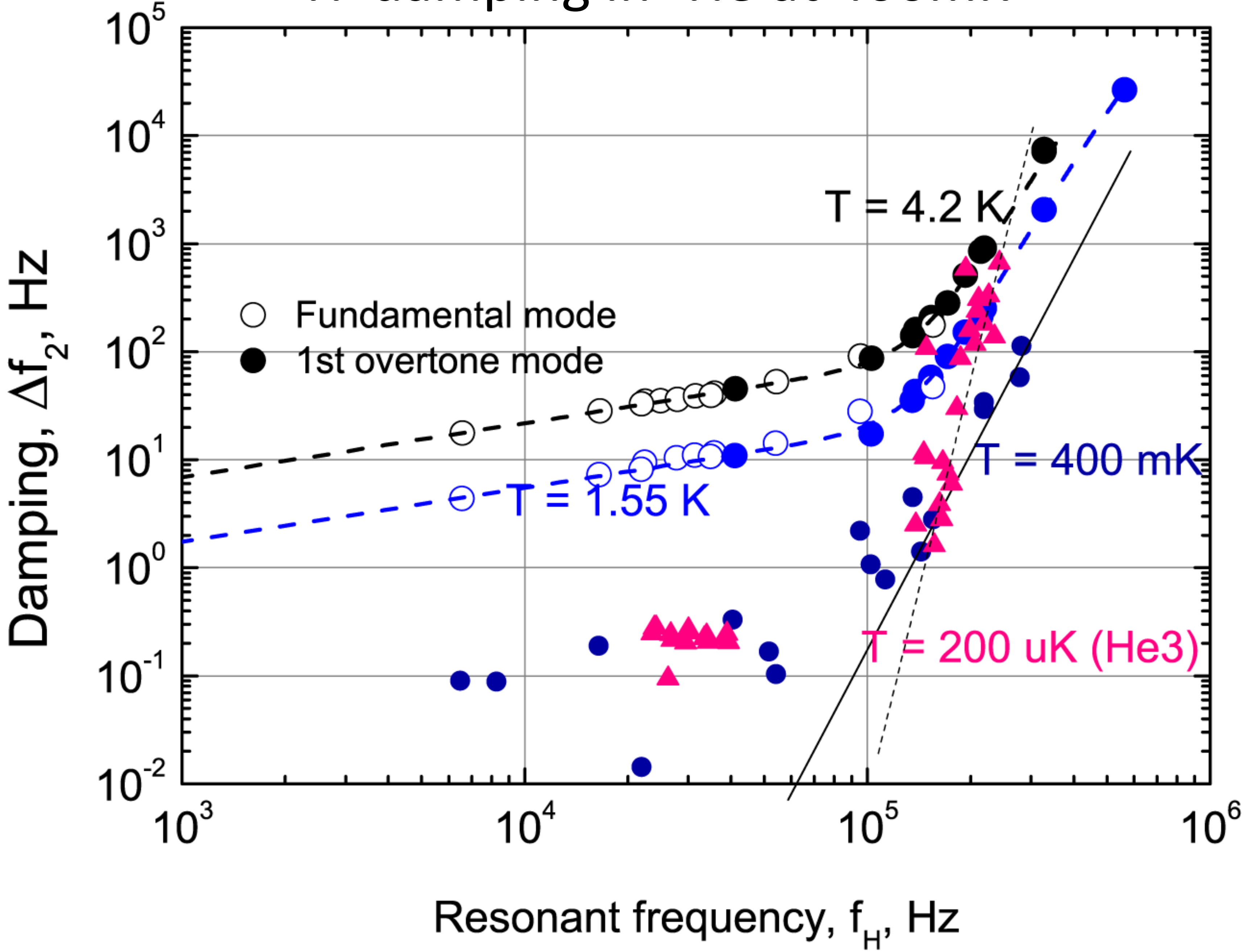


PHYSICAL REVIEW B 85, 014501 (2012)

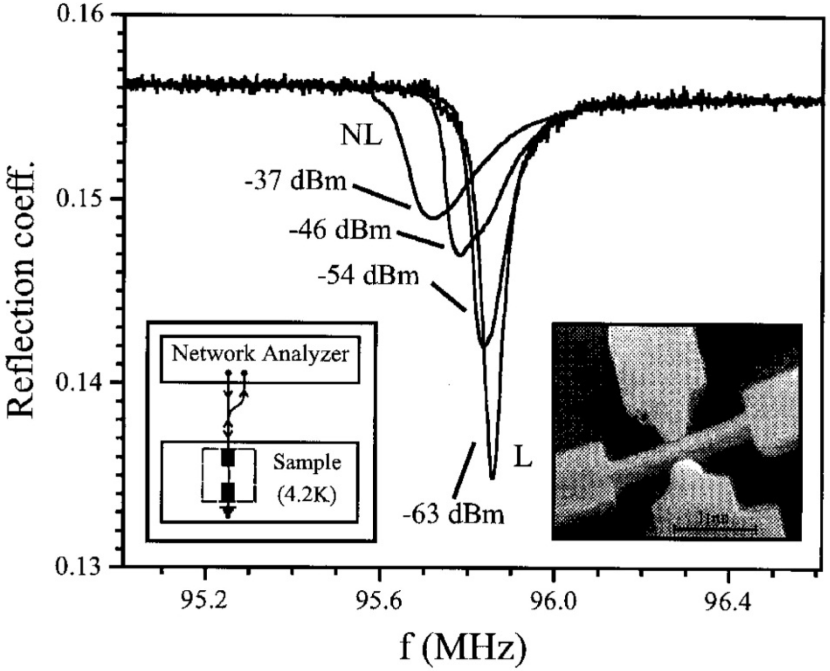
TF damping in ^{4}He at 400mK

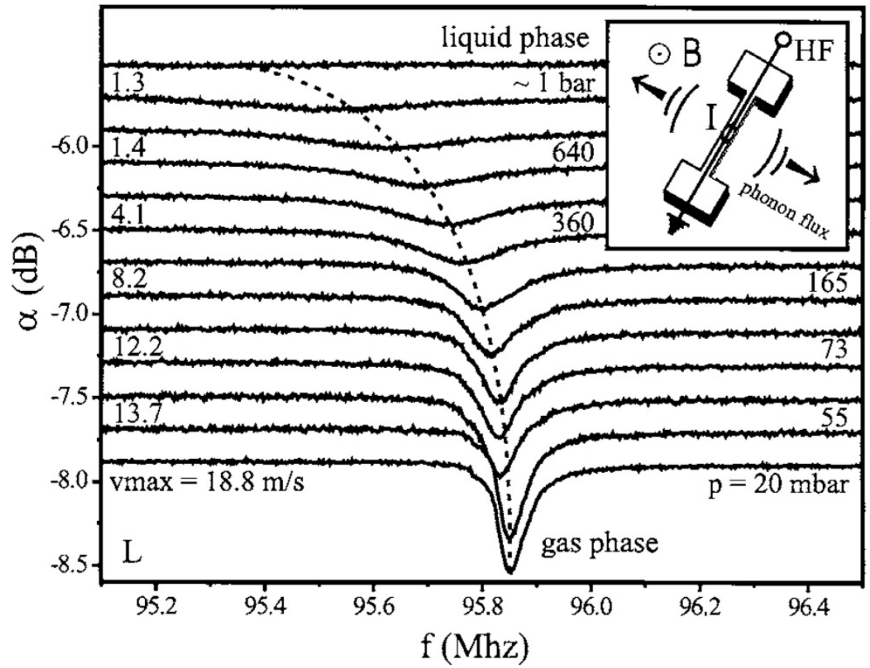


TF damping in ^4He at 400mK



Nano-mechanical beam 100 MHz (Munich Group)





SOI 200nm, additional 50 nm Au
Beam length 1 µm, width of 200 nm

Need to try superconducting beams of various length and thickness

Acoustic probing, turbulence nucleation, in 3He crossover from first to zero sou
Coherence length in 4He is sub-nanometer, in 3He 15 - 80nm.

Nanotechnology 11 (2000) 165

Summary

- ❖ Quartz tuning forks support up to 4 flexure modes with high Q values. Velocity of the tip of the fork can be easily obtained using experimental fork constant for any of these modes.

- ❖ Fork damping is governed by Stocks drag at low frequencies, and acoustic emission at high frequencies.

- ❖ Frequency dependence of the critical velocity for turbulence nucleation using quartz tuning forks is consistent with expected ½ powerlaw dependence.

- ❖ The drag in superfluid He4 at high temperatures and moderate velocities can be accounted for by the normal fluid alone [no drag from the superfluid]