# Summer School: Granular Materials – from Simulations to Astrophysical Applications

***Hosted by CSCAMM and the University of Maryland Burgers Program in Fluid Dynamics***

## Organizers:

Derek Richardson, Astronomy

Wolfgang Losert, Physics

Eitan Tadmore, CSCAMM

## Support:

Burgers Program for Fluid Dynamics

Center for Theory and Computation

National Science Foundation

European Space Agency

[NASA support requested]

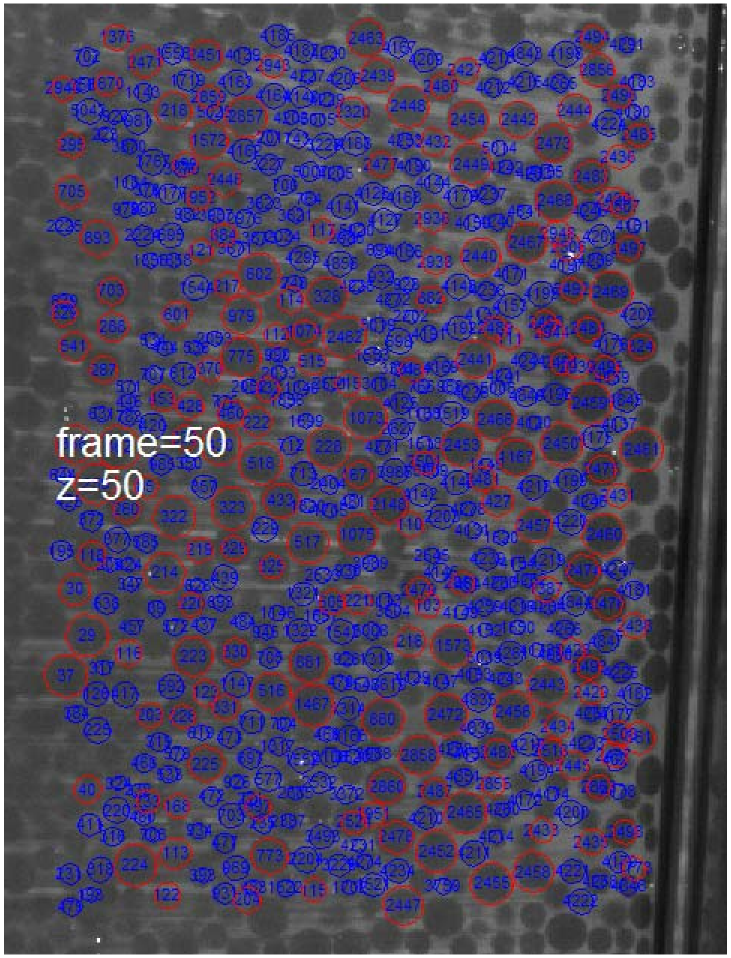
# Labtours Friday June 17th

2pm Neutral Buoyancy Facility (test of weightless robotics)

2.30pm Dynamo Experiment (self generation of magnetic fields)

3pm Three dimensional imaging of granular flows

3.30pm Fluid Dynamics Lab (tentative)



# Outline

Intro:  What are granular materials?

Granular Materials Jam

Granular Materials Age and Strengthen

Granular Flow

Granular Gas

Segregation

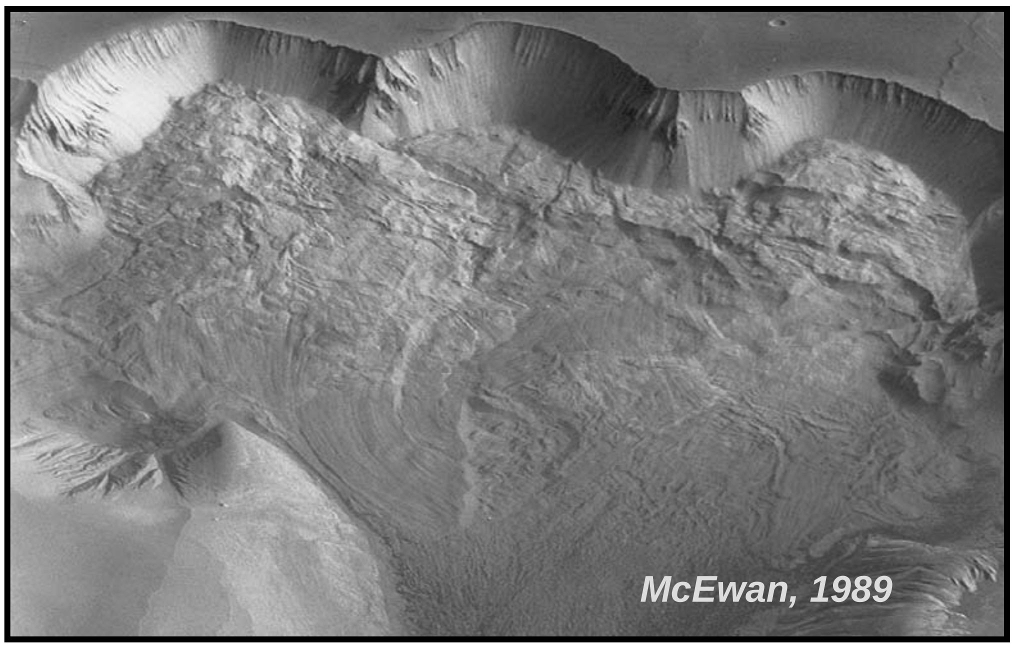
Astrophysical Applications

# Granular materials



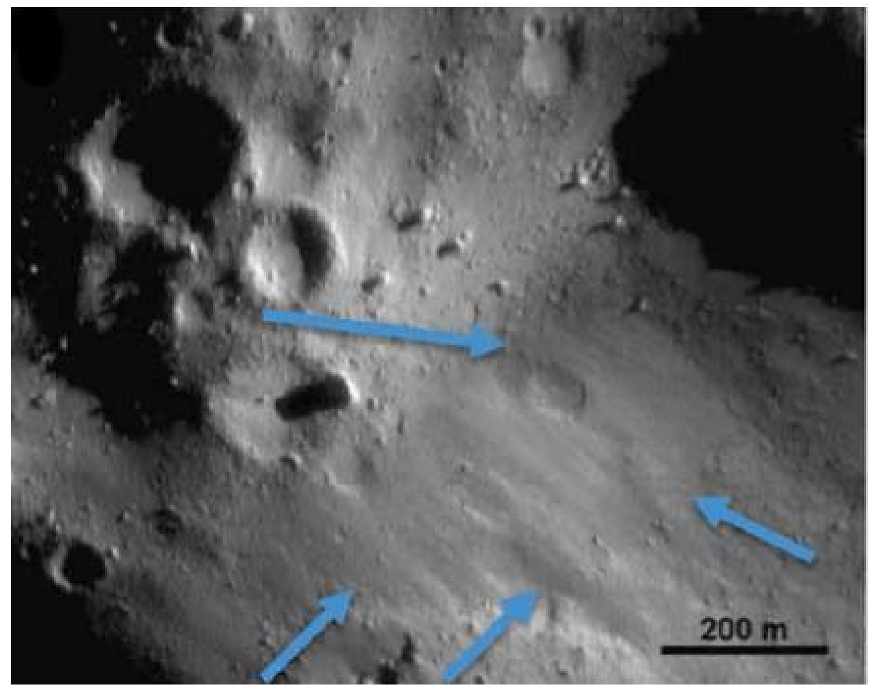

# Astrophysical granular matter

MARS




Mars rock avalanche. The landslide fell 5 miles and ran out 65 miles.

ASTEROID




Regolith migration on Eros

# Static Granular Materials

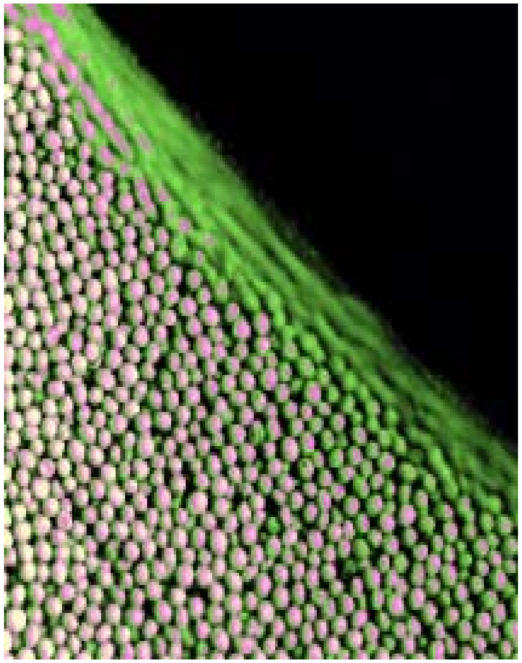

http://www.photos-voyages.com/selection/sand-dune.html

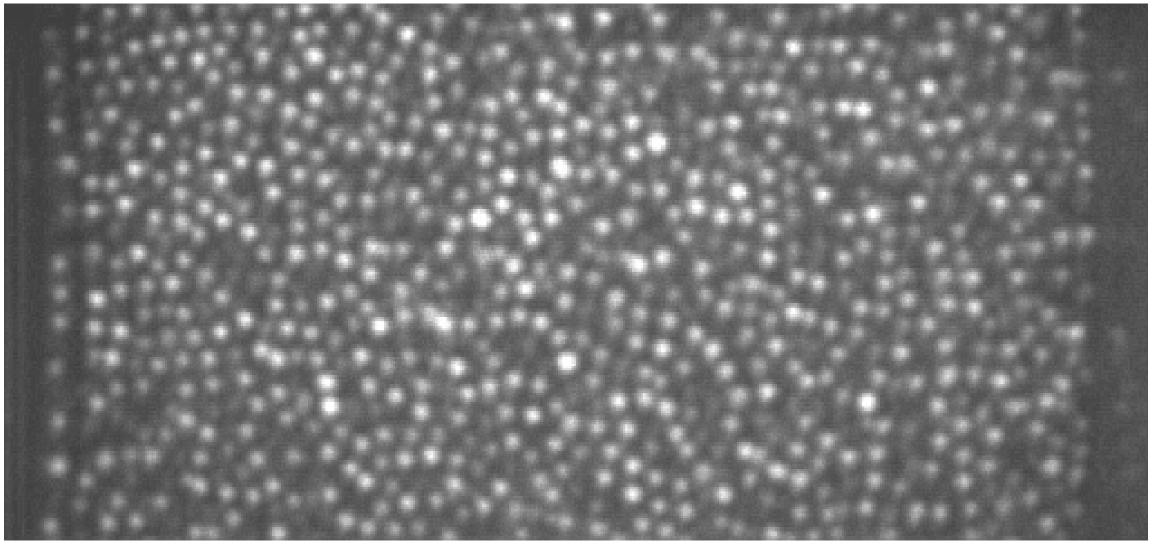
Nature, 387 (1997)

# Flow of Granular Matter

## Avalanches

## Shear Flows



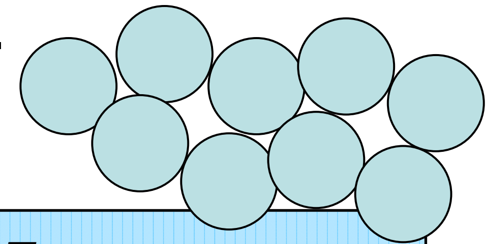


http://www.youtube.com/watch?v=5Xw0NPSviAk

http://www.youtube.com/watch?v=6qVwIuznFW0&feature=related
http://www.youtube.com/watch?v=UOFMIjDmw6A&feature=fvst
http://www.youtube.com/watch?v=2IItP7dVoYc&playnext=1&list=PL7E11AEC3A4A077BE&inde
x=3
http://video.google.com/videoplay?docid=4401583576558606021#

# Granular Materials

Made up of many solid particles >> 1 micron.



Lifting 1 mm bead by one bead diameter: $\frac{k_b T}{mgd} \approx 10^{-12}$

Motion requires energy input >> thermal energy

Interaction between grains (Friction and inelastic collisions) dissipates kinetic energy.

System not in thermal equilibrium

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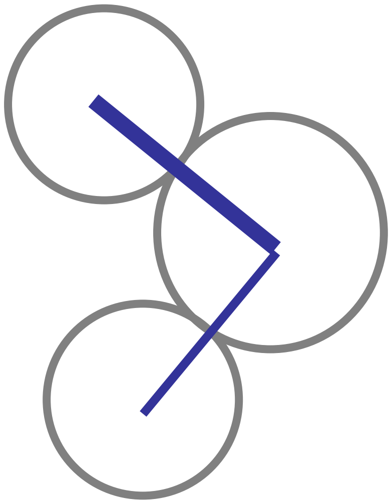
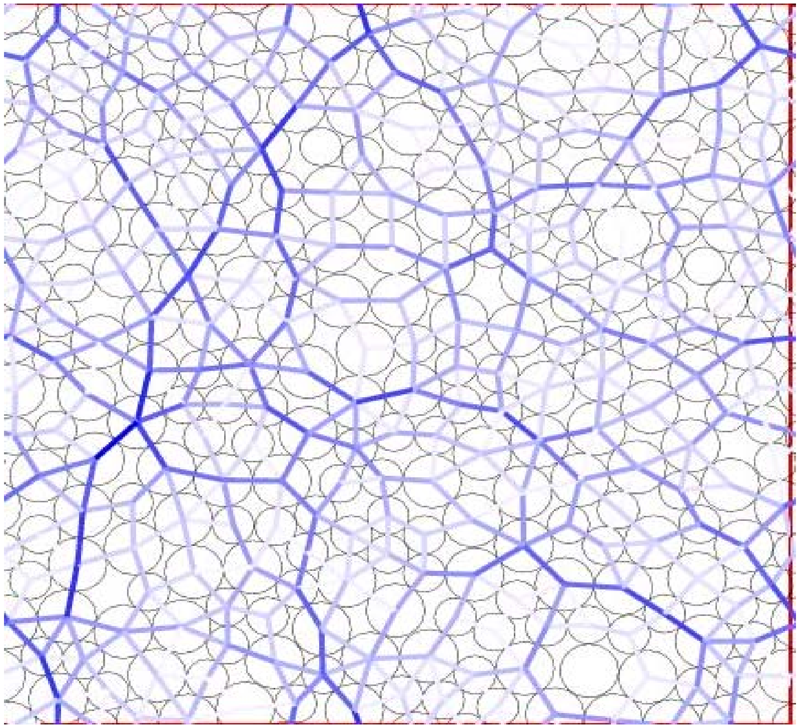
Wolfgang Losert wlosert@umd.edu

# Static granular matter: jammed state

Without energy input, in confinement,
granular matter is jammed



Blue line: Contact force
brightness ~ Magnitude



From Corey O'Hern

Significant progress in past 10 years to define and characterize an idealized jamming transition for hard spheres without friction.
(Liu, Makse, Nagel, O'Hern, Radjai, Snoijer, Saarloos, etc)

# Challenges in modeling jamming

Since kT is too small to move grains noticeably, the system does not equilibrate

Physical principles that rely on a thermal equilibrium reference state  (e.g. minimization of free energy, maximization of entropy) do not apply.

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# Experiments on Aging and Strengthening

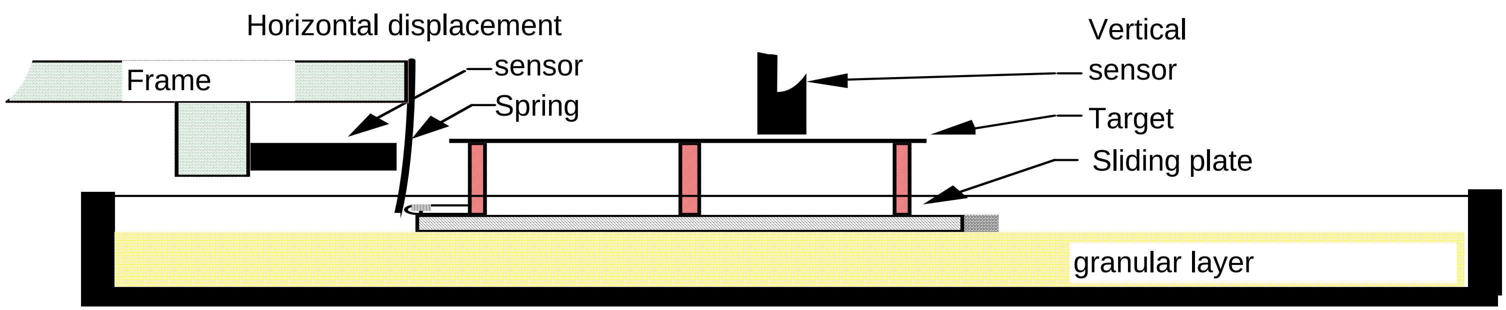



Plate weight: 10-50 g
Granular material: **Glass beads** 70-100 μm DIA
Layer depth: 3 mm
Spring constant: 189.5 N/m

High Sensitivity Measurements

Displacement sensors: $\delta h = 0.1\ \mu m$

Force measurement: $\Delta F / F = 0.01\ \%$

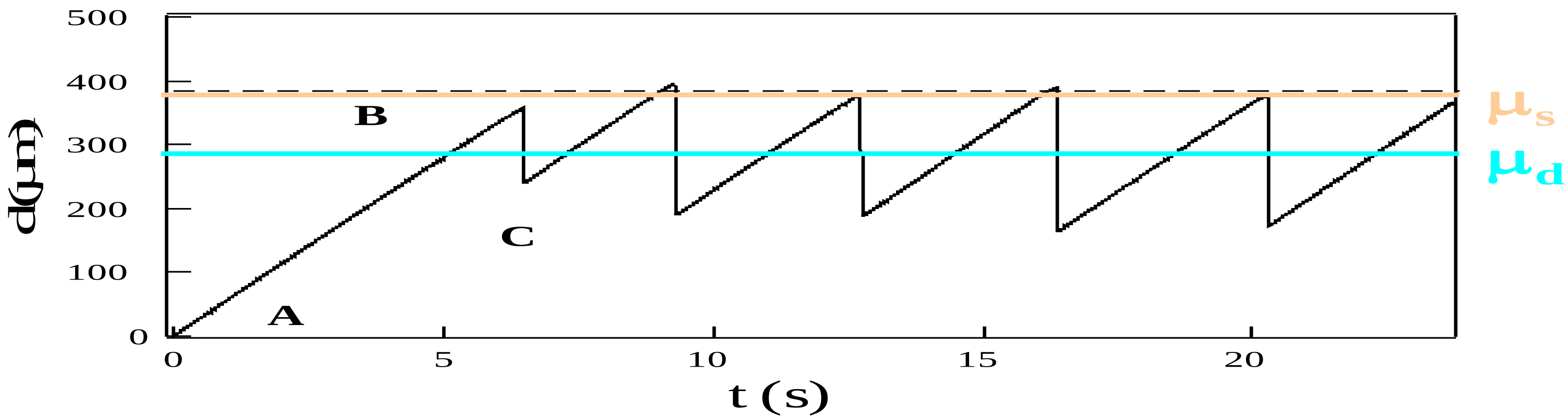
W. Losert et al *Phys. Rev. E.* ***61****, 4060 (2000)*

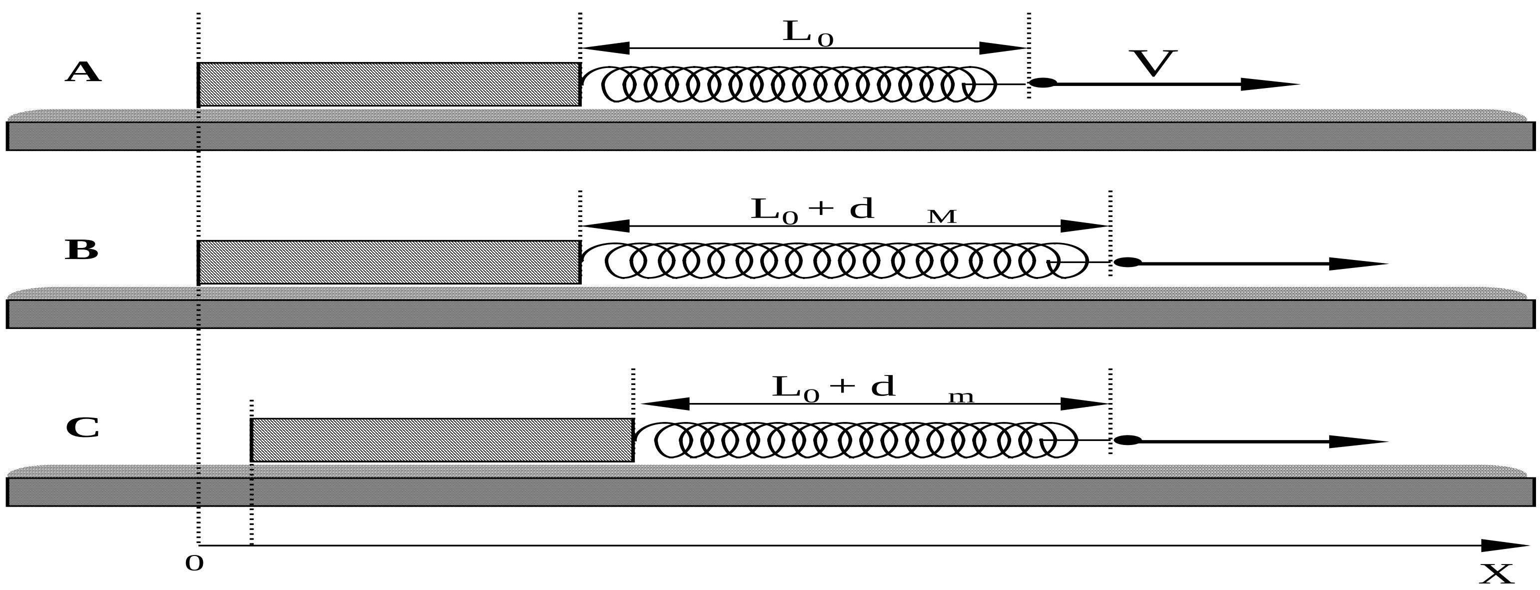
# Friction between two solid objects

Static friction coefficient: $\mu_S = F_S \,/\, F_N$

Dynamic friction coefficient: $\mu_D = F_D \,/\, F_N$

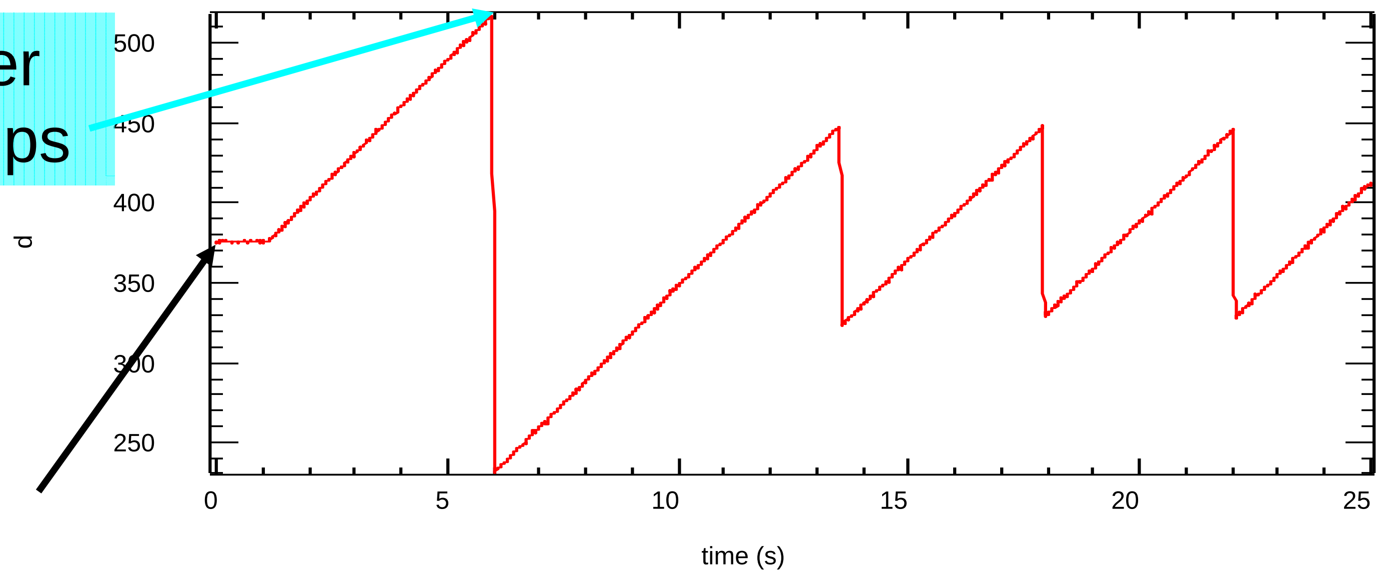
# Dynamics:  Stick-Slip Motion



# Friction in granular material kept under shear stress for 10 hours

$\mu_s$ of first slip larger than $\mu_s$ of other slips




Shear Stress for 10 hours

Stick-Slip motion: m=26.6g, k=189 N/m 11/29/98 experiment

Strengthening of granular layer under stress

# Friction between two solid objects

Static friction coefficient: $\mu_S = F_S / F_N$

Dynamic friction coefficient: $\mu_D = F_D / F_N$

*The above are (very good!) ***approximations.***

Static friction increases with stick time

$$\mu_S = \mu_{S0} + \beta \ln\left(\tau / \tau_0\right)$$

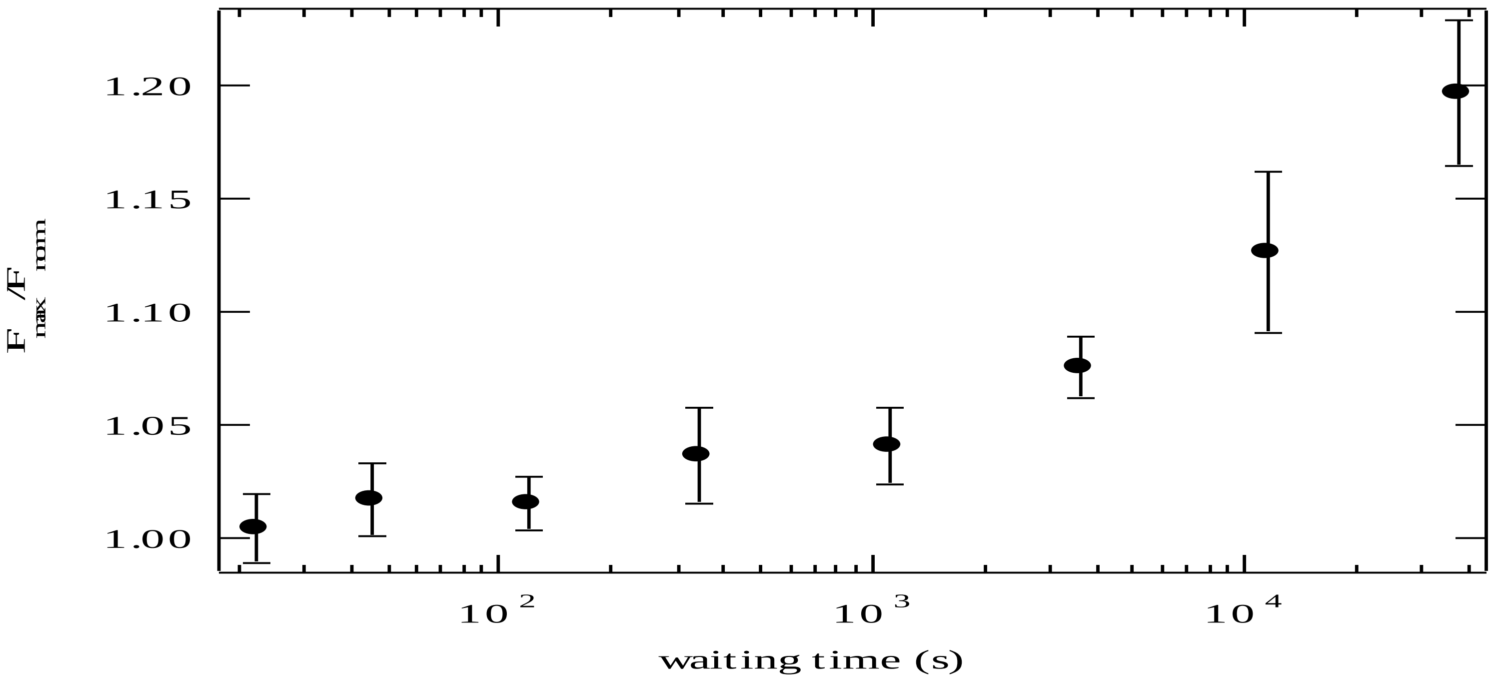
$\beta$ is $O(10^{-2})$

Dynamic friction decreases with sliding speed

$$\mu_D(V) = \mu_{D0} - \beta \ln\left(V / V_0\right)$$

Hahner and Spencer, Phys. Today **51**, 23 (1998)
Krim, MRS Bull. **23**, 20 (1998)

# Waiting Time Strengthening




Friction increases roughly logarithmically with waiting time
(for t > 500 s)

# Geophysical friction laws for granular materials: Dietrich/Ruina

$$\mu_D(V) = \mu_{D0} - \beta \ln\left(\frac{V}{V_0}\right) + \gamma \ln\left(\frac{V_0 \Theta}{D_C}\right)$$

## *Strain dependent strengthening*

A. Ruina, J. Geophys. Res. **88**, 10359 (1983):

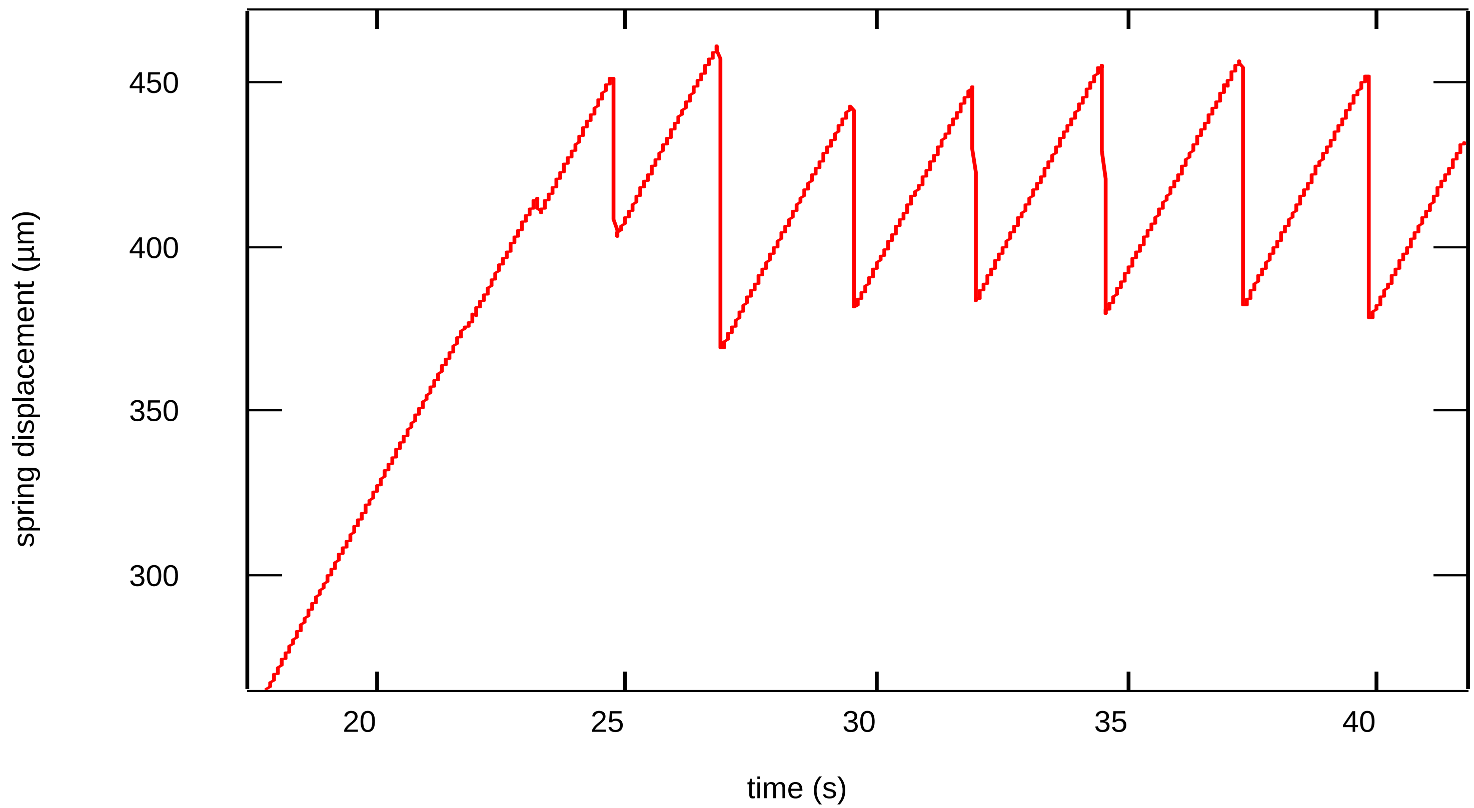
$$(1)\,\frac{d\Theta}{dt} = \frac{-V\Theta}{D_C} \ln\left(\frac{-V\Theta}{D_C}\right)$$

## *Time dependent Strengthening*

J.H. Dieterich, J. Geophys. Res. **84**, 2161 (1979)

$$(2)\,\frac{d\Theta}{dt} = 1 - \frac{-V\Theta}{D_C}$$

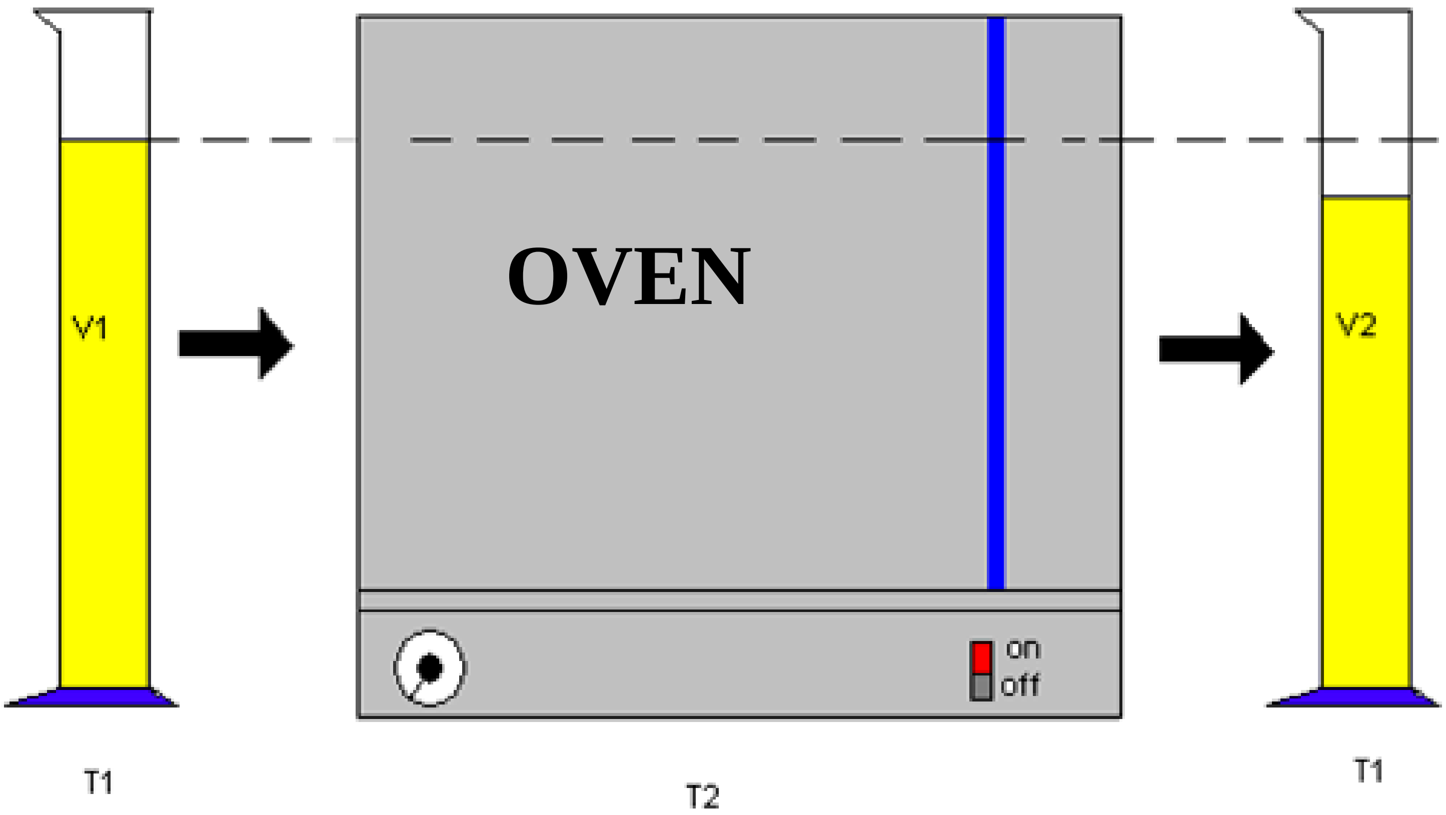
# Waiting without shear stress for 16 hours




•No strengthening without applied stress

•No strengthening, if direction of shear stress during waiting and during motion are opposite (not shown)

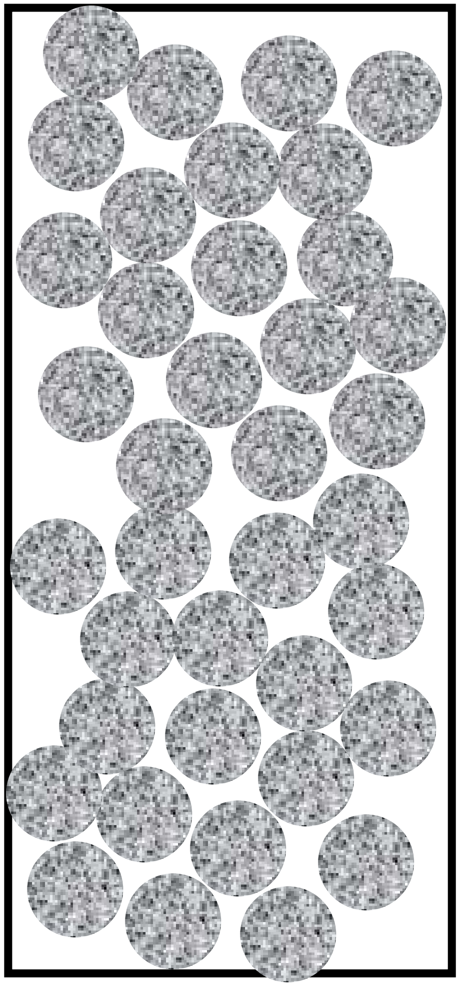
# Aging under thermal cycling




Glass beads and plastic container

From: Peter Schiffer, Penn State

# Compaction through thermal cycling



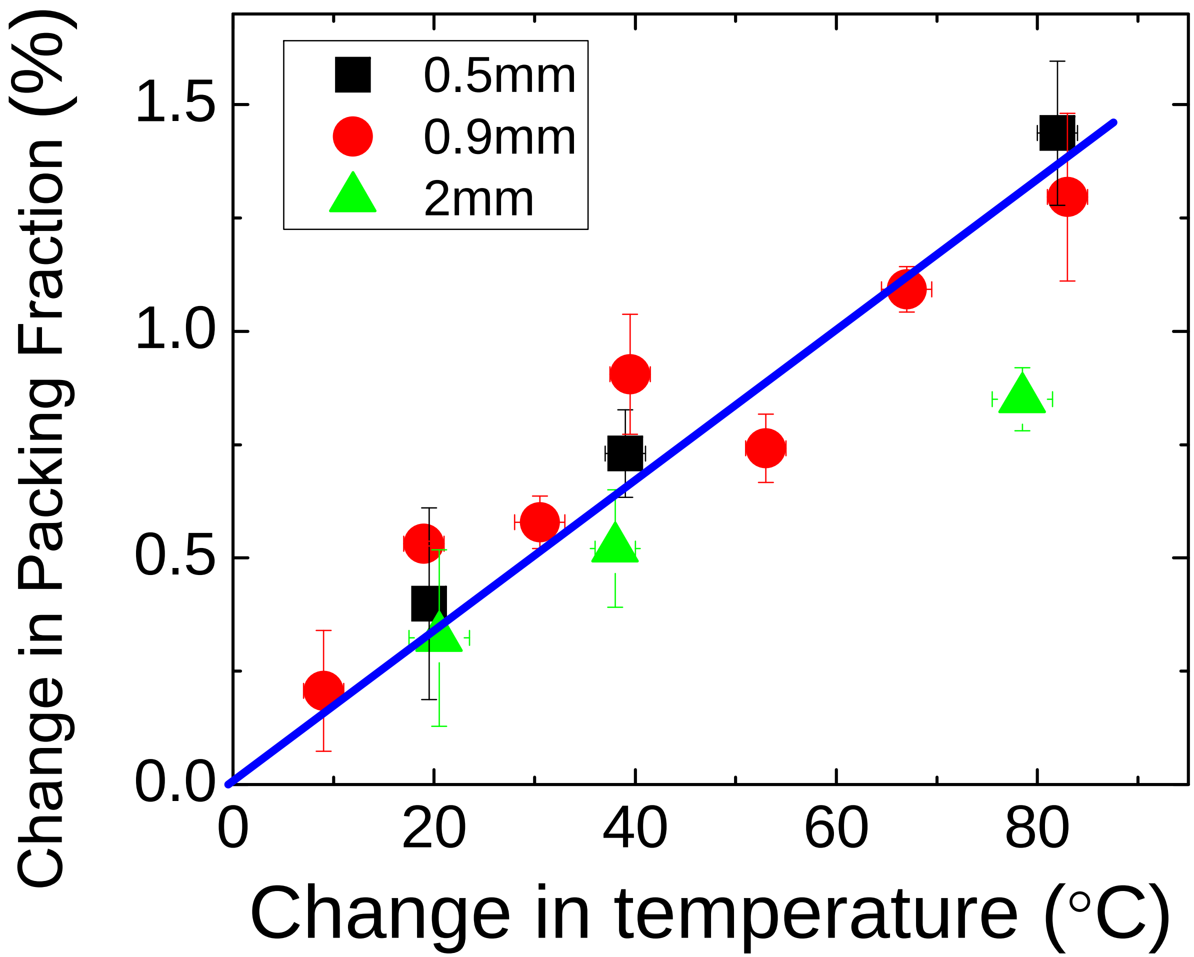
***System:*** glass container filled with plastic beads (or vice versa)

Heating expands plastic more than glass (Schiffer group, *Nature*, 2006)

Slow compaction of granular matter (without giving individual grains significant kinetic energy)

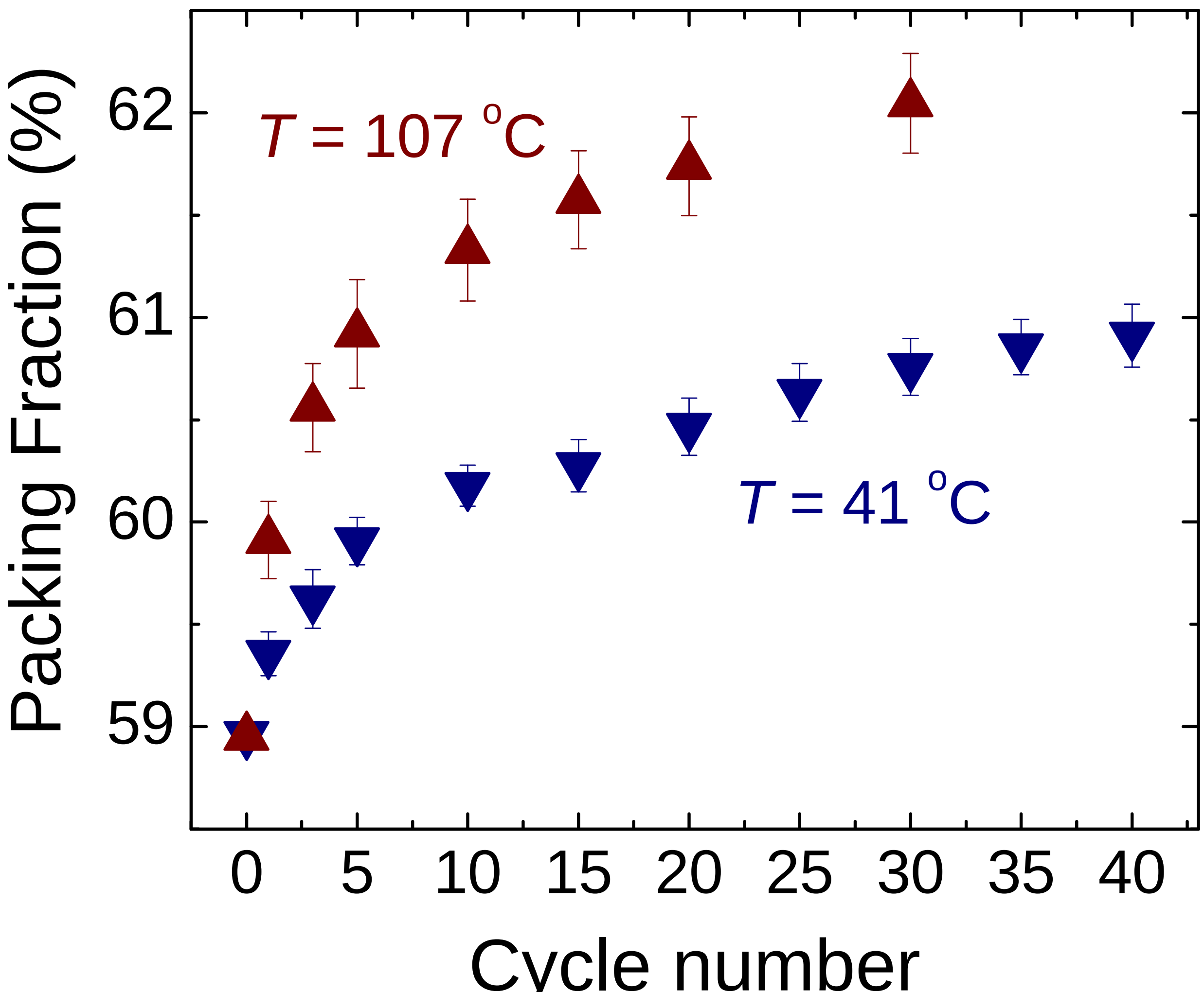
# Simple thermal cycling results

Clear and systematic change in packing fraction!



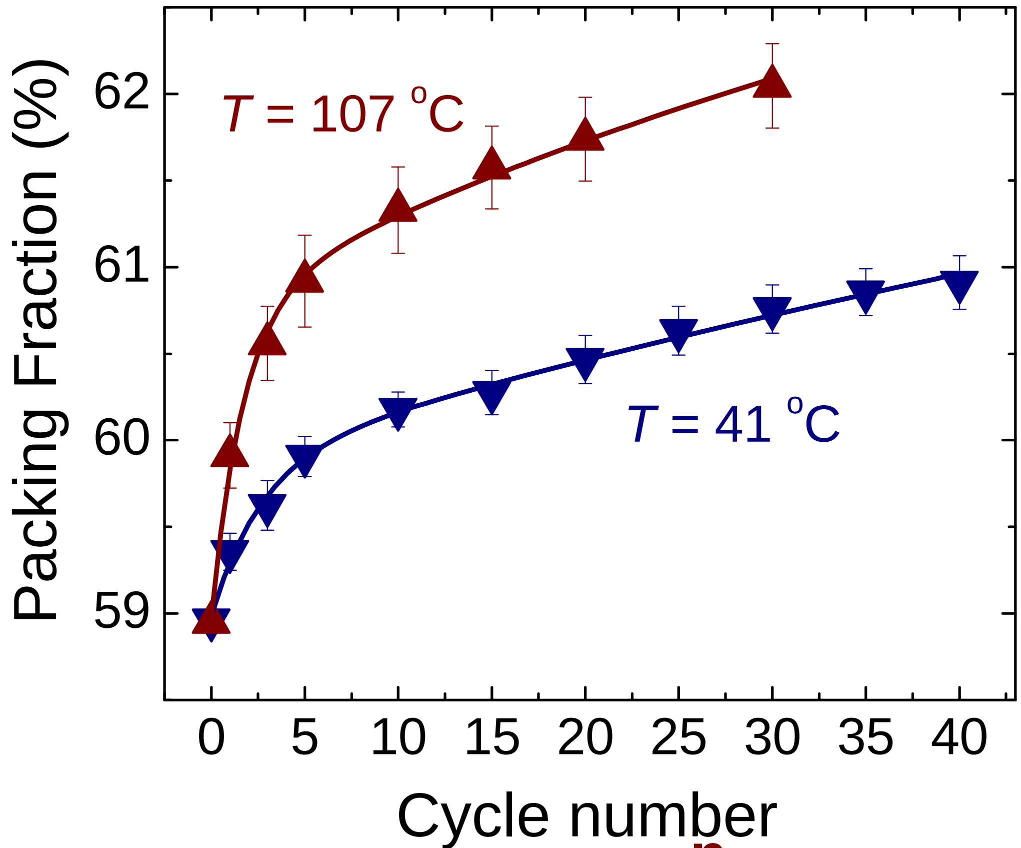

From: Peter Schiffer, Penn State

# Thermal packing dependence on repeated cycles




Peter Schiffer, Penn State

# Effect of repeated cycles can be understood through simple two-component model




$$PF = PF_{max} - A_1 e^{-\frac{n}{\tau_1}} - A_2 e^{-\frac{n}{\tau_2}}$$

Peter Schiffer, Penn State

**Barker and Mehta**

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Segregation

Astrophysical Applications

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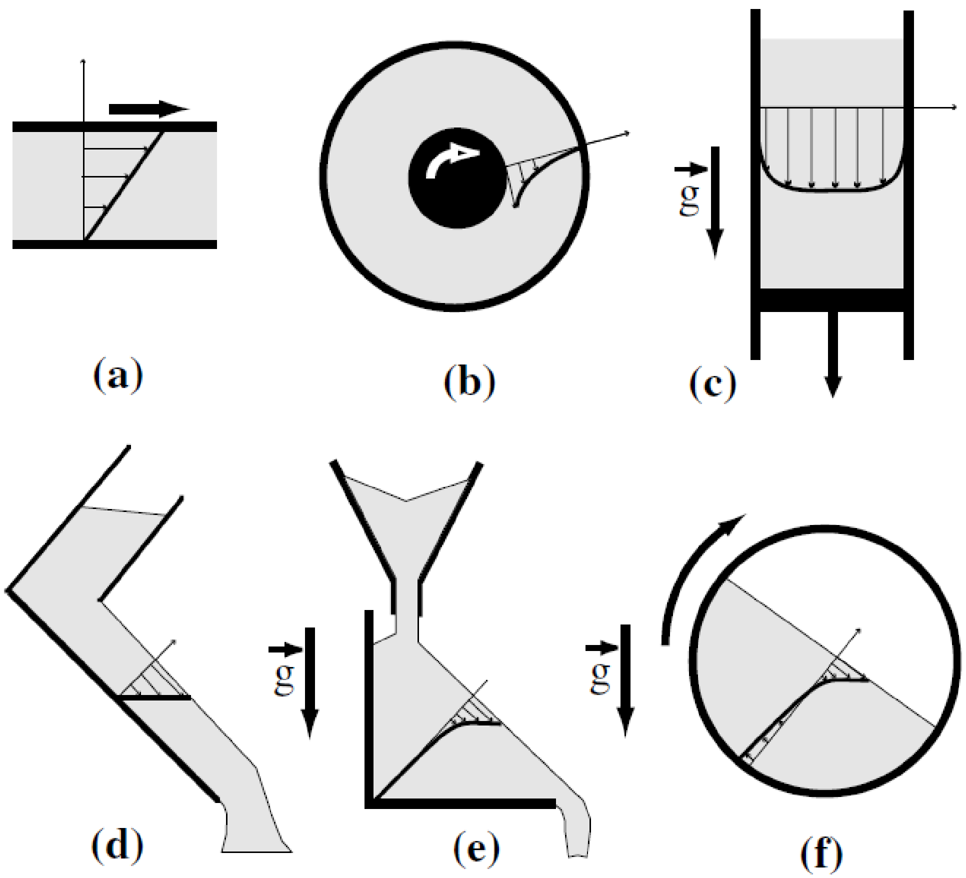
# Granular Flow




Eur. Phys. J. E **14**, 341–365 (2004)
DOI 10.1140/epje/i2003-10153-0

**On dense granular flows**

GDR MiDi[a]

Groupement De Recherche Milieux Divisés, CNRS, GDR2181, France

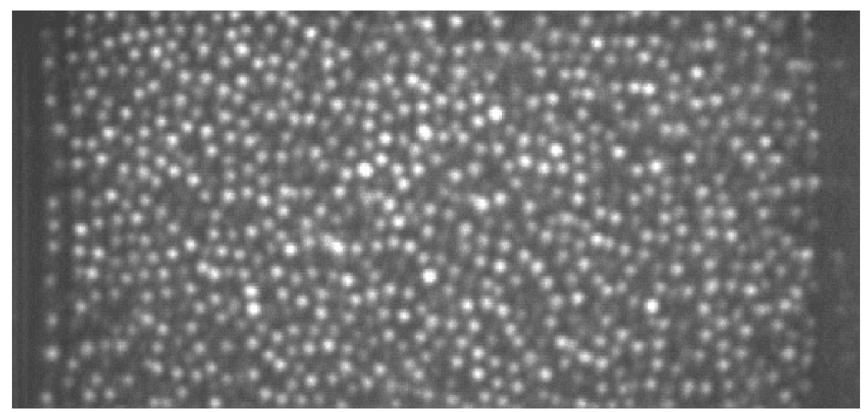
$$\mu = \mu_s + (\mu_2 - \mu_s)/(1 + I_0/I)$$

Inertia Number I

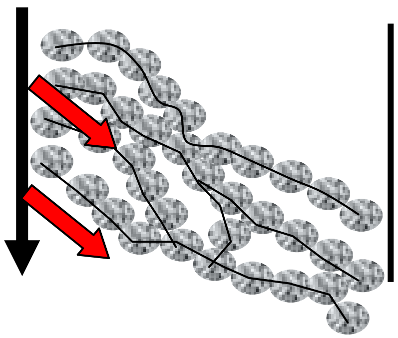
$$I = |\dot{\gamma}| d/\sqrt{P/\rho}$$

d: particle diameter

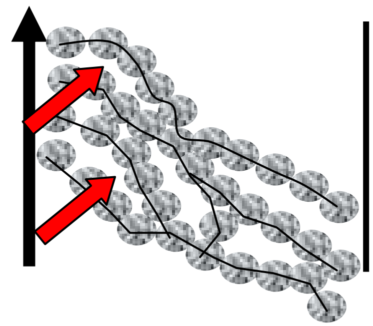
ρ: particle density



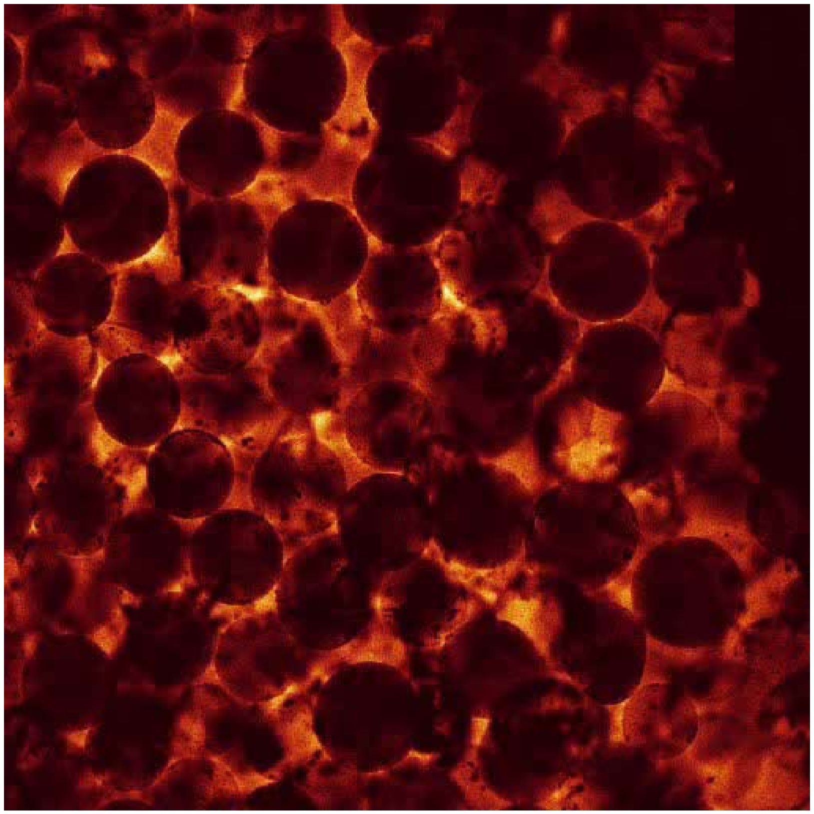
# Effects of mesoscale structure



*Schematic*
Contact network
**steady shear**



*Schematic*
Contact network
**shear reversal**



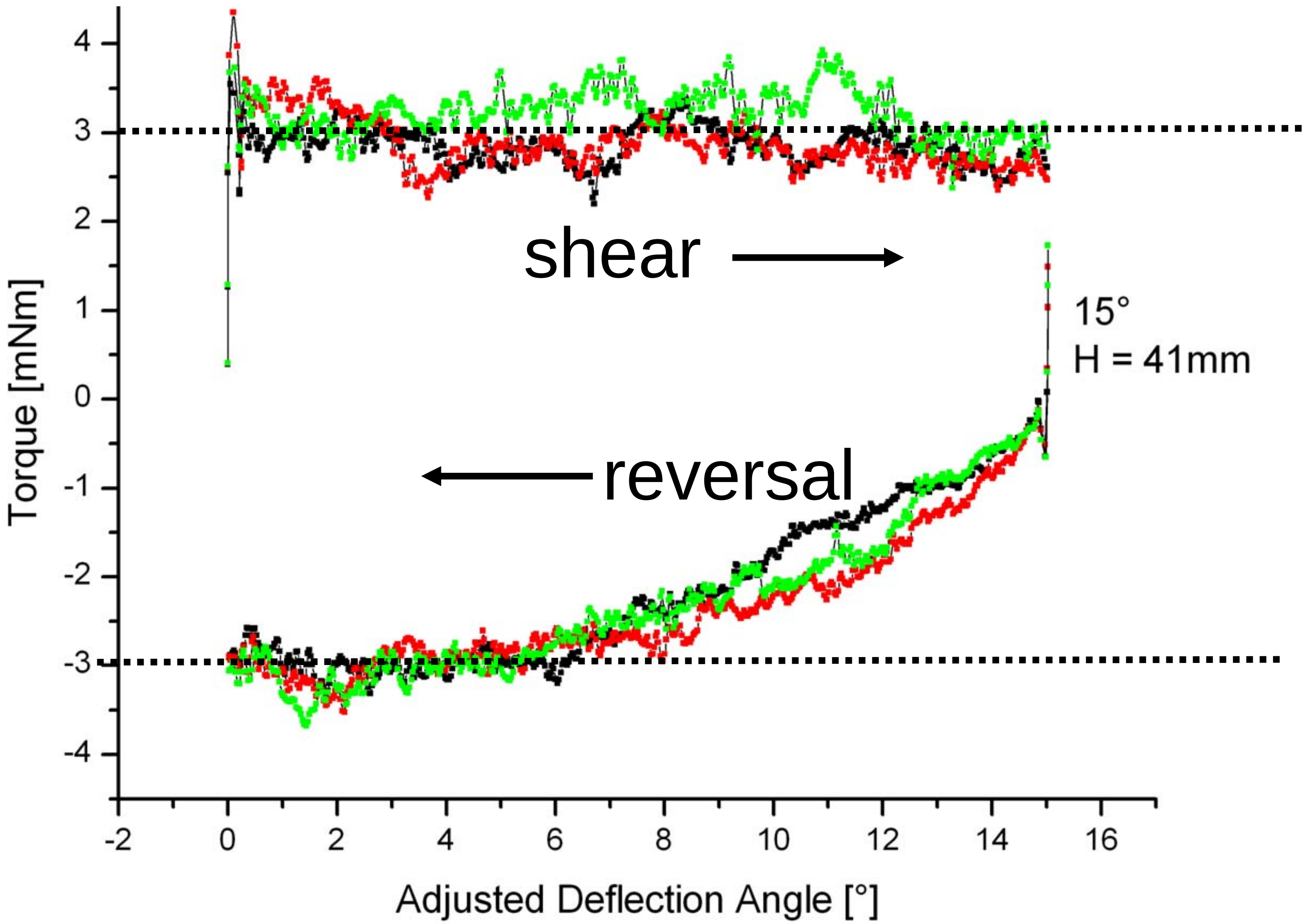
Toiya *et al.* PRL 2004

Masahiro Toiya

**Observations**

- Notable rolling/sliding during steady shear
- Significantly different motion during shear reversal

# Small initial torque during shear reversal




**Derek Updegraaf** with
E. Wandersman, J. Dijksman, M. van Hecke

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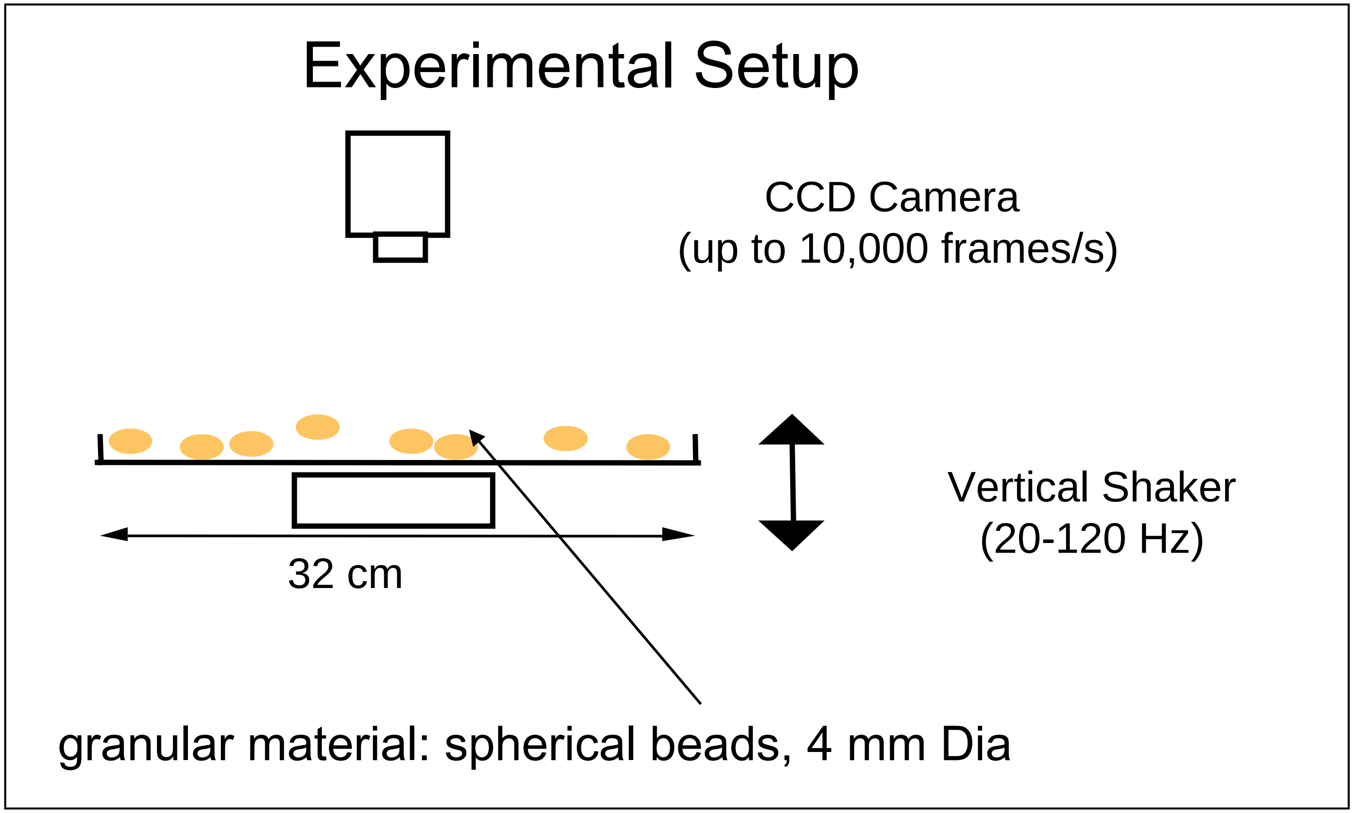
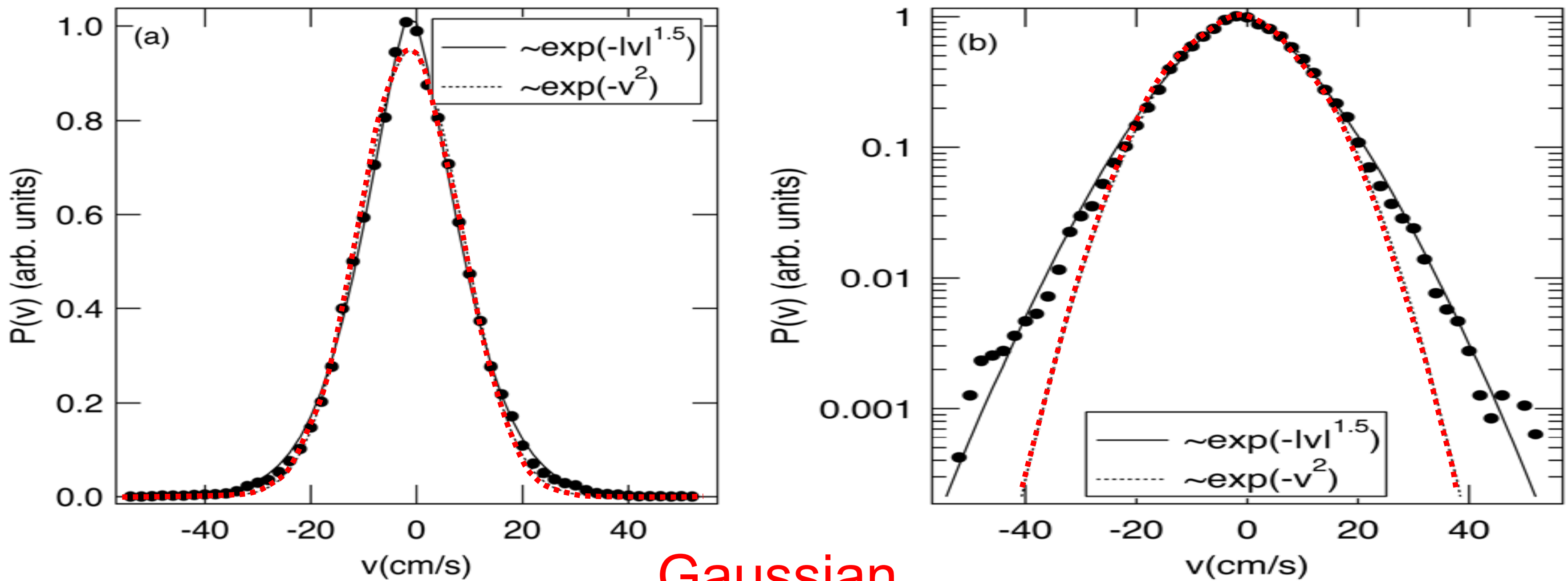
# Excited Granular Matter

An example of a granular gas
Energy input into a granular gas



# Velocity Distribution

Acceleration= 5g ; frequency = 100Hz ; coverage = 0.42

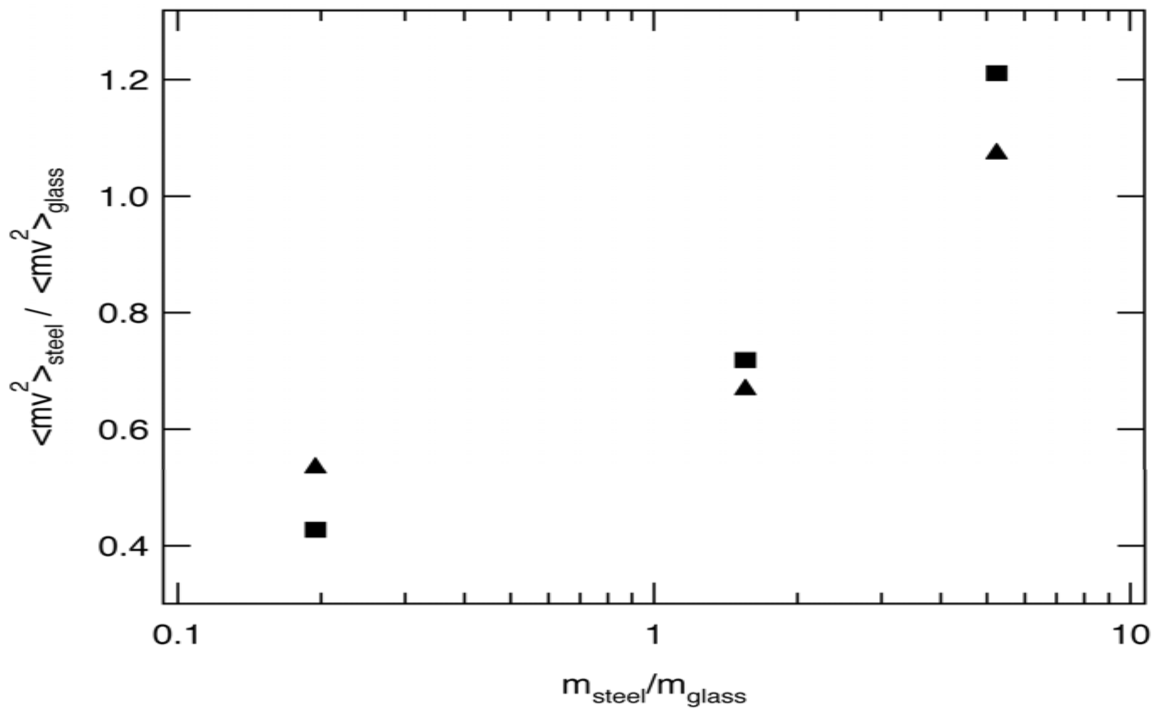



Gaussian

Velocity distribution best fit by $P(v) \propto e^{-|v|^{1.5}}$
in agreement with recent theoretical predictions.

Granular gases have non-Gaussian velocity distribution

# Energy of particle mixtures




No Equipartition of energy

# Bistability

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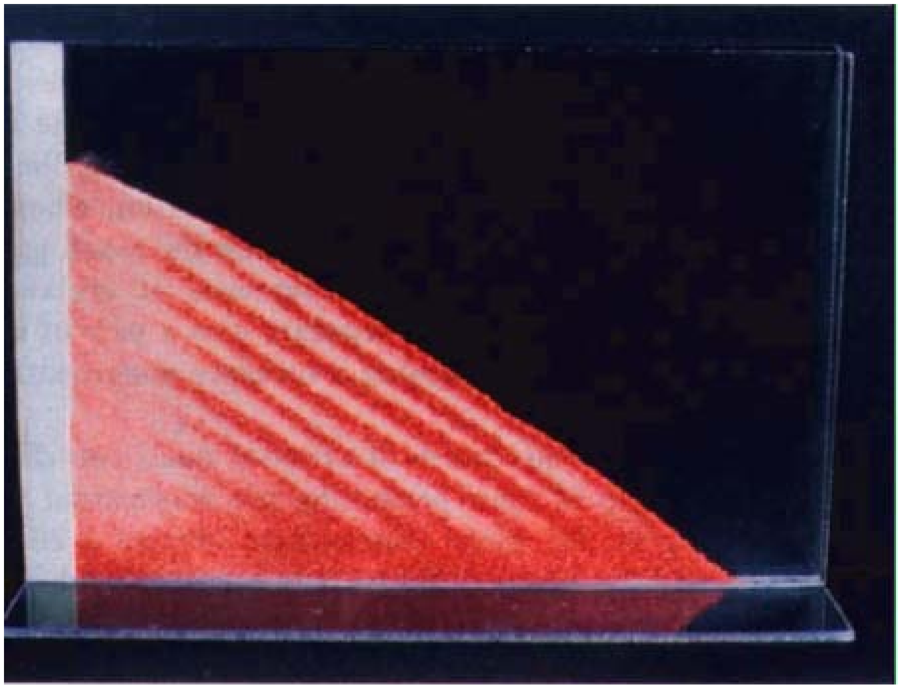
# Granular Segregation



(Image by H. Makse)

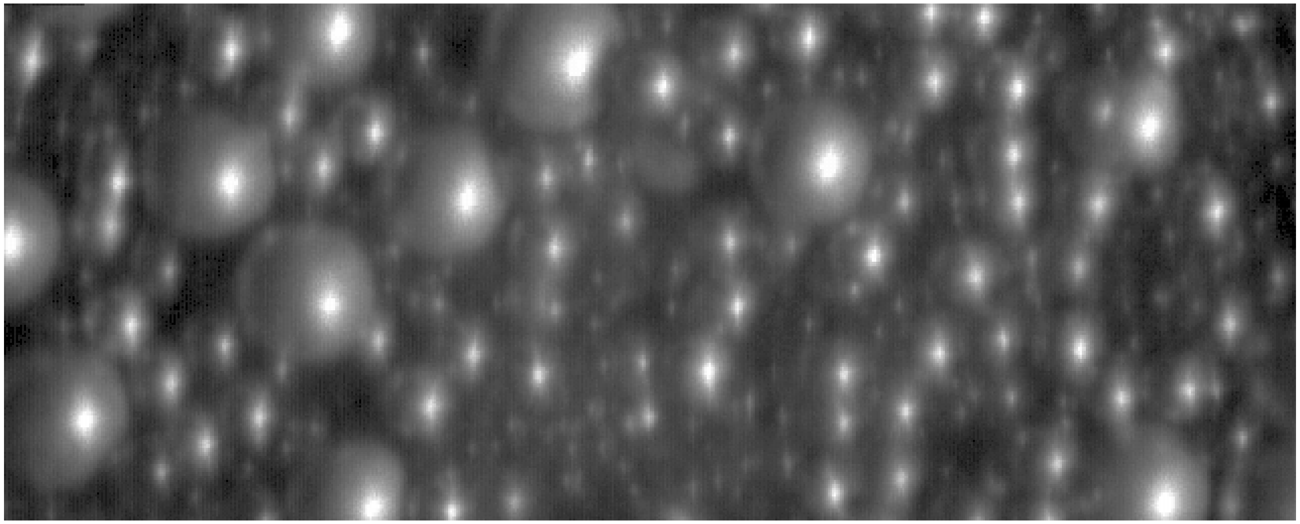
Flowing granular materials segregate according to particle properties (size, density, shape, and more).

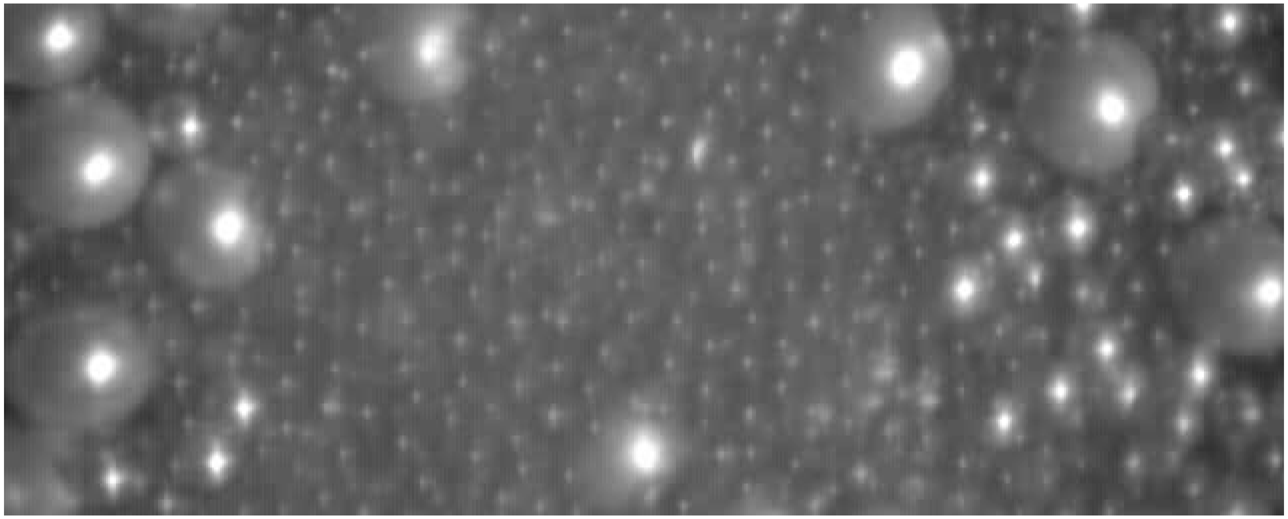
(Image by H. Makse)

# Axial Bands

See Newey et al. Europhysics Letters 2004

# Particle Speed on Surface





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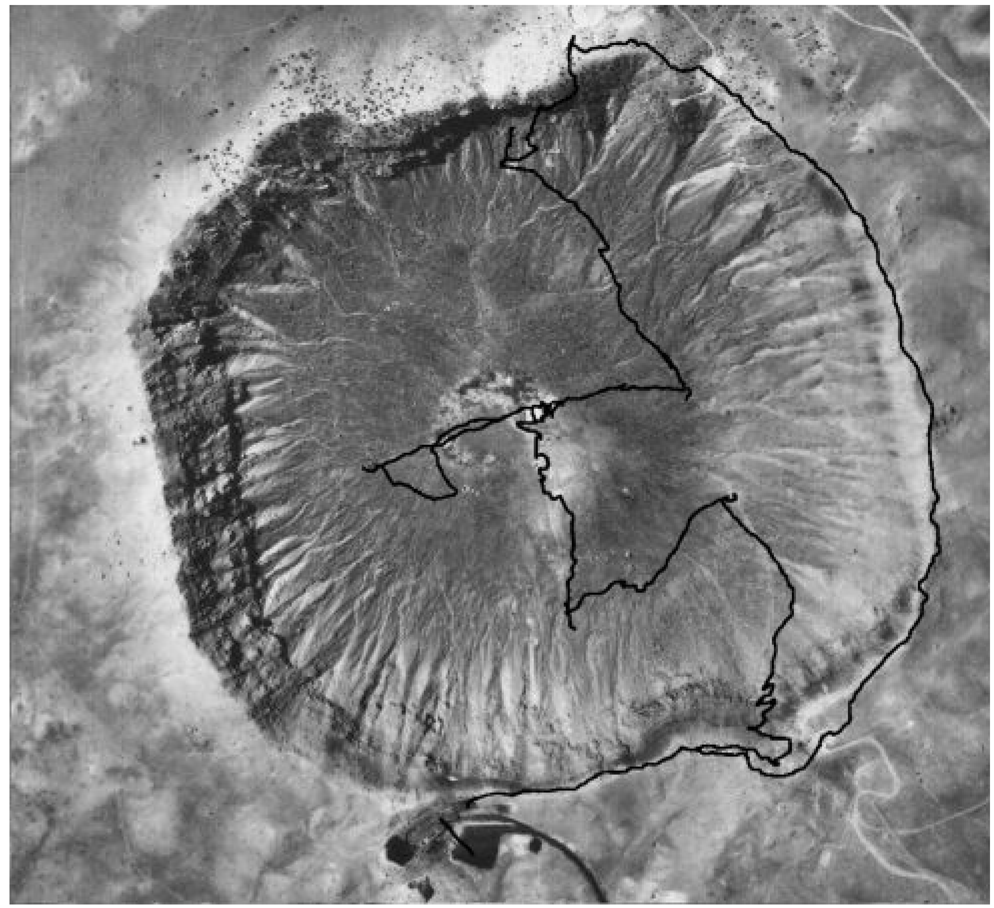
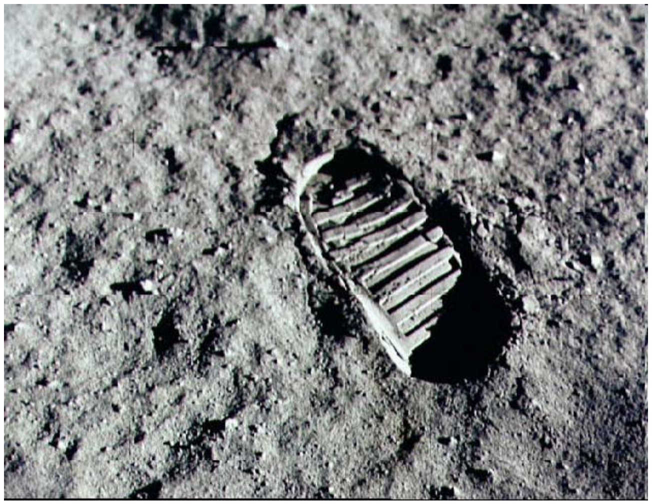
# Anisotropic yield surface



# Aging/Strengthening in Astrophysics?

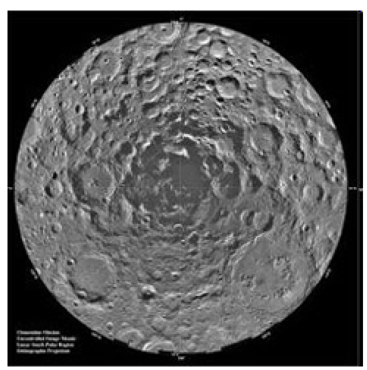


Thermal Cycling on the Moon

Daytime: +120$^{o}$C

Night: -150$^{o}$C

[lunarpedia.org]

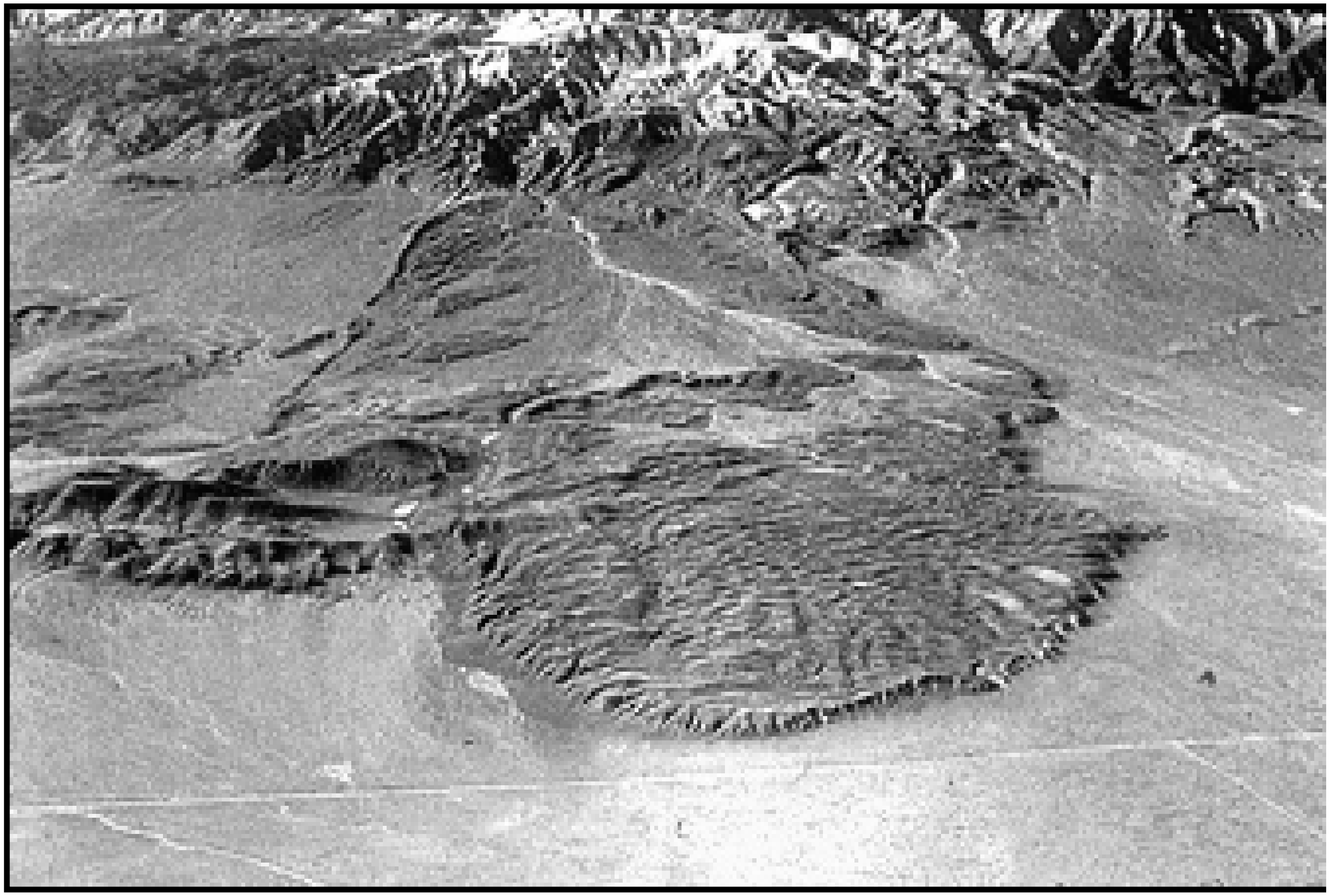


The pole is a regions not exposed to thermal cycling. Will it be equally compacted?

DEMO

# Long Runout Rock Avalanches

The Blackhawk event in California



**Field Data:** Rock avalanche probabilities are correlated with the direction of prior shear

(Friedmann, Kwon & Losert, J. Geophys. Res 2003)

# Forces in Astrophysical Applications

**Holding Granular Matter together:**

Gravity

Van der Waals

Charges

**Rearranging Granular Matter:**

Tidal forces

Seismic forces

Centrifugal forces

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