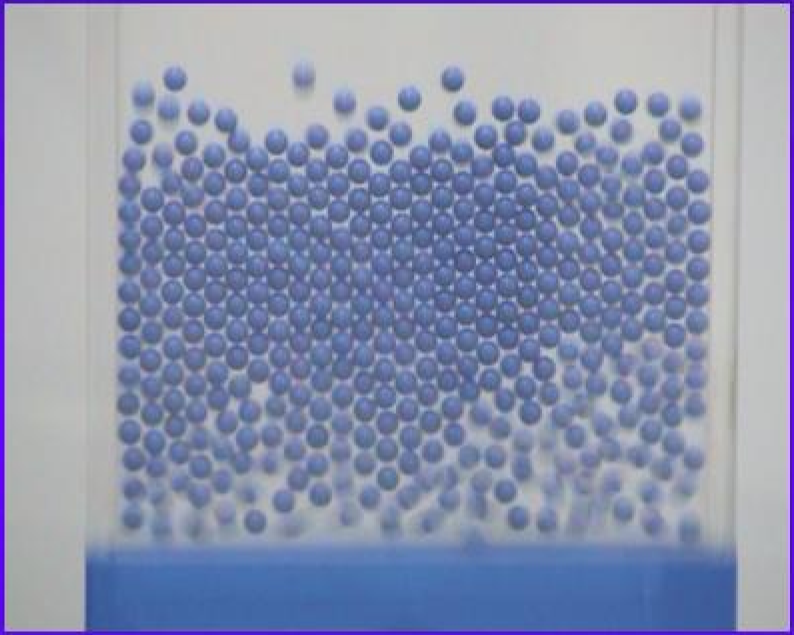
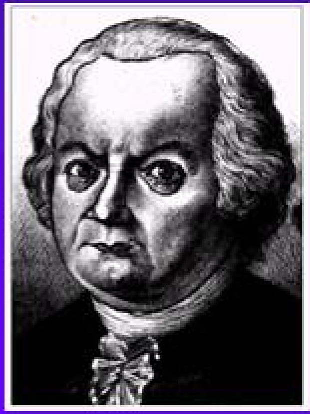
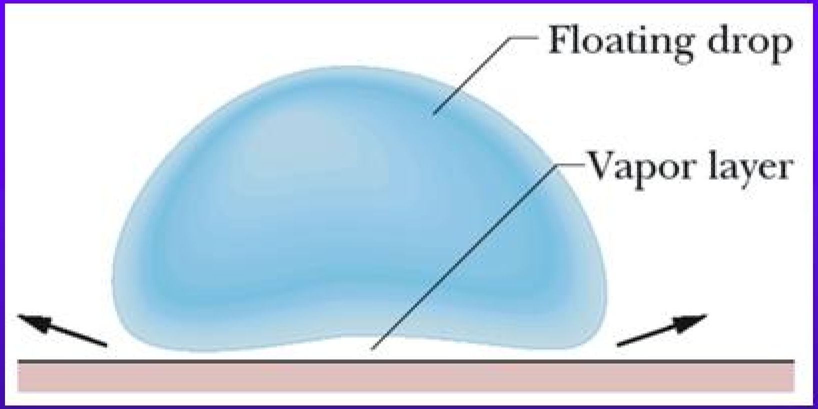
# Granular Leidenfrost Effect




**Peter Eshuis**
Ko van der Weele
Devaraj van der Meer
Detlef Lohse

# Johann Gottlob Leidenfrost (1756)



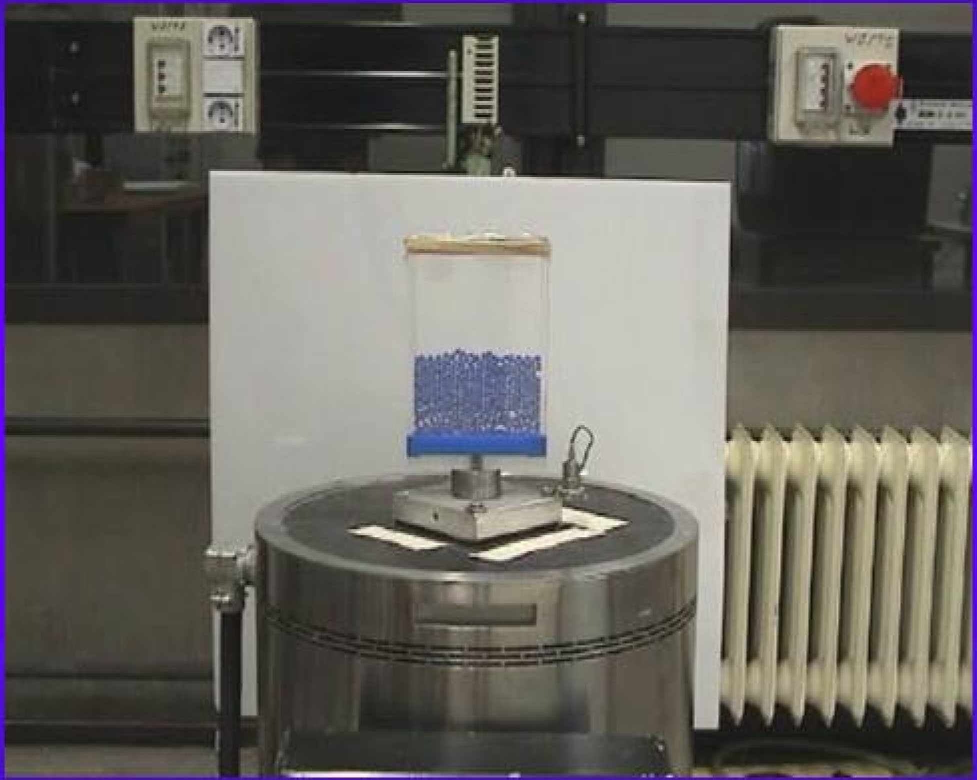




Drop of water on a hot plate (≈220° C)

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 strength

F = number of particle layers

A = a/d = shaking amplitude

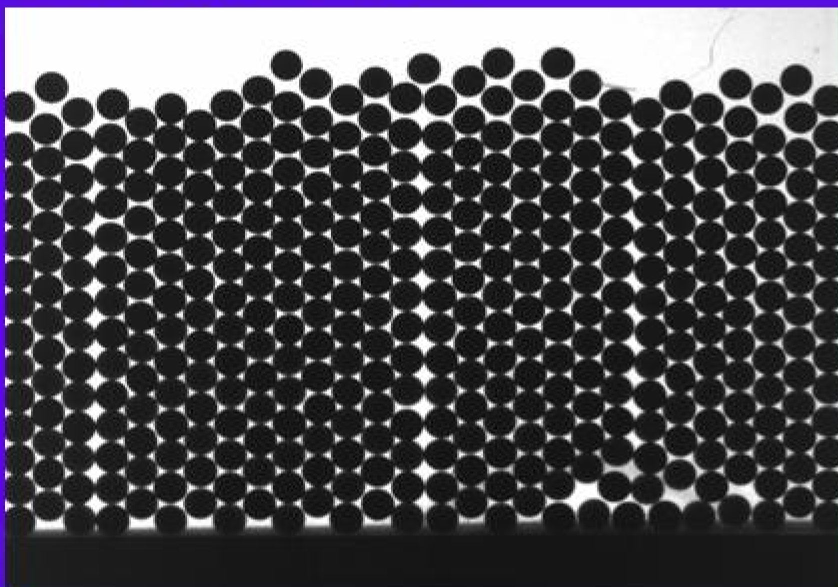
$\varepsilon = (1-e^2)$ = inelasticity

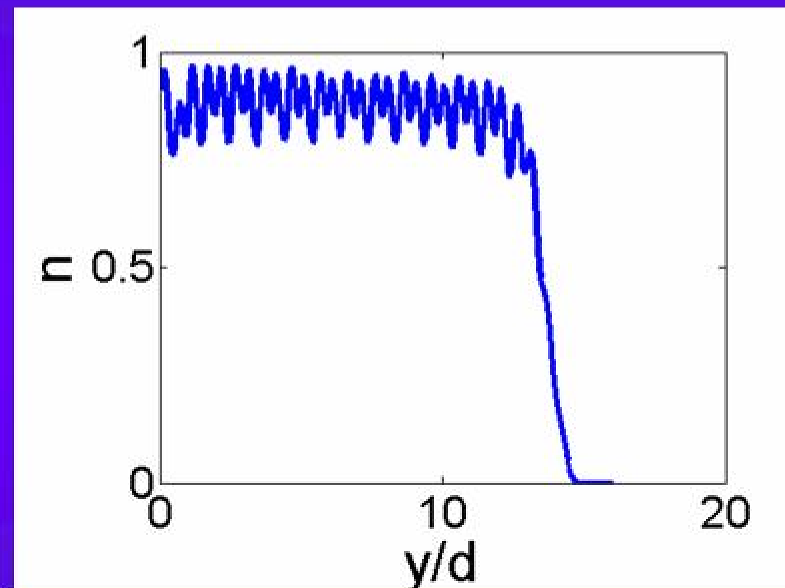
Experiment

# Leidenfrost state beyond critical shaking strength $\Gamma_c$

F=16 layers, f=80Hz

y






$\Gamma = 25$

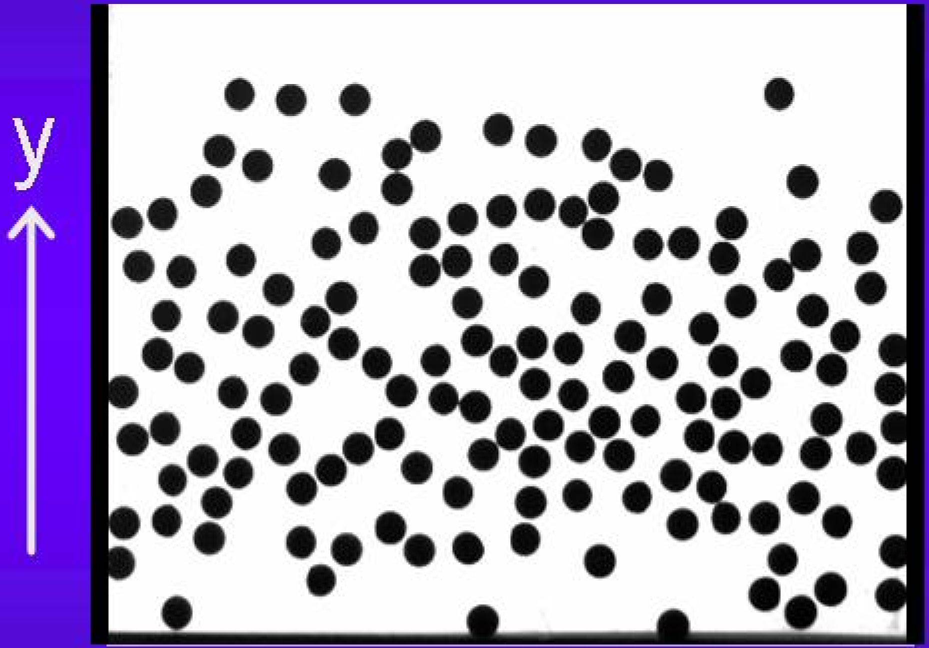
**Leidenfrost state**

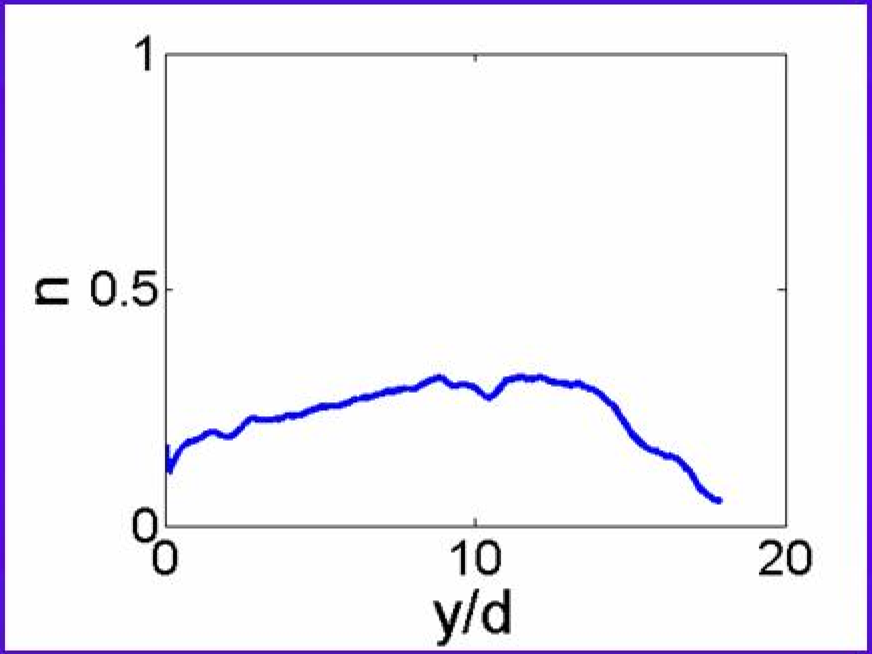
$\Gamma_c \approx 25$ ( for F = 16 layers )

Experiment

# Critical number of layers

Γ=51.5 @ 1000 fps




**F = 6 layers**

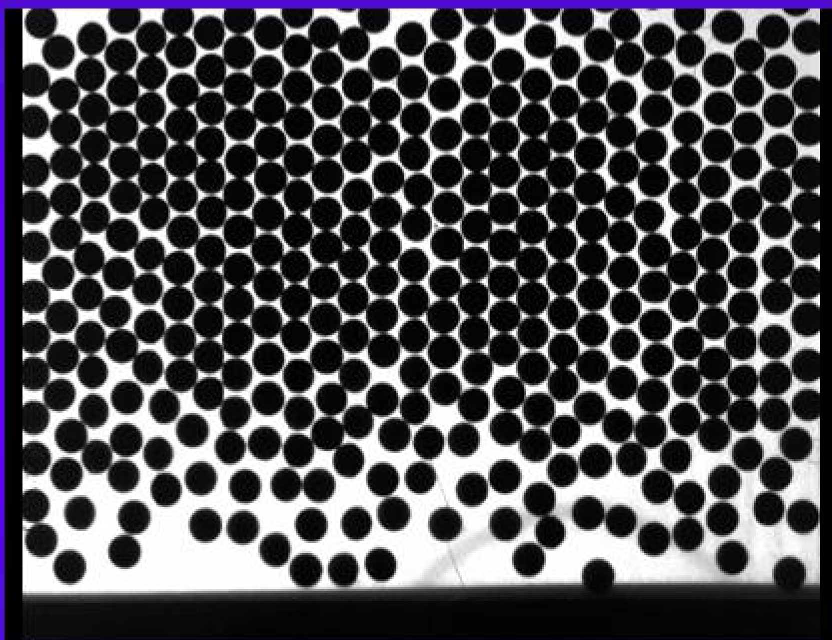
**Gaseous state**

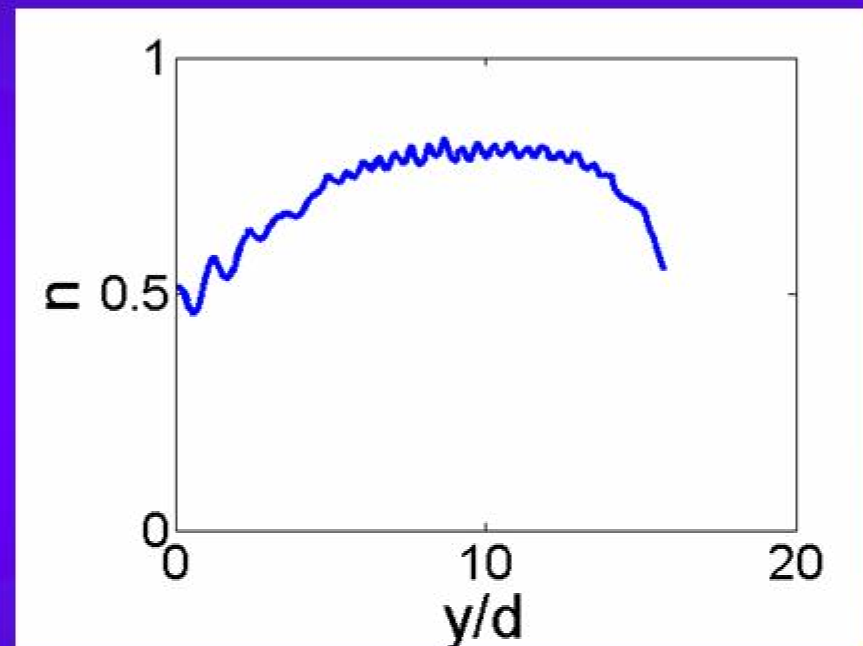
Experiment

# Critical number of layers

Γ=51.5 @ 1000 fps

y






**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?

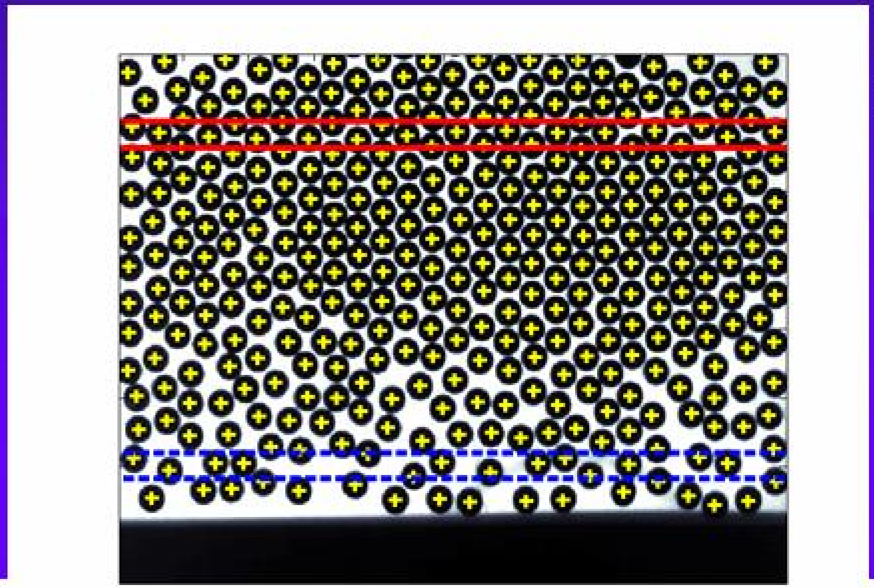
→ Employ the concept of *pair correlations*:

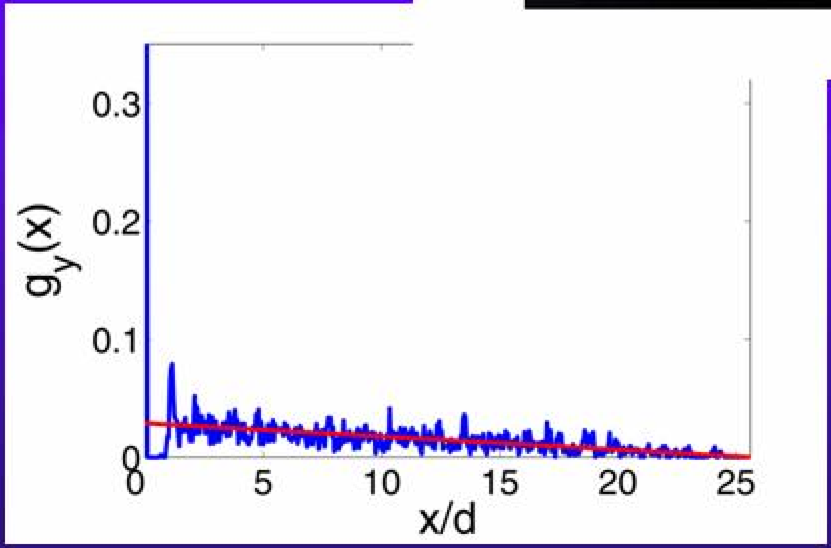
$$g_y(x) = \frac{1}{N} \sum_{i,j \; in \, (y, y+dy)} \sum_{i \neq j} \delta\left(x - \left(x_i - x_j\right)\right)$$

Experiment

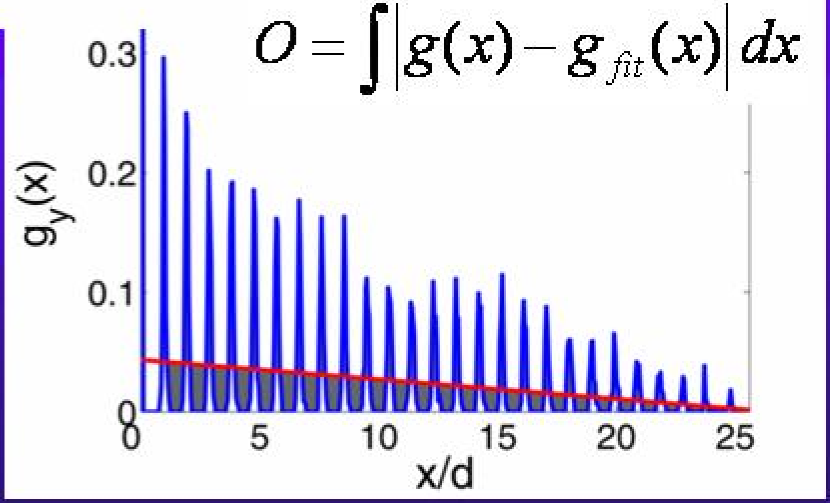
# Identifying the order parameter

F=16 layers
$\Gamma$=64.4



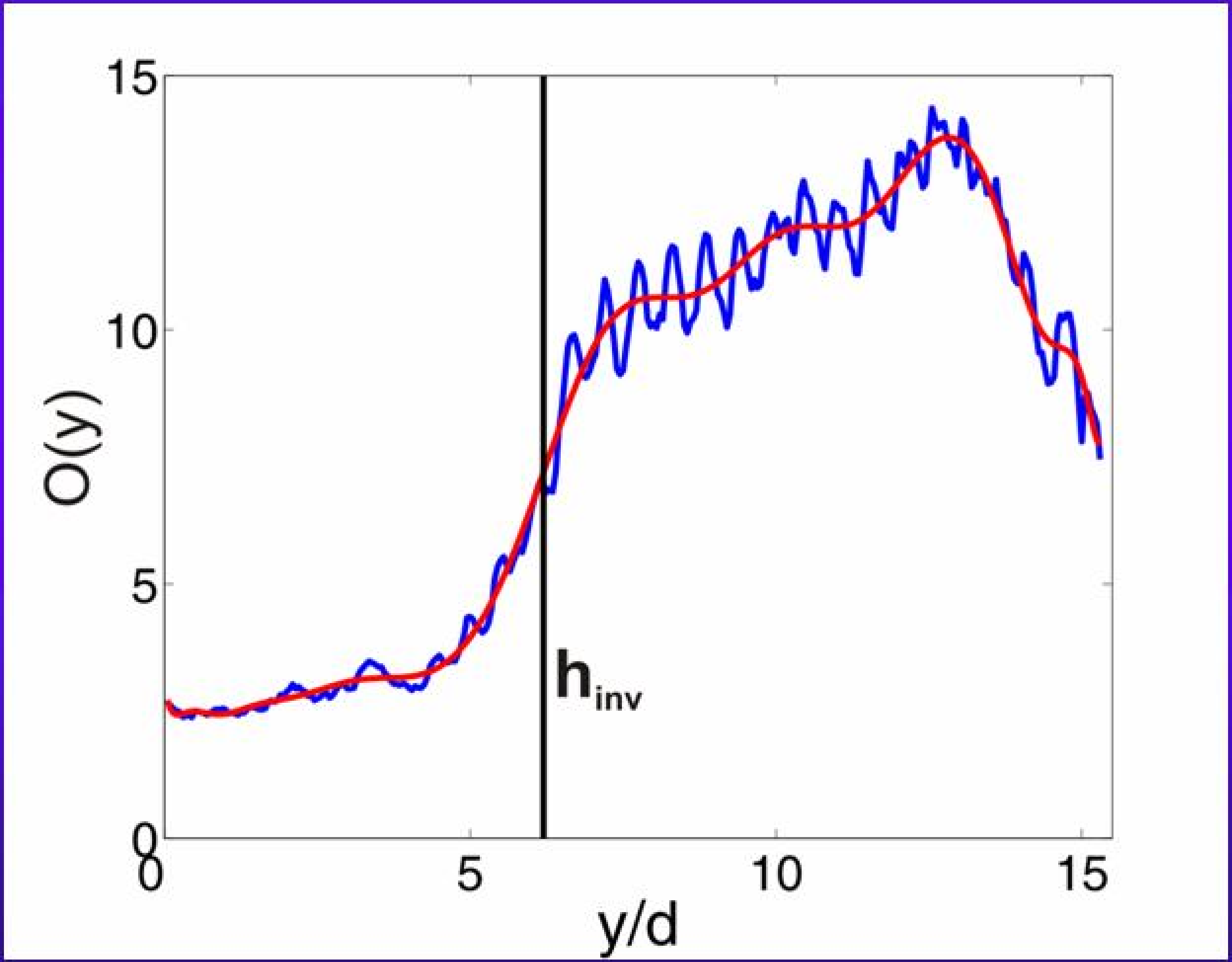



$$O = \int \left| g(x) - g_{fit}(x) \right| dx$$



Experiment

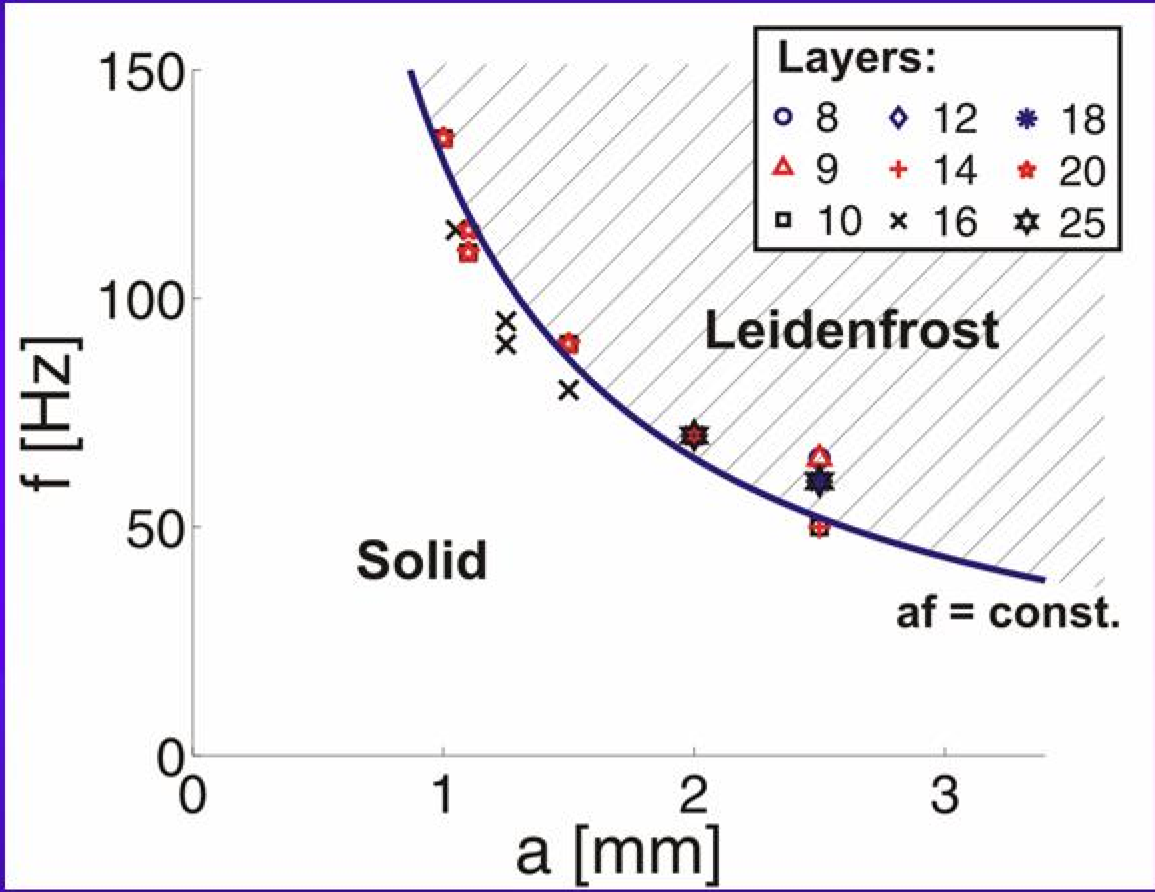
# Order parameter *O* determines inversion height:




F=16 layers
Γ=64.4

Experiment

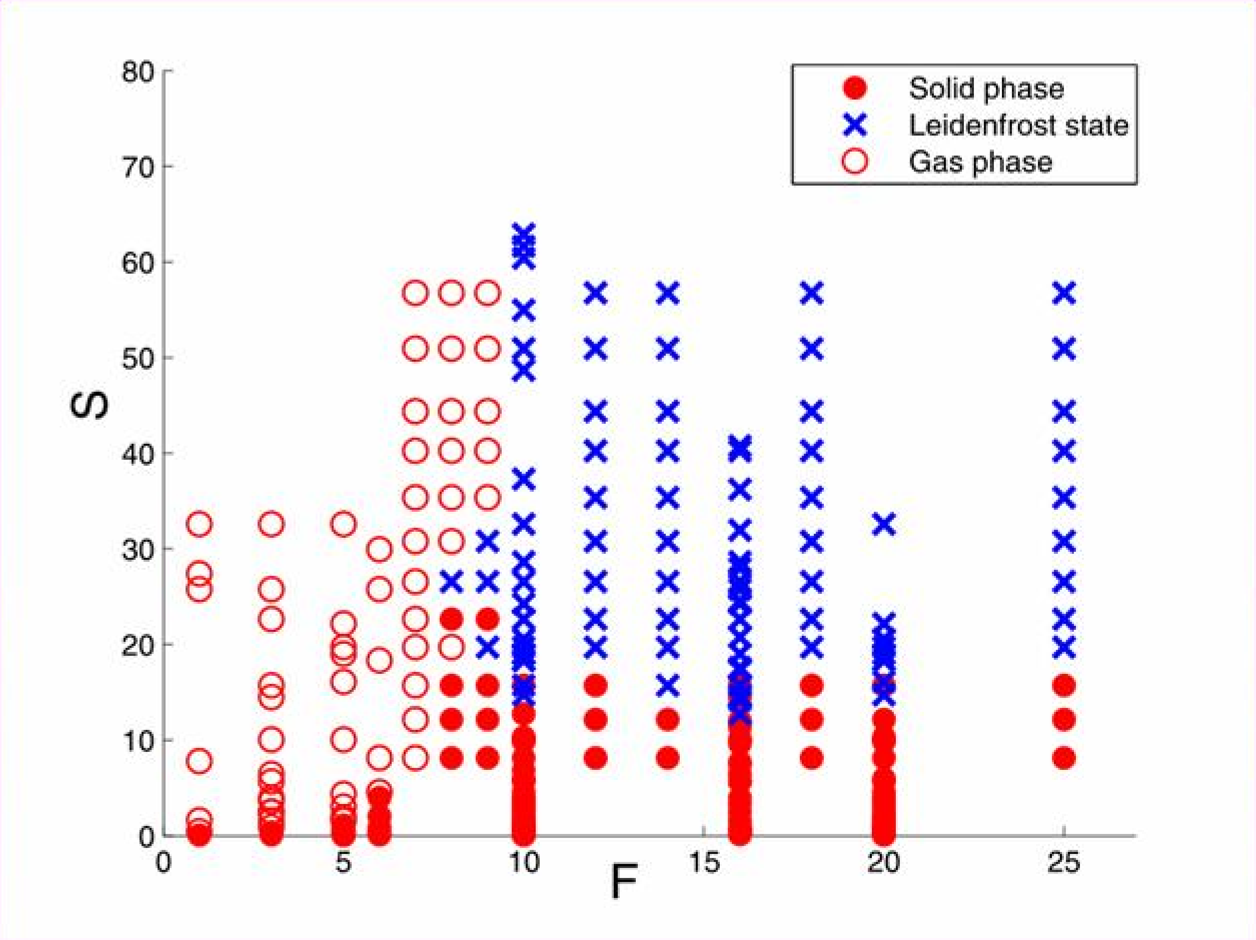
# Leidenfrost threshold




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

Experiment

# Phase diagram in S-F plane



Theory

# Hydrodynamic 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)

Theory

# Boundary conditions

- Constant 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: $S = \frac{m\left(a2\pi f\right)^2}{mgd}$

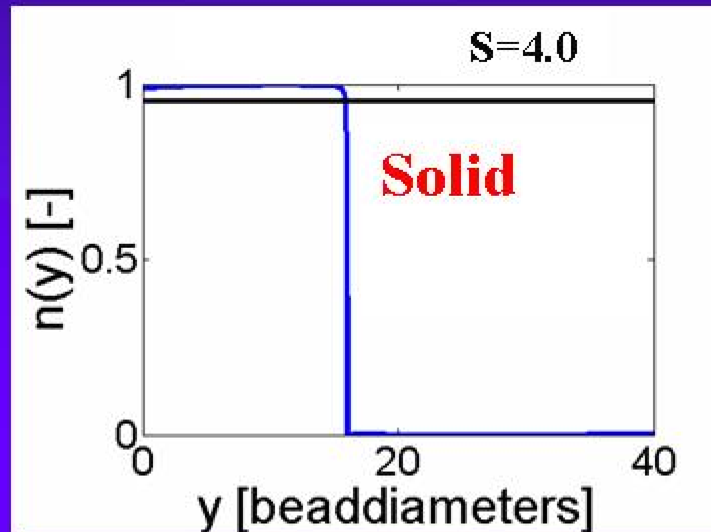
Inelasticity: $\varepsilon = (1 - e^2)$

Number of layers: $F$

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

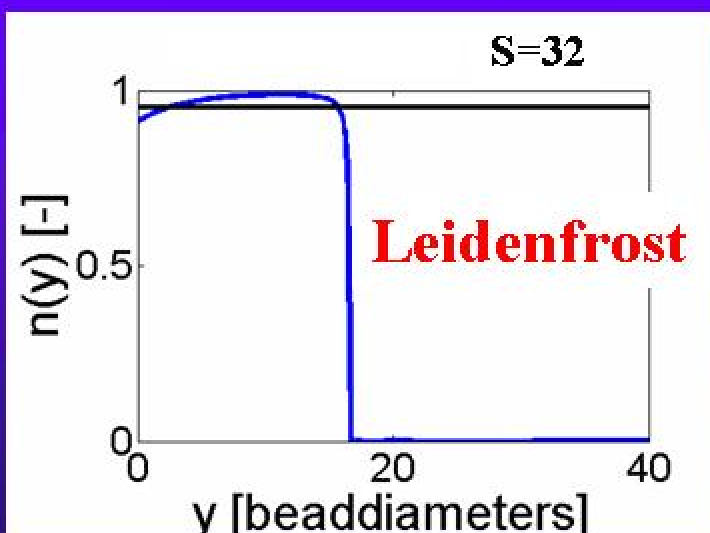
Theory

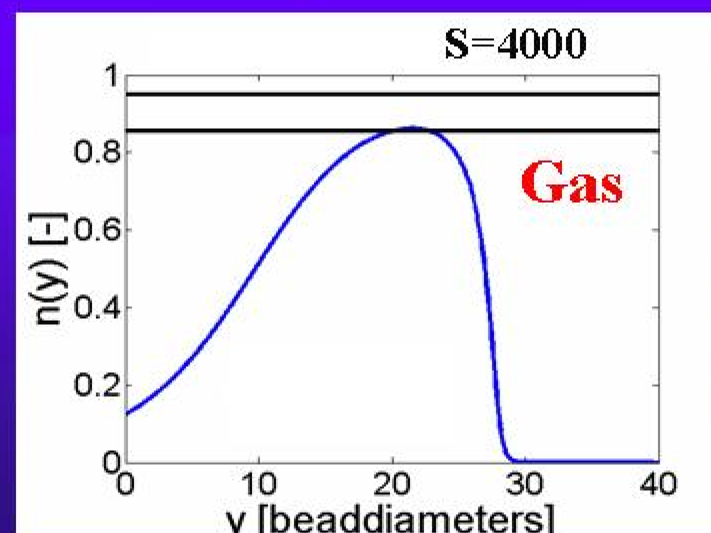
# Density profiles from model:




F = 16 layers

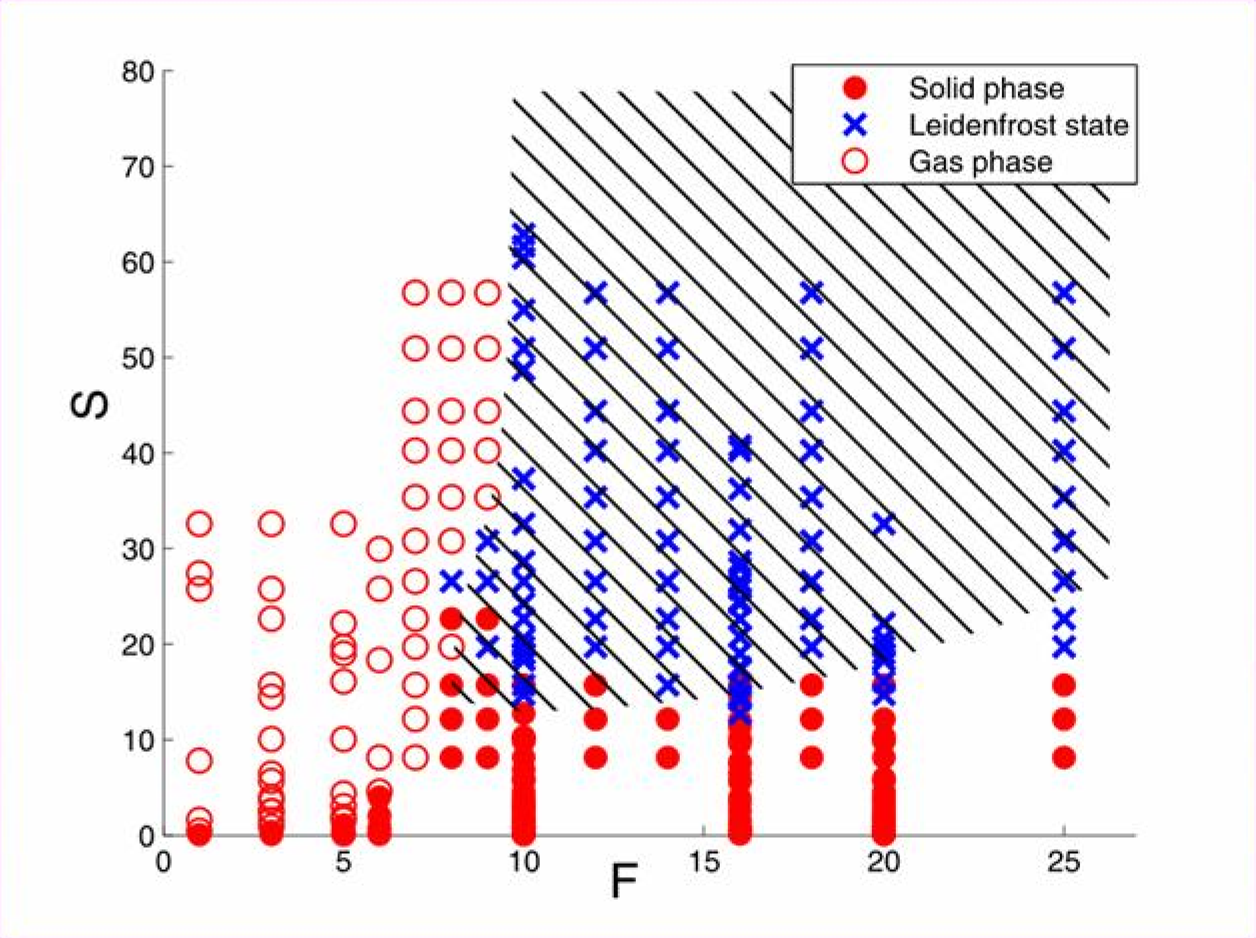
ε = 0.9



Experiment vs. Theory

# Phase diagram in S-F plane




Experiment and theory agree!

# Conclusions

- Granular Leidenfrost effect observed in experiment.
- Three relevant control parameters: $S$, $\varepsilon$, $F$ in experiment *and* theory.
- Phase diagram from experiment and theory *quantitatively* agree.