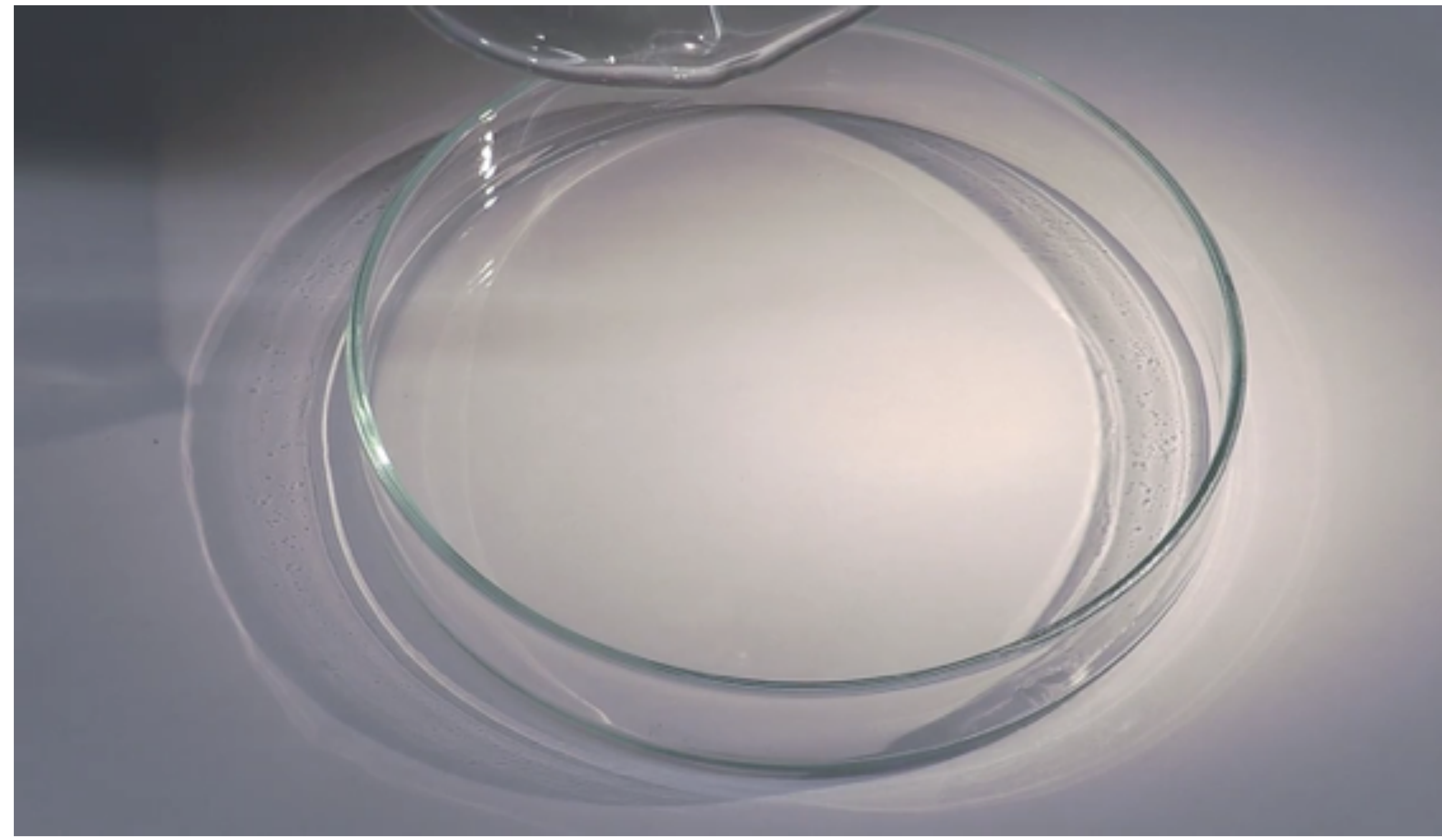
Contact forces and particle interactions in shear thickening suspensions

John R. Royer
Joseph French
Julien Sindt
Jin Sun
Wilson Poon

Shear thickening

+



Video from ETH Zurich Soft Materials youtube channel

Shear thickening

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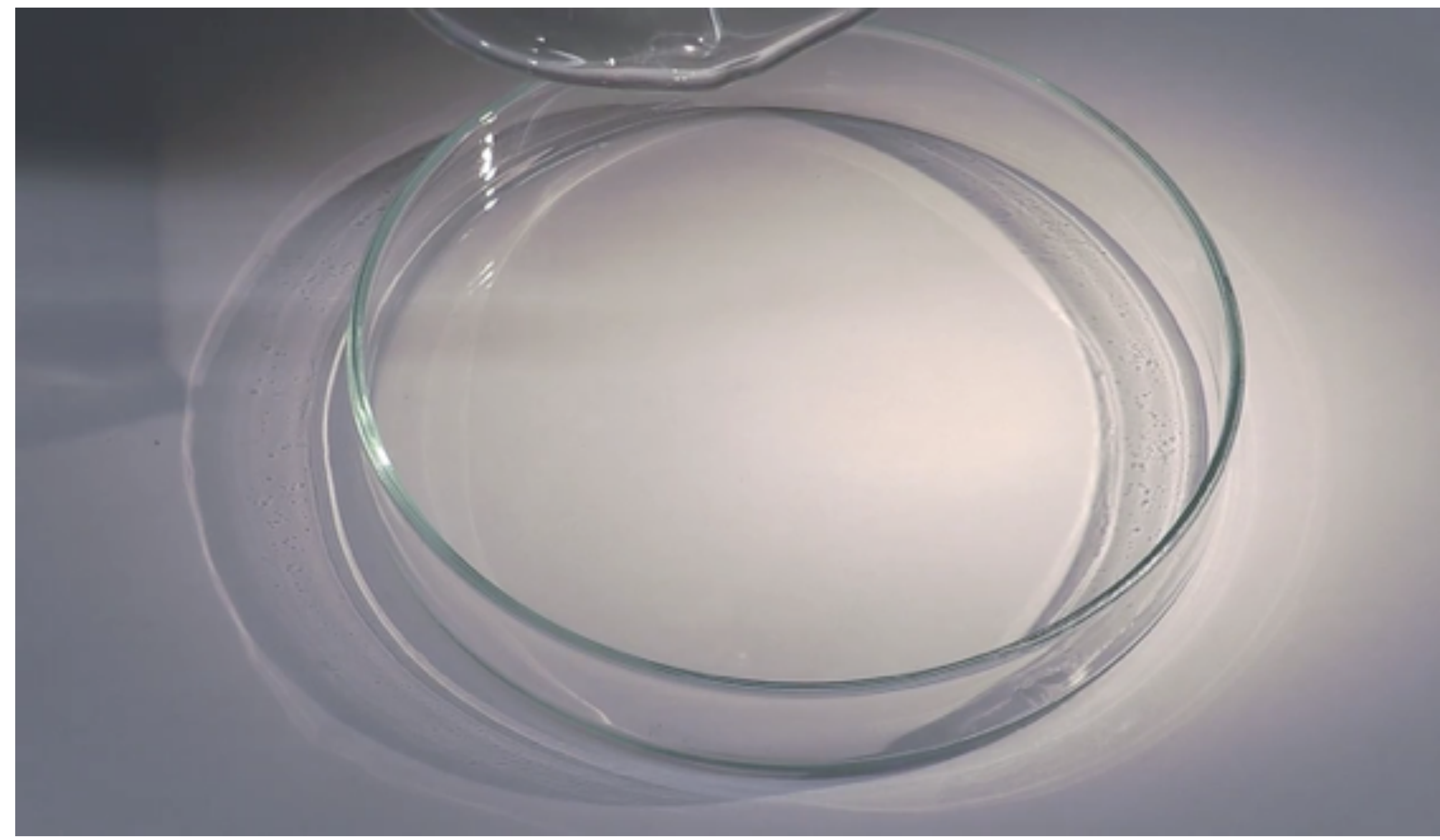

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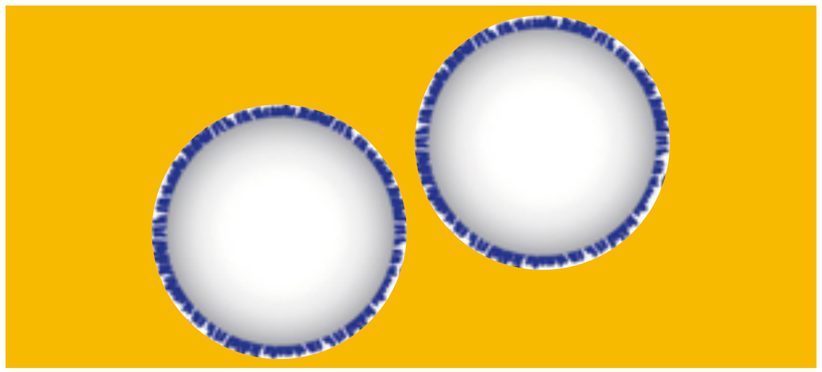
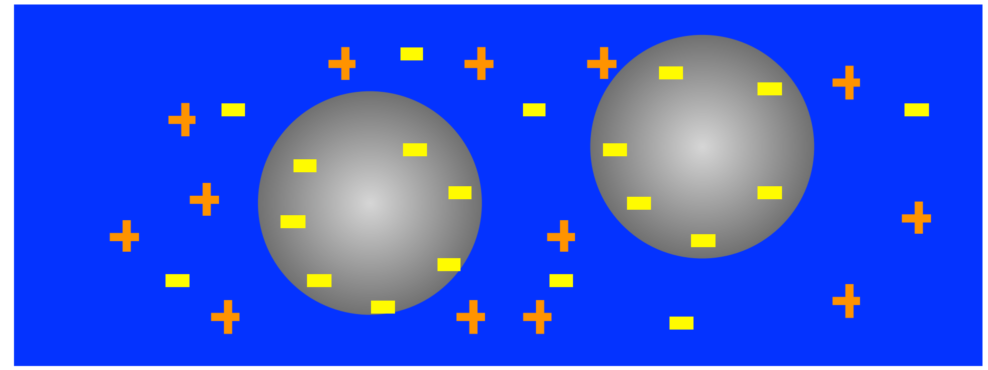
Continuous Shear Thickening

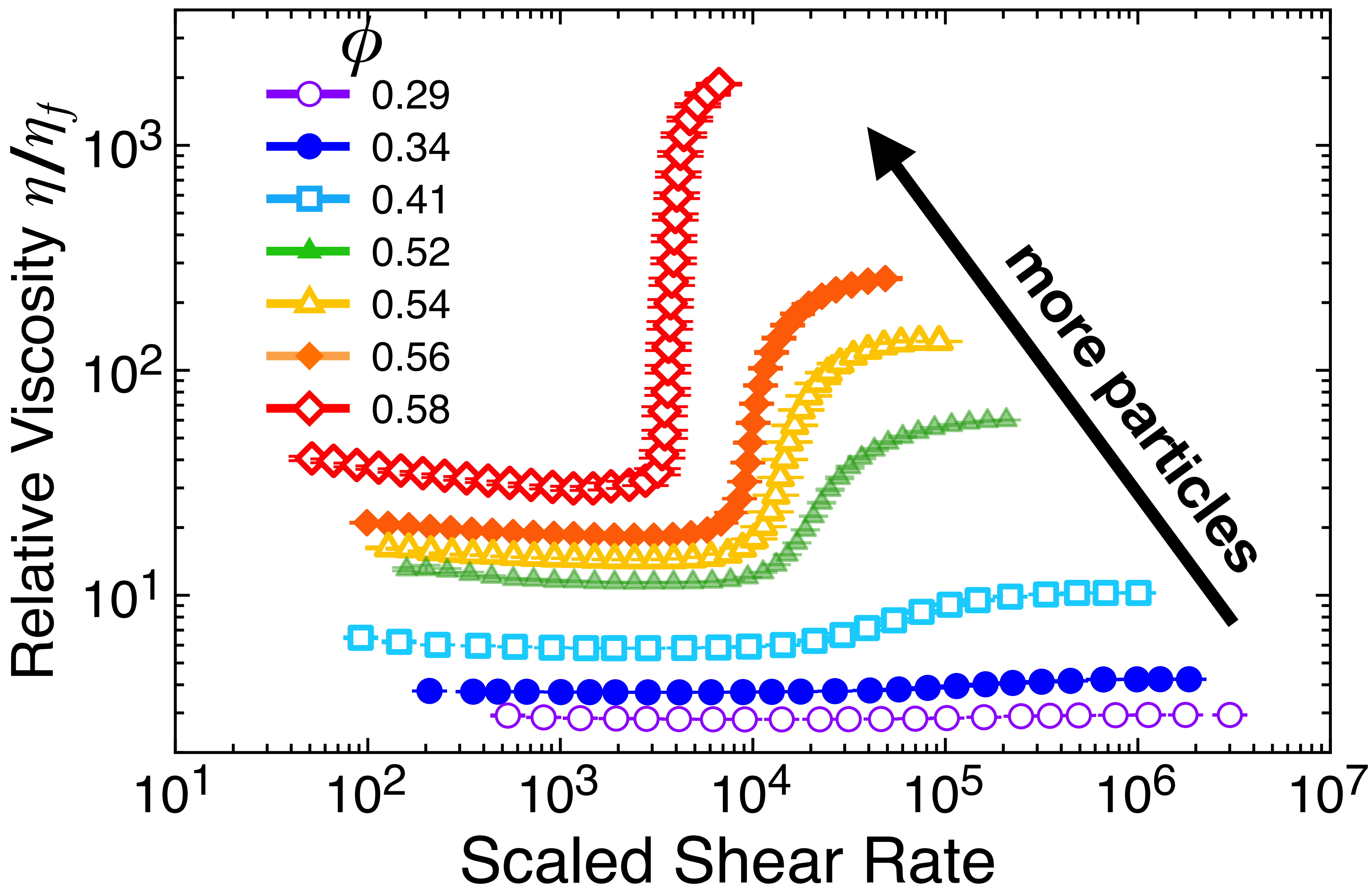


sterically stabilised particles

or

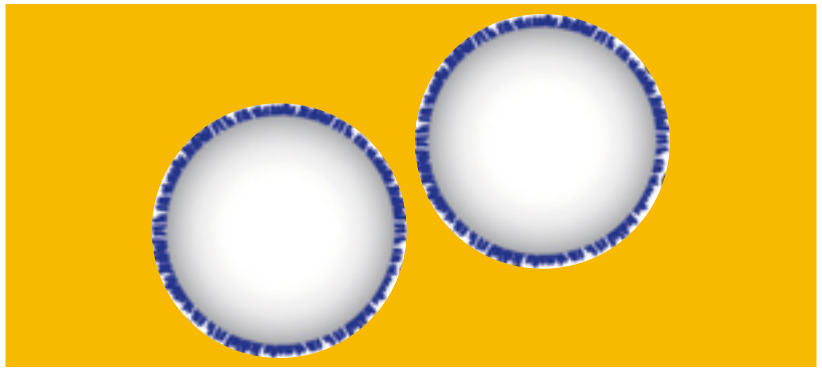


charge stabilised particles



Guy, Hermes, Poon, PRL 2015
Royer, Blair, Hudson PRL 2016

Continuous Shear Thickening



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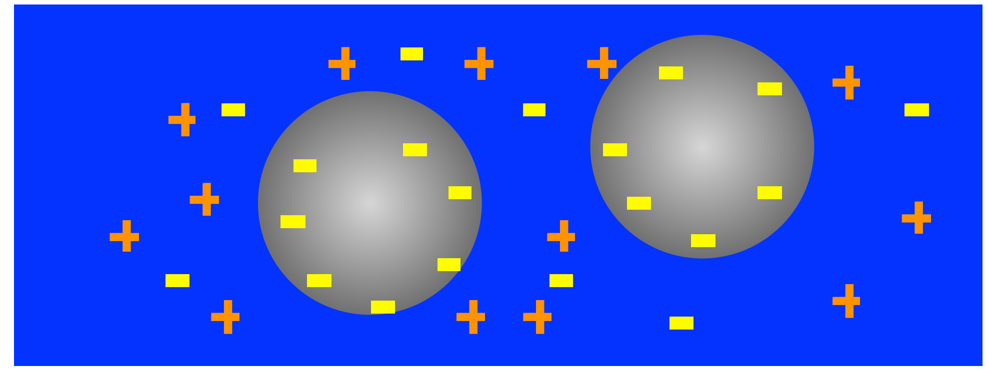
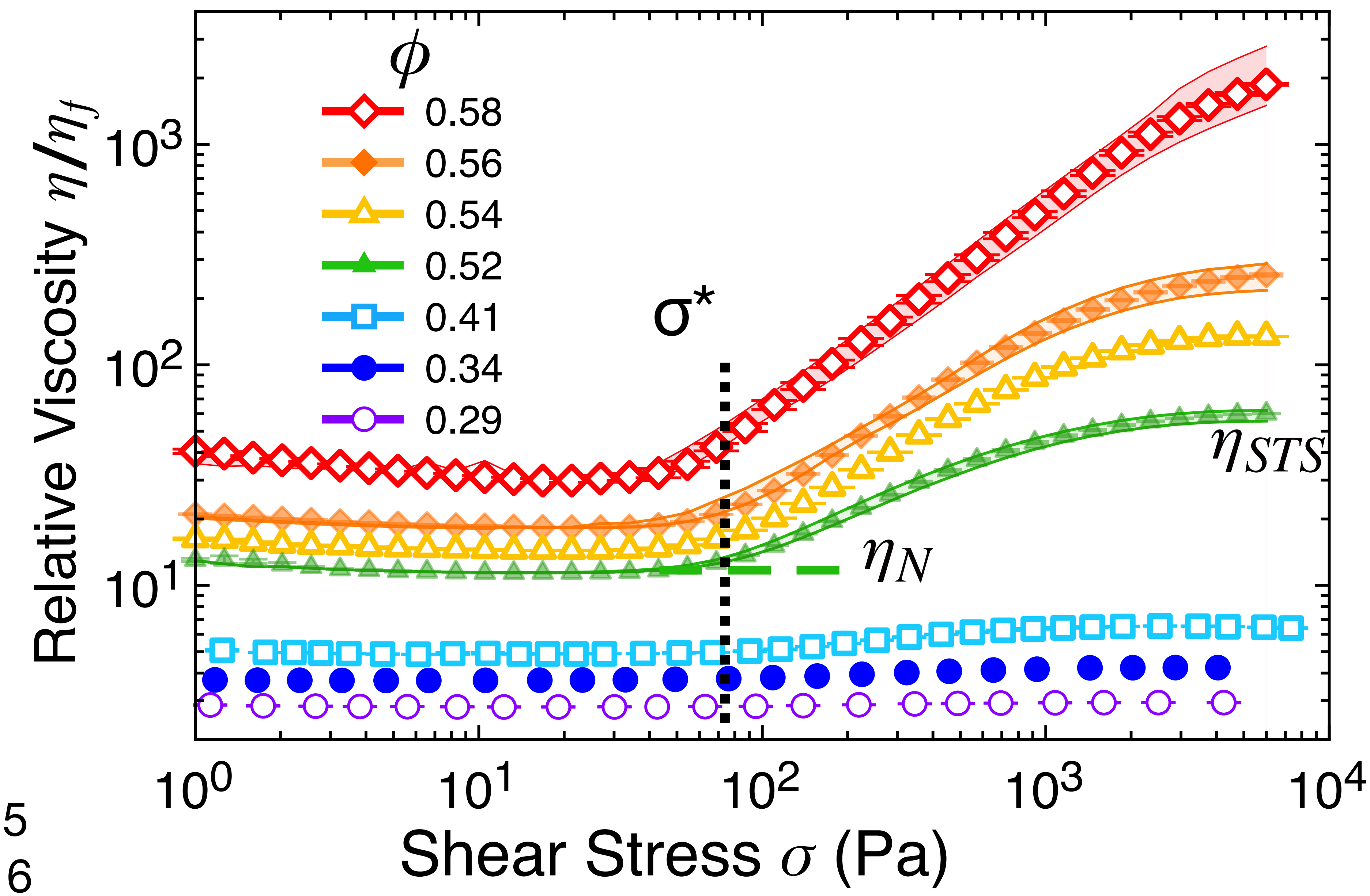


charge stabilised particles

Characteristic stress σ* independent of solids concentration.

$$\phi = \frac{V_{part}}{V_{total}}$$



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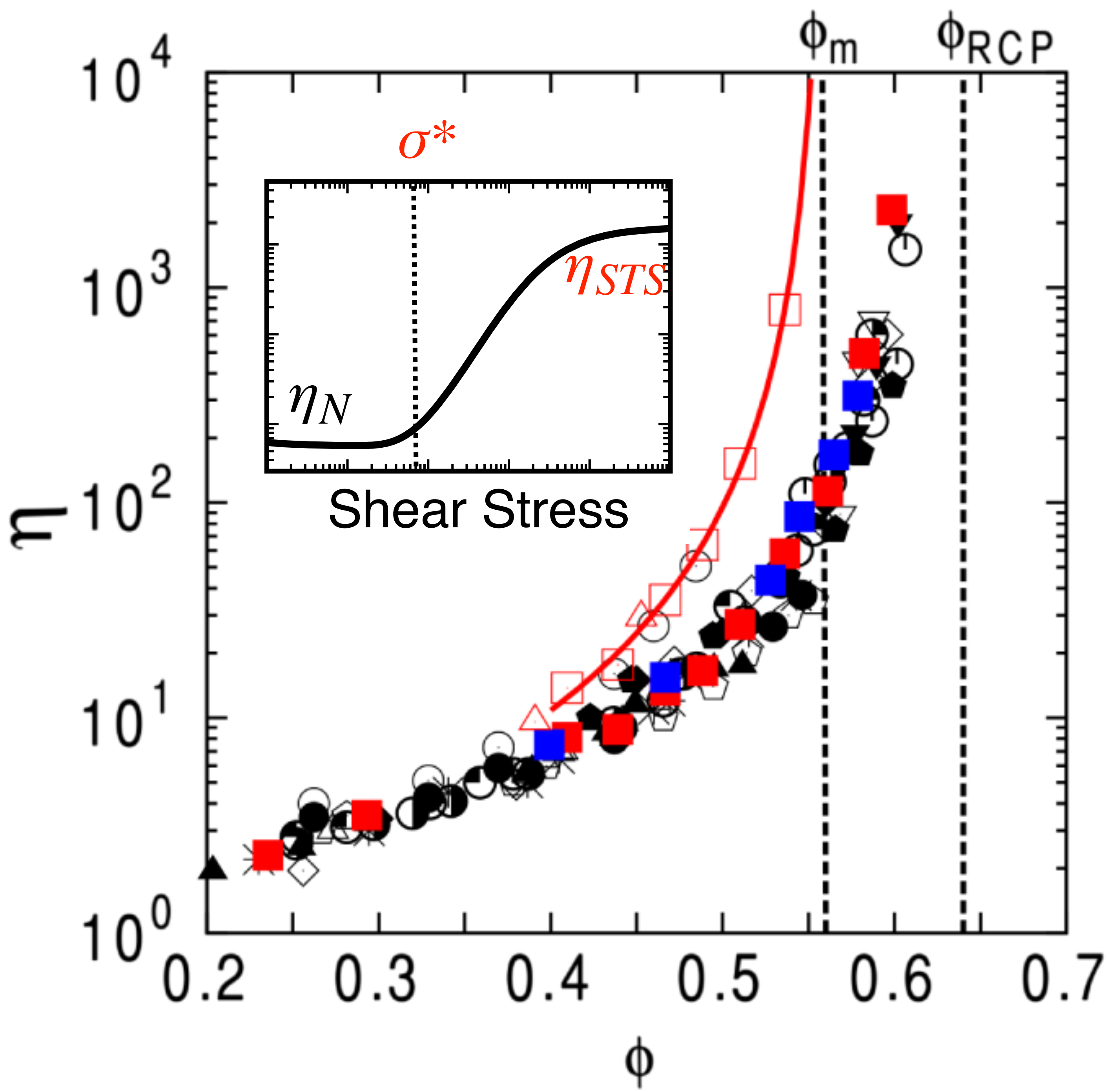
Shear Thickening - Jamming below RCP



Guy, Hermes & Poon, PRL 2015

Wyart and Cates, PRL 2014

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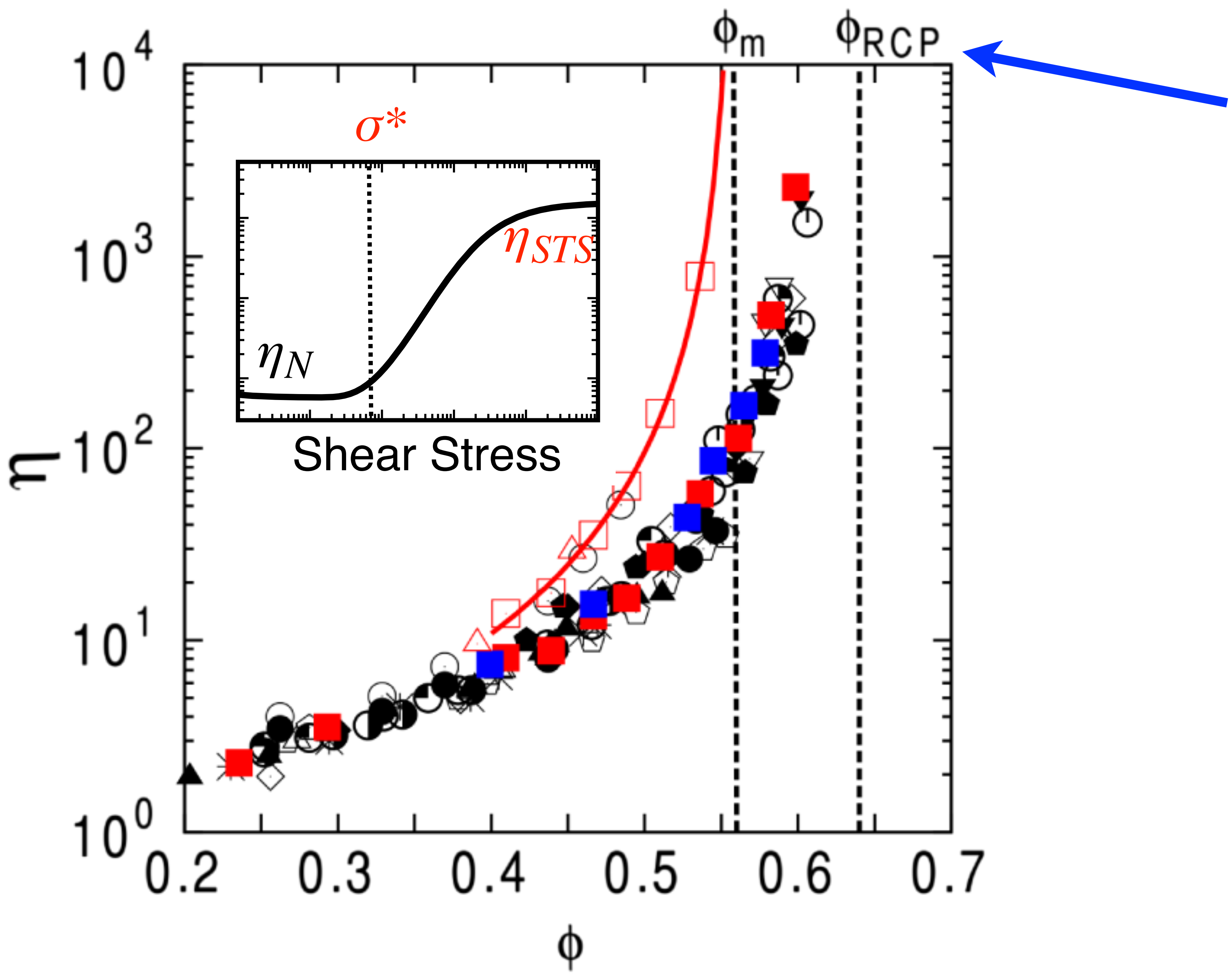
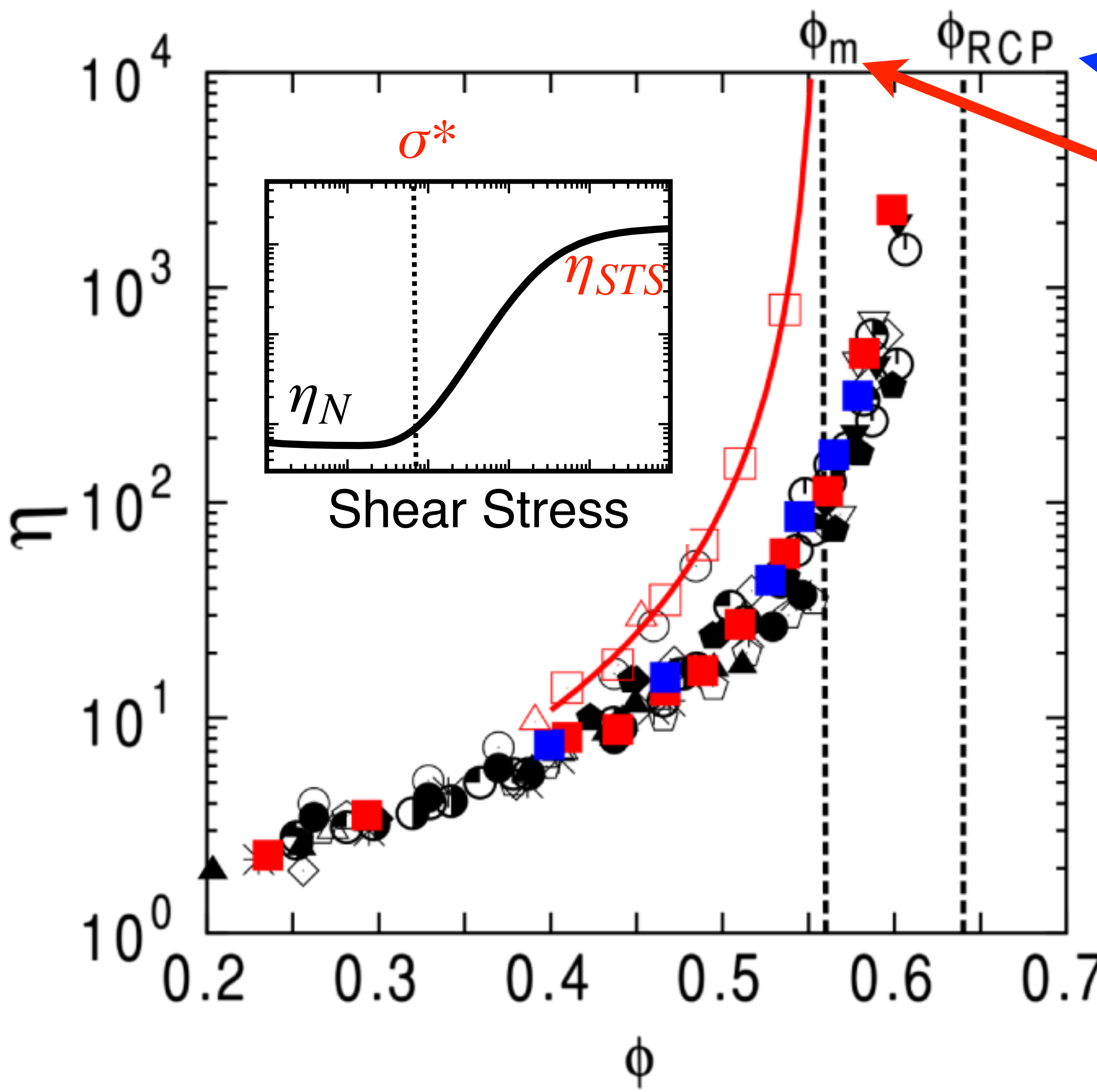


"Random close packing" for frictionless spheres

Guy, Hermes & Poon, PRL 2015

Wyart and Cates, PRL 2014

Shear Thickening - Jamming below RCP



“Random close packing” for frictionless spheres

Shear thickened viscosity diverges earlier

Guy, Hermes & Poon, PRL 2015

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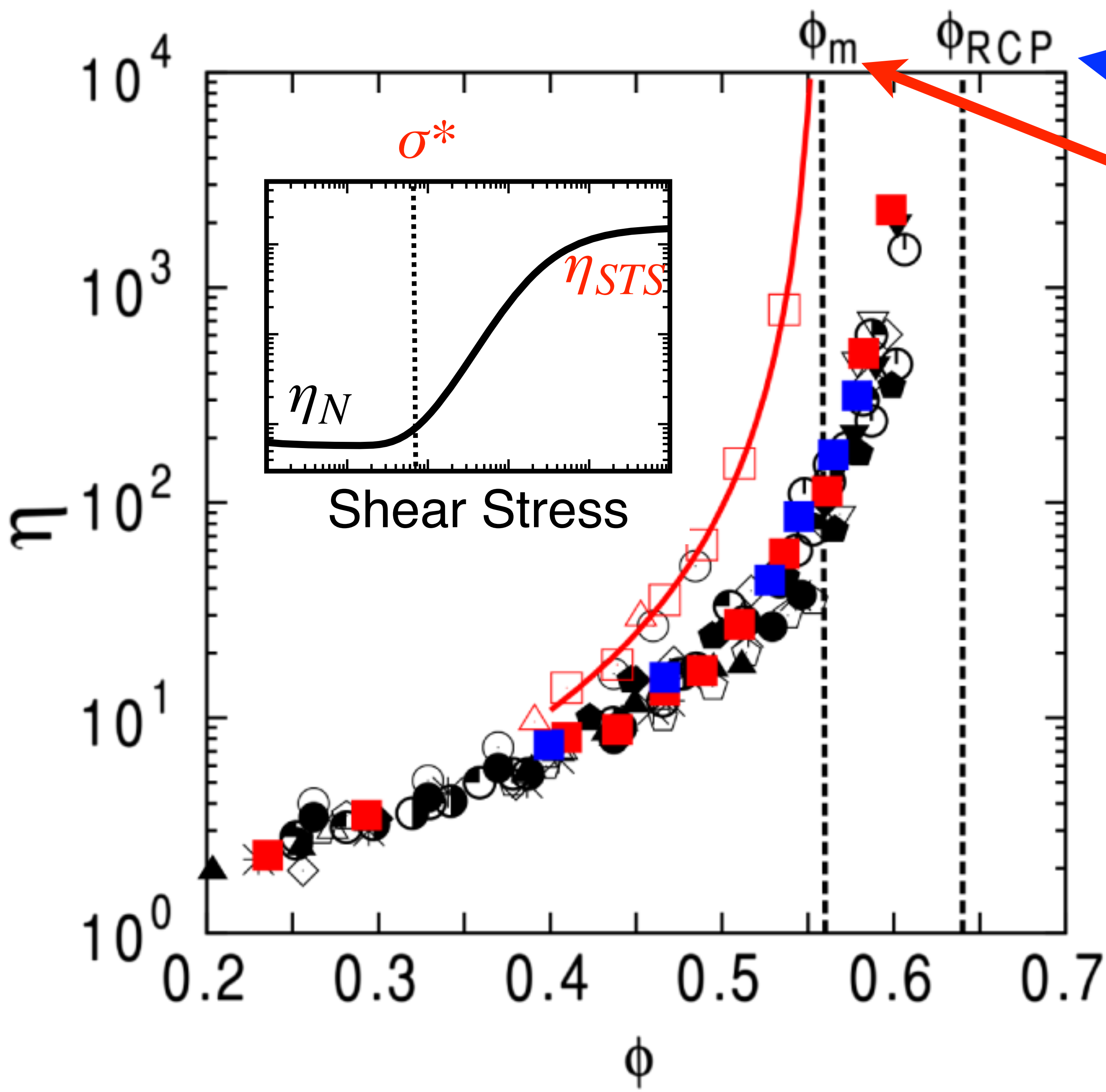
Shear Thickening - Jamming below RCP



“Random close packing” for frictionless spheres

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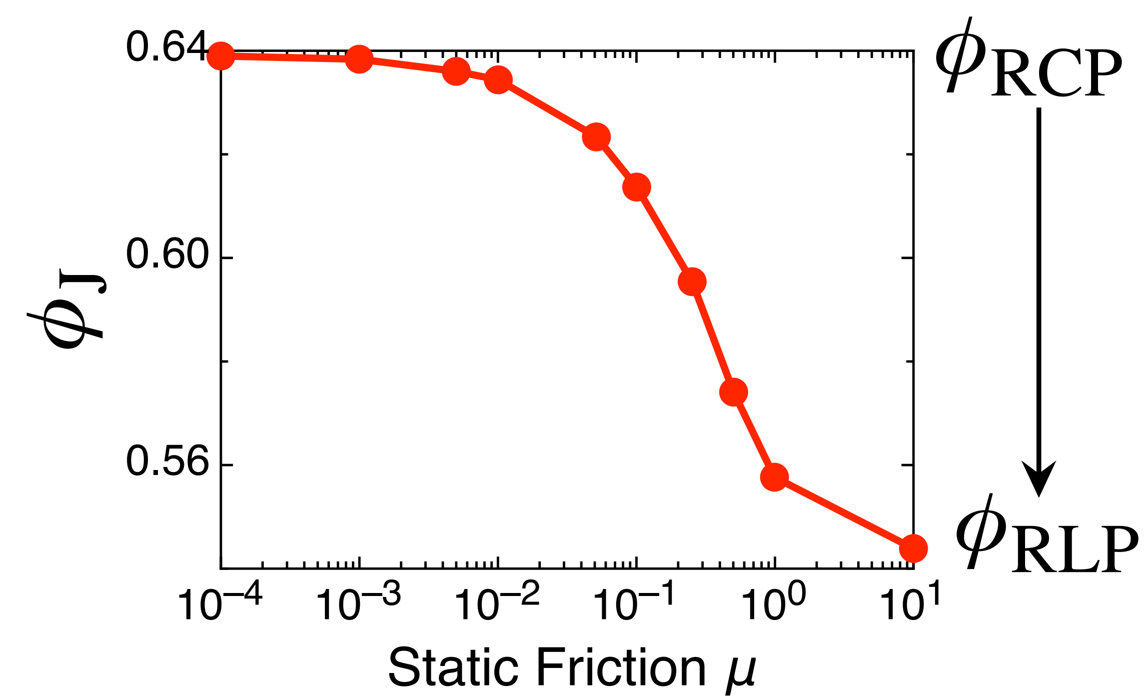
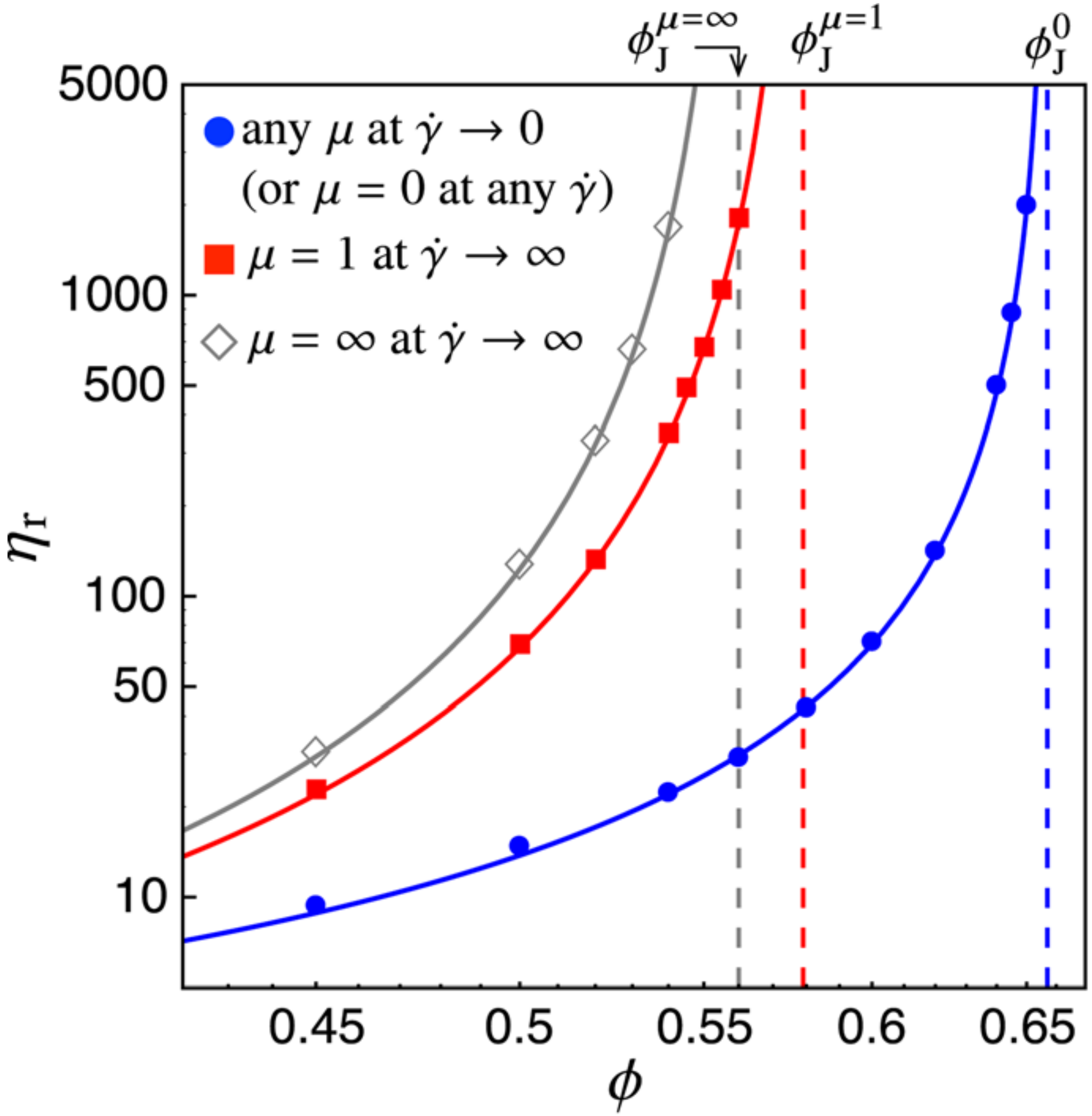


Silbert, Soft Matter 2010

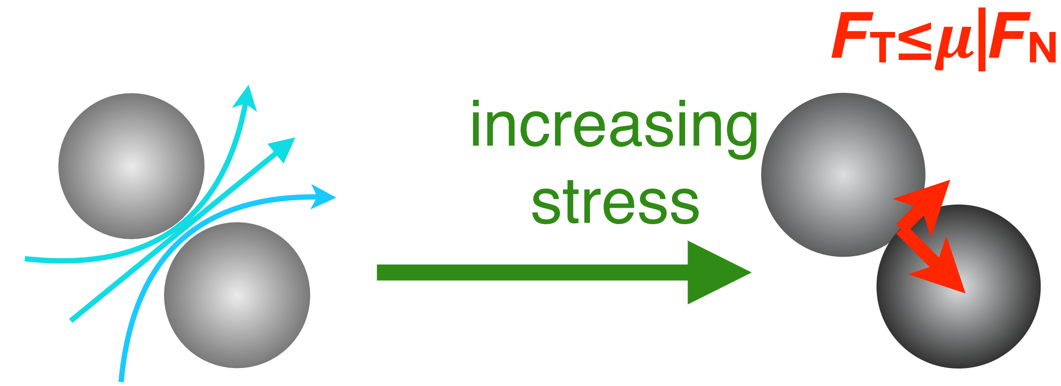
Guy, Hermes & Poon, PRL 2015

Wyart and Cates, PRL 2014

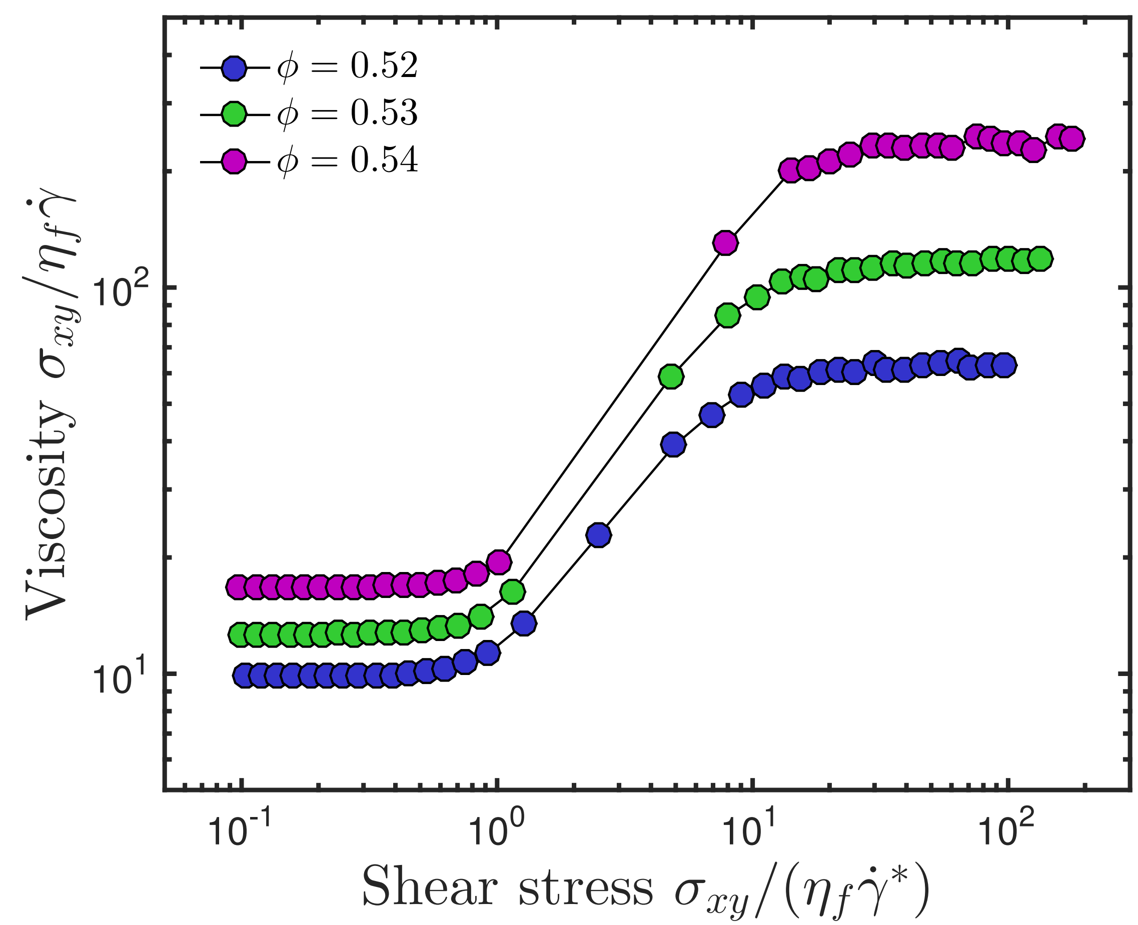
Shear Thickening and Friction



Mari, Seto, Morris, JoR 2014

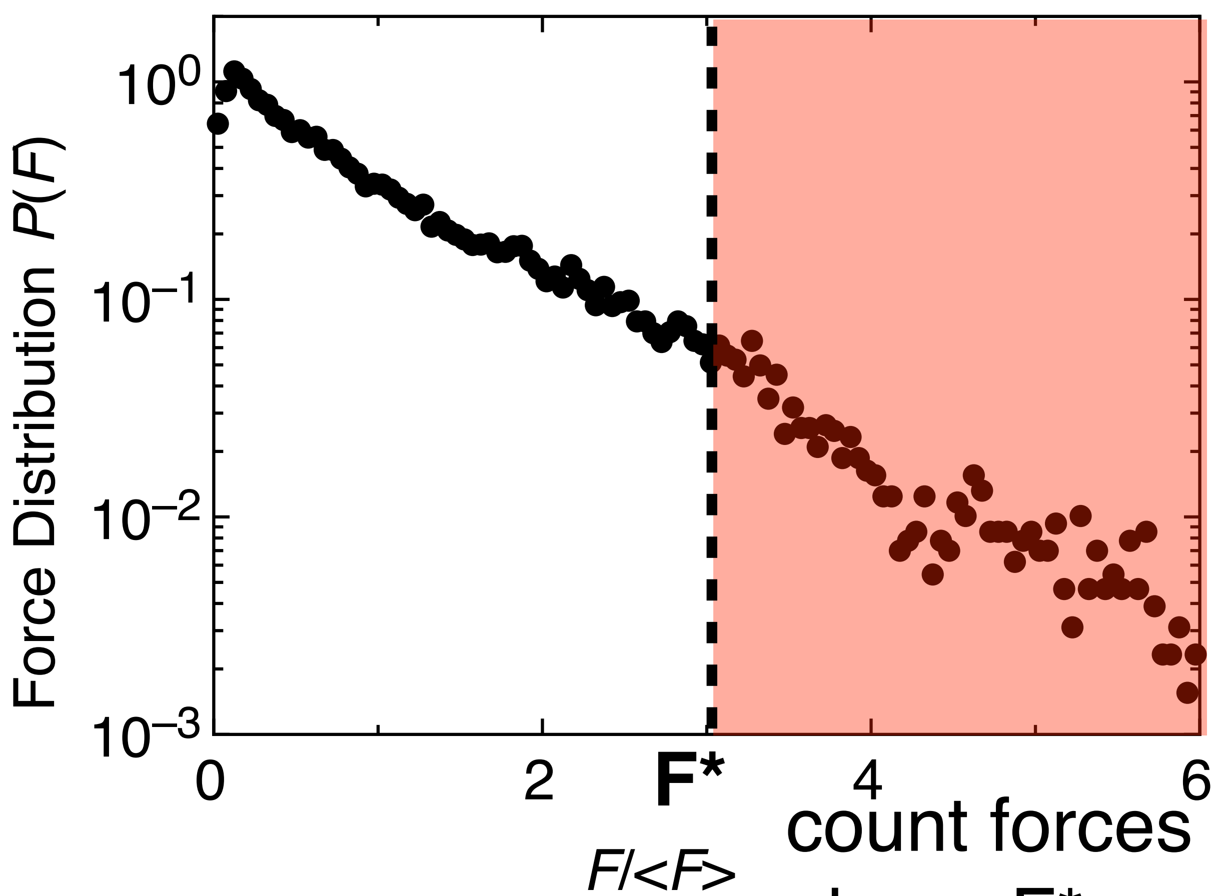


Simulations with stress activated frictional contacts

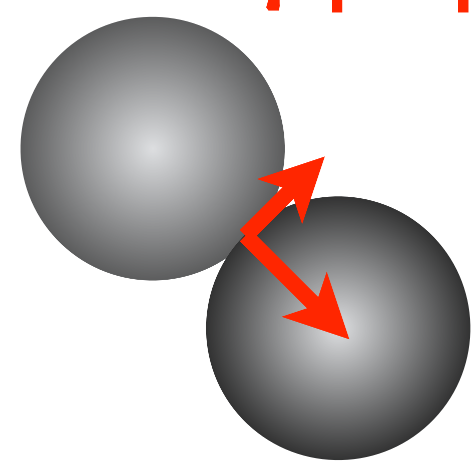


Ness and Sun, Soft Matter 2016

Stress activated friction



$F_T \leq \mu |F_N|$ *if* $F_N > F^*$



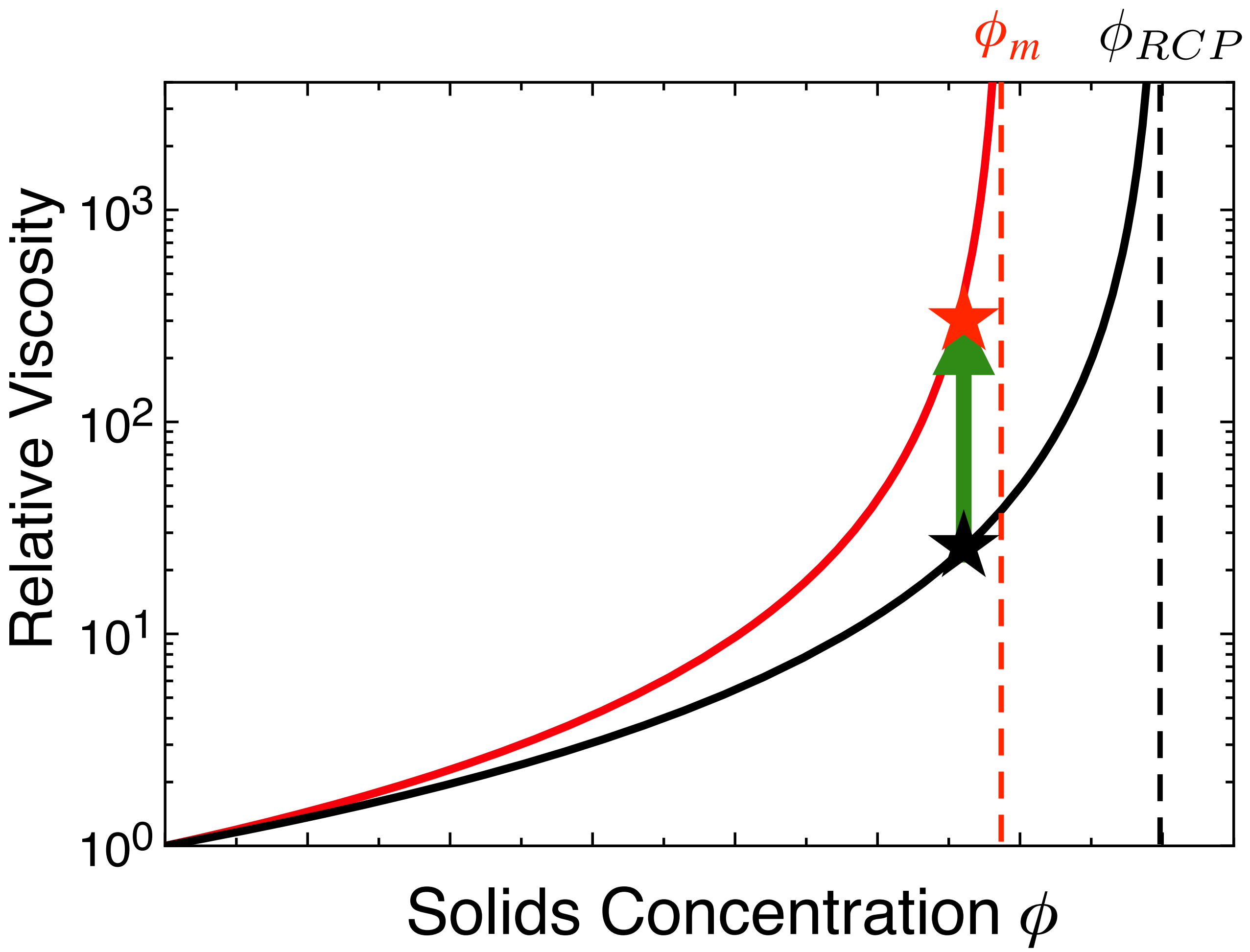
$f(\sigma)$ = 'fraction of frictional contacts'

$$P(F) \sim e^{-F/\langle F \rangle} \longrightarrow f(\sigma) \sim e^{-\sigma^*/\sigma}$$

$$\sigma^* \sim F^*/d^2$$

Guy, Hermes & Poon, PRL 2015

Analytic model for shear thickening rheology



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

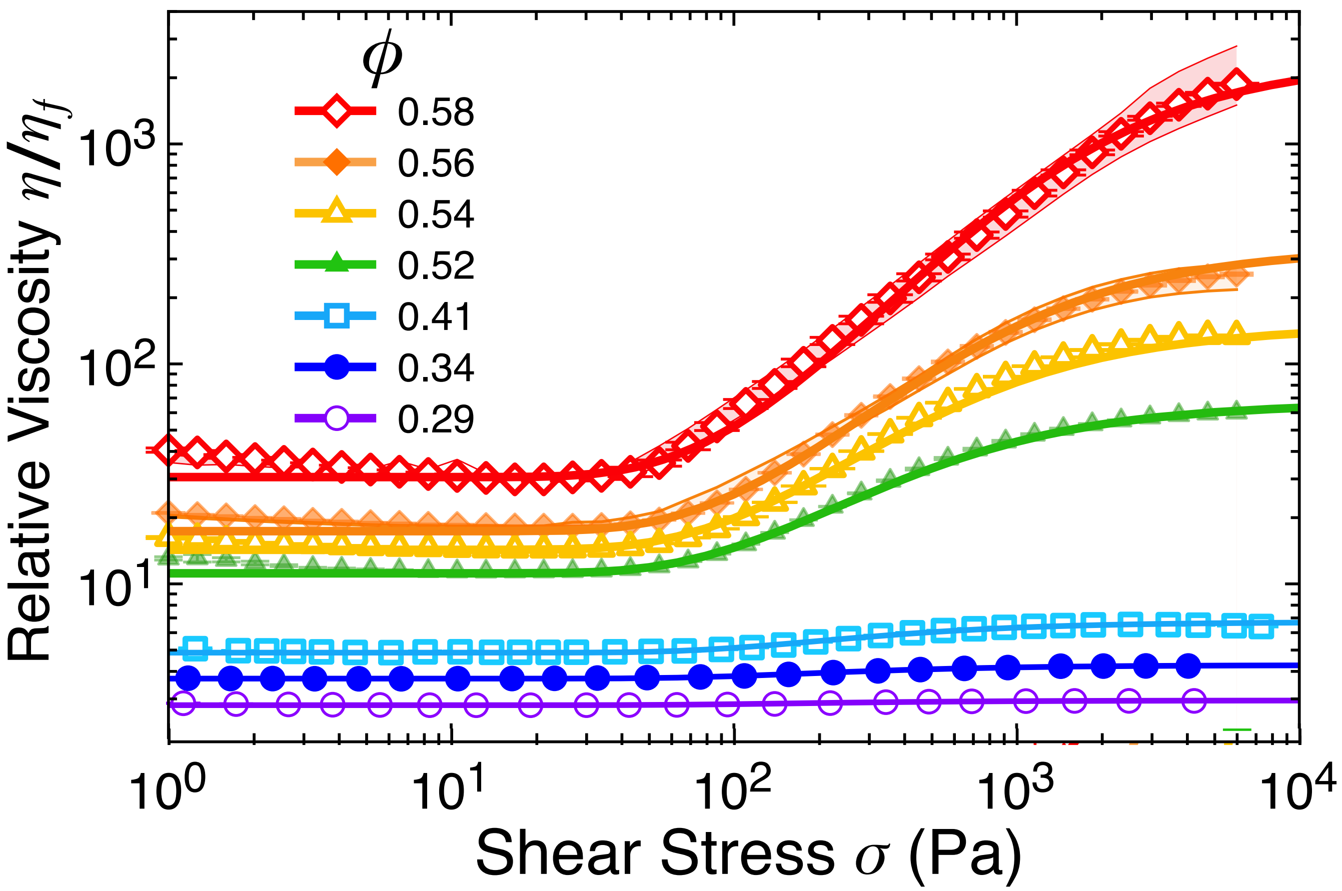
$$\phi_J(\sigma) = \phi_m f(\sigma) + (1 - f(\sigma))\phi_0$$

$$f(\sigma) \sim e^{-\sigma^*/\sigma}$$

$$\sigma^* \sim F^*/d^2$$

Wyart and Cates PRL, 2014

Analytic model for shear thickening rheology



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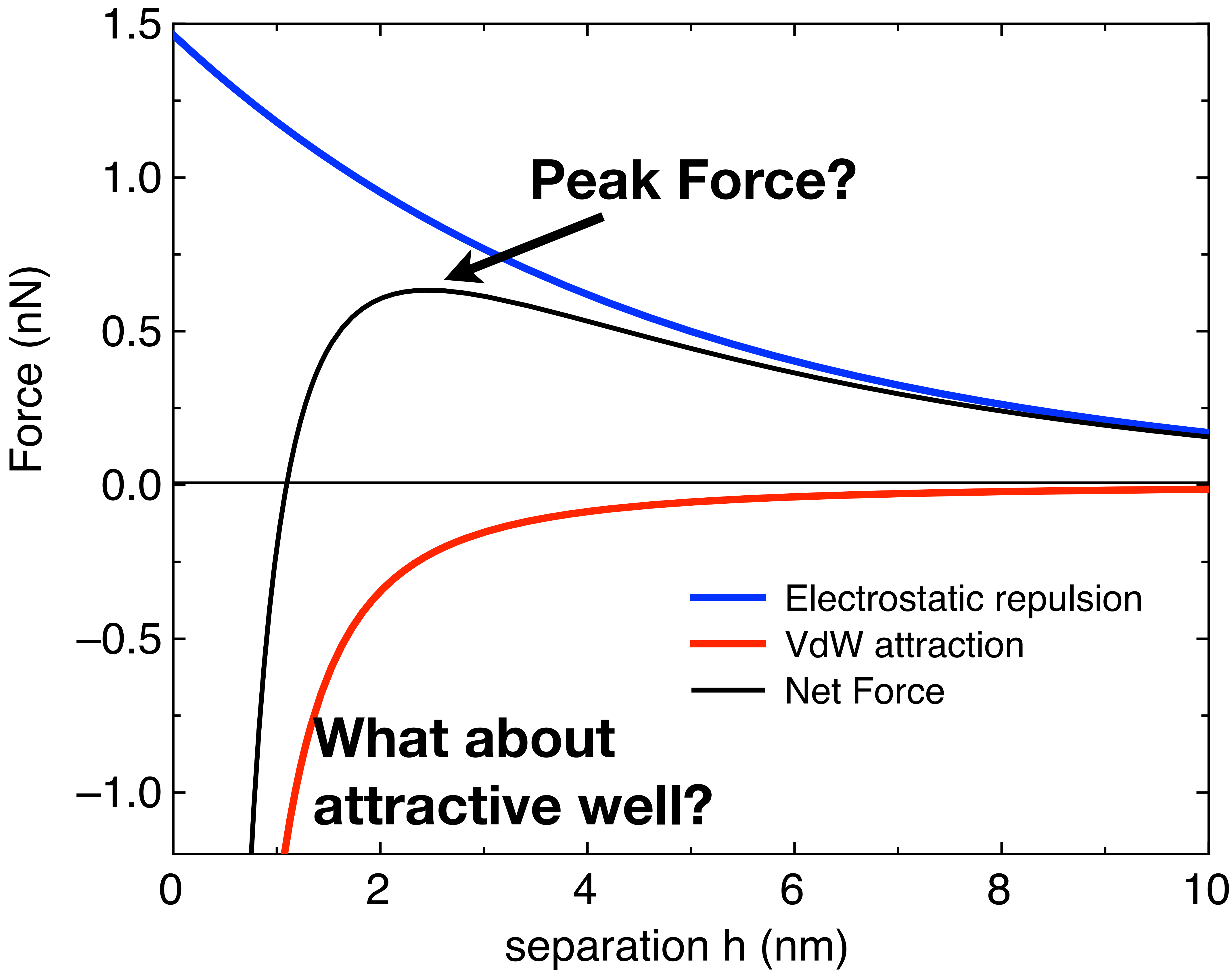
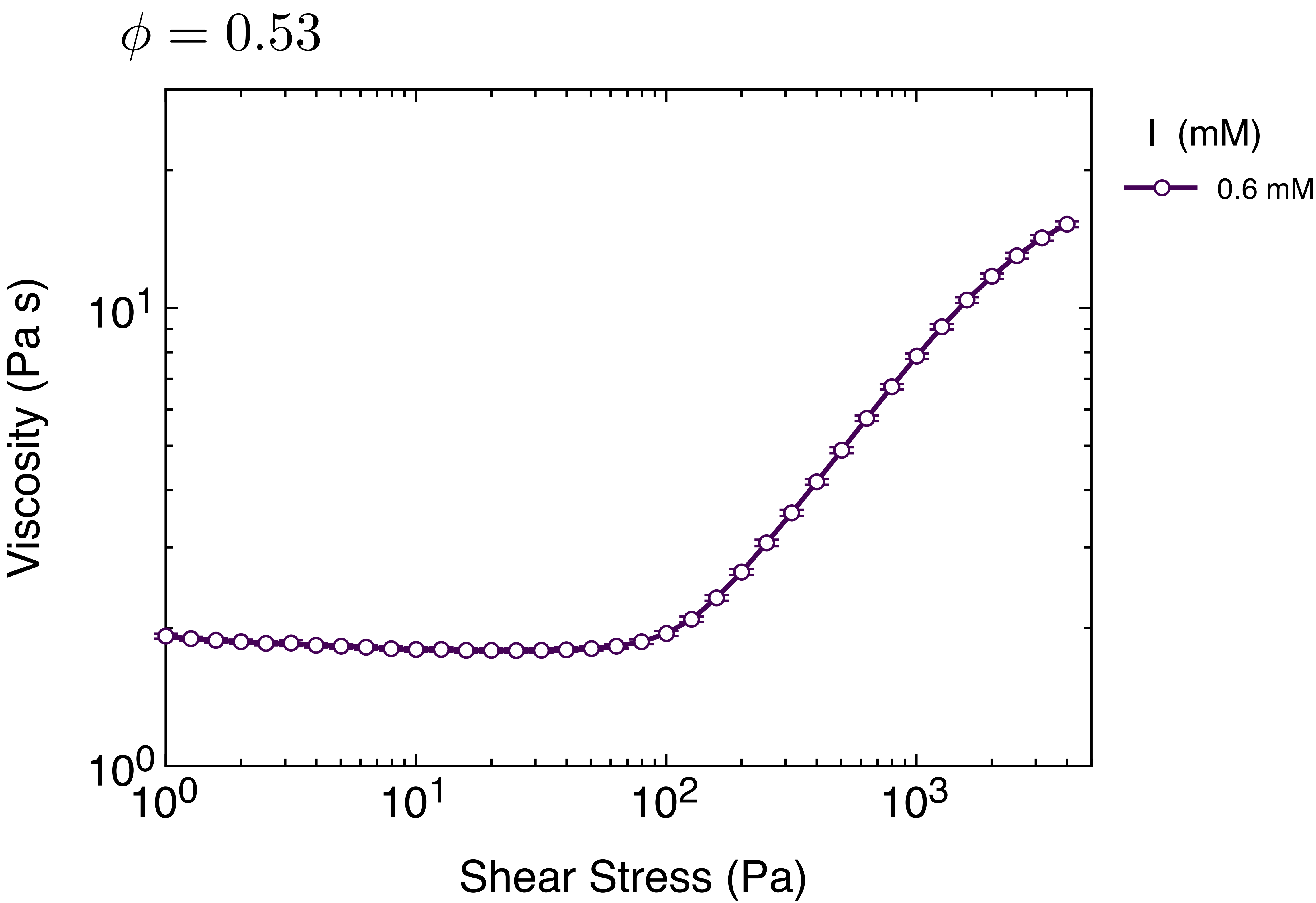
Wyart and Cates PRL, 2014

What sets the onset stress?



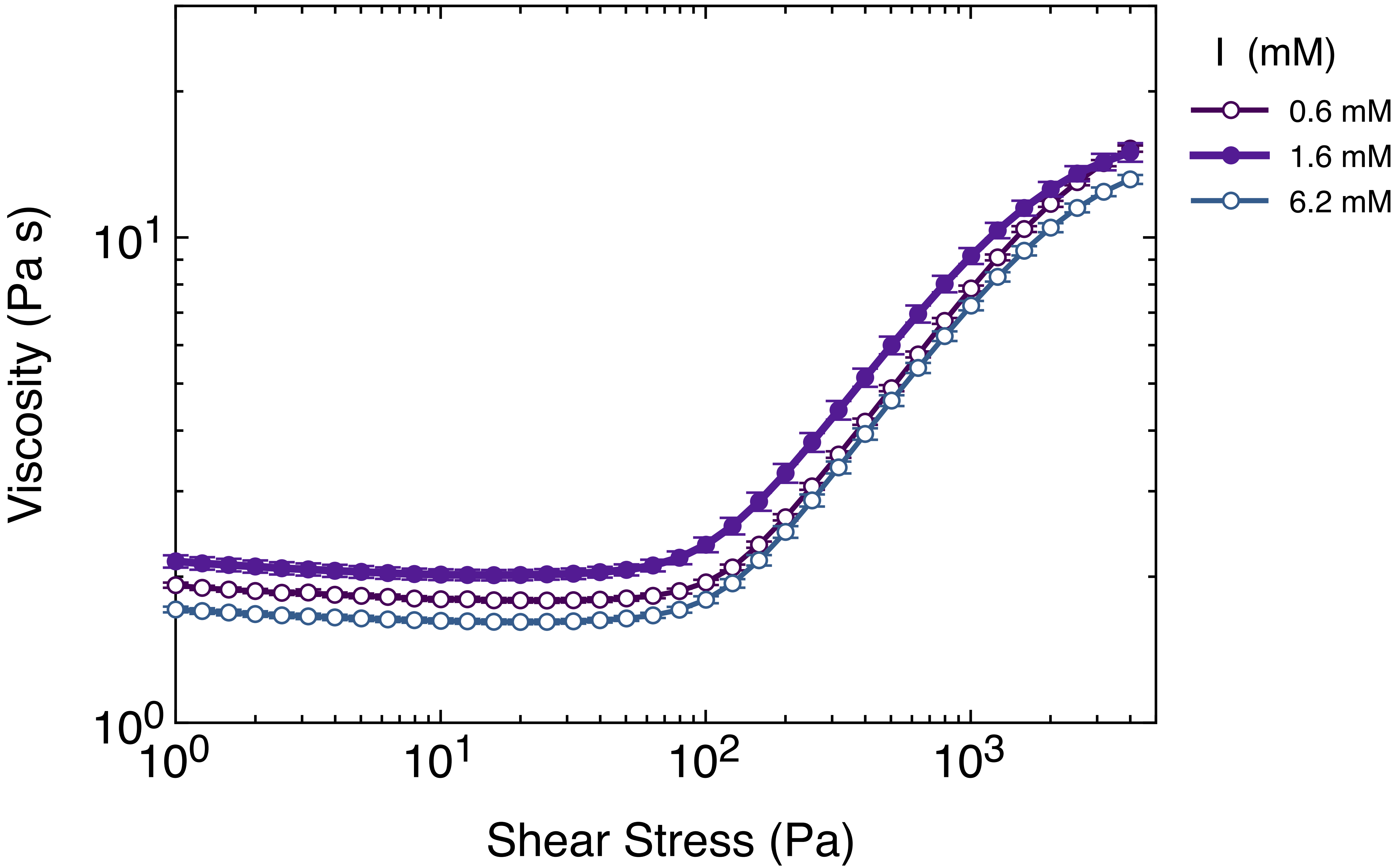
Charge stabilised spheres



d=1.5 µm Silica spheres in 85% w/w glycerol/water

Charge stabilised spheres

$\phi = 0.53$



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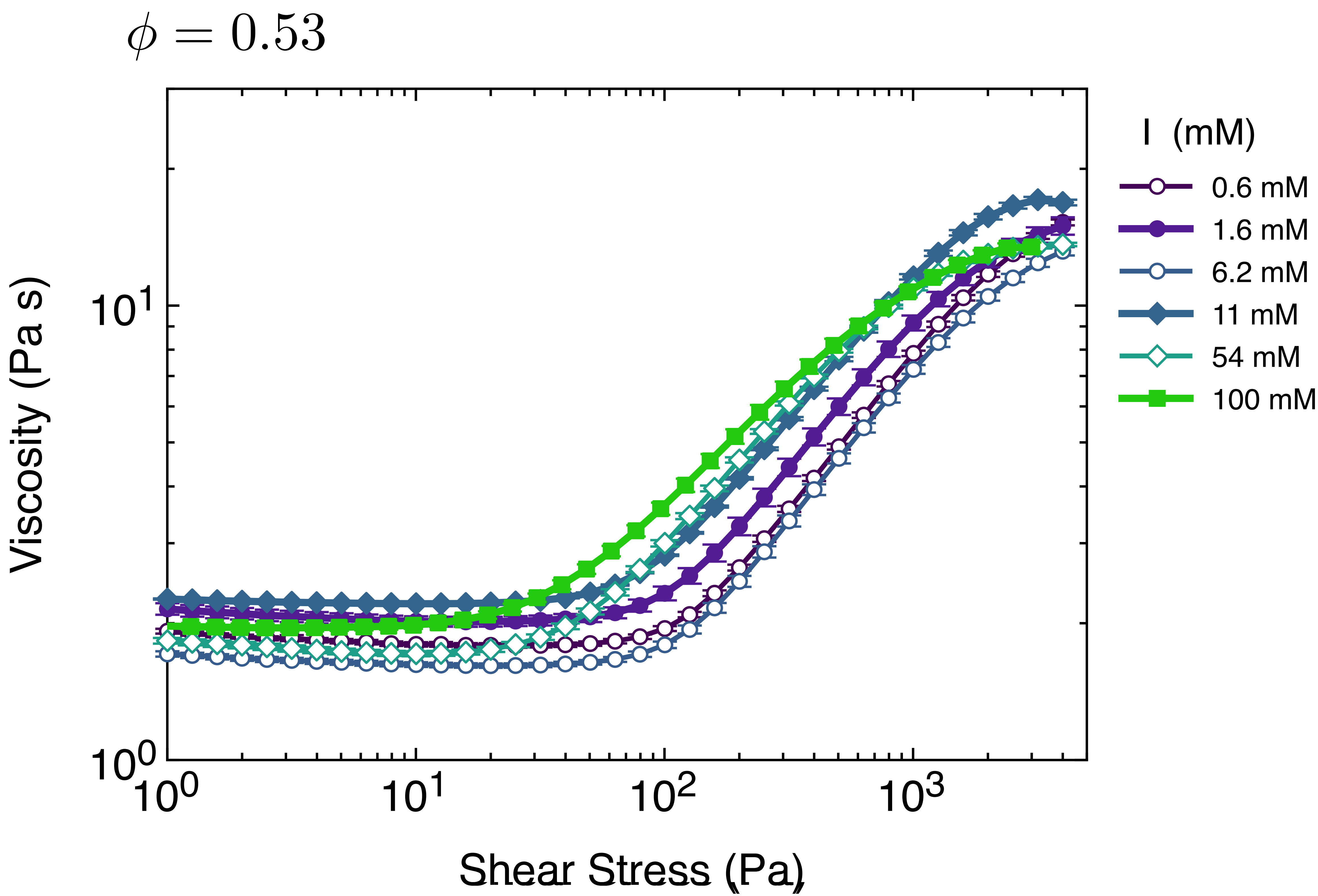

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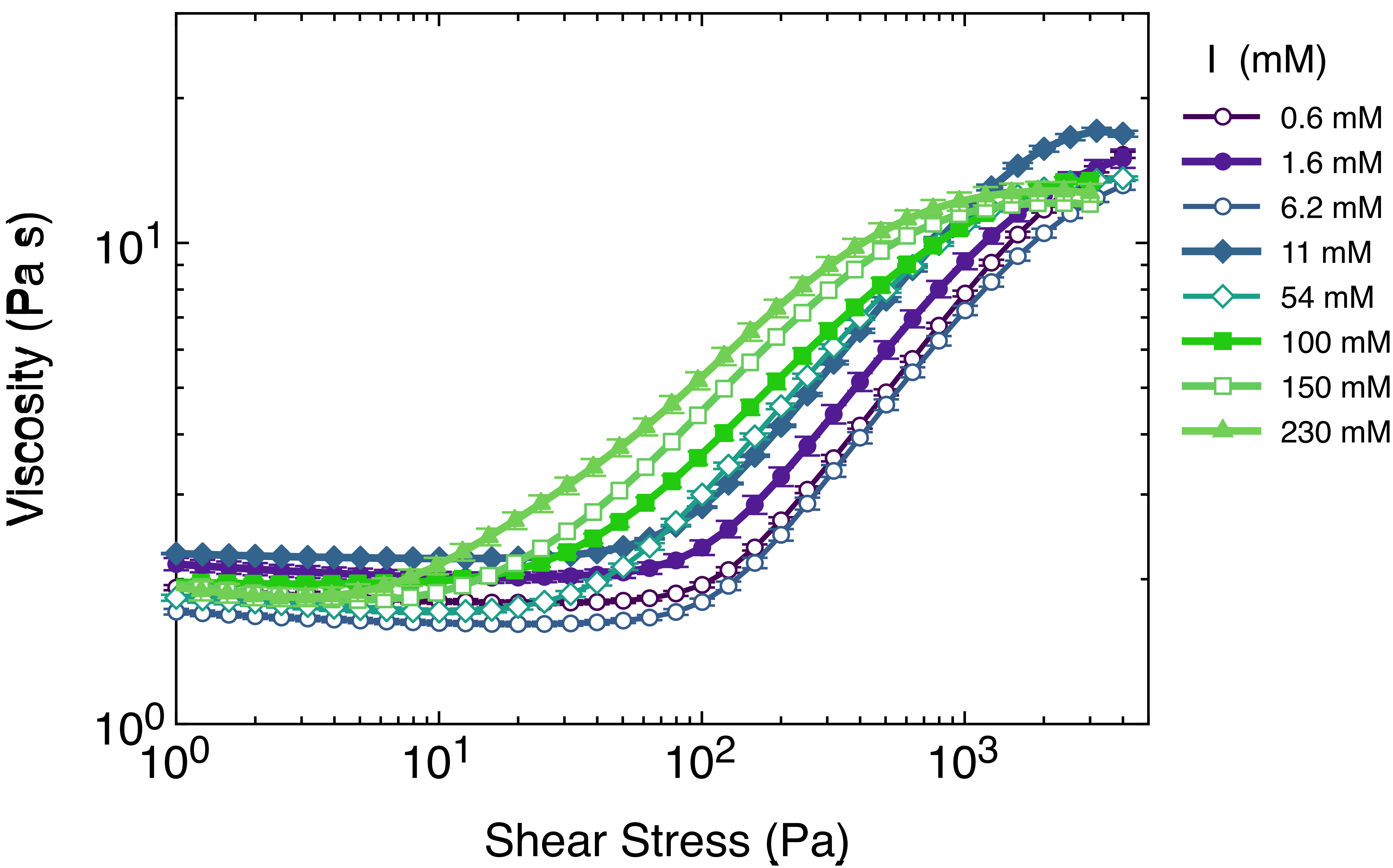

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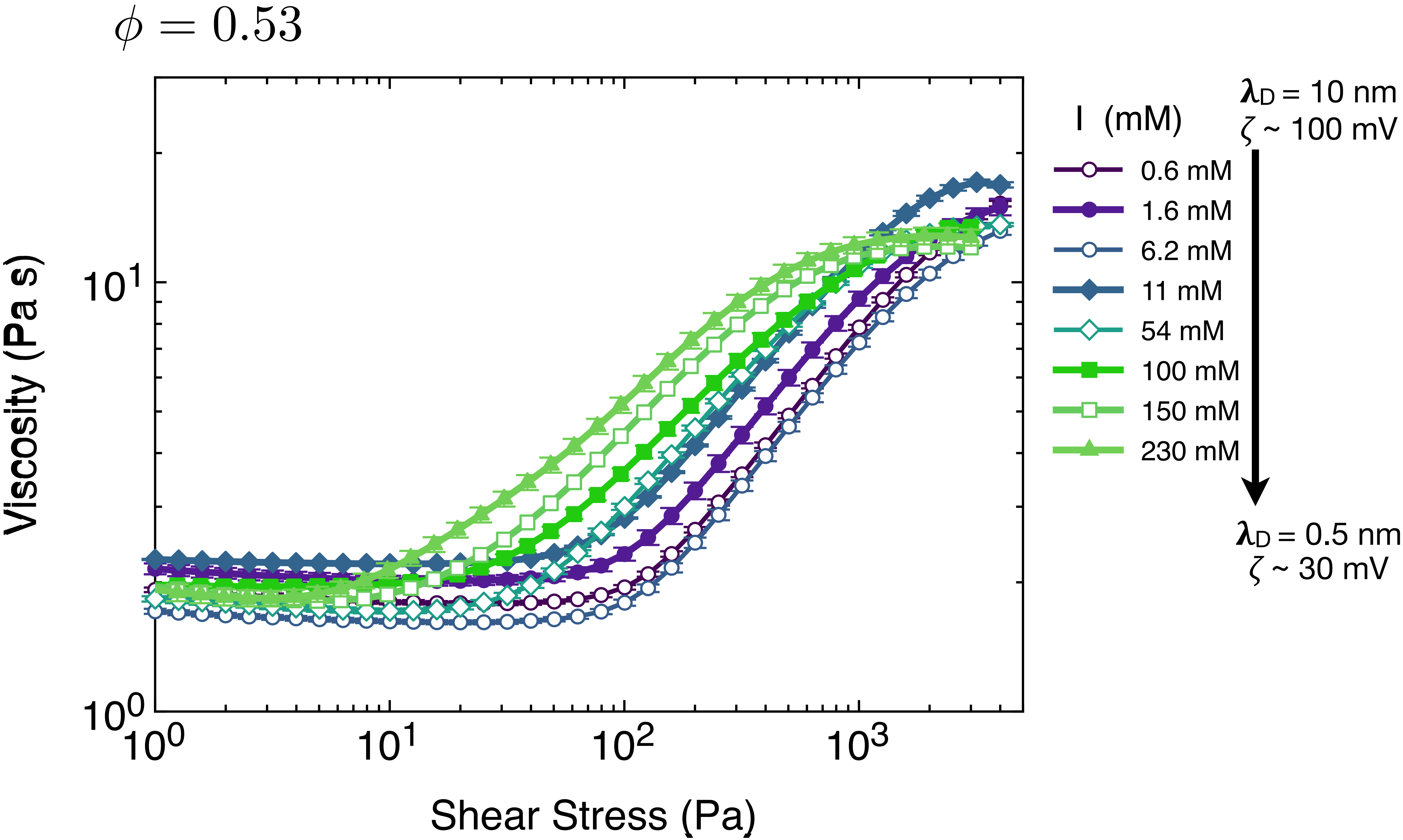

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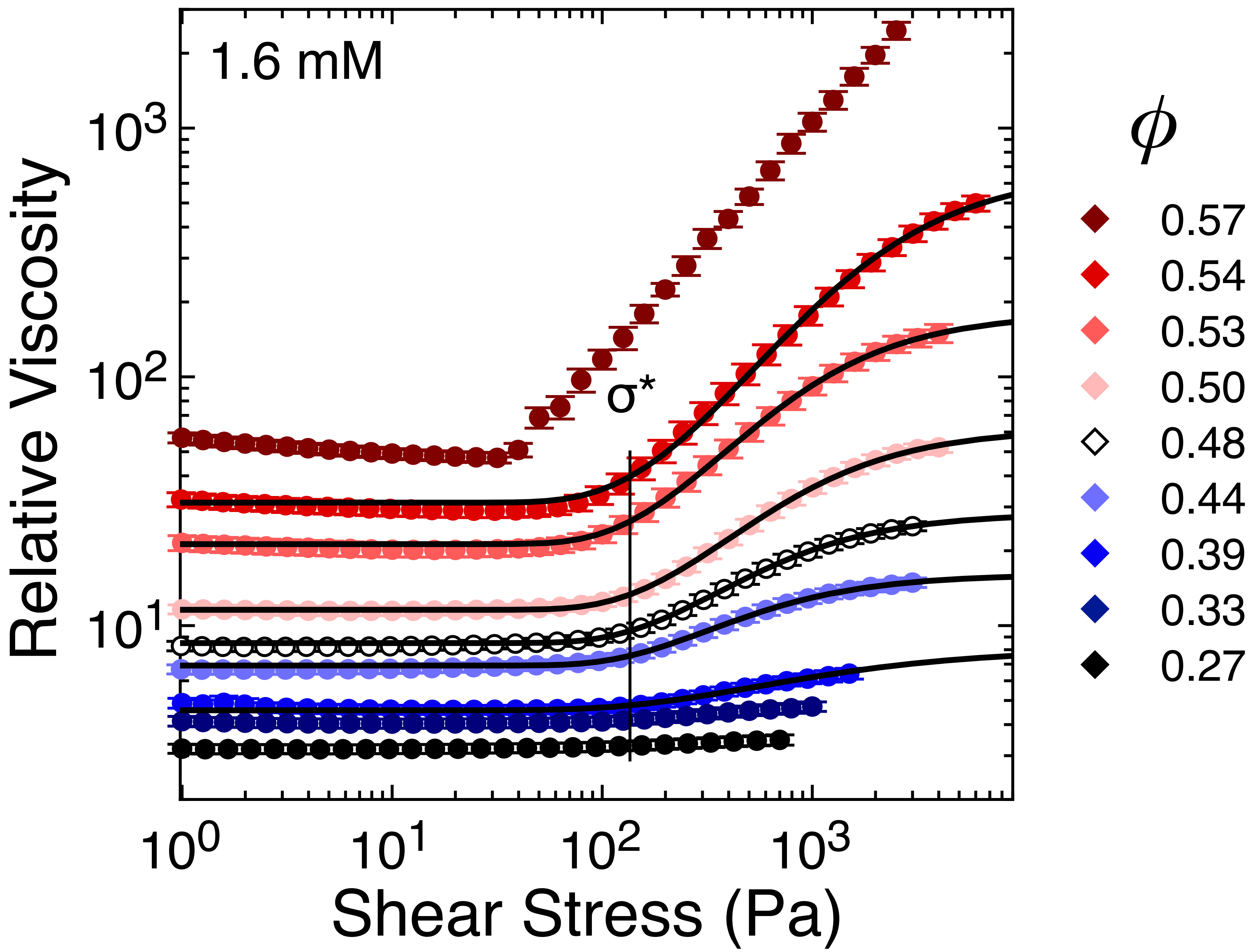
Shear thickening charge stabilised suspensions



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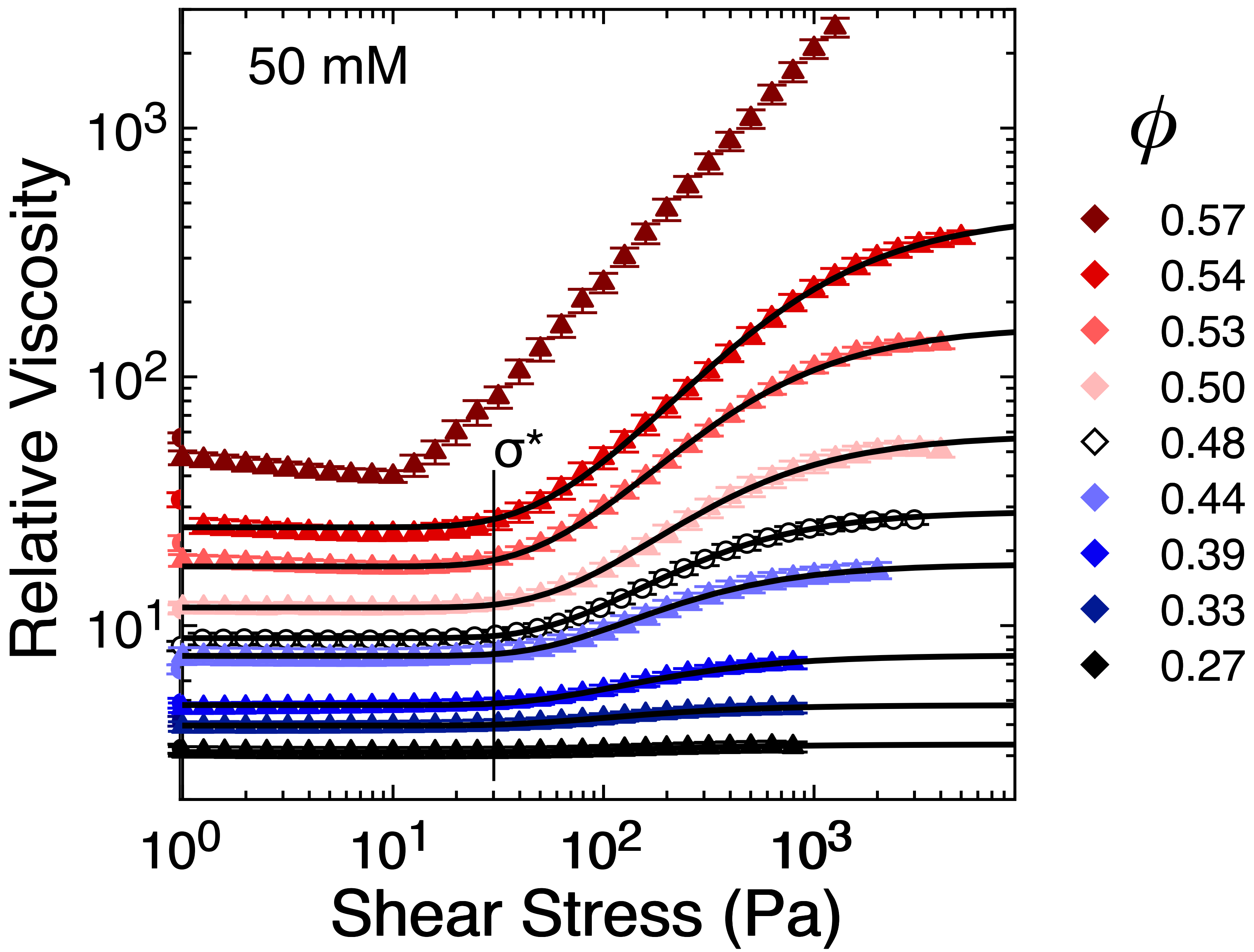

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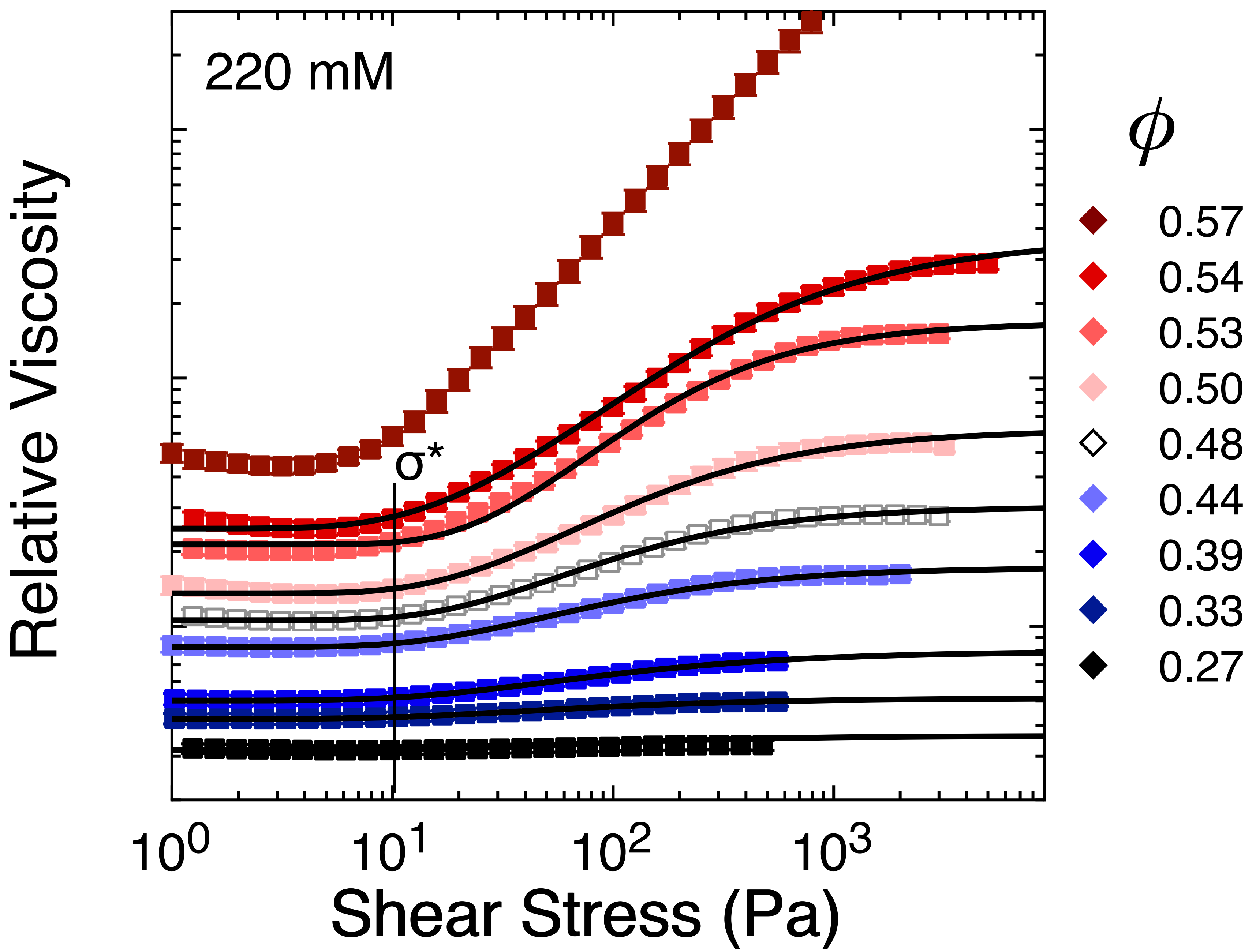
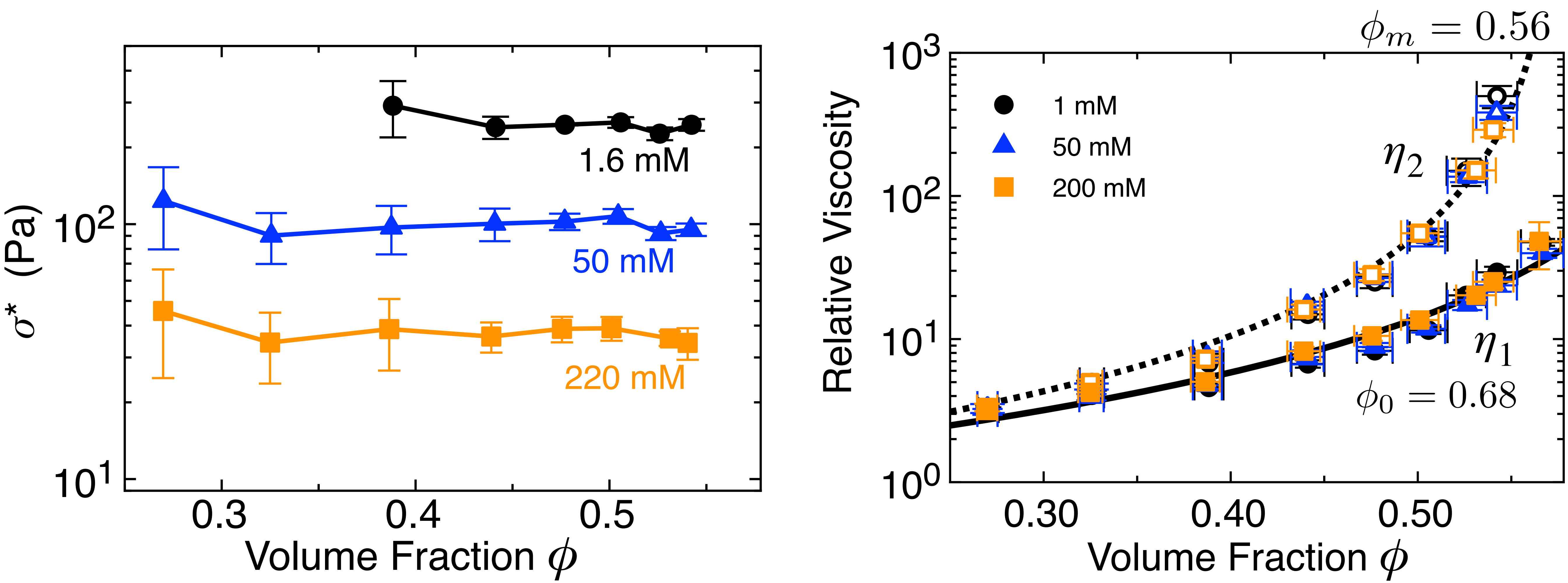


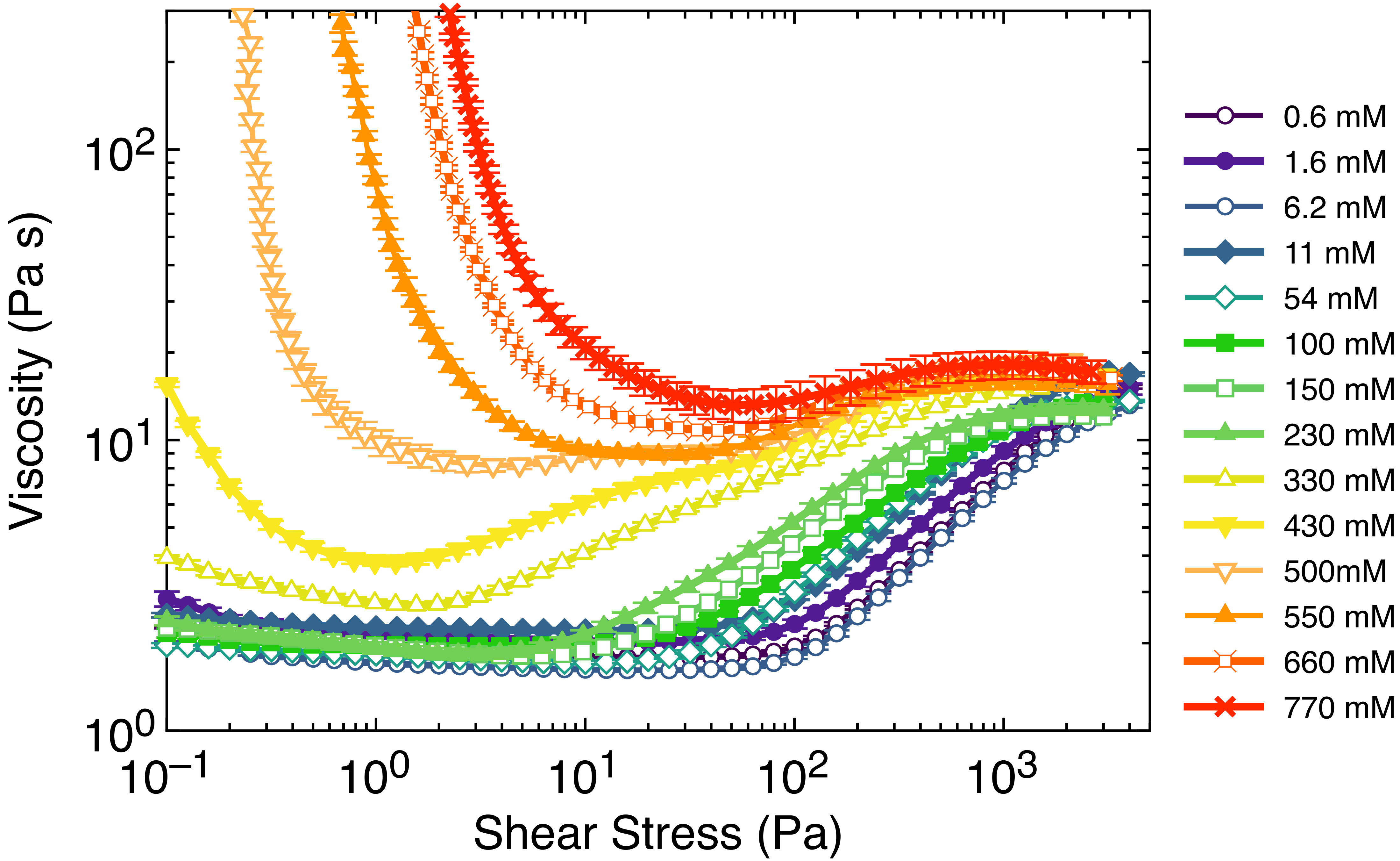
d=1.5 µm Silica spheres in 85% w/w glycerol/water

Shift in thickening onset, ϕ_m unchanged



Further increasing salt concentration: thickening to yielding

$\phi = 0.53$

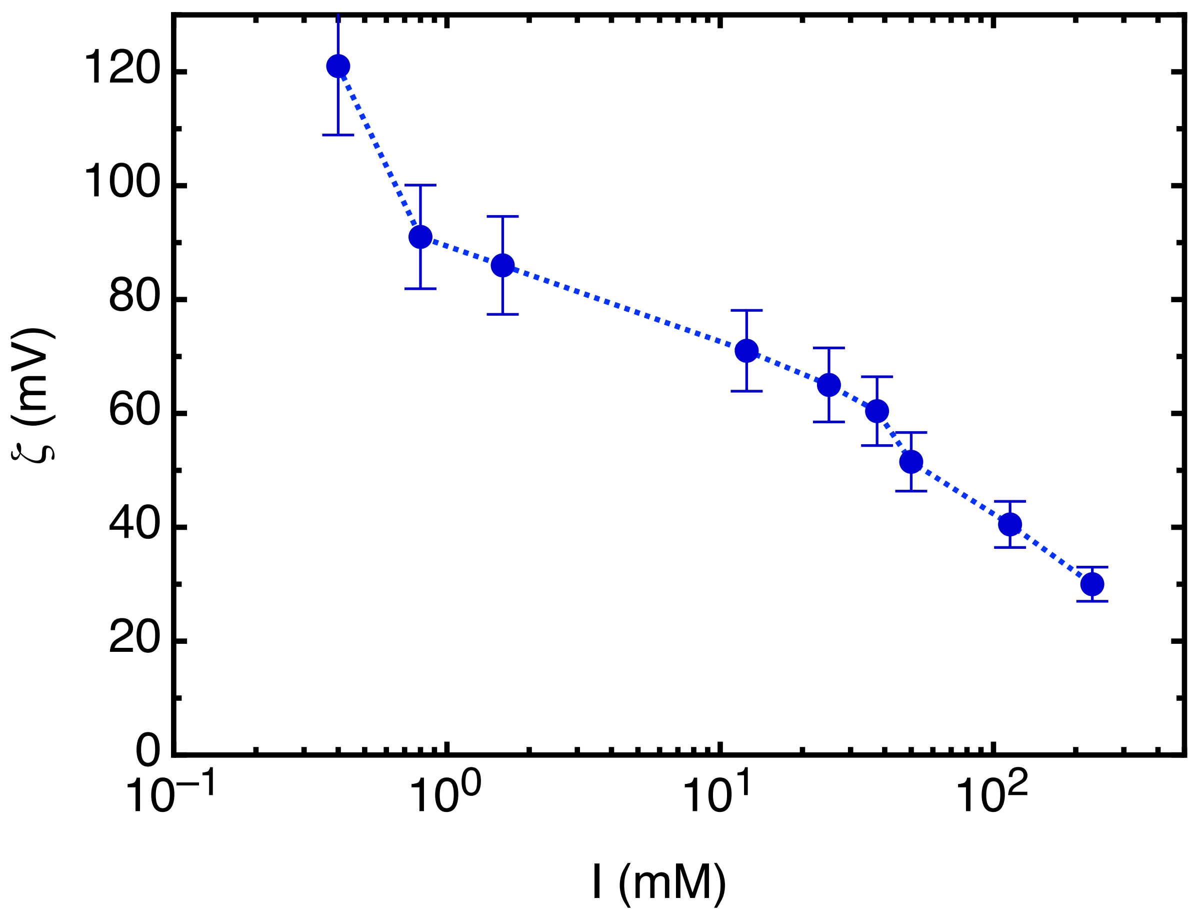


also see: Brown et al, Nature Mat. 2009, Clavaud et al, PNAS 2017

Simple picture of particle interactions

$$F_{DLVO} = \pi \epsilon \epsilon_0 \psi^2 (d/\lambda_D) e^{-h/\lambda_D} - \frac{A_H d}{6h^2}$$

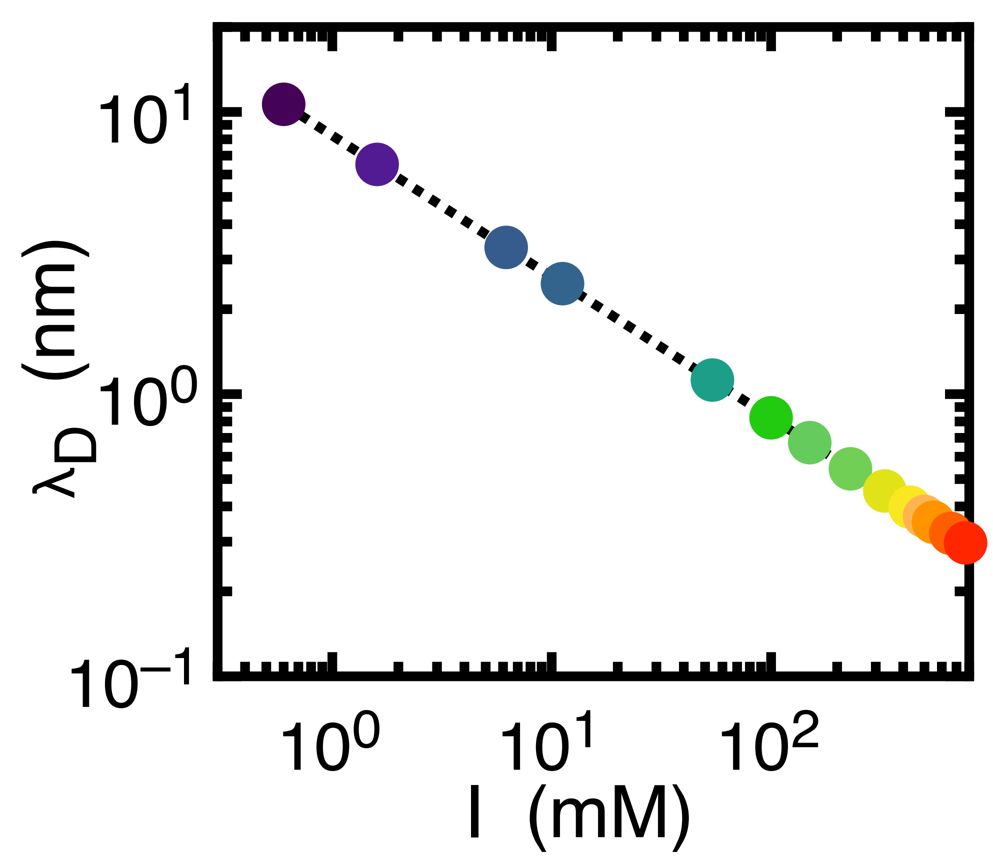
measure zeta potential



calculate A_H from Lifshitz theory

$$A_H \simeq 0.6 k_B T$$

calculate screening length λ_D



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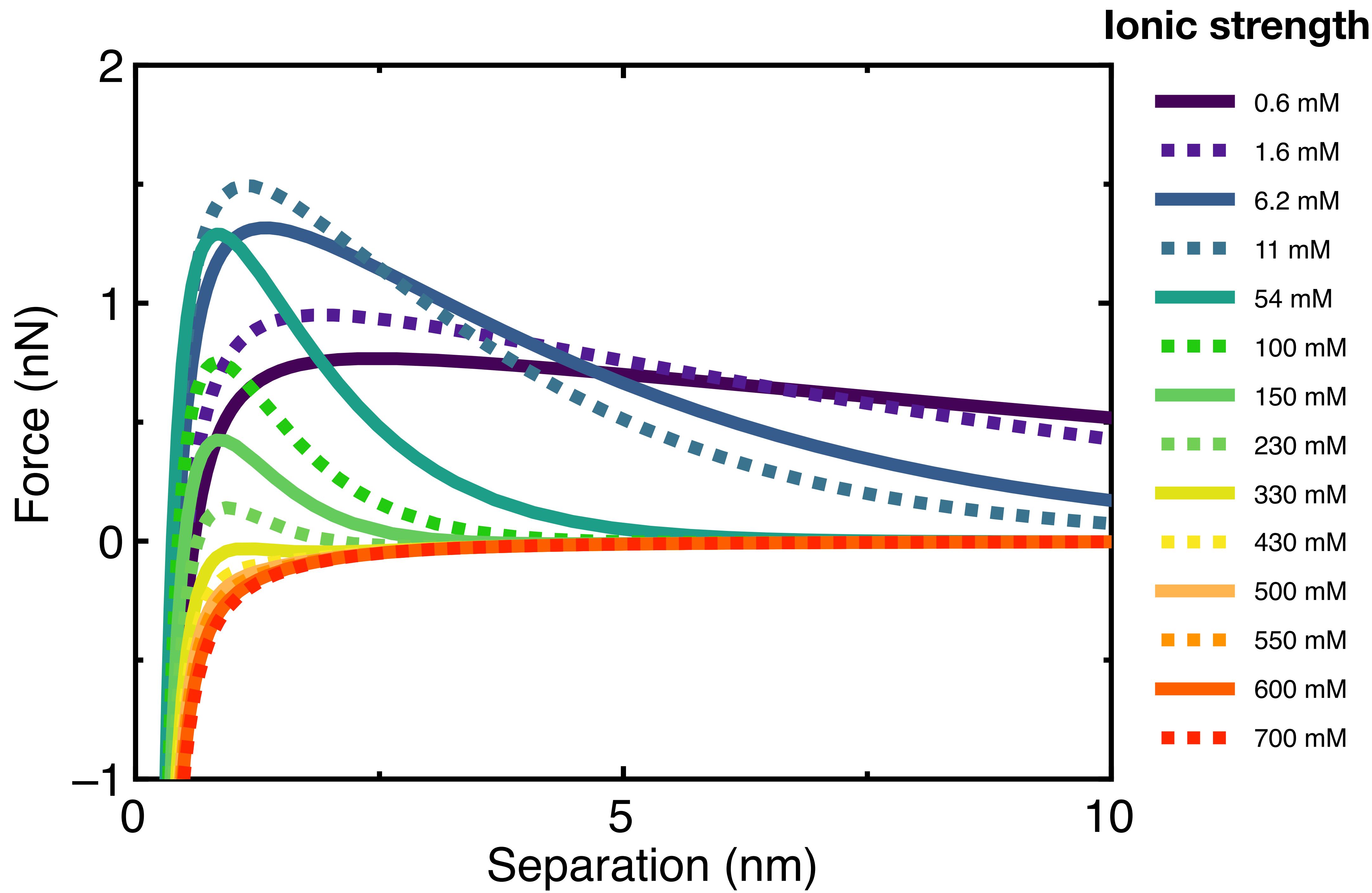
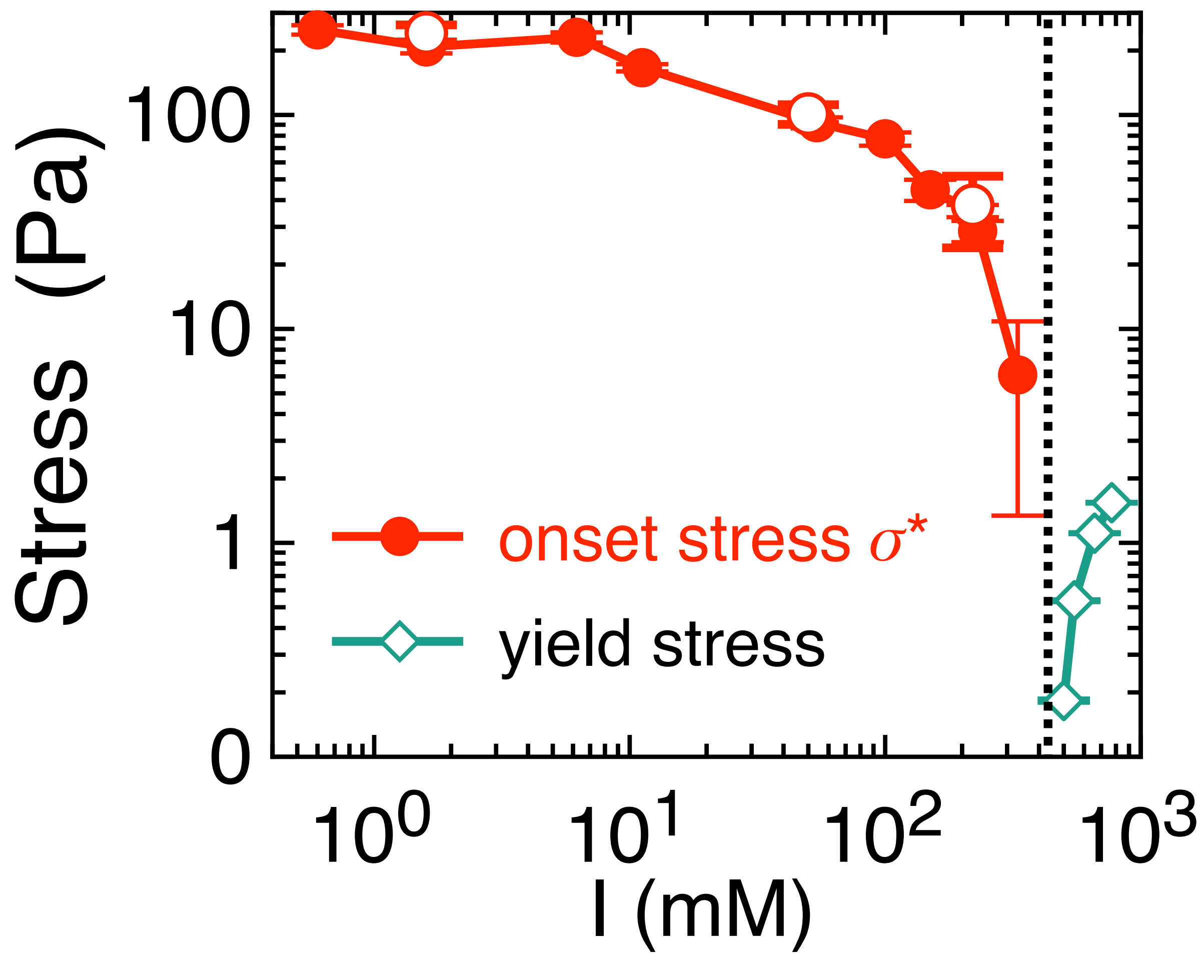
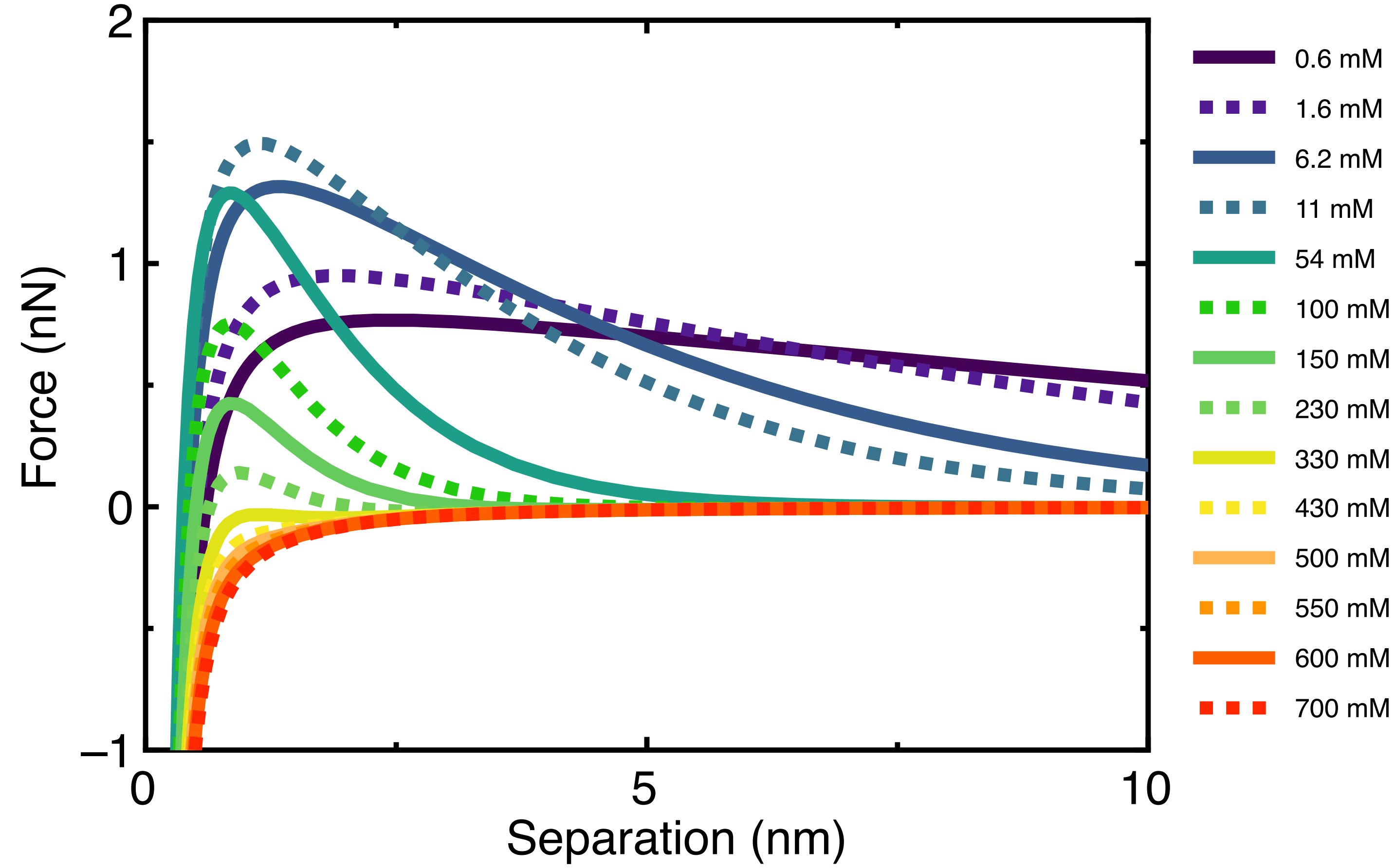


Connect rheology to interactions?





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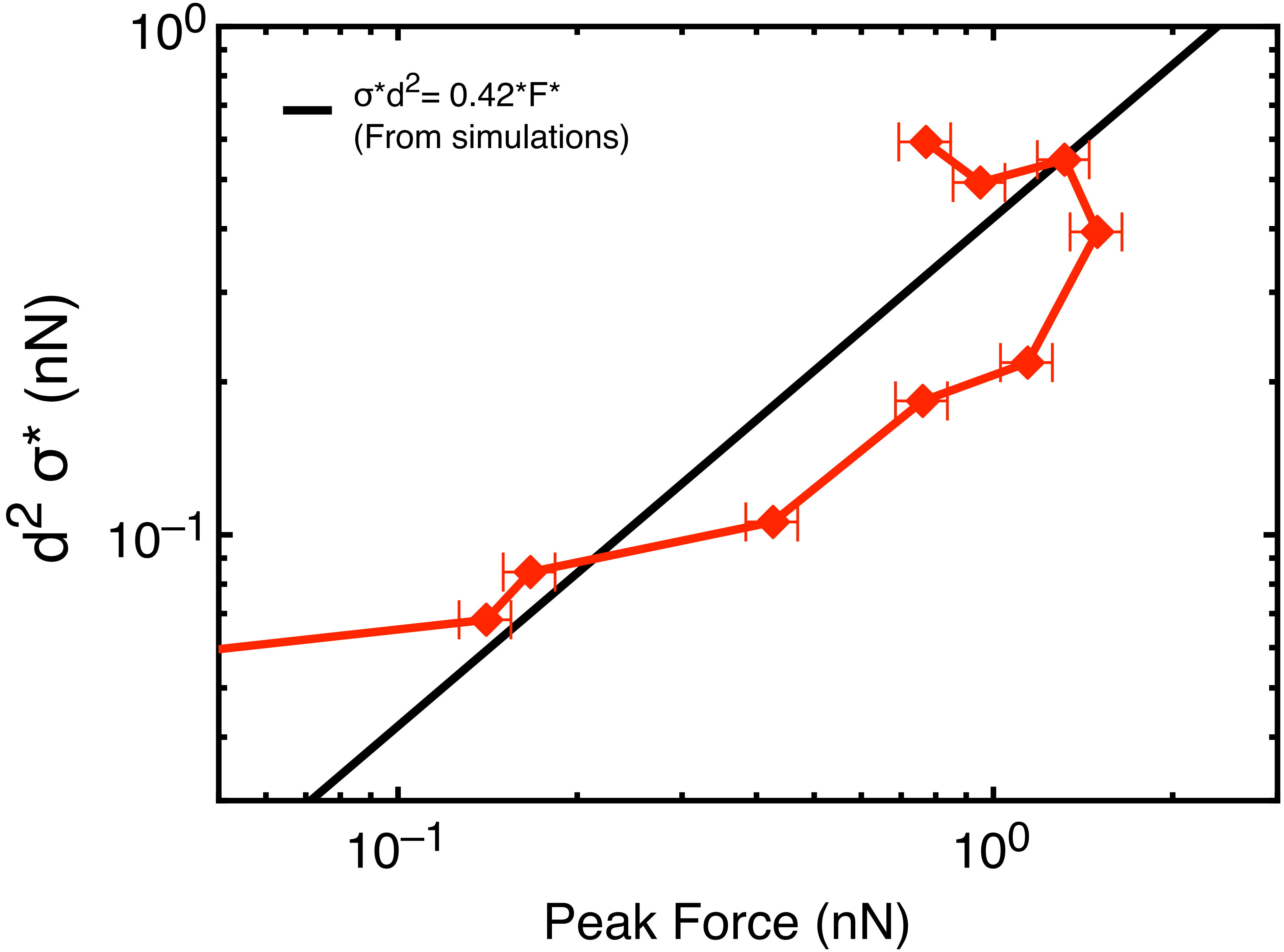

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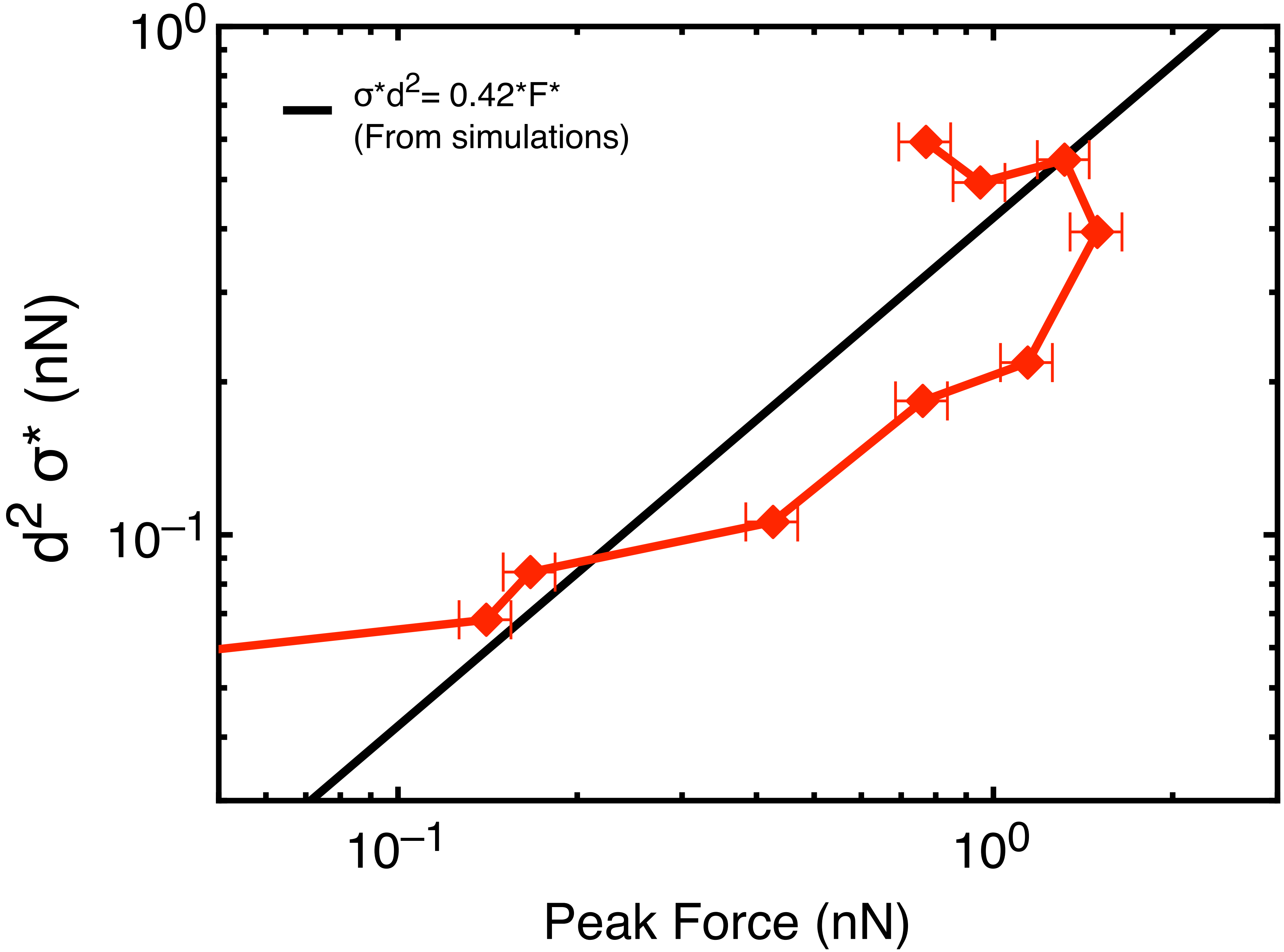
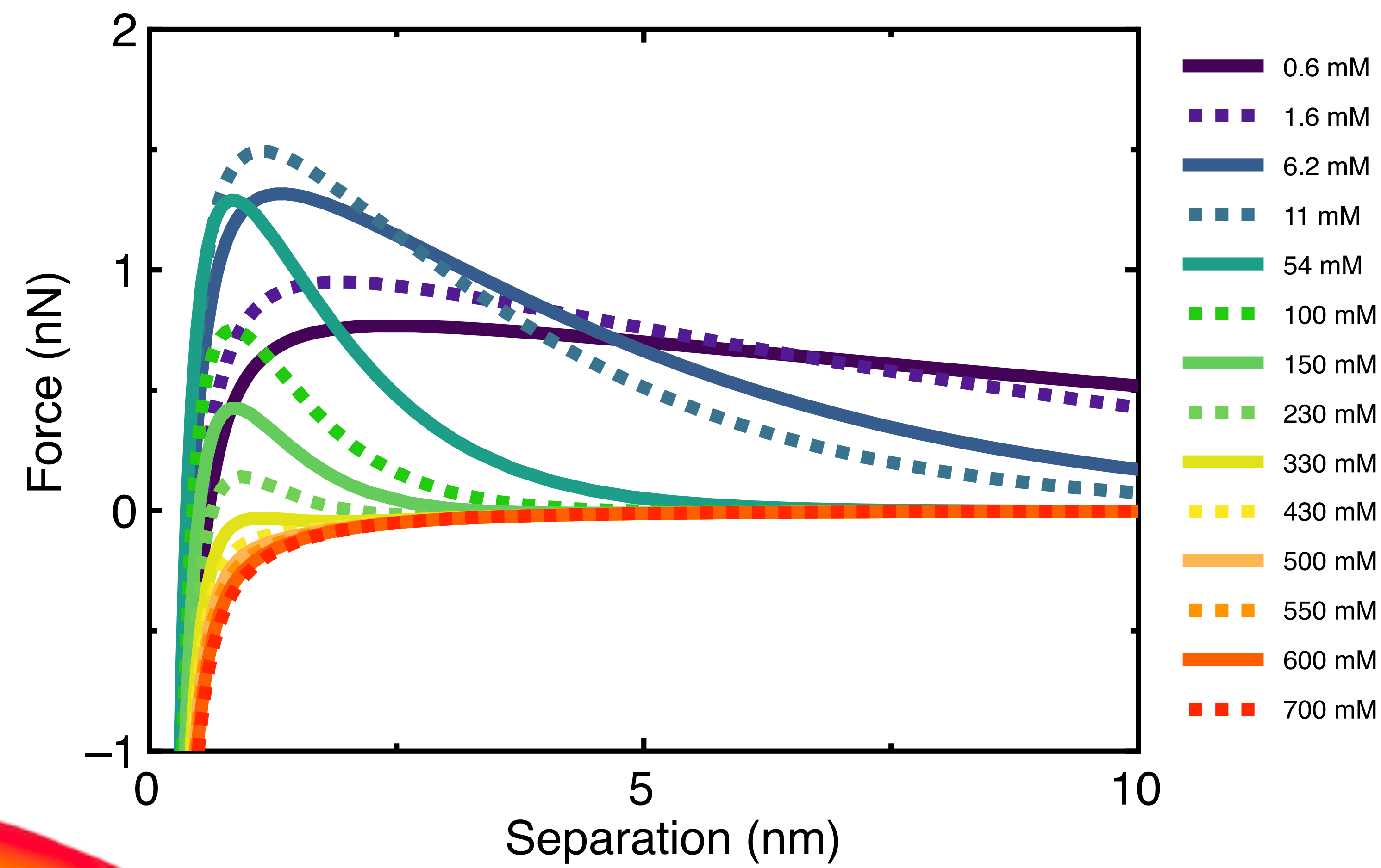
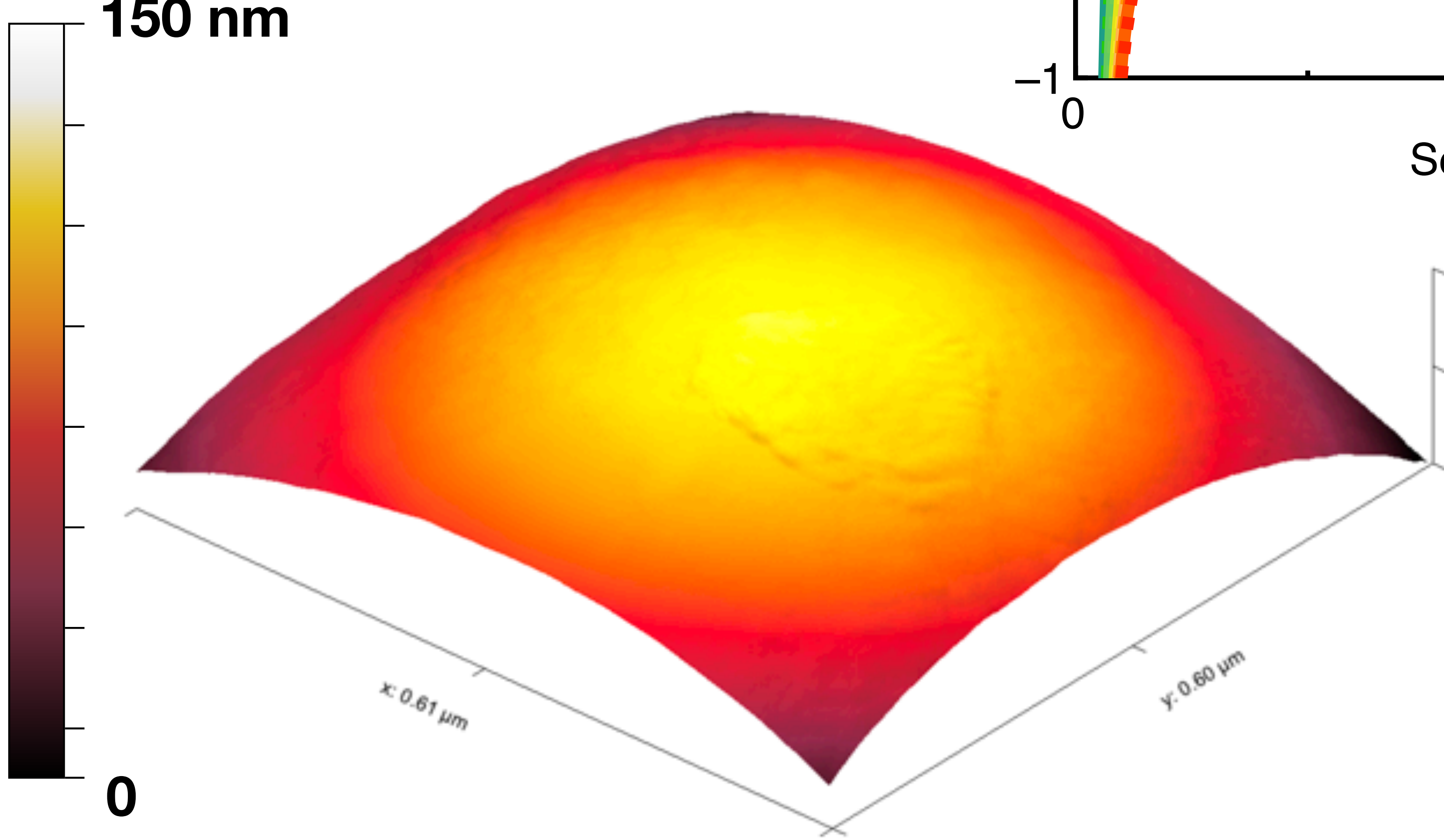


Ok agreement … what about VdW minimum?

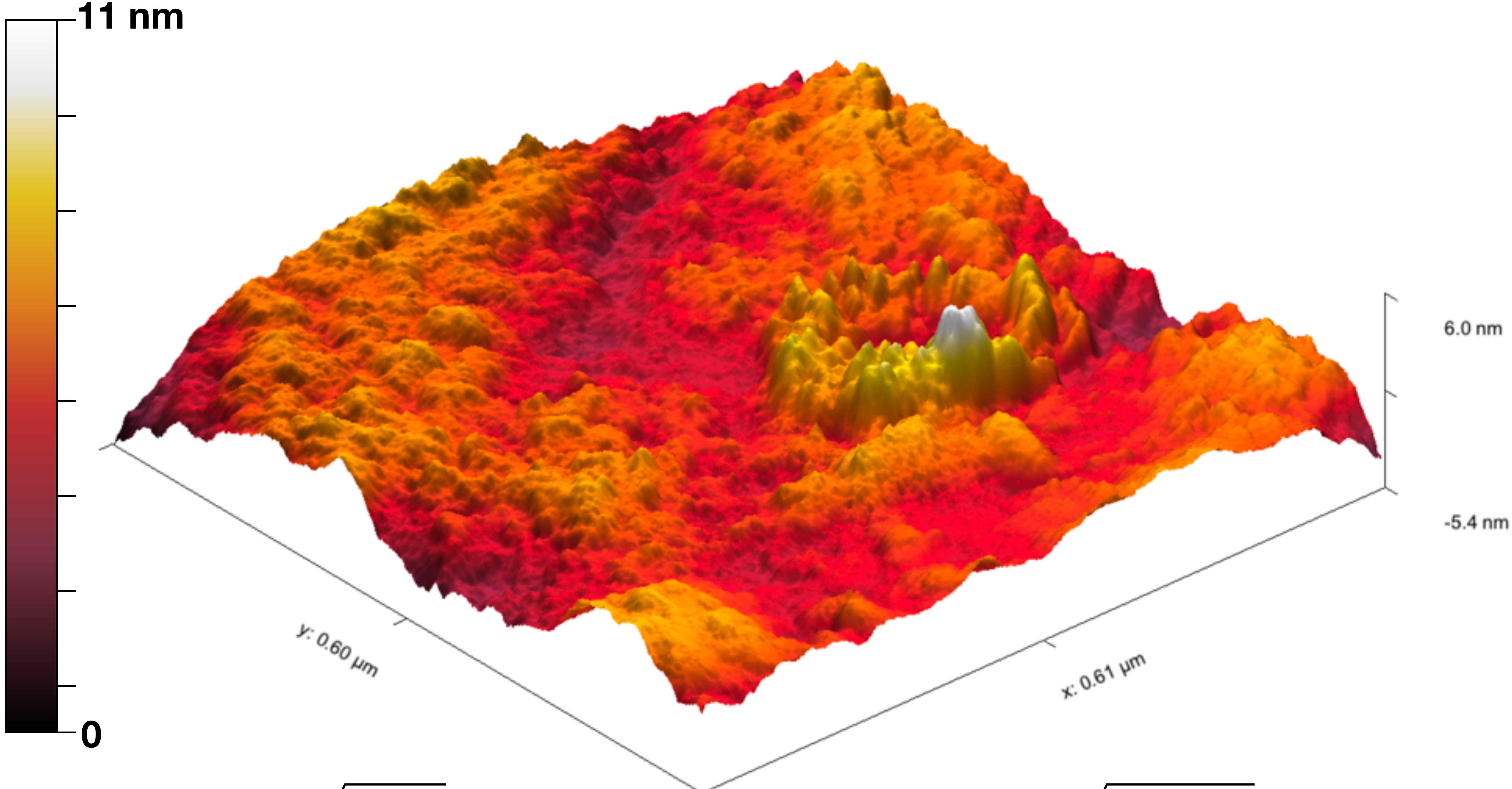
DLVO: interactions for smooth spheres





screening length λ_D, peak location: ~nm or below

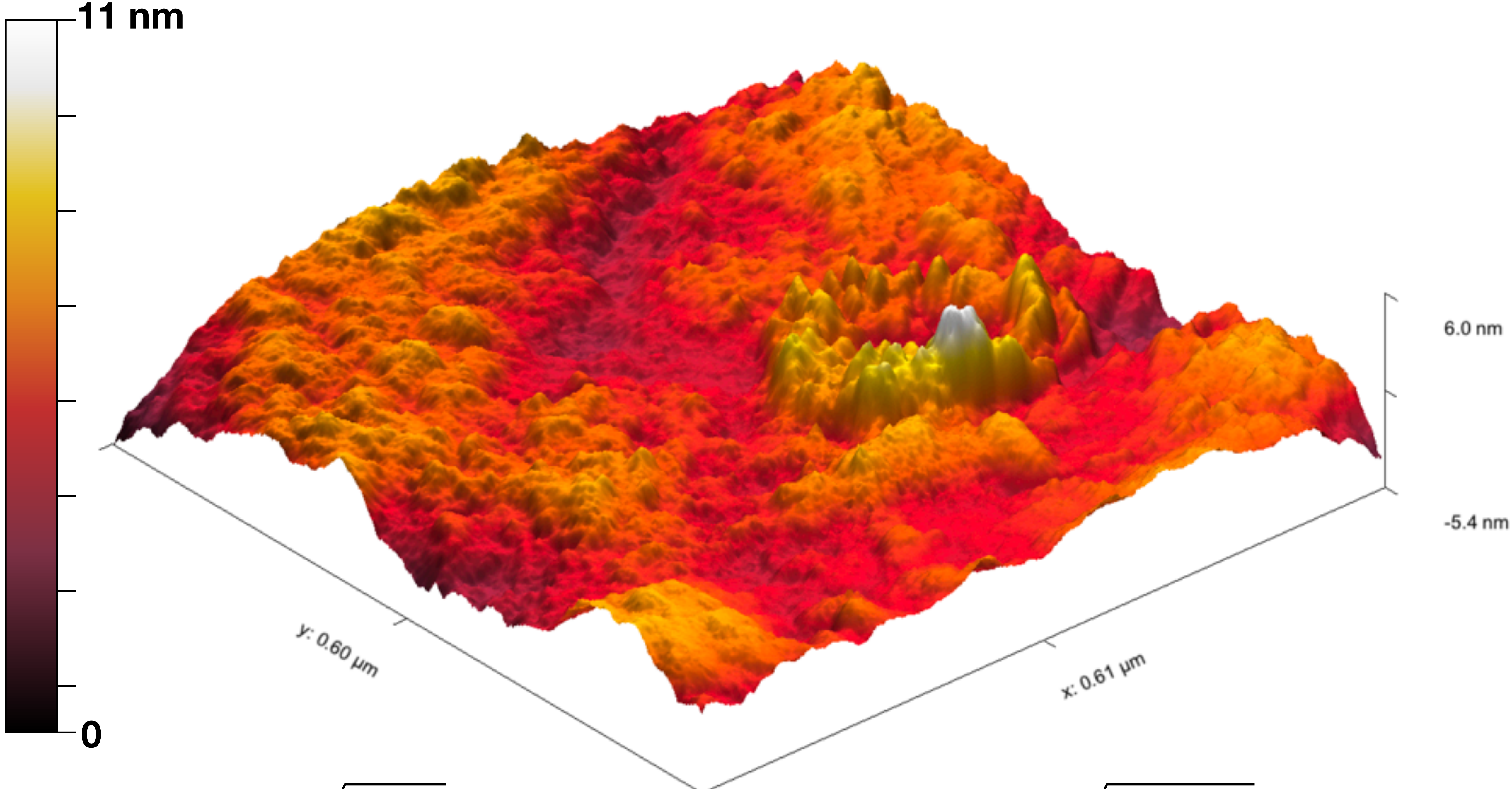
Our particles aren't smooth



$$h_{rms} = \sqrt{\langle h^2 \rangle} \simeq 1.1 \text{ nm} \qquad h'_{rms} = \sqrt{\langle \nabla h^2 \rangle} \simeq 0.1$$

http://tribo.iam-cms.kit.edu/contactapp/

Our particles aren't smooth
(if you look close enough)



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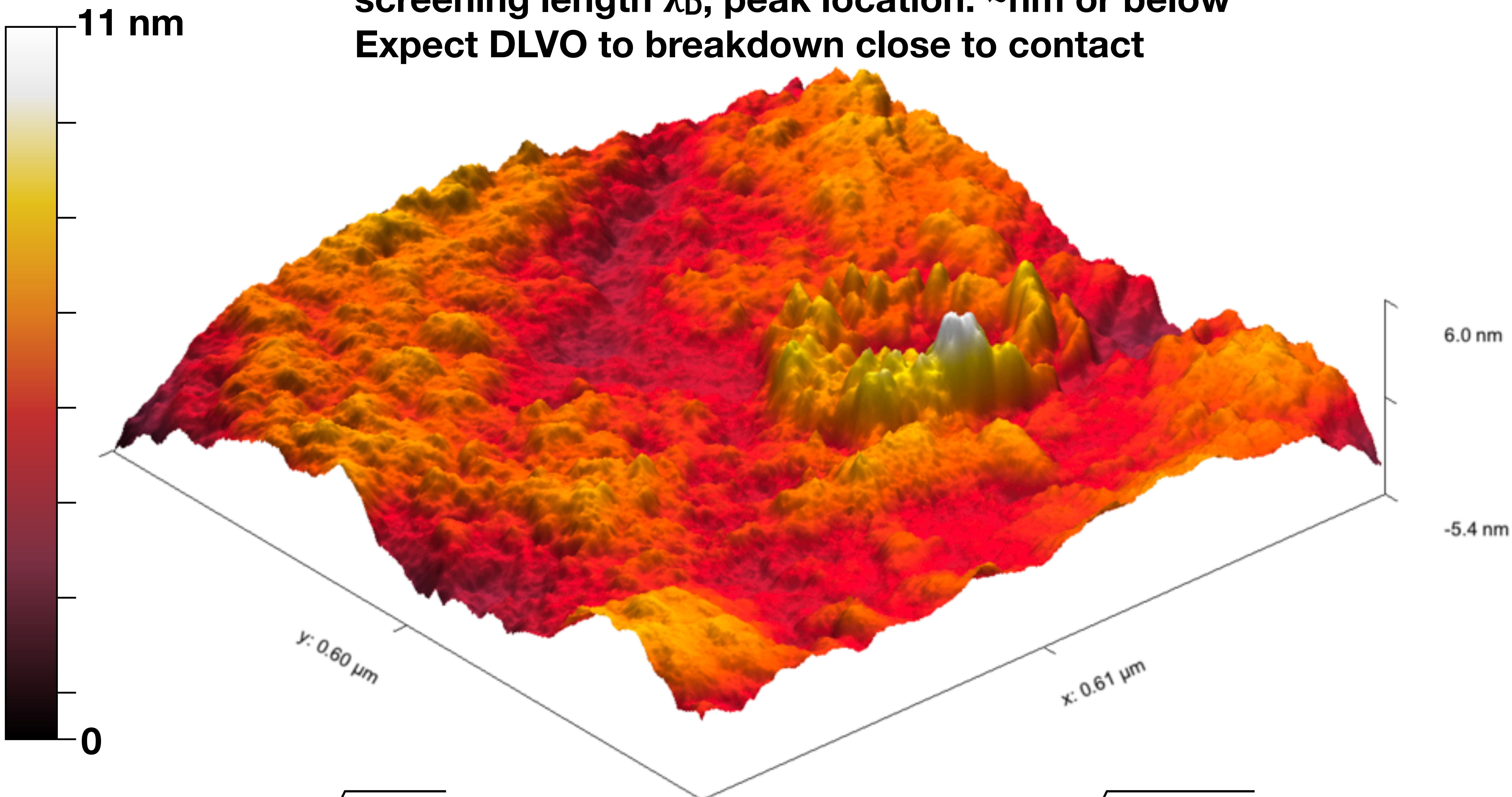
Our particles aren’t smooth

(if you look close enough)

screening length λ_D, peak location: ~nm or below
Expect DLVO to breakdown close to contact



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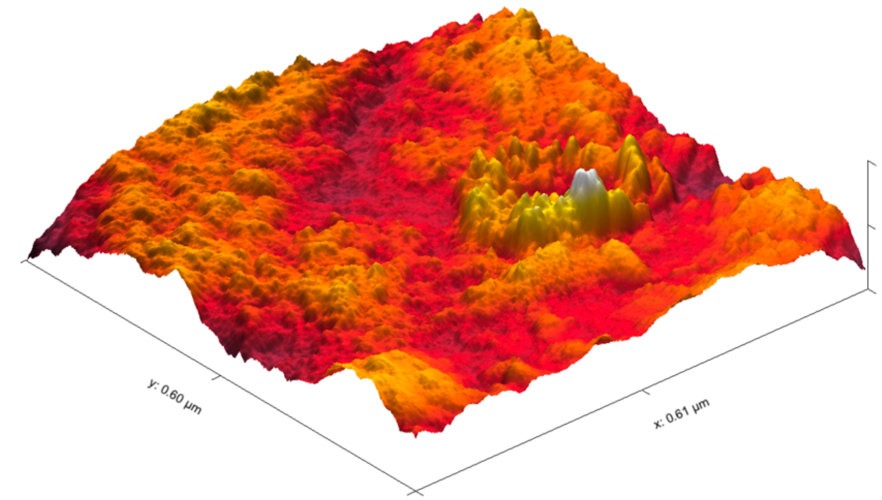
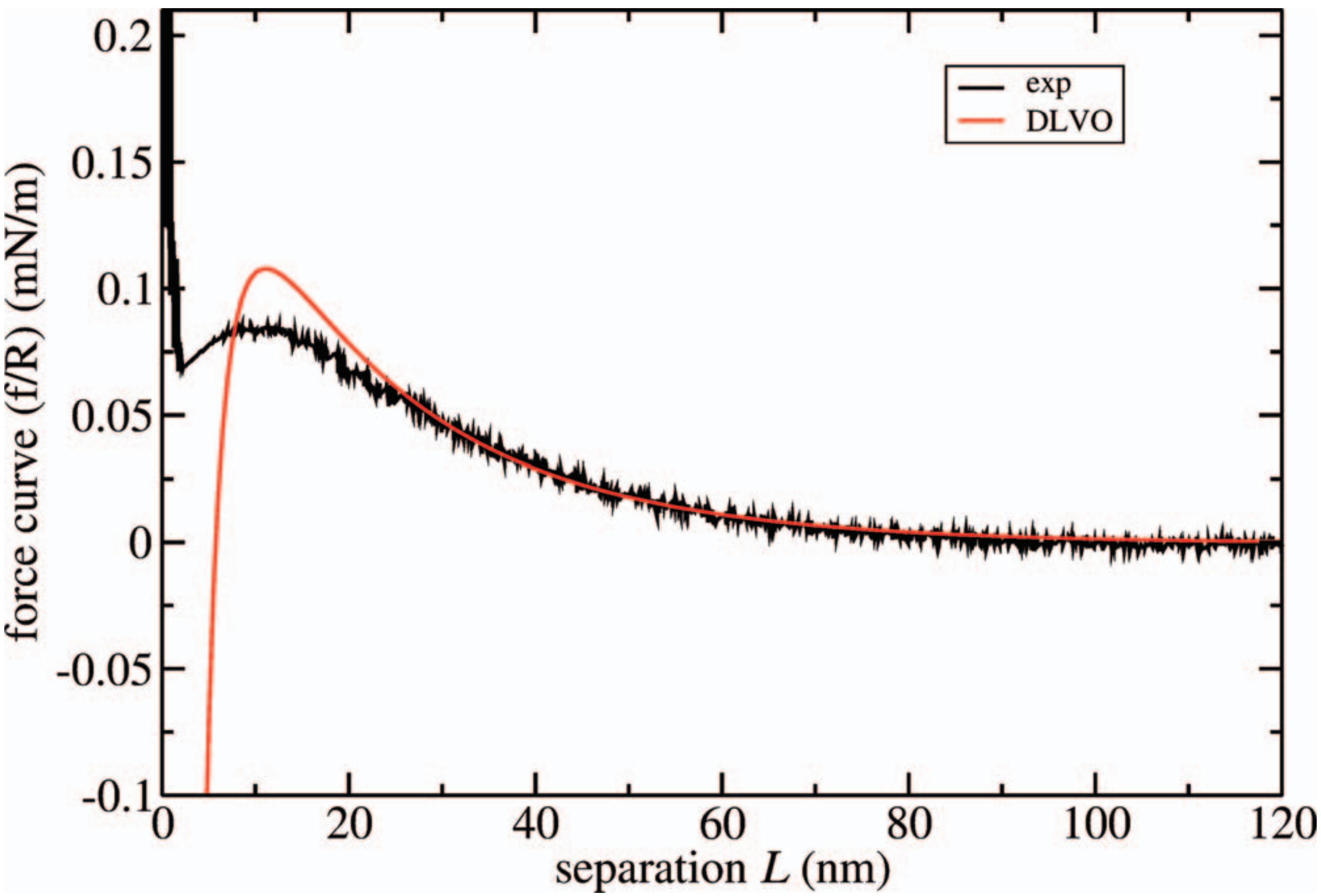
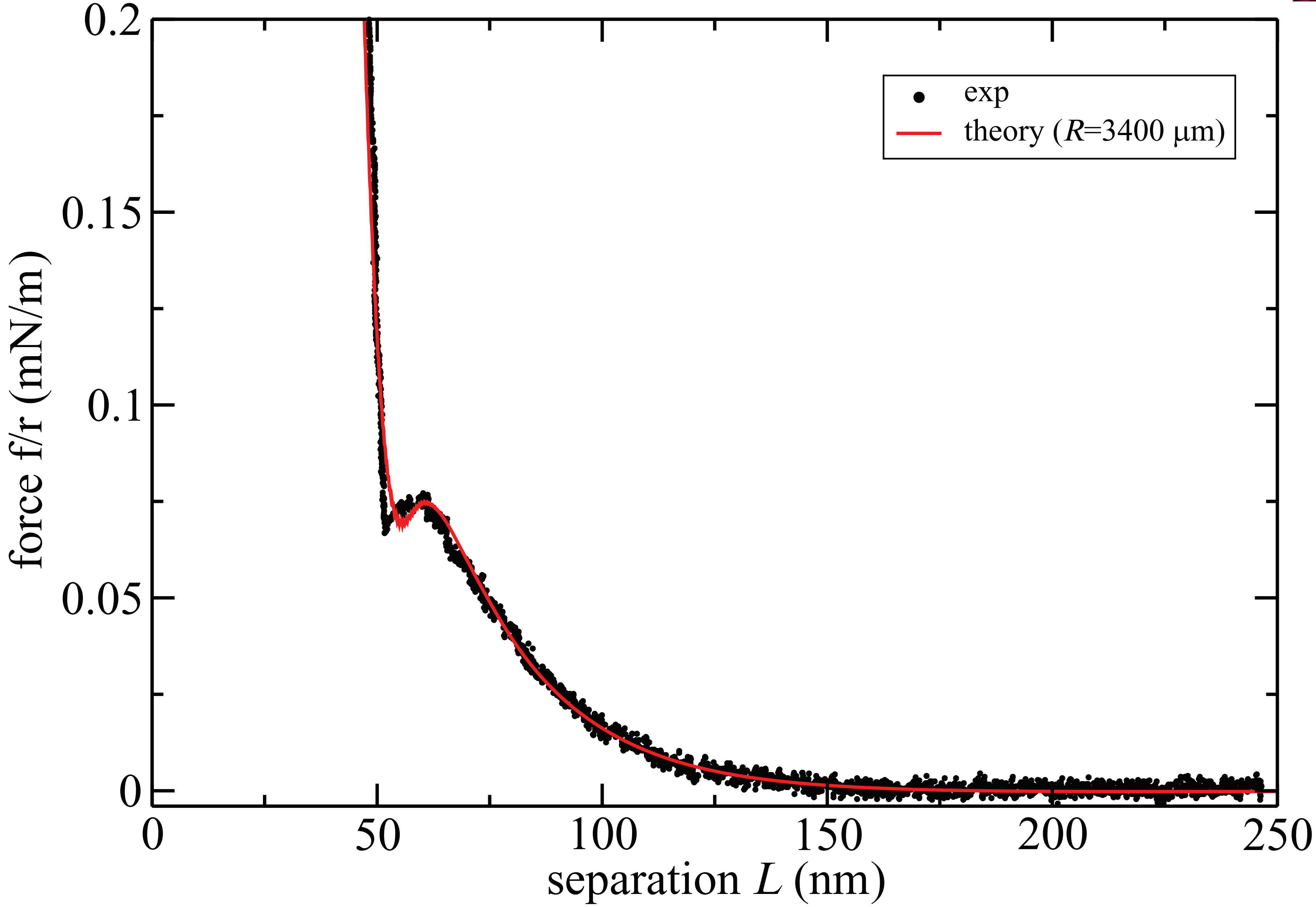
Interaction model with roughness?

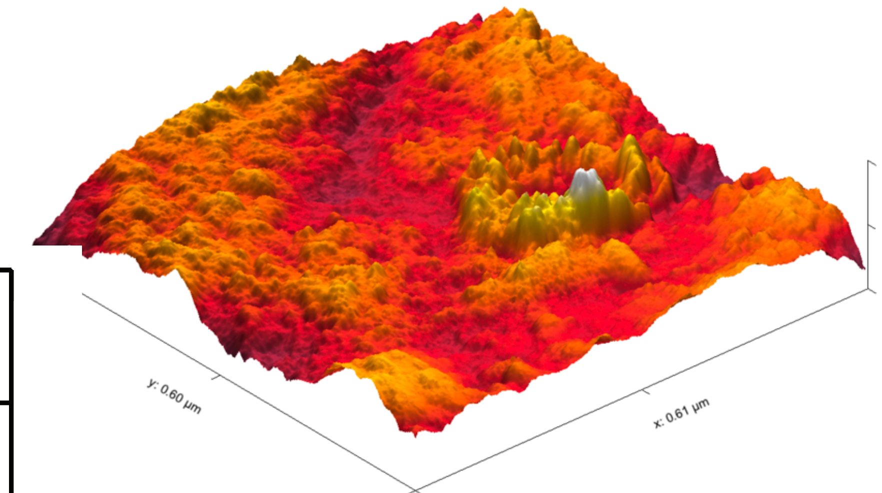




Parsons, Walsh, Craig, J. Chem. Phys. 2014

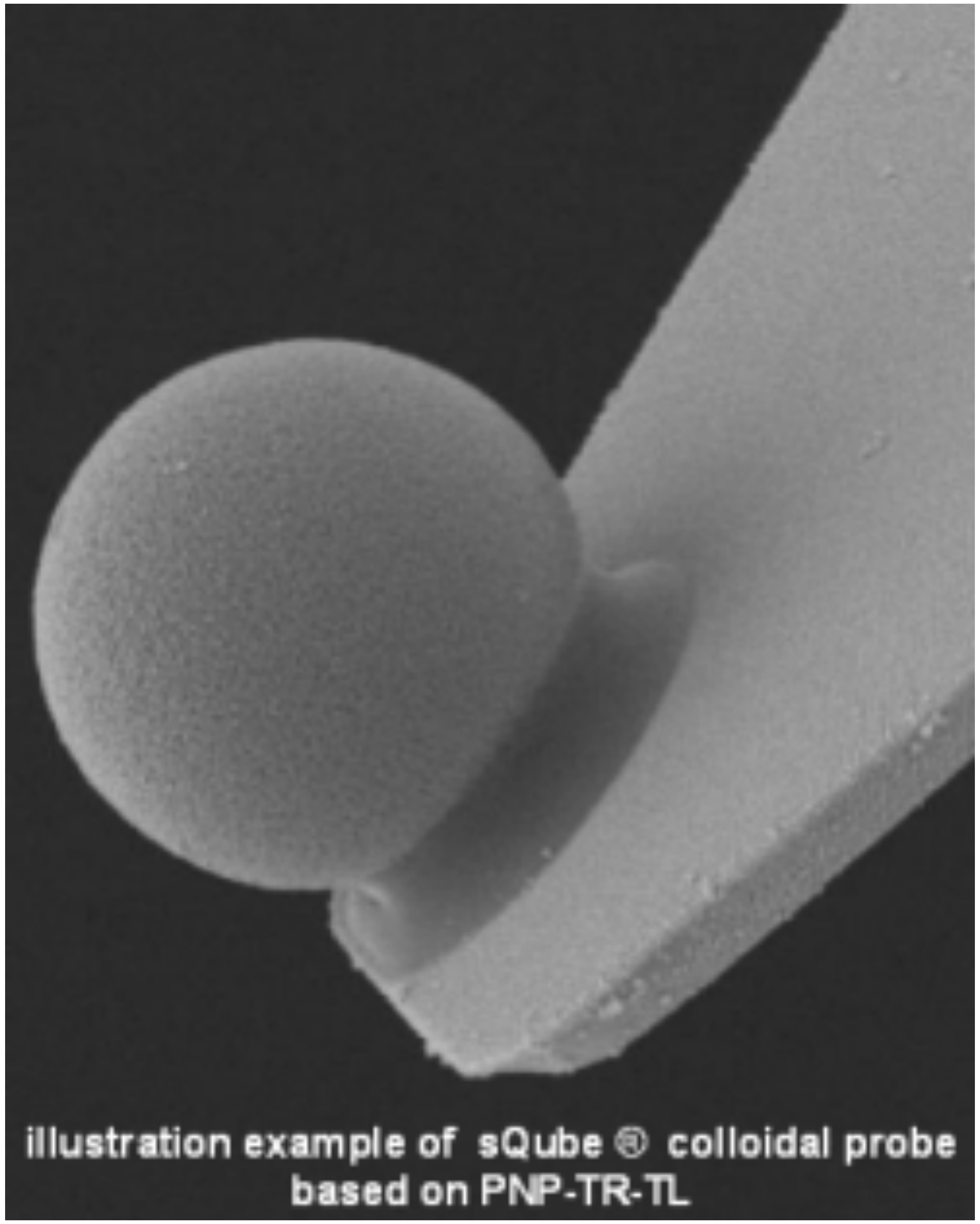
Interaction model with roughness?

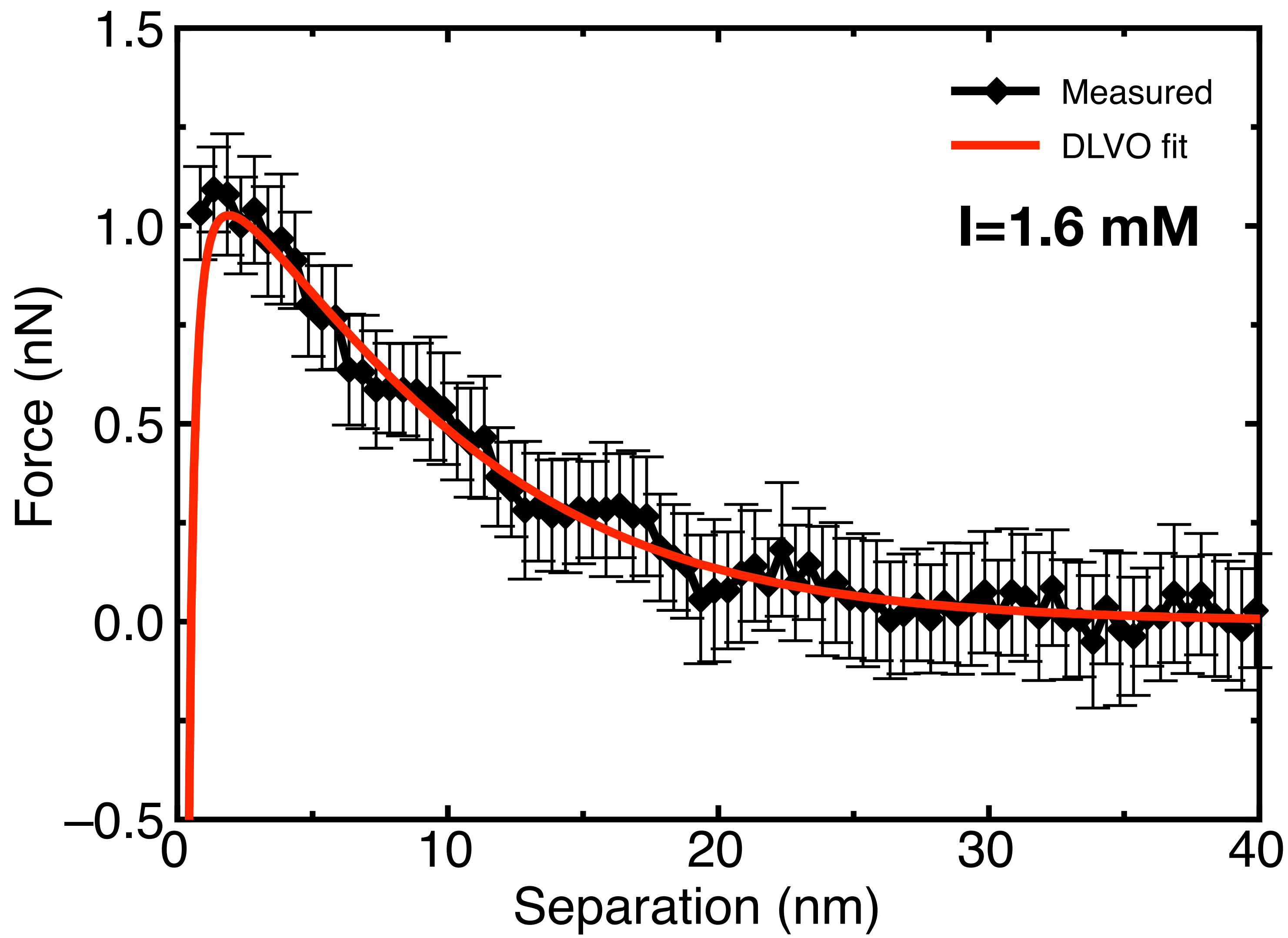




Parsons, Walsh, Craig, J. Chem. Phys. 2014

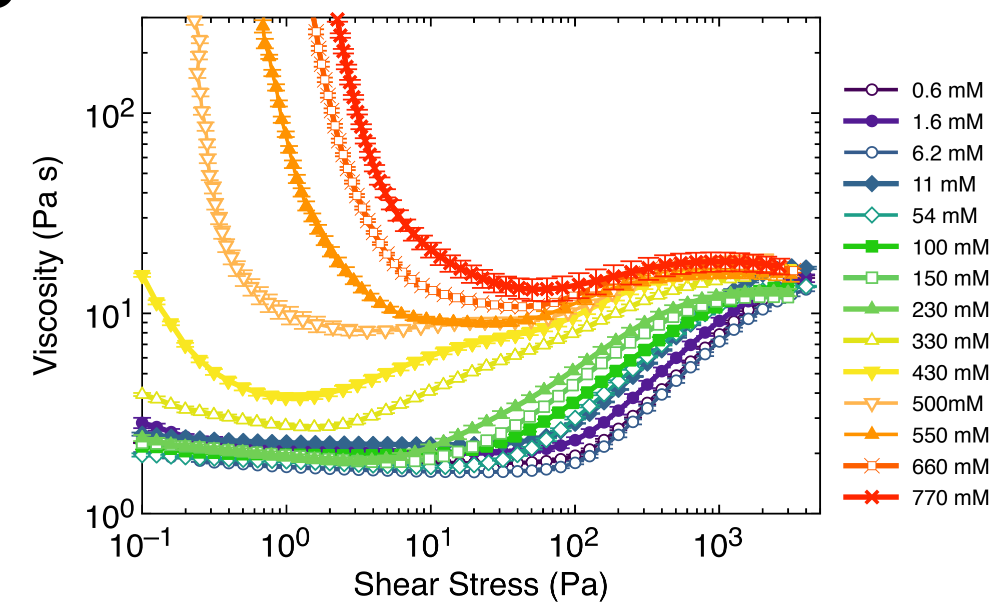
Direct Force Measurements



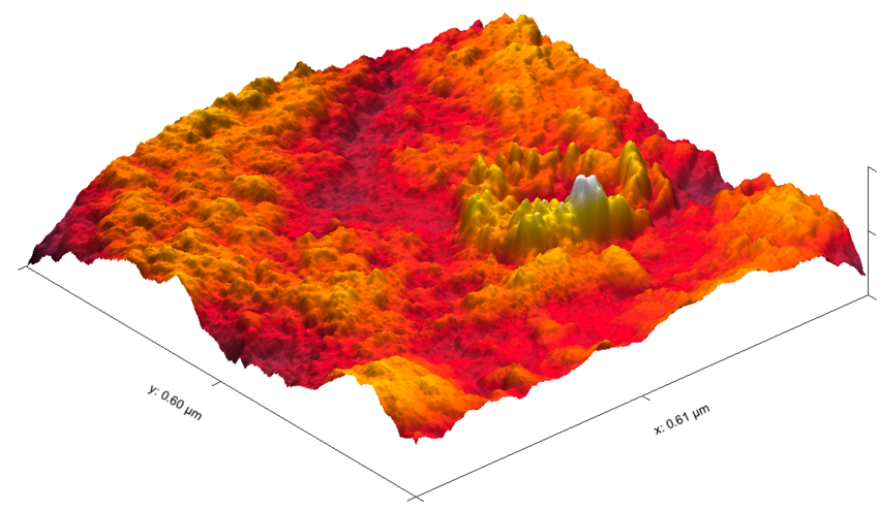


Conclusions

- **Shear thickening onset controlled by repulsive particle interactions**
- **smooth particle interactions capture trend**



- **Shear thickening persists even as repulsive length scales approach surface roughness**
- **ϕ_m , and hence μ, unchanged by interaction details**



- Need for particle contact model incorporating roughness