The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

IAEA International Atomic Energy Agency

2023-4

Workshop on Topics in Quantum Turbulence

16 - 20 March 2009

Visualization and Characterization of Quantum Turbulence

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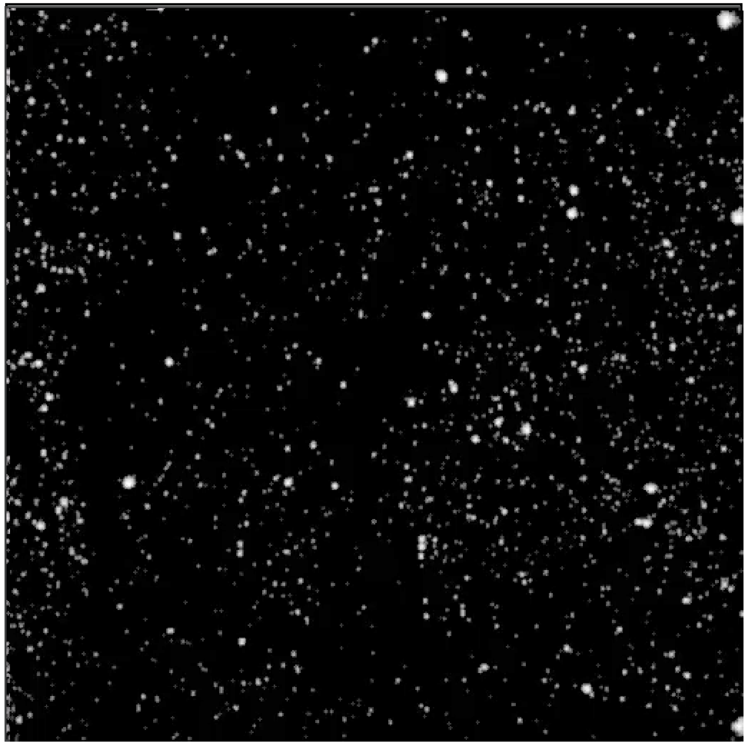
U.S.A.

Visualization and Characterization of Quantum Turbulence

Vortex Reconnection



Quantum Turbulence

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Dissipation in Quantum Turbulence

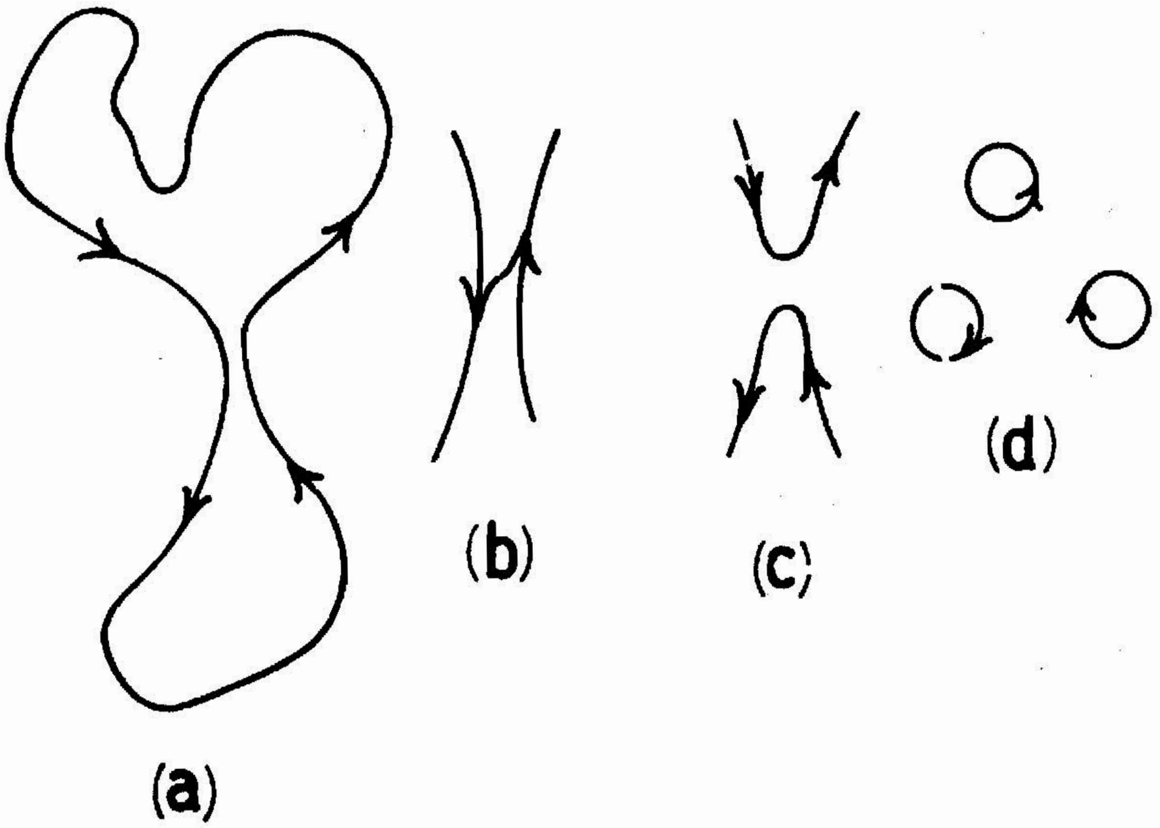


Fig. 10. A vortex ring (a) can break up into smaller rings if the transition between states (b) and (c) is allowed when the separation of vortex lines becomes of atomic dimensions. The eventual small rings (d) may be identical to rotons.

R. P. Feynman, Prog. Low Temp. Phys. **1**, 17 (1955)

Dissipation at Low Temperatures

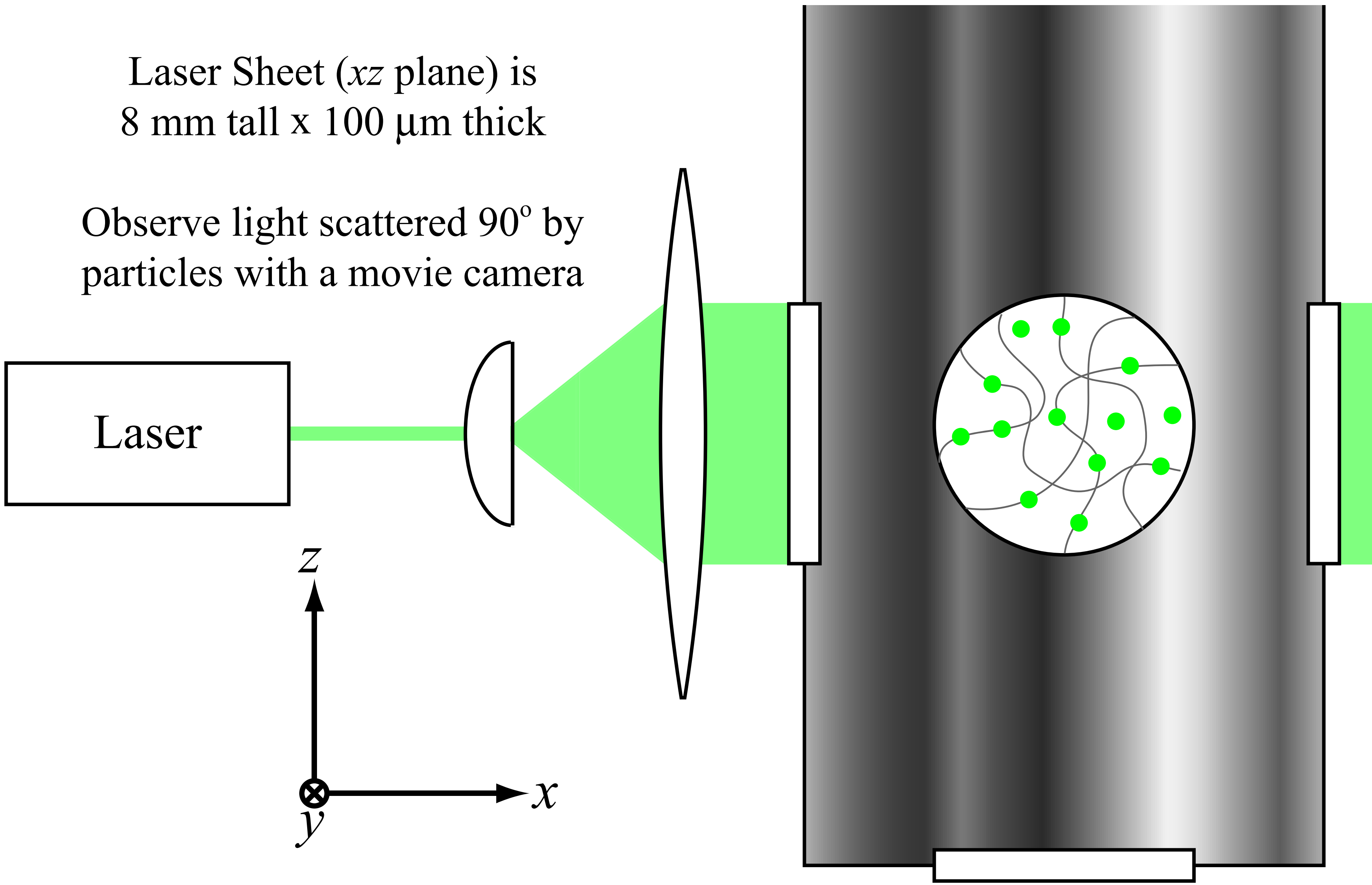
Reconnection, vortex ring dynamics and
Kelvin waves all essential dissipative mechanisms

Can we better understand the dynamics and global
effects of such events through visualization?

Visualization Technique

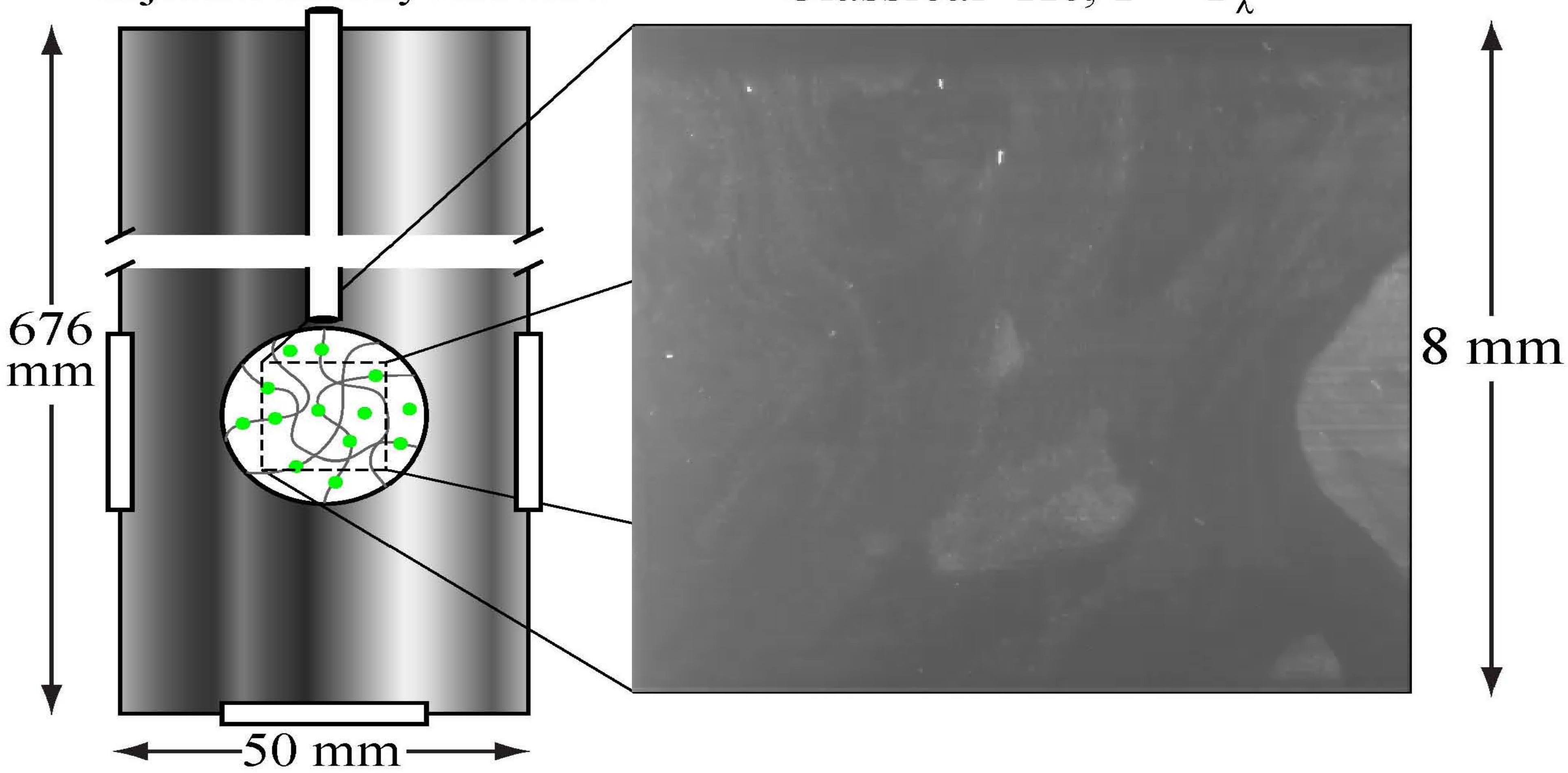
Laser Sheet (*xz* plane) is
8 mm tall x 100 µm thick

Observe light scattered 90° by
particles with a movie camera



Hydrogen Particle Production

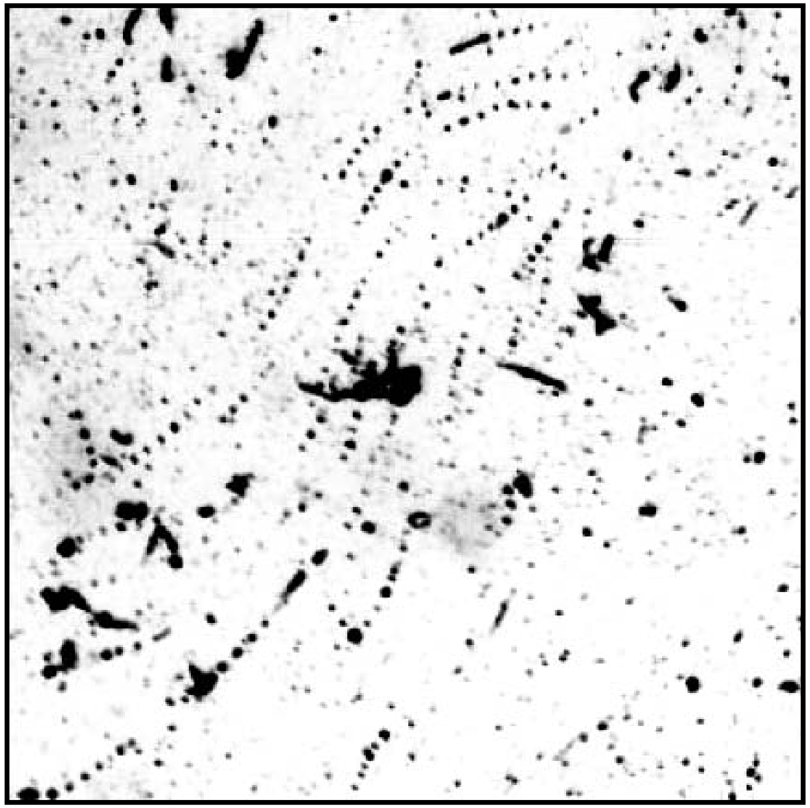
Gaseous mixture 1 H_2 : χ ^4He; $\chi\sim100$
Injected directly into He I



Visualizing Superfluid Vortices in He II

- Below T_λ hydrogen particles collect onto filaments

- Previous work has shown these filaments are particles trapped on the superfluid vortices (Bewley, *et al.*, *Nature* 2006)

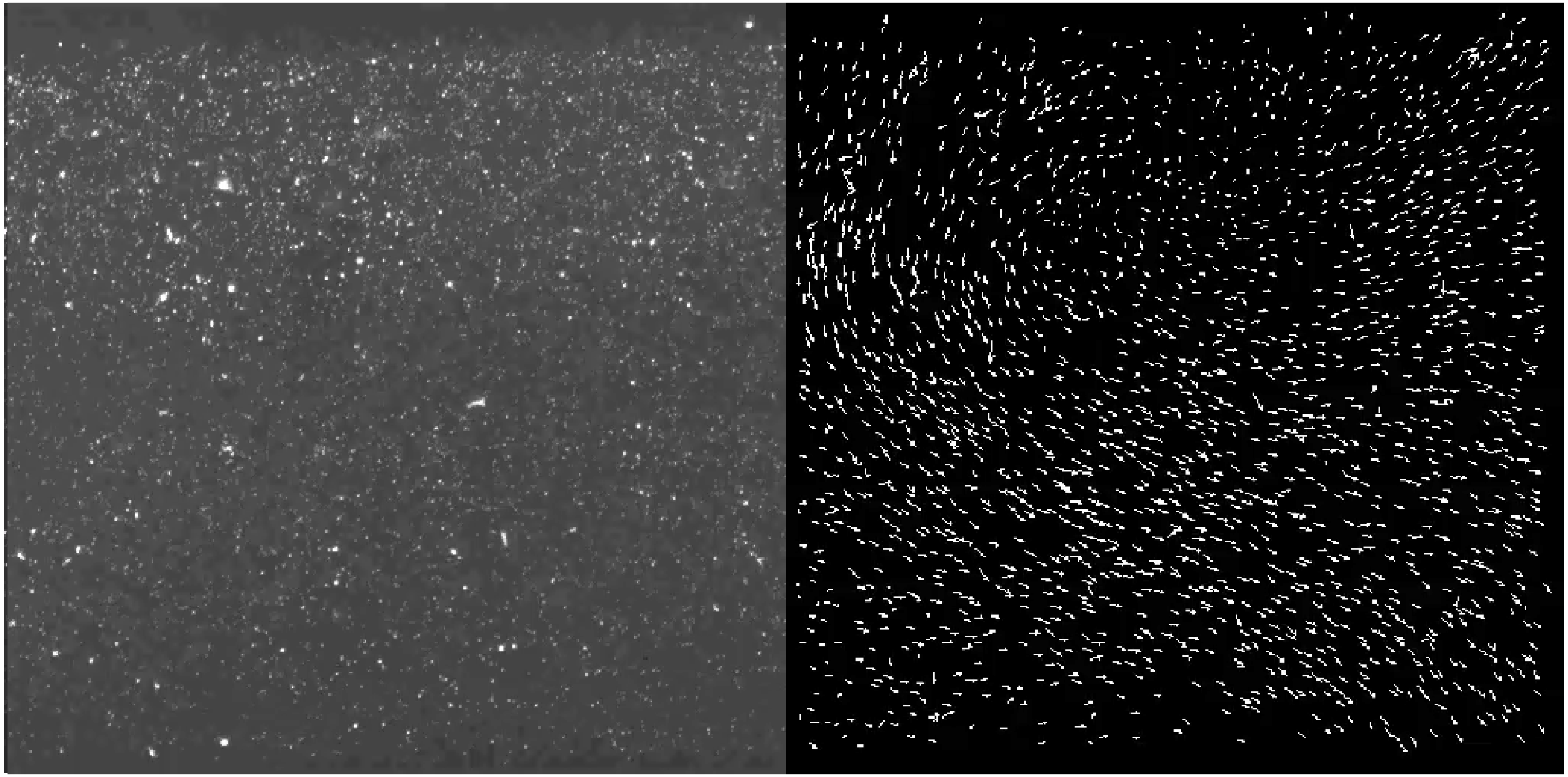


8 mm

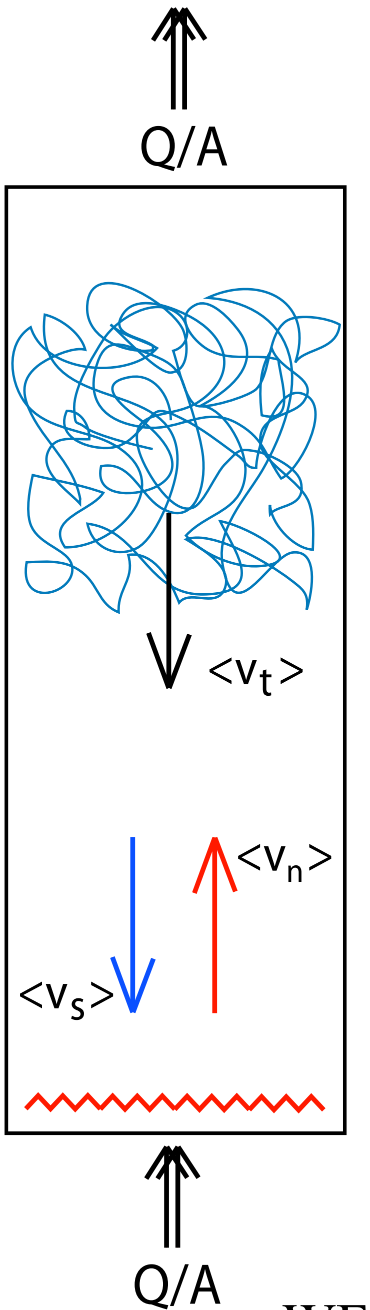
Particle Tracking

Particle-tracking allows us to analyze the particle dynamics without assuming smooth velocity fields (as in PIV)

Particle-tracking software from Eric Weeks and John Crocker



Thermal Counterflow



Reproducibly drive turbulence by applying a heat flux Q/A to the bottom of the channel

$$\frac{dL}{dt} = \alpha \left|\mathbf{v}_{ns}\right| L^{3/2} - \beta\kappa L^2$$

$$L = \frac{\text{vortex line length}}{\text{volume}}, \ \mathbf{v}_{ns} = \mathbf{v}_n - \mathbf{v}_s$$

The spatially averaged velocites are of:

$\langle v_n \rangle$ - the viscous component,

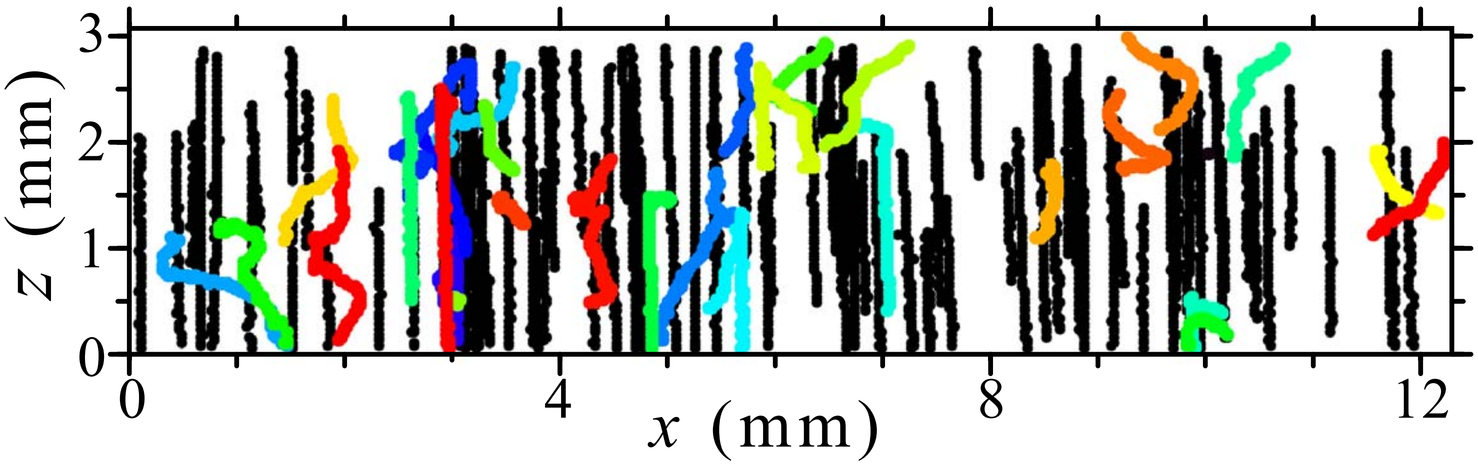
$\langle v_s \rangle$ - the superfluid,

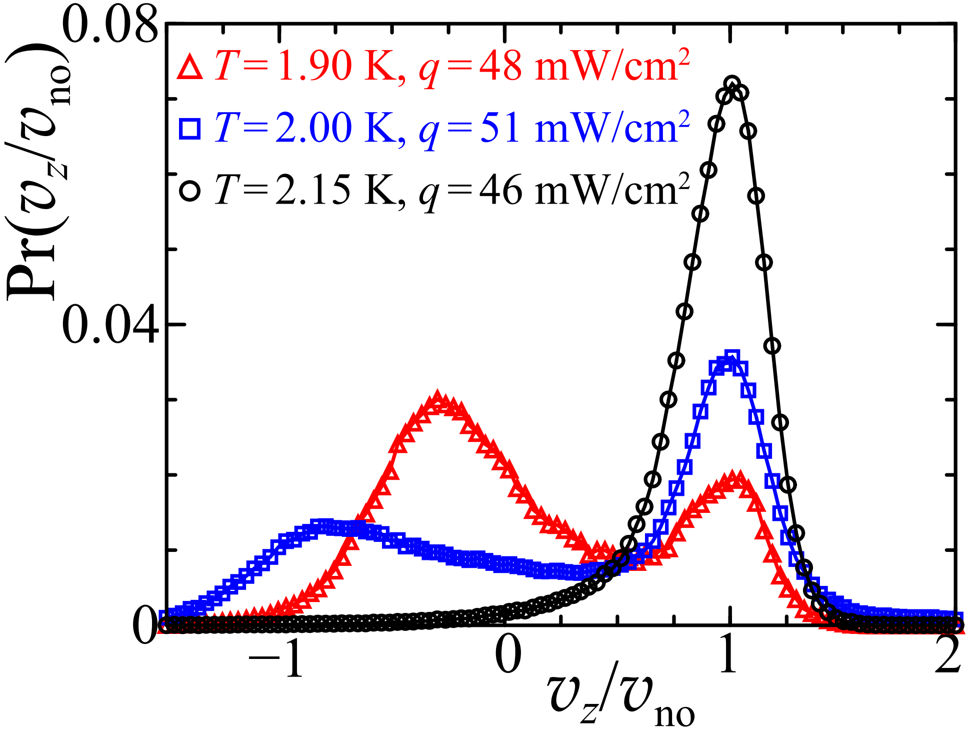
$\langle v_t \rangle$ - the quantized vortex tangle

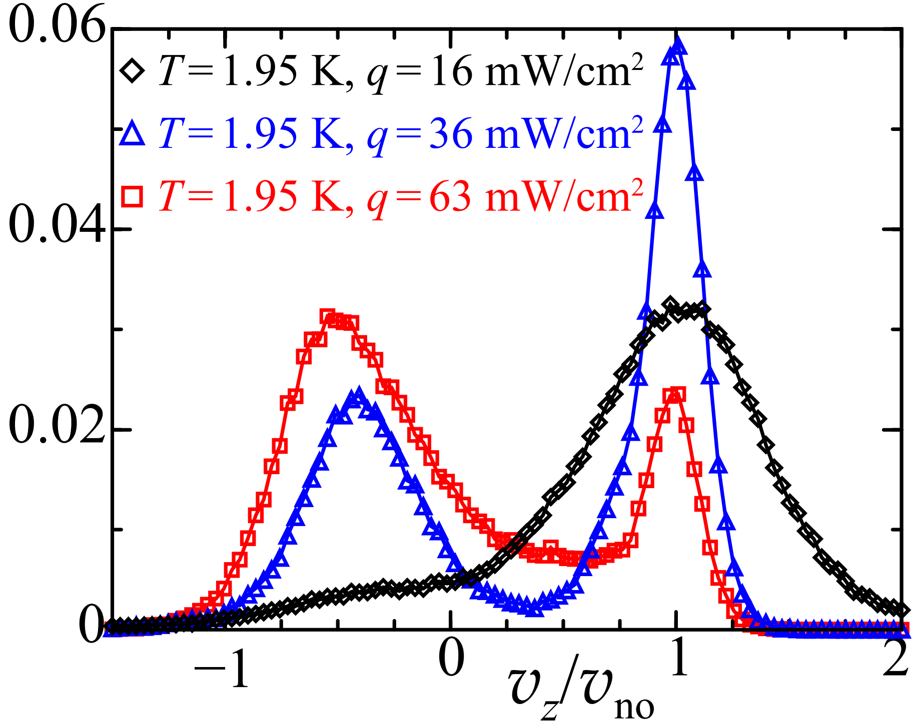
WF Vinen: Proc. R. Soc. London Ser. A **242**, 493 (1957)

MSP, Fiorito, Sreenivasan, and Lathrop, J. Phys. Soc. Japan **77**, 111007 (2008)

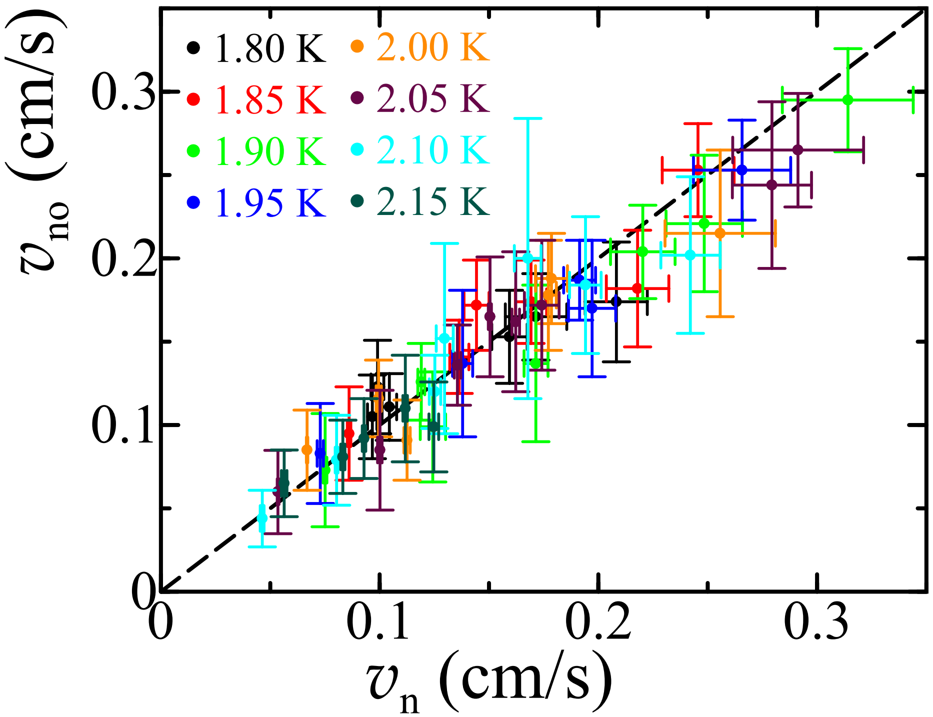
Thermal Counterflow Velocity Statistics



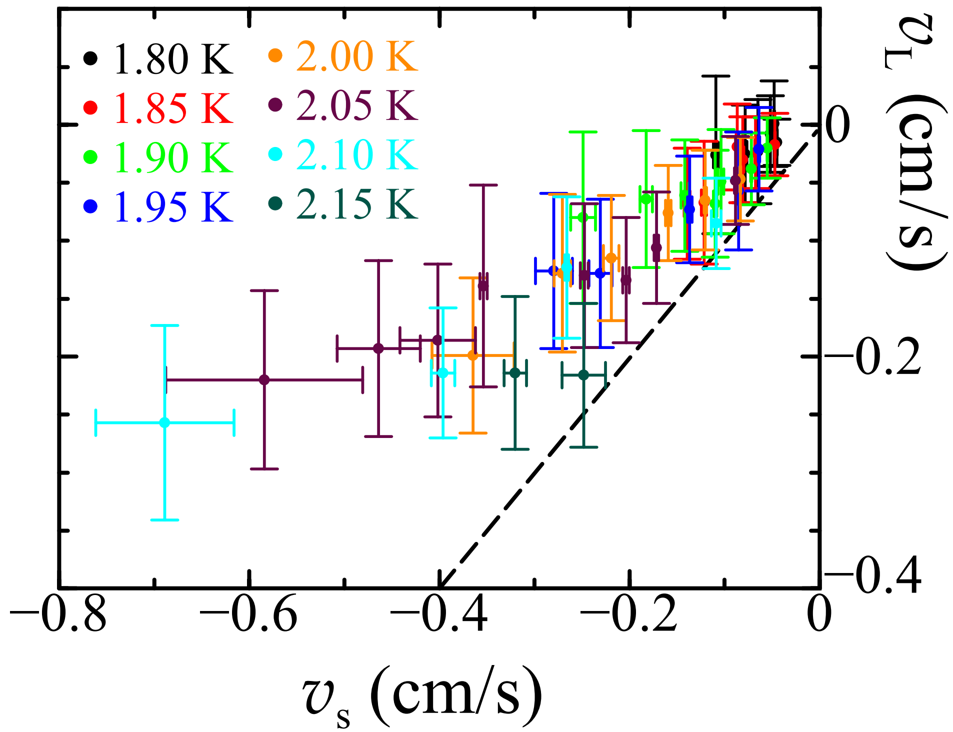




Thermal Counterflow Velocities



Observed normal fluid velocities match those predicted for all tempeartures and heat fluxes



Observed vortex line velocities are always below v_s, likely due to mutual friction

Decaying Quantum Turbulence

Previous experimental studies:

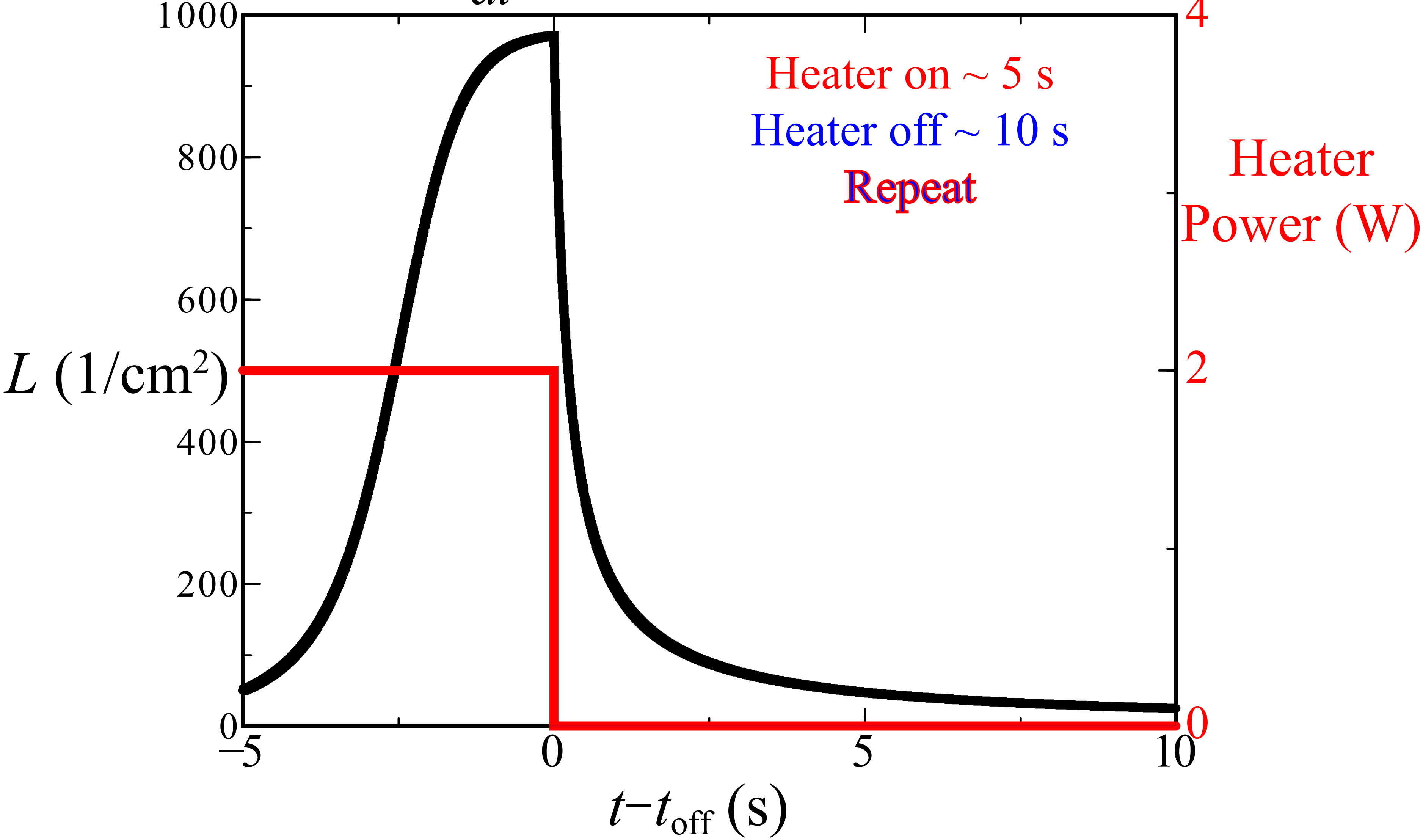
- Smith *et al.*, PRL 1993 (grid, second sound)
- Skrbek *et al.*, PRL 2000 (grid, second sound)
- Skrbek *et al.*, PRE 2003 (counterflow, second sound)
- Gordeev *et al.*, JLTP 2005 (counterflow, second sound)
- Niemela *et al.*, JLTP 2005 (grid, secound sound)
- Chagovets *et al.*, PRE 2007 (counterflow, second sound)
- Walmsley *et al.*, PRL 2007 (spin down, negative ions)
- Walmsley *et al.*, JLTP 2008 (spin down, negative ions)
- Walmsley *et al.*, PRL 2008 (ion jet, negative ions/CVRs)

Previous measurements are global averages of dynamics

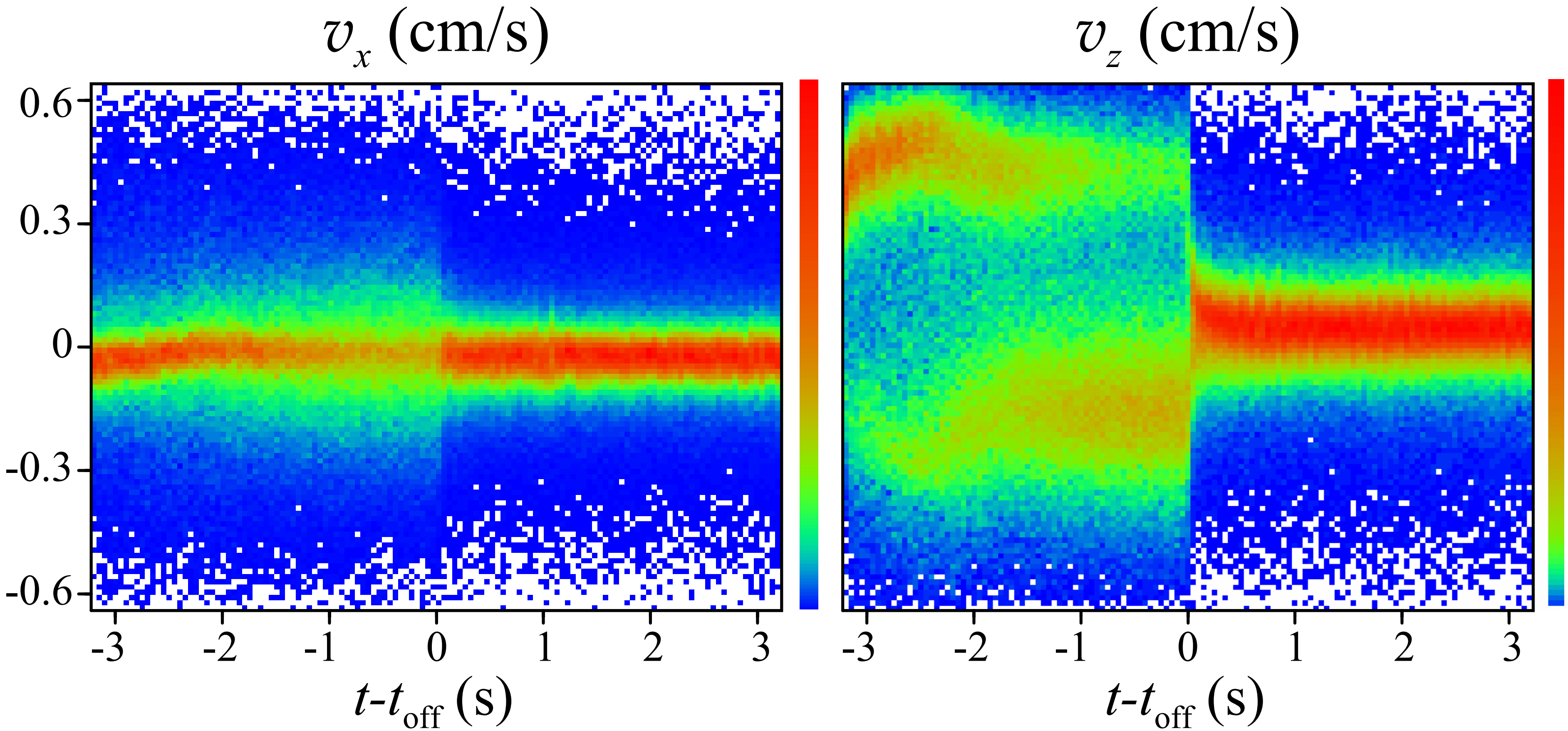
Supplement previous work using visualization to locally probe decaying quantum turbulence

Decaying Counterflow Turbulence

$$\frac{dL}{dt} = \alpha \left| \mathbf{v}_{ns} \right| L^{3/2} - \beta \kappa L^2$$



Pulsed Counterflow Velocities

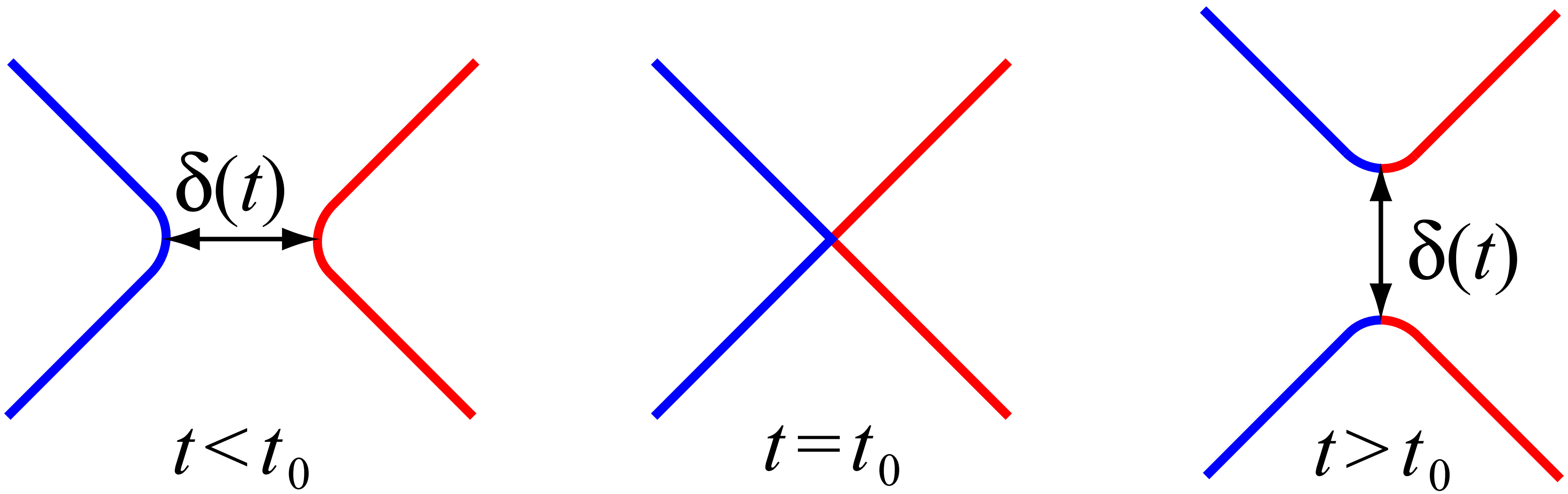


What is the source of high velocity trajectories when heater is off?

Superfluild Vortex Reconnection

Feynman, Prog. LTP (1955)
Schwarz, PRB (1985)
Schwarz, PRB (1988)
Tsubota and Maekawa, JPSJ (1992)
Koplik and Levine, PRL (1993)
de Waele and Aarts, PRL (1994)
Lipniacki, EJ Mech. B-Fluids (2000)
Nazarenko and West, JLTP (2003)

Previous theoretical studies predict that when two vortices cross they reconnect and that the dynamics are (nearly) time-reversible



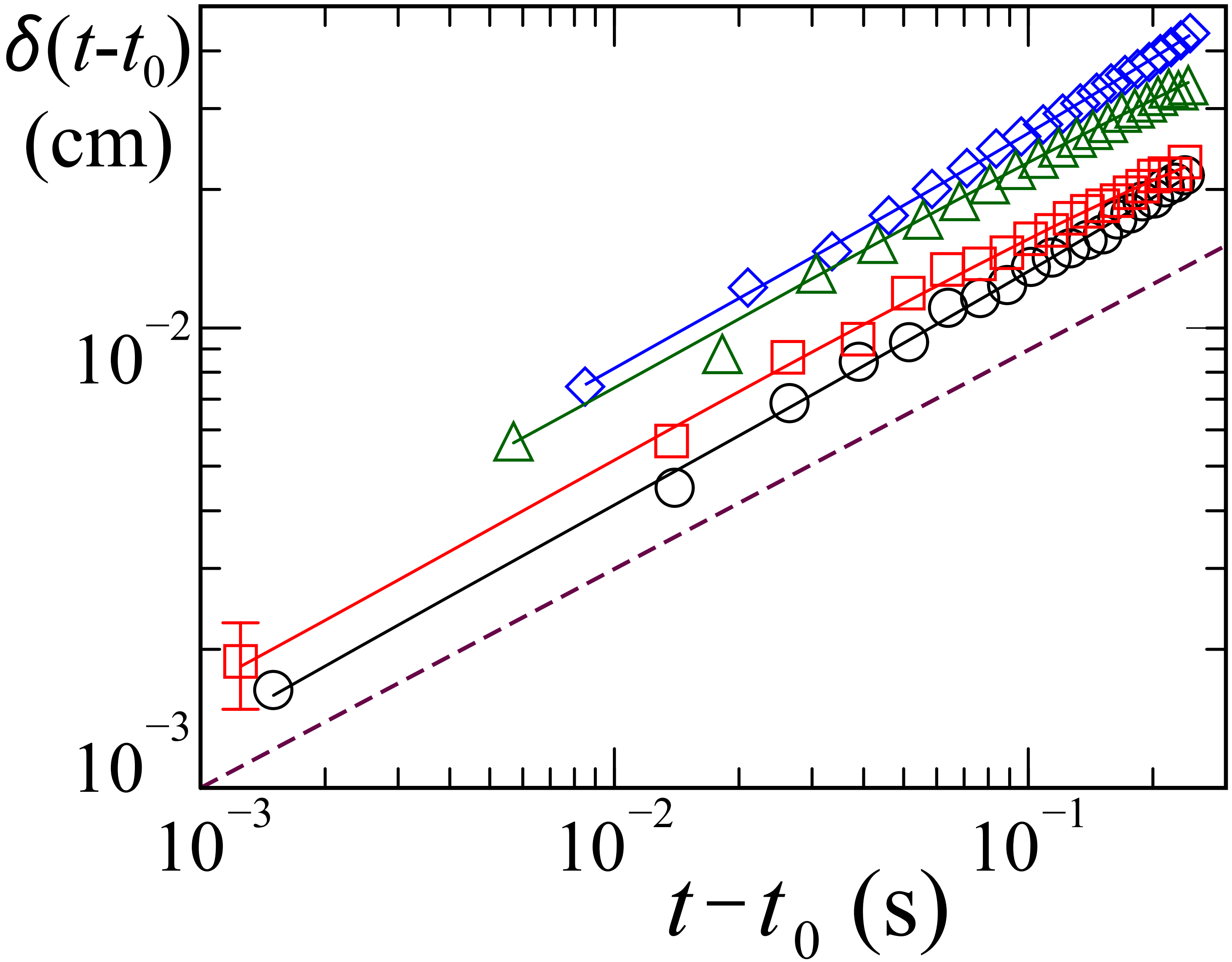
$\delta(t) = A[\kappa(t_0 - t)]^{1/2}$

$\delta(t) = A[\kappa(t - t_0)]^{1/2}$

Bewley, MSP, Sreenivasan and Lathrop, PNAS **105**, 13707 (2008)

Reconnection Dynamics

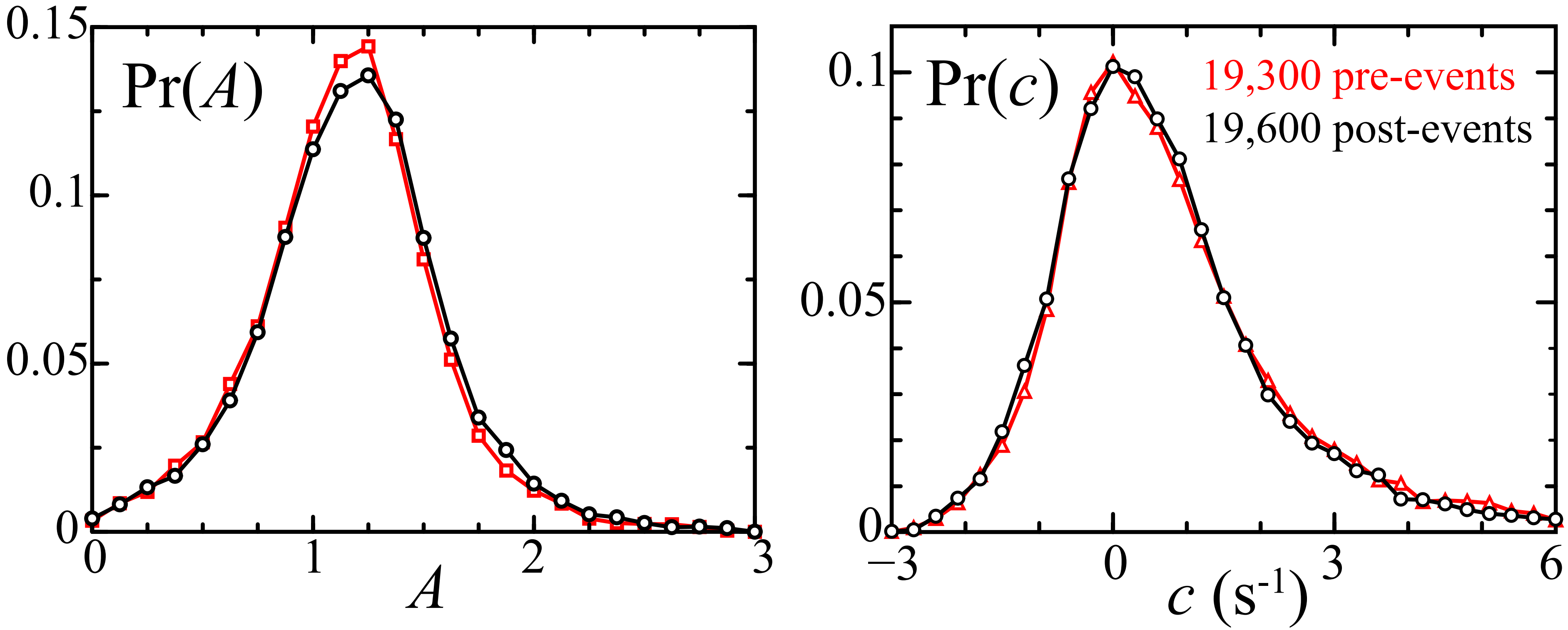
$$\delta(t) = A[\kappa(t\text{-}t_0)]^{1/2}[1+c(t\text{-}t_0)]$$



Correction-Factor Expression

Pre-reconnection: $\delta(t) = A[\kappa(t_0-t)]^{1/2}[1+c(t_0-t)]$

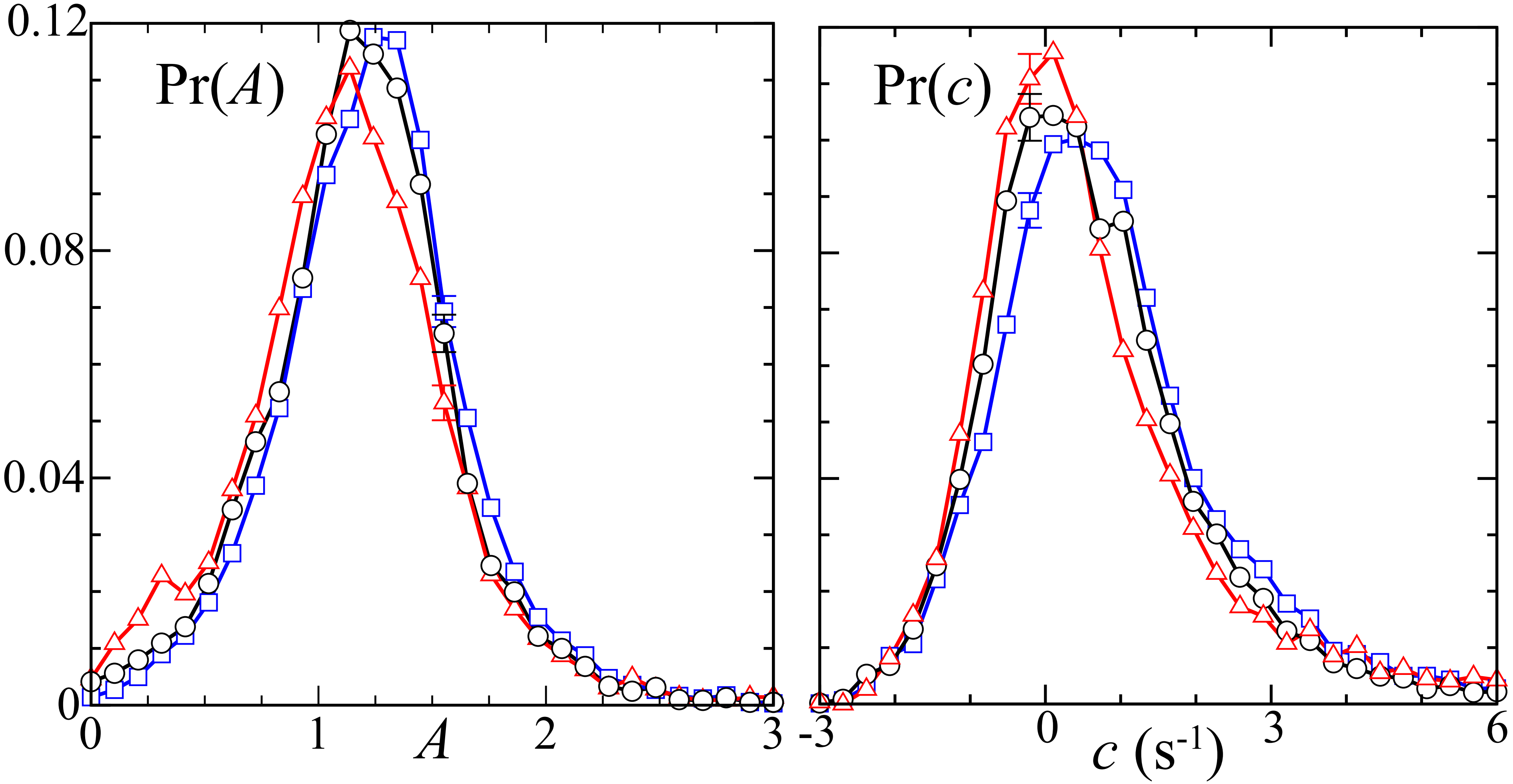
Post-reconnection: $\delta(t) = A[\kappa(t-t_0)]^{1/2}[1+c(t-t_0)]$



MSP, Fisher, and Lathrop, Physica D in press

Temperature Dependence

1.70 K < *T* < 1.88 K   1.88 K < T < 1.96 K   1.96 K < T < 2.05 K



MSP, Fisher, and Lathrop, Physica D in press

Why $c \neq 0$?

Always expect sub-dominant corrections for crossover between scales

Effects of local environment (Tsubota studying numerically)

Influence of neighboring vortices – convert c to a length l

$$c|t - t_0| \equiv \pm\kappa|t - t_0|/l^2$$

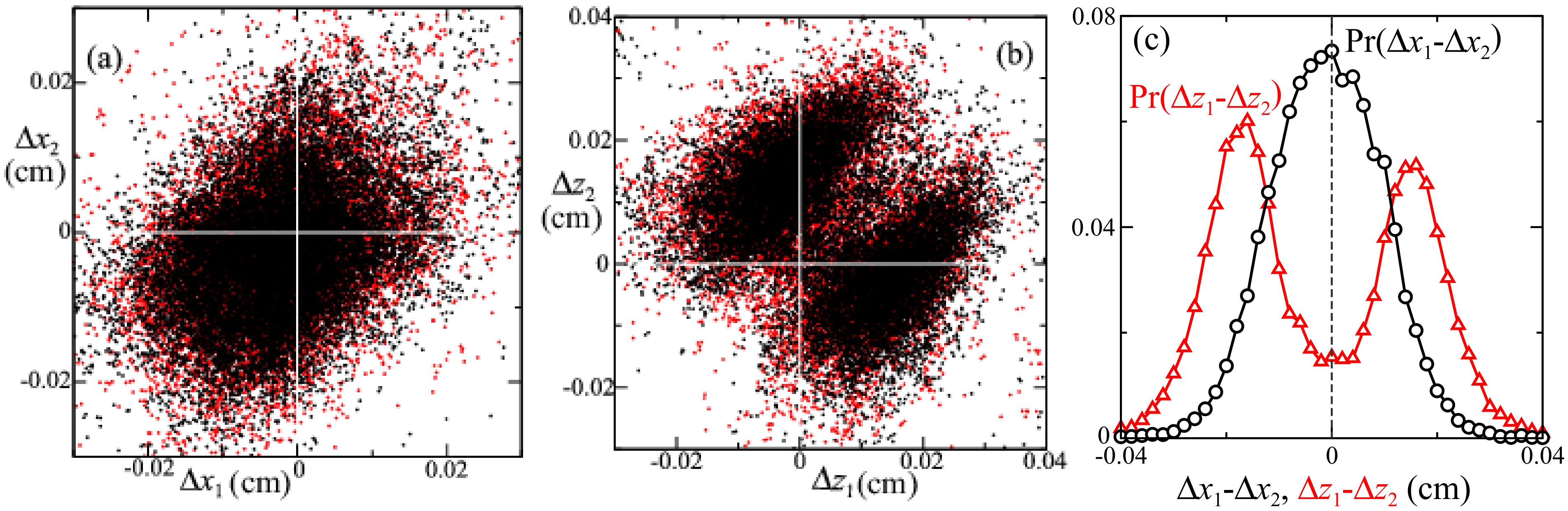
$$l_{\text{mean}} = 0.40 \text{ mm}$$

(typical intervortex spacing 0.1 – 1 mm)

Reconnection Displacement Vectors

Pre-reconnection: $\Delta\mathbf{r}_i = \mathbf{r}_i(t-0.25\text{ s})-\mathbf{r}_i(t)$

Post-reconnection: $\Delta\mathbf{r}_i = \mathbf{r}_i(t+0.25\text{ s})-\mathbf{r}_i(t)$



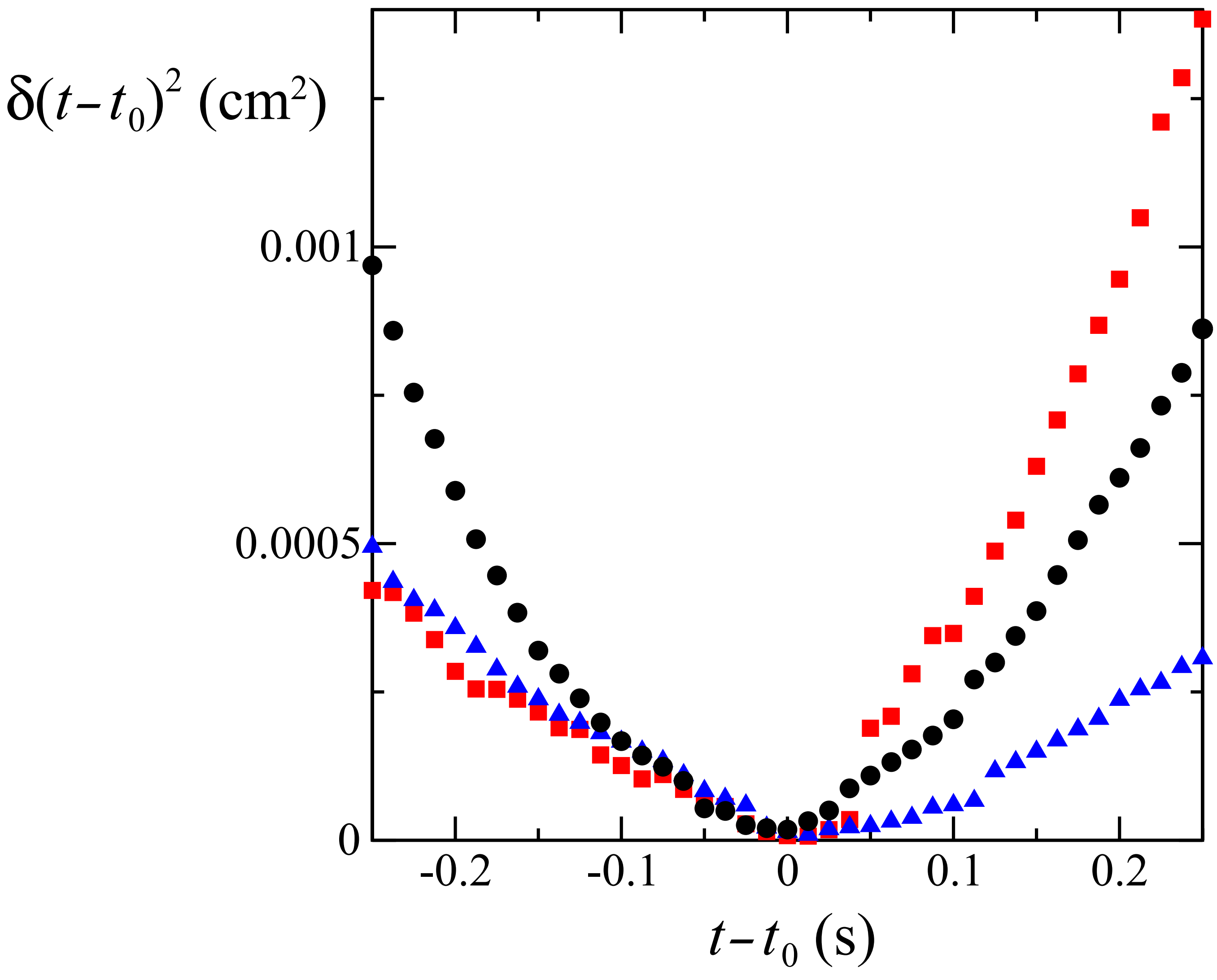
Displacements show anisotropy along direction of driving counterflow (z)

All measured *statistics* time-reversal symmetric

Time-Reversibility

Pre-reconnection: $\delta(t) = A\_[\kappa(t_0\text{-}t)]^{1/2}[1+c\_(t_0\text{-}t)]$

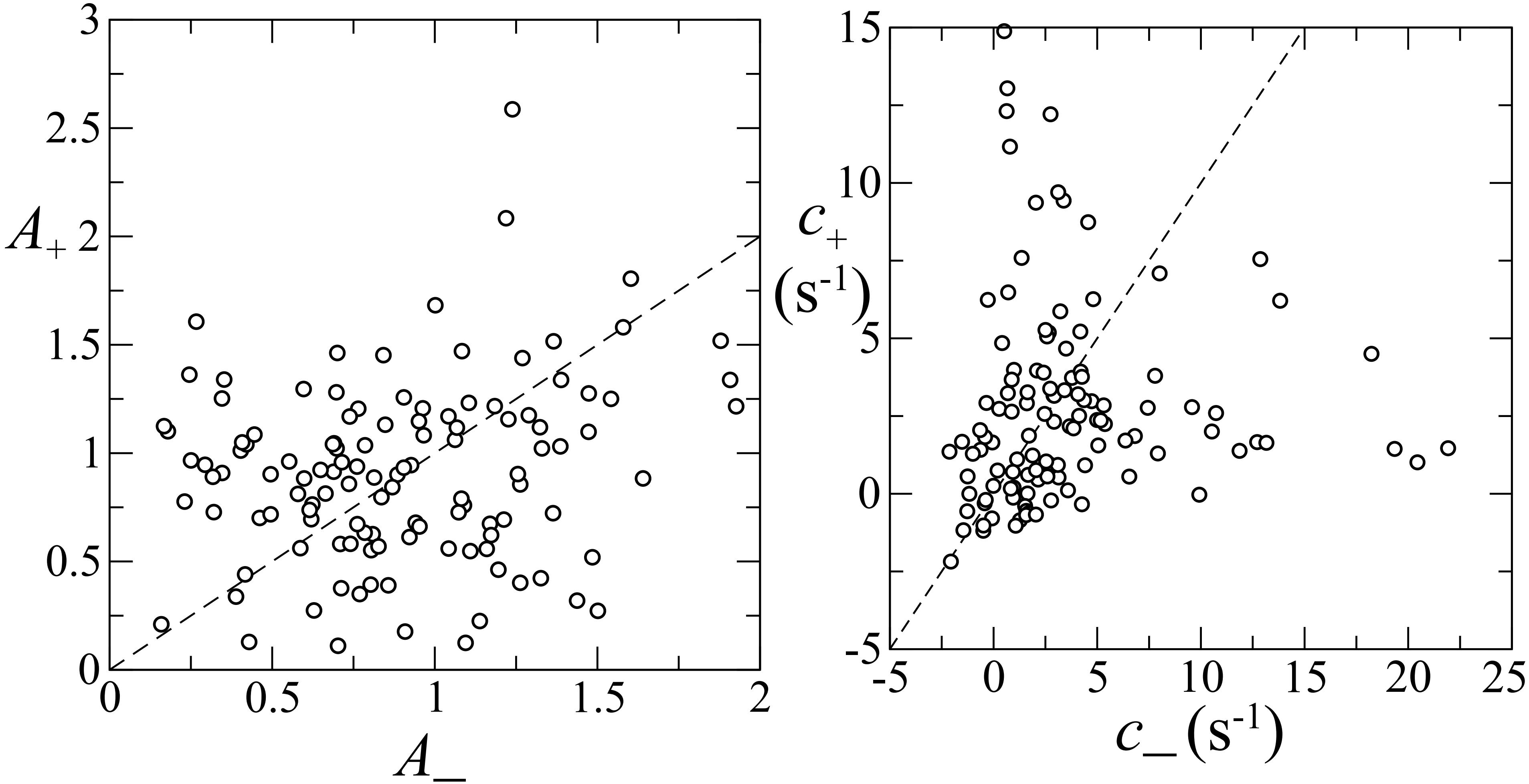
Post-reconnection: $\delta(t) = A_+[\kappa(t\text{-}t_0)]^{1/2}[1+c_+(t\text{-}t_0)]$



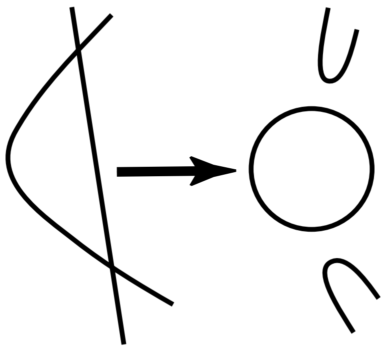
Time-Reversibility

Pre-reconnection: $\delta(t) = A\_[\kappa(t_0\text{-}t)]^{1/2}[1+c\_(t_0\text{-}t)]$

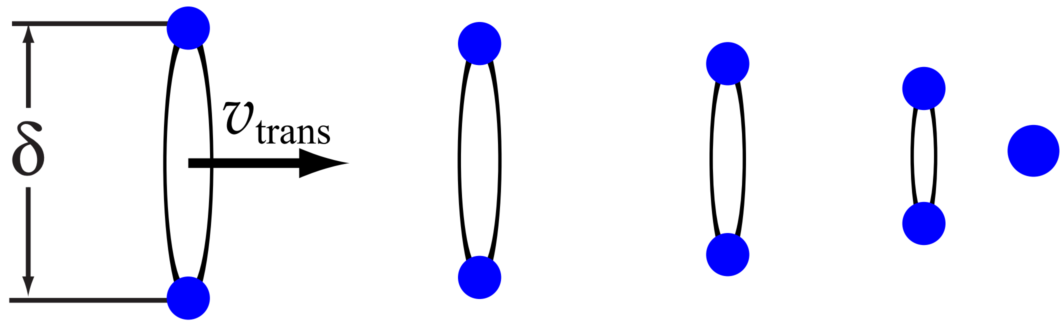
Post-reconnection: $\delta(t) = A_+[\kappa(t\text{-}t_0)]^{1/2}[1+c_+(t\text{-}t_0)]$



Quantized Vortex Rings



Reconnection can produce vortex rings

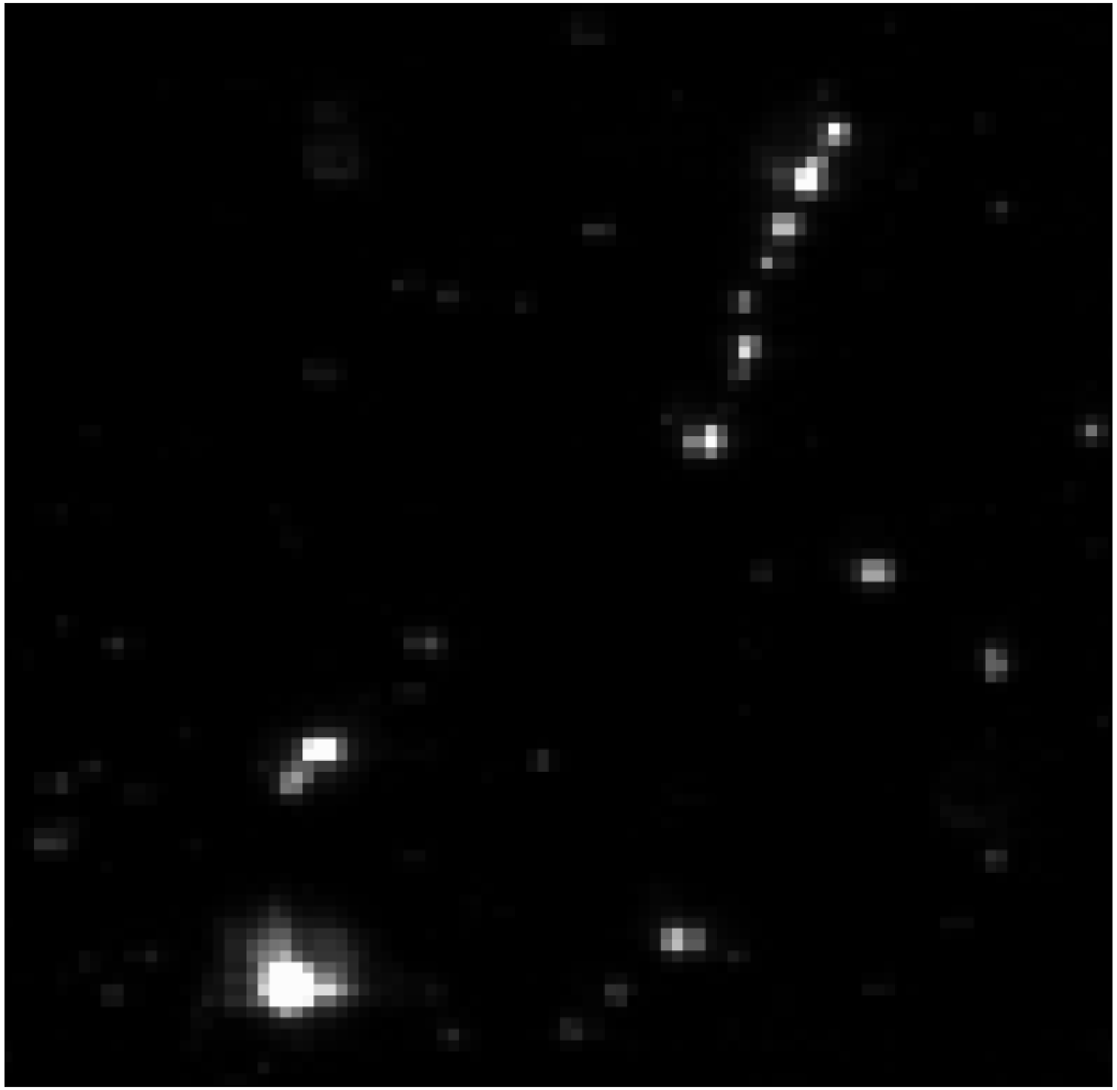


Pair of particles may allow for visualization of collapsing rings

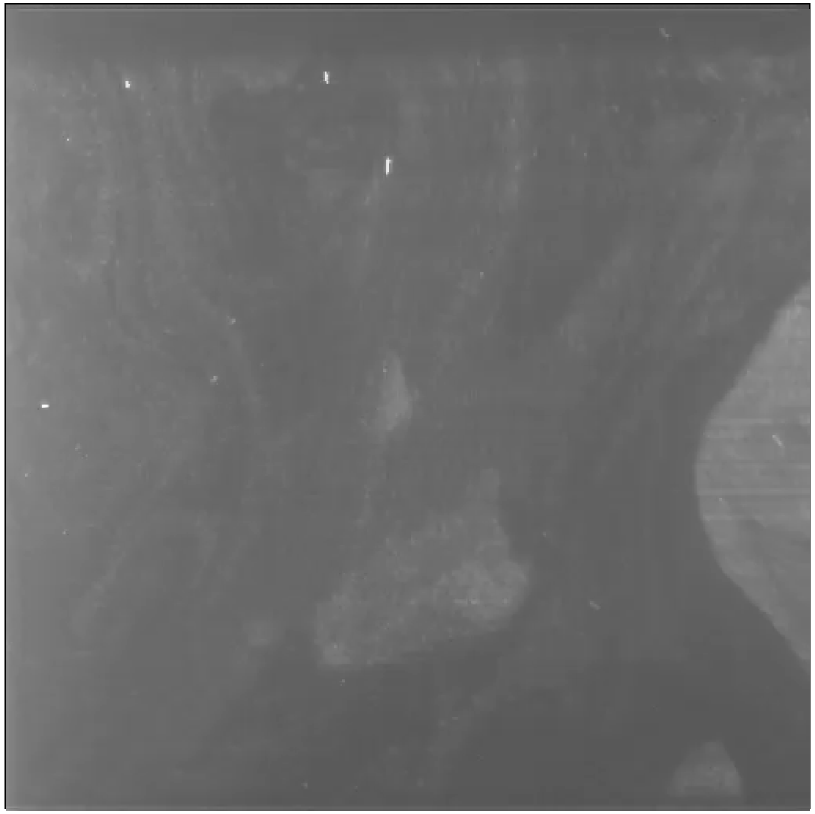
Hydrogen can affect ring collapse at high mass fractions

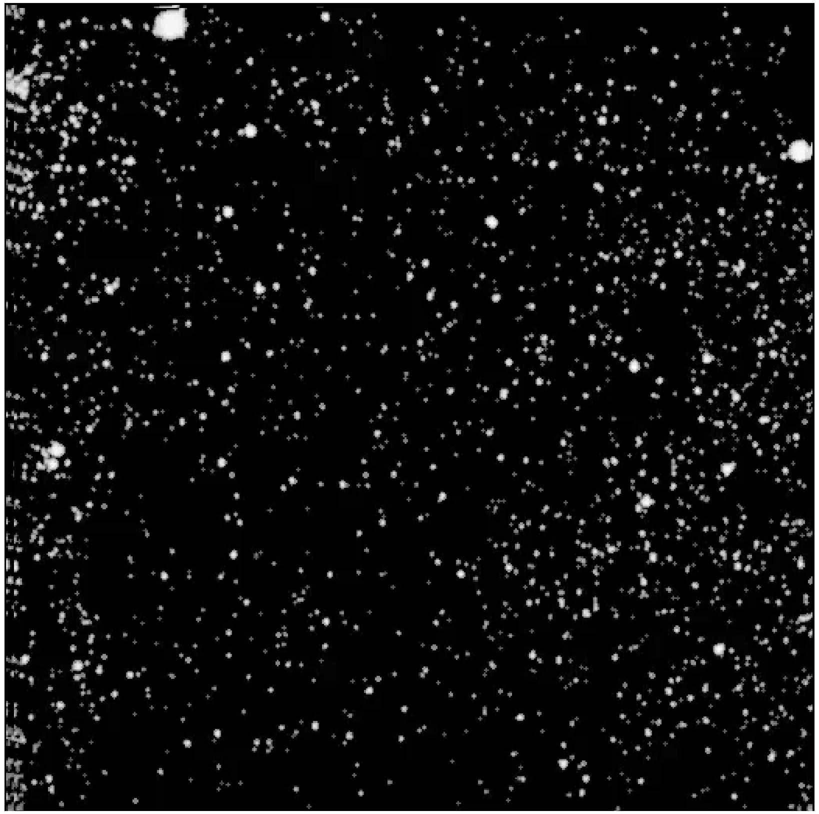
Kelvin Waves

Future possibility; visualizing Kelvin waves ?



Classical vs. Quantum Turbulence

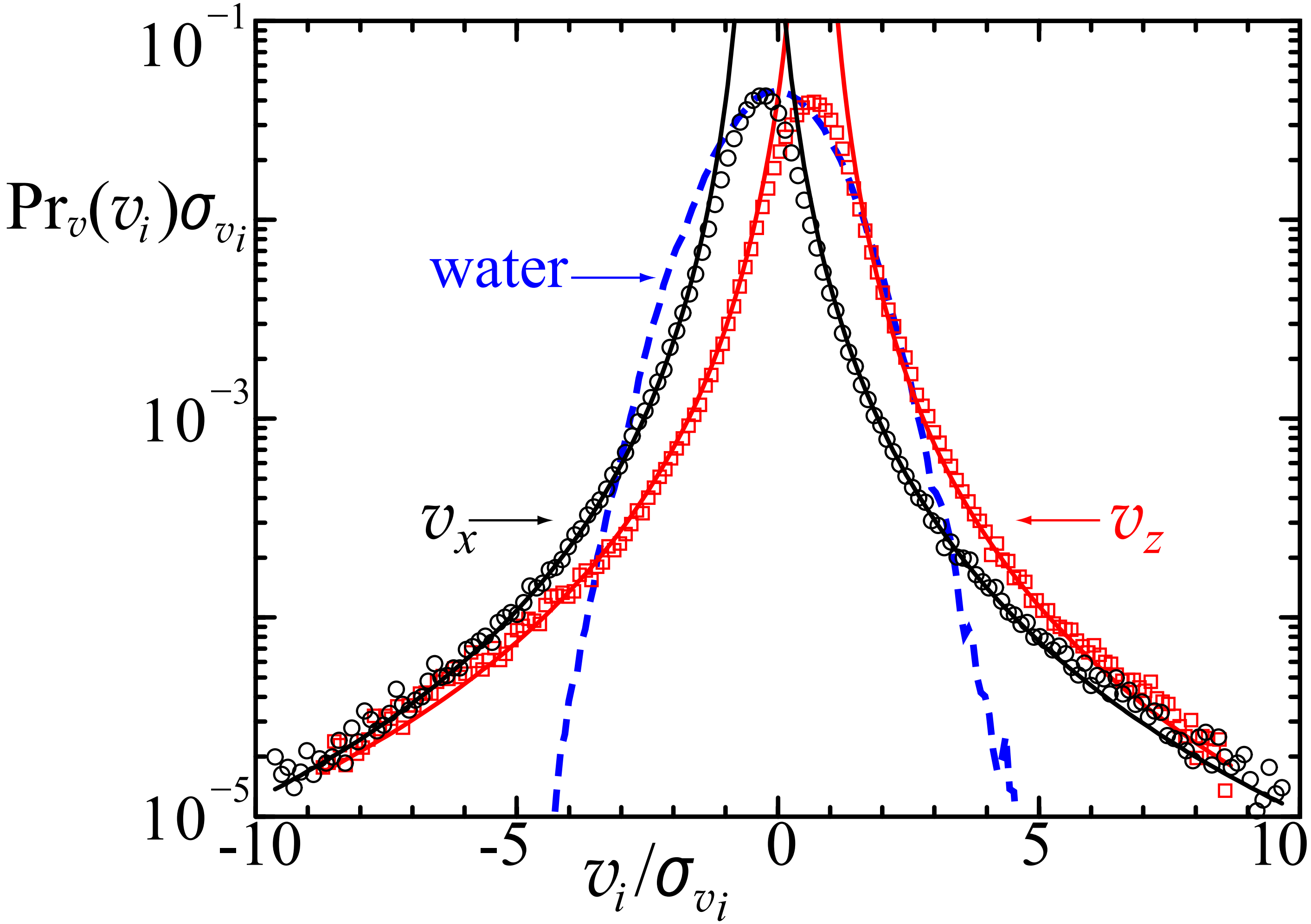




Classical ^{4}He
Velocity smoothed by viscosity
Vorticity diffuses
Interactions spanning many
length- and time-scales

Quantum ^{4}He
Two-fluid nature
Topological constraints
on vorticity produces
large, atypical velocities

Velocity Statistics



$v(t) \sim \kappa^{1/2}|t - t_0|^{-1/2}$

$\mathrm{Pr}(v)dv = \mathrm{Pr}(t)dt$

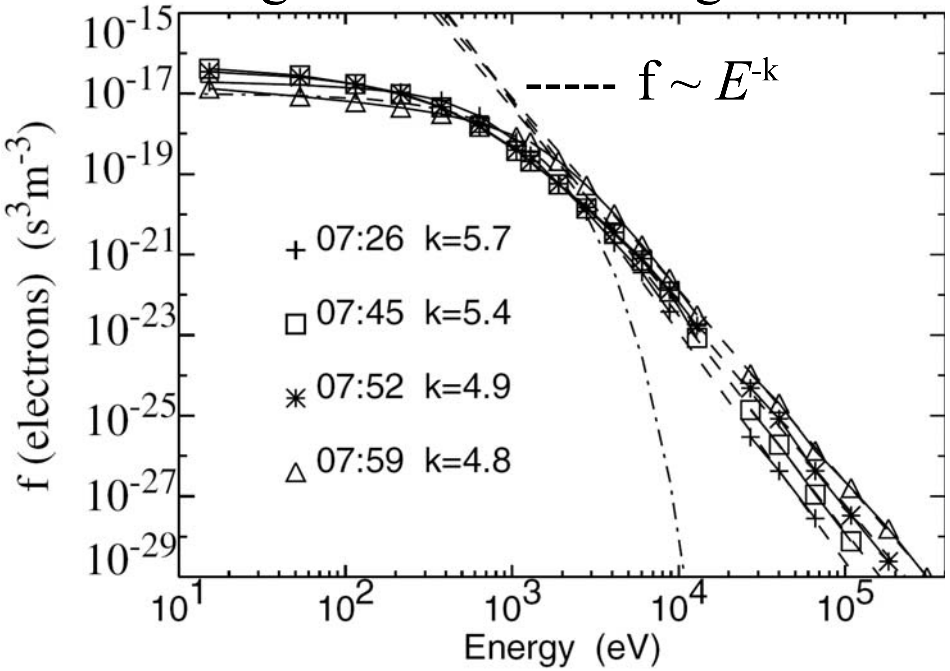
$\mathrm{Pr}(v) \sim |dt/dv|$

$\mathrm{Pr}(v) \sim v^{-3}$

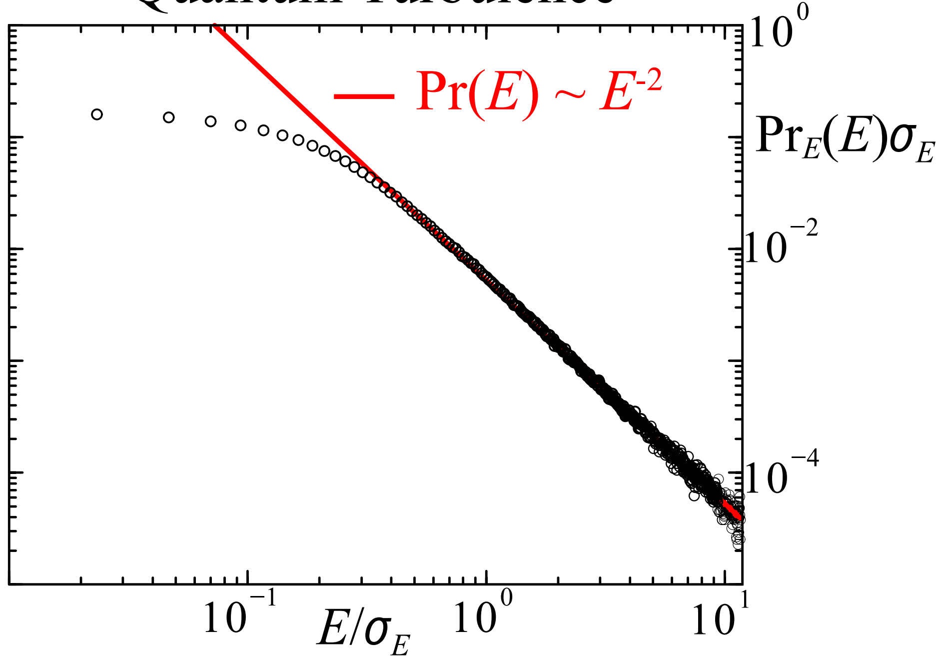
MSP, Fisher, Sreenivasan, and Lathrop, PRL **101**, 154501 (2008)

Analogies with MHD Turbulence

Magnetic Reconnection Diffusion Region of Earth's Magnetotail



Reconnection-dominated Quantum Turbulence



Magnetic field lines in highly-magnetized plasmas reconnect producing similar power-law distributions of energy

M. Oieroset *et al.*, PRL **89**, 195001 (2002)

Conclusions

"Visualization of Superfluid Helium Flow"

- MSP, Fiorito, Sreenivasan, and Lathrop, *JPSJ* **77**, 111007 (2008)

"Characterization of reconnecting vortices in superfluid helium"

- Bewley, MSP, Sreenivasan, and Lathrop, *PNAS* **105**, 13707 (2008)

"Velocity Statistics Distinguish Quantum Turbulence from Classical Turbulence"

- MSP, Fisher, Sreenivasan, and Lathrop, *PRL* **101**, 154501 (2008)

"Reconnection Dynamics for Quantized Vortices"

- MSP, Fisher, and Lathrop, *Physica D* in press

All available at arxiv.org

Thanks to: Makoto Tsubota, Carlo Barenghi, Nigel Goldenfeld, Joe Vinen, Christopher Lobb, Marc Swisdak, and James Drake, NSF, and NASA