the influence of

shape SiZe and density distribution

on microplastic transport in environmental flows

Margaret L. Byron

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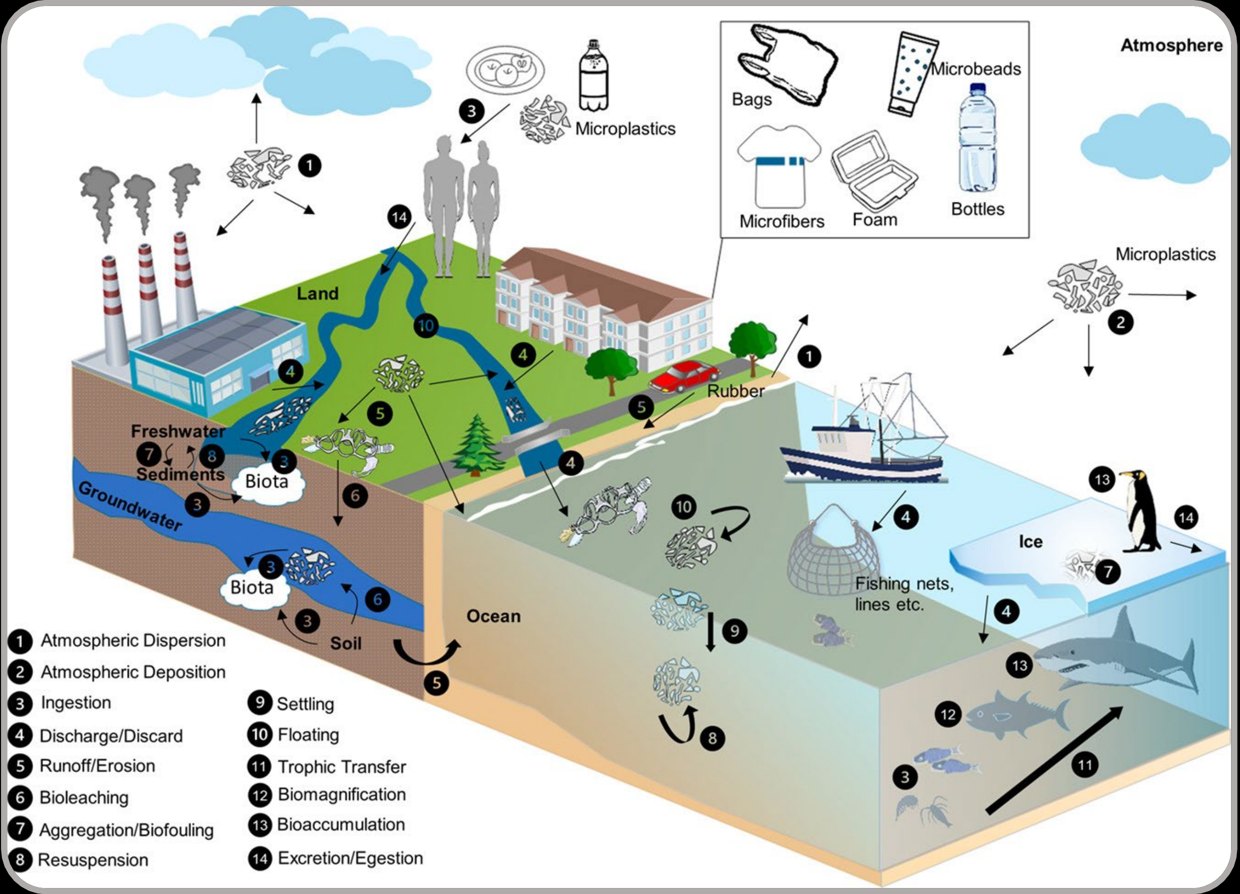
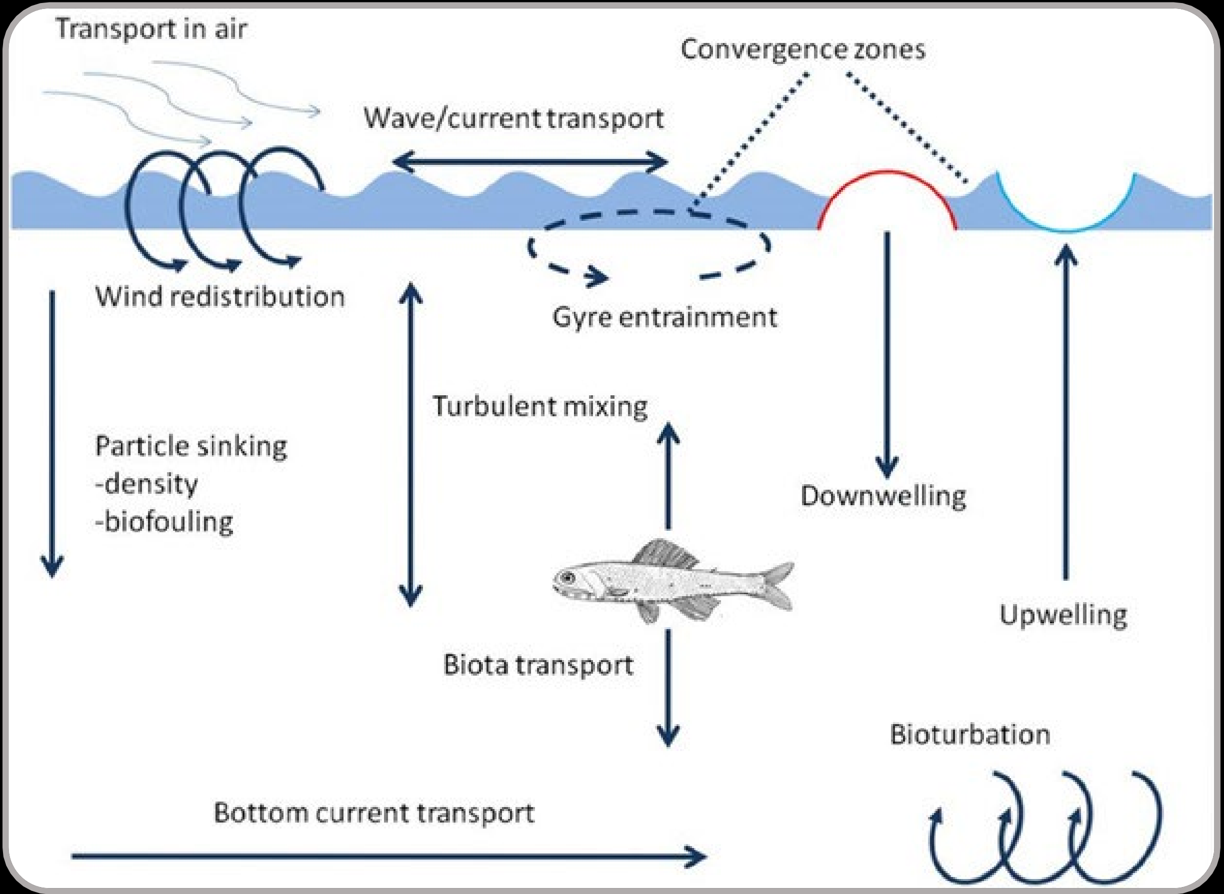
"Predicting Pathways for Microplastic Transport in the Ocean"

Banff International Research Station/Online

February 24, 2022

How do microplastics move around in the environment?

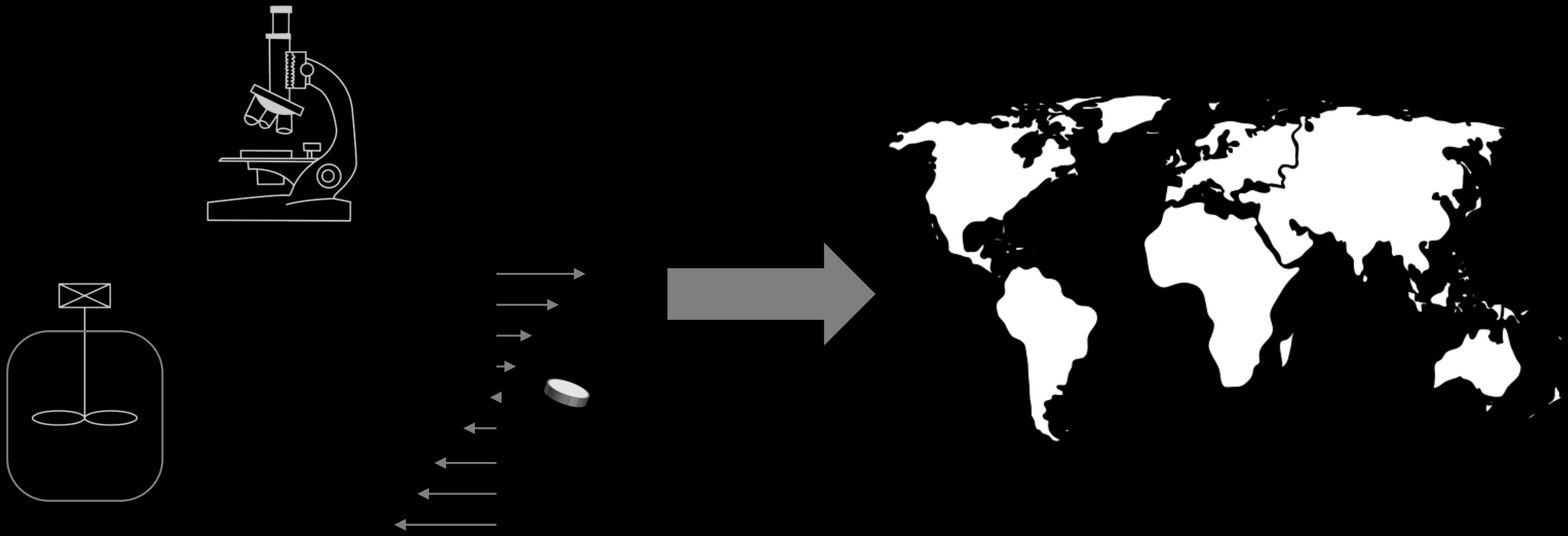




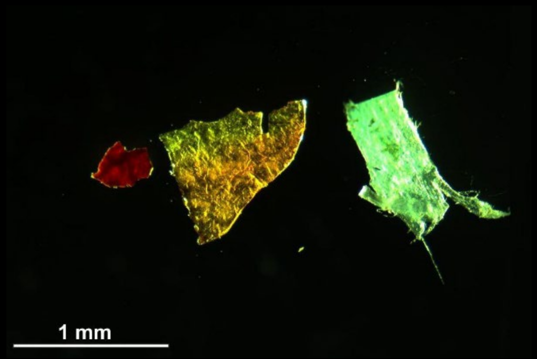
Petersen and Hubbart 2020, *Sci. Total Environ.*

Welden and Lusher 2017, *IEAM*

What particle characteristics impact transport the most?

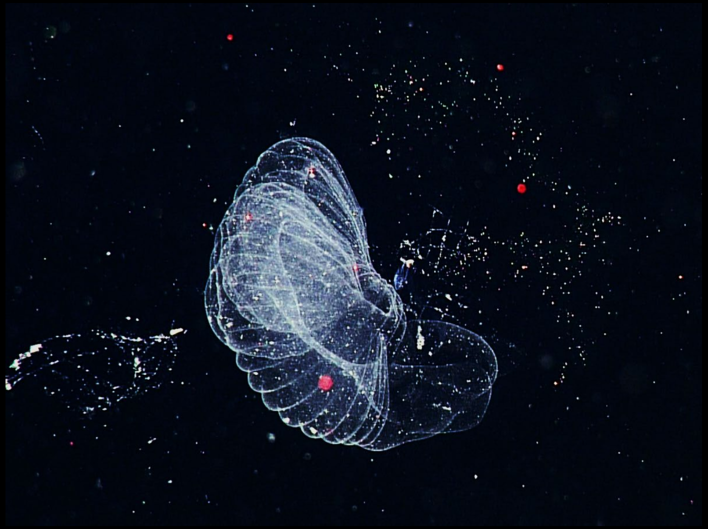


Long-term goal: help parametrize large-scale models by determining how much inter-particle variability matters



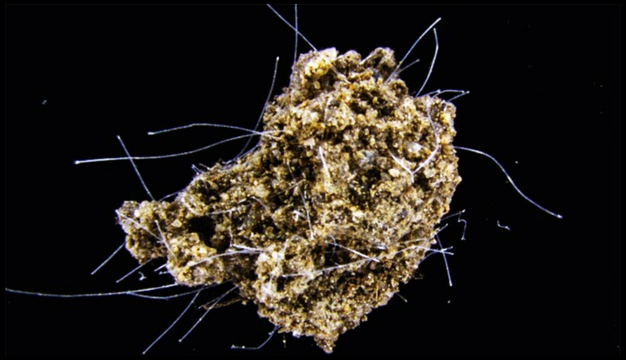
size

shape



density

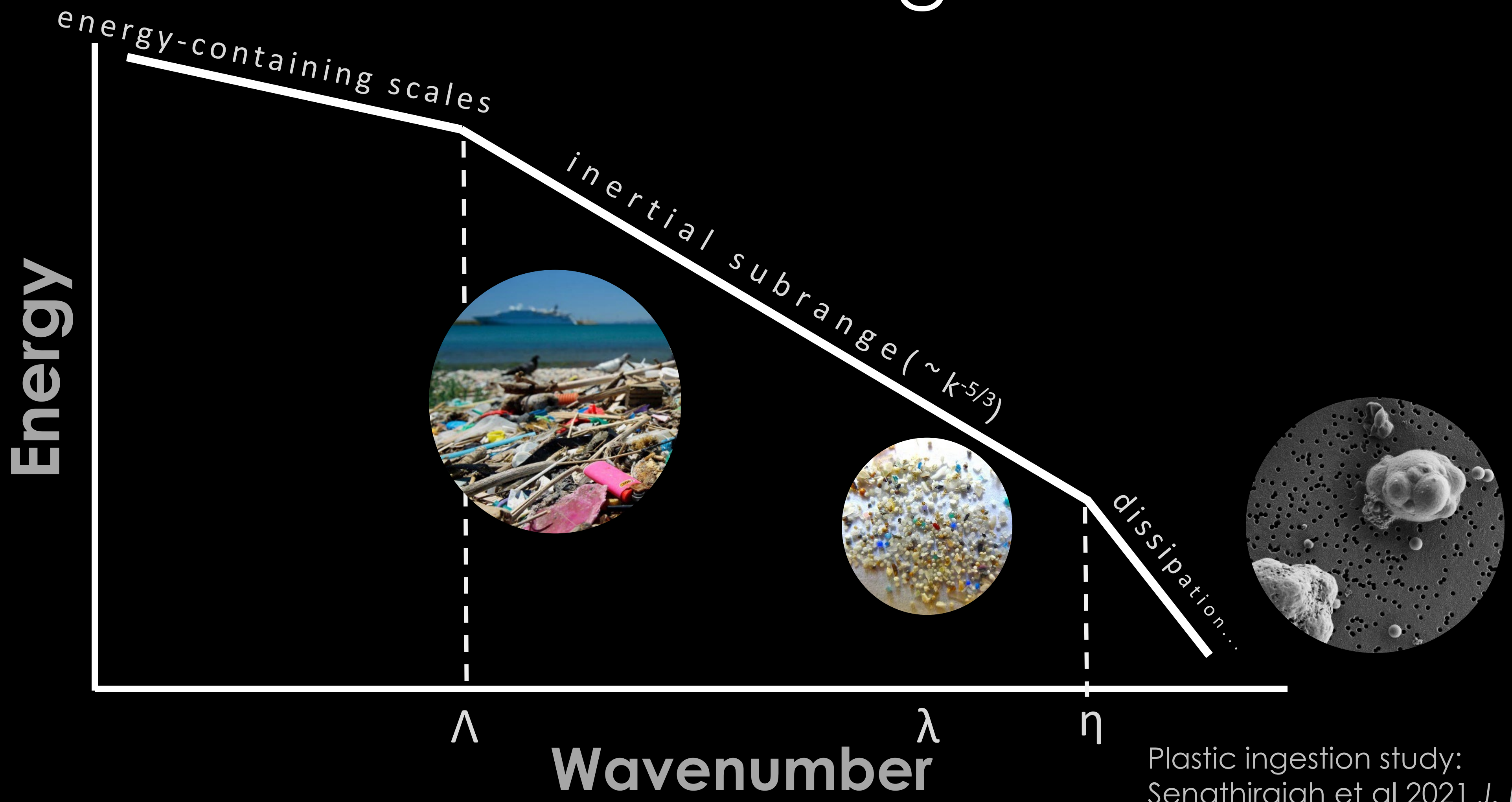
Where do we go from here?



density ***distribution***

Images: Kane & Clare 2019, *Front. Earth Sci.*
CC-BY-NC 2.0, Will Parson (Chesapeake Bay Program)
Monterey Bay Aquarium Research Institute
Rillig and Lehmann 2020, Science

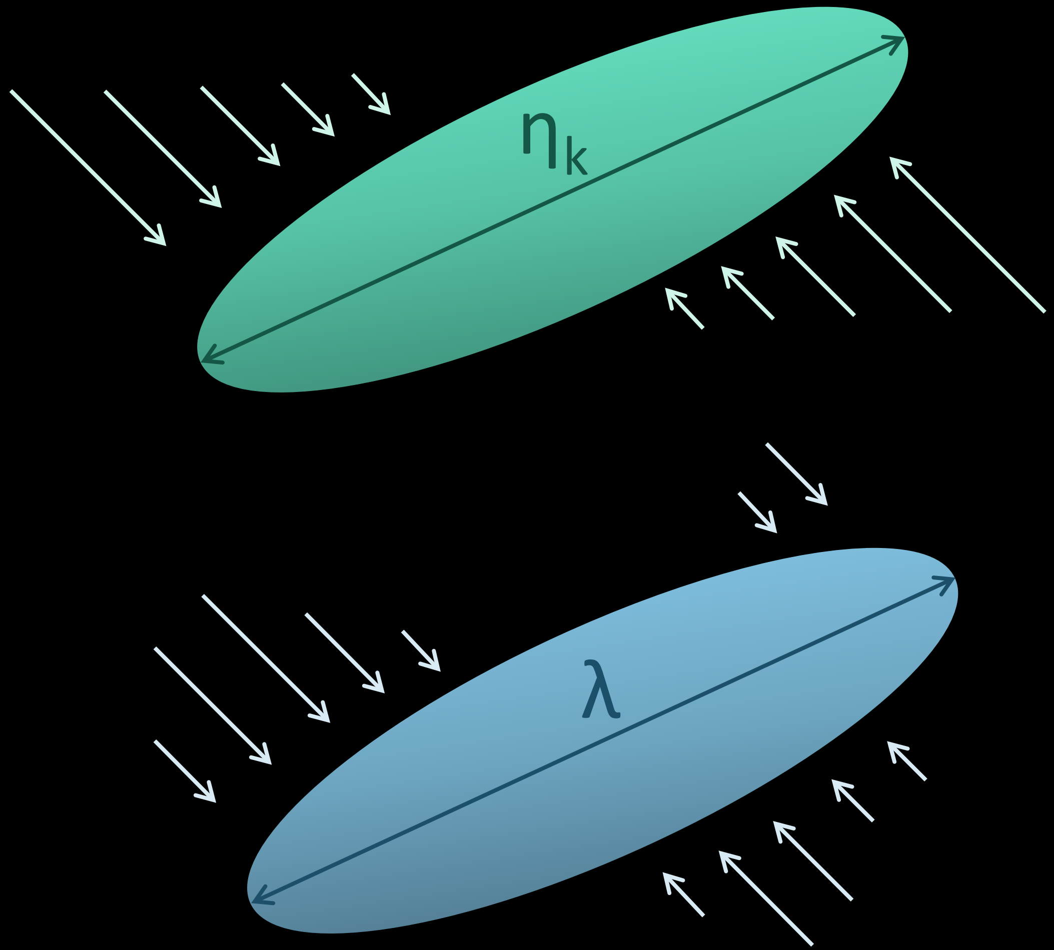
The size of a particle influences how it experiences the surrounding turbulence.



Plastic ingestion study:
Senathirajah et al 2021 *J. Haz. Mat.*

Images: Milos Bicanski. World Wildlife Federation (UK) / 5Gyres and Oregon State University / F. Vollnhals, INAM

Inertia comes not only from the mass of a particle, but also from its size.



$$St = \frac{\tau_p}{\tau_f} \qquad \tau_p \equiv \frac{\rho_p d_p^2}{18\rho_f \nu_f}$$

$$m_p \frac{d\boldsymbol{u}_p}{dt} = (m_p - m_f)\boldsymbol{g} + m_f \frac{D\boldsymbol{u}_f}{Dt} - \frac{1}{2} m_f \frac{d}{dt}\left(\boldsymbol{u}_p - \boldsymbol{u}_f - \frac{1}{10}R^2\nabla^2\boldsymbol{u}_f\right) - 6\pi R\mu(\boldsymbol{u}_p - \boldsymbol{u}_f) - \frac{1}{6}R^2\nabla^2\boldsymbol{u}_f - 6\pi R^2\mu\int_0^t \left(\frac{\frac{d}{d\tau}\left(\boldsymbol{u}_p(\tau) - \boldsymbol{u}_f(\tau) - \frac{1}{6}R^2\nabla^2\boldsymbol{u}_f\right)}{(\pi\nu(t-\tau))^{\frac{1}{2}}}\right)$$

Gravity + Buoyancy

Pressure gradients

Acceleration Reaction force

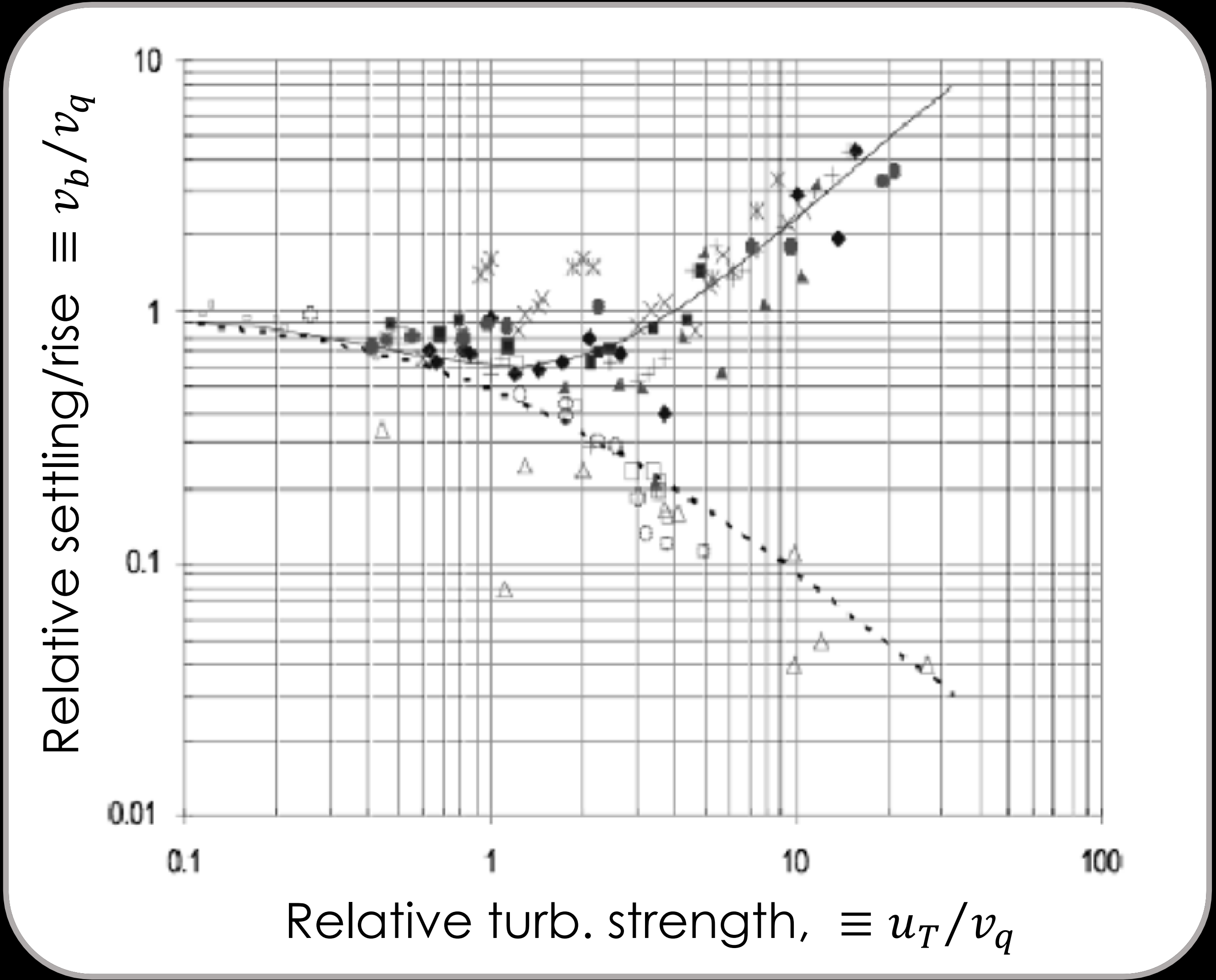
Faxén corrections (for finite size)

Steady (Stokes) drag

More Faxén corrections

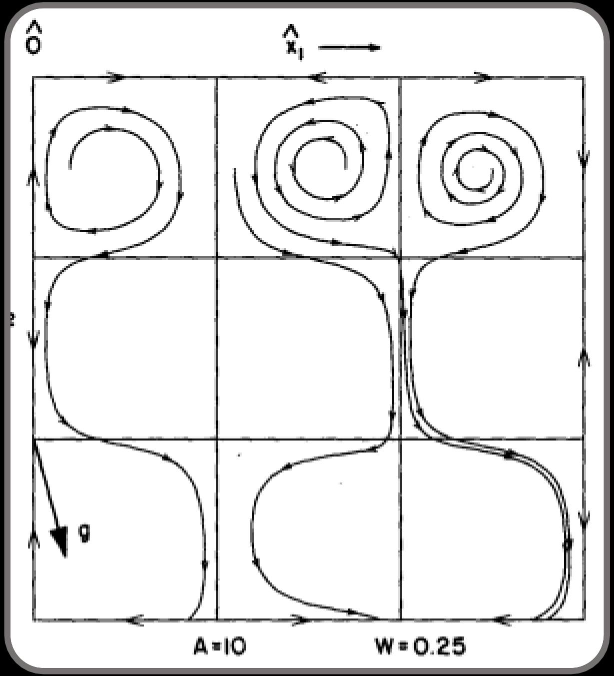
Basset history force, including unsteady drag effects

A particle's settling velocity in turbulence isn't the same as it is in still water.

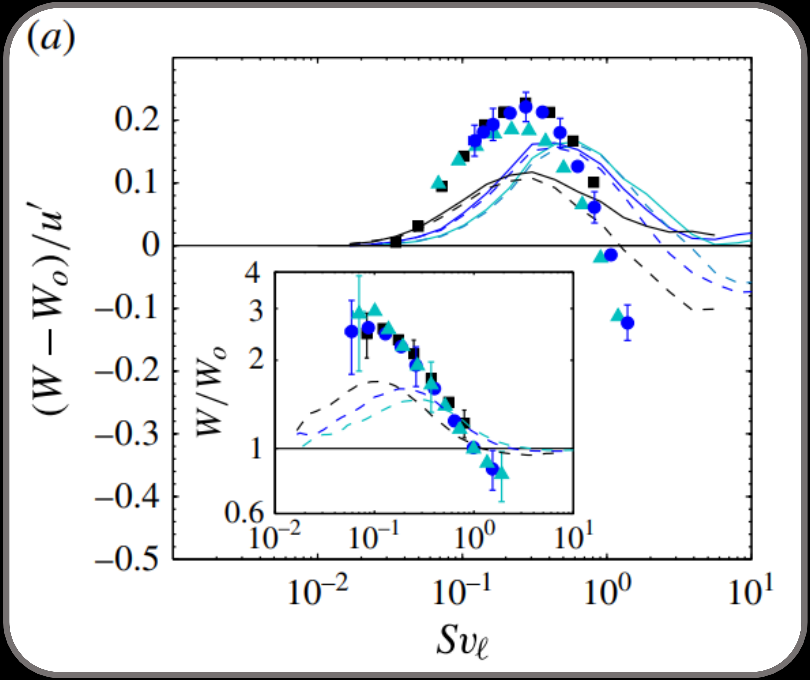


From Nielsen 2007, "Mean and variance of the velocity of solid particles in turbulence"

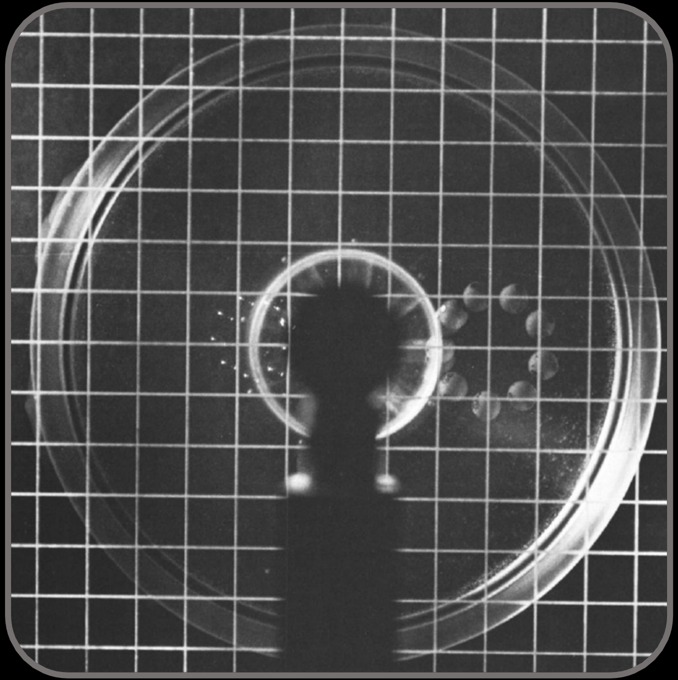
Different mechanisms act on particles of different size/density.



Maxey and Corrsin 1986, *J. Atmos. Sci*



Good et al 2014, *J. Fluid Mech.*



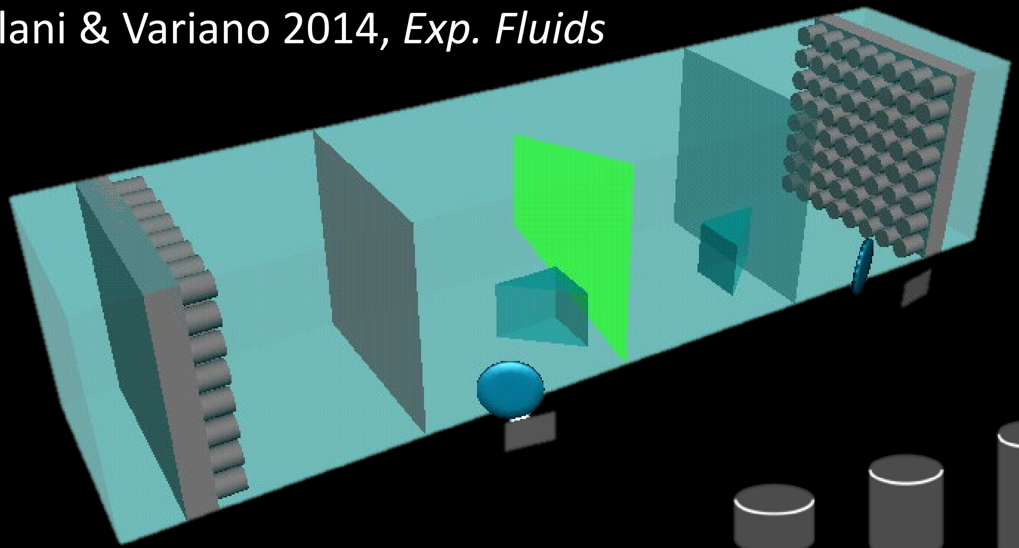
Tooby, Wick, and Isaacs 1977 *J. Geophys. Res.*

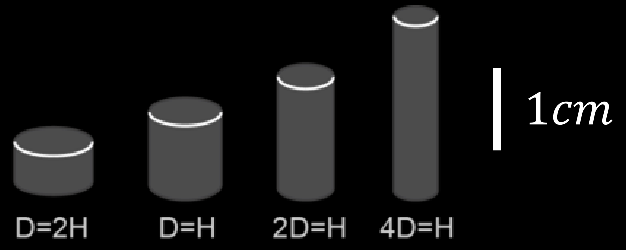
How do the size and shape of **near-neutrally buoyant** particles affect their motion relative to the surrounding flow?

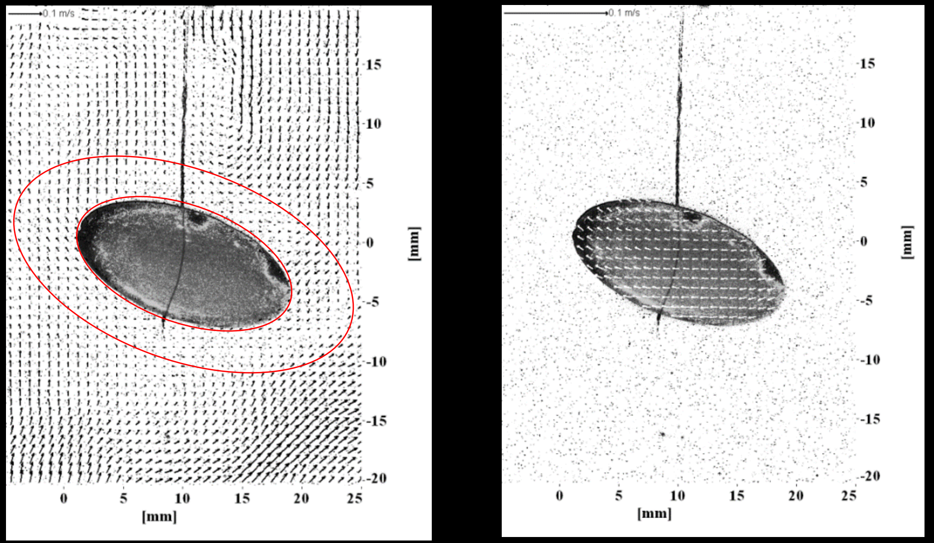
We placed particles of 4 different shapes and 2 different mass densities in a laboratory turbulent flow.

$\vec{u}_s = \vec{u}_p - \vec{u}_f$

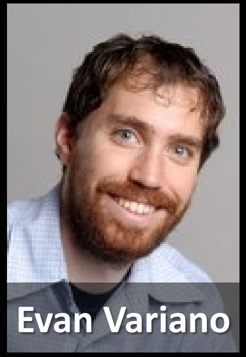
Bellani & Variano 2014, *Exp. Fluids*







Byron & Variano 2013, *Exp. Fluids*



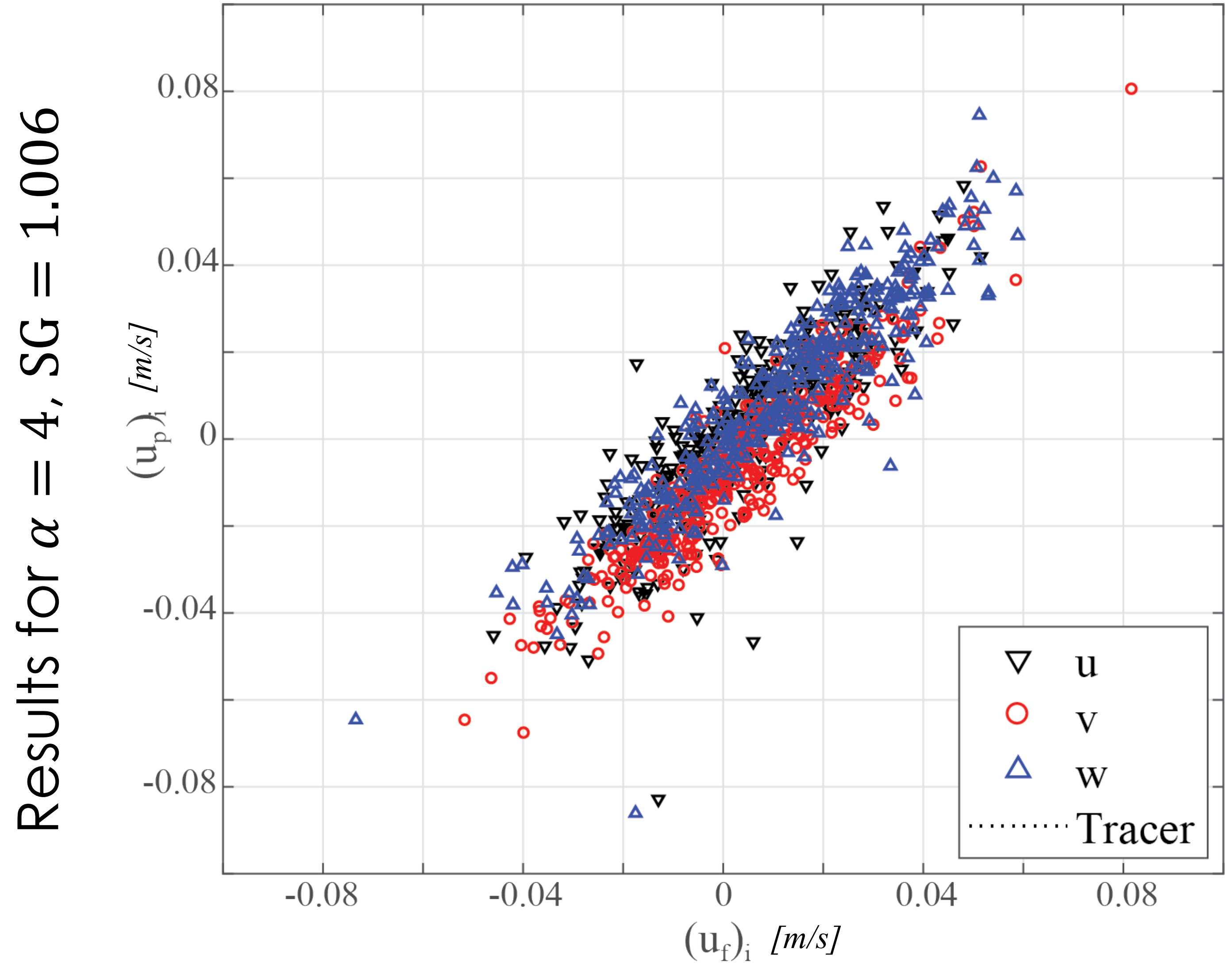
$SG_1 = 1.003$

$SG_2 = 1.006$

Ocean Turbulence		Tank Properties	
TKE = [2, 14] cm^2/s^2	Re_λ = [200, 10^4]	TKE = 6.47 cm^2/s^2	Re_λ = 310
ε = [10^{-7}, 10^{-4}] m^2/s^3	η = [0.3, 2] mm	ε = 4.95·10^{-5} m^2/s^3	η = 0.50mm

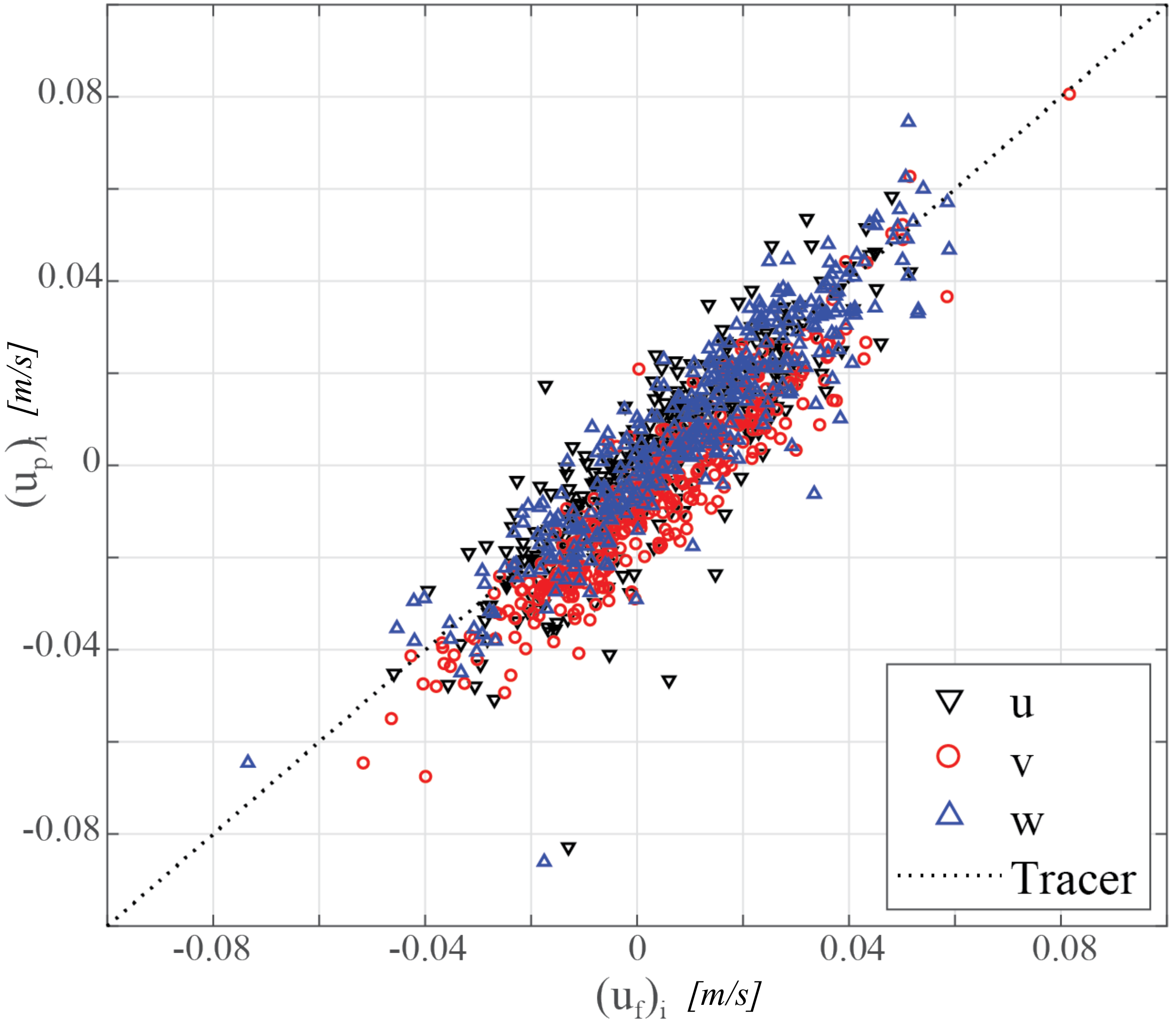
(from Jiménez 1998, *Oc. Lit. Rev.*)

All 3 velocity components follow a linear trend, *despite* the influence of history.



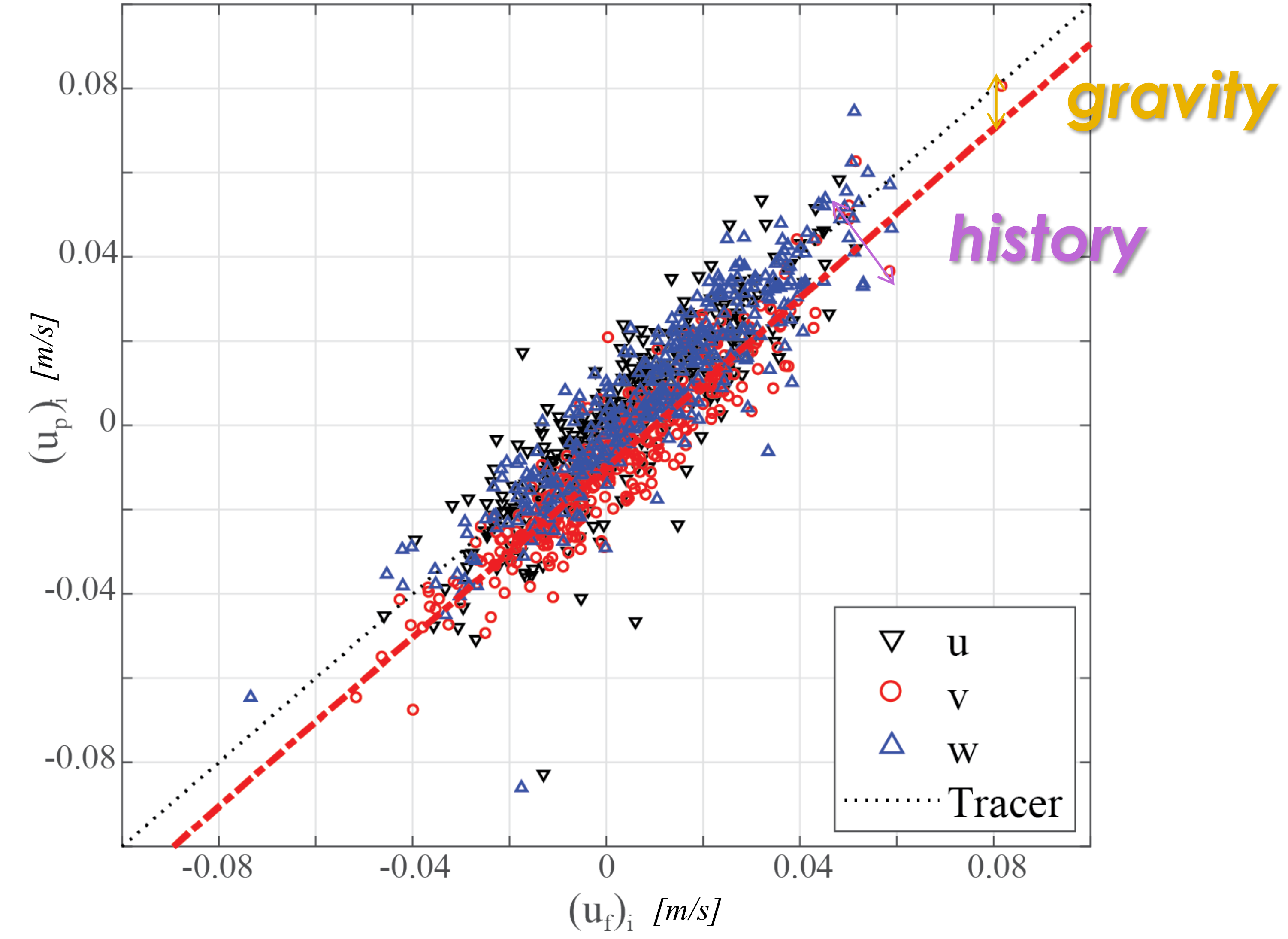
The particles are NOT behaving as perfect tracers, but scatter is uniform across range.

Results for $\alpha = 4$, SG = 1.006



The gravity-coupled component (v) is substantially offset from the others.

Results for $\alpha = 4$, SG = 1.006



We define two different "slip" velocities: one for buoyancy and one for history effects.

$$\vec{u}_s(\vec{x},t) = \langle \vec{u}_s \rangle + \vec{u}_s{}'(\vec{x},t) = \vec{u}_b + \vec{u}_\varepsilon\left(\int \vec{x}_p\, dt, t\right)$$

$\vec{u}_s = \vec{u}_p - \vec{u}_f$
(instantaneous slip)

(ensemble average)

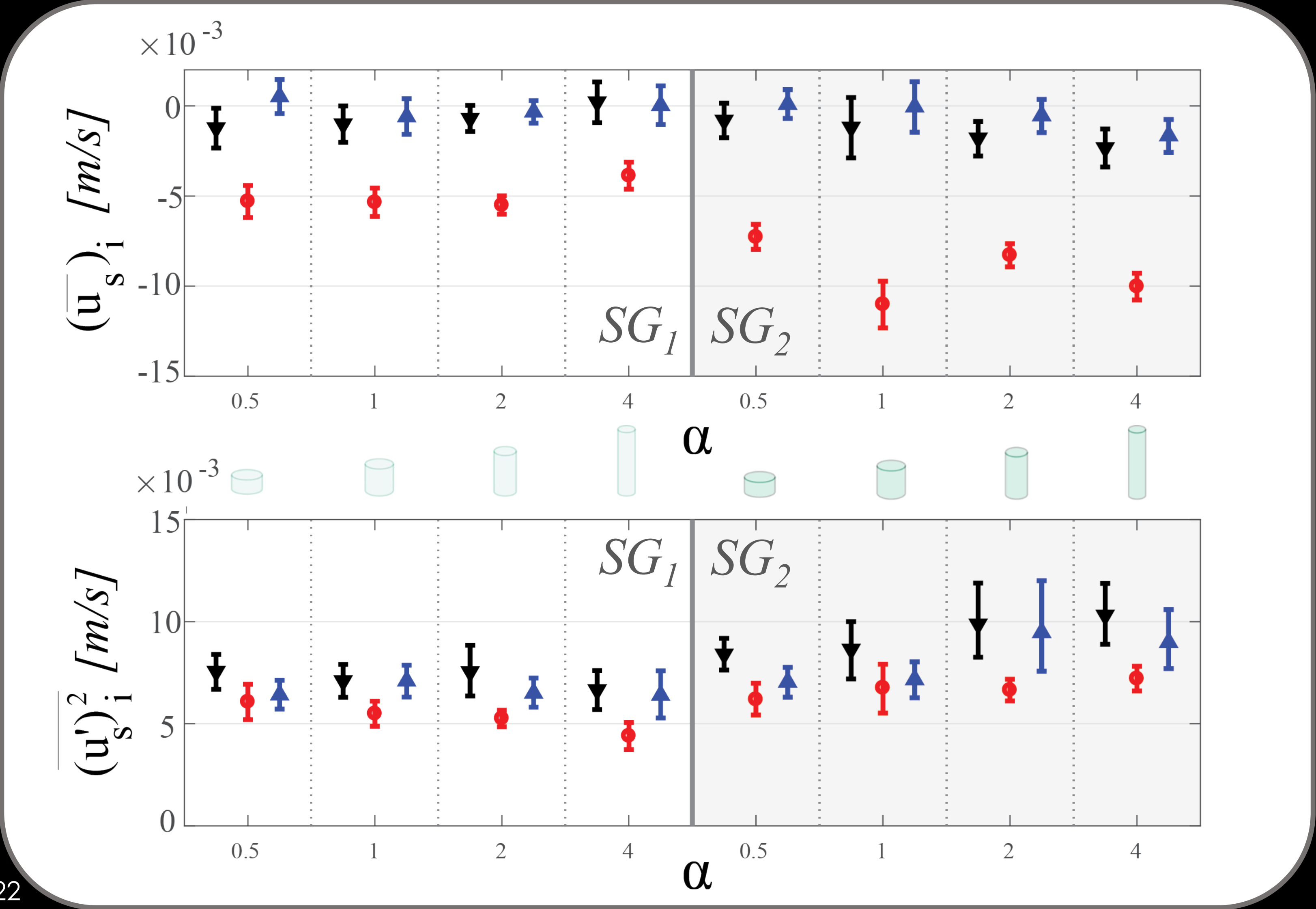
(inst. fluctuations)

(buoyancy effects)

(history effects)

$$\langle \vec{u}_s \rangle = \vec{u}_b = \begin{bmatrix} u_b \\ v_b \\ w_b \end{bmatrix} \approx \begin{bmatrix} 0 \\ v_b \\ 0 \end{bmatrix}$$

Gravity, mass, and shape/size effects are not equivalent… but maybe not independent.



(Heavier particles fall faster)

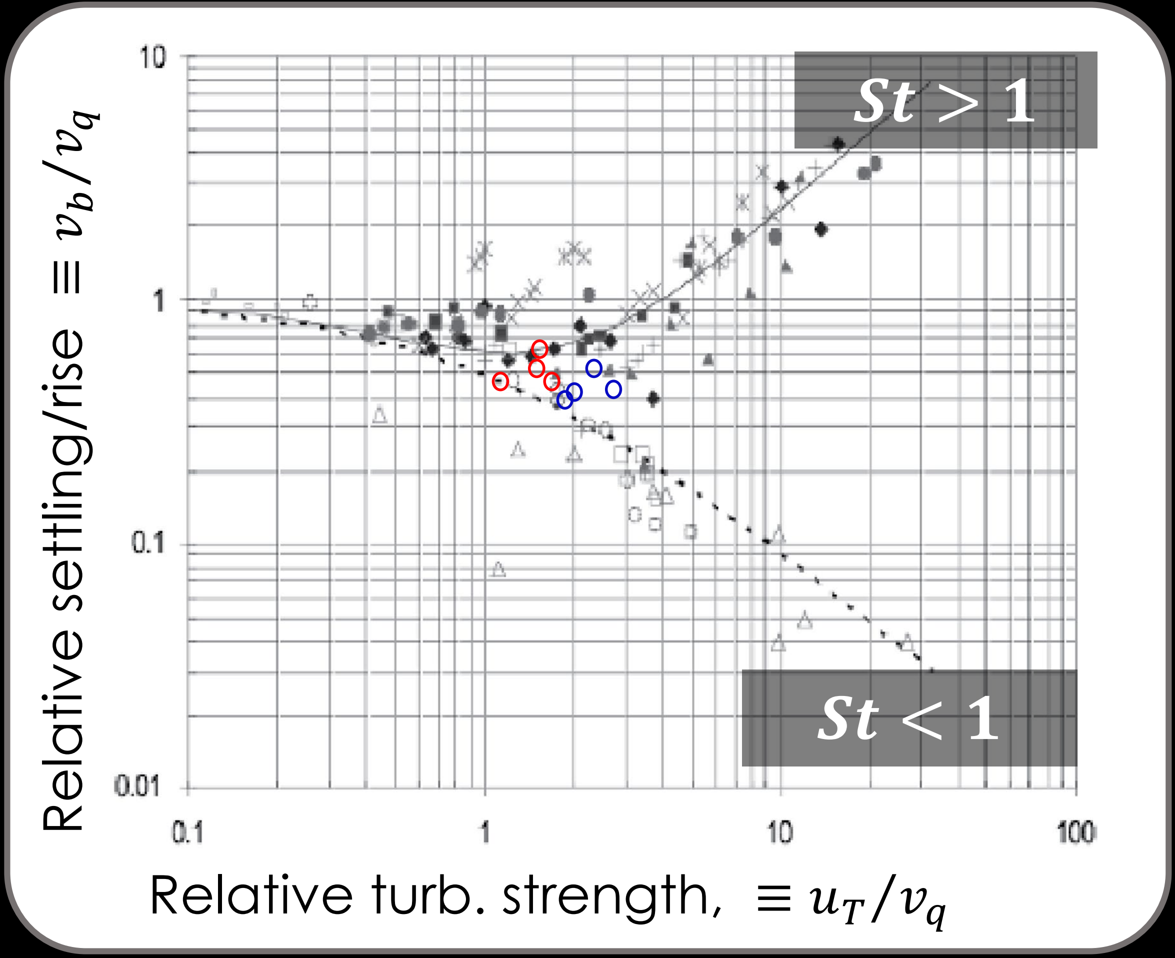
more mass→ more slip

Gravity still matters!

Byron et al 2019, *Int. J. Multiphase Flow*

Gravitational slip is significantly reduced compared to quiescent settling velocities.

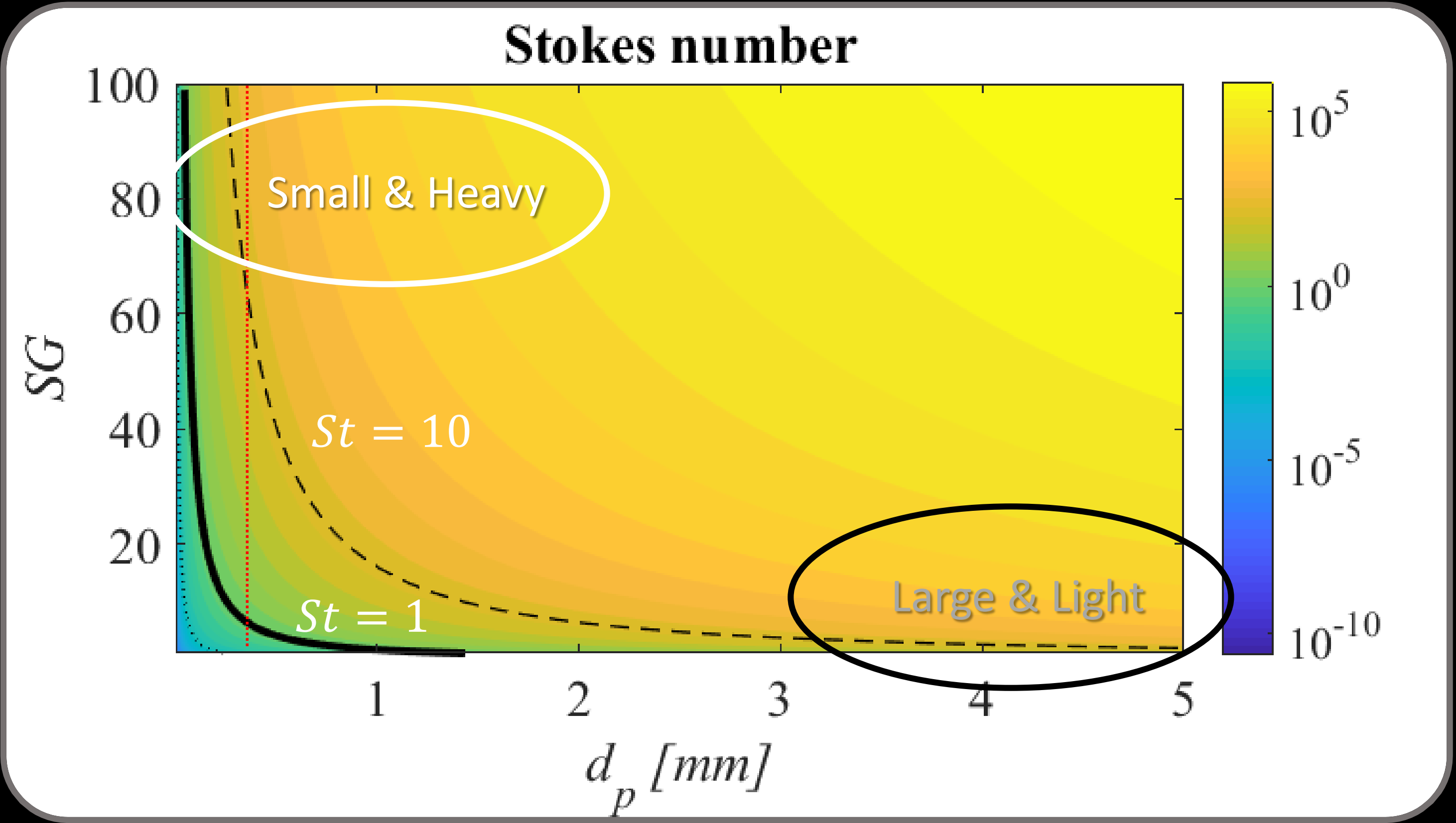
% reduction: $1 - \frac{v_b}{v_q}$		
α	SG_1	SG_2
0.5	57%	46%
1	52%	49%
2	45%	43%
4	55%	32%



From Nielsen 2007, "Mean and variance of the velocity of solid particles in turbulence"

This brings us back to the (perhaps inadequate) Stokes number…

CLASSIC VIEW: $\tau_p \equiv \dfrac{\rho_p d_p^2}{18\rho_f \nu_f}$ $\quad \tau_f = \tau_\eta \left(\dfrac{d_p}{\eta}\right)^{\frac{2}{3}}$



$$St = \frac{\tau_p}{\tau_f}$$

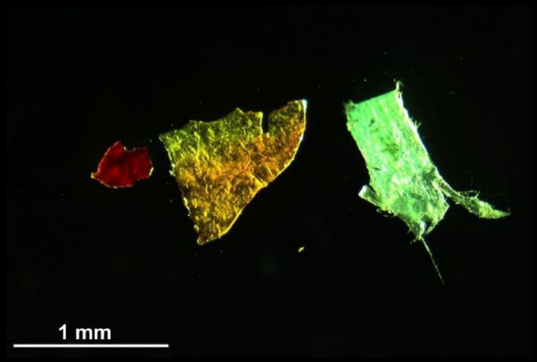
$$= SG_p d_p^{4/3} \left(\frac{\eta^{2/3}}{18\nu_f \tau_\eta}\right)$$

constant for a given flow

Scaling analysis from Bordoloi and Variano 2017, J. Fluid Mech.

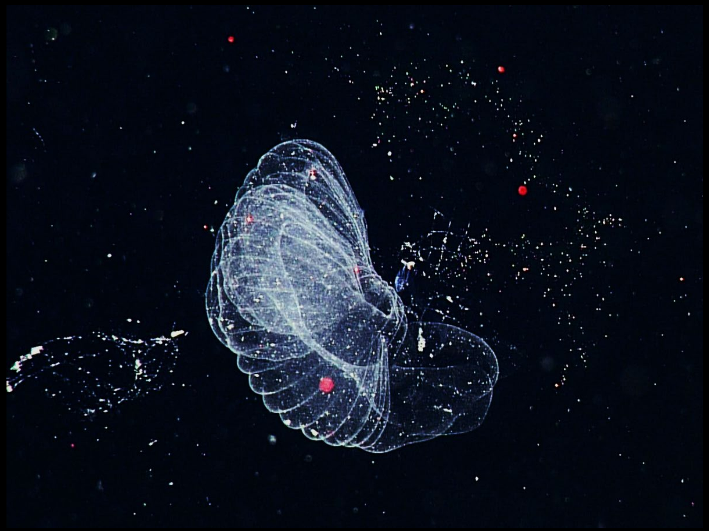
So, for large inertial particles…

- $v_b < v_q$: Settling is reduced in turbulence
- Shape doesn't matter much near neutral buoyancy for either slip/settling (OR rotation).
- Mass and size effects are *not* independent when gravity is involved. **Buoyancy effects remain even in the (ostensibly) non-gravity coupled term.**
- Stokes number can't fully describe particle inertia for large (>η_k) particles.



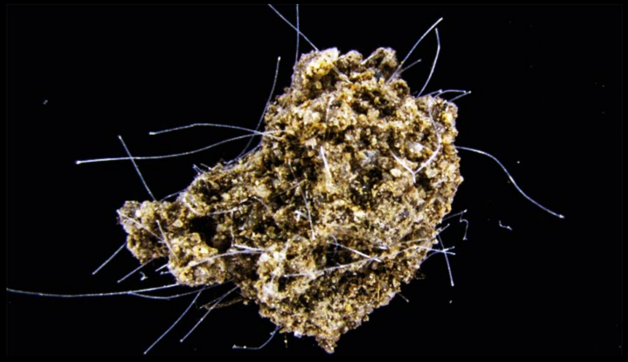
size

shape



density

Where do we go from here?



density ***distribution***

Images: Kane & Clare 2019, *Front. Earth Sci.*
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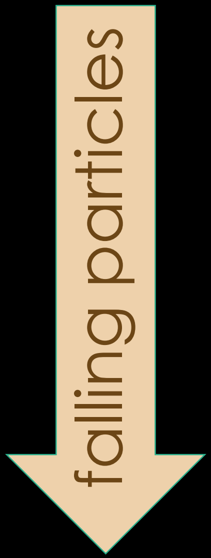
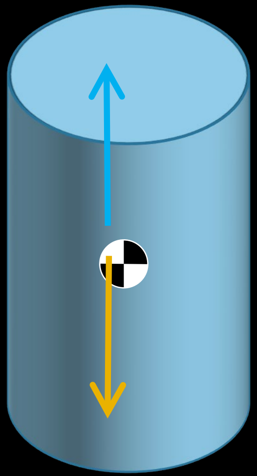
Monterey Bay Aquarium Research Institute
Rillig and Lehmann 2020, Science

Mass distribution isn't always uniform in microplastics!





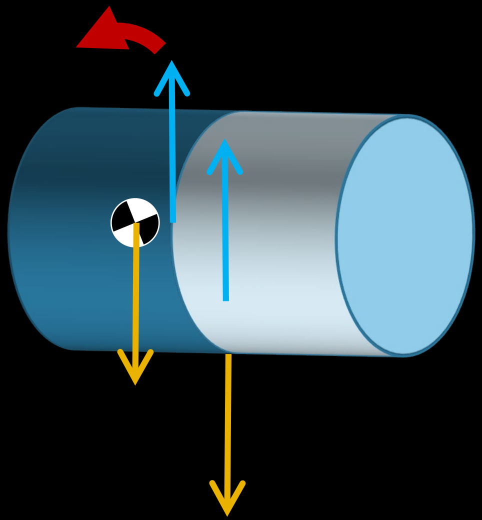
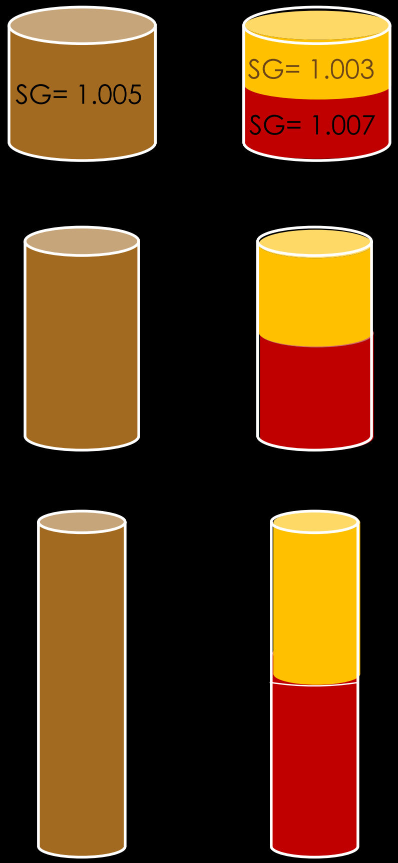


Image: Shutterstock/Rich Carey

Uniform particle:
- Gravity and buoyancy are co-located
- No net buoyant torques

Compound particle:
- Gravity and buoyancy are *not* co-located
- Buoyant torque stabilizes… or does it?

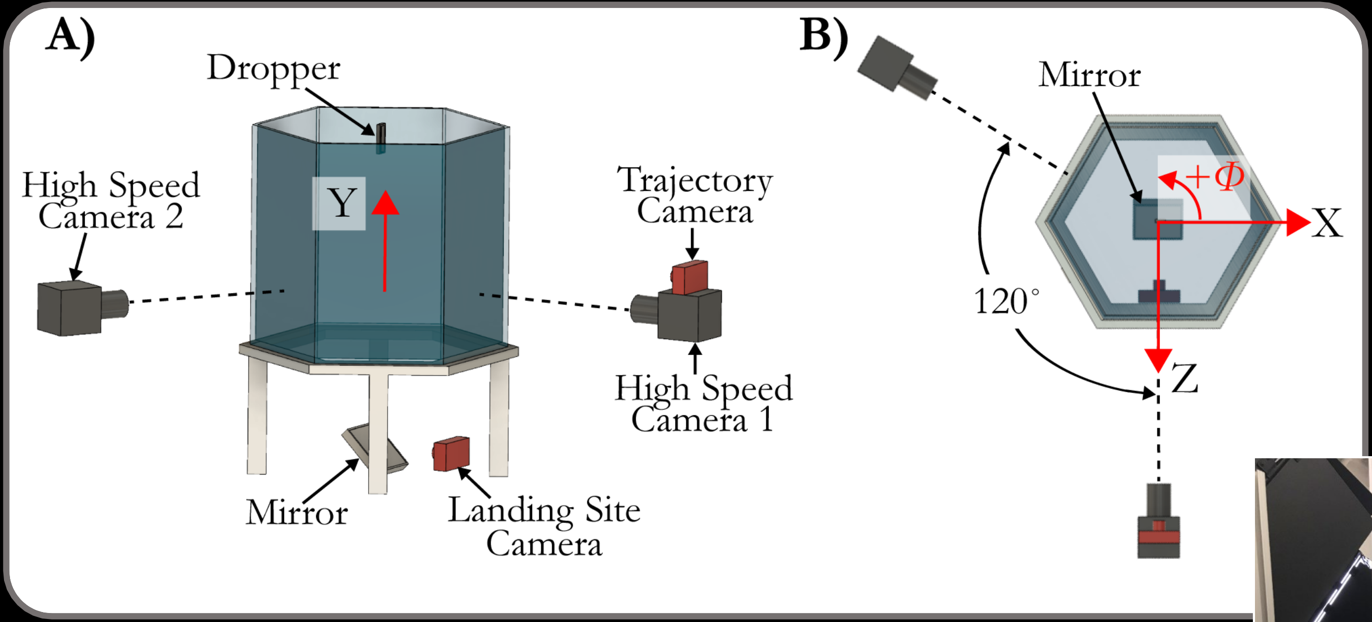
How do compound particles fall compared to uniform particles?

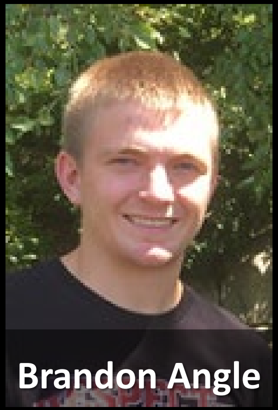


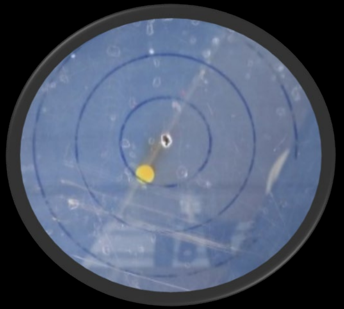
$\alpha = 1$:
$Re_p = 207$
$L = 8mm$
$D = 8mm$

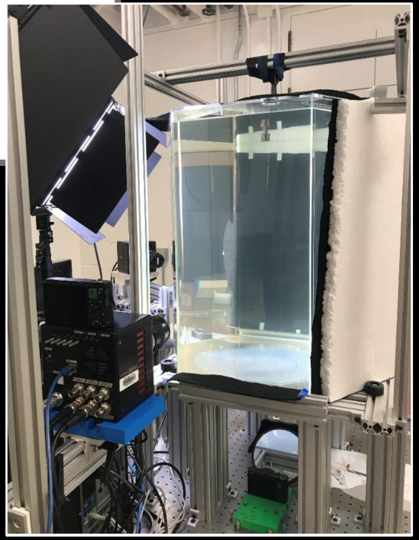
$\alpha = 2$:
$Re_p = 228$
$L = 14mm$
$D = 7mm$

$\alpha = 4$:
$Re_p = 215$
$L = 24mm$
$D = 6mm$

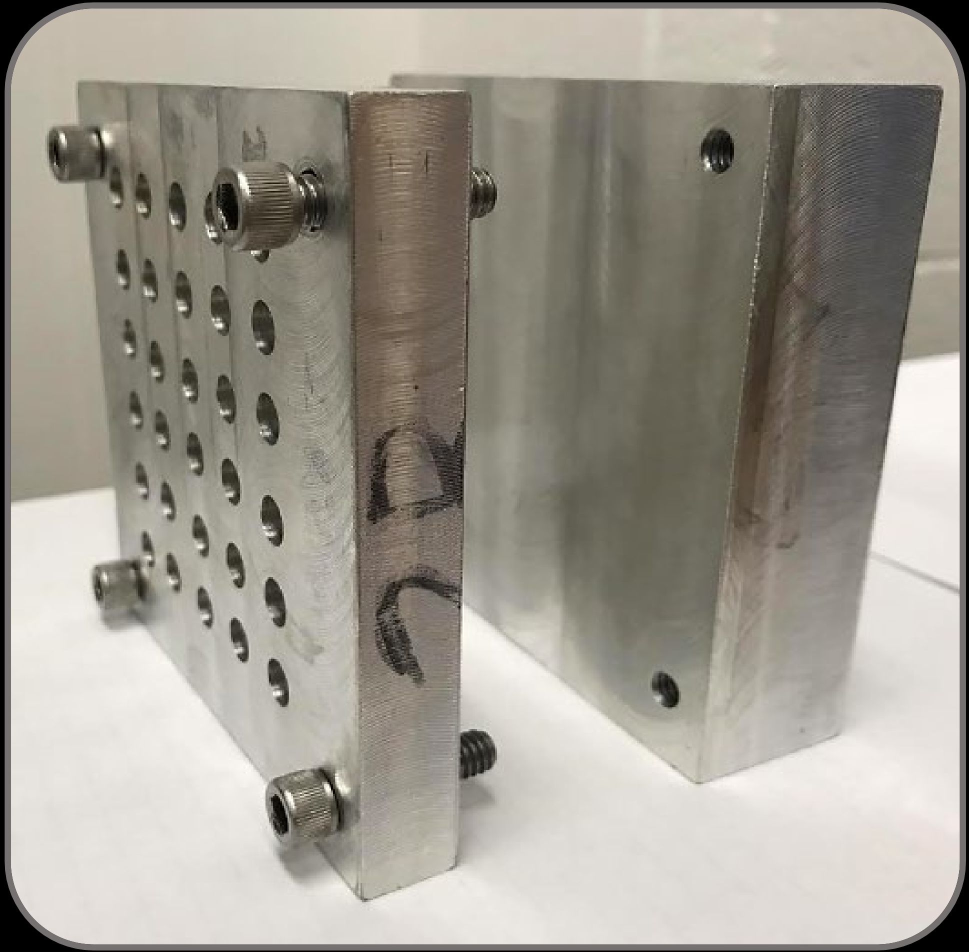




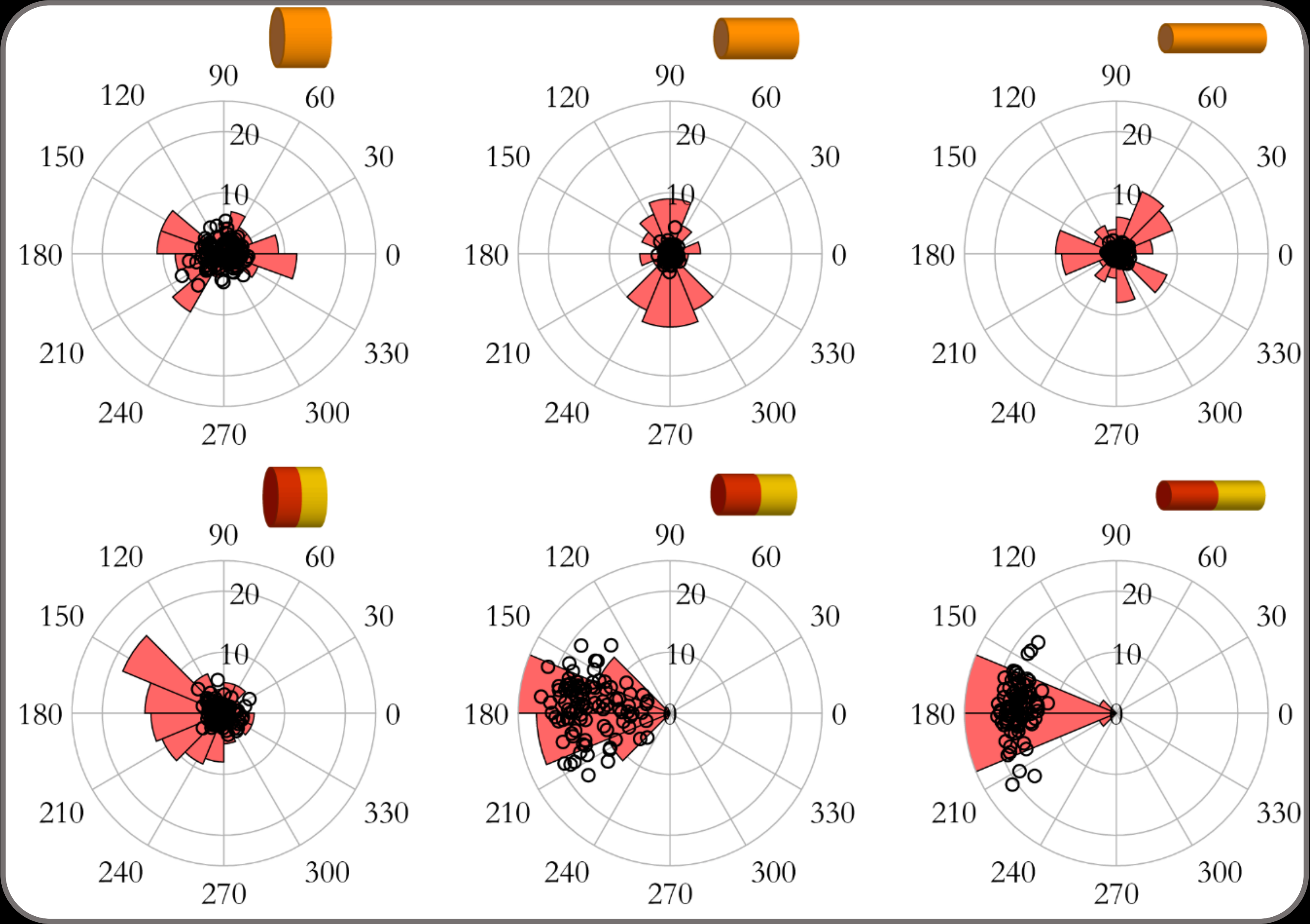




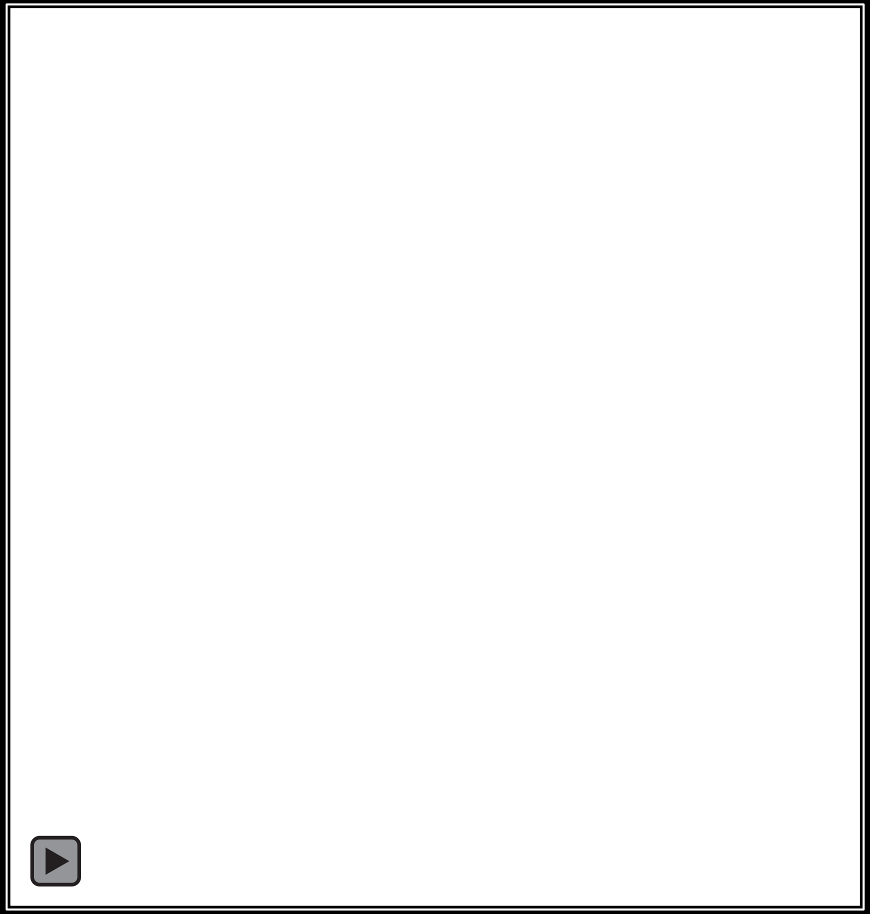
The hydrogel method allows for ease of optical access for PIV.

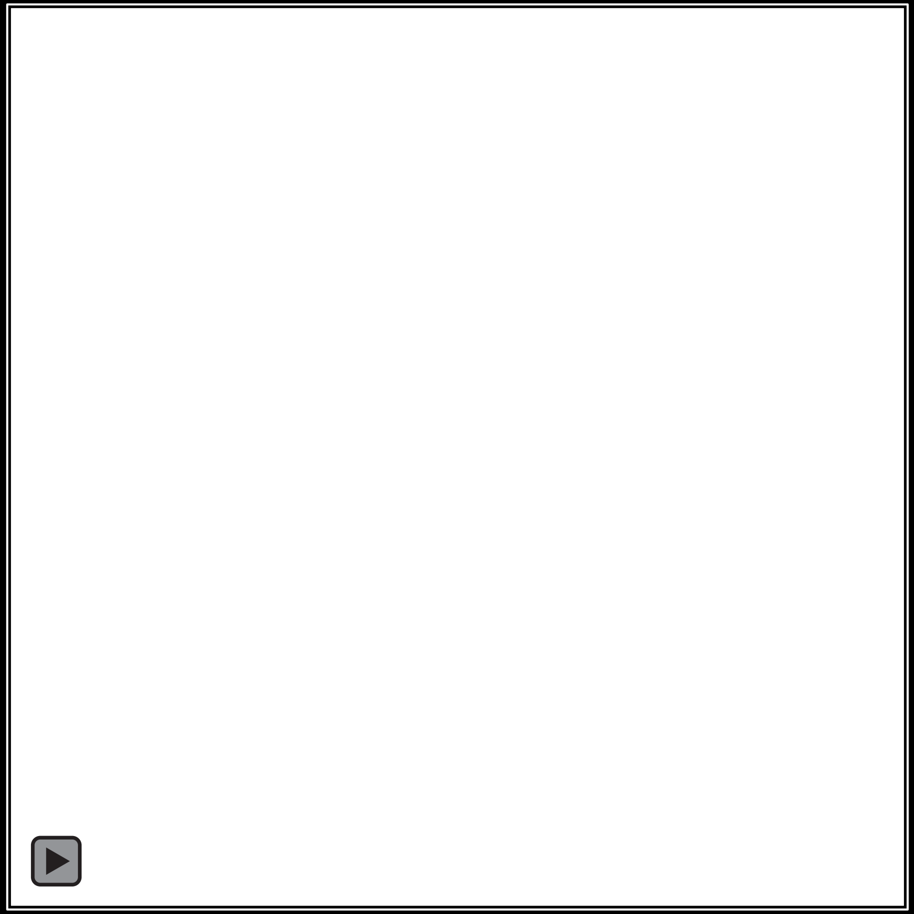


Compound density cylinders drift to the side, and initial orientation matters dramatically.



Short cylinders oscillate as they fall; compound-density cylinders fall more stably.





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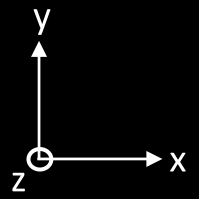

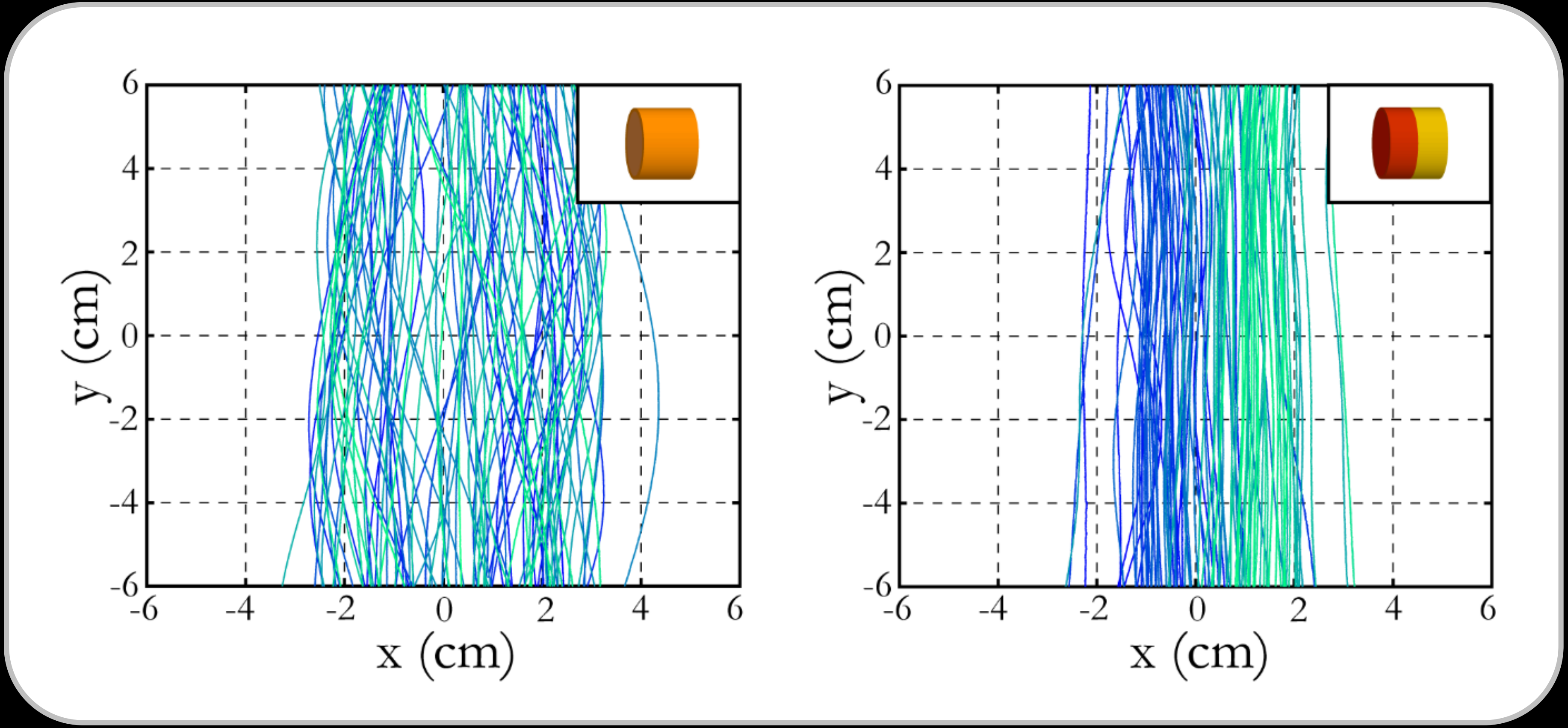

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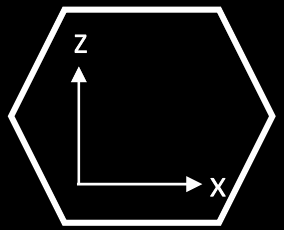

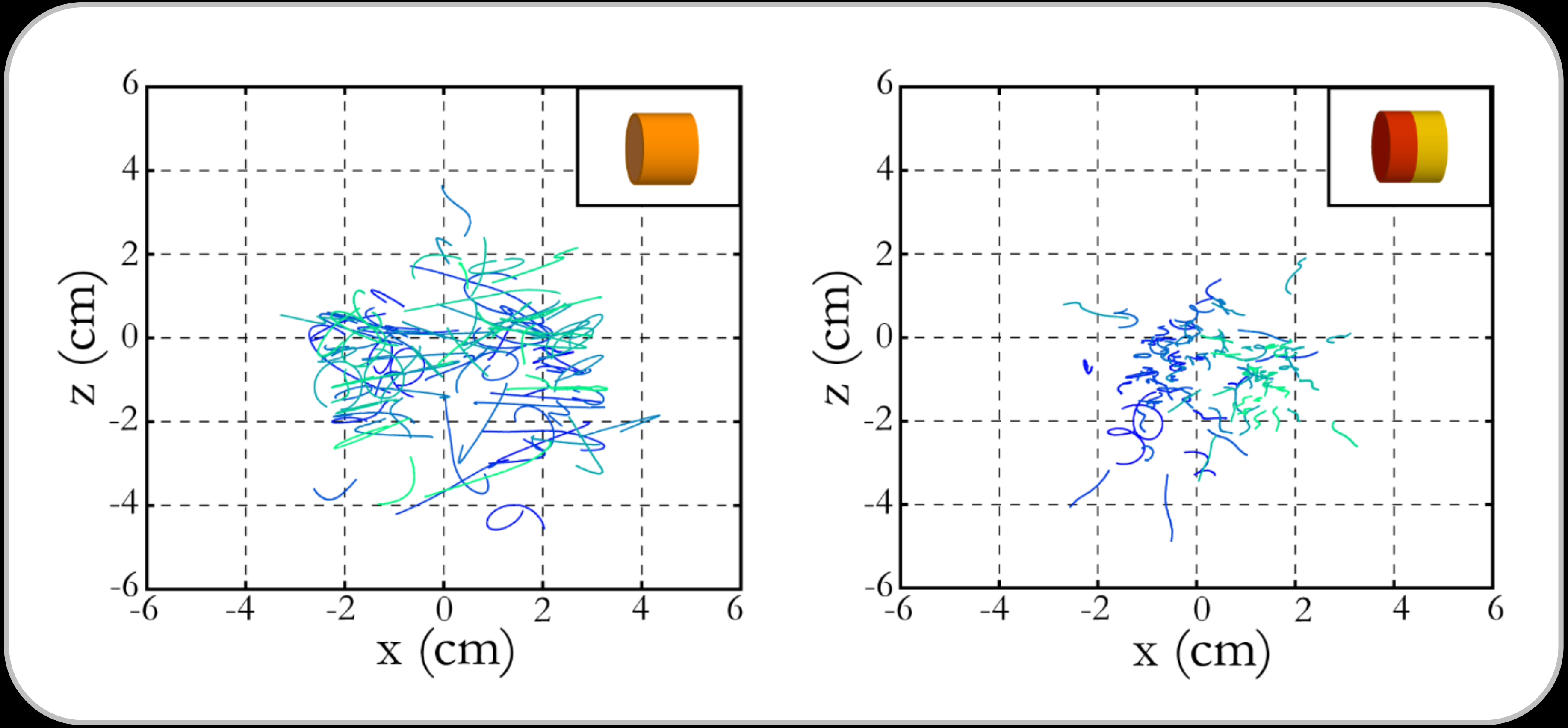

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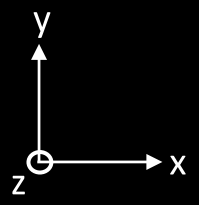
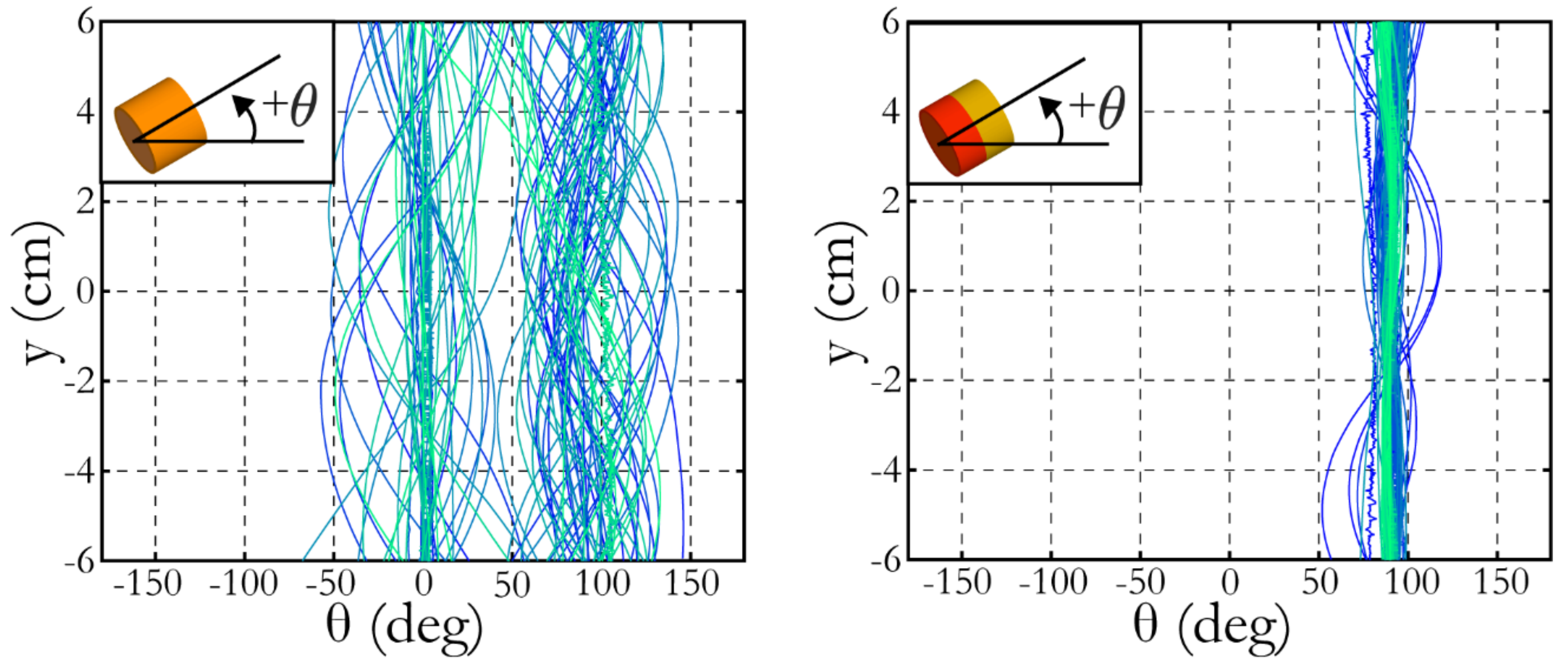
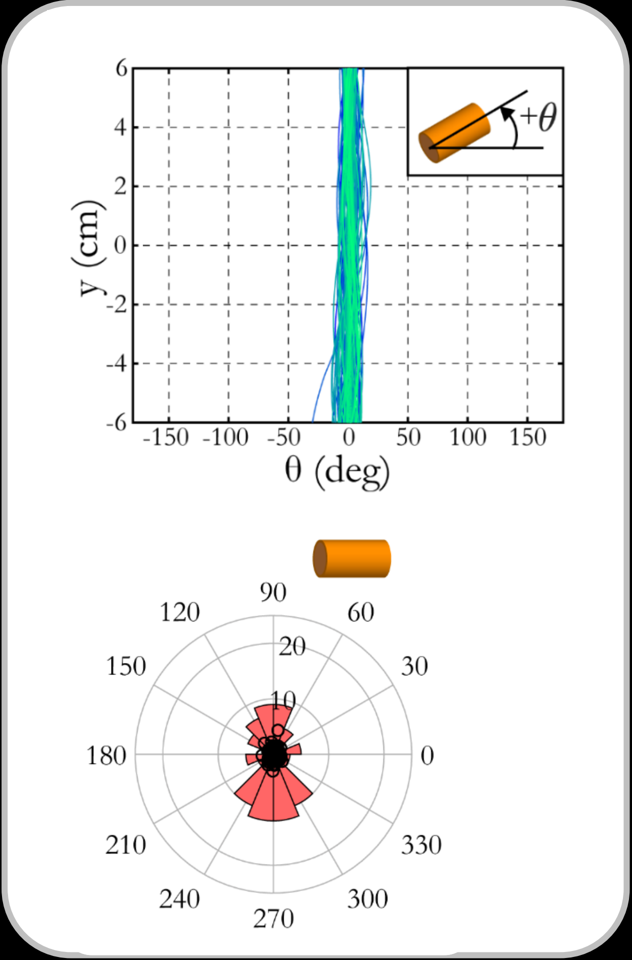
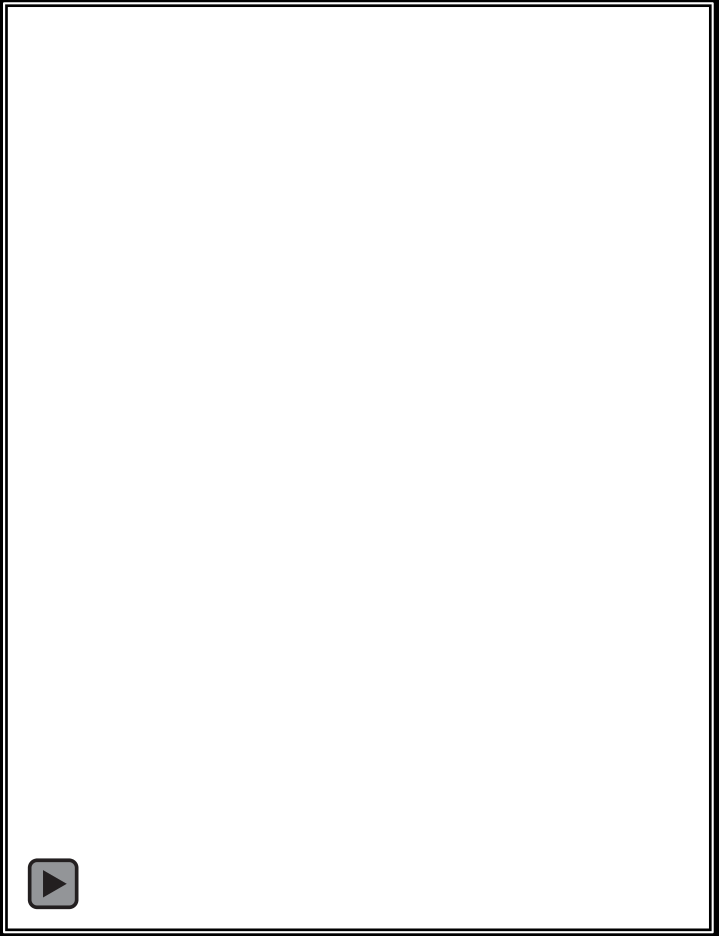
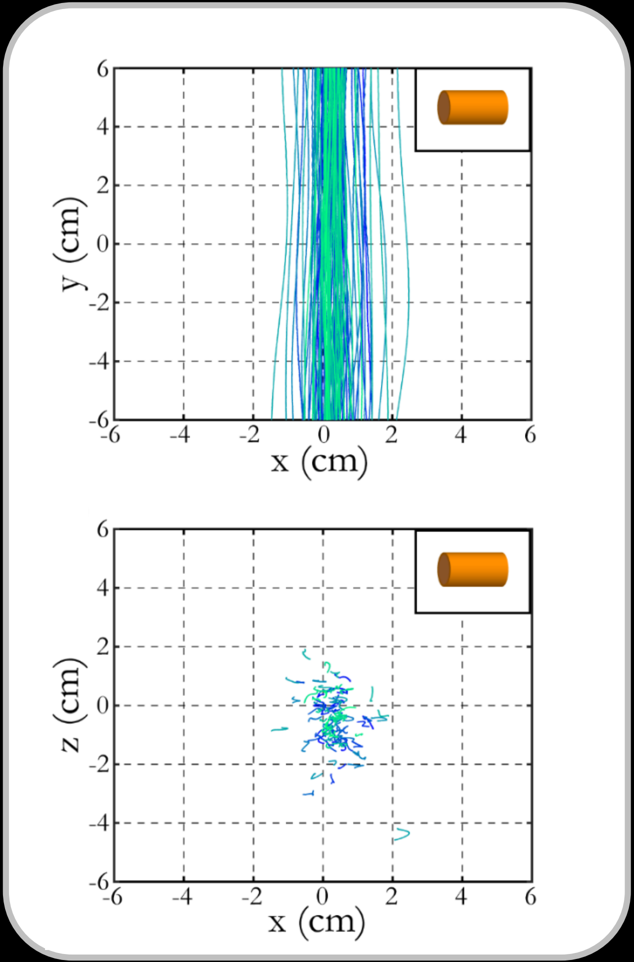


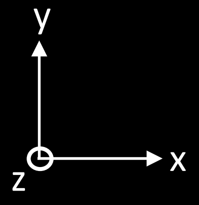


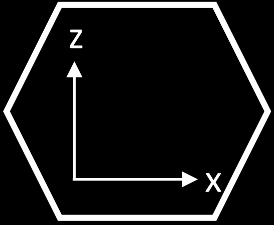
Uniform medium length cylinders ($\alpha = 2$) fall stably broadside, with minimal oscillation.



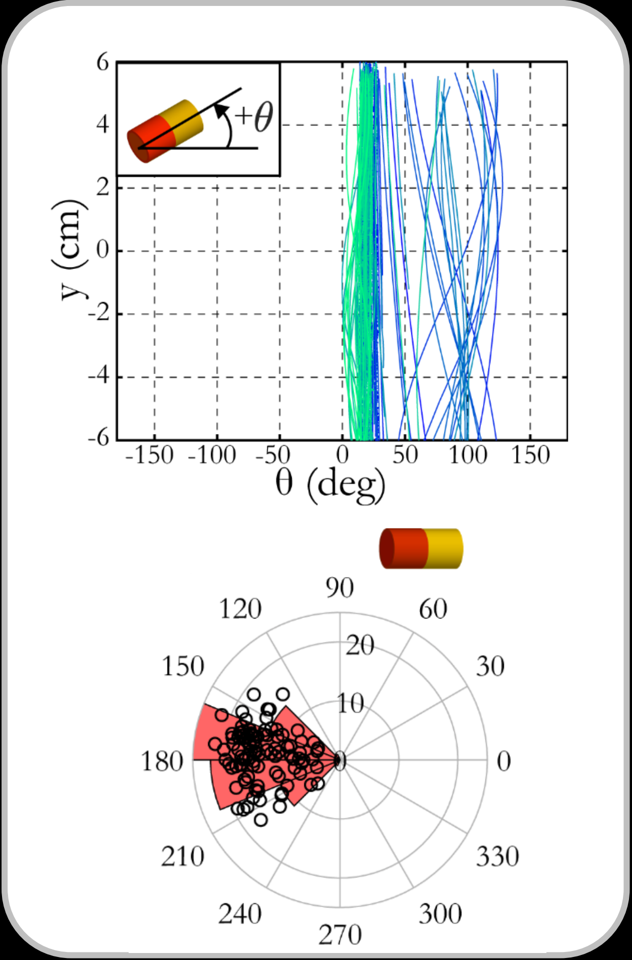


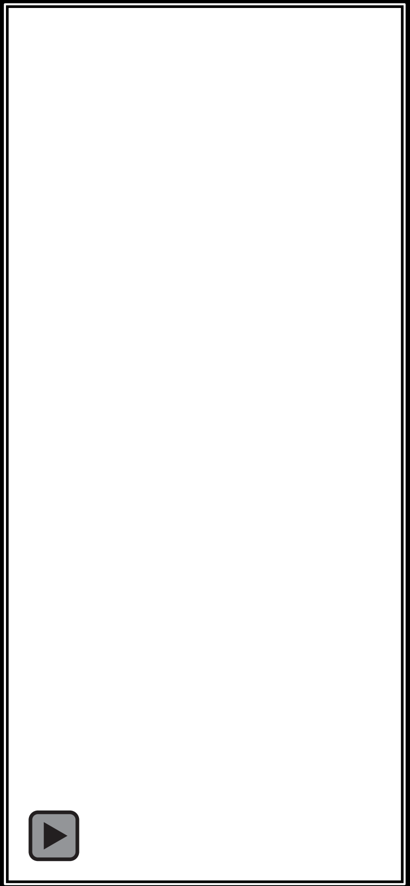


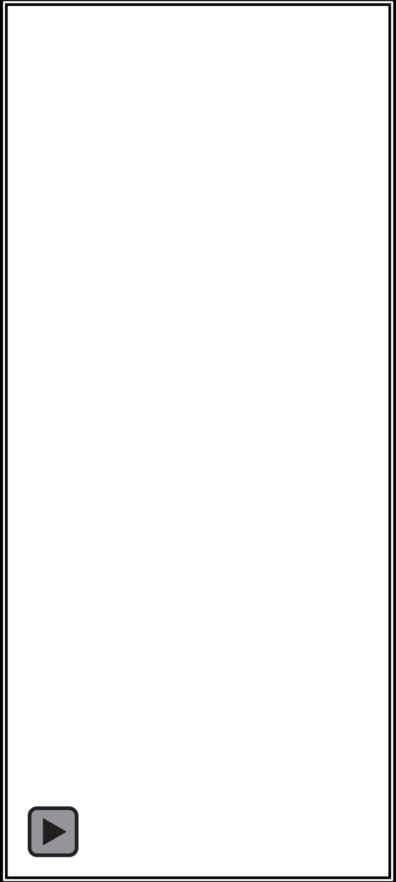


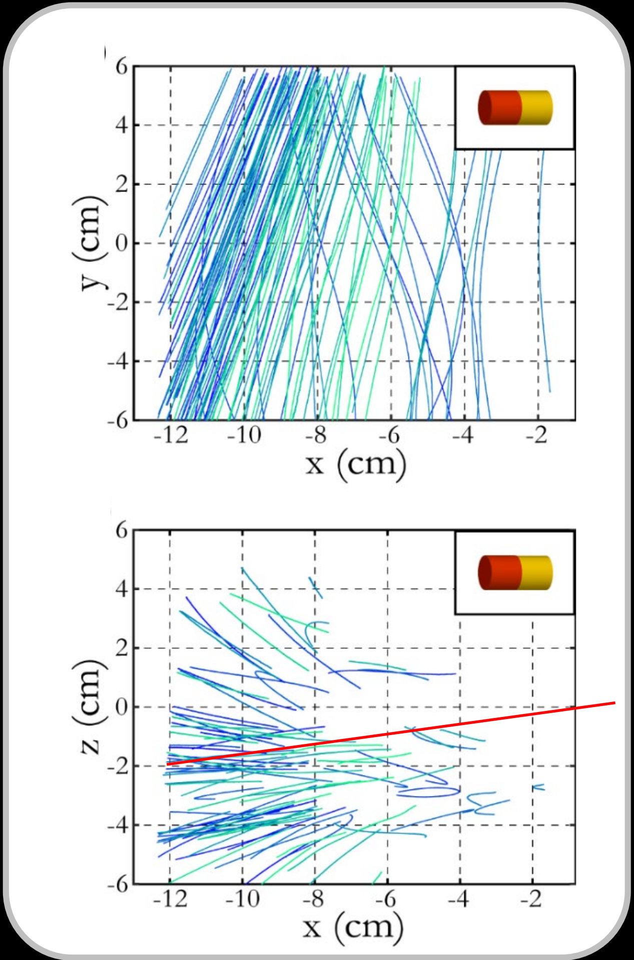


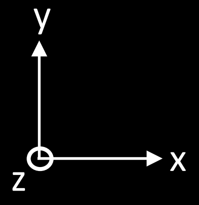
Compound-density cylinders at α=2 fall in two distinct classes: stable and oscillating.

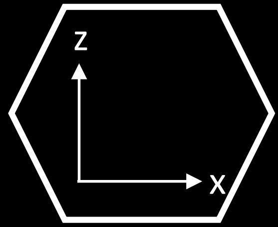




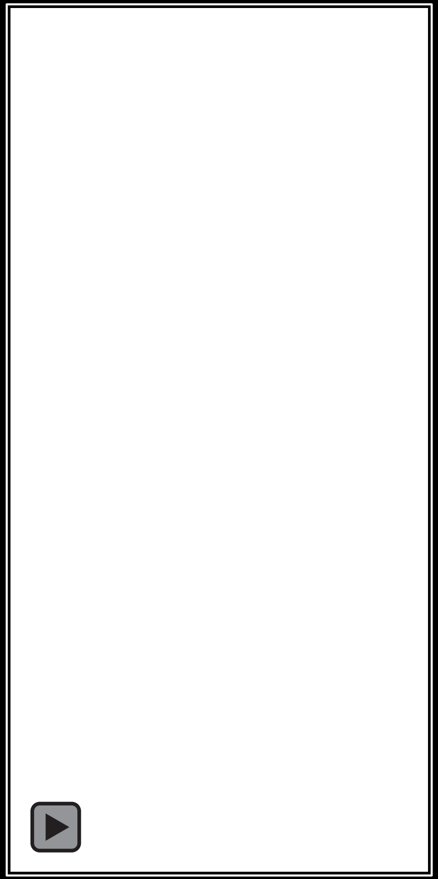


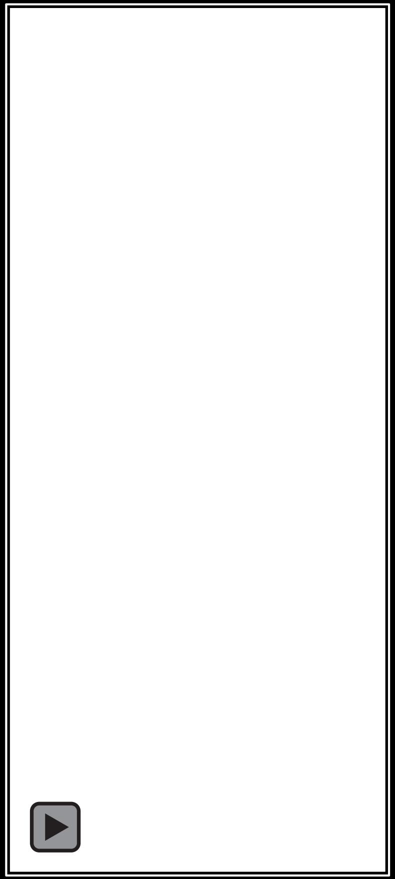


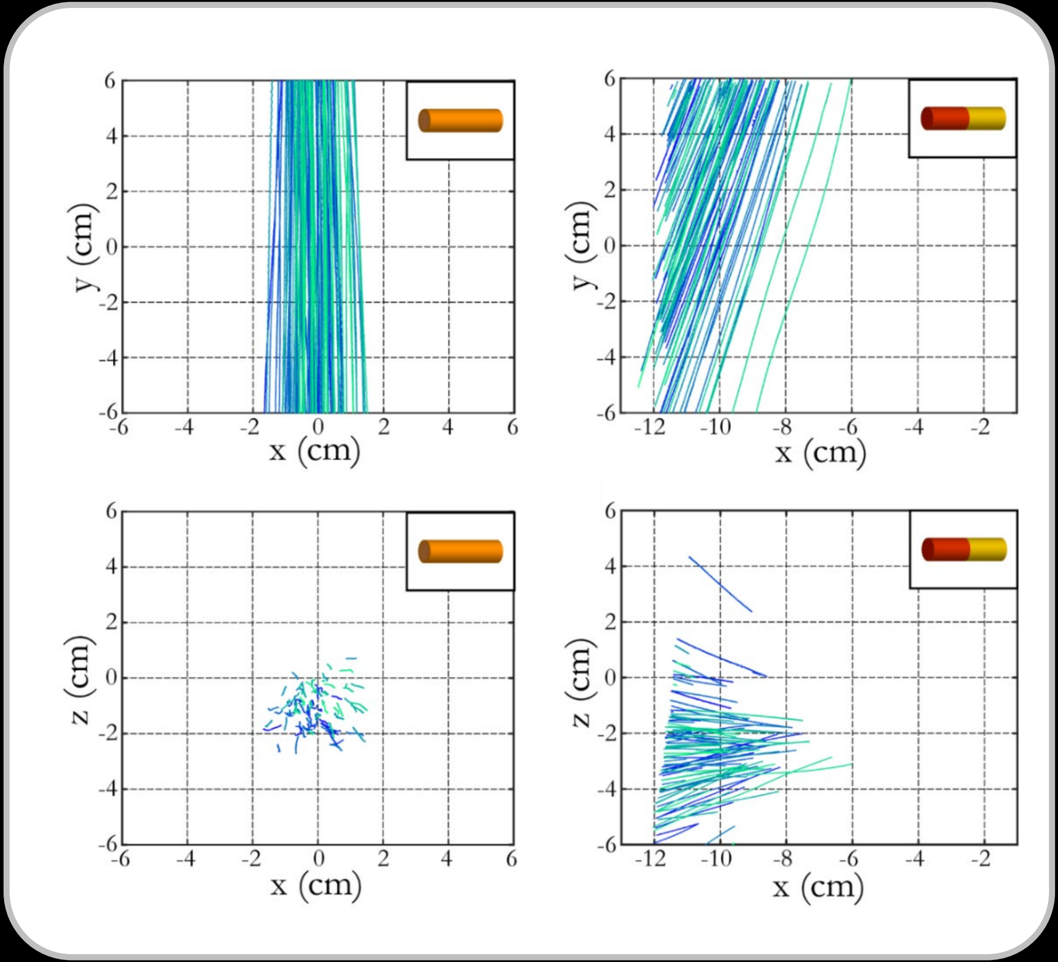


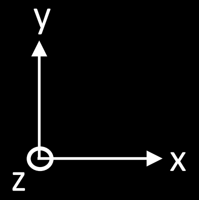


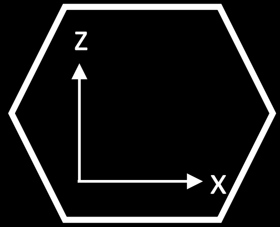
Long cylinders fall straight down if uniform; if compound, they fall at a stable angle.



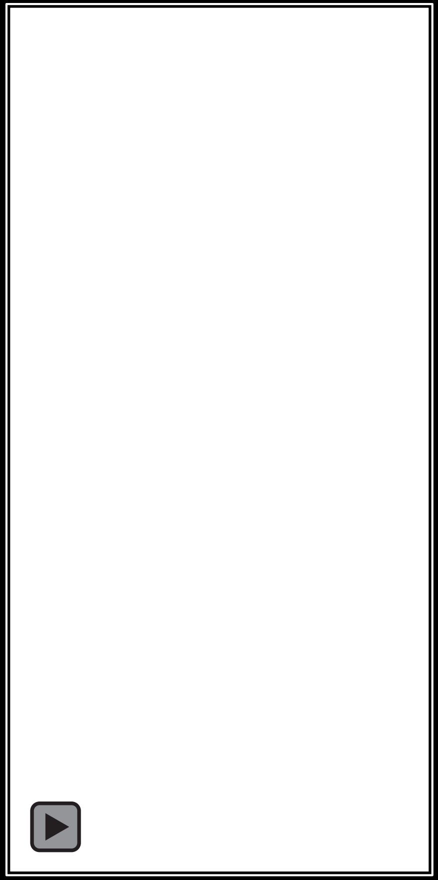


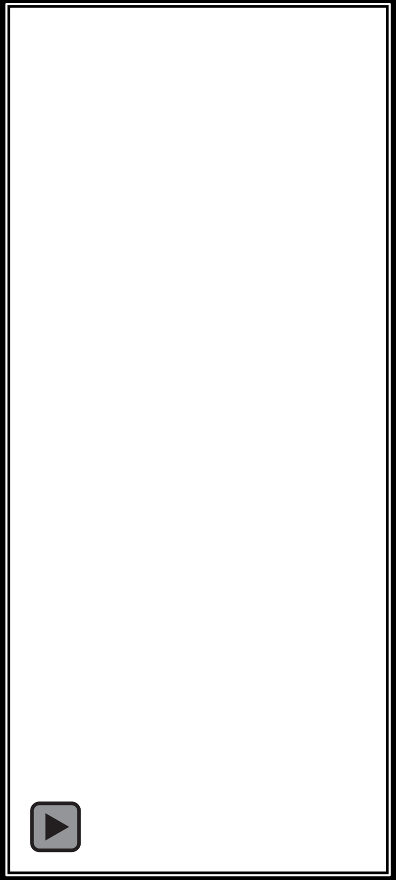


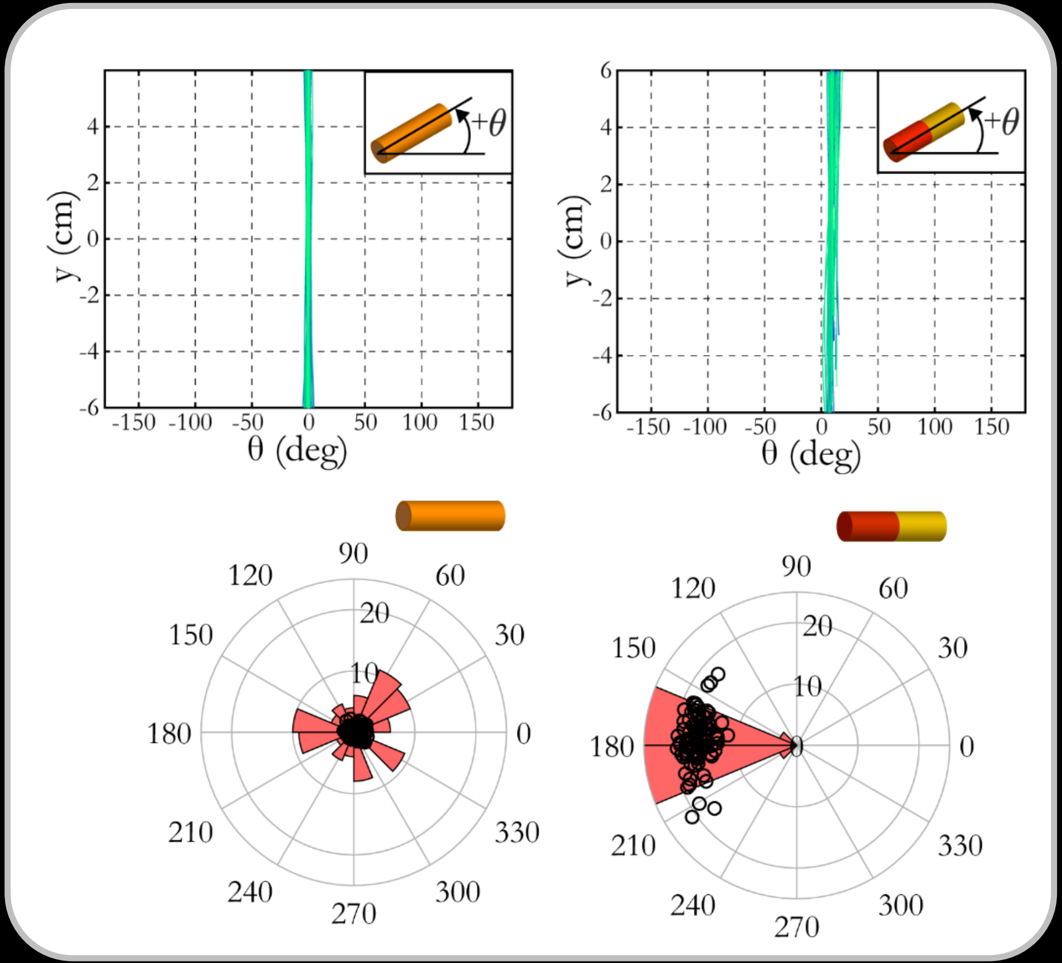




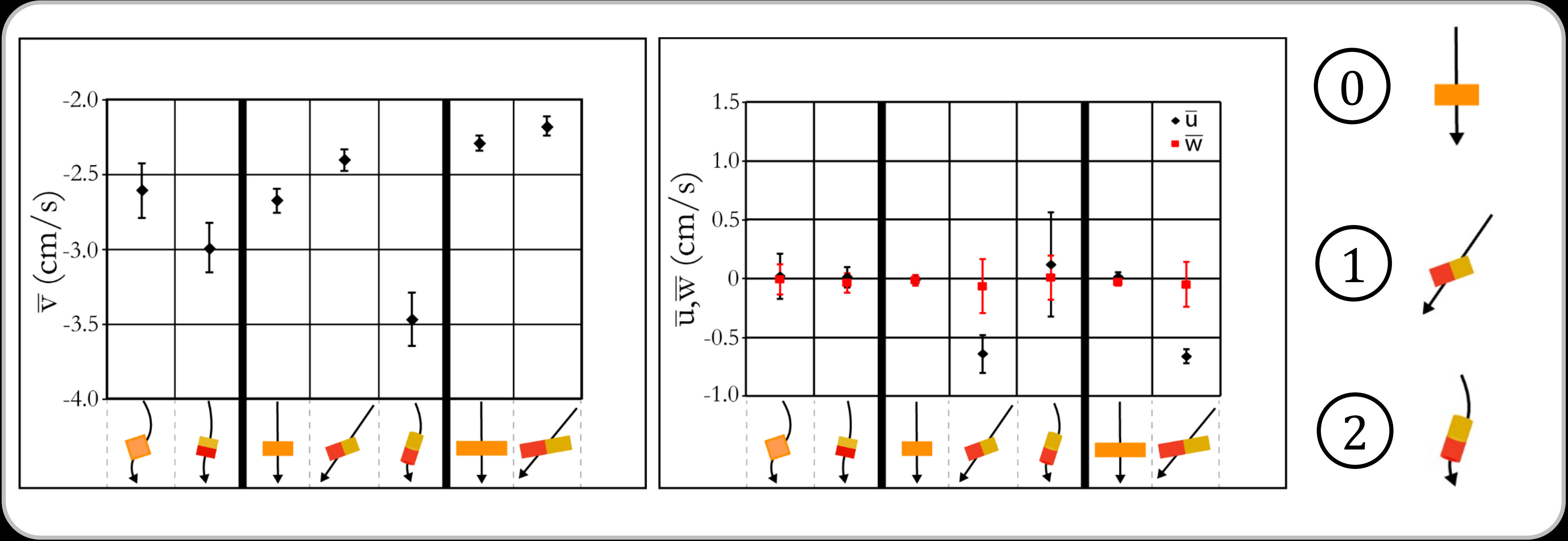
Long cylinders fall straight down if uniform; if compound, they fall at a stable angle.







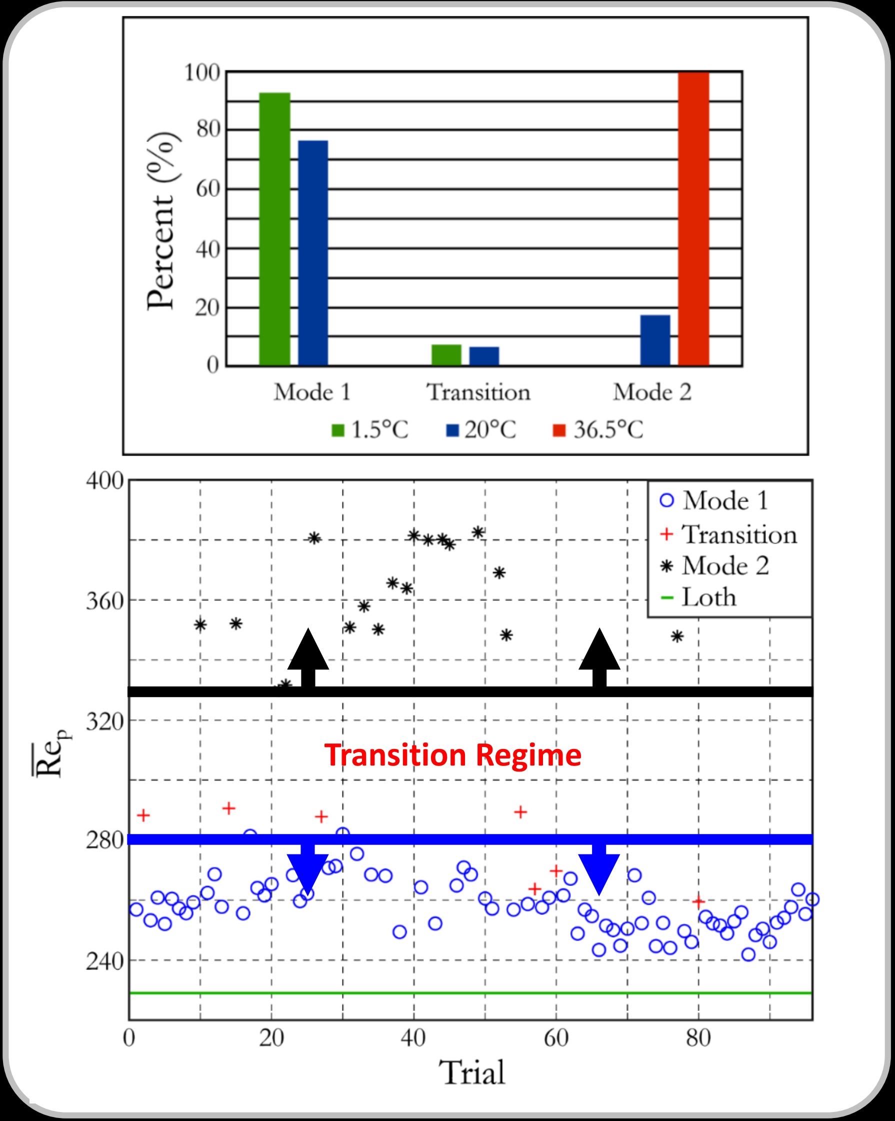
Fall velocity depends on fall orientation (which determines cross-sectional area).



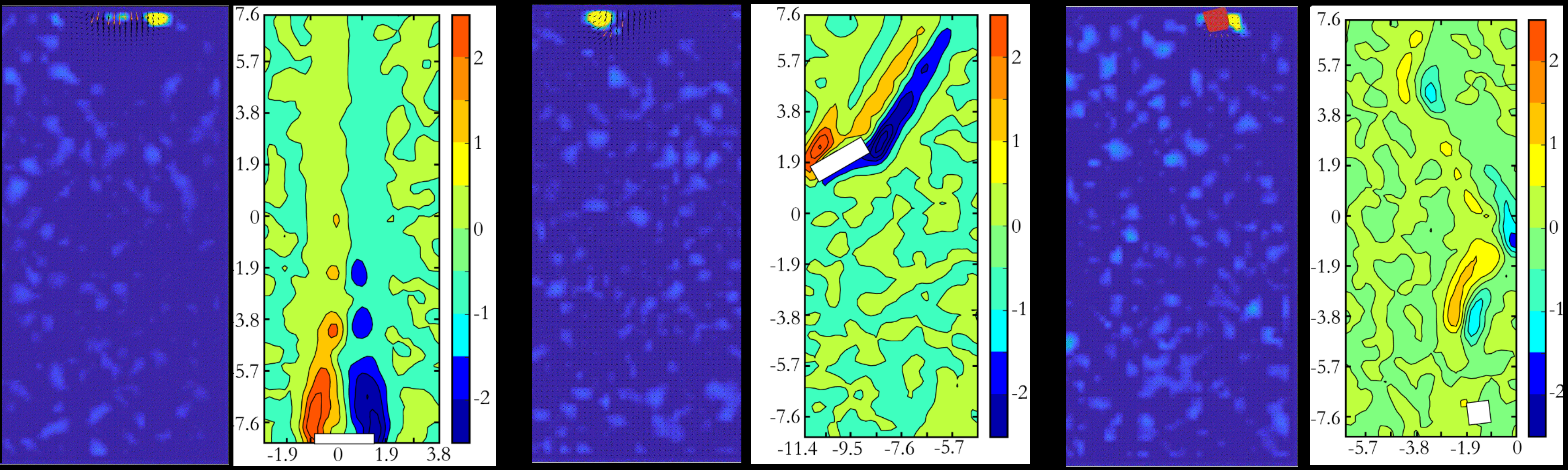
Transitions between falling modes may be **highly** sensitive to Re.

1.5°C

36.5°C

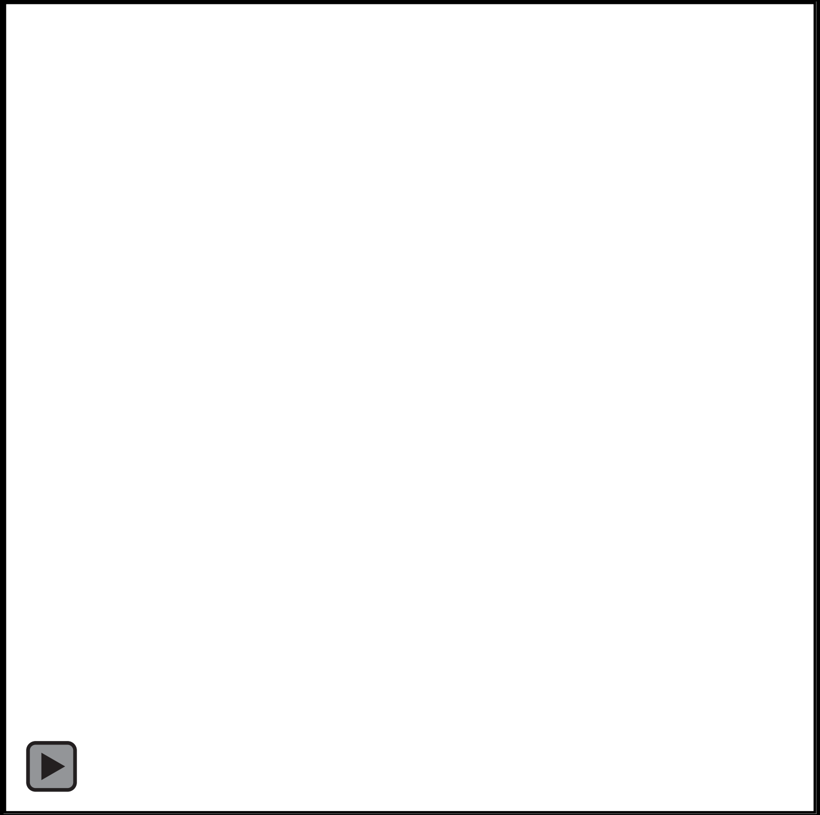


Wake structure provides some explanation, but we need more data.

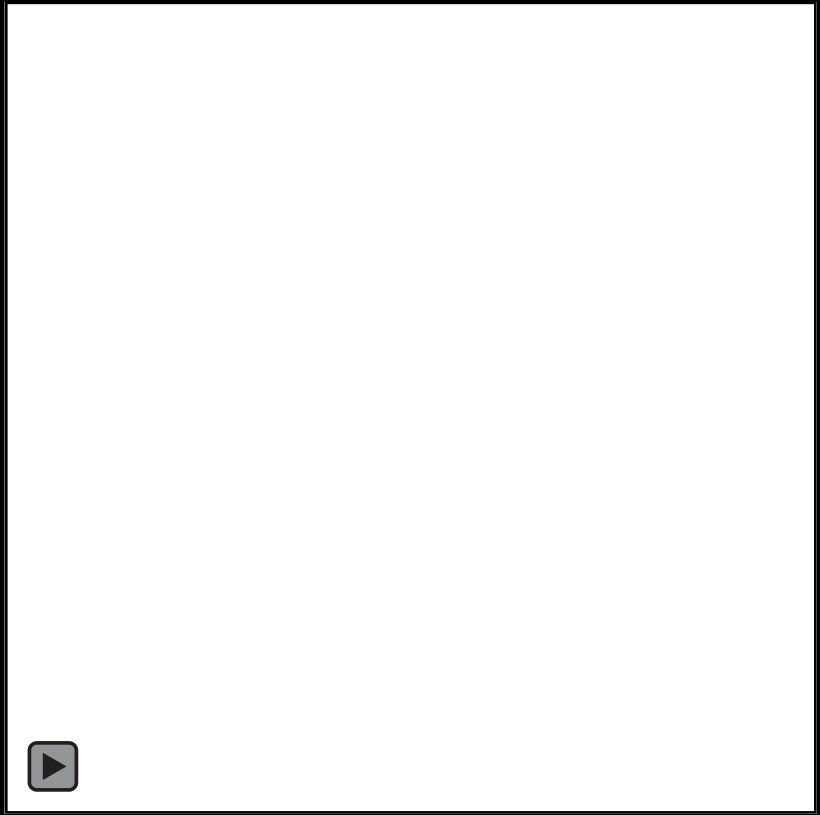


⓪ ① ②

We are exploring more shapes and mass distributions, and will extend to turbulence.



25% PETG, 75% ASA
$\alpha = 2$

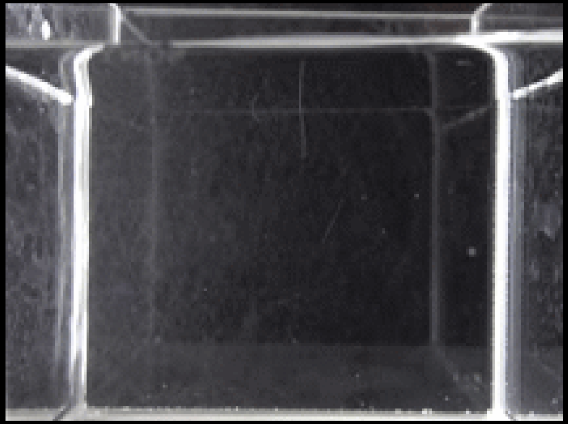


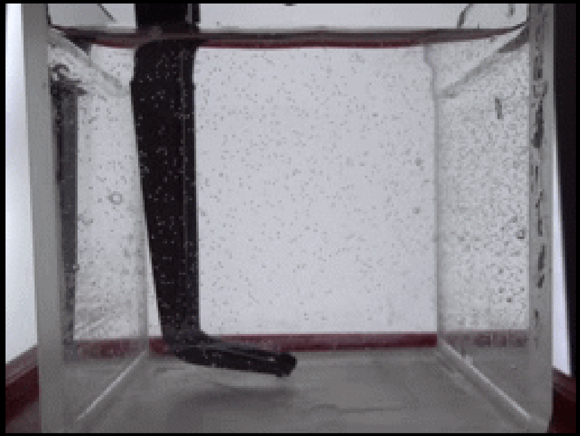
75% PETG, 25% ASA
$\alpha = 2$

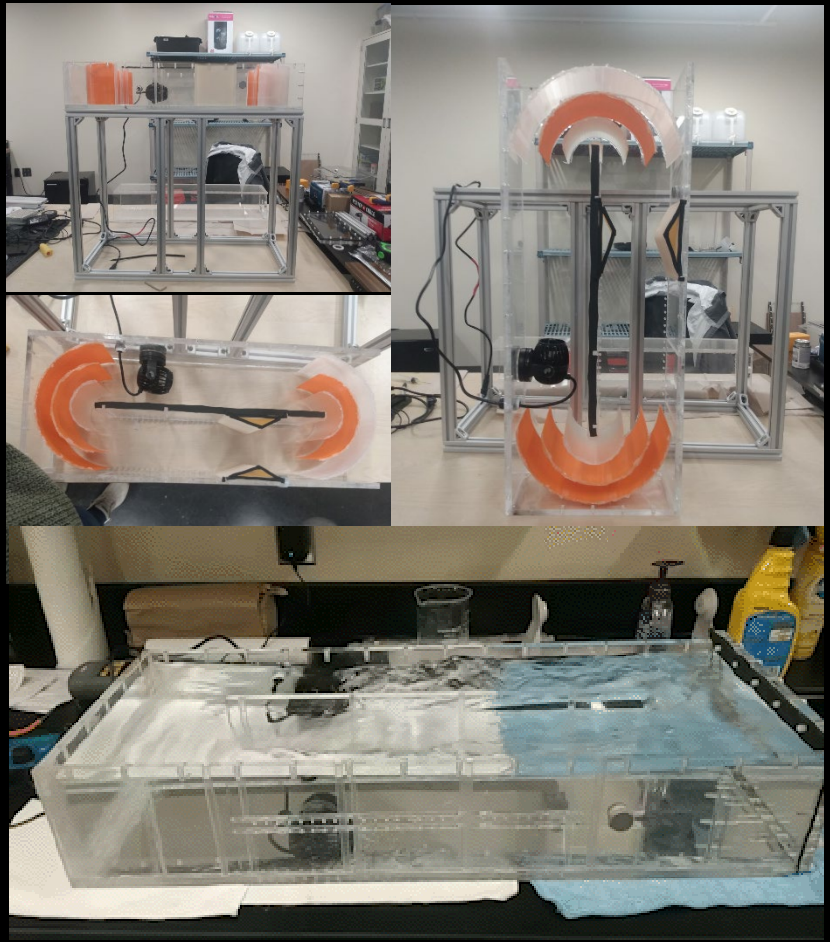
$\rho_{PETG} = 1.27 g/cm^3$

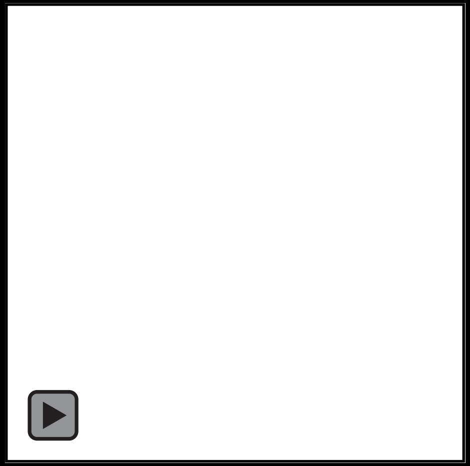
$\rho_{ASA} = 1.07 g/cm^3$

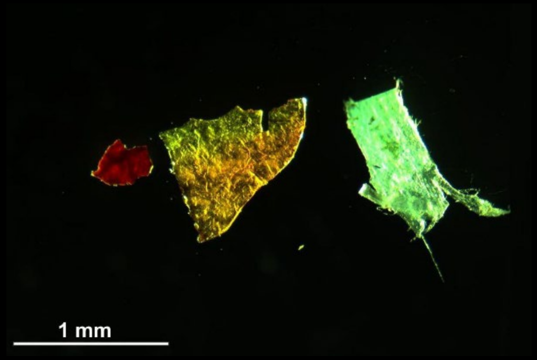
We are also investigating how the presence of biofilms and/or degradation affect settling velocity in still water and turbulence.





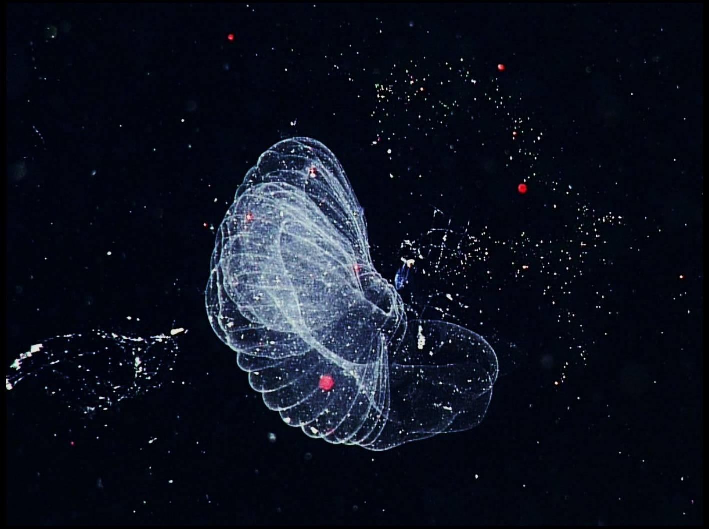






size

shape



density

Where do we go from here?

density ***distribution***

Images: Kane & Clare 2019, *Front. Earth Sci.*
CC-BY-NC 2.0, Will Parson (Chesapeake Bay Program)
Monterey Bay Aquarium Research Institute
Rillig and Lehmann 2020, Science

Some conclusions for nonuniform cylinders… and implications for microplastics

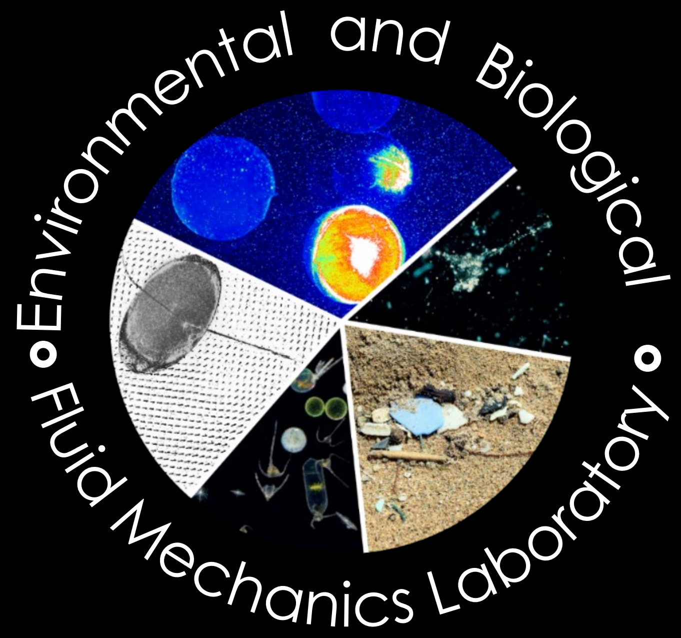
CYLINDERS

1. Cylinders fell in three different modes.
2. Falling mode depends on both aspect ratio and density distribution.
3. Transition between modes may be linked to critical Re
4. Density distribution affects cylinder landing site.

MICROPLASTICS

1. Nonuniform density affects **settling velocity**
2. Shape matters.
3. Very subtle changes in density can create big changes in settling
4. Nonuniform density affects **dispersion**

Thank you!



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