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Normal Stresses in Frictional Granular Flows

PRESENTED BY

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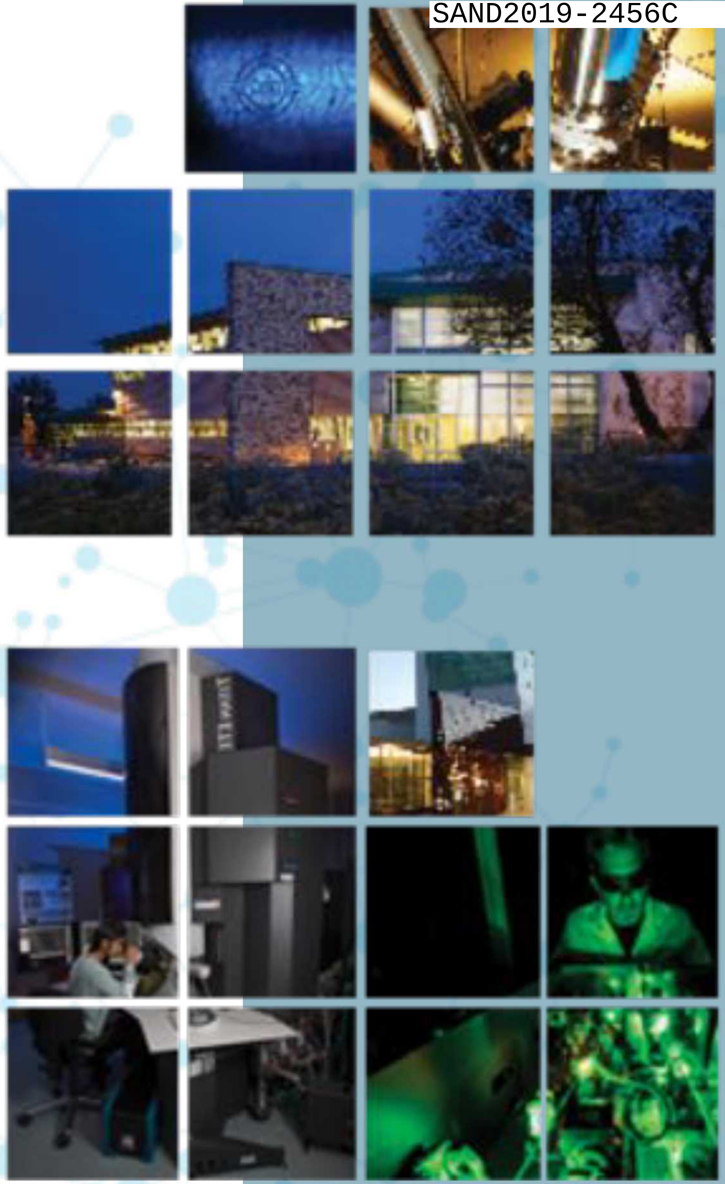

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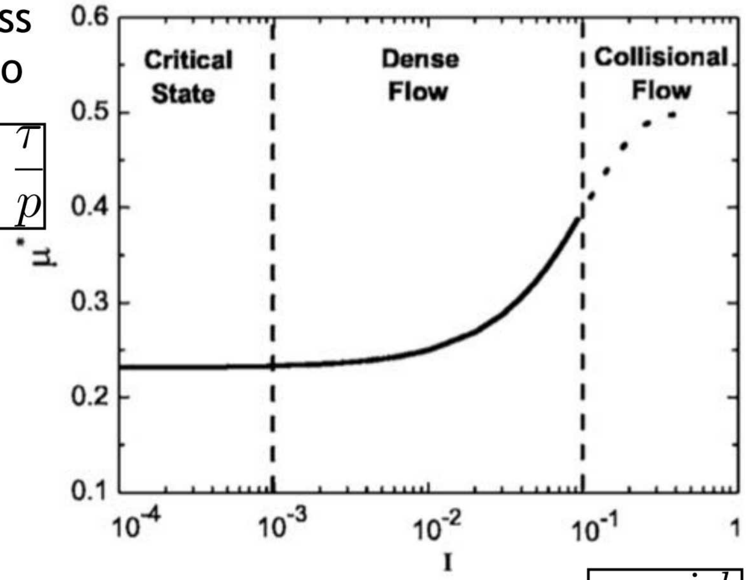
Dense Granular Rheology

$\mu(I)$ rheology

stress ratio

$$\boxed{\mu = \frac{\tau}{p}}$$



inertial number

$$\boxed{I = \frac{\dot{\gamma} d}{\sqrt{\frac{p}{\rho}}}}$$

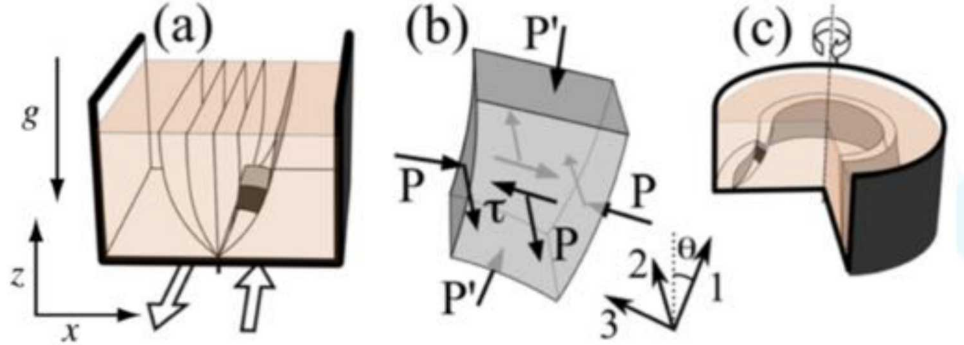
da Cruz et al., Phys. Rev. E, 72 (2005)

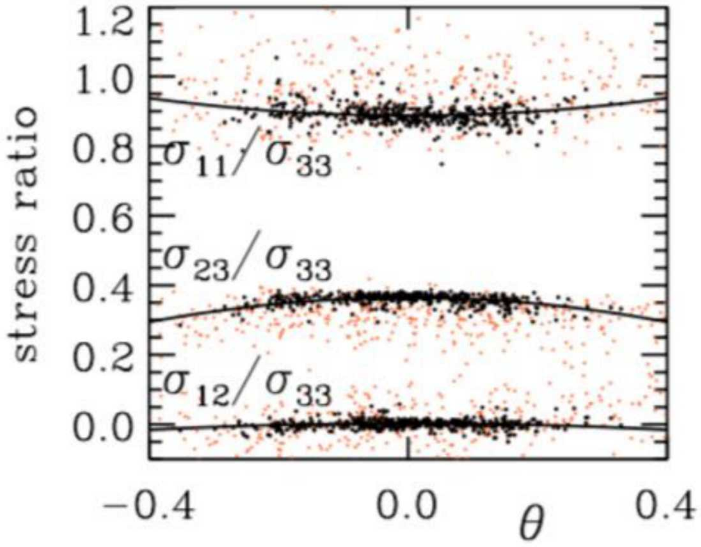
co-directional flow

$$\mathbf{L} = \begin{pmatrix} 0 & \dot{\gamma} & 0 \\ \dot{\gamma} & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$$\Downarrow$$

$$\boldsymbol{\sigma} = \begin{pmatrix} p & \tau & 0 \\ \tau & p & 0 \\ 0 & 0 & p \end{pmatrix}$$





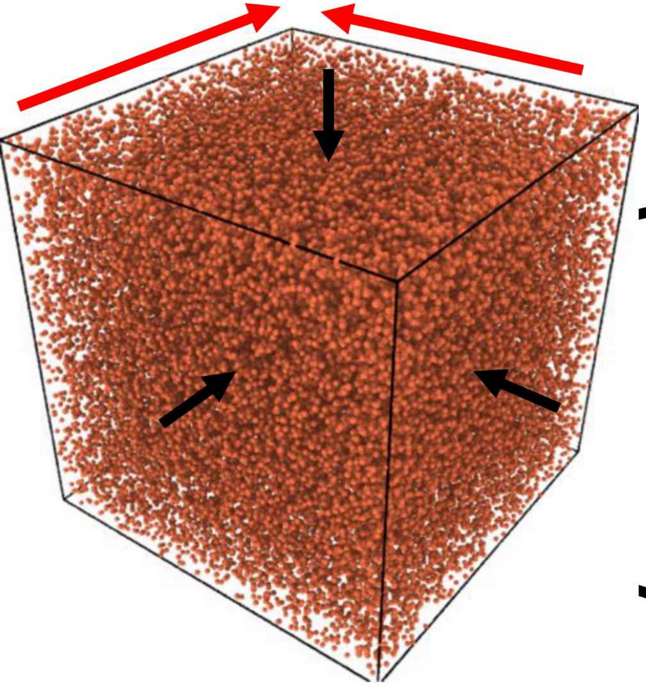
$$\begin{pmatrix} p' & 0 & 0 \\ 0 & p & \tau \\ 0 & \tau & p \end{pmatrix}$$

Depken et al., EPL, 78 (2007)

Fully Stress-Controlled Simulations

initial dilute system

$\phi = 0.05$

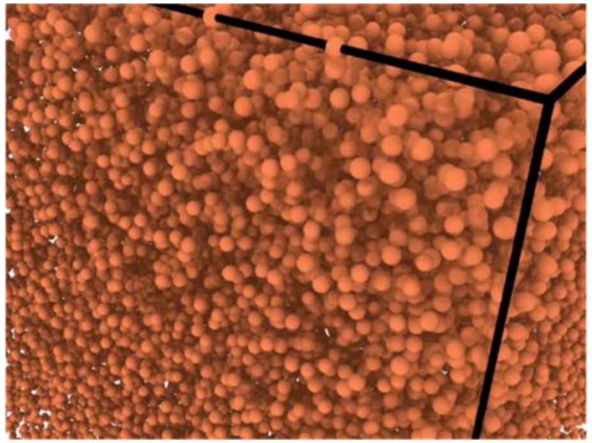


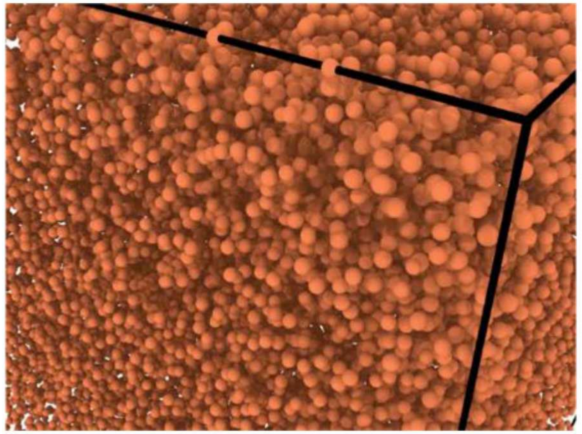
Parinello-Rahman dynamics
constant pressure + shear

applied stress

$$\sigma_a = p_a I + \begin{bmatrix} 0 & \tau_a & 0 \\ \tau_a & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

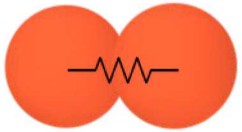
shear arrest



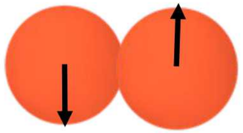


steady flow

harmonic contacts



Coulomb microscopic friction



$$||F_s|| < \mu_s ||F_n||$$

Macroscopic Observables:

volume fraction: $\phi(t)$

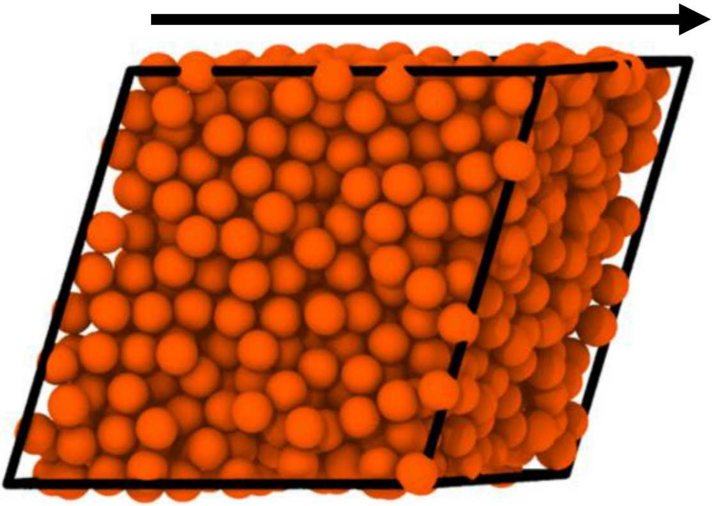
deformation rate (3D): $\mathbf{L}(t)$

internal stress (3D): $\boldsymbol{\sigma}(t)$

Srivastava et al., Phys. Rev. Lett., 122 (2019)

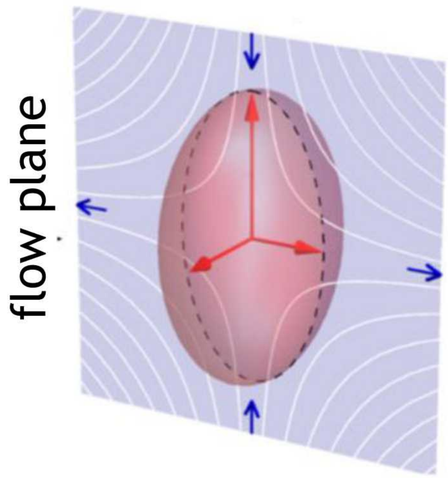
Rheology: Plane Shear Flows

$$\mathbf{L} = \mathbf{D} + \mathbf{W}$$



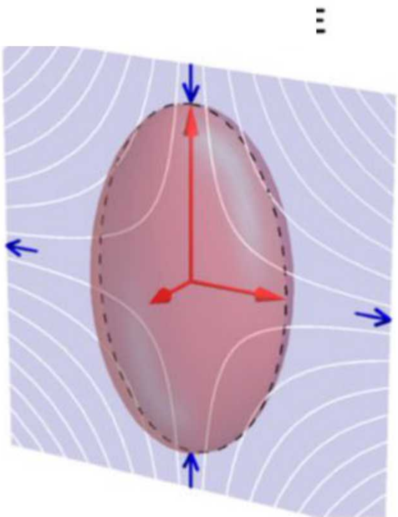
$$\sigma_a = p_a I + \begin{bmatrix} 0 & \tau_a & 0 \\ \tau_a & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

co-directional flow



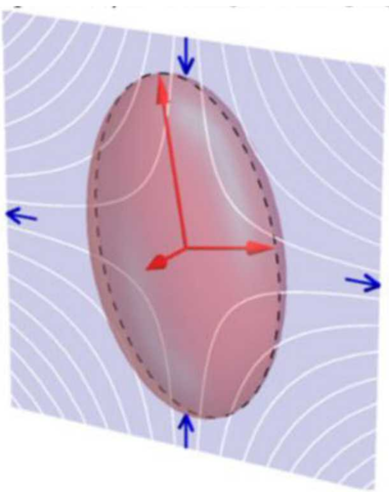
$$\frac{\boldsymbol{\sigma}}{|\boldsymbol{\sigma}|} = \frac{\mathbf{D}}{|\mathbf{D}|}$$

co-axial flow



principal directions
of stress and strain rate
tensors coincide

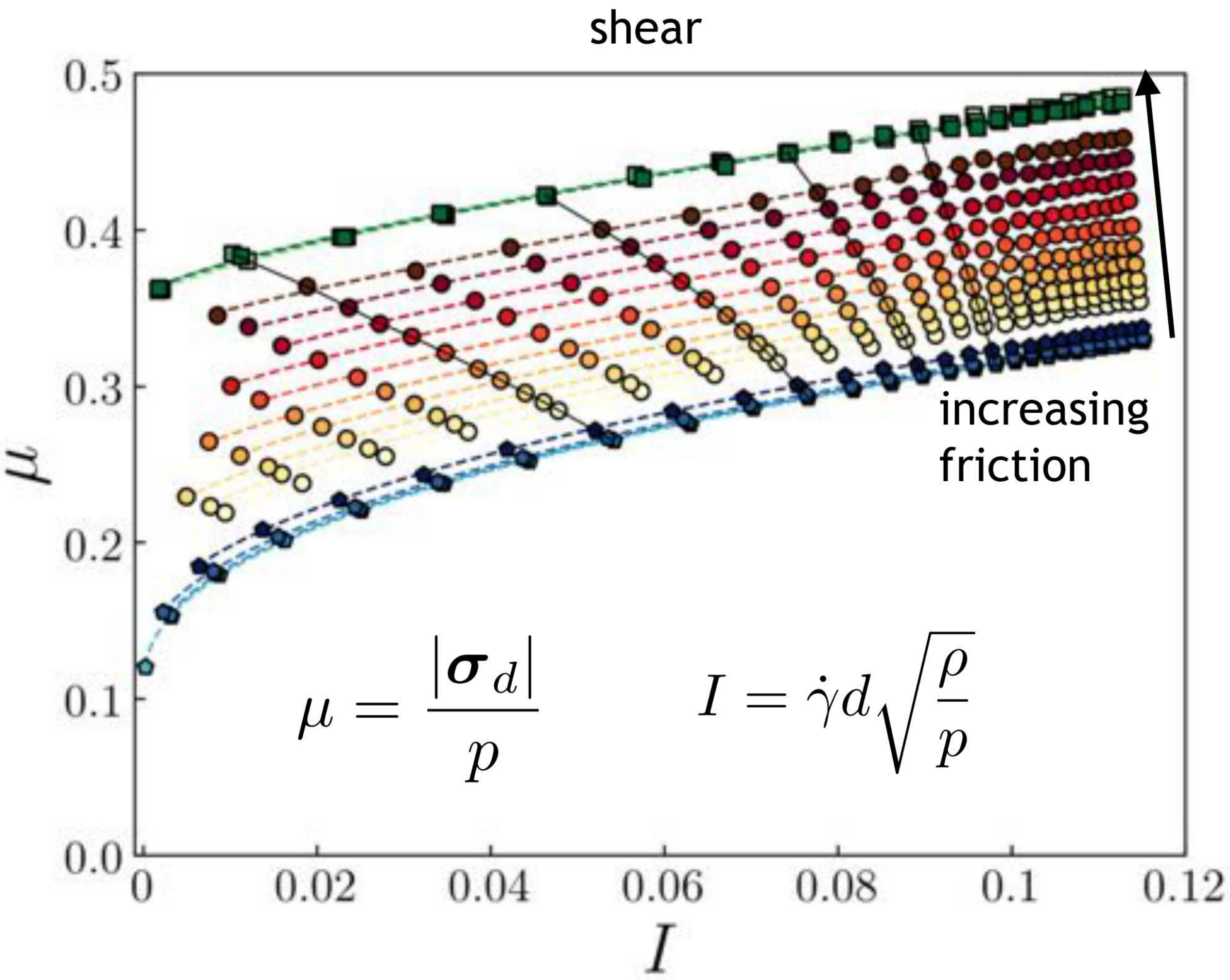
complex flow



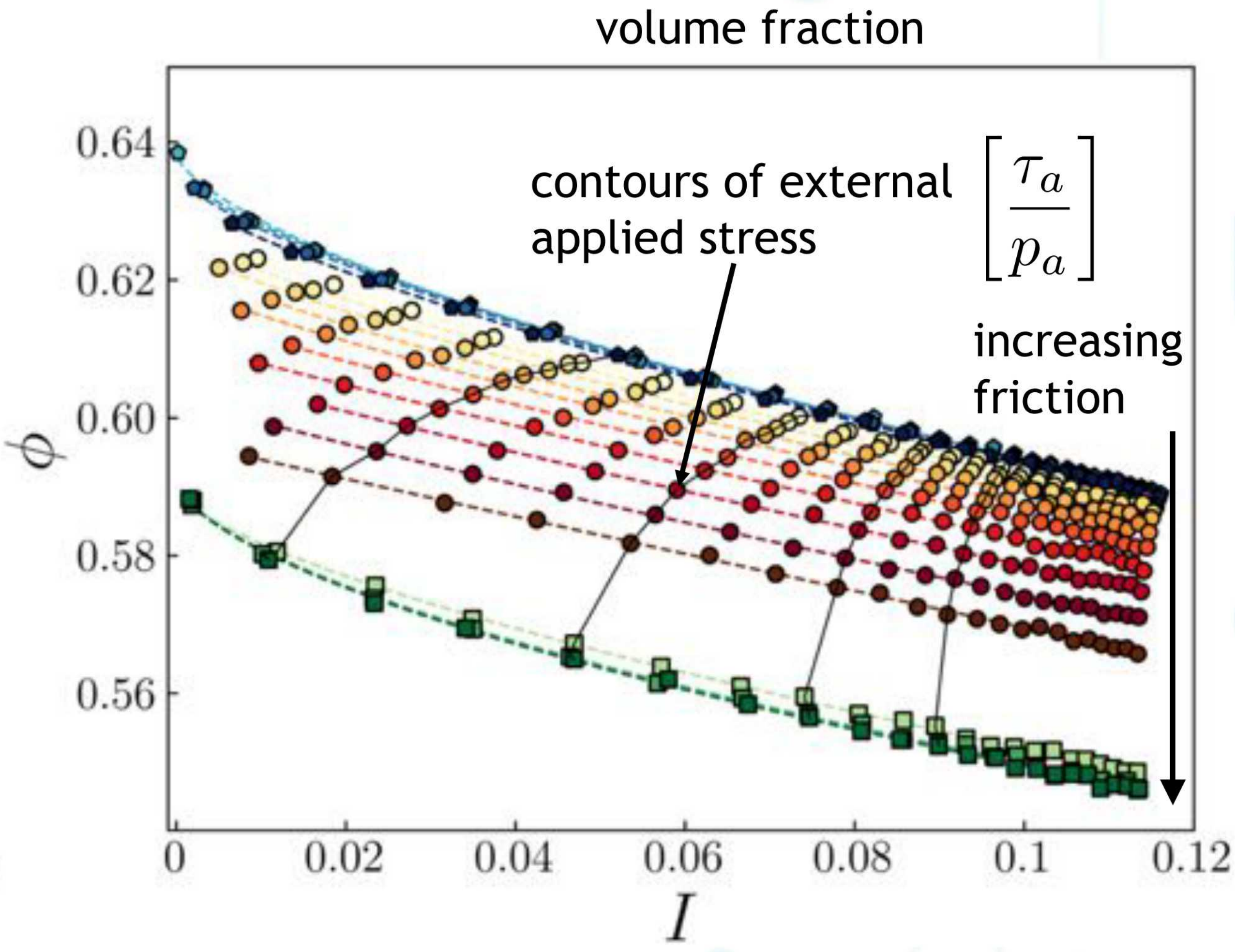
principal directions
of stress and strain rate
tensors do not coincide

Giusteri and Seto, J. Rheology, 62 (2018)

Steady-State Rheology: Shear

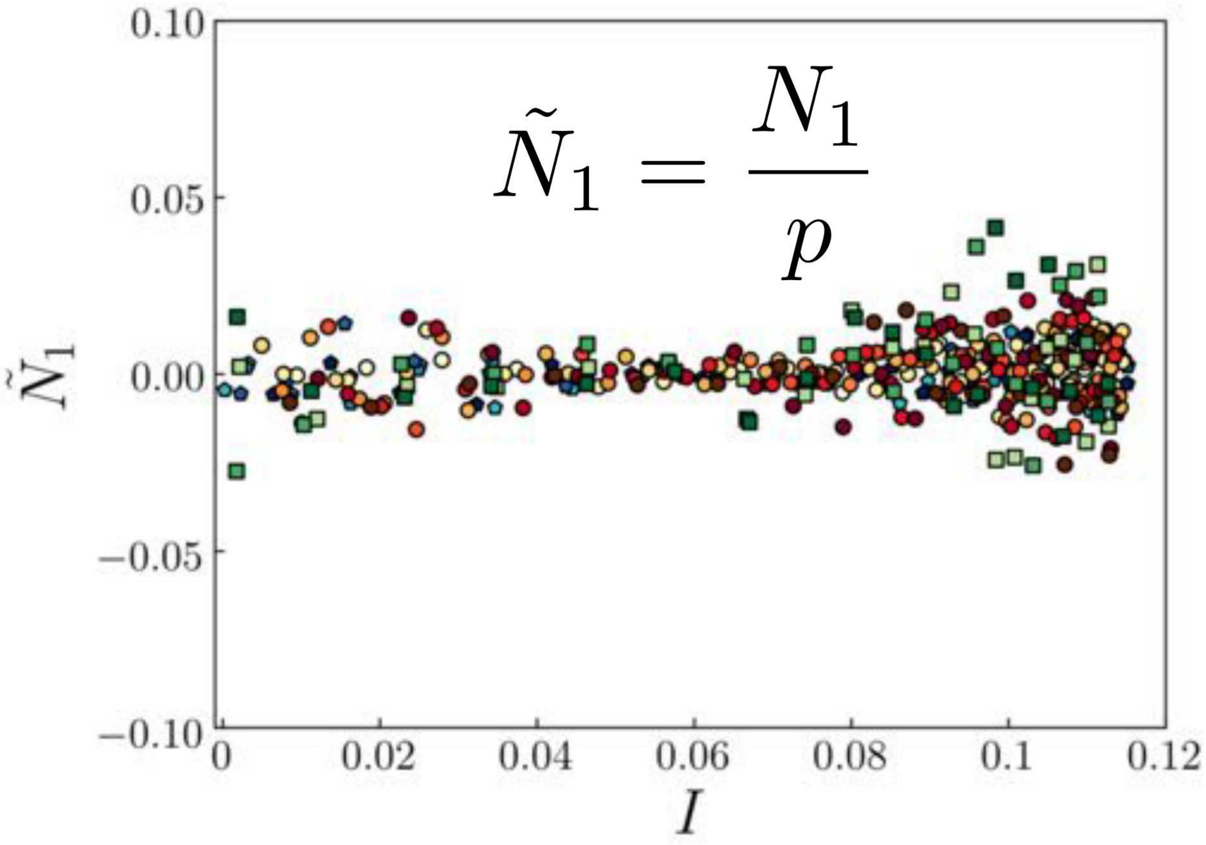


$$\mu = \mu_0 + aI^{\alpha}$$

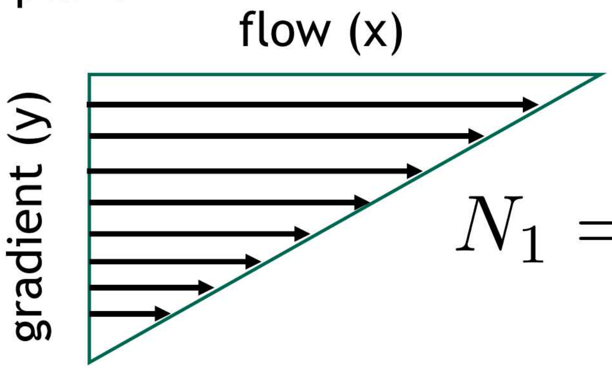


$$\phi = \phi_0 - bI^{\beta}$$

Steady-State Rheology: Co-axial Flow

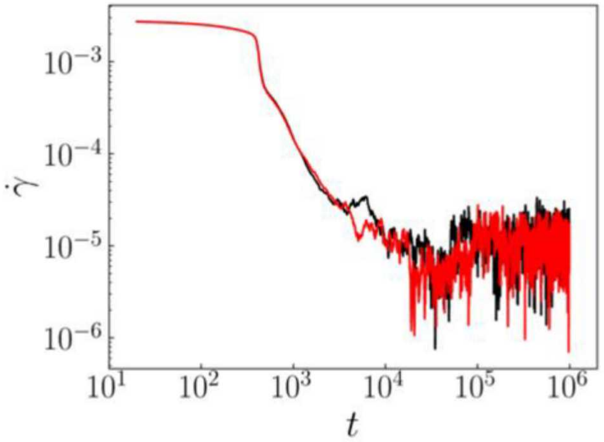


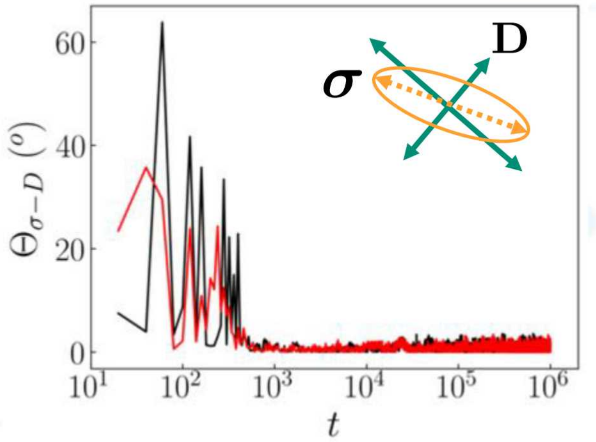
flow plane



$$N_1 = \sigma_{yy} - \sigma_{xx}$$

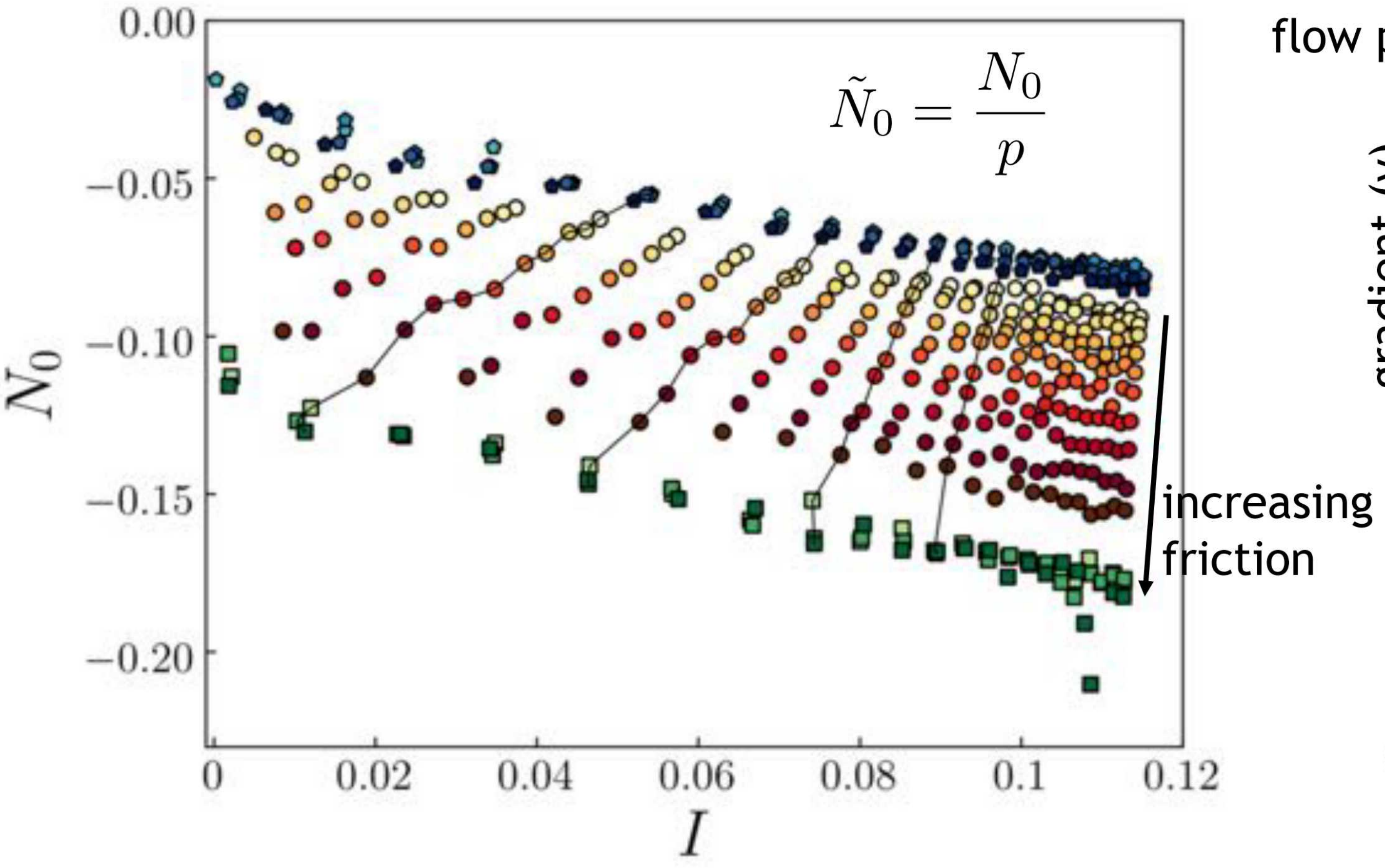
steady flow evolution



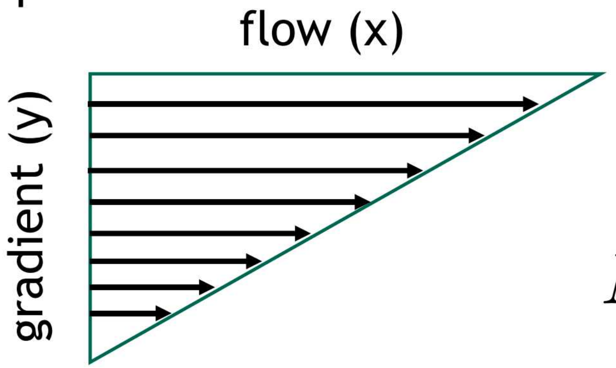


granular flows in simple shear are co-axial

Steady-State Rheology: Co-directional Flow?

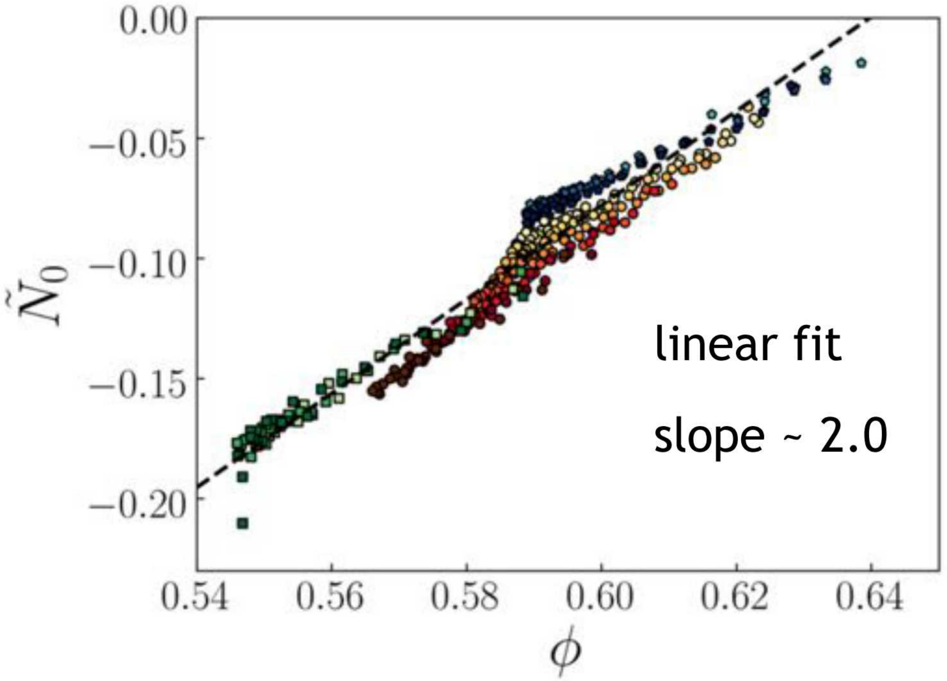


flow plane



$$N_2 = \sigma_{zz} - \sigma_{yy}$$

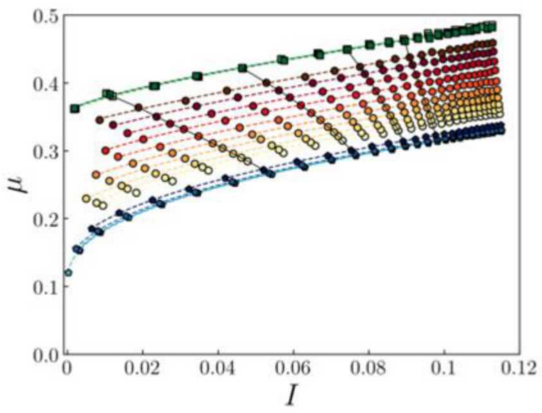
$$N_0 = N_2 + \frac{N_1}{2}$$

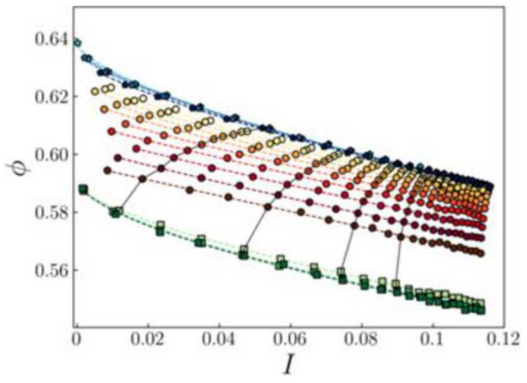


granular flows in planar shear are not co-directional

more compaction in the shear plane than normal to it

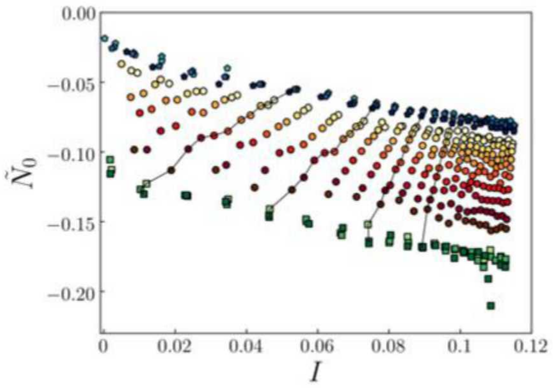
Conclusions & Outlook





stress tensor in planar xy-shear

$$\boldsymbol{\sigma} = \begin{pmatrix} p & \tau & 0 \\ \tau & p & 0 \\ 0 & 0 & p' \end{pmatrix} \quad p' < p$$

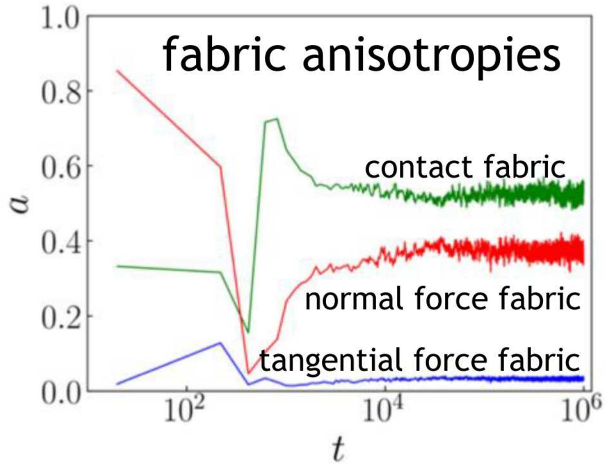


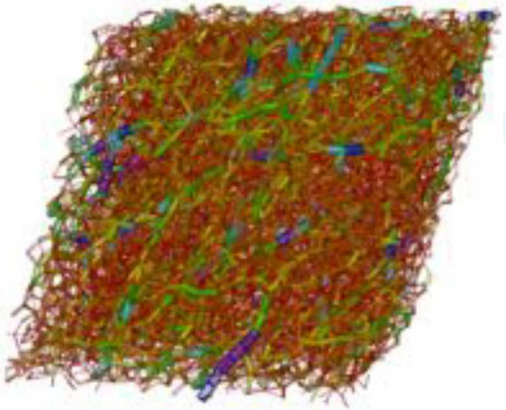
flow functions in dense granular flows

$$\mu(I) \quad \phi(I) \quad \tilde{N}_0(I)$$

- How about non-planar shear flows? Triaxial compression/extension? Nature of stress tensor in complex loading scenarios?

- Correlate evolution of internal fabric to the normal stress difference for micromechanical constitutive modeling





Srivastava et al., arXiv (online on 03/05/19)
Srivastava et al., Phys. Rev. Lett., 122 (2019)