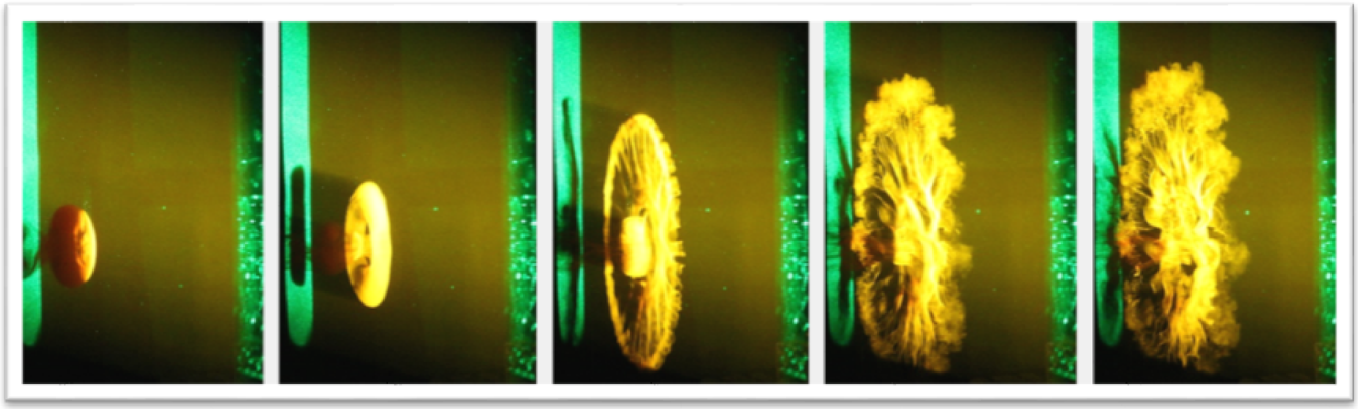
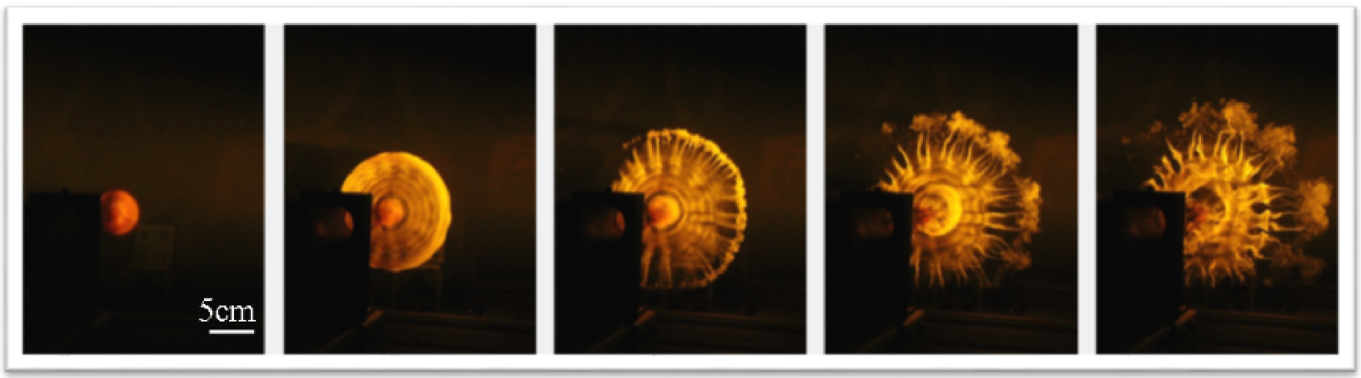
Colliding Vortex Rings; Rapid Breakup of Coherent Structures

(or, The *temporal* behavior of turbulent energy cascades…)

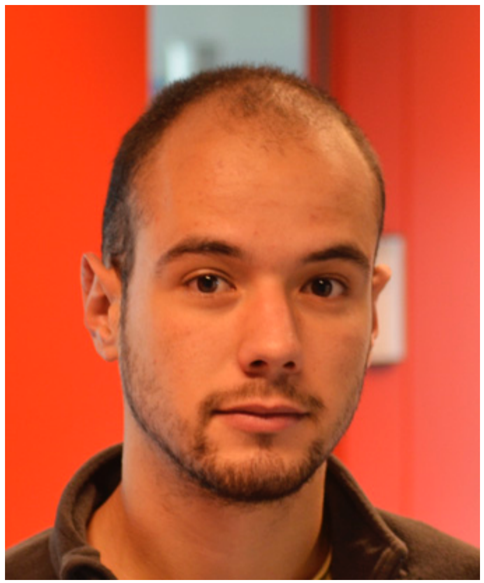




Shmuel M. Rubinstein
School of Engineering and Applied Sciences, Harvard

Colliding Vortex Rings; Rapid Breakup of Coherent Structures

(or, The *temporal* behavior of turbulent energy cascades…)



Ryan McKeown

Rodolfo Ostilla Monico

Michael Brenner

Alain Pumir

Shmuel M. Rubinstein
School of Engineering and Applied Sciences, Harvard University

Mechanism of the Production of Small Eddies from Large Ones

By G. I. TAYLOR, F.R.S., and A. E. GREEN, B.A.

(*Received* 12 *October*, 1936)

indicated by (5) and (6).

It is difficult to express these ideas in a mathematical form without assuming some definite form for the disturbance, but it is almost impossible to suggest an initial form which has the characteristics of the statistical isotropic turbulent motion to which (5) and (6) apply. Accordingly, we have searched for types of initial motion which have a definite scale and also have some of the properties of statistically uniform isotropic turbulence with a view to tracing the subsequent motion and finding out whether anything analogous to the process of the grinding down into smaller and smaller eddies occurs.

$$u = A \cos ax \sin by \sin cz$$

$$v = B \sin ax \cos by \sin cz$$

$$w = C \sin ax \sin by \cos cz$$

Taylor, G. I., and A. E. Green. "Mechanism of the production of small eddies from large ones. " Proceedings of the Royal Society of London… 158.895 (1937): 499-521.

Mechanism of the Production of Small Eddies from Large Ones

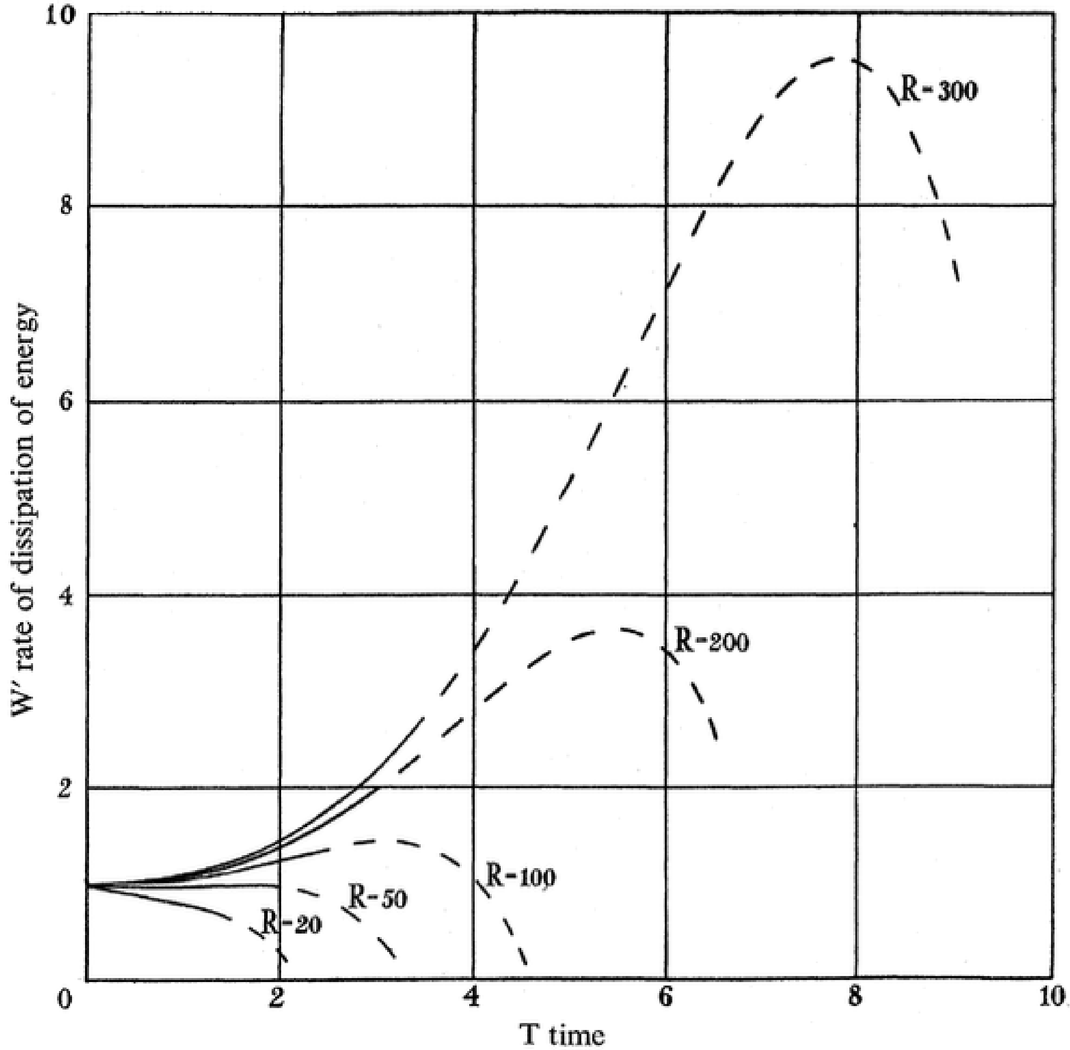
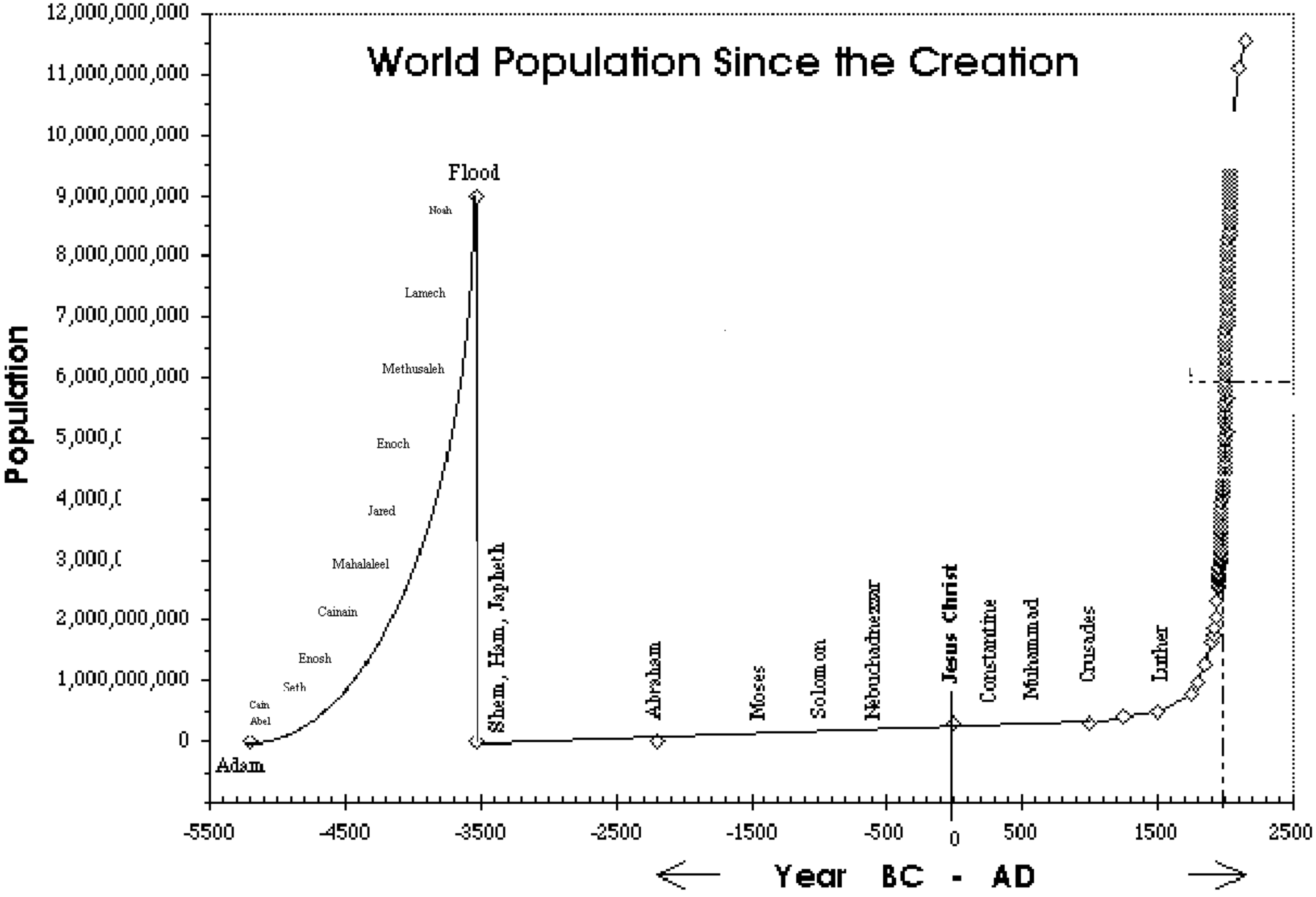


Fig. 1.

Taylor, G. I., and A. E. Green. "Mechanism of the production of small eddies from large ones. " Proceedings of the Royal Society of London… 158.895 (1937): 499-521.



It is hard to identify a real singularity

A Beautiful experiment

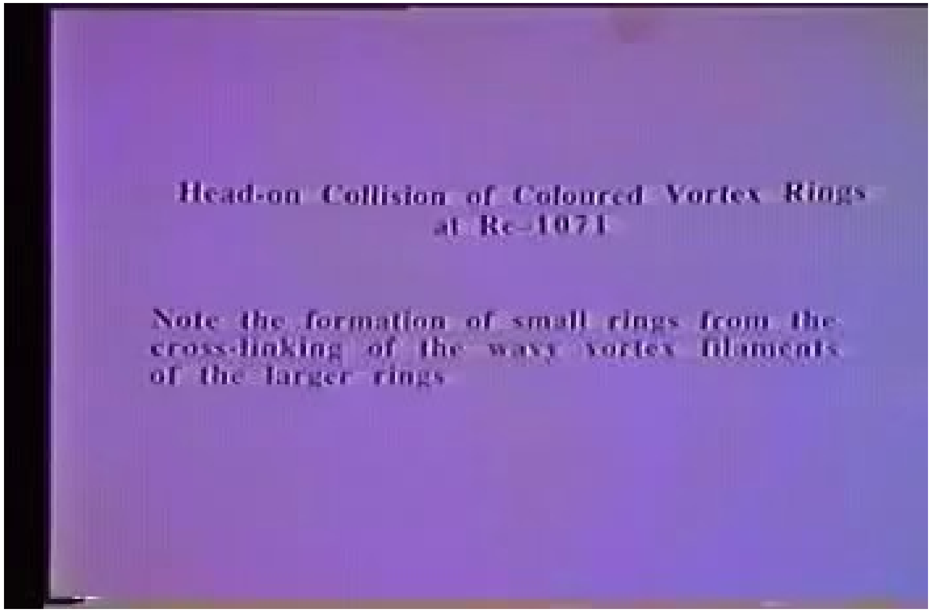
Instability and reconnection in the head-on collision of two vortex rings

T. T. Lim & T. B. Nickels

Department of Mechanical & Manufacturing Engineering,
University of Melbourne, Parkville 3052, Australia

NATURE · VOL 357 · 21 MAY 1992

Lim and Nickels (1992)



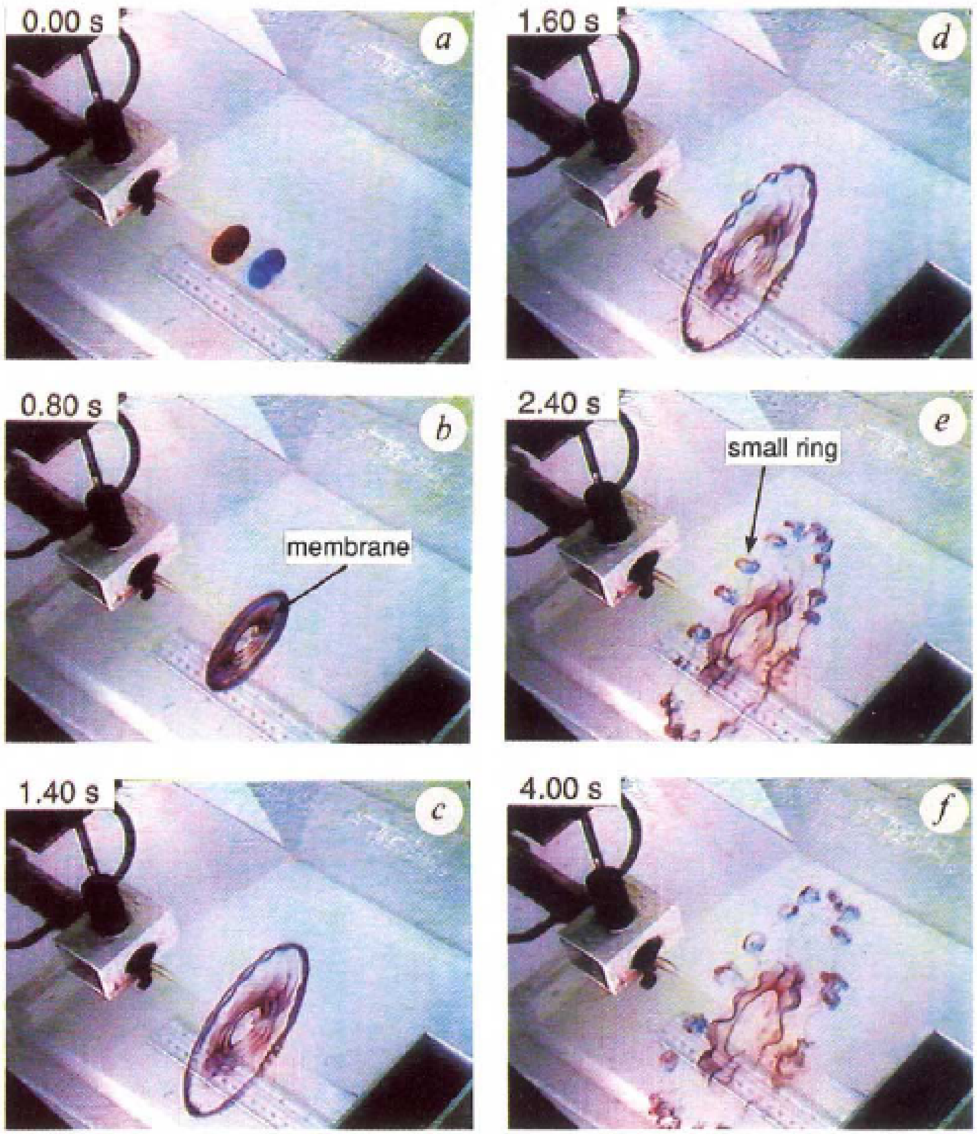
Re=1071

Secondary Vortices

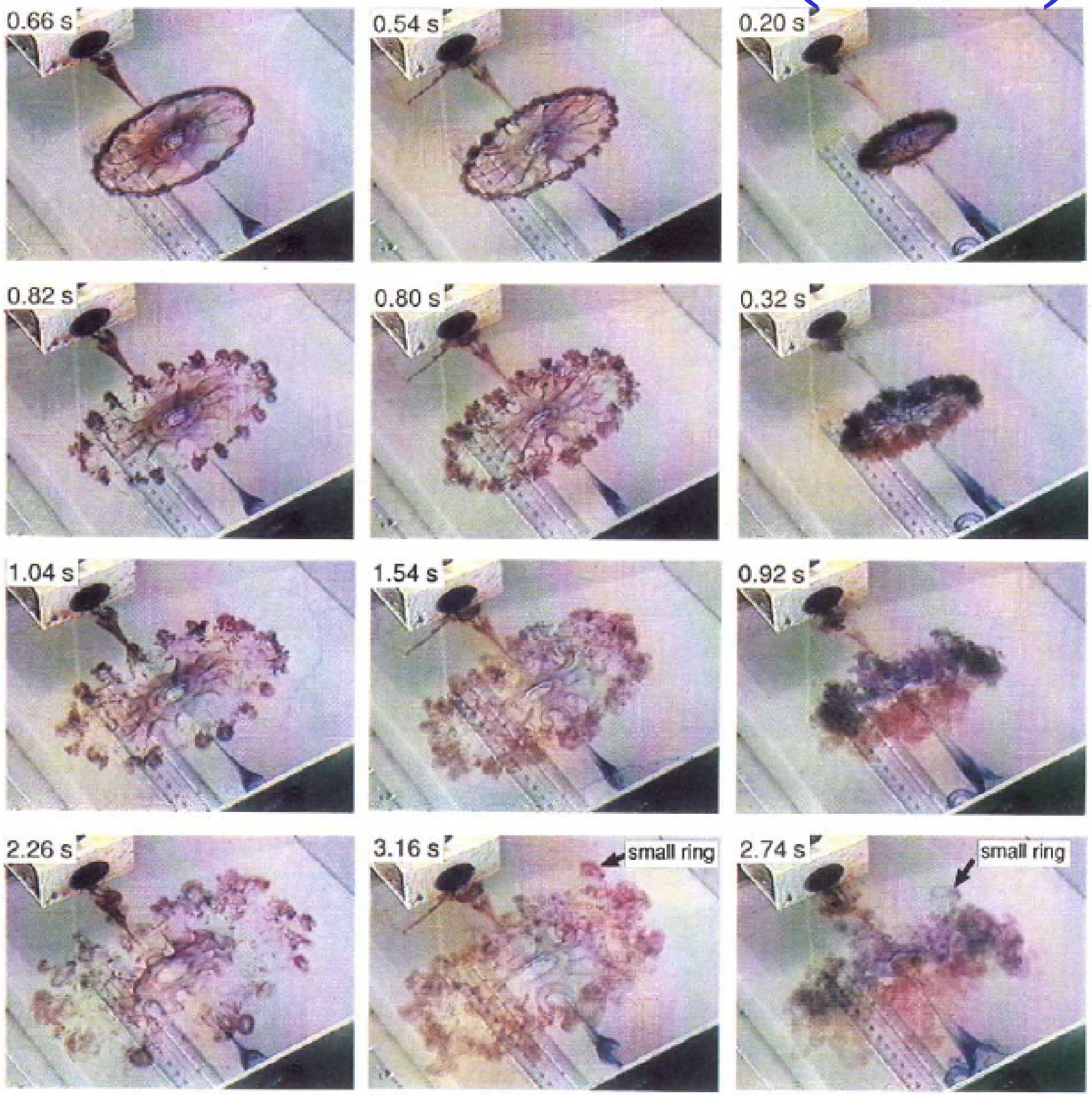
Re=1573

Turbulent Cloud

Lim and Nickels (1992)



Lim and Nickels (1992)

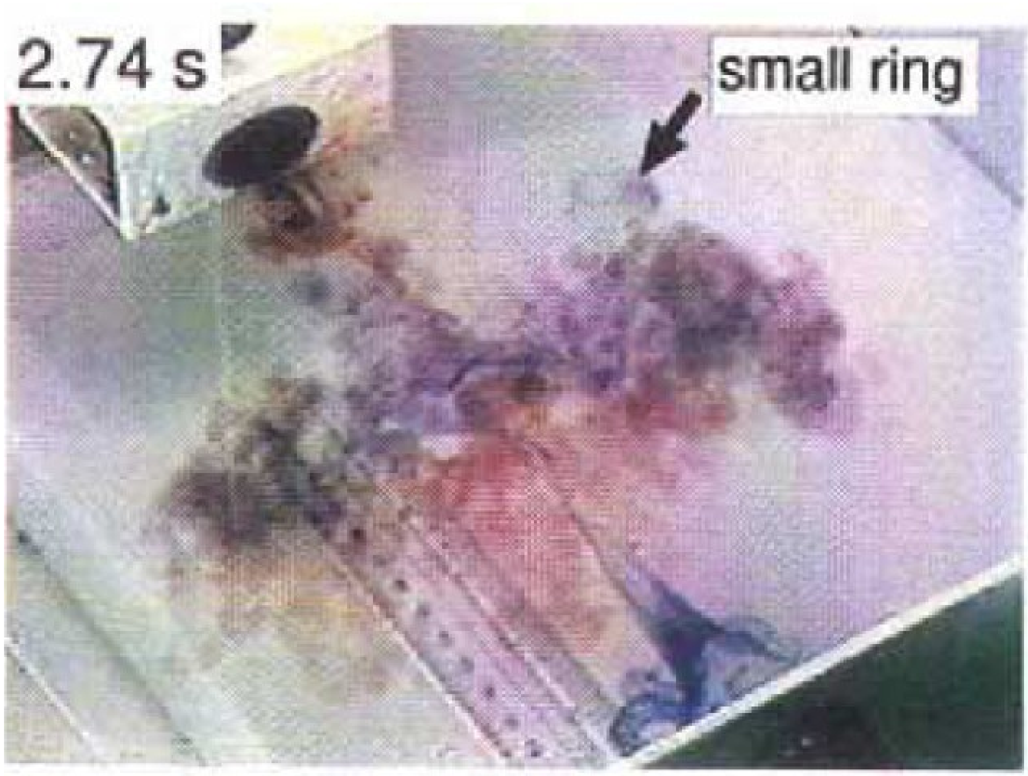


1450 1850 3500

The Question

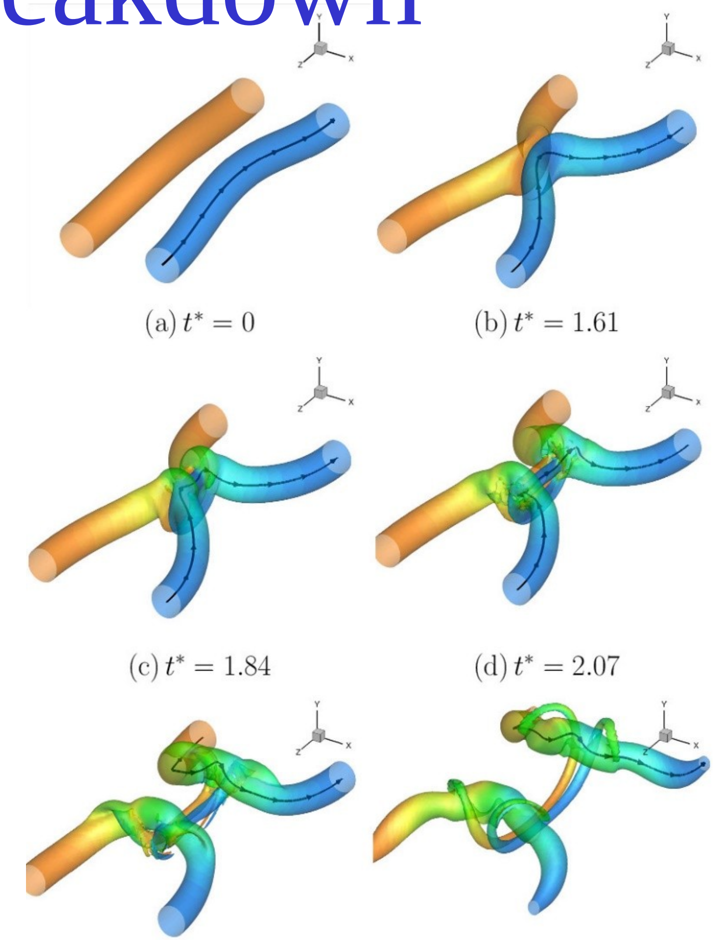
What is the mechanism for energy to transfer so quickly from large scales to small scales?

(Is it Singular?)



Vortex reconnection \ breakdown

- Antiparallel vortex tubes stretch and flatten upon contacting and partially reconnect through the diffusion of vorticity
- After reconnecting, secondary vortex threads are left behind
- If Re is high enough, the vortex threads will also reconnect and repeat this cycle
- Possible mechanism for energy cascade



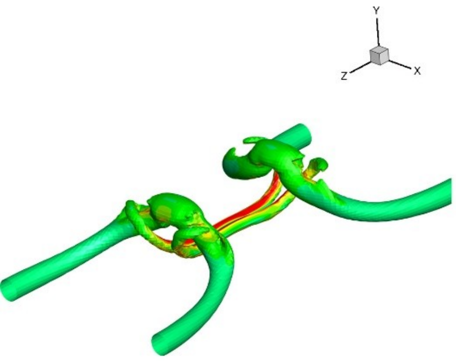
(a) $t^* = 0$ (b) $t^* = 1.61$ (c) $t^* = 1.84$ (d) $t^* = 2.07$ (e) $t^* = 2.30$ (f) $t^* = 2.77$

$$t^* = t/(2\pi b^2/\Gamma_z)$$

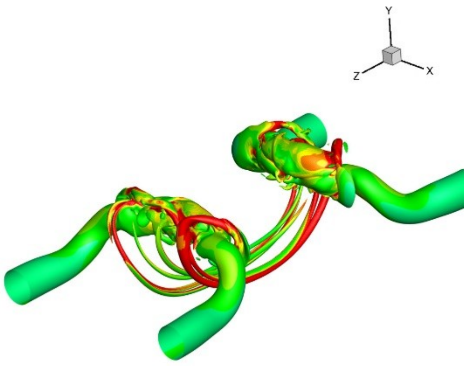
*Vorticity magnitude isosurfaces at 40% of maximum initial vorticity (shaded with contours of axial vorticity) for Re=2000.

- Hussain, F., and Duraisamy, K. "Mechanics of viscous vortex reconnection." *Physics of Fluids* 23.2 (2011): 021701.
- Kida, Shigeo, and M. Takaoka. "Vortex reconnection." Annual Review of Fluid Mechanics 26.1 (1994): 169-177.

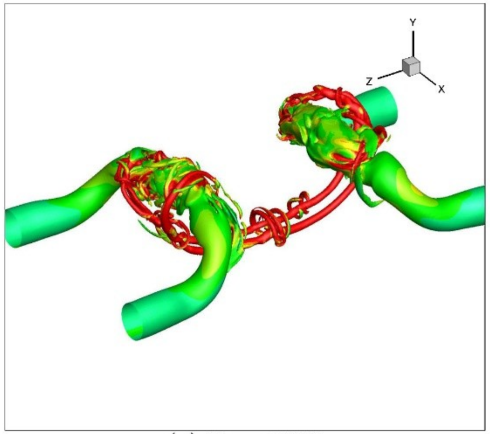
Vortex reconnection \ breakdown



(a) Re=2000



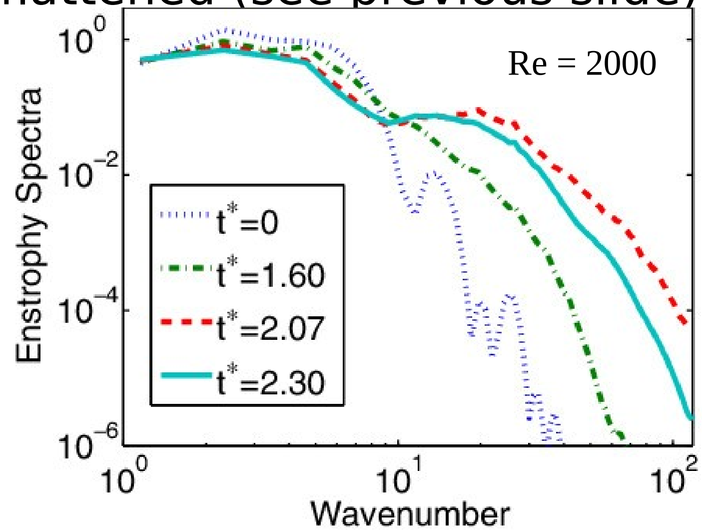
(b) Re=6000



(c) Re=7500

λ_2 isosurfaces (shaded with vorticity magnitude) at t*≈4.95.

- Small-scales emerge from reconnection zone where the vortex lines have high curvature and are locally stretched
- At high Re, this forms sheet-like structures that break down into small scales
- Enstrophy transfer spectrum shows that kinetic energy is injected into small scales when the vortex cores are flattened (see previous slide)



- Hussain, F., and Duraisamy, K. "Mechanics of viscous vortex reconnection." *Physics of Fluids* 23.2 (2011): 021701.

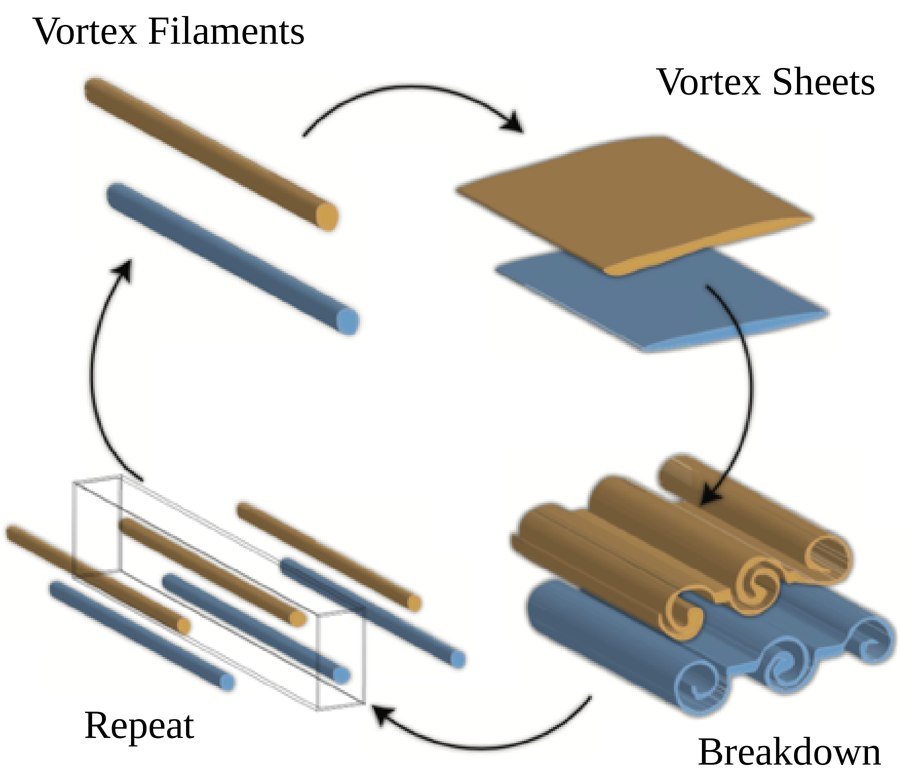
PHYSICAL REVIEW FLUIDS **1**, 084503 (2016)

Potential singularity mechanism for the Euler equations

Michael P. Brenner,[1] Sahand Hormoz,[2,3] and Alain Pumir[4]
[1] *School of Engineering and Applied Sciences and Kavli Institute for Bionano Science and Technology, Harvard University, Cambridge, Massachusetts 02138, USA*
[2] *Kavli Institute for Theoretical Physics, University of California, Santa Barbara, Santa Barbara, California 93106, USA*
[3] *Division of Biology and Biological Engineering, California Institute of Technology, Pasadena, California 91125, USA*
[4] *Université Lyon, Ecole Normale Supérieure de Lyon, Université Claude Bernard Lyon 1, and CNRS, 69007 Lyon, France*
(Received 22 June 2016; published 28 December 2016)

Singular solutions to the Euler equations could provide essential insight into the formation of very small scales in highly turbulent flows. Previous attempts to find singular flow structures have proven inconclusive. We reconsider the problem of interacting vortex tubes, for which it has long been observed that the flattening of the vortices inhibits sustained self-amplification of velocity gradients. Here we consider an iterative mechanism, based on the transformation of vortex filaments into sheets and their subsequent instability back into filaments. Elementary fluid mechanical arguments are provided to support the formation of a singular structure via this iterated mechanism, which we analyze based on a simplified model of filament interactions.

Energy Cascade



- Interaction of antiparallel vortex filaments
- Possible mechanism for energy cascade
- Cascade becomes iterative in the inviscid limit
- Generates small-scale flow structures in the viscous case

Difficult to resolve cascade numerically because vortex sheet thickness quickly approaches the mesh size

Brenner, M. P., Hormoz, S., and Pumir, A *Physical Review Fluids* 1.8 (2016): 084503.

Instabilities of the Vortex Core

The stability of short waves on a straight vortex filament in a weak externally imposed strain field

By CHON-YIN TSAI AND SHEILA E. WIDNALL
Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, Cambridge

(Received 9 June 1975 and in revised form 6 November 1975)

The stability of short-wave displacement perturbations on a vortex filament of constant vorticity in a weak externally imposed strain field is considered. The circular cross-section of the vortex filament in this straining flow field becomes elliptical. It is found that instability of short waves on this strained vortex can occur only for wavelengths and frequencies at the intersection points of the dispersion curves for an isolated vortex. Numerical results show that the vortex is stable at some of these points and unstable at others. The vortex is unstable at wavelengths for which $\omega = 0$, thus giving some support to the instability mechanism for the vortex ring proposed recently by Widnall, Bliss & Tsai (1974). The growth rate is calculated by linear stability theory. The previous work of Crow (1970) and Moore & Saffman (1971) dealing with long-wave instabilities is discussed as is the very recent work of Moore & Saffman (1975).

Instabilities of the Vortex Core

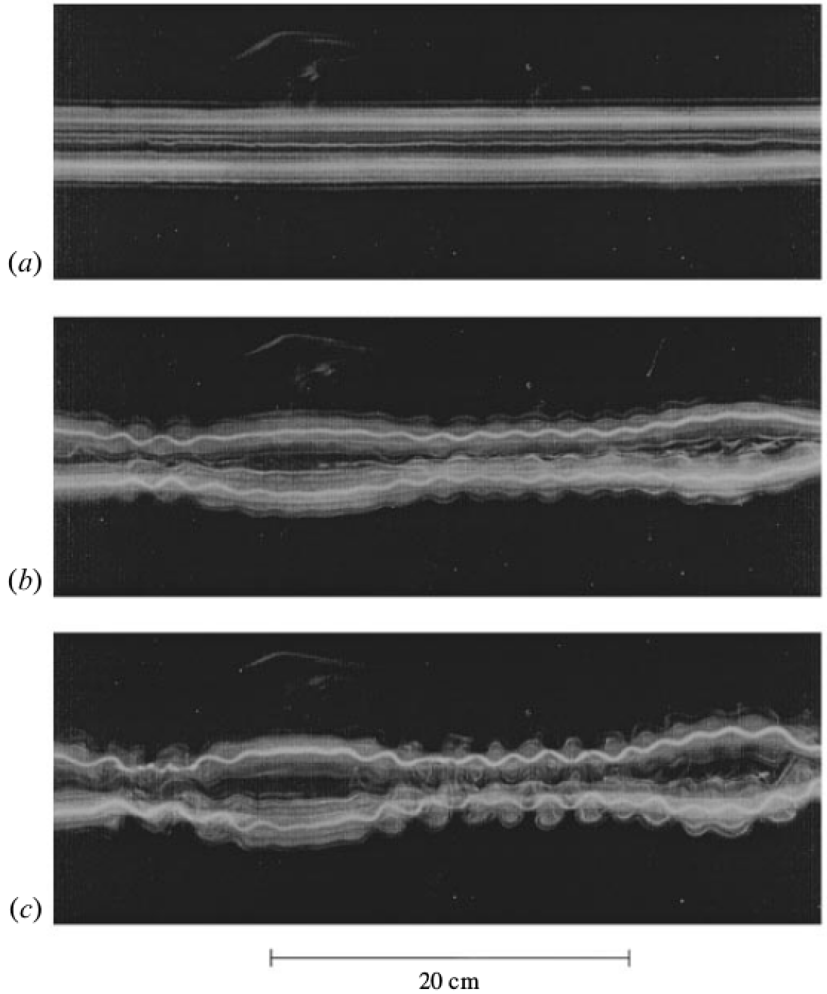


FIGURE 4. Visualization of vortex pair evolution under the combined action of long-wavelength (Crow) and short-wavelength instabilities. $Re = 2750$. The pair is moving towards the observer. (*a*) $t^* = 1.7$, (*b*) $t^* = 5.6$, (*c*) $t^* = 6.8$.

Leweke & Williamson, J. Fluid Mech., 360, 85-119 (1998)

Smashing 2 antiparallel vortex rings

Wim van Rees and Petros Koumoutsakos

The Question

- The critical question is to resolve the (generic) *temporal mechanism for energy to transfer* from large scales to small scales in a high Re fluid flow?
- How does viscosity modify the temporal dynamics in a flow with increasing Reynolds number?

The Question

- The critical question is to resolve the (generic) *temporal mechanism for energy to transfer* from large scales to small scales in a high Re fluid flow?
- How does viscosity modify the temporal dynamics in a flow with increasing Reynolds number?

The Working Hypothesis

- Simulations very rapidly run out of resolution.

Numerical simulations performed to date probe large r_0/R_0 and might miss interesting phenomena.

- Experiments: Events happen too quickly and at too small of spatial scales to be resolved.

The Question

- The critical question is to discover the (generic) *temporal mechanism for energy to transfer* from large scales to small scales in a fluid flow [at high Re]?
- How does viscosity modify the temporal dynamics in a flow with increasing Reynolds number?

The Working Hypothesis

- Simulations very rapidly run out of resolution.

Numerical simulations performed to date probe large r_0/R_0 and might miss interesting phenomena.

- Experiments: Events happen too quickly and at too small of spatial scales to be resolved.

Current experimental advances (Rubinstein/McKeown) show that the phenomenology is quite rich and needs to be resolved.

The Question

- The critical question is to discover the (generic) *temporal mechanism for energy to transfer* from large scales to small scales in a fluid flow [at high Re]?
- How does viscosity modify the temporal dynamics in a flow with increasing Reynolds number?

The Working Hypothesis

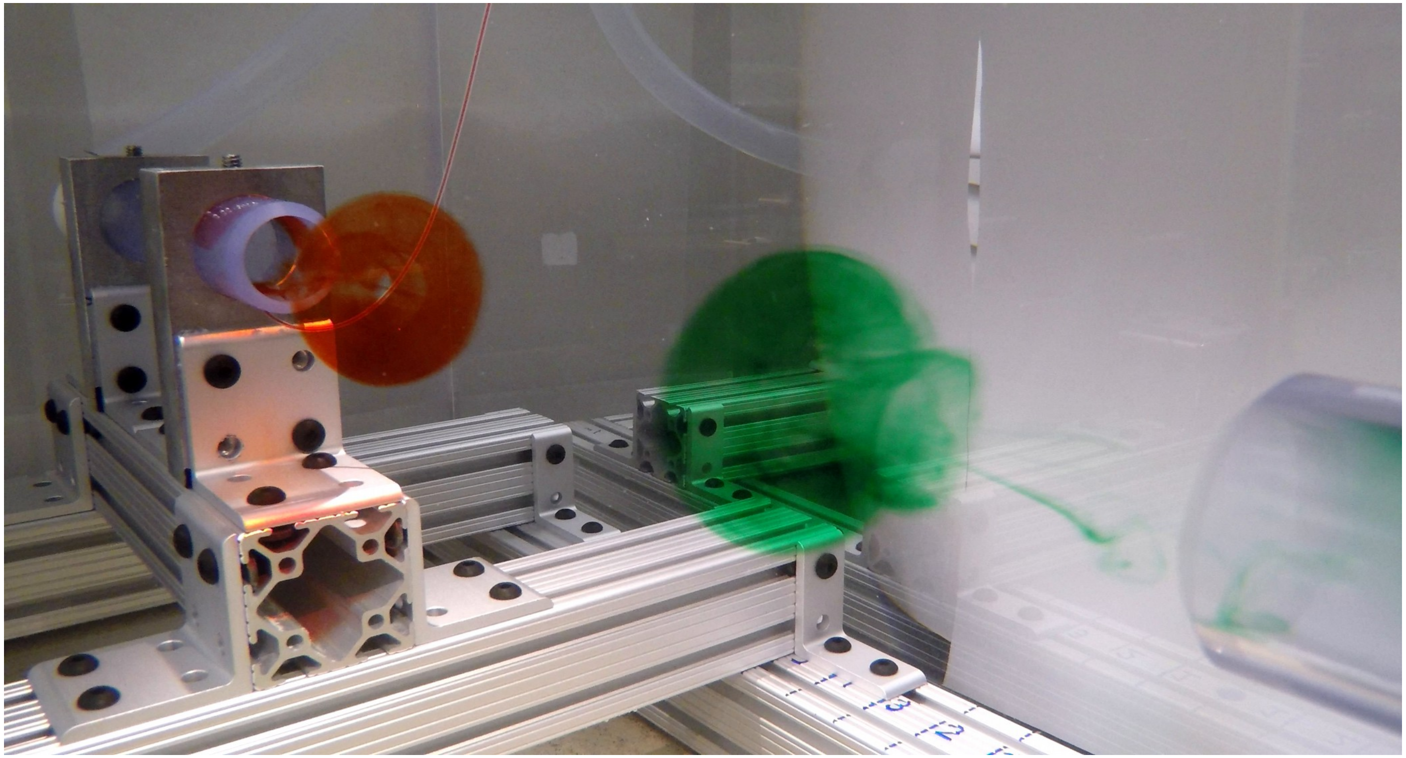
- Simulations very rapidly run out of resolution.

Numerical simulations performed to date probe large r_0/R_0 and might miss interesting phenomena.

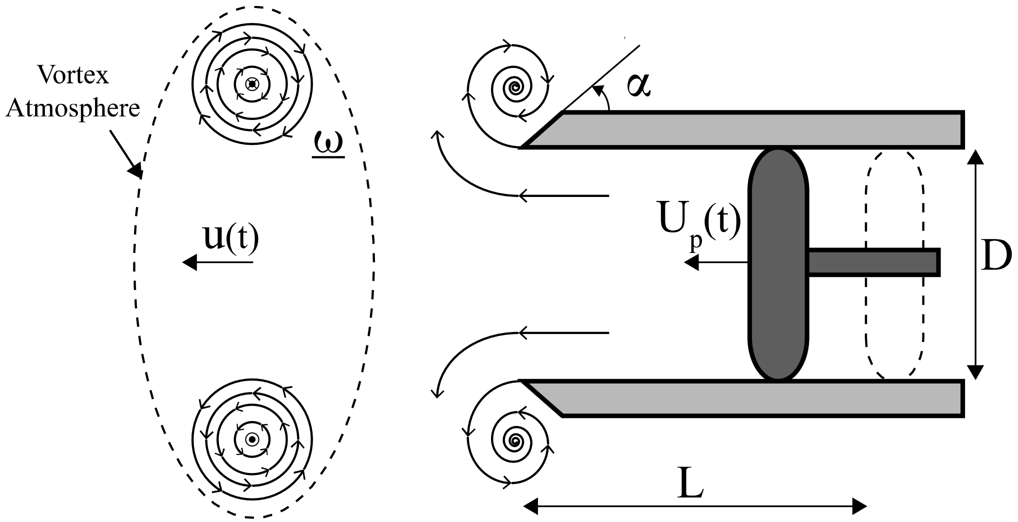
- Experiments: Events happen too quickly and at too small of spatial scales to be resolved.

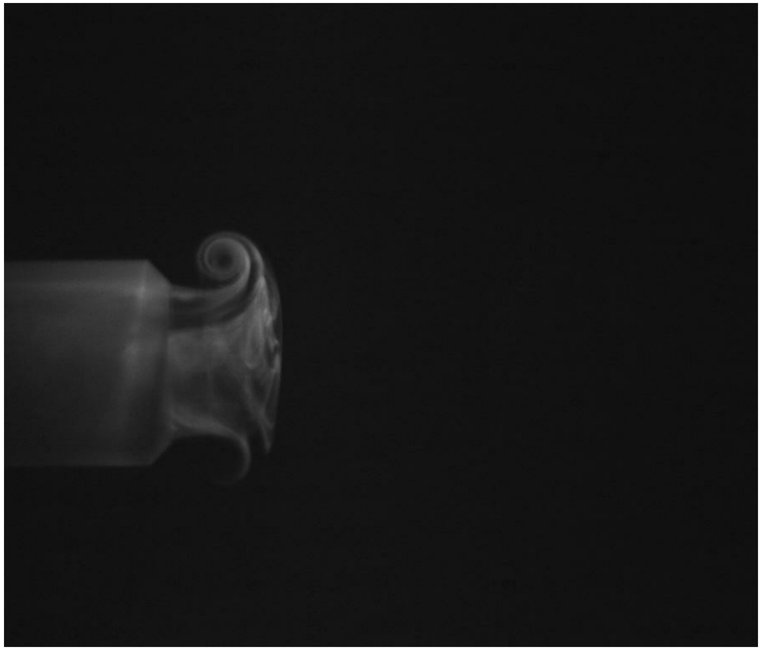
Current experimental advances (Rubinstein/McKeown) show that the phenomenology is quite rich and needs to be resolved.

Experimental Setup



Blowing a Vortex Ring: Recipe



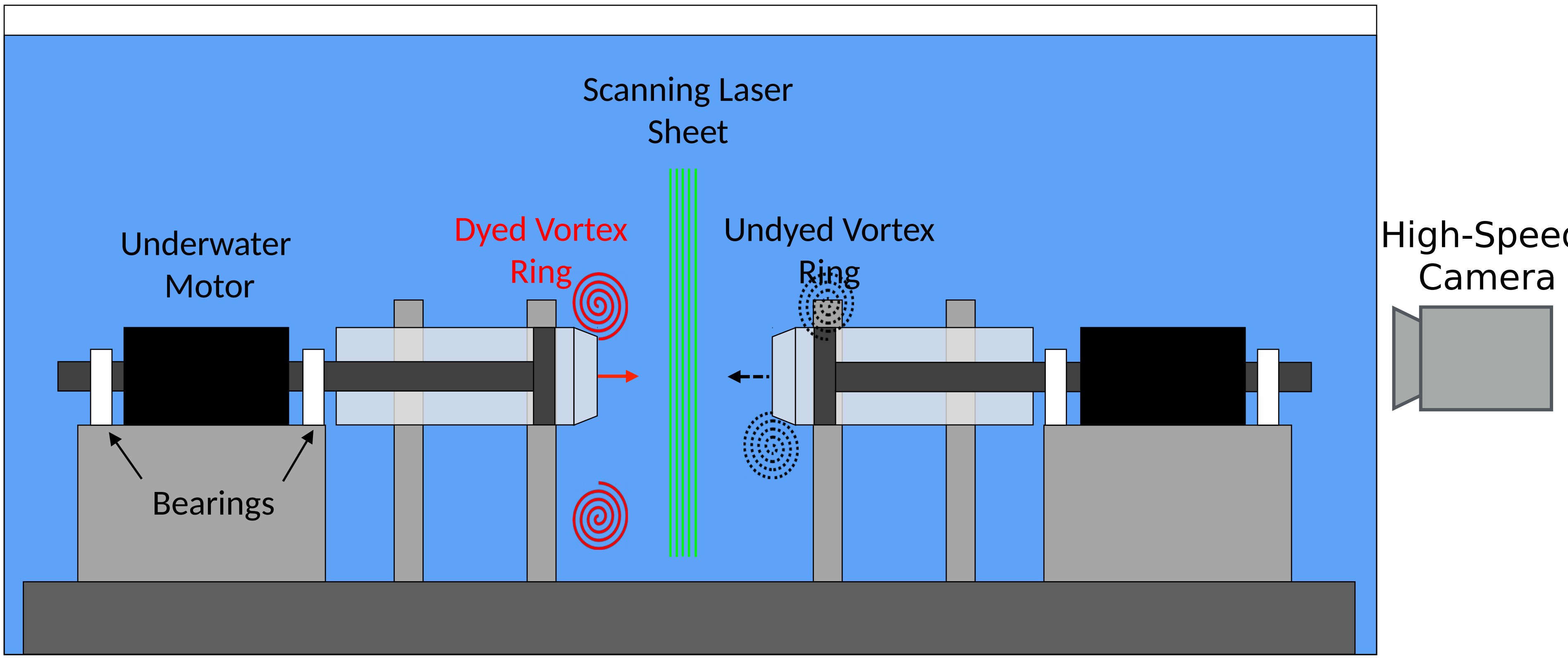


$$Re = \frac{DU_{p,max}}{\nu}$$

- Flow Separation at the edge
- Viscous interaction between the ejected and ambient fluids

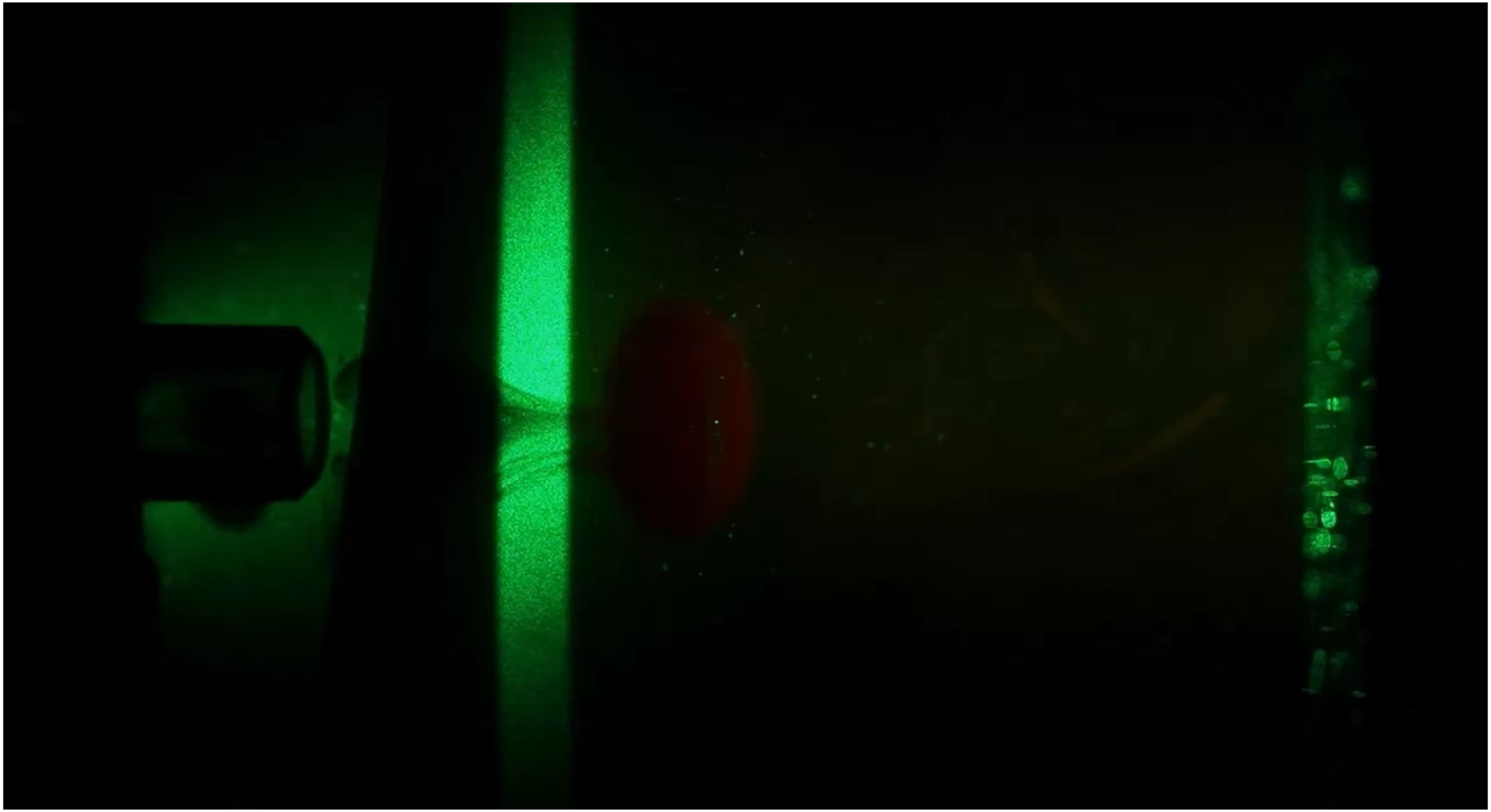
Adjustable Parameters: L/D, Re

Experimental Setup

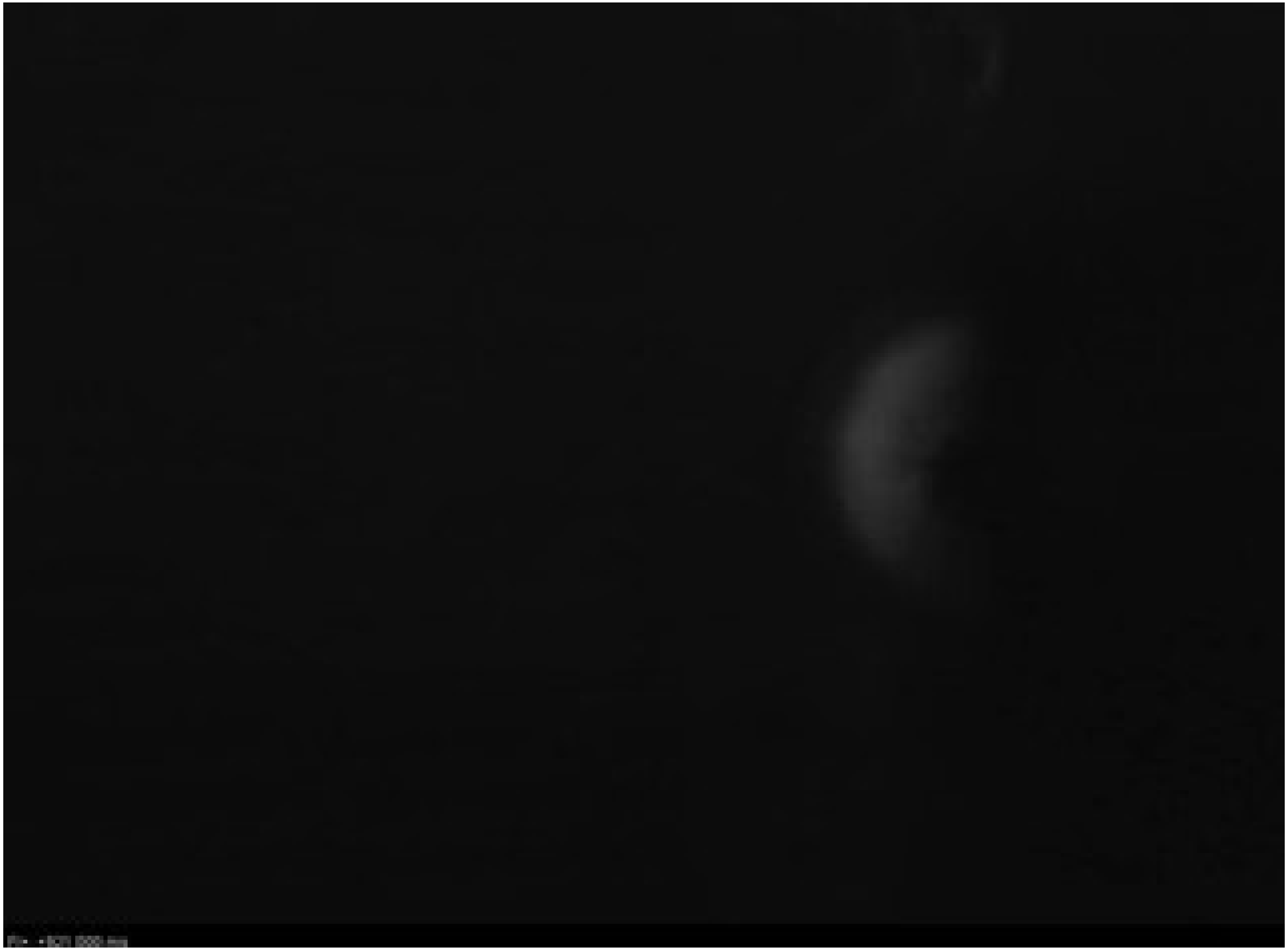


Current capabilities: 1500 scans/sec in 3D (25 slices/scan)
Spatial resolution: 140 microns/voxel

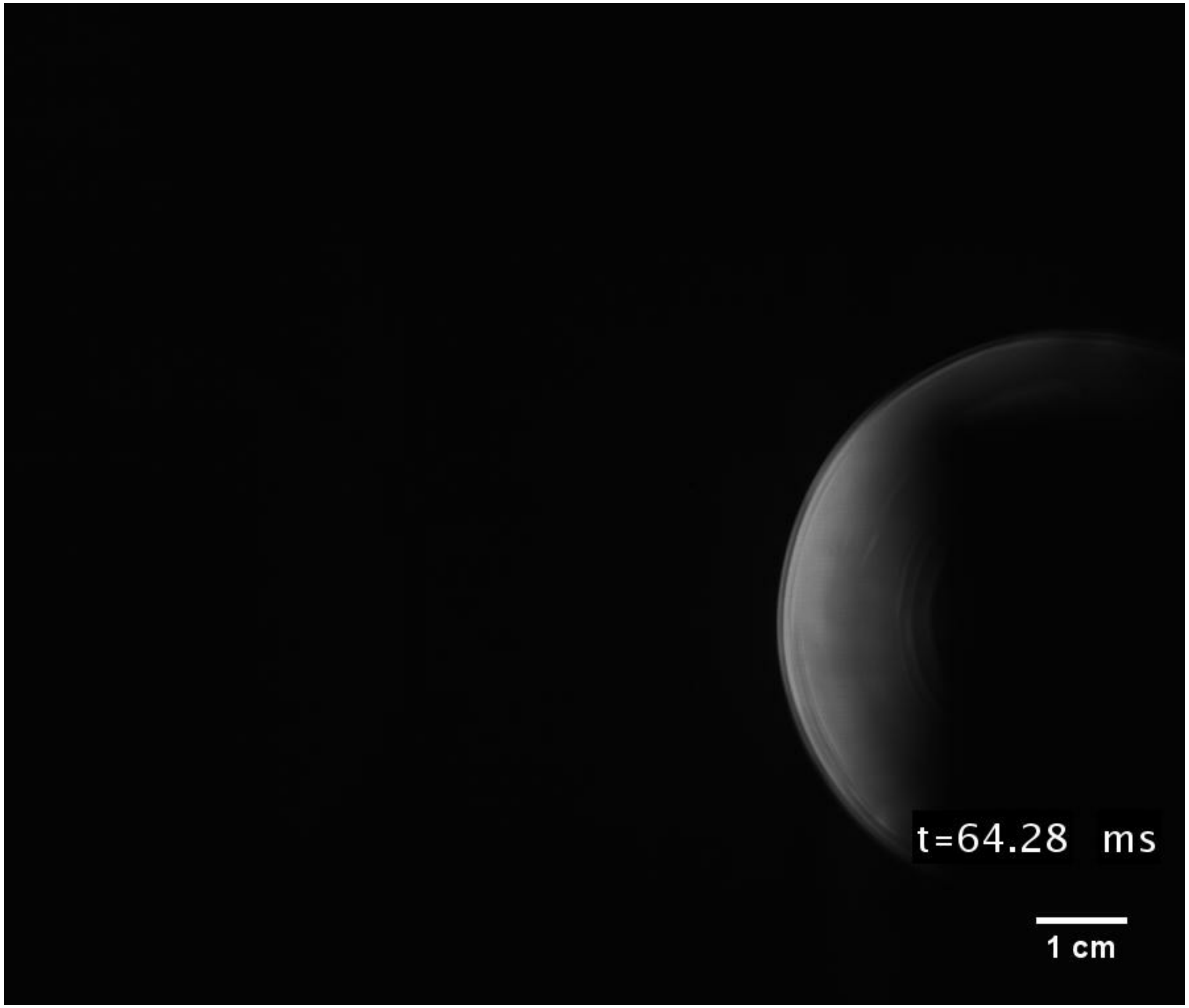
Colliding Rings: Side View

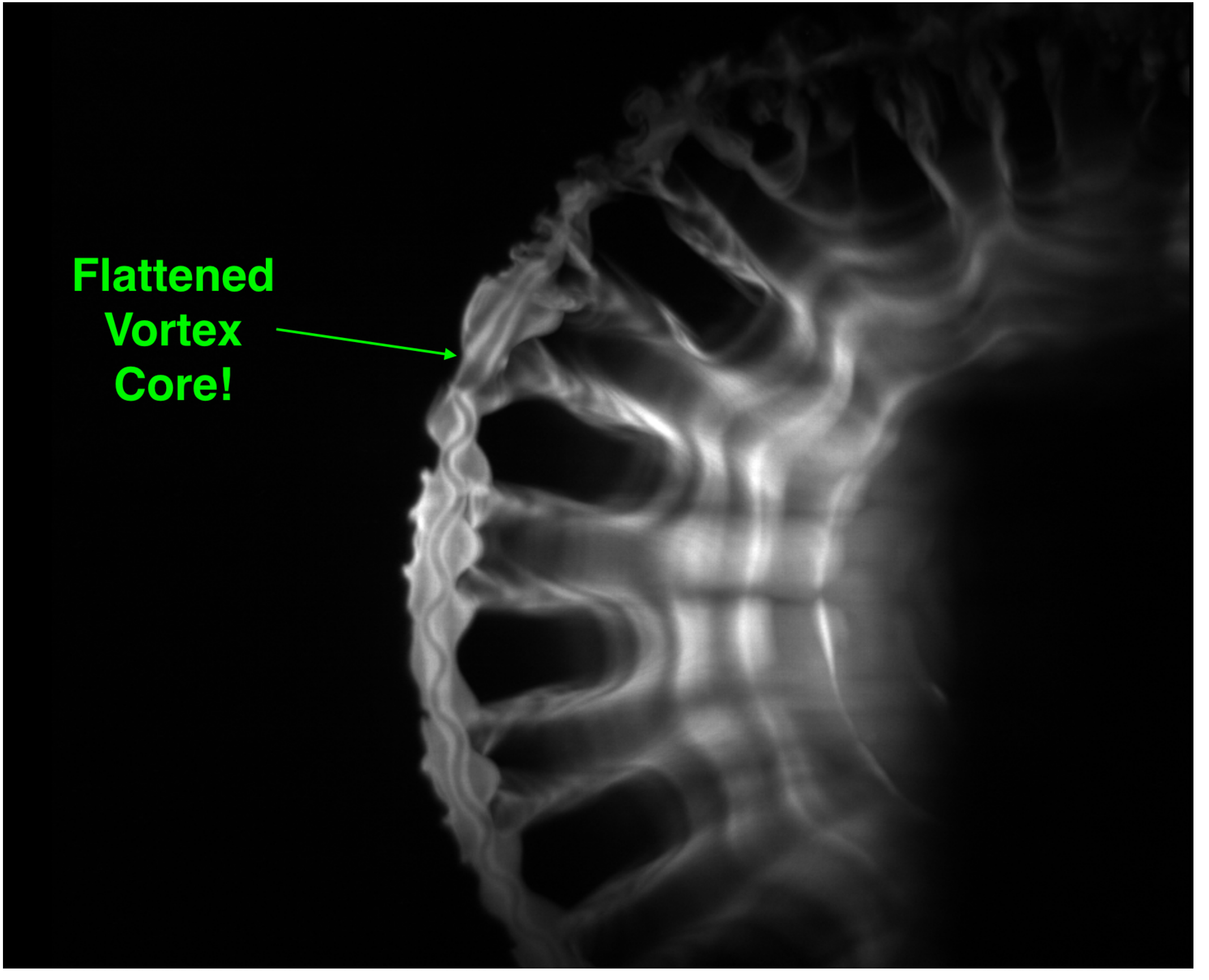


Colliding Rings: 2D slice

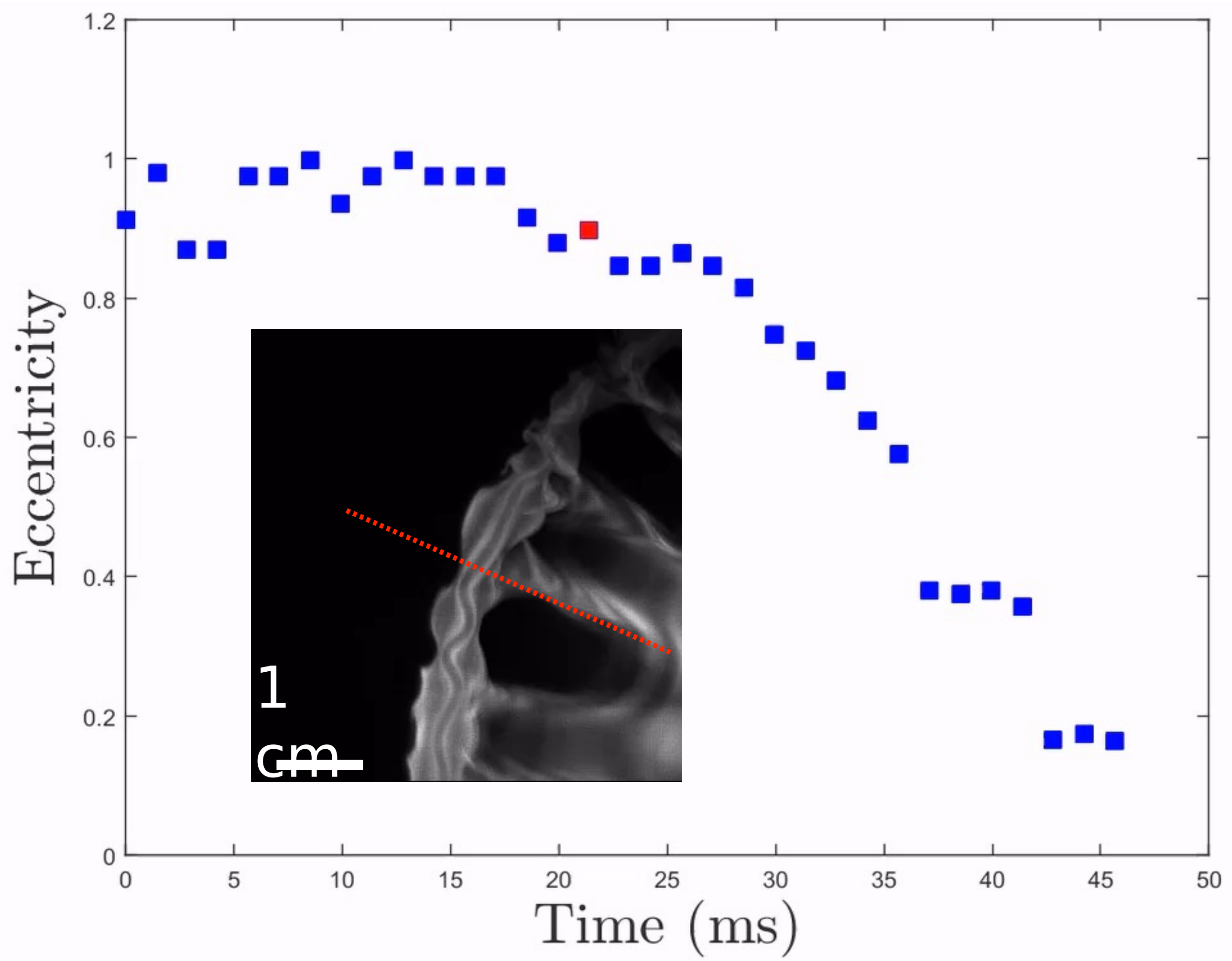


Colliding Rings: 3D rendering




Flattened
Vortex
Core!

Flattened of Vortex Core..



Summary

- Vortex ring collision a good experimental & numerical tool for studying the turbulent cascade stationary in lab frames
- Experimental setup capable of producing smoke but not of fully resolving all the dynamics… yet.
- Underlying Biot-Savart singularities may be the cause the intense stretching
- Reynolds number critical in determining reconnection or turbulent cloud: onset of a elliptic instability or iterated instability?