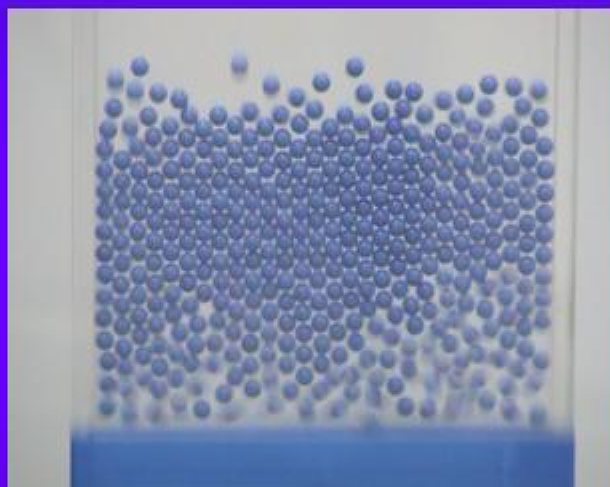
Leidenfrost Effect and Coarsening in a Granular Gas

Peter Eshuis, August 29th 2003



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Outline

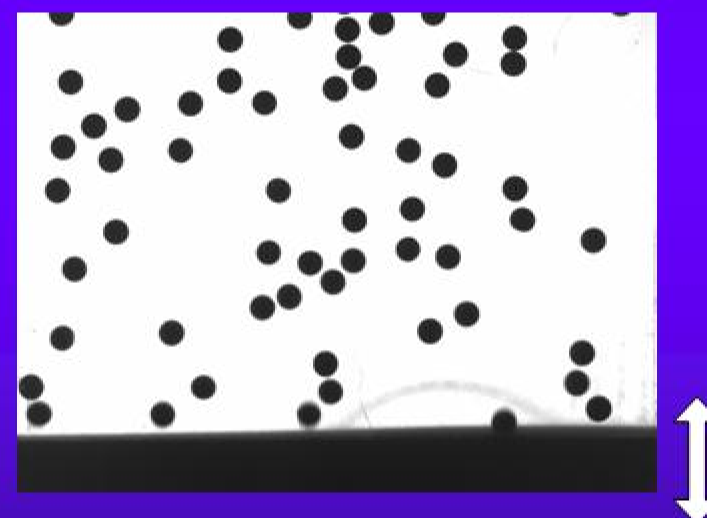
- What is Granular Matter?
- Granular Leidenfrost Effect:
  – Experiments vs. Theory
- Coarsening in a Granular Gas:
  –Experiments vs. Theory

What is Granular Matter?

It is all around us: sand, salt, sugar, etc…

solid

liquid



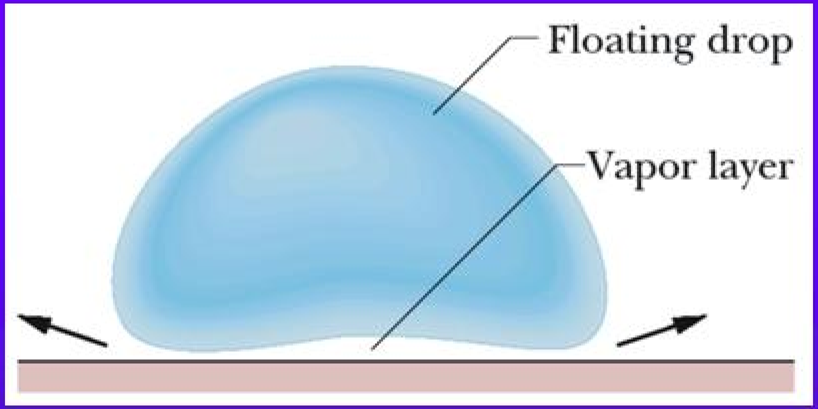
gas

What is Granular Matter?

- Fundamental importance
- Many industries involved in Granular Matter

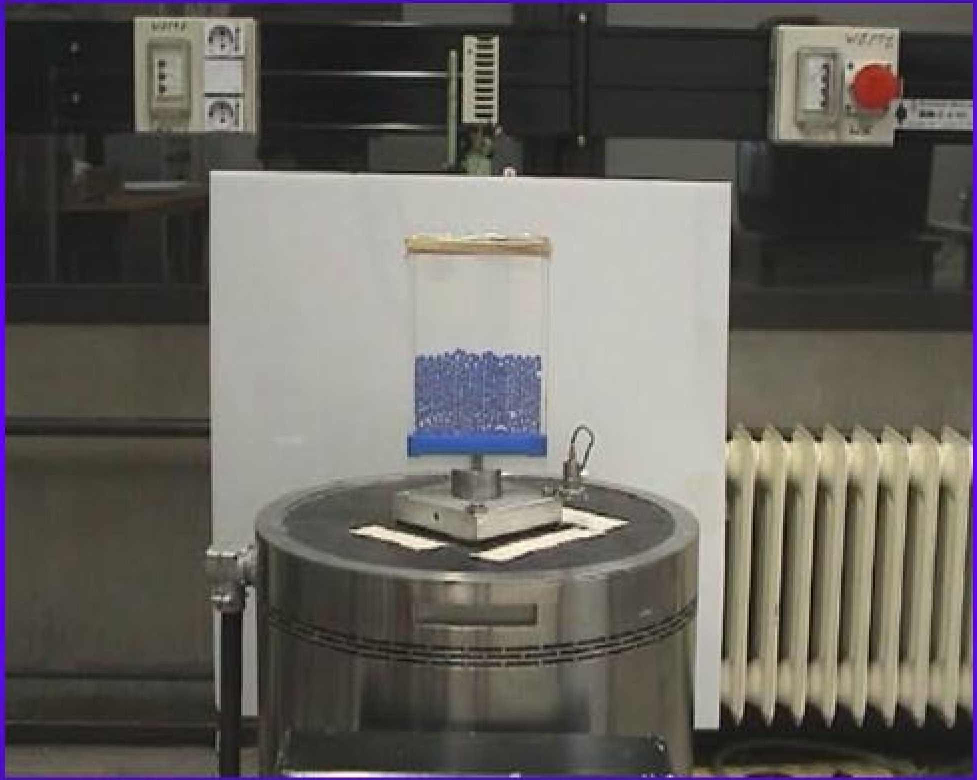
Original Leidenfrost effect

Johann Gottlob Leidenfrost, 1756



Drop of water on a hot plate (≈220° C)

Granular Leidenfrost effect



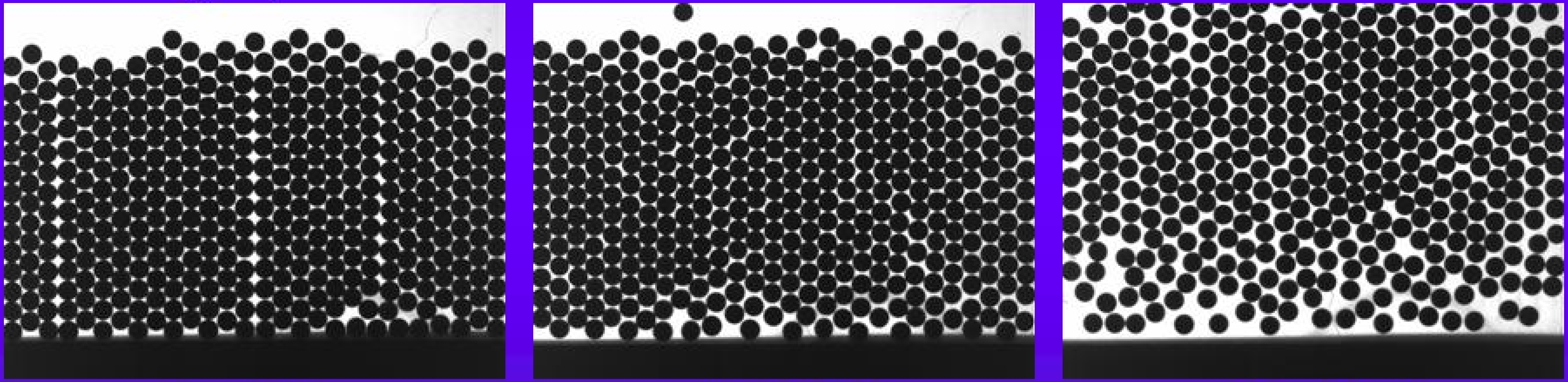
Quasi-2D container: 10x0.45x14cm

Glass beads: d=4mm, ρ=2.5g/cm^3, **$e<1$**

Experiments: shaking strength

$$\Gamma = \frac{a(2\pi f)^2}{g}$$

F=16 layers, f=80Hz

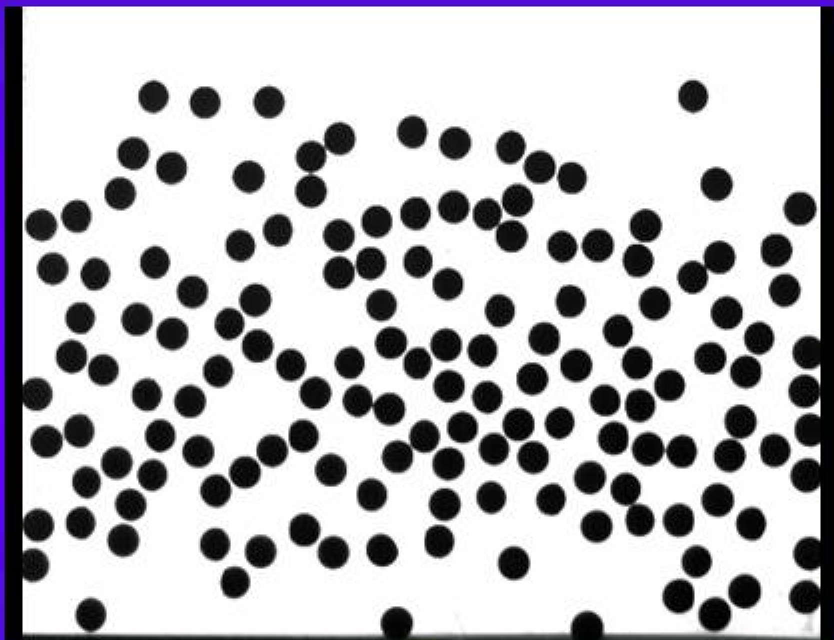


Γ=7.7 Γ=25.8 Γ=51.5

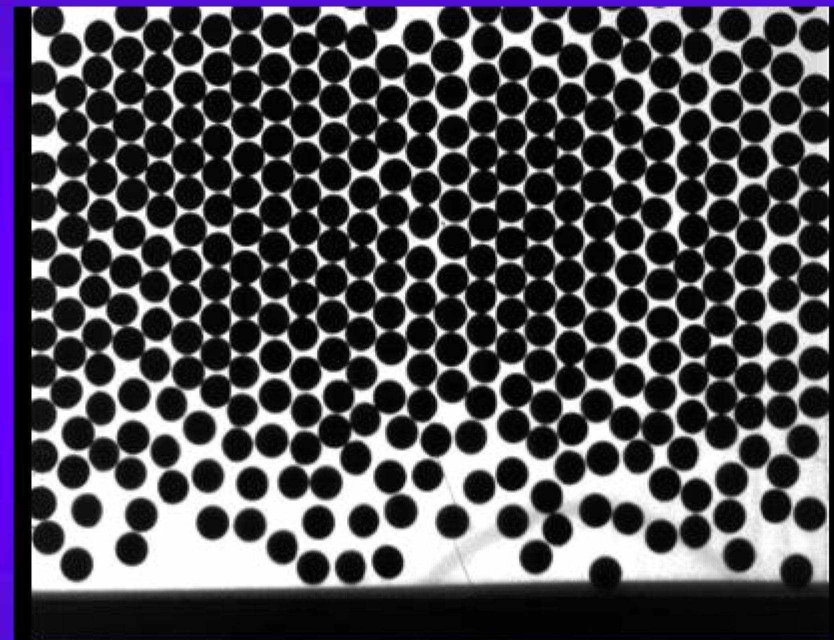
Density Inversion for Γ_c>25 (for F=16)

Experiments: number of layers

Γ=51.5 @ 1000 fps



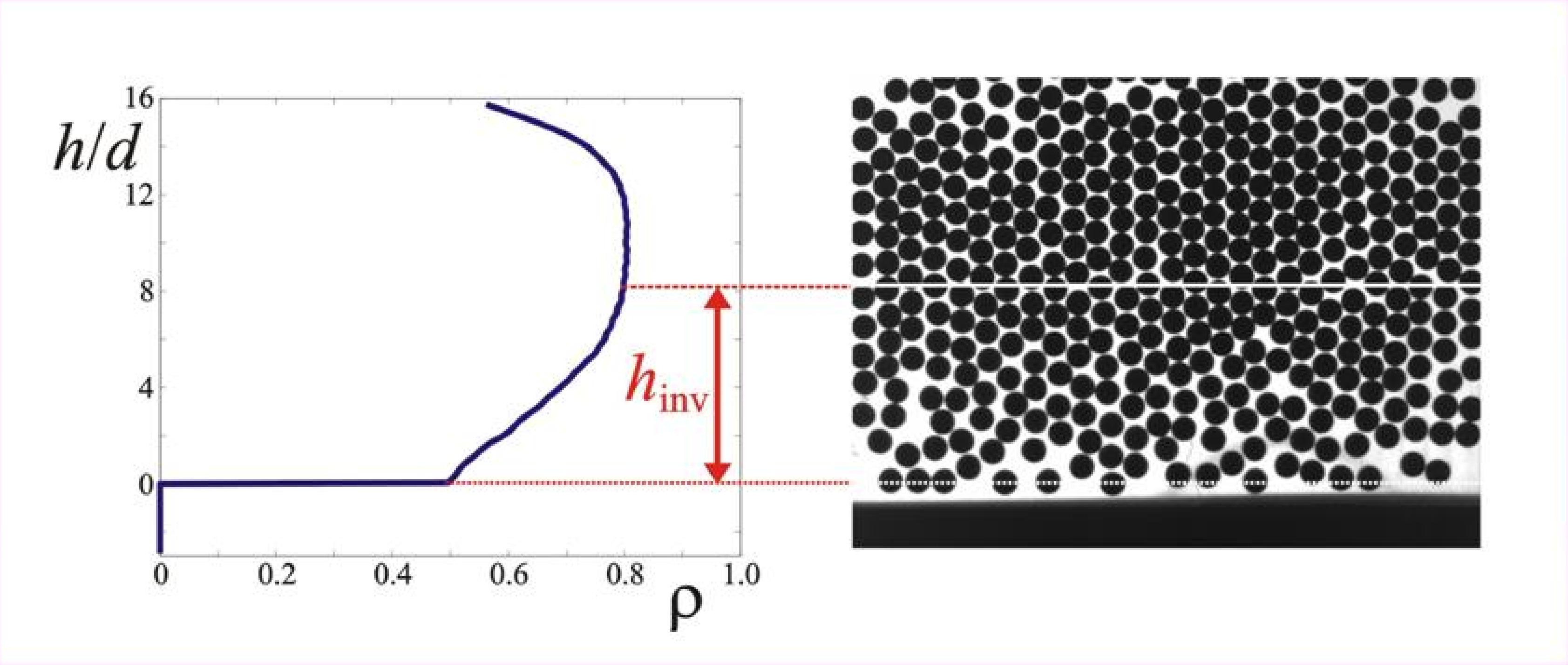
F=6 layers



F=16 layers

Density Inversion only for F≥10

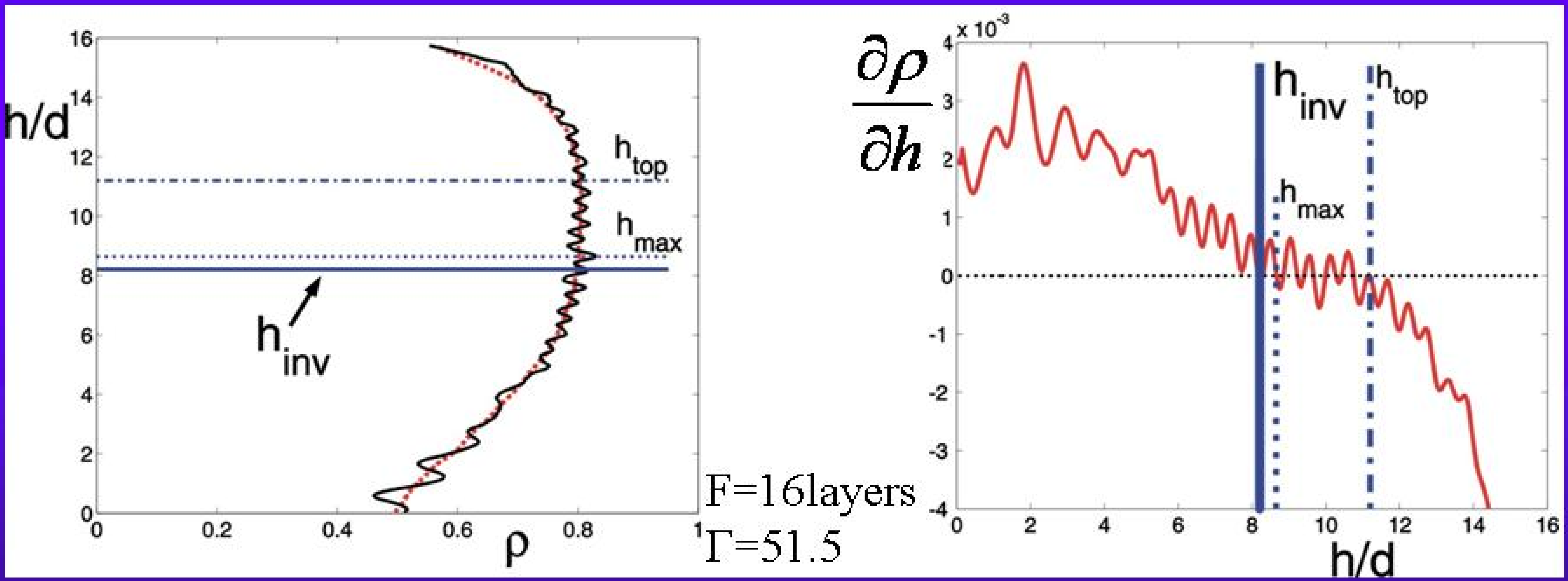
Experiments: inversion height



(F=16 layers, Γ=51.5)

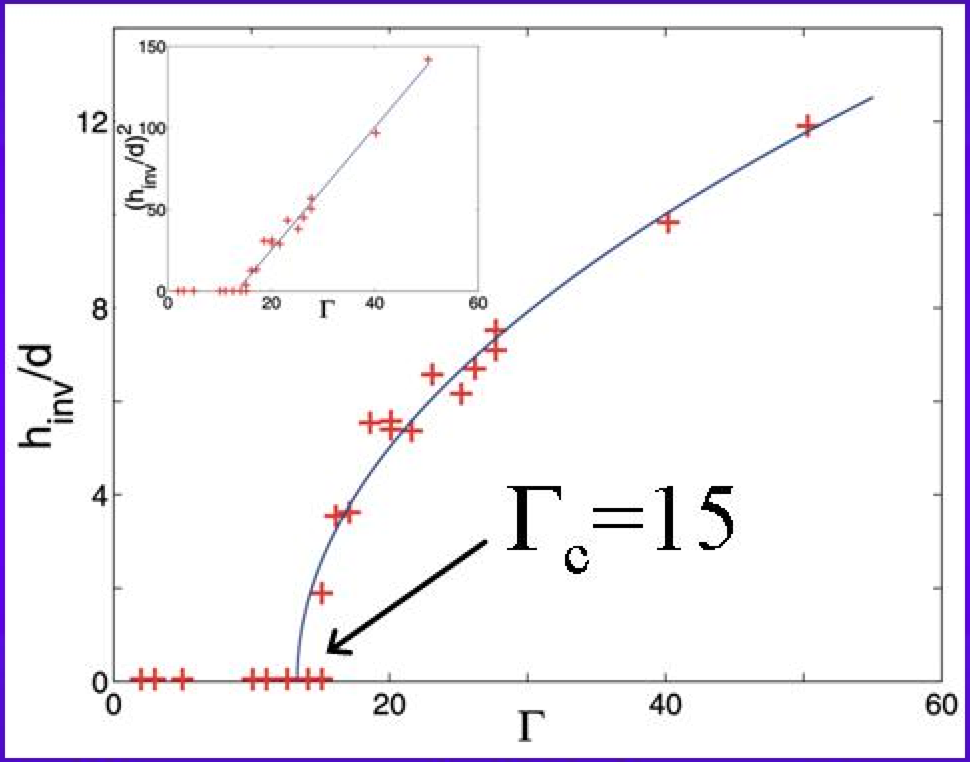
Experiments: inversion height

first zero derivative → h_{inv}



Averaged over 300 experimental pictures

Experiments: phase transition for h_{inv}



(F=10 layers constant, f=50Hz, a varied)

$$h_{inv} \propto (\Gamma - \Gamma_c)^{1/2}$$

2nd order, continuous phase transition

Theory: hydrodynamic model

Equation of state: $$p = nT\frac{n_c + n}{n_c - n}$$

Force balance: $$\frac{dp}{dz} = -mgn$$

Balance between heat flux and dissipation:

$$\frac{d}{dz}\left\{\kappa T^{1/2}\frac{dT}{dz}\right\} = \lambda n^2 T^{3/2}$$

Theory: heat balance

$$\frac{d}{dz}\left\{\kappa T^{1/2}\frac{dT}{dz}\right\} = \lambda n^2 T^{3/2}$$

Thermal conductivity: $\kappa T^{1/2} \propto$ mean particle velocity $\langle v \rangle$

-Energy loss per collision: $(1-e^2)T$

-Total number of collisions: $n^2 v \propto n^2 T^{1/2}$

For 2D particles of diameter d:

$$\kappa = \frac{2m}{\sqrt{\pi}\, d} \qquad \lambda = 2\sqrt{\pi}\, m d (1-e^2)$$

Theory: boundary conditions

-Constant Granular temperature at bottom:

$$T_0 = m(af)^2$$

-Zero heat flux at the top:

$$\left.\frac{dT}{dz}\right|_{z\to\infty} = 0$$

-Conservation of total number of particles:

$$\int_0^\infty n(z)dz = \frac{N}{L_x} = Fdn_c$$

Theory: dimensionless form

Two equations ($\tilde{z} = z/d, \quad \tilde{n} = n/n_c, \quad \tilde{T} = T/T_0$):

$$\frac{d}{d\tilde{z}}\left\{\tilde{n}\tilde{T}\,\frac{1+\tilde{n}}{1-\tilde{n}}\right\} = -\frac{1}{\Gamma A}\tilde{n}, \quad \rightarrow \quad S = \Gamma A$$

$$\frac{d\tilde{T}^{3/2}}{d\tilde{z}} = 2\pi\varepsilon\tilde{n}^2\tilde{T}^{3/2}$$

Boundary conditions:

$$\tilde{T}_0 = 1 \qquad \left.\frac{d\tilde{T}}{d\tilde{z}}\right|_{\tilde{z}\to\infty} = 0 \qquad \int_0^\infty \tilde{n}(\tilde{z})\,d\tilde{z} = F$$

Theory: control parameters

Shaking strength: $\Gamma = \frac{a(2\pi f)^2}{g}$

Shaking amplitude: $A = \frac{a}{d}$

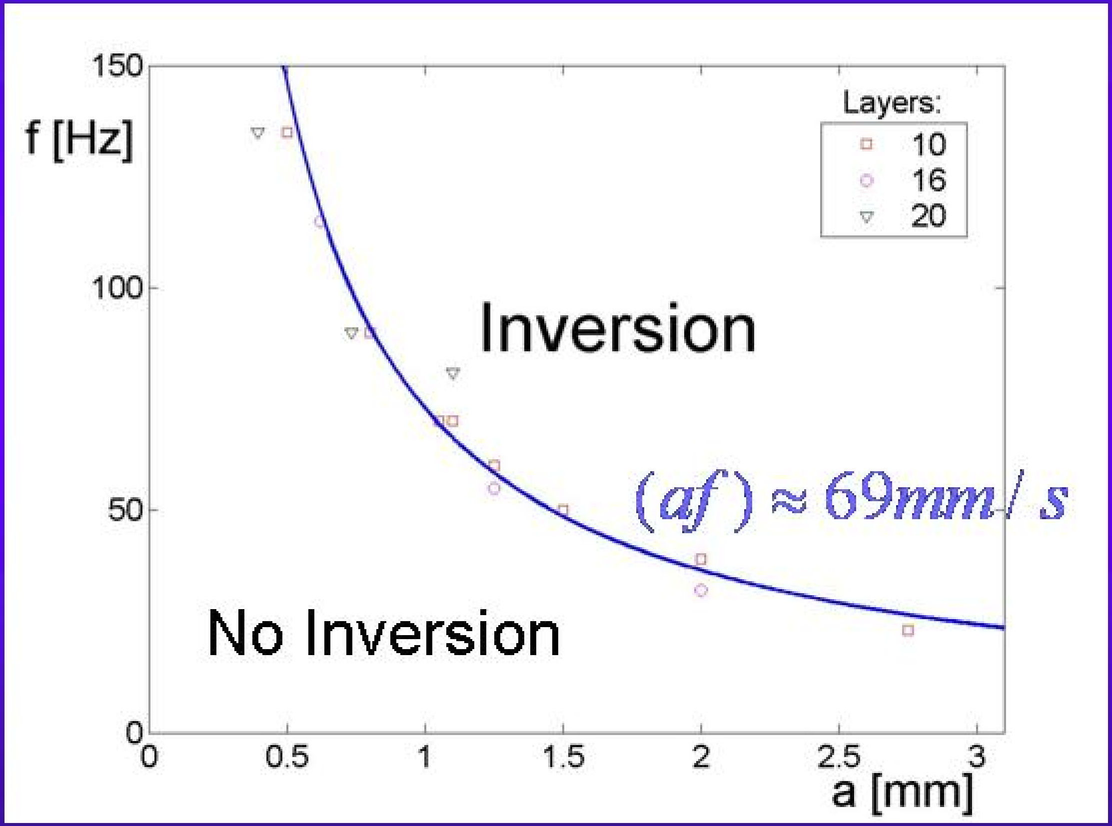
$\left.\begin{matrix}\Gamma \\ A\end{matrix}\right\} S = \Gamma A$

Filling height: $F = \frac{h}{d}$

Inelasticity of particles: $\varepsilon = (1 - e^2)$

Experimental evidence

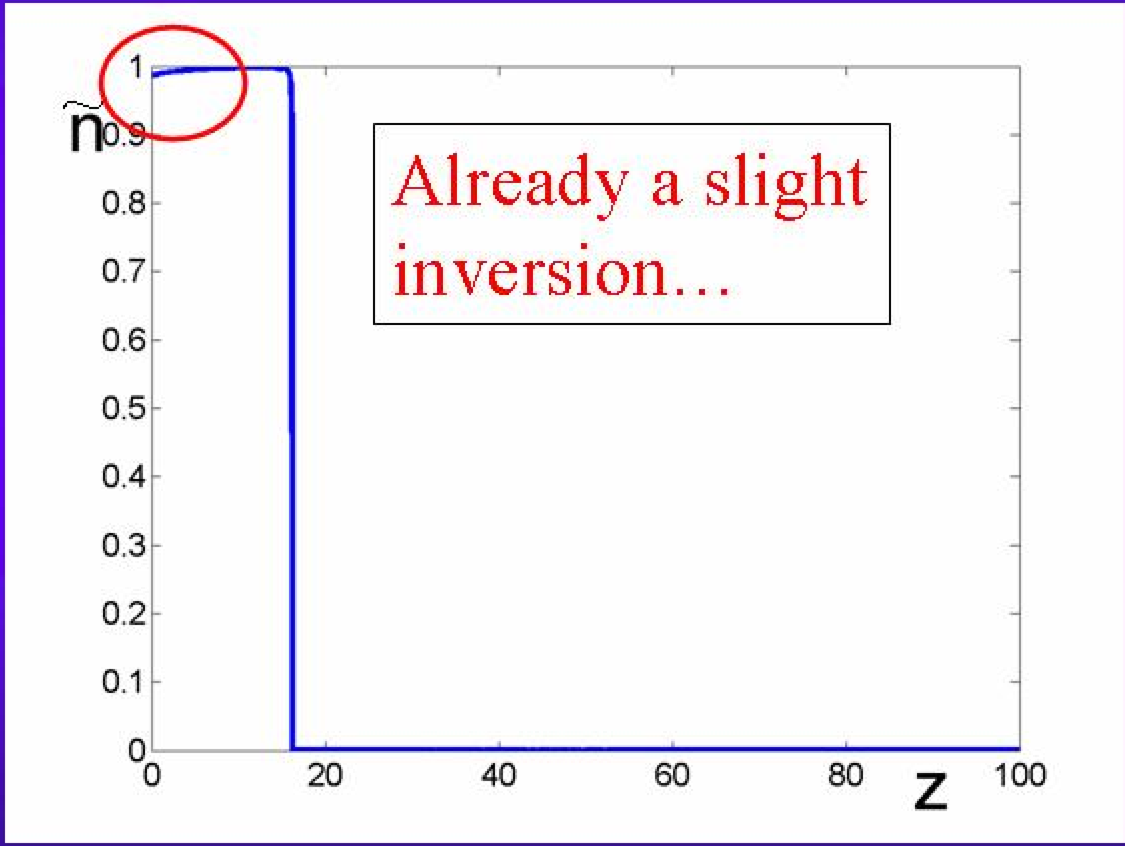
Critical values of a and f at phase transition:



Transition at constant $S \propto (af)^2$

Theory: density profiles

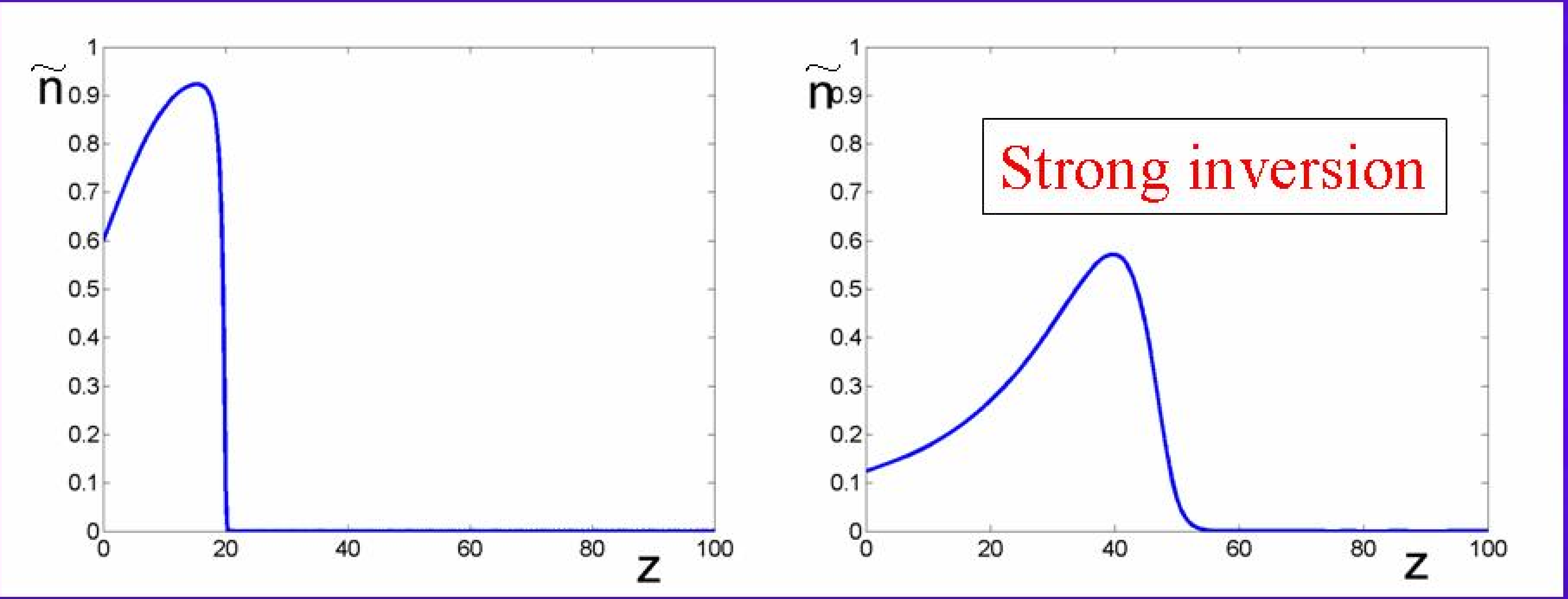
$(\tilde{n} = n / n_c)$



F=16 layers,
Mild shaking:
S=ΓA=0.11

Theory: density profiles

F=16 layers

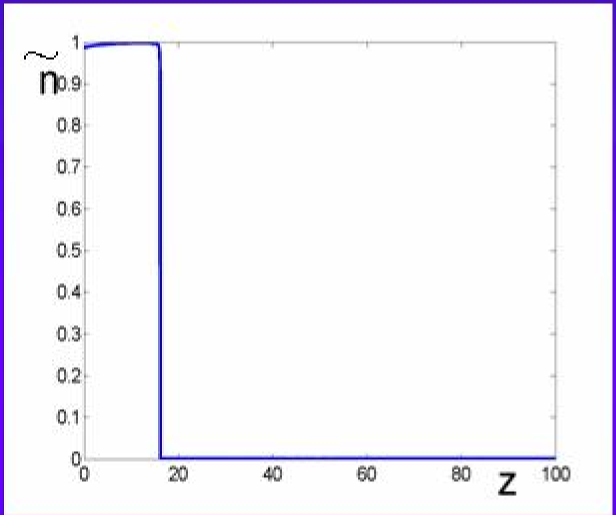


Moderate shaking:
S=ΓA=6.7

Vigorous shaking:
S=ΓA=10

Exp vs. Theory: phase transition

Theoretical model shows
- Density Inversion for all shaking strengths (for F>3)



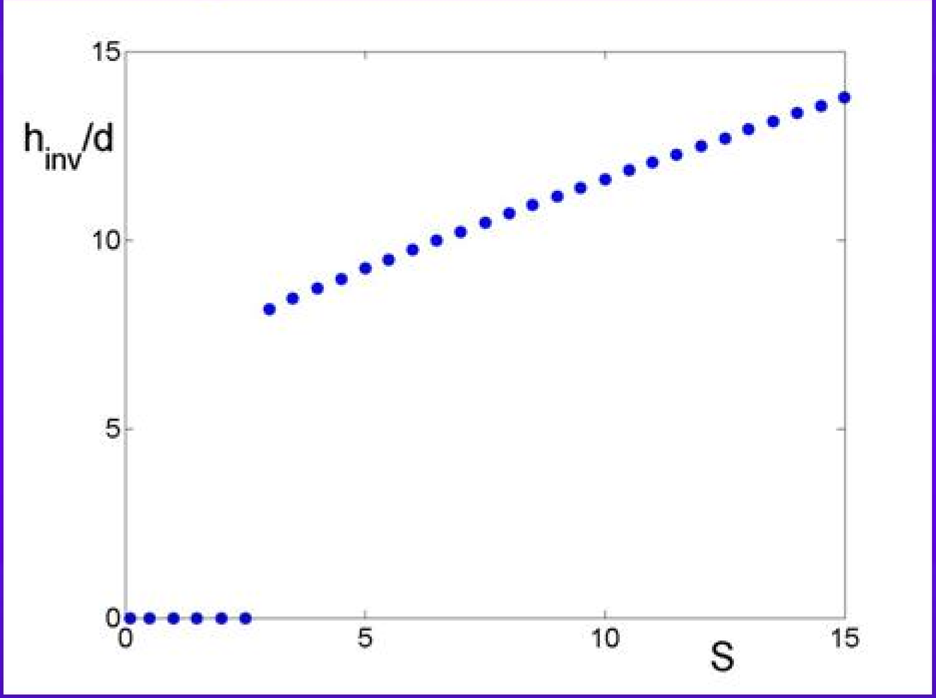
F=16 layers
Mild shaking:
$S=\Gamma A=0.11$

↓

Disqualify all inversions until $\tilde{n}_0 < \tilde{n}_{thresh} = 0.68$

Exp vs. Theory: phase transition

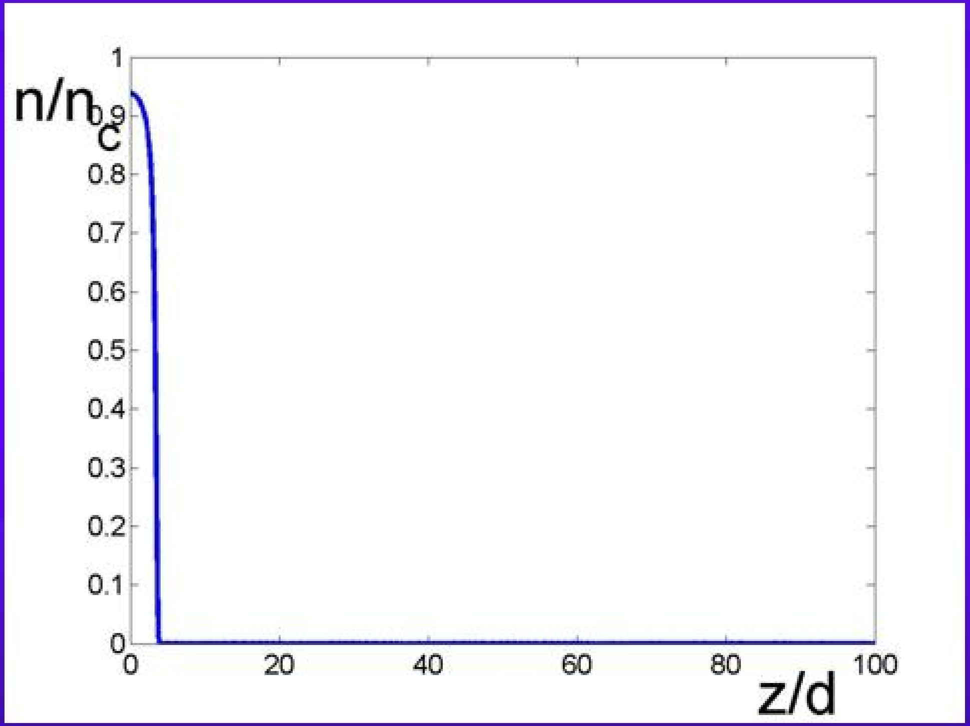
F=10 layers



No 2nd order phase transition

Exp vs. Theory: phase transition

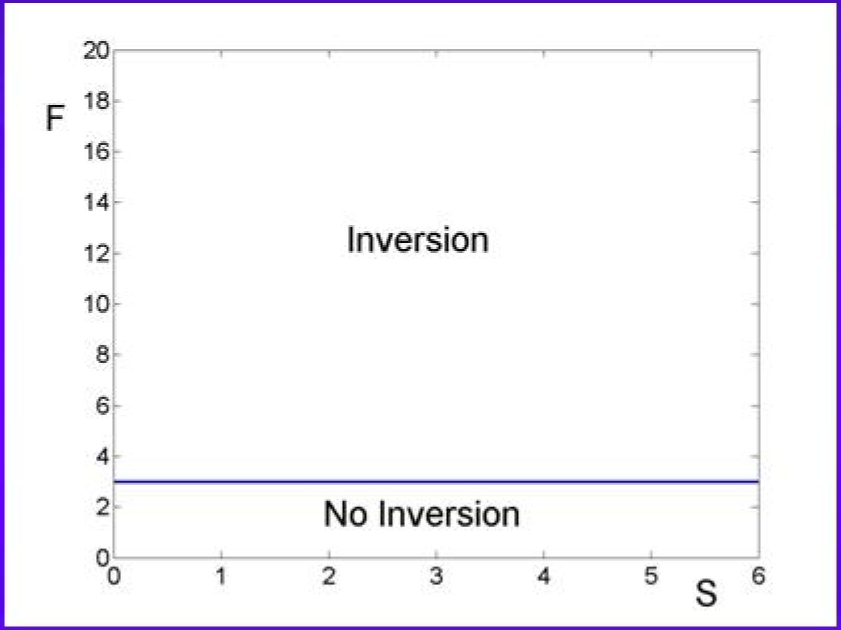
Theoretical model: *never* Inversion for F≤3

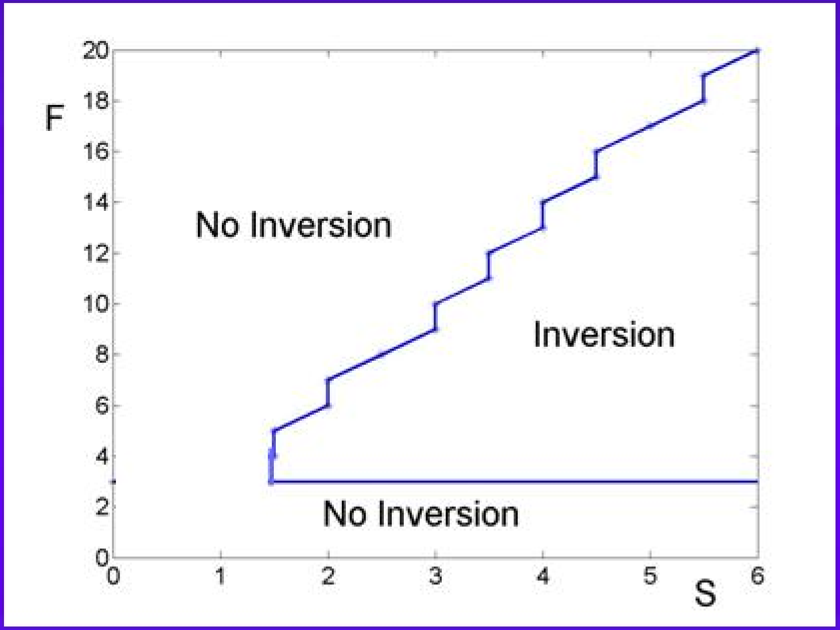


F=3 layers,
S= ΓA=0.1

Transition for increasing nr. of layers F

Phase transition for increasing F





With h_{inv} as in the experiments: first height with zero derivative.

Extra structure with the additional threshold criterion.

Conclusions & Outlook

- Current model describes Granular Leidenfrost effect *qualitatively*.
- No plateau in density profiles,
  no 2^{nd} order phase transition.

- Use different relations for κ and λ:

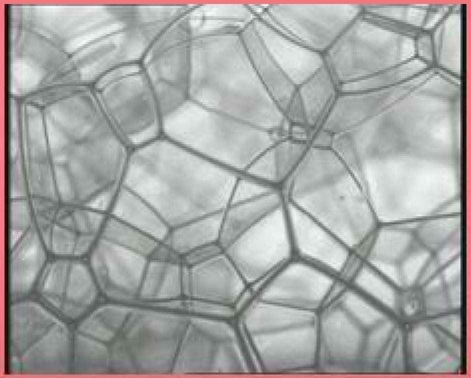
$$\kappa \propto \frac{n(\alpha l + d)^2}{l}, \qquad \lambda \propto \frac{(1-e^2)}{l}$$

with $l = \frac{1}{\sqrt{8}nd}\frac{n_c - n}{n_c - an}$ mean free path.

(Grossman et al. 1997, Meerson et al. 2003)

What is Coarsening?

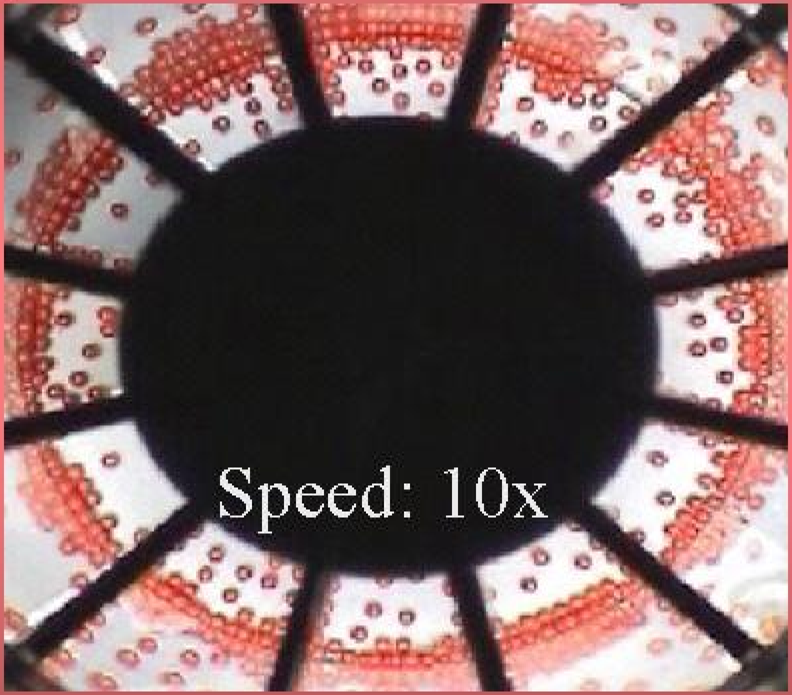
Larger foam cells grow at the expense of the smaller ones: coarsening.



Ring setup,
12 compartments

Granular Coarsening

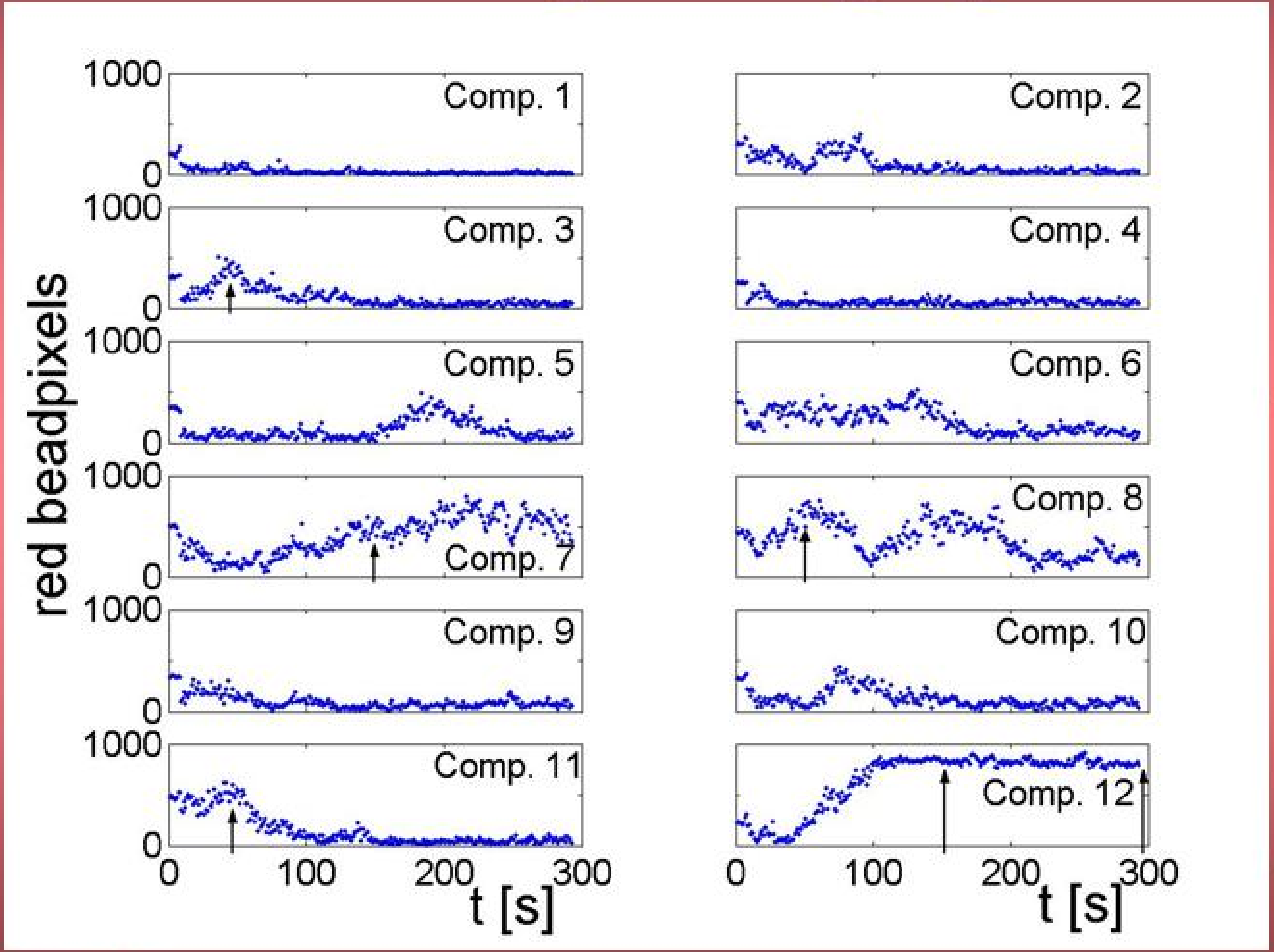
Starting from a uniform distribution:



Transient states (with more than 1 cluster):

large clusters grow at the expense of smaller ones.

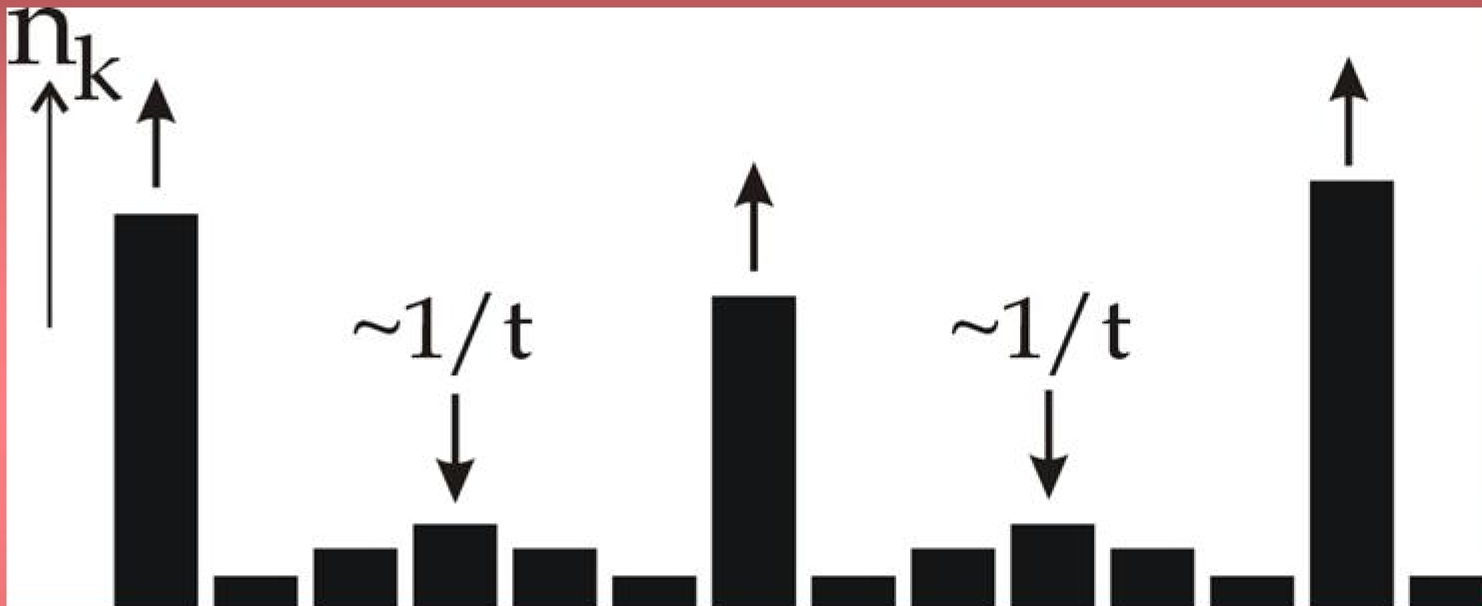
Coarsening: image processing



t[s]	Cluster
50	3,8,11
150	7,12
300	12

f=37Hz

1st Coarsening regime: cluster growth



Theoretical prediction for the intermediate hills between clusters:

$$n_k(t) \propto \frac{1}{t}$$

2^{nd} regime: cluster-to-cluster dynamics

Larger clusters eat up the smaller ones. For two clusters, theory predicts that the time this takes is proportional to their distance d:

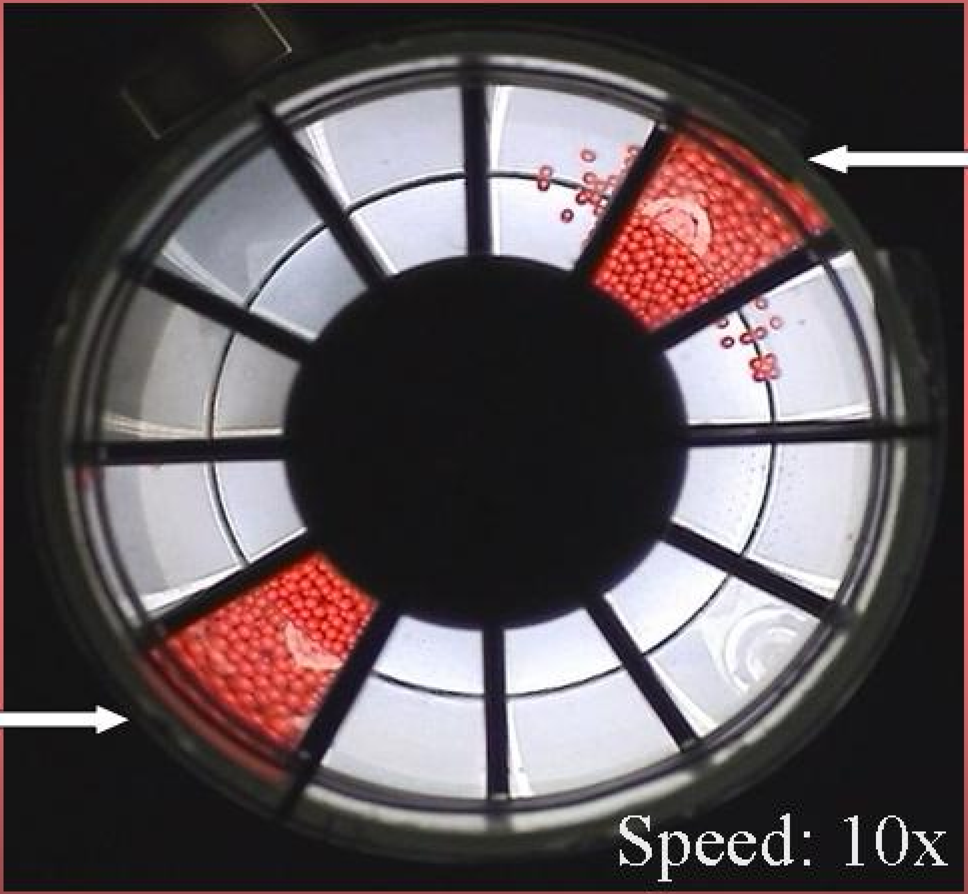
$$t_{breakdown} = d t_0$$

In ring setup: two interaction paths, which leads to:

$$t_{breakdown} = d t_0 (1 - d/12)$$

Two Clusters

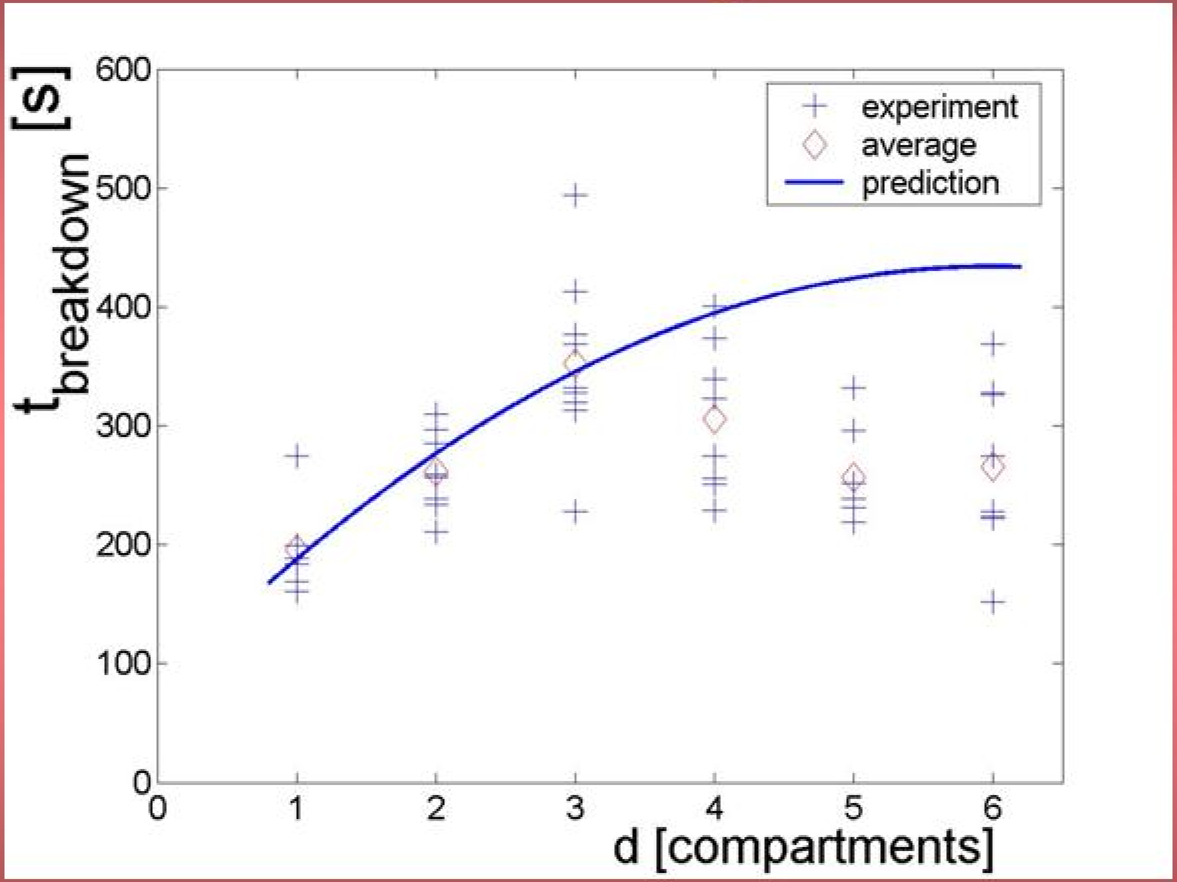
P=200 beads



P=280 beads

f=41Hz, a=1mm

Two Clusters: Exp vs. Theory

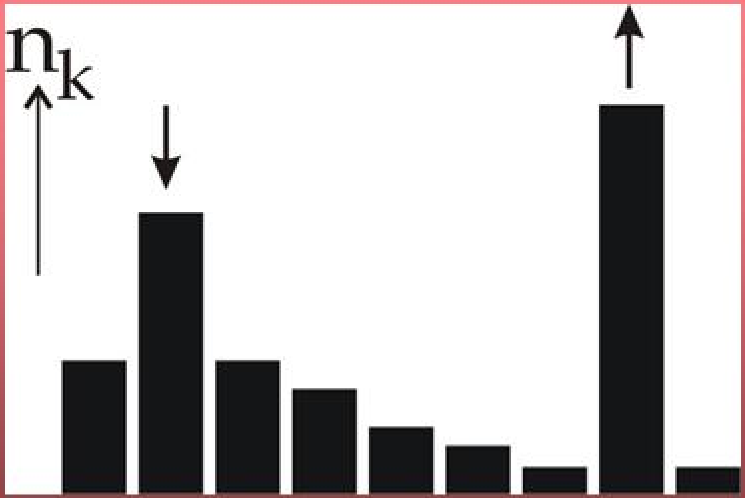


$$t_{breakdown} = dt_0(1 - d/12) \begin{cases} \text{valid for } d \leq 3 \\ \text{but not for } d \geq 4 \end{cases}$$

Proposed explanation for saturation

For d≥4, we measure in fact the "sudden collapse" time for *independent* P=200 cluster.

We do not have the standard transport bands between the clusters (starting from a uniform distribution):



Instead, the intermediate compartments are initially empty. Sudden collapse occurs before the transportband has built up.

Proposed explanation: check

Experimentally measured sudden-collapse time for a single P=200 cluster at f = 41 Hz:

$t_{collapse} = 438$ s

Lies roughly 100 s above saturation value!

Probable reason:
Drier atmospheric conditions → more static electricity built up in glass beads → cluster stays longer together.

Conclusions & Outlook

- Theoretical prediction for Two-Cluster coarsening verified for distances $d \leq 3$.
- Redo experiments with *metal* beads to clarify whether the saturation in the breakdown is indeed sudden collapse.
- Accompany experiments with Molecular Dynamics simulations.

Questions?