MANCHESTER 1824
The University of Manchester

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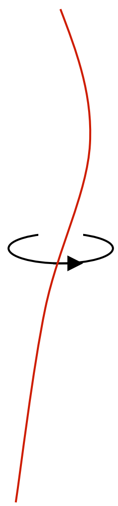
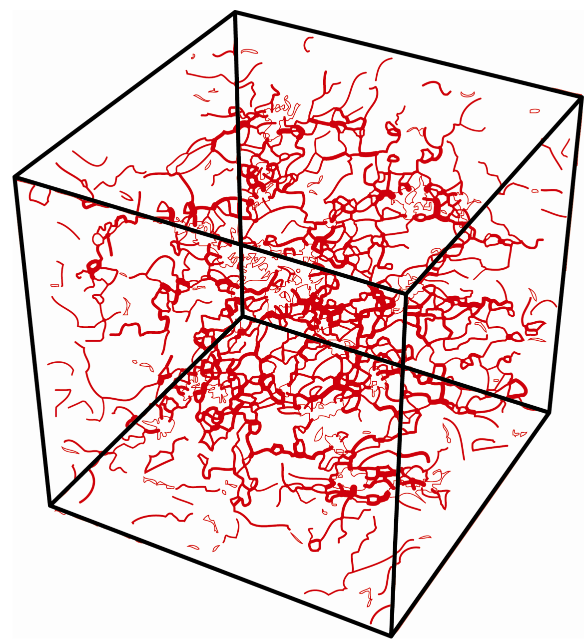
Grand Challenges in QFS, UB 6-8 Aug. 2015

Quantum Turbulence (QT) in the *T*=0 limit

(*T* < 0.5K for ^{4}He, *T* < 0.1-0.3mK for ^{3}He-B)

Challenge: with known properties of a vortex line at *T*=0, ***understand*** behaviour of a vortex tangle





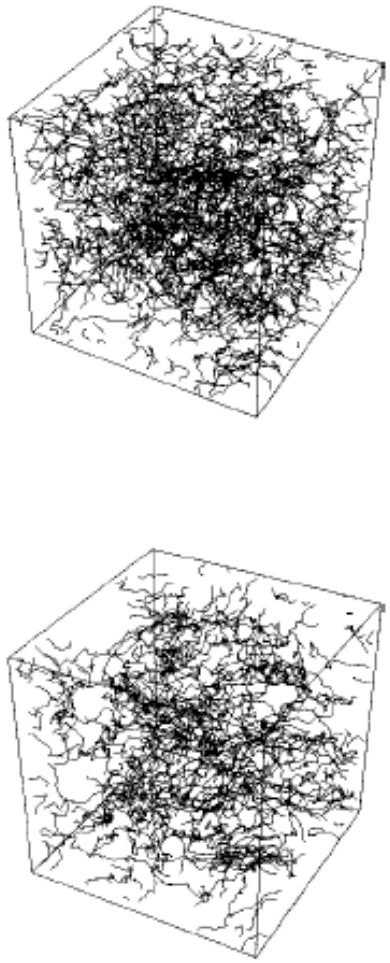
Plan:

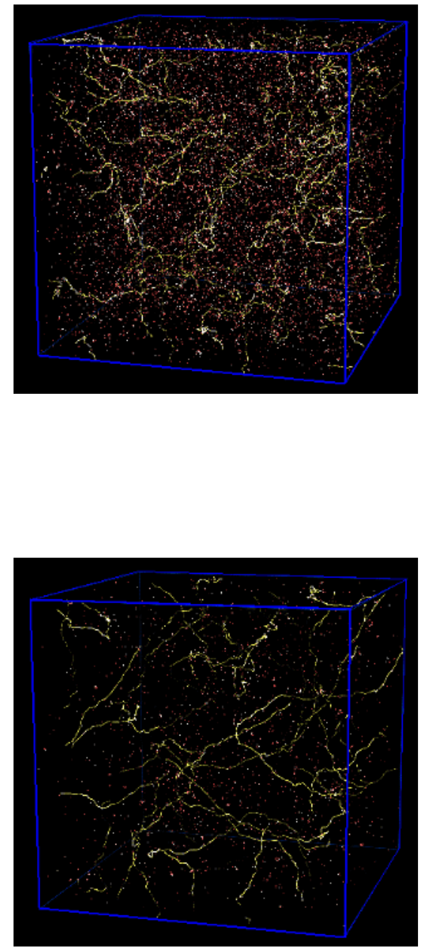
1. Outline current understanding and its *loose ends*;
2. Discuss existing and *desired* experimental techniques.

Motivation: a new type of turbulence

Relevance to other problems:

- QT can mimic classical turbulence (e.g. large Re)
- QT has features of wave turbulence (Kelvin waves)
- Analogies with other line defects: dislocations, Abrikosov vortices, cosmic strings





Computer simulations of the evolution of a vortex tangle (Tsubota, Araki, Nemirovskii)

Computer simulations of the evolution of cosmic strings (Cambridge)

Descriptions of vortex dynamics

$R \approx \xi$ Microscopic level

Gross-Pitaevskii equation for superfluid

$$i\hbar \frac{\partial \Psi}{\partial t} = -\frac{\hbar^2}{2M}\nabla^2\Psi + V_0|\Psi|^2\Psi - E_0\Psi$$

$R \gg \xi$ Intermediate level (filament model)

$$\mathbf{s}(\zeta, t) \qquad \mathbf{s}' = d\mathbf{s}/d\zeta$$

- Vortex lines move with local $\mathbf{u}_s$
- $\mathbf{u}_s$ is function of the configuration of the tangle
- Reconnections ad-hoc

$$\frac{d\mathbf{s}}{dt} = \mathbf{u}_{si}$$

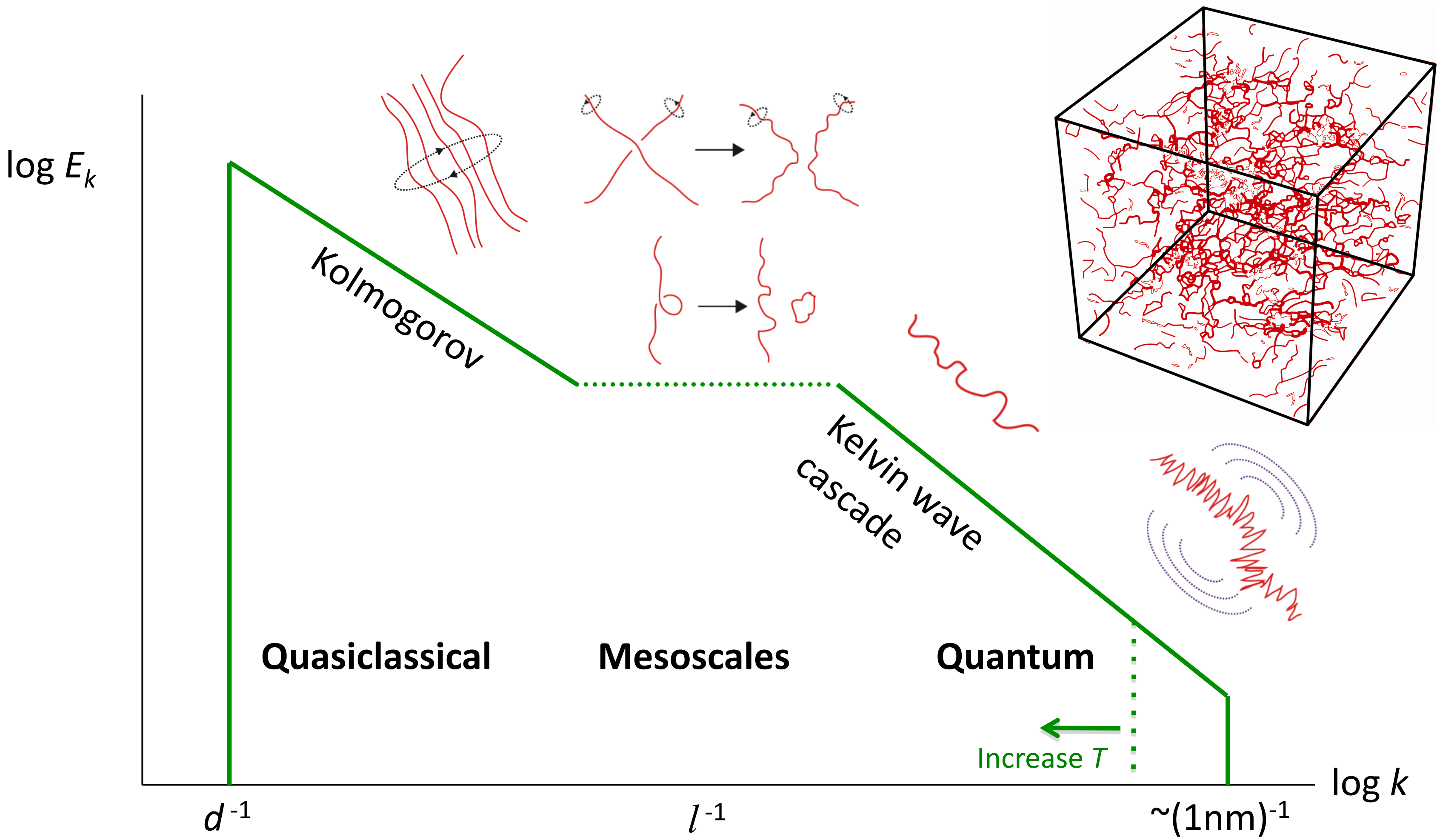
$$\mathbf{u}_{si}(\mathbf{s}) = \frac{\kappa}{4\pi}\oint_{\mathcal{L}} \frac{(\mathbf{s}_1 - \mathbf{s}) \times d\mathbf{s}_1}{|\mathbf{s}_1 - \mathbf{s}|^3}$$

$R \gg \ell$ Macroscopic level,

- Coarse-grained equations
- Cannot account for quantum cascade

$$\frac{\partial \mathbf{v}_s}{\partial t} + (\mathbf{v}_s \cdot \nabla)\mathbf{v}_s = -\frac{1}{\rho}\nabla p + f(L, ?)$$

QT at T=0 was studied since 2000. Our *beliefs* after 15 years:



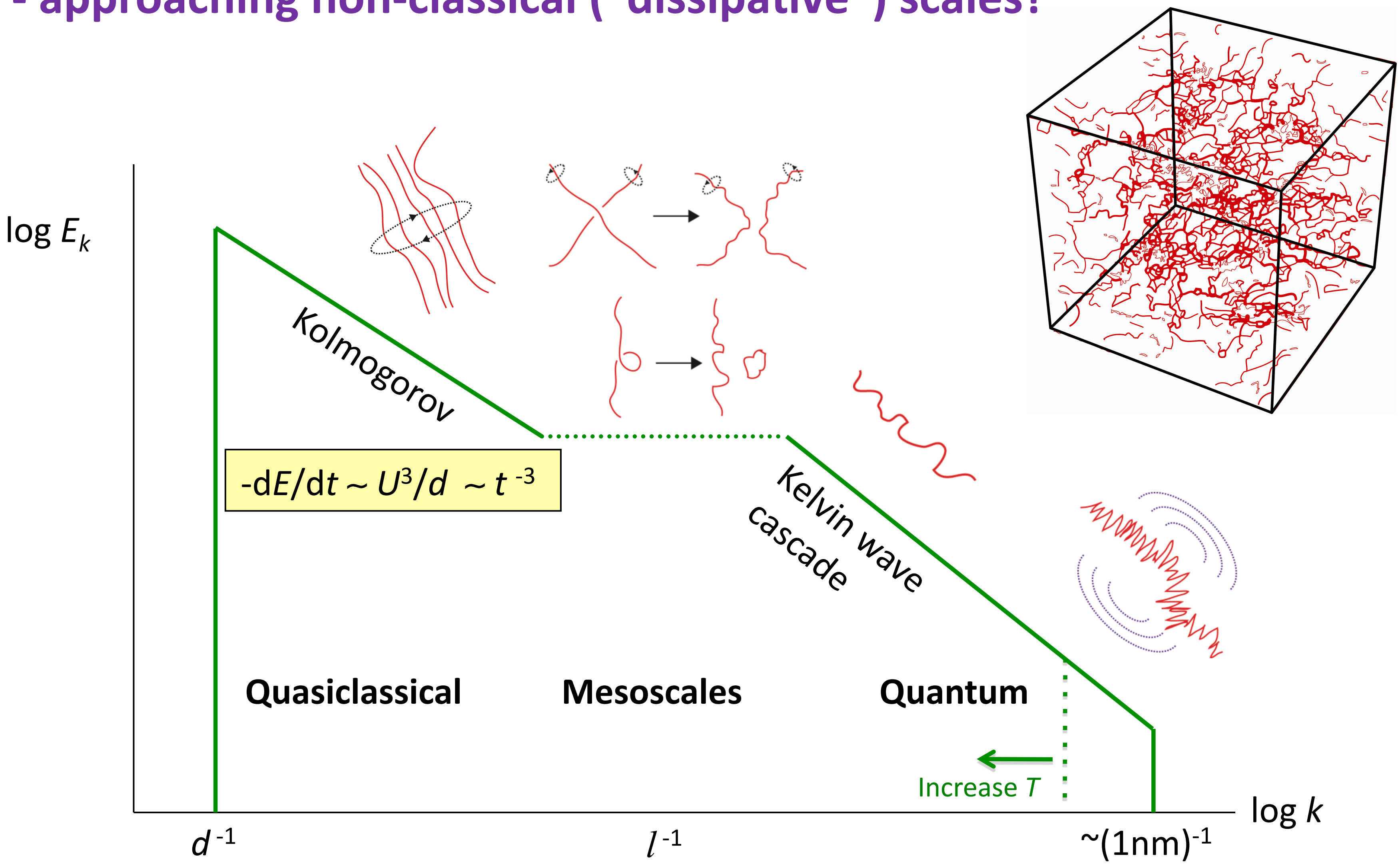
Assumed energy spectrum of QT (HIT)

1. Quasi-classical behaviour:

Can coarse-grained flow be described by quasi-classical equations:

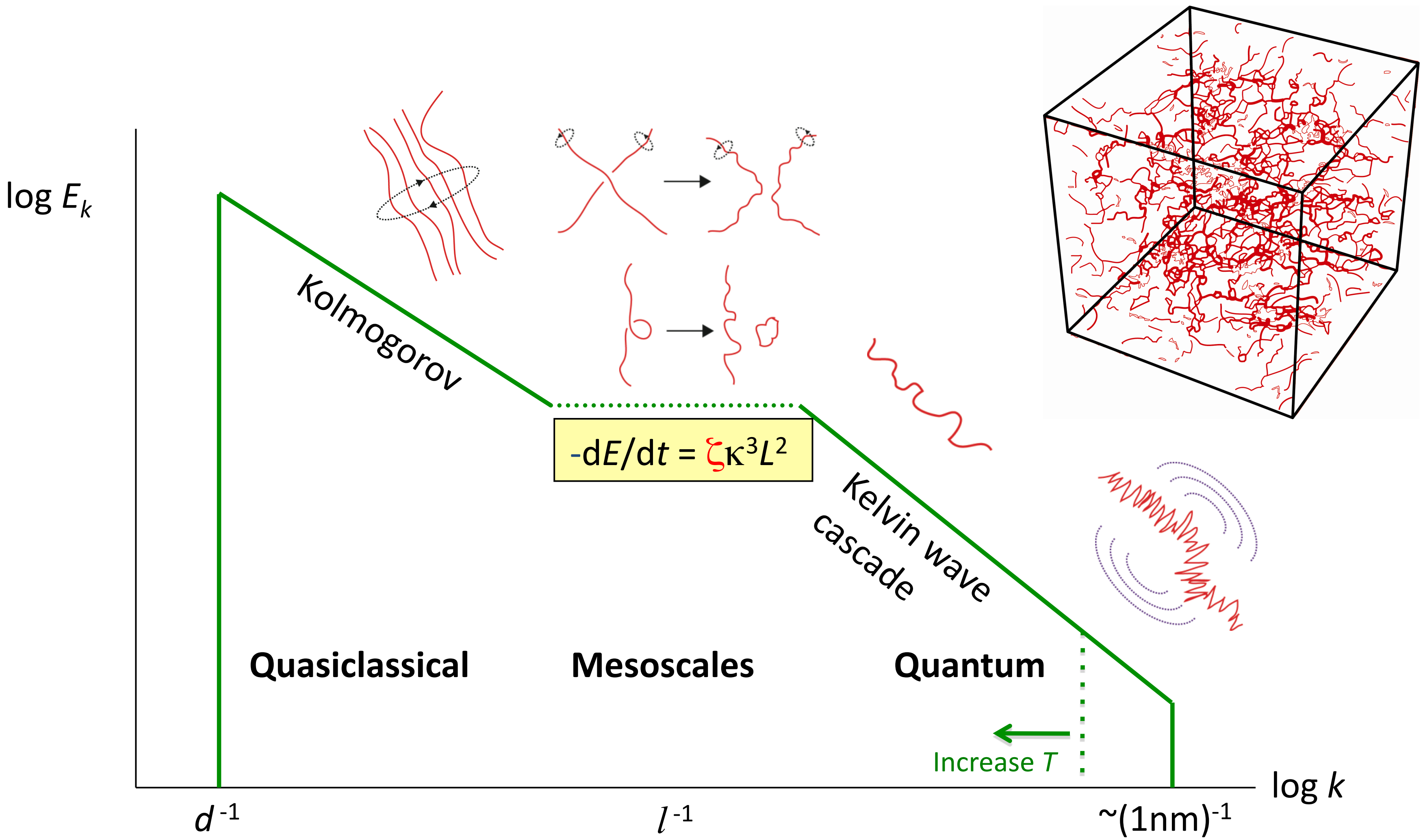
- at the generation stage (vortex nucleation/multiplication)?

- approaching non-classical ("dissipative") scales?



2. QT at quantum length scales

- Which processes maintain energy cascade to non-classical scales?
- Dominant mechanism of energy removal?
- Derivation of the formula for the rate of energy removal?



Dissipation rate: Classical vs. Quantum

Classical fluid:
Inertial cascade; energy flux determined by Navier-Stokes equation

$$\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla)\mathbf{v} = -\frac{1}{\rho}\nabla p + \nu \nabla^2 \mathbf{v}$$

Dissipation at small lengths through shear viscosity (where ν is a material parameter):

$$\epsilon_c = \nabla\cdot(v_i\sigma_{ik}) + \sigma_{ij}\frac{\partial v_i}{\partial x_j} = \nabla\cdot(v_i\sigma_{ik}) + \frac{\nu}{2}\left(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i}\right)^2 \qquad -\dot{\mathcal{E}}_c = \int \epsilon_c dV = \nu \int_V \omega^2 dV$$

$dE/dt = -\nu\,(\mathrm{curl}\,\boldsymbol{v})^2$

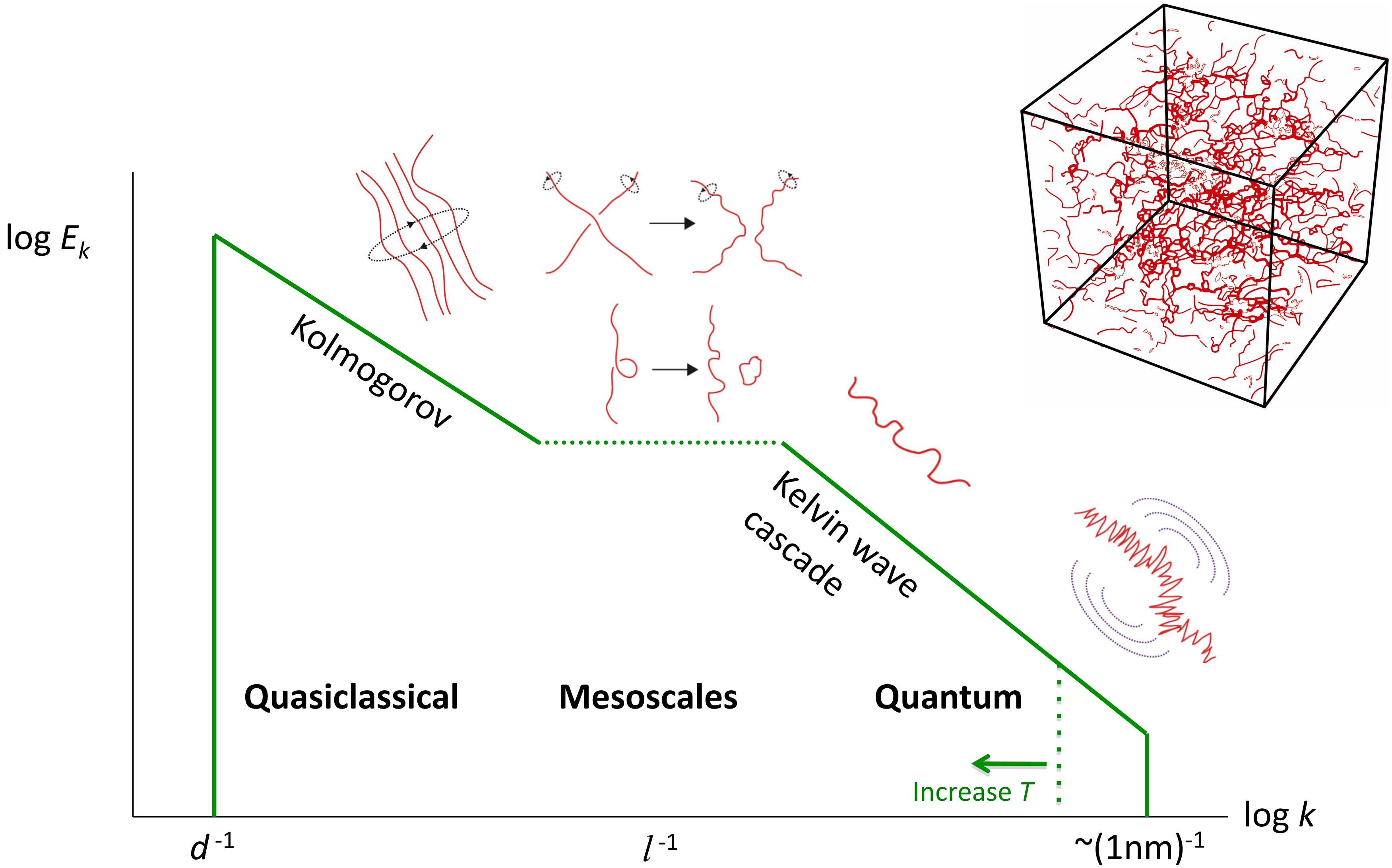
Superfluid quasi-classical flow:
Inertial cascade; energy flux is, perhaps, determined by "quasi-Navier-Stokes" equation

$$\frac{\partial \mathbf{v}_s}{\partial t} + (\mathbf{v}_s \cdot \nabla)\mathbf{v}_s = -\frac{1}{\rho}\nabla p + f(L, ?)$$

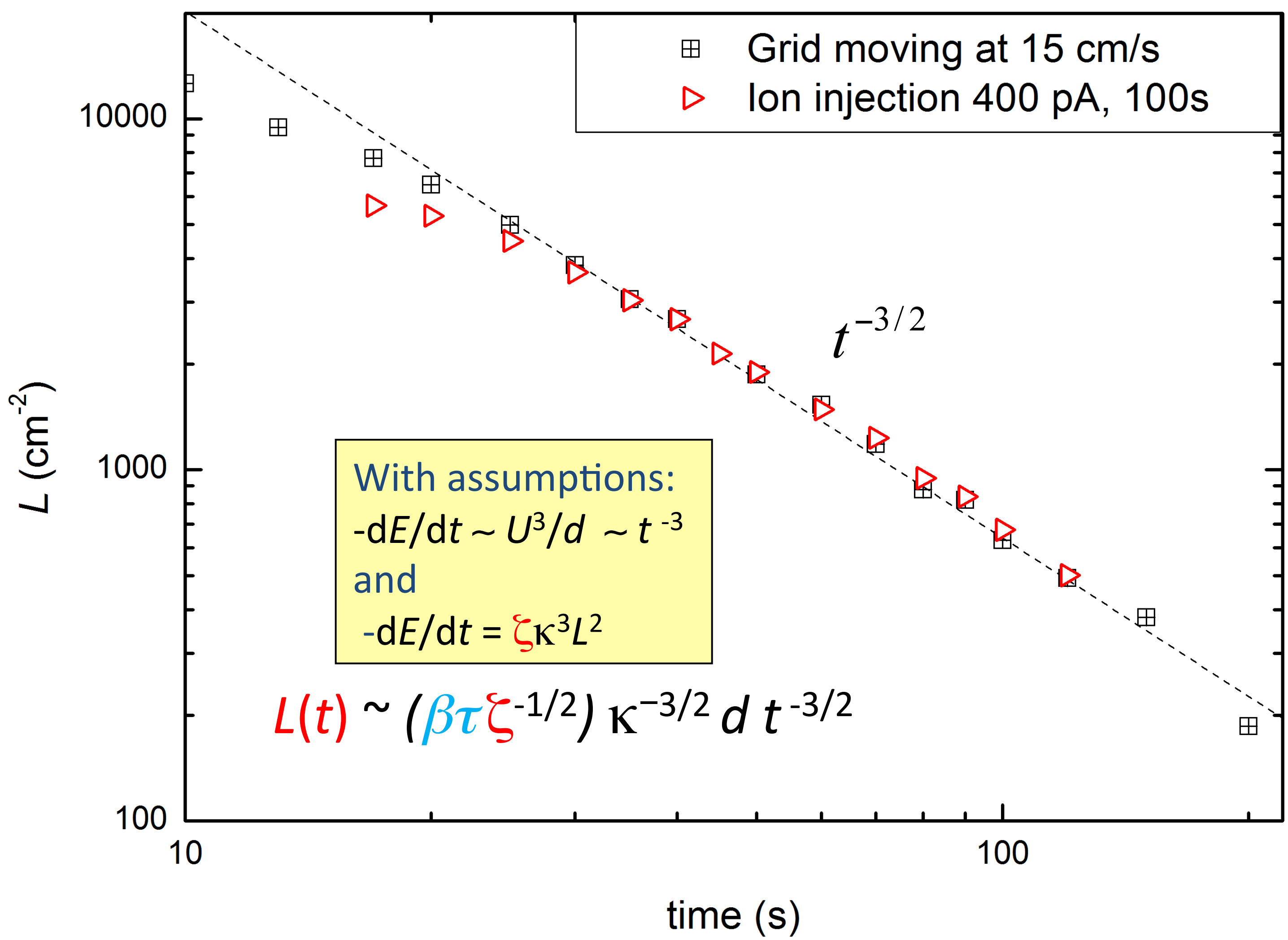
Energy flux, maintained by vortex lines (where $\nu' = \zeta\kappa$ is a an effective parameter, $\zeta \sim 1$):

Assumption: $dE/dt = -\nu'\kappa^{23}L^2$

3. Role of solid boundaries in confined QT?
- Effective boundary conditions: `slip’ or `no-slip’?



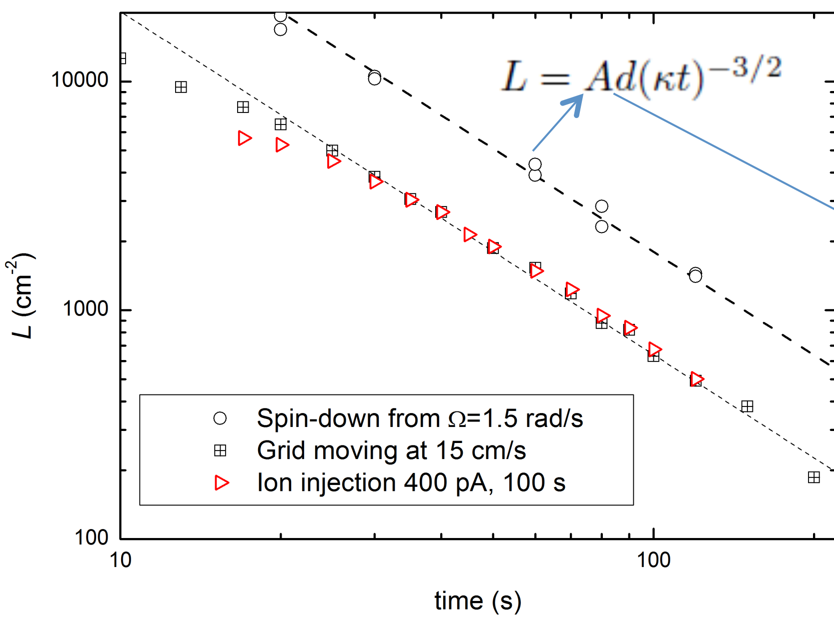
Circumstantial evidence for quasi-classical cascade

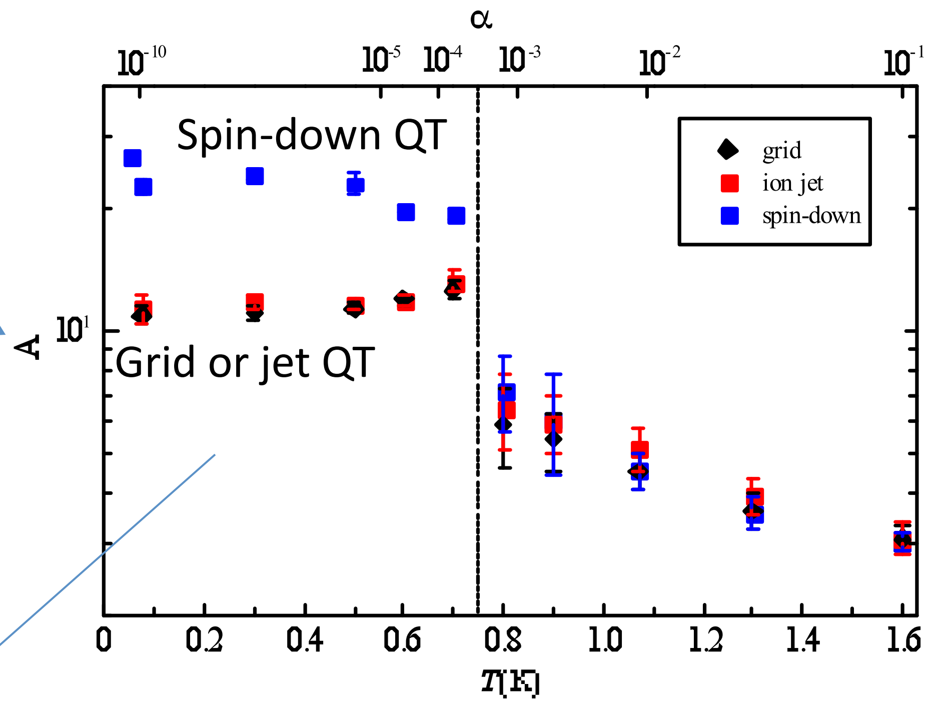


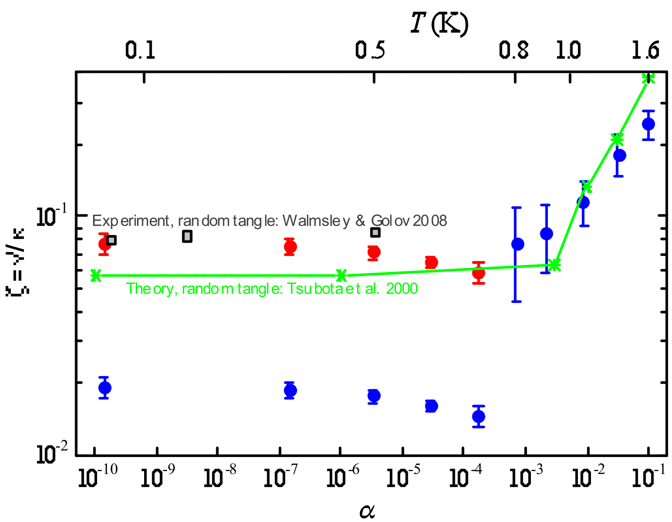
Free decay of QT
T=90 mK
P=0.1 bar

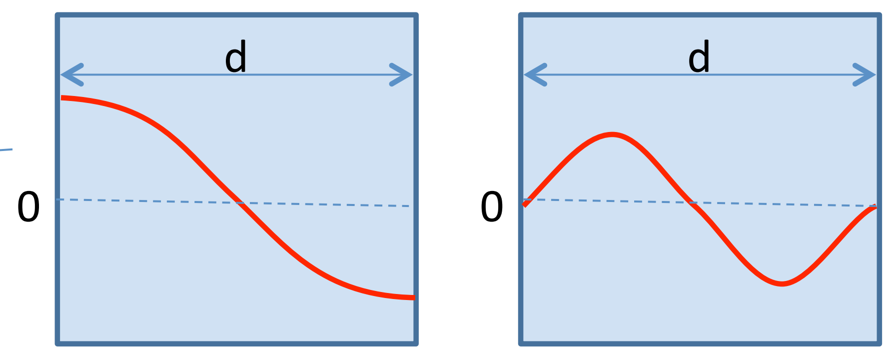
Zmeev et al., submitted to PRL (2015)

At T<0.8K, spin-down turbulence differs from HIT: long-lived angular momentum





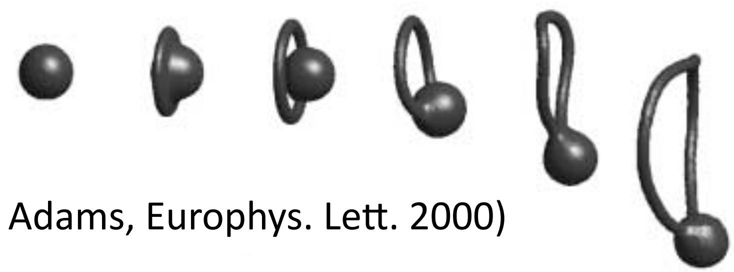




Zmeev et al., submitted to PRL (2015)

Our Detection Method: Scattering of Charged Vortex Rings off Vortex Lines

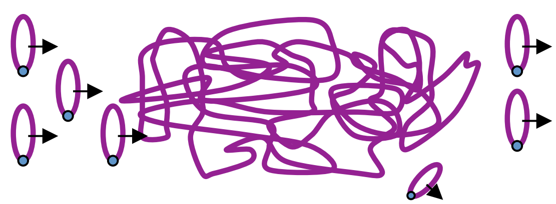
In helium at $T < 0.7$K, an electron (inside bubbles of $R \sim 20$Å) nucleates a vortex rings and travels with it.

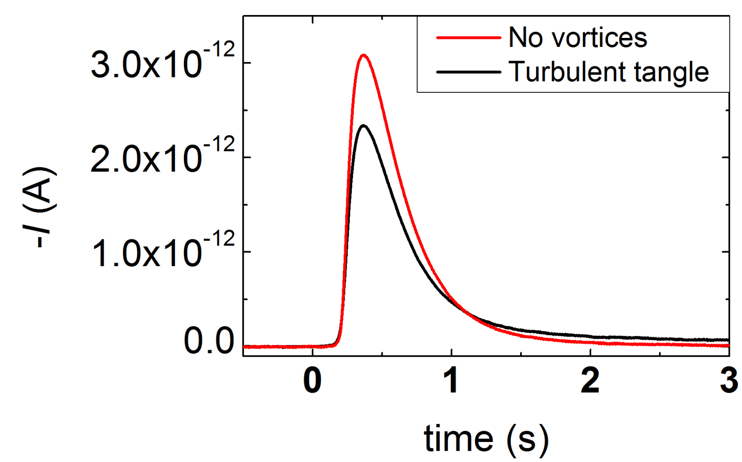


(image from Winiecki and Adams, Europhys. Lett. 2000)

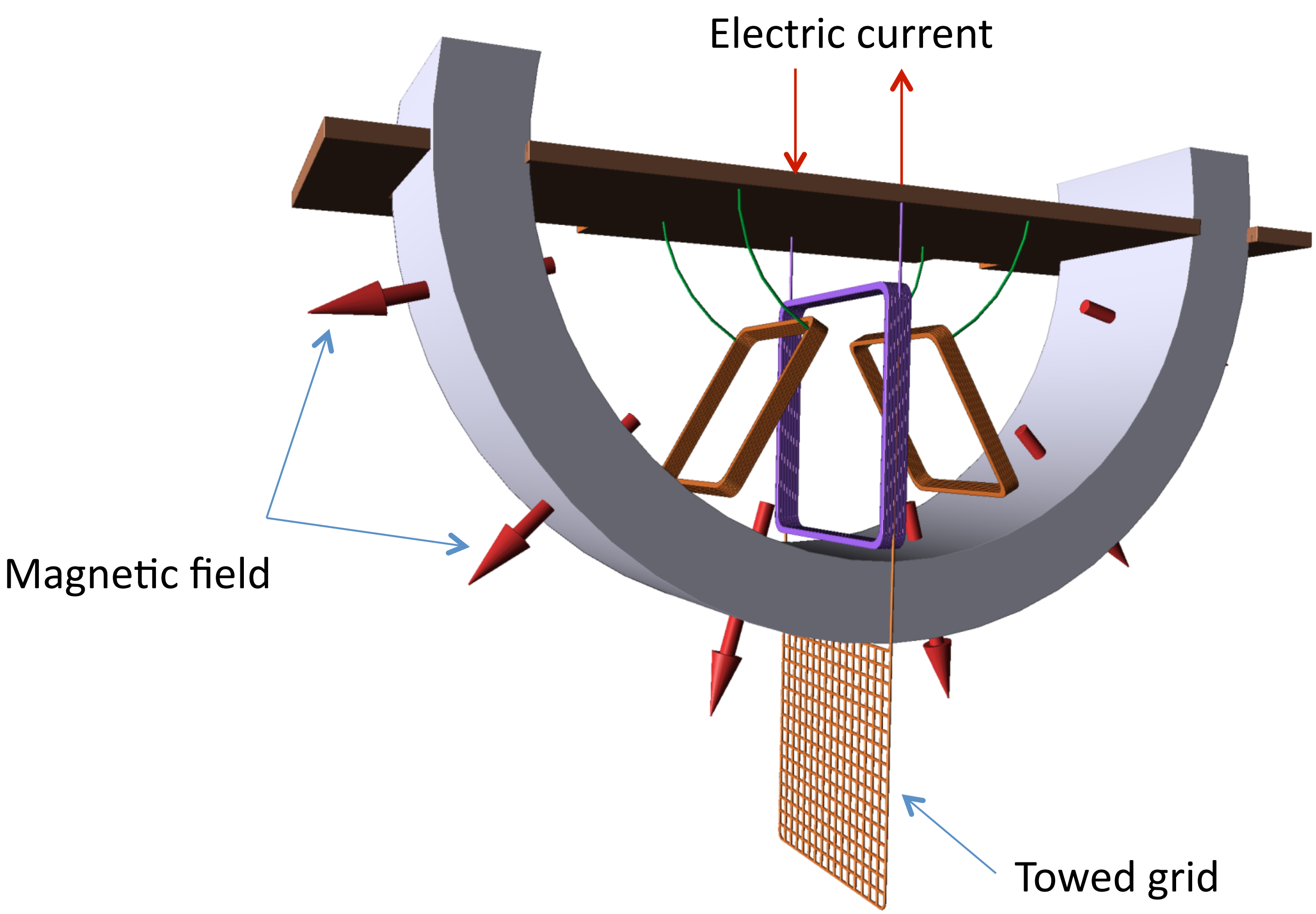
Charged vortex rings of suitable radius (~1 μm) are used as detectors of vortex length *L*

L can be calculated from attenuation of the electric current due to CVRs

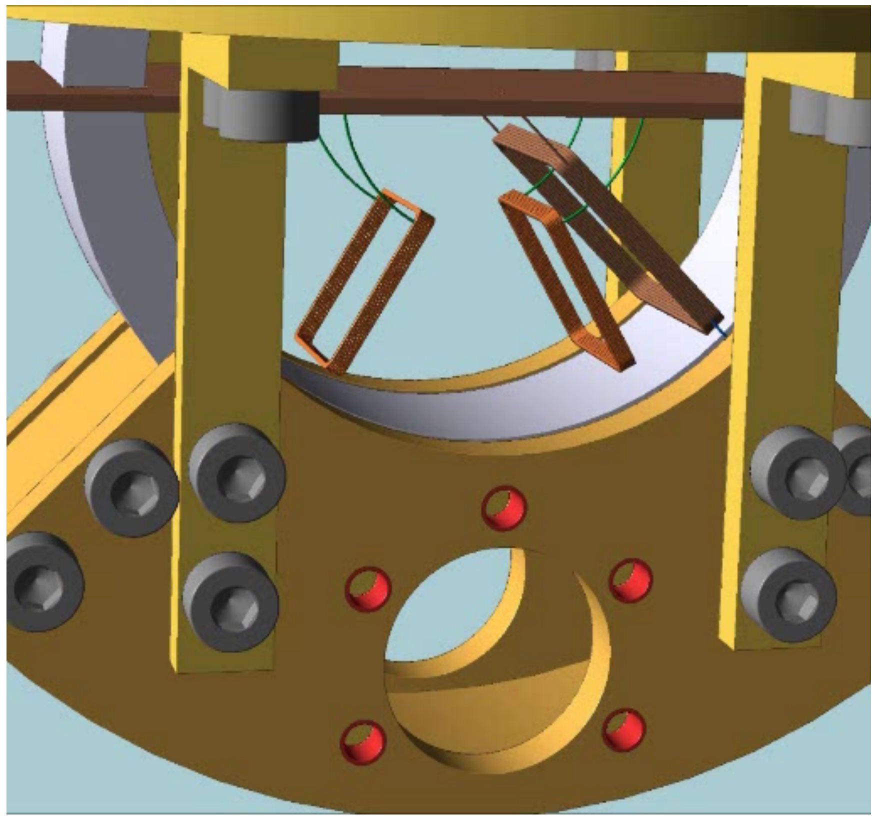




Towed Grid that works at *T*<100mK



Towed Grid



We monitor the free decay of the turbulence after towing the grid through the channel.

Zmeev, J. Low Temp. Phys (2014)

Need for new experiments

1. Generation (existing):

- vibrating objects (Lancaster, Osaka, Kharkov)
- non-steady rotation of a cryostat (Manchester, Helsinki)
- ion jet (Manchester)
- towed grid (Manchester) – talk by Zmeev at QFS

Generation (desired):

- steady flow
- simple flow (pipe, piston, classical vortex ring , or straight vortex (tornado)

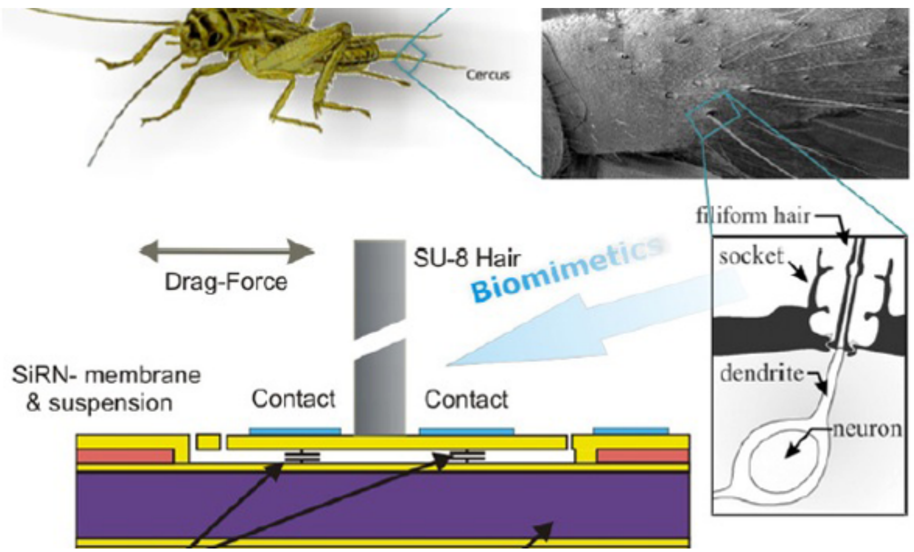
2. Detection of vortex lines (existing):

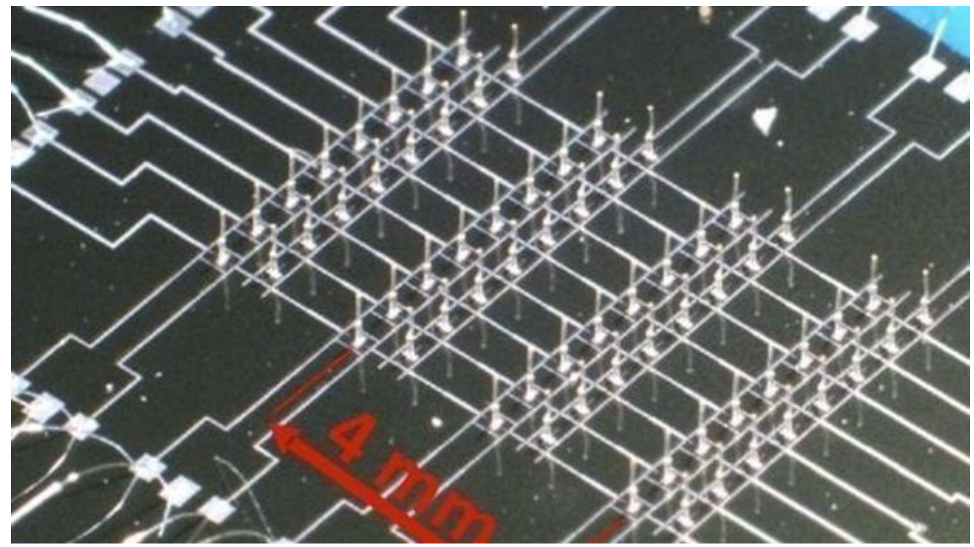
- Interaction with vibrating objects (Lancaster, Osaka)
- Scattering of quasiparticles in ^{3}He-B (Lancaster)
- NMR in ^{3}He-B (Helsinki)
- Scattering of charged vortex rings (Manchester) – talk by Golov at QFS
- Transport of trapped ions (Manchester) – talk by Walmsley at QFS

Detection (desired):

- Mapping velocity, vorticity, pressure fields
- Measuring drag on immersed objects and traction at solid walls
- Visualisation of individual vortices (seeded by fluorescent nanoparticles)

For inspiration:





"Towards a high-resolution flow camera using artificial hair sensor arrays for flow pattern observations"

Dagamseh et al., Bioinspir Biomim. **7**, 046009 (2012), Univ. of Twente