The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific and
Cultural Organization

IAEA
International Atomic Energy Agency

2023-18

Workshop on Topics in Quantum Turbulence

16 - 20 March 2009

Experiments on Vibrating Structures in 3He

BRADLEY David Ian
University of Lancaster
Department of Physics
LA1 4YB Lancaster
UNITED KINGDOM

Strada Costiera 11, 34014 Trieste, Italy - Tel. +39 040 2240 111; Fax +39 040 224 163 - sci_info@ictp.it, www.ictp.it

Experiments on Turbulence with Vibrating Structures in Superfluid ^3He

Ian Bradley

LANCASTER UNIVERSITY
Department of Physics

Plan of talk

- Basic superfluid ^{3}He
  - Vortices
  - Andreev scattering

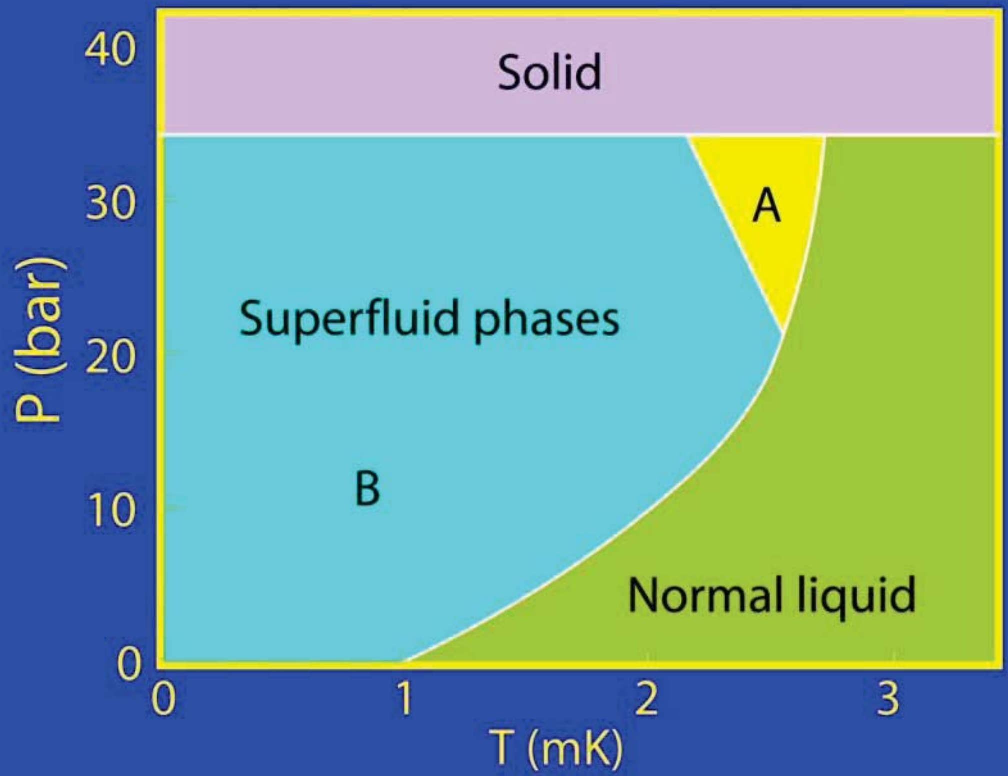
- Vibrating Wire experiments

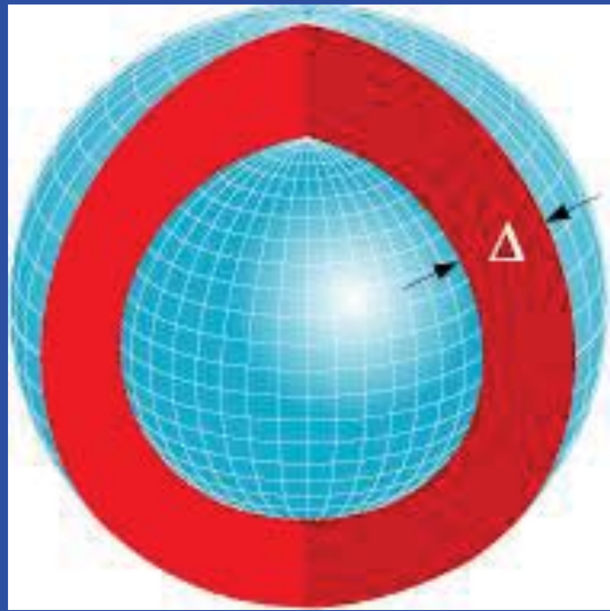
- Vibrating Grid experiments

- Tuning Forks

^{3}He Phase Diagram

Superfluid phases formed by Cooper pairs with S=1, L=1





At low temperatures, quasiparticle excitation number falls rapidly

$n_{ex} \propto \exp(-\Delta/k_B T)$

Mean free path virtually infinite – ballistic quasiparticles

Vibrating objects

at reasonable oscillation amplitudes are simple
driven damped harmonic oscillators with motion governed by

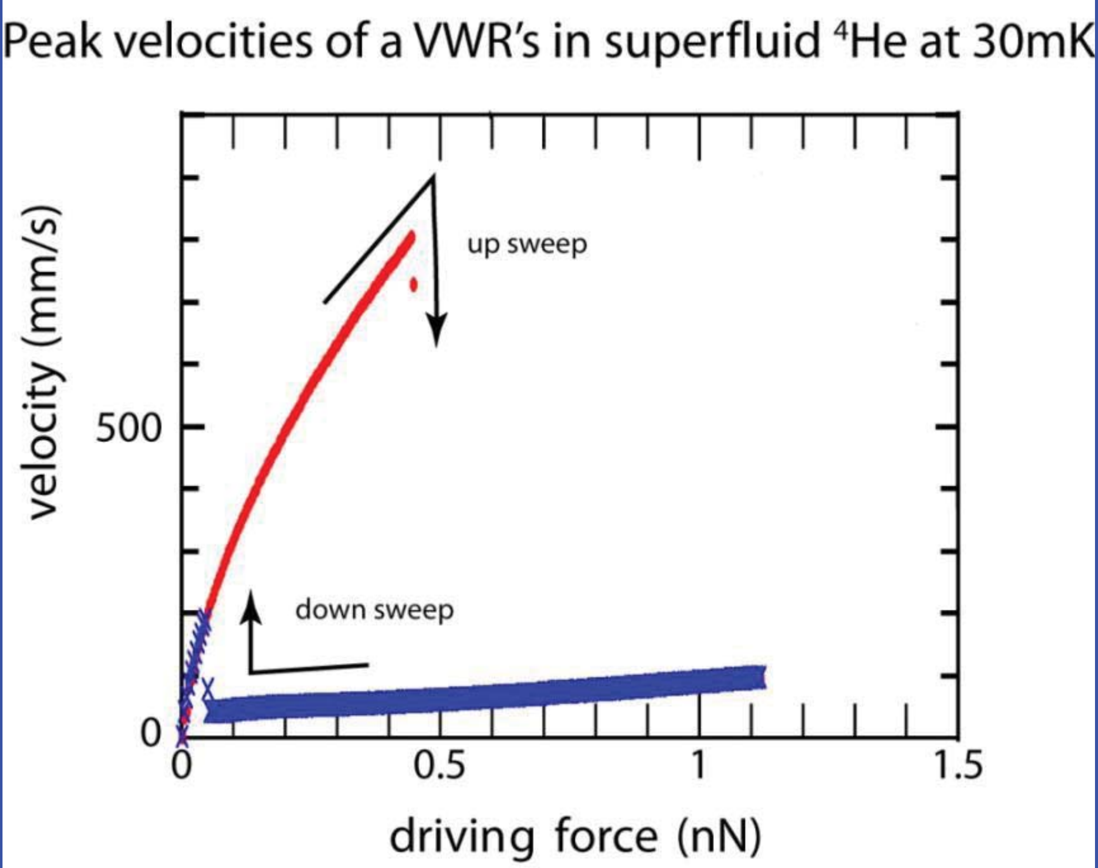
$$\boxed{m\ddot{x} + \mathcal{F}(\dot{x}) + kx = F_{drive}}$$

with *m* a mass parameter, *k* a restoring force parameter,
and $\mathcal{F}$(v) describing the damping.

$$\boxed{\begin{aligned} &\mathcal{F}(v) \propto v \ \text{ for viscous drag} \\ &\mathcal{F}(v) \propto v^2 \ \text{ for turbulent drag} \end{aligned}}$$

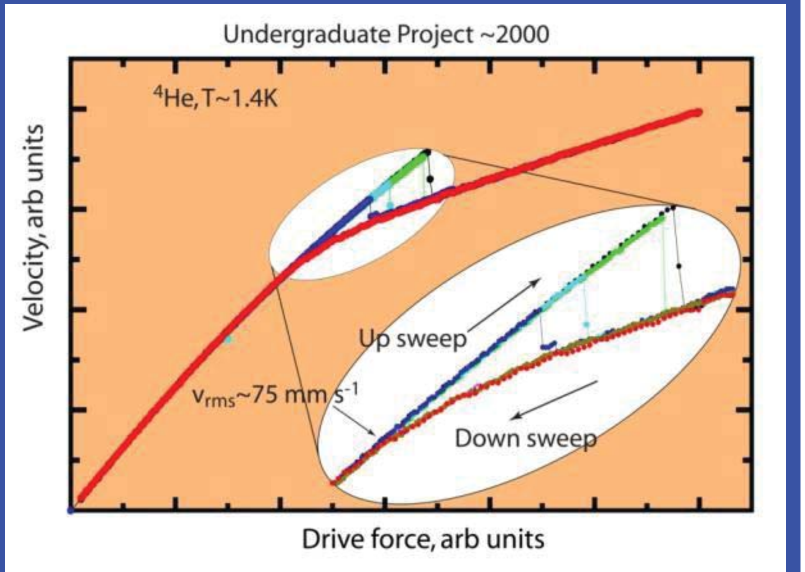
Quickly look at the response for a vibrating wire

In ^{4}He, there is a clear hysteretic transition from a low damping regime to a high turbulent damping regime

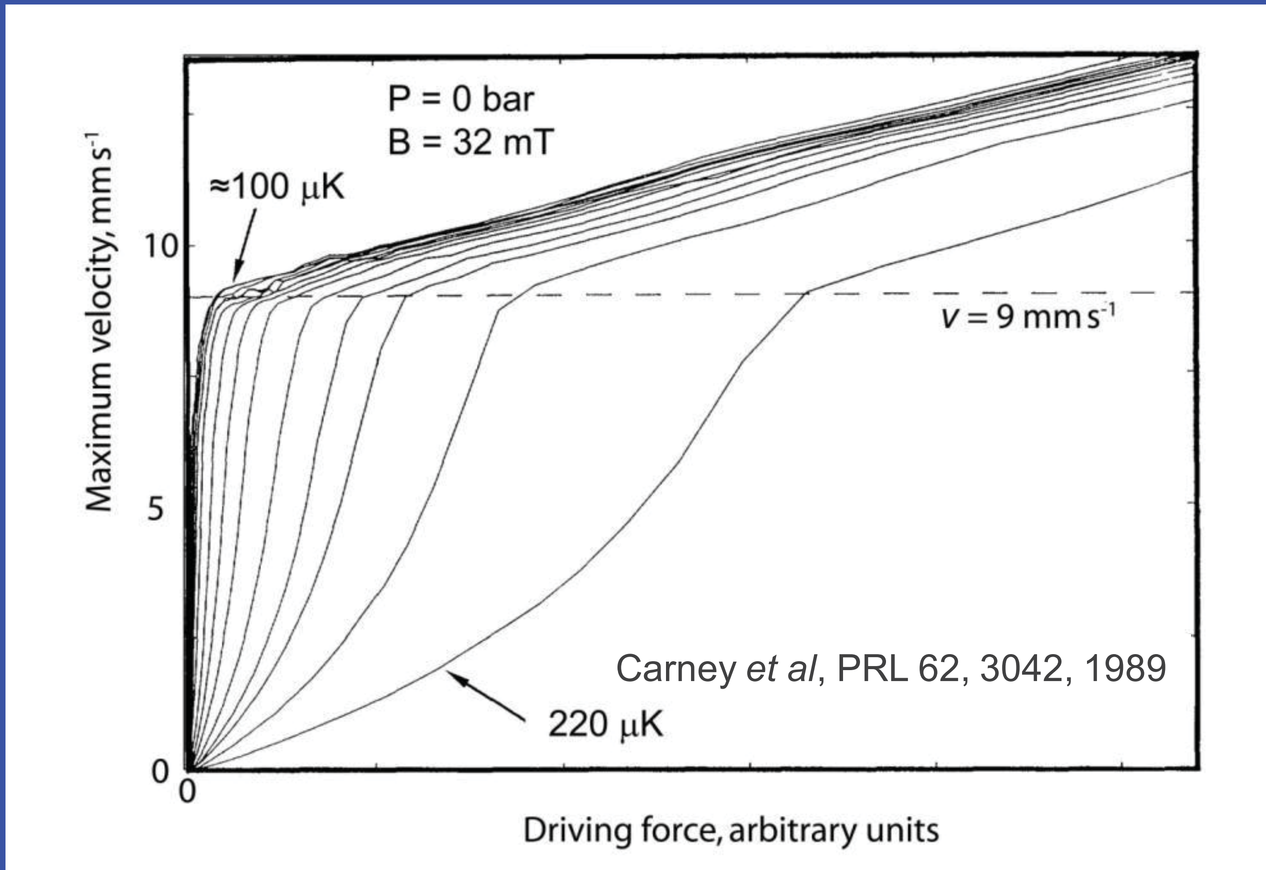


Goto *et al* PRL 100, 045301, 2008

results from vibrating wires

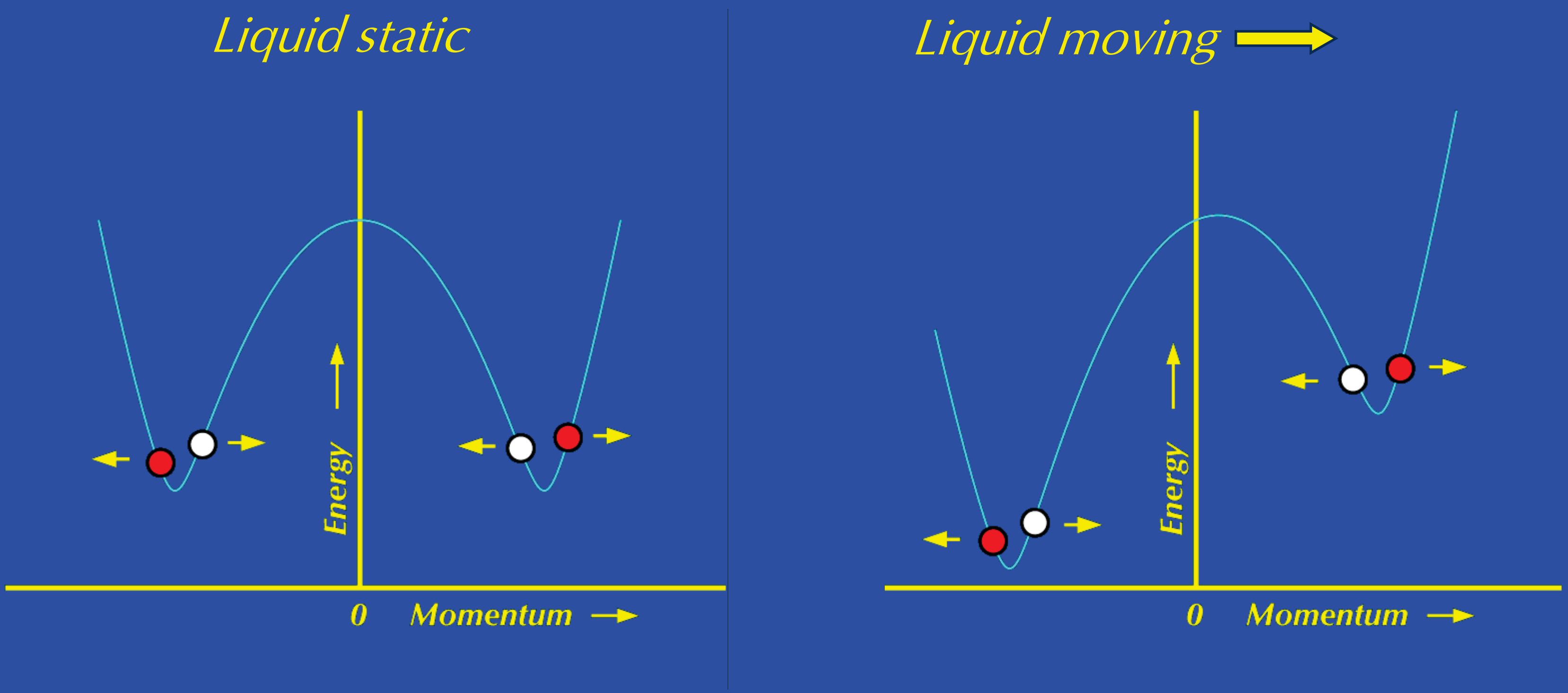


In ^{3}He-B, life is more complicated. Again, results for a vibrating wire.



- critical velocity to pair breaking regime
- temperature dependent non-linear damping – **Andreev Scattering**
- no clear sign of turbulence

If the liquid is in motion, then we see the dispersion curve in a moving frame of reference. Excitations approaching will have higher energies by ~ $p_F v$ and those receding lower energies by the same amount



- quasiparticles move with constant energy
- if one moves into a region where there is no available state it Andreev reflects

negligible change in momentum

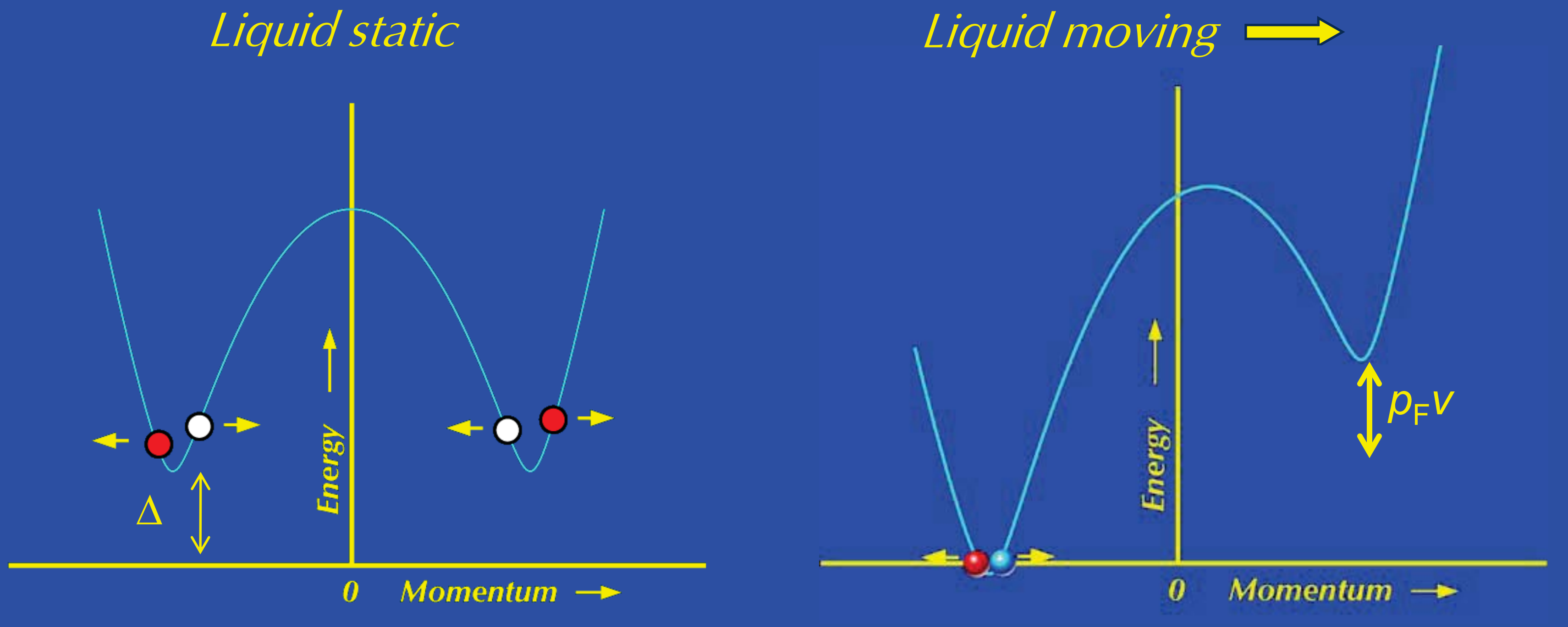
➢ changes state from a quasiparticle to a quasihole (or vice versa)

   - result is that as the wire moves faster, less quasiparticles are able to scatter off the wire resulting in a reduced damping

   - wire moves even faster for a given driving force
   - higher temperature, more thermally excited quasiparticles, therefore larger effect

Andreev scattering of quasiparticles by the turbulence flow field gives rise to the main turbulence detection technique move object even quicker…

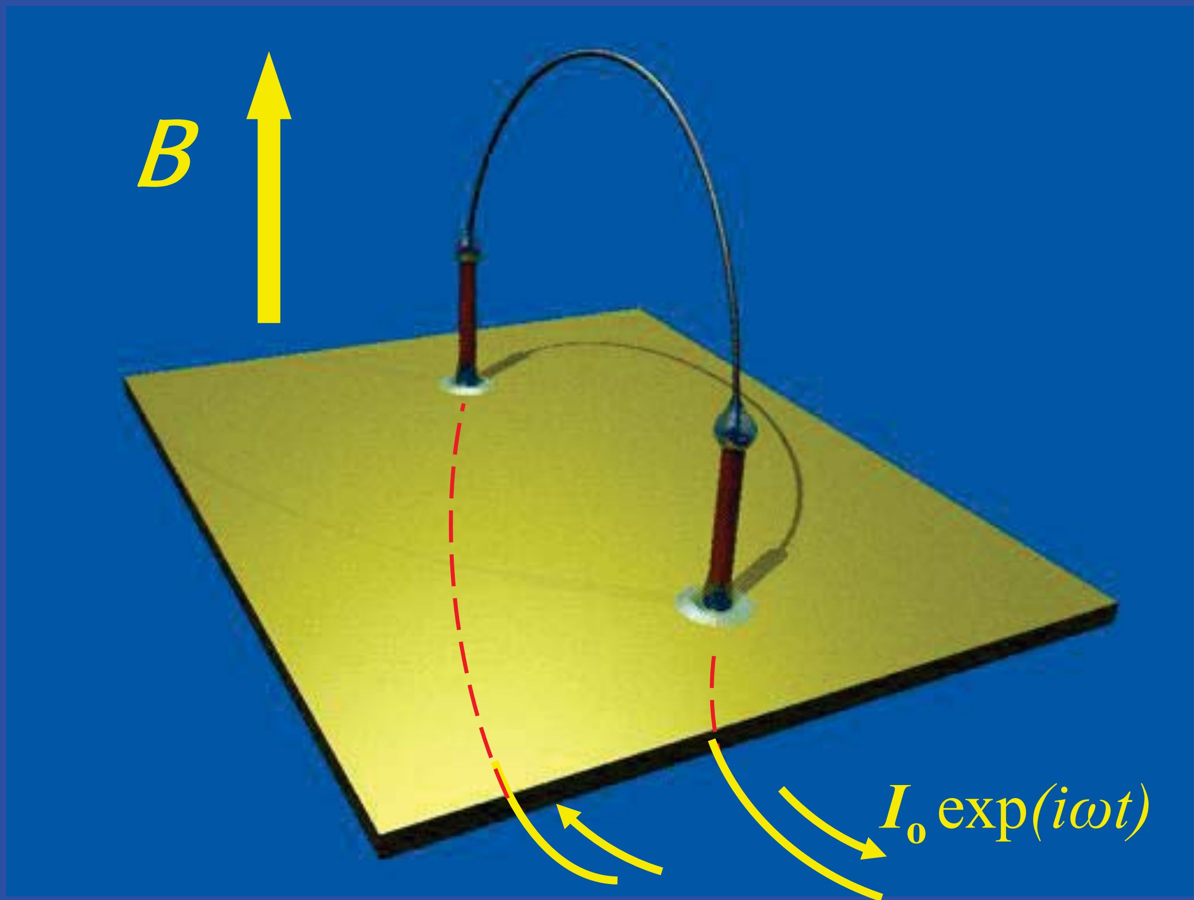
When the distortion in the dispersion curve, $p_F v$, becomes as large as the gap Δ, the minimum in the dispersion curve goes to zero and thus quasiparticles can be freely created. Cooper pairs are broken and superfluidity begins to be destroyed at a velocity of Δ/p_F.



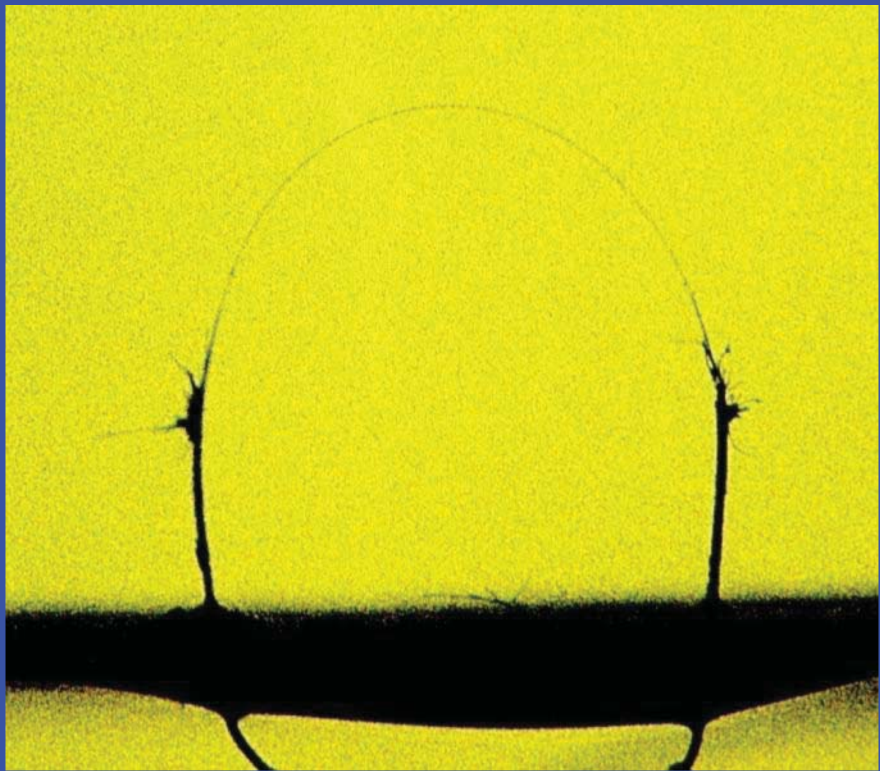
This makes analysis of the damping due to turbulence difficult as pair breaking and turbulence generation seem to occur together

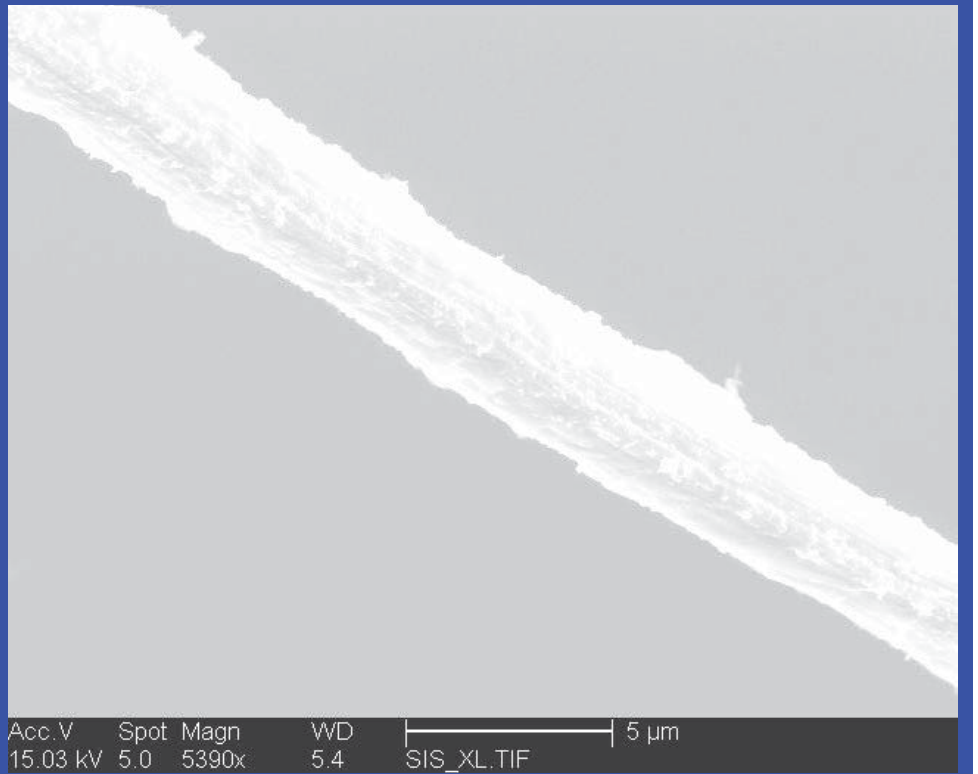
Vibrating wires

Most commonly used wires made from multi-filamentary superconducting wire removing all but one of the filaments (typically 60 or so!)

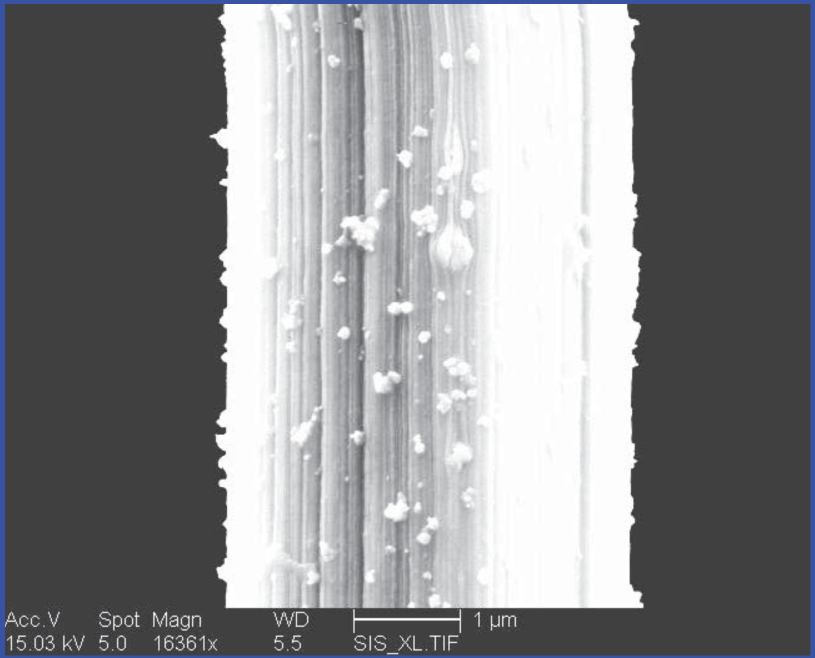


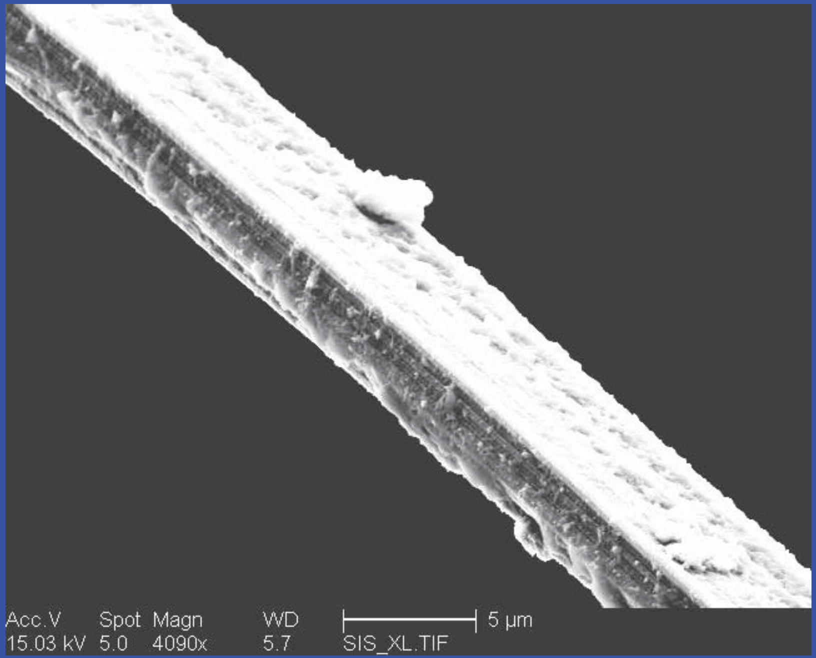
Typical 4.5 μm vibrating wire with a 2.64 mm leg spacing prior to cleaning up the ends of the legs





Two filaments from the same multifilmentary wire



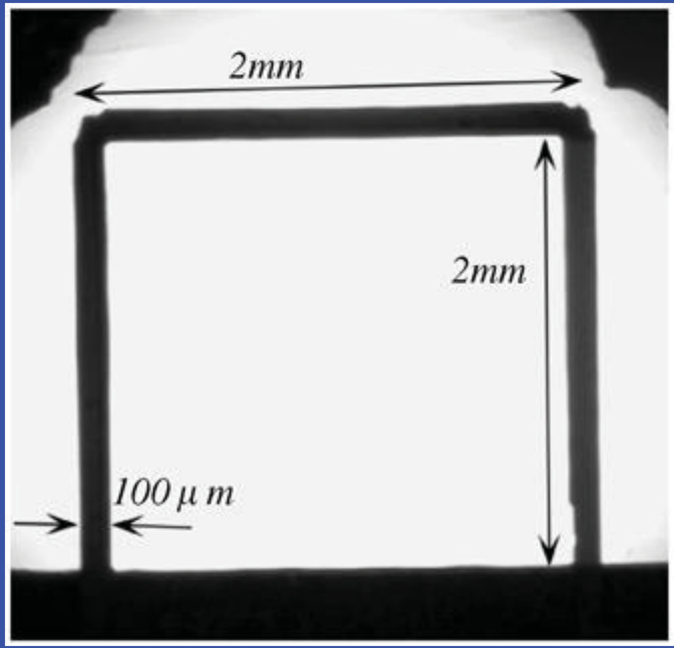


central filament in bundle

edge filament in bundle

Wires are not smooth or necessarily round!

Micro-fabricated wires have also been proposed for quantum turbulence studies



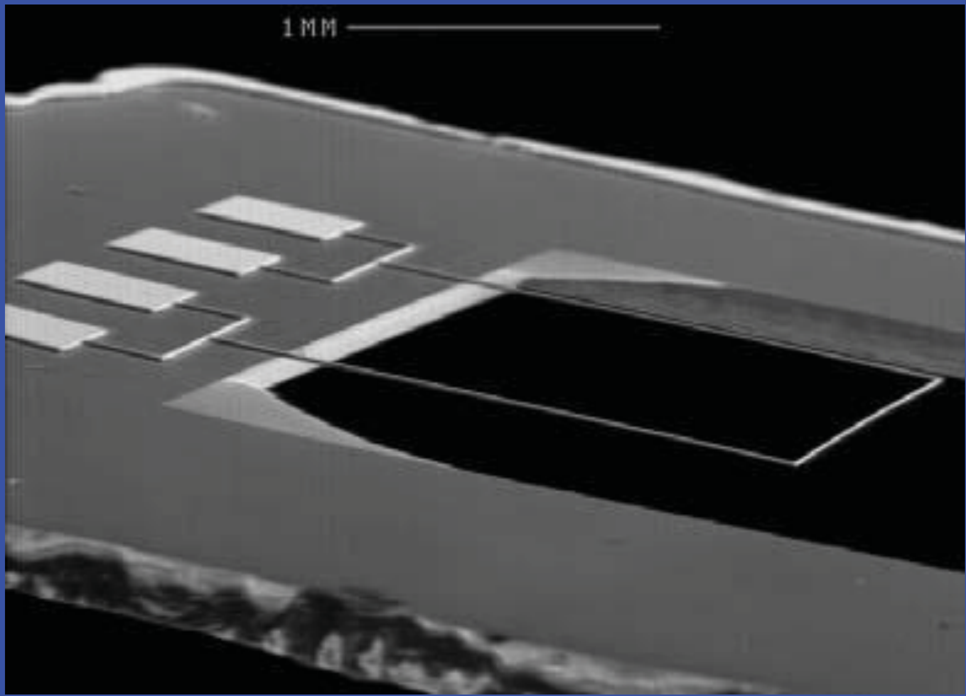
A silicon vibrating wire fabricated by reactive chemical etching with KOH.

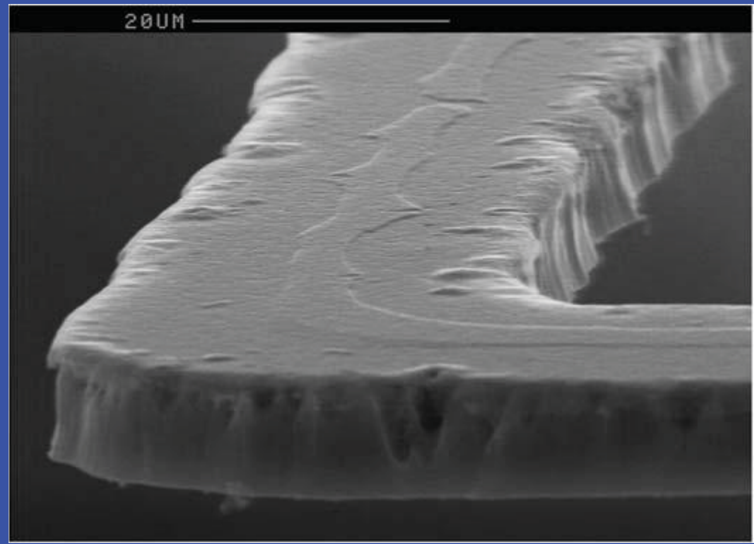
The wire surface is smoother by chemical etching than by reactive ion etching.

The roughness of the surface is ~1 μm.

resonant frequency 8.7kHz, $Q \sim 10^5$

Hayashi, Nakagawa, Yano, Ishikawa and Hata, Physica B 329–333, 108, 2003



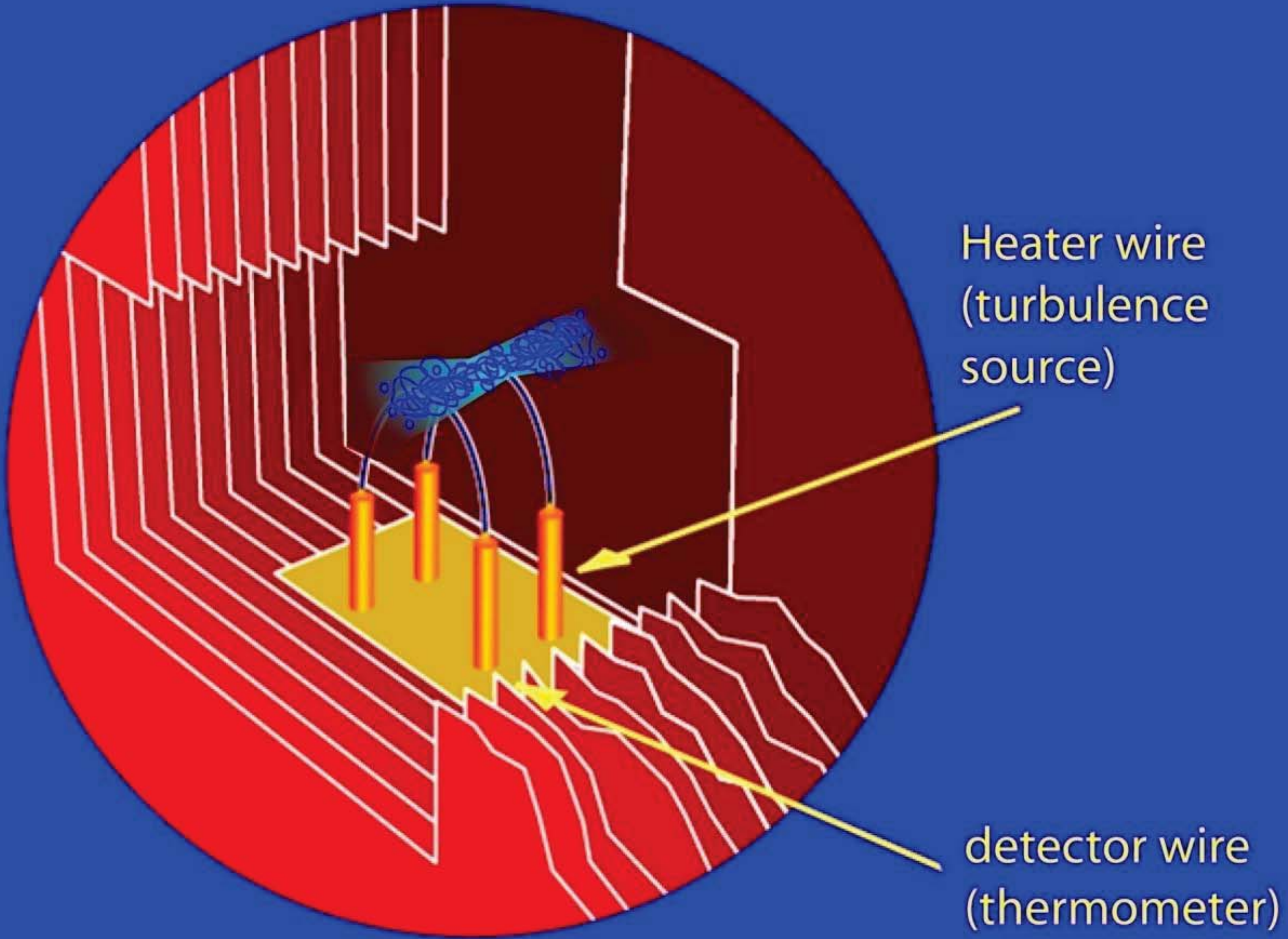


Prototype silicon vibrating goal post structures 10μm x 20μm formed by a combination of chemical etching and reactive ion etching. “The poor straightness of the Silicon shape is due to the rather poor quality of the optical lithography.”

resonant frequency 4.7kHz, $Q \sim 10^4$ (ULTIMA project)

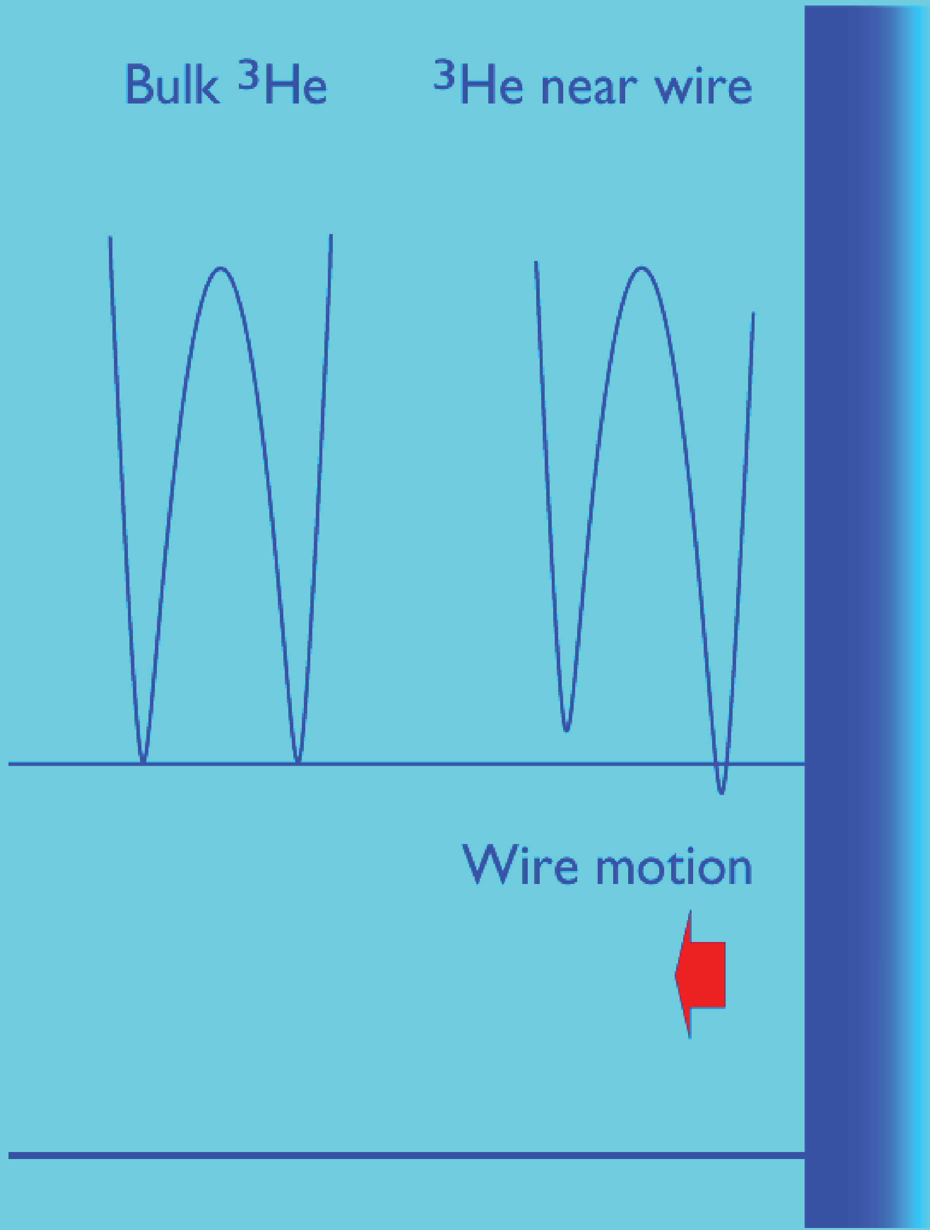
Triqueneaux *et al*, Physica B 284, 2141, 2000
Collin *et al*, JLTP 150, 739, 2008

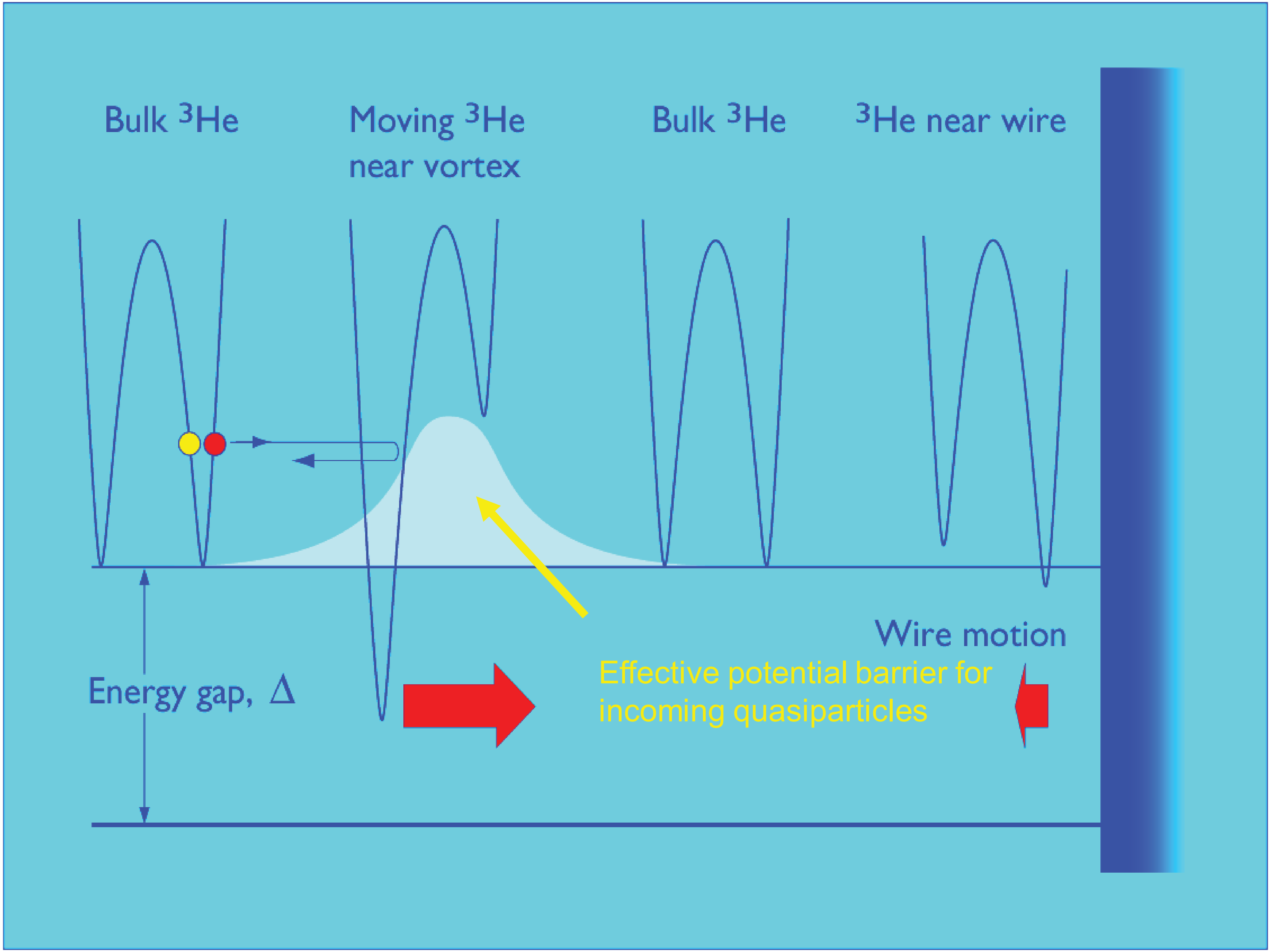
Detection of turbulence by a moving wire



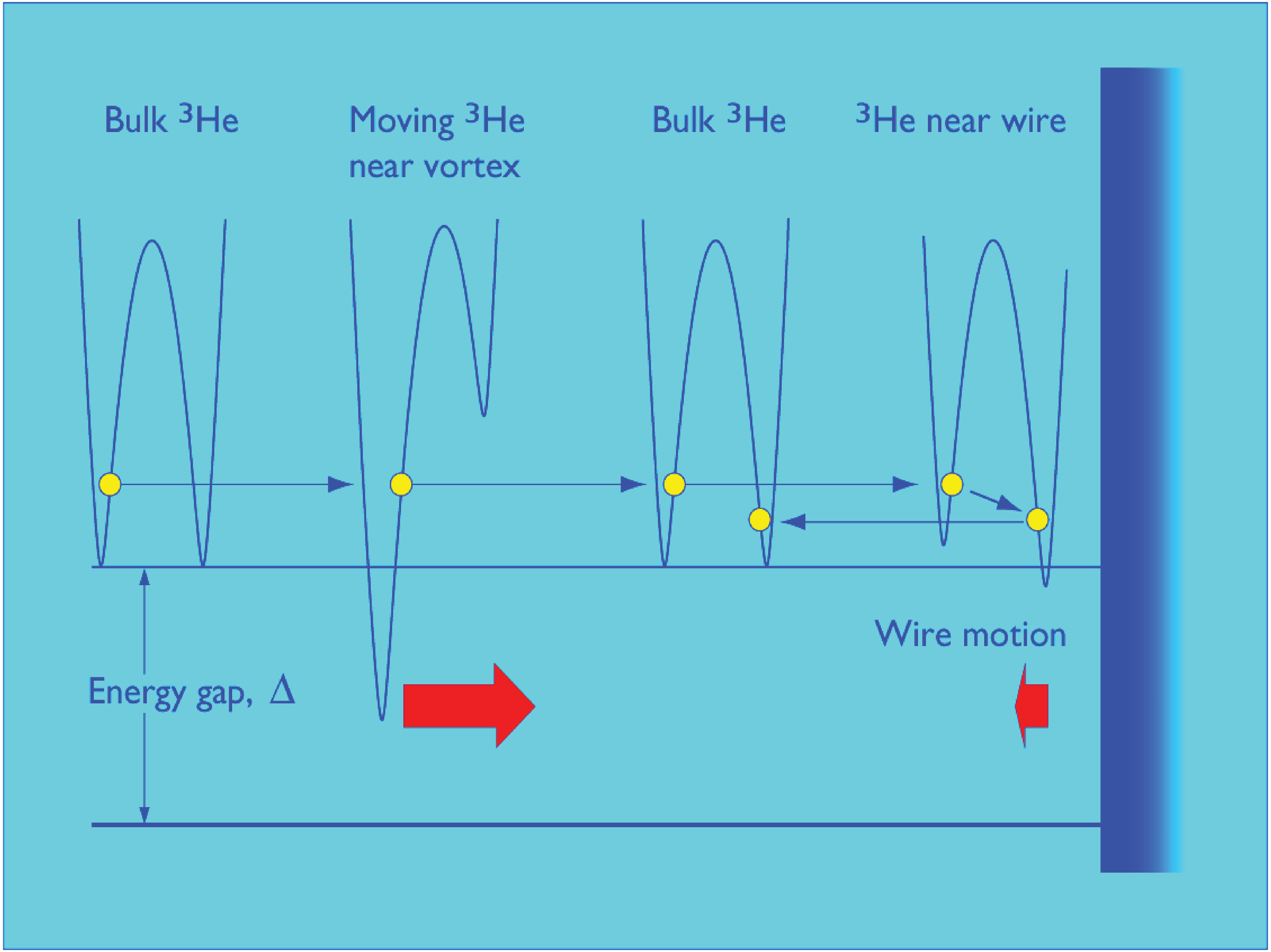
S.N. Fisher *et al*, *PRL* 86, 244, 2001

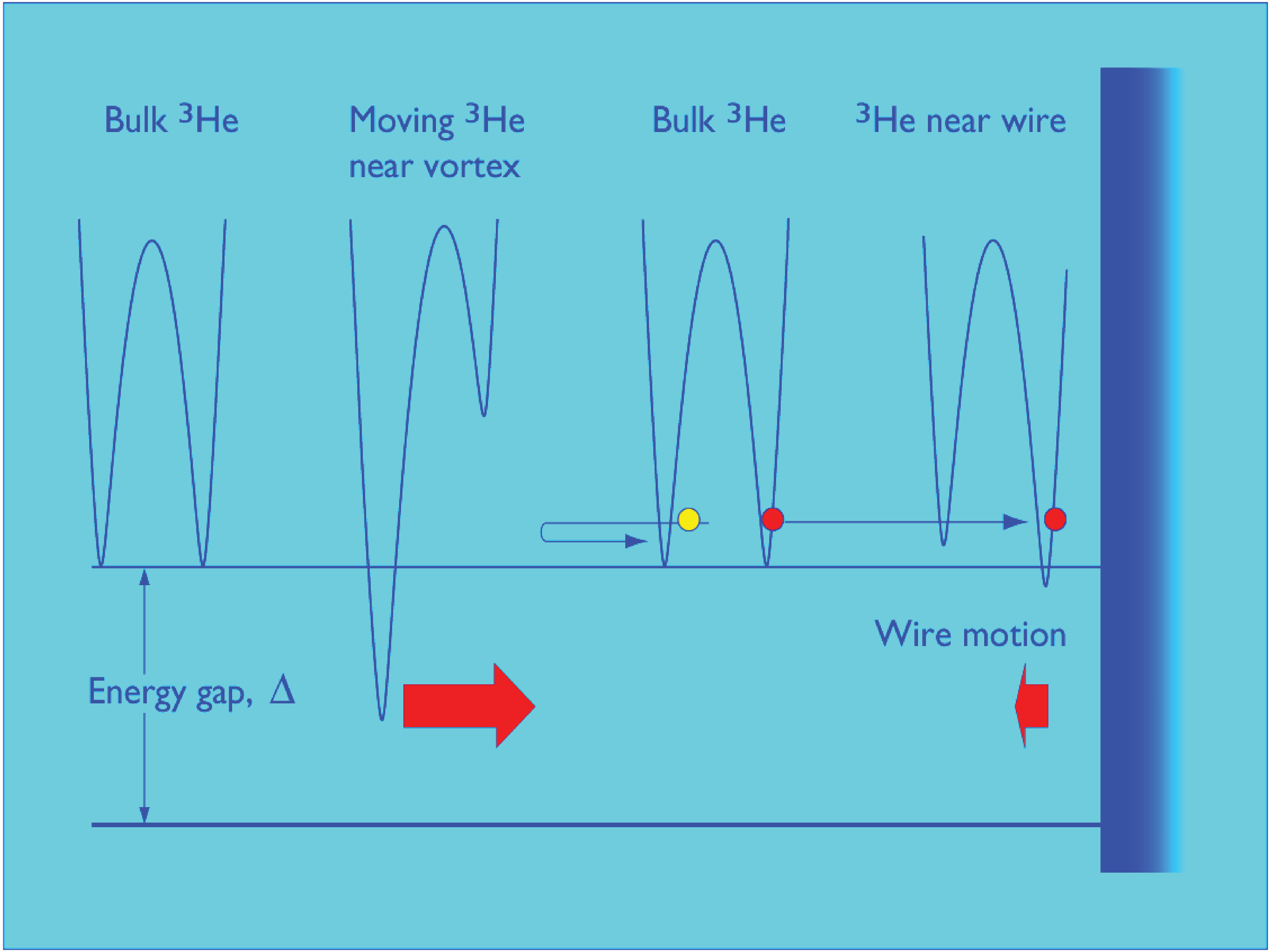
Turbulence Detection & Andreev reflection



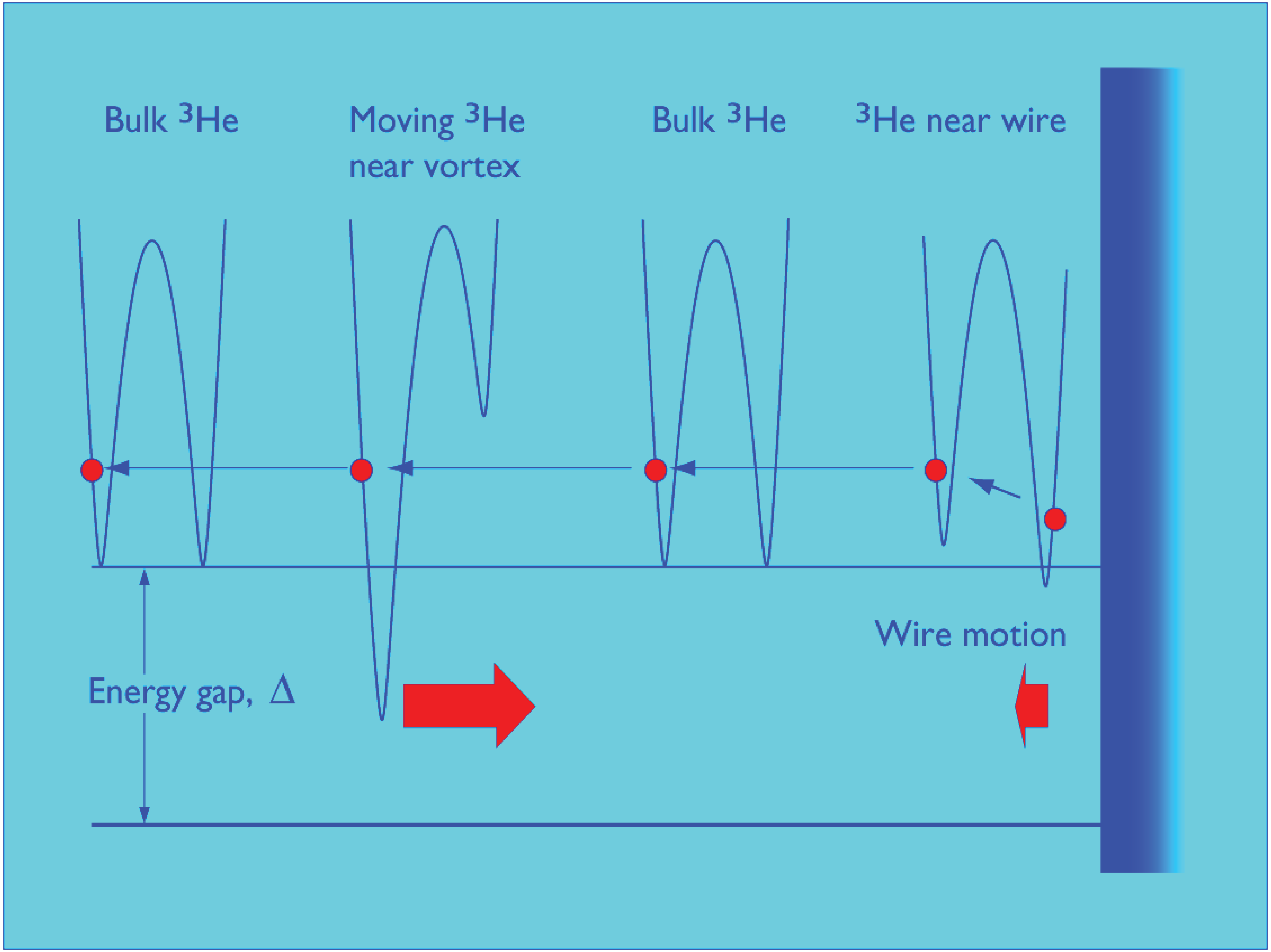


Bulk ^{3}He
Moving ^{3}He near vortex
Bulk ^{3}He
^{3}He near wire
Wire motion
Effective potential barrier for incoming quasiparticles
Energy gap, Δ


Bulk ^{3}He
Moving ^{3}He near vortex
Bulk ^{3}He
^{3}He near wire
Energy gap, Δ
Wire motion



Bulk ^{3}He
Moving ^{3}He near vortex
Bulk ^{3}He
^{3}He near wire
Wire motion
Energy gap, Δ

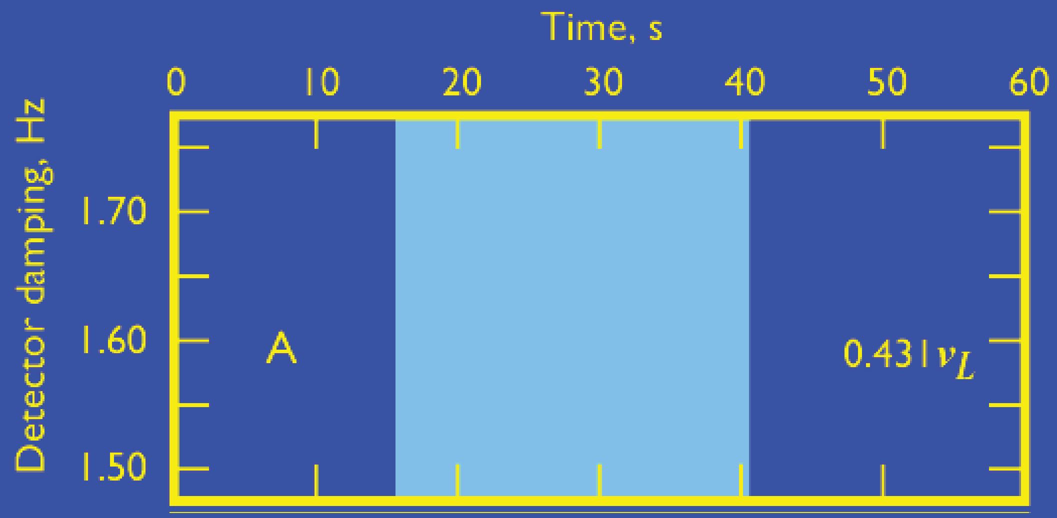

Bulk ^{3}He
Moving ^{3}He near vortex
Bulk ^{3}He
^{3}He near wire
Wire motion
Energy gap, Δ

So, in one dimension both incoming quasiholes and quasiparticles must make <u>one</u> Andreev reflection process.

Therefore an incoming quasihole goes out as a quasiparticle and an incoming quasiparticle goes out as a quasihole.

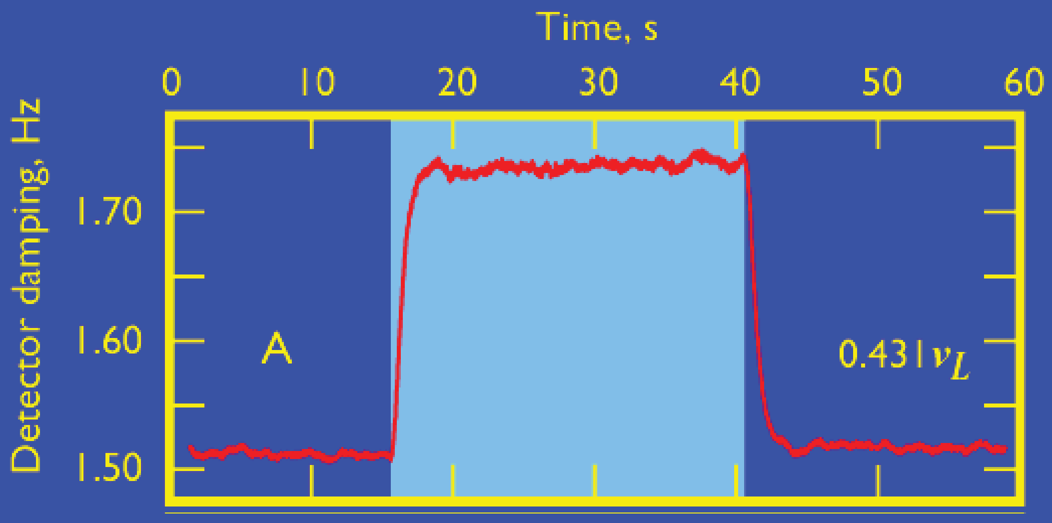
In both cases, <u>no</u> momentum is exchanged with the wire.

How does this affect the damping?



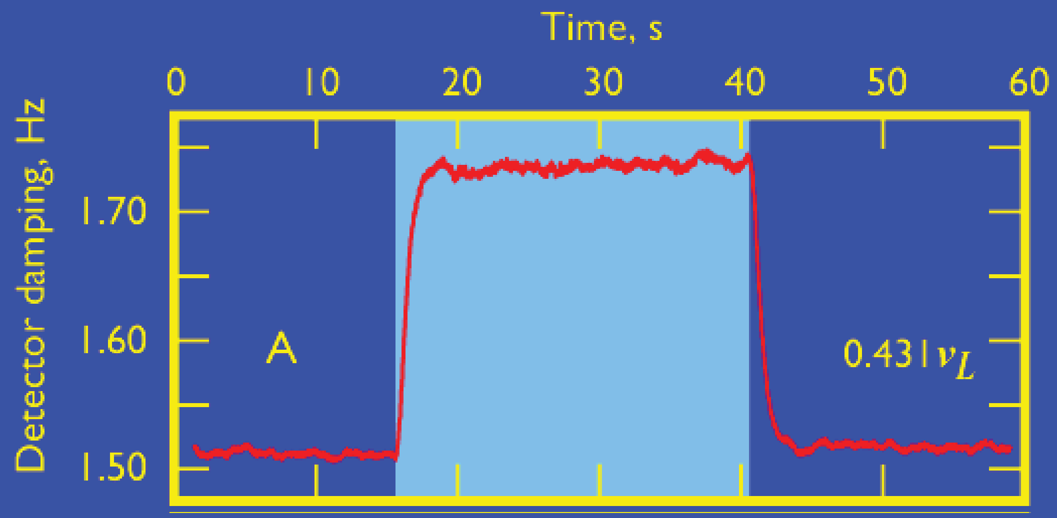
Look at the response of the "detector wire" as we drive the source wire at just above the critical velocity

S.N. Fisher, A.J.Hale, A.M.Guénault, and G.R.Pickett, *PRL* 86, 244, 2001



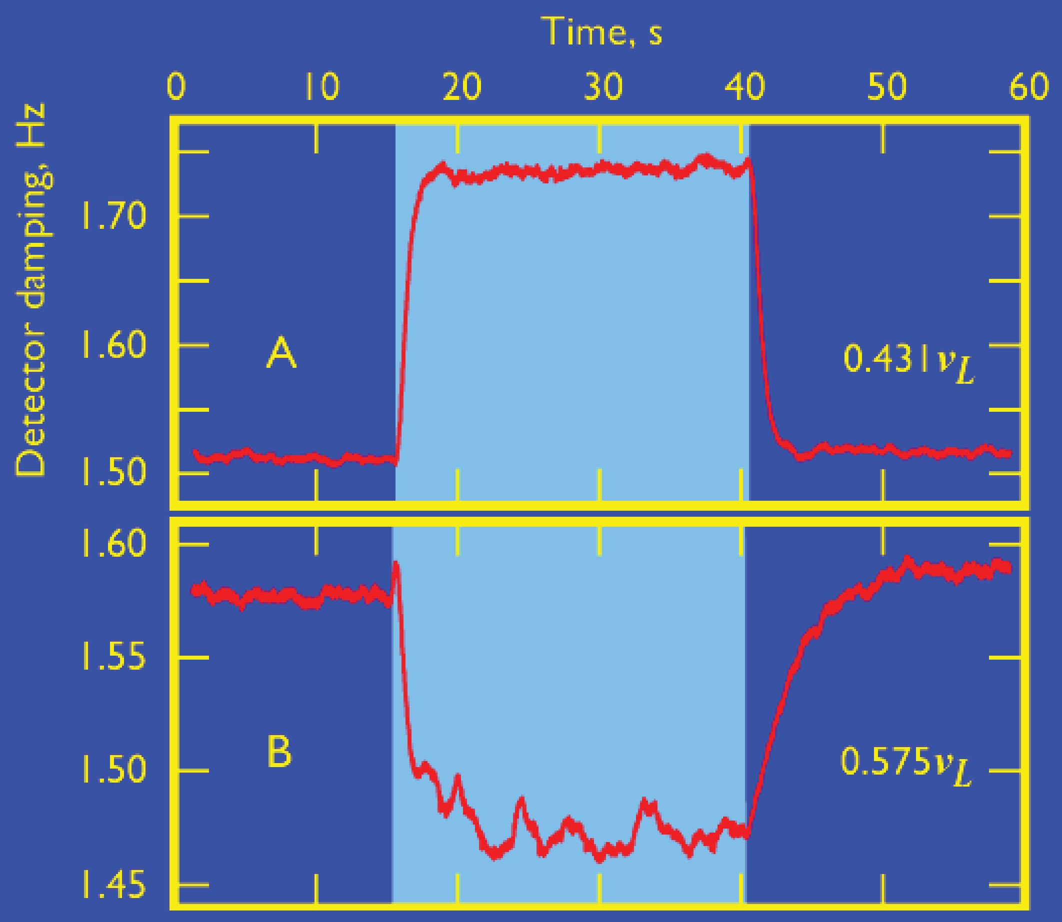
While we drive the source wire beyond the critical velocity the quasiparticle wind increases the damping on the second wire simply because there are more excitations to provide damping.

S.N. Fisher, A.J.Hale, A.M.Guénault, and G.R.Pickett, *PRL* 86, 244, 2001



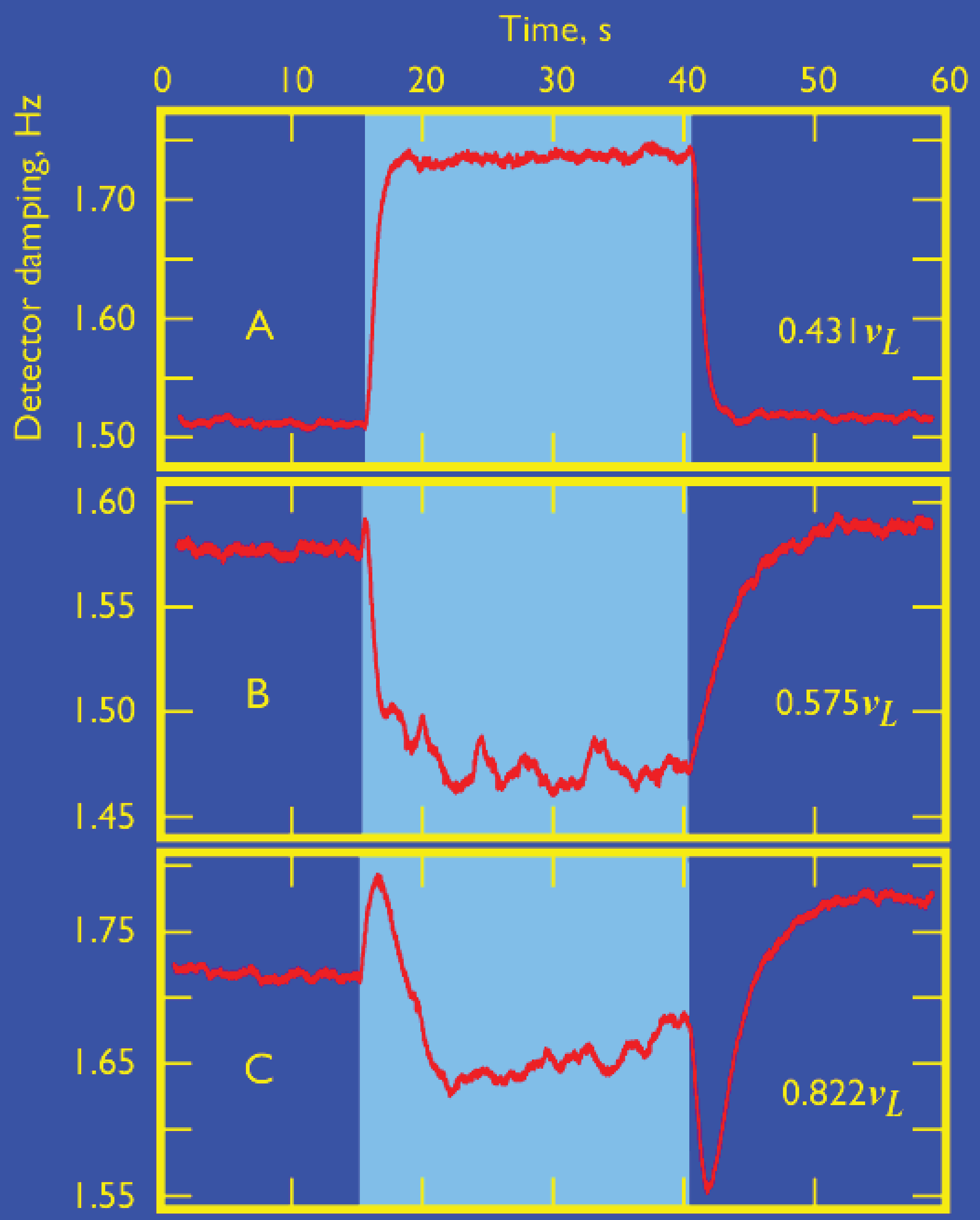
If try higher velocities.

S.N. Fisher, A.J.Hale, A.M.Guénault, and G.R.Pickett, *PRL* 86, 244, 2001



- clear fall in damping while source wire is driven
- noisy signal
- effectively a rather blurry one pixel camera looking at the shadows cast by the local turbulence

S.N. Fisher, A.J.Hale, A.M.Guénault, and G.R.Pickett, *PRL* 86, 244, 2001



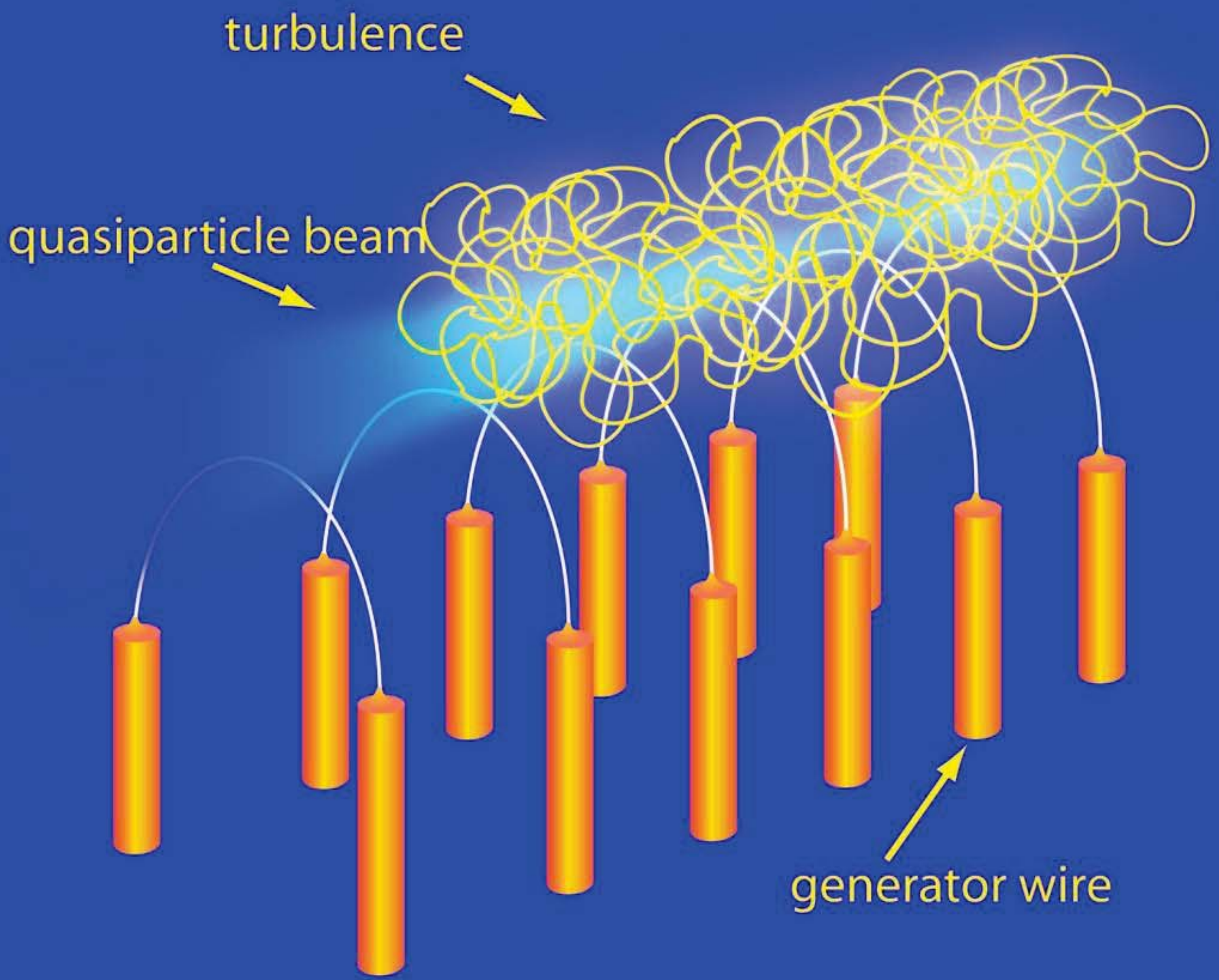
S.N. Fisher, A.J.Hale, A.M.Guénault, and G.R.Pickett, *PRL* 86, 244, 2001

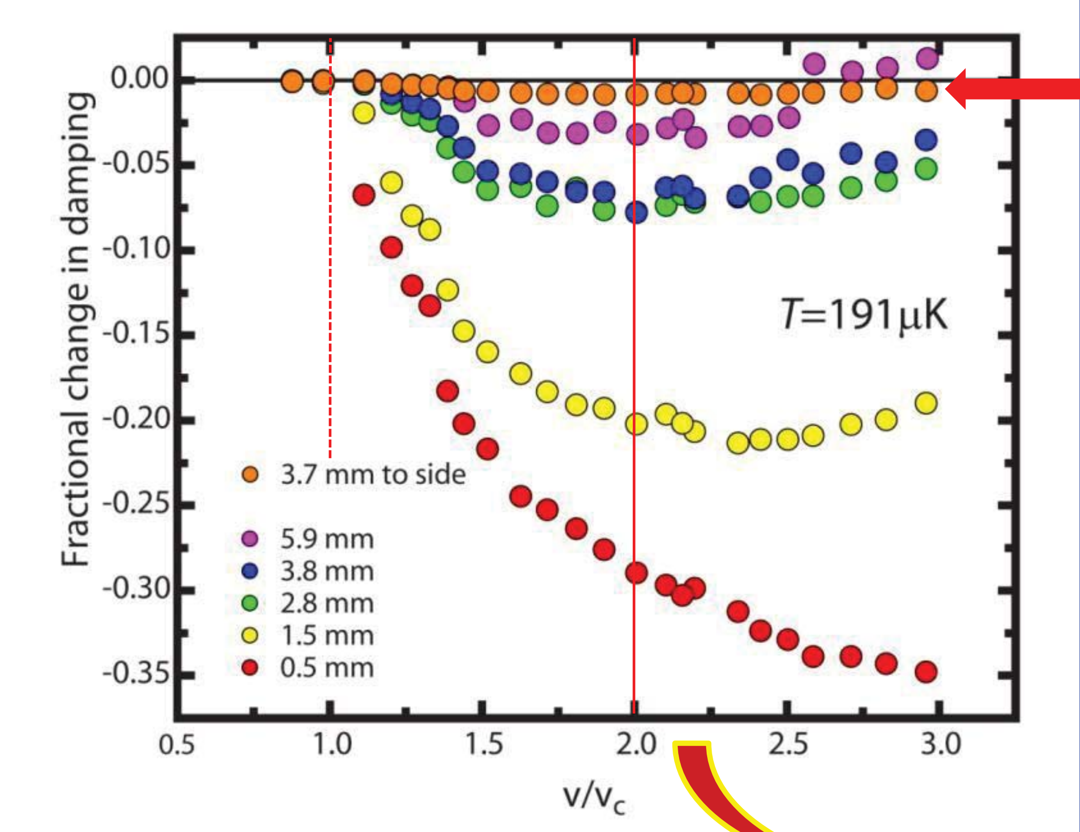
Conclusion

We detect the presence of turbulence as a fall in the damping by incoming thermal excitations on the detector wire because of the shadowing effect of the turbulence

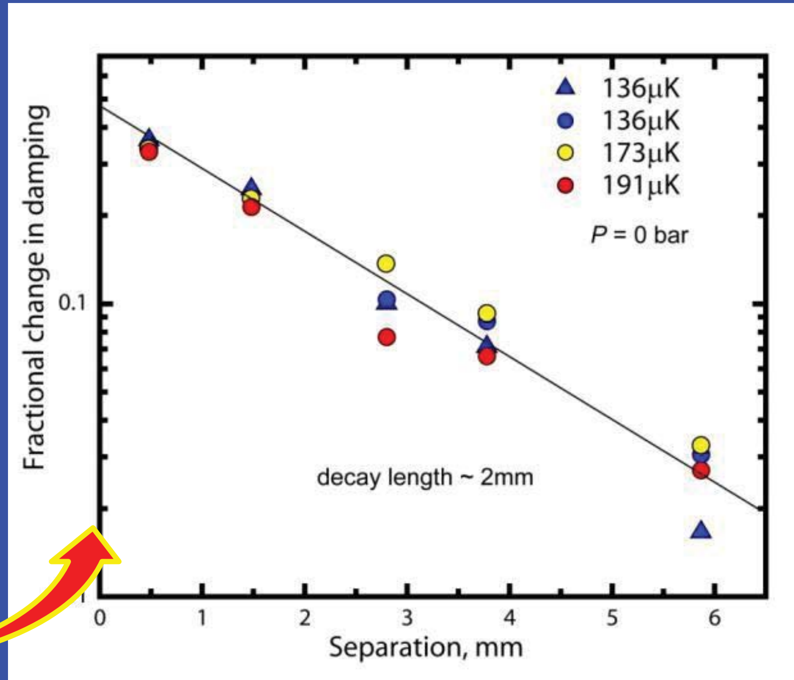
S.N. Fisher, A.J.Hale, A.M.Guénault, and G.R.Pickett, *PRL* 86, 244, 2001

Production of turbulence by a moving wire





3.7 mm to the side

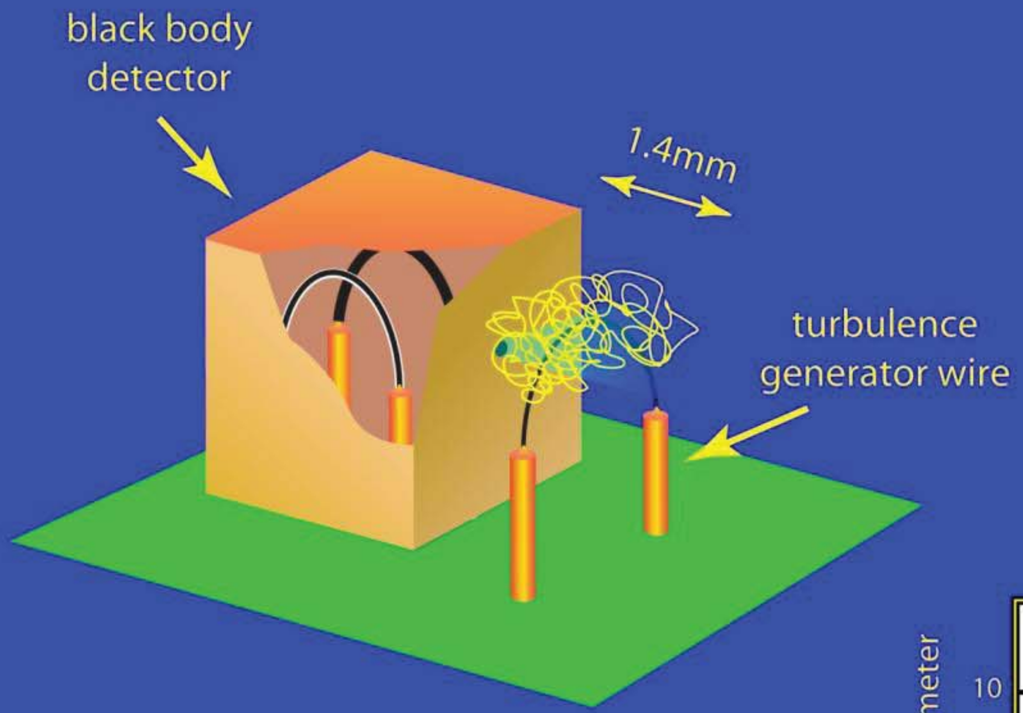


- clear turbulence onset at pair breaking critical velocity

- VWR to the side sees no shielding, similarly a VWR above array sees nothing
- conclude turbulence along direction of quasiparticle beam

- turbulence extent falls roughly exponentially over length scale ~2mm

Bradley et al, *Physica* B 329, 104, 2003



B lack body radiator contains

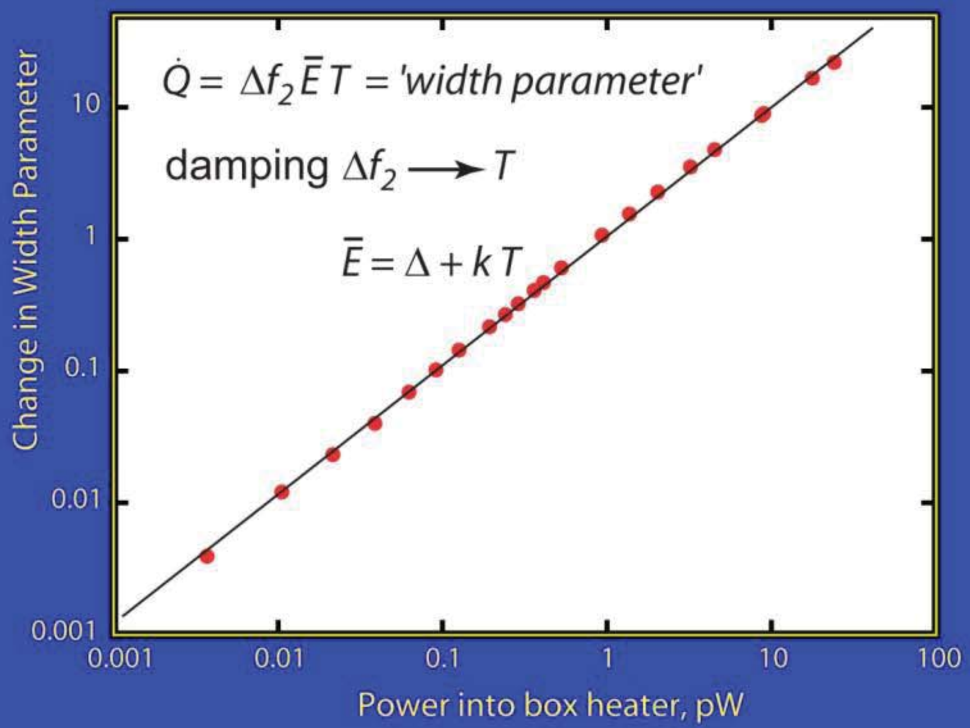
- a small hole
- a vibrating wire thermometer
- a vibrating wire heater

heat box to produce a quasiparticle beam

turn on generator wire to produce turbulence

measure the additional power reflected into the box by Andreev reflection of quasiparticles from the beam by the turbulence

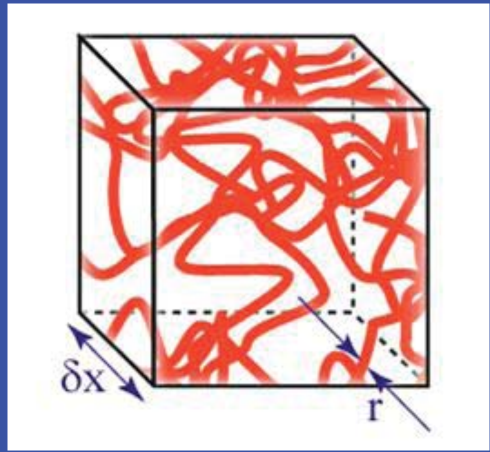
relate fraction reflected to the vortex line density



Know how to relate the reflected fraction to the line density from previous work (Bradley et al, *Physica* B 329, 104, 2003)

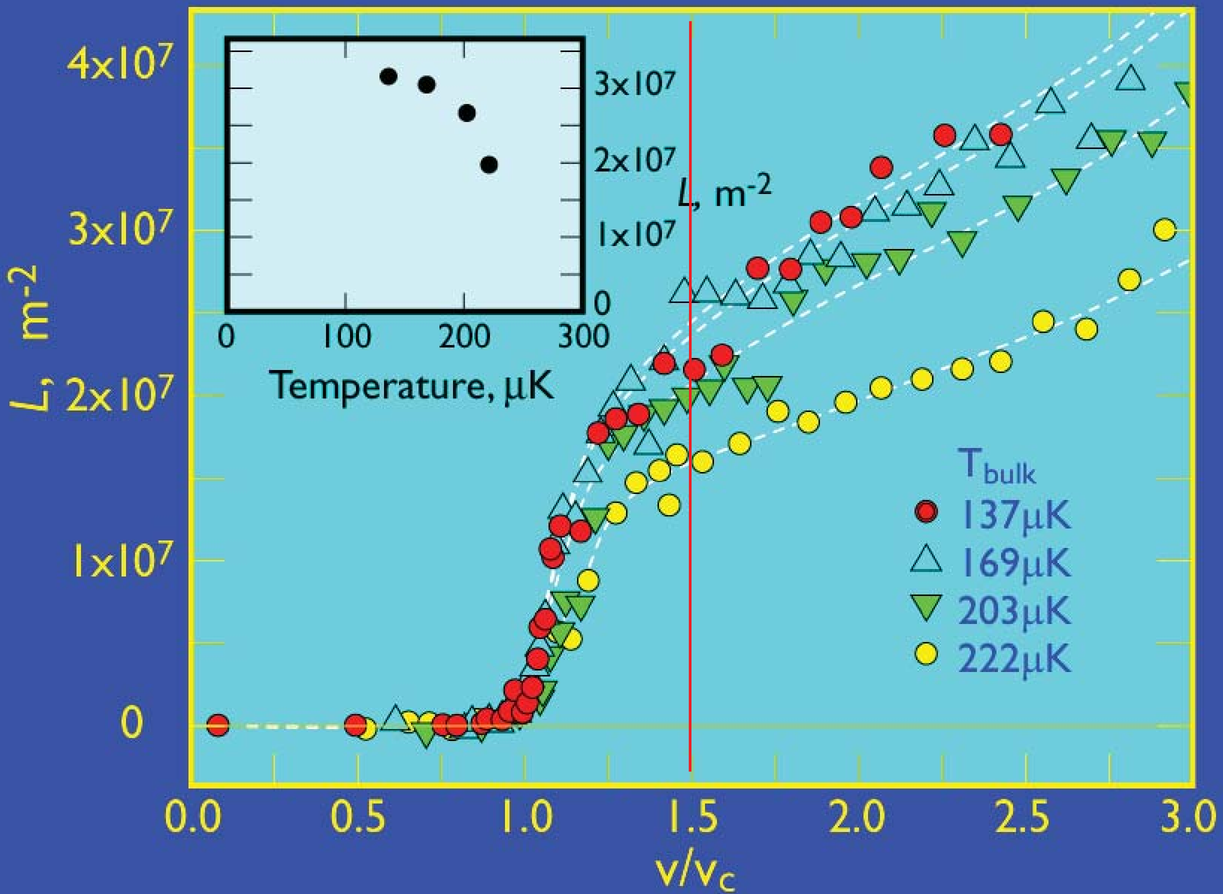
result is that *L* proportional to the reflected fraction *f* and the extent of the turbulence *x*

$$\boxed{L = f \frac{2 m_3 k_B T}{p_F \hbar x}}$$



Although, as we heard on Tuesday, more sophisticated calculations suggest that the reflected fraction for complex systems is less than simply the sum of the fraction expected from single vortices…

So our *L* is a lower limit!



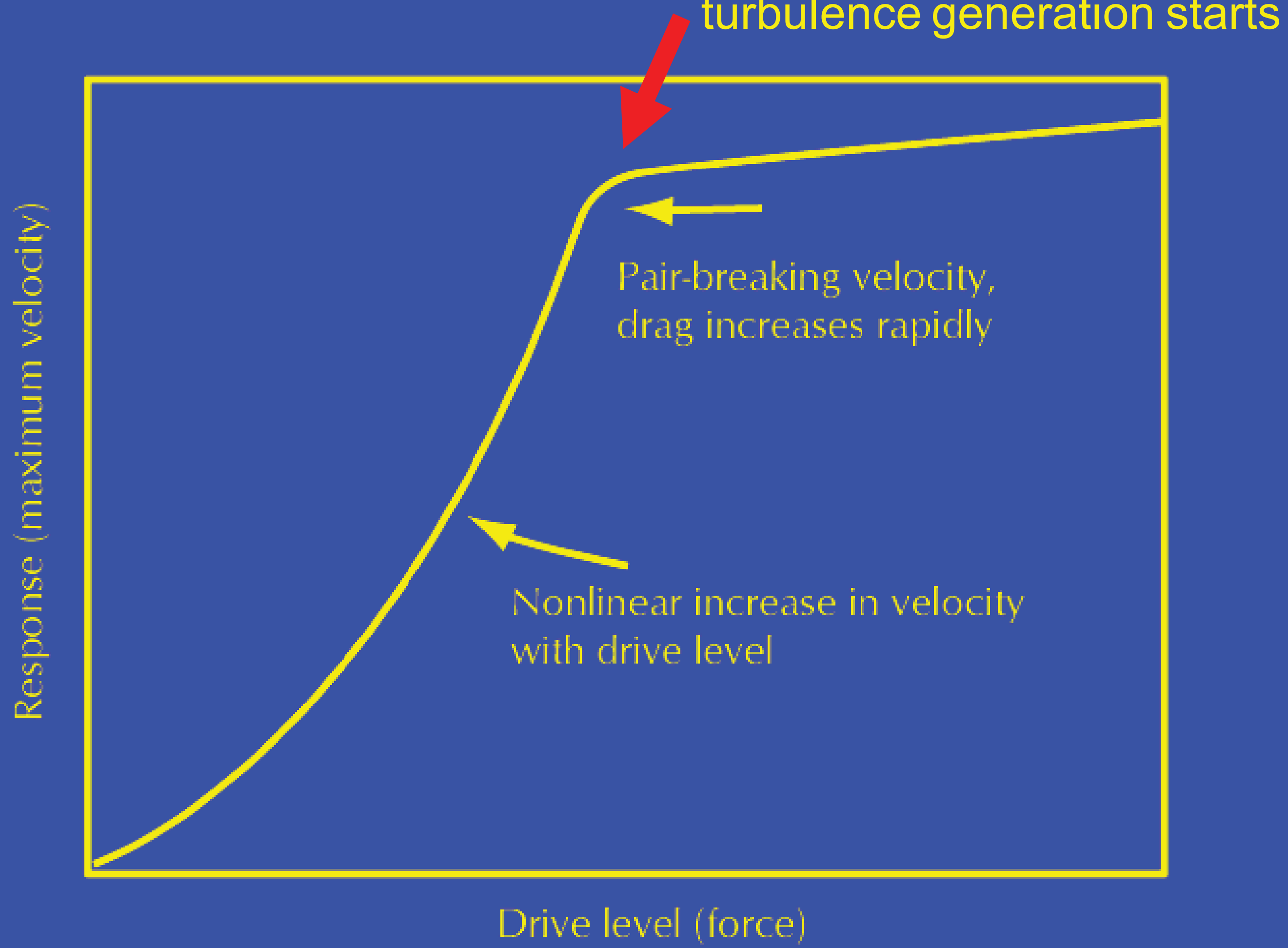
- again clear onset at the pair breaking velocity

- inset is the temperature dependence at $v/v_c = 1.5$
- suggests reaching the low temperature limit

PRL 93, 235302 (2004)

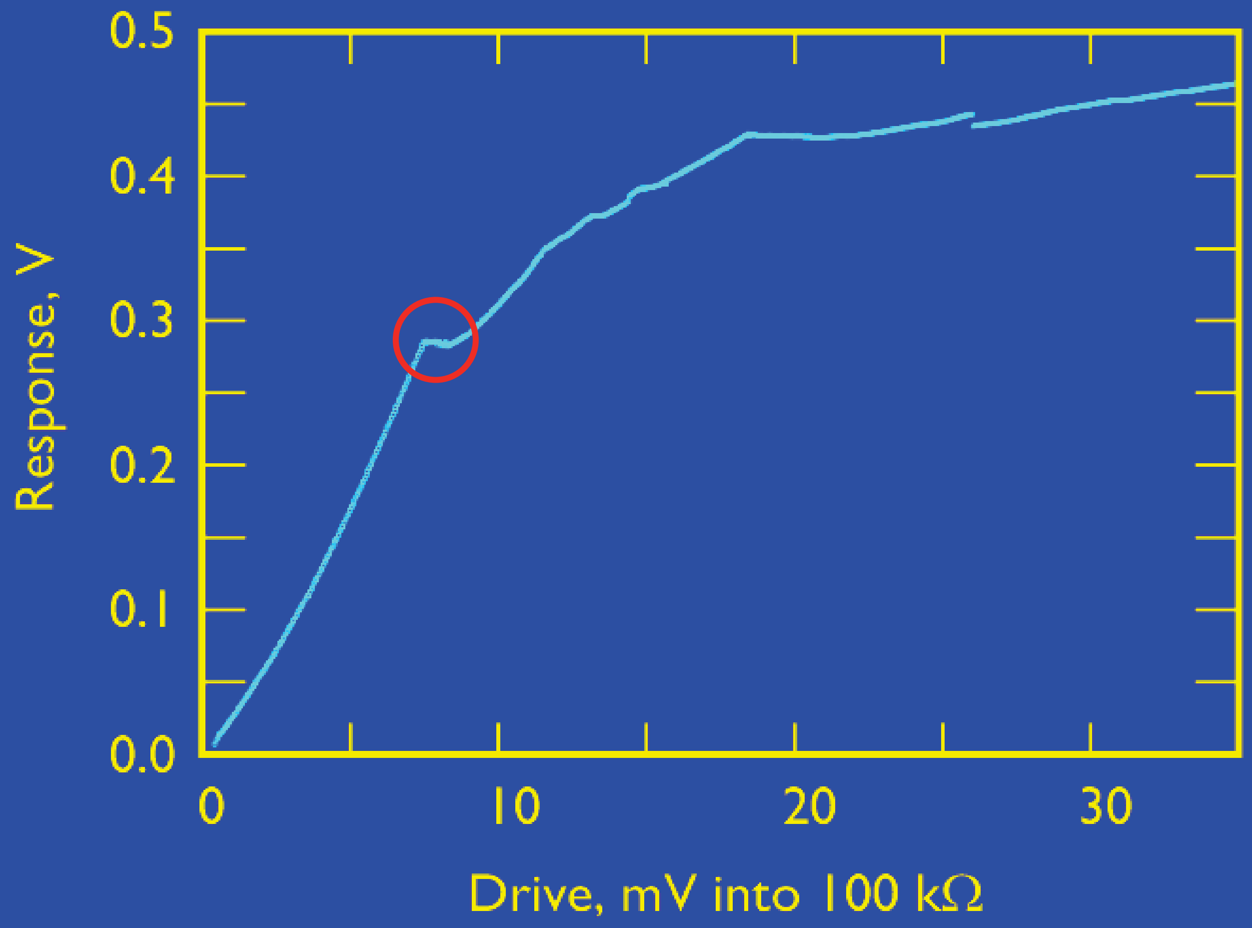
Turbulence only generated once the wire exceeds the pair breaking velocity

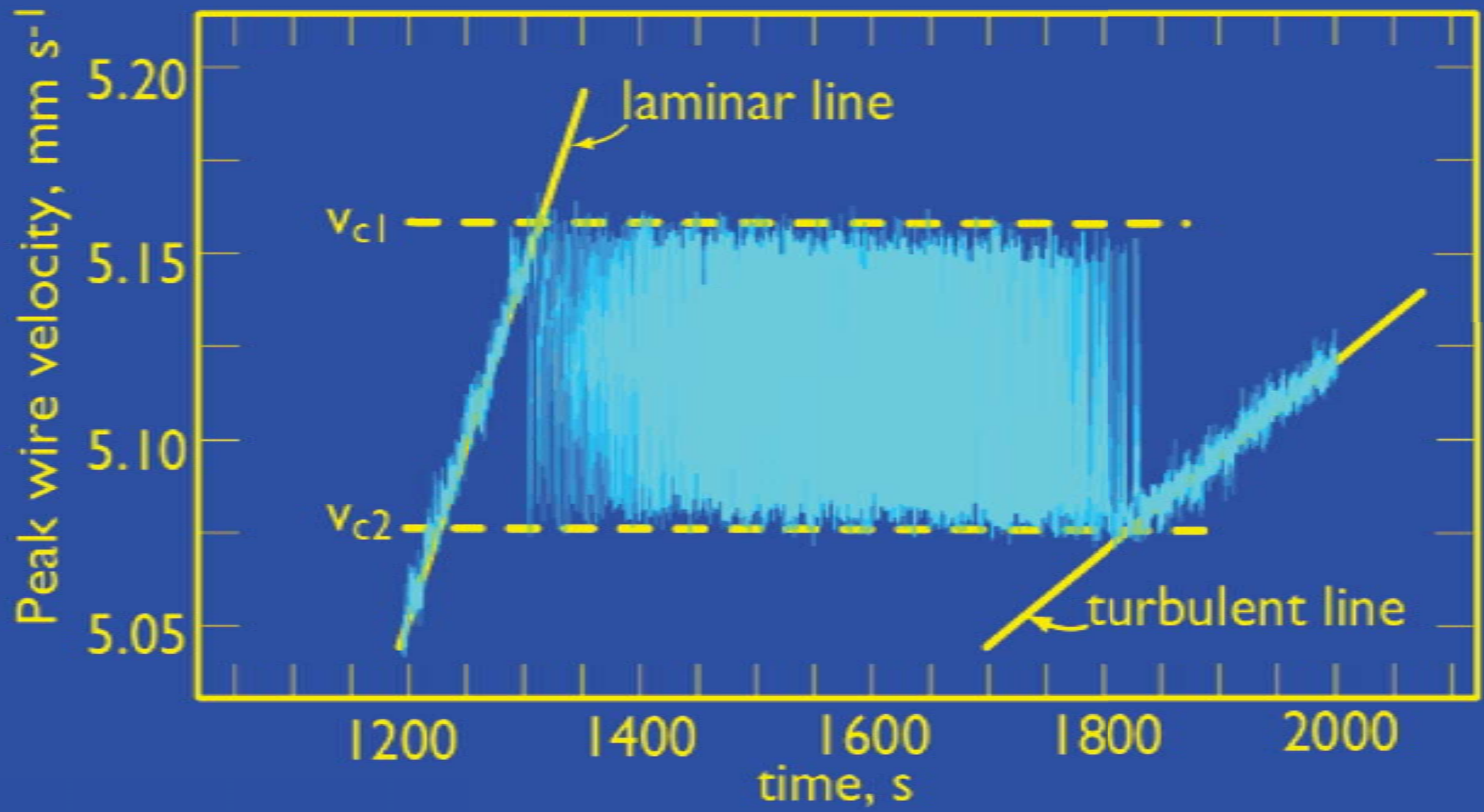
- is this true?



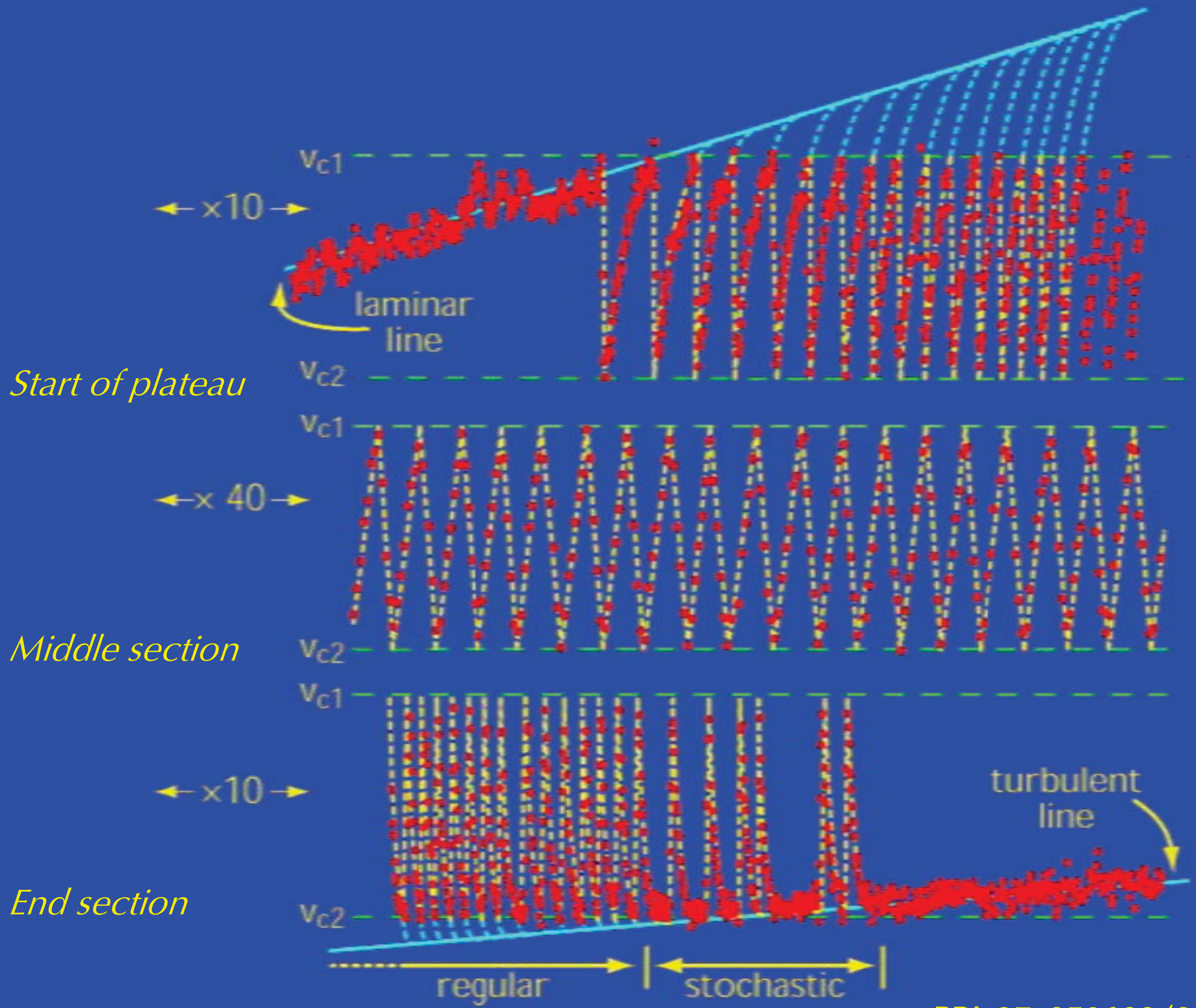
The dependence of velocity on drive: the ideal case

The Dependence of Velocity on Drive: the Reality

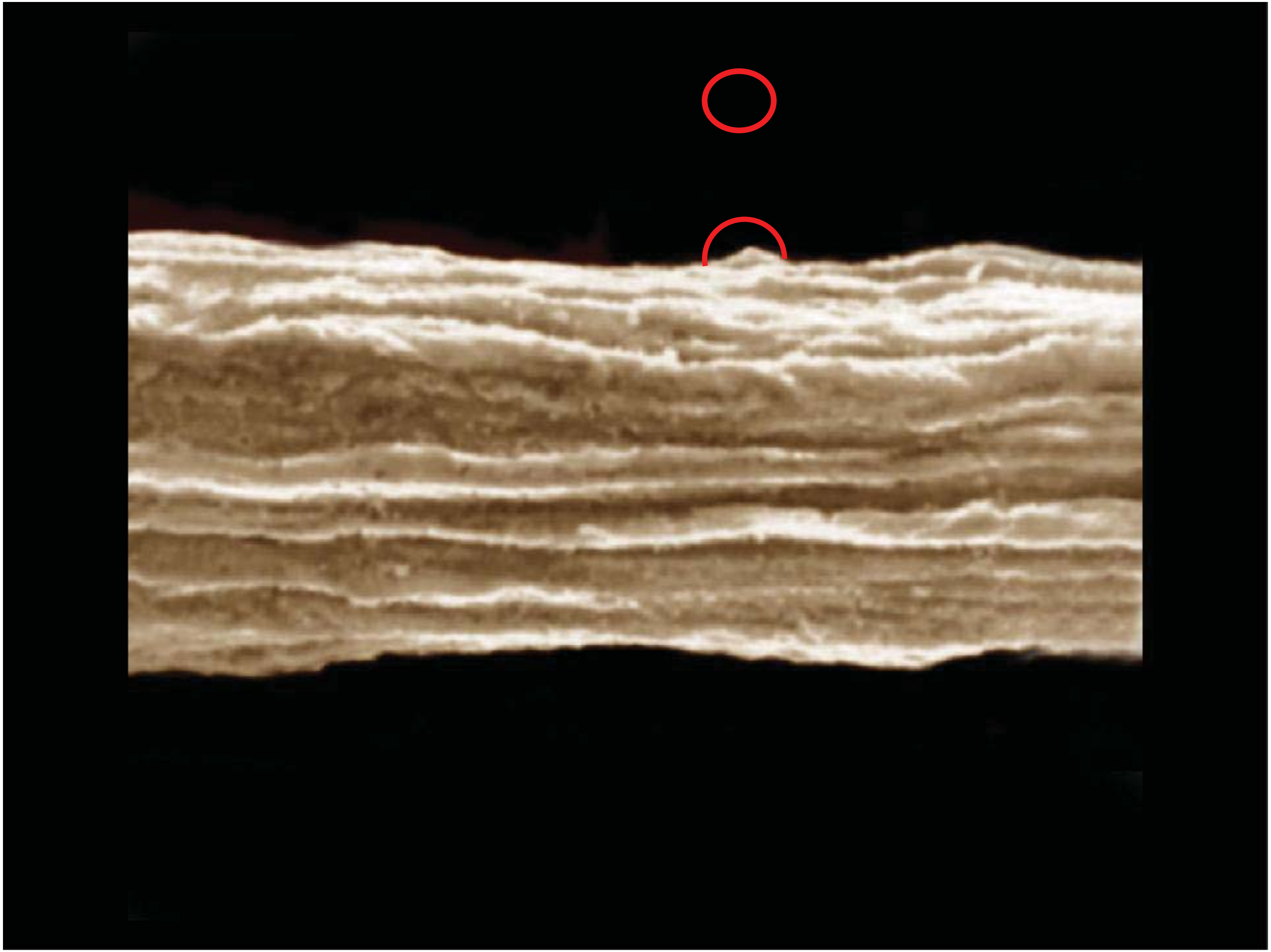




PRL 84, 1252 (2000).



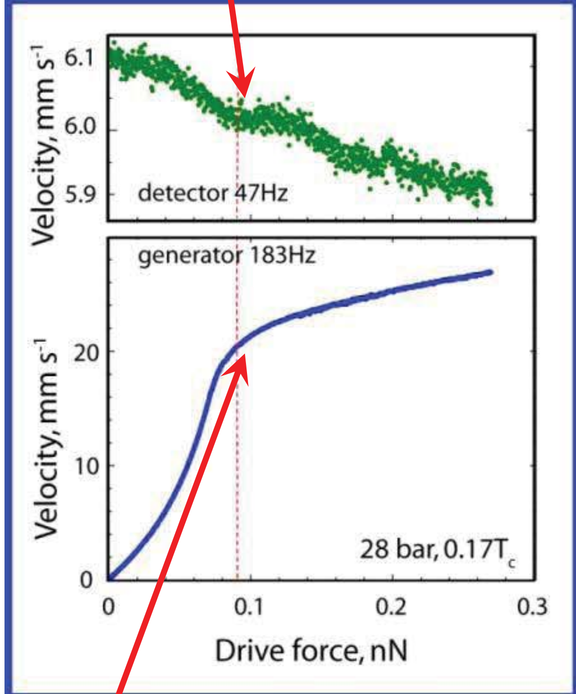
PRL 87, 059602 (2001).



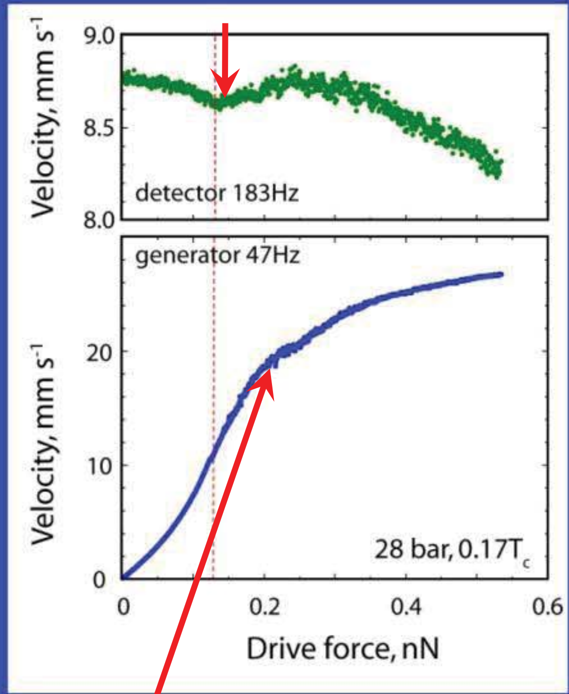
Osaka City group – two VWR's at 183Hz and 47Hz
used one as turbulence generator and one as detector

observed pair breaking and turbulence production in both

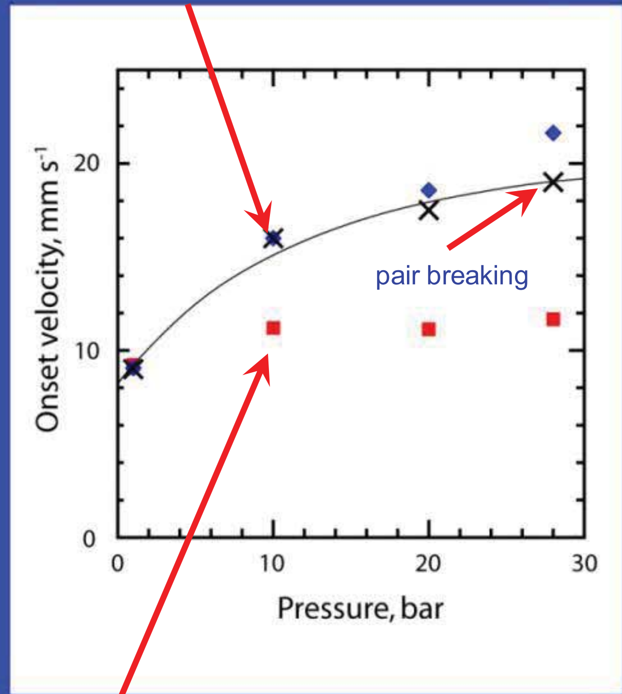
turbulence production



turbulence production



183Hz turbulence production



Nago et al Proc LT25

Nago et al Proc ULT2008

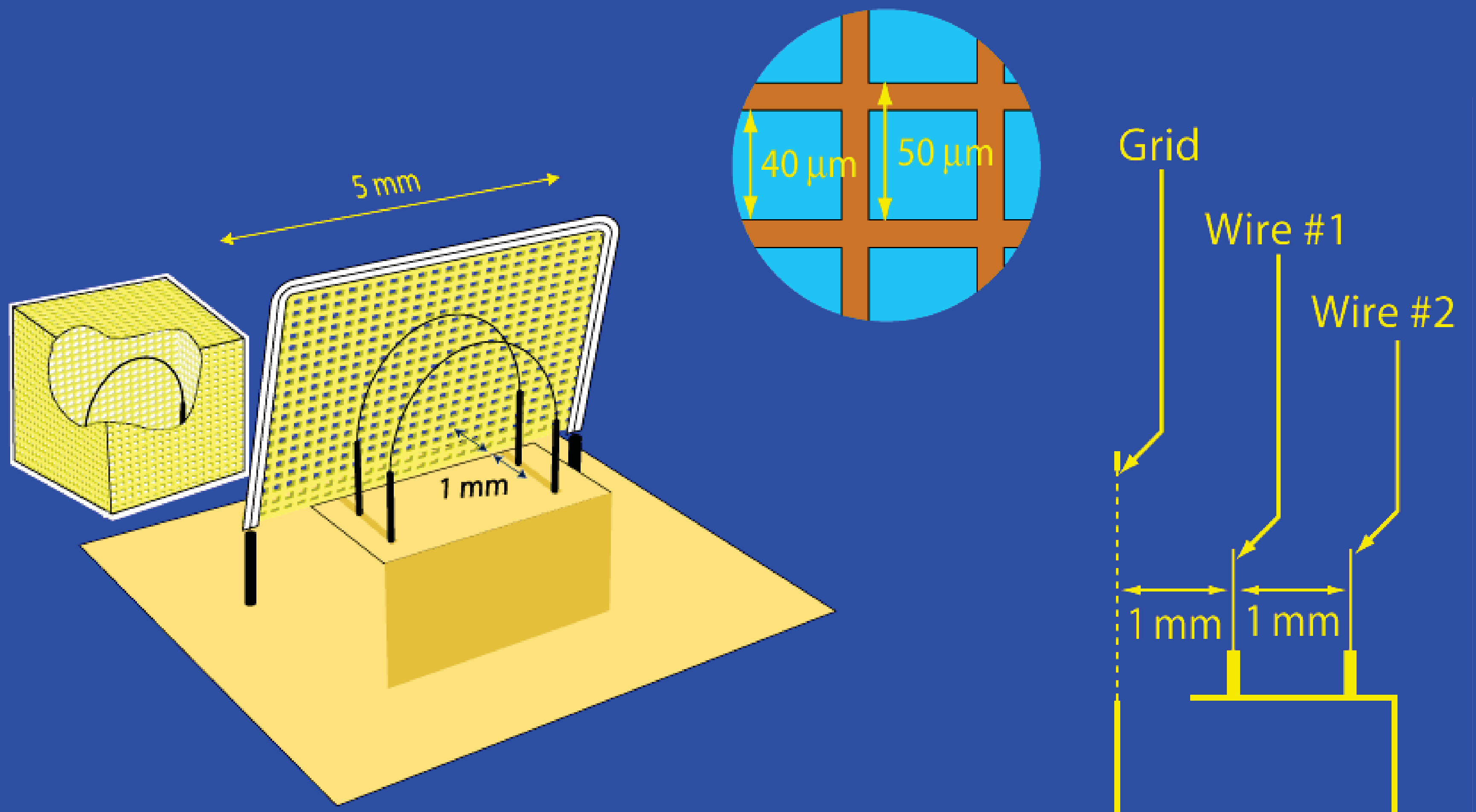
pair breaking

pair breaking

47Hz turbulence production

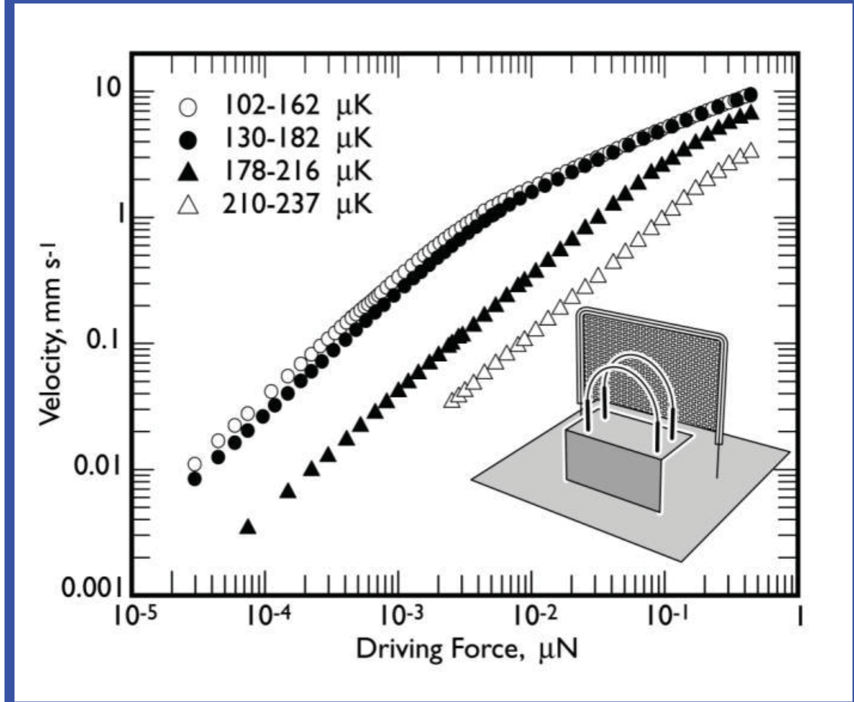
Is this a manifestation of the suggested frequency dependence of some critical velocity?

The Vibrating Grid Resonator

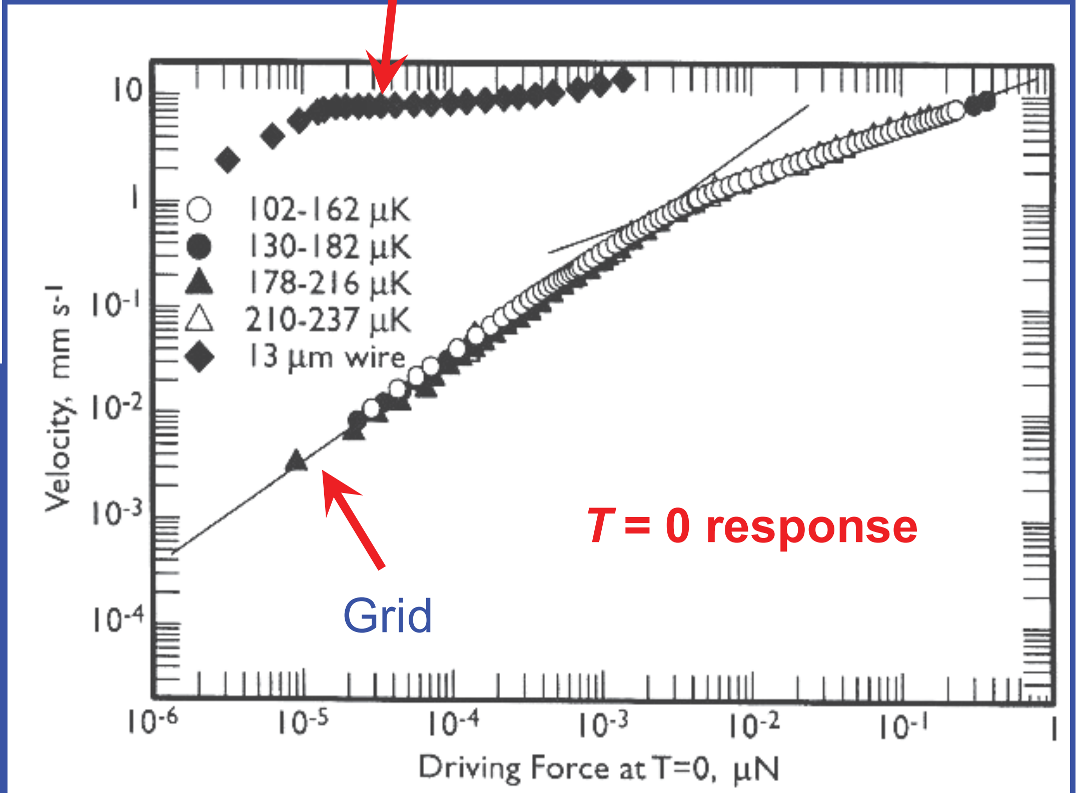


Grid response as a function of driving force for several temperature ranges

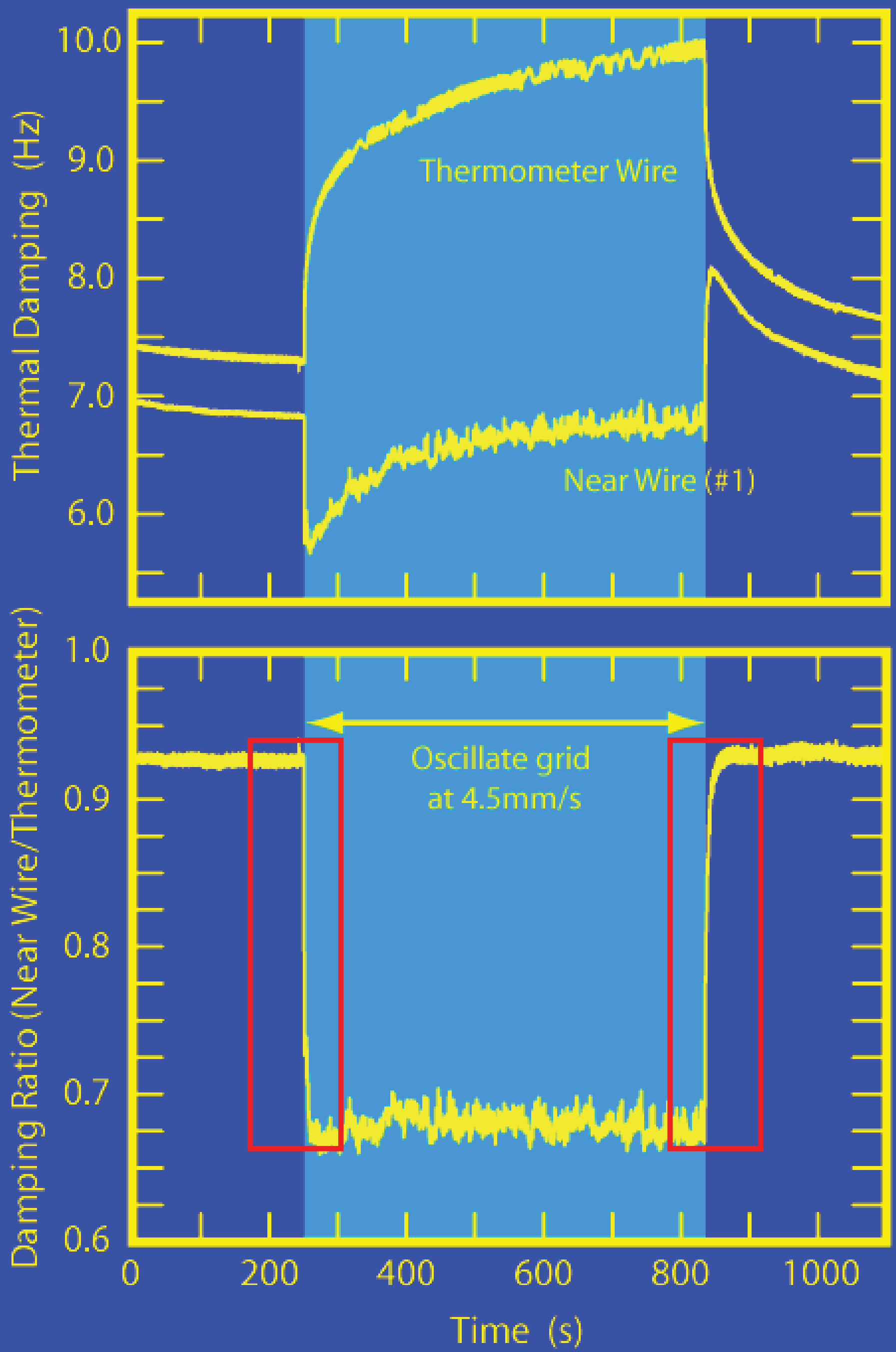
- additional warming due to heating at high drives



VWR for comparison

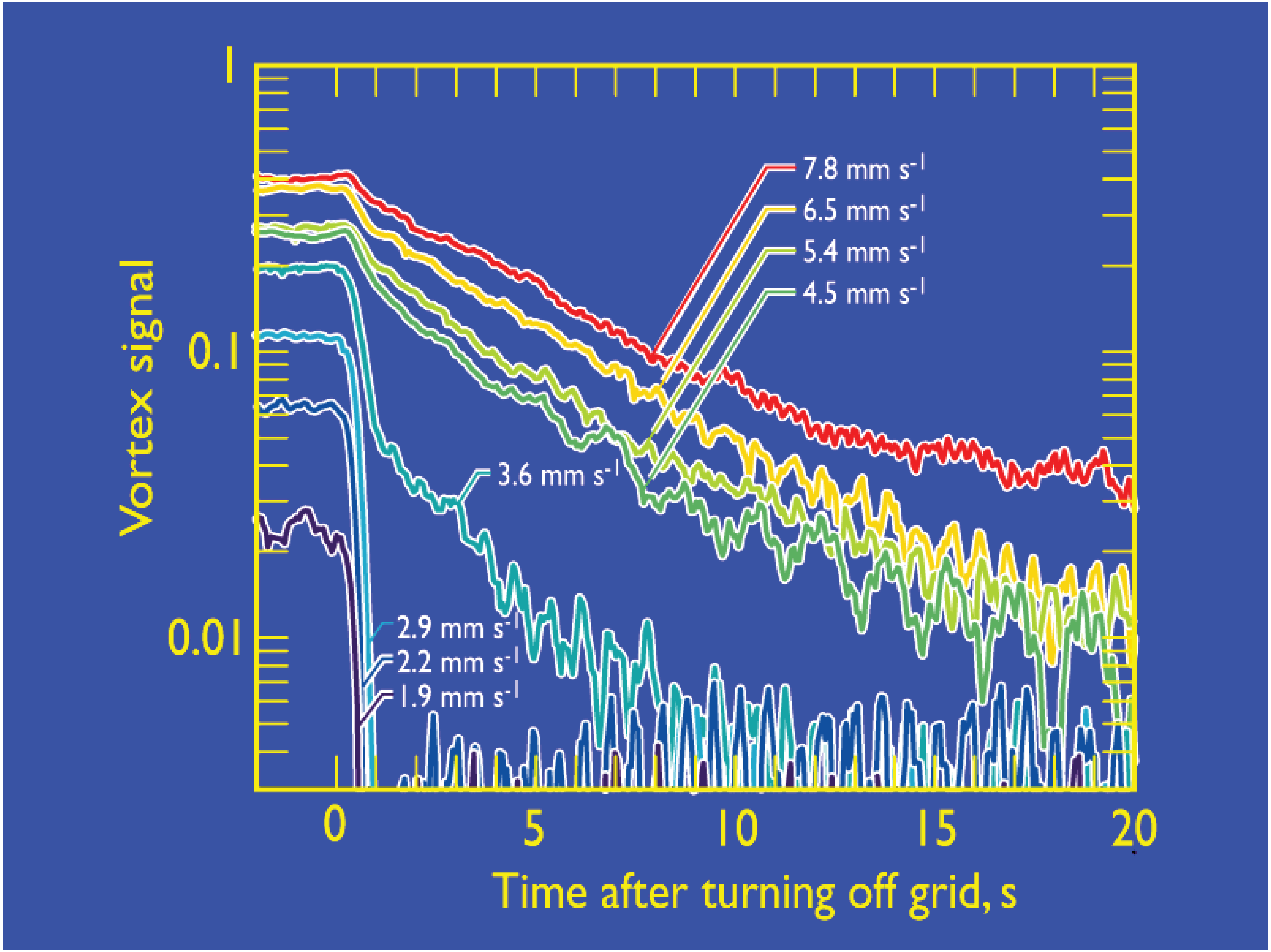


Remove heating effect using the thermometer wire

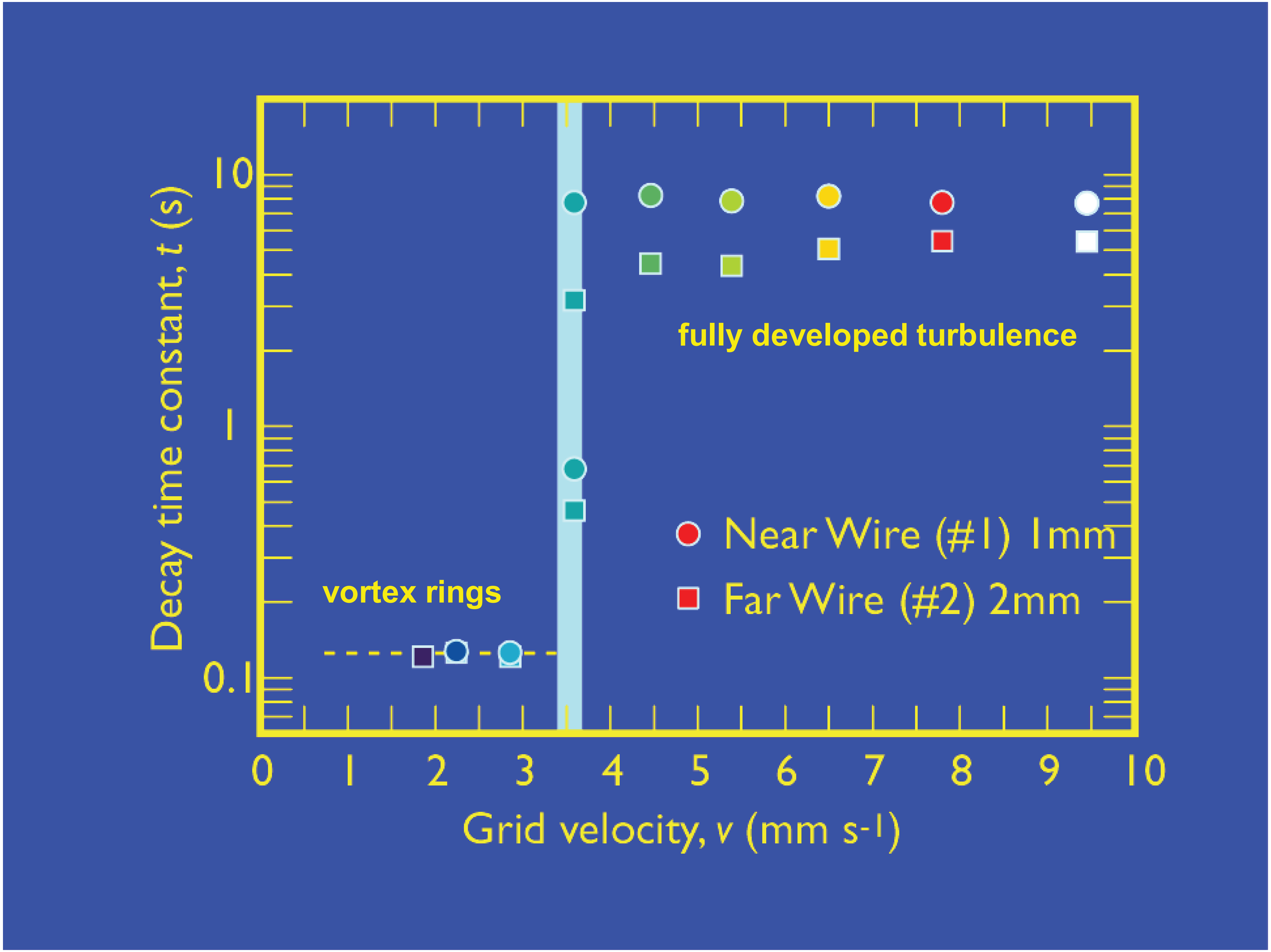


Ratio the two signals gives the damping suppression by turbulence.

Investigate build up and recovery of turbulence signal



Vortex signal
1
0.1
0.01
0
5
10
15
20
Time after turning off grid, s
7.8 mm s-1
6.5 mm s-1
5.4 mm s-1
4.5 mm s-1
3.6 mm s-1
2.9 mm s-1
2.2 mm s-1
1.9 mm s-1



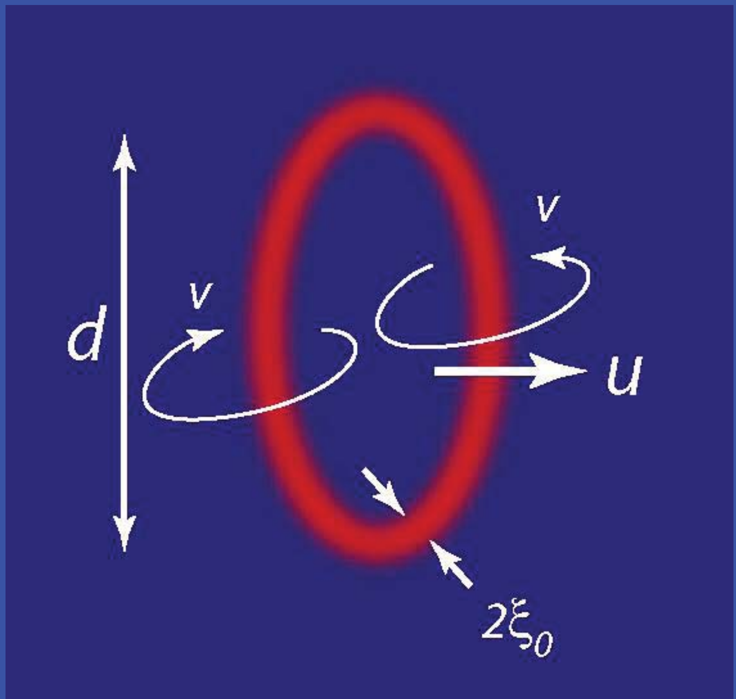
10
1
0.1
Decay time constant, t (s)
fully developed turbulence
vortex rings
Near Wire (#1) 1mm
Far Wire (#2) 2mm
0
1
2
3
4
5
6
7
8
9
10
Grid velocity, v (mm s-1)

Vortex rings

Ballistic emission of vortex rings

The turbulence is measured at a distance of 1 mm from the grid.

For such a short time constant of ~0.1 sec, the rings must travel at ~10 mm s^{-1}

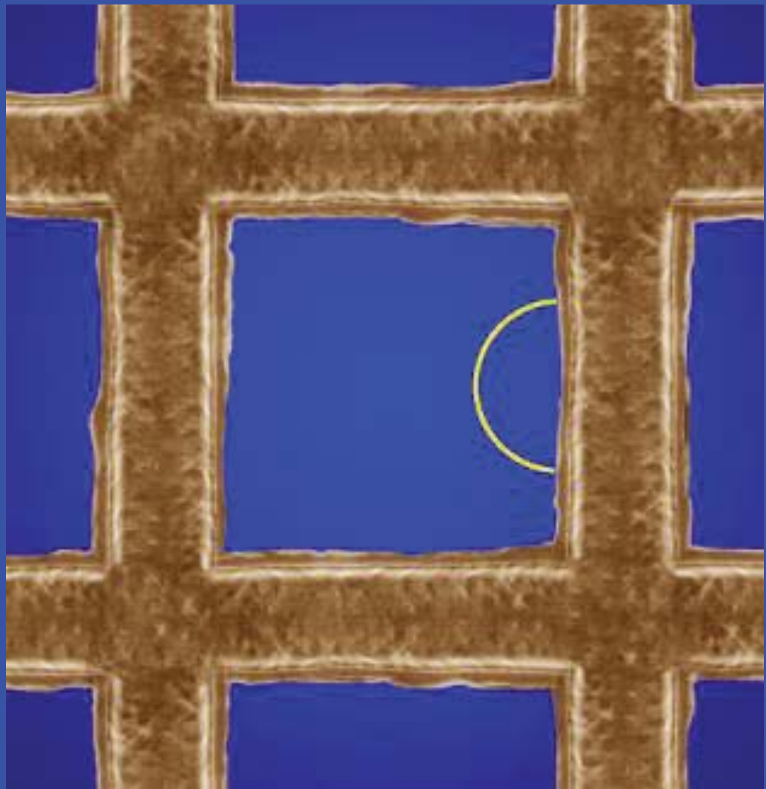


self-induced motion of vortex ring.

ring propagation speed:

$$u \cong \kappa / 2\pi d$$

$$u \sim 10 \text{ mm s}^{-1} \Rightarrow d \sim 5 \ \mu\text{m}$$



Grid frequency is 1250 Hz

First Kelvin wave resonance
for loops of order ~5 μm

and generates ~5 μm rings

Grid thus produces a cloud
of similar sized rings

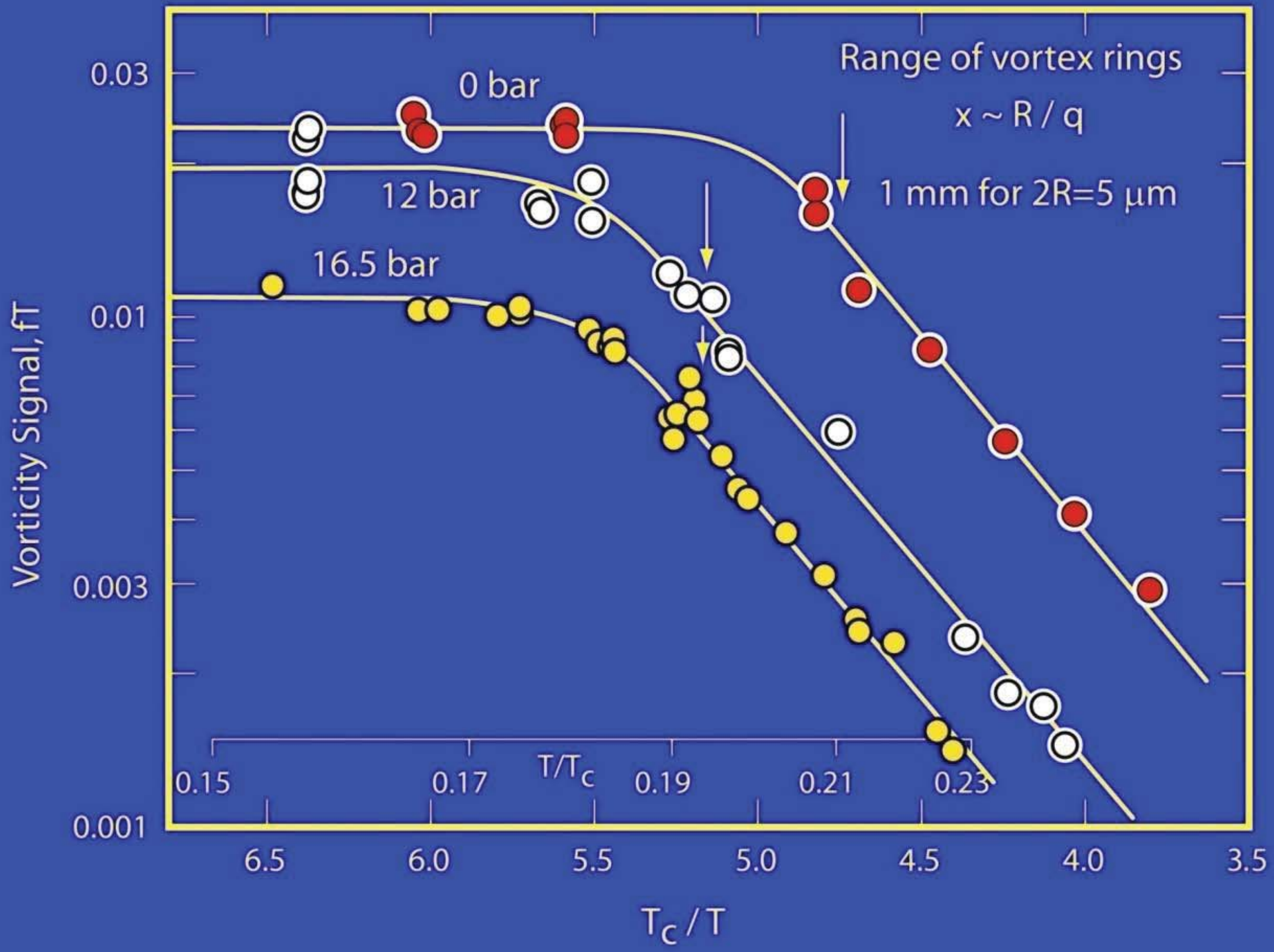
Vortex rings shrink due to mutual friction

estimated range for vortex ring size R is $x \sim R / q$ (Donnelly)

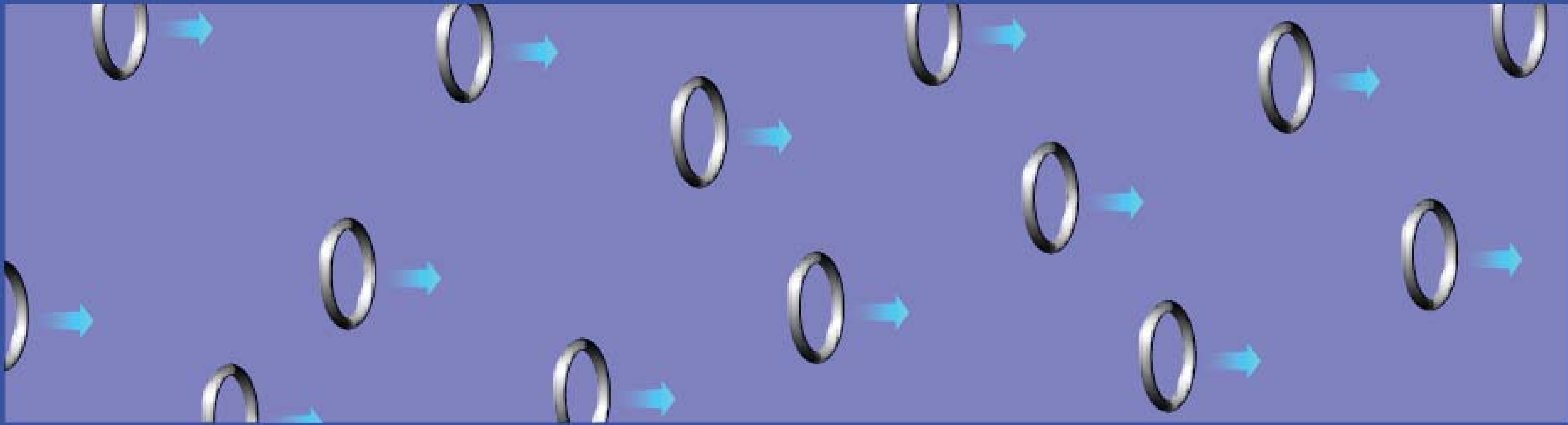
The mutual friction parameter q is strongly temperature and pressure dependent

Extrapolating the published higher temperature data experimental data (Bevan et al JLTP 109, 423, 1997) allows estimates of the temperatures at which the rings can just reach the nearest detector wire for different pressures…

so we measure the signal size as a function of temperature…

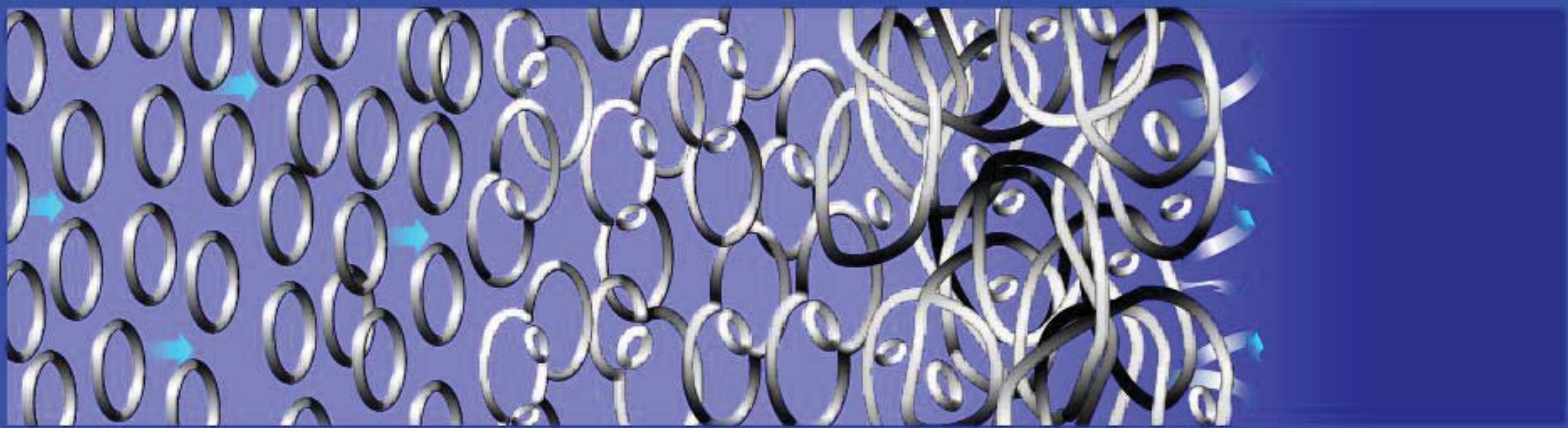


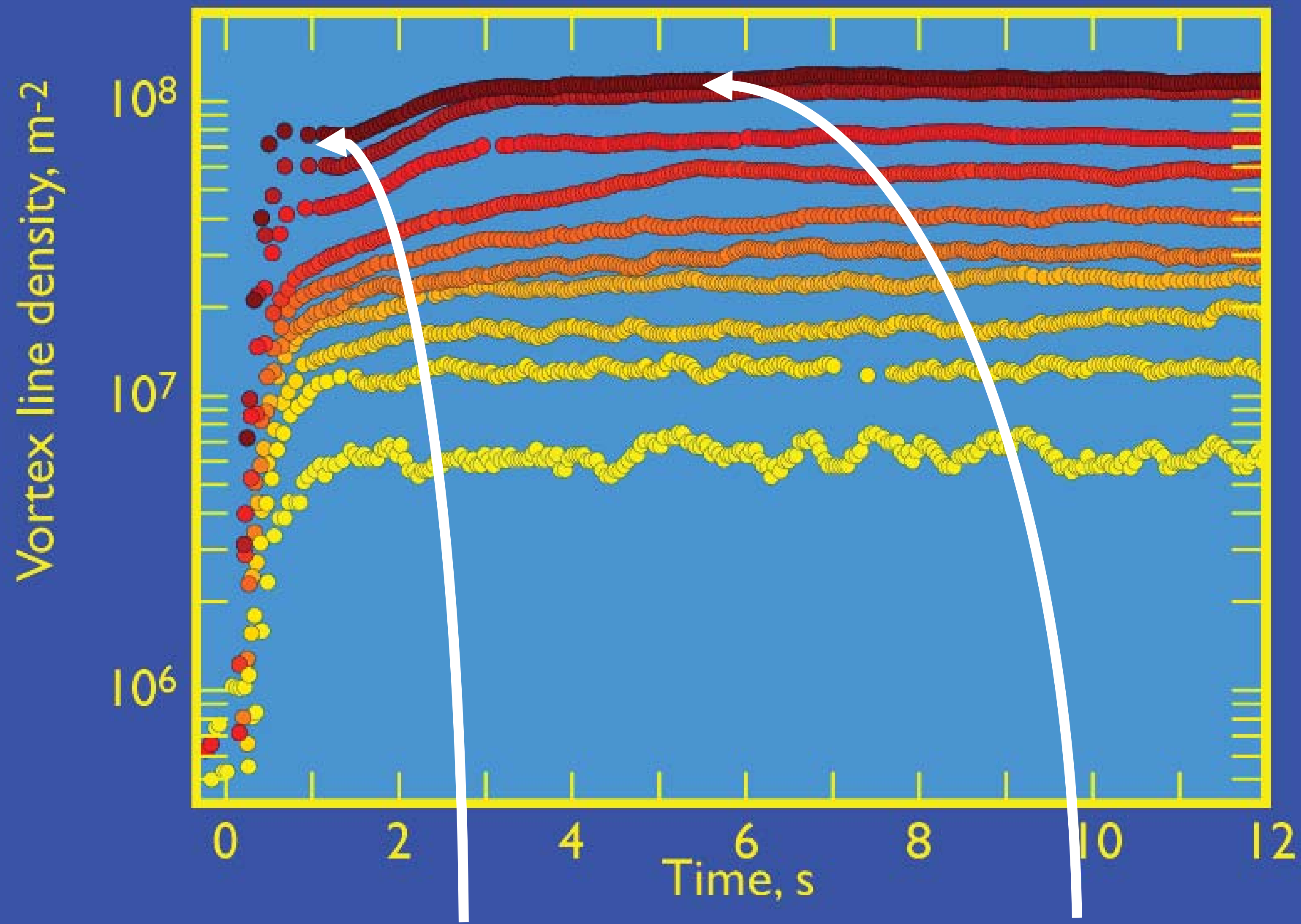
Data consistent with the range estimates



At low grid velocities, independent loops are created which travel fast (~10 mm/s) and disperse rapidly.

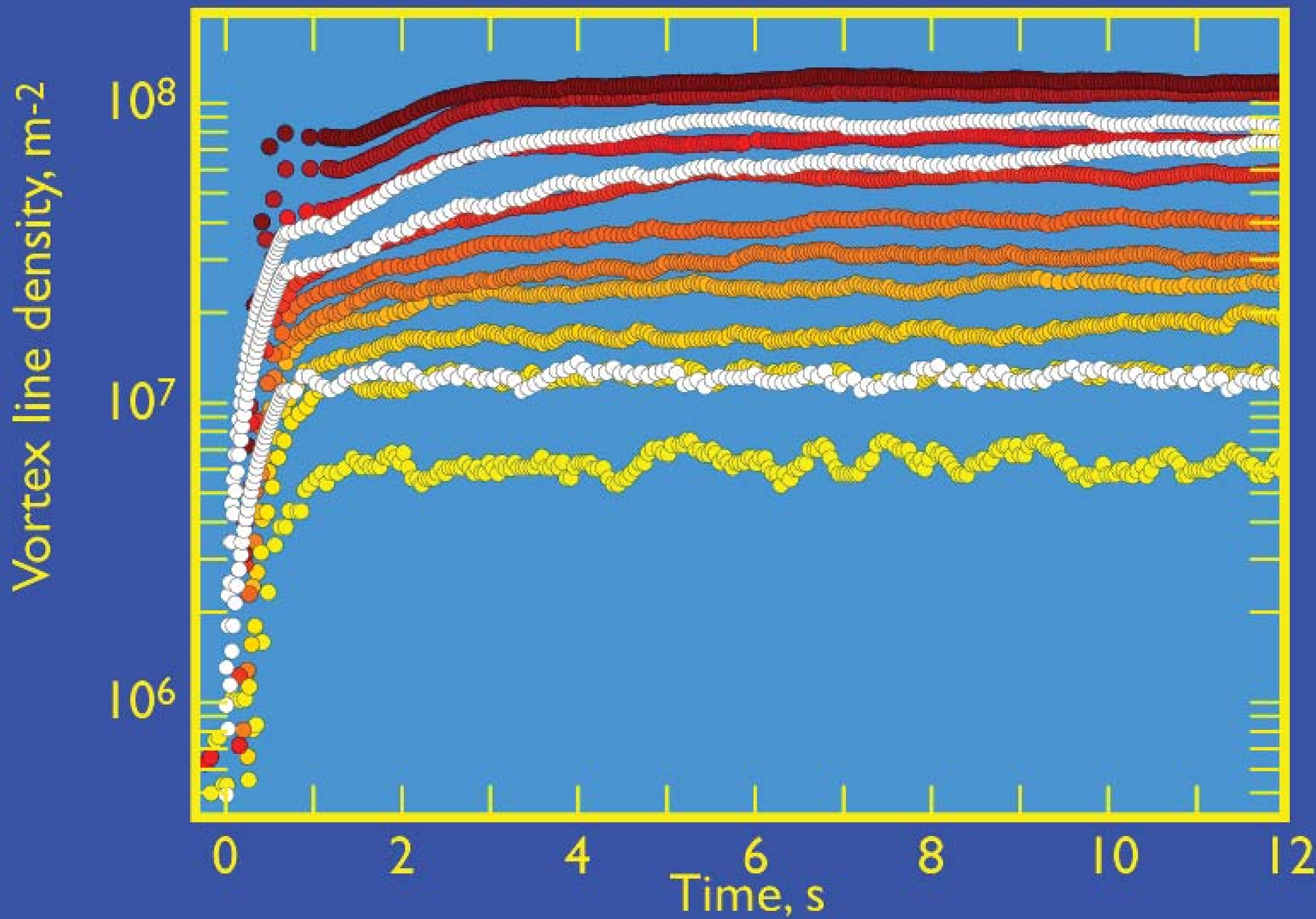
Above a critical grid velocity, the ring density becomes high enough for a cascade of reconnection to occur, rapidly creating fully-developed turbulence which disperses only slowly.



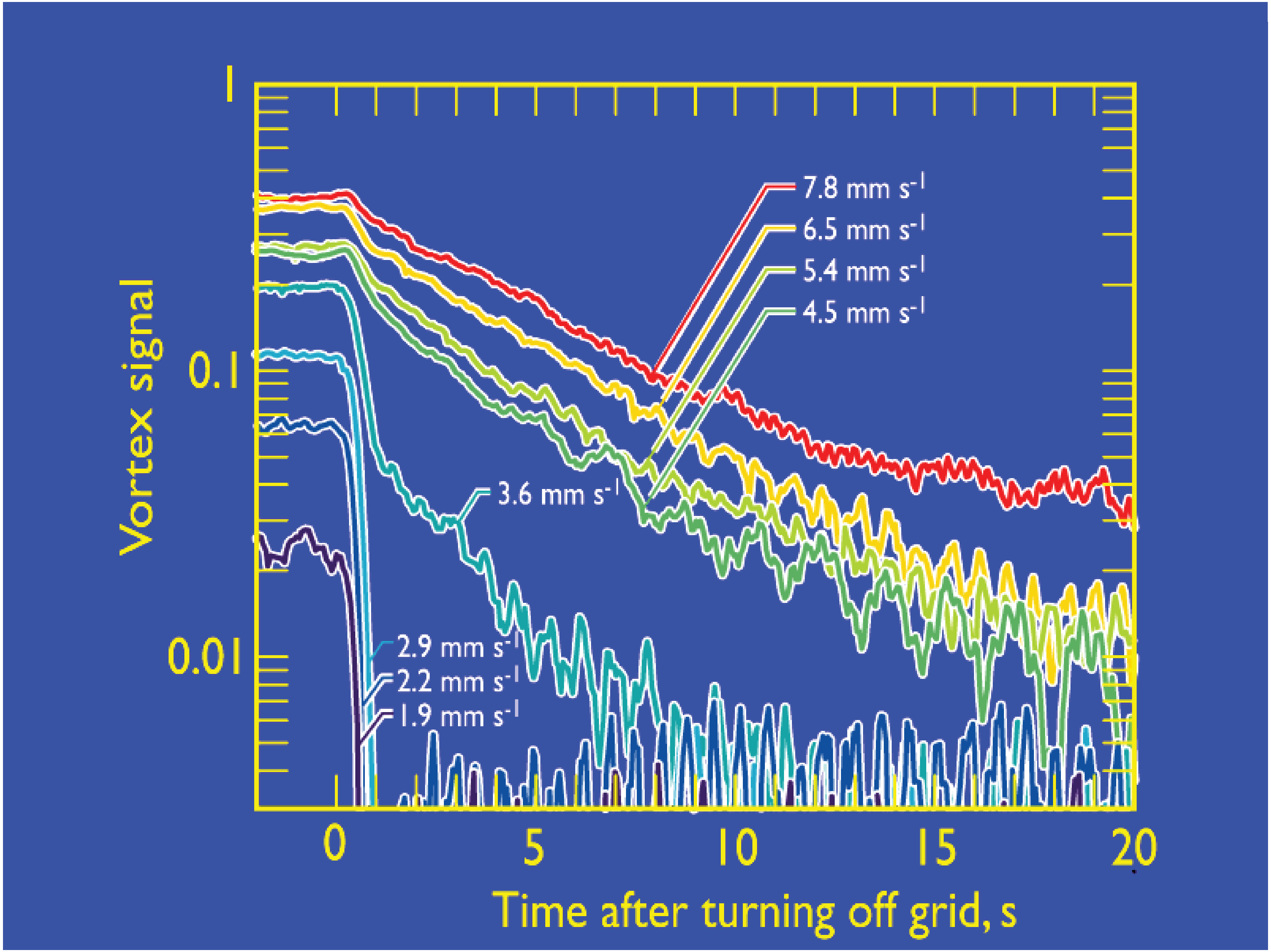


This is the level reached when the region fills with separate rings.

and when the turbulent tangle has developed.



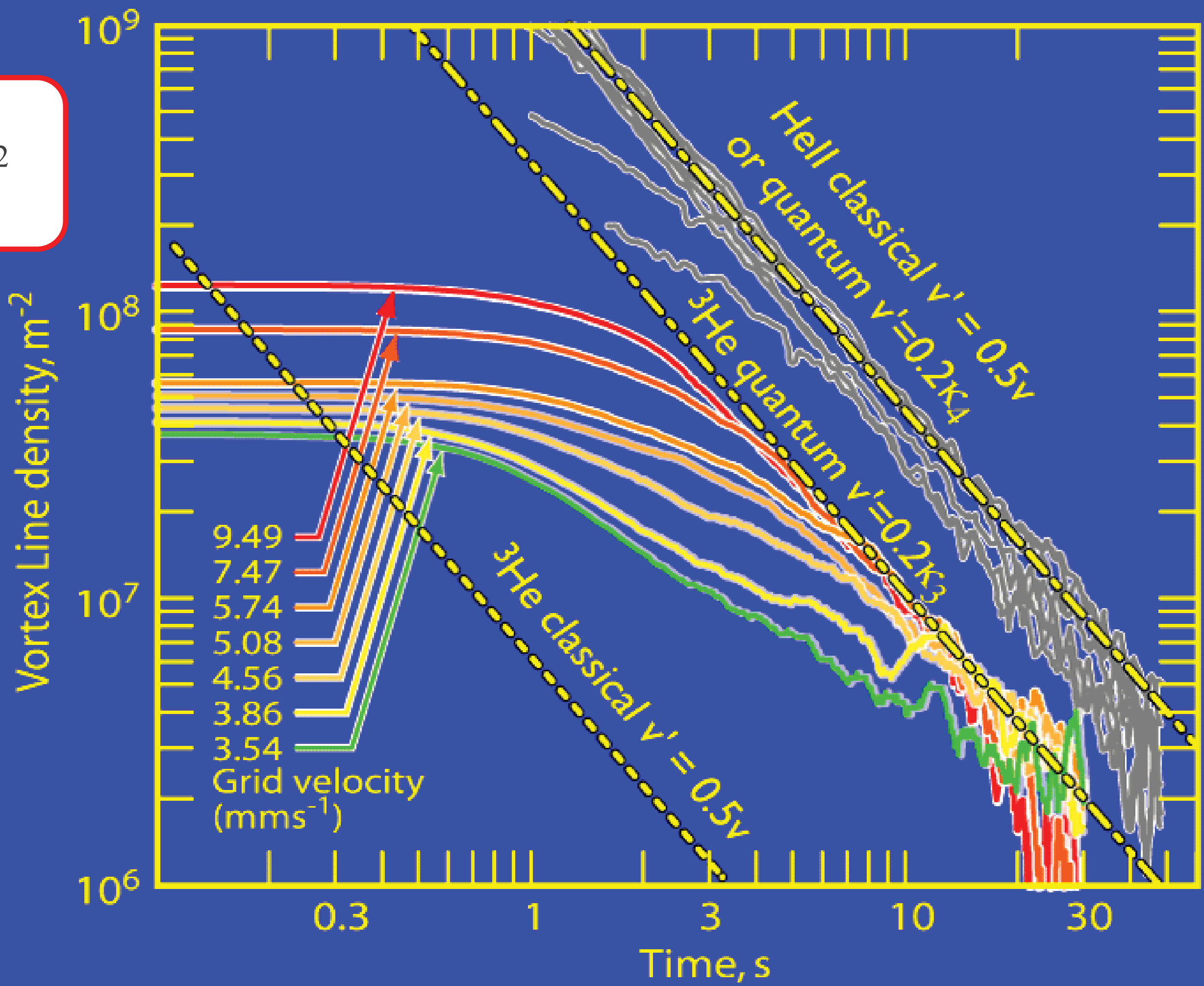
The white points are taken from Akira's calculation.



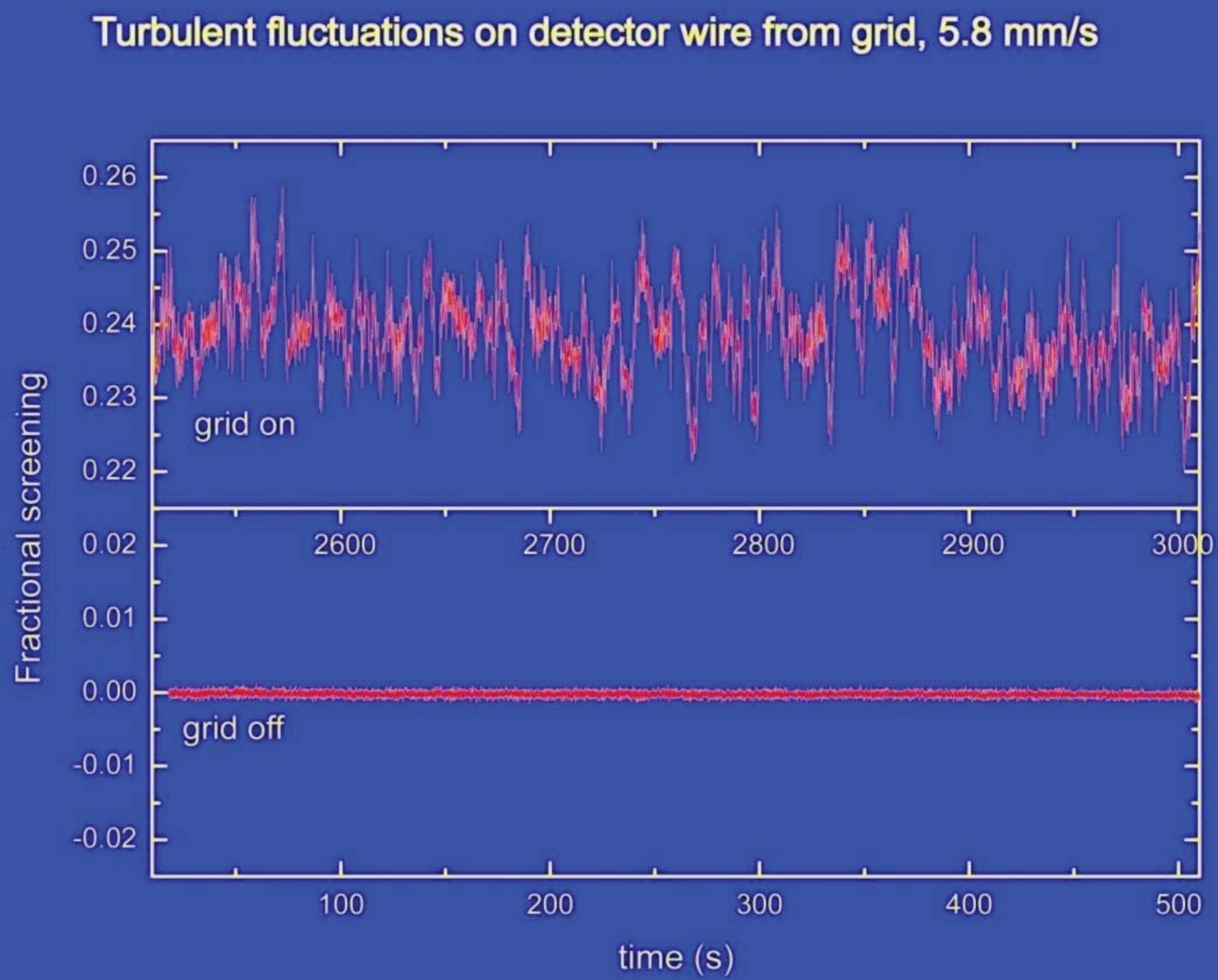
1
0.1
0.01
Vortex signal
7.8 mm s-1
6.5 mm s-1
5.4 mm s-1
4.5 mm s-1
3.6 mm s-1
2.9 mm s-1
2.2 mm s-1
1.9 mm s-1
0
5
10
15
20
Time after turning off grid, s

Estimated vortex line density from the shielding
compared to ^{4}He data and Komolgorov-like $t^{-3/2}$ decay
^{4}He parameter fit of an effective kinematic viscosity of $\nu'=0.5\nu$ fails for ^{3}He
Vinen' suggestion of effective kinematic viscosity of $\nu' \propto \kappa$ fits both

$$L(t) = \frac{d}{2\pi\kappa}\sqrt{\frac{27C^3}{\nu'}}t^{-3/2}$$



• turbulent signals appear noisy due to fluctuations in the line density
• dominant fluctuations on time scales of the order of a few seconds or more



• look for correlations in the fluctuations between detector wires

Define the instantaneous fluctuation in the line density $\delta L(t)$ as the deviation from the time averaged value $<L>$

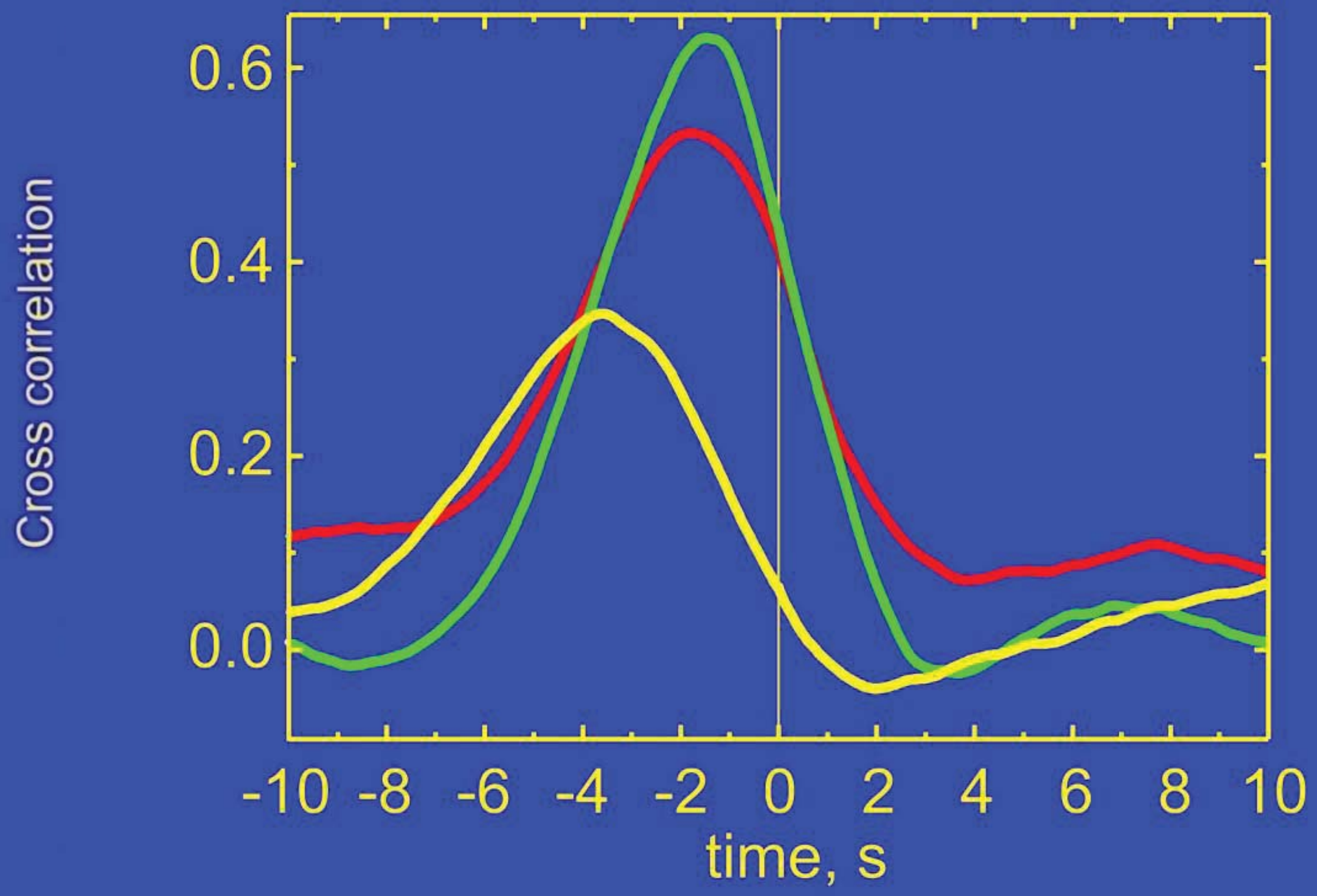
$$\delta L(t) = L(t) - \langle L \rangle$$

Then the correlation between the two detector wires as a function of the delay time Δt

$$R_{1,2} = \frac{\langle \delta L_1(t)\, \delta L_2(t - \Delta t) \rangle}{\sqrt{\langle \delta L_1^2 \rangle}\ \sqrt{\langle \delta L_2^2 \rangle}}$$

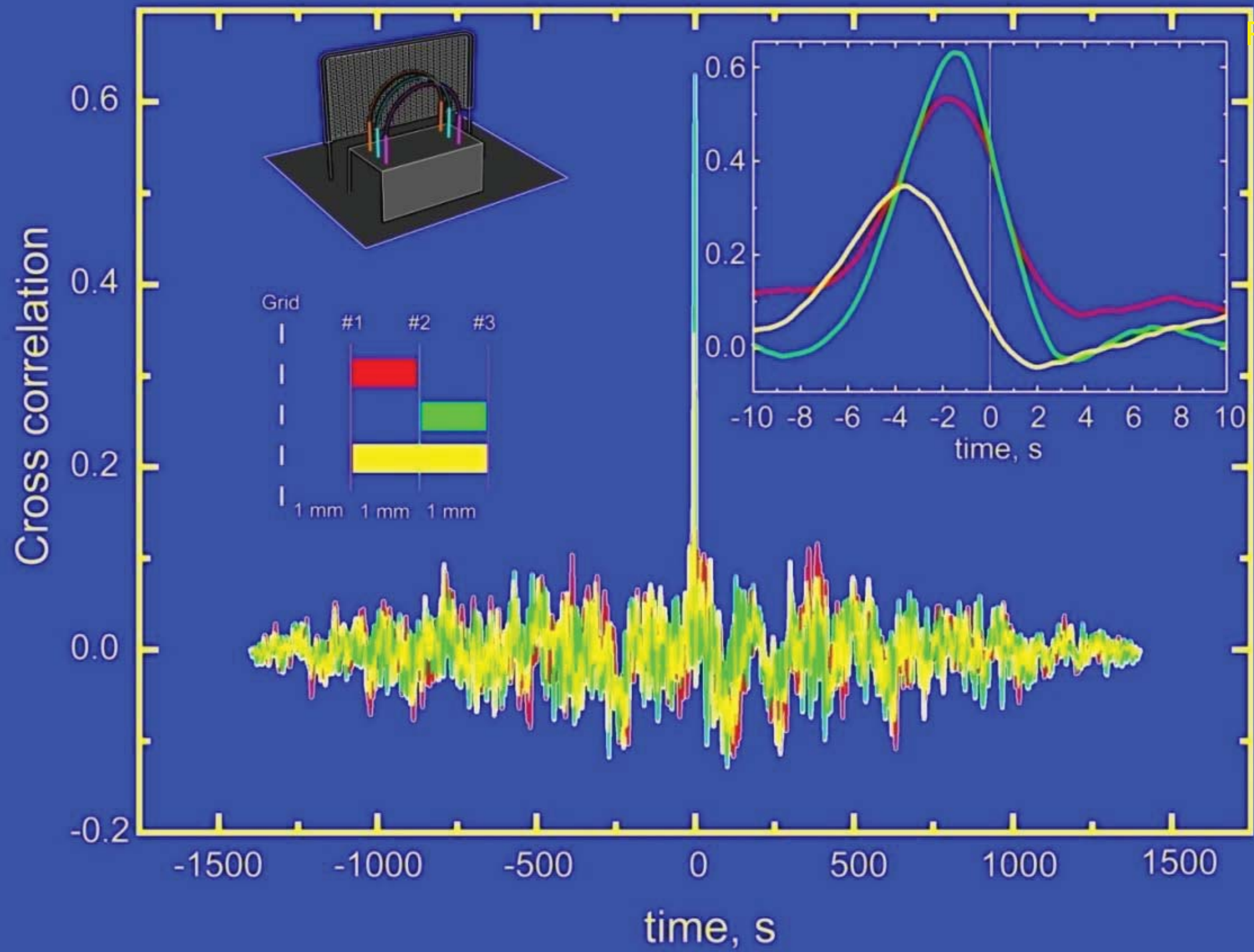
(detector 1 is nearest the grid)

01, 065302, 2008



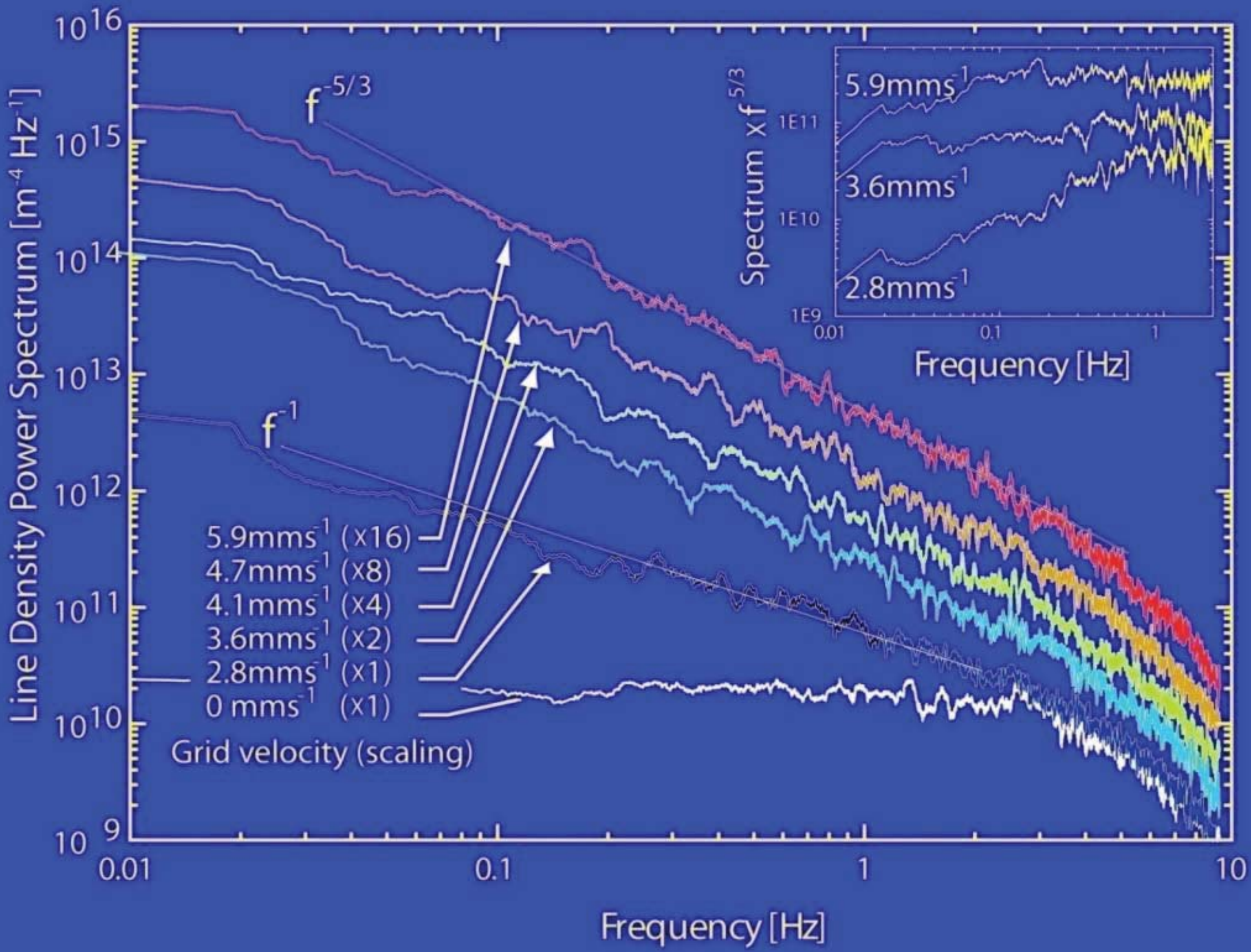
- delay ~2 secs between the wires 1 mm apart
- delay ~4 secs between the two wires 2 mm apart
- implies turbulence is long-lived on scale of a few seconds
- mean flow of turbulence away from the grid of ~0.5 mm s^{-1}

PRL 101, 065302, 2008



- delay ~2 secs between the wires 1 mm apart
- delay ~4 secs between the two wires 2 mm apart
- implies turbulence is long-lived on scale of a few seconds
- mean flow of turbulence away from the grid of ~0.5 mm s^{-1}

Power spectrum of fluctuations on detector wire 1mm from grid



- above 3 mms^{-1} grid velocity (developed turbulence) power law $f^{-5/3}$ above 0.1Hz
- below 3 mms^{-1} grid velocity (ballistic rings) power law f^{-1}
- use mean flow 0.5 mms^{-1} to estimate turbulence length scales ($\lambda \sim v / f$)
  - a few millimetres at start of $f^{-5/3}$ power law behaviour
  - ~0.1 mm where $f^{-5/3}$ power law merges with noise

Quartz Tuning Forks

Small, cheap, reliable
First proposed for LT work by the Nottingham group
Clubb et al *JLTP 136, 1, 2004*

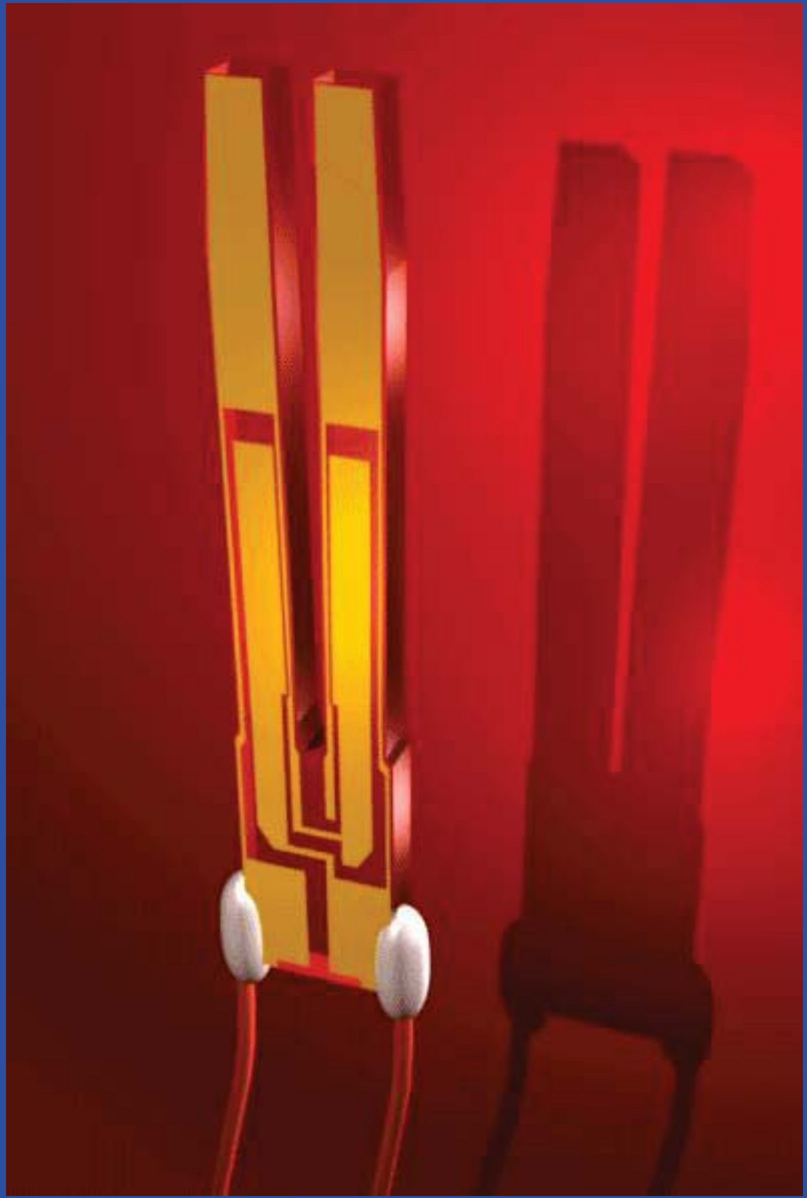
Developed further by Helsinki, Kosice/Prague & Lancaster groups

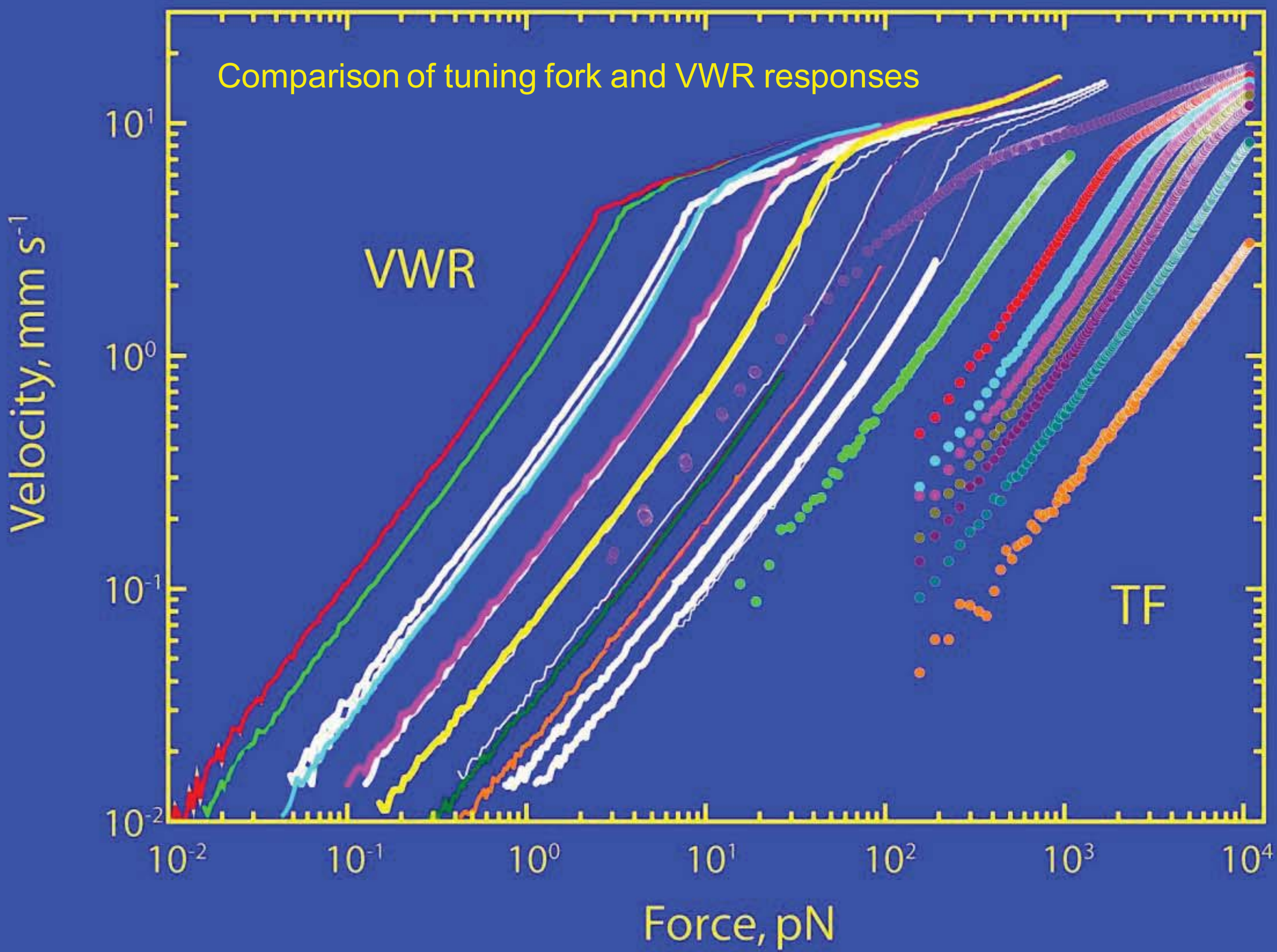
To date, used to detect quantum turbulence in ^{3}He only in a qualitative manner

e.g. Blažková et al, JLTP 150, 525, 2008

but little quantitative although this is developing

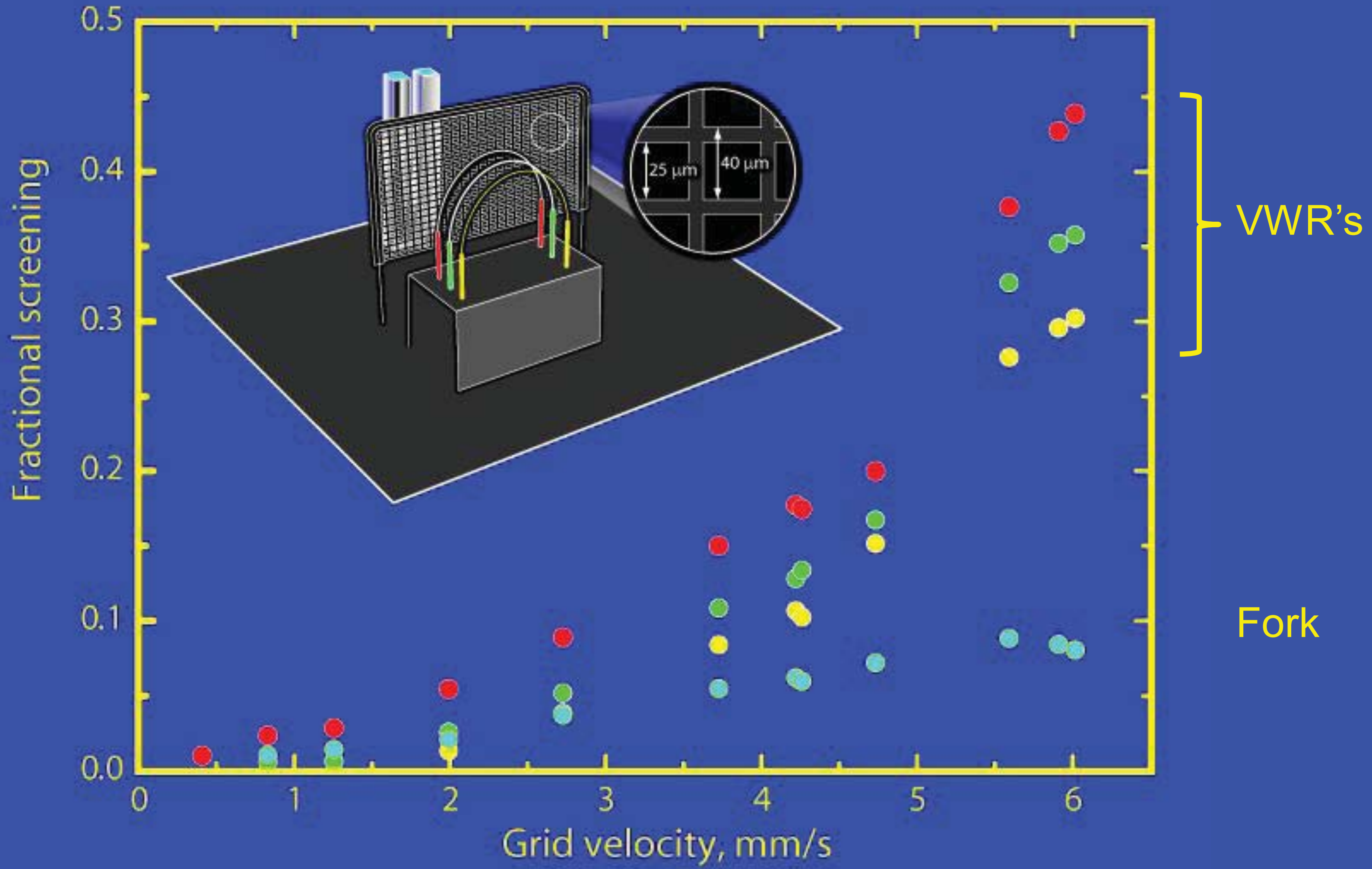
Excite tuning fork and measure the current.
Key point current $\propto$ velocity





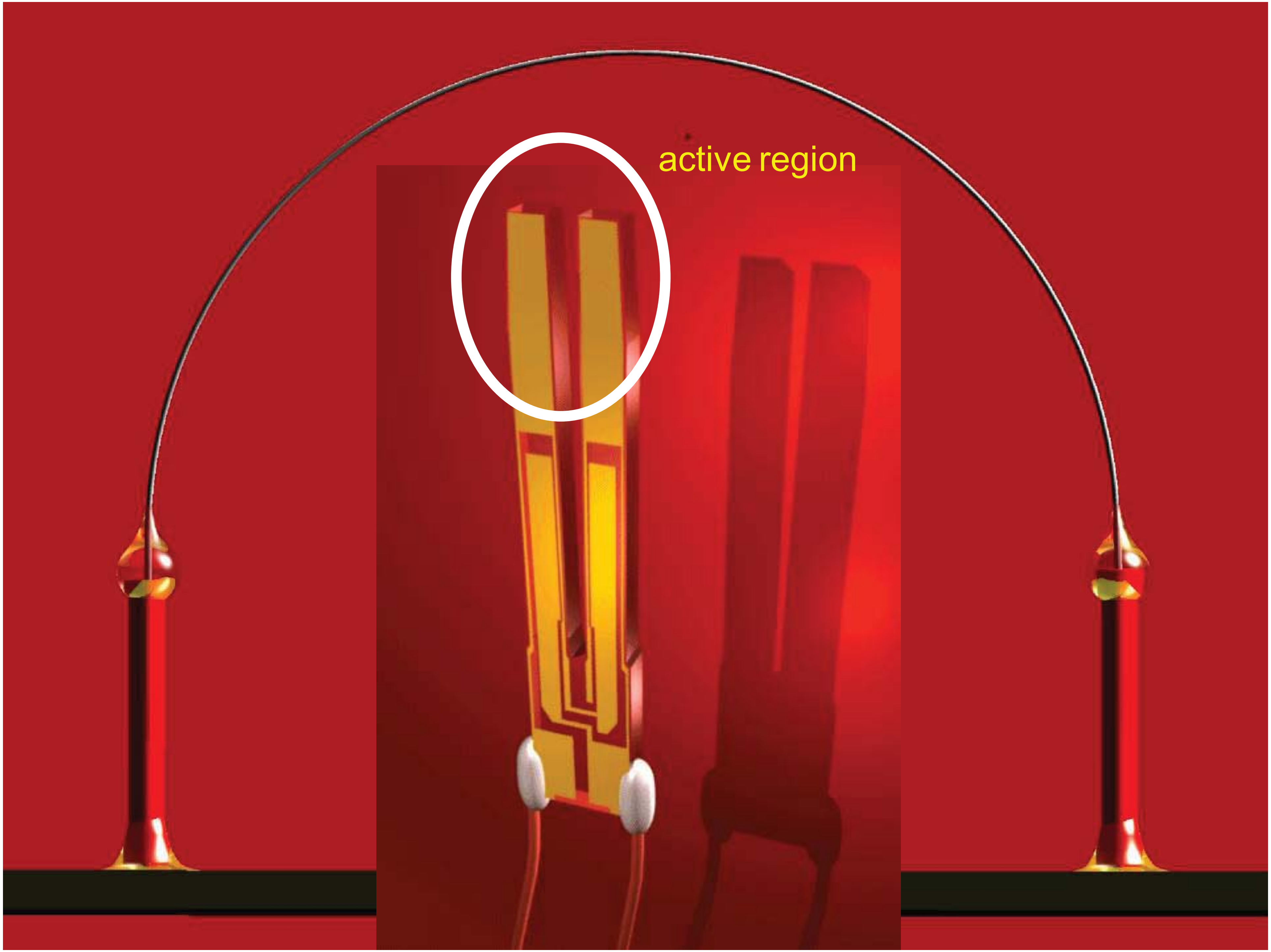
- similar pair breaking velocities
- tuning fork sees non-linear damping expected for oscillating object in ^{3}He-B
- tuning fork damping ~x12 greater than that of wire
- VWR more sensitive than this particular fork

Fork 1.5 mm away from grid
VWR's 1, 2 and 3 mm away from grid



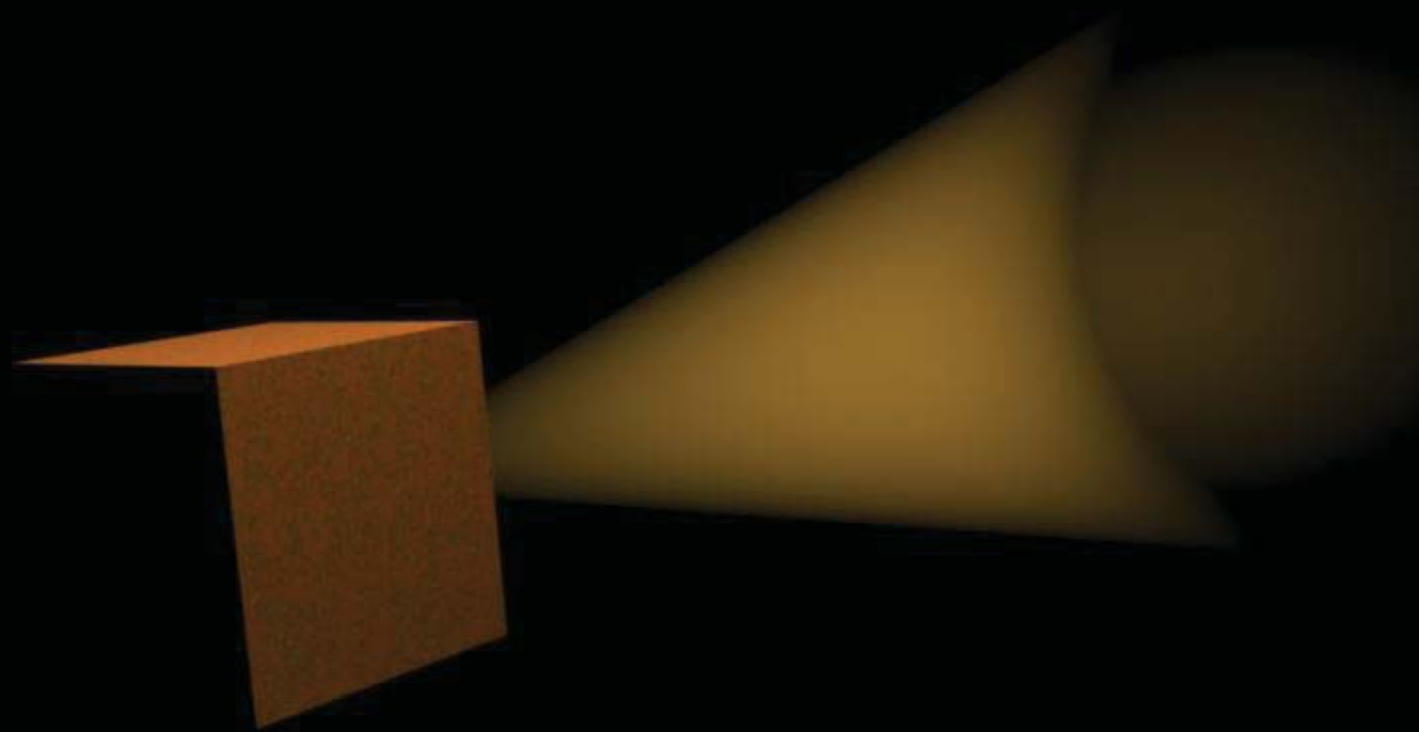
Fractional screening seen by tuning fork much less than that seen by VWR's
Do we need smaller forks?

Our wires have typical dimensions and active regions covering several mms.

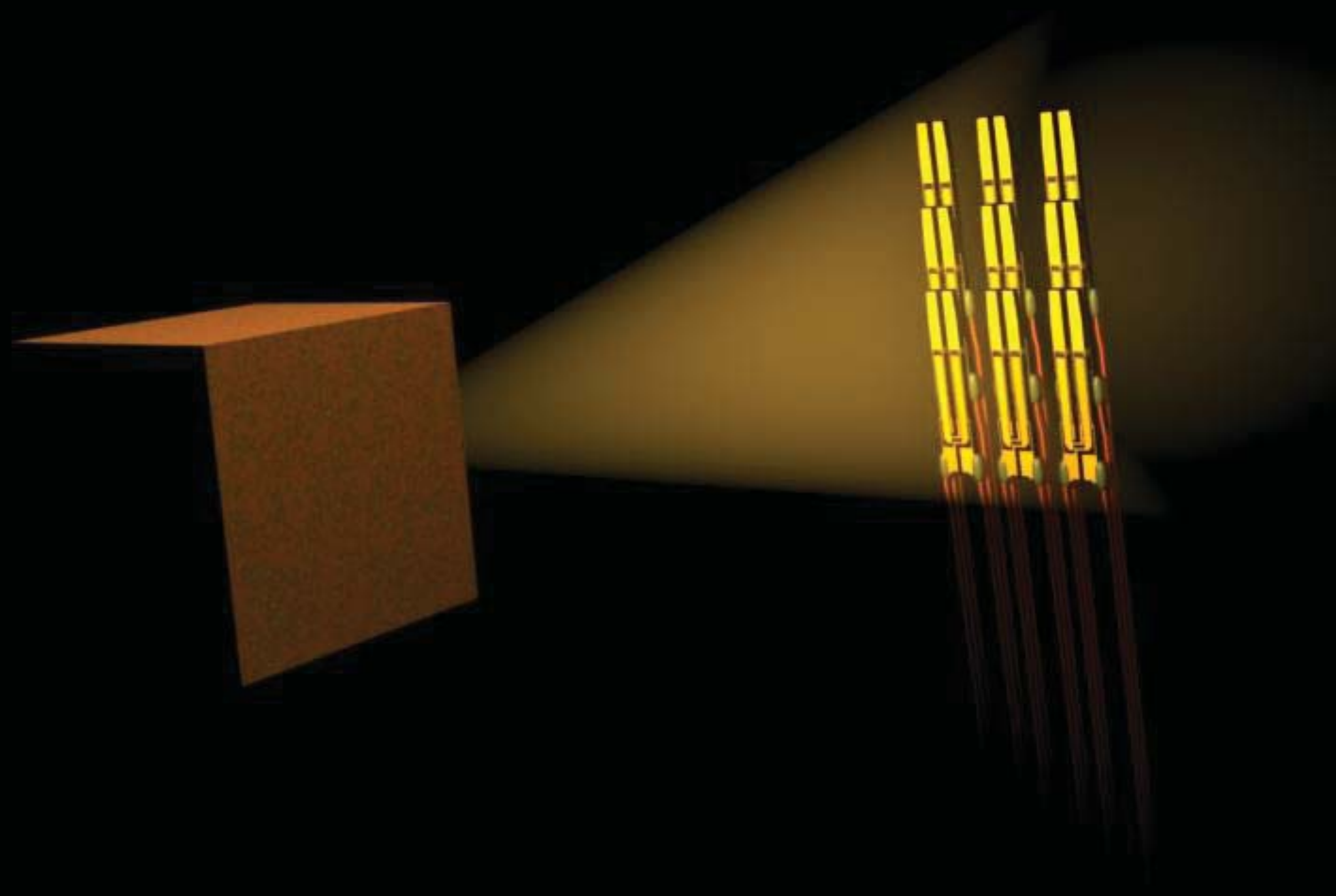

active region

What about a real digital vortex video camera – say with 9 pixels?

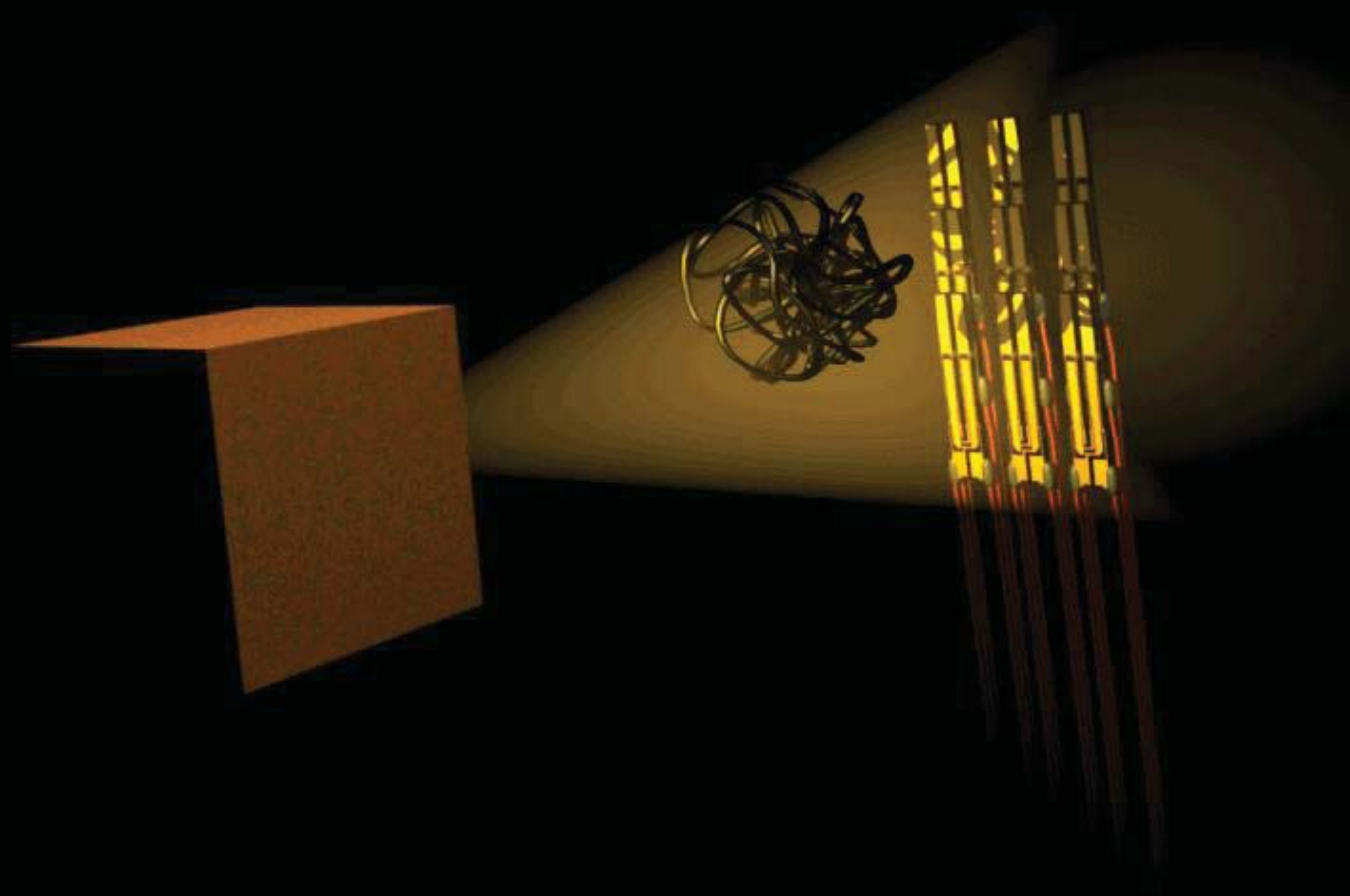
We start with a black-body radiator emitting a beam of excitations.



Then add three x three quartz detectors, to create an array.



Then add turbulence.



Conclusions

• Turbulence easily generated by vibrating wires and grids

• vortex line densities

Wire L ~ few x10^7 m^{-2}

Grid L ~ few x10^8 m^{-2}

• grid initially produce rings which at high production rates reconnect to form developed static turbulence

• Fluctuation correlations between detectors and power spectrum analysis suggests Richardson cascade and Komogorov-like energy spectrum

• Tuning forks can detect the shielding of quasiparticles by turbulence but currently, sensitivity is relatively small