Summer School: Granular Materials
from Simulations to Astrophysical Applications

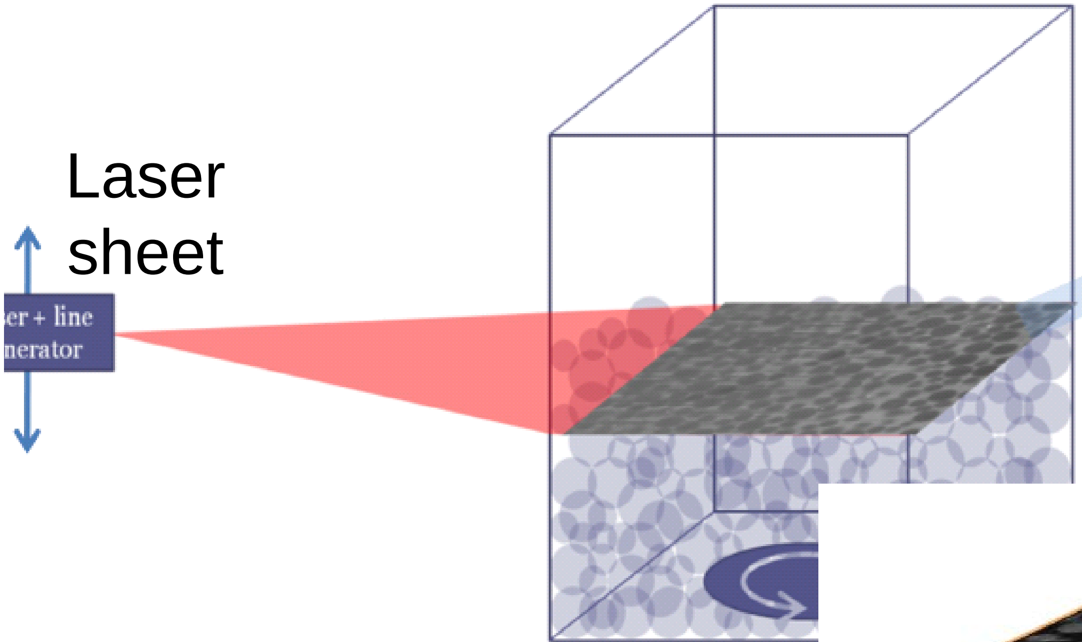
Hosted by CSCAMM and the University of Maryland
Burgers Program in Fluid Dynamics

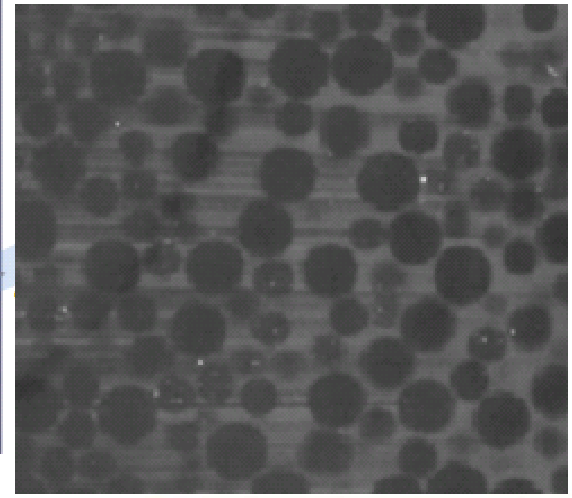
Segregation

Wolfgang Losert, Department of Physics
University of Maryland

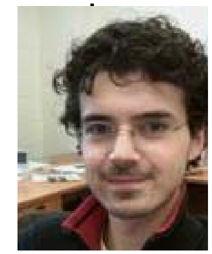
Outline

- Binary Mixture Slow Shear
- Binary Mixtures in Tumblers
- Polydisperse Tumbler Flows
- Polydisperse Materials under Vertical Vibration

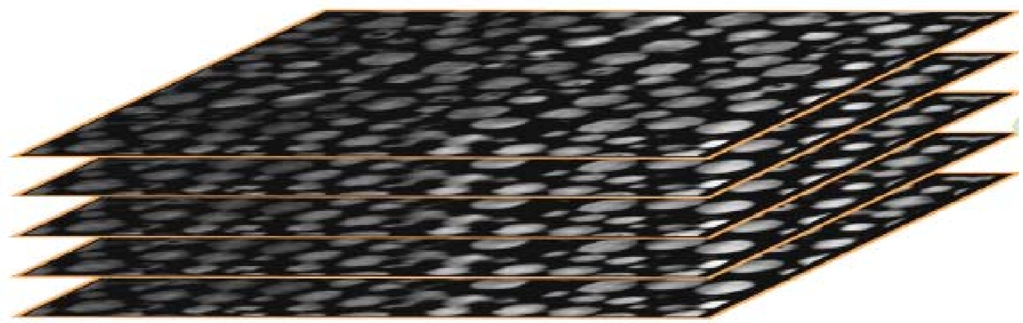


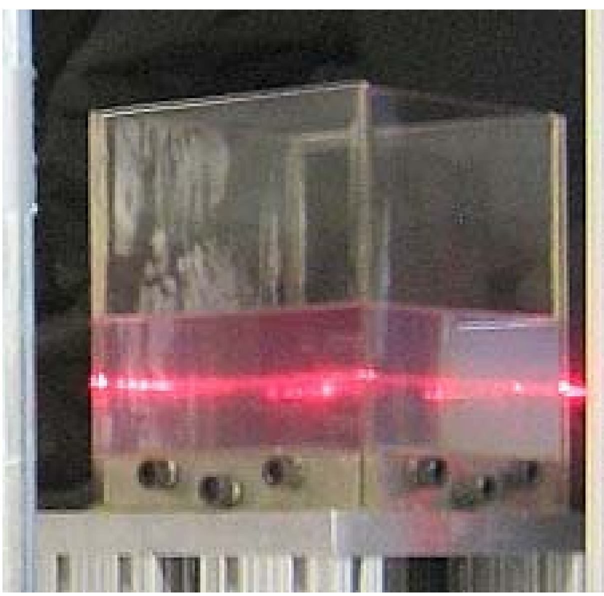


Steven
Slotterbac



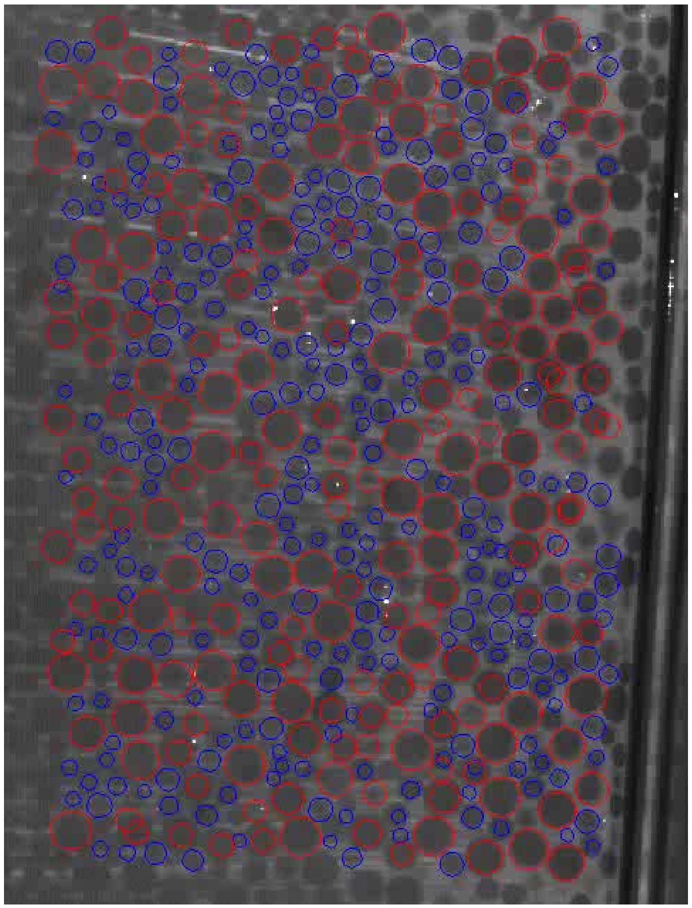
Joshua
Dijksman





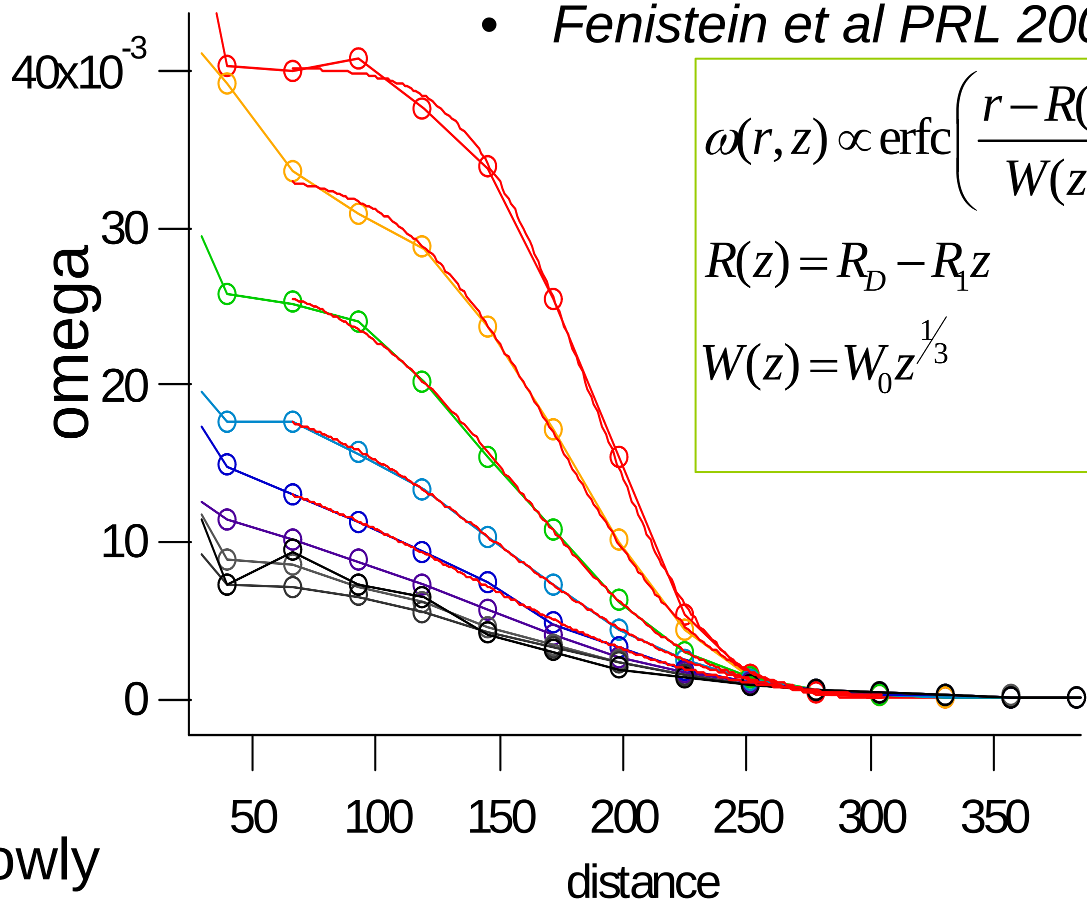
Toiya *et al.*
Granular Matter (2007)
Slotterback *PRL*
(2008)

3D imaging of flow - continuum flow fields



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

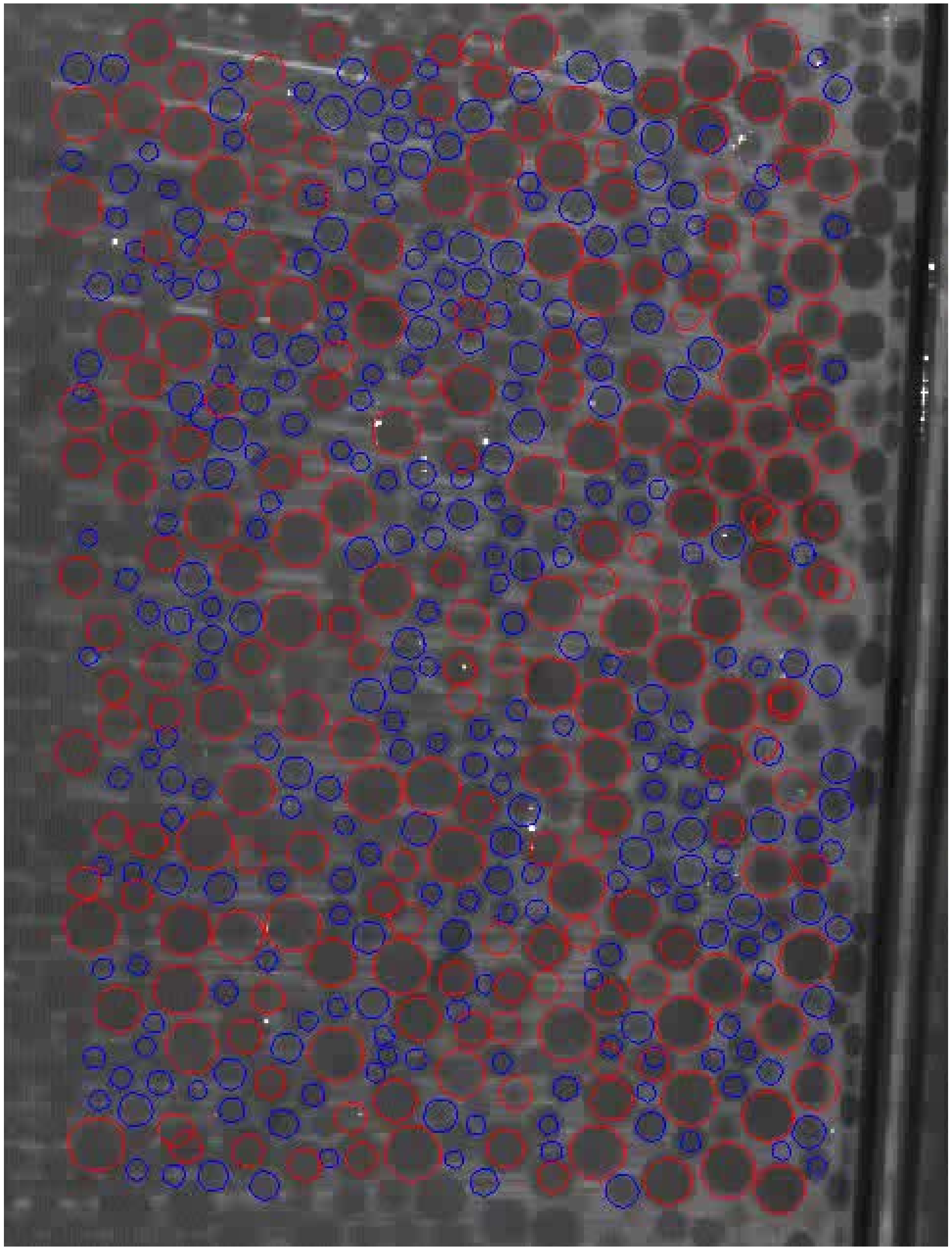
- Flow Profile matches
- **dry, continous** flow
- *Fenistein et al PRL 2004*



$$\omega(r,z) \propto \mathrm{erfc}\left(\frac{r-R(z)}{W(z)}\right)$$

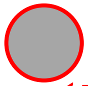
$$R(z) = R_D - R_1 z$$

$$W(z) = W_0 z^{1/3}$$



Segregation in systems with two particle sizes

Small (3mm)

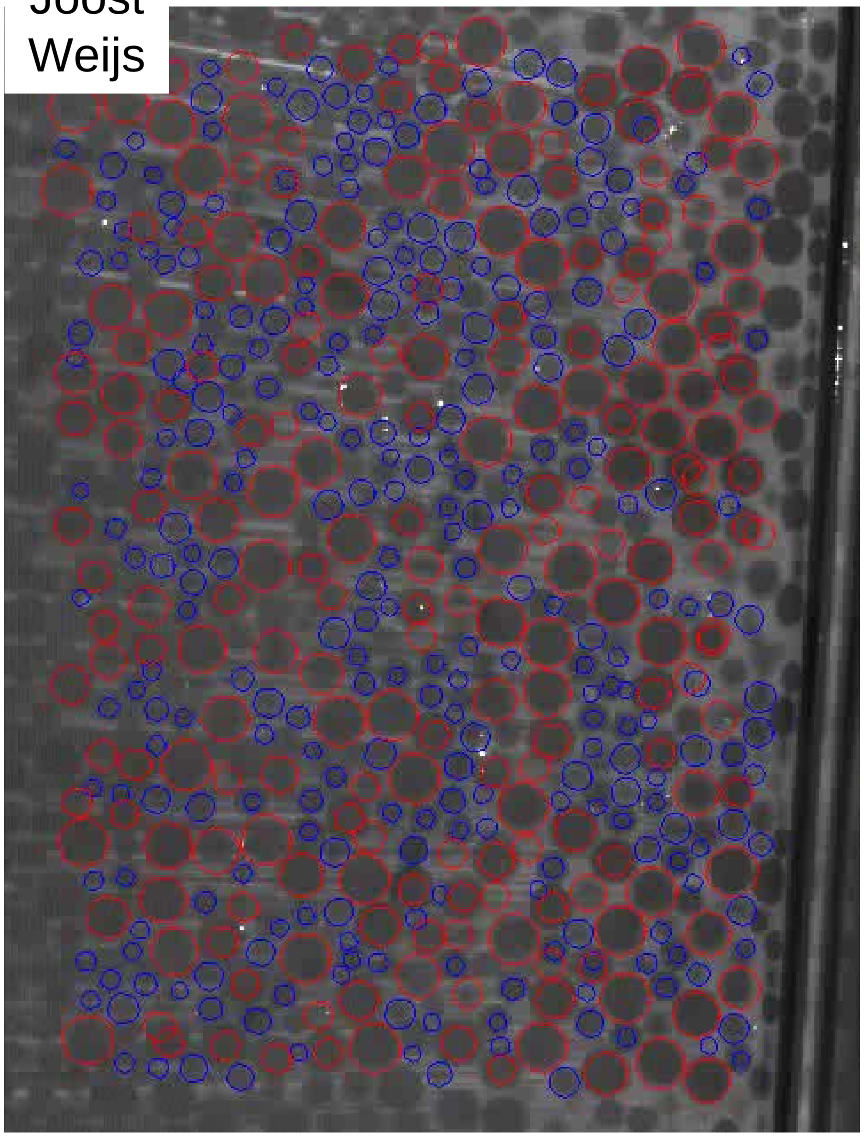


Large (5mm)

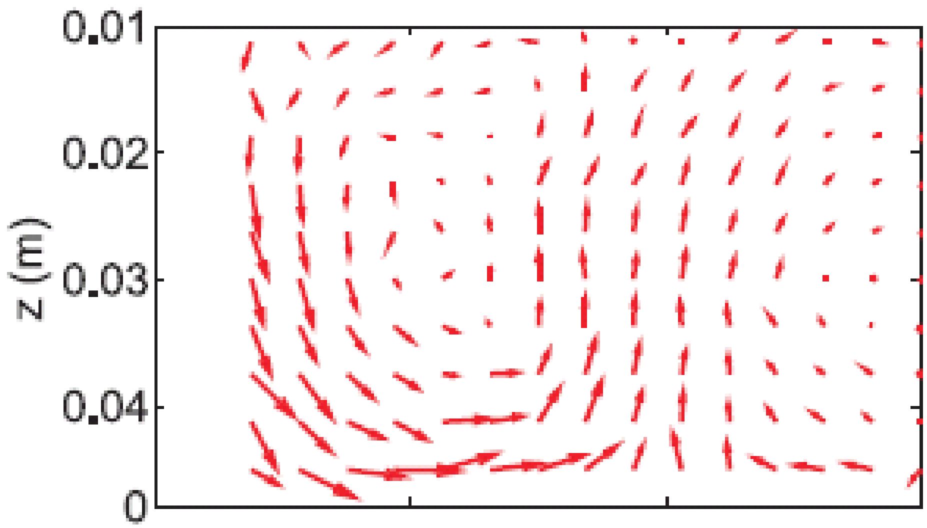
Joost Weijs
University
of Twente

Joost Weijs

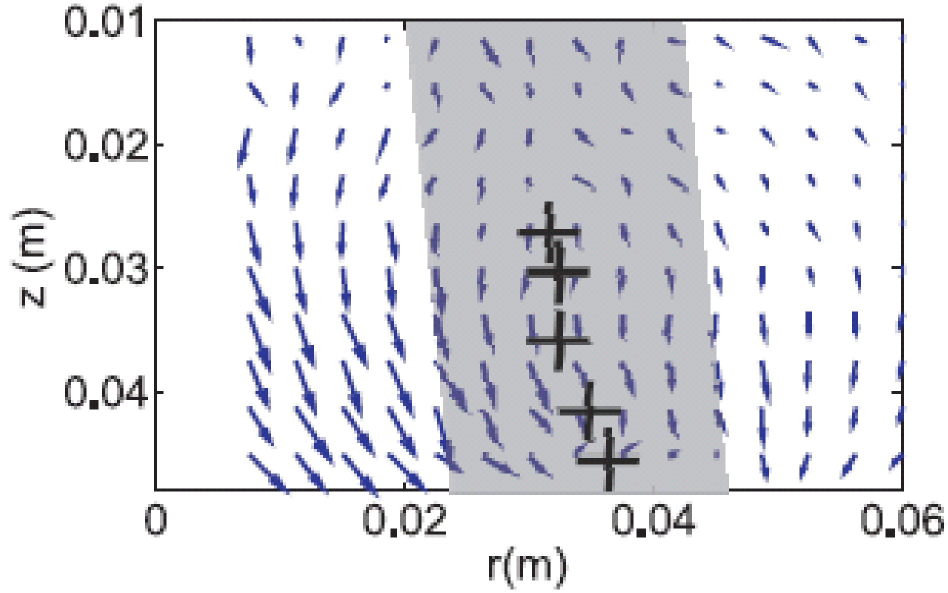
Convection Rolls during “step”-flow



- Large Particles

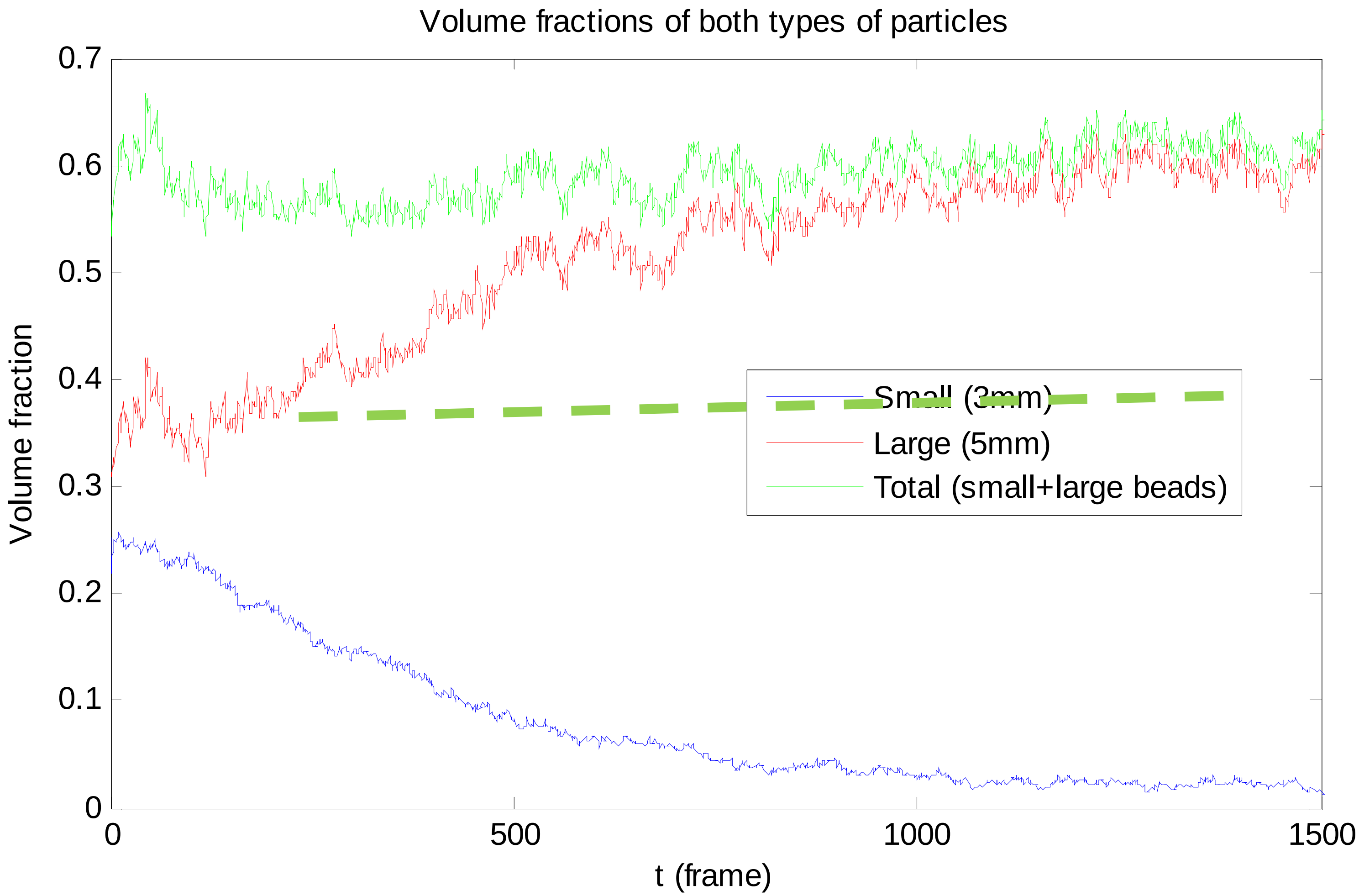


- Small Particles



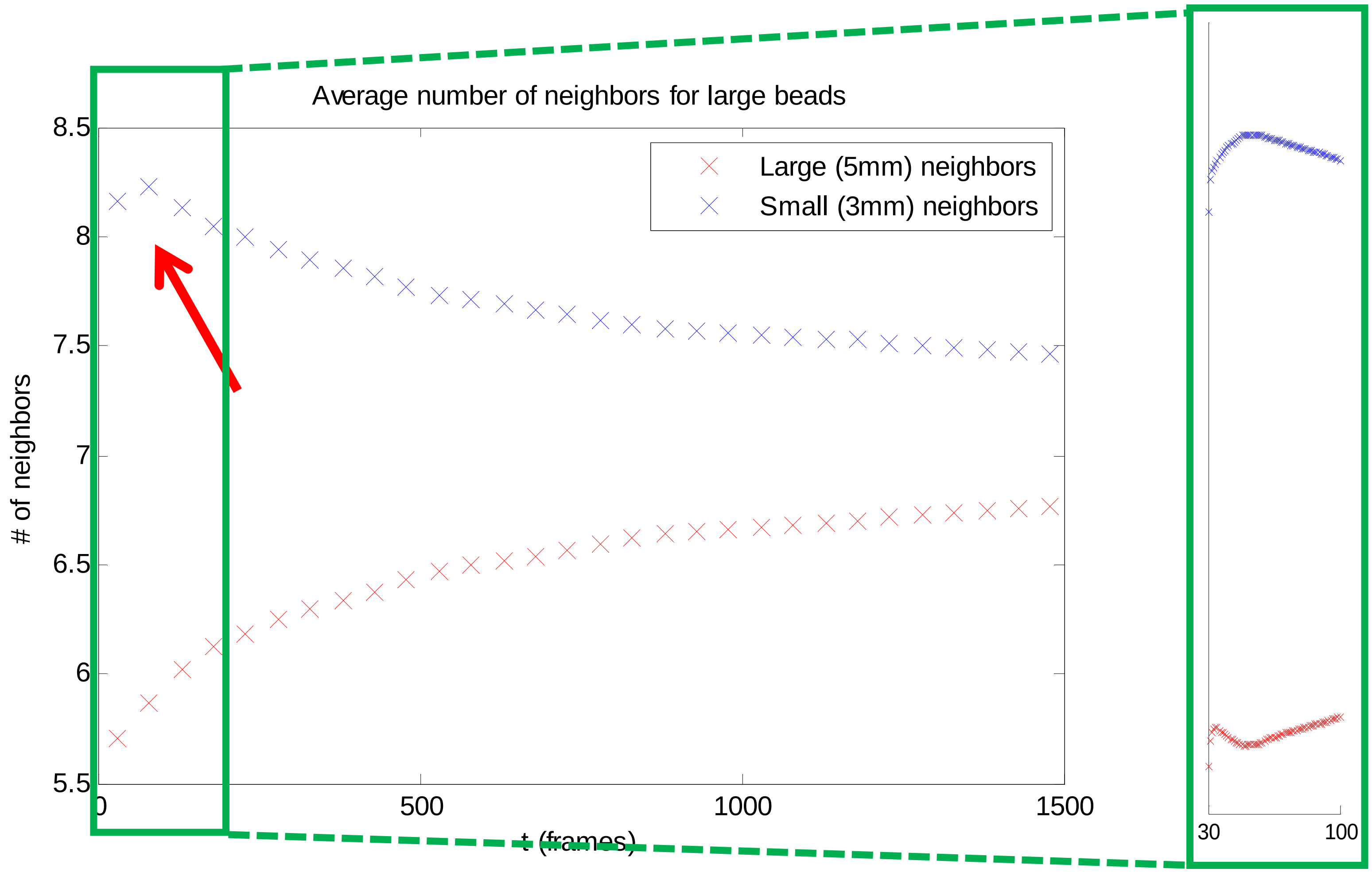
Volume fraction

– Top of shear zone:

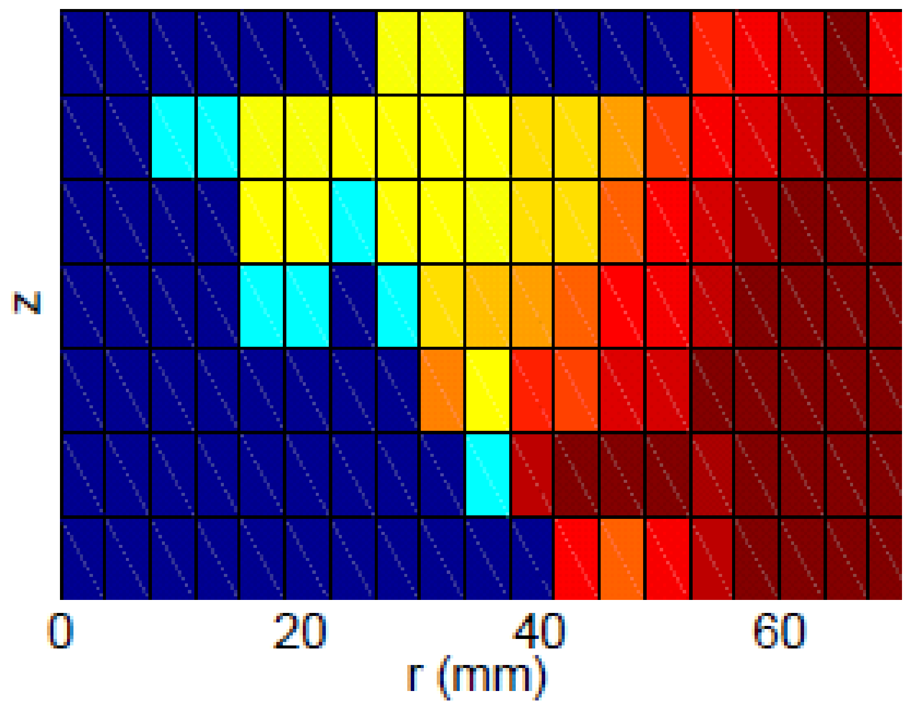


Neighbors

- Looking at *all* large particles, how does the *average* number of neighbors evolve?



Dynamics of Segregation



Blue area segregates within 20 rotations, dark red area has not segregated after 600 rotations

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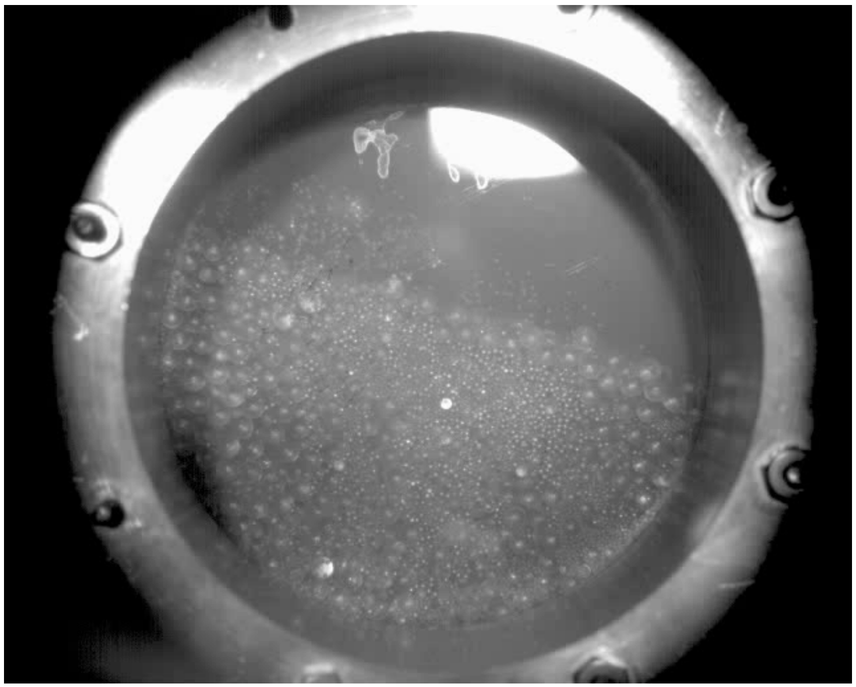
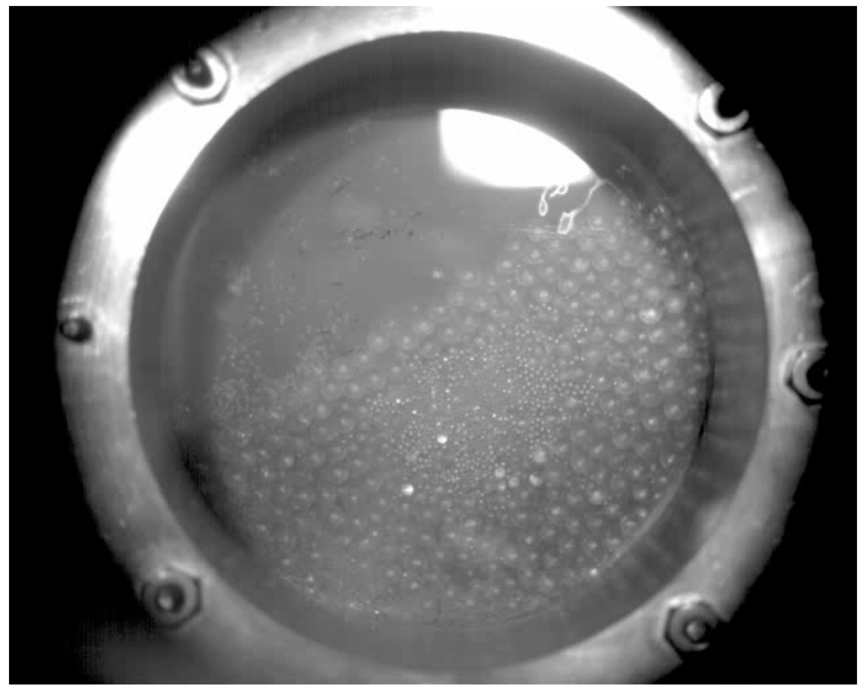
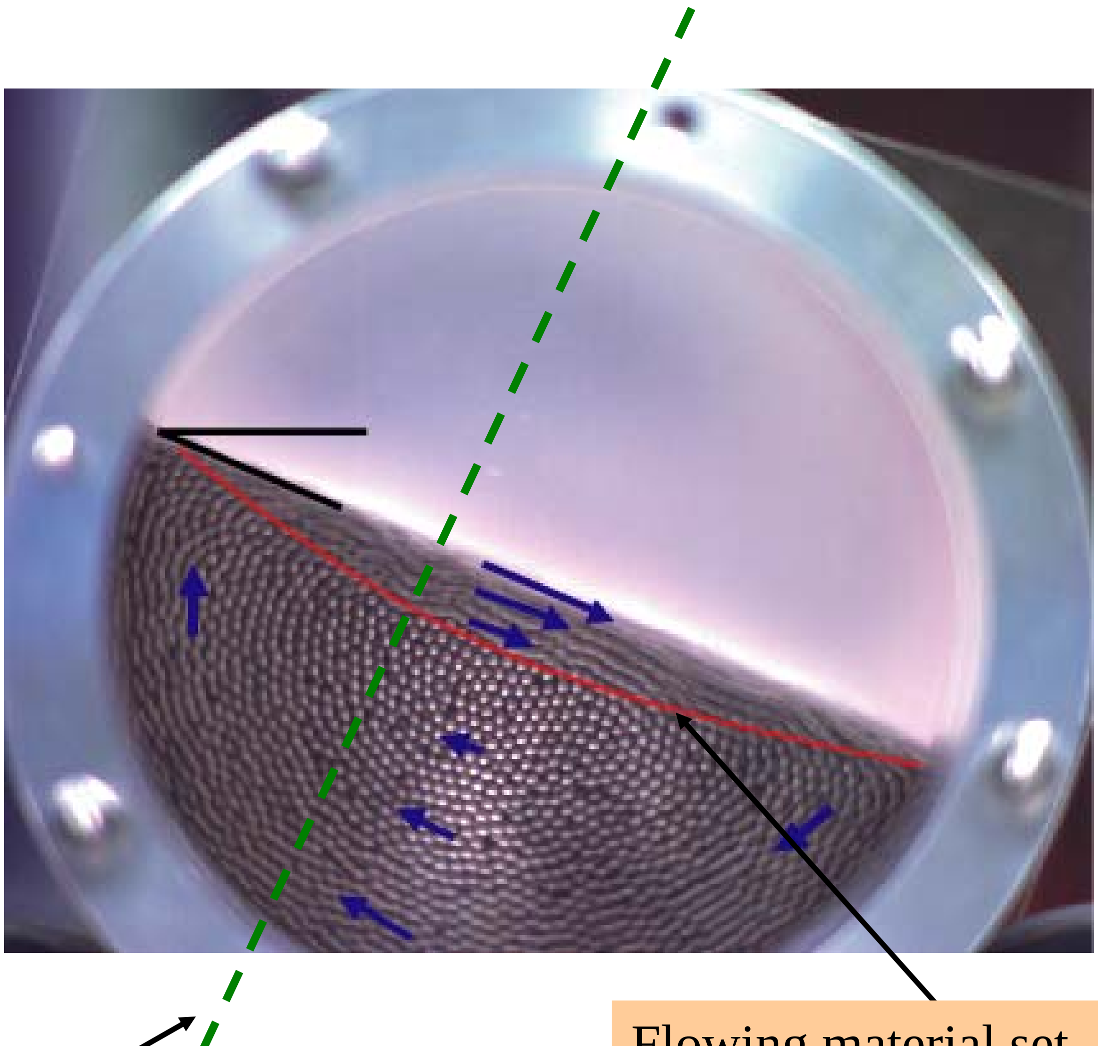
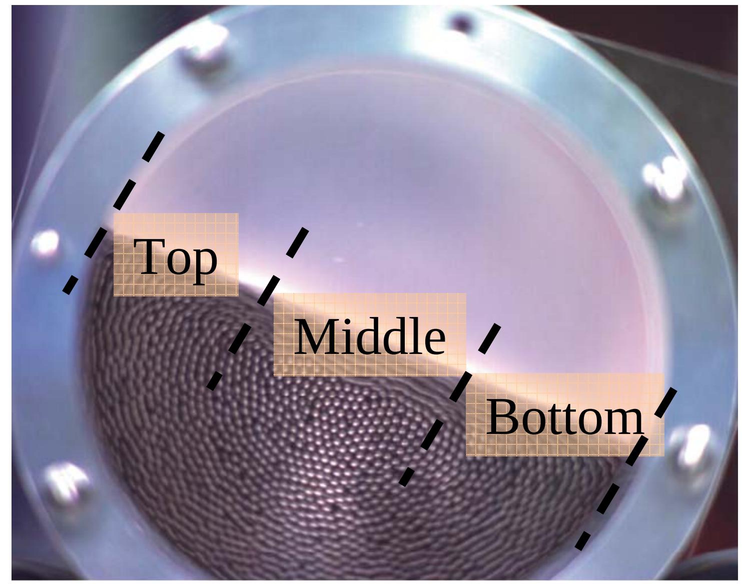
Segregation in a tumbler

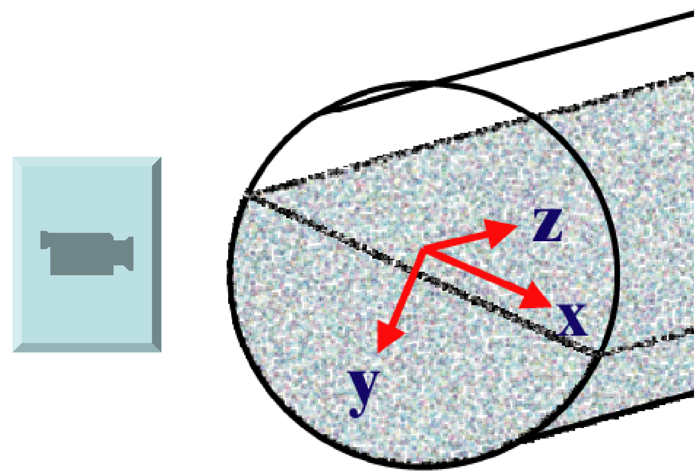




Model System: Rotating Drum



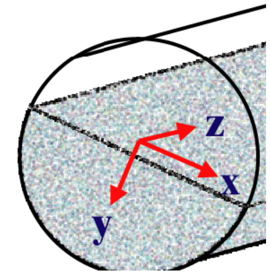


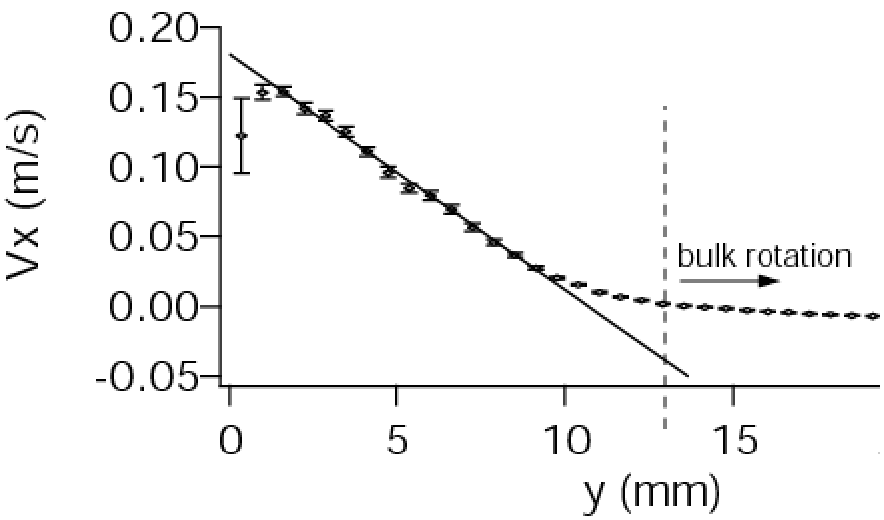


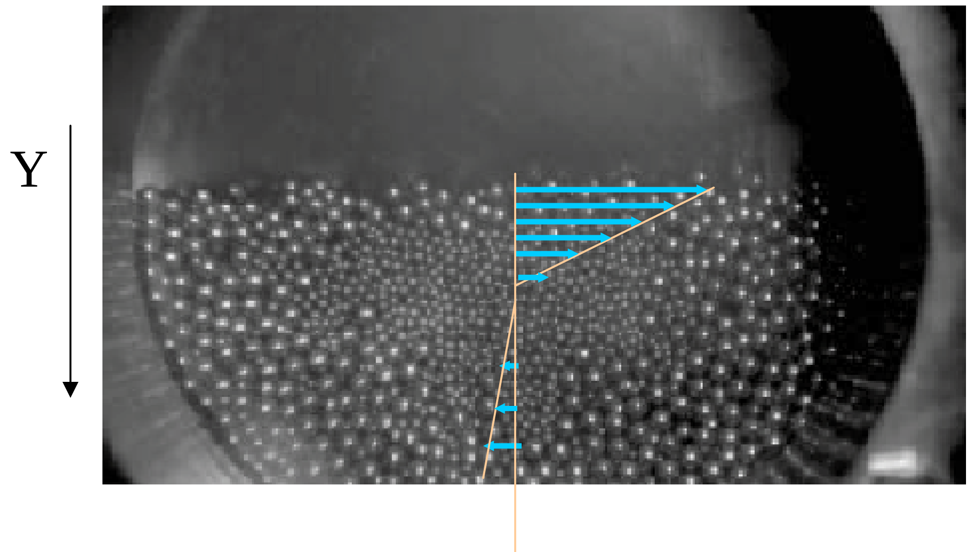
Flowing material set apart by red line.

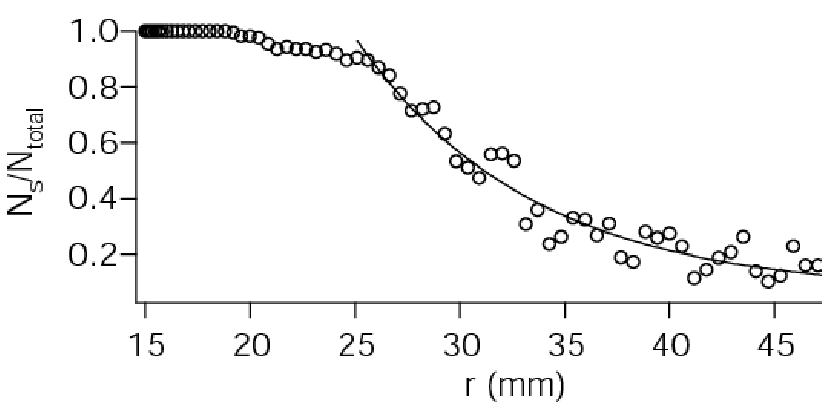
Total mass flux is zero across any line

Velocity Profile









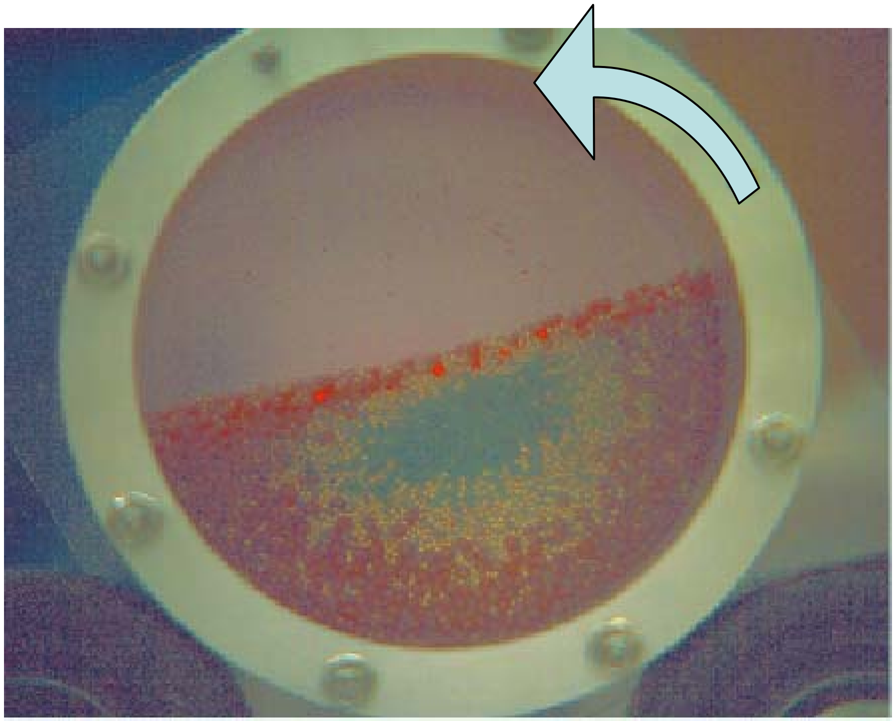
Linear decrease in velocity, no transition from large to small particles.

Radial segregation is not strong.

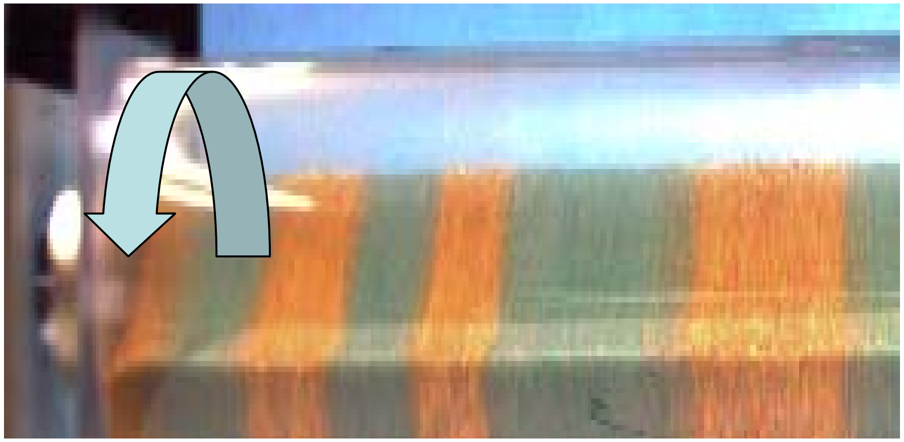
Radial and Axial Segregation

Michael Newey

Supported by NASA and NSF-CTS



Radial segregation
~ 3-4 revolutions

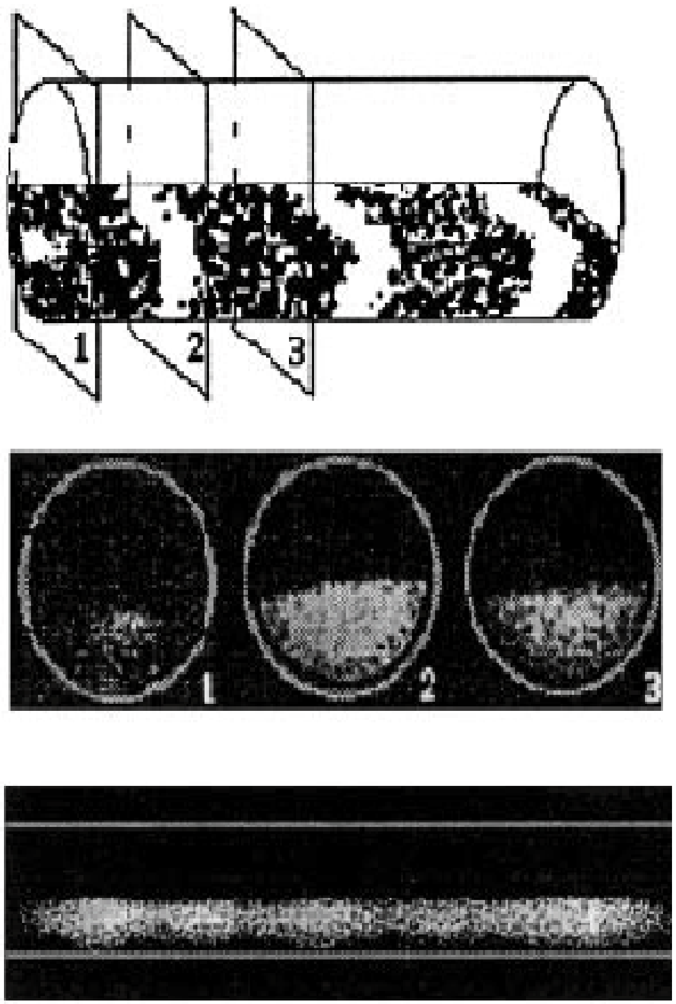


Axial banding
~ 50-100 revolutions

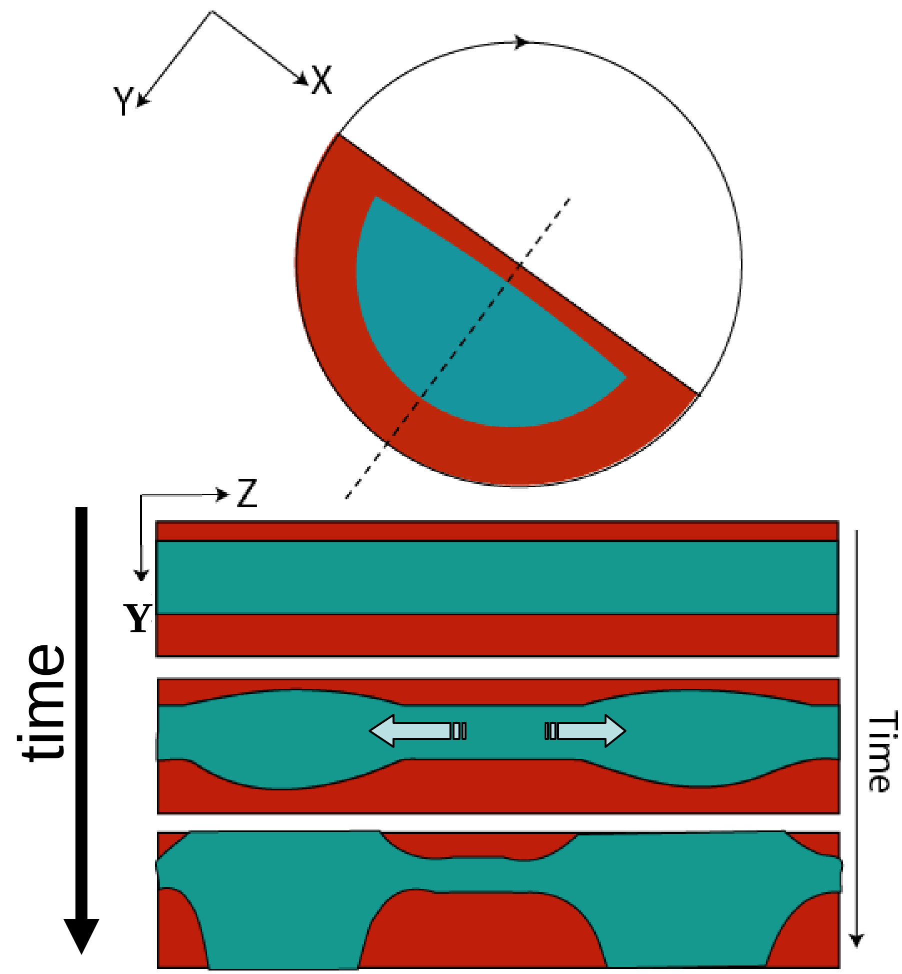
What processes drive axial band formation?

Connection between axial banding and radial segregation

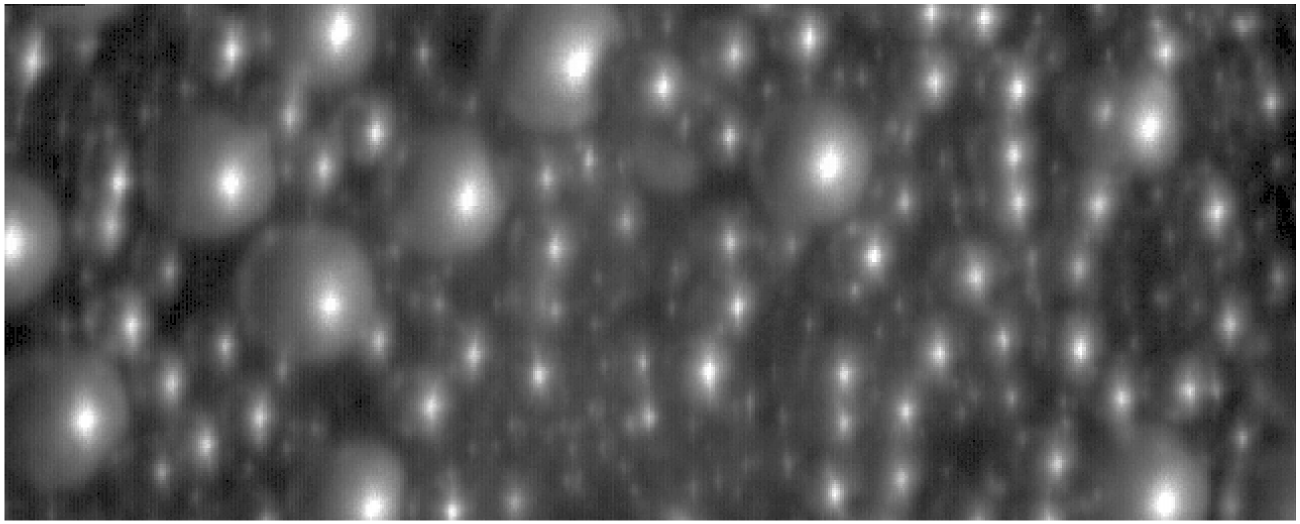
MRI – Kakalios, Hill: “smaller” particles labeled in MRI

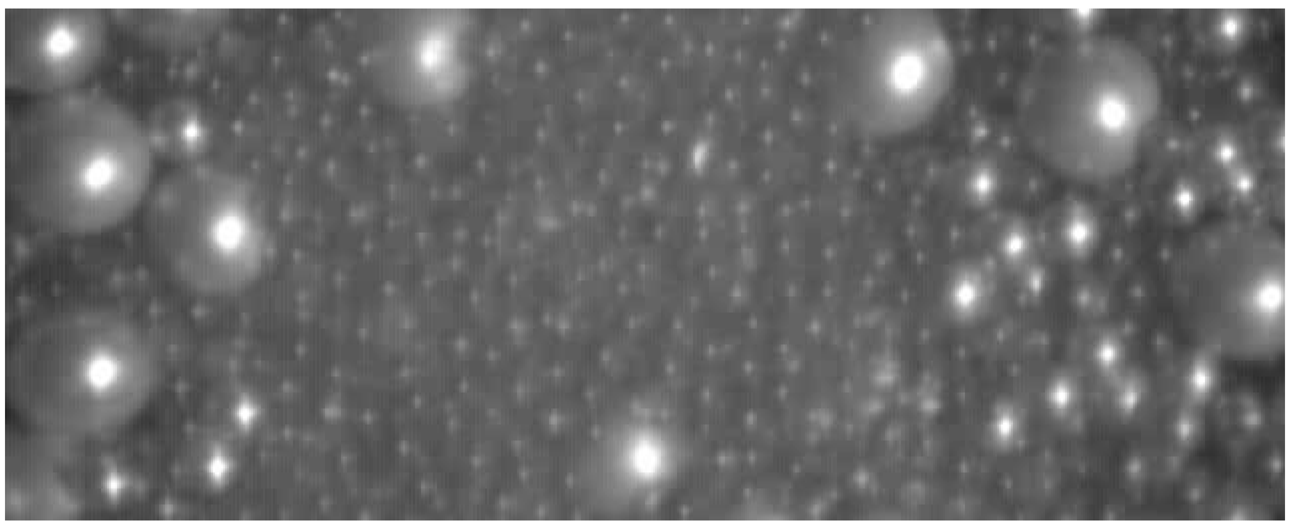


Schematic

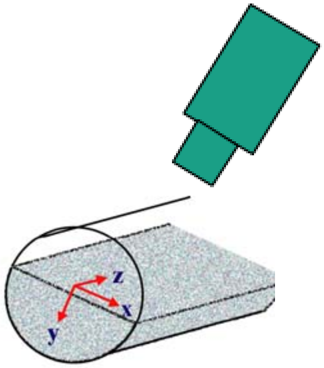


Particle Speed on Surface



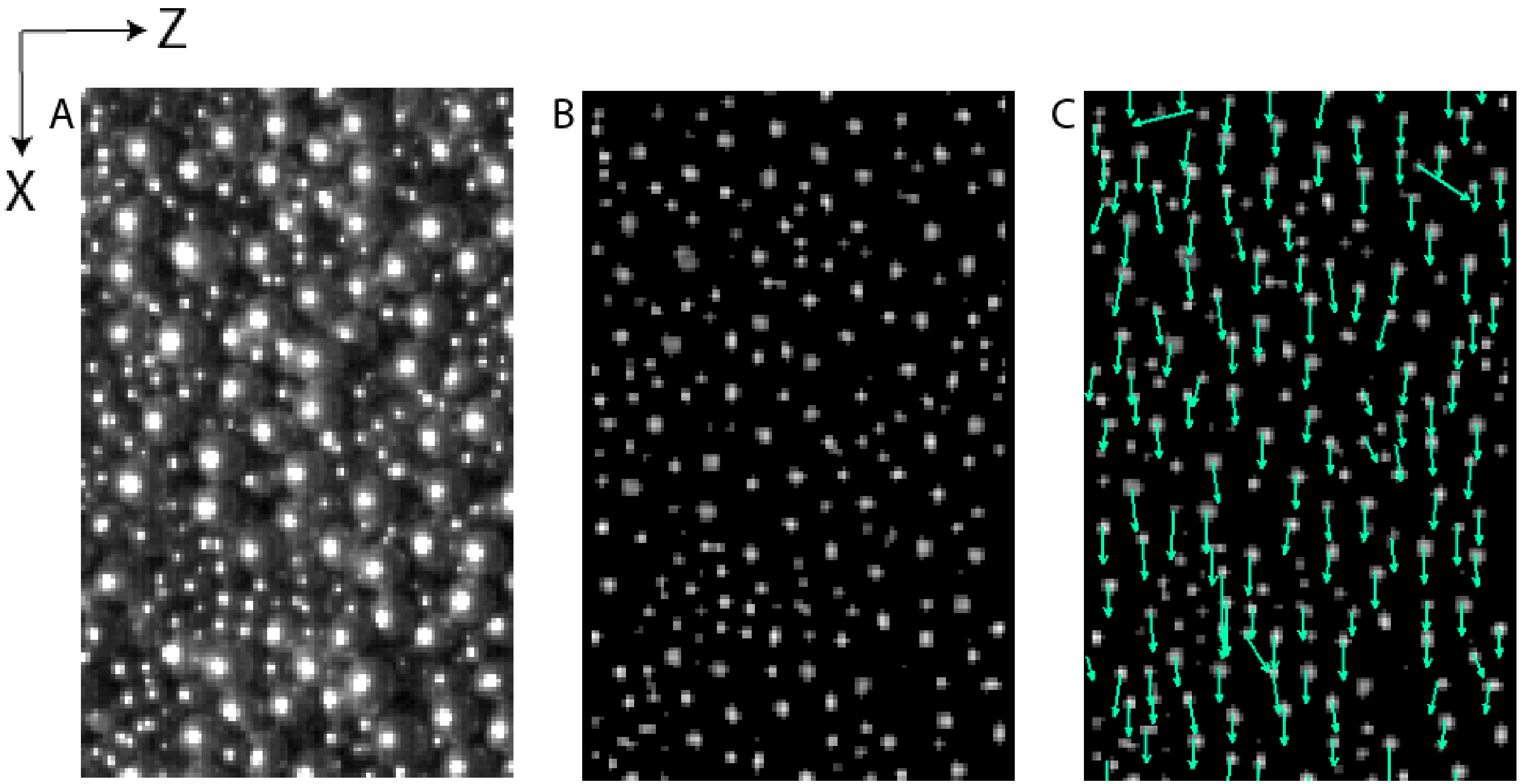


Particle Tracking:

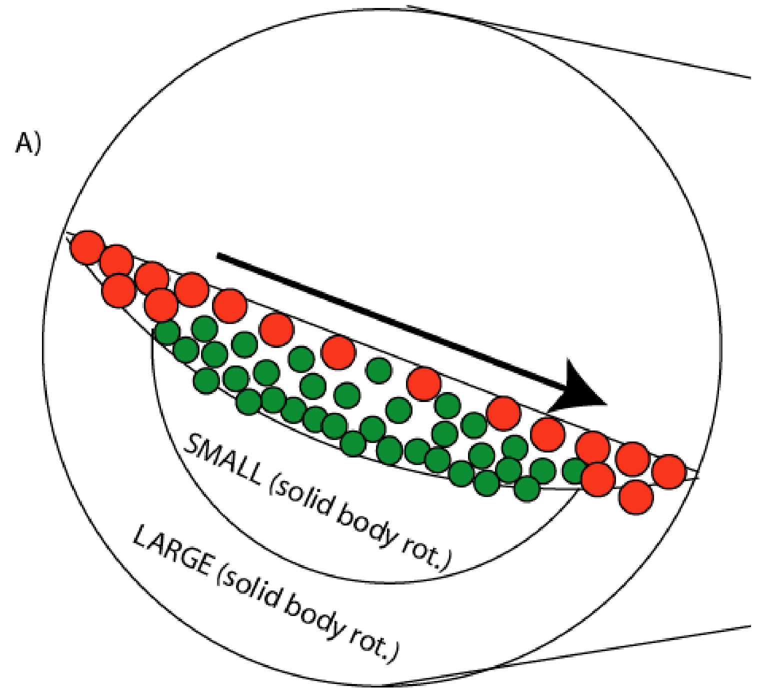


*We track thousands of particles of the banded state in a rotating drum.

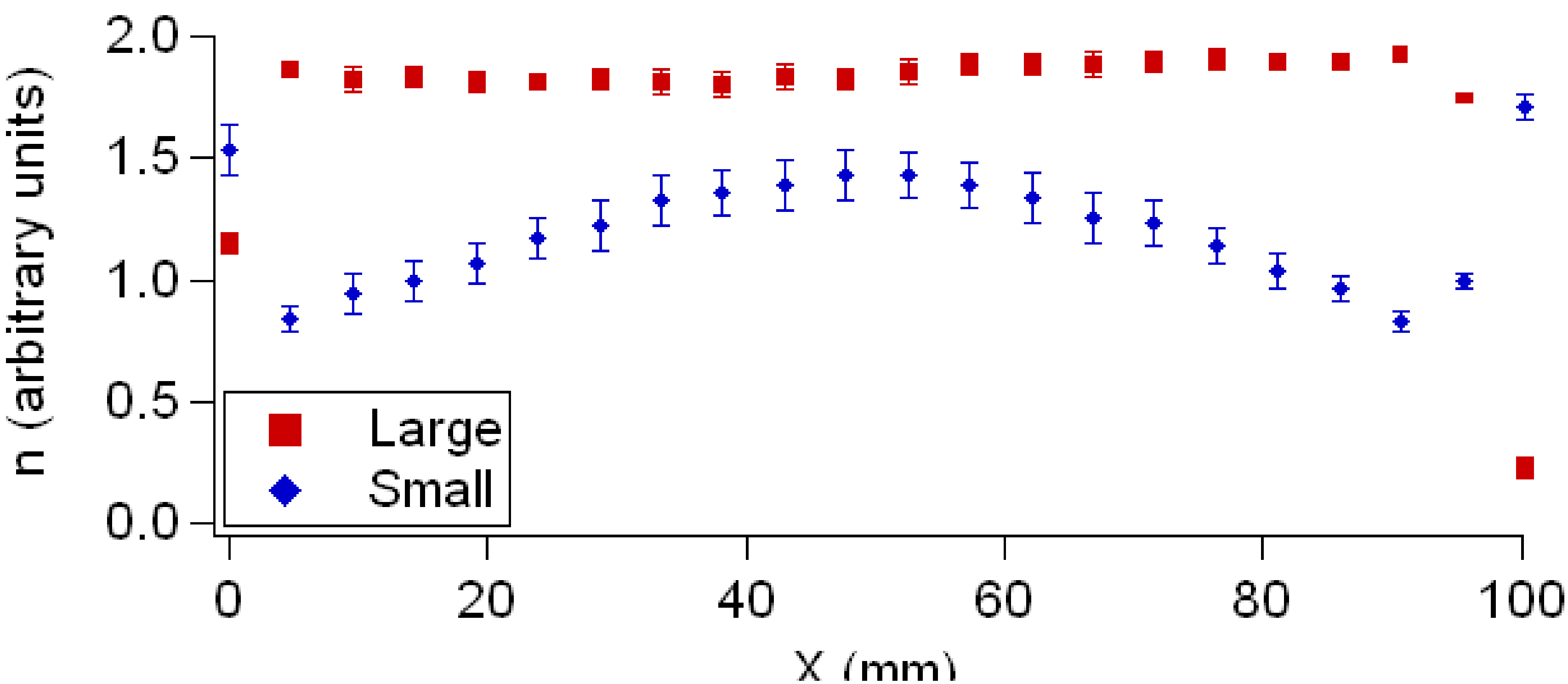
*We can distinguish between large and small particles.



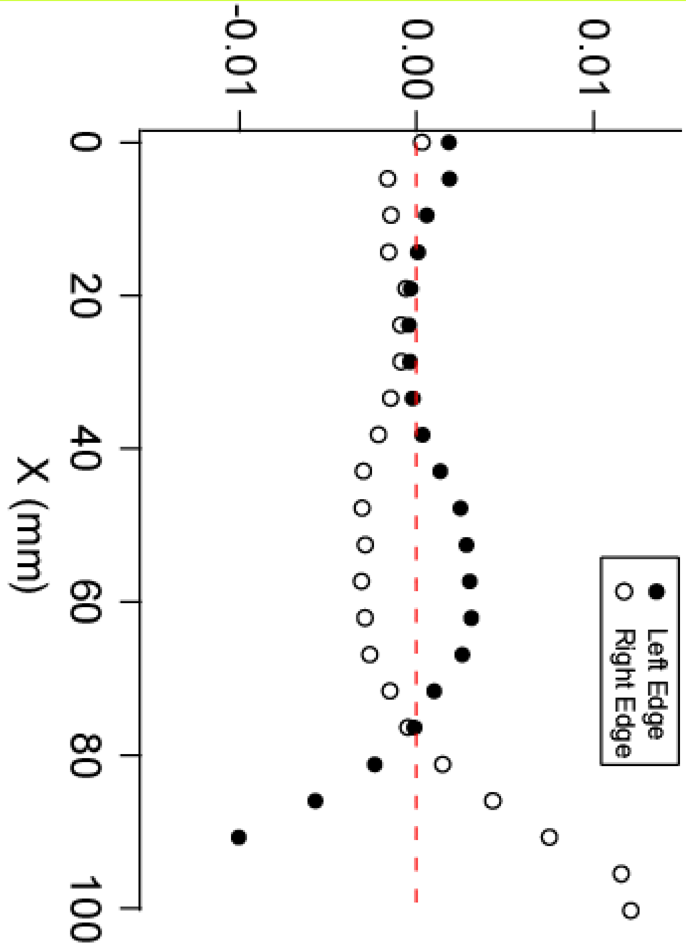
Number of small particles visible on surface

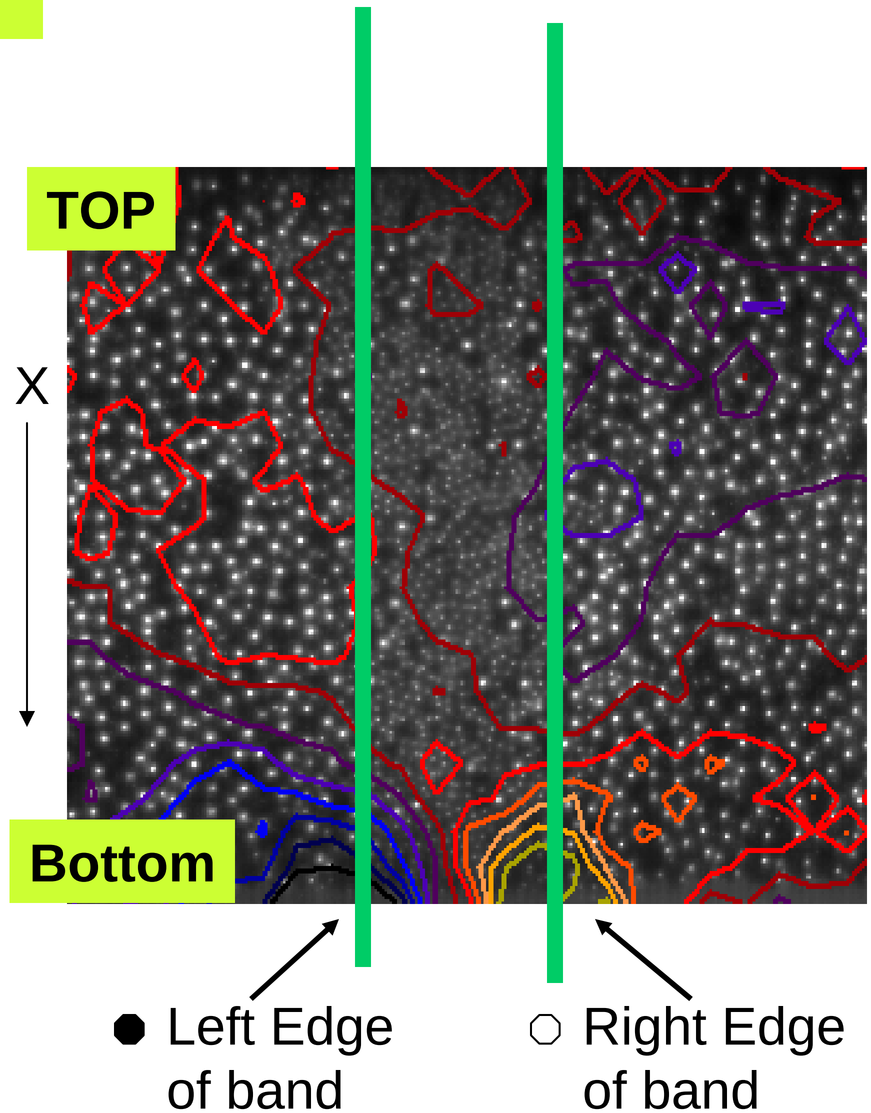


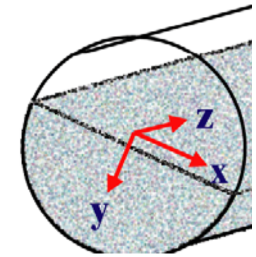
(during band formation process)



Axial drift



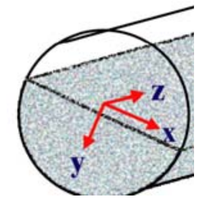


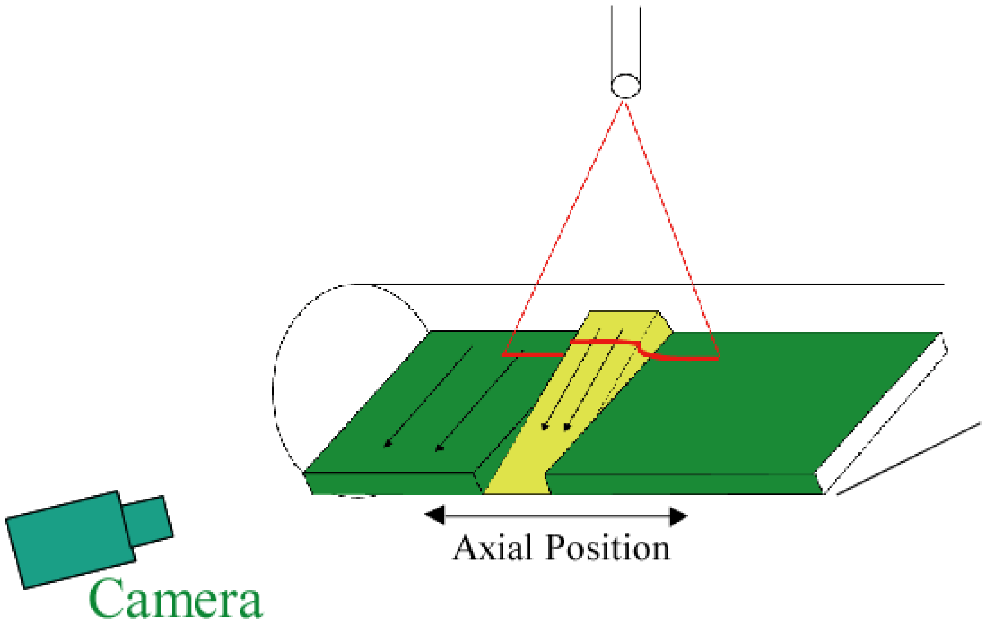


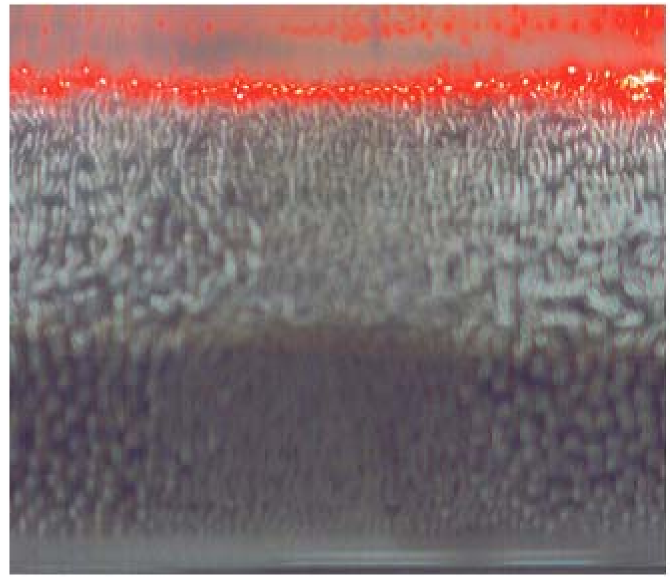
Drift of small/large particles different?
Physical process that leads to drift?

$$\frac{dc}{dt} = -\beta \frac{d^2 c}{dz^2} + D \frac{d^2 c}{dz^2}$$

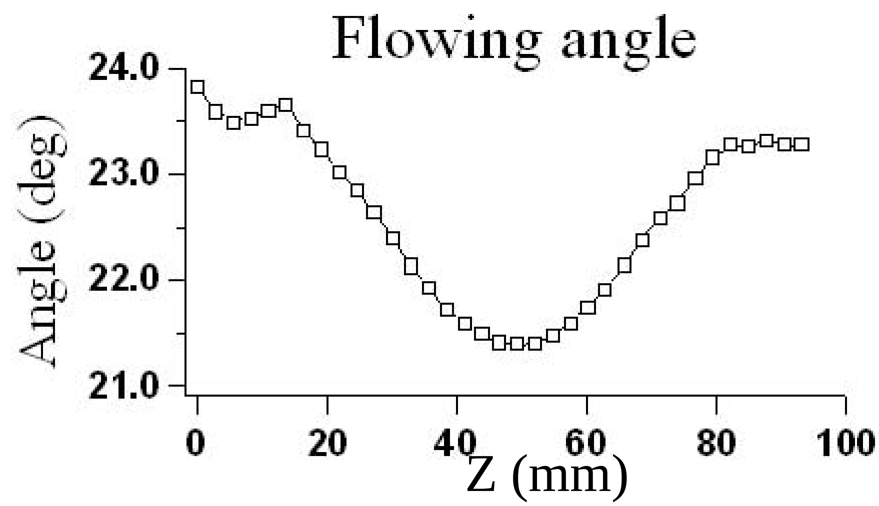
Laser line angle over a band





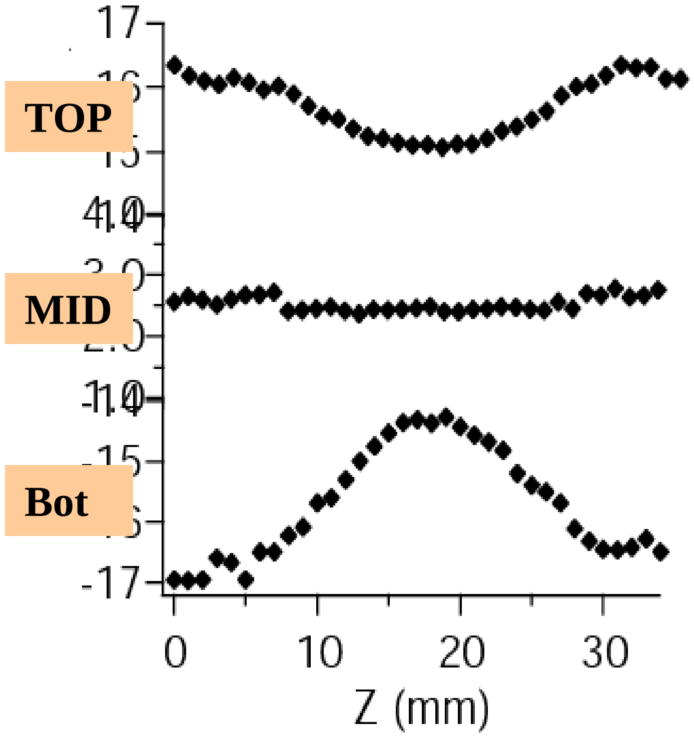


*Flowing angle lower over a small particle band.

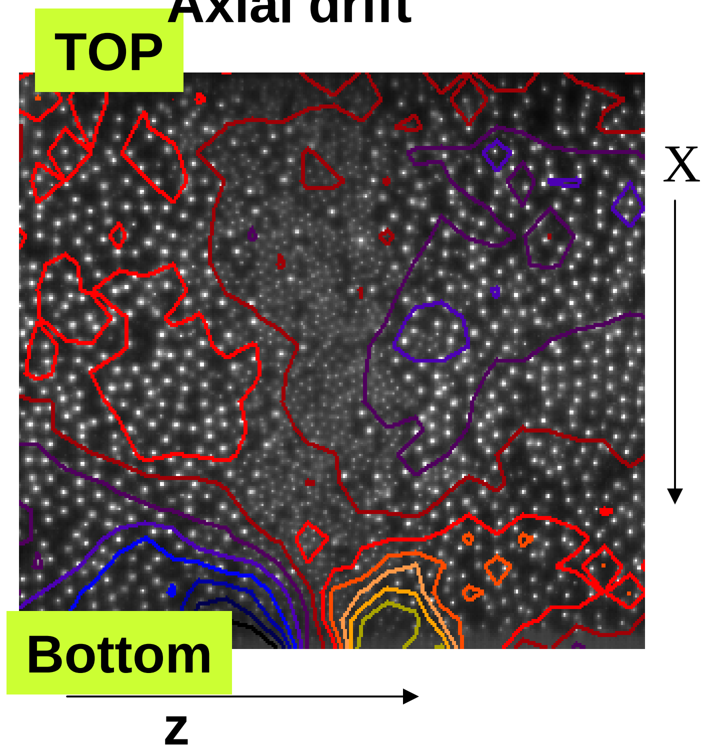


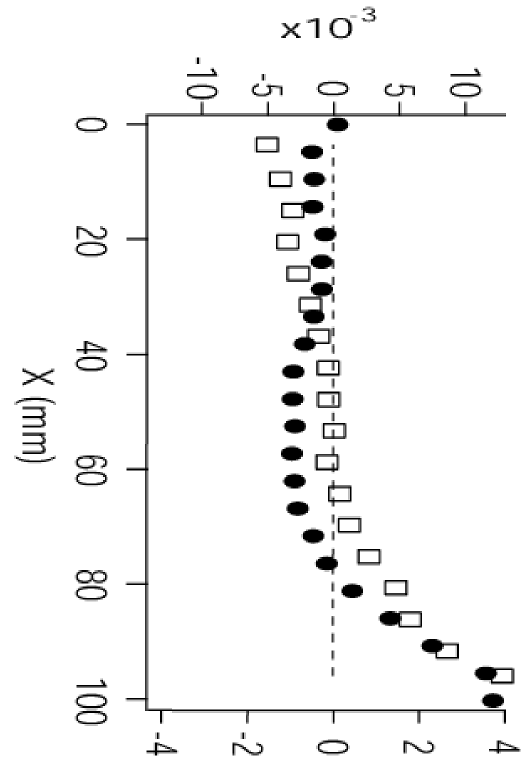
Is drift in the direction of steepest descent?

SURFACE HEIGHT



Axial drift



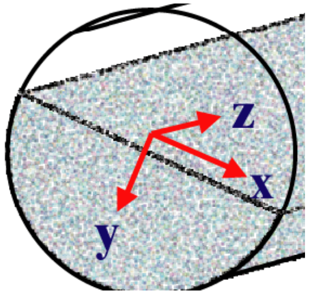


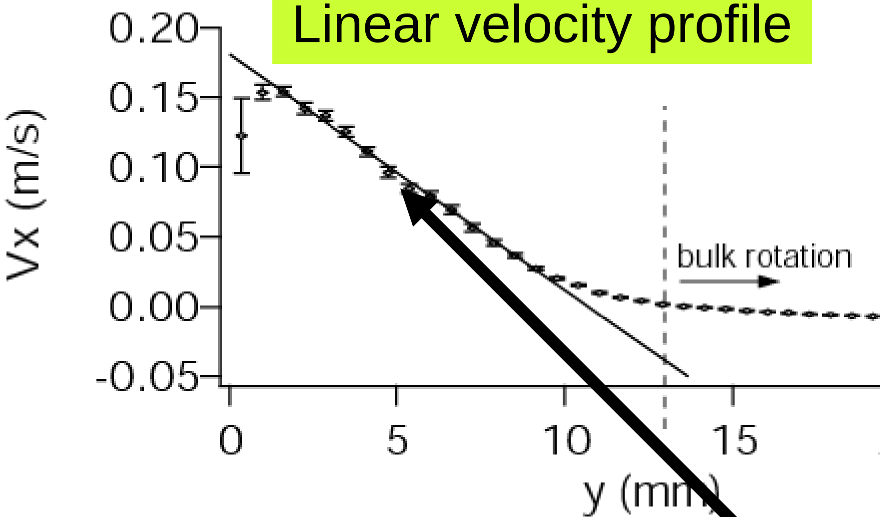
⬢ Left edge Vz

□ Height difference

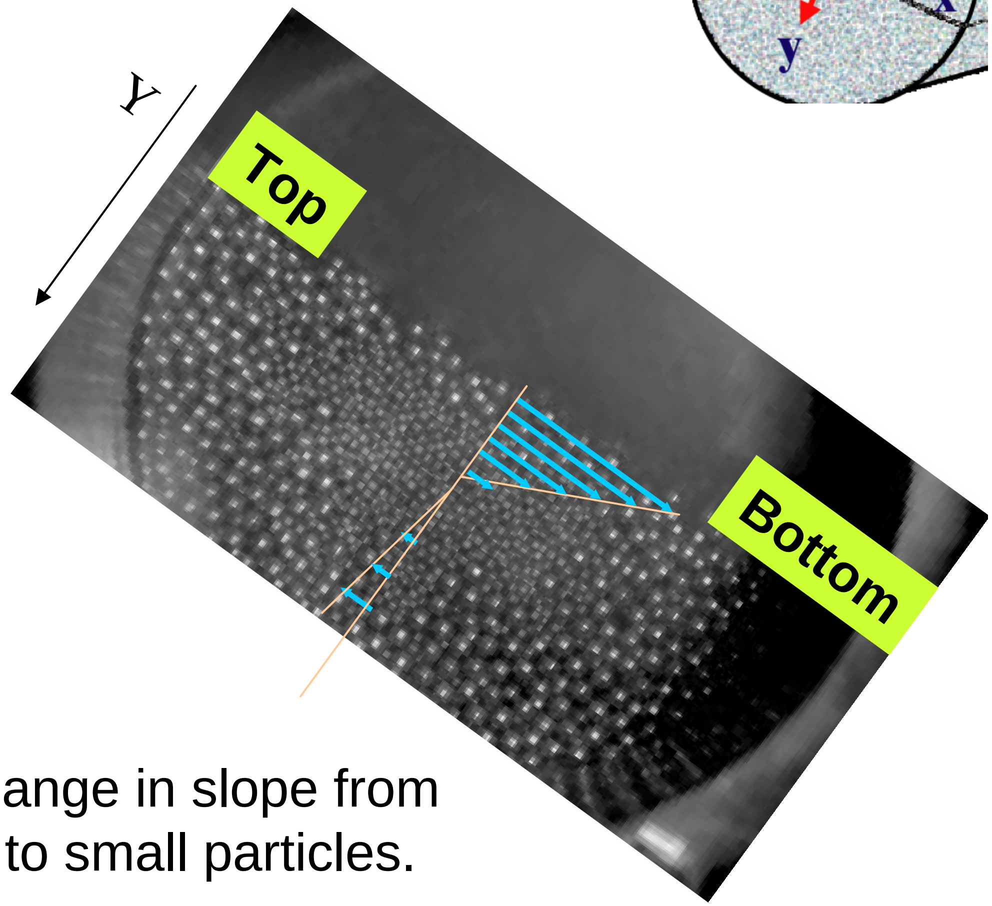
Drift is in the direction of steepest descent at the bottom

Radial velocity and concentration

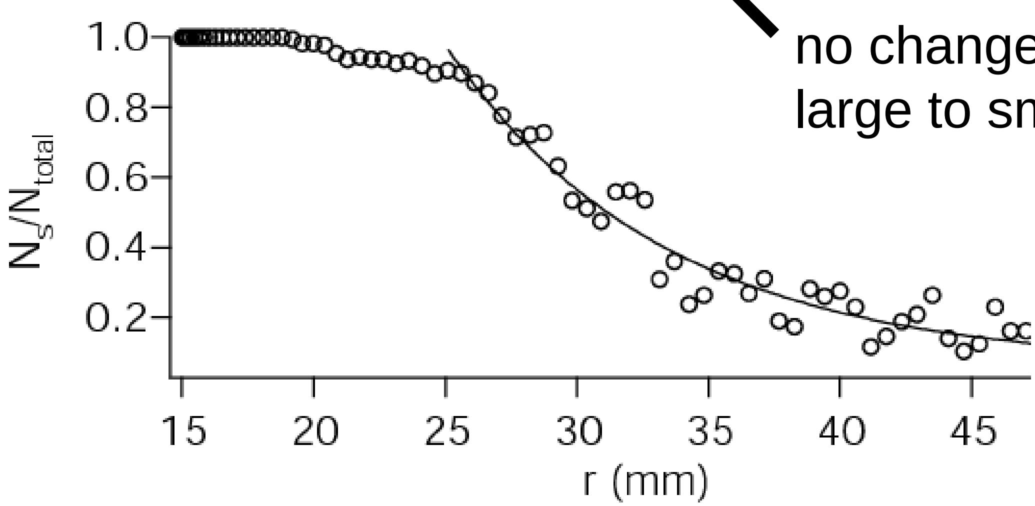




Linear velocity profile

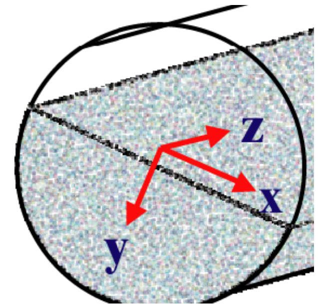


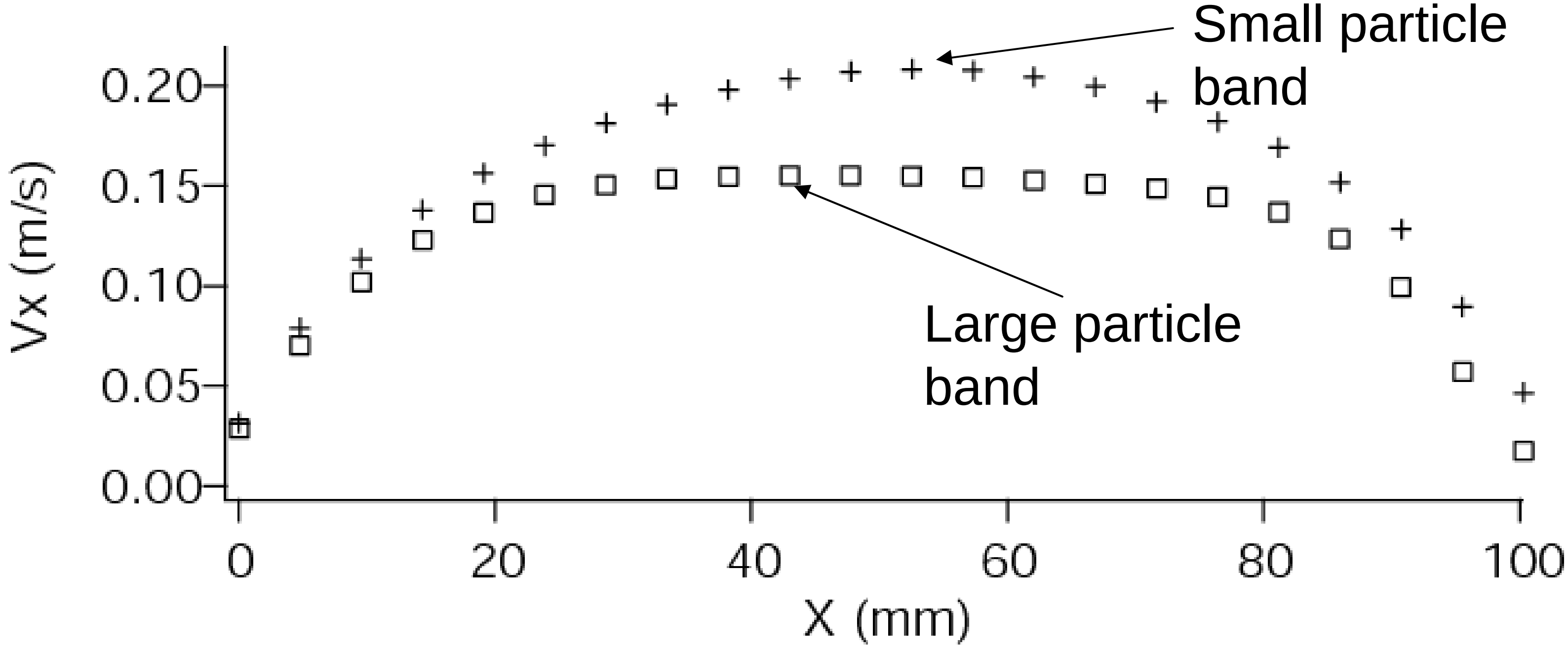
no change in slope from large to small particles.



Radial segregation not complete.

Downhill Velocity

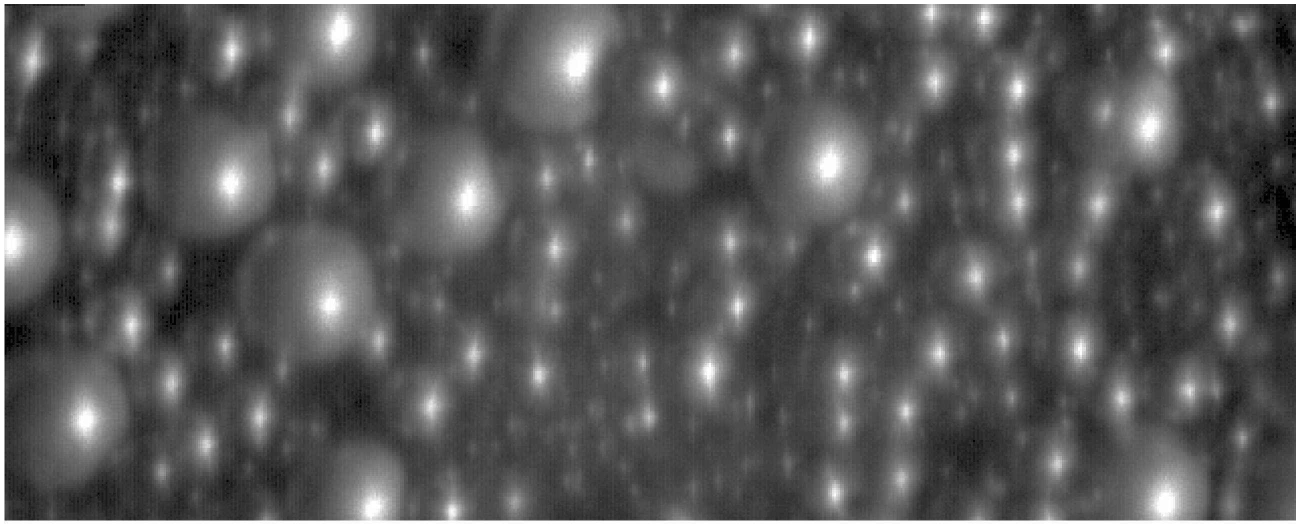


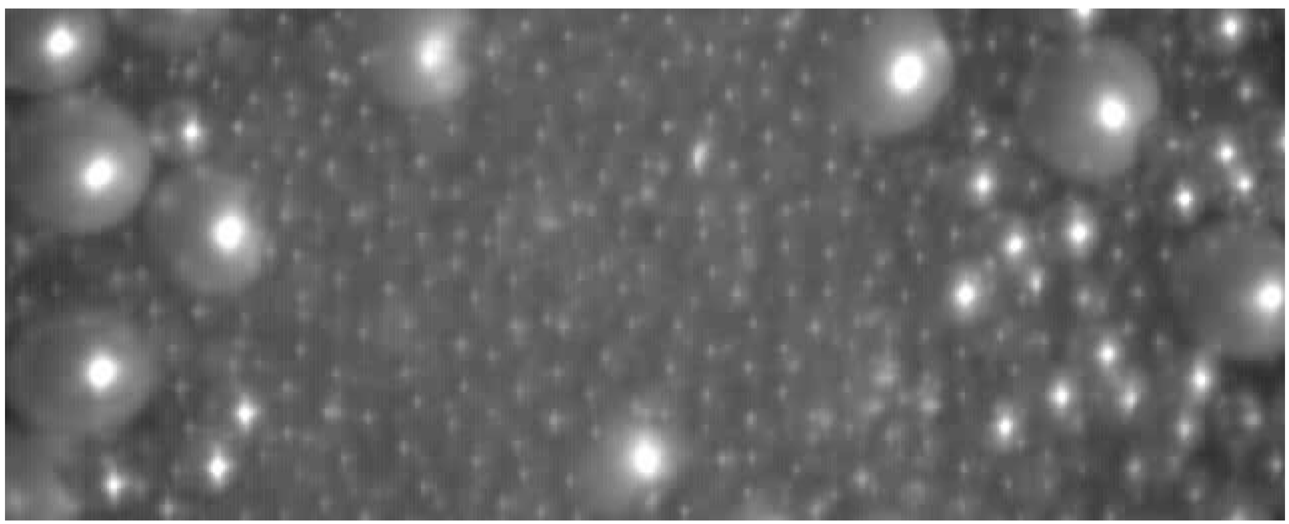


Velocity proportional to concentration of small particles

Newey, Losert, JSTAT, to appear

Particle Speed on Surface

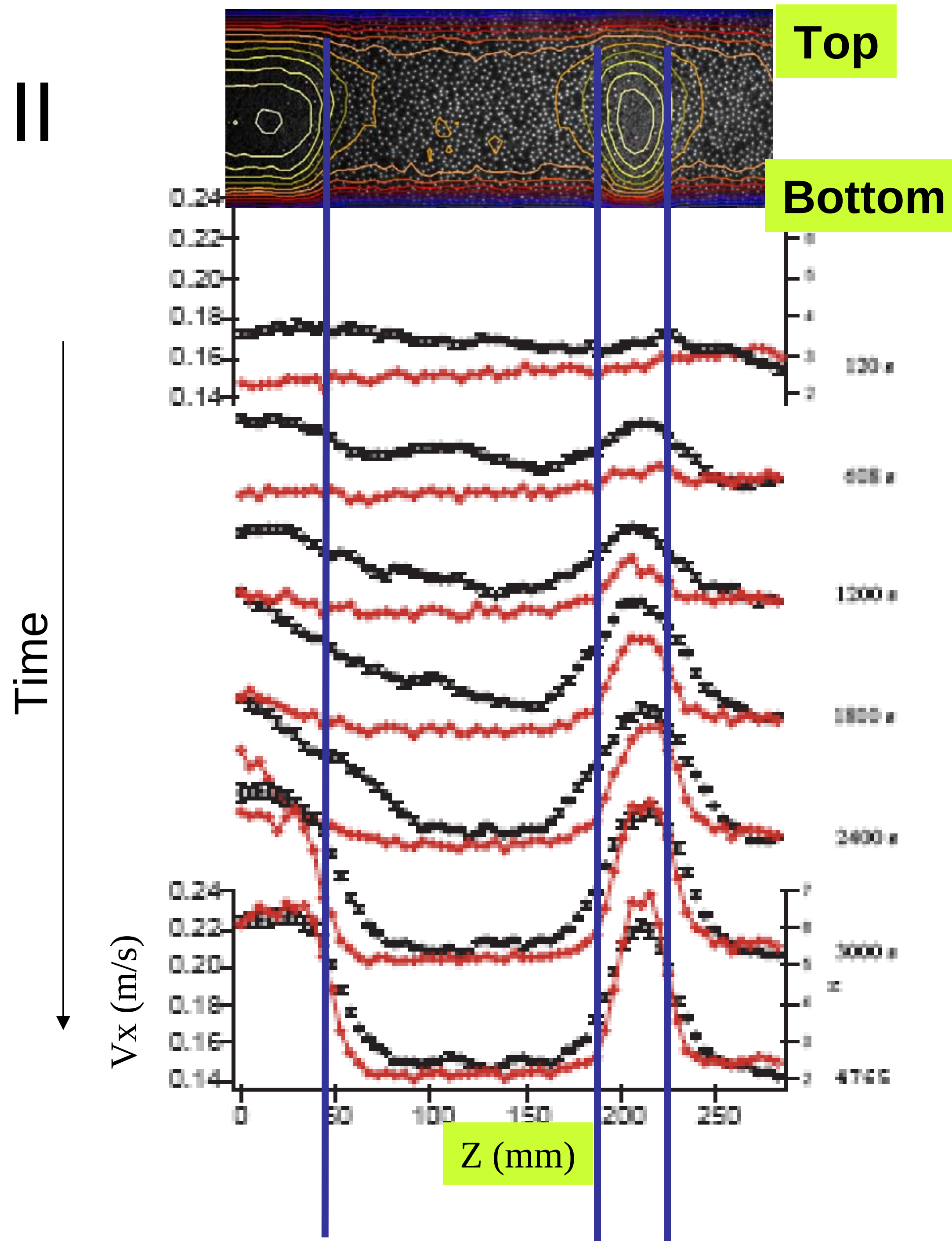




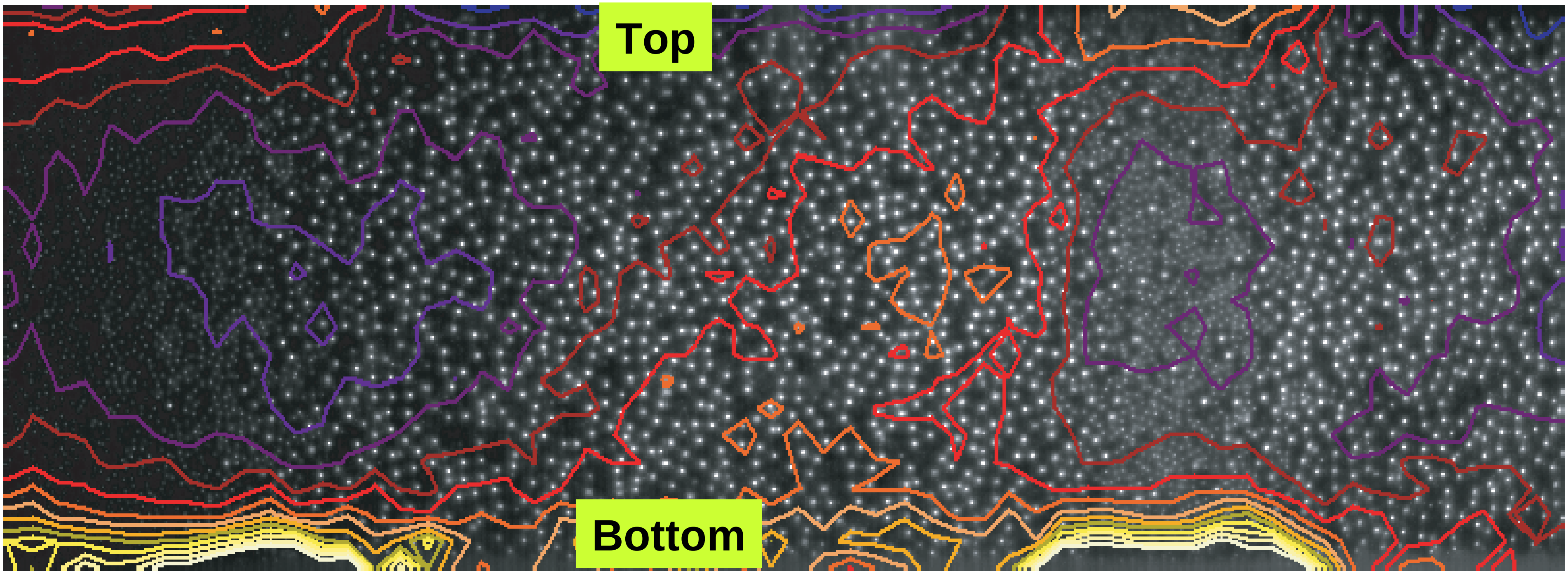
Downhill Velocity, II

Velocity increases before number of small particles on surface increases

-> Velocity depends on subsurface small particles

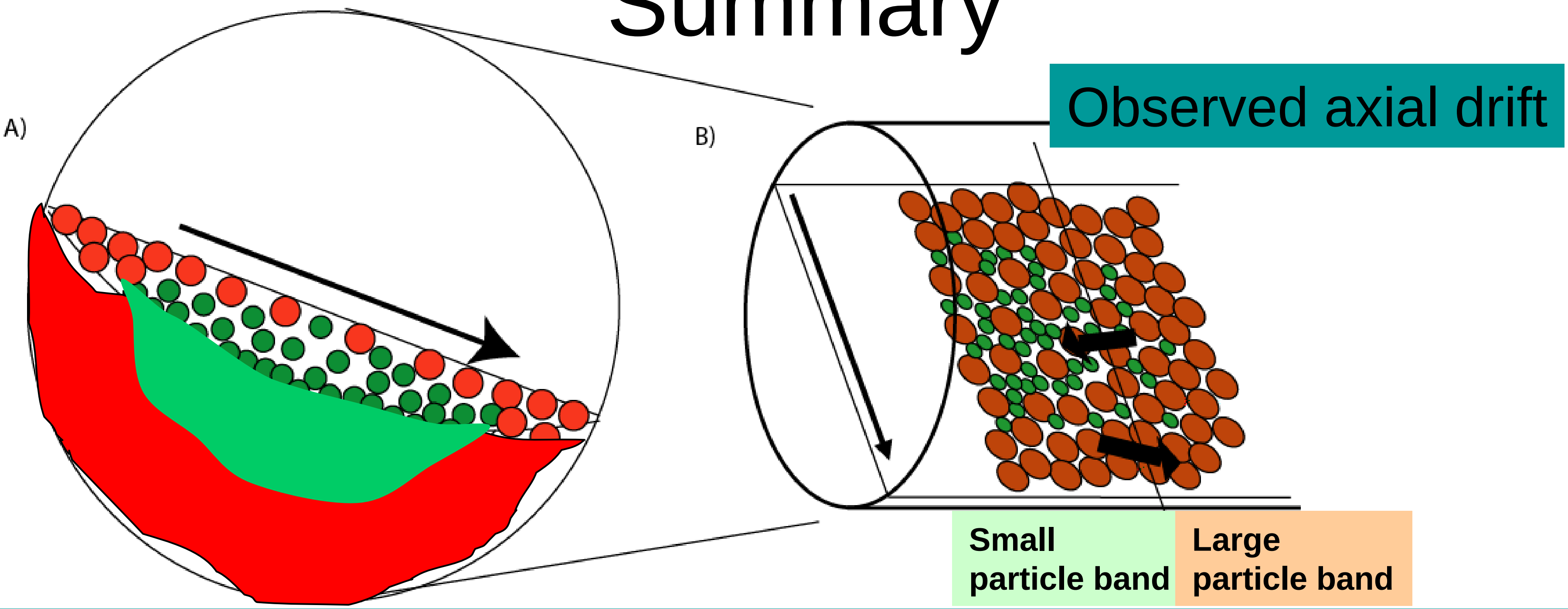


Top and bottom are at different granular temperature



Top - **Particle acceleration** - **low temperature**
Bottom - **Particle deceleration - high temperature**

Summary



<u>Processes that could lead to drift:</u>

Middle: $V_{Surface} \sim \sqrt{\frac{1}{d}}$

- Axial drift into higher surface velocity region

Bottom: higher "temperature" than top

- Axial drift out of high velocity region

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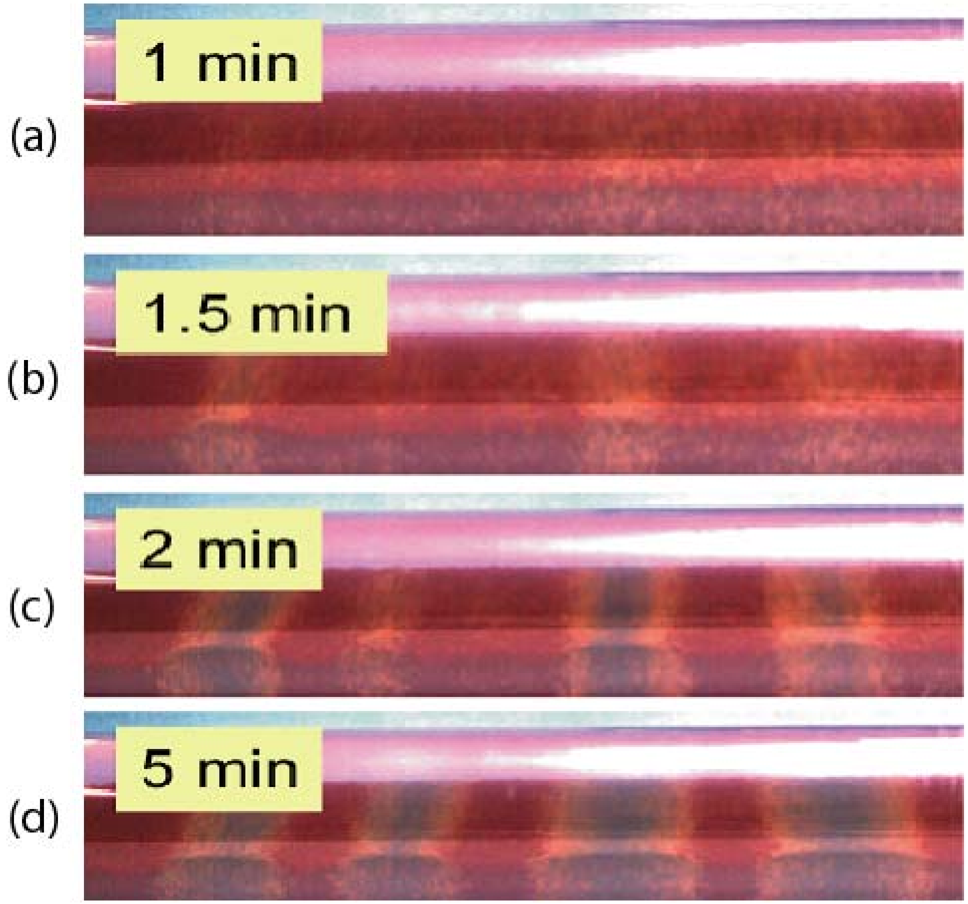
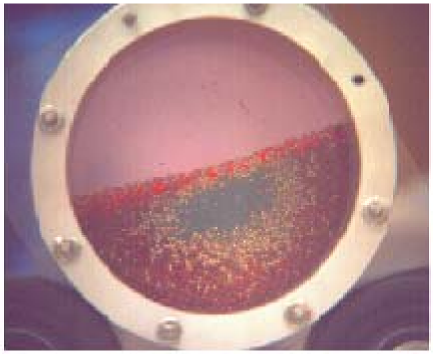
- Polydisperse Materials under Vertical Vibration

Ternary mixtures

Green/blue = 0.5 mm   Gold = 1.0 mm   Red = 2.0 mm



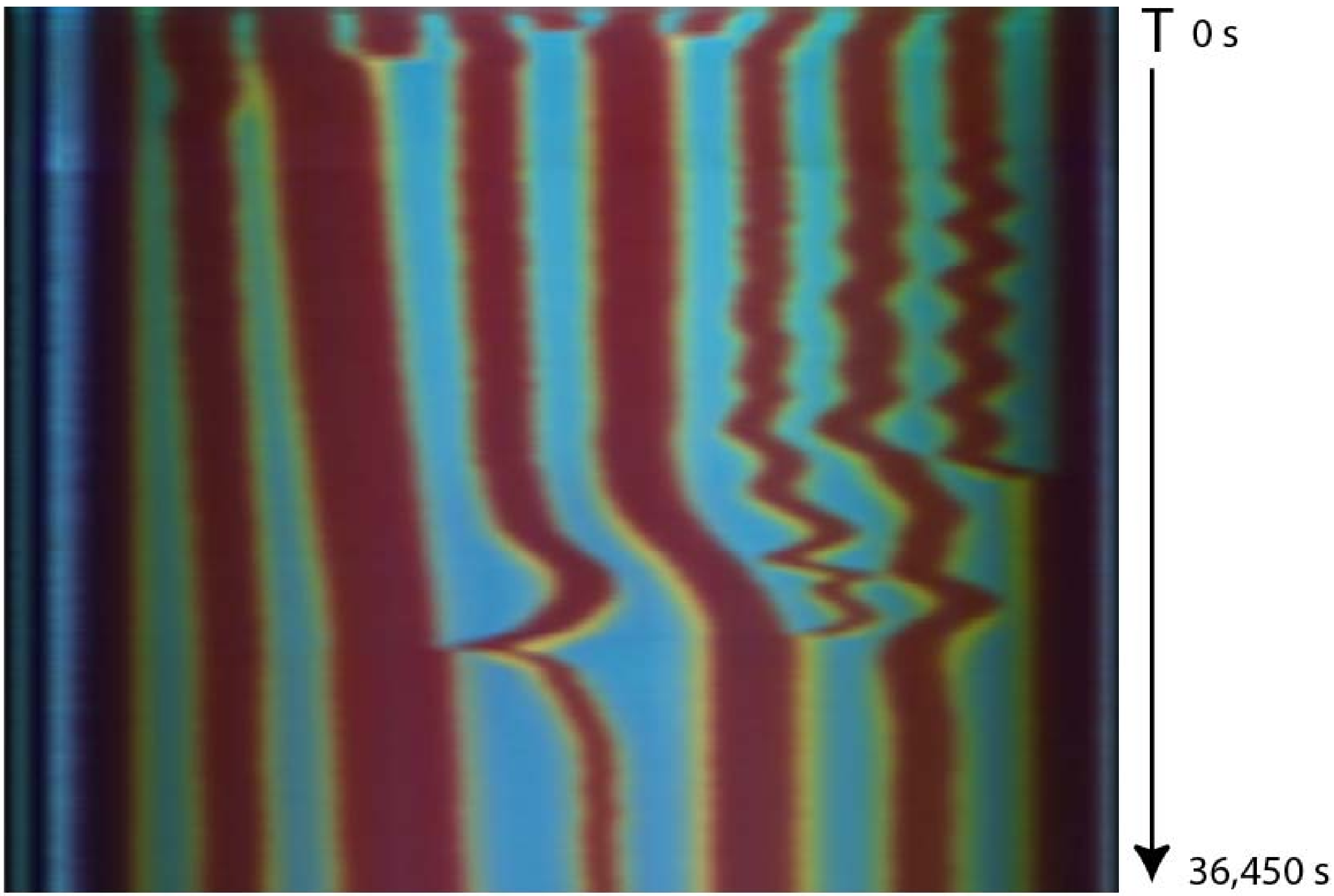


*Band within band formation

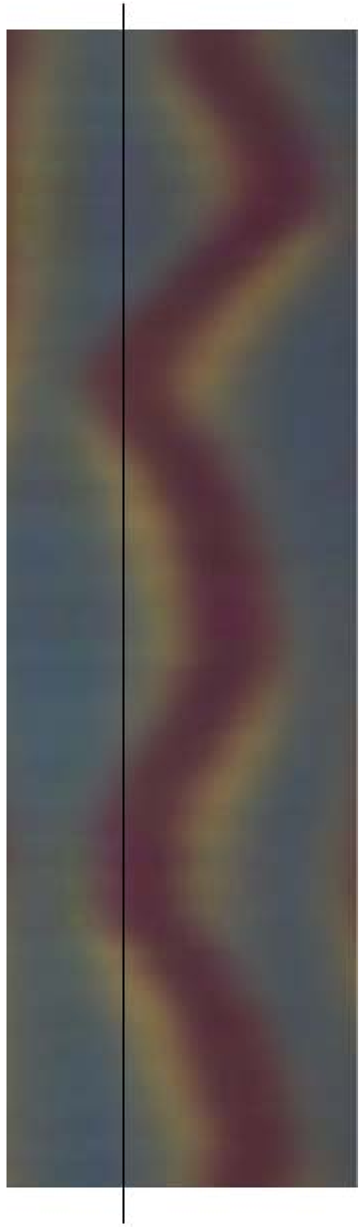
Newey et al.

Europhysics Letters, 2004

Oscillating patterns



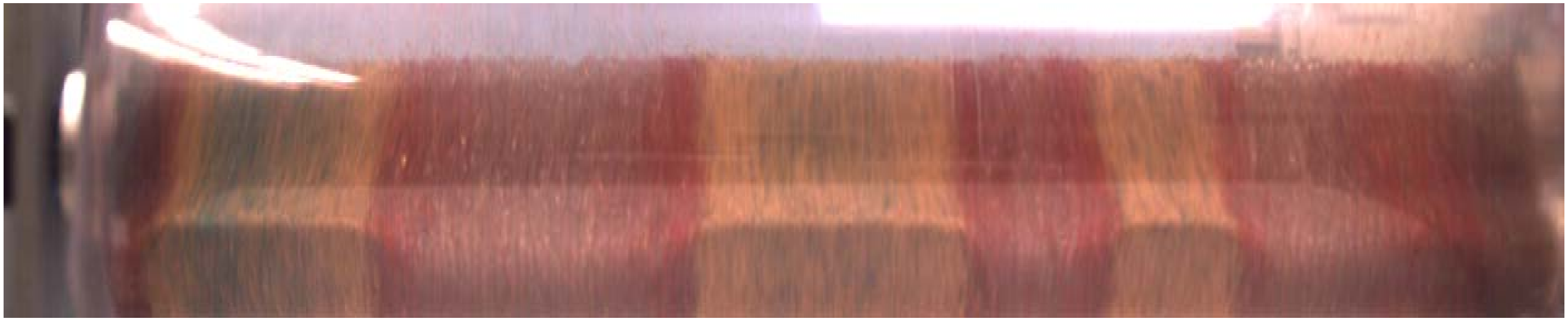
Oscillations




30 min.
0 s
6,831 s

Quaternary Mixtures:
Bands Within Bands Within Bands

not as pronounced.



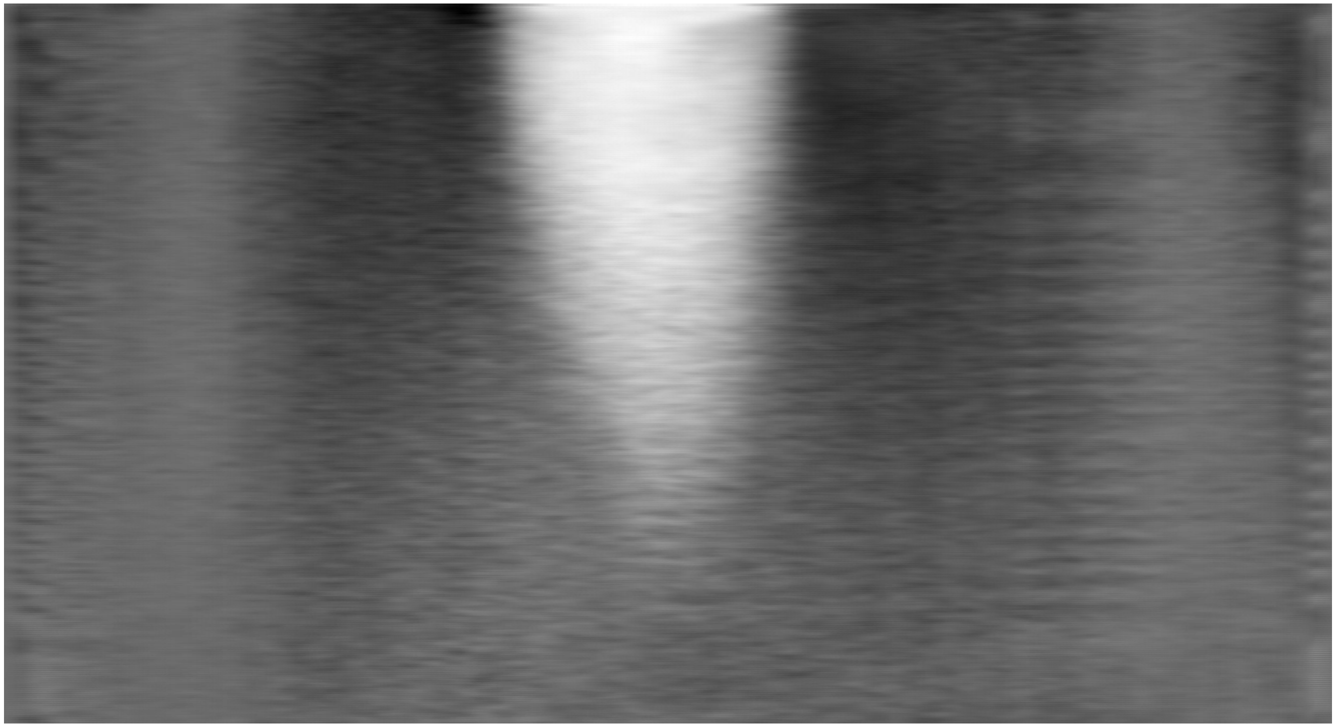
Bands disappear at rotation rates below 15 rpm. Process is reversible.

Mixtures of 5 or More Particle Sizes

*Pronounced radial segregation observed, but no axial bands formed.

*Initially pre-segregated axial bands quickly disappear.

*WHY no bands?



Outline

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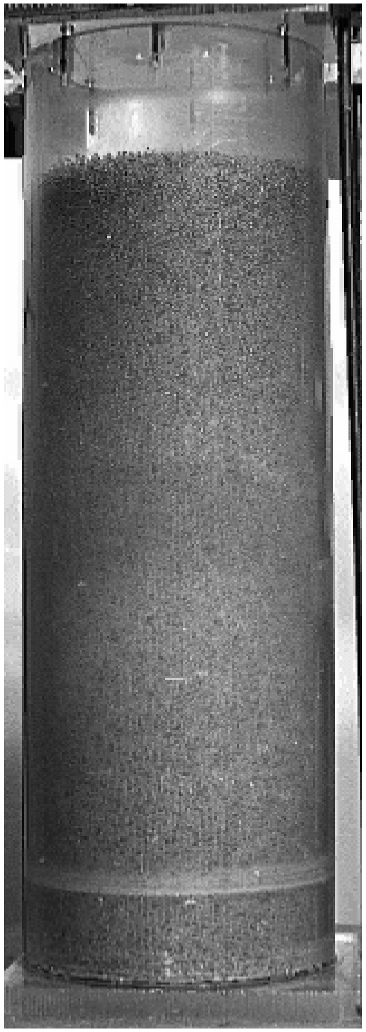
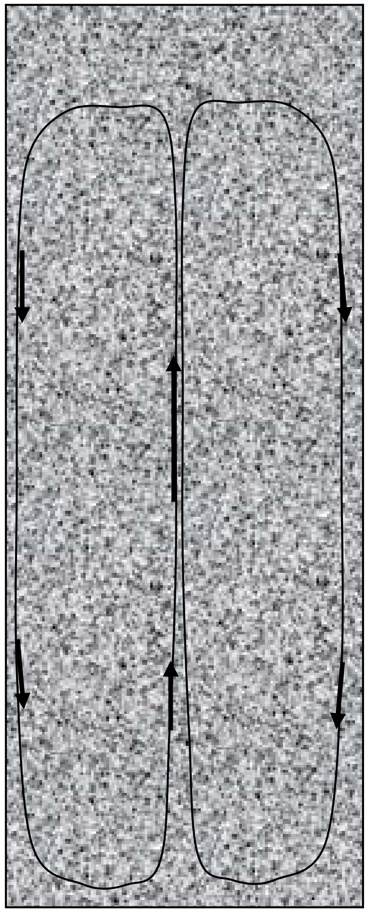
Convection under vertically shaking



Monodisperse:
1mm glass spheres

Convection



Vertical Excitation 50 Hz, 11 g

Binary mixture (1mm and 4mm):

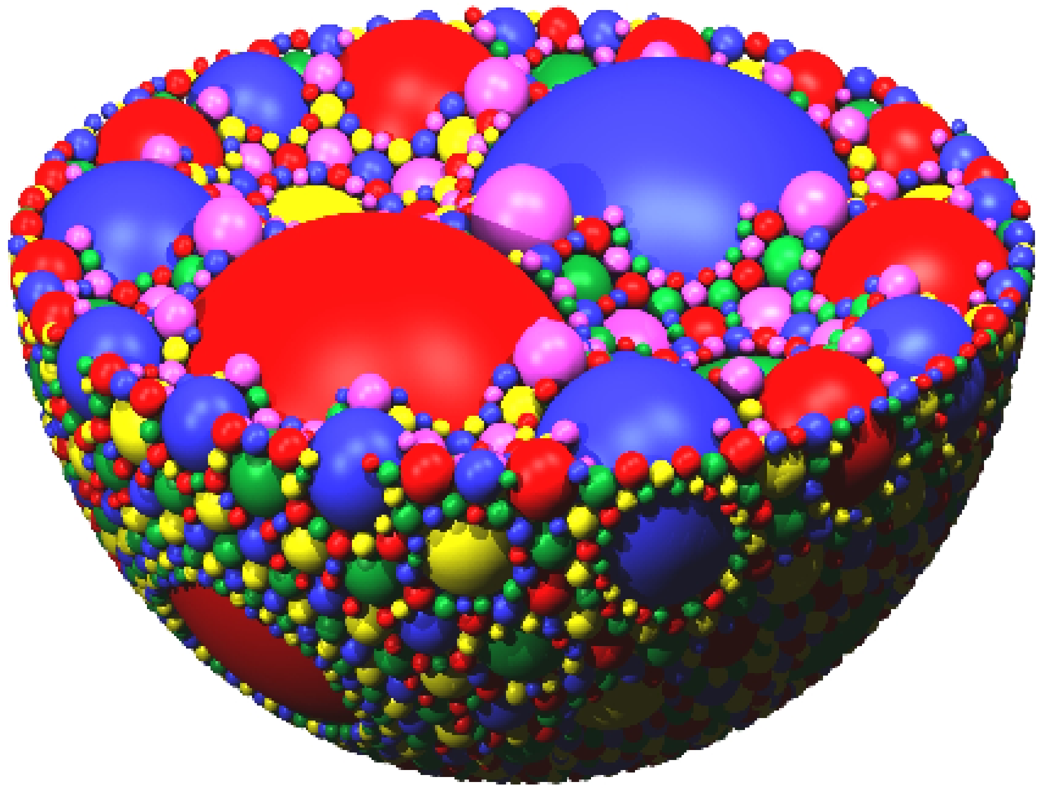
- Slightly higher density
- No qualitative change in behavior

Polydisperse Mixtures

- Mixture of particles glass beads 30 micron – 14 mm Diameter
  - Very dense packing possible in principle

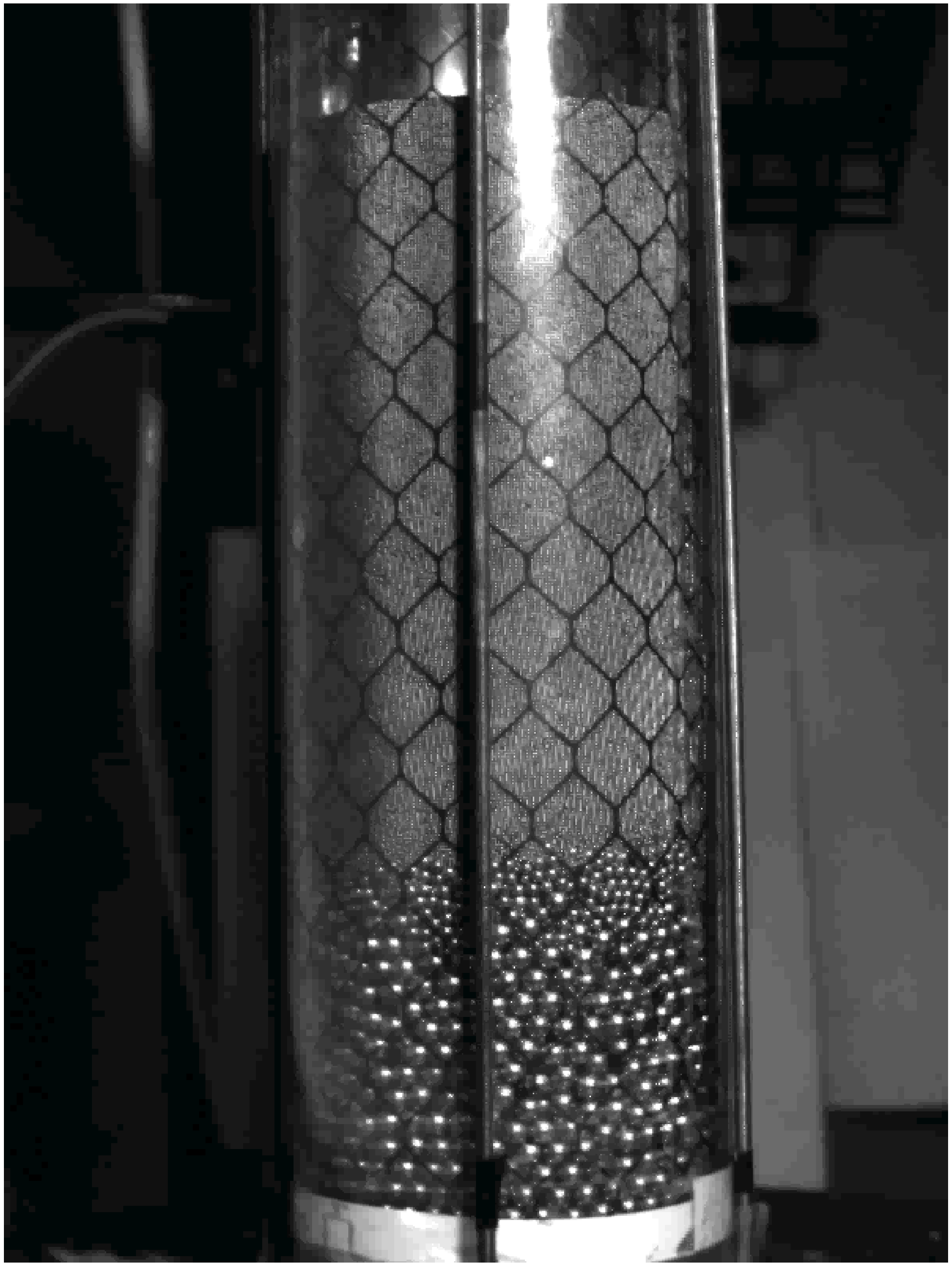
<u>Questions:</u>

- When will the system pack densely, when will it segregate?
- Effect of multiple lengthscales?
  - 2.5 orders of magnitude in particle radius r
- Effect of multiple energy scales?
  - 10 orders of magnitude in characteristic energy m*g*r



Part of a 3D appolonian packing

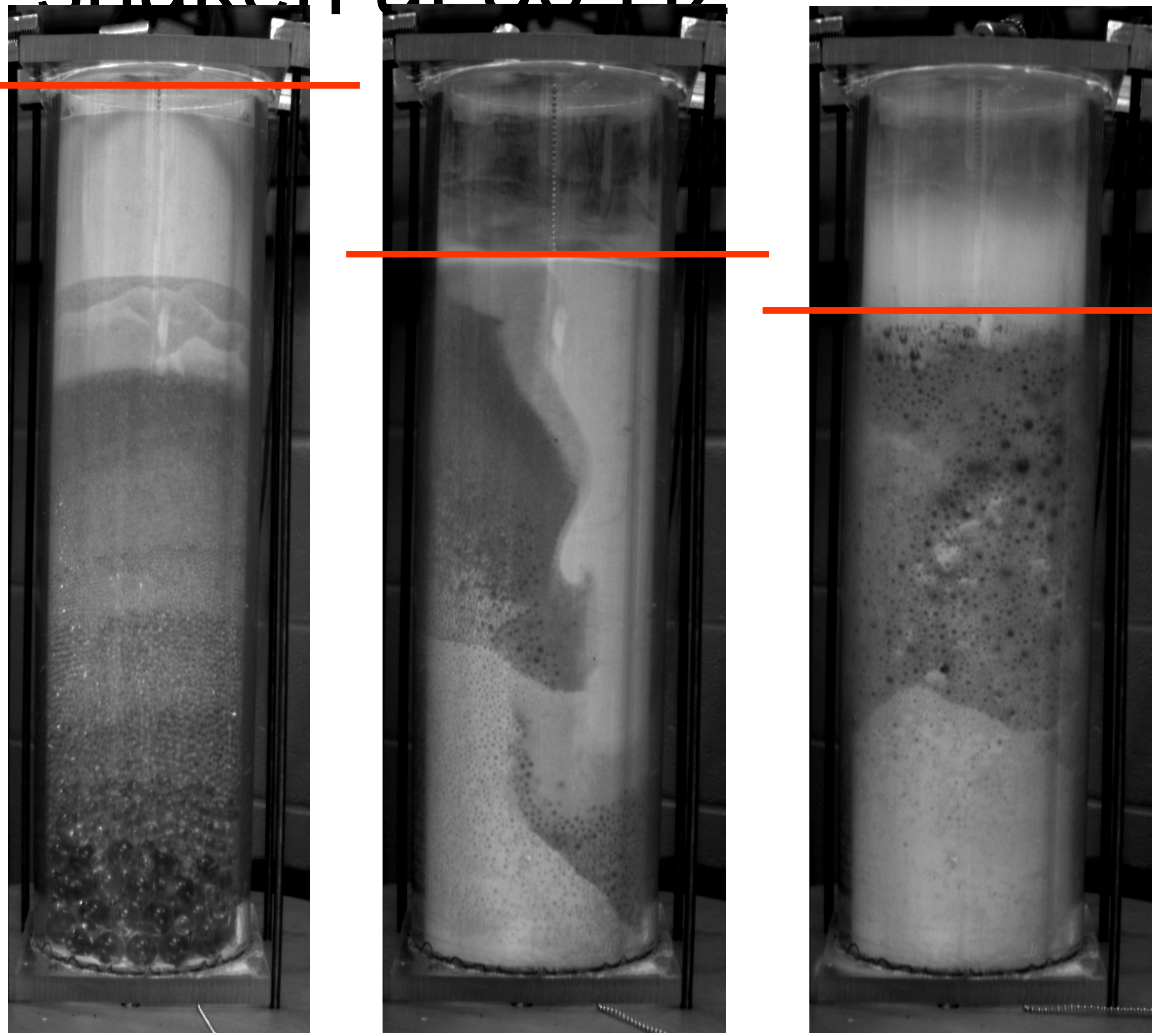
M. BORKOVEC and W. DE PARIS, R. PEIKERT, *Fractals*, Vol. 2, No. 4 (1994) 521-526



Polydisperse mixture vertically shaken at 50 Hz

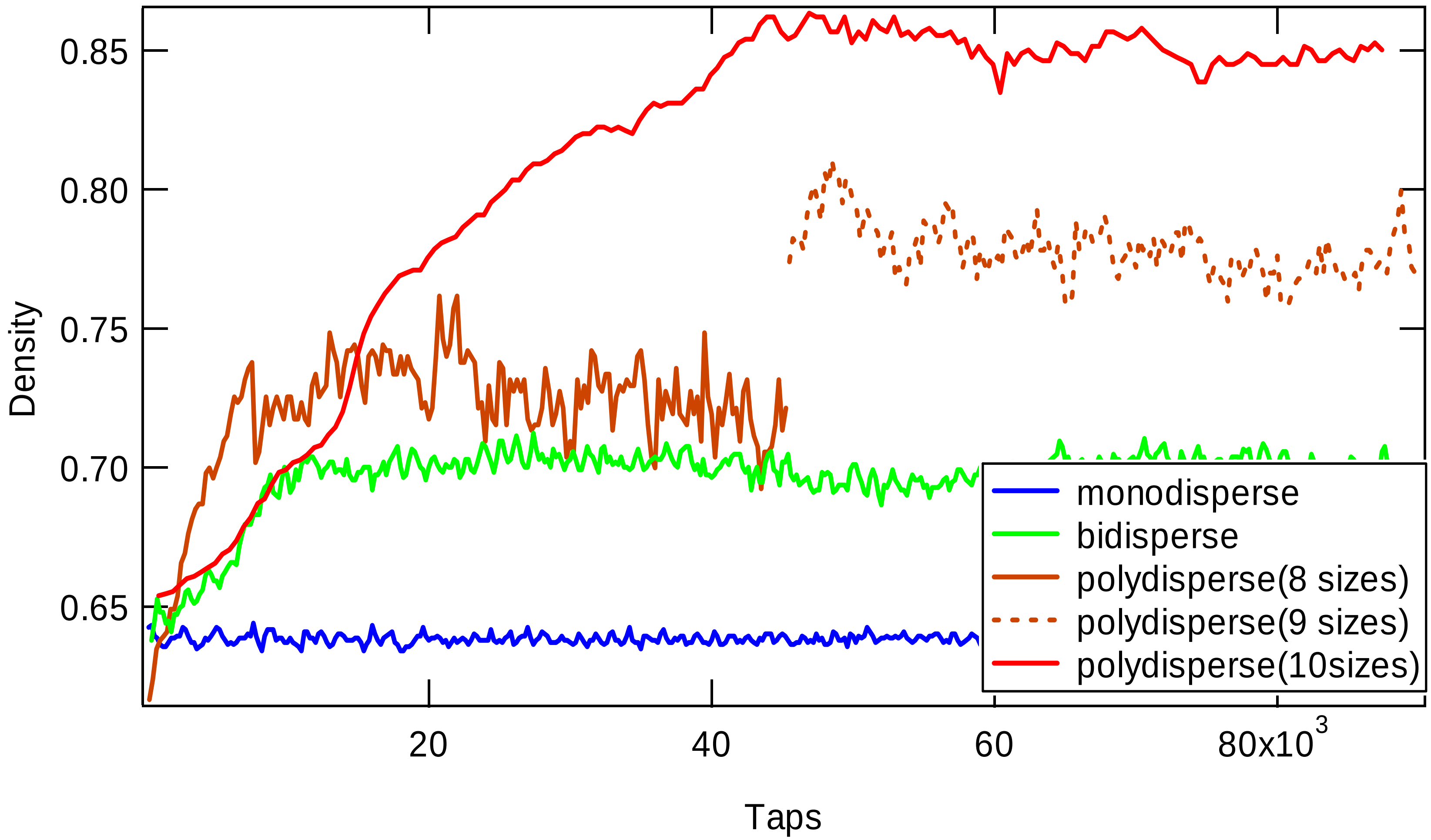
Mixture of 10 sizes:
(450 g each)

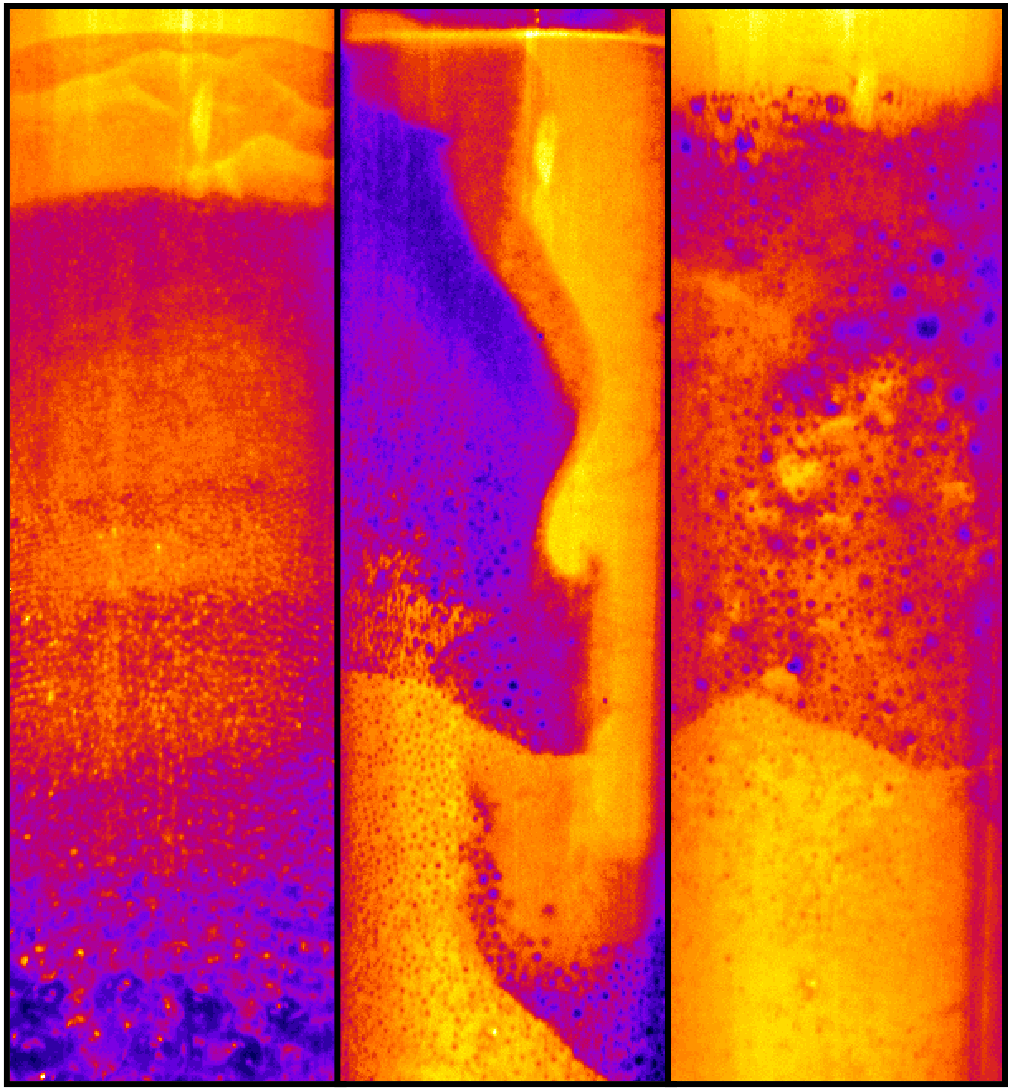
14mm
8mm
4mm
2mm
1mm
0.6 mm
0.35 mm
0.085 mm
0.055 mm
0.030 mm

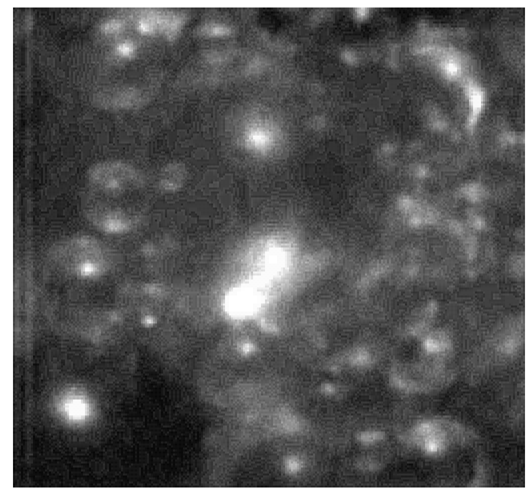


System mixes for a finite range of frequencies and amplitudes

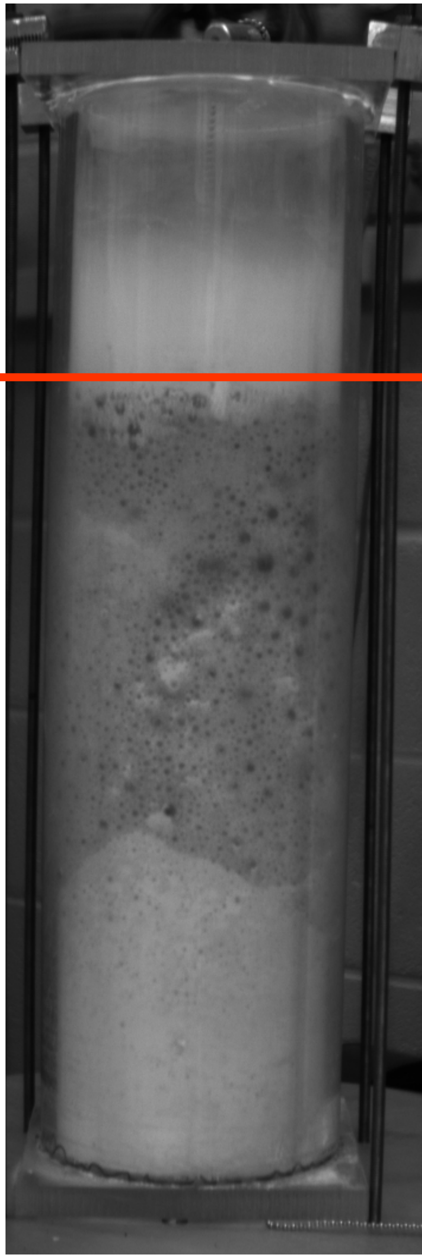
Packing fraction







Reversible segregation



Segregation by size when shaken below threshold frequency (~ 20 Hz)

Segregation accompanied by dilation

Role of Mixing Ratio

Total mass of particles of size r:

$m(r) \sim r^3 * N(r)$

N(r): Number of particles with radius r

$N(r) \sim r^{-D}$

$m(r) \sim r^{3-D}$

D: Mixing ratio

D=3 Equal mass packing

D=0: Equal number of particles for each radius

D=2.3 ~Applolonian Packing
(optimal packing)

D=2.6 observed in geology