Segregation in granular material

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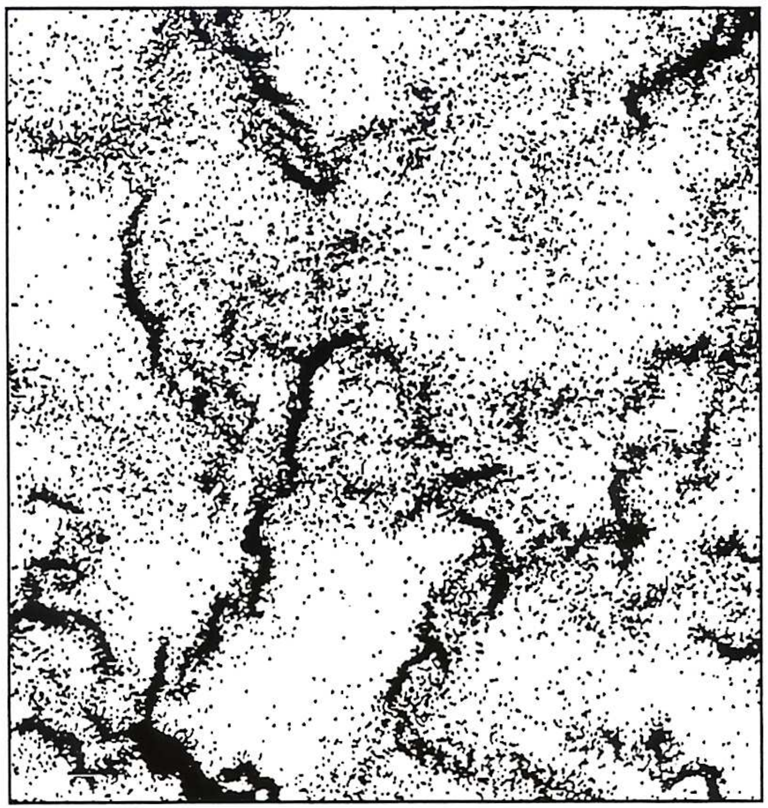
Introduction

- Pattern formation

Inelastic collapse and clustering in cooling granular gases

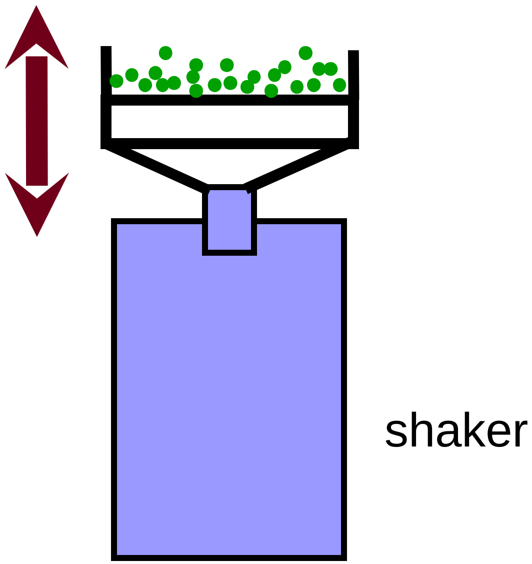


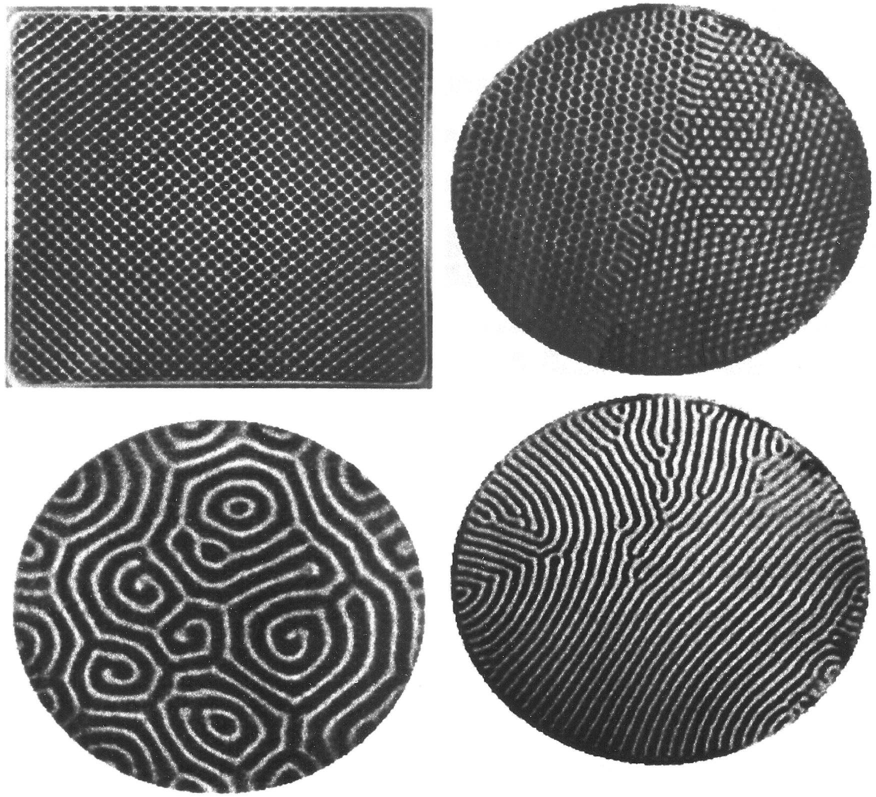
I. Goldhirsch and G. Zanetti, Phys. Rev. Lett. 70, 1619 (1993).

Introduction

- **Pattern formation**

granular layers subjected to vertical shaking





Swinney et al.

Introduction

- Pattern formation in granular material

sand dunes and ripples
wind- or water-driven

Introduction

- Segregation:

grains of different species (size, density, shape, friction, inelasticity…) under vibration or shear may seperate

Examples
rock & snow avalanches, corn flakes, powder mixing

Brazil nut effect

Segregation under vibration:

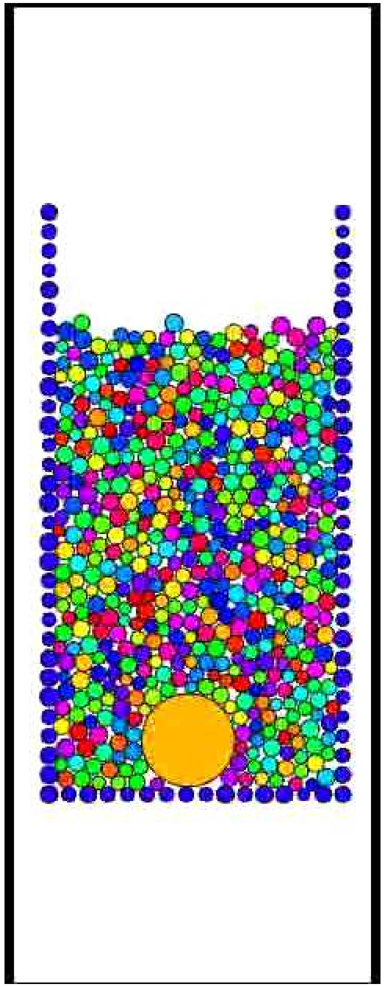
The larger nuts rise at the surface (Brazil nuts)

The smaller nuts sink at the bottom (peanuts)

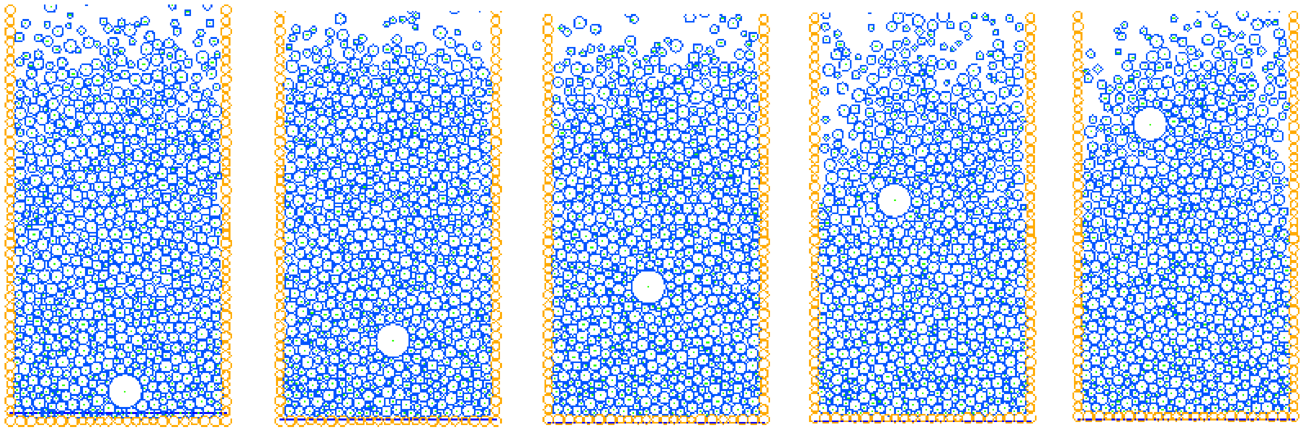
Brazil nut effect

Simpler case
One large grain among smaller grains
under vertical vibrations (a sin ωt, $a\omega^2 > g$)

(2D DEM simulations)



Brazil nut effect



→ the large intruder rises at the surface

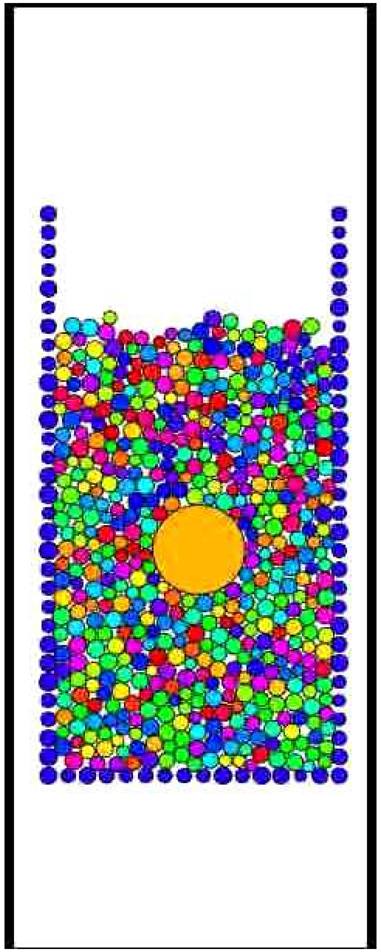
Brazil nut effect

Time-laps movie

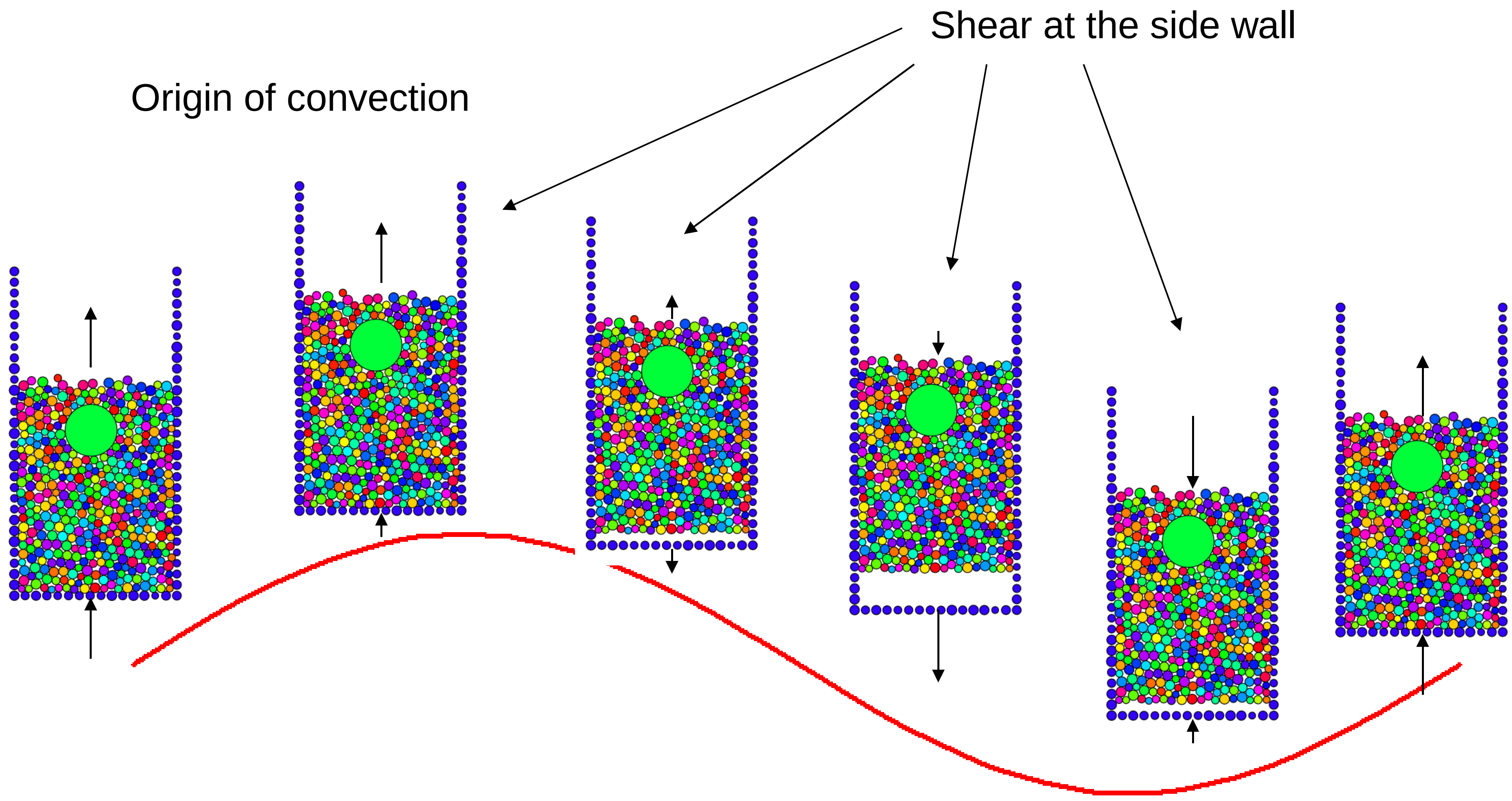
Snapshot taken every 5 cycles

Shows two convection rolls of size ~2d

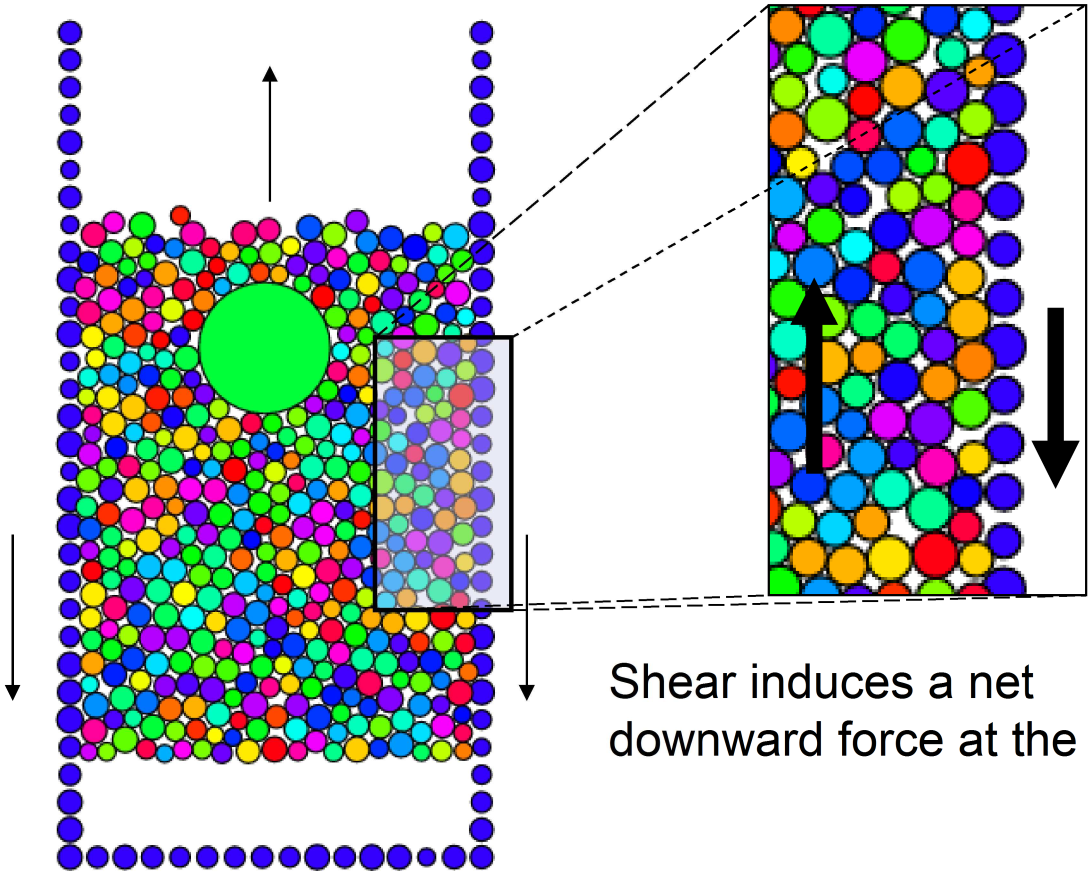
Large grain rises to and stays at the surface



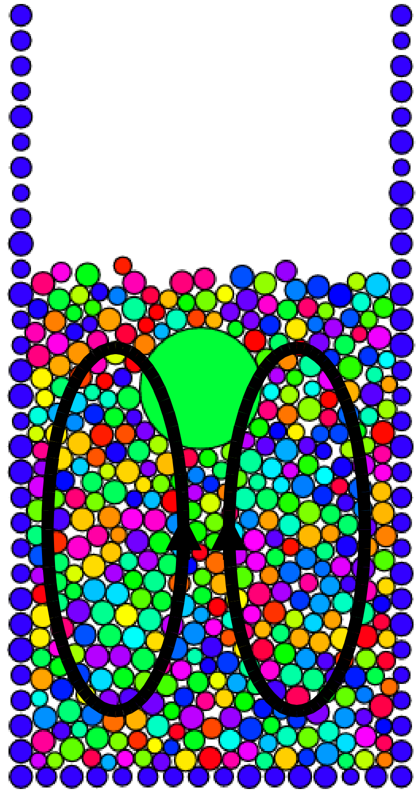
Brazil nut effect



Brazil nut effect



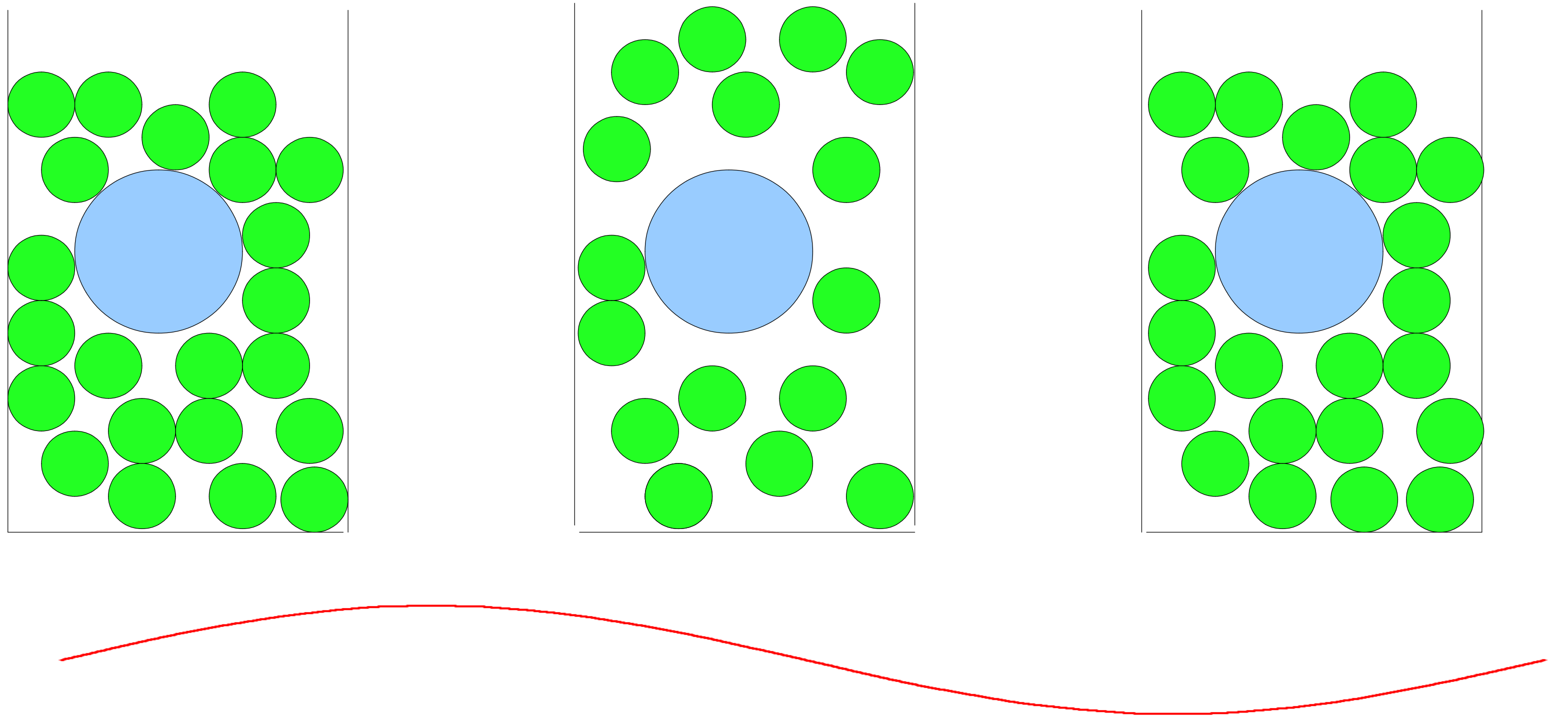
Shear induces a net downward force at the sidewall



Mass conservation leads to two convection rolls

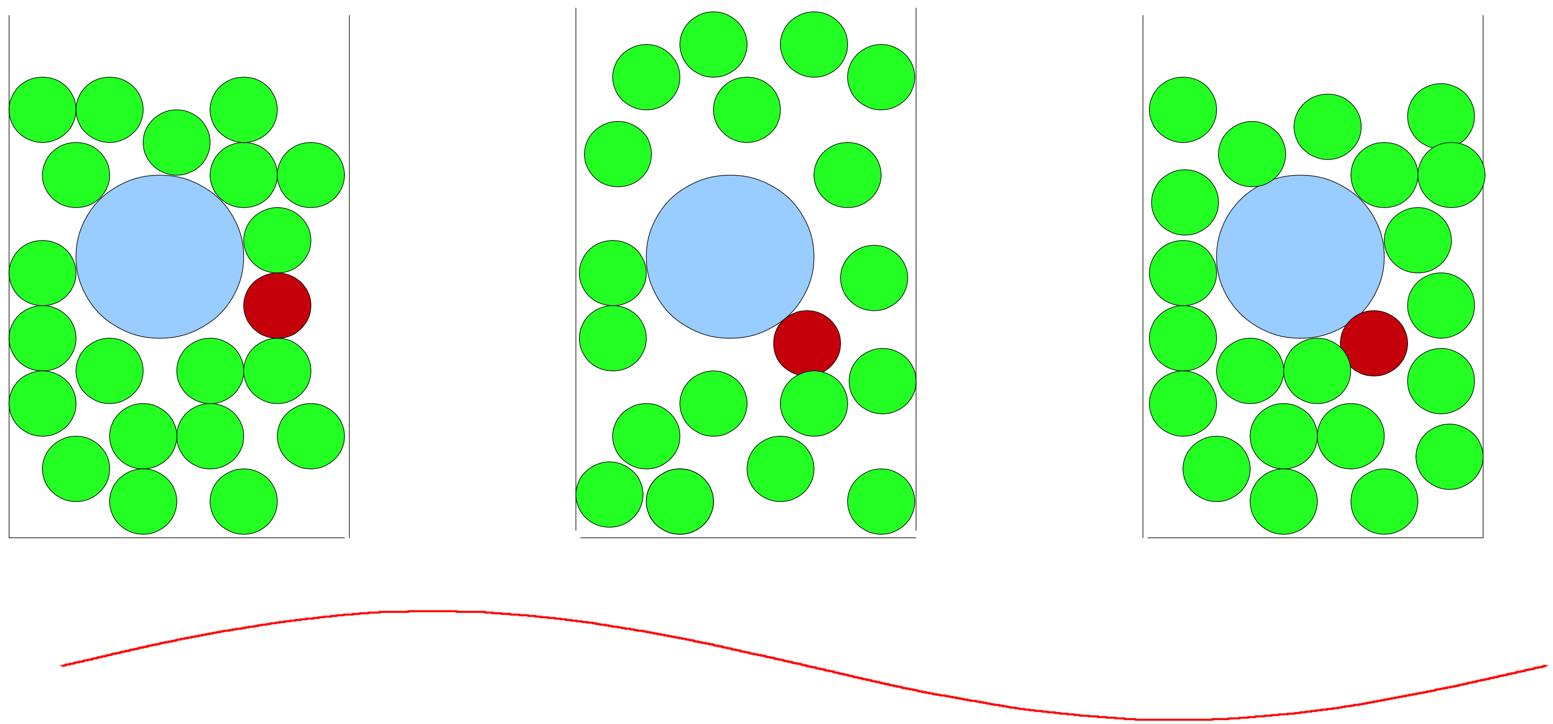
Brazil nut effect

- Other mechanism: percolation



Dense packing → Dilation → Free flight → Compaction

Brazil nut effect



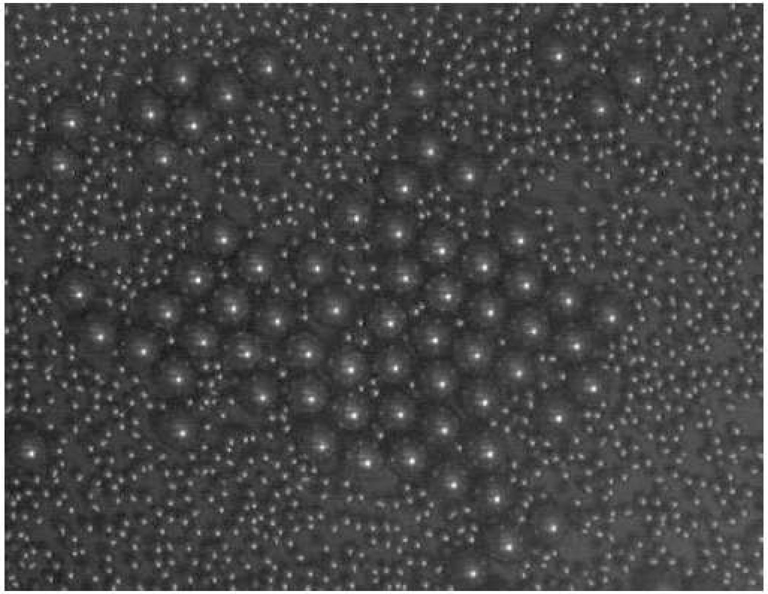
During the recompaction process,
smaller grain can slide underneath larger grains
Causing the larger grain to rise

The higher the size difference, the faster the segregation

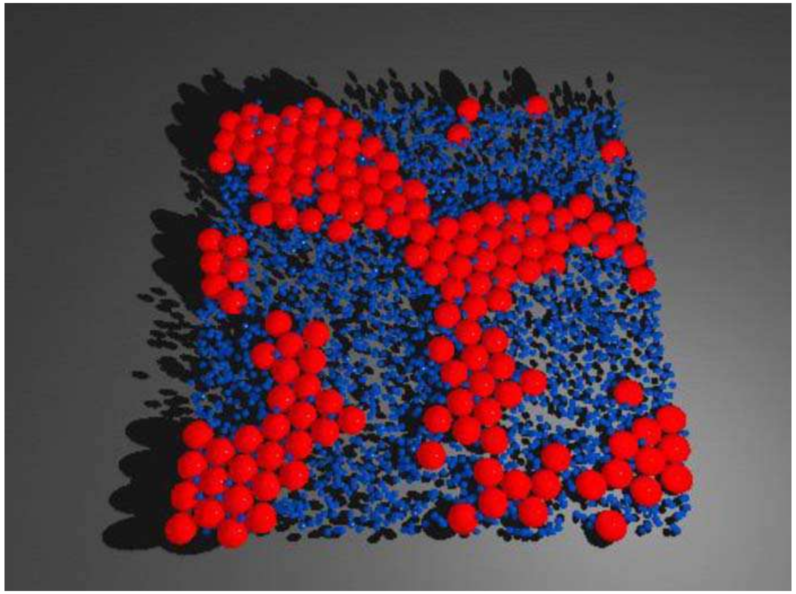
Segregation under horizontal vibrations

Melby et al. PRE (2007):
Small and large grains in a horizontal plate shaken vertically

Low packing fraction (density)



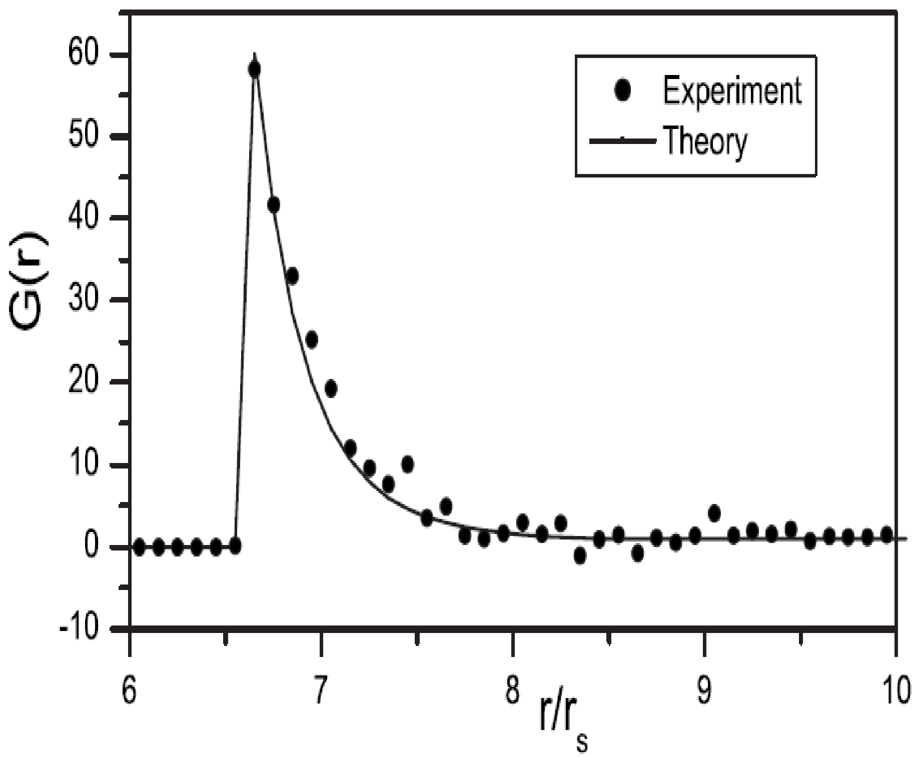
Experiments



DEM simulations

→ size segregation

Segregation under horizontal vibrations



Pair correlation function:

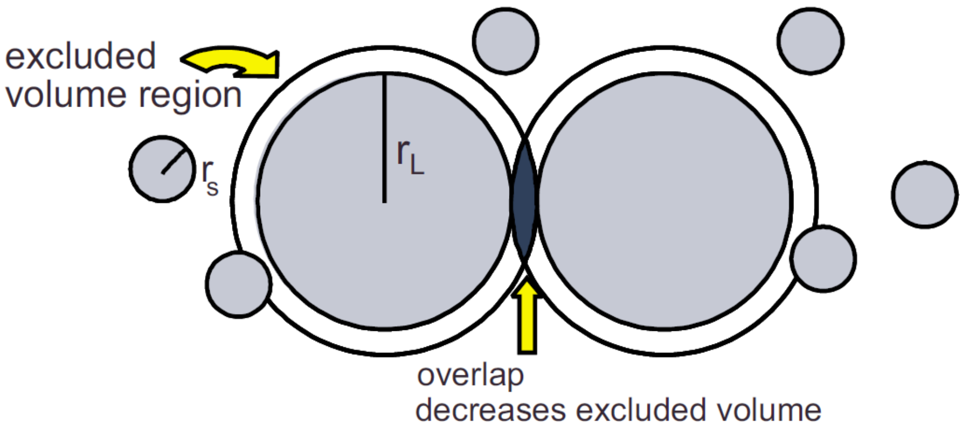
Probablity to find a large particle at distance r

Decreases with increasing r

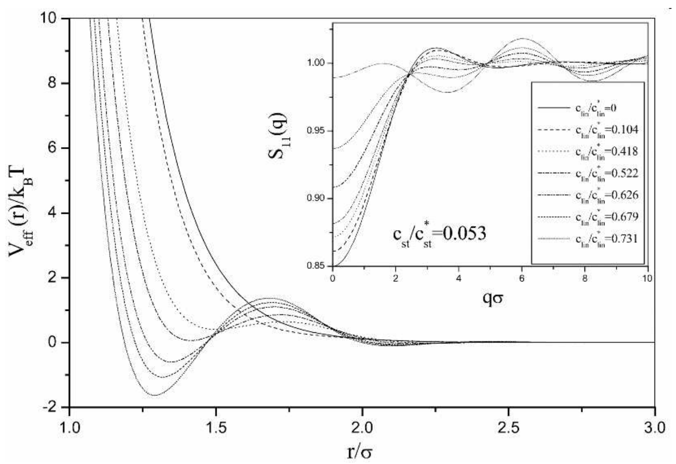
Effective attractive force between large particles

Segregation under horizontal vibrations

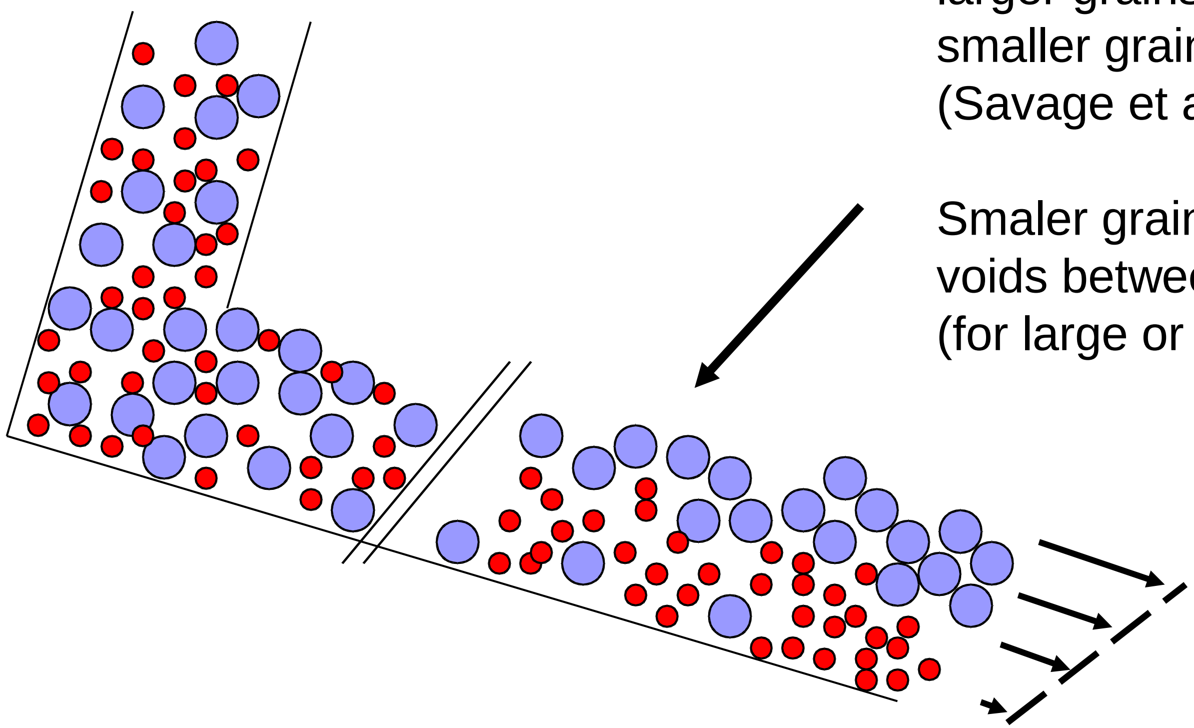
Mechanism: depletion forces



Well-known in colloidal suspensions
Stiakakis, EPL (2005)



Segregation under flow



Binary mixture under flow

Dynamic sieving causes
larger grains to rise to the surface
smaller grains to sink to the bottom
(Savage et al, 1988)

Smaler grains percolate through the
voids between the larger grains
(for large or small size ratio)

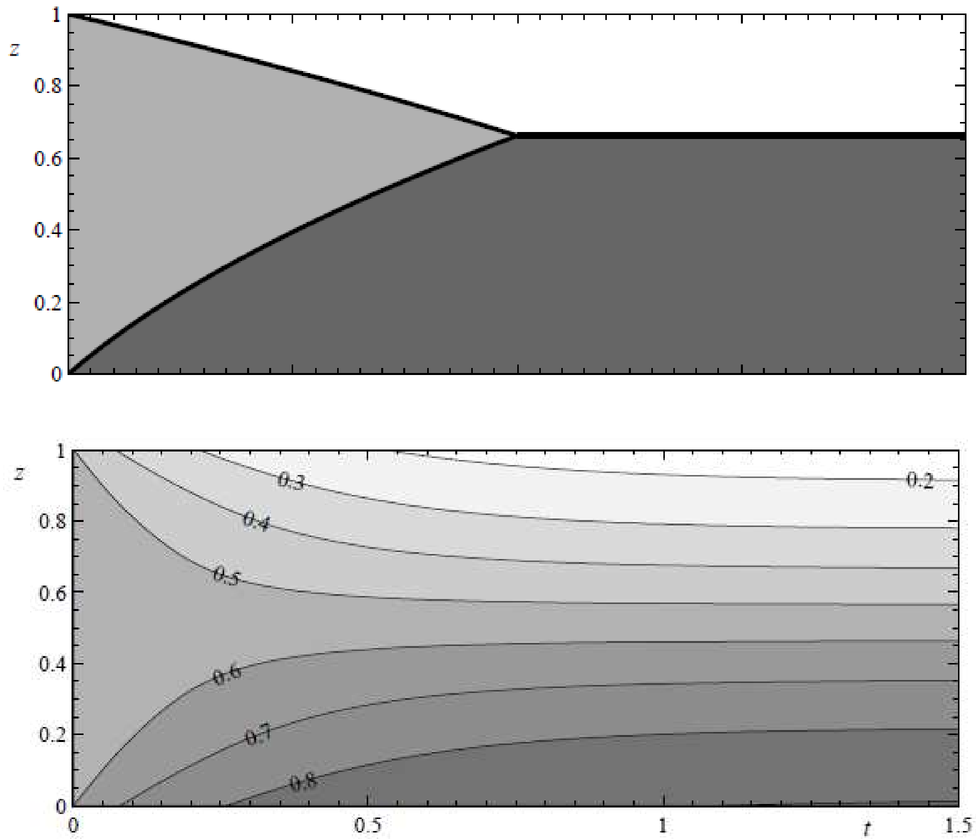
Segregation under flow

Models for segregation (Gray 2010)

•Initial uniform concentration

•Phase seperation after critical distance

•Compute concentration profiles



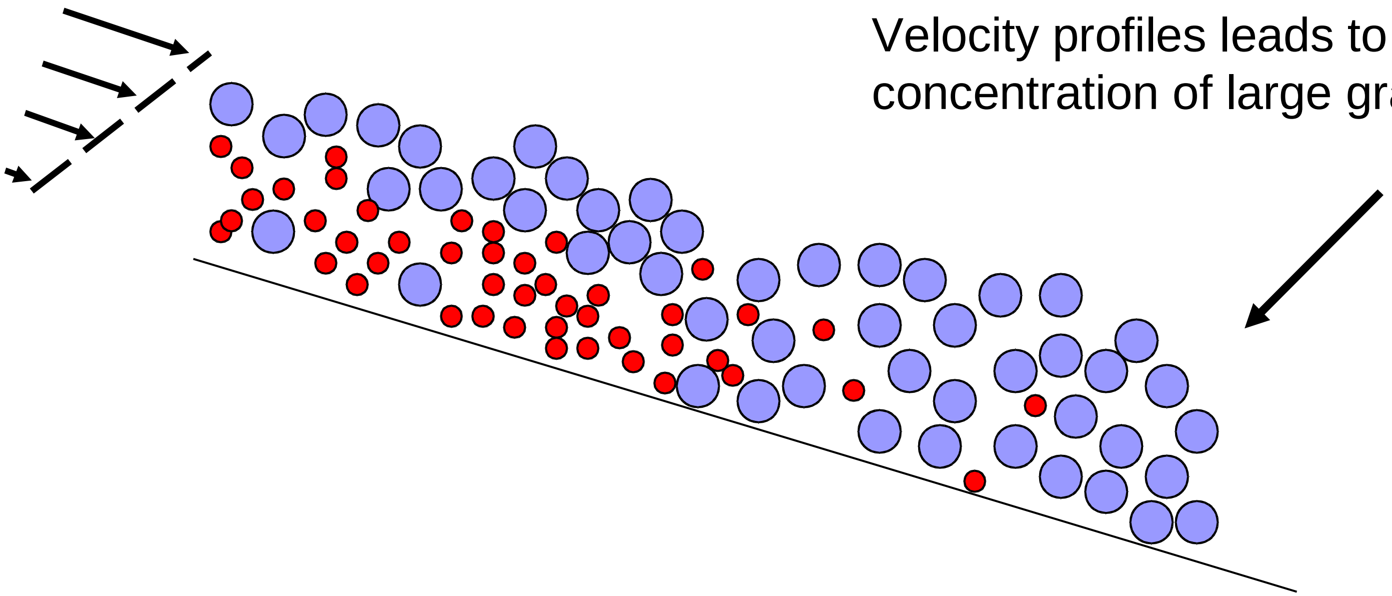
Gray (2010)

Segregation under flow

Binary mixture under flow

Dynamic sieving causes
larger grains to rise to the surface
smaller grains to sink to the bottom

Velocity profiles leads to a high
concentration of large grain near the front



Segregation under flow

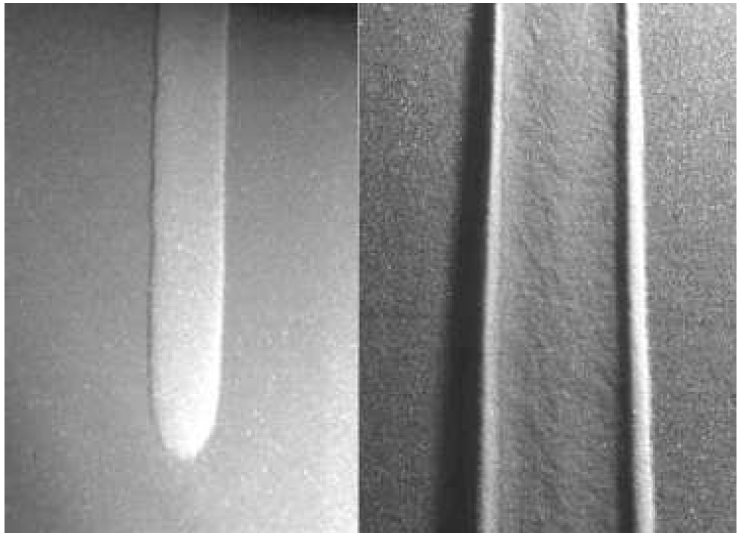
- Unconfined flows :
  formation of levees

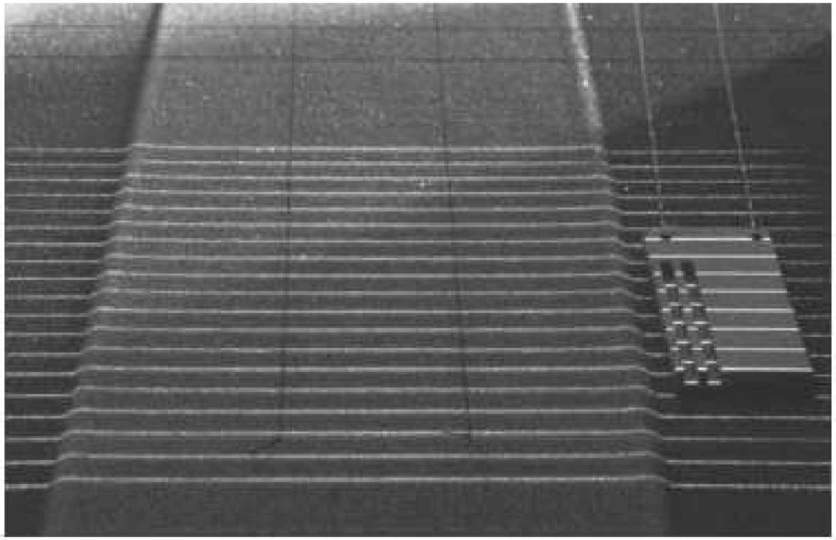
  Granular material is constantly released onto a flat inclined plate

  A tongue-shaped flow travels down the slope

Segregation under flow

- After the flow has stoped
  lateral borders remain : levees





Felix et al. (2004)

Segregation under flow

Formation of levees

Felix et al. (2004)

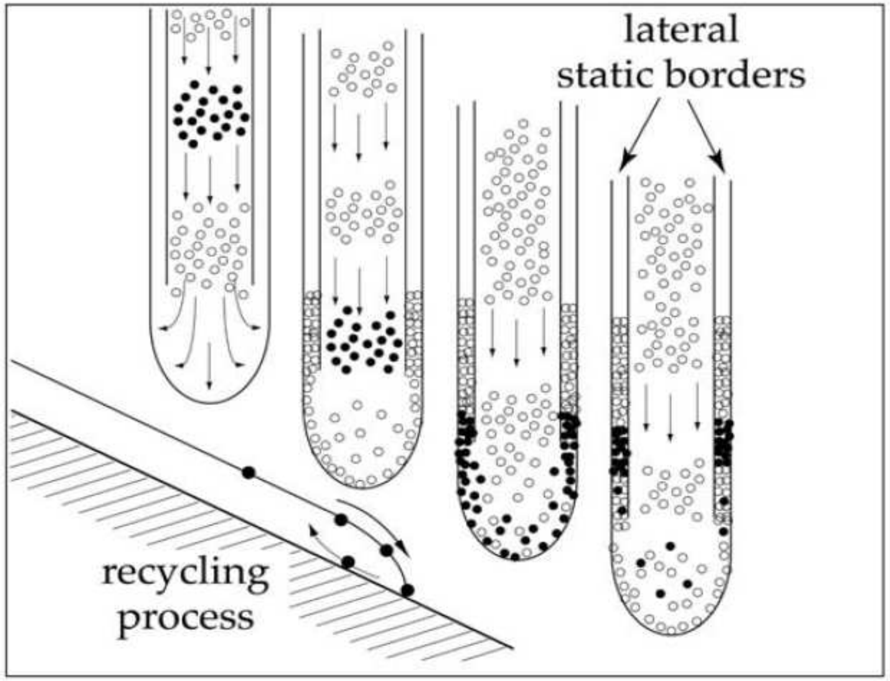
In geophysical flows, the levees show strong **size segregation**

Segregation under flow

The levees form at the front and barely evolve later on

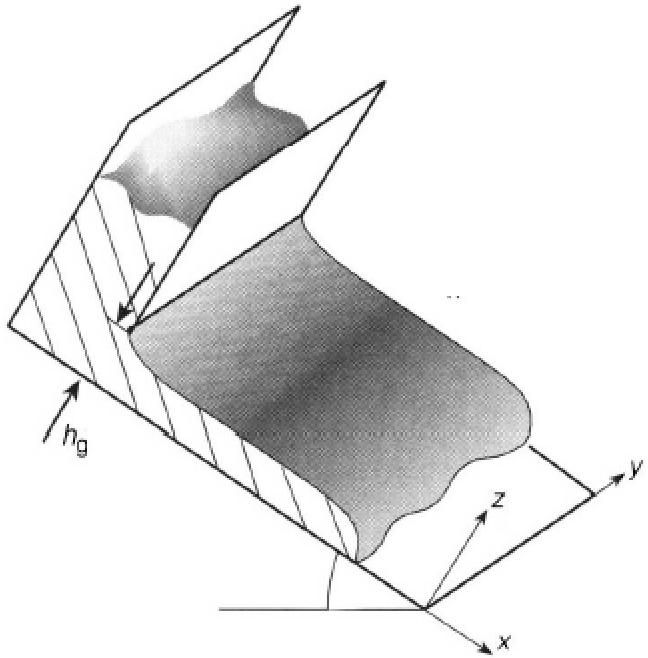
Therefore « recording » the composition of the front

The front is richer in large particles, leading to levees richer in larger particles

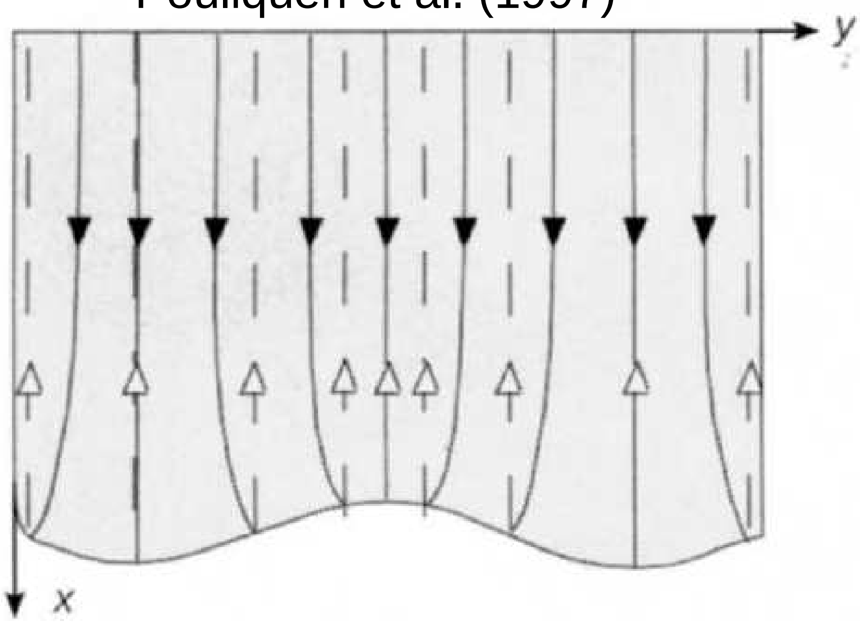


Felix et al. (2004)

Fingering instability



Pouliquen et al. (1997)



At the front, the surface is rich in larger grains

If a dip forms, the larger grains fall into the dip, following the highest slope

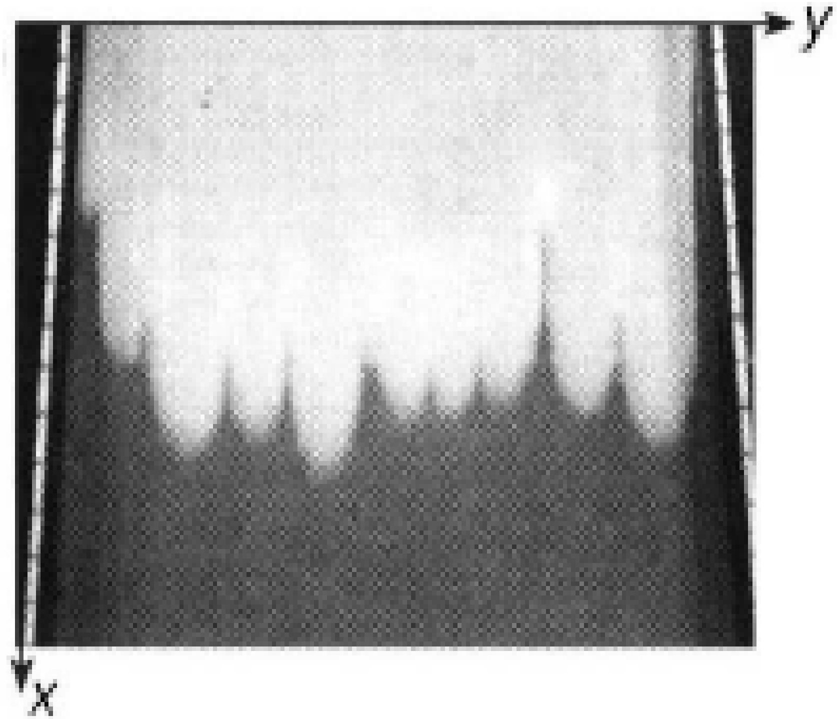
Leading to a higher concentration of large grains on the plane in the dip

Fingering instability

If the larger **grains are more frictional** than the small grains, the **flow slows down** in the dips

the deeper the dips, the stronger the segregation → the instability grows

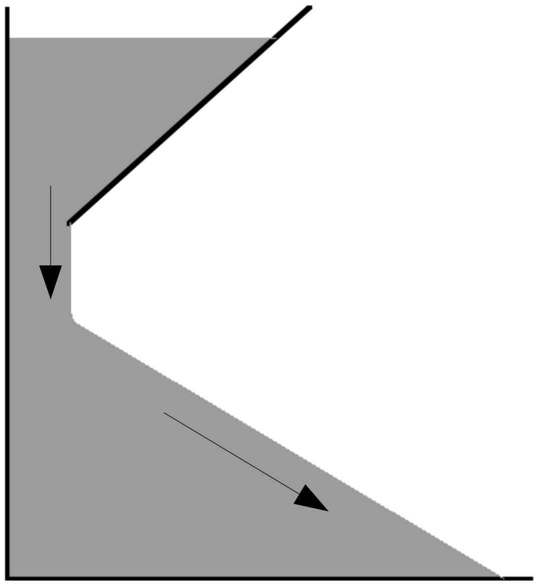
Size segregation causes the fingering instability



Pouliquen et al. (1997)

Segregation under flow

Flow of binary mixtures over a granular pile
Gray (1997), Makse (1998)



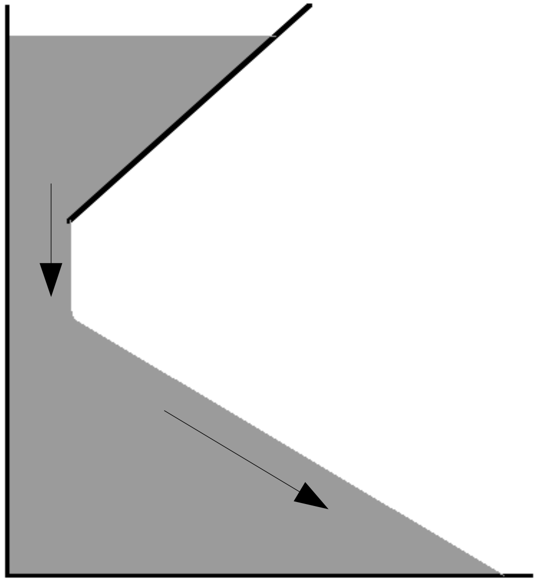
Intermitent regime

A mass a grains flows down the pile, reaches the bottom, and freezes

A freezing front travels upstream until a new avalanche is triggered

Segregation under flow

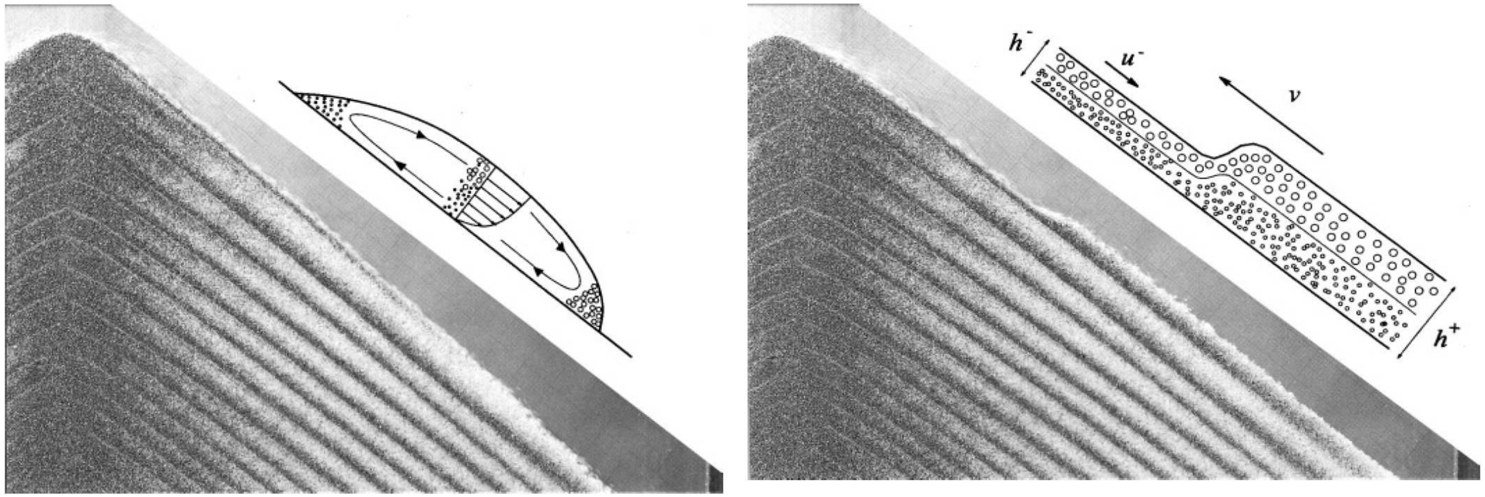
Flow of binary mixtures over a granular pile
Gray (1997), Makse (1998)



The larger grains (white) seperate from the smaller grains (black)

Individual avalanches have an avalanche front rich in large grains
Causing them to travel further than smaller grains

Segregation under flow

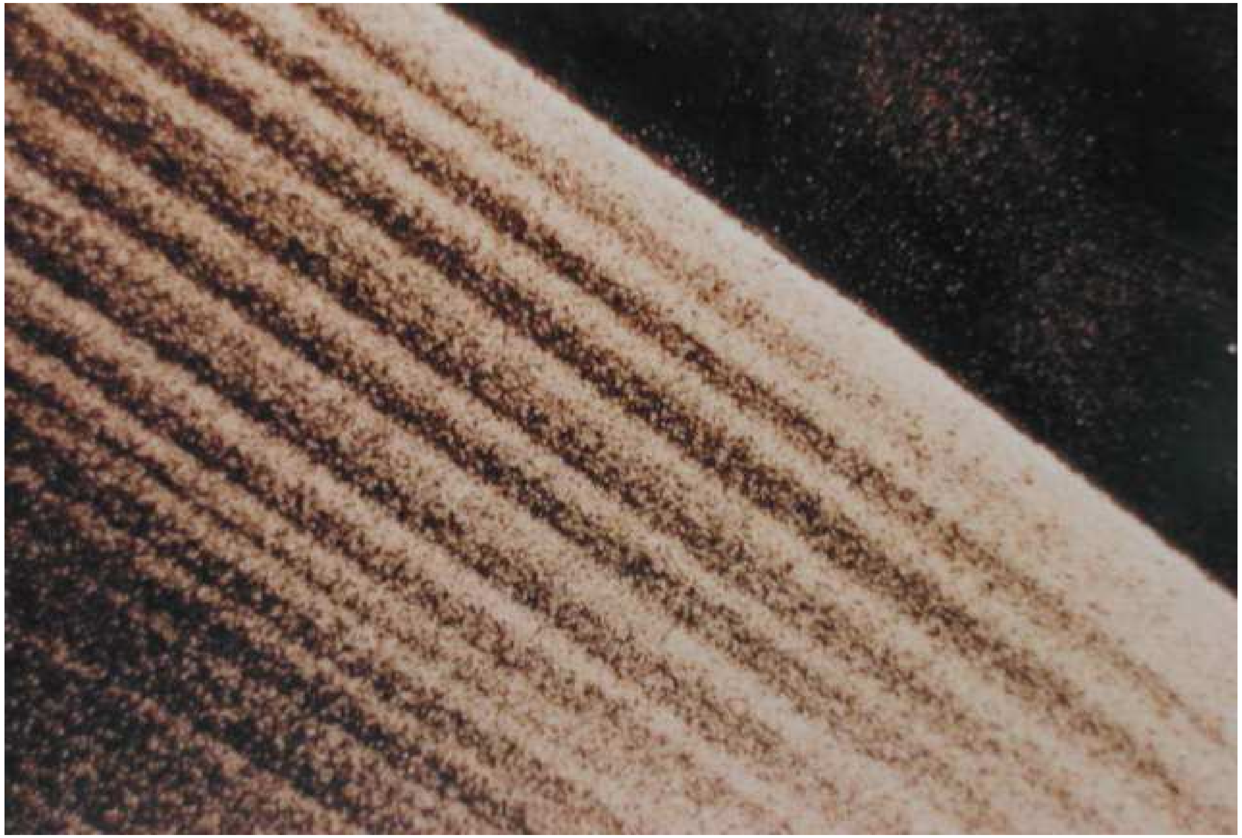


Gray & Hutter (1997)

During individual avalanches,
the smaller grains may sink
to the bottom causing **strata**

Observed on the slip face of sand dunes

Segregation under flow



Makse et al. (1998)

Segregation under flow

Segregation strata in geophysical flows (Felix 2004)

Segregation in a rotating drum

- **Radial segregation**

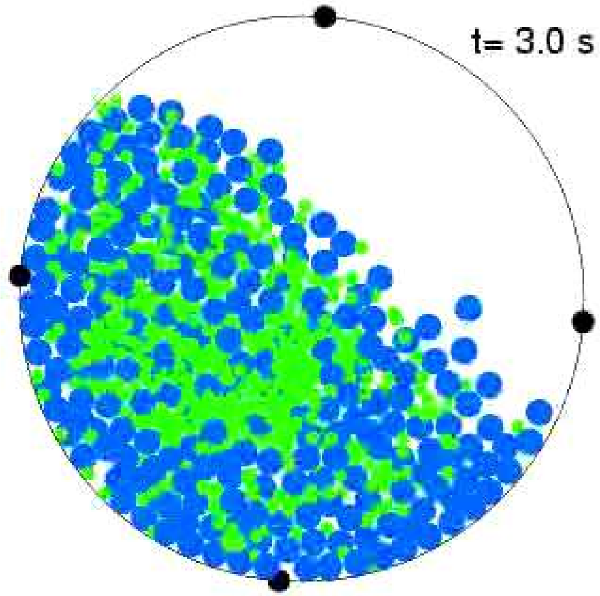
Binary mixture placed in a rotating drum

After a few rotations, the smaller grain gather near the center of the drum

whereas the larger grains concentrated on the outside

→ **radial segregation**

Very robust phenomenon (size ratio, rotation speed, filling fraction...)

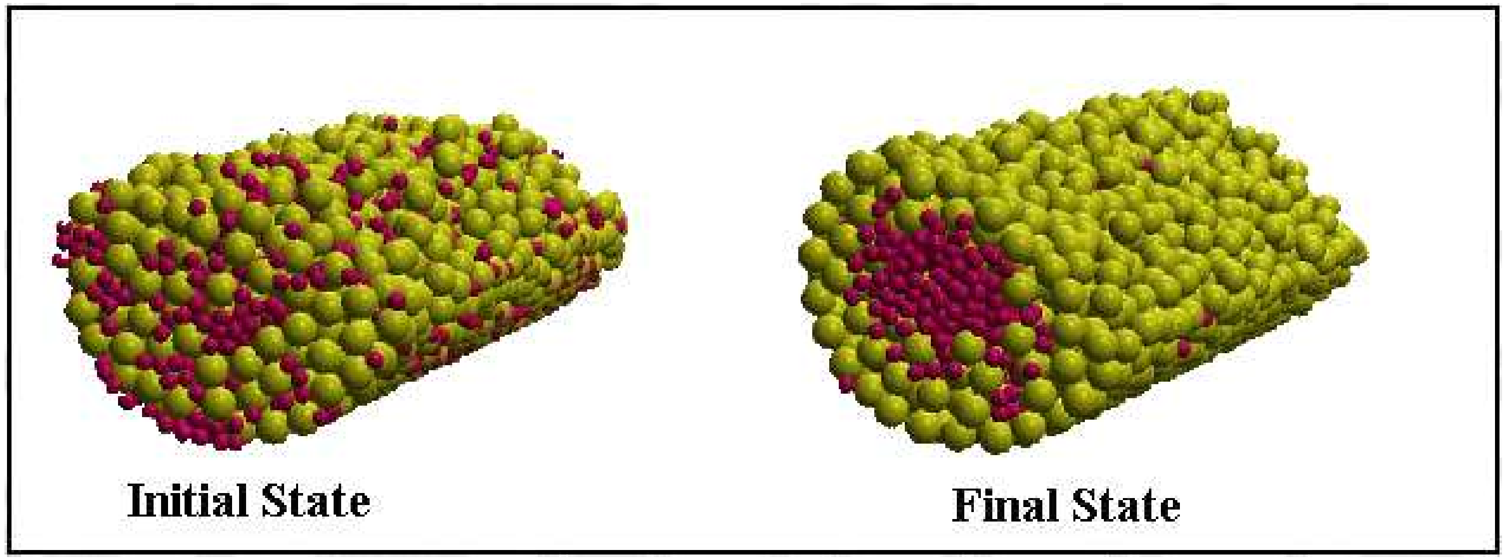


DEM simulations

Segregation in a rotating drum

- **Wider drum :**

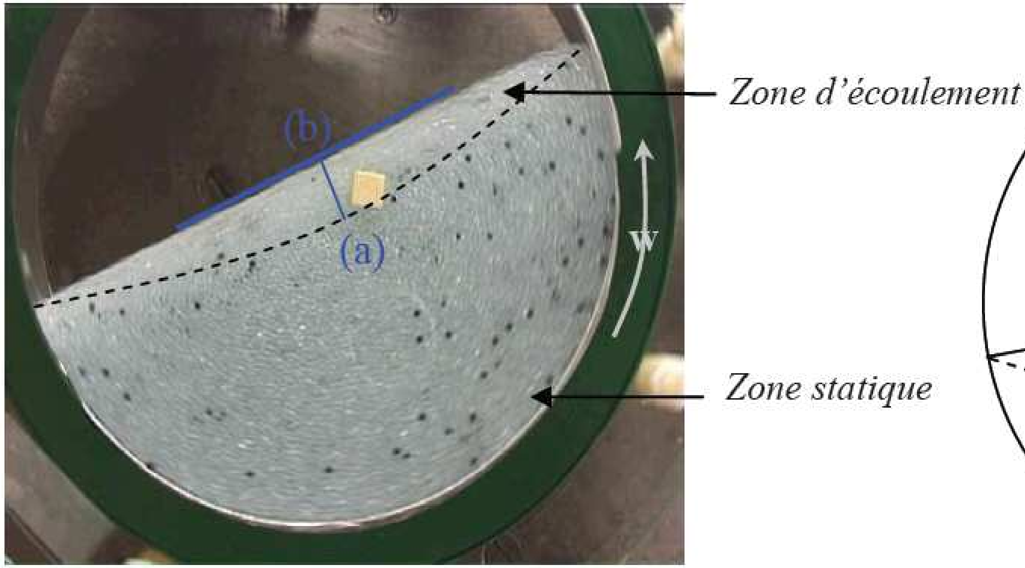
Formation of a radial core
Almost no small particles left at the surface of the flow

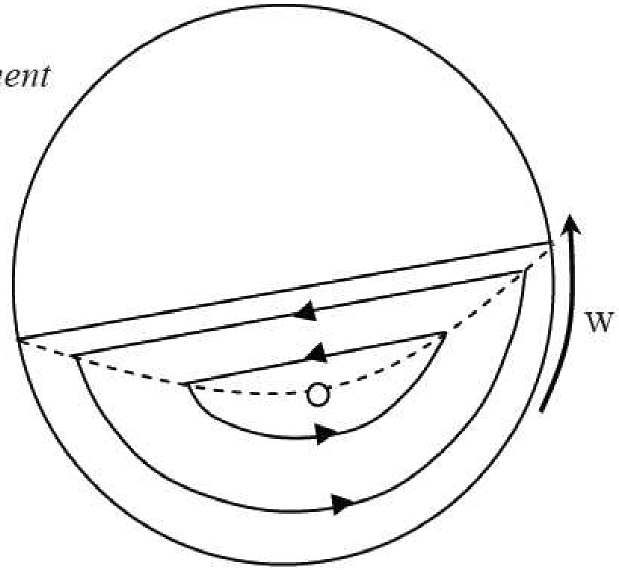


Segregation in a rotating drum

- **Mechanism : dynamic sieving**

In a rotating drum : flowing surface layer, solid-body rotation underneath



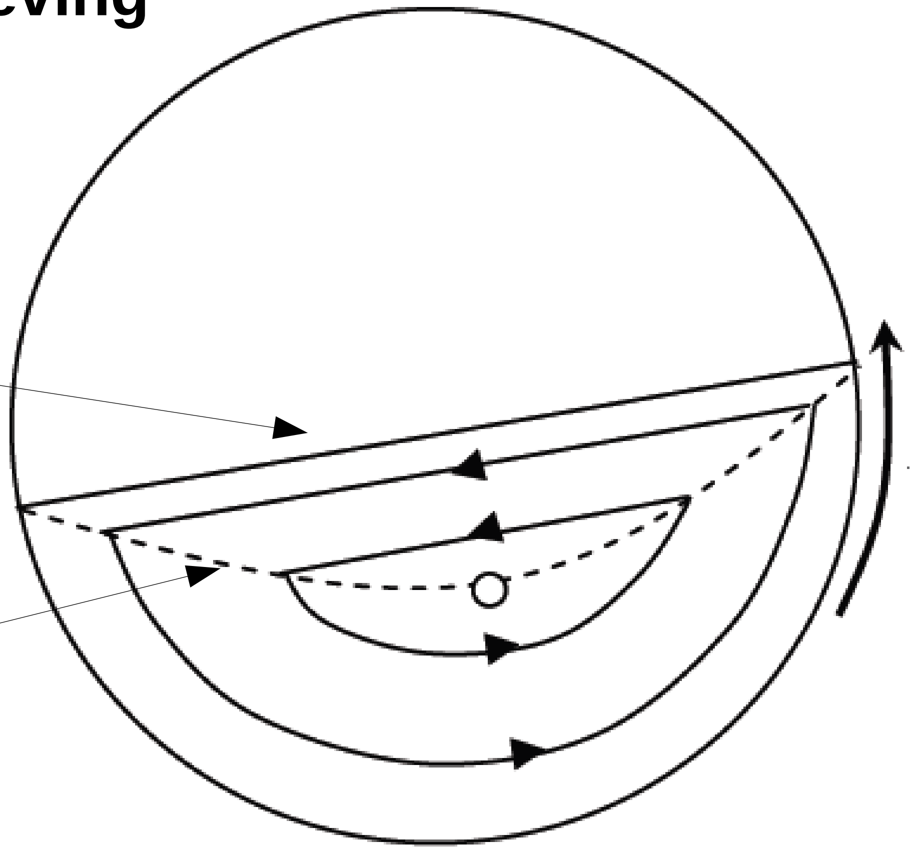


Segregation in a rotating drum

- **Mechanism : dynamic sieving**

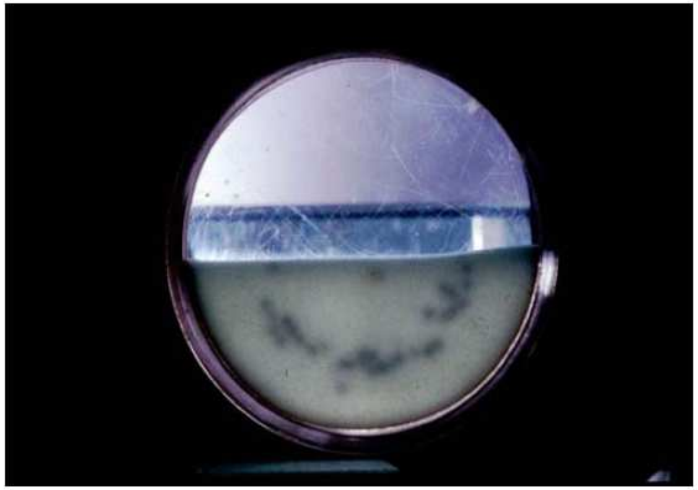
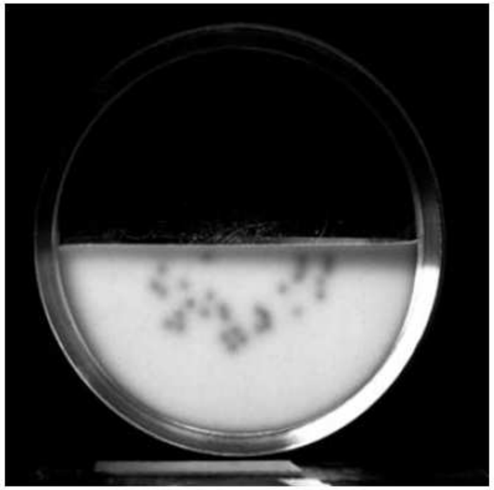
Large grains at the surface travel further

Small grains sink at the bottow and freeze after the center



Segregation under flow

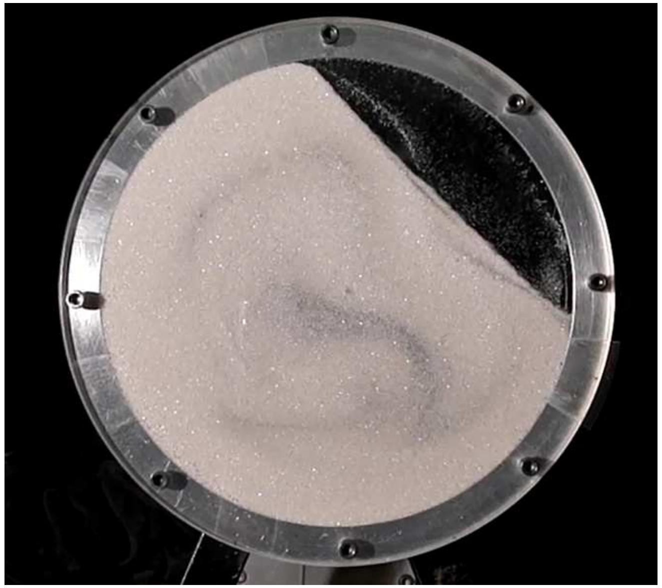
Not so simple...

Thomas (2002) : size segregation can be compensated by **adjusting density** :
if heavy enough, large grain can segregate to the center of the drum
(or to any given radius)

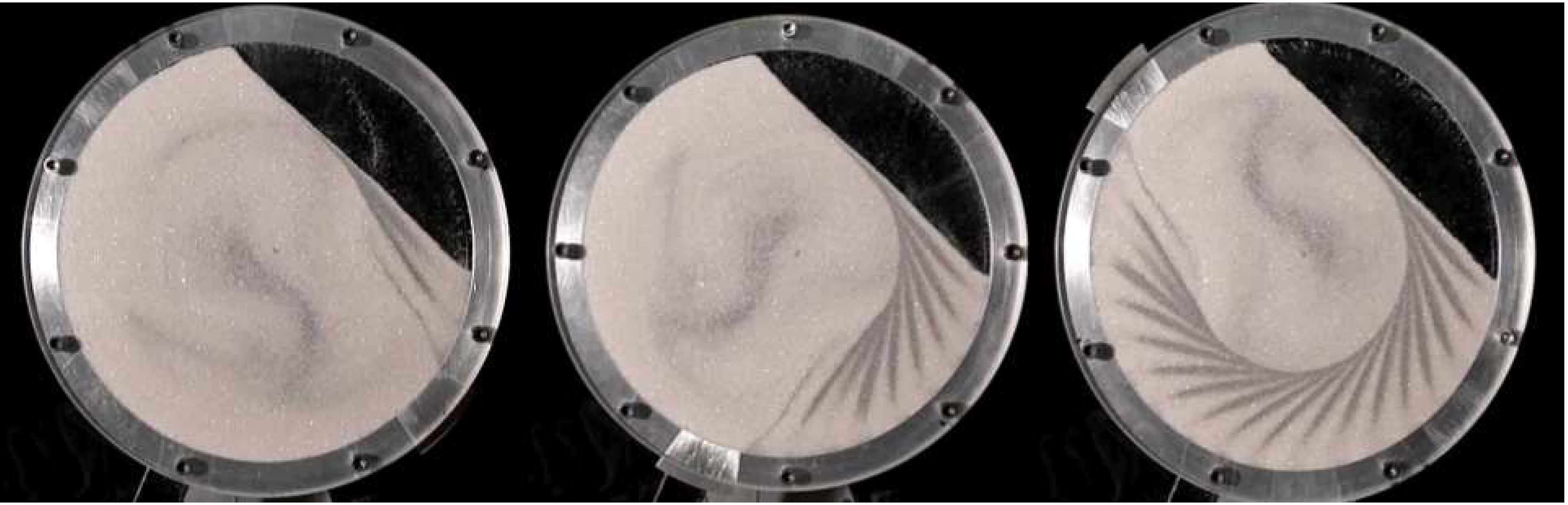
Segregation in a rotating drum

Intermittent regimes : formation of strata



Segregation in a rotating drum

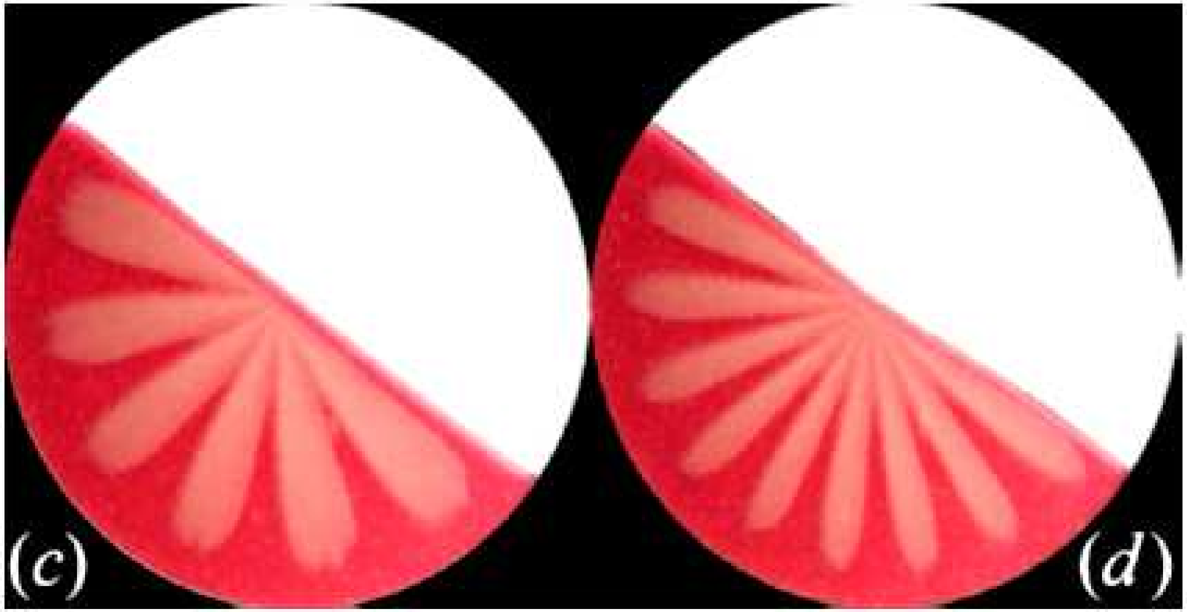
Intermittent regimes : formation of strata



Segregation in a rotating drum

- **Instability of radial core: formation of petals**

For rotation speeds between continuous flow and intermitent avalanching : formation of petals (well defined wave-length)

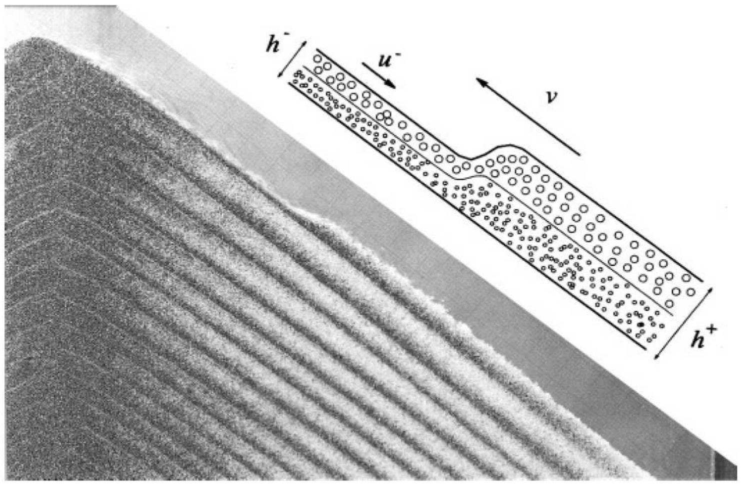


Zurigel (2009)

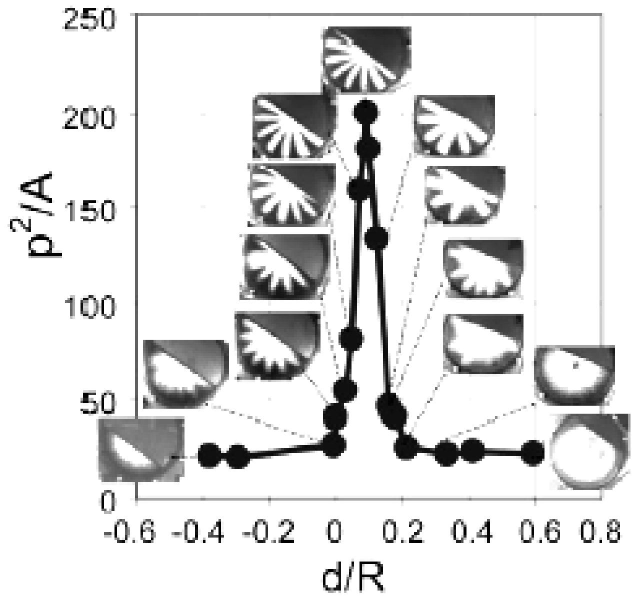
Segregation in a rotating drum

- **Instability of radial core: formation of petals**

If a **freezing front** appears and has time to **travel upstream** to the center of the drum, a layer of large particle may freeze and reach the center

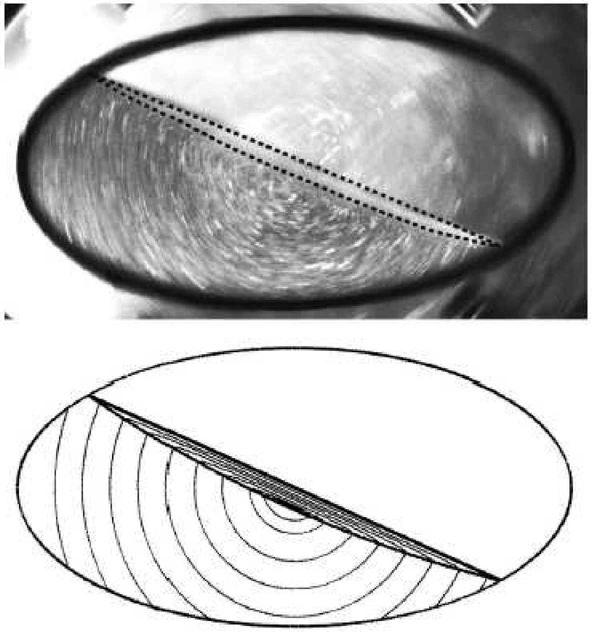


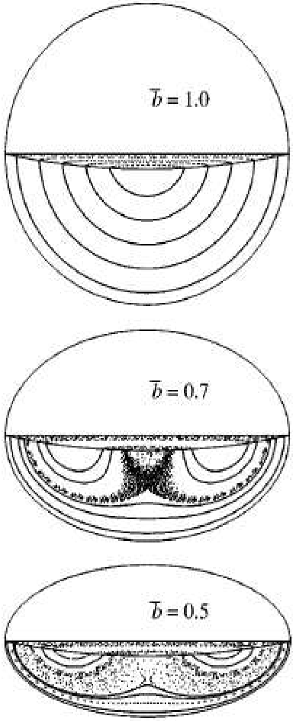
Pattern very sensitive to **rotation speed and filling fraction**

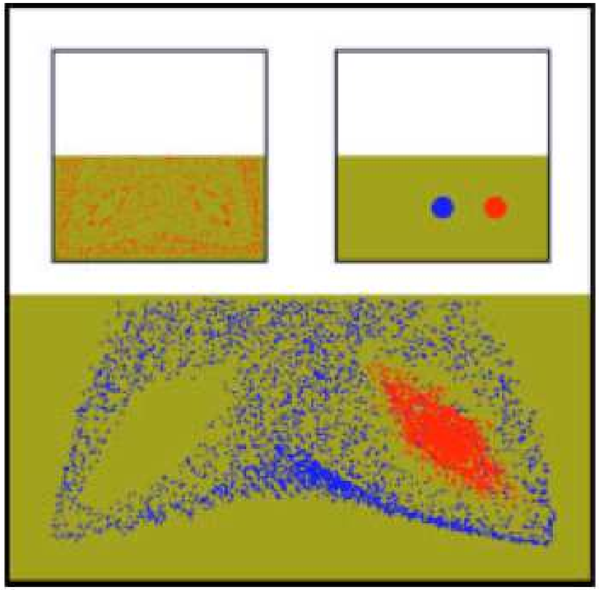


Chaotic mixing

Using non-circular drums : Khakhar et al. (1999)



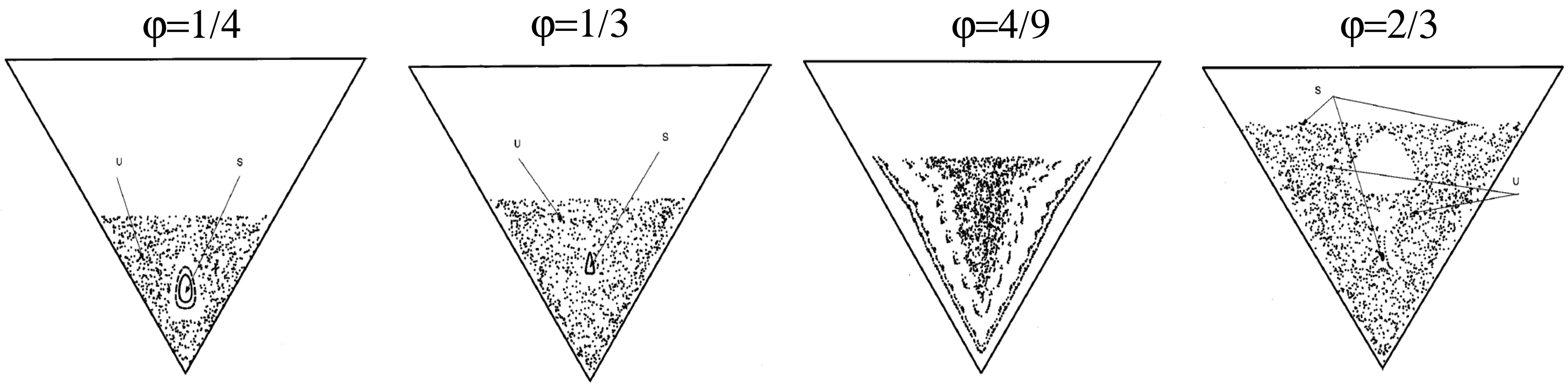




Chaotic mixing

Using triangular drums : Elperin et al. (1999)

Strong dependance on filling fraction



Segregation in a rotating drum

- **Instability of radial core: axial segregation**

Bands of small and large grains apprear
→ **axial segregation**

Slow pattern coarsening

Well-defined wavelength
(which depends on size ratio,drum size, rotation speed, filling ratio...)

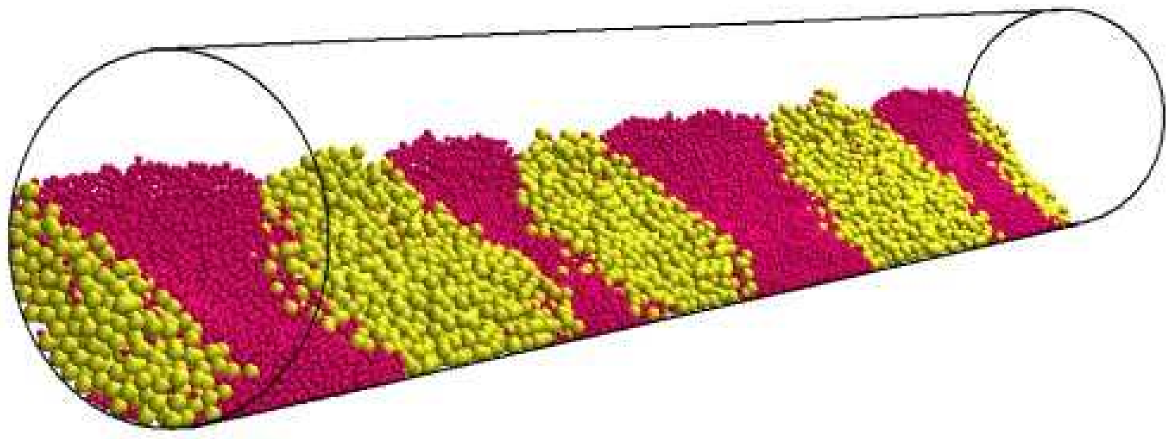
Segregation in a rotating drum

After a few rotations (2 to 5), a radial core forms

The radial core becomes unstable : grows and shrinks, and after a few tens of rotations reaches the surface

→ **axial segregation** (or banding)

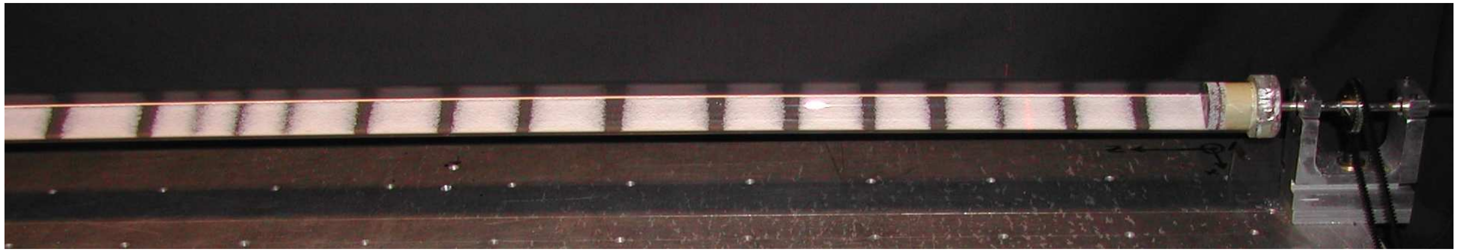
Mechanism remains unclear

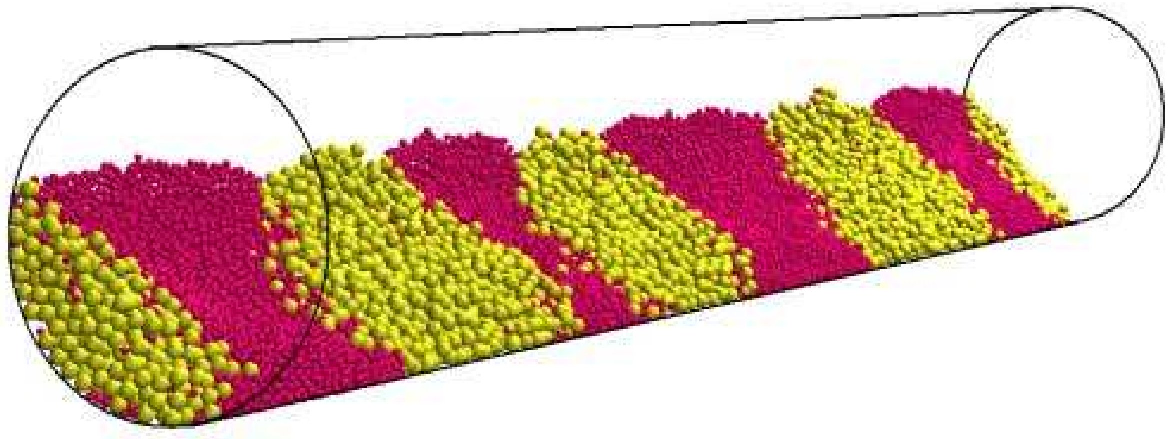


Segregation in a rotating drum

Steady state ?
Complete axial segregation is not steady

If initialy state is fully segregated mixing and banding will occur

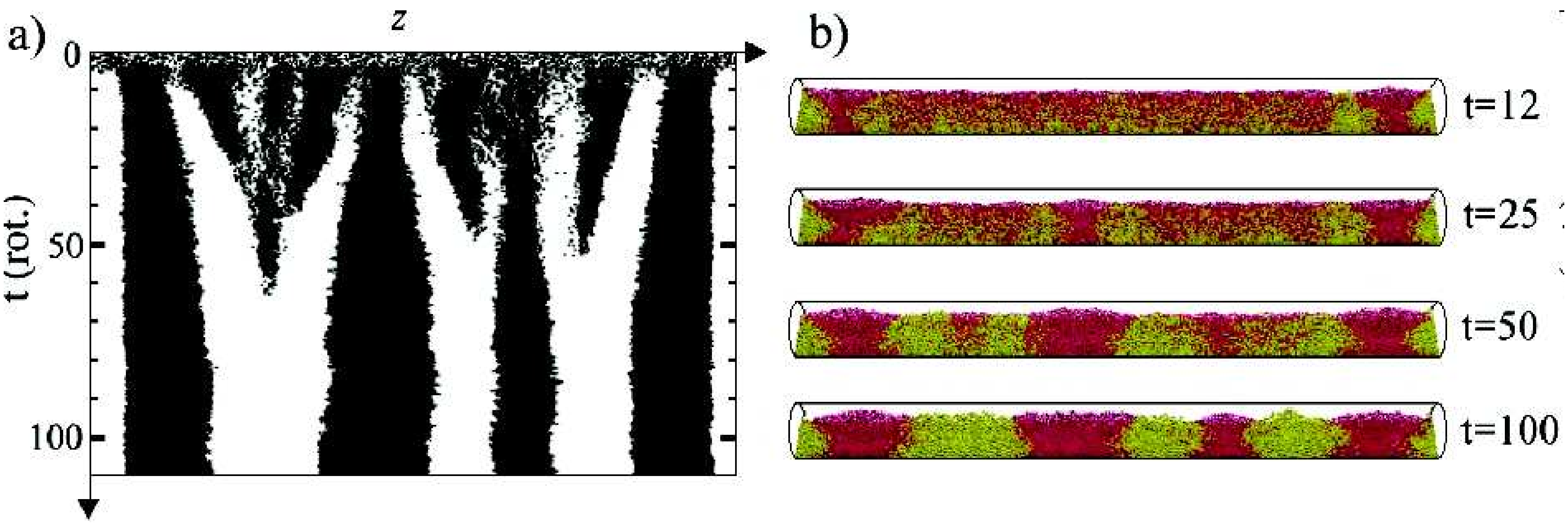




Segregation in a rotating drum

- **Axial segregation : a complex dynamics**

Bands can merge or appear

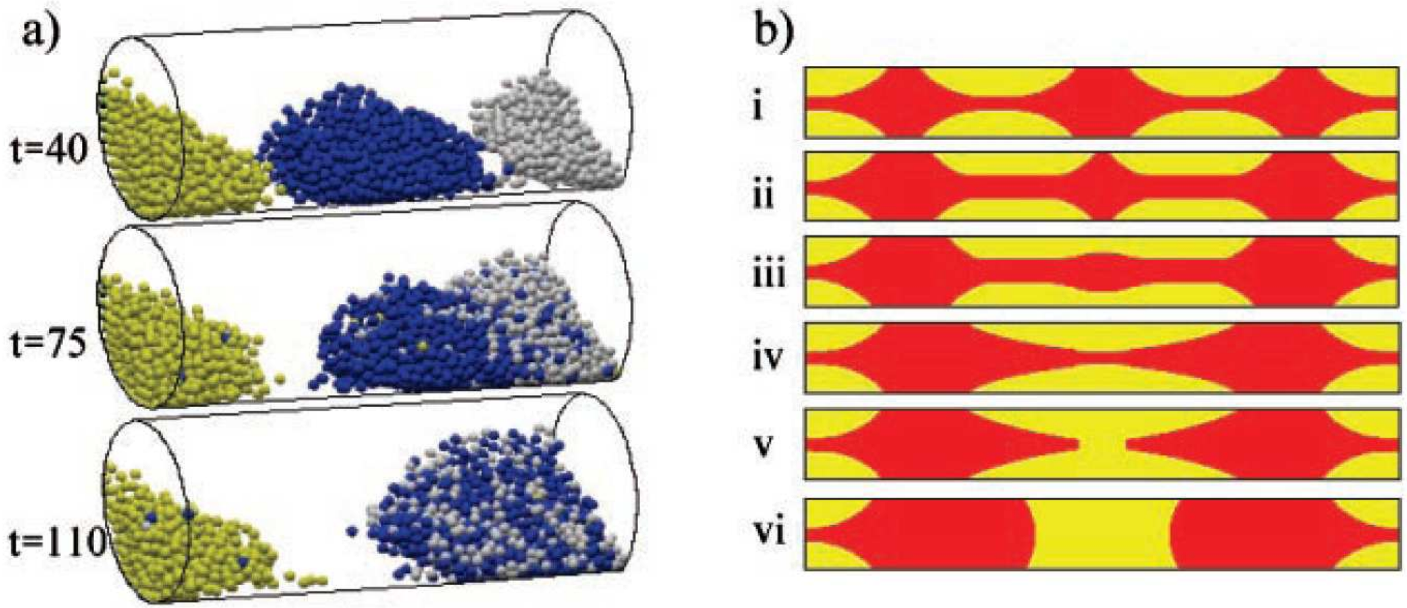


Taberlet (2004)

Segregation in a rotating drum

- **Axial segregation : a complex dynamics**

Bands can merge or appear

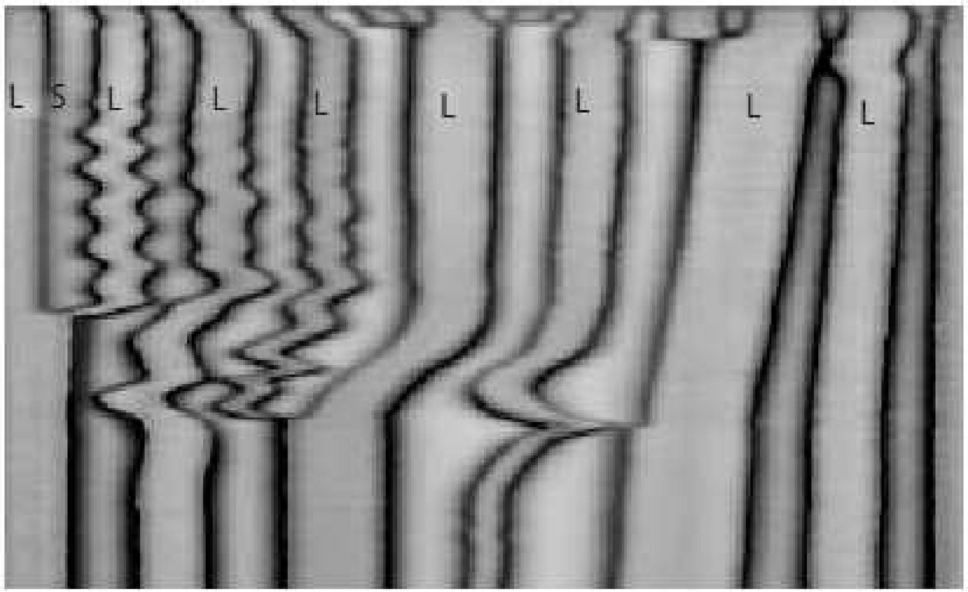


Taberlet (2004)

Segregation in a rotating drum

- **Axial segregation : a complex dynamics**

Bands can oscillate

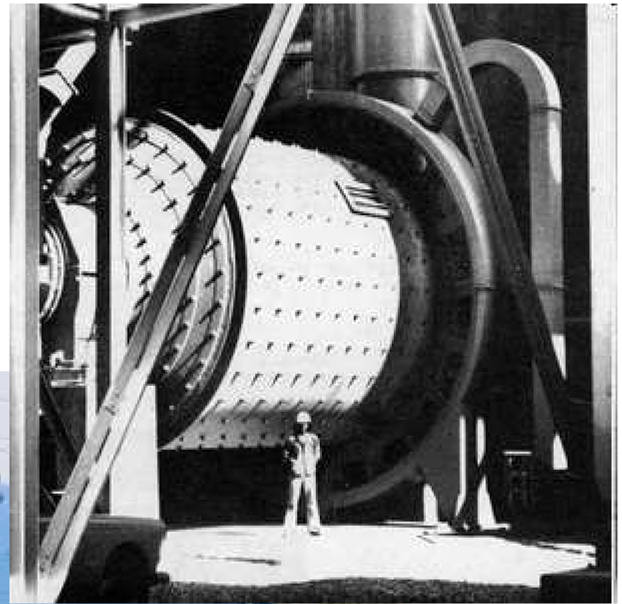


Newey et al. (2004)

Axial segregation

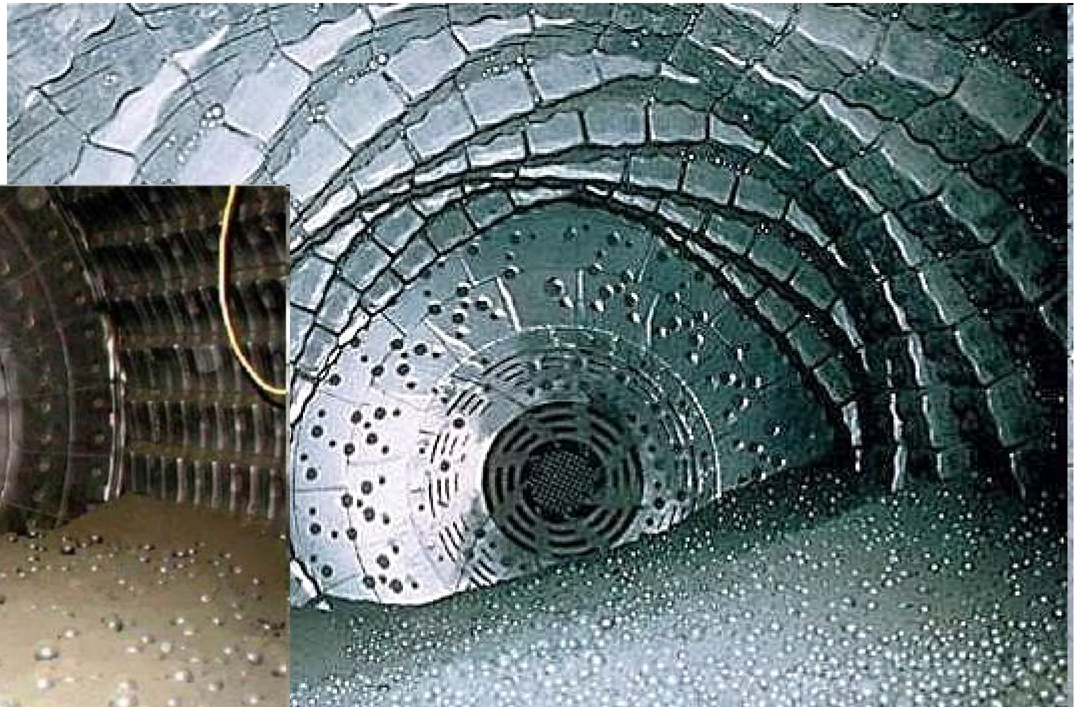
Industrial crusher for concrete production

rotating drum with steel balls
used for crushing limestone



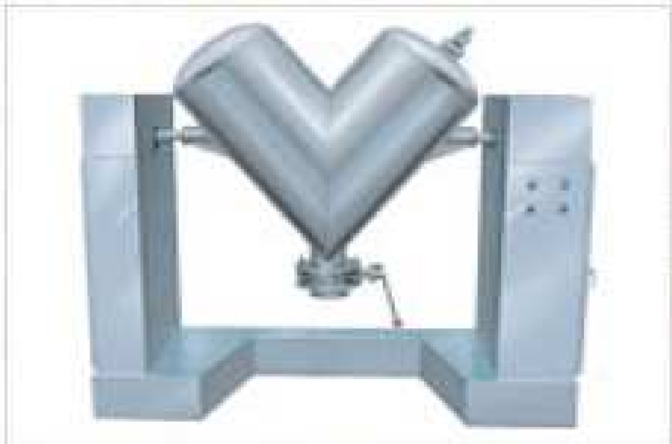
Axial segregation

Industrial crusher:
rotating drum with steel balls



Segregation in a rotating drum

- **Industrial mixers**



Rotating blenders