Listening to quantum turbulence with second sound tweezers

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€ : ANR QUTE-HPC
€ : EC MicroKelvin

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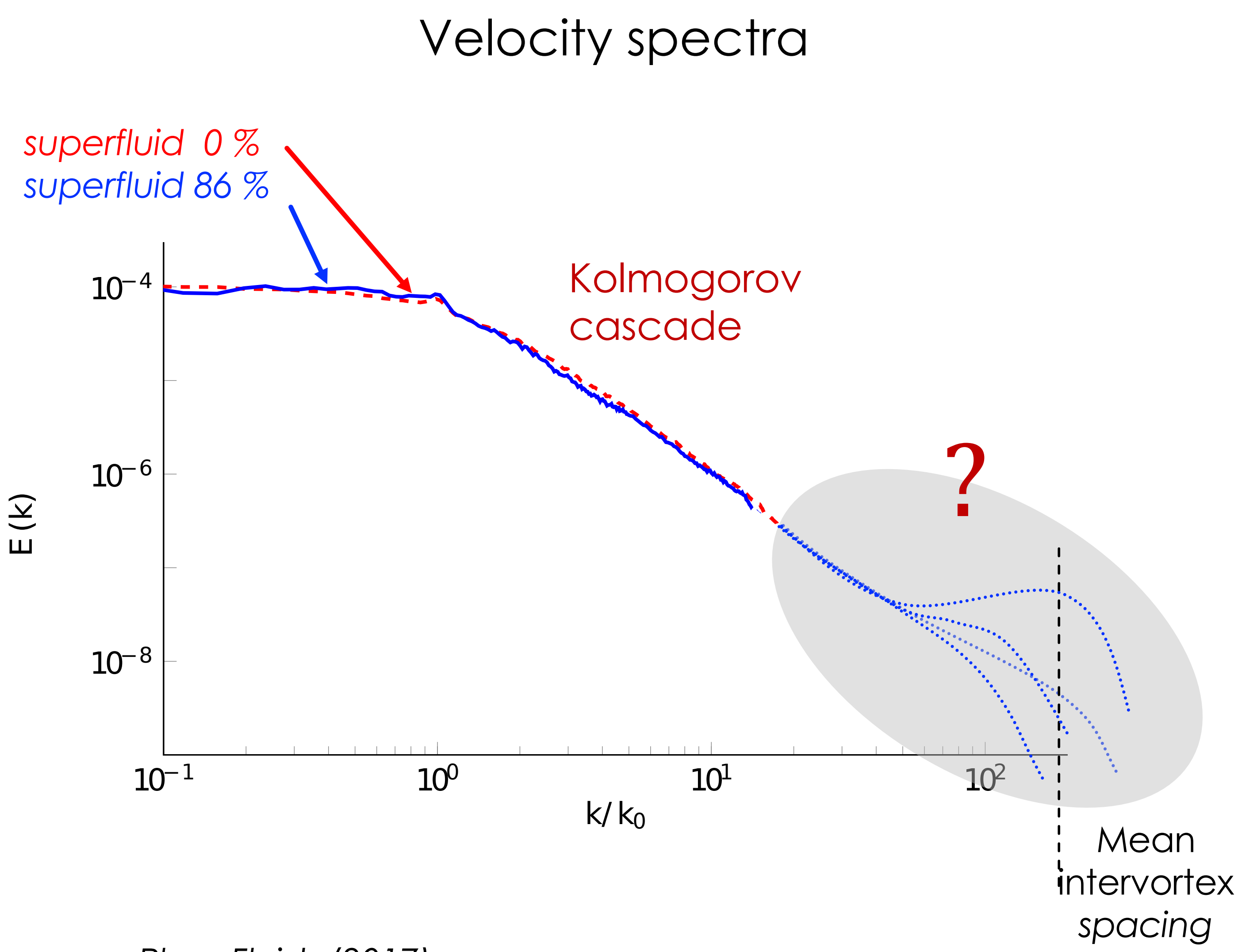
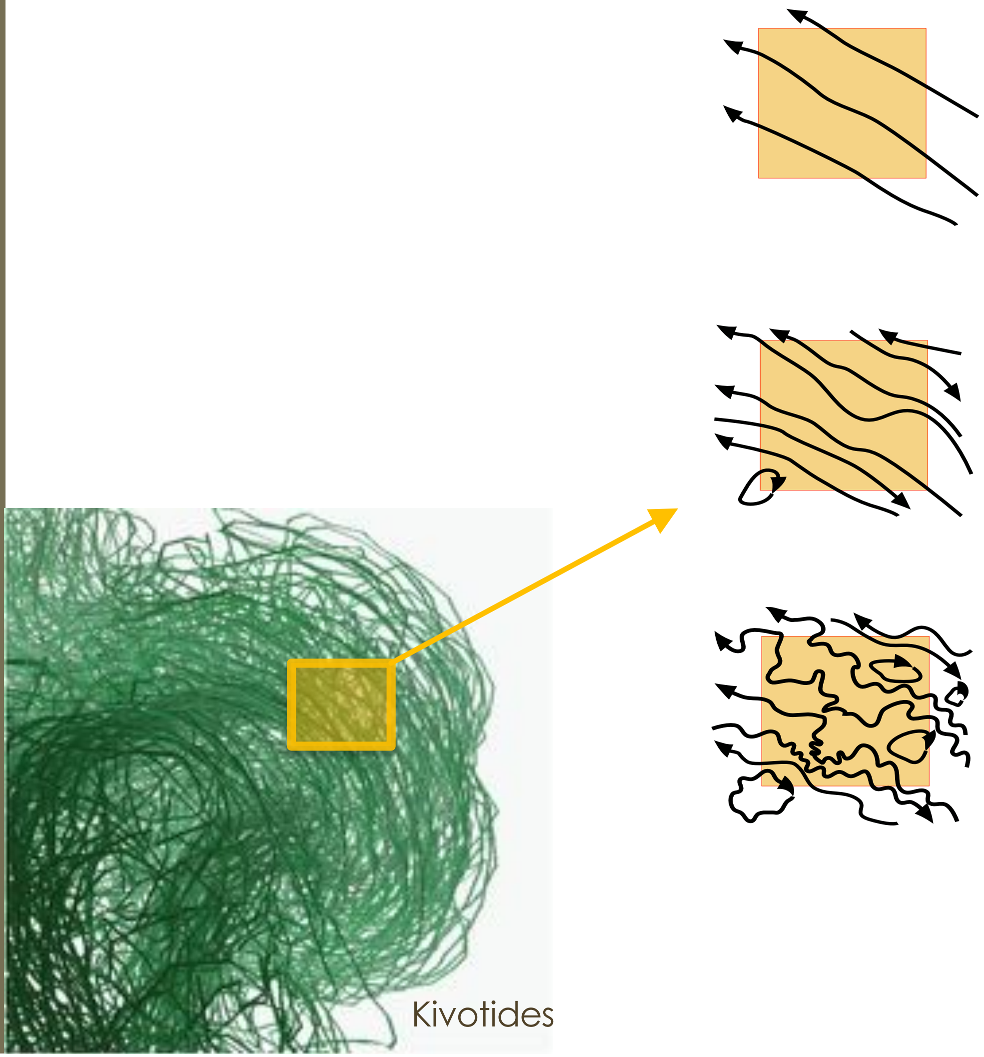
Motivation : the mesoscales of QT



Spectra : *Rusaouen, Phys. Fluids (2017)*

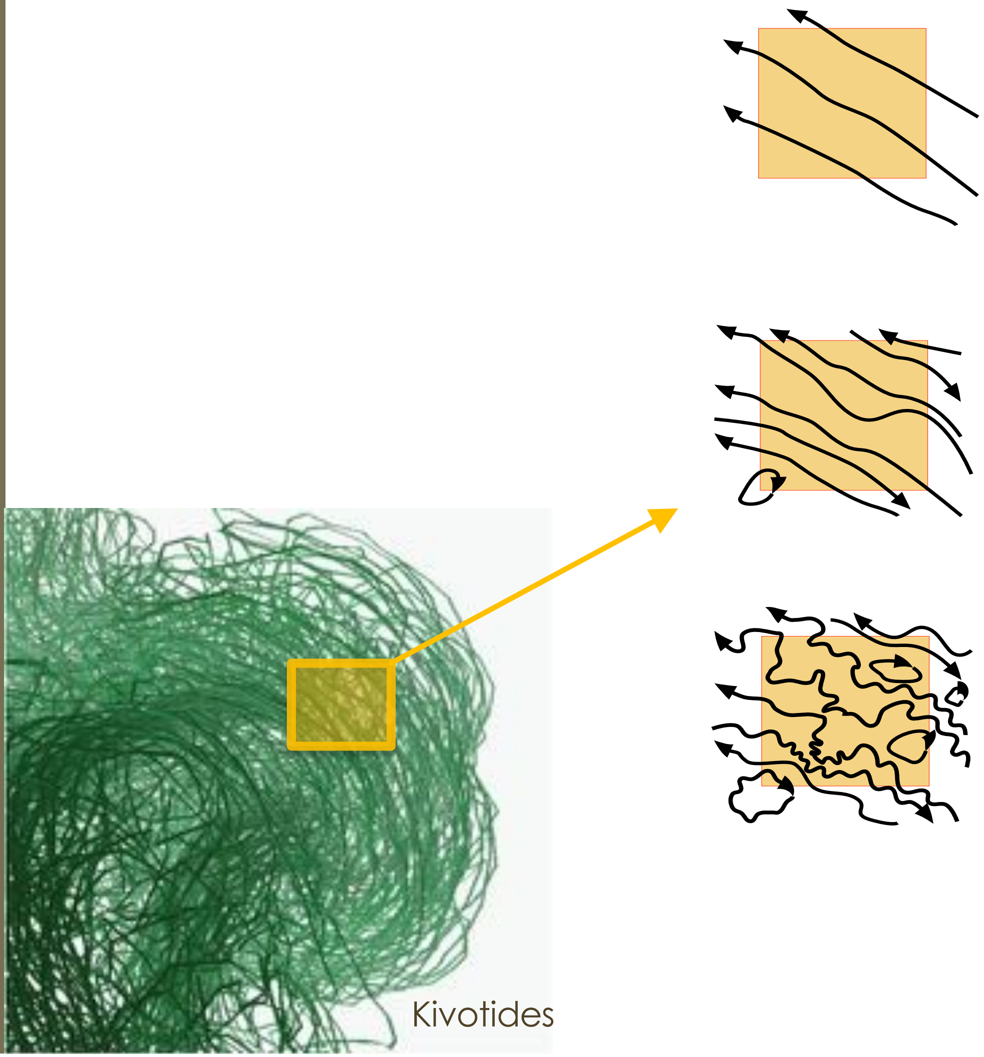
The local length of vortex lines
An inertial-scale indicator of small scale physics



Same total	« vorticity »
Different total	« vortex length »

The local length of vortex lines

An inertial-scale indicator of small scale physics



The vortex length depends on small-scale processes

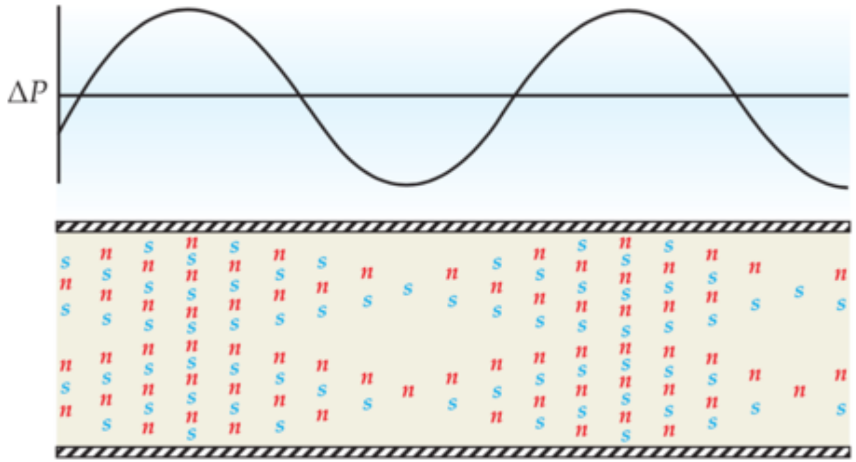
- dissipation,
- reconnexion,
- Kelvin wave cascade
- …

Experimental approach to mesoscales:

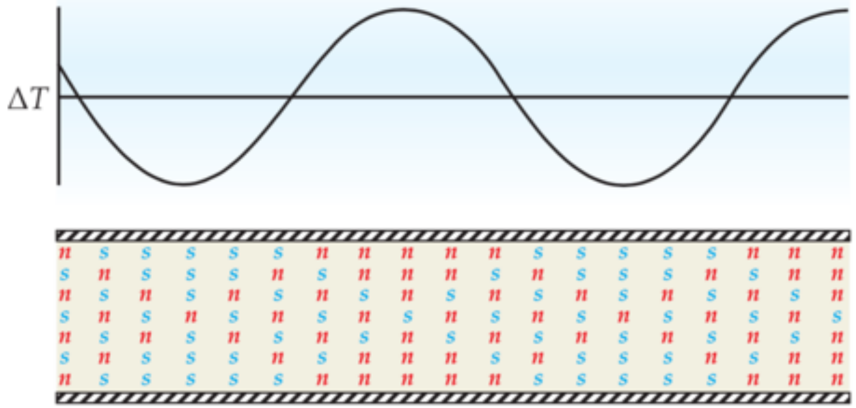
measure the local density of vortex lines.

What is second sound ?

First sound



Second sound



In He-II, temperature follows a wave equation

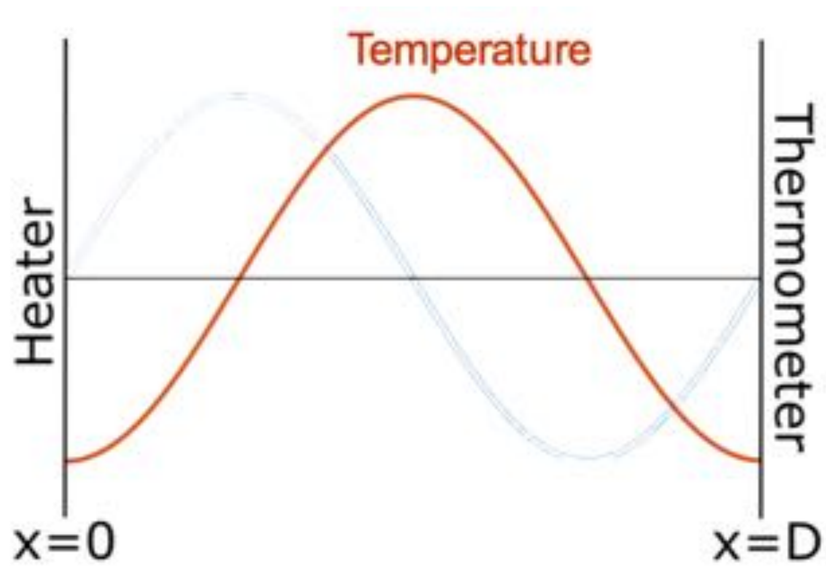
$$\frac{\partial^2 T}{\partial t^2} - c_2^2 \Delta T = 0$$

$$c_2 \approx 10 - 20 \mathrm{m}/s$$

n : normal fluid component
s : superfluid component

Picture from *R.J. Donnelly, Phys. Today, (2010)*

A resonant cavity for temperature waves



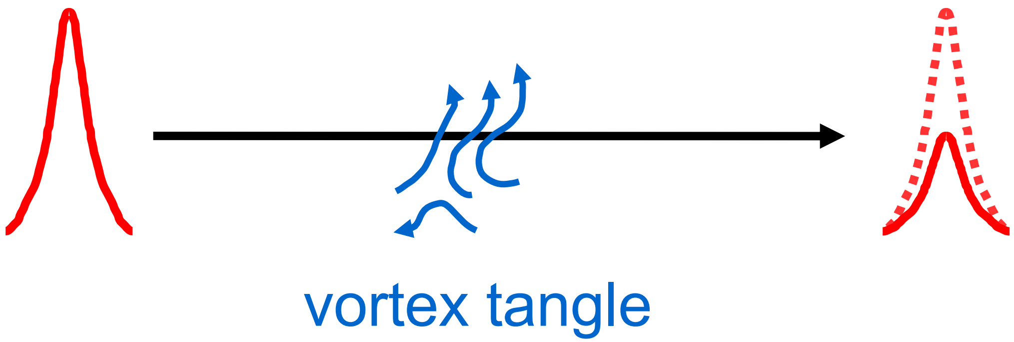
Usually of the cm size and imbedded in the walls of a superfluid flow (e.g Hall & Vinen 1956).

Second sound is damped by quantum vortices

- With quantum vortices, the dispersion relation is

$$k = \frac{\omega}{c_2} + \underbrace{i\alpha(T)\mathcal{L}_\perp}_{\text{attenuation}}$$

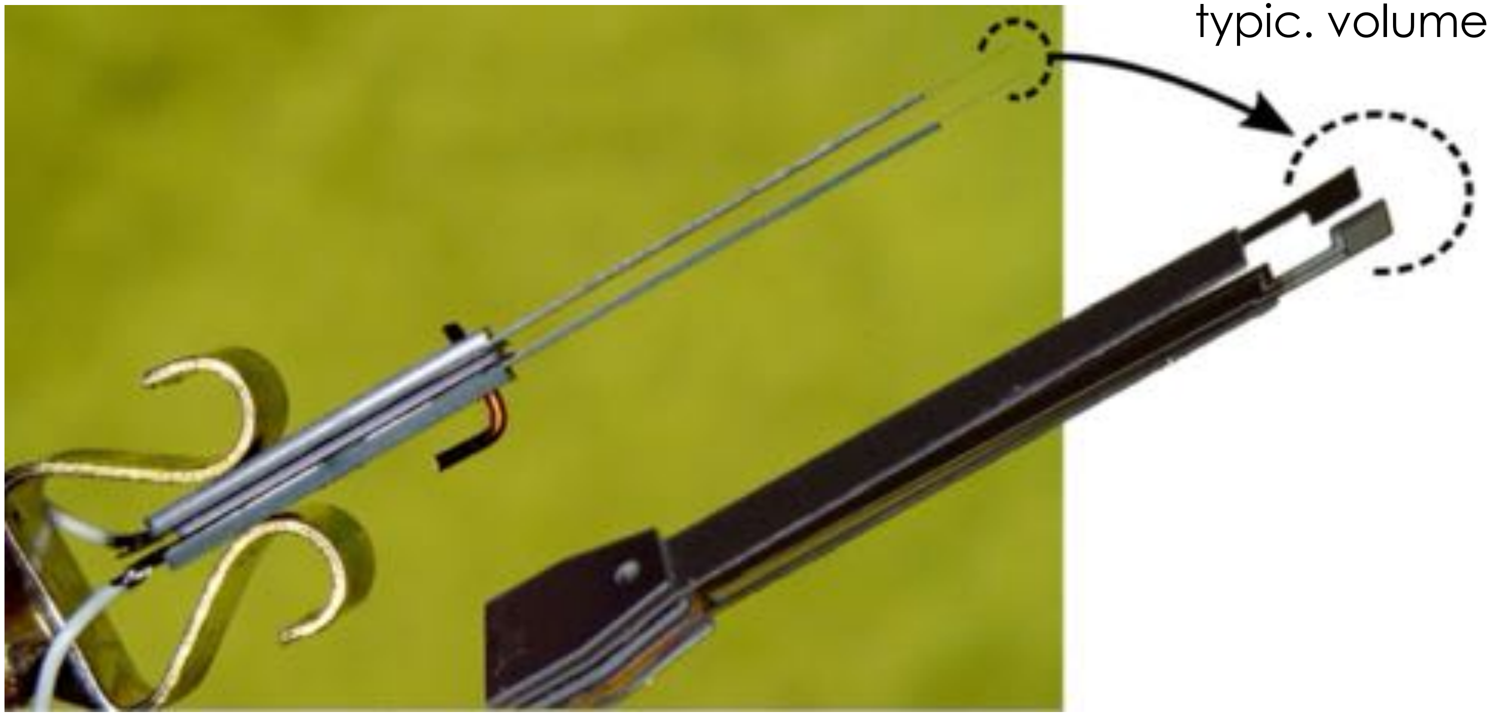
$\mathcal{L}$ is the density of quantum vortex lines (or « *superfluid enstrophy* »)



Second sound tweezers

designed as a non-invasive probe

Second sound cavity
typic. volume (500 µm)^3



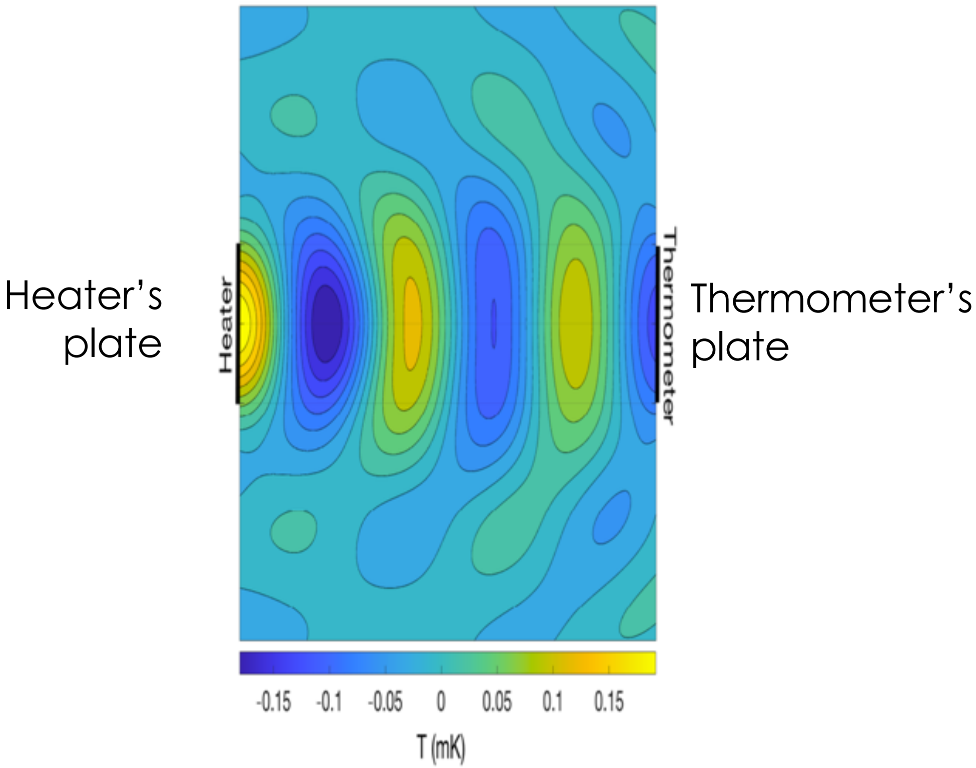
Design, modelling, fabrication recipe, operation and data processing methods, detailled in: *Woillez et al, Rev. Sci. Instrum [in press]*

Standing wave in the open cavity
modelled with the Huyggens-Fresnel principle

$$G(\mathbf{r}) = \frac{1}{|\mathbf{r}|} e^{-ik|\mathbf{r}|}$$

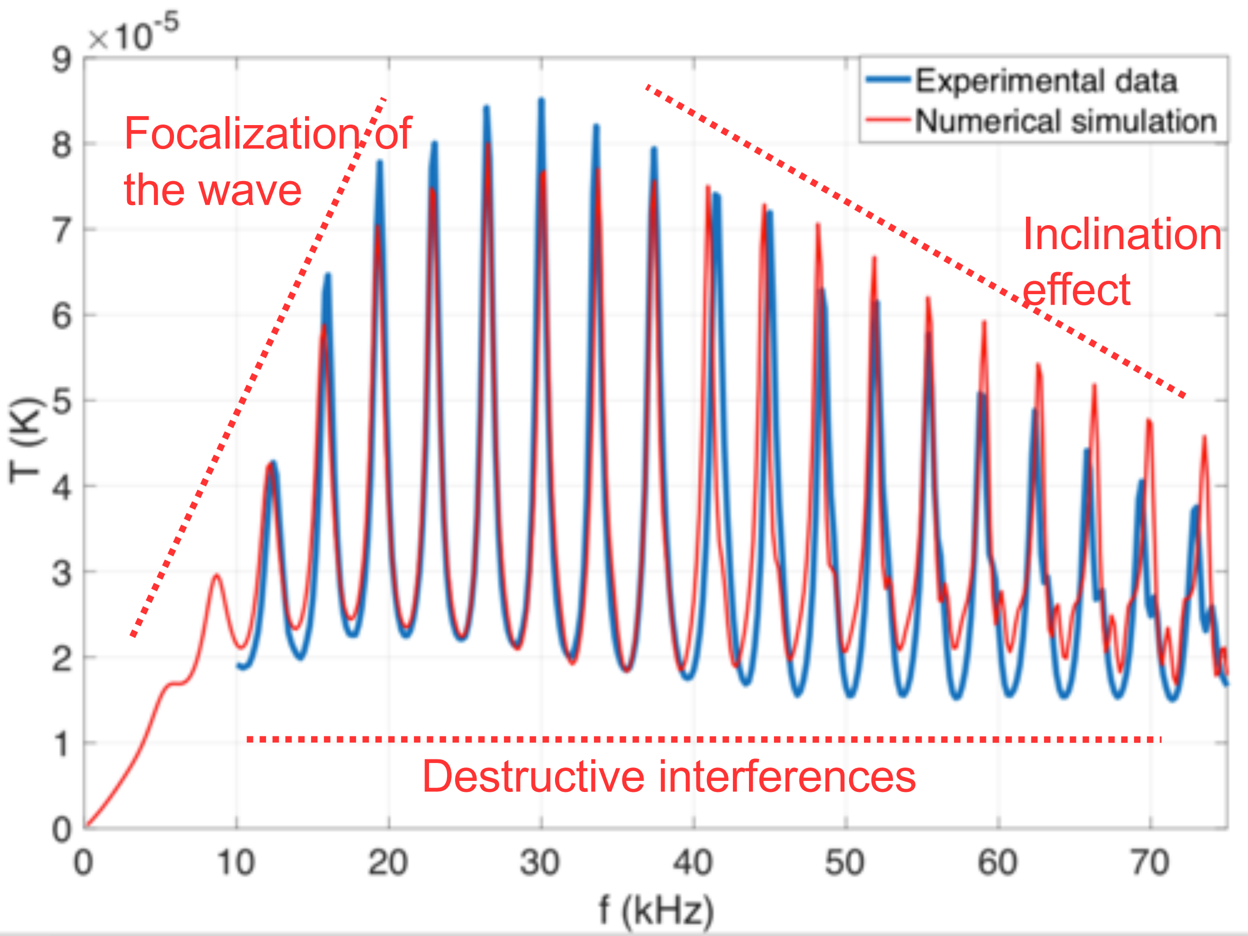
- Near field diffraction
- Advection

Temperature field

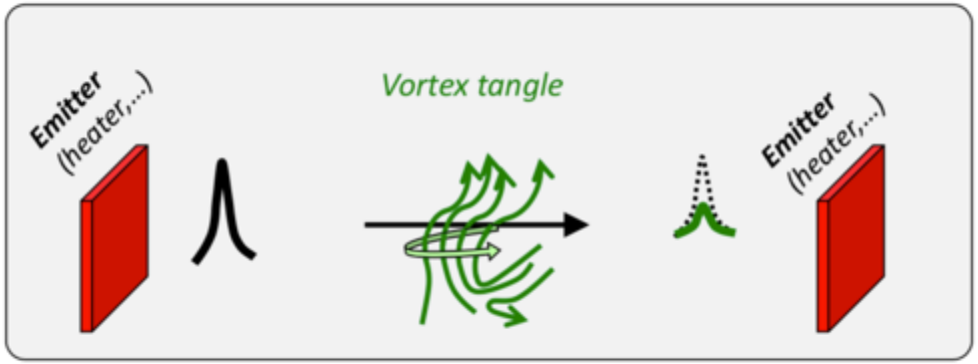


Second sound tweezers

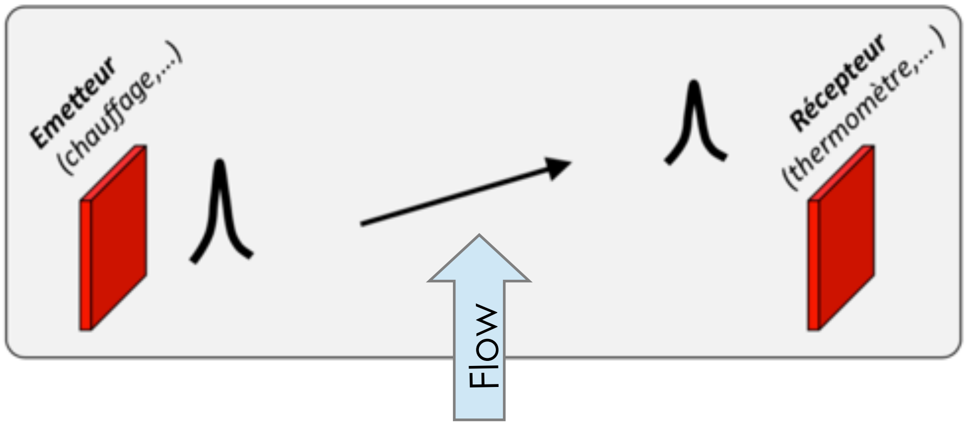
The model predicts the features of the spectrum



Second sound tweezers
sensitive to both quantum vortices and velocity

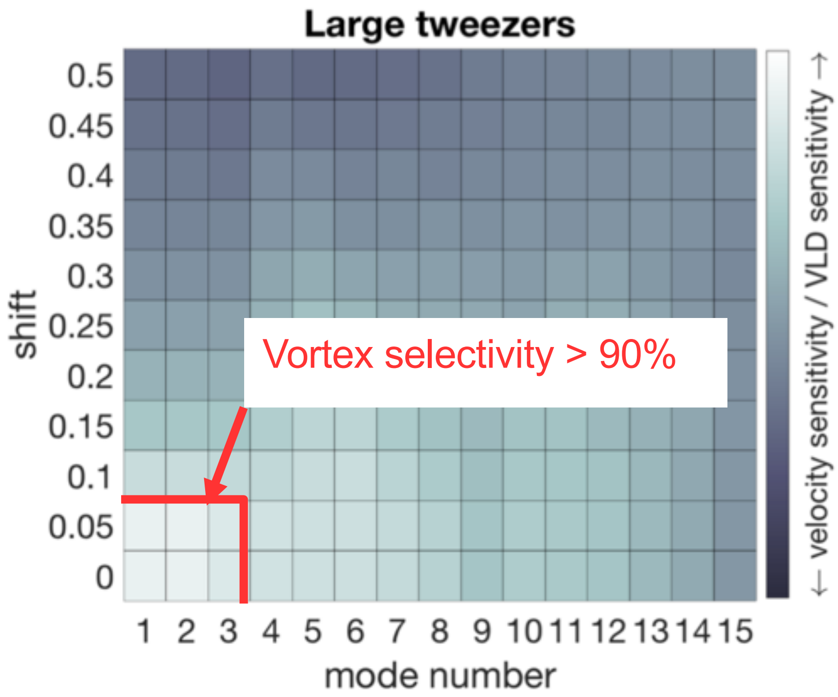


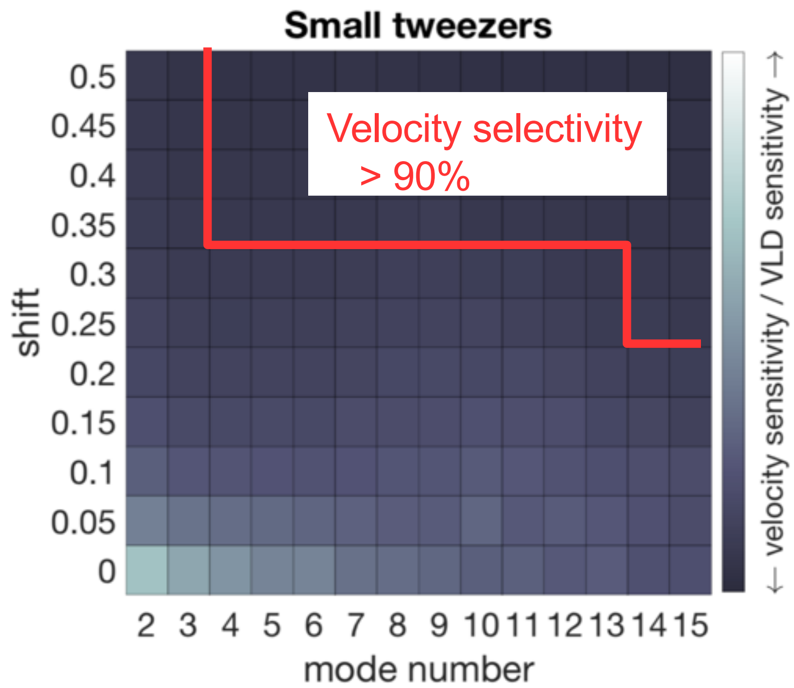
Attenuation proportional to the density of quantum vortices



Ballistic advection by the flow creates an extra attenuation with phase shift

Second sound tweezers
Optimization to favor vortex or velocity selectivity





Large symmetric tweezers are used to measure the density of **quantum vortices**

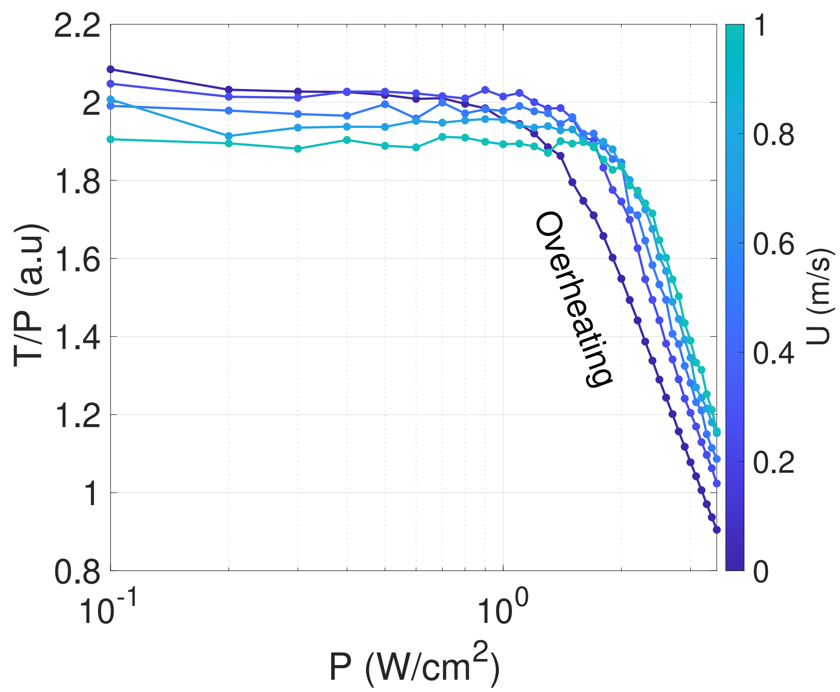
Small asymmetric tweezers are used to measure the **velocity**

Side slide :

An alternative method to sense both vortices or velocity using the same tweezers

Low drive vs high drive

Normalized amplitude of the standing wave

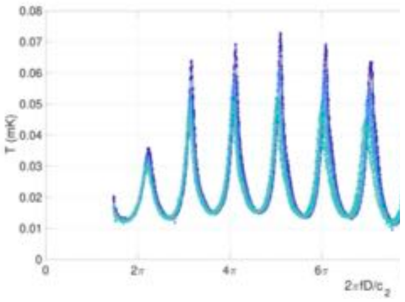


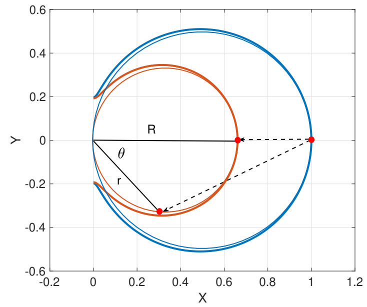
Heating power driving the resonator

Woillez, RSI [in press]

Three new mathematical processing methods

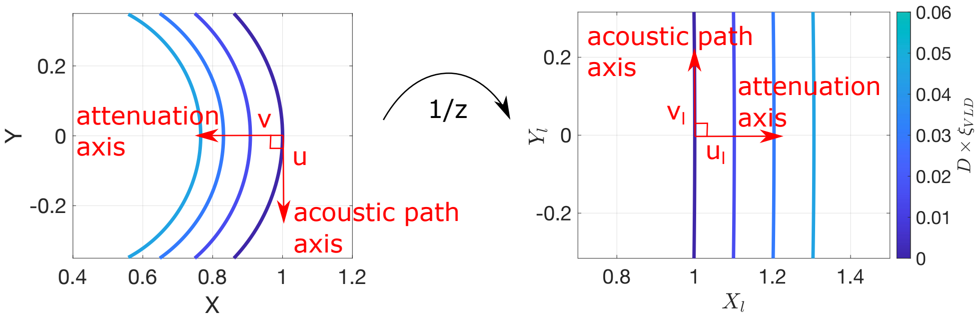
- o bulk attenuation and velocity deflection can be distinguished in the phase-quadrature plane.
- o the noise from a drifting resonant frequency can be cancelled

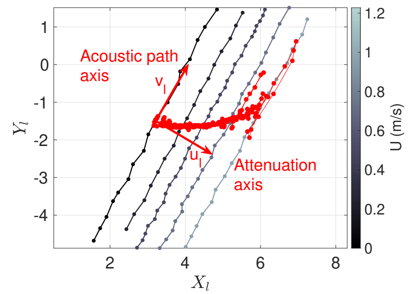


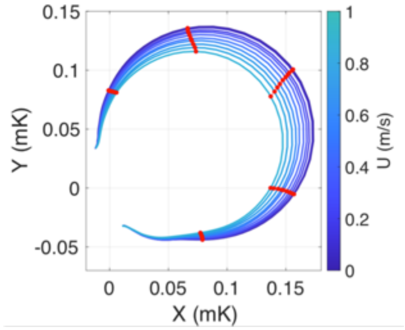


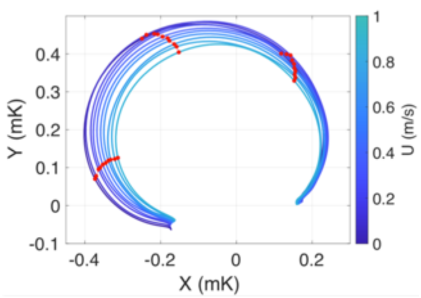
Attenuation in presence of phase shift

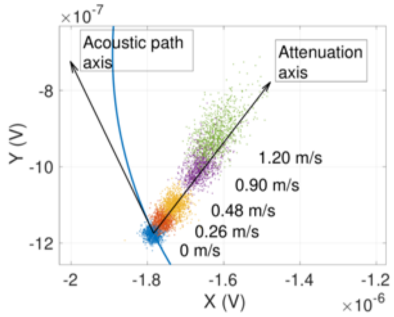
$$\xi_{VLD} = \frac{1}{D}\operatorname{asinh}\left(\frac{\overline{T}_0\cos\theta}{\overline{T}(f_0)e^{-i\theta}}\sinh(\xi_0 D)\right) - \xi_0.$$









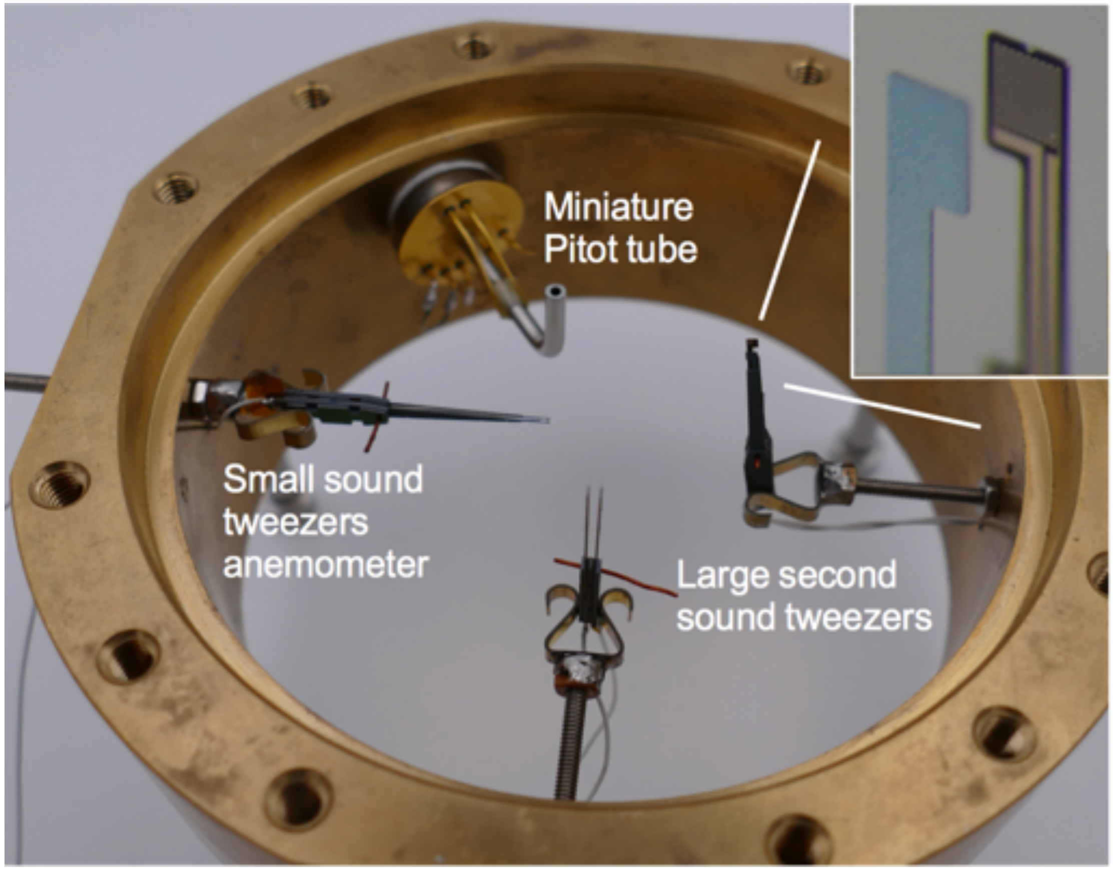


GRID TURBULENCE EXPERIMENT

TOUPIE superfluid wind-tunnel

Wind-tunnel
Φ76 mm

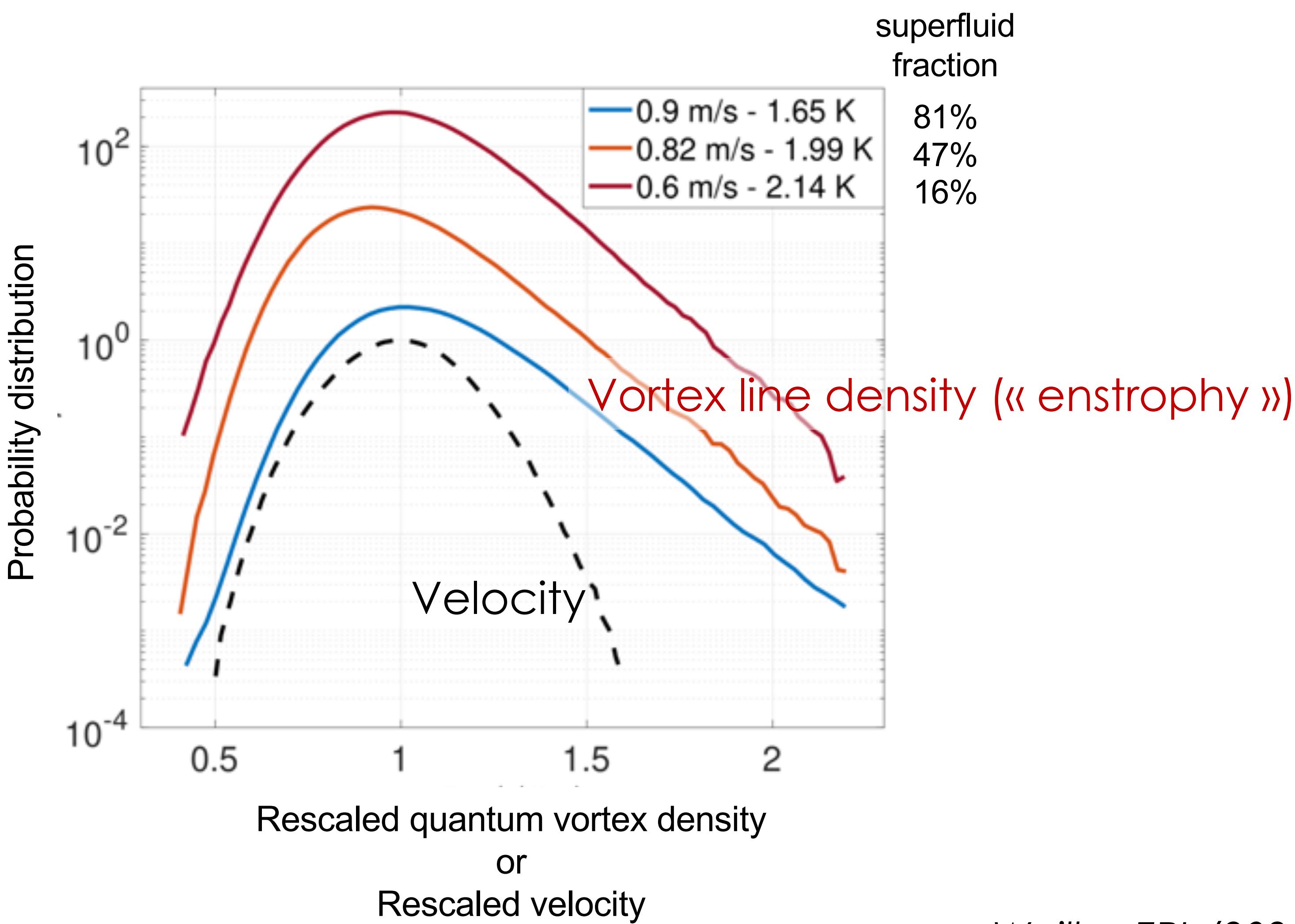
Grid wake :
- near field @ 10M
- porosity : 0.58



Acknowledgements to B. Chabaud

GRID TURBULENCE EXPERIMENT

Highly skewed vortex line density



Woillez EPL (2021)

Main findings on second sound resonators

- 2^{nd} sound tweezers can probe **both vortices and velocity**
- **New processing methods** in the complex plane eliminate out-of-phase signal

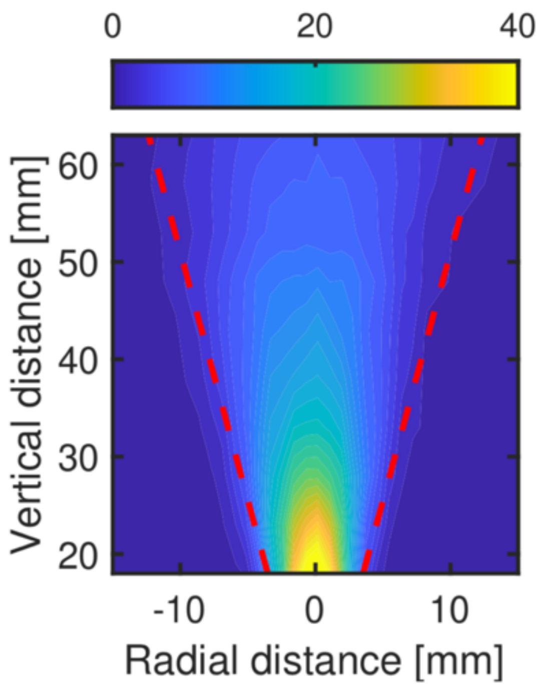
Main findings of the grid turbulence experiment

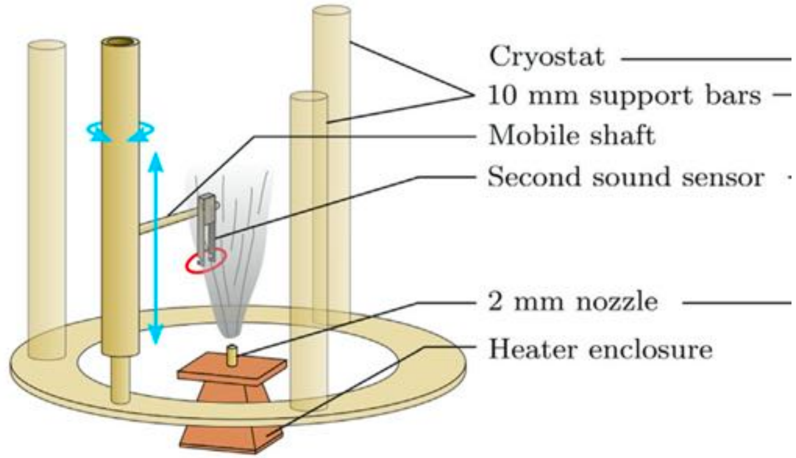
- PDF of the vortex line density :
  - Strong asymmetry.
  - Independent of the superfluid fraction.
    Also relevant to Navier-Stokes turbulence ?
- Spectra (not shown) :
  - All vortex density spectra collapse independently of the superfluid fraction.
  - The shape of the spectral master curve is unexpected (no power law)

JET EXPERIMENT
Mapping the superfluid enstrophy of a jet

In collaboration with P. Švančara and M. La Mantia

Quantum vortex density (10^{-9} m^{-2})

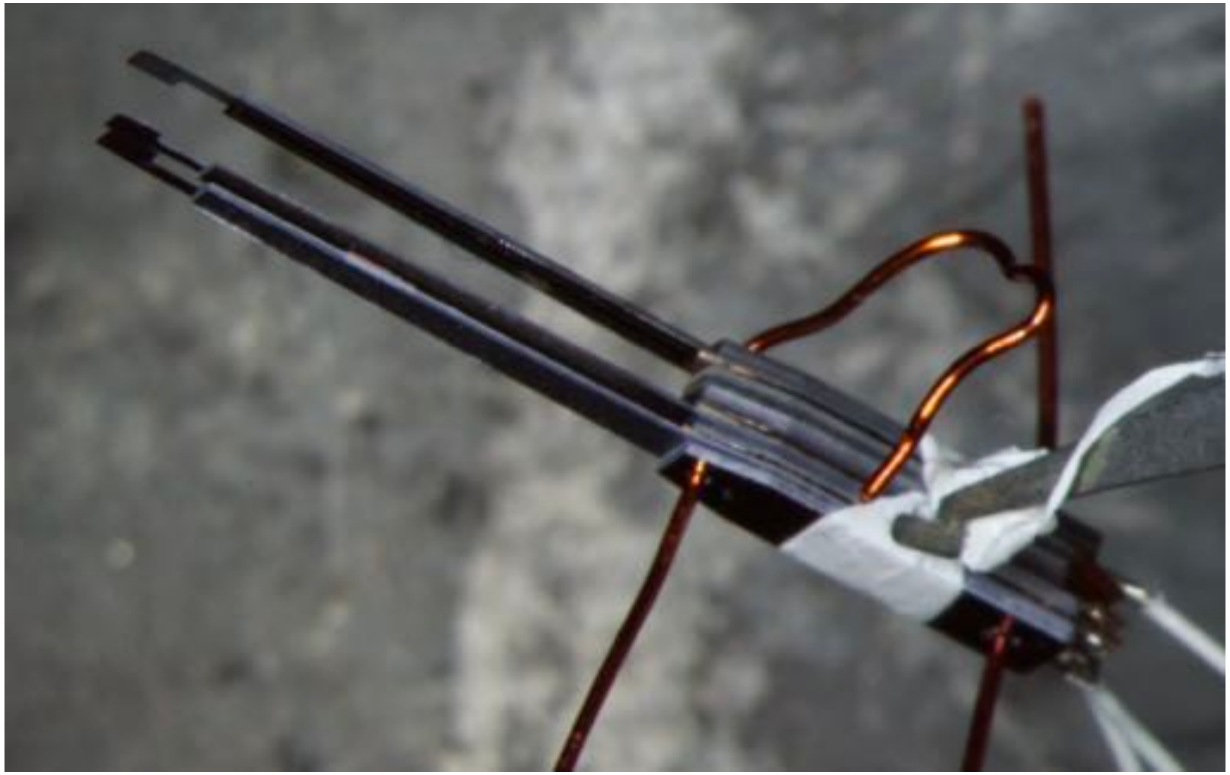




$$\mathcal{L}(r,z,P) \propto \frac{P^{3/2}}{(z-z_0)^2} \exp\left\{-\left[\frac{r}{\beta_L (z-z_0)}\right]^2\right\}$$

Švančara, Phys. Fluids (2023)

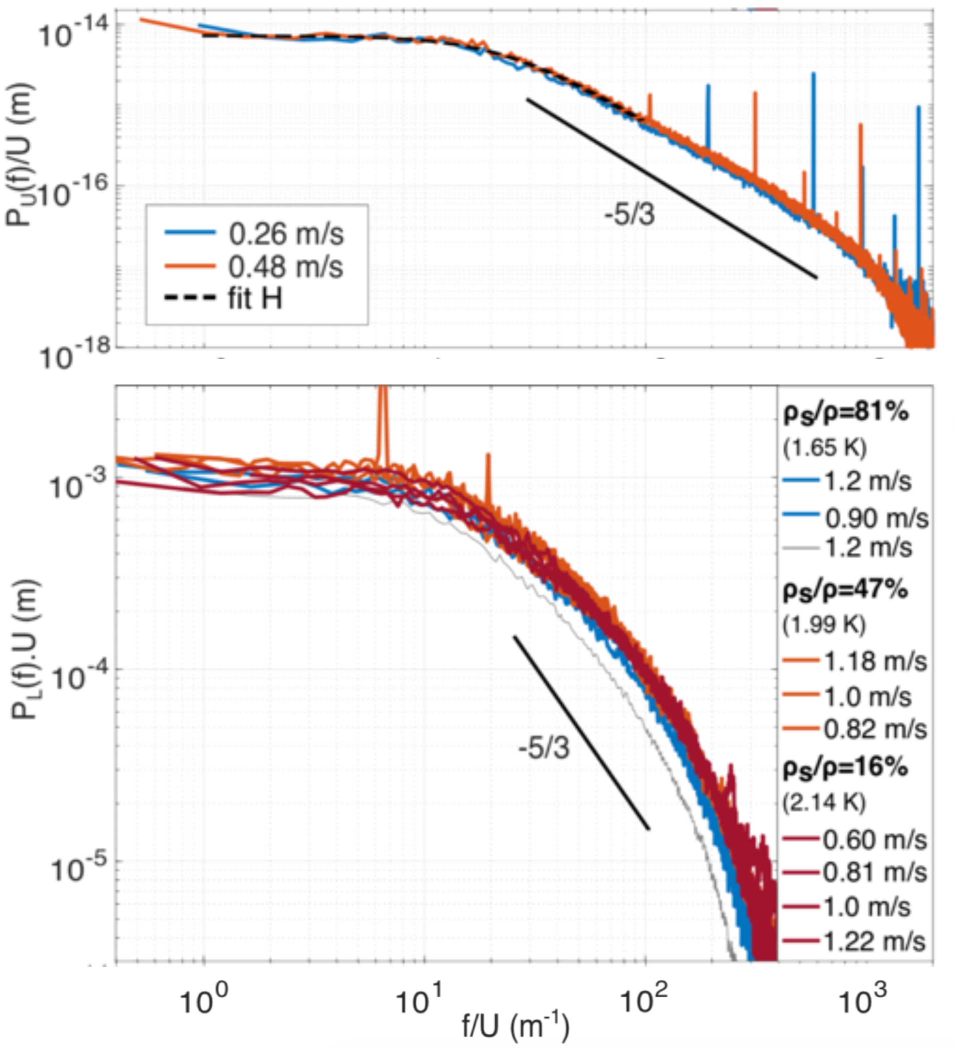
PERSPECTIVE
Joint local measurements



Joint local measurements : velocity and vortex line, gradient, …

GRID TURBULENCE EXPERIMENT

We observe an original shape of the vortex density spectrum



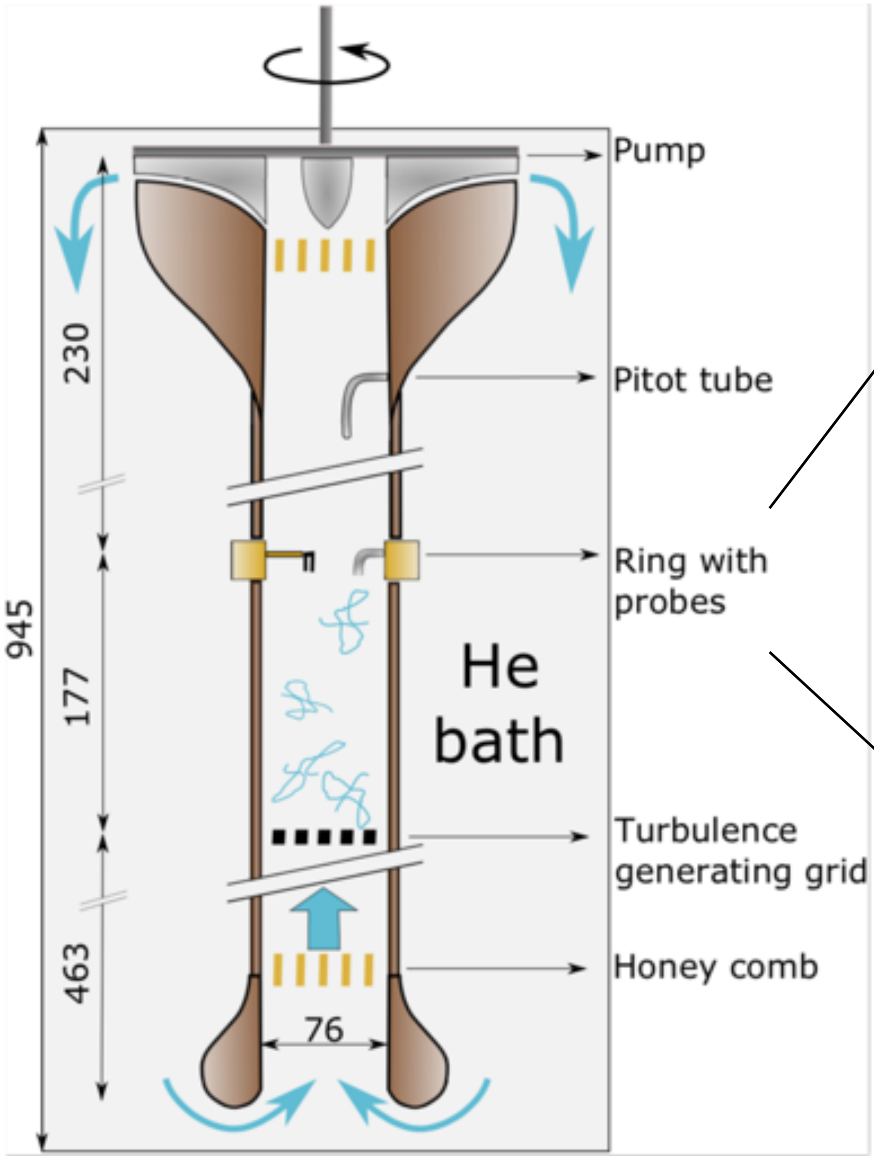
Spectrum of velocity

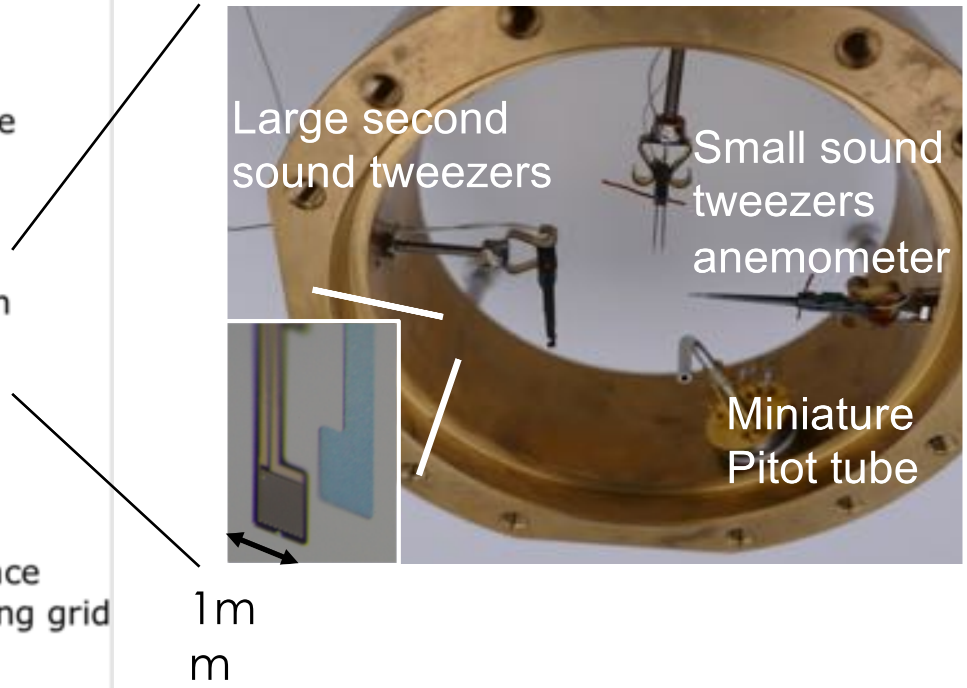
spectrum of the superfluid enstrophy.

Woillez EPL (2021)

Experimental results

Probing the quantum enstrophy in grid turbulence





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