ETH zürich

soft materials and interfaces

Tribology of Wet Systems: from Hydrodynamic to Boundary Contacts

D MATL.

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IFPRI
International Fine Particle Research Institute

Outline

- Introduction of lubricated contacts: hydrodynamic and boundary lubrication
- Connection between lubrication and rheology of concentrated suspensions (shear thickening)
- The impact of tribology beyond viscosity and flow curves
- Measuring single-particle friction
- Modifying boundary friction coefficients
- Open questions and interesting directions for future work

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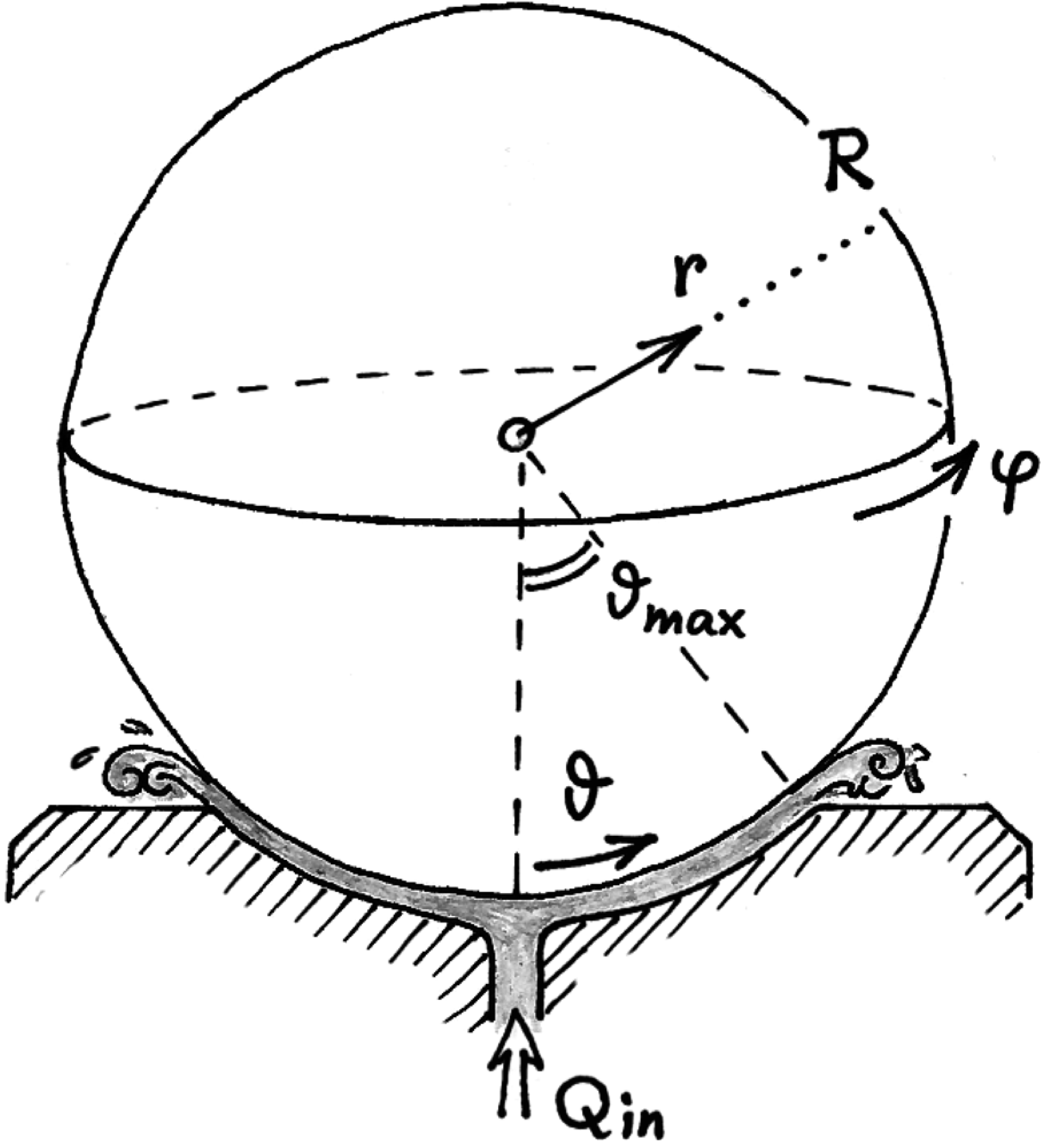


American Journal of Physics 82, 1029 (2014)

$$F_g = F_{\mathrm{up}} = \iint_{A_{\mathrm{sub}}} [P(\theta) - P_{\mathrm{atm}}] \cos\theta \, dA$$

$$m = (4/3)\pi R^3 \rho_{\mathrm{gr}} = 1440\,\mathrm{kg}$$

$$h_{\mathrm{sph}} = \left[\frac{9}{2\pi}(1 - \cos\theta_{\max})\right]^{1/3} \left(\frac{\mu Q_{\mathrm{in}}}{R g \rho_{\mathrm{gr}}}\right)^{1/3}$$

$R = 0.5$ m

$\theta_{max} = 0.6$ rad

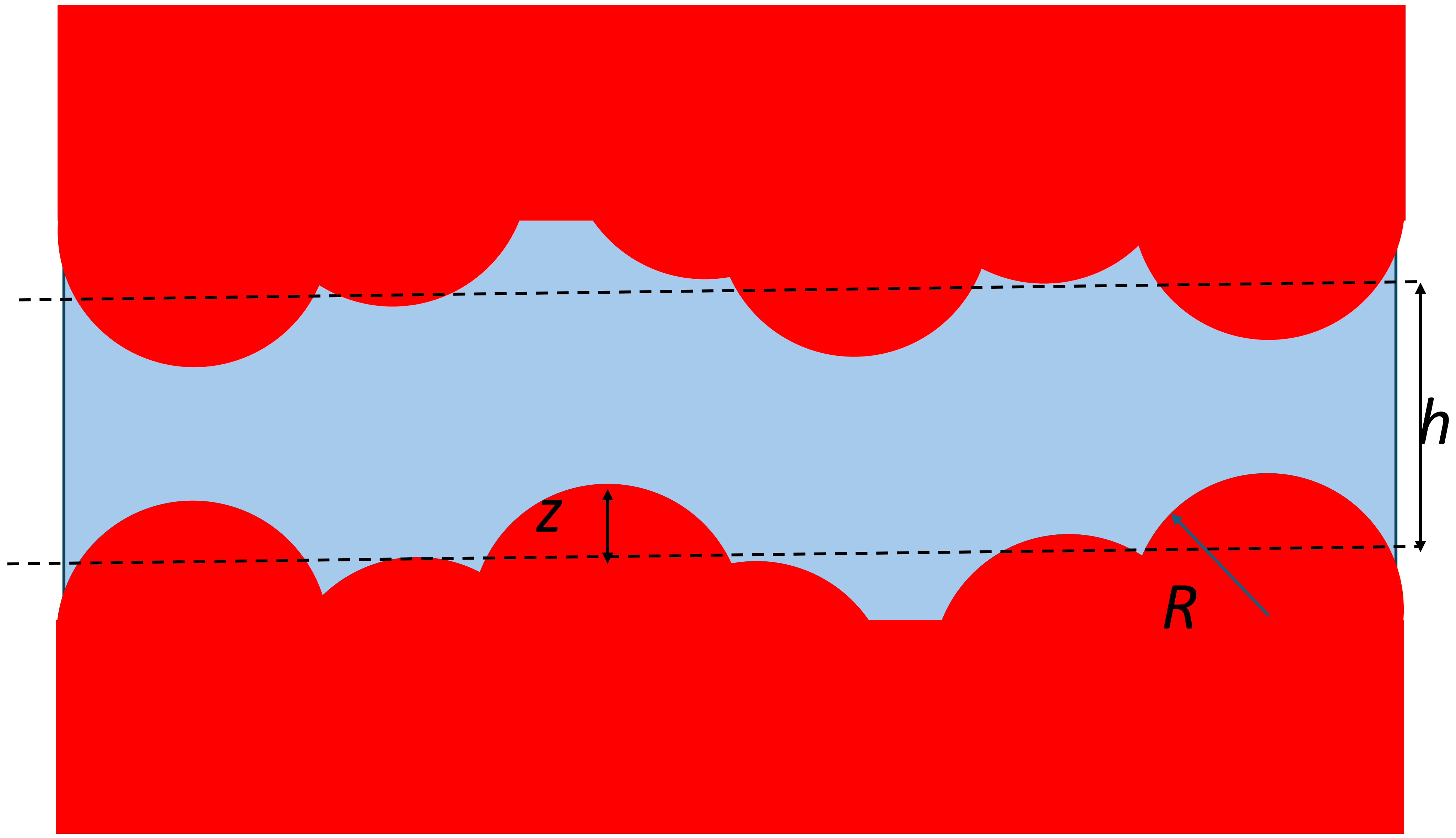
$\mu = 10^{-3}$ Pa s

$Q_{in} = 1.5$ L/s

$\rho_{gr} = 2750$ kg/m^3

$h_{sp} = 0.3$ mm

Lubricated Contacts



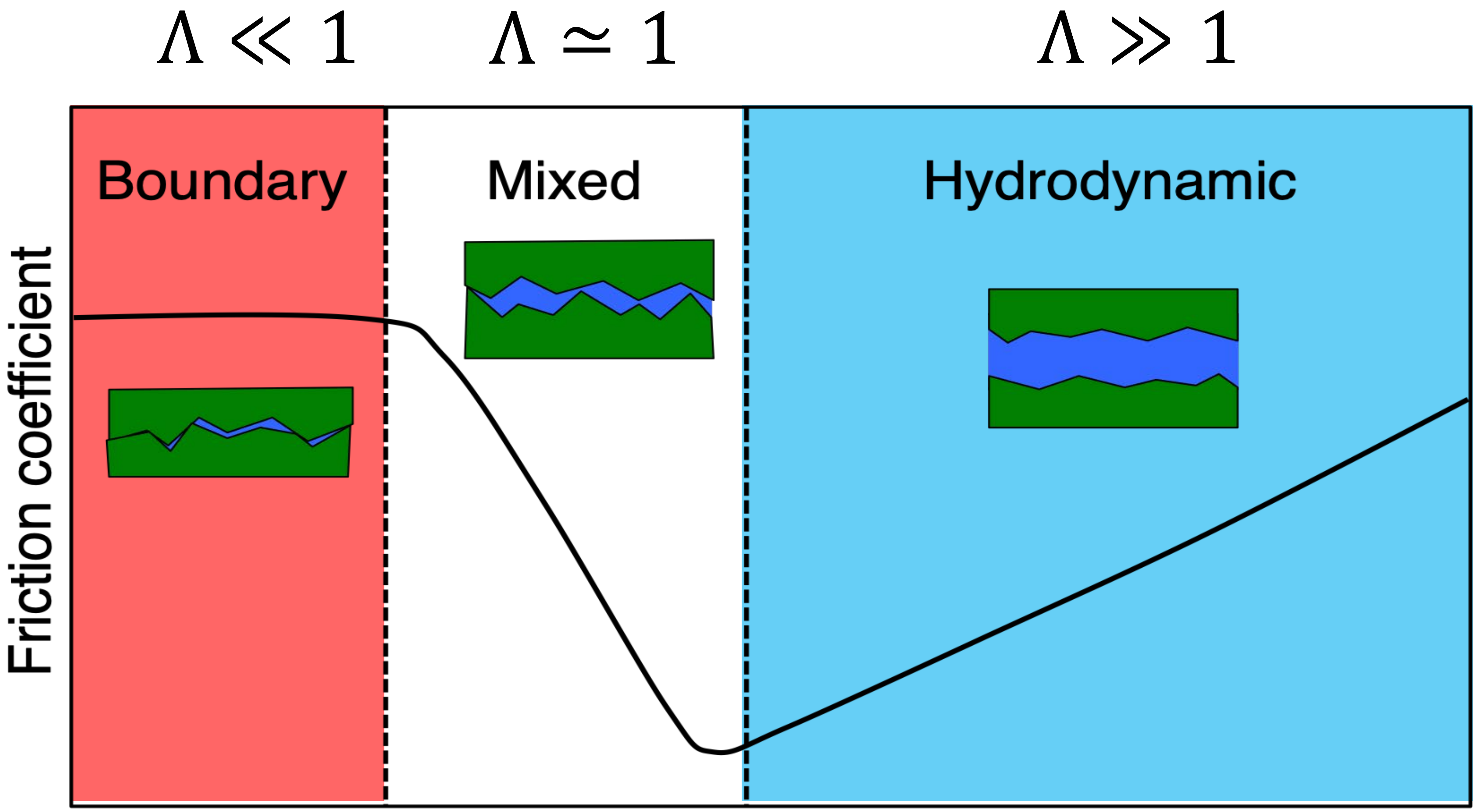
$$R_q = \sqrt{\frac{1}{L^2}\int_0^L \int_0^L (z(x,y) - z_0)^2 dx dy}$$

RMS roughness

$$\Lambda = \frac{h}{R_q}$$

Lambda ratio

Stribeck curve



$$S \text{ or } H = \frac{\eta_f \, v \, a}{N}$$

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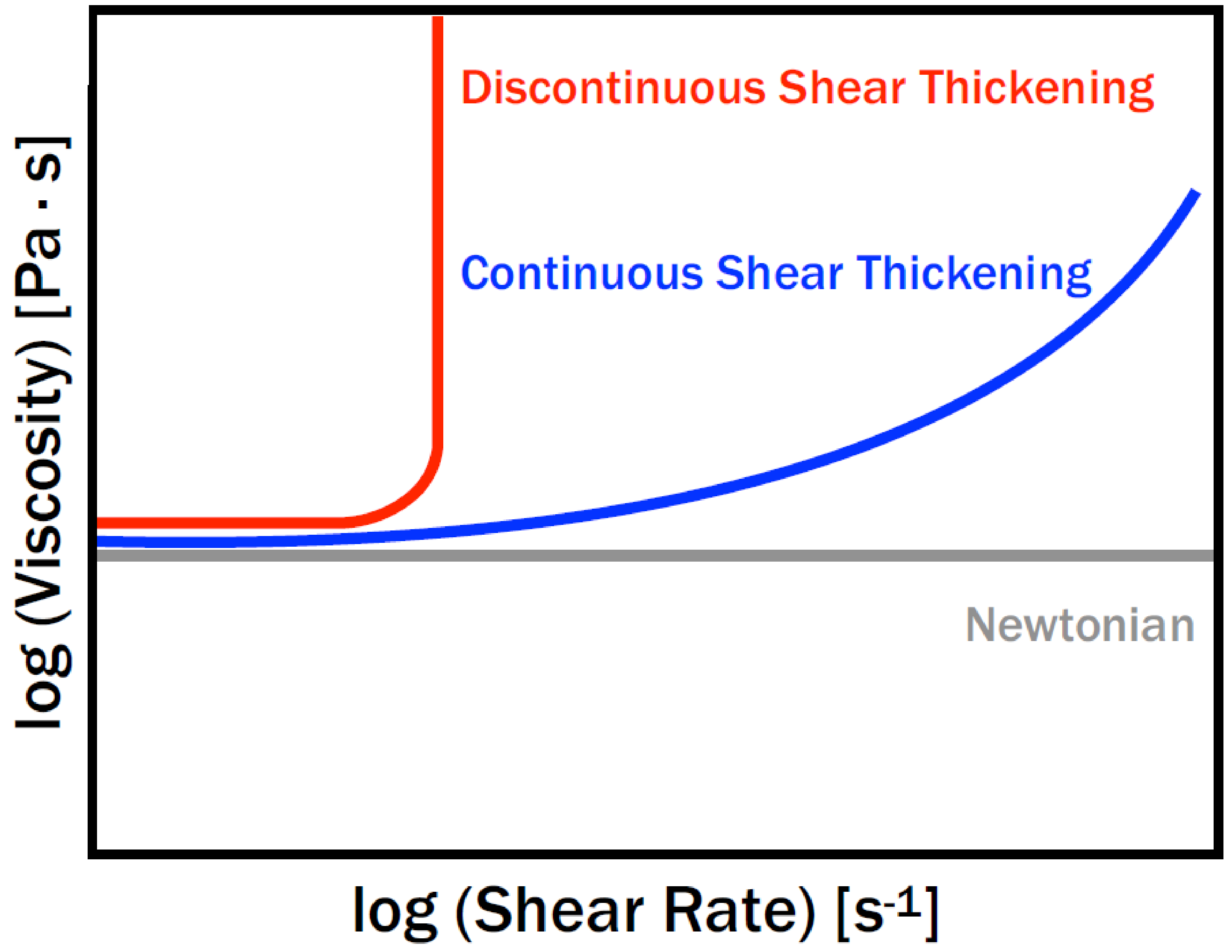
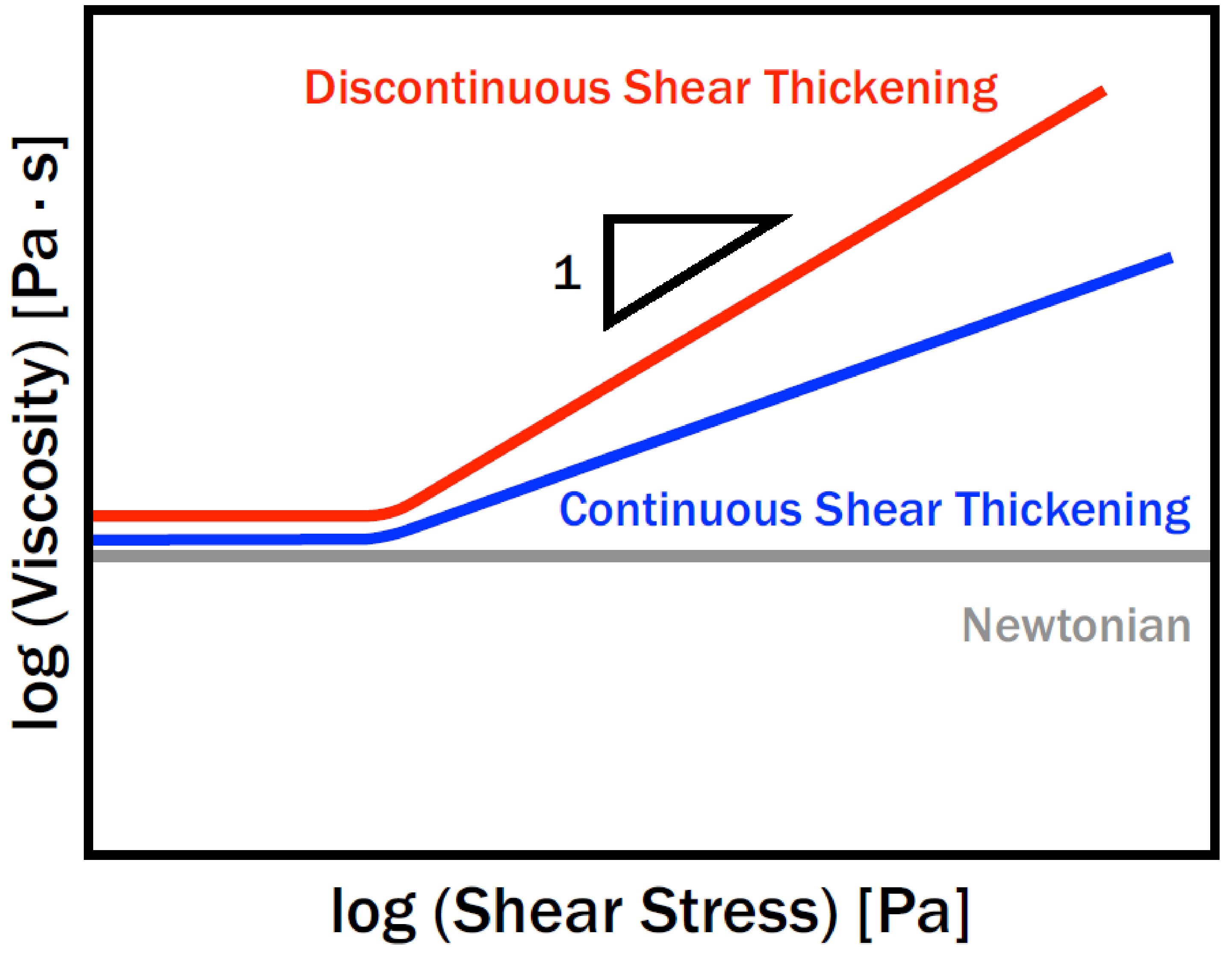
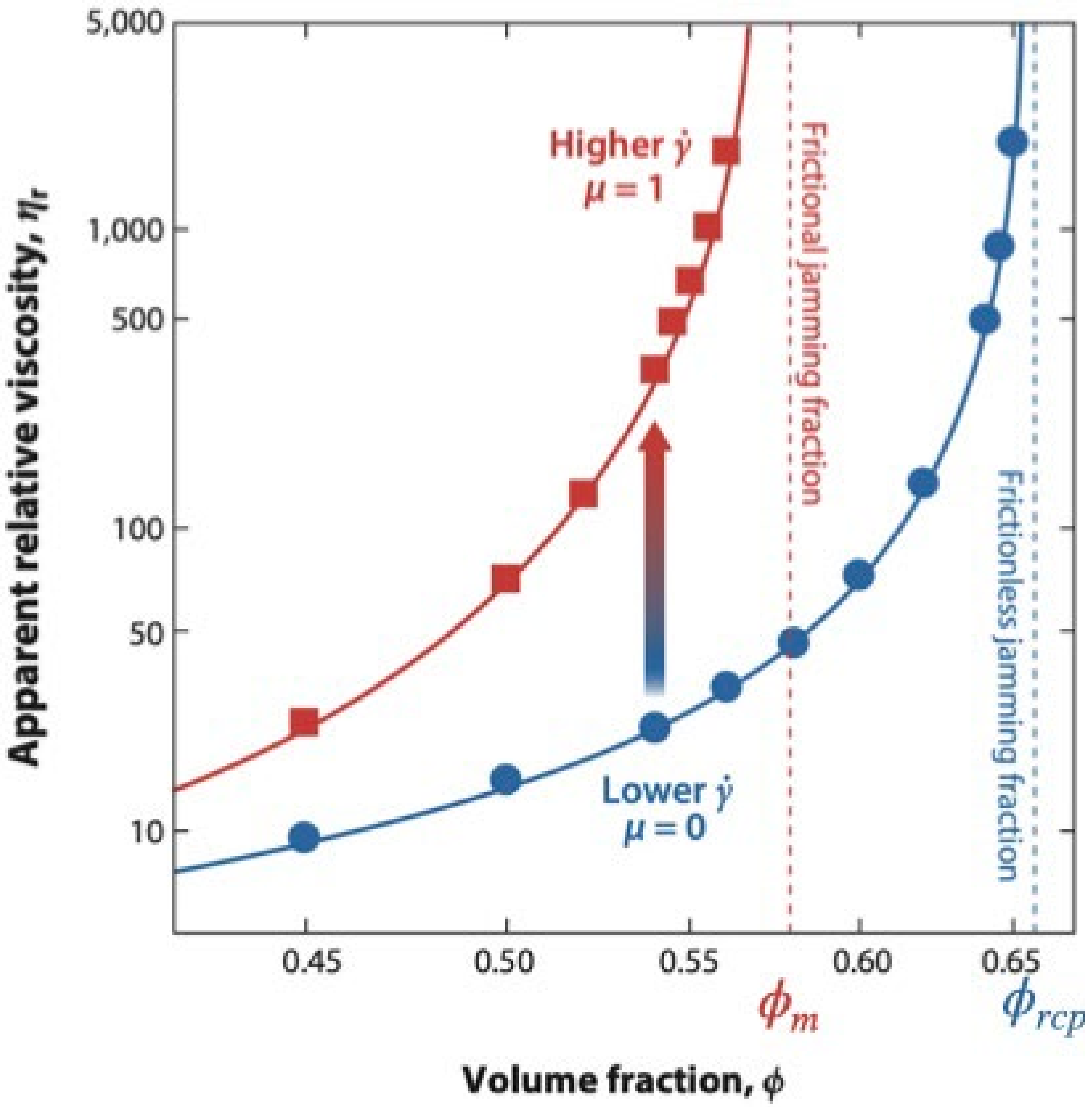
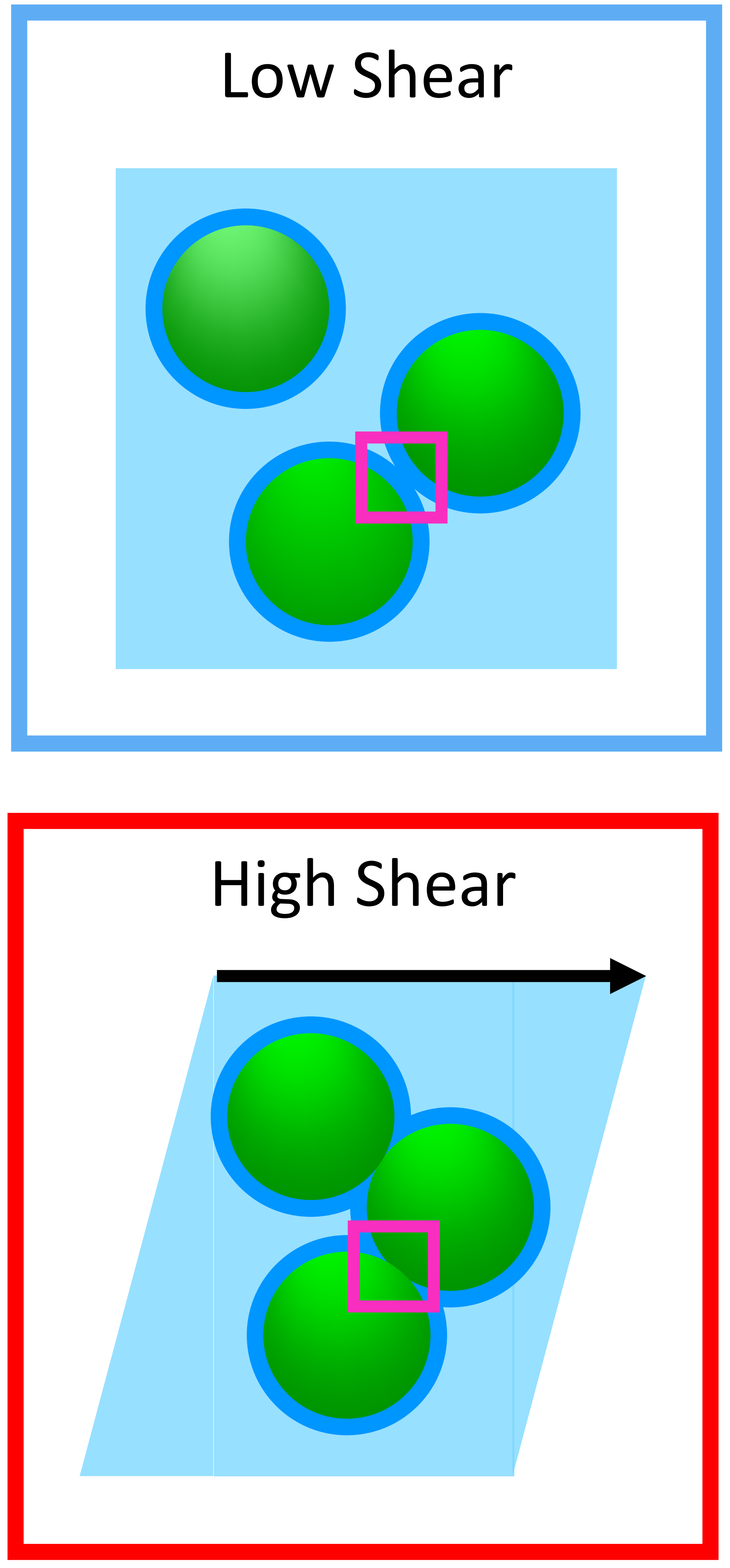
Non-Linear Rheology

Hydrodynamic-to-Boundary Transition



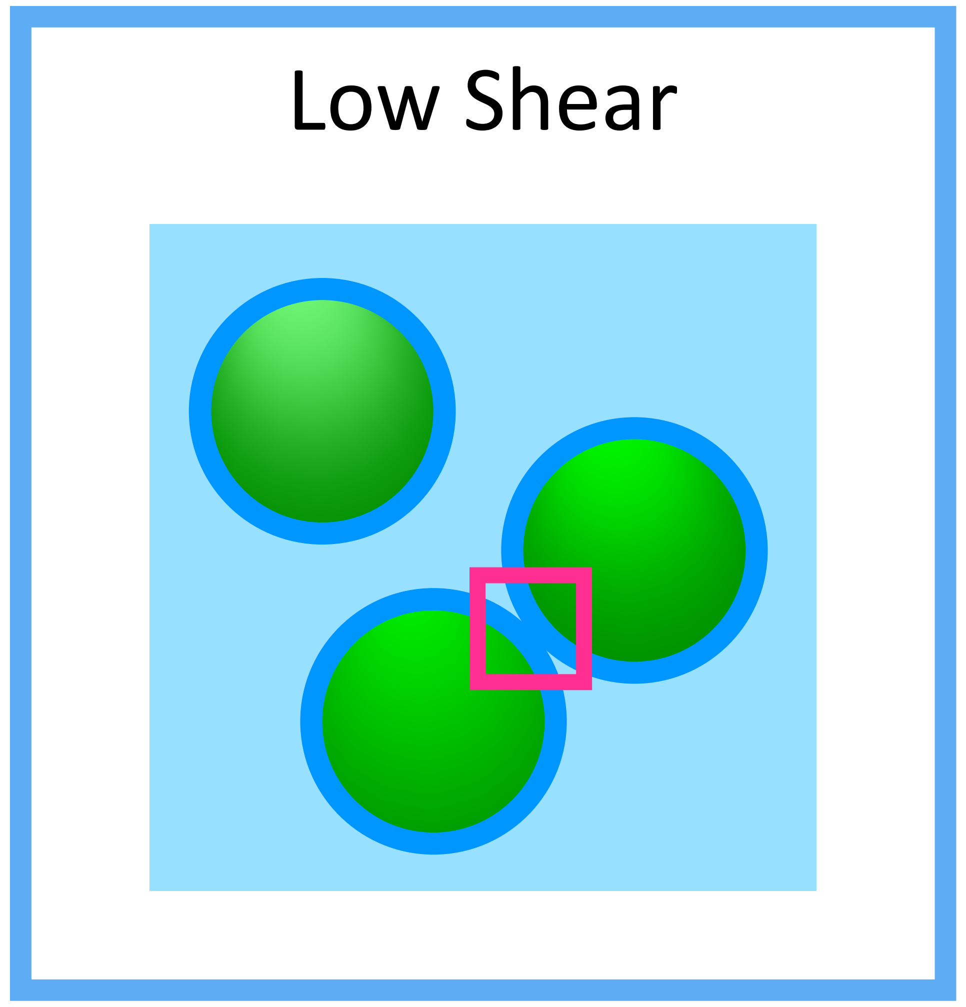


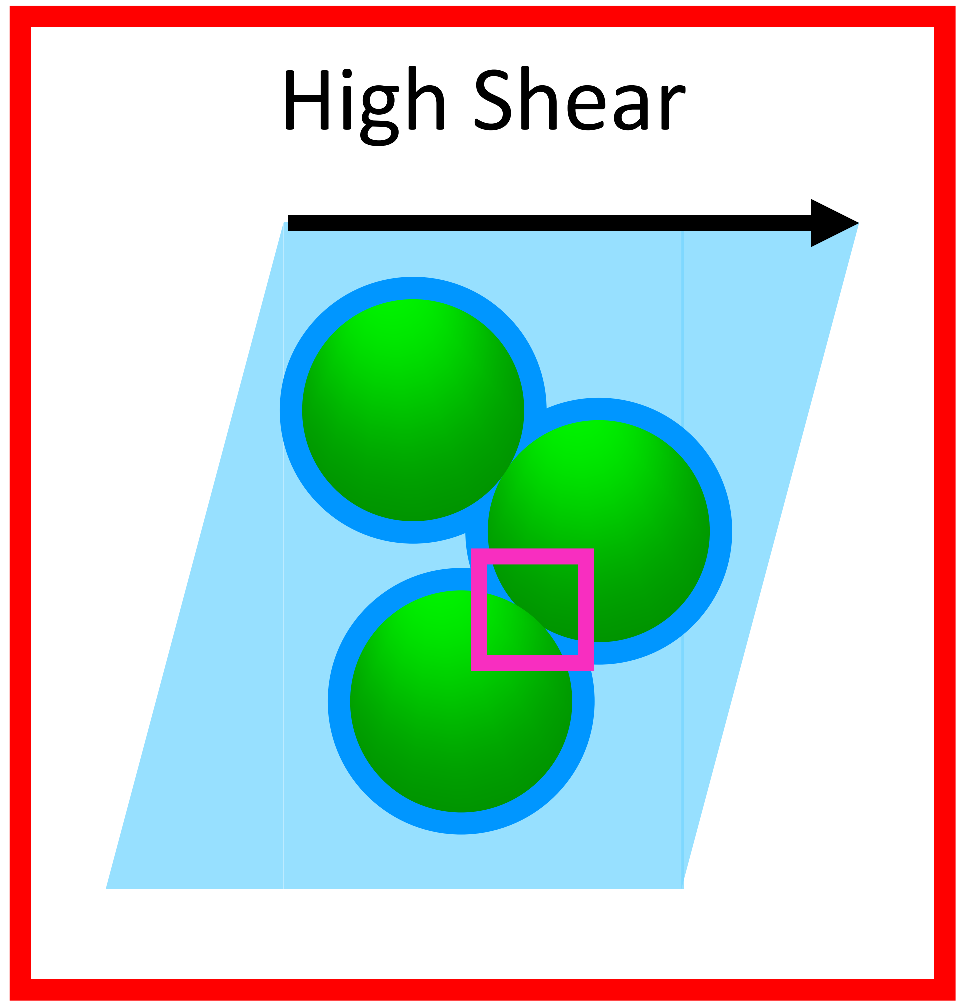


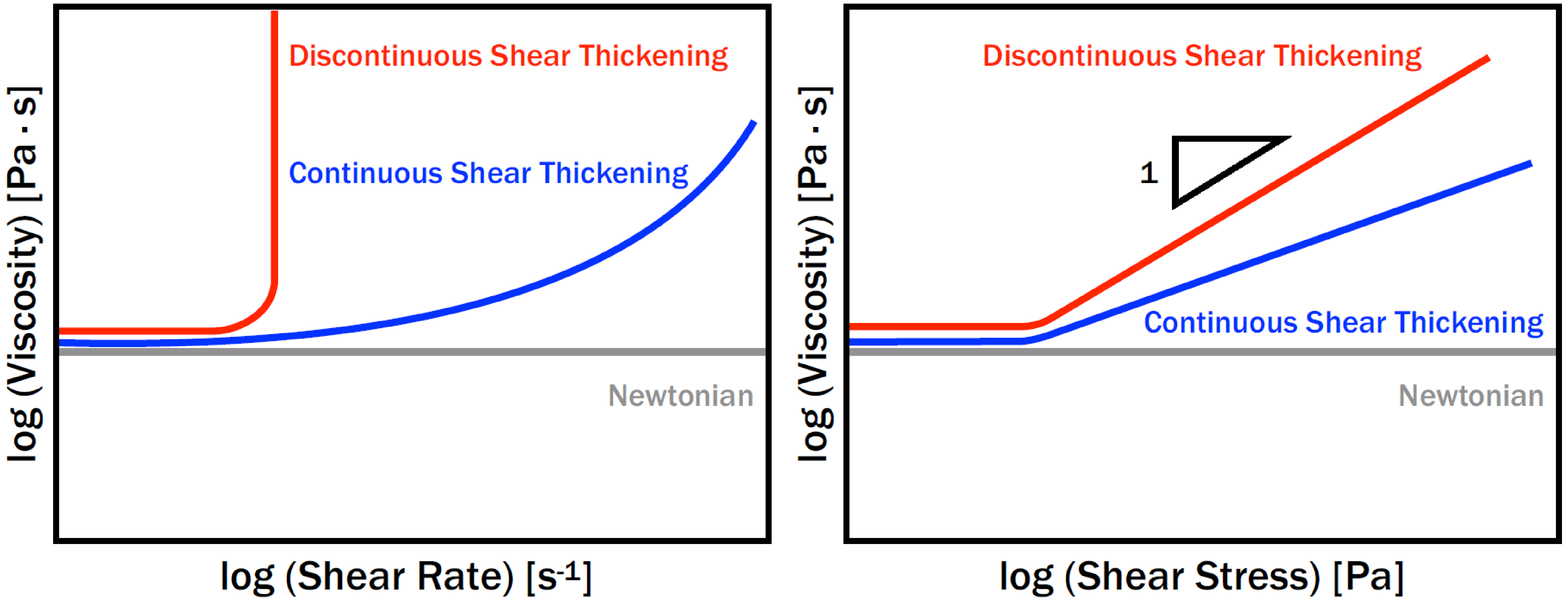


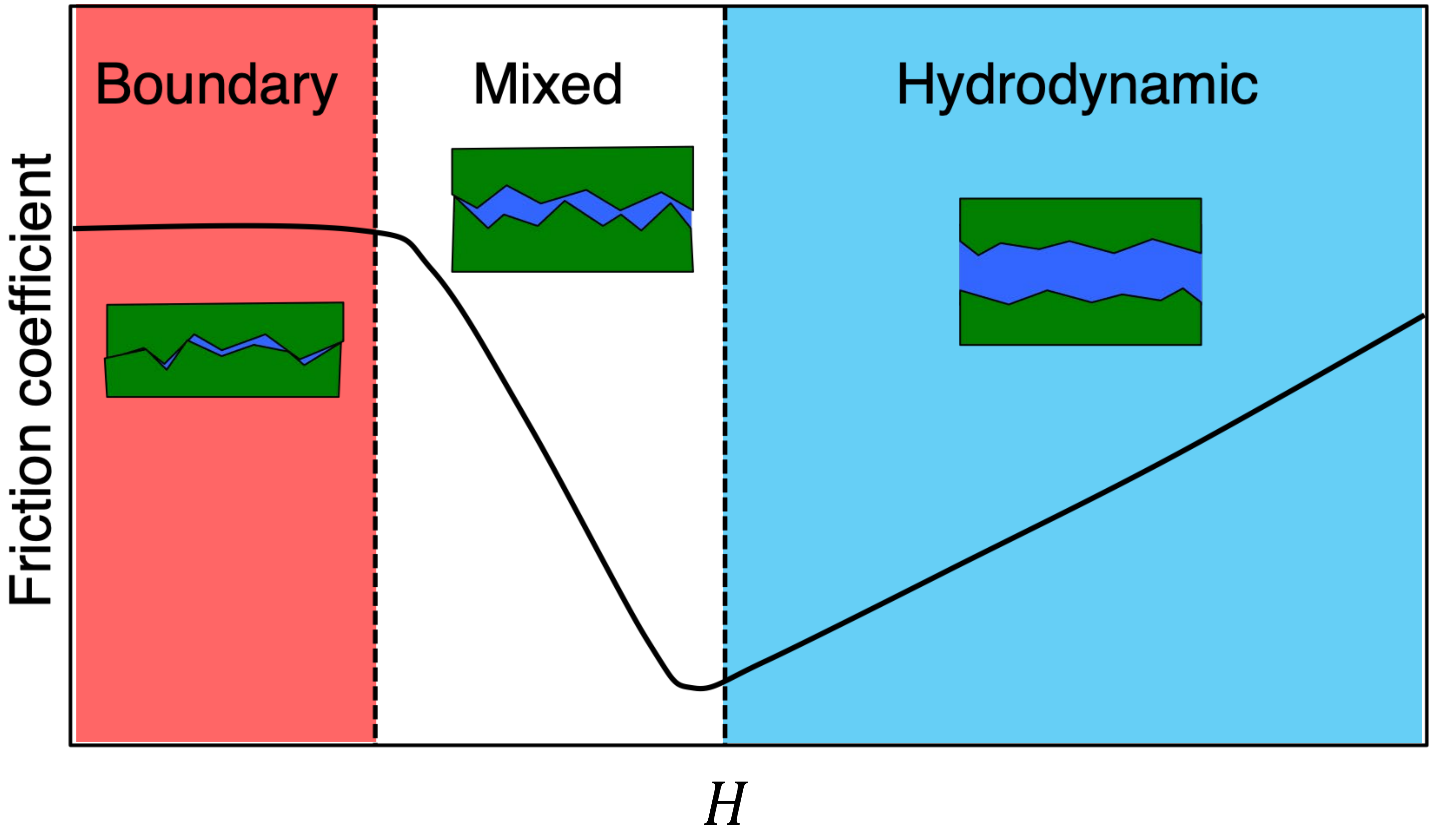
Morris, Wyart, Cates, Poon, ….

Hydrodynamic-to-Boundary Transition









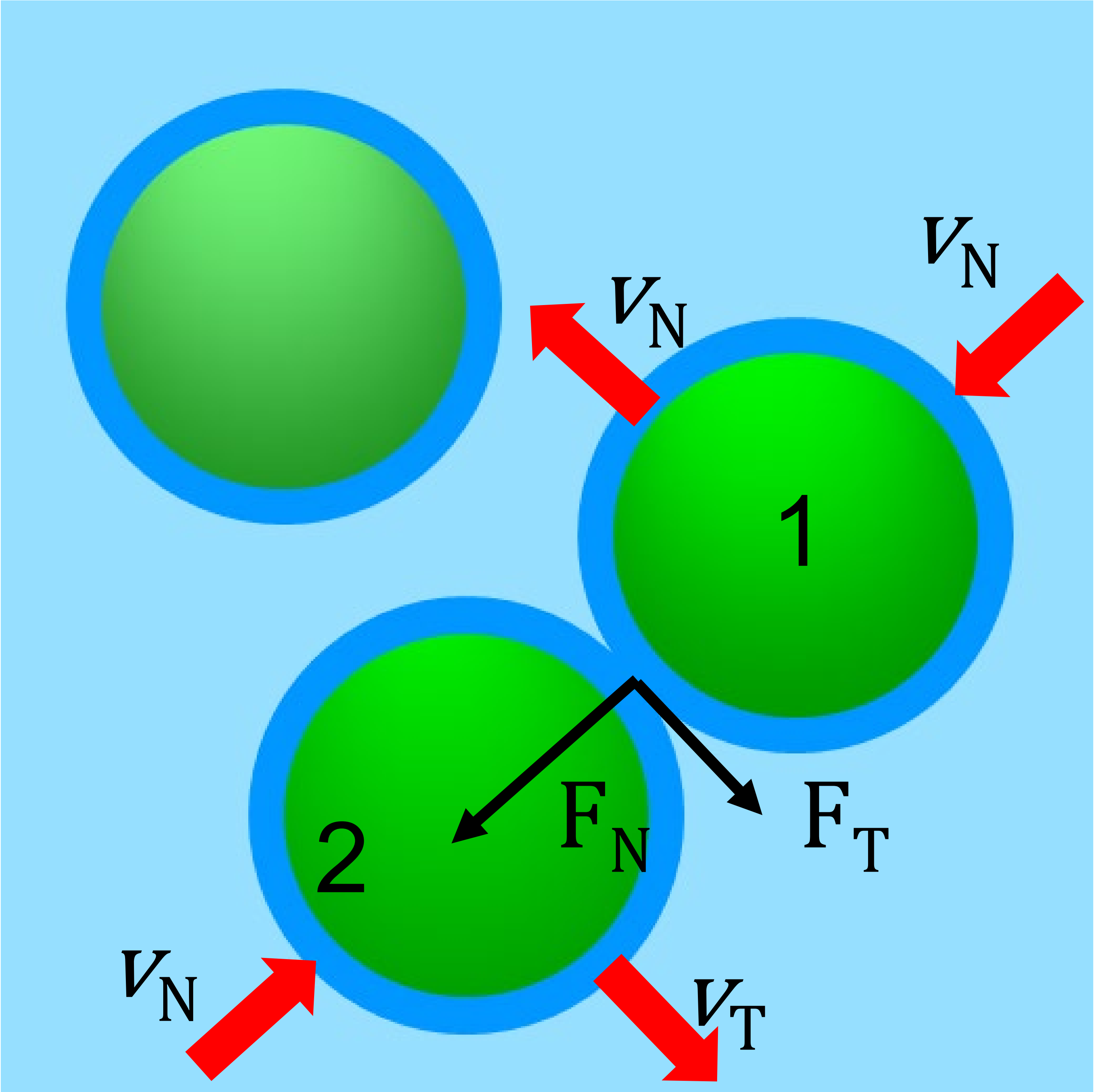
$$H = \frac{\eta_f \, v \, R_p}{N} = \frac{\eta_f \, \dot{\gamma}}{P_p}$$

$$P_p \propto \eta \dot{\gamma}$$

$$\eta = \eta_f \eta_0 \dot{\gamma}^{n-1}$$

$$H \propto \frac{1}{\eta_0 \dot{\gamma}^{n-1}}$$

Hydrodynamic-to-Boundary Transition



$$\mathbf{F}^{HD}_{1\to 2} = \frac{\pi}{10}\eta_f R_p \begin{bmatrix} -15h^{-1} & 12h^{-\frac{1}{2}} \\ 0 & -10ln(h^{-1}) \end{bmatrix} \begin{bmatrix} v_N \\ v_T \end{bmatrix}$$

Hydrodynamic forces diverge at contact

Cut-off distance for hydrodynamic to boundary transition

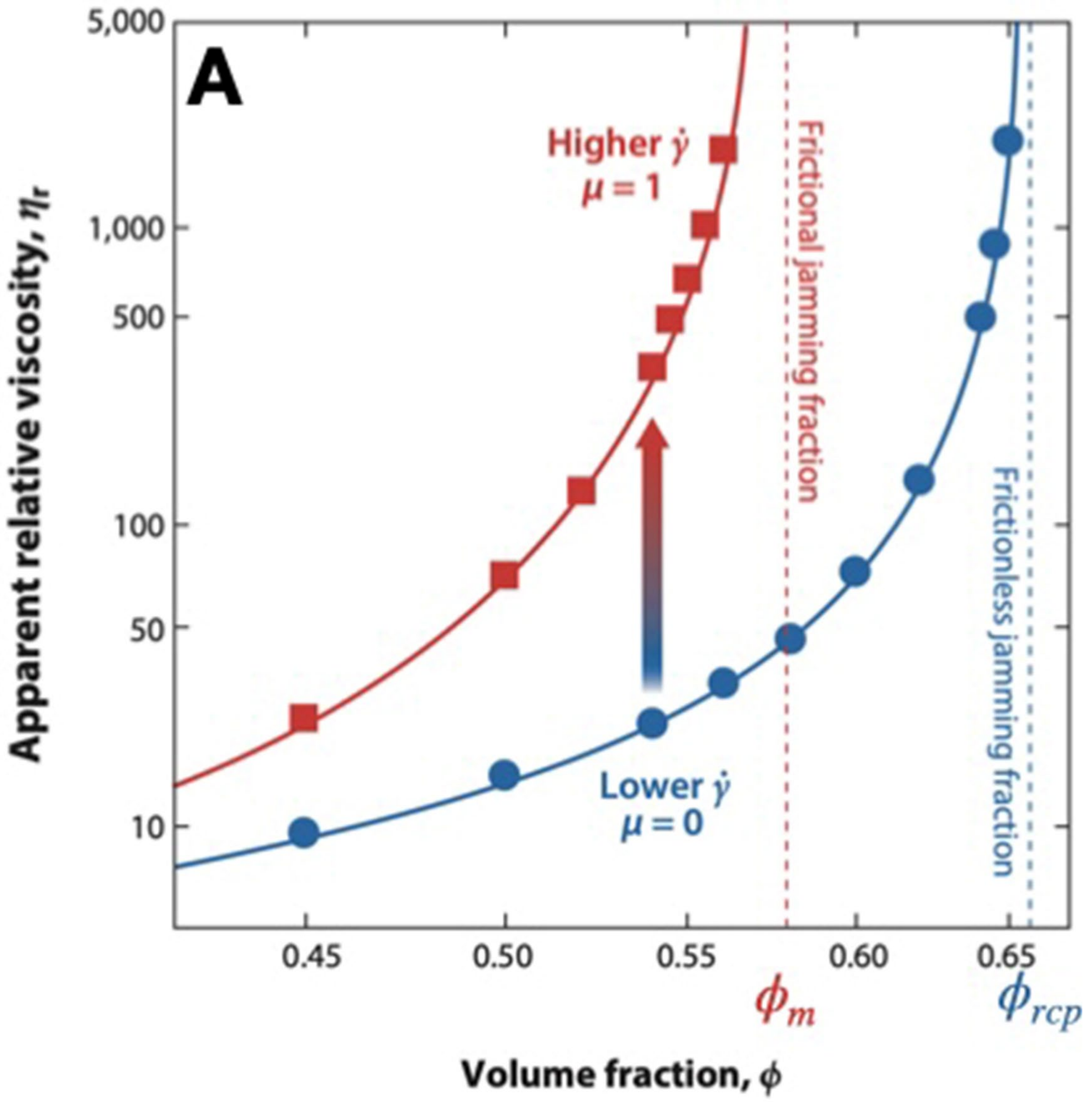
Inertia
(Large particles)
Fernandez et al PRL 2013

Overcoming a potential barrier
(e.g. charge-stabilized particles)
distance for which P=P*
Wyart& Cates PRL 2014

Surface roughness

$$\Lambda = \frac{h}{R_q} \approx 1$$

Hydrodynamic-to-Boundary Transition



$$\eta \propto (\phi_m - \phi)^{-2}$$

and

$$\phi_m = \phi_m(\mu)$$

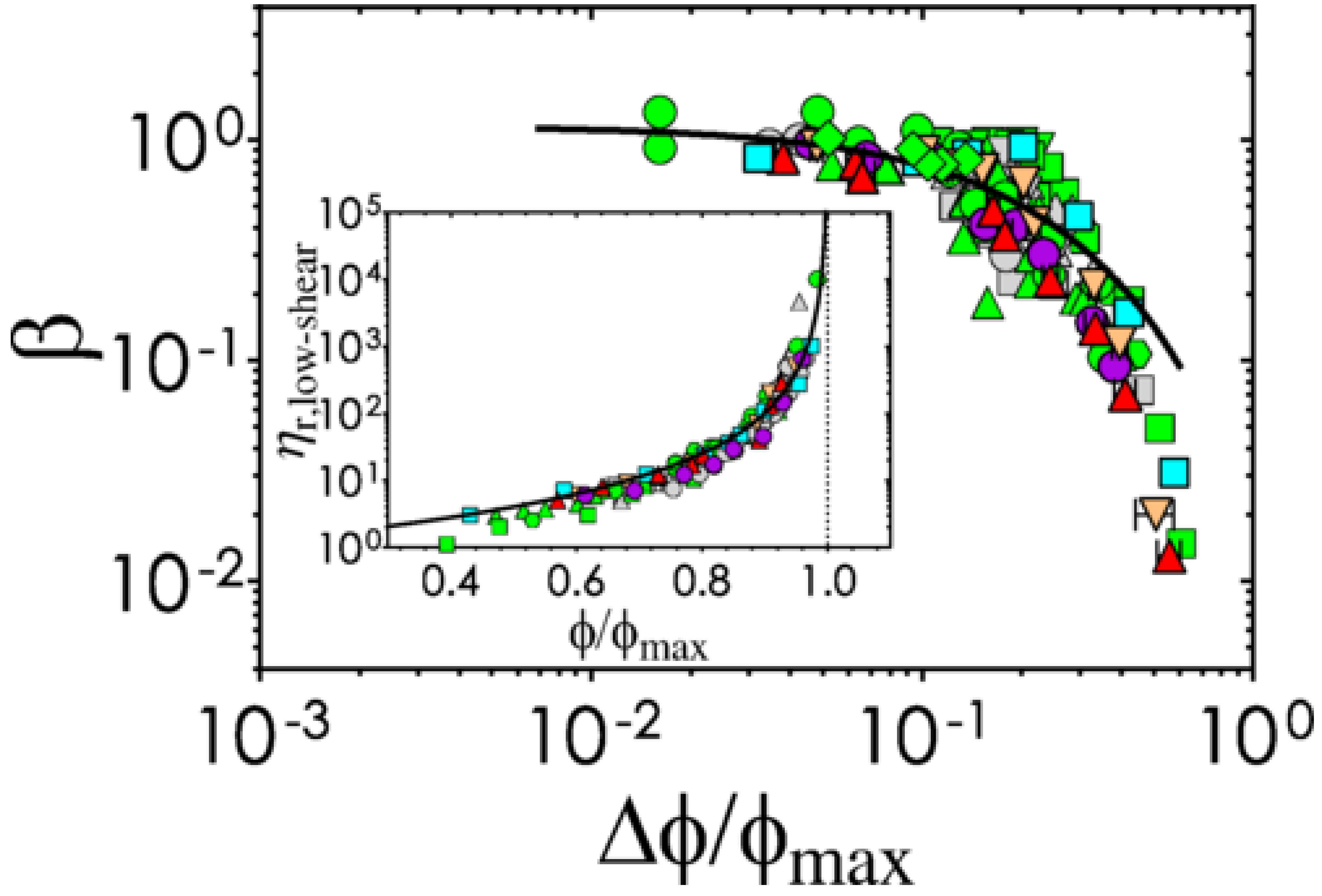
Friction Coefficient

Wyart&Cates, PRL, 2014

PHYSICAL REVIEW LETTERS 127, 158002 (2021)

Jamming Distance Dictates Colloidal Shear Thickening

Shravan Pradeep,[1] Mohammad Nabizadeh,[2] Alan R. Jacob,[1] Safa Jamali,[2] and Lilian C. Hsiao[1,*]



"…colloids with surface asperities interacting via lubrication (square) [11], spheres with sliding friction (upper triangle) [22], spheres with sliding and rolling friction (circle) [19]…"

Constraints, Friction & Rheology

PHYSICAL REVIEW LETTERS 121, 128001 (2018)

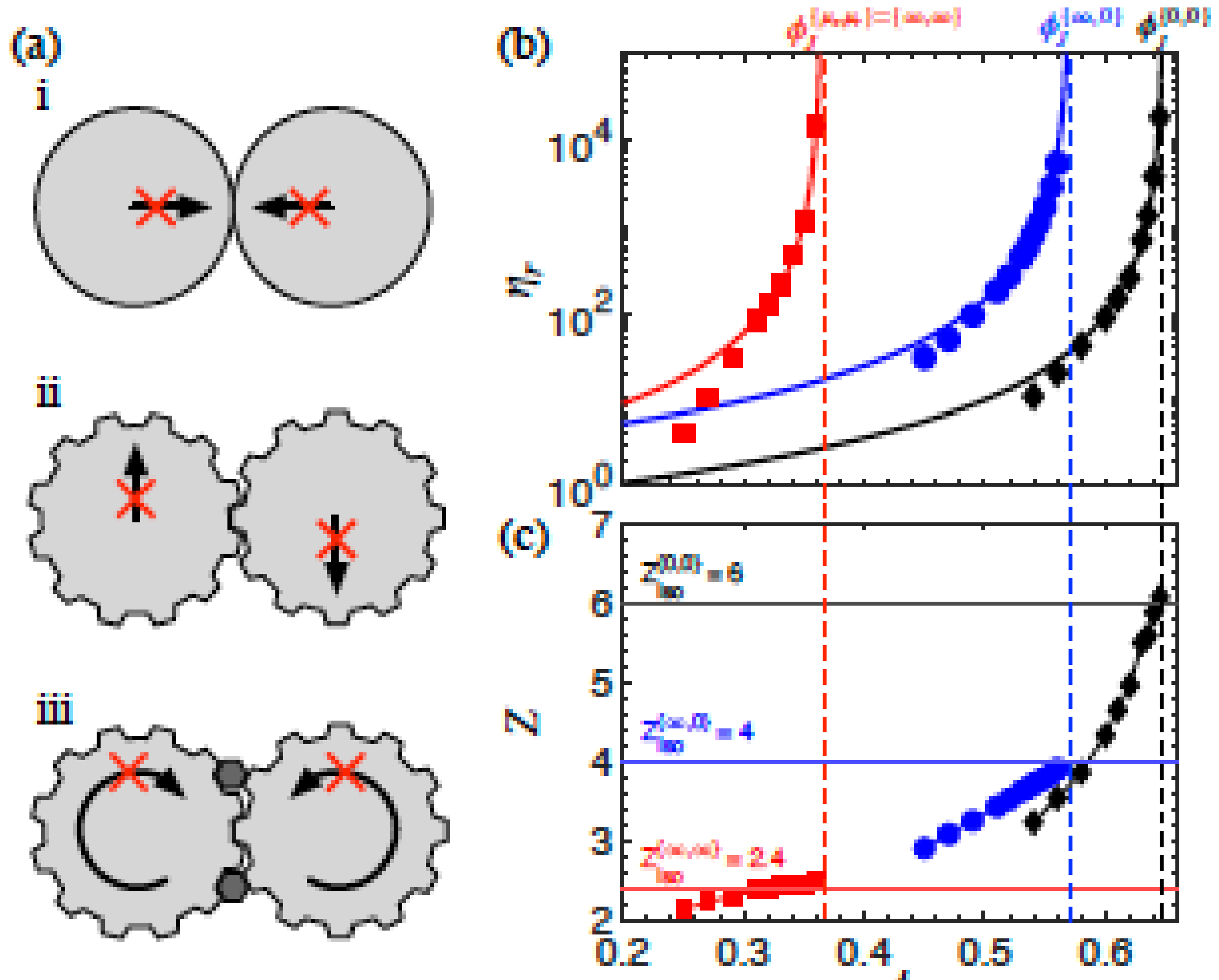
Constraint-Based Approach to Granular Dispersion Rheology

B. M. Guy,* J. A. Richards,† D. J. M. Hodgson, E. Blanco, and W. C. K. Poon
SUPA, School of Physics and Astronomy, The University of Edinburgh, King's Buildings, Peter Guthrie Tait Road, Edinburgh EH9 3FD, United Kingdom

(Received 10 May 2018; published 17 September 2018)

We present a phenomenological model for granular suspension rheology in which particle interactions enter as constraints to relative particle motion. By considering constraints that are *formed* and *released* by stress respectively, we derive a range of experimental flow curves in a single treatment and predict singularities in viscosity and yield stress consistent with literature data. Fundamentally, we offer a generic description of suspension flow that is independent of bespoke microphysics.

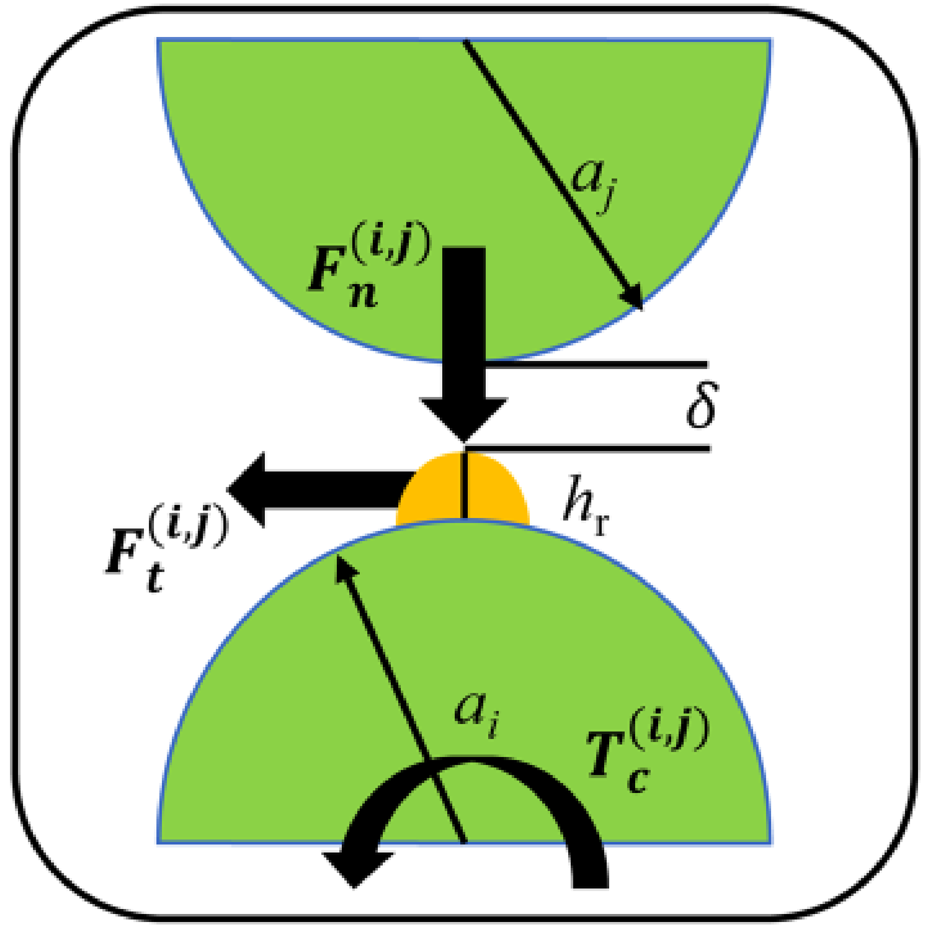
DOI: 10.1103/PhysRevLett.121.128001



Singh et al. *Phys. Rev. Lett.* 124, 248005 (2020)

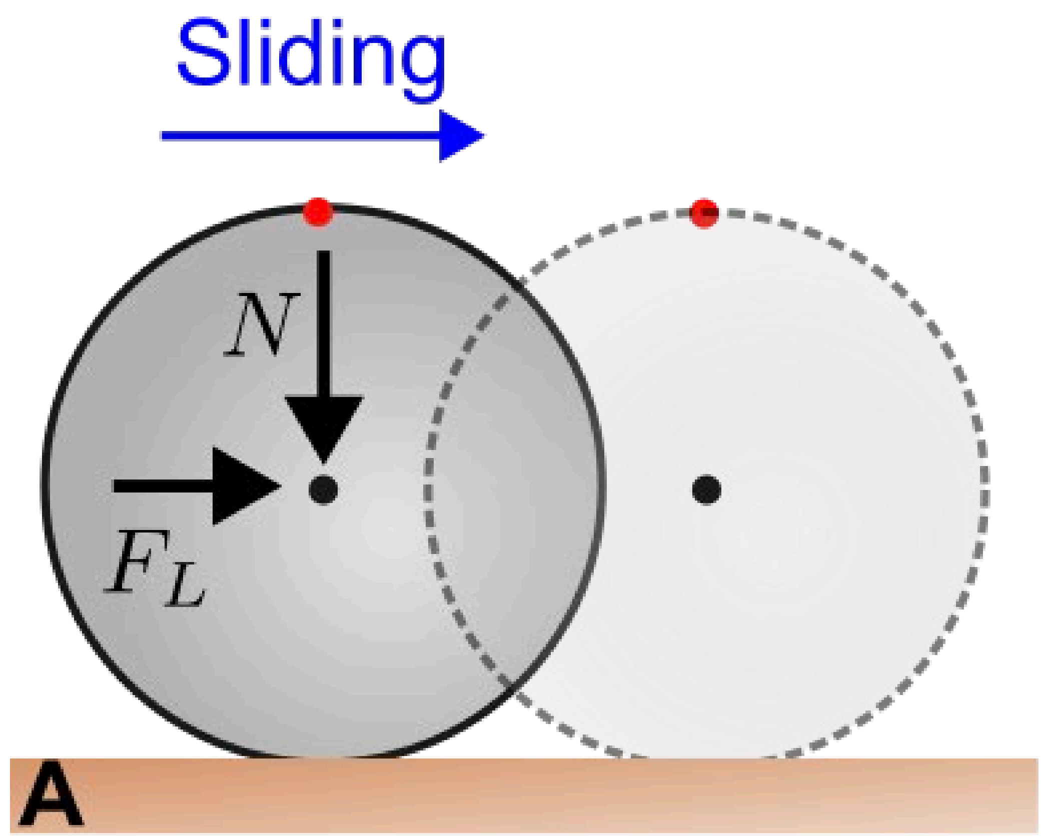
ϕ

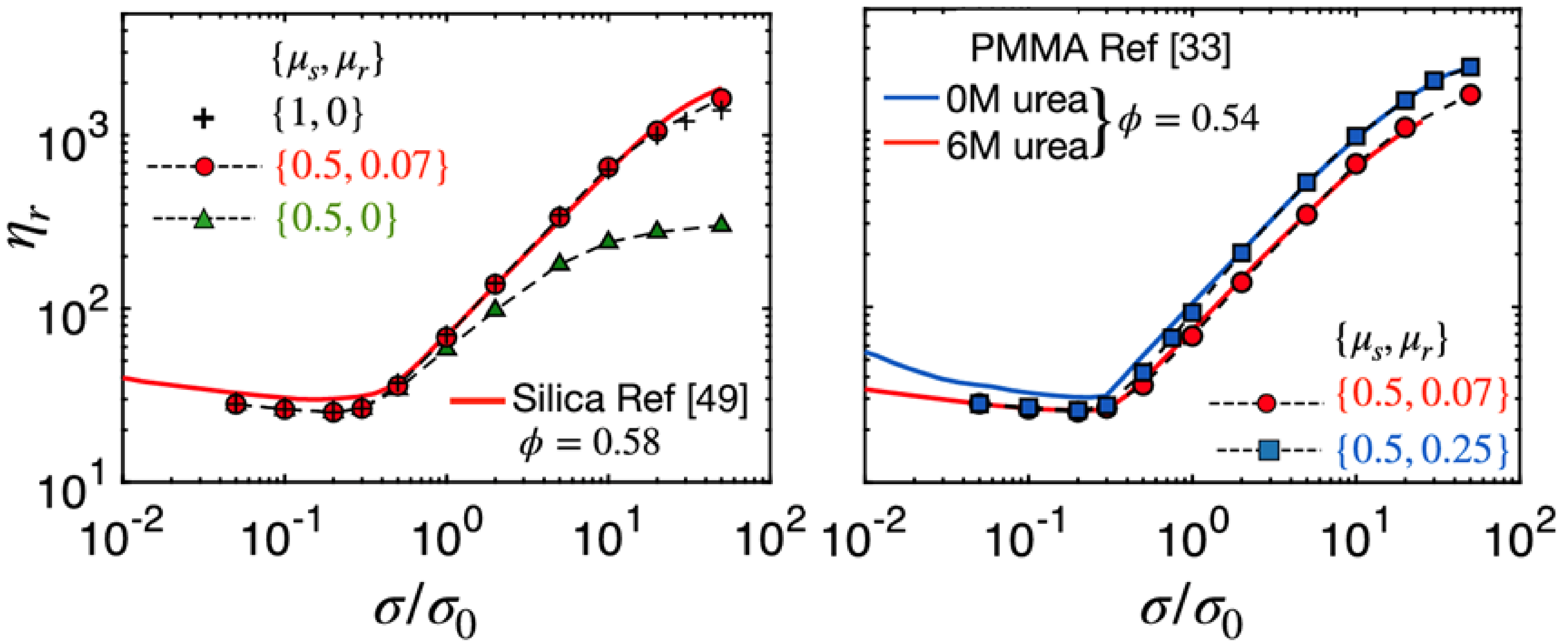
- There is a mapping between the friction coefficient and ϕ_m
- ϕ_m depends on the details of the frictional contact



Moore and Ardekani, *J. Rheol. 64*, 1107 (2020)

Friction Coefficients Determine Rheology





A. Singh *et al.*, **PRL** (2020)

$$F_L = \mu_s N + F^0{}_L$$

Friction force; Sliding friction coefficient (dynamic); Normal load; Friction force at zero load (adhesion)

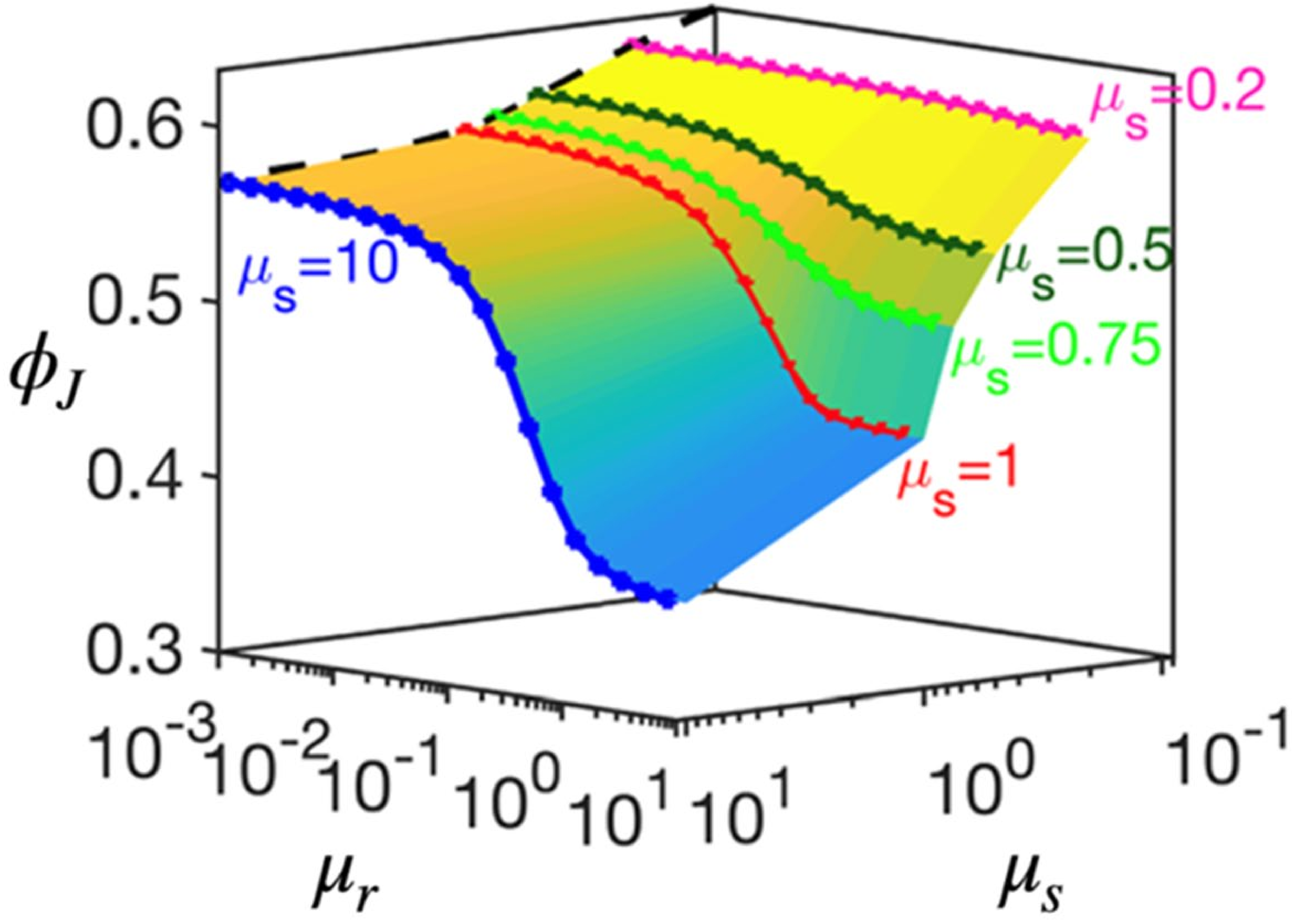
$$M = \lambda N + M^0$$

$$\frac{M}{R_p} = \mu_R N + \frac{M^0}{R_p}$$

Particle radius; Rolling friction coefficient (dynamic)

The rheology is defined by a combination of μ_s and μ_R

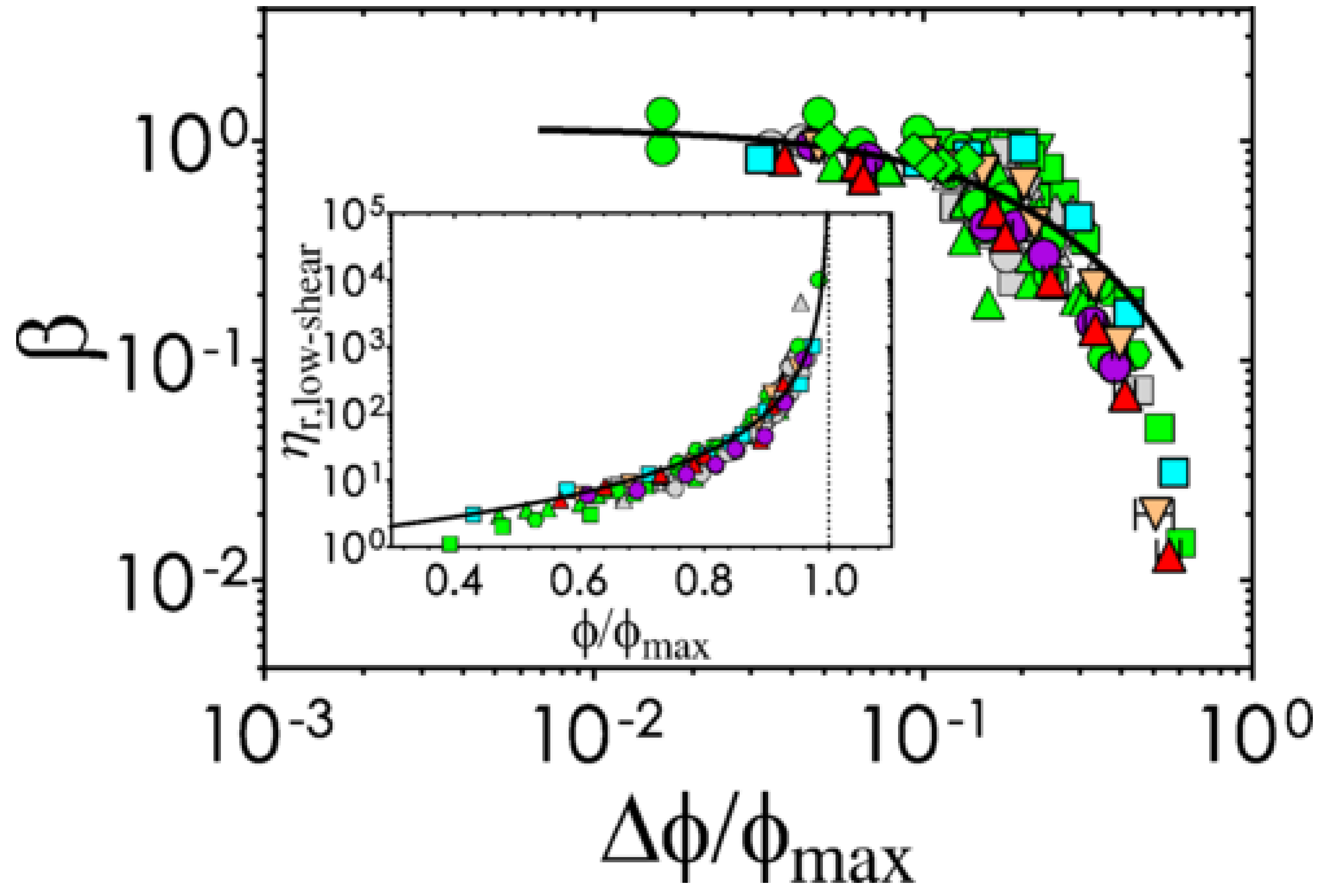
Friction Coefficients Determine Rheology



A. Singh *et al.*, **Phys. Rev. Fluids** (2022)

μ_s and μ_R determine ϕ_m

The distance from ϕ_m determines η



S. Pradeep *et al.*, **Phys. Rev. Lett.** (2021)

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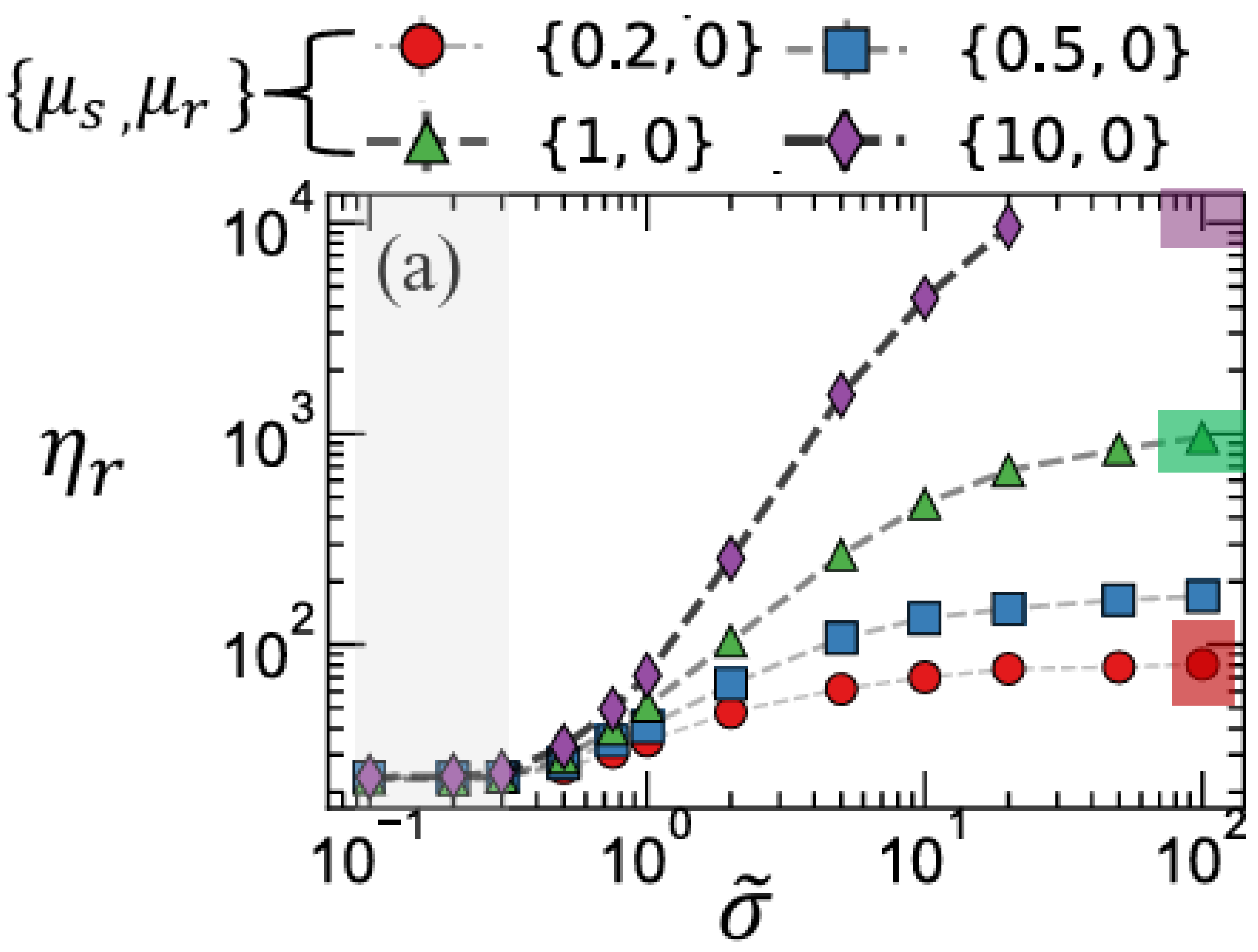
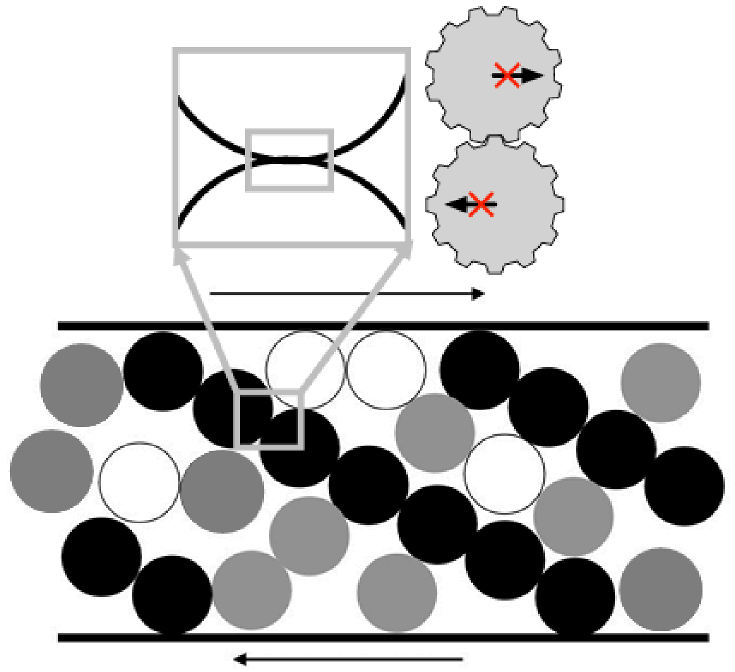
Friction Coefficients Determine Rheology

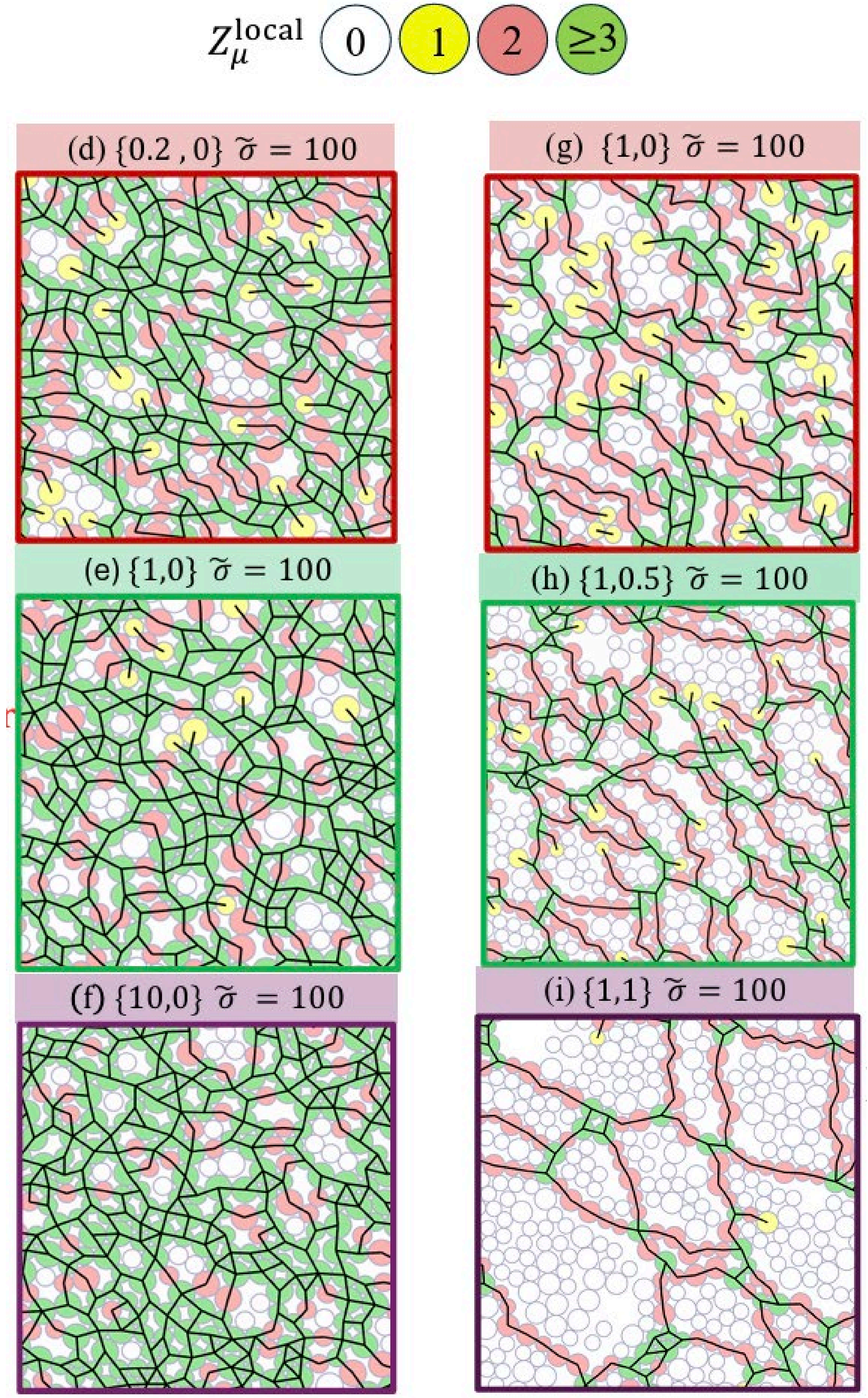
Sliding constraint only

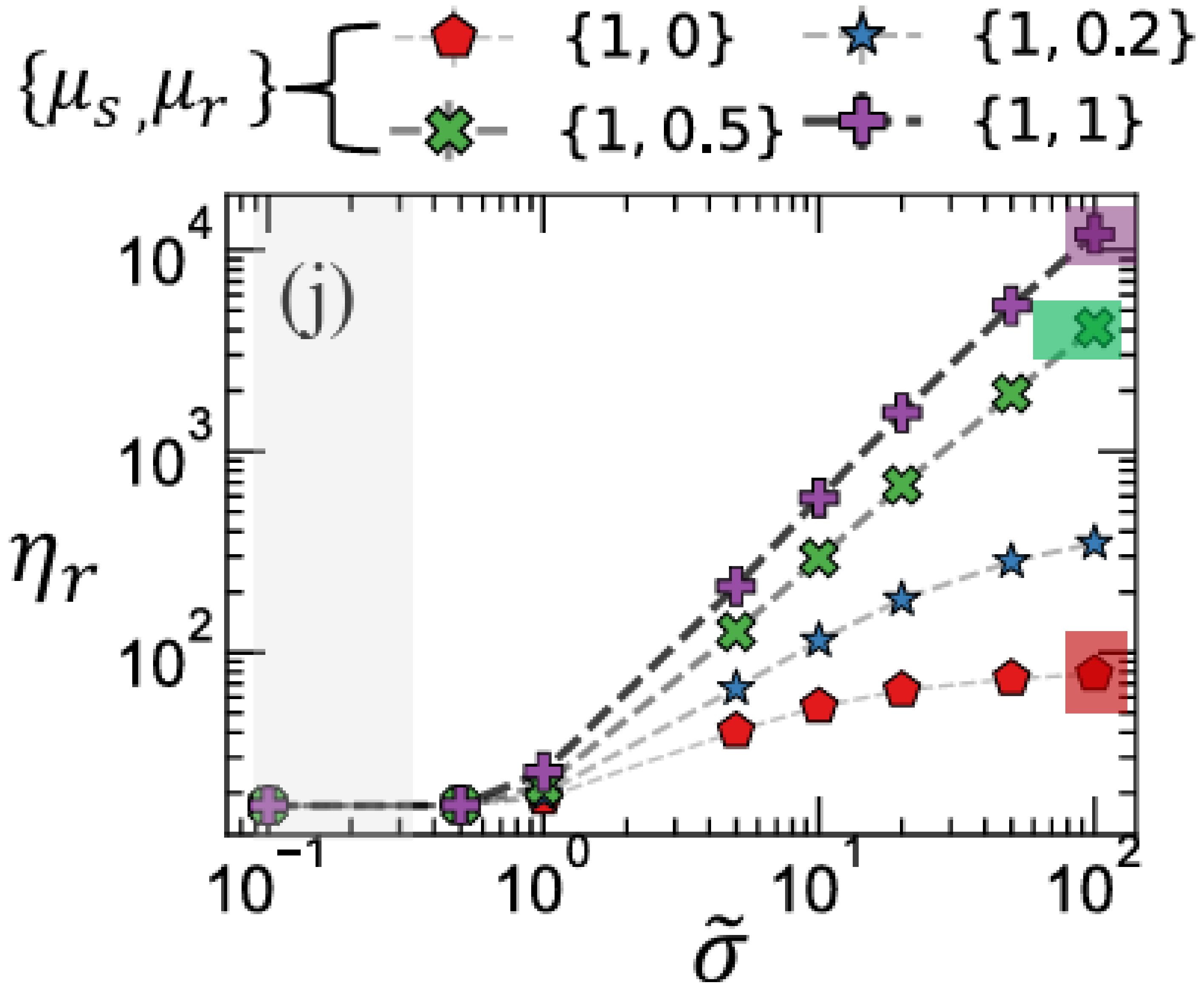
Sliding and Rolling constraint



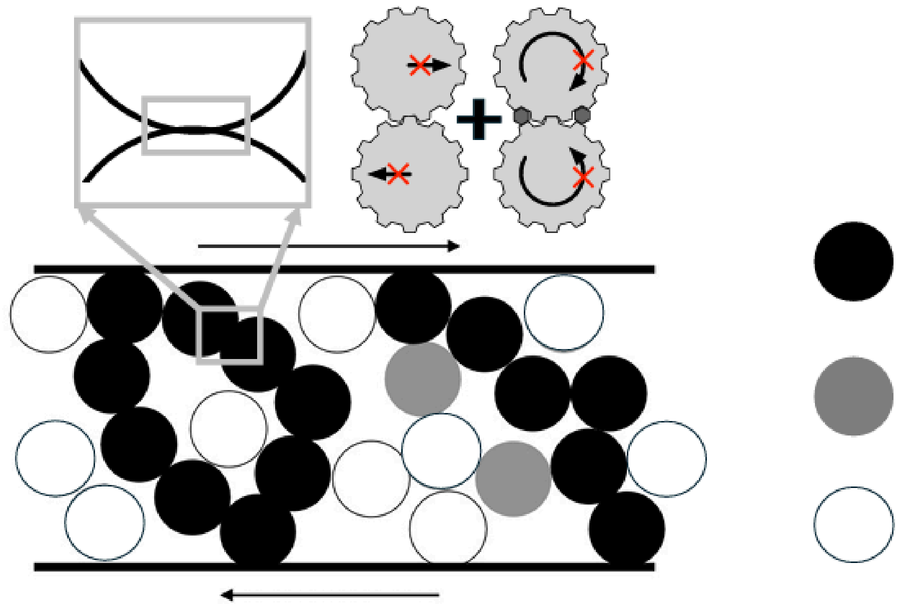
(a) Sliding constraint only







(b) Sliding and Rolling constraint



S. Sharma *et al.*, **Newton** (2025)

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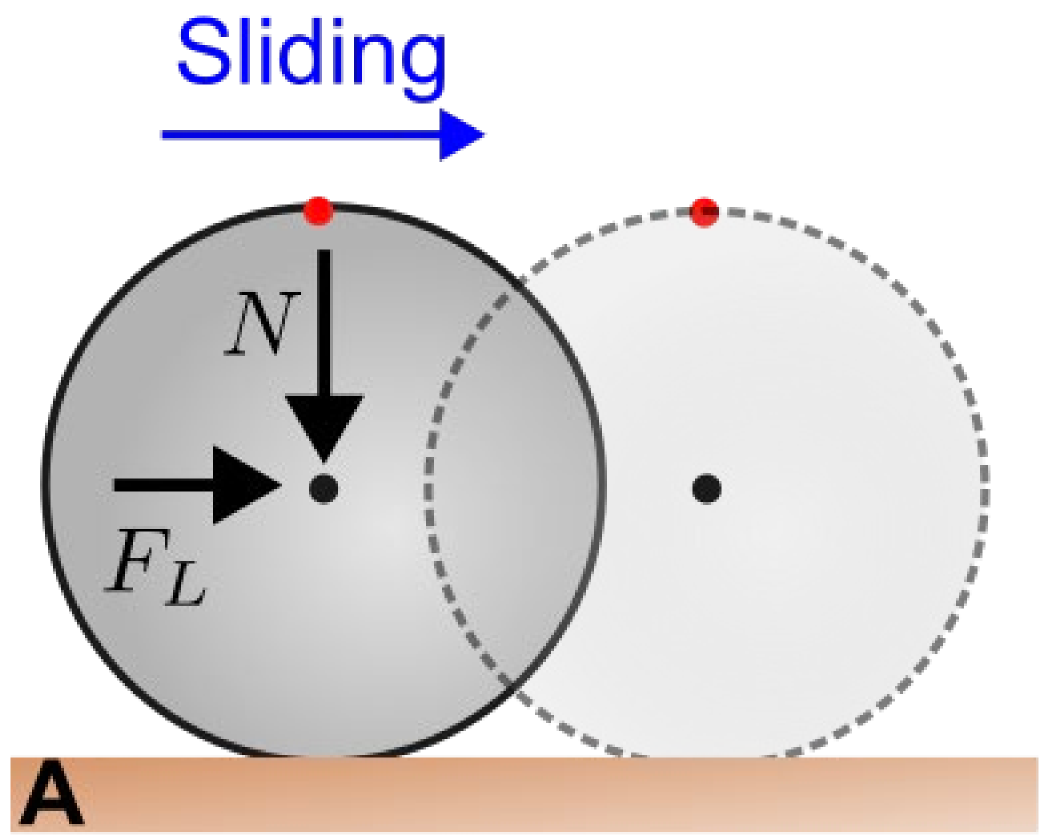
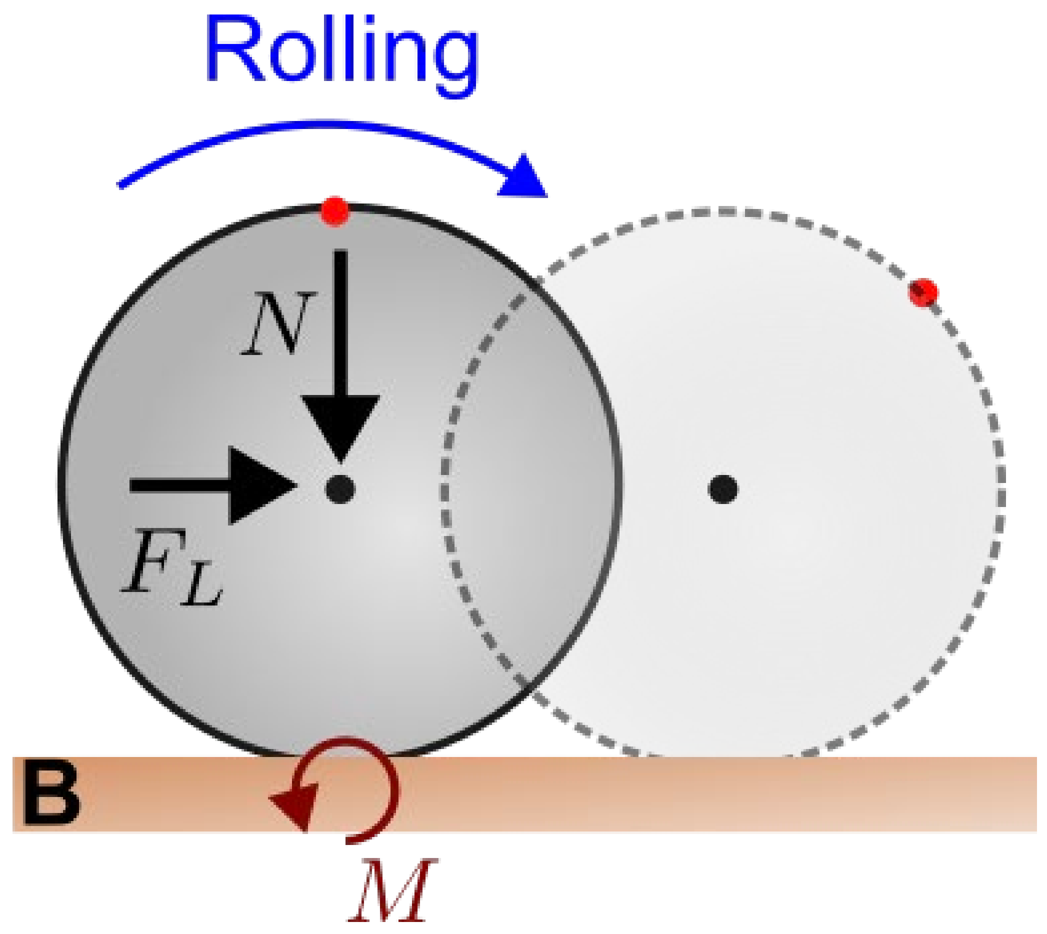
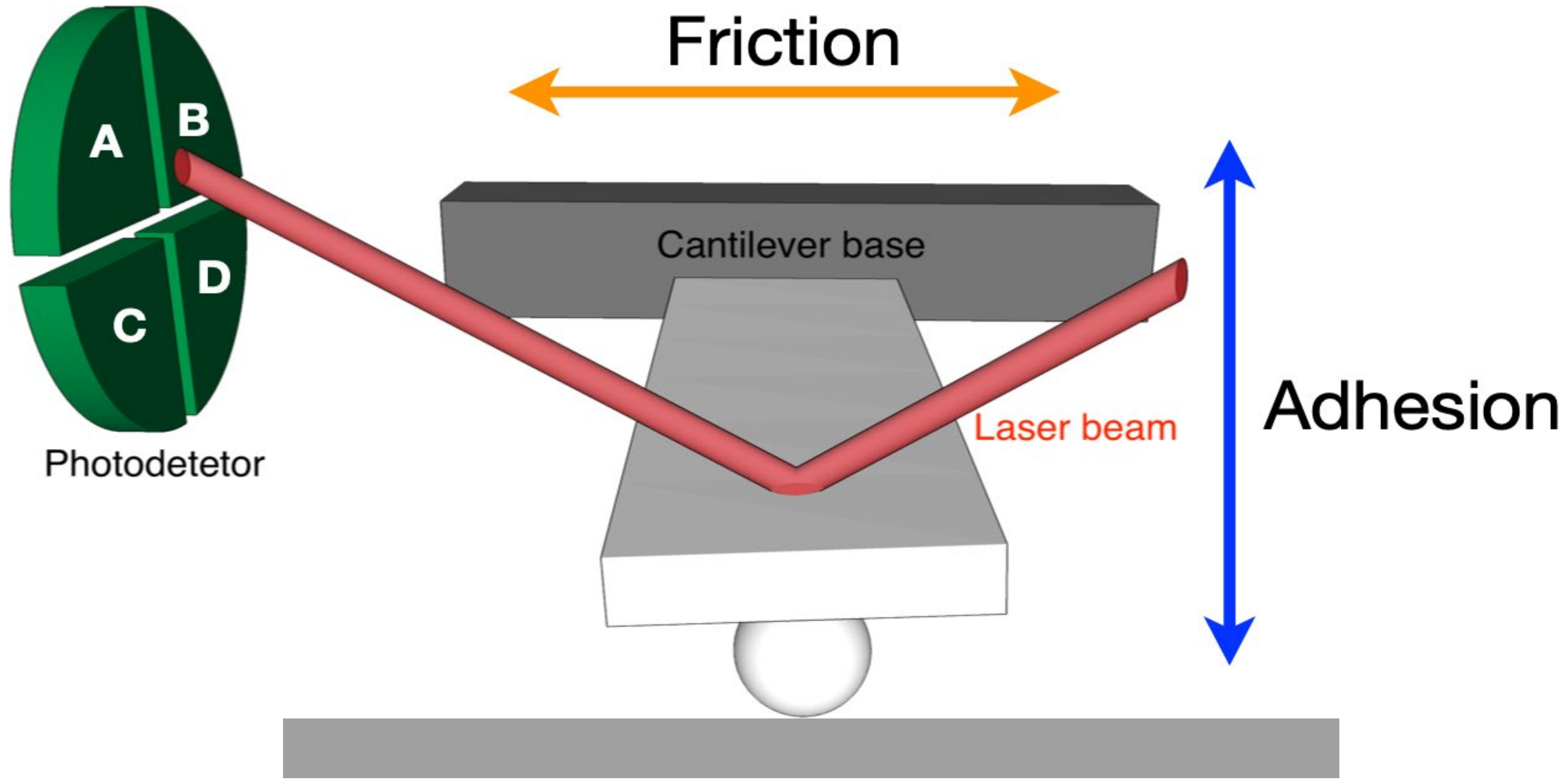
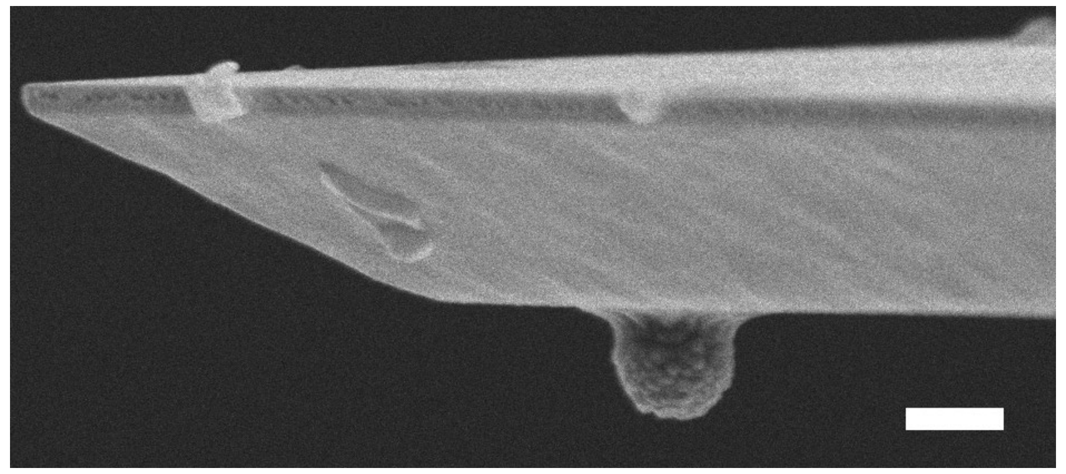
Measuring Friction Coefficients

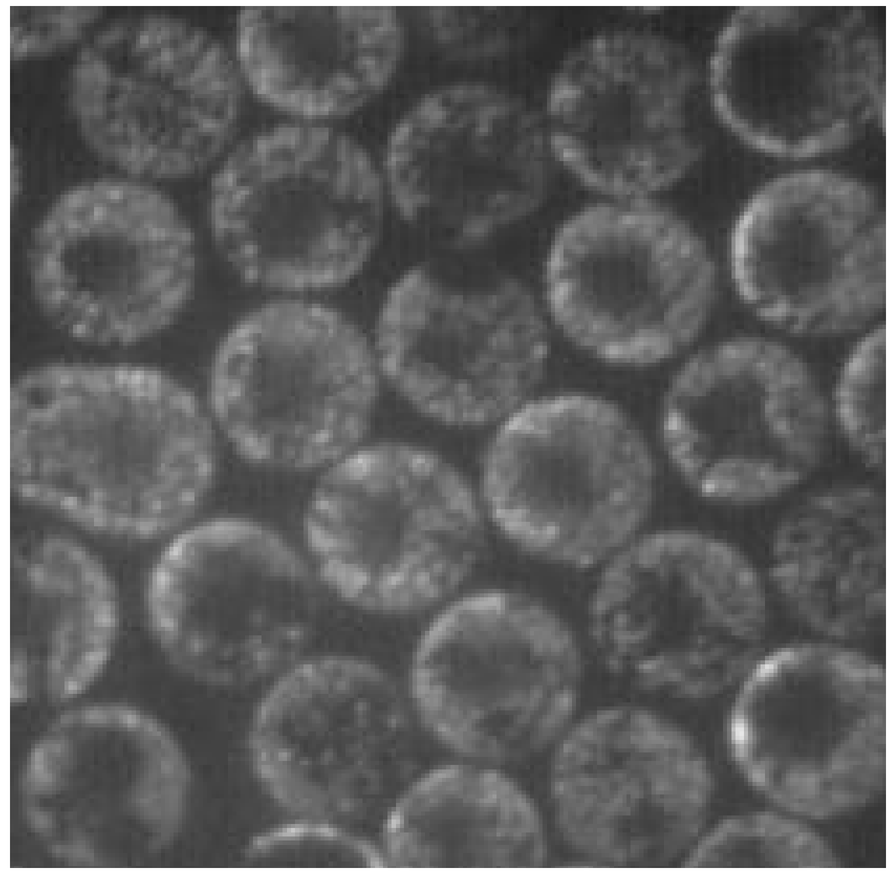


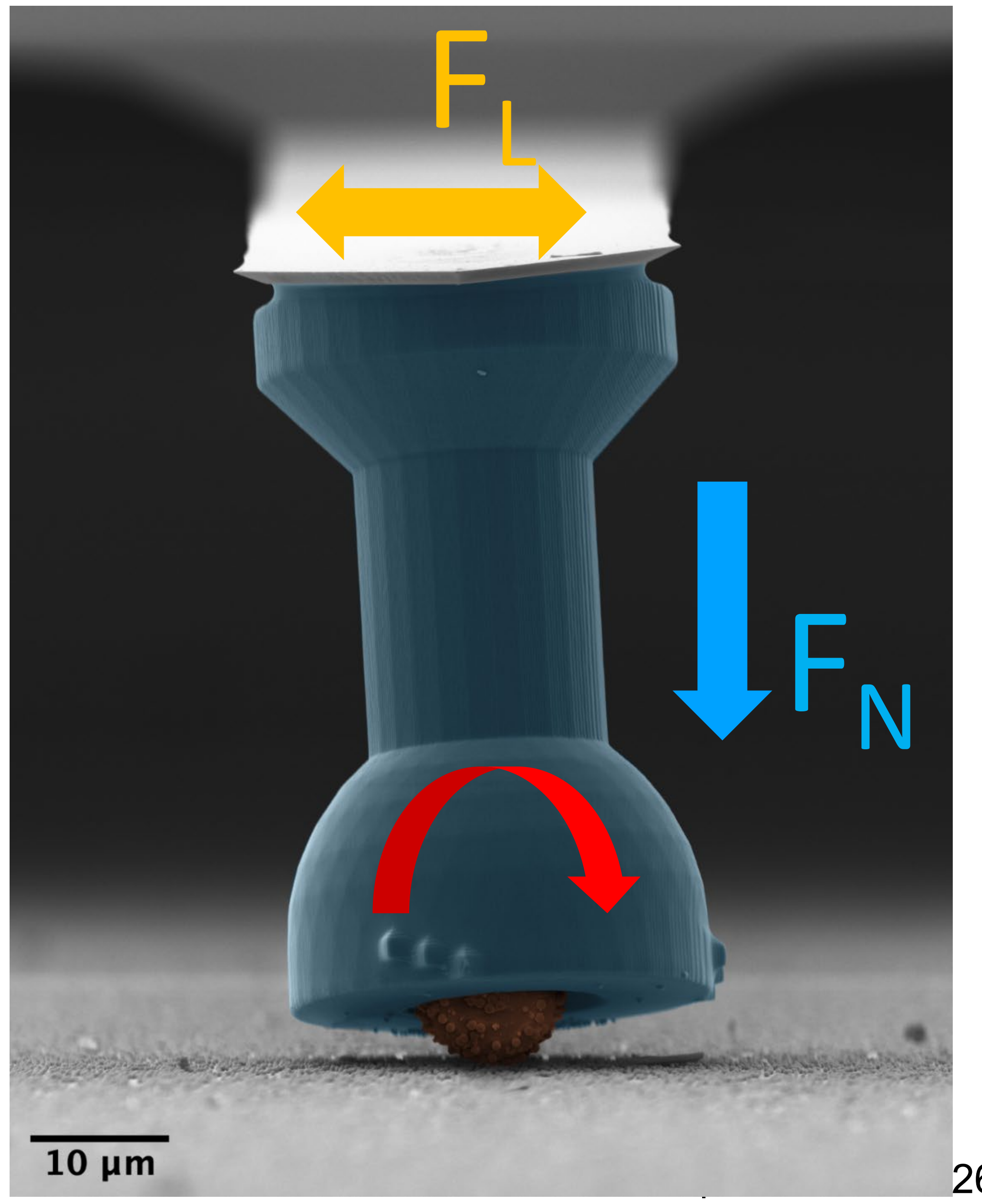
- Simultaneous detection of normal and lateral forces
  - Detection of the kinematics of the contact (sliding, rolling or mixed)











C. P. Hsu *et al.*, *PNAS* 115, (2018).

S Scherrer et al. *Langmuir*, 2024, 40, 13, 6750–6760

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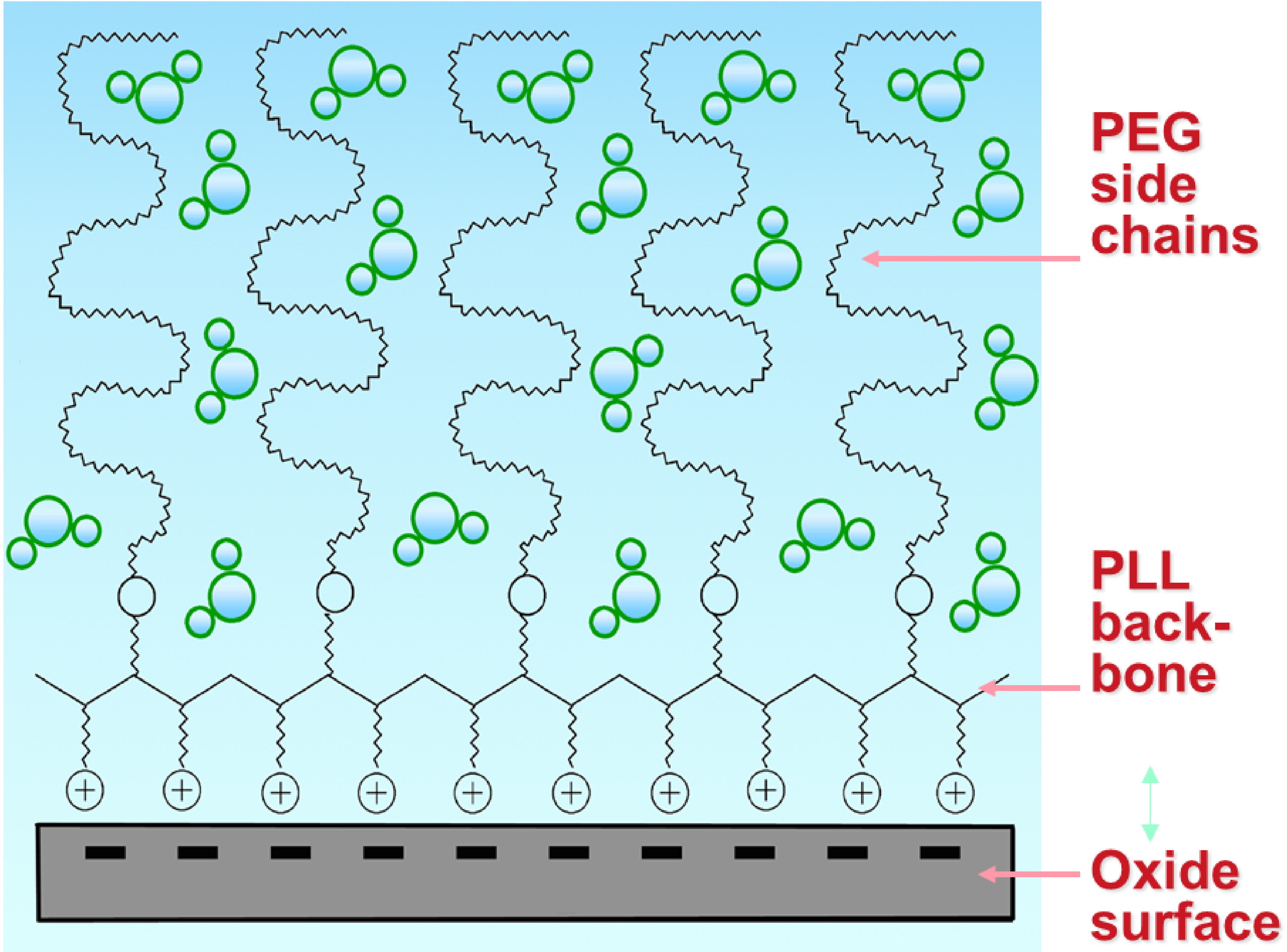
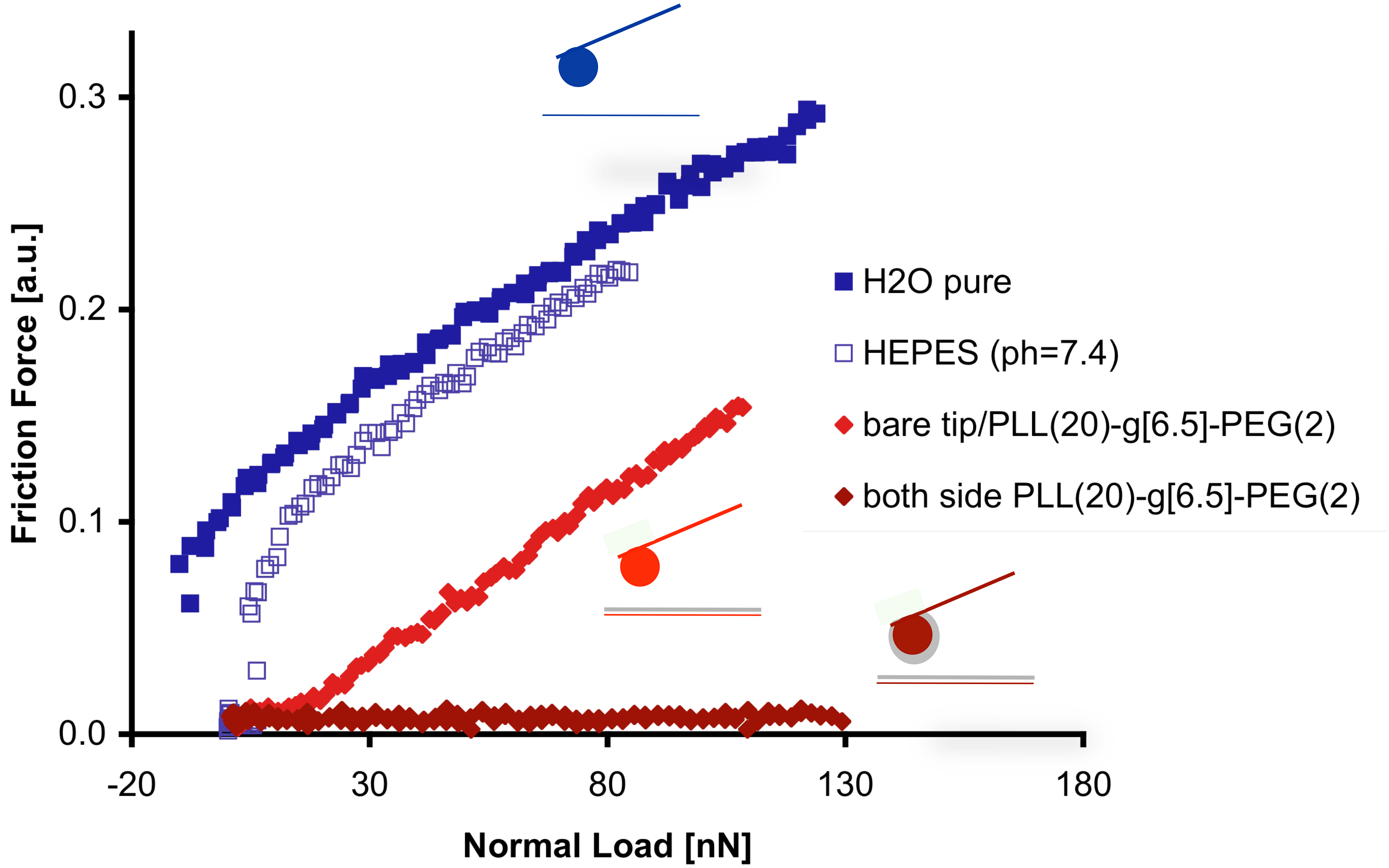
Modifying Friction Coefficients

Coating surfaces with polymer brushes



Poly-l-lysine (PLL)-*g*-polyethylene glycol (PEG)

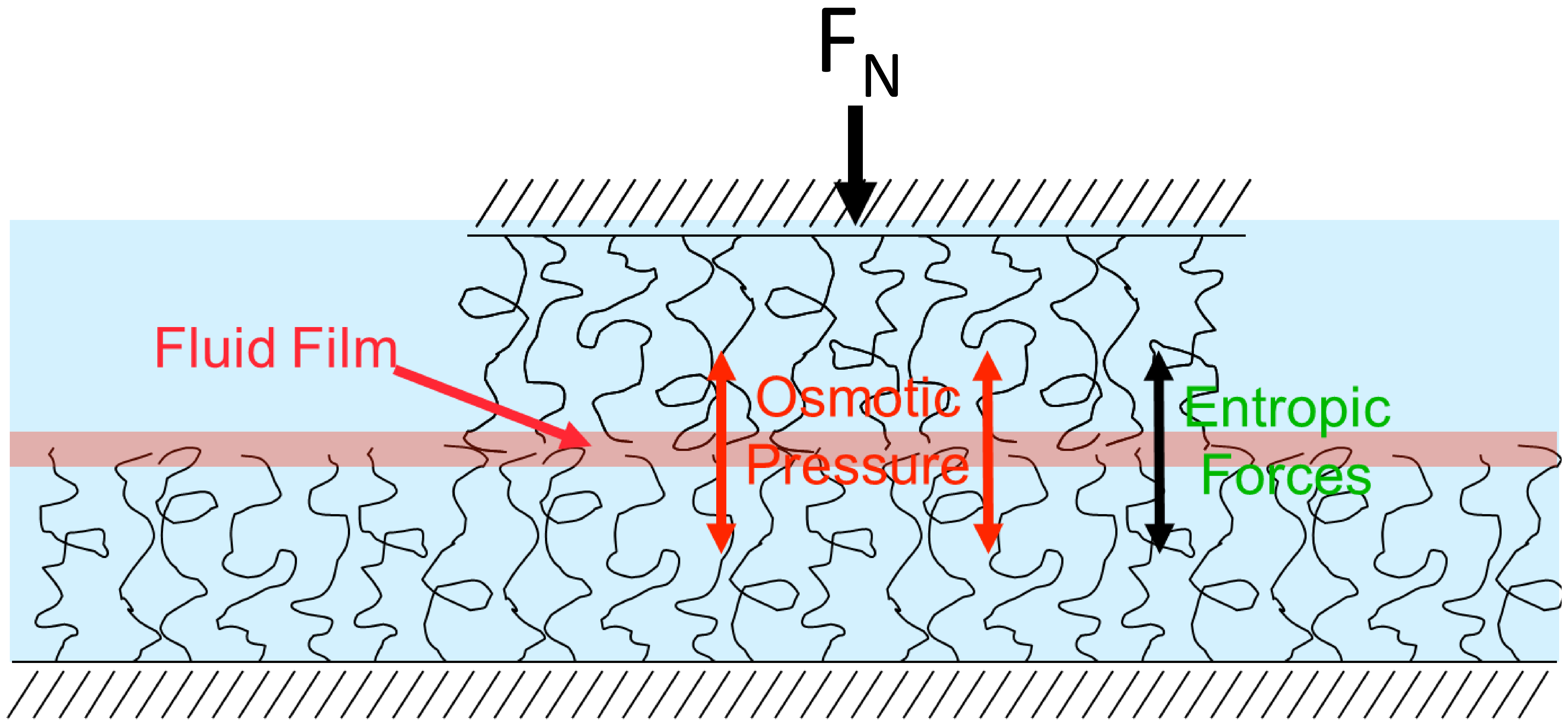


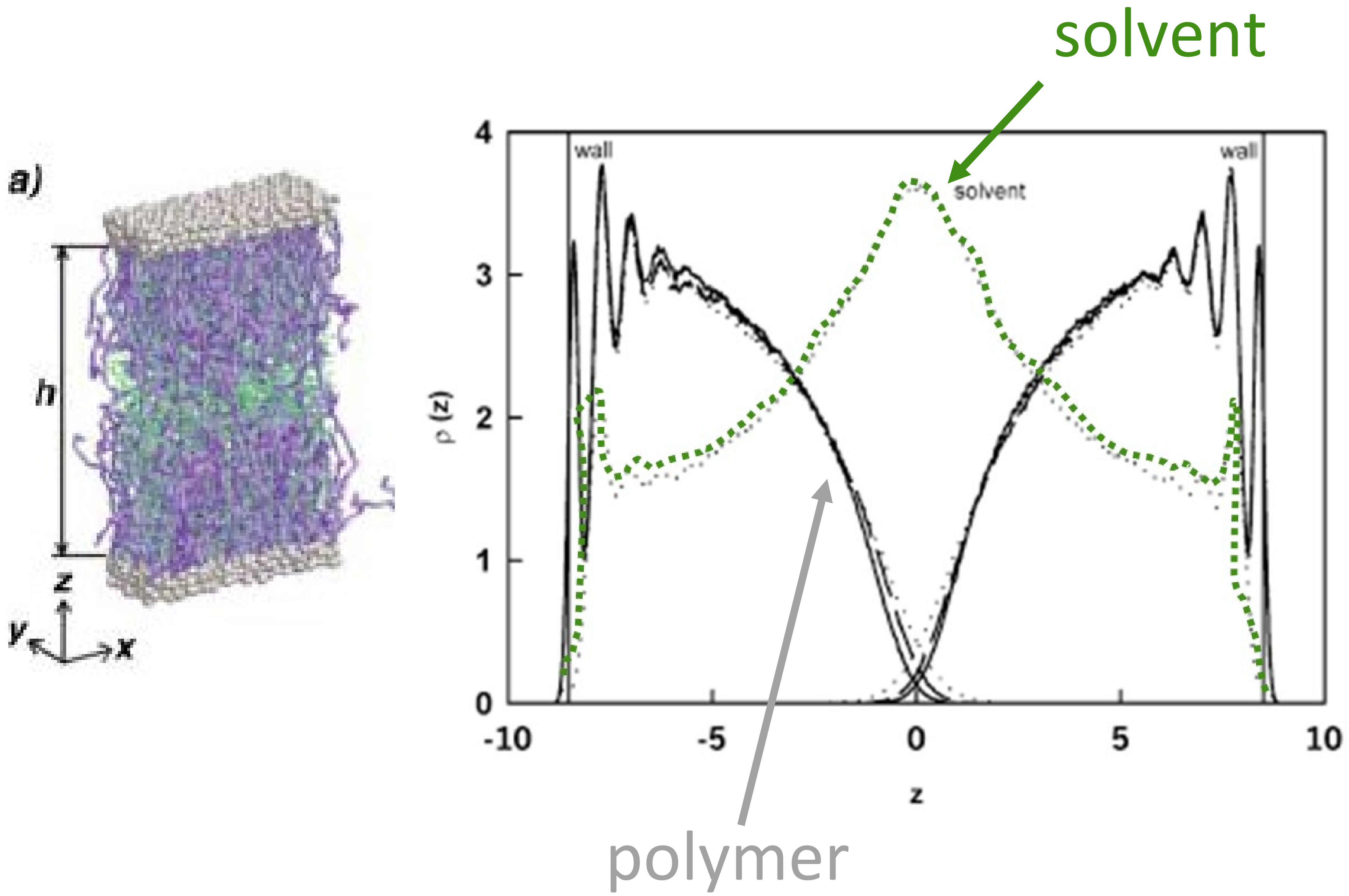
X. Yan et al. *Langmuir* 2004, *20,* 423-428

Massive reduction of μ_s

MODIFYING FRICTION COEFFICIENTS

"Enforced" Fluid-Film Lubrication by Polymer Brushes





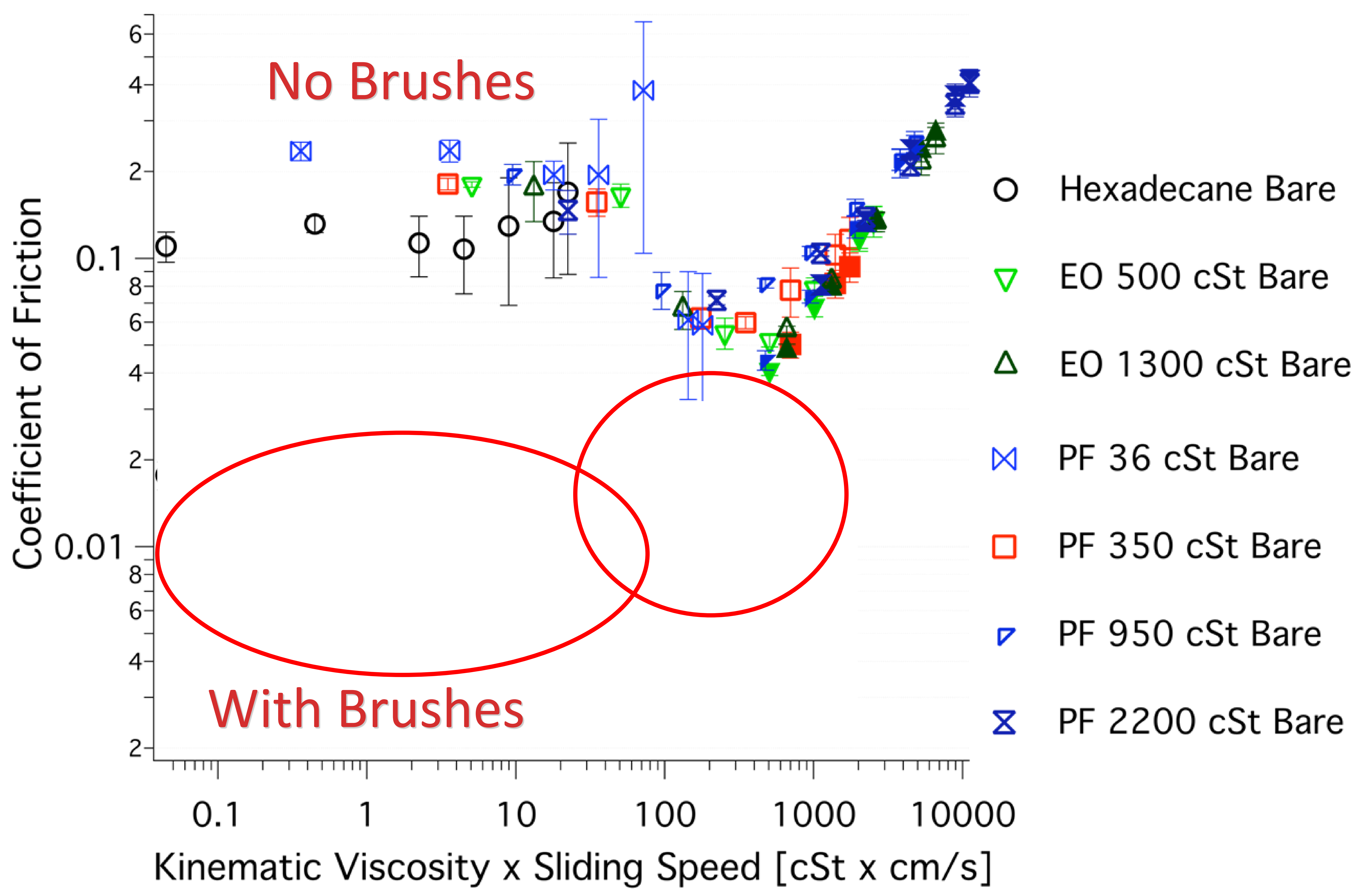
By retaining liquid within the brush and keeping the surface apart, polymer brushes reduce boundary lubrication coefficients μ_s

D. Irfachsyad et al. Phys. Chem. Chem. Phys., 2002,4, 3008-3015

MODIFYING FRICTION COEFFICIENTS

Stribeck Curve in Microtribometer: 7 Oils, Bare Borosilicate Against Brush or Si Wafer

250nm (dry) Poly(dodecyl methacrylate), 20 mN, rotating, reciprocating, 20 cycles per point



R. M. Bielecki et al. Tribol Lett (2013) 49:263–272

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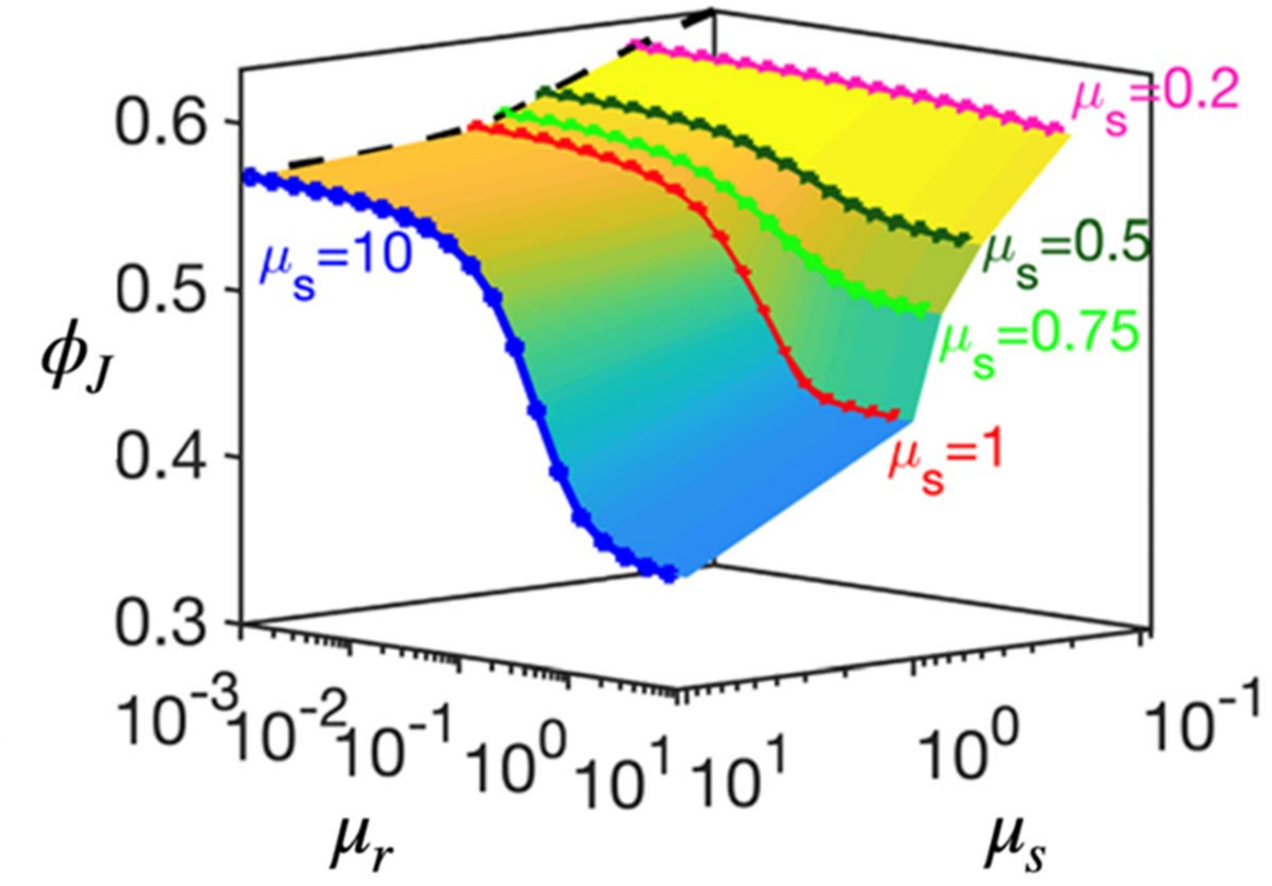
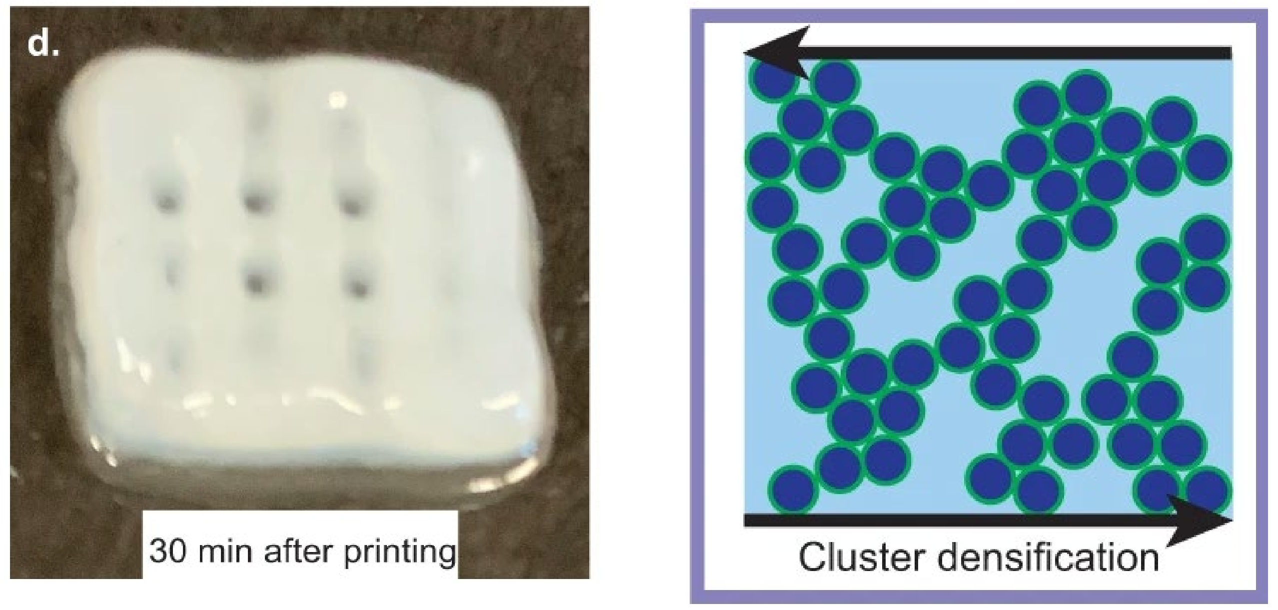
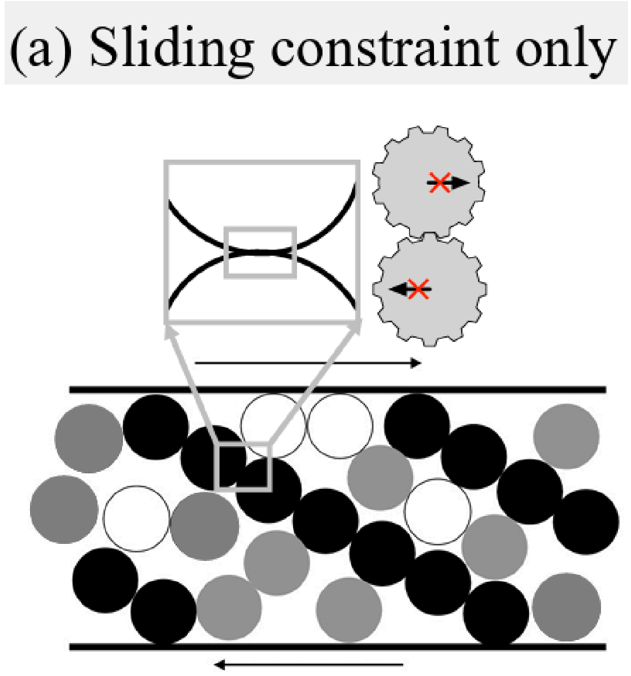
OPEN QUESTIONS



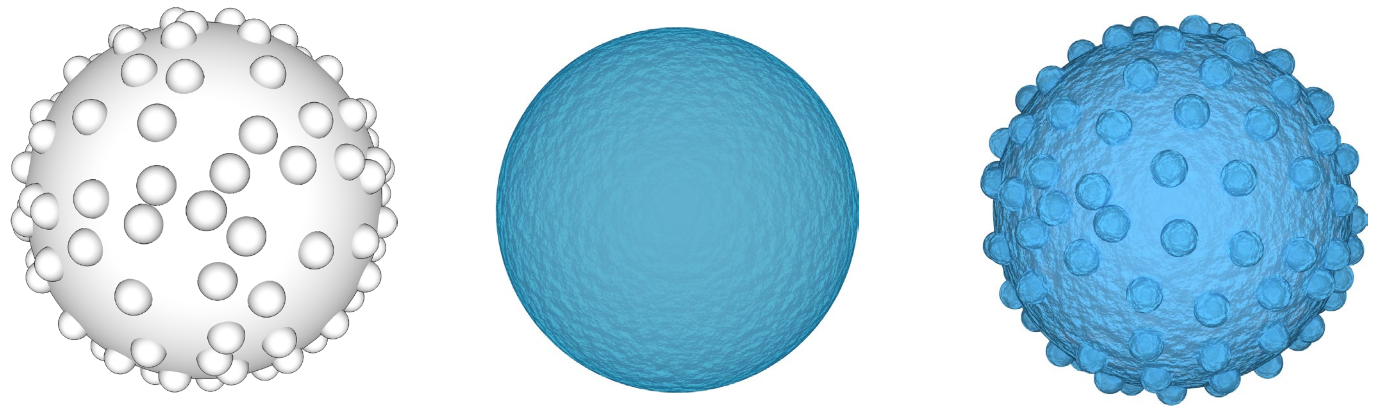


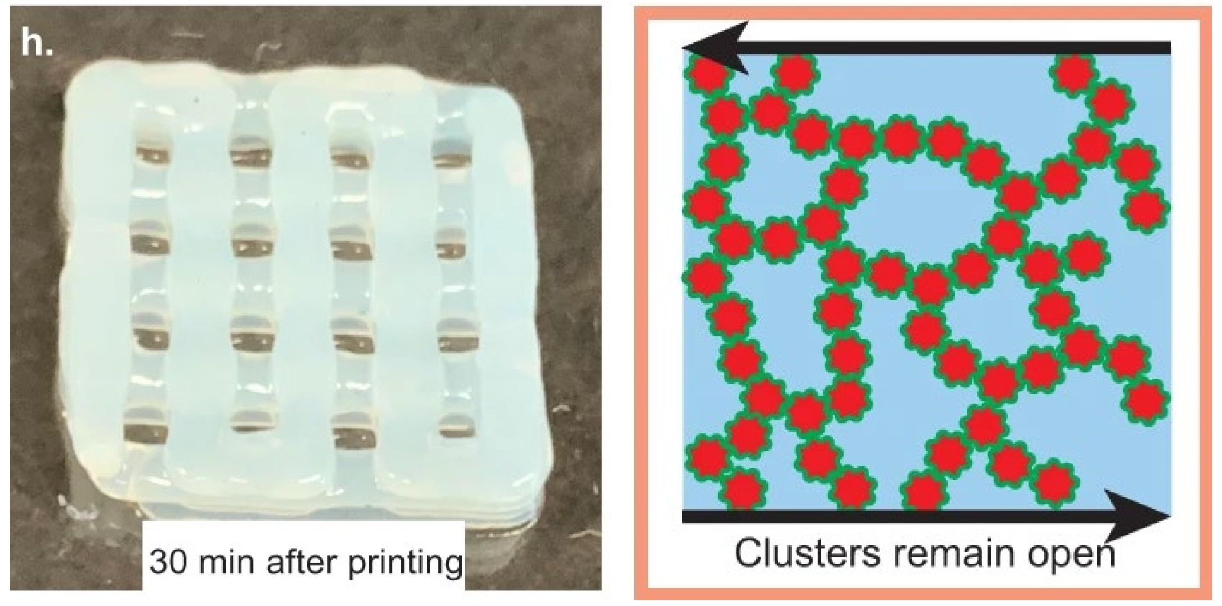


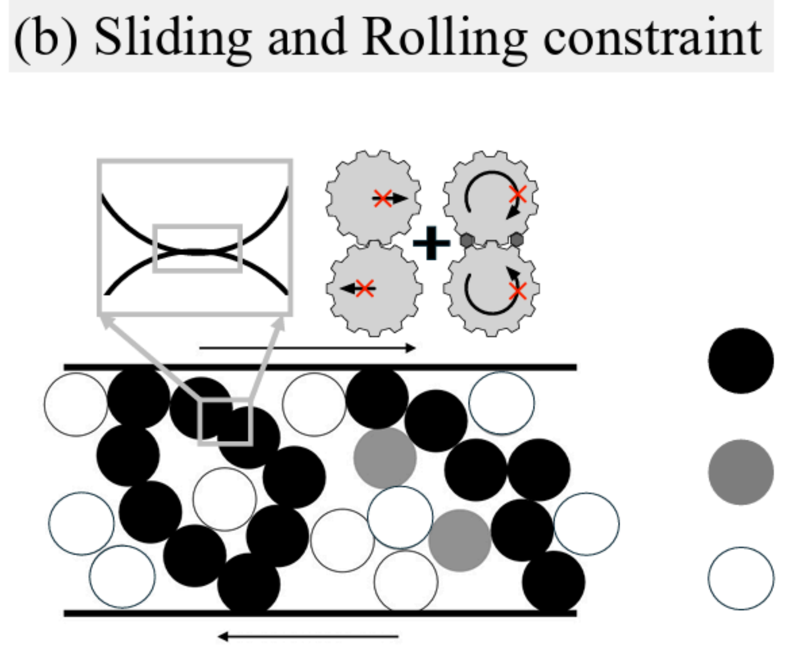
How do I engineer μ_s and μ_R during particle synthesis/fabrication to control ϕ_m?

What is the role of adhesion and static friction in addition to μ_s and μ_R in materials such as gels?

Are there other rheological signatures of interest beyond steady shear viscosity in and how do we measure them?







F. Müller et al. *Nat Commun* **14**, 5309 (2023).