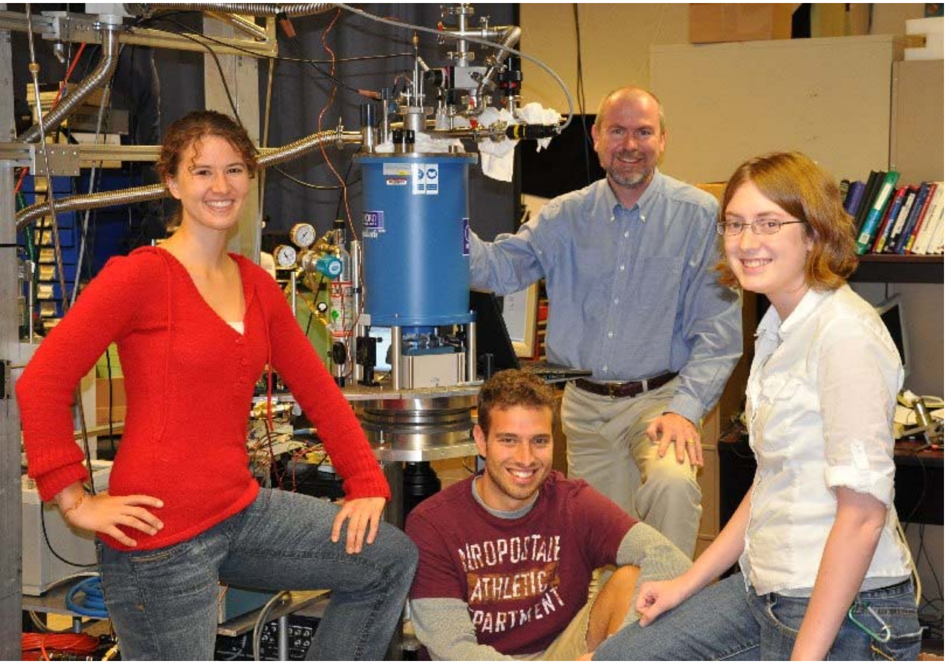
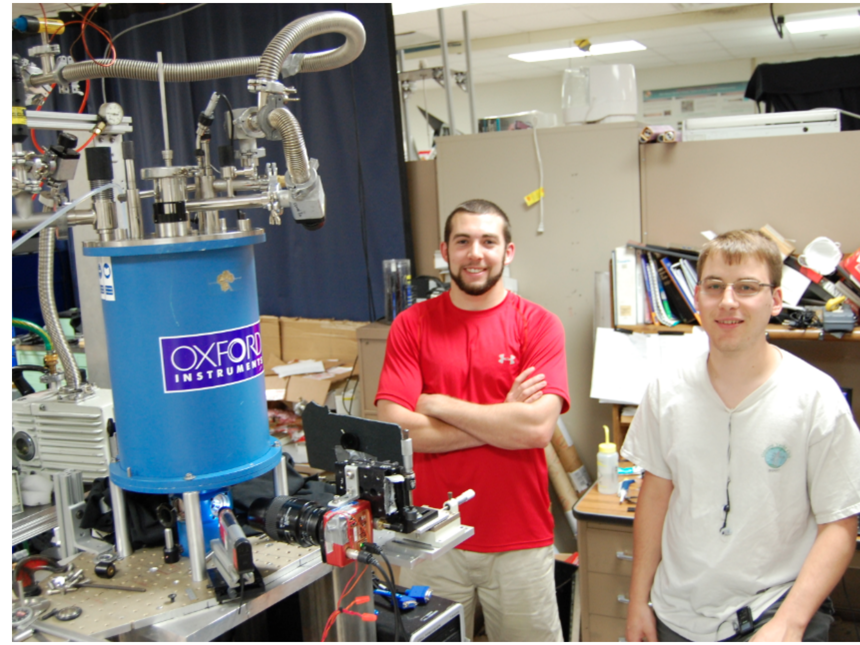
Visualization in quantum fluids

Dan Lathrop



Kristy (Gaff) Johnson **Matt Paoletti** **Kaitlyn Tuley**

University of Maryland
National Science Foundation

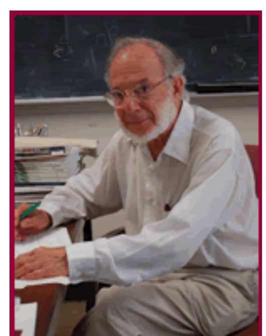


Chris Boughter and David Meichle

Enrico Fonda

Greg Bewley

K.R. Sreenivasan



Michael Fisher

Peter Megson

Quantum Fluids

A state of matter with long range quantum order

Type of synchronization

partial phase sync of the individual atomic wave functions

E.g.

- BEC atomic systems
- ^4He
- ^3He
- Cooper pair electrons in superconductors
- Physical vacuum

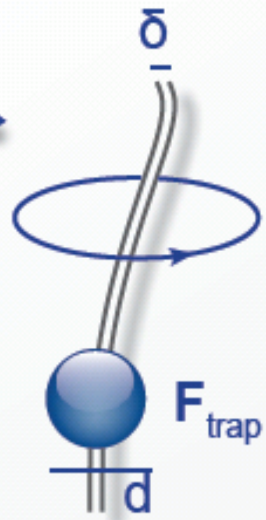
Quantum fluid dynamics and quantum disorder

Why does it matter?

Visualization of vortices - particle trapping

$$P = -\frac{\rho_s \kappa^2}{8\pi^2 r^2}$$

$$\mathbf{F} = \oint_{\partial\Omega} P \hat{n}\, dA$$



Decrease of energy $\Delta\varepsilon = \frac{\rho_s \kappa^2}{4\pi} d \ln \frac{d}{2\delta} = |\mathbf{F}_{trap}| d$

$$\frac{F_{trap}}{V} \propto \frac{\ln d}{d^3}$$

Particles get trapped on vortex cores →

Ions in liquid He ⊝ 16 Å ⊕ 6 Å

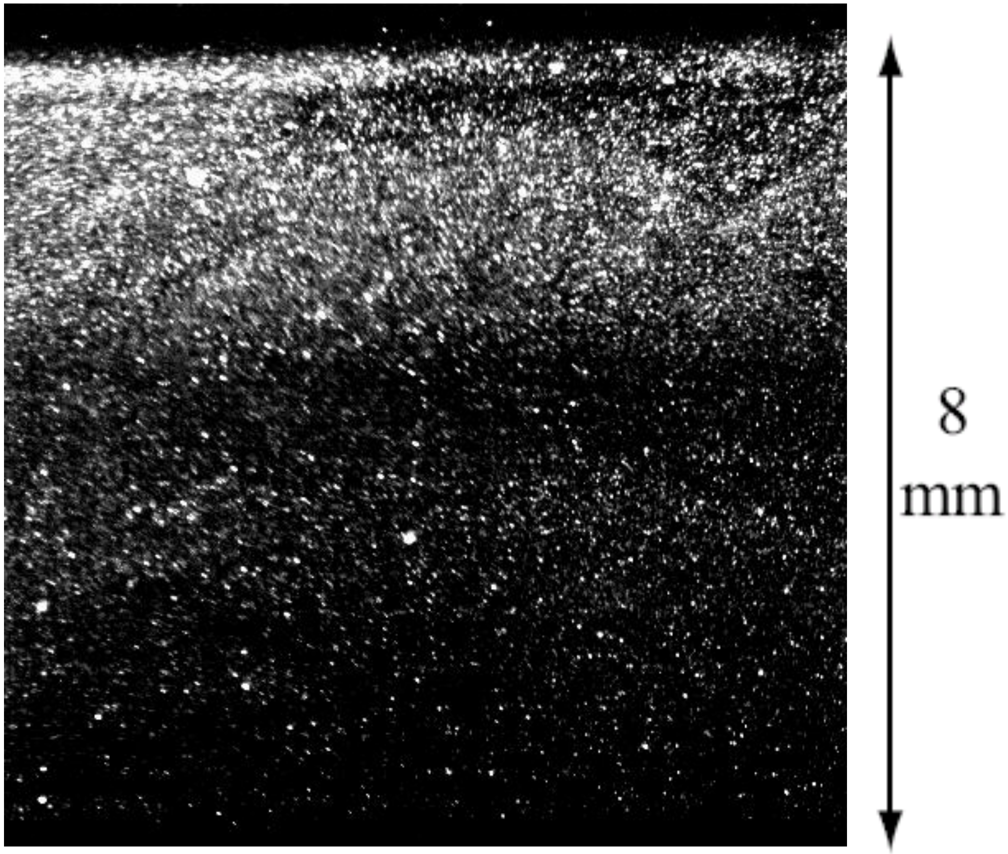
Parks and Donnelly (1966), Williams and Packard (1974)

Solid hydrogen particles >1µm

Bewley, Lathrop, Sreenivasan, Nature 441 588 (2006)

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)



Movie in real time
Begins 180 s after transition
T_λ - T ~ 50 mK

Sounds through transition caught with MEMS microphone

Vortex reconnection

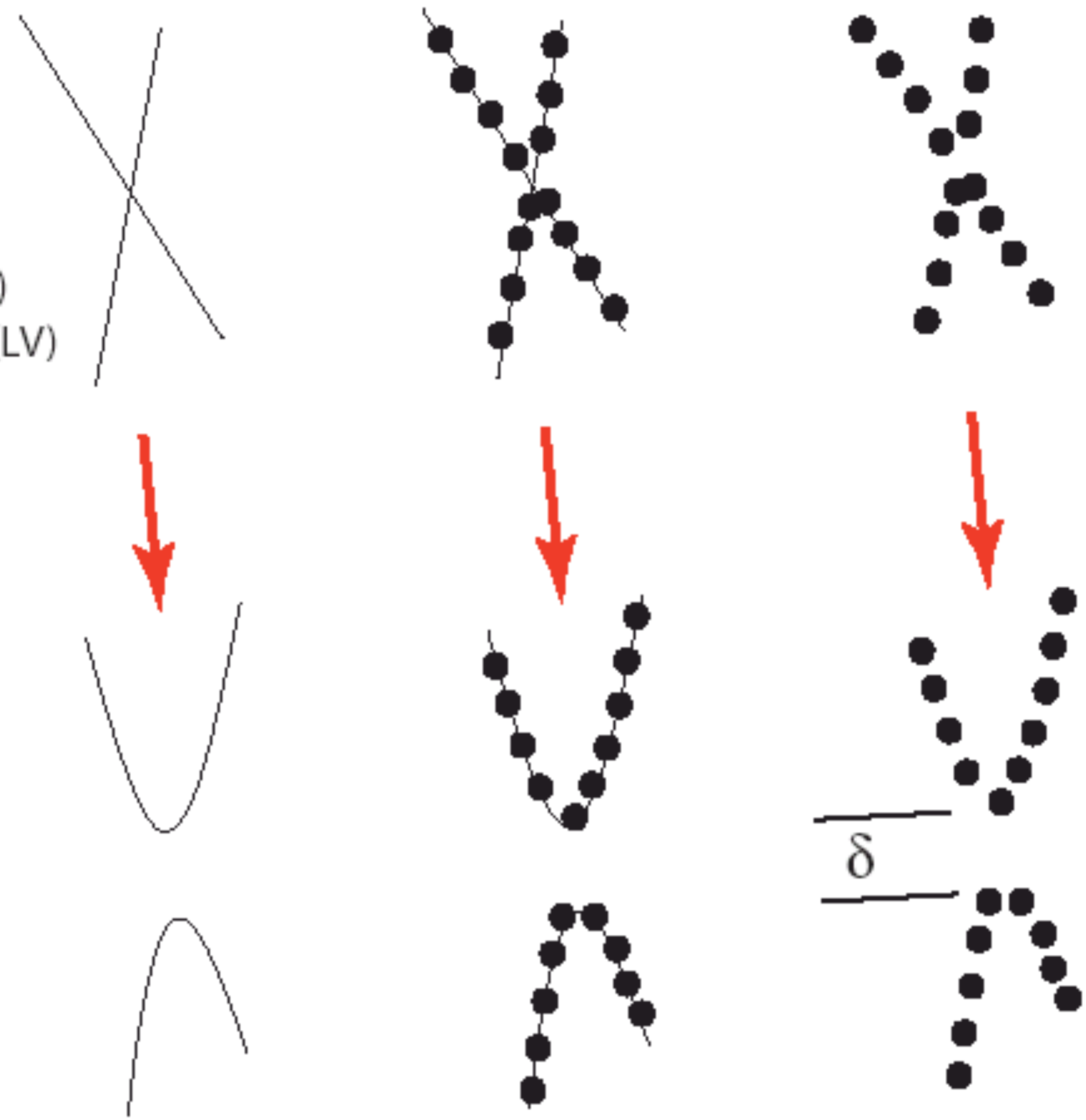
Theoretical work

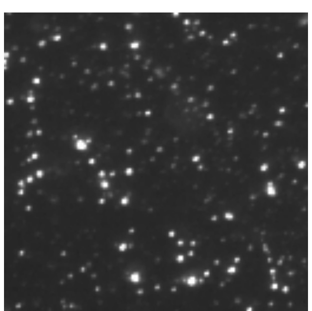
Schwarz, PRB 1985 (LV)
de Waele and Aarts, PRL 1994 (LV)
Koplik and Levine, PRL 1993 (NLSE)
Tsubota and Maekawa, JPSJ 1992 (LV)
Nazarenko and West 2003 (NLSE)

Much more recent work!
Kerr PRL 2011 (NLSE)

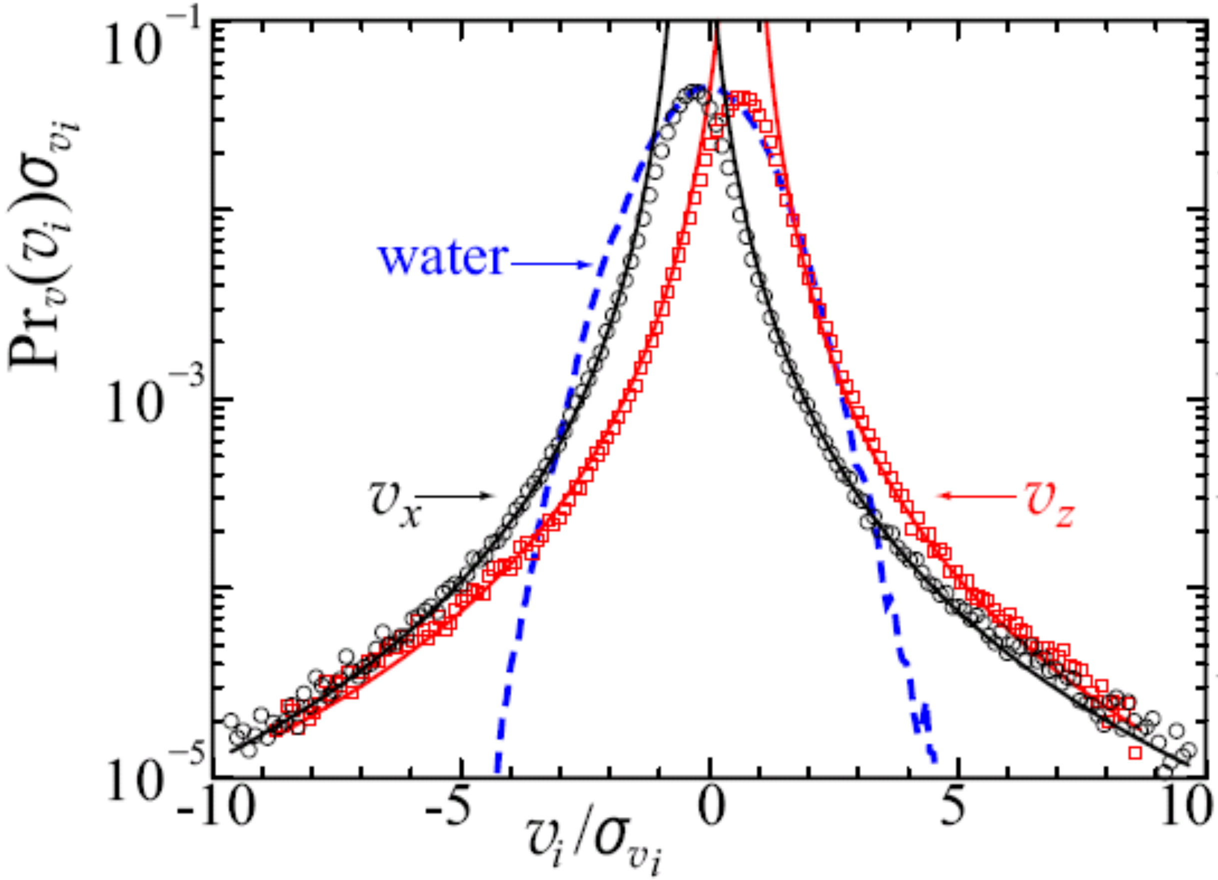
$$\delta \sim \kappa^{1/2}(t_0 - t)^{1/2}$$

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





Velocity Statistics



$$\delta = A\,\kappa^{1/2}\,(t-t_o)^{1/2}$$

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

$$P(\mathbf{v})\,d\mathbf{v} = P(t)\,dt$$

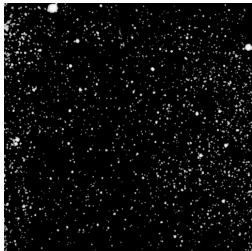
$$P(\mathbf{v}) \sim \left|\frac{dt}{d\mathbf{v}}\right|$$

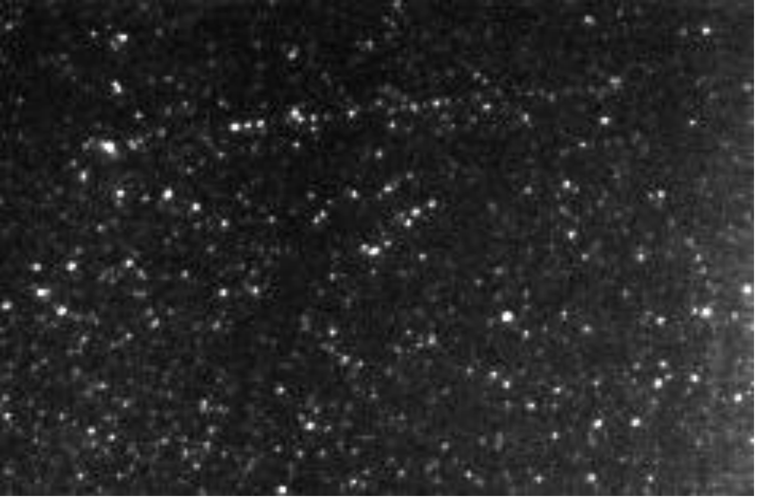
$$P(\mathbf{v}) \sim \left|\frac{1}{\mathbf{v}^3}\right|$$

Reconnection produces predictable power-law velocity tails quite distinct from classical turbulence

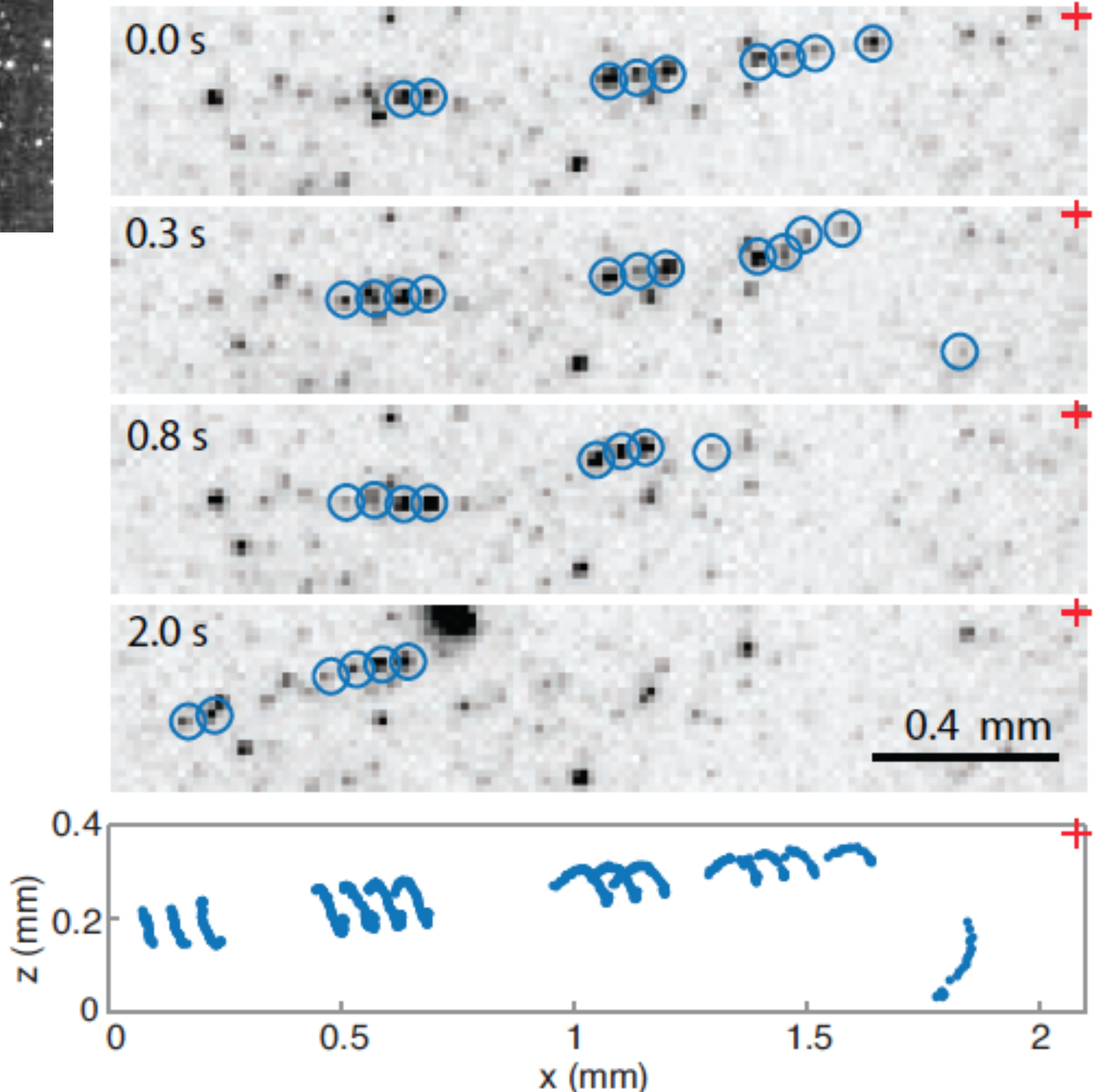
M.S. Paoletti, M.E. Fisher, K.R. Sreenivasan, and D.P. Lathrop, "Velocity statistics distinguish quantum from classical turbulence," Phys. Rev. Lett. (2008)

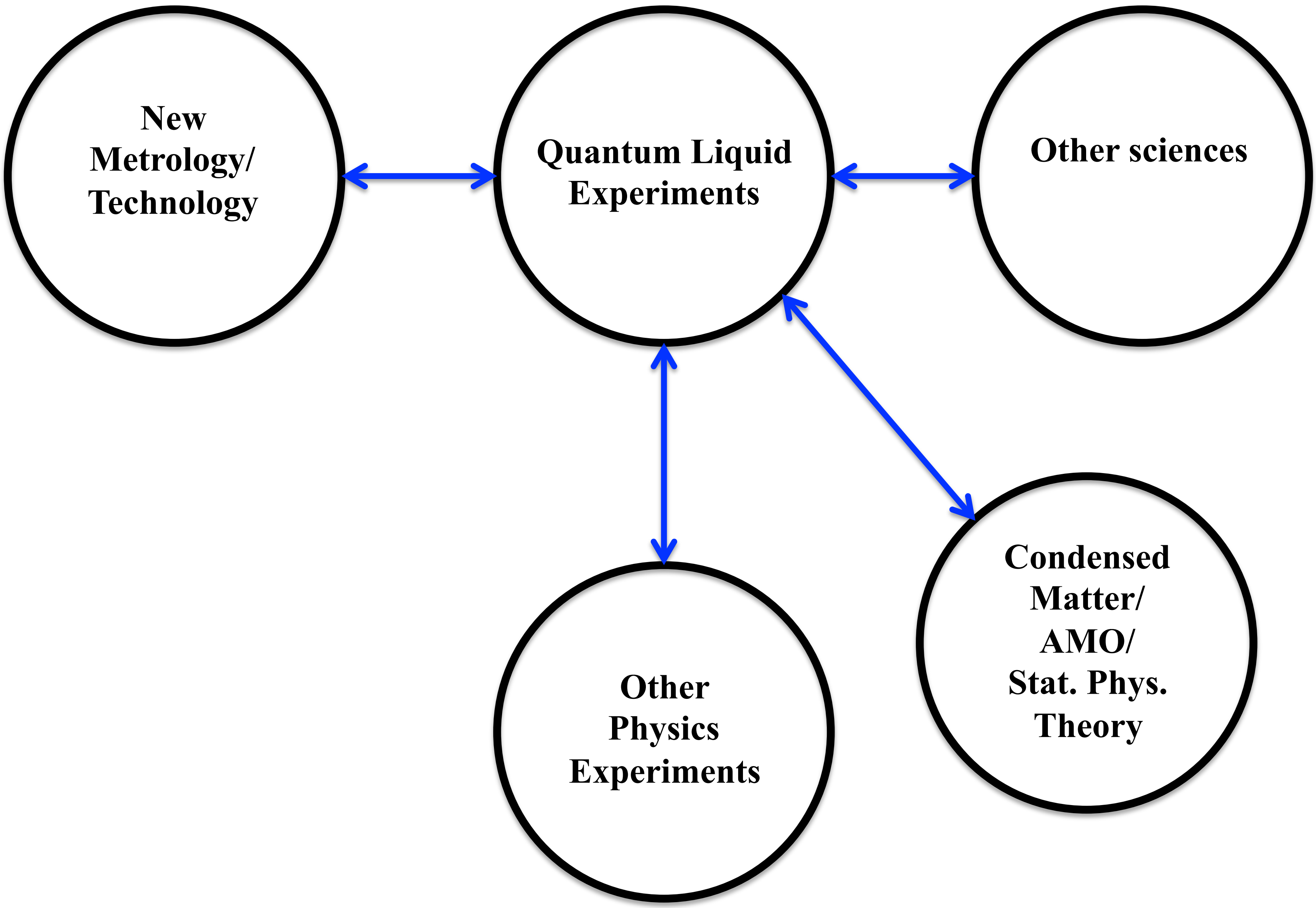
Baggaley and Barenghi, PRE (2011).

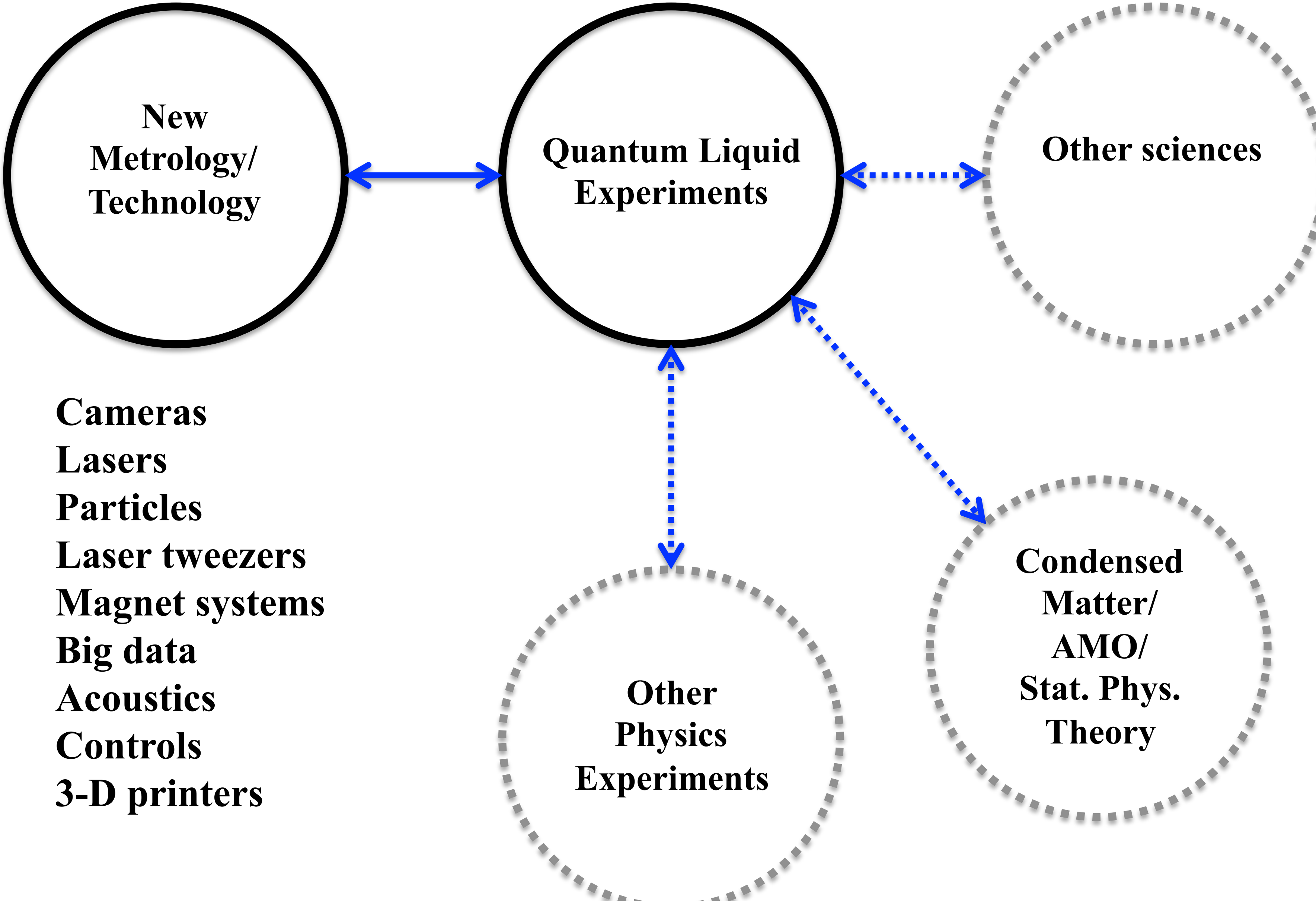




Kelvin waves!




New Metrology/ Technology
Quantum Liquid Experiments
Other sciences
Condensed Matter/ AMO/ Stat. Phys. Theory
Other Physics Experiments


New Metrology/ Technology
Quantum Liquid Experiments
Other sciences
Cameras
Lasers
Particles
Laser tweezers
Magnet systems
Big data
Acoustics
Controls
3-D printers
Other Physics Experiments
Condensed Matter/ AMO/ Stat. Phys. Theory

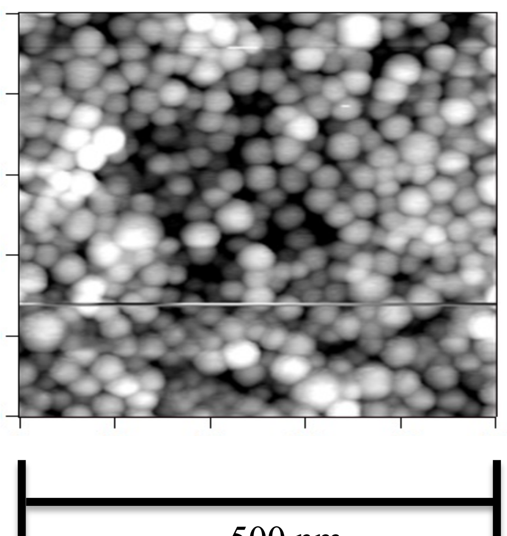
Fluorescent Nanoparticle Dispersion

Particle type	Manufacturer	Part number	Shipped form	Size (nm)	Excitation & Emission(nm)
Quantum Dots	Ocean Nanotech	QSP600	Powder	5	532 / 602
Gold Nanorods	Nanopartz	E16-532	Organic Solvent	25x35	533 / 556
FluoroSpheres	Life Technologies	F8784	Aqueous	20	532 / 575
FluoroSpheres	Life Technologies	F8800	Aqueous	100	540 / 560
FluoroSpheres	Life Technologies	F8819	Aqueous	1000	535 / 575

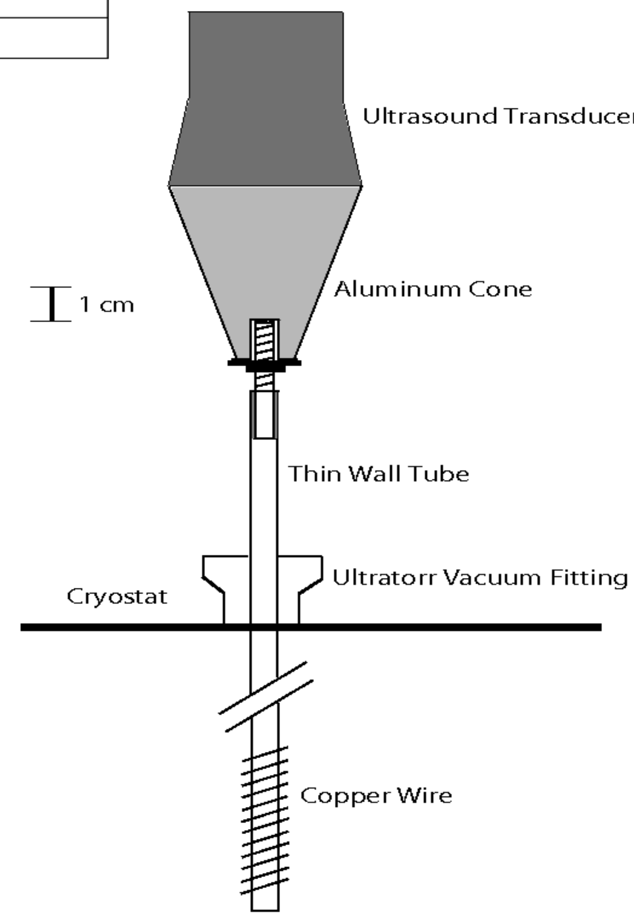
TABLE I. Details of all particle types successfully dispersed in both liquid helium and nitrogen.

D.P. Meichle and D.P. Lathrop. "Nanoparticle dispersion in superfluid helium." *Rev. Sci. Inst.* 85.7 (2014): 073705.

Provisional Patent 2014, Application No. US 62/014,564

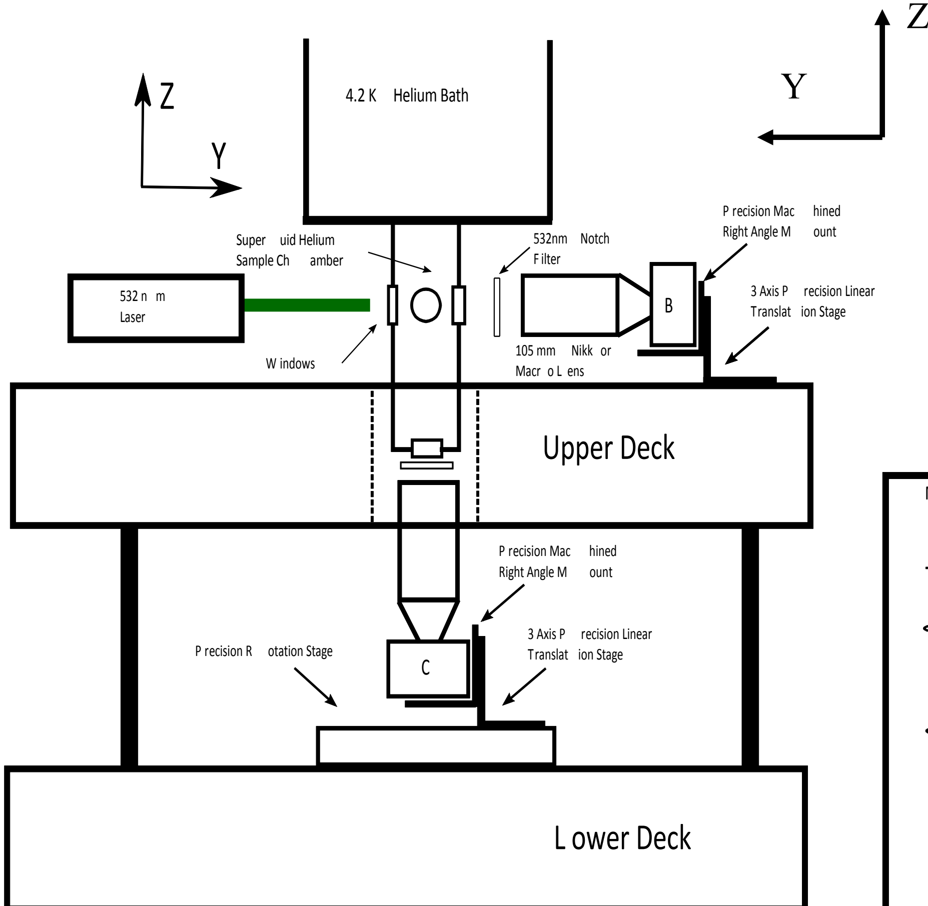


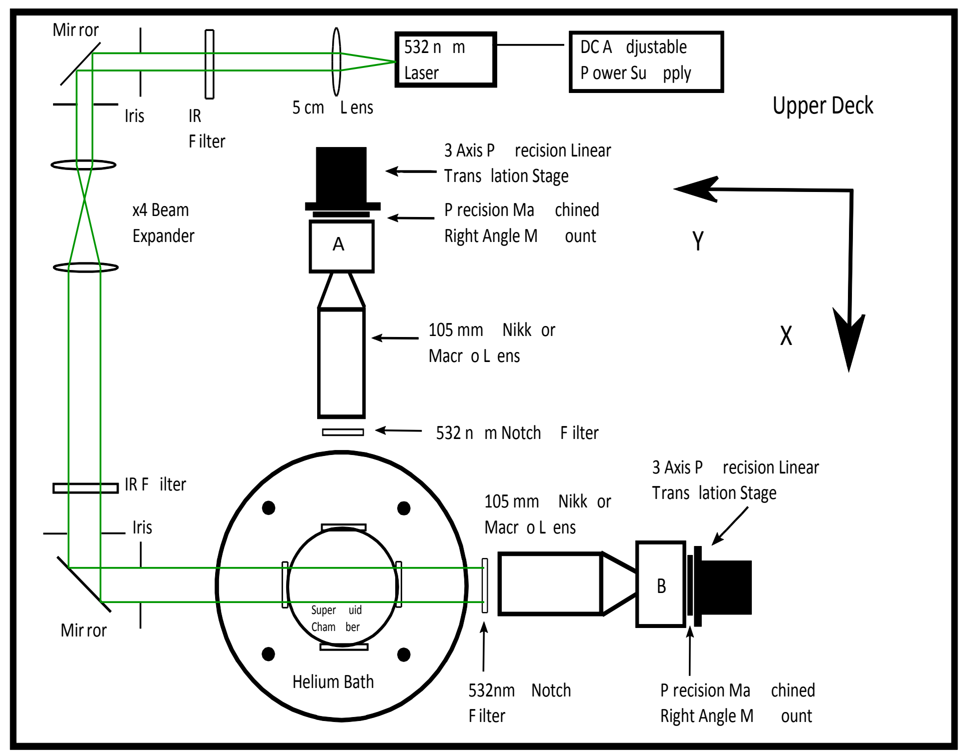
AFM Image Courtesy of Joe Garrett at UMD



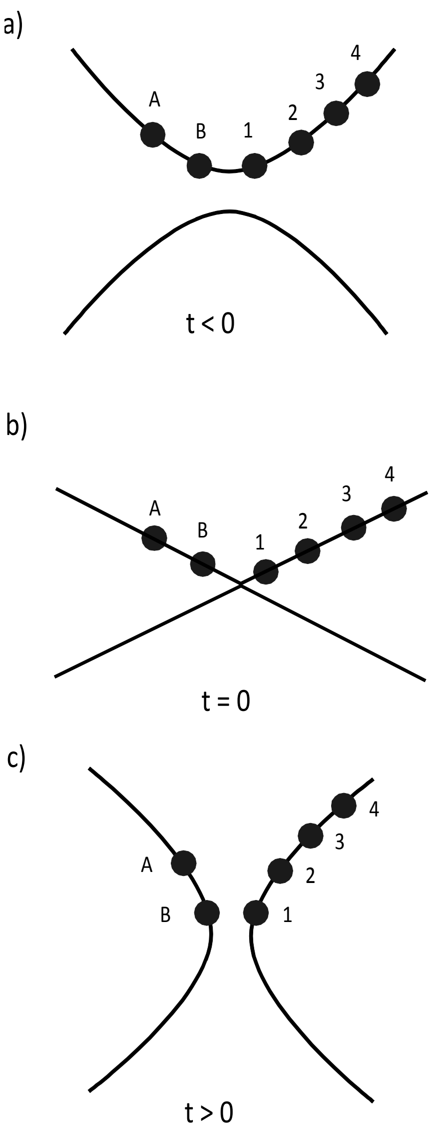
3D Stereographic Microscope Setup

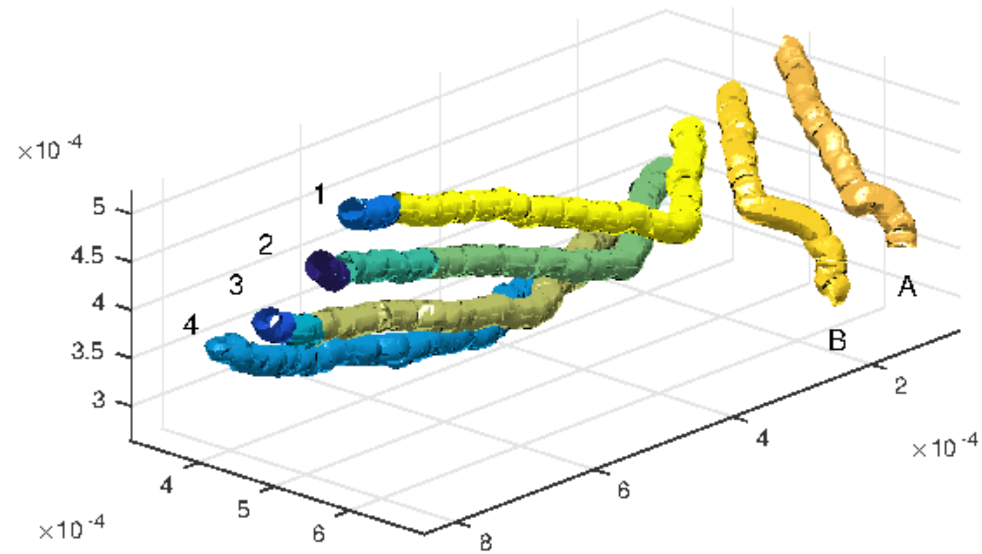
- Camera mounts hand-machined and aligned to .001 inch and .1 degree tolerances
- All three cameras mutually perpendicular and share axes

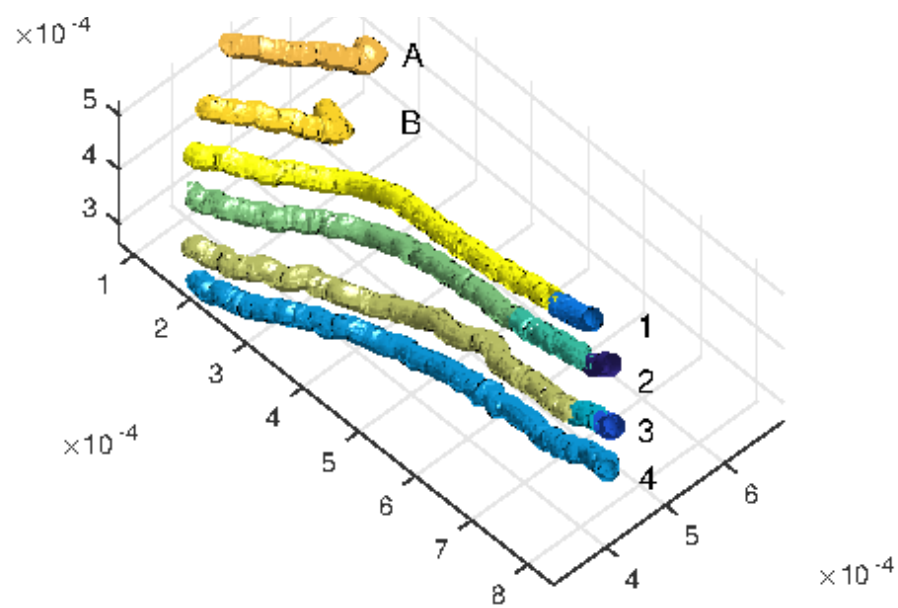




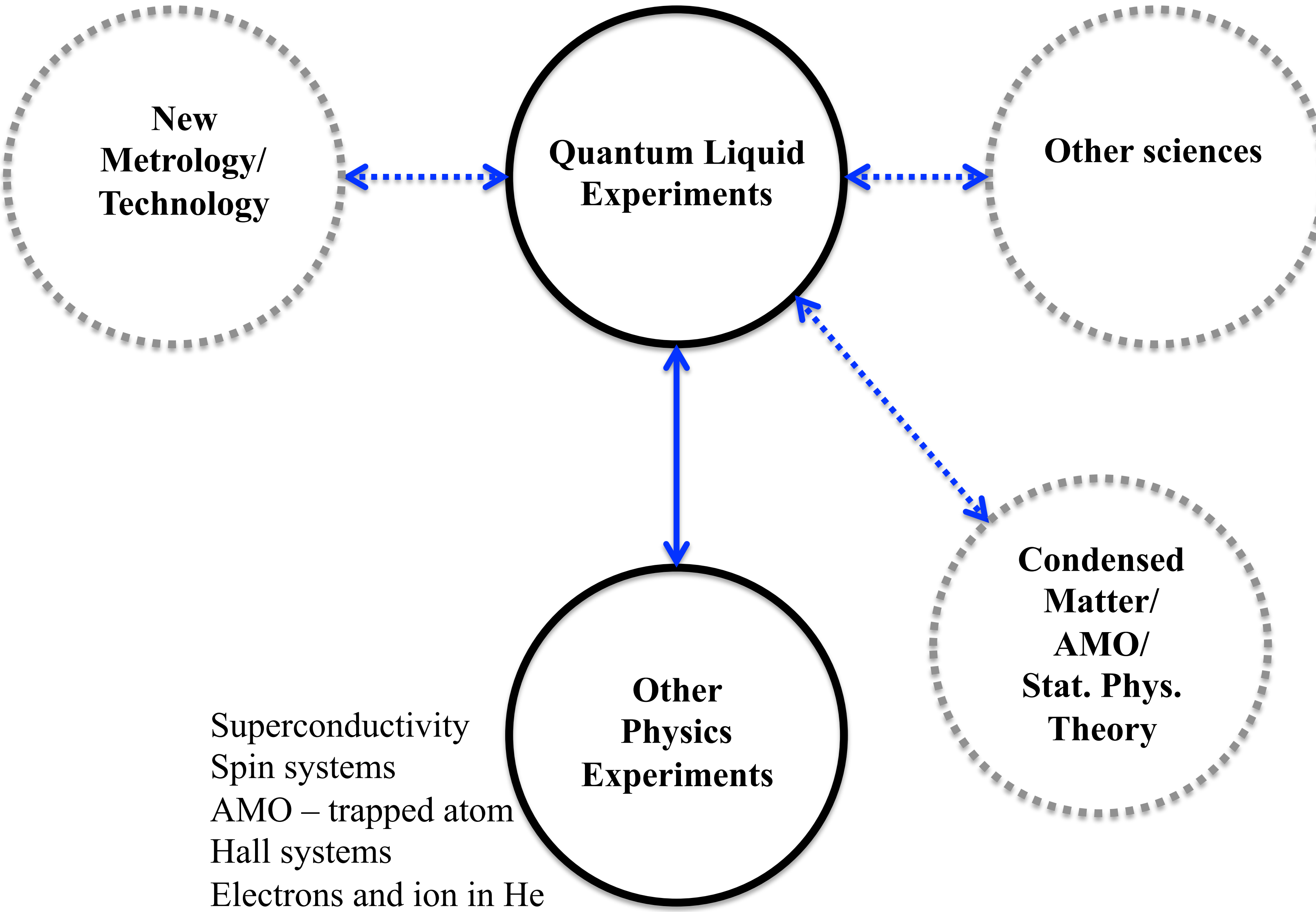
First 3D Vortex Reconnection

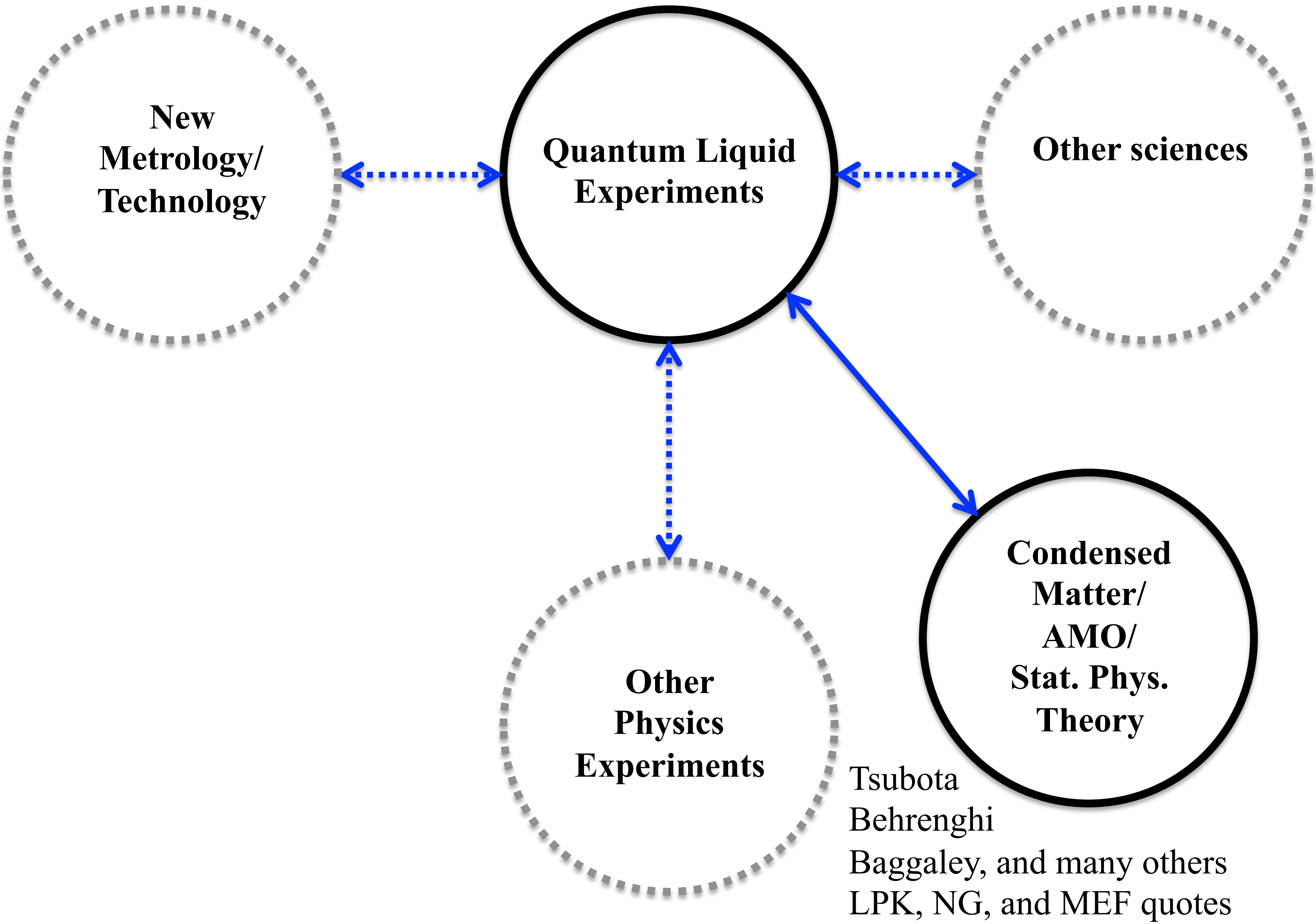






^{3}He experiments with nanoparticles


New
Metrology/
Technology
Quantum Liquid
Experiments
Other sciences
Condensed
Matter/
AMO/
Stat. Phys.
Theory
Other
Physics
Experiments
Superconductivity
Spin systems
AMO – trapped atom
Hall systems
Electrons and ion in He


New Metrology/ Technology
Quantum Liquid Experiments
Other sciences
Other Physics Experiments
Condensed Matter/ AMO/ Stat. Phys. Theory
Tsubota
Behrenghi
Baggaley, and many others
LPK, NG, and MEF quotes

E. Fonda, D.P. Meichle, S. Hormoz, N.T. Ouellette, D.P. Lathrop. "Direct observation of Kelvin waves excited by quantized vortex reconnection." *Proc. Nat. Acad. Sci. USA*. 111. Supplement 1 (2014): 4707-4710. (Special Feature Cover)

Quantum fluid dynamics theory snapshot

Nonlinear Schrödinger – Gross Pitaevskii equation
Biot-Savart Models
Line interaction models
Other models involving Euler equations – caution!

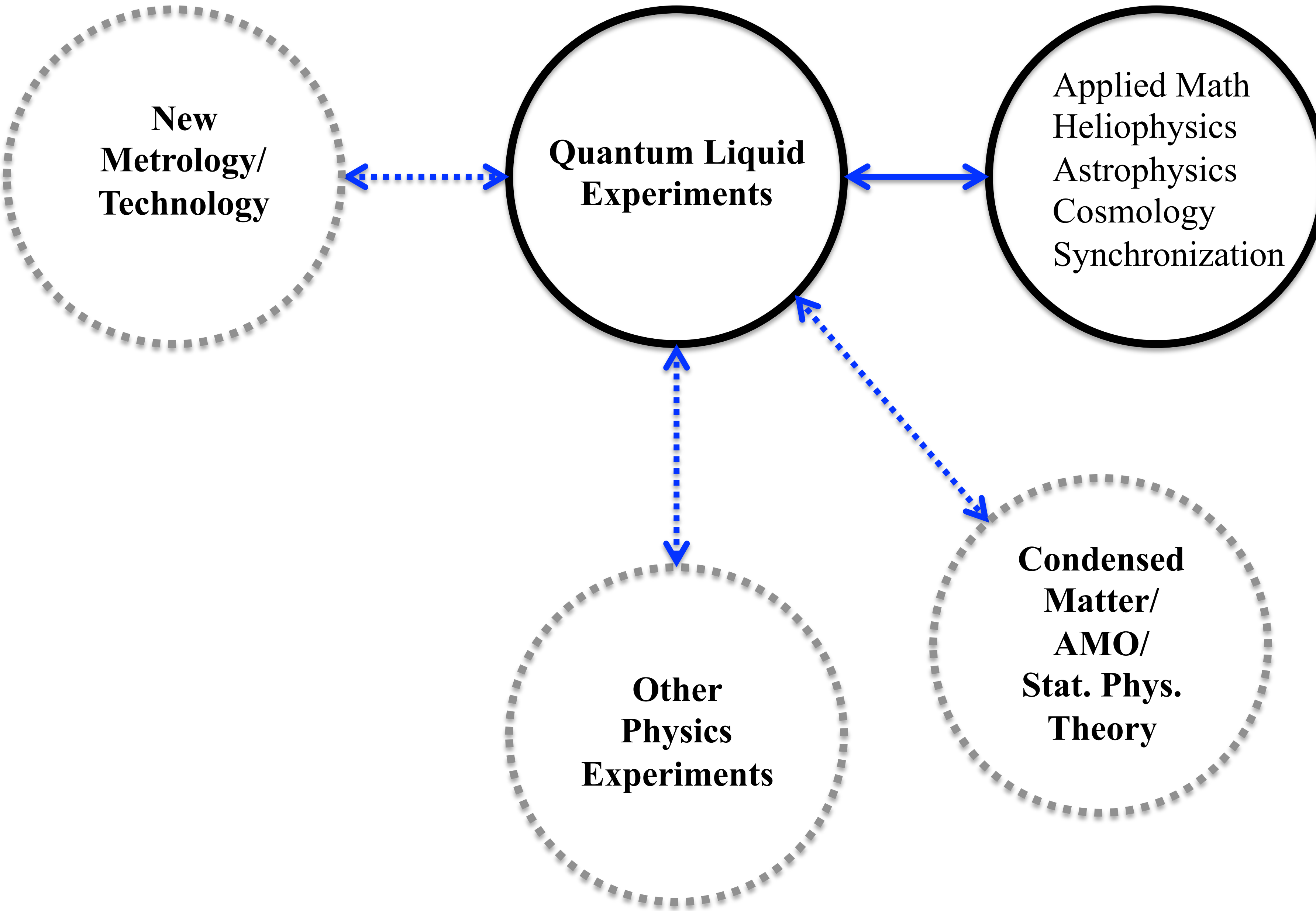
Superfluid Vortex Models

Microscopic (Angstrom Scale)

- Quantum Mechanical
- Zero Temperature Only
- Captures Vortex Reconnection Intrinsically
- Time Reversal Symmetric & Conservative

Macroscopic (Micrometers and larger)

- Heuristic / Phenomenological
- Includes Mutual Friction
- Ad-Hoc Reconnection Only
- Non-Conservative, Dissipative


New
Metrology/
Technology
Quantum Liquid
Experiments
Applied Math
Heliophysics
Astrophysics
Cosmology
Synchronization
Other
Physics
Experiments
Condensed
Matter/
AMO/
Stat. Phys.
Theory

The formation of vortices as one cools below transition:

We always see vortices

Possible formation mechanisms:

1) Kibble-Zurek mechanism

transition happens too quickly for phase uniformity
coherence length relevant

2) Remnant vortices

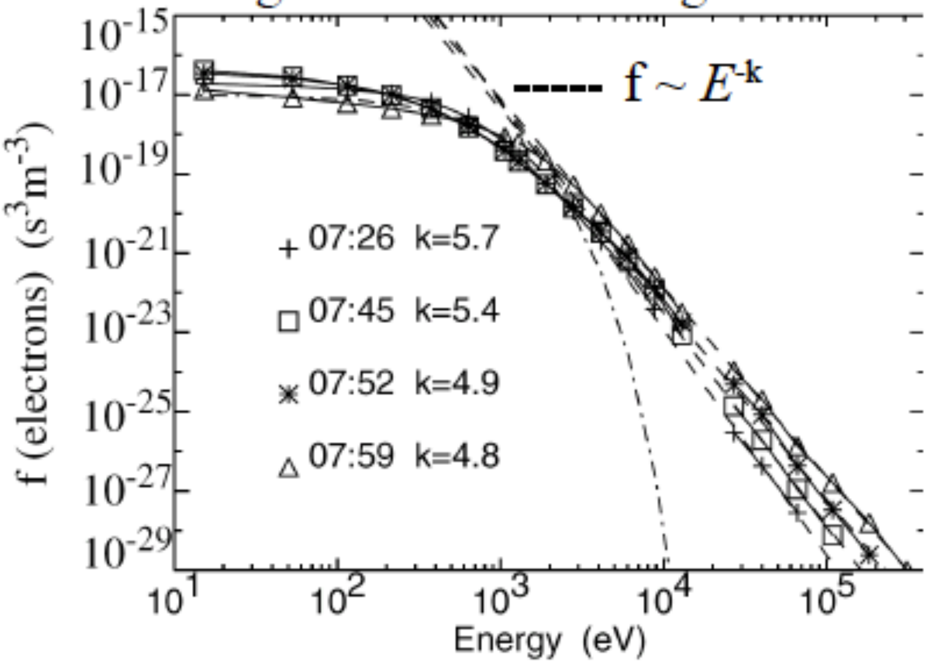
momentum and angular momentum in normal component goes to Psi as rho_n decreases

3) Counterflow vortices created just below transition

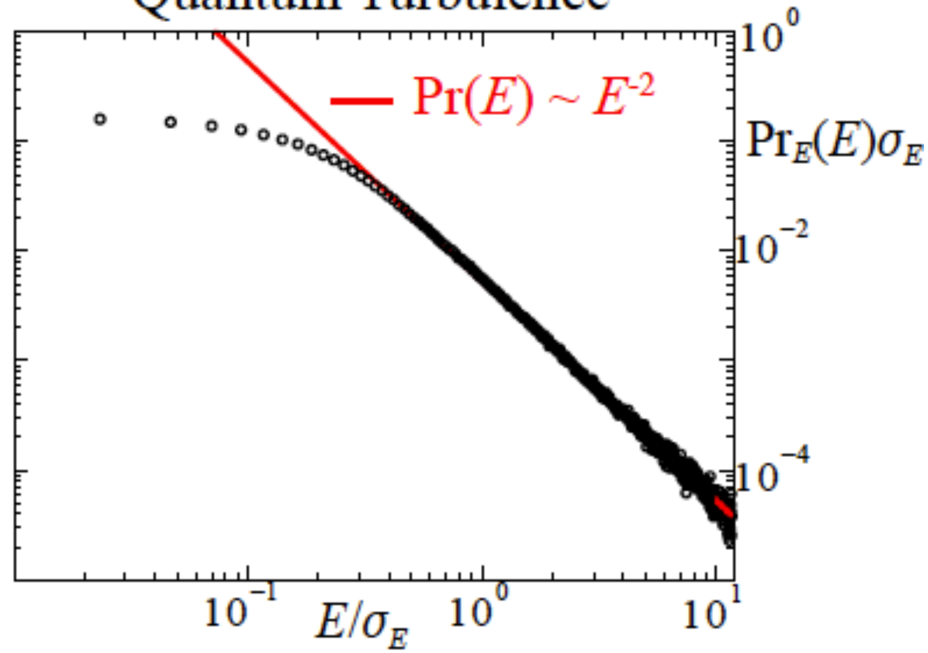
v_c is exceeded near transition no matter how little heat flows

Analogies with MHD Turbulence

Magnetic Reconnection Diffusion Region of Earth's Magnetotail



Reconnection-dominated Quantum Turbulence



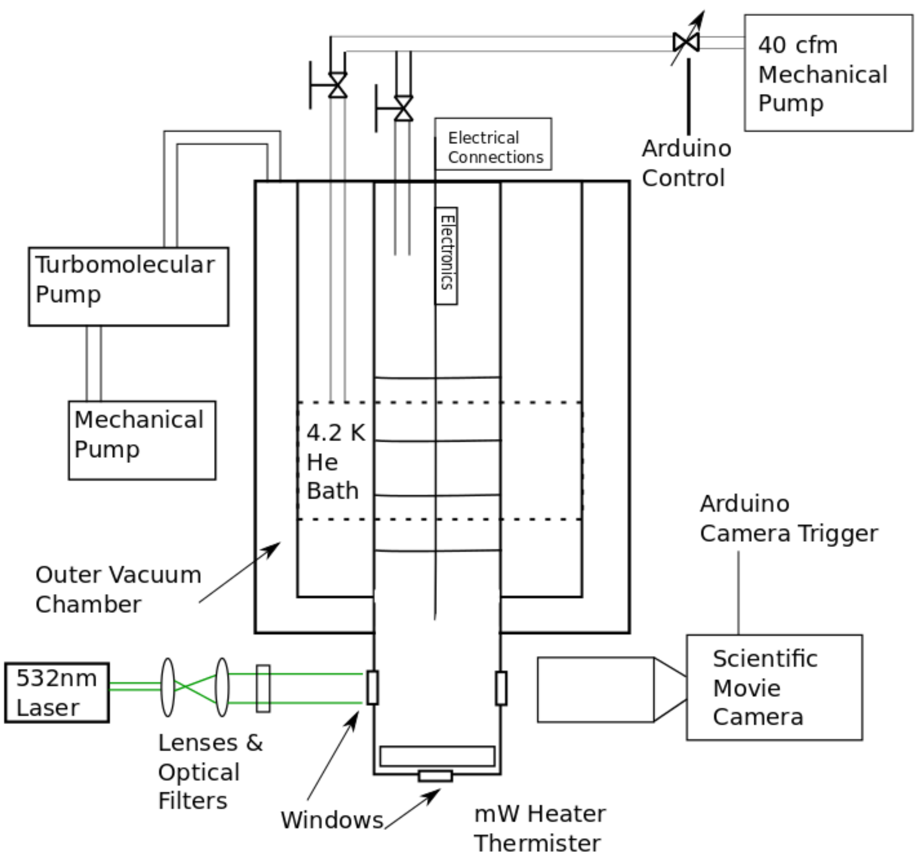
Magnetic field lines in highly-magnetized plasmas reconnect producing similar power-law distributions of energy

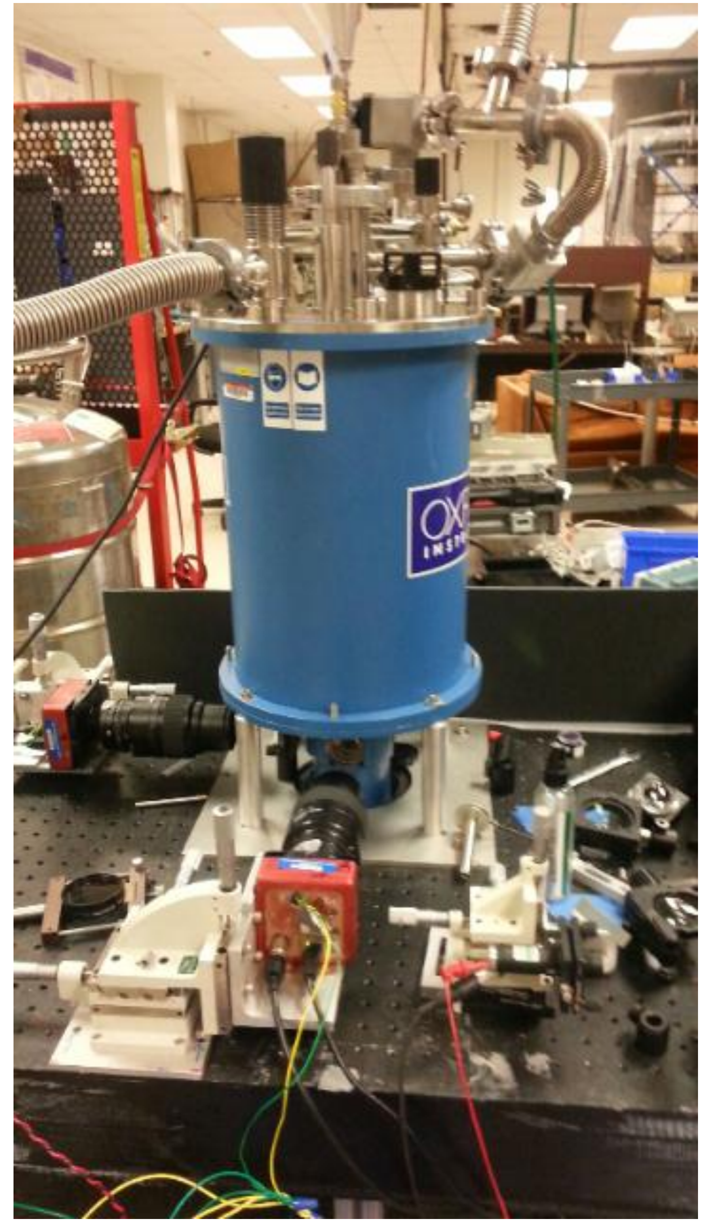
M. Oieroset *et al.*, PRL **89**, 195001 (2002)

Dissertations: complex.umd.edu
Youtube channel: n3umh

Bewley, Lathrop, and Sreenivasan Nature 2006
Bewley, Sreenivasan, and Lathrop, Exp. in Fluids 2008
Paoletti, Fiorito, Sreenivasan, and Lathrop, J. Phys. Soc. Japan 2008
Bewley, Paoletti, Sreenivasan, and Lathrop, Proc. Nat. Acad. Sci. 2008
Paoletti, Fisher, Sreenivasan, and Lathrop, PRL 2008
Paoletti, Fisher, and Lathrop, Physica D 2008
Paoletti and Lathrop, Ann. Rev. of Cond. Matter Phys. 2011
Meichle, Rorai, Fisher, and Lathrop, PRB 2012
Fonda, Meichle, Ouellette, Hormoz, and Lathrop PNAS 2014
Meichle and Lathrop Rev. Sci. Inst. 2014

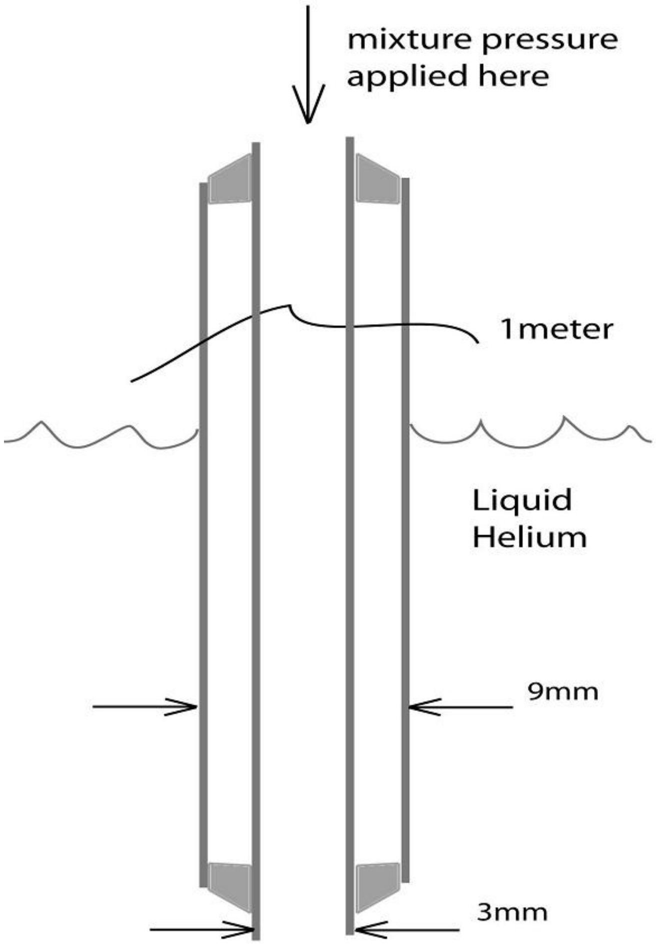
- 4.2 K to 1.48 K by evaporative cooling, superfluid fraction nearly 90%
- Disperse particles (either frozen hydrogen, atmosphere or fluorescent nanoparticles) into Helium
- Illuminate with 532 nm CW laser
- Image particles with CCD movie camera and track with sub-pixel localization (~ 3 microns) up to 200 fps



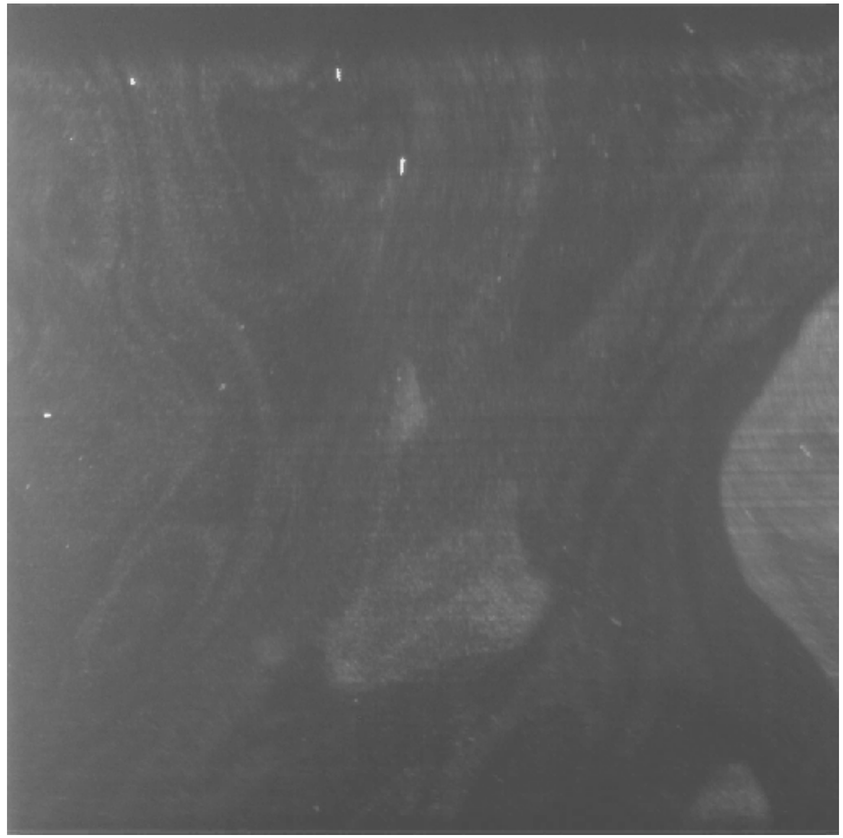


Particle Production

$1\ H_2 : \chi\ He \quad \chi >> 1$

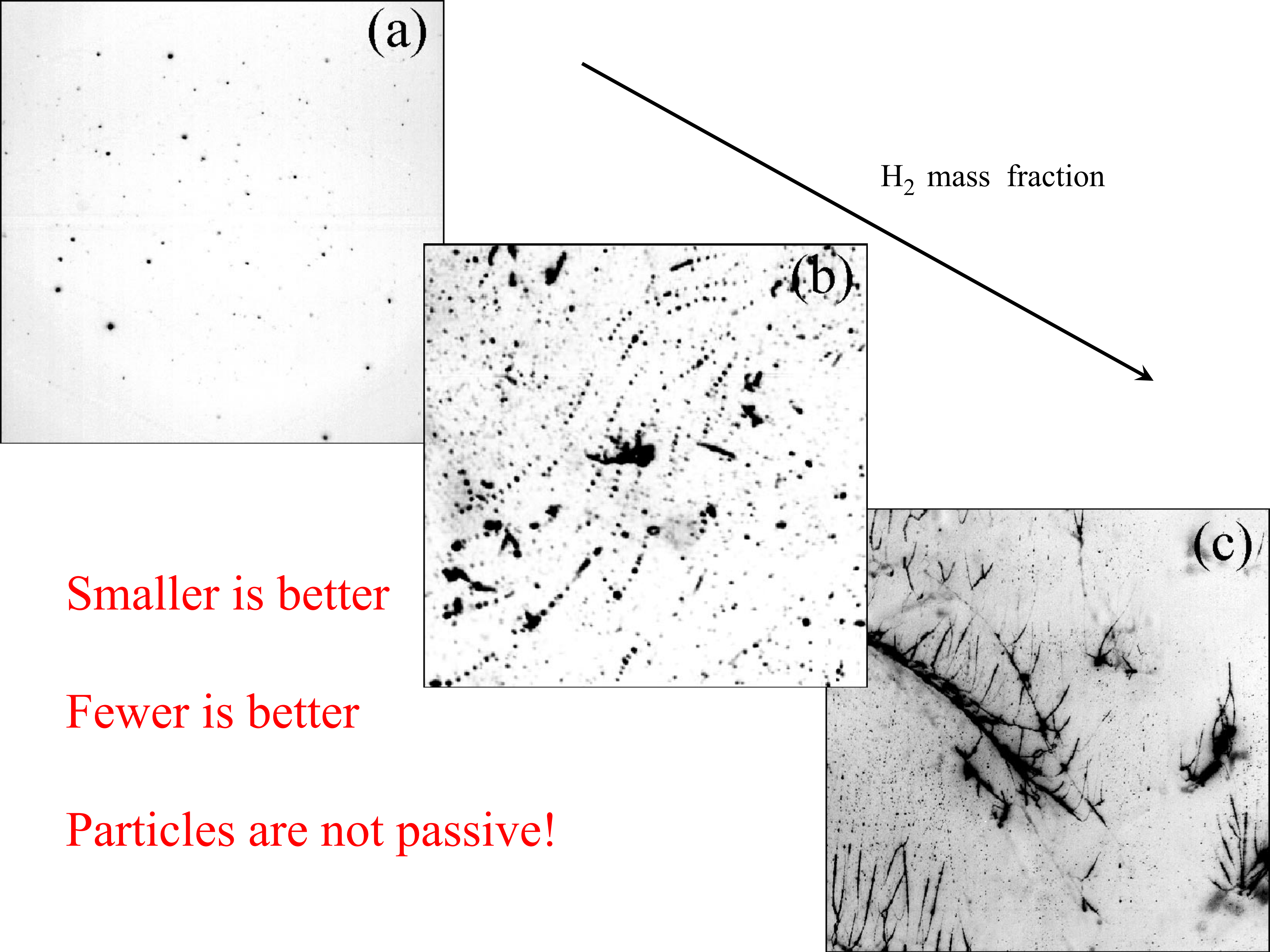


$T > T_\lambda$



1/2 image 8 mm

Bewley et al., *Experiments in Fluids 2008*

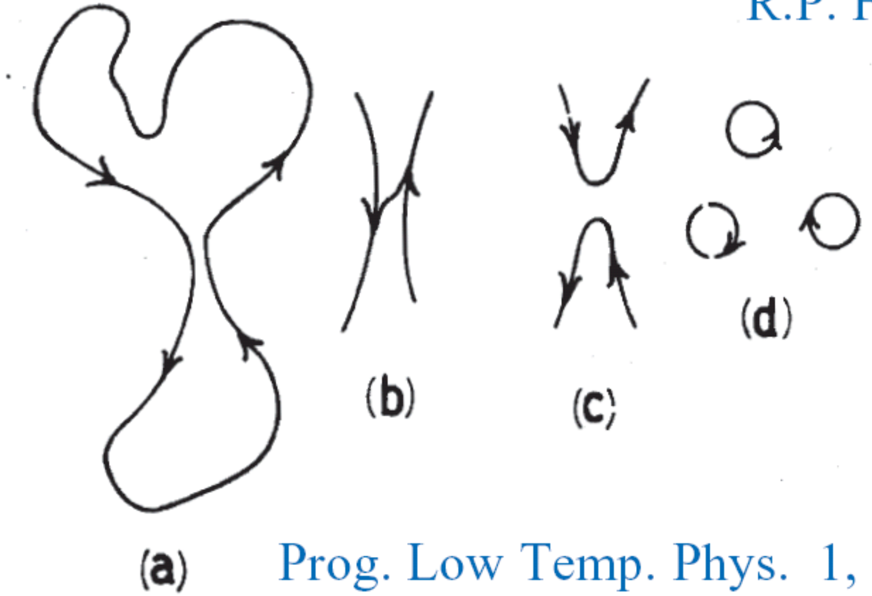


Smaller is better

Fewer is better

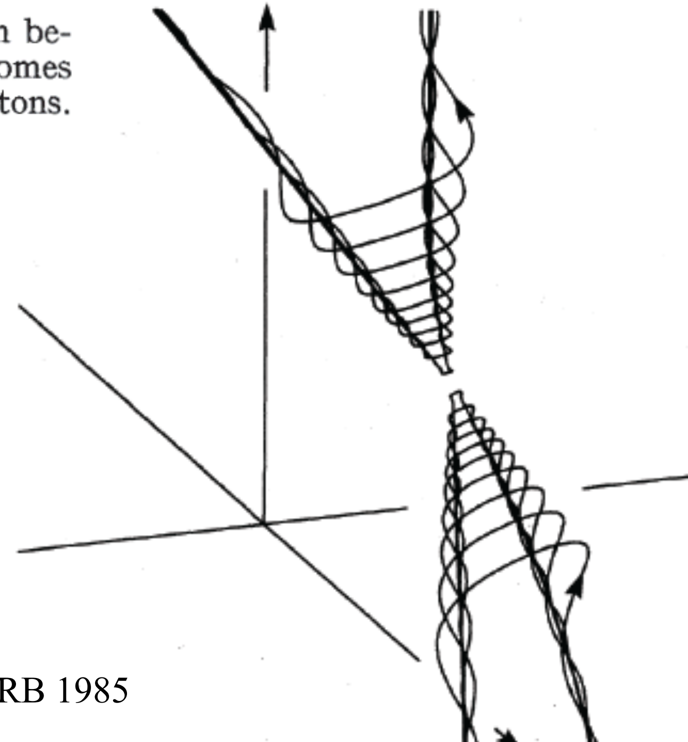
Particles are not passive!

R.P. Feynman



Prog. Low Temp. Phys. 1, 17 (1955)

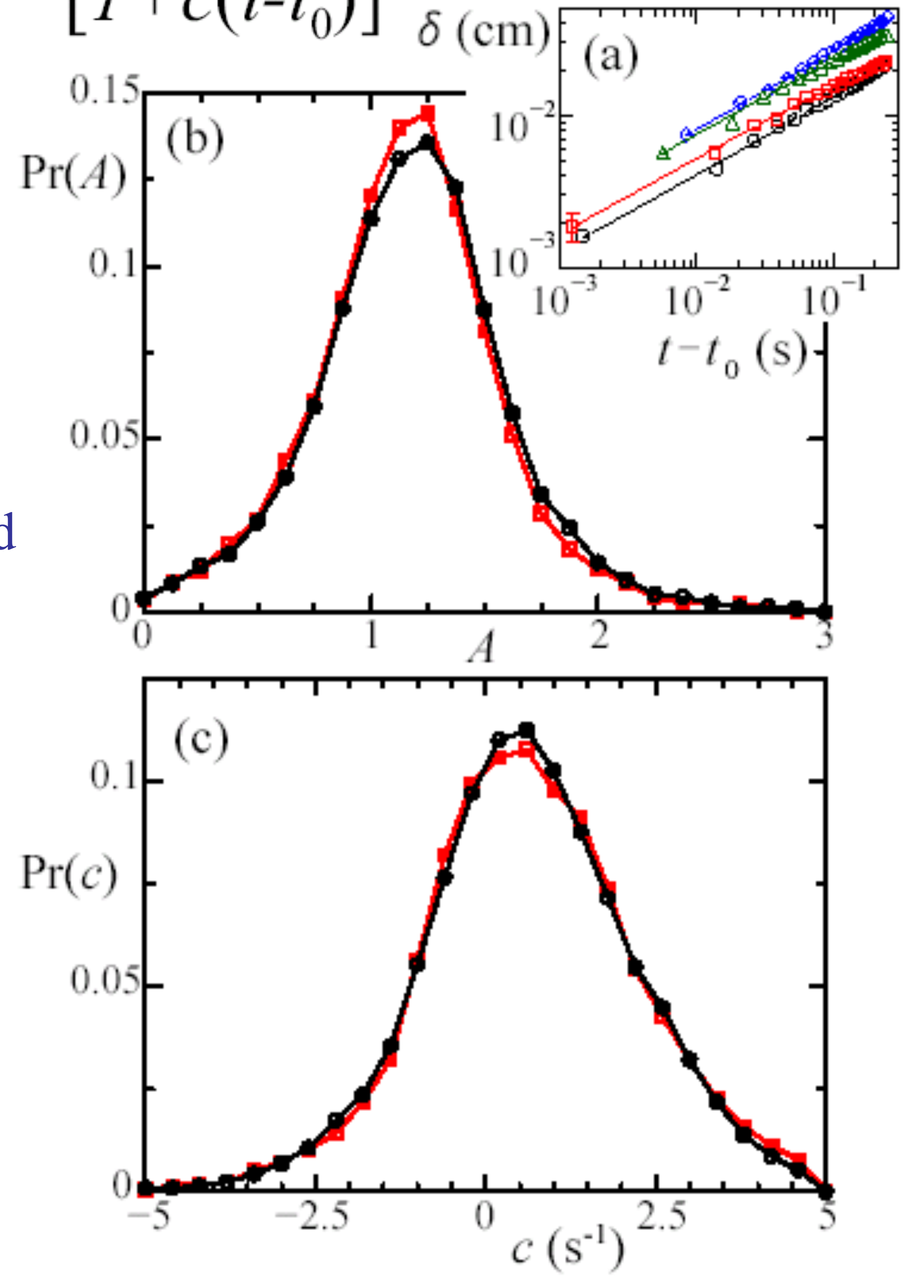
Fig. 10. A vortex ring (a) can break up into smaller rings if the transition between states (b) and (c) is allowed when the separation of vortex lines becomes of atomic dimensions. The eventual small rings (d) may be identical to rotons.



From Schwarz PRB 1985

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

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



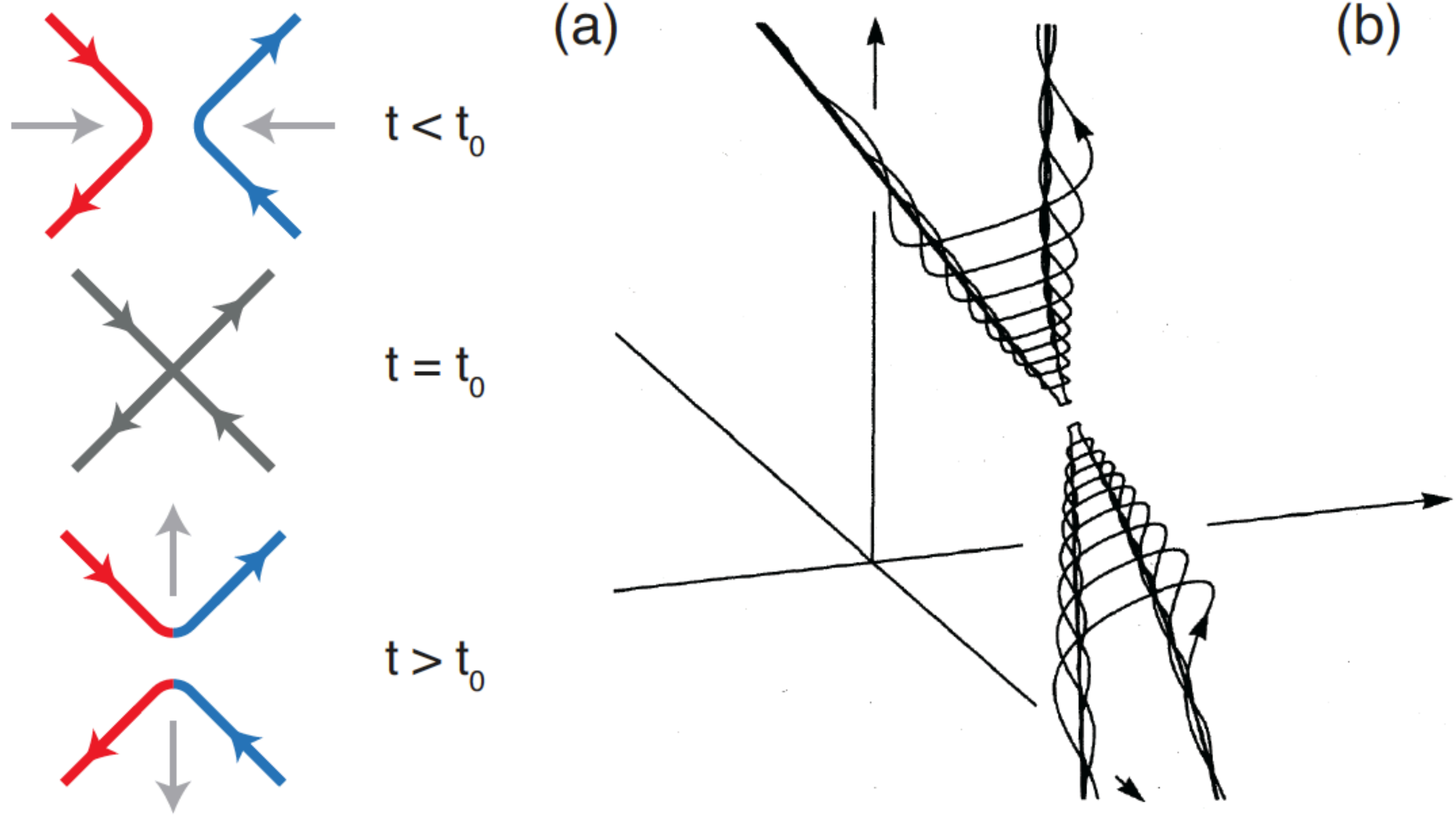
Only small pre- and post- differences

c may represent the affect of local strains

reconnection and ring collapse represented

NEARLY TIME REVERSIBLE!

M.S. Paoletti, M.E. Fisher, and D.P. Lathrop, "Reconnection dynamics for quantized vortices," Physica D (2010)



(a)
(b)
t < t0
t = t0
t > t0

Vortex Filament Models

- Local Induction Approximation (LIA)

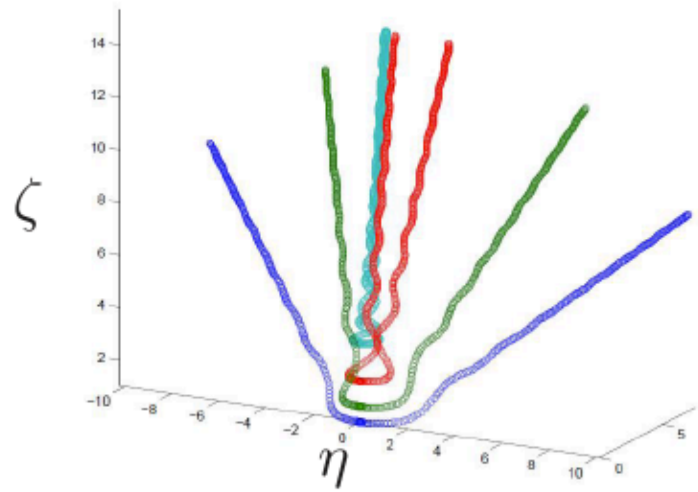
$$\frac{\partial \vec{s}(\sigma,t)}{\partial t} = \beta \frac{\partial \vec{s}(\sigma,t)}{\partial \sigma} \times \frac{\partial^2 \vec{s}(\sigma,t)}{\partial \sigma^2} + \alpha(T) \frac{\partial^2 \vec{s}(\sigma,t)}{\partial \sigma^2}$$

- LIA has one-parameter family of self-similar solutions in dimensionless similarity coordinates

- Adopt dimensionless similarity coordinates

$$\eta = (x - x_0)/\sqrt{\kappa(t - t_0)}$$
$$\zeta = (z - z_0)/\sqrt{\kappa(t - t_0)}$$

LIA Curves vs Vortex Angle

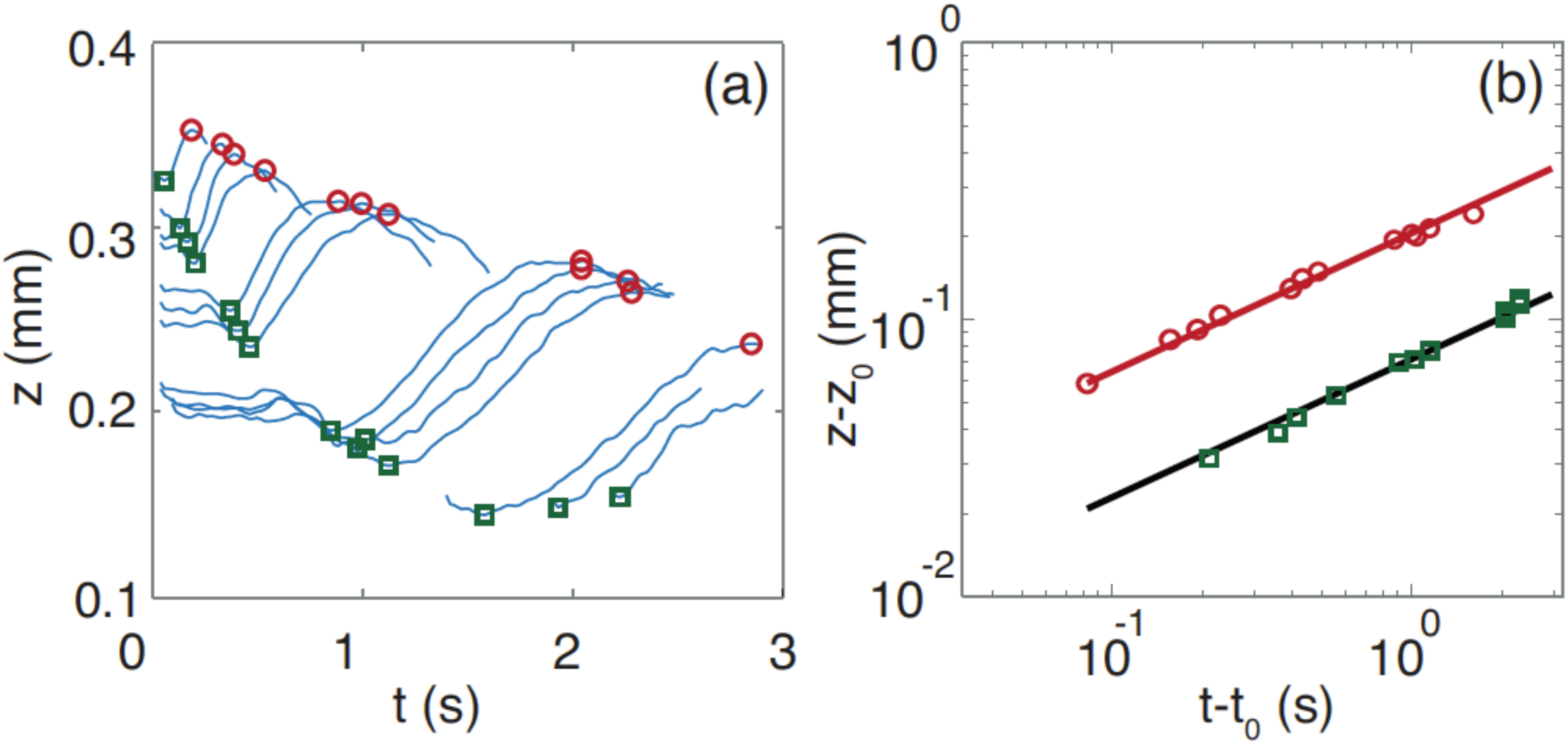


Eur. J. Mech. B - Fluids 19 (2000) 361–378

S0997-7546(00)00123-0/FLA

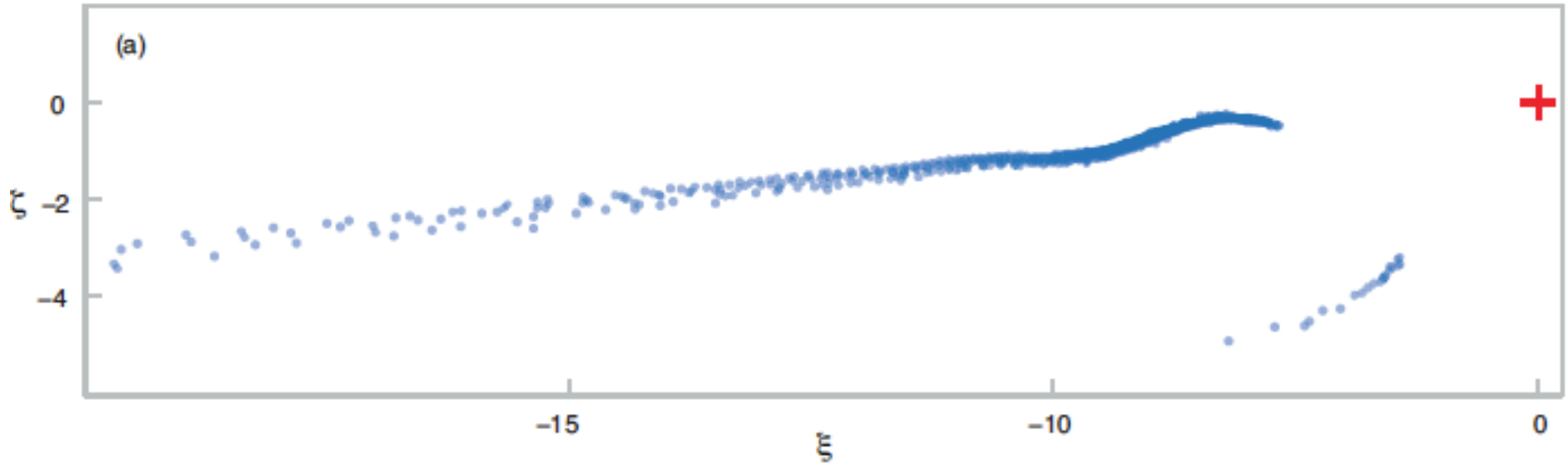
Evolution of quantum vortices following reconnection

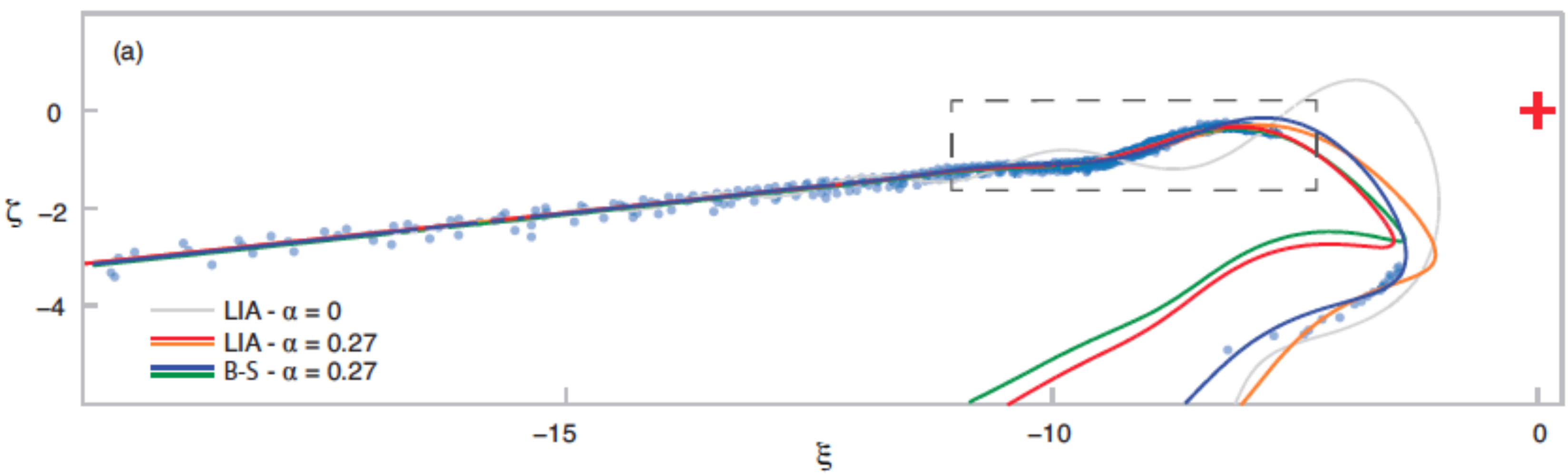
Tomasz Lipniacki *



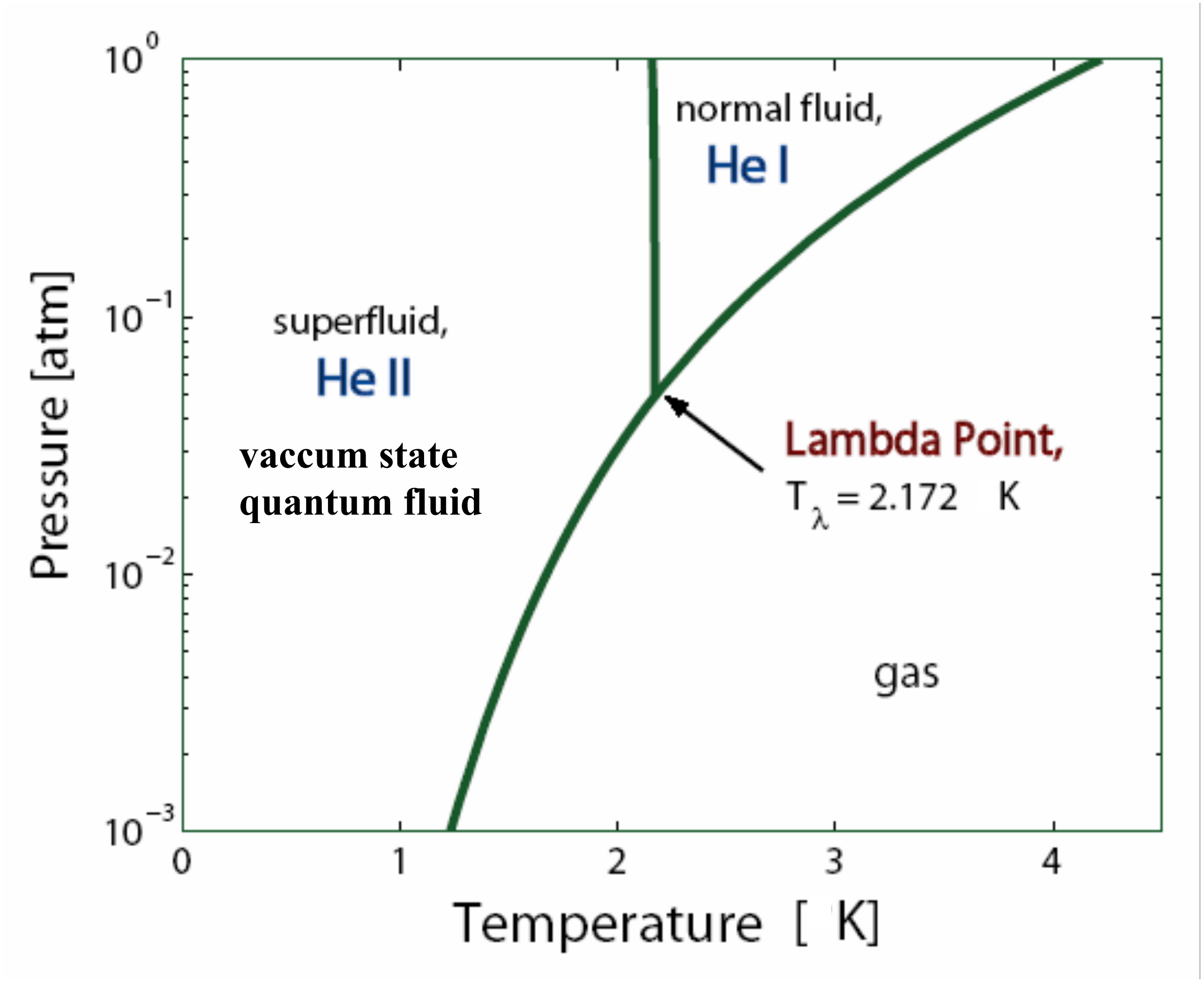
$$\zeta = (z - z_o)/\sqrt{\kappa(t - to)}$$

$$\xi = (x - xo)/\sqrt{\kappa(t - to)}$$


(a)
0
ζ -2
–4
–15
–10
0
ξ


(a)
0
ζ -2
–4
LIA - α = 0
LIA - α = 0.27
B-S - α = 0.27
–15
–10
0
ξ

Background: Superfluid Helium



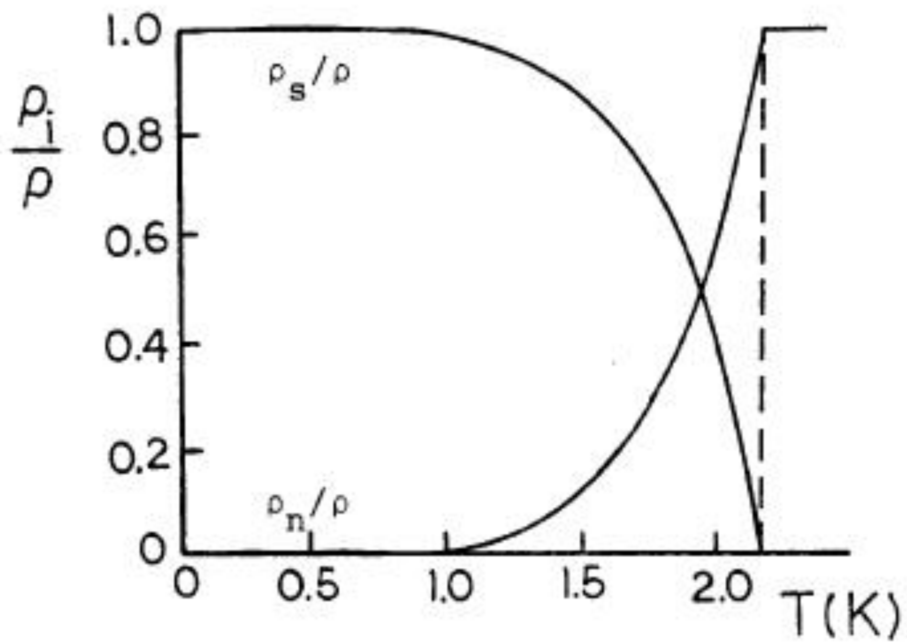
Two-Fluid Model

- Order parameter for superfluid helium is a complex field,

$$\Psi(\mathbf{x}) = Ae^{i\phi}$$

A is amplitude,

and ϕ is the phase



- Superfluid velocity given by

$$v_s = \kappa \nabla \phi \qquad \kappa = \frac{h}{m}$$

h = Planck's constant

m = mass of helium atom

Circulation Quantization

Superfluid order parameter described by a complex field

$$\Psi = \sqrt{\rho(r)}\, e^{i\phi(r)}$$

Superfluid velocity field is the gradient of the wave function's phase

$$\vec{v}_s \propto \nabla\phi$$

Superfluid is an irrotational fluid in the bulk, but permits circulation around line-like phase defects called **quantized vortices**

$\zeta \sim 1$ Å

Vorticity Vanishes

$$\omega = \nabla \times \vec{v}_s = \nabla \times (\, \nabla\phi(r)\,) = 0$$

$$\Gamma = \oint_C \vec{v} \cdot \vec{dl} = \oint_C \kappa\, \nabla\phi(r) \cdot \vec{dl} = \kappa\Delta\phi = (2\pi n)\kappa$$

Circulation Quantized

$$\kappa = h/m_{He} \approx 9.97 \cdot 10^{-8}\ \mathrm{m}^2/\mathrm{s}$$

$$n = 0, 1, 2\ \ldots$$

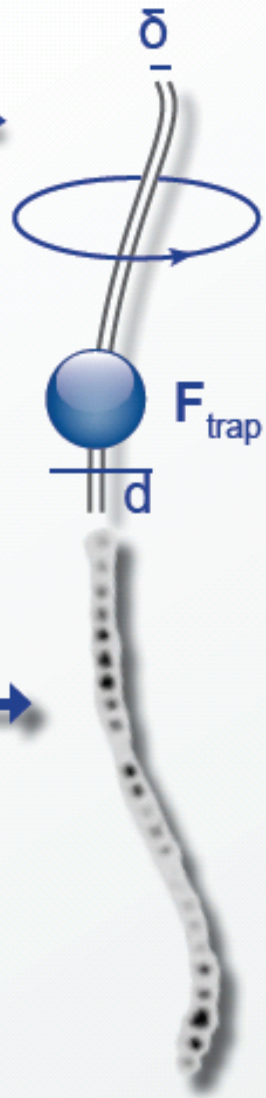
Visualization of vortices - particle trapping

$$P = -\frac{\rho_s \kappa^2}{8\pi^2 r^2} \qquad \mathbf{F} = \oint_{\partial\Omega} P\hat{n}\,dA$$

Decrease of energy $\Delta\varepsilon = \frac{\rho_s \kappa^2}{4\pi} d \ln \frac{d}{2\delta} = |\mathbf{F}_{trap}| d$

$$\frac{F_{trap}}{V} \propto \frac{\ln d}{d^3}$$

Particles get trapped on vortex cores →



Ions in liquid He ⊖ 16 Å ⊕ 6 Å

Parks and Donnelly (1966), Williams and Packard (1974)

Solid hydrogen particles >1μm

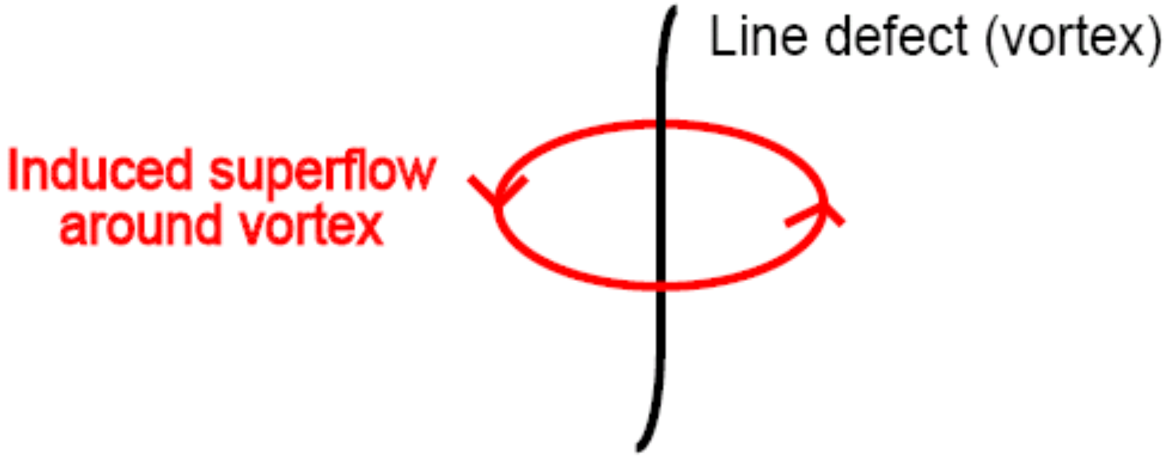
Bewley, Lathrop, Sreenivasan, Nature 441 588 (2006)

Quantized Vortices

- Lowest energy state: n=1, so ϕ wraps 2π around a defect
- Induces a superflow around the line:

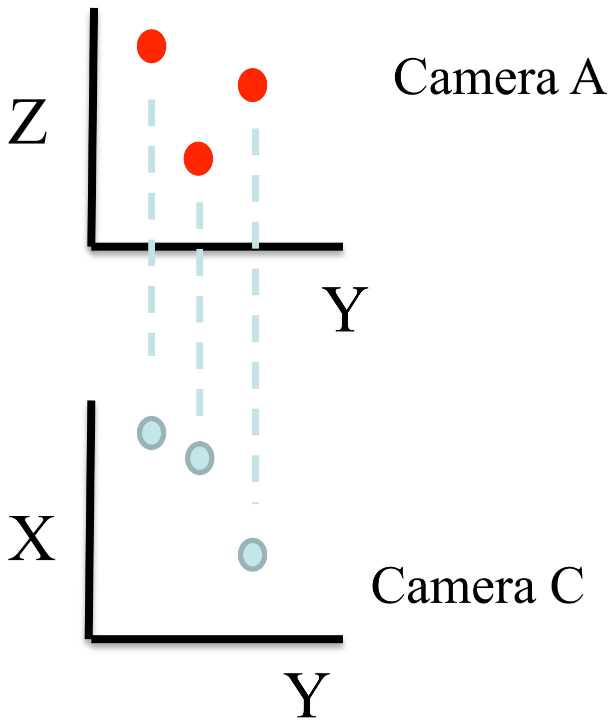
$$\mathbf{v}_{\Phi} = \frac{\kappa}{r}$$

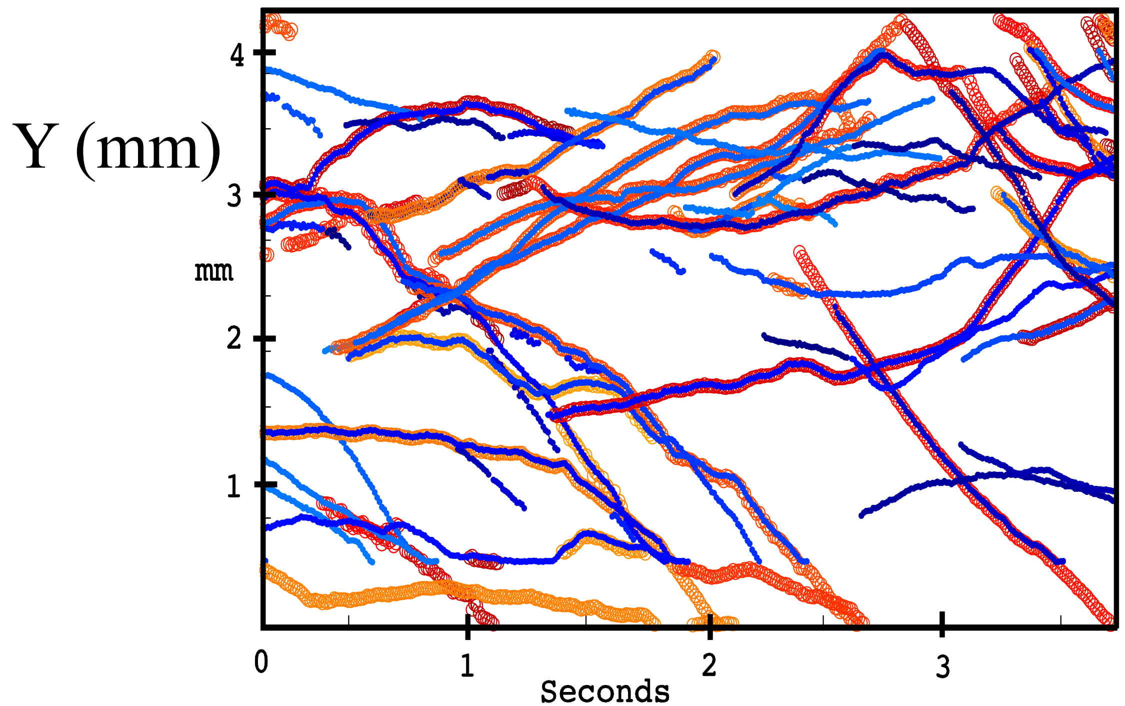
s is distance from defect



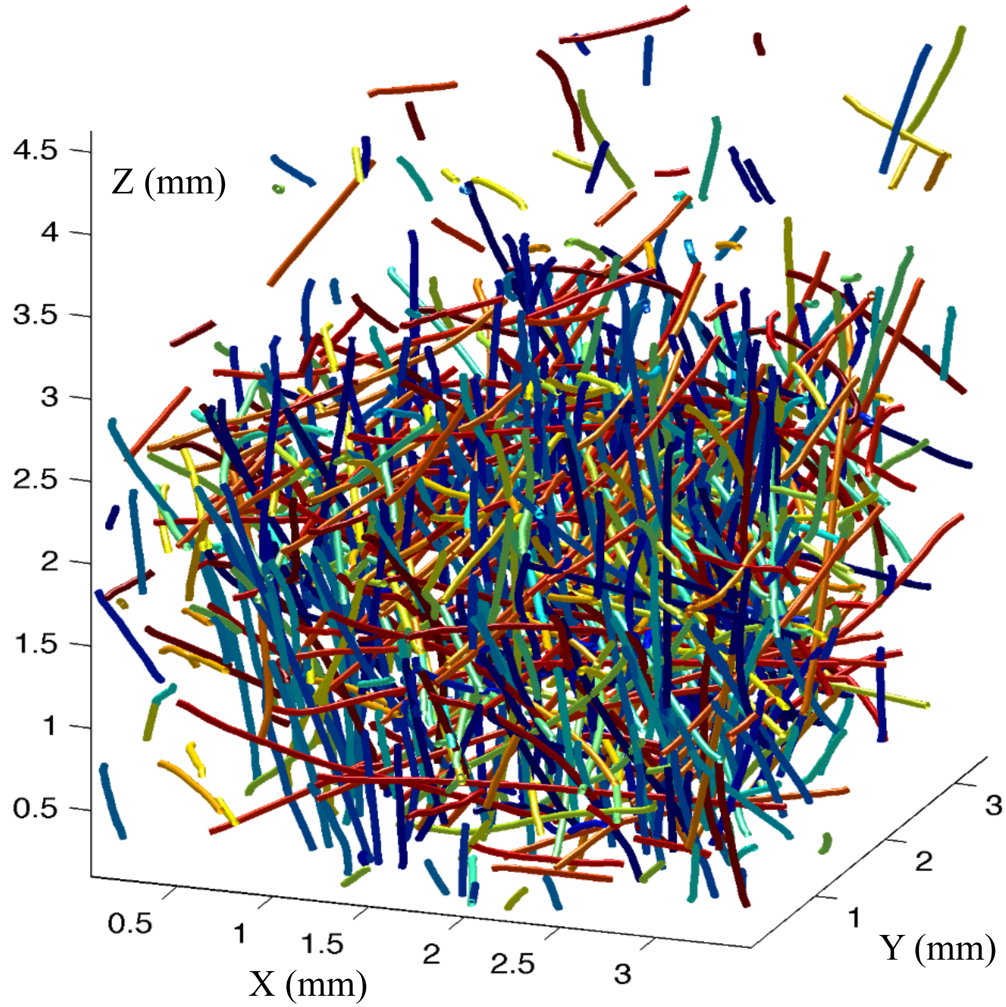
3D Stereomatching

3D trajectory reconstruction requires identifying particles mutually between two cameras





- ‘Shared’ coordinate between two cameras
- Normalized distance between tracks used to stereomatch



Single Particle Tracks in 3D

Rendering code by
Nick Ouellette