Granular Flows

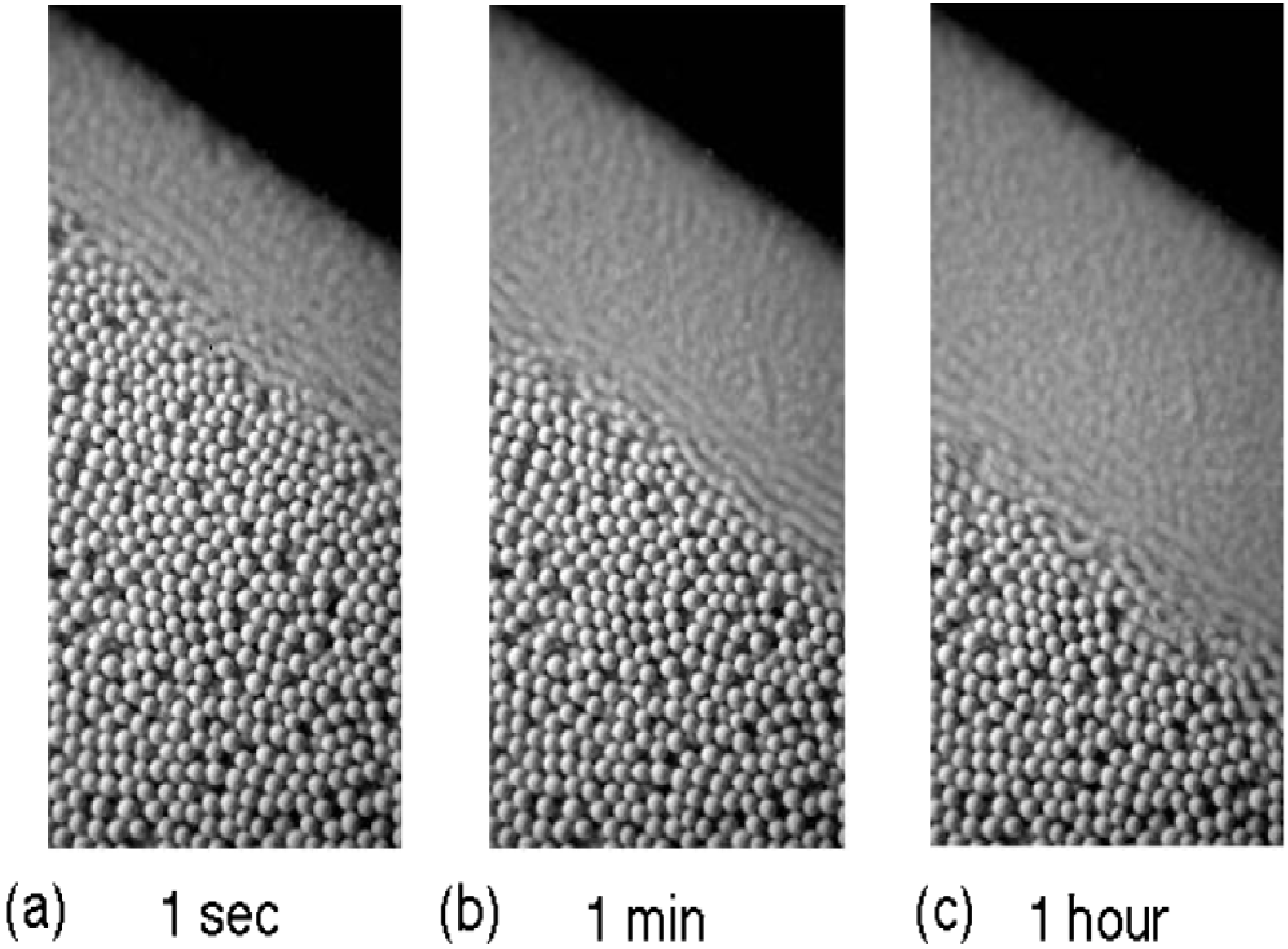
Collisional flow

Inertial flow

<u>Plastic flow</u>

Solid

Granular Flows



Komatsu *et. al*. PRL (2001)

Granular Flows

Collisional flow

Inertial flow

<u>Plastic flow</u>

Solid???

Plastic vs Inertial Flow: $I = \dot{\gamma} d / (P/\rho)^{1/2}$

Slow Granular Flows

Shear Bands

Classical Picture based on Friction

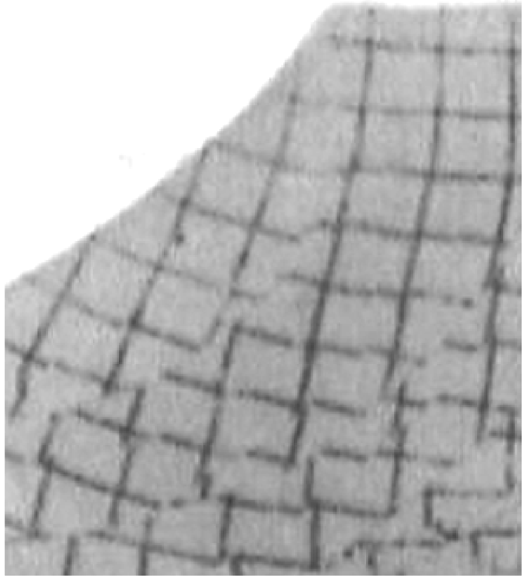
Experiments on Wide Shear Zones

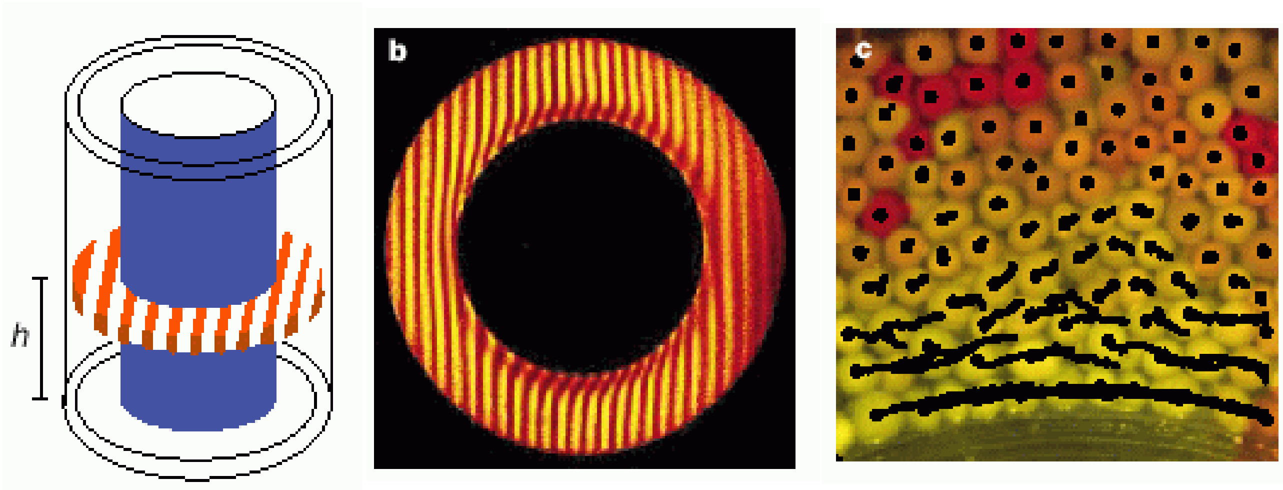
What's inside?

Viscous vs Frictional

Melting Sand by Stirring

Shear Bands





D.M. Mueth *et al.*,
Nature **406**, 385 (2000)

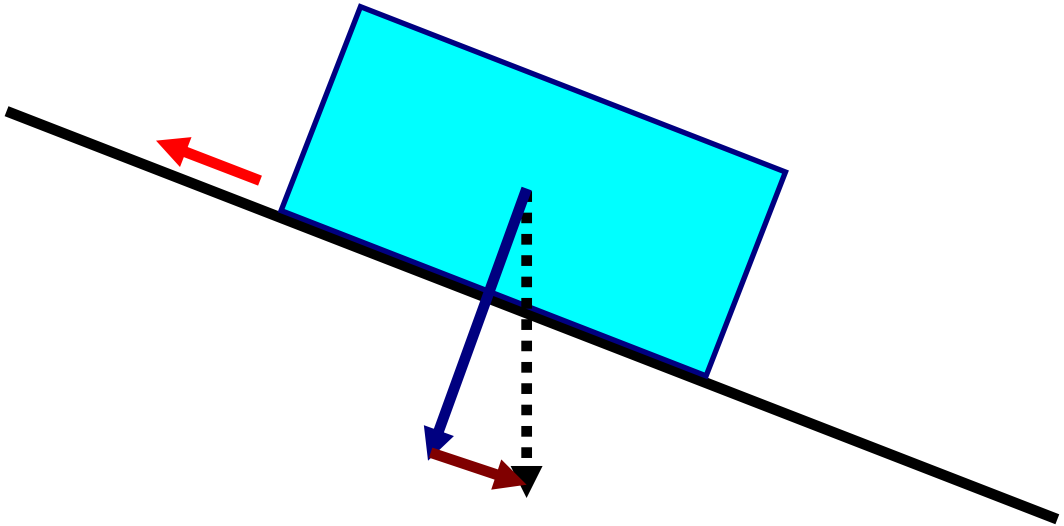
Granular Media: Stationary vs Flowing

Yield Criterion

Granular Media: Analogy with Friction

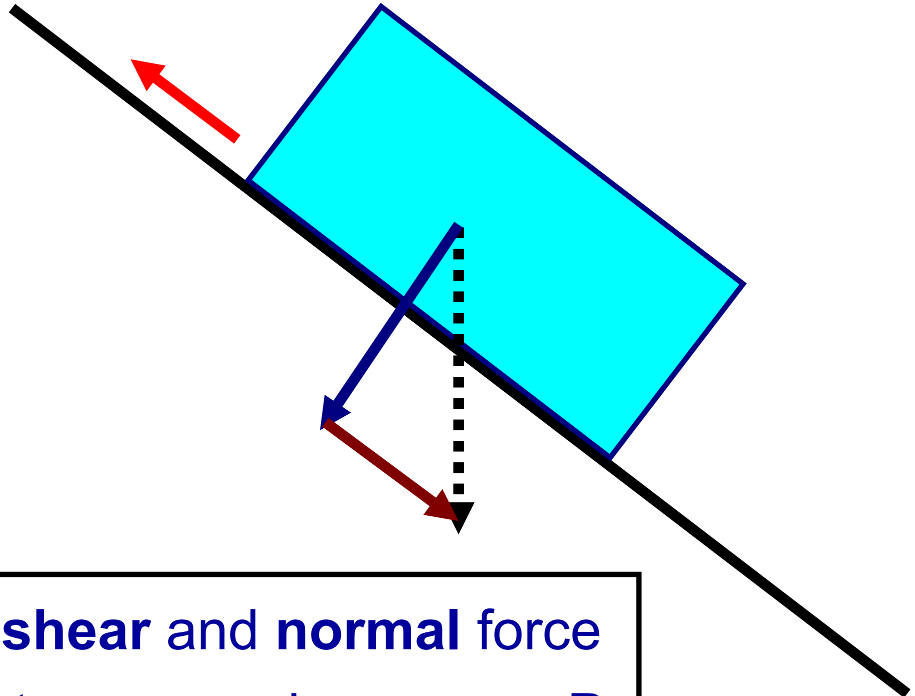
Yield Criterion

$$\frac{\text{Shear Force}}{\text{Normal Force}} \le \mu$$



Granular Media: Analogy with Friction

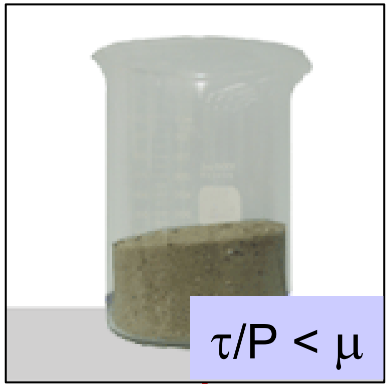
Yield Criterion

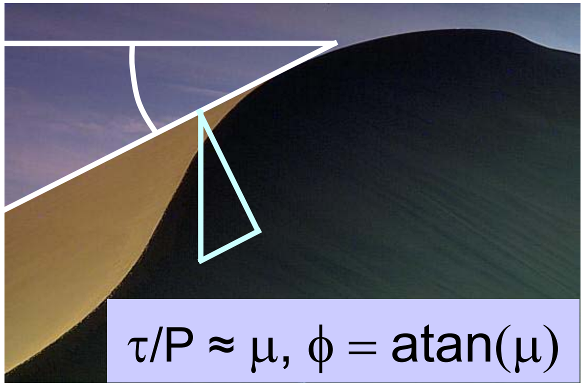


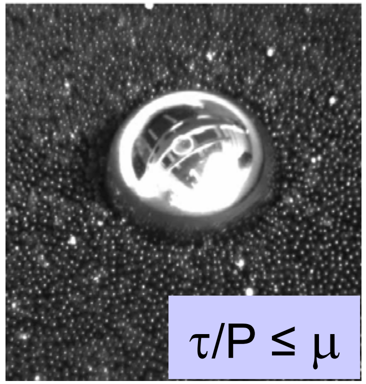
$$\frac{\textbf{Shear Force}}{\textbf{Normal Force}} > \mu$$

Translate **shear** and **normal** force to **shear stress** τ and **pressure P**

Granular Media: Yield Criterion

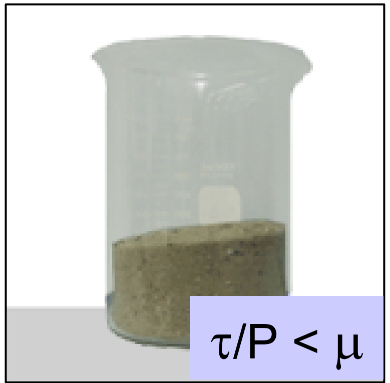


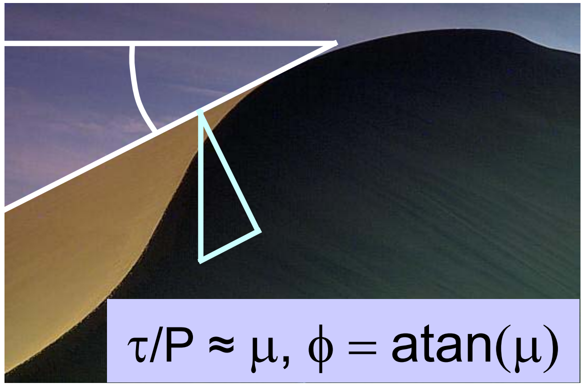


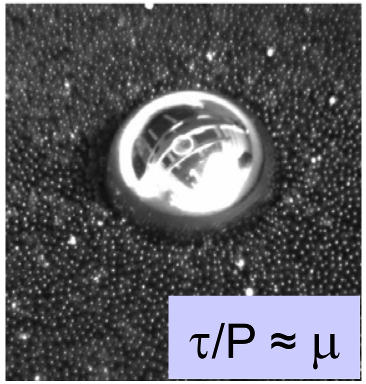


Yield Criterion

Granular Media: Yield Criterion







Yield Criterion

Stresses $\longrightarrow$ Normal, shear components

Solid: $\tau/P < \mu_{solid}$

Flow: $\tau/P = \mu_{sliding} < \mu_{solid}$

Narrow shearbands follow naturally

Granular Flows – Classical Picture

Narrow shear bands

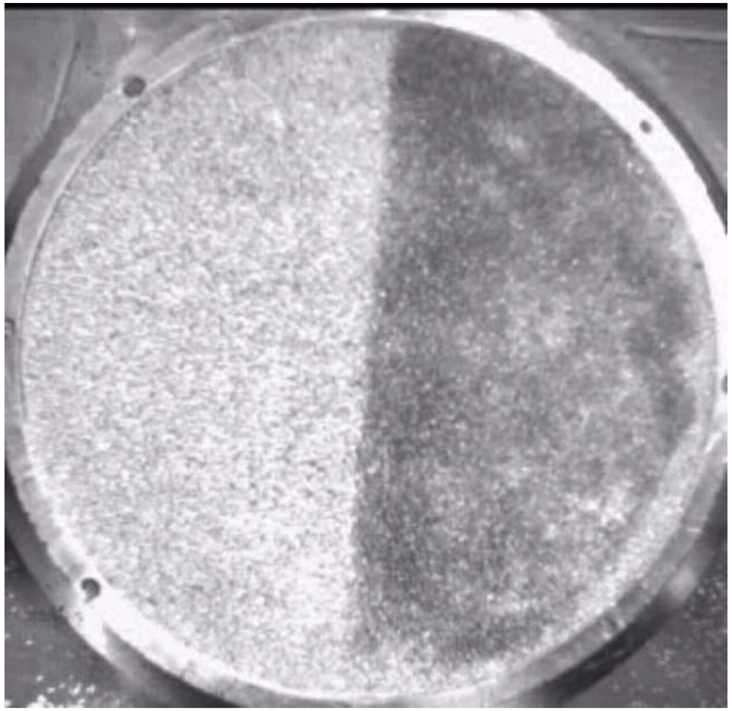
Grain details matter

Solid-like regions

Constant sliding friction.

Well ...

Smooth Granular Flows



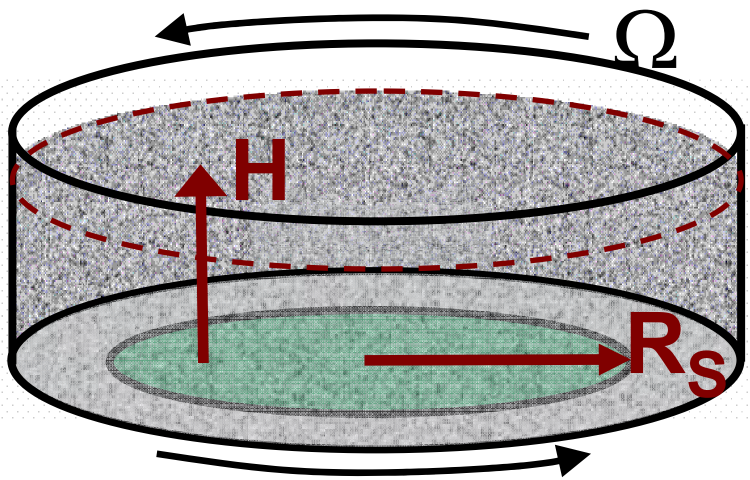
Surface Velocity Profiles

Rate independent

Short transients

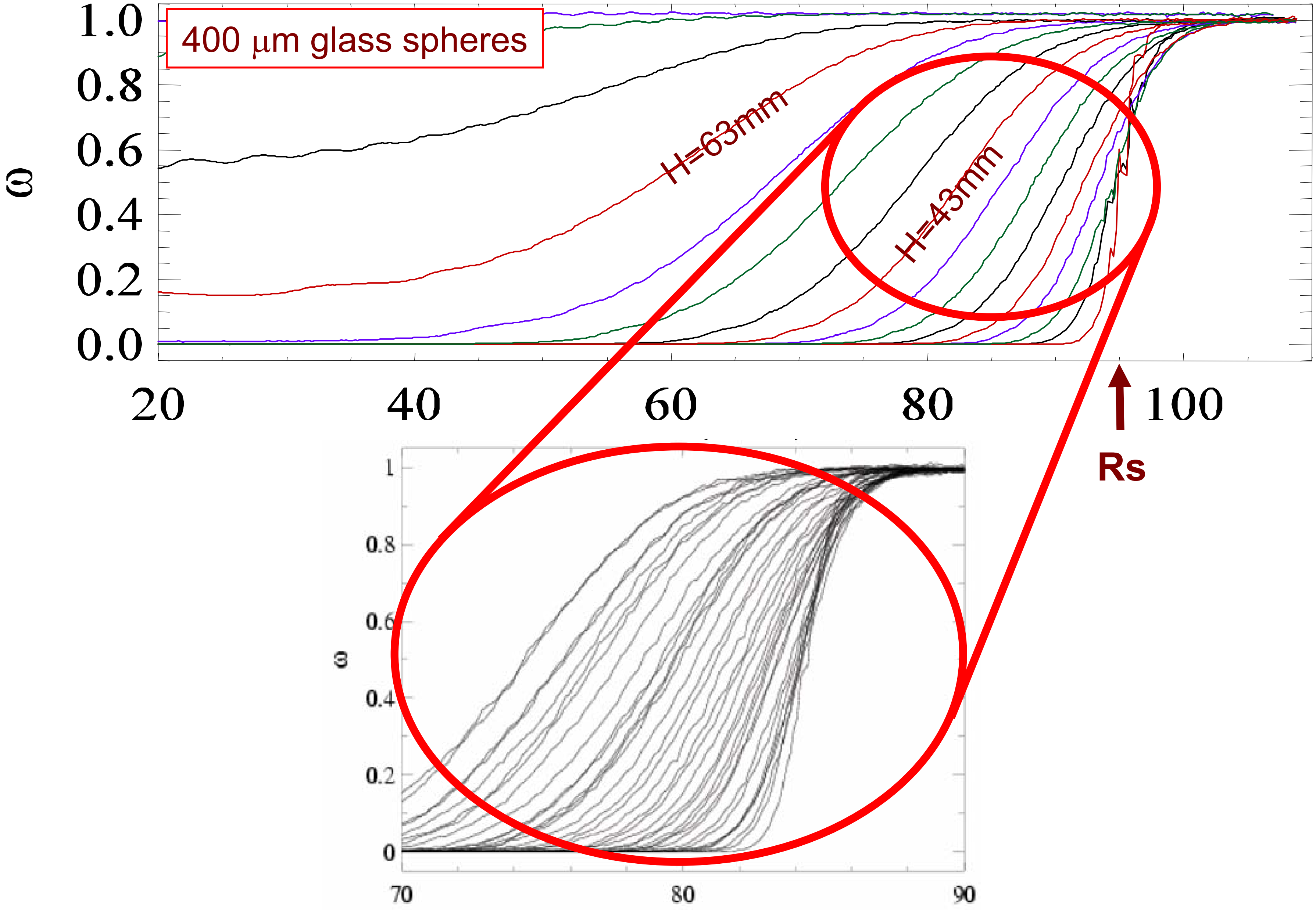
Azimuthal

$$\omega(r) := \omega_{dim}(r)/\Omega$$

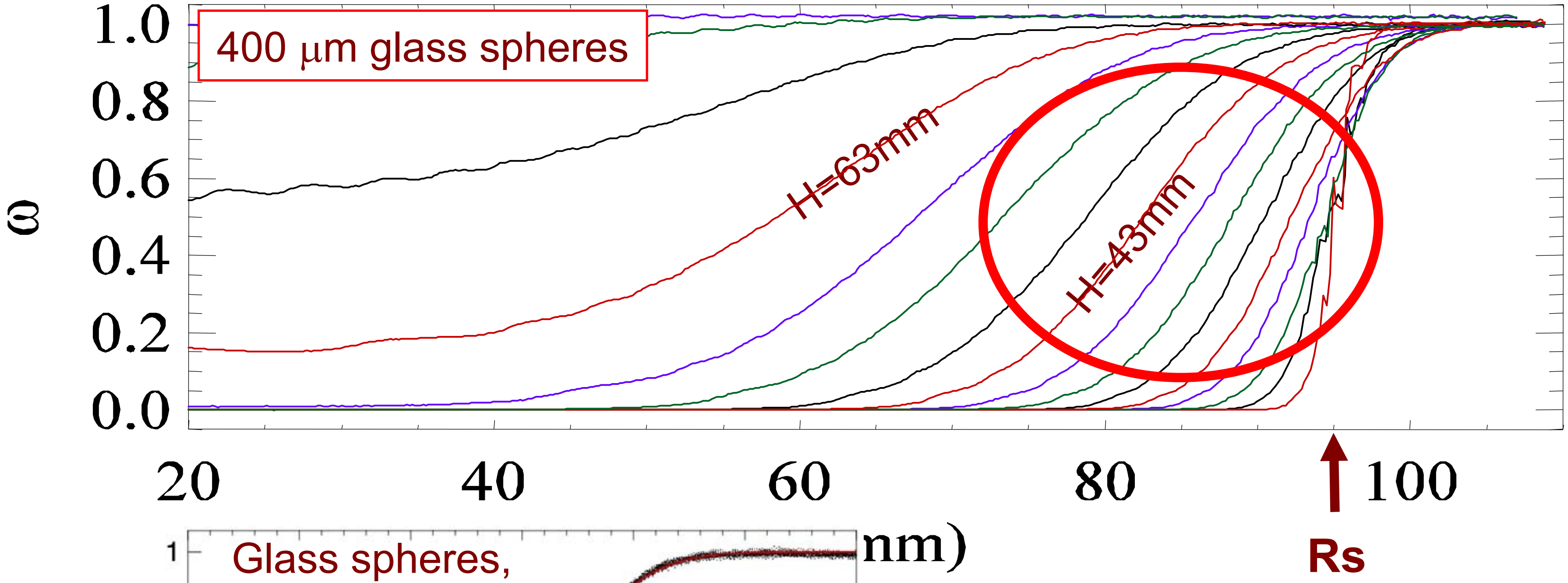


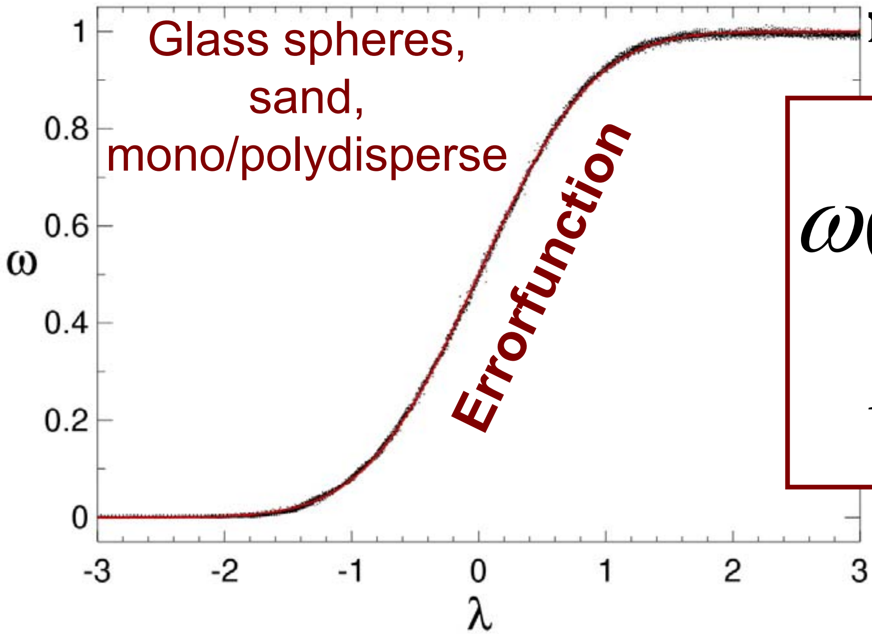
D. Fenistein, JW. van de Meent and MvH, *PRL.* **92**, 094301 (2004); **96,** 118001 (2006).
D. Fenistein and MvH, *Nature* **425**, 256 (2003).

Shallow Layers



Shallow Layers



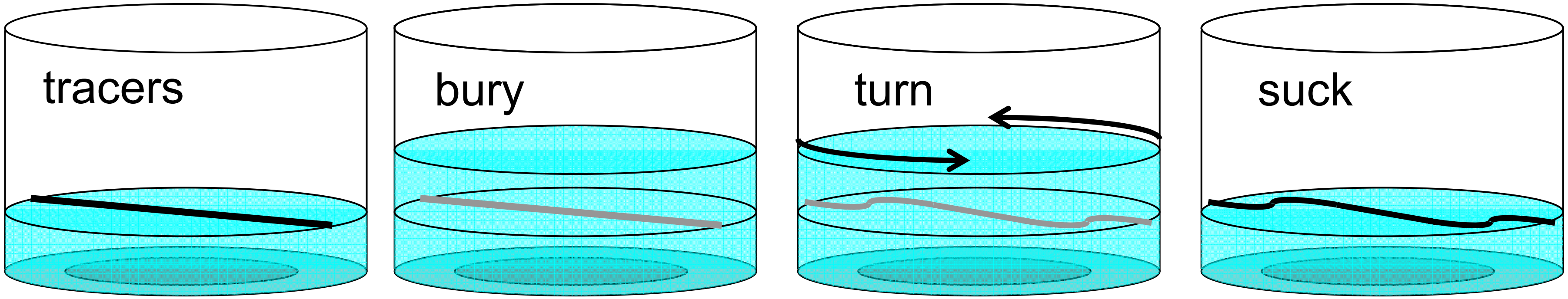


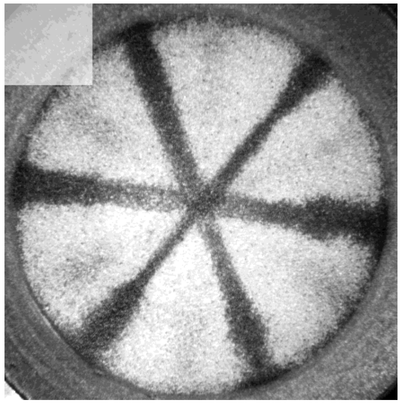
$$\omega(r) = \frac{1}{2} + \frac{1}{2} erf\left(\frac{r - R_c}{W}\right)$$

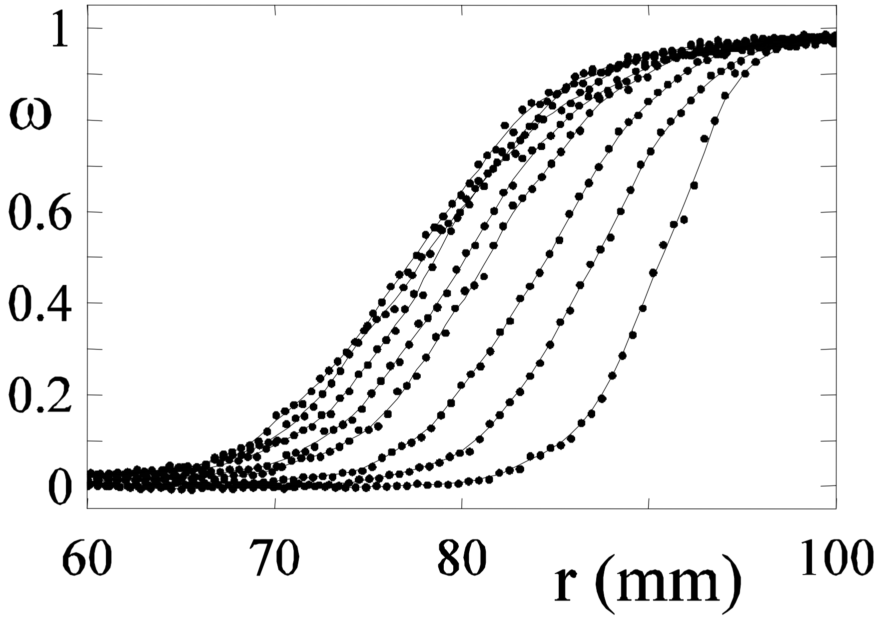
$$R_c, W : functions(R_s, H, d, \ldots)$$

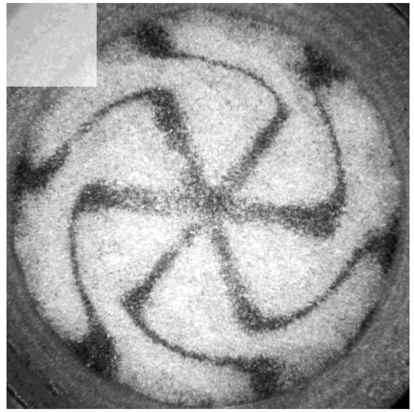
3D Profile: What happens inside?

3D Profile: What happens inside?

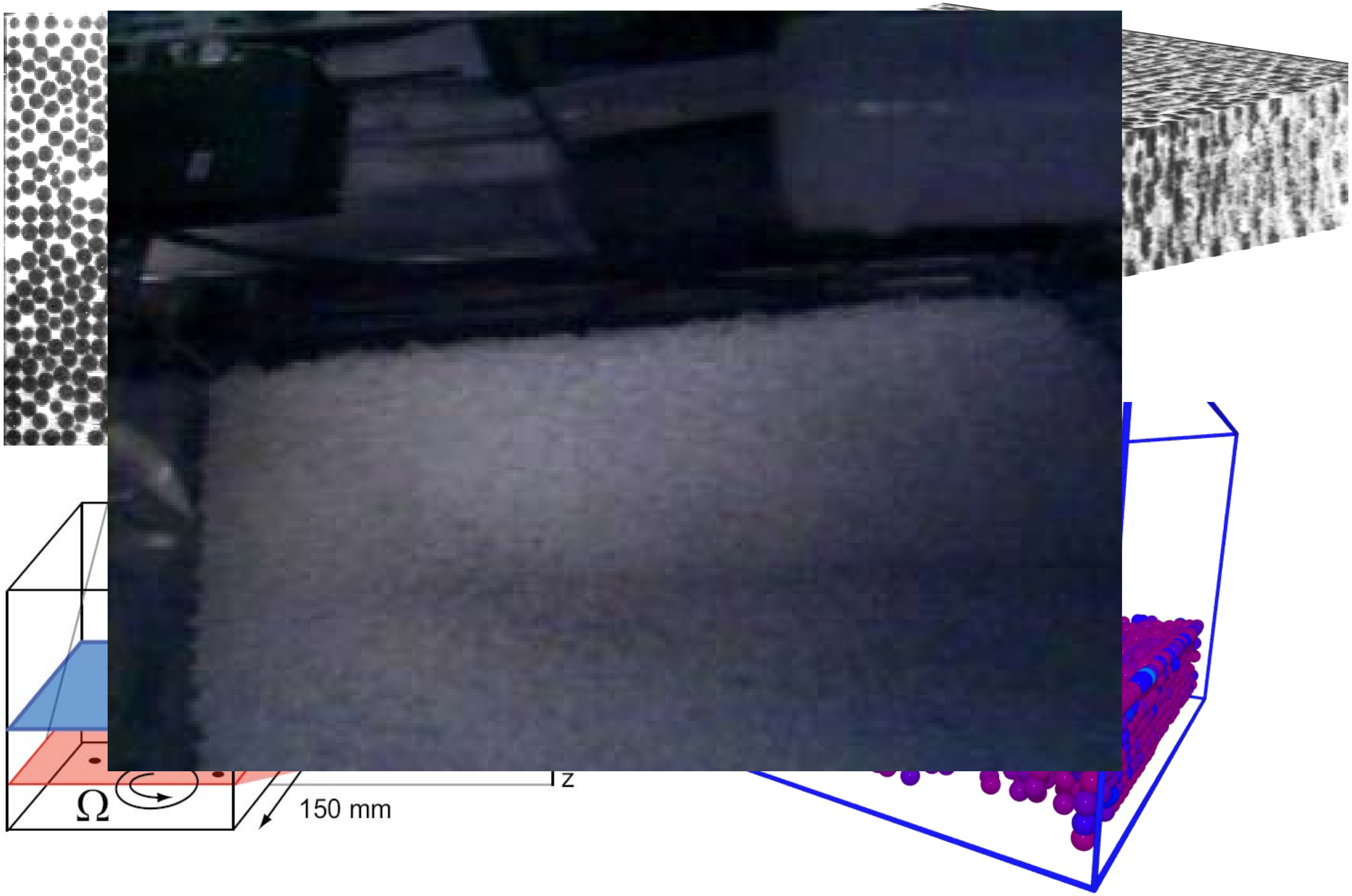




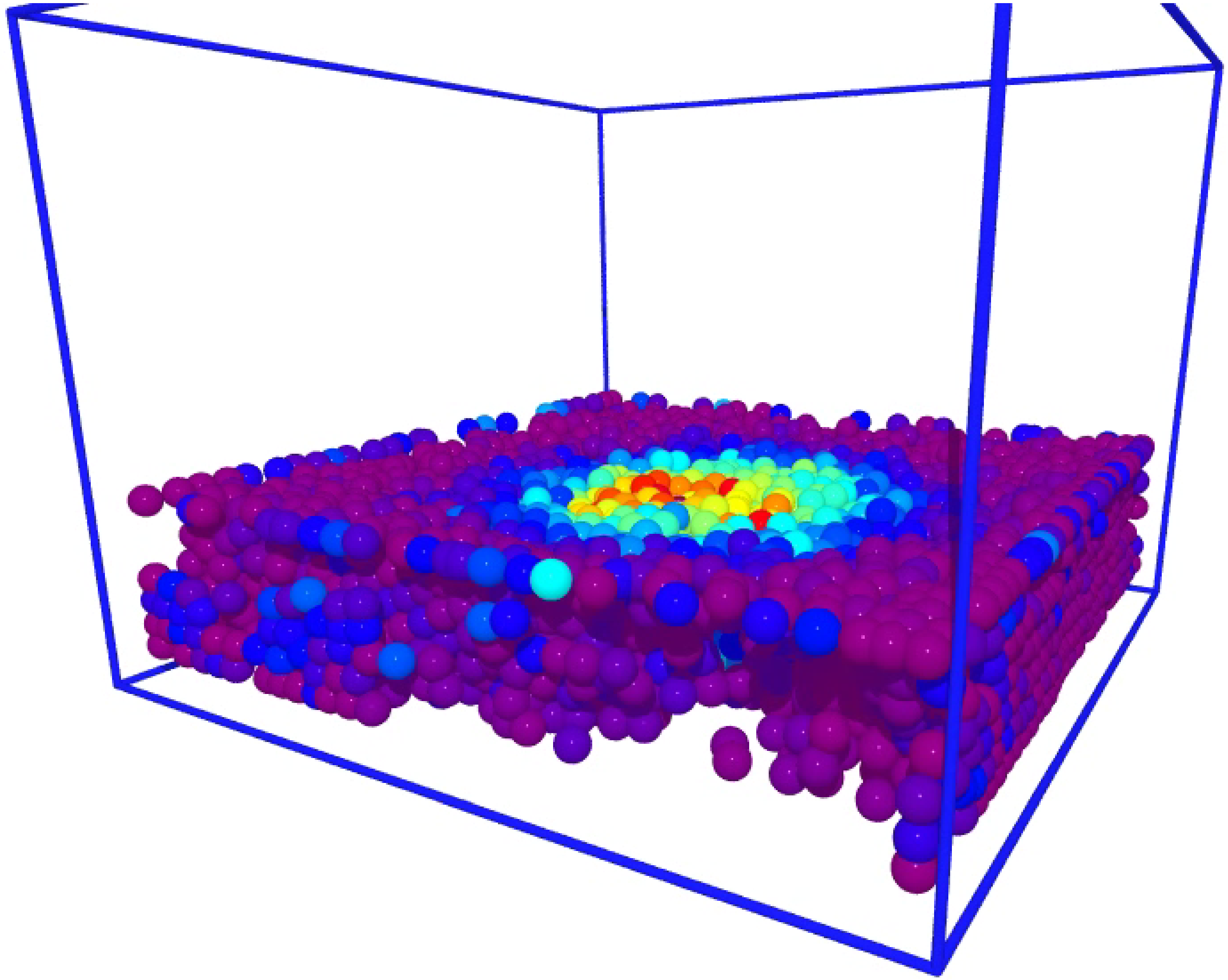




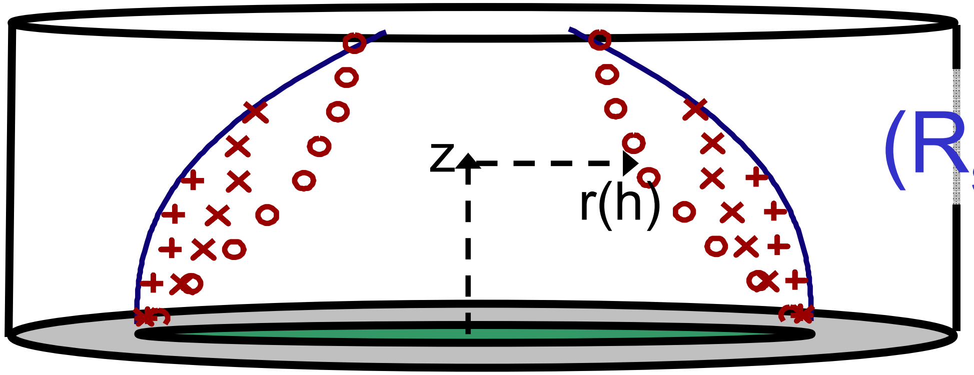
Direct 3D Imaging!



Direct 3D Imaging!



Location in Bulk



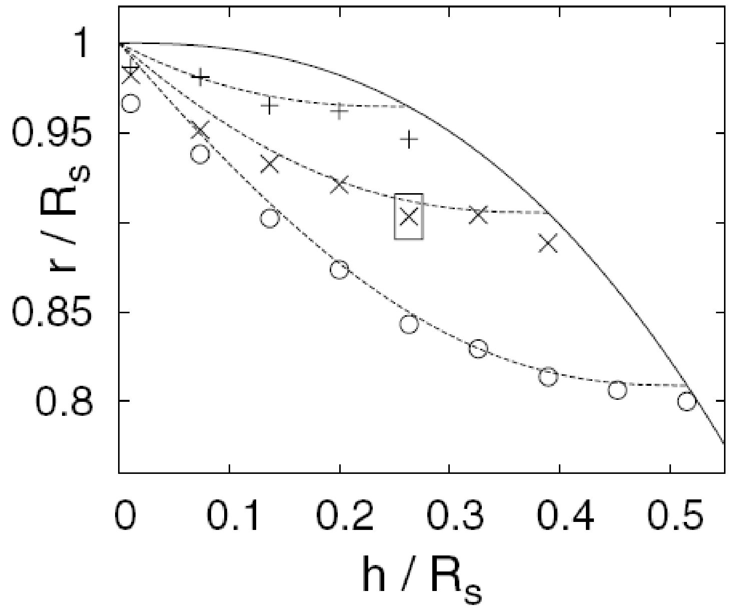
$$(R_s - R_c)/R_s = (H/R_s)^{5/2}$$

R_c in bulk: Scaling argument virtual bottom OK

$$R_c(R_s, H) = R_c(r, H - h).$$

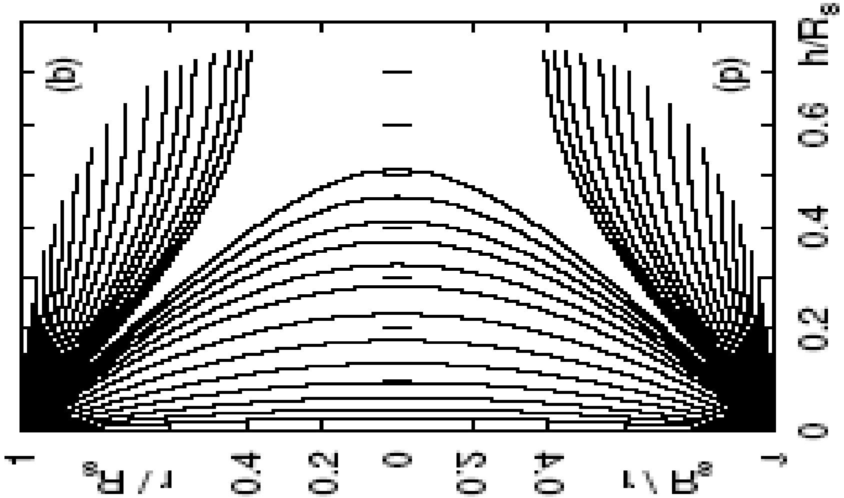
$$h = H - r\left[1 - \frac{R_s}{r}[1 - (H/R_s)^\alpha]\right]^{1/\alpha}$$

α=5/2



T. Unger, J. Török, J. Kertèsz and D. E. Wolf, PRL **92**, 214301(2004)

Model: Friction in Continua



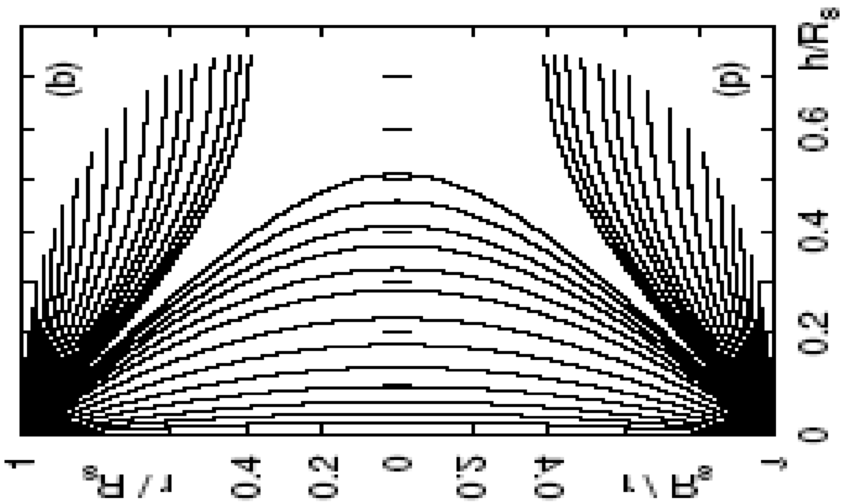
Constant Friction

Torque minimalization

$$\int dz\, r^2(z)\sqrt{r'^2+1}\,(H-z)$$

Theory: first order transition

Model: Friction in Continua



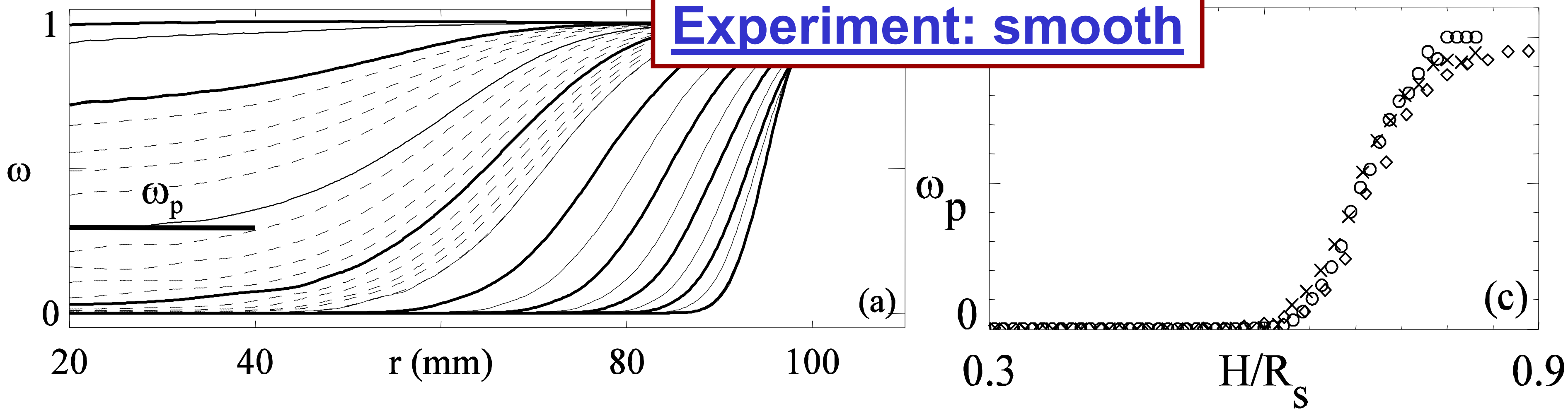
Constant Friction

Torque minimalization

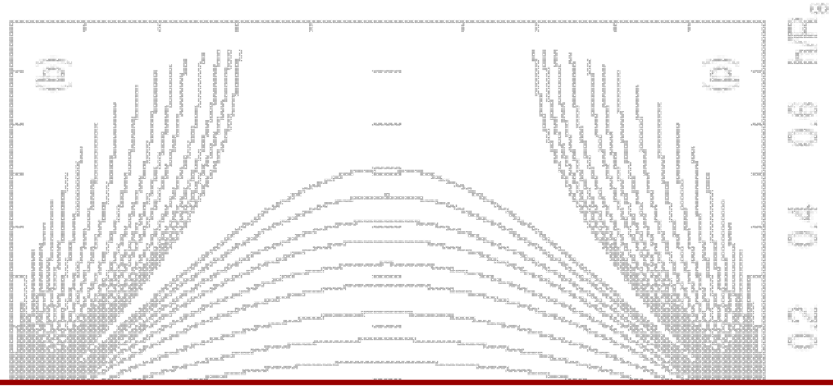
$$\int dz\, r^2(z)\sqrt{r'^2+1}\,(H-z)$$

Theory: first order transition

Experiment: smooth



Model: Friction in Continua



Constant Friction

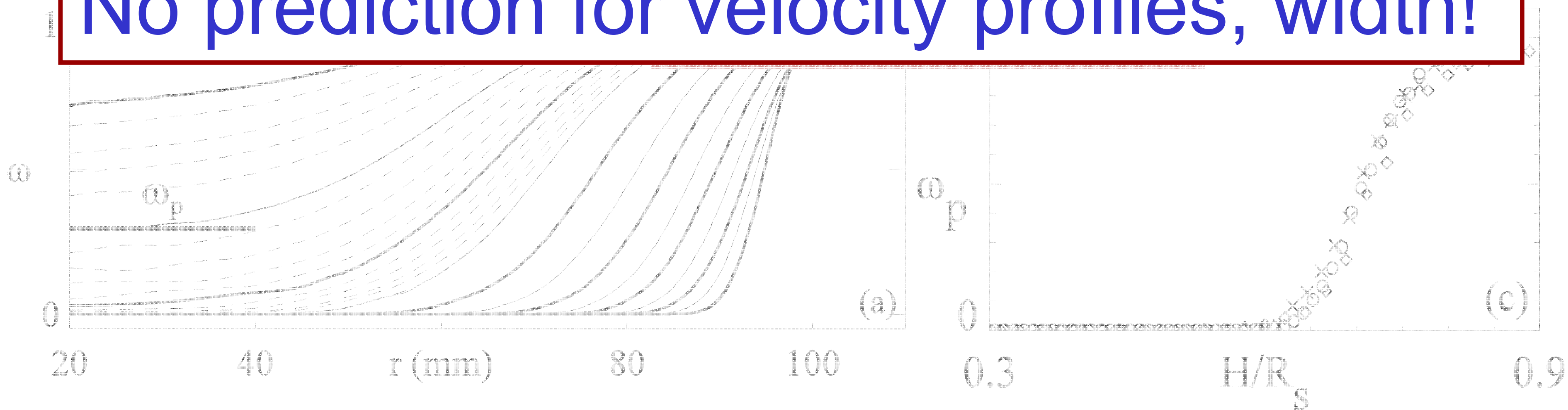
Torque minimalization

$$\int dz\, r^2(z)\sqrt{r'^2+1}\,(H-z)$$

Onset of precession: roughly ok, but is smooth in experiment

3D shearband phenomenology: position ok.

No prediction for velocity profiles, width!



Break

Wide Shear Zones

Limits of Frictional Picture

3D Imaging

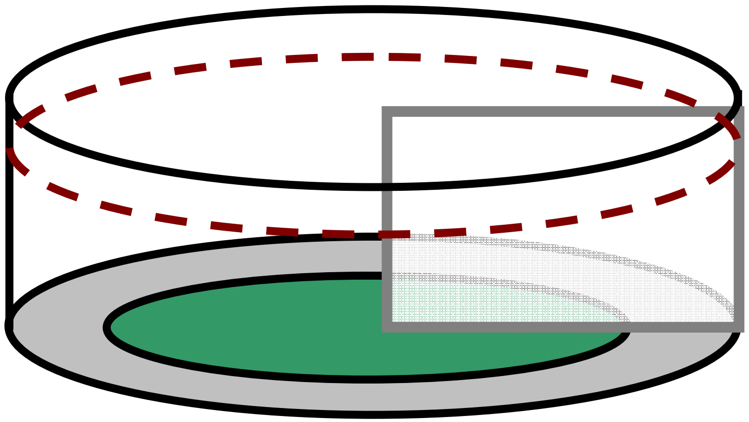
Viscous vs Frictional

Why Wide?

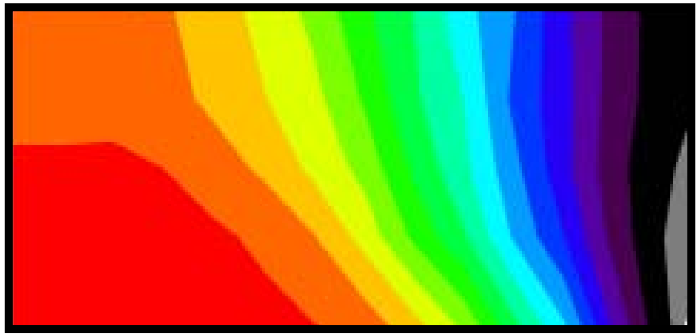
From Frictional To Stokes

What is the influence of fluid on suspensions flows?

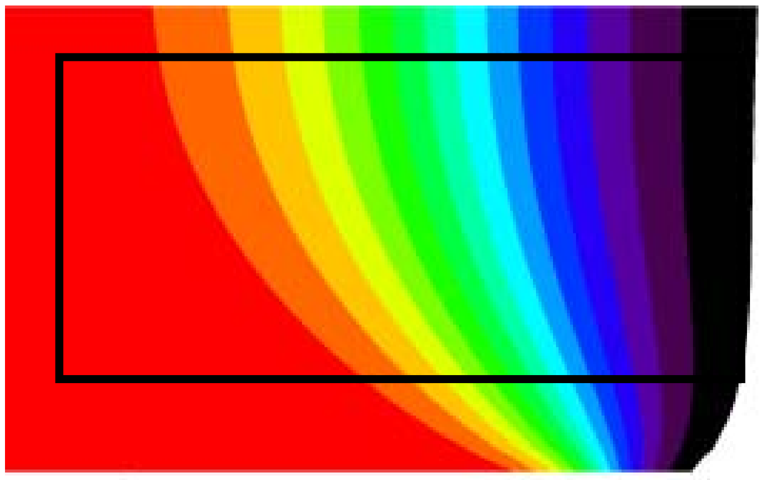
Compare Dry and Wet (Slow)



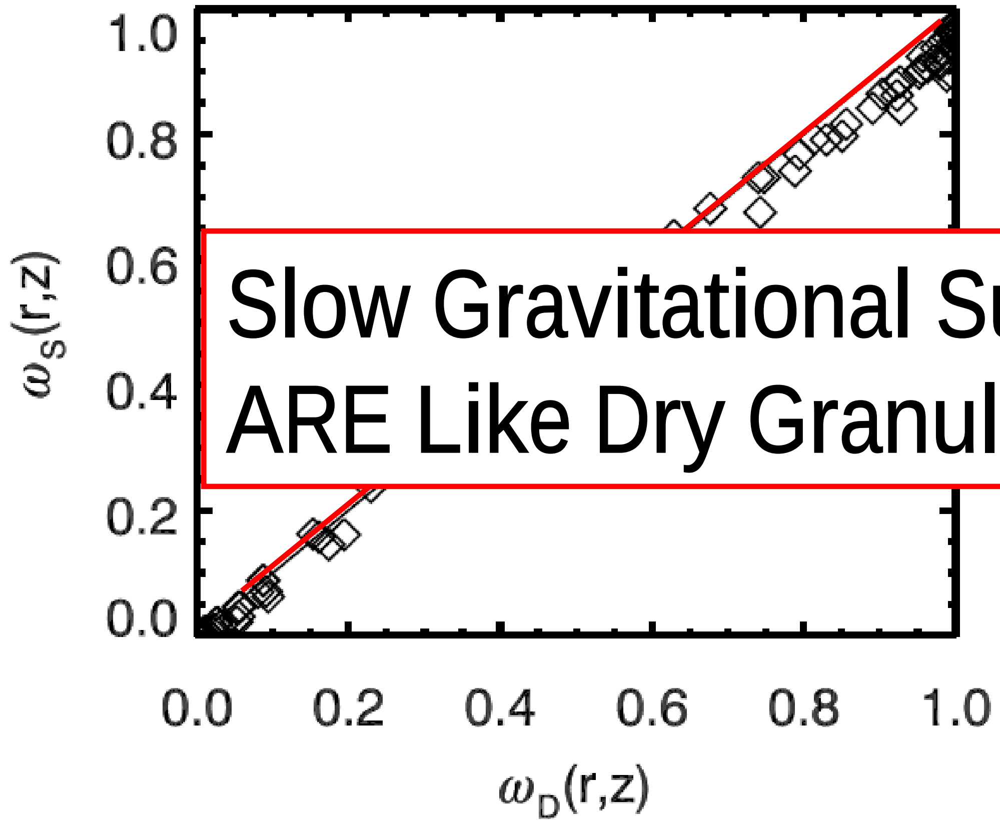
suspension



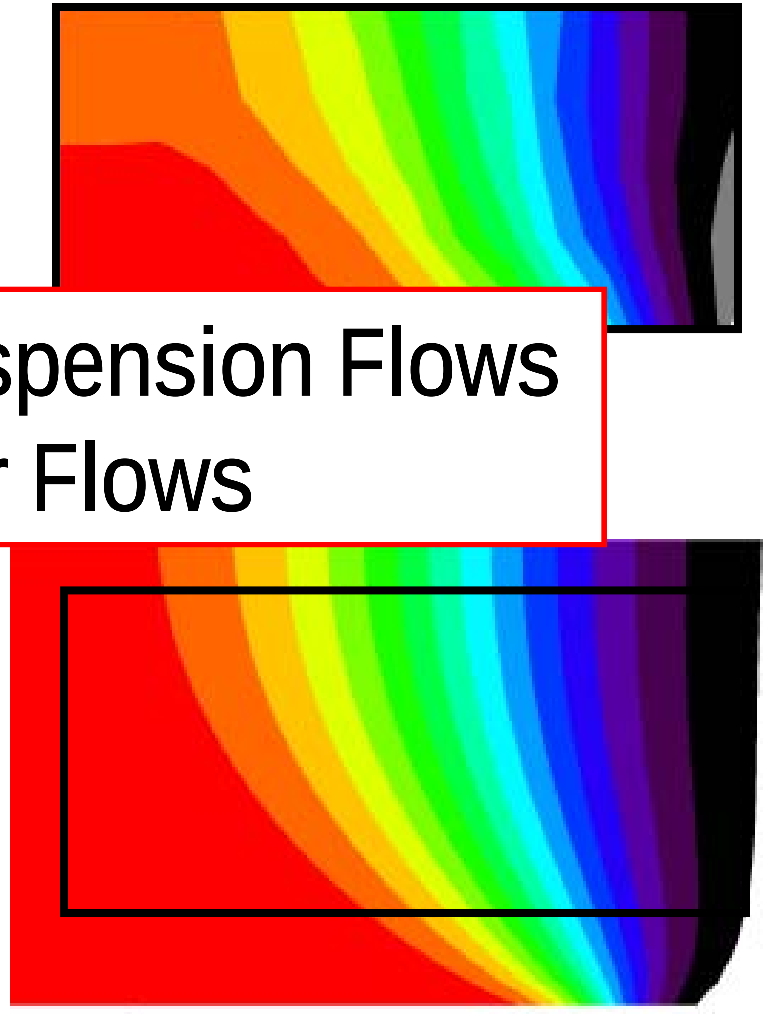
dry grains



Compare Dry and Wet (Slow)



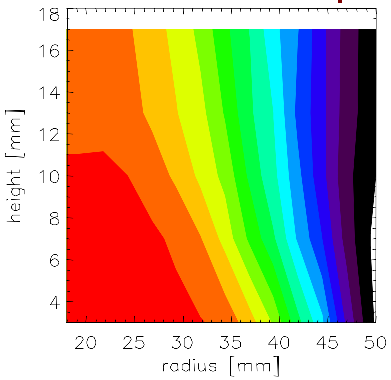
suspension



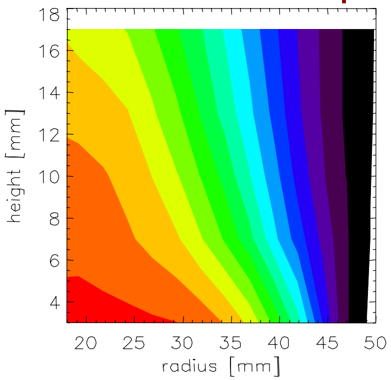
Slow Gravitational Suspension Flows ARE Like Dry Granular Flows

From Frictional To Stokes

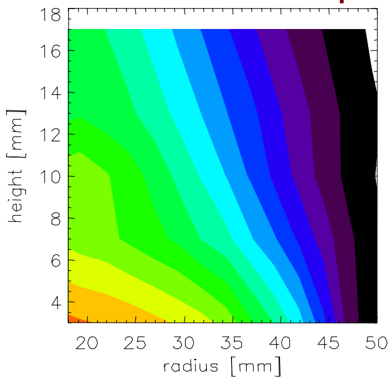
$\Omega = 8.3 \times 10^{-5}$ rps



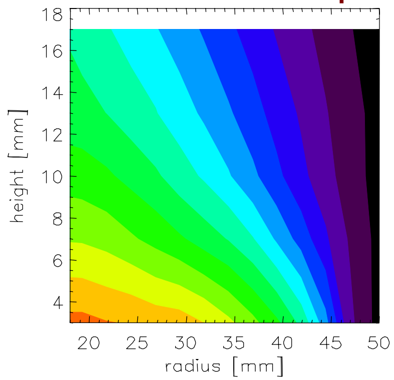
$\Omega = 8.3 \times 10^{-4}$ rps



$\Omega = 8.3 \times 10^{-3}$ rps

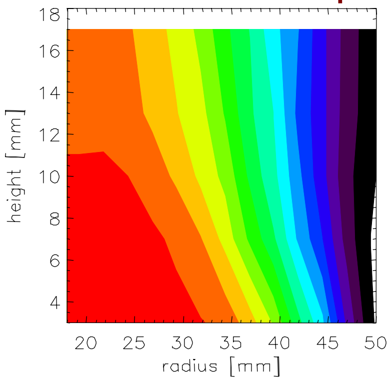


$\Omega = 8.3 \times 10^{-2}$ rps

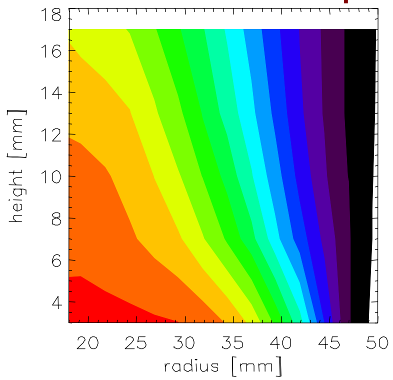


From Frictional To Stokes

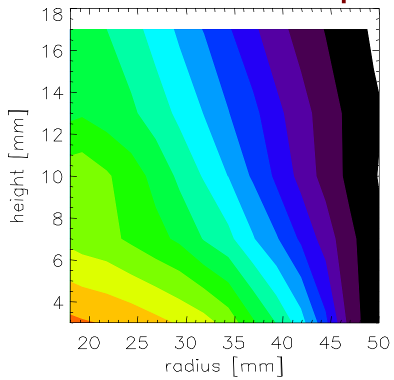
$\Omega = 8.3 \times 10^{-5}$ rps



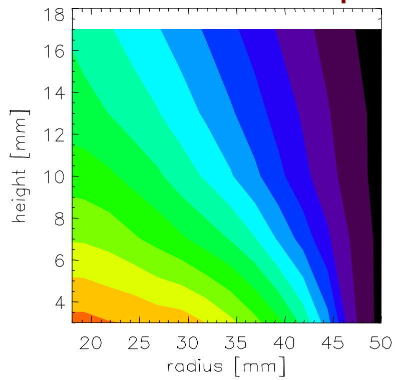
$\Omega = 8.3 \times 10^{-4}$ rps

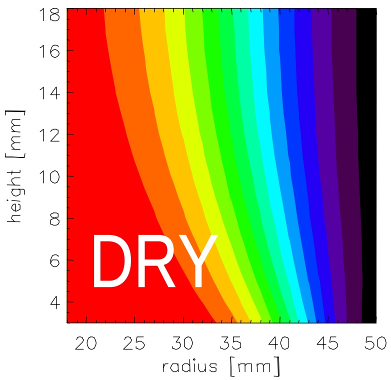


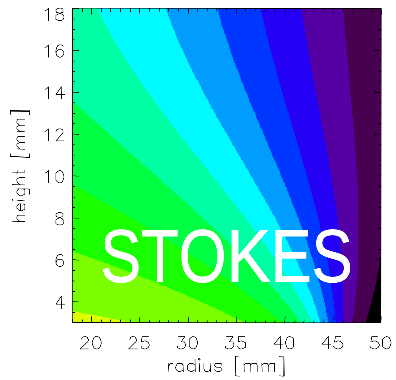
$\Omega = 8.3 \times 10^{-3}$ rps



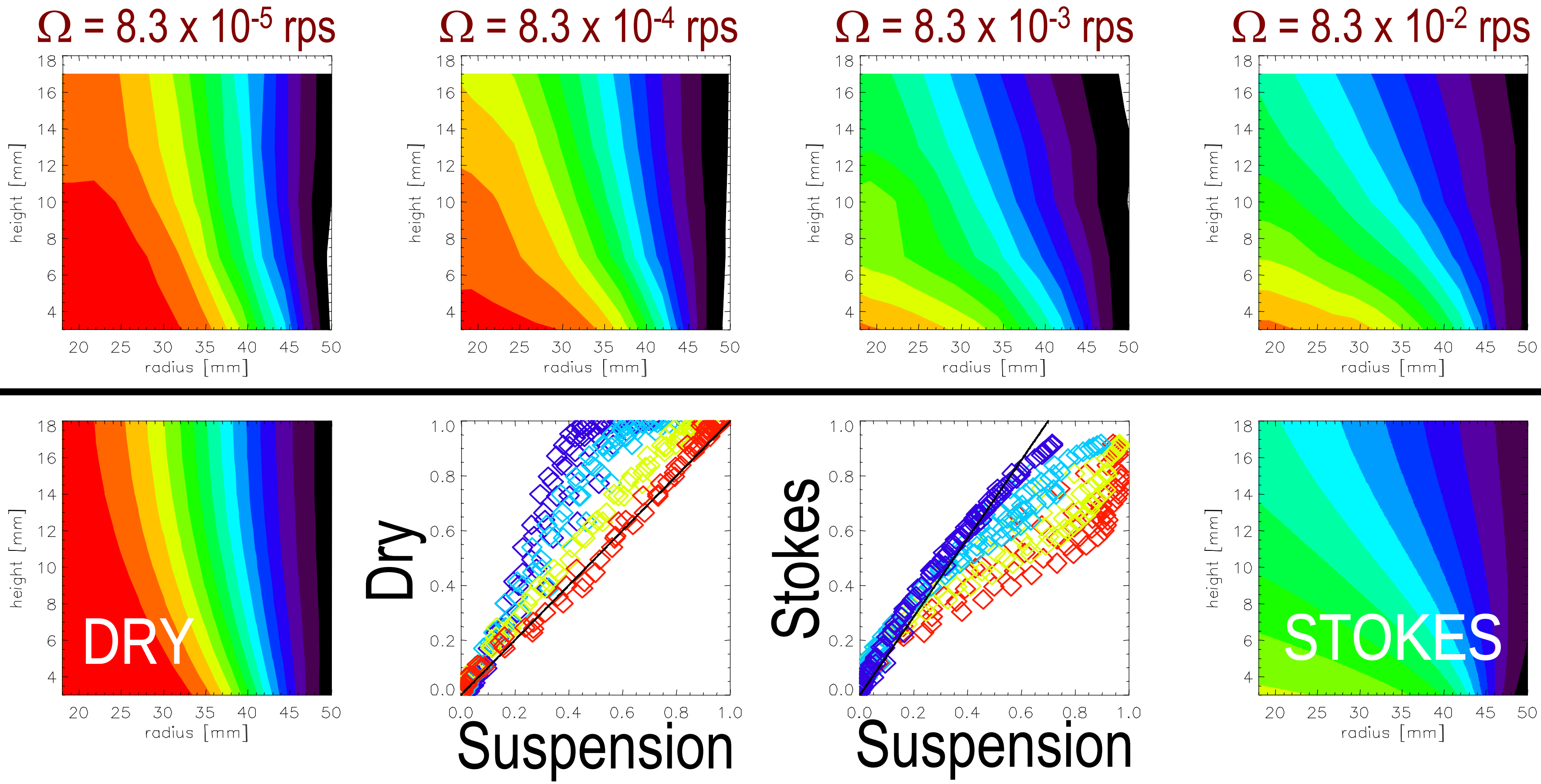
$\Omega = 8.3 \times 10^{-2}$ rps





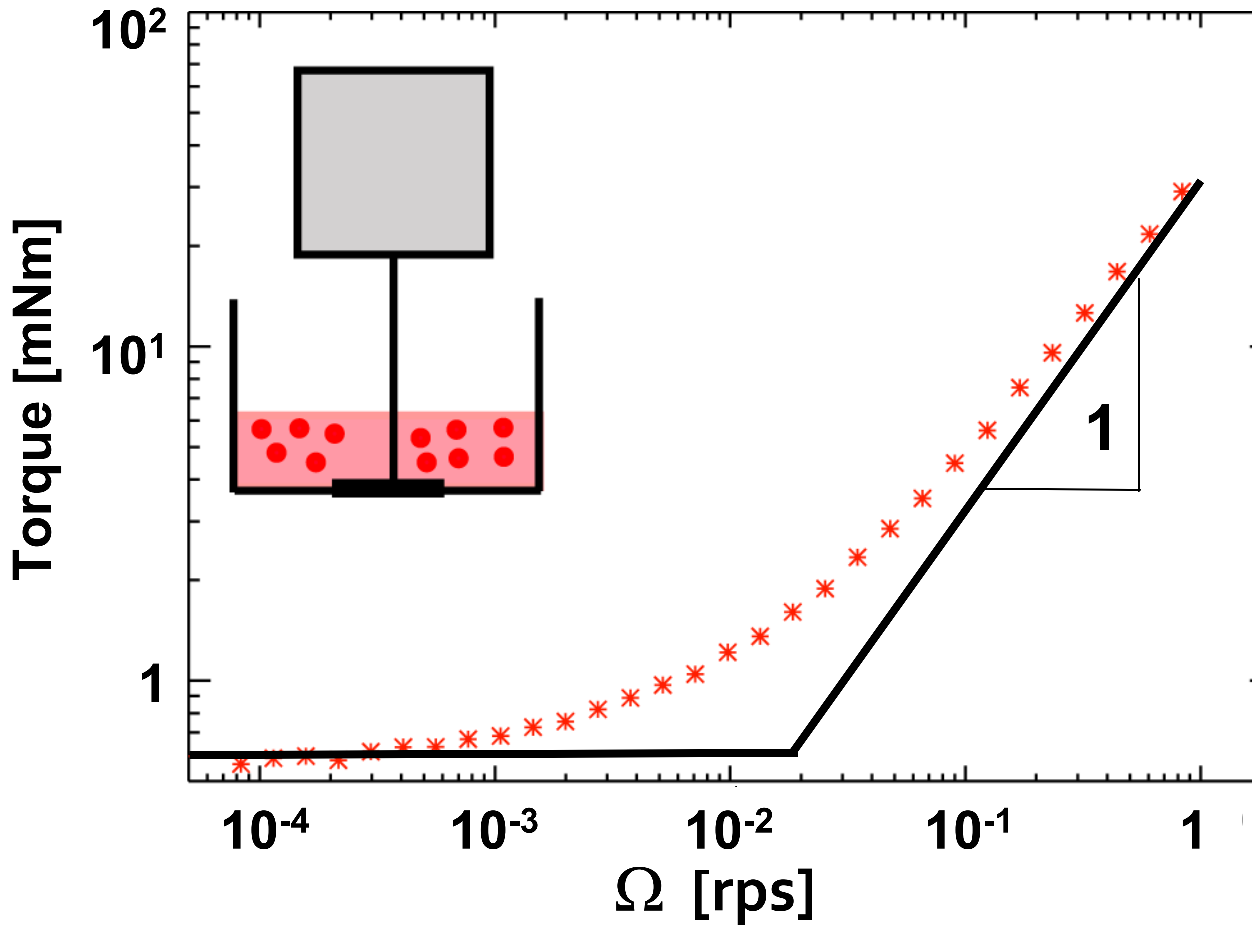


From Frictional To Stokes

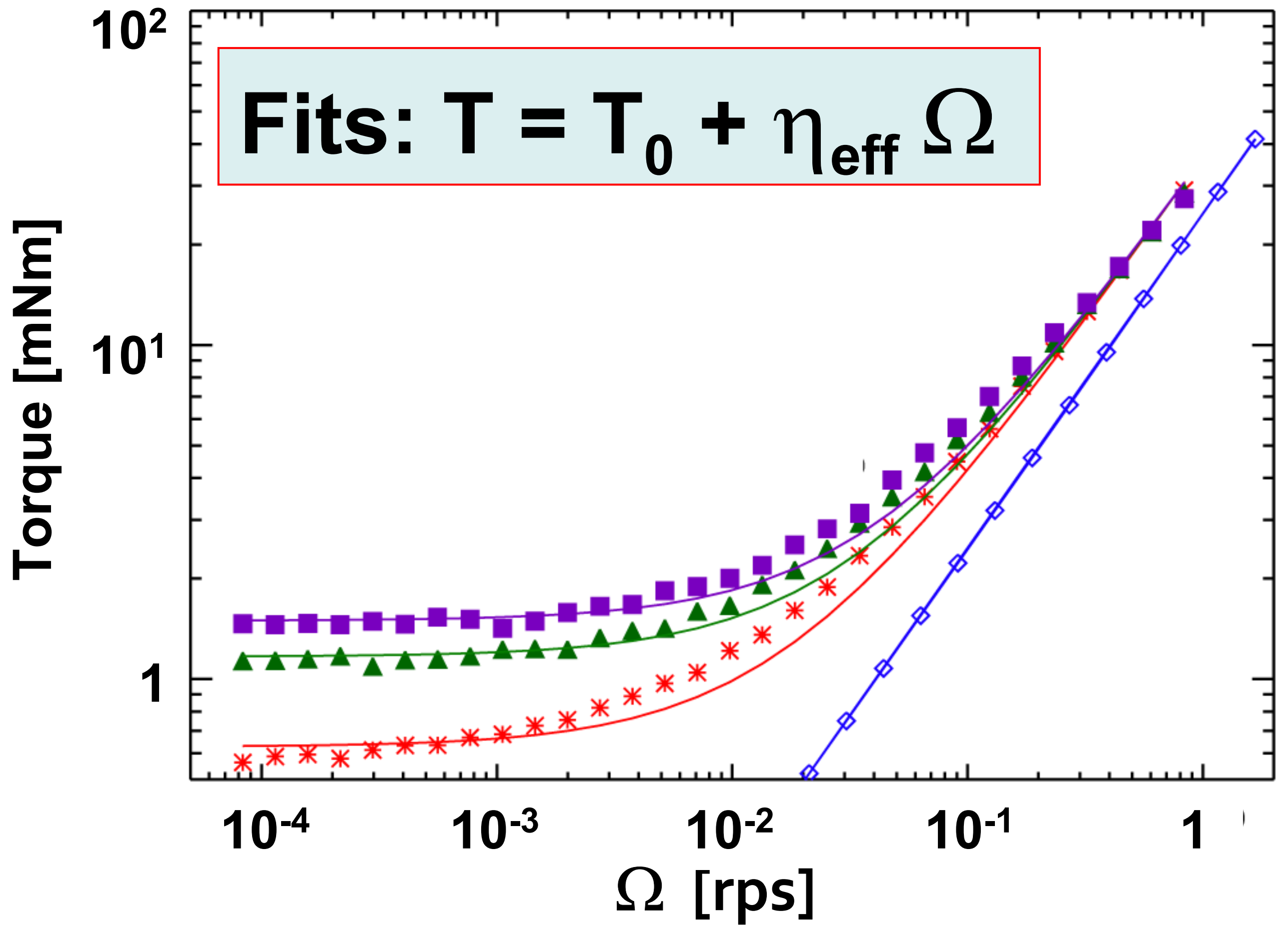


J. Dijksman et al in preparation

Rheology: Two Limits



Rheology: Two Limits



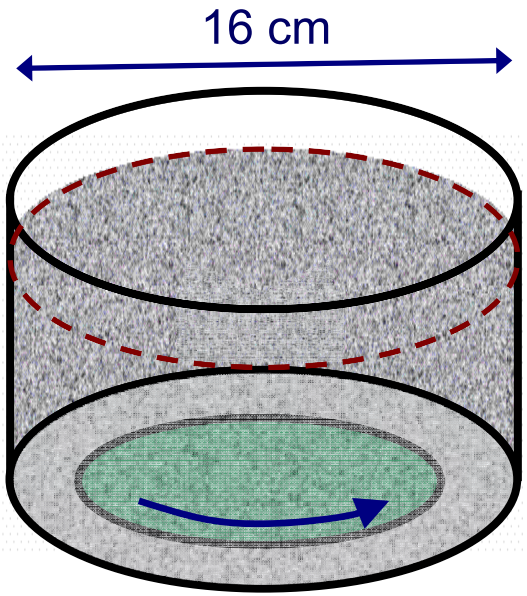
Conclusions

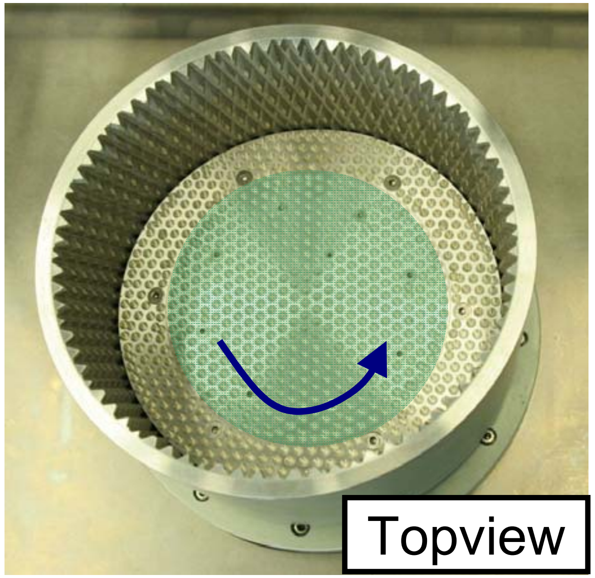
Slow Suspensions = Slow Dry Grains

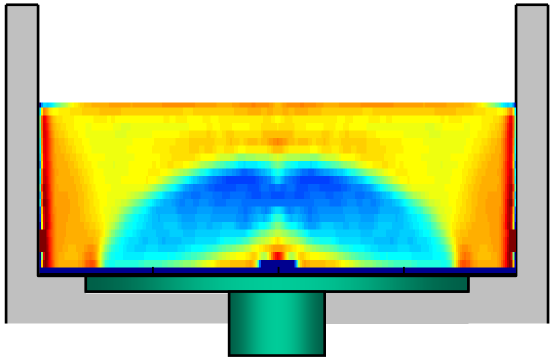
Faster Suspensions = Stokes

What About Inertial Nr Framework?

Setup

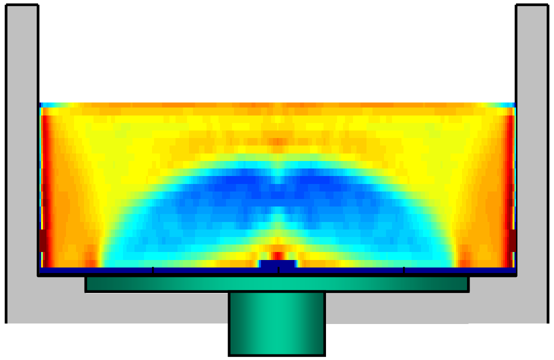


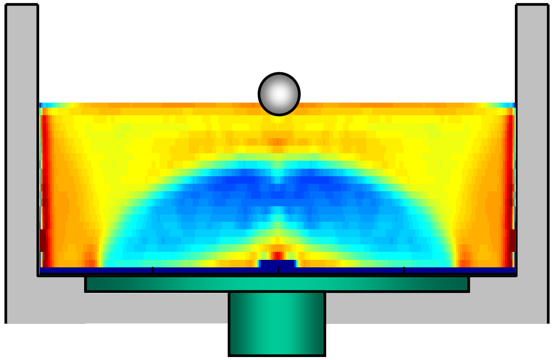




Yield Criterion in presence of flow?

Yield stress is lowered!!!





K. Nichol et al, accepted for PRL

A Stationary Granular Fluid

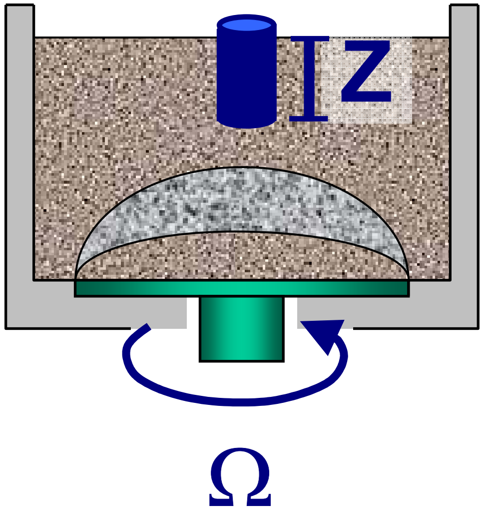
What happened to yield stress?

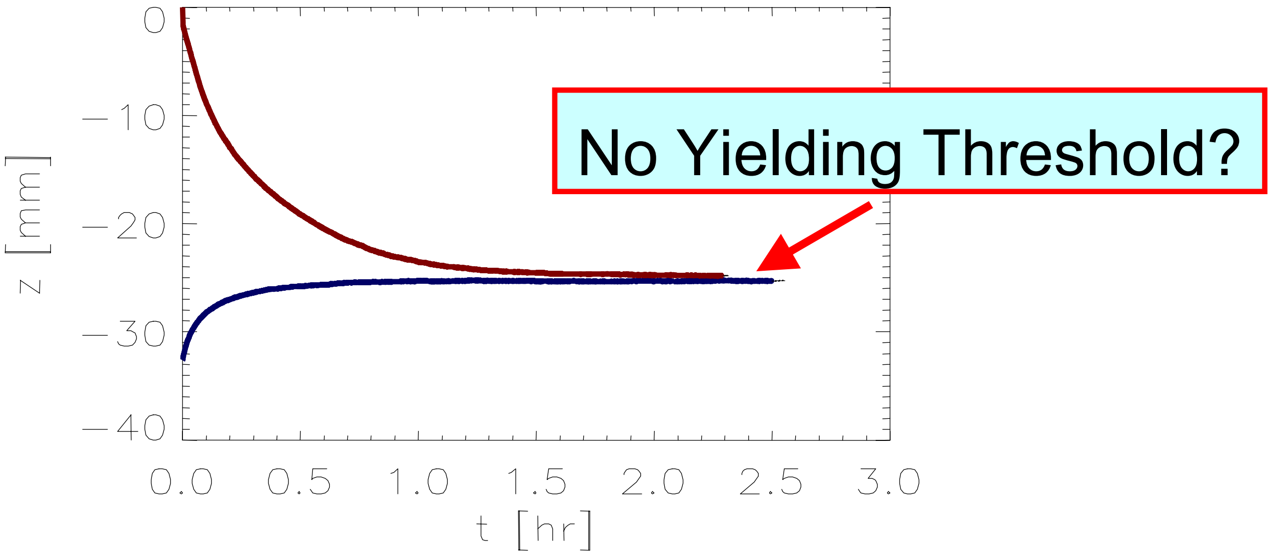
Yield stress vanishes - Archimedes Law

Mechanism?

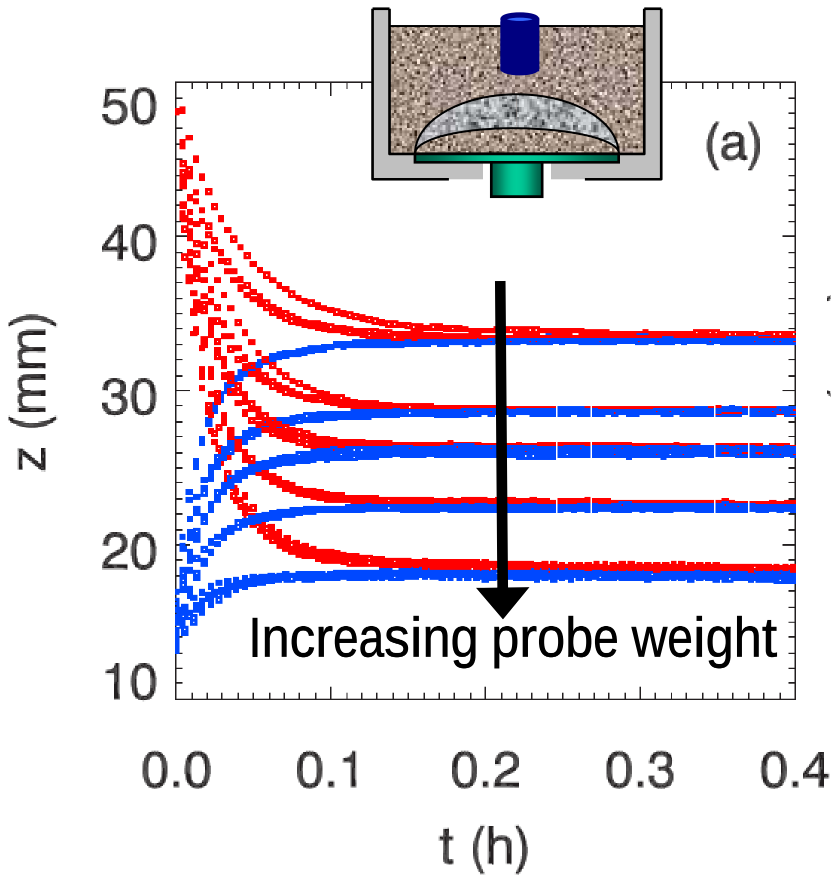
Agitations - Nonlocal

Floating in Sand

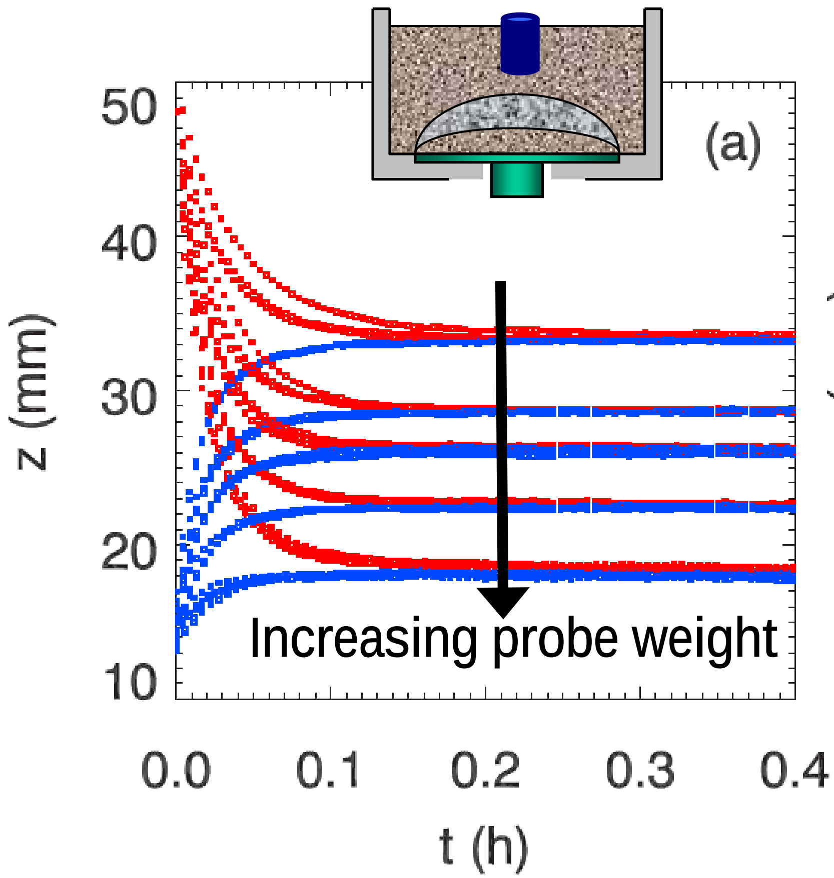


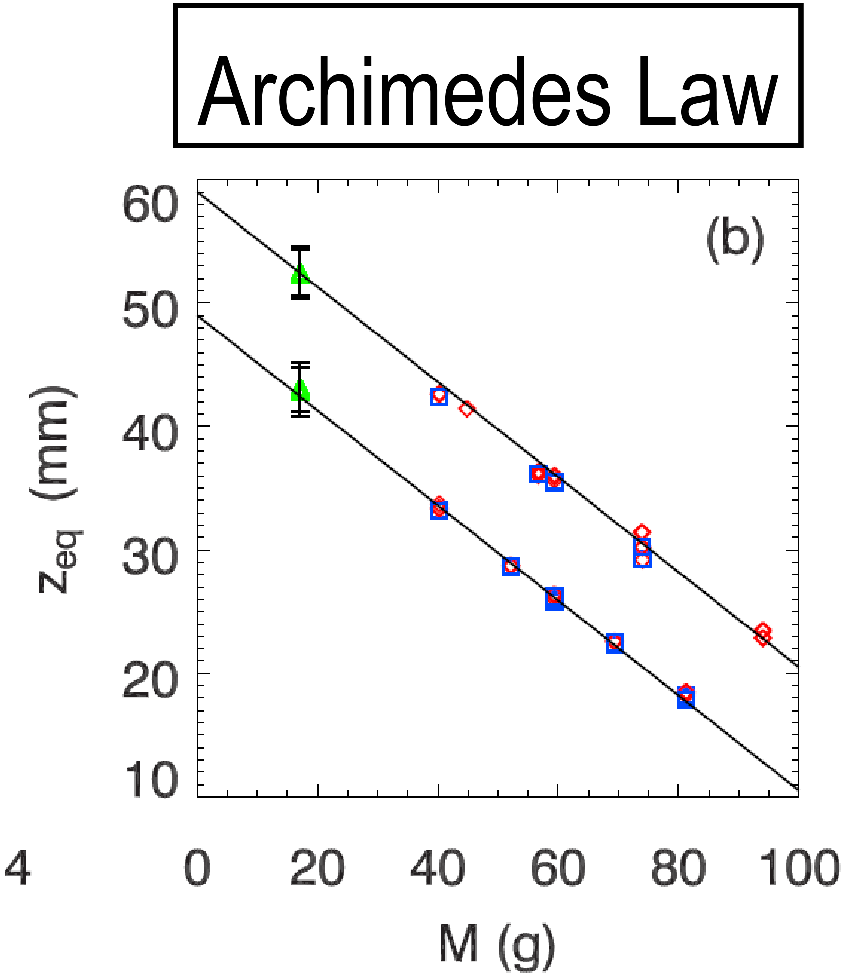


Floating in Sand

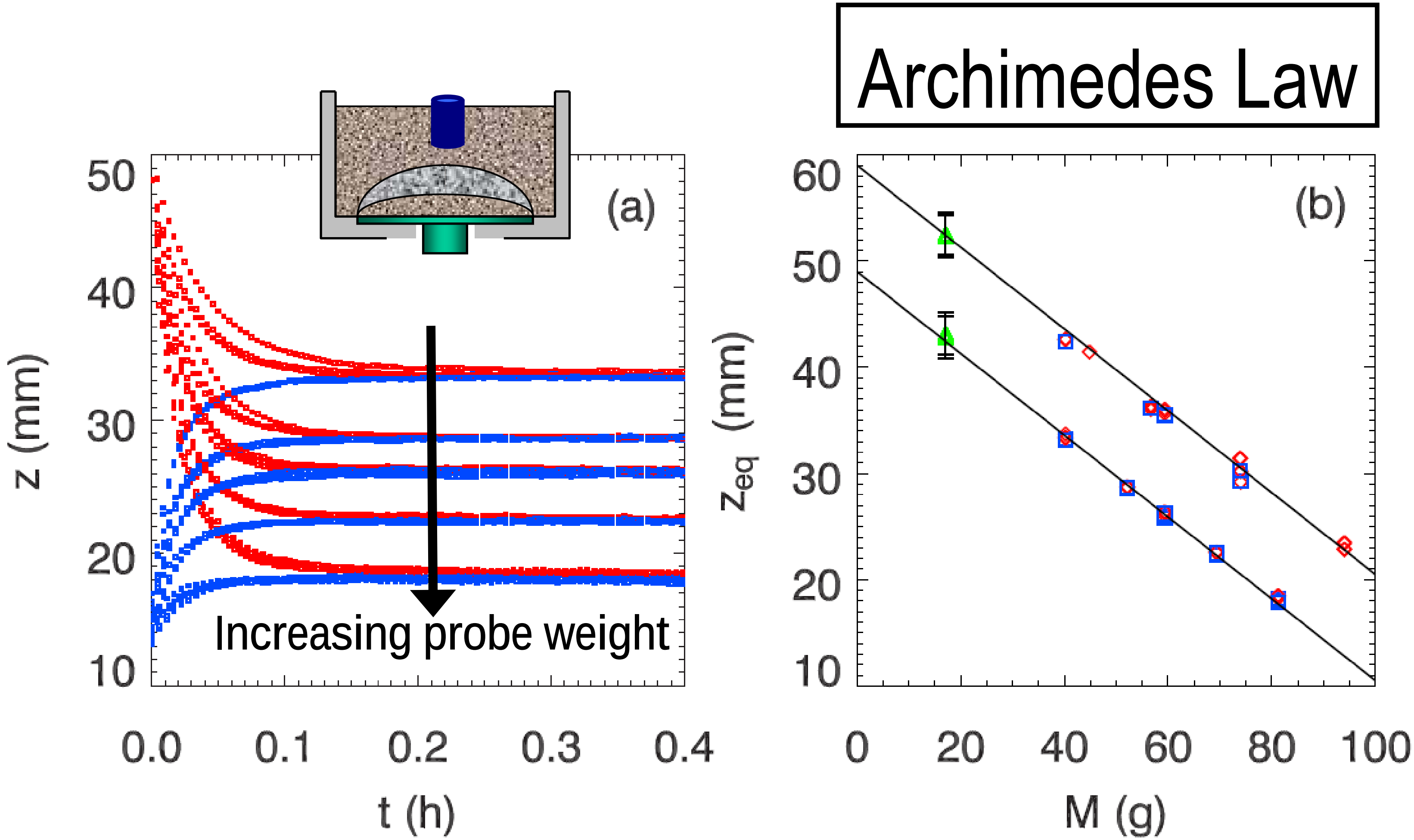


Floating in Sand



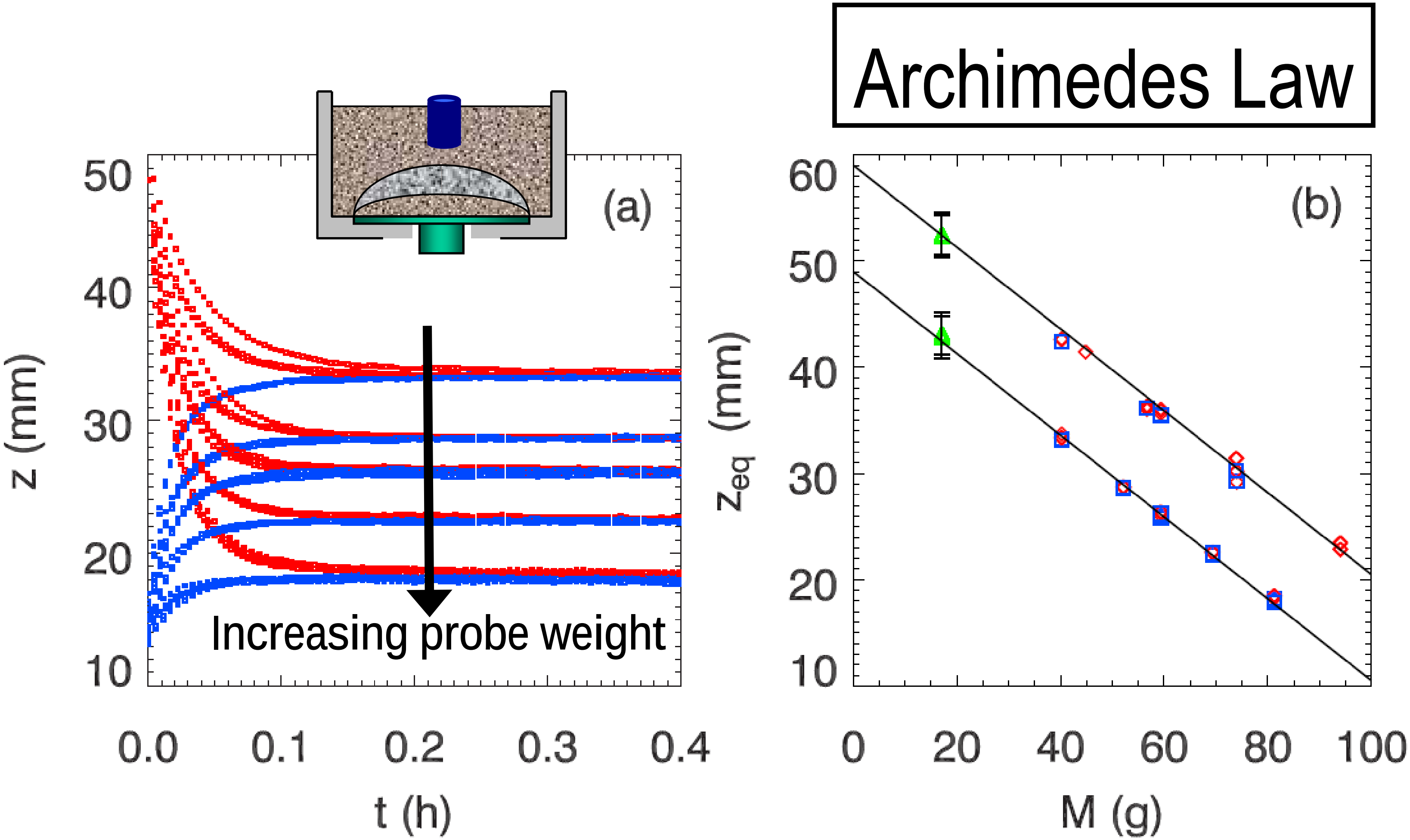


Floating in Sand



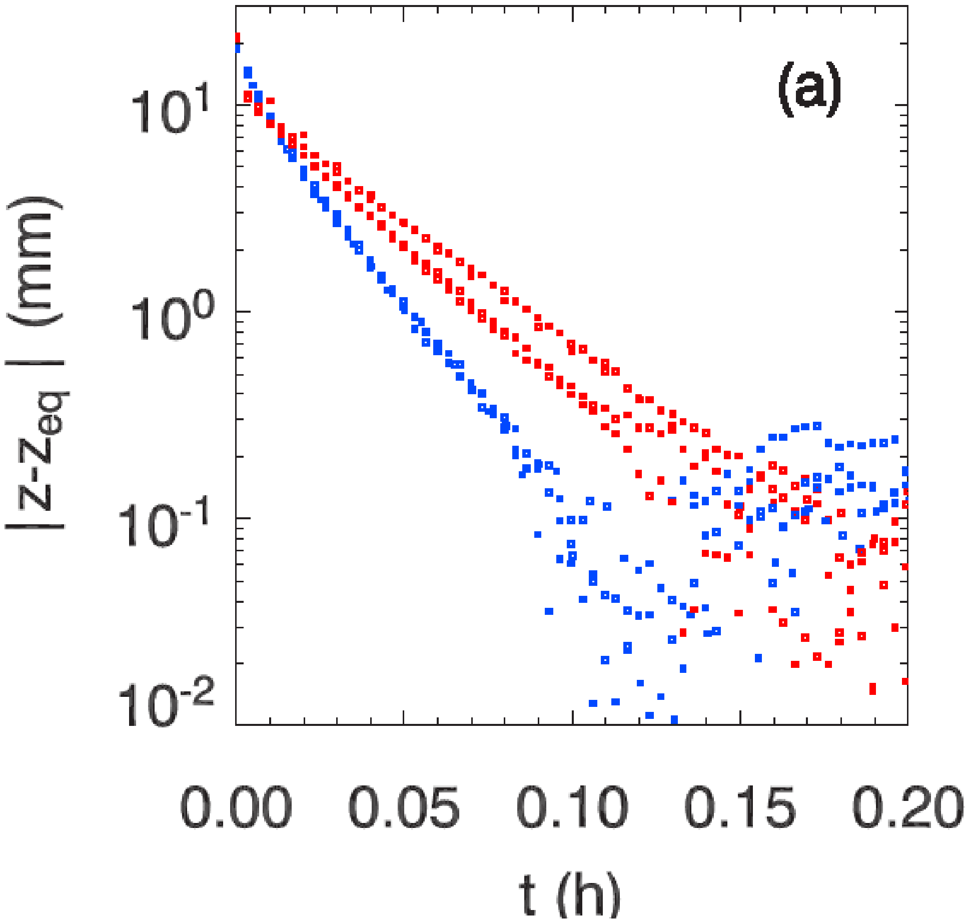
No yielding threshold in presence of flow

Floating in Sand



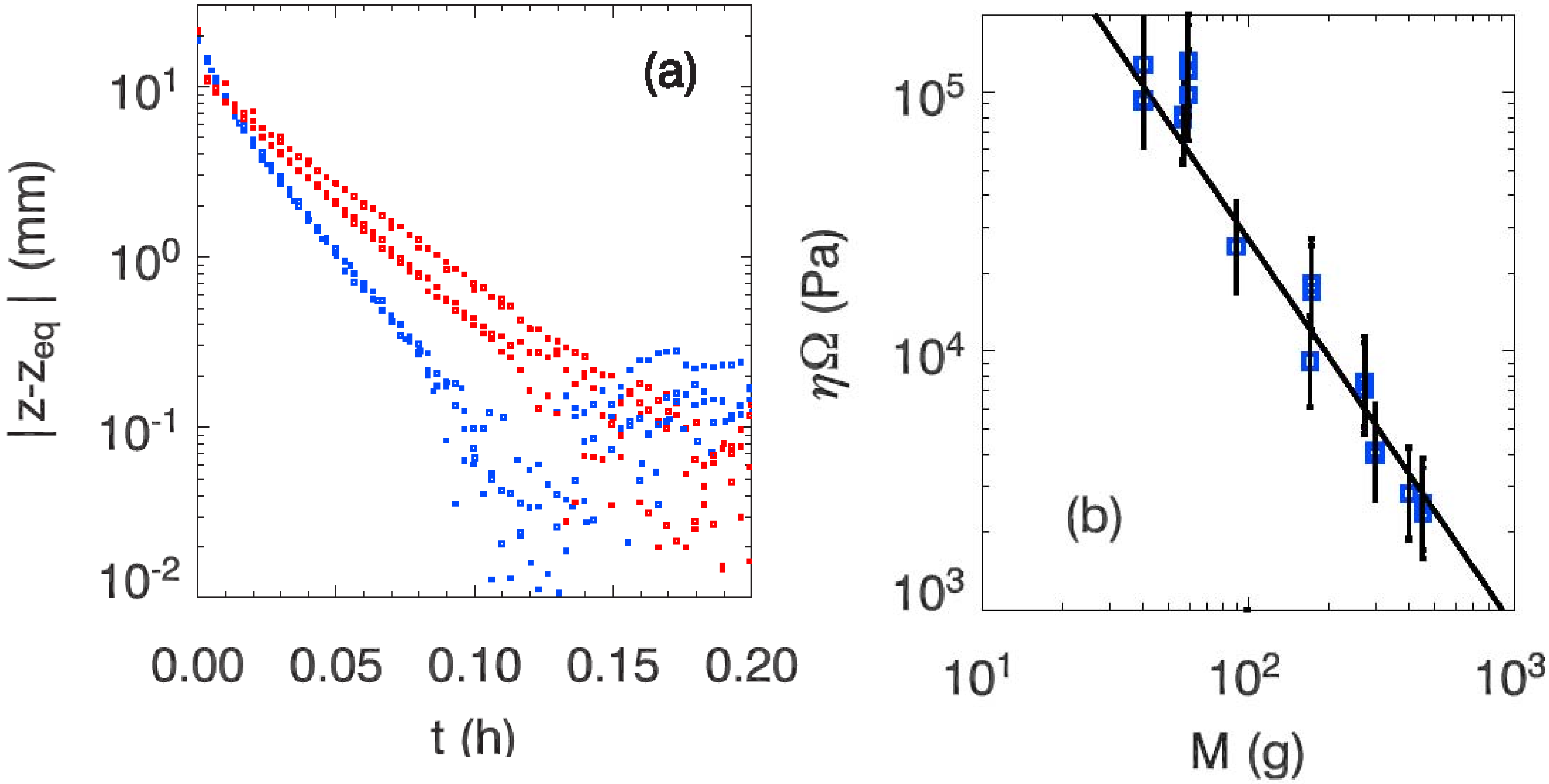
Mohr Coulomb --- yeah right

Floating in Sand



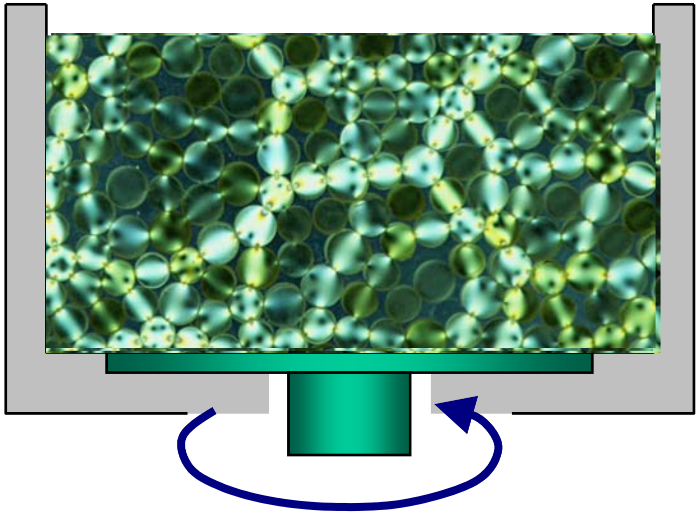
Viscous!!!

Floating in Sand



Viscous!!!

A Stationary Granular Fluid: Agitations



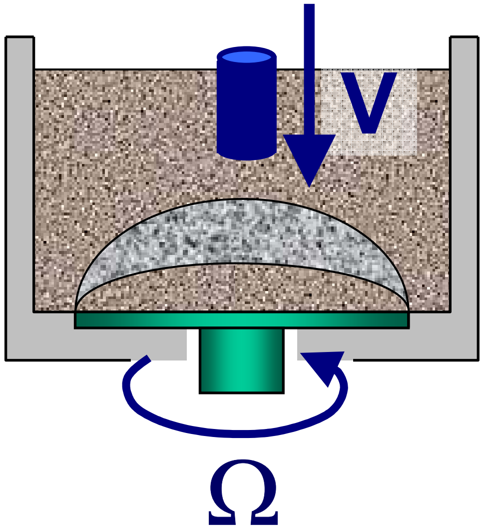
Contact Forces + Flow

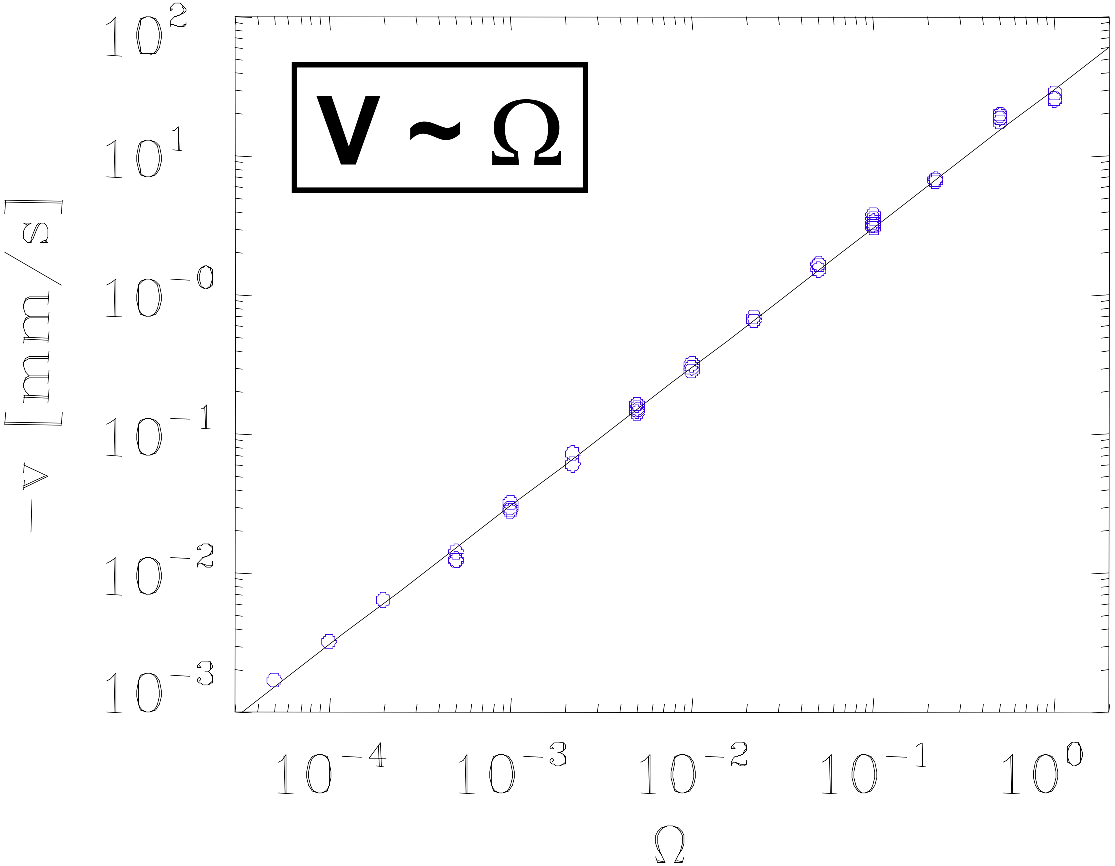
Fragile (heating 1 grain by 1C....)

Hard Grains (mm/nm)

Rotation rate Ω sets probe speed?

A Stationary Granular Fluid: Mechanism





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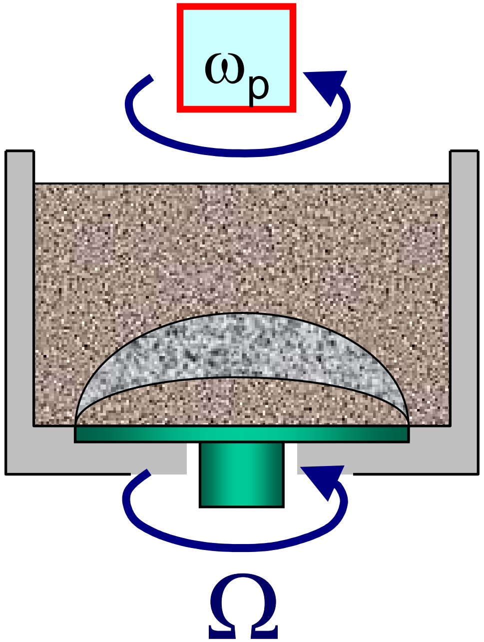
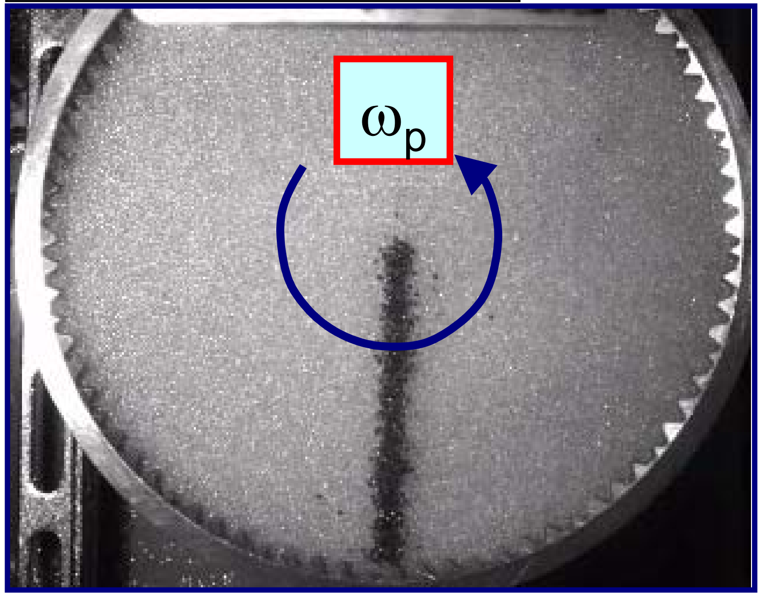


1 frame / 5 rotations



$\omega_p \sim \Omega$ & $\mathbf{V} \sim \Omega$

Local flow sets sinking speed???

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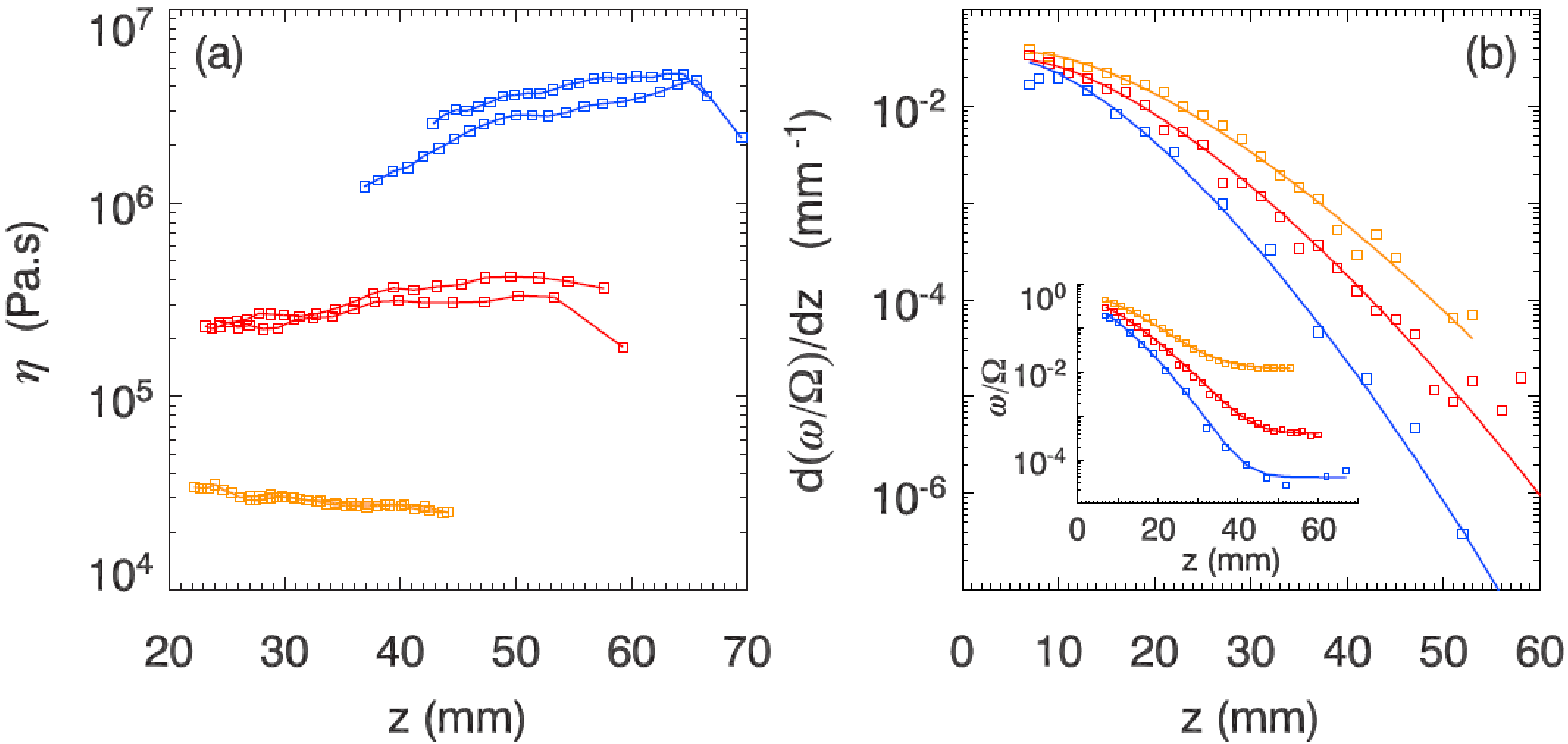


NONLOCAL:
Flowrate in A, determines flowrate in B

Slow Granular Flows

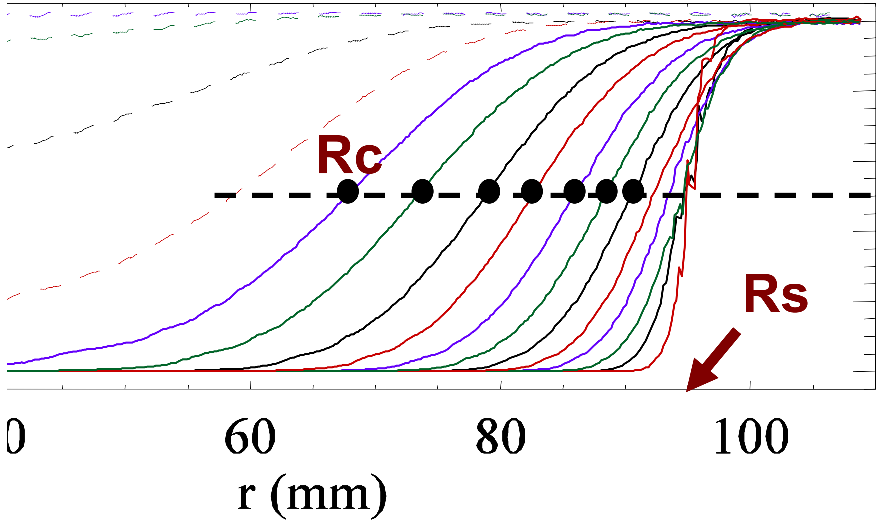
Not Always Shear Bands

Classical Picture based on Friction **Fails**

Suspensions & Dry Grains

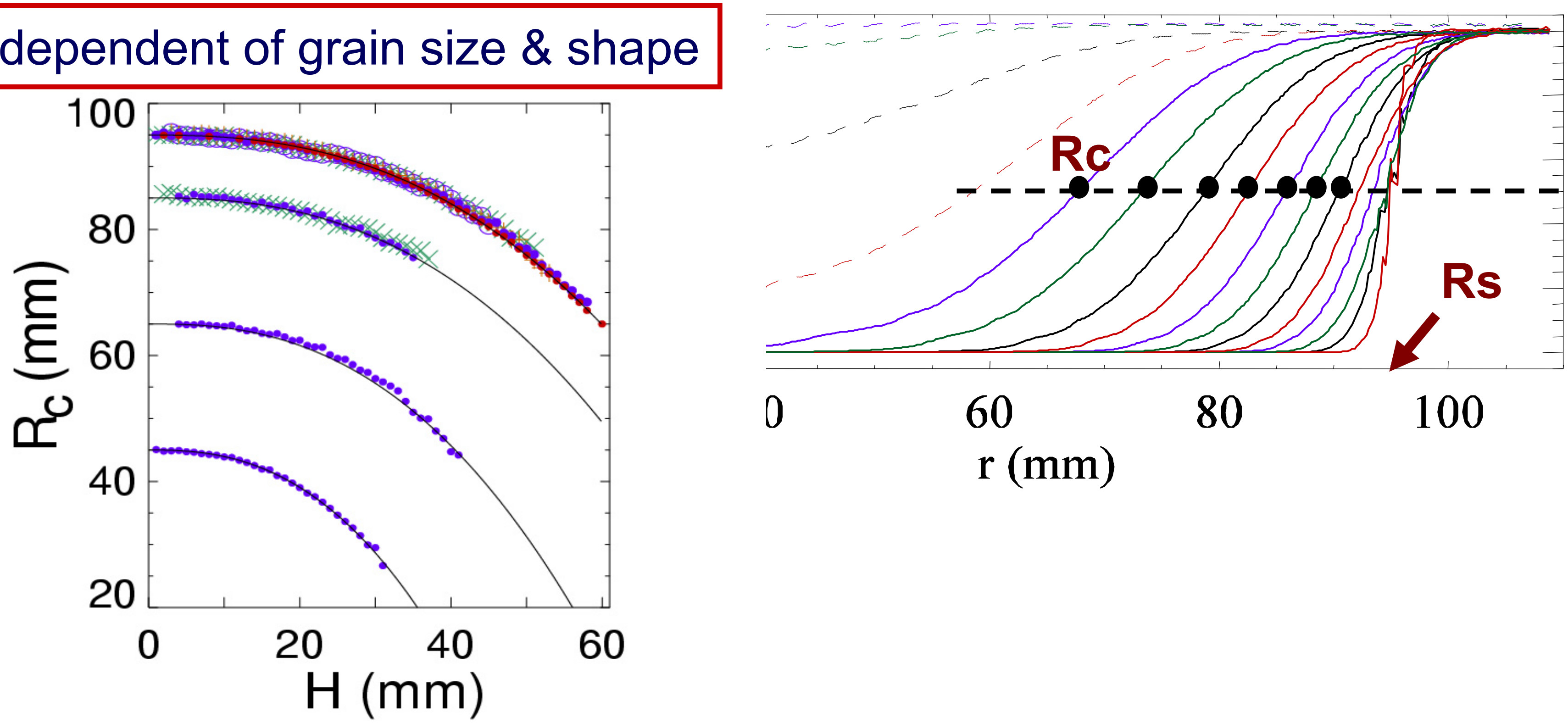
Experiments: **Melting** Sand by Stirring

Bonus: Shallow Layers: R_c



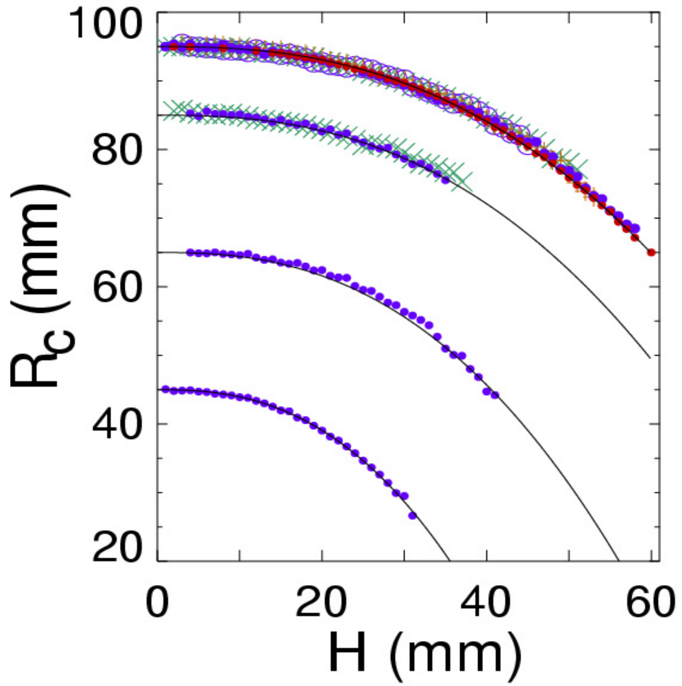
Bonus: Shallow Layers: R_c

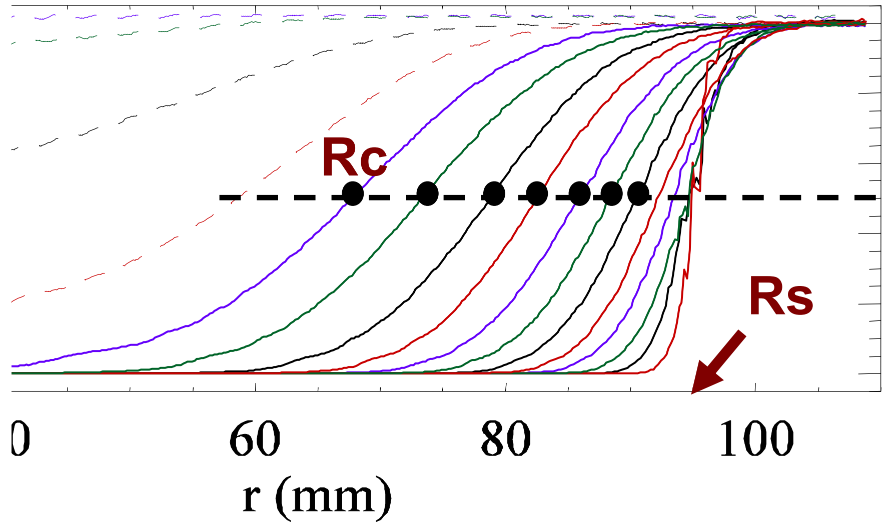
independent of grain size & shape

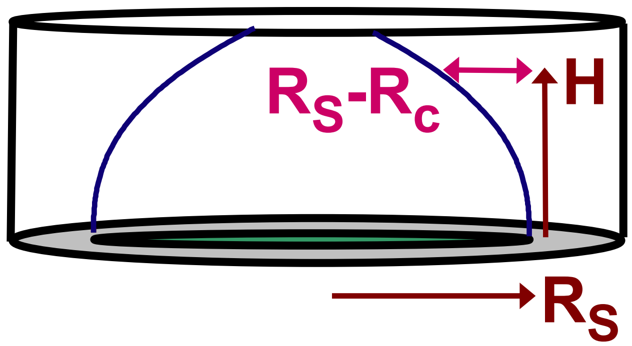


Bonus: Shallow Layers: R_c

independent of grain size & shape

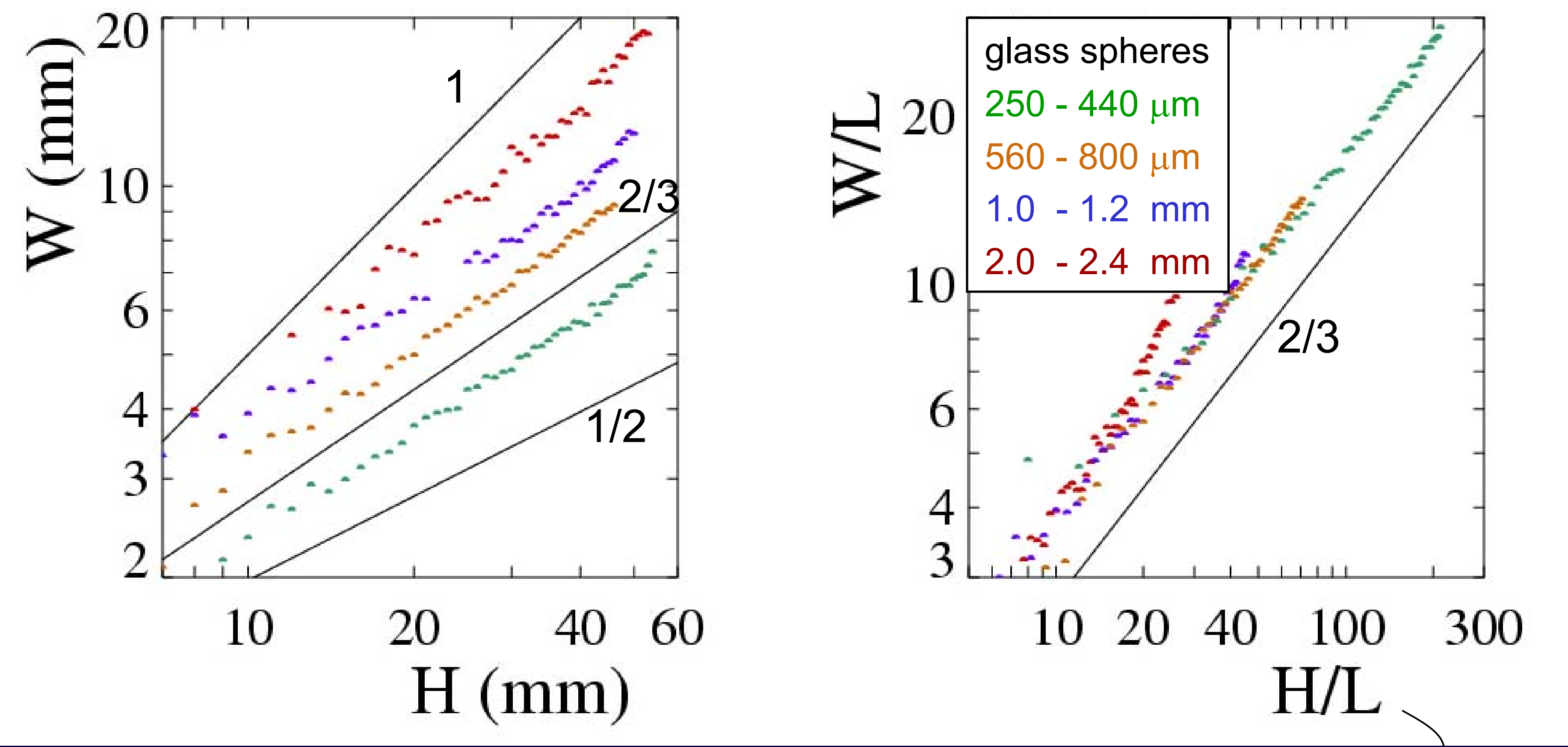






$$(R_s - R_c)/R_s = (H/R_s)^{5/2}$$

Bonus: Shallow Layers: W



1.1 mm bronze: W 30% smaller

L: best fits, 0.25, 0.65, 1.1, 2.2 mm

$W/L \sim (H/L)^{2/3}$, $L \approx d$

Bonus: Wide & Universal Shear Zones

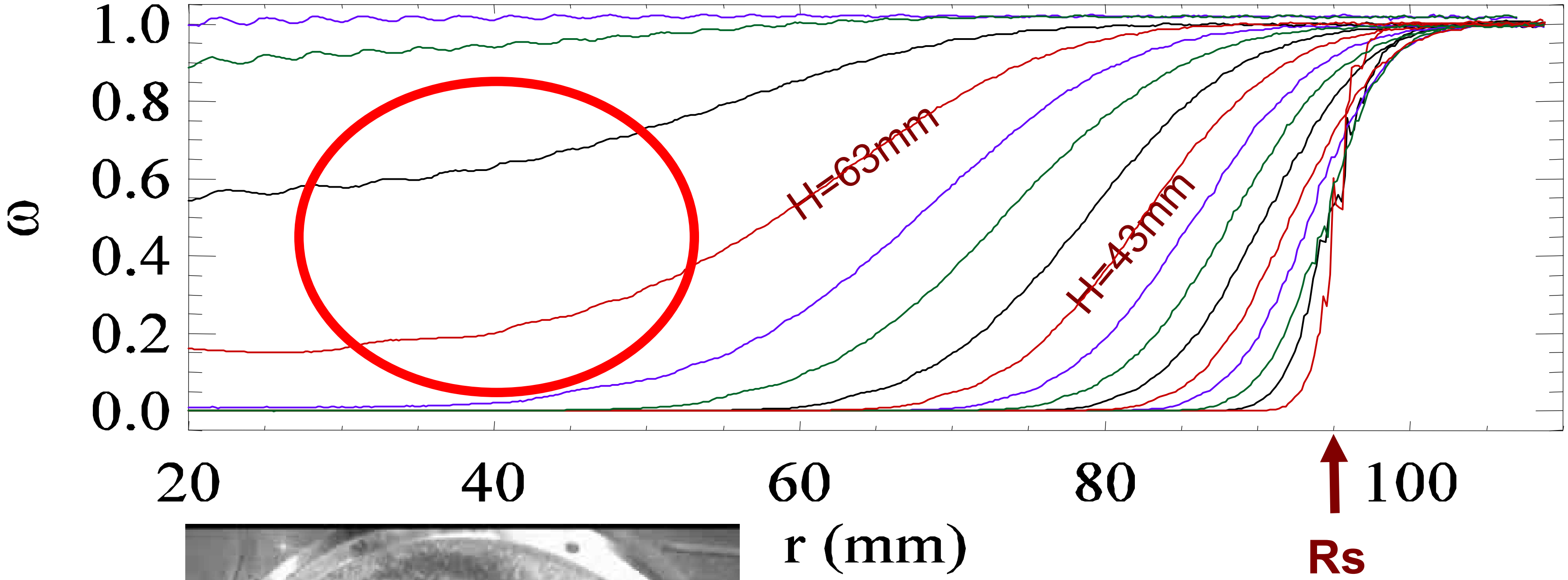
$\omega(r)=1/2+1/2\ \mathrm{erf}[(r-R_c)/W]$

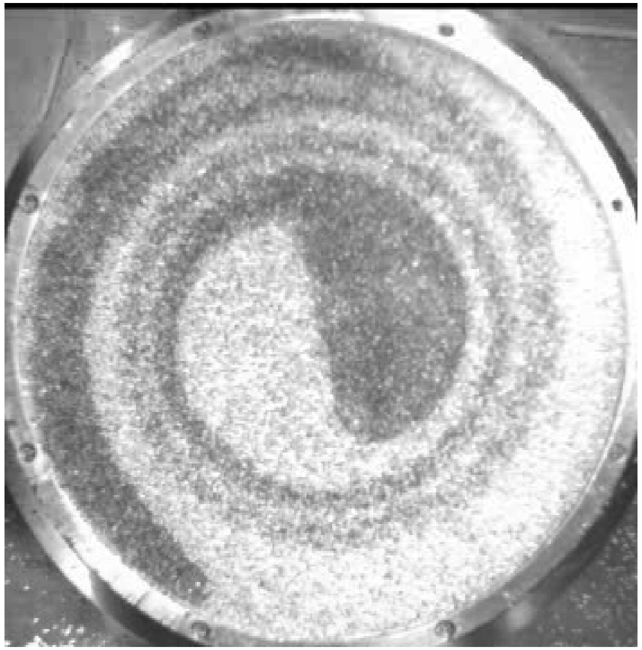
$(R_s-R_c)/R_s = (H/R_s)^{5/2}$: Independent of particles

$W/d \sim (H/d)^{2/3}$: Independent of R_s

D. Fenistein, JW. van de Meent and MvH, *Phys. Rev. Lett.* **92**, 094301 (2004); **96,** 118001 (2006).
D. Fenistein and MvH, *Nature* **425**, 256 (2003).

Bonus: Deep Layers





Precession

Bonus: Deep layers: Core Precession