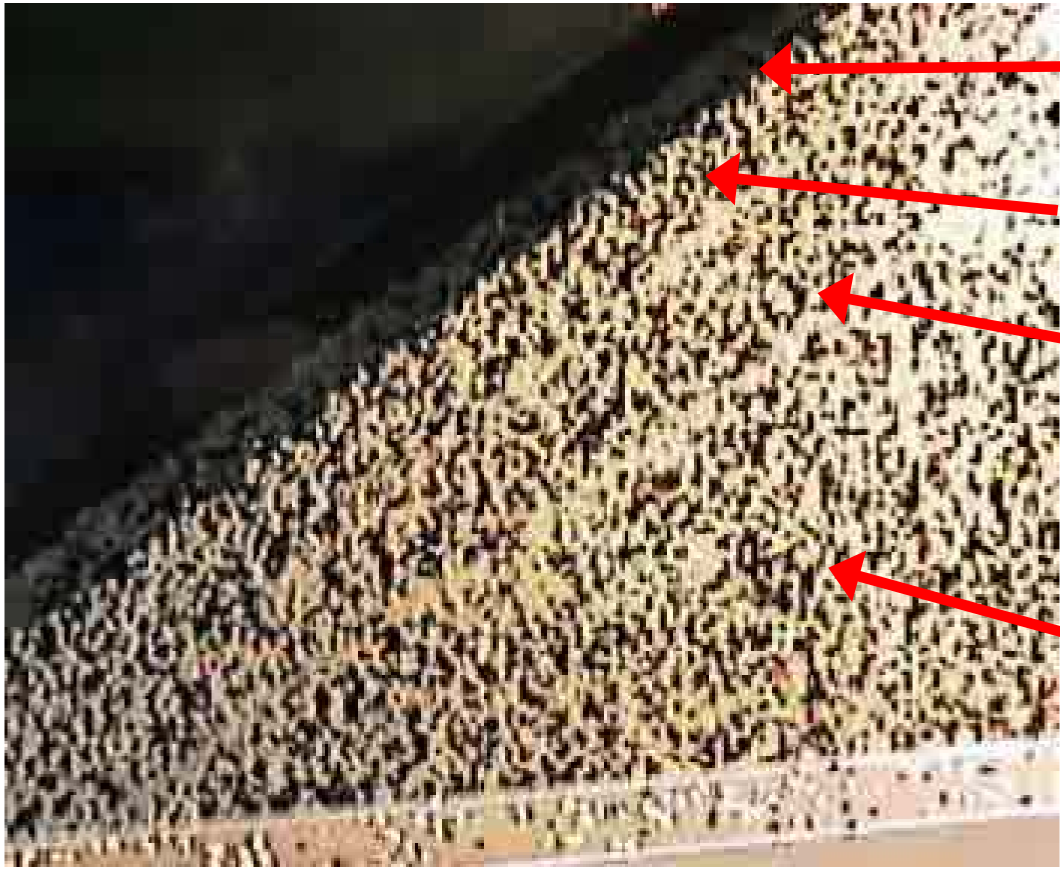
Granular Flows



Slow Granular Flows

Shear Bands

Classical Picture based on Friction

Experiments on Wide Shear Zones

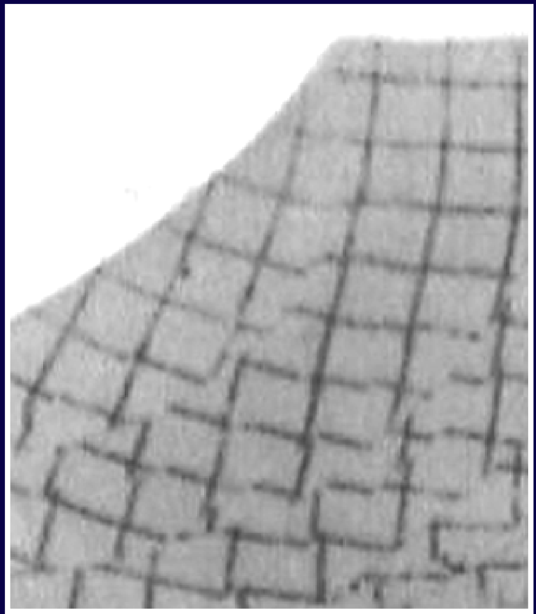
Comparison Experiments – Classical Picture

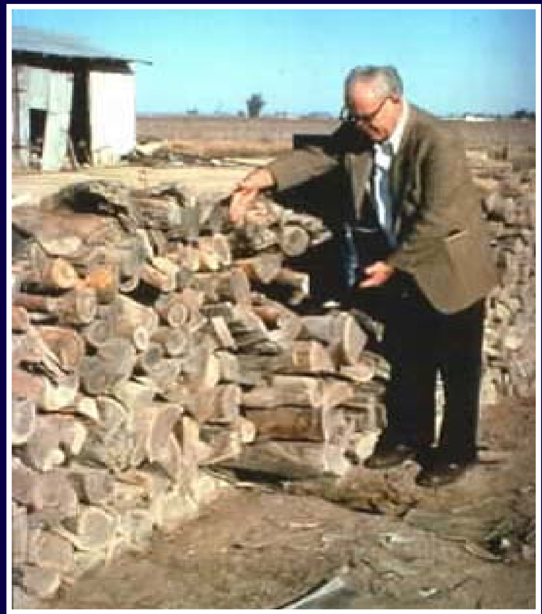
New Framework: Shear Free Sheets

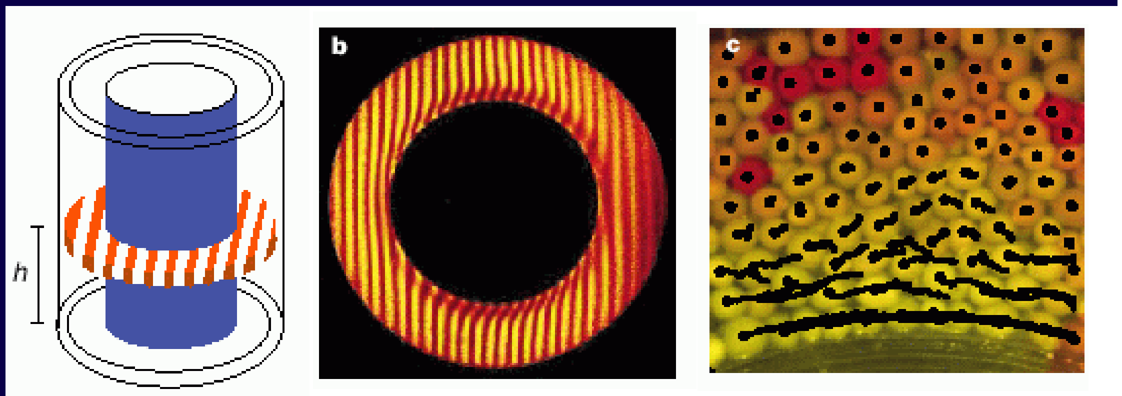
Experiments: Melting Sand by Stirring

Outlook

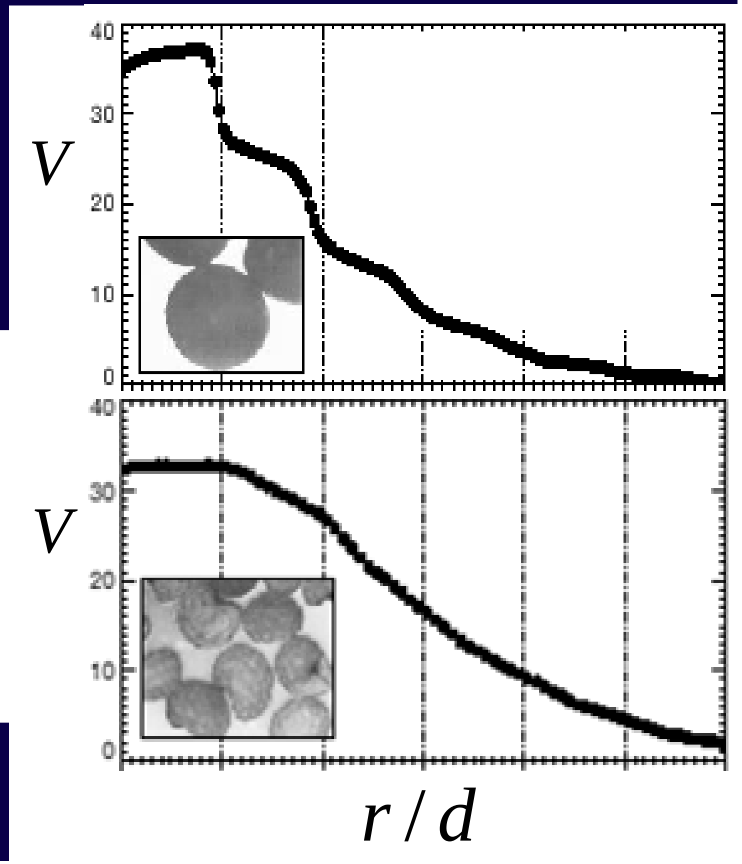
Shear Bands & Grain Details







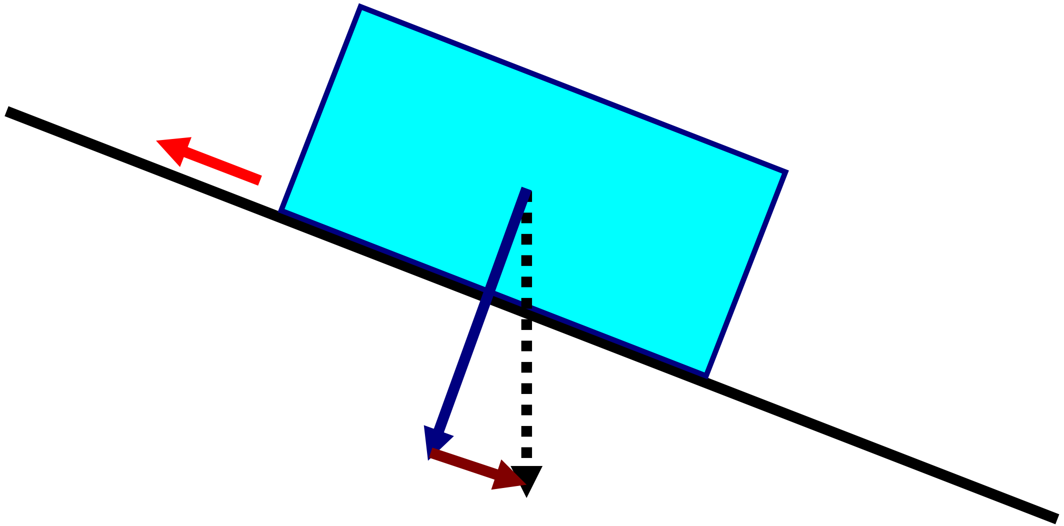
D.M. Mueth *et al.*,
Nature **406**, 385 (2000)



Granular Media: Analogy with Friction

Yield Criterion

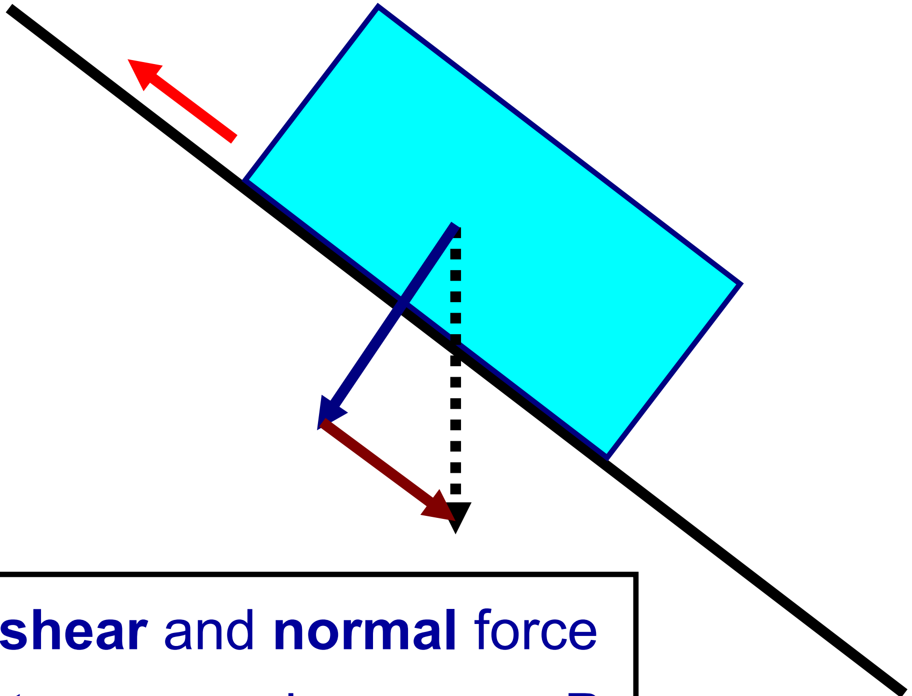
$$\frac{\text{Shear Force}}{\text{Normal Force}} \leq \mu$$



Granular Media: Analogy with Friction

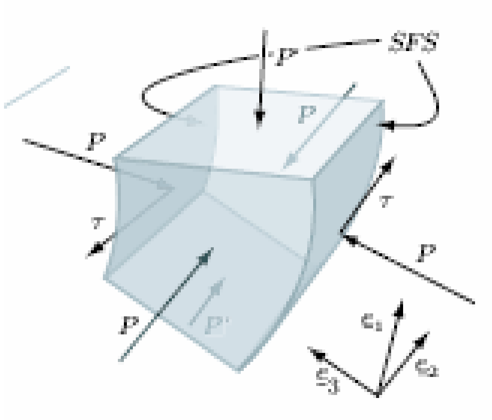
Yield Criterion

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



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

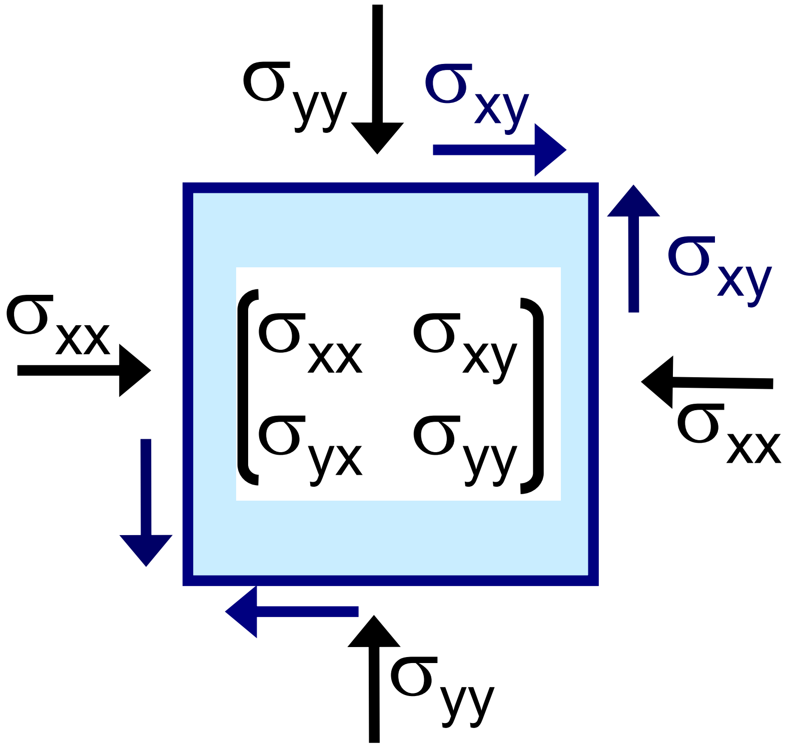
Intermezzo: Tensors

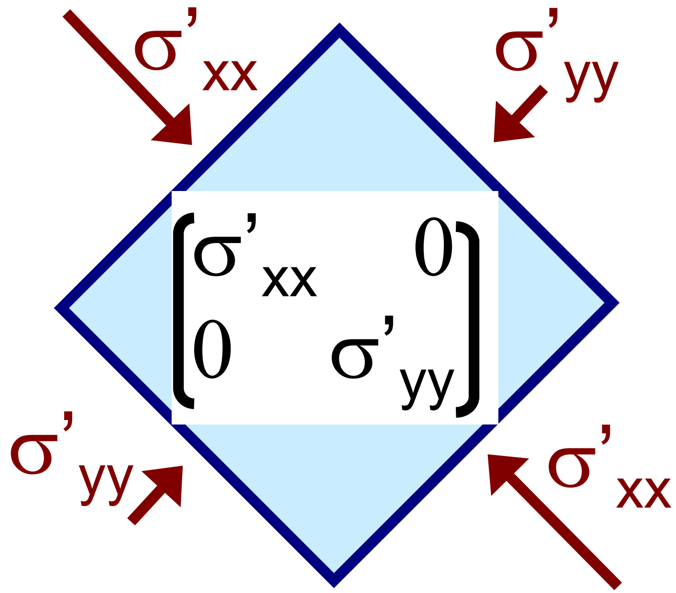


Stress = Force / Area

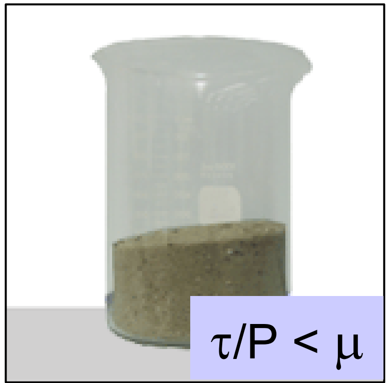
$\sigma_{xy} = \sigma_{yx} = F_x/Area_y = F_y/Area_x$

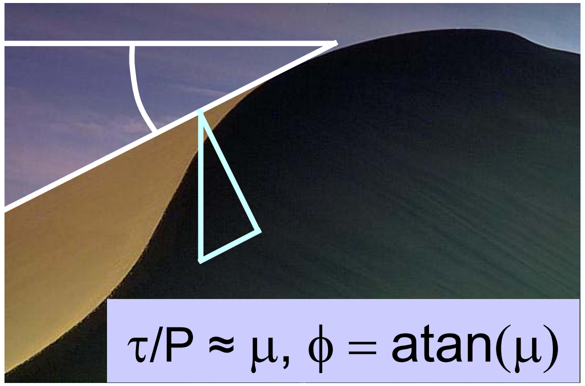
Principle Directions

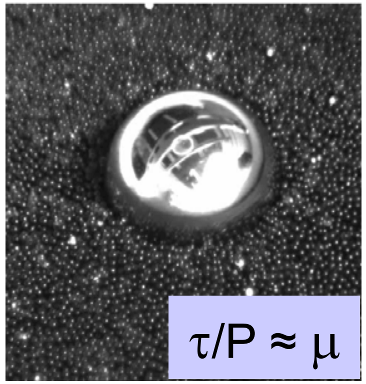




Granular Media: Yield Criterion







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 – Accepted Wisdom

Narrow shear bands

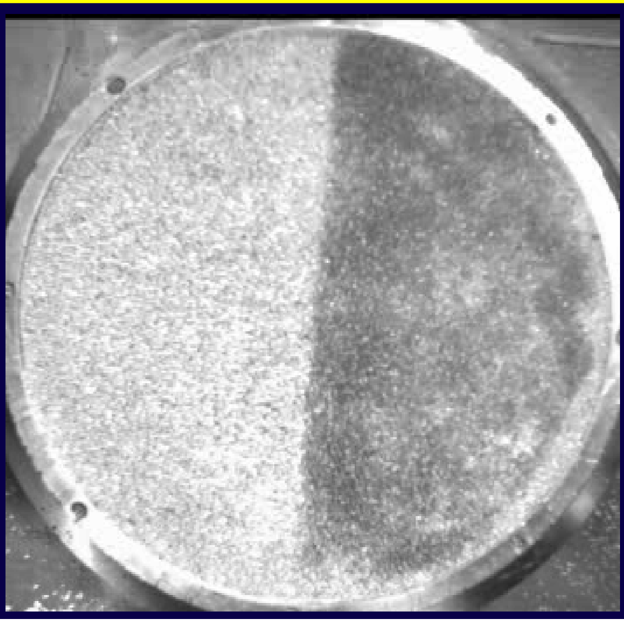
Grain details matter

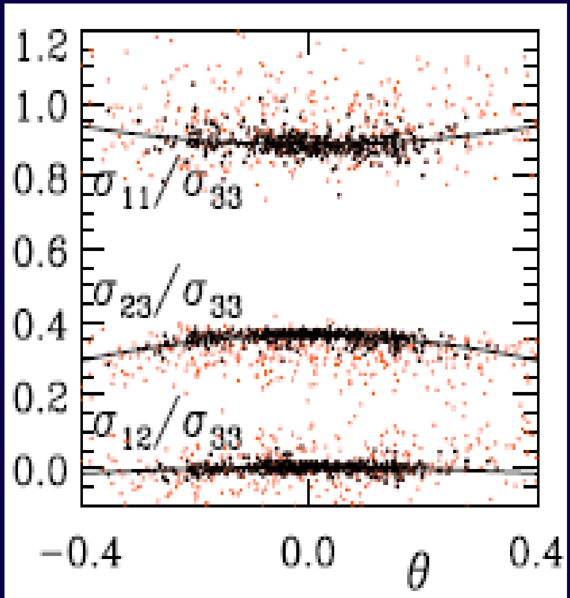
Solid-like regions

Constant sliding friction.

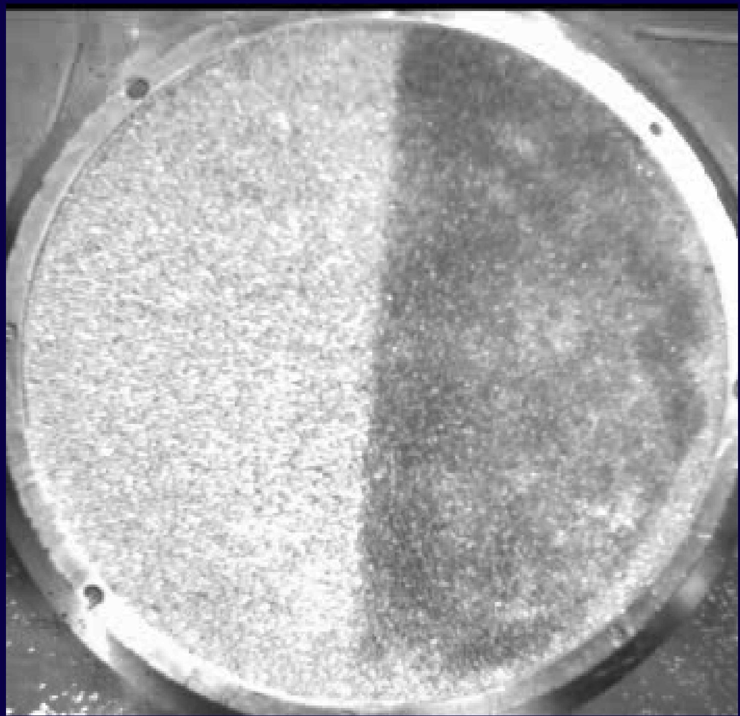
Kiri Nichol

And now ...





Smooth Granular Flows



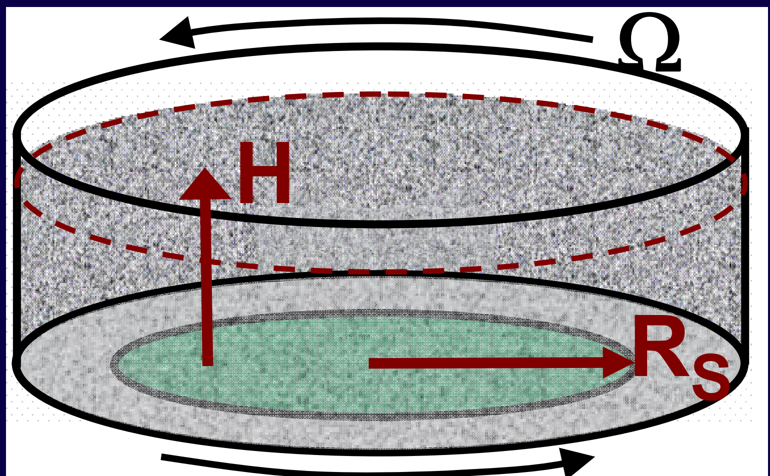
Surface Velocity Profiles

Rate independent

Short transients

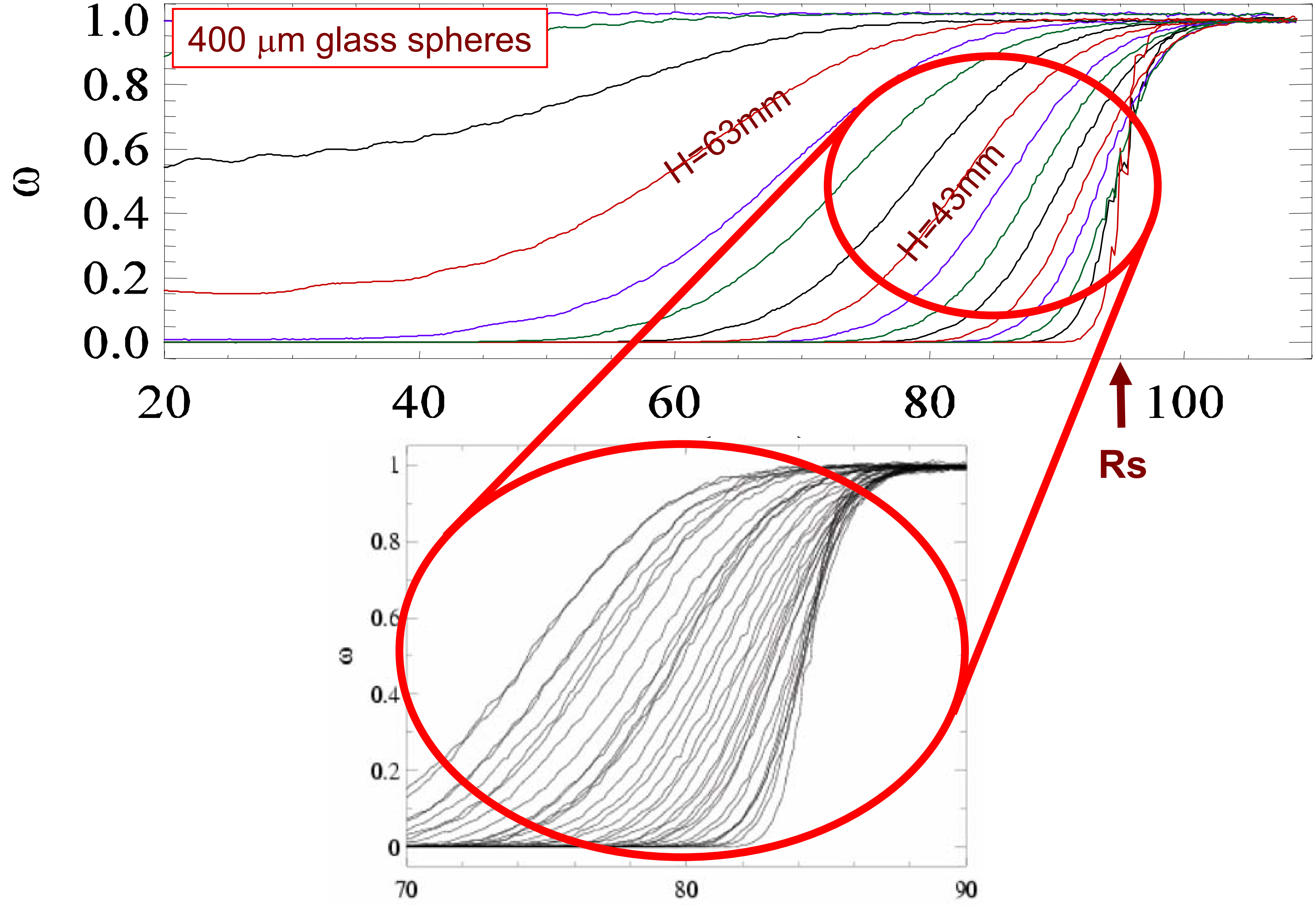
Azimuthal

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

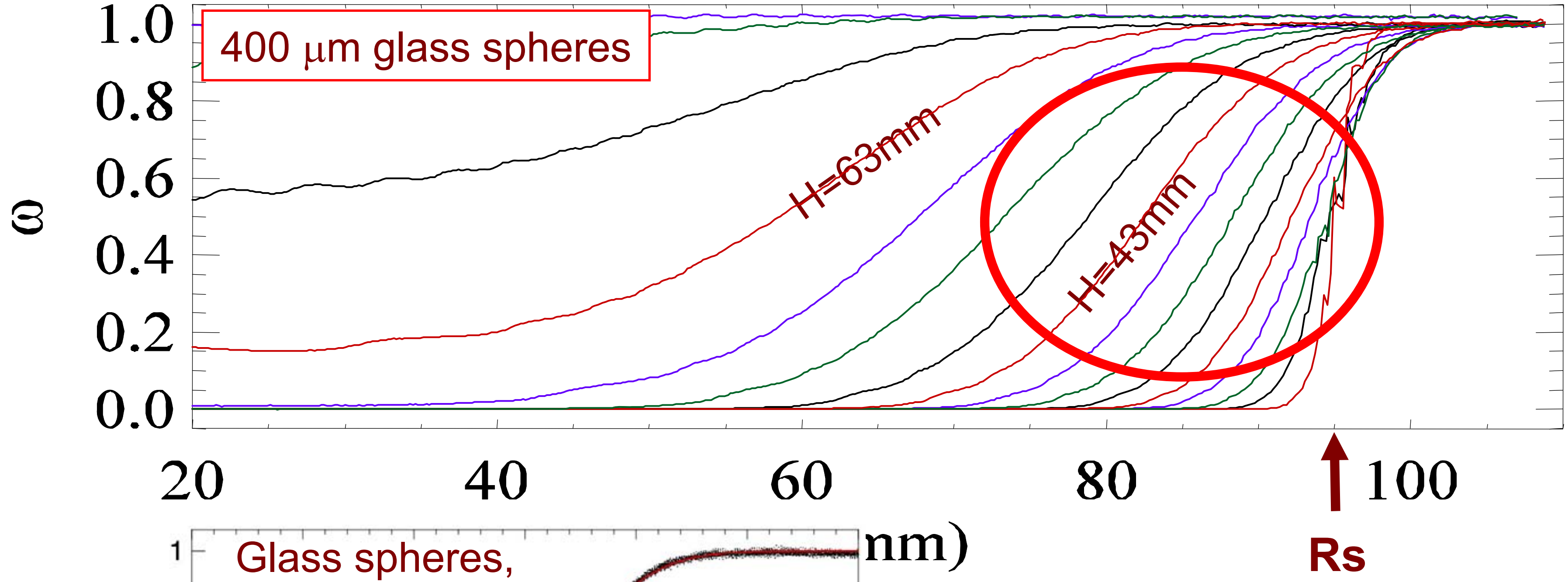


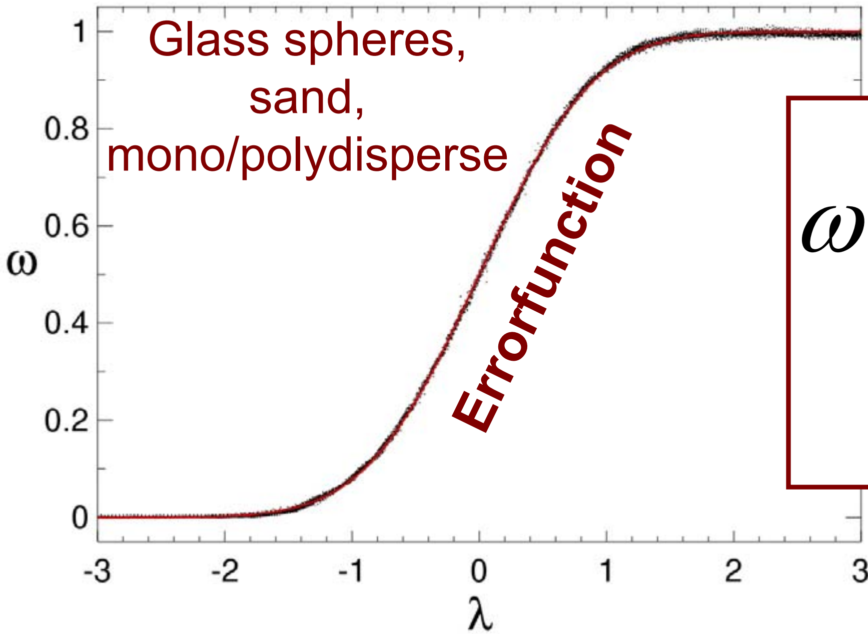
D. Fenistein, JW. van de Meent and MvH, *PRL.* **92**, 094301 (2004); **96,** 118001 (2006).
D. Fenistein and MvH, *Nature* **425**, 256 (2003).

Shallow Layers



Shallow Layers



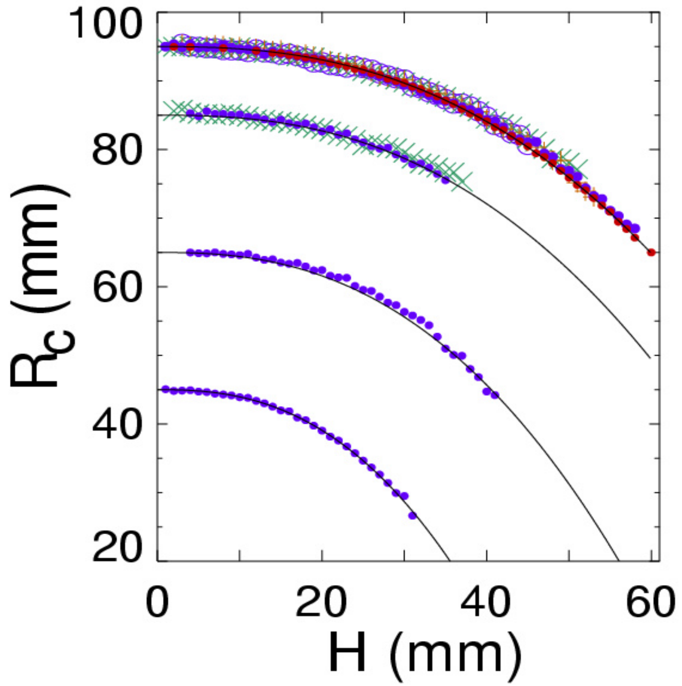


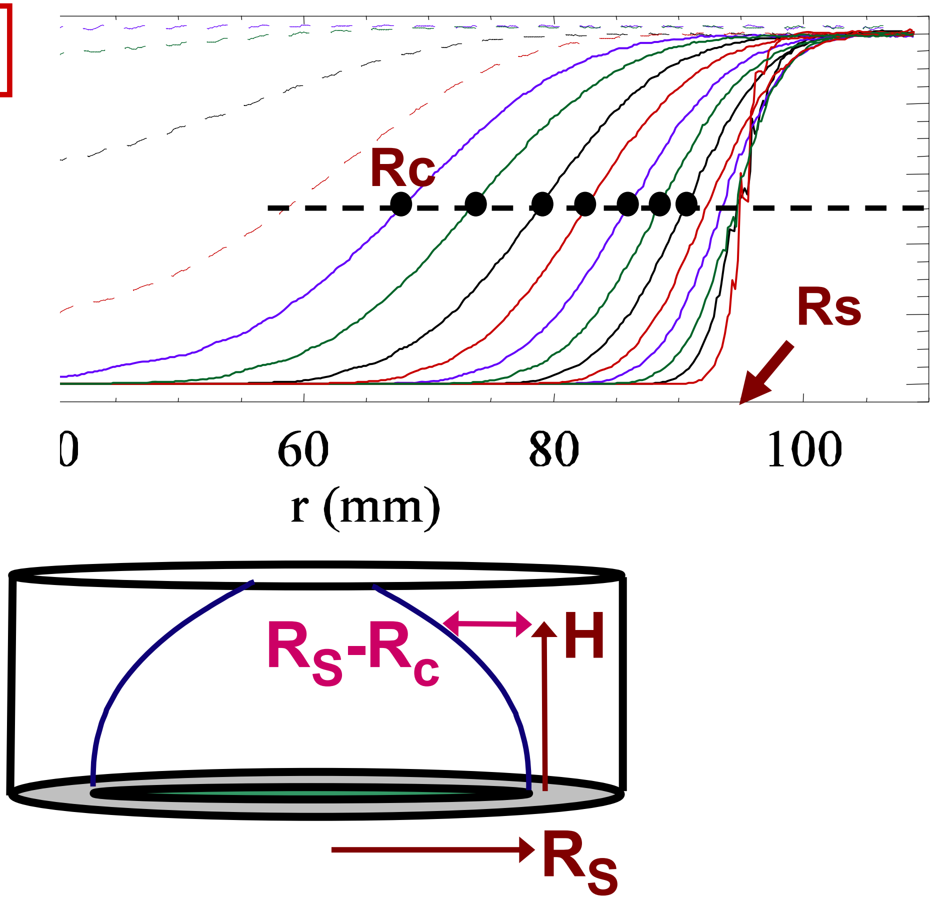
$$\omega(r) = \frac{1}{2} + \frac{1}{2} erf\left(\frac{r - R_c}{W}\right)$$

$R_c, W : functions(R_s, H, d, ...)$

Shallow Layers: R_c

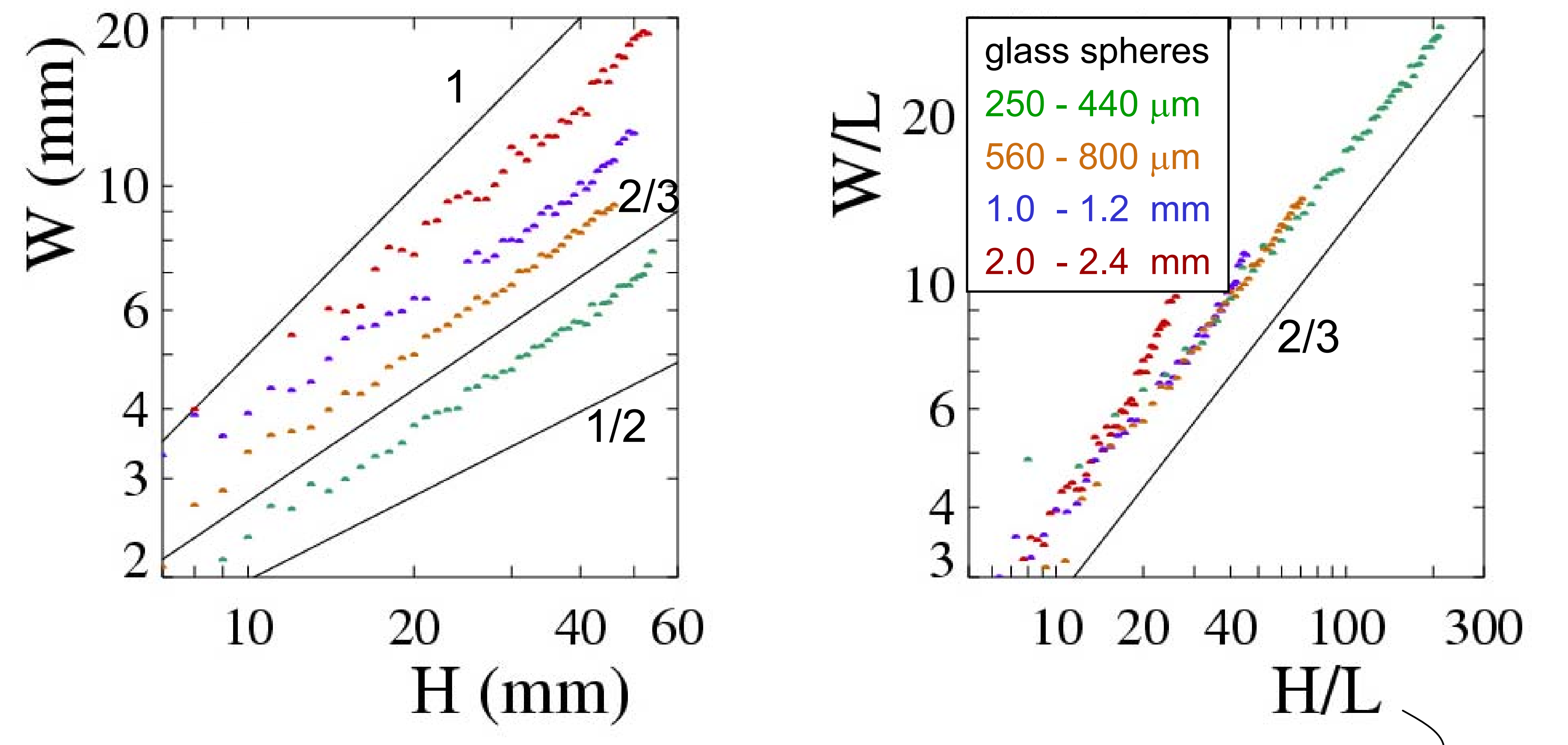
independent of grain size & shape





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

Shallow Layers: W



1.1 mm bronze: W 30% smaller

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

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

Wide & Universal Shear Zones

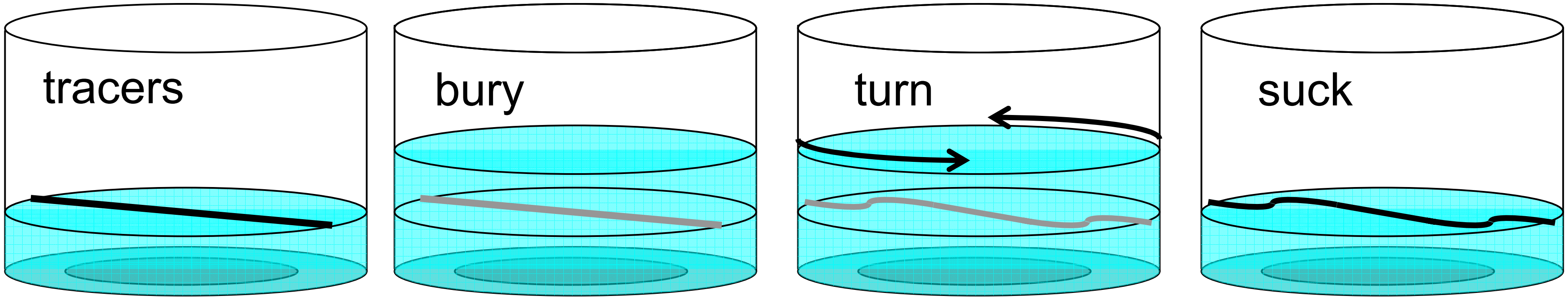
$\omega(r) = 1/2 + 1/2 \ \mathrm{erf}[(r - R_c)/W]$

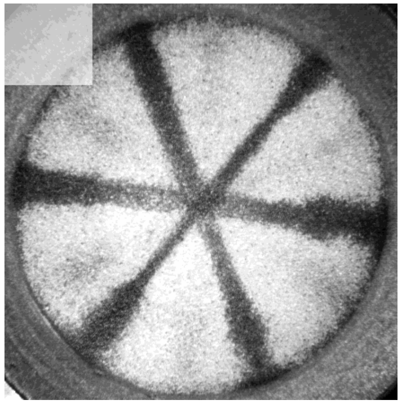
$(R_s - R_c)/R_s = (H/R_s)^{5/2}$: Independent of particles

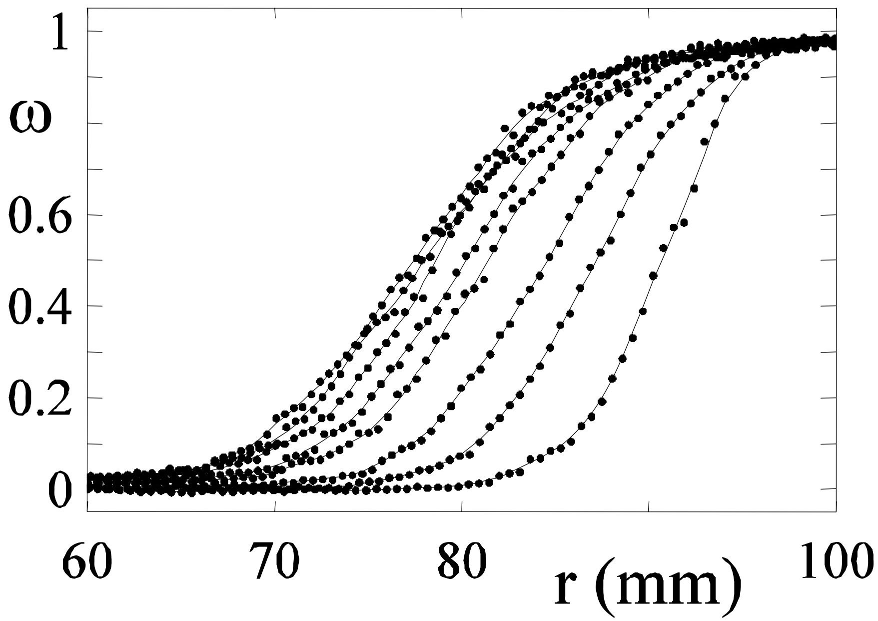
$W/d \sim (H/d)^{2/3}$: Independent of R_s

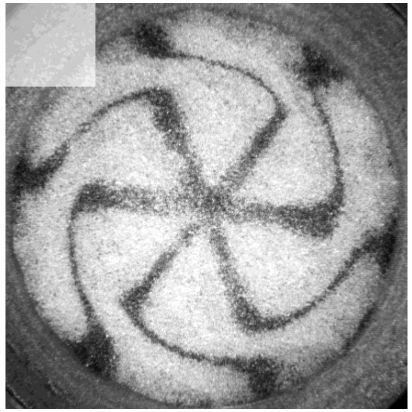
D. Fenistein, JW. van de Meent and MvH**,** *Phys. Rev. Lett.* **92**, 094301 (2004); **96,** 118001 (2006).
D. Fenistein and MvH, *Nature* **425**, 256 (2003).

3D Profile: What happens inside?

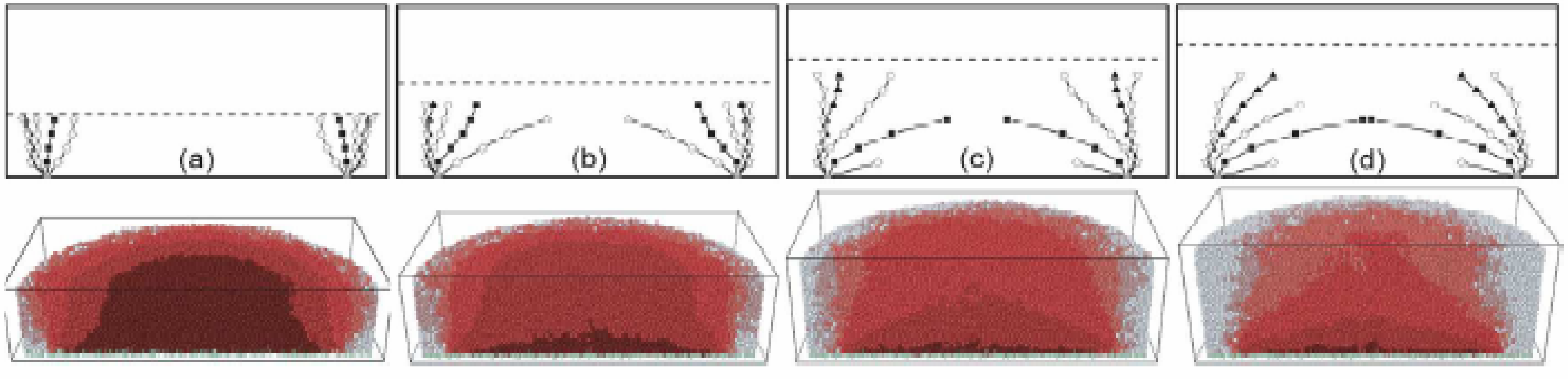


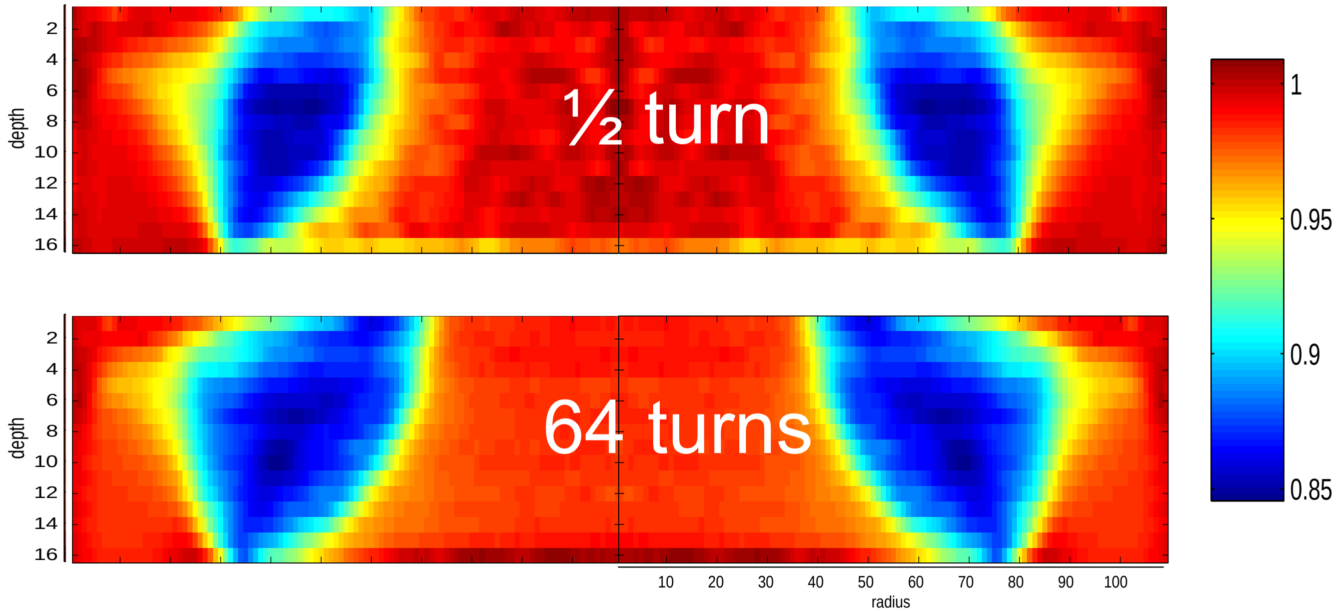






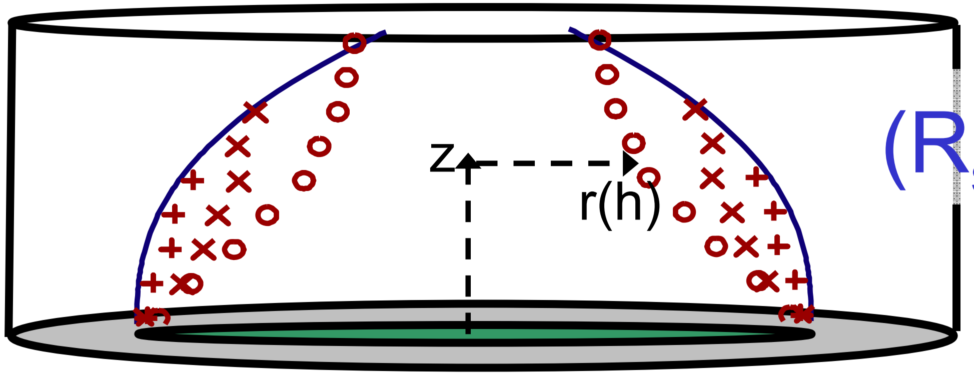
More 3D Data





X Cheng, JB Lechman, AF Barbero, GS Grest, HM Jaeger, GS Karczmar, ME Möbius, SR Nagel, Phys. Rev. Lett., 96 (2006) 038001.
P B Umbanhowar, MvH et al, in prep PREPRINT

Location in Bulk



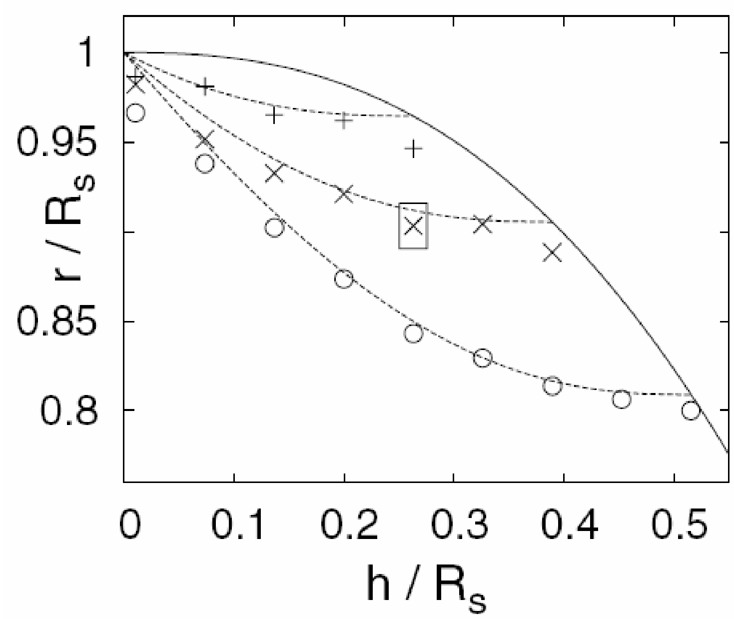
$(R_s - R_c)/R_s = (H/R_s)^{5/2}$

R_c in bulk: Scaling argument virtual bottom OK

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

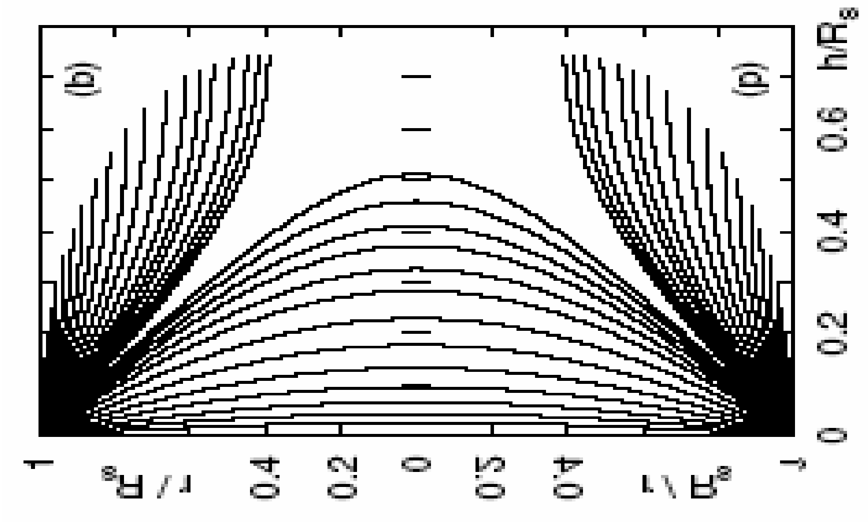
$\alpha = 5/2$

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



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

Model: Friction in Continua

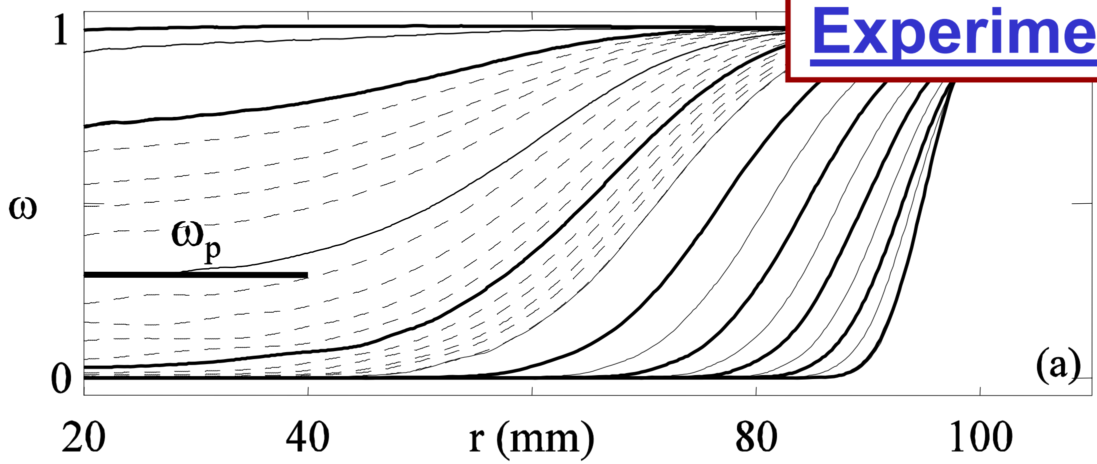


Constant Friction

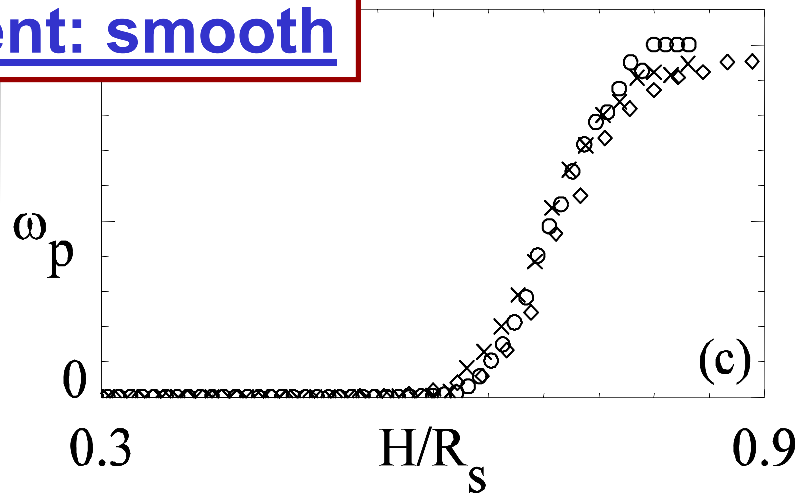
Torque minimalization

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

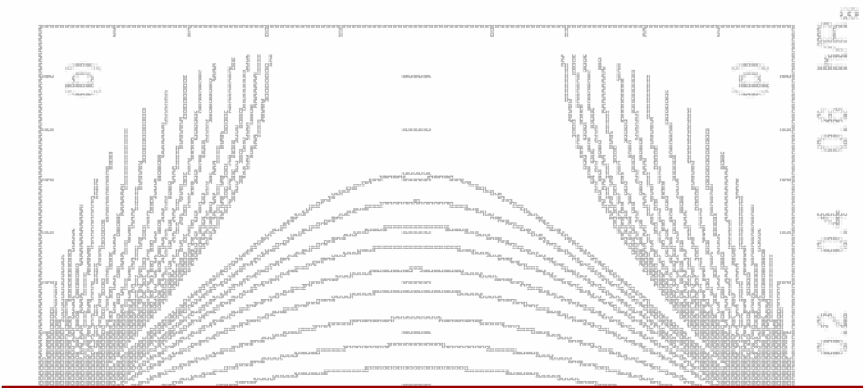
Theory: first order transition



Experiment: smooth



Model: Friction in Continua



Constant Friction

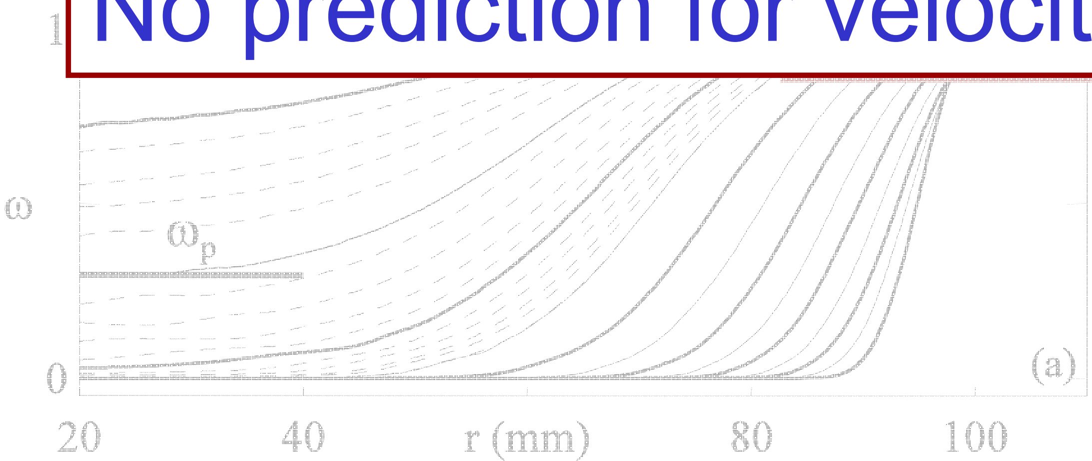
Torque minimalization

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

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

3D shearband phenomenology: position ok.

No prediction for velocity profiles, width!



Break

Not Always Narrow Shearbands

No Theory for Wide Shear Zones

What do these flows imply for **Stress & Rigidity**

Stresses in Smooth, Slow, Dense Granular Flows

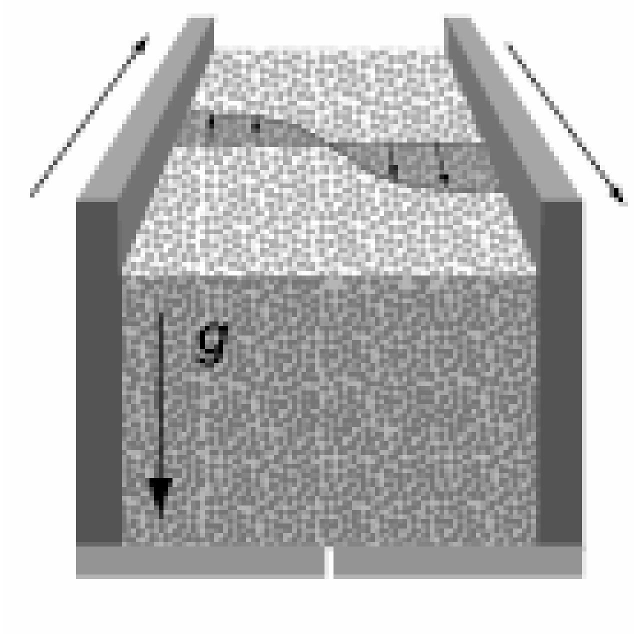
Rate Indepence: Stresses independent of driving rate.
Velocity profiles independent of driving rate

Wide Shear Zones

Stress fluctuations relax fast :
stresses are dynamically generated
(no elastic stresses)

M. Depken, W. van Saarloos and MvH., Phys. Rev. E 73, 031302 (2006).
M. Depken, J. B. Lechman, MvH, W. van Saarloos and G. S. Grest, EPL 78, 58001 (2007).

Linear Geometry: Shear Free Sheets



Rate Independence: Stresses independent of driving rate.

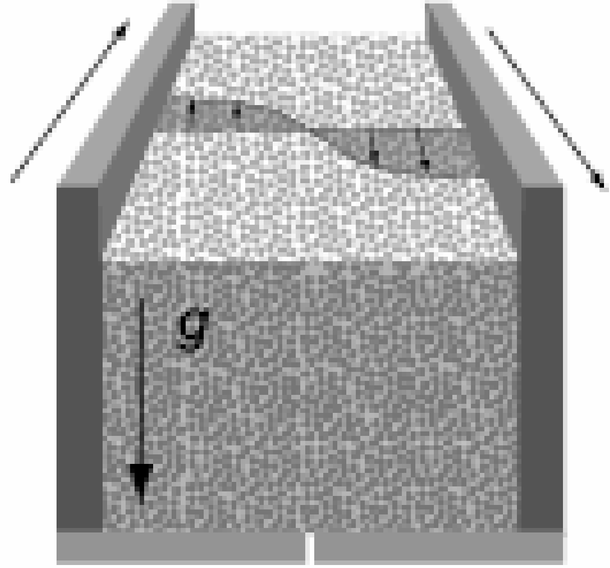
Wide Shear Zones

Stress fluctuations relax fast : No shearflow, no shear stress

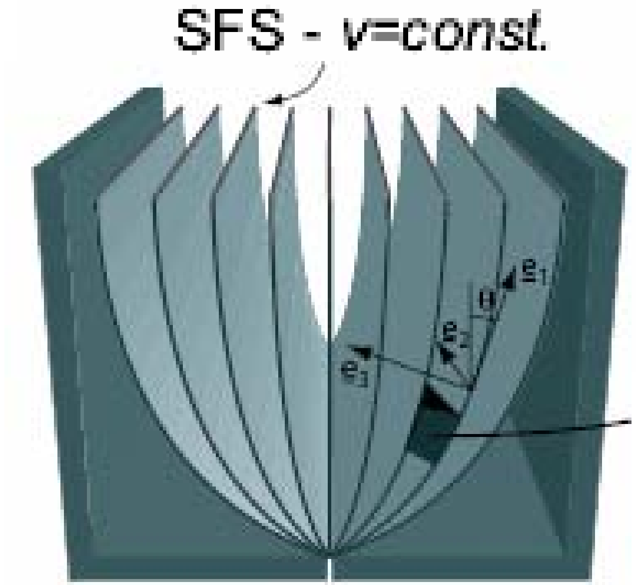
M. Depken, W. van Saarloos and MvH., Phys. Rev. E 73, 031302 (2006).

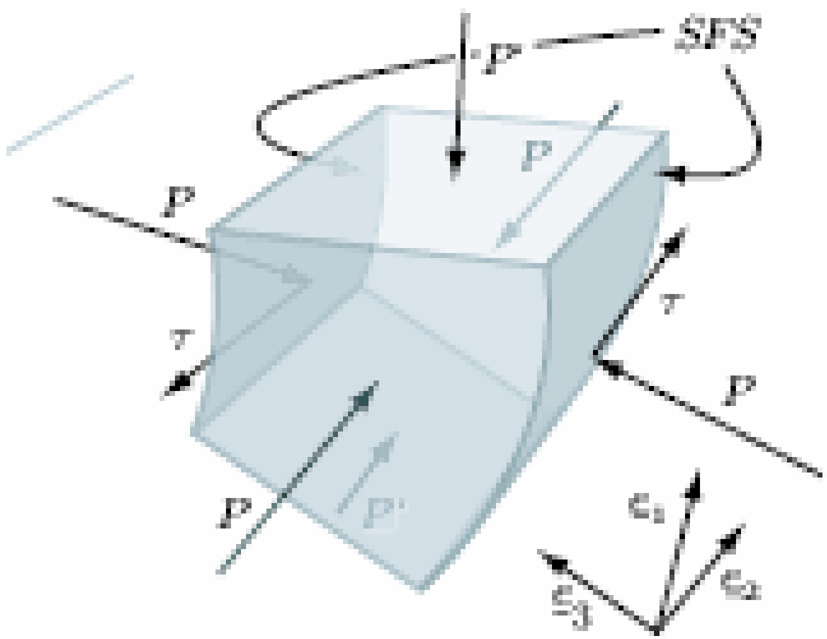
M. Depken, J. B. Lechman, MvH, W. van Saarloos and G. S. Grest, EPL 78, 58001 (2007).

Linear Geometry: Shear Free Sheets



$$(\underline{\underline{\sigma}})_{\mathrm{SFS}} = \begin{pmatrix} P' & 0 & 0 \\ 0 & P & \tau \\ 0 & \tau & P \end{pmatrix}$$



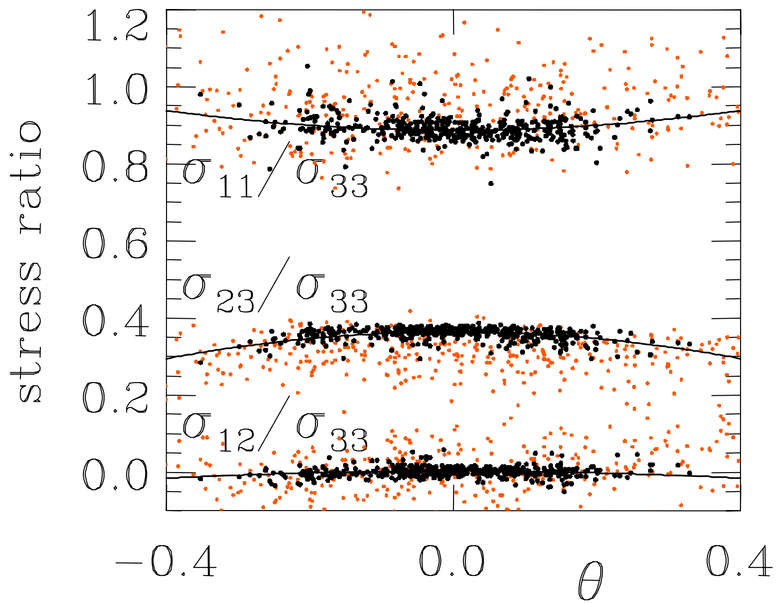


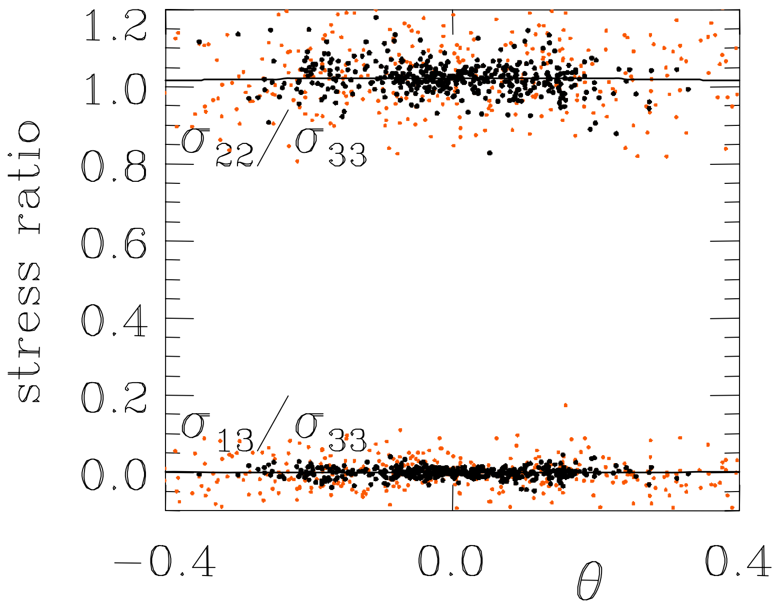
Test Stress Tensor

$$\begin{pmatrix} P' & 0 & 0 \\ 0 & P & \tau \\ 0 & \tau & P \end{pmatrix}$$

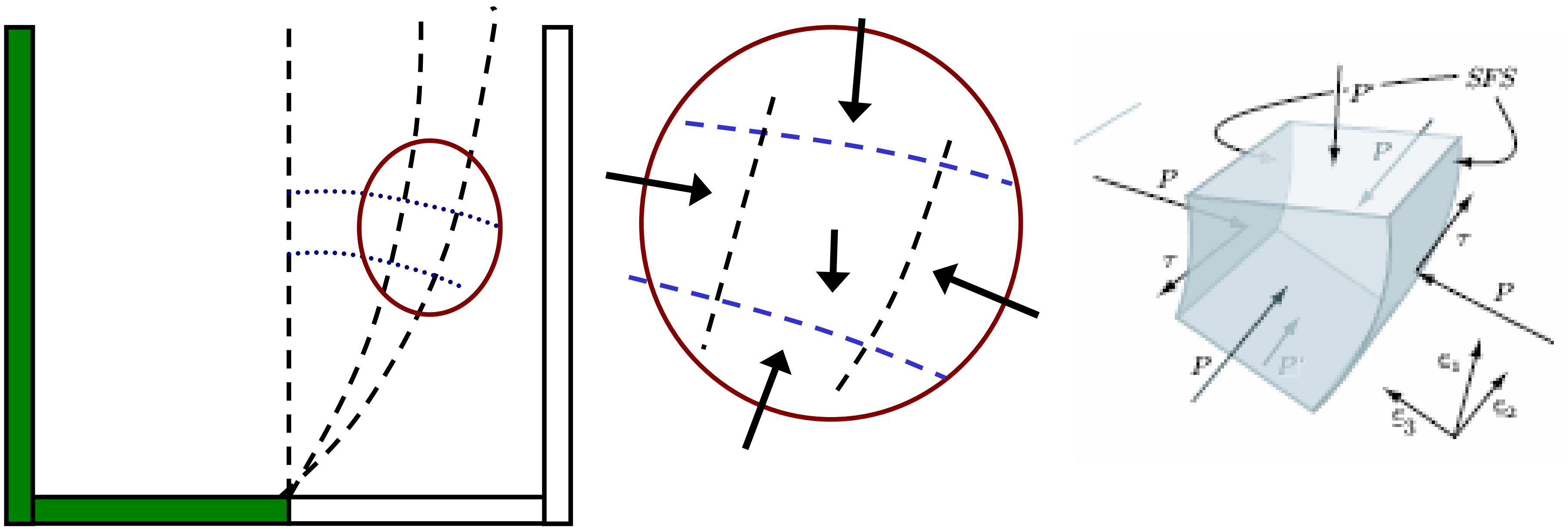
$\sigma_{11}/\sigma_{33} = ?$ $\sigma_{12}/\sigma_{33} = 0$ $\sigma_{13}/\sigma_{33} = 0$

$\sigma_{22}/\sigma_{33} = 1$ $\sigma_{23}/\sigma_{33} = \mu = ?$





Effective friction cannot be constant!

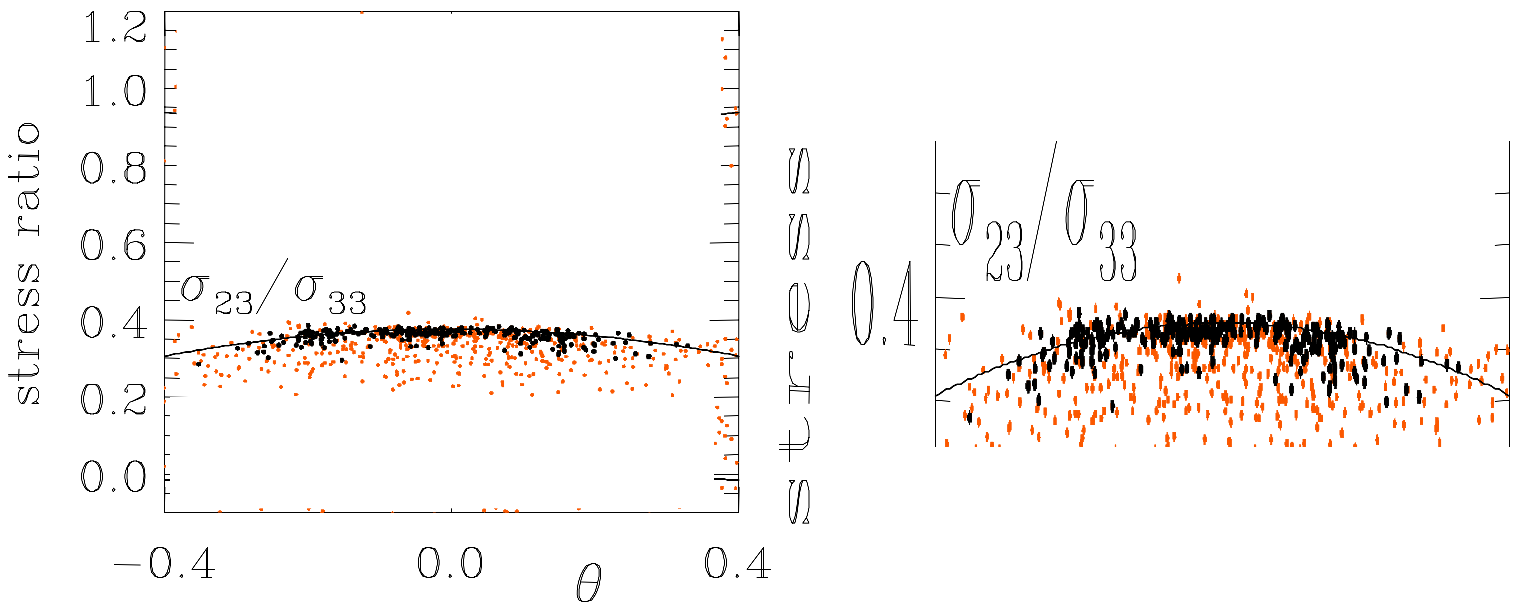


μ constant: NO Force balance

↓

μ has to decrease away from vertical SFS

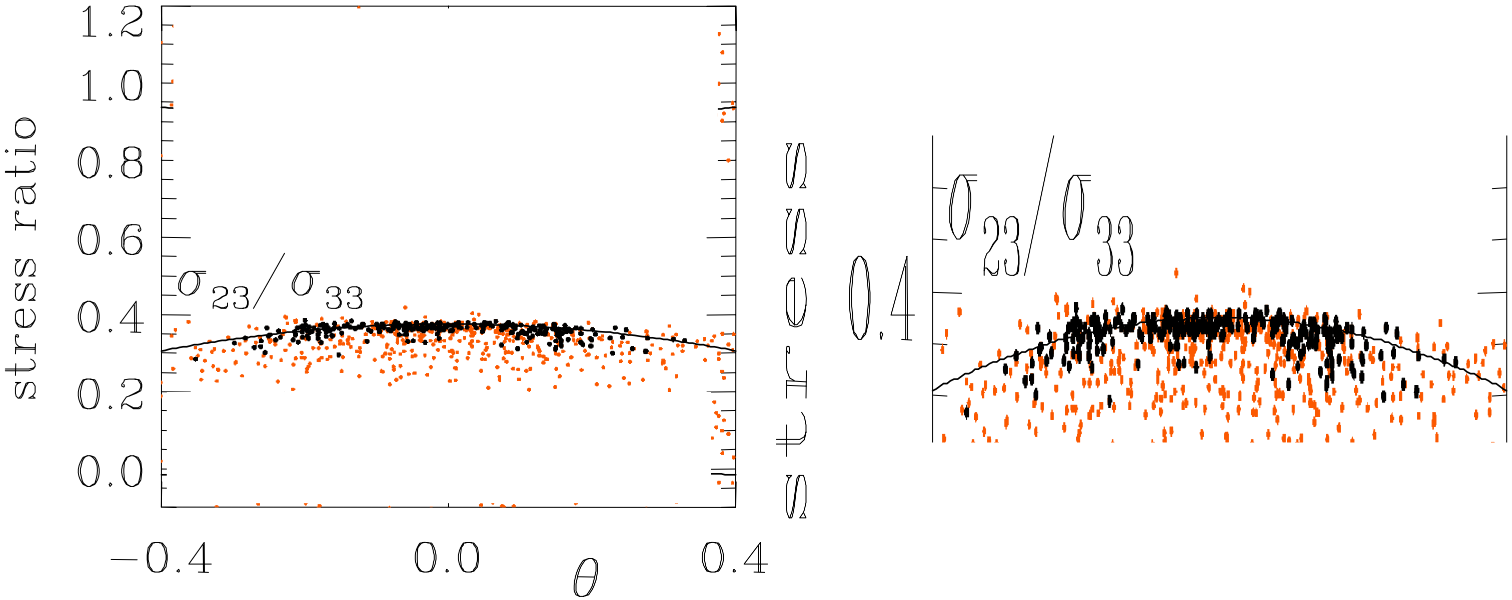
Effective friction cannot be constant!



μ constant: NO Force balance

μ has to decrease away from vertical SFS

Effective friction cannot be constant!



Subtle, but necessary

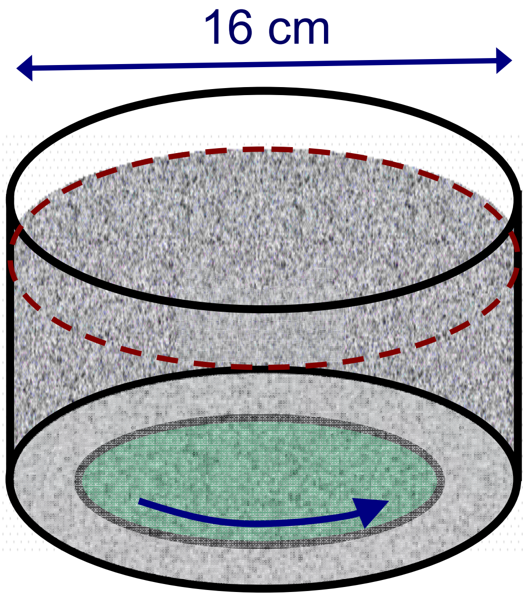
Consistent with width shear zones

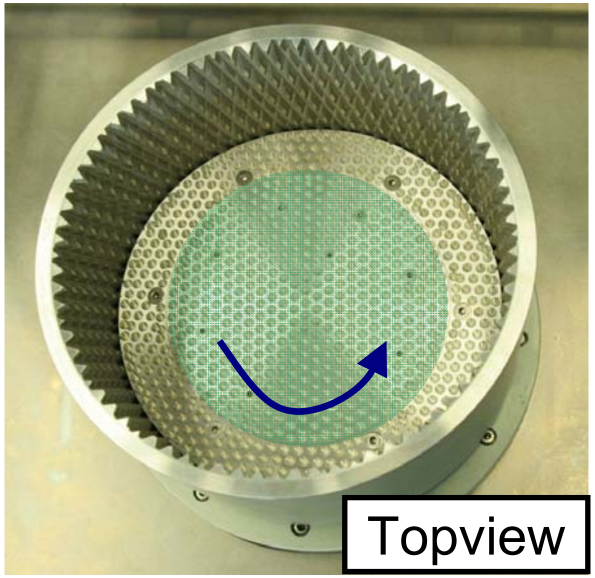
Unger et al see similar variation in μ in zero gravity simulations (PRE 2007)

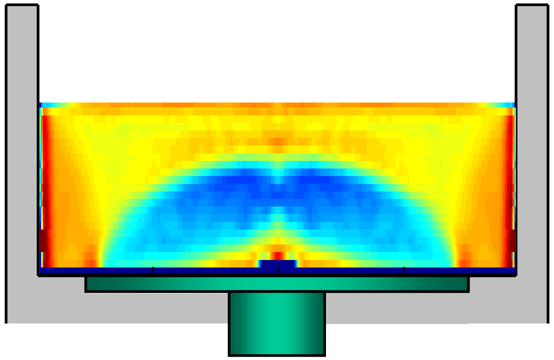
Classical constant friction picture fails

... what about this stress relaxation?

Setup

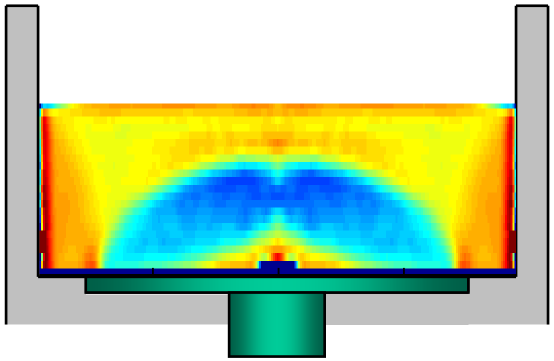


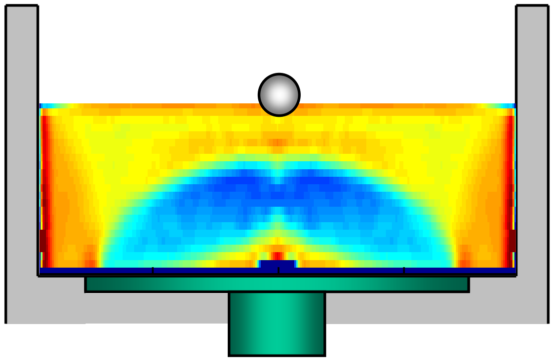




Yield Criterion in presence of flow?

Yield stress is lowered!!!





A Stationary Granular Fluid

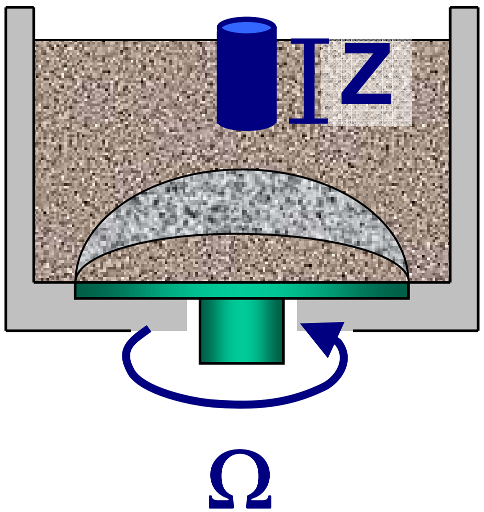
What happened to yield stress?

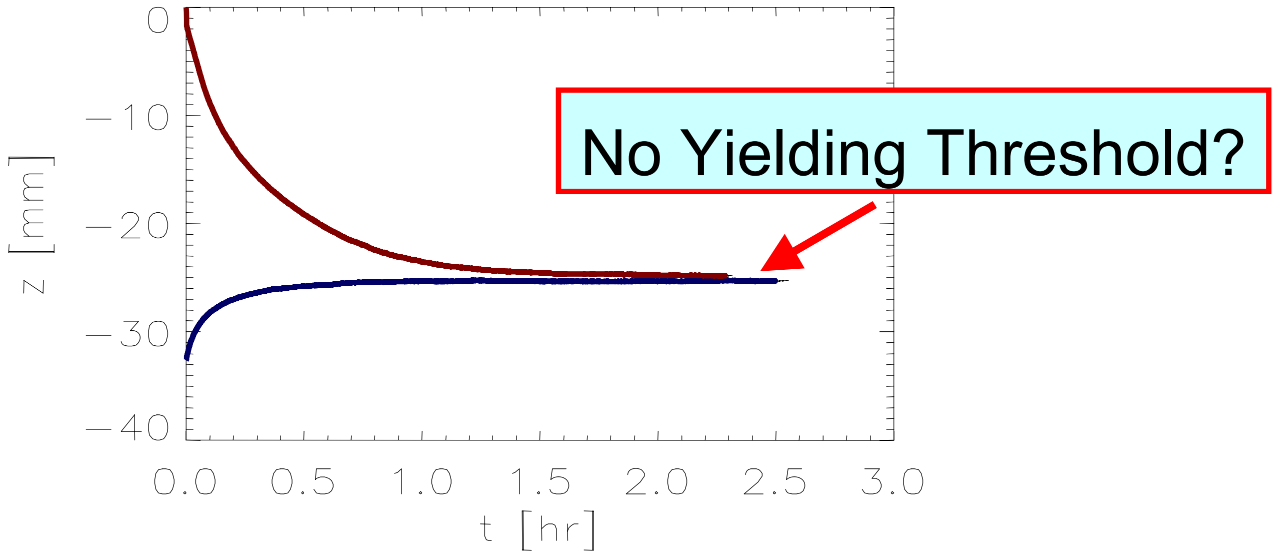
Yield stress vanishes - Archimedes Law

Mechanism?

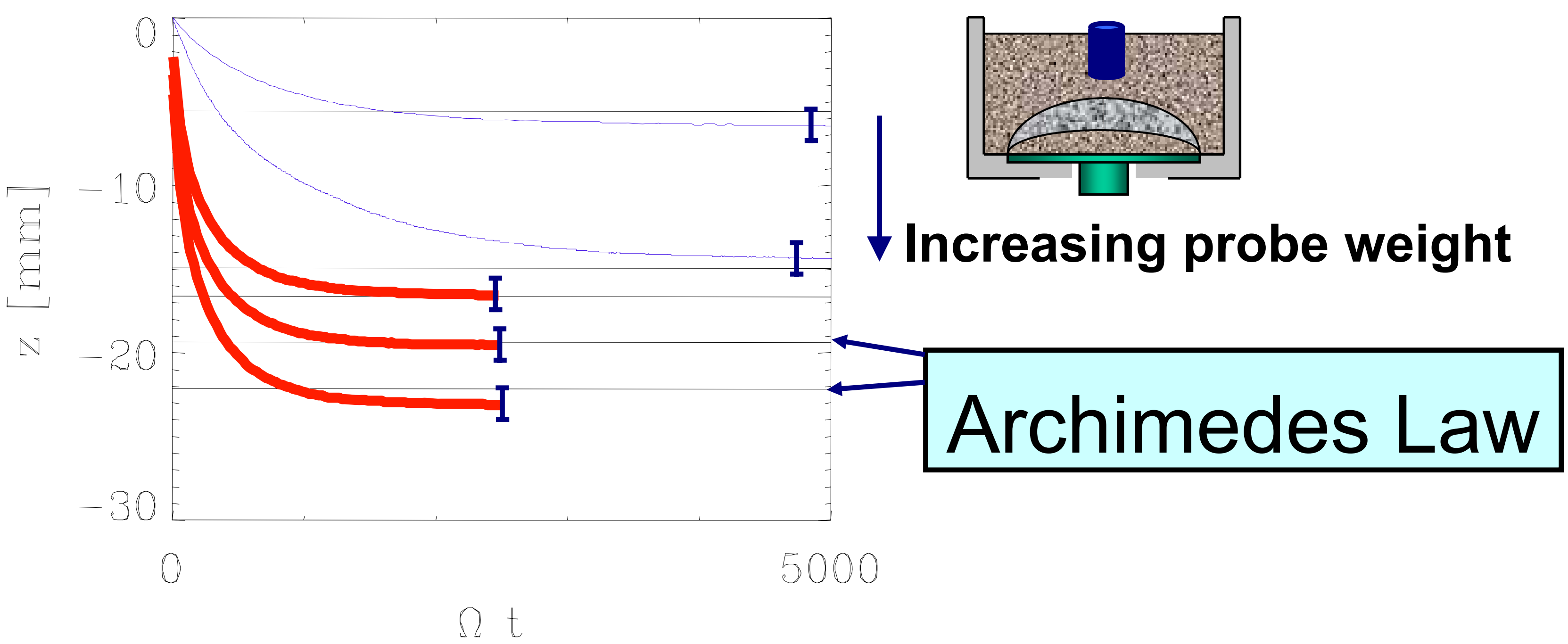
Agitations - Nonlocal

Floating in Sand



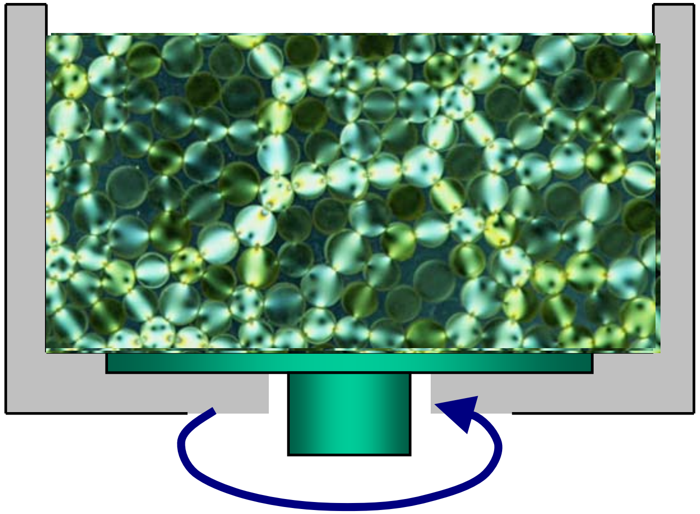


Floating in Sand



No yielding threshold in presence of flow

A Stationary Granular Fluid: Agitations



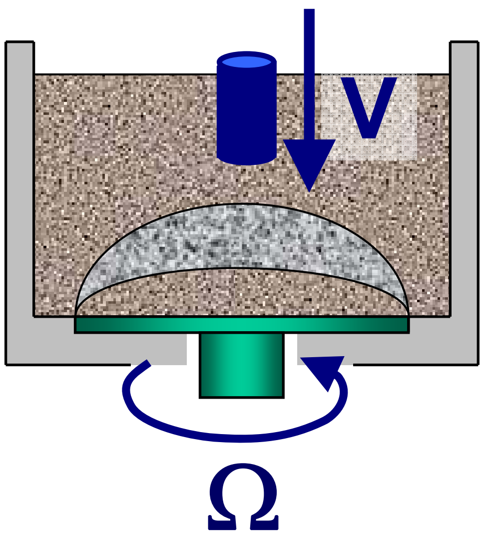
Contact Forces + Flow

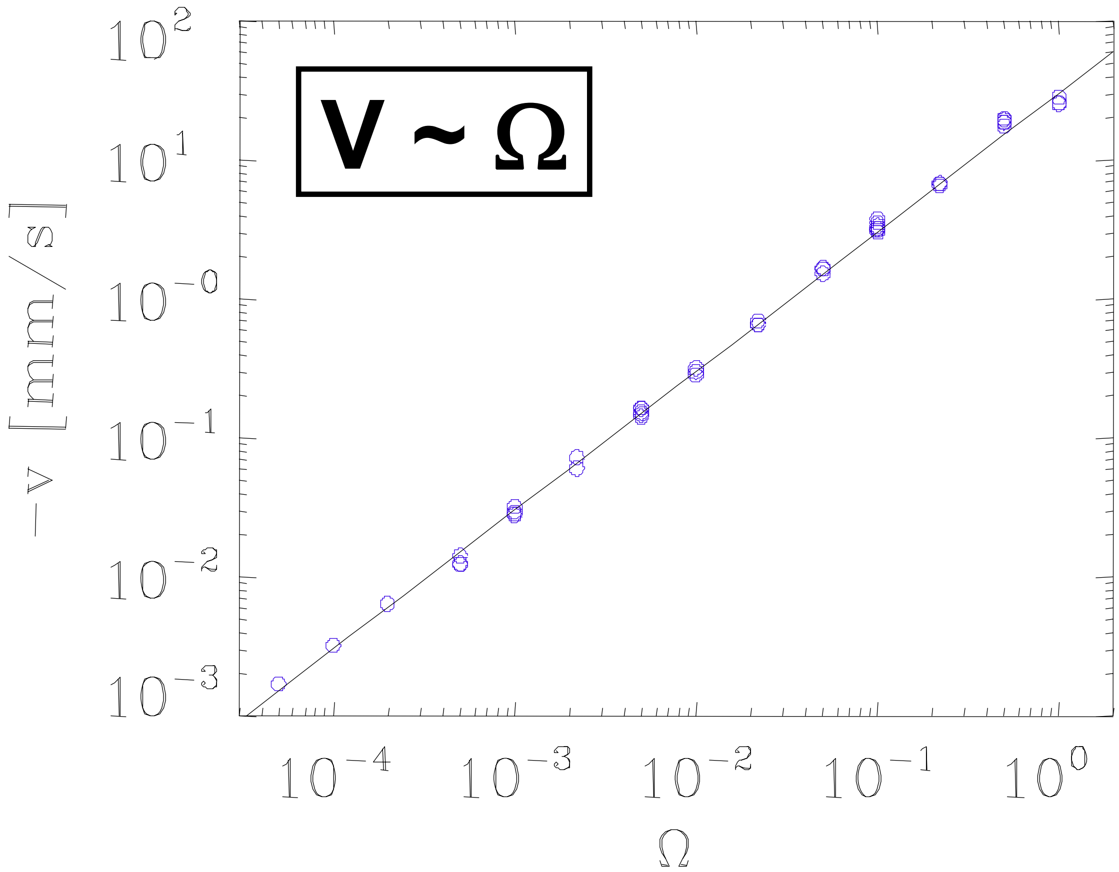
Fragile (heating 1 grain by 1C....)

Hard Grains (mm/nm)

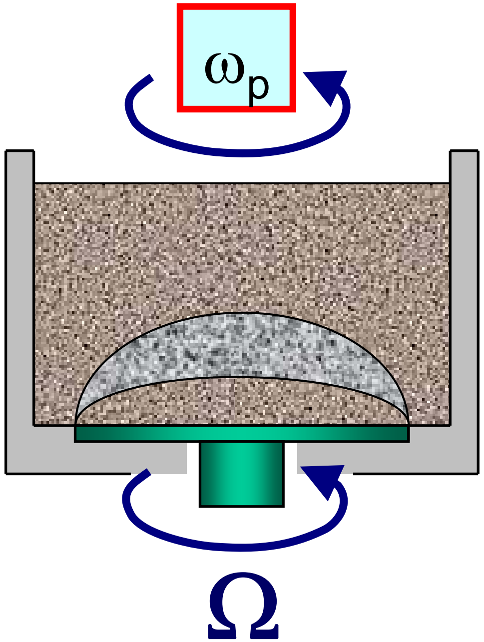
Rotation rate Ω sets probe speed?

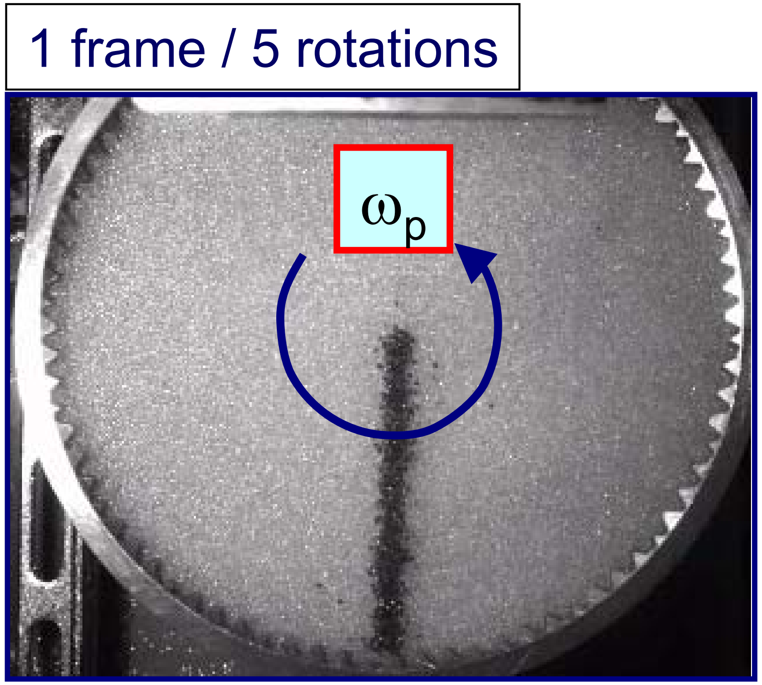
A Stationary Granular Fluid: Mechanism





A Stationary Granular Fluid: Mechanism

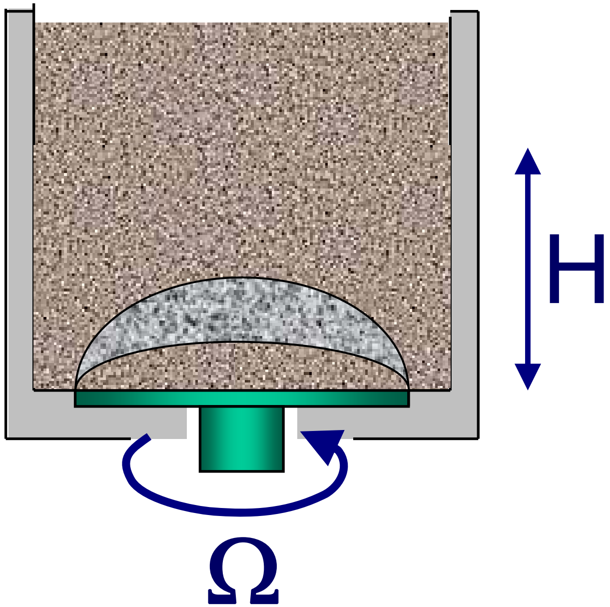


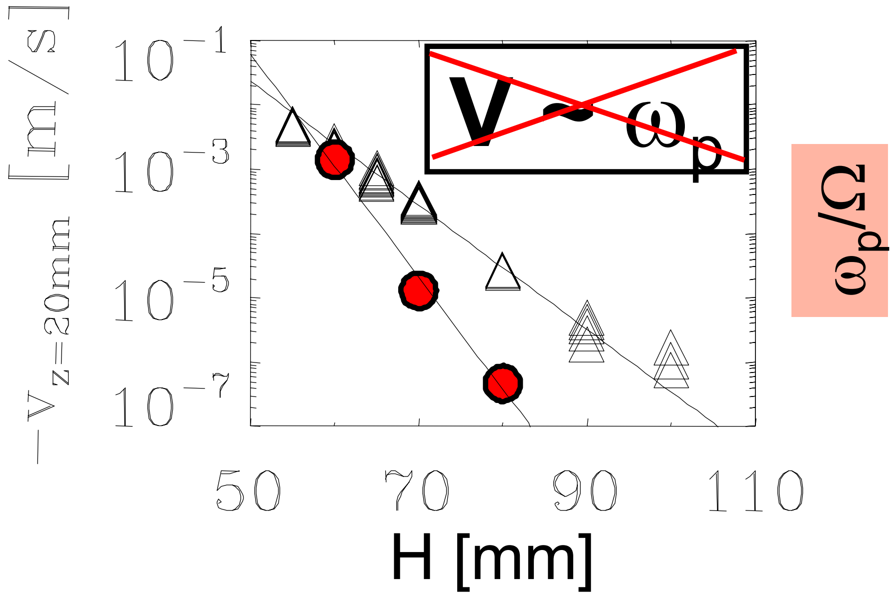


$\omega_p \sim \Omega$ & $\mathbf{V} \sim \Omega$

$\mathbf{V} \sim \omega_p$?

A Stationary Granular Fluid: Mechanism





NONLOCAL:
Flowrate in A, determines flowrate in B

Slow Granular Flows

Not Always Shear Bands

Classical Picture based on Friction **Fails**

New Framework: **Shear Free Sheets**

Experiments: **Melting** Sand by Stirring

Outlook: Agitation Field

Relations with fast and wet flows

Openings for grad students and postdocs

www.physics.leidenuniv.nl/sections/cm/grm