The collective behavior of particles with "noisy" interactions but no thermal noise

Indeterminate/noisy interactions: friction, adhesion,…

Why do we look to statistical mechanics ?

Distributions are reproducible

How do we think of micro states ?

Normally: {particle positions, momenta}, interactions known

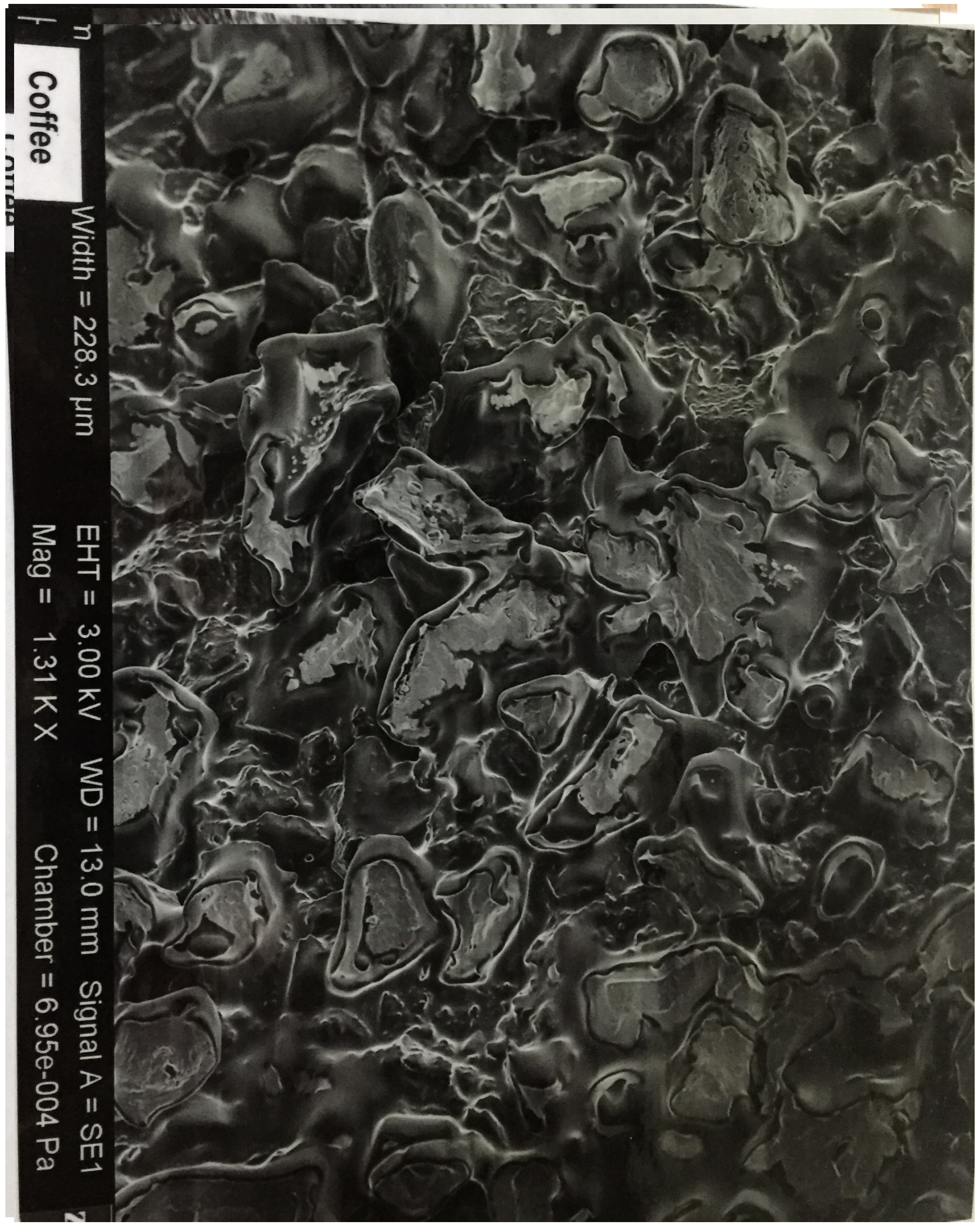
Pivot to: {particle positions, forces}

How do we think of statistical ensemble ?

Analogs of microcanonical, canonical, etc.

Let's start with some phenomenology & Thought Experiments

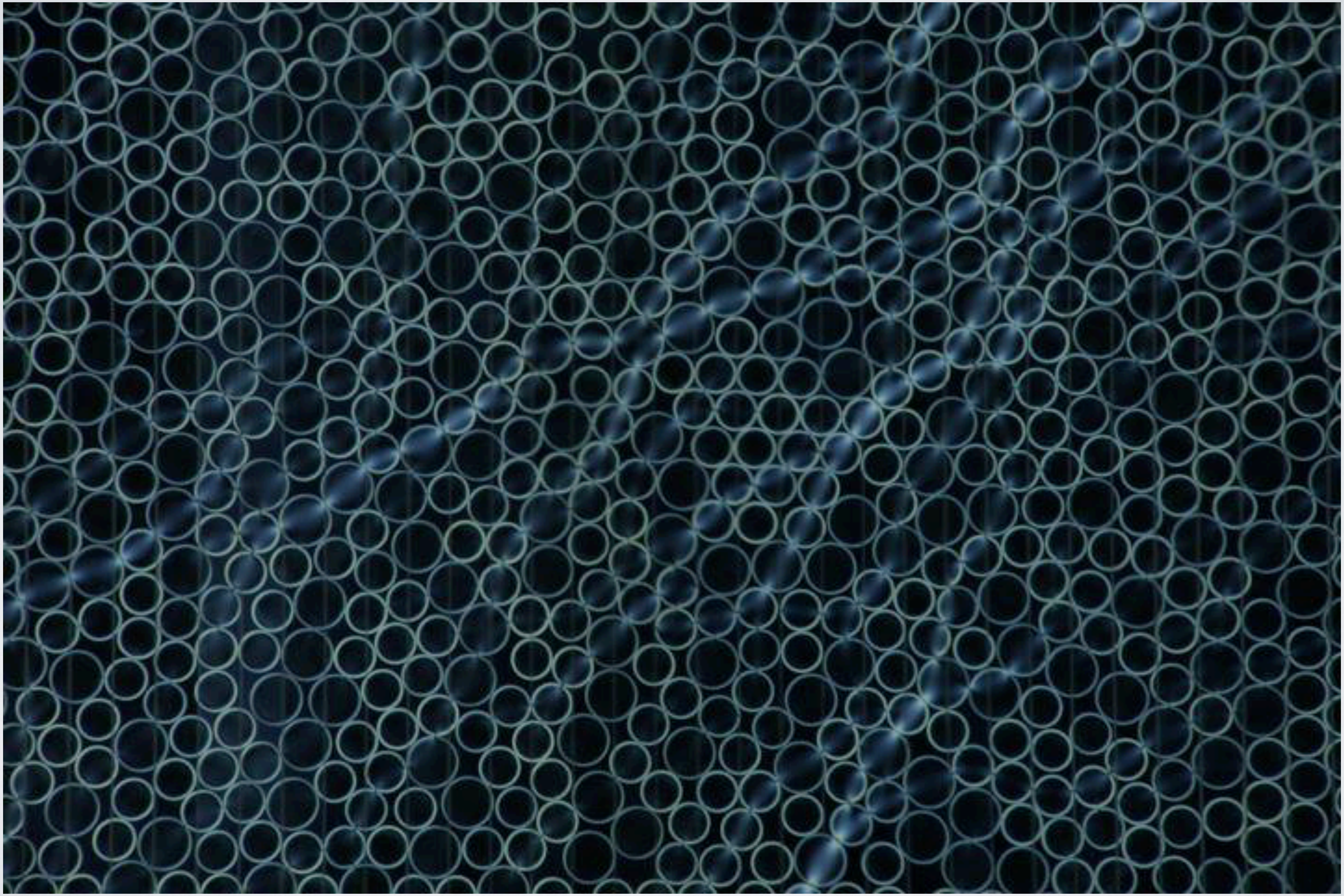
WHAT TYPE OF MATERIALS?



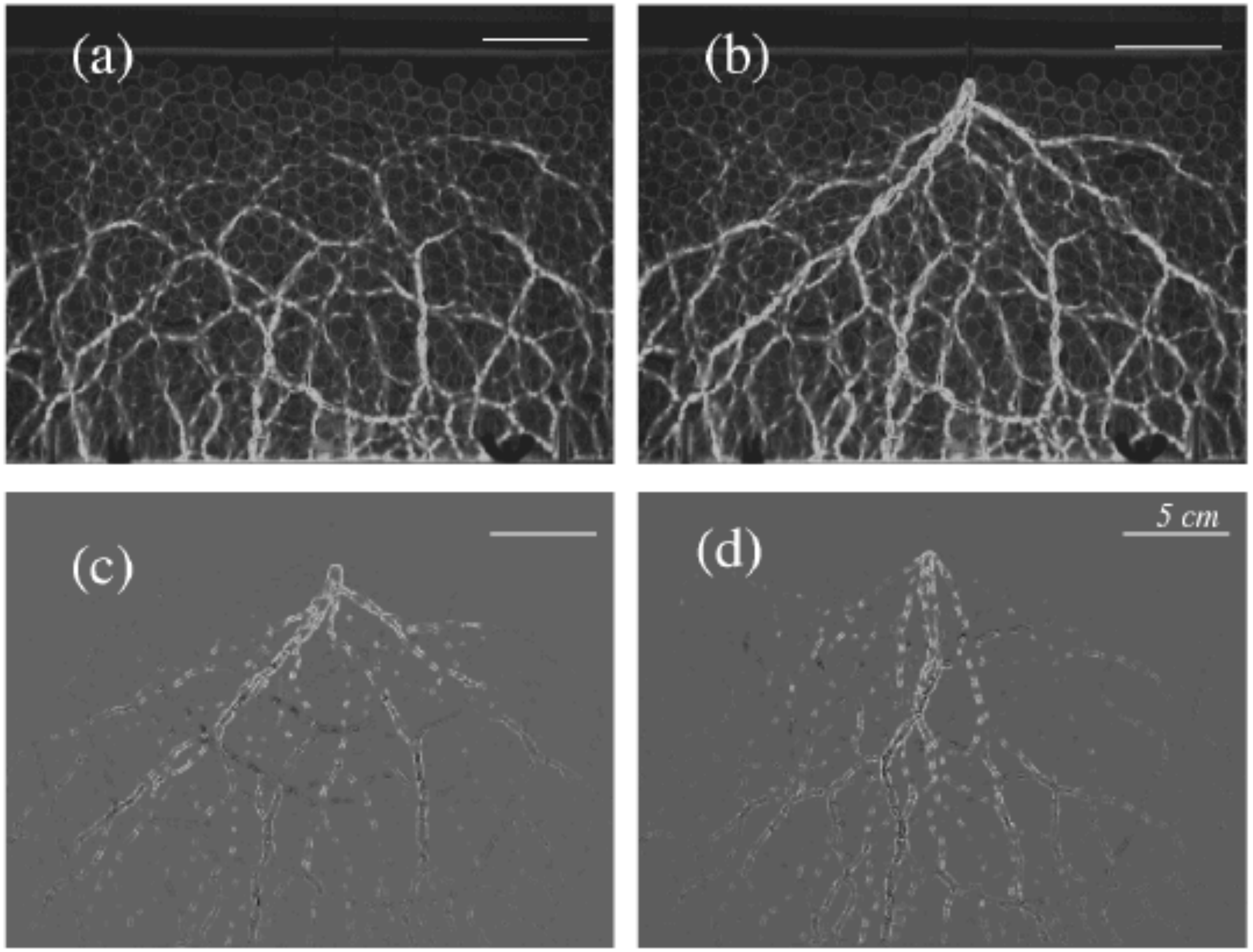
- **Collection of macroscopic objects**
- **Purely repulsive, contact interactions.**
- **No thermal fluctuations to restore or create contacts**
- **Particles are rough**
- **Friction: Forces are independent degrees of freedom. No Hamiltonian.**
- **States controlled by driving at the boundaries or body forces: shear, gravity**
- **Non-ergodic in the extreme sense: stays in one configuration unless driven**

- **No thermal or quantum fluctuations, yet states are characterized by broad distributions that are reproducible: definition of solid ? fluid ?**
- **Stress-driven transitions: triggered by changes in grain-grain interactions due to driving.**

Behringer: Looking inside "sand"



Experiments: Stress Transmission

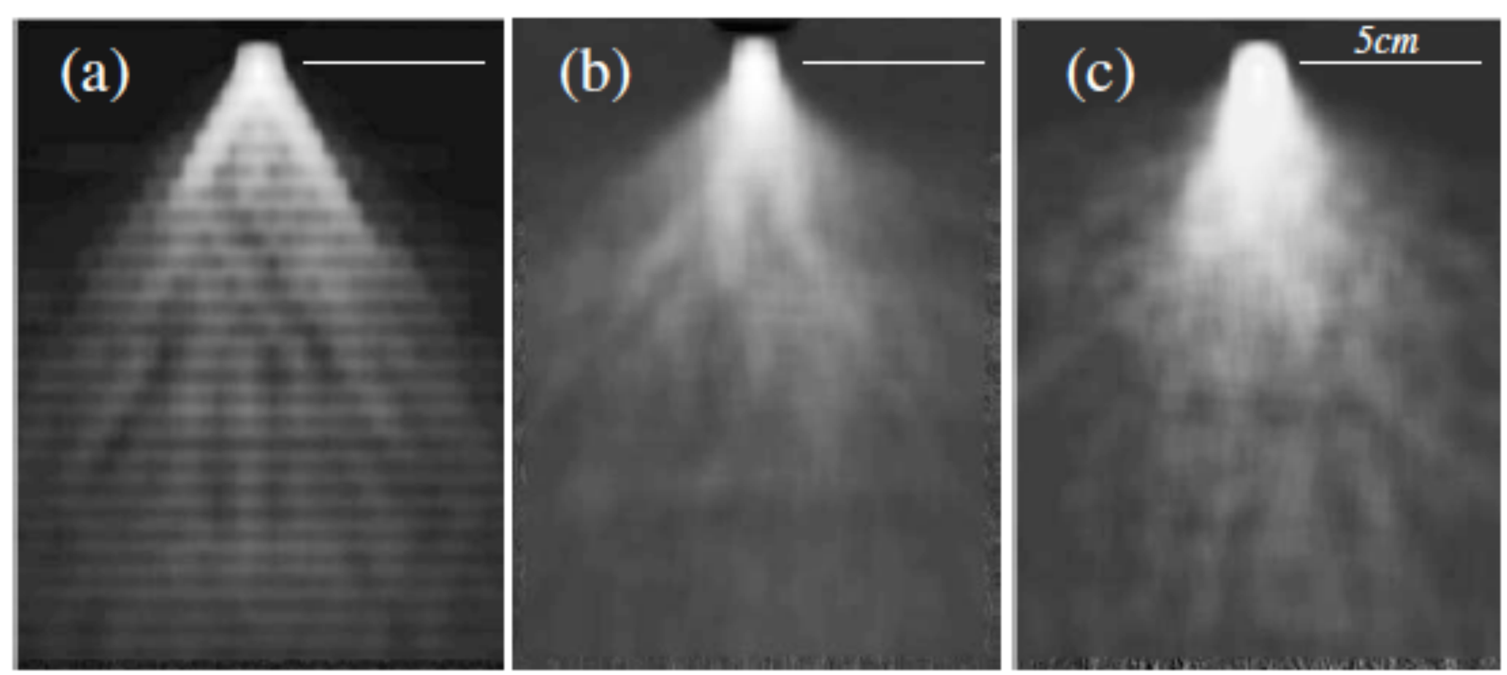


"Forces are carried primarily by a tenuous network that is a fraction of the total number of grains" Geng et al, PRL (2001)

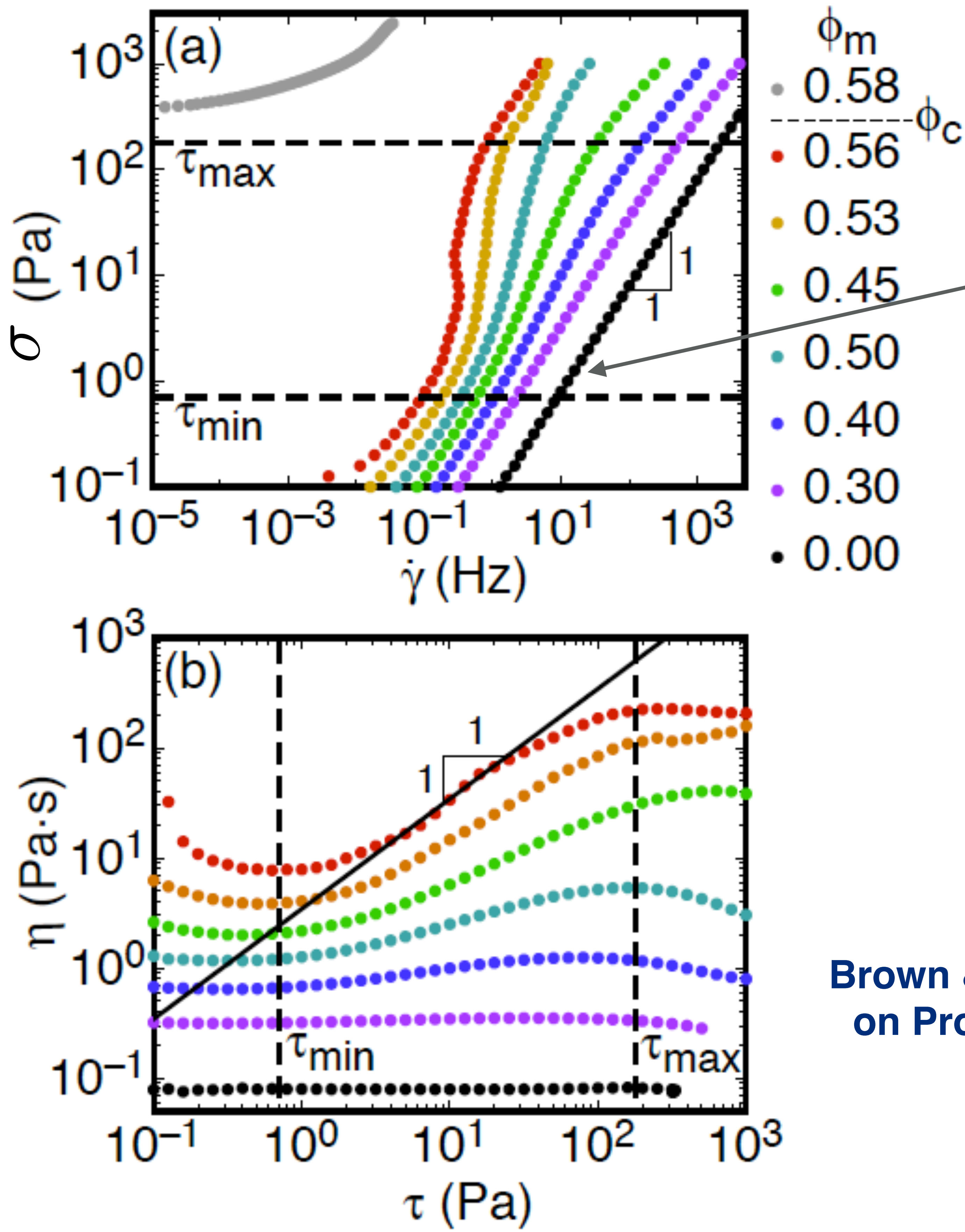
We will see that there is an analogy between these "force chains" and charge propagation in a kind of E&M theory with vector charges

Ensemble averaged patterns of response are sensitive to nature of underlying spatial disorder

Granular media are like dielectrics in this strange E&M: network determines the polarizability

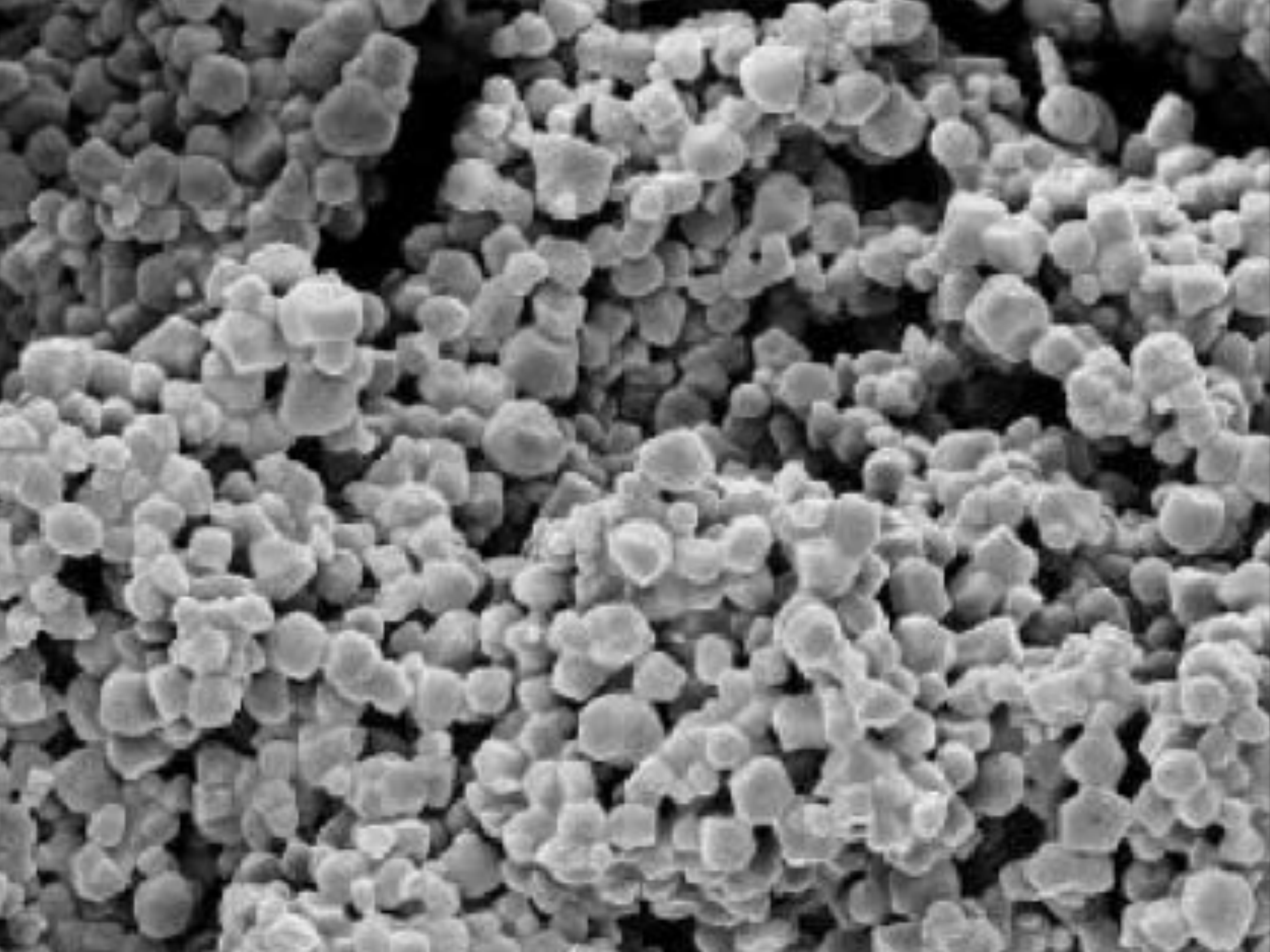


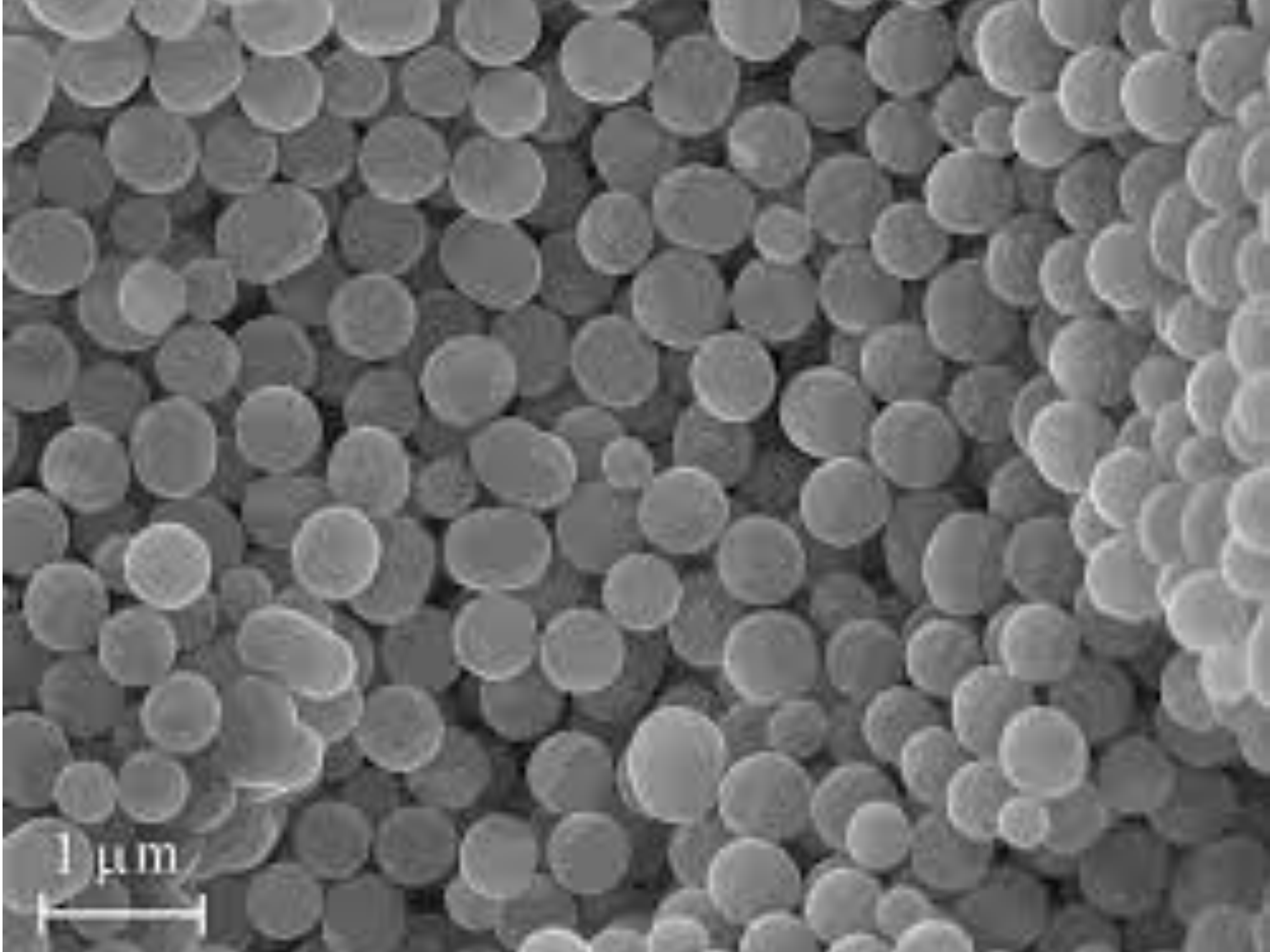
Discontinuous Shear Thickening (DST)



Newtonian Fluid

Brown & Jaeger: Reports on Progress in Physics (2013)

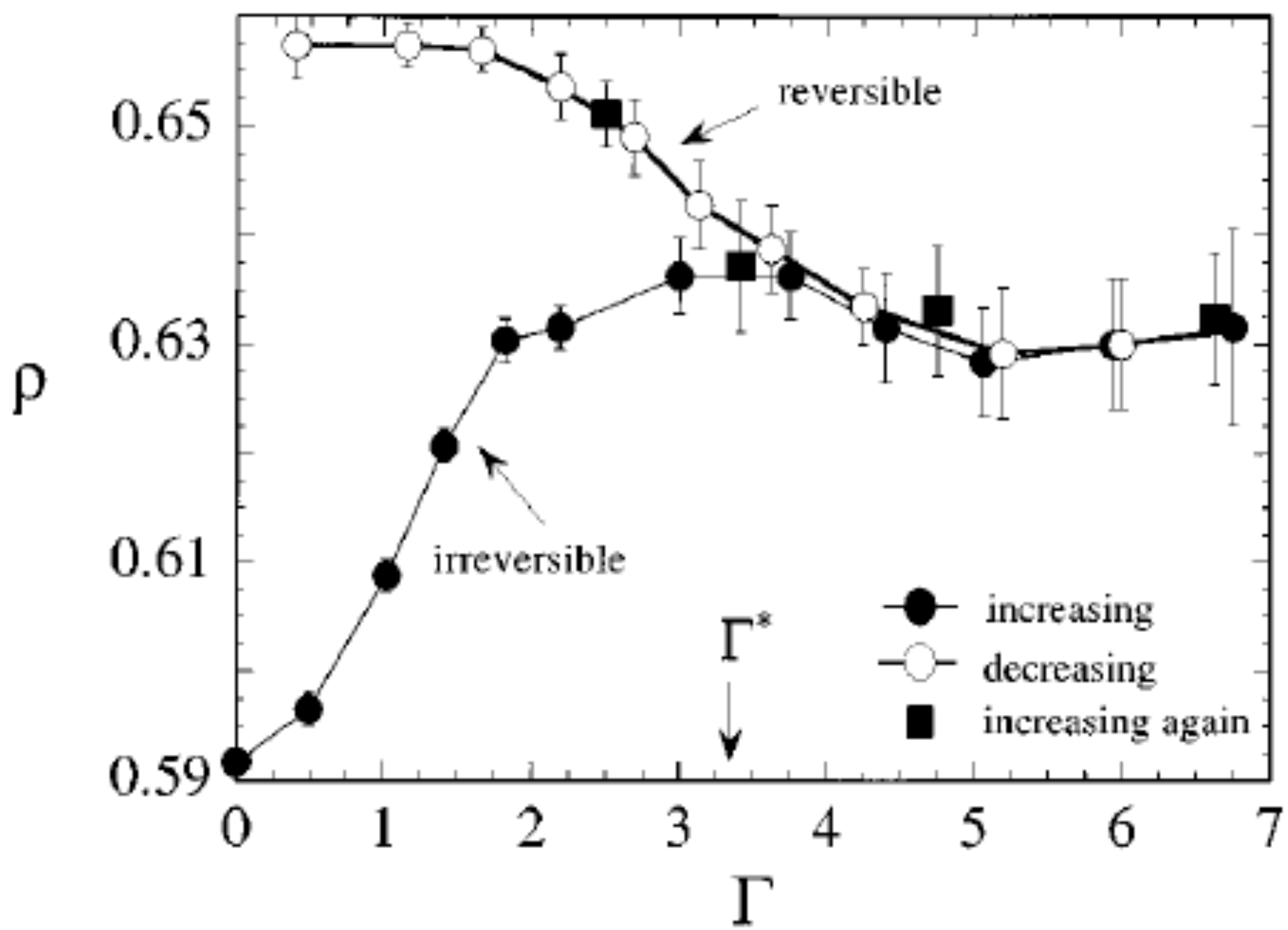



1 μm

Fluctuations

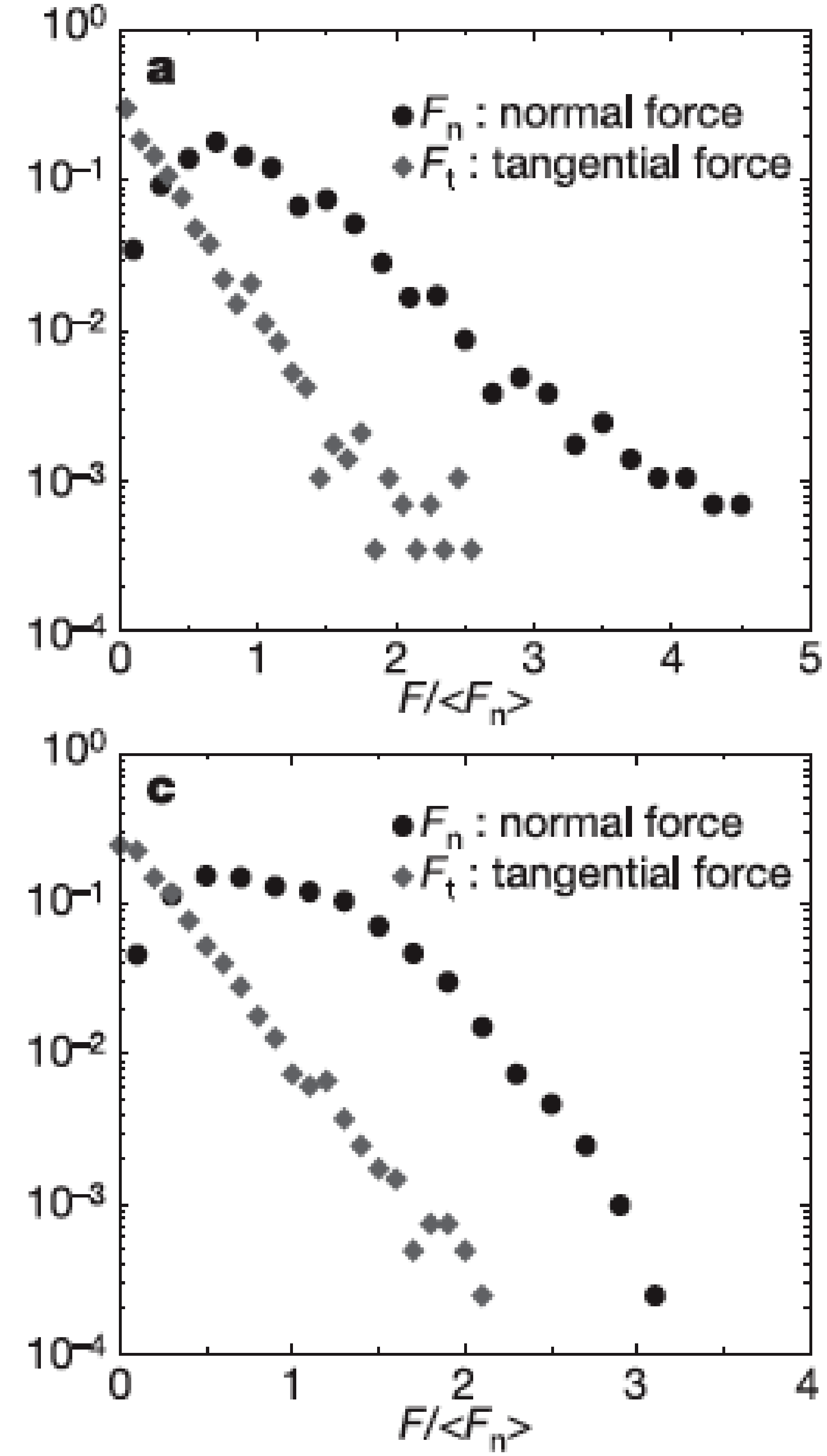
One of the salient features of noncohesive granular materials is that they can be packed over a range of densities and still retain their resistance to shear. For example, a stable conglomeration of monodisperse spheres can exist with a packing fraction ρ ranging from $\rho \approx 0.55$ (the random loose packed limit) to $\rho \approx 0.64$ (the random close packed limit) and even to $\rho \approx 0.74$ (the crystalline state). Because thermal energies, $k_B T$, are insignificant when compared to the energy it takes to rearrange a single particle, each metastable configuration will persist indefinitely until an external vibration comes along to knock it into another state. Thus, no thermal averaging takes place to equilibrate the system. The density of the material is determined both by its initial preparation and by the manner in which it was handled or processed, since such activities normally introduce some vibrations into the material. The phase space for the granular medium is explored not by fluctuations induced by ordinary temperature but by fluctuations induced by external noise sources, such as vibrations. It is the goal of this paper to provide an experimental foundation for the use of such fluctuations as a probe of the dynamics as well as the microstructure of granular media in the quasistatic, densely packed limit.

Statistics of Fluctuations (slow, broad)



Slow Dynamics

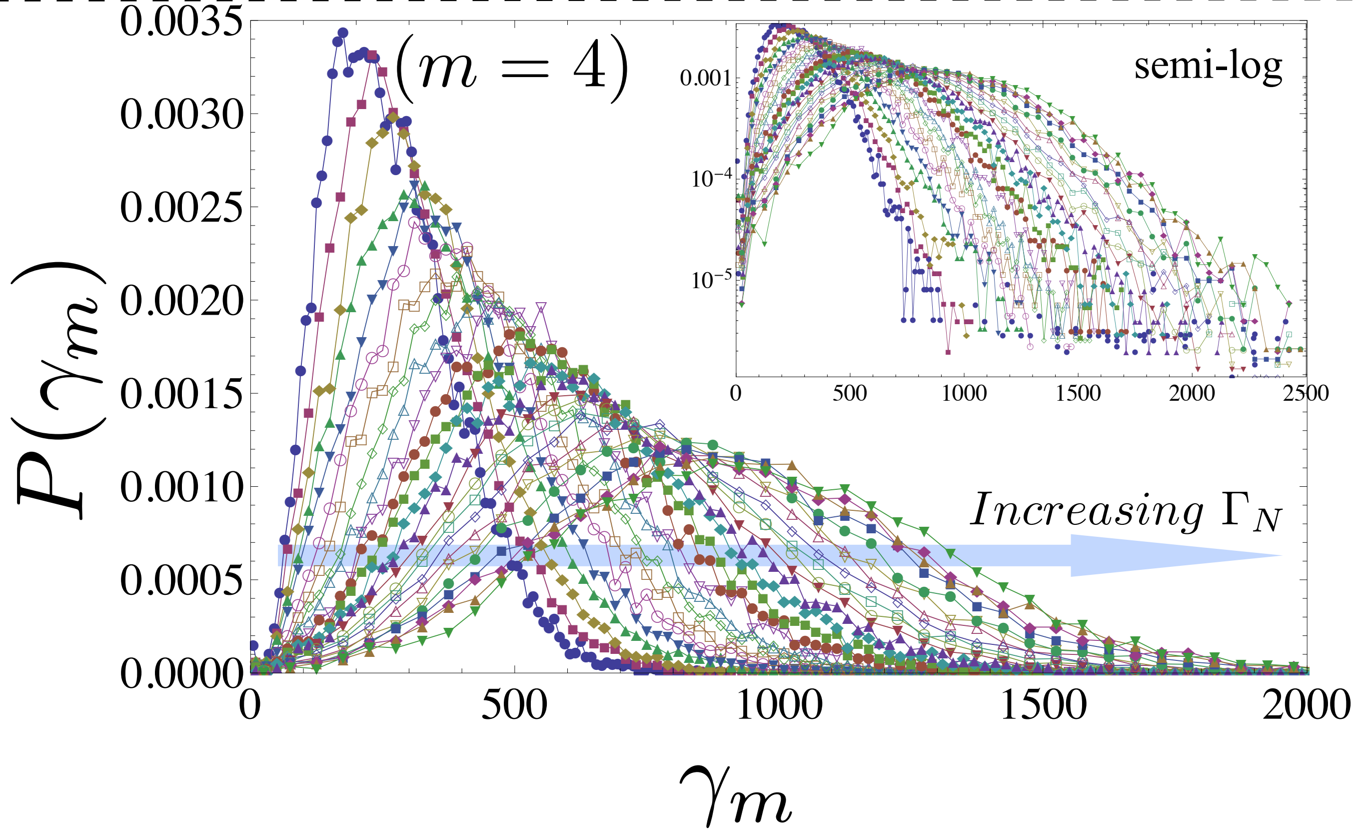
E. R. Nowak et al Phys Rev E (1997)

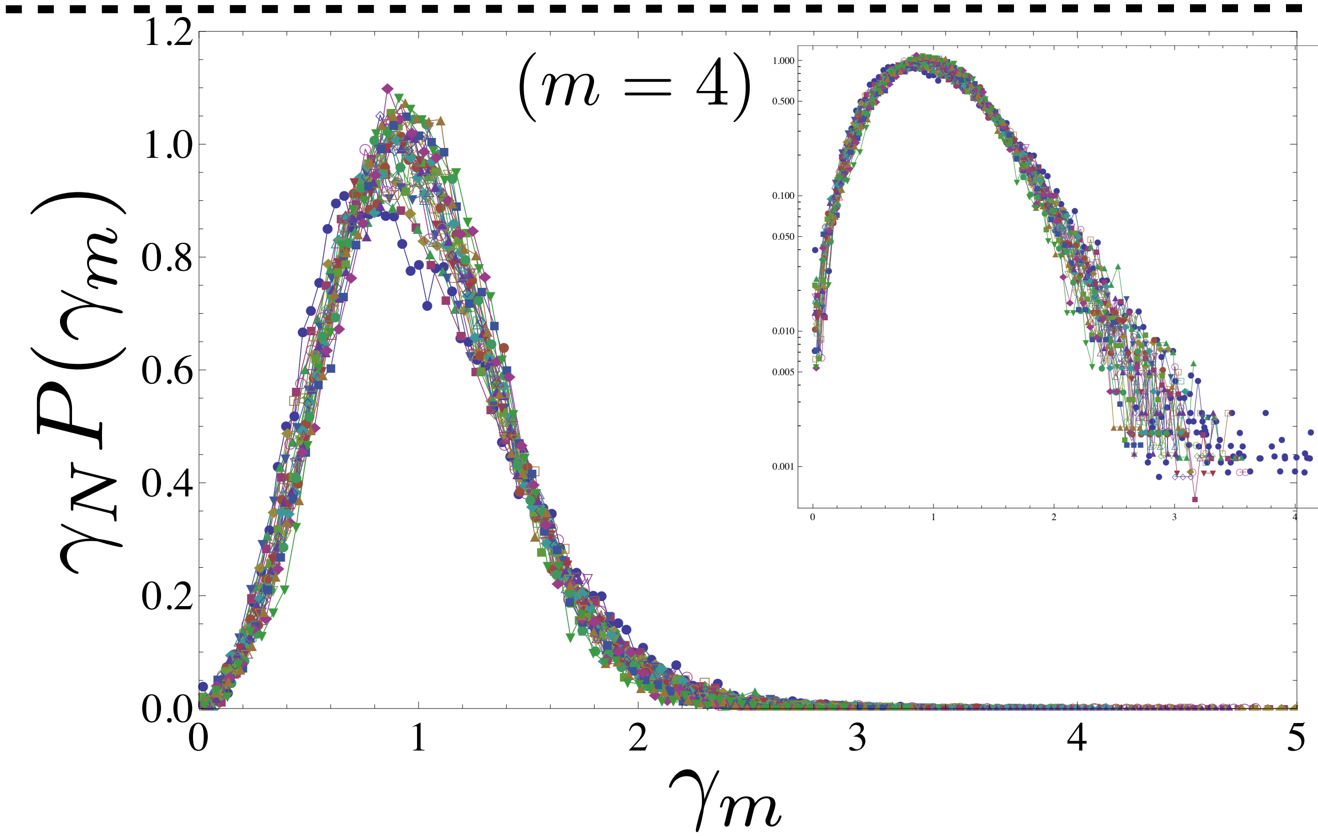


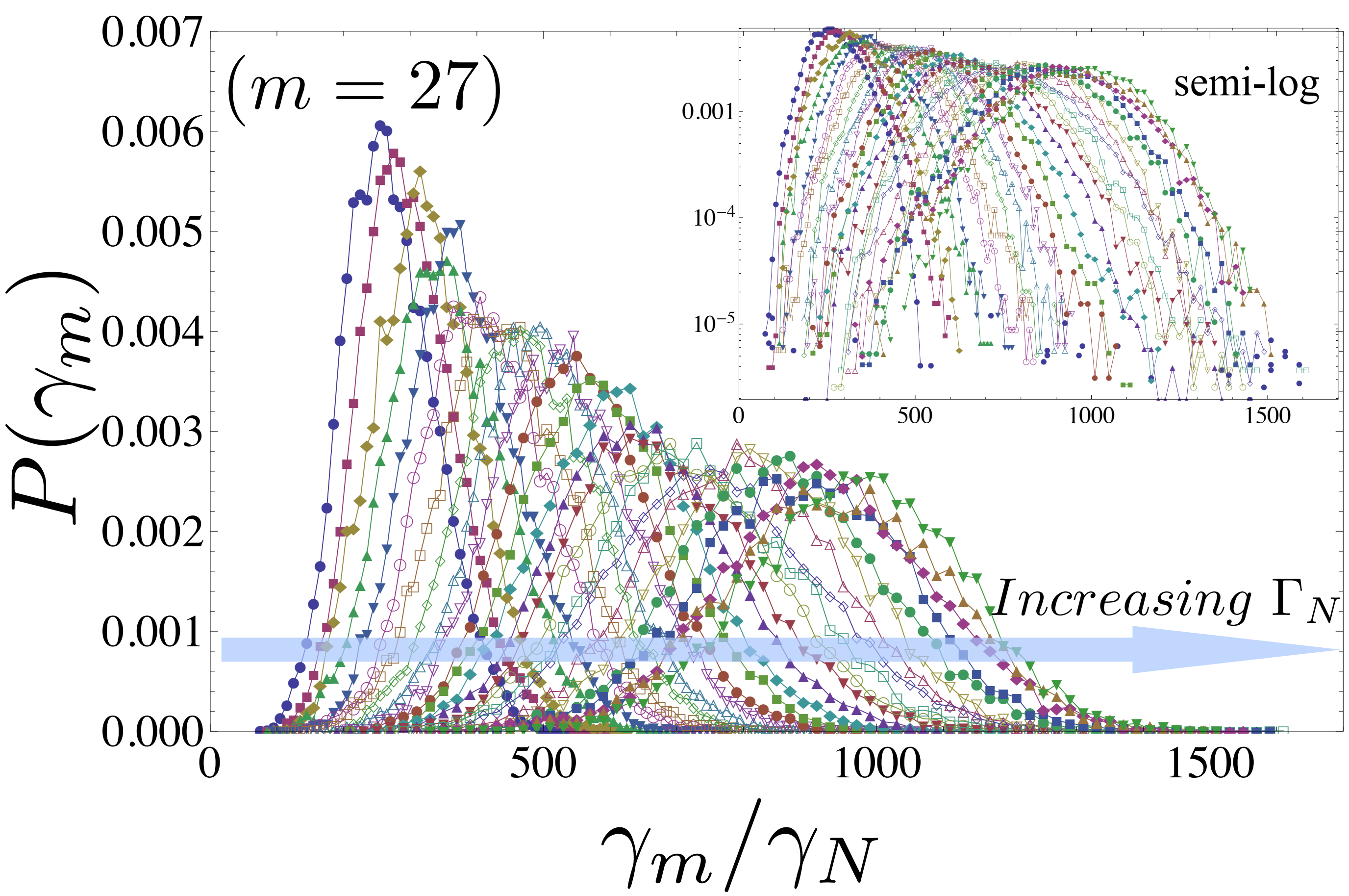
T. S. Majmudar & R. P. Behringer Nature, June, 2005

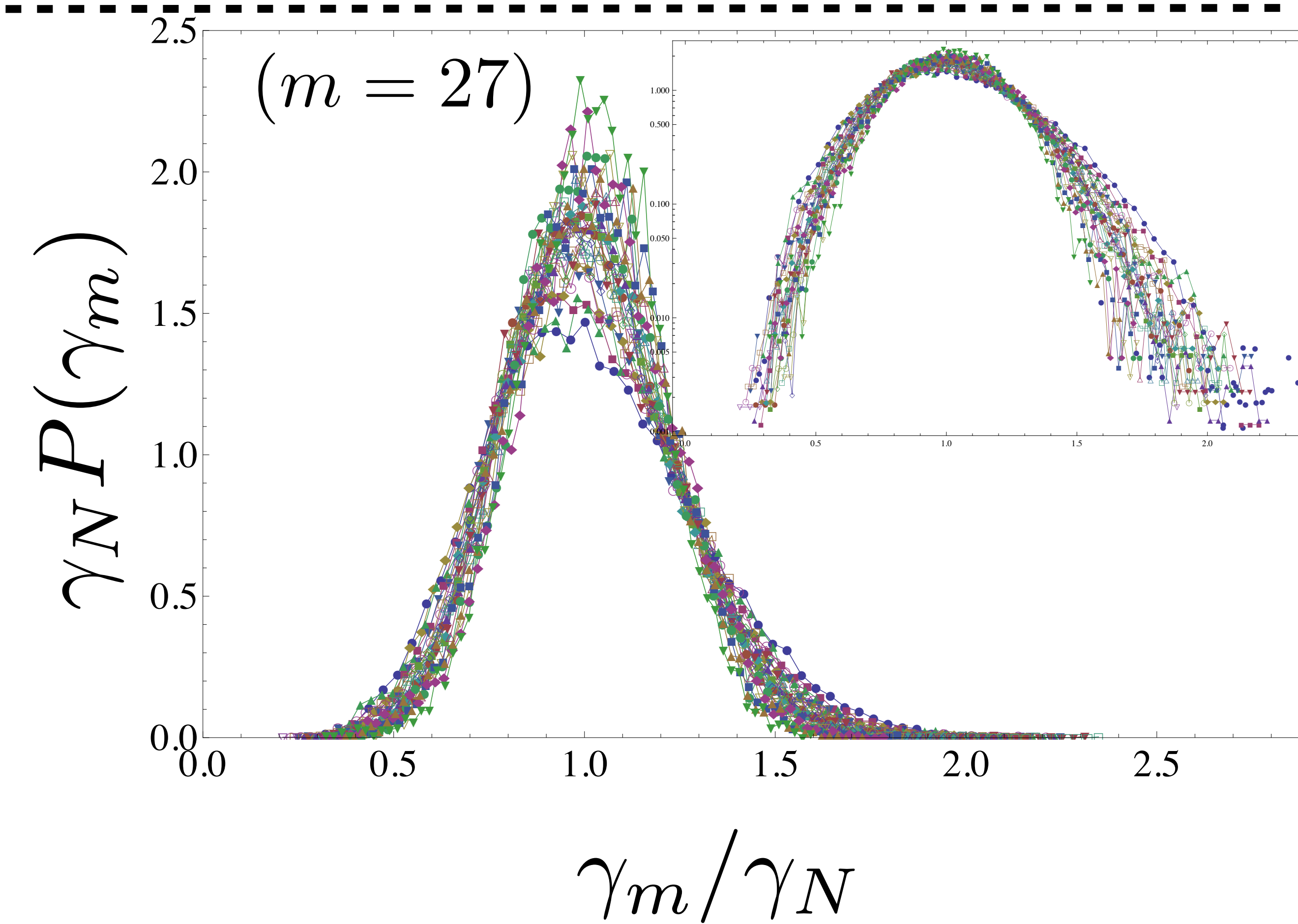
Local Stresses

onto a universal scaling function when the subregion (local) pressure is scaled by the external pressure. This holds for all coarse-graining sizes.

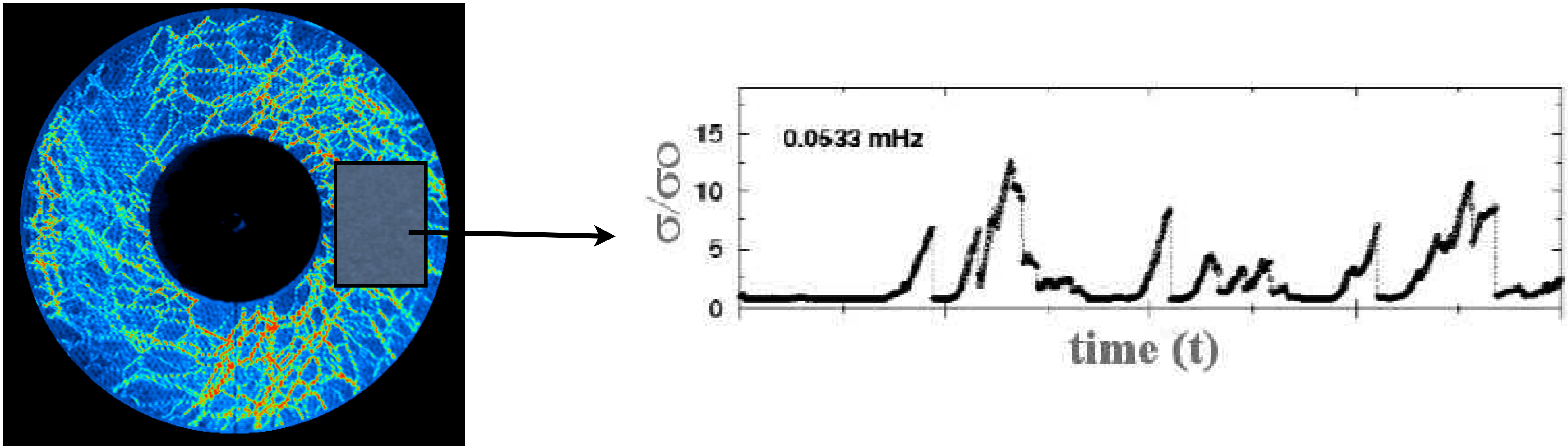


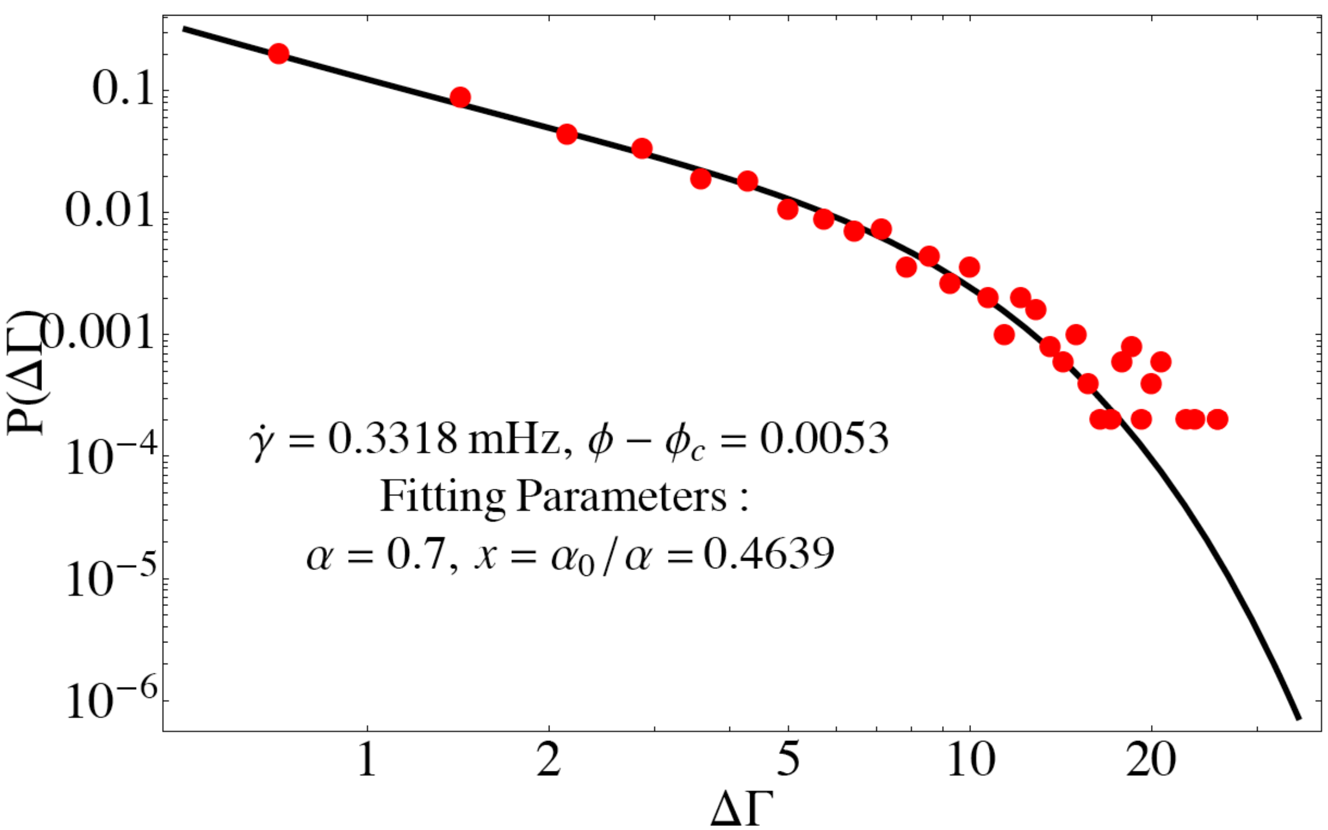


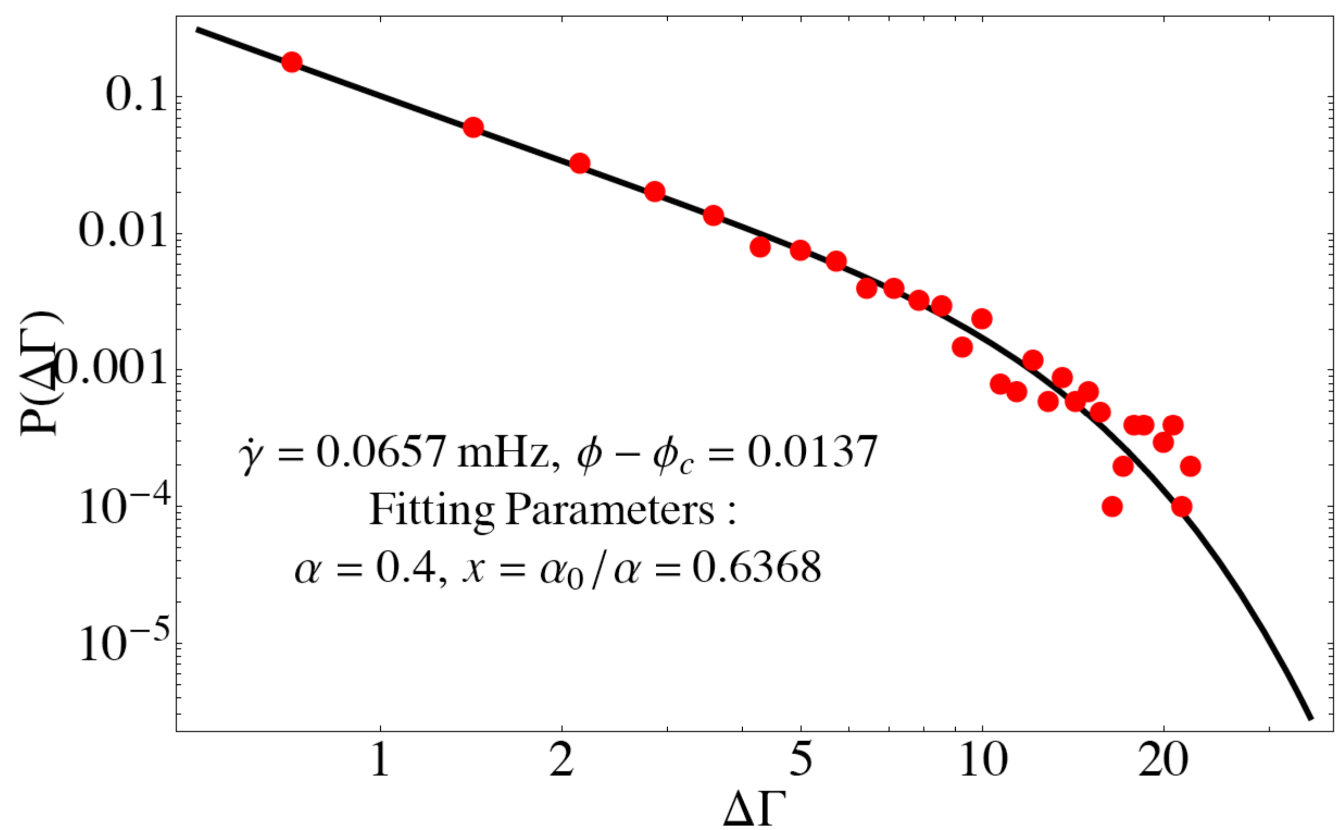




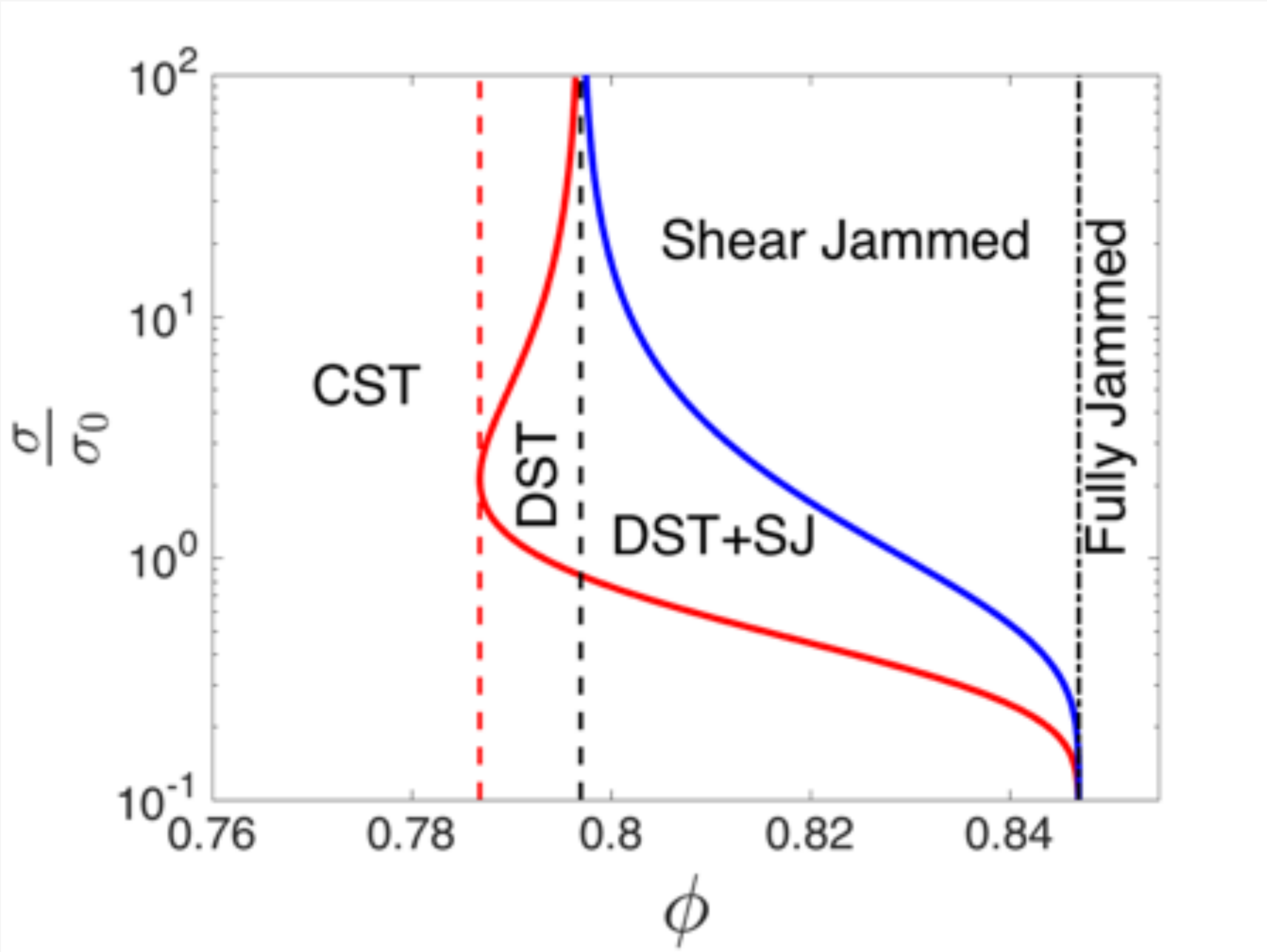
Quasistatic Flows

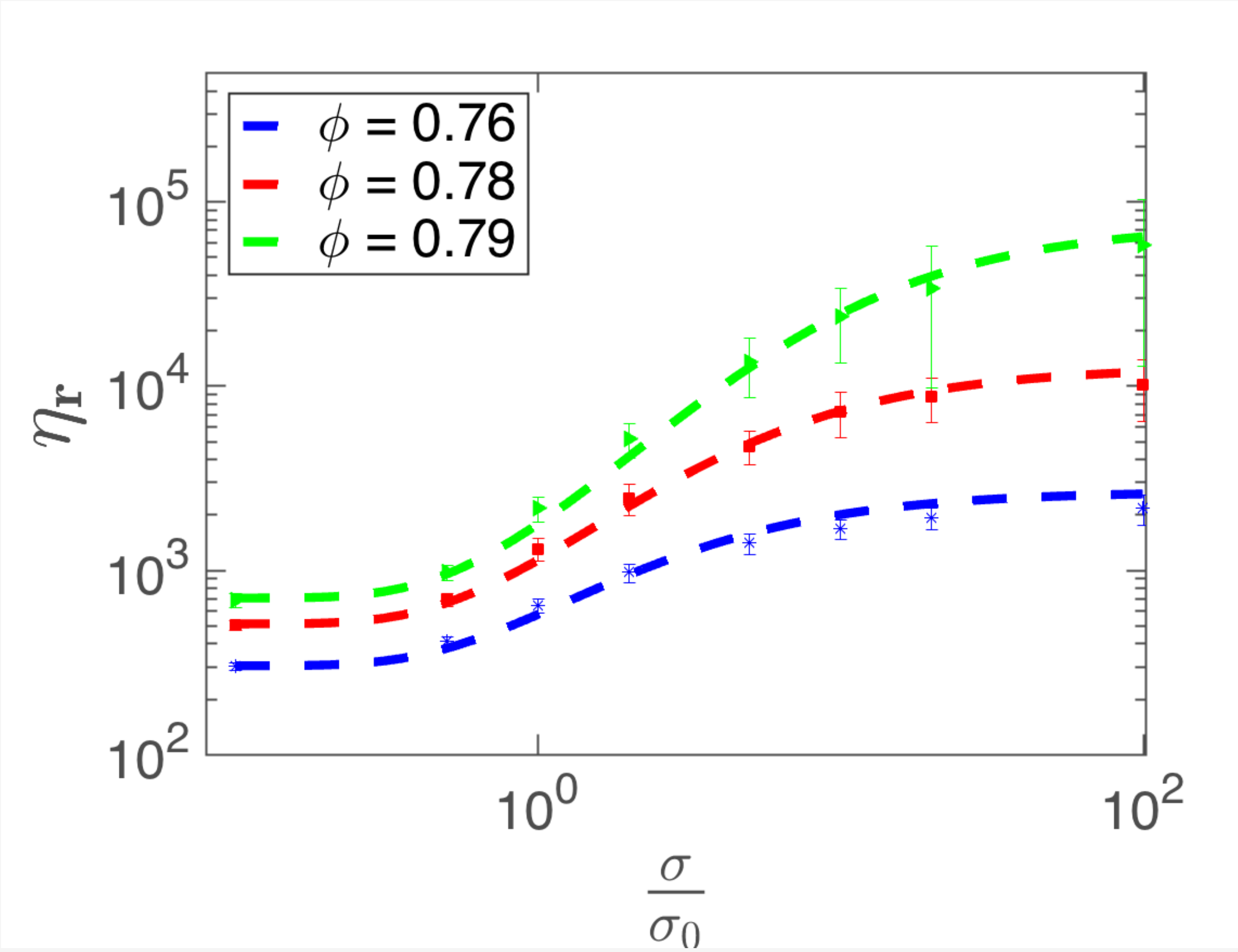


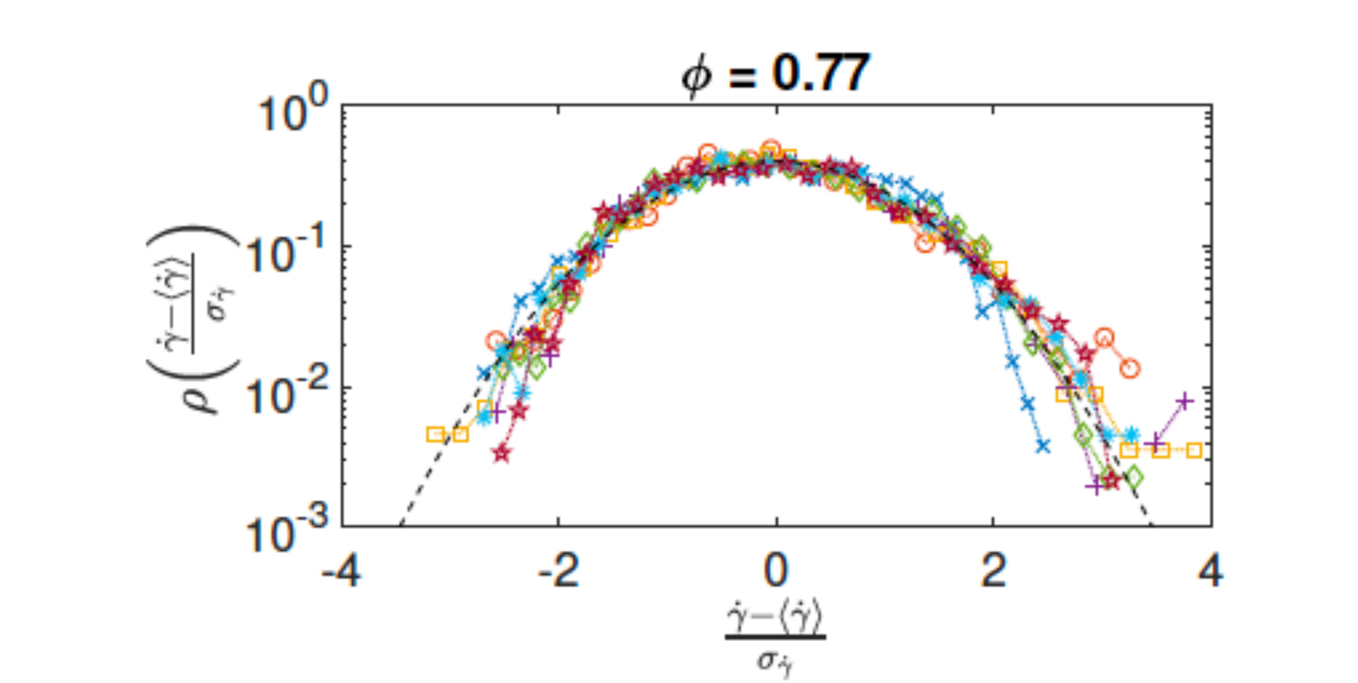


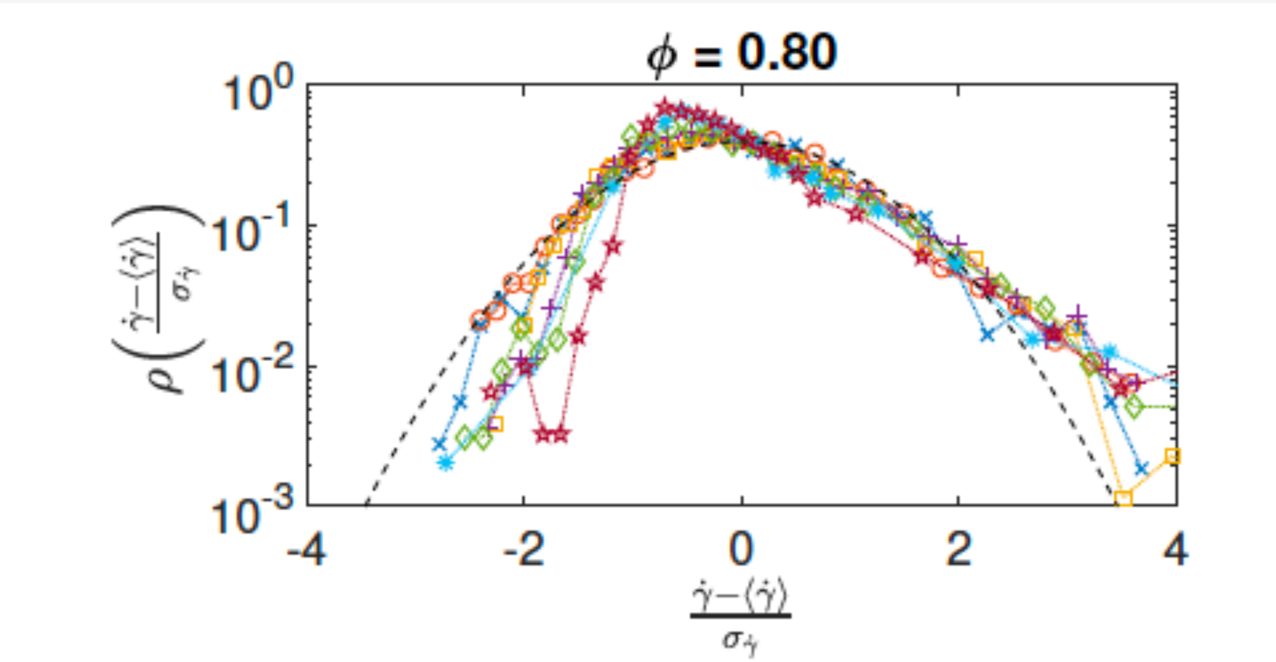


Simulations in 2D (Morris group)

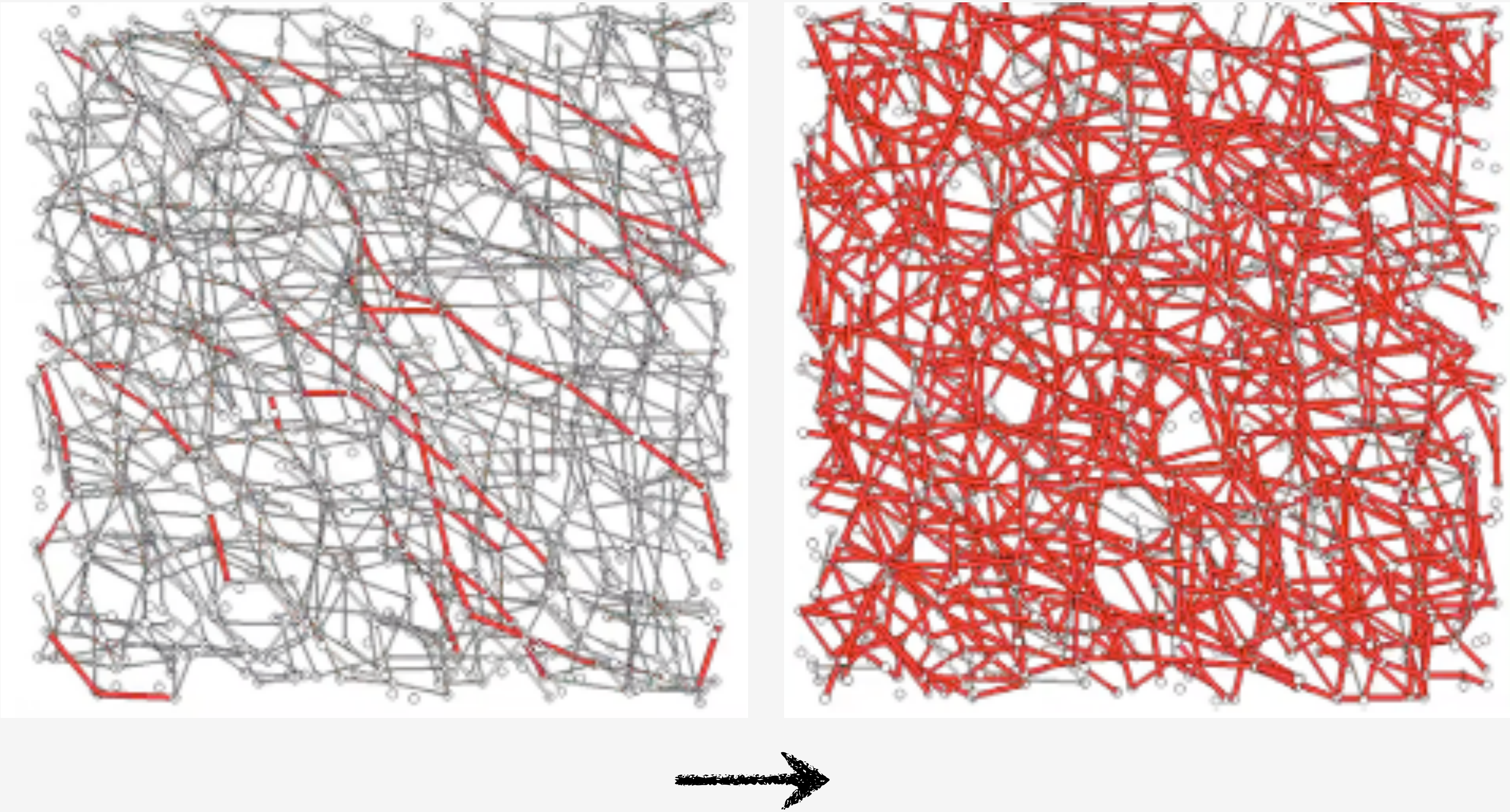








Transition from lubricated to frictional



Increasing Shear Stress