Oobleck Exposed! Microscopic Measurements of Shear Thickening Fluids

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Vikram

"If yo don't know what you're talking about
just show a lot of fun animations and tell jokes"
-Itai Cohen

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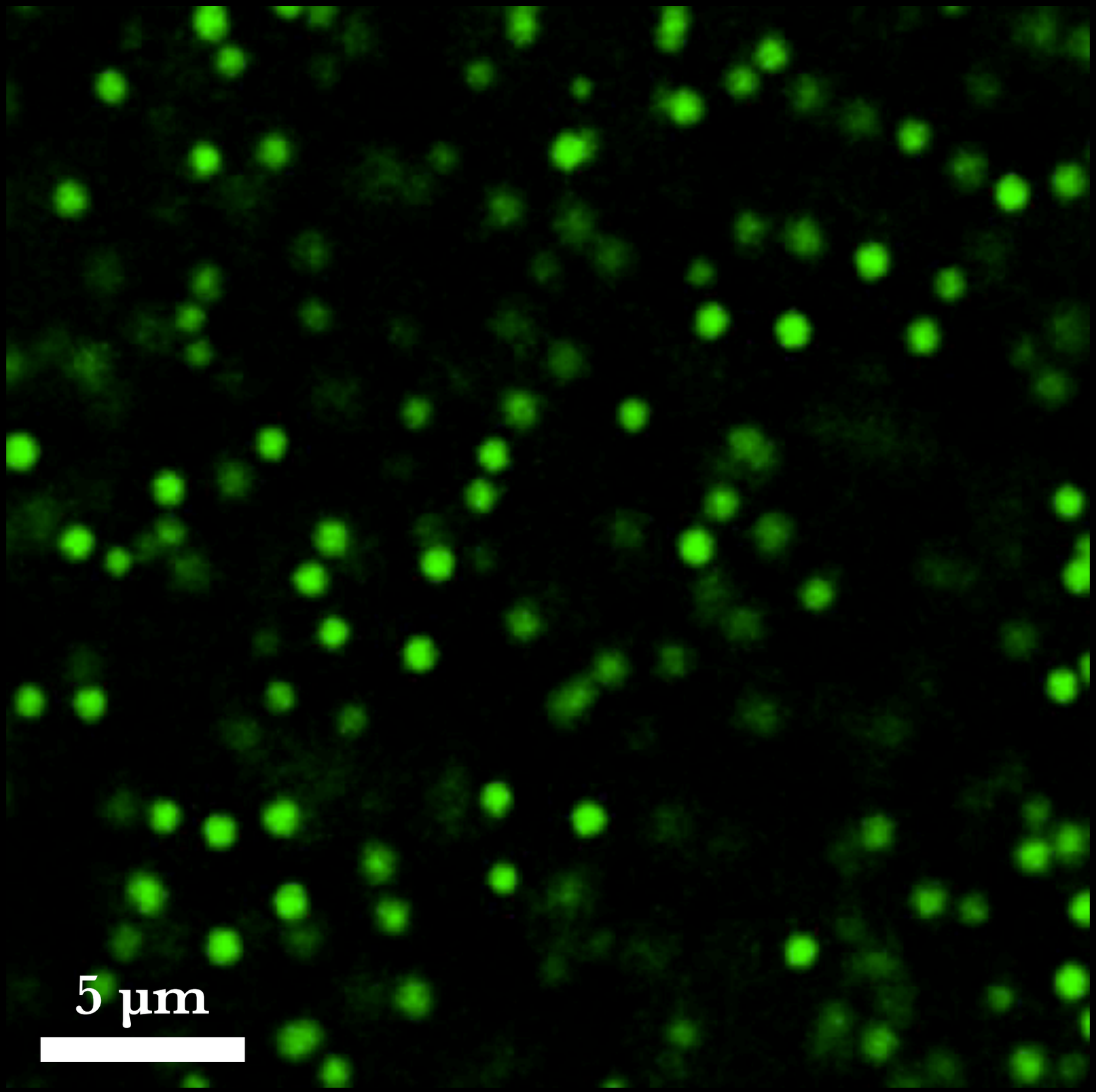
"If you want to convince someone you know what
you're talking about, invent/use an acronym."

-Itai Cohen

Brief Outline

- Shear Thickening in Thermal Systems
- Boundary Stress Microscopy
- Colloid Science
- Shear Thickening Fluids (colloids)
  - Macroscopic Dynamics
  - Microscopic Understanding
- What's coming next…

Colloidal Suspensions



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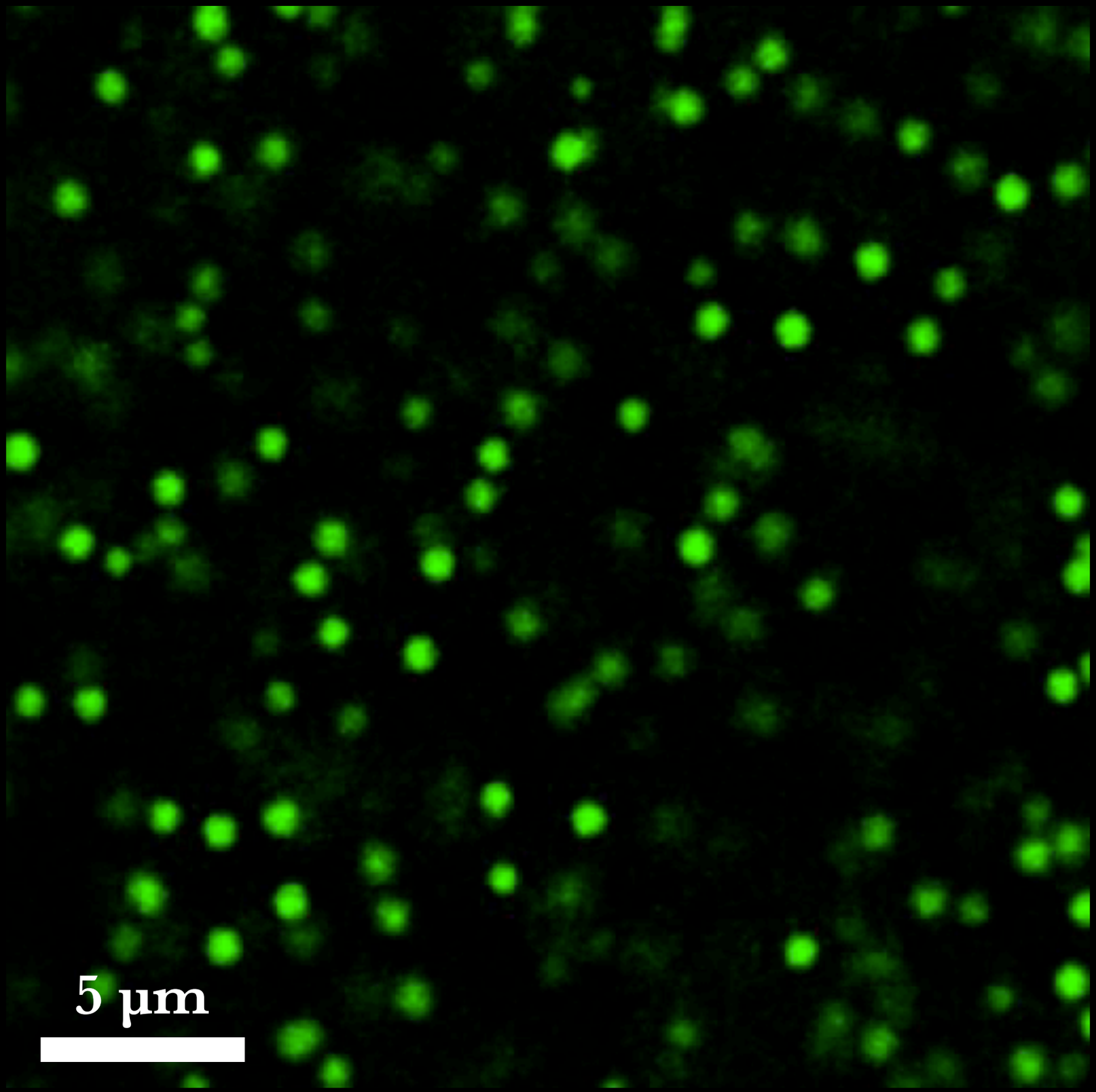

Central Dogma of Colloid Science

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Colloidal Particles "Stick" When in Contact

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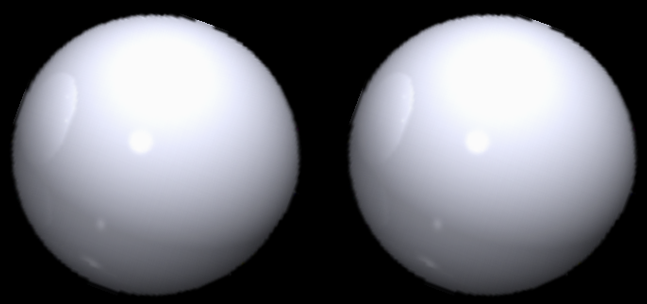

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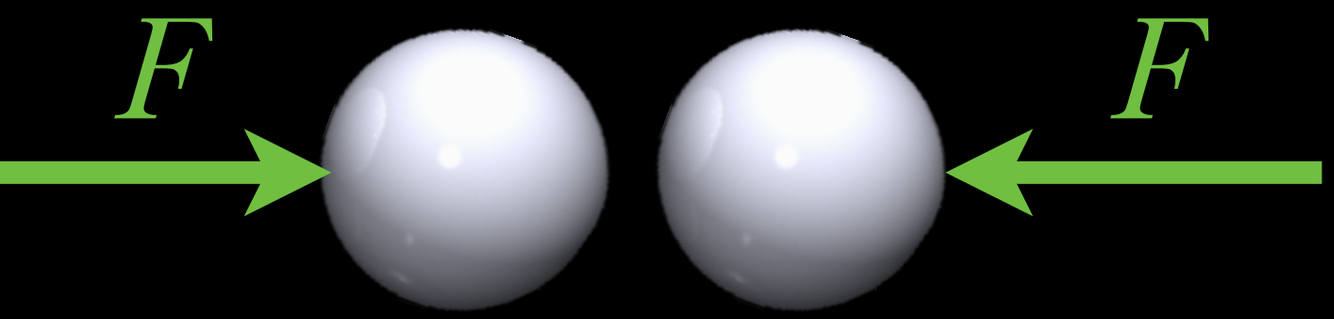

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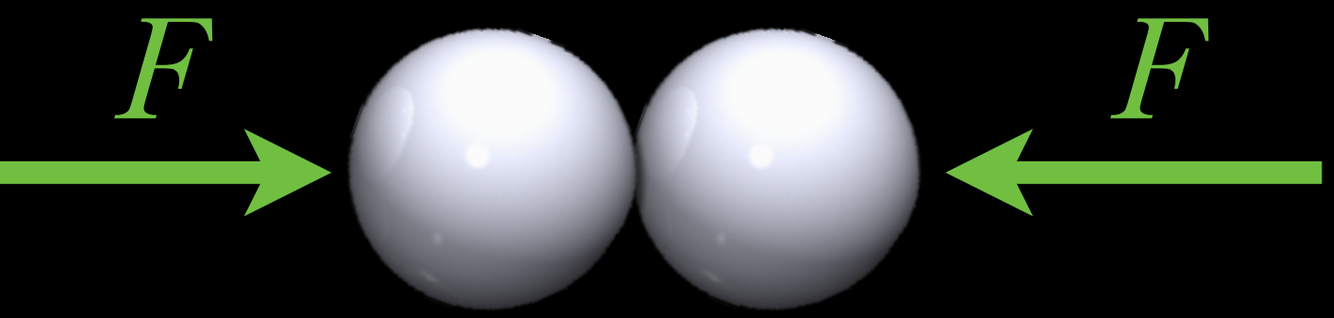

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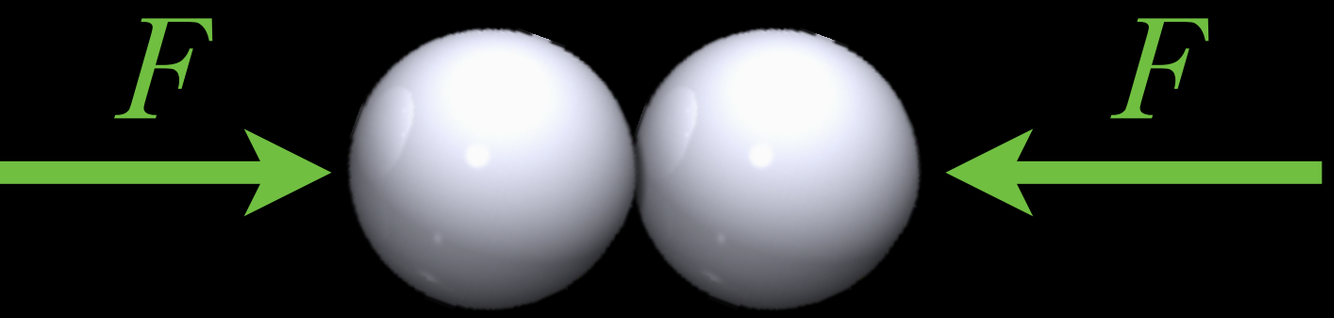

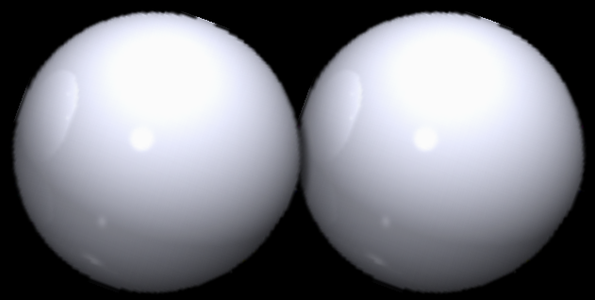

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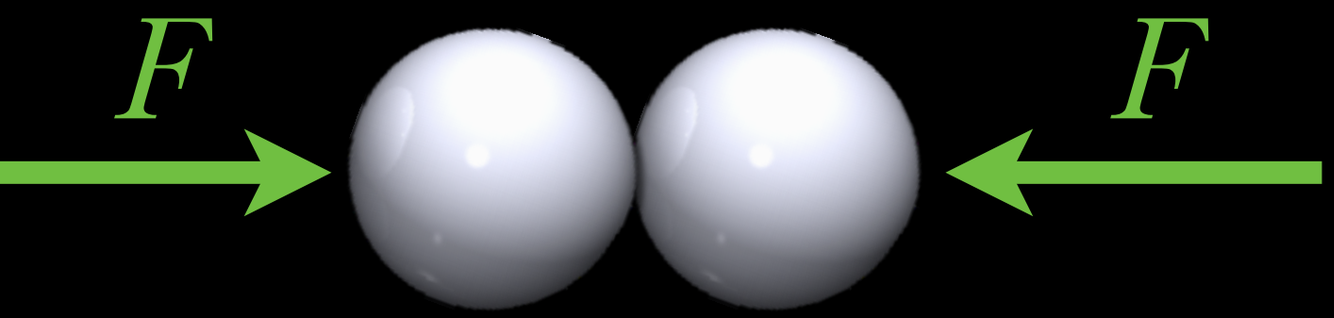

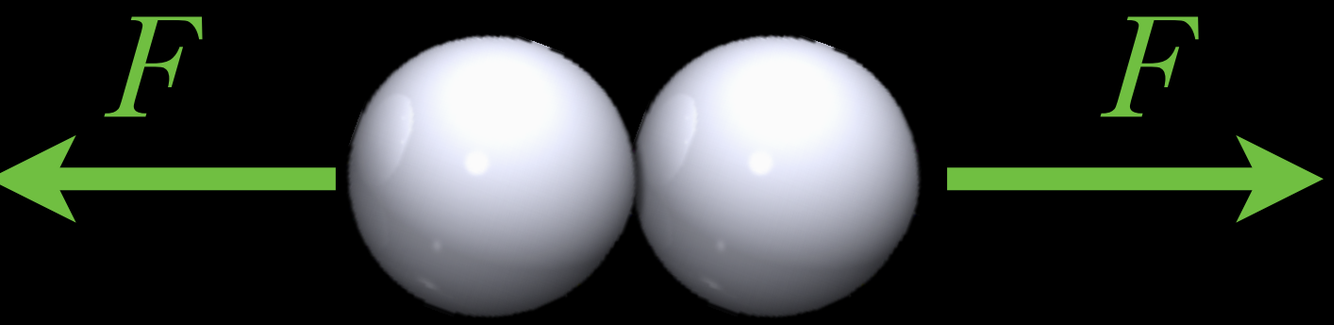

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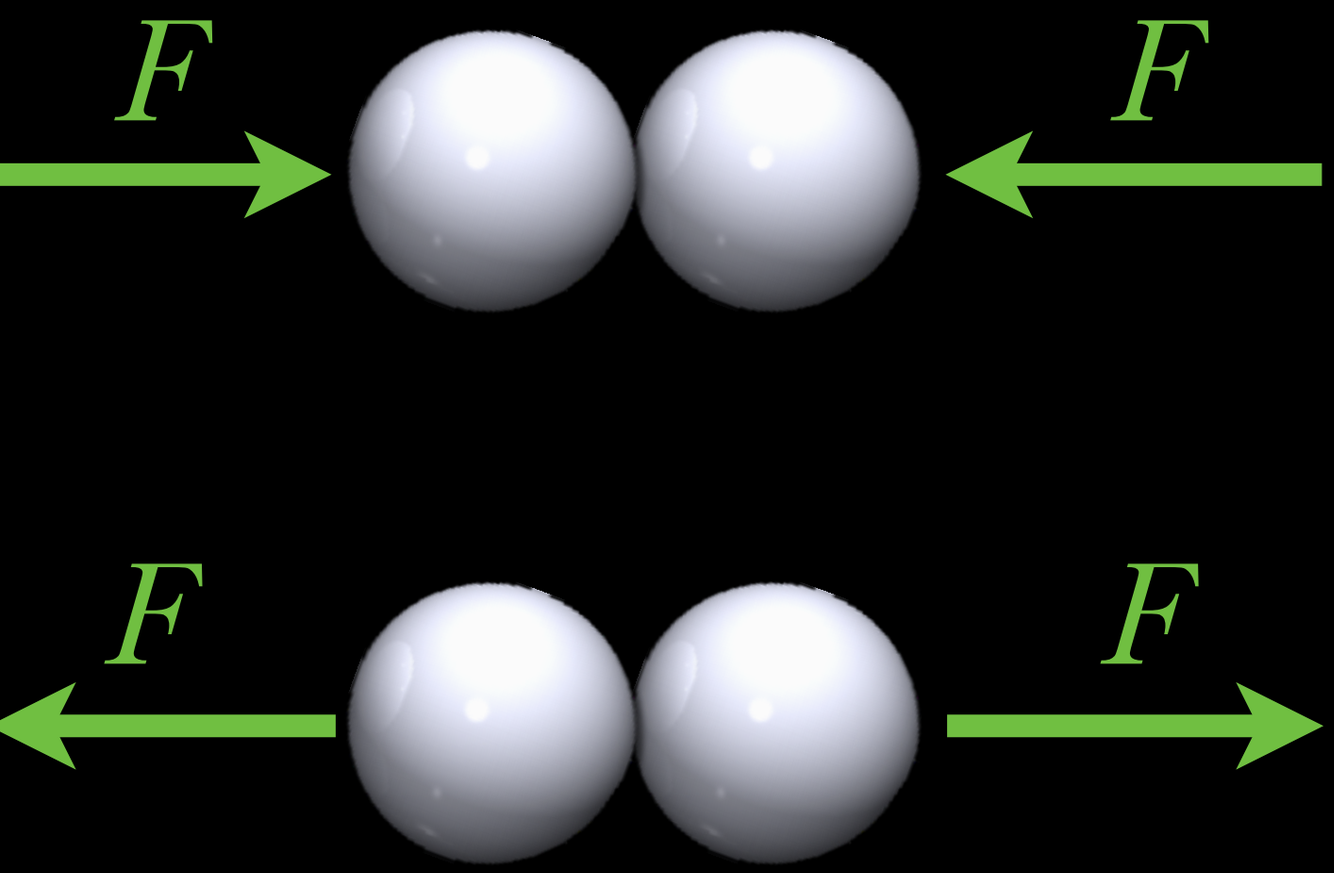

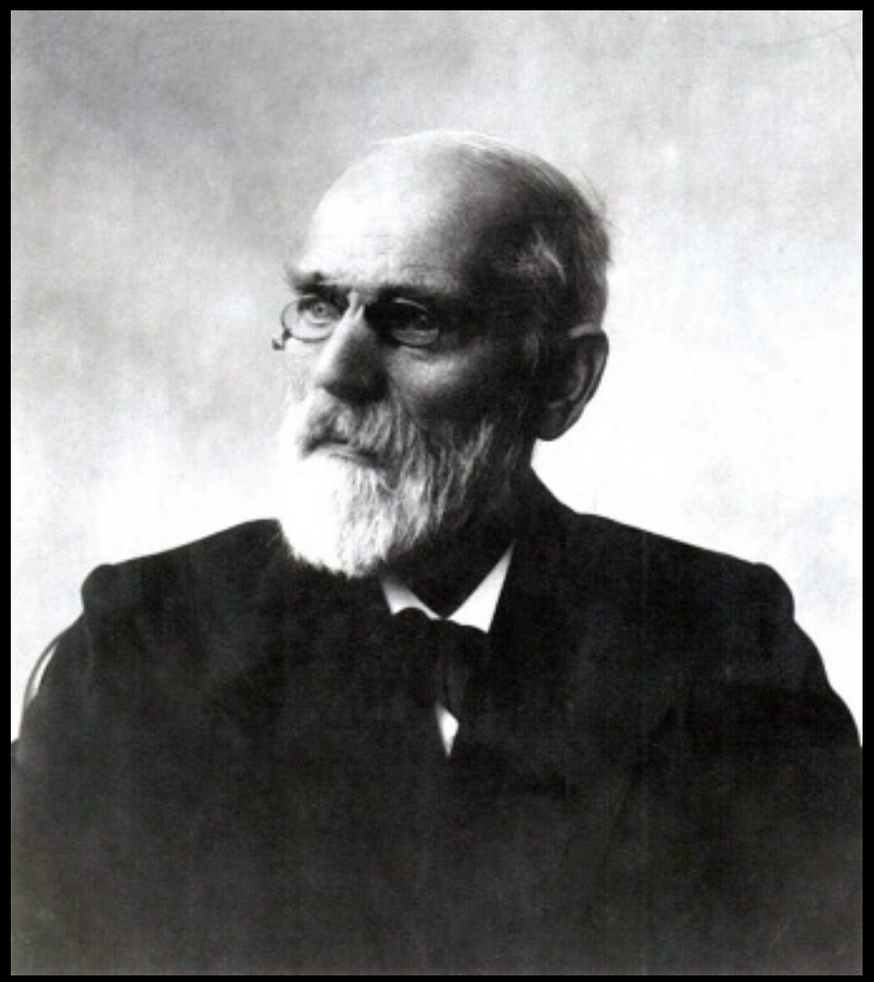

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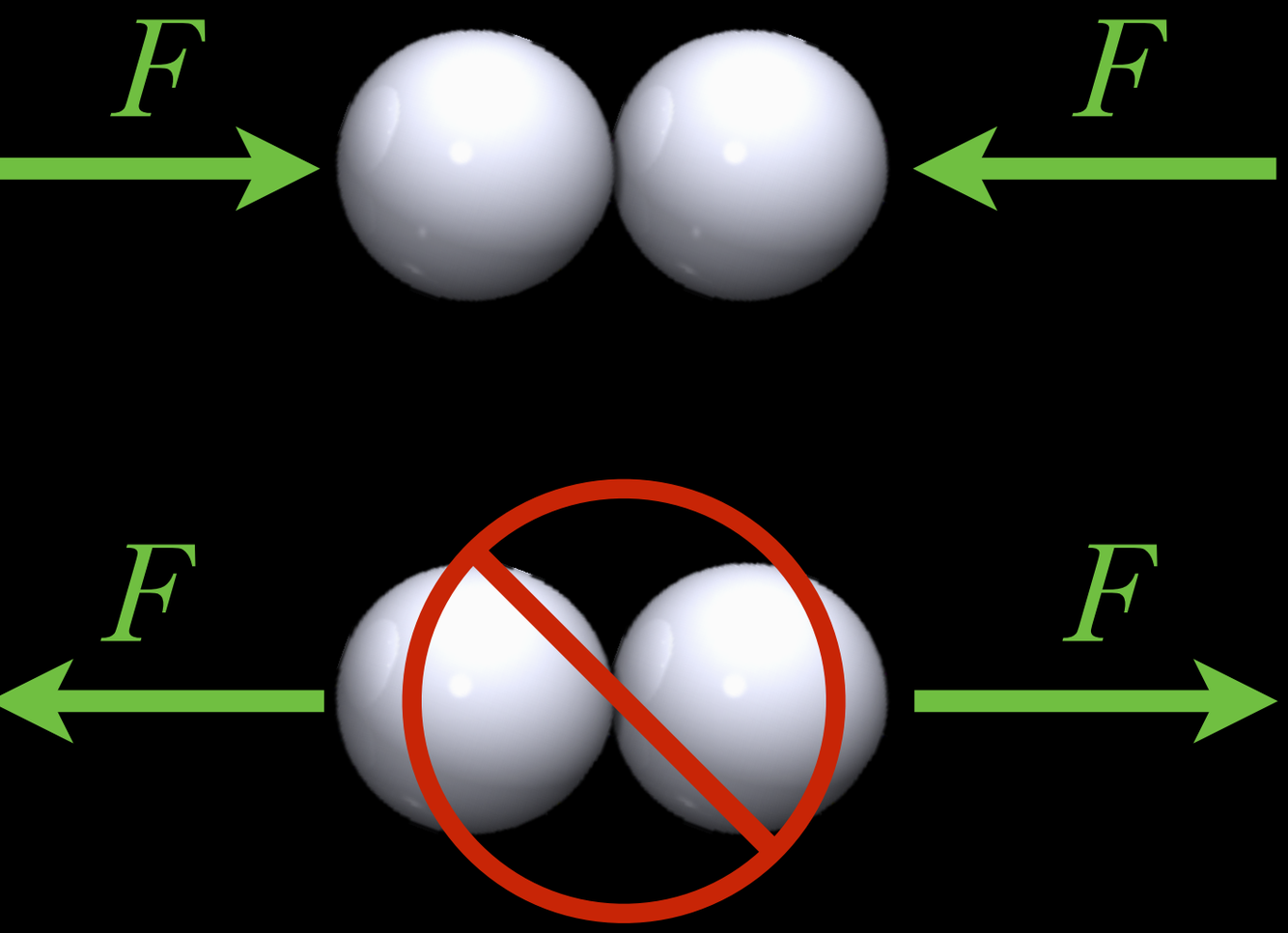

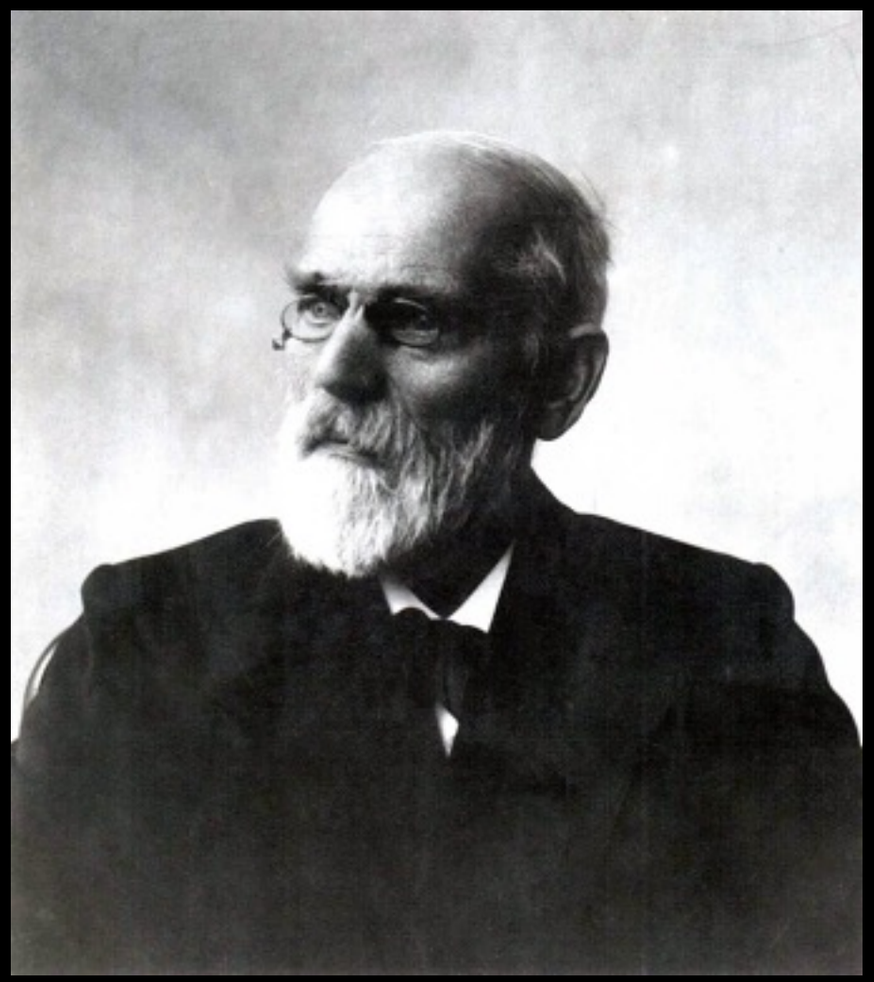

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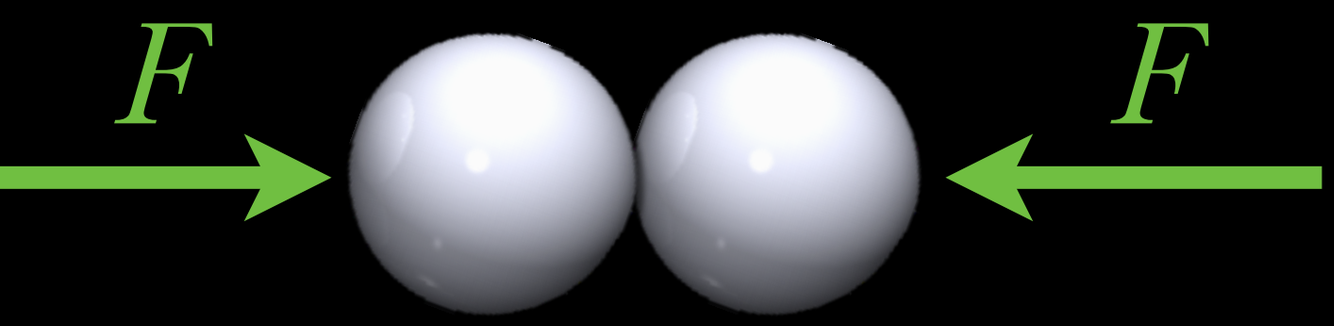

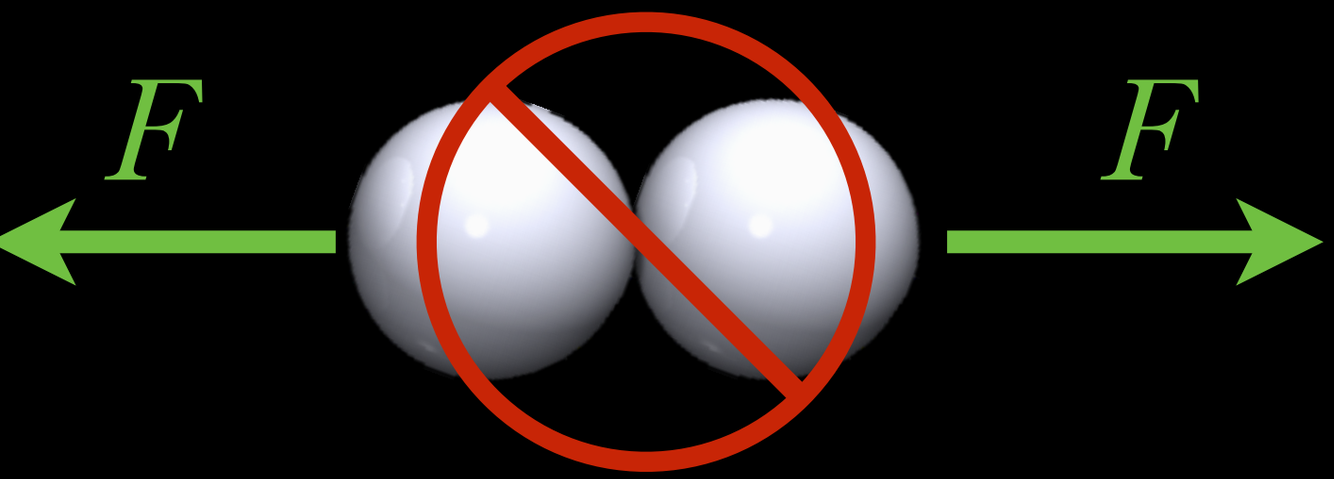

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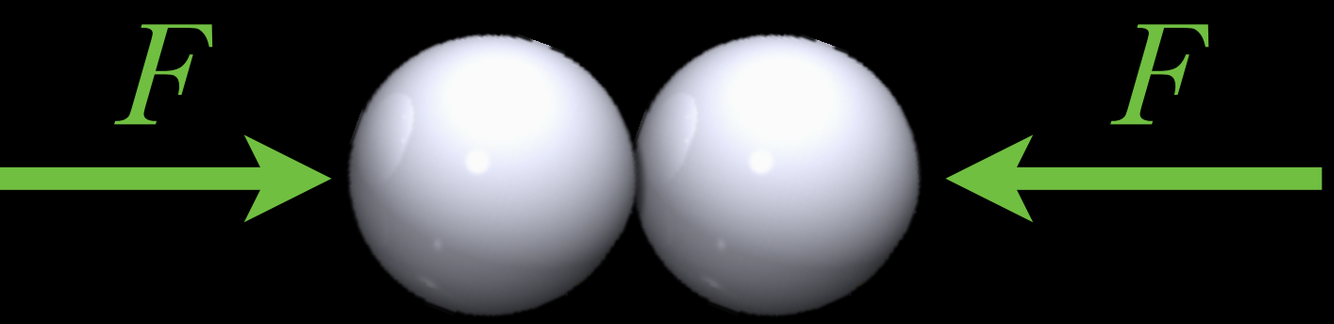

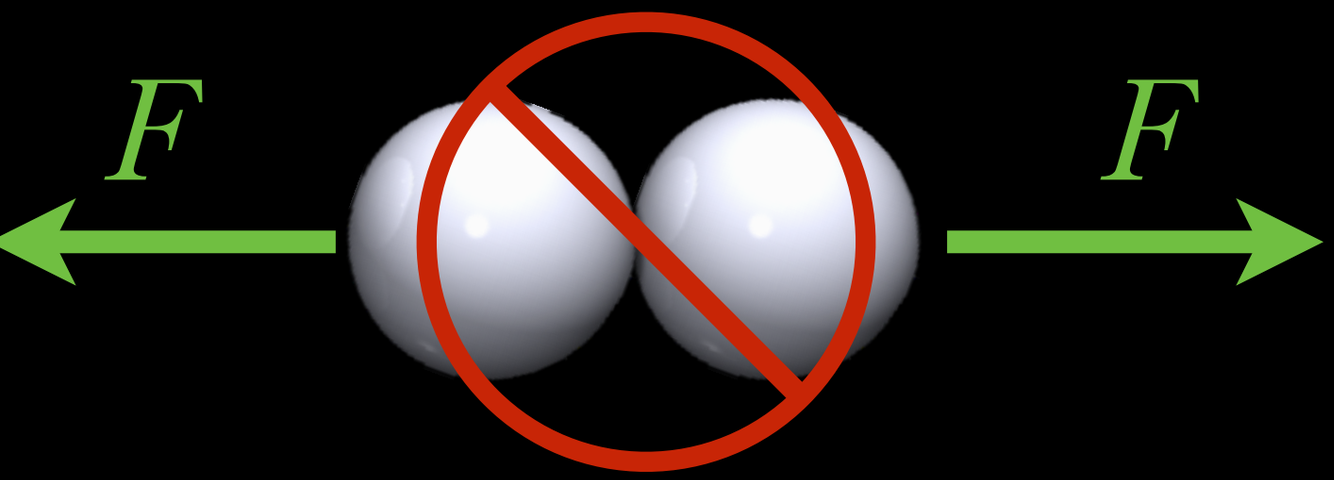

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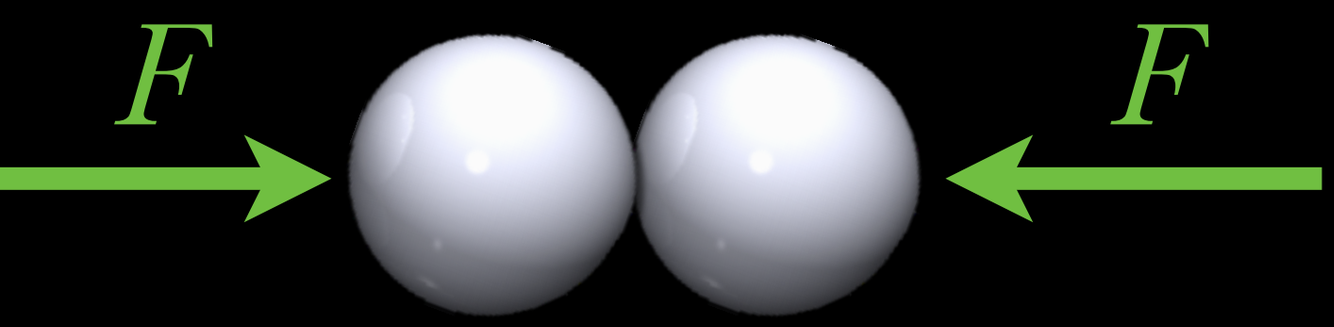

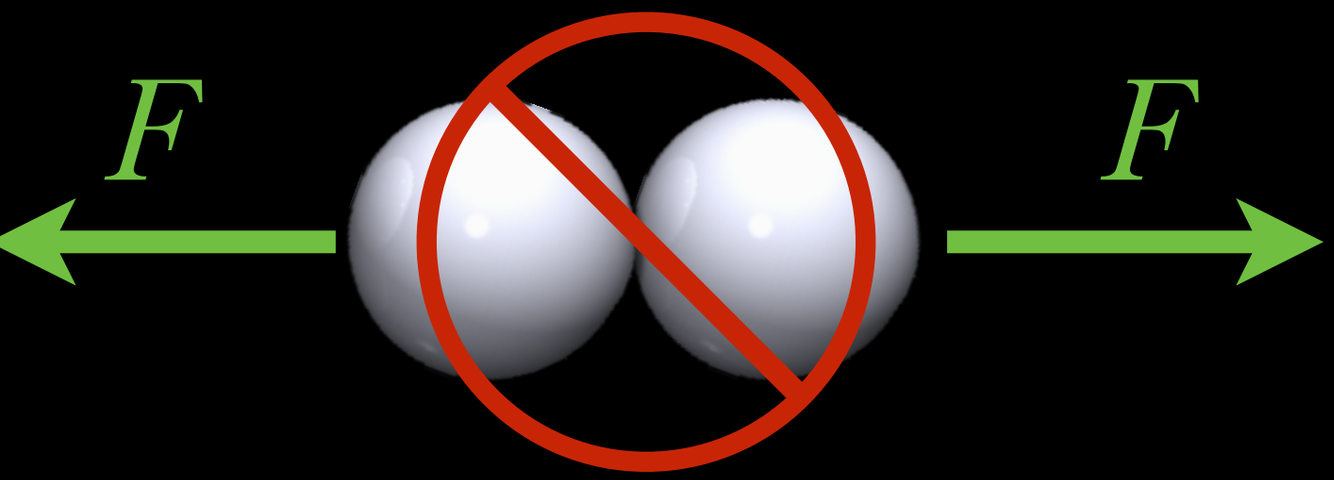

Q: Can there be friction between colloids?

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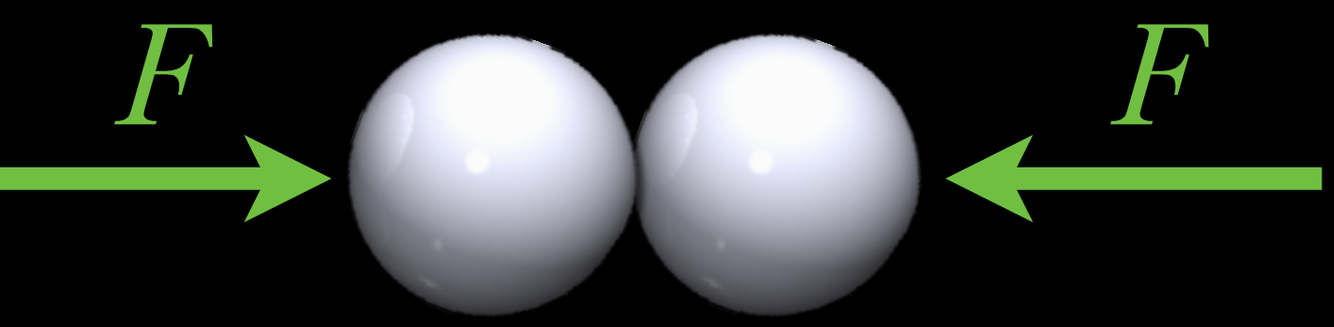
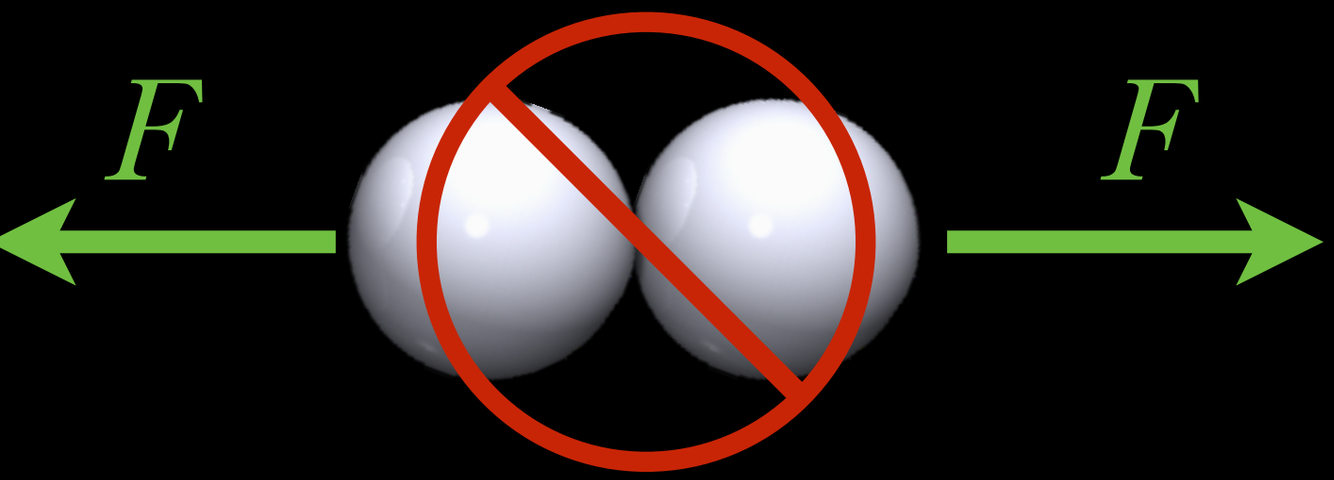
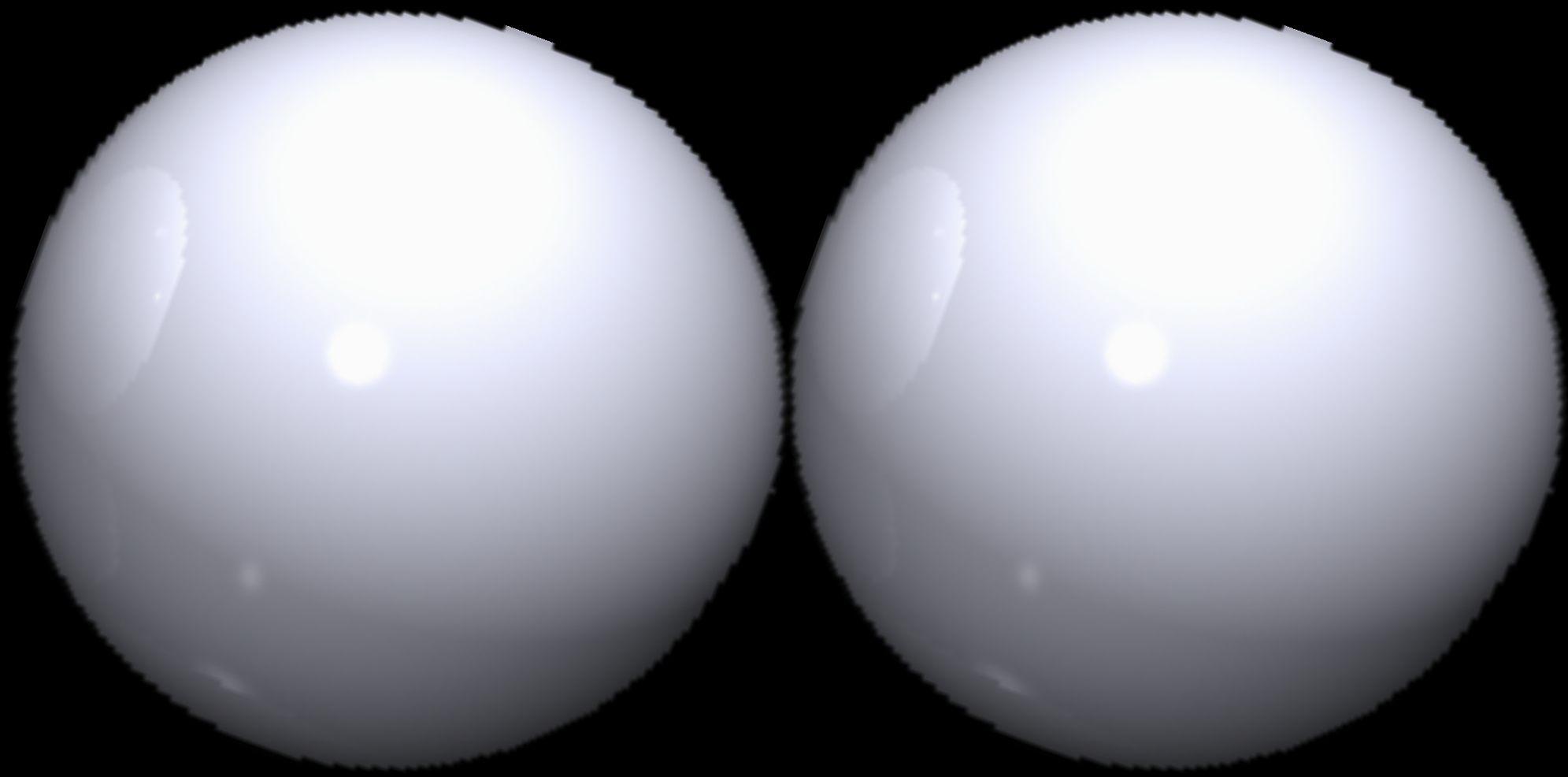




Q: Can there be friction between colloids? Does it Matter?

Are hard spheres enough?



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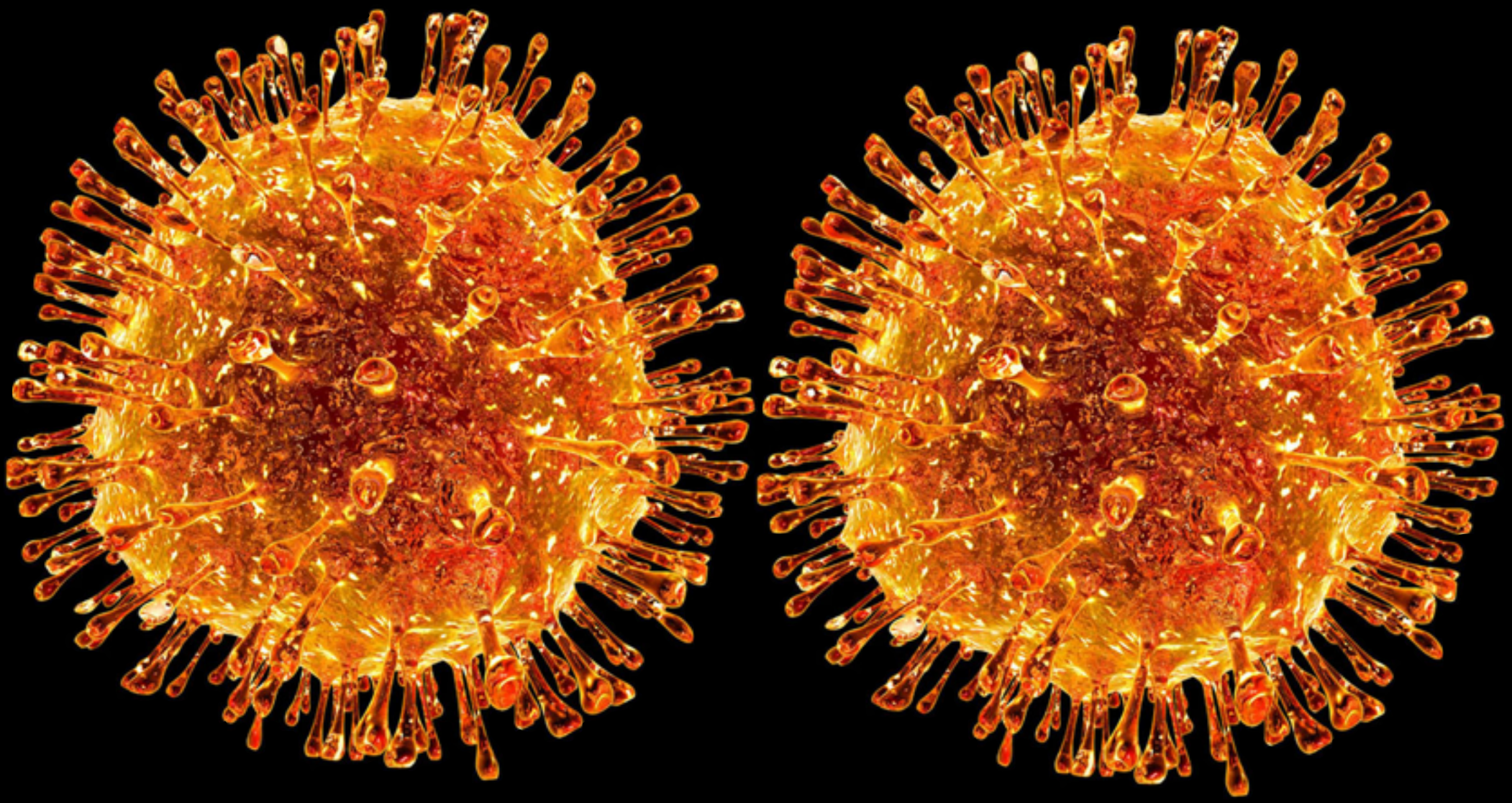

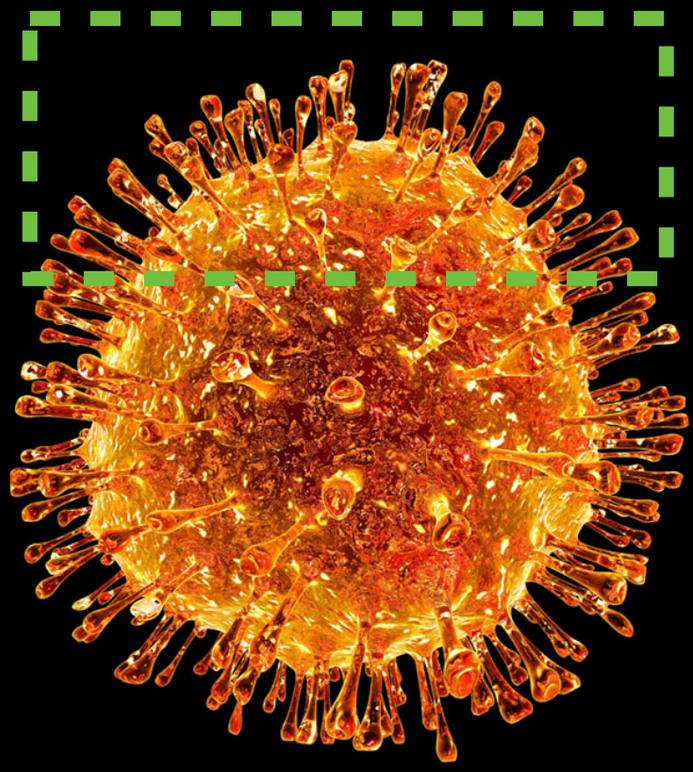

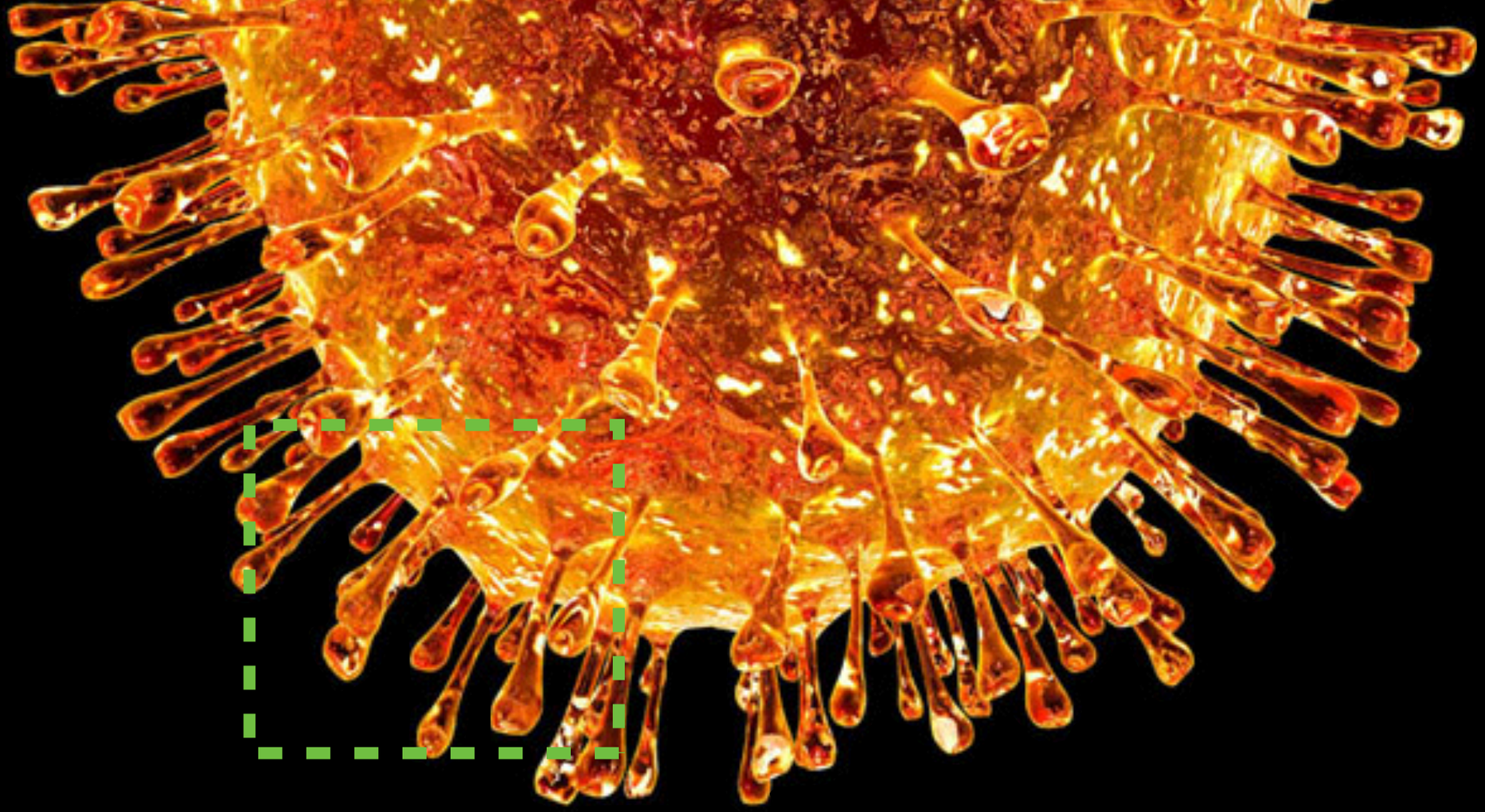

H1N1

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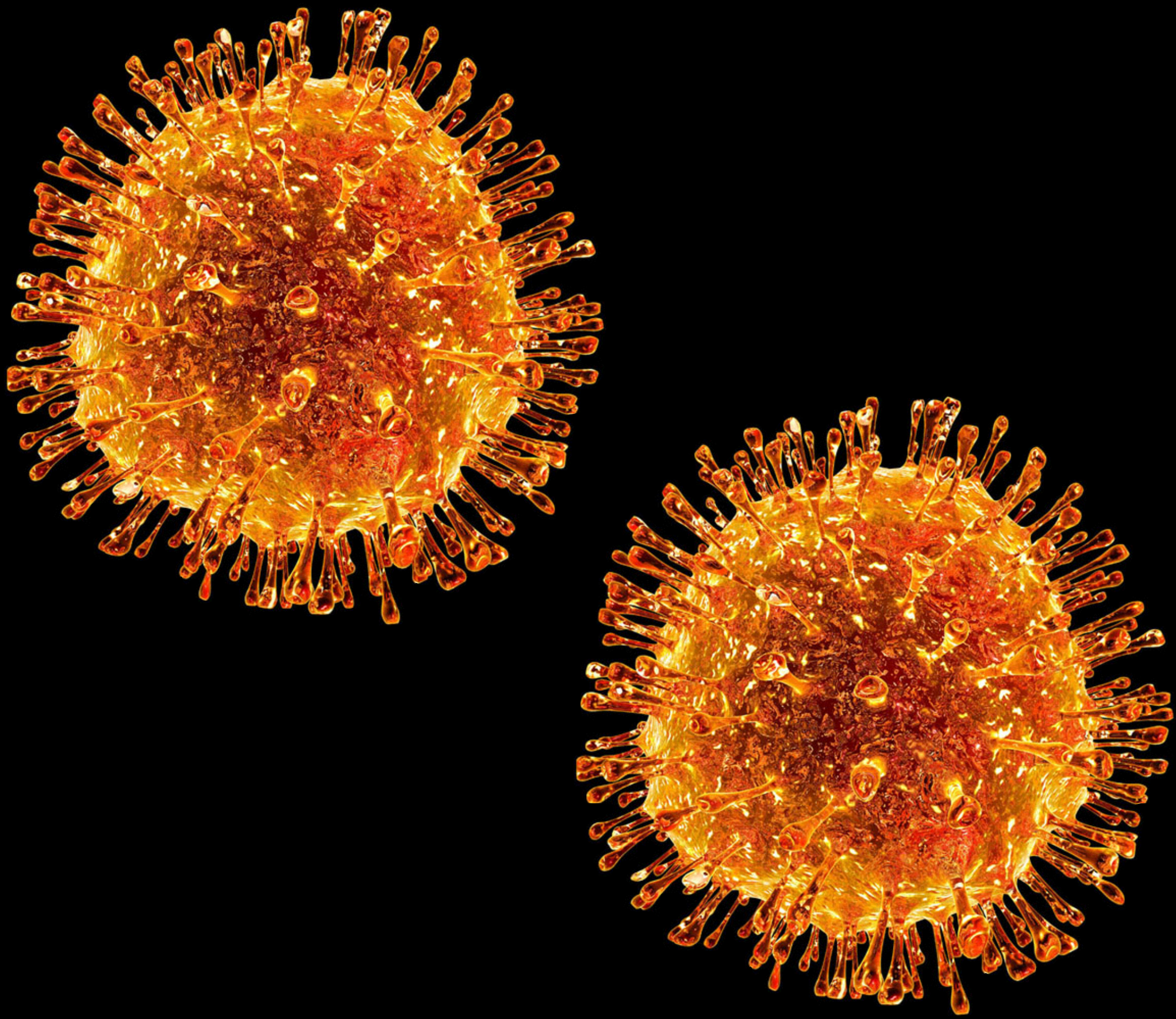
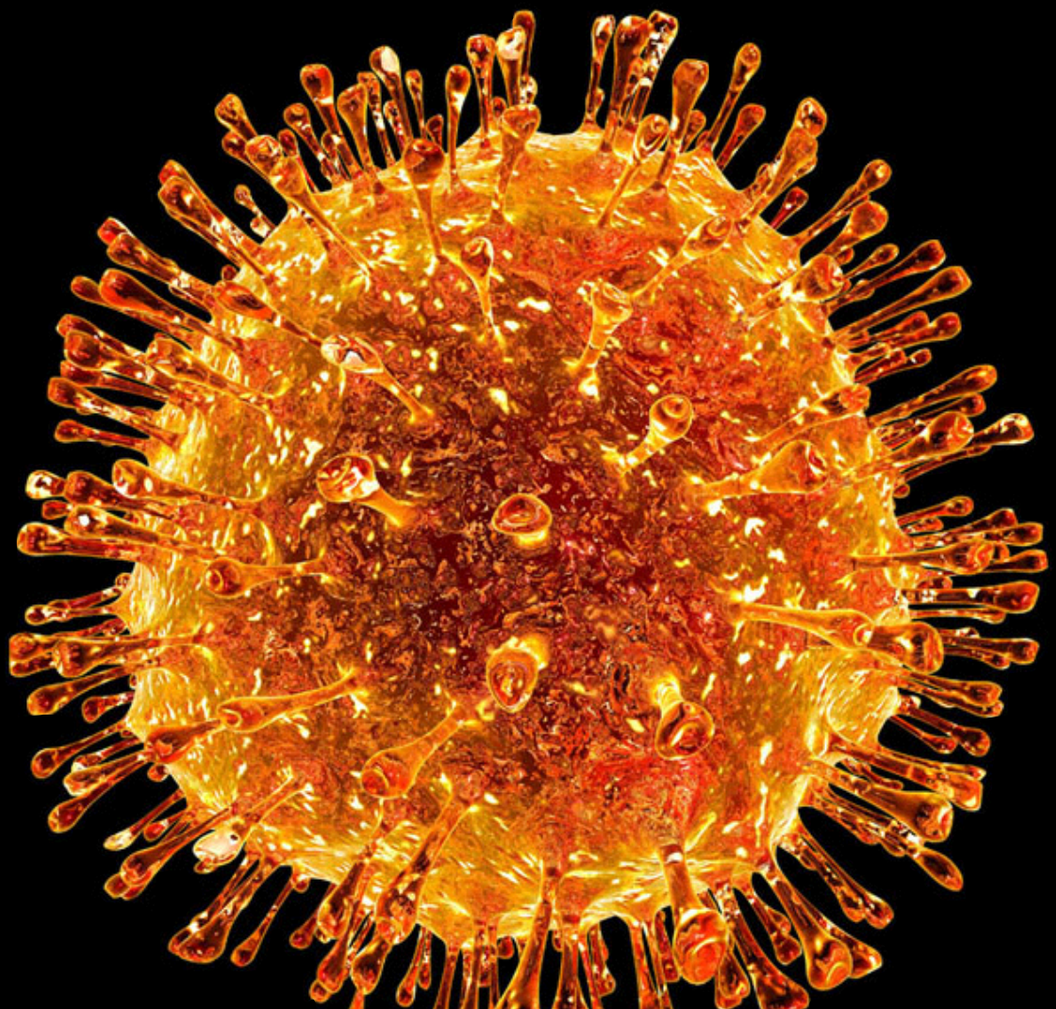
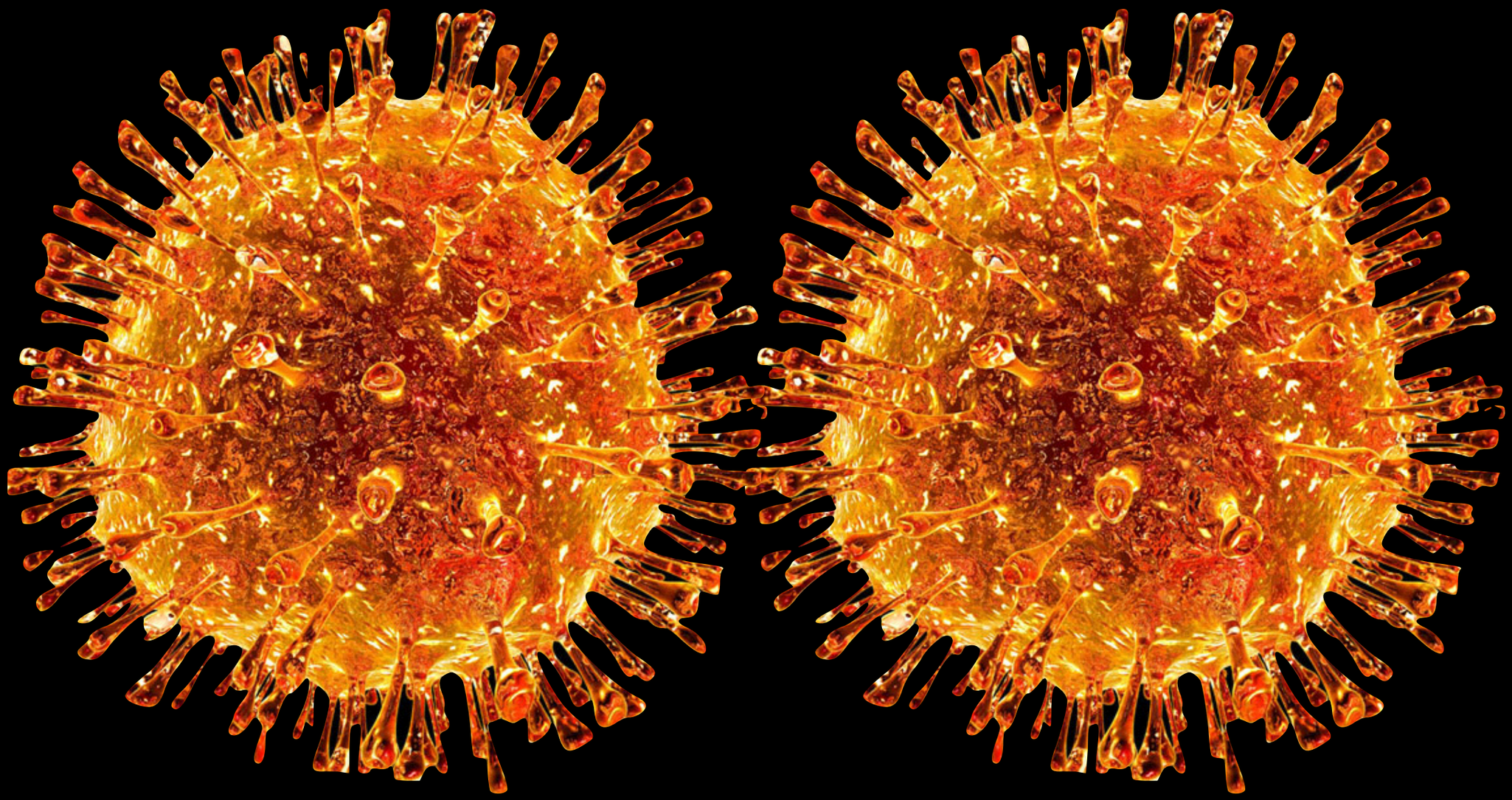
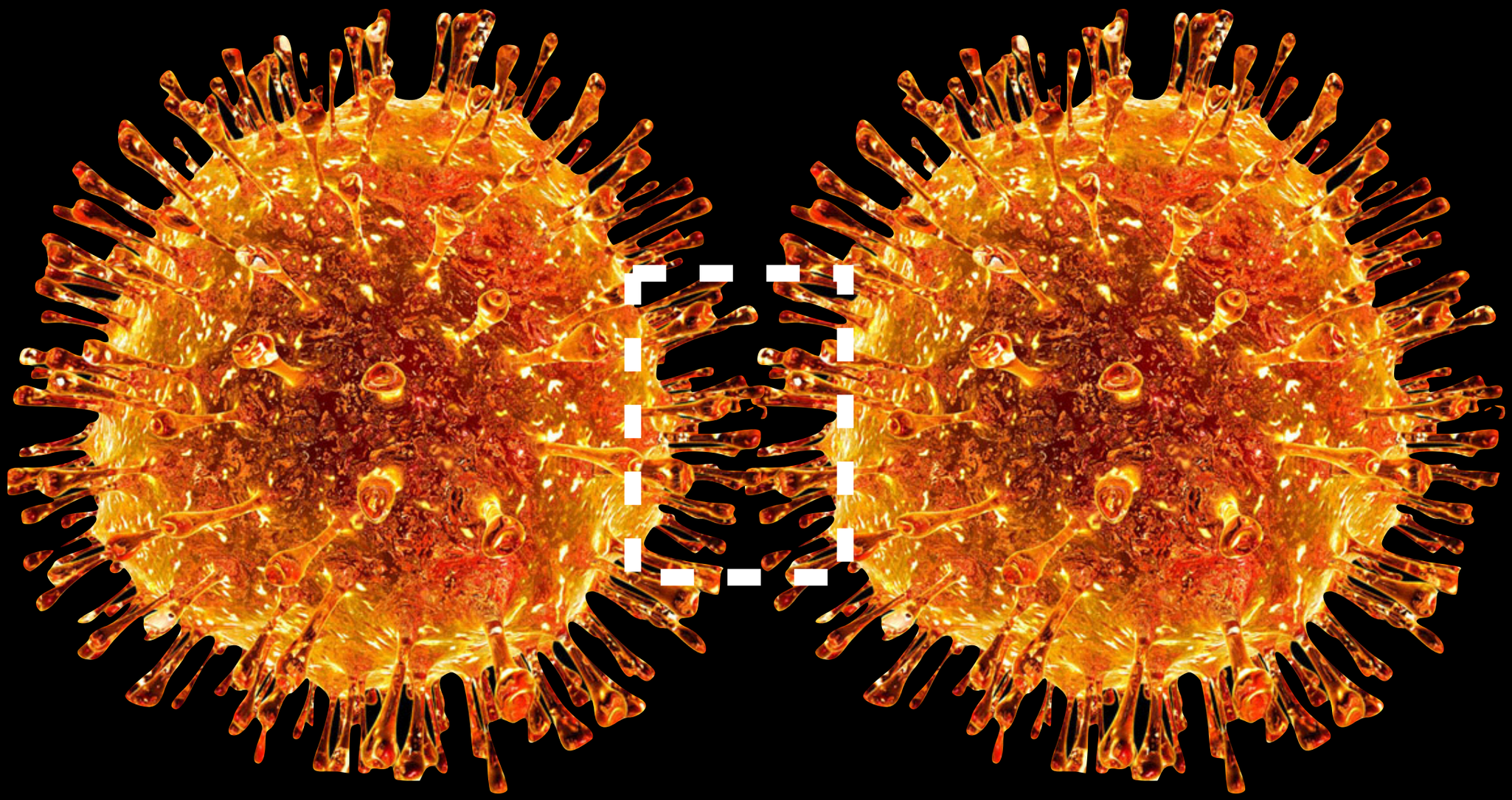
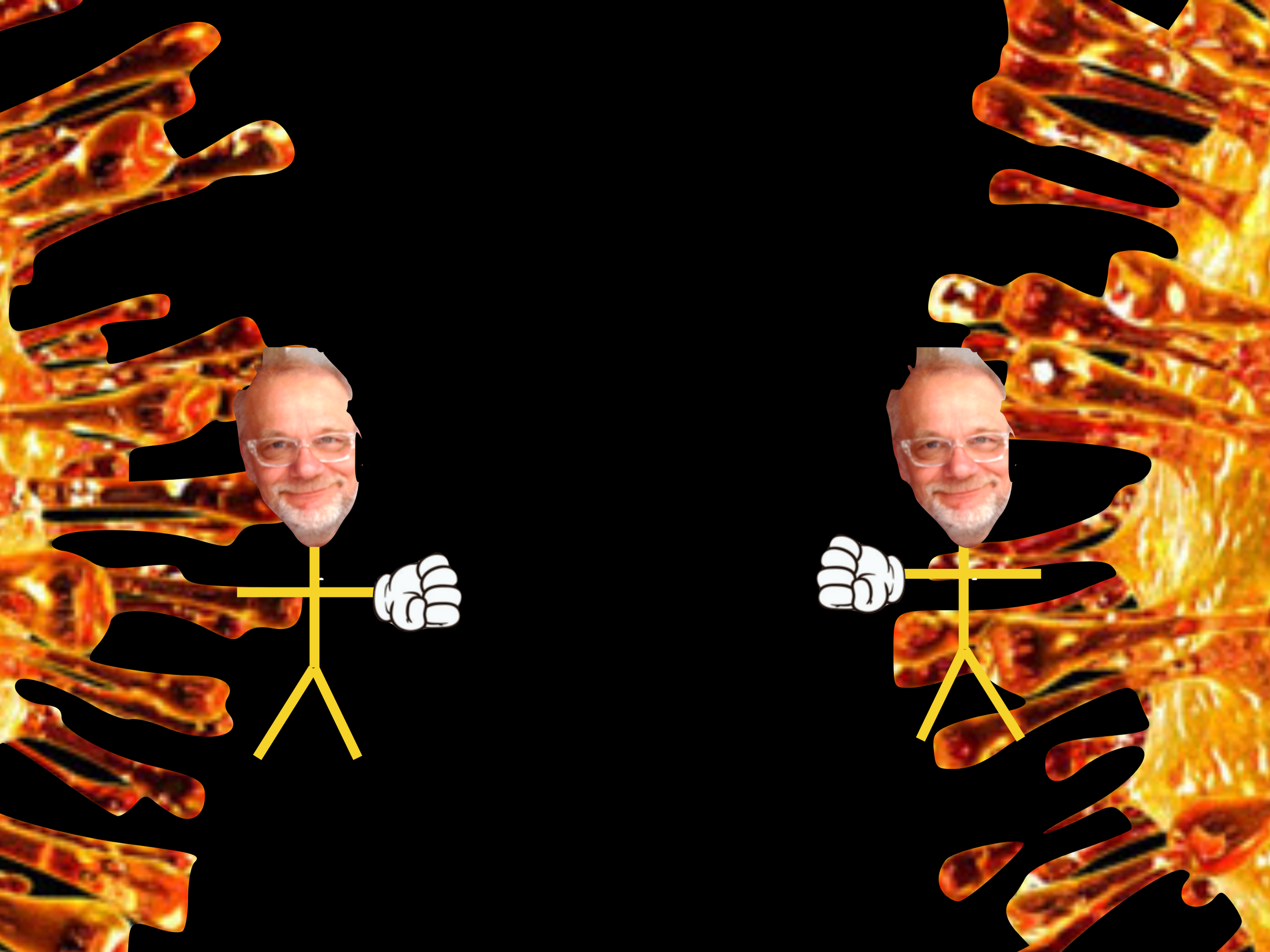
HEINRICH

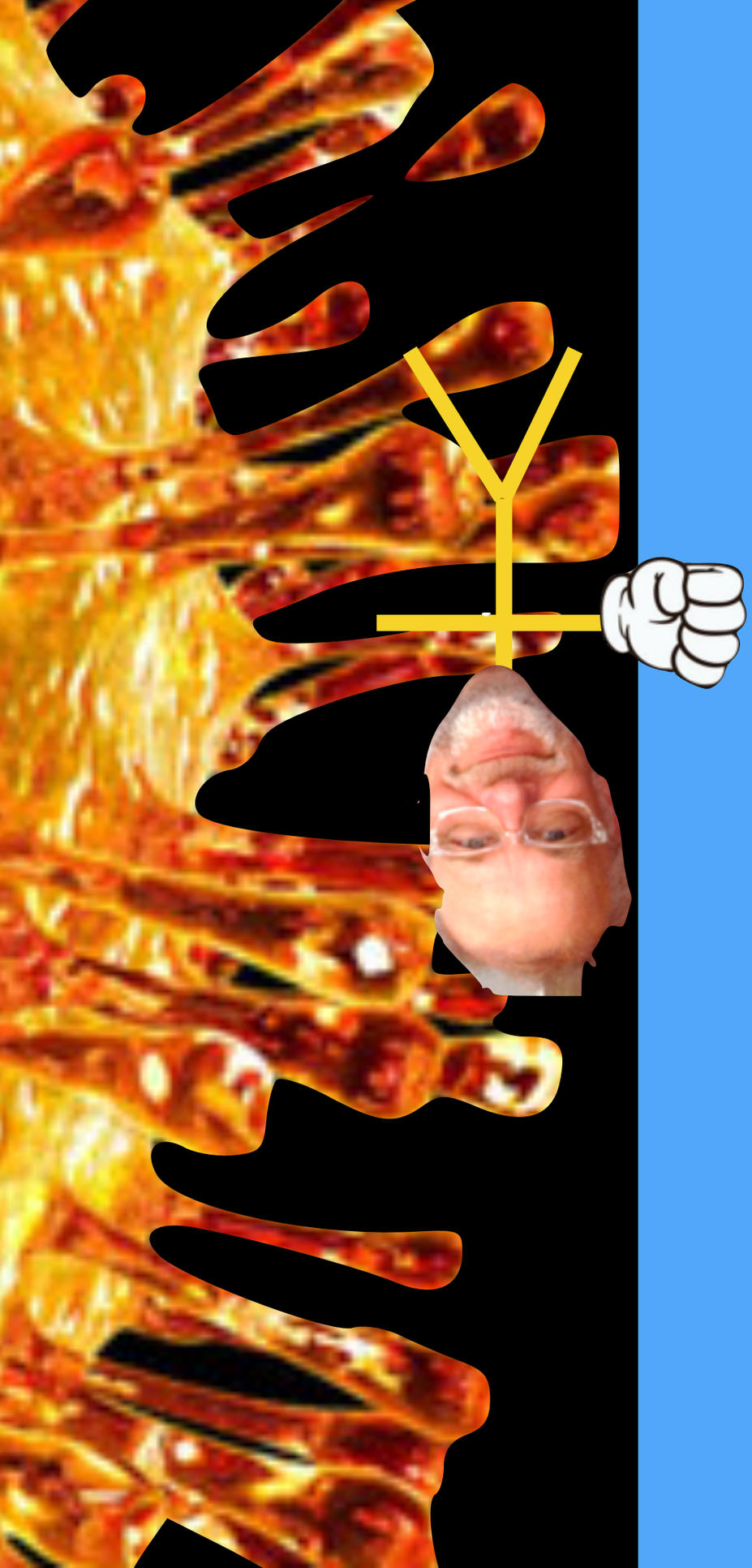
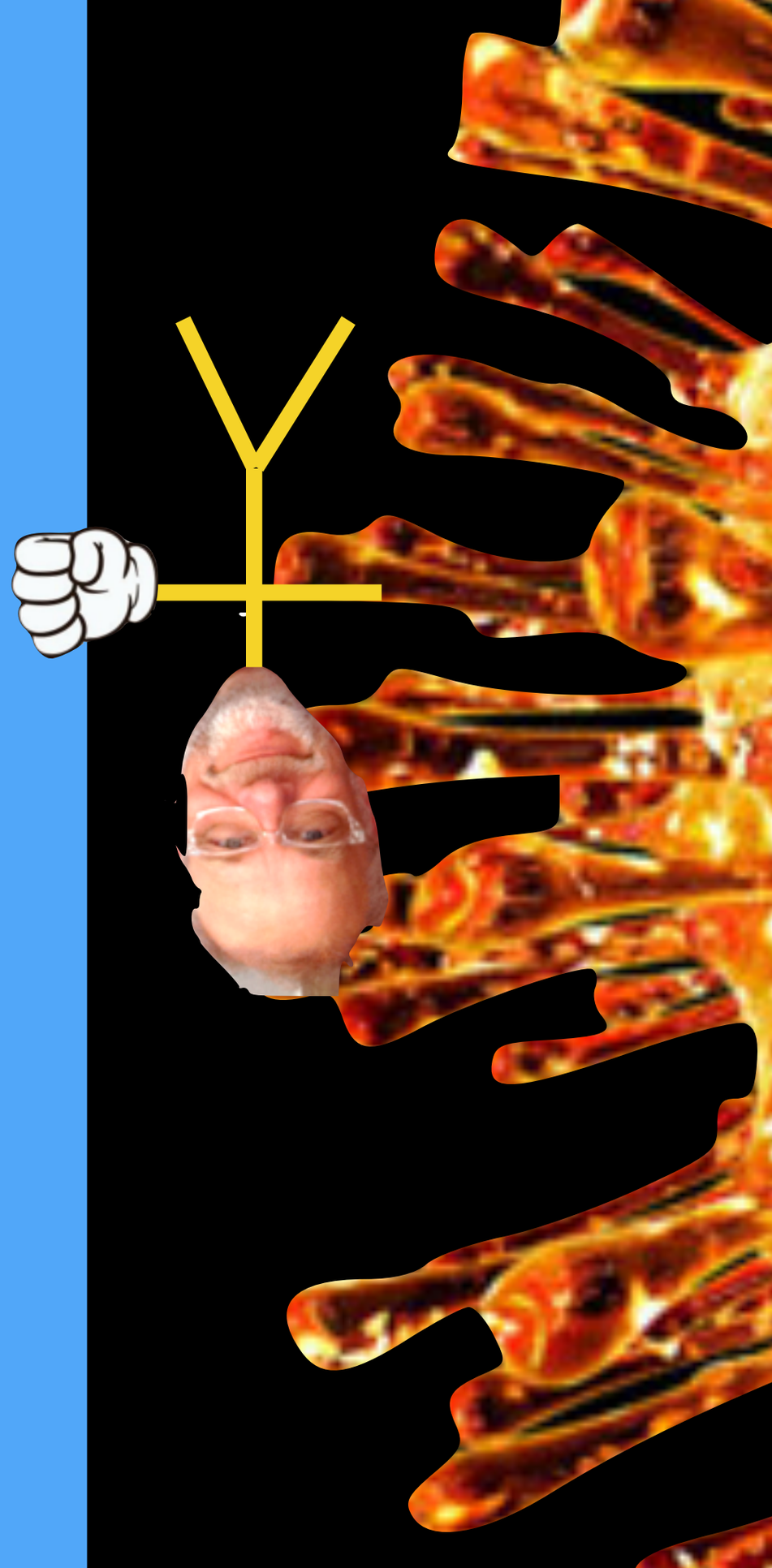


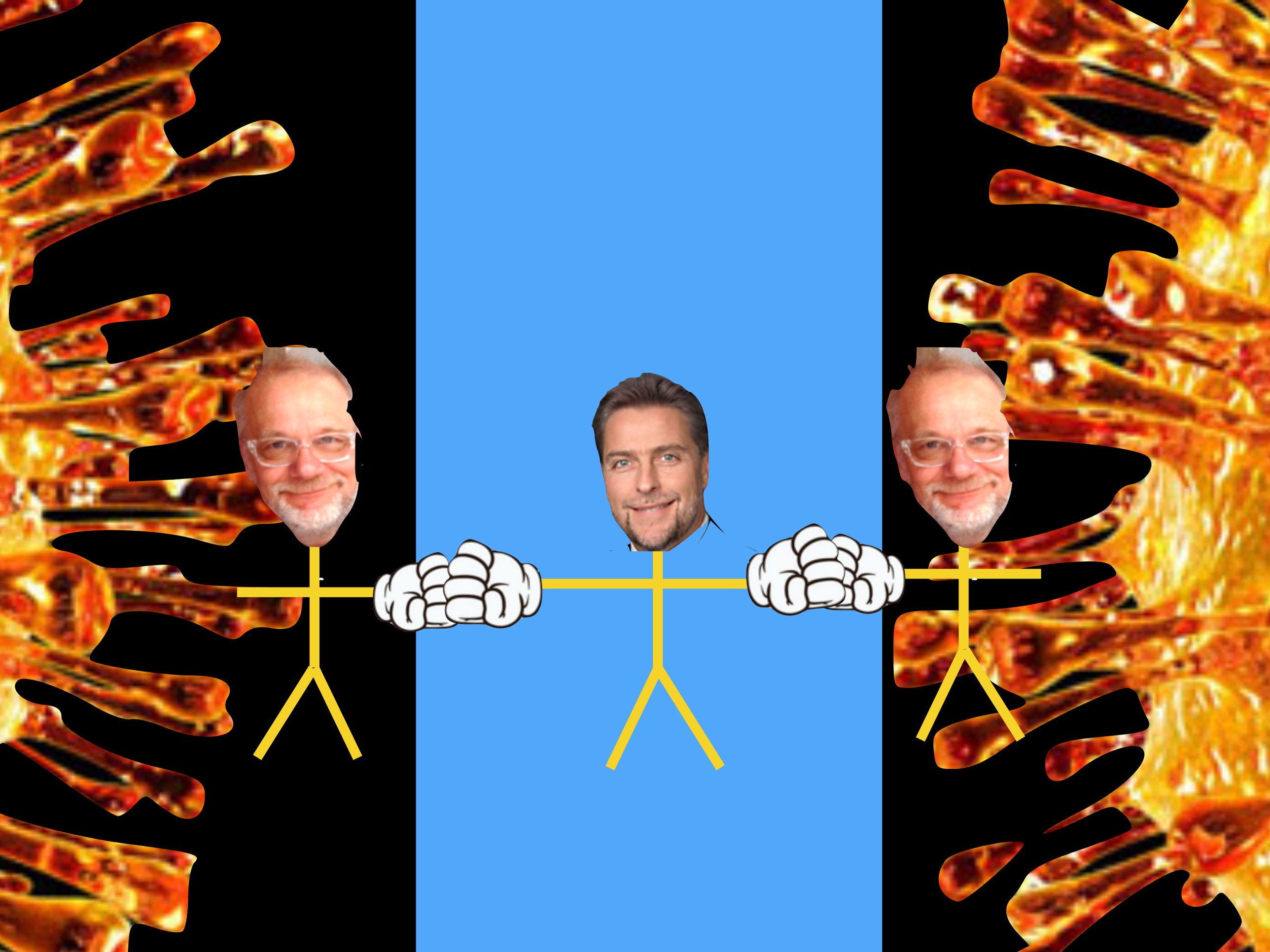


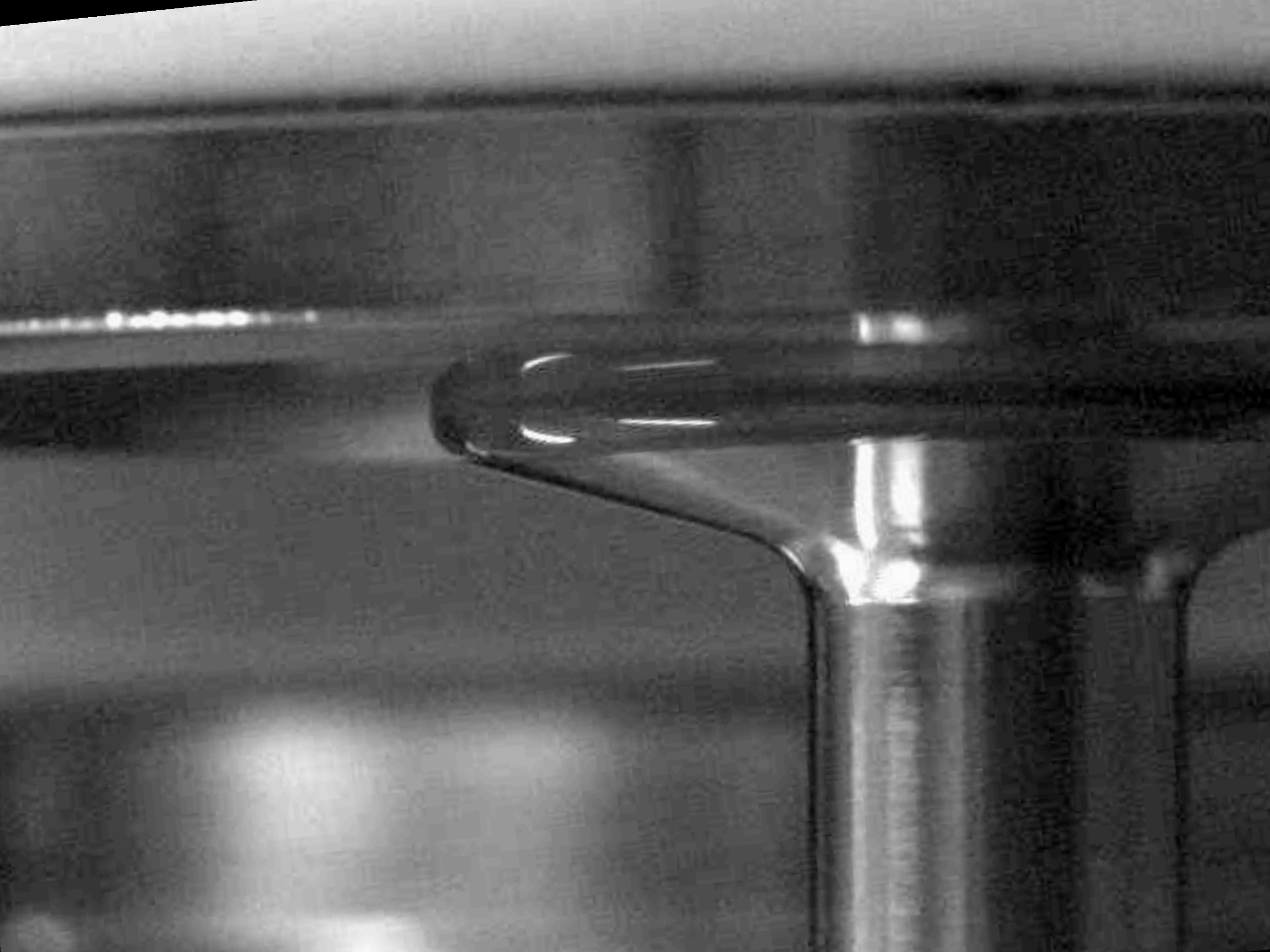


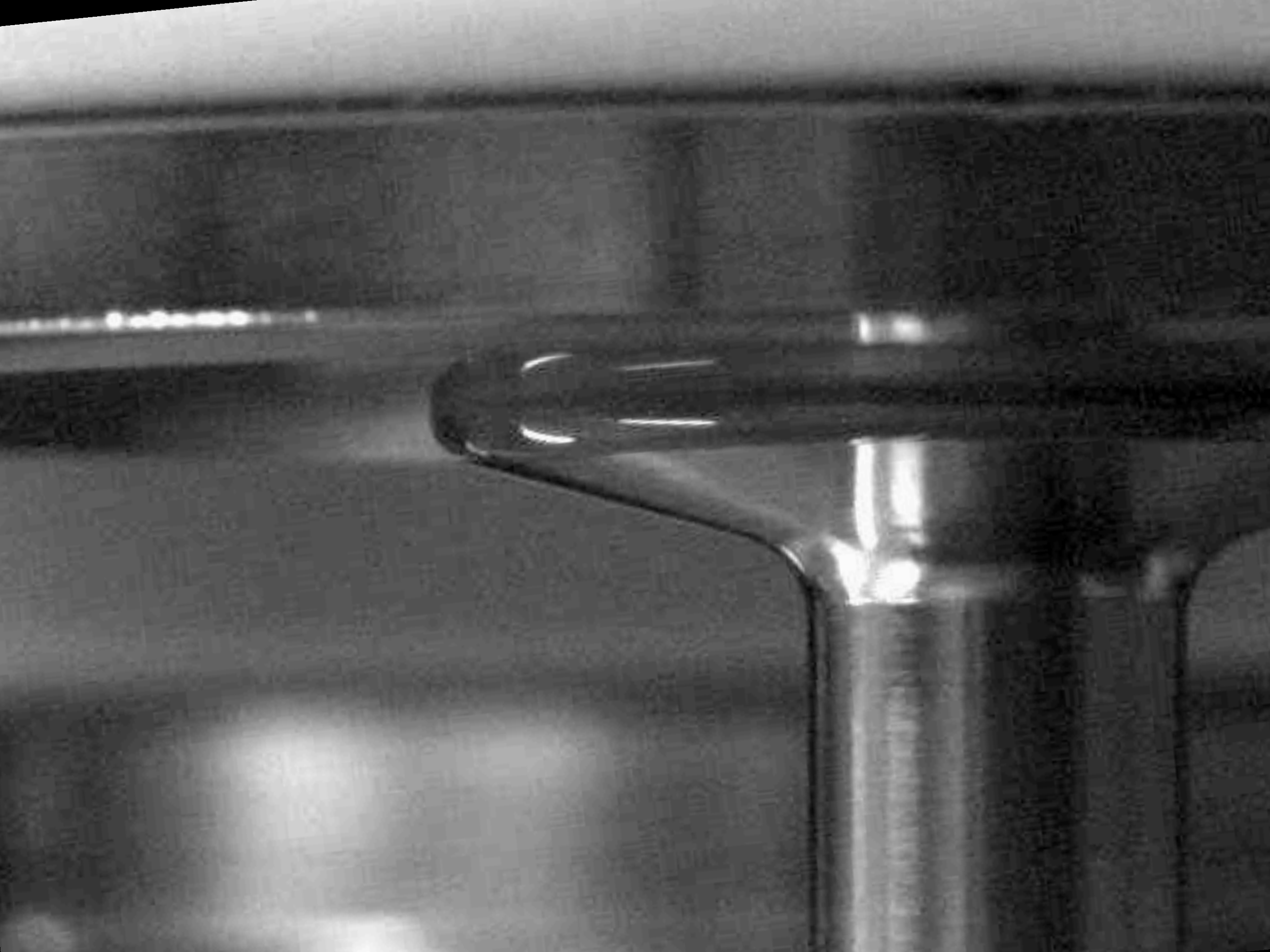




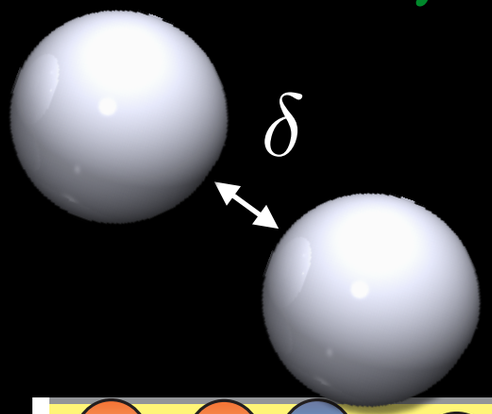




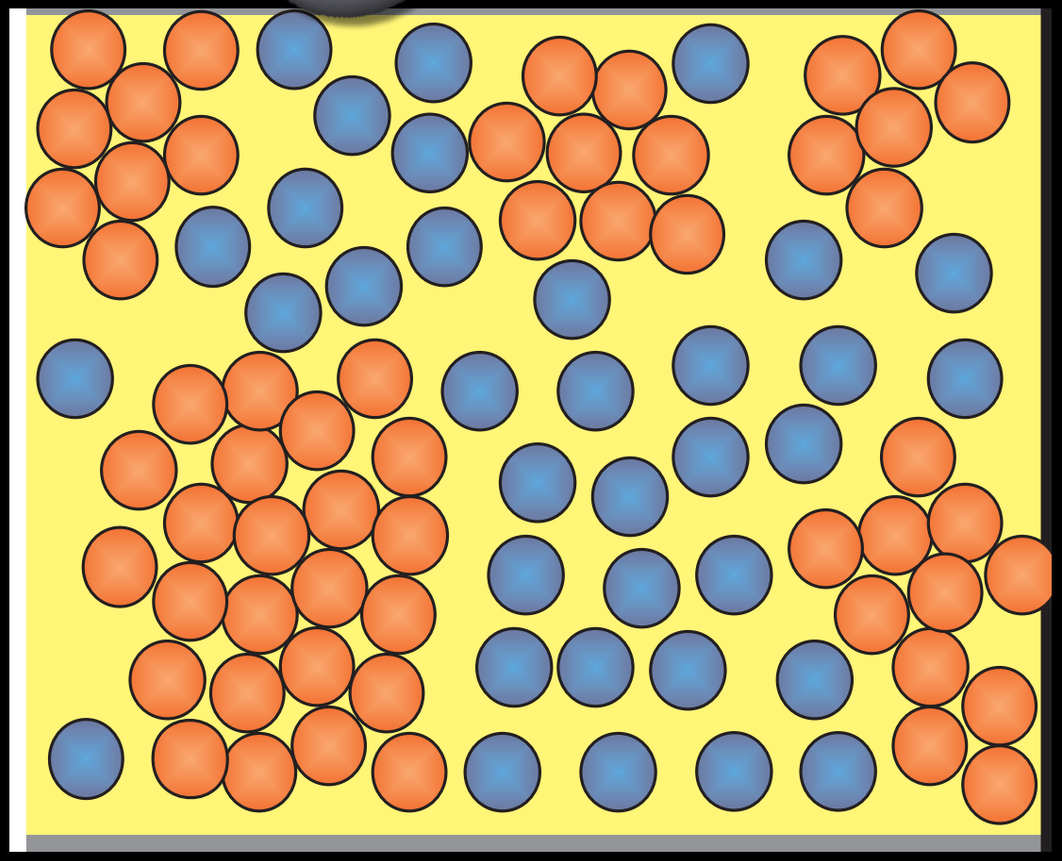


Shear Thickening Mechanisms

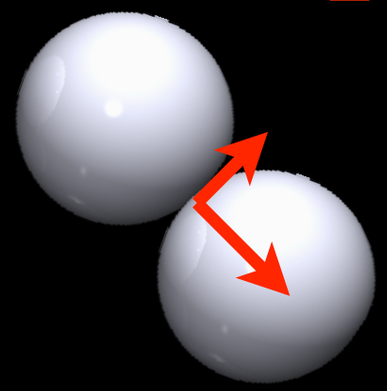
‘Hydroclusters’ VS ‘Friction’



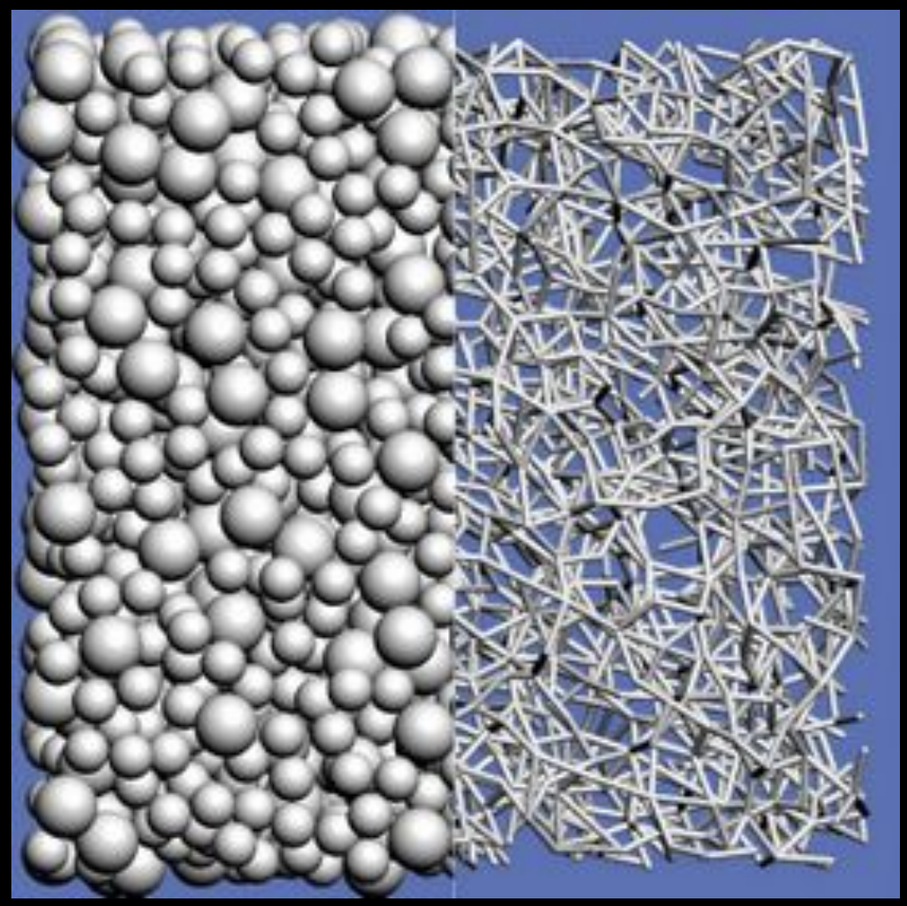
$$F_{lub} \propto \frac{1}{\delta}$$



Wagner, Brady Phys. Today 2009



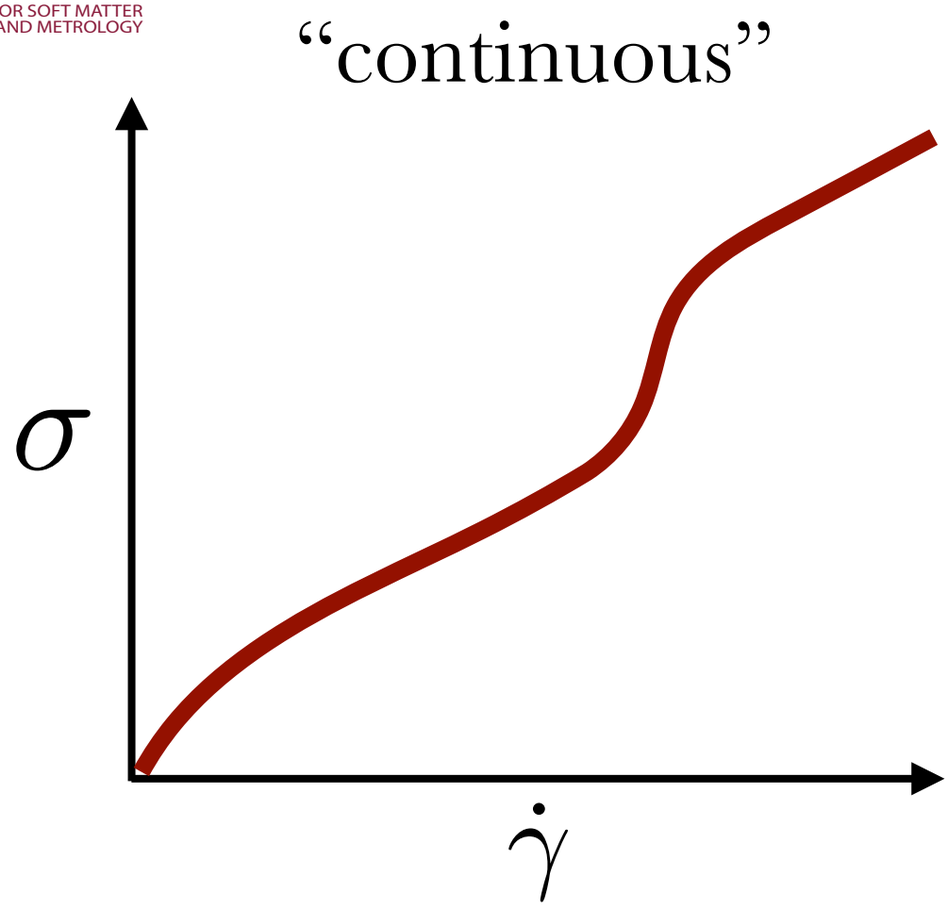
$$F_T \leq \boldsymbol{\mu} |F_N|$$

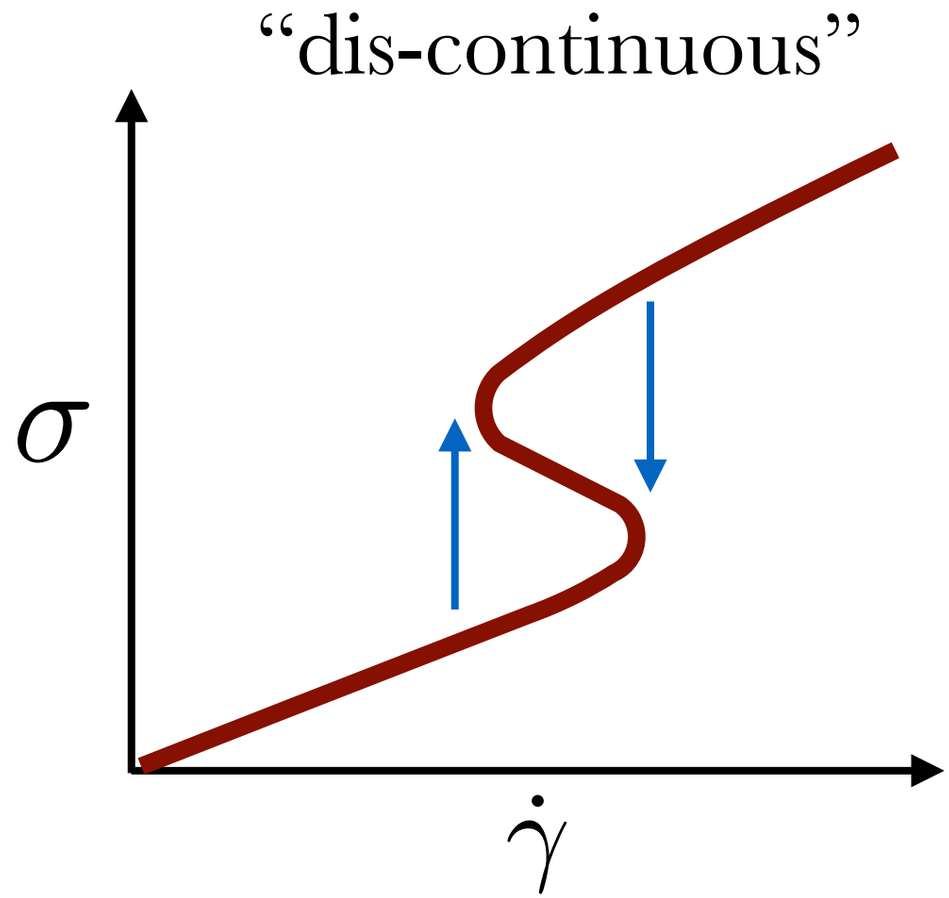


Seto et al PRL 2013
Wyart & Cates, *PRL* 2014

Shear Thickening

I(SM)2
INSTITUTE FOR SOFT MATTER SYNTHESIS AND METROLOGY





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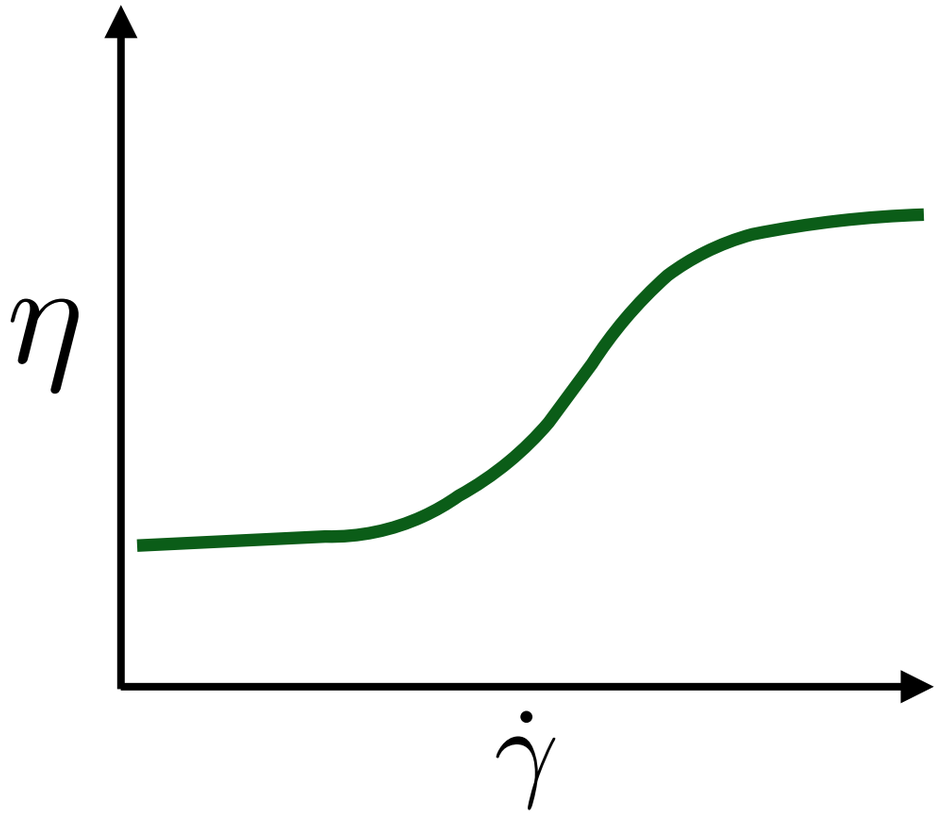
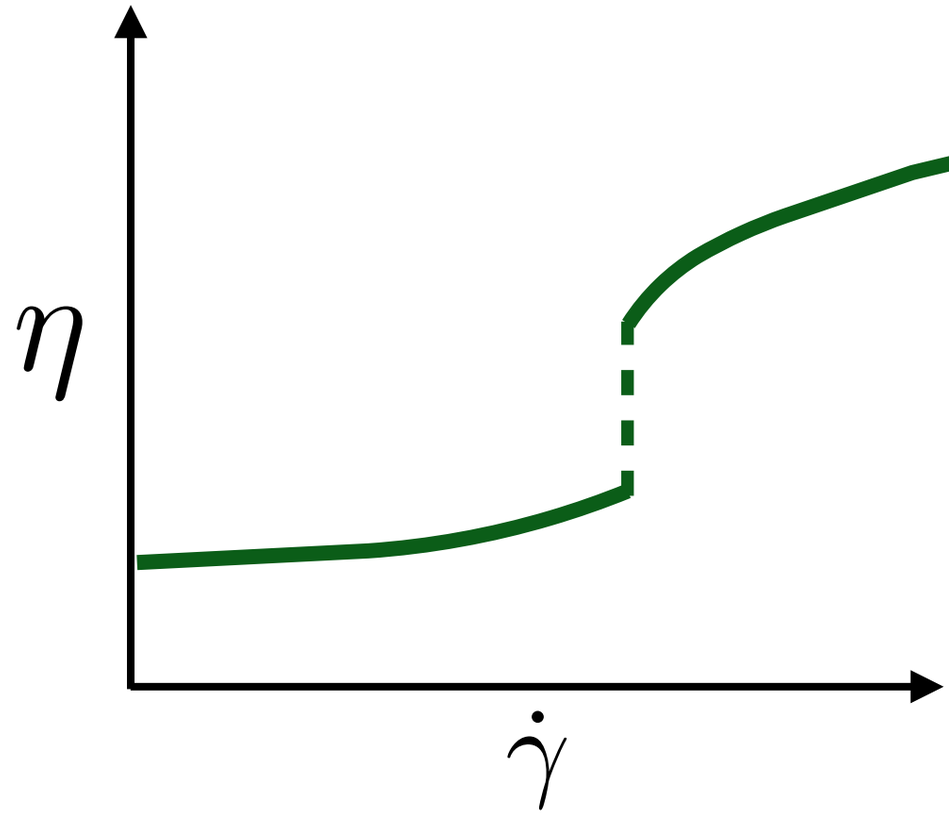
Shear Thickening

"continuous"



"dis-continuous"



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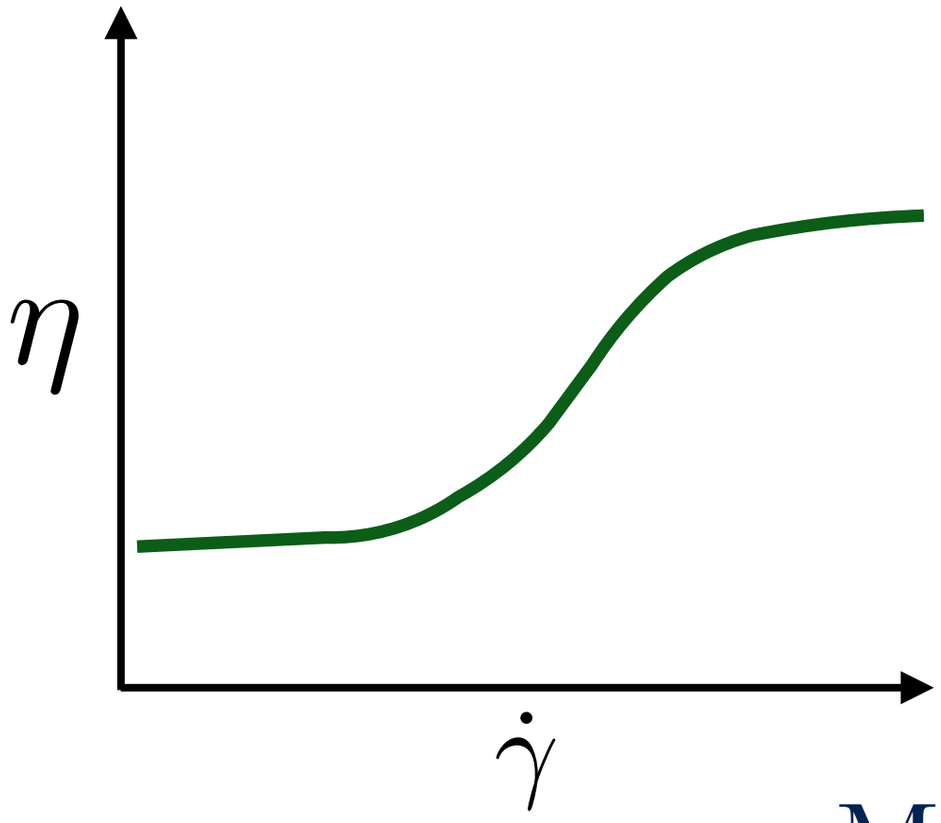

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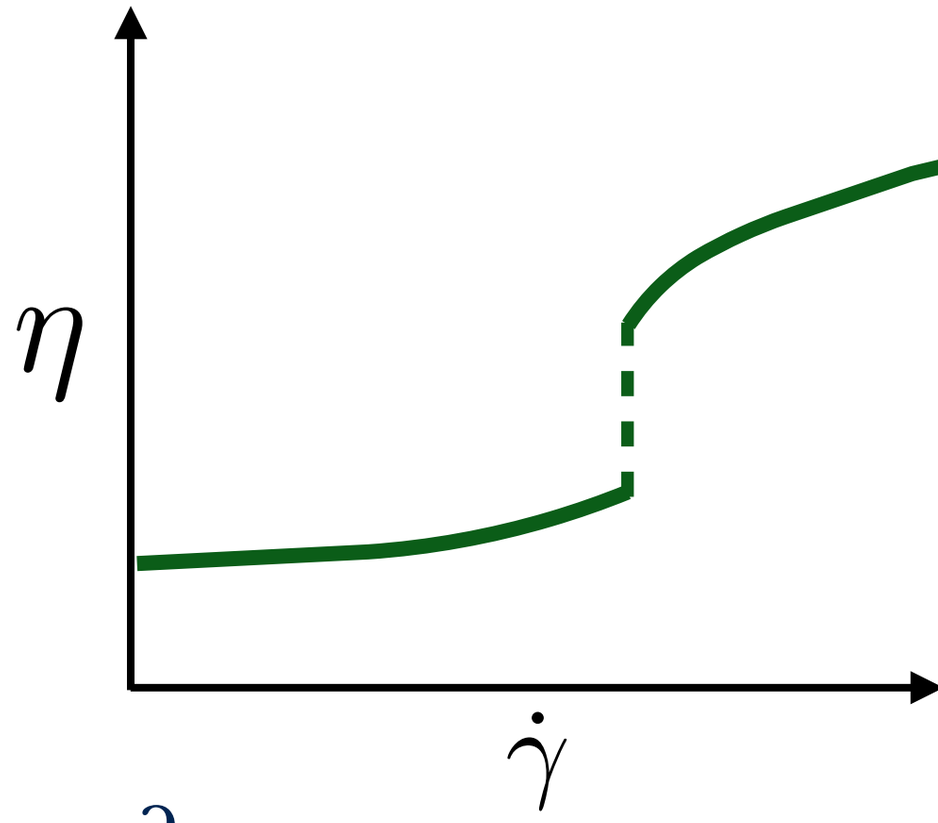

Mechanisms?

Shear Thickening

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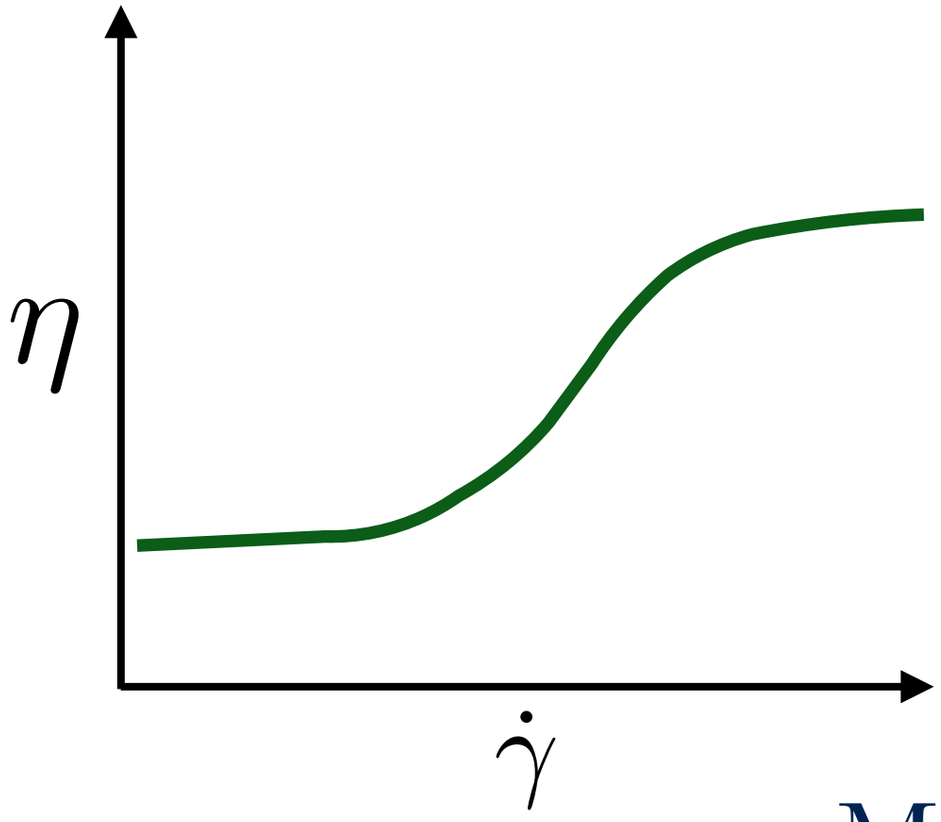

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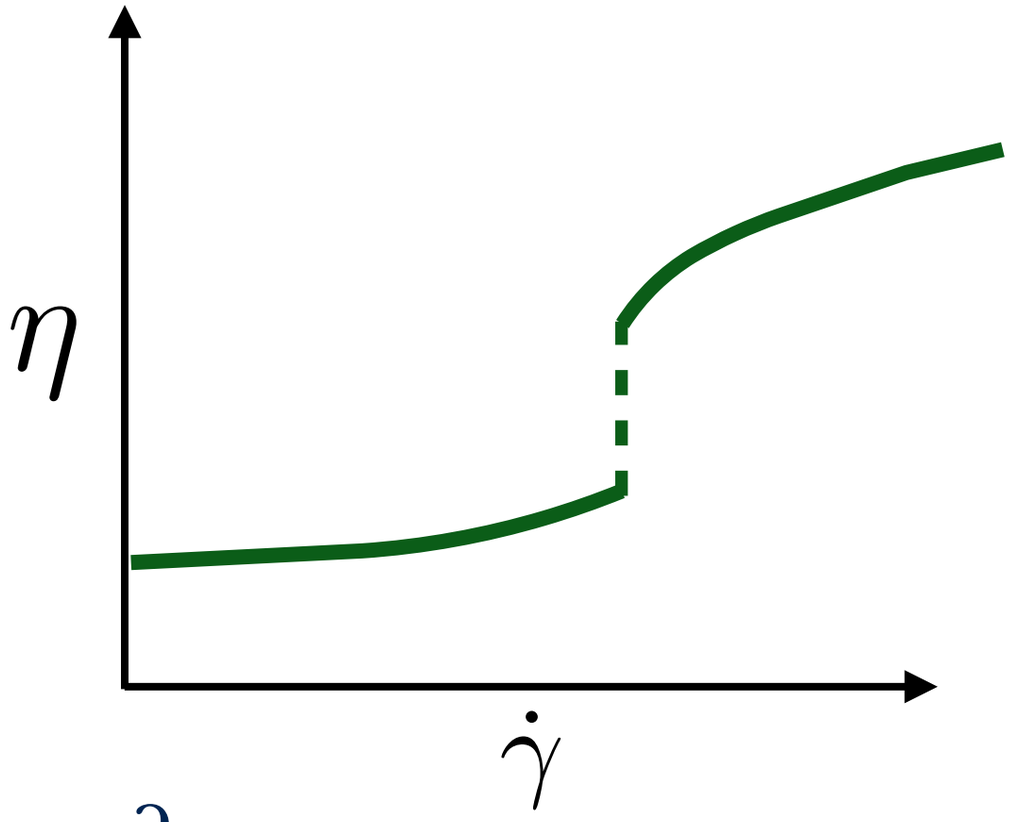
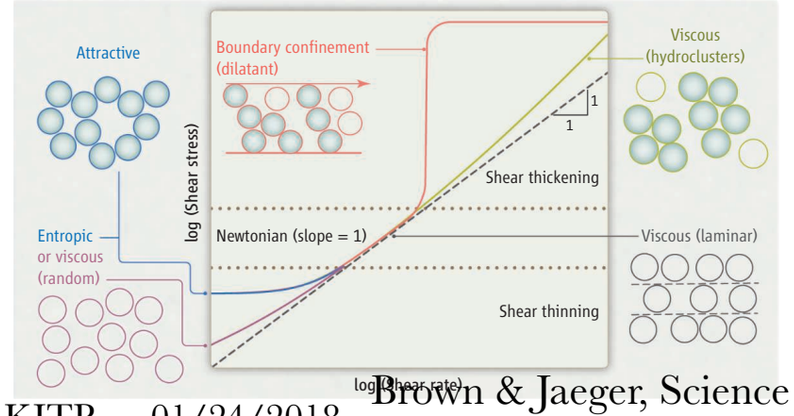


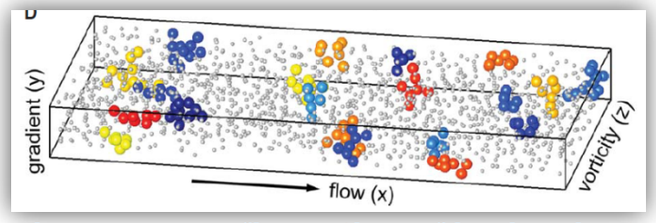
Mechanisms?

Hydrodynamics (*i.e.* hydroclusters)

Frictional interactions (*i.e* dilatantcy, granularity)

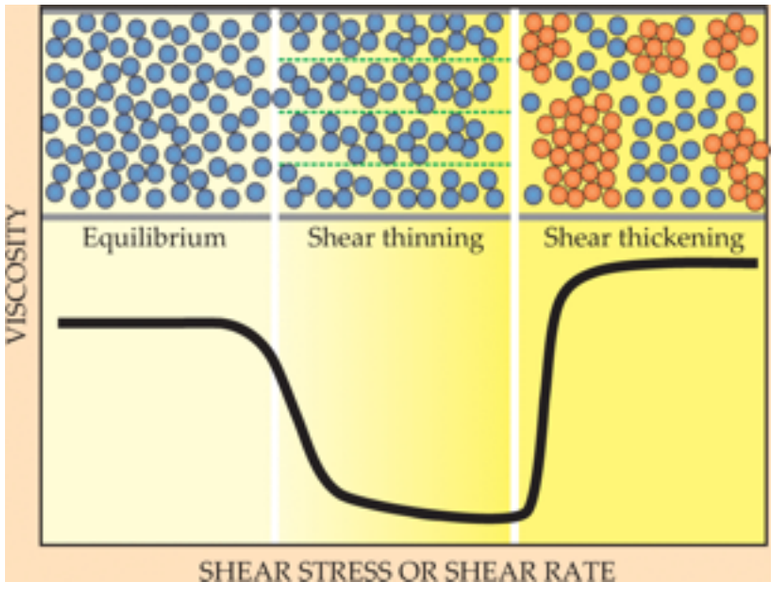


Brown & Jaeger, Science



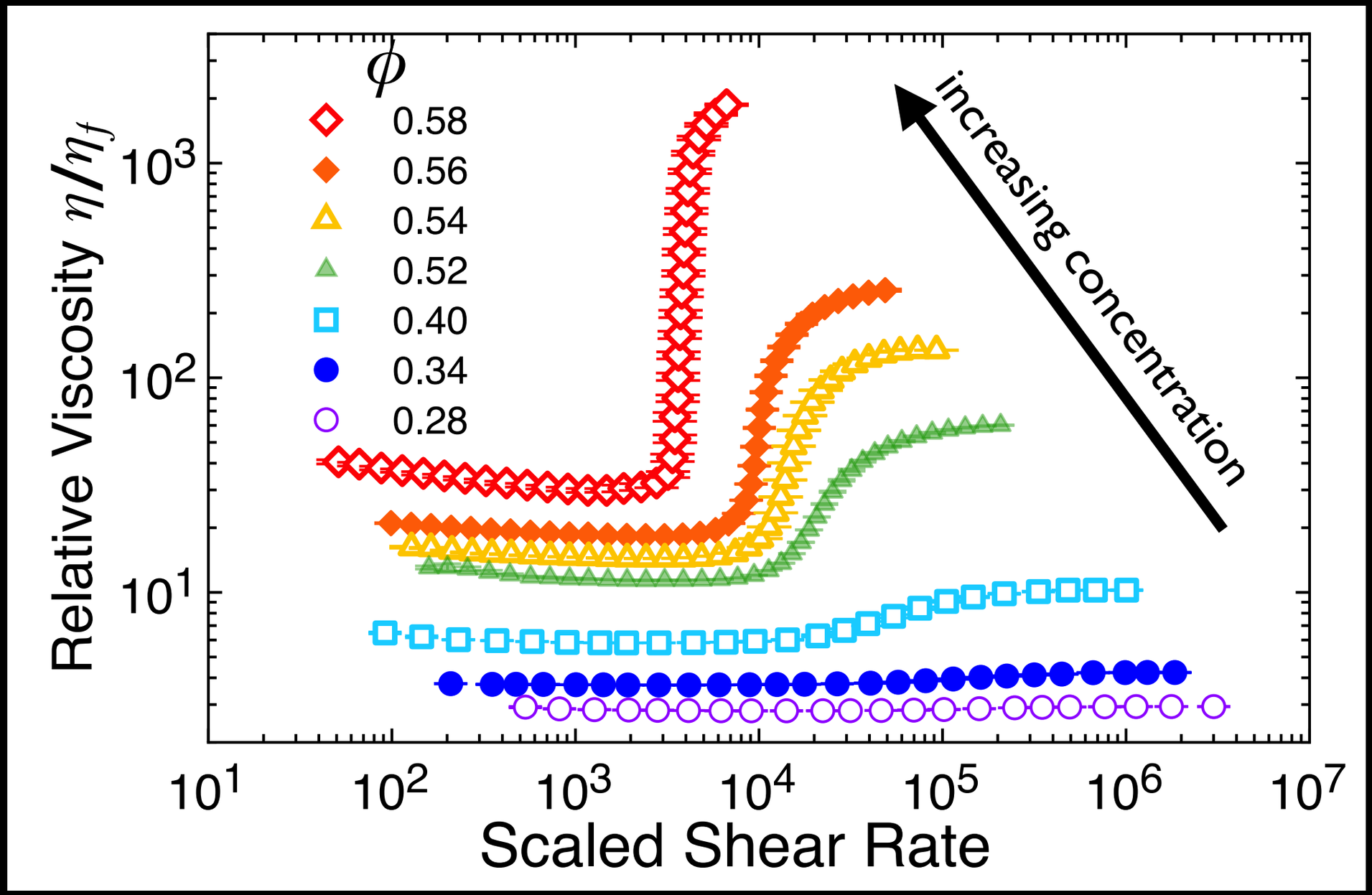
Real- space configuration of hydroclusters

Cheng, *et al.*, science 333, 1276-1279 (2011)



Brady & Wagner, Phys. Today

Continuous shear thickening



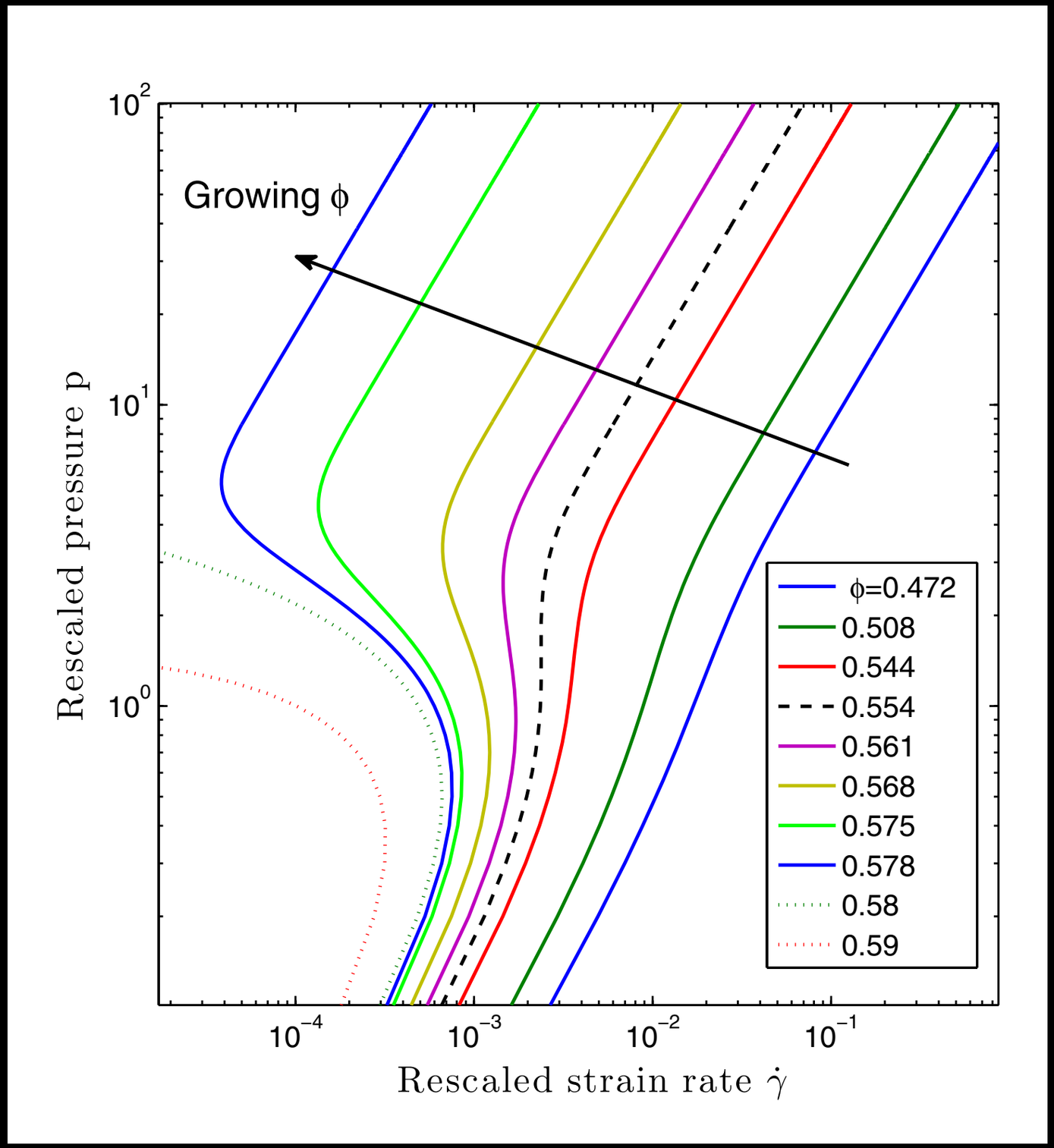
J. Royer, DLB, S.Hudson, PRL 2016

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

particles: 1.5 μm silica colloids

solvent: glycerol/water

Continuous shear thickening



Wyart & Cates, *PRL* 2014

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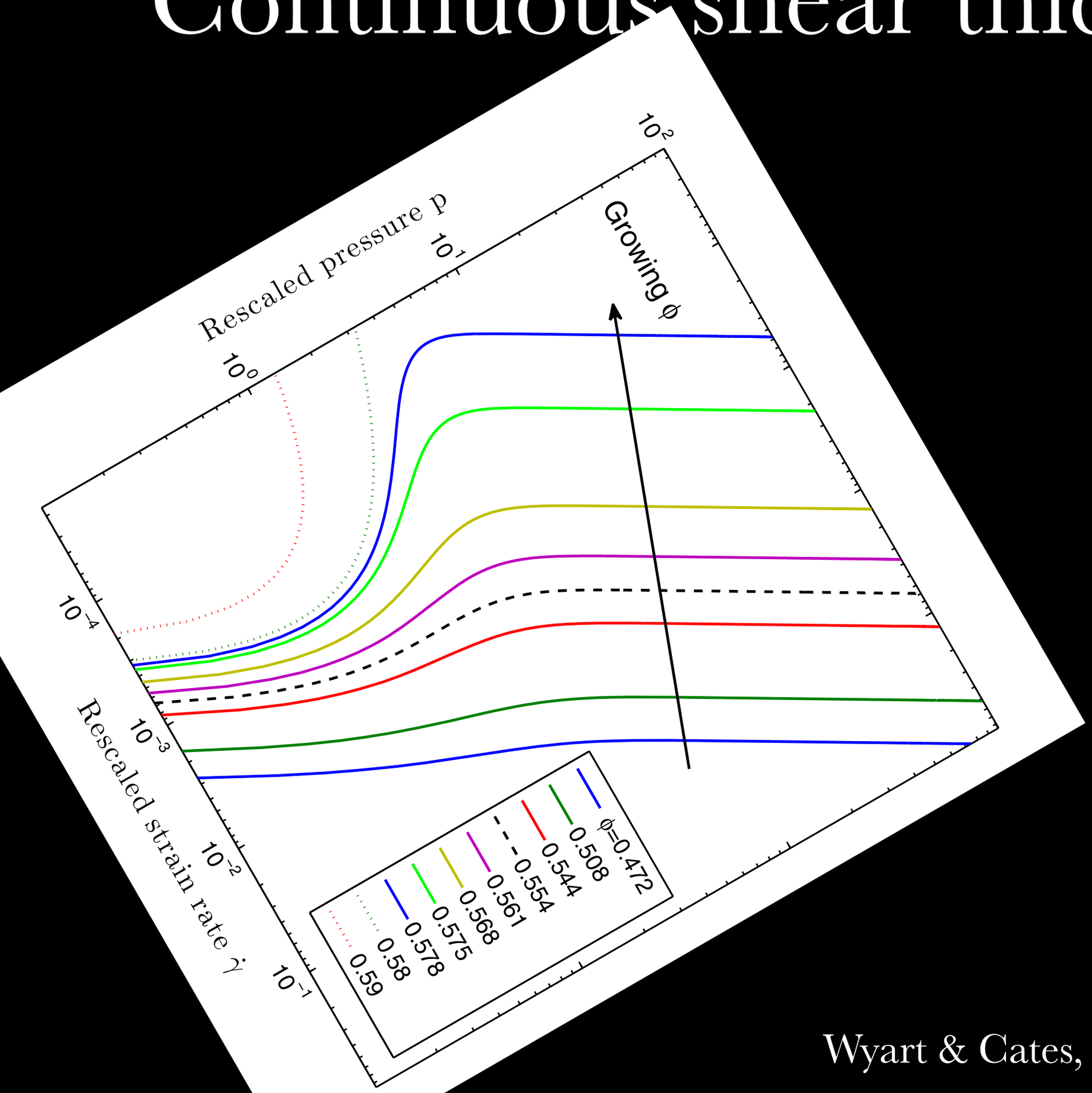

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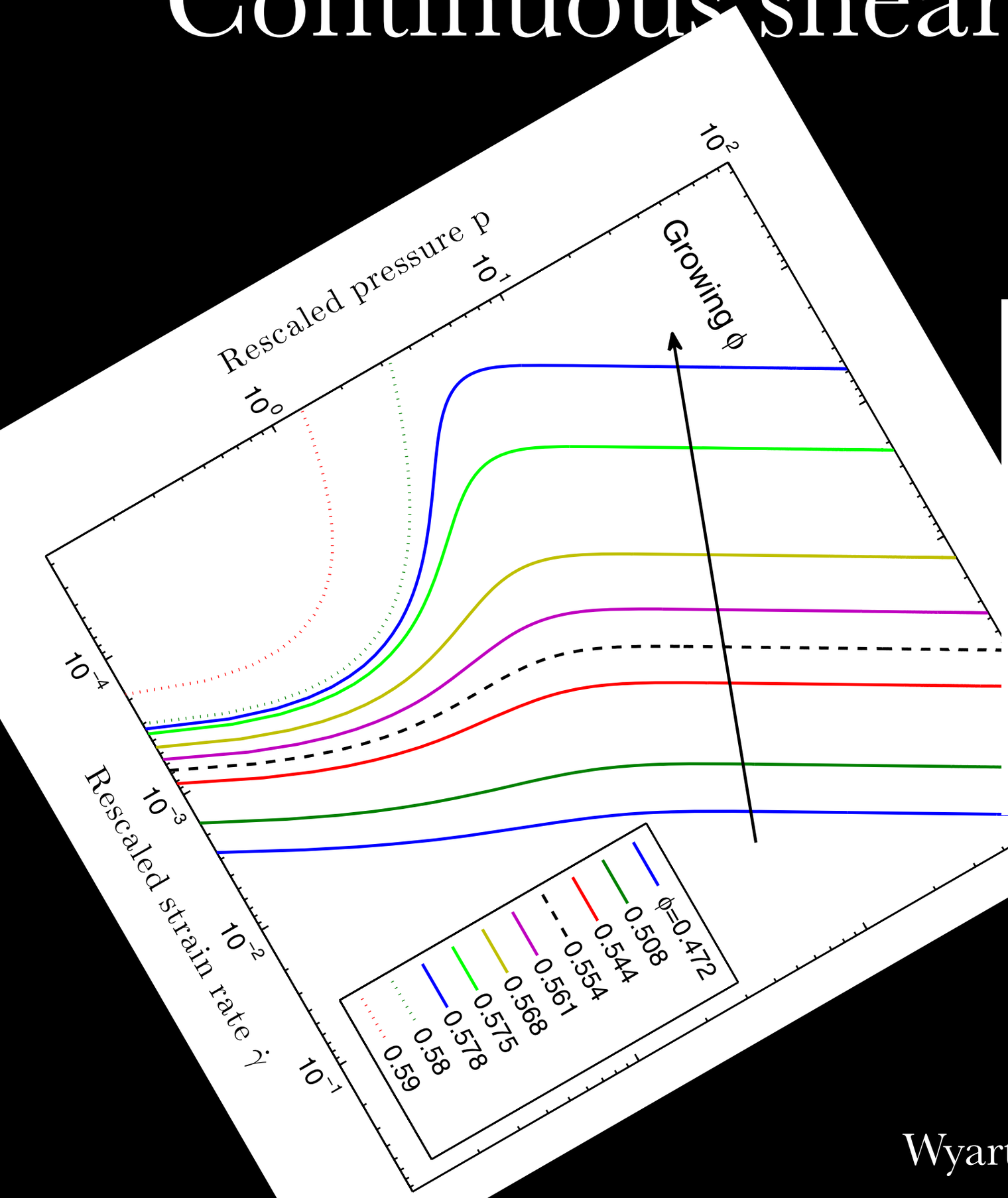
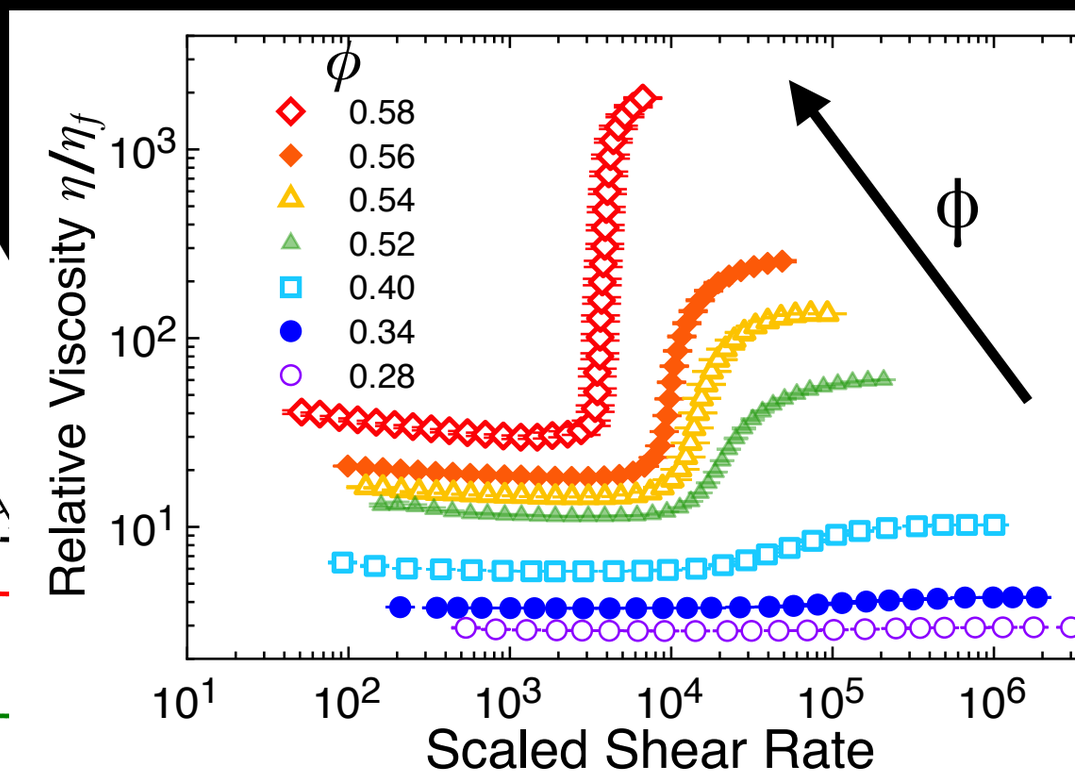
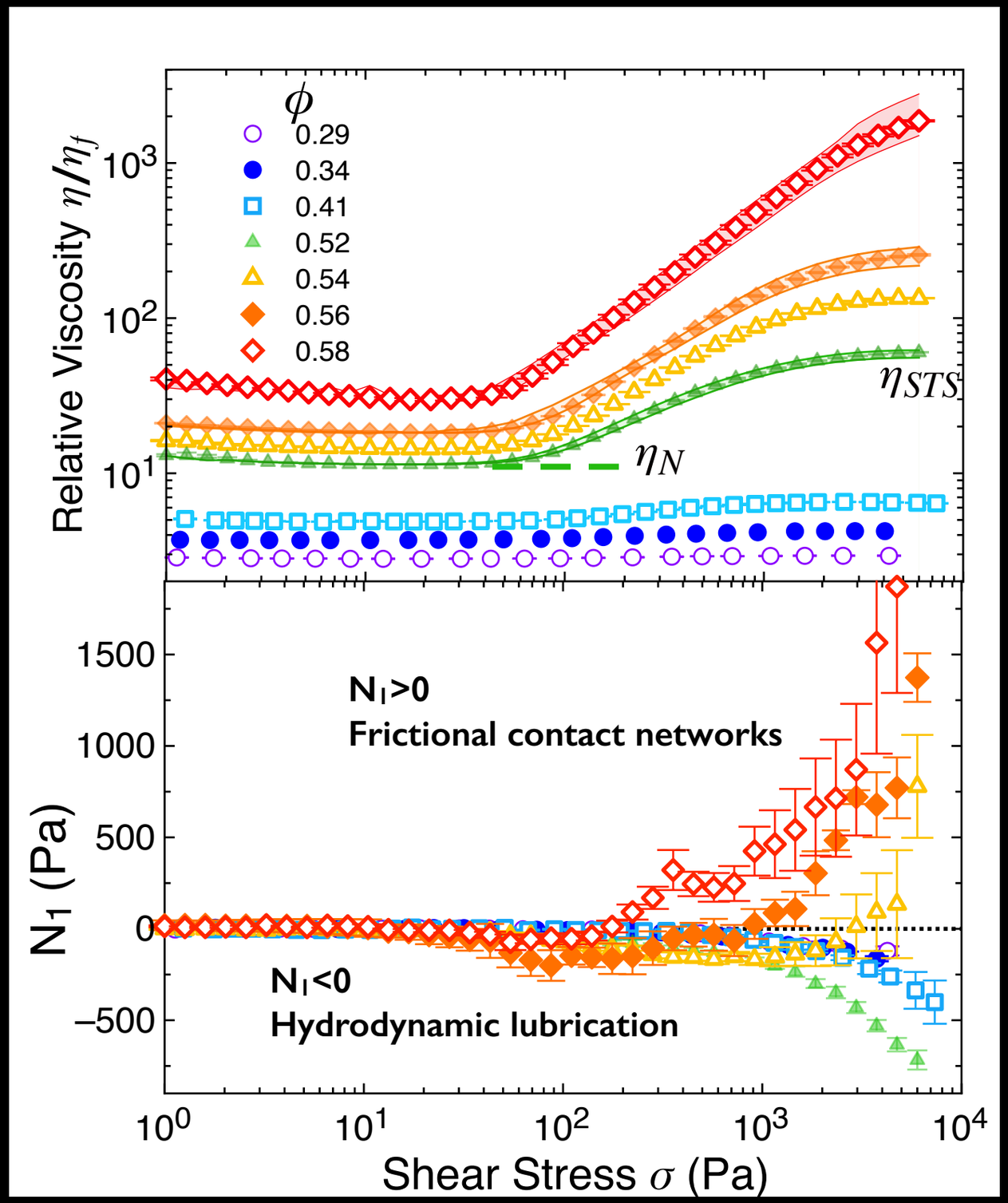




Wyart & Cates, *PRL* 2014

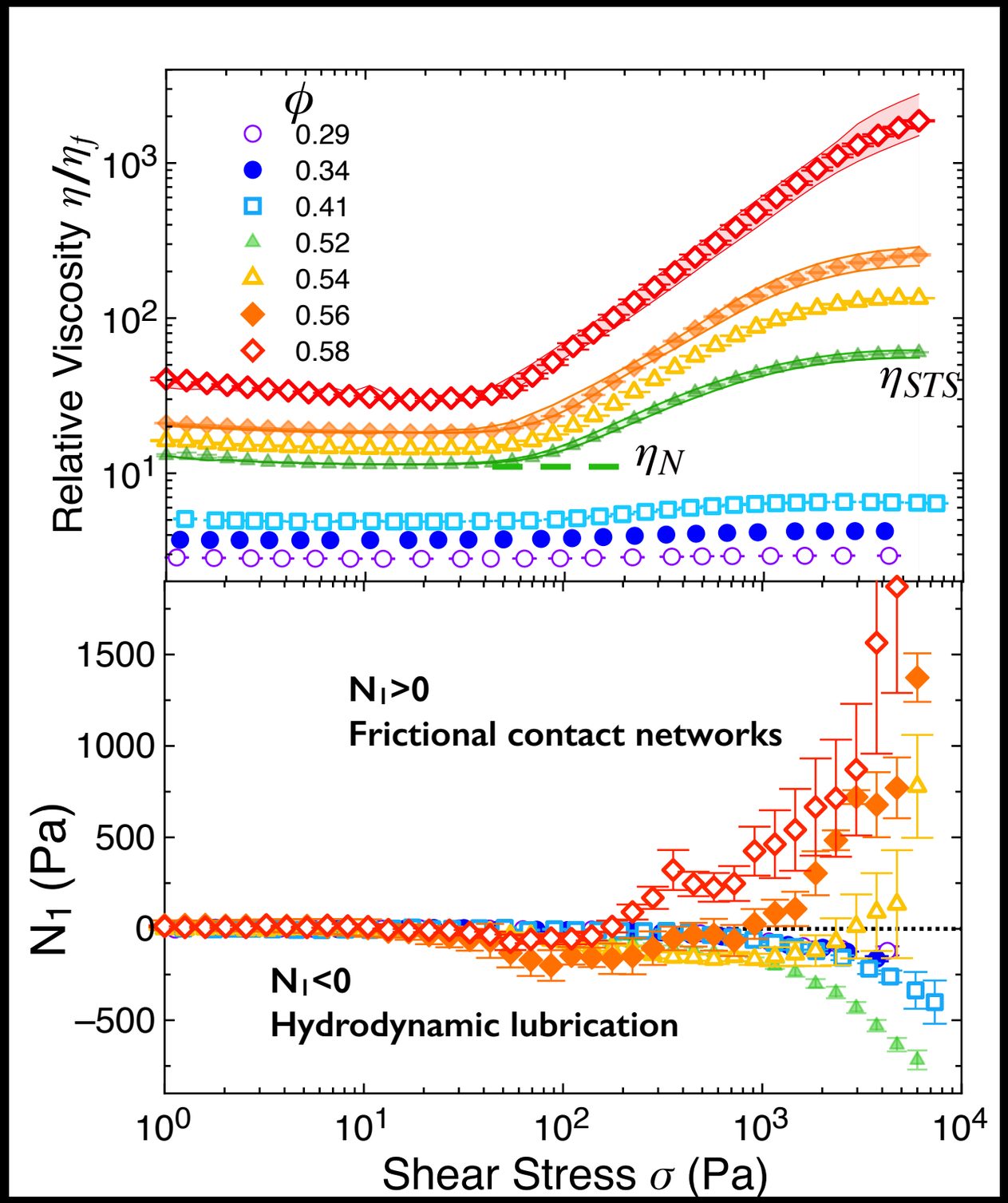
$\mathcal{N}_1$ Reveals New Transition



Change in N_1

J. Royer, DLB, S.Hudson, PRL 2016

$\mathcal{N}_1$ Reveals New Transition

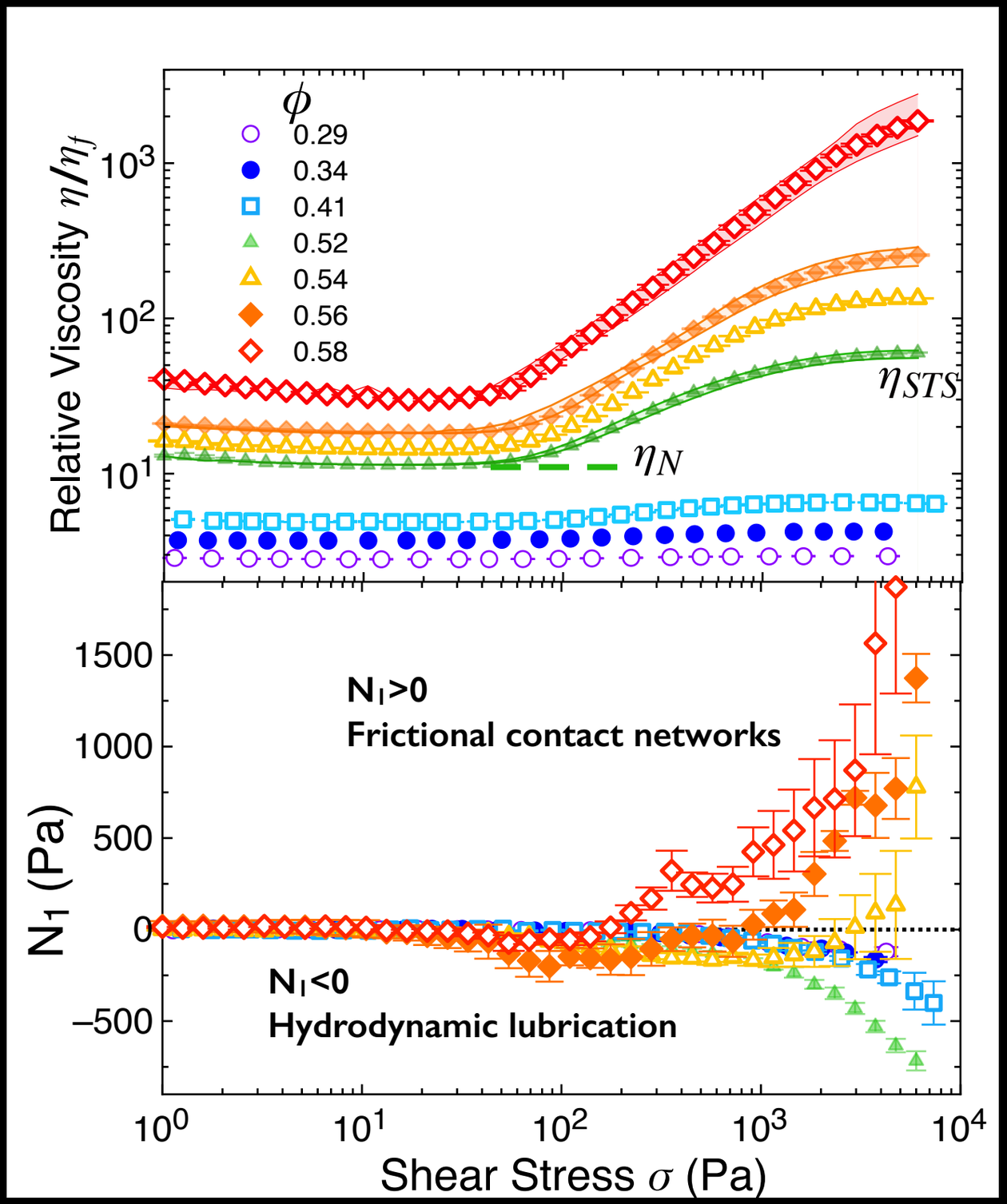


Change in N_1

No signature in viscosity

J. Royer, DLB, S.Hudson, PRL 2016

$\mathcal{N}_1$ Reveals New Transition



J. Royer, DLB, S.Hudson, PRL 2016

Change in N_1

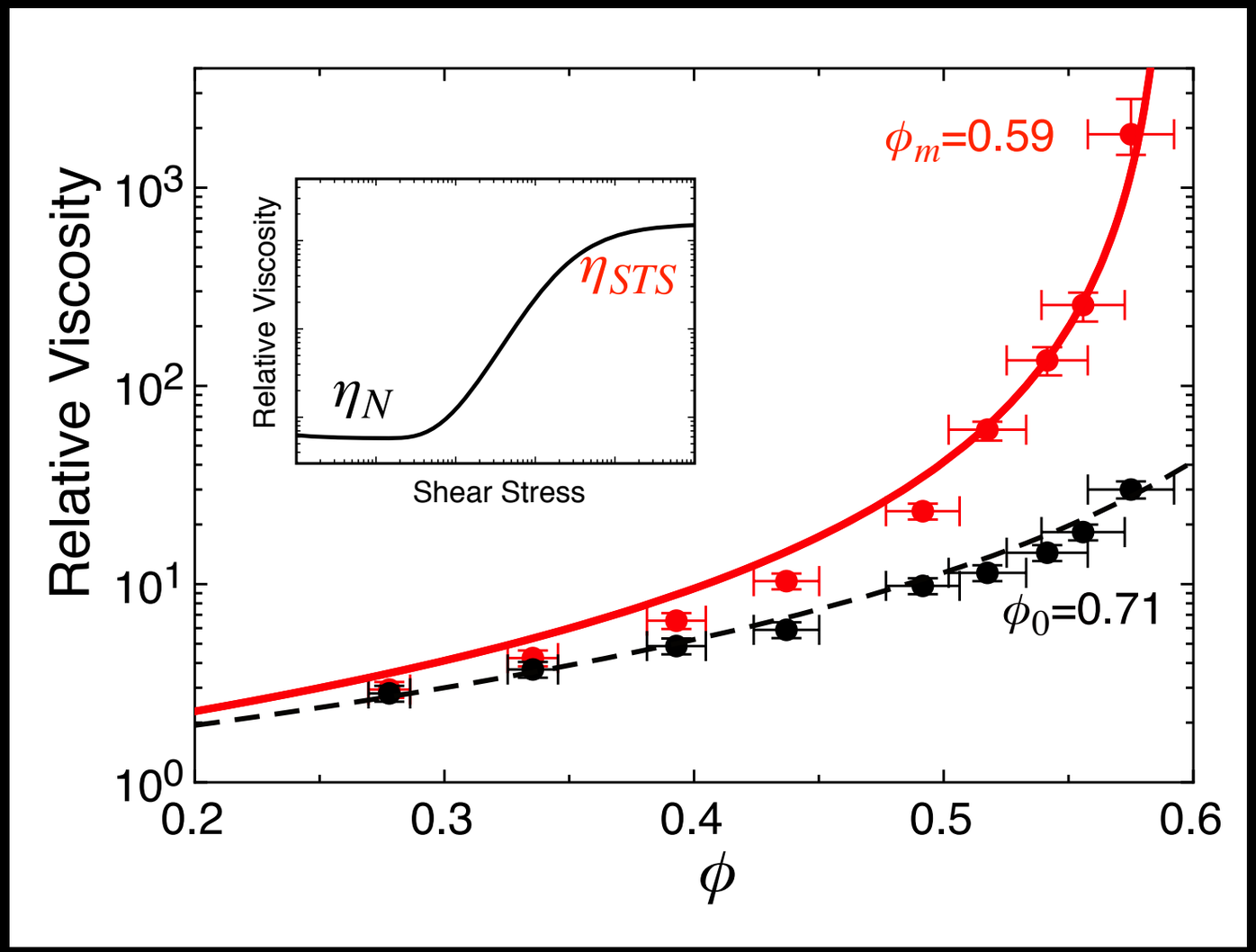
No signature in viscosity

What does this tell us?

Friction-based model

Shear thickening: stress activated frictional contacts

- Wyart and Cates PRL, 2014
- Guy, Hermes & Poon, PRL 2015



$$\eta_r = \left(1 - \frac{\phi}{\phi_c(\sigma)}\right)^{-2}$$

J. Royer, DLB, S.Hudson, PRL 2016

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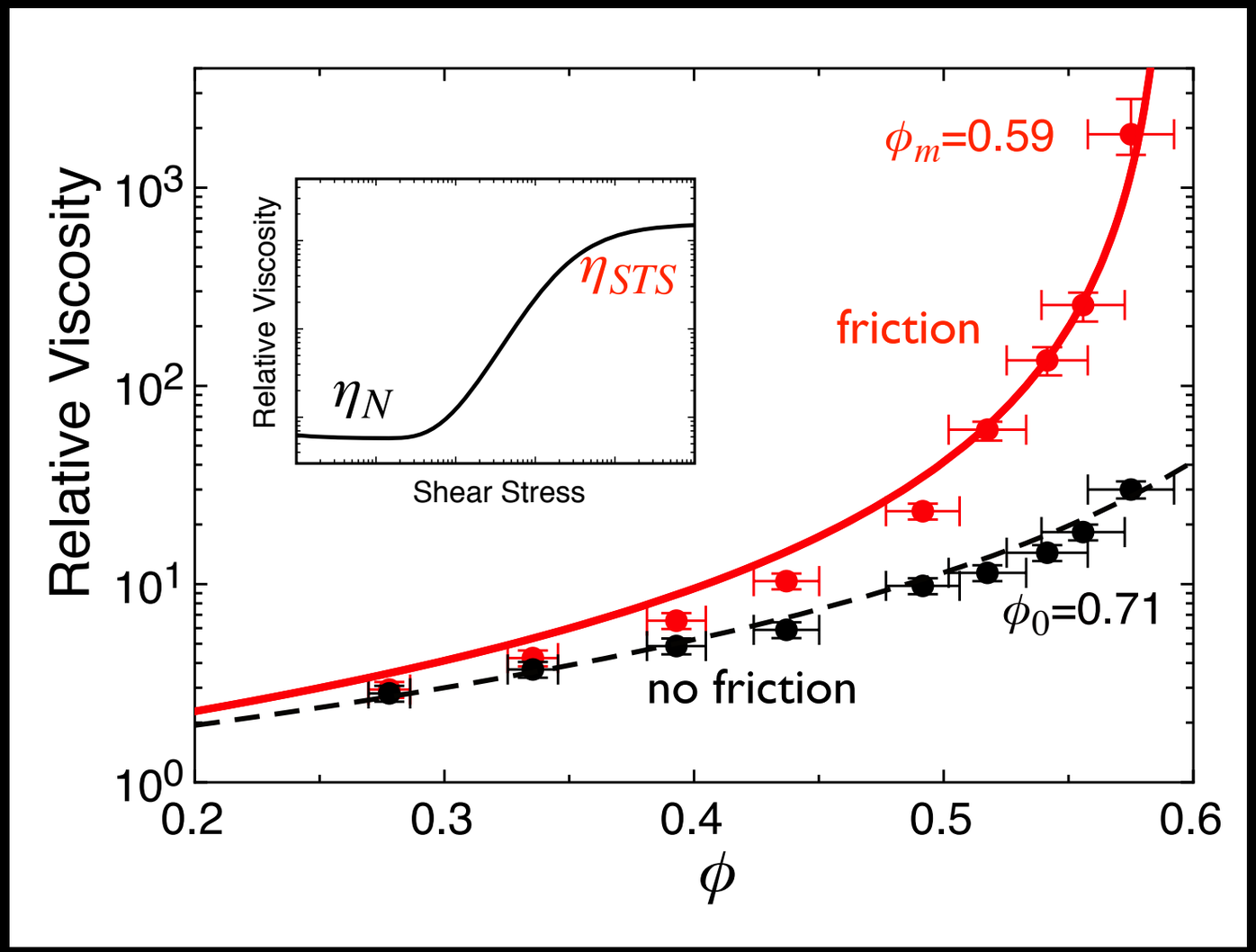

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J. Royer, DLB, S.Hudson, PRL 2016

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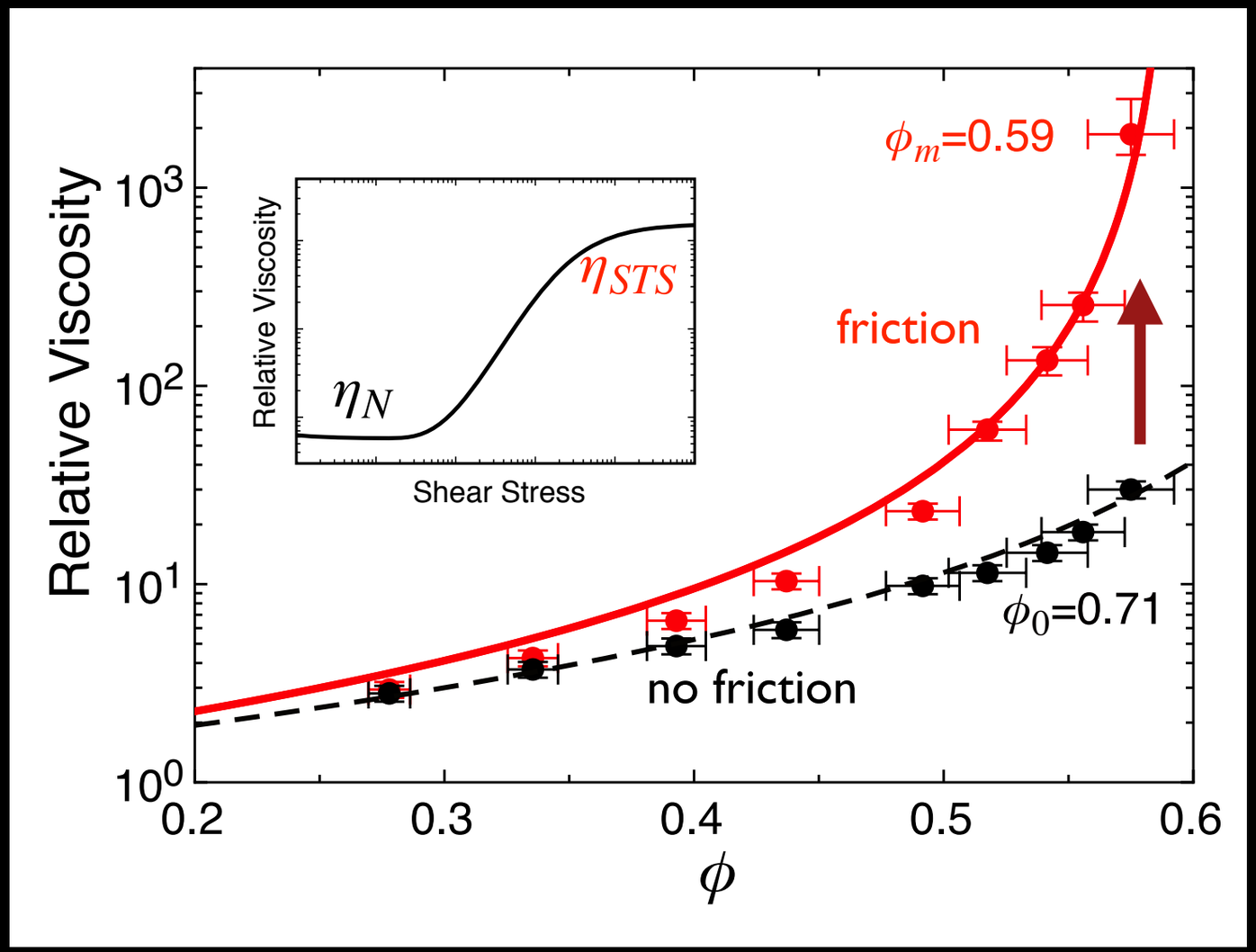


$$\eta_r = \left(1 - \frac{\phi}{\phi_c(\sigma)}\right)^{-2}$$

$$\phi_c(\sigma) = f\phi_m + (1-f)\phi_0$$

f = fraction of frictional contacts

J. Royer, DLB, S.Hudson, PRL 2016

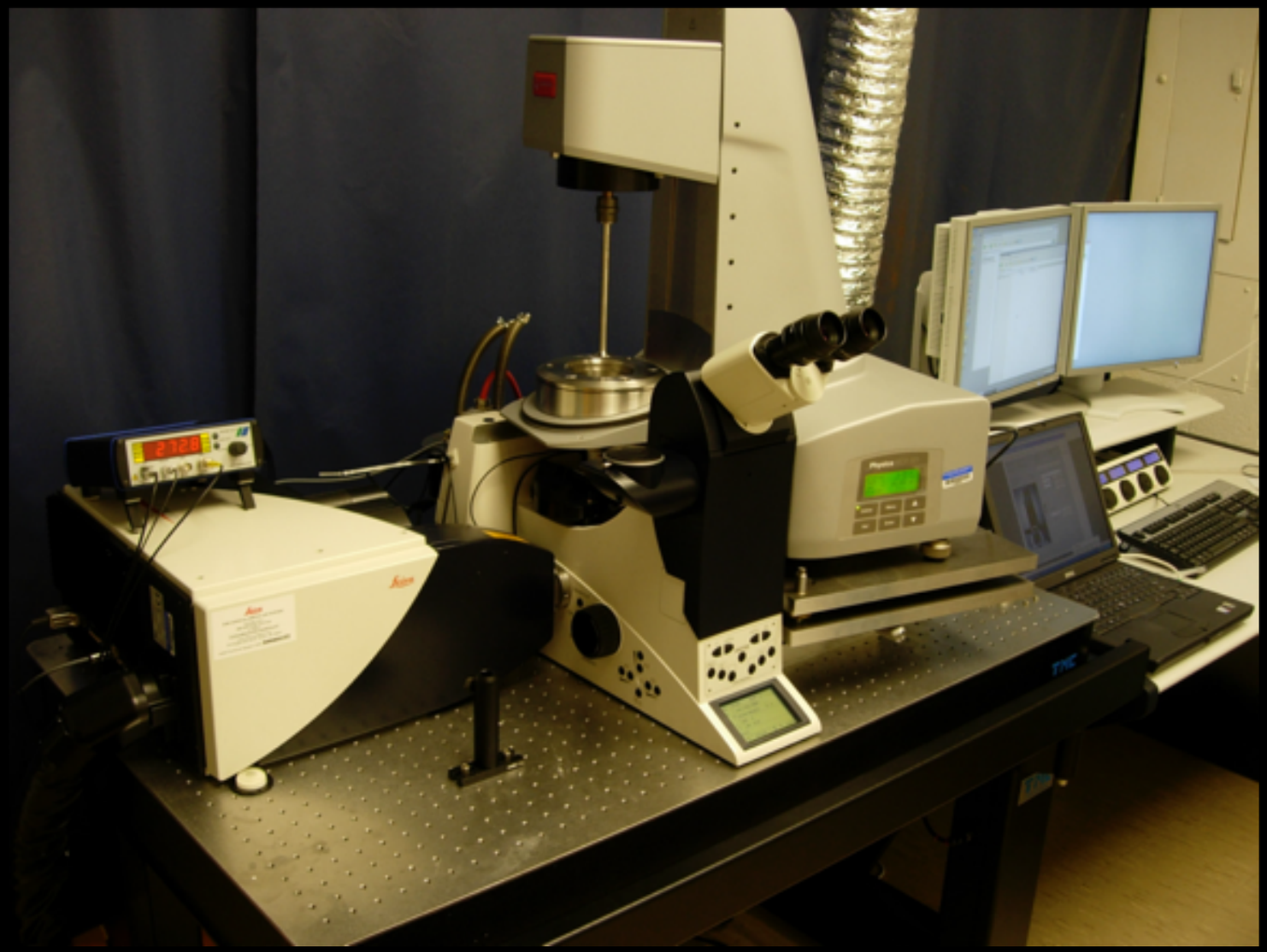
Confocal-Rheology Platform

Anton-Paar MCR-301

Leica SP5

S. K. Dutta, A. Mbi, R.C. Arevalo, and DLB Rev. Sci. Instrum. 84, 063702 (2013)

Confocal-Rheology Platform



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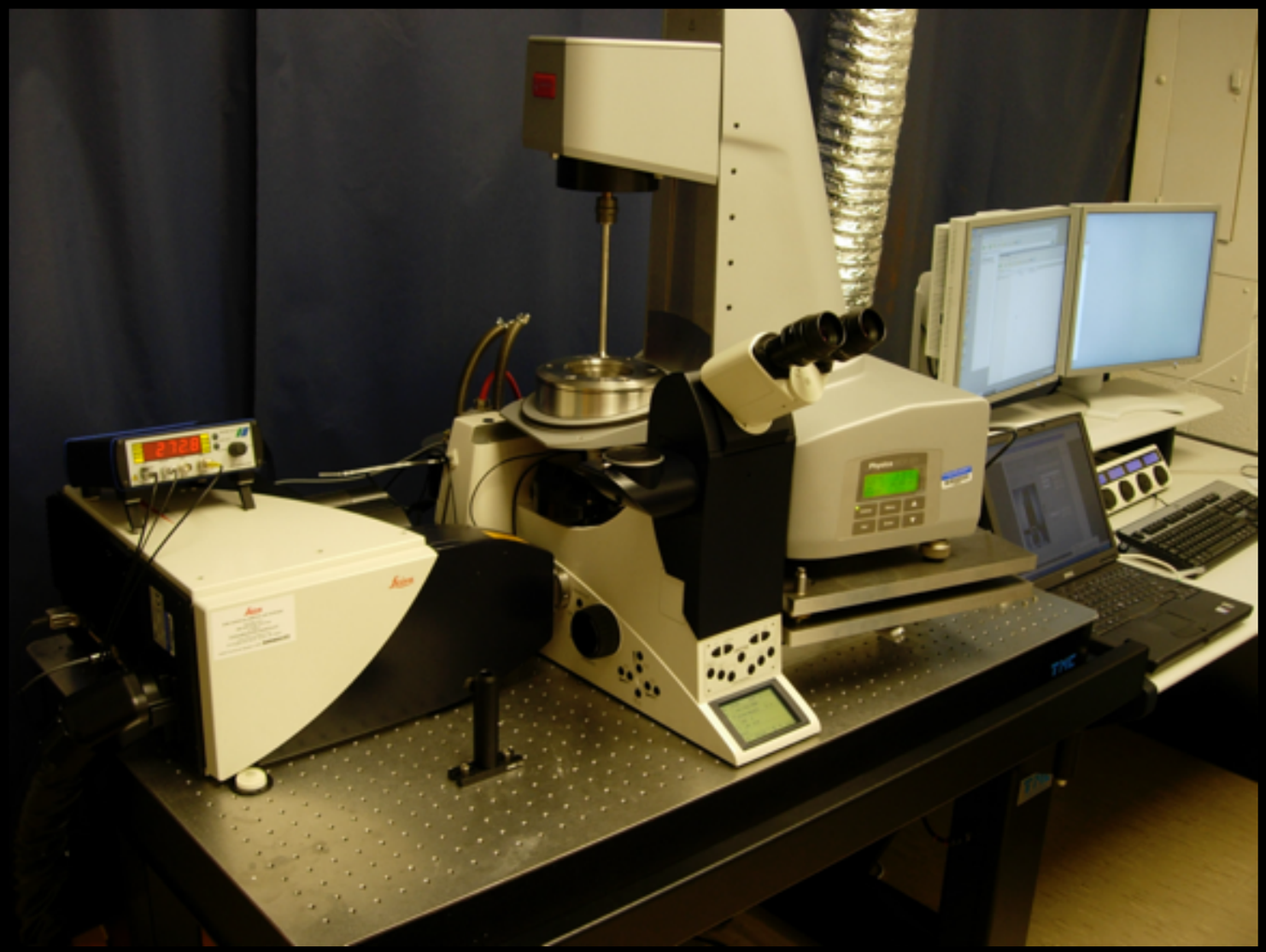
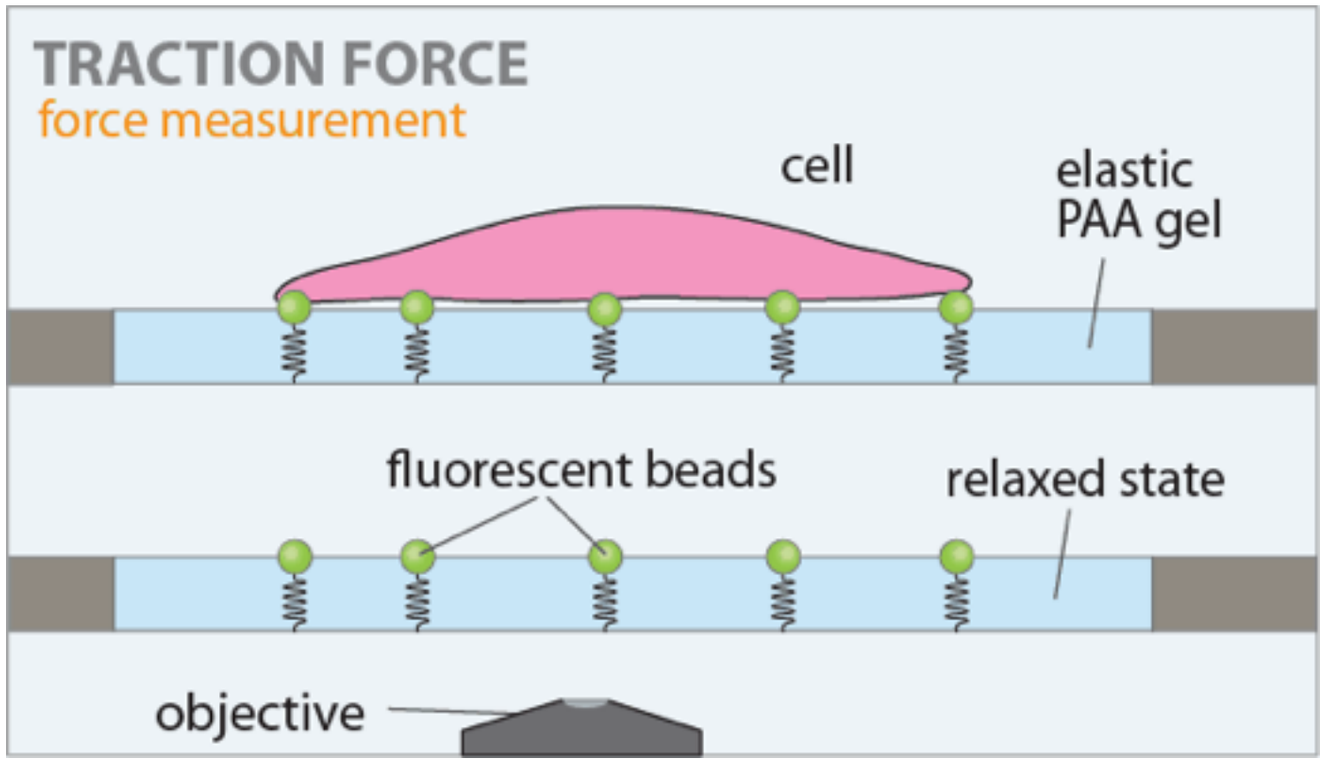
Confocal-Rheology Platform

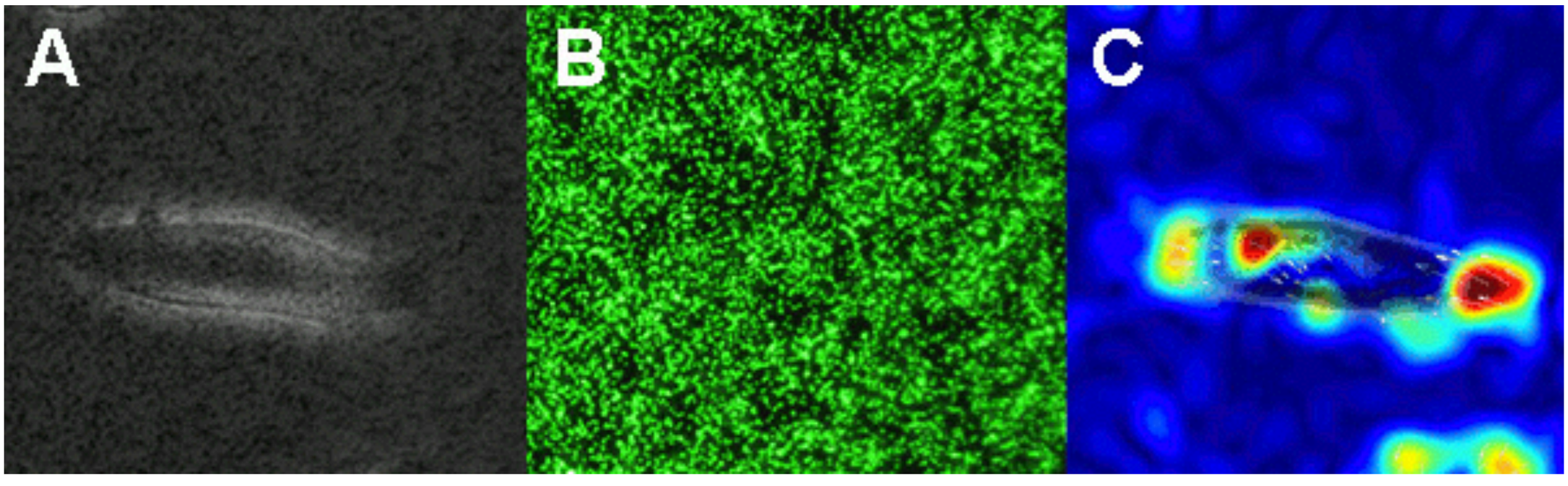


Confocal-Rheology (con-rheo)

S. K. Dutta, A. Mbi, R.C. Arevalo, and DLB Rev. Sci. Instrum. 84, 063702 (2013)

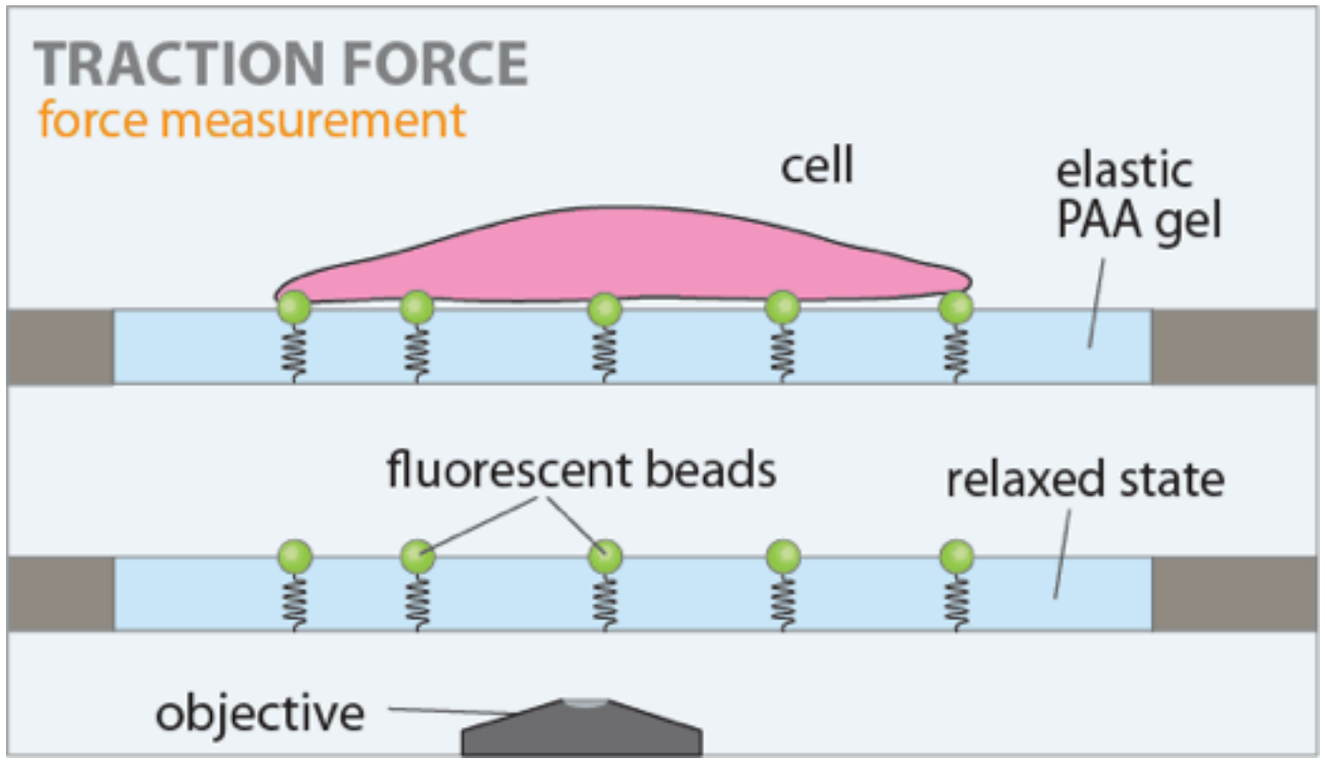
Traction Forces/Boundary Stresses

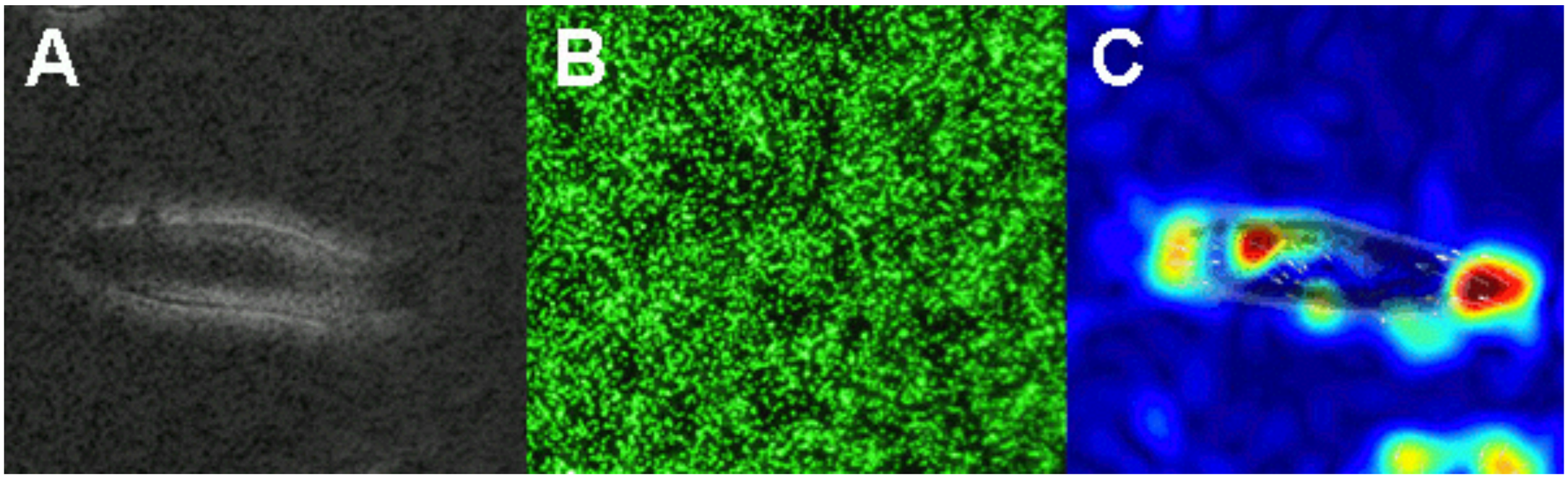




http://www.cellmechanics.de/Methods/Tractions.html

Traction Forces/Boundary Stresses





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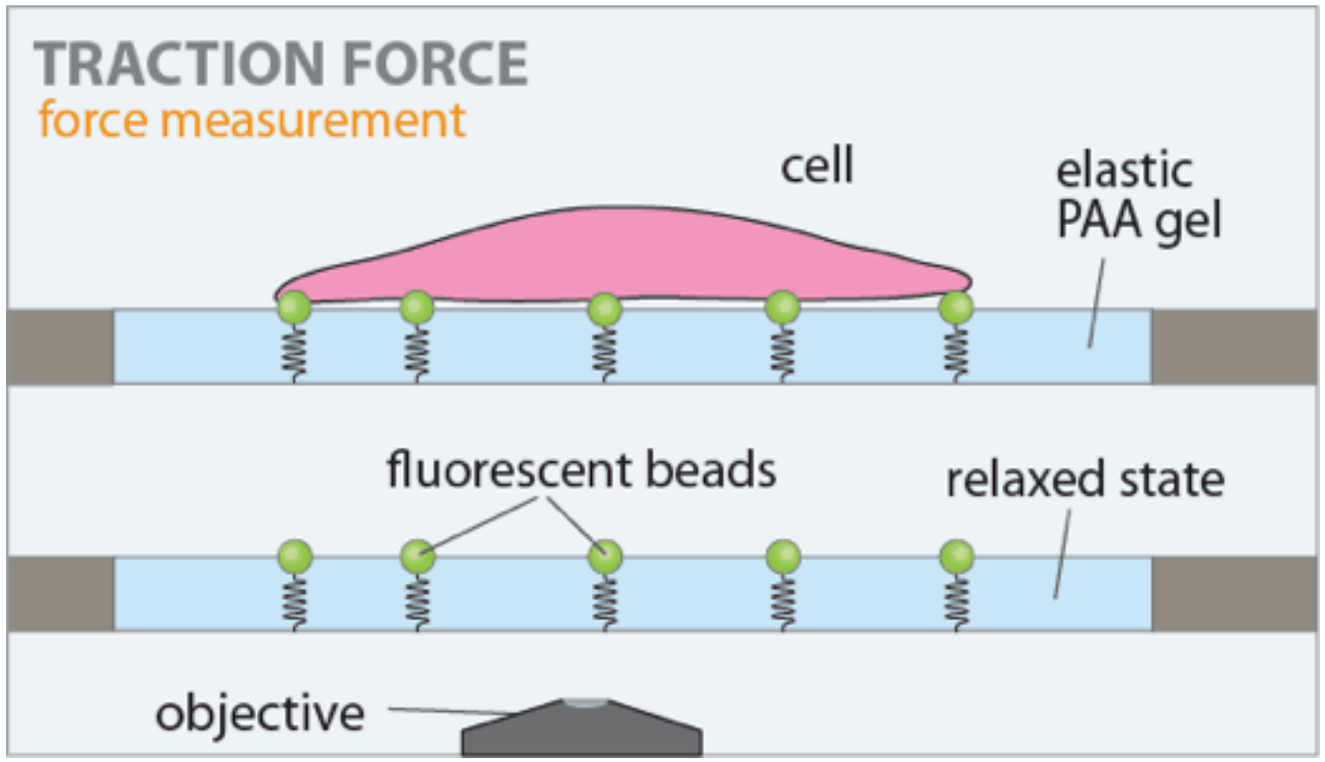
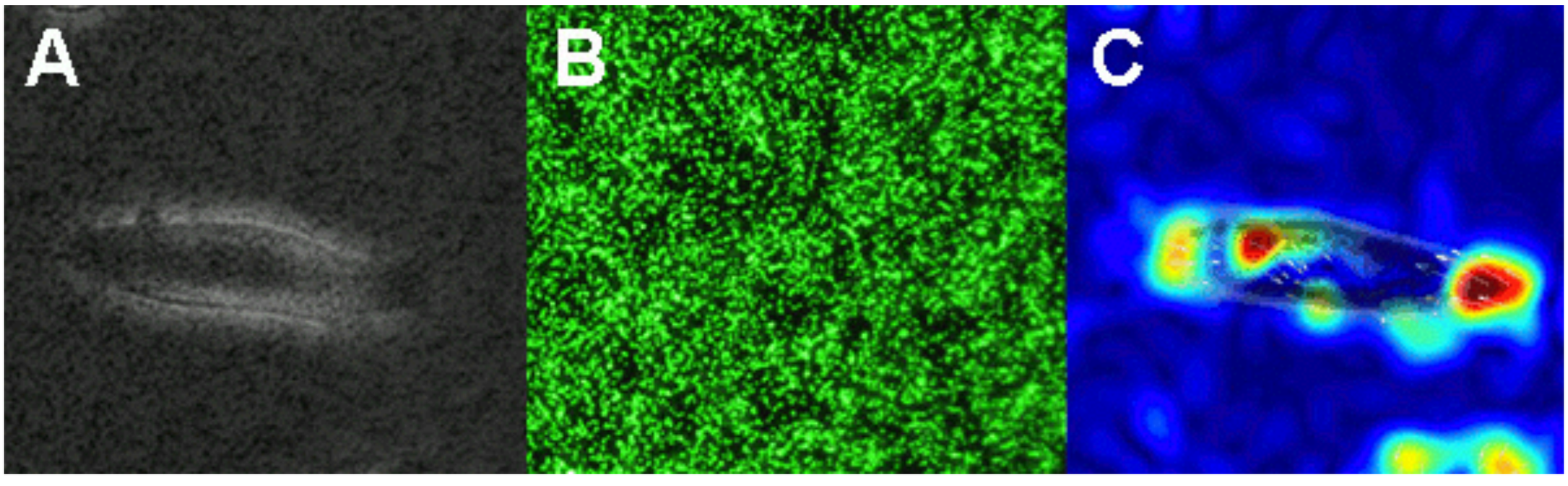
Traction Forces/Boundary Stresses





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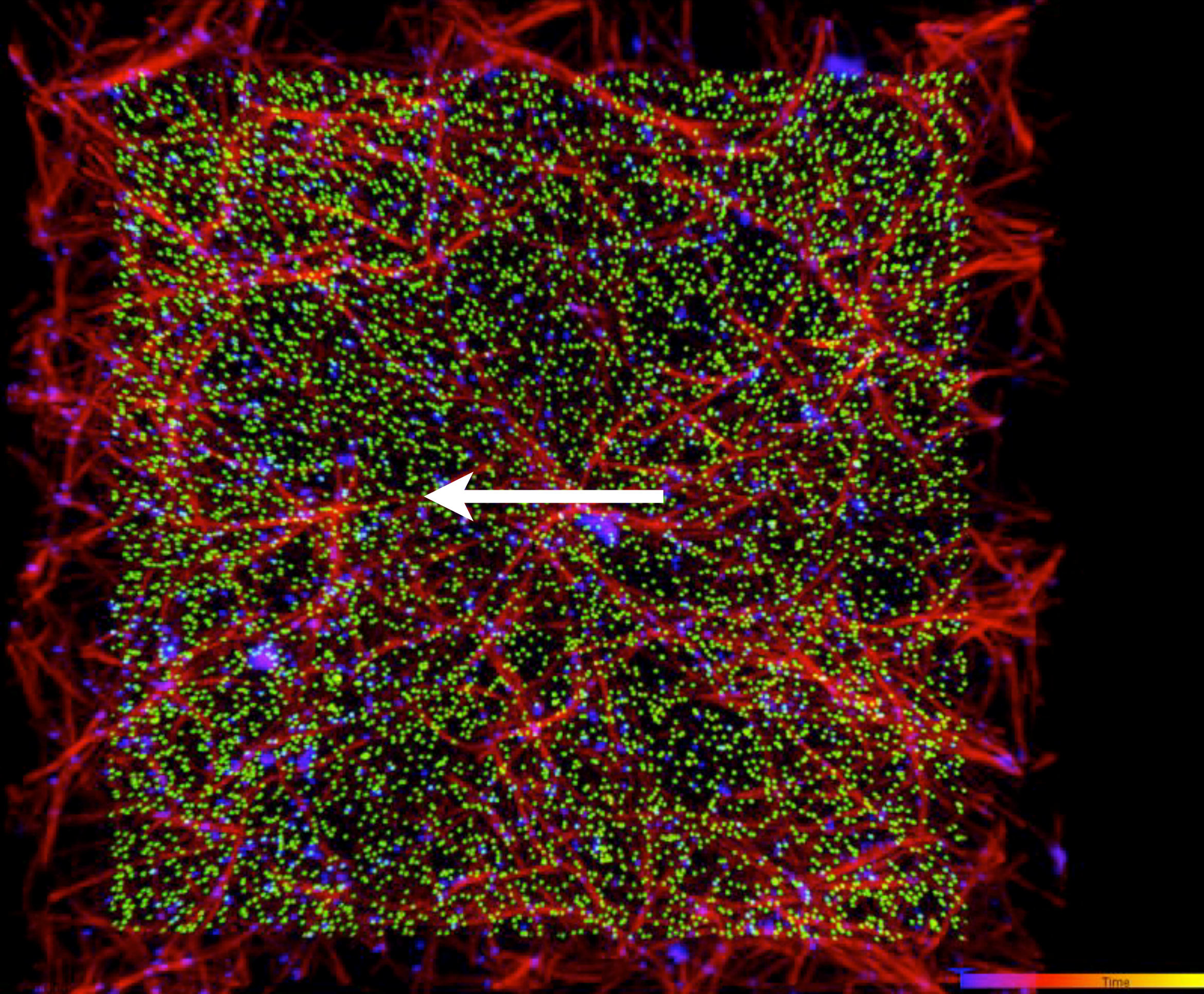
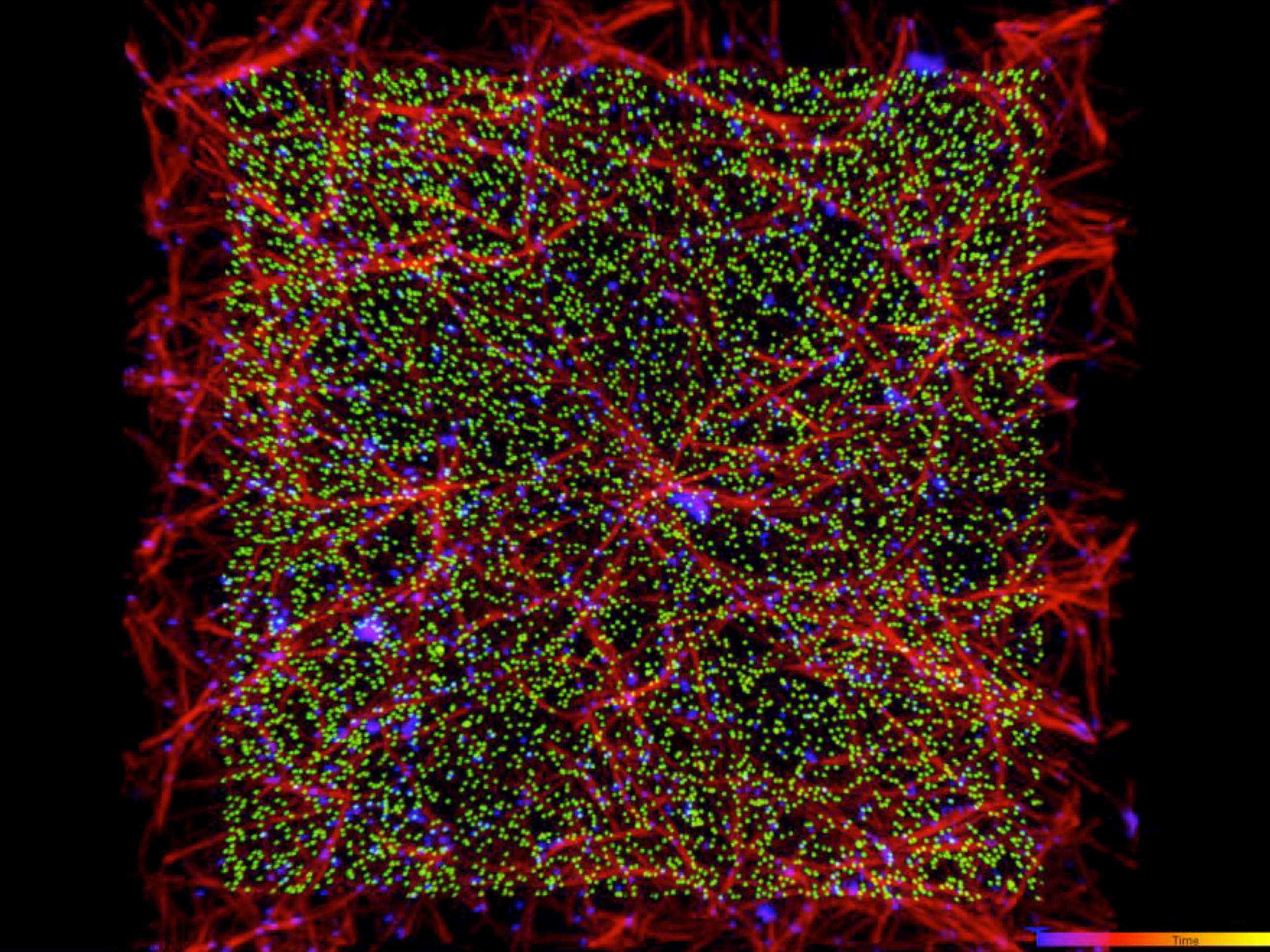
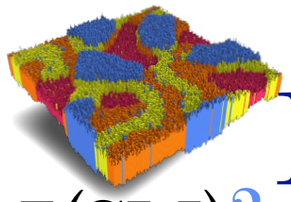
Time


Time


Time


Time



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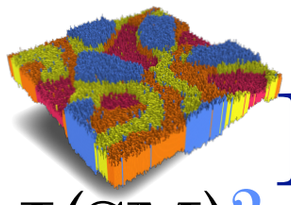
Boundary Stress Microscopy (BSM) For Shear Thickening

arXiv:1702.02068, *PNAS* (on the way)



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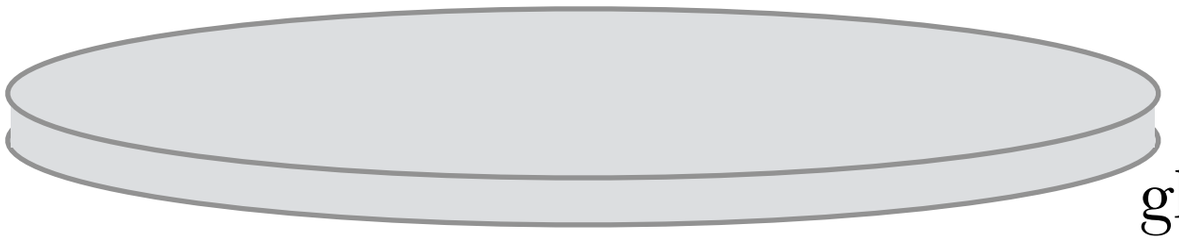

glass coverslip

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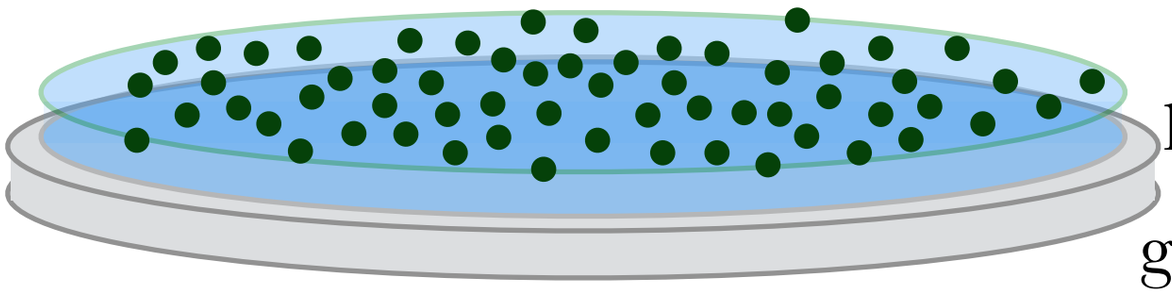

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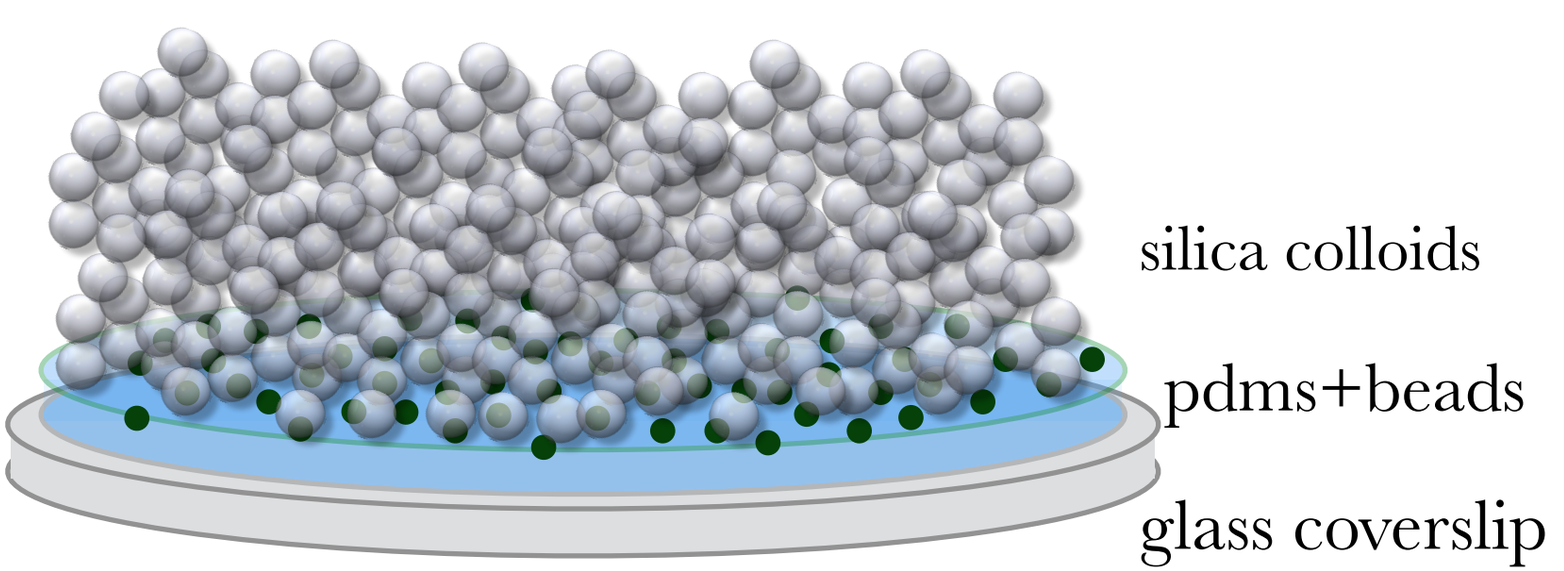

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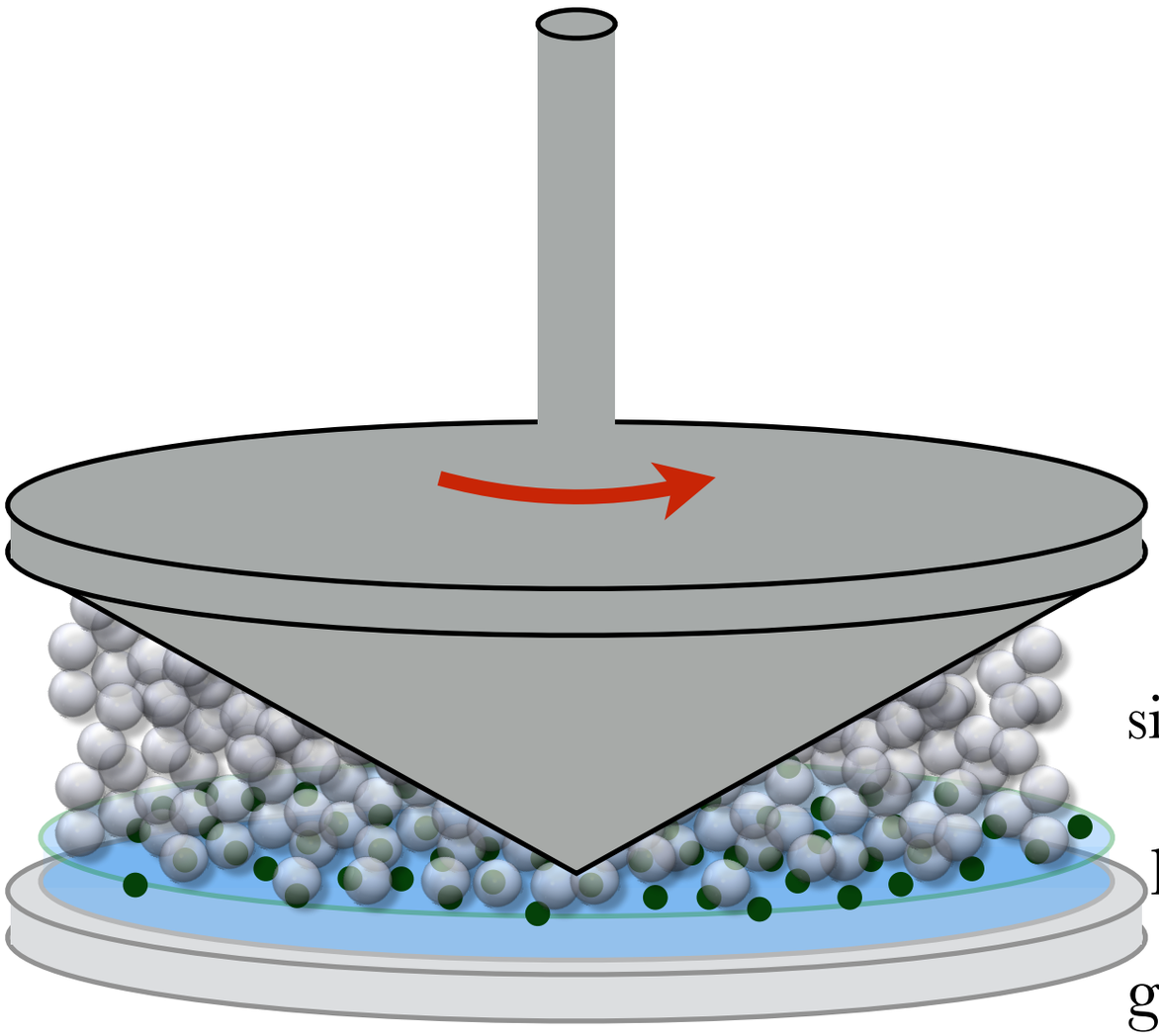

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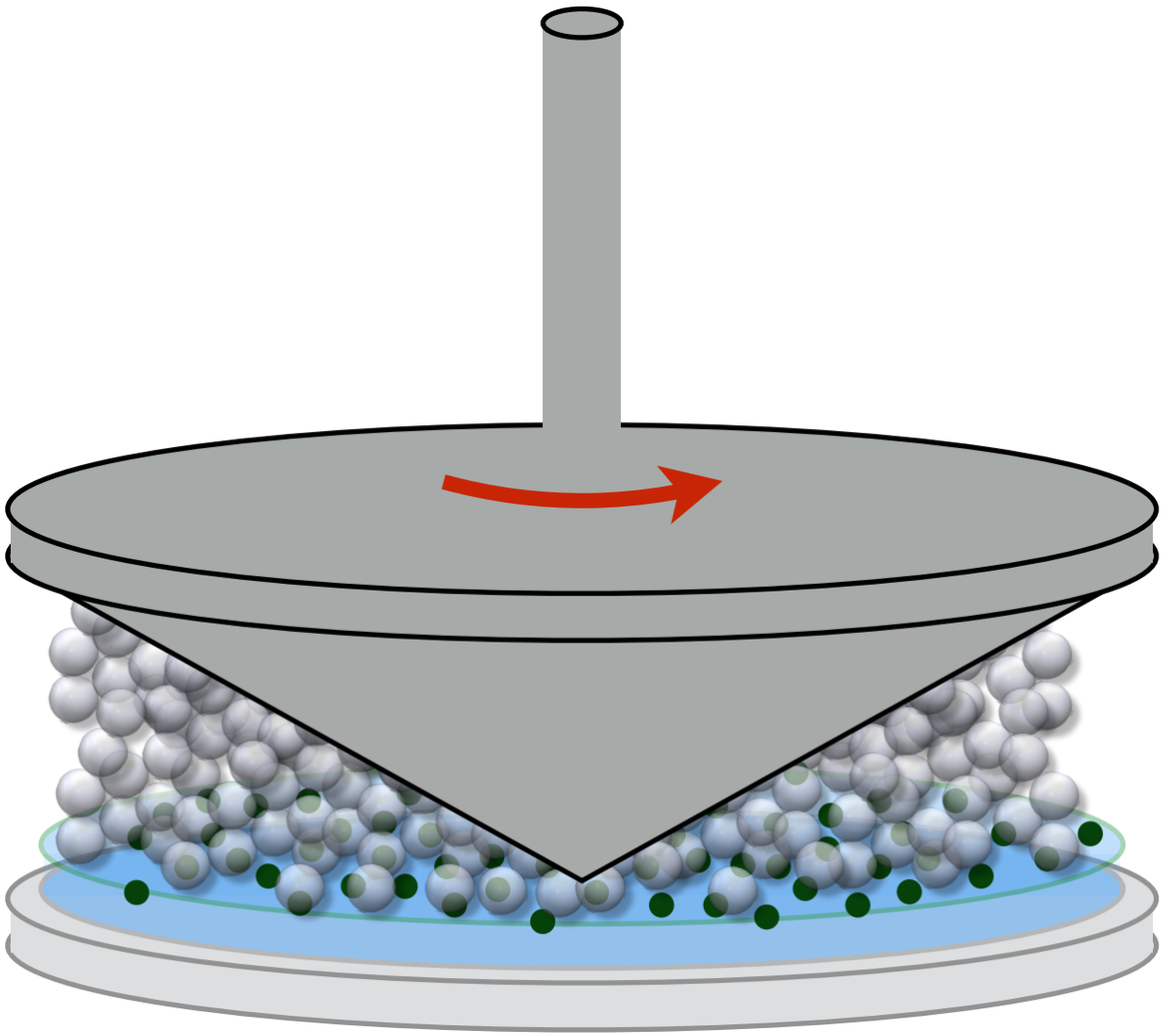

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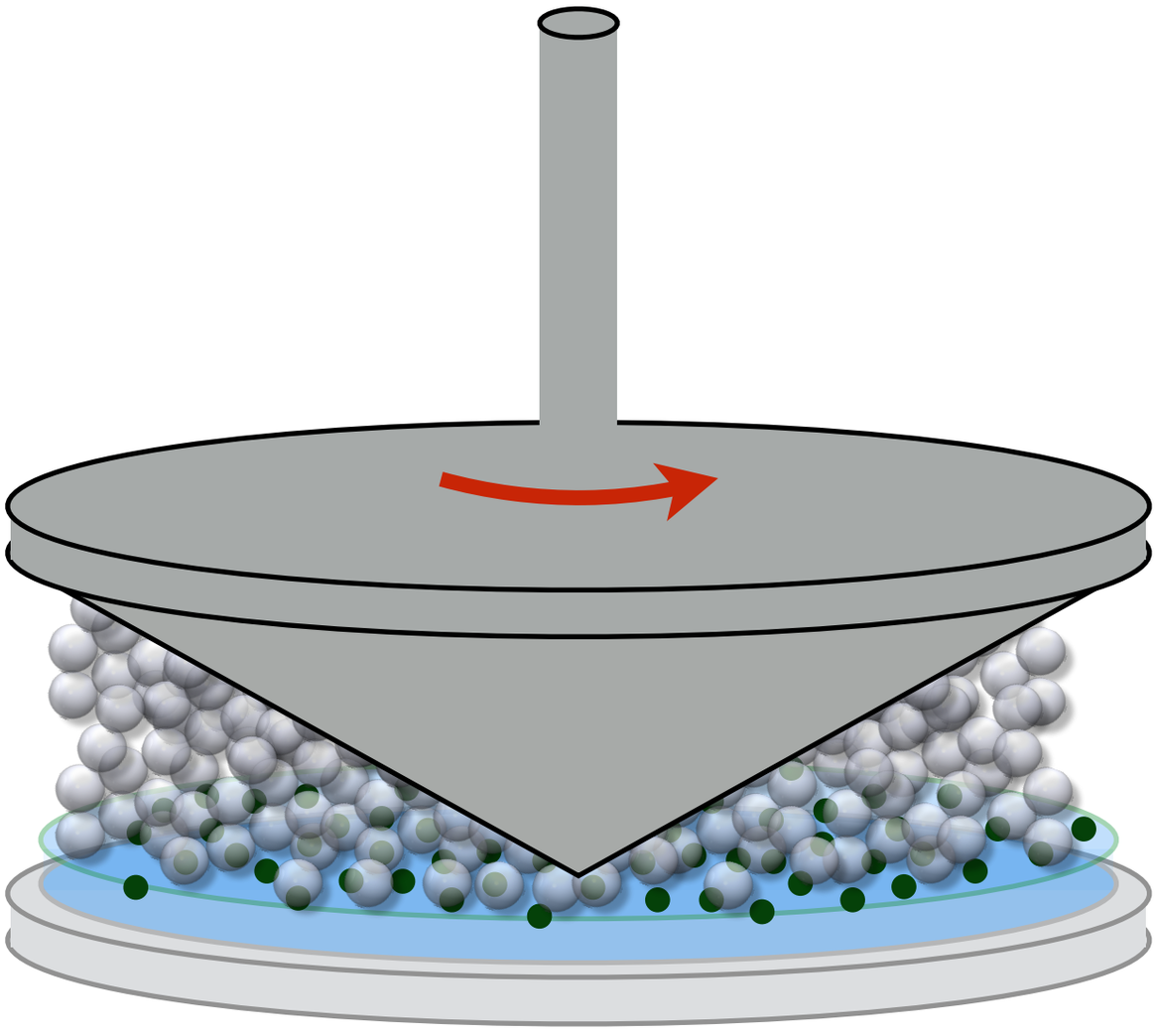

System Details

- Suspension:
  silica — 2a = 0.96 μm
  glycerol/water

- Boundary
  PDMS — Υ = 10 kPa
  markers — 2a = 1.0 μm

arXiv:1702.02068, *PNAS* (on the way)

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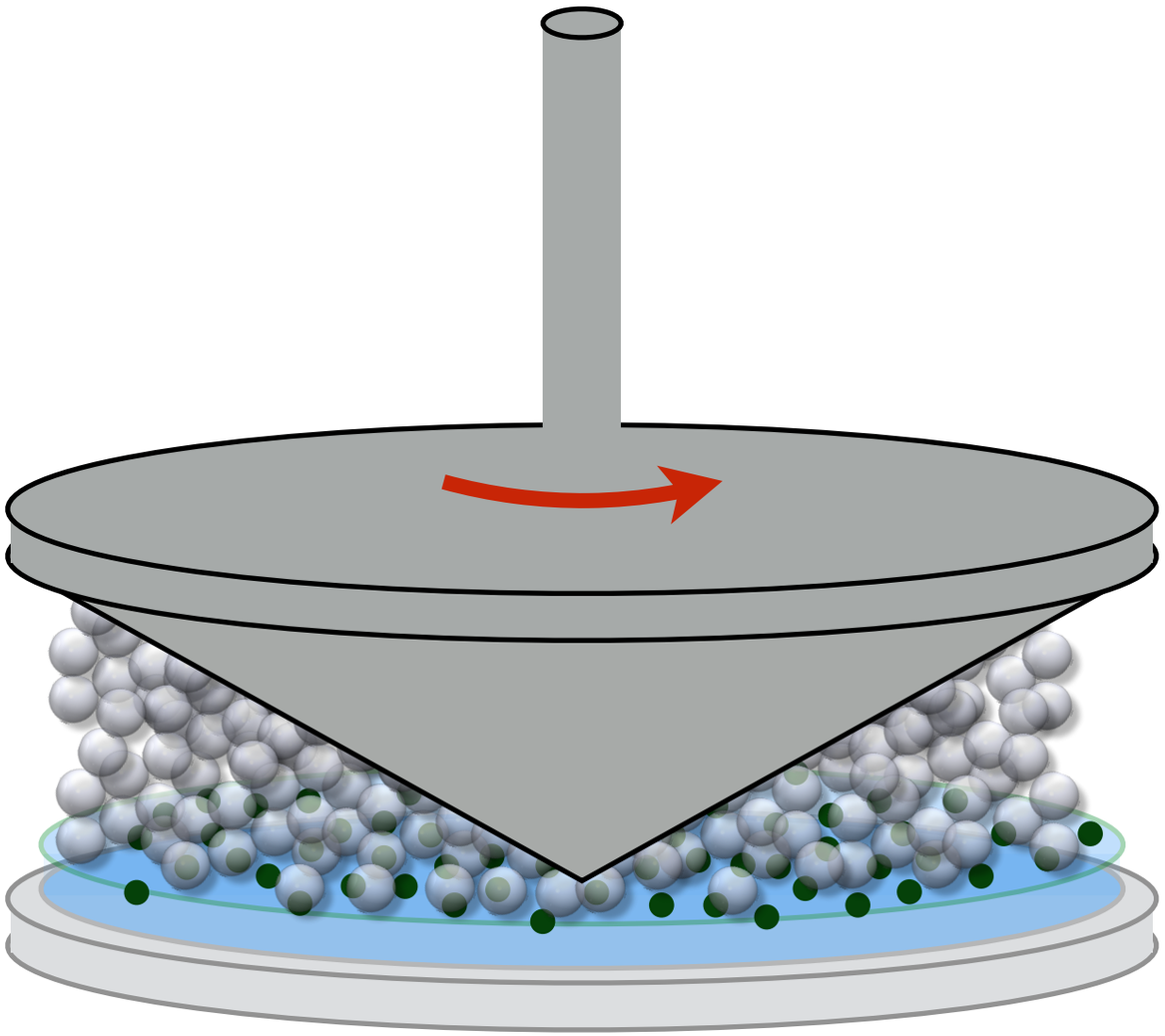
Boundary Stress Microscopy (BSM) For Shear Thickening



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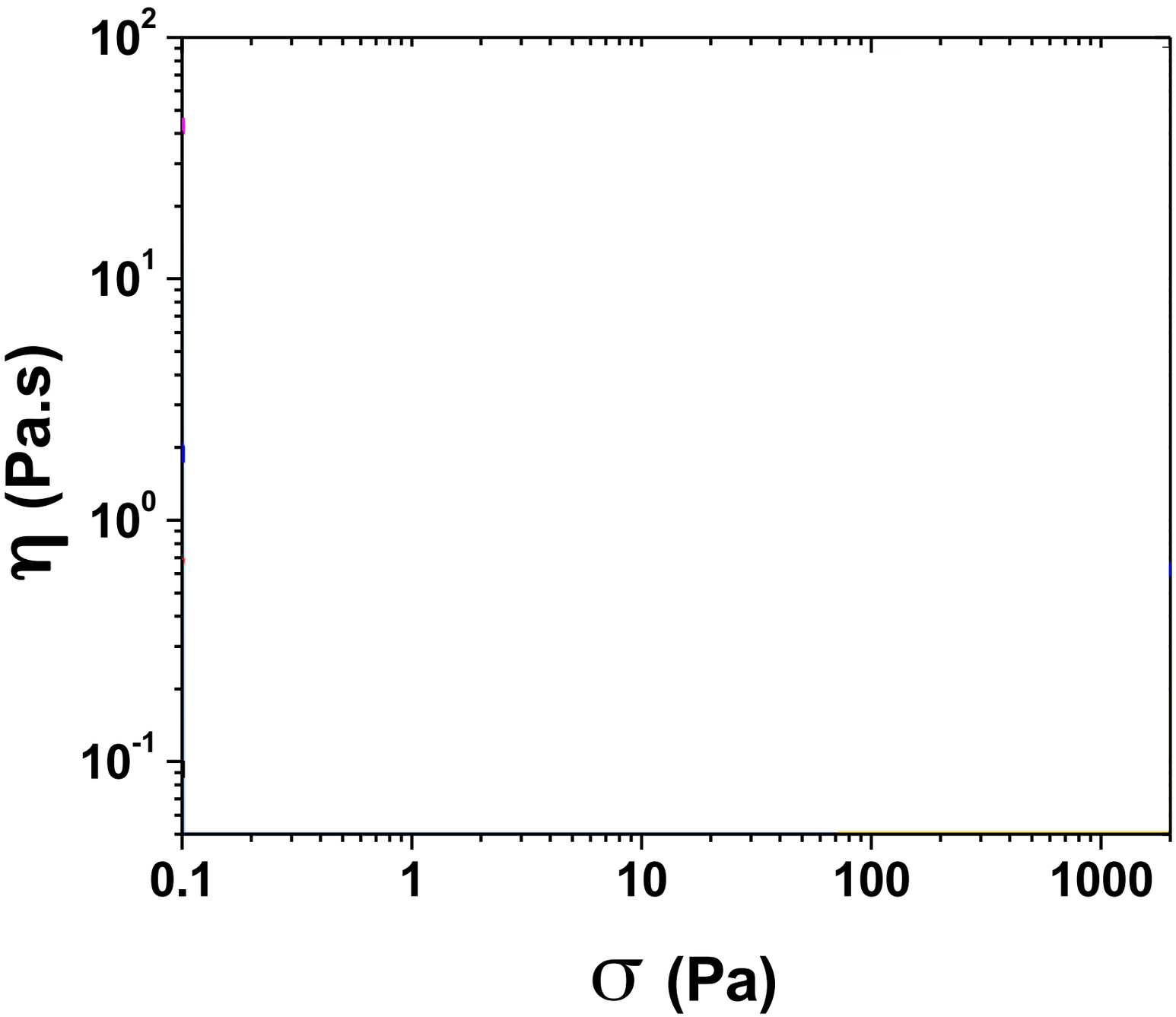
Continuous Shear Thickening Rheology



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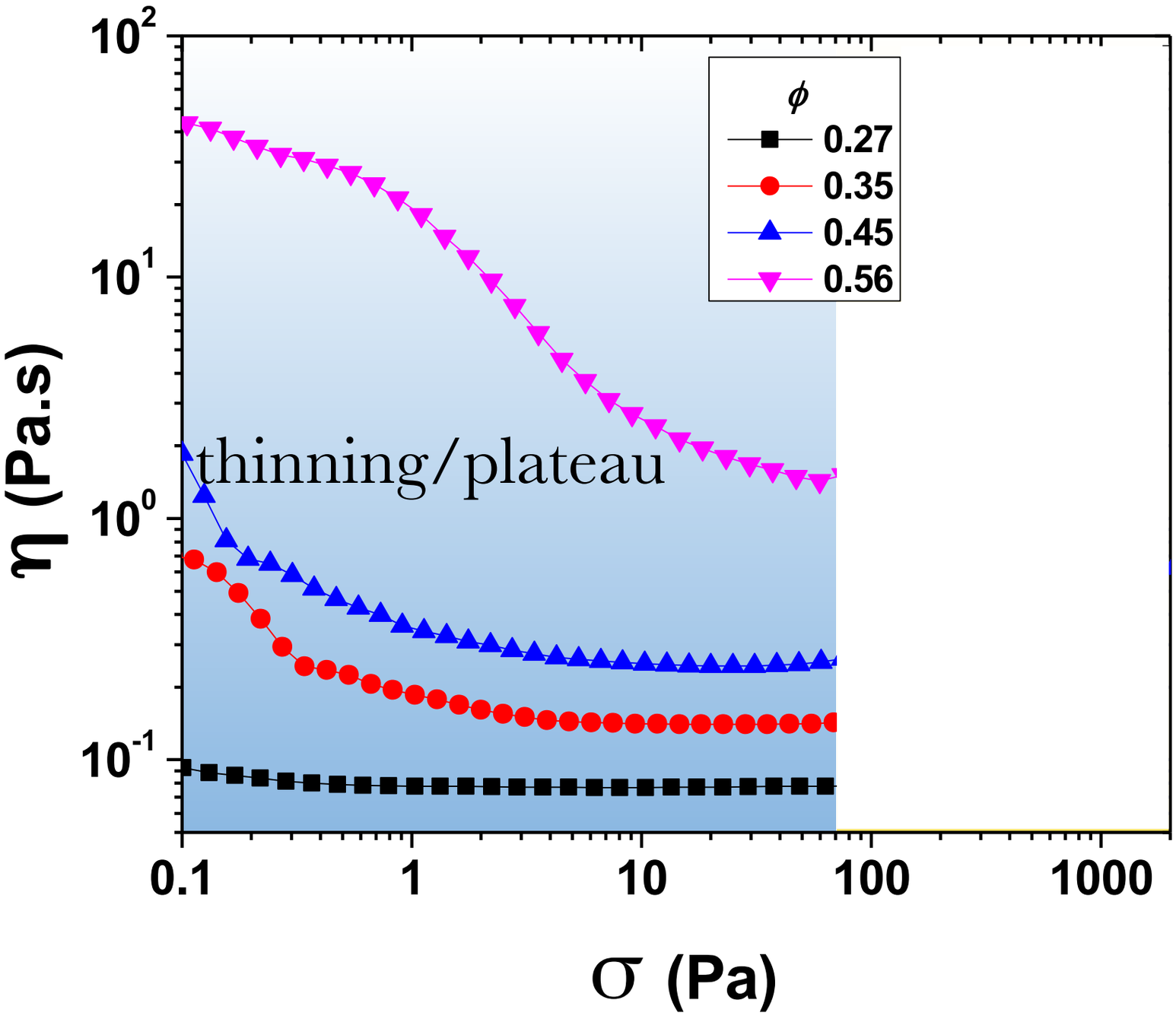

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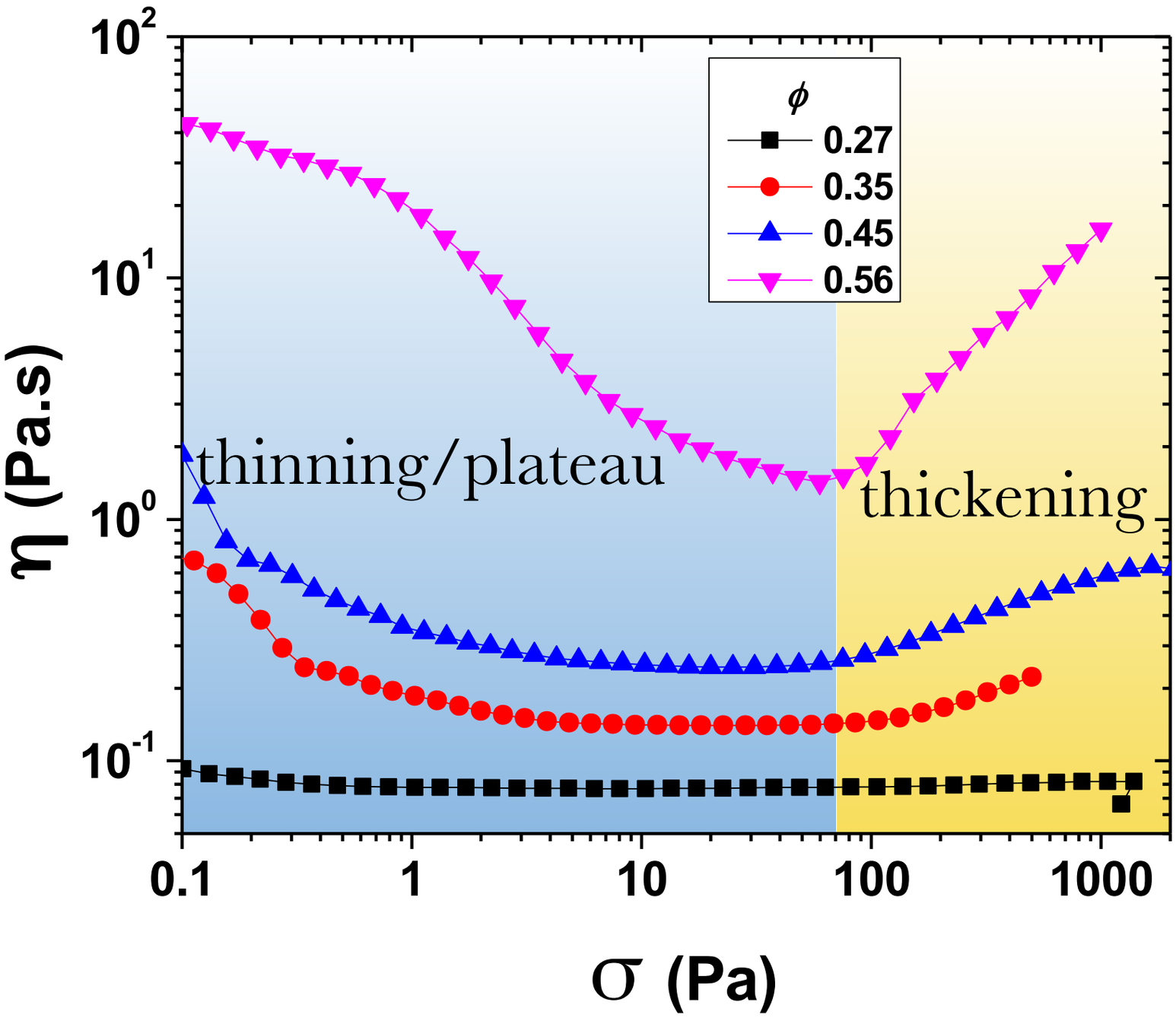

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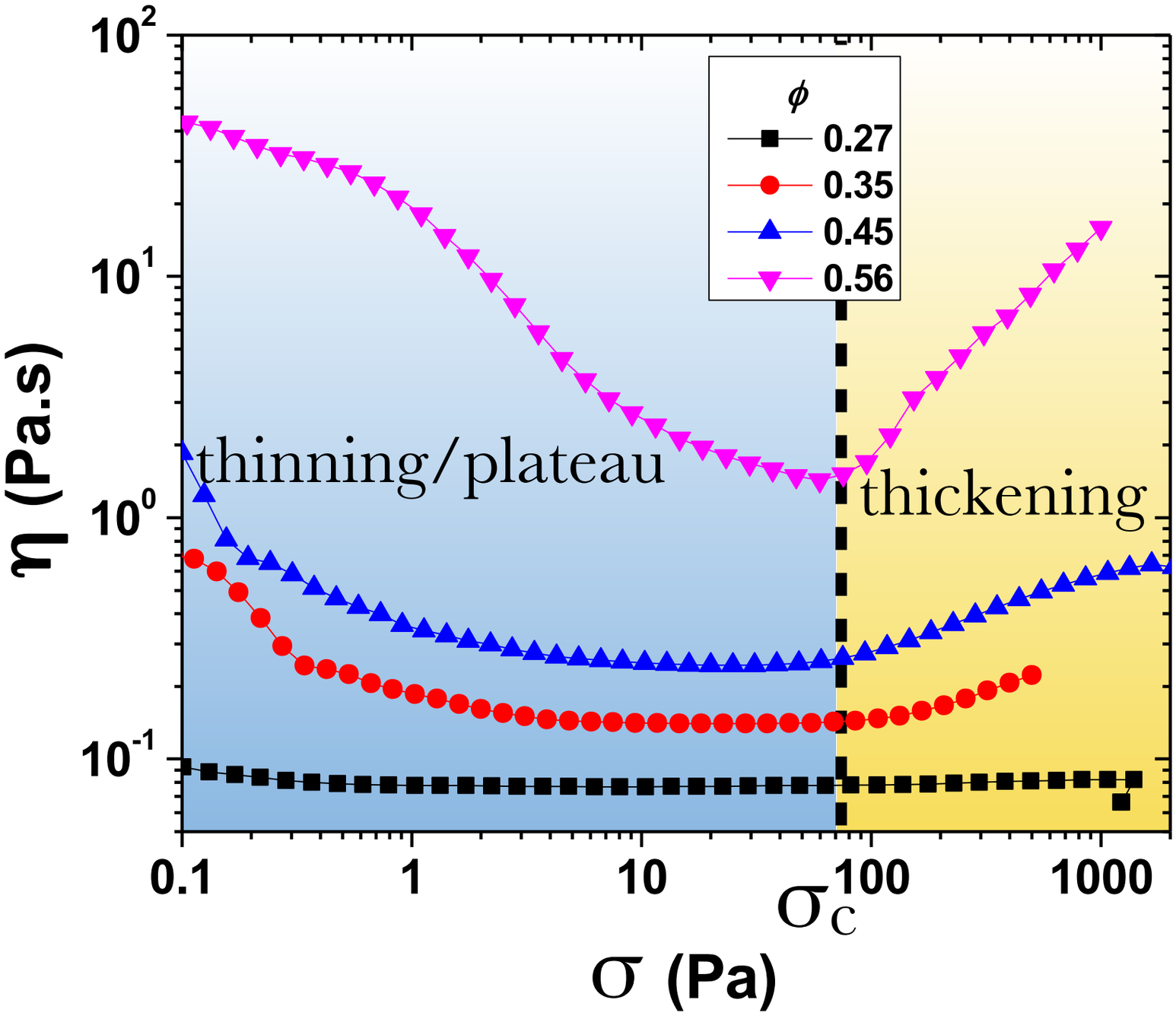
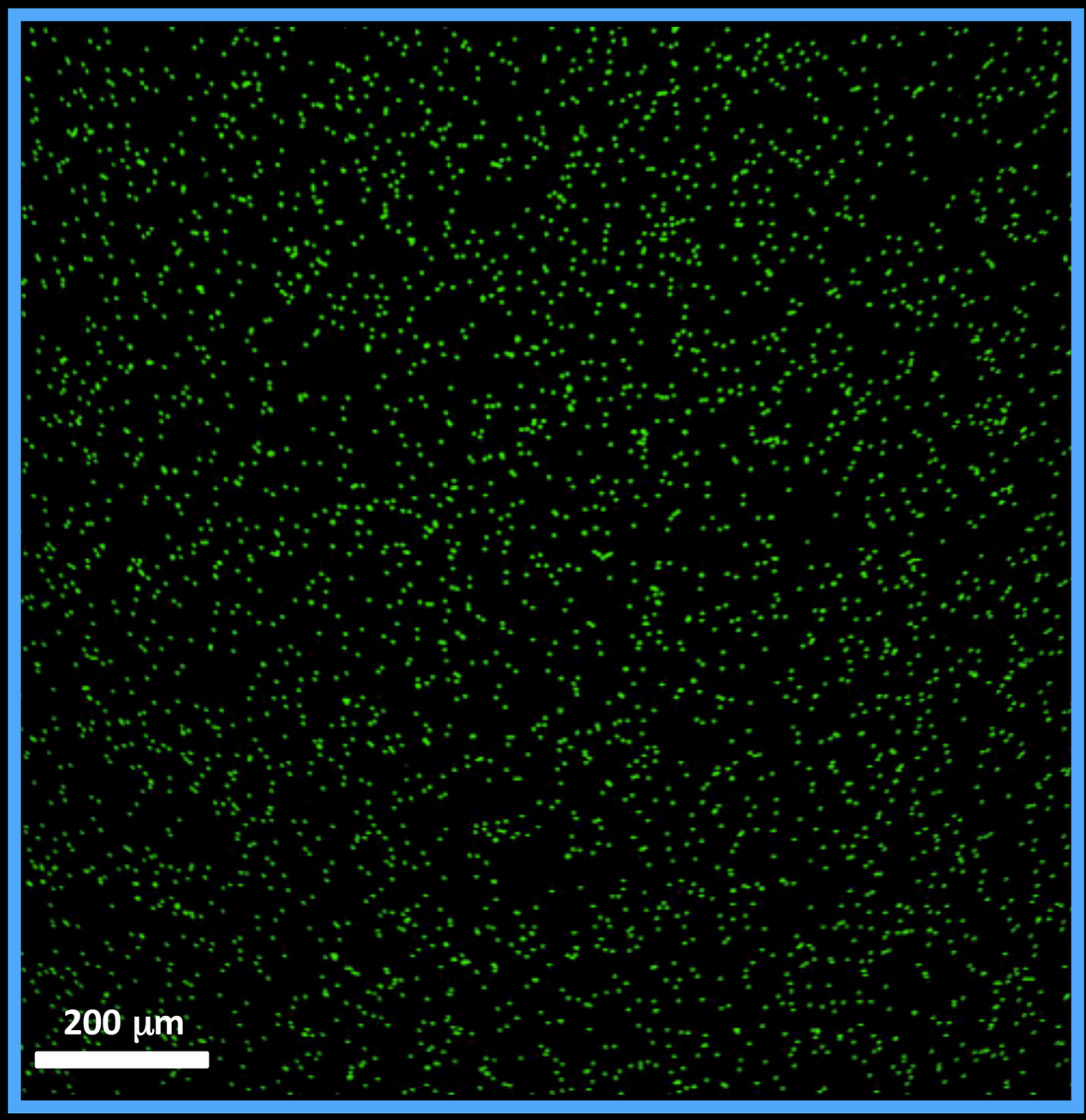
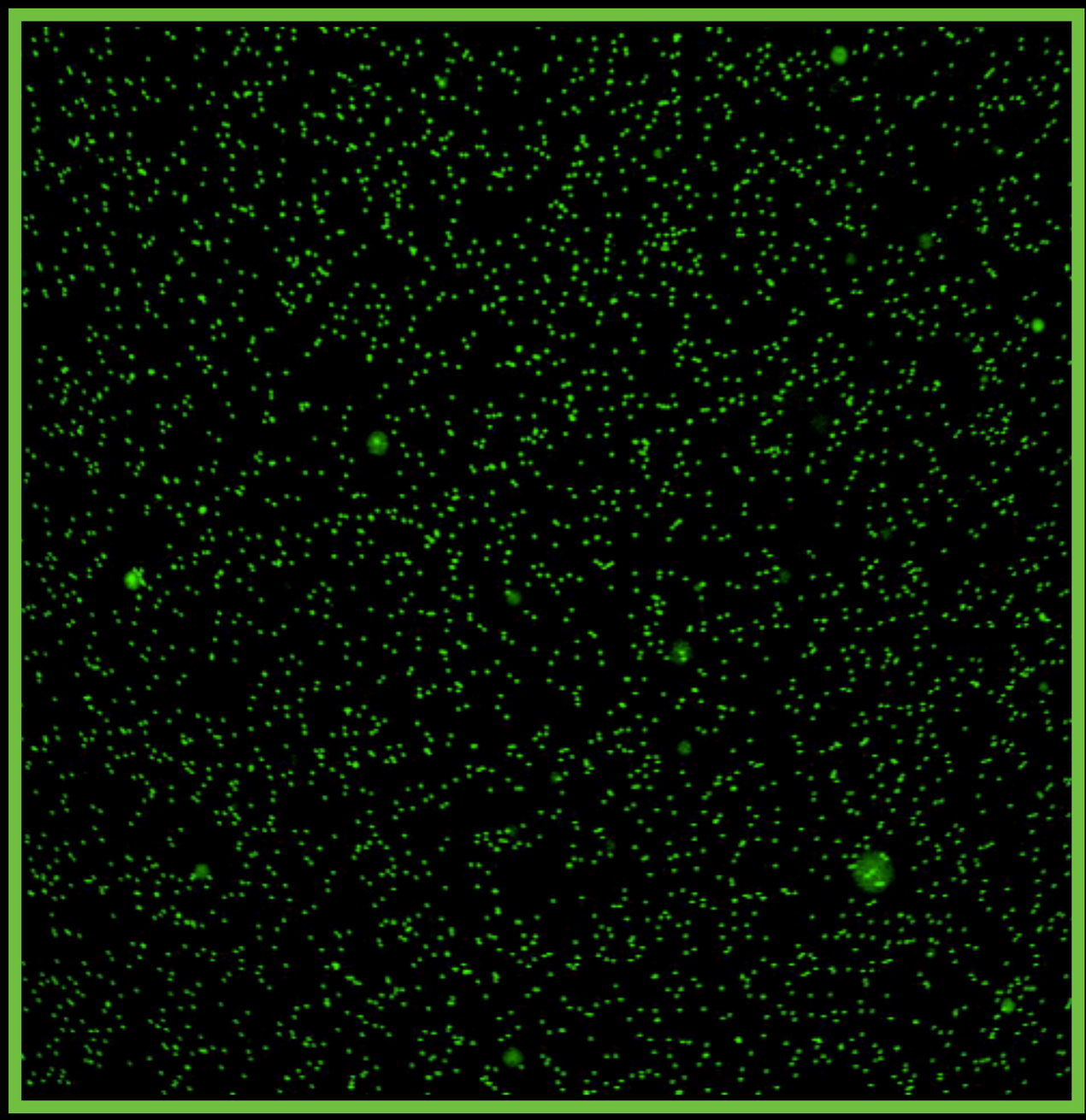


Boundary Stresses: $\phi = 56\%$

Displacements





$\sigma = 100$ Pa

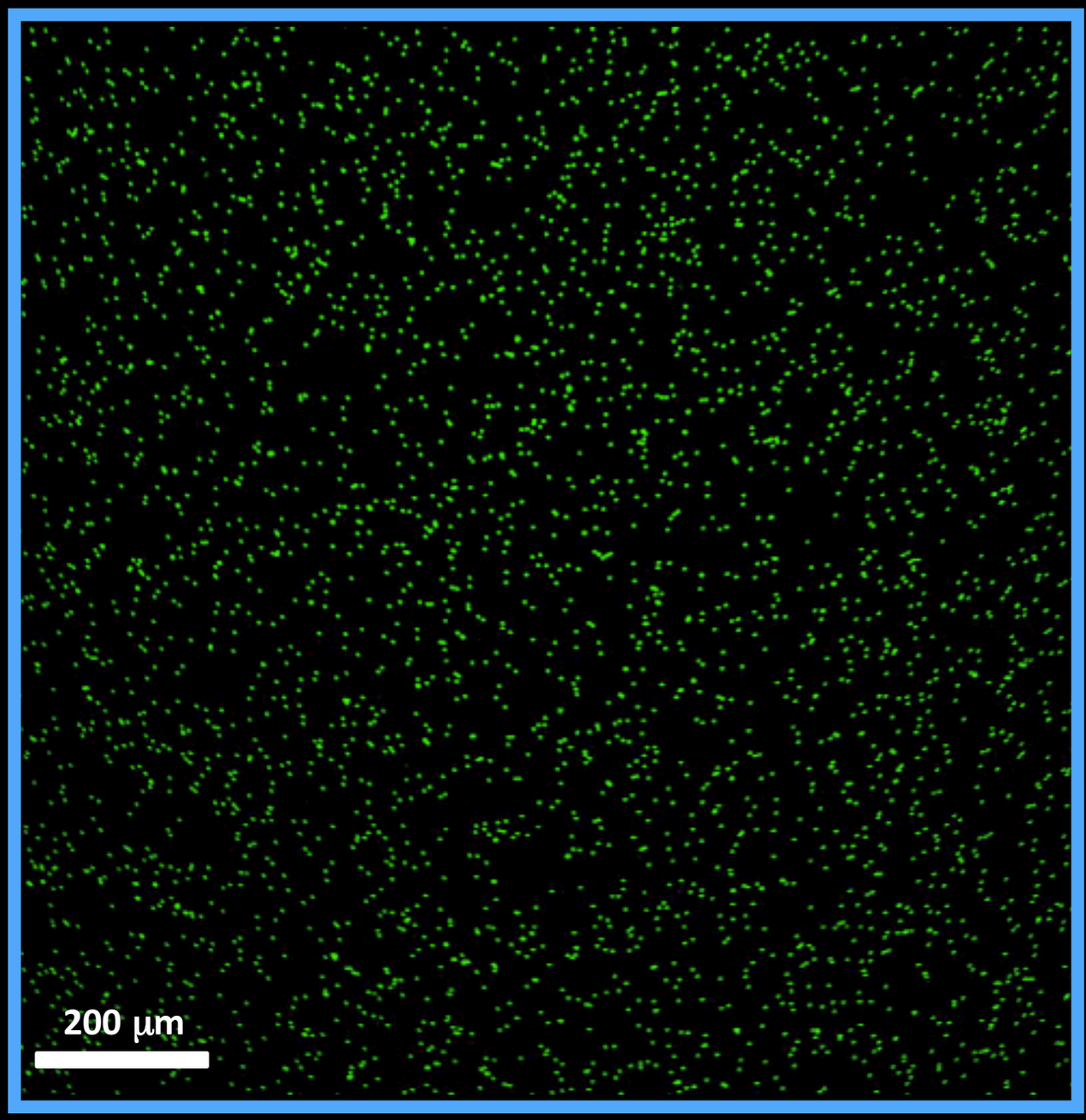
$\sigma = 1000$ Pa

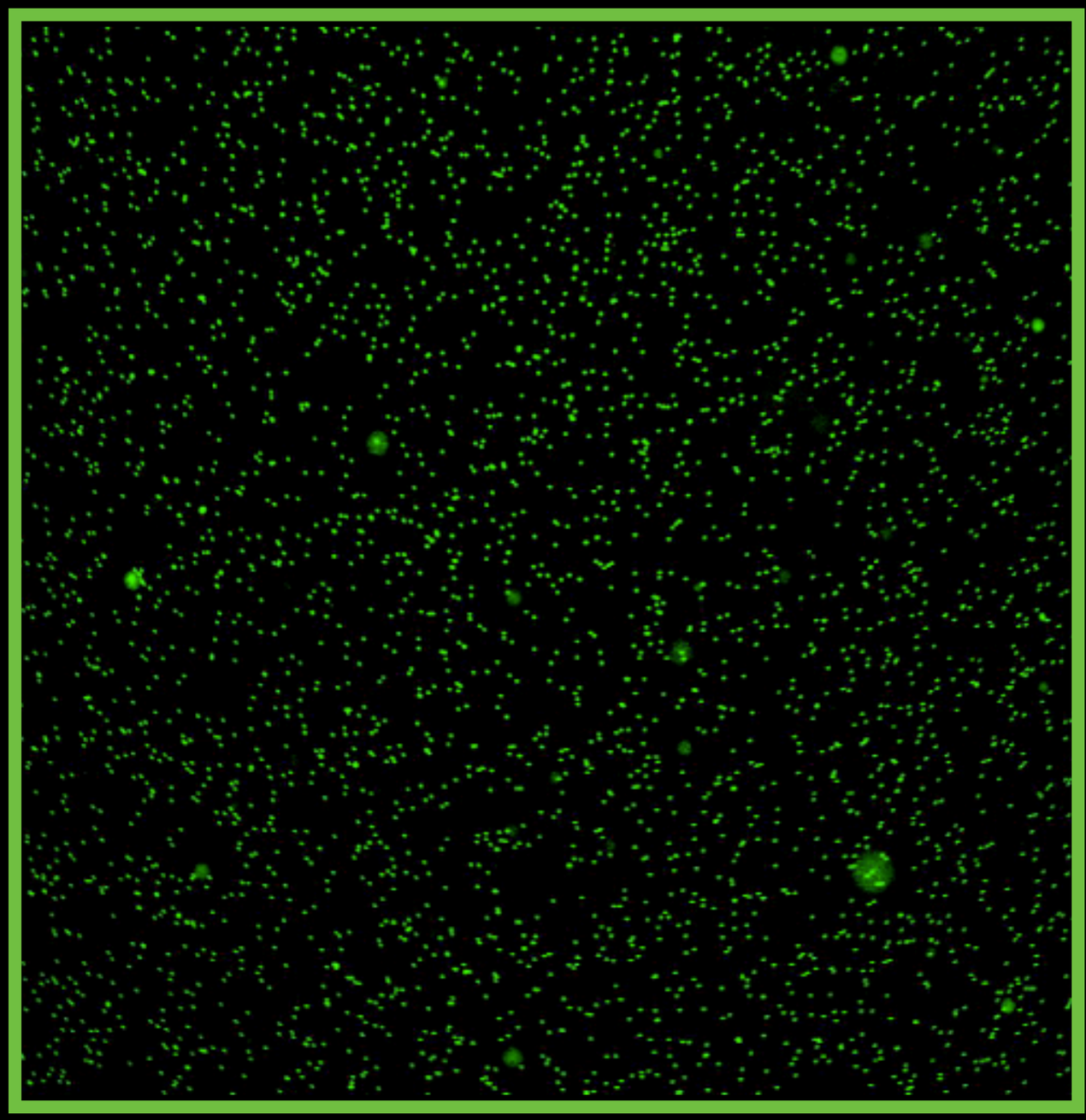
vorticity

velocity

Boundary Stresses: $\phi = 56\%$

Displacements





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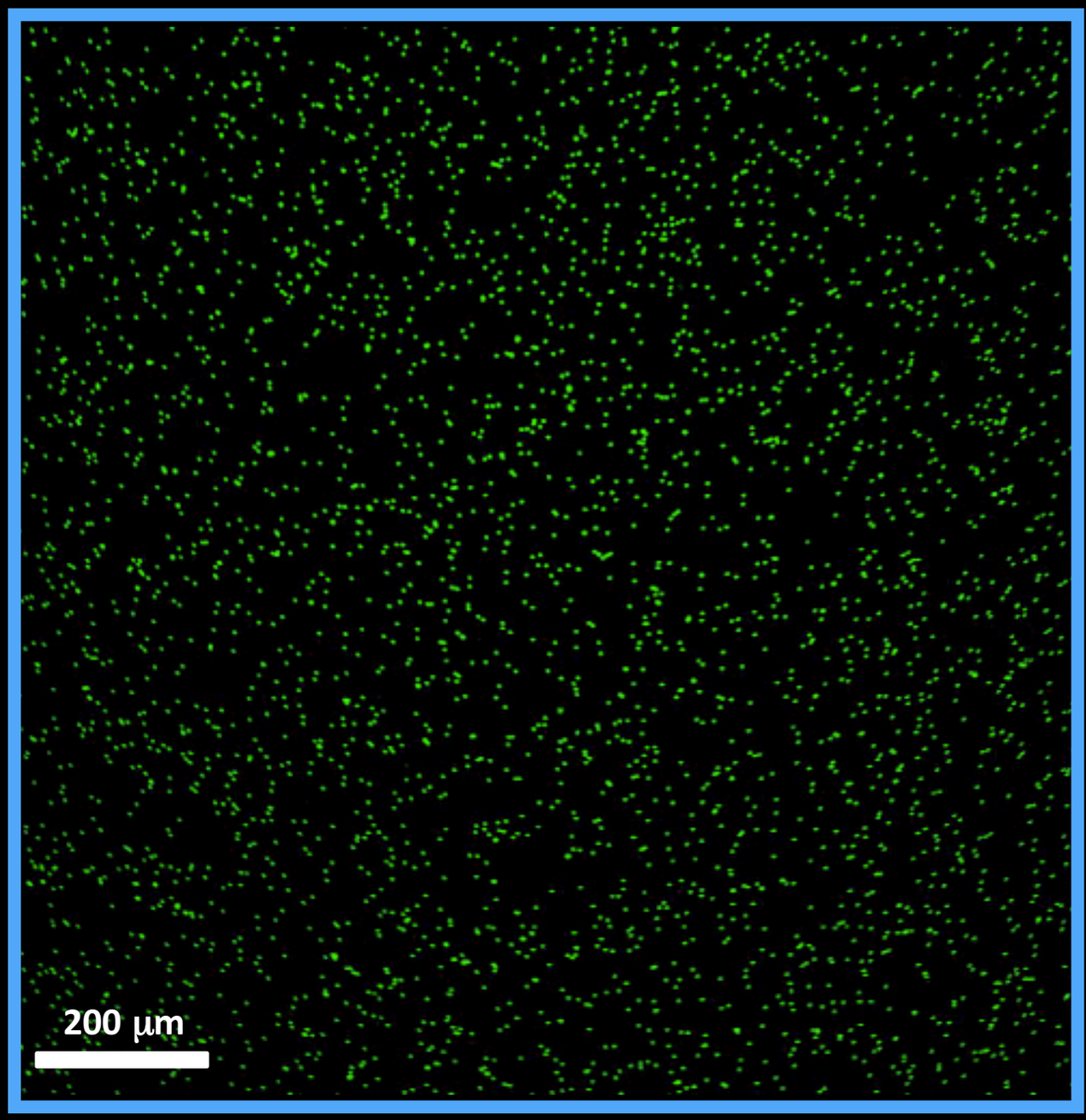

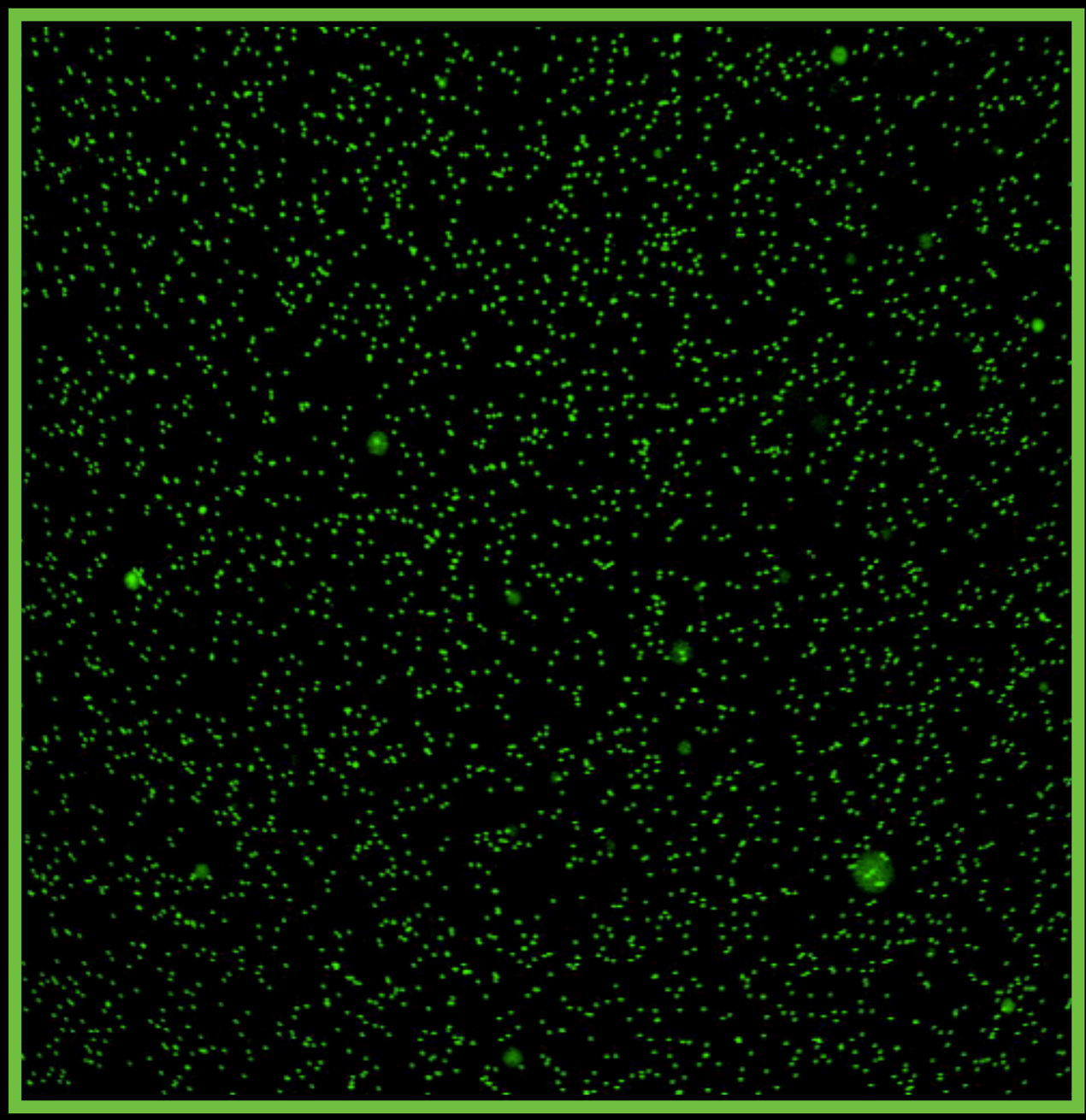

$\sigma = 100$ Pa

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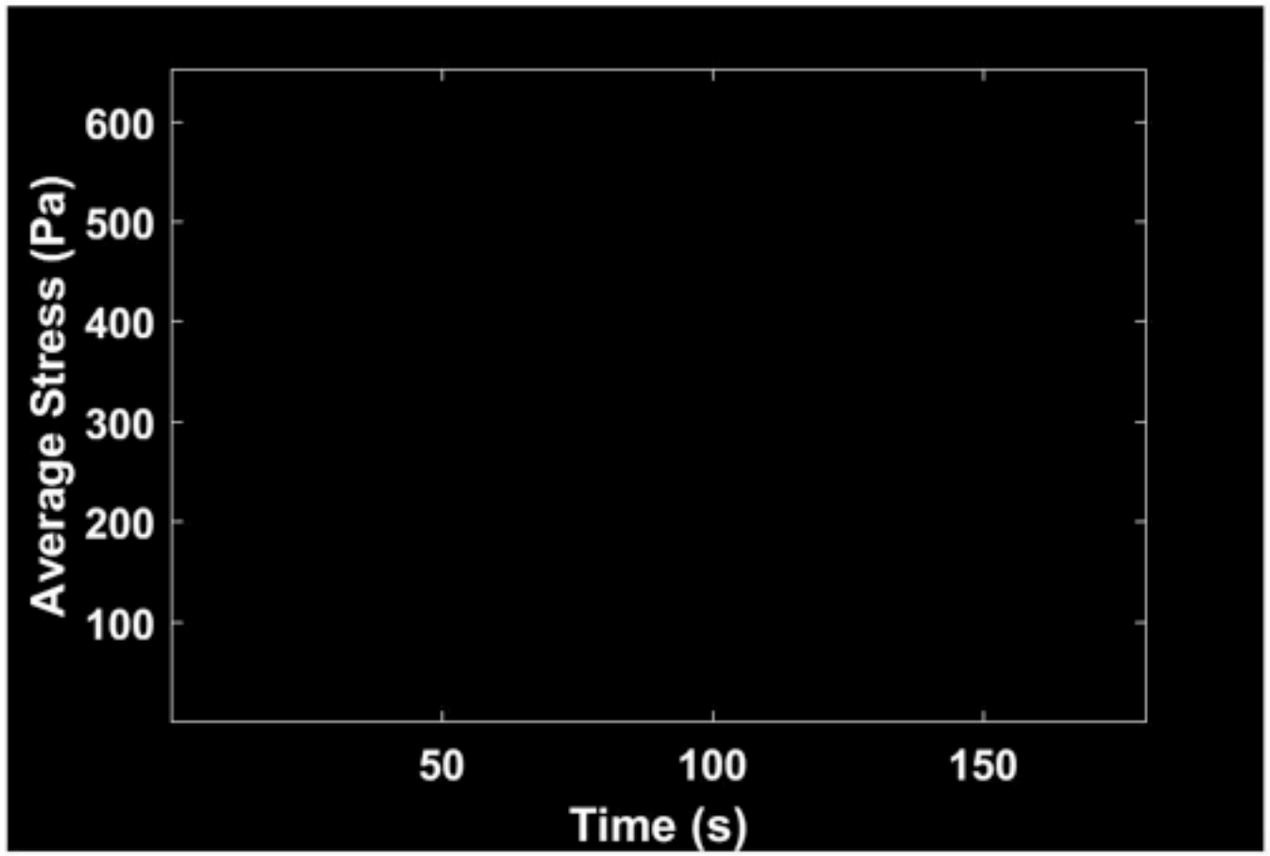
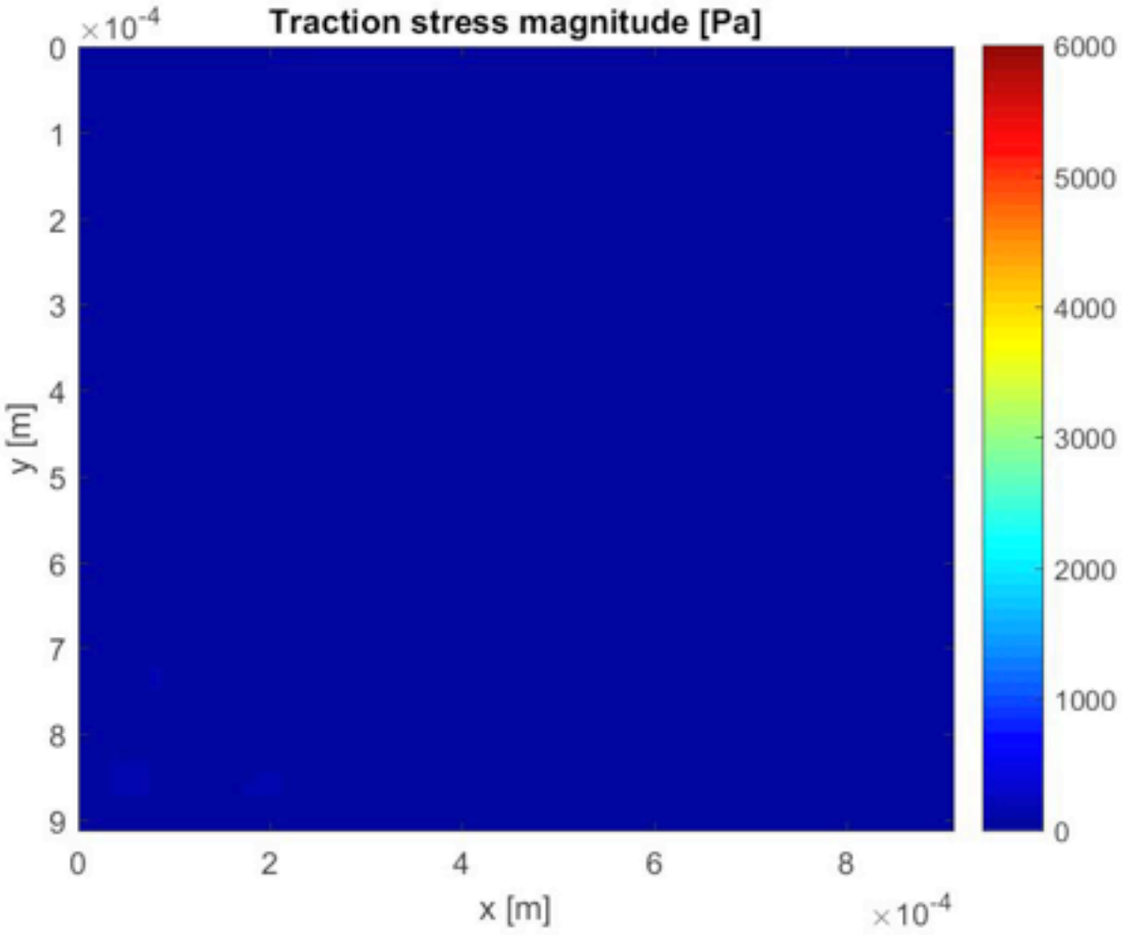
vorticity

velocity

Boundary Stresses: $\phi = 56\%$

Stress at the Interface

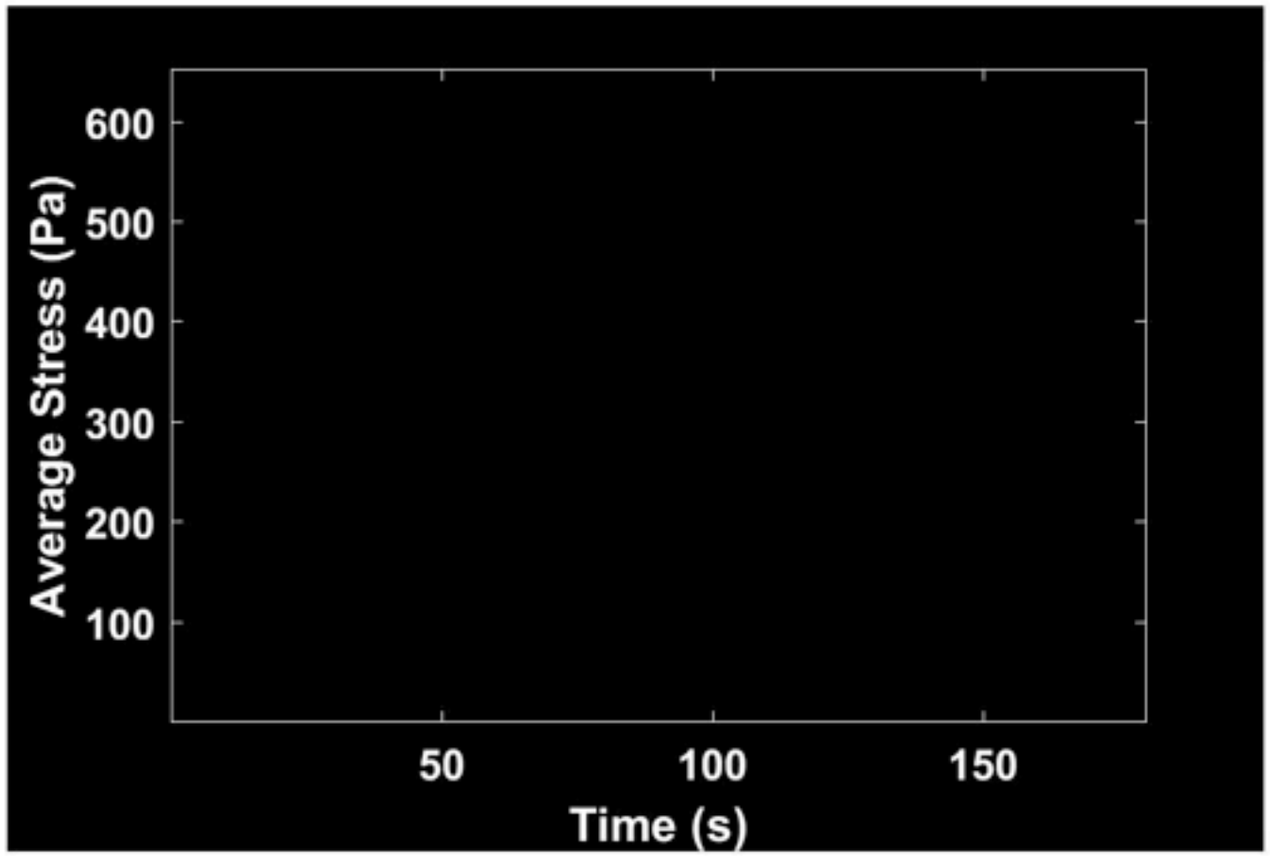


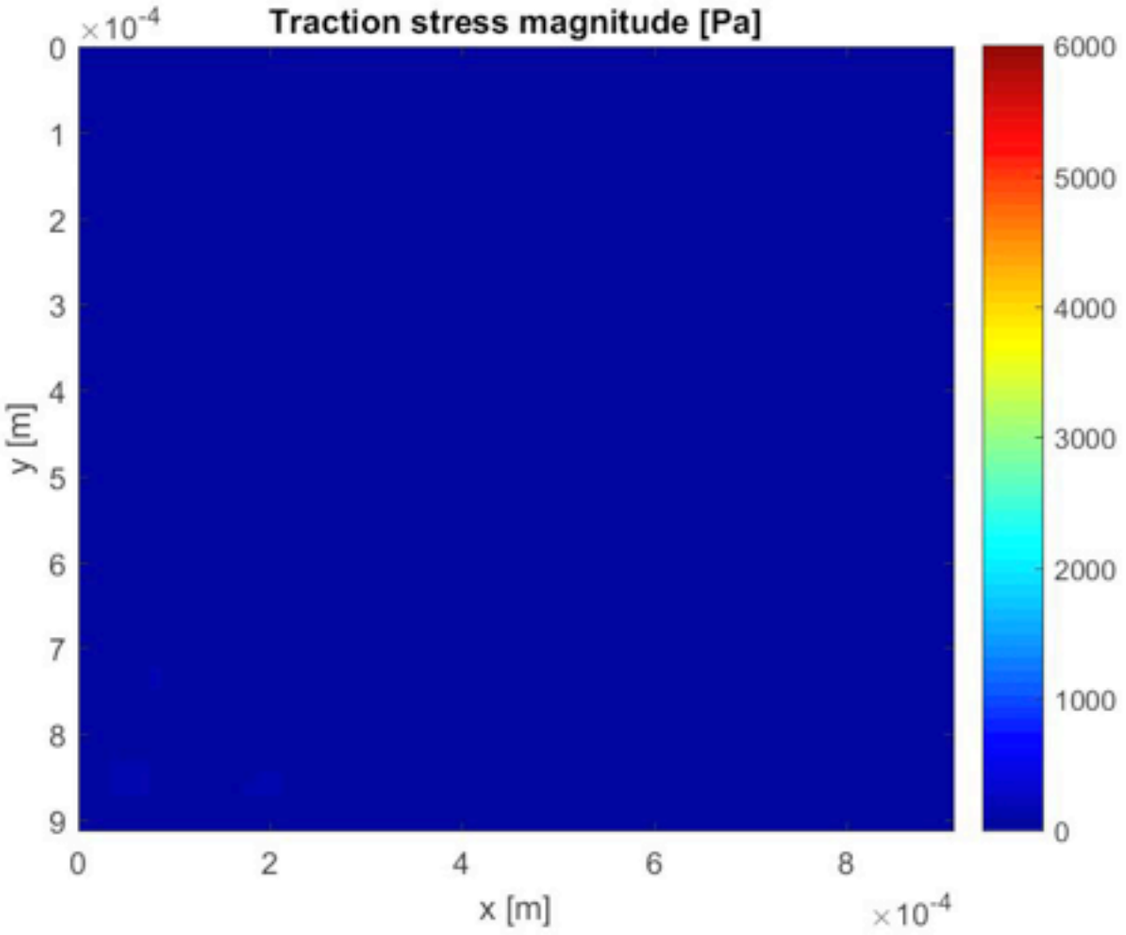


Applied Stress: $\sigma = 100$ Pa

Boundary Stresses: $\phi = 56\%$

Stress at the Interface





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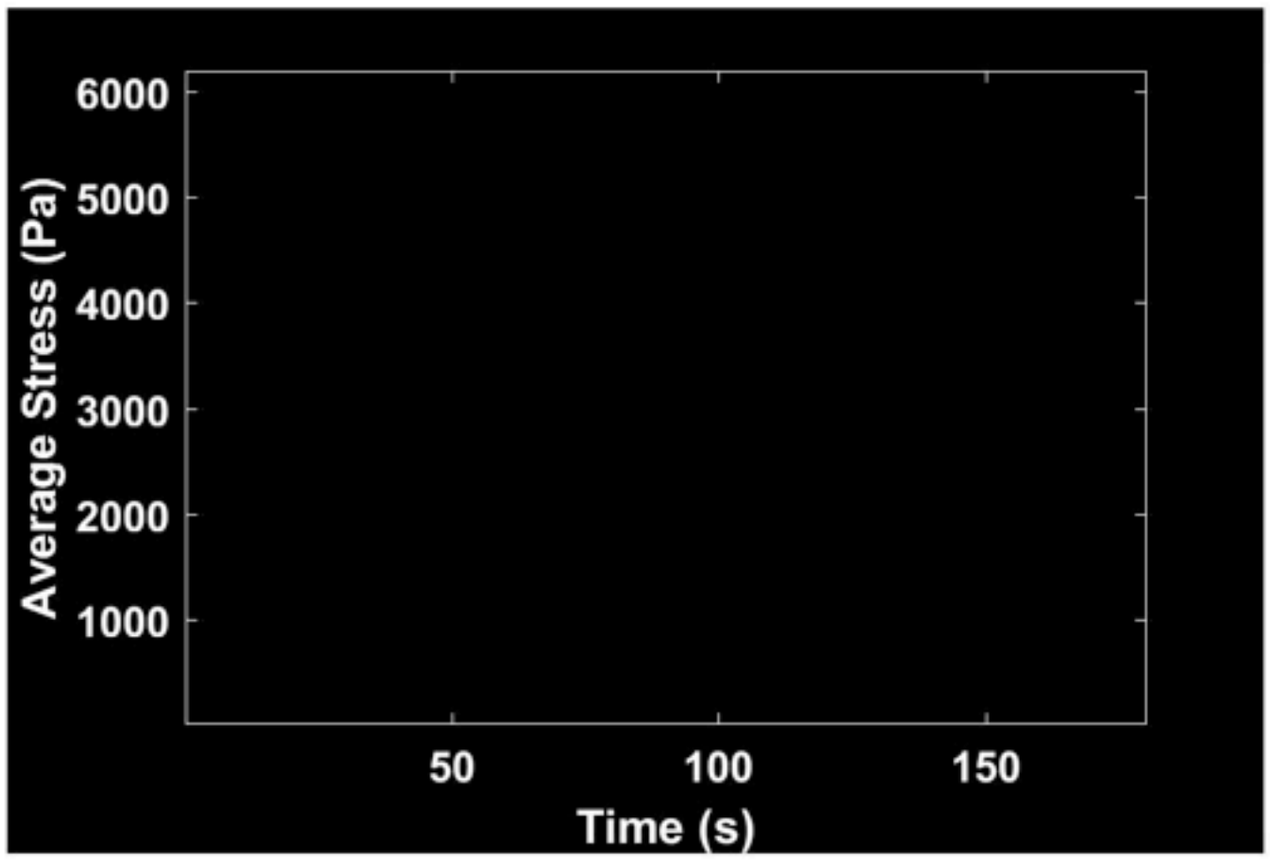

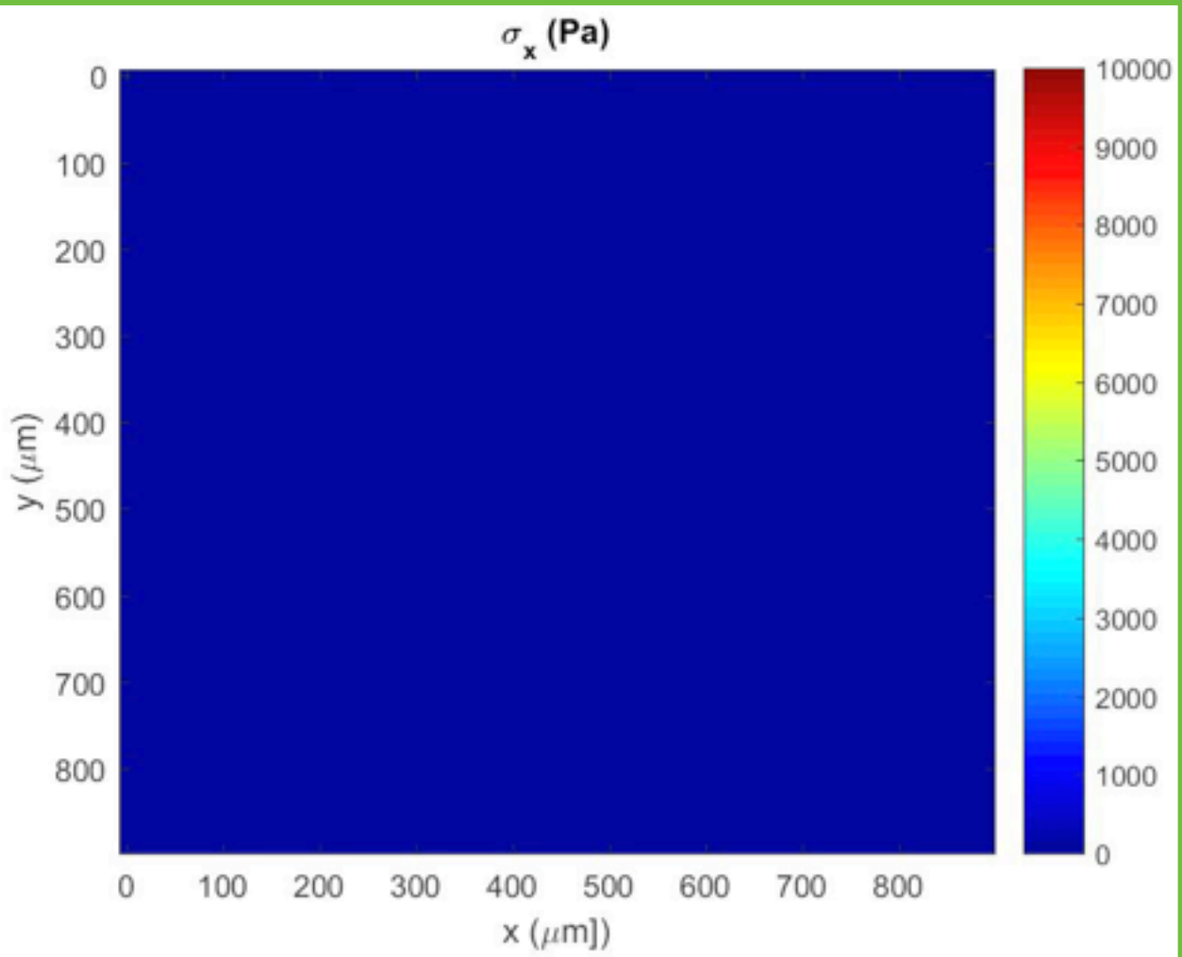

Applied Stress: $\sigma = 1000$ Pa

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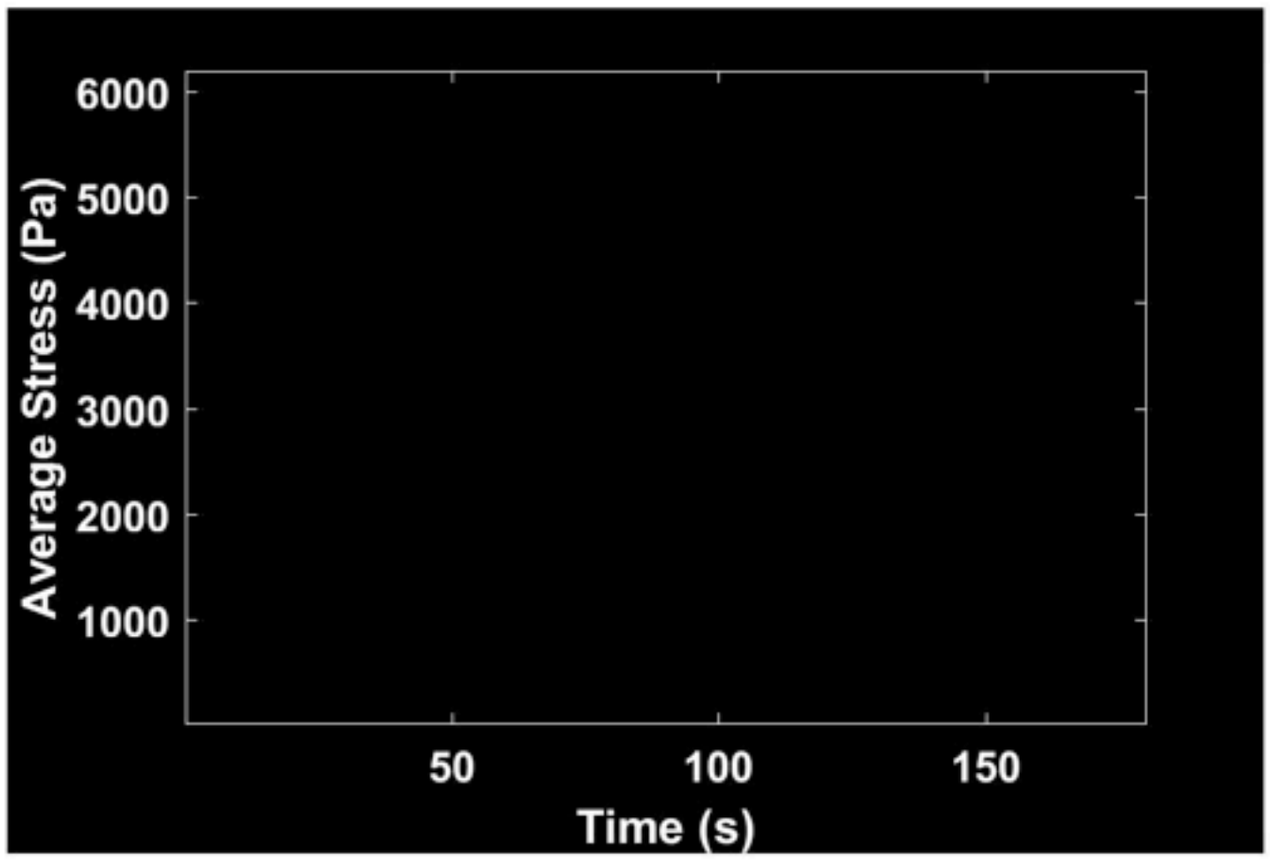
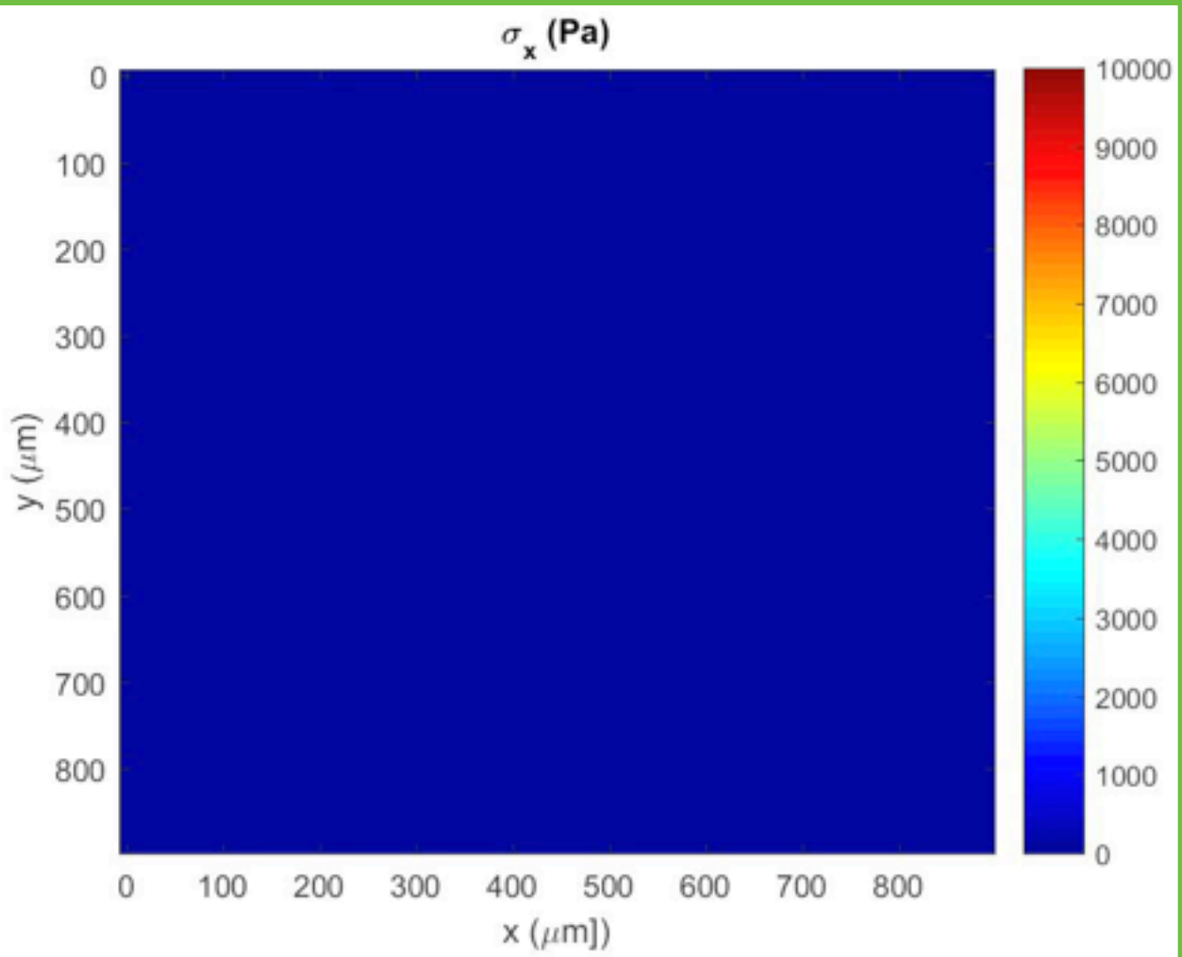


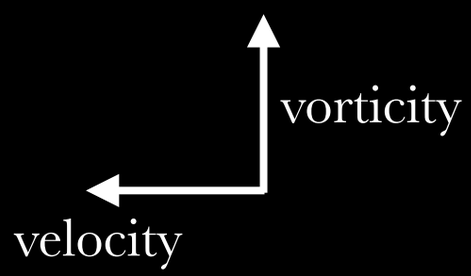


Applied Stress: $\sigma = 1000$ Pa

Boundary Stresses: $\phi = 56\%$

Stress Fields

$\sigma = 100$ Pa



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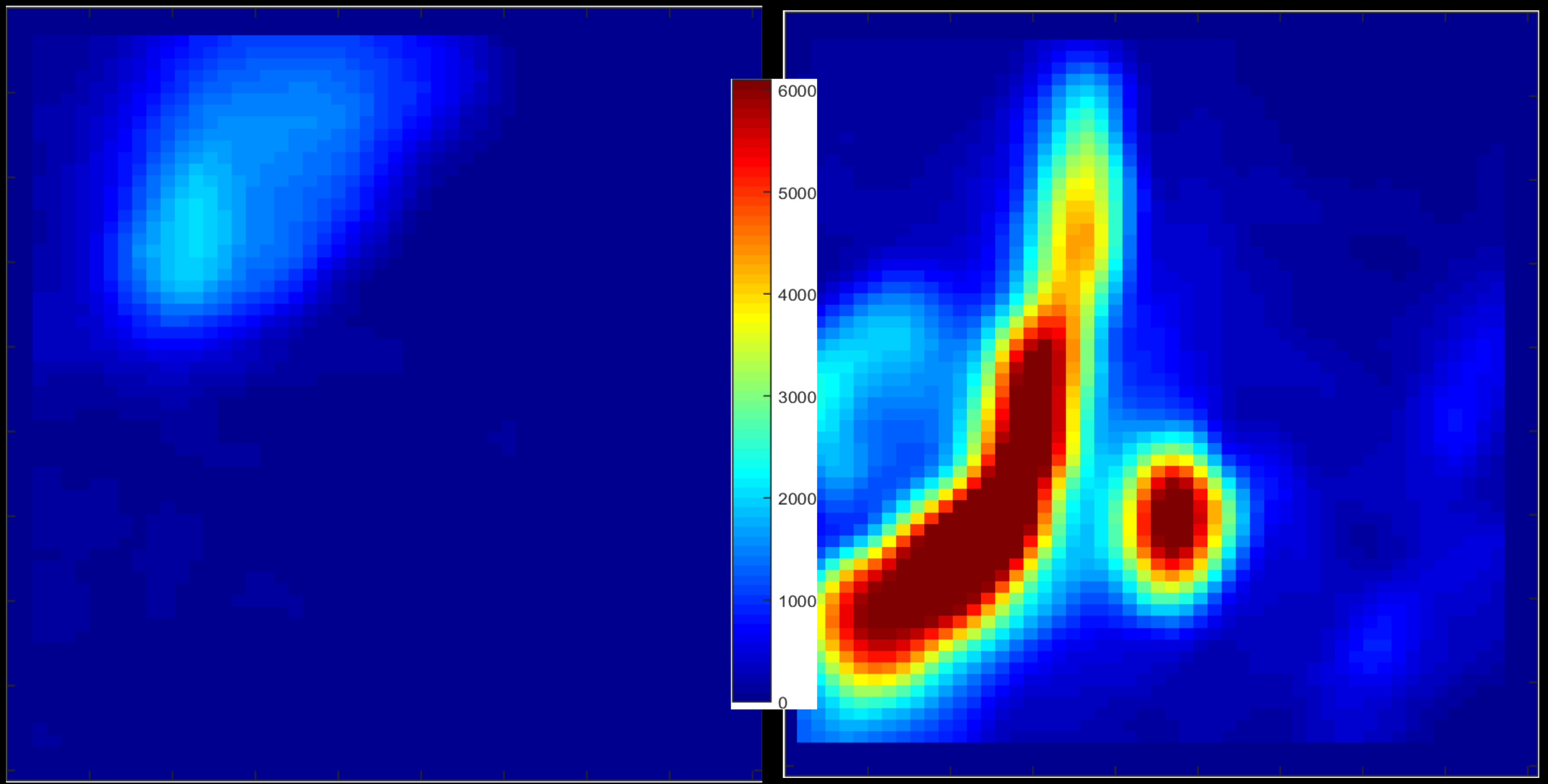
Boundary Stresses: $\phi = 56\%$

Stress Fields



Time Resolved Rheology

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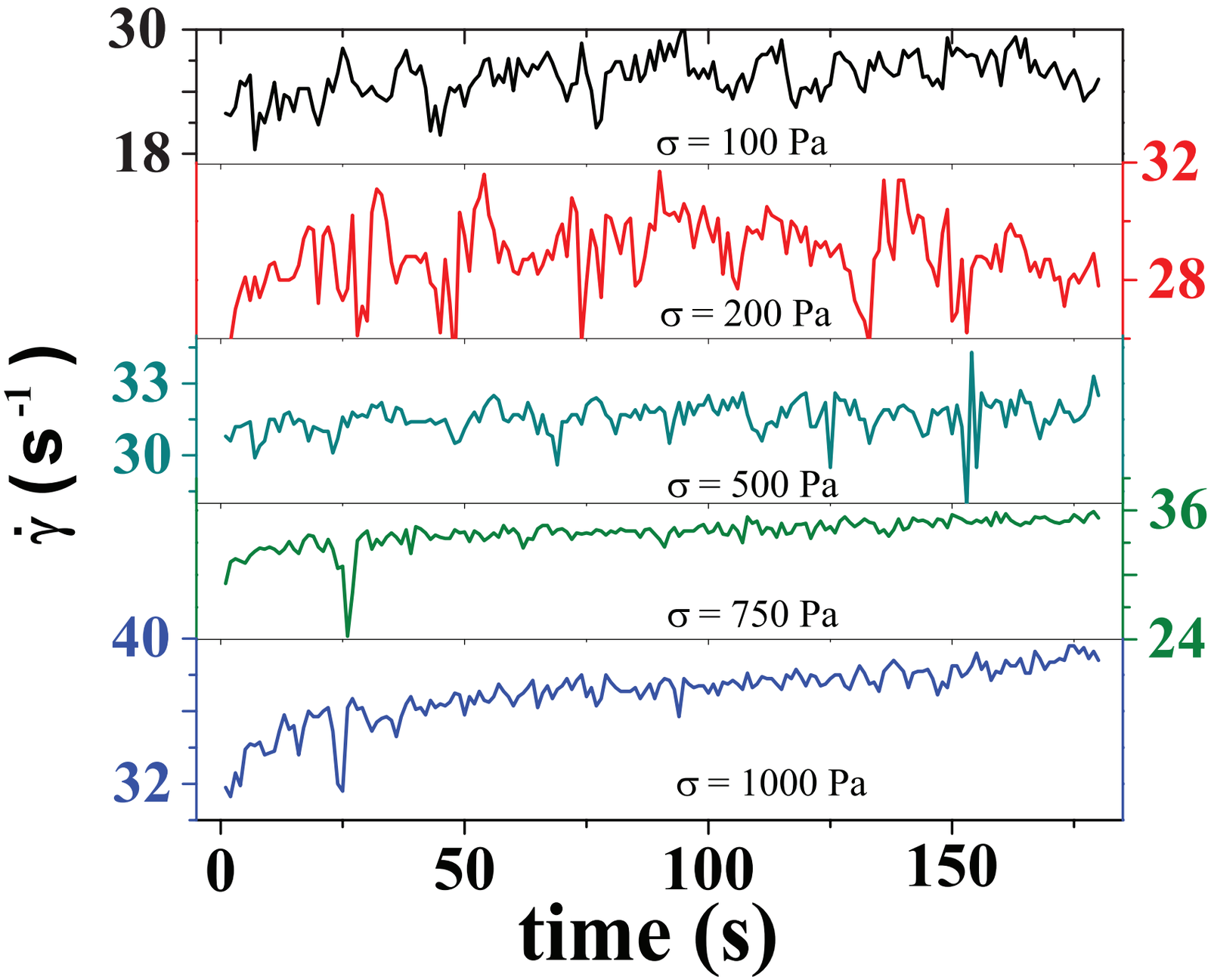

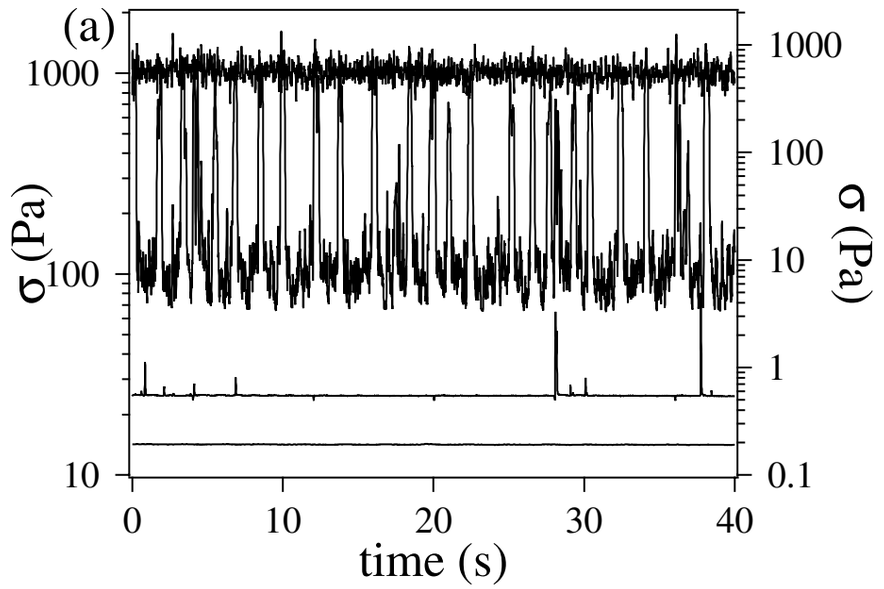

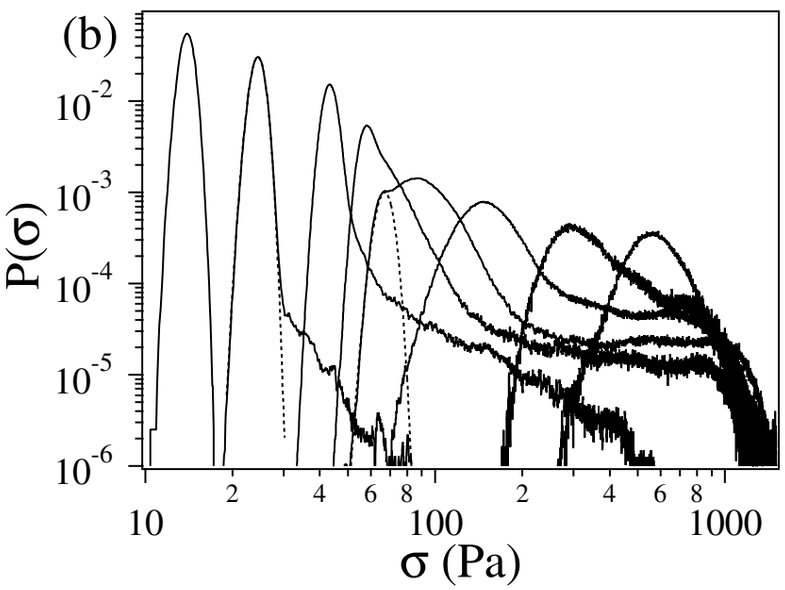

Lootens *et al.*, PRL 2003

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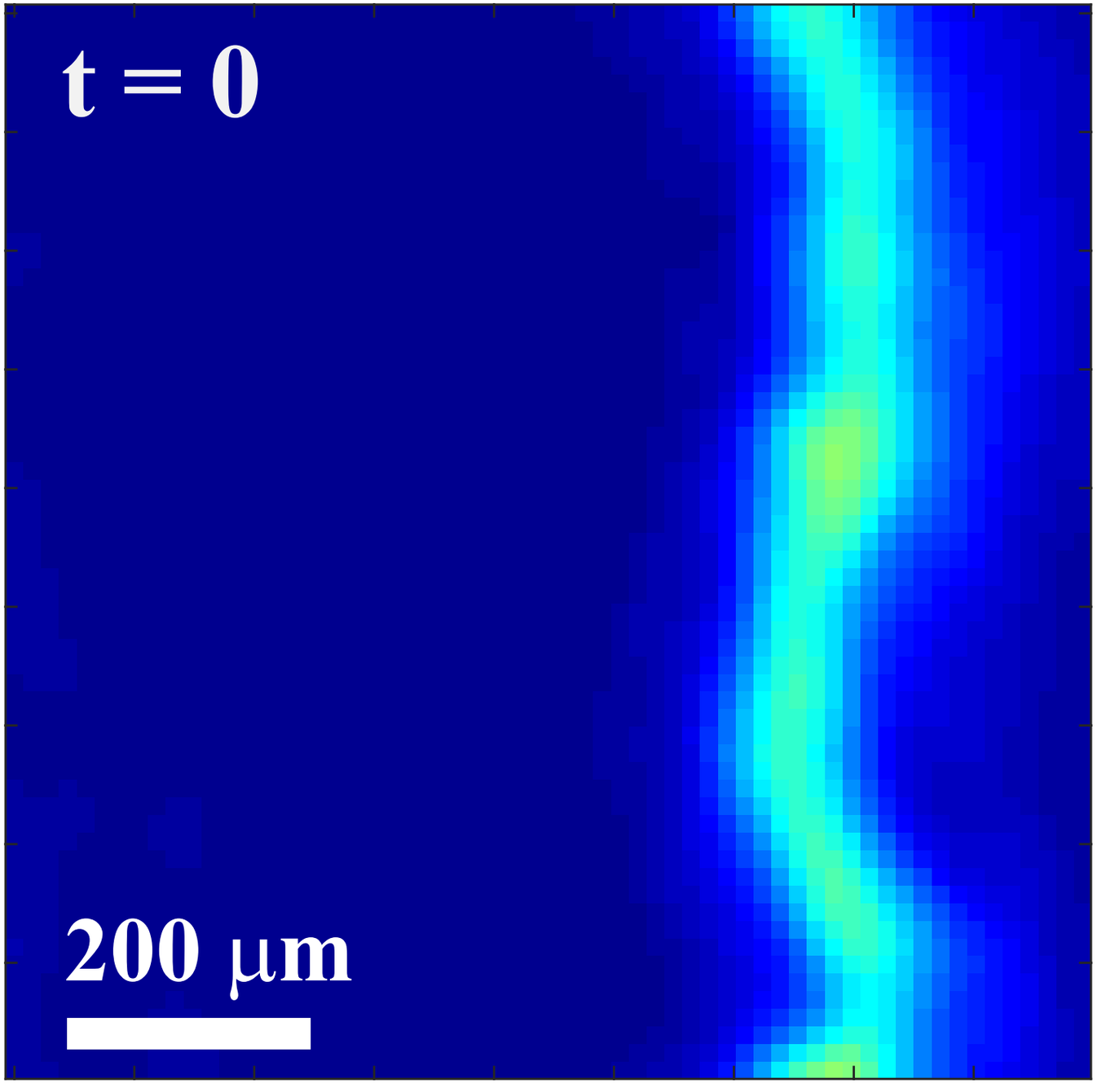
Tracking the Dynamics



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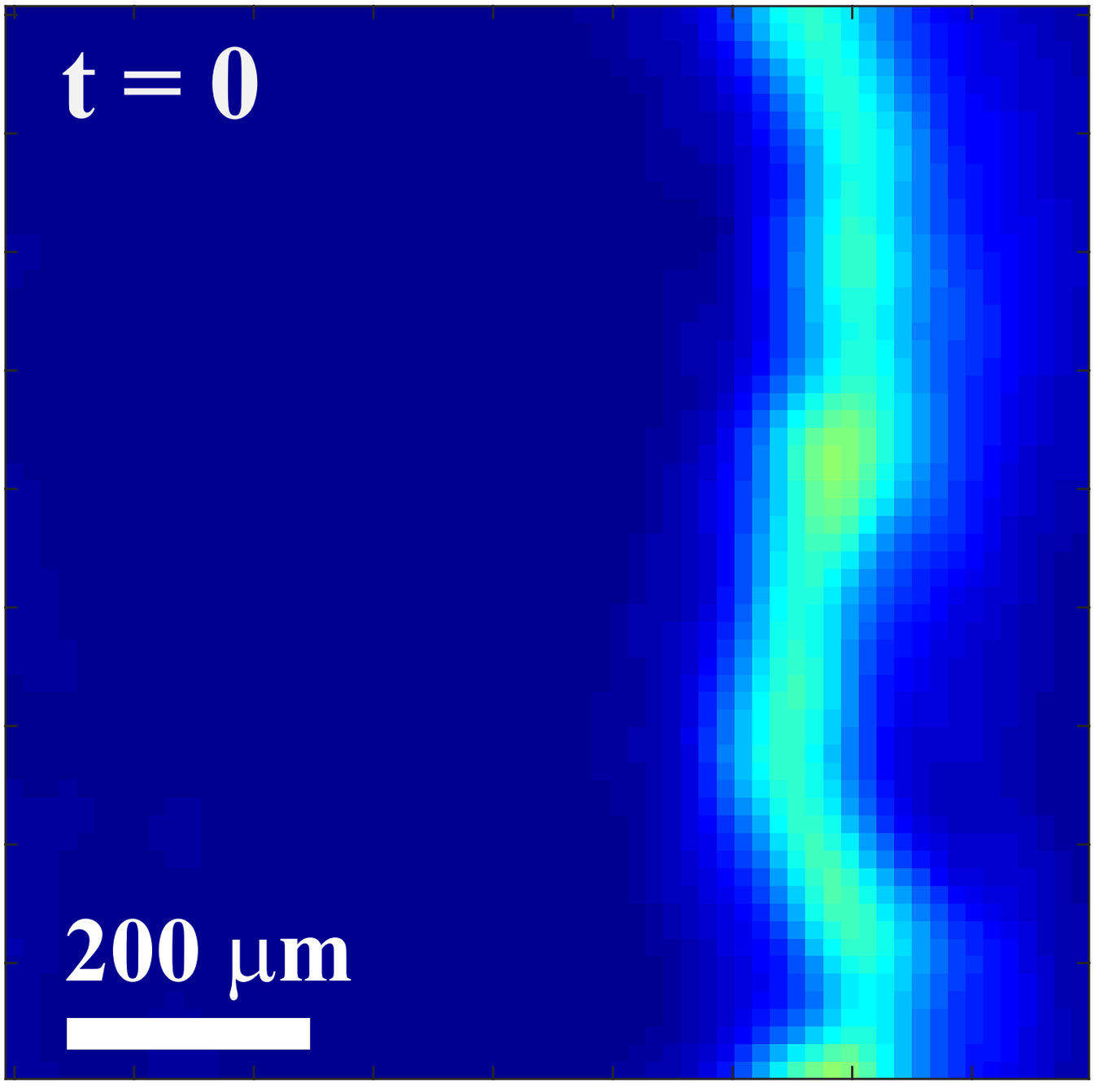

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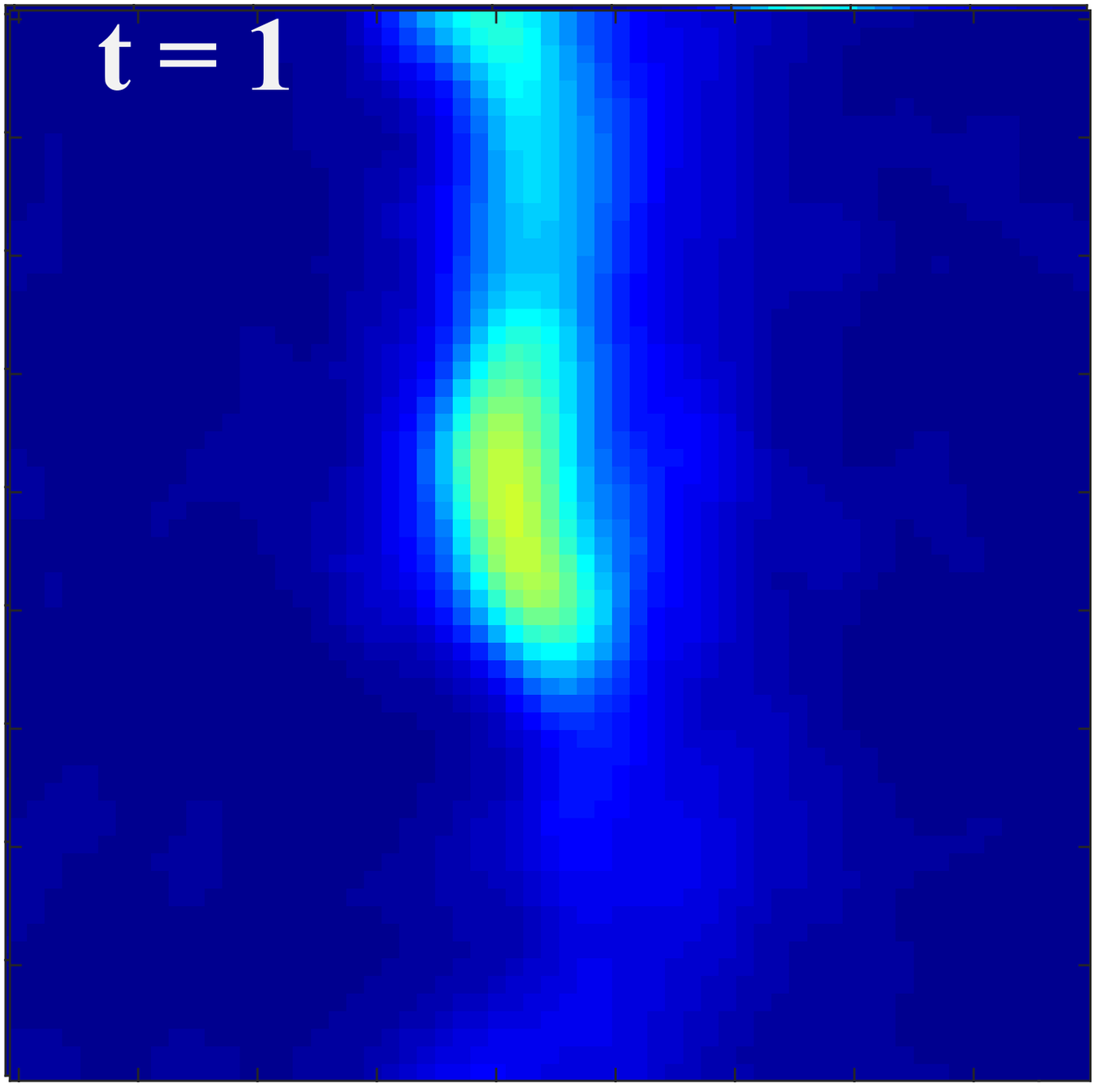
Tracking the Dynamics



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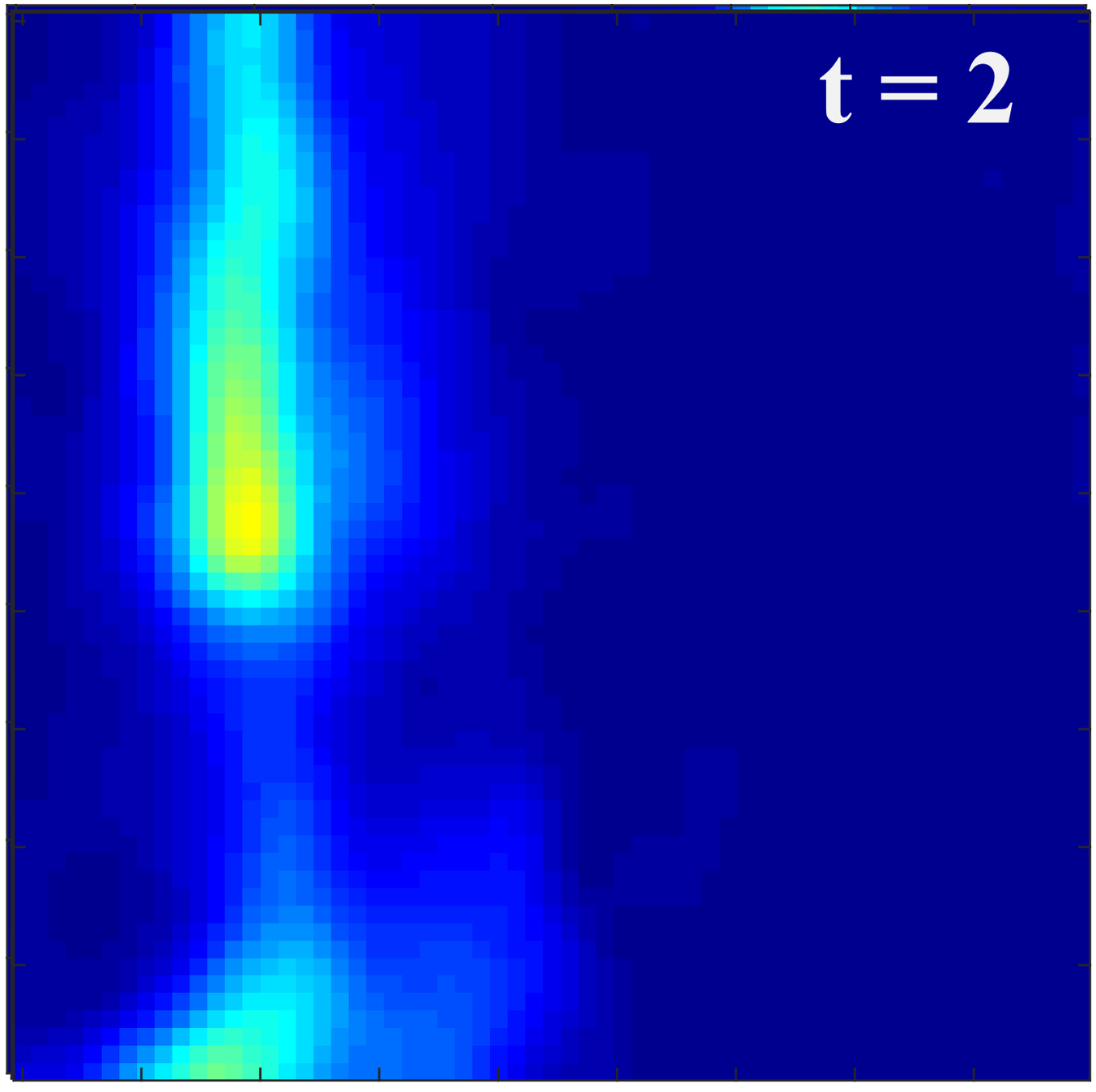
Tracking the Dynamics



Tracking the Dynamics

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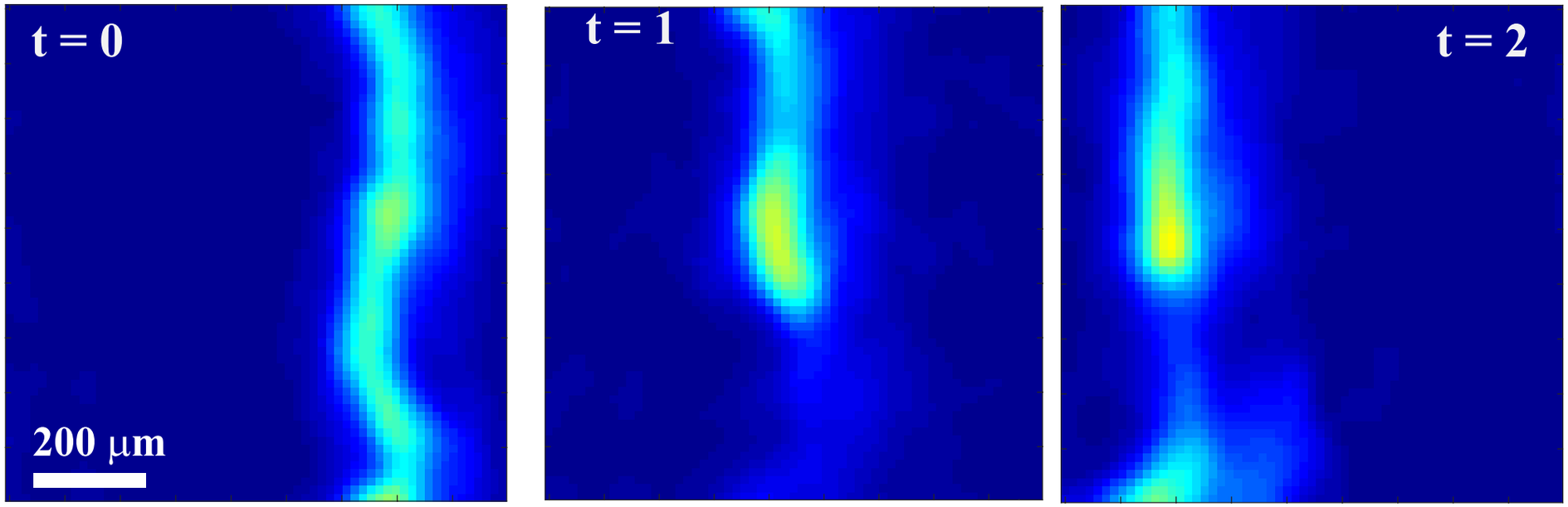
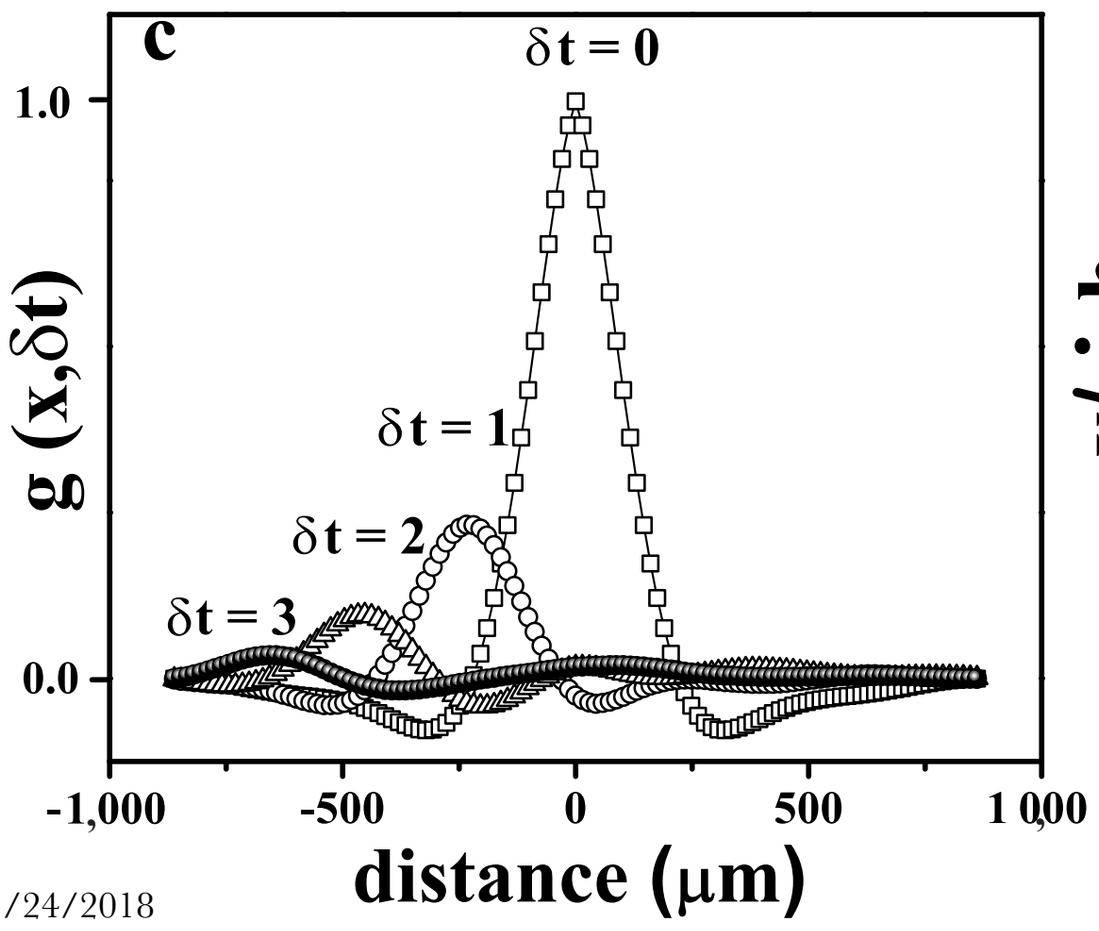
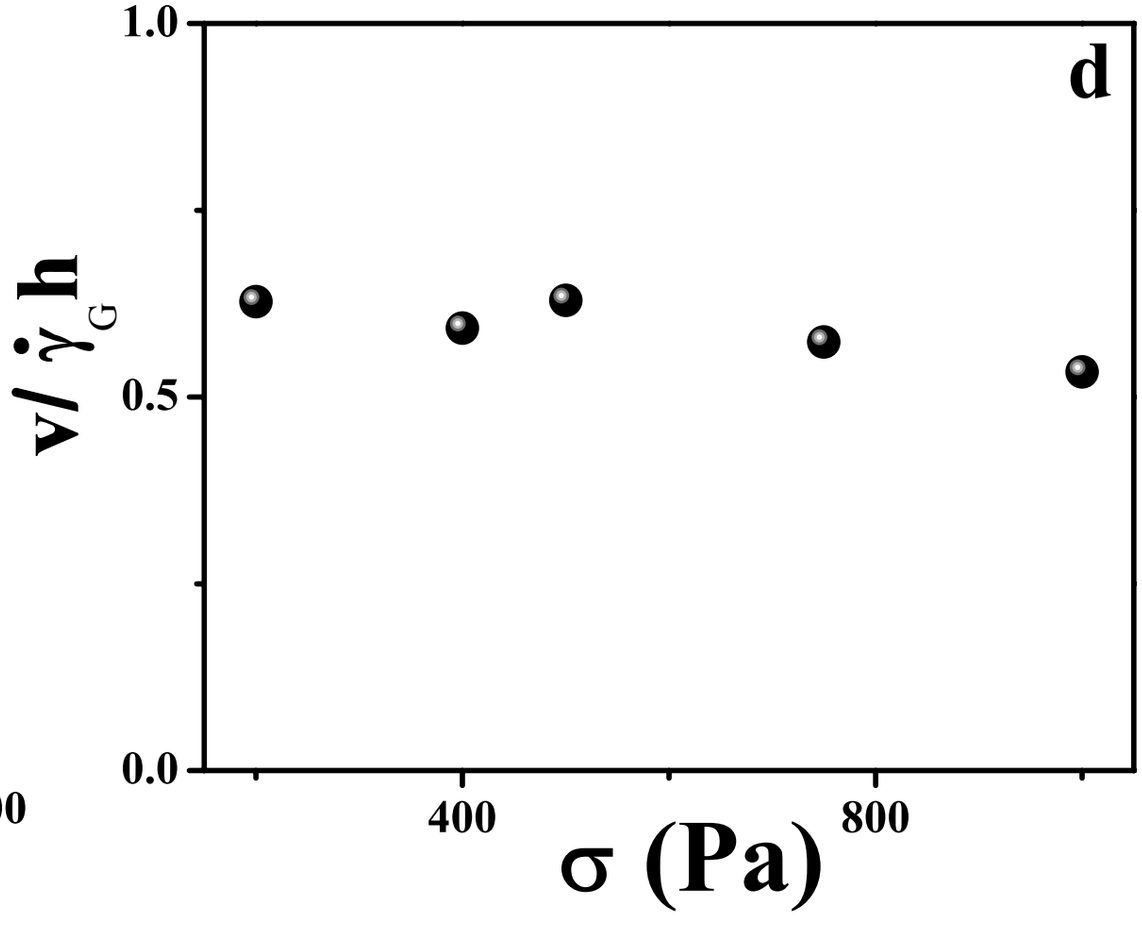
Tracking the Dynamics







What Are These High Stress Regions?

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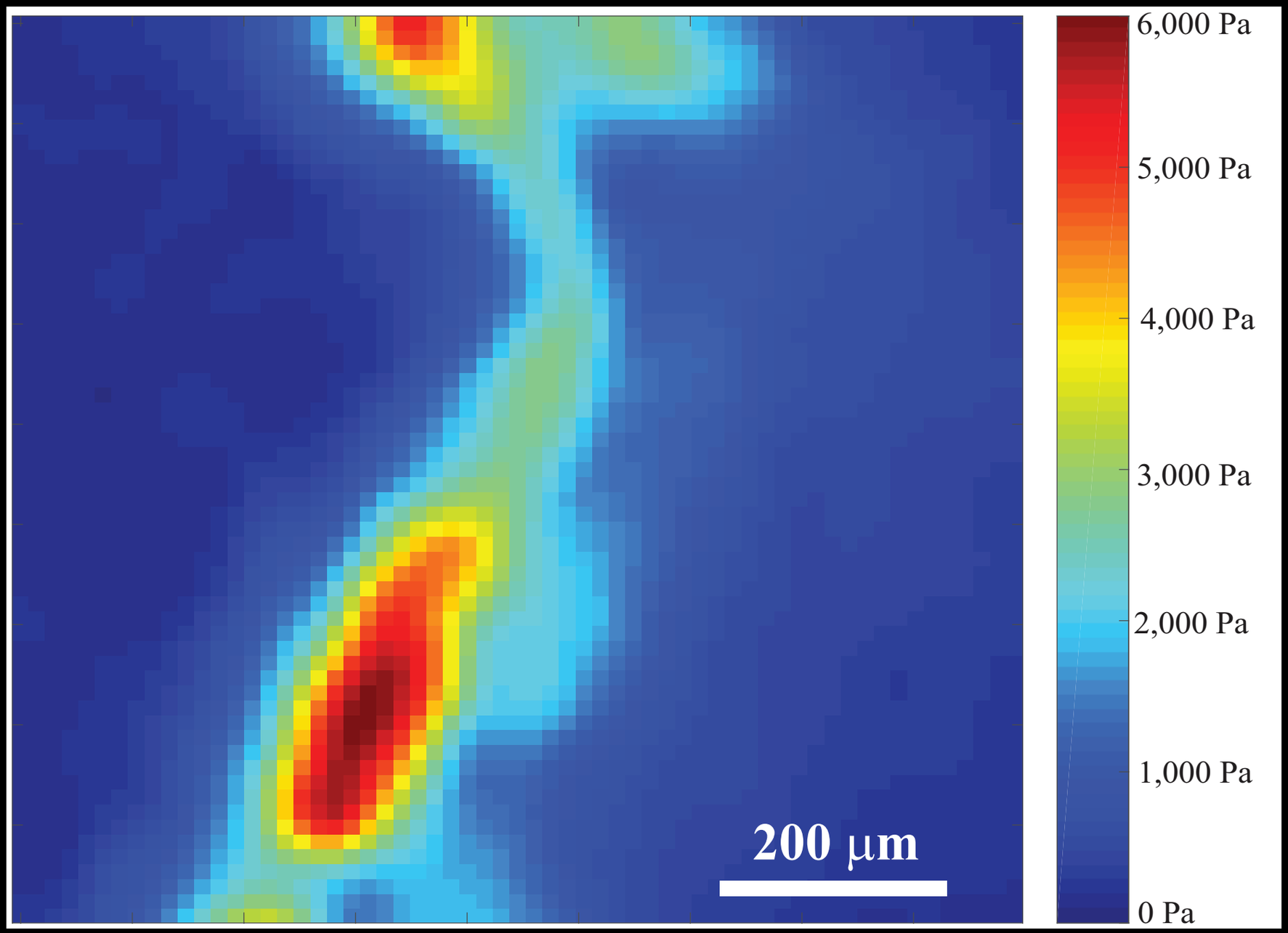

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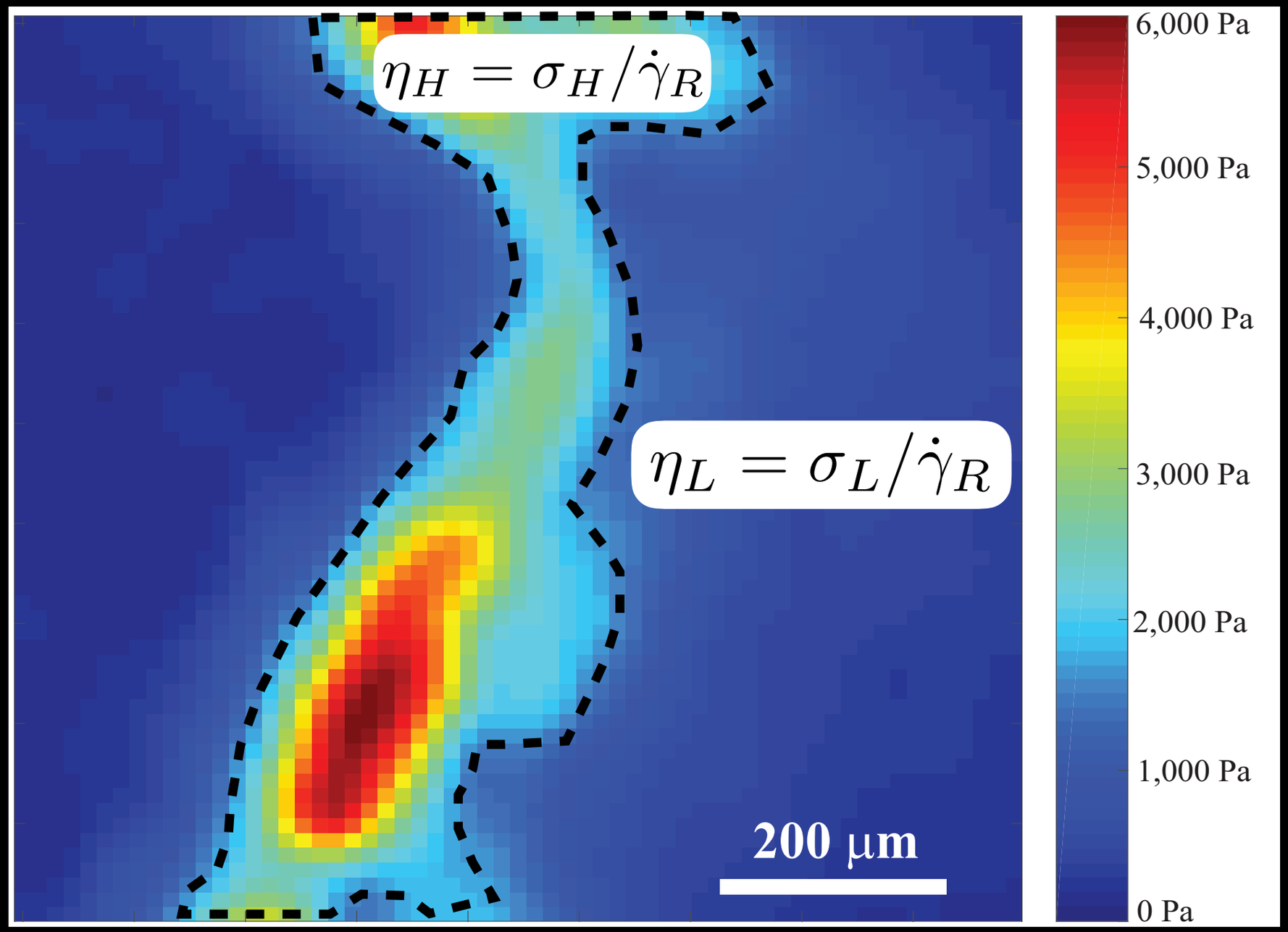

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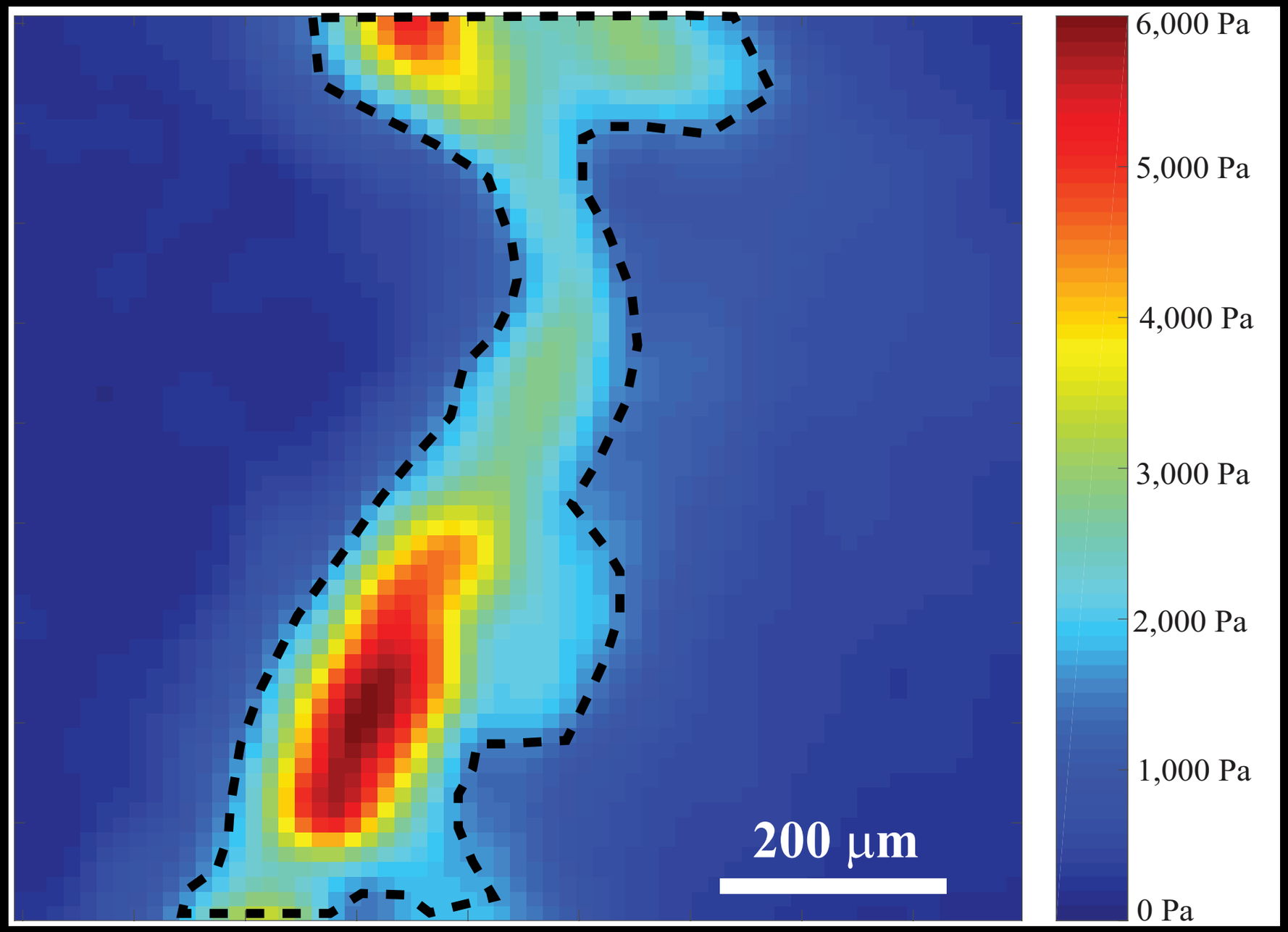
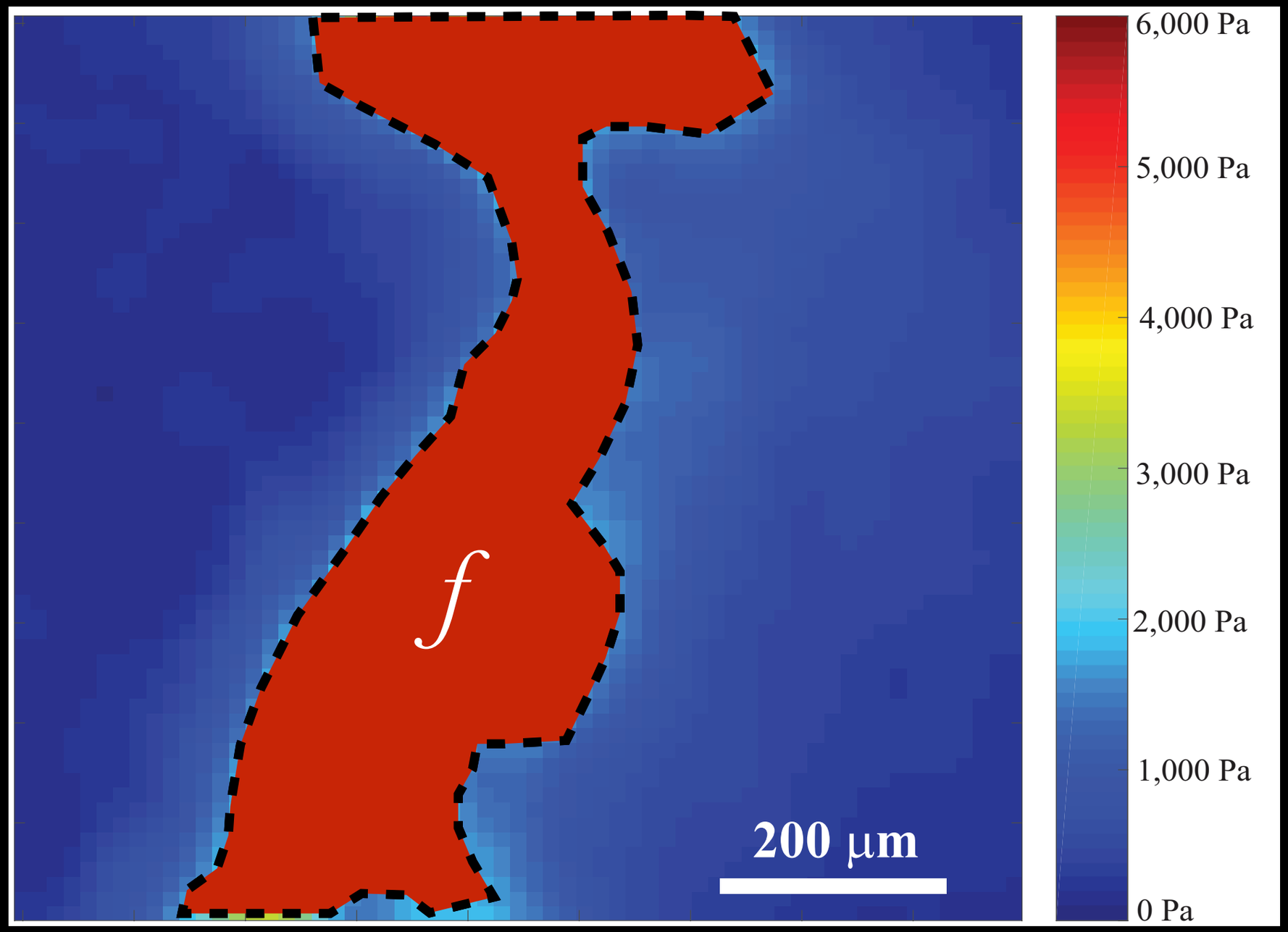


$$\eta_H = \sigma_H / \dot{\gamma}_R$$

$$\eta_L = \sigma_L / \dot{\gamma}_R$$

What Are These High Stress Regions?



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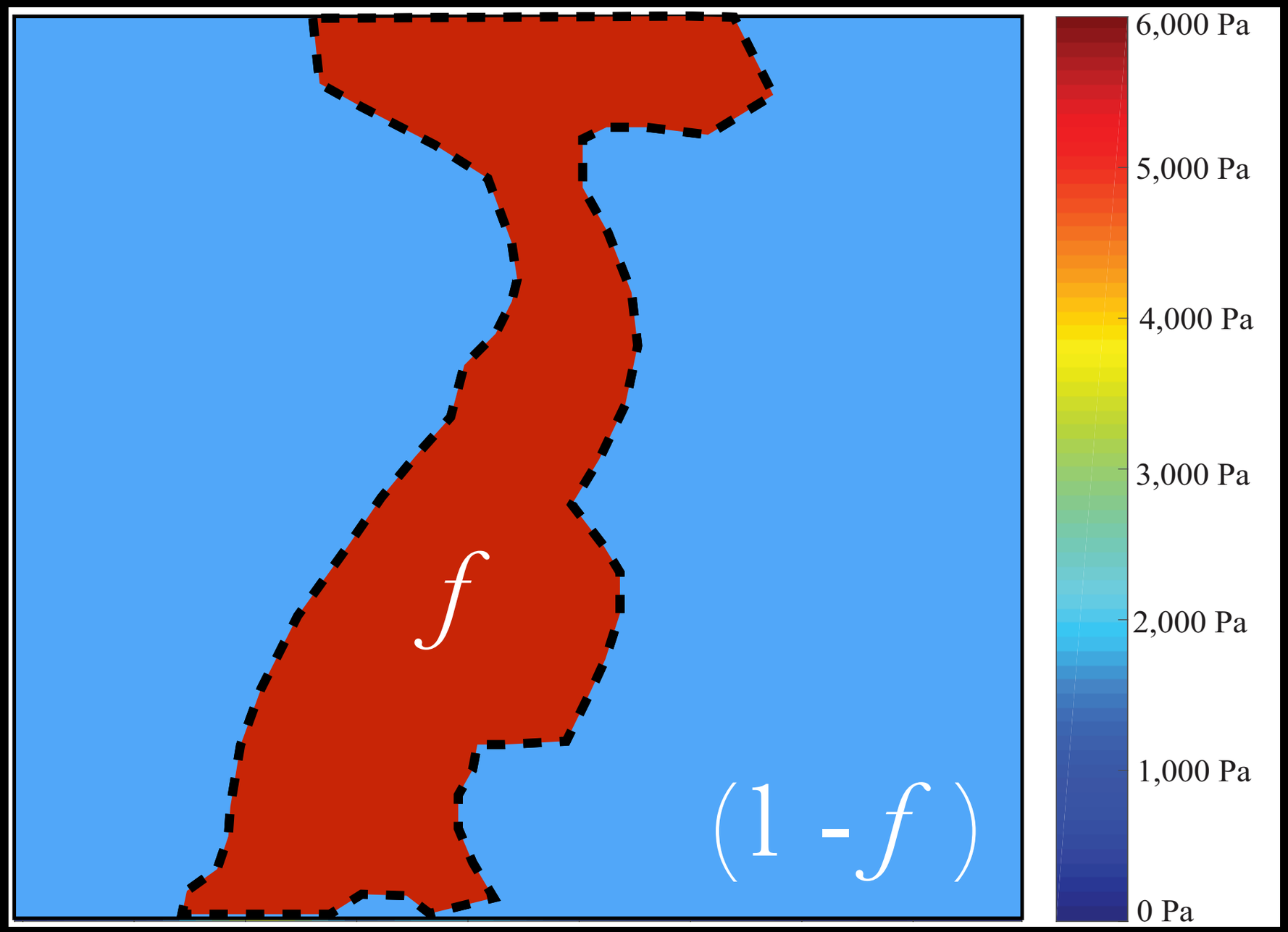
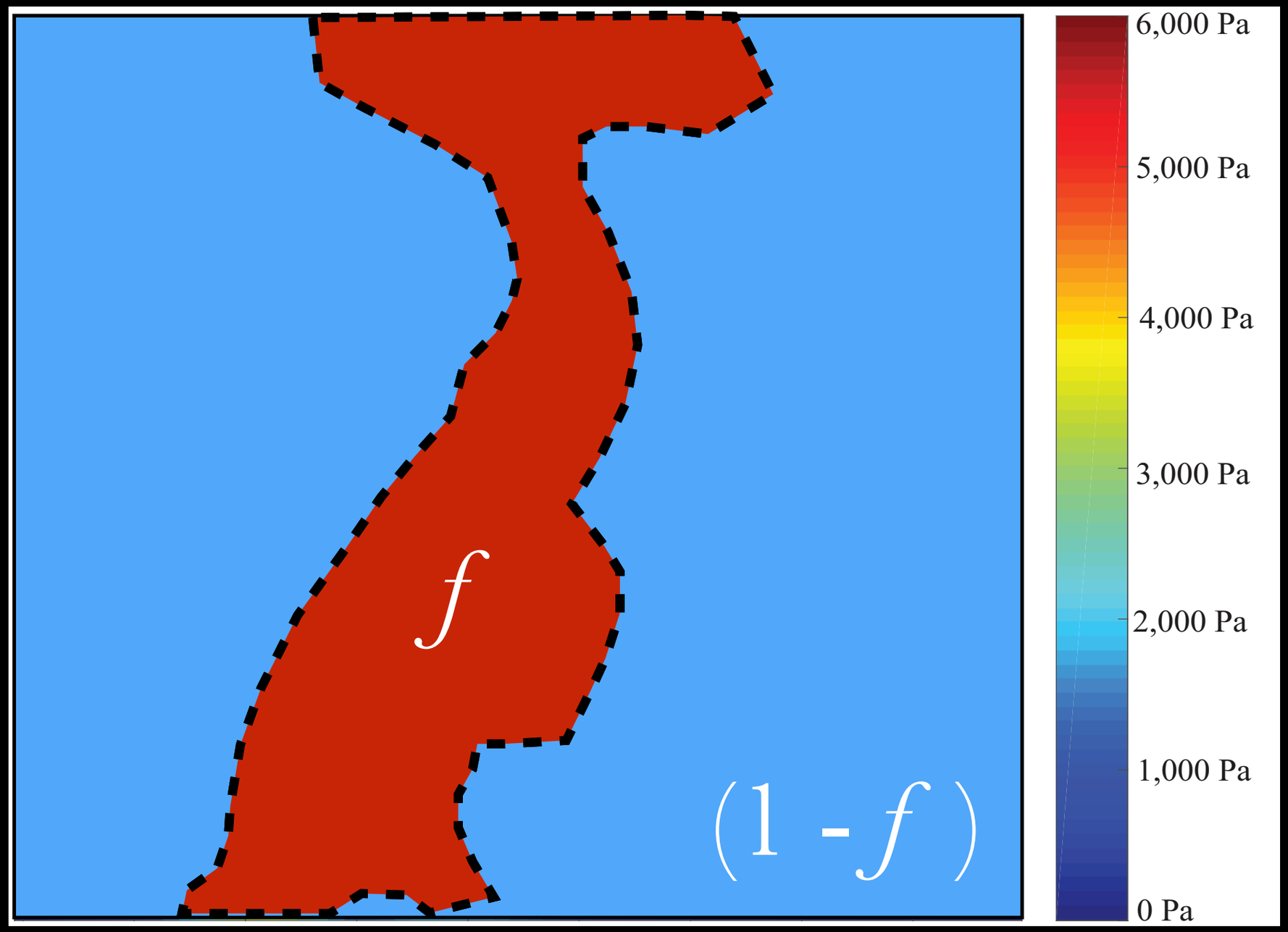


What Are These High Stress Regions?



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

f — area fraction of high stress

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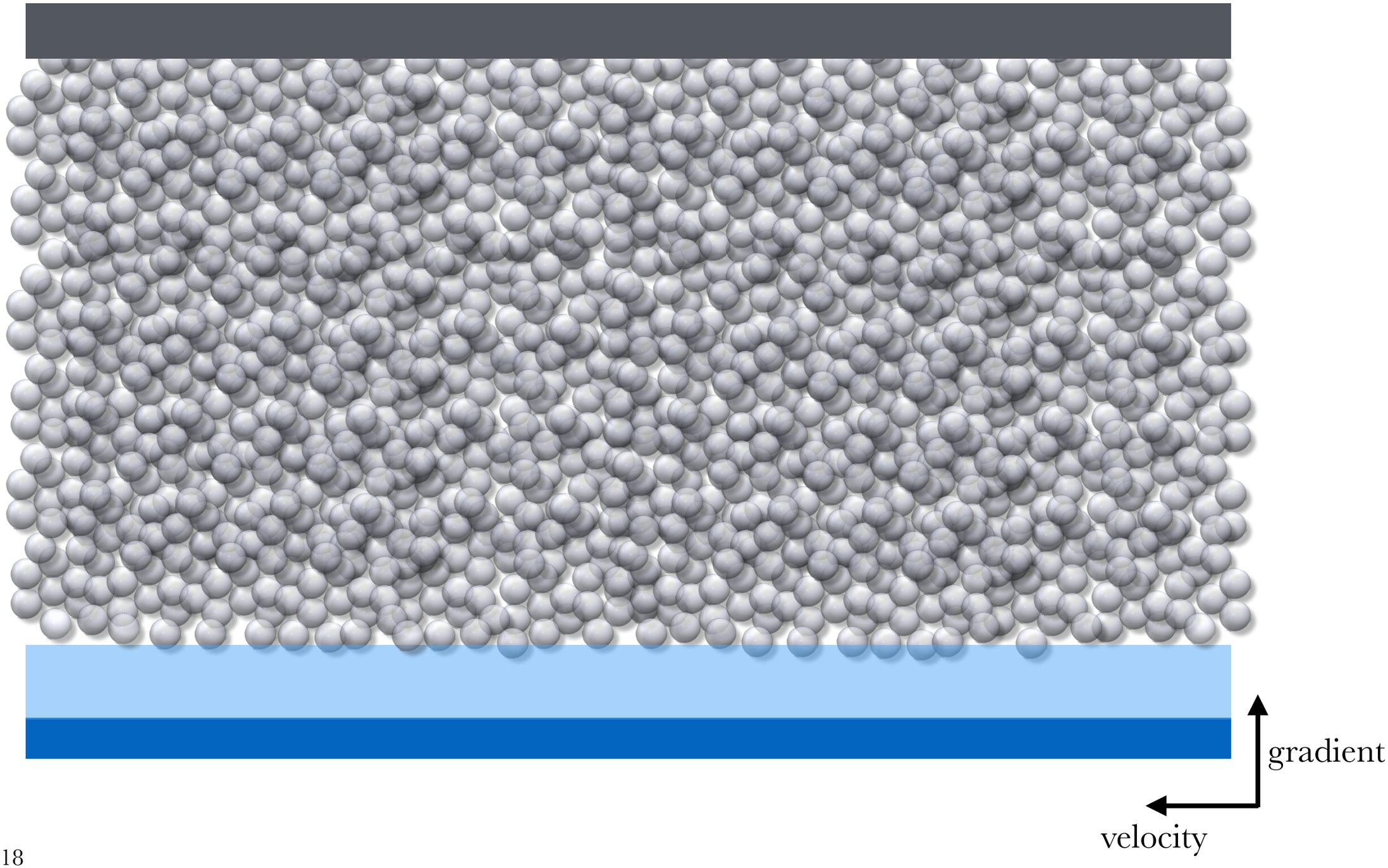
Our Simple Picture



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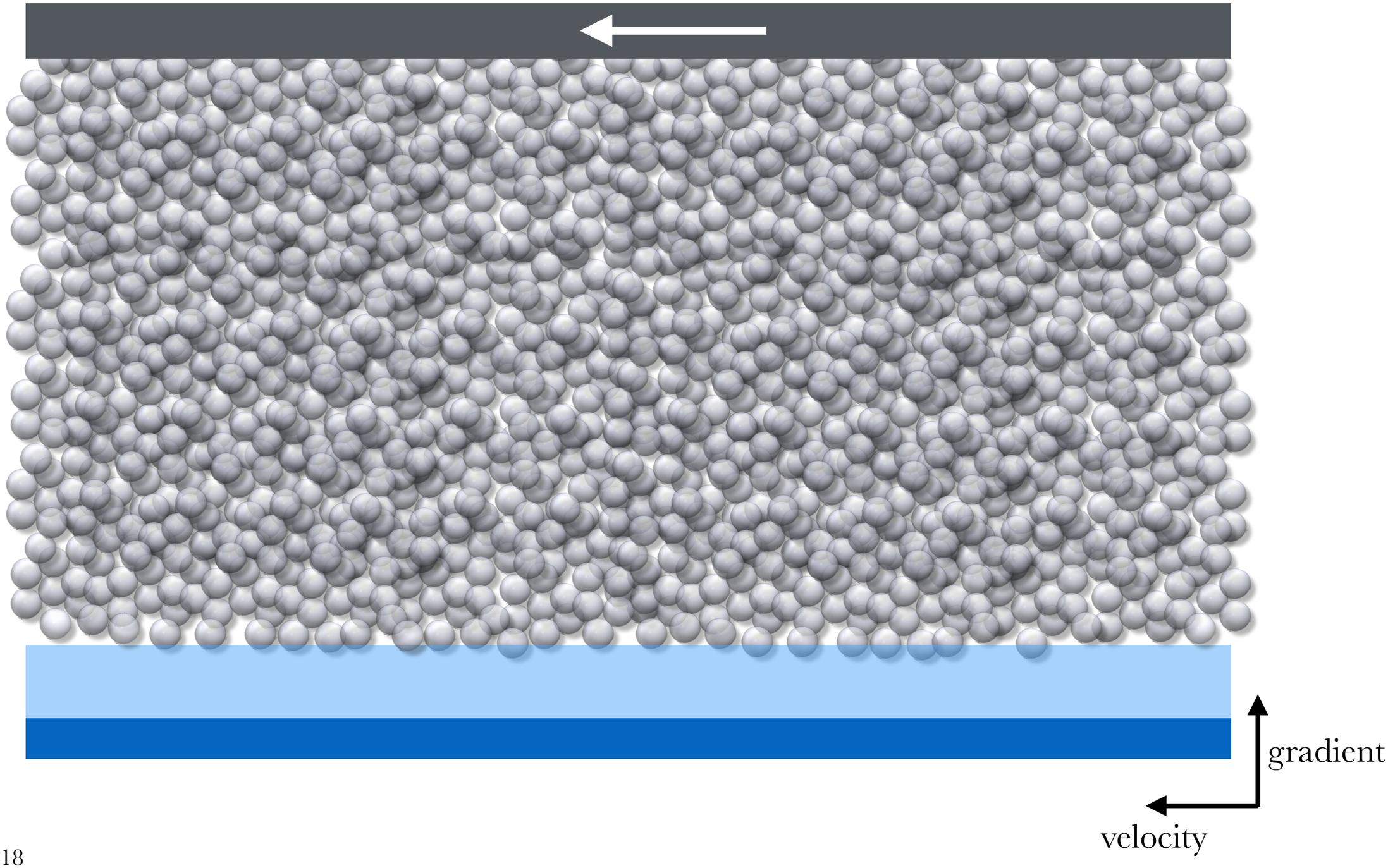

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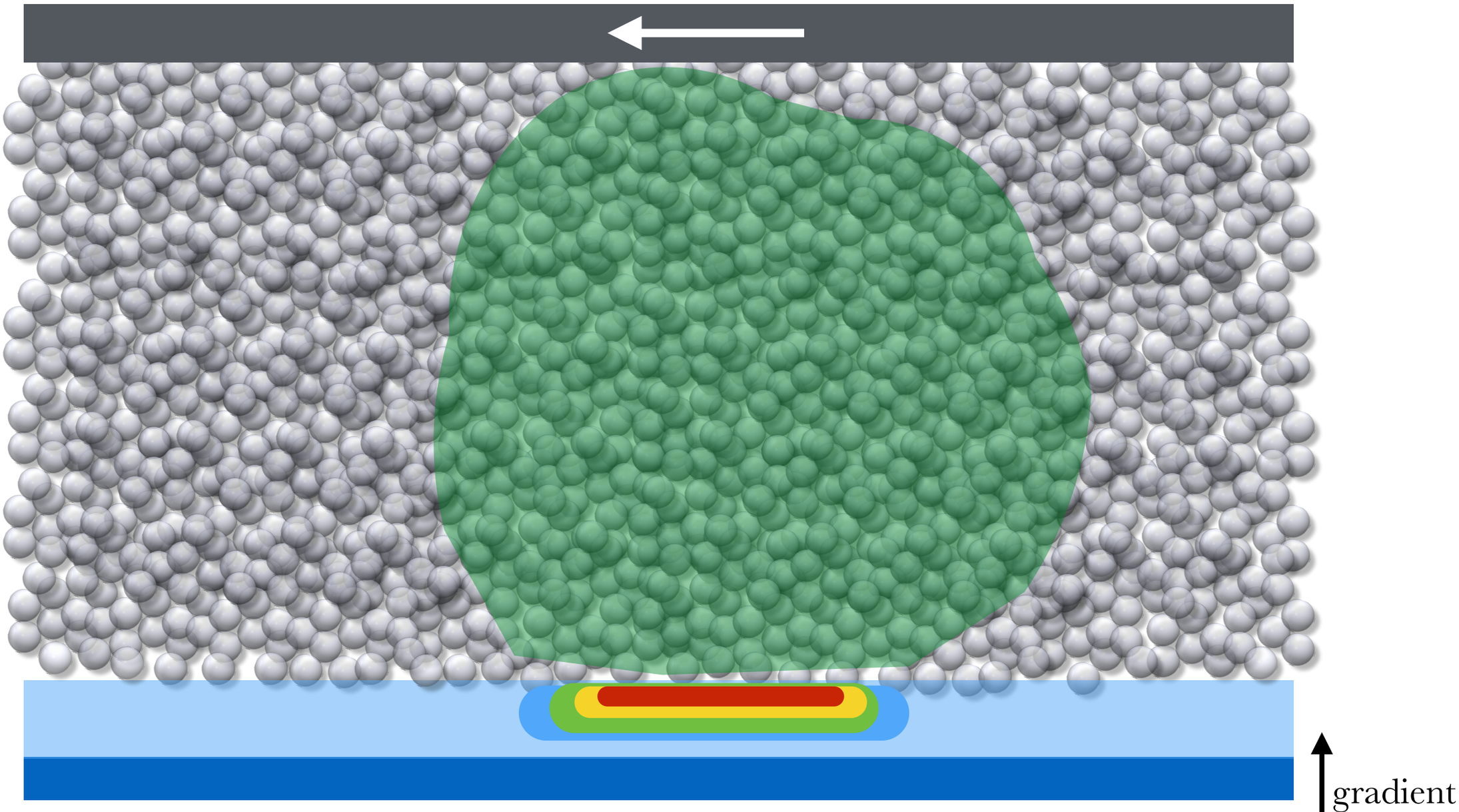

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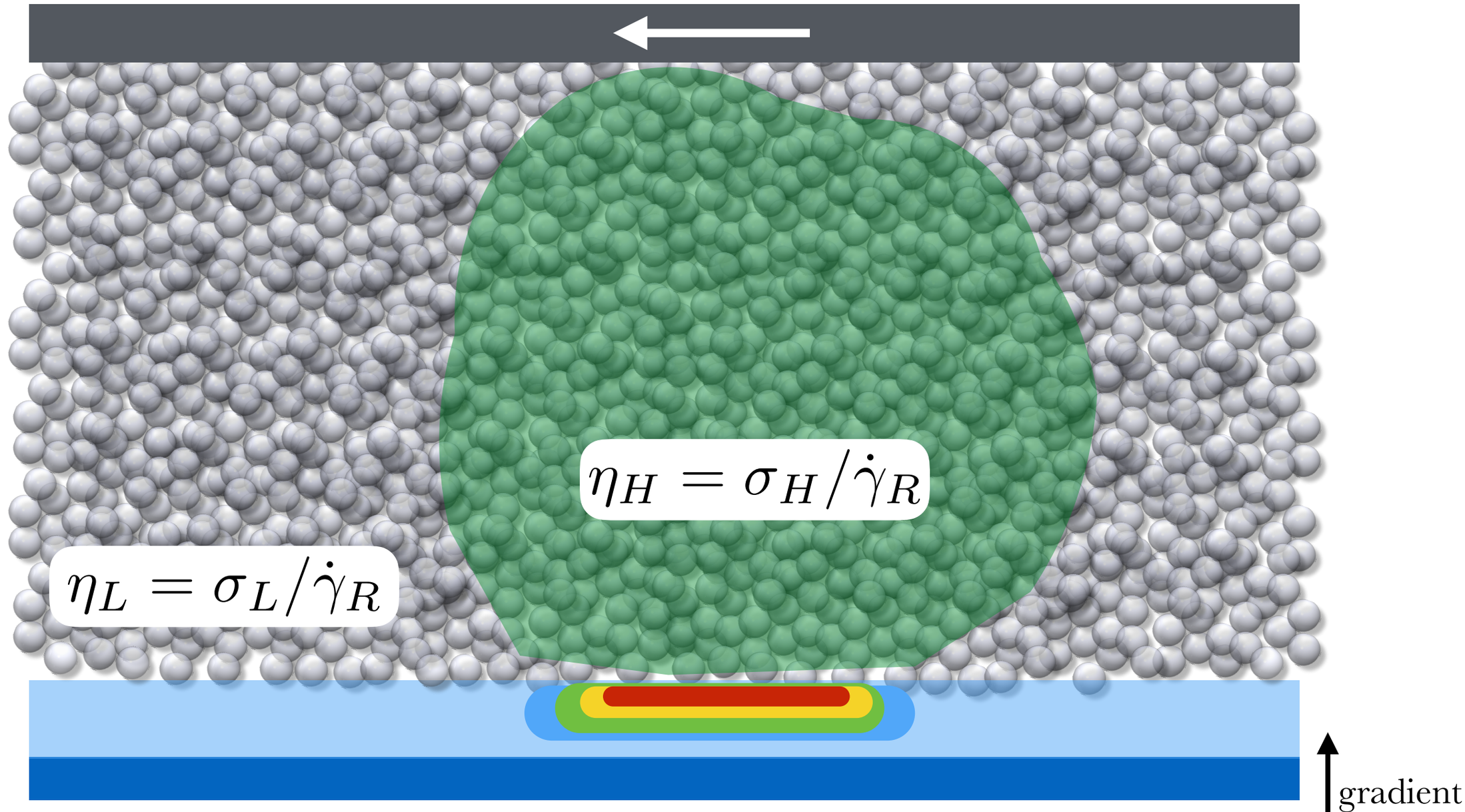

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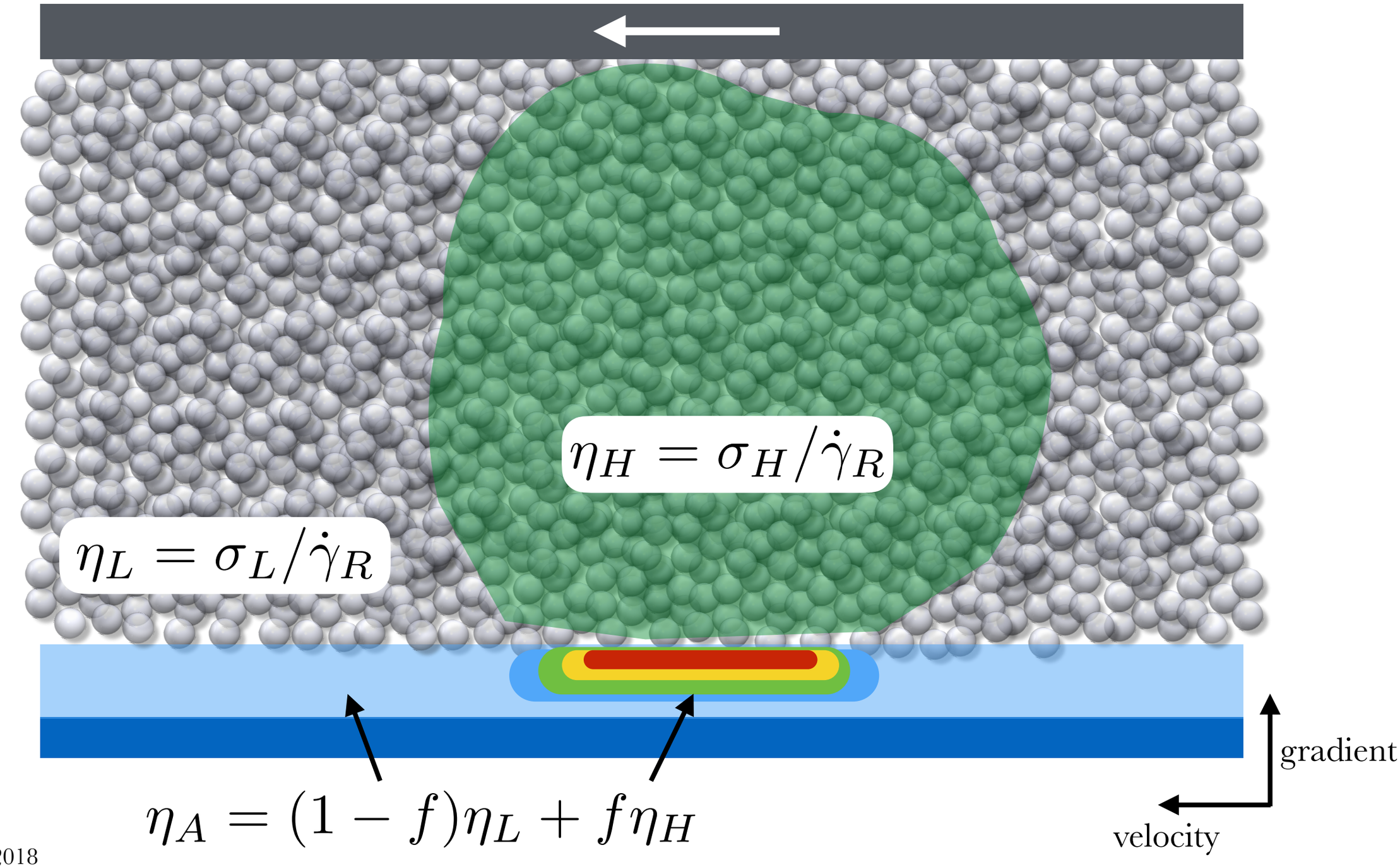
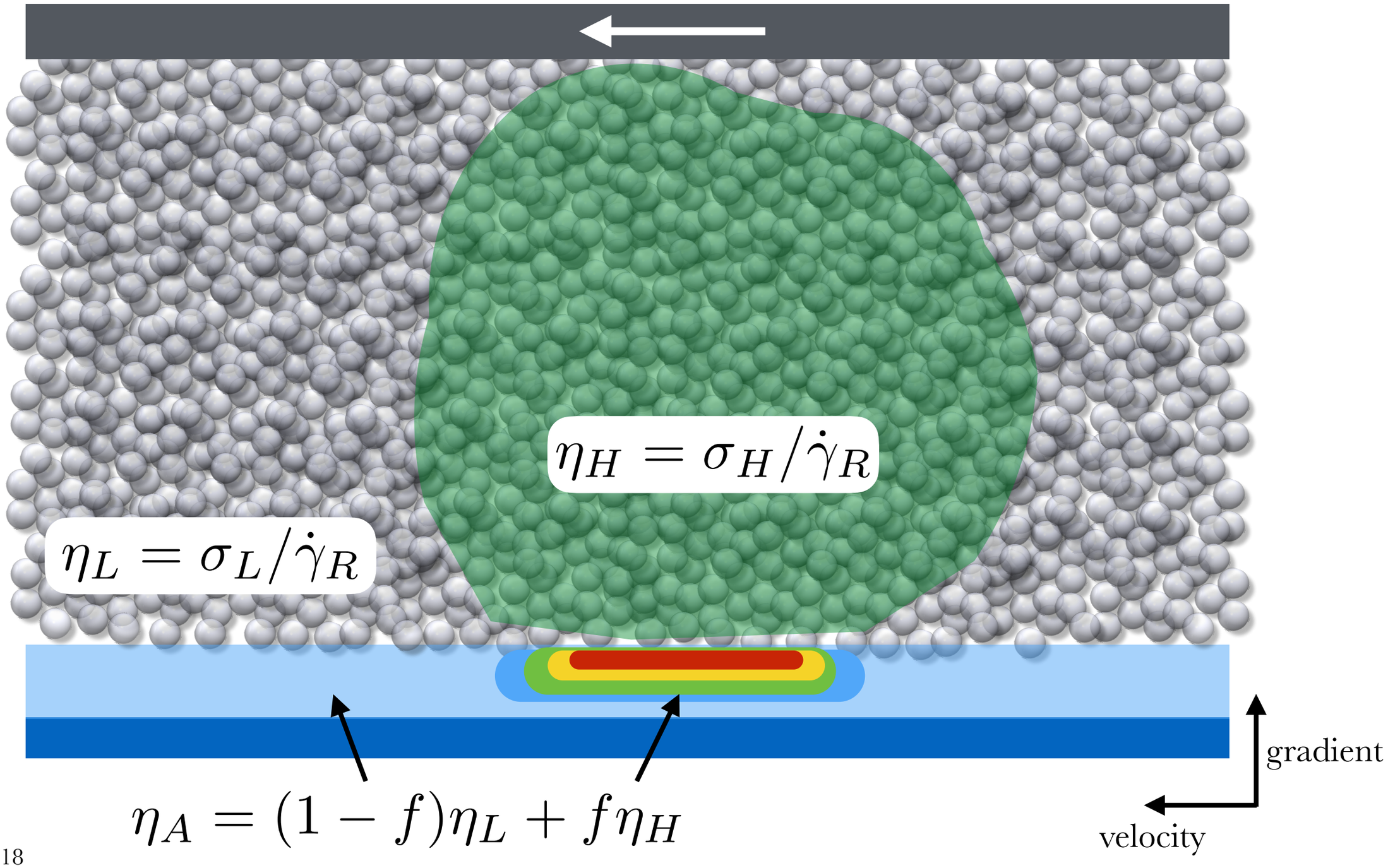


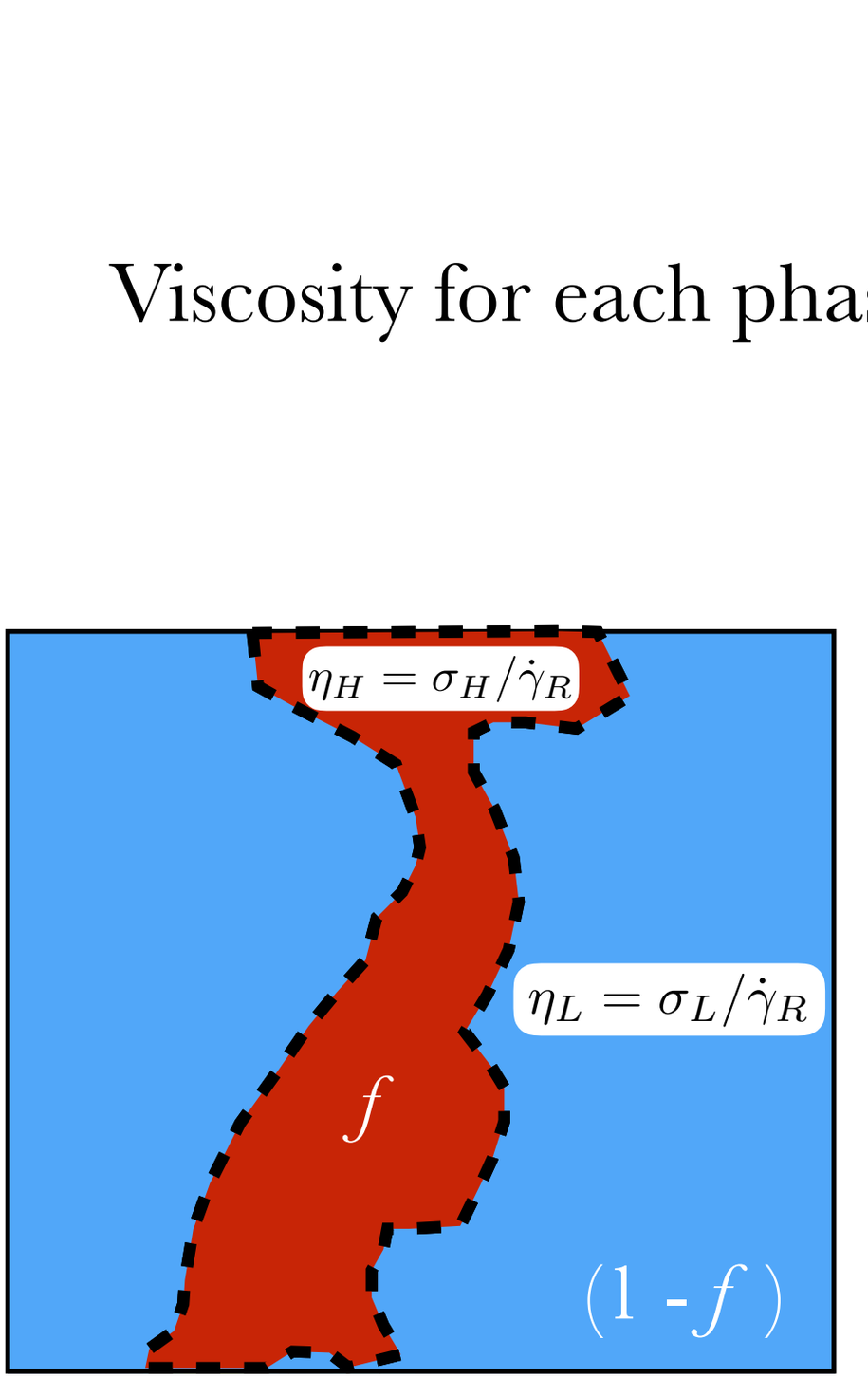
Our Simple Picture

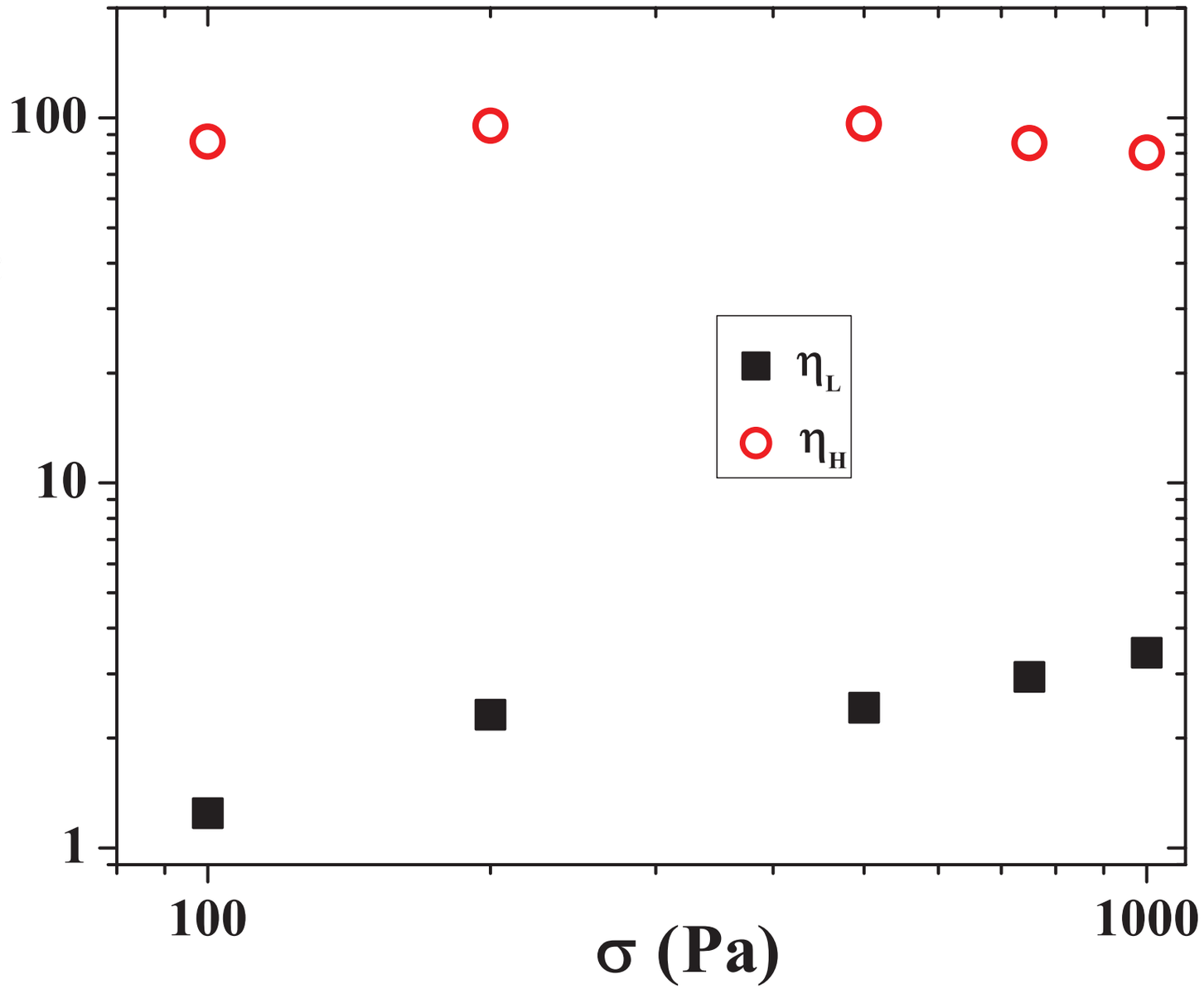
Two fluid model: Distinct Viscosities



Locally Shear Thickened

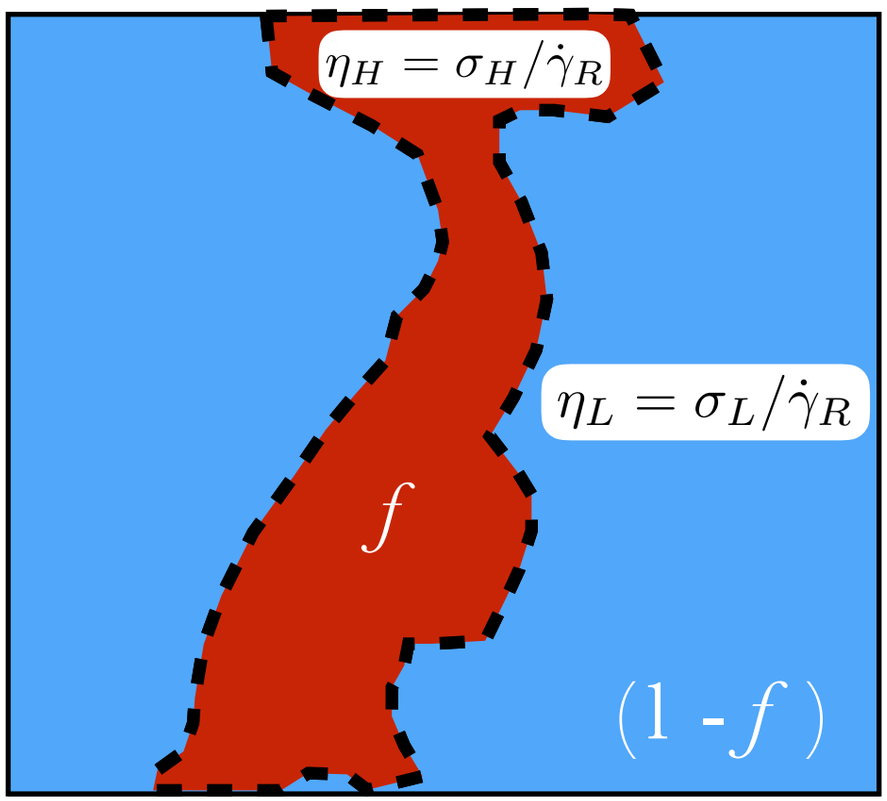
Viscosity for each phase

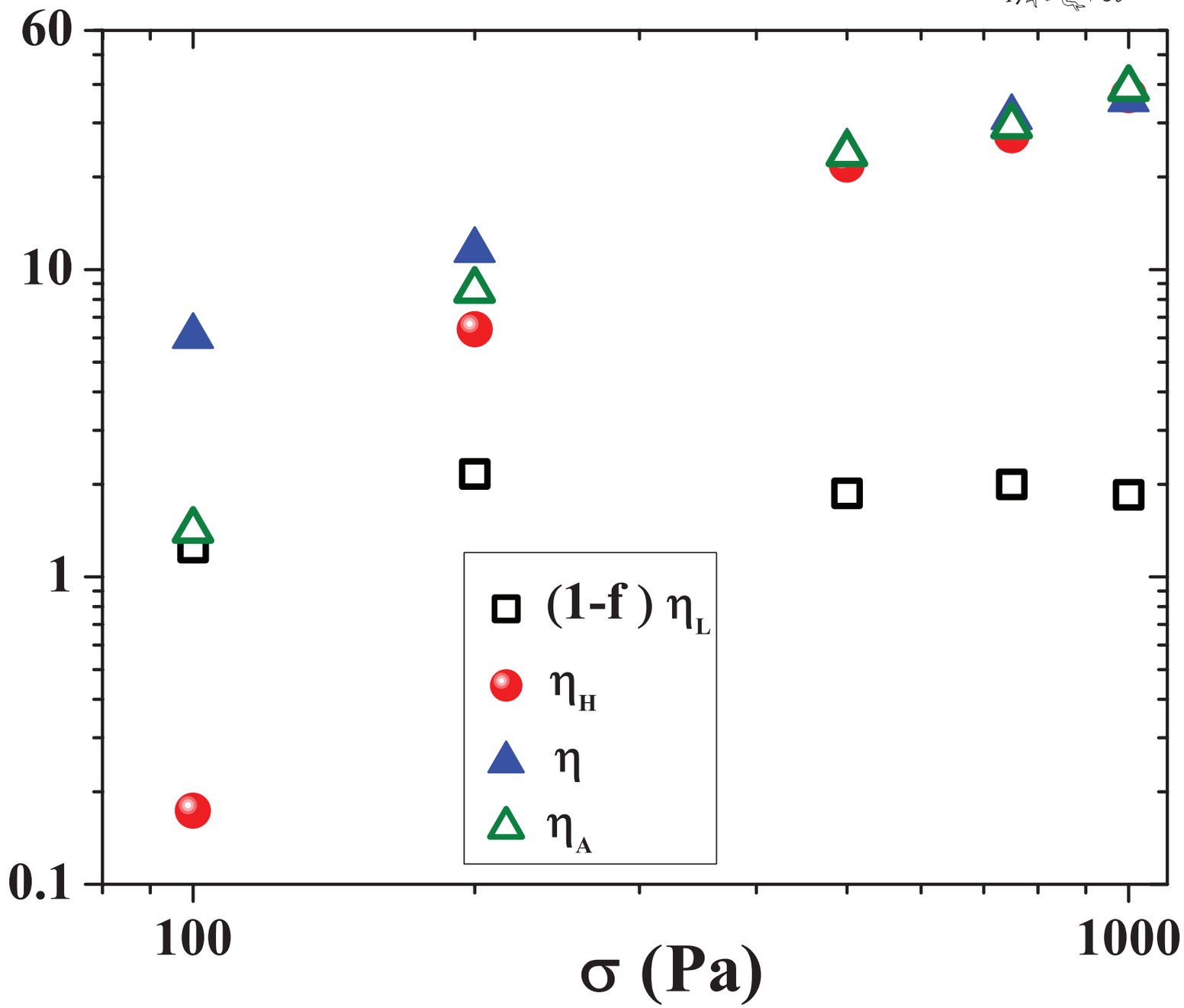




Viscosity of Distinct Phases

f — area fraction

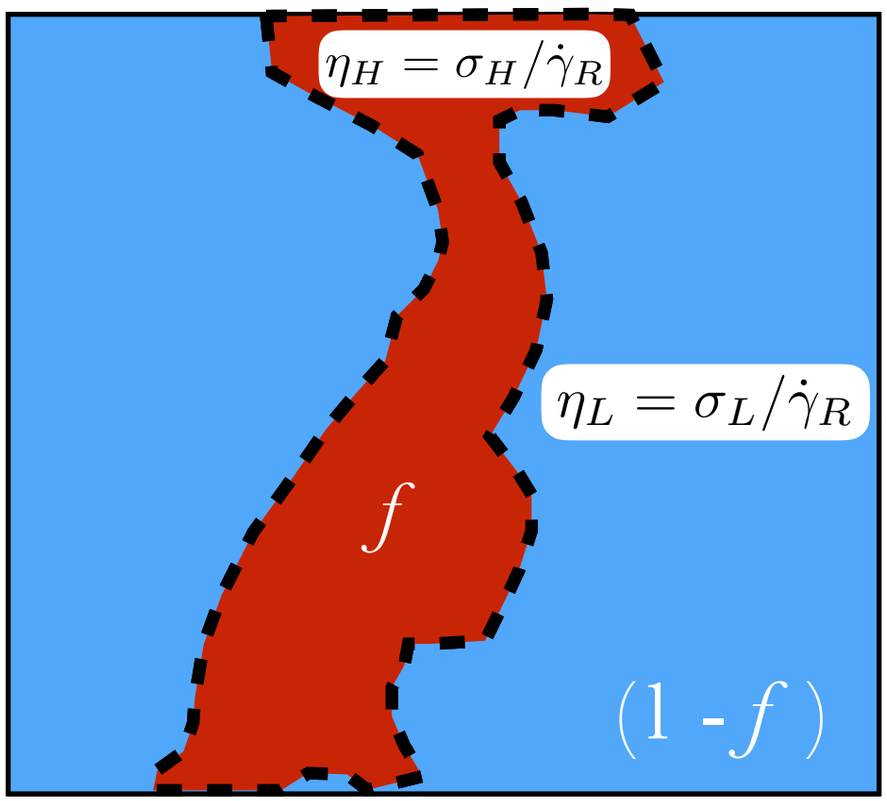


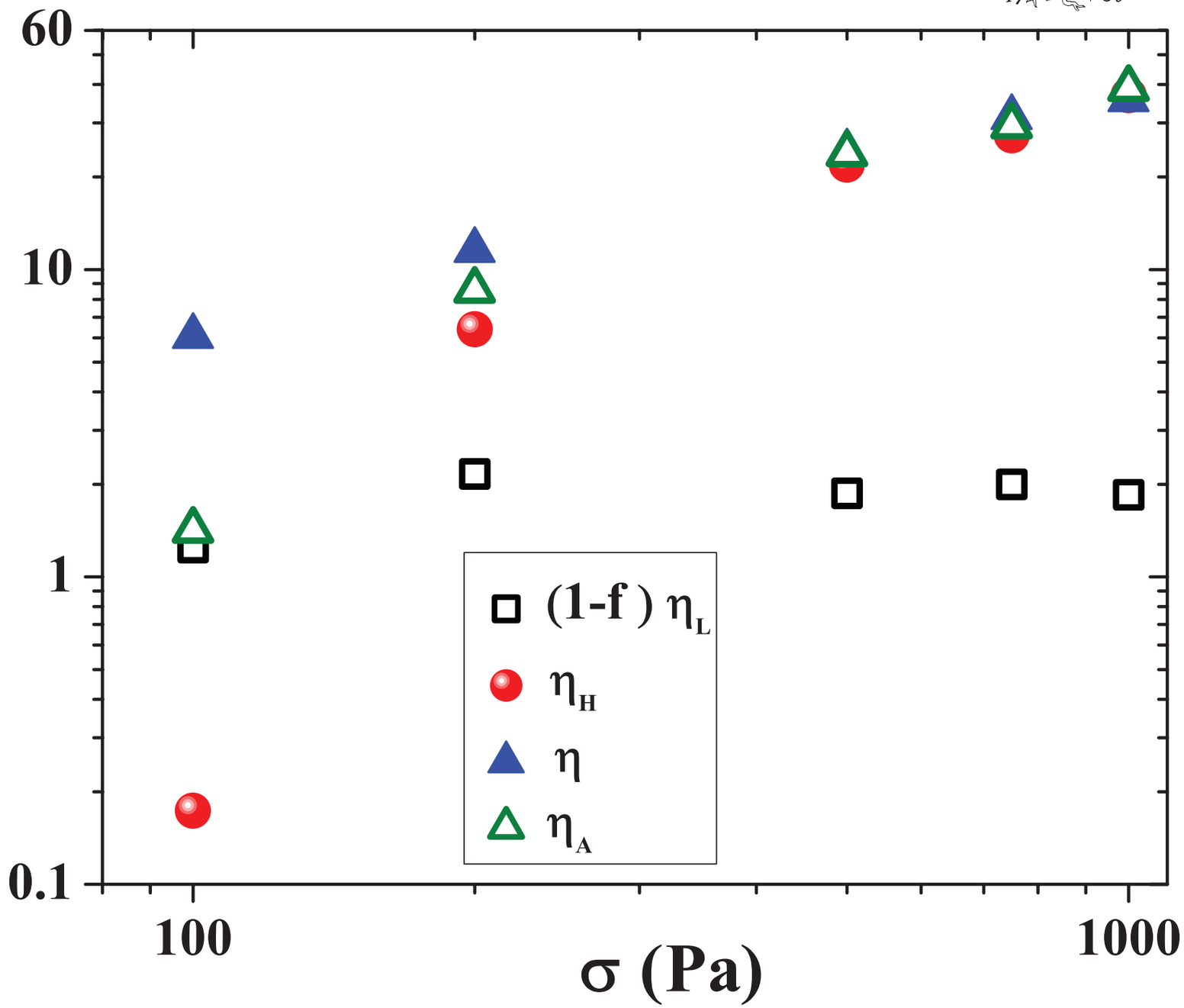


Viscosity of Distinct Phases

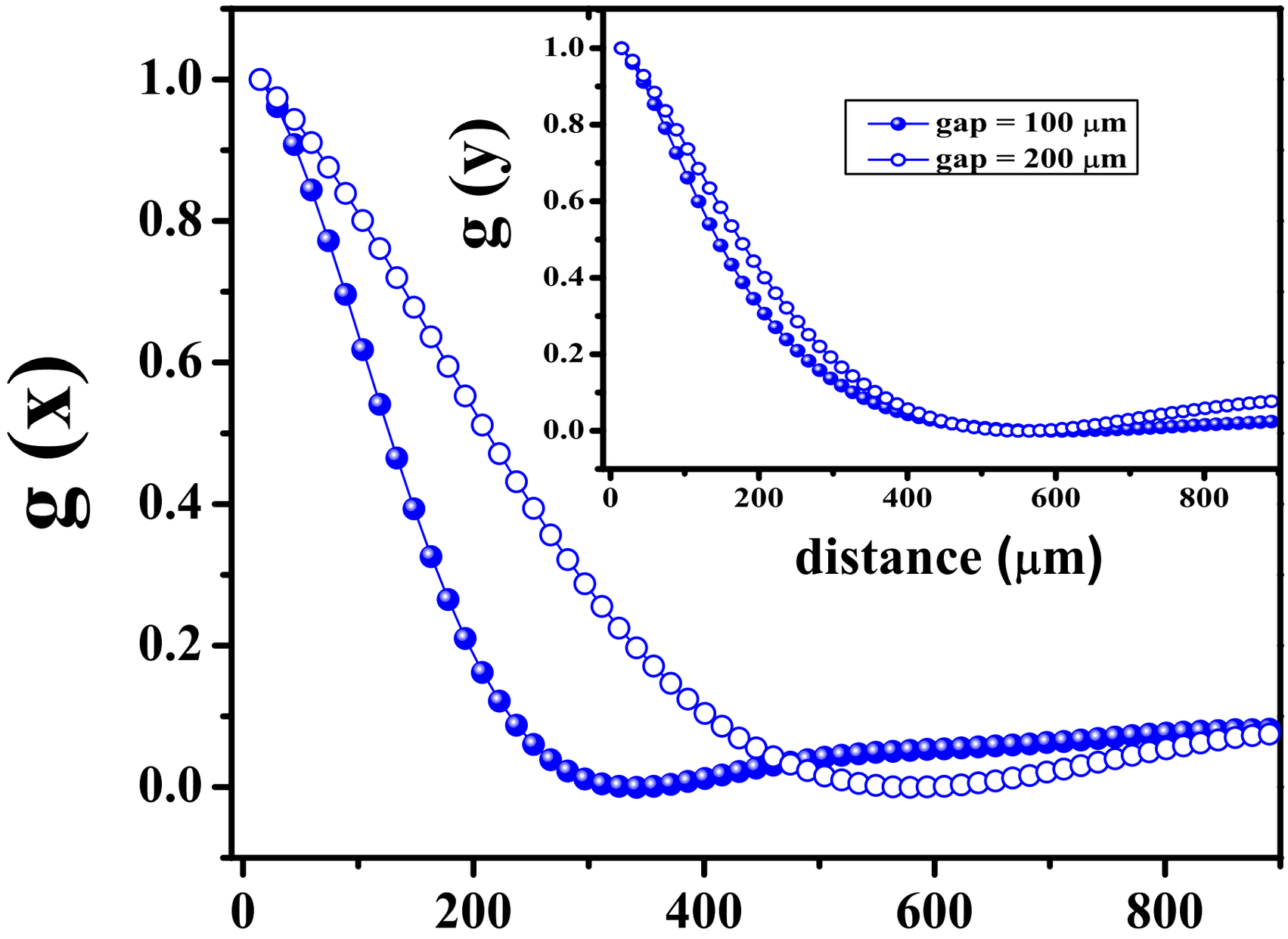
$$\eta_A = (1-f)\eta_L + f\eta_H$$

f — area fraction





Gap Determines Scale



$$g(\delta r) = \frac{< \delta\sigma_x(\vec{r},t)\delta\sigma_x(\vec{r}+\vec{\delta r},t) >}{< \delta\sigma_x(0,t)^2 >}$$

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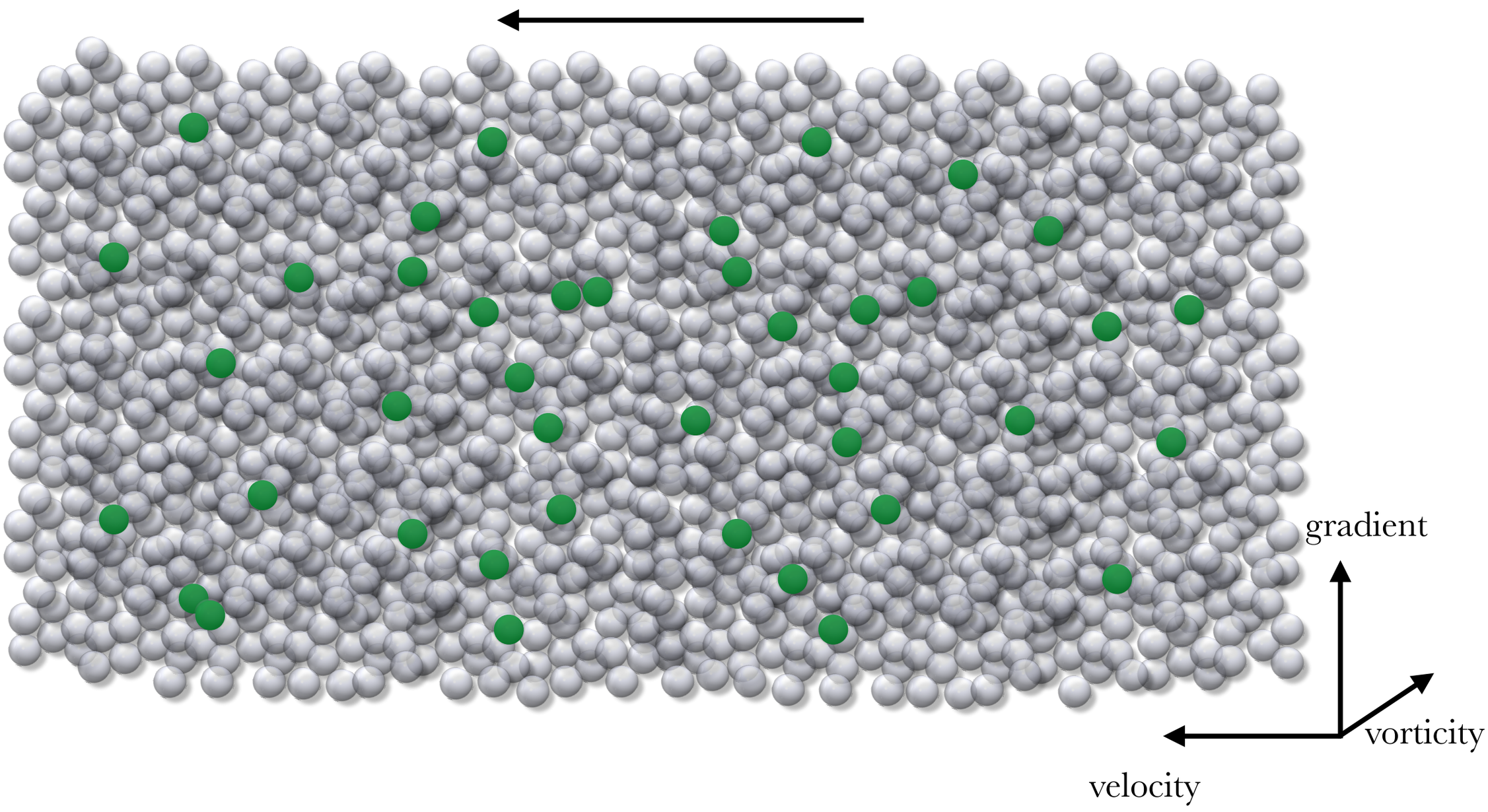
Shear Jamming/DST



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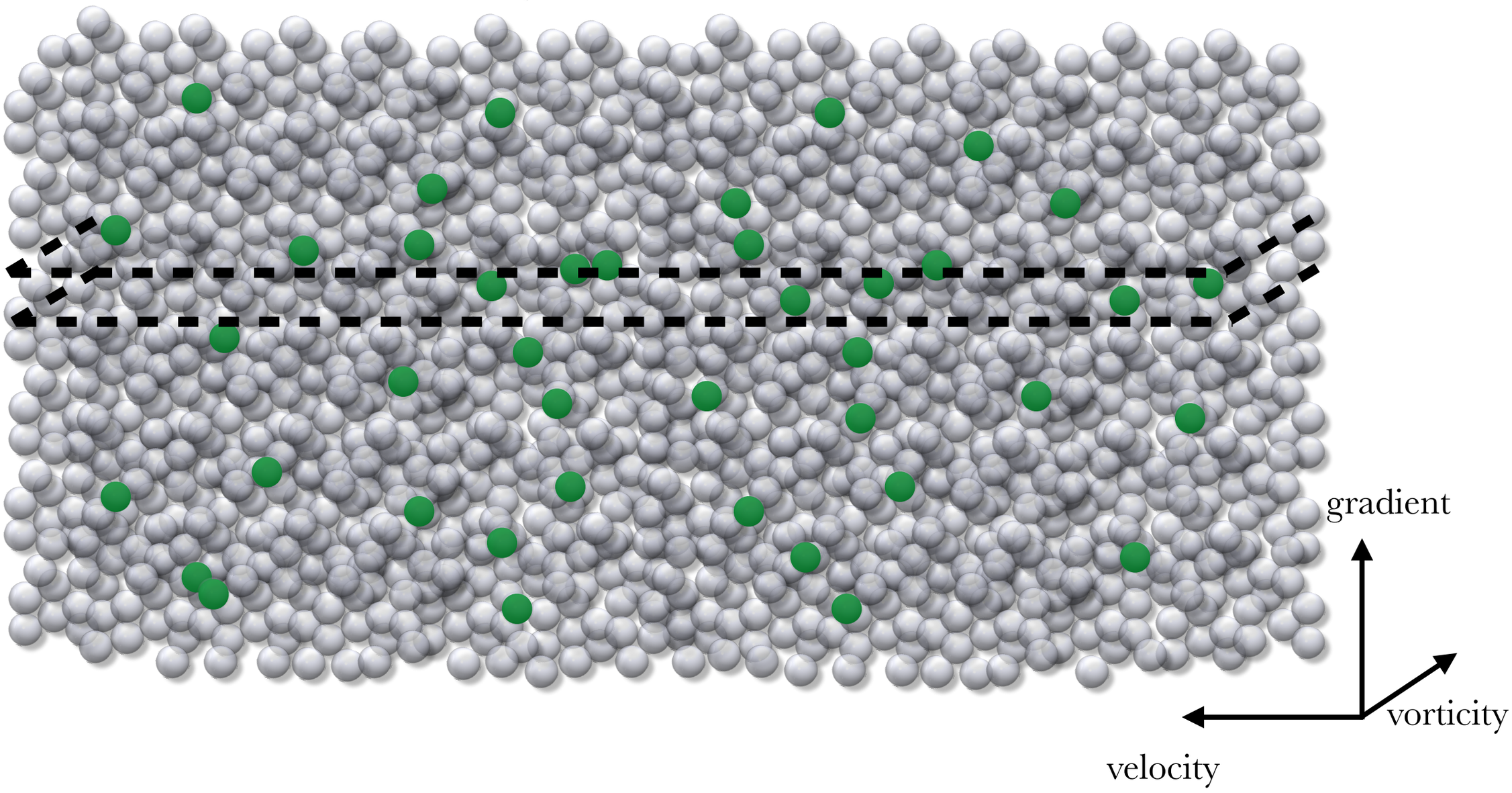
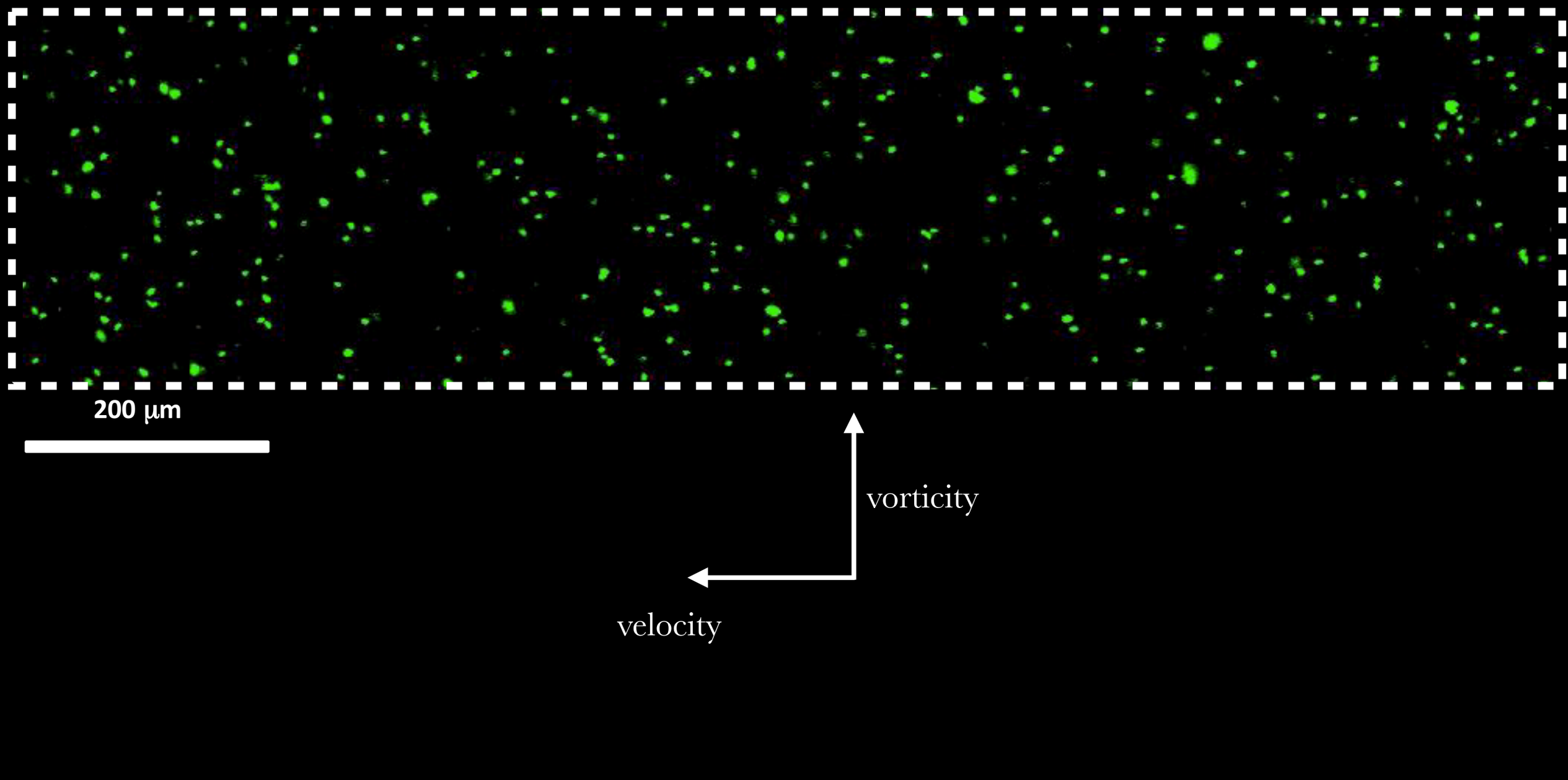


Bulk Flow Behavior: Constant Stress

$\sigma = 2200$ Pa



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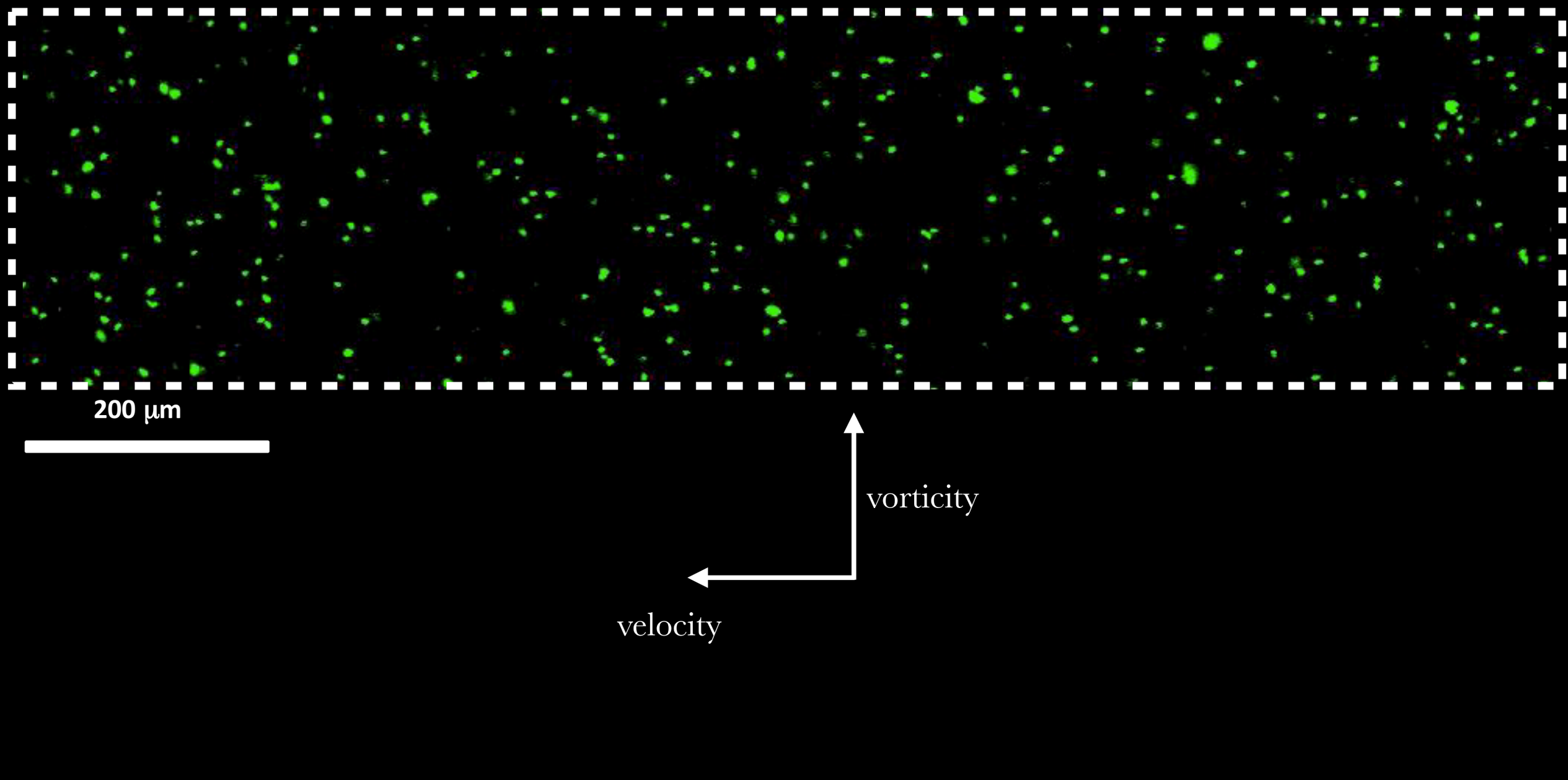

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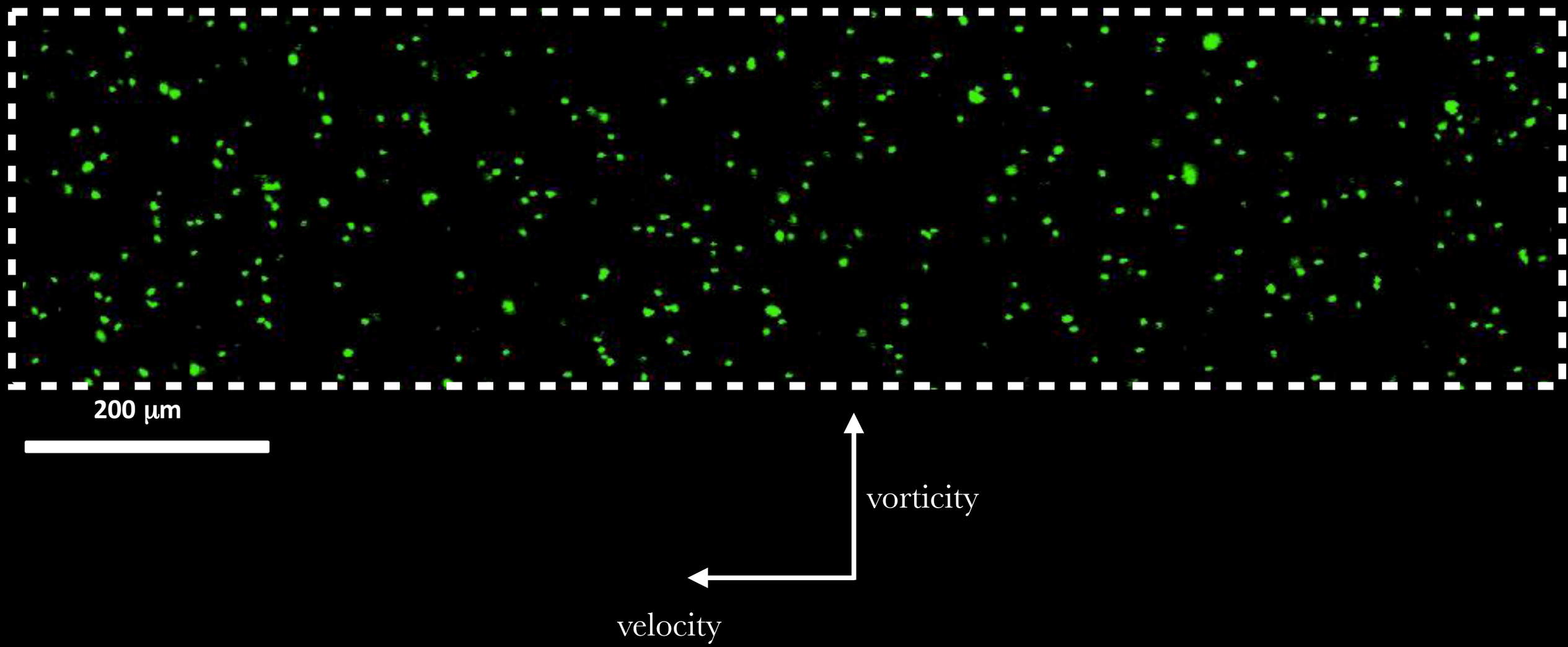
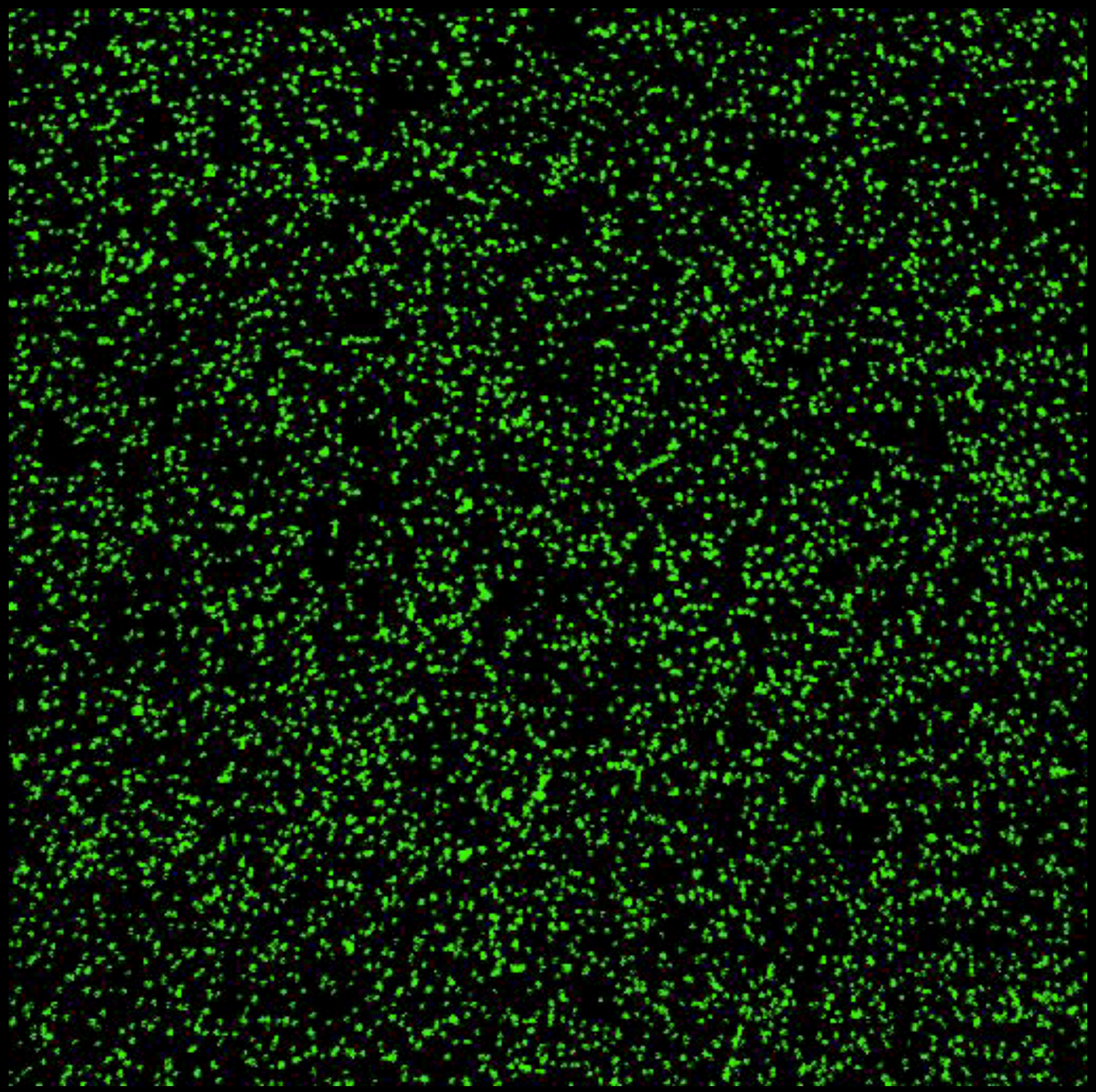


when flow stops: dilatancy?

Boundary Stresses: Dilatancy

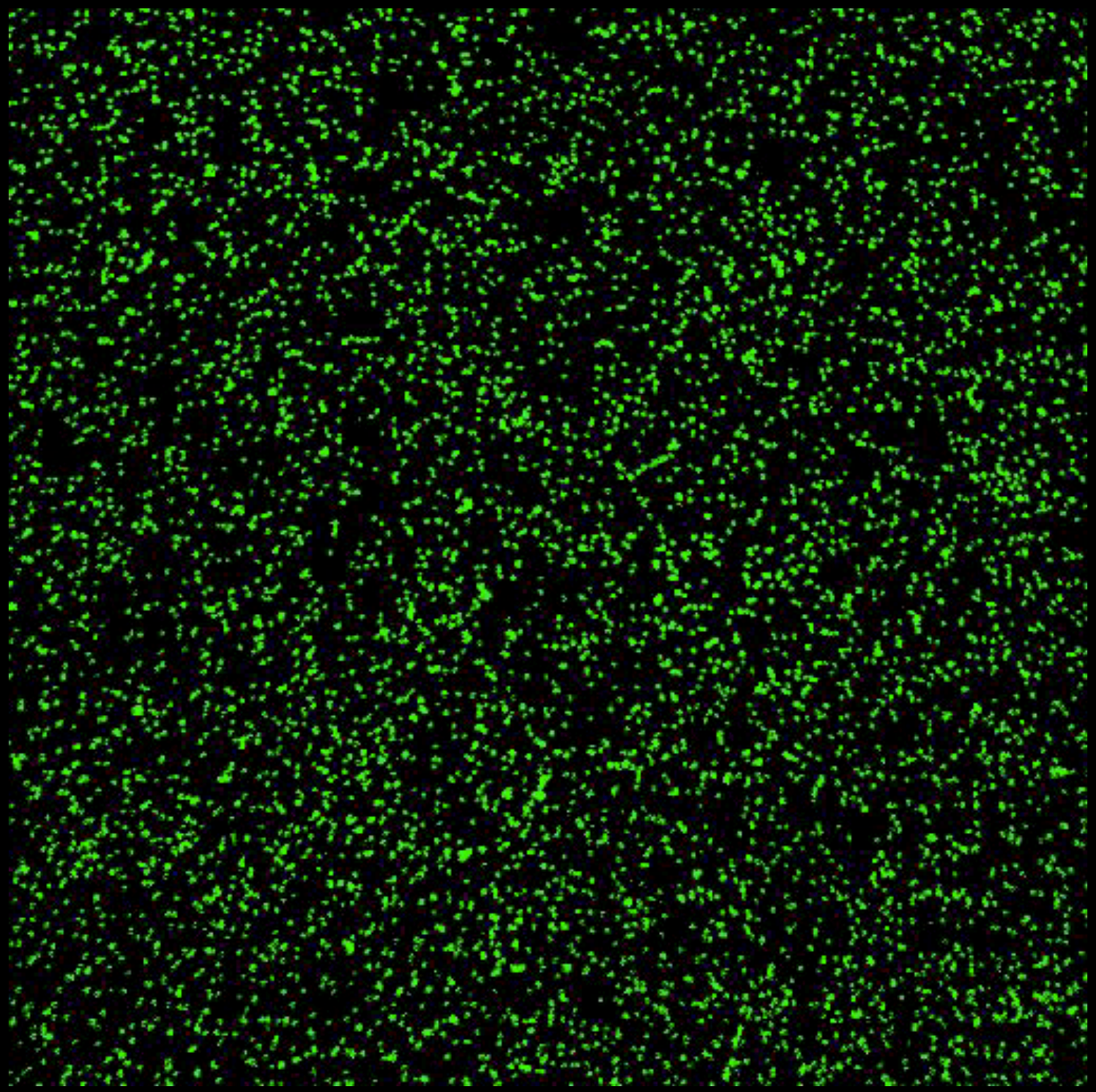


vorticity

velocity

σ = 2200 Pa

Boundary Stresses: Dilatancy



vorticity

velocity

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vorticity

velocity

grad

pdms

velocity

vorticity

velocity

focal plane

pdms

velocity

grad

vorticity

velocity

focal plane

pdms

velocity

grad

vorticity

velocity

focal plane

pdms

velocity

grad

So, What's Next?

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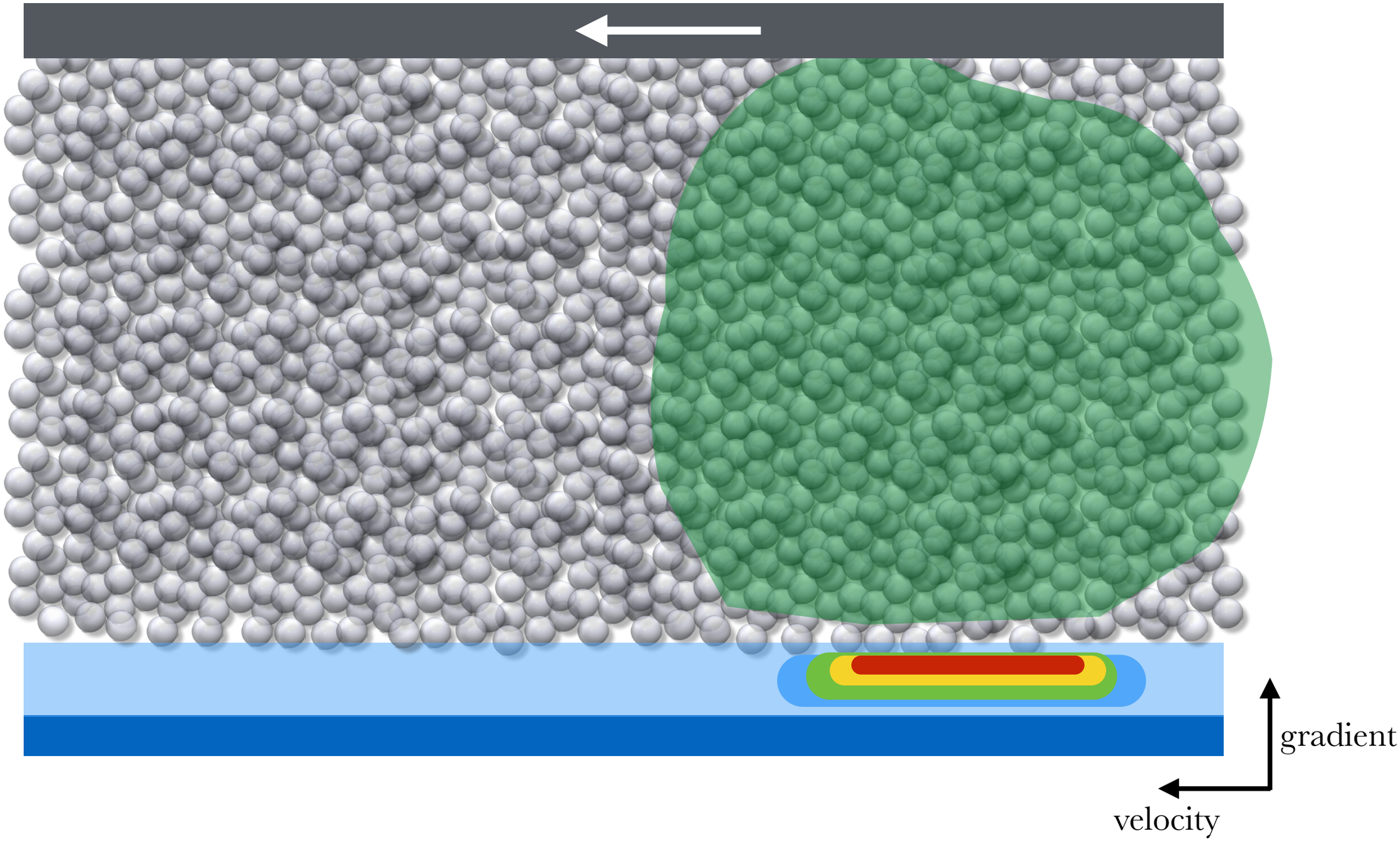
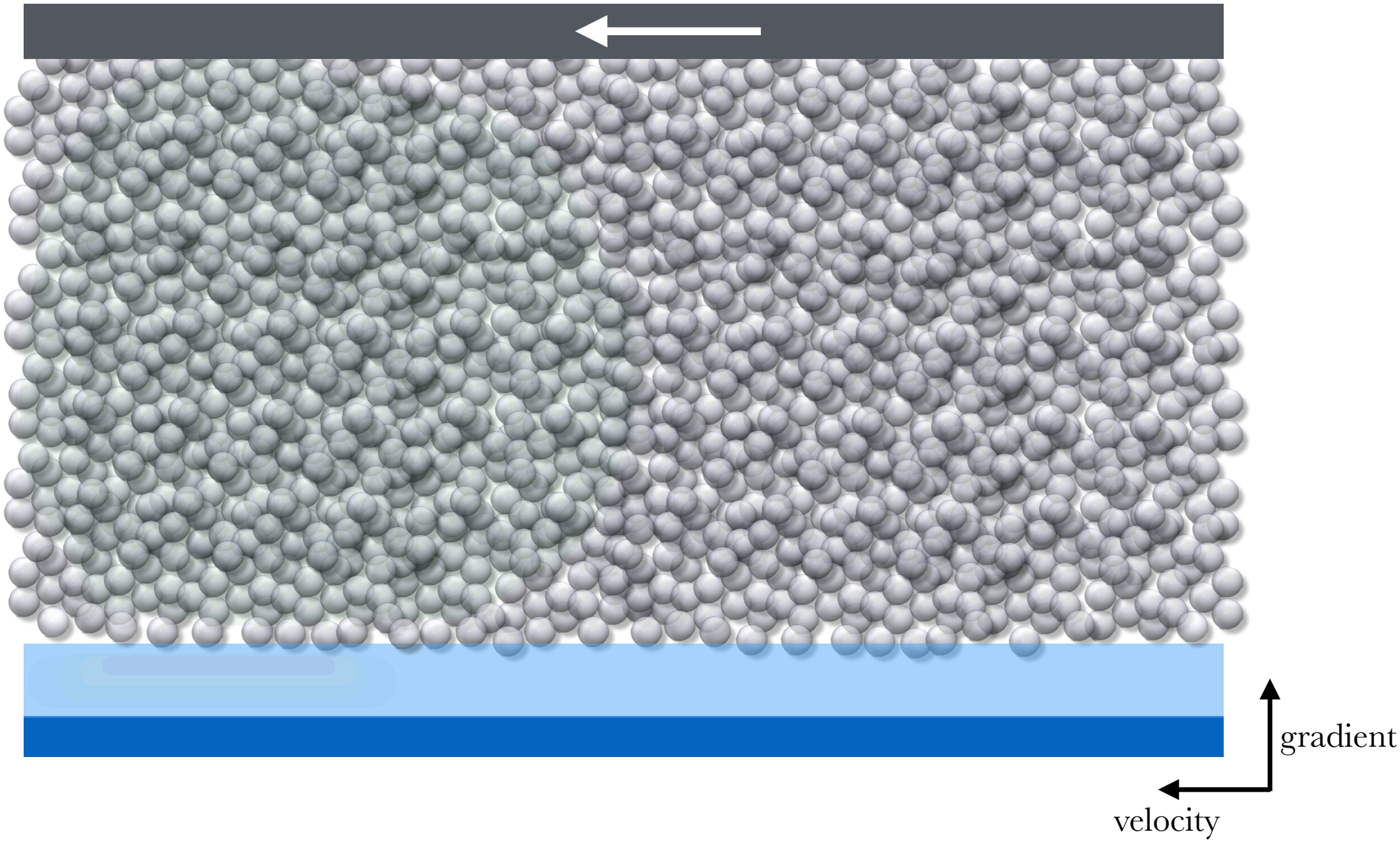
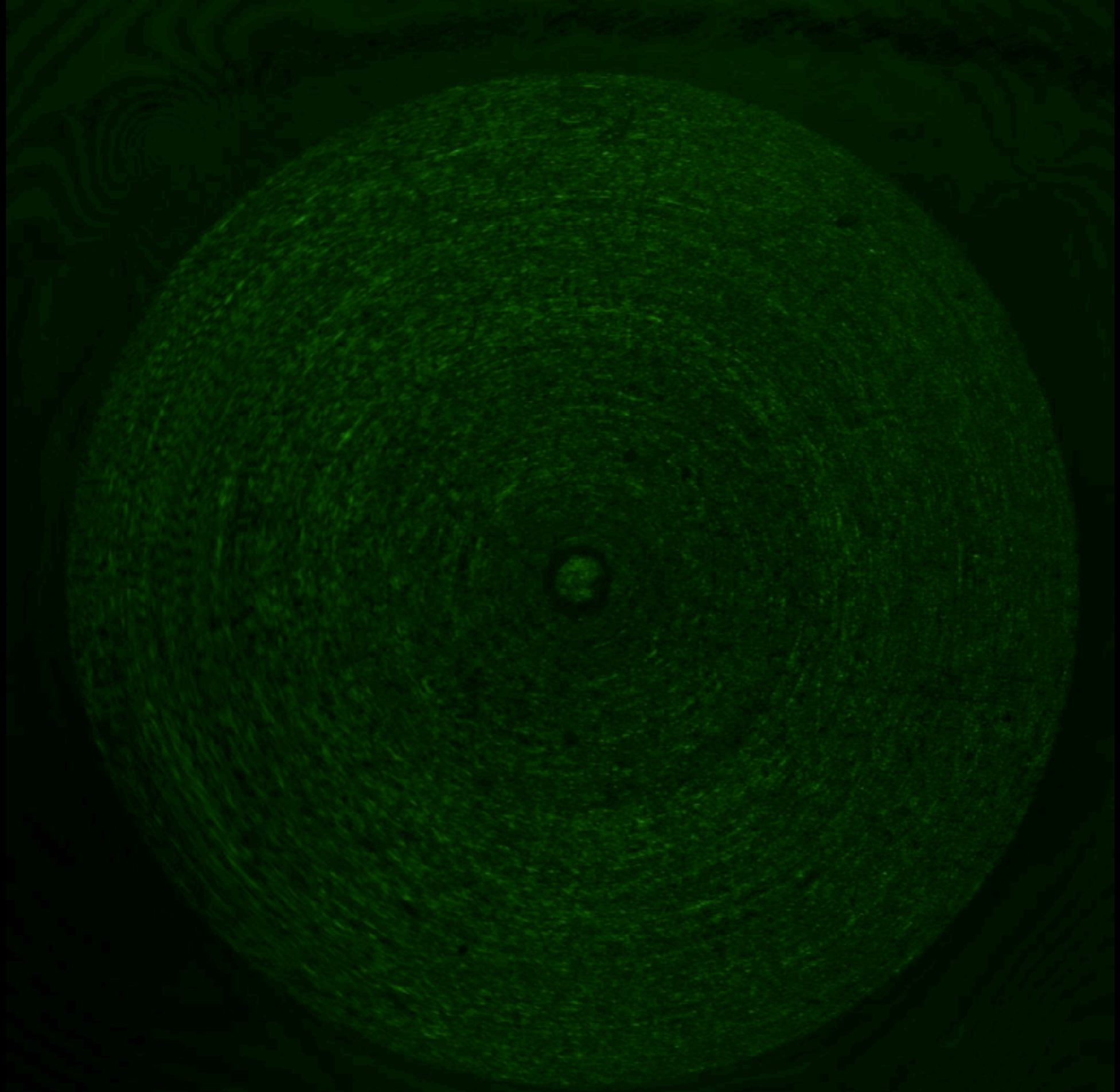
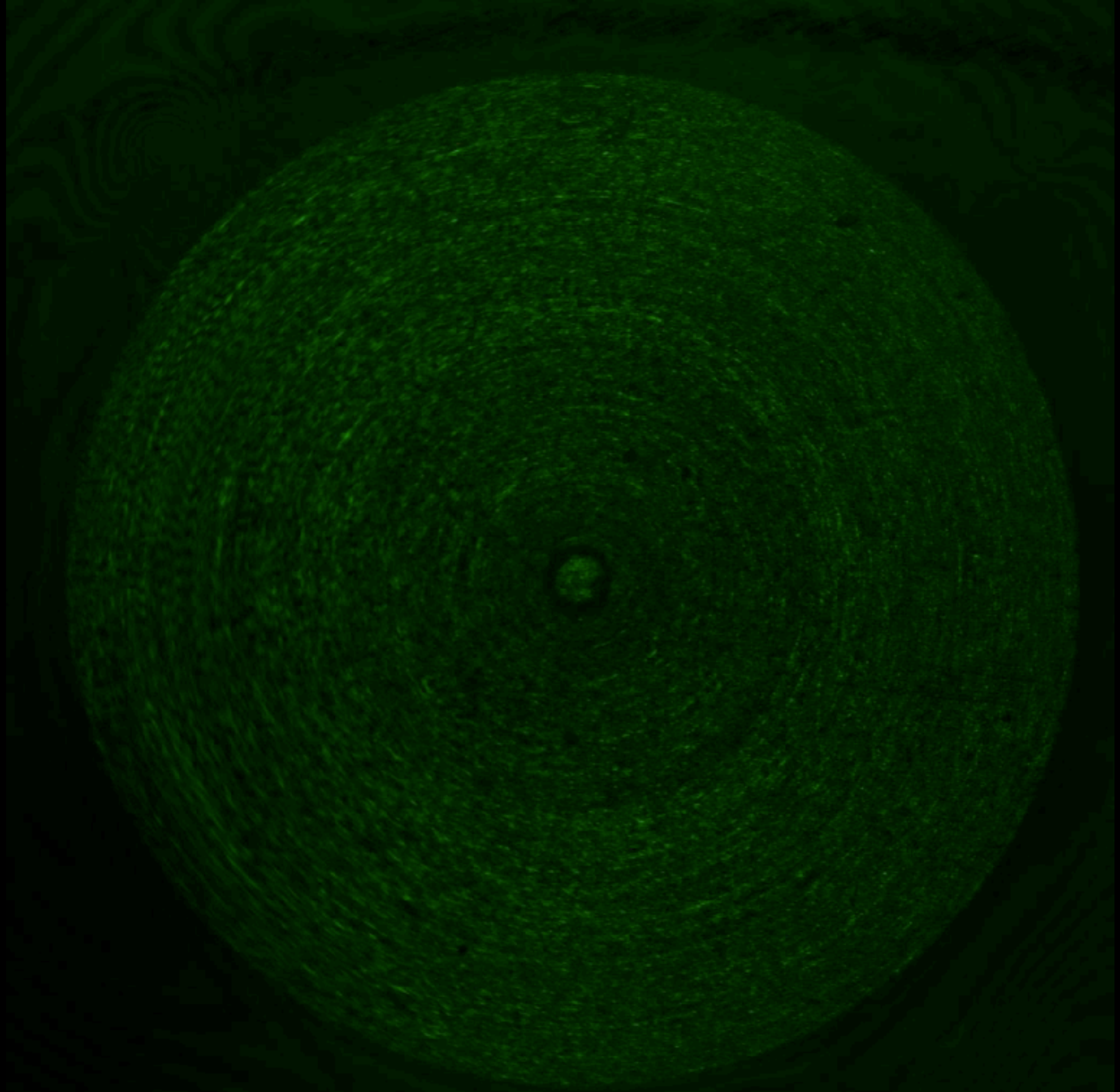
What Controls the Lifetime?



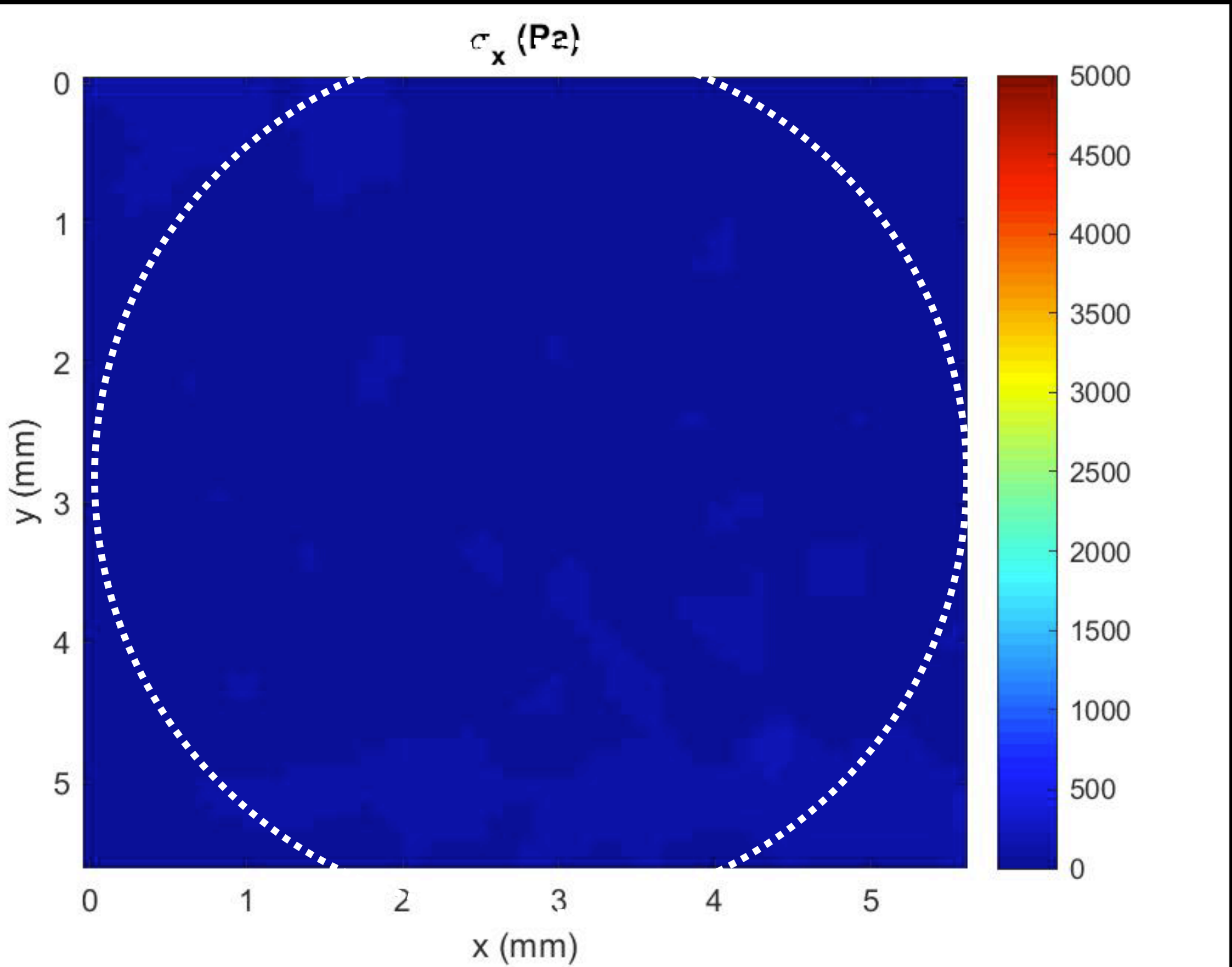
What Controls the Lifetime?







75 Pa h=300μm ϕ=56% d = 1.5μm



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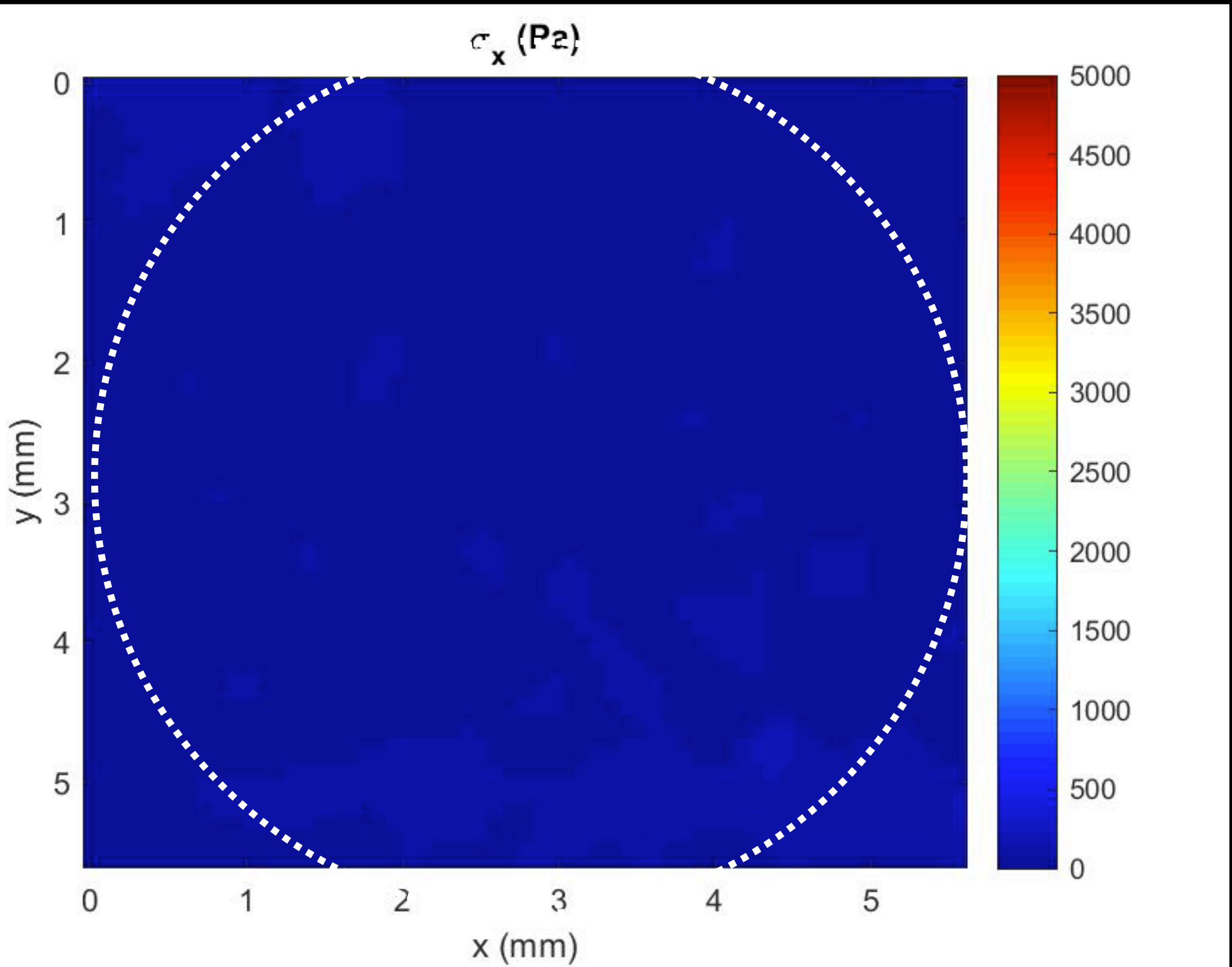
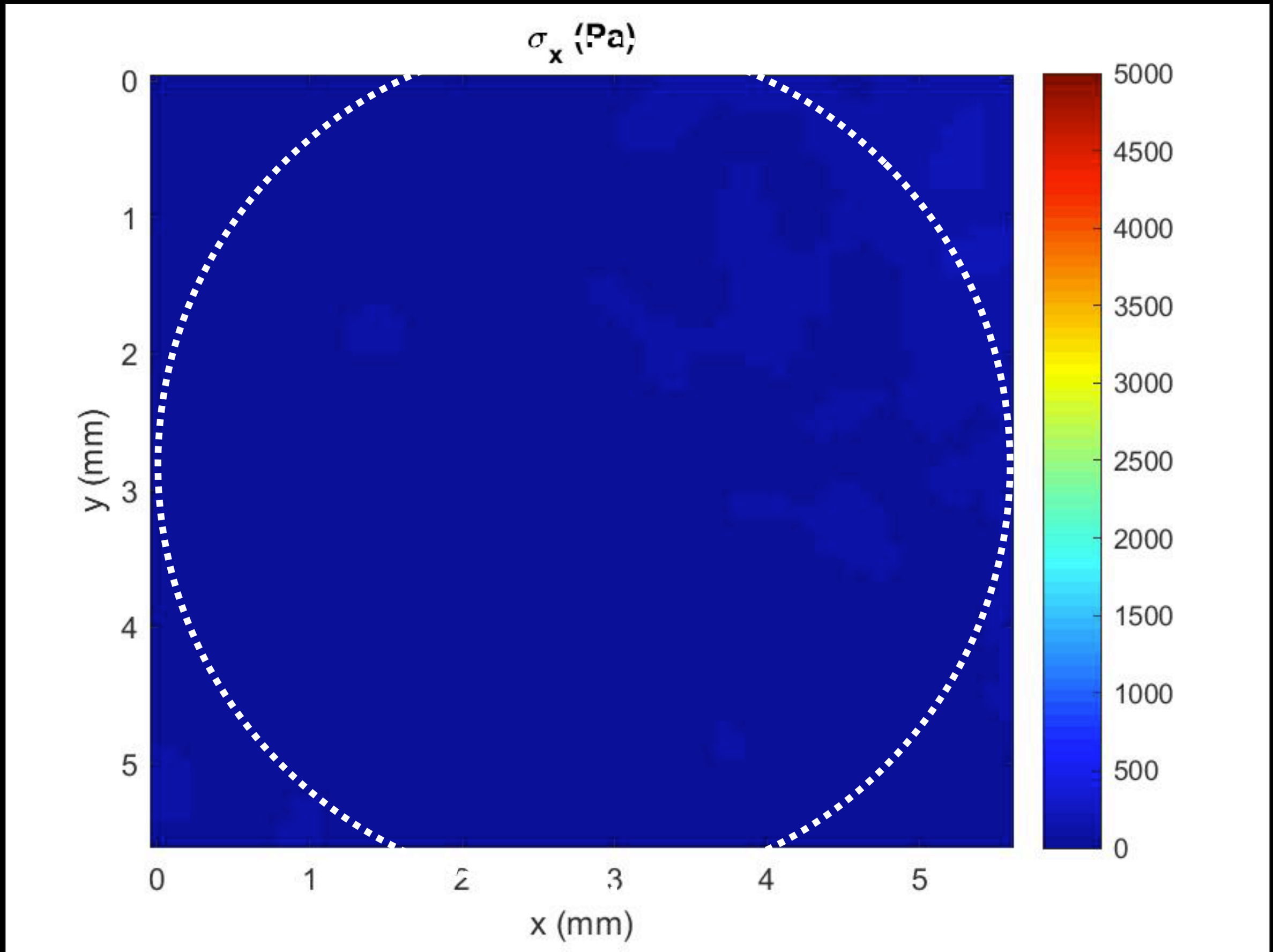


200 Pa h=200μm ϕ=56% d = 1.5μm



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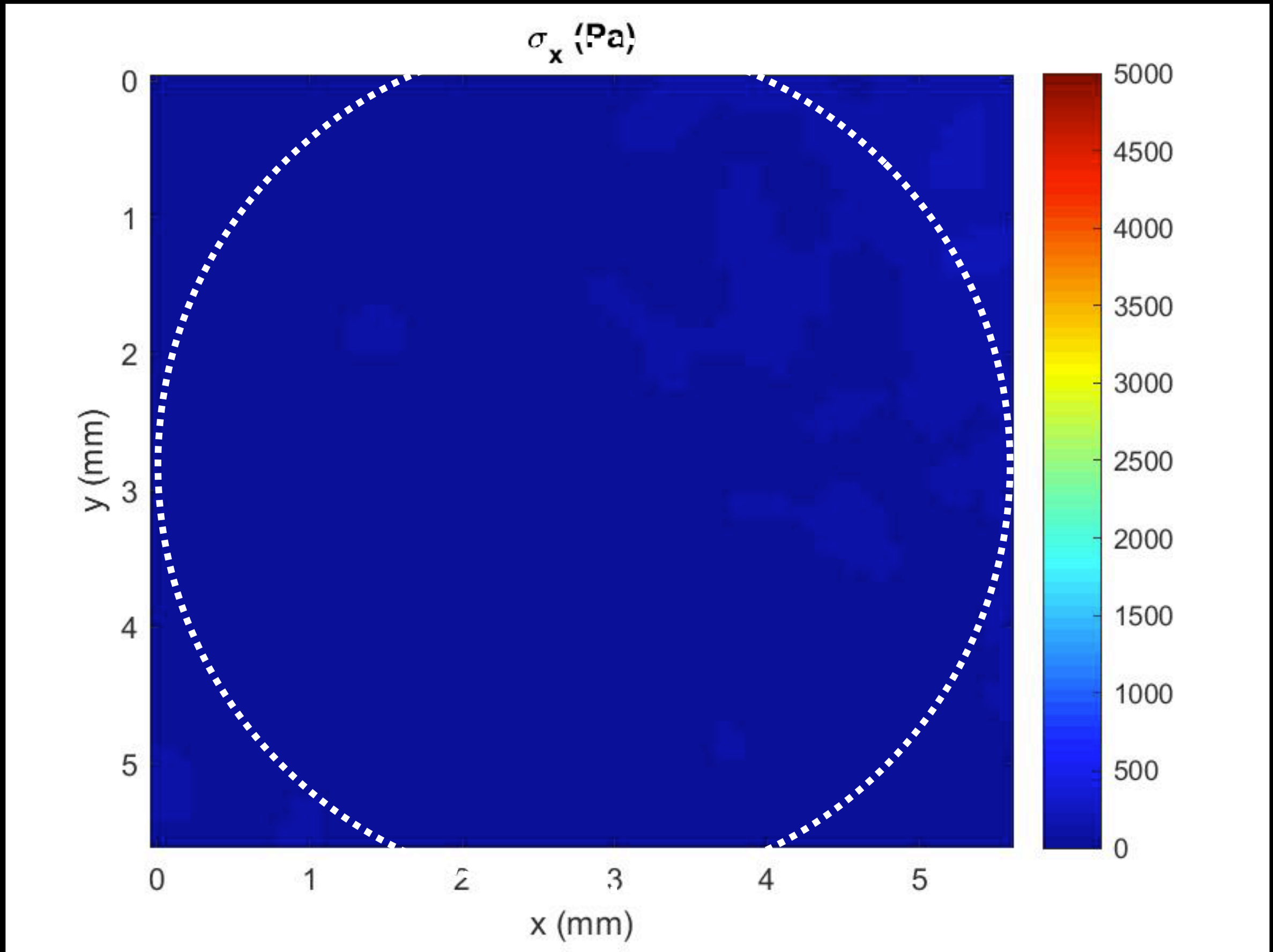
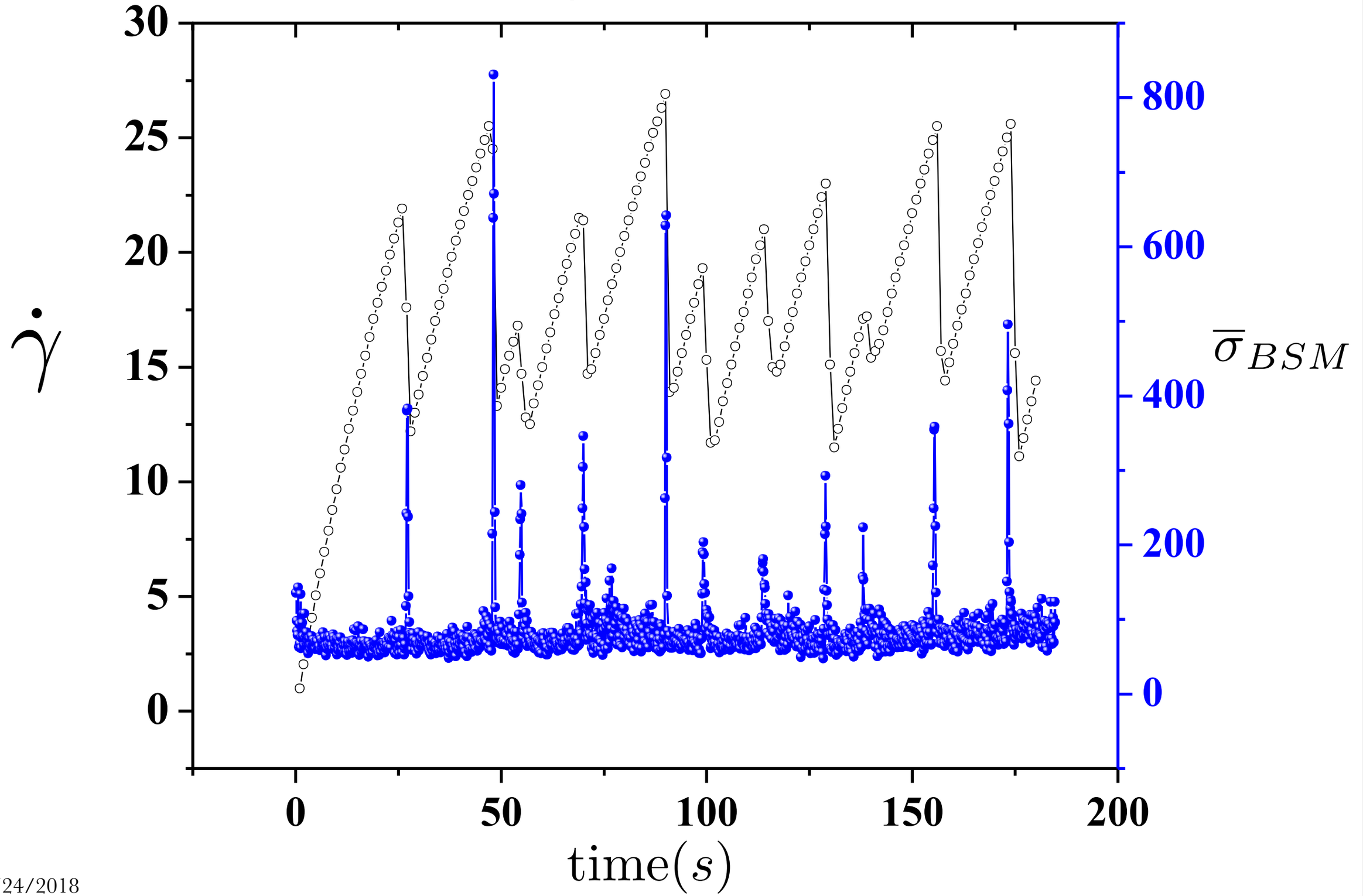


Local and Global Fluctuations

τ = 75 Pa, ϕ = 0.56, PP 5.2



Local and Global Fluctuations

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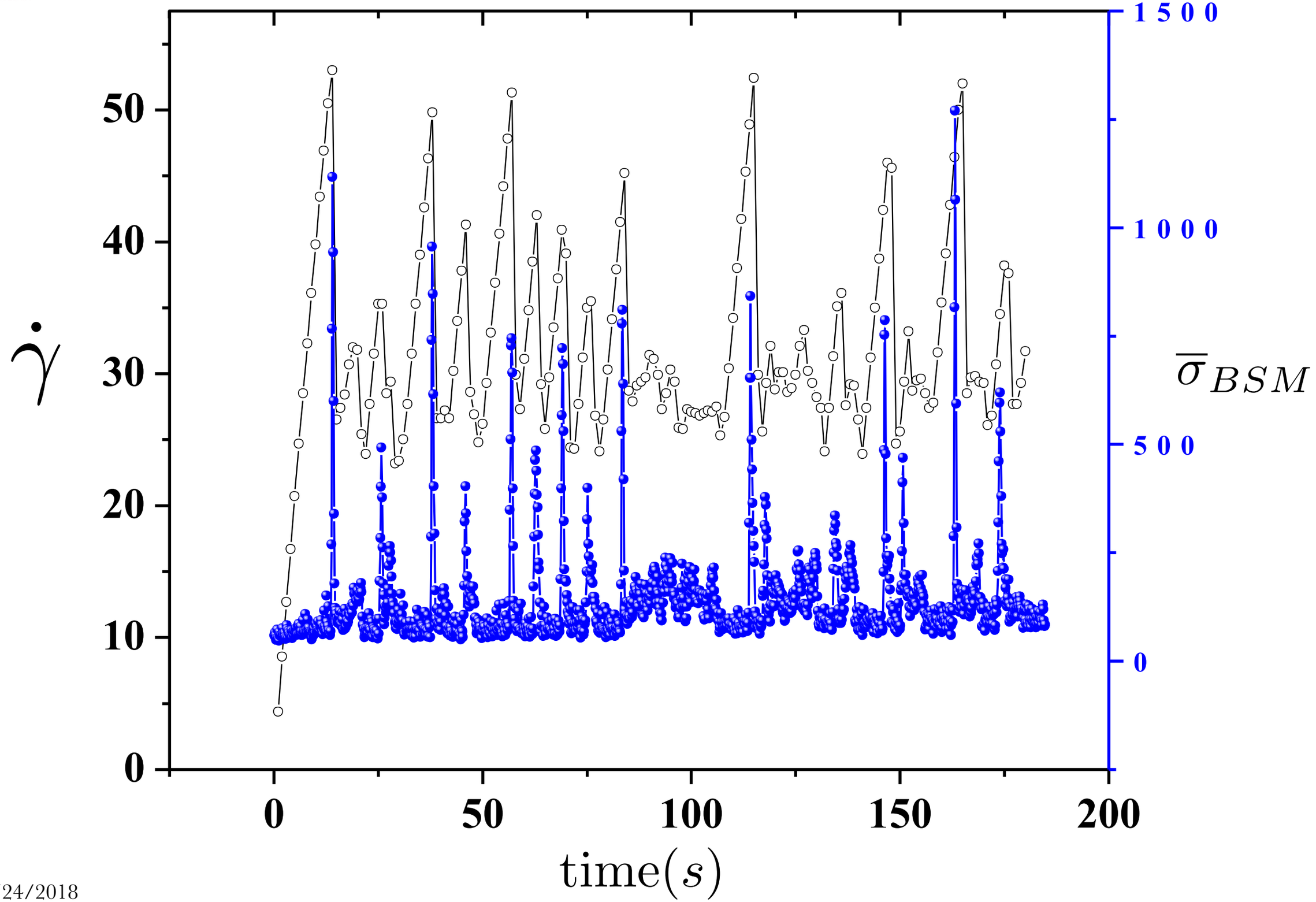

Conclusions

- Shear Thickening — frictional /dilatant
- Phase separation process — low/high viscosity
- Surface Stress Reveals Intermittency
- The Boundary Reveals New Rheology

The Boundary is Cool

Thank You For Your Attention

- Blair-lab Members
  - Vikram Rathee (post-doc)
  - Rich Arevalo (grad student)
  - Pasha Tabatabai (now at Yale)
  - Kara Googins (grad student