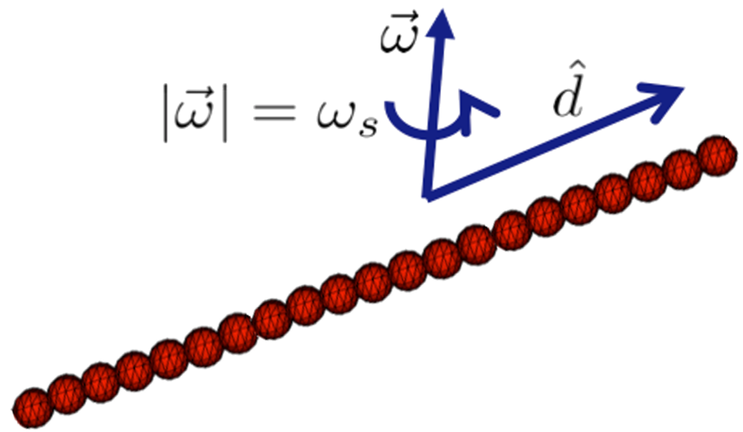
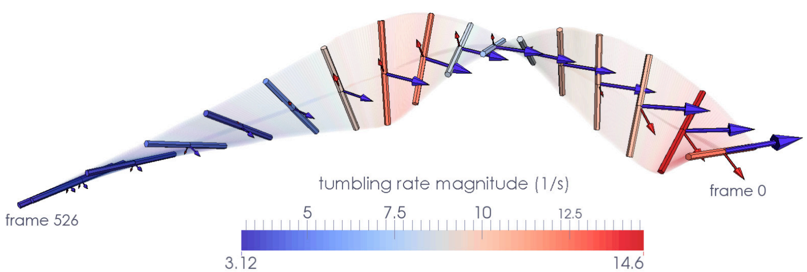
Previous work: rods in turbulence

Tumbling



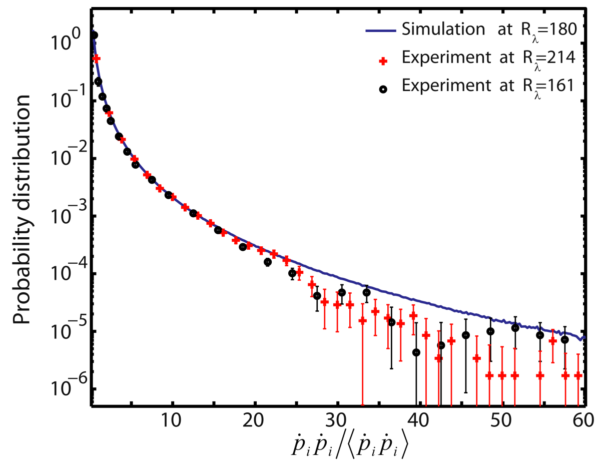


Rui Ni, Stefan Kramel, Nicholas T. Ouellette and Greg A. Voth, "Measurements of the coupling between the tumbling of rods and the velocity gradient tensor in turbulence." *Journal of Fluid Mechanics* 766, 202225 (2015).

Jeffery equation

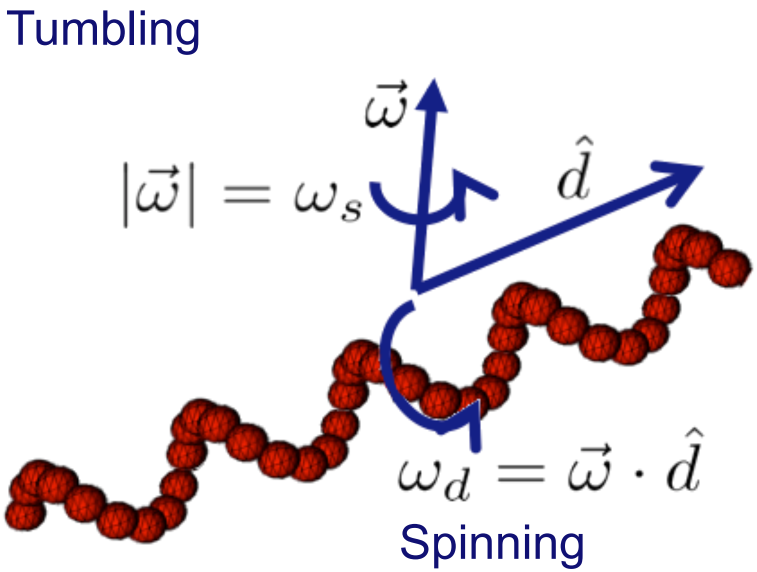
$$\dot{d}_i = \Omega_{ij} d_j + \frac{\alpha^2 - 1}{\alpha^2 + 1} \left(S_{ij} d_j - d_i d_k S_{kl} d_l \right)$$

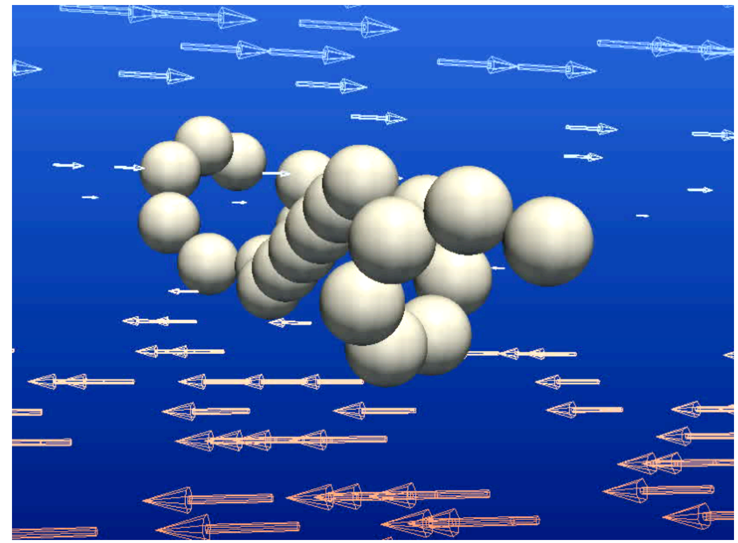
G. B. Jeffery, *The motion of ellipsoidal particles immersed in a viscous fluid.* Proc. R. Soc. Lond. A, 102 (1922)



Shima Parsa, Enrico Calzavarini, Federico Toschi, and Greg A. Voth, "Rotation Rate of Rods in Turbulent Fluid Flow" *Physical Review Letters*, 109, 134501 (2012).

First idea: Chiral particles

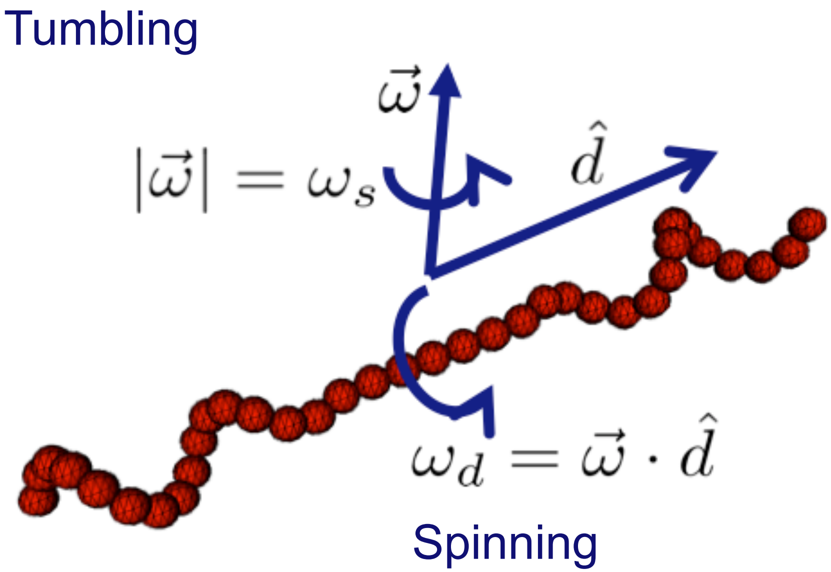


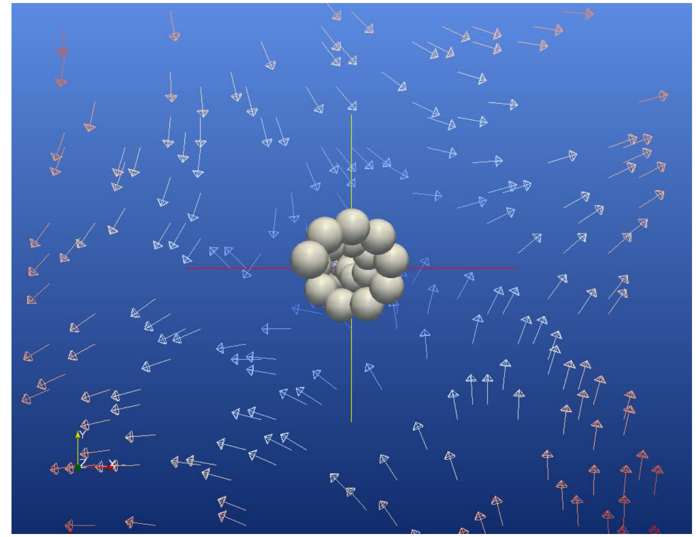


Particle with preferential rotation in turbulent flow?
No.

- Spinning due to rotation of flow field ϖ.
- Force and torque are coupled.
- Drift in the direction of ϖ.

Recent work: Chiral dipole





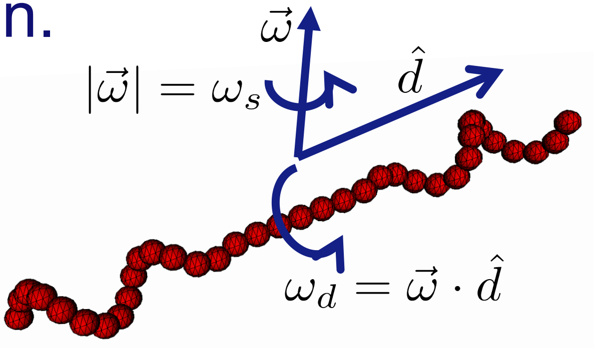
Chiral dipole is a particle with preferential rotation in turbulence:

- Coupling to rotational and strain field.
- No drift due to rotational flow ϖ.
- Chiral dipole aligns with material lines.
    - ➢ Same behavior as rod.

✧ Spinning rate is proportional to the stretching of the material lines.

Analytical model for chiral dipoles

- Tumbling modeled with Jeffery equation.



- Spinning rate ω_d modeled with

$$\omega_d = \beta \vec{d}(\vec{d}\nabla)\vec{u} + \varpi_{flow} \cdot \vec{d}$$

β depends on the geometry

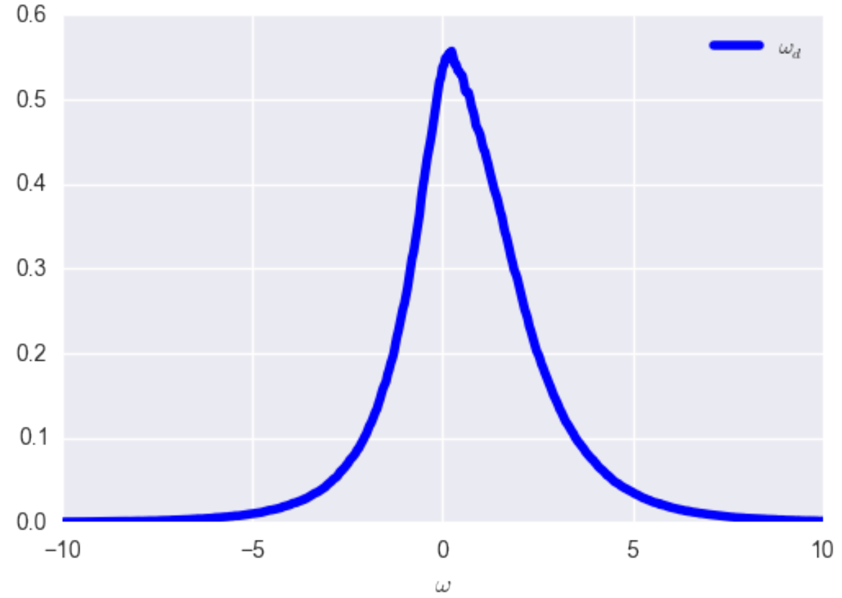
➢ obtained with CSD simulations

u is the velocity vector

ϖ_{flow} is the rotational part of the flow field

Results in turbulence

- a-posteriori calculation of spinning rate for tracer particles
- Re_λ= 400 in homogeneous isotropic turbulence
- Histogram of 3000 particles
- Dataset available in TurBase (EuHIT database)



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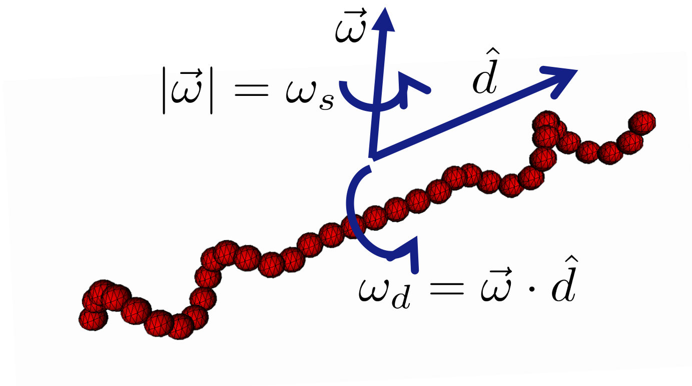

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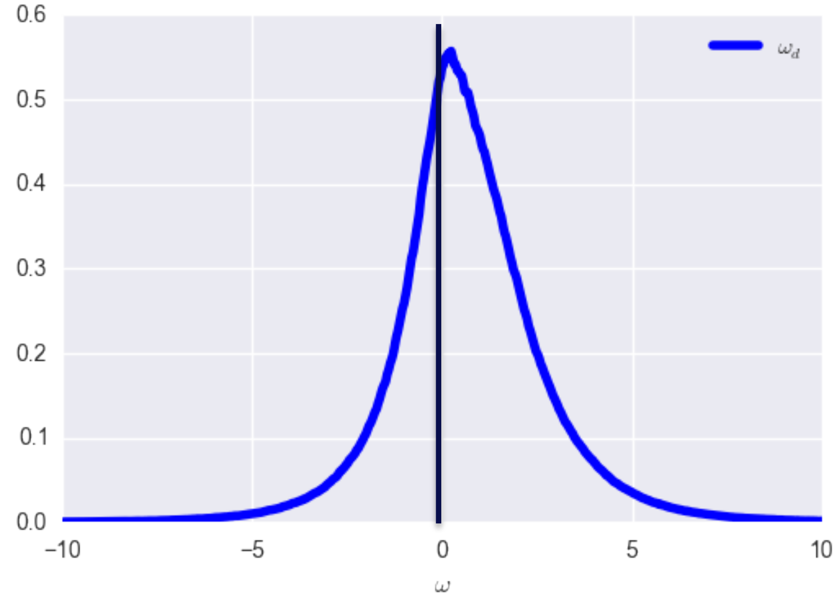

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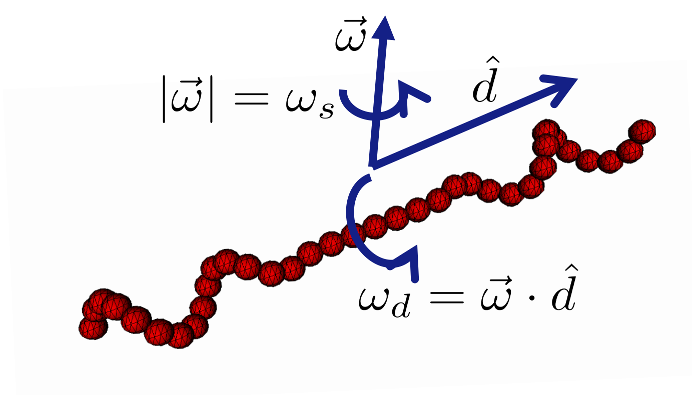

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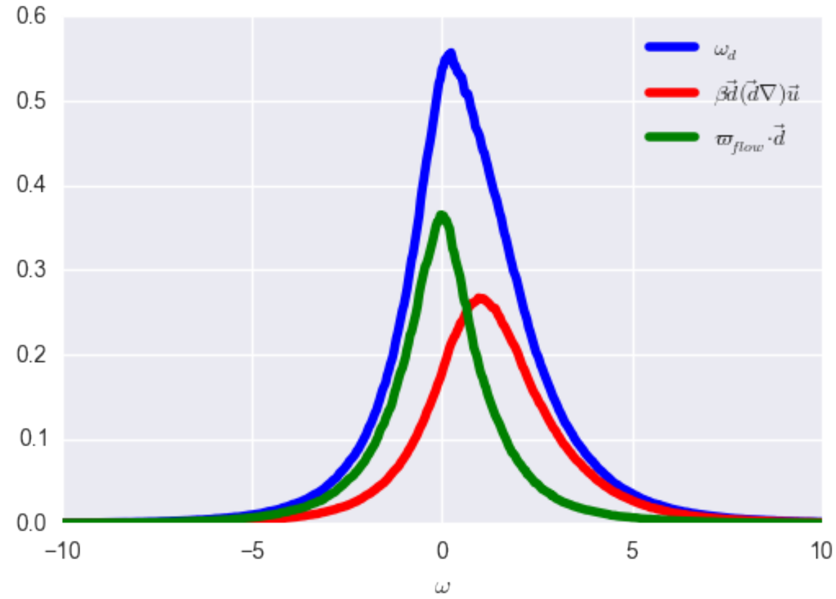

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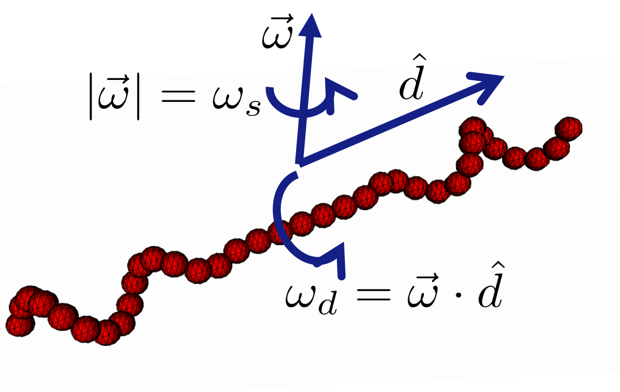
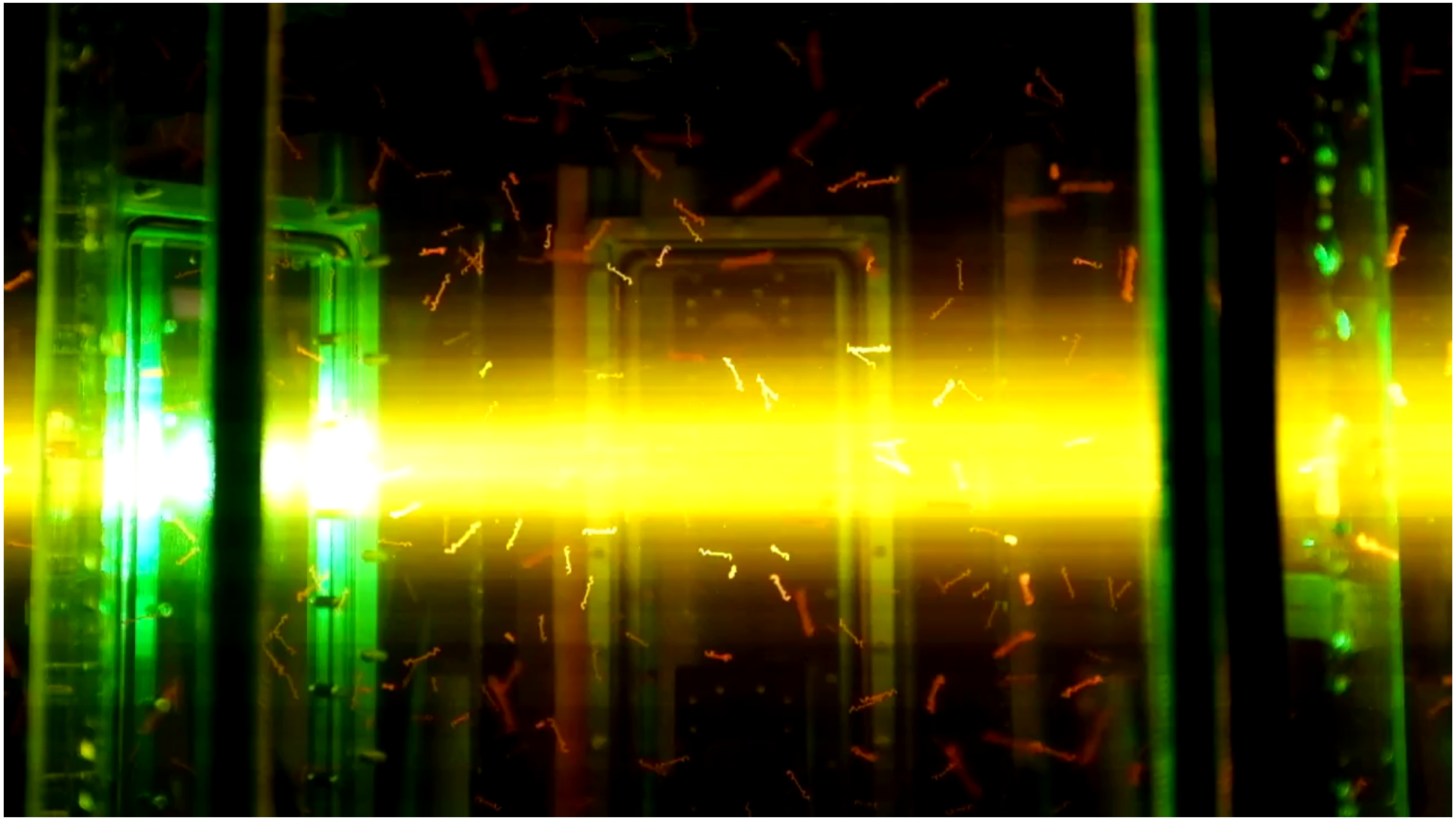


non-zero mean spinning rate due to the strain-field

Experimental methods



Gridfrequency	η (mm)	τ_η (s)	Re_λ	u (mm s^{-1})	L (mm)	ν (m^2 s^{-1})
1 Hz	0.562	0.158	90	20	60	$2.00 \cdot 10^{-6}$

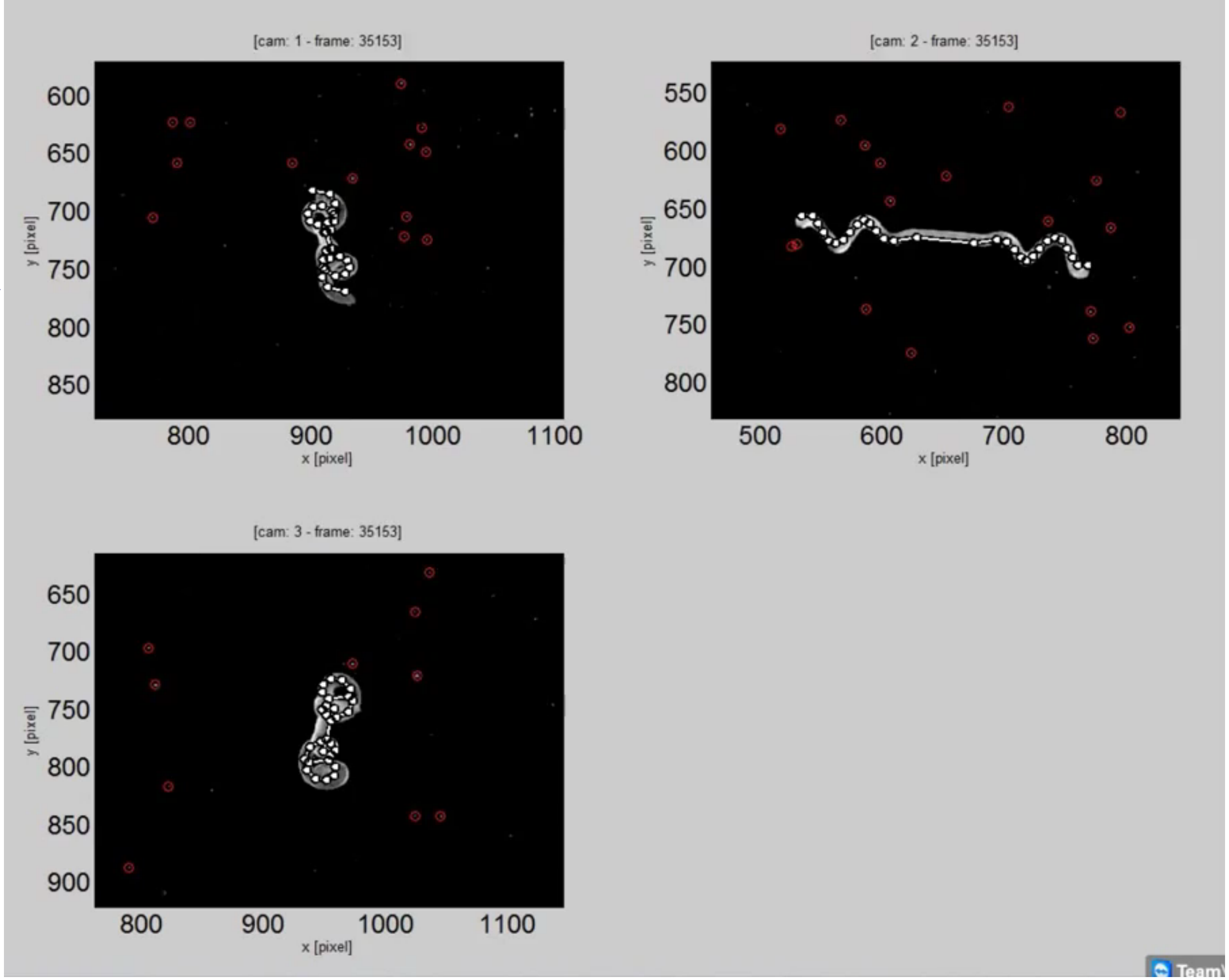
Experiments: output

Grayscale images from all four cameras, zoomed-in to show chiral dipole.

Plotted on top is a projection of the computer generated model of a chiral dipole with the measured Euler angles.

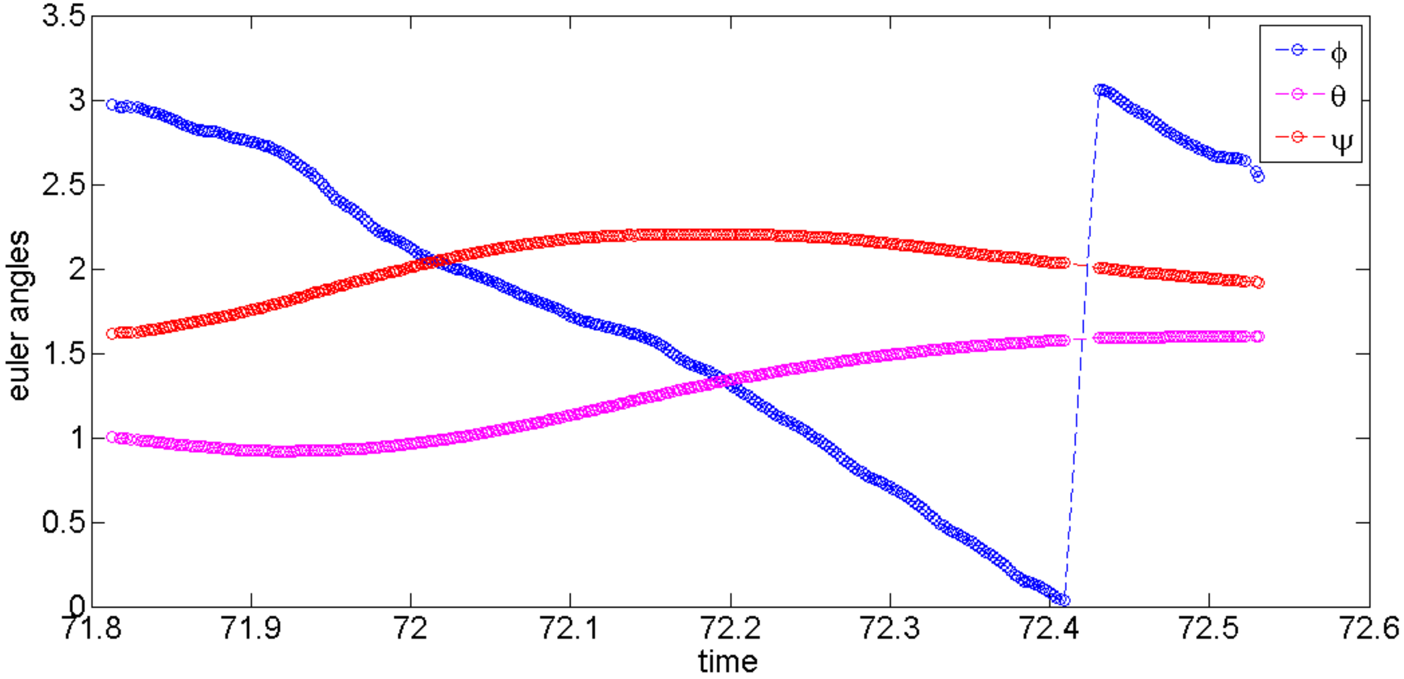
The model consists of 30 rods (the end-points are drawn as white circles).

The red circles show the tracers around the chiral dipole that were tracked simultaneously.



Experiments: Euler angles

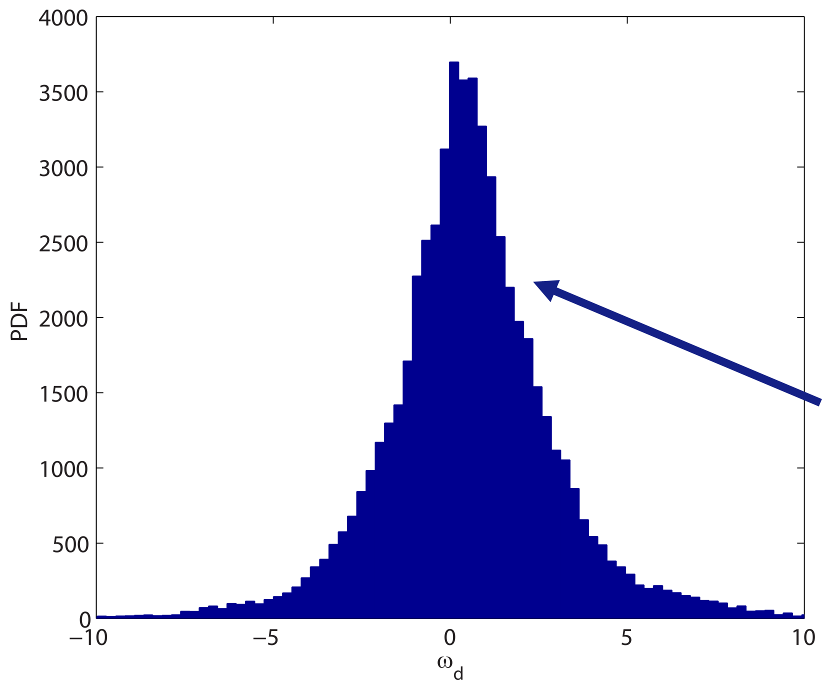
Euler angles versus time for the previously shown trajectory of a chiral dipole



Experiments: Results

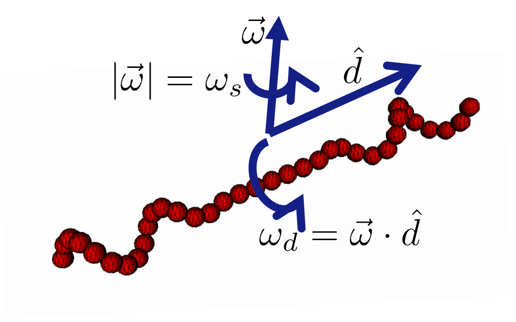
<u>Preliminary data analyzed:</u>
3 out of 17 data sets at low grid frequency (1Hz)
→ 1.5 million frames out of 8.5 million frames
→ roughly 100.000 accurate orientation and velocity measurements
→ We expect roughly ½ million good measurements in total

<u>Still to do:</u>
- Analyze high grid frequency (3Hz) data
- Analyze tracer data

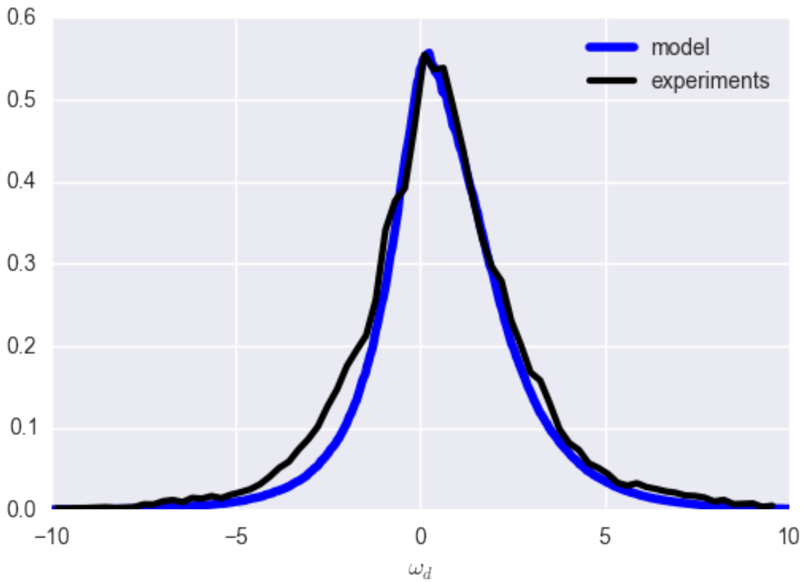


mean:
$\omega_d = 0.56\ s^{-1}$

non-zero mean rotation around chiral dipole vector, preferential rotation due to the coupling to the strain-field



Comparison

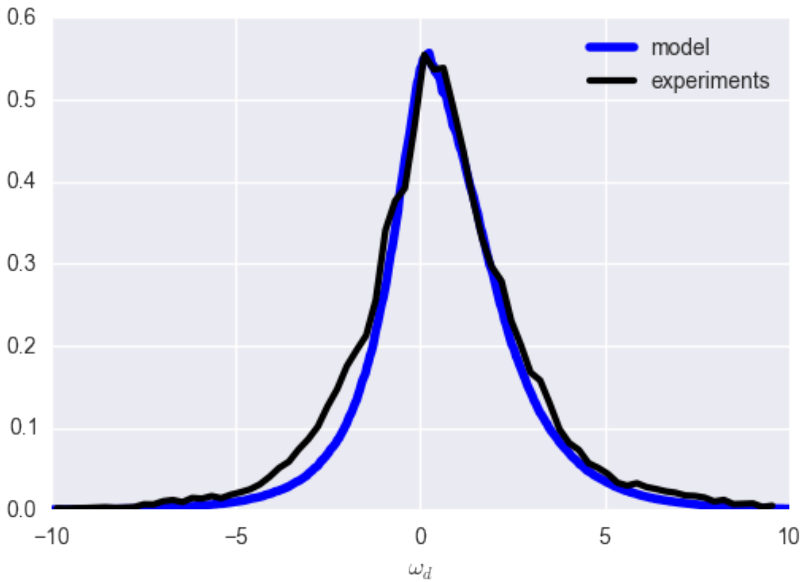


- Very good agreement between experiments and numerical model
- Mean spinning rate is about:

$$\omega_d = 0.56\ s^{-1}$$

- Stretching of material lines can be measured with chiral dipoles.

Conclusion



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Thank you for your attention!

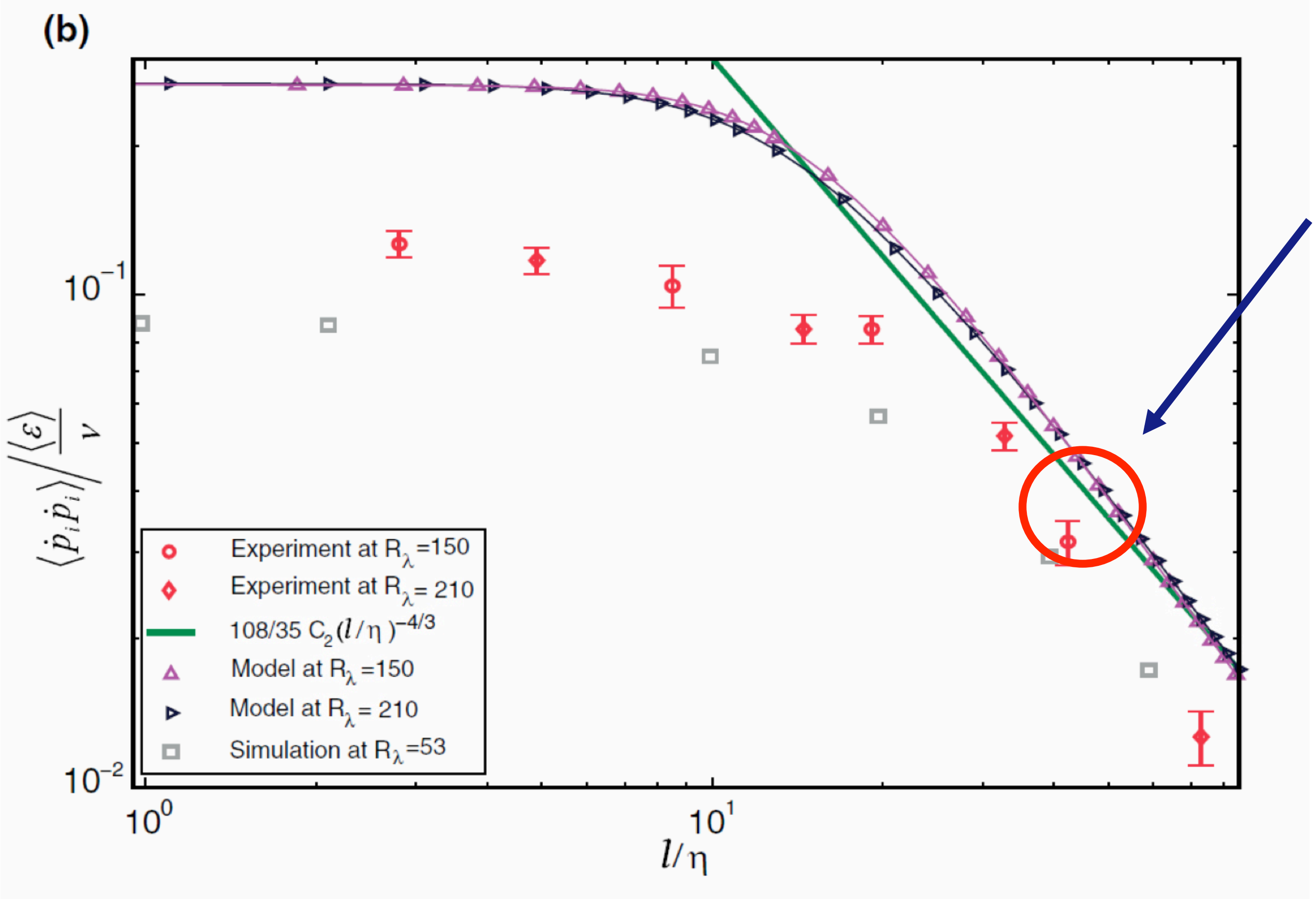
Numerical Method: Stokesian Dynamics

- Stokes force F, torque L and stress S of a sphere used to calculate velocity u and velocity gradient
- Mobility matrix M depends on geometry
- Constraints to keep shape of aggregate
- Superposition of linear solution for all spheres

$$\mathcal{M}^{-1} \cdot \begin{pmatrix} -\vec{u} \\ -\vec{\Omega} \\ -\vec{E} \\ \vec{0} \\ \vec{0} \end{pmatrix} = \begin{pmatrix} \vec{F} \\ \vec{L} \\ \vec{S} \\ -\vec{u}_{cm} \\ -\vec{\omega}_{cm} \end{pmatrix}$$

L. Durlofsky and J.F. Brady. *Dynamic simulation of hydrodynamically interacting particles*. Journal of Fluid Mechanics (1987)

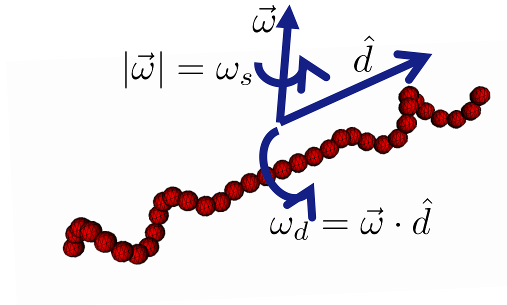
Tumbling rate of chiral dipoles and rods



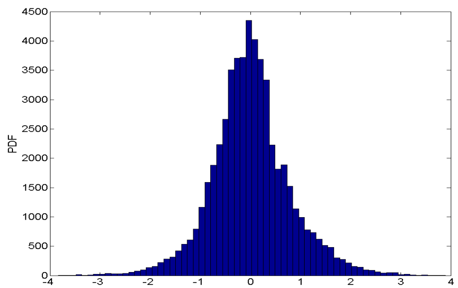
Measured mean-squared tumbling-rate, normalized by the Kolmogorov time agrees with the predicted tumbling rates for long rods

Shima Parsa, and Greg A. Voth, “Inertial Range Scaling in Rotations of Long Rods in Turbulence”; *Physical Review Letters*, 112, 024501 (2014)

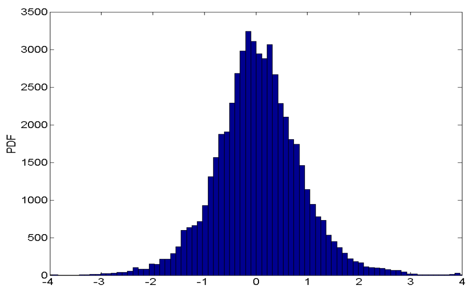
Experiments: Tumbling rate



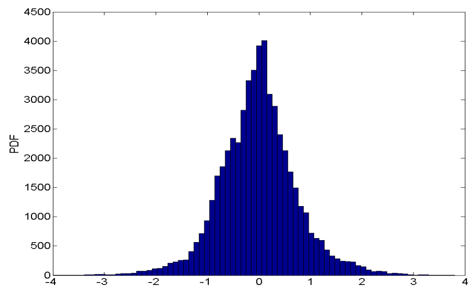
Measured distributions of the components of the tumbling rate



$$\dot{d}_x$$



$$\dot{d}_y$$



$$\dot{d}_z$$

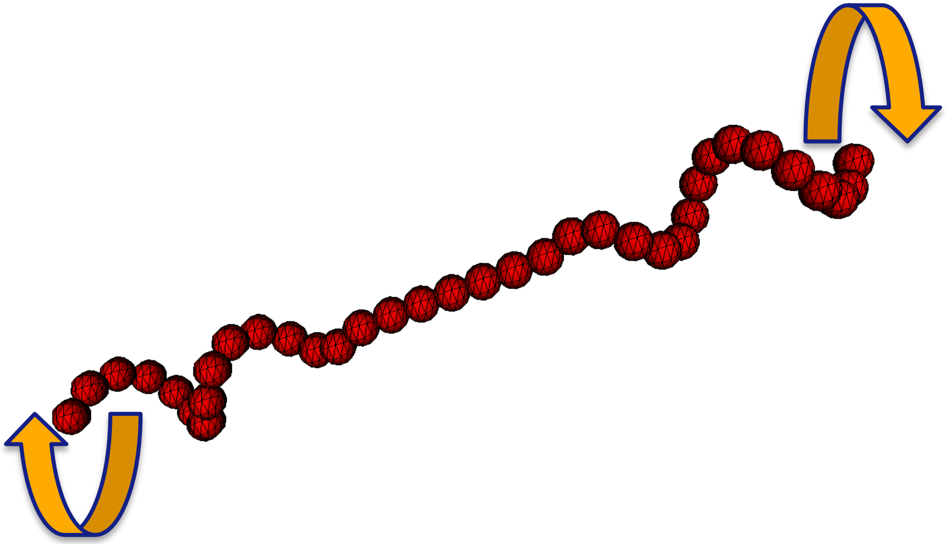
(as expected the means are about zero)

Outline

Numerical simulation with Classical Stokes Dynamics

Analytical model with numerical turbulent flow

Experiments (conducted at Wesleyan University)



Conclusion

- We study **chiral dipoles** in turbulent flow using numerical and experimental tools.
- Classical Stokesian dynamics show that the **spinning** rate of the chiral dipole is **proportional to the strain** rate of the flow field.
- Our analytical model allows to calculate the spinning rate in turbulence **a-posteriori**. We predicted a shift in the PDF.
- Experiments in homogeneous turbulence validates this shift.
  - ➢ Preferred spinning rate in turbulent flow

Thank you for your attention!