Origin of two distinct stress relaxation regimes in shear jammed dense suspensions

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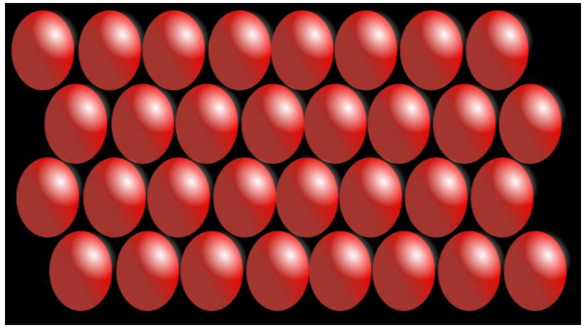
Introduction

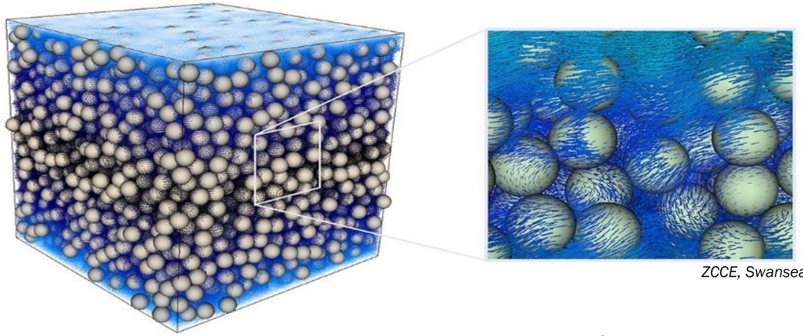


Solid Particle

+

Liquid

=

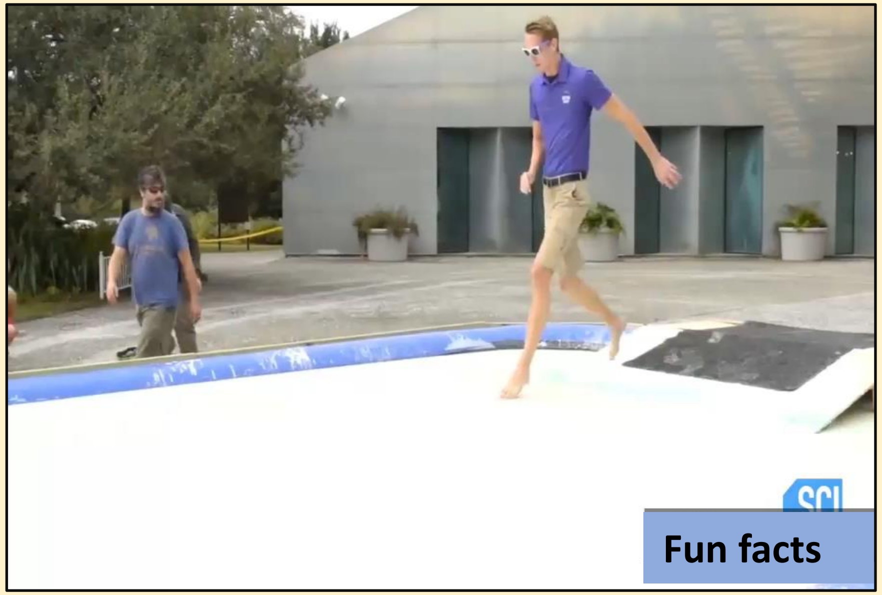


Dense Suspension

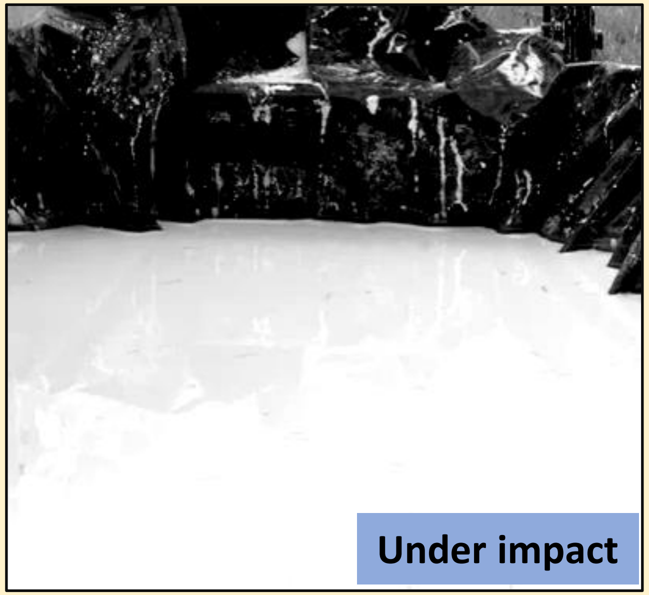
(High volume fraction)

Can't be understood from the properties of liquid and solid

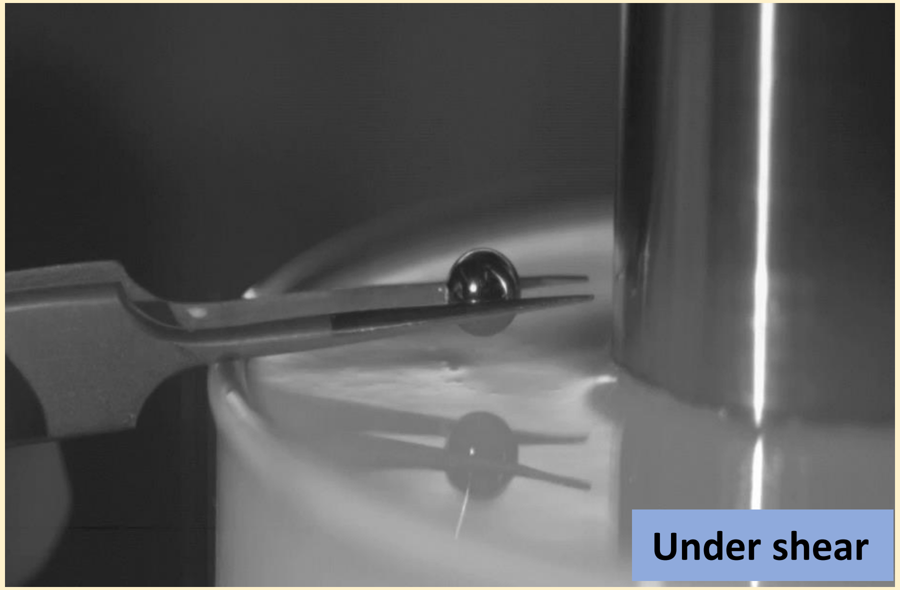
Reversible liquid-solid transition



https://www.youtube.com/watch?v=JJfppydyGHw&t=52s

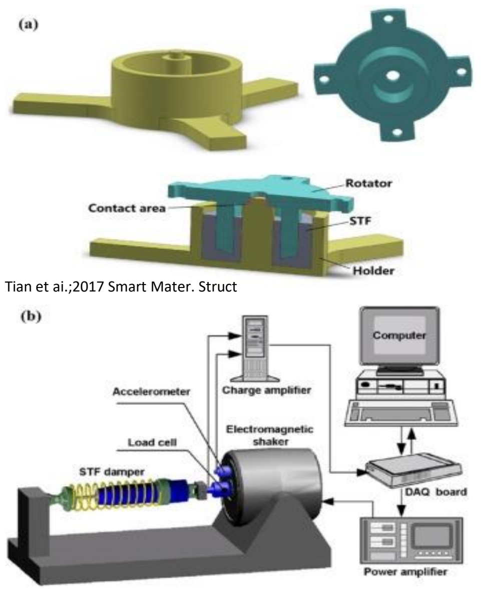


Ben Allen, Yale University



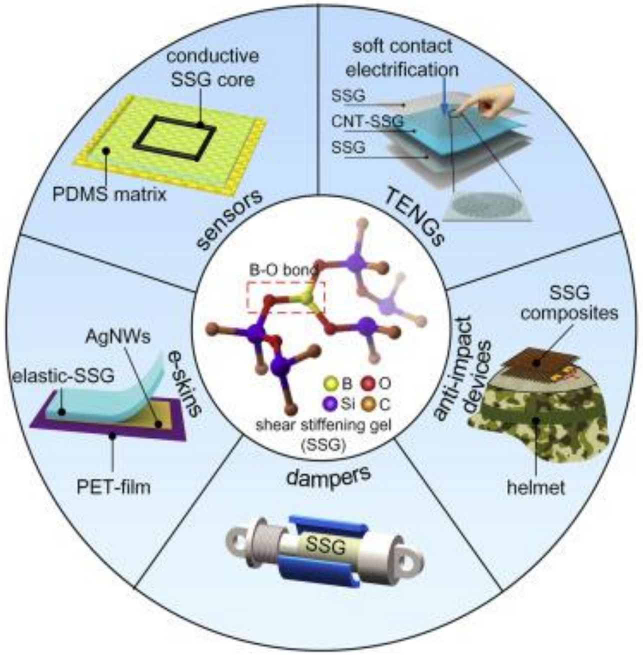
Peters, Majumdar and Jaeger, Nature (2016)

Relaxation of shear jammed fluid: Why care ?



Tongfei Tian et ai.;2017 Smart Mater. Struct

X Z Zhang; Smart Mater. Struct. 17 (2008)



Chunyu Zhao et al.; Cell Reports Physical Science 1, 2020

https://newatlas.com/new-shear-thickening-fluid-stf-enables-flexible-comfortable-armor/5995/

Adaptive Material Development

Liquid Body Armor

Microscopic mechanism: *hydrodynamics, contact interaction, additional constraints…*

- ***Transient relaxation is equally important for potential applications.***

Transient stress relaxation in dense suspensions poorly understood

Experiments

Dense suspension of…	Relaxation behavior…
Cornstarch →	Deviates from a generalized Newtonian model [Maharajan and Brown; PRF (2017)]
PSt-EA nano particles →	Captured by multi-element viscoelastic model [Cao et al.; Smart Mater. Struct. (2018)]
PMMA nano particle →	Shows two distinct relaxation behavior [D’haene et al.; J. Colloid and interface sci. (1993)]

Numerical modelling

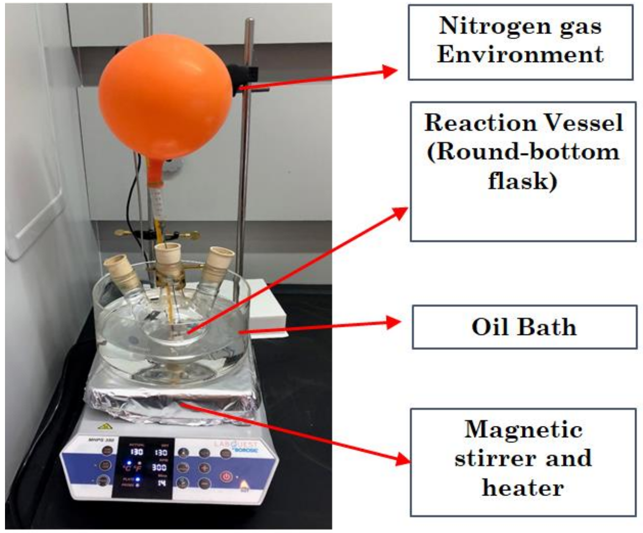
- Relaxation and plasticity of force chain structure
  [Baumgarten and Kamrin; PNAS (2019); JOR (2020)]
- Transient relaxation in over-damped athermal dense suspensions of frictionless spheres close to jamming
  [Hatano; PRE (2009); Ikada et al.; PRL (2020)]

Strongly non-exponential/multi mode relaxation behavior close to jamming

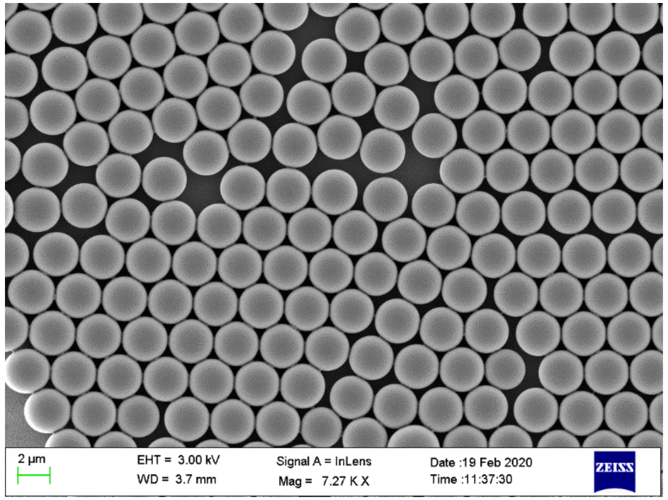
Particle-scale dynamics controlling the transient relaxation not explored

System Studied

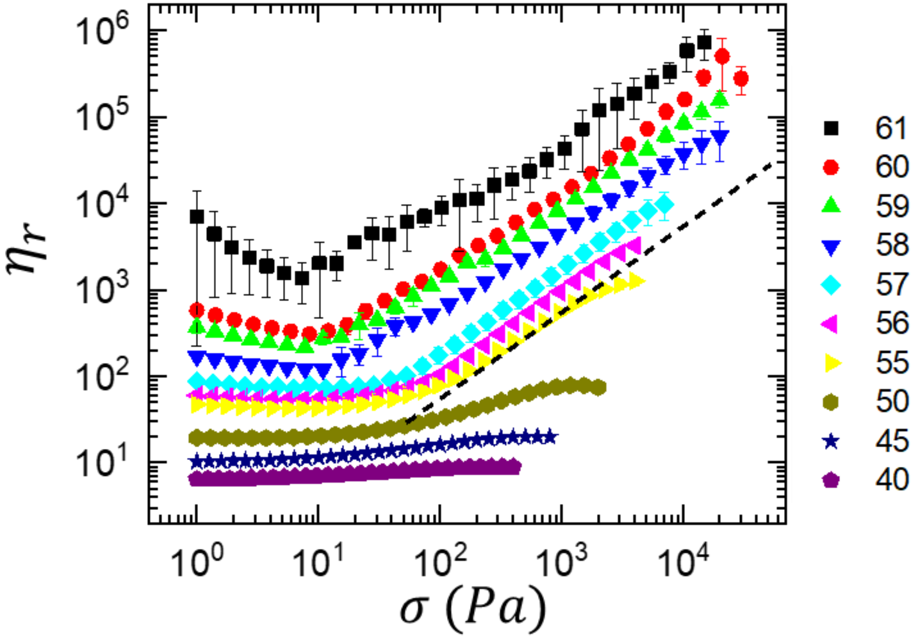
Dense suspension of Polystyrene Particles in Polyethylene Glycol (PEG 400).



Setup for polystyrene microsphere synthesis



Polystyrene Particles



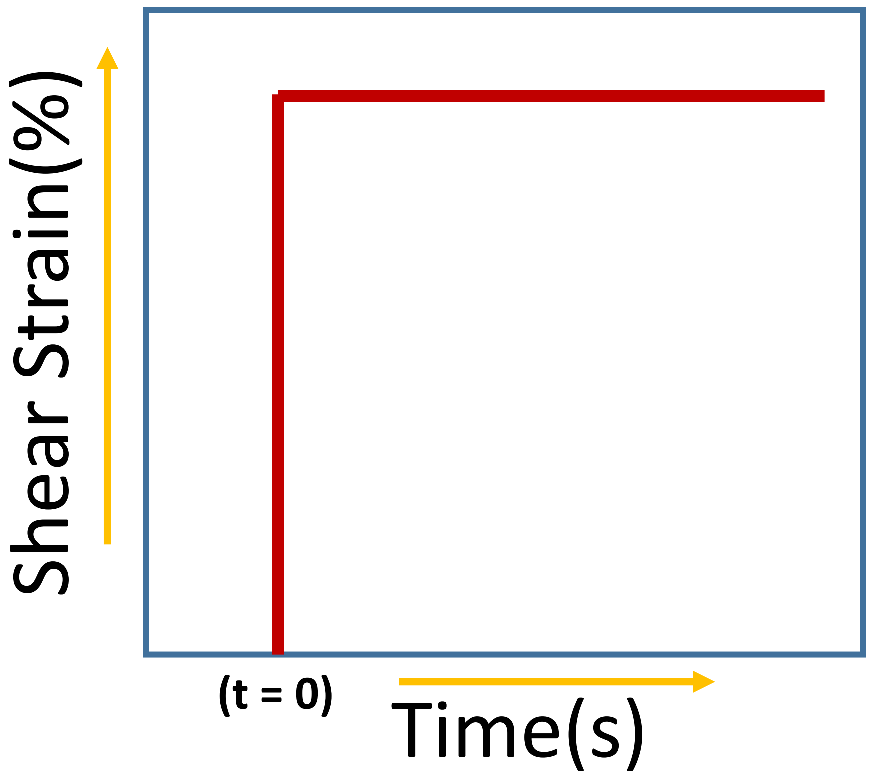
Relative Viscosity

$$\eta_r = \frac{\eta}{\eta_l}$$

At higher volume fractions and higher stresses system shows shear-thickening/ jamming

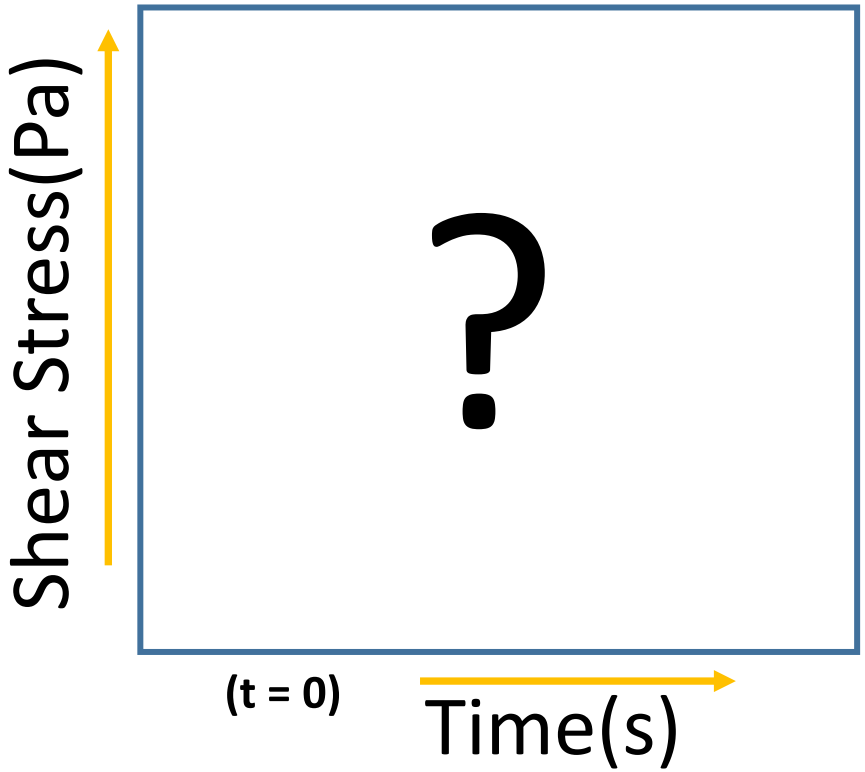
Experimental Protocol

Applied



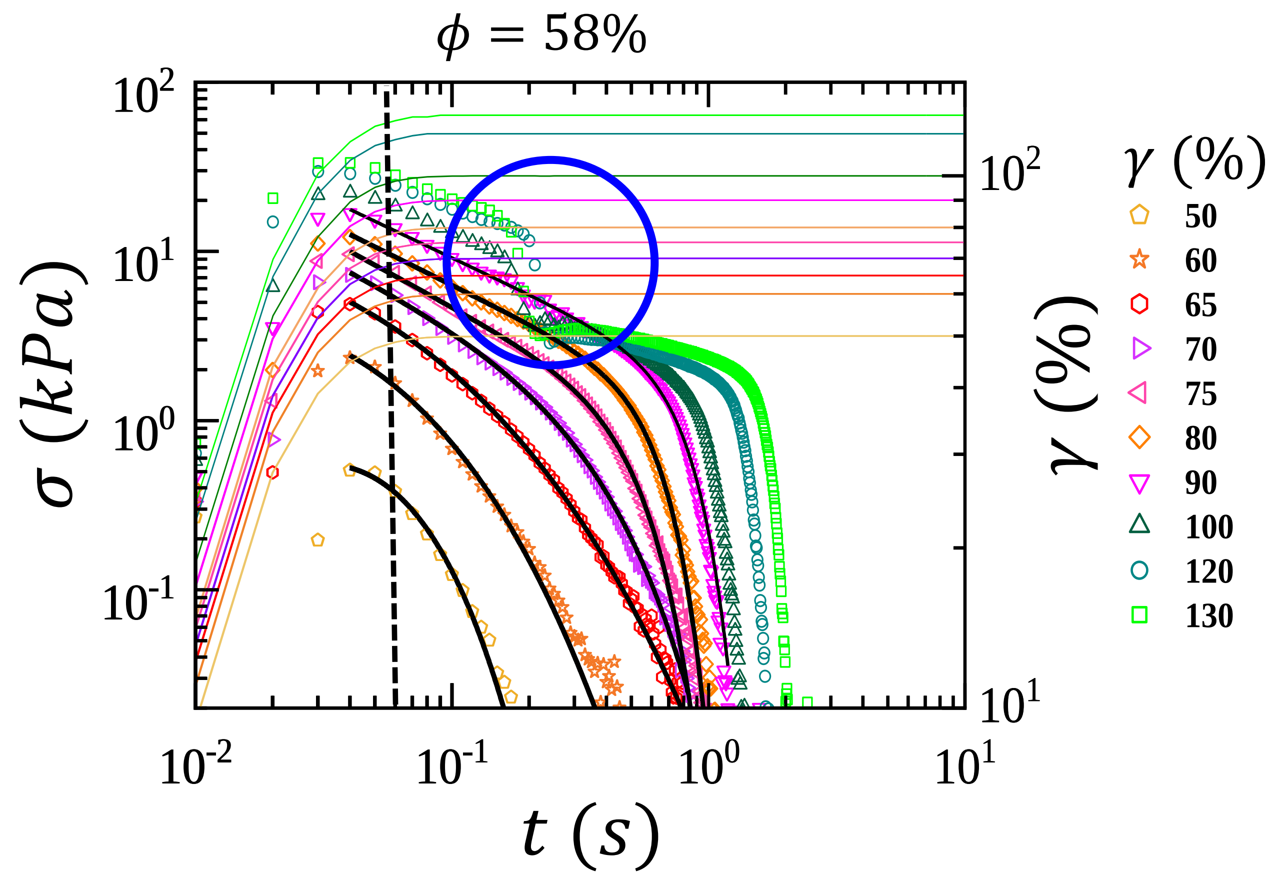
Constant Strain is applied for certain period of time

Observed



Stress relaxation is observed for that period of time

Transient stress relaxation under a step- strain perturbation



Fitting function :

$$\sigma(t) \sim t^{-\alpha}\, e^{-(t/\tau)^{\beta}}$$

(Power-law cut-off by a stretched exponential)

Similar functional form is observed in simulation for relaxation of dense frictionless suspension close to jamming

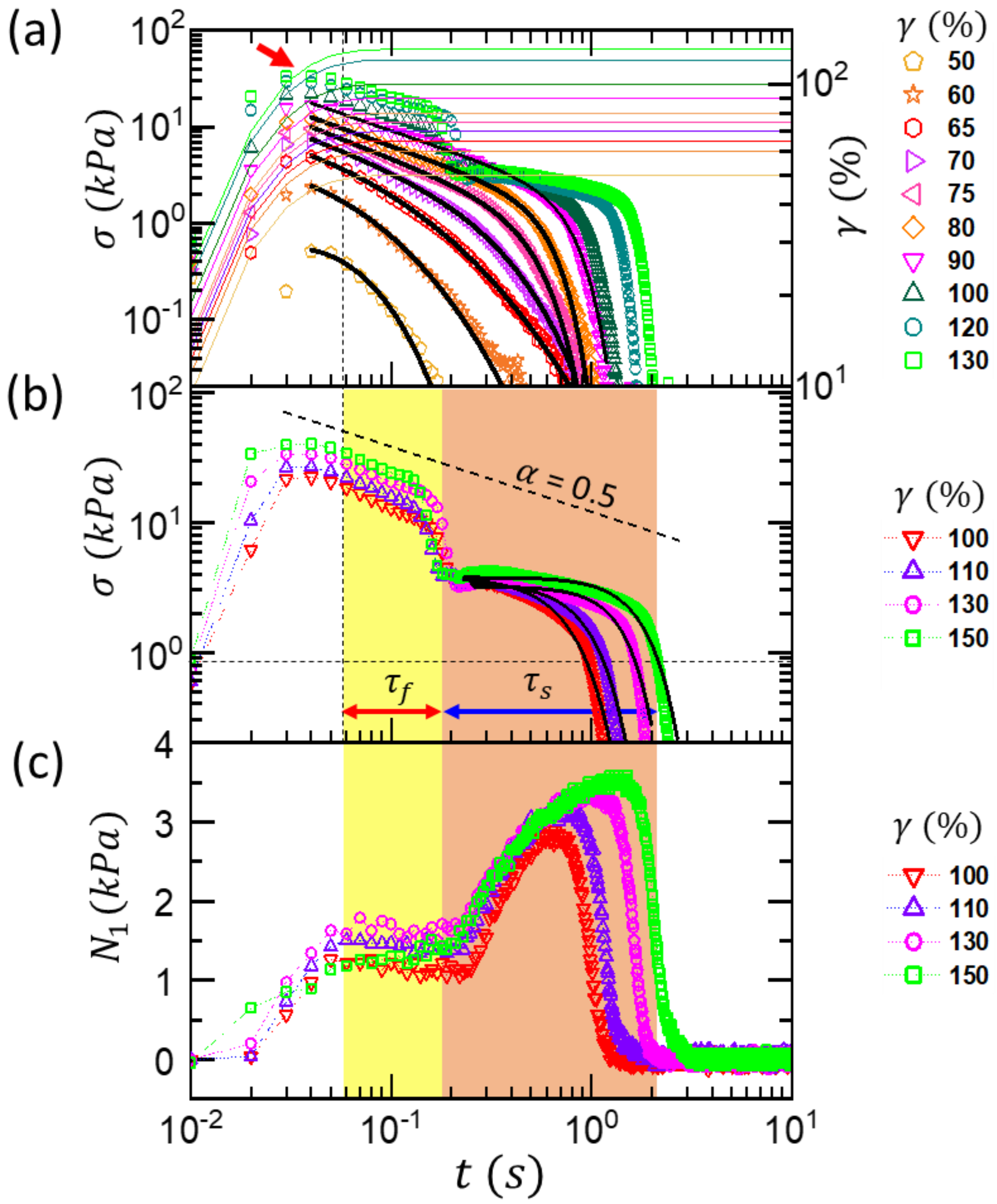
***[Hatano;* PRE(2009), *Ikada et al.;* PRL(2020)]**

Low peak-stress value: *Continuous relaxation*

High peak-stress value: *Discontinuous stress drop*

Large scale stress drop and discontinuity

Normal stress response during transient stress relaxation



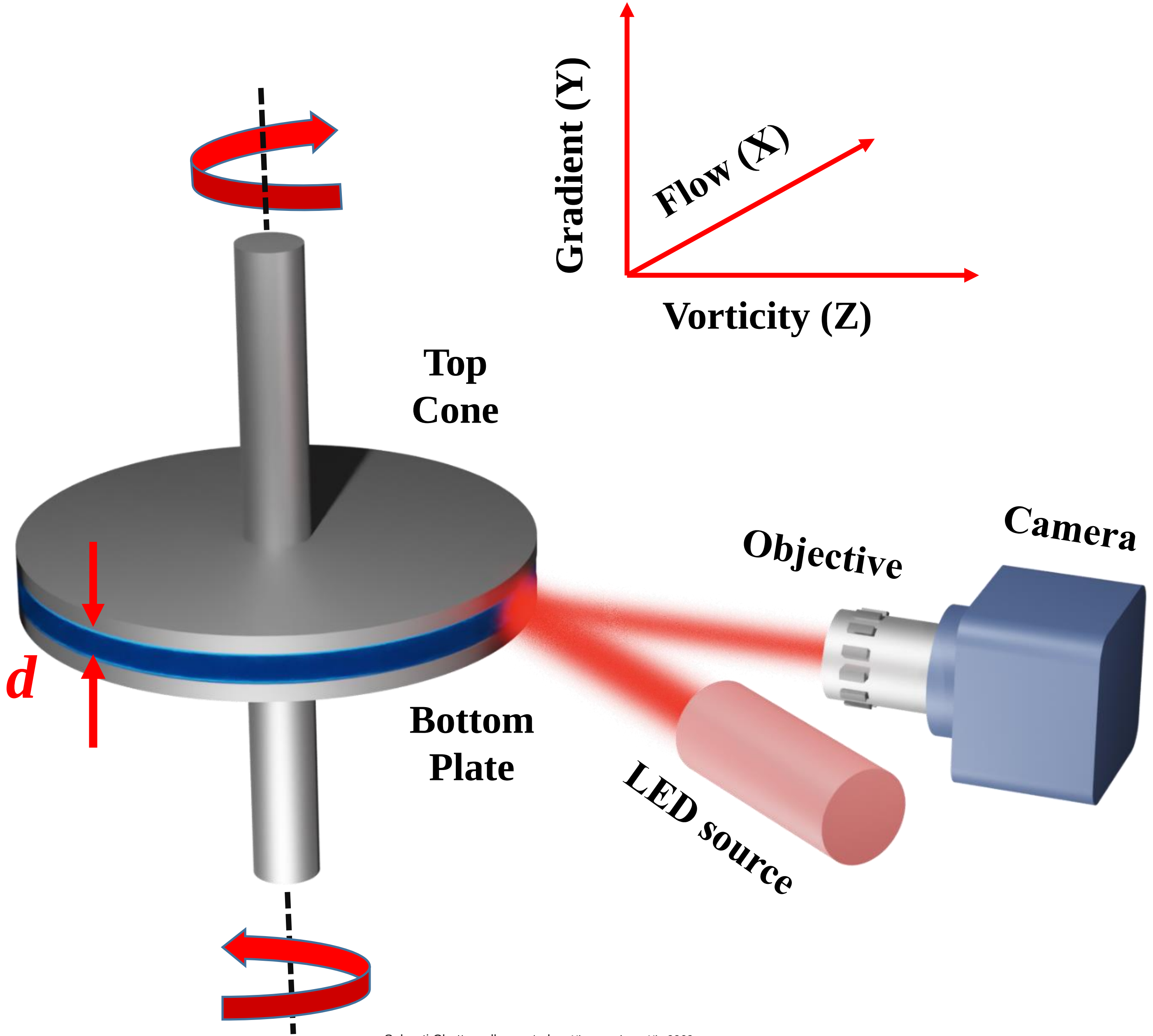
$$N_1 = \frac{2F_N}{\pi r^2}$$ → 1st Normal stress difference

F_N: Normal force on cone/plate

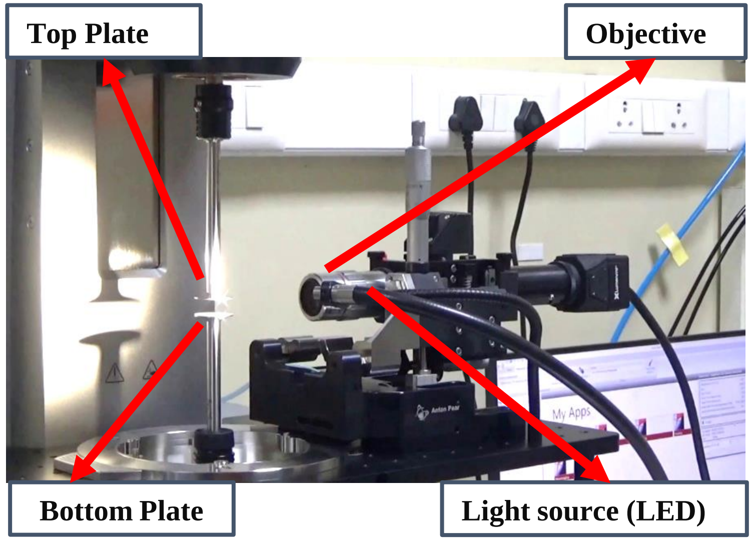
r: Radius of cone/plate

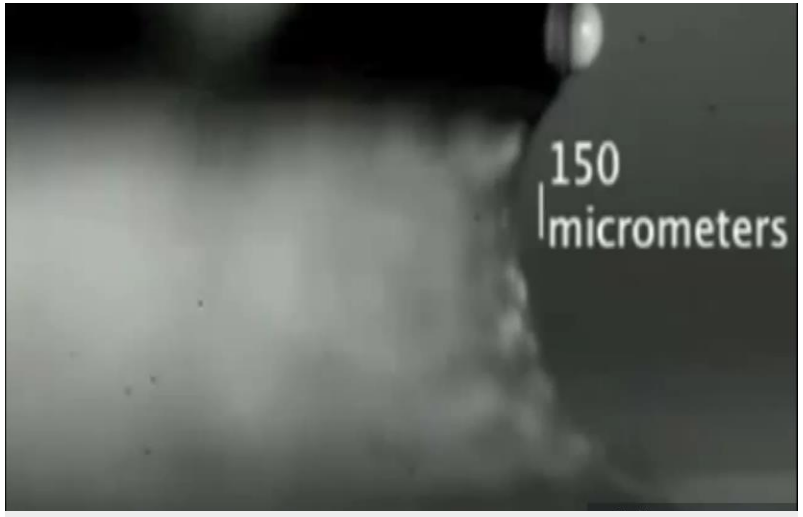
- **For high peak stress value, two distinct relaxation regimes**
- **Stronger normal force response during the slower relaxation process**

Rheology and in-situ boundary imaging



Sebanti Chattopadhyay et al.; arXiv preprint arXiv:2202



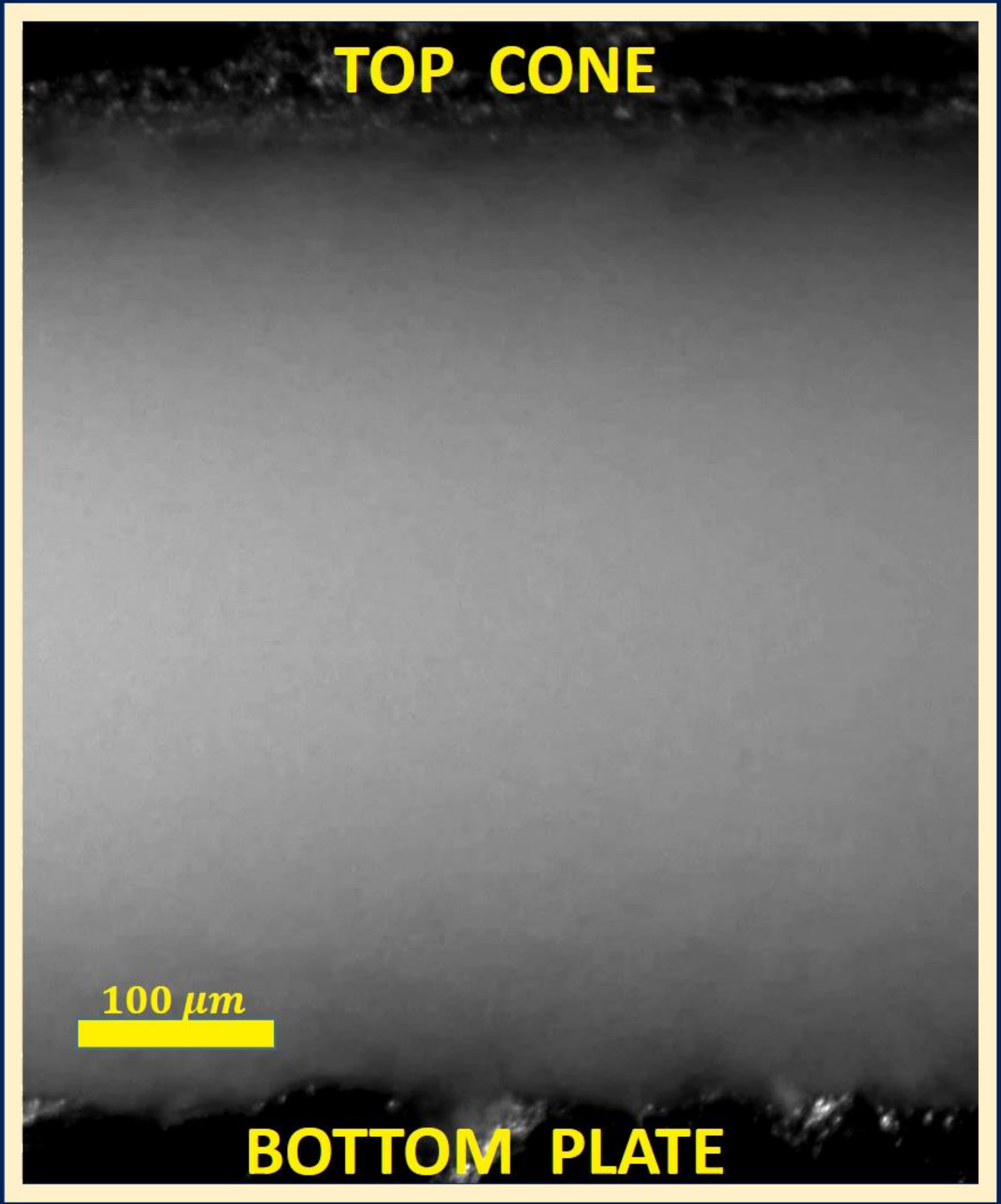


Dilation in STF due to shear

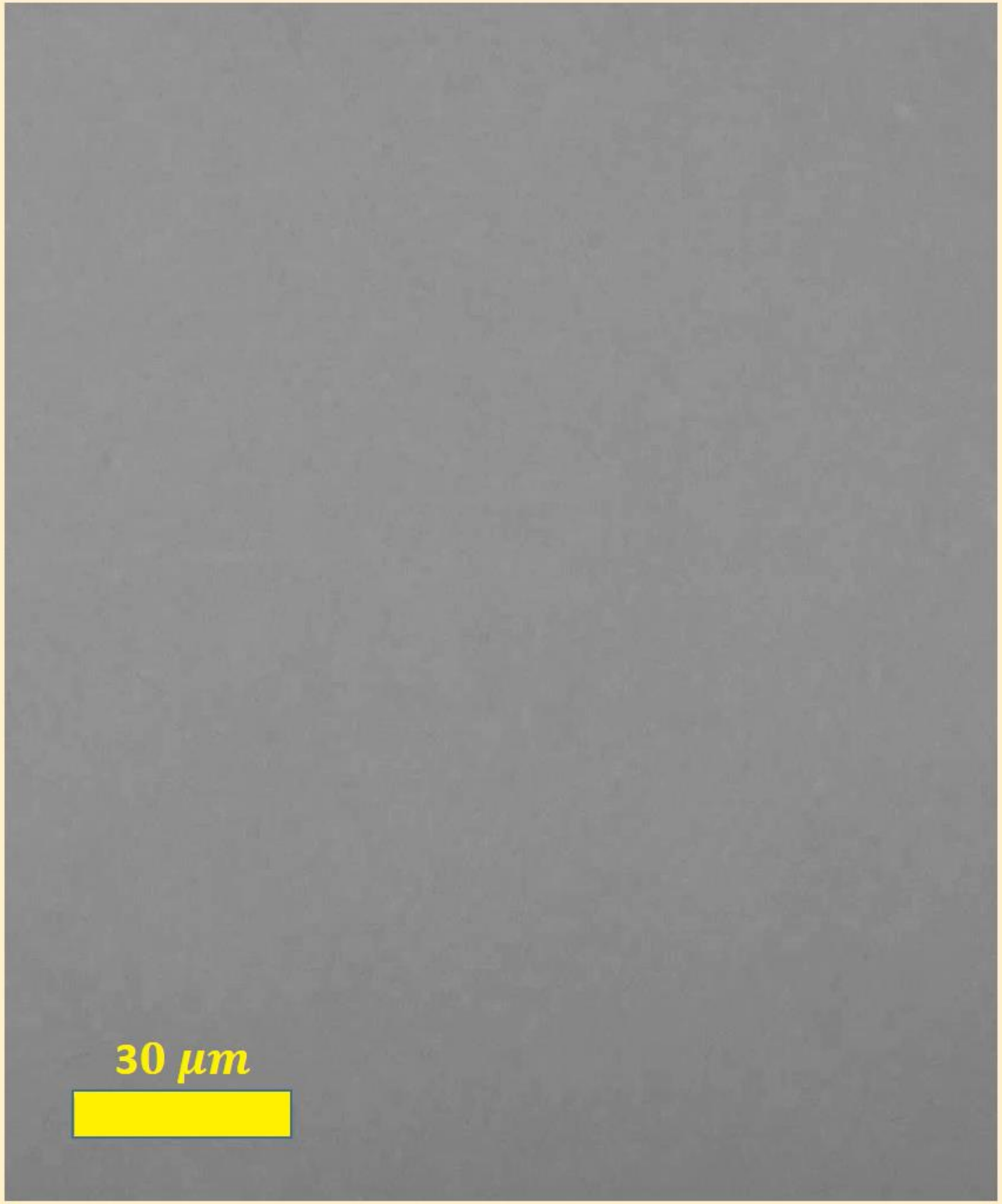
Eric Brown and Heinrich M Jaeger 2014 Rep. Prog. Phys. 77 046602

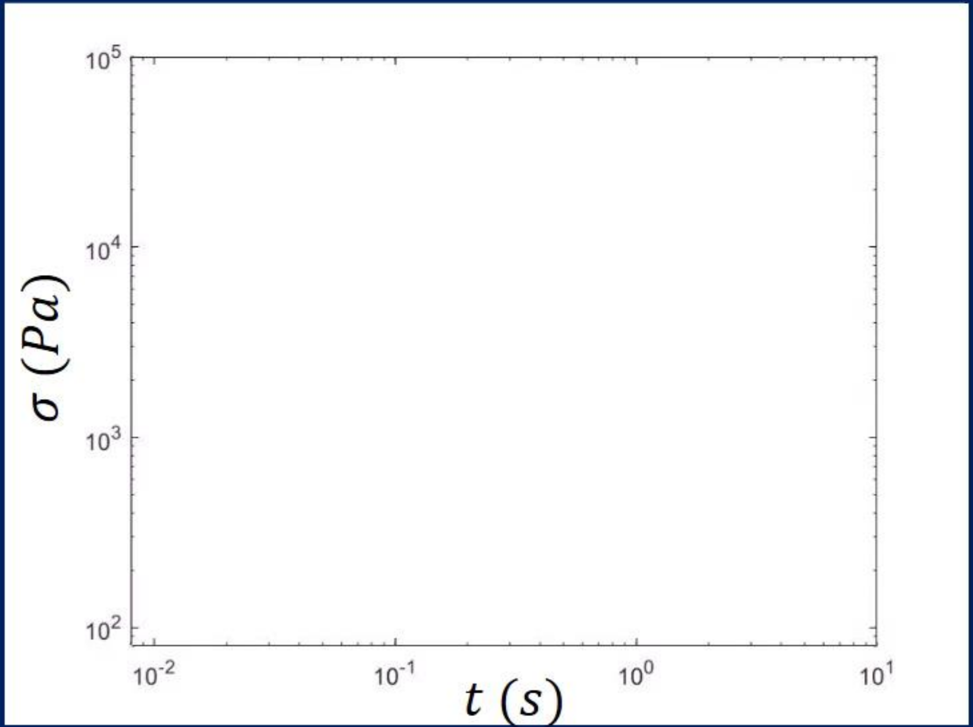
Strain :

OFF

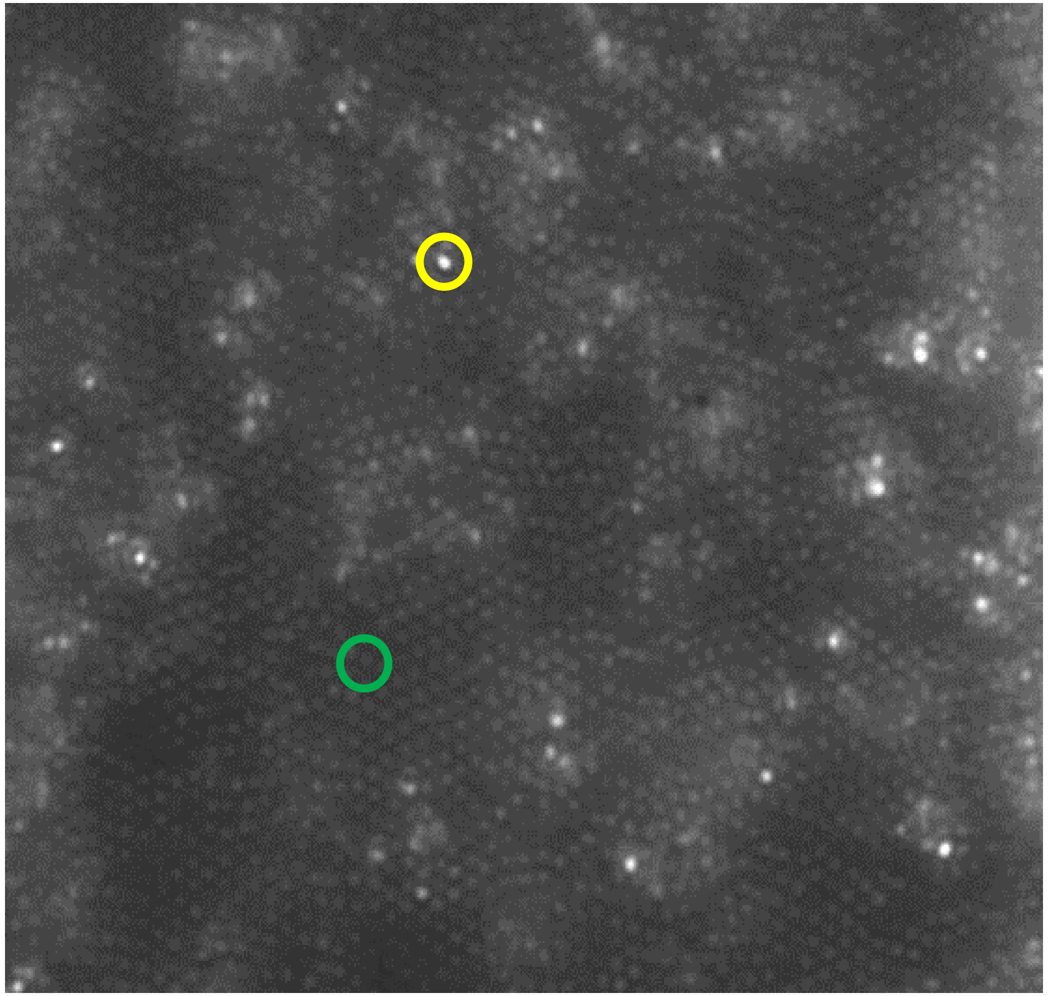


Strain :
OFF

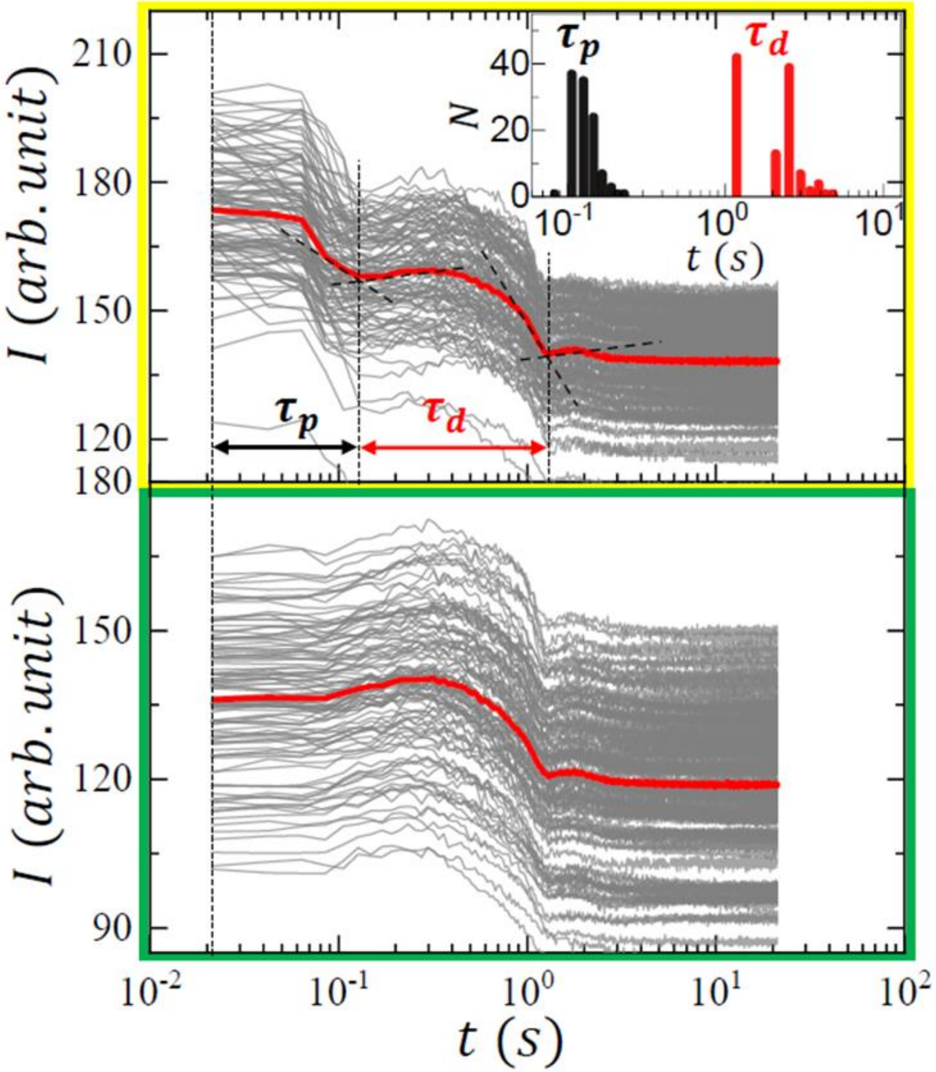




Plastic center and dilation relaxation



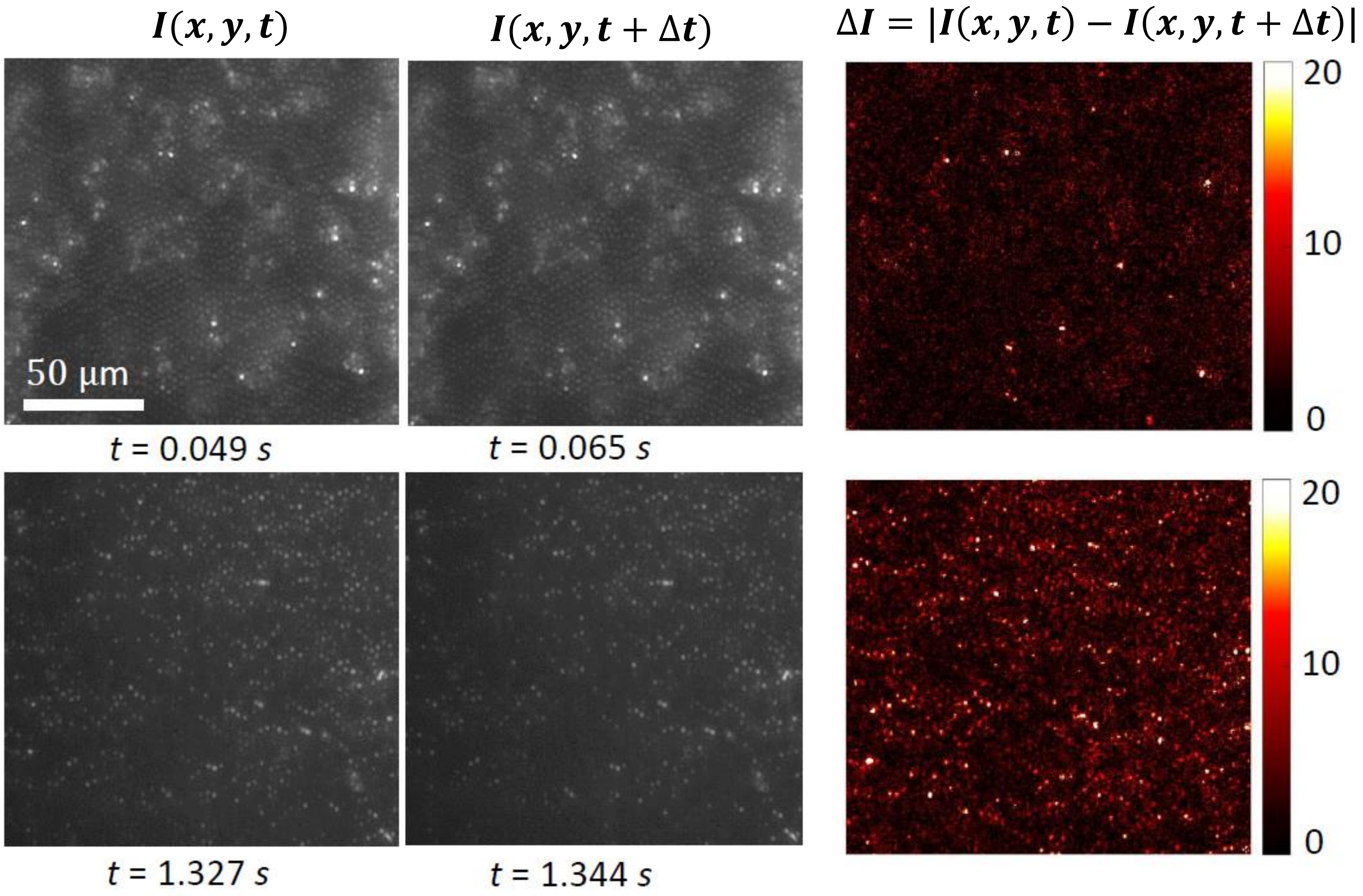
Bright spots are localized plasticity



Localized vs system spanning particle rearrangements

Plastic center relaxation

Dilation relaxation

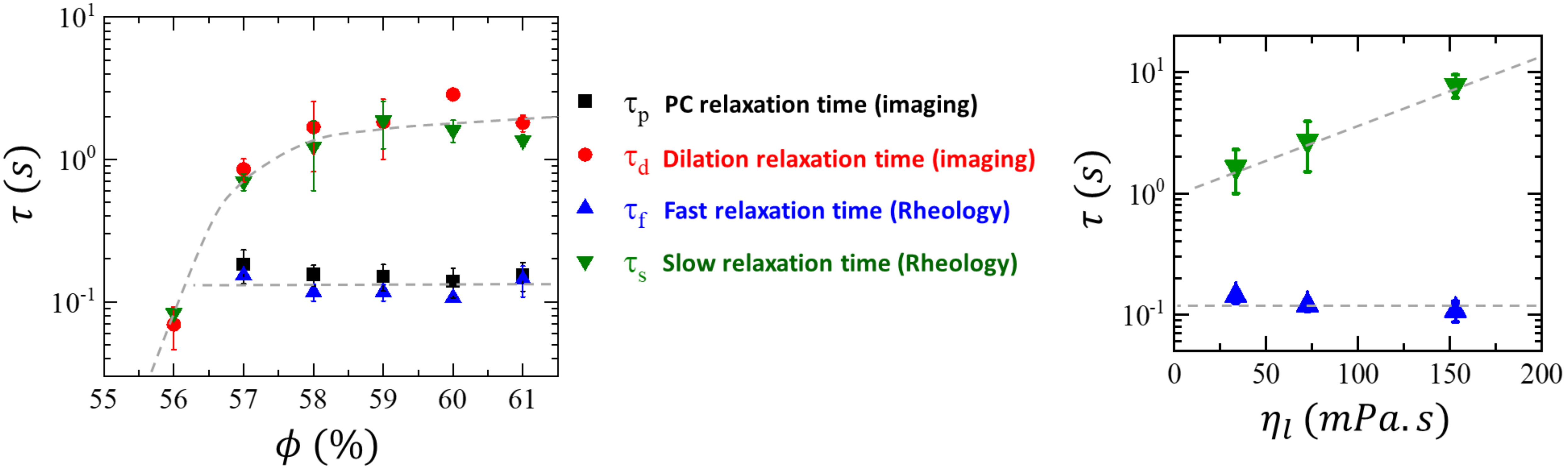


Localized particle rearrangements

System-spanning particle reorganizations

Origin of fast and slow relaxation times

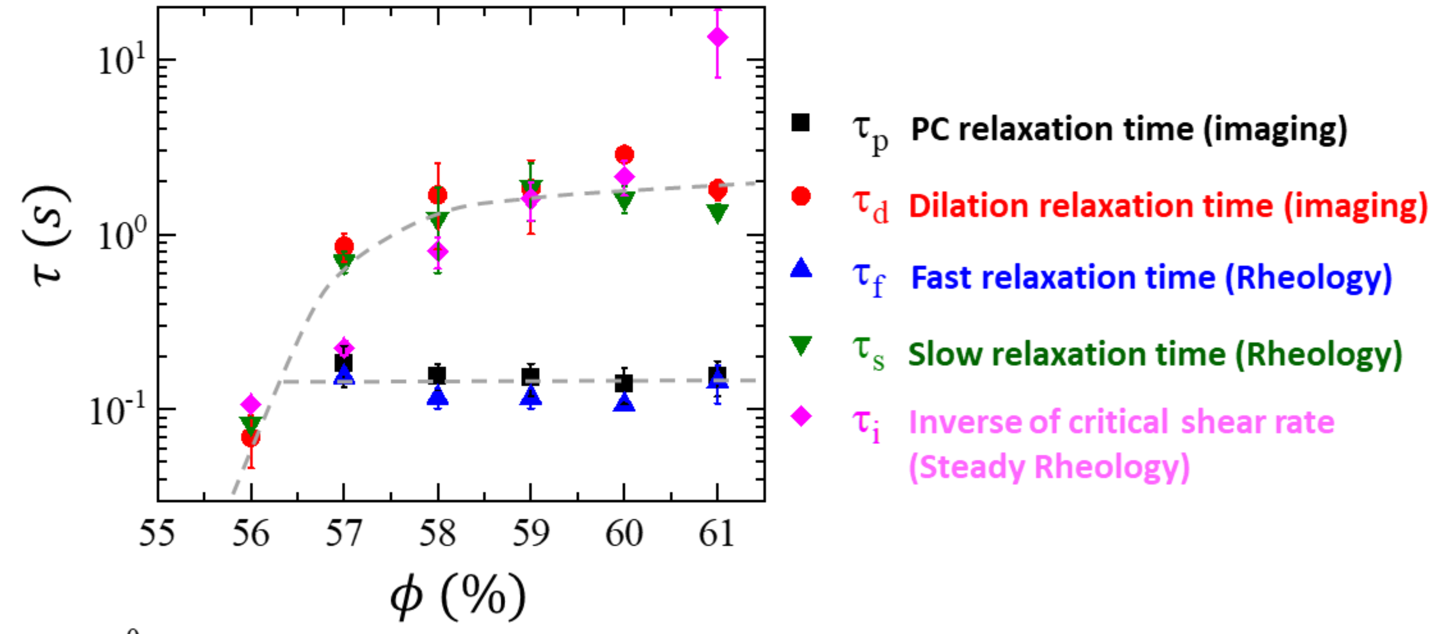
Excellent agreement between the time scales obtained from rheology and boundary imaging



Slow relaxation time sensitive to the solvent viscosity and particle volume fraction

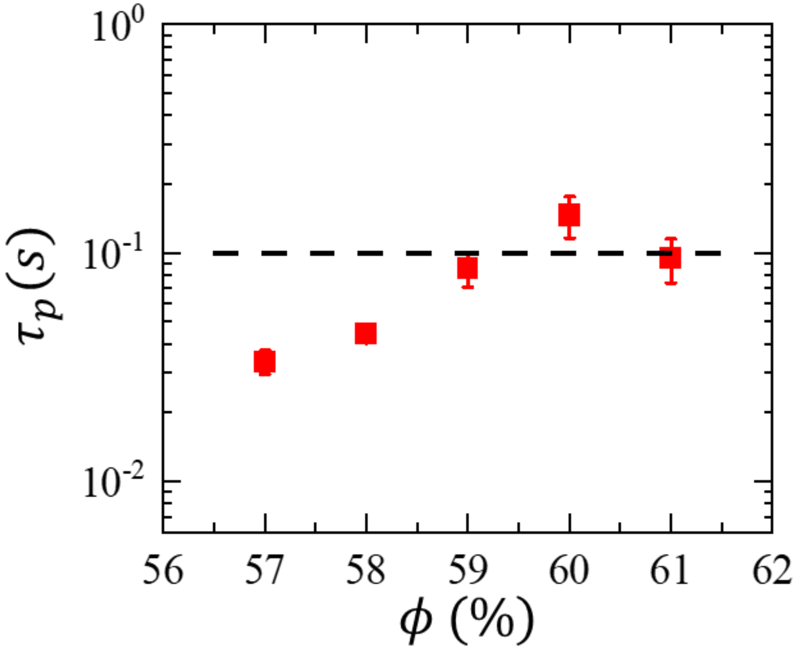
Fast relaxation time remains unaffected, since it is governed by particle-scale plasticity.

Quantitative estimation of time scales



$$\tau_i = \frac{1}{\dot{\gamma}_c}$$

$\dot{\gamma}_c$= Shear rate onset for steady state shear thickening



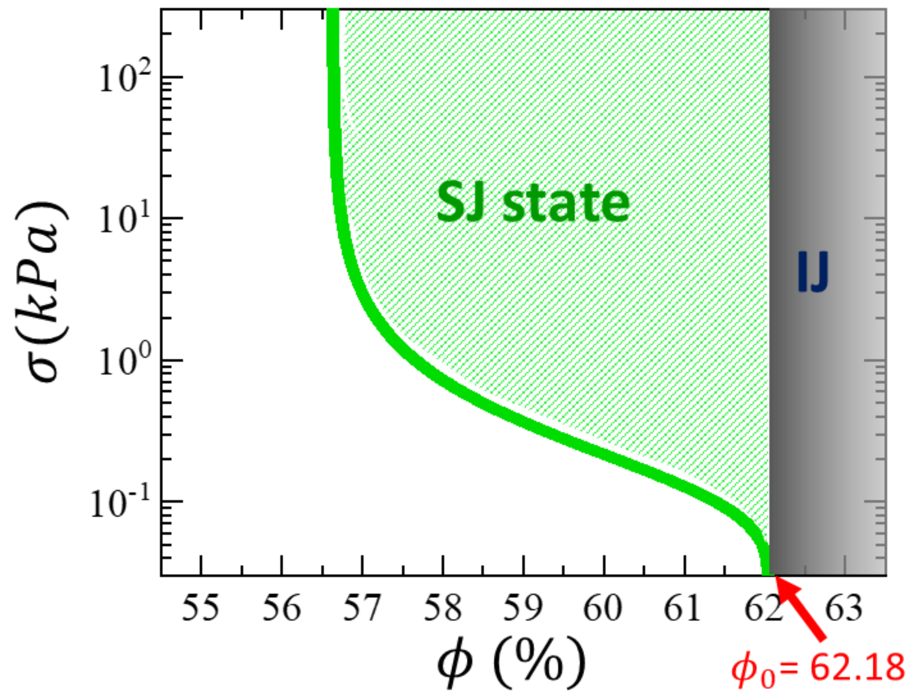
$$t \sim \frac{\eta_t a}{\Gamma}$$

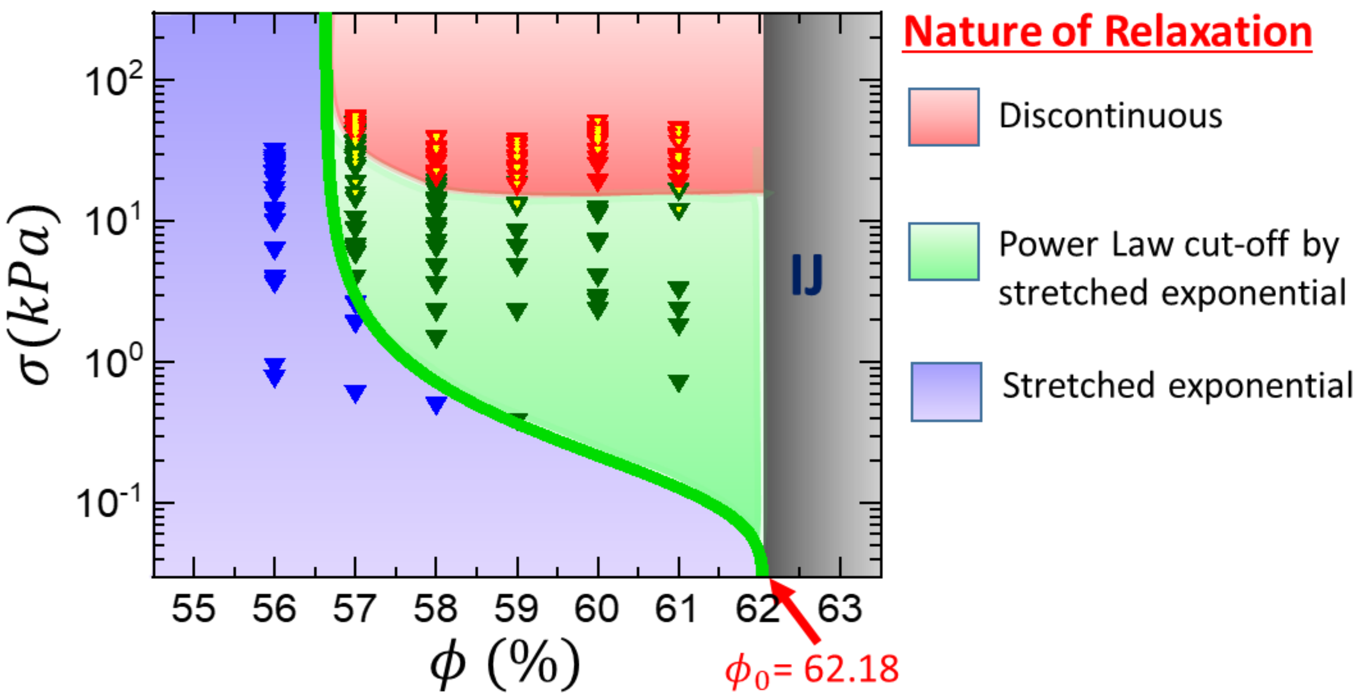
$\eta_t = \frac{peak\ stress\ (\sigma_p)}{maximum\ shear\ rate(\dot{\gamma}_p)}$ = Transient local viscosity

Γ = Solvent-air surface tension

a = Particle diameter

Connection of transient relaxation with steady state SJ phase diagram





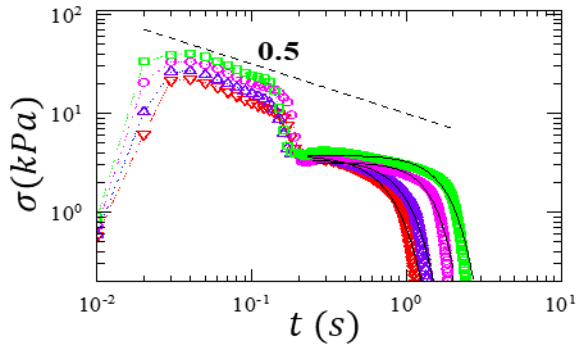
$$\sigma = \frac{\sigma^*}{\ln\left(\frac{\phi_0 - \phi_m}{\phi_0 - \phi}\right)}$$

→ Shear-Jamming boundary

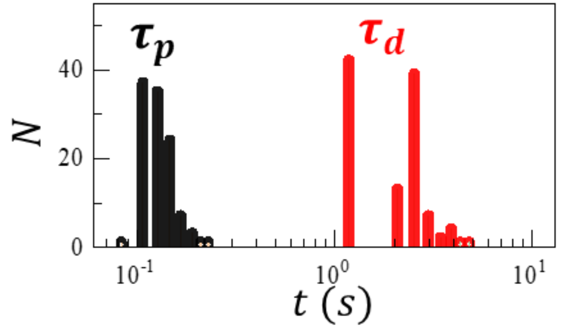
Parameters : ϕ_0, ϕ_m and σ^* are estimated from steady state flow curve using Wyart Cates Model

Conclusions and outlook

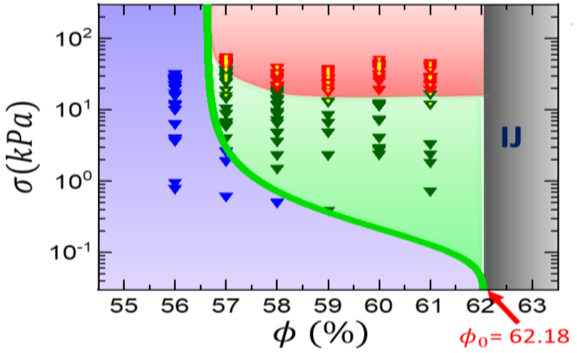
1. We identify two distinct transient stress relaxation regimes in shear jamming dense suspensions.



2. We correlate these time scales with localized plastic events and system spanning dilation. Changing particle volume fraction and solvent viscosity such mechanism is further confirmed.



3. Intriguing correlation between nature of transient relaxation and steady state phase diagram obtained from Wyart Cates model.



Microscopic nature and dynamics of such plasticity together with its connection to a more general frame work of soft glassy rheology is still an open challenge.

Acknowledgement

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Lab members

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Akhil Mohanan

Shibil Adam

Dr. Sayantan Majumdar

RRI

THANK YOU