Measurements of Rotation and Alignment of Anisotropic Particles in Turbulence

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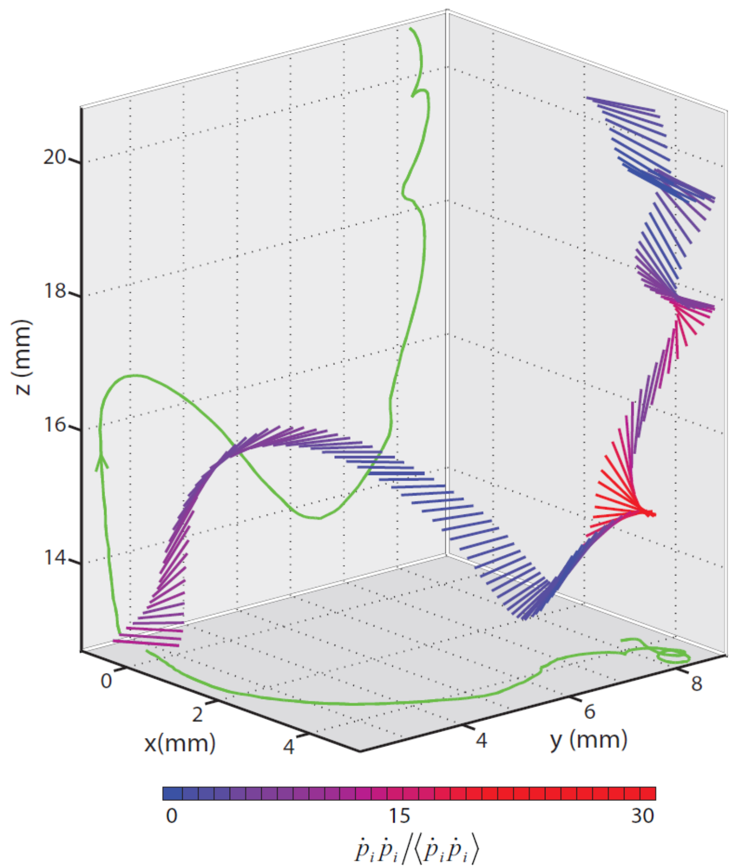

Conference on Dynamics of Particles in Flows

Co-workers

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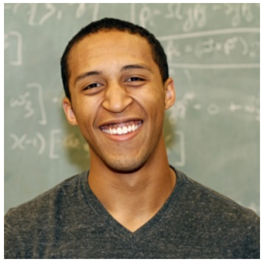
PhD student



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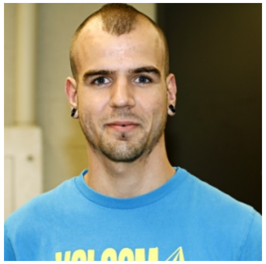

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Eindhoven, Netherlands

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Why study anisotropic particles in turbulence?

Applications:
- Many biological organisms are non-spherical particles in a turbulent fluid
- Dynamics of cellulose fibers in paper industry
- Drag reduction from rods
- Ice crystals in clouds

Fundamental Turbulence Research:
The rotations and alignment a small particles are determined by the velocity gradients which are dominated by the nearly universal small scales of turbulence.

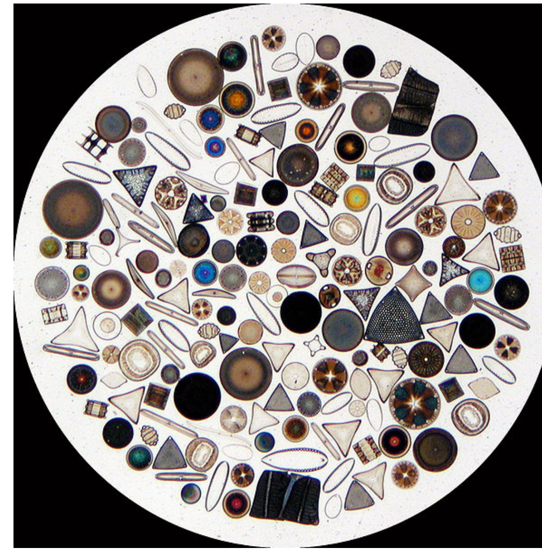
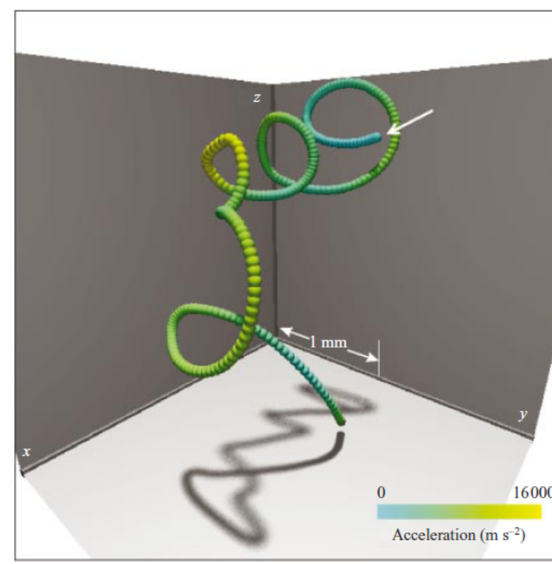


Image: Wikimedia commons, Credit: Wipeter
Marine Diatoms (phytoplankton)



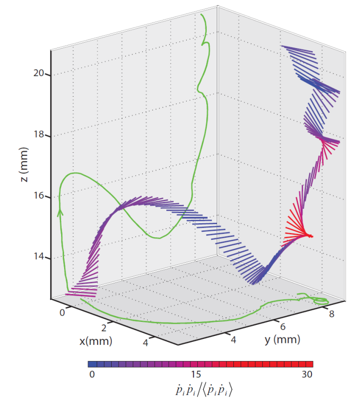
Main Points:

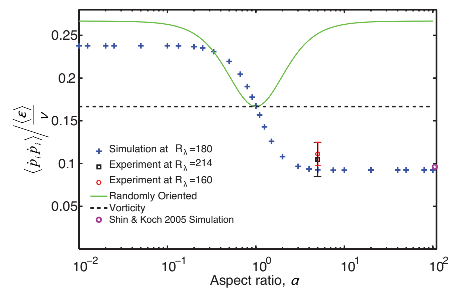
1) Time resolved 3D measurements of rotations of anisotropic particles can be made with many different shapes.

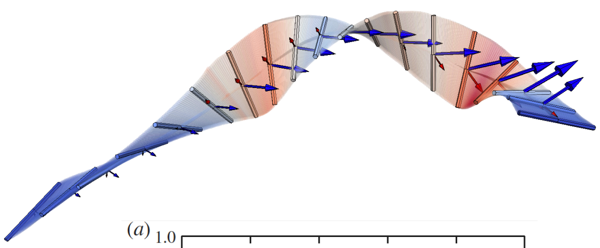
2) The tumbling rate of ellipsoids can be understood as a result of alignment of the long axis of particles with the vorticity, but available model are not quantitatively successful for disks.

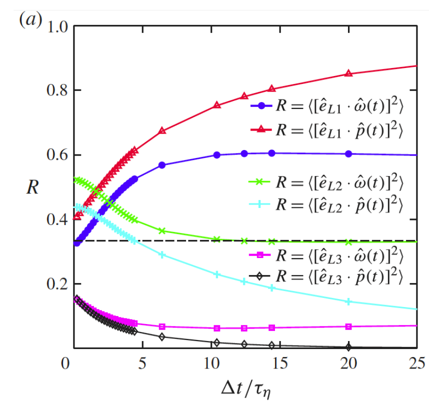
3) Rod motion can be accurately measured simultaneously with the velocity gradients in the fluid surrounding the rods.

4) The Cauchy-Green strain tensors provide a powerful tool for understanding alignment of vorticity and particles in flows.



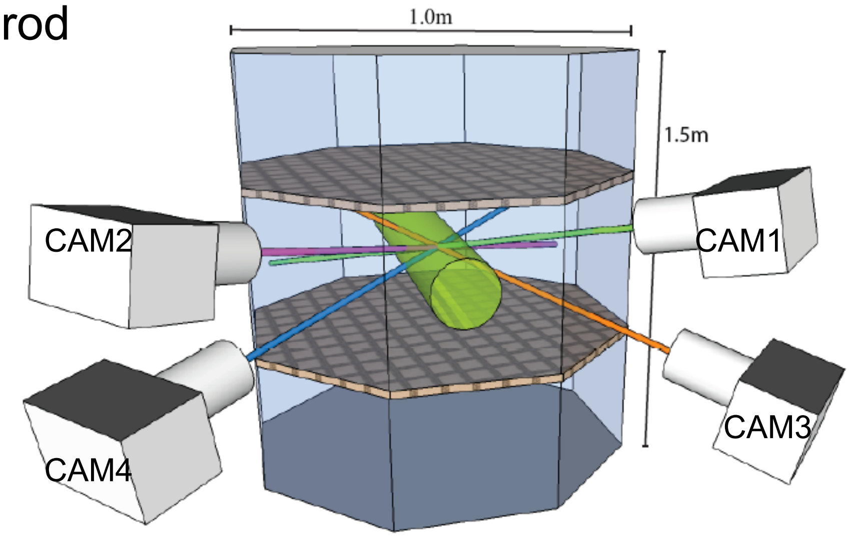






Experimental Tracking of Rod Trajectories

Stereoscopic imaging allows measurement of rod position and orientation as a function of time.
We use 4 cameras with real time image compression. (1024 X 1280 @ 500 Hz)



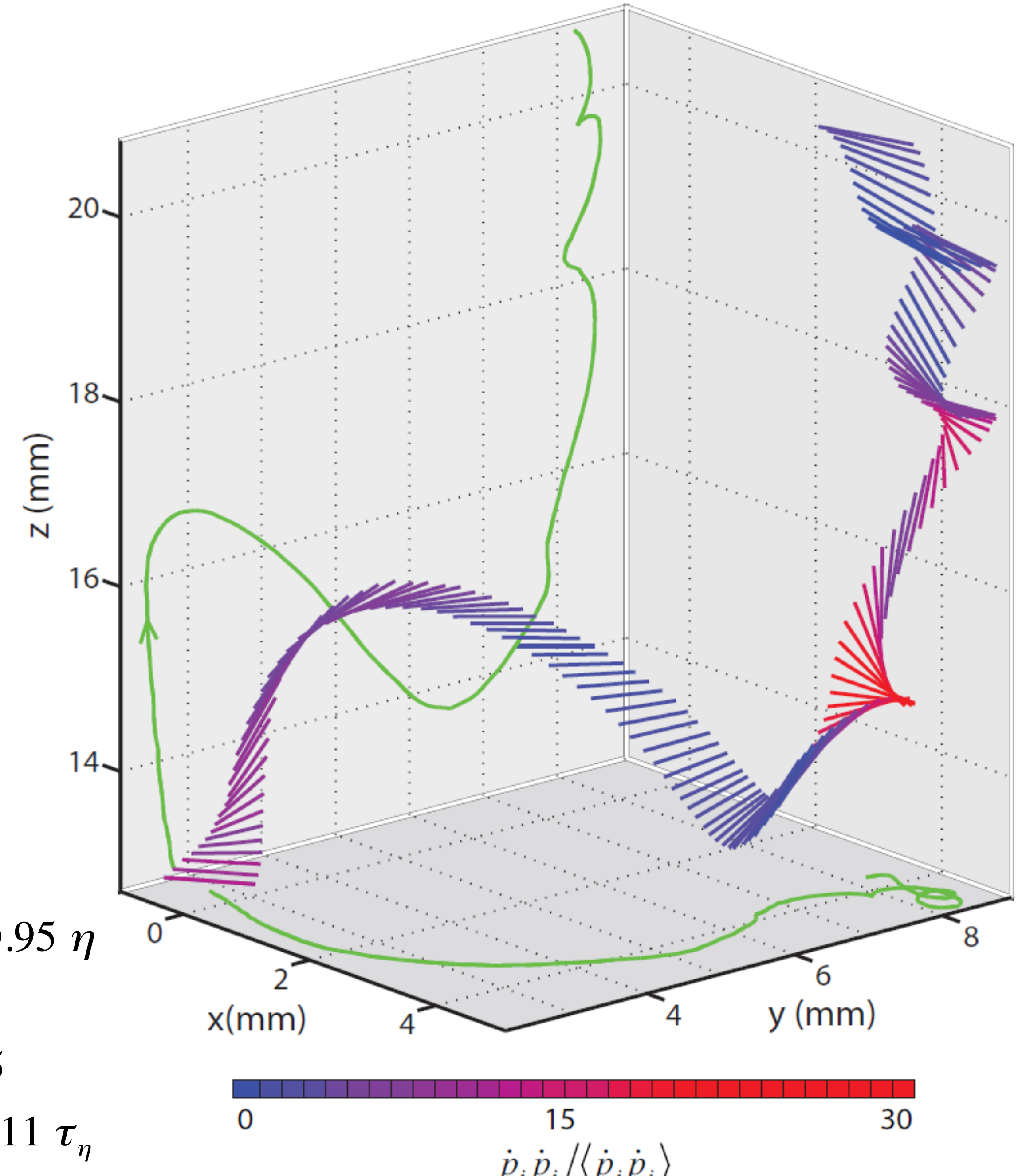
Turbulent flow between oscillating grids:
Octagonal tank 1x1x1.5 m
Grid mesh size = 8cm

Rods are fluorescently dyed Nylon fibers
Density, ρ=1.15 g/cm^3

Fluid density matched with particles with dissolved $CaCl_2$.

Grid Frequency (Hz)	ν (mm^2/s^3)	R_λ $\sqrt{15\tilde{u}L/\nu}$	$\varepsilon(=\tilde{u}^3/L)$ mm^2/s^3	$\eta = (\nu^3/\varepsilon)^{1/4}$ mm	$\tau_\eta = (\nu/\varepsilon)^{1/2}$ ms
1.5	1.8	161	354	0.375	71
3	1.8	214	2940	0.211	25

A Rod Trajectory



$R_\lambda = 214$

diameter $d = 0.2$ mm $= 0.95\ \eta$

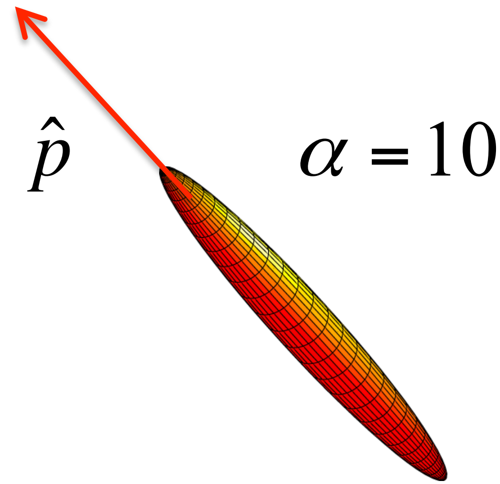
length L=1mm $= 4.7\eta$

aspect ratio $\alpha = L/d = 5$

track duration: 284ms = 11 τ_η

Axisymmetric Ellipsoids

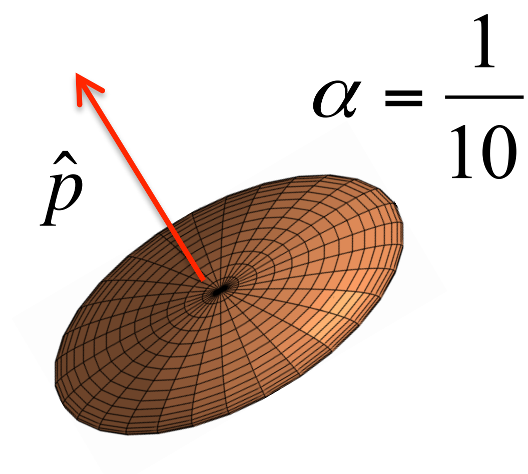
• The simplest class of anisotropic particles are axisymmetric ellipsoids. Defined by their length and aspect ratio:



α= Length / diameter

α > 1 prolate spheroid, **rod**

α < 1 oblate spheroid, **disk**

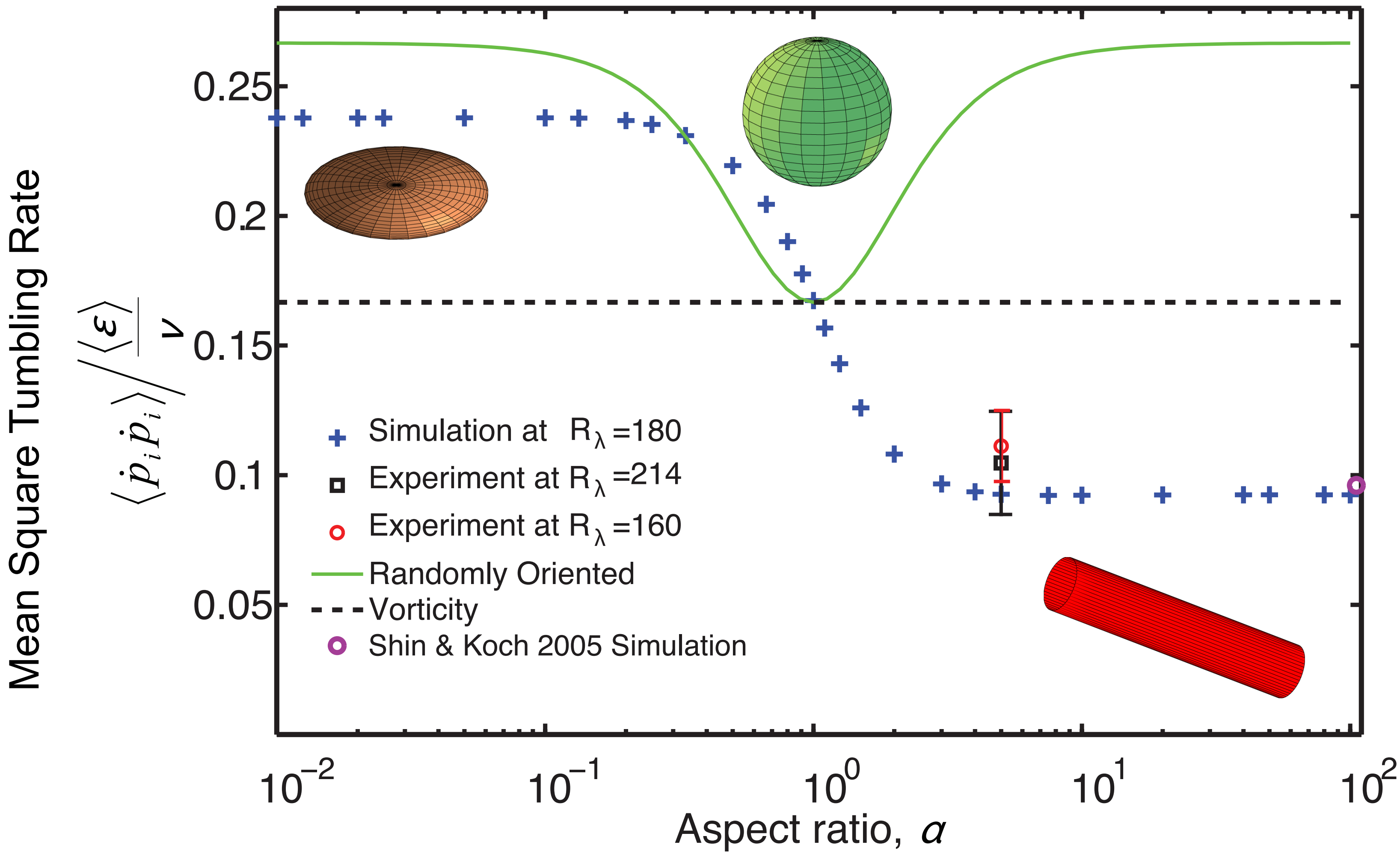


• Orientation is defined by a unit vector along the symmetry axis: $\hat{p}$

Axi-symmetric ellipsoids obey Jeffery's equation:

$$\dot{p}_i = \Omega_{ij}p_j + \frac{\alpha^2-1}{\alpha^2+1}\left(S_{ij}p_j - p_ip_kS_{kl}p_l\right)$$

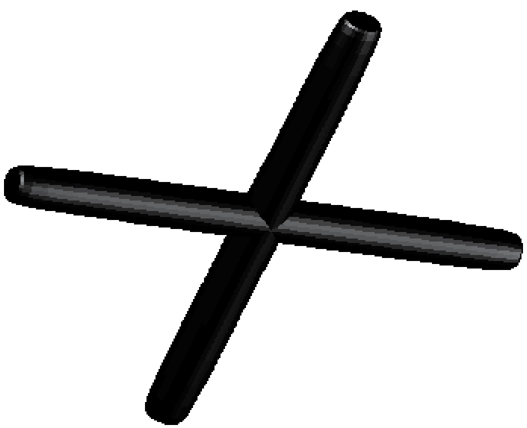
Mean square tumbling rate as a function of aspect ratio



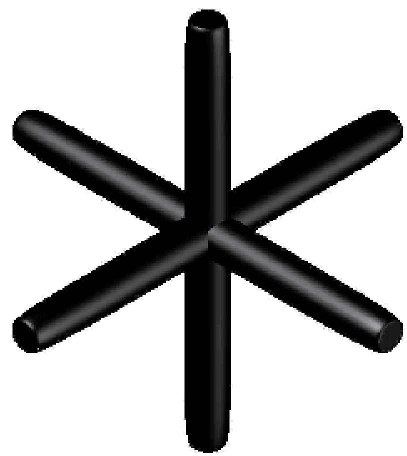
Parsa, Calzavarini, Toschi, and Voth, PRL 2012

Using resistive force theory we can show:
(Alternatively see Bretherton. J. Fluid Mech, 14:284 (1962))

Crosses rotate like disks

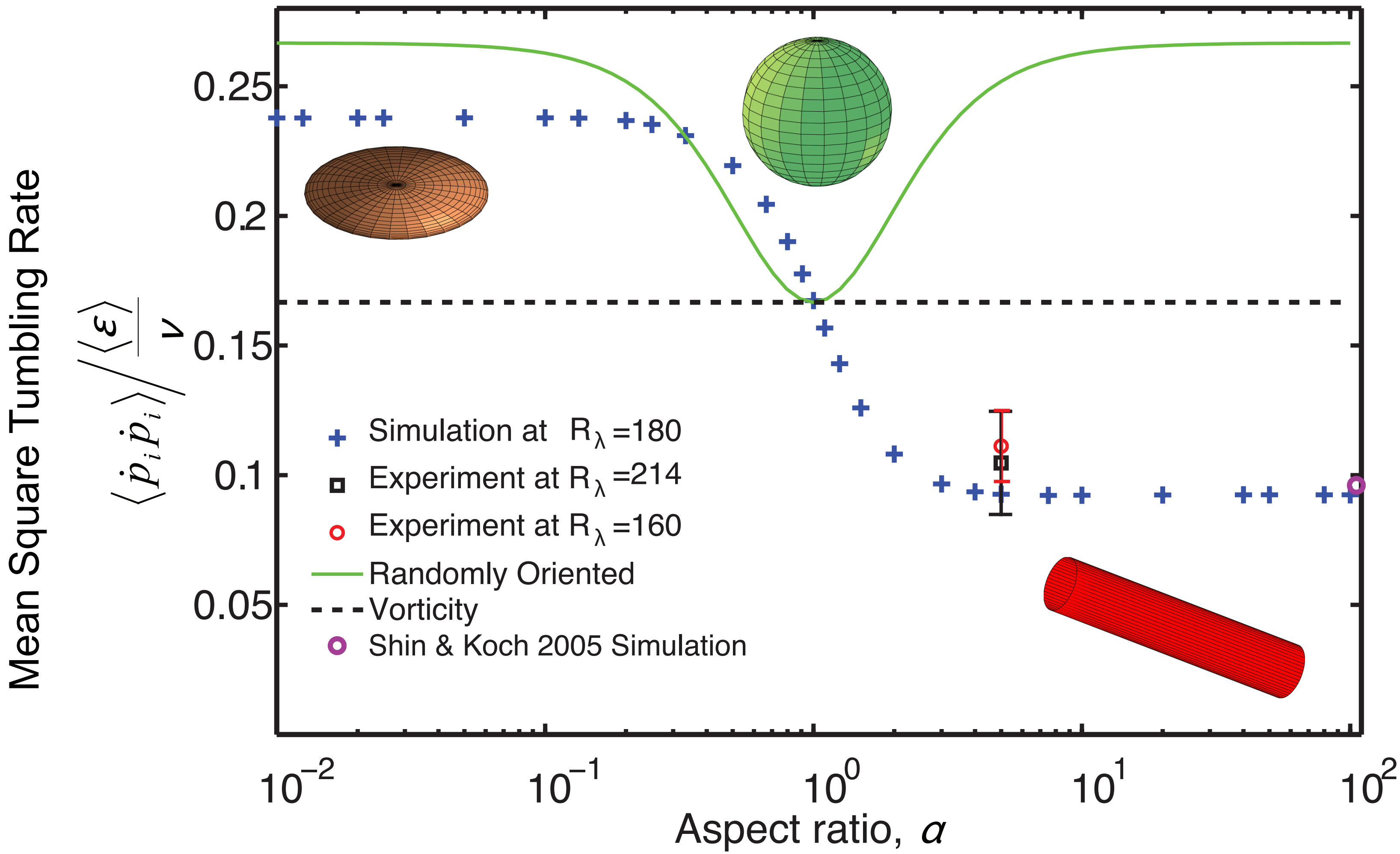


Jacks rotate like spheres



Rods are Rods

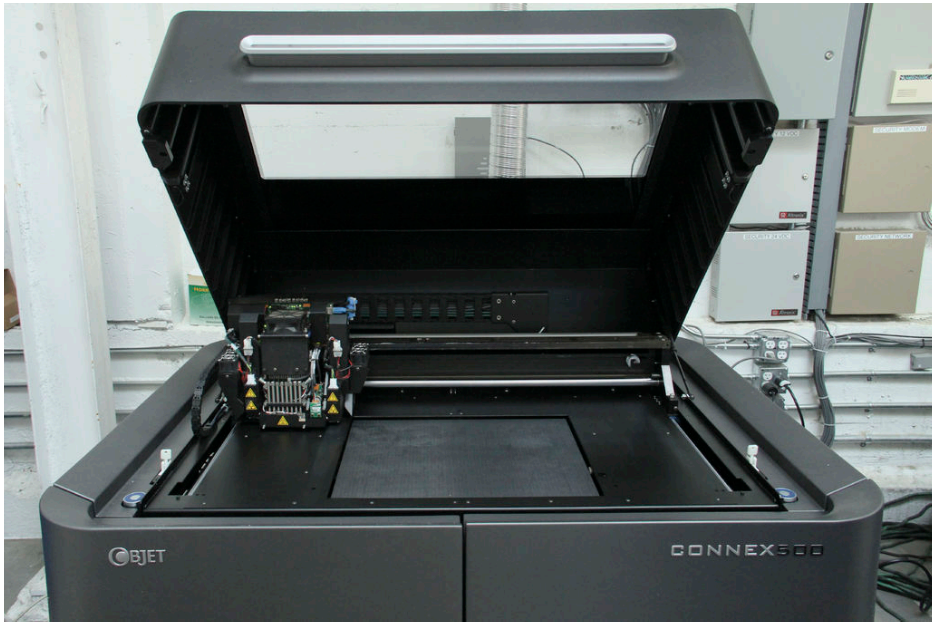
Mean square tumbling rate as a function of aspect ratio



Parsa, Calzavarini, Toschi, and Voth, PRL 2012

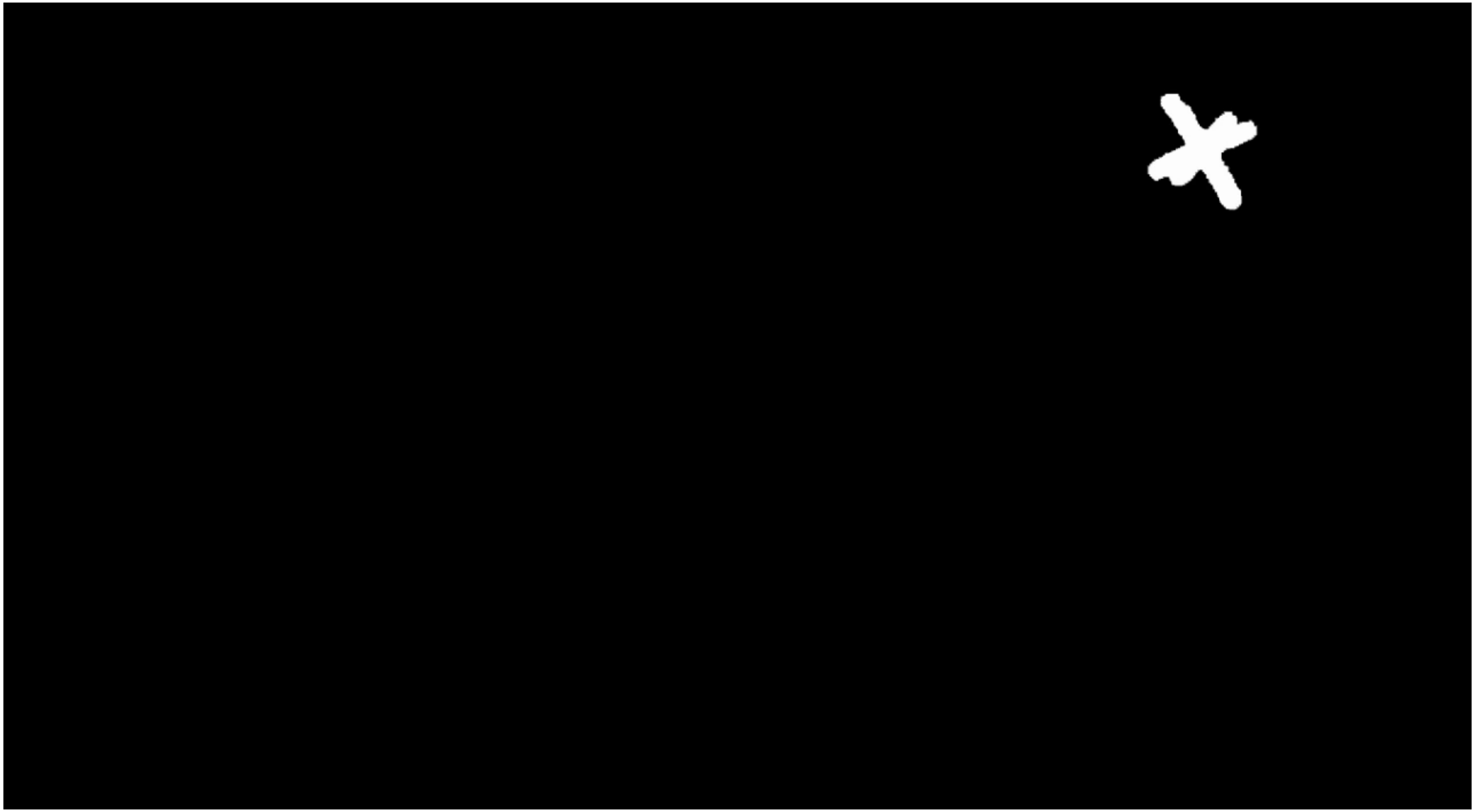
3D Printing of Complex Shapes

- We use 3D printing to fabricate small scale rods, crosses, and jacks
- The smallest dimension of 300 microns is at the resolution limit of present technical capabilities
- Arm length is 3mm or 5.3η
- We dye the particles using a solution of Rhodamine B
- The fluid is density matched using $CaCl_2$

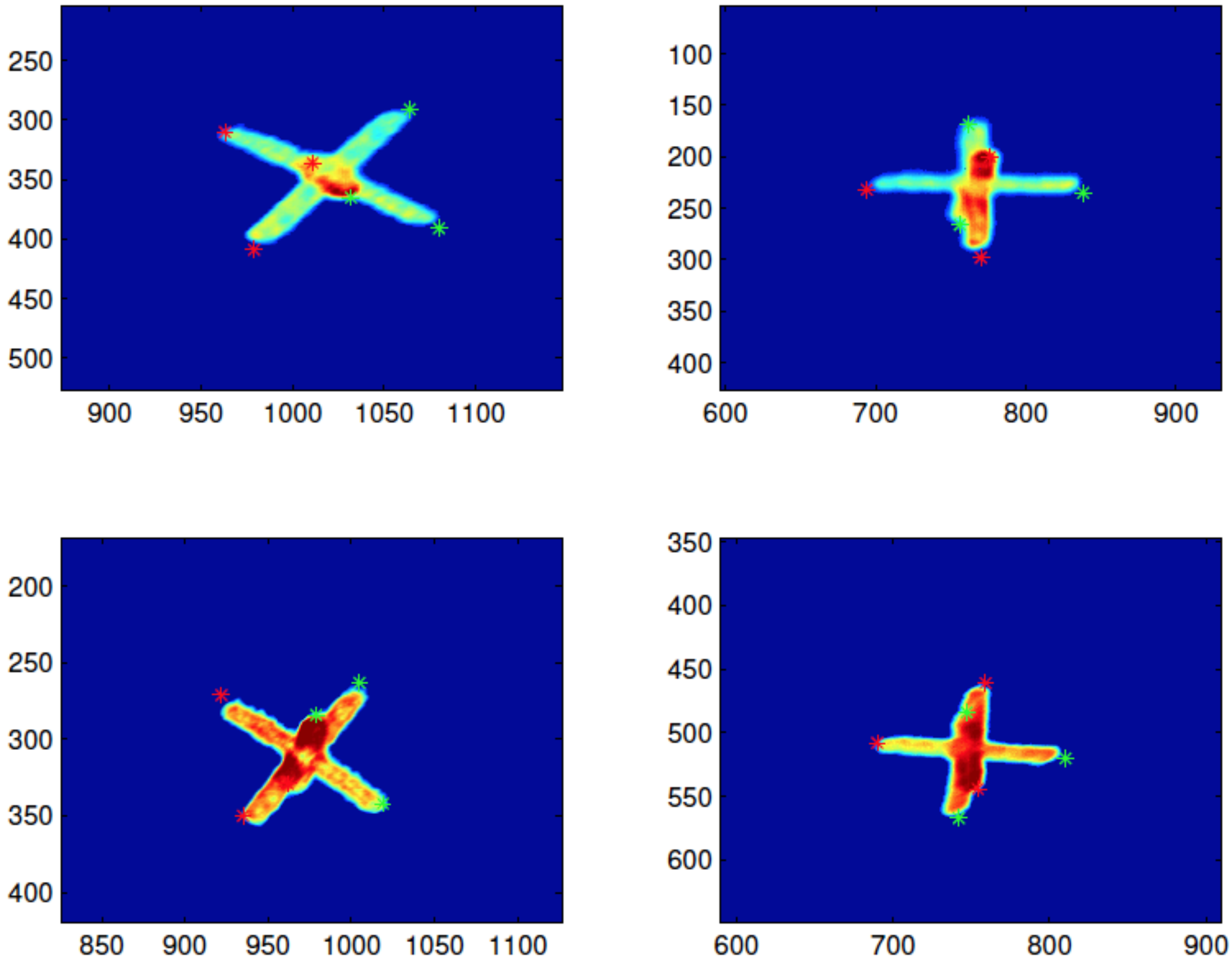


R_λ	l/η	ρ (g/cm^3)
189	12.2	1.21±0.01
112	5.3	1.21±0.01

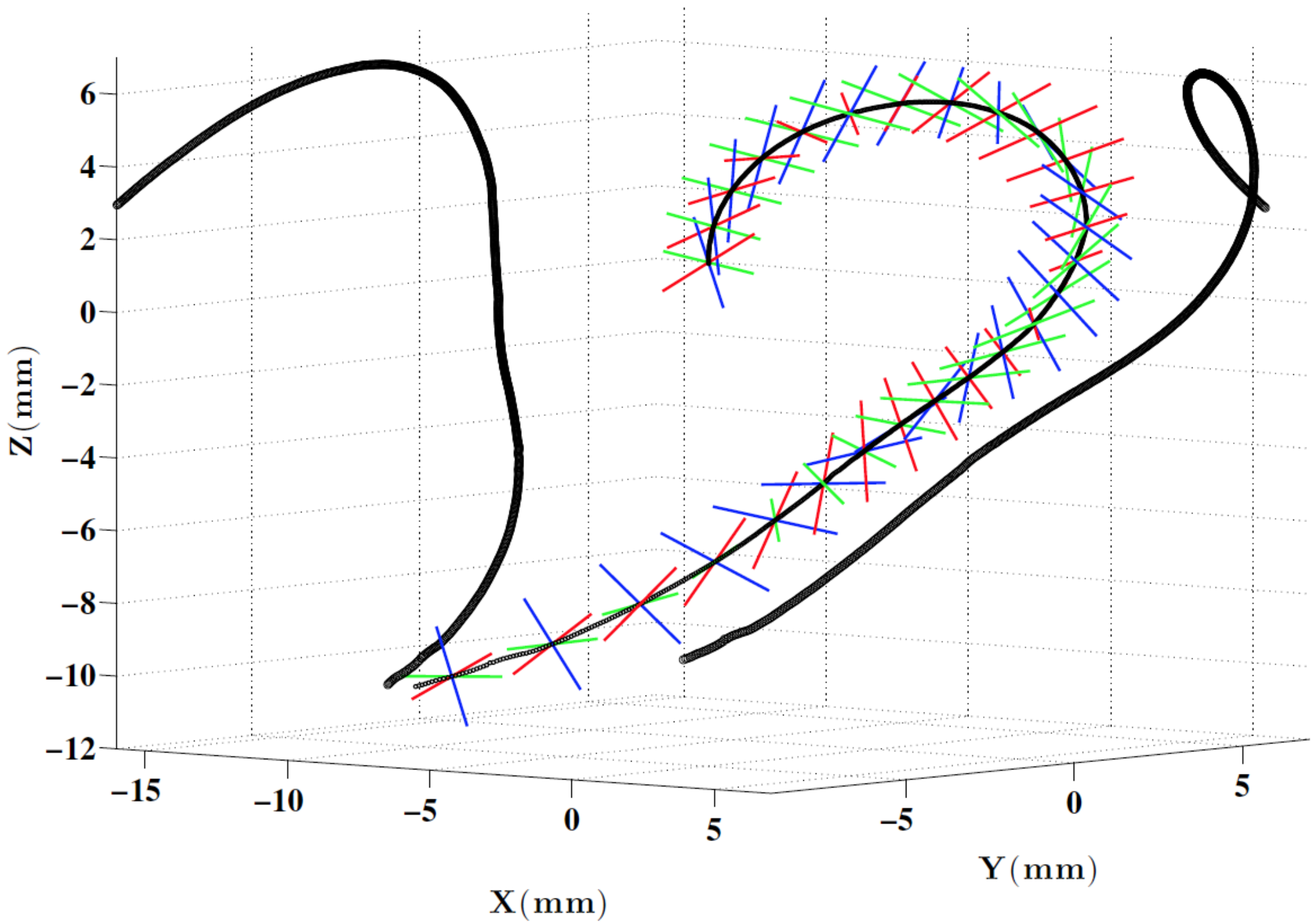
Video from One Camera



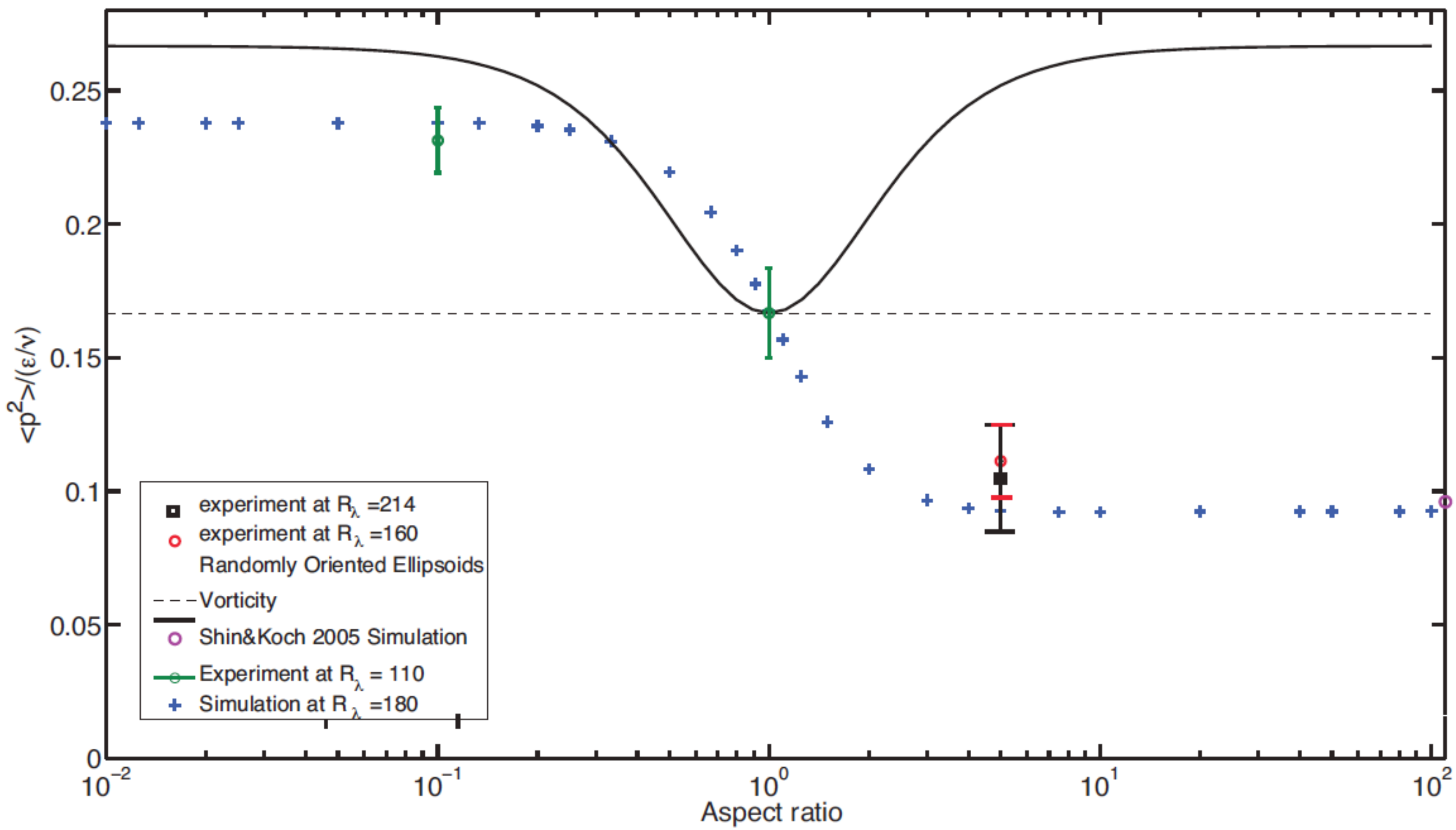
Reconstructing Jack Orientation from 4 images



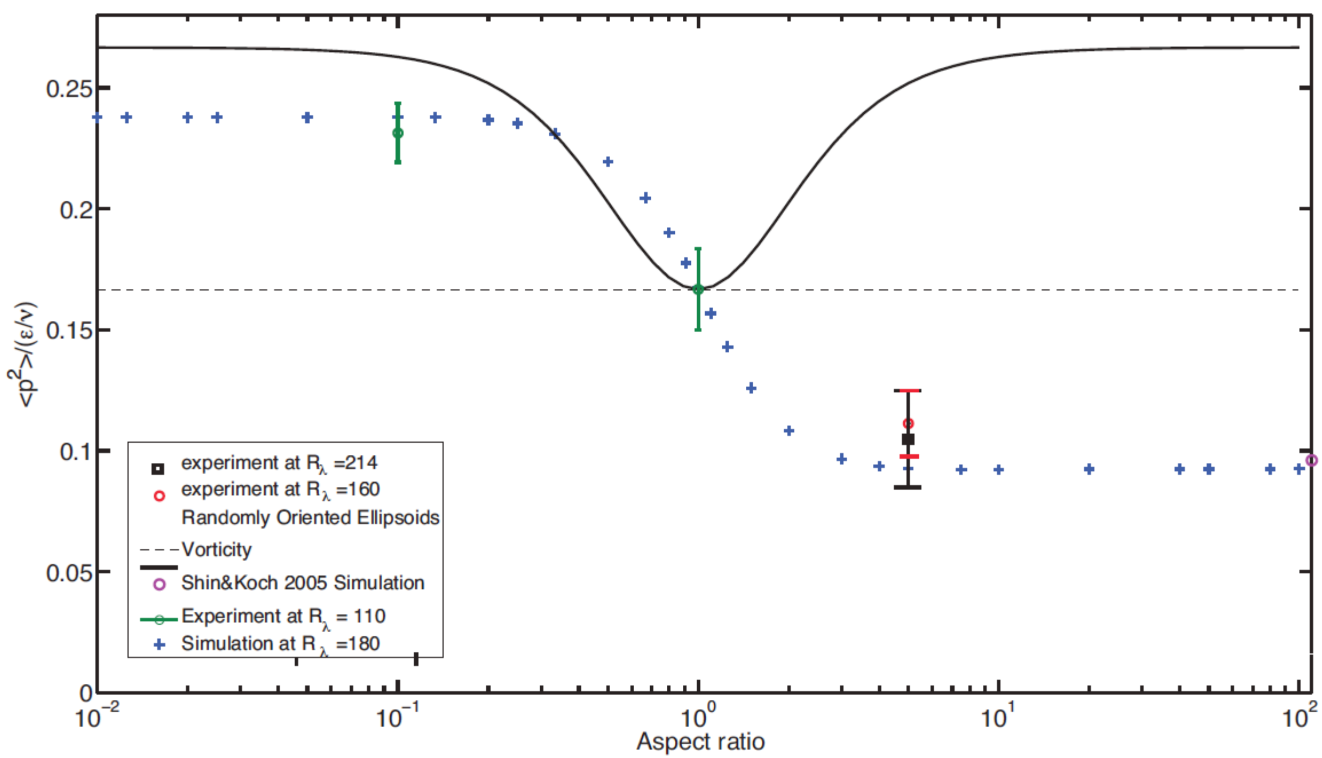
Example Trajectory of a Jack



Mean Square Tumbling Rate of Jacks and Crosses

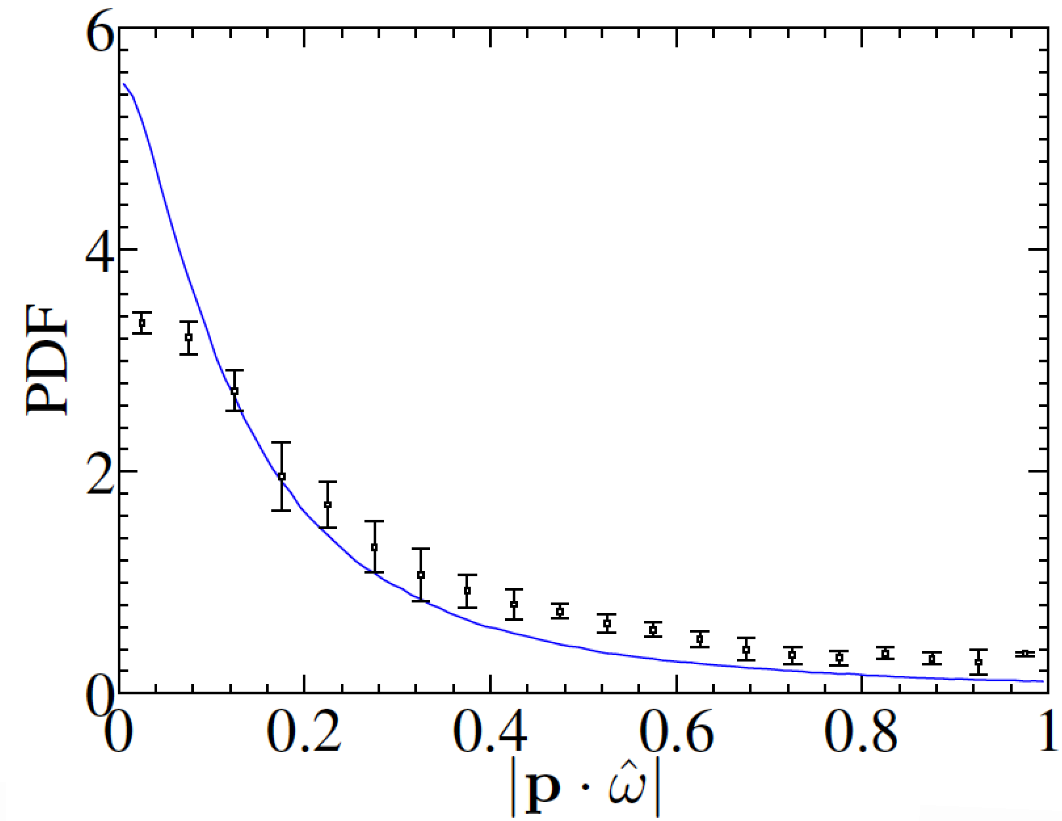


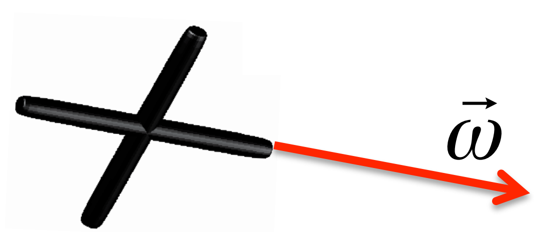
Mean Square Tumbling Rate of Jacks and Crosses

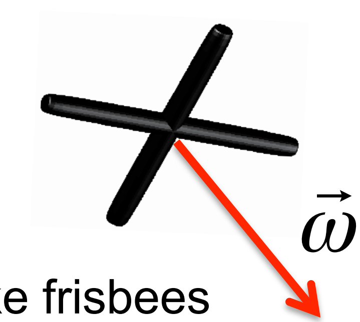


Main Point #1: Time resolved 3D measurements of rotations of anisotropic particles can be made with many different shapes.

Experimental measurements of alignment of crosses with their solid body rotation vector

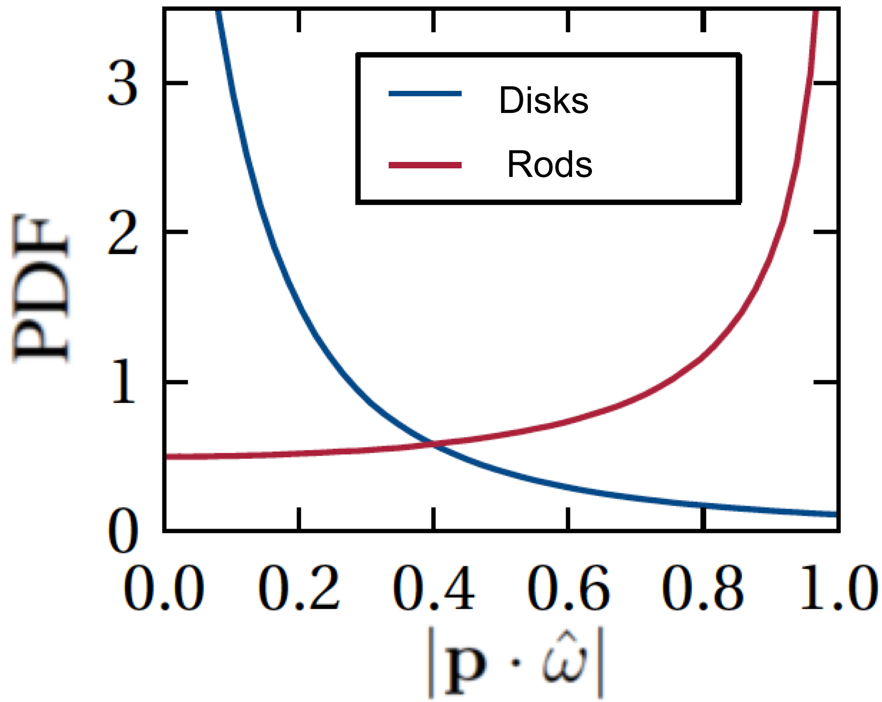


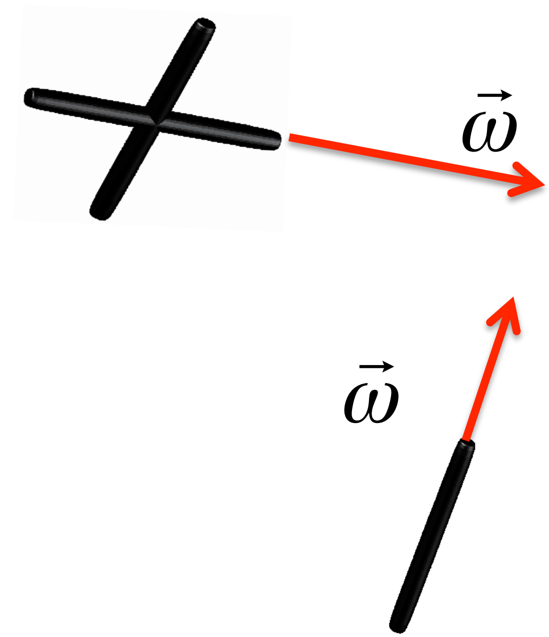




In turbulence, crosses rotate like spinning coins, not like frisbees

Alignment of Crosses with their solid body rotation vector

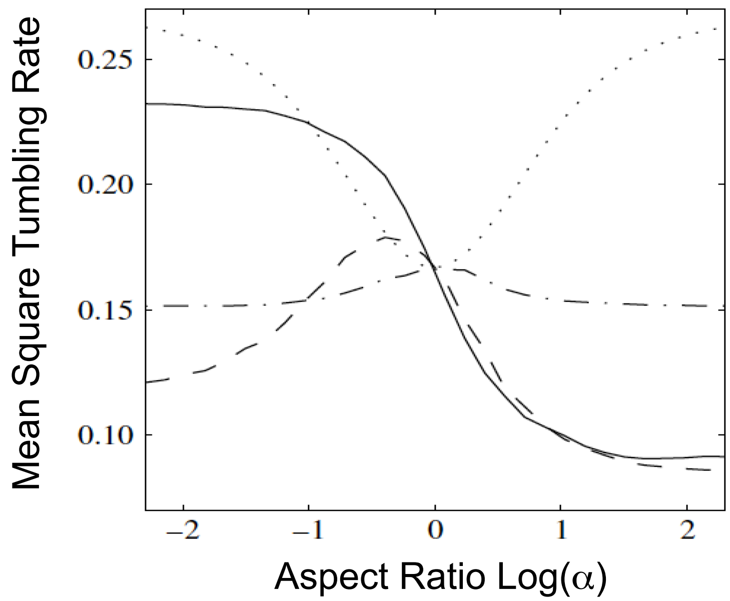


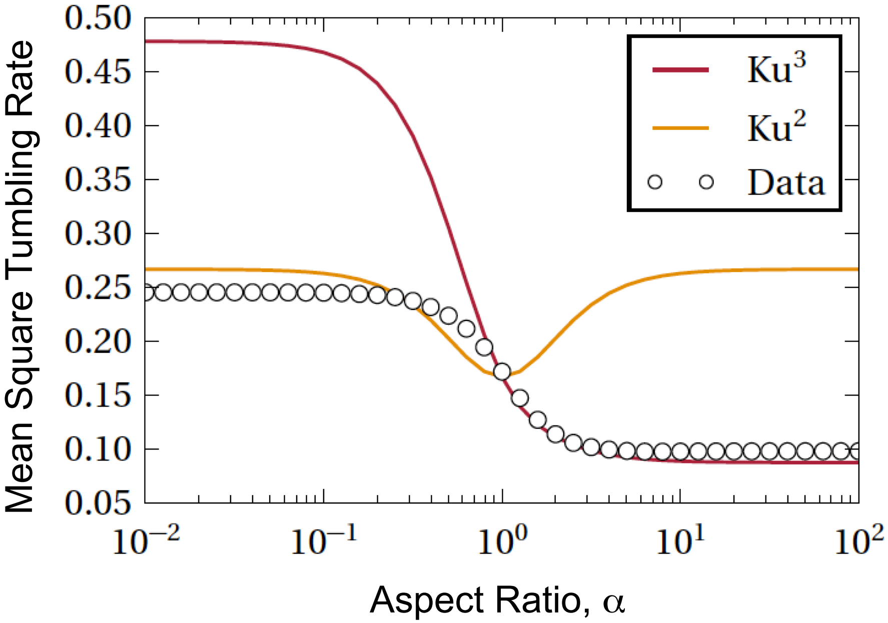


Gustavsson, Einarsson, Mehlig PRL 2014

Particles align their long axis with the vorticity of the flow. This leads to rapid tumbling of disks and slow tumbling of rods.

Can We Model the Tumbling Rate of Ellipsoids?

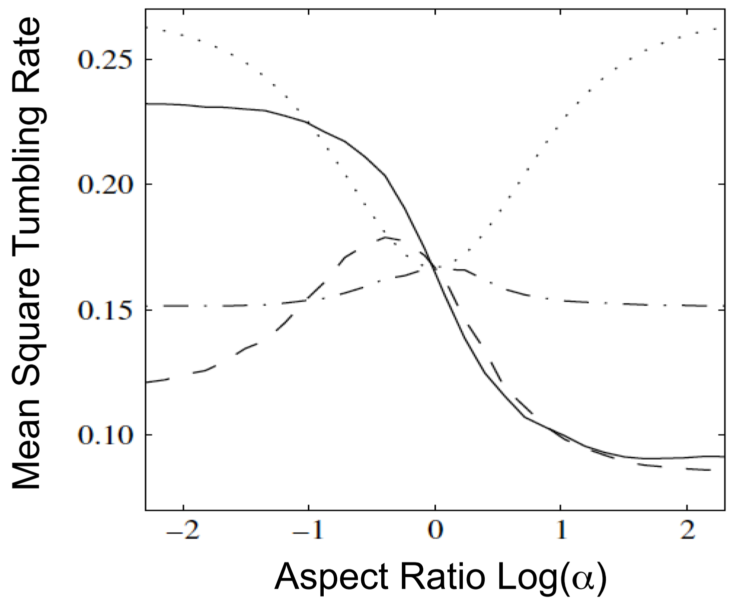


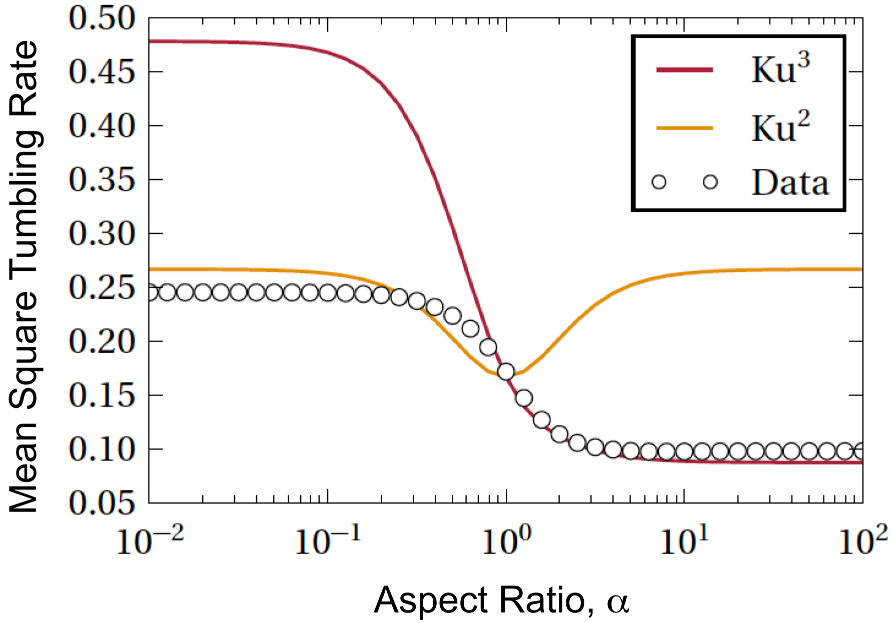


Chevillard and Meneveau, JFM 2013

Gustavsson, Einarsson, Mehlig PRL 2014

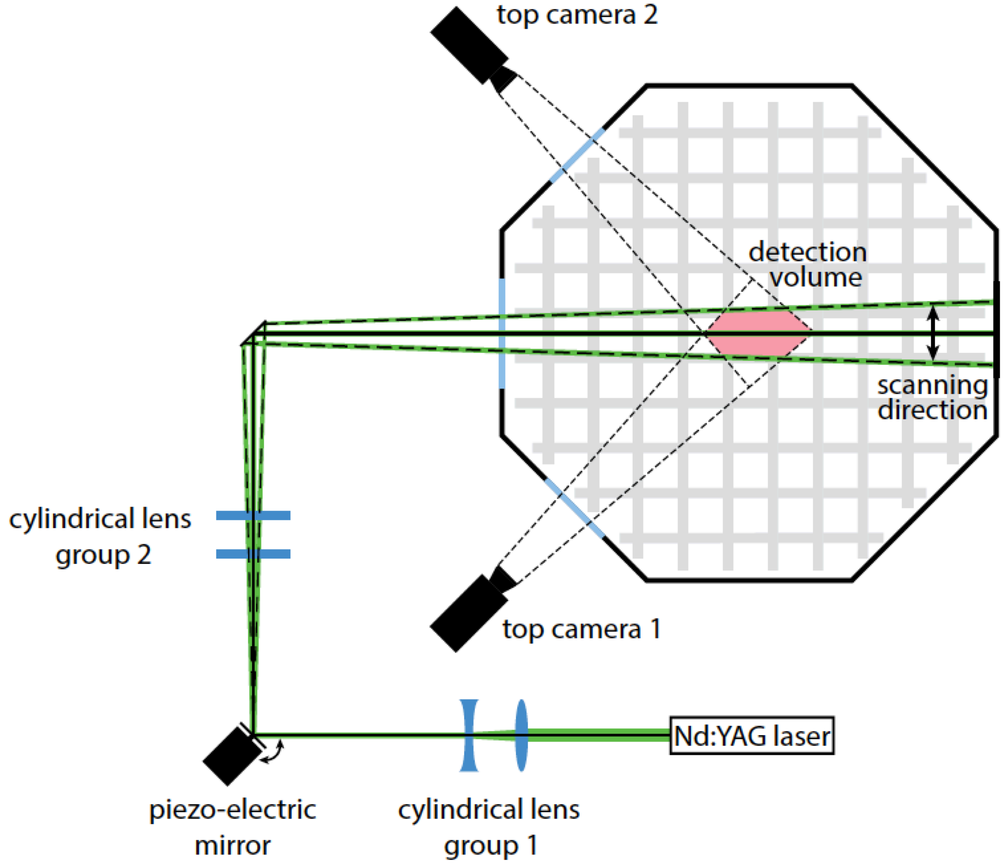
Can We Model the Tumbling Rate of Ellipsoids?





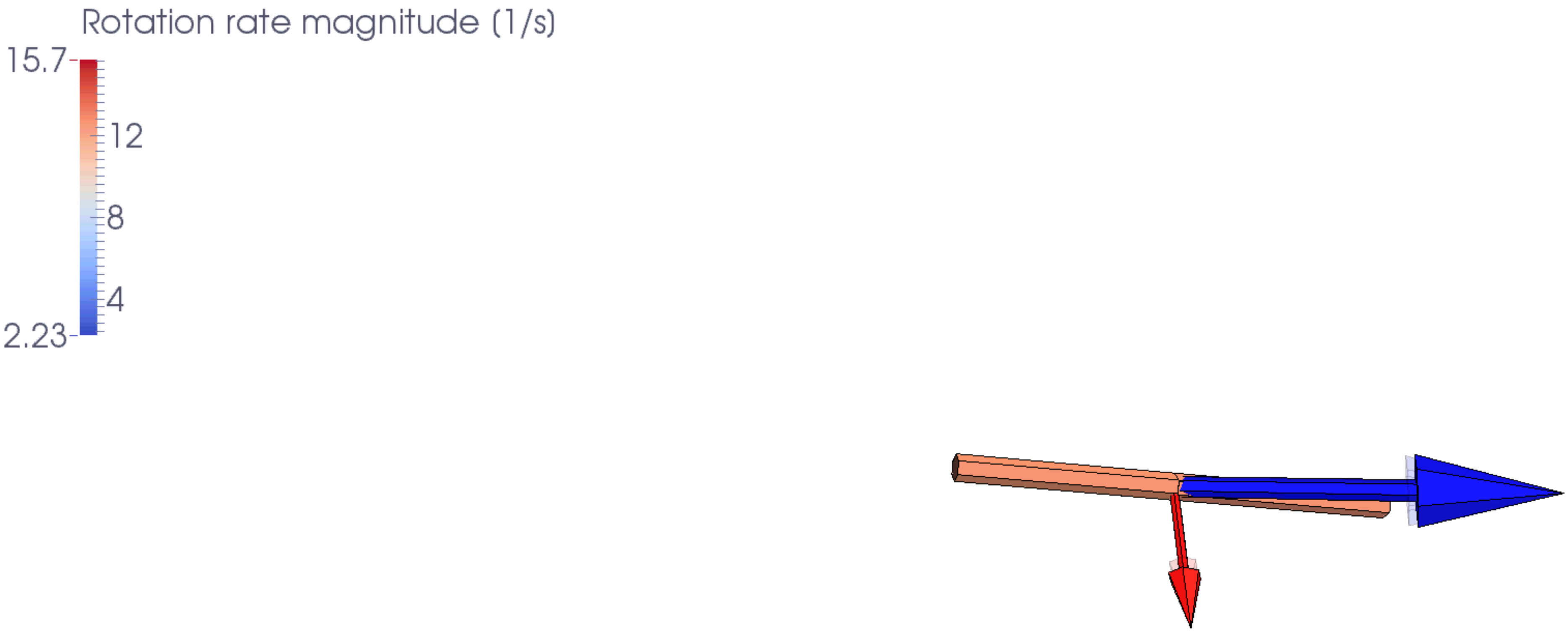
Main Point #2: The tumbling rate of ellipsoids can be qualitatively understood as a result of alignment of the long axis of particles with the vorticity, but available models are not quantitatively successful for disks.

Simultaneous Measurements of Rod Rotations and Fluid Velocity Gradients



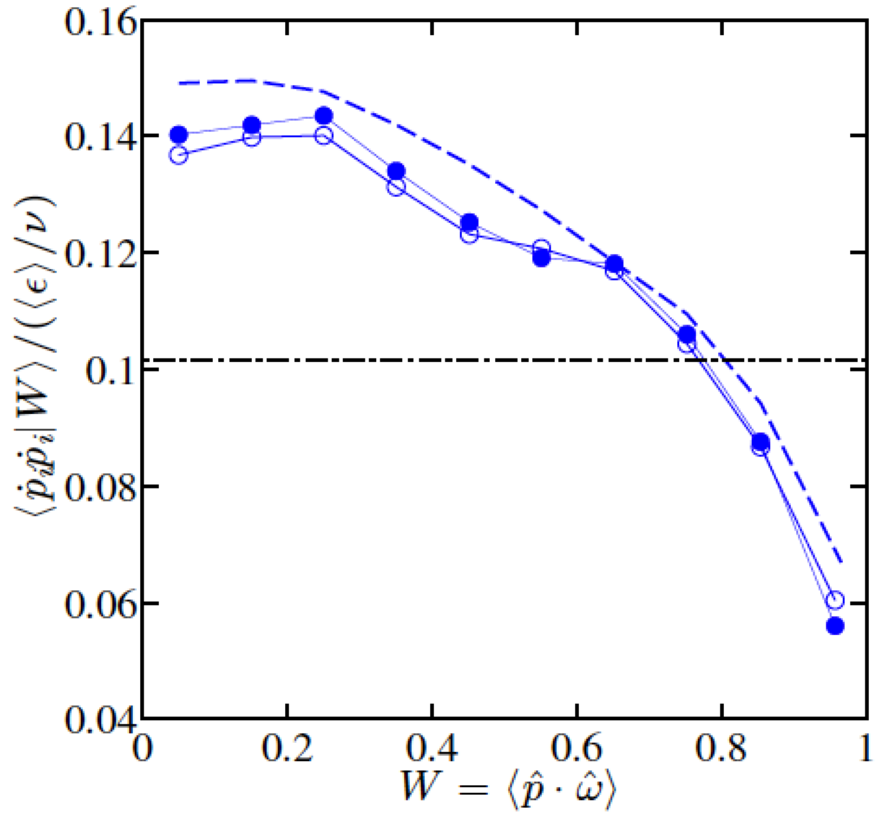
Scanned PTV system allows very high seeding density for measuring gradients: Hoyer, Holzner, Lüthi, Guala, Liberzon & Kinzelbach, Exp. Fluids 39: 923 (2005)

Simultaneous Measurements of Rod Rotations and Fluid Velocity Gradients



Blue: Vorticity Vector
Red: Eigevenctor of the strain rate corresponding to maximum eigenvalue.

Simultaneous Measurements of Rod Rotations and Fluid Velocity Gradients

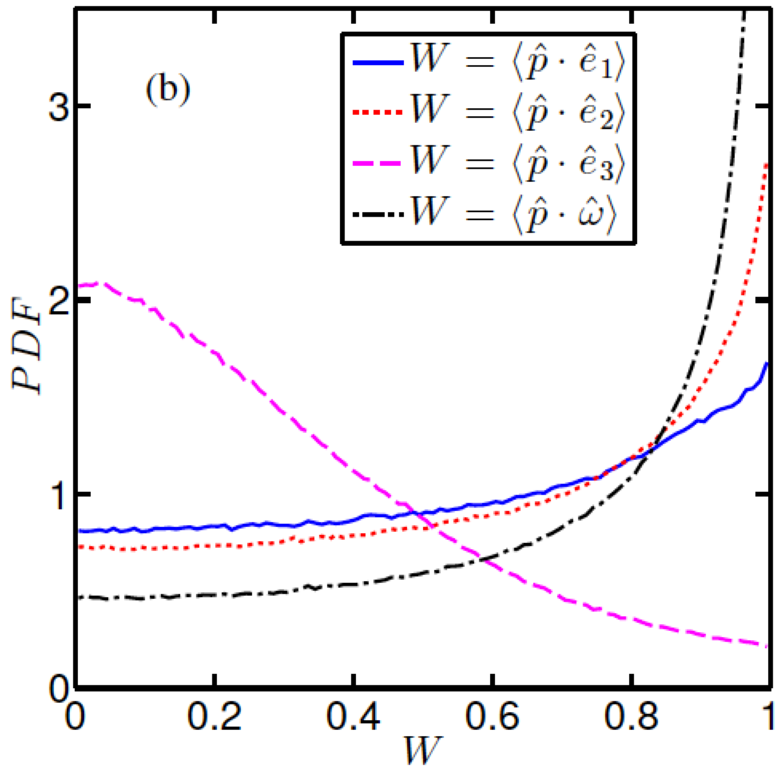


Main Point #3: Rod motion can be accurately measured simultaneously with the velocity gradients in the fluid surrounding the rods.

Open symbols: Measured Rod Tumbling Rate
Closed Symbols: Tumbling Rate predicted by Jeffery's equation using measured velocity gradients.
Dashed Line: DNS

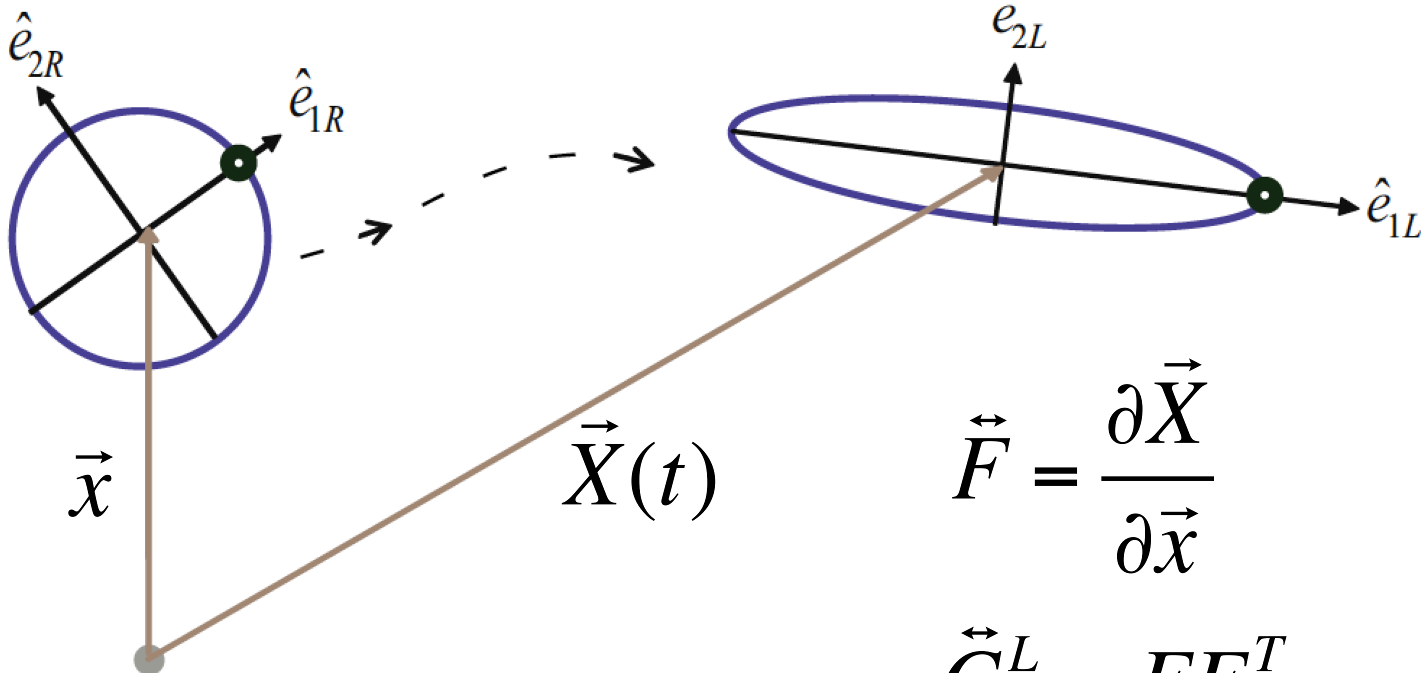
Why do particles align with the vorticity?

Alignment PDF
(DNS of isotropic turbulence)



Rods align with the intermediate eigenvector of the strain rate tensor, not the maximum eigenvector! (Pumir and Wilkinson NJP 2011)

Lagrangian Stretching

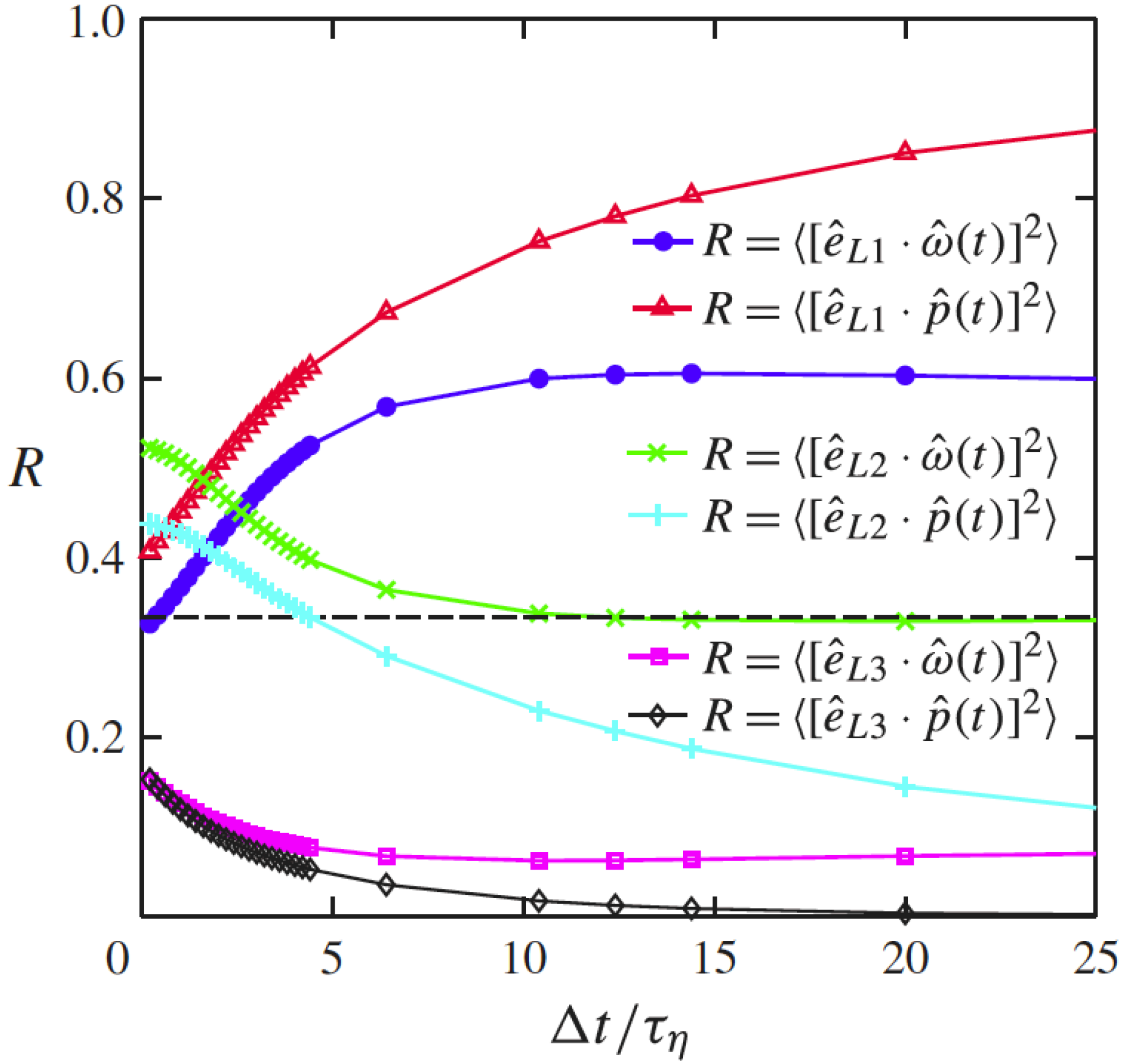


$$\overleftrightarrow{F} = \frac{\partial \vec{X}}{\partial \vec{x}}$$

$$\overleftrightarrow{C}^L = FF^T$$

$$\overleftrightarrow{C}^R = F^T F$$

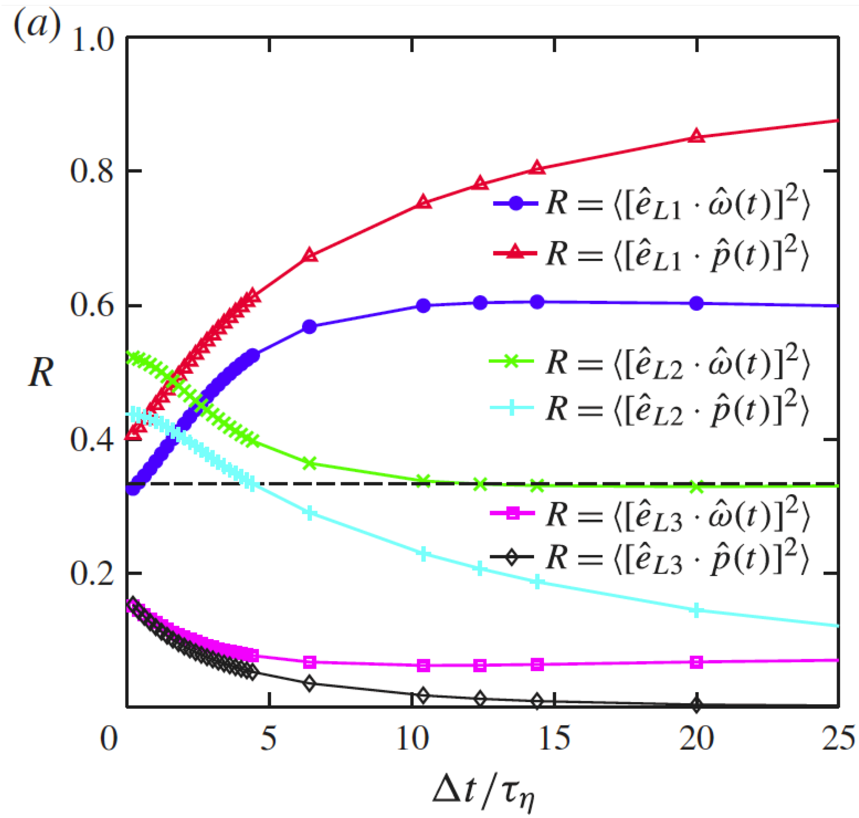
Alignment of Rods and Vorticity with the eigenvectors of the Cauchy-Green strain tensor



Data from DNS of isotropic turbulence

Ni, Ouellette, and Voth, JFM 743:R3 (2014)

Alignment of Rods and Vorticity with the eigenvectors of the Cauchy-Green strain tensor



Main Point 4: The Cauchy Green Stain Tensors provide a powerful tool for understanding alignment of vorticity and particles in flows.

Ni, Ouellette, and Voth, JFM 743:R3 (2014)

Conclusions

1) Time resolved 3D measurements of rotations of anisotropic particles with many different shapes are possible.
2) The tumbling rate of ellipsoids can be qualitatively understood as a result of alignment of the long axis of particles with the vorticity, but available model are not quantitatively successful for disks.
3) Rod motion can be accurately measured simultaneously with the velocity gradients in the fluid surrounding the rods.
4) The Cauchy-Green strain tensors provide a powerful tool for understanding alignment of vorticity and particles in flows.