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Two-Dimensional Particle Motions during Rarefied Transport in a Static Bath: Implications for Bedload Diffusion

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November 24, 2022

Abstract

Most particle motions on Earth's surface are fundamentally stochastic and often occur under rarefied transport conditions. Every particle makes a unique path along the bed, similar but distinct from the paths of all other particles in motion, until it loses enough kinetic energy to become disentrained. The details of a particle's motion are determined by the amount of energy added and extracted during each moment of travel. Thus, particle motions physically reflect the complex energy dynamics at play and are a building block of morphodynamic theory. A full appreciation of this energy balance is needed to properly describe the motion of particles and associated disentrainment under different transport conditions. Often multidimensional behaviors occur during transport as both a result of and influence on these particle scale energy dynamics. One such phenomenon is that of particle-scale random walking during transport which results in diffusion over short timescales in both the downstream and transverse directions. We have adopted the Galton board as the fundamental conceptual model on which to create a mechanistic yet probabilistic formulation of particle diffusion. Here we provide a data set of two-dimensional particle travel distances supplemented with high-speed videos of particle-surface collisions collected during laboratory experiments to characterize the influence of shedding fluid vortices and angularity on collisional distances and two-dimensional travel for particles at low Reynolds numbers. Such a description is consistent with diffusion from the top-down and may be distinct from the bottom-up, or surface roughness, controlled random walking that other studies have explored. Preliminary analysis shows that spherical particles experience jiggling motions resulting in transverse displacement in the absence of surface roughness and this behavior is further exaggerated for particles of natural angularity. We hope to clarify the influence of the particle Reynolds number in top-down and bottom-up spreading.

Wednesday,
15 December 2021,
8:00 - 9:15 CST

VANDERBILT UNIVERSITY

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Implications for Bedload Diffusion

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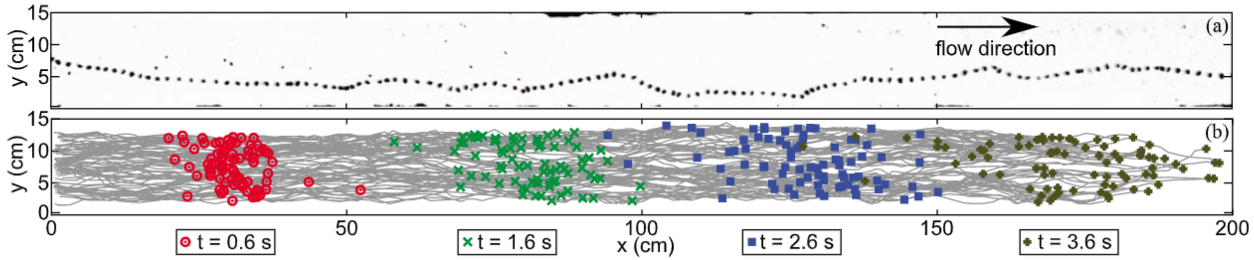
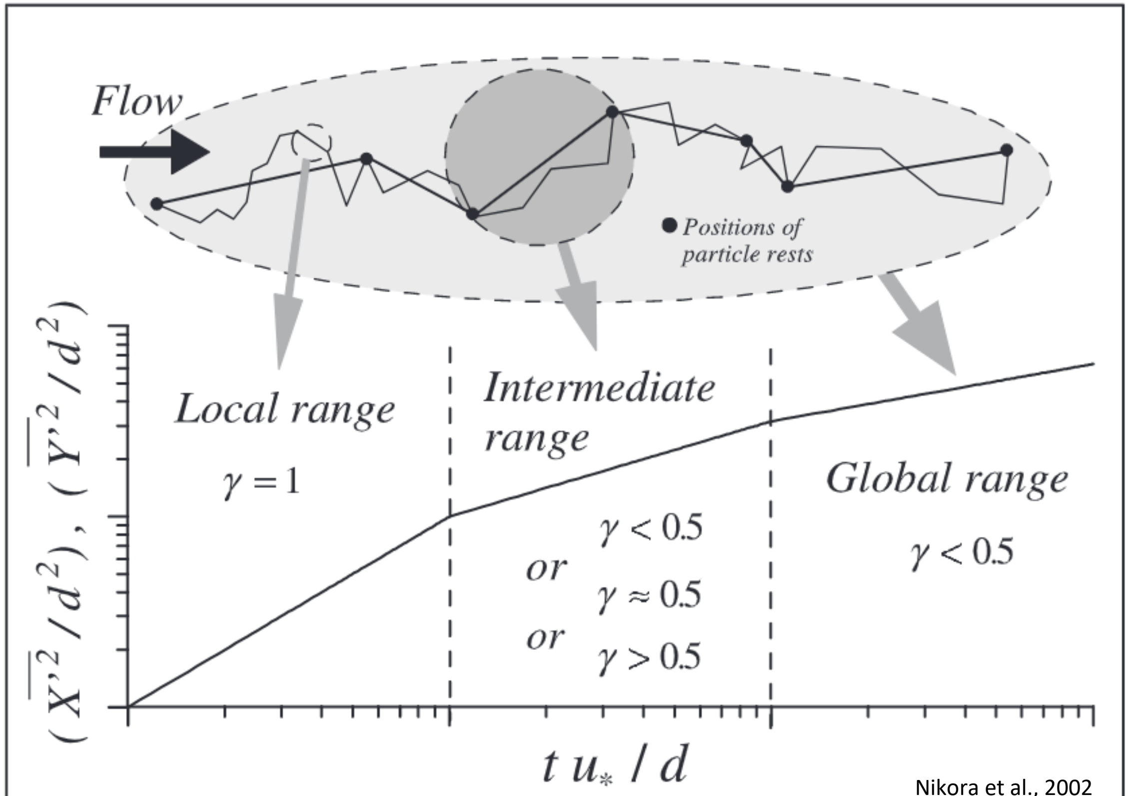
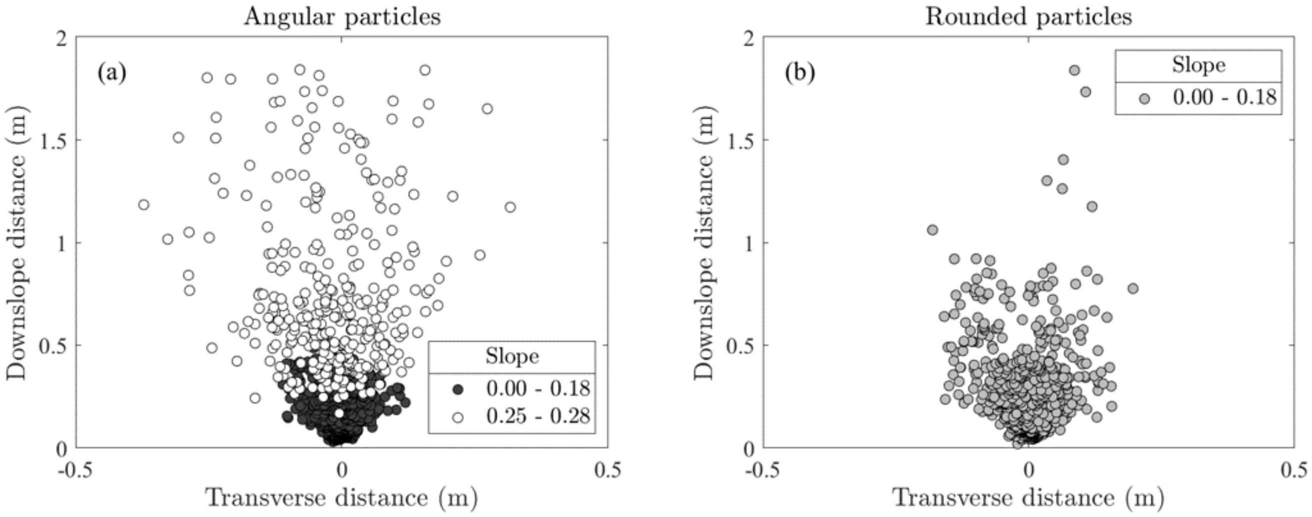
Diffusion is a key element of sediment transport

Martin et al., 2012





Nikora et al., 2002



Williams and Furbish, 2021

Can a toy describe sediment diffusion?

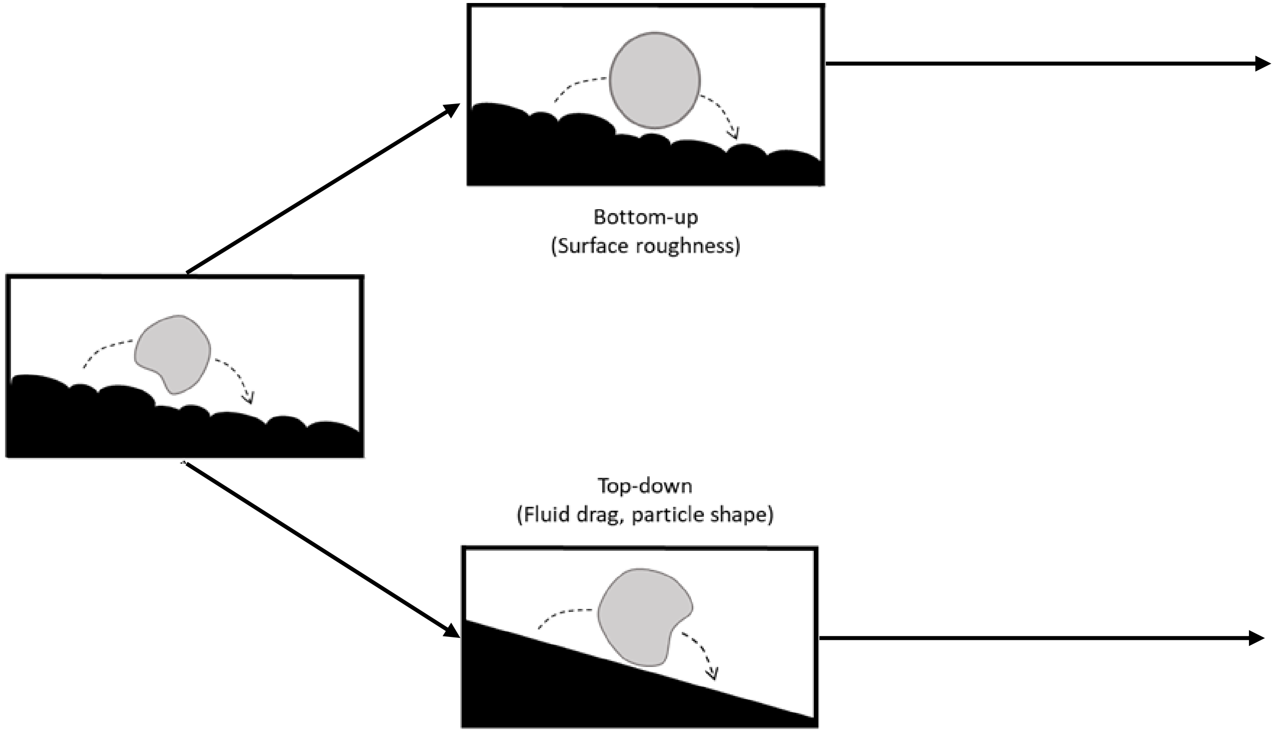
Lateral variance:

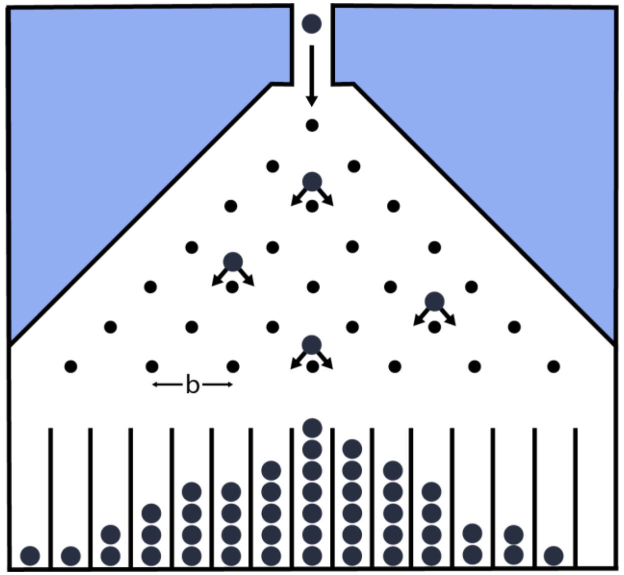
$$\sigma_y \sim \pm\, b\sqrt{np(1-p)}$$

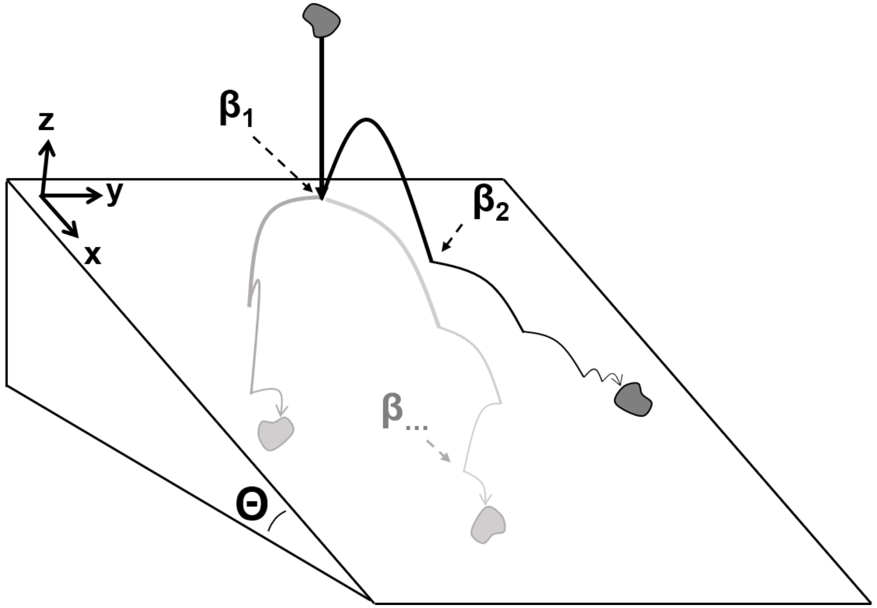
Transverse diffusivity:

$$\kappa_y \sim f b^2$$

Controls on diffusion

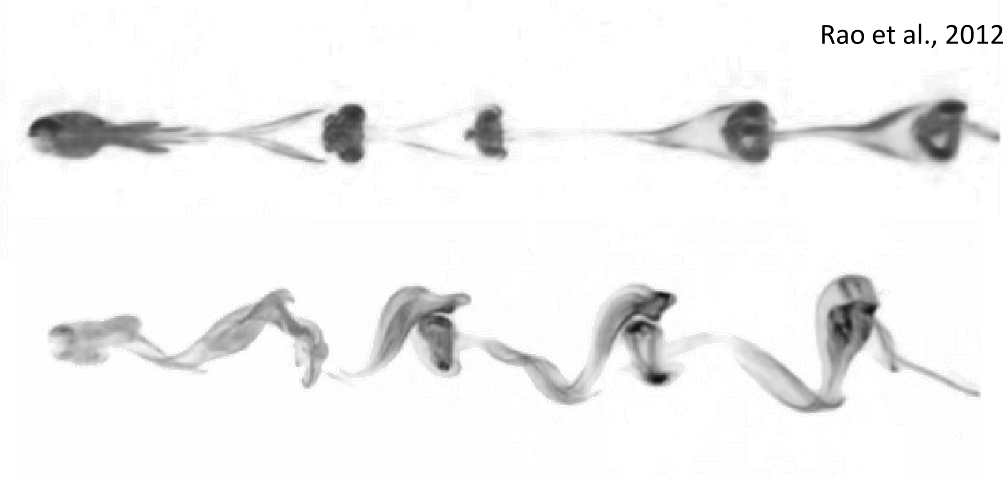


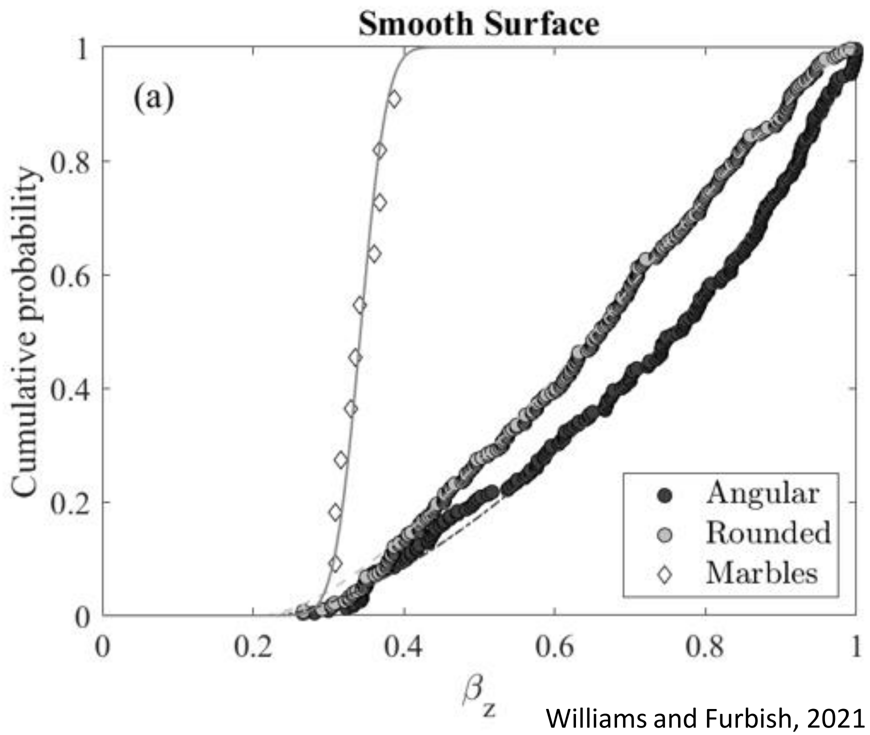




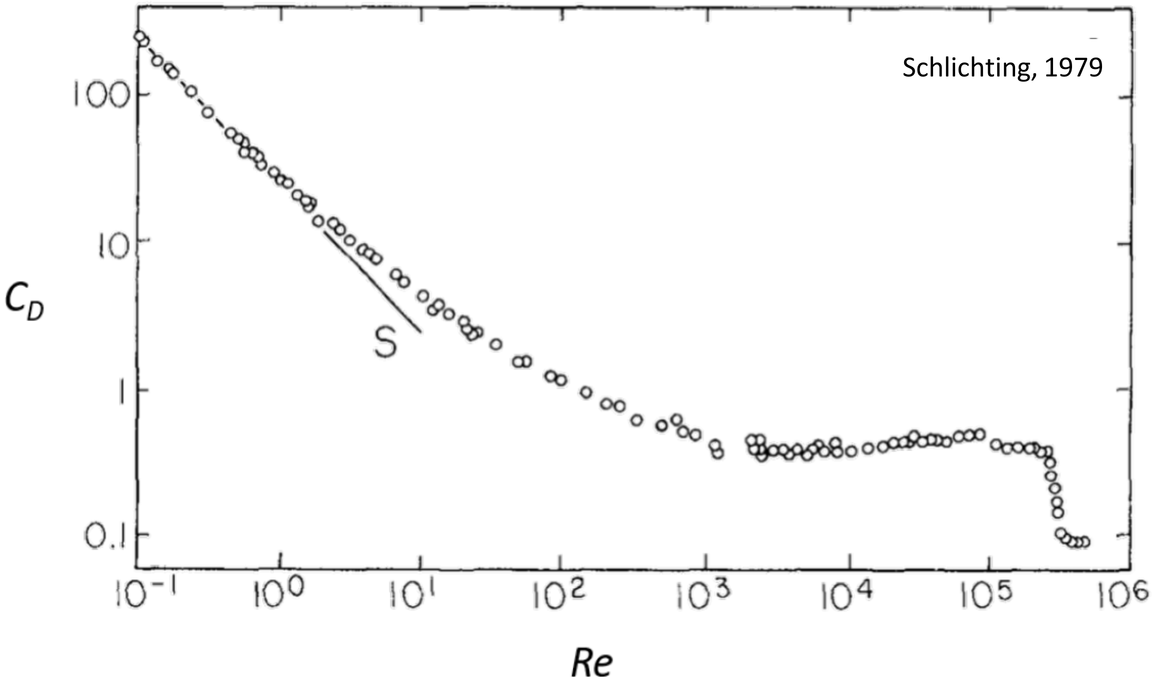
Top-down:
Particle shape
Fluid drag

Rao et al., 2012



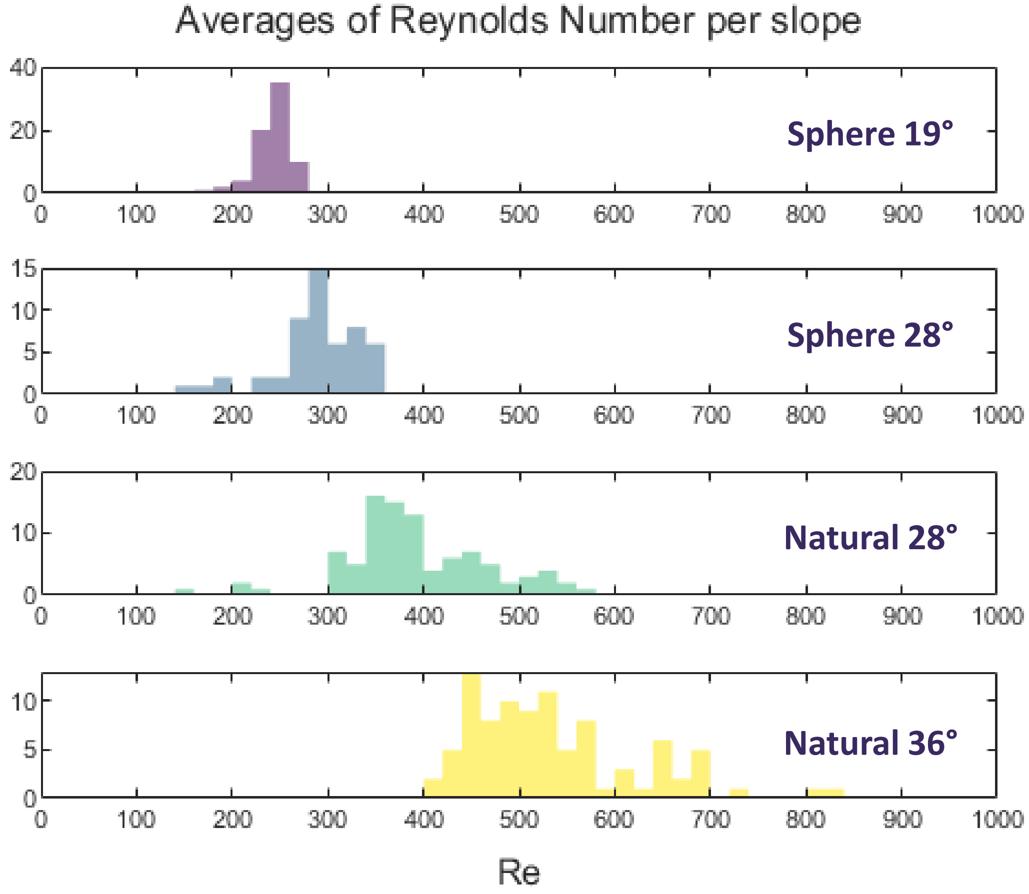


Williams and Furbish, 2021

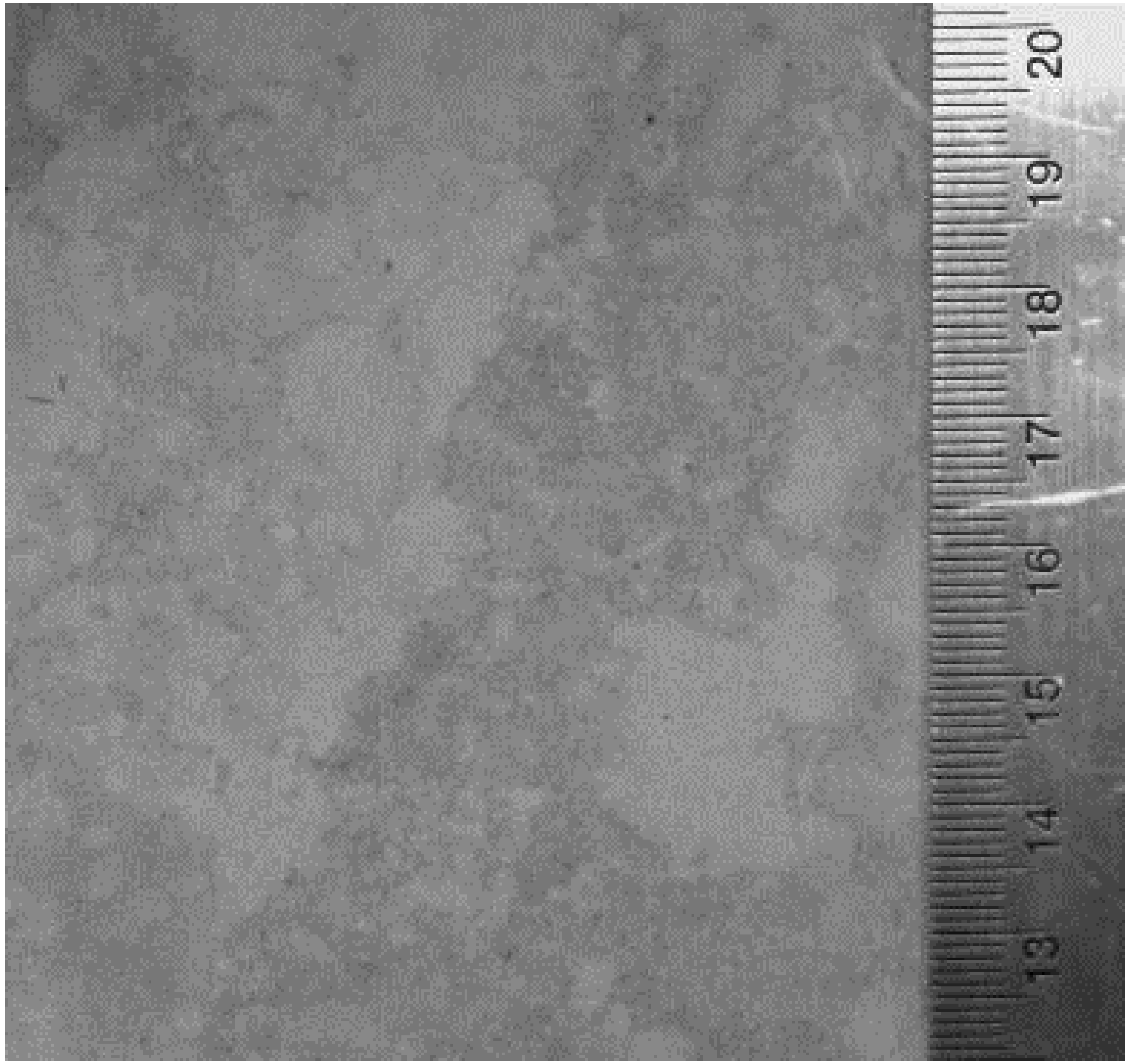


Schlichting, 1979

Experiments in a static water bath

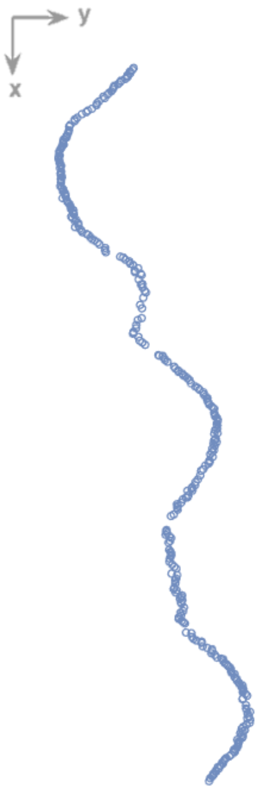


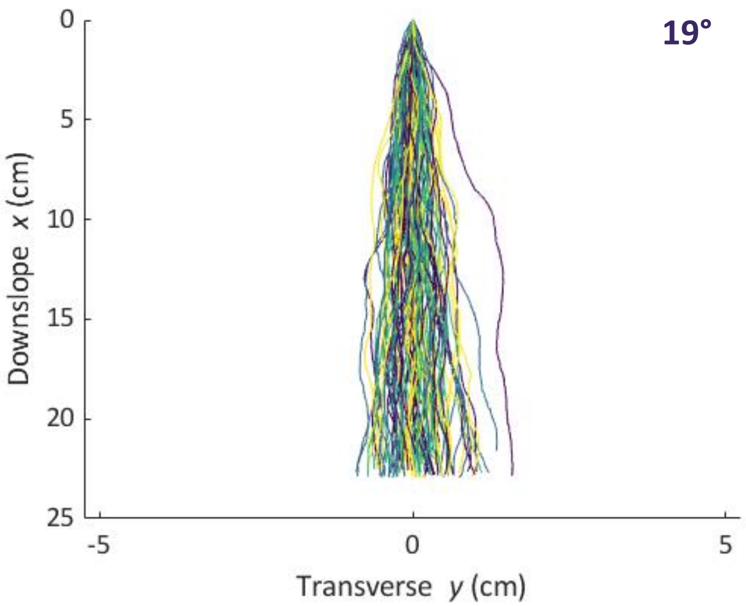
Glass spheres (3 mm)

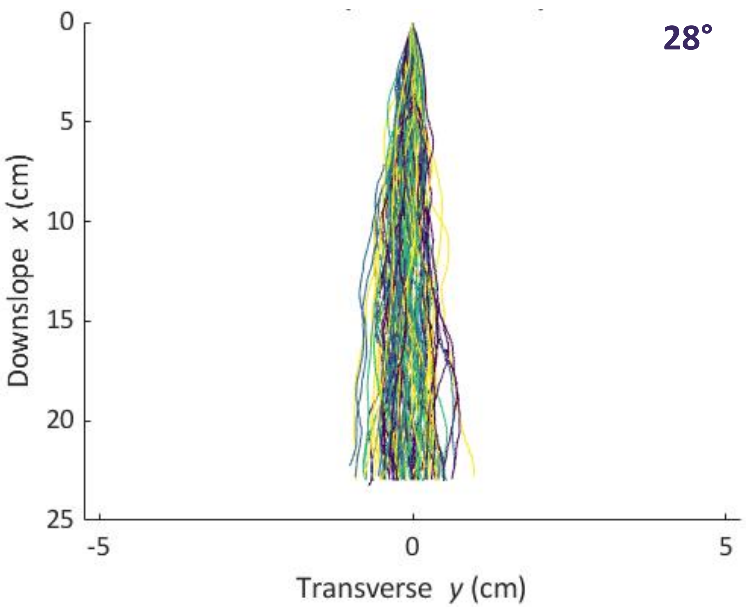


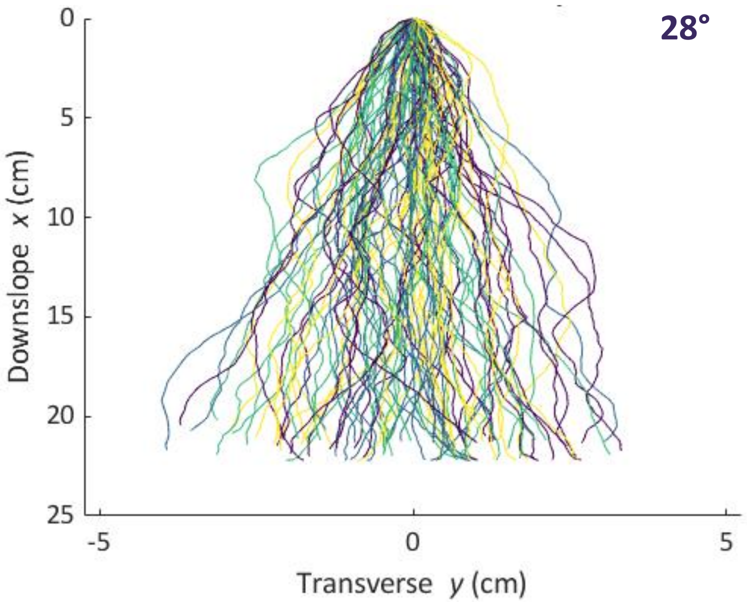
Natural Particles (avg a: 6.8 ± .9 mm)

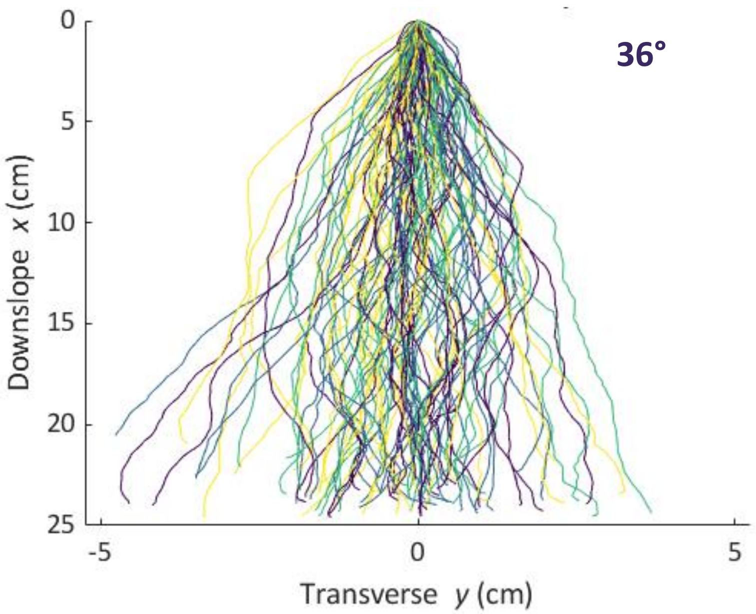
Glass Spheres





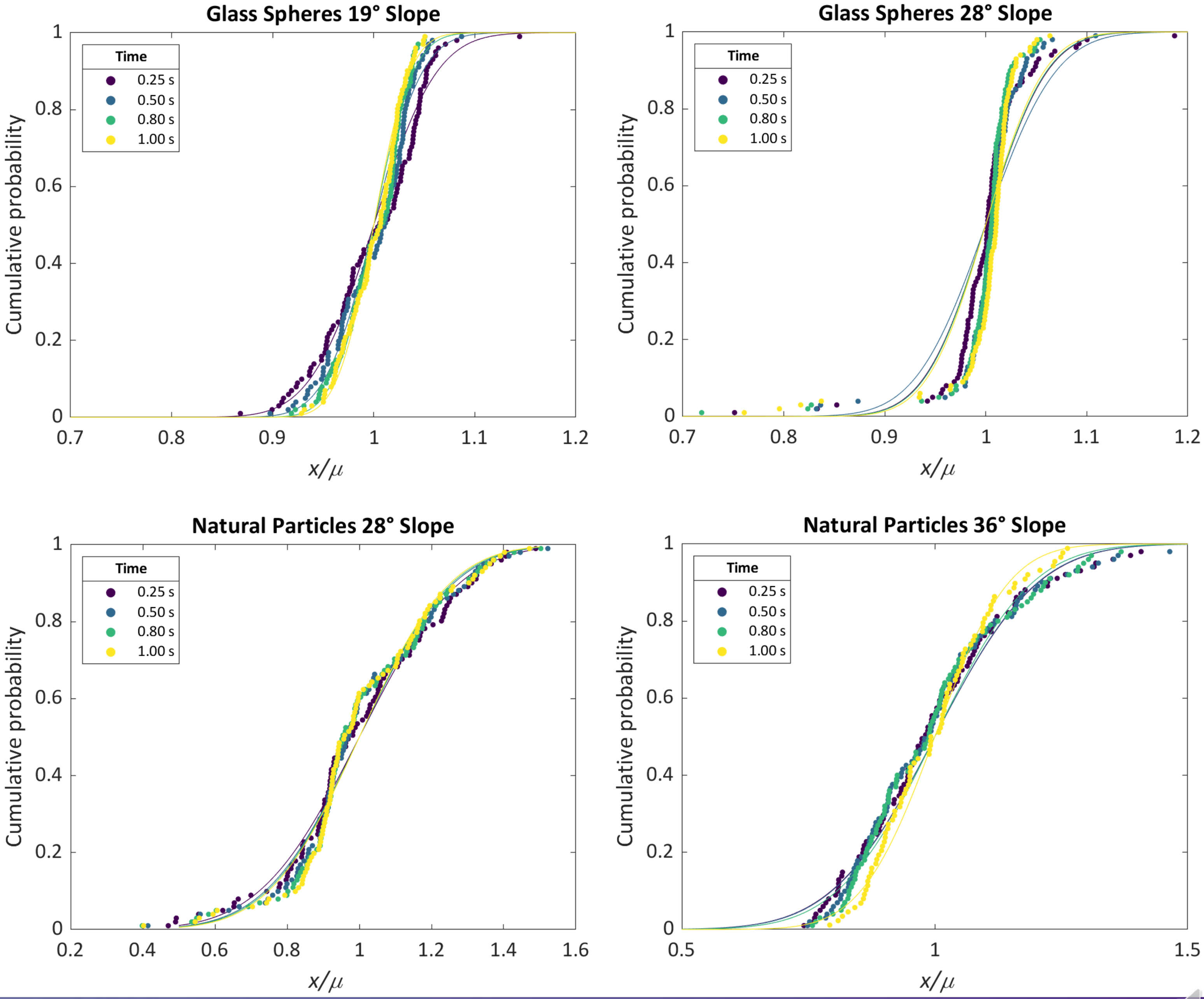




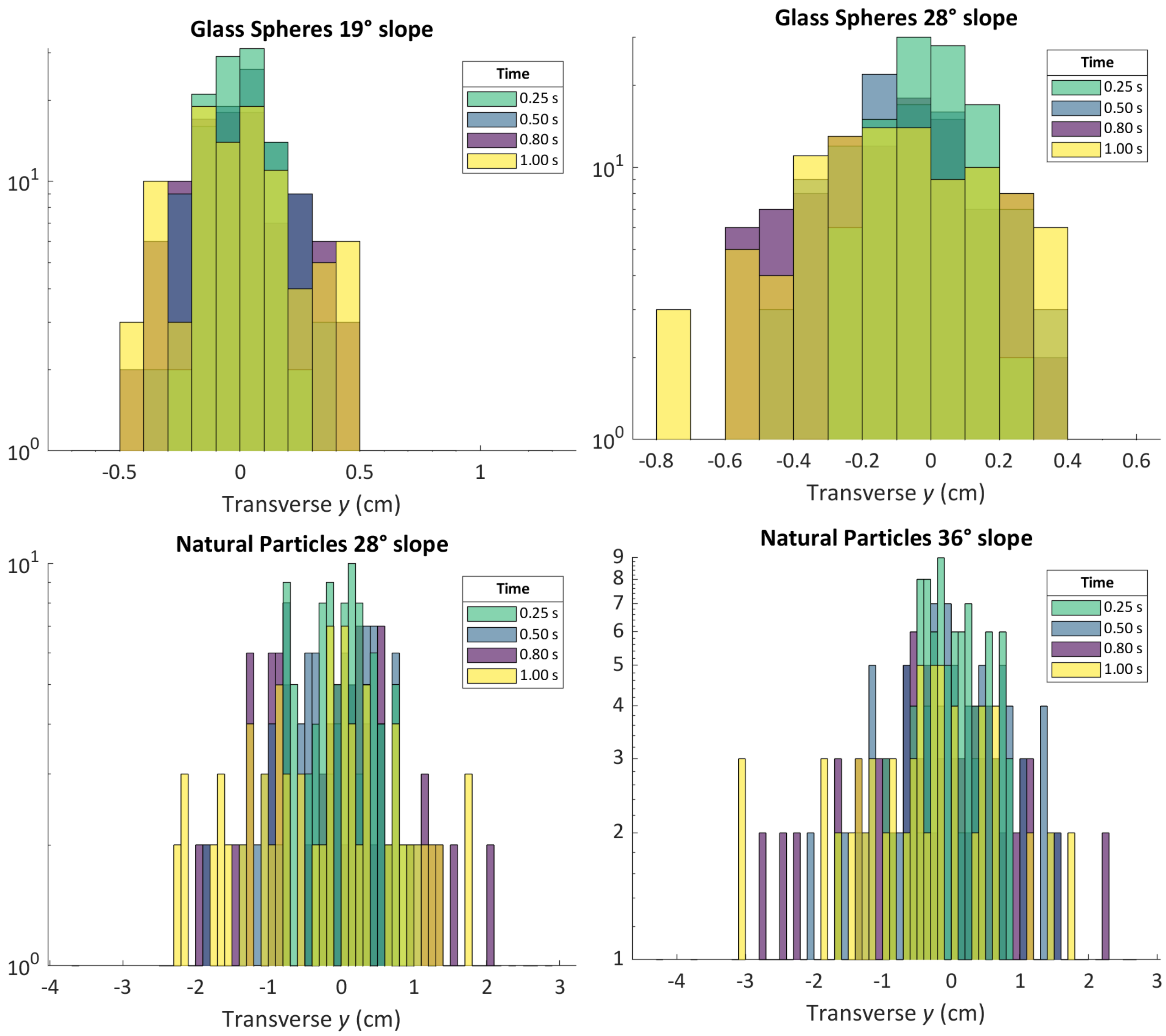


Natural Particles

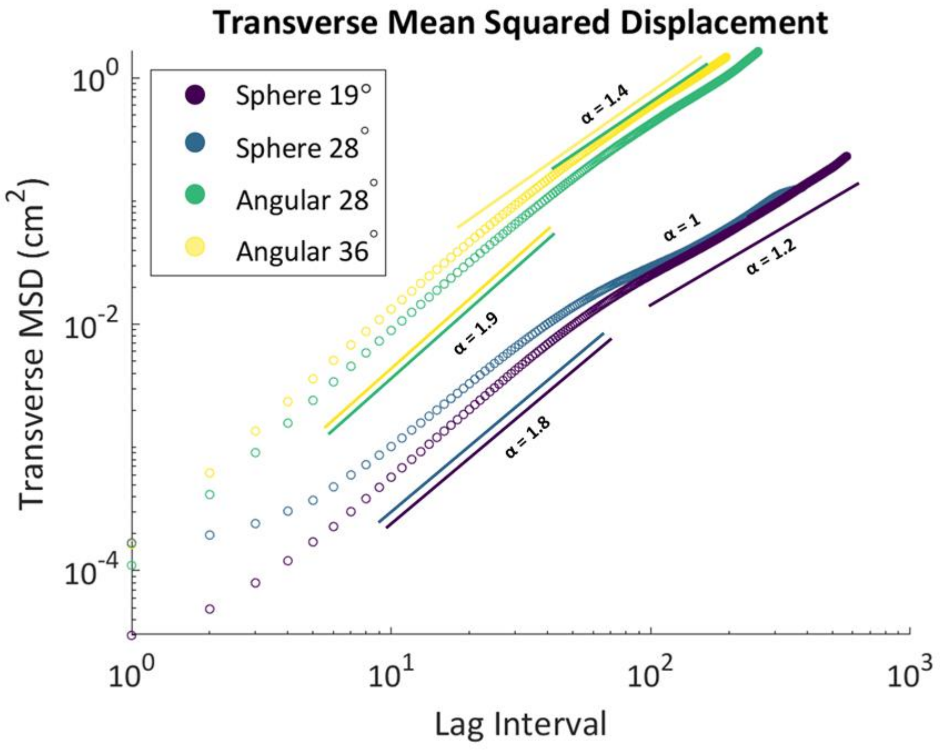
Downslope spreading isn’t necessarily Gaussian

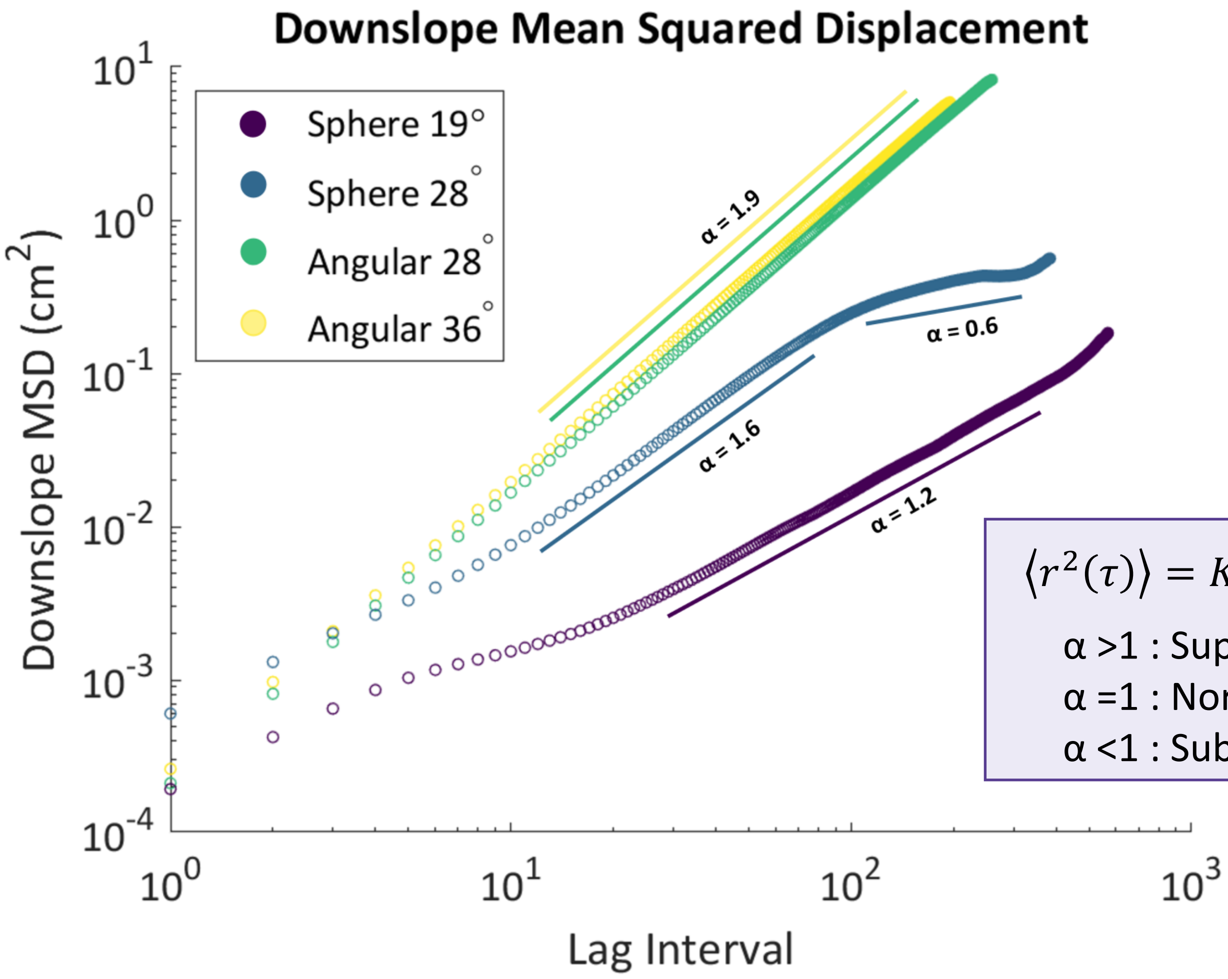


Neither is transverse spreading



Natural : Superdiffusive Spheres: Normal





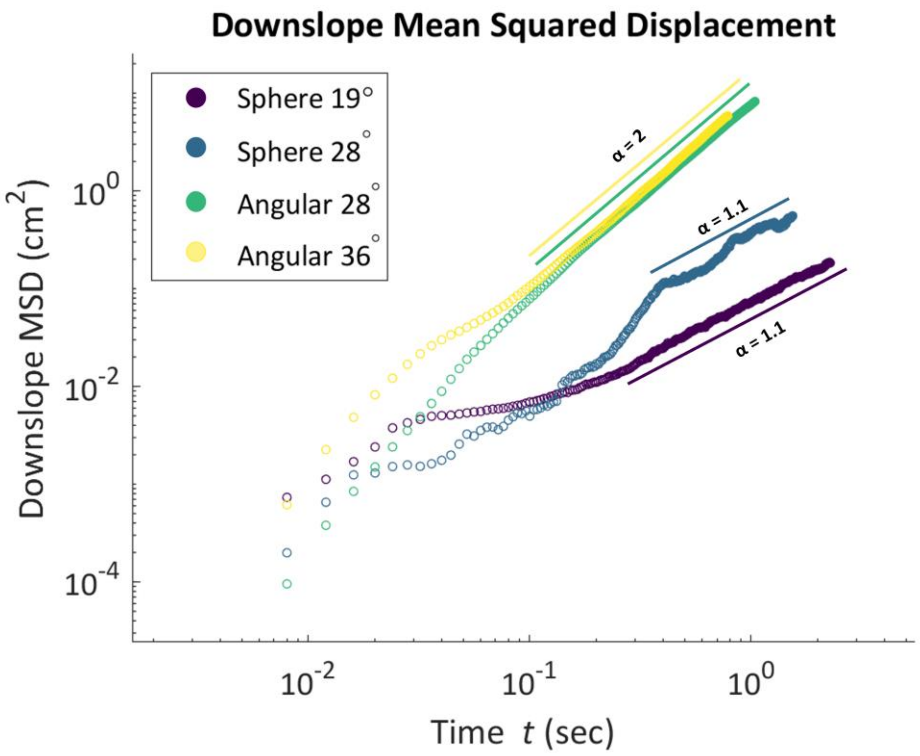
$$\langle r^2(\tau) \rangle = K_\alpha \tau^\alpha$$

α >1 : Super

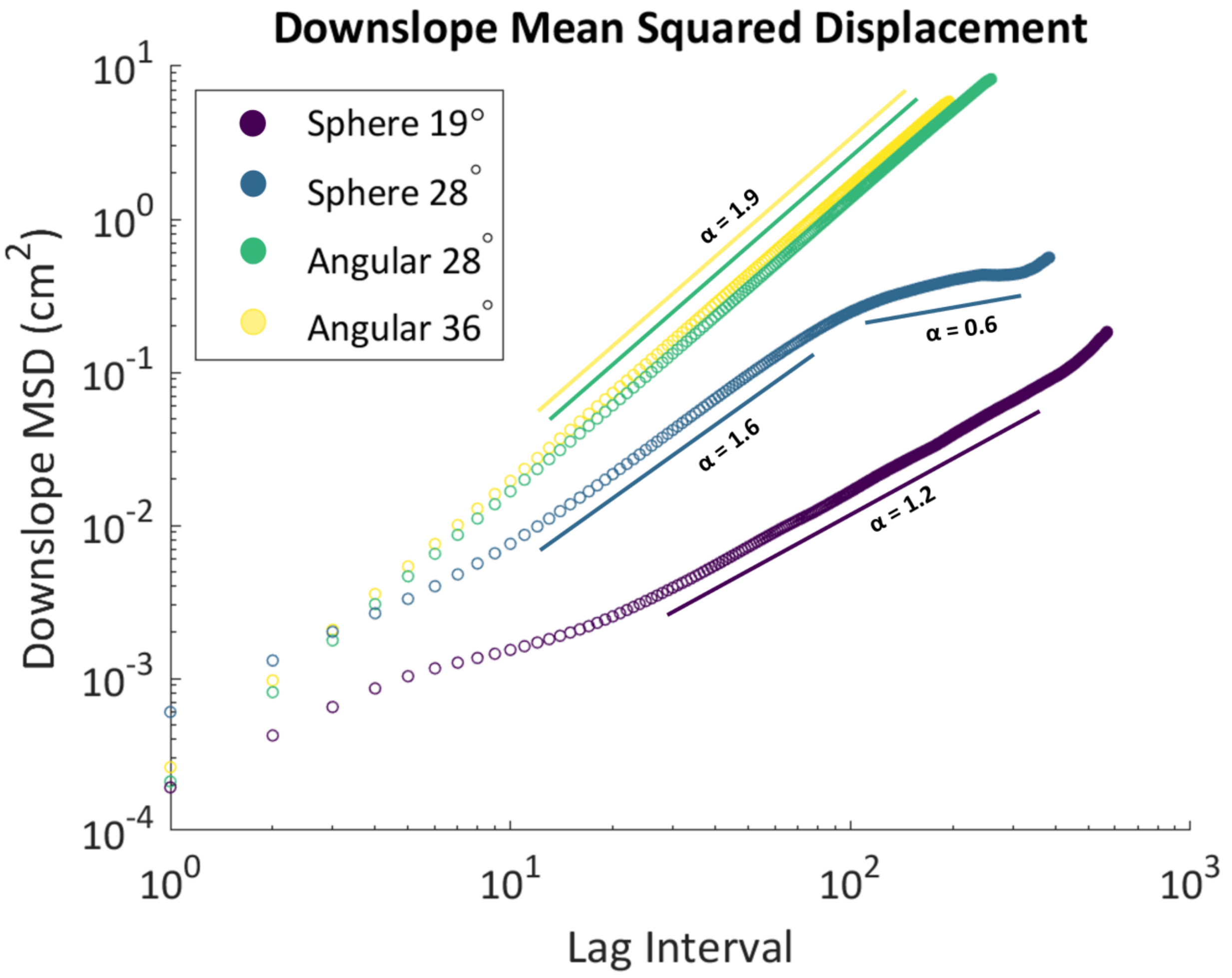
α =1 : Normal

α <1 : Sub

Non-ergodic?

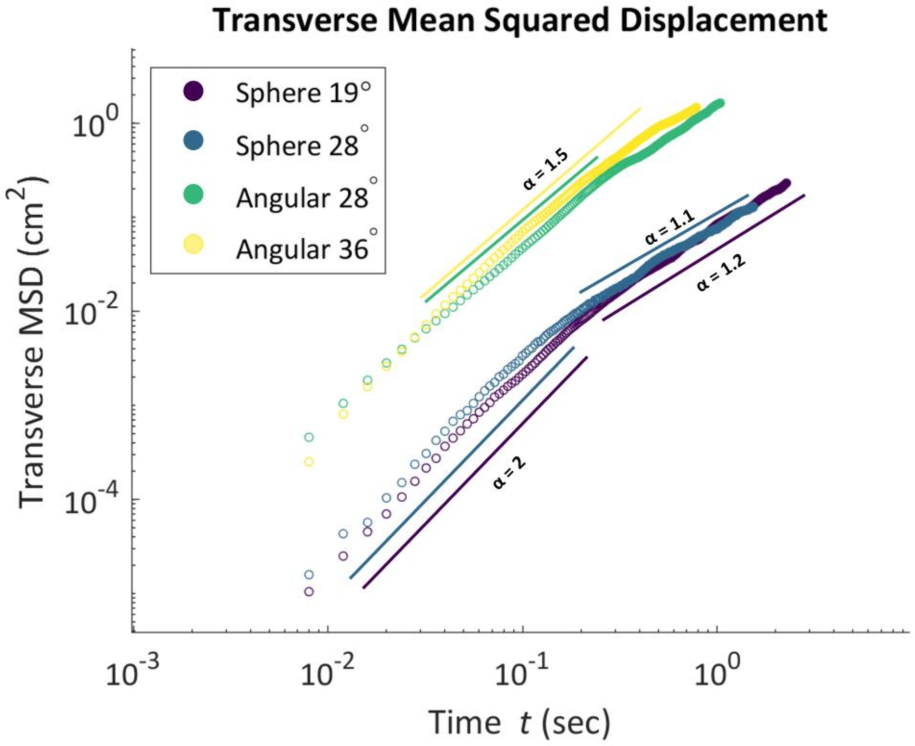


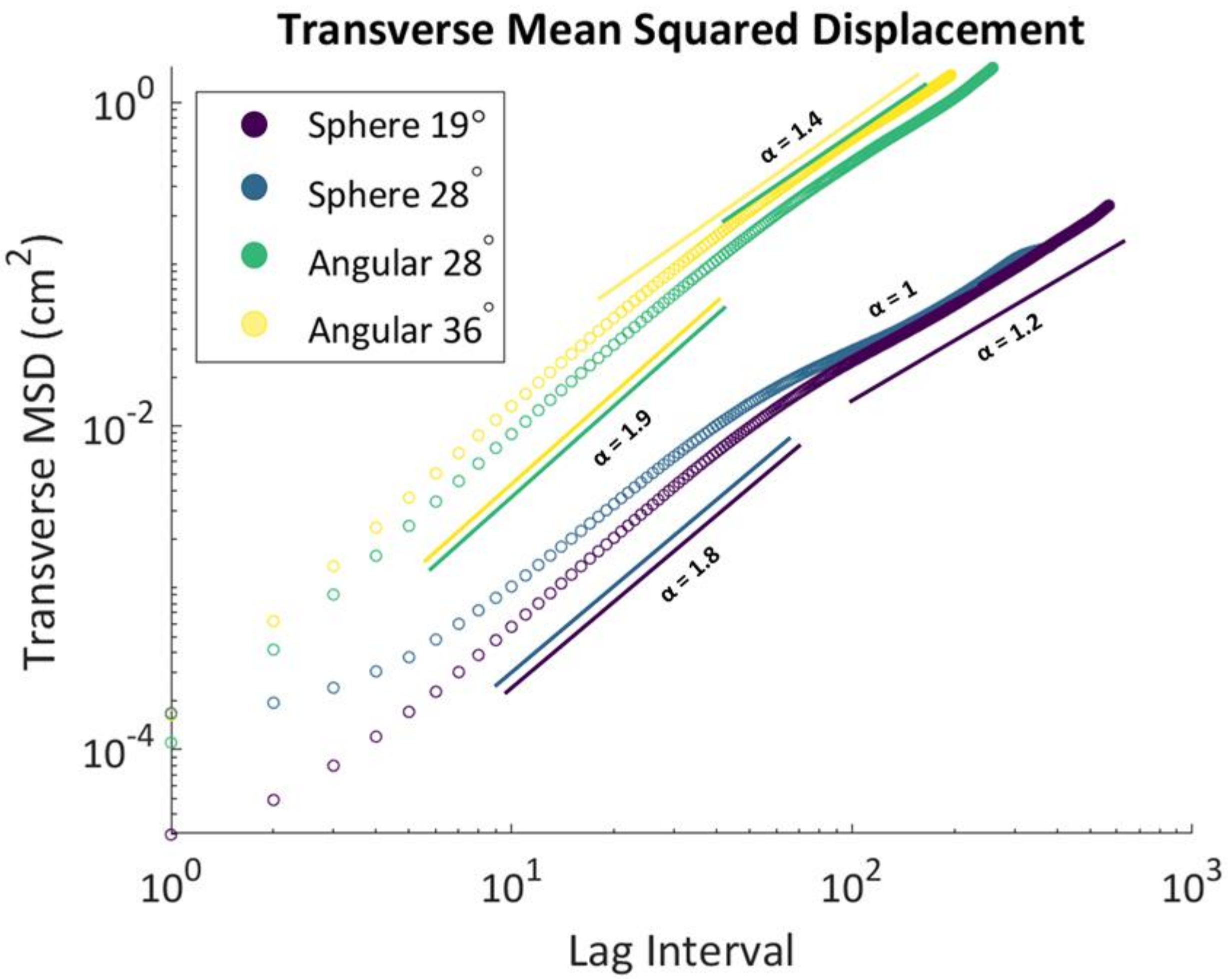
Downslope Mean Squared Displacement
Sphere 19°
Sphere 28°
Angular 28°
Angular 36°
α = 2
α = 1.1
α = 1.1
Downslope MSD (cm²)
Time t (sec)



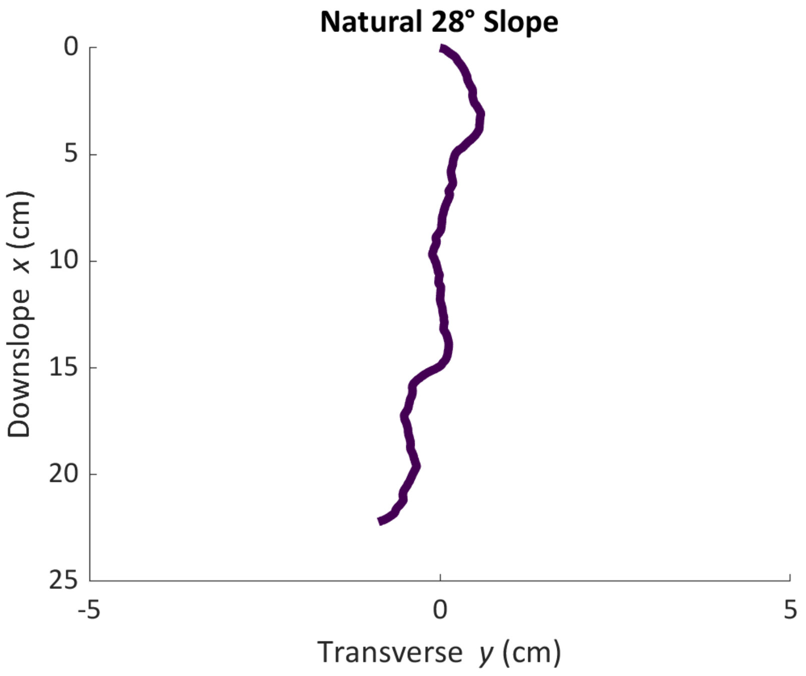
Downslope Mean Squared Displacement
Sphere 19°
Sphere 28°
Angular 28°
Angular 36°
α = 1.9
α = 0.6
α = 1.6
α = 1.2
Downslope MSD (cm²)
Lag Interval

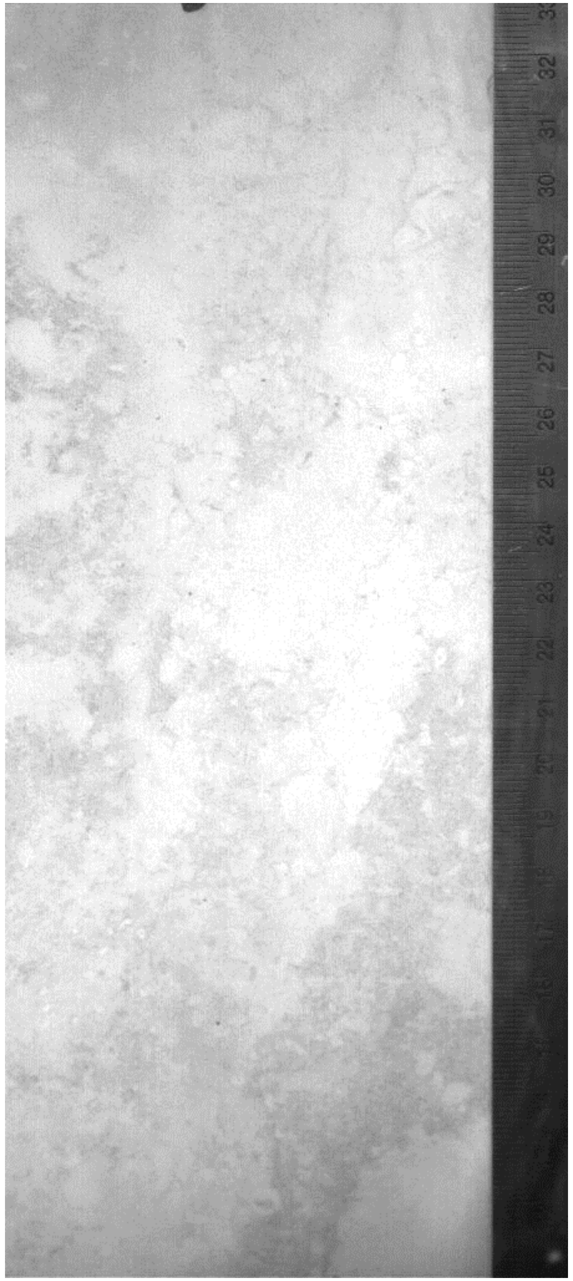
Non-ergodic?

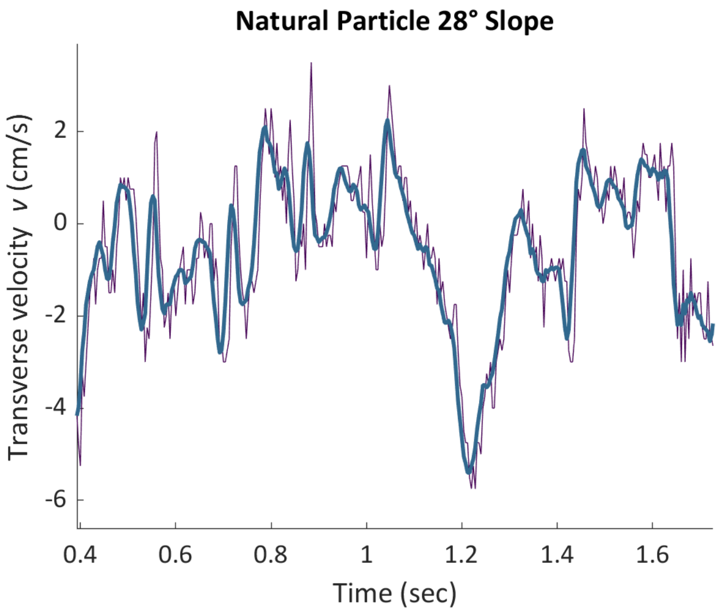

Transverse Mean Squared Displacement
Sphere 19°
Sphere 28°
Angular 28°
Angular 36°
α = 1.5
α = 1.1
α = 1.2
α = 2
Transverse MSD (cm²)
Time t (sec)

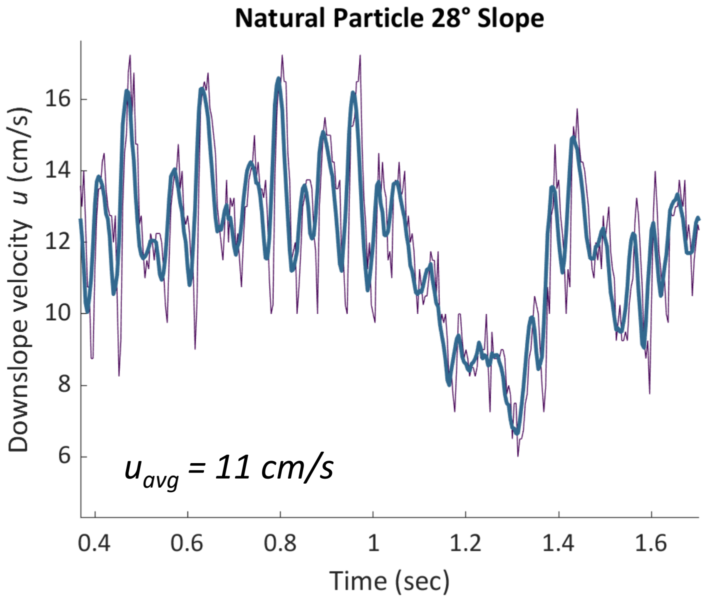

Transverse Mean Squared Displacement
Sphere 19°
Sphere 28°
Angular 28°
Angular 36°
α = 1.4
α = 1
α = 1.2
α = 1.9
α = 1.8
Transverse MSD (cm²)
Lag Interval

Why superdiffusive?

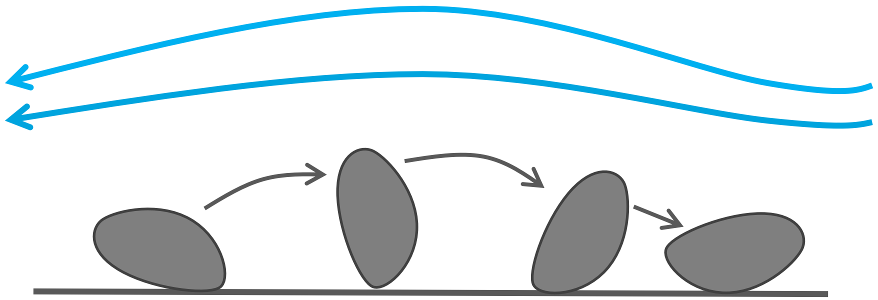








Particle orientation is changing



Area changes with reorientation

↓ ↑

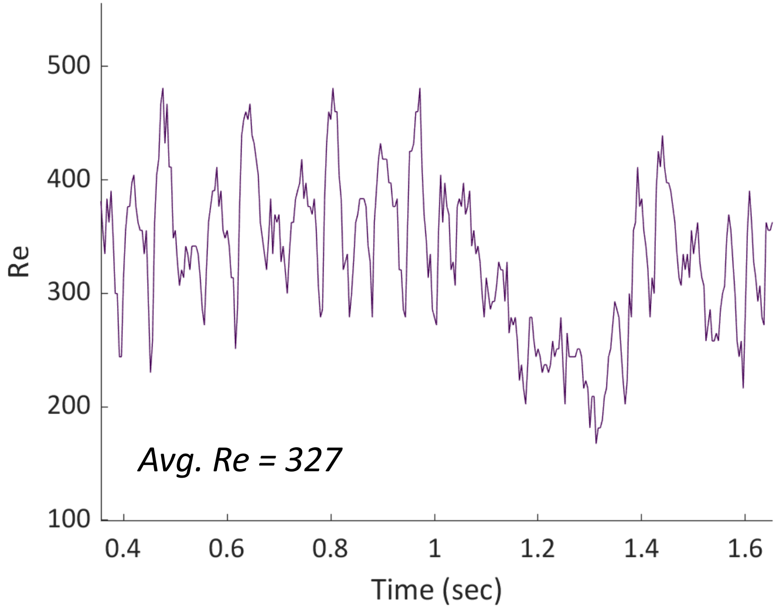
Drag force fluctuates

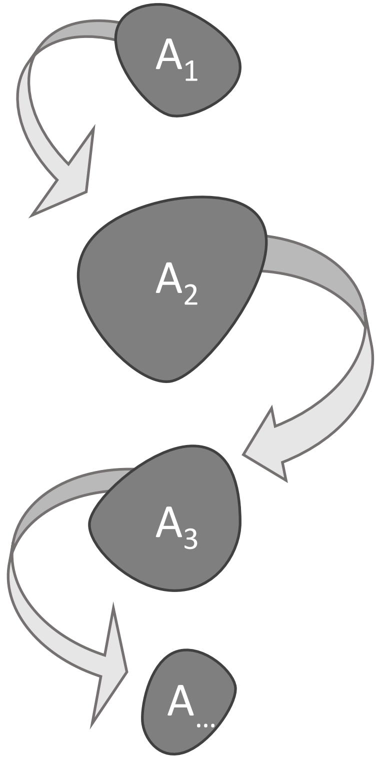
↓ ↑

Velocity fluctuates

↓ ↑

Reynolds number fluctuates





Next Steps

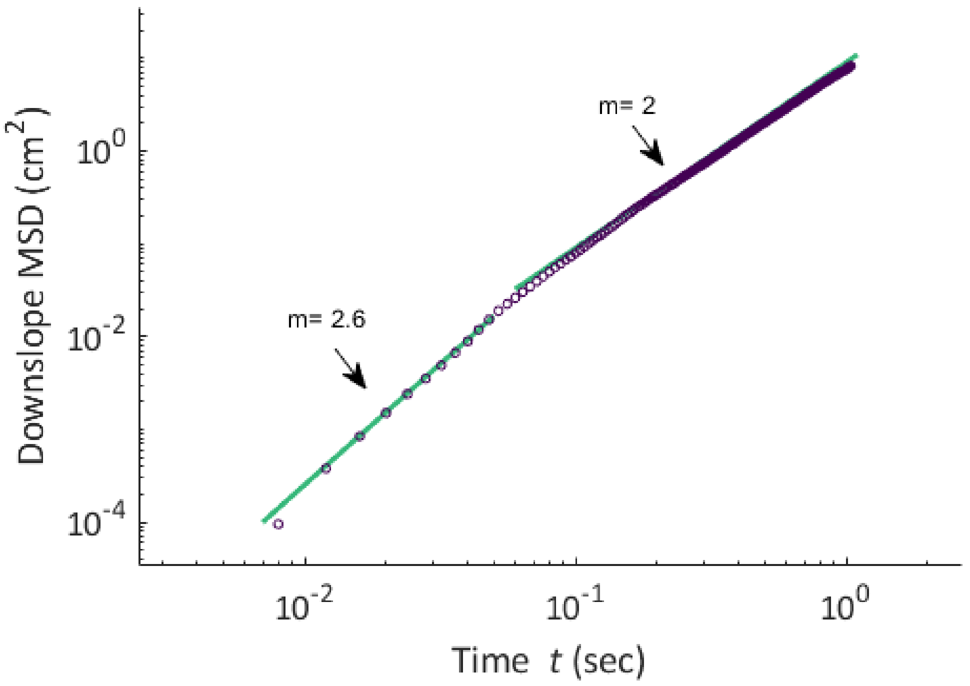
- Determine Re C_D relationship for natural particles
- Force balance / Two-range diffusion
- Parameter space experiments
- Bottom-up experiments

$$m'\ddot{x} = mg\sin\theta - 6\pi r(t)\mu\dot{x} - F \; *$$

$$(m' + I/R^2)\ddot{x} = mg\sin\theta - 6\pi r(t)\mu\dot{x} \; *$$

Natural Particles 28° Slope

Downslope Mean Squared Displacement



* Courtesy of Kevin Pierce

Final thoughts

- Particle angularity matters
- Orientation affects force balance on particle
- Particles diffuse in the absence of roughness and rests
- General behaviors of many possible particles
- Apply and adapt a Galton board-like model