QUANTUM TURBULENCE AT ULTRA-LOW TEMPERATURES

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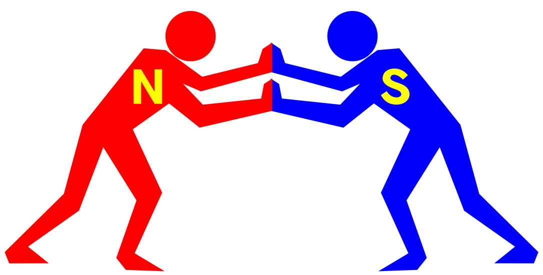
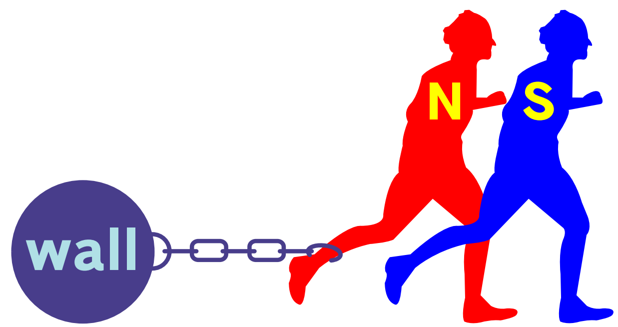
Turbulence in superfluids: Normal and Superfluid components

Damping



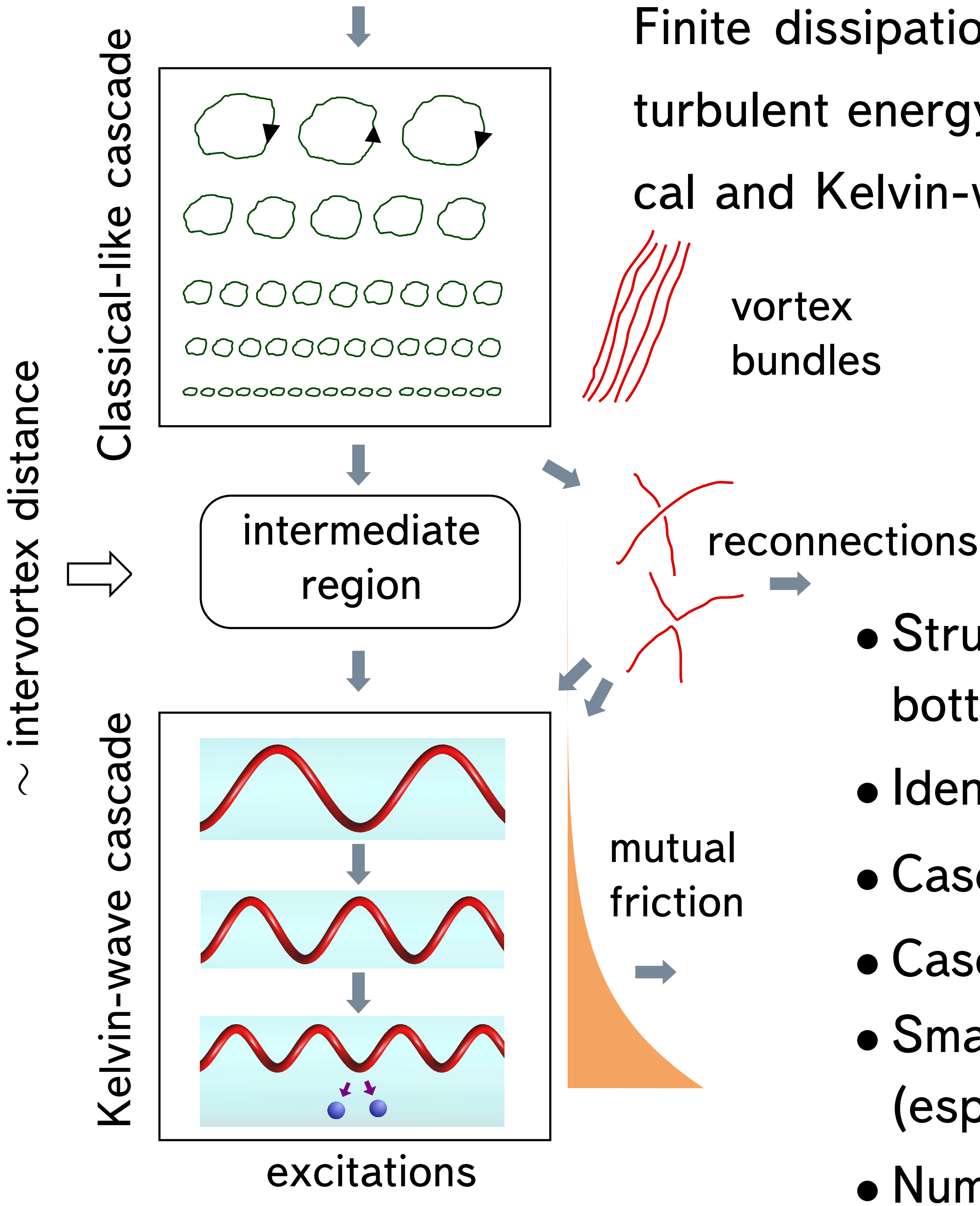
Coupling



What happens when $T \to 0$ and $\rho_{\rm n} \to 0$?

TURBULENT ENERGY CASCADE: GENERALLY ACCEPTED VIEW

Finite dissipation in the $T \to 0$ limit due to the turbulent energy cascade consisting form classical and Kelvin-wave parts.

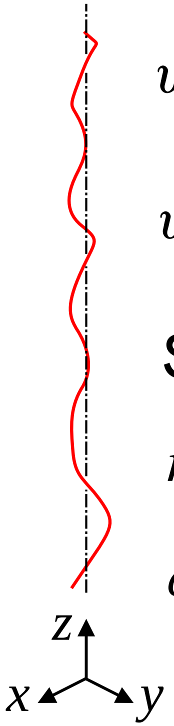


Still many questions:

- Demonstration of vortex bundles, validity of coarse-grained hydrodynamics
- Structure of the intermediate region, bottleneck, role of reconnections
- Identification of Kelvin waves
- Cascade nature (V, KS, LN)
- Cascade *vs* cusps *vs* friction
- Smallest scales, friction, core physics (esp. Fermi systems)
- Numerics $\gg$ experiments

IDENTIFICATION OF KELVIN WAVES

In simulations: easy for an almost straight vortex, hard for a tangle.



$$w(z) = x(z) + iy(z)$$

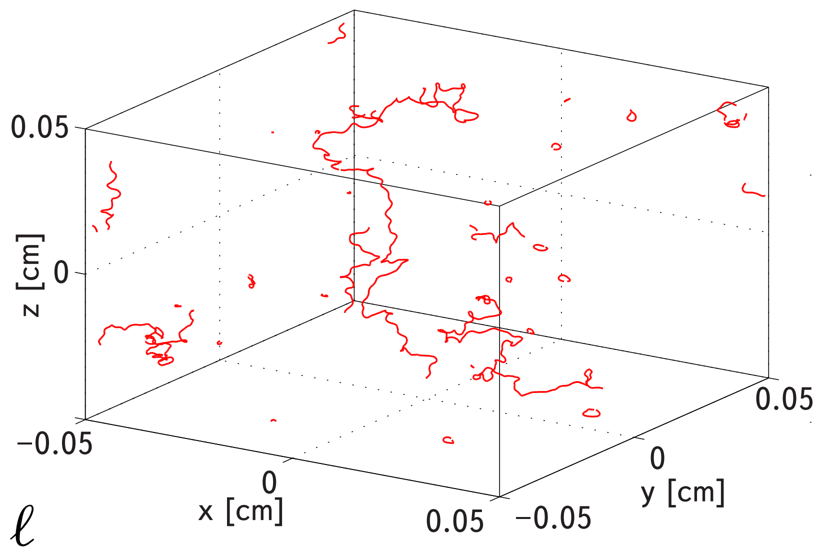
$$w(z) = \sum_k w_k e^{ikz}$$

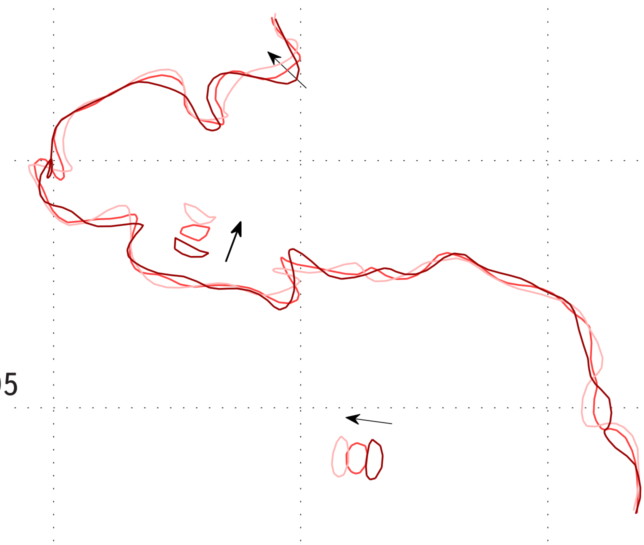
Spectrum:

$$n(k) = |w_k|^2 + |w_{-k}|^2$$

$$\omega(k) = \frac{\kappa\Lambda}{4\pi}k^2, \quad \Lambda = \ln\frac{\ell}{a_0}$$

$$E(k) \propto k^2 n(k)$$





Kozik & Sivstunov, PRL **92**, 035301 (2004)

Hänninen & Hietala, JLTP **171**, 485 (2013)

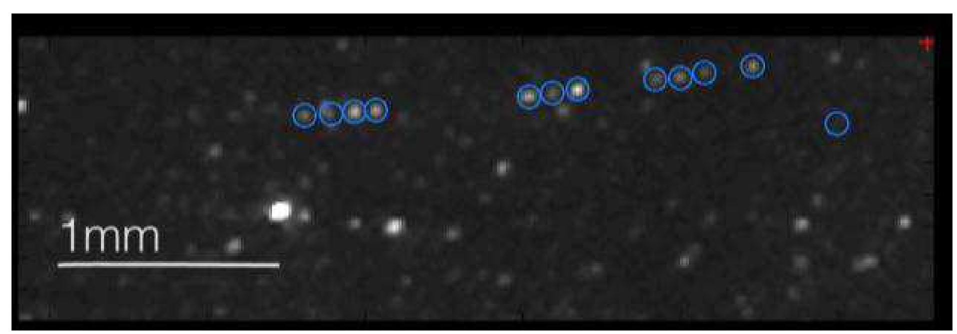
Kondaurova *et al*, PRB **90**, 094501 (2014)

Using more robust parameters, like rms curvature

$$c_{\mathrm{rms}}^2 = \frac{1}{L}\int c(\xi)^2 d\xi \approx \frac{4\pi}{\Lambda\kappa^2}\int_{k_{\mathrm{min}}}^{k_{\mathrm{max}}} k^2 E(k)$$

In experiments: need both spacial and *time* resolution for visualization

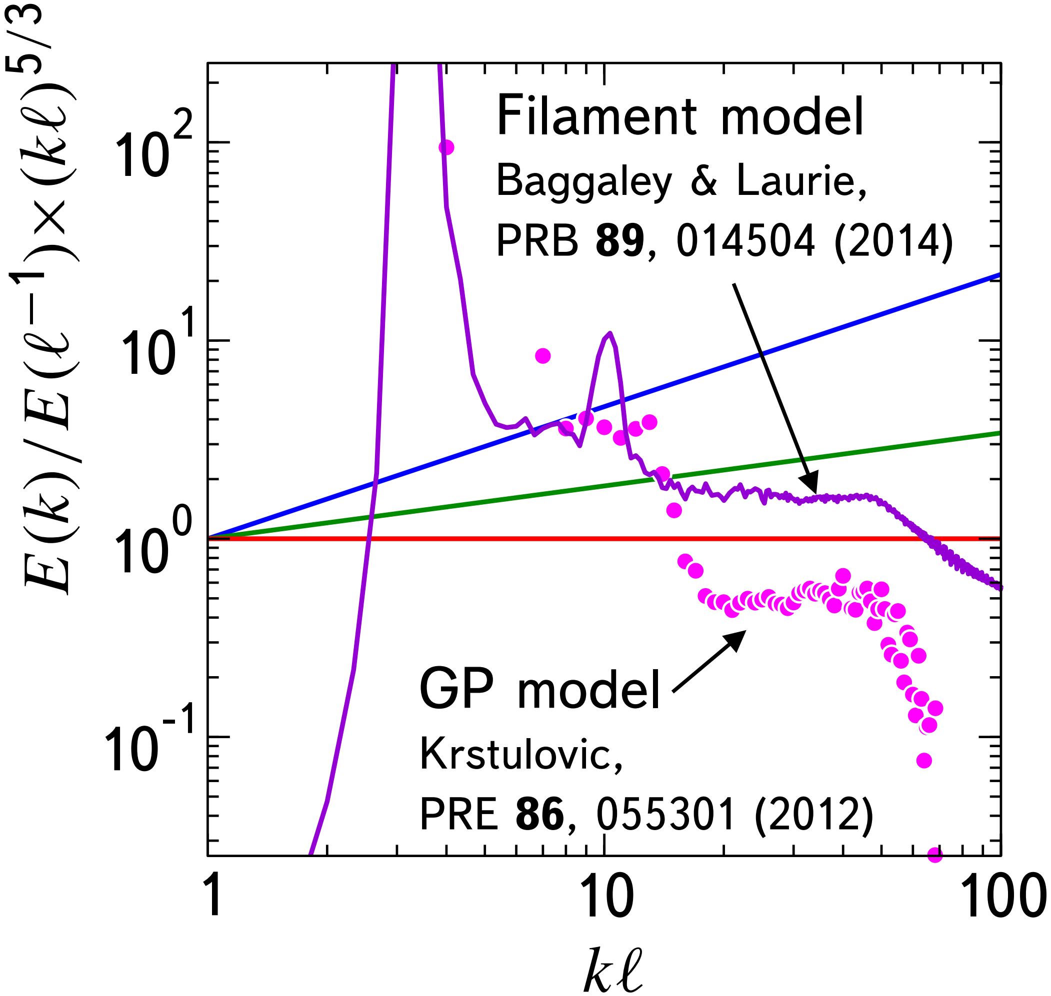
$$\frac{2\pi}{k} = 10^{-3}\mathrm{cm} \sim \frac{\ell}{10} \Rightarrow \frac{\omega}{2\pi} \approx 6\,\mathrm{kHz}$$



Fonda *et al*, PNAS **111**, 4707 (2014)

KELVIN-WAVE CASCADE

Different predictions for KW energy spectrum and controversy.



Vinen $E(k) \propto k^{-1}$

JLTP **128**, 167 (2002)

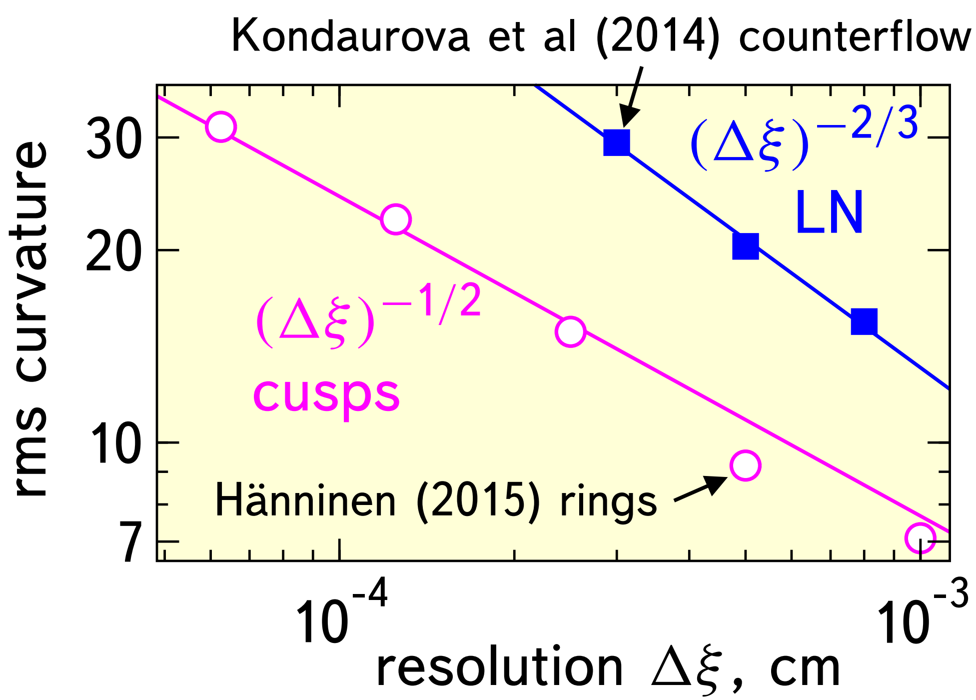
Kozik and Svistunov $E(k) \propto \ell^{-2/5} k^{-7/5}$

PRL **92**, 035301 (2004)

L'vov and Nazarenko $E(k) \propto \ell^{-2/3} k^{-5/3}$

JETP Lett **91**, 428 (2010)

What happens in realistic tangles?

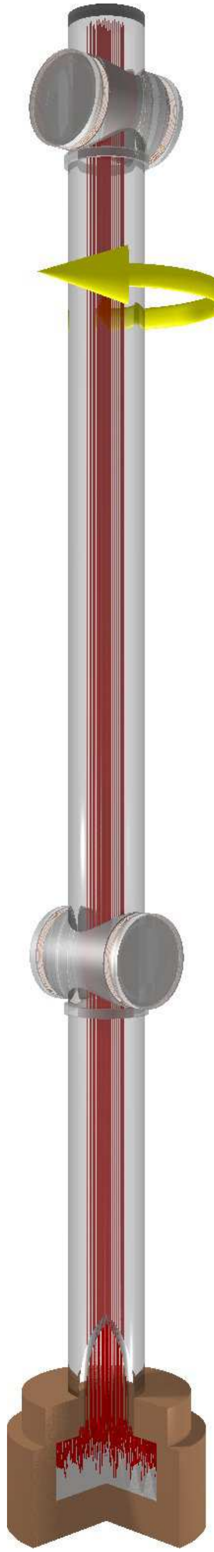


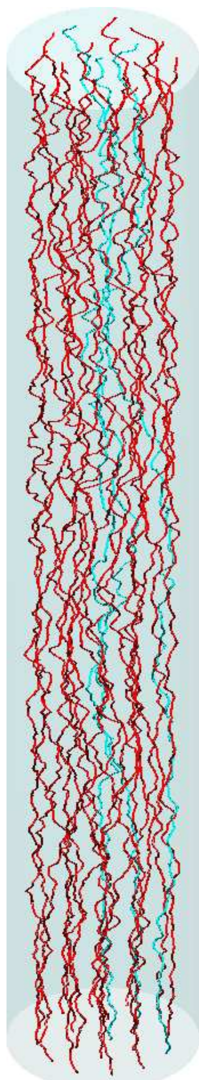
Flow type and, in particular, polarization, may be important.

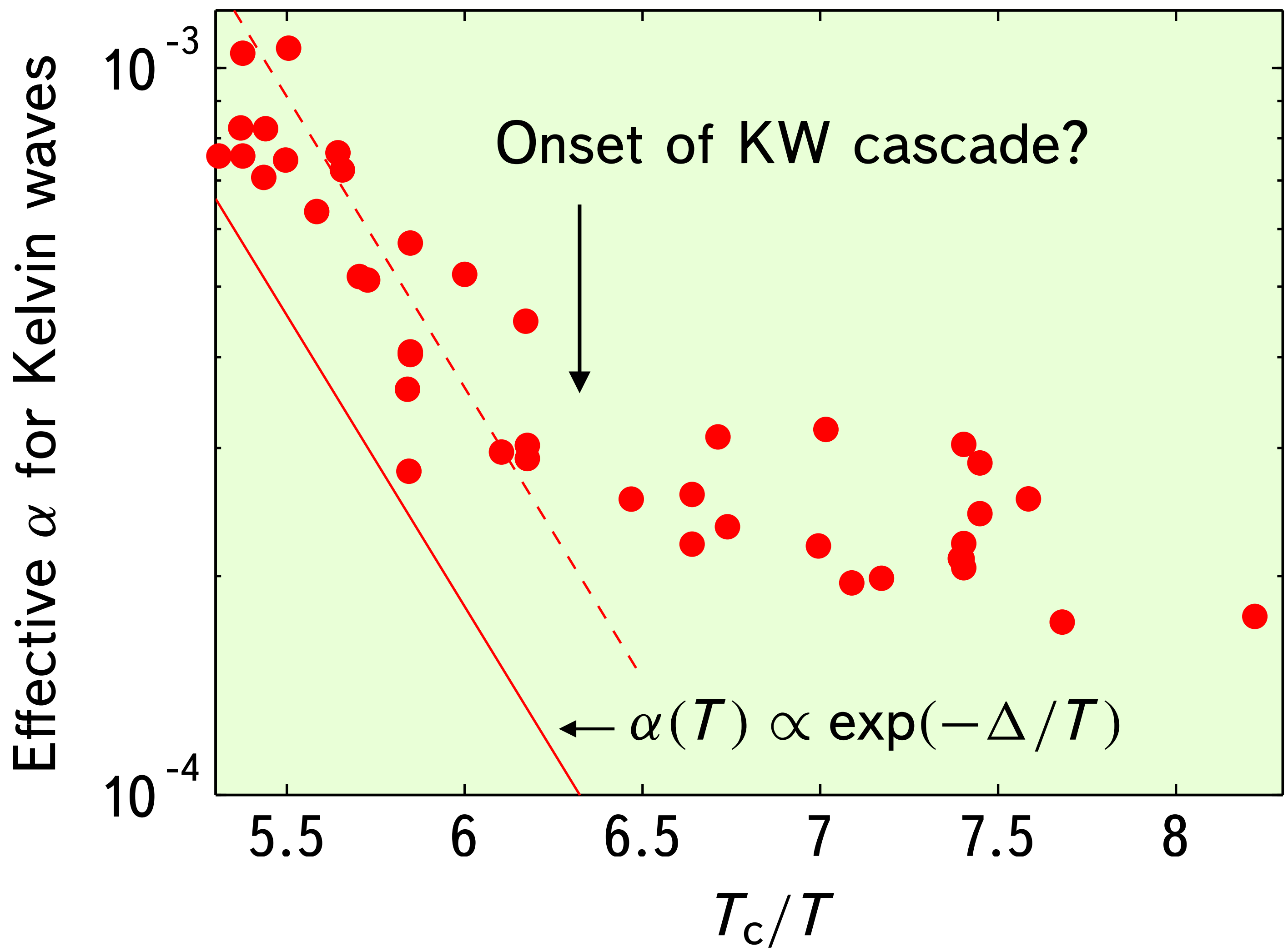
EXPERIMENT ON DECAY OF KELVIN WAVES IN SUPERFLUID ^{3}He-B

Wave turbulenve without reconnections excited by librating motion

$$\Omega(t) = \Omega_0 + \Omega_1 \sin(\omega_{ex} t).$$

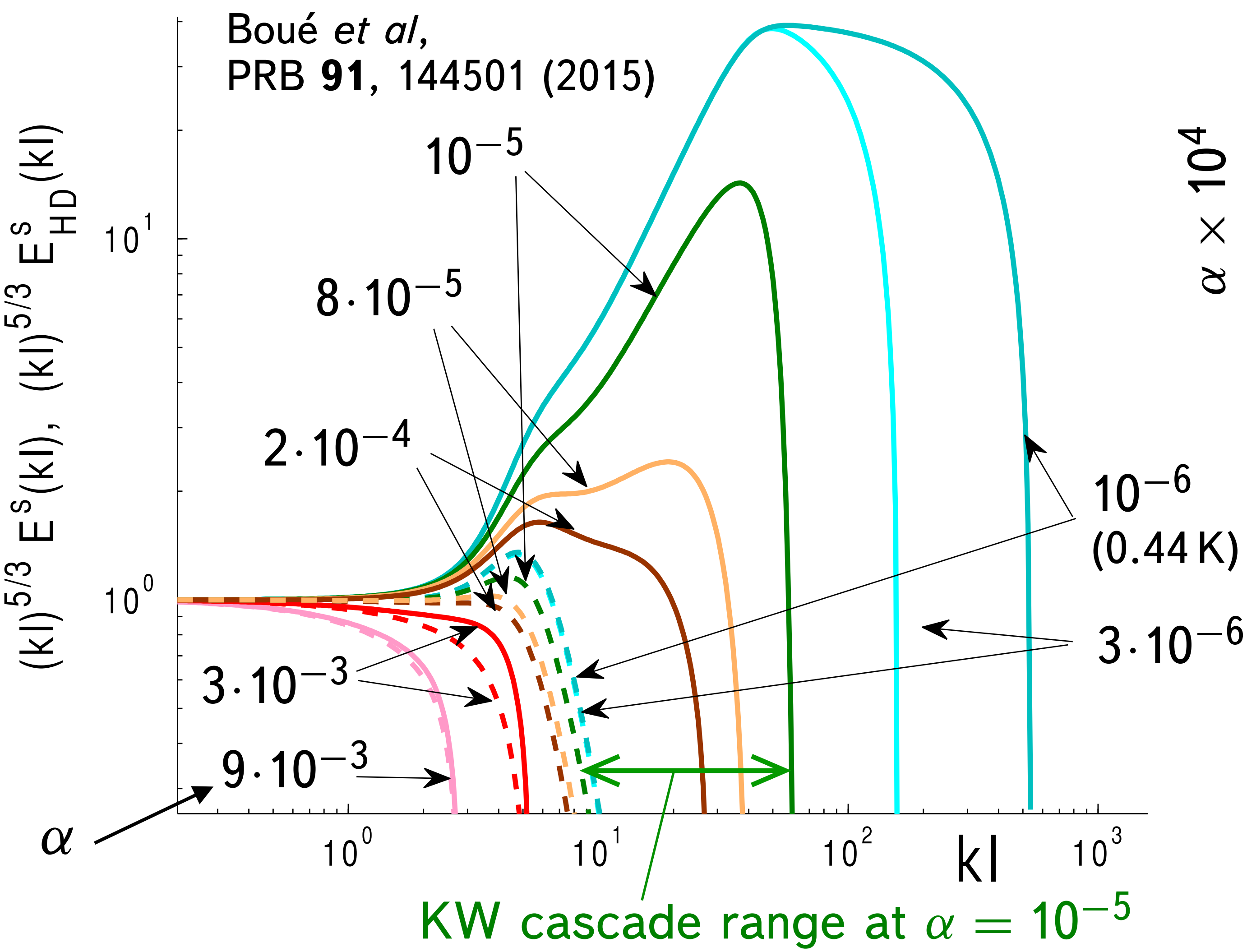


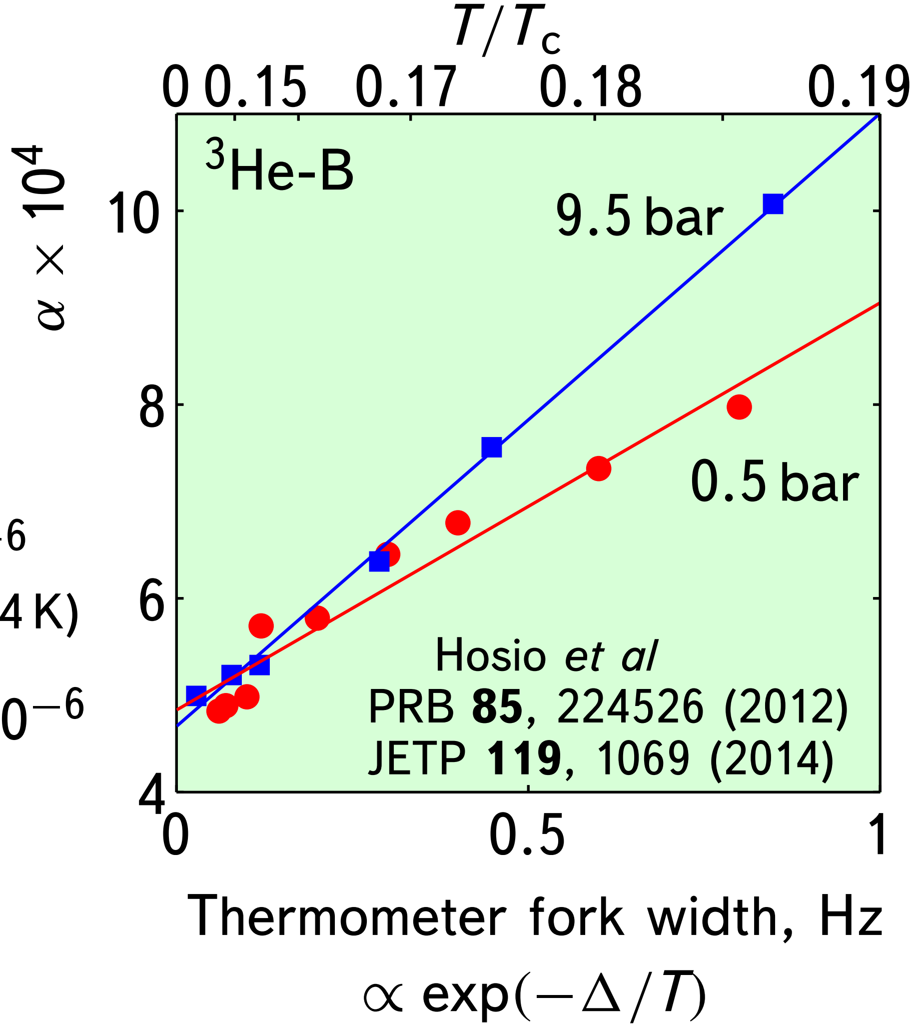




ROLE OF THE MUTUAL FRICTION

KW cascade is easily suppressed by the mutual friction and requires low T.





Do we know mutual friction at ultra-low temperatures?

Theory: Straight vortex, $\Leftarrow$ QT violates all that
constant velocity,
normal component in thermal equilibrium.

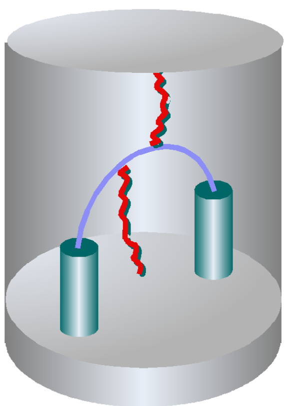
Silaev, PRL **108**, 045303 (2012): finite friction at $T = 0$ from oscillating motion

DYNAMICS OF INDIVIDUAL VORTICES

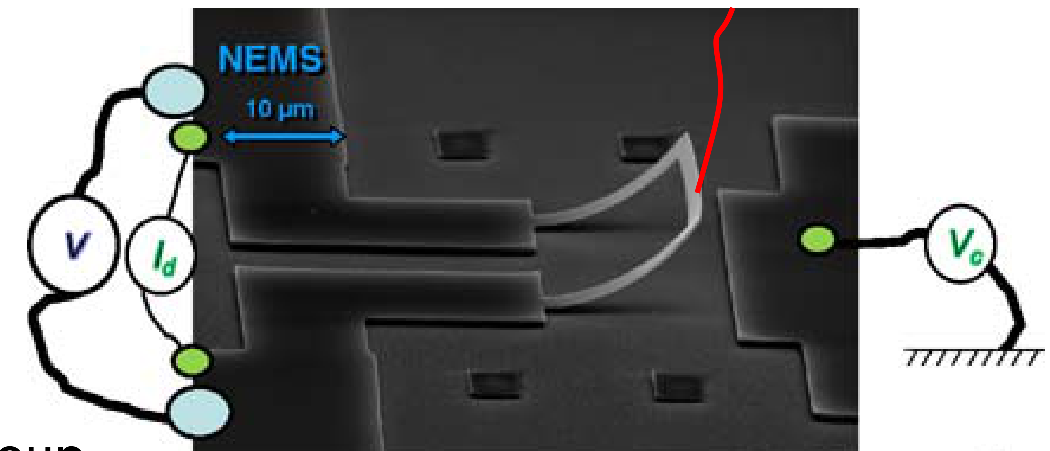
Single-vortex dynamics in the $T \to 0$ limit is important for QT understanding.

In Fermi systems links to non-trivial core physics and topological properties.

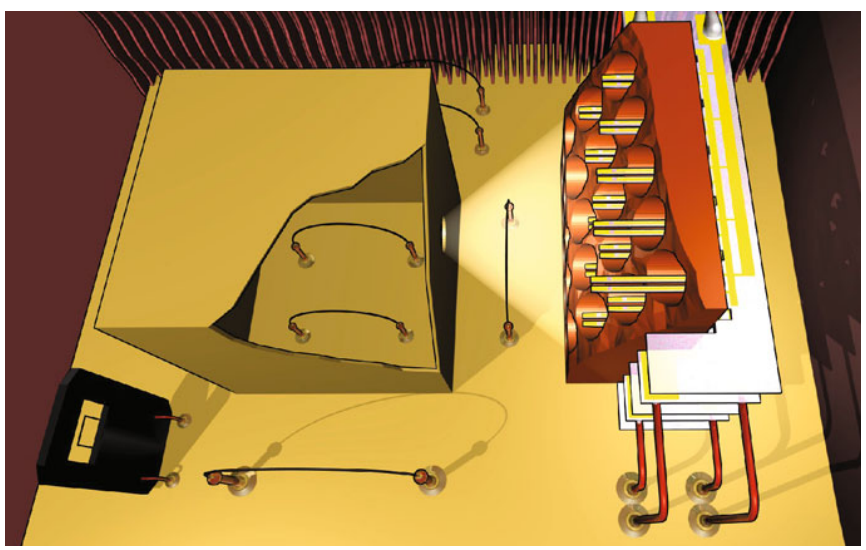
Nanotechnology possibly can provide actuators/sensors.



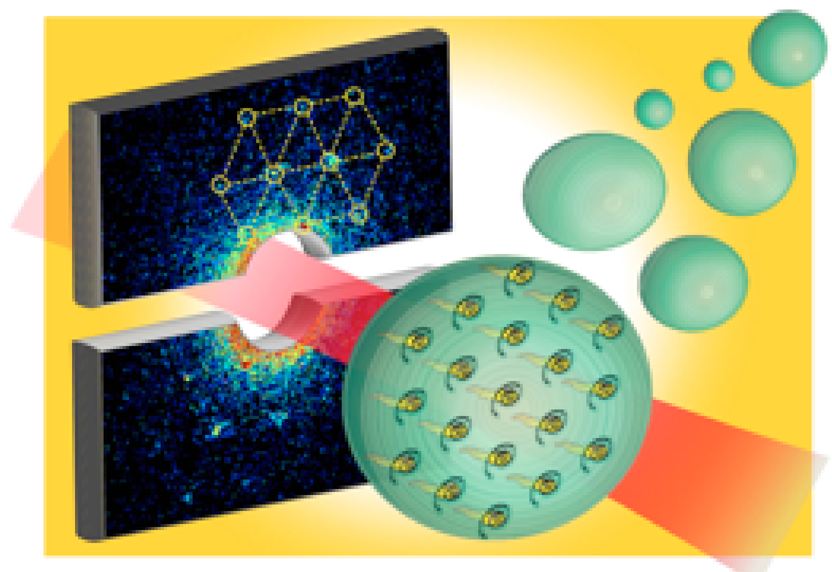
Osaka group



Grenoble group



Lancaster group

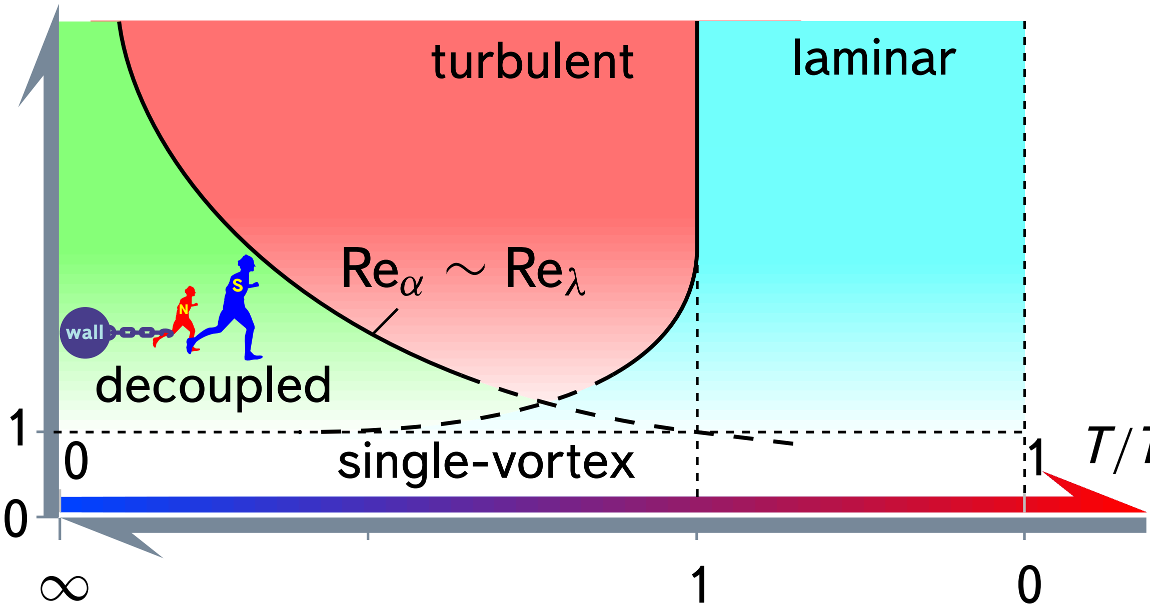


Vilesov group (USC,...)

REGIMES OF SUPERFLUID HYDRODYNAMICS

$$\mathrm{Re}_\lambda = \frac{UR}{\lambda}$$

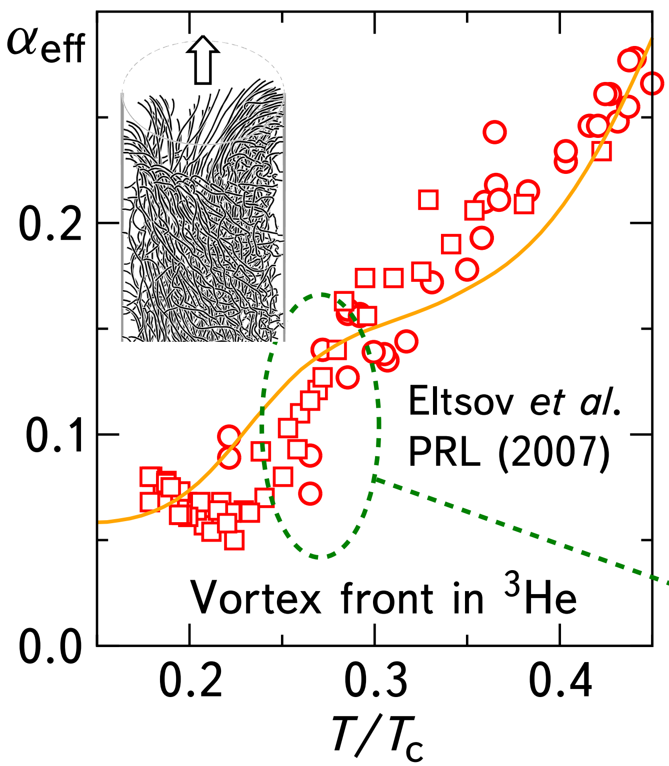
U - velocity
R - spatial scale
$\lambda \approx \kappa$

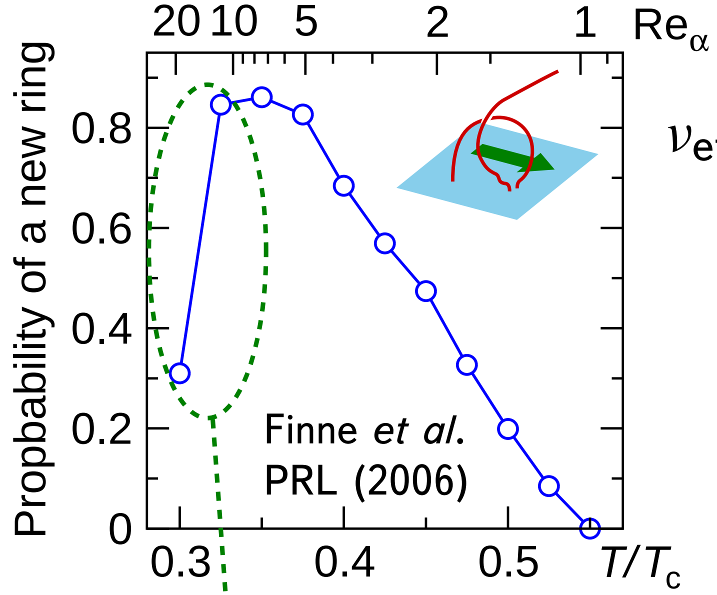


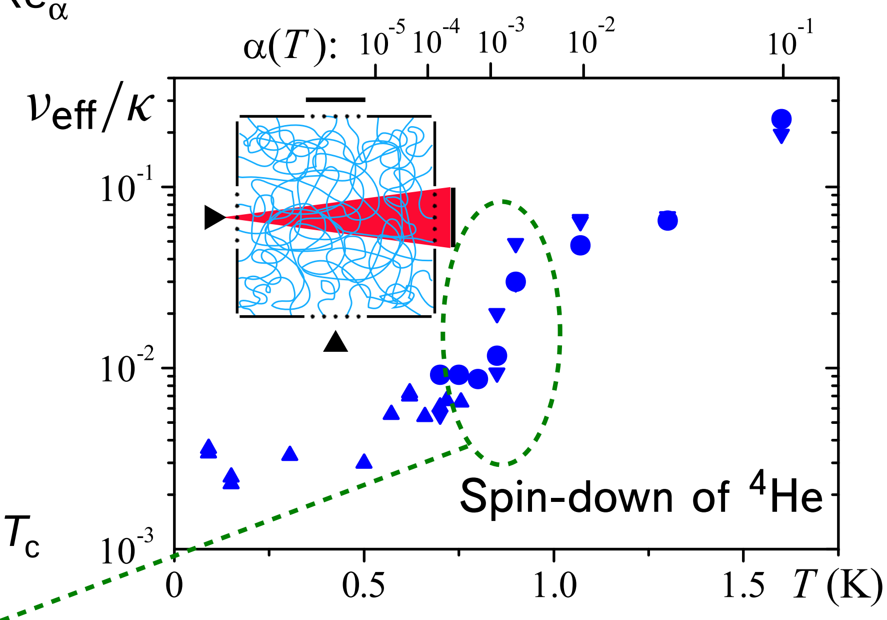
In ^{3}He-B with $\mathbf{v}_n = 0$ and no pinning

PNAS **111**, 4711 (2014)

$$\mathrm{Re}_\alpha = \frac{1-\alpha'(T)}{\alpha(T)}$$







Walmsley *et al.* PRL **99**, 265302 (2007)

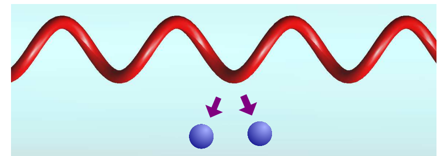
$$\mathrm{Re}_\alpha \sim \mathrm{Re}_\lambda$$

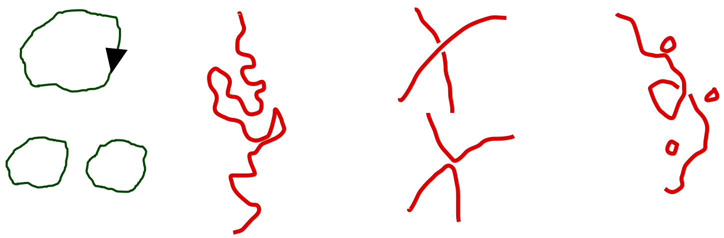
In general, how to identify different regimes? Appropriate "Re"?

CHALLENGES

Understanding quantum turbulence and vortex dynamics in general in the $T \to 0$ limit still (after a decade of research) present many challenges:

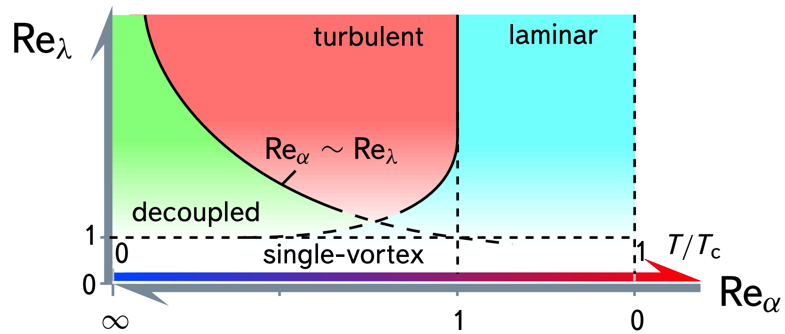
- Interplay of energy cascades of different nature and non-cascading redistribution of energy across the scales.



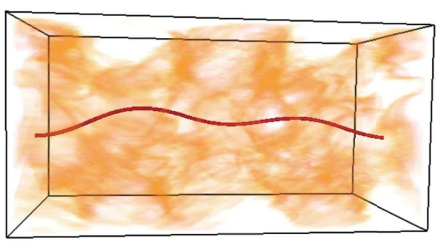


- Different microscopic dissipation mechanism: friction, emission of quasiparticles, non-equilibrium normal component.

- Role of momentum, drag, decoupling.



- Different regimes of QT, similar flows, relevant parameters.



- Simulations models, difficulty to address range of scales, to include new physical phenomena.

- Experiments are scarce, needs for dynamics of individual vortices, visualisation with spatial and time resolution, detectors for non-equilibrium quasiparticles. . .

OUTREACH

- Understanding $T \to 0$ dissipation in Fermi superfluids is important for all topological matter: Common feature of topological materials are zero-energy states (Majorana, Dirac, Weyl fermions), which should play essential role in the ultra-low-temperature behavior.

- Detectors for fast and small-scale liquid motion, for low-energy excitations may find other uses.

- Quantized vortices are nano-scale objects which can carry charges and topologically non-trivial bound states, can apply controlled forces. These properties might be used in novel quantum devices.

- Cooling of nanoelectronics by superfluids is emerging technology. QT can affect the performance of the heat exchange and behavior of NEMS components.