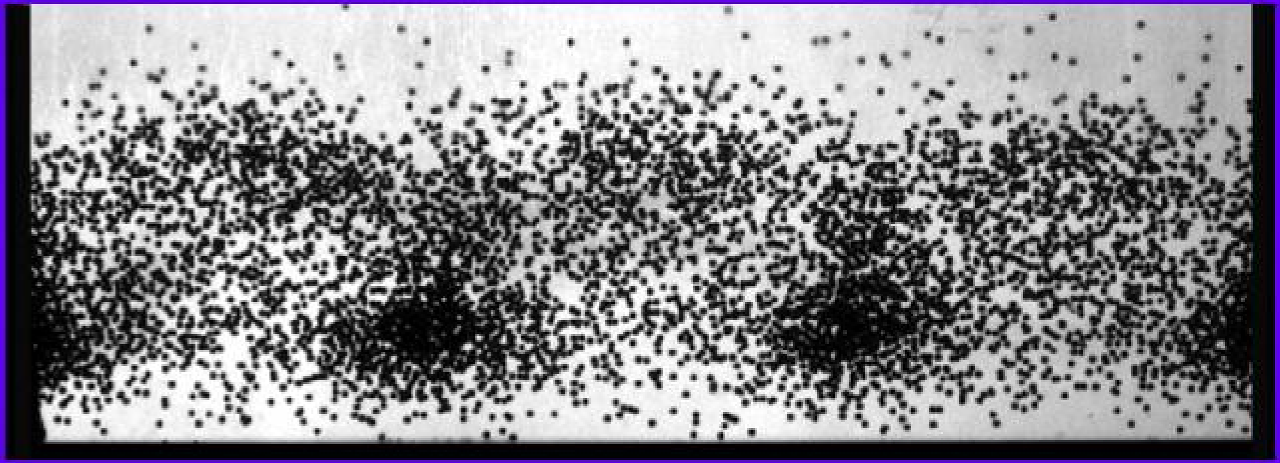
Rapid granular matter at its edge:
Exploring critical phenomena and ratchets



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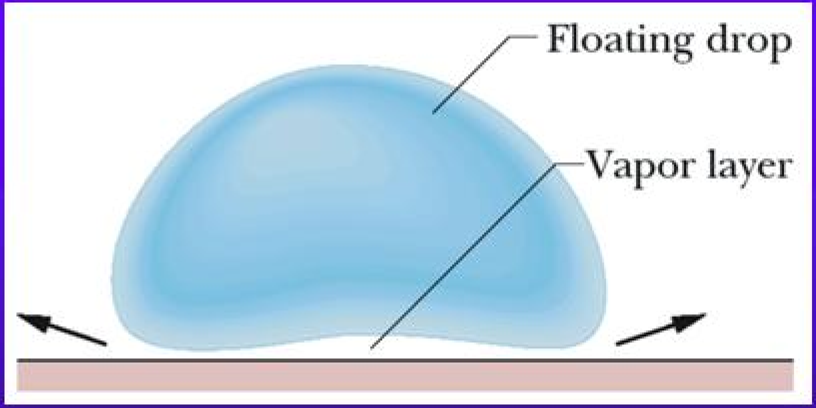
FOM

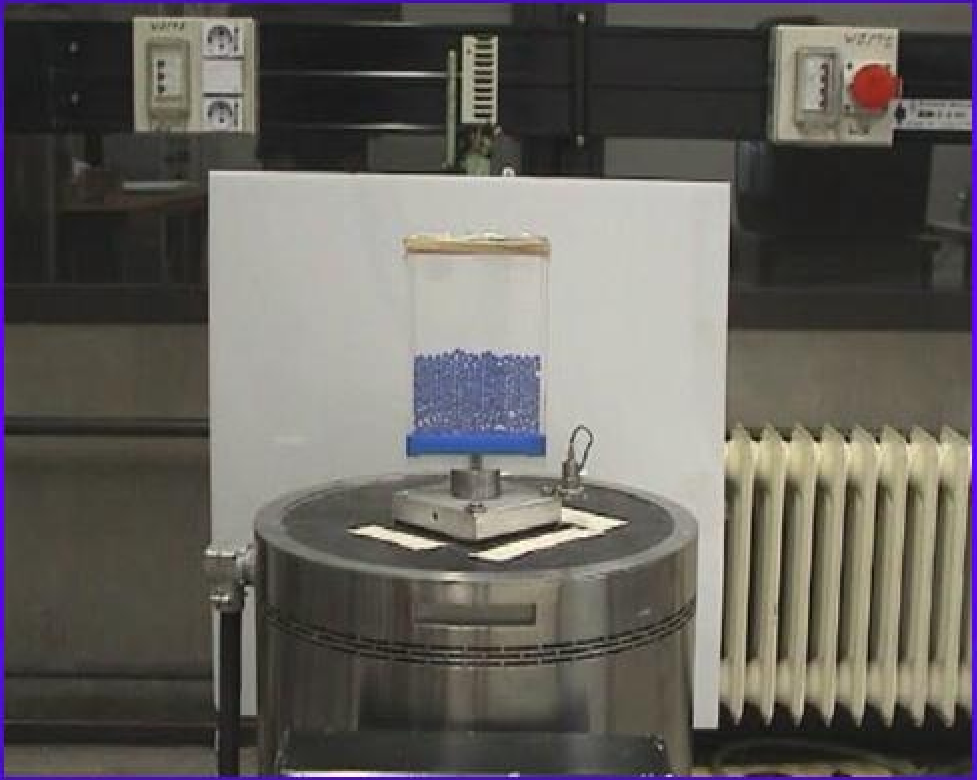
Johann Gottlob Leidenfrost (1756)



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

Experiment

The granular version:



Granular temperature at bottom ~ Shaking strength

2D container: $10 \times 0.45 \times 14$cm, Glass beads: $d = 4$mm, $\rho = 2.5 g/cm^3$, $e \approx 0.9$

What are the dimensionless control parameters?

$\Gamma = a(2\pi f)^2/g$ = shaking acceleration

F = number of particle layers

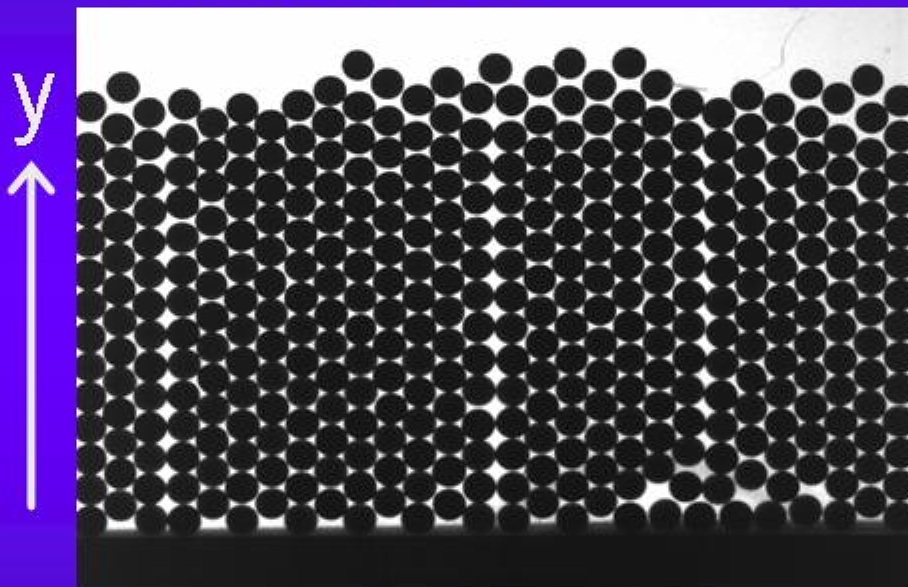
A = a/d = shaking amplitude

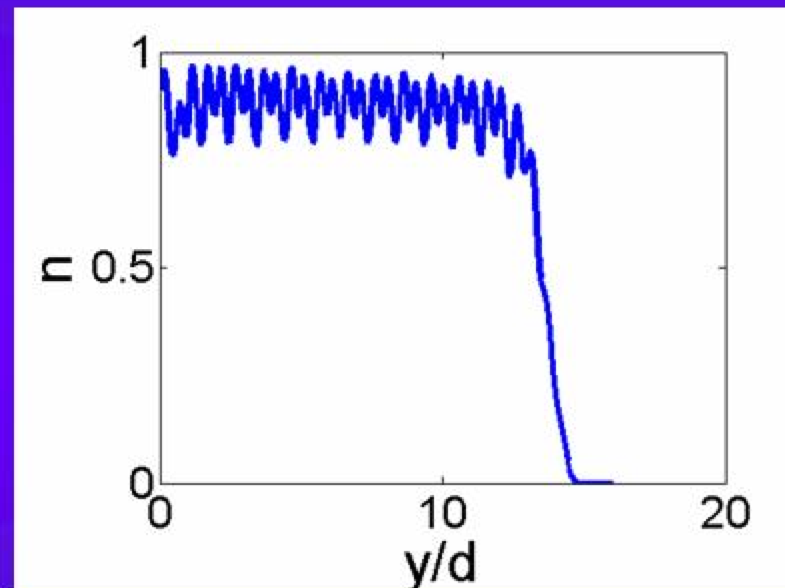
$\varepsilon = 1 - e^2$ = inelasticity (≈ 0.1)

Experiment

Leidenfrost state beyond critical acceleration Γ_c

F=16 layers, f=80Hz





$\Gamma = 25$

Leidenfrost state

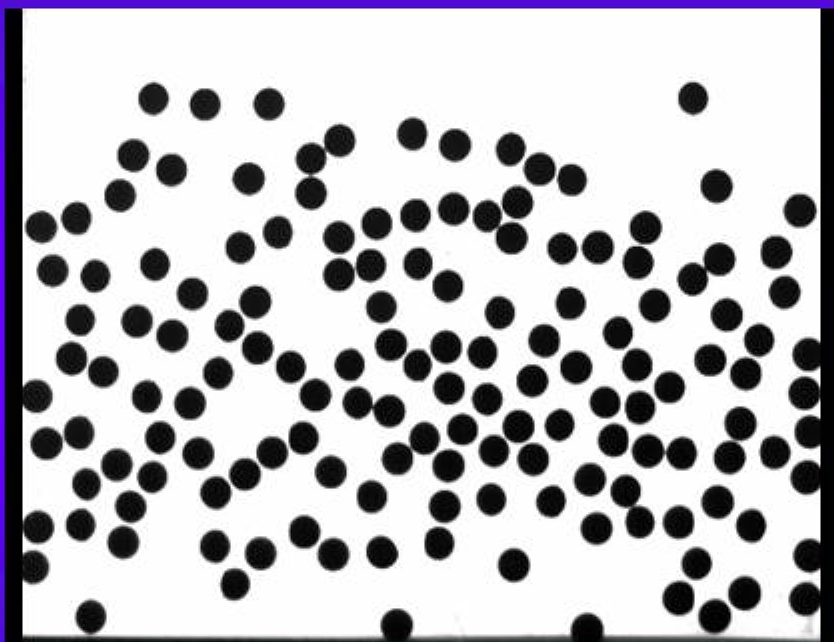
$\Gamma_c \approx 25$ (for F = 16 layers)

Experiment

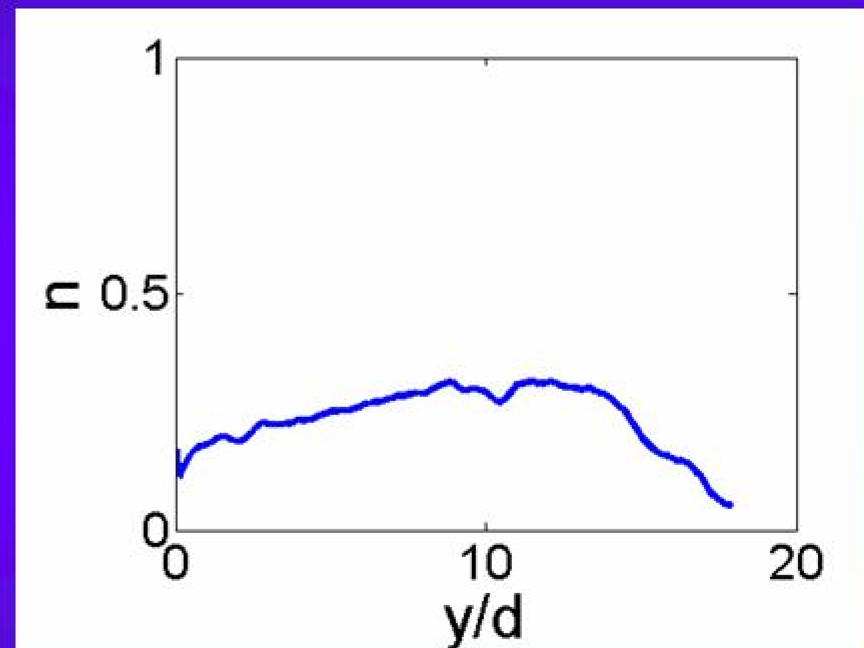
Critical number of layers

Γ=51.5 @ 1000 fps

y



F = 6 layers

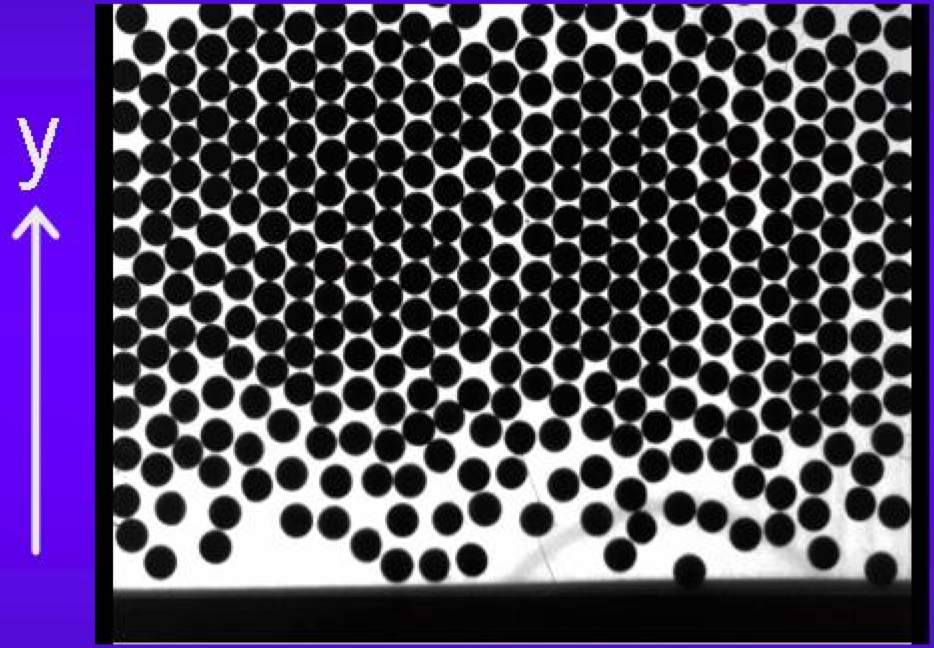


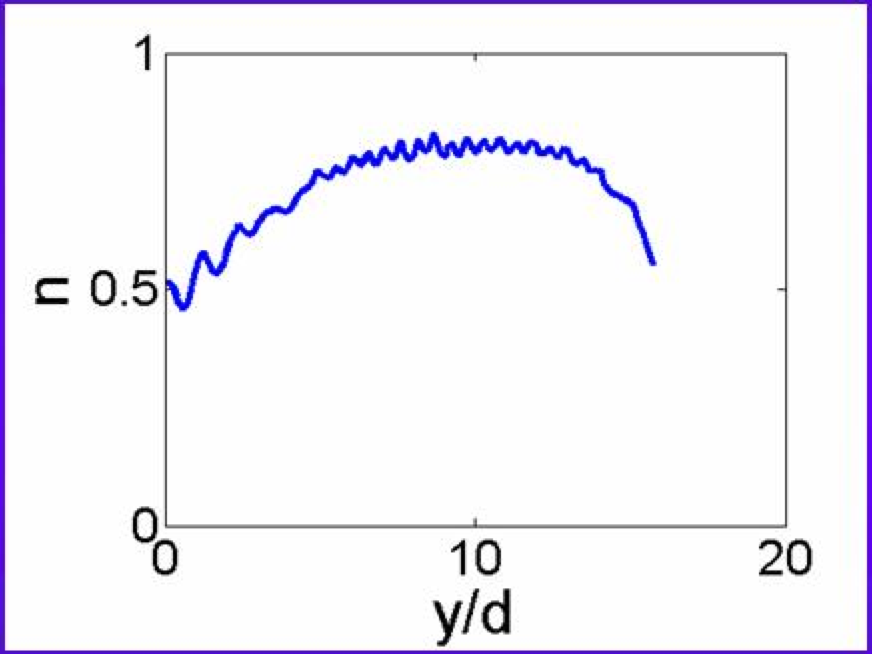
Gaseous state

Experiment

Critical number of layers

Γ=51.5 @ 1000 fps





F = 16 layers

Leidenfrost state

Granular Leidenfrost effect only for F ≥8

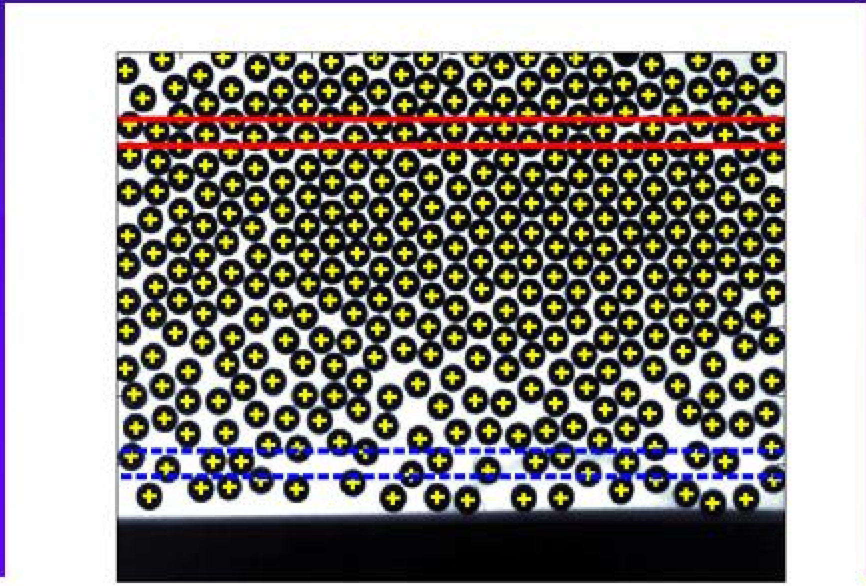
Experiment

What's a suitable ***order parameter*** to distinguish between the different phases in the Leidenfrost state?

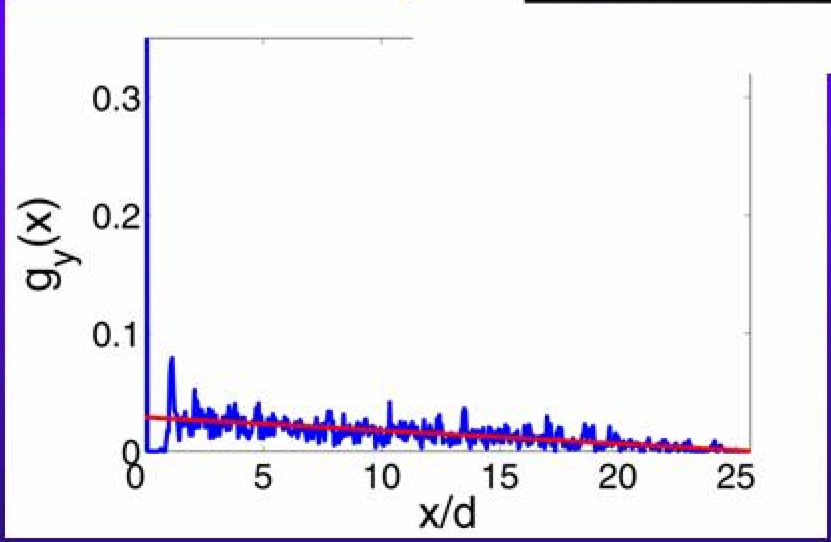
→ Employ the concept of *pair correlations:*

$$g_y(x) = \frac{1}{N} \sum_{i,j\ in\ (y,y+dy)} \sum_{i \neq j} \delta\left(x - \left(x_i - x_j\right)\right)$$

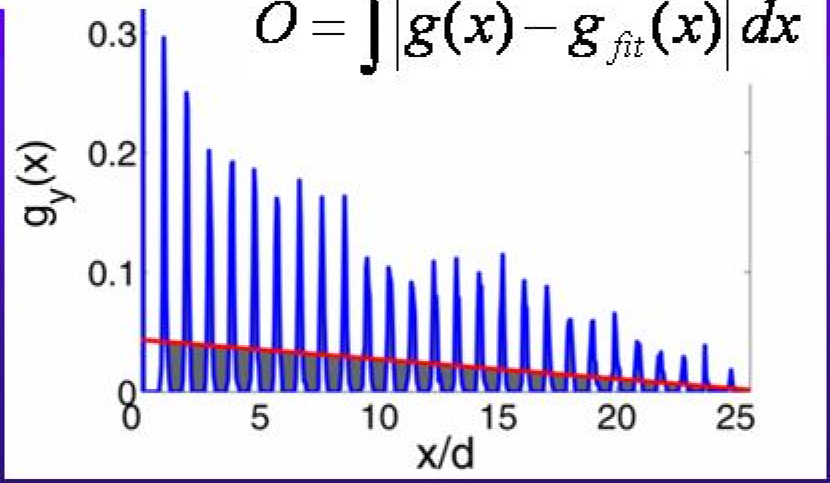
Identifying the order parameter



F=16 layers
Γ=64.4

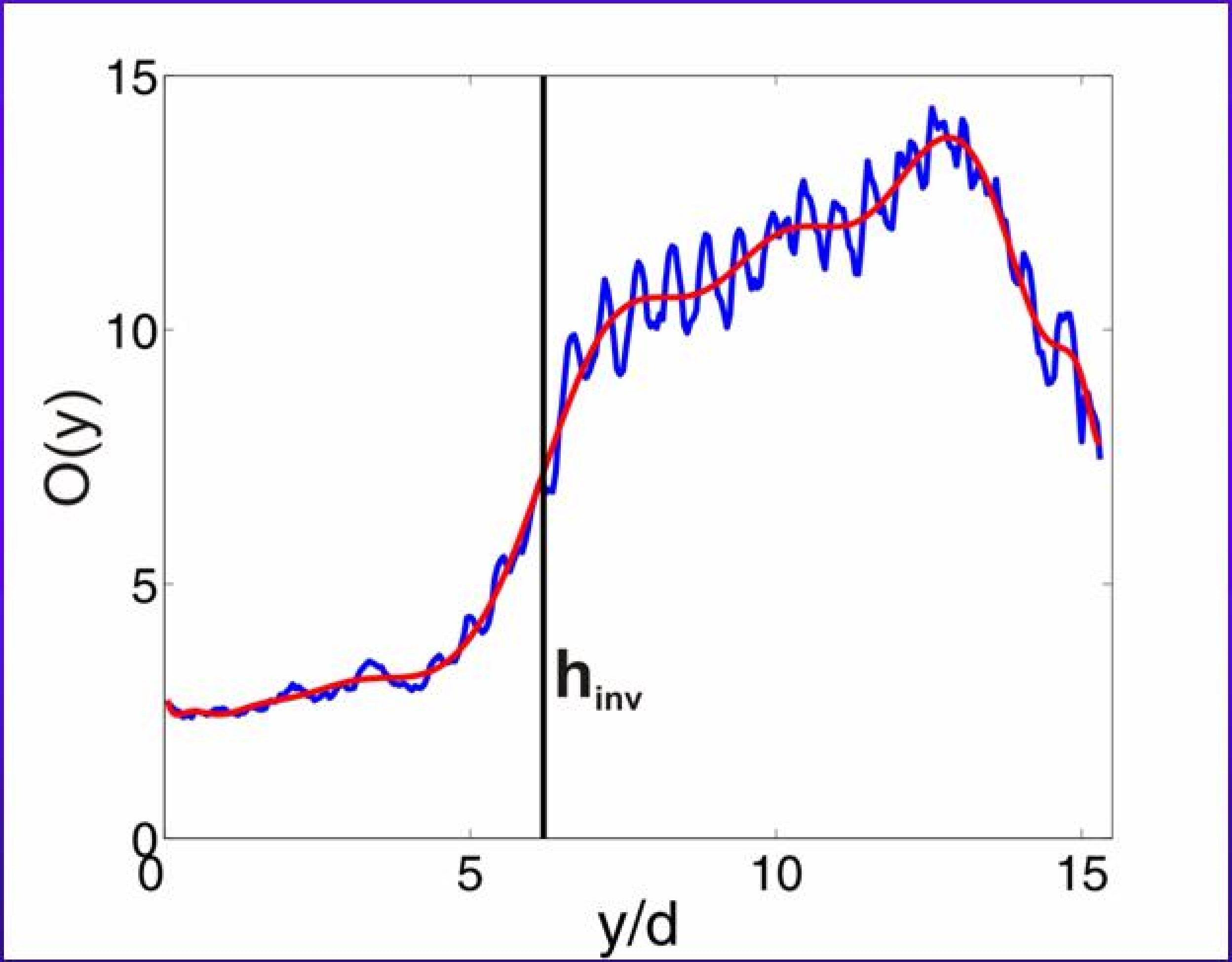


$$O=\int\left|g(x)-g_{fit}(x)\right|dx$$



Experiment

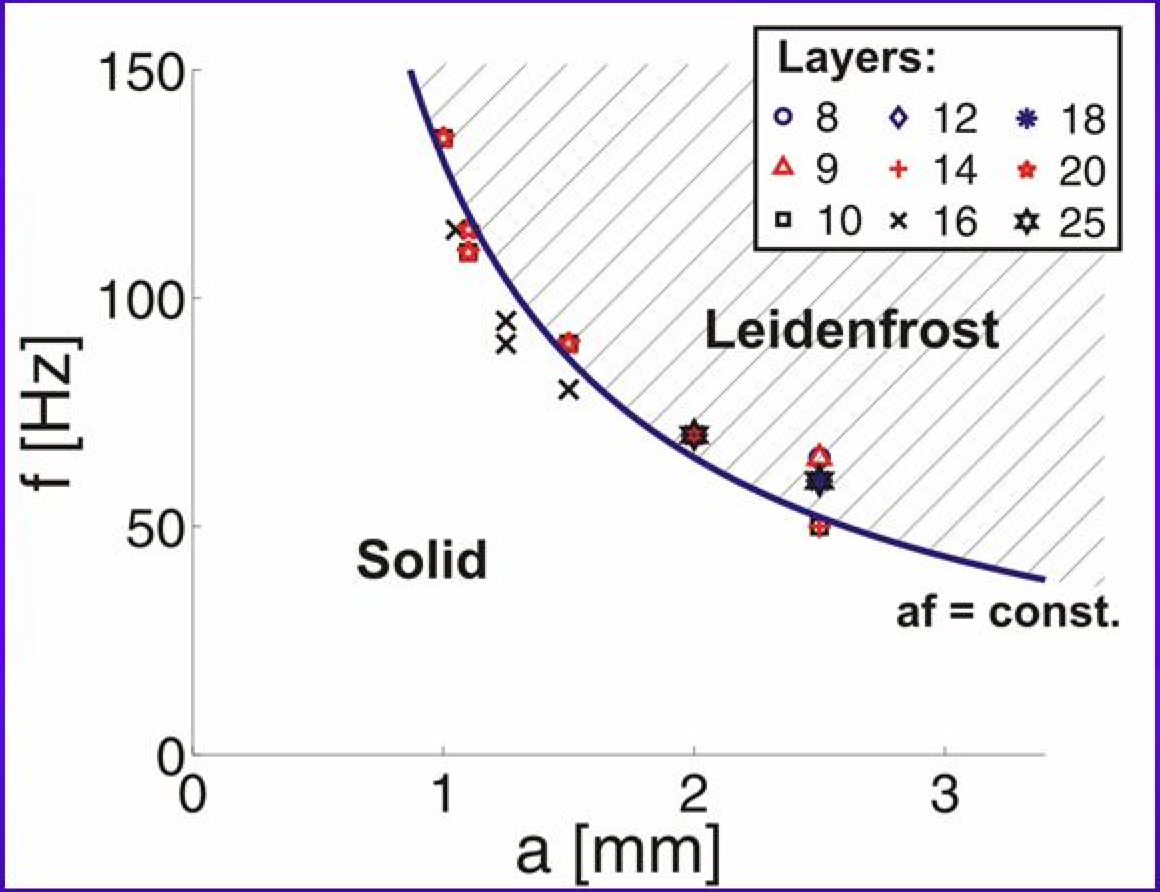
Order parameter *O* determines inversion height:



F=16 layers
Γ=64.4

Experiment

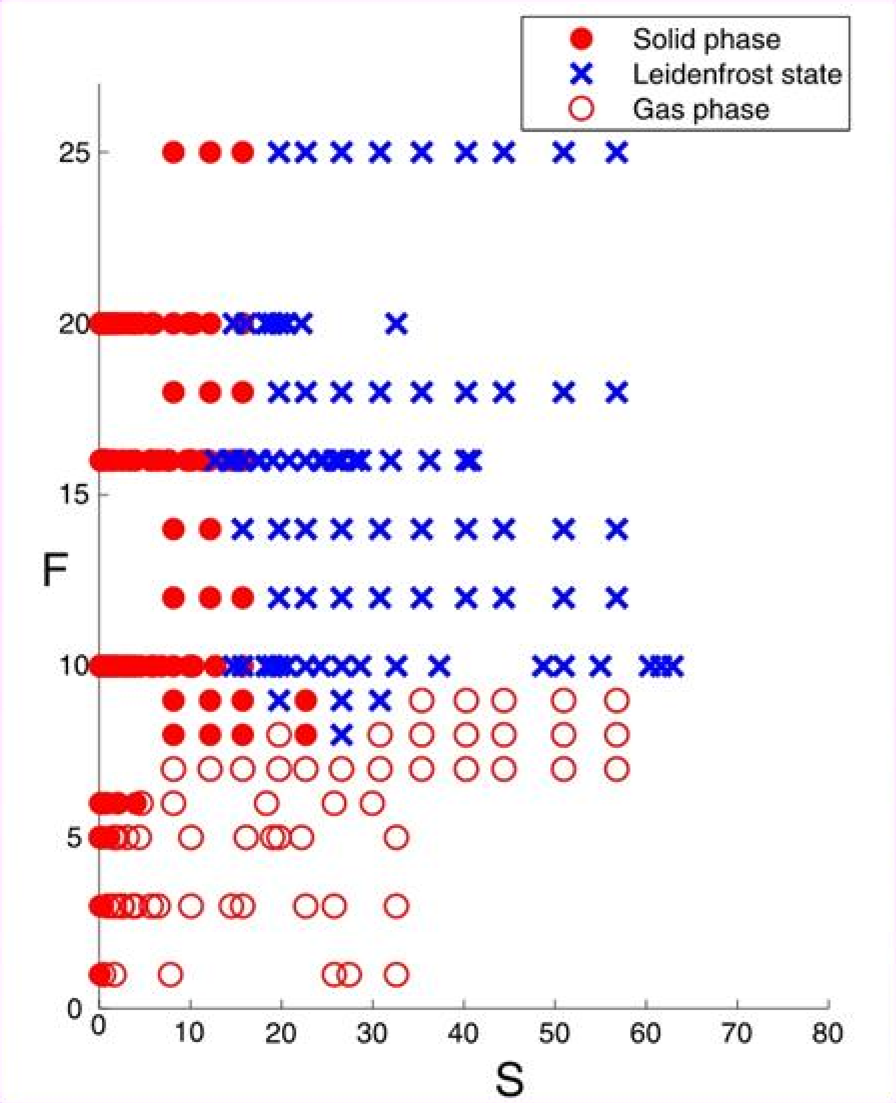
Leidenfrost threshold



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

Experiment

Phase diagram in S-F plane



Hydrodynamic 1D-model

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

Balance between heat flux and dissipation:

$$\frac{d}{dy}\left\{\kappa \frac{dT}{dy}\right\} = \frac{\mu}{\gamma l} \varepsilon n T^{3/2}$$

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

cf. Meerson *et al.*, PRL **91** (2003)

Boundary conditions

- **Prescribed granular temperature at bottom:**

$$T_0 \propto (af)^2$$

- **Zero heat flux at the top:**

$$\lim_{y\to\infty}\left(\kappa(y)\frac{dT}{dy}\right) = 0$$

- **Conservation of total number of particles:**

$$\int_0^\infty n(y)dy = F\, n_{cp} d$$

Theory

Dimensionless control parameters

Energy input: $S = \frac{4\pi^2 (af)^2}{gd}$

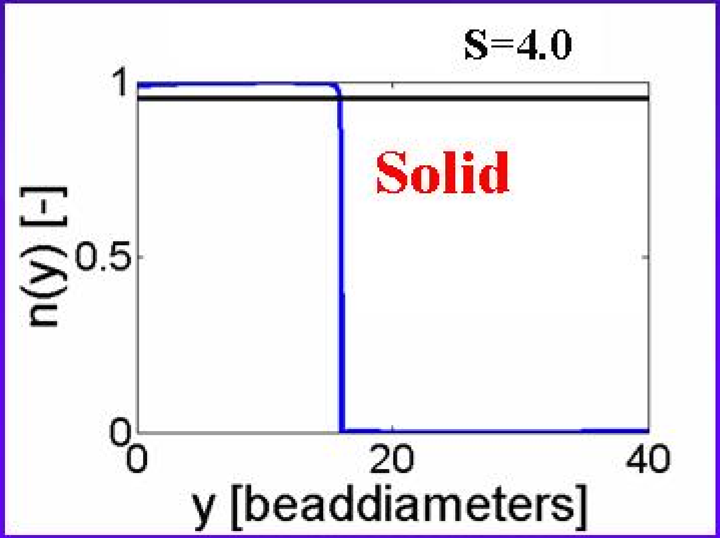
Inelasticity: $\varepsilon = (1 - e^2)$

Number of layers: F

Note: Relevant shaking parameter is not Γ, but $S \equiv \Gamma A$

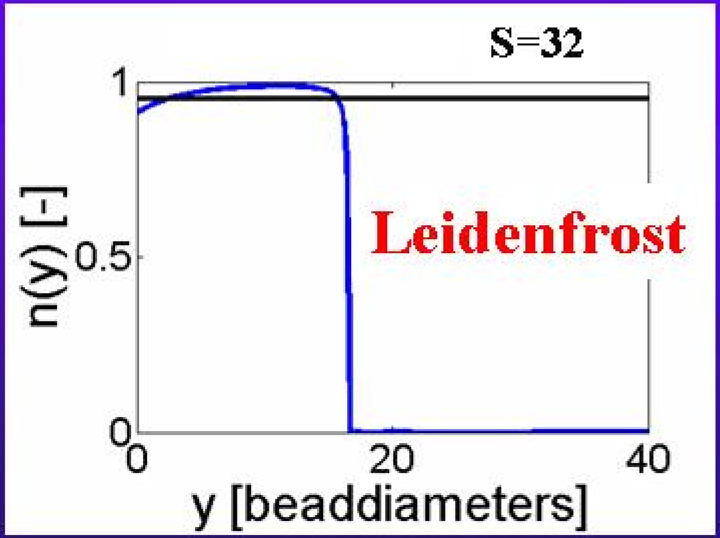
Theory

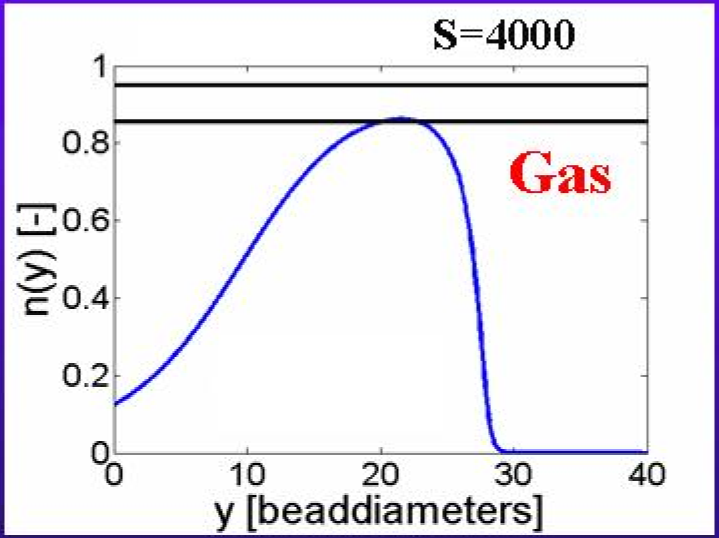
Density profiles from model:



F = 16 layers

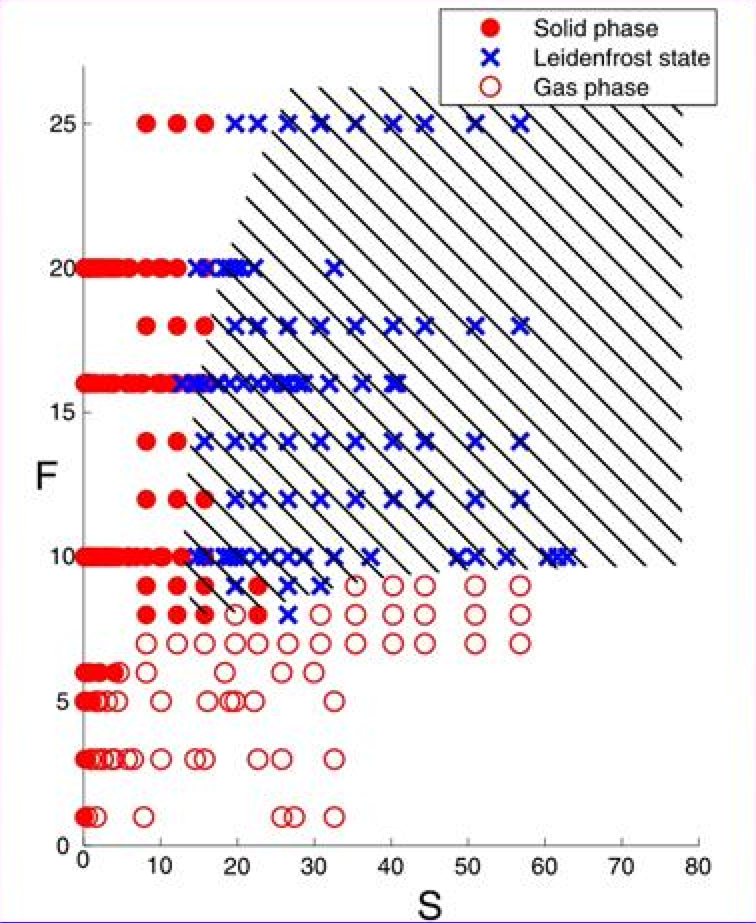
ε = 0.1





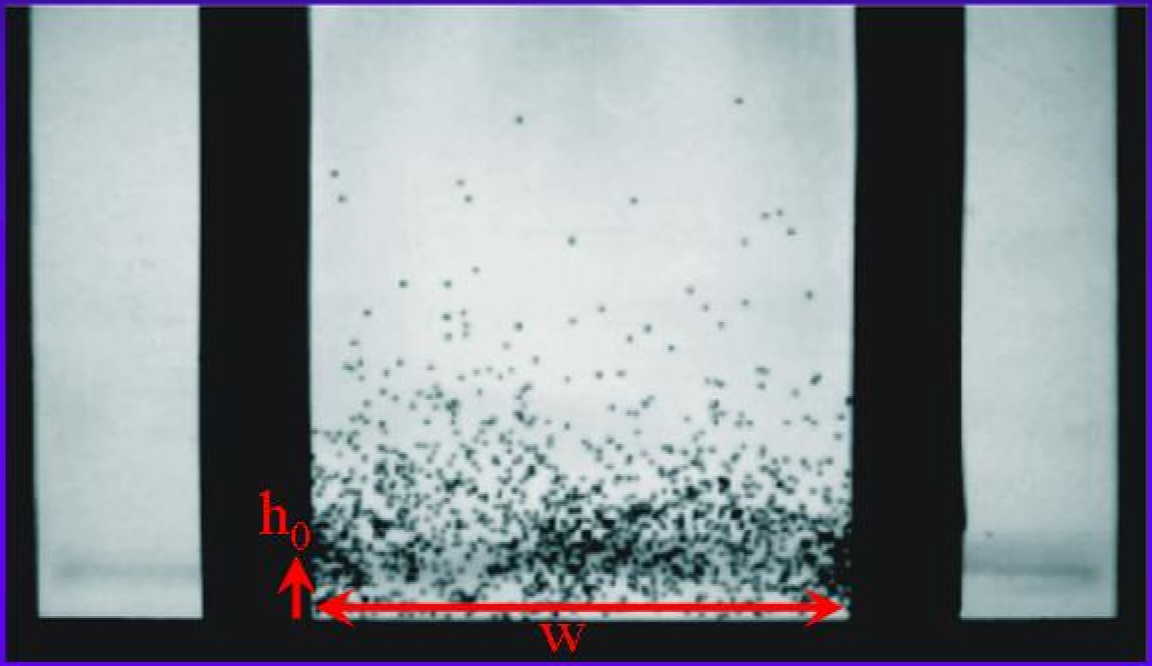
Experiment vs. Theory

Phase diagram in S-F plane



Experiment and theory agree!

Extension to 2D



Adjustable sidewalls, smaller beads (d = 1mm)

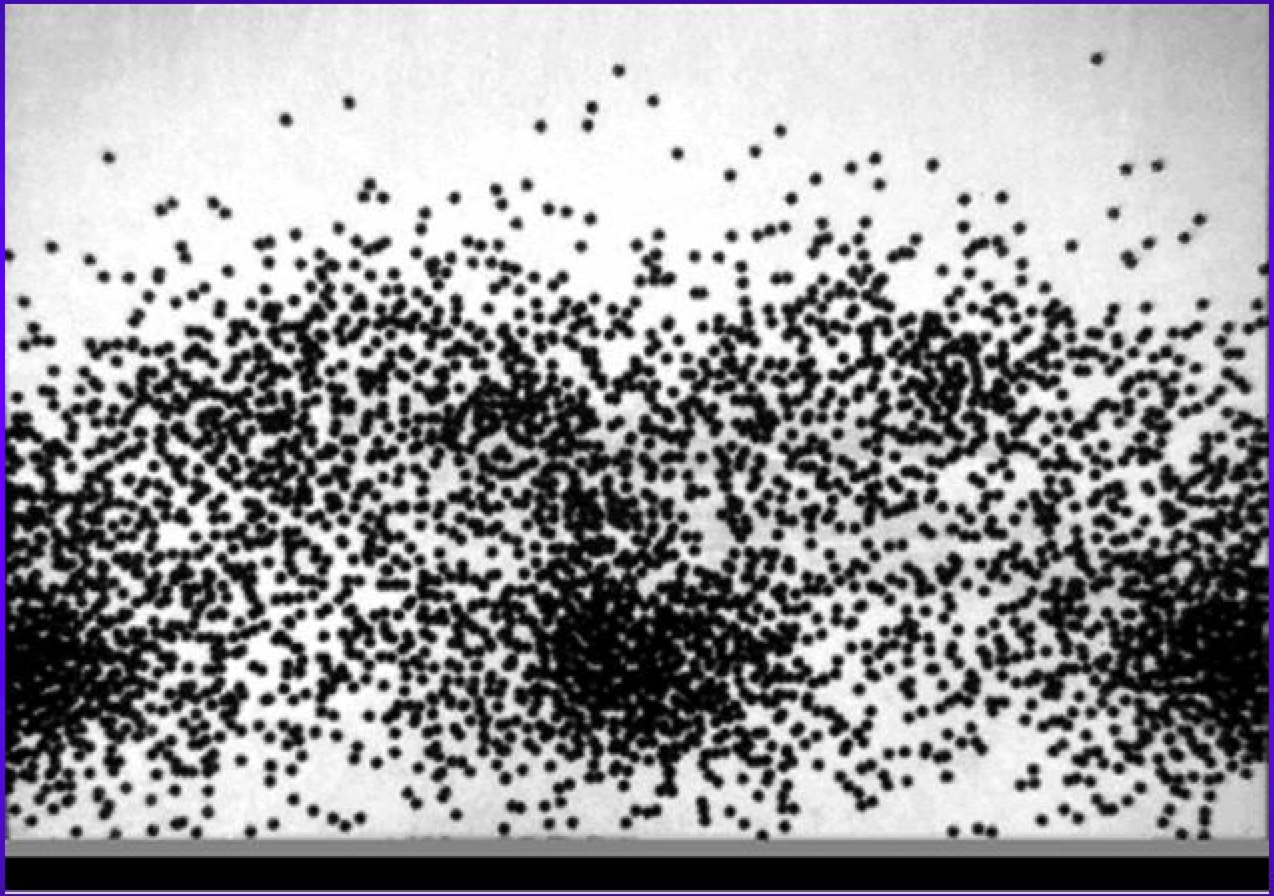
Additional dimensionless parameter:
$\beta = w/h_0$ = aspect ratio

2D: A new phenomenon…

We start from the granular Leidenfrost effect,
and increase the shaking strength S:

Convection rolls (Rayleigh-Bénard)

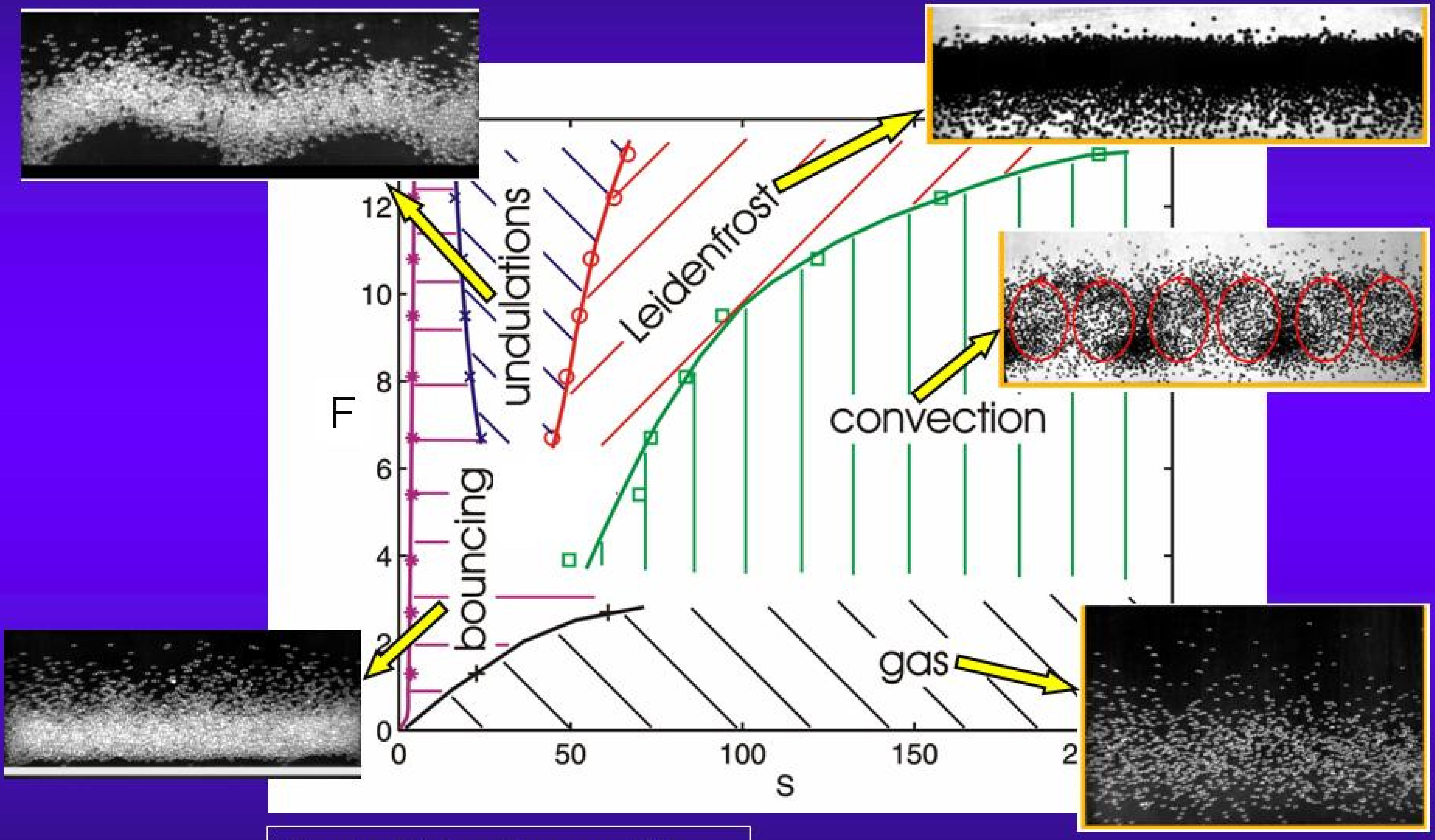
Convection rolls



1mm steel beads

Relevant parameters: S, F, ε *and* aspect ratio $\beta = w/h_0$

Experimental Phase Diagram

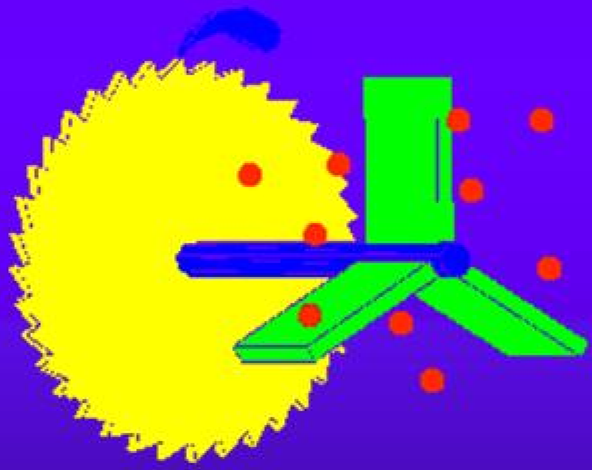


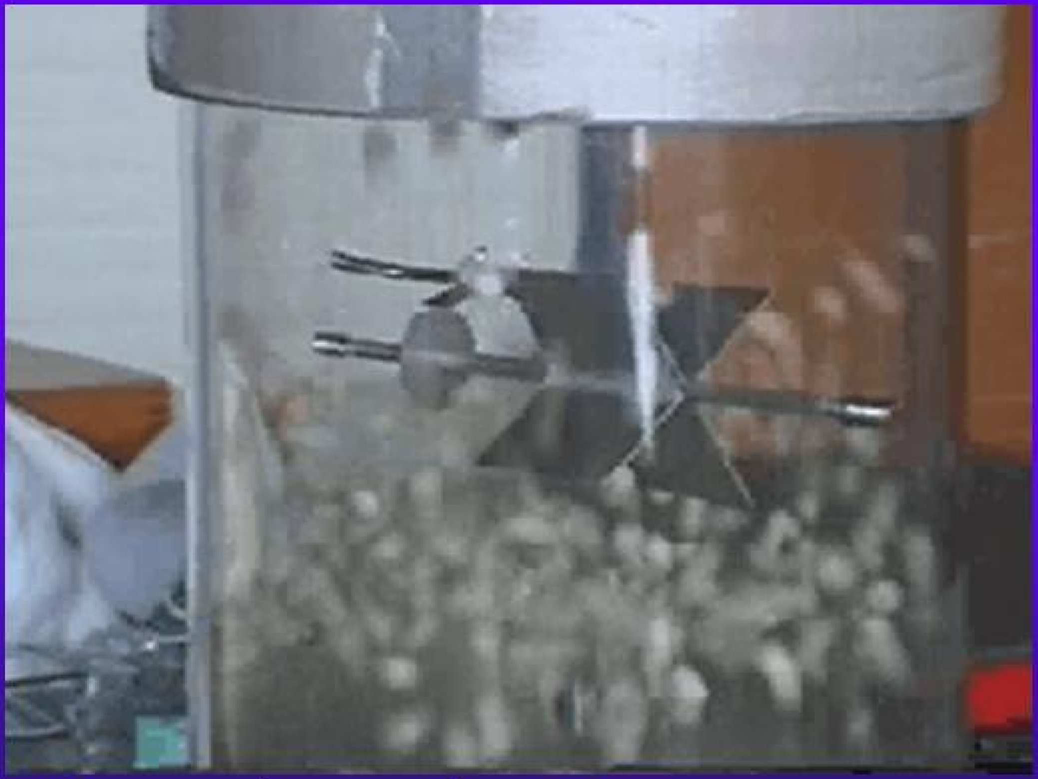
Fixed: ε≈0.1, a=3mm, w=101mm

3D: Granular Smoluchowski ratchet

Brownian motor:

Random forcing yielding *directed* motion.





Devaraj van der Meer

We want to study:

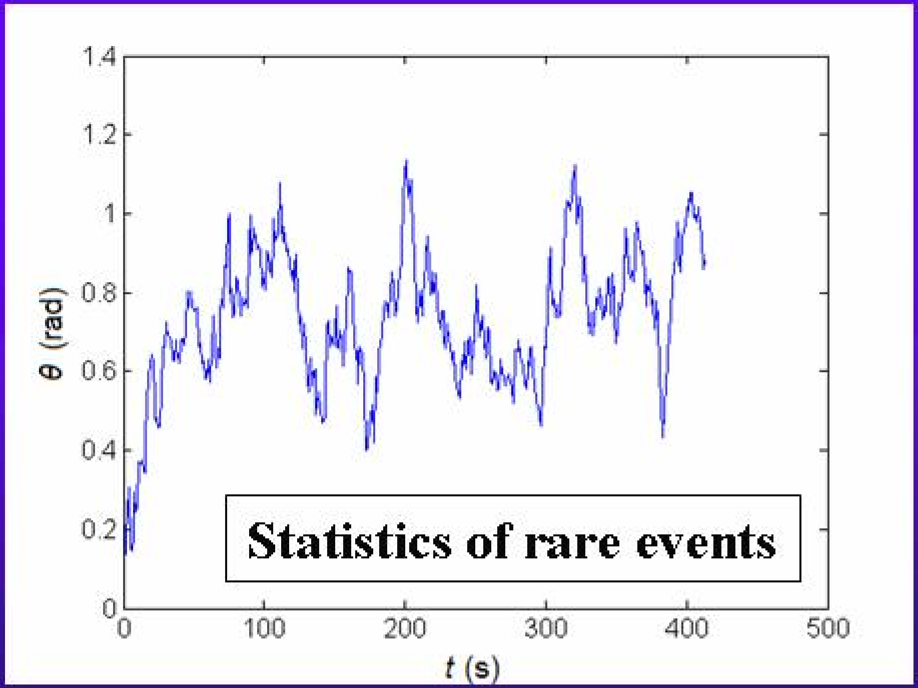
Without pawl (no ratchet yet):

•Dependence Brownian motion on S, F, ε and height of vanes above bottom.

With pawl (ratchet):

•Efficiency of ratchet for control parameters: S, F, ε and height of vanes.

Precision rotational sensor: $4.8 \cdot 10^{-6}$ rad



Conclusions

- 1D:

  Granular Leidenfrost effect explained: experiment and theory agree.

- 2D:

  Convection rolls: hydrodynamic model including aspect ratio β.

- 3D:

  Smoluchowski ratchet:

  experiment, theory & numerics.

P. Eshuis, K. van der Weele, D. van der Meer, and D. Lohse, *Granular Leidenfrost effect: Experiment and theory of floating particle clusters*, submitted to PRL (2005)