**Workshop on Interpretation of measurements in $^4$He superfluid turbulence, Saclay, 2015**

# The decay of counterflow turbulence in superfluid $^4$He

## An attempt at some interpretation

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# Introduction and outline

To what extent do we now understand various aspects of counterflow turbulence, with particular reference to the preceding two experimental presentations?

Concerned mainly with the ***decay*** of counterflow turbulence, but first a summary of what we know and understand about the ***steady state***.

Relevant experiments:

- Attenuation of second sound → vortex line densities, *L.*
- Visualization of the flow of the normal fluid with $He_2$ excimer molecules.

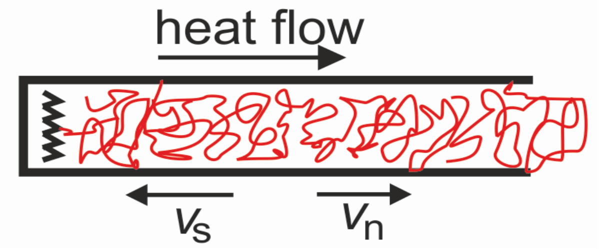
Plan:

- The steady state: extent of our present understanding of its essential features.
- The decay: reminder of the essential features that we have to explain.
- Can we understand these features of the decay? Yes, to some extent.
- Unsolved problems.

# The meaning of counterflow turbulence

Turbulence generated in the superfluid component by a forced relative motion of the two fluids; may be accompanied by turbulence in the normal fluid.

Most easily studied in thermal counterflow, when there is no net mass flow



Other forms of counterflow turbulence: eg bellows-driven superflow, in which there is no net flow of the normal fluid.

We focus mainly on thermal counterflow, because we know more about it.

# Steady state thermal counterflow

The forced relative motion of the two fluids generates a tangle of vortex lines in the superfluid component.

Steady-state vortex line density , to some extent independently of channel size. Homogeneous turbulence?

Essential elements of an understanding of the generation of a vortex tangle came from computer simulations by Schwarz, based on vortex filament model, local induction approximation, and assumed reconnections, with many later refinements (eg Tsubota's demonstration that proper description requires full Biot-Savart). Tolerable agreement with observed
and observed The vortex tangle predicted to be essentially random, so that there is motion only on length scales ~ vortex line spacing

But there remain serious problems:

- Sometimes experiment reveals different regimes, with different as the heat flux increased.
- The theory was based on unrealistic assumptions - spatially uniform flow, unbounded by channel walls; laminar and spatially uniform.
- Observed decay very different from that predicted by simulations.

# Development of the theory

The suggestion by Melotte & Barenghi that jumps in with increasing heat flux might be associated with a transition to turbulence in the normal fluid, with an argument that laminar flow of the normal fluid in a finite channel would be unstable above a critical velocity.

Various simulations (Aarts & de Waele, Baggaley, Tsubota …) to study the effect on the vortex tangle of more realistic forms of normal-fluid flow:

- different prescribed laminar profiles
- different prescribed turbulent velocity fields.

Big effects, but still unrealistic in the sense that one ought to determine what the normal fluid is doing in a dynamically self-consistent computation of the flow pattern in both fluids. Nevertheless a strong suggestion that a transition to turbulence in the normal fluid could be important.

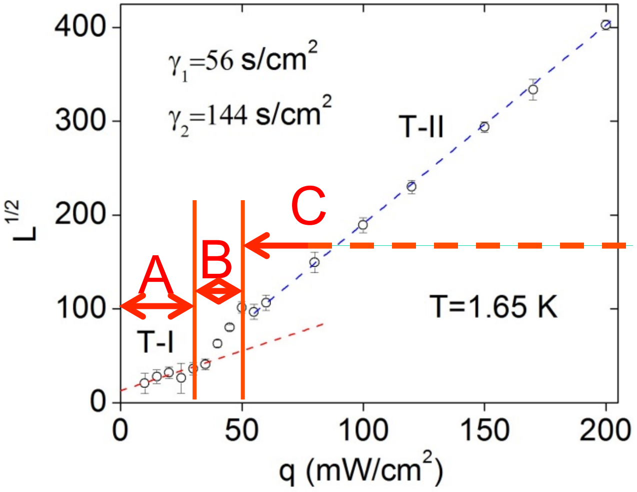
We need experiments to tell us whether the normal fluid can be turbulent, and if so what are the characteristics of that turbulence.

# Visualization of steady state

- Skrbek *et al*: motion of $H_2$ particles indicate some form of large scale motion.

- Guo *et al*: detailed study of flow of normal fluid with $He_2$ excimer molecules. In 10 mm$^2$ channel three regimes of steady-state normal fluid flow with increasing heat flux:

A :Laminar flow with parabolic velocity profile
B Laminar flow with distorted profile.
C Large scale turbulent flow with
and .



But no abrupt increases in *L.*

Confirms that, above critical heat flux, the flow of the normal fluid is turbulent.

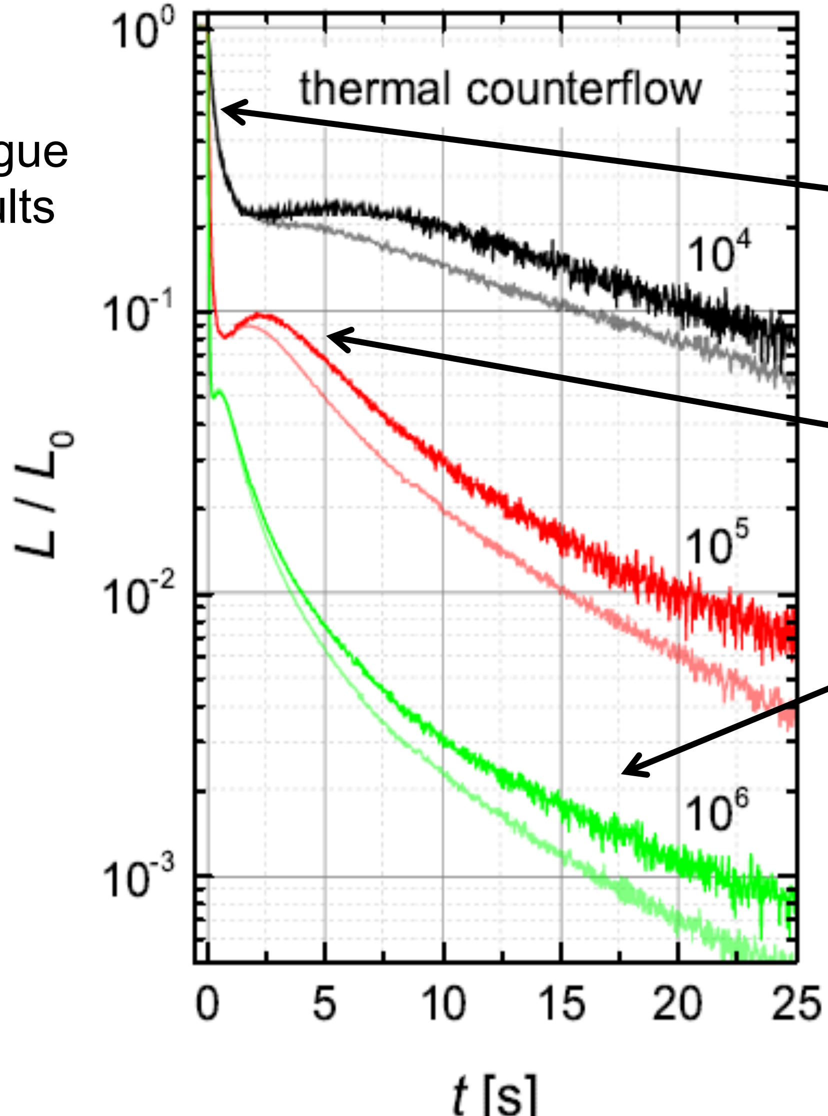
- Questions: Nature of normal-fluid instability? Why Why so intense? Coupling to superfluid? Answers not generally known.
- Let us accept the empirical findings about steady state, and see whether we can then understand the decay processes.

# Observations of the decay with second sound I

**Large initial heat current (turbulent normal fluid)**

Simple-minded prediction

Prague results



Sharp initial fall, possibly consistent with simple-minded view at very small times

The “bump”

Same form of final decay

Final decay:

; due to decay through classical cascade of energy-containing eddies limited in size by channel width. Origin of such large-scale eddies?

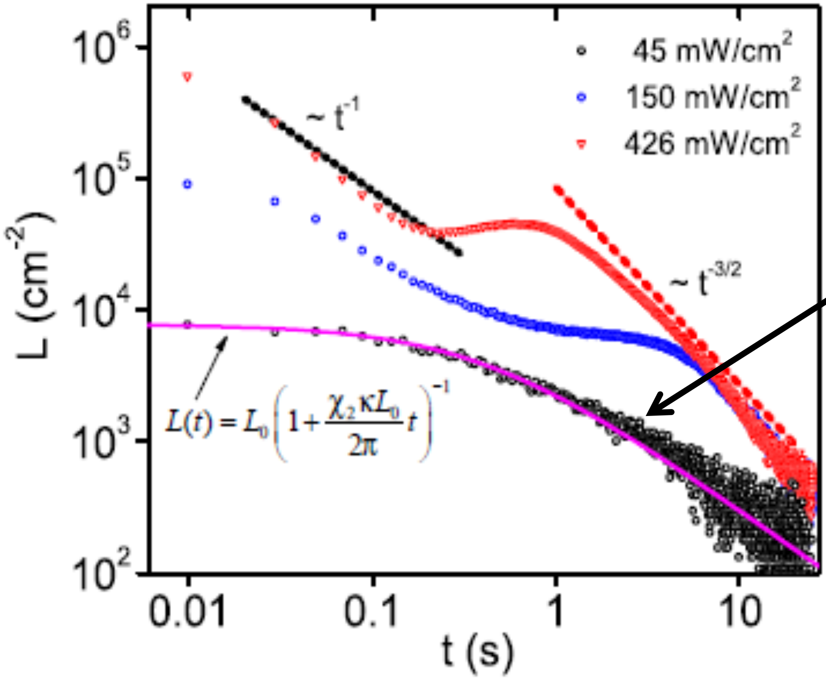
5

# Observations of the decay with second sound II

Is the anomalous behaviour of the decay from large heat fluxes associated with large-scale turbulence in the normal fluid? (Note decay at large *t.)*

**Small initial heat current (laminar normal fluid)**

Simple-minded prediction



Tallahassee results

holds at all times from steady-state small heat fluxes in which normal fluid is not turbulent.

**Therefore anomalous decays are indeed associated with large-scale normal fluid turbulence in steady state**

Large-scale turbulence required for the decay already present in steady state

# Observations of the decay with $He_2$ excimers

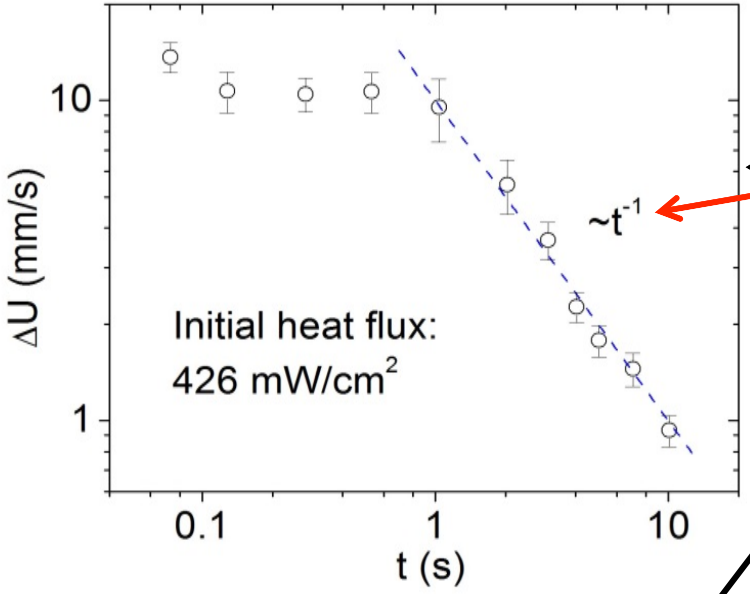
**Decays from large heat flux: turbulent n-fluid**

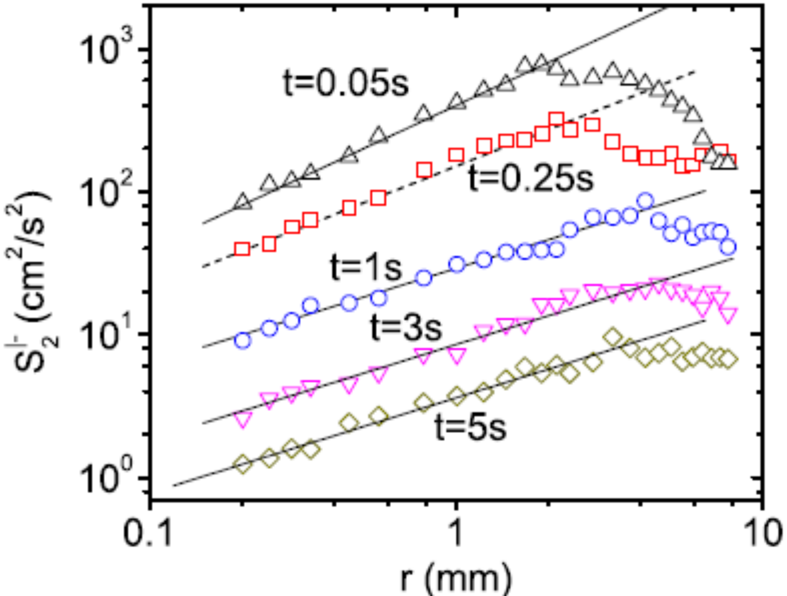
Note ; consistent with Kolmolgorov and saturated large eddy size

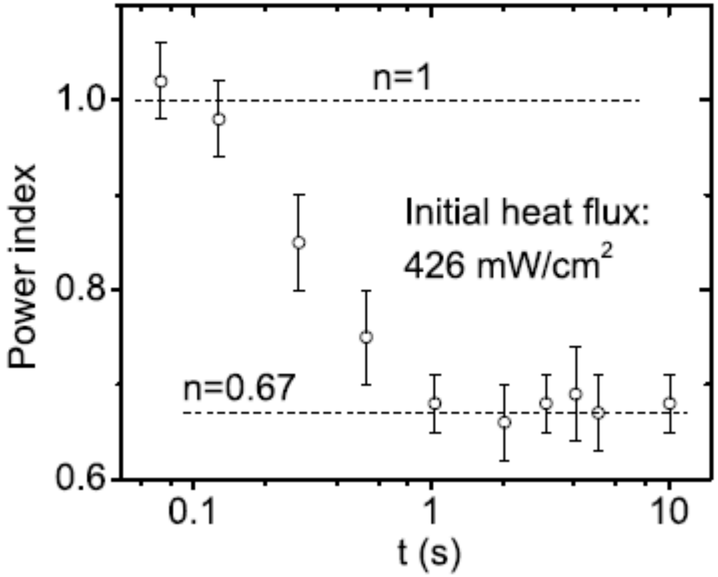
Decay of rms velocity fluctuation (||W) in the normal-fluid turbulence

Evolution of second-order transverse structure function with time.

Evolution of exponent *n* in







# Coupling of large-scale turbulent motion in the two fluids

Adopt view that, once the average velocities of the two fluids have decayed, mutual friction eliminates any difference in the two large-scale turbulent velocity fields in a time

. Typically very small (~ 2 ms in previous slide).

But to what extent does coupling exist already in steady state?

If no large scale turbulence in superfluid in the steady state, velocity fluctuations would fall by factor ~ 0.2 (1.65K) when coupling sets in.

In fact velocity fluctuations fall by factor ~ [Changes in anisotropy?]

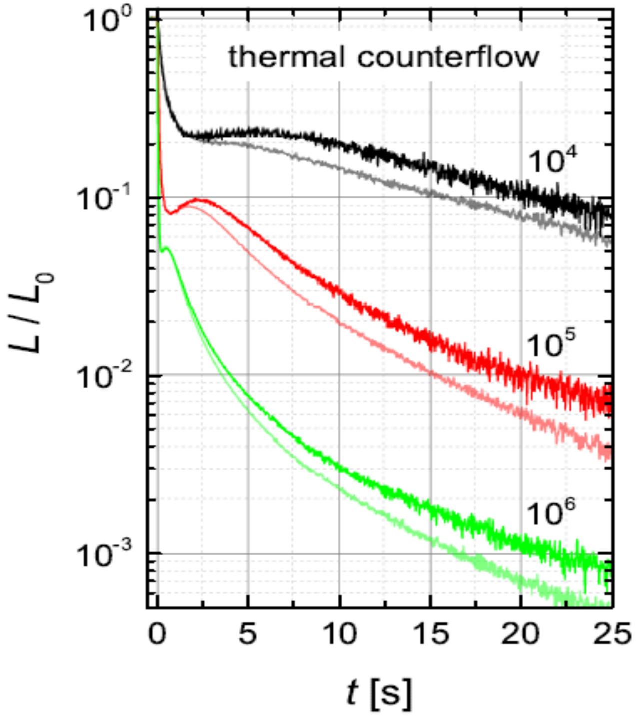
Suggests substantial (but not complete) coupling even in steady state.

# Development of a model to explain decays in line density

Introduce a simple model to explain decay of line density *L* when there is large-scale turbulence

Assume that size of largest eddies is fixed and limited by channel size.

*Assume first that the energy spectrum associated with the largest scales is Kolmogorov.*



Then we can write down an equation for the time-dependent line density

*= velocity in energy-containing eddies, size*

Rate of change of energy on scale

Rate of energy dissipation on scale

Rate of input of energy to scale from cascade ( in )

# Time-dependence of vortex-line density

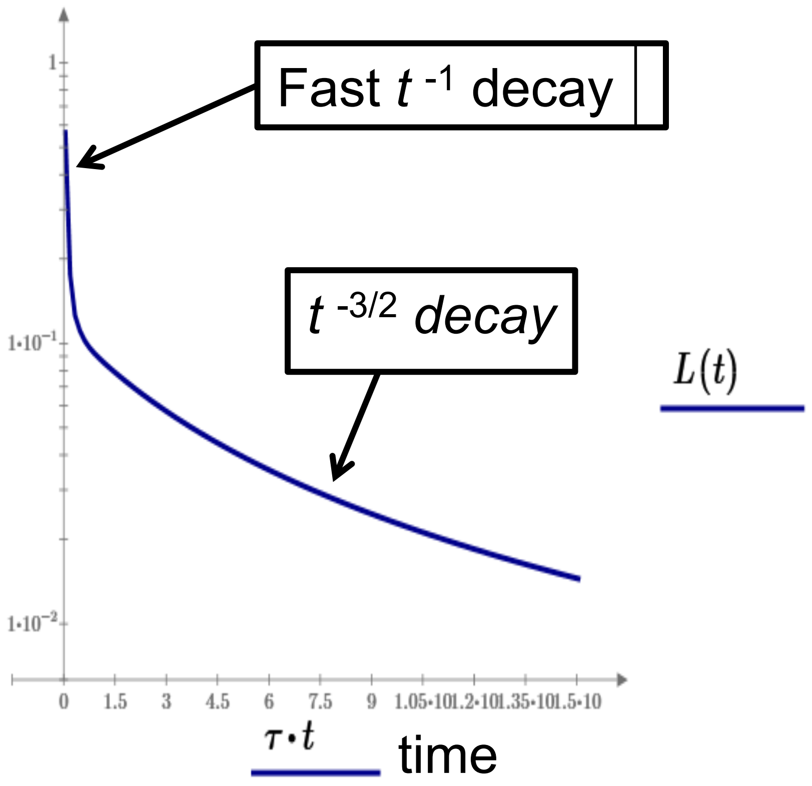
We know how *U* decays: , *where*

where

Solve this differential equation with the appropriate initial values at i.e with known values of from visualization and from second sound.

OK, but no bump.

Why?



Fast $t^{-1}$ decay

$t^{-3/2}$ *decay*

# Evolution of the energy spectrum

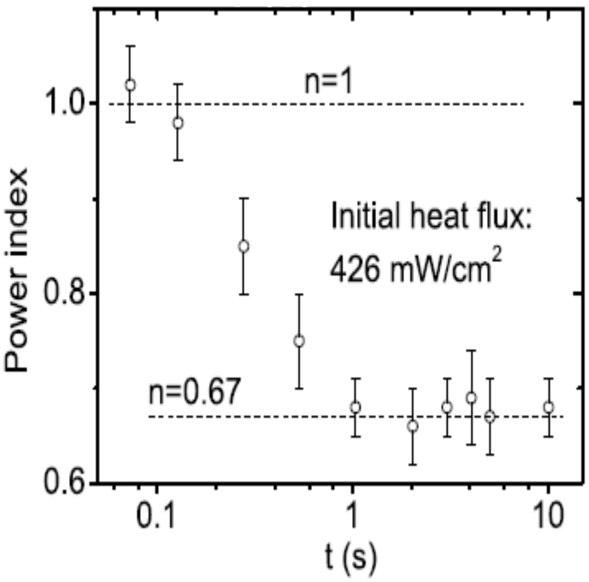
We have assumed that large length-scale energy spectrum is Kolmogorov.

Visualization tells us that in fact at the start of the decay.

Is the bump associated with this modified spectrum? Argue: Yes.
(Other explanations have not stood test of time.)

## *Evolution of the $k^{-2}$ energy spectrum*

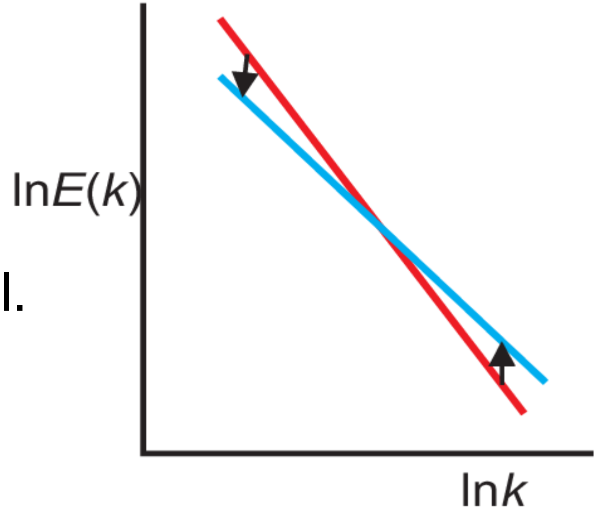
- This spectrum exists in the steady state because there is dissipation on all length scales.
- When has fallen to zero, the two fluids become fully coupled, and this dissipation disappears: the spectrum gradually evolves into a Kolmogorov spectrum.
- This evolution can be studied by solving the Leith equation. Study by Emil Varga showed that this evolution can lead to a bump in the vorticity.
- Here we present a simpler argument, based on a correction to our equation for .



# A corrected equation for $dL/dt$

Our earlier equation was based on the assumption that the loss of energy from the big eddies resulted in an immediate gain in energy on scale .

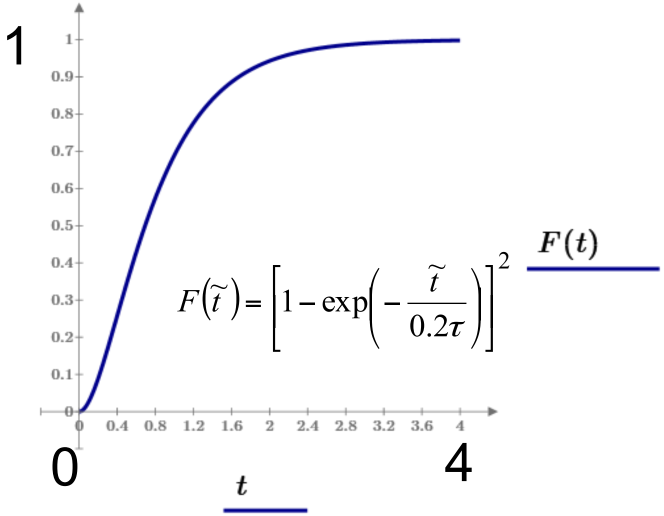
Not the case while the spectrum is evolving, because energy is then required to increase the energy at intermediate *k*.



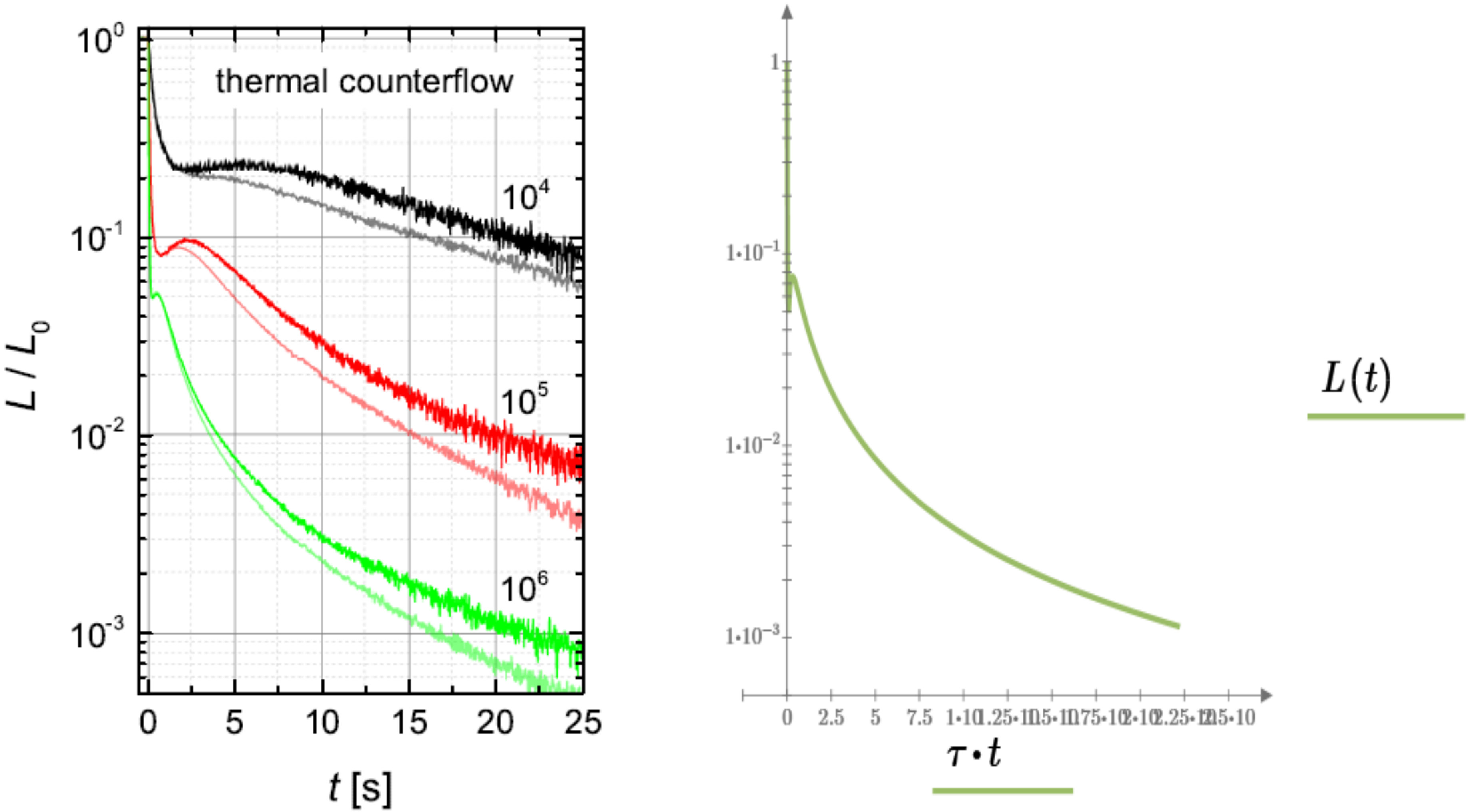
Initially flux of energy at is very small.

This flux grows to its Kolmogorov value in a time that is some fraction of the turn-over time of the big eddies.

Then our equation for the evolution of the line density becomes



# Comparison with experiment



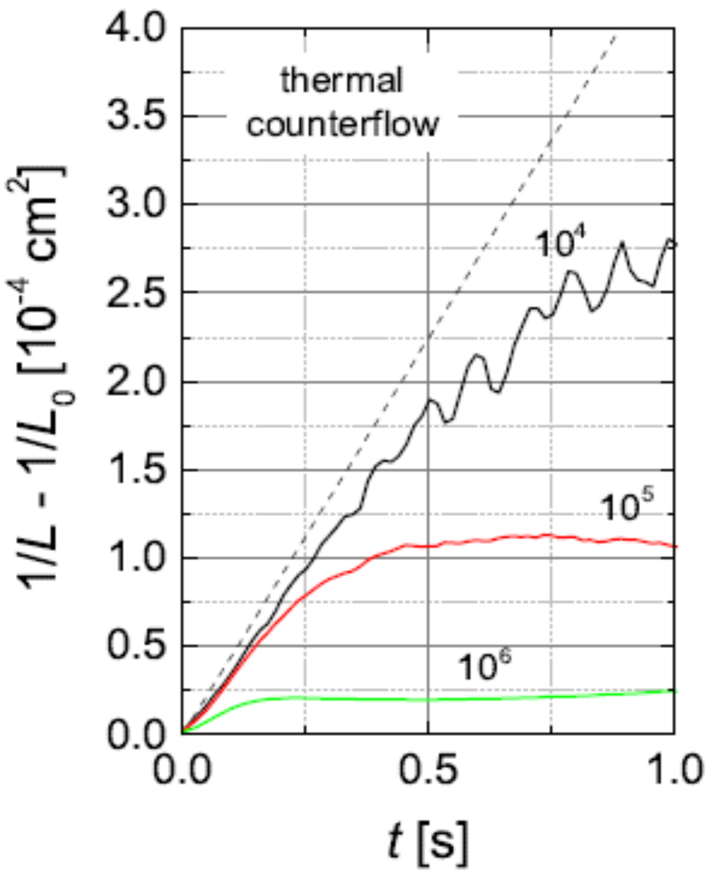
Practically no adjustable parameters!

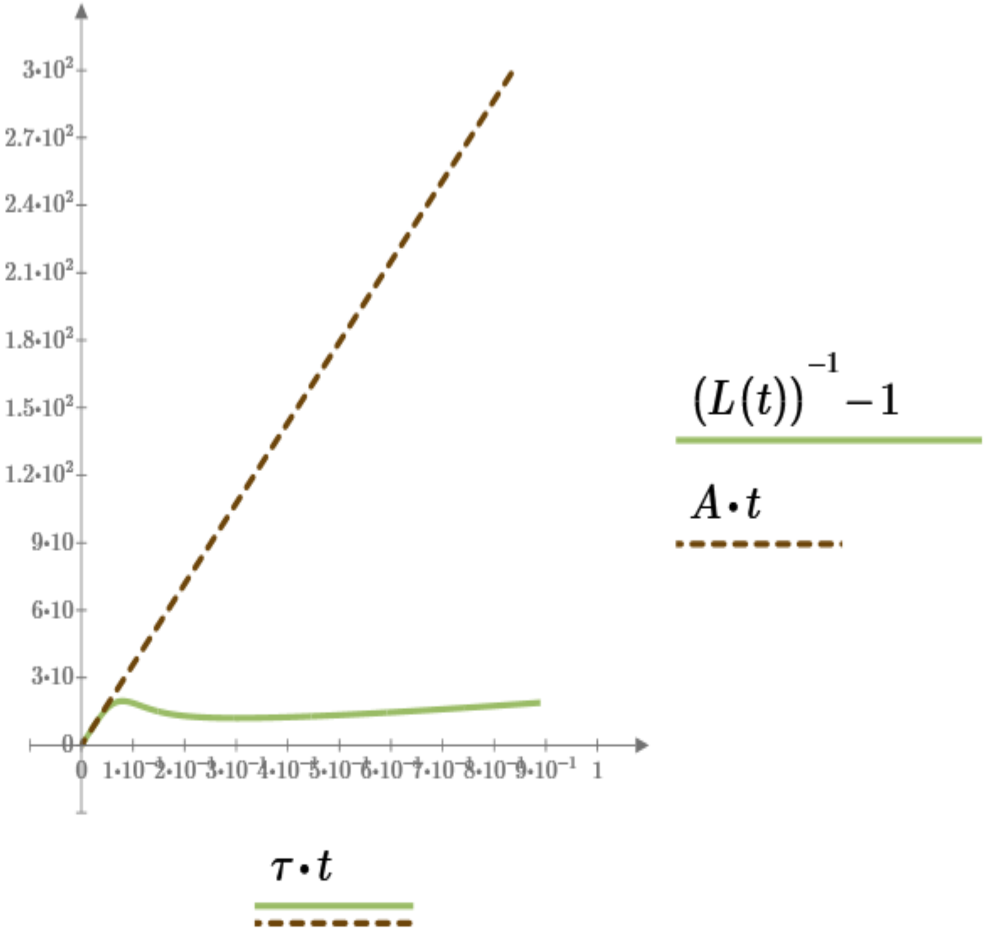
Hopefully, on the right track towards on explanation.

# Comparison with experiment (cond)

Behaviour at small times: S

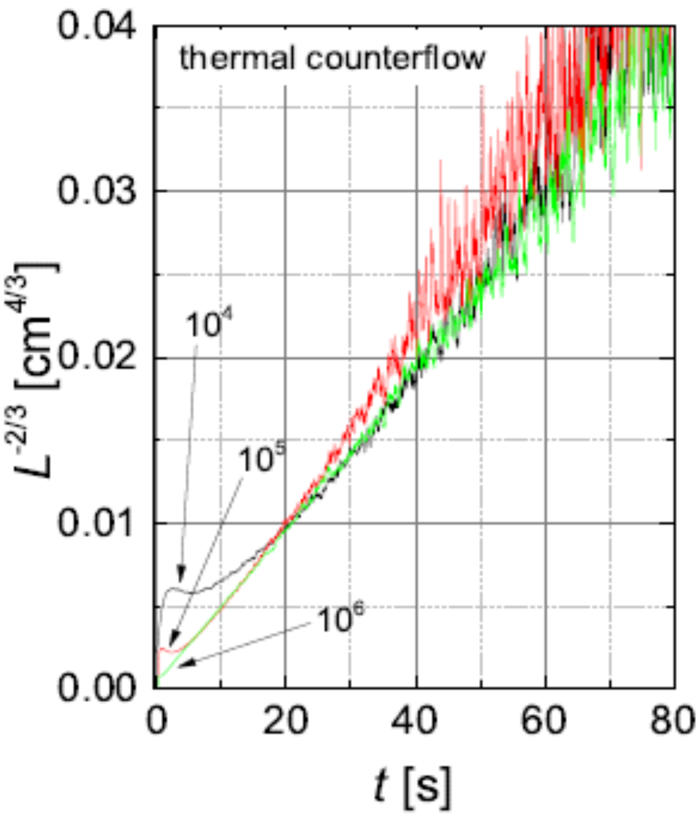
plots of v

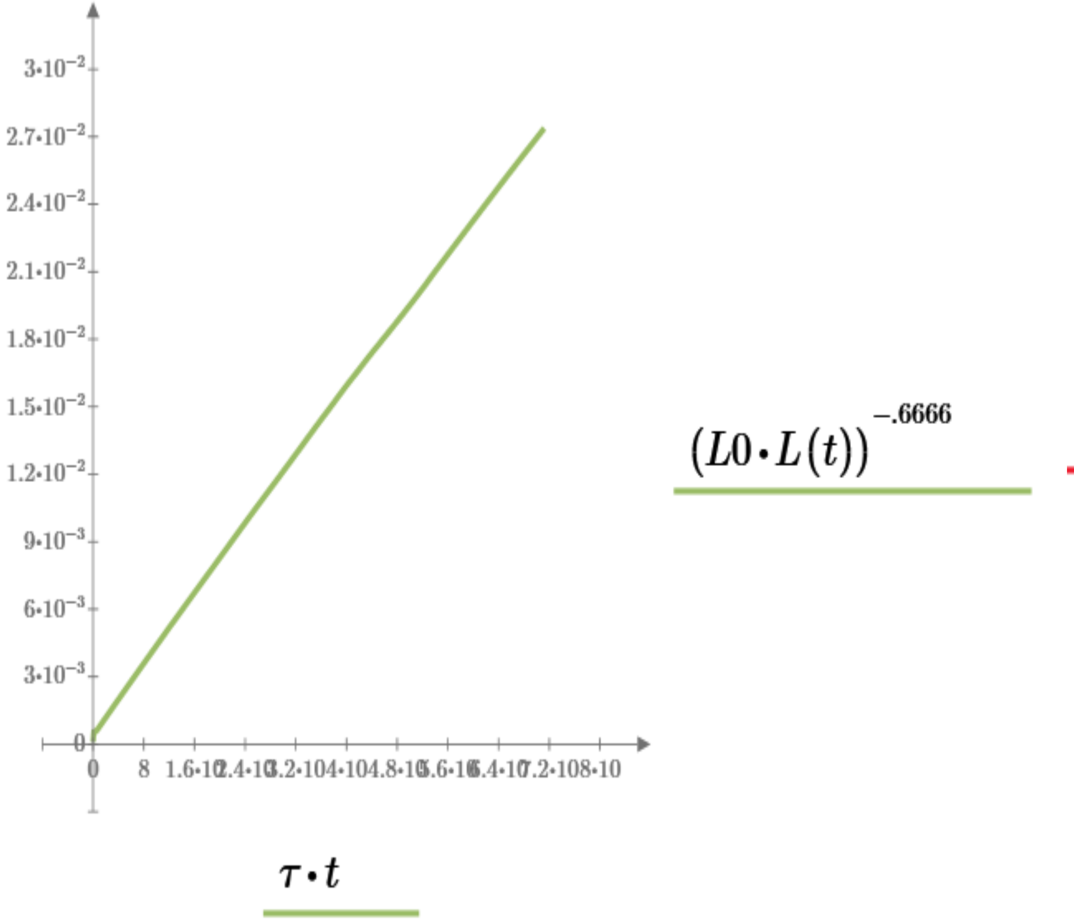




# Comparison with experiment (cond)

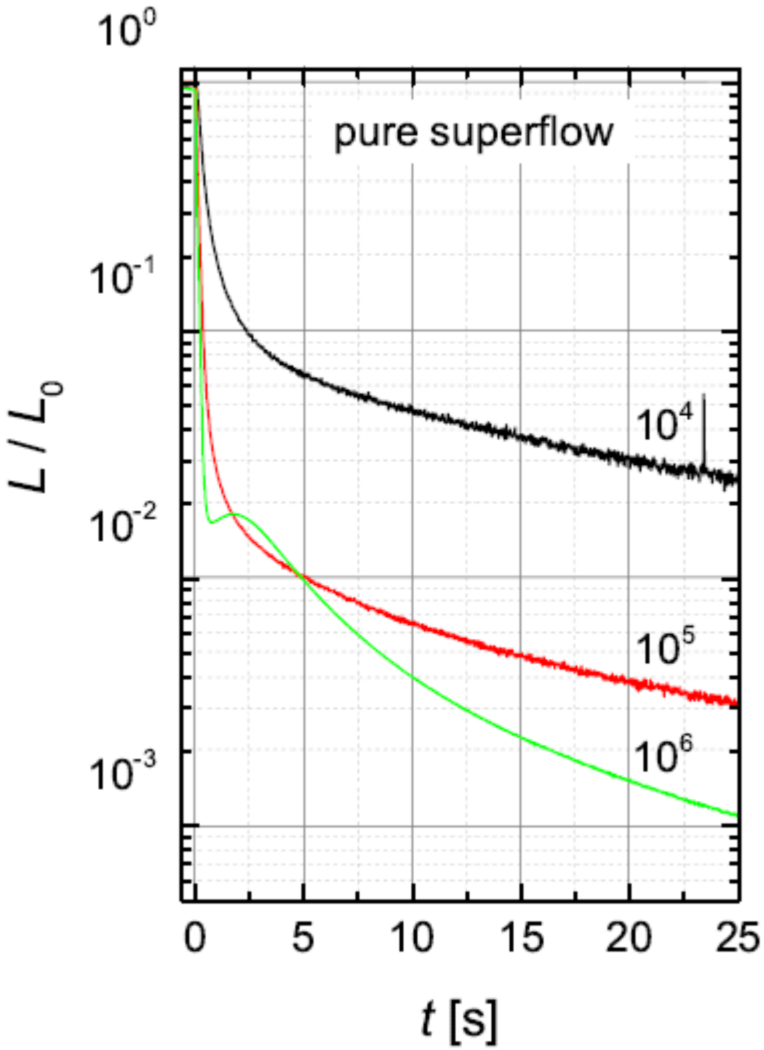
Behaviour at large times:
plots of v

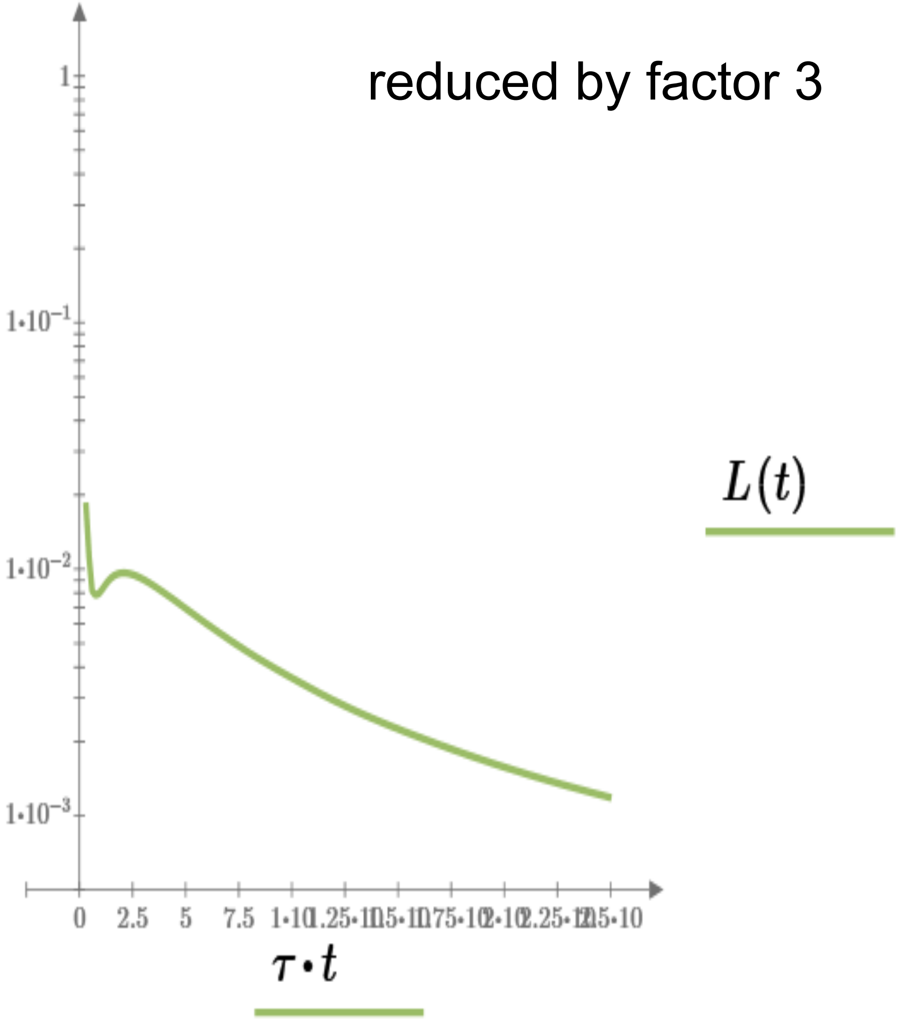




# Bellows driven superflow

No help from visualization!




reduced by factor 3

Large-scale turbulence weaker than in thermal counterflow

# Conclusions

Given our empirical knowledge of the steady state in counterflow, we can formulate a plausible theory to account for various forms of decay.

But our understanding of the steady state is still seriously incomplete.

We have a reasonable understanding of the *small-scale turbulence in the steady state* (Schwarz and refinements).

We lack an understanding of the *large-scale flow regimes in the steady state*, particularly

- The existence of three such regimes, two involving laminar flow, one involving large-scale turbulent flow.
- The characteristics of the large-scale turbulence: its energy spectrum and its intensity.

Looks complicated. But is it? looks simple!

Little study so far of the build-up of counterflow turbulence and of entry-length problems.

# Thank you