Friction reduces degrees of freedom: impact in dense suspensions

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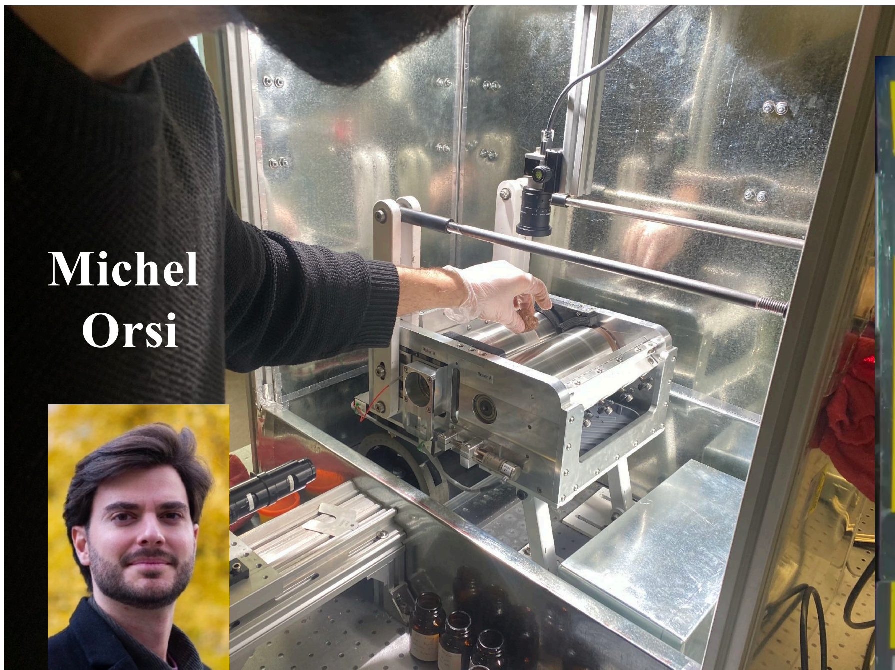
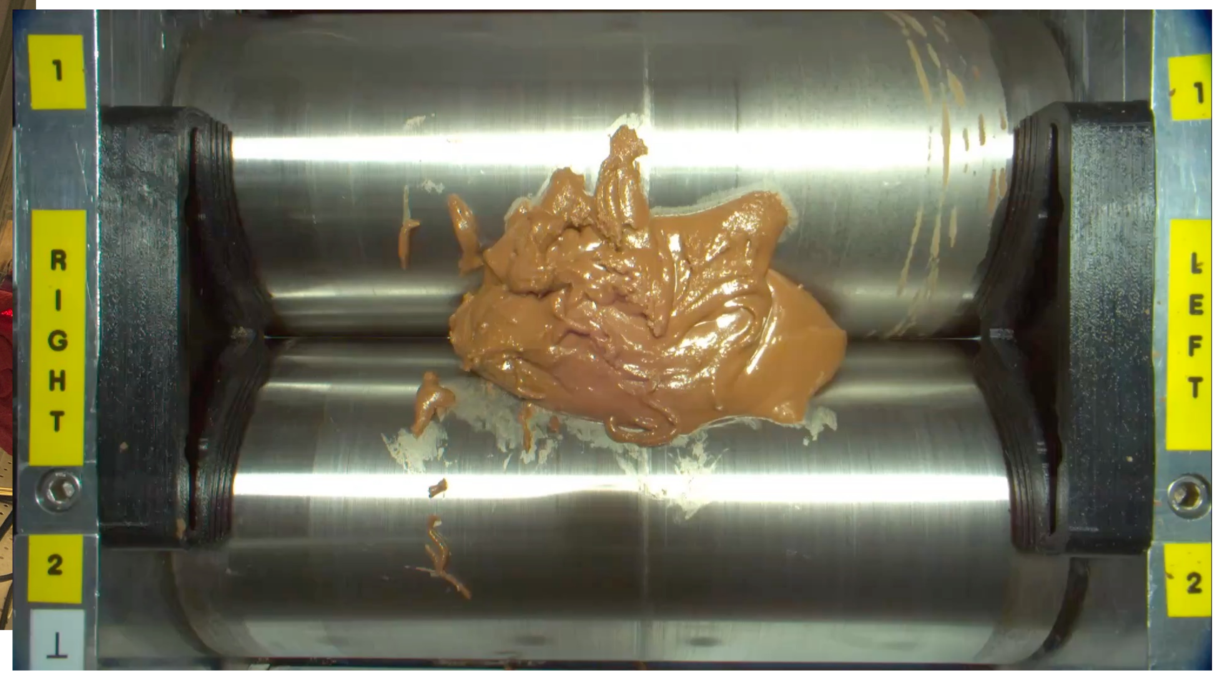
International Fine Particle Research Institute
Workshop – Friction and Adhesion in Wet and Dry Systems
Amsterdam: January 20, 2026

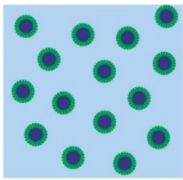
A favorite frictional-adhesive suspension: pre-refined chocolate paste

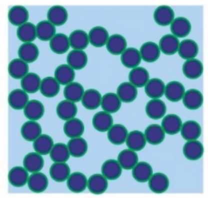


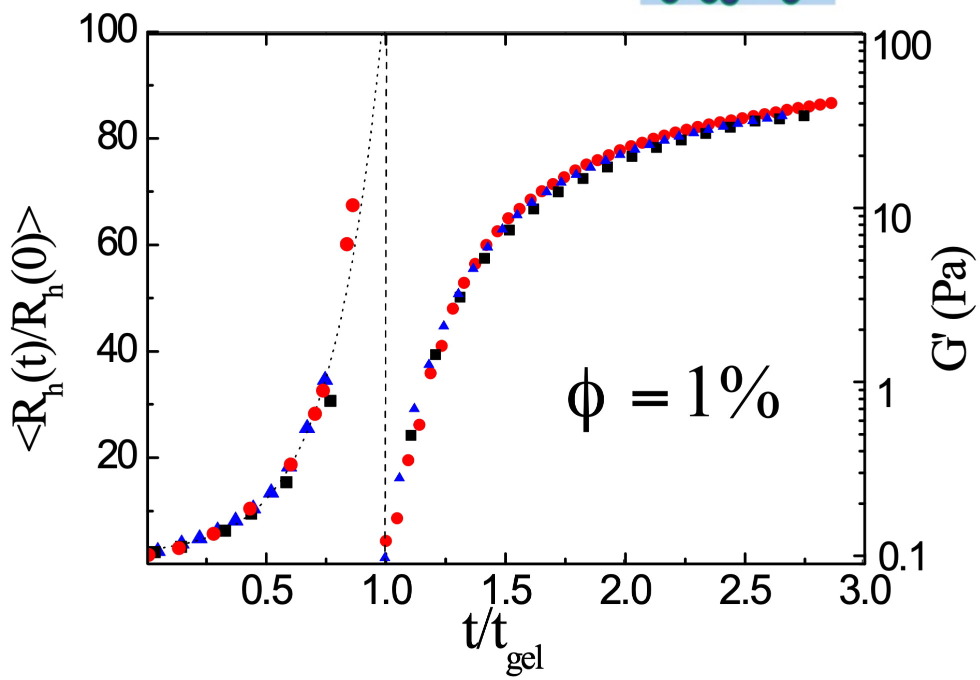


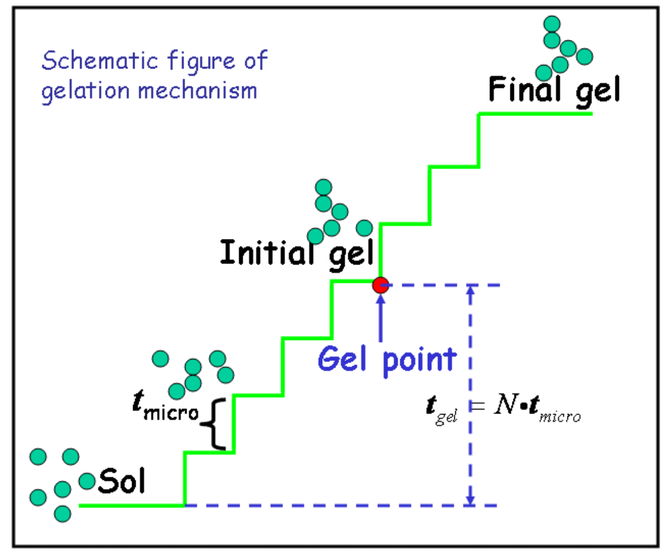
With Dr. Tom Curwen and team, Mondelēz International
Properties – Orsi et al. *Rheologica Acta* (in press) 2026
Processing – Orsi, Addasi et al. (in prep)

Coupling degrees of freedom: dilute sol-gel examples



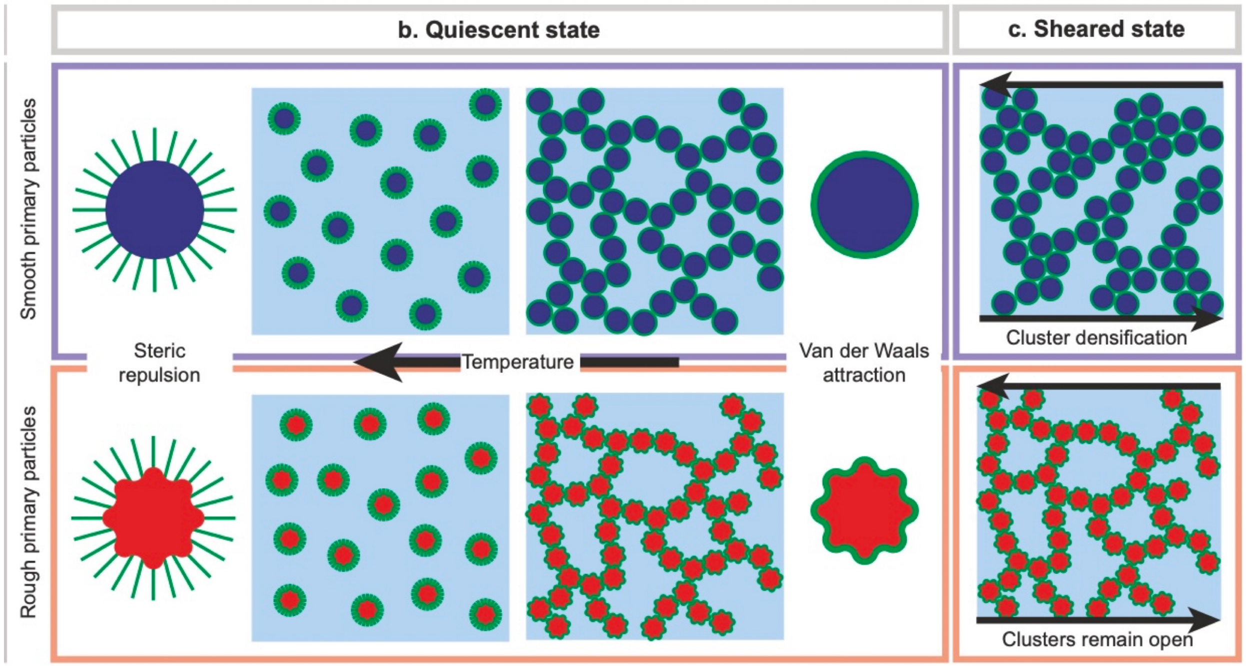


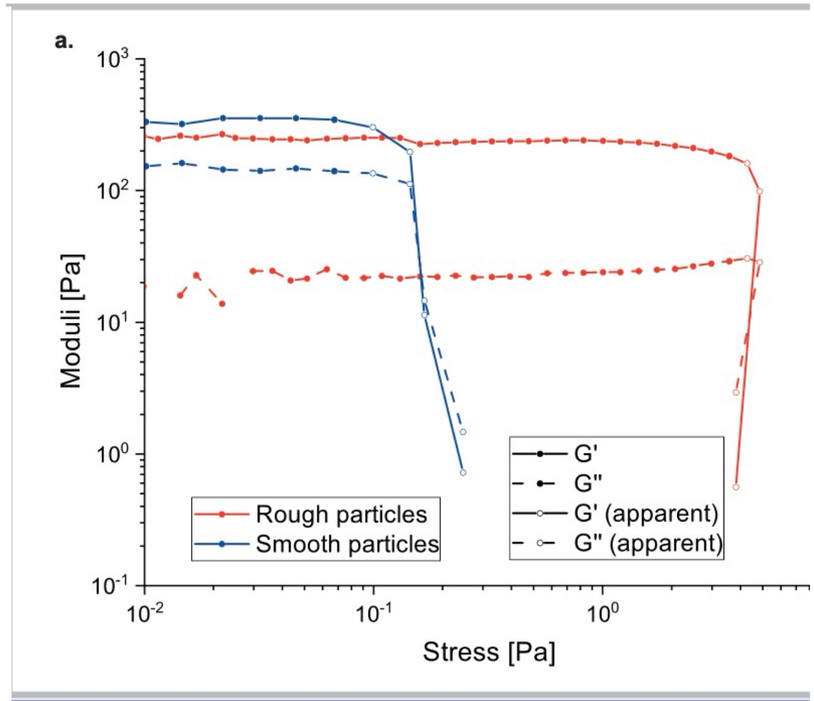




Cao, Cummins, Morris *Soft Matter* 2010

Coupling degrees of freedom: dilute sol-gel examples





Muller, Isa, Vermant *Nature Comms.* 2023

Two points:

1. Interparticle forces result in system spanning clusters – coupling particle motions and developing elastic properties

2. Roughness and resulting friction / rolling friction reduce relaxation – *even in very dilute systems*

Simulation:Friction in viscous suspensions
Lubricated flow-DEM (LF-DEM)

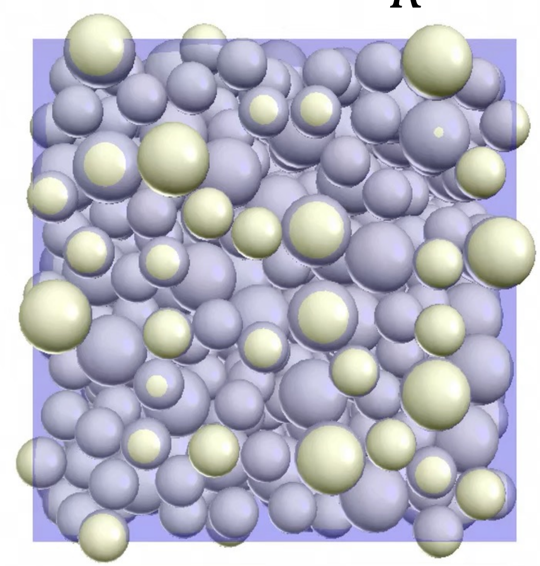
- Hydrodynamic interactions: ***Lubrication only*** F_H
- Contact model: discrete-element modeling (DEM) ***Friction at contact*** F_C

  DEM — Cundall & Strack *Geotechnique* 1979
- Conservative stabilizing repulsion force: ***Charge or polymer coating*** F_R

$$0 = F_H + F_R + F_C$$

$$F_H = R \cdot U$$

$$\dot{E} = U \cdot R \cdot U$$

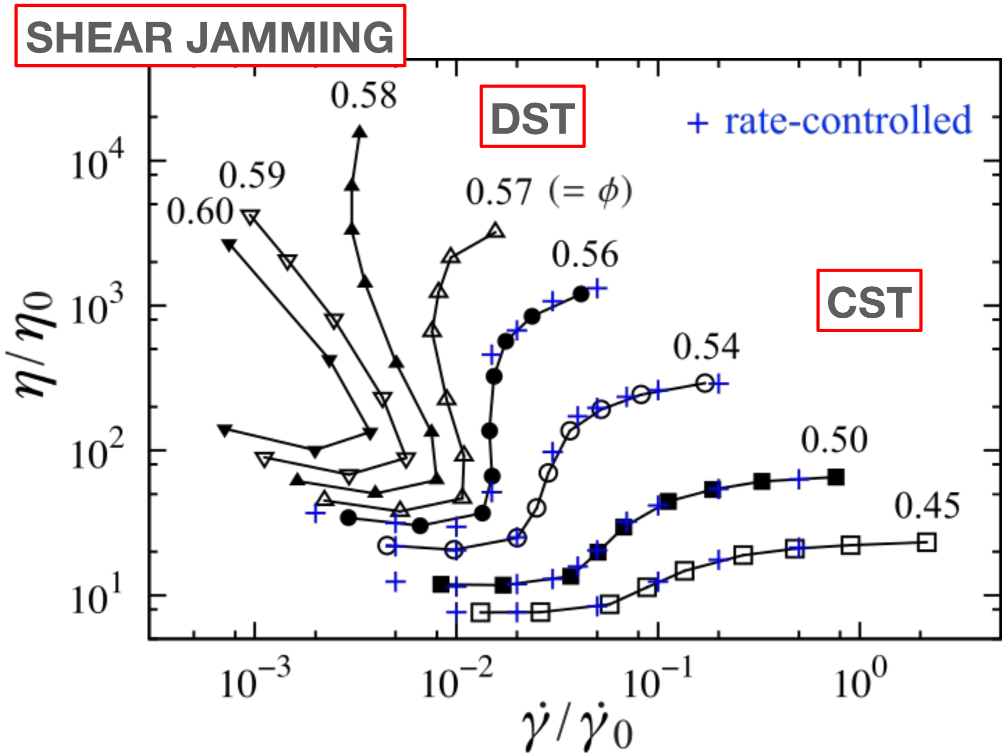


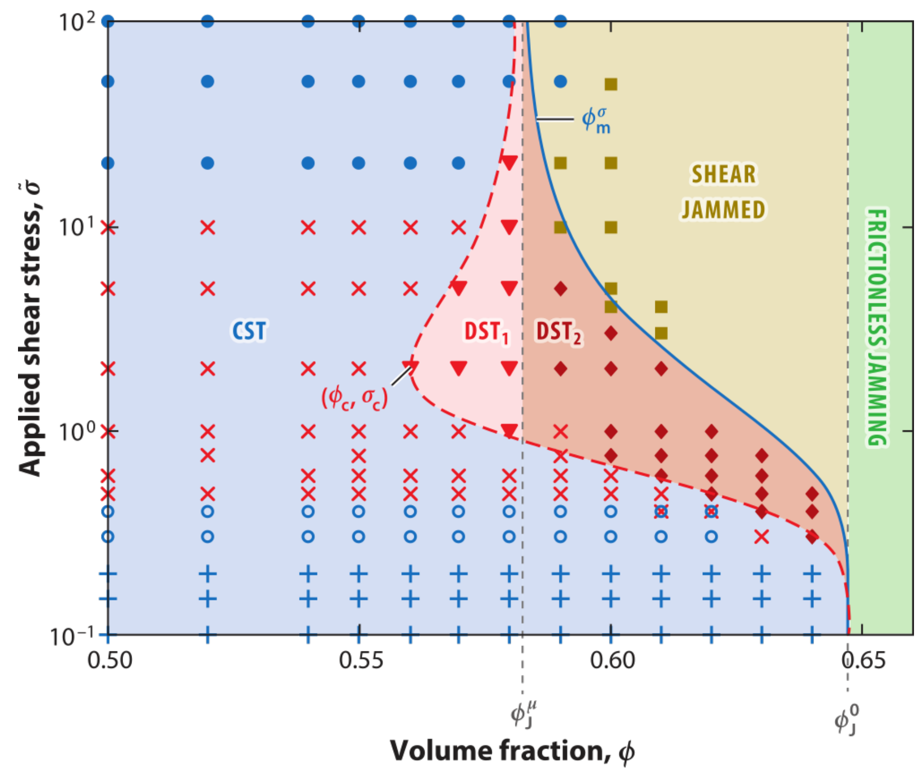
Seto, Mari, Morris & Denn *PRL* 2013
Mari, Seto, Morris & Denn *J. Rheol.* 2014
Theory: Wyart & Cates *PRL* 2014

SHEAR THICKENING: LUBRICATED-TO-FRICTIONAL SCENARIO

Particle interactions: lubricated-to-frictional at critical stress

$$\sigma_o = F_R / a^2 \implies \dot{\gamma}_o = \sigma_o / \eta_o$$





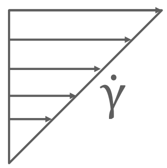
Wyart & Cates PRL 2014; Mari et al. JOR 2014; Morris PRF 2018, Ann Rev Fluid Mech 2020

MOTION ANALYSIS: Fluctuations

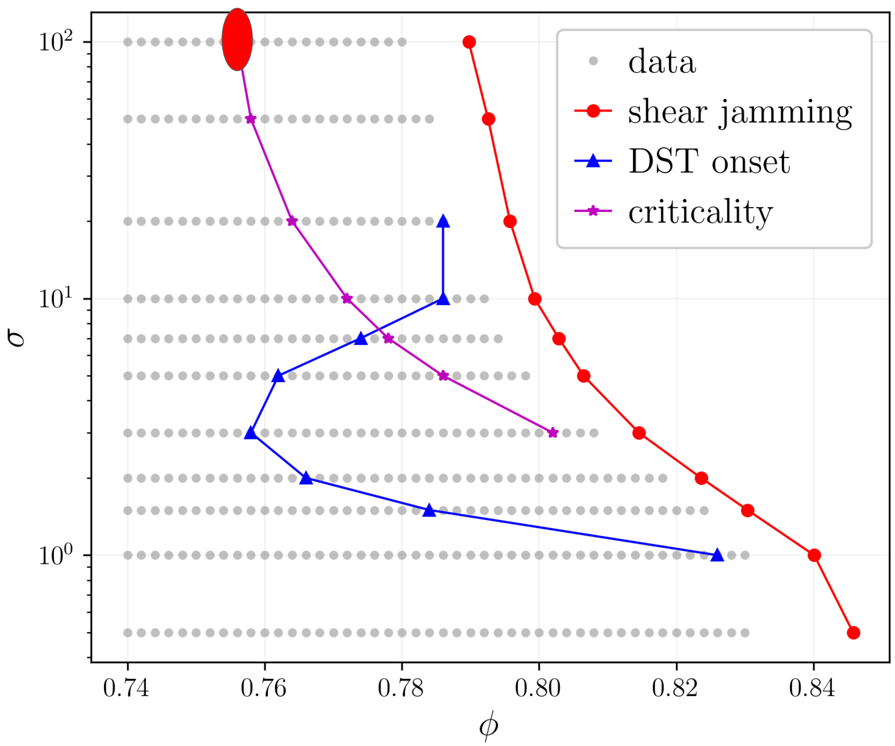
Affine motion removed:

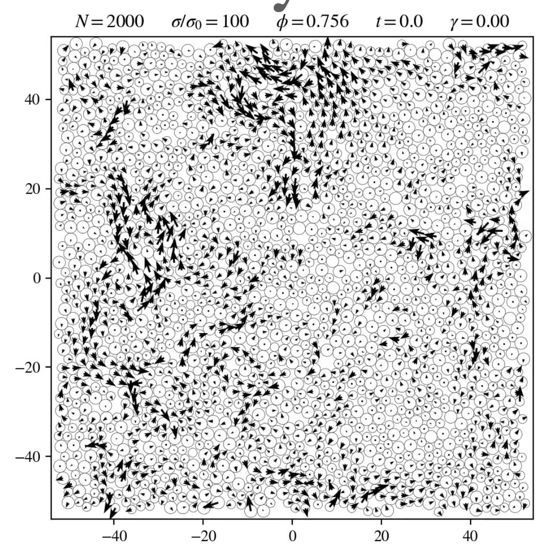
$$u' = u_x - \dot{\gamma} z$$

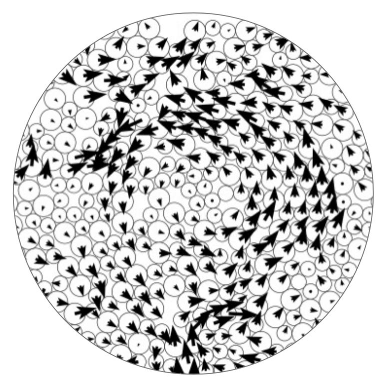
$$\omega' = \omega_y - 0.5\dot{\gamma}$$

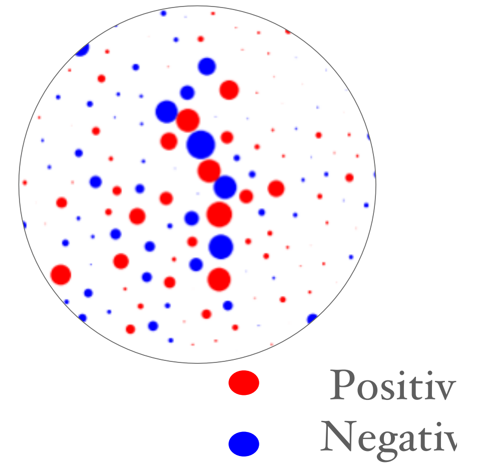


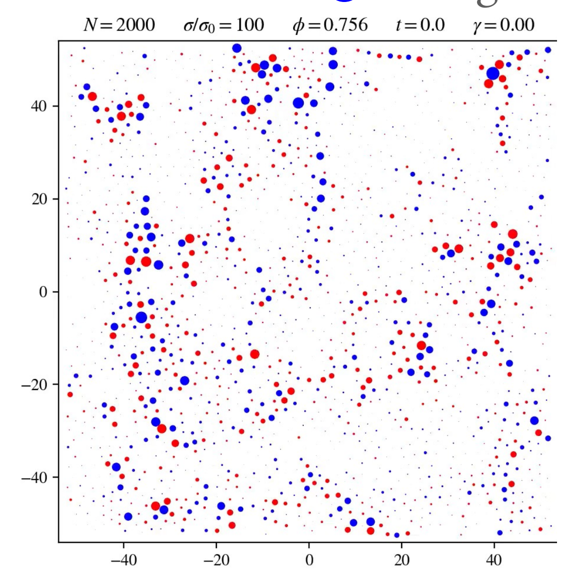
Here: 2D monolayer





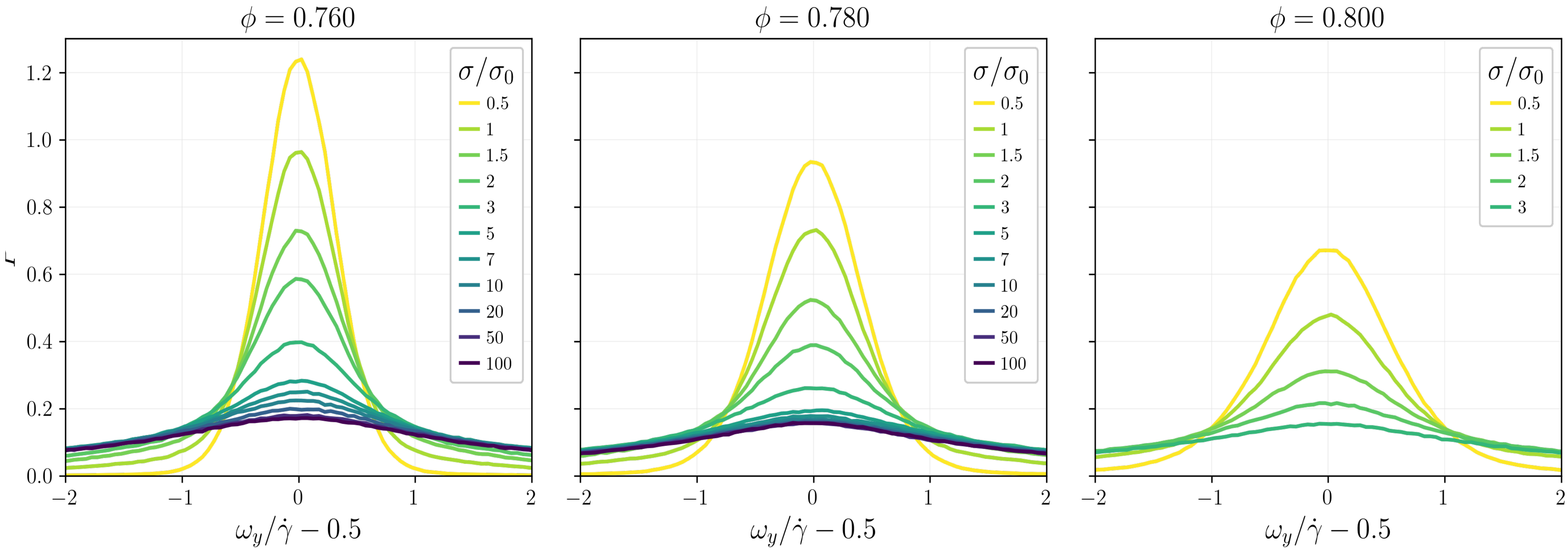






ANGULAR VELOCITY

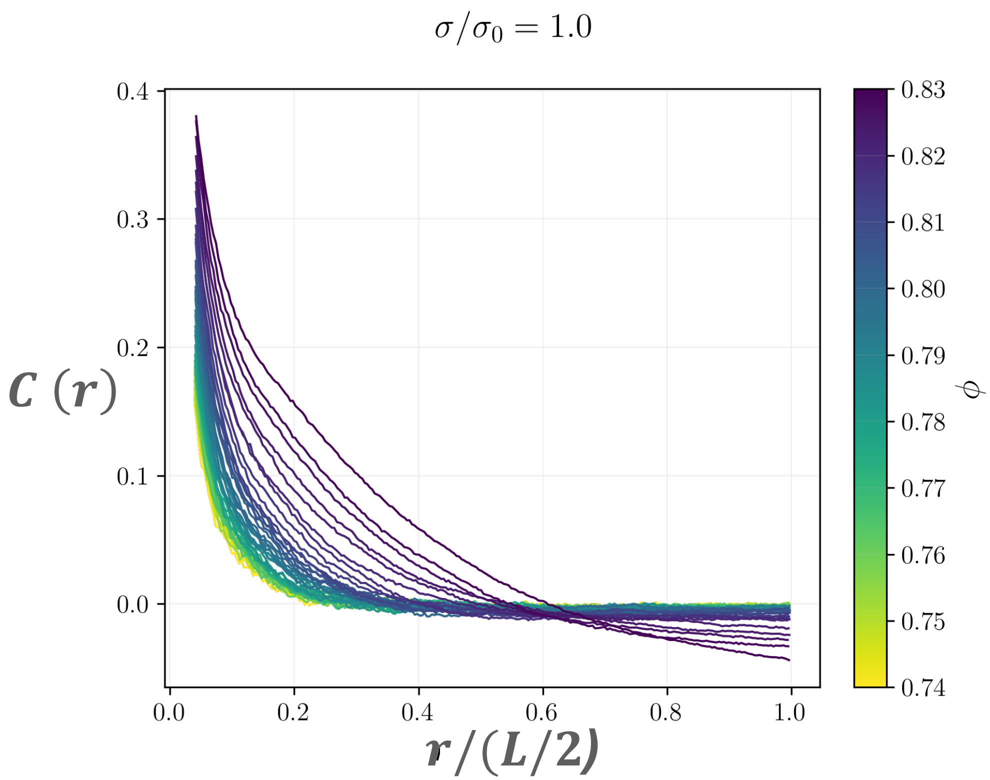
Distribution becomes flatter and wider with increasing ϕ and σ.



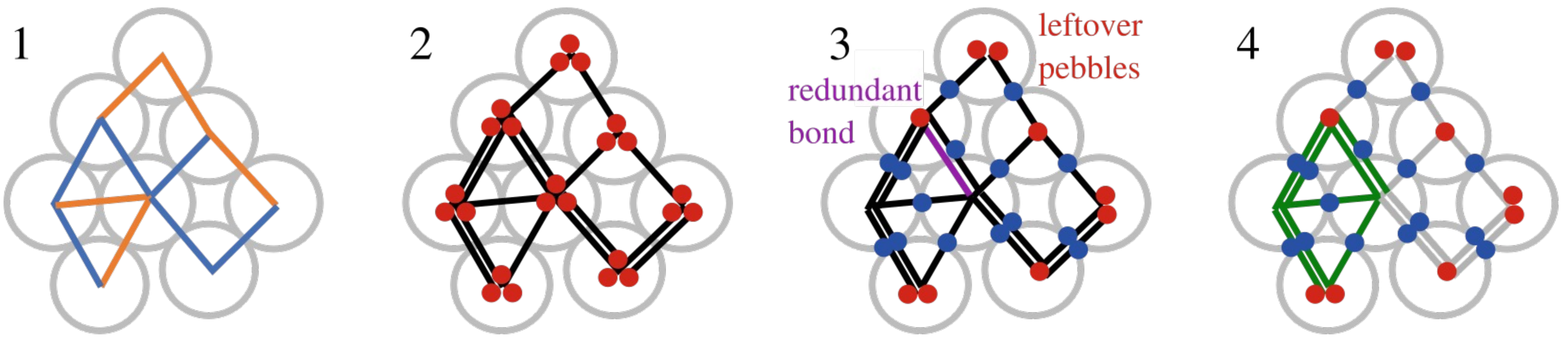
VELOCITY CORRELATION

$$C(r) = \langle u'(0)u'(r) \rangle$$

Sign change – shifts to larger *r* with increasing ϕ and σ.



RIGIDITY ANALYSIS: (3,3) PEBBLE GAME- 2D



frictional contact
sliding contact

3 pebbles / particle
2 bonds / frictional contact
1 bond / sliding contact

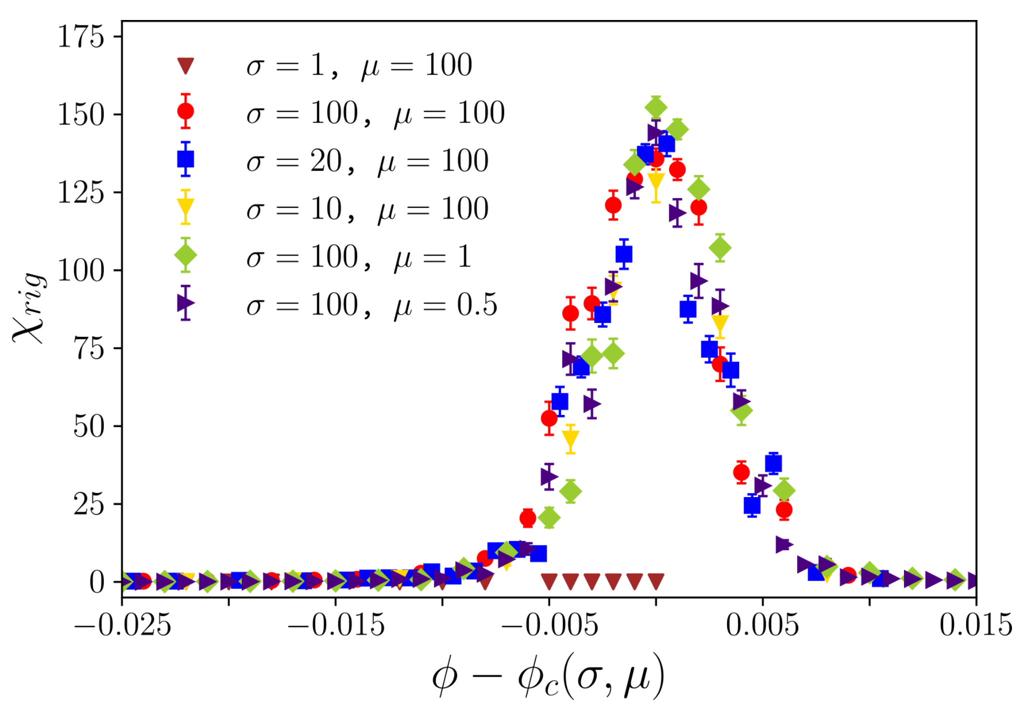
Cover bonds with pebbles
Leave 3 pebbles for
global dof

Decompose into rigid
clusters and floppy bonds

Silke Henkes: https://github.com/silkehenkes/RigidLibrary
Mike Van Der Naald: https://github.com/mikevandernaald/rigidCluster_LFDEM

RIGIDITY ORDER PARAMETER – 2D

ϕ_c: location of peak in variance of the rigidity order parameter



Rigid fraction: $m_{\text{rig}} = \frac{1}{N} \sum_{i=0}^{N} n_i$ $\quad rigid: n_i = 1$

Order parameter: $f_{\text{rig}}(\phi, \sigma) = \langle m_{\text{rig}} \rangle \equiv \frac{1}{M} \sum_{\alpha=1}^{M} m_{\text{rig},\alpha}$

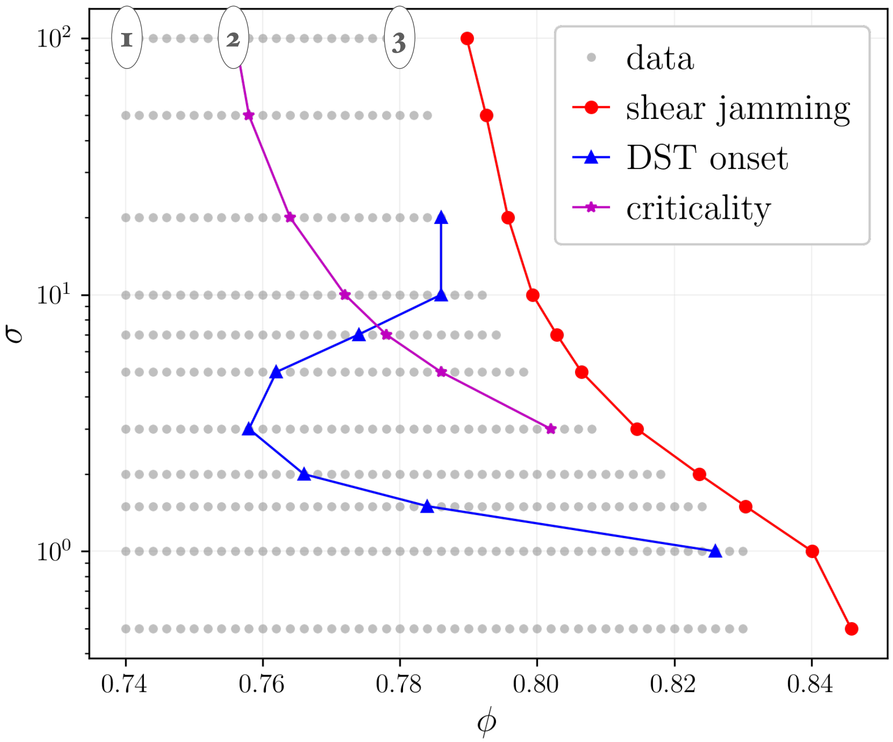
$\delta m_{rig} = m_{rig} - f_{rig}$

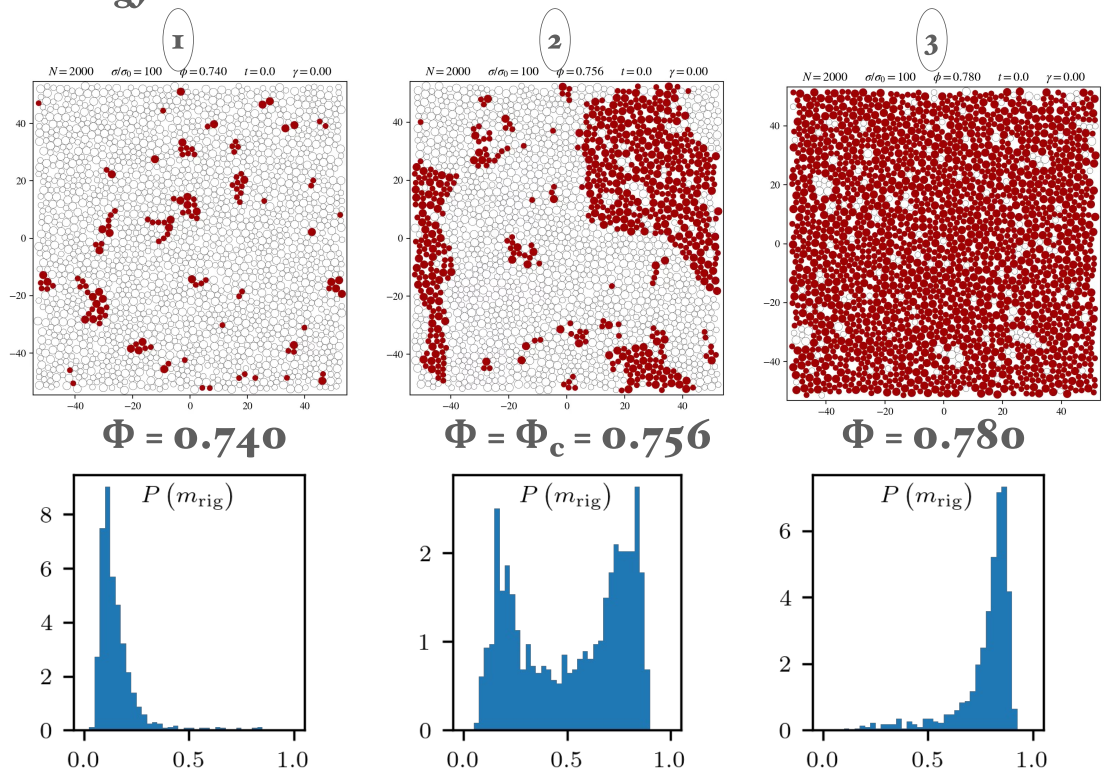
Net rigidity fluctuations: $\chi_{\text{rig}} = N \left\langle \delta m_{\text{rig}}^2 \right\rangle$

Critical fraction: $\phi_c(\sigma, \mu) = \phi\big|_{\max(\chi_{\text{rig}})}$

JAMMING PRECURSOR

Santra A., Orsi M., Chakraborty B., Morris J.F., ***Phys. Rev. Research*** 2025
Pandare R., Orsi M., Shattuck M., Morris J.F., in press ***J. Rheology*** 2026





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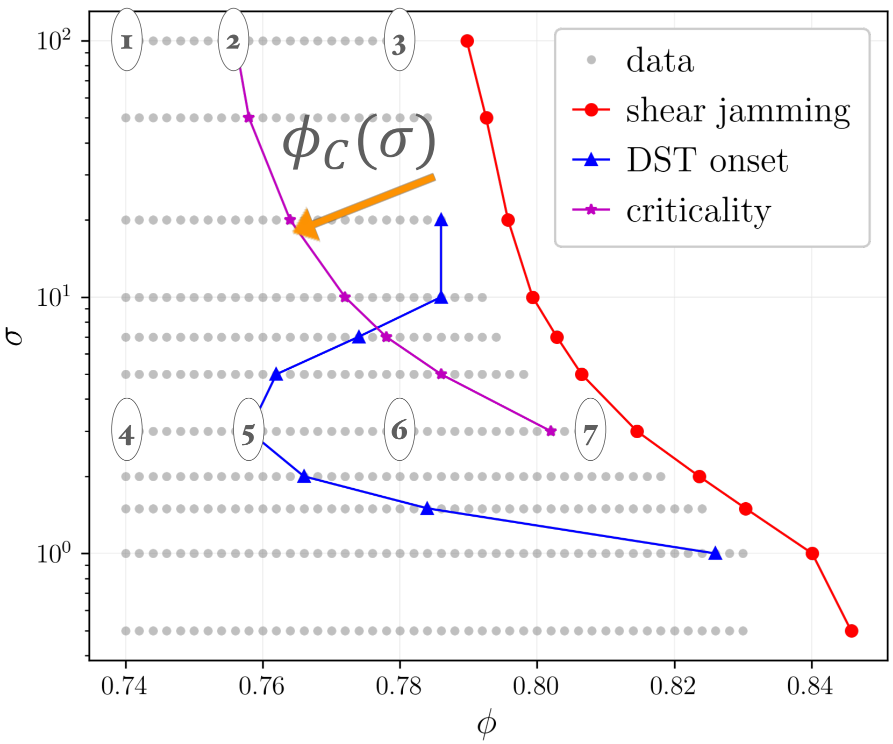
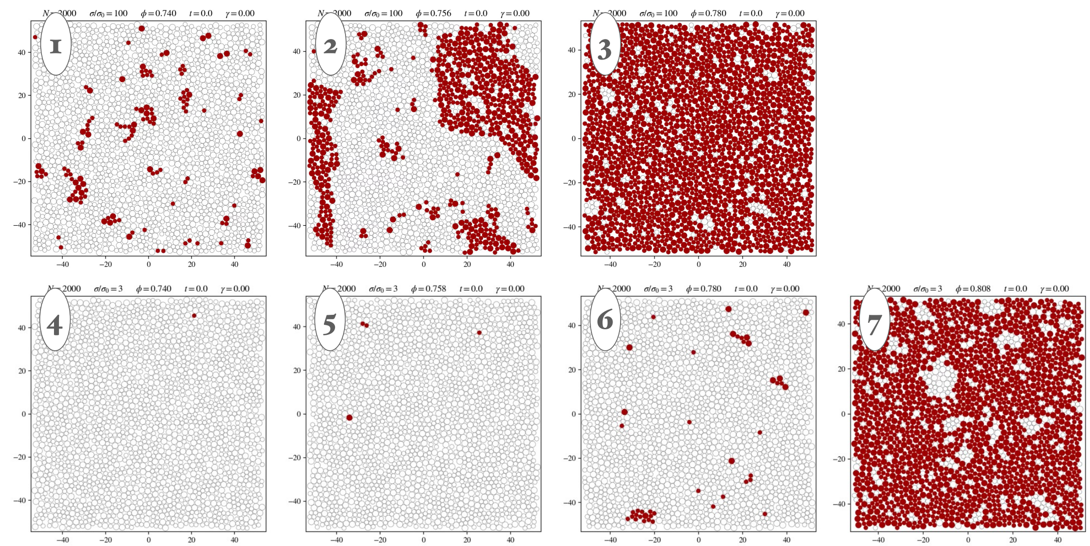
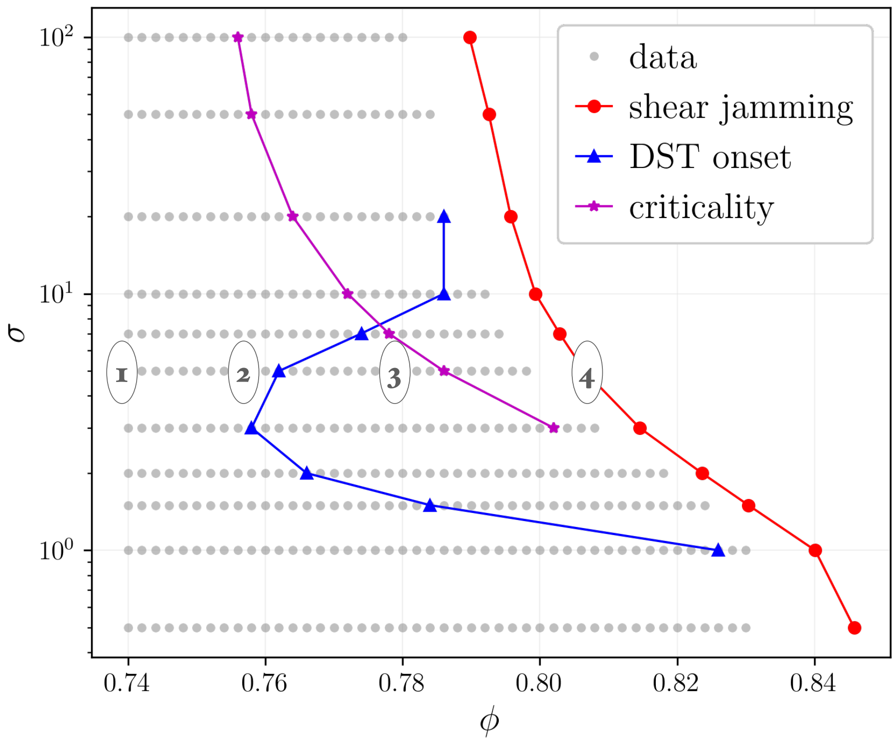


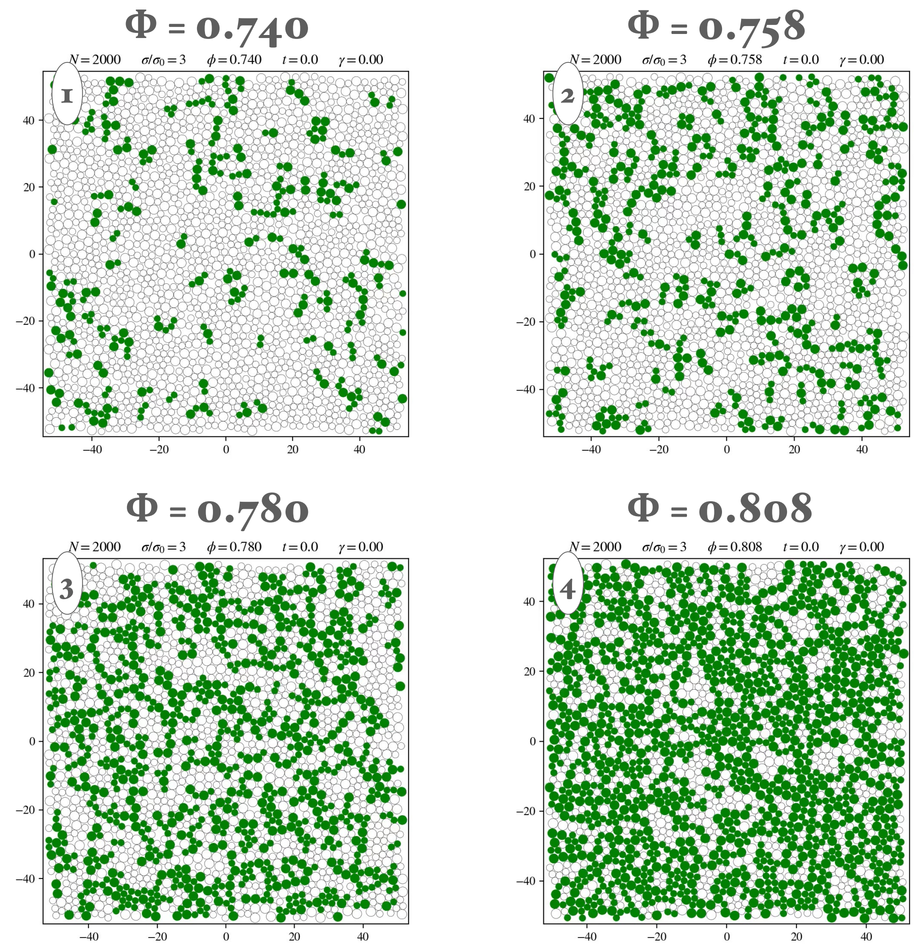


Santra A., Orsi M., Chakraborty B., Morris J.F., ***PR Research*** (2025)
Pandare R., Orsi M., Shattuck M., Morris J.F., in press ***J. Rheology*** (2026)

DST : k3-CONTACT CLUSTERS (2D)

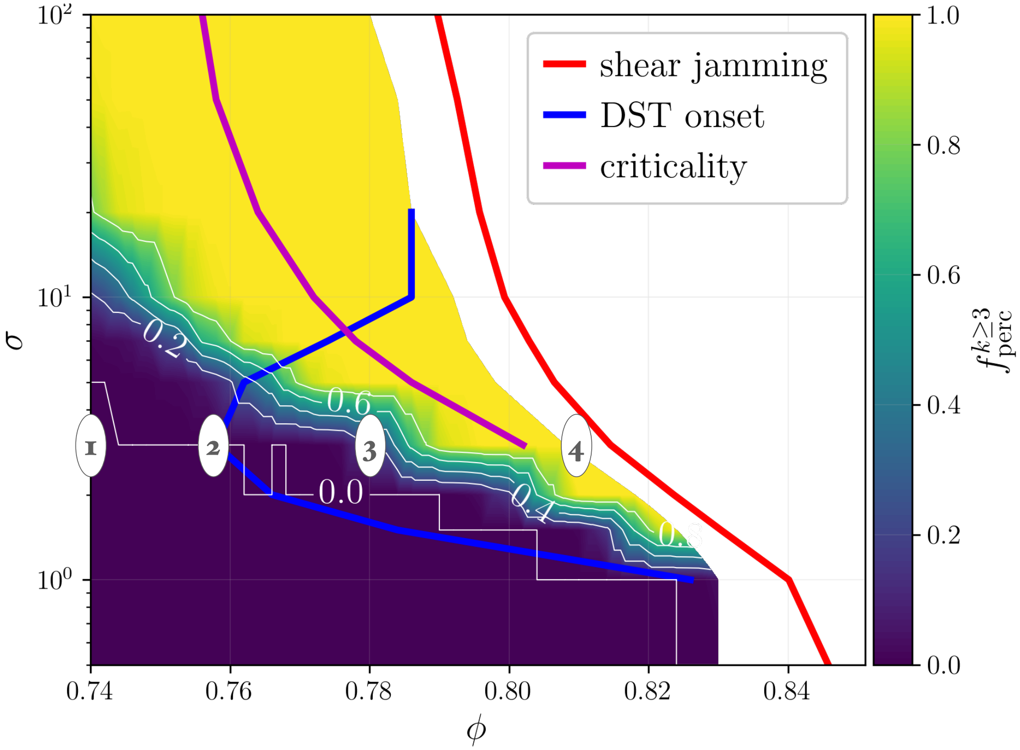
Goyal, Martys, & Del Gado *J. Rheol.* 2024: viscosity overshoot corresponds to percolating k4-neighbors clusters in 3D. Consider k3 clusters in 2D.

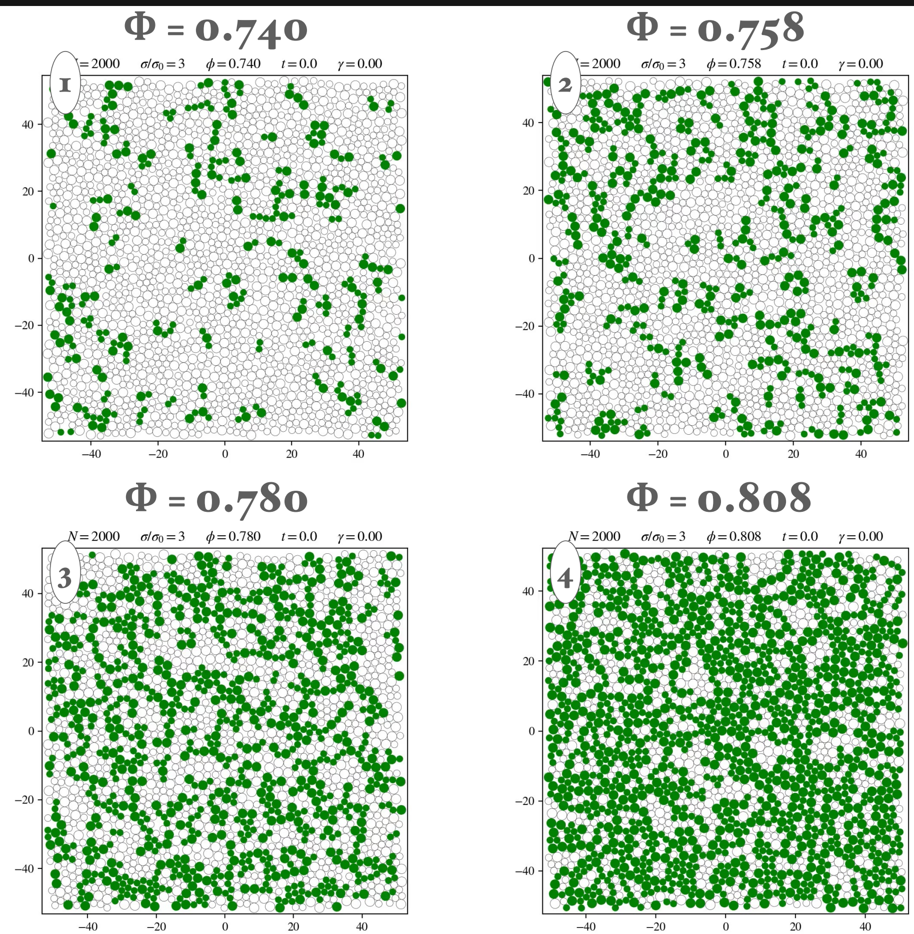




k3-CONTACT CLUSTERS (2D)

The fraction of time with percolating k3-neighbor clusters becomes non-zero on the lower branch of DST.





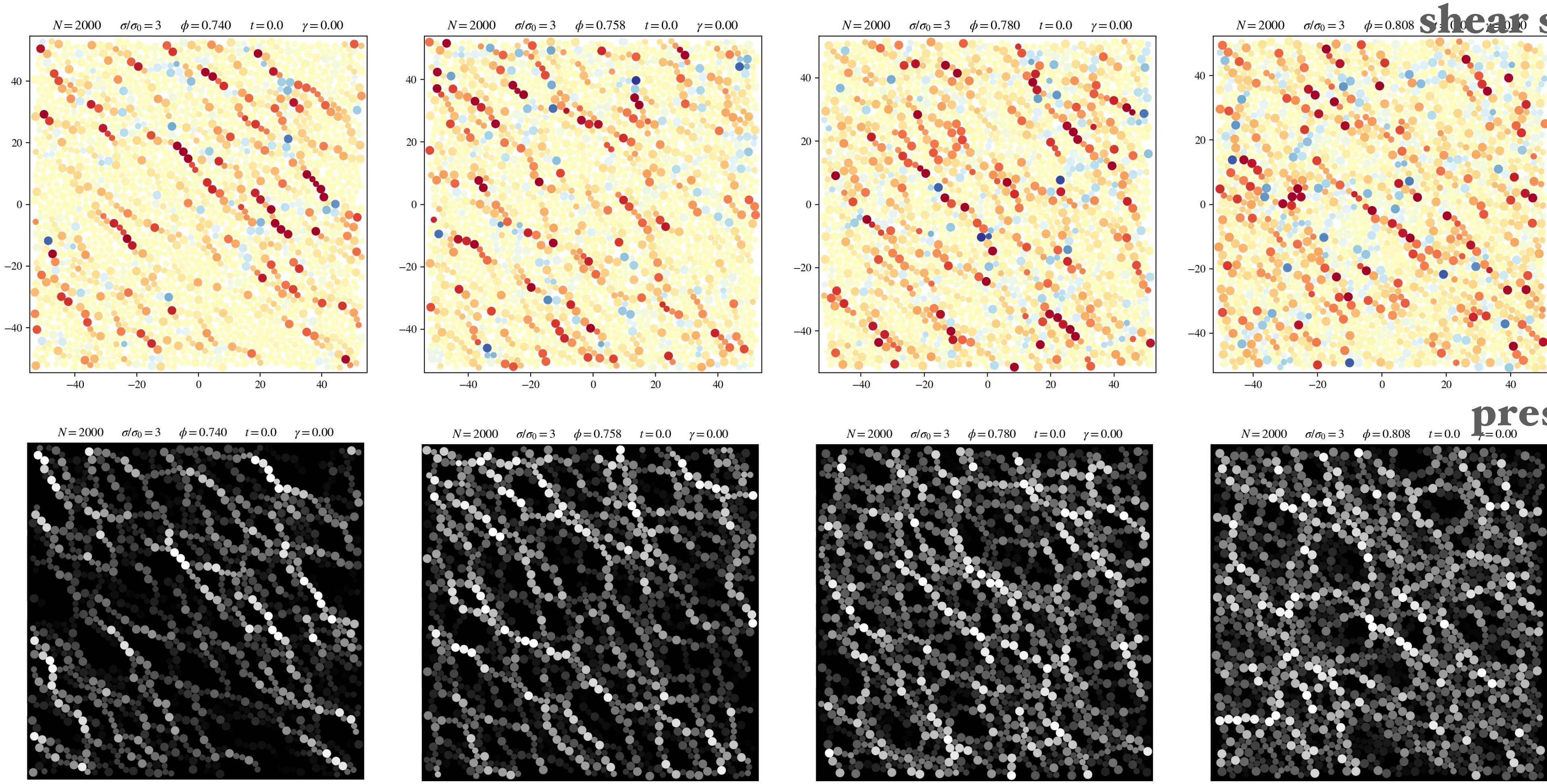
ONGOING WORK: STRESS CORRELATIONS

shear stress

σ^c_{xy}

pressure

σ^c_{π}



SUMMARY

- Friction leads to

  Highly correlated motion on approach to jamming: **transient rigid clusters**.

  These clusters interact like larger frictional particles (strong rotational coupling) and exhibit widely distributed angular velocities and long-range velocity correlations.

  k=3 frictional contacting clusters begin to percolate on low stress branch of DST. *No clear signature of motion is currently identified.*