

Controlling Rheology via Boundary Conditions in Dense Granular Flows

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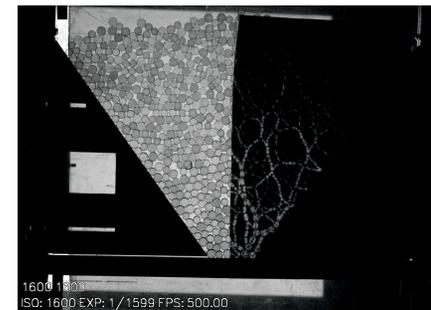
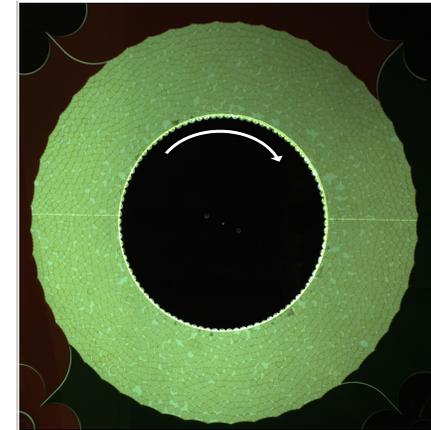
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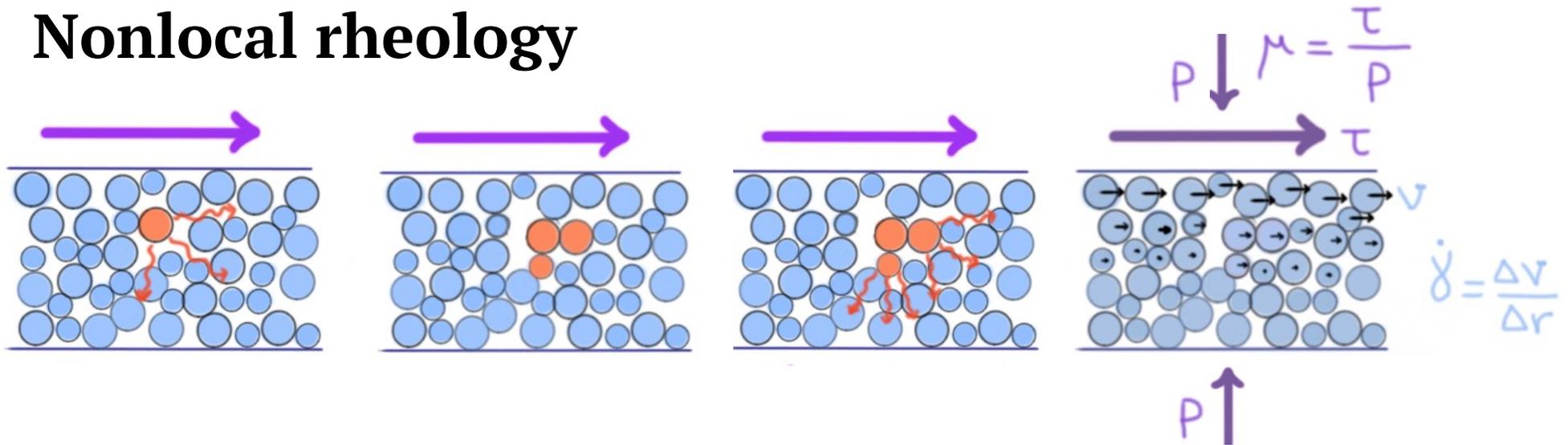


Granular rheology: **Years 1-3**, **Years 4-6**

- **Original questions:** for a given set of particles, can we
 - make flow measurements in one geometry
 - determine the constitutive parameters
 - predict flows in other geometries, up to intermediate regime
- **Years 1-6:** nonlocal rheology successfully models granular flows across **different packing densities**, **particle sizes/shape/stiffness**, and **shear rates**; including **local measurements of forces**
- **New in Year 7:** **harder geometries & faster flows**
 - separate which properties are set by the particles vs. walls
 - experiments in hopper flows



Nonlocal rheology



Local rearrangement induces rearrangements in nearby particles

A	b	μ_s	} Material properties?
Nonlocal parameter	Local parameter	Yield criterion	

GDR MiDi *Eur. Phys. J.*, 2004
 Kamrin and Koval, *Phys. Rev. Lett*, 2012 & Hennan et al. *PNAS*, 2013

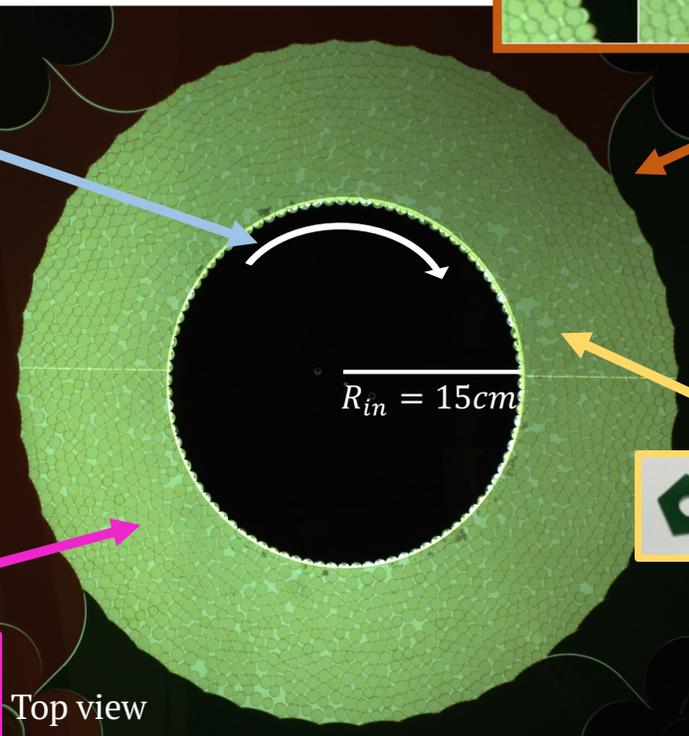
What do model parameters (A , μ_s , b) depend on ?

$$2 \frac{d}{s}, 0.2 \frac{d}{s}, 0.02 \frac{d}{s}, 0.002 \frac{d}{s}$$

Speed



Laser-cut wall



Particle shape and material

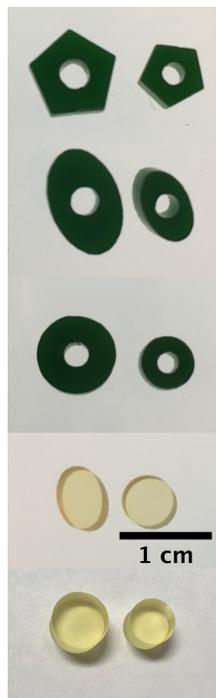
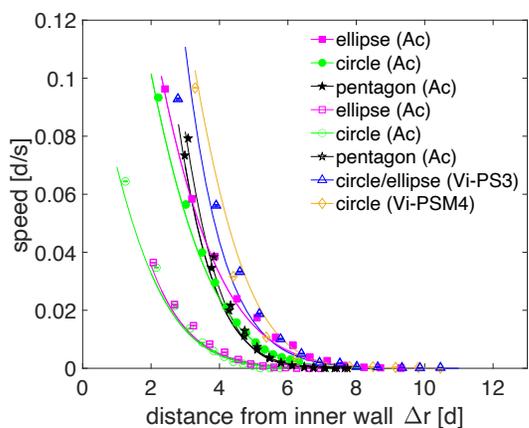
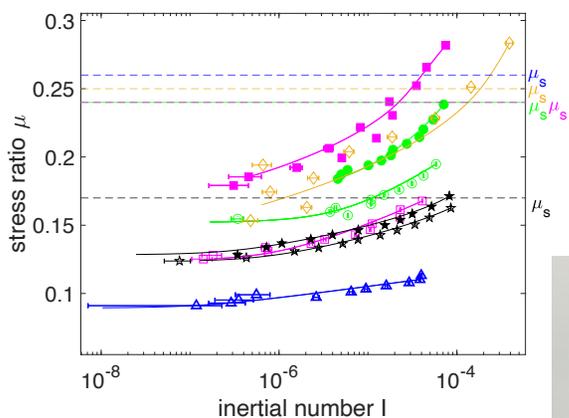


Packing density

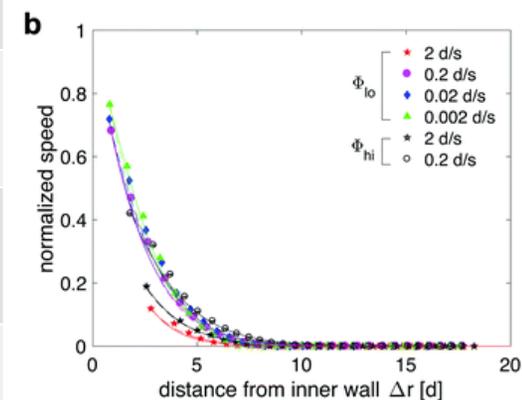
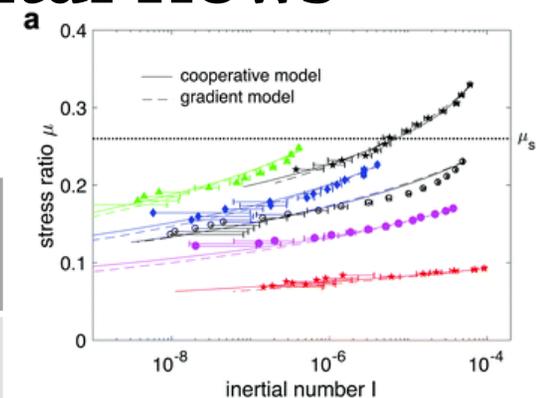
$$\phi_{high} = 0.840, \phi_{low} = 0.816$$

Top view

Nonlocal rheology describes experimental flows

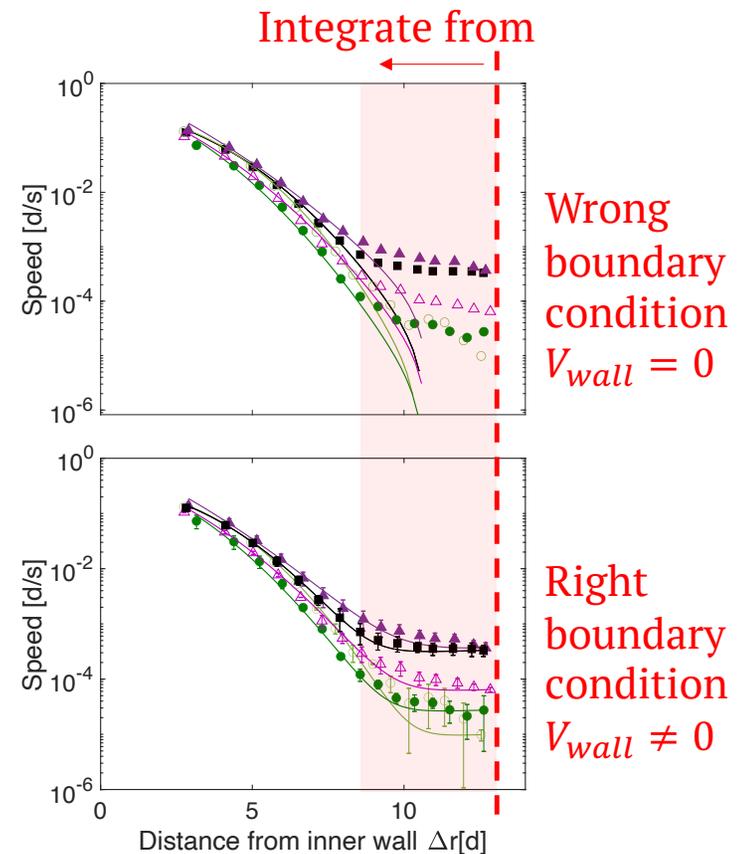


$b(\text{local})$	μ_s	$A(\text{nonlocal})$
1.1 ± 0.5	0.17 ± 0.01	0.13 ± 0.02
1.1 ± 0.5	0.24 ± 0.02	0.28 ± 0.01
1.1 ± 0.5	0.24 ± 0.02	0.30 ± 0.02
1.1 ± 0.5	0.26 ± 0.01	0.41 ± 0.02
1.1 ± 0.5	0.25 ± 0.01	0.22 ± 0.03

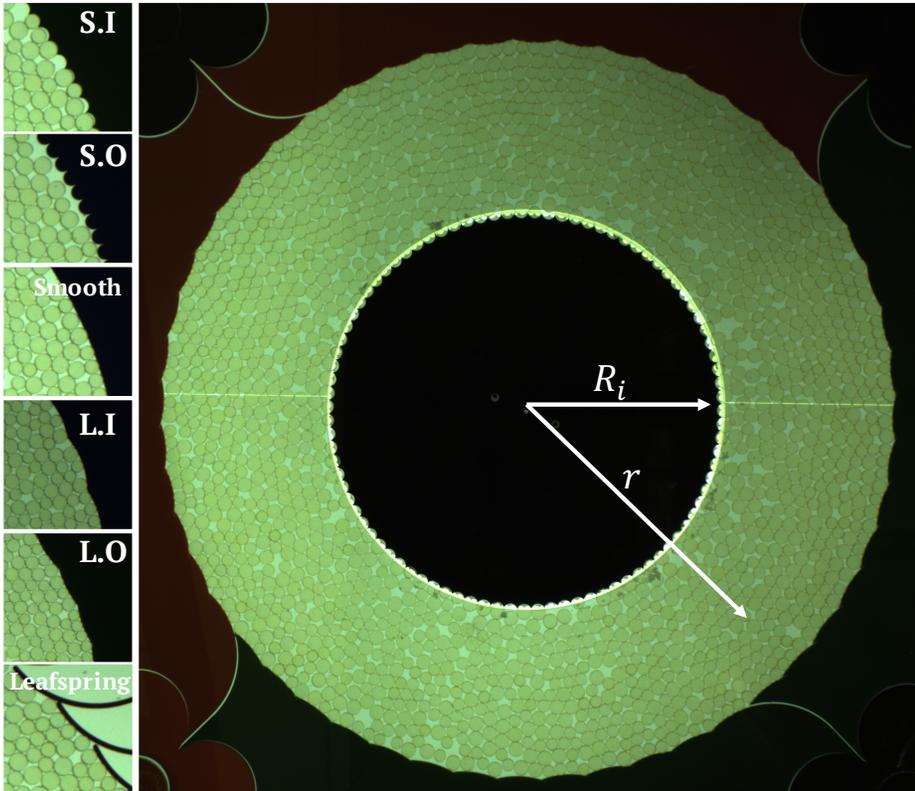


Research aim

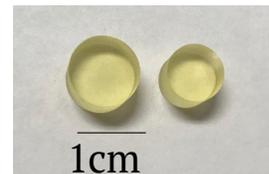
- **Status:** nonlocal rheology successfully models granular flows across different packing densities, particle properties, and shear rates
 - but also need to know wall velocities a priori
- **Aim:** understand which aspects of a dense granular flow can be controlled by the choice of boundary condition
 - develop predictive model for wall slip



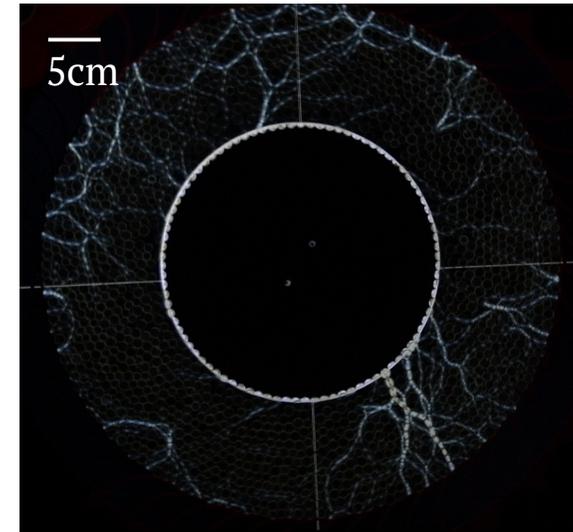
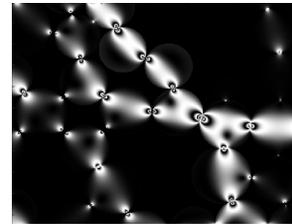
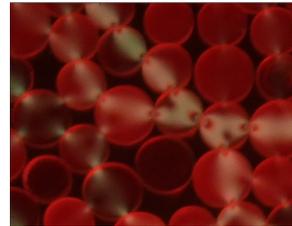
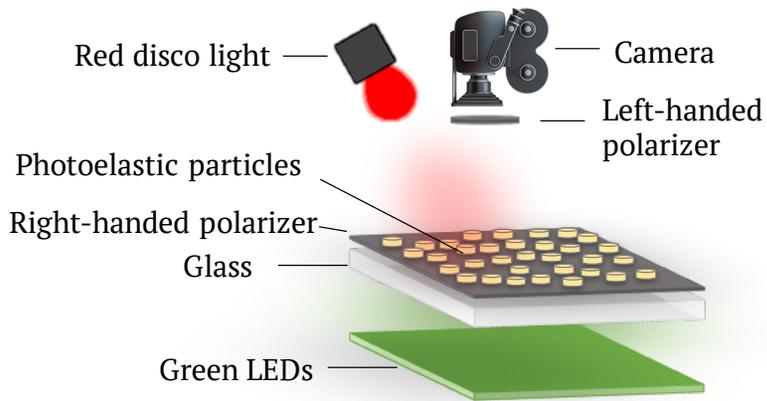
The effect of boundary properties



- Stationary outer wall with 6 different roughness and compliance
- Constant packing density: $\phi = 0.65$
- Photoelastic circular disks ($\mu_s = 0.25$)
- $speed = 1.1 \frac{d}{s}$
- Velocity profile from particle tracking
- Shear and normal stresses from photoelasticity



Stress measurement

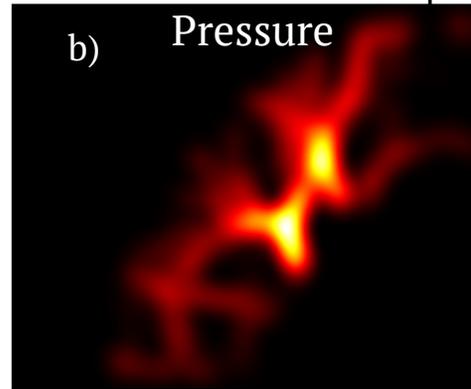
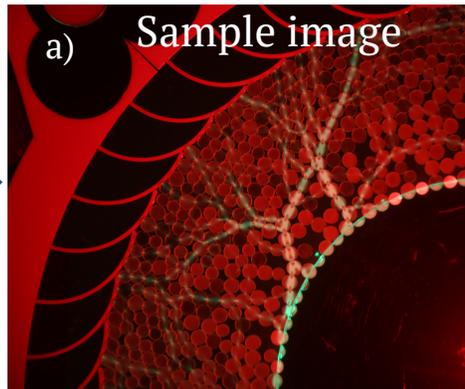


2000 frames

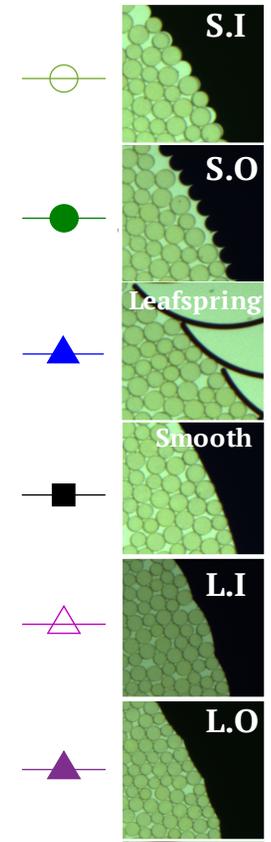
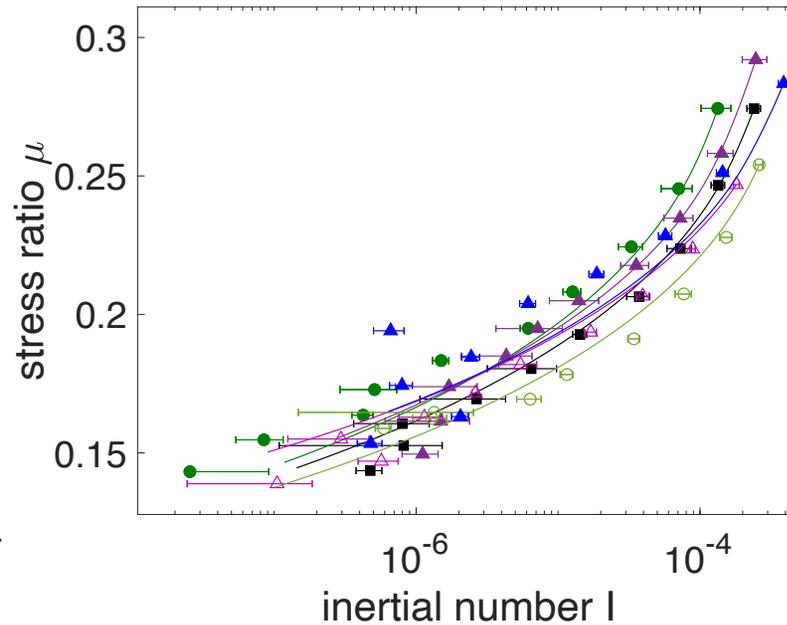
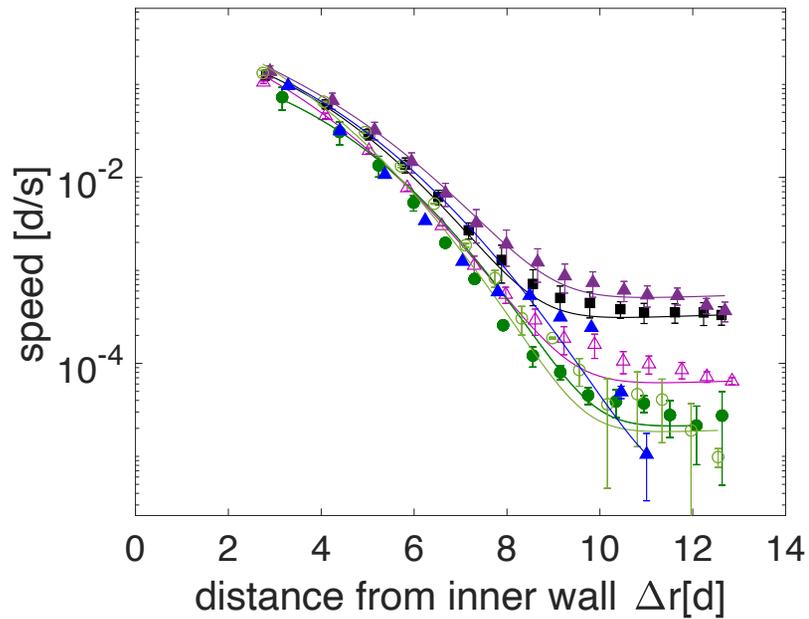
Daniels, Kollmer, Puckett. Rev. Sci. Inst. (2017) <https://github.com/jekollmer/PEGS>

Coarse graining
(Lucy function)
 $\omega = 1.3 d$

Weinhart, Hartkamp,
Thornton, Luding,
Phys. Fluids, 2013

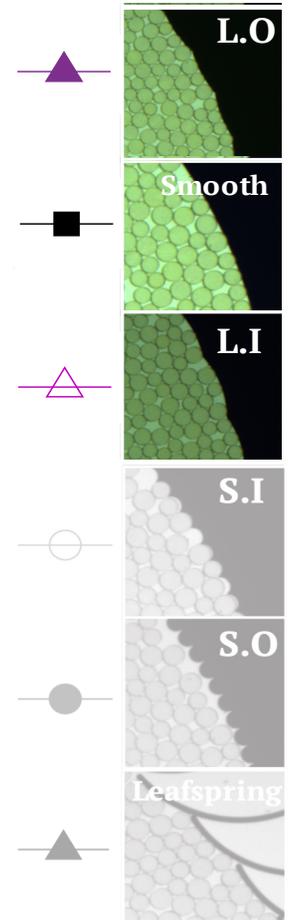
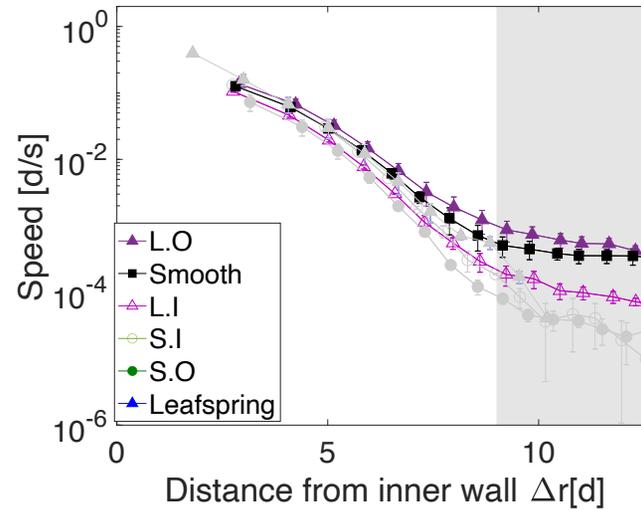
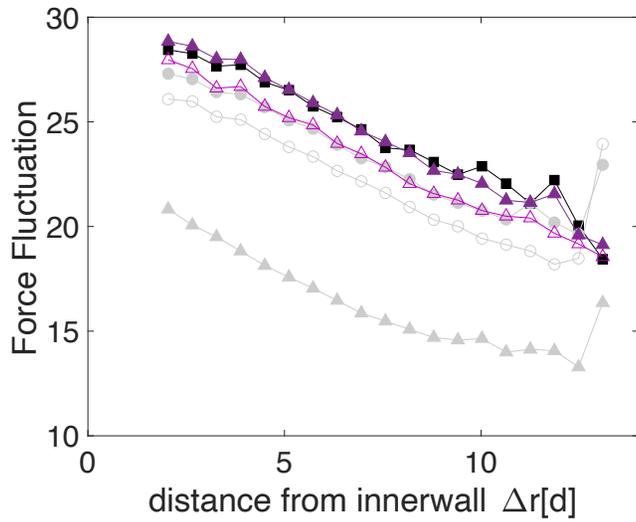


Success of nonlocal rheology for various boundary properties

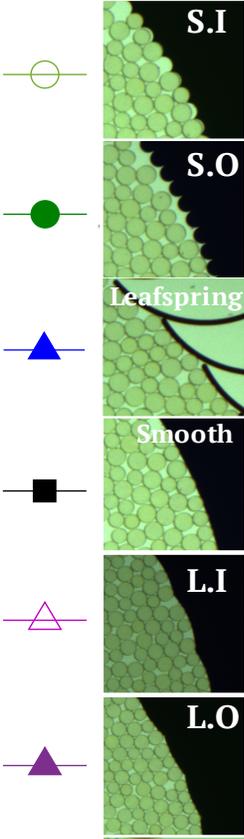
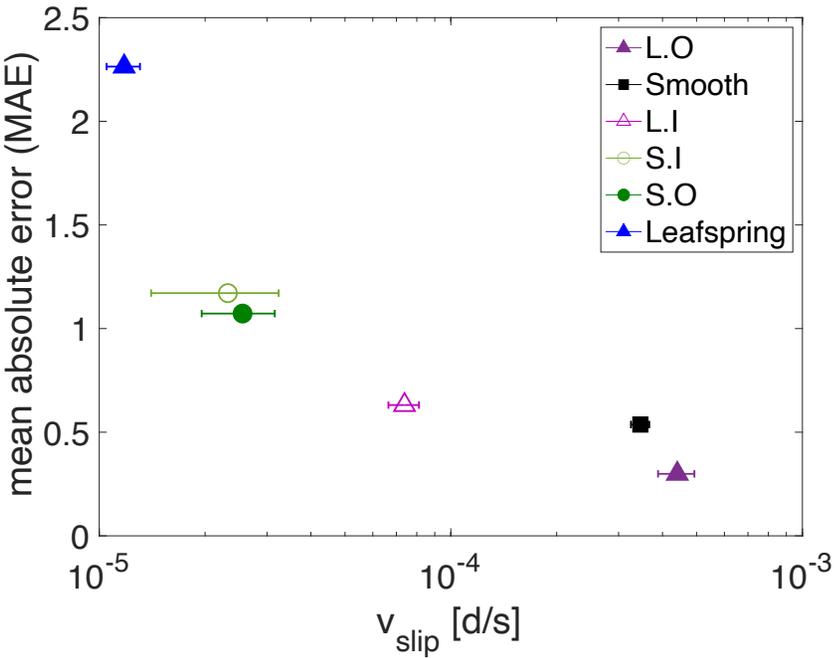
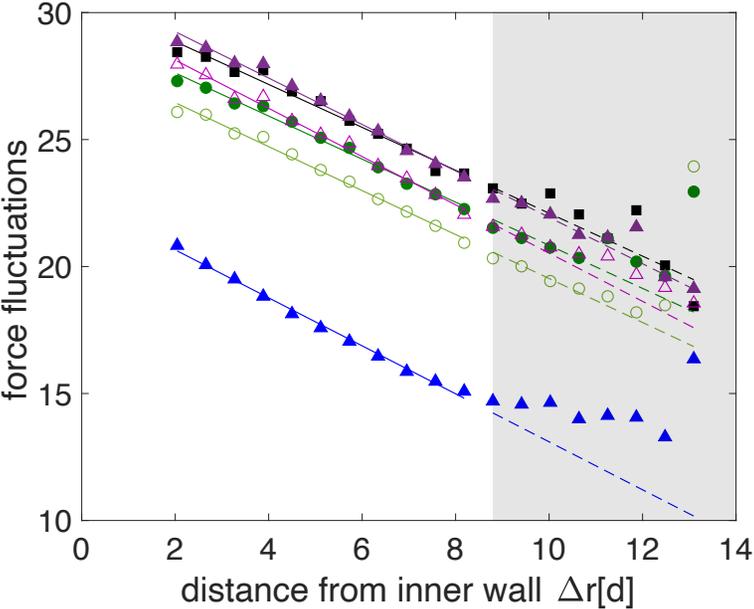


$A(\text{nonlocal})$	$b(\text{local})$	μ_s
0.22 ± 0.03	1.1 ± 0.5	0.25 ± 0.01

Wall slip is associated with wall force fluctuation



Empirical prediction of wall slip



$$MAE = \frac{\sum |predicted\ value - measured\ value|}{number\ of\ data\ points}$$

Conclusions from the annulus

- Nonlocal rheology successfully models granular flows across different:
 - ✓ packing densities
 - ✓ shear rates
 - ✓ particle shapes and materials
 - ✓ Boundary roughness and compliance
- We qualitatively predict wall slip associated with wall properties using force fluctuations

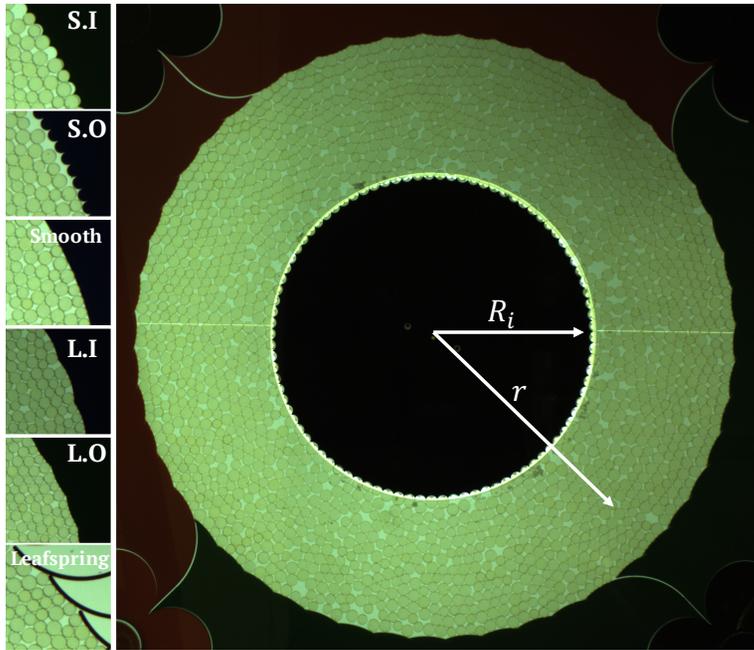
Next question

- How does geometry and inertial number affect our observations and wall slip prediction?

Annular shear apparatus

vs.

Hopper



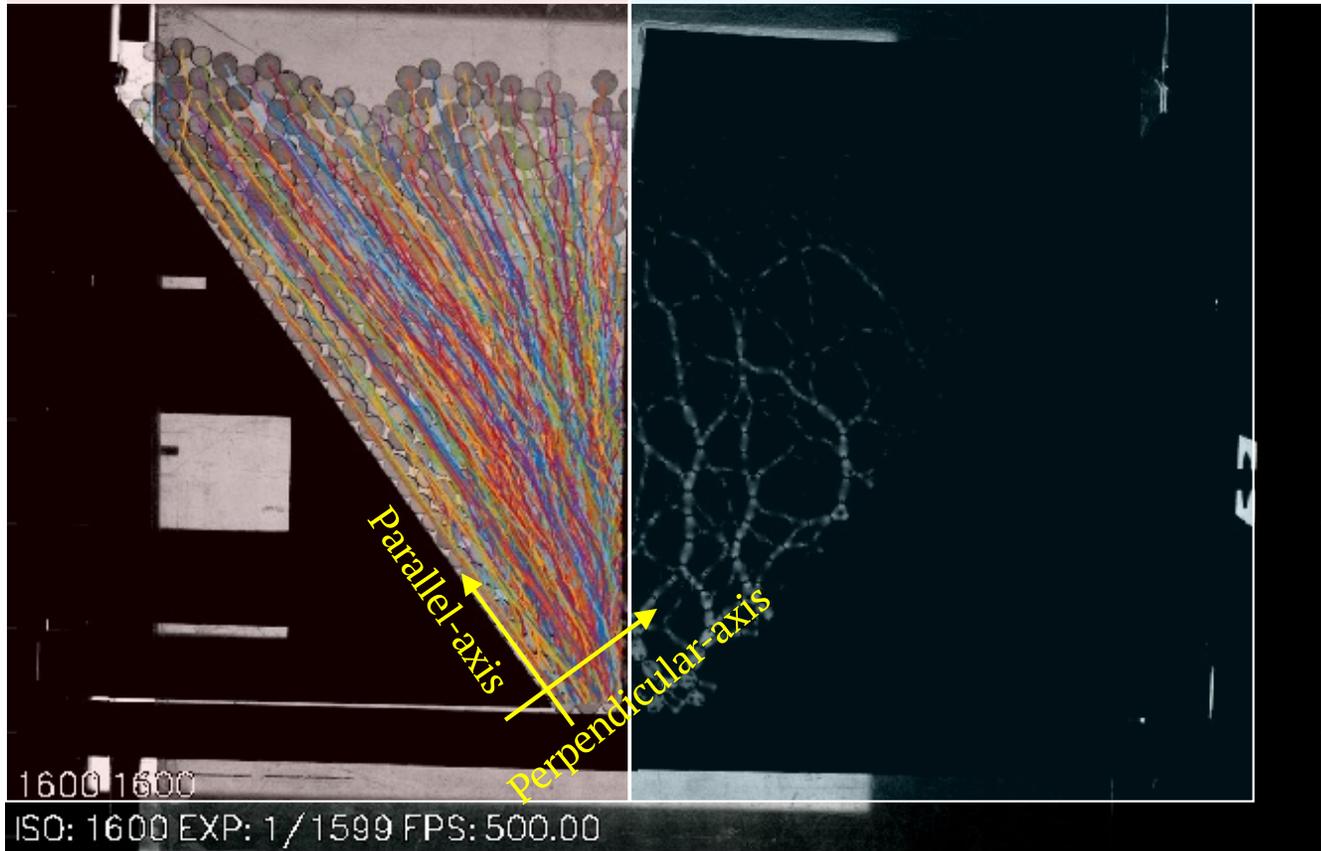
Apparatus: Brzinski & Daniels.
PRL (2018)



Apparatus: Bob Behringer
IFPRI report FRR 56-06
Tang & Behringer *EPL* (2016)

Particle tracking

Force visualization

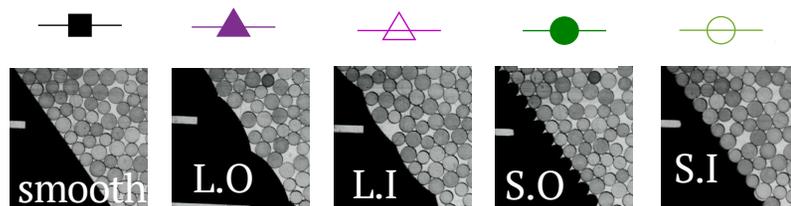
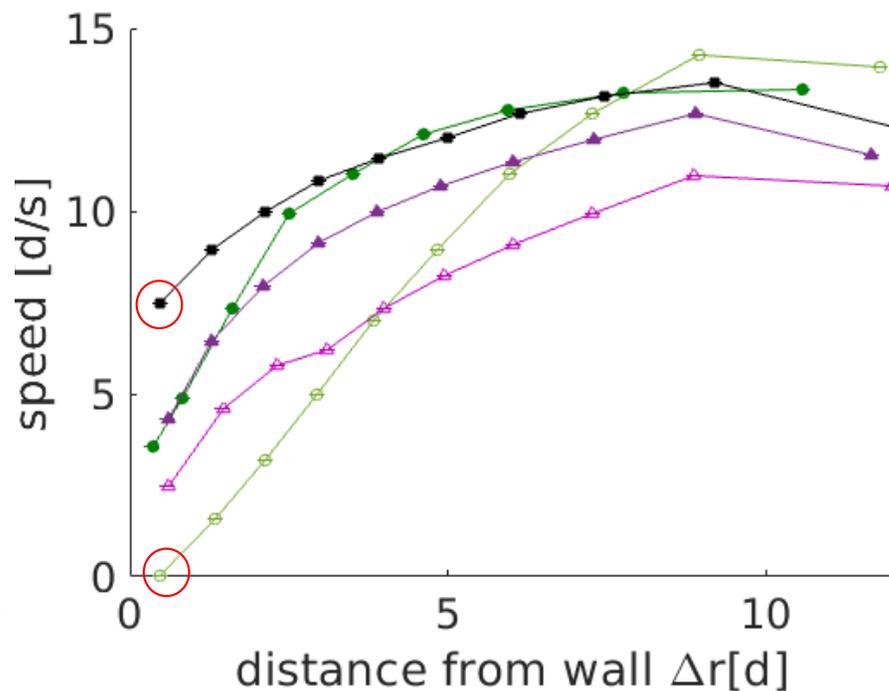
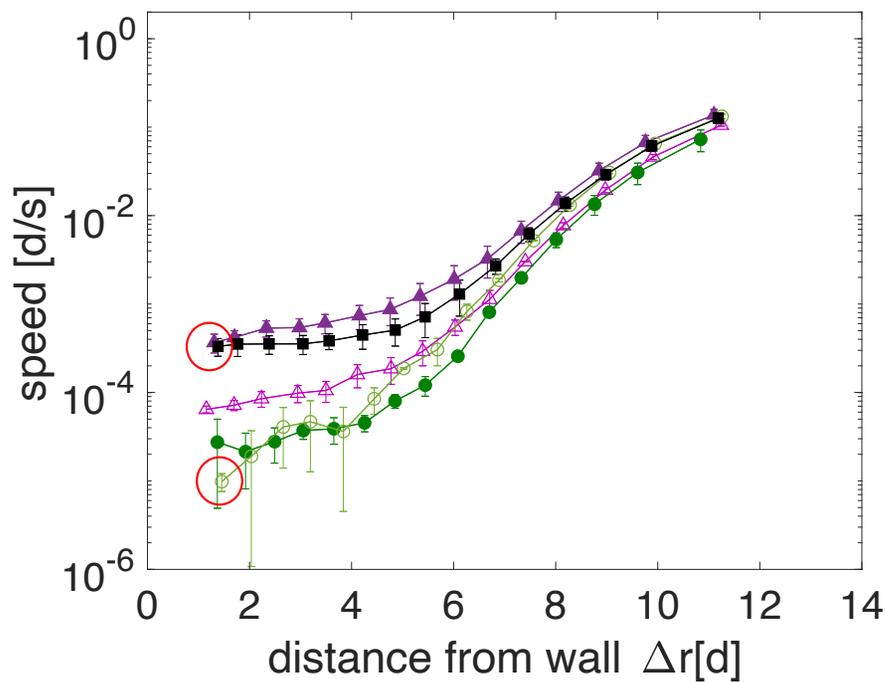


Emily Cecchini

Annulus

vs.

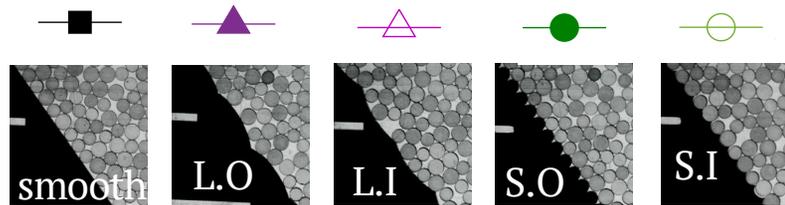
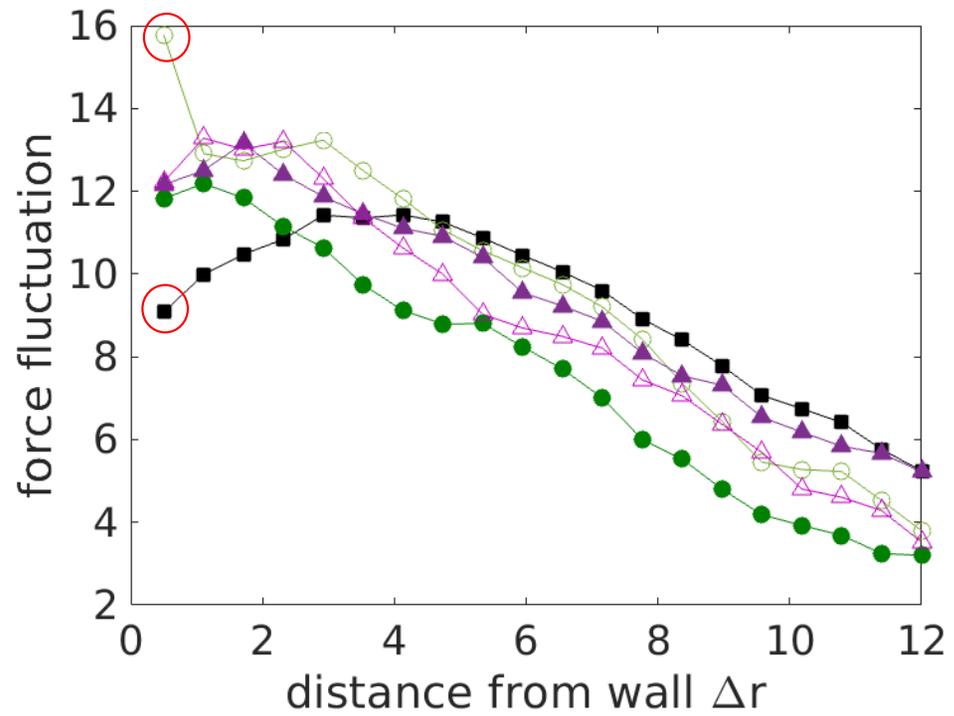
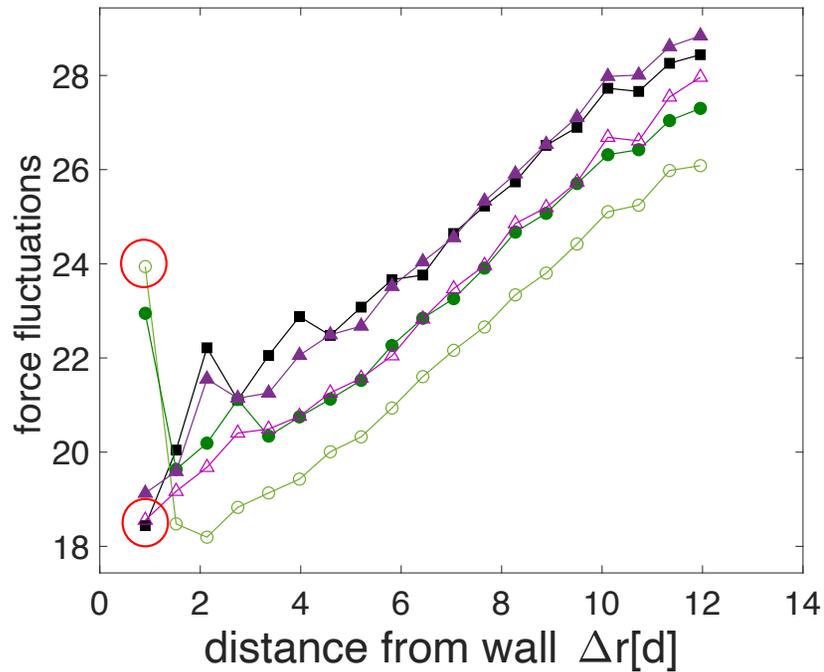
Hopper



Annulus

vs.

Hopper



Conclusion

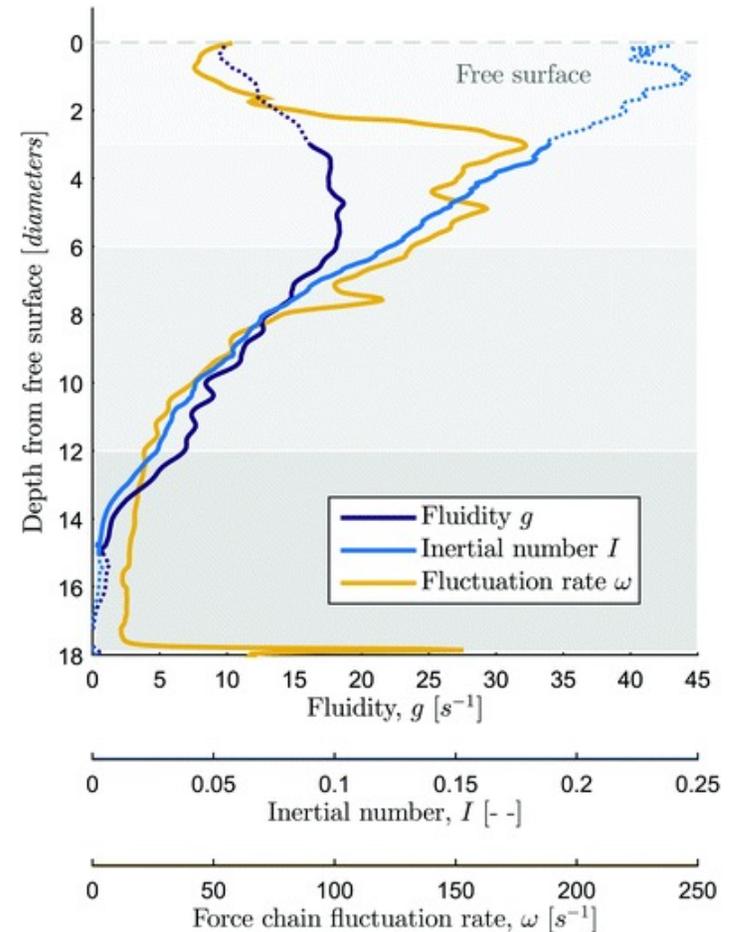
- Nonlocal rheology successfully models granular flows across different:
 - ✓ packing densities
 - ✓ shear rates
 - ✓ particle shapes and materials
 - ✓ Boundary roughness and compliance
- We qualitatively predict wall slip associated with wall properties using force fluctuations

Comparing geometries: (annular shear apparatus vs. hopper)

- In extreme cases (very smooth and very rough boundaries) flow behavior is similar near the wall
- Geometry affects the flow characteristics

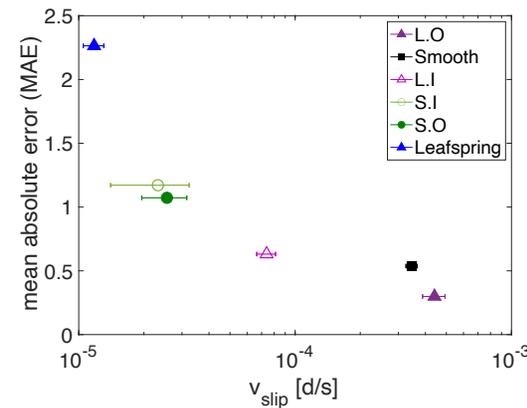
Bonus Material

- 2018-19: IFPRI-funded collaboration with Nathalie Vriend & Amalia Thomas
 - experiments in Cambridge chute flow (higher inertial number)
 - observe rearrangements of the force network extending into the quasi-static layer where shear rates vanish
- Thomas, Tang, Daniels, Vriend. *Soft Matter* (2019)
- 2022: IFPRI-funded collaboration with Prabhu Nott
 - test an additional non-local rheology (Dsouza & Nott, *JFM* 2020) that accounts for coupling between shear and dilation
 - visit planned by graduate students to NCSU



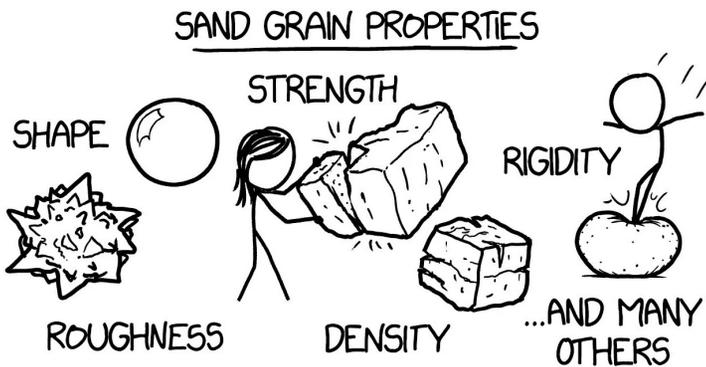
Outlook: DEMS will close some gaps

- **Open Question 1:** how does particle shape & stiffness quantitatively set the nonlocal parameter A ?
- **Open Question 2:** can we predict the wall slip velocity from the wall roughness and particle properties, alone?
- Once these two questions are settled, a nonlocal rheology can be used *predictively*, rather than only descriptively



	$A(\text{nonlocal})$
	0.10 ± 0.001
	0.23 ± 0.003
	0.28 ± 0.003
	0.40 ± 0.003

1 cm



Randall Munroe

<https://www.nytimes.com/2020/11/09/science/what-makes-sand-soft.html>