Summer School: Granular Materials
from Simulations to Astrophysical Applications

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

Granular Experiments

Wolfgang Losert, Department of Physics
University of Maryland

Outline

On Monday

- Intro: What are granular materials?
- Granular Materials Jam
- Granular Materials Age and Strengthen

Today

- Granular Gas (Particle tracking)
- 2D Granular Flow (PIV and flow fields)
- 3D Granular Flows (3D imaging approaches)
- Shape Analysis

Wolfgang Losert wlosert@umd.edu

Granular Gas – 2D particle tracking

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

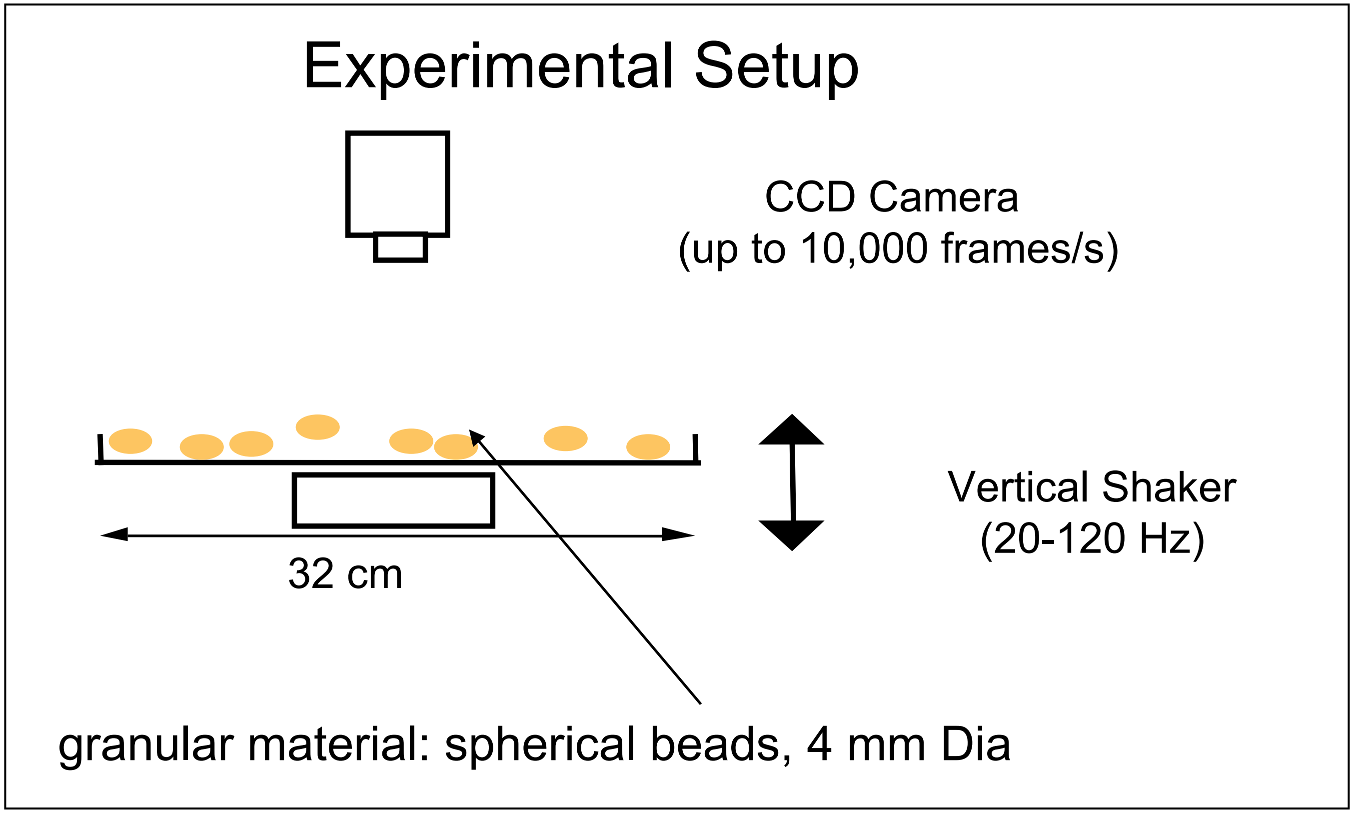


Image analysis

Implementations

Eric Weeks (Emory, IDL)
http://www.physics.emory.edu/~weeks/idl/

Dan Blair (Georgetown, Matlab)
http://physics.georgetown.edu/matlab/

Steps in 2D particle tracking
http://www.physics.emory.edu/~weeks/idl/tracking.html
[subtract mean image]

Bandpass

Threshold

Interpolate

Notes on 2D particle tracking

Interpolation yields location of particle with better than pixel accuracy

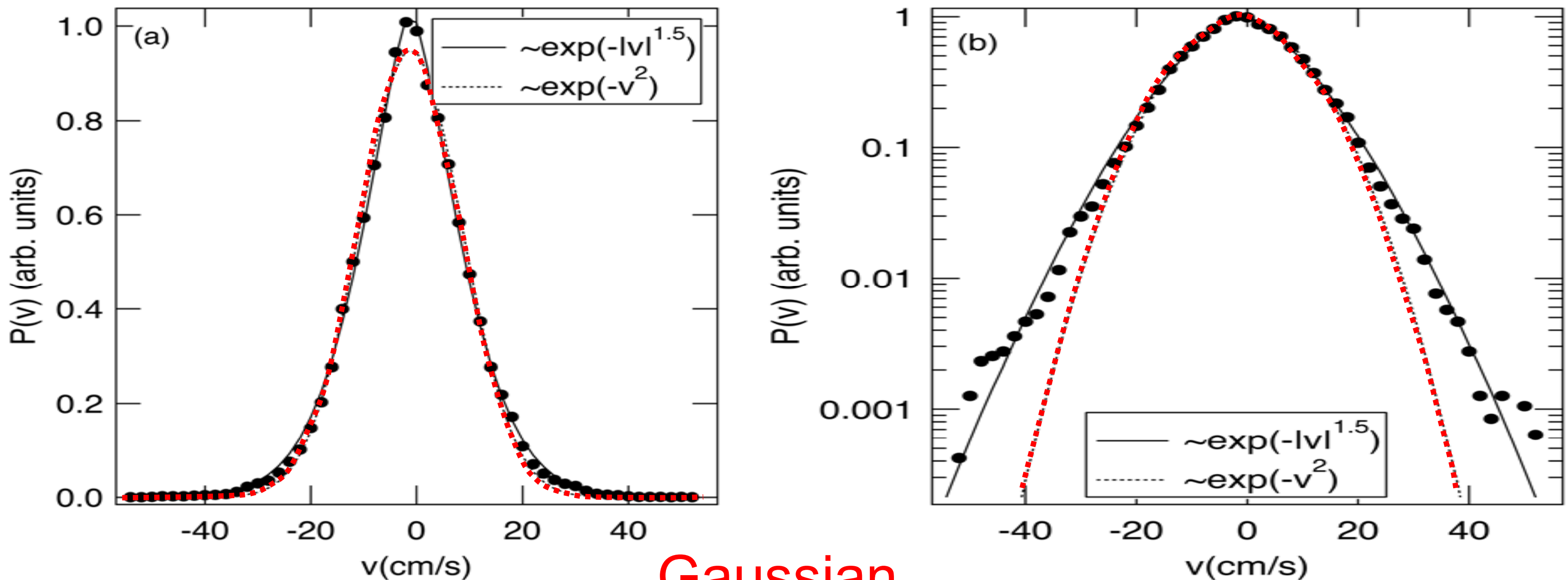
Can distinguish between different particle types (e.g. large and small particles) by the width and height of the interpolated peak

Be careful about pixelation

Tracking assumes no mean flow

Velocity Distribution

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

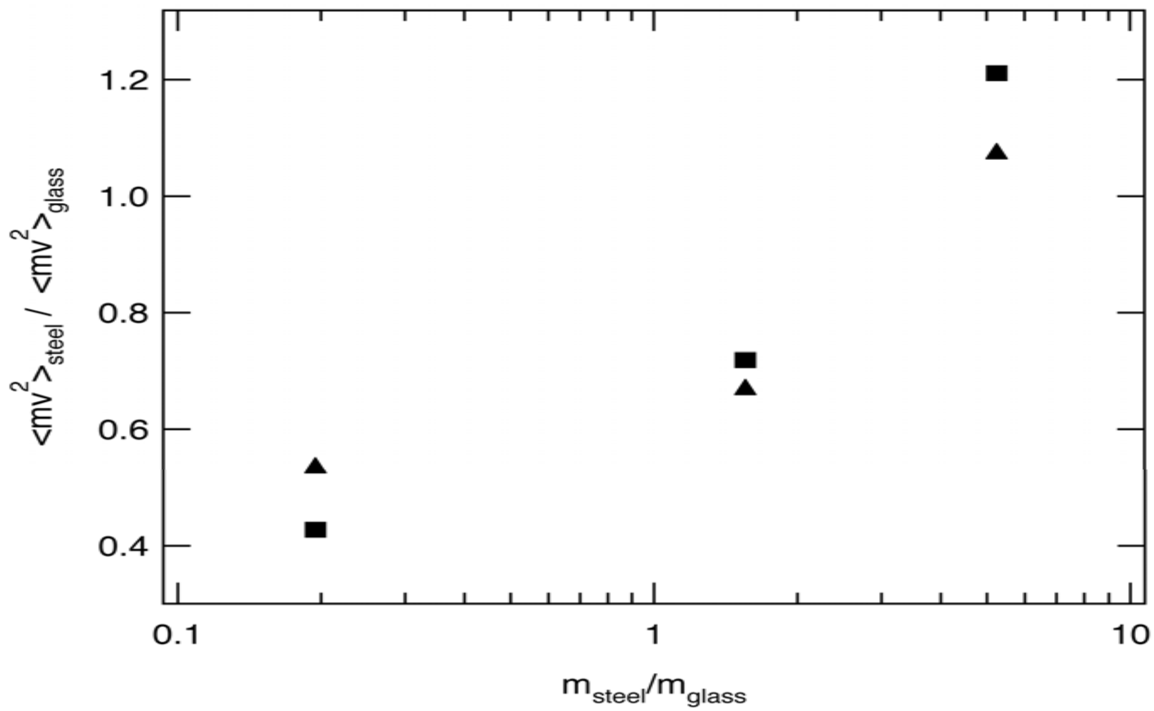


Gaussian

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

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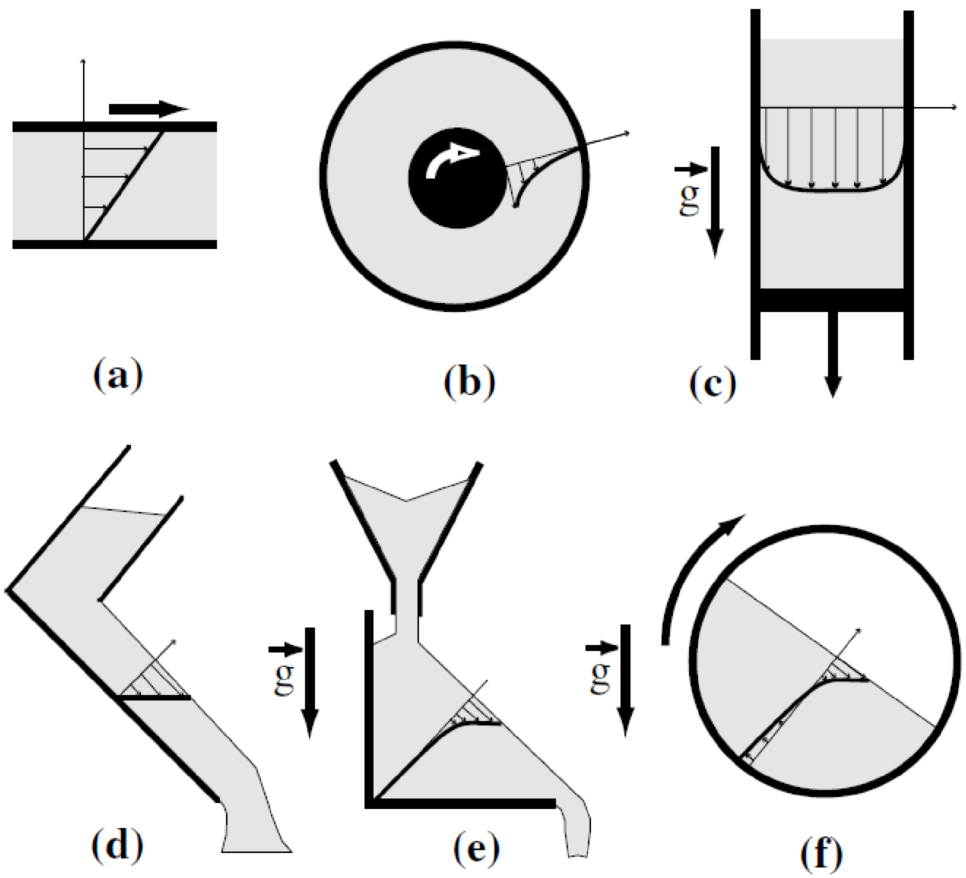
Granular Flow

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

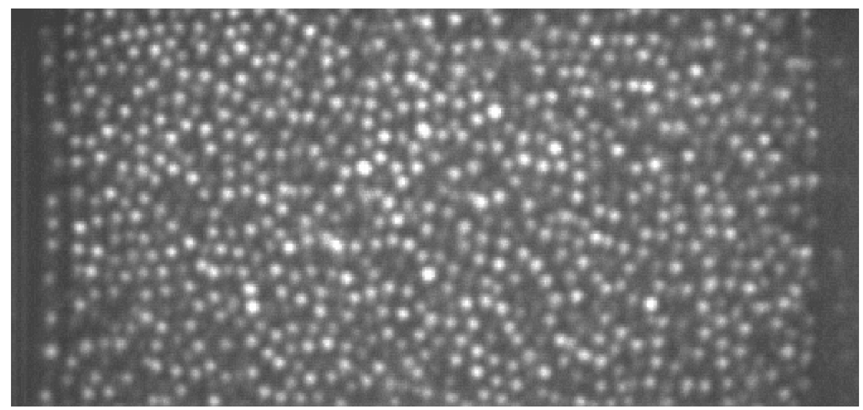


Inertia Number I

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

d: particle diameter

ρ: particle density



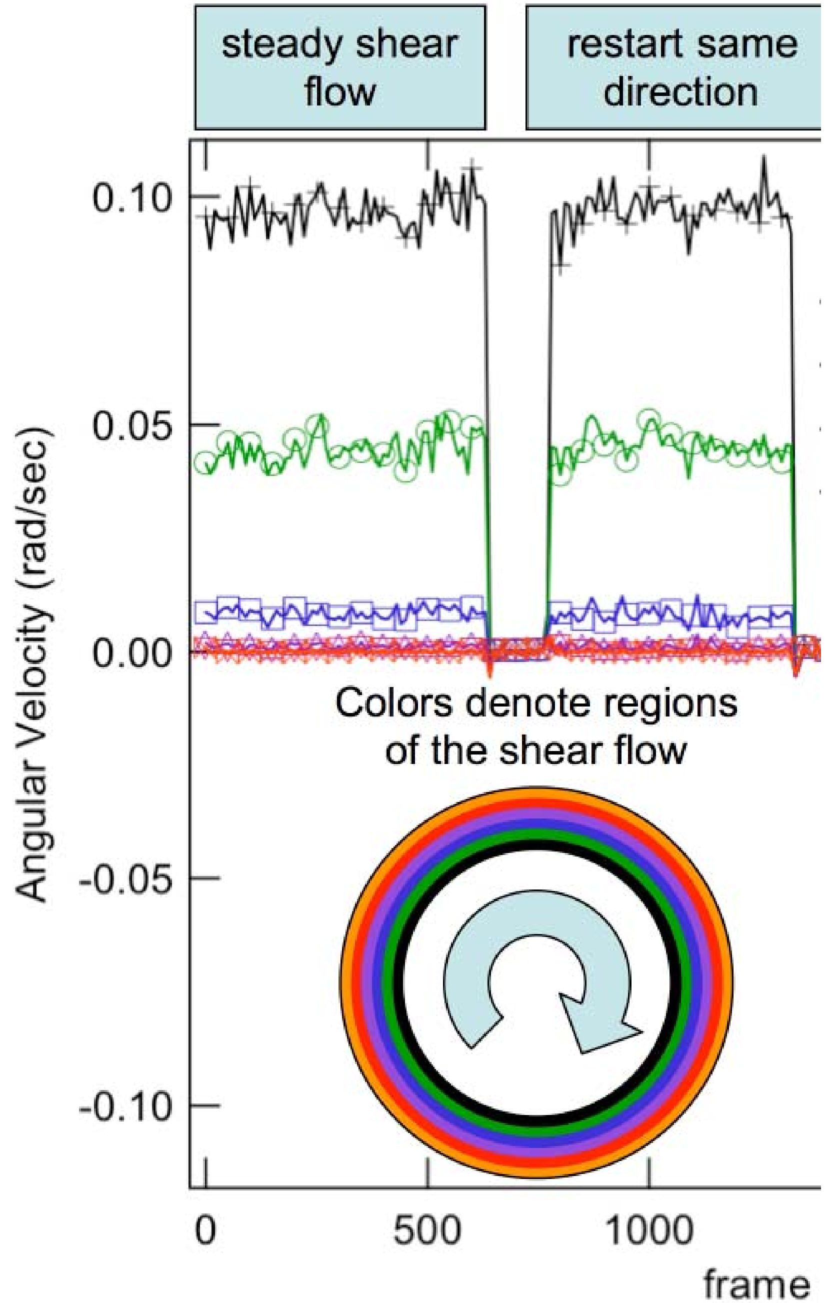
Eur. Phys. J. E **14**, 341–365 (2004)
DOI 10.1140/epje/i2003-10153-0

On dense granular flows

GDR MiDi[a]

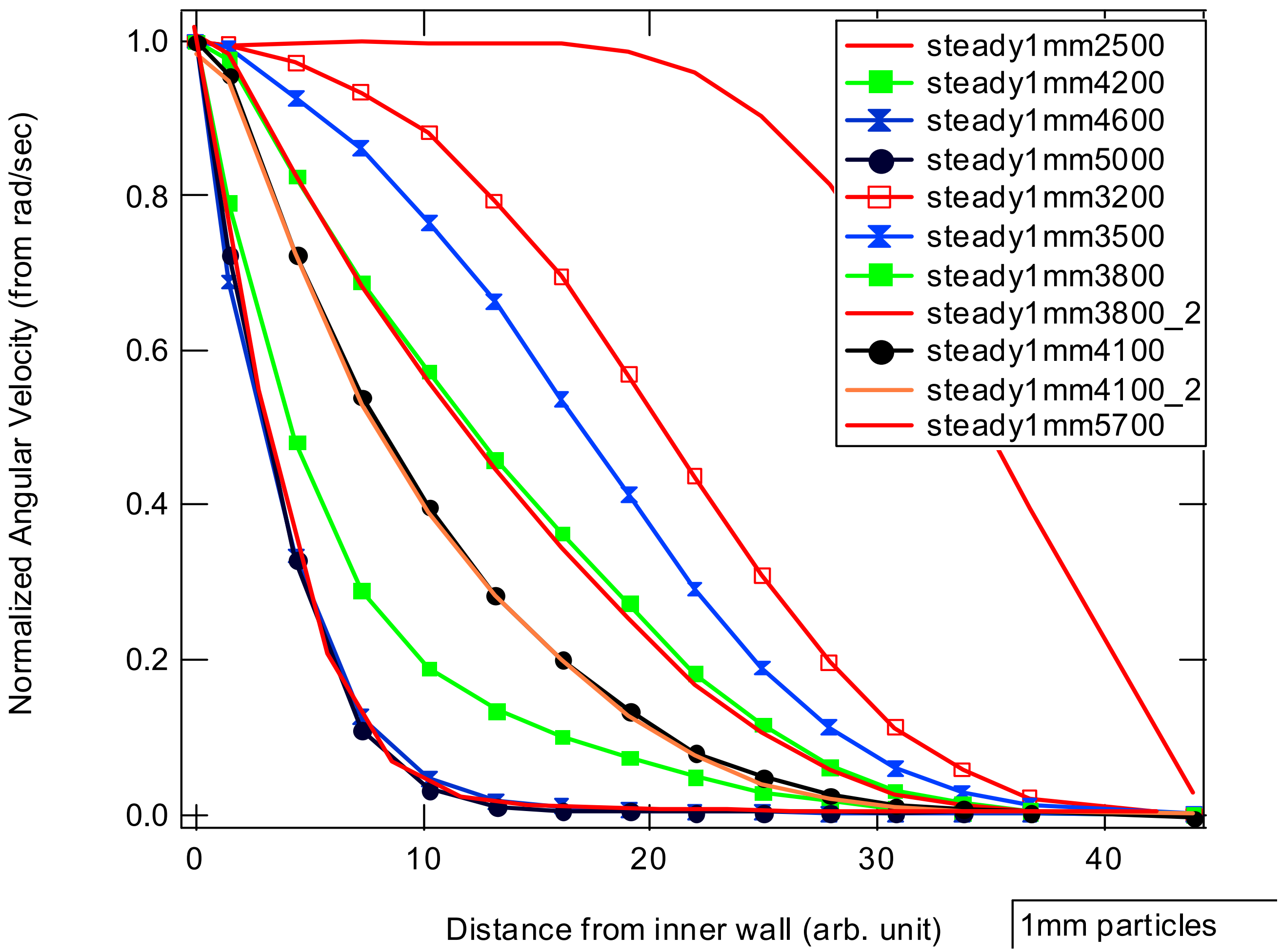
Groupement De Recherche Milieux Divisés, CNRS, GDR2181, France

Steady state flow reached immediatel



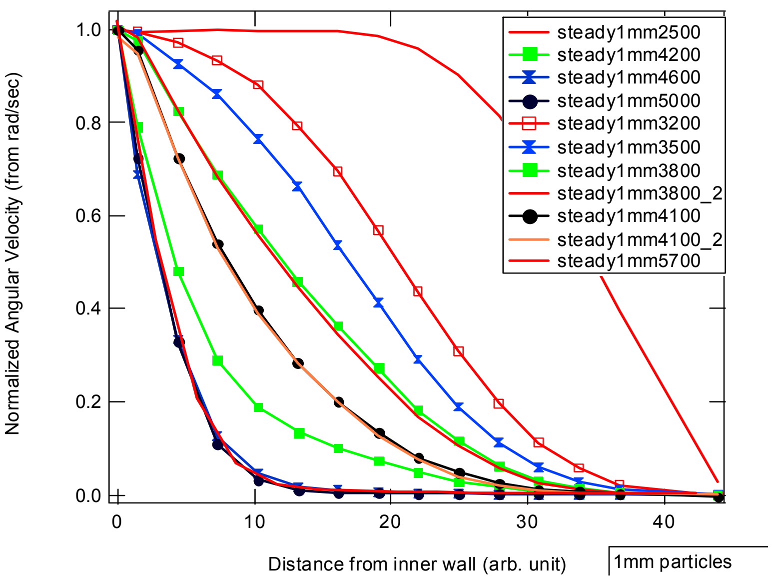
Falk, Toiya, and Losert

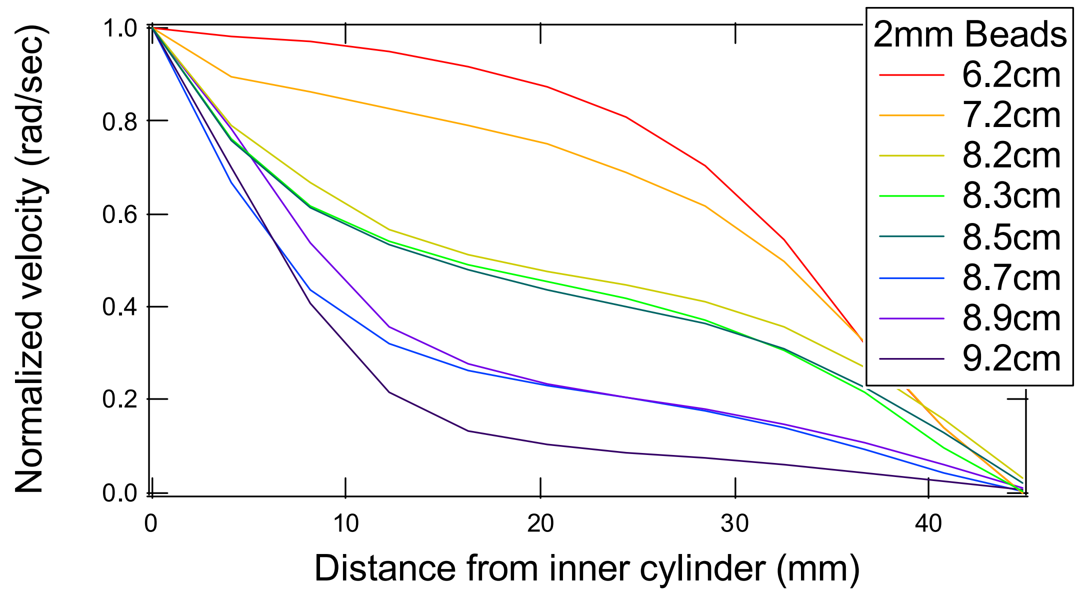
Puzzle: Role of the boundary in the localization of the shear band



Rough bottom connected to inner cylinder:

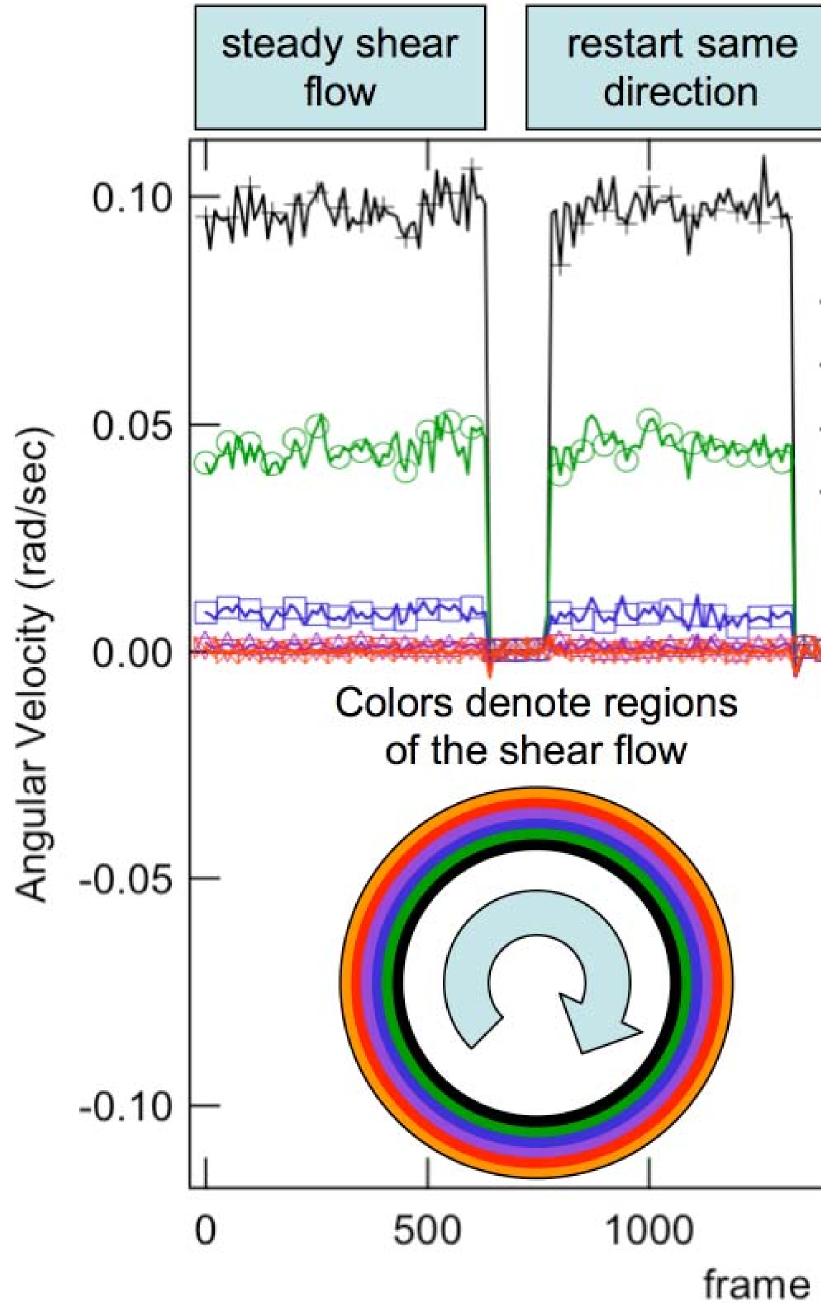
Puzzle: Role of the boundary in the localization of the shear band





Shear Band position depends on particle size

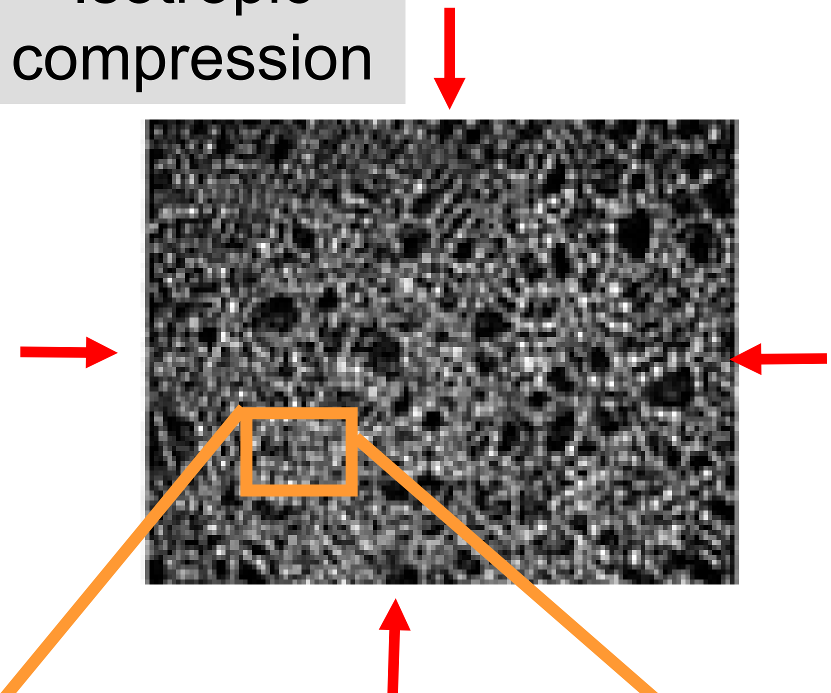
Steady state flow reached immediatel

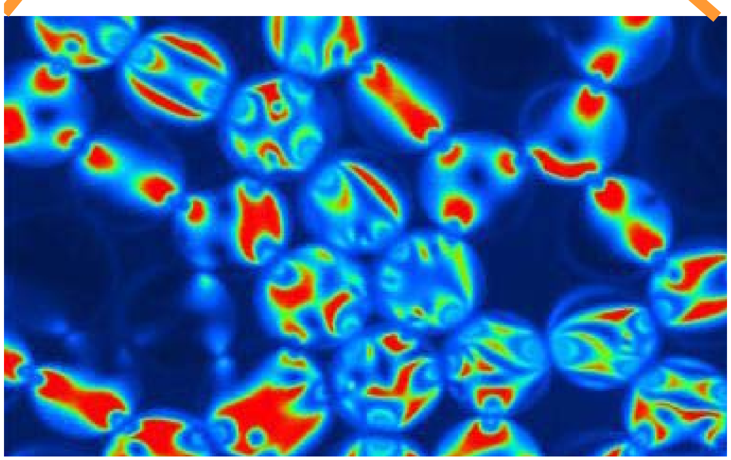


Falk, Toiya, and Losert

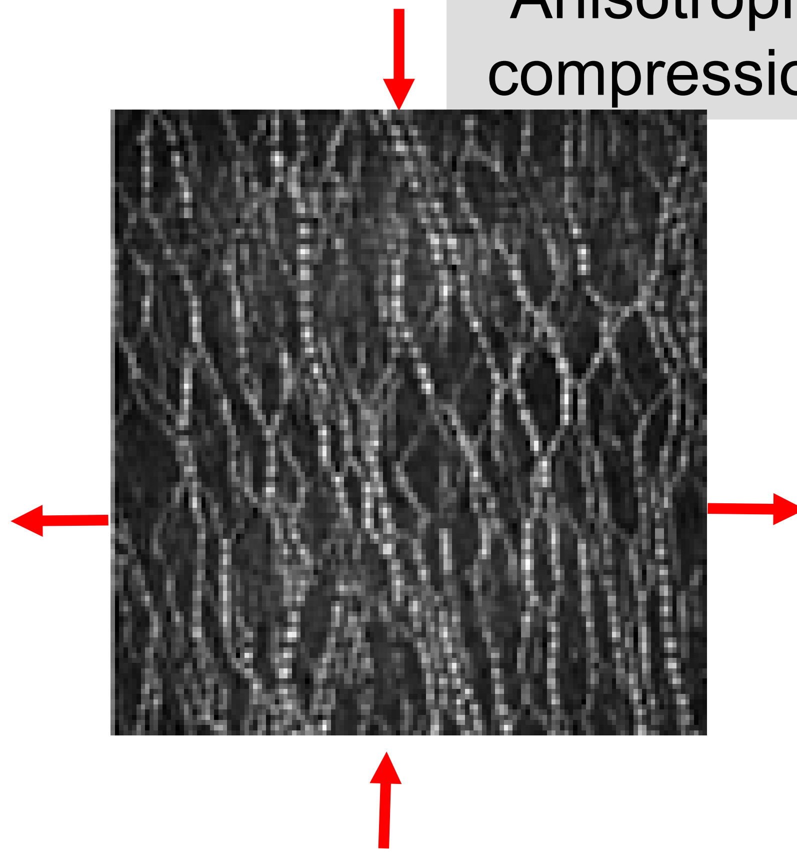
Contact network depends on jamming history

Isotropic compression



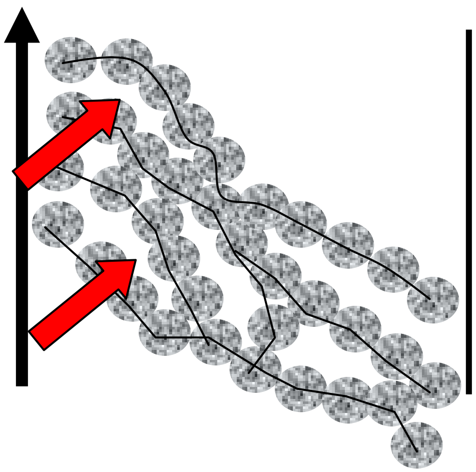


Anisotropic compression

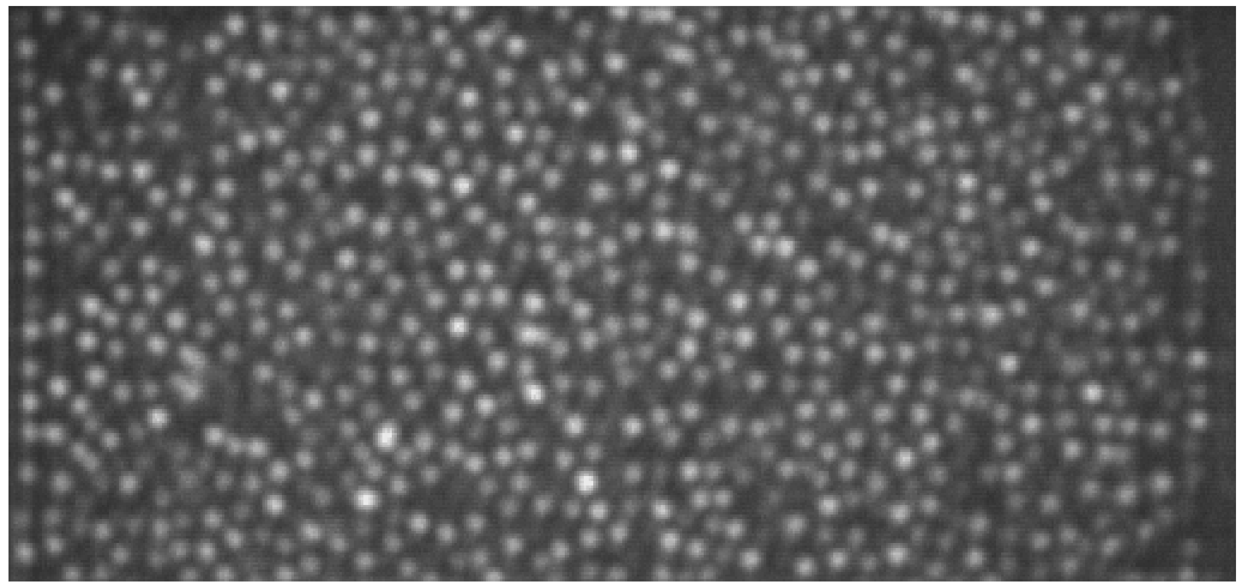


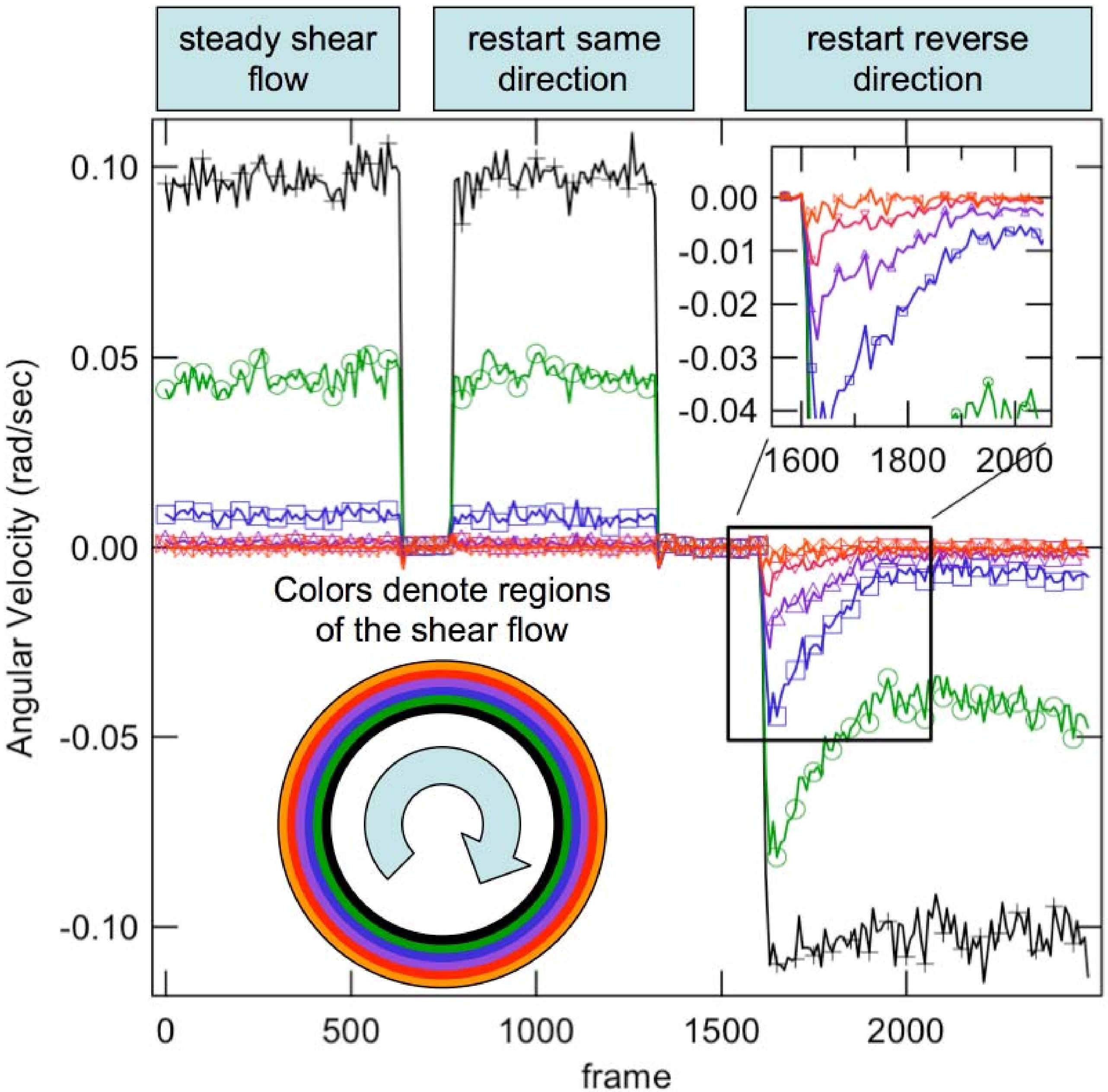
Direct imaging of forces in 2D
From Majumdar/Behringer, Nature, 2005

Reversal of shear direction



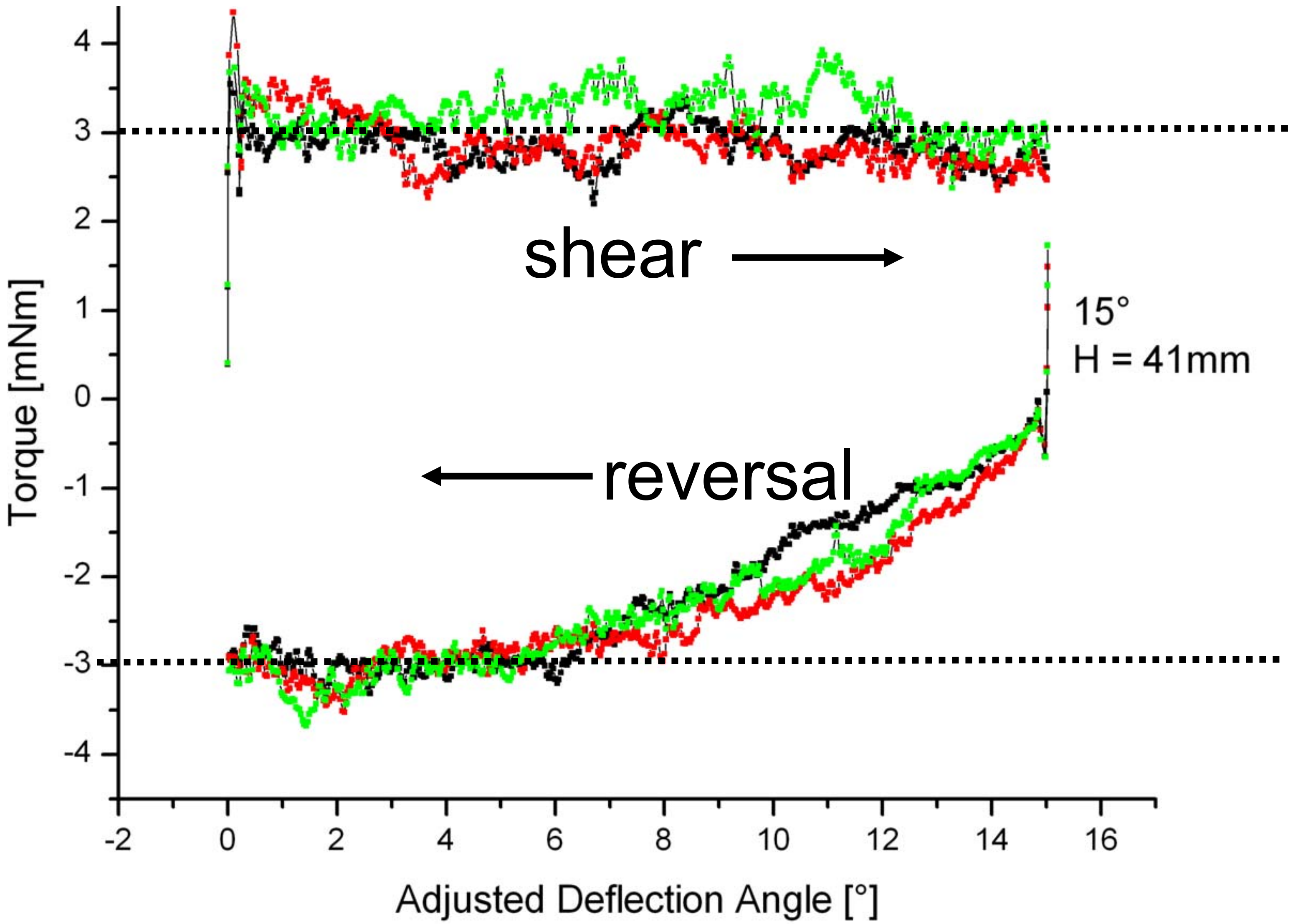
Forces





Falk, Toiya, and Losert

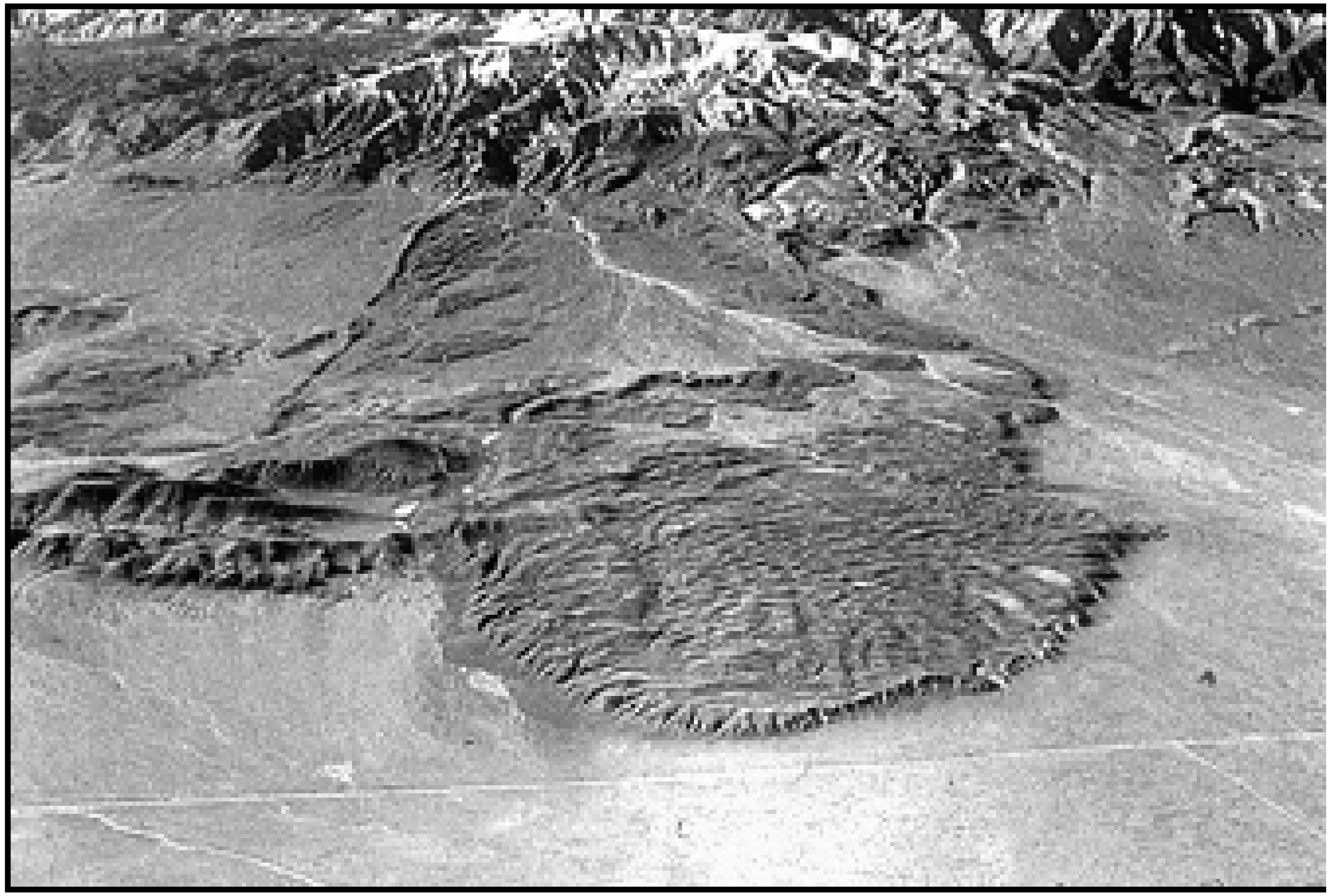
Small initial torque during shear reversal



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

Long Runout Rock Avalanches

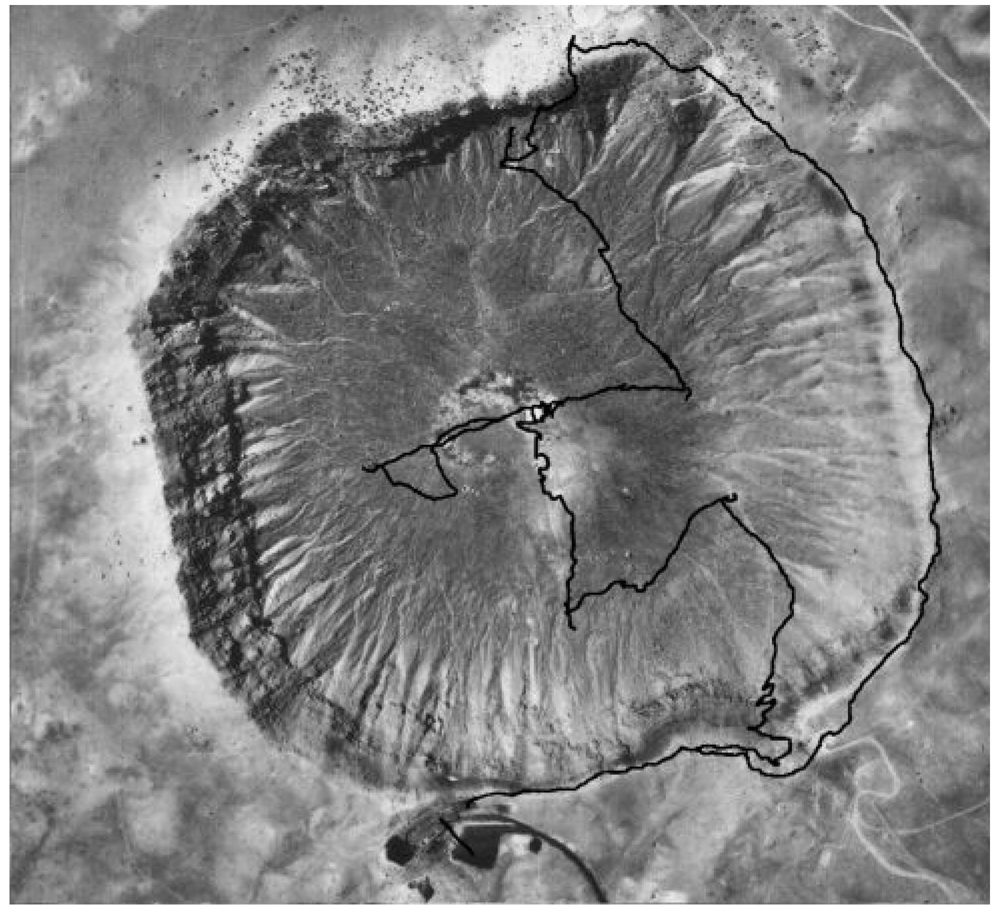
The Blackhawk event in California



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

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

Anisotropic yield surface



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3D imaging approaches

MRI

Jaeger Group University of Chicago

X-ray microtomography

Delannay Group, Rennes

Confocal microscopy

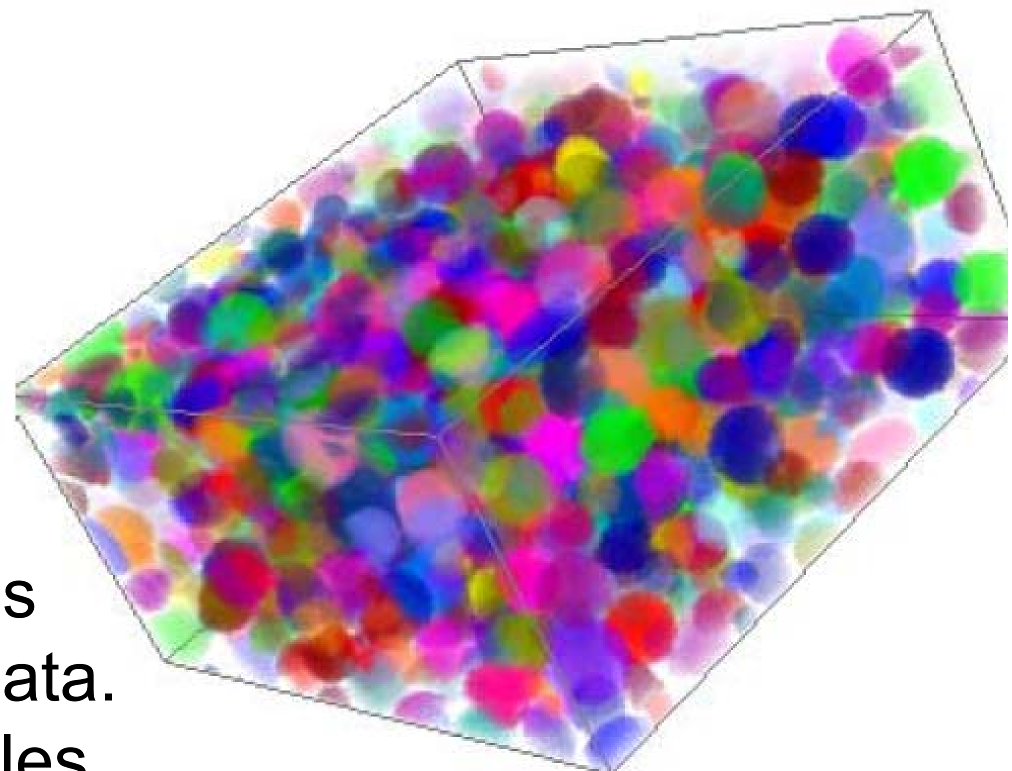
Refractive Index Matched Scanning (RIMS)

Synchrotron X-ray tomography

(with R. Delannay and P. Richard, Univ. Rennes)

Useful for a range of **dry** granular materials

Few images can be taken (large, shared facility, >=10 min per 3D image)



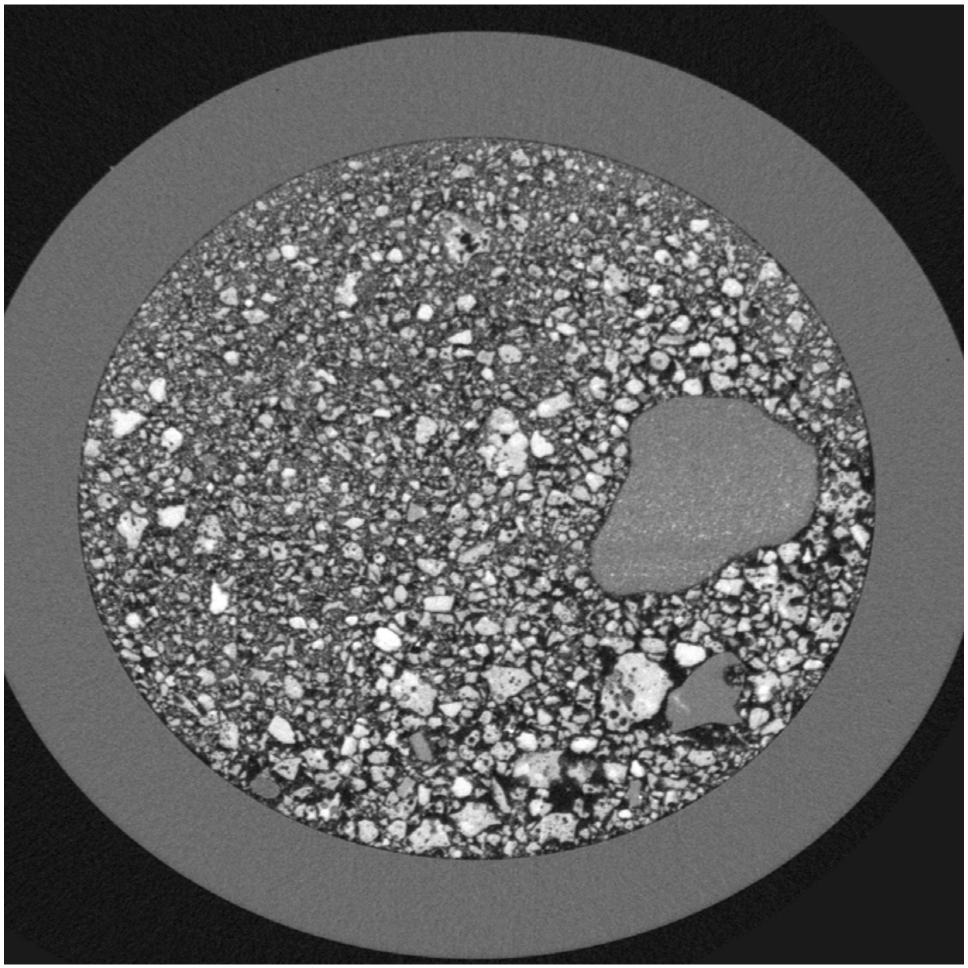
Grain shapes and positions extracted from tomography data.
Colored to distinguish particles
10 μm pixel resolution

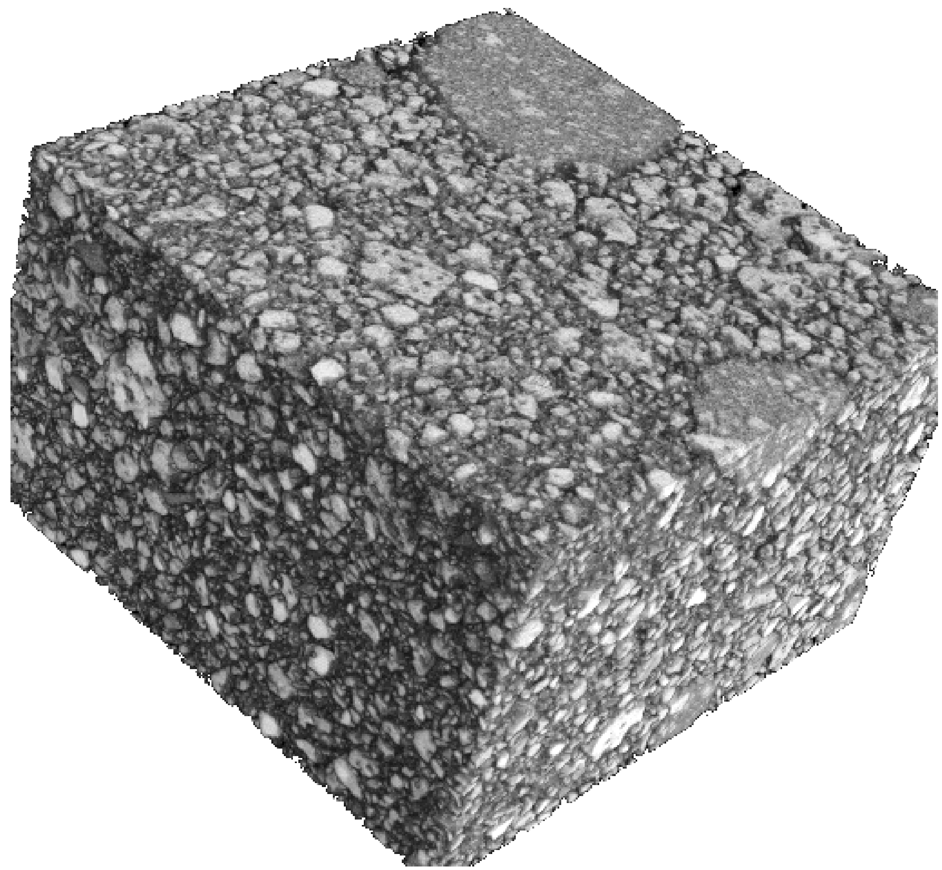
PHYSICAL REVIEW E **68**, 020301(R) (2003)

Analysis by x-ray microtomography of a granular packing undergoing compaction

Patrick Richard,[1,*] Pierre Philippe,[2] Fabrice Barbe,[3] Stéphane Bourlès,[1] Xavier Thibault,[4] and Daniel Bideau[1]

X-ray tomography images of lunar simulant
(M. Toiya, w. R. Delannay and P. Richard, Univ Rennes)





3D imaging approaches

MRI

Jaeger Group University of Chicago

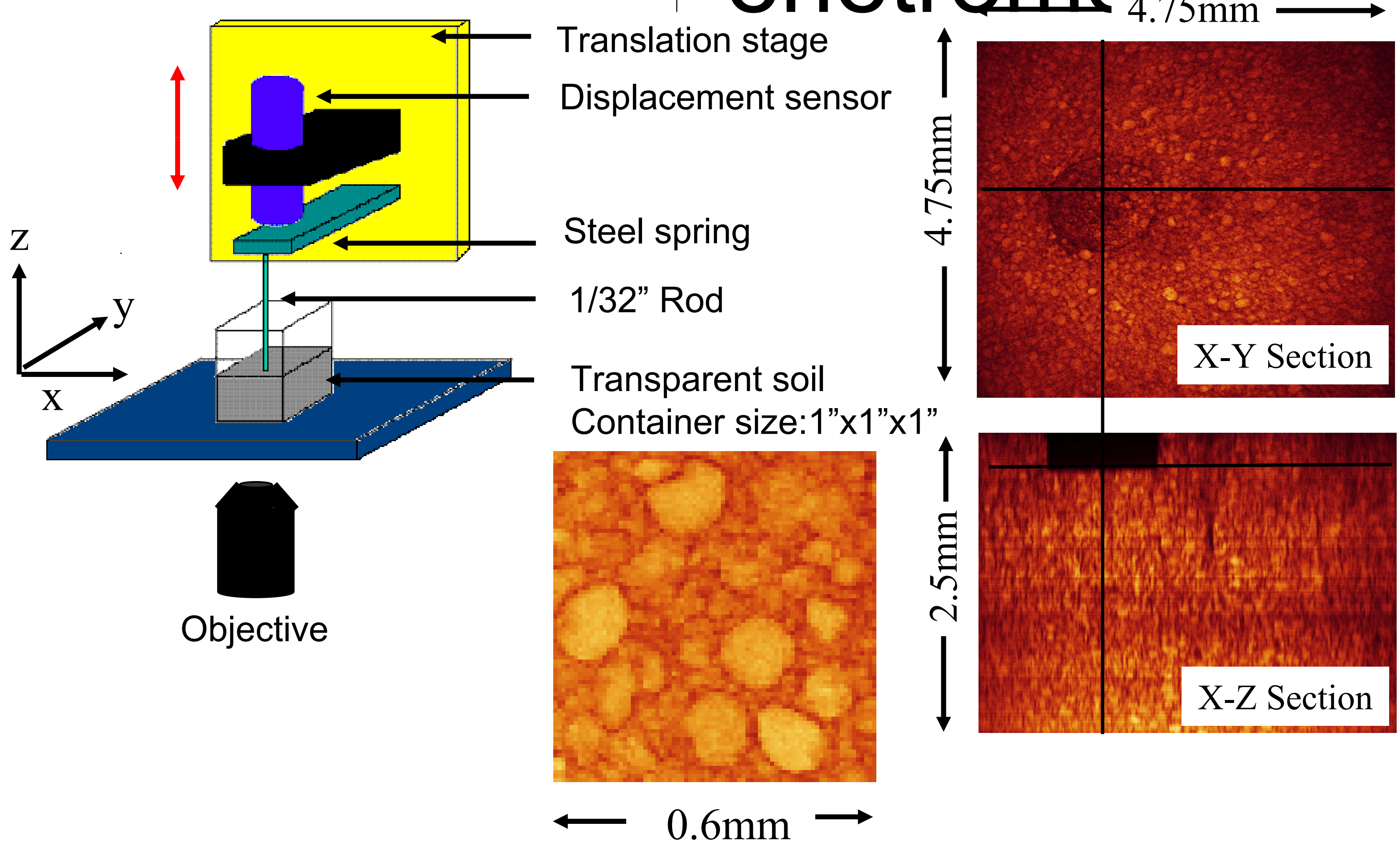
X-ray microtomography

Delannay Group, Rennes

Confocal microscopy

Laser Sheet Scanning

Soil and Penetrometer



- Non-spherical amorphous silica particles 2~150µm and index matching oil produce transparent model soil.
- Imaging by confocal or 2-photon laser scanning microscopy.

Refractive Index Matched Scanning (RIMS)

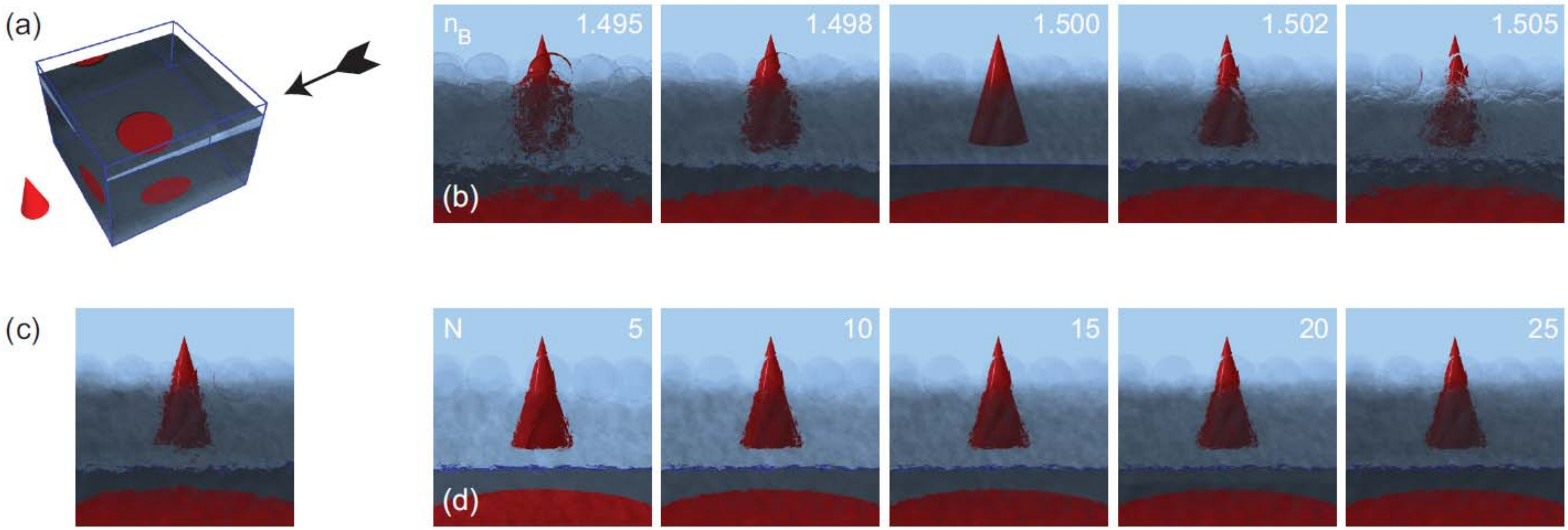
Refractive Index Matched Scanning of Dense Granular Materials

Joshua A. Dijksman,[1,2] Frank Rietz,[3,4,5] Kinga A. Lőrincz,[6] Martin van Hecke,[2] and Wolfgang Losert[7]

Submitted to Review of Scientific Instruments

material	index $n20_D$	diameter range [mm]	price	company
soda lime	~1.52	0.1-10	++	Sigmund Lindner
crystal	~1.59	3	++++	Sandoz Fils SA
borosilicate	~1.5	0.1-5	++	Sigmund Linder
fused silica	1.45-1.46	2-3	+++++	Sandoz Fils SA
BK7	1.5168	2-3	+++++	Worf Glaskugeln GmbH
PMMA	1.47-1.50	0.1-10	++++	Engineering Labs/Spherotech
Hydrogel	1.33-1.34	10-100	+	Educational Innovations

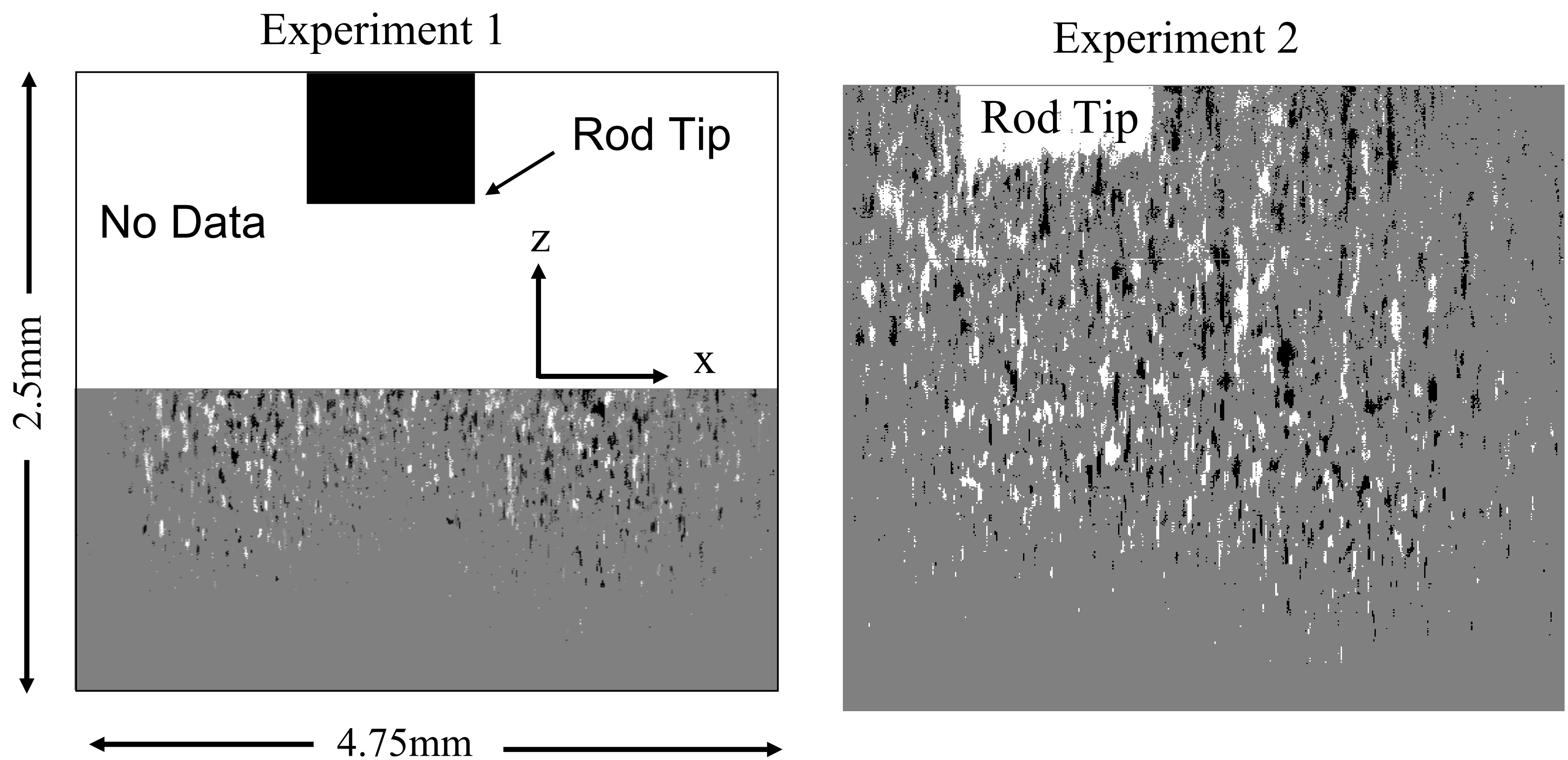
solvent	n_D (range)
Triton X-100	1.49
DMSO	1.479
1-Methylnaphthalene	1.615
SodiumPolyTungstate (aq)	1.33-1.55
Eugenol	1.541
NaI (aq)	1.33-1.502
Methyl Salicylate	1.536
CS_2	1.627
Cargille index matching liquids	1.30-2.11
Cyclohexyl bromide	1.495
Glycerine	1.474
Sucrose (aq)	1.33-1.49
para-Cymene	1.49



(a)
n_B
1.495
1.498
1.500
1.502
1.505
(b)
(c)
N
5
10
15
20
25
(d)

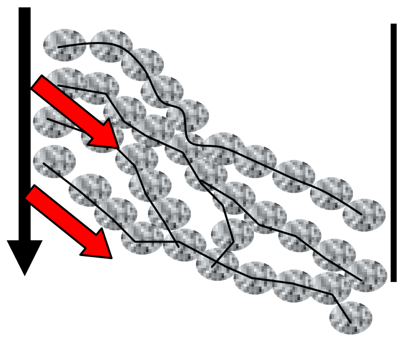
dye	λ_{abs} [nm]	λ_{emi} [nm]
Nile Blue 690 Perchlorate	633	650 - 690
Rhodamine 6G	530	555-585
Atto 633	633	650
Pyrromethene 597-8C9	525	590
Pyrromethene 567A	523	543

Particle Motion Revealed by Difference Images

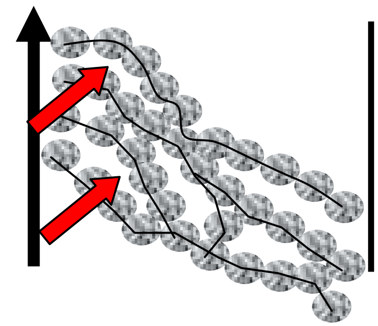


- The shear zone extends 3-4 rod diameters ahead of the tip.
- Note the shape of the shear zone.

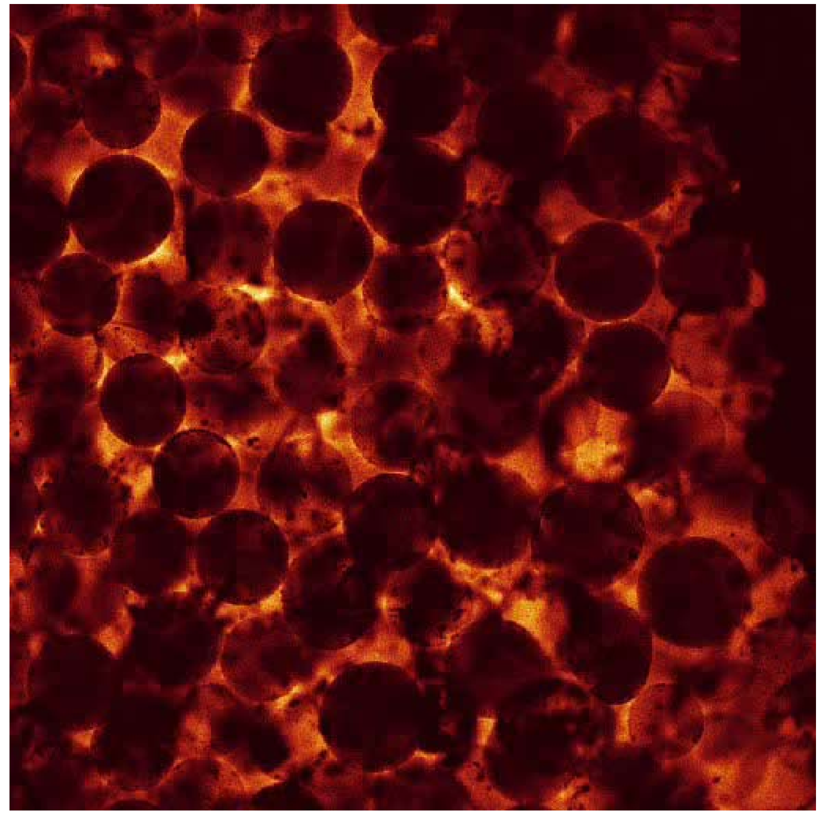
Confocal Imaging



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

3D imaging approaches

MRI

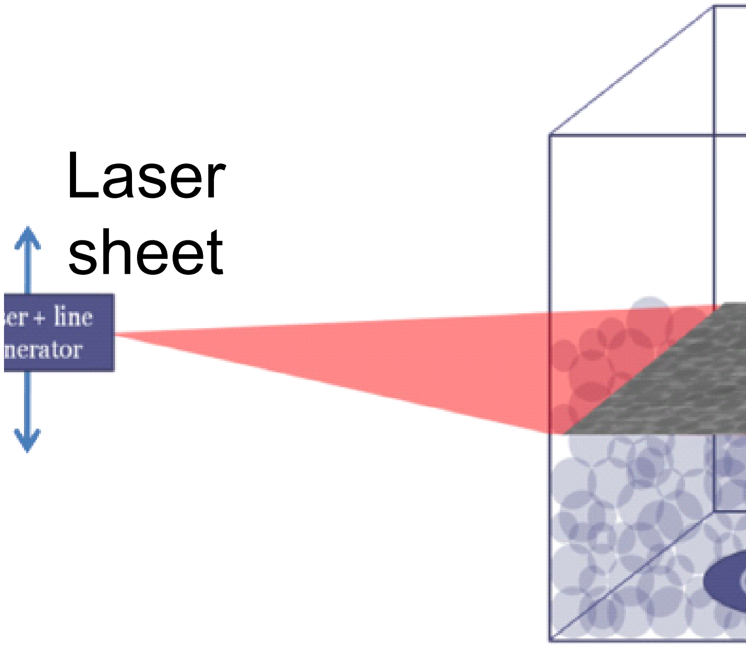
Jaeger Group University of Chicago

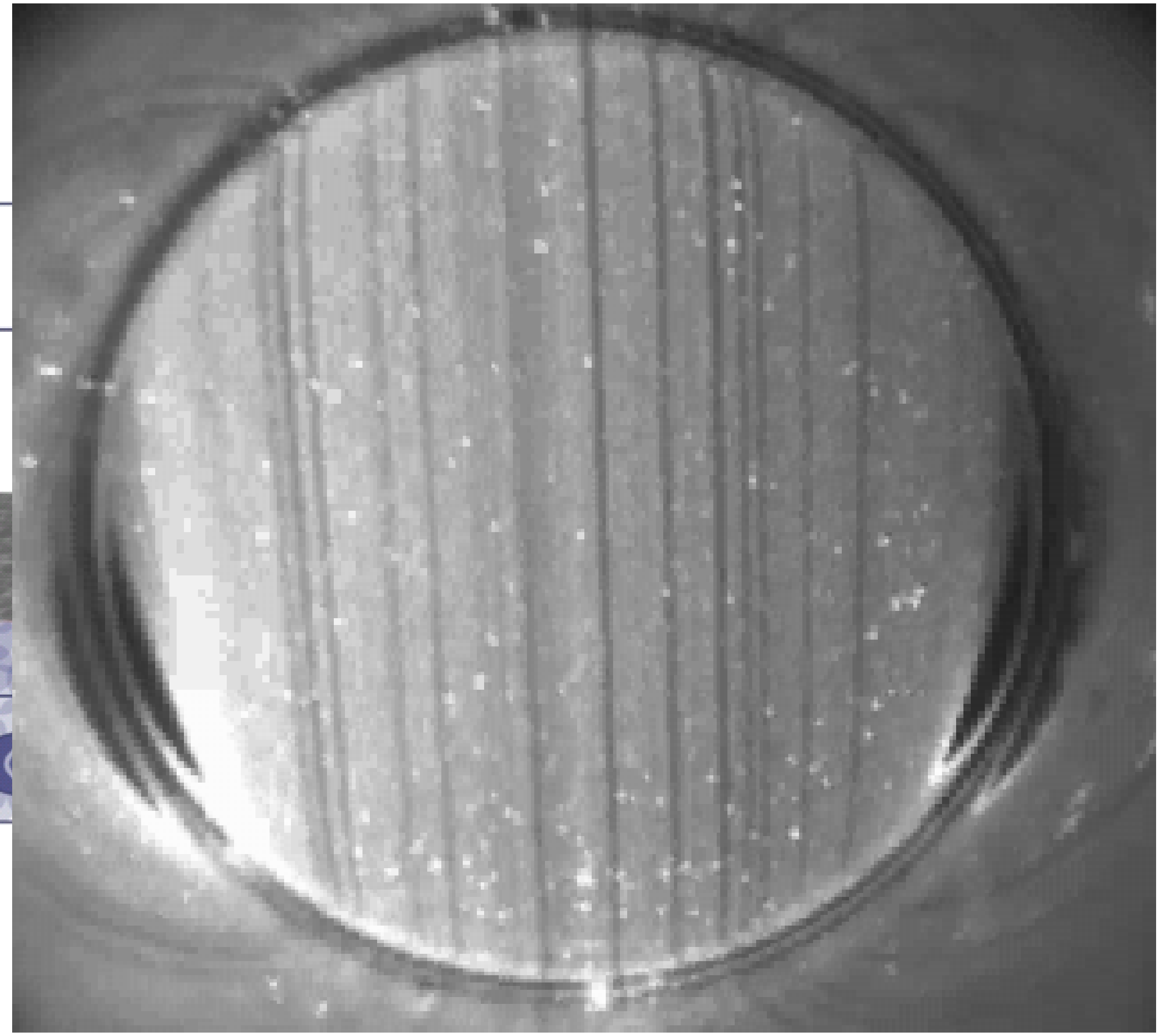
X-ray microtomography

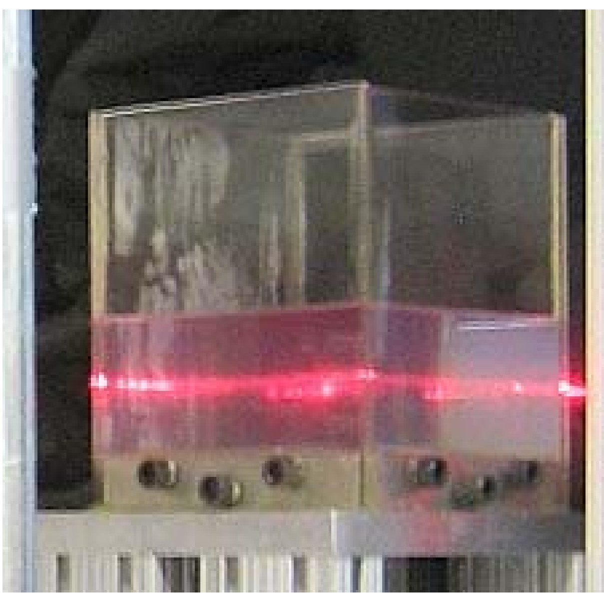
Delanney Group, Rennes

Confocal microscopy

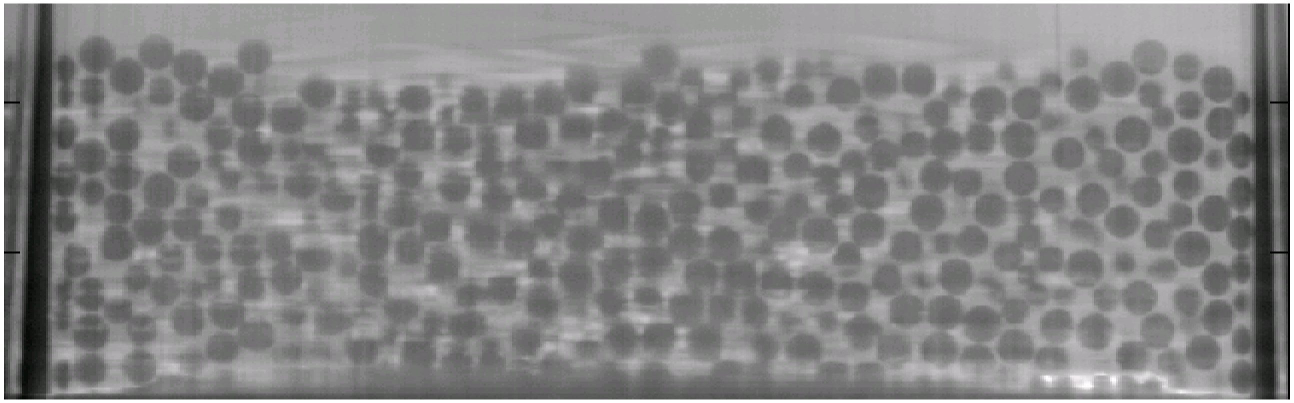
Refractive Index Matched Scanning (RIMS)



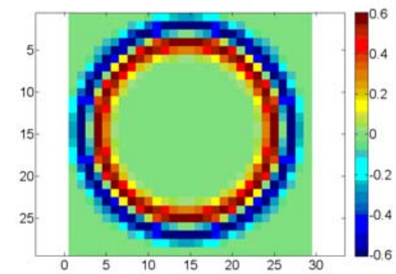


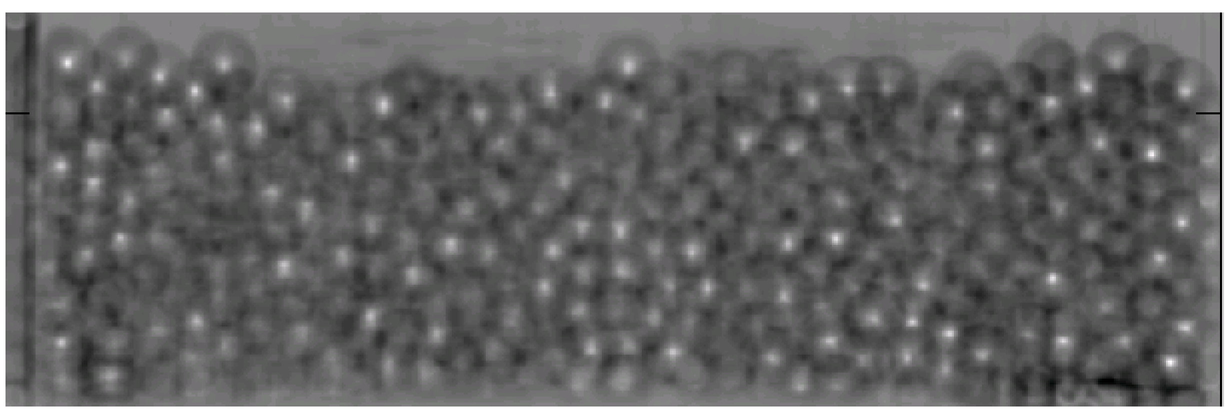


Toiya *et al.*
Granular Matter (2007)
Slotterback *PRL*
(2008)



3D convolution (see Gollub/Tsai for 2D version)

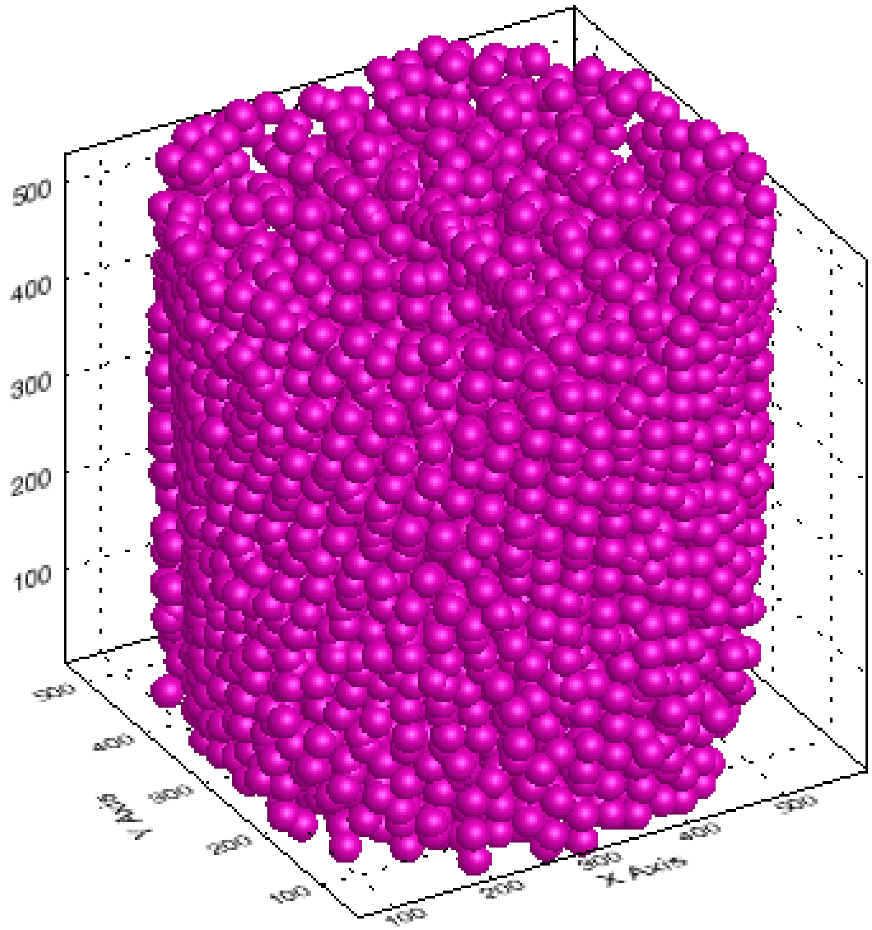


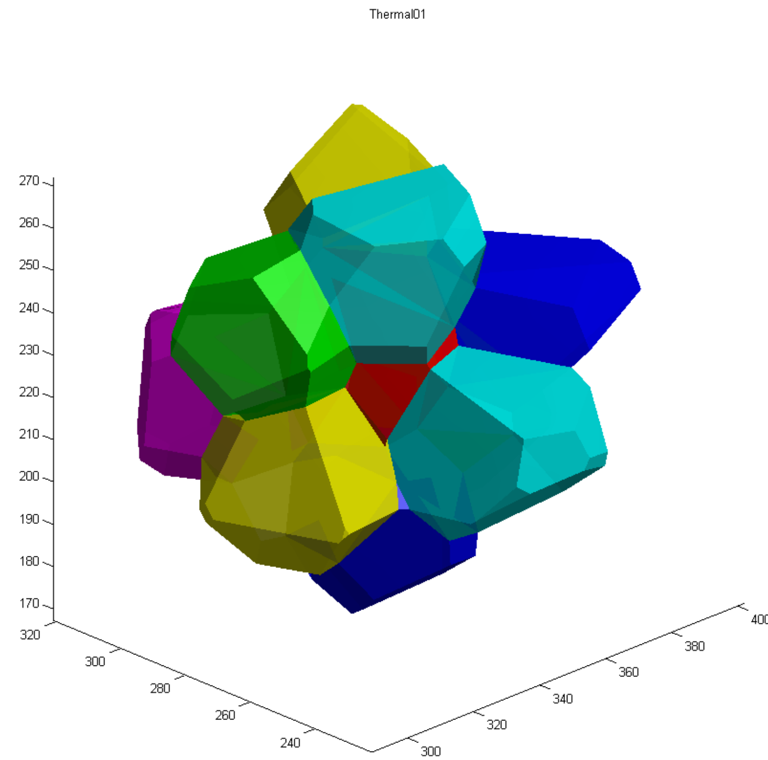


3D imaging yields local structure

Steven Slotterbac k

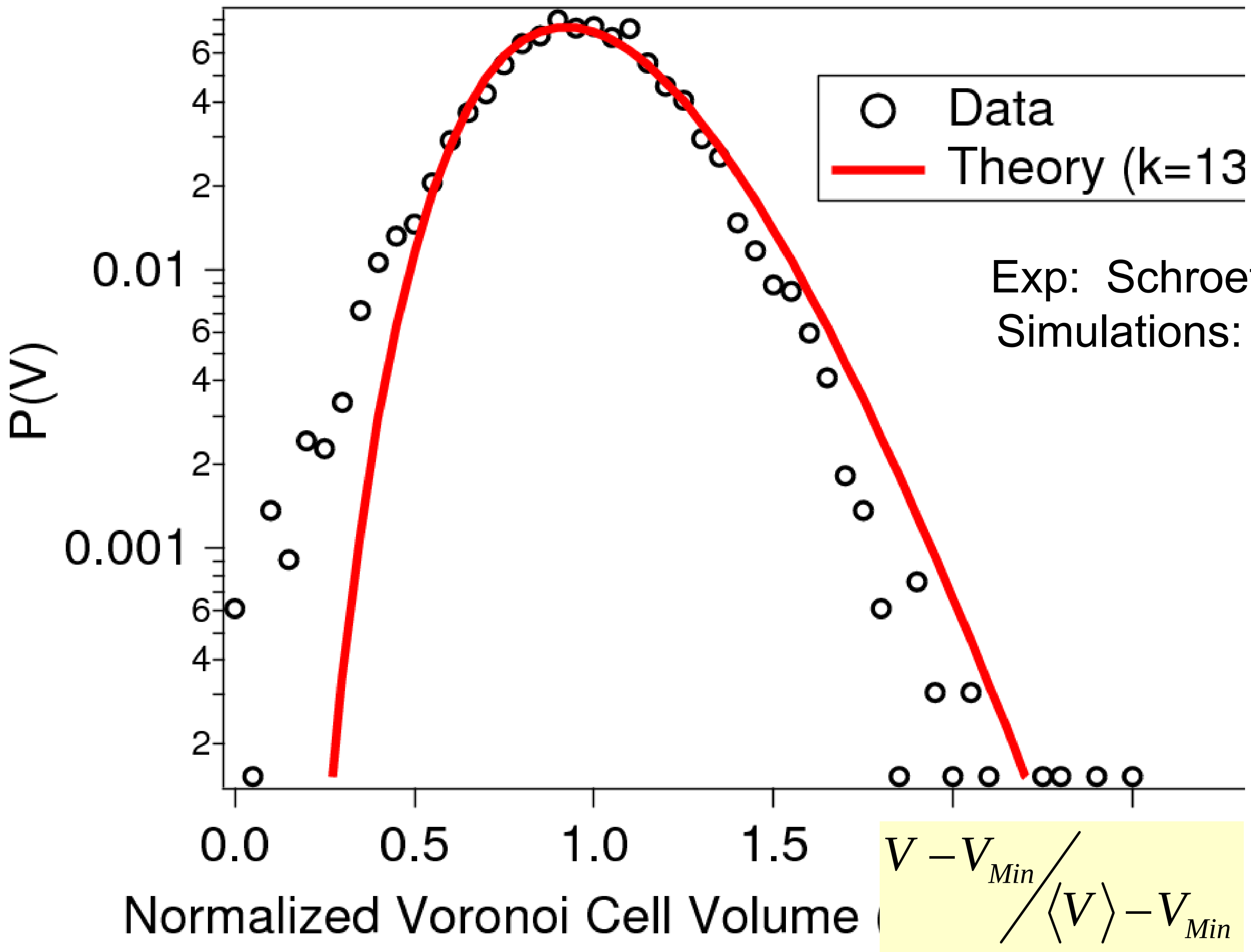
Masahir o Toiya





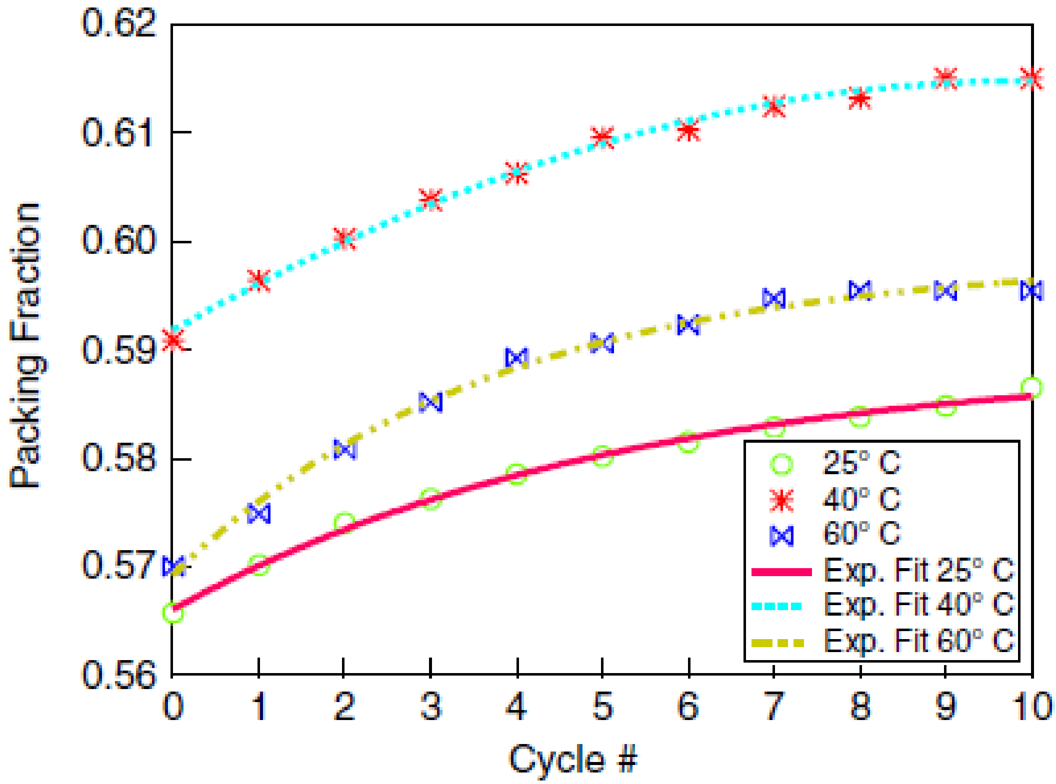
Slotterback *et al* PRL (2008)

Voronoi volume distribution

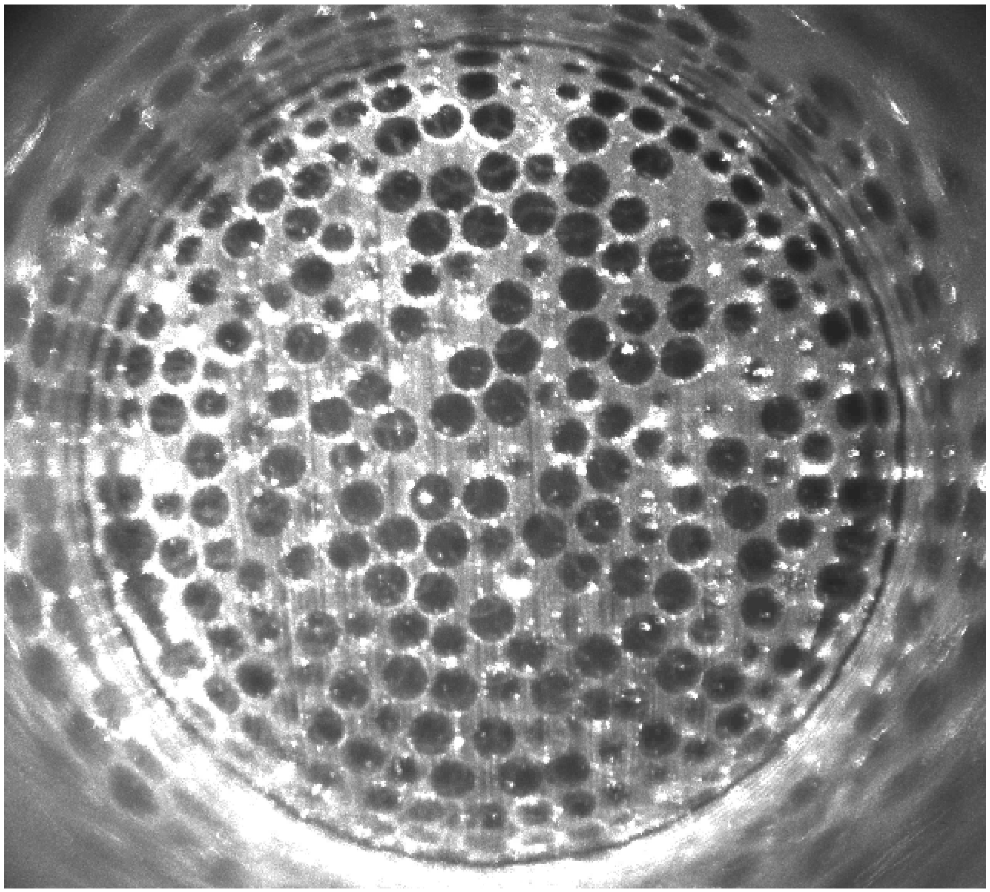


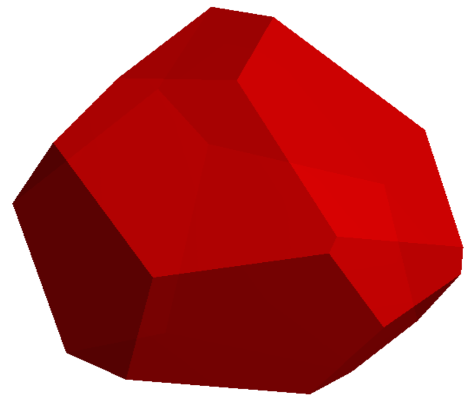
Exp: Schroeter, Aste, Swinney
Simulations: J.F. Douglas et al

Compaction through thermal cycling



Dynamics viewed at the particle level





Voronoi volume vs time

Cross section through sample vs time

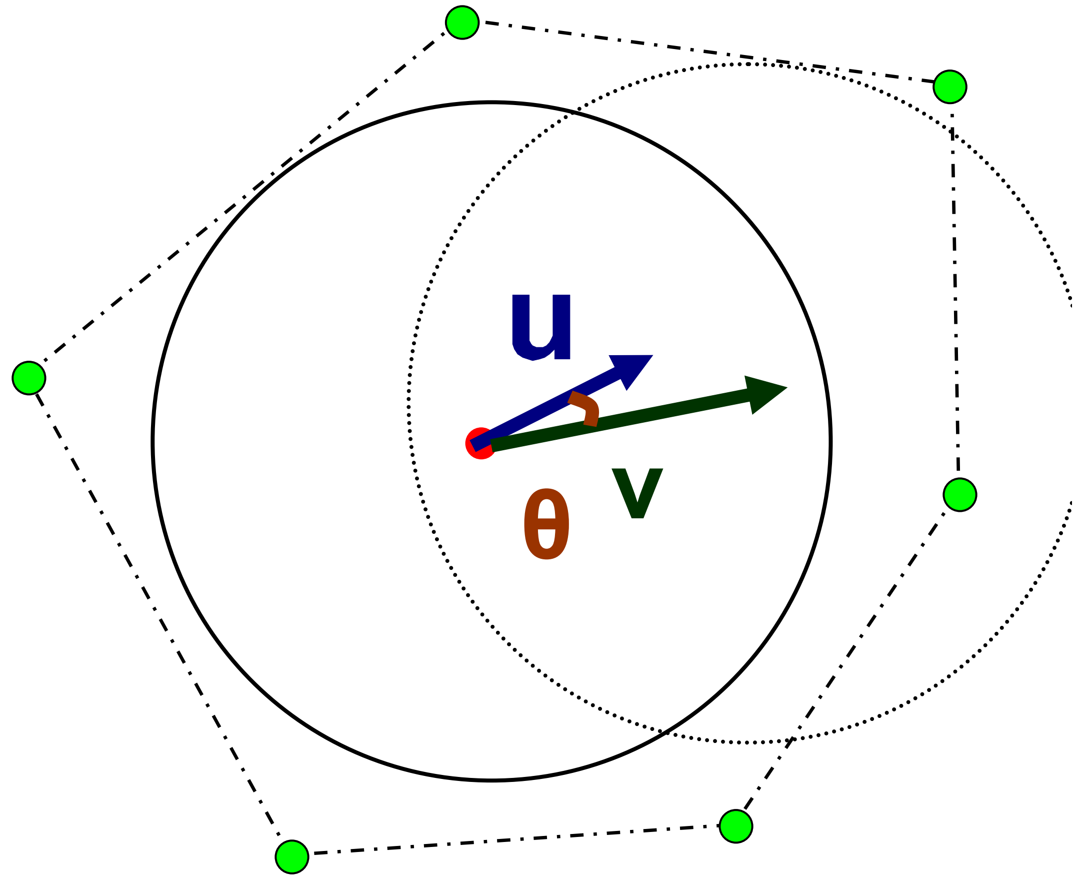
A. Rahman, JCP (1966): Computer simulations of local liquid structure

Shape of Voronoi volume related to displacement of particles

- **u** vector pointing toward center of voronoi vertices
- **v** displacement of particle at following time step.

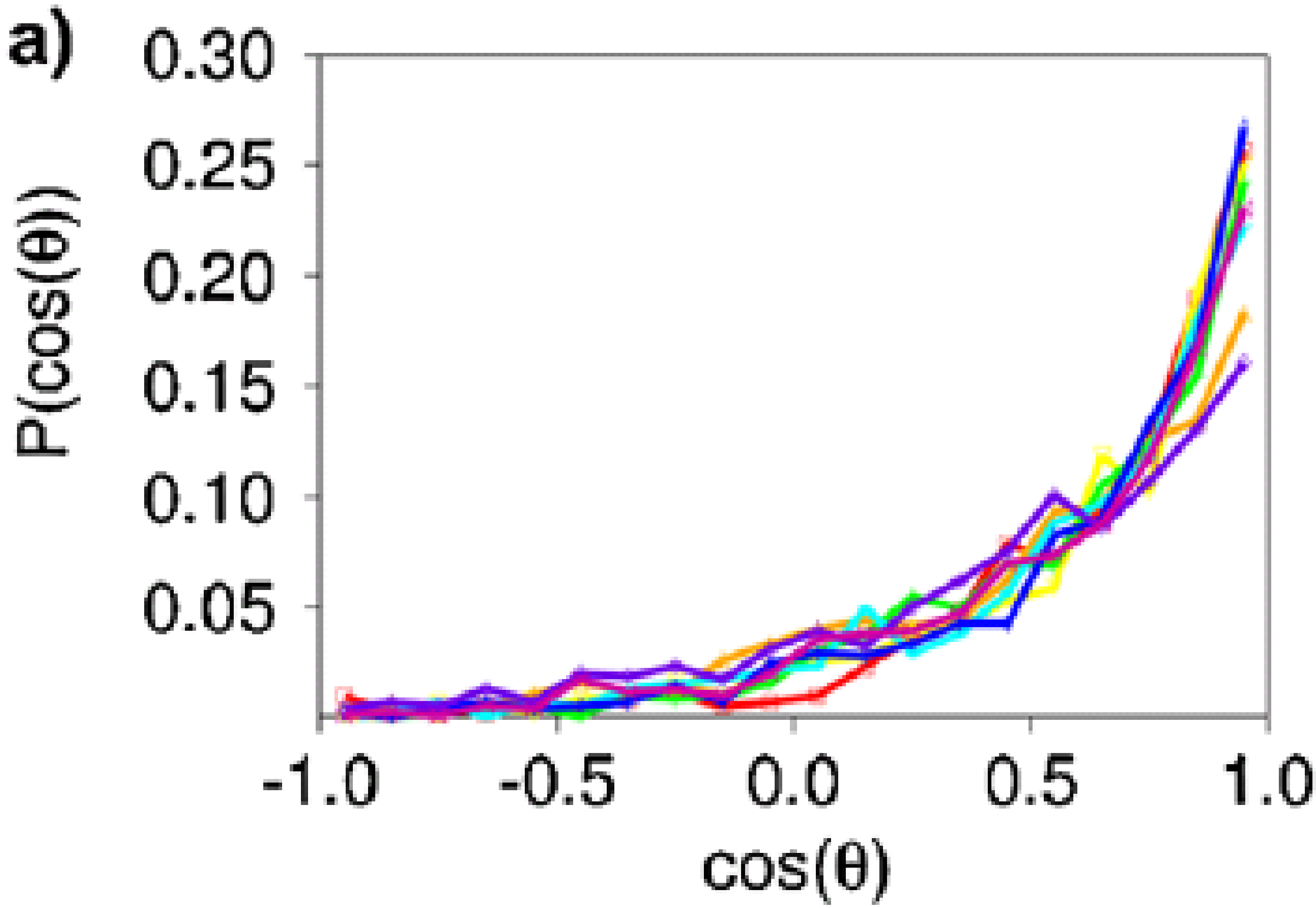
θ Angle between **u** and **v** (in three dimensions)

$$\cos\theta = \frac{\vec{\mathbf{u}} \bullet \vec{\mathbf{v}}}{\mathbf{uv}}$$



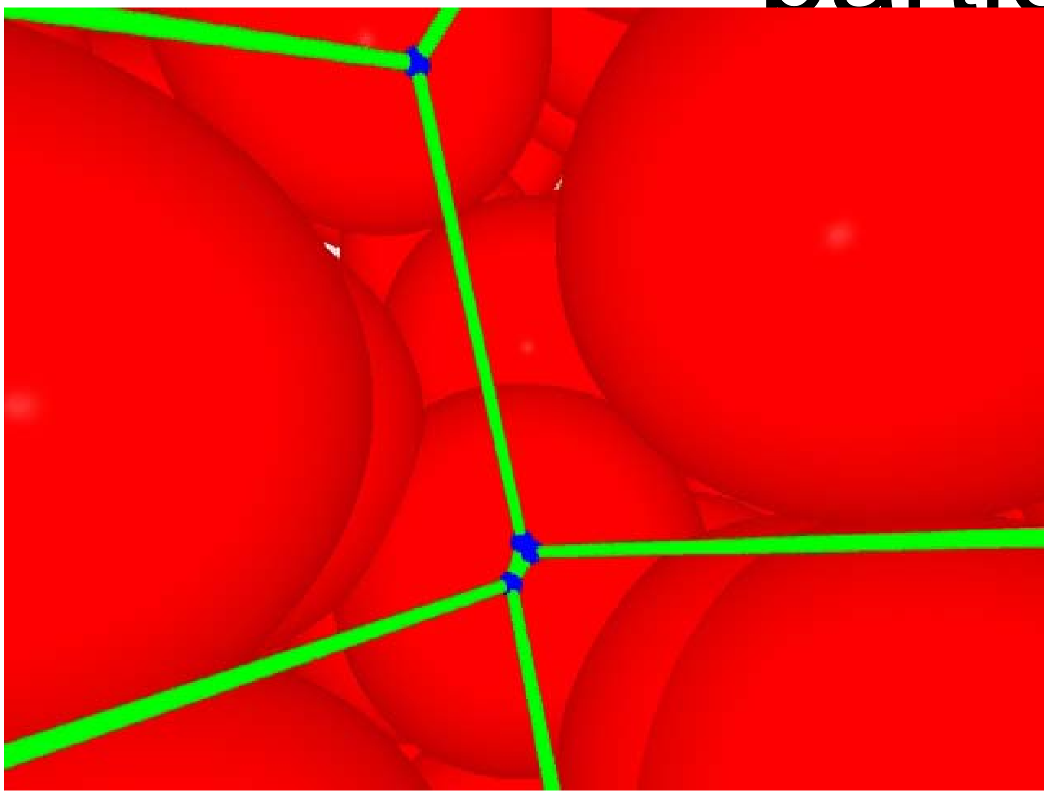
Slotterback *et al* PRL (2008)

Motion in direction of center of Voronoi vertices

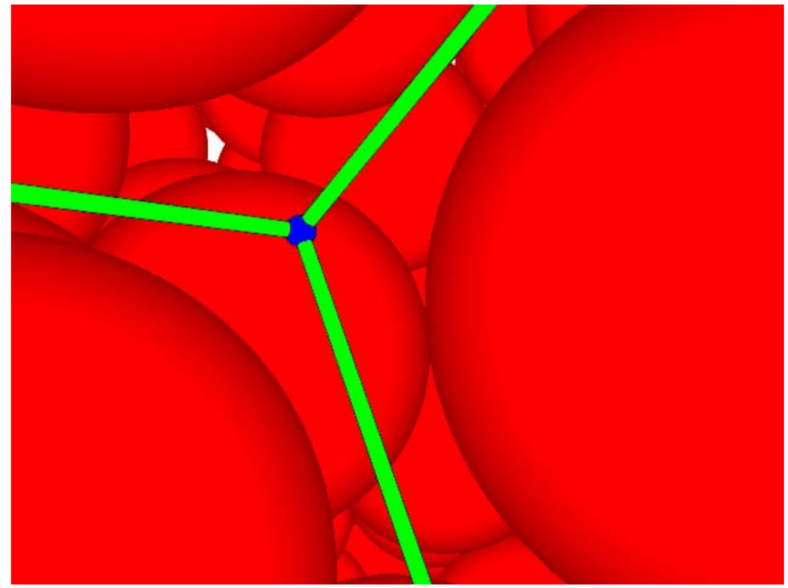


Slotterback *et al* PRL (2008)

From the perspective of the particle

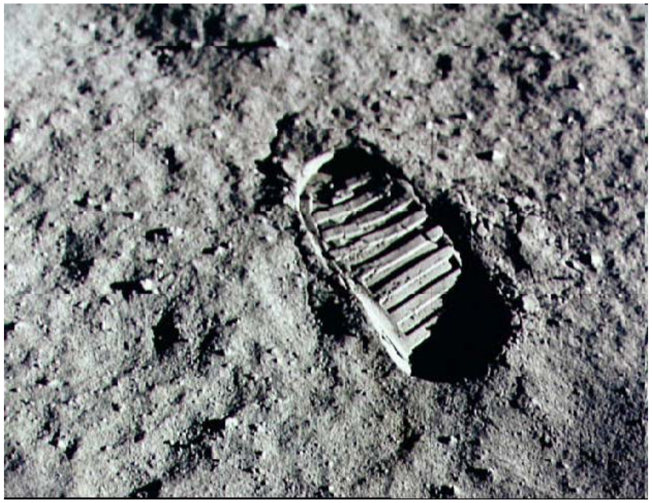


View along u vector



Vertices of Voronoi volume =
“Escape directions” of particle from local cage

Aging/Strengthening in Astrophysics?

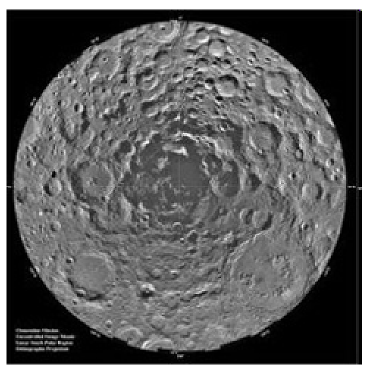


Thermal Cycling on the Moon

Daytime: $+120^{o}C$

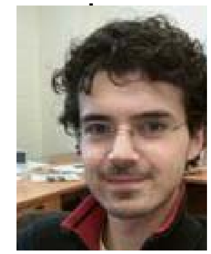
Night: $-150^{o}C$

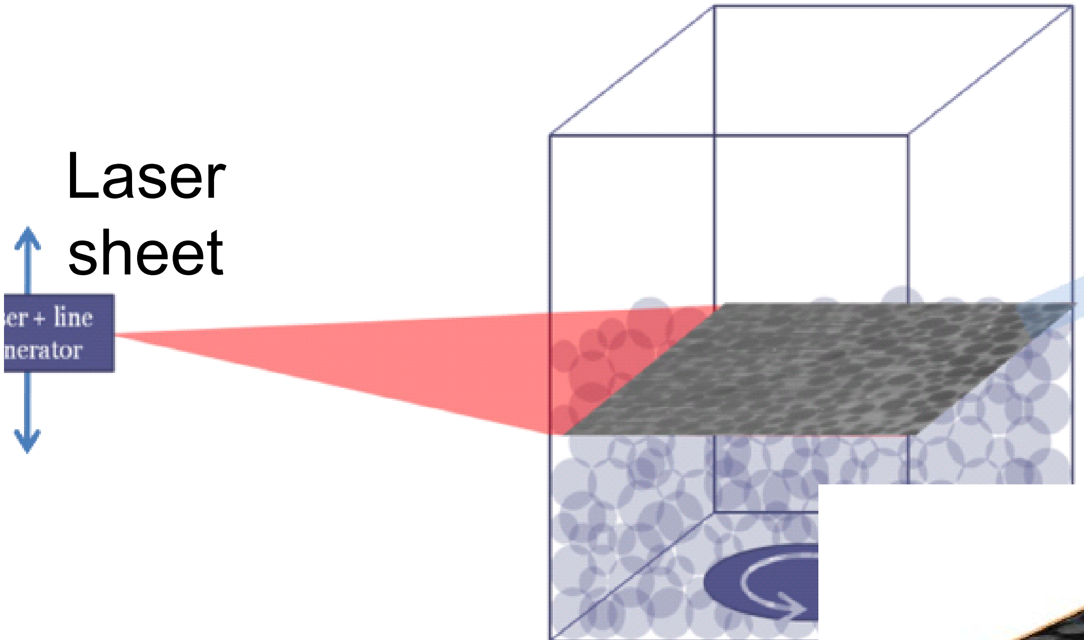
[lunarpedia.org]

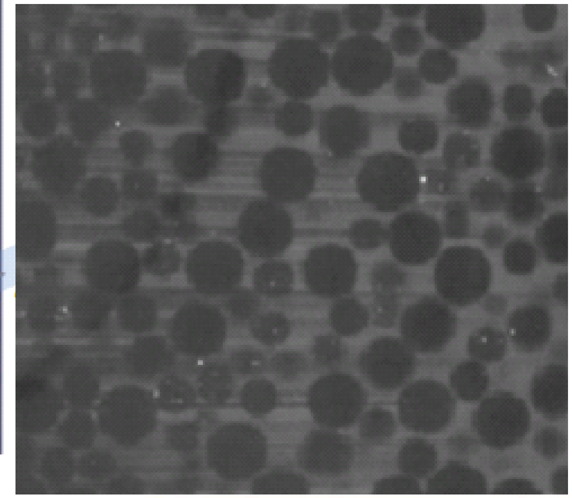


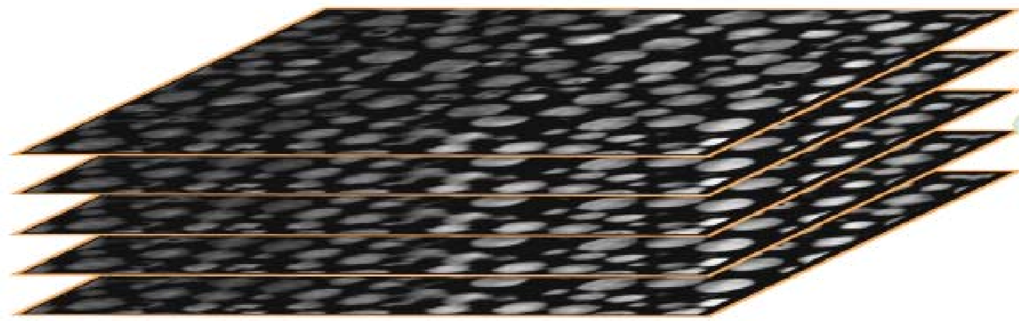
The pole is a regions not exposed to thermal cycling. Will it be equally compacted?

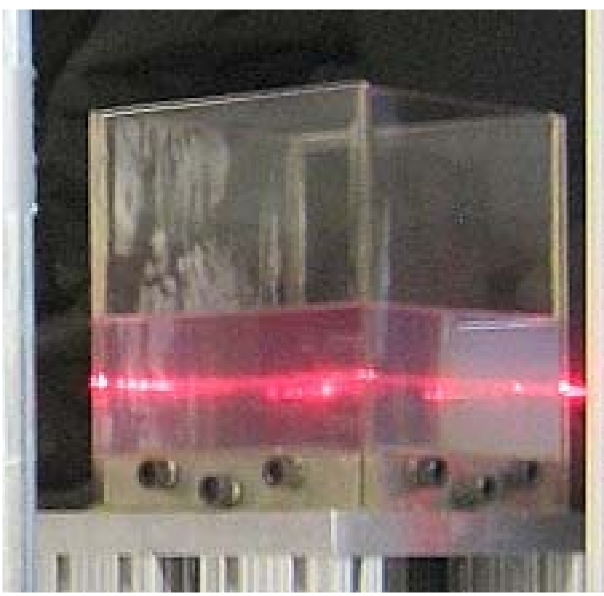
DEMO





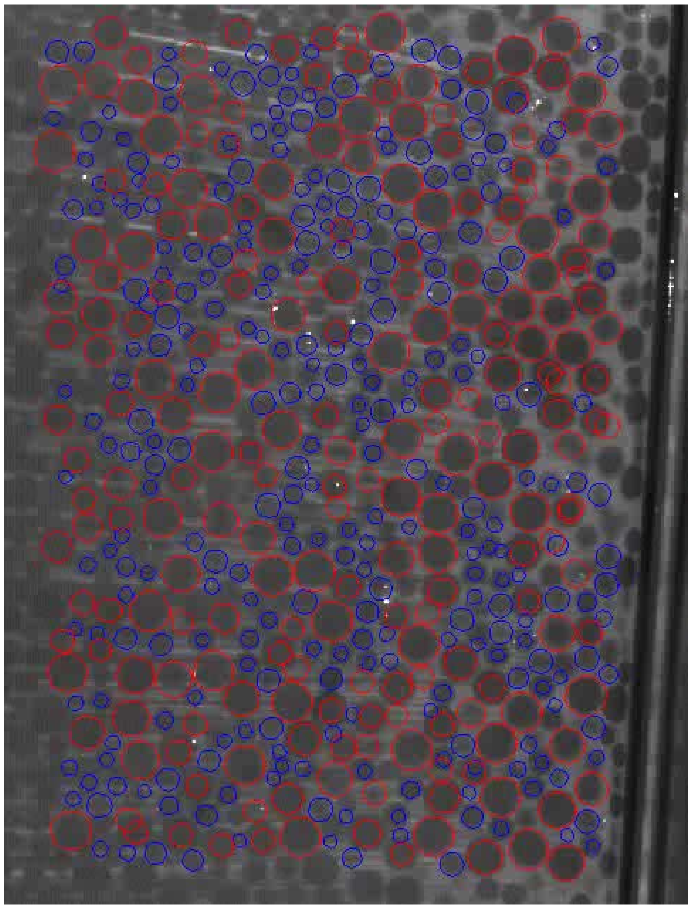




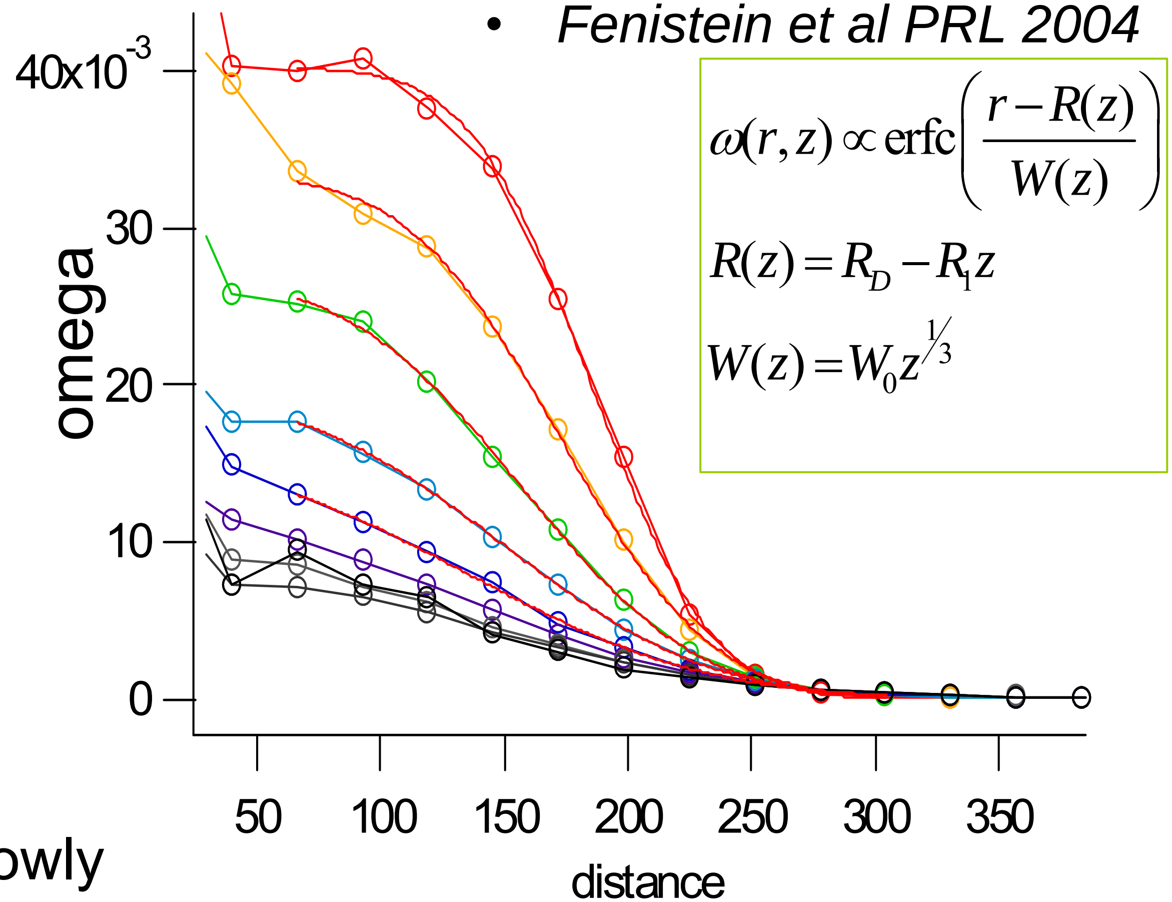


Toiya *et al.*
Granular Matter (2007)
Slotterback *PRL*
(2008)

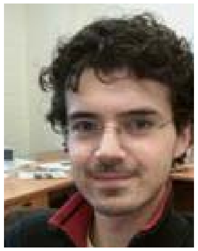
3D imaging of flow - continuum flow fields



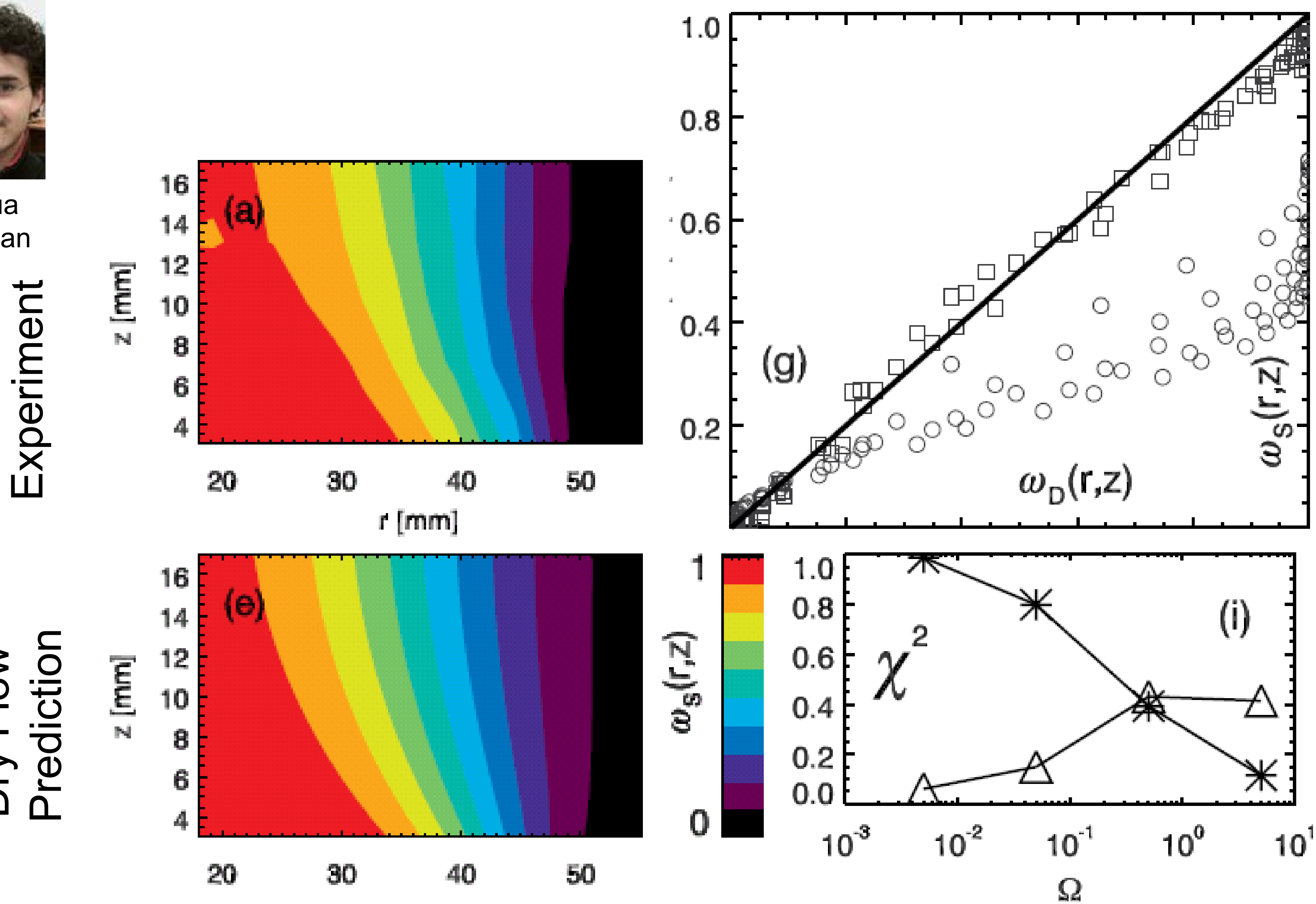
- Flow Profile matches
- **dry, continous** flow
- *Fenistein et al PRL 2004*



Move bottom disk in 3^o slowly
Stop to take a 3D picture



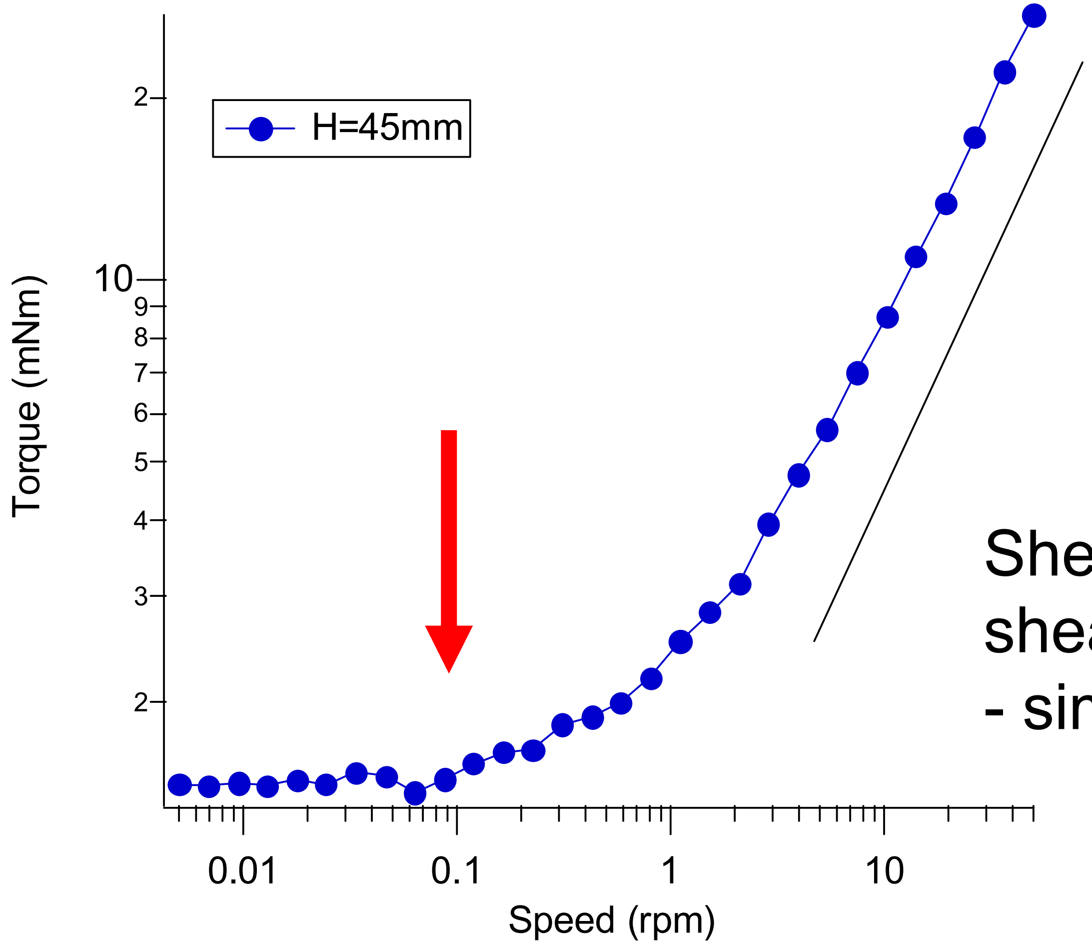
Joshua Dijksman



J. Dijksman, E. Wandersman, S. Slotterback, C. Berardi, M. van Hecke, W. Losert **PRE 060301 (2010)**

Shear force


Chris
Berardi

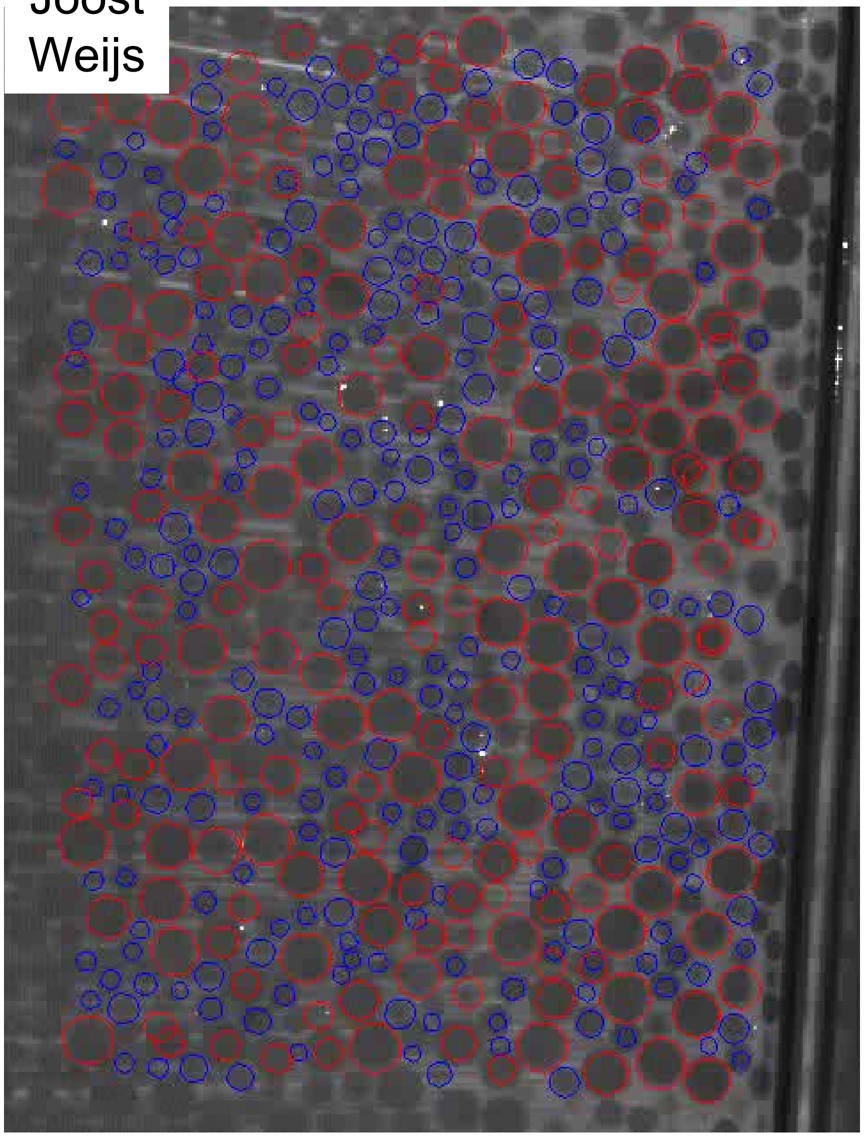


Shear force is independent of shear rate at slow shear rates - similar to dry granular flow

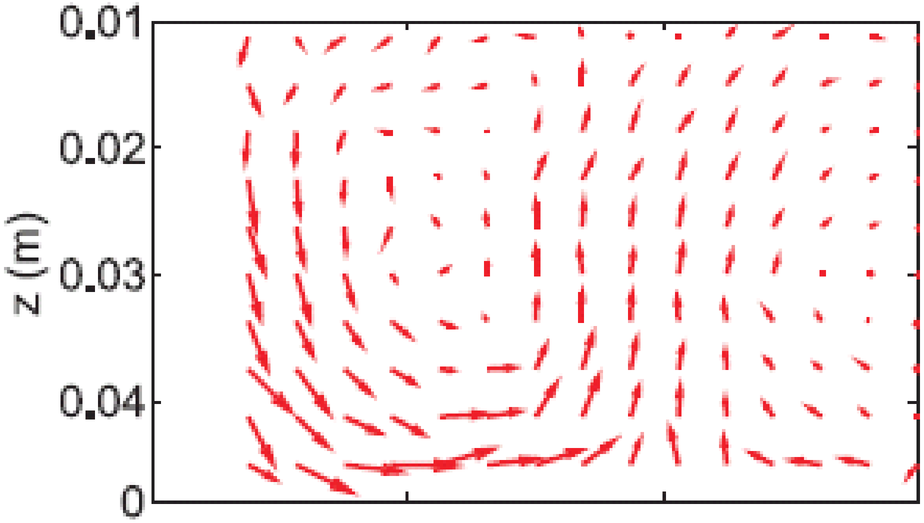
J. Dijksman, E. Wandersman, S. Slotterback, C. Berardi, M. van Hecke, W. Losert **PRE 060301 (2010)**

Joost Weijs

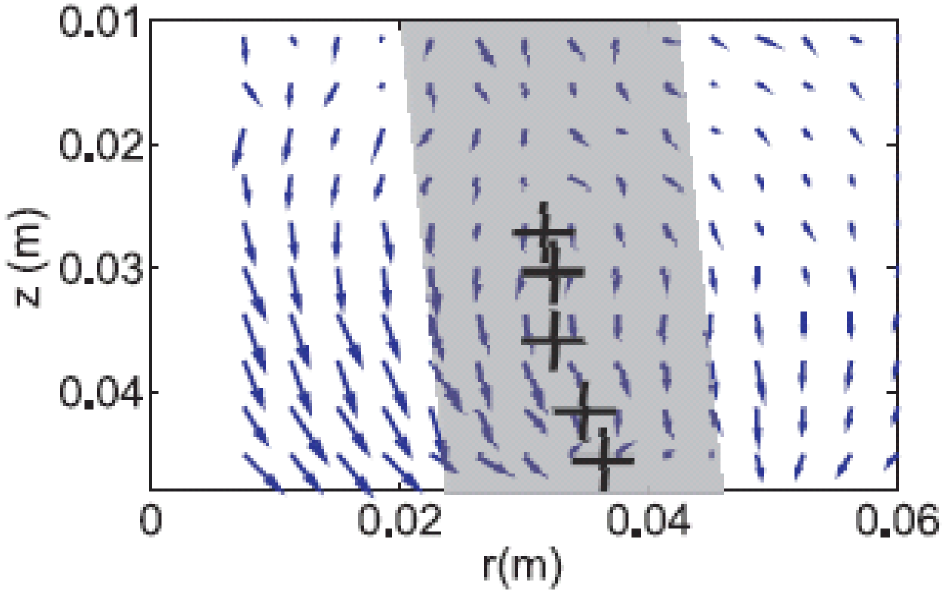
Convection Rolls during “step”-flow



- Large Particles

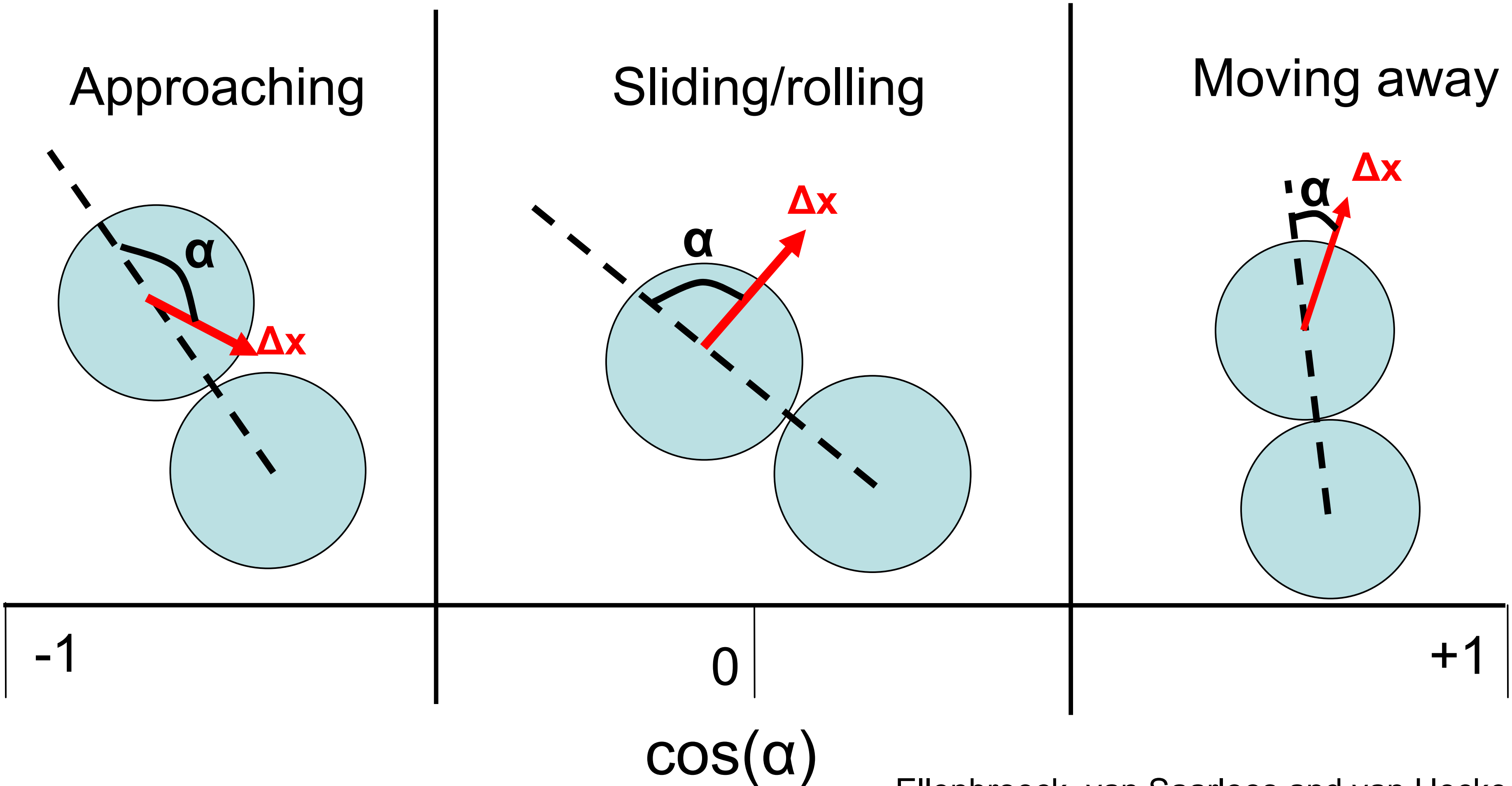


- Small Particles



Characterizing motion of two neighboring particles: Angle α

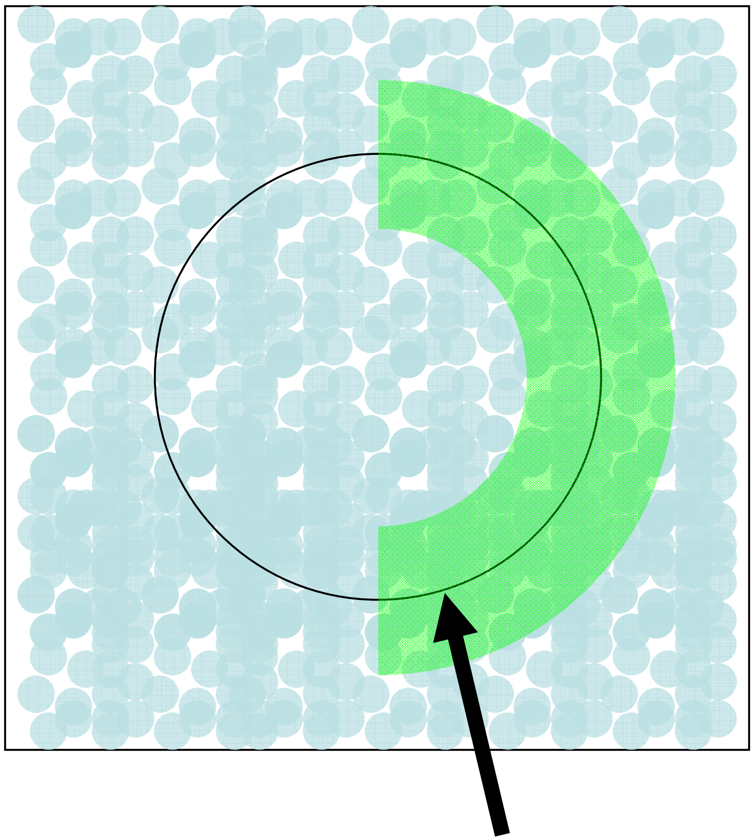
Steven Slotterback



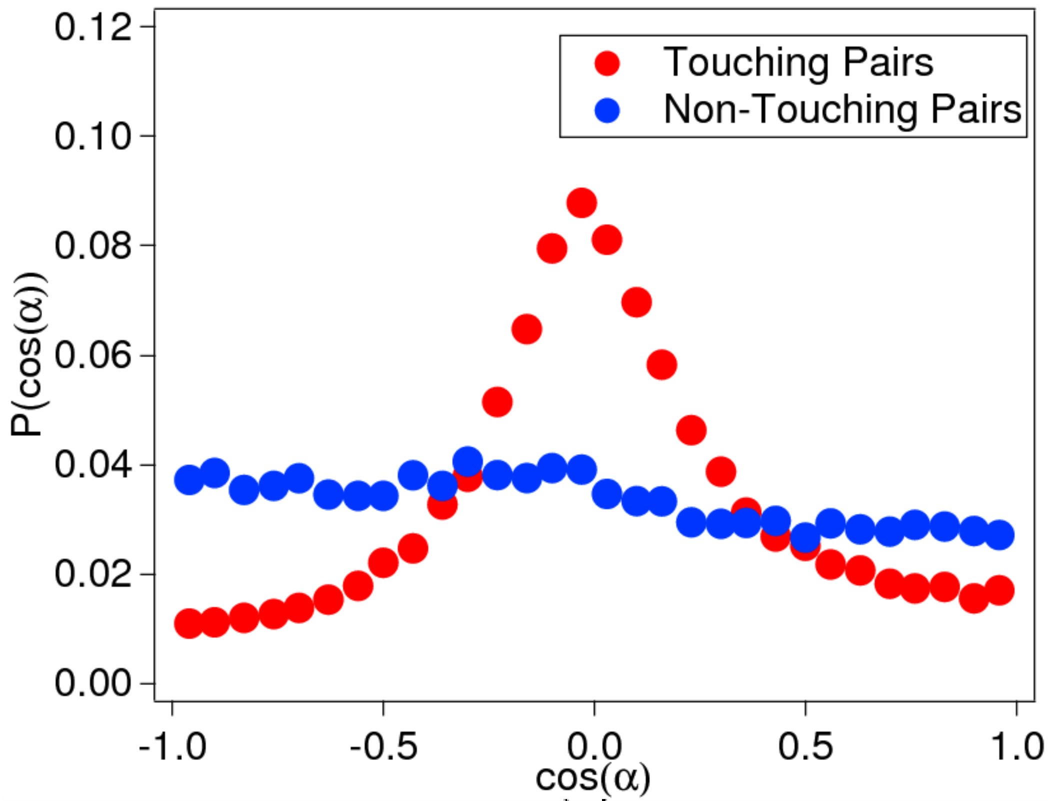
Ellenbroeck, van Saarloos and van Hecke

Motion of nearby particles in steady shear

Region of Interest



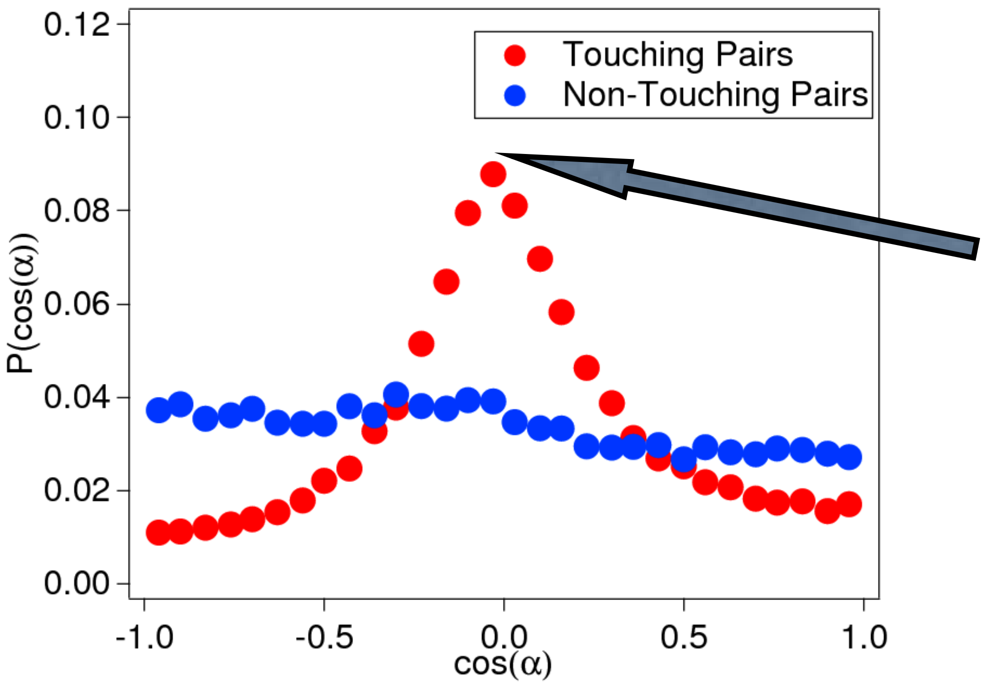
Disk Edge +/- 3 D

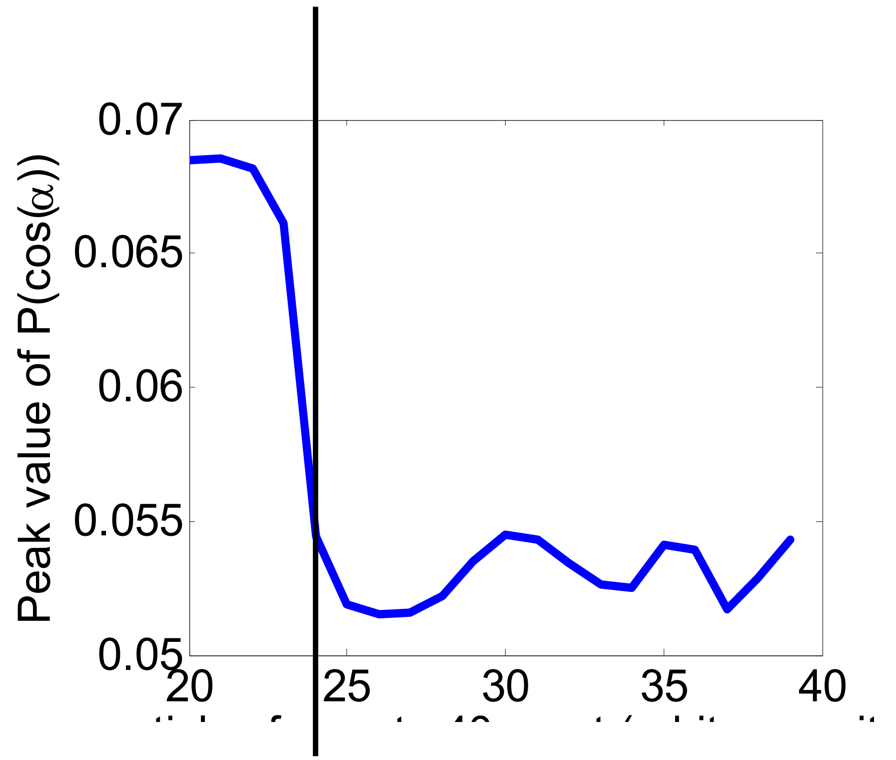


dr ≤ 1.04 D → "Touching"

dr > 1.04 D → "Not-Touching"

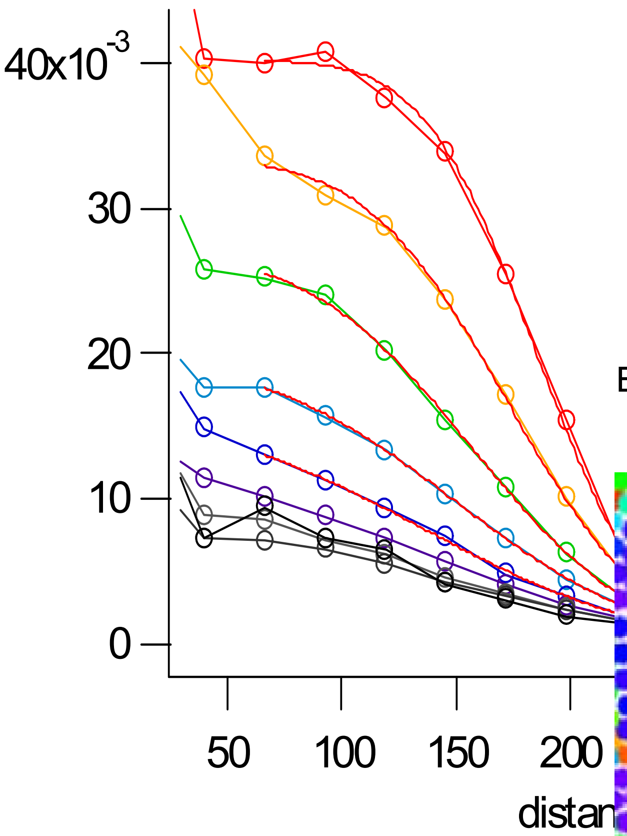
Which particles are neighbors?

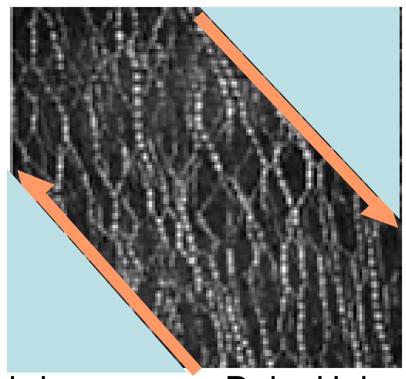




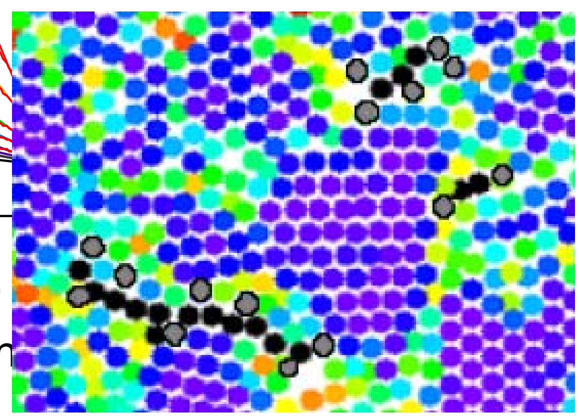
Granular flow on the mesoscale

- Quantification of mesoscale structure and dynamics?

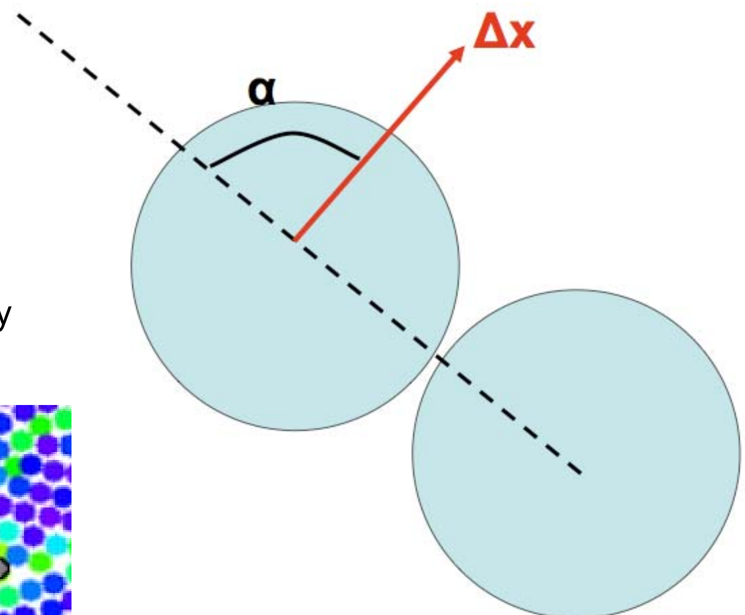




Behringer group Duke University



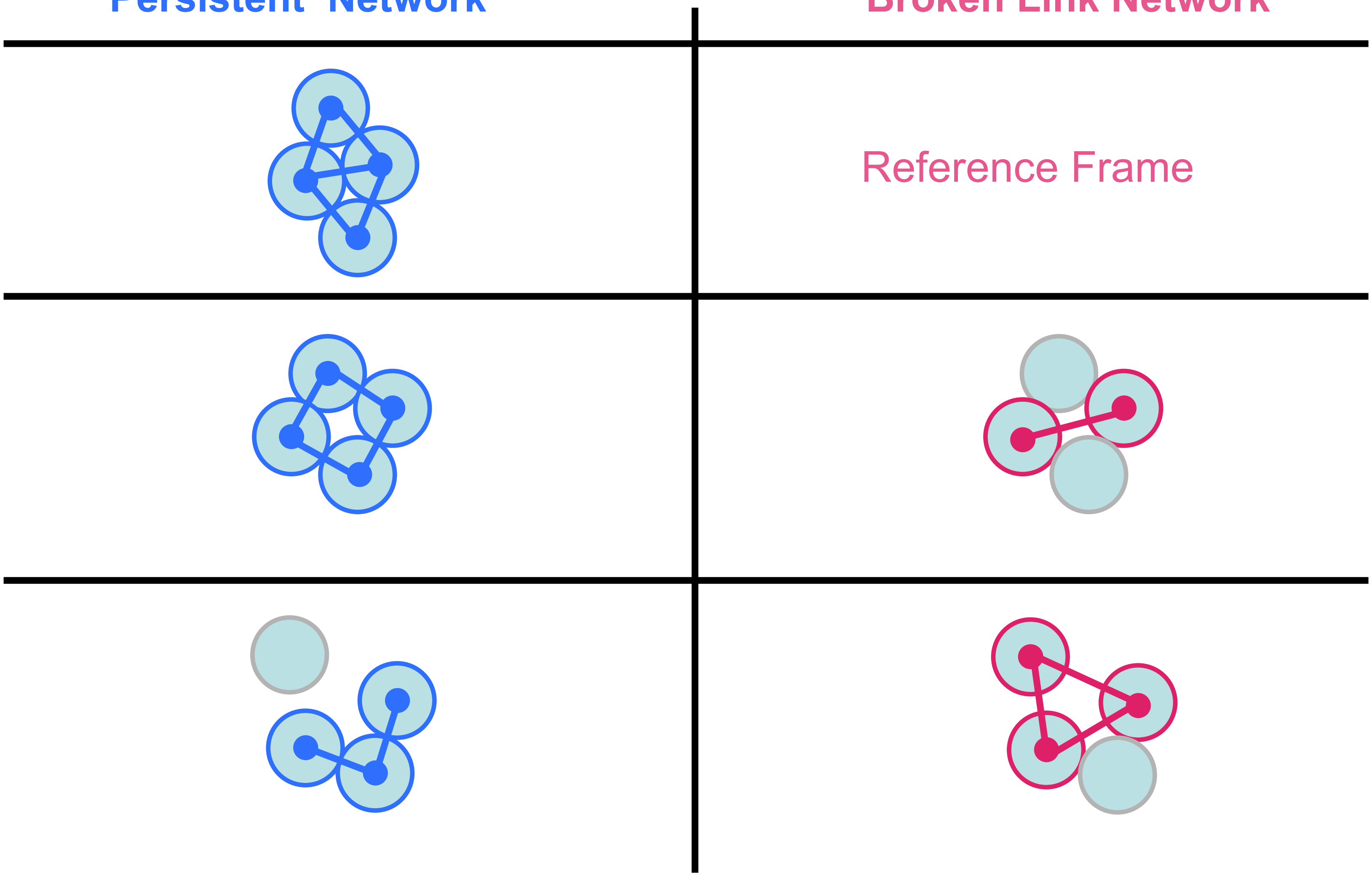
Berardi, Douglas, Losert, PRE (2010)

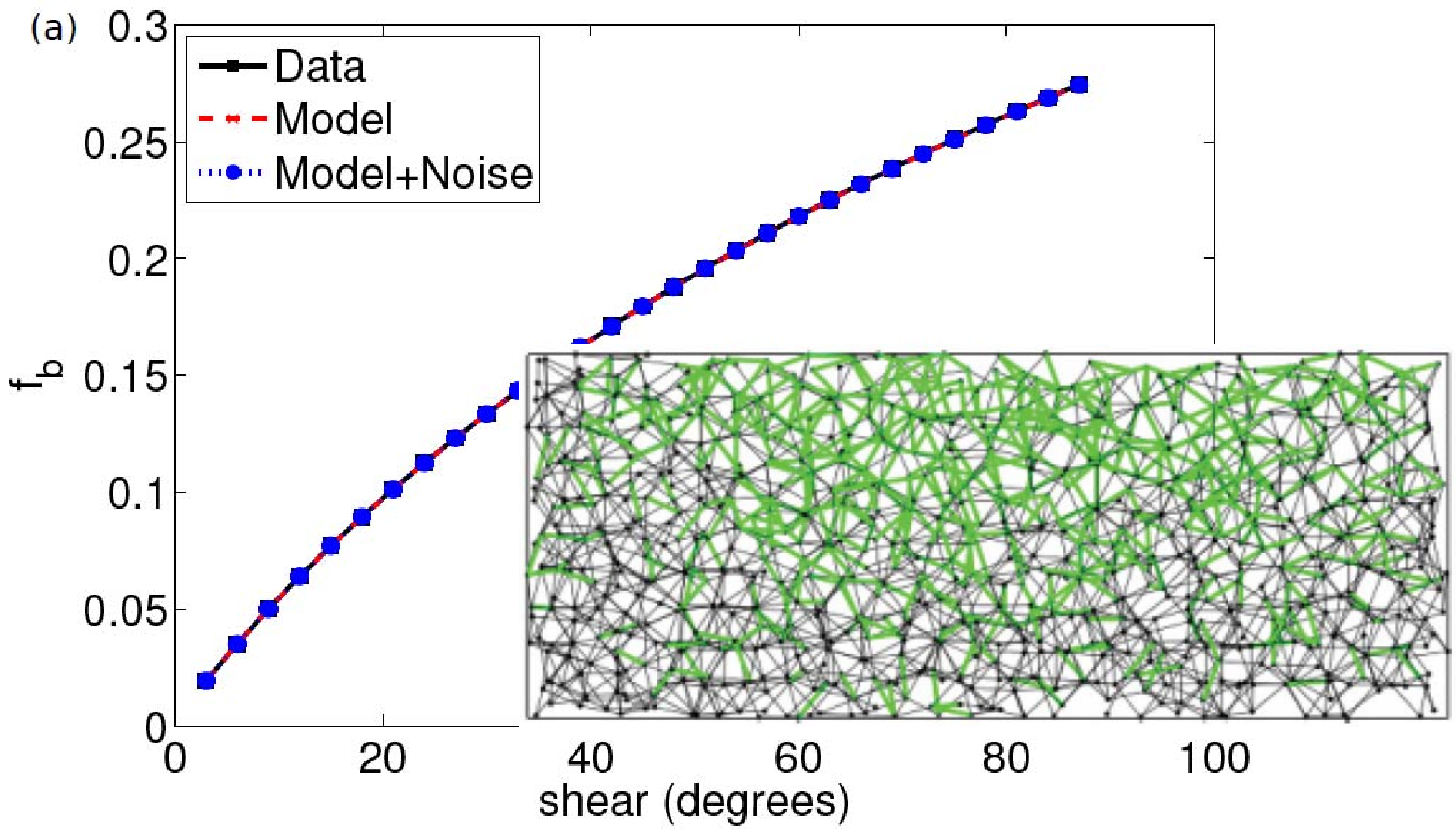


Mark
Herrera

Network characterization of granular **dynamics**

Persistent Network | **Broken Link Network**

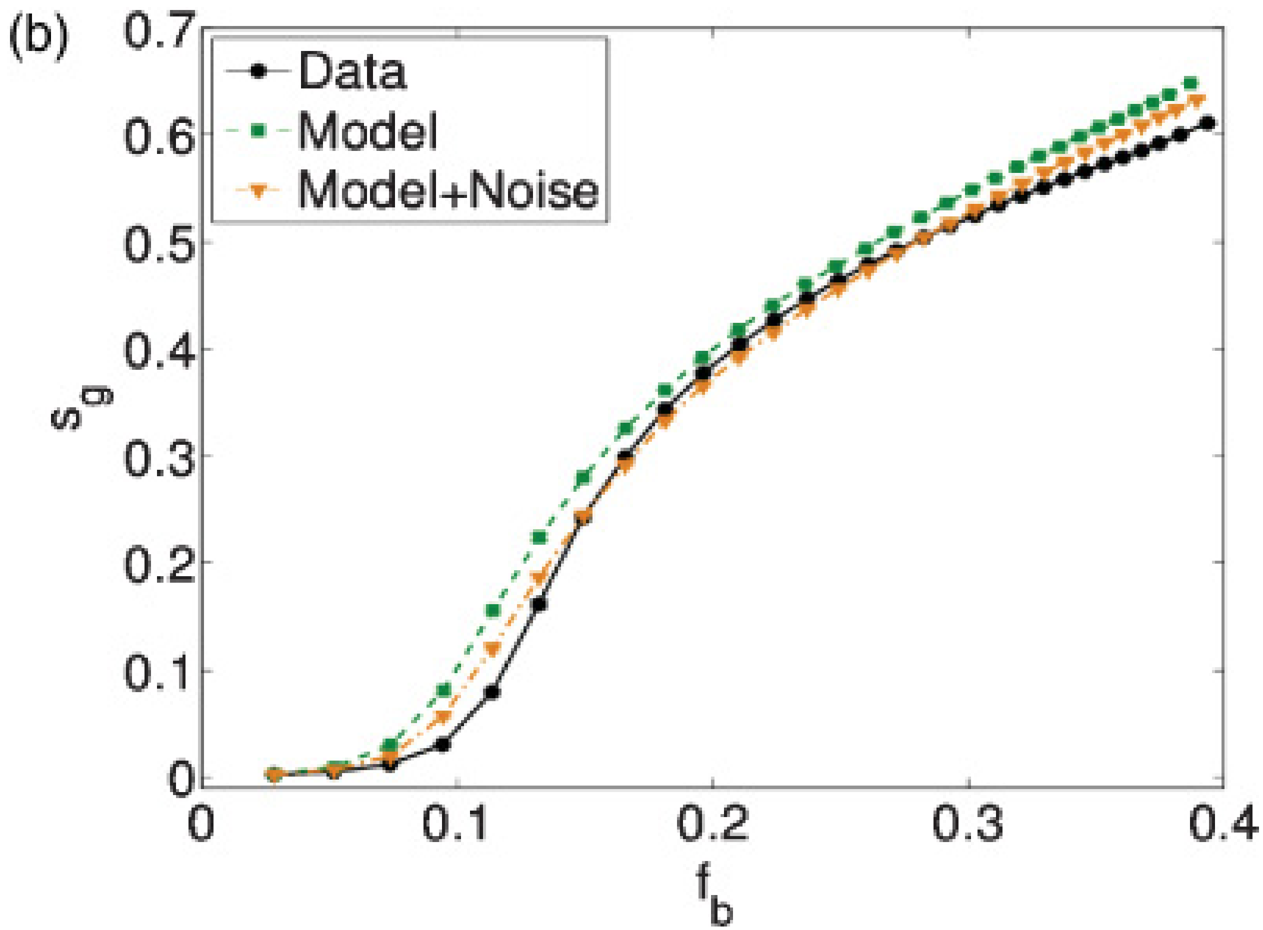




Experimentally observed fraction of broken links used as input in the model

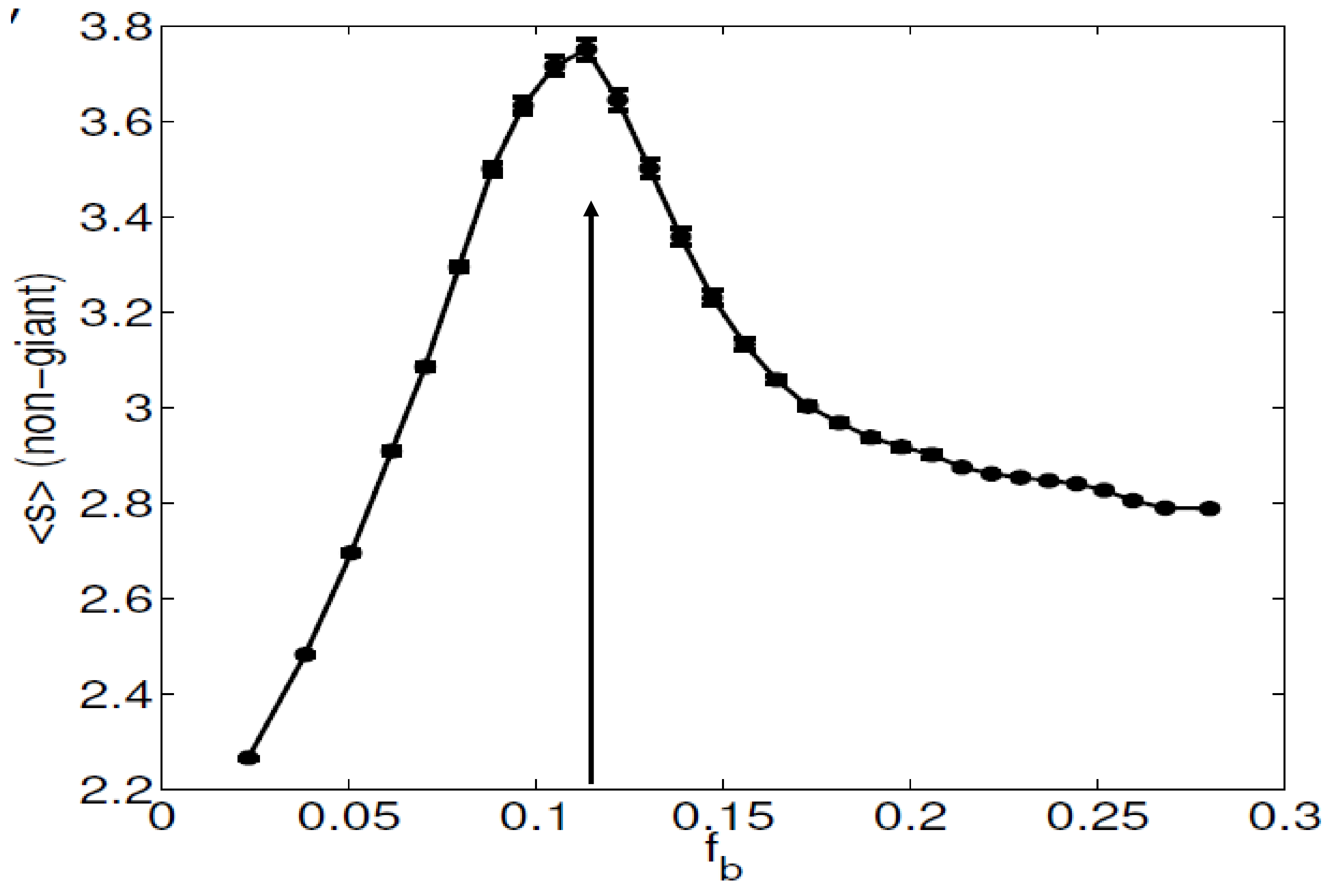
Breaking probability ~local longitudinal strain

Giant Component of the Network

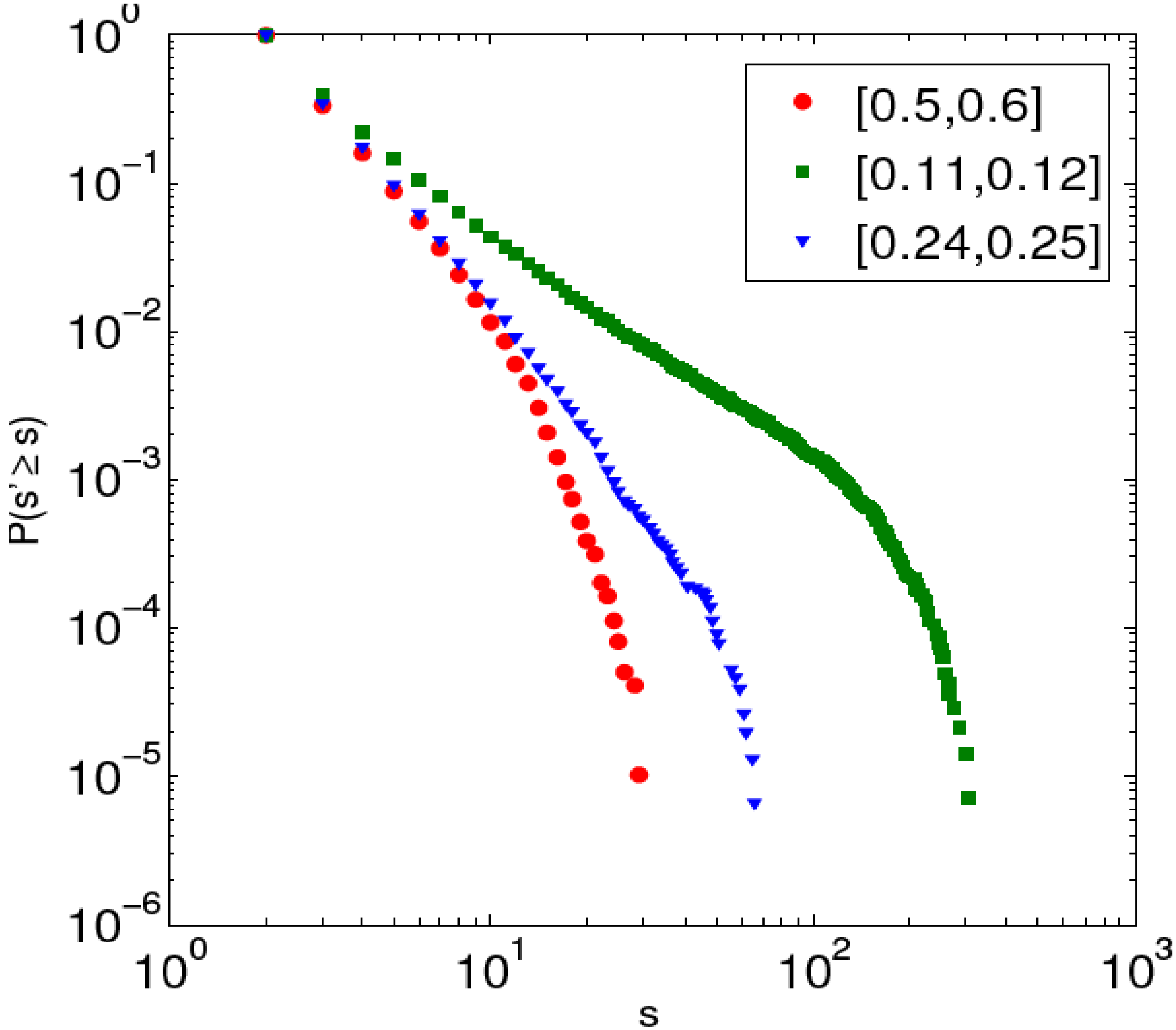


Percolation transition

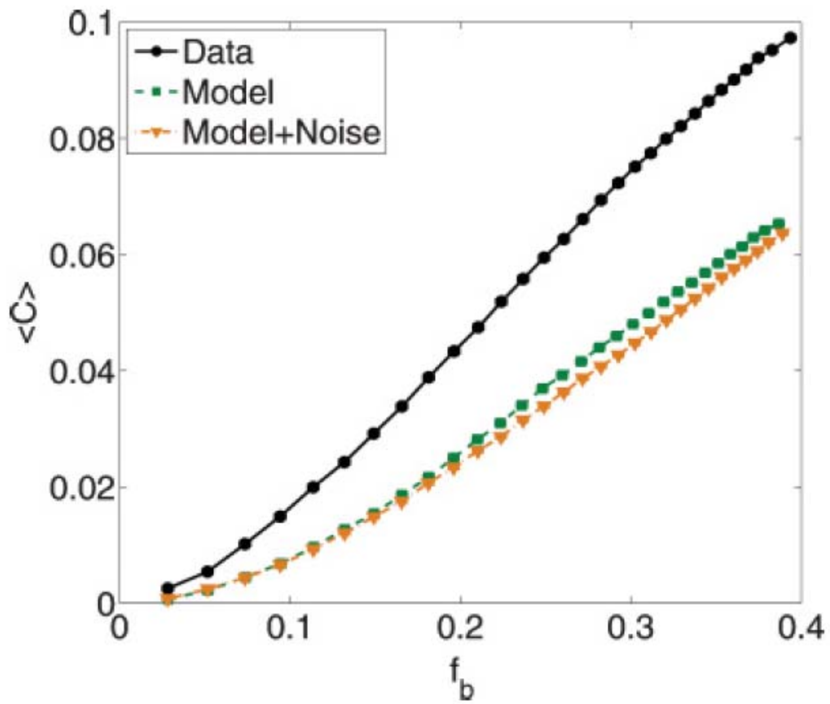
Average non-giant cluster size



Cumulative Size distribution



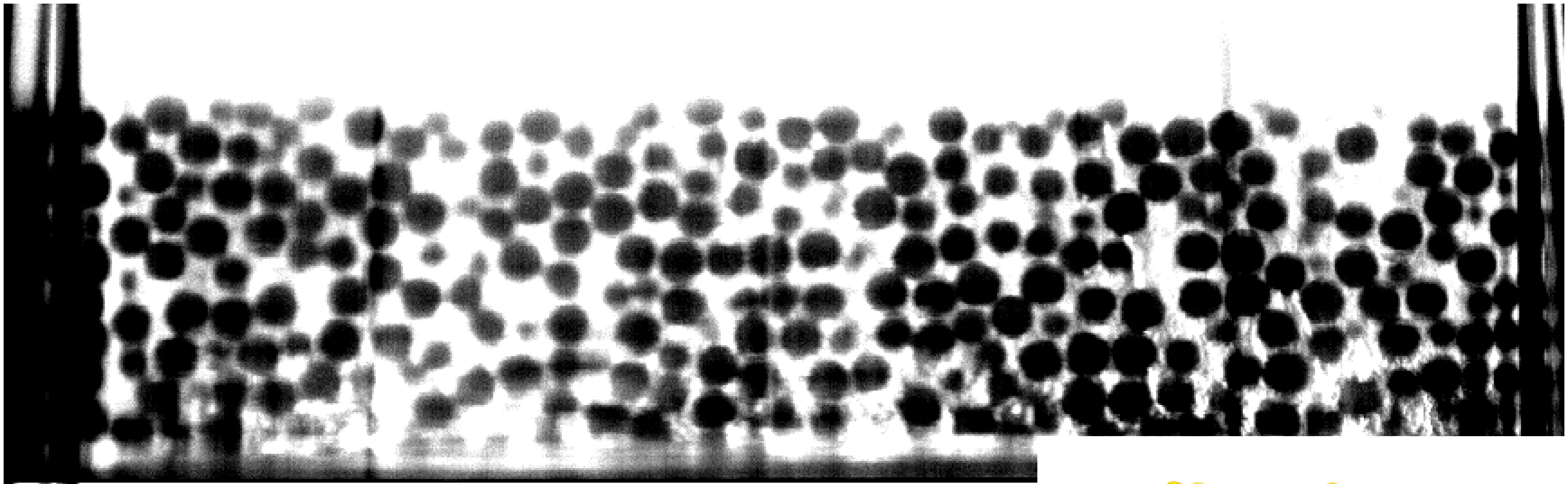
Clustering Coefficient



$$c_j = \frac{2T(j)}{(k_j)(k_j - 1)}$$

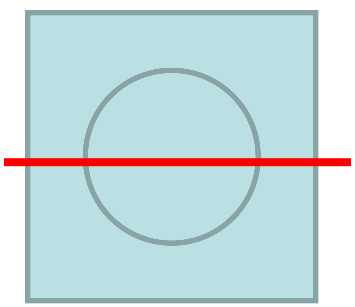
Data are more clustered

Imaging of Cyclic Shear Flow

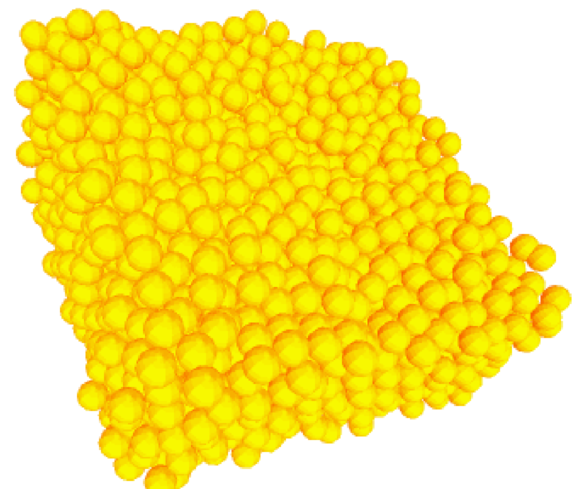


Peak to Peak Amplitude 10º (~1.5 D)
2º steps between frames

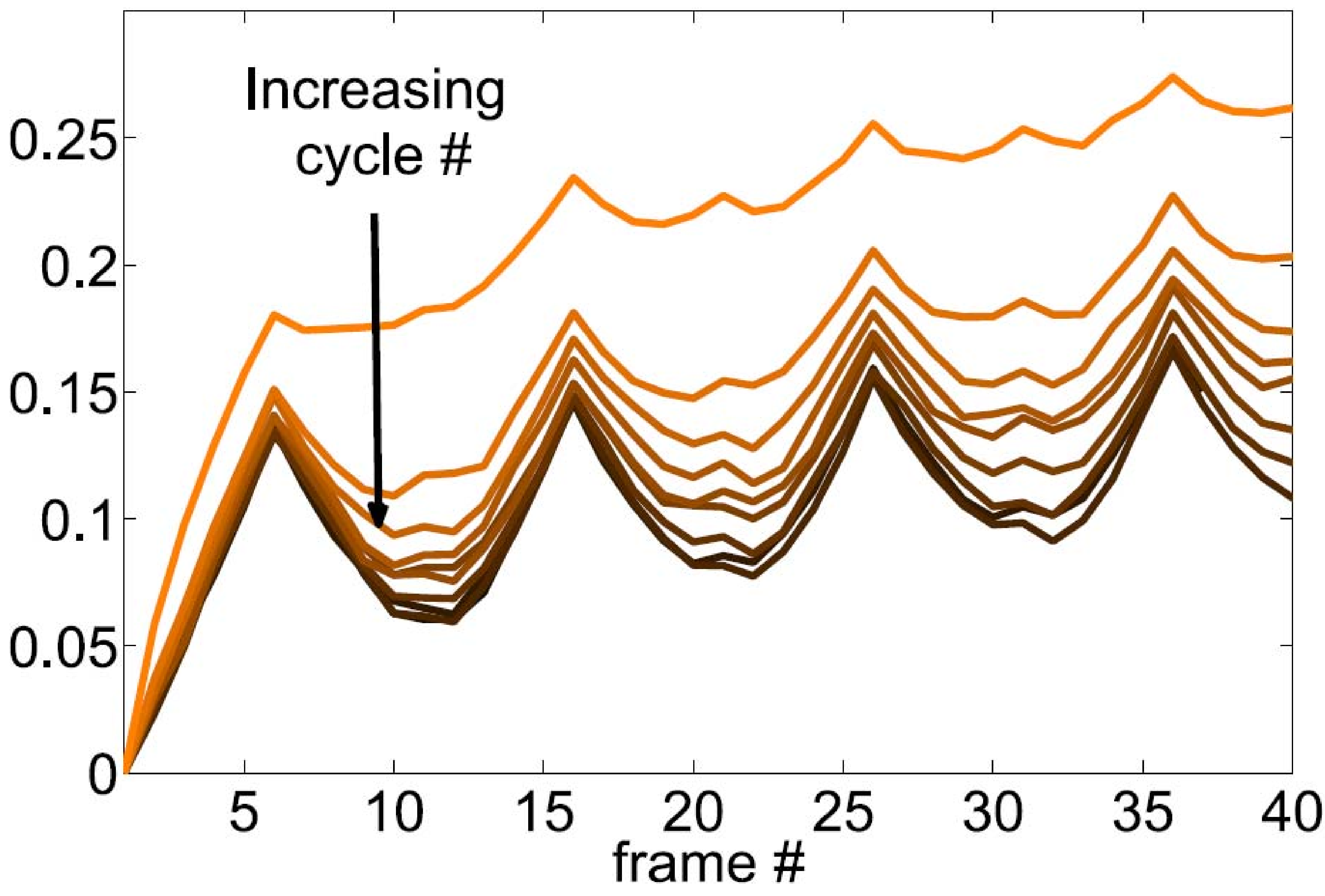
Contrast enhanced for easy viewing



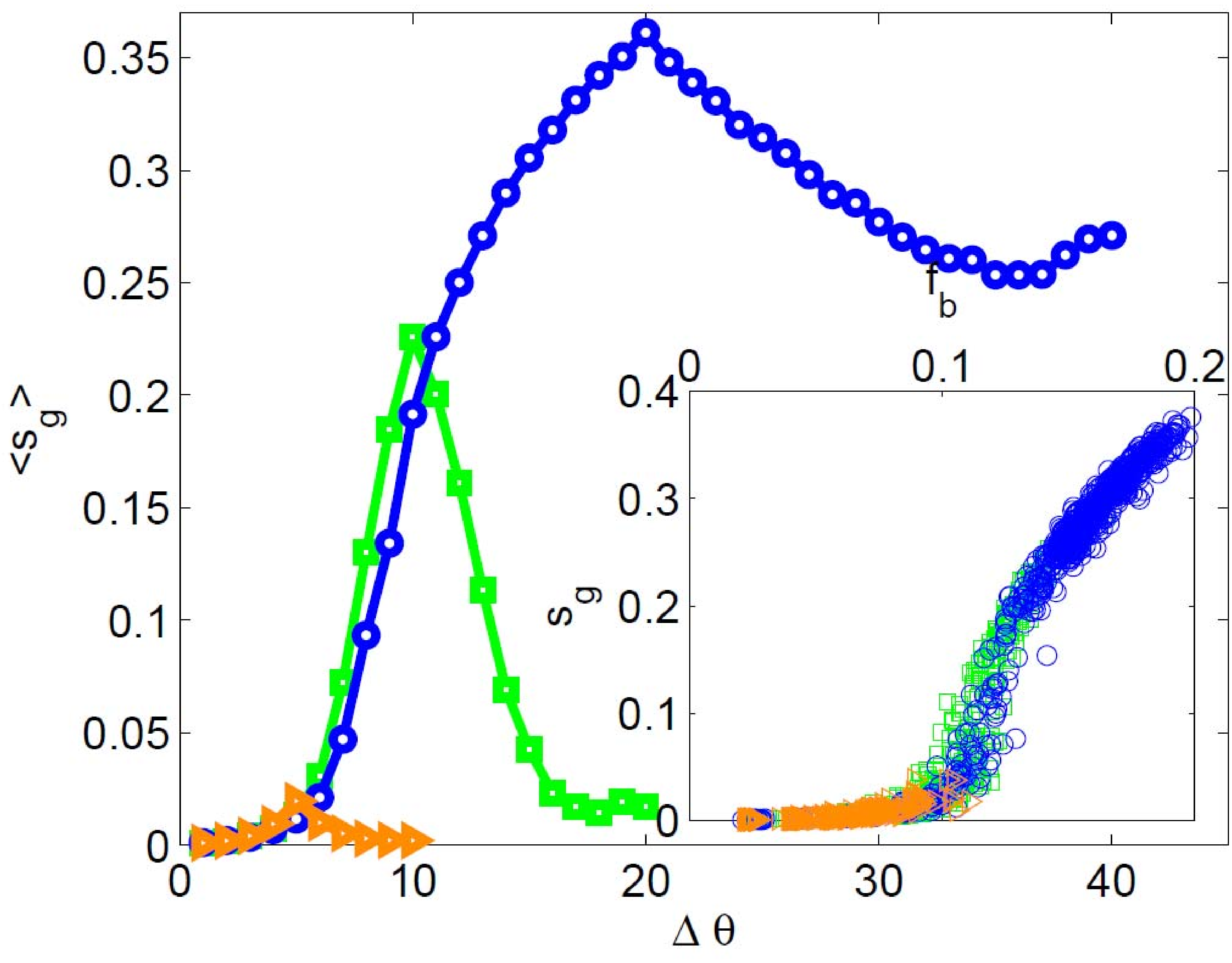
View from above



3D reconstruction
¼ of the system
Credit: Mitch Mailman



Increasing
cycle #
0.25
0.2
0.15
0.1
0.05
0
5
10
15
20
25
30
35
40
frame #



0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
<s_g>
0
10
20
30
40
Δ θ
f_b
0
0.1
0.2
0.4
0.3
0.2
0.1
0
s_g

3D imaging approaches

MRI

Jaeger Group University of Chicago

X-ray microtomography

Delannay Group, Rennes

Confocal microscopy

Refractive Index Matched Scanning (RIMS)

Outline

On Monday

Intro: What are granular materials?

Granular Materials Jam

Granular Materials Age and Strengthen

Today

Granular Gas (Particle tracking)

2D Granular Flow (PIV and flow fields)

3D Granular Flows (3D imaging approaches)

Shape Analysis

Wolfgang Losert wlosert@umd.edu

Forces in Astrophysical Applications

Holding Granular Matter together:

Gravity

Van der Waals

Charges

Rearranging Granular Matter:

Tidal forces

Seismic forces

Centrifugal forces