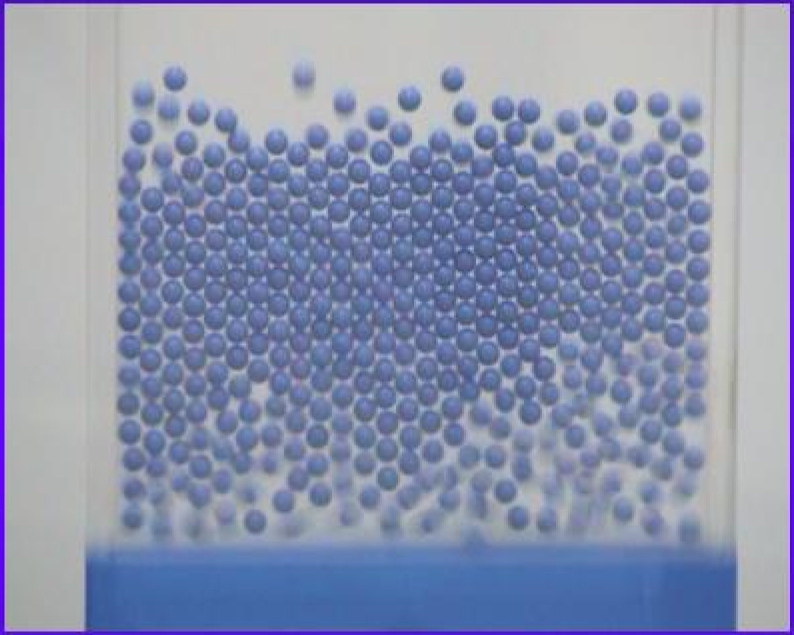
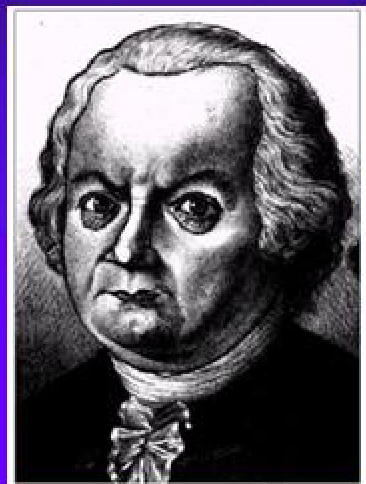
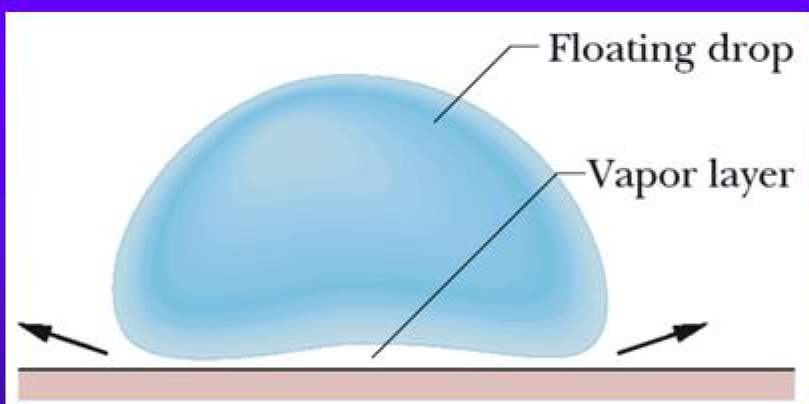
Granular Leidenfrost Effect



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

Johann Gottlob Leidenfrost (1756)

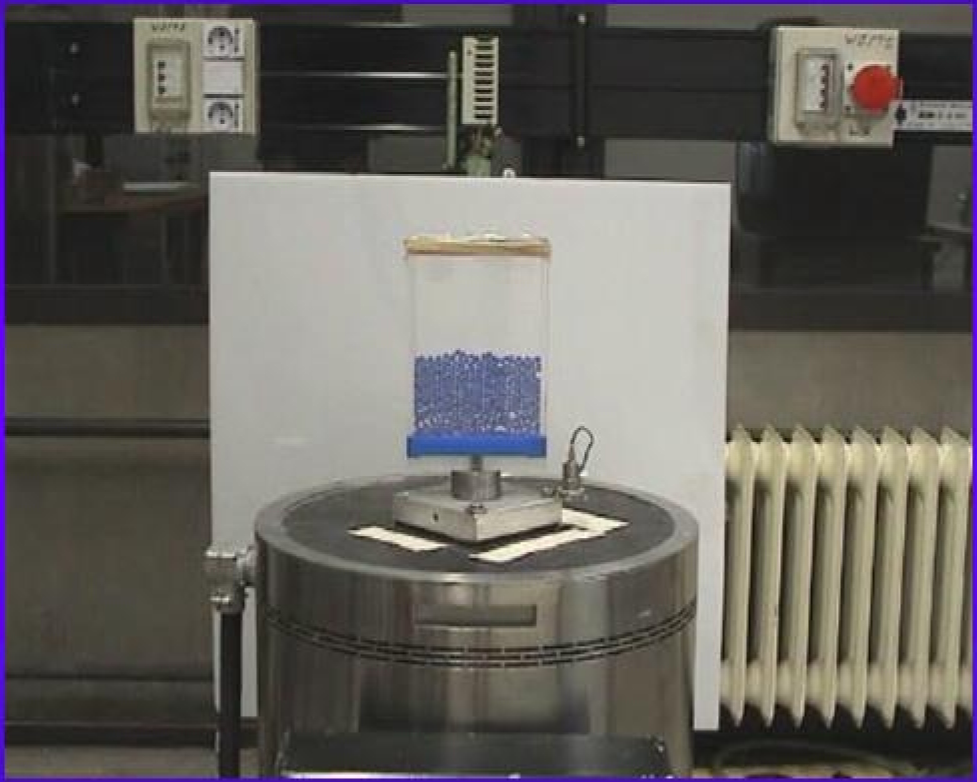




Drop of water on a hot plate (≥ 220° C)

Experiment

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

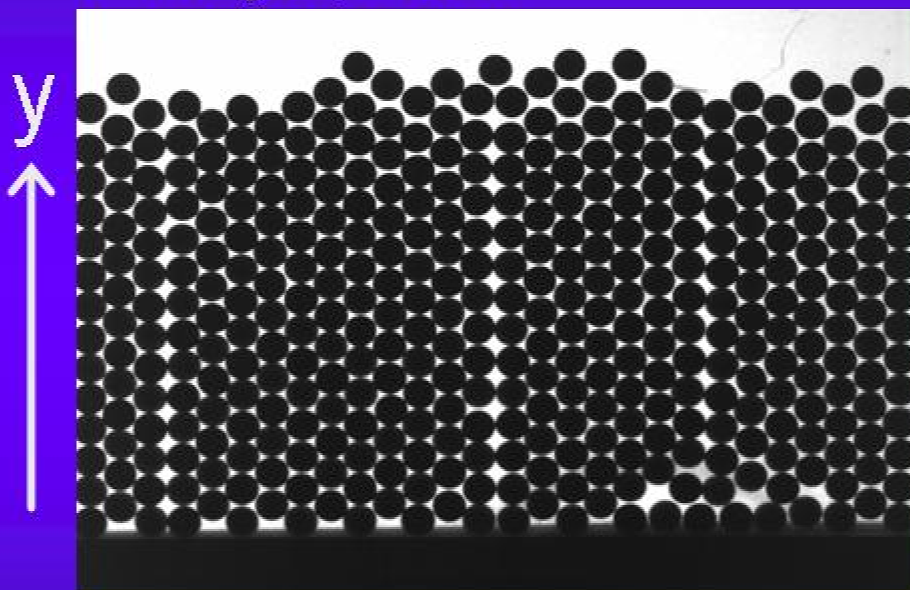
A = a/d = shaking amplitude

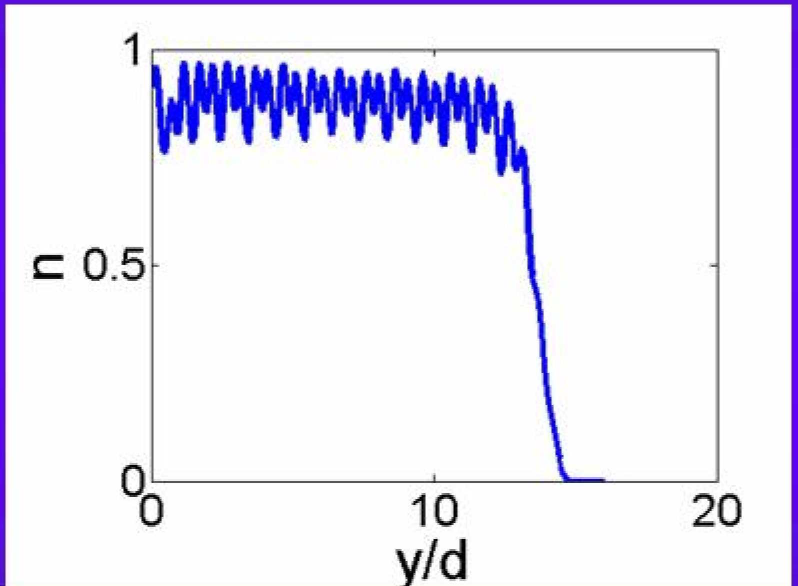
$\varepsilon = (1-e^2)$ = inelasticity (≈ 0.1)

Experiment

Leidenfrost state beyond critical acceleration Γ_c

F=16 layers, f=80Hz





$\Gamma =$ [illegible]

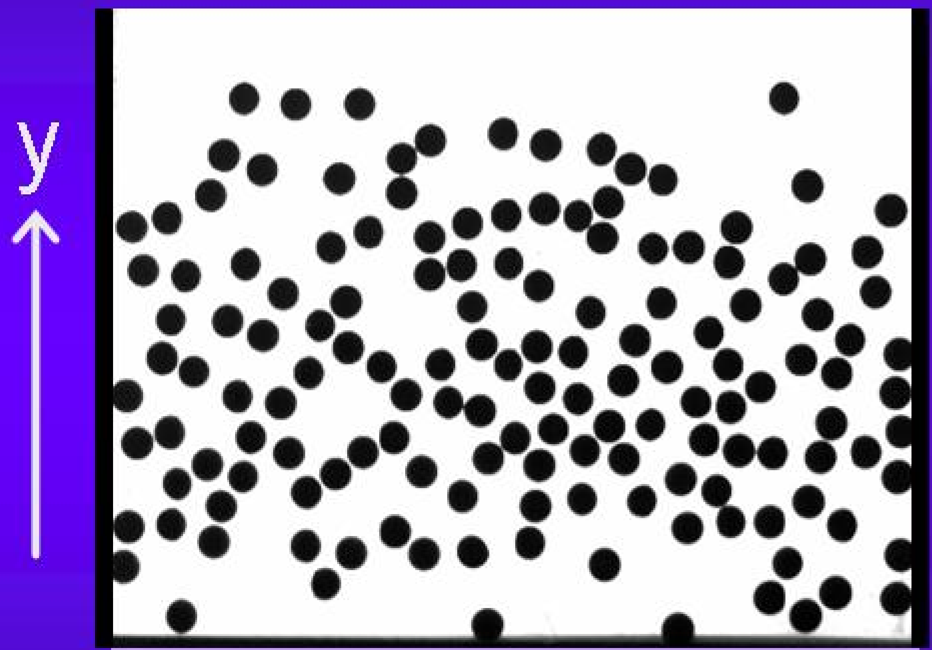
Leidenfrost state

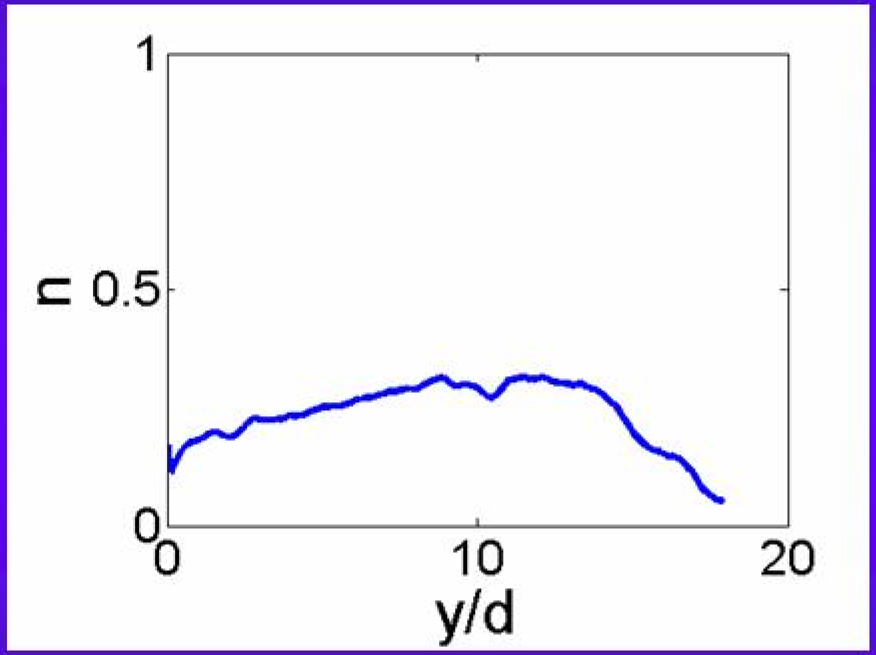
$\Gamma_c \approx 25$ (for F = 16 layers)

Experiment

Critical number of layers

Γ=51.5 @ 1000 fps



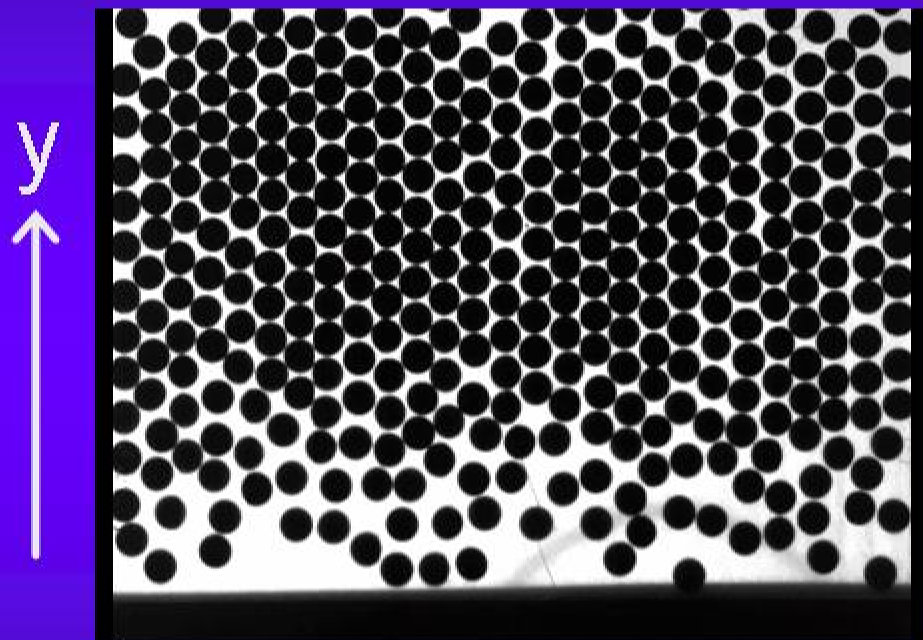


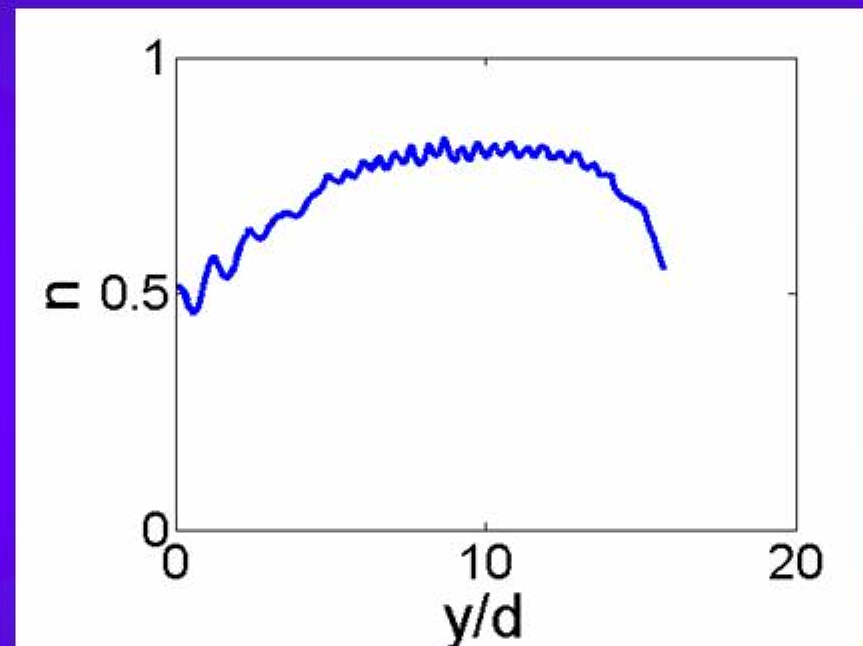
F = 6 layers

Gaseous state

Critical number of layers

Γ=51.5 @ 1000 fps





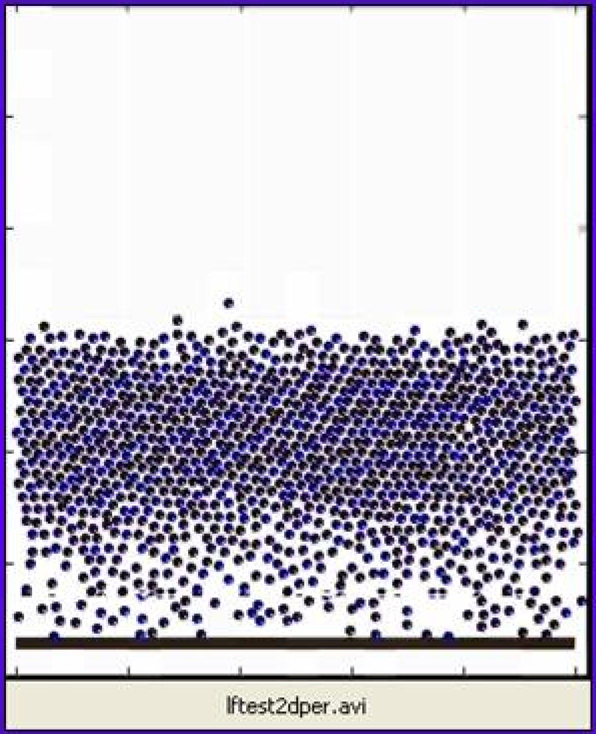
F = 16 layers

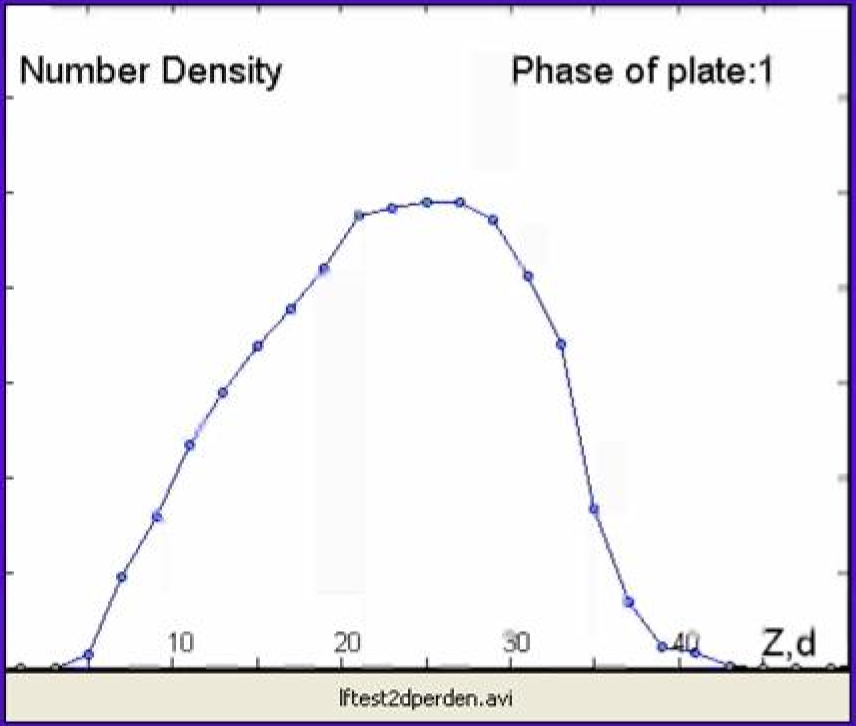
Leidenfrost state

Granular Leidenfrost effect only for F ≥8

Simulations by Jennifer Kreft

F=20, Γ=50, e=0.97





2D system: width 50d (periodic) × height 300d

Van Zon, Kreft, Goldman, Miracle, Swift, and Swinney, PRE 70, 040301(R), 2004

Experiment

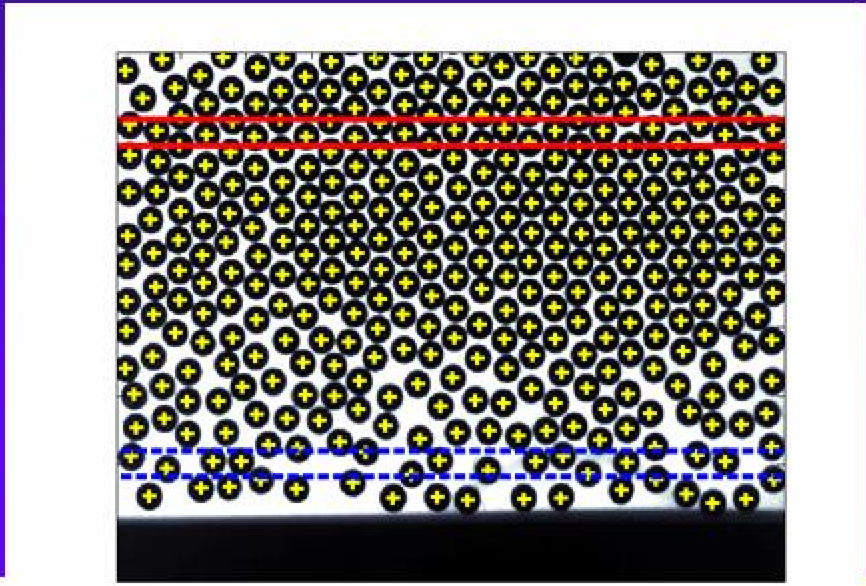
What's a suitable ***order parameter*** to distinguish between the different phases in the Leidenfrost state?

→ Employ the concept of *pair correlations:*

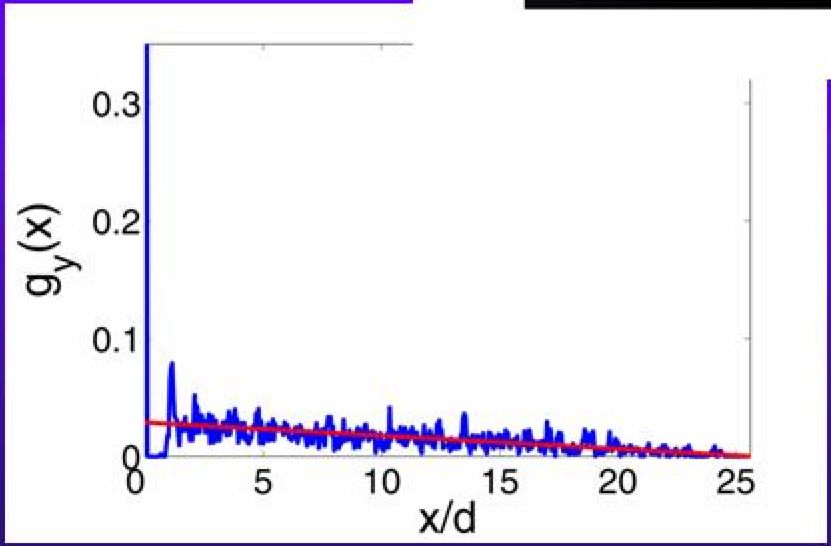
$$g_y(x) = \frac{1}{N} \sum_{i,j\ in\ (y, y+dy)} \sum_{i \neq j} \delta\left(x - \left(x_i - x_j\right)\right)$$

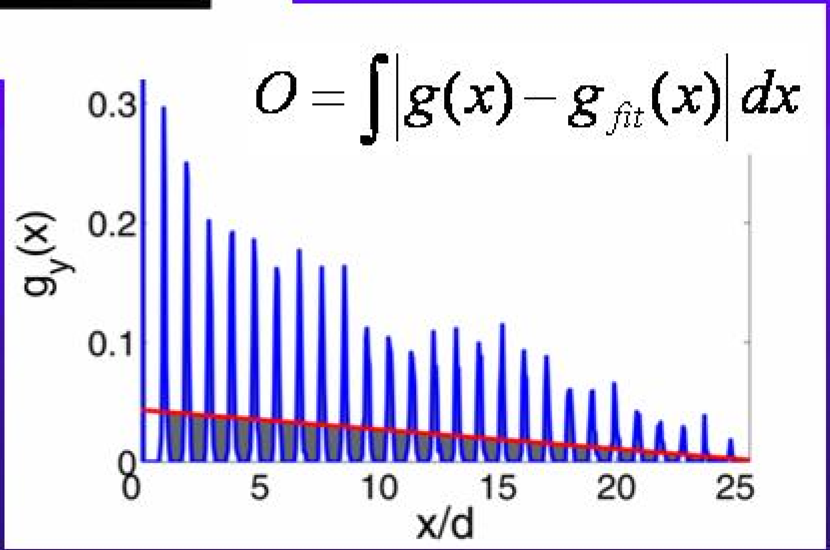
Experiment

Identifying the order parameter



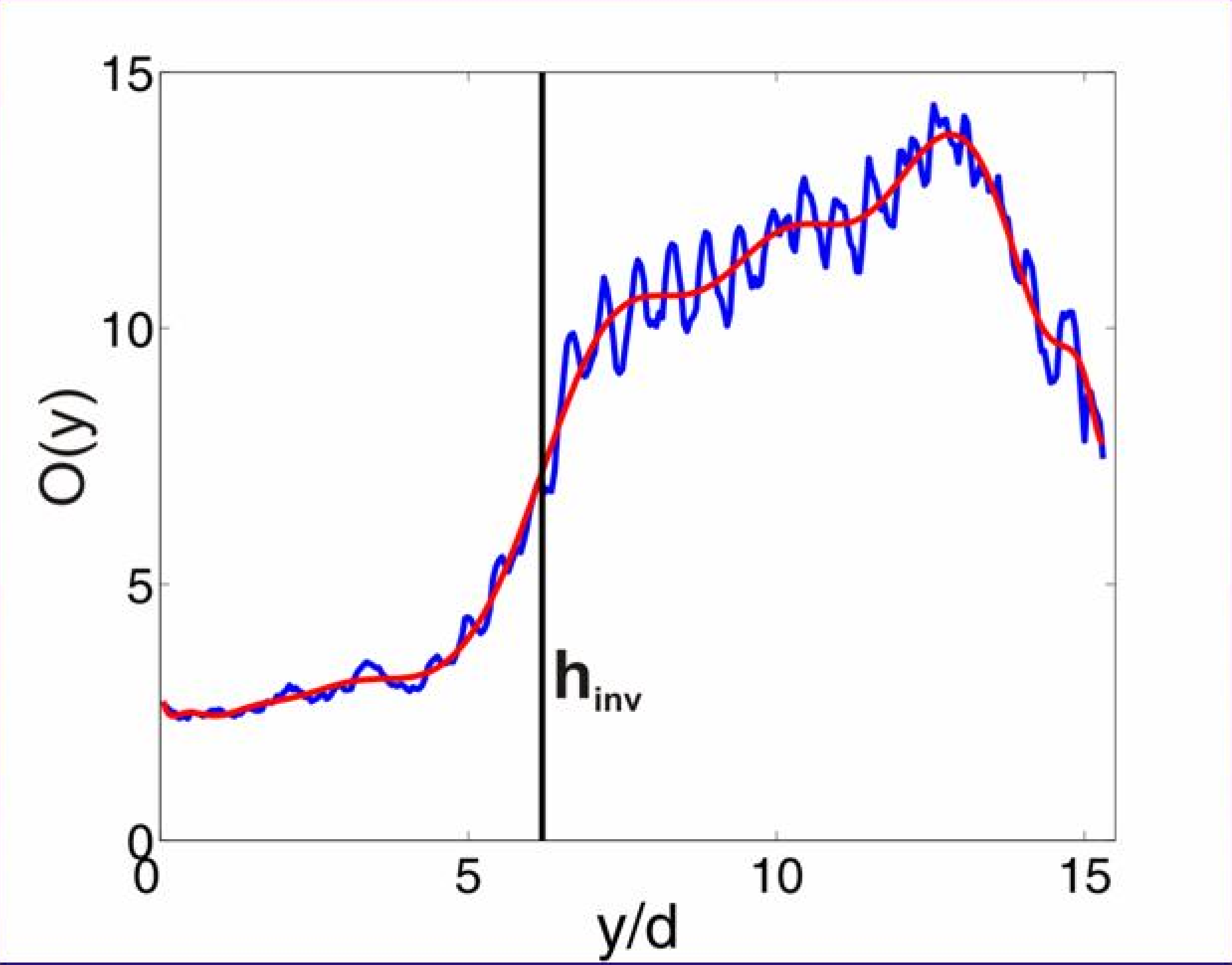
F=16 layers
Γ=64.4





Experiment

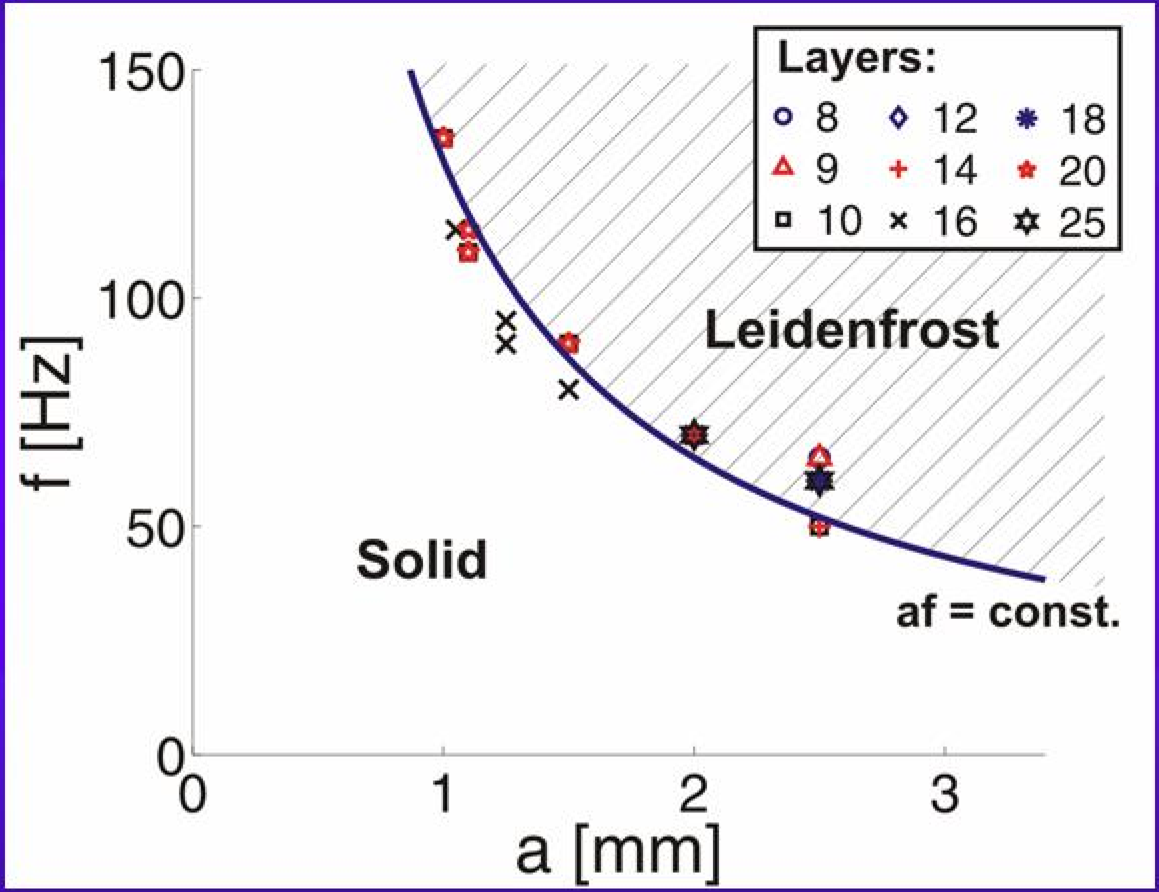
Order parameter *O* determines inversion height:



F=16 layers
Γ=64.4

Experiment

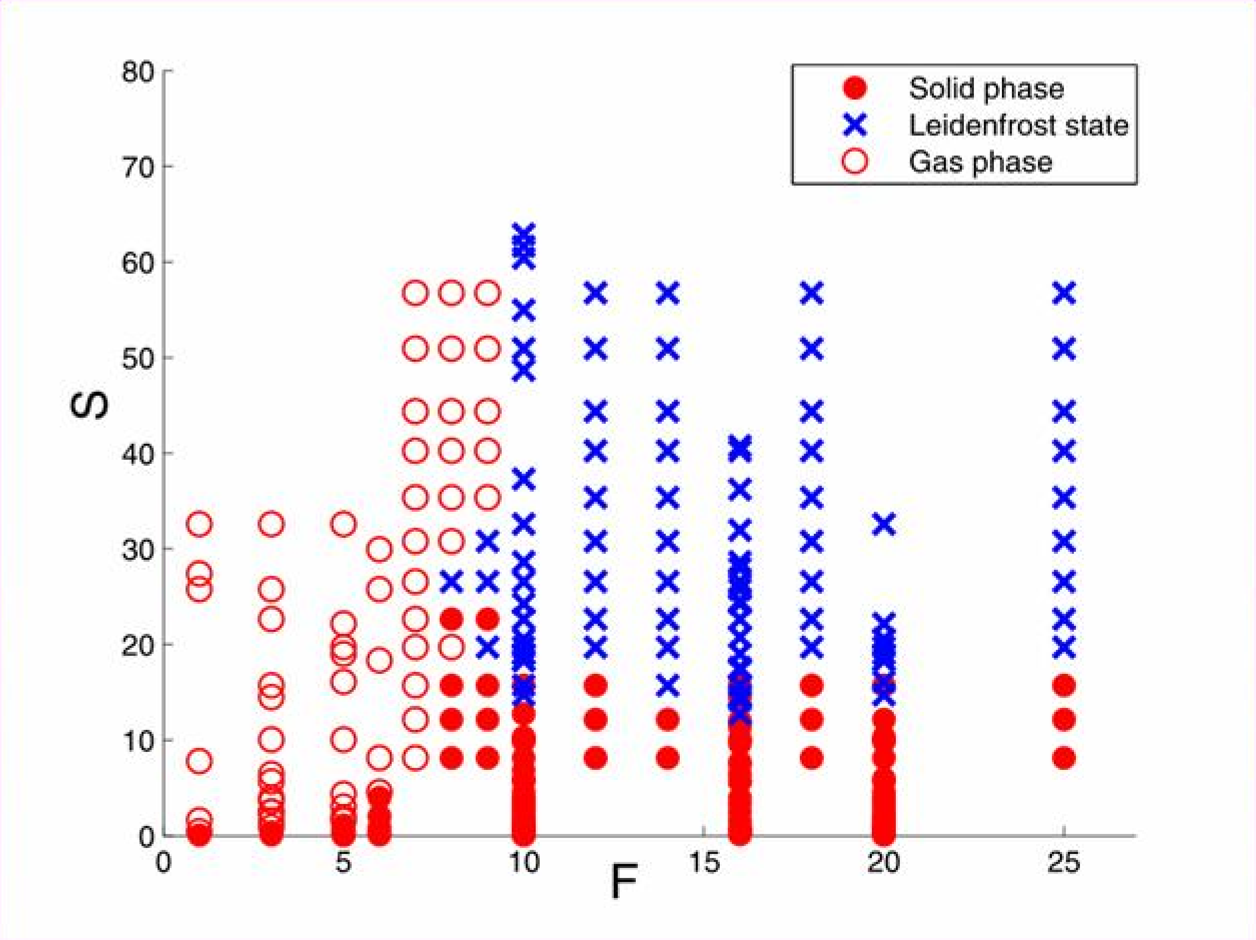
Leidenfrost threshold



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

Experiment

Phase diagram in S-F plane



Theory

Hydrodynamic model

(1) **Force balance:**

$$\frac{dp}{dy} = -mgn$$

(2) **Balance between heat flux and dissipation:**

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

(3) **Equation of state:** $p = nT\dfrac{n_{cp}+n}{n_{cp}-n}$

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

Theory

3 Boundary conditions

- **Prescribed granular temperature at bottom:**

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

- **Zero heat flux at 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

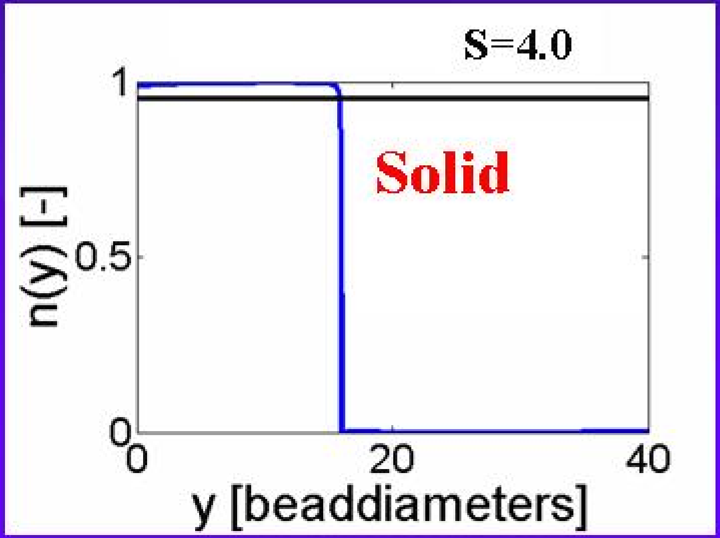
Just as in experiment, the relevant shaking parameter is $S \equiv \Gamma A$ (not Γ)

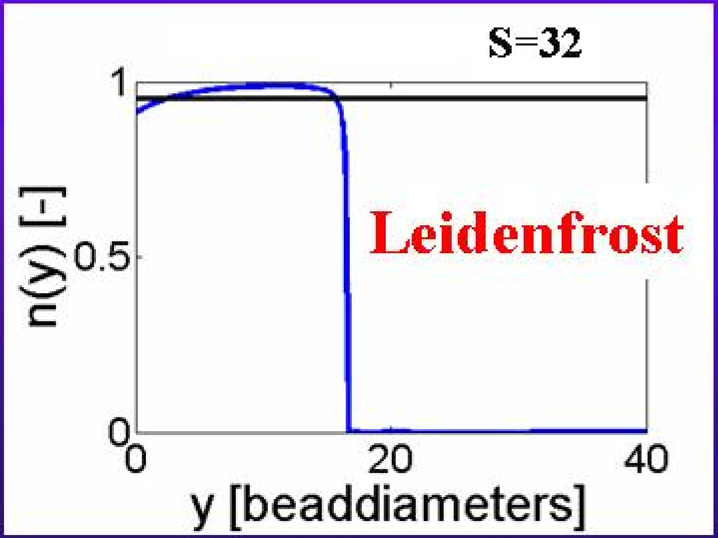
Theory

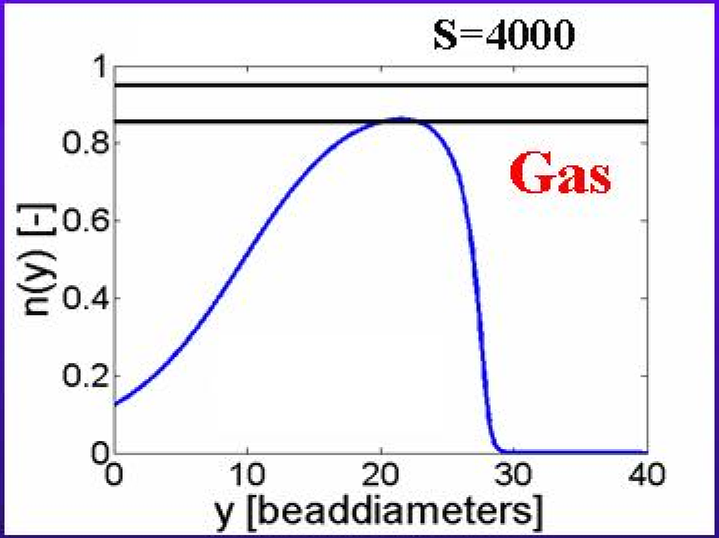
Density profiles from model:

F = 16 layers

ε = 0.1

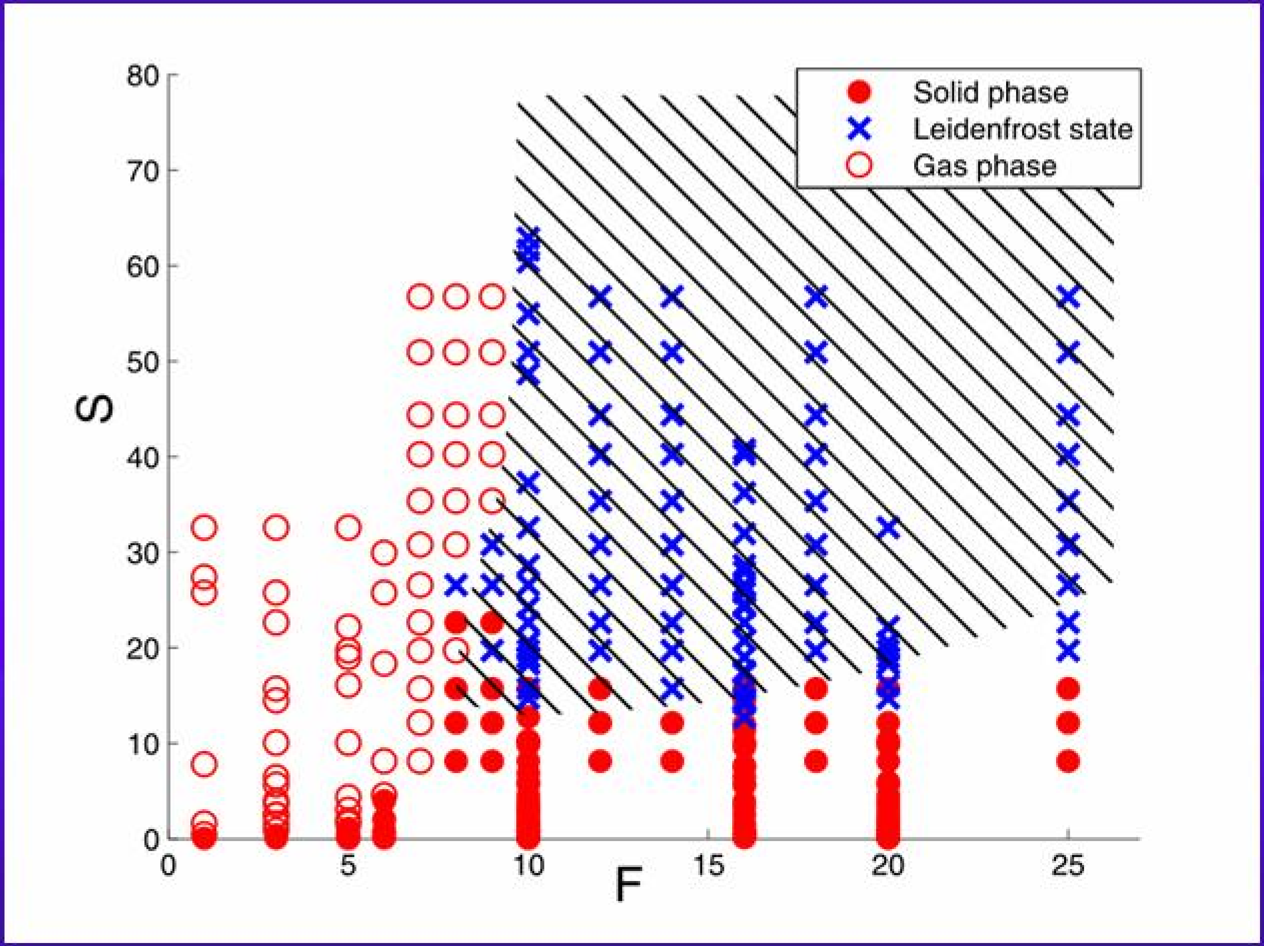






Experiment vs. Theory

Phase diagram in S-F plane



Experiment and theory agree!

Conclusions

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

P. Eshuis, K. van der Weele, D. van der Meer, D. Lohse, *Granular Leidenfrost effect: Experiment and theory of floating particle clusters*, PRL **95** (in press, 2005).