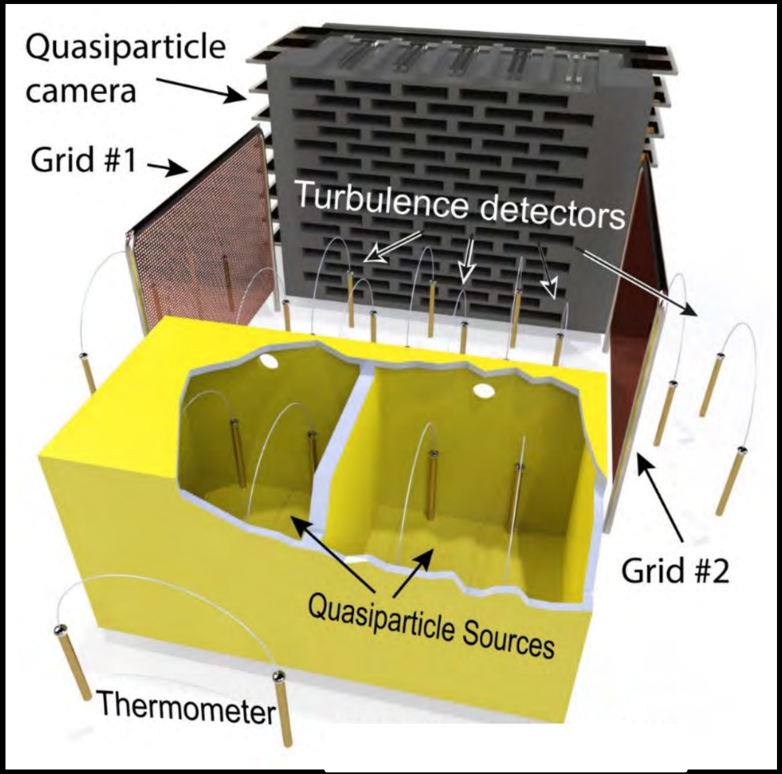
Viktor Tsepelin

Lancaster University

Probing quantum fluids using mechanical oscillators

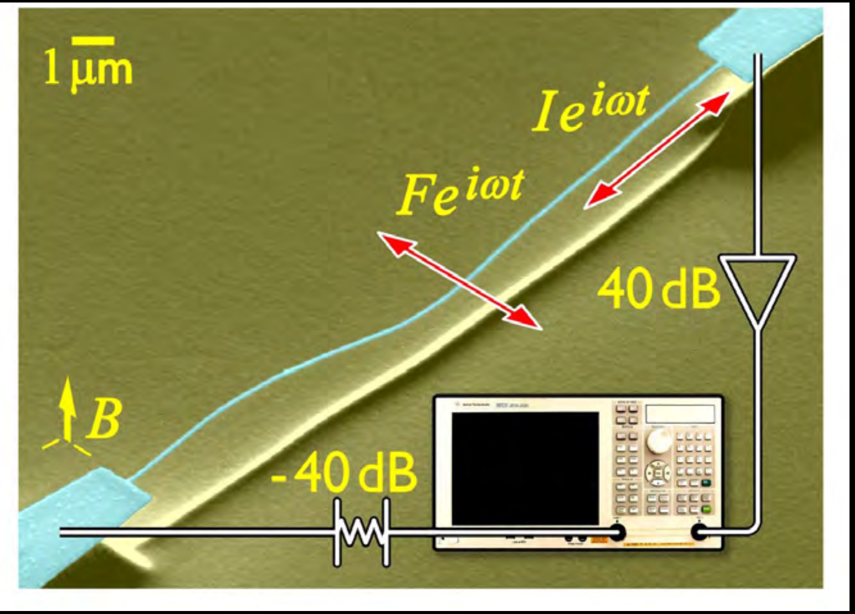
Cargese, 05 July 2023

Visualizing Quantum Turbulence in Superfluid ^{3}He-B using Quasiparticles



Quantum Tangles

Real-Time Interaction of NEMS with Quantum Vortices in Superfluid-4



Individual vortex, Kelvin waves

Lancaster Low Temperature Group

Physics | Lancaster University

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Oleg Kolosov
Yuri Sergeev
Makoto Tsubota

EMP European Microkelvin Platform
EPSRC Engineering and Physical Sciences Research Council

emplatform.eu

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European Microkelvin Platform

The European Microkelvin Platform (EMP) is a consortium of 17 partners which have an extensive portfolio of capacities and expertise in ultralow temperature physics. The EMP has been established in 2014 und provides access to the milli- and microkelvin temperature regime. Since the lowest accessible temperatures are continuously falling, we also lay considerable weight on improving and upgrading our infrastructure. These advances allow us, and our users from across Europe, to study new phenomena, thereby generating new knowledge, applications and commercial opportunities. We have a particular interest in the benefits of ultralow temperature physics for driving forward the inter-related areas of quantum materials, nanoscience, and quantum technology. The activities of the EMP hold enormous potential for innovation.

If we raised your interest, you can find detailed information on the available facilities, how to submit your application and how to contact us. In case of questions, do not hesitate to contact our Project Manager (Project-Manager@emplatform.eu).

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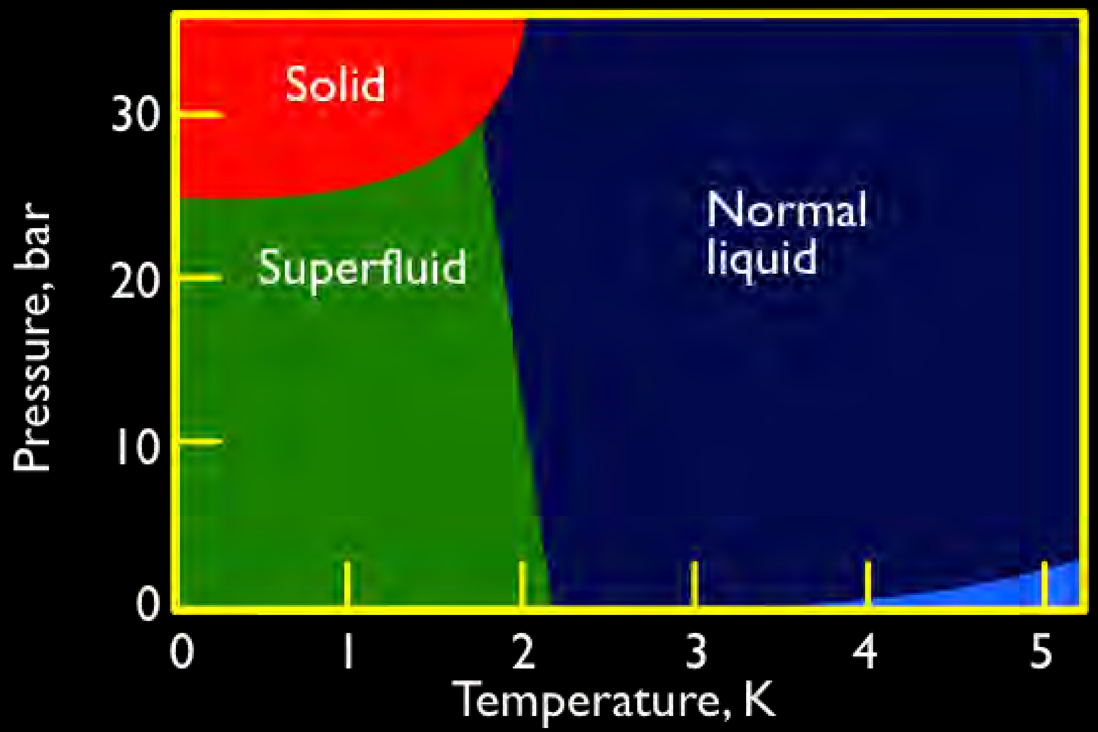
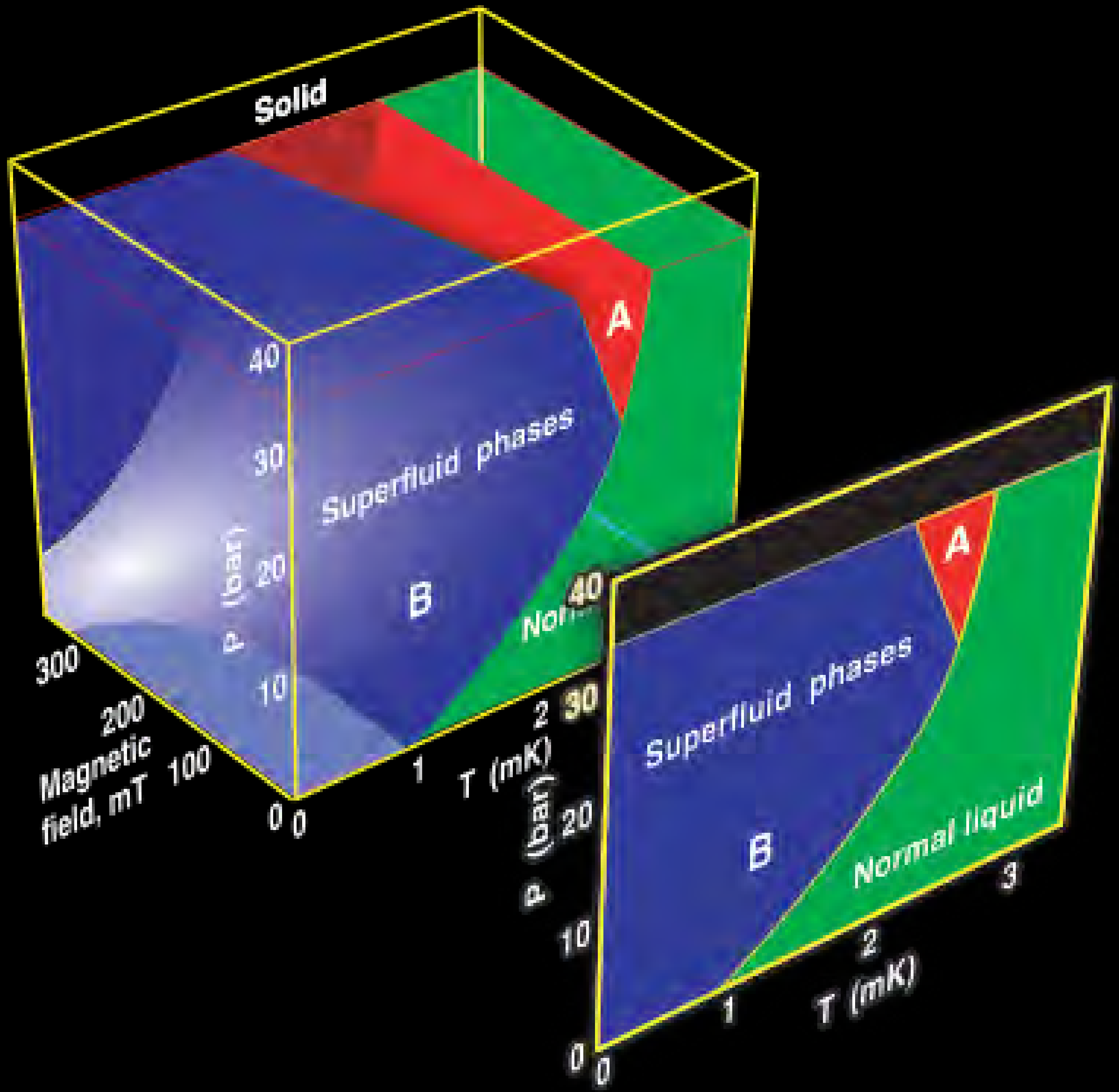
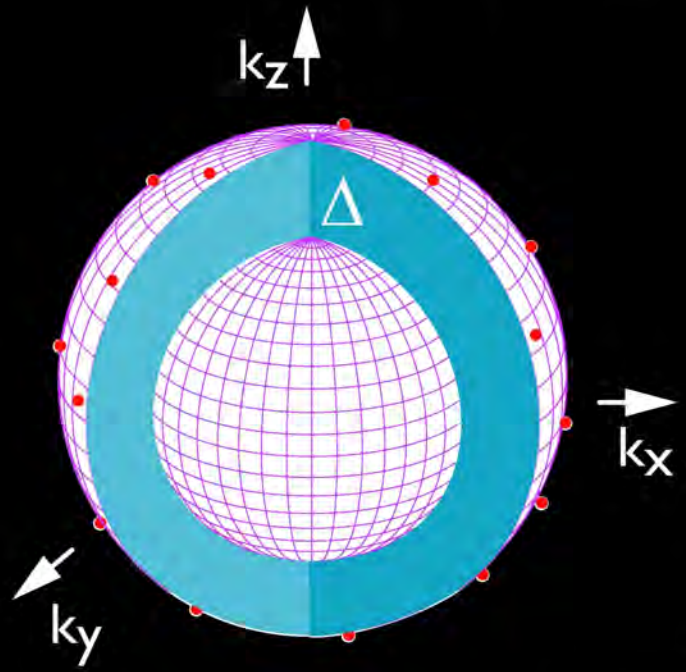
HELIUM-4



HELIUM-3



The B-phase of Superfluid ^3He



Superfluid below 1 milliKelvin

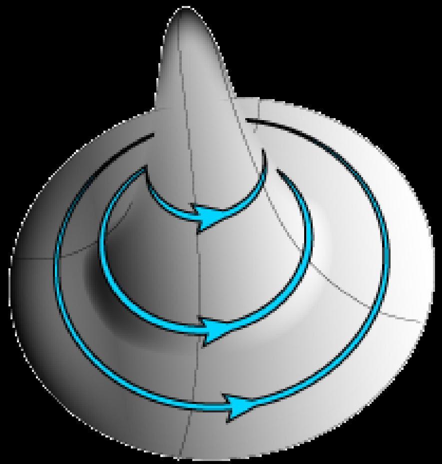
"Neutral superconductor"

One ^4He impurity in 10^{2000} atoms

Density of quasiparticle excitations (normal component) falls rapidly $n_{ex} \sim \exp(-\Delta/kT)$

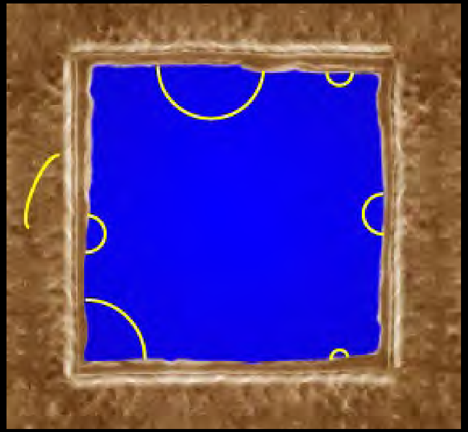
Mean free path - virtually infinite (ballistic excitations)

Quantum Vortices in ^{3}He-B

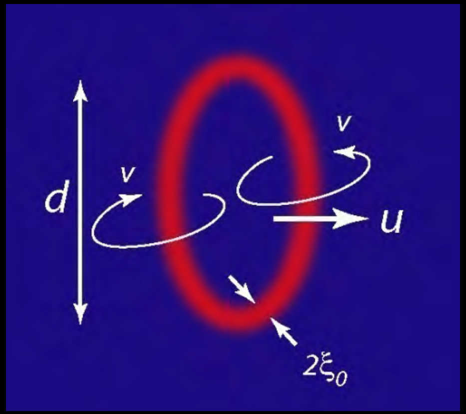


Formed by a 2π phase change in the wavefunction around the core

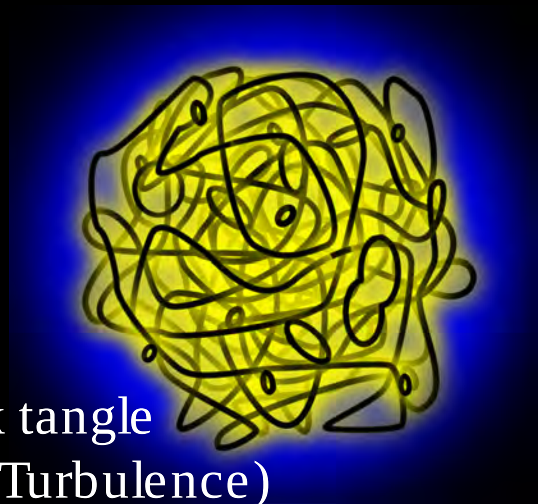
vortices singly quantised with circulation : $\kappa_3 = h/2m_3$
superfluid flows around core with velocity, $v_S = \kappa/2\pi r$



Vortices can end on cell walls



self propagating rings
$u \cong \kappa/2\pi d$
(d~5μm $\Rightarrow$ u~10mm s^{-1})

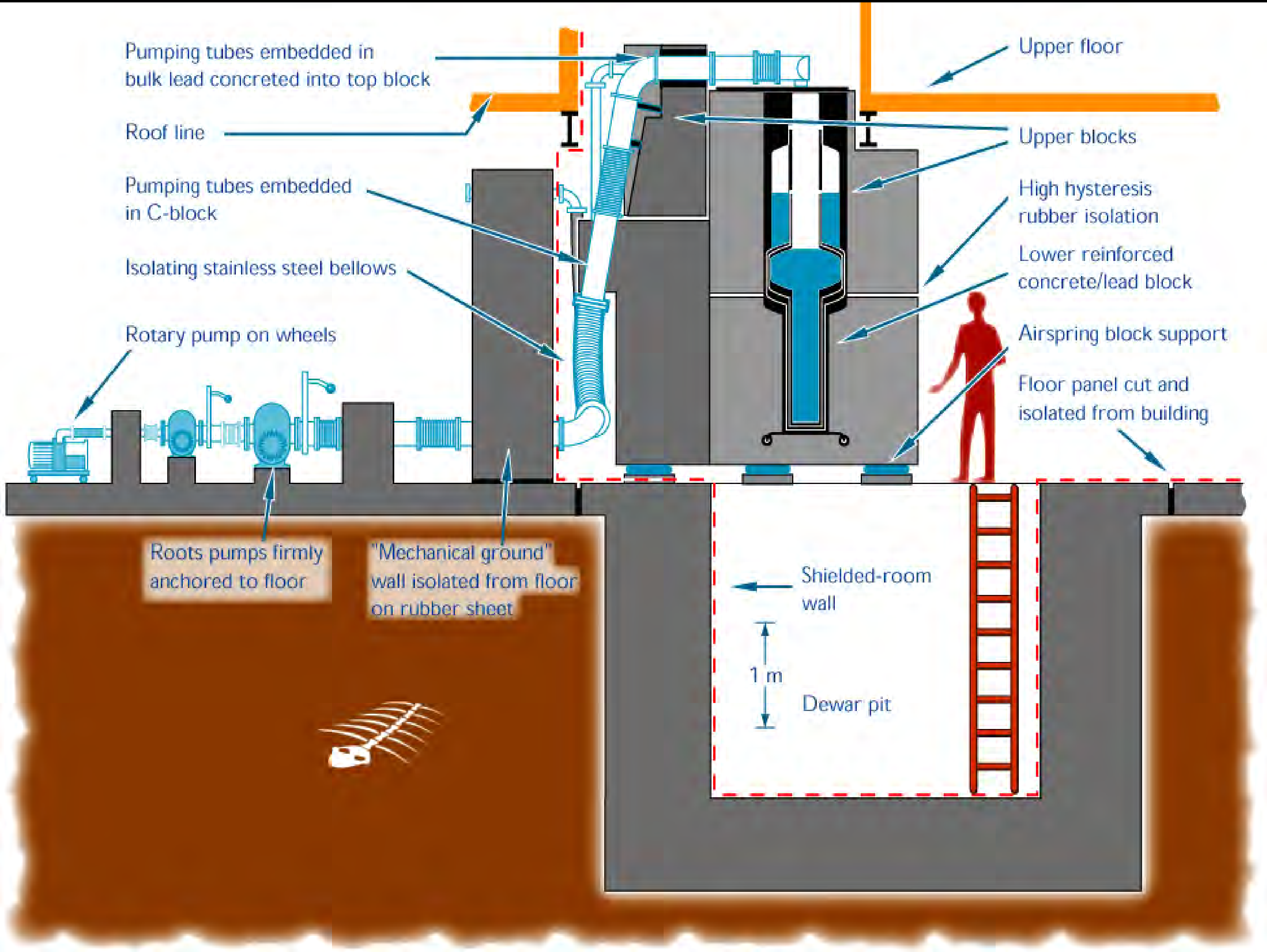


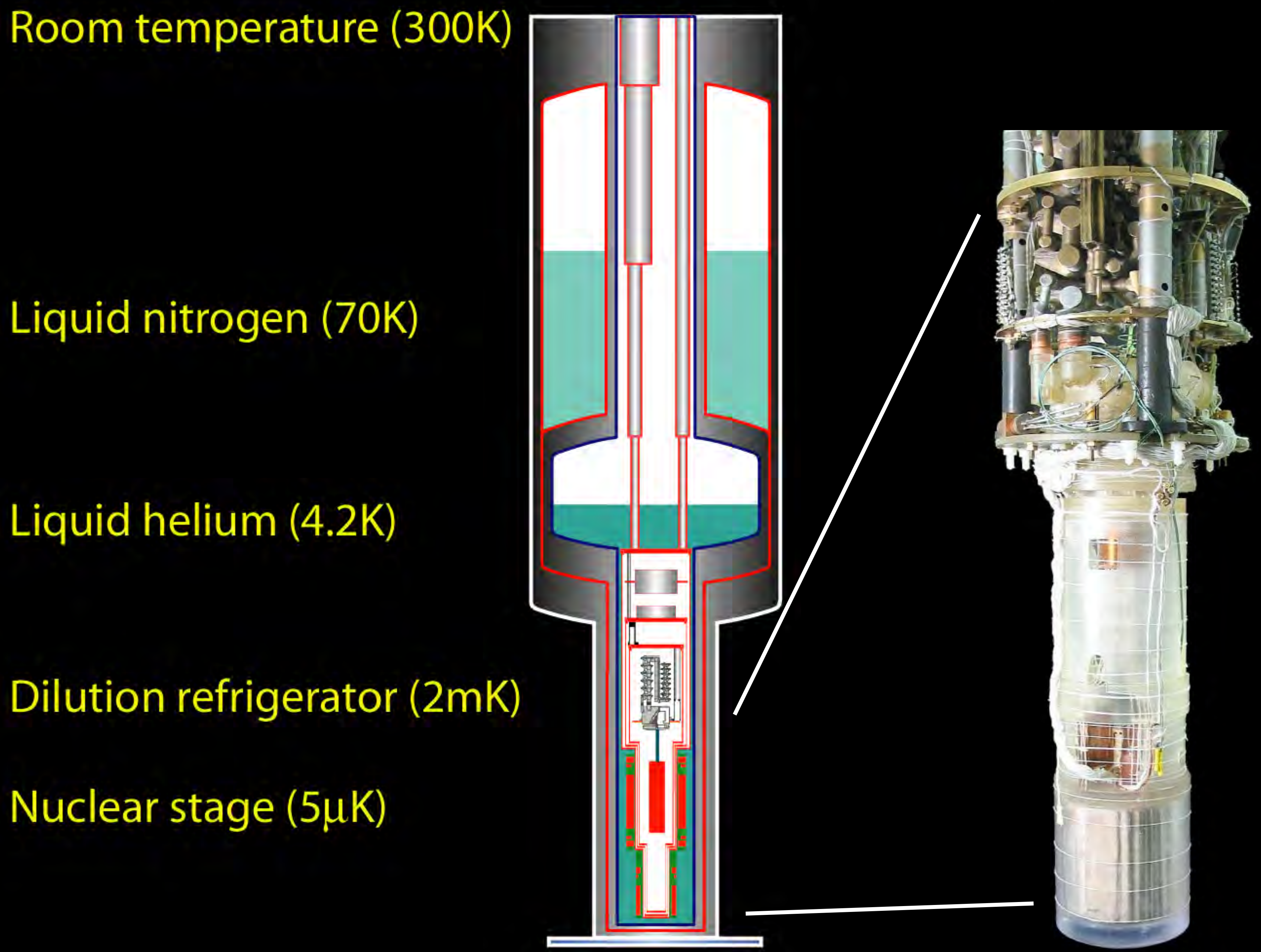
vortex tangle
(Quantum Turbulence)

^{3}He-B → T>0.3 T_c Normal component is at rest: NMR, vibrating objects

→ low T Ballistic regime vibrating objects, BBR, NMR

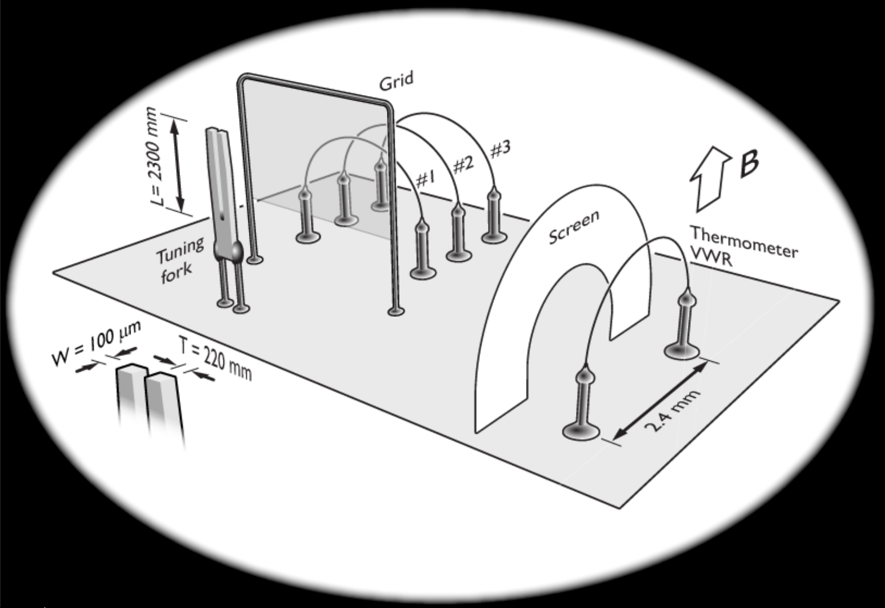
TECHNIQUES AND TECHNOLOGY

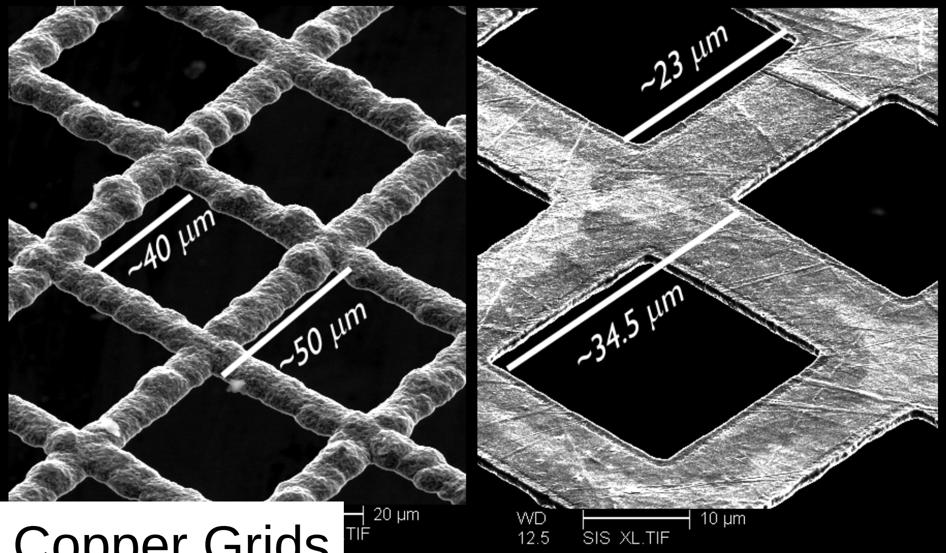



Room temperature (300K)
Liquid nitrogen (70K)
Liquid helium (4.2K)
Dilution refrigerator (2mK)
Nuclear stage (5μK)

Experimental Cell- Nuclear Stage

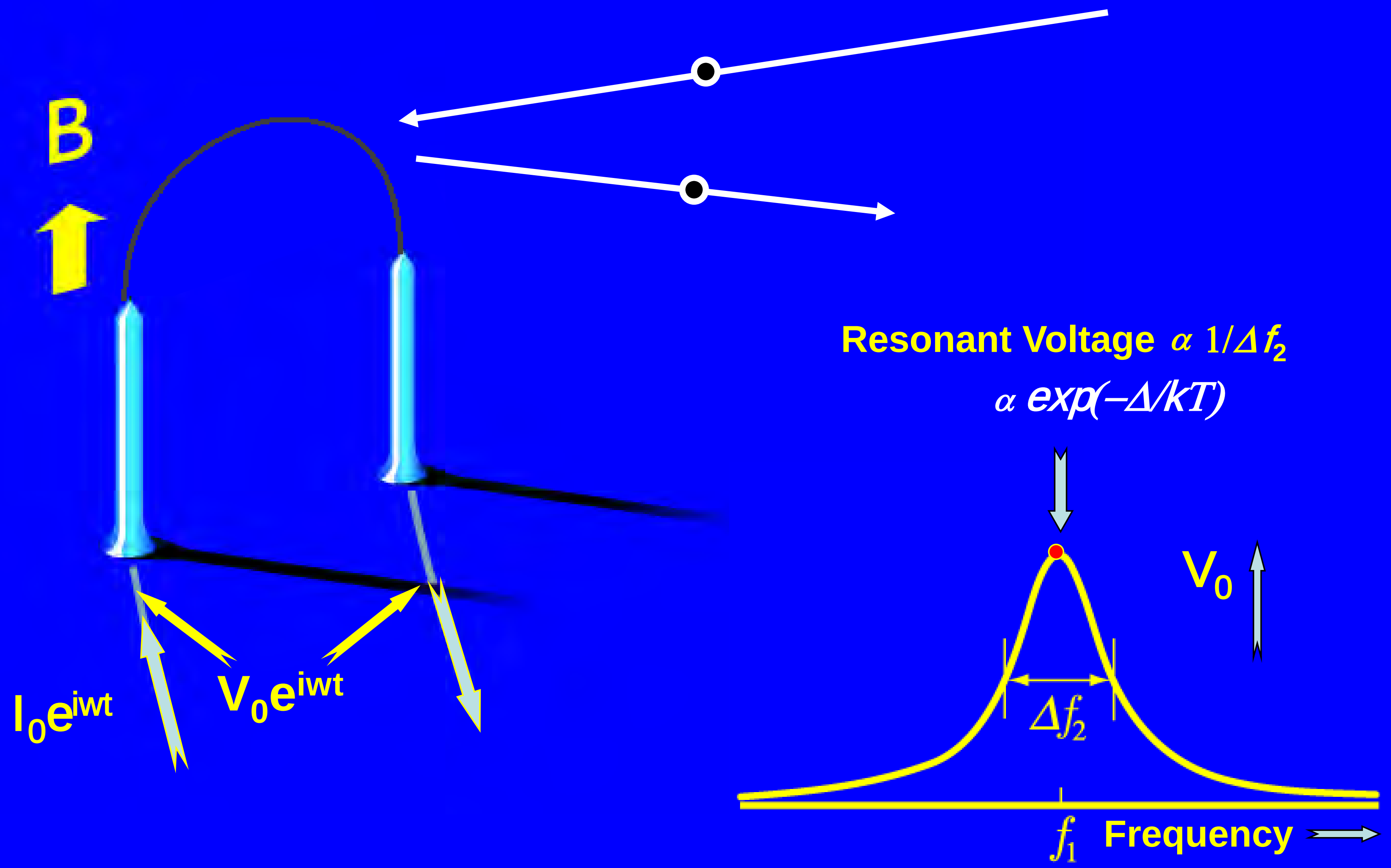
Temperature 100μK



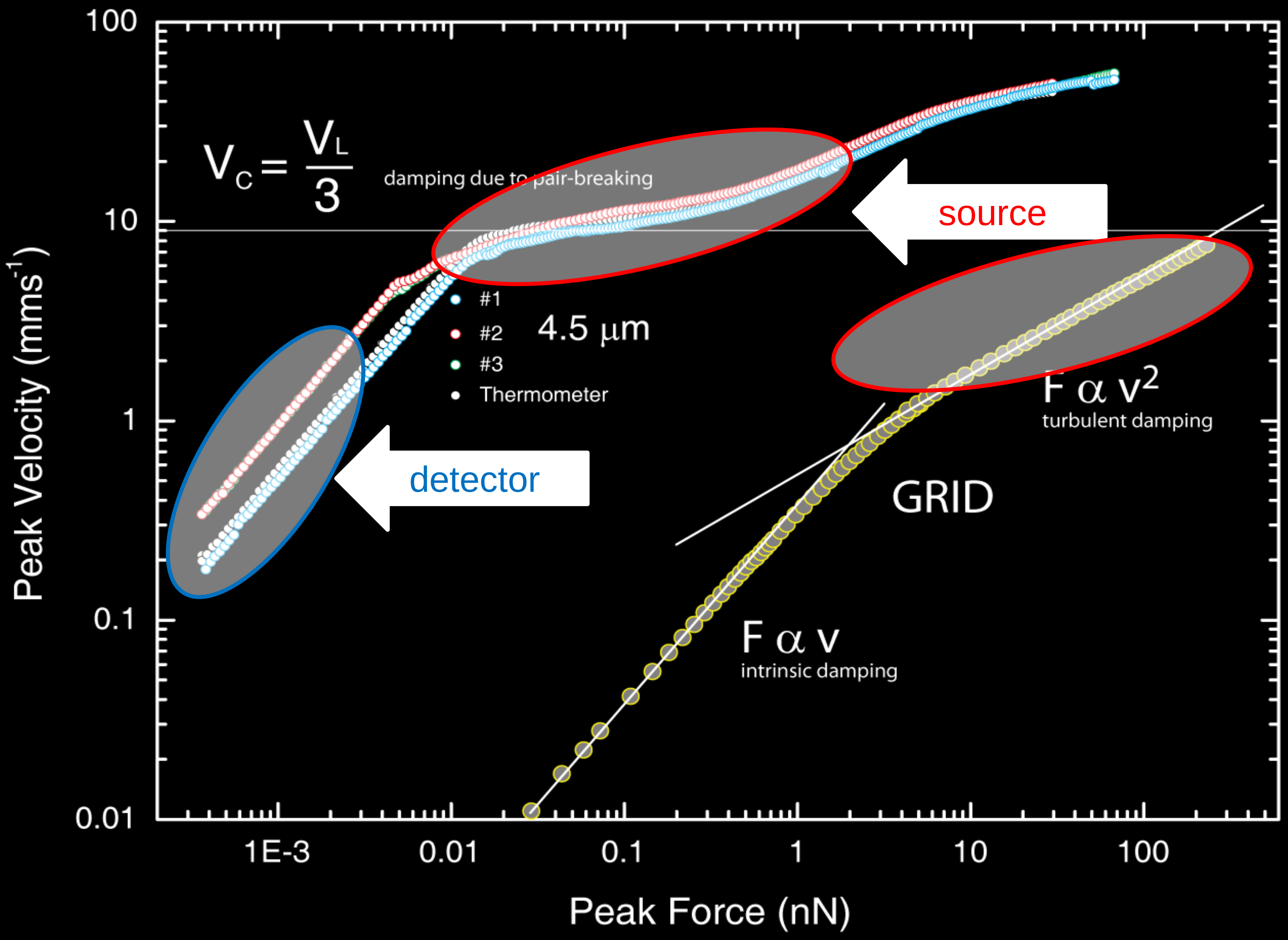


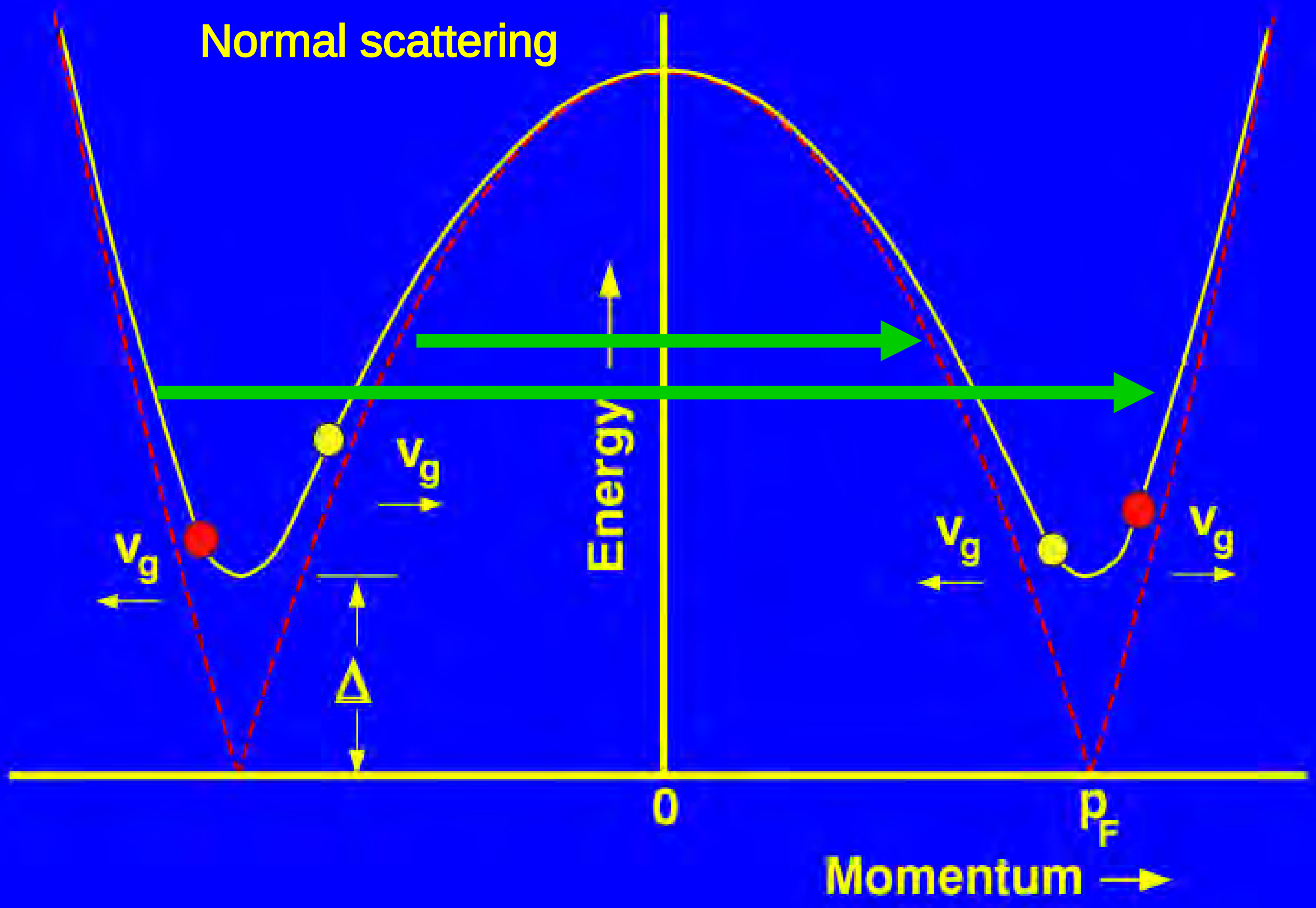
Copper Grids

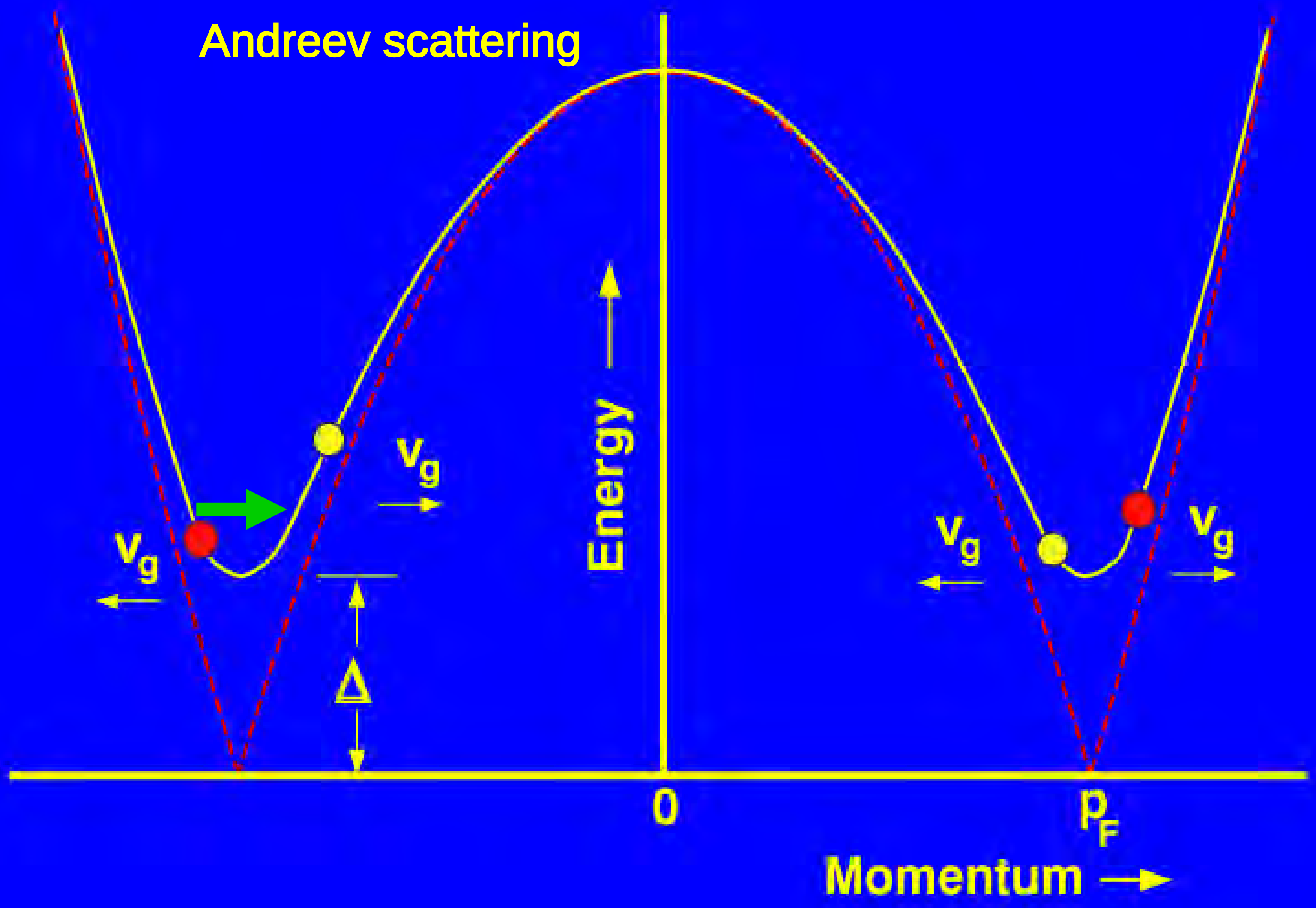
Vibrating wire resonator(Ballistic regime)



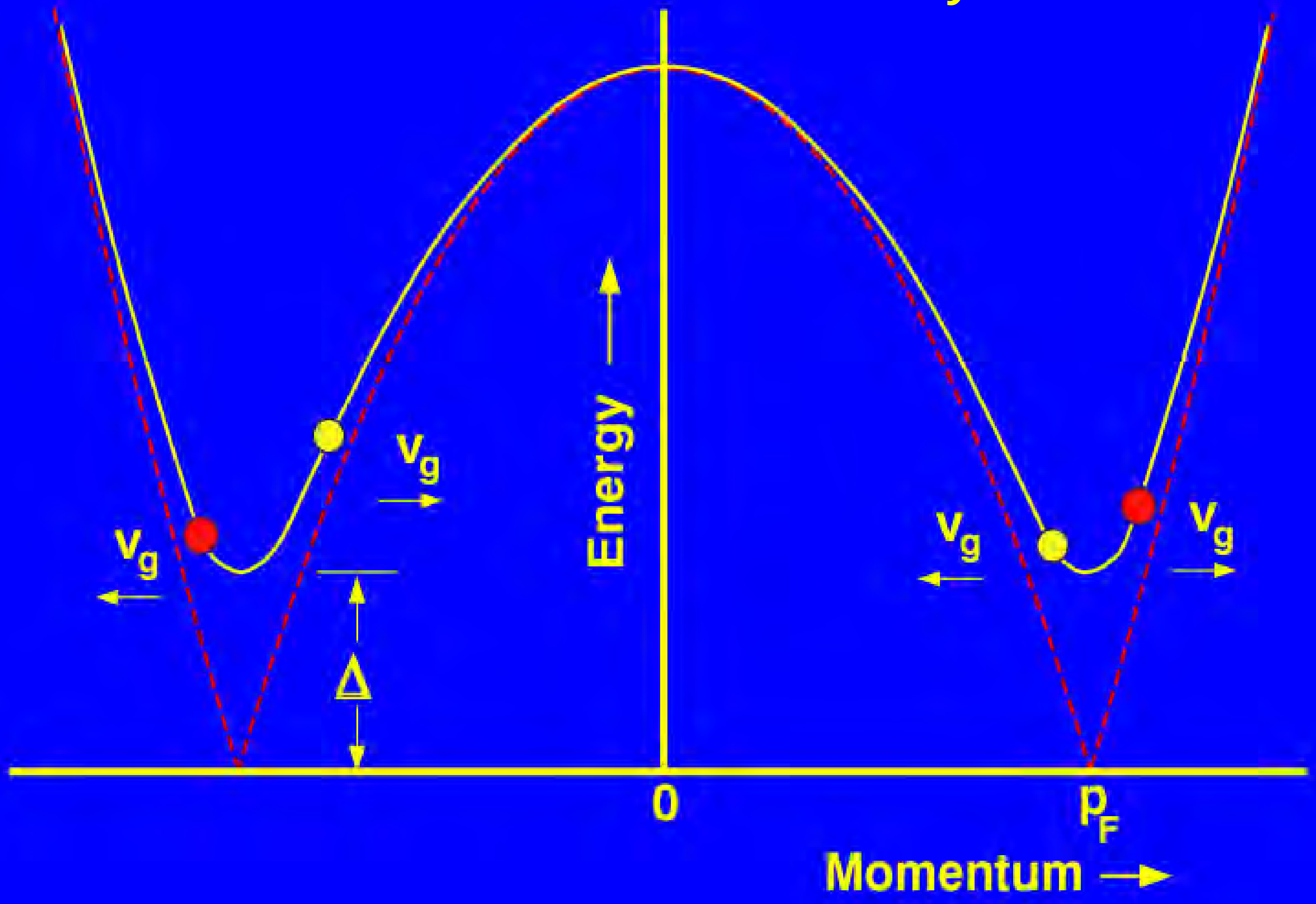
Resonators responses in ballistic regime of ^3He-B



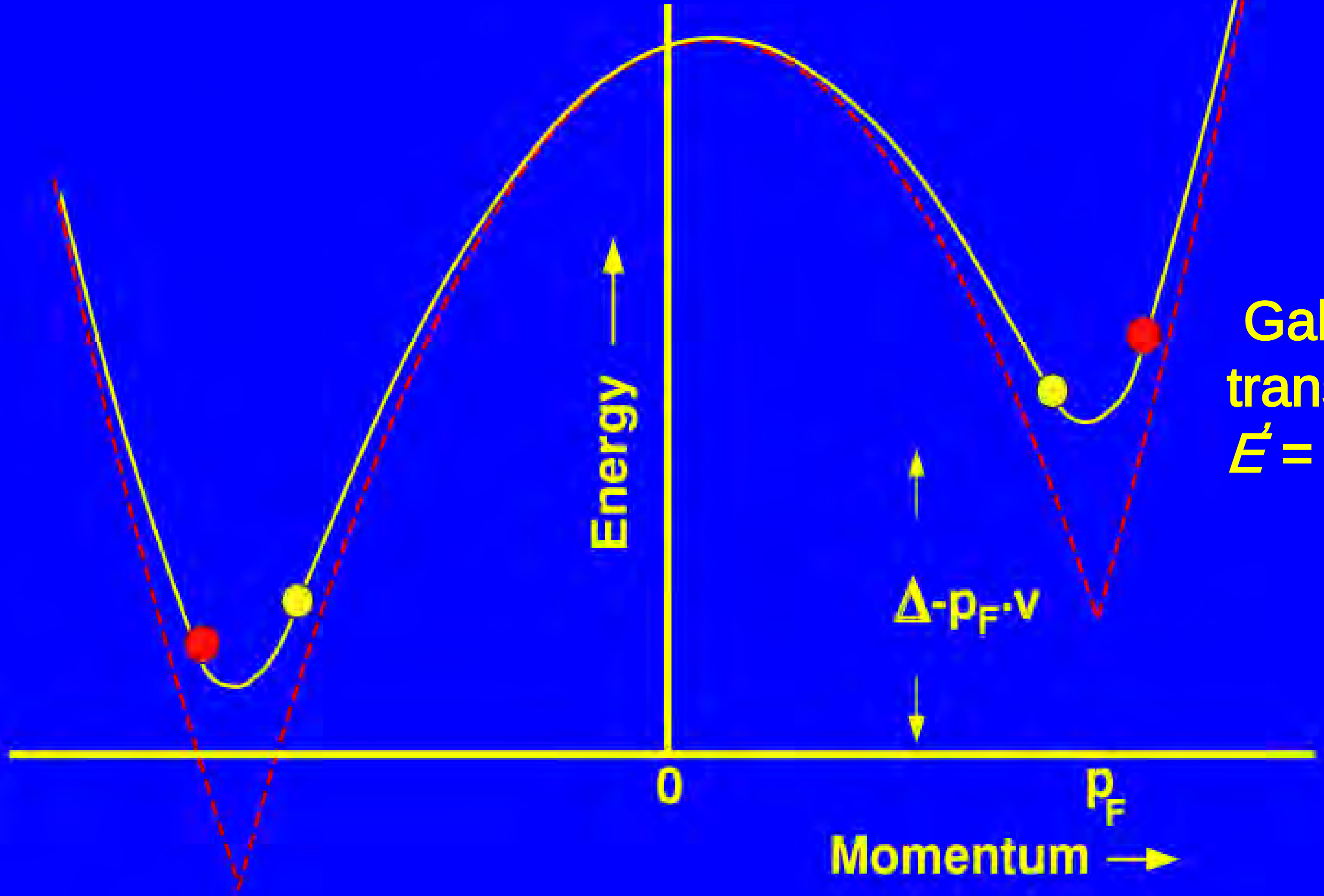

Normal scattering
Energy
v
g
v
g
v
g
v
g
Δ
0
p
F
Momentum


Andreev scattering
Energy
v_g
v_g
v_g
v_g
Δ
0
p_F
Momentum

Observer stationary

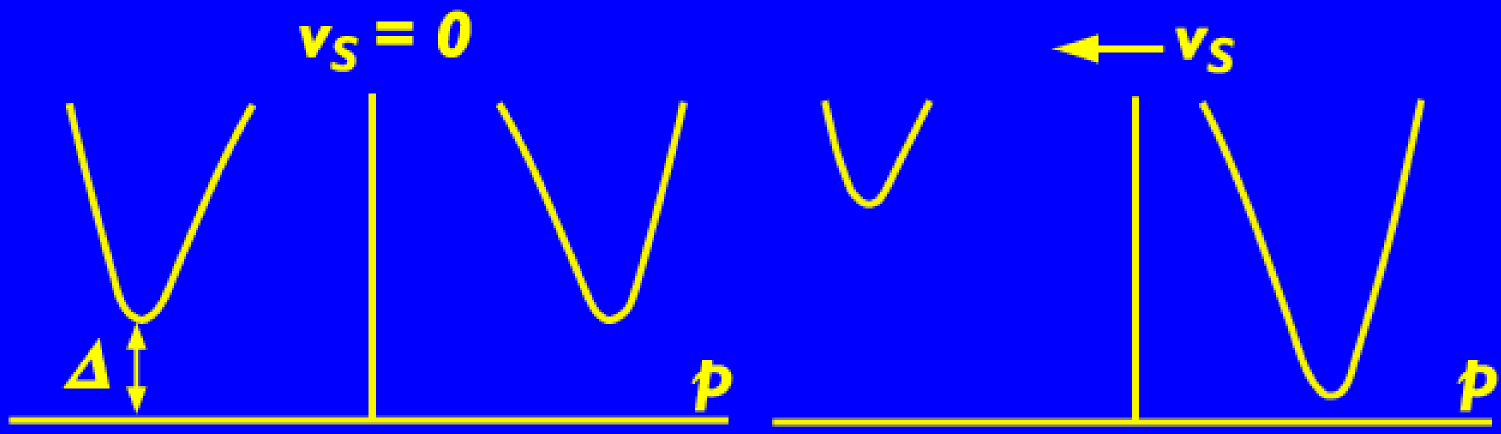


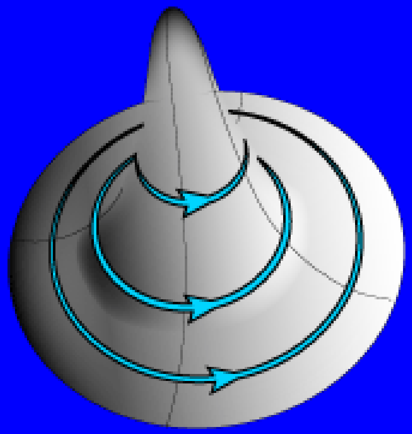
Or of liquid



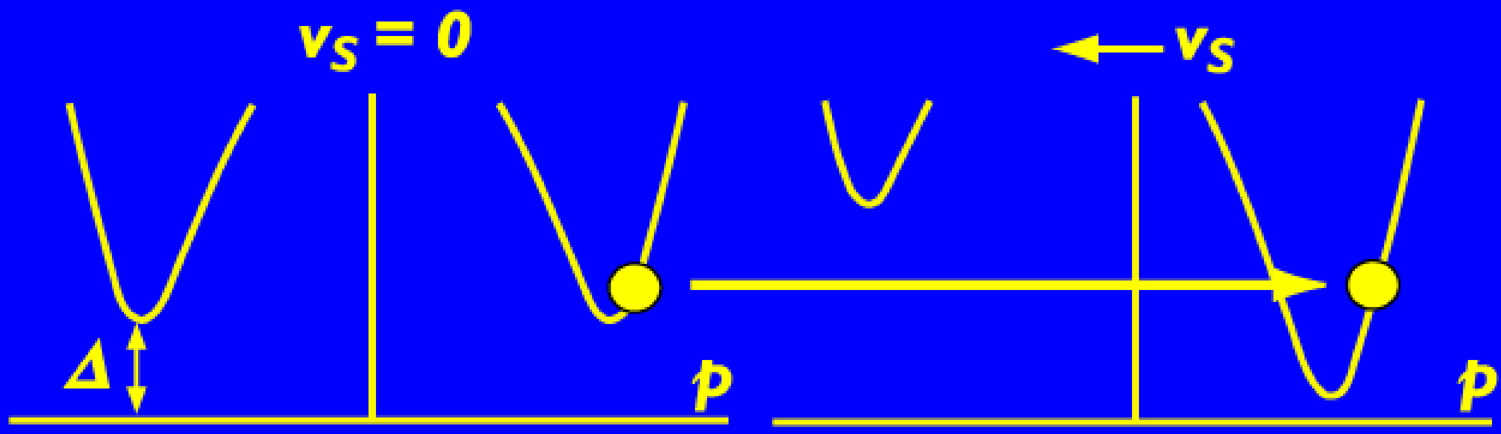
Galilean transform
$E' = E - p \cdot v$

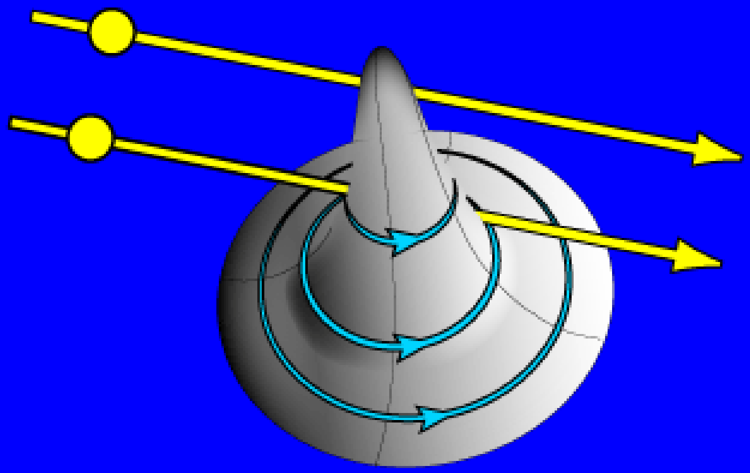
Andreev's Reflection

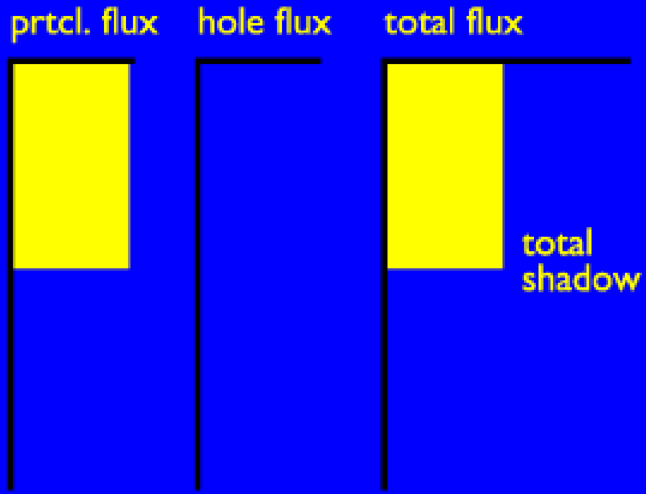




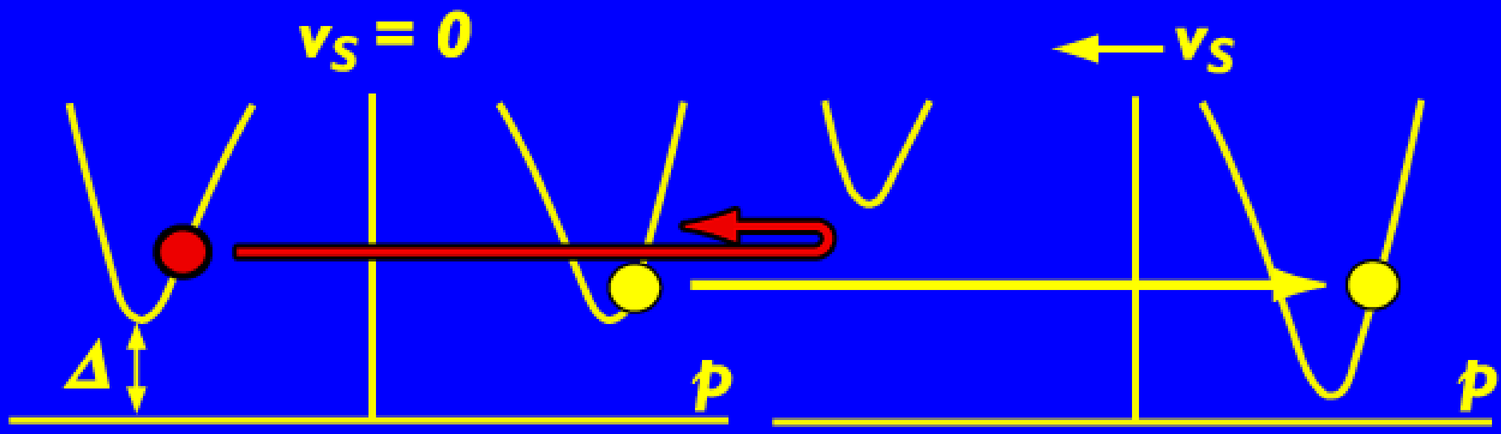
Andreev's Reflection

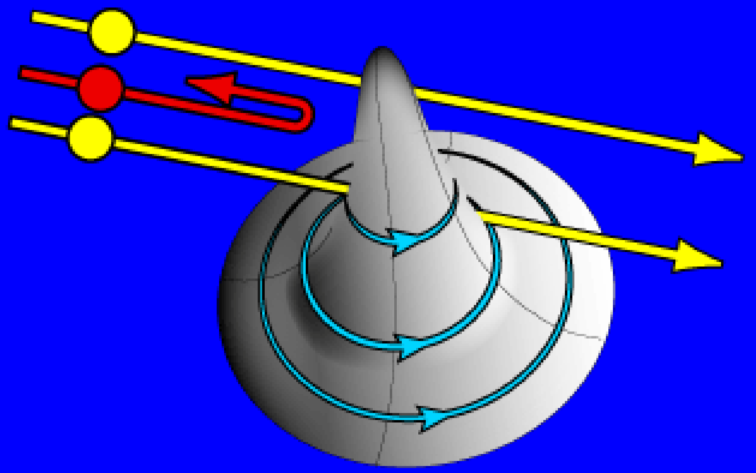


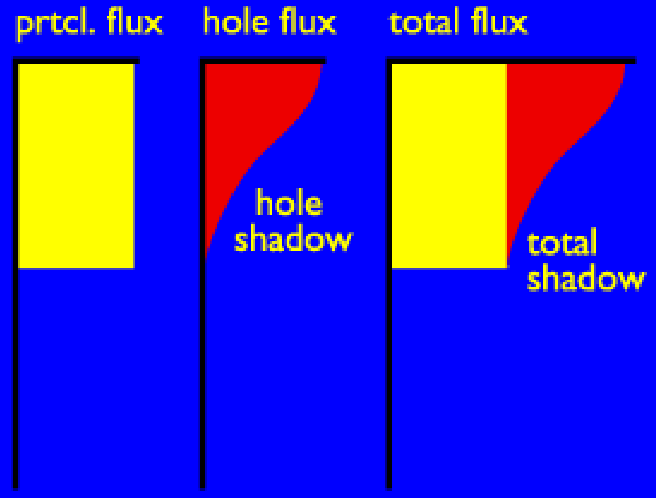




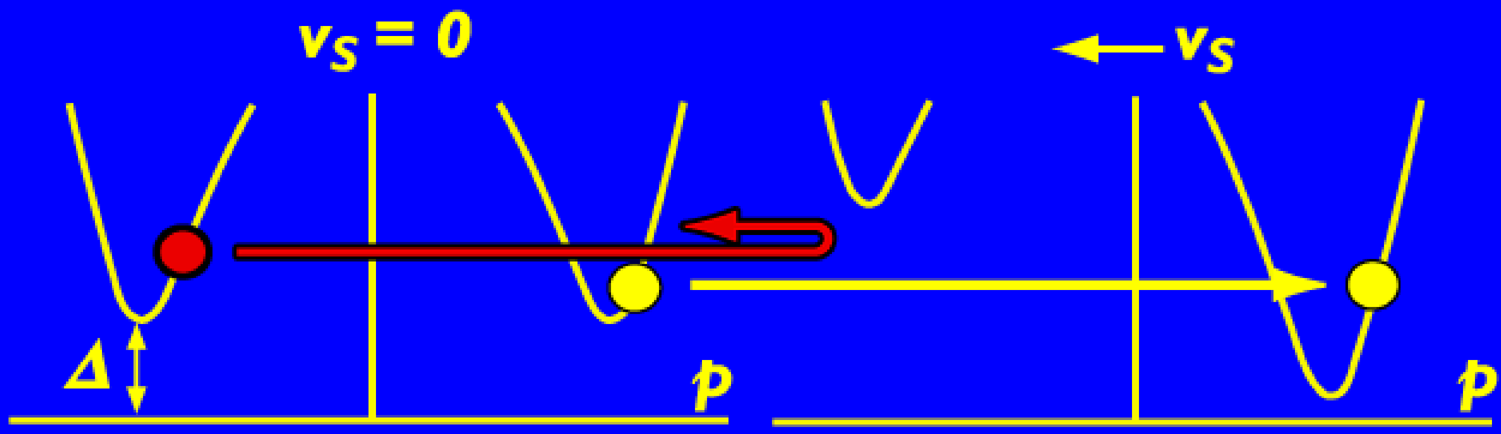
Andreev's Reflection

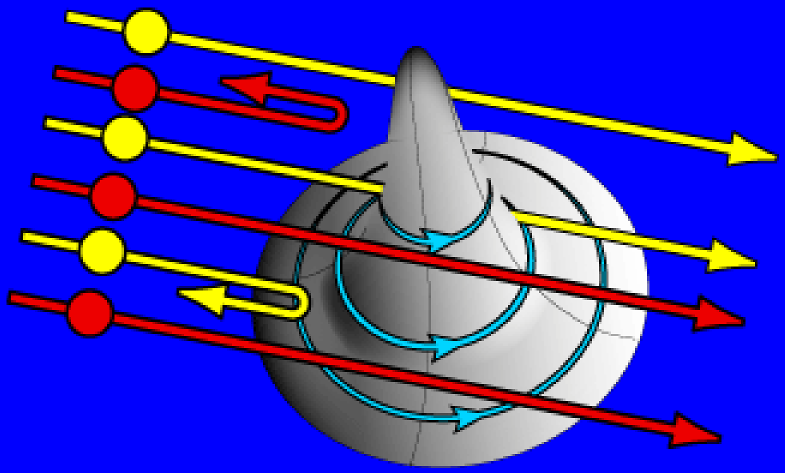


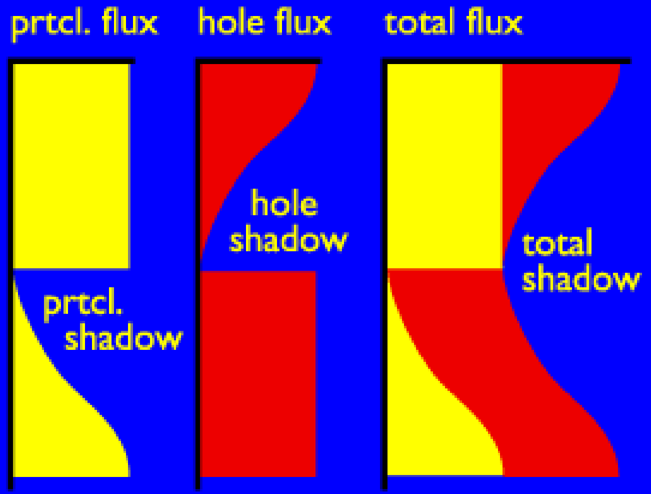




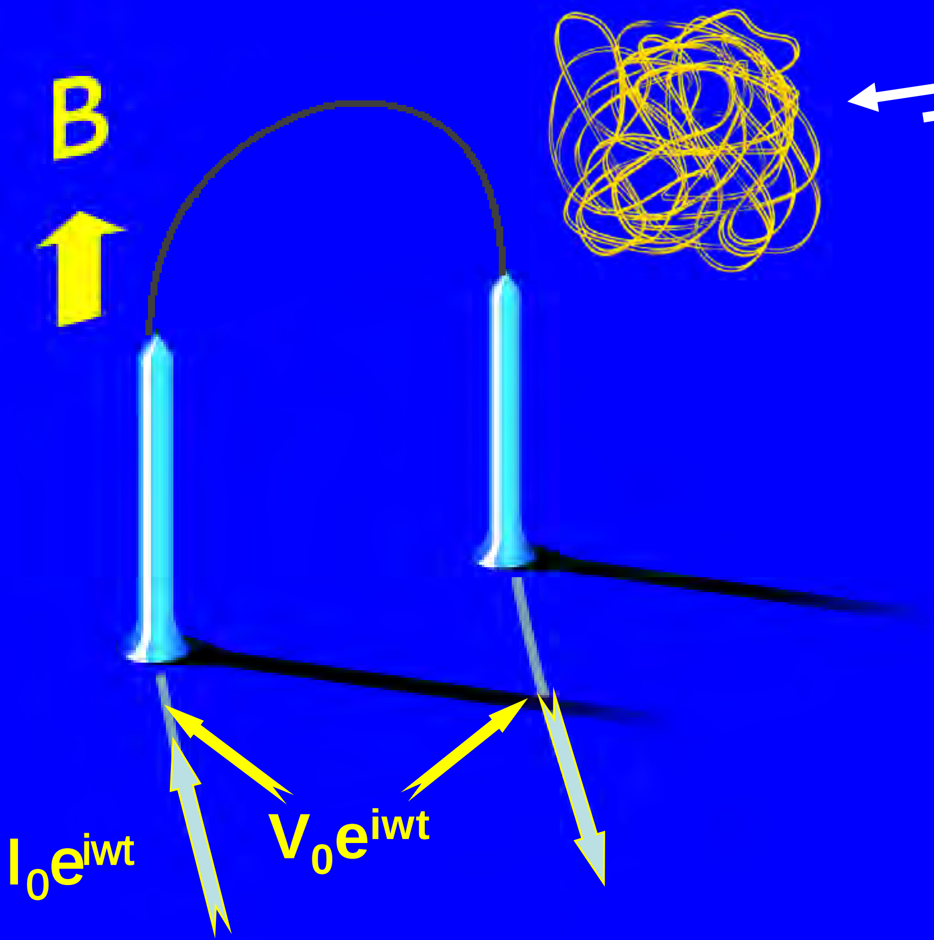
Andreev's Reflection

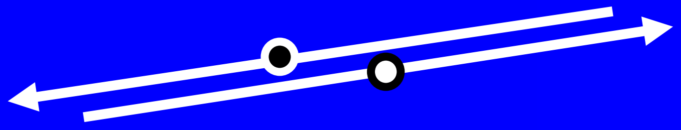






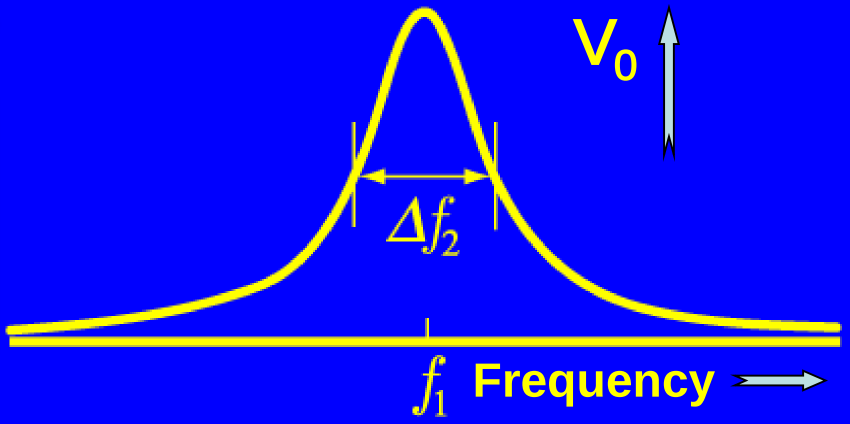
Turbulence Detection



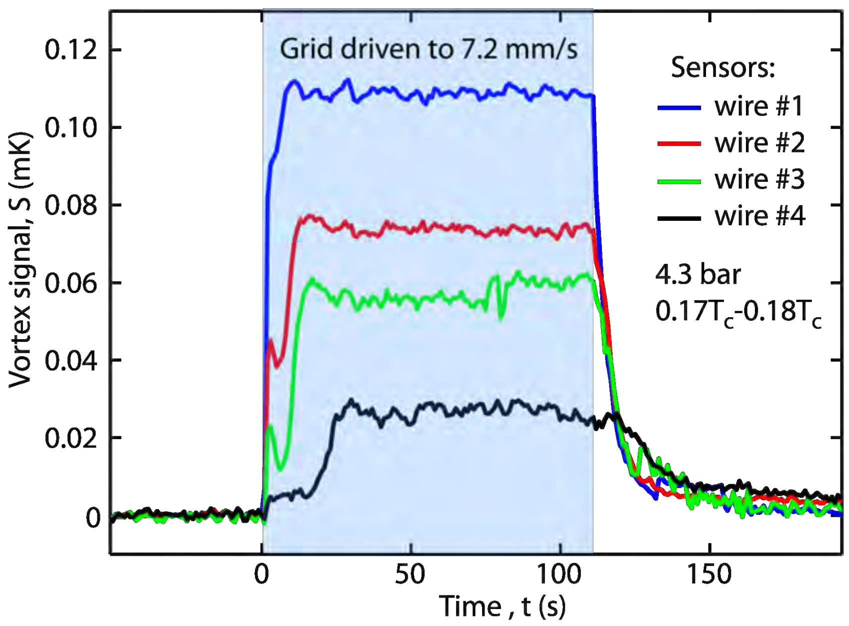


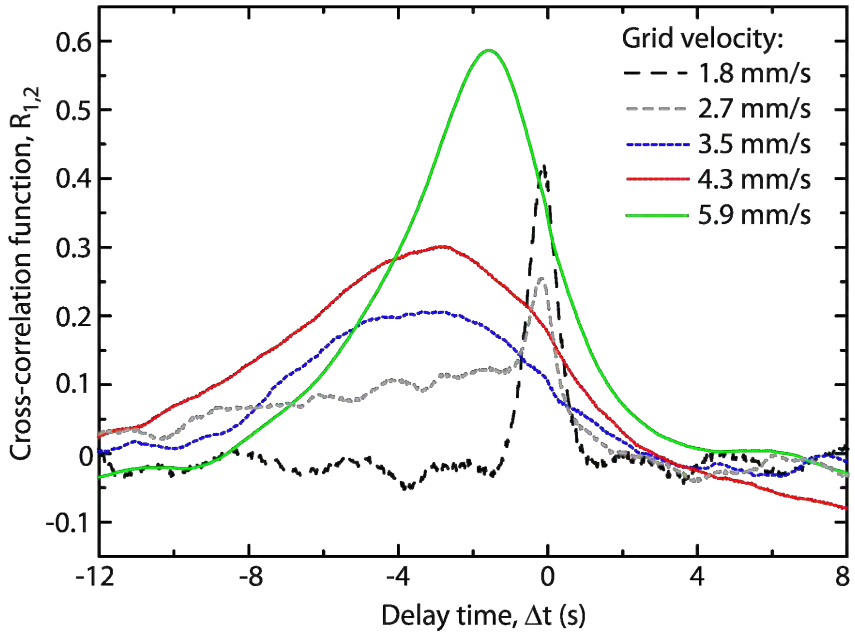
fraction f of quasiparticles are
Andreev-reflected
giving rise to a reduced damping

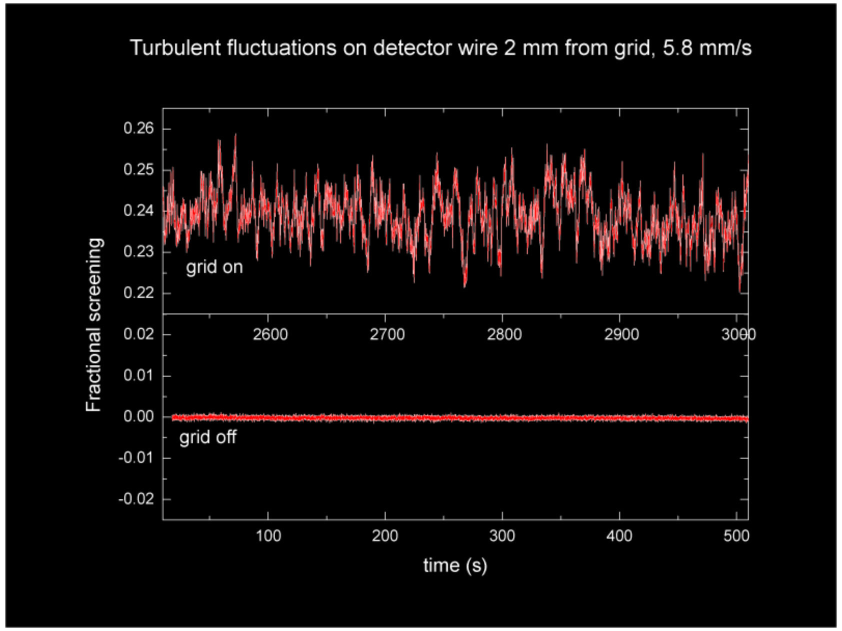
$$\Delta f_2(turb, T) = (1 - f)\,\Delta f_2(nonturb, T)$$

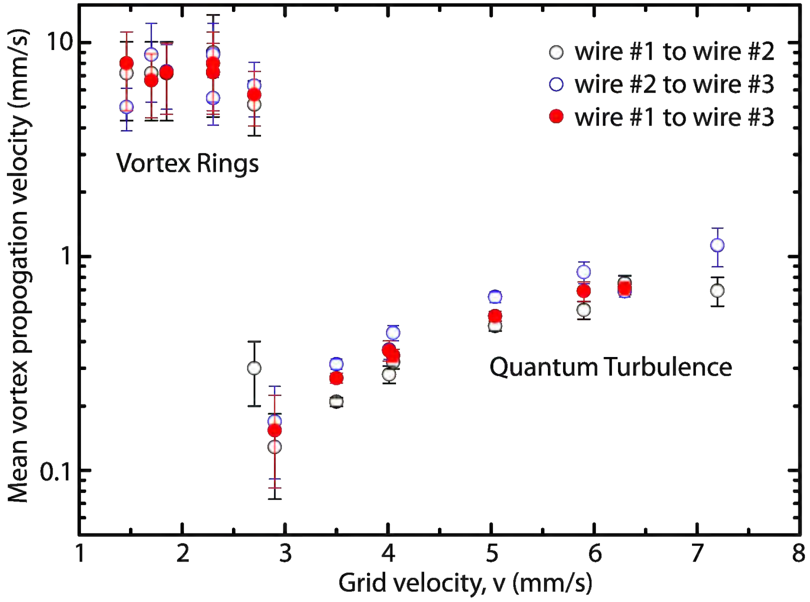


Experimental Turbulence detection



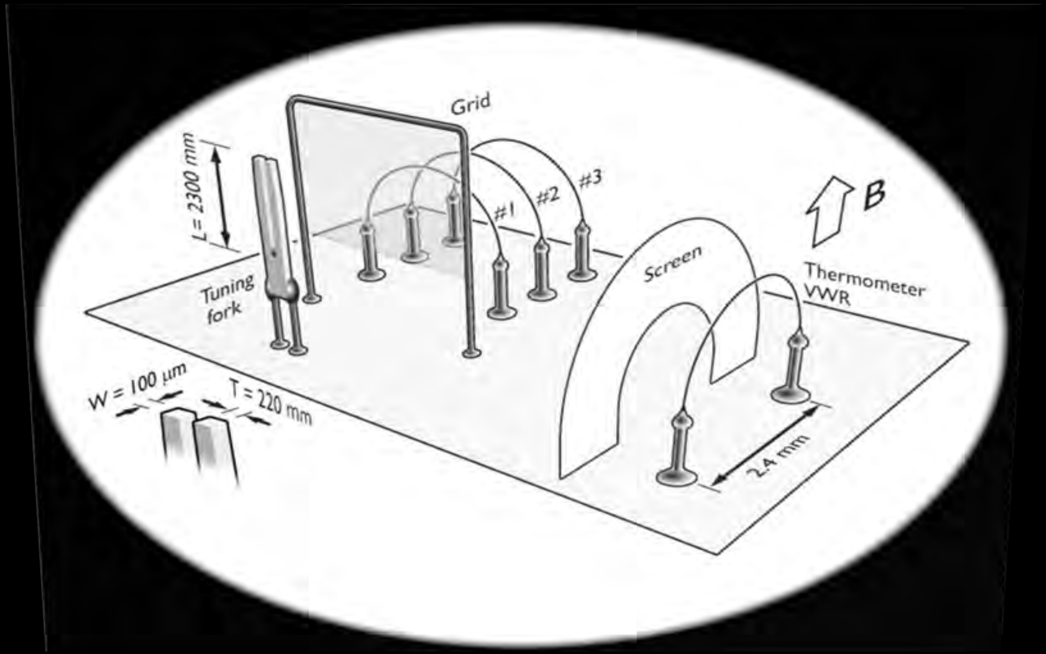




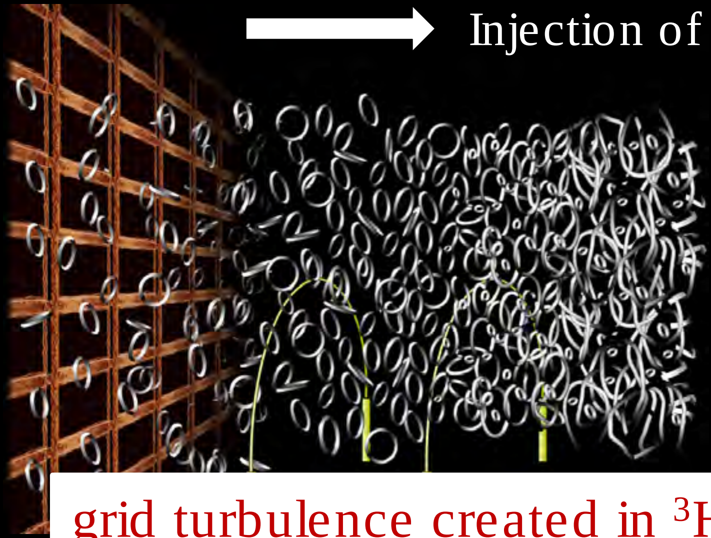


S. N. Fisher et al, PNAS *111 (Supplement 1) 4659-4666* (2014)

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

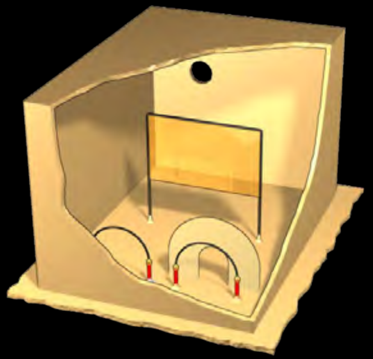


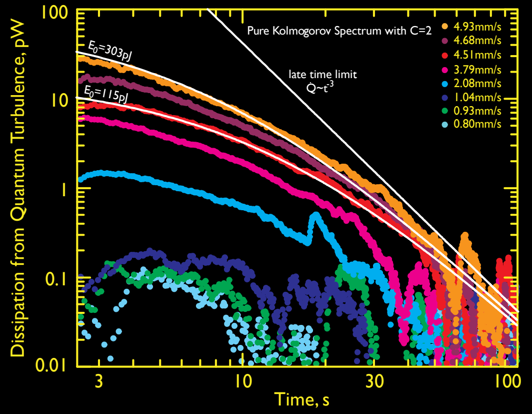
Injection of rings



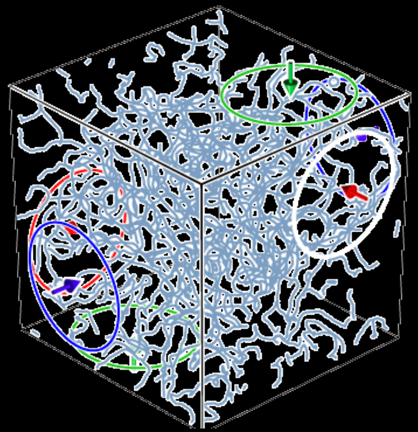
grid turbulence created in ^{3}He at high velocities is polarised

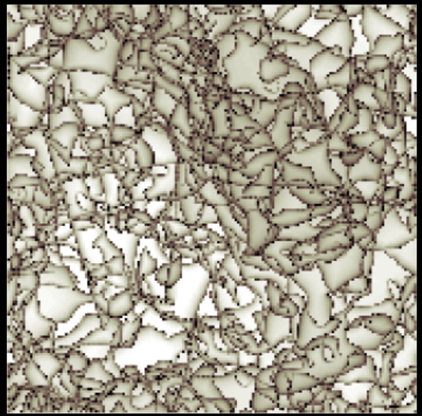
PRL 96 (2006) 035301





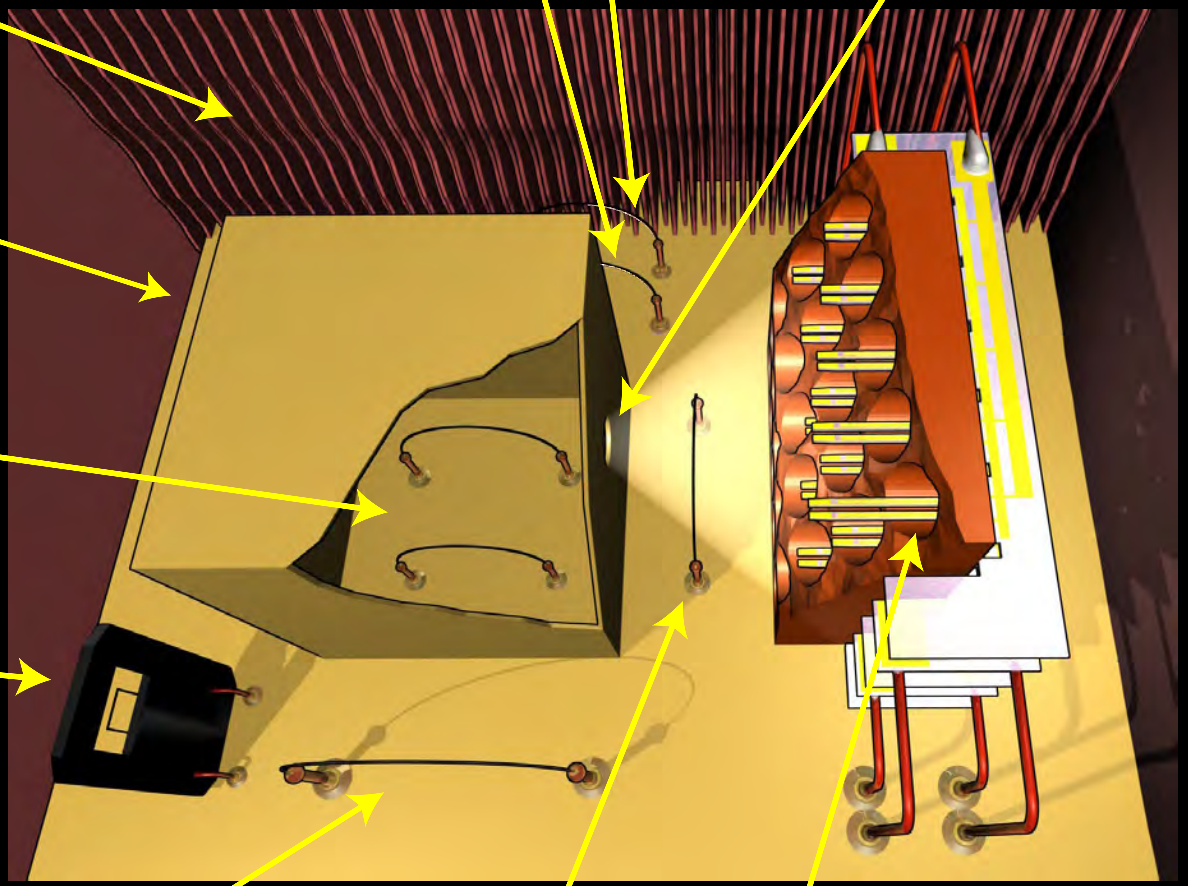
QT has Kolmogorov like energy spectrum,
Nature Physics 7 (2011) 473



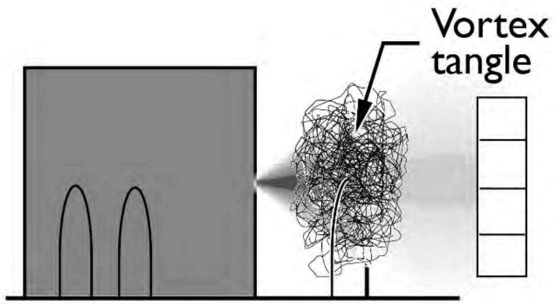


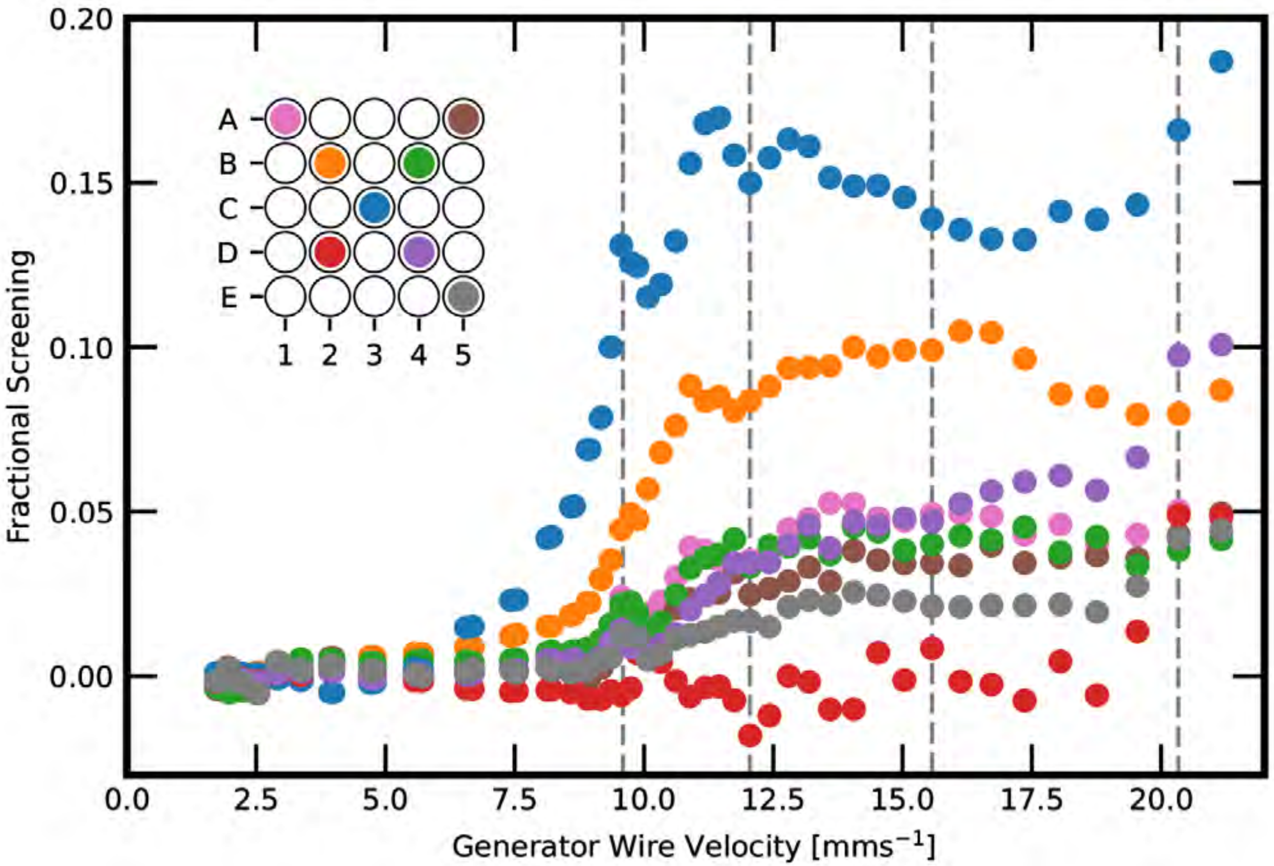
Correlation of Andreev reflection and VLD,
PRL 115 (2015) 015302, PRB 96 (2017) 054510

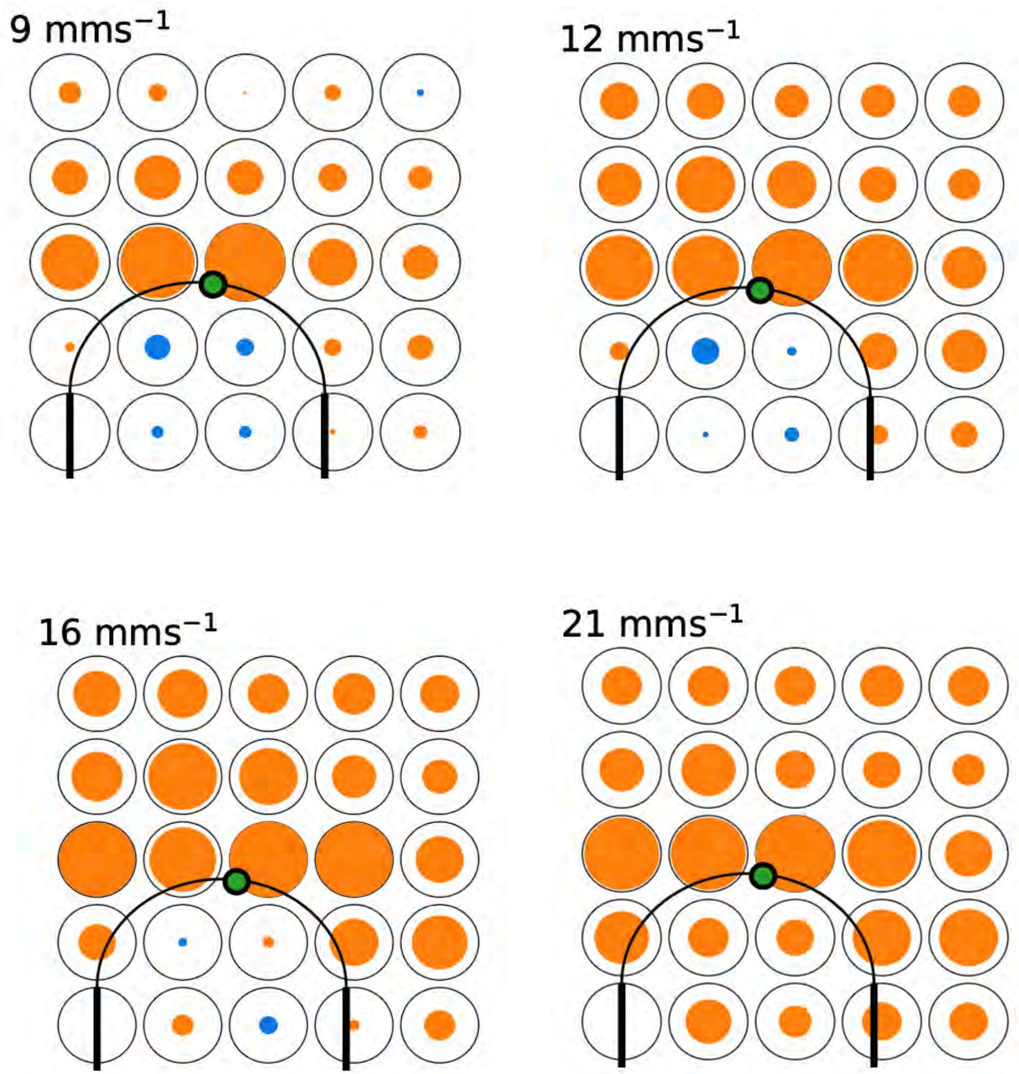
Quasiparticle Imaging Experiment



Turbulence generated by a 4.5 μm generator wire

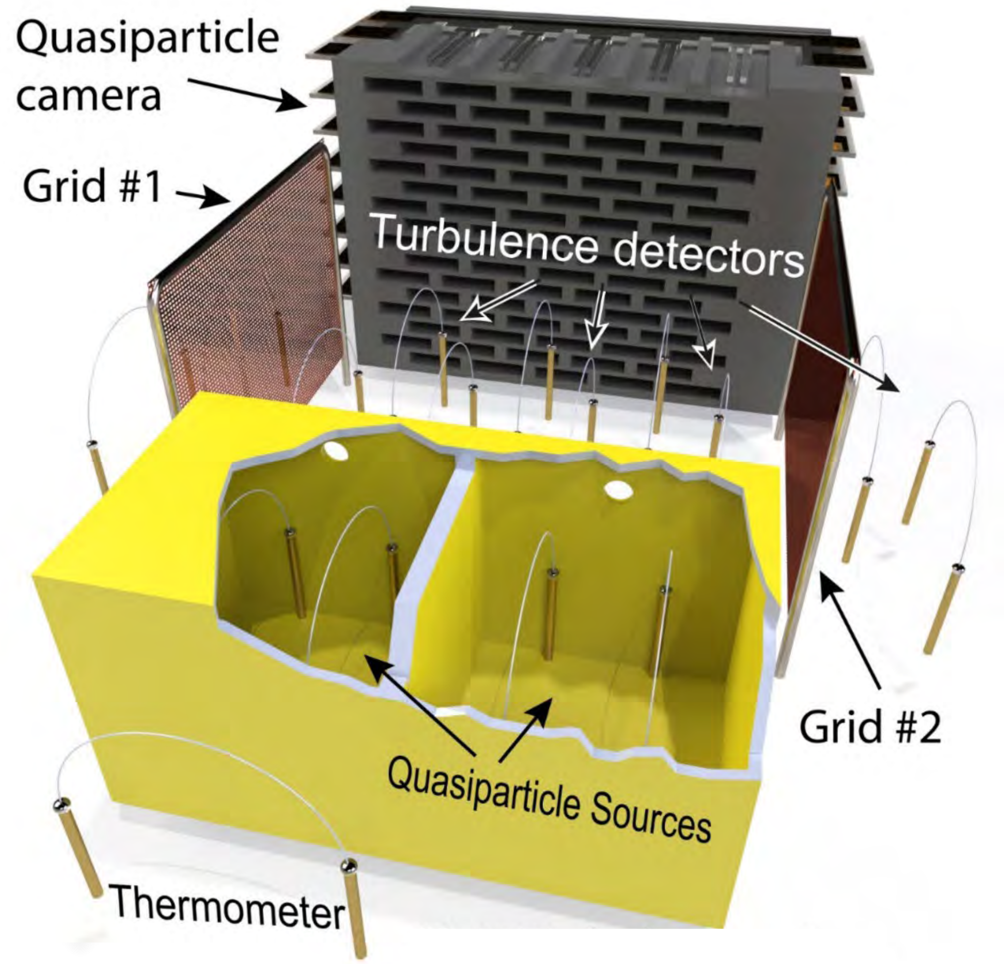


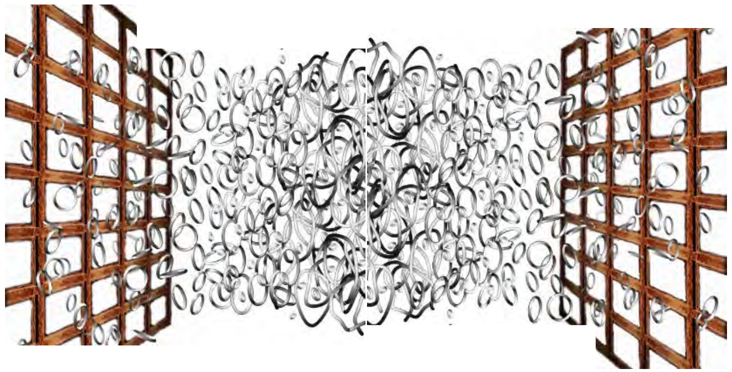


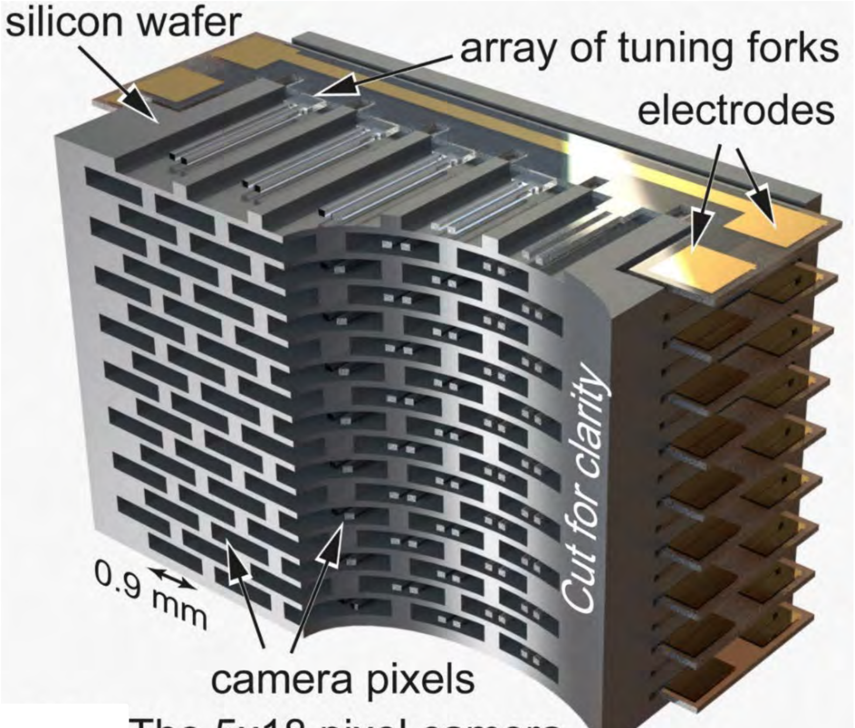


PRB105, 174515 (2022)

Study of non-polarized tangles



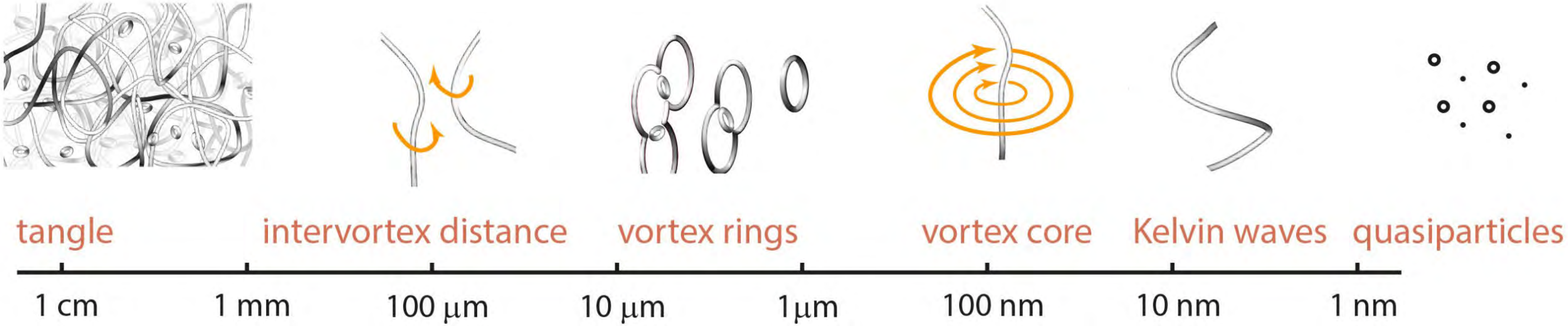




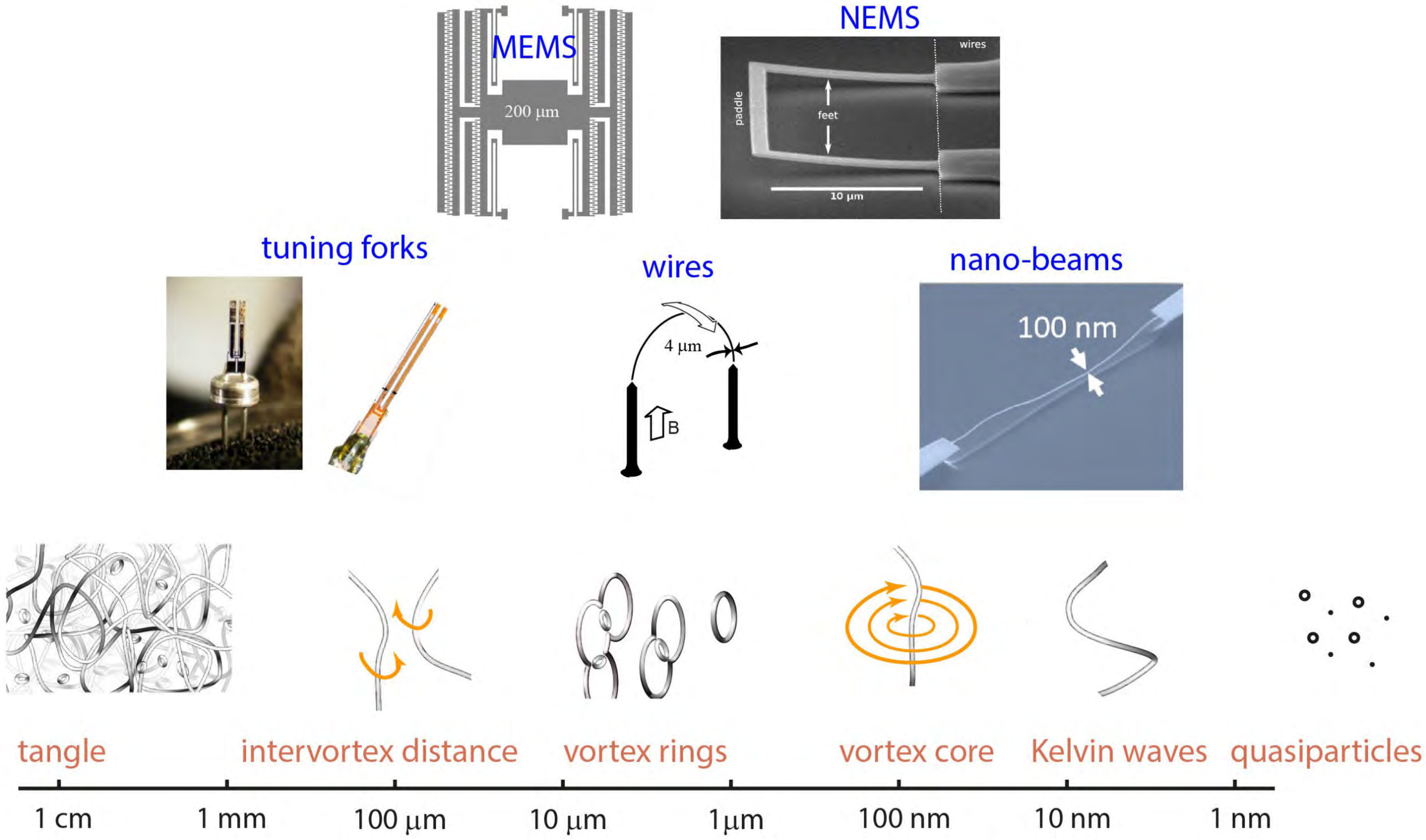
The 5x18 pixel camera.

Develop NEMS devices to improve sensitivity tenfold and to probe ^{3}He at length scales similar to the coherence length

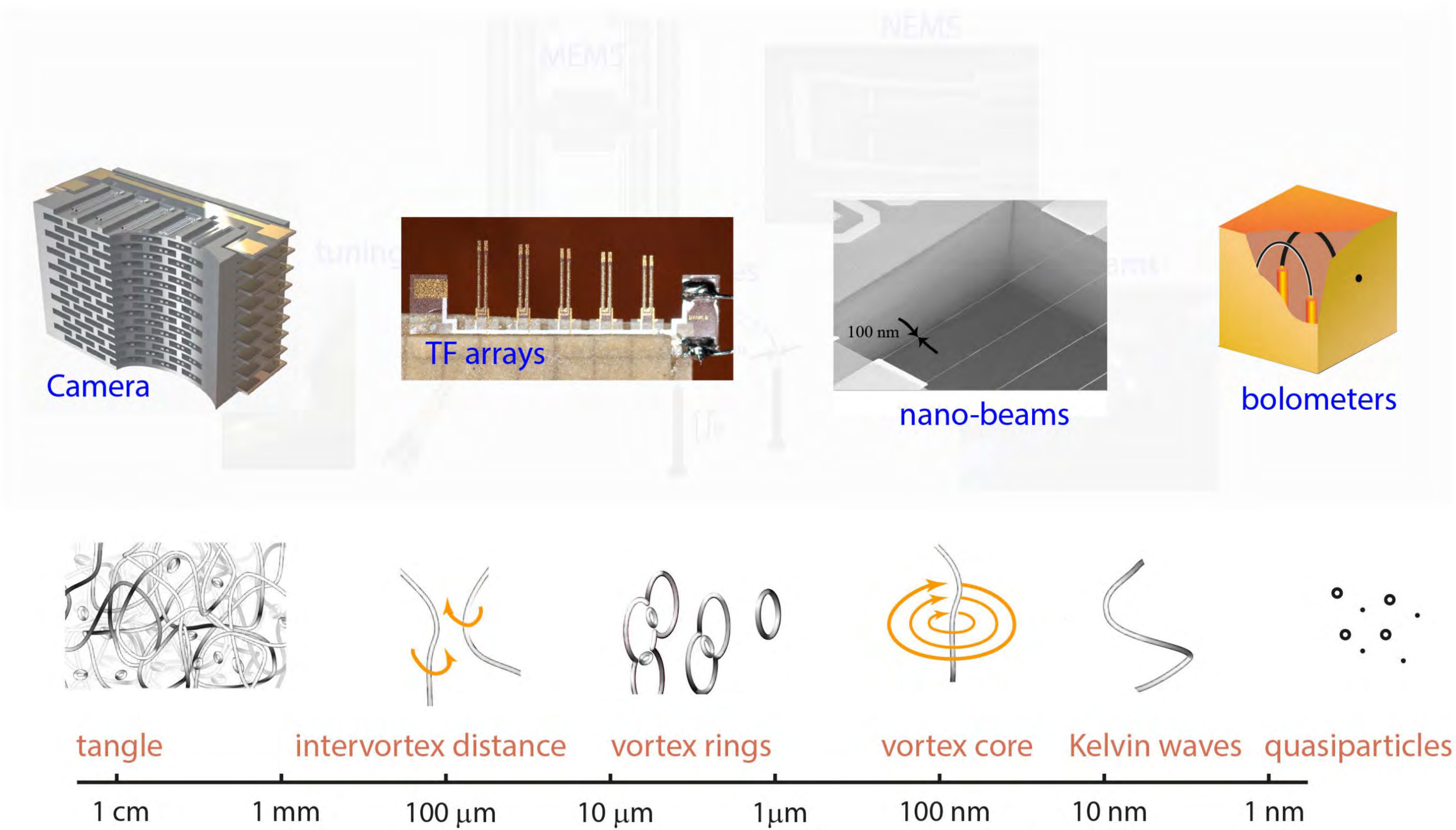
Turbulent length scales and mechanical devices in quantum fluids



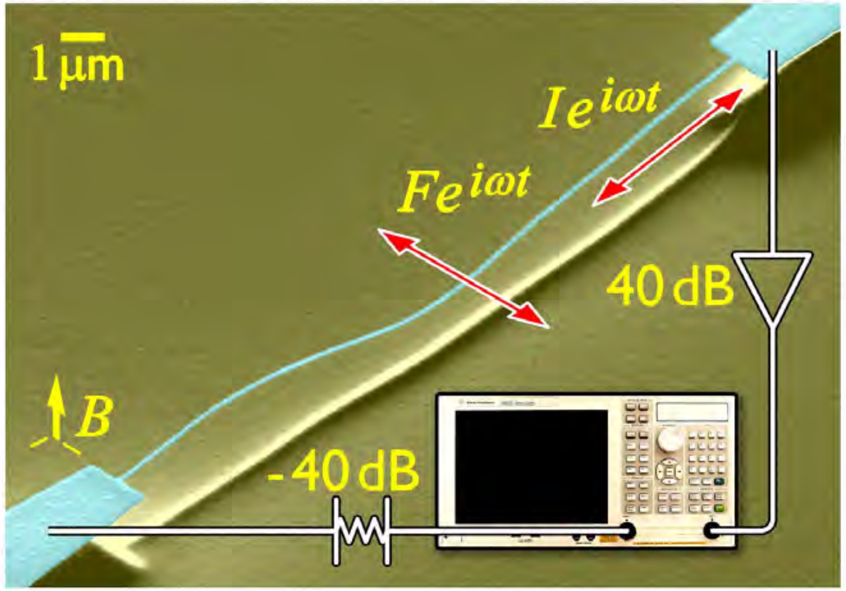
Turbulent length scales and mechanical devices in quantum fluids

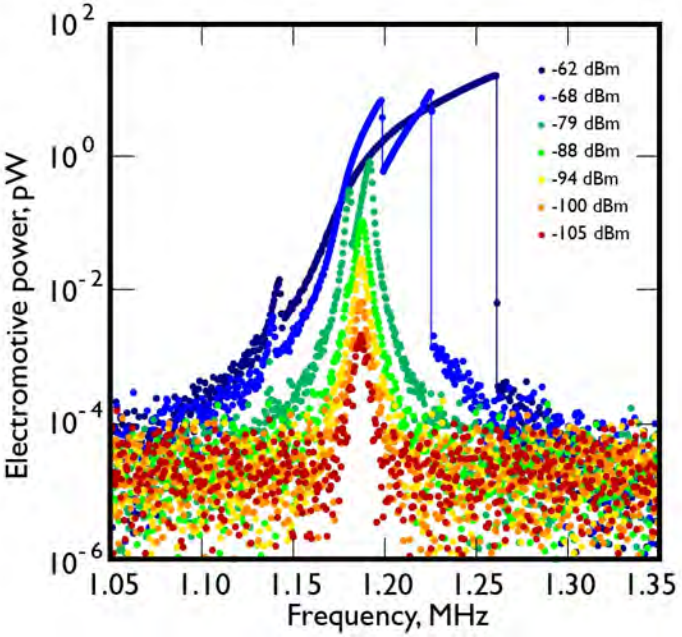


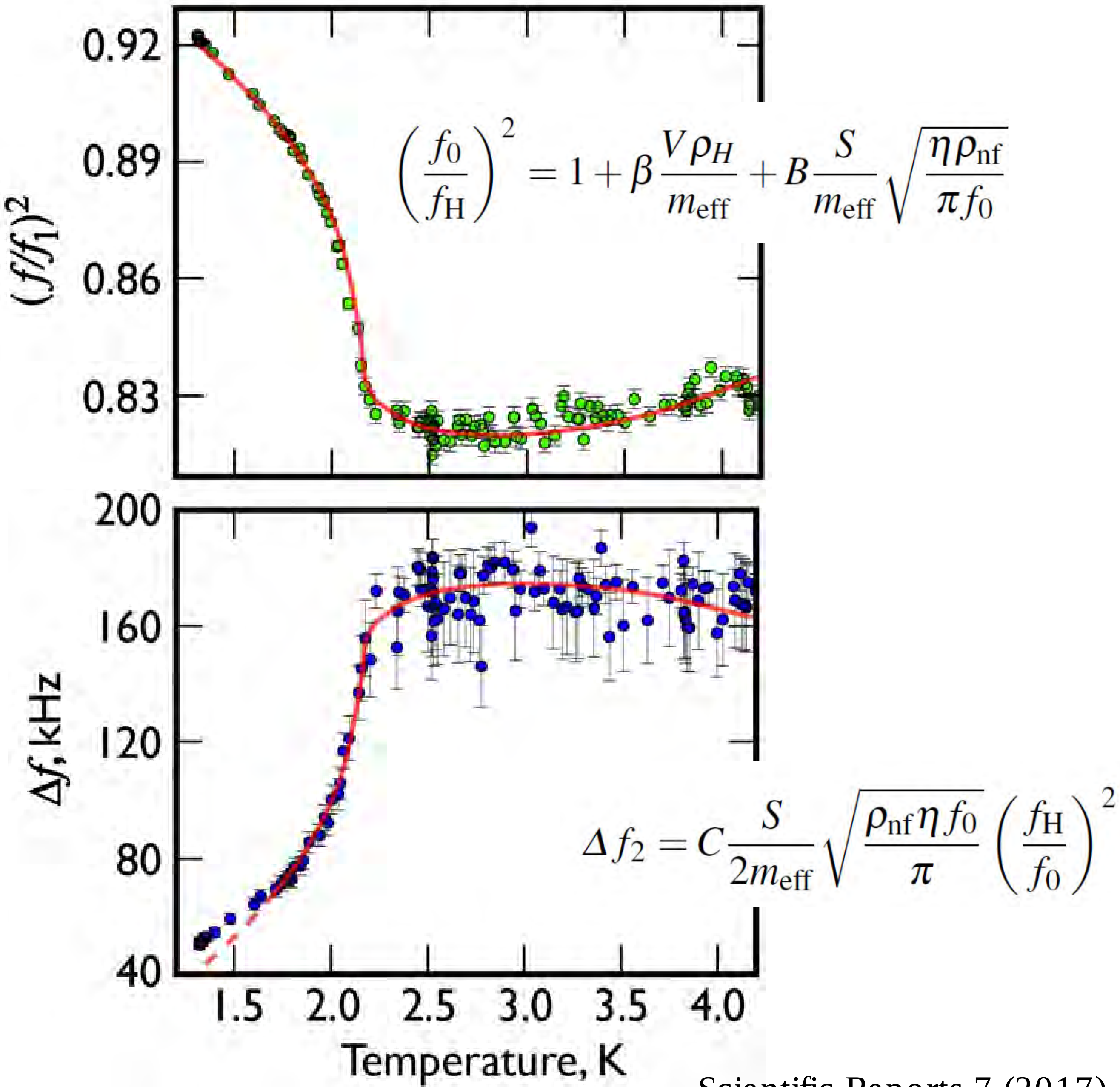
Turbulent length scales and mechanical devices in quantum fluids



Doubly clamped Al-beam in vacuum and ^{4}He

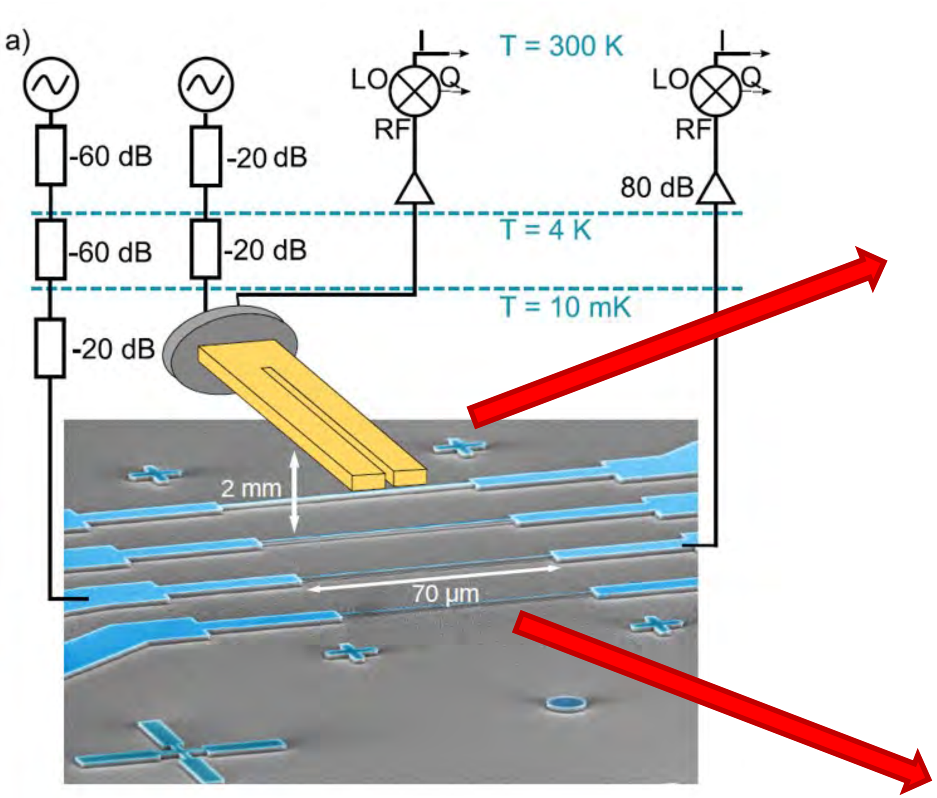


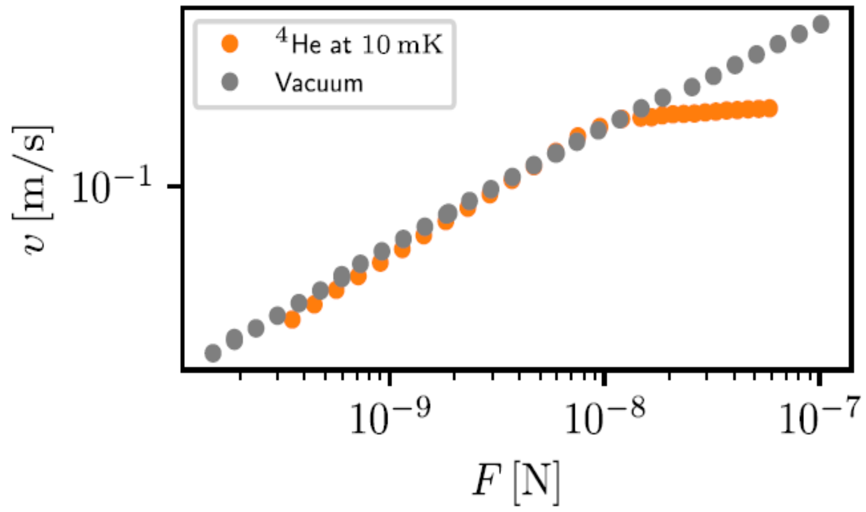


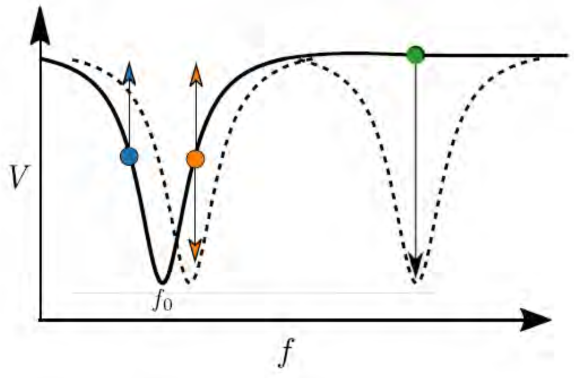


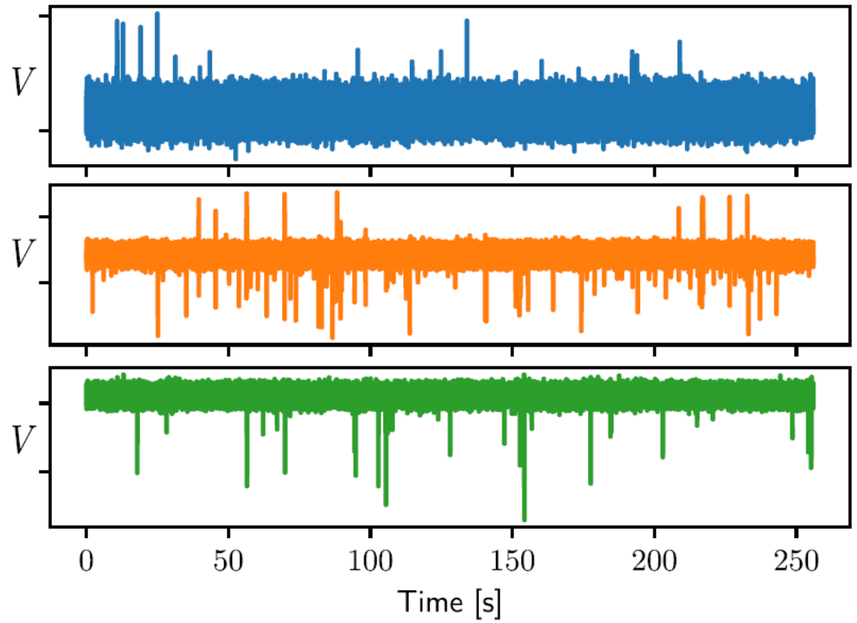
Scientific Reports 7 (2017) 4876

Detection of turbulence using SiN-Al-beam in ^{4}He



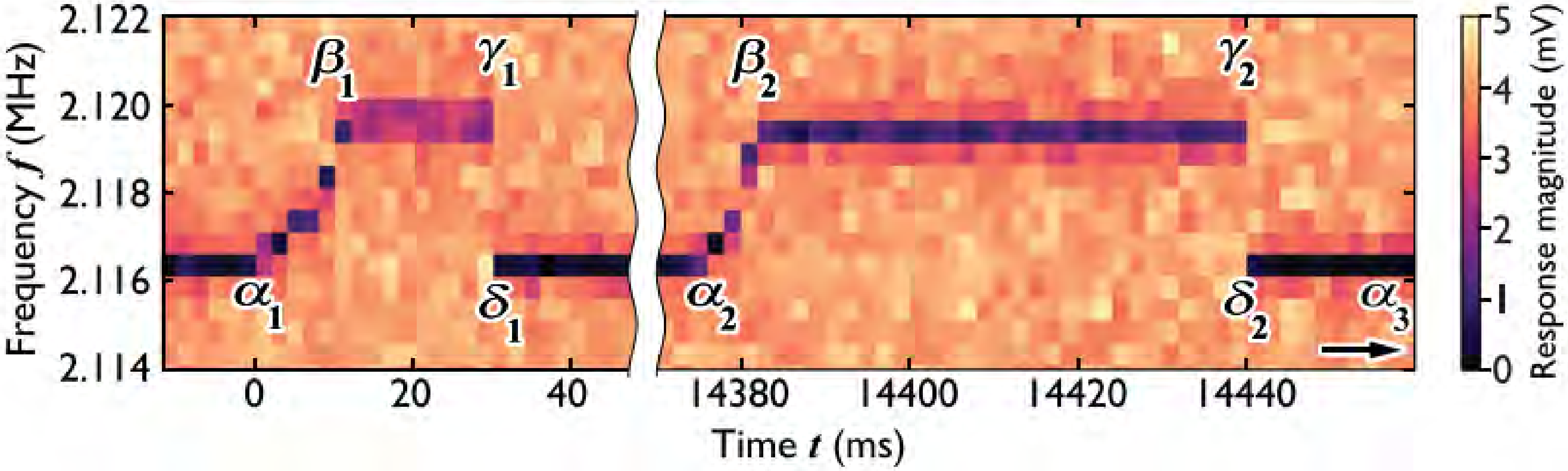






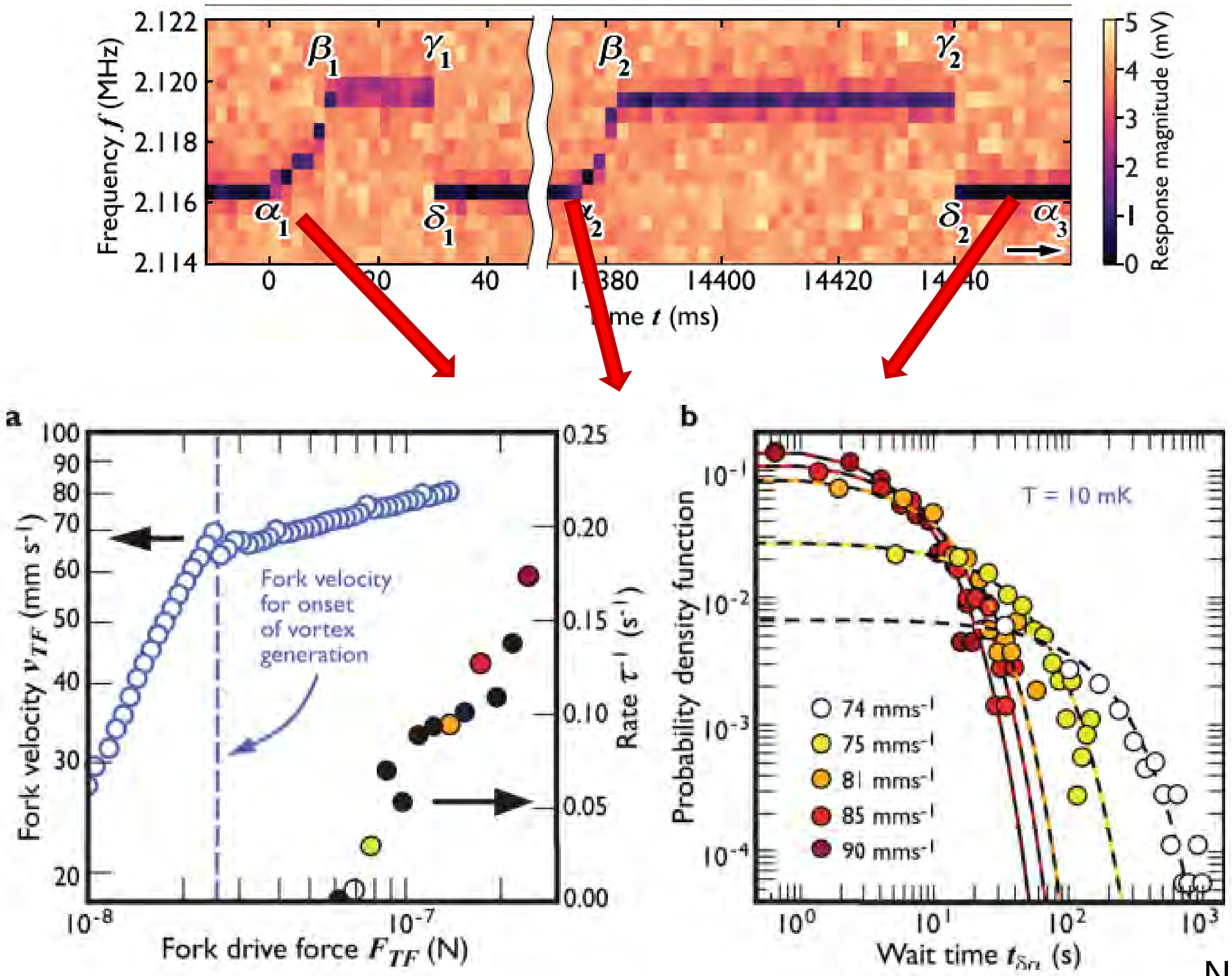
Nature Comms **12**, 2645 (2021)

Multi-frequency Lockin Amplifier Detection of turbulence



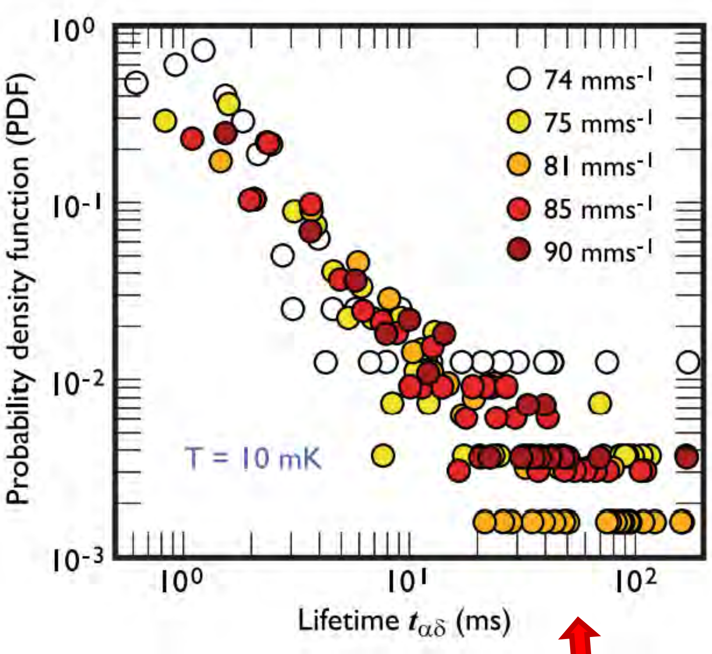
Rev. Sci. Instrum. **82** (2011) 026109 JLTP **184** (2016) 1080 Nature Comms **12**, 2645 (2021)

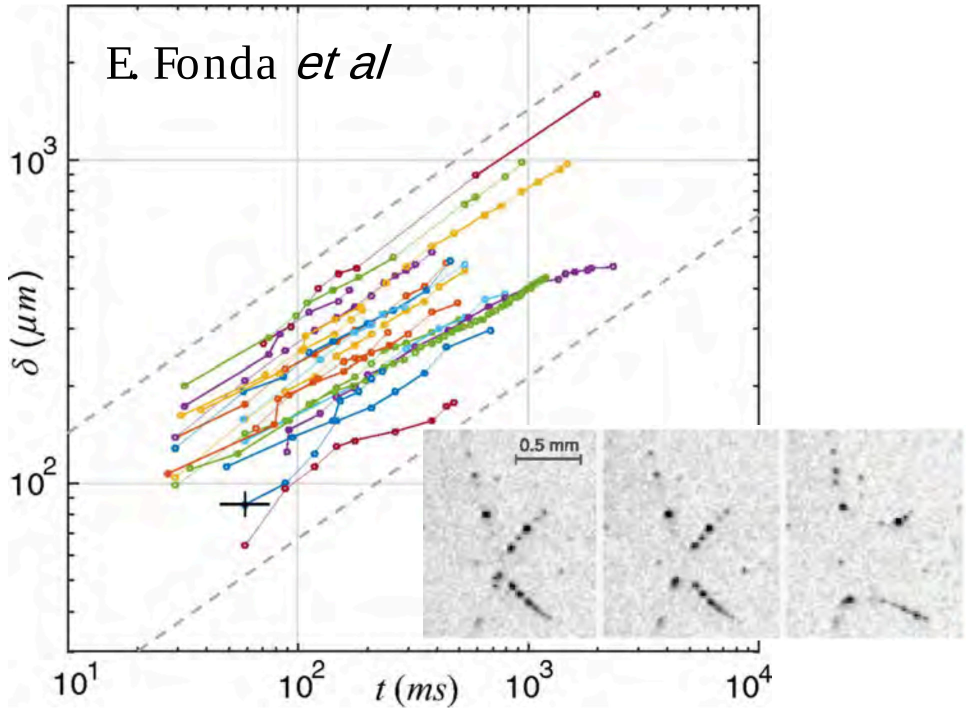
Detection of turbulence using SiN-Al-beam in ^{4}He



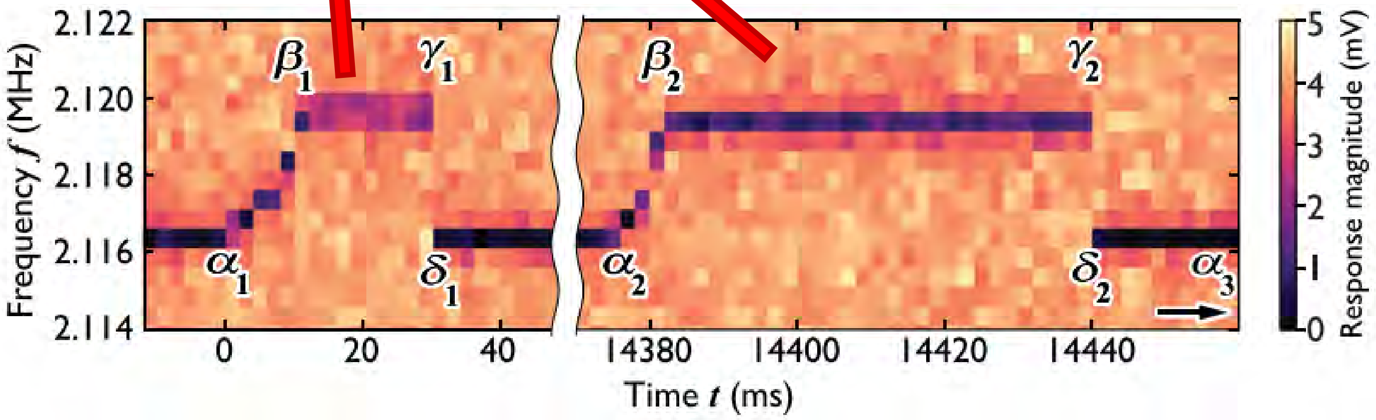
Nature Comms **12**, 2645 (2021)

Detection of turbulence using SiN-Al-beam in ^{4}He





PNAS 116 (2019) 1924



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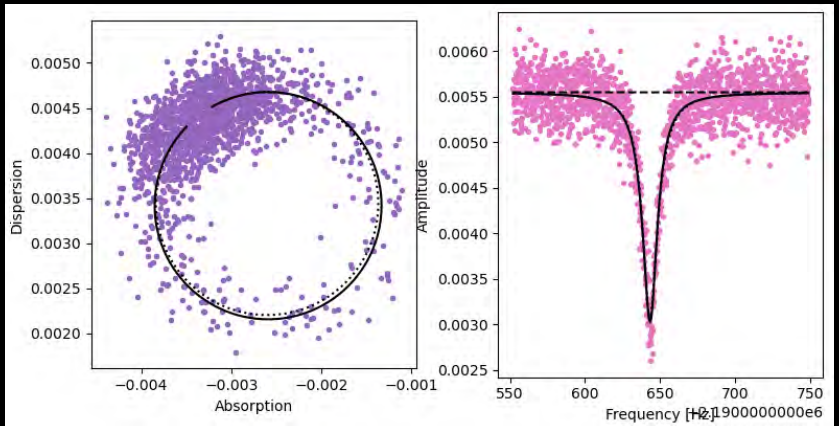
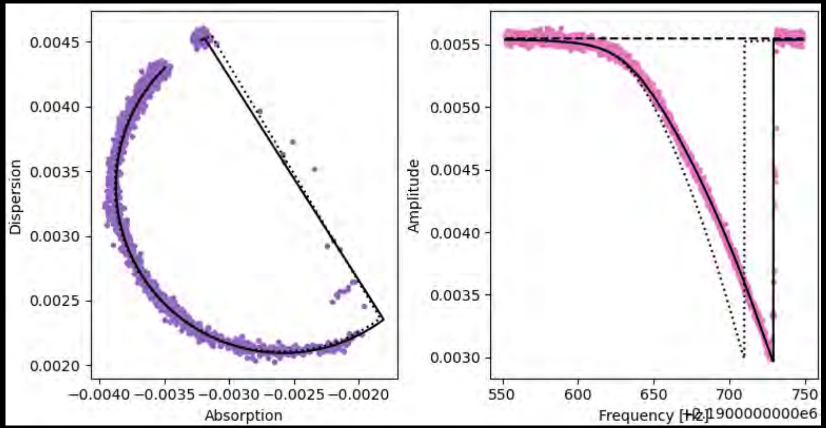
Work in progress

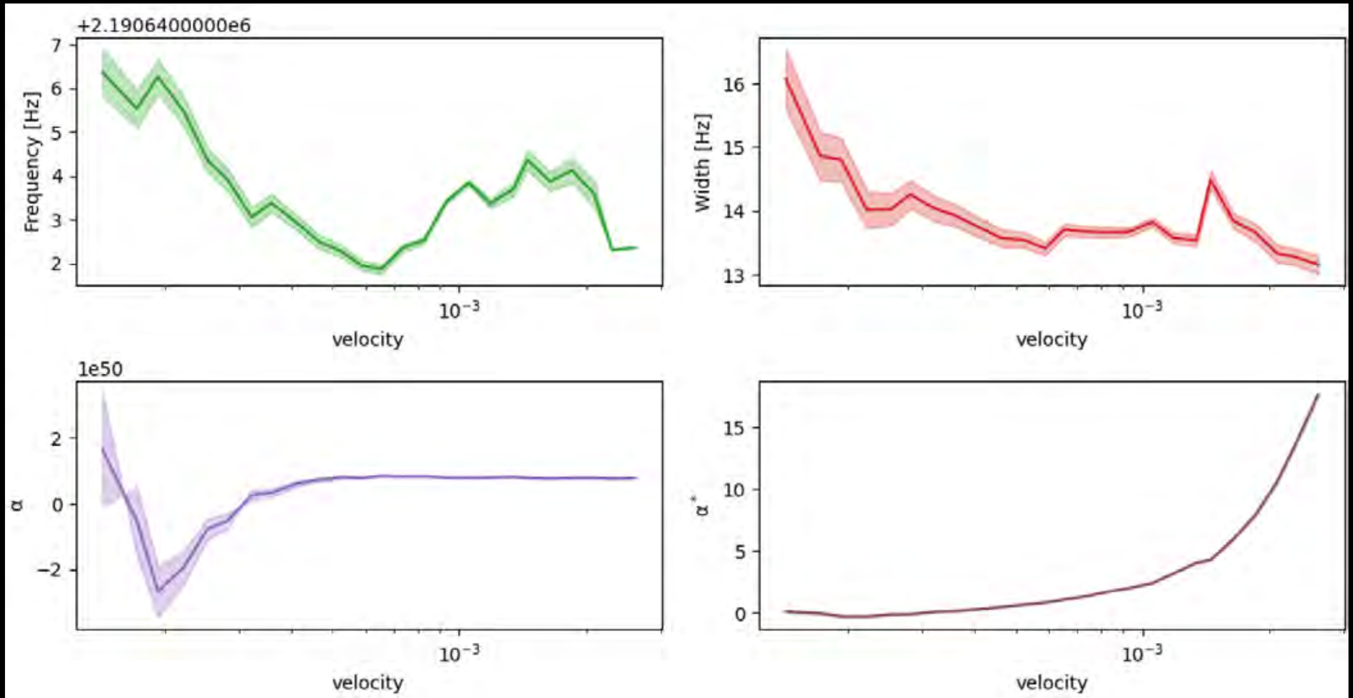
S21 Amplitude dependence – similar responses in vortex free state and trapped parallel vortex

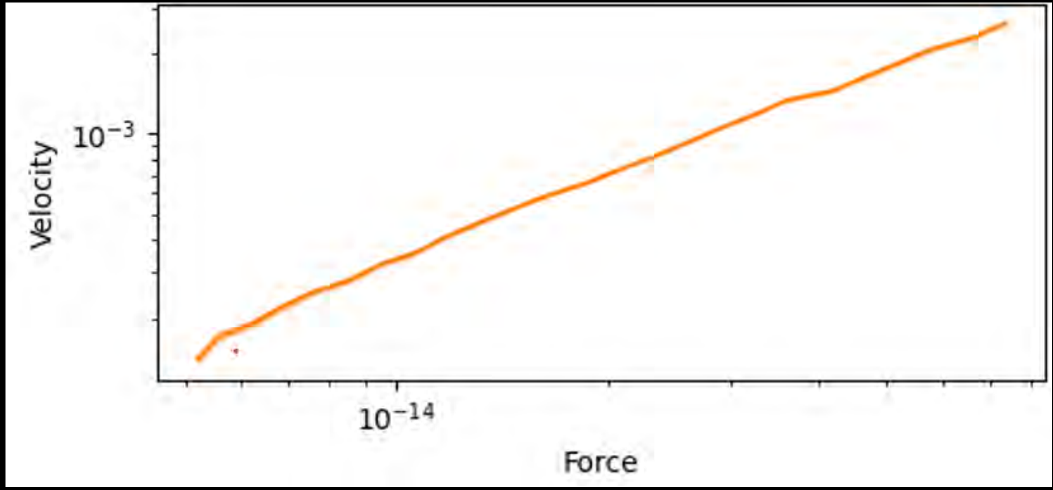




Fitted by Duffing equation with constant damping:

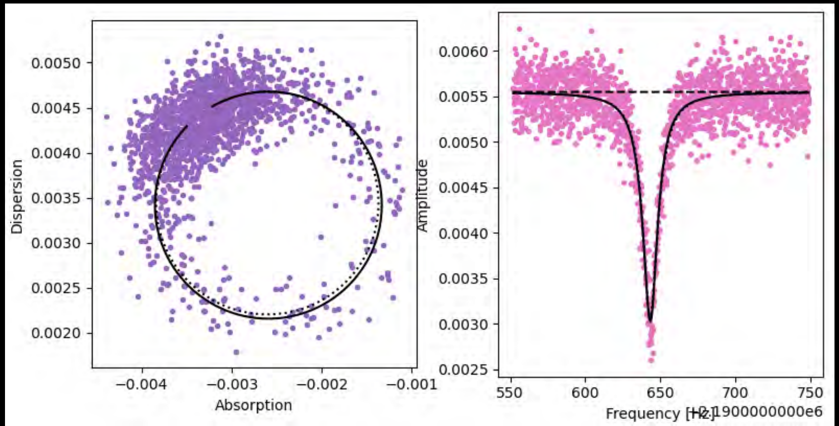
$$m\ddot{x} + m\lambda\dot{x} + m\omega_0^2 x + m\alpha x^3 = F_0 e^{i\omega t}$$

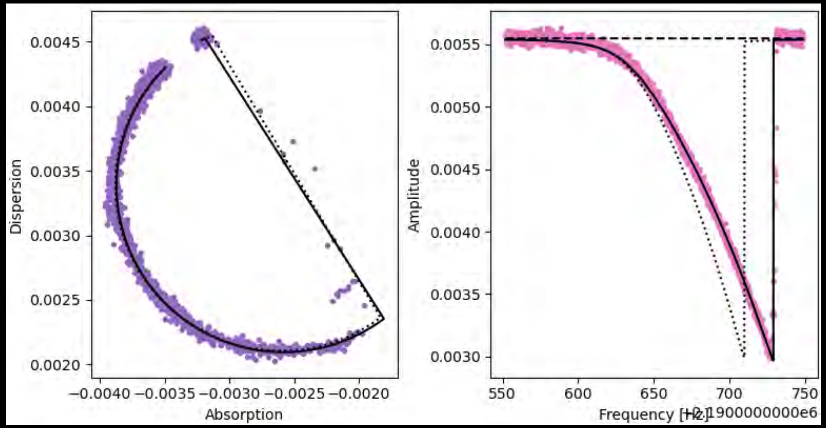




Work in progress

S21 Amplitude dependence – similar responses in vortex free state and trapped parallel vortex

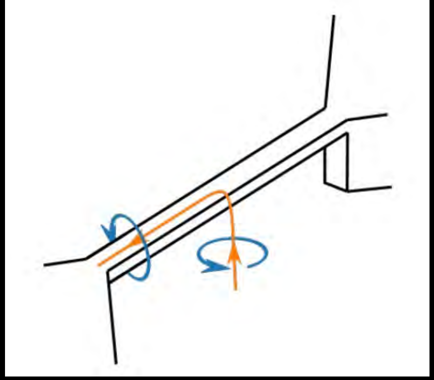


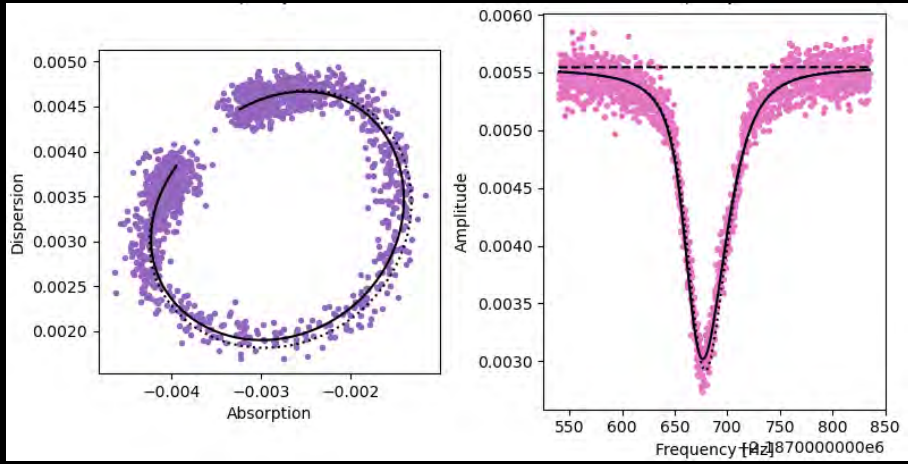


Fitted by Duffing equation with constant damping:

$$m\ddot{x} + m\lambda\dot{x} + m\omega_0^2 x + m\alpha x^3 = F_0 e^{i\omega t}$$

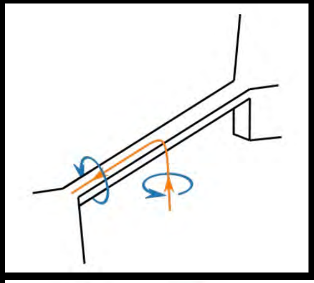
S21 Amplitude dependence in states with a higher damping



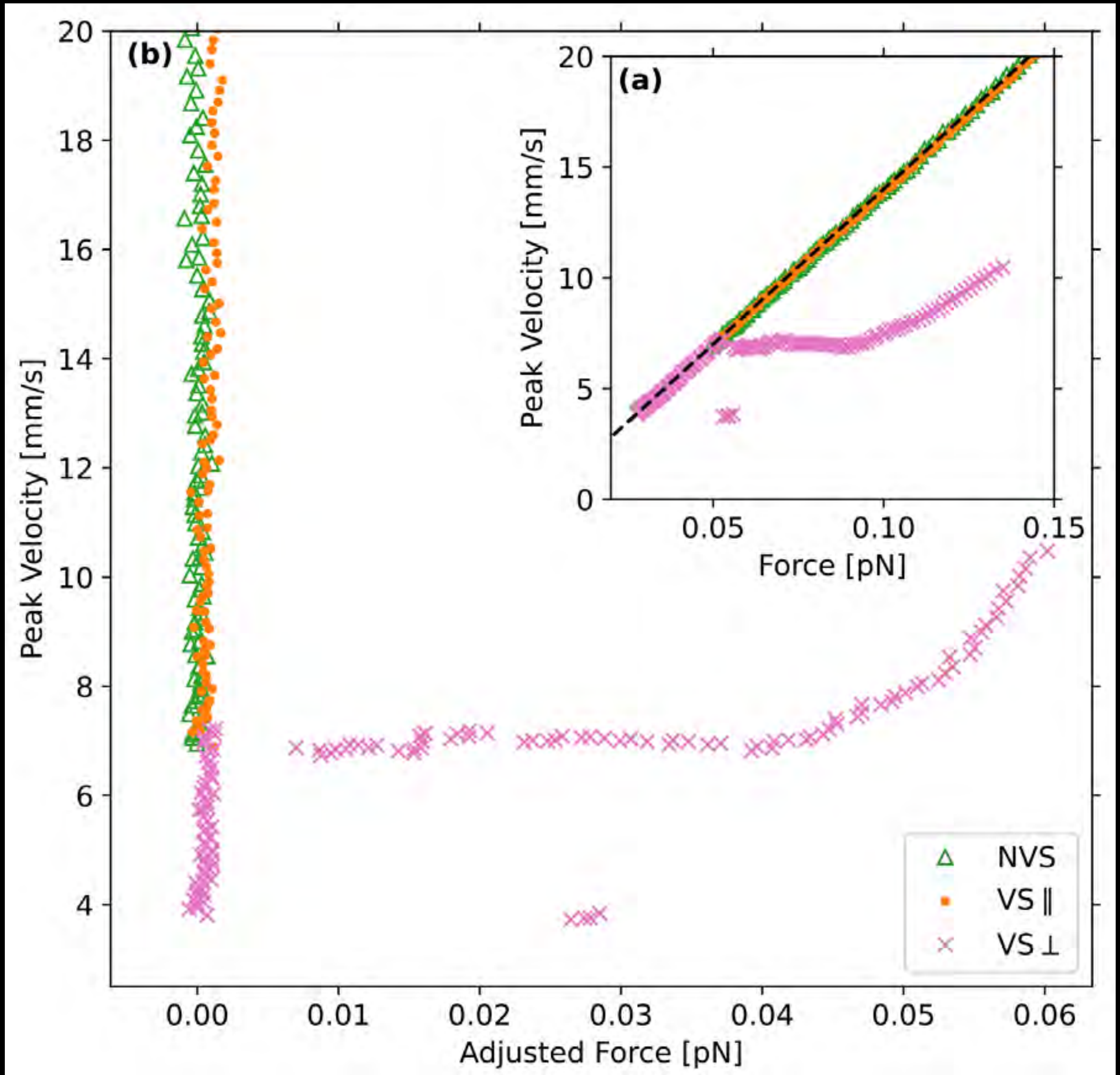


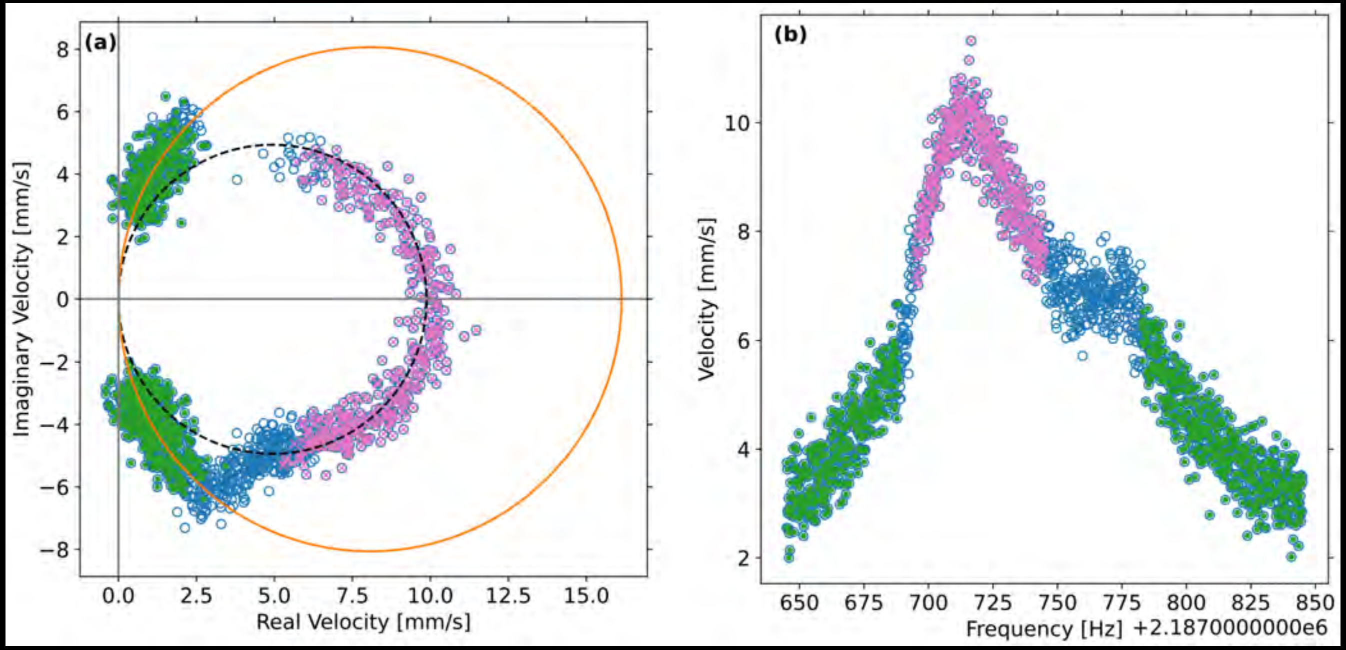
Complicated behaviour:
Example fitted by Duffing equation with non-linear damping term:

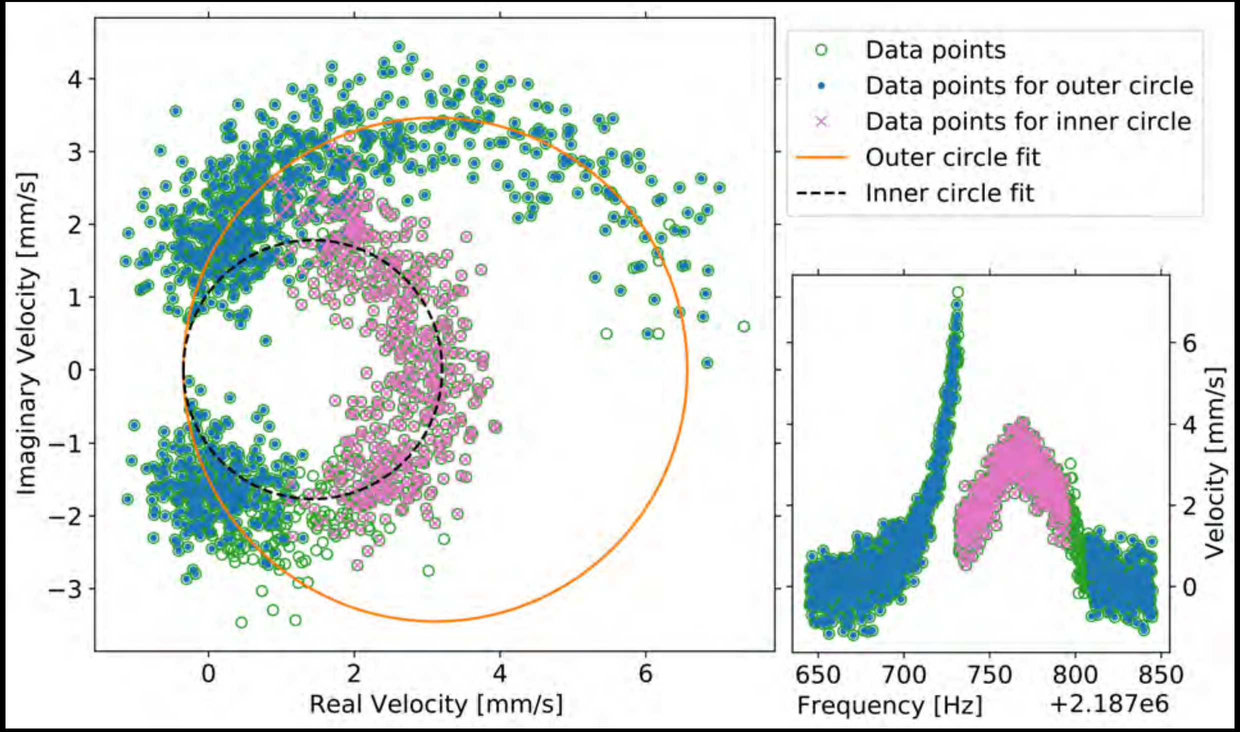
$$m\ddot{x} + m\lambda\dot{x} + m\eta x^2\dot{x} + m\omega_0^2 x + m\alpha x^3 = F_0 e^{i\omega t}$$

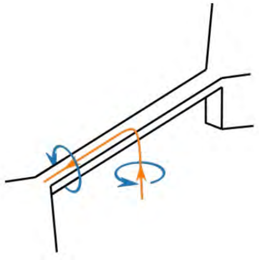


Work in progress

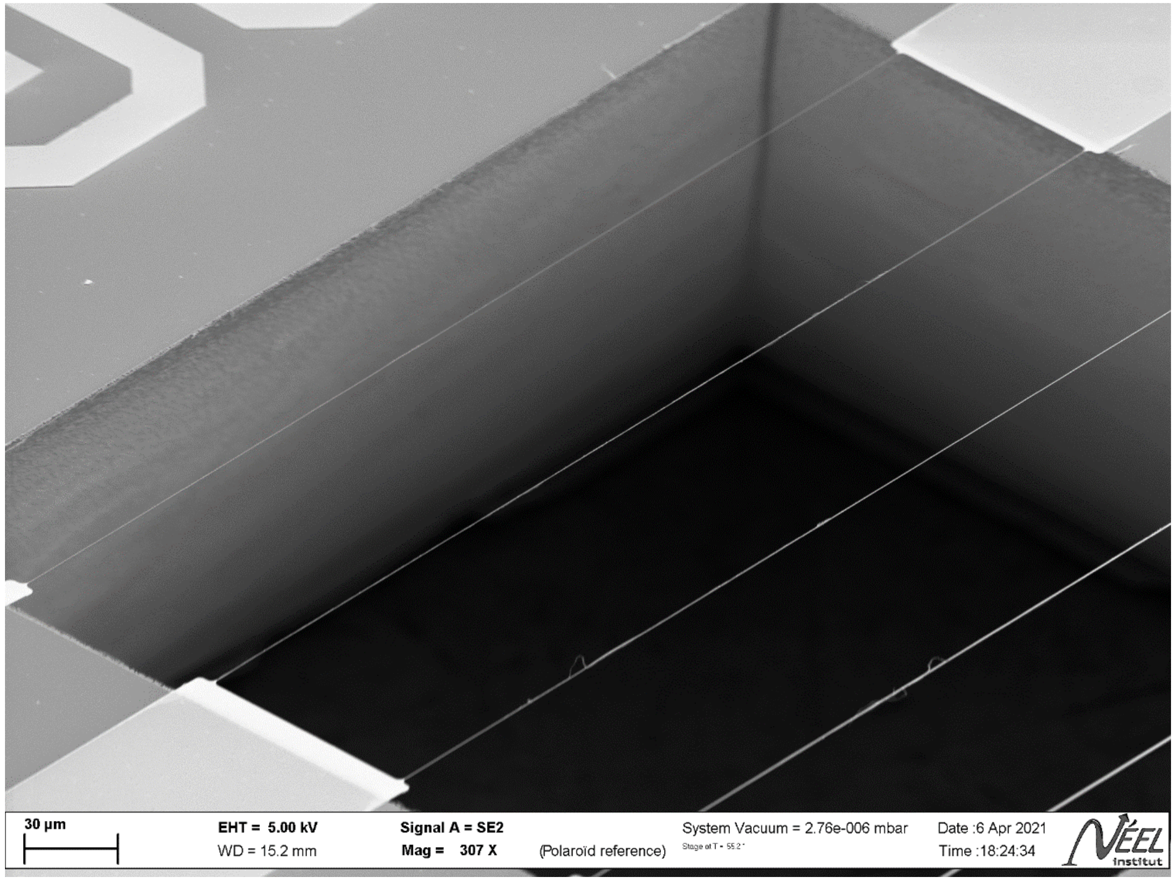


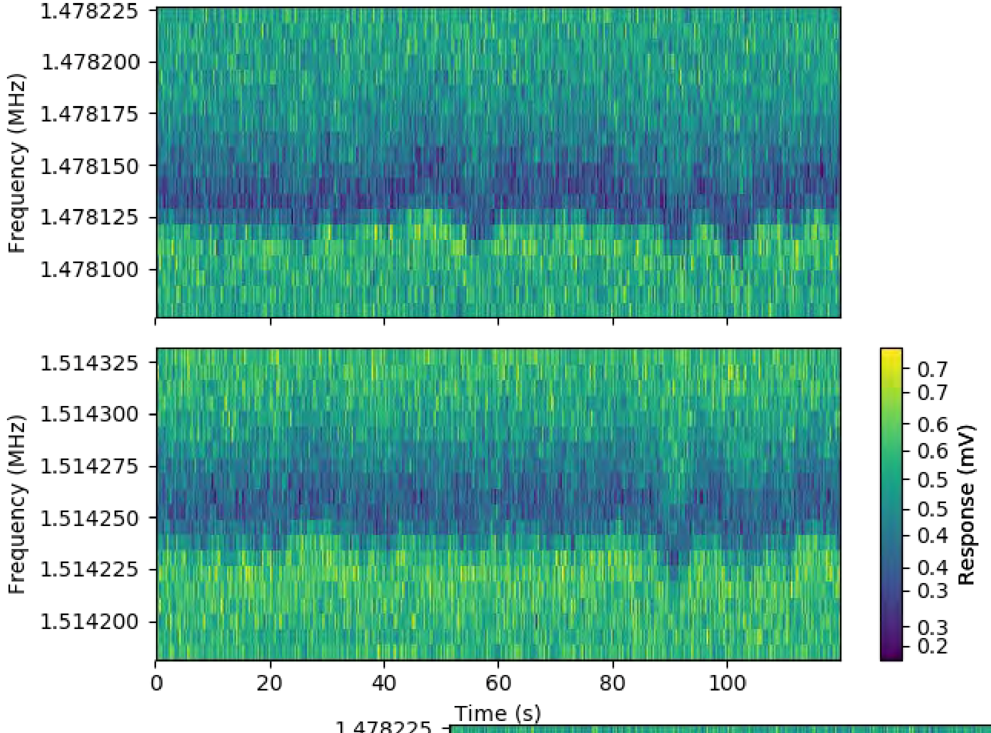


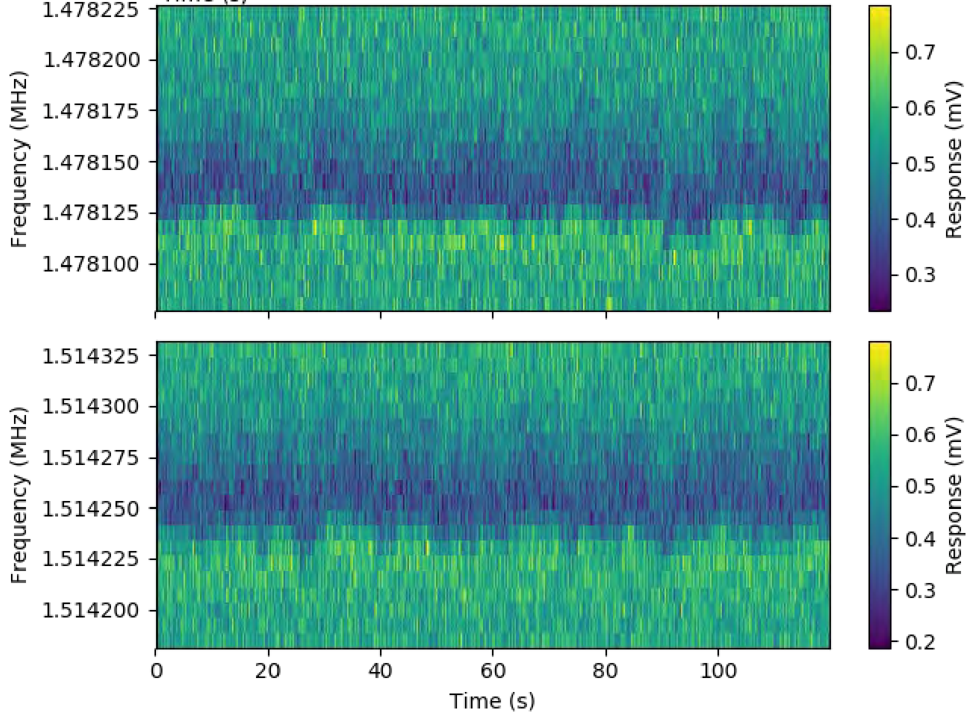




Work in progress







Summary

- A vibrating objects are excellent tools to generate tangles (quantum turbulence) in ^{4}He and ^{3}He. Furthermore, oscillators are excellent detectors of vortices in ^{3}He.
- Nano sized beams are good probes of thermal excitations in superfluid ^{4}He
- Nano-sized beams allow single vortex trapping in ^{4}He and probing turbulence
- Theoretical and numerical support is really appreciated