Heterogeneous stresses and aggregation in sheared suspension of spheres and rods

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Outline and Acknowledgements

1. Localized stress fluctuations in dense suspensions of spherical particles: Summary, recent results, open questions (Vikram Rathee, Dan Blair)
2. Shear thinning and thickening in dense rod suspensions (Silica, Cellulose Nanocrystals): Very preliminary results, plans, open questions (Vikram Rathee, Xiangwen Lai, Matt Sartucci, Jeff Gilman, Bharath Natarajan)
3. Shear-induced aggregation in suspensions of attractive rods: Summary of results from model system, simulations (Pramukta Kumar, Justin Stimatze, Dave Egolf, Aparna Baskaran)

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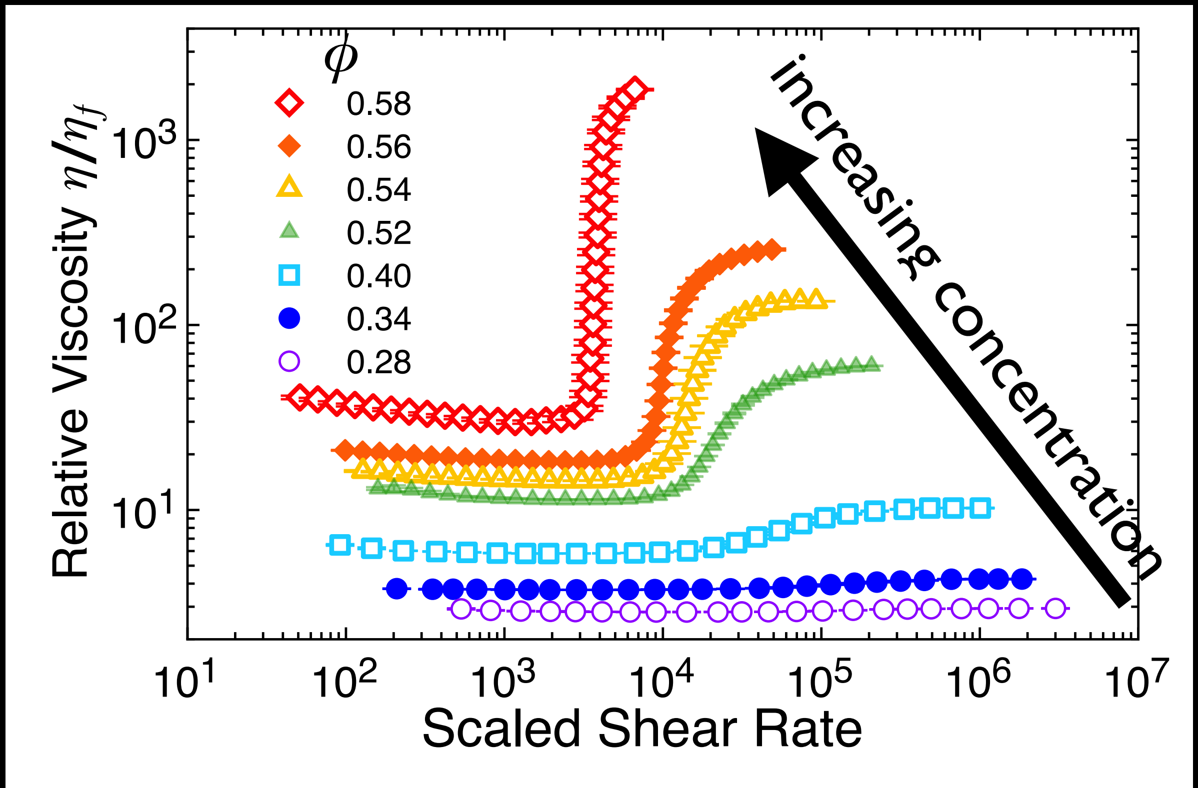
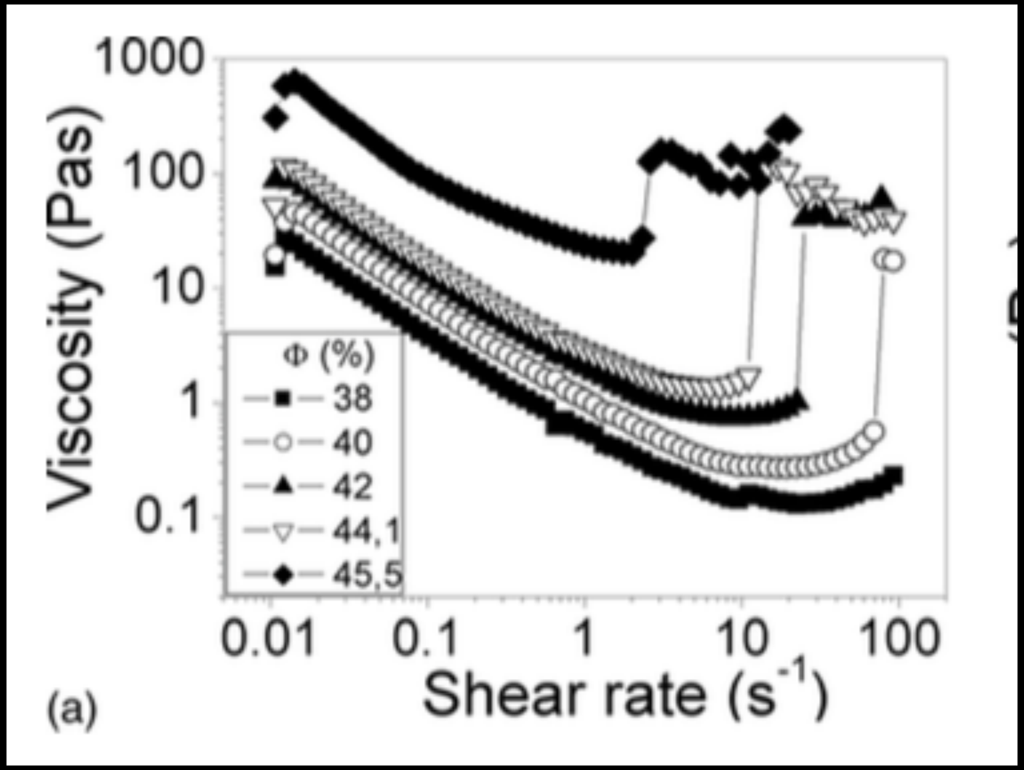
Rheology of Dense Suspensions





J. Royer, Dan Blair, S.Hudson, PRL 2016

1.5 μm silica+ Glycerol/water

Fall et al., JoR 2012

Cornstarch + water

Volume Fraction: $\phi = \dfrac{V_{part}}{V_{total}}$

Bulk rheology only gives average stresses (net torque)

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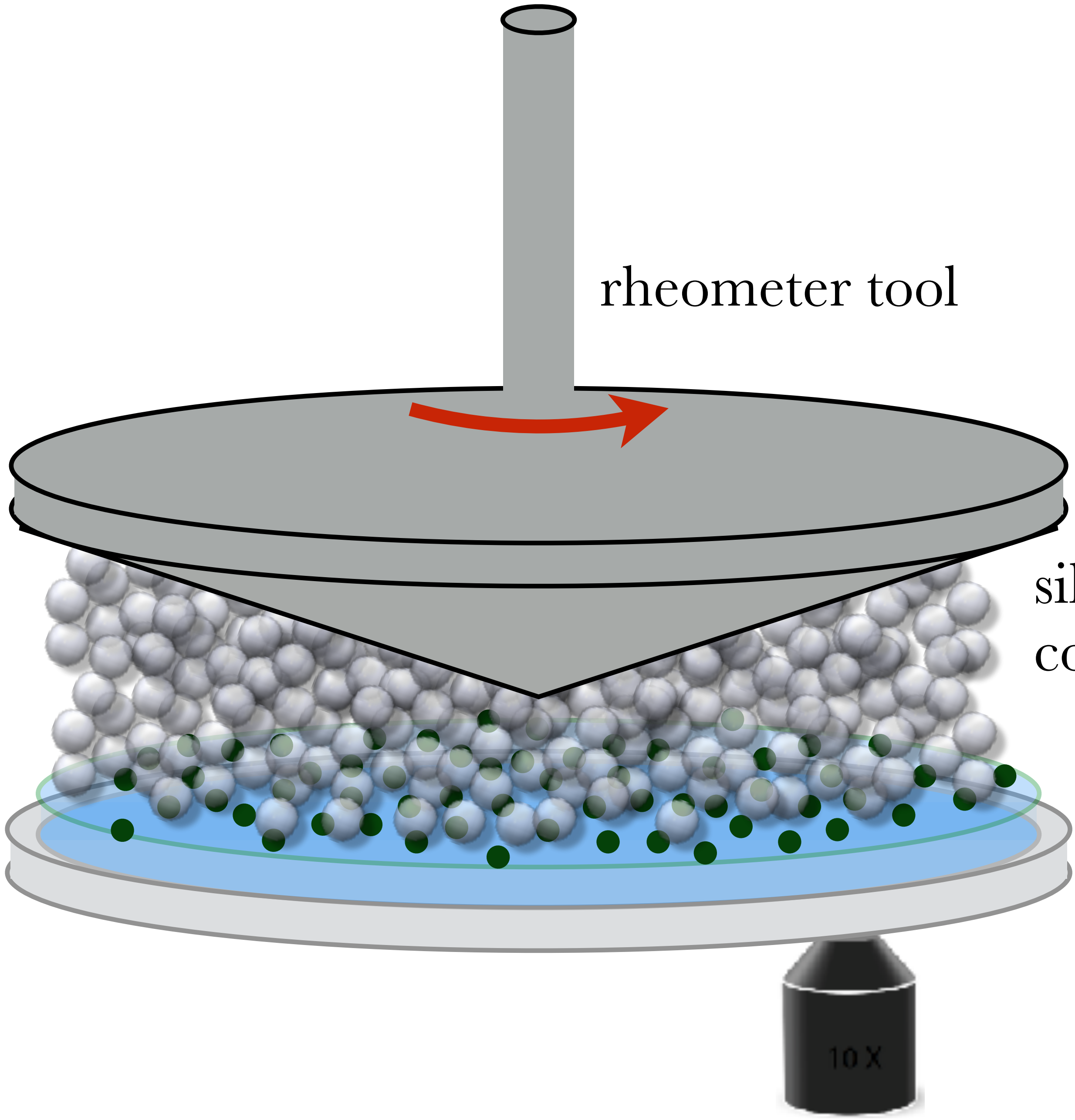
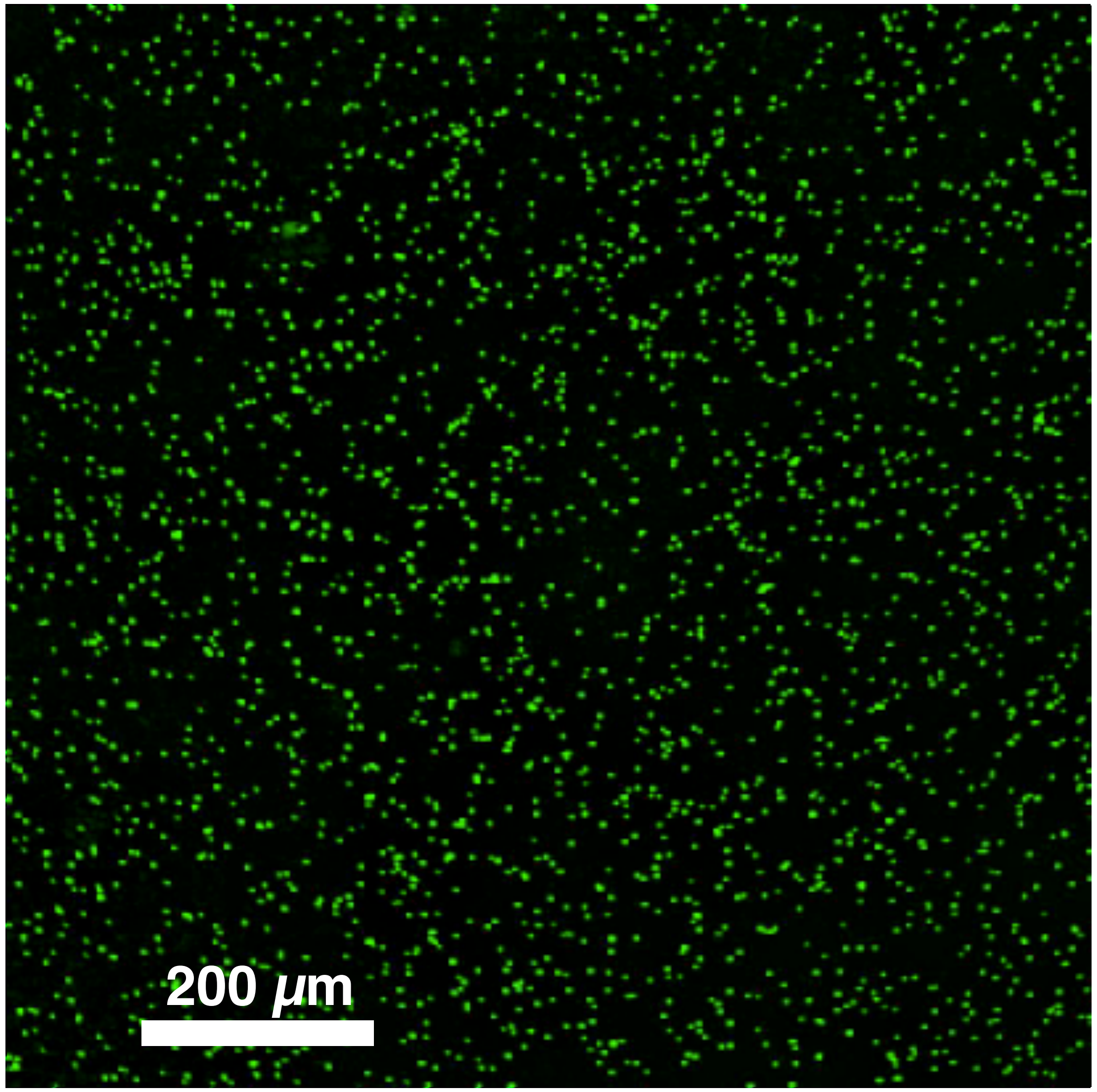
Experimental Technique : Boundary Stress Microscopy (BSM)



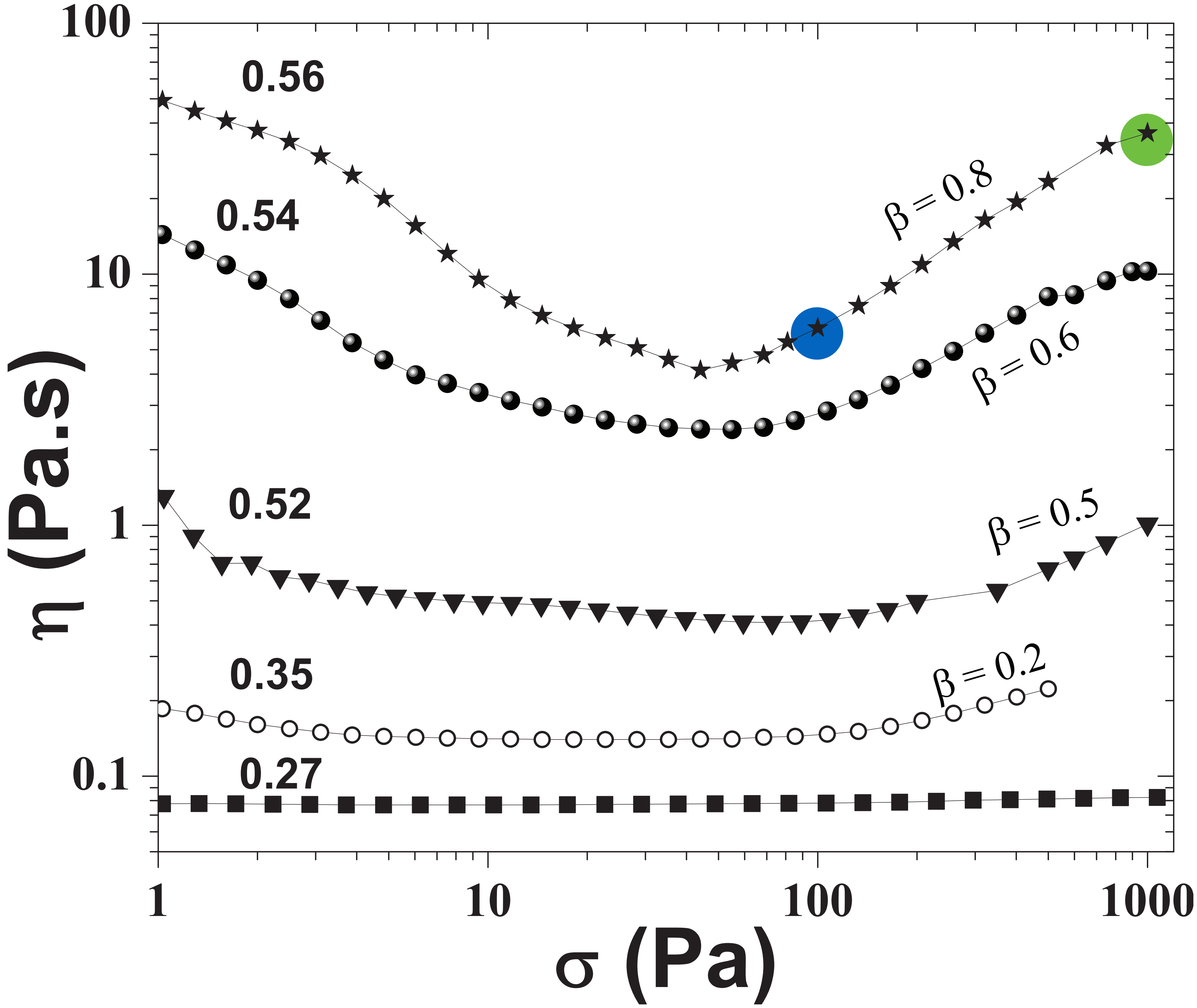


VR, DLB, JSU; PNAS 114 (33), 8740 (2017)

BSM: reveal heterogeneous stresses

R. Arevalo, P. Kumar, J. S. Urbach, D. L. Blair, Plos One 10(3): e0118021 (2015)

Continuous Shear Thickening

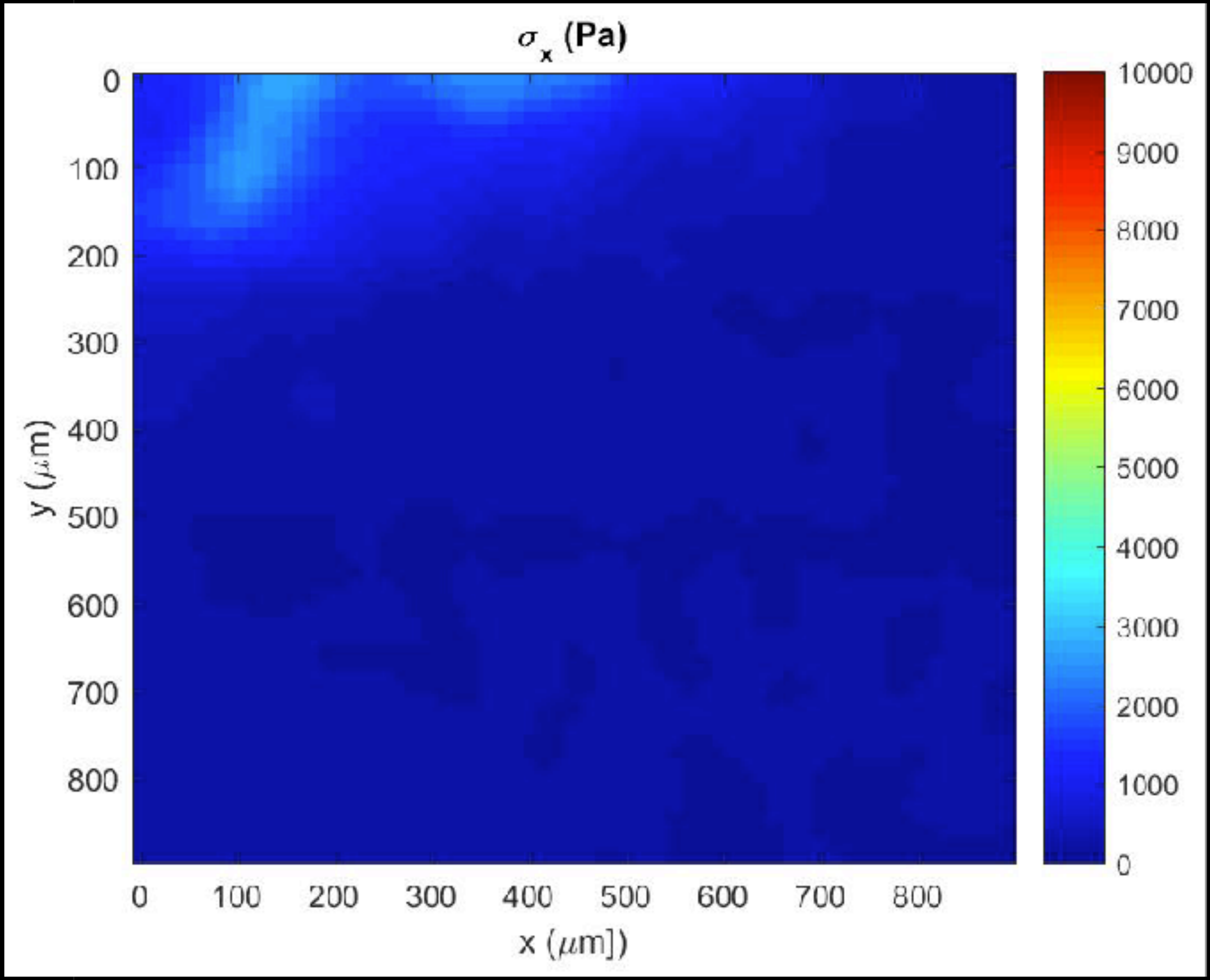


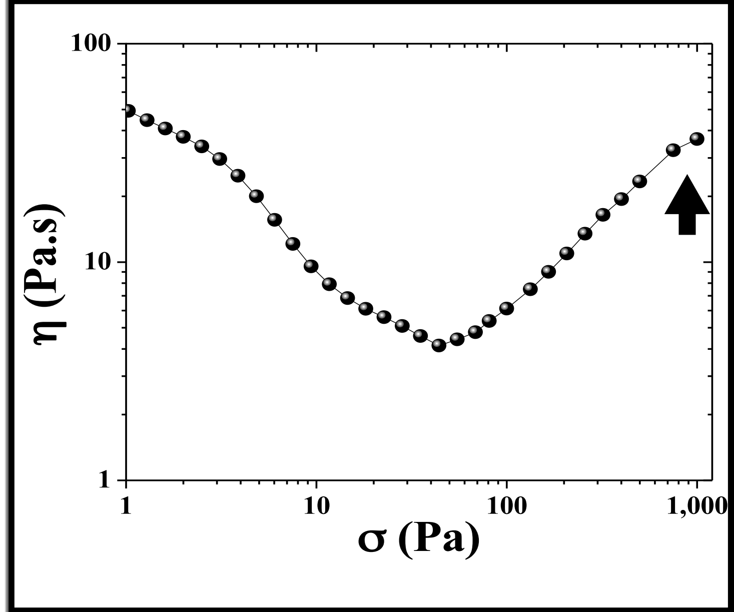
1 μm diameter silica in glycerol/water

Note: Stress changes x10, but shear rate ~x1.5

Boundary Stresses: $\phi = 0.56$

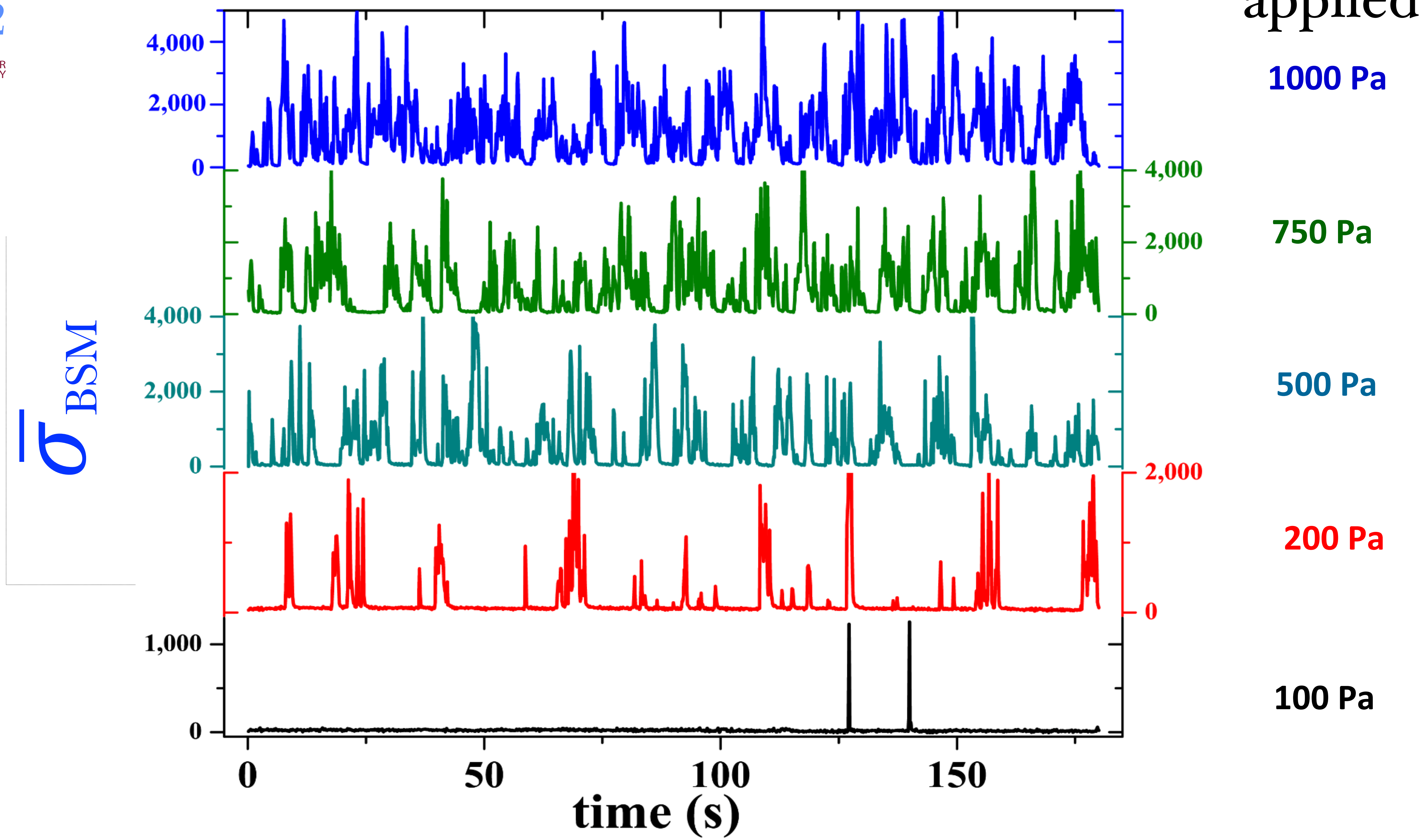
Stress at the Interface at $\sigma = 1000$ Pa





heterogeneous stresses propagate in shear direction

BSM at different applied stresses



Conclusion 1: CST is associated with intermittent, localized high stresses at the suspension boundary, frequency increases with applied stress

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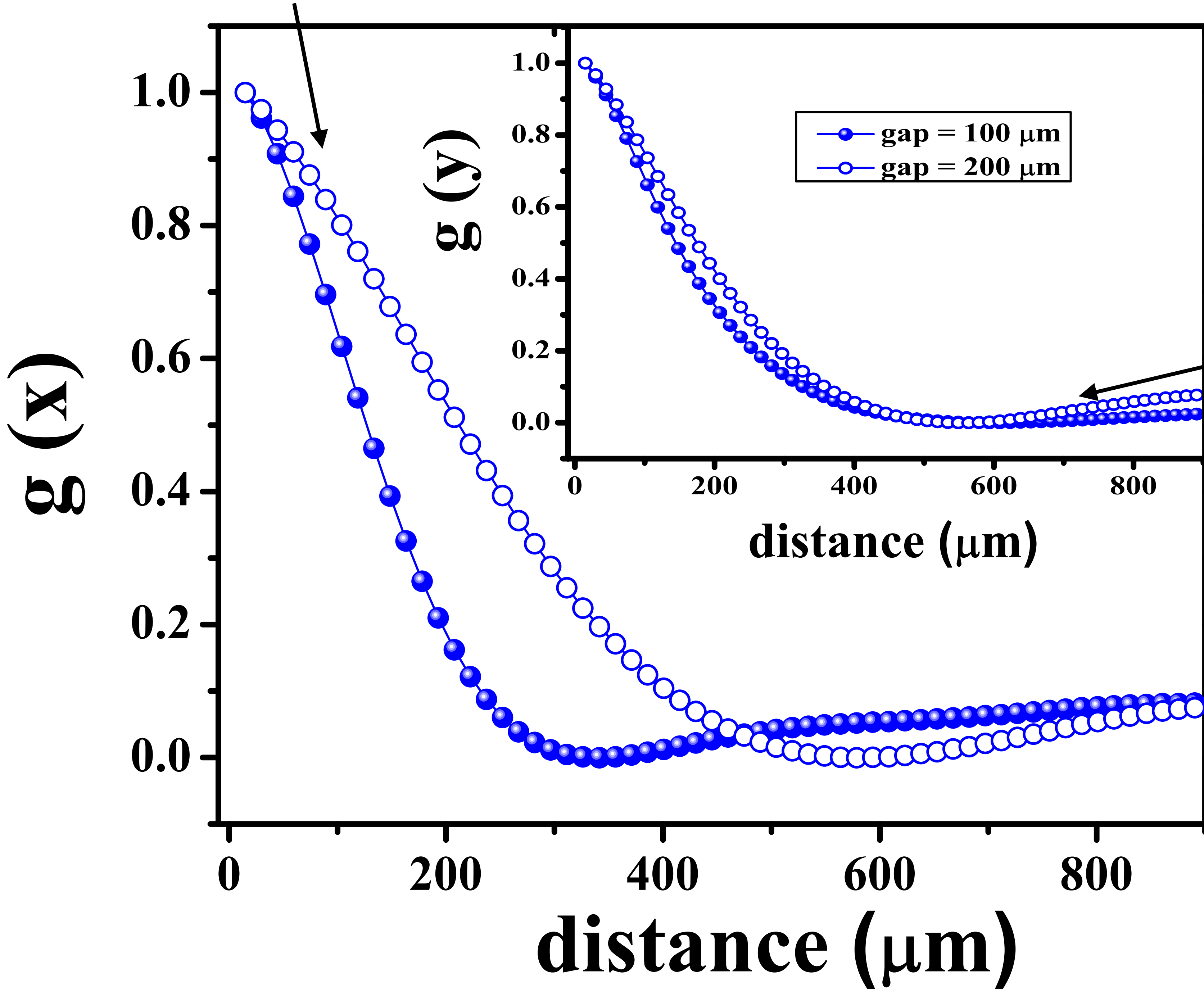
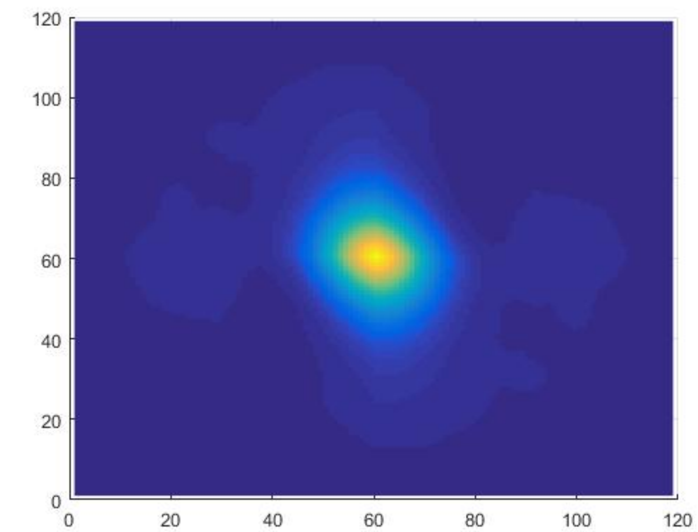
Spatial Autocorrelation

$< \delta\sigma_x(\vec{r})\delta\sigma_x(\vec{r}+x) >$

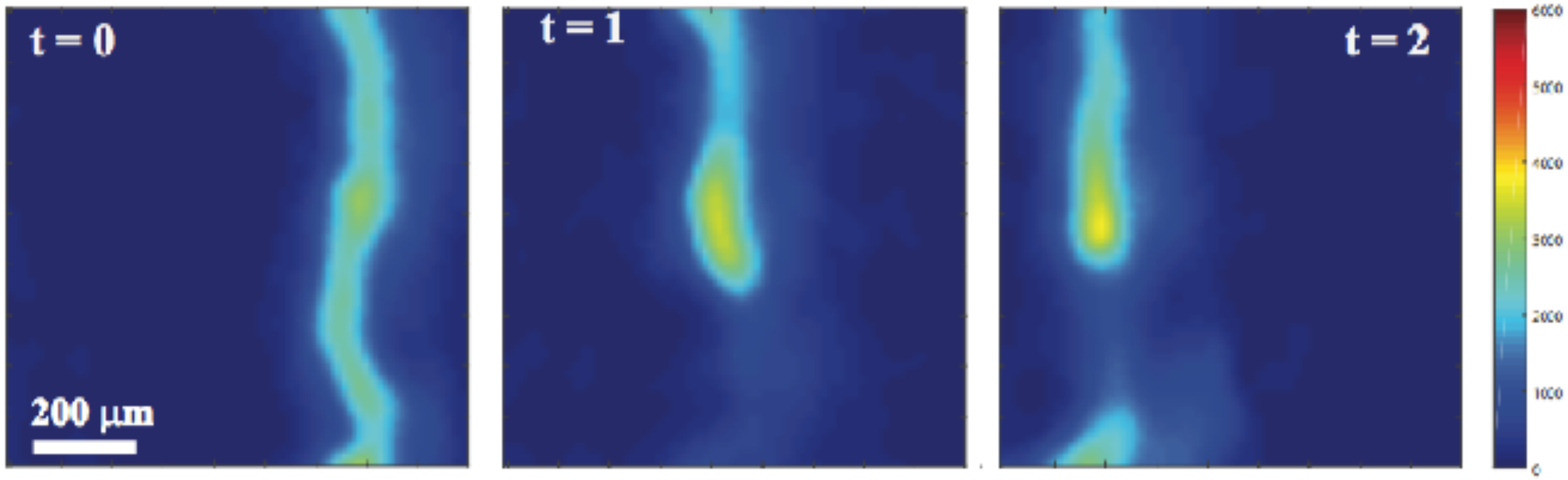


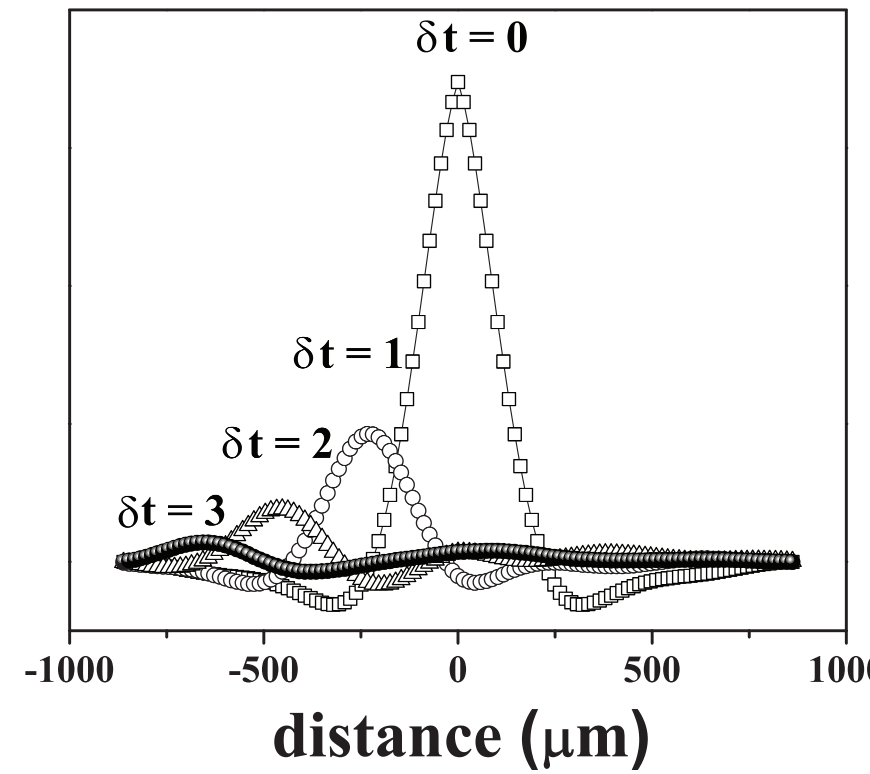
$< \delta\sigma_x(\vec{r})\delta\sigma_x(\vec{r}+y) >$



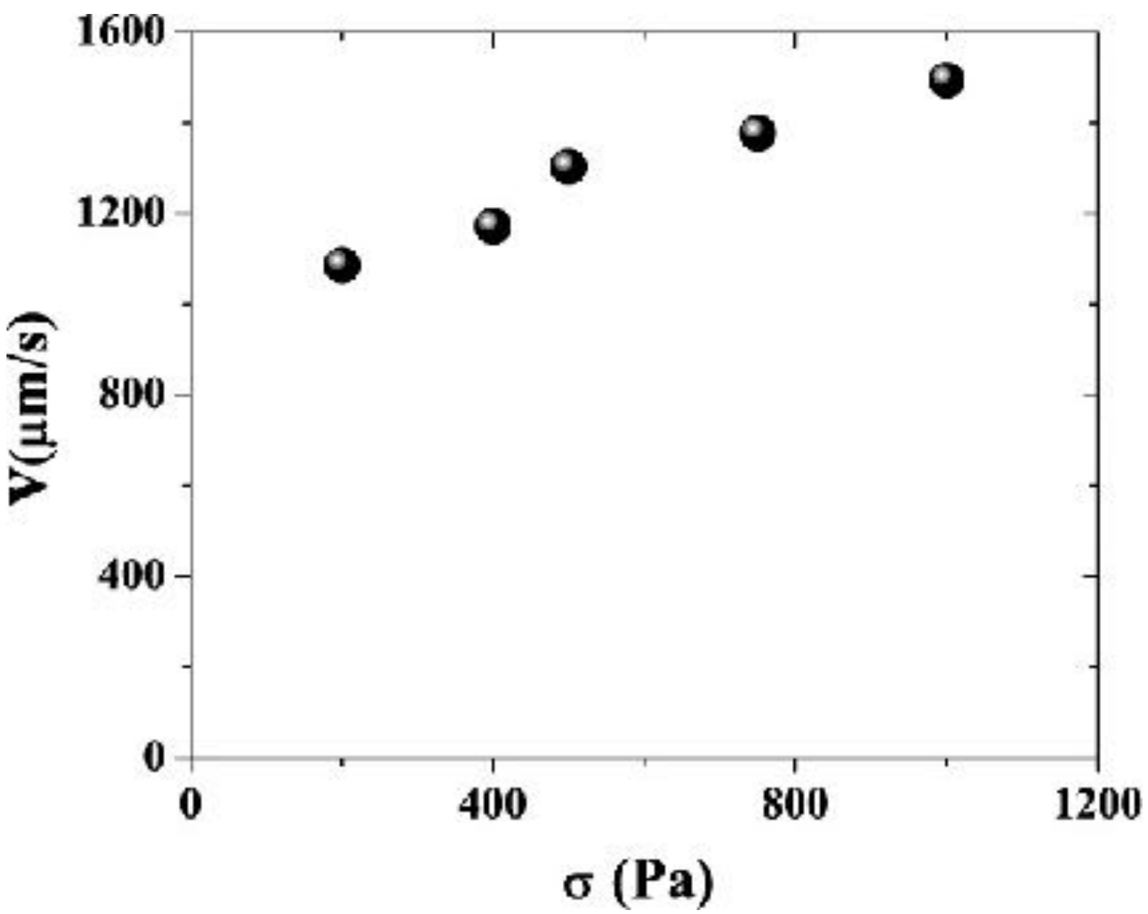
Conclusion 2: Characteristic size of high stress regions in flow direction set by gap.

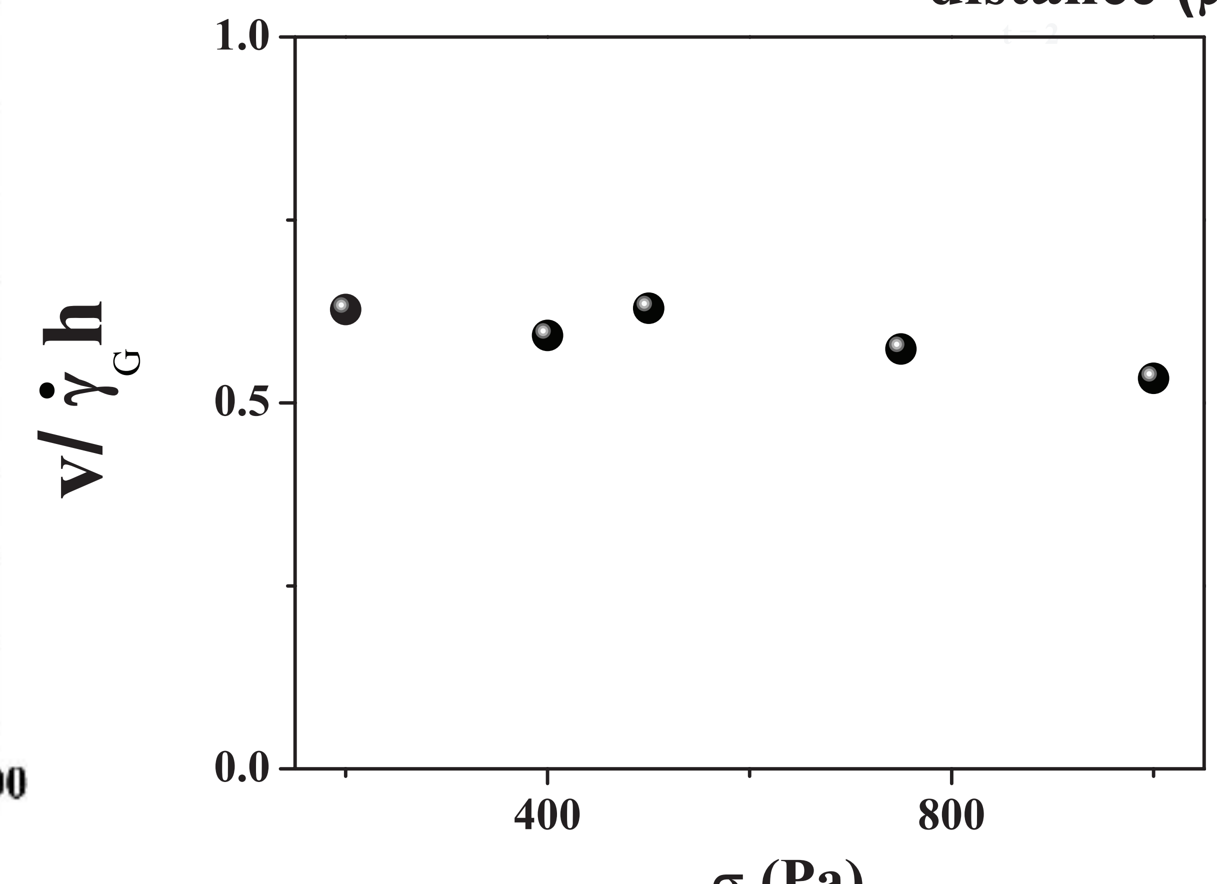
Temporal Cross-Correlation





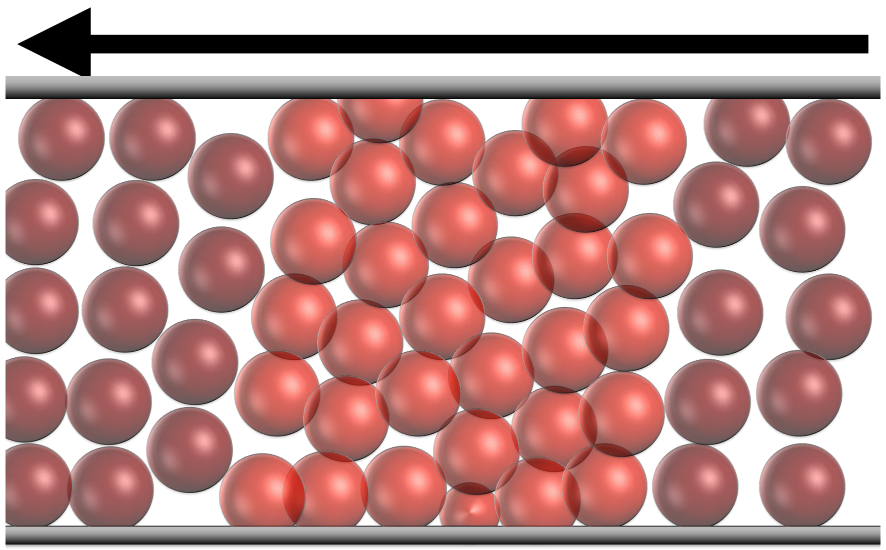
Large stresses propagate in velocity direction



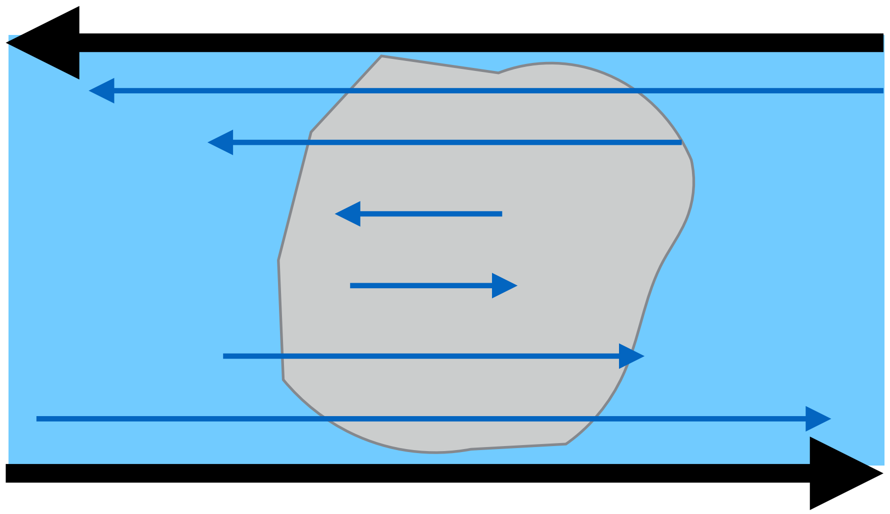


Conclusion 3: Regions propagate (on average) in the flow direction with speed of the suspension mid-plane (assuming symmetric flow profile).

Two-fluid Model

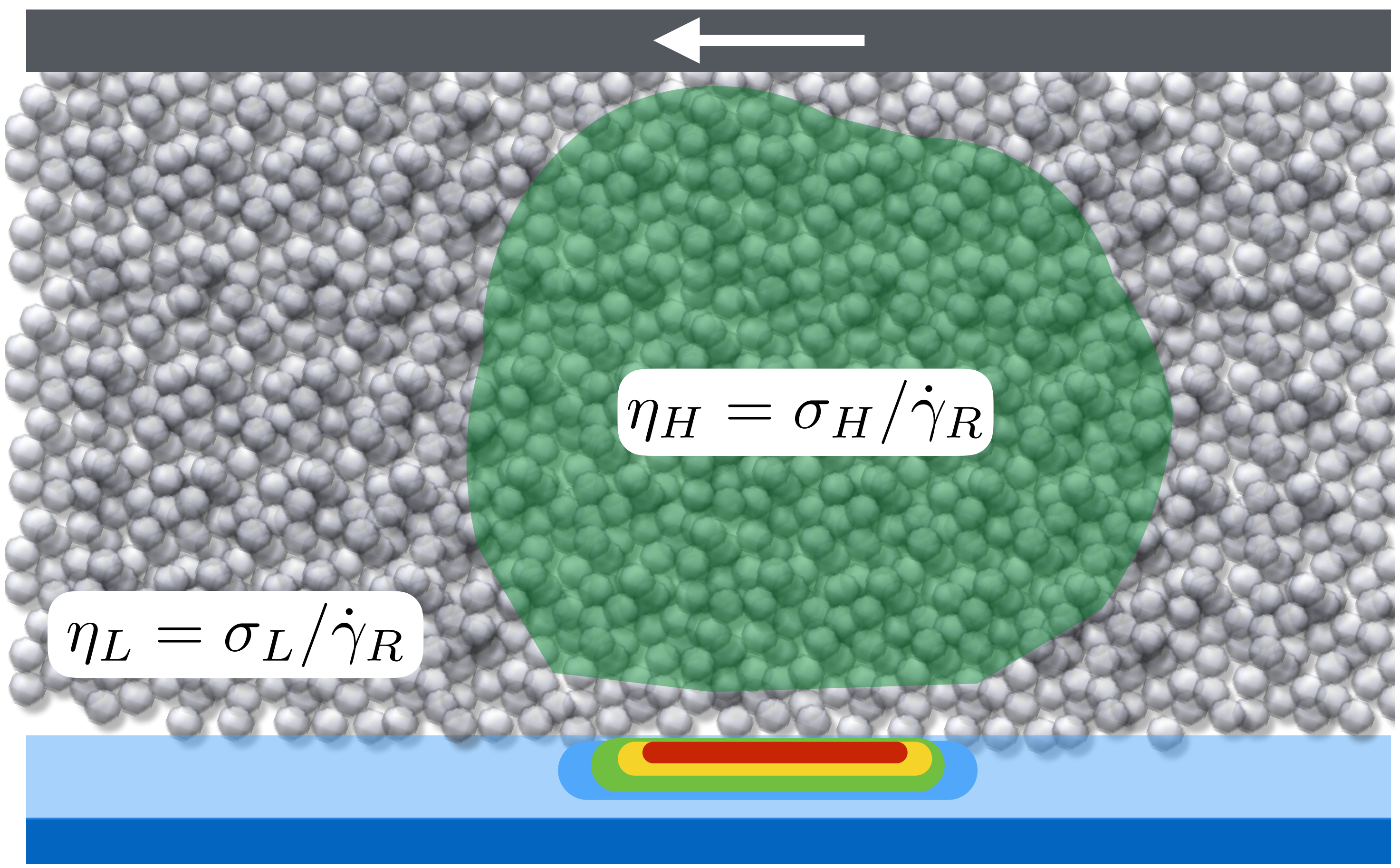


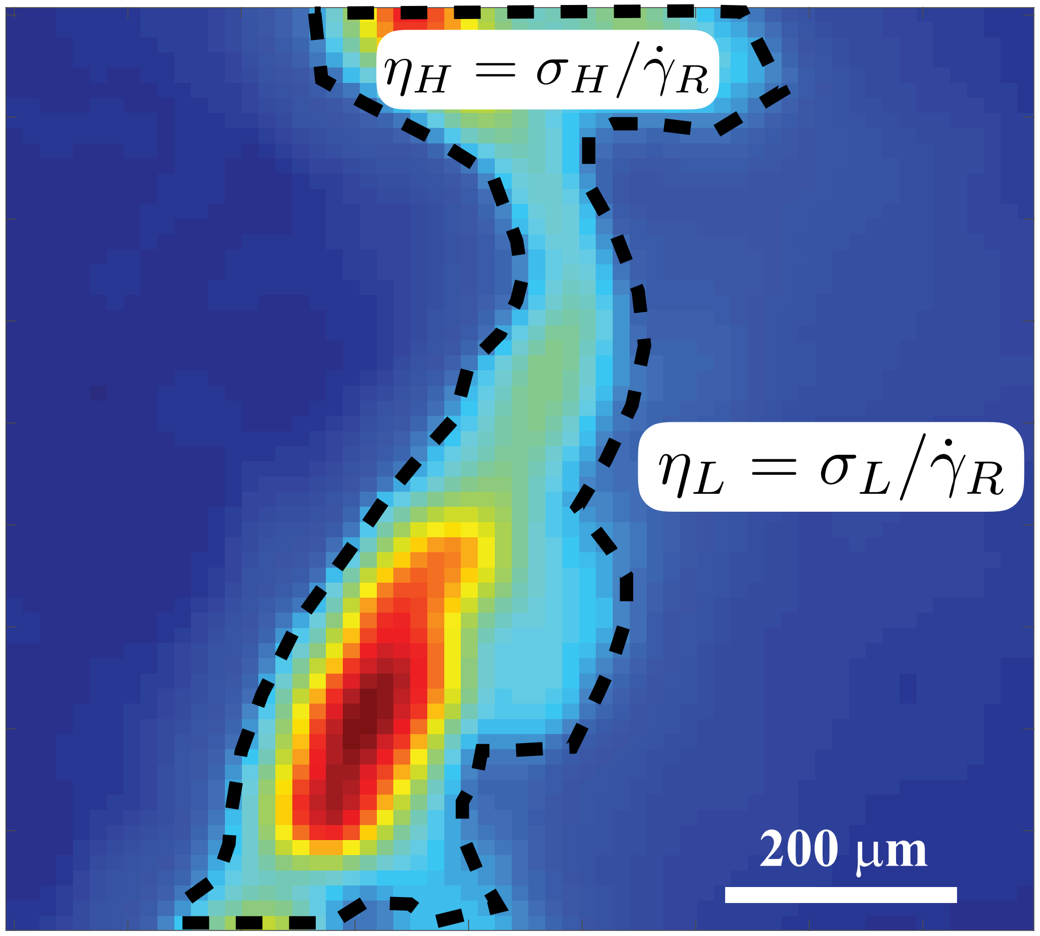
Lab Frame



Center of mass frame.

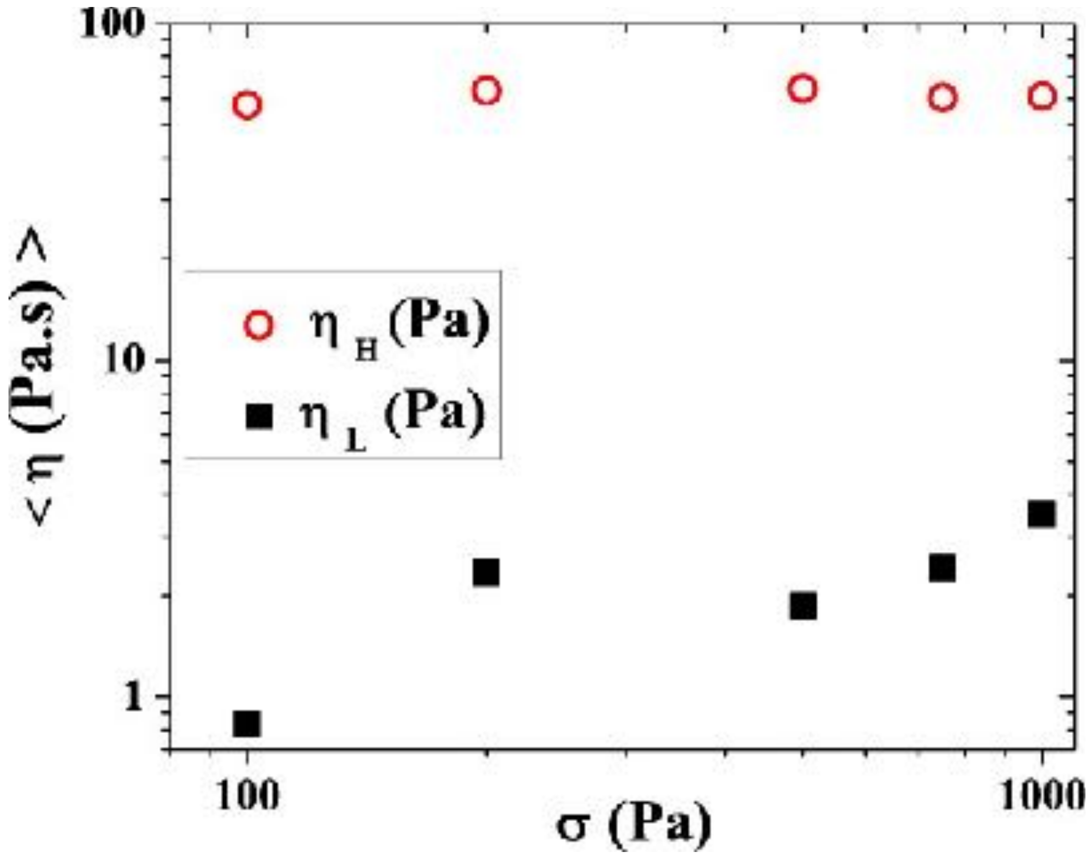
Percolating network of high inter-particle forces - spans gap, at rest in CM frame. Size determined by shearing boundaries.



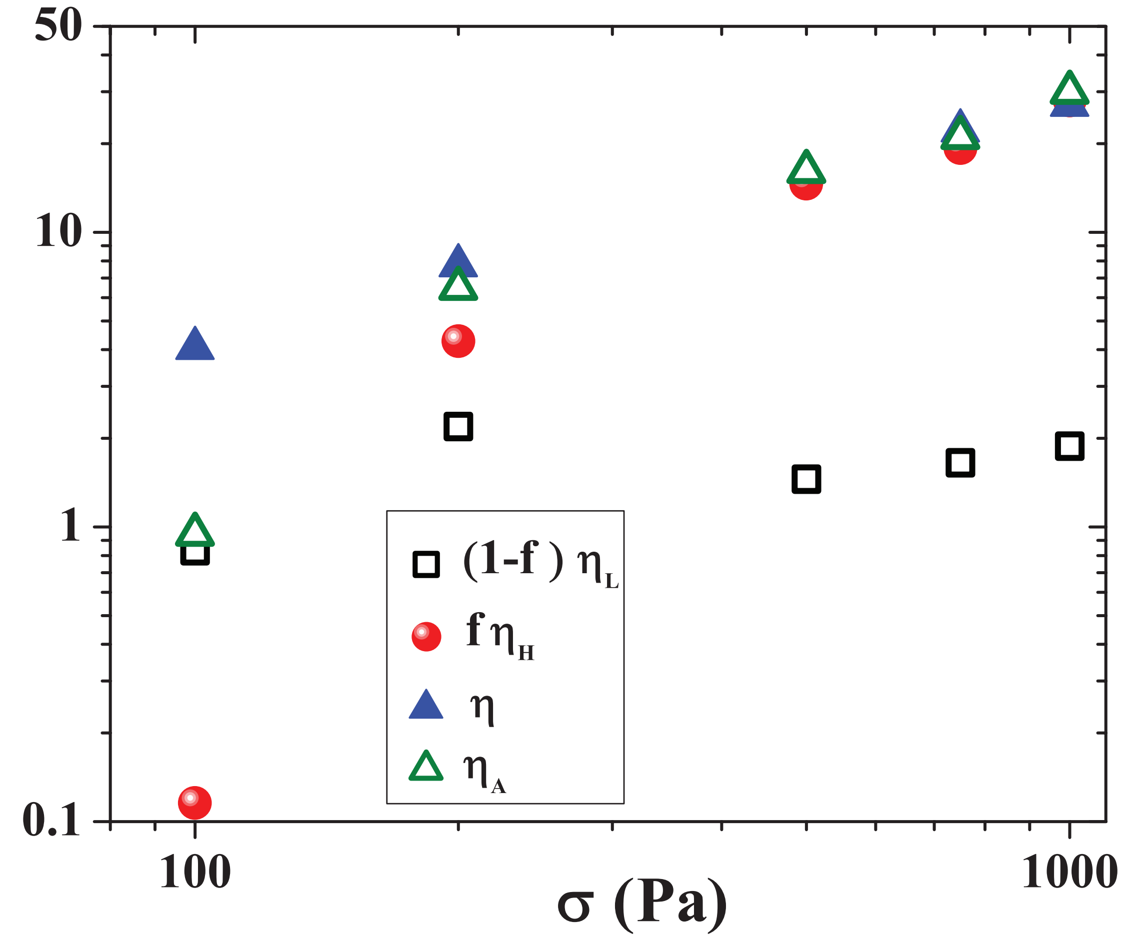


Two-fluid Analysis

$\phi = 0.56$ Viscosity



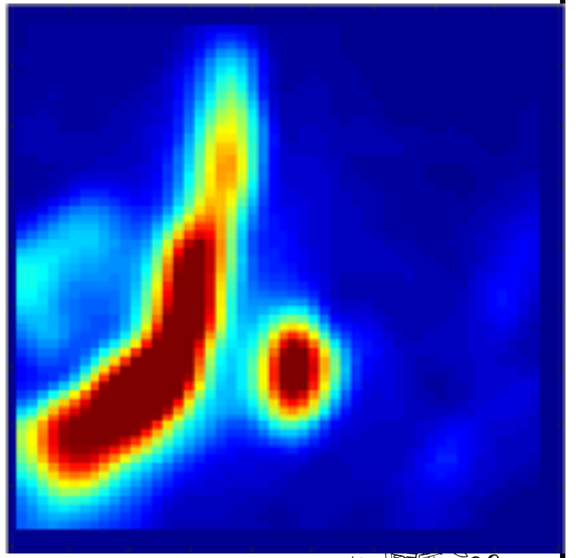
Contribution to Total



f = high viscosity fraction

$$\eta_A = (1 - f)\eta_L + f\eta_H$$

Conclusion 4: CST arises from an increasing fraction of the suspension existing in the high (effective) viscosity phase



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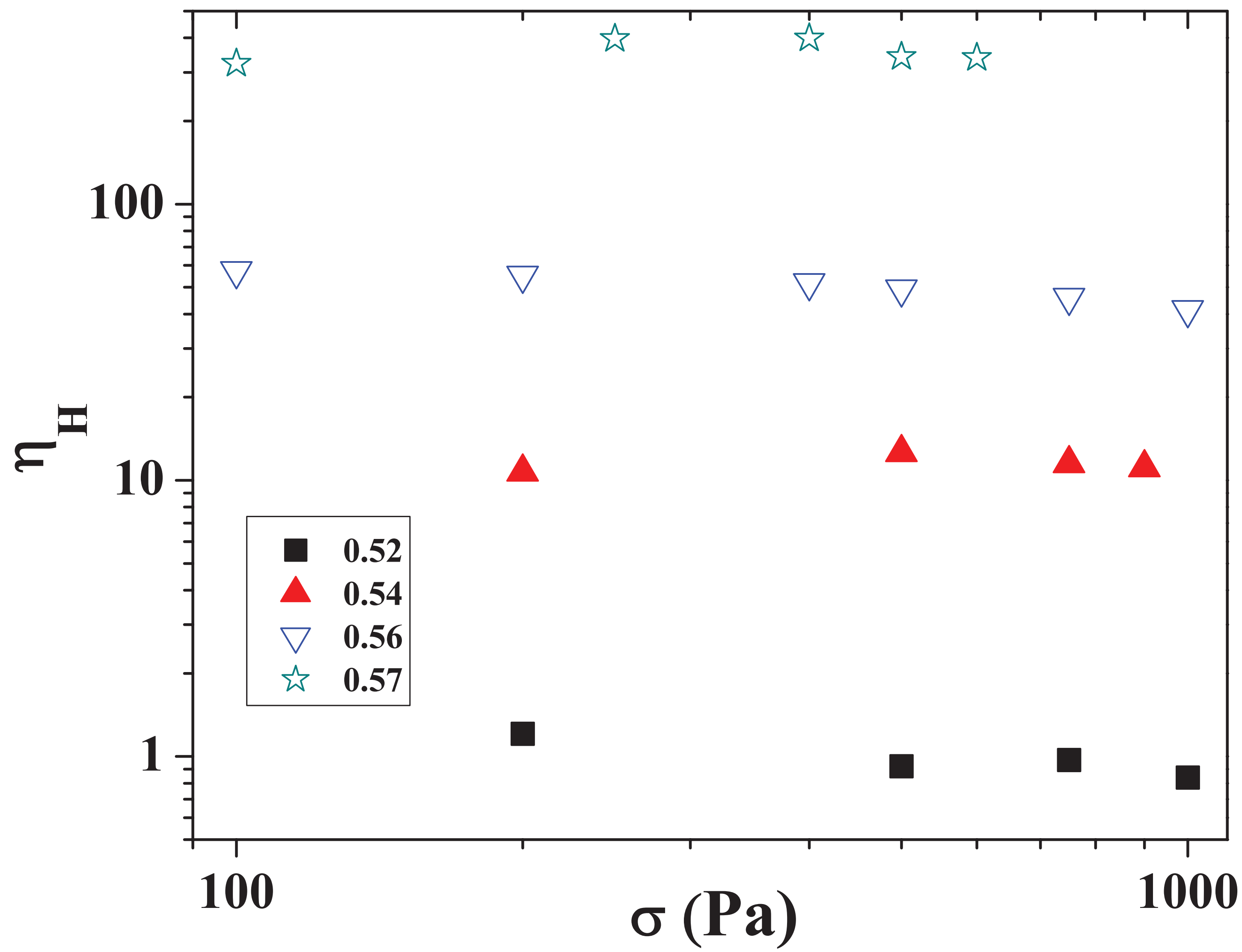
Concentration Dependence



Conclusion 5: High viscosity phase has roughly Newtonian viscosity that increases rapidly with concentration over a relatively large range of concentrations.

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Summary, Open Questions and Work in Progress

1. *CST is associated with intermittent, localized high stresses at the suspension boundary, frequency increases with applied stress*
2. *Characteristic size of high stress regions in flow direction set by gap.*
3. *Regions propagate in the flow direction with speed of the suspension mid-plane*
4. *CST arises from an increasing fraction of the suspension existing in the high viscosity phase*
5. *High viscosity phase has roughly Newtonian viscosity that increases rapidly with concentration*

VR, DLB, JSU; PNAS 114 (33), 8740 (2017)

Some Open Questions

1. Connection between stress and velocity, density fluctuations.
2. Role of boundaries, boundary slip
3. Evolution of high stress regions
4. Connection to normal force
5. Connection to DST, shear jamming
6. Relevance to other systems (different particles, different geometries)
7. Connection to simulations, theory

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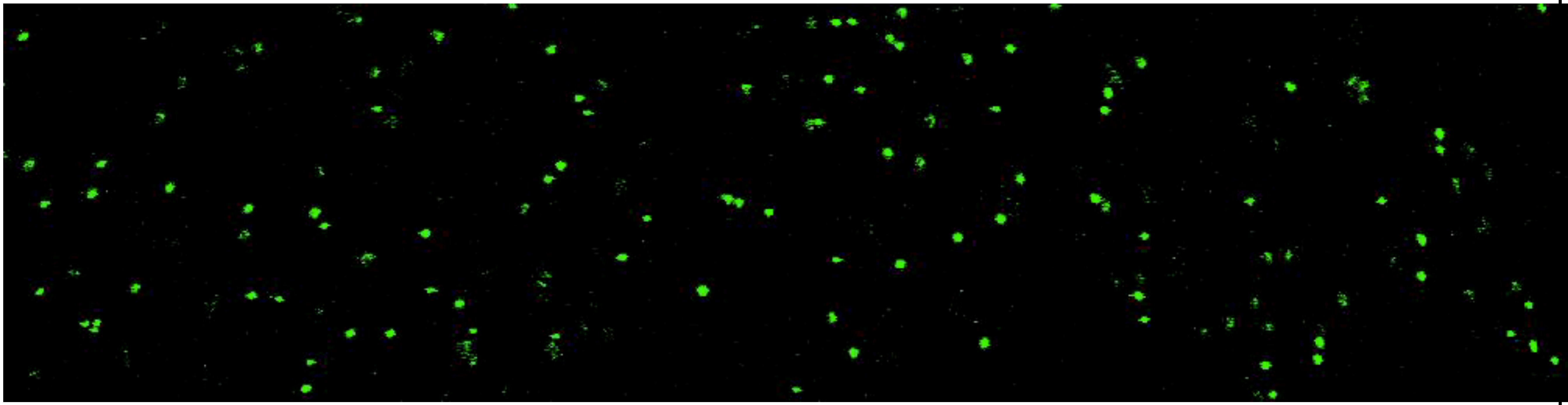
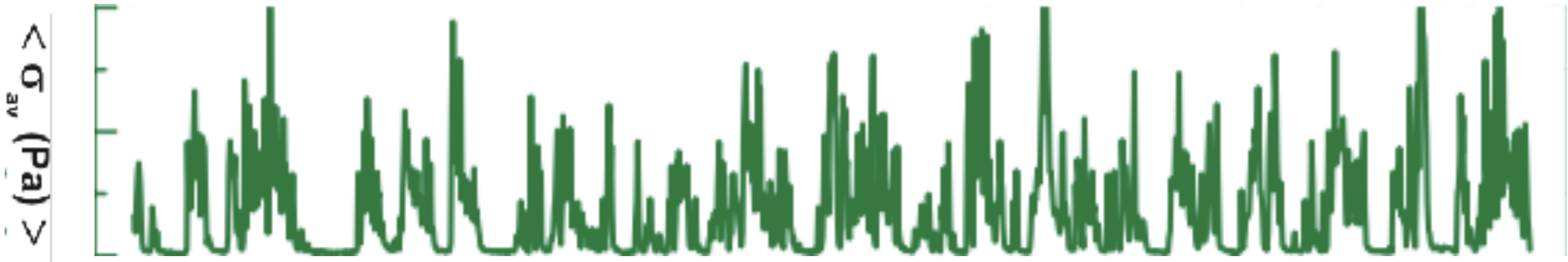
Motion of Tracer Particles

Tracking flow in first ~5 microns from the bottom of the suspension.



$\phi = 0.56$

$\sigma = 500$ Pa



Substantial non-affine flow, but continually straining

Fluctuations small compared to speed of high stress regions.

No substantial flow in gradient direction

Likely fluctuations in slip velocity.

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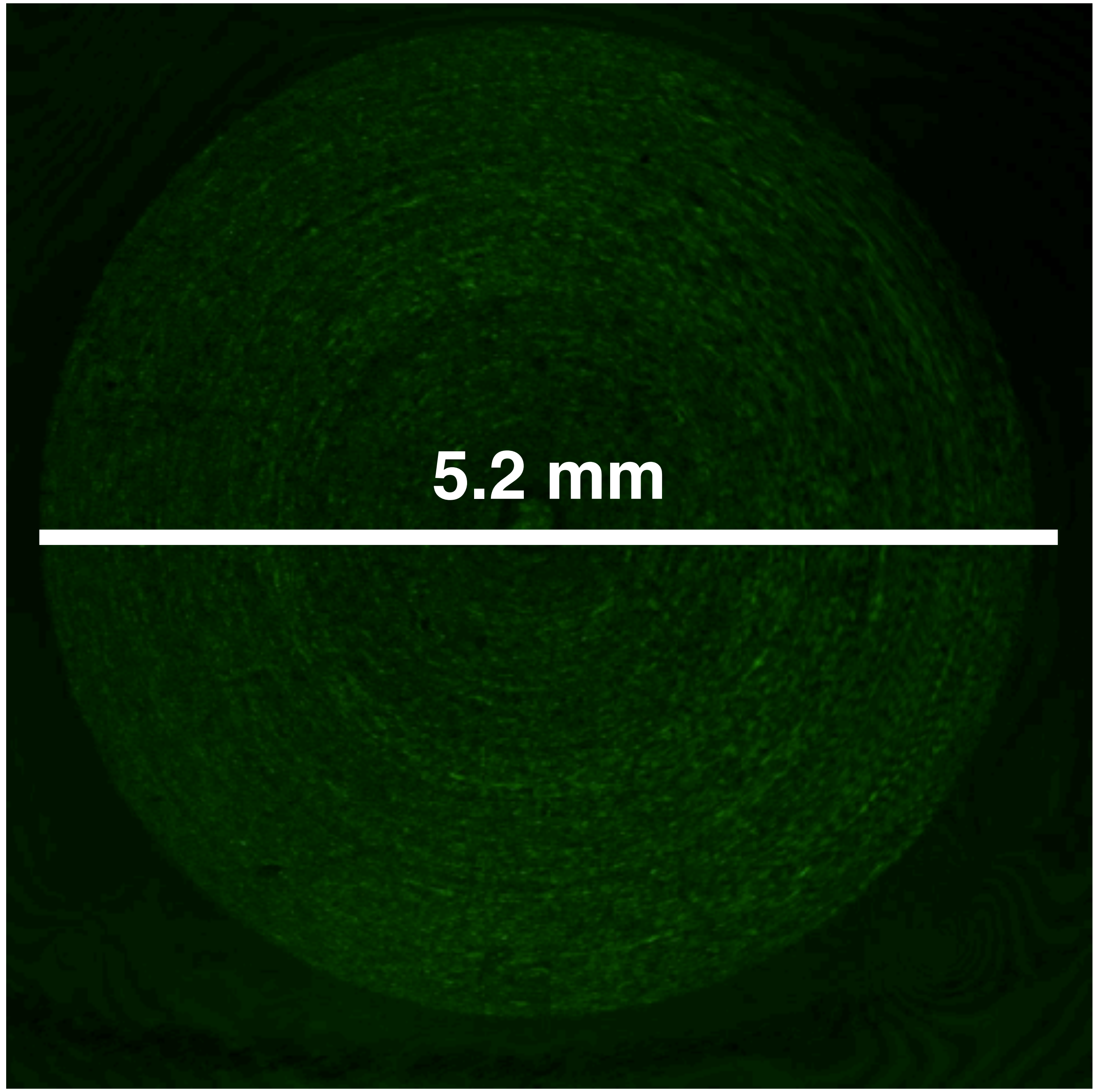
Lower magnification, smaller tool



Can visualize entire suspension.

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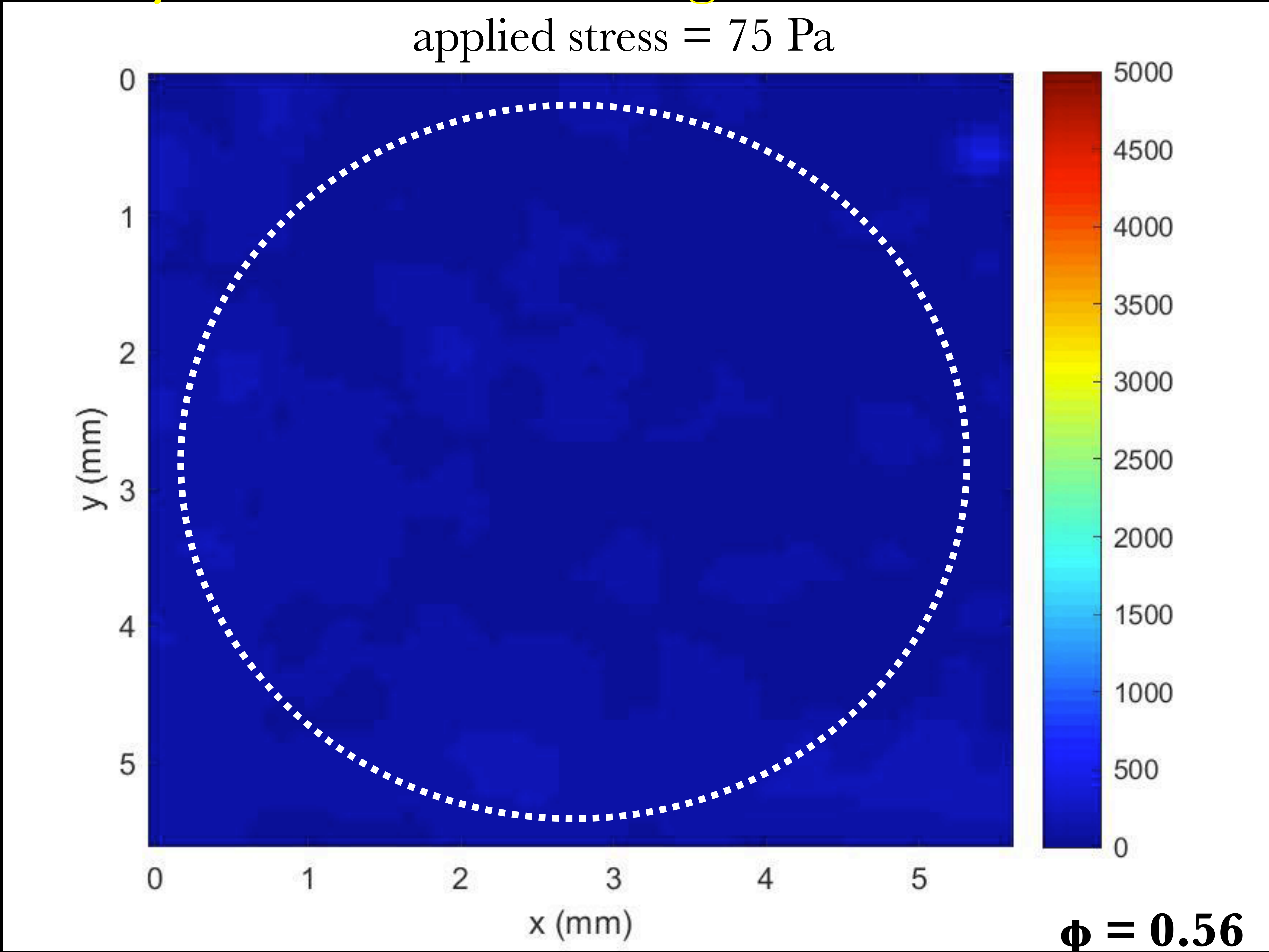
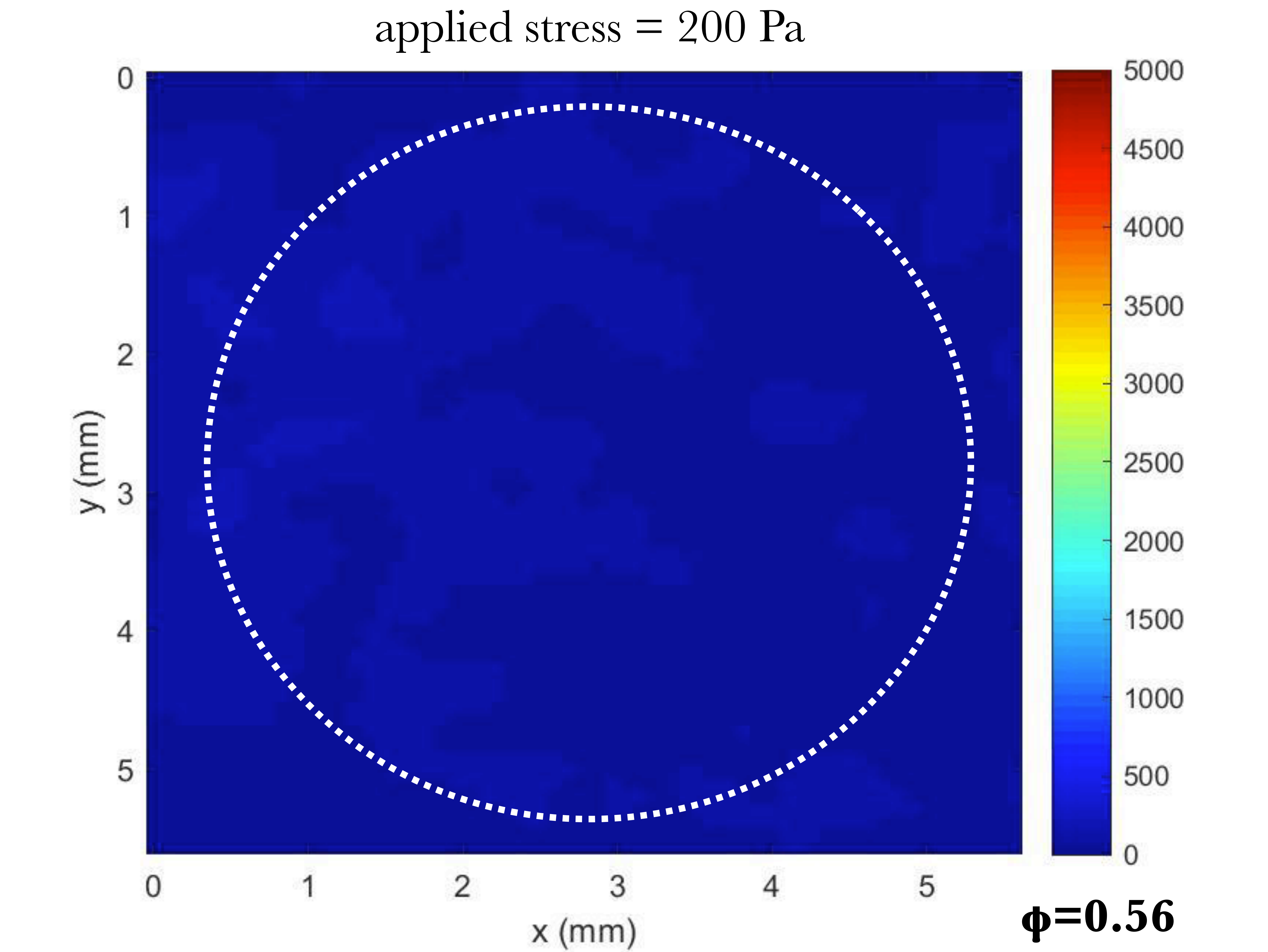
Dynamics of heterogeneous events



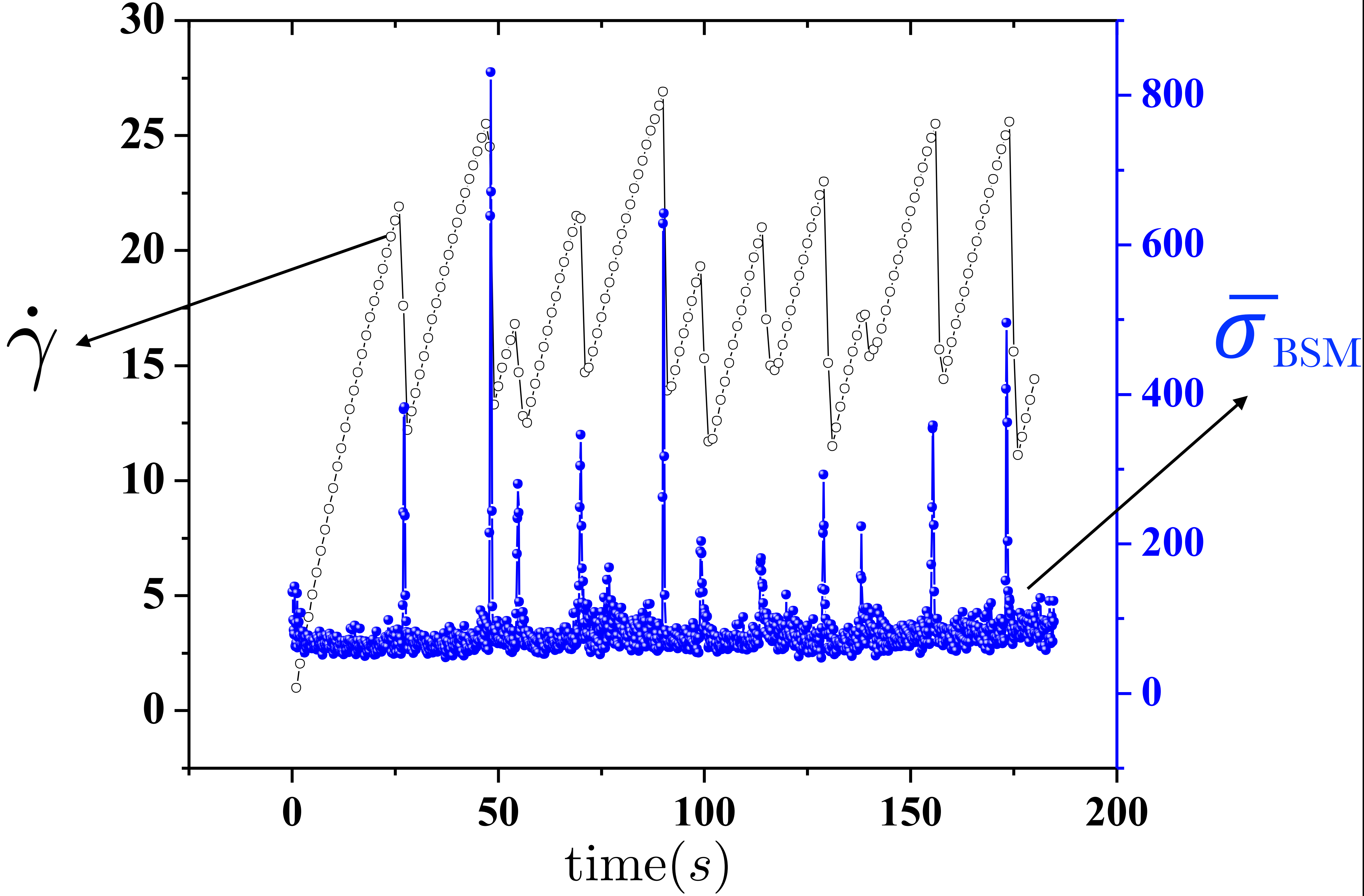
ϕ = 0.56



applied stress = 200 Pa
y (mm)
x (mm)
0
1
2
3
4
5
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
φ=0.56

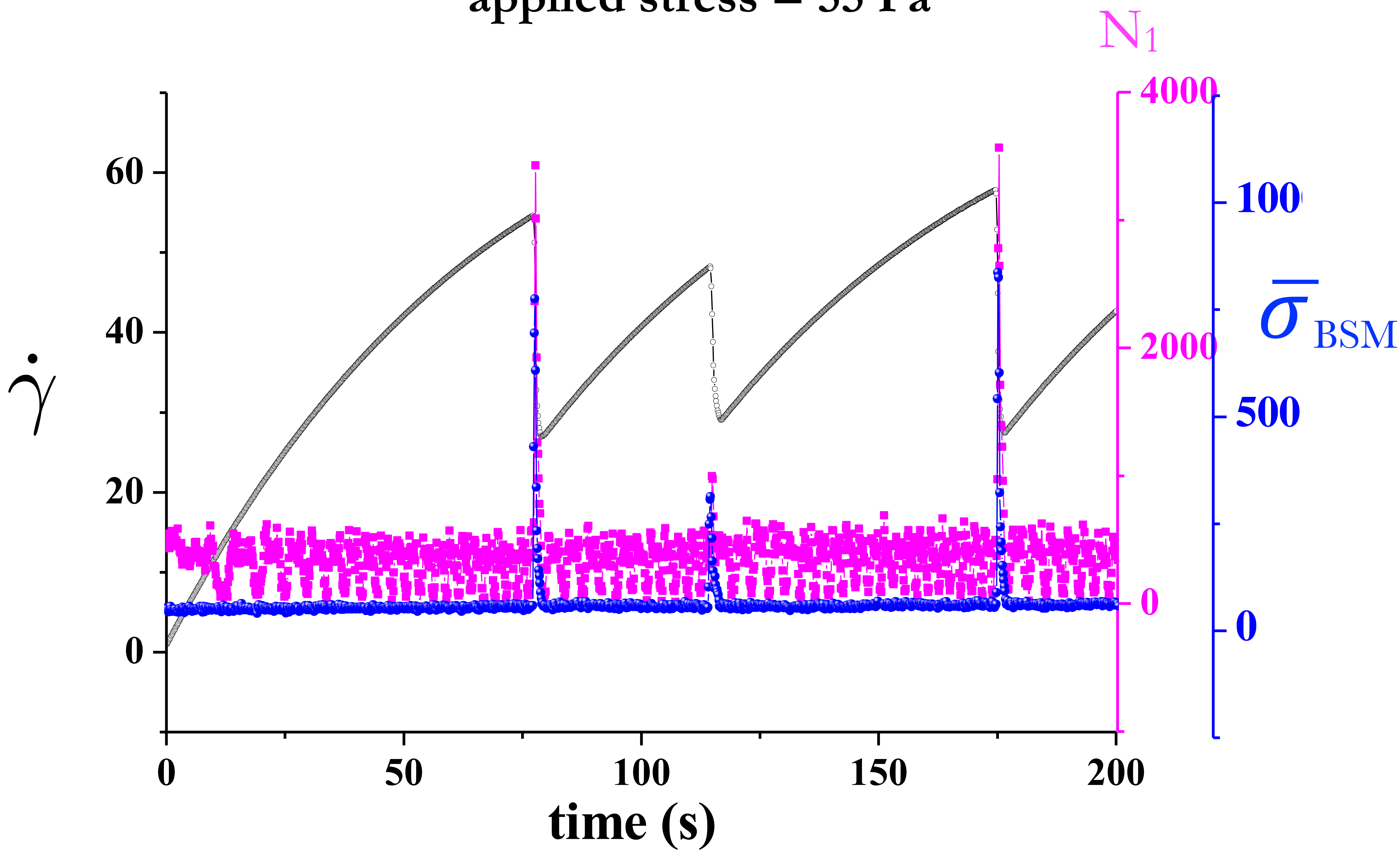
Small tool has complicated dynamics

applied stress = 75 Pa



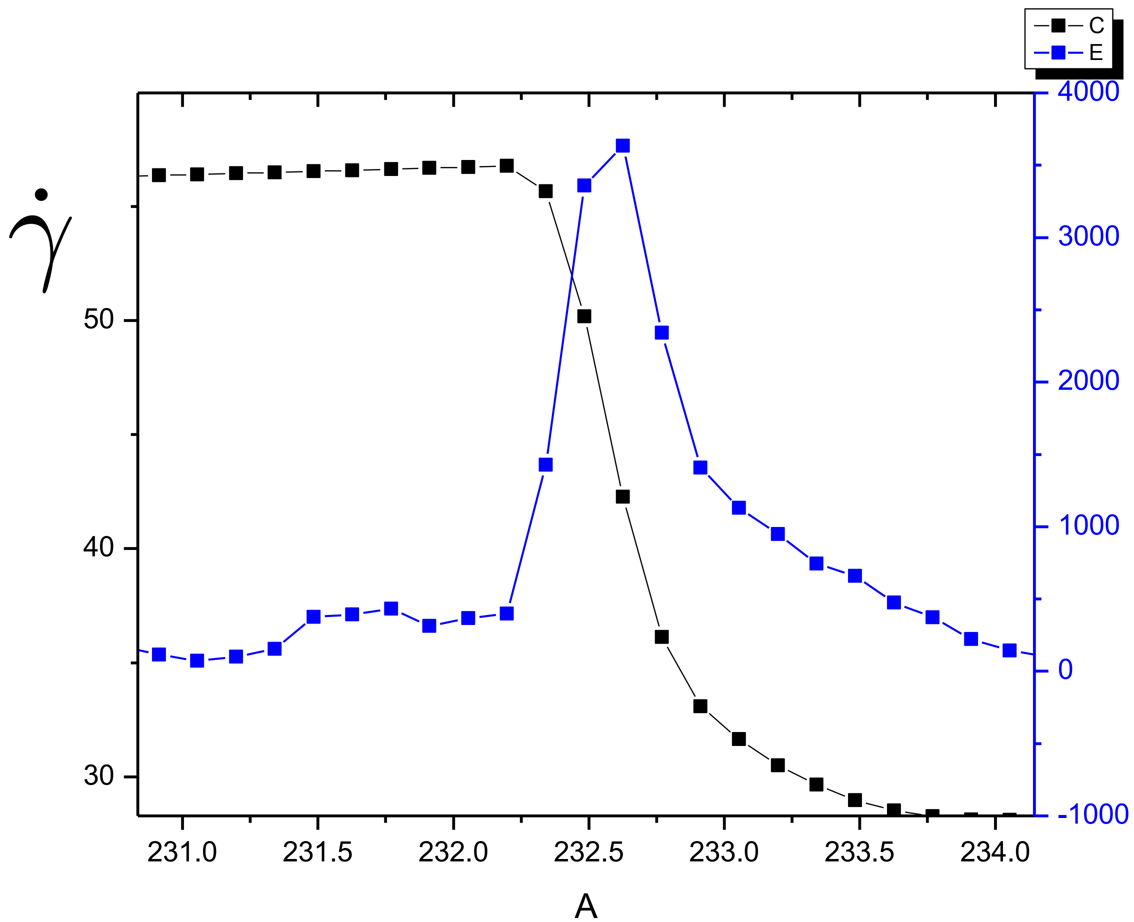
Connection to Normal Force

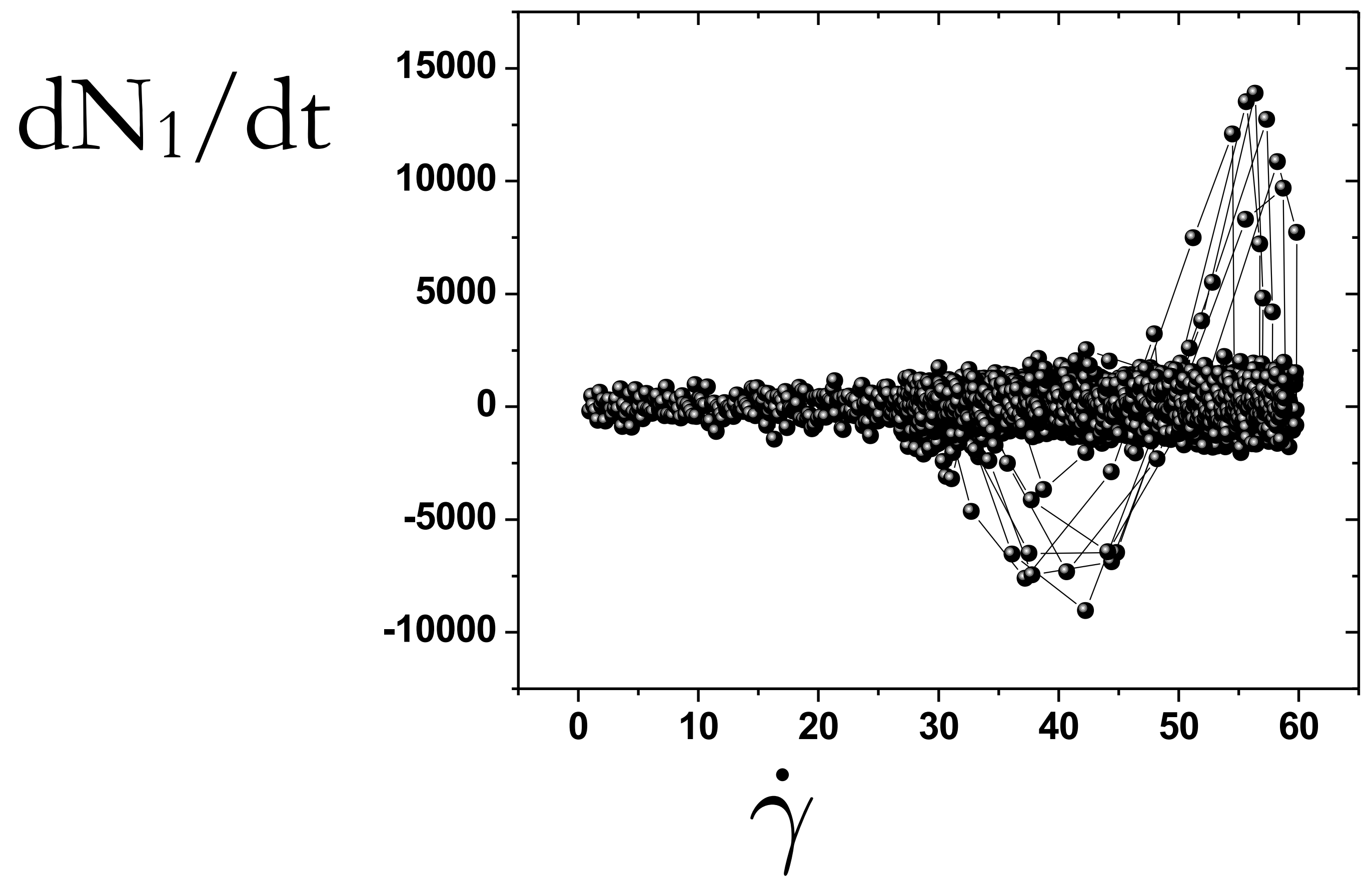
applied stress = 55 Pa



Normal Force Dynamics

applied stress = 55 Pa





Tentative Additional Conclusions:

(a) High stress regions are associated with large positive normal stress.

(b) Regions appear above a critical shear rate, with a probability of nucleation that increases with shear rate.

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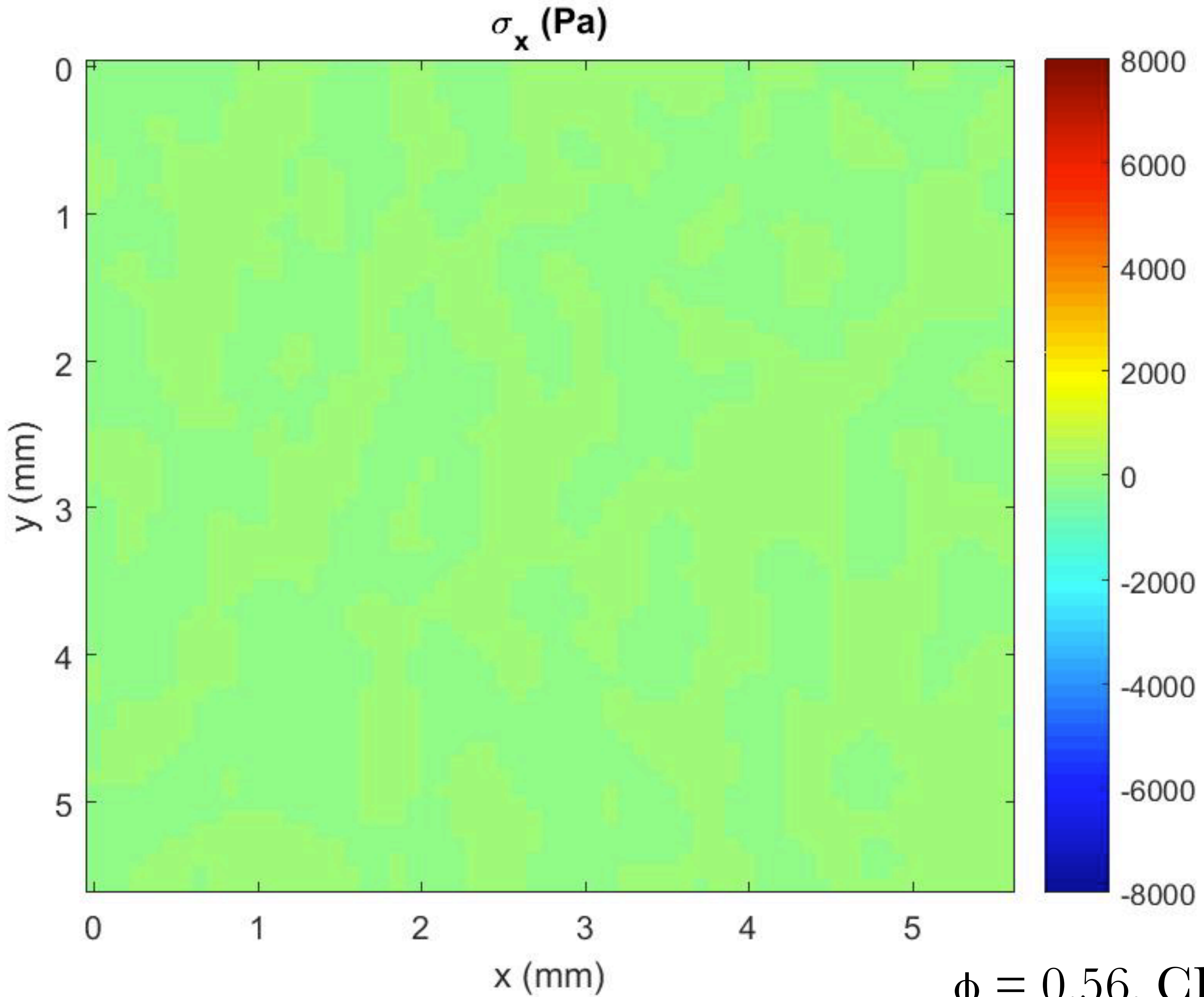
Oscillatory Shear - 1 rad/sec, γ =25



ϕ = 0.56, CP25

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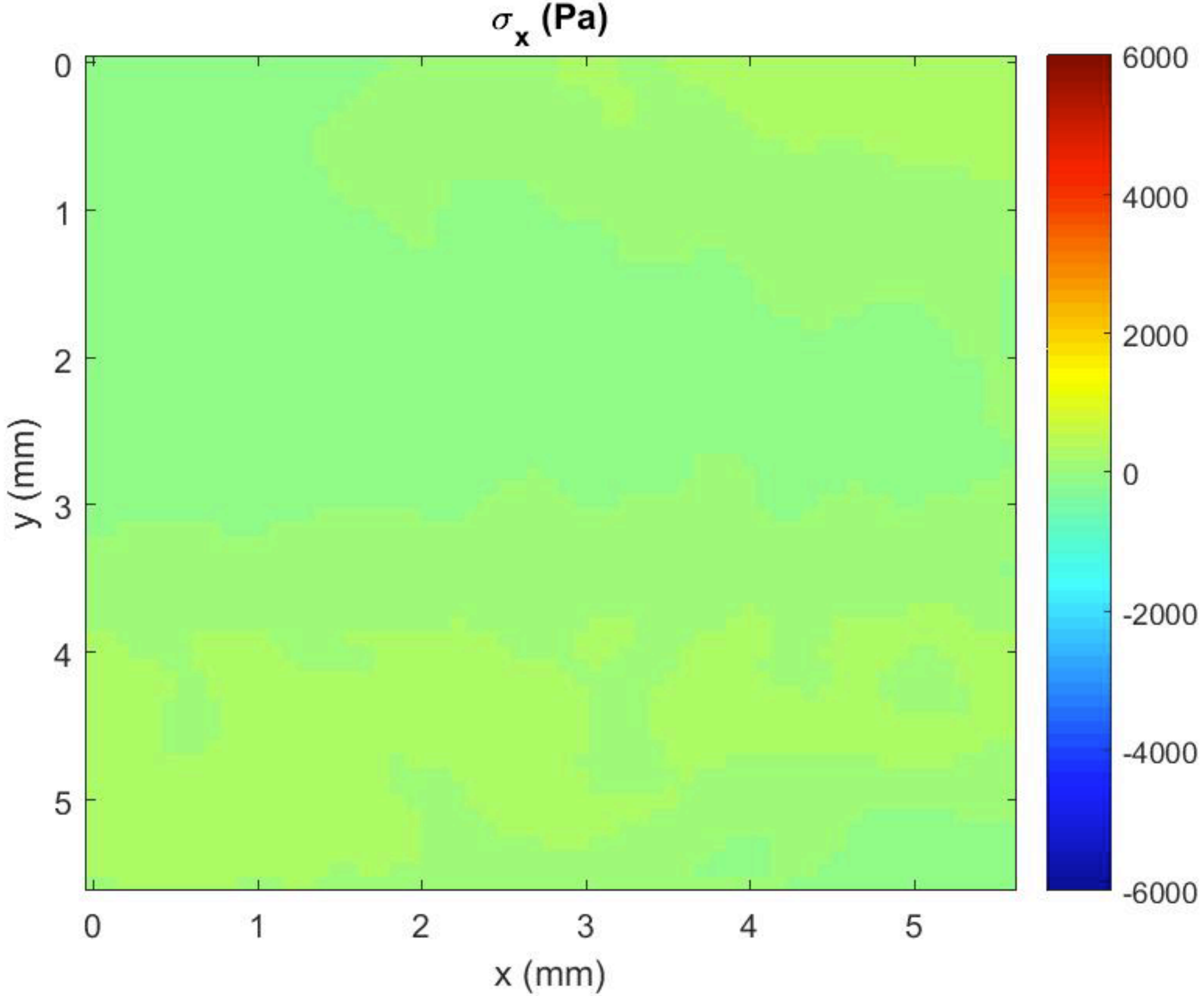
Oscillatory Shear - 10 rad/sec, $\gamma = 3$



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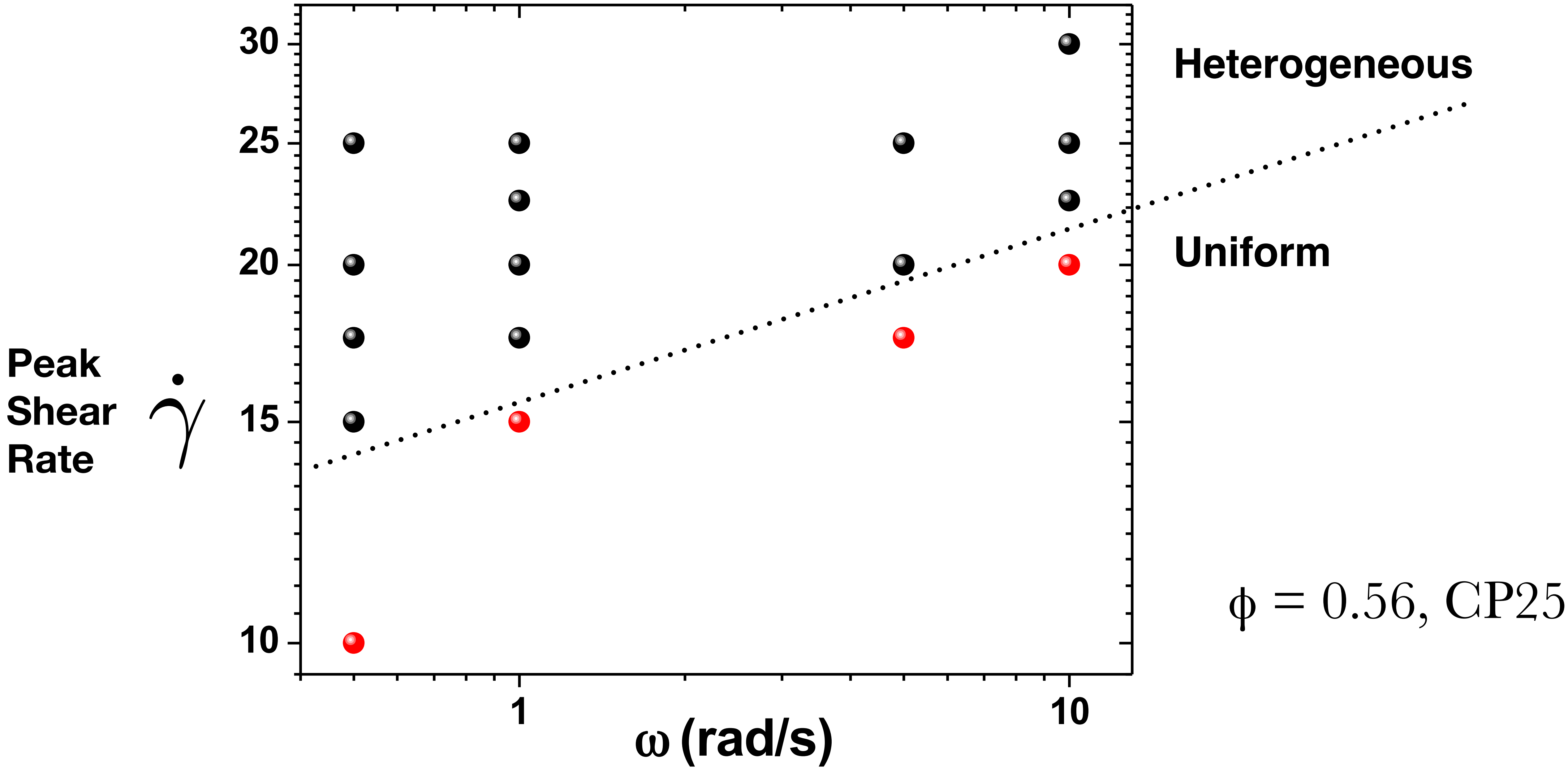
Pipkin Diagram



- Peak shear rate primary determinant, modest period dependence.
- Instability can have some periodicity in flow direction

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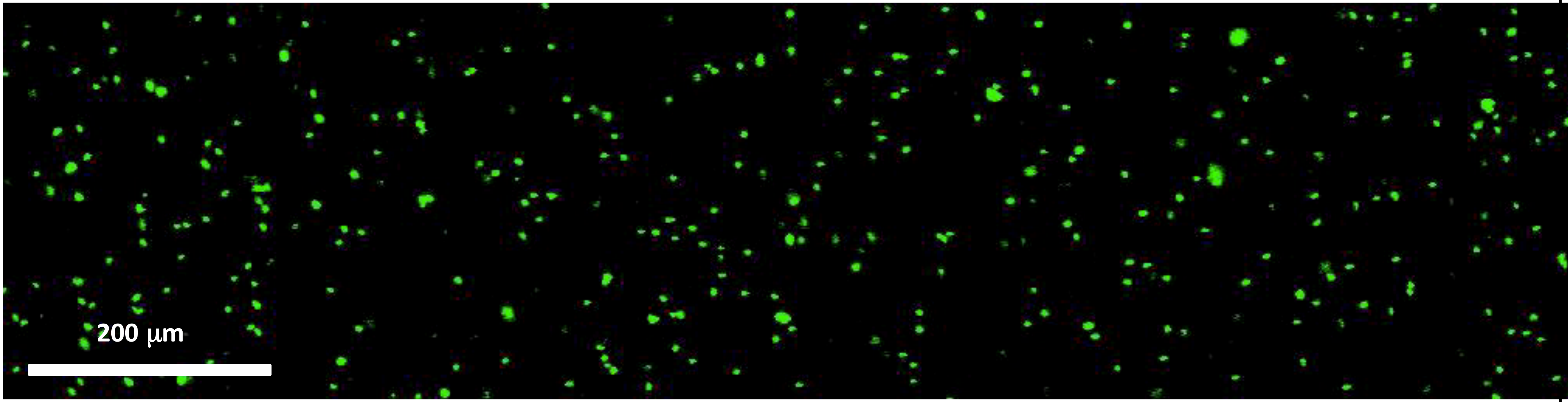
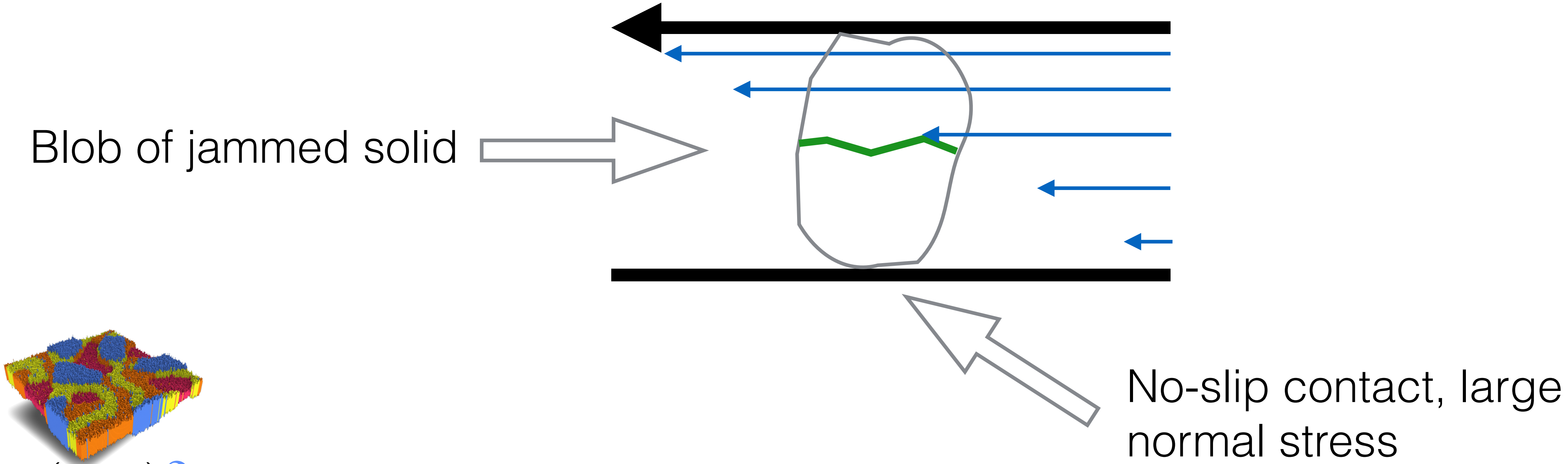
Close to DST

$\phi \sim 0.58$, 2200 Pa





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