Discontinuous Shear Thickening fluids: Shear-induced system spanning structures

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Discontinuous Shear Thickening (DST) fluids

suspension of cornstarch in water

- Problem: why does shear lead to solid-like properties in DST fluids?

➡ a transiently jammed region develops in response to shear and supports a load when it spans between solid boundaries

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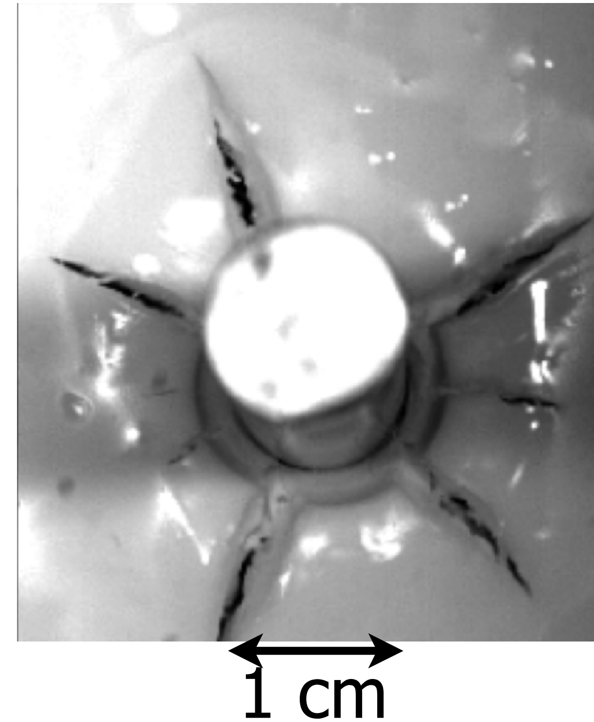

- Roche et al. PRL 2013

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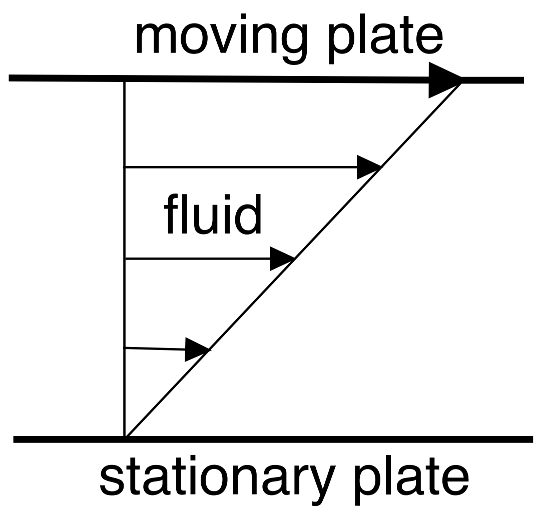
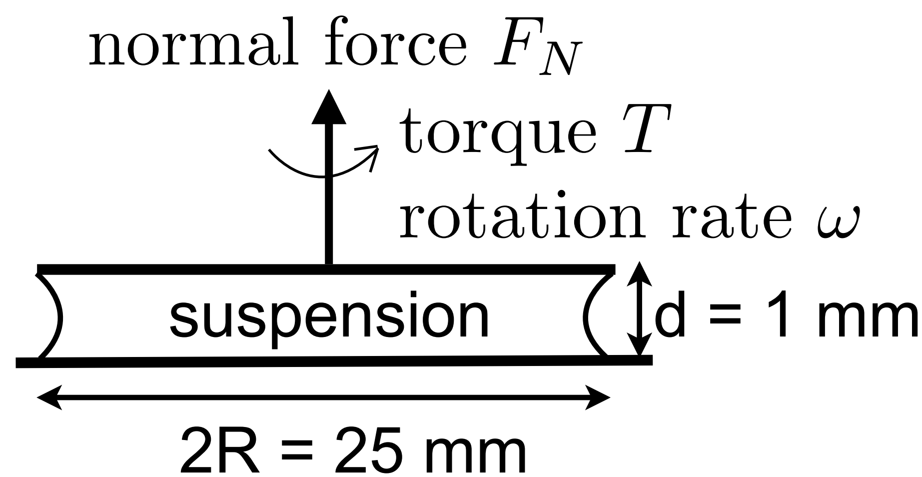
steady state rheology measurements:





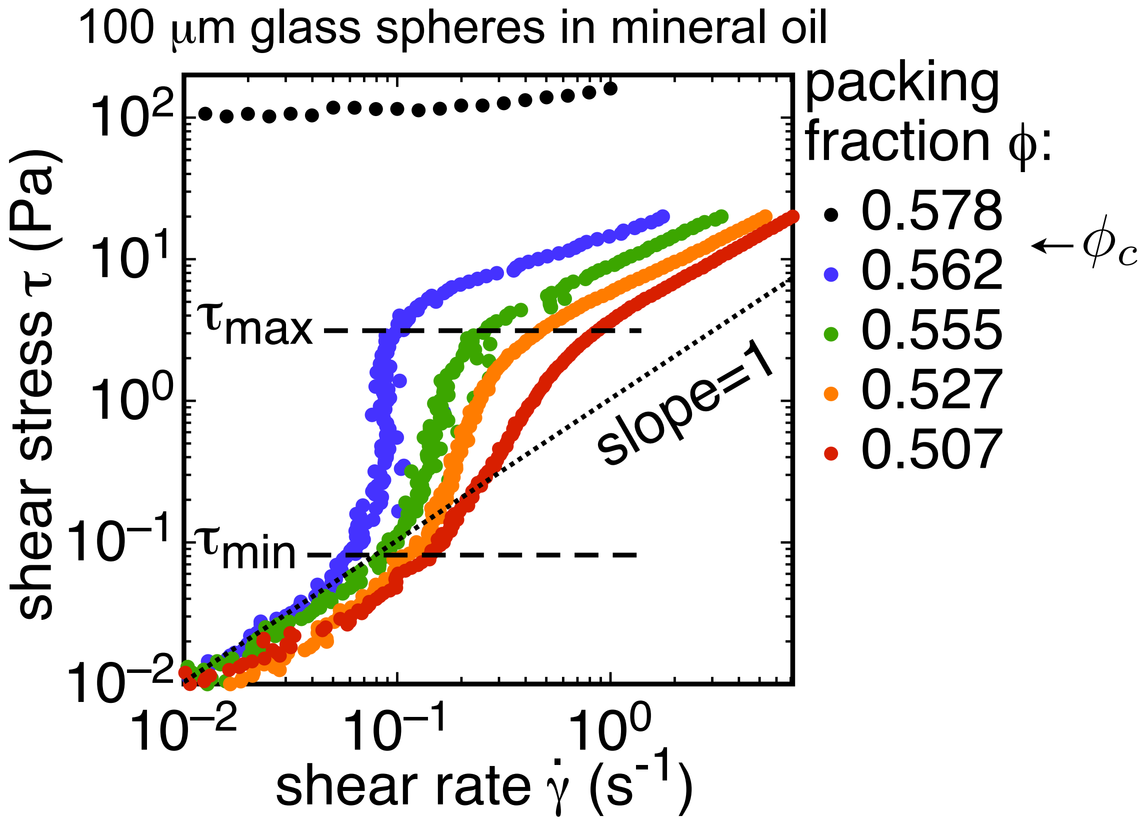
shear rate $\dot{\gamma} = \omega R/d$ (average velocity gradient)

shear stress $\tau = 2T/\pi R^3$ (average shear force/area)

viscosity $\eta = \tau/\dot{\gamma}$

viscosity is a measure of globally averaged energy dissipation rate in steady state flow

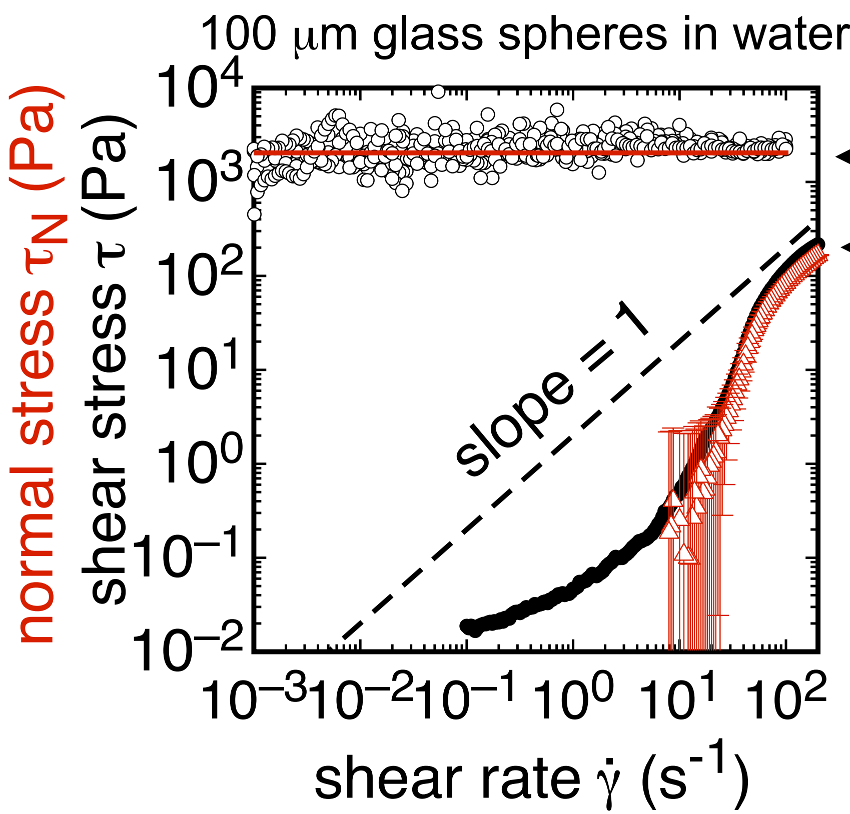
Discontinuous Shear Thickening

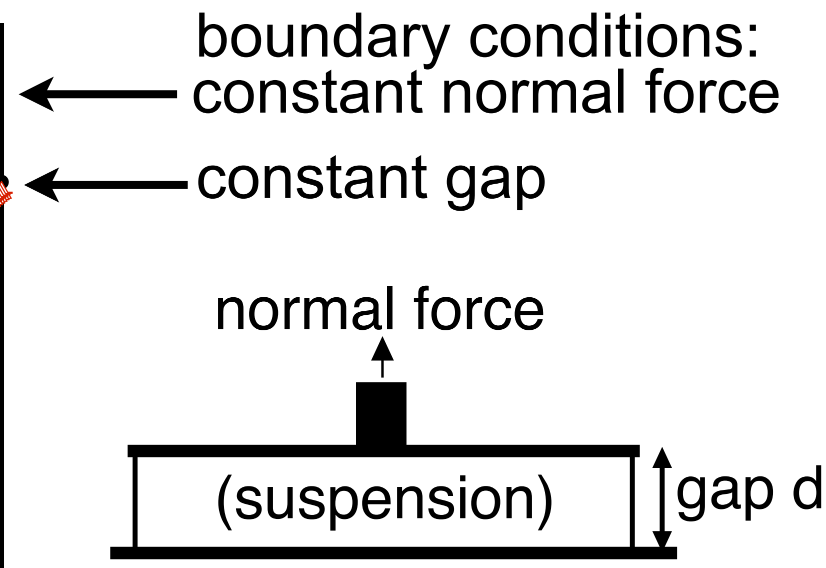


- slope diverges as second order phase transition
  - -critical point ϕ_c is the jamming transition [Brown & Jaeger, PRL 2009]
- occurs generally in sufficiently concentrated suspensions of hard, frictional, non-attractive particles

What causes the stress increase in the DST regime?

Frictional relation between shear and normal stress

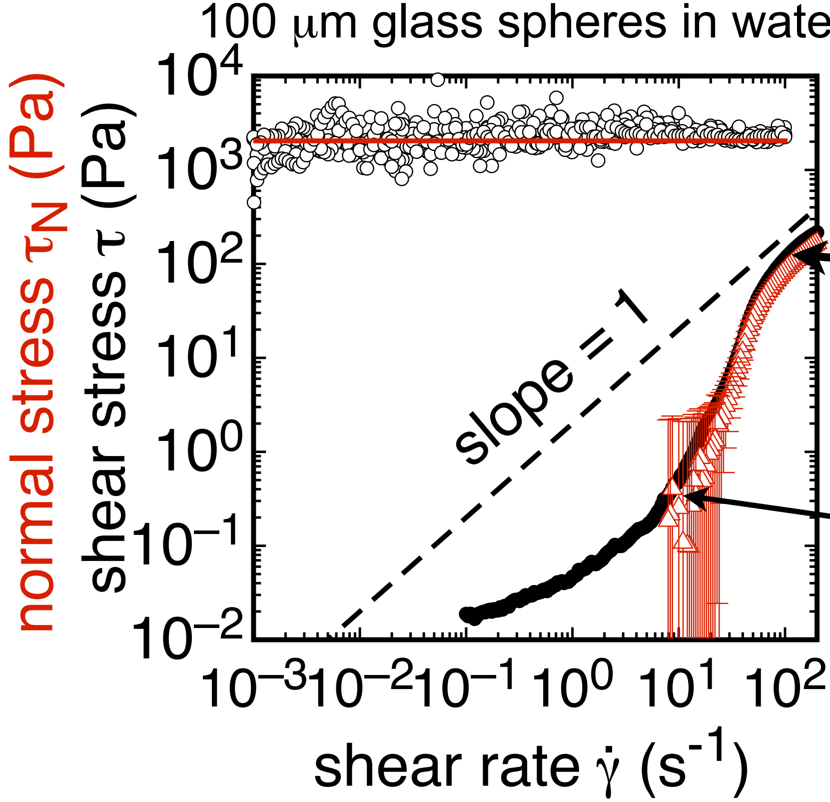


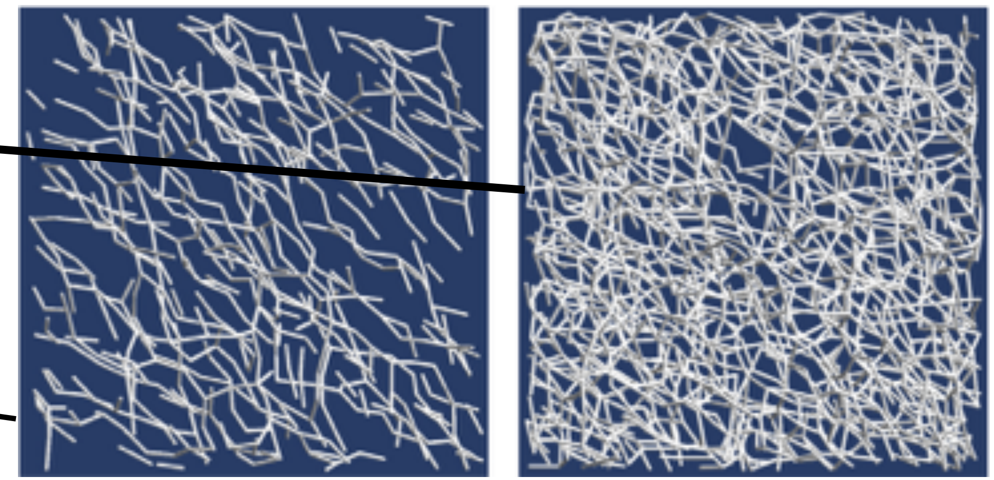


- shear stress (black) proportional to normal stress (red)
  - ➡ friction (Lootens et al. PRL 2003, 2005, Brown & Jaeger J. Rheol. 2012)
- existence of DST depends on boundary conditions
  - ➡ not a bulk constitutive relation dependent on local shear rate

  (Fall et al. PRL 2008, Brown & Jaeger J.Rheol. 2012)

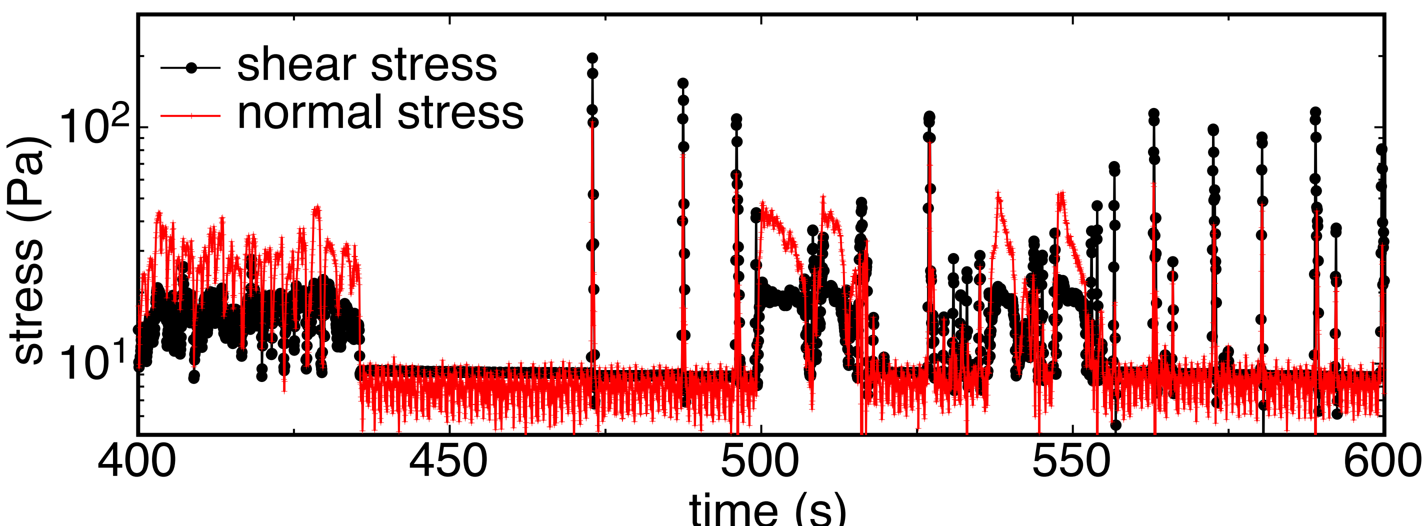
Dynamic force chain formation





- force chains in DST regime

(Seto et al. 2013)

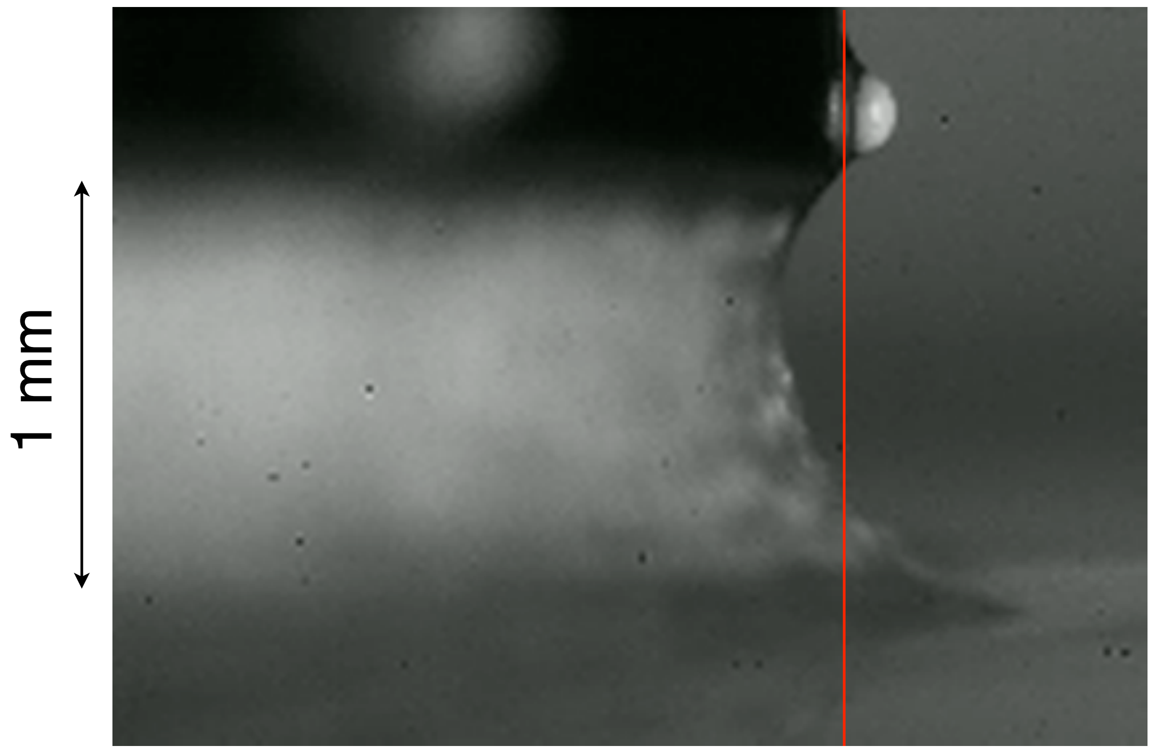


- giant fluctuations (Lootens et al. PRL 2003, 2005)

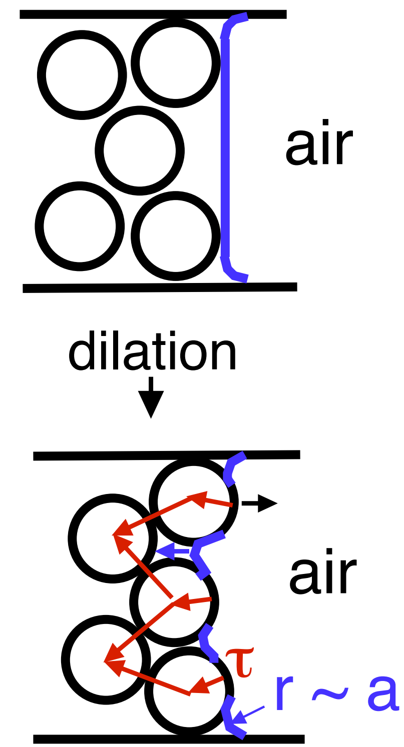
What supports the stress?
Dilation against liquid-air interface
-> confining stress from surface tension

150 μm ZrO_2 in mineral oil

side view (tangent to surface), shear rate = 3 s^{-1}, 0.33x



Brown & Jaeger J. Rheol. 2012



maximum confining stress:

$$\tau_{max} \approx \frac{\gamma}{r} \sim \frac{\gamma}{a}$$

γ = surface tension

a = particle diameter

Cates et al. 2005

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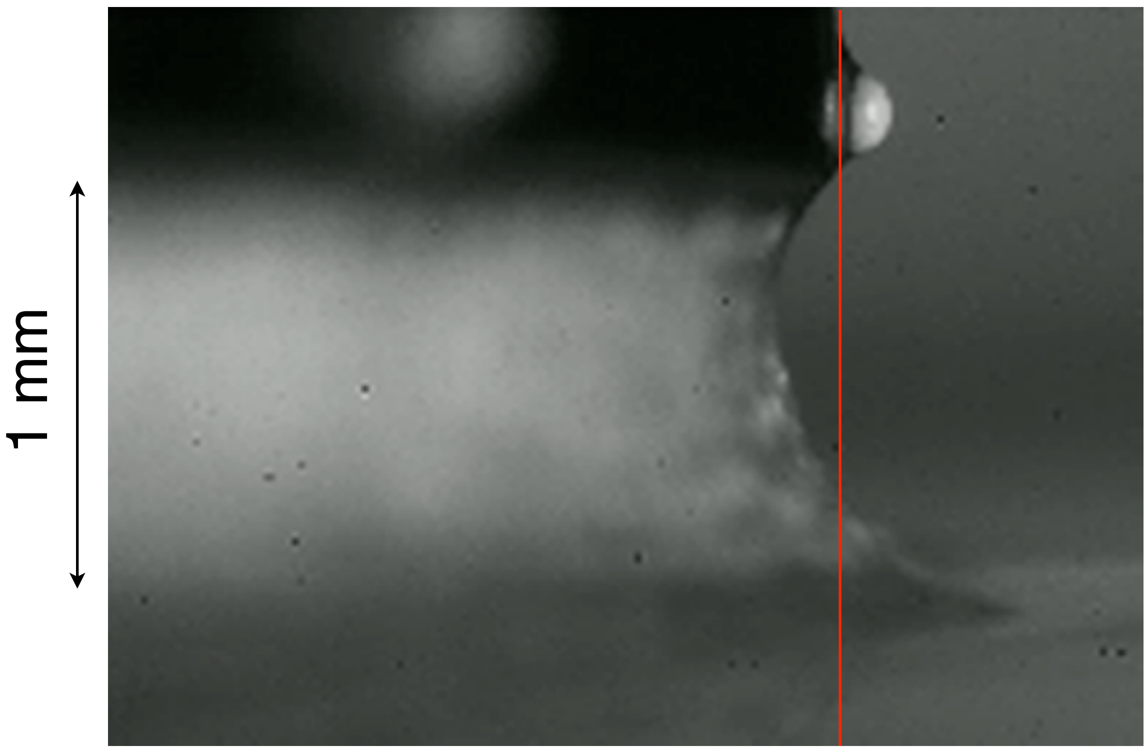

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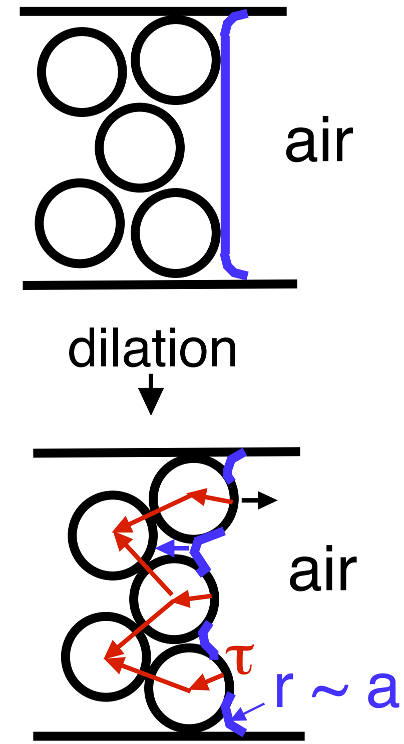

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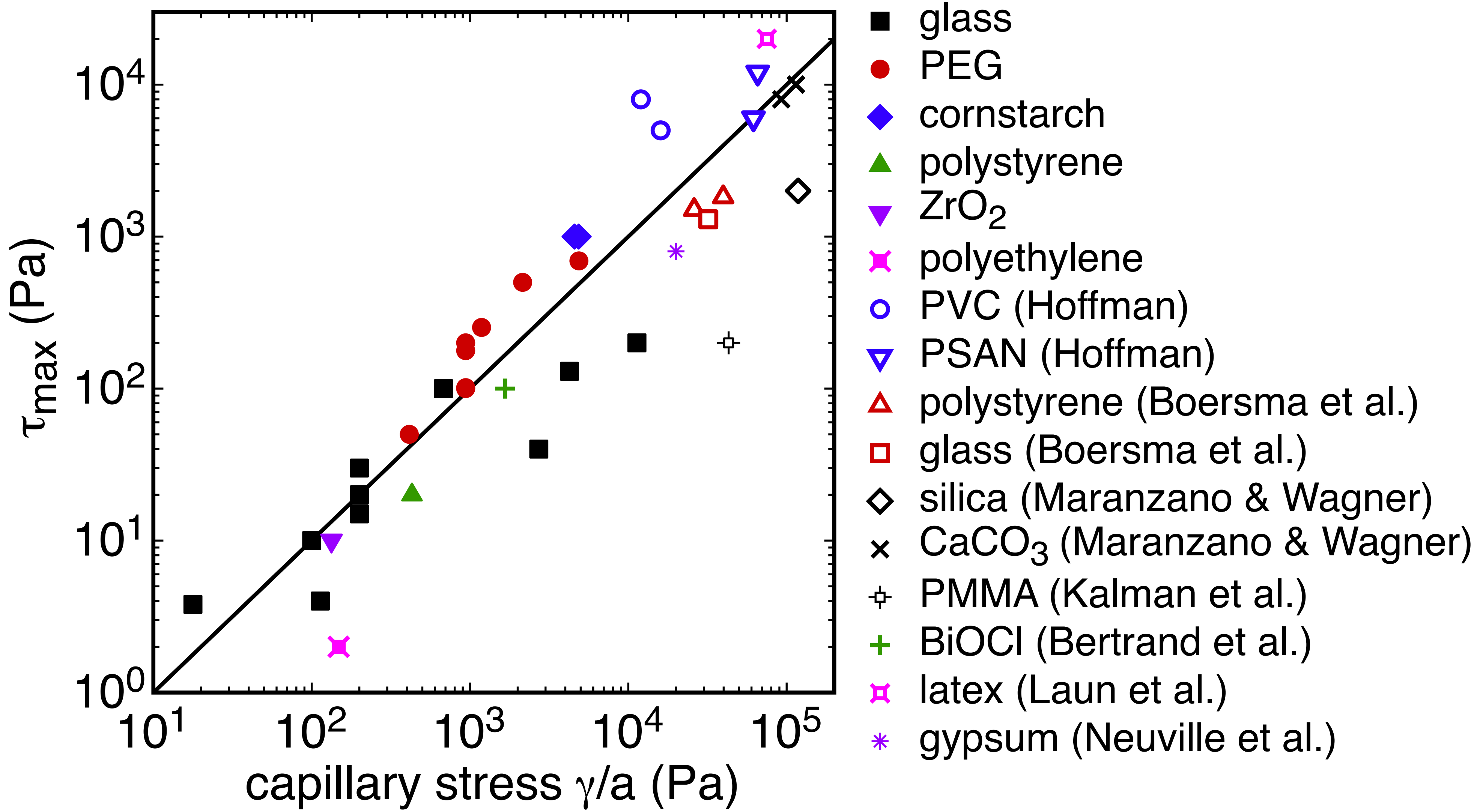
Cates et al. 2005

maximum stress (τ_{max}) in DST limited by surface tension



Brown & Jaeger J. Rheology 2012

Summary of steady state DST:

DST occurs in dense suspensions of hard, frictional, non-attractive particles

-dilation leads to a dynamically jammed state with contact between particles

- •shear stress must exceed all stresses that prevent dilation
  - gravity for settling particles (Brown & Jaeger J. Rheol. 2012)
  - electrostatic forces (Hoffman 1982, Maranzano & Wagner 2001)
  - osmotic pressure (colloids) (Bergenholtz et al. 2002, Maranzano & Wagner 2002)

-stress is transmitted along force chains of frictional solid-solid contacts

-DST is not a local relationship between stress and shear rate -> it depends on boundary conditions

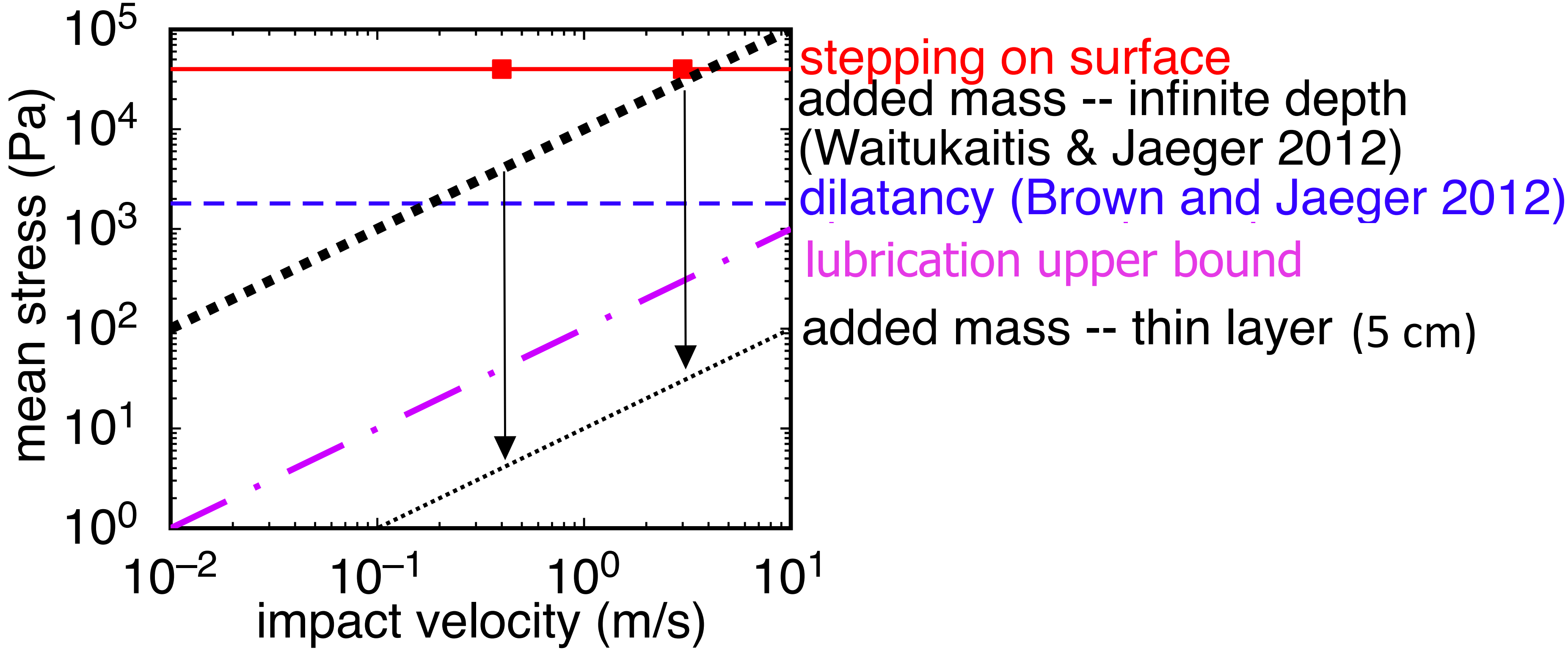
- •stress is limited by smaller stiffness of:
  - boundary (usually surface tension) (Brown & Jaeger J. Rheol. 2012)
  - particle (Otsuki & Hayakawa 2010, Seto et al PRL 2013)
- •DST does not occur under certain boundary conditions if confining stress does not increase in response to dilation

for a review, see Brown & Jaeger, Reports on Progress in Physics, 2014

Open Problem:

-Most of the dynamic phenomena of DST fluids remain unexplained
- -i.e. How can a suspension support a person’s weight under impact?

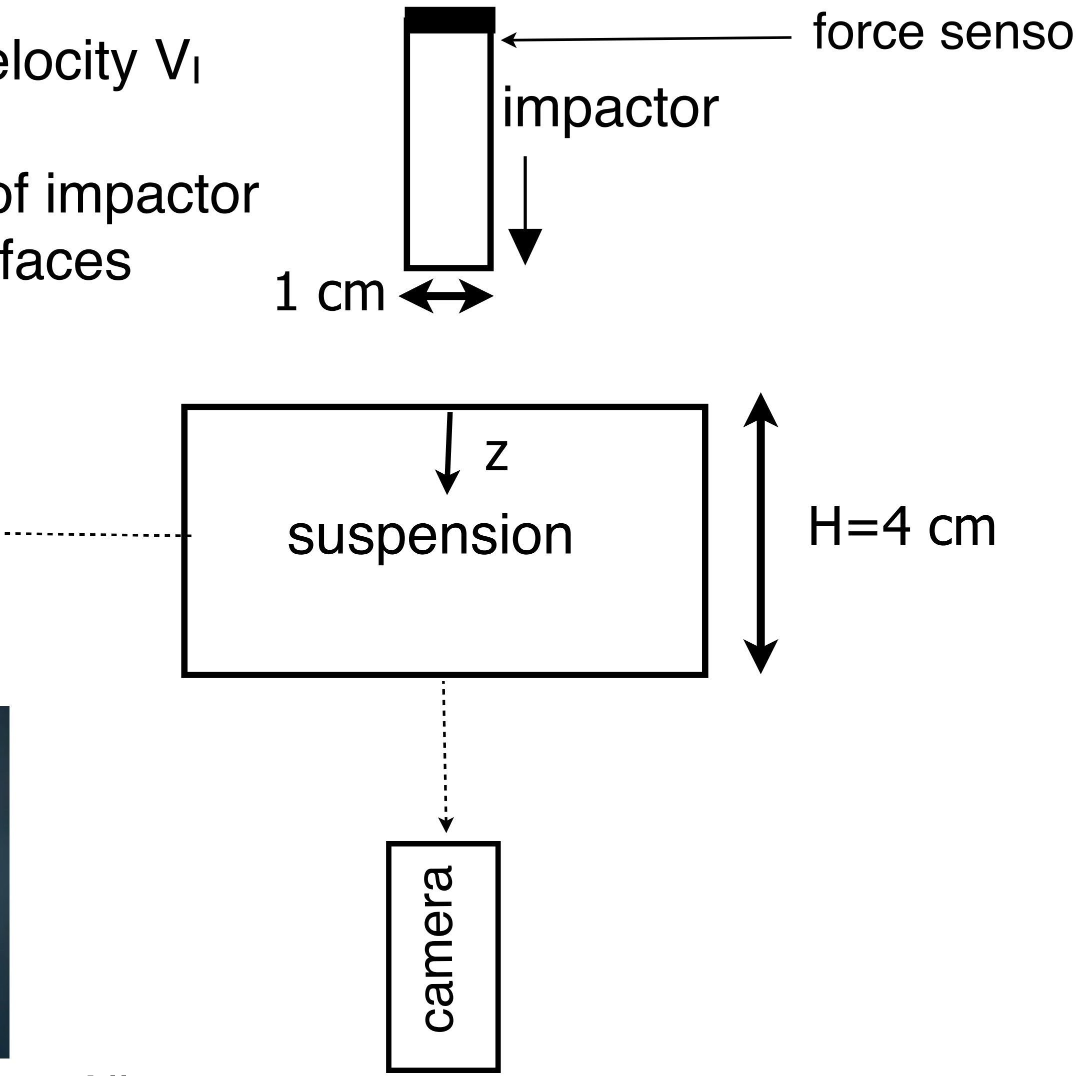
Steady state models can't explain large scale of transient stress during impact



➡New mechanism needed to explain impact response, especially in regime of thin layers important for impact protection applications

A model experimental system for impacts

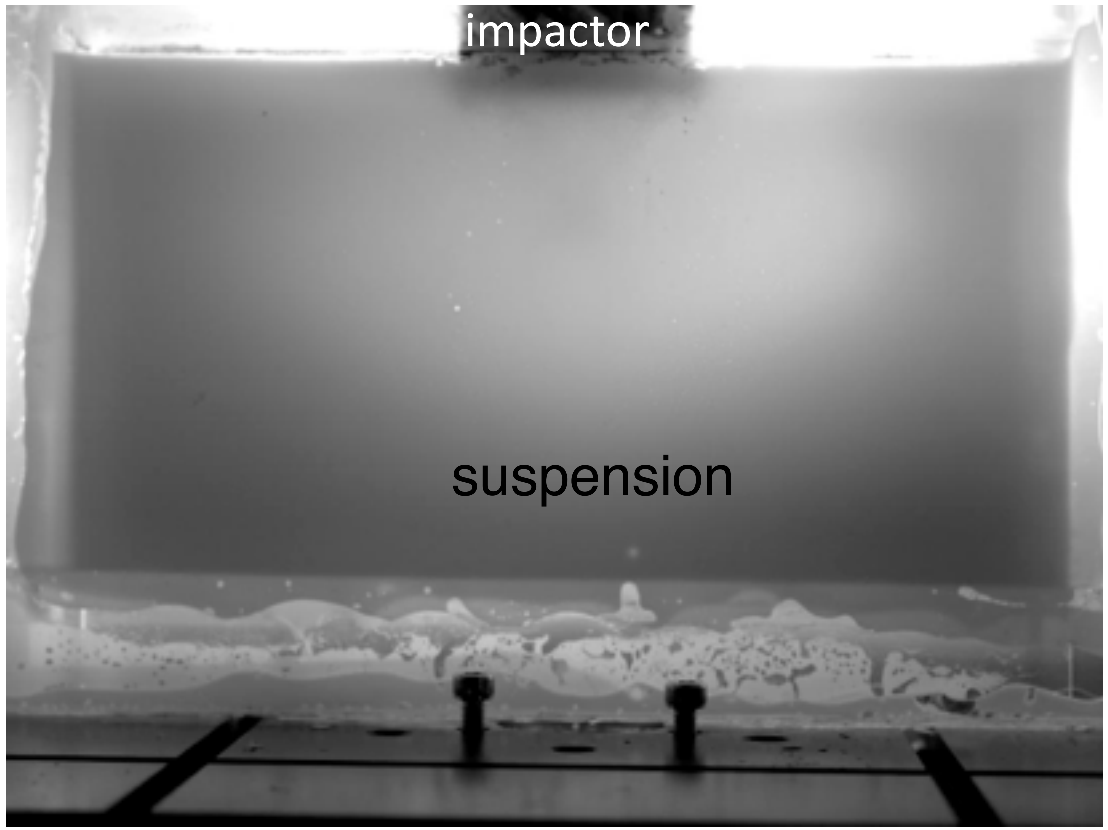
- impact at constant downward velocity V_I into suspension
- measure force & displacement of impactor with simultaneous imaging of surfaces



Shomeek Mukhopadhyay & Ben Allen
arXiv:1407.0719

Dynamically jammed region propagates in front of impact proposed by Waitukaitus and Jaeger, Nature 2012

15 cm



side view of quasi 2-dimensional experiment (0.5 cm thin layer)

- cracks suggest the region in front of the impactor can transmit stress like a solid/jammed system

Hypothesis: If the dynamically jammed region spans to a boundary, then it can support stress like a solid

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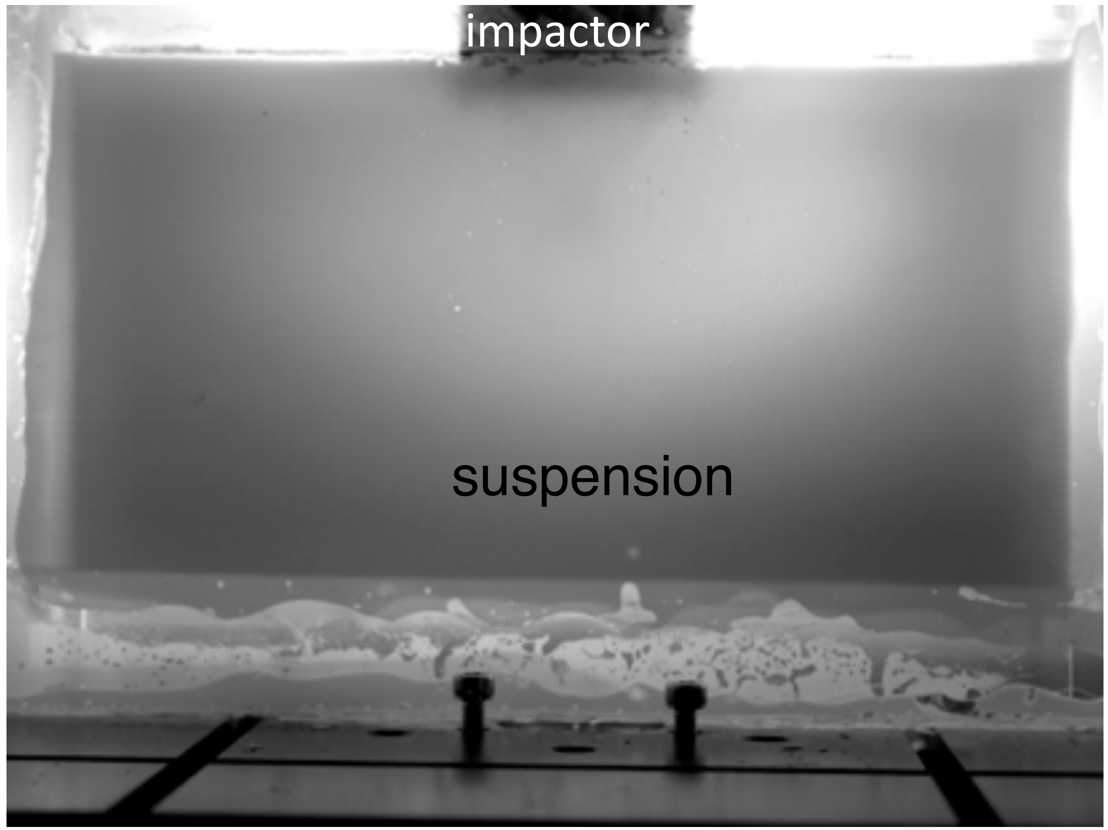

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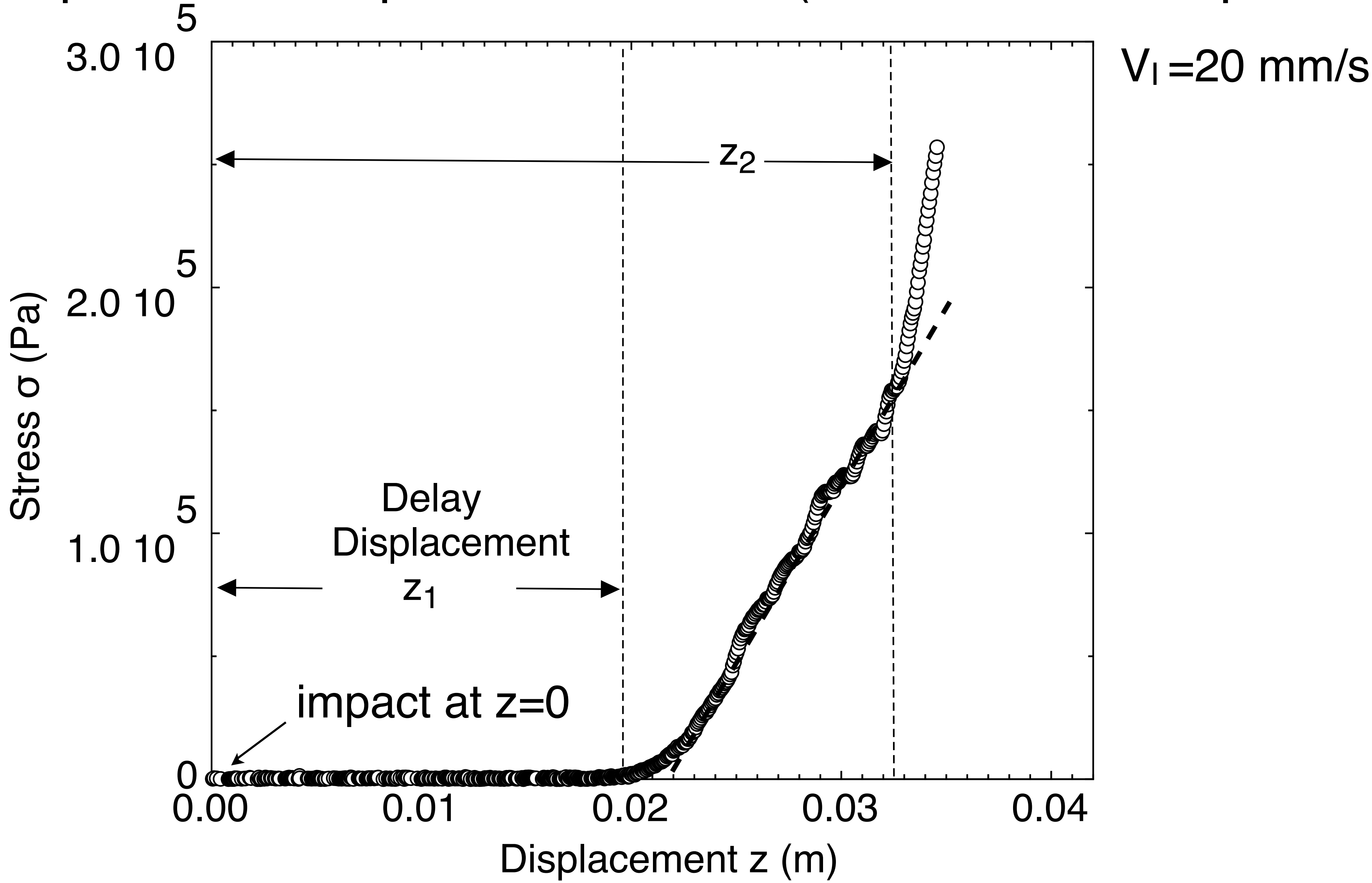
Example stress-displacement curve (3-dimensional experiment)

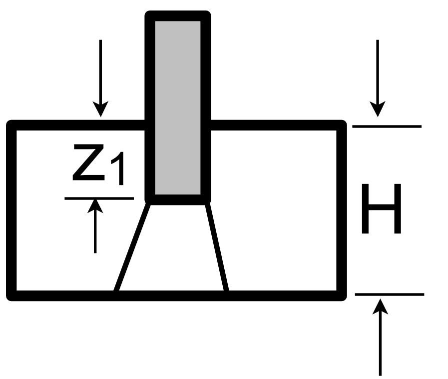


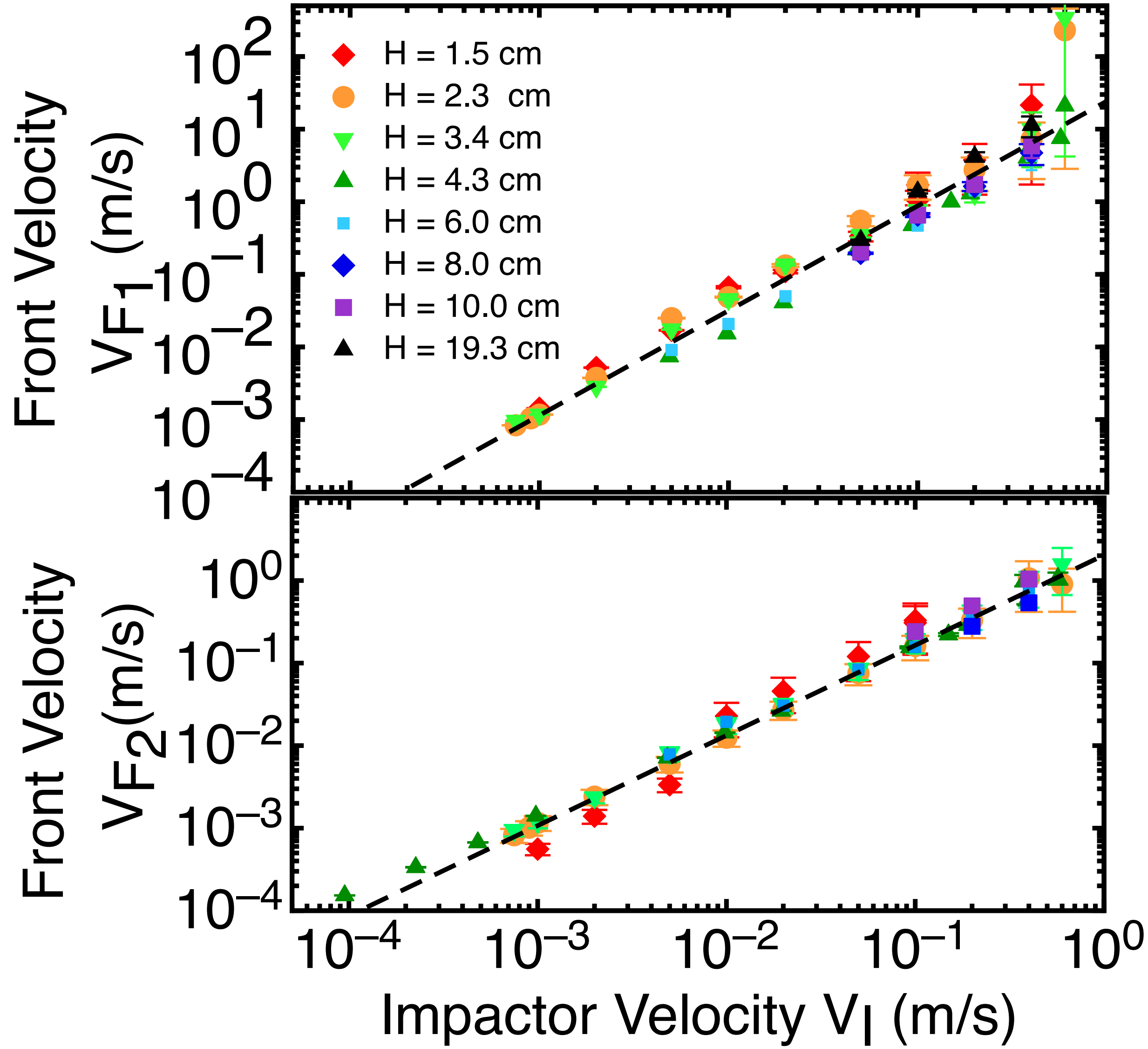
- delay z_1 between impact and increasing force response
  - bulk models predict stress $\sigma < 10^3$ Pa (buoyancy, inertia, lubrication)
  - stress enough to hold up a person's weight (4×10^4 Pa)

Is delay before force increase due to time required for front to reach boundary?

delay time $T_1 = z_1/v_I$

front velocity
$V_{F1} = H/T_1$

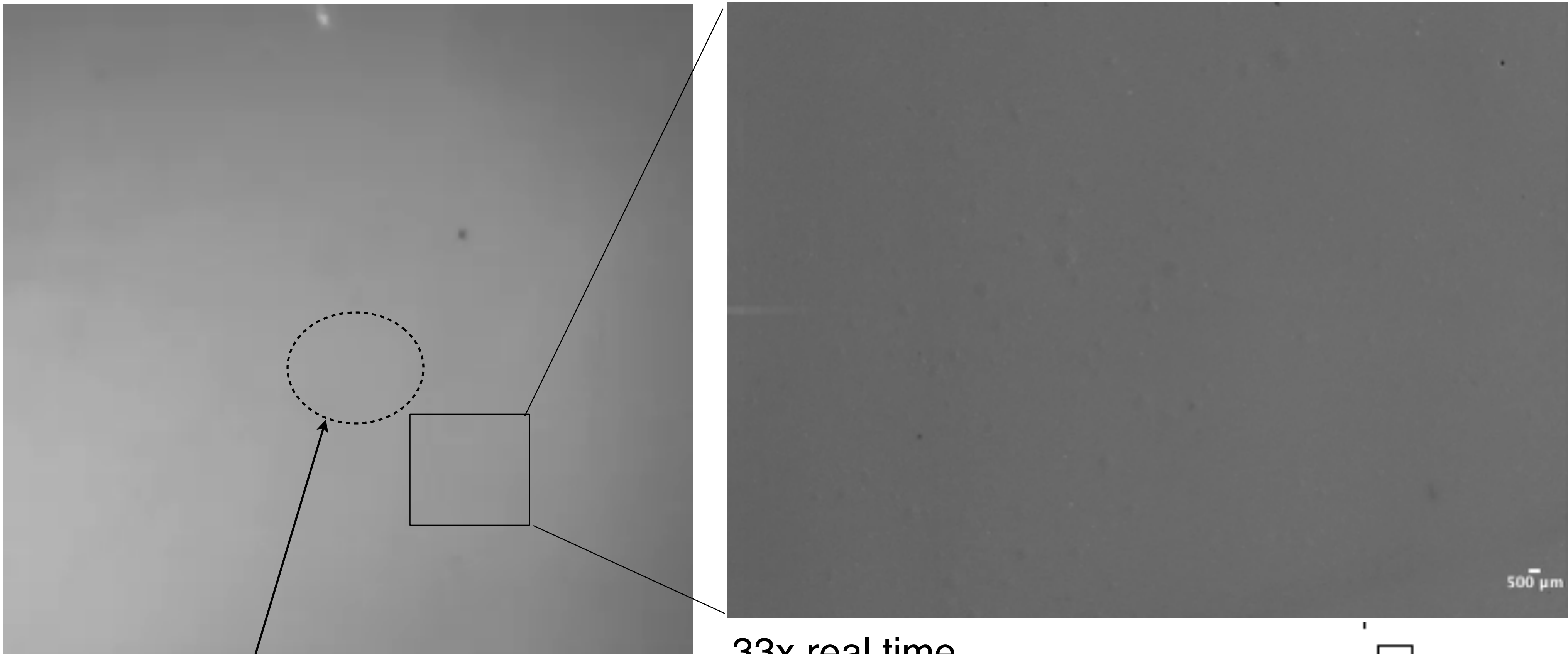




- Delay time T_1 before force increase scales with fluid depth H

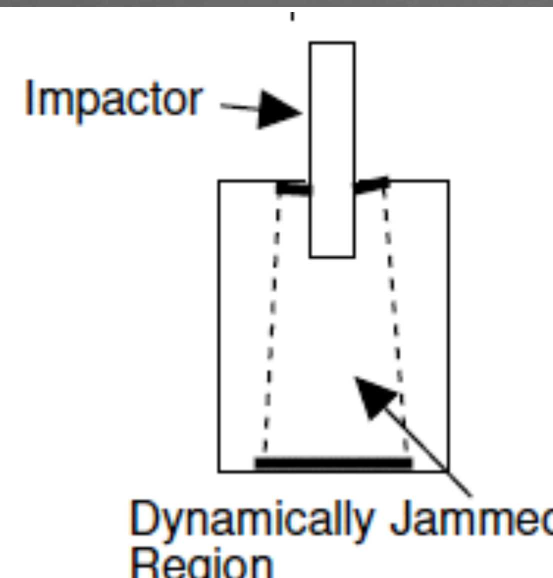
➡ stress increase due to propagating fronts reaching the boundary

Voids in pores appear at bottom surface after a delay



33x real time

impactor diameter d=12.7 mm
20x real time



- rough surface (result of dilation) also observed at top

➡ dynamically jammed region spans from top to bottom

➡ stress isn't limited by surface tension in transient if it can be supported by solid boundaries

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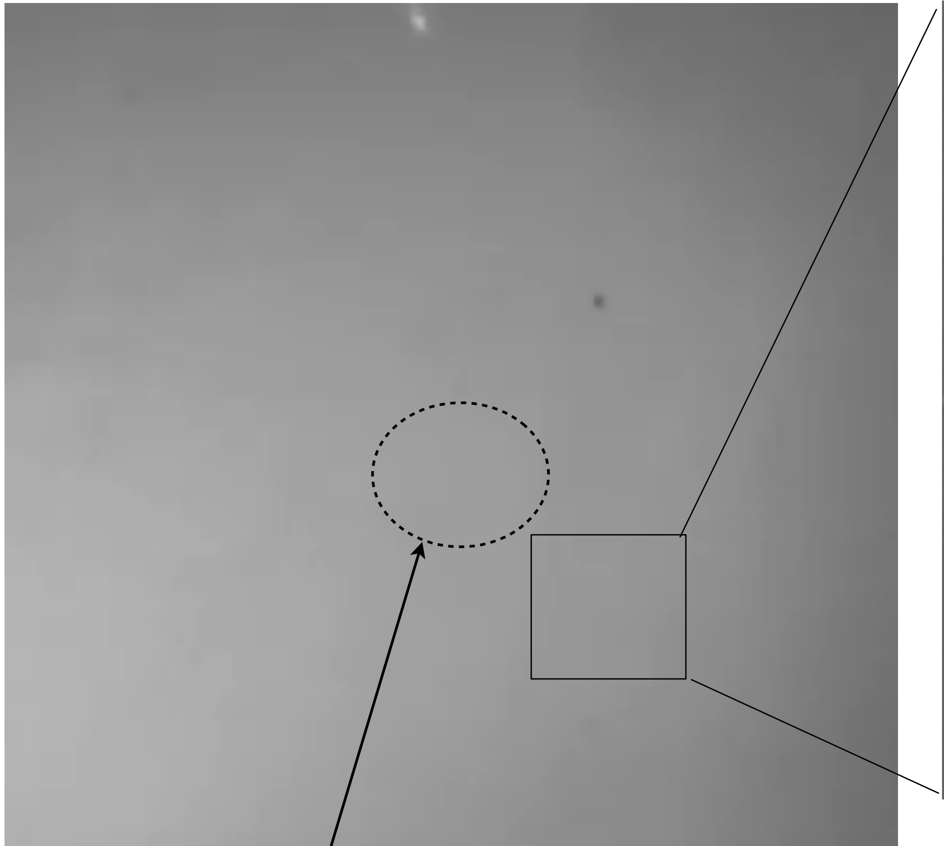

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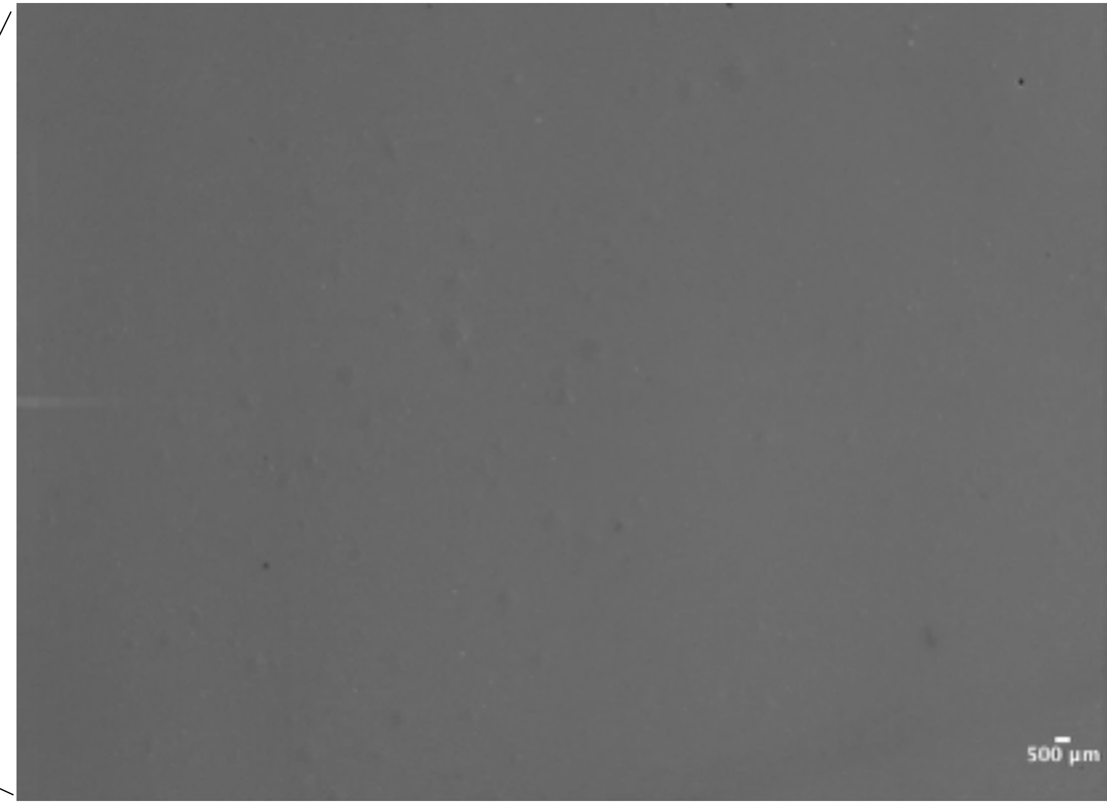

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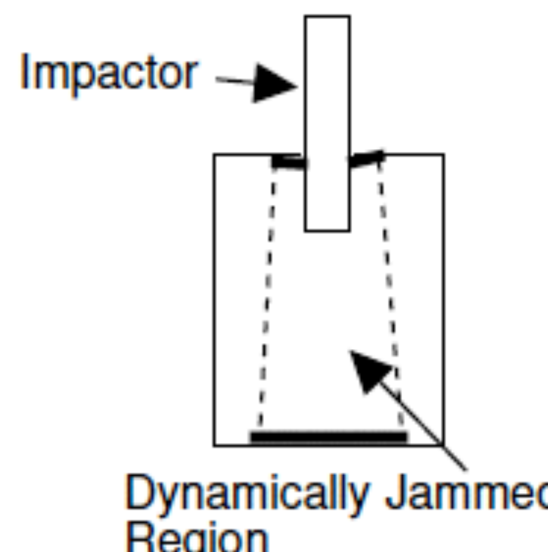

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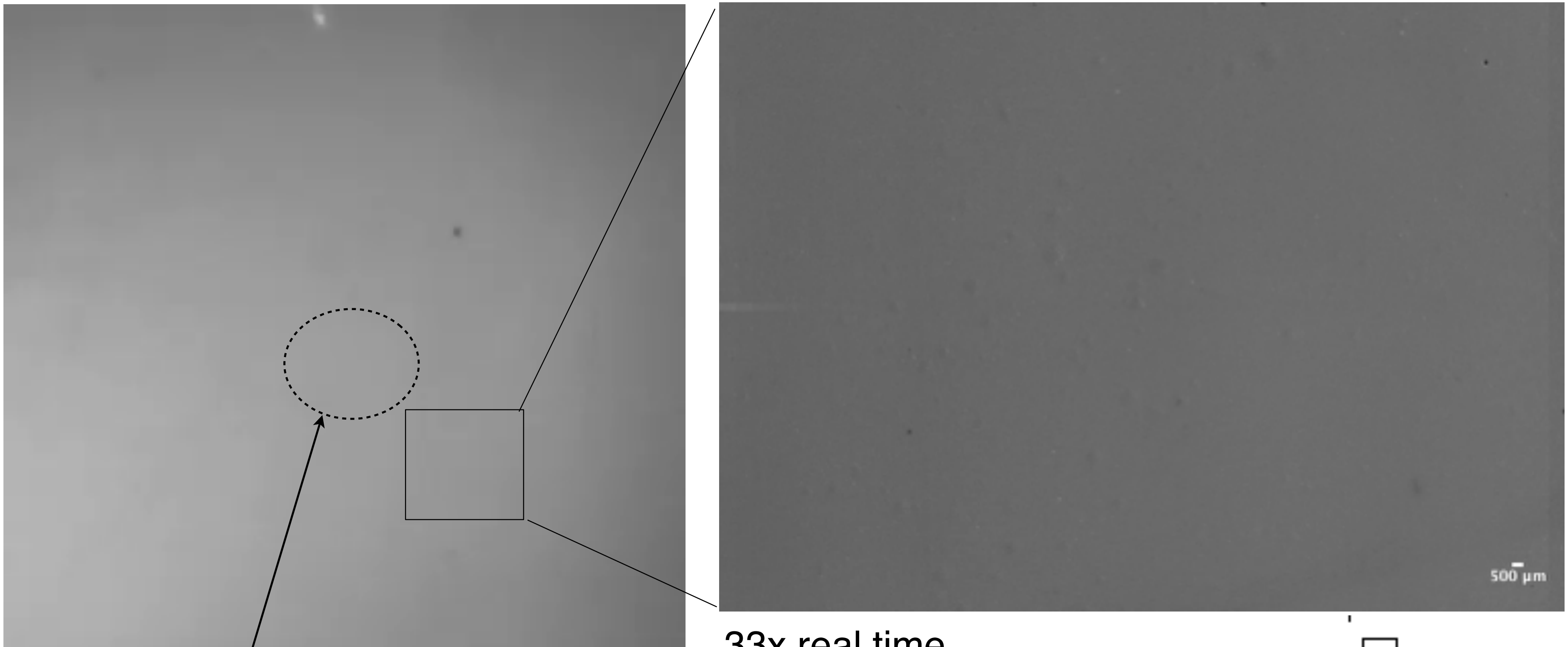

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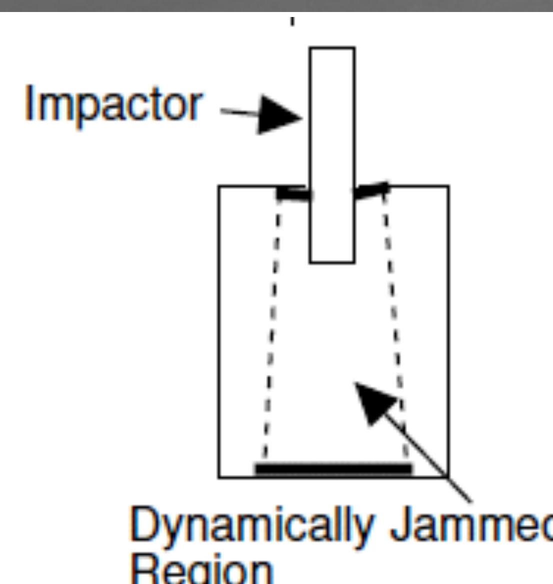

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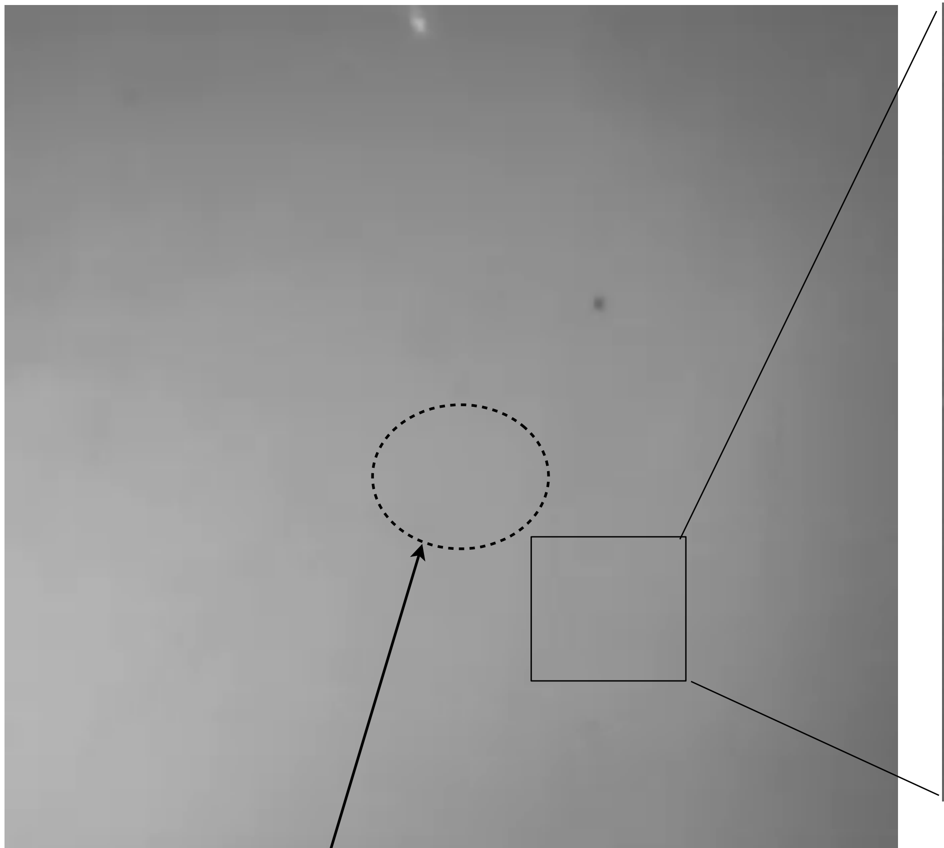

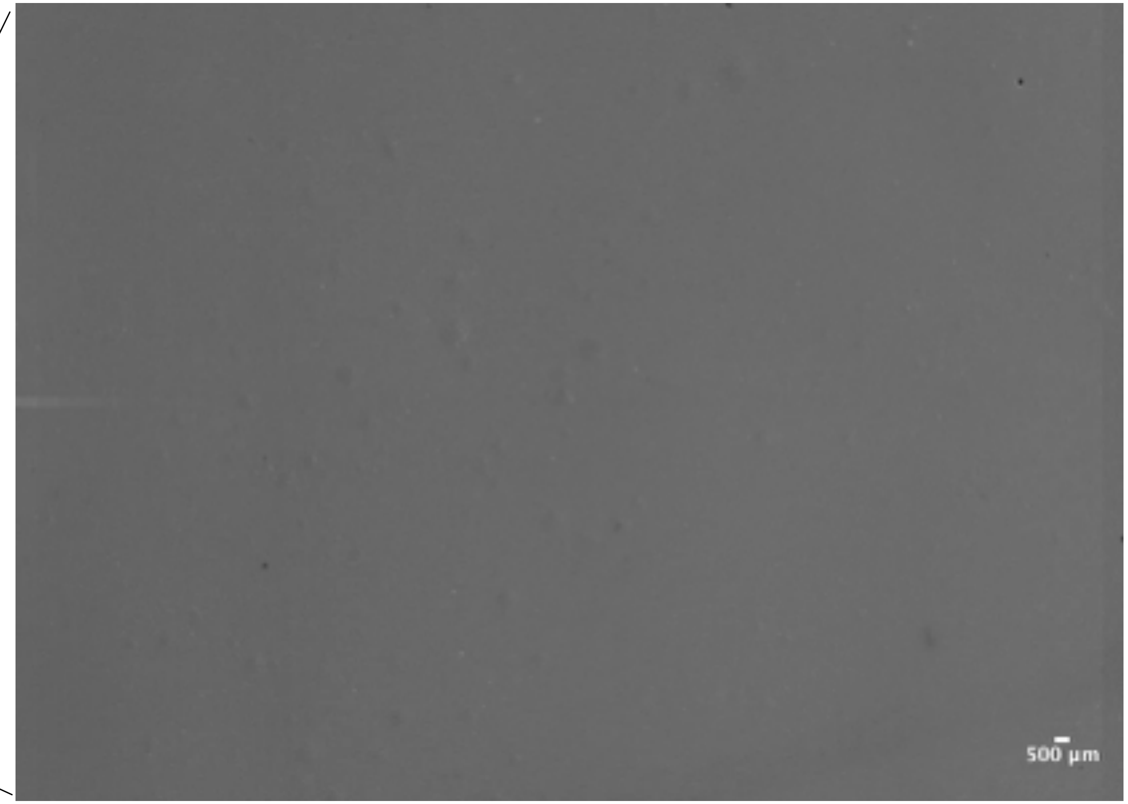

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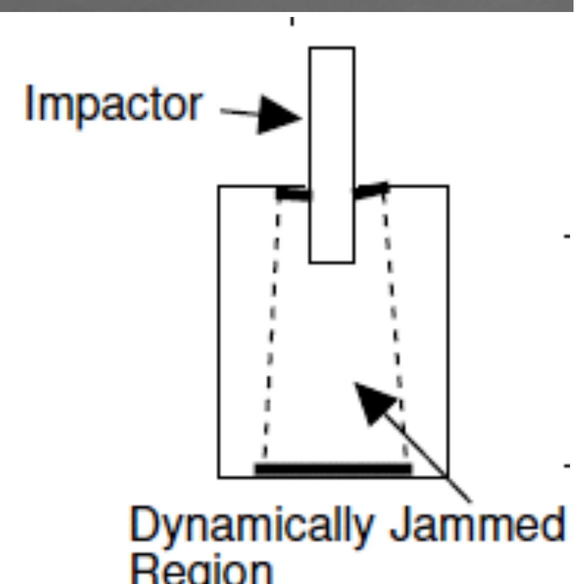

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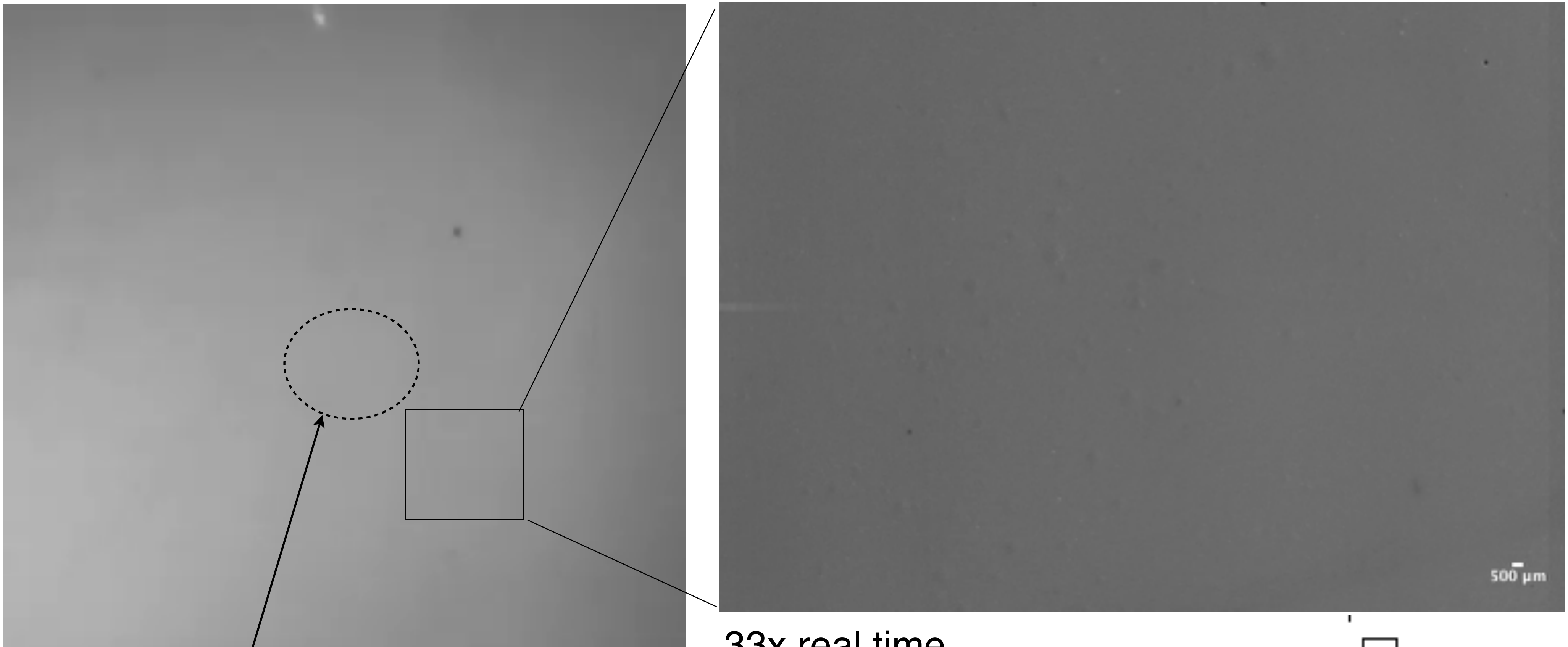

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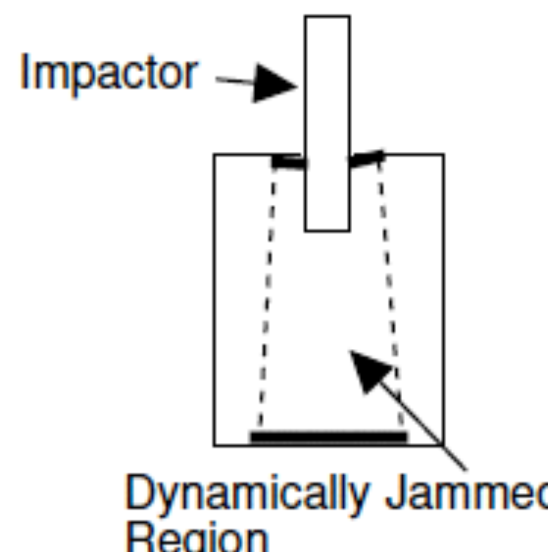

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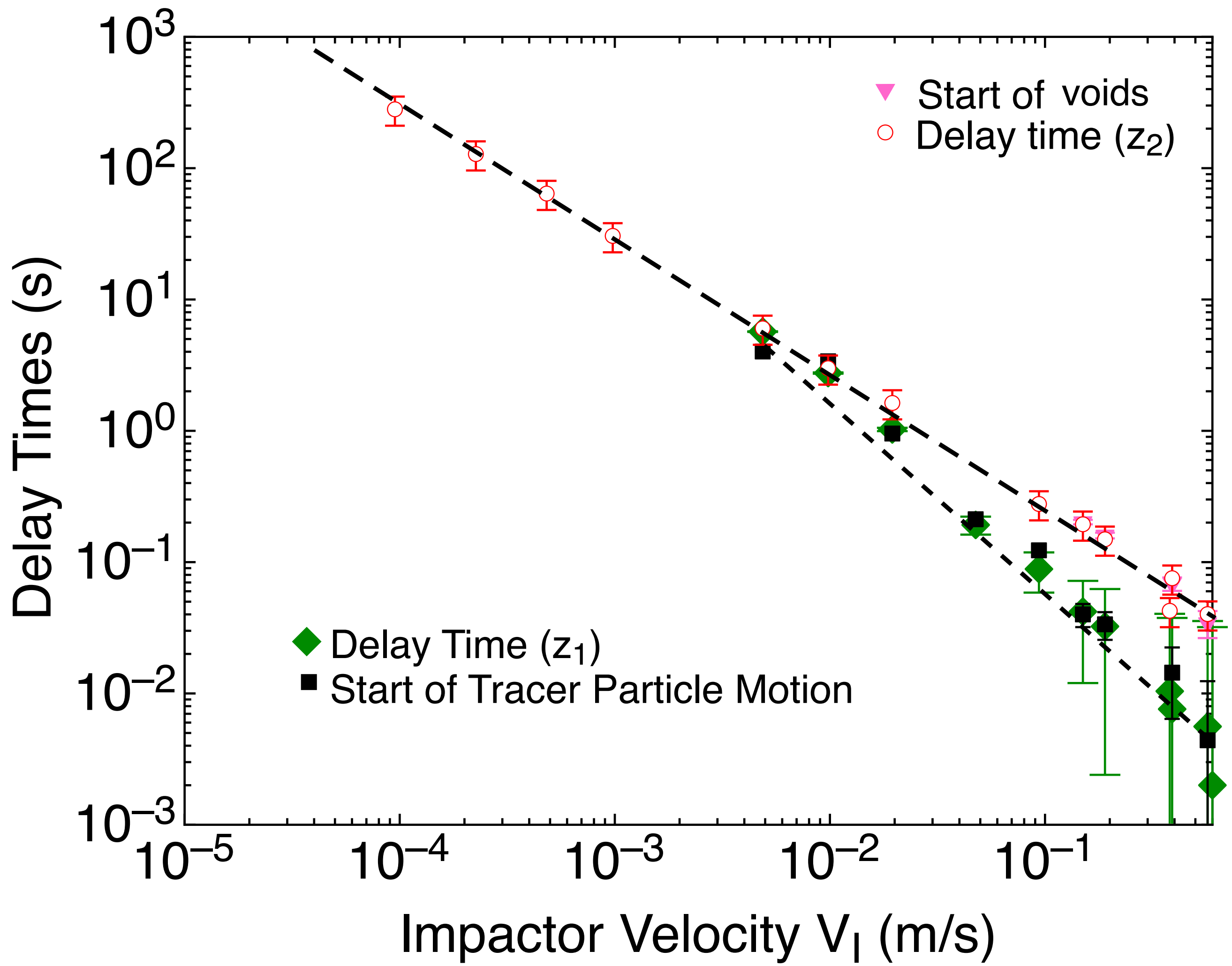
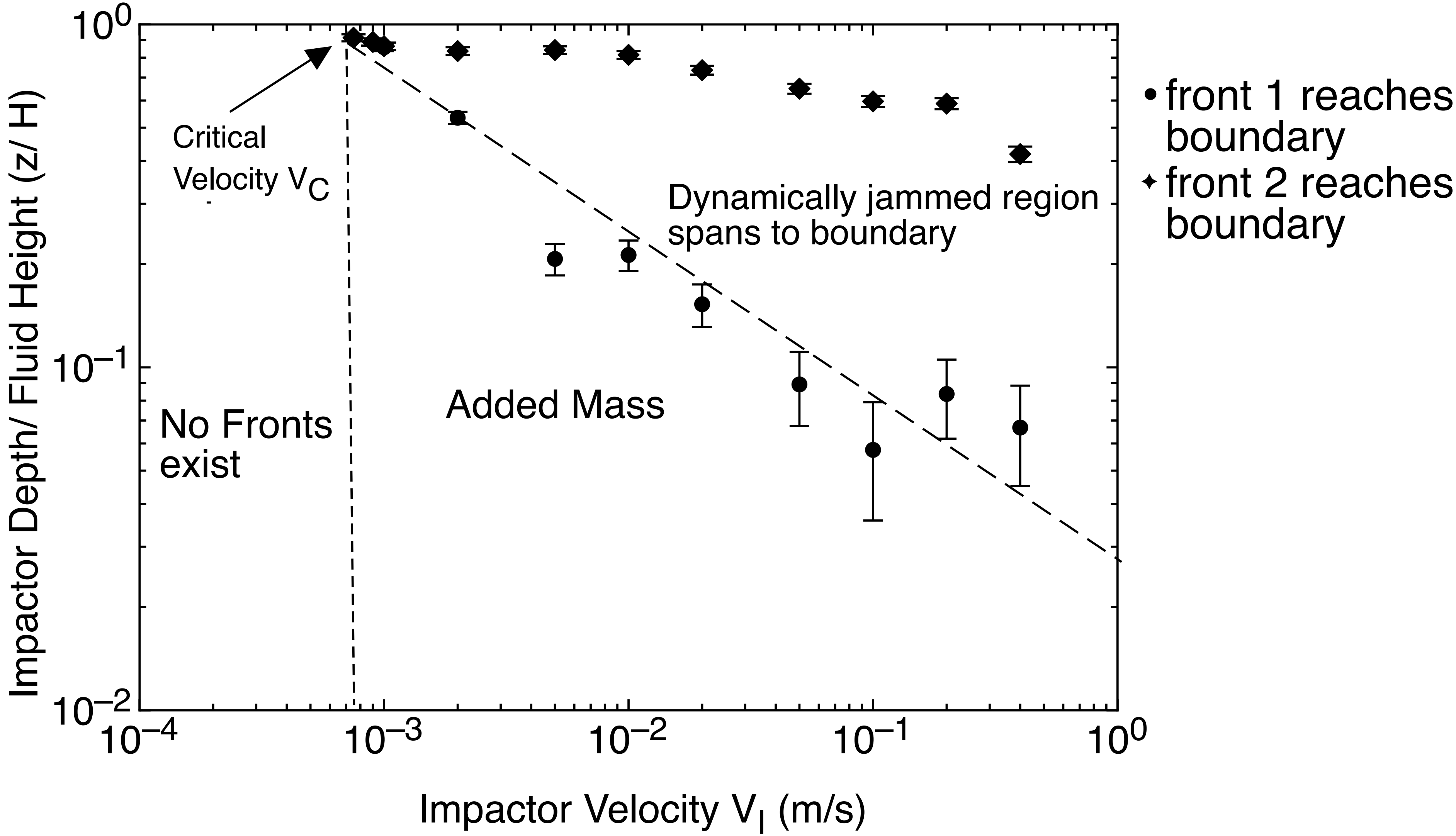
Stress increases at same time as structural changes at boundary



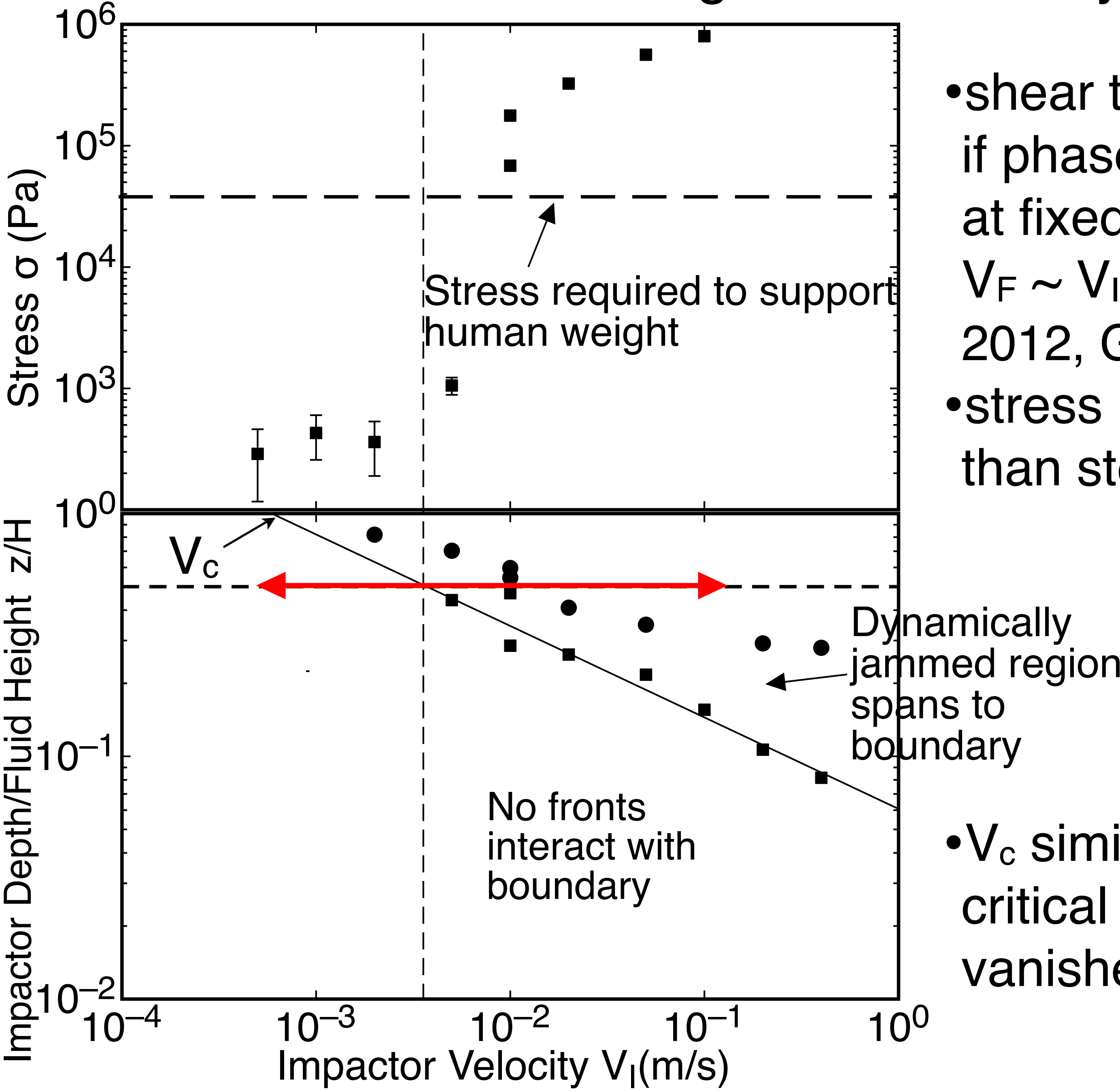
- front 1 is same as Waitukaitis & Jaeger, Nature 2012

Phase diagram



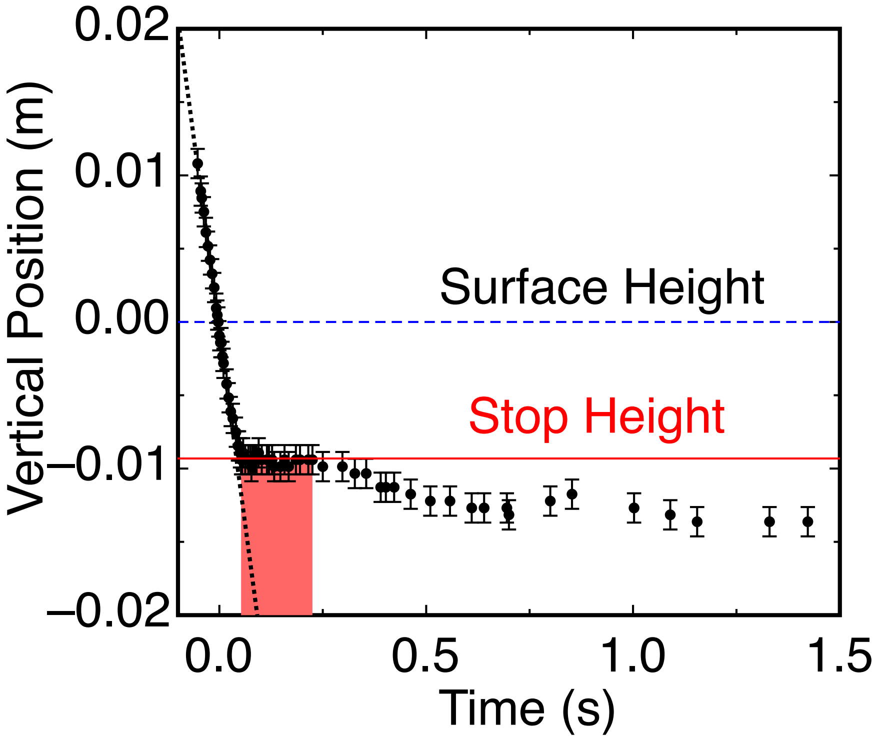
- critical velocity V_c required for front propagation

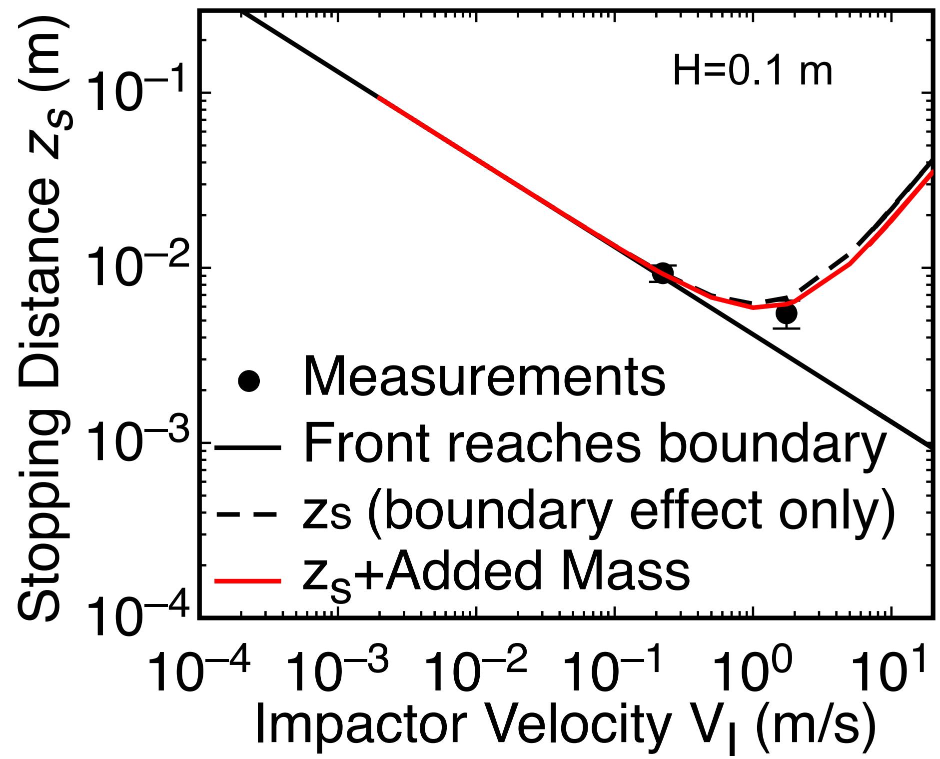
discontinuous shear thickening transition due to front reaching solid boundary



- shear thickening transition if phase boundary crossed at fixed z/H (no transition if $V_F \sim V_I$ [Waitukaitis & Jaeger 2012, Gomez et al. 2012])
- stress is ~10^2 times larger than steady state DST
- V_c similar to a 1st order critical point (discontinuity vanishes as $V_I \to V_c$)

Walking on cornstarch and water





•foot stops abruptly with delay after hitting surface due to time for front to reach boundary

•foot continues to sink after relaxation time

•stopping distance determined by balance of work done by fluid and kinetic energy

Conclusions about impact response of DST suspensions

- a critical (minimum) velocity is required to observe front propagation and the dynamically jammed region
- a discontinuous shear thickening transition results from a front colliding with a solid boundary above the critical velocity
    - the solid-like regime can support enough stress to hold up a person’s weight