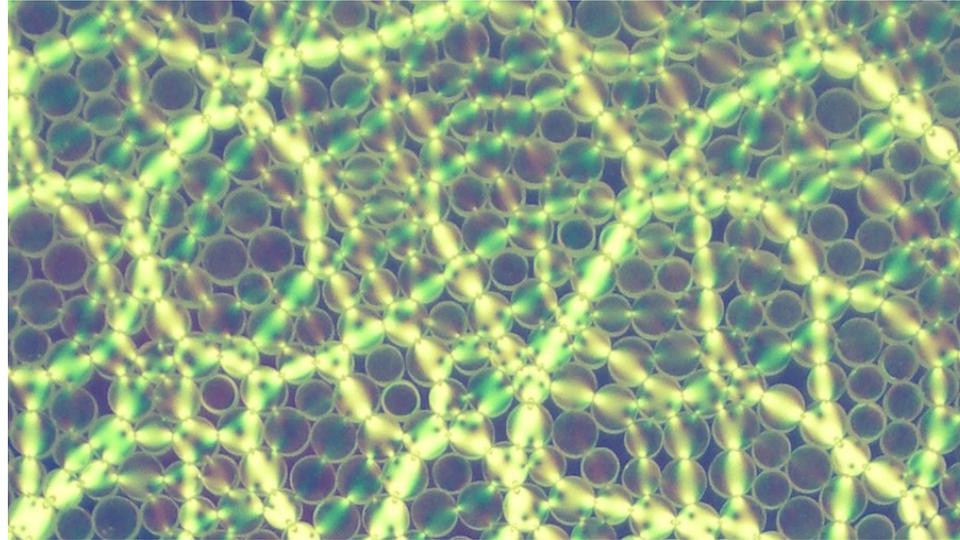


# Shapes, Forces, and Nonlocality in the Flow of Powders and Grains



Karen Daniels  
Dept. of Physics

**NC STATE UNIVERSITY**

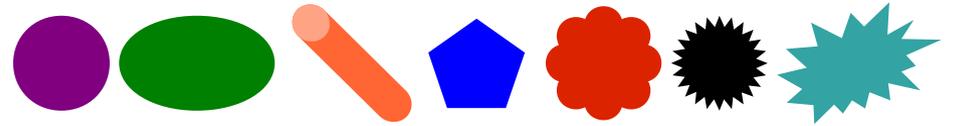


**JAMES S. McDONNELL FOUNDATION**



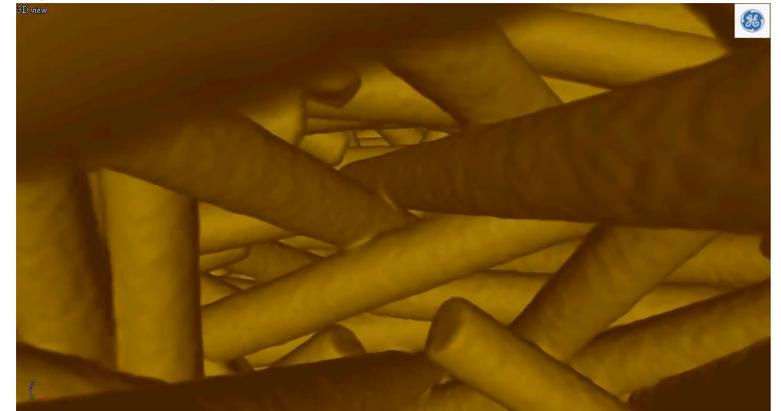
# New Experimental Capabilities

- bespoke particles
  - new opportunity to create controlled experiments on shape/roughness
- internal forces
  - friction and particle shape imprint memory on a particulate material
- tomography
  - 3D dynamics are now widely accessible



→ these will drive a new understanding of underlying mechanisms

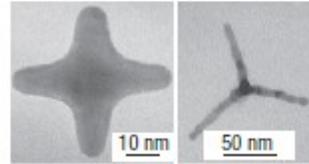
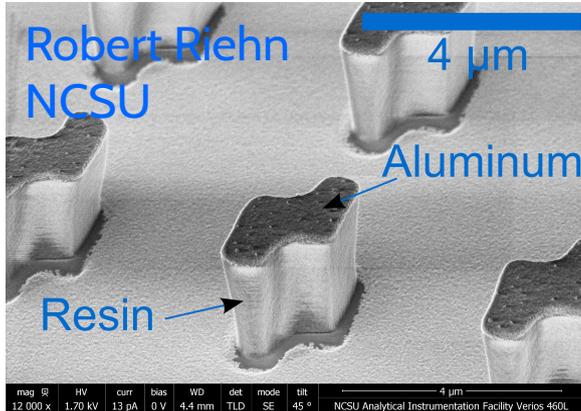
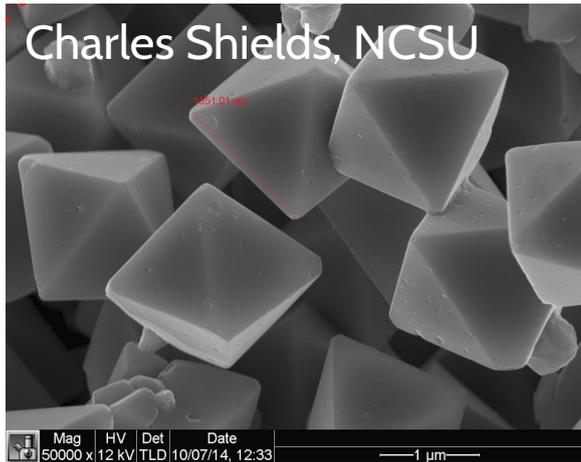
<https://www.youtube.com/watch?v=76Z1Bbj7CtQ>



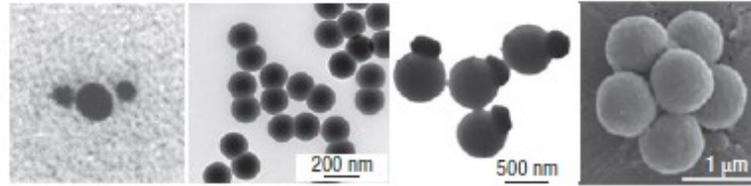
Matthias Schröter (Göttingen/Erlangen)

# Bespoke Colloids

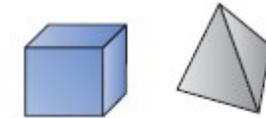
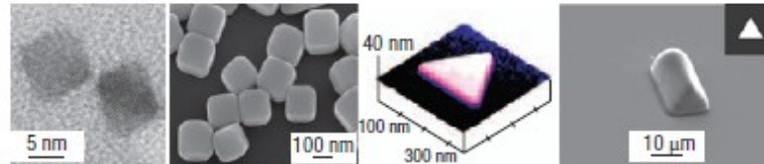
Glotzer & Solomon.  
*Nature Materials* (2007)



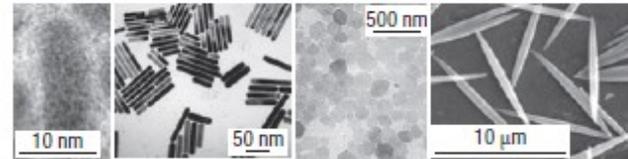
Branched



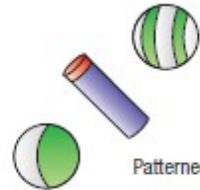
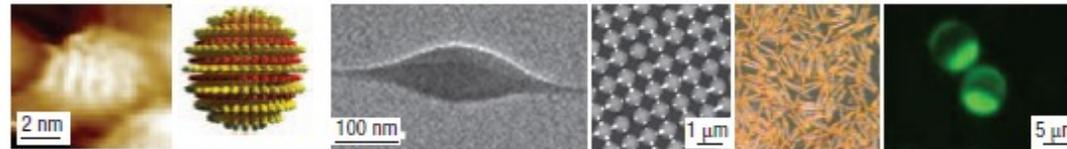
Colloidal molecules



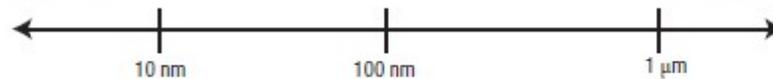
Faceted polyhedra



Rods and ellipsoids



Patterned

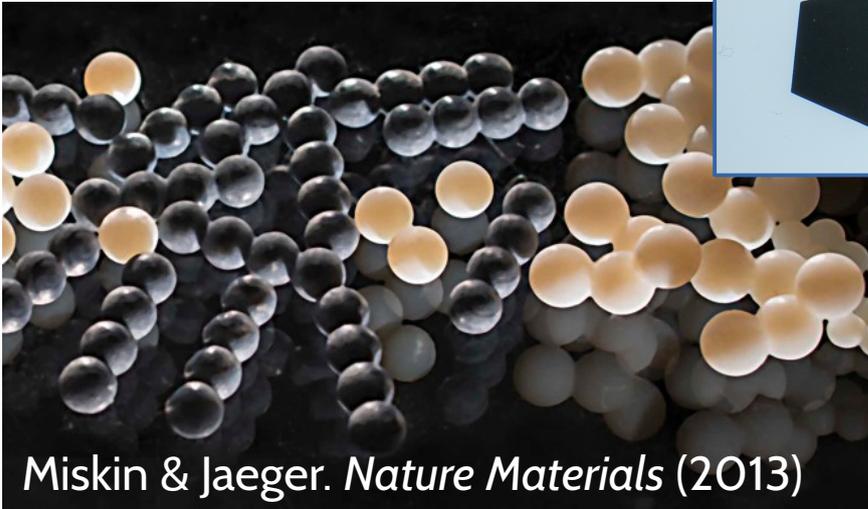
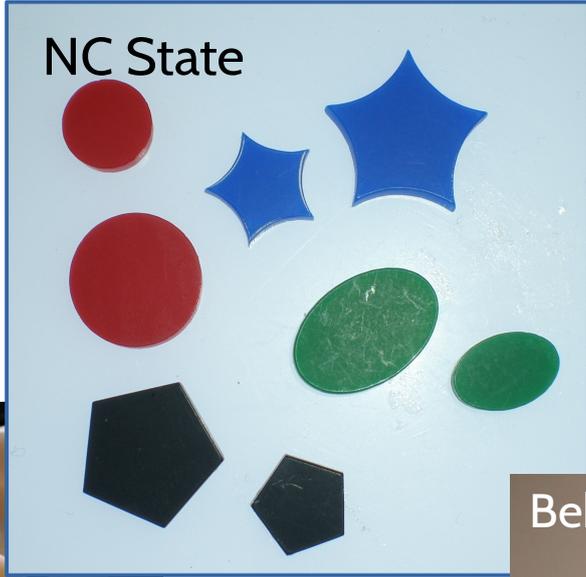


# Bespoke Particles

Neudecker, Ulrich,  
Herminghaus,  
Schröter. *PRL* (2013)

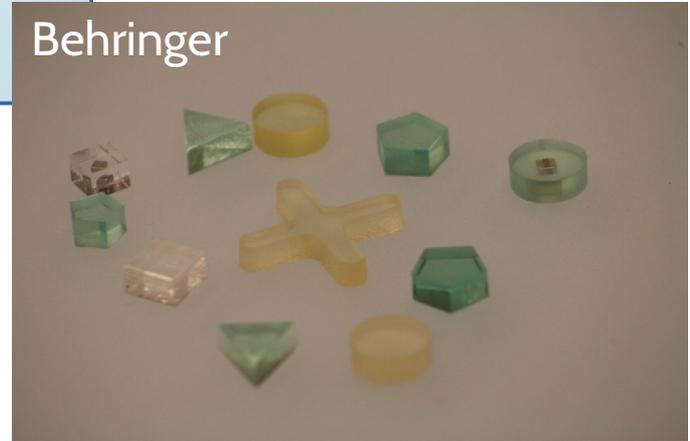


NC State

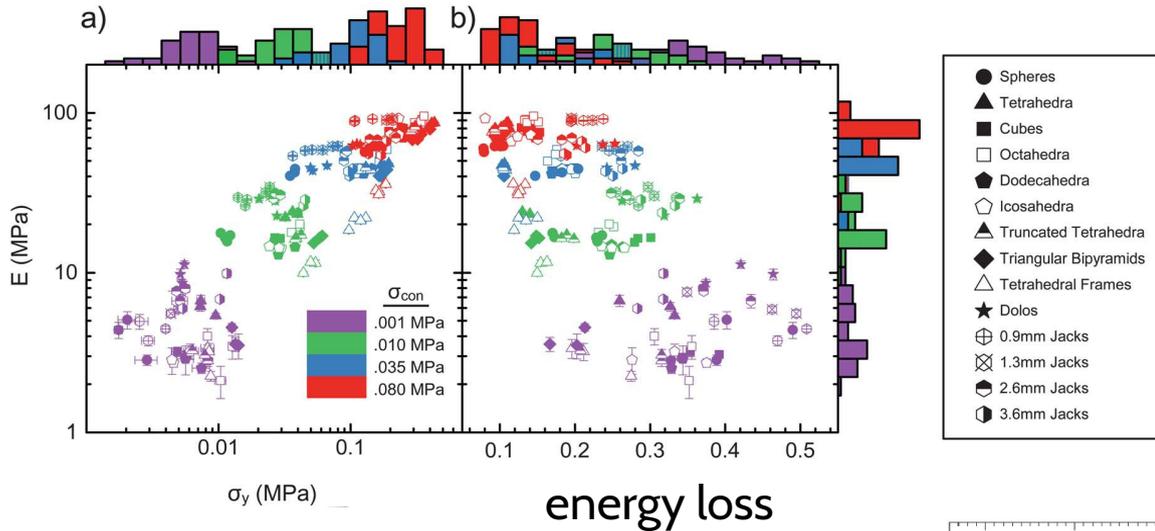


Miskin & Jaeger. *Nature Materials* (2013)

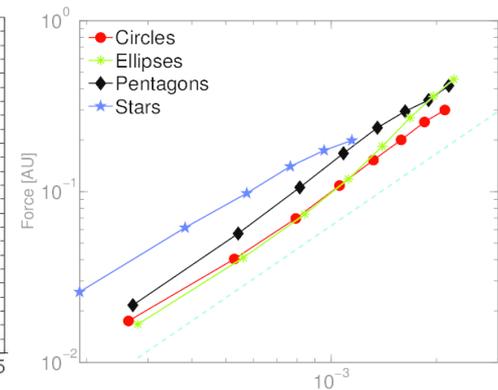
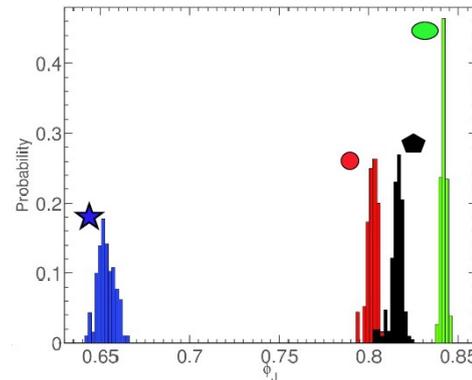
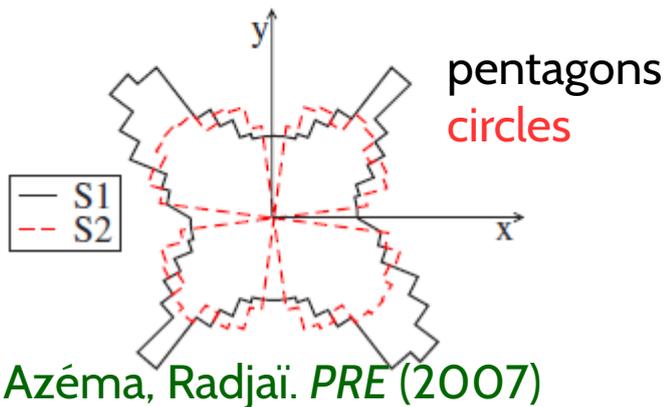
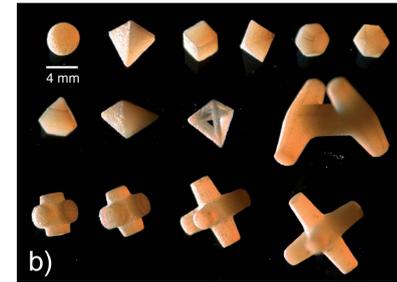
Behringer



# Isolating Shape Effects



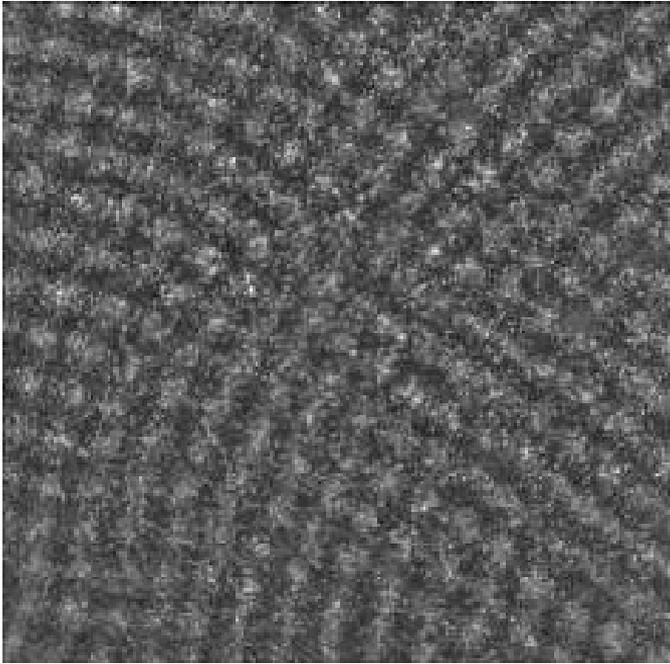
Athanassiadis...Jaeger. *Soft Matter* (2014)



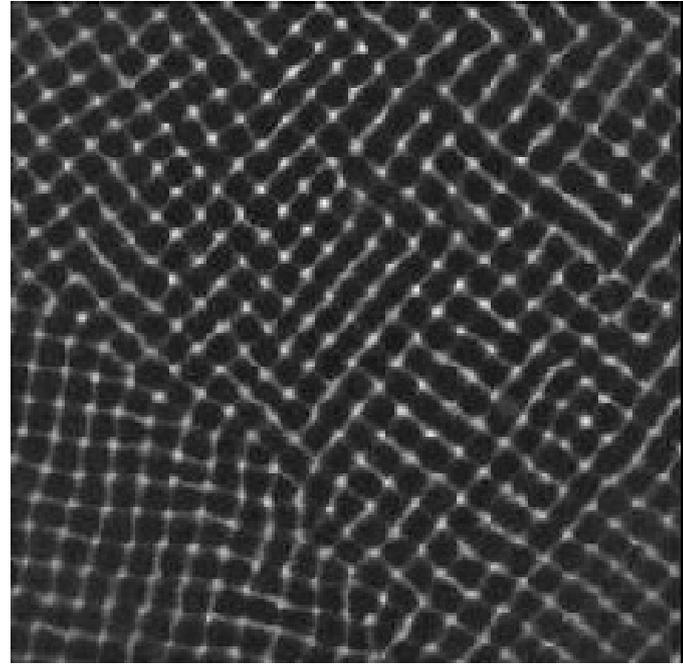
# Addition of Fines

Faraday patterns for 4 layers of 165  $\mu\text{m}$  bronze spheres

Dan Goldman, 2002 (PhD thesis)

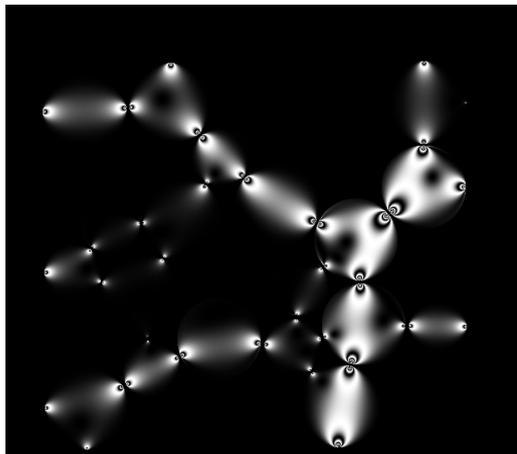
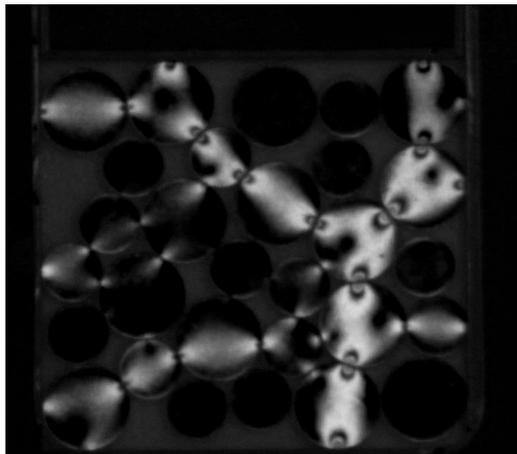


cleaned in acetone and  
methanol



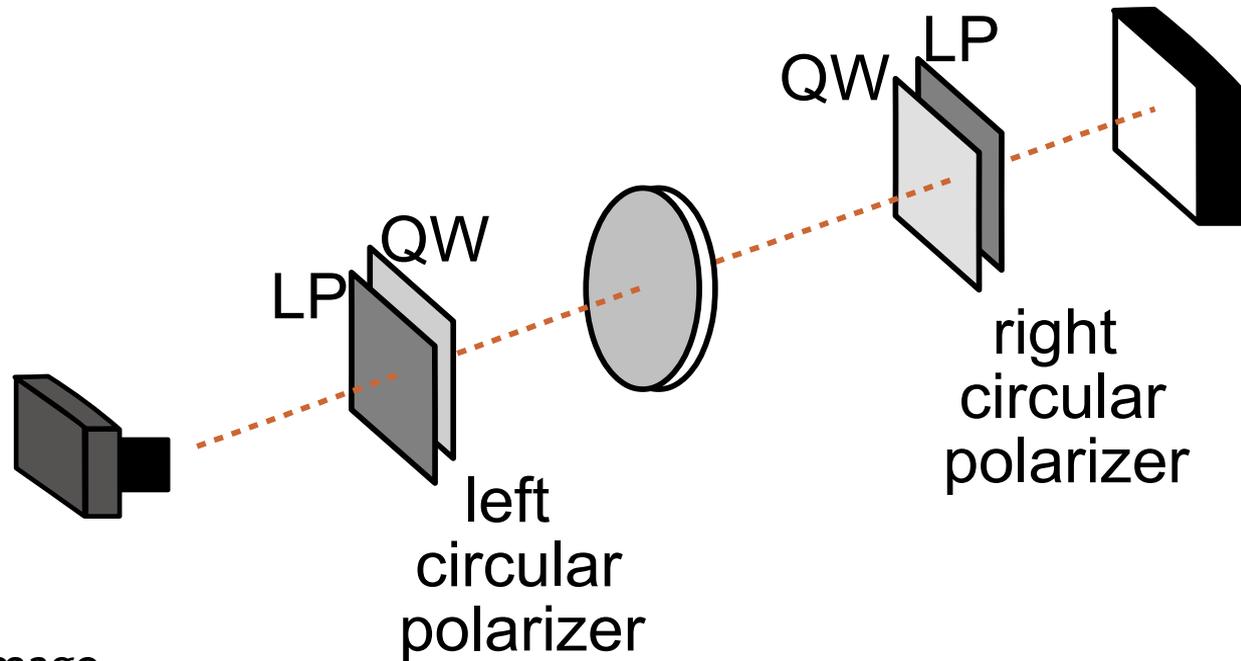
cleaned + a small amount of  
graphite powder

# Measuring Vector Forces



image

pseudoimage



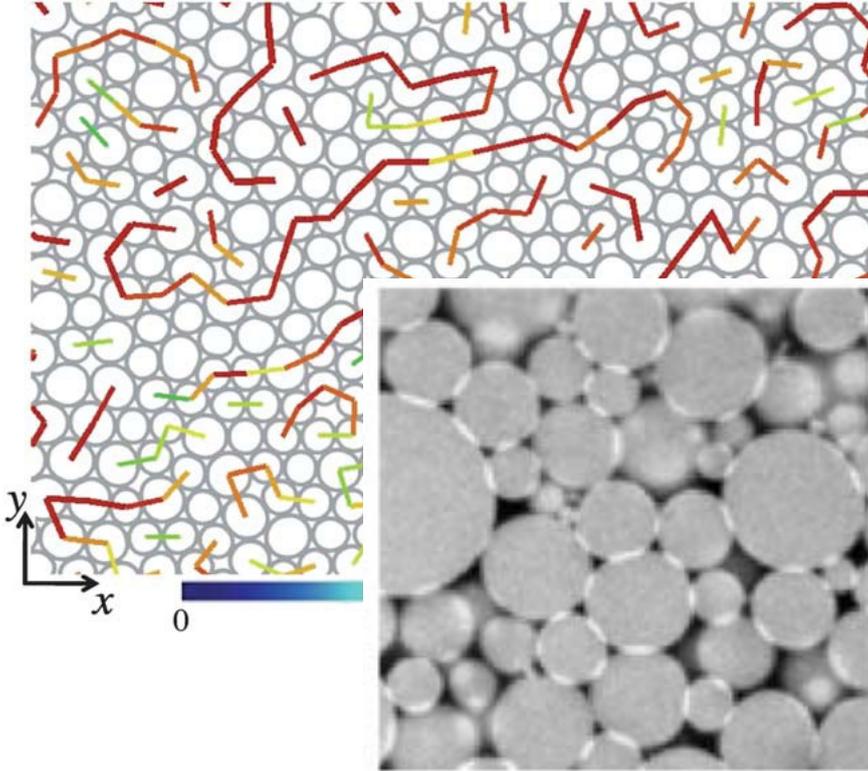
<https://arxiv.org/abs/1612.03525>  
<https://github.com/jekollmer/PEGS>

# Generality of Force Chains

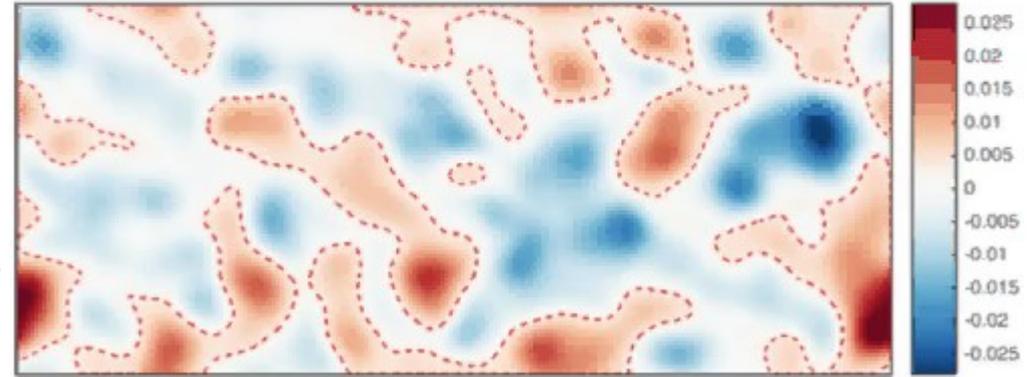
Lin .... Cohen. *Nature Materials*. (2016)

Desmond & Weeks. *Soft Matter* (2013)

2D emulsion



3D colloid

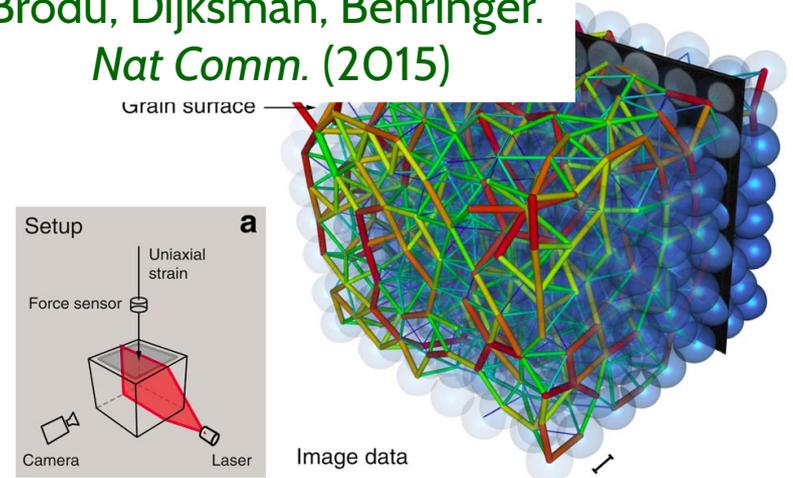


3D emulsion

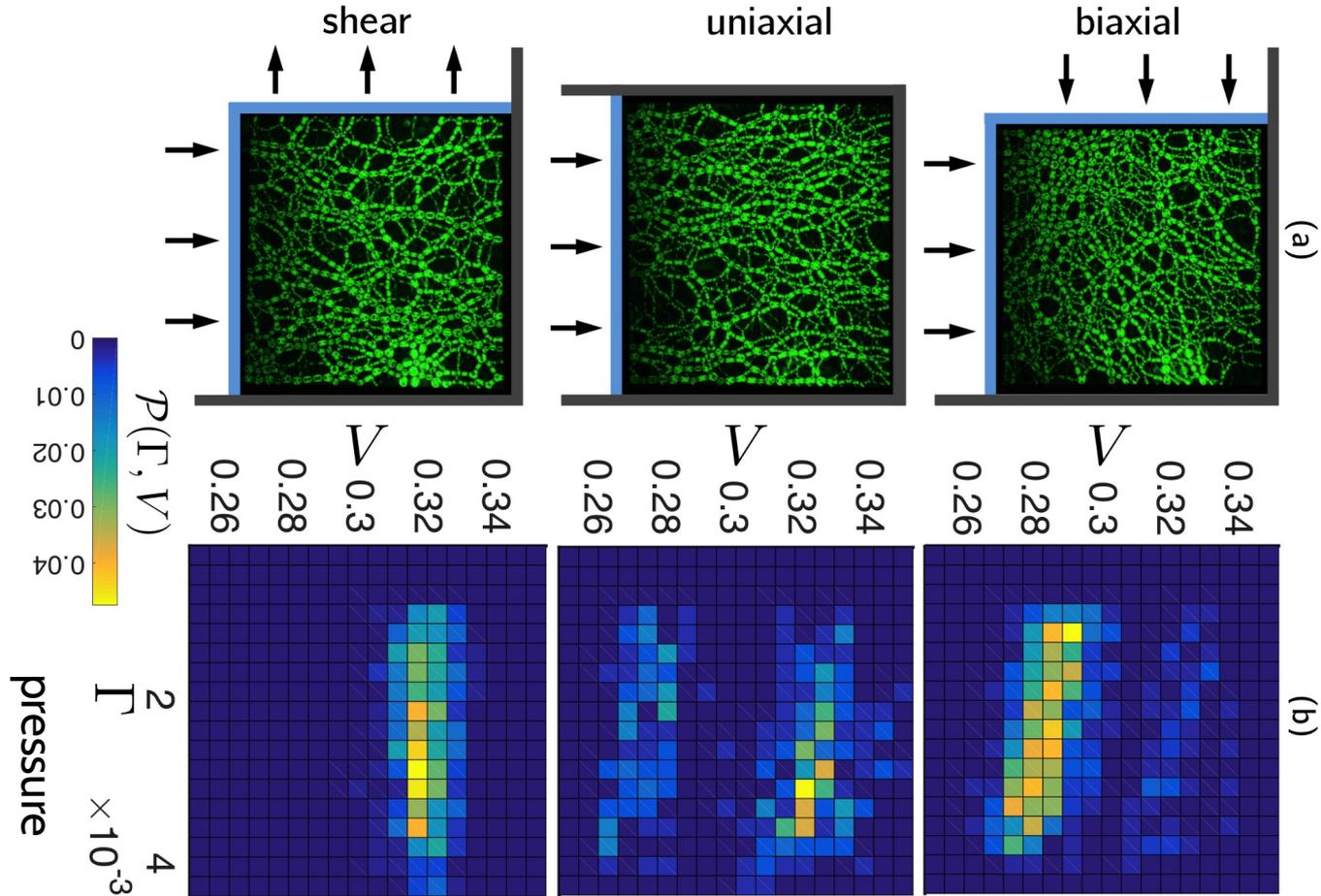
Brujic et al. *Physica A* (2003)

Brodu, Dijksman, Behringer. *Nat Comm*. (2015)

3D gel beads

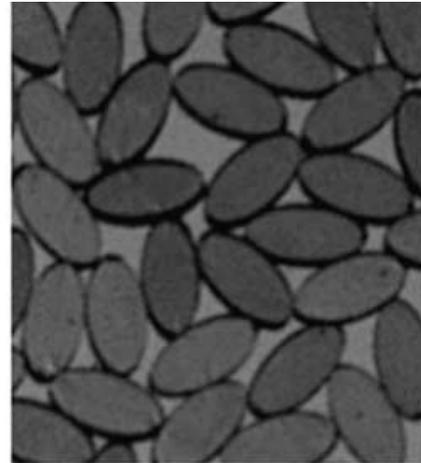
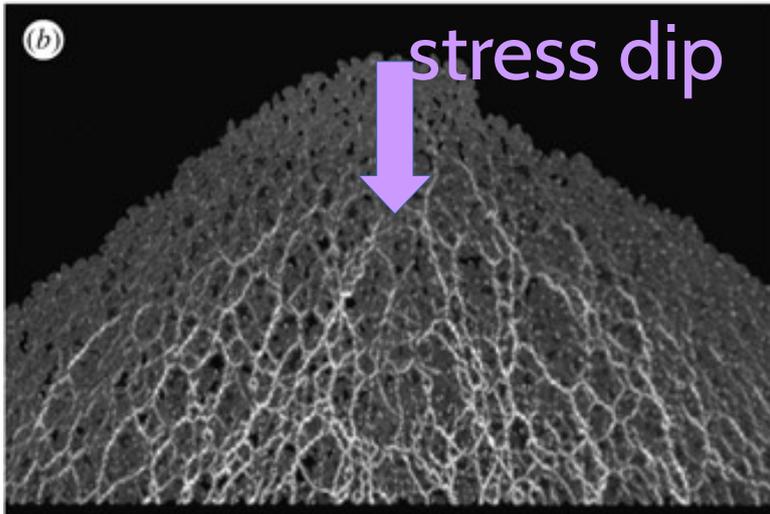
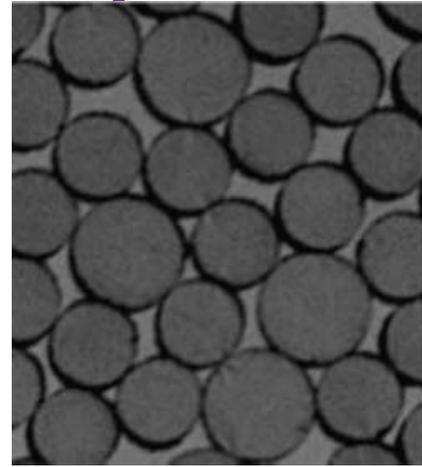
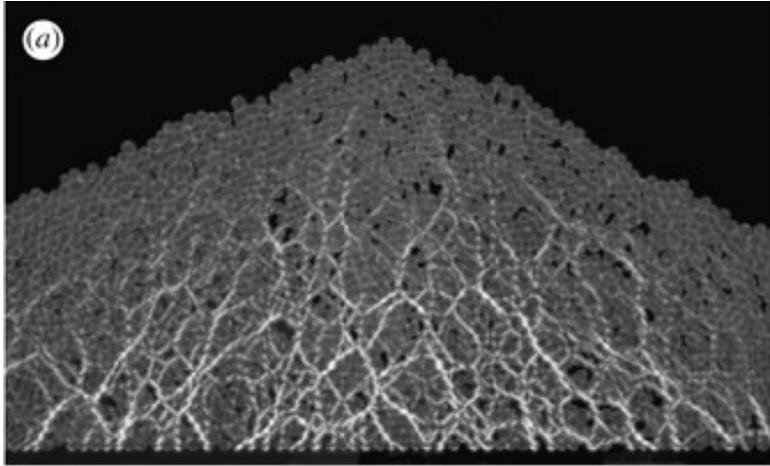


# Forces & History



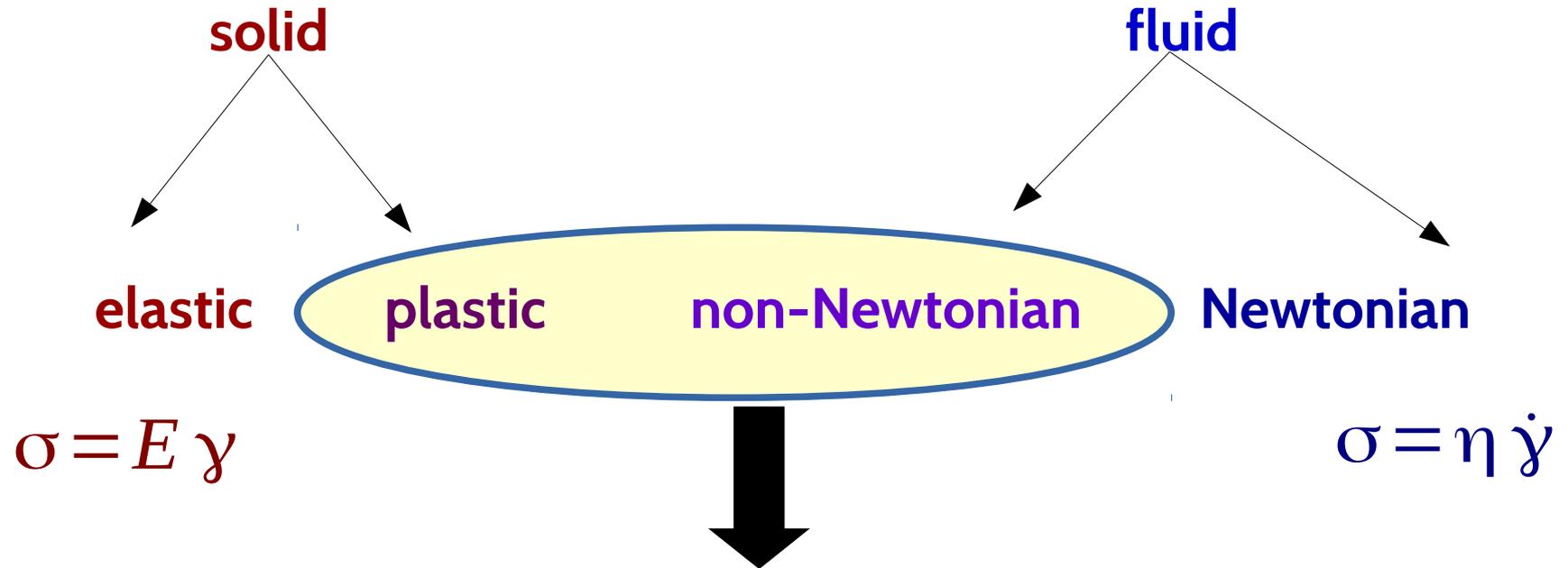
Bililign & Daniels  
(unpub)

# Forces & Shapes



Zuriguel, Mullin.  
*Proc Roy Soc A*  
(2008)

# Rheology



# Goal: .... take this input



- time taken for a powder to flow through an orifice
- force required to shear a disk through a prepared sample
- angle of repose

... output a constitutive law

# Key Failures of Local Rheology

- cannot quantitatively capture the transition from inertial to quasistatic (but still creeping) flow

Koval, Roux, Corfdir, Chevoir. EPJE (2009)

- boundary-driven flows form shear bands whose dimensions depend on both the geometry and the grain size

GDR MiDi. EPJE (2004)      Fenistein & van Hecke. *Nature* (2003)      Cheng, Lechman, ... Nagel. PRL (2006)

- shear/vibration in one region of a granular material can fluidize regions far from the perturbation

Nichol, Zanin, Bastien, Wandersman, van Hecke. PRL (2010)

Reddy, Forterre, Pouliquen. PRL (2011)

Wandersman & van Hecke. PRL (2014)

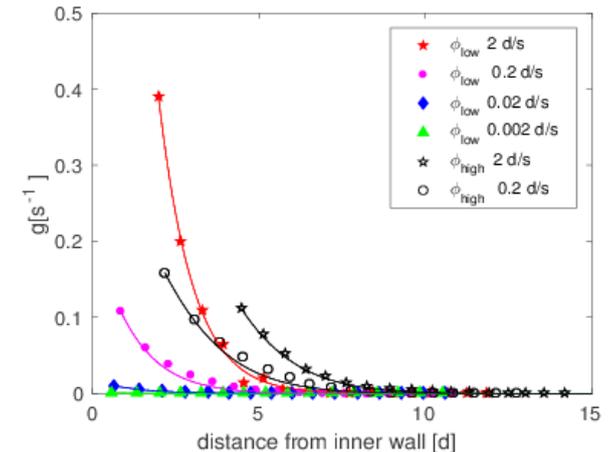
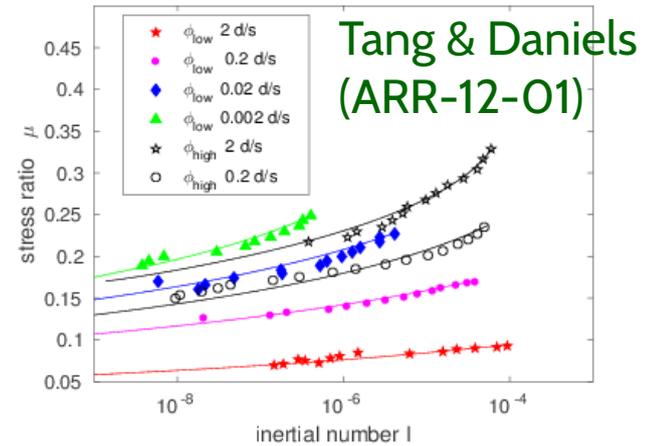
# Nonlocal Rheologies

- fluidization happens by a combination of local Coulomb failure and non-local activation
- granular fluidity  $g = g_{loc} + \xi^2 \nabla^2 g$

Kamrin & Koval. *PRL* (2012). Bouzid et al. *PRL* (2013).

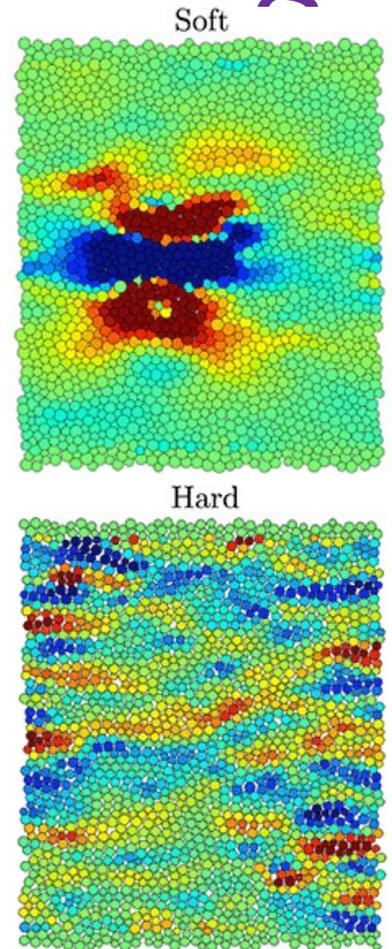
## Key Challenges

- direct tests of local vs. nonlocal effects
- understanding how  $g_{loc} = \frac{\dot{\gamma}}{\mu}$  and cooperativity length  $\xi$  depend on empirical  $\mu(I)$  and other grain-scale parameters
- transient behaviors (Hennan & Kamrin 201xyz)

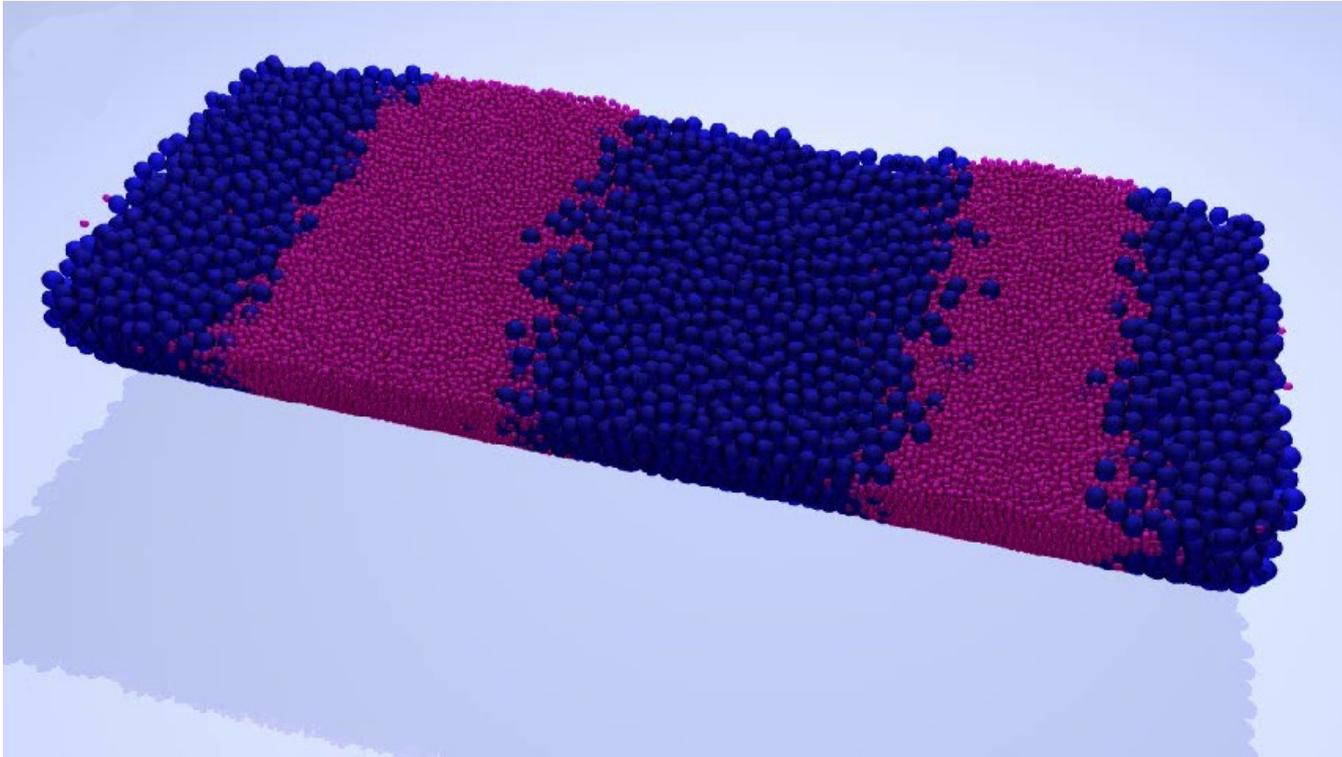


# Observations of Nonlocal Rheologies

- Bouzid et al. EPJE (2015) observations:
  - hard/soft particles matters
  - $\xi(\mu)$  doesn't distinguish models
- what about particle shape?
- need to directly test underlying assumptions
  - role of force chains in transmitting nonlocality?



# Tomography

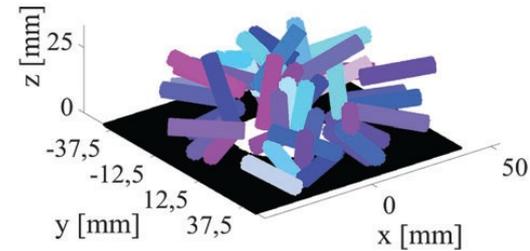
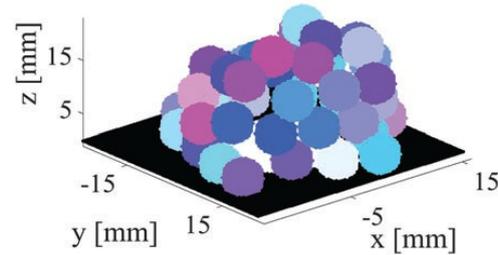
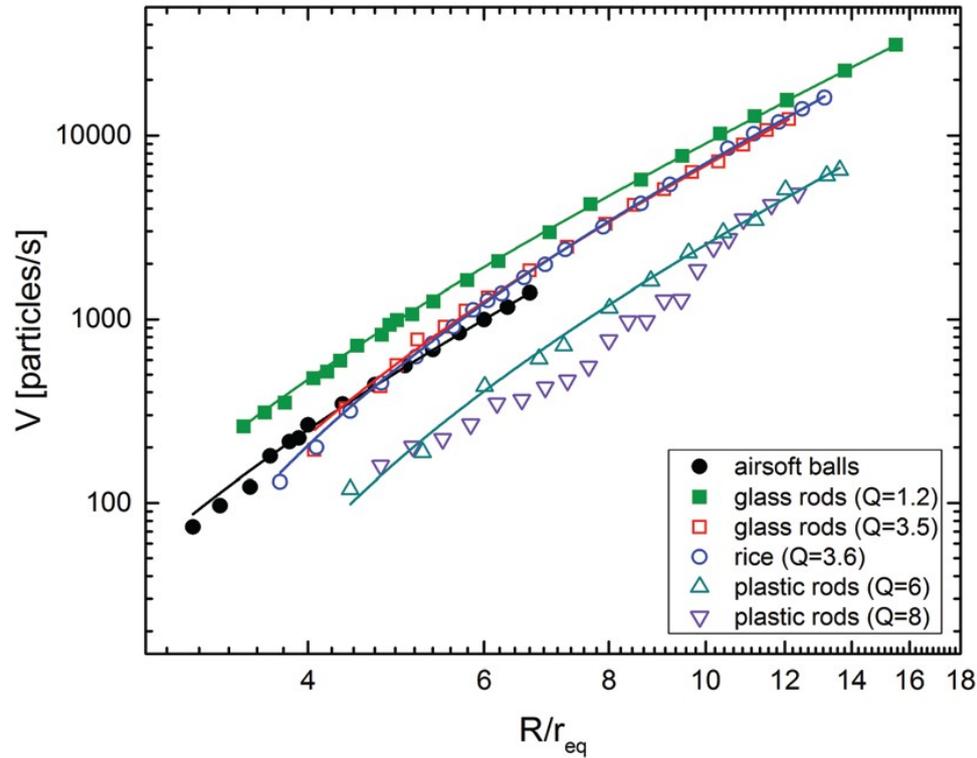


upcoming  
*Rev Sci Inst.*  
“Focus on  
Granular  
Imaging”

<https://www.youtube.com/watch?v=dN0145p38dU>

Matthias Schröter (Göttingen/Erlangen)

# Tomography → Shape & Flow



Ashour, Wegner, Trittel, Börzsönyi,  
Stannarius. *Soft Matter* (2017).