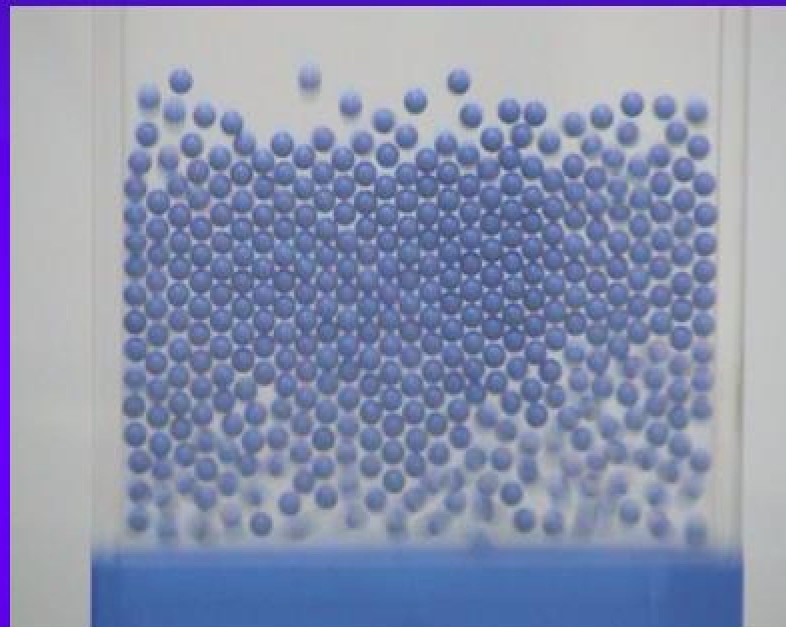
Granular Leidenfrost Effect



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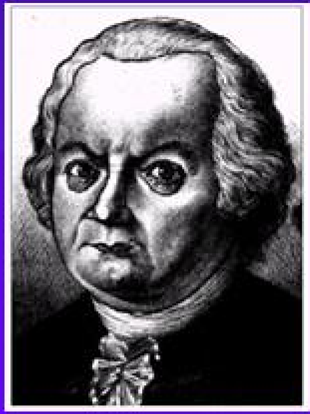
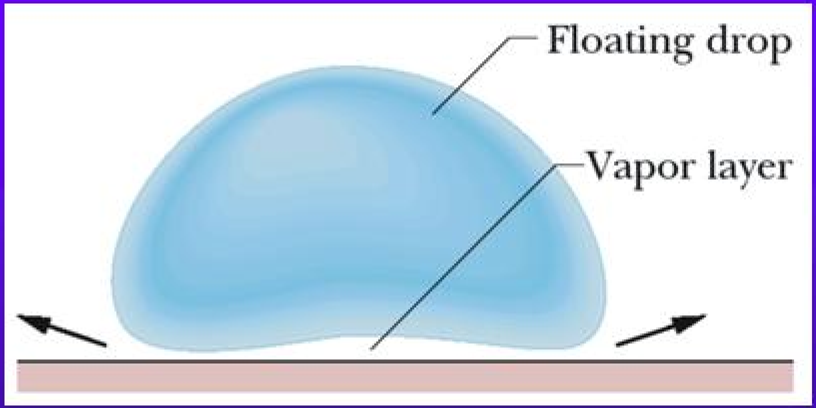
FOM

Johann Gottlob Leidenfrost (1756)

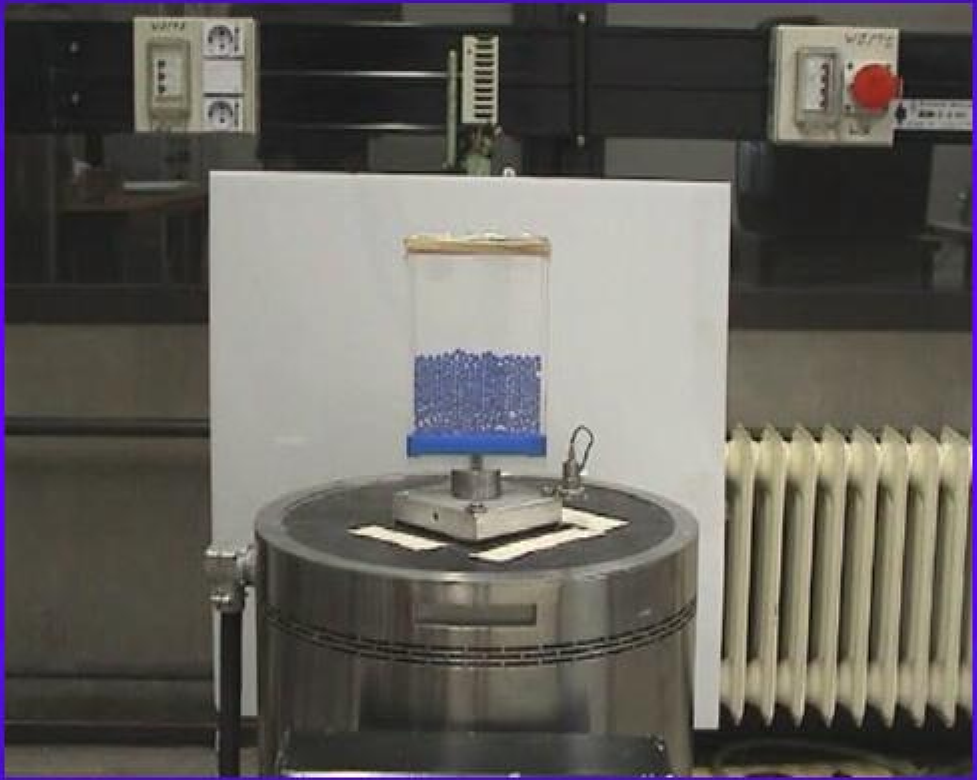




Drop of water on a hot plate ($\approx$220° C)

Experiment

The granular version:



Granular temperature at bottom ~ Shaking strength

2D container: 10x0.45x14cm, Glass beads: d=4mm, ρ=2.5g/cm^3, e$\approx$0.9

What are the (dimensionless) control parameters?

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

F = number of layers

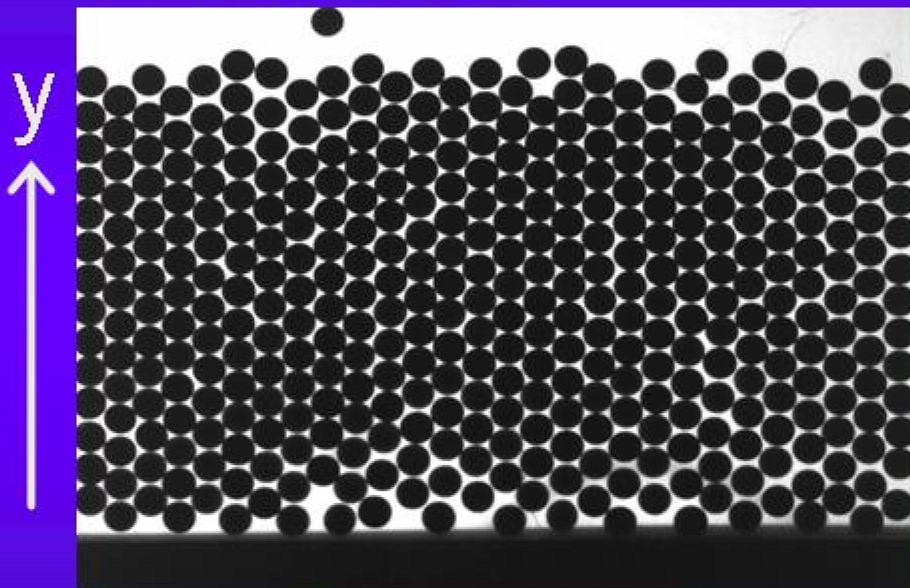
A = a/d = shaking amplitude

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

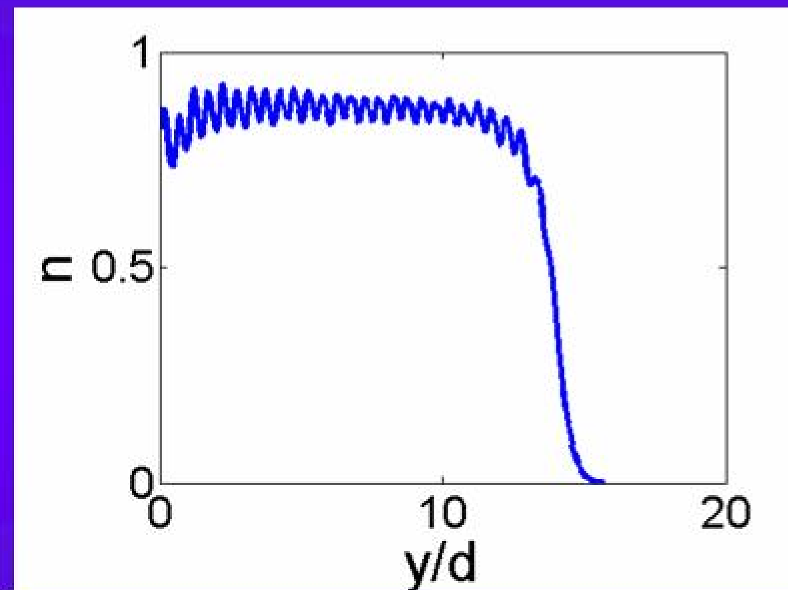
Experiment

Leidenfrost state beyond critical shaking strength Γ_c

F=16 layers, f=80Hz



$\Gamma = 25.8$

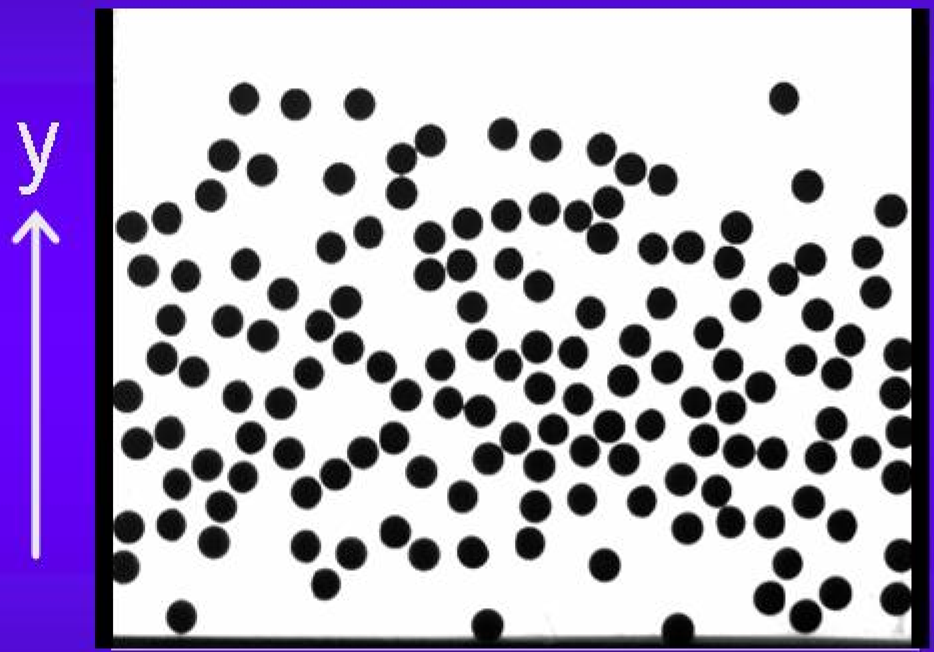


Transition

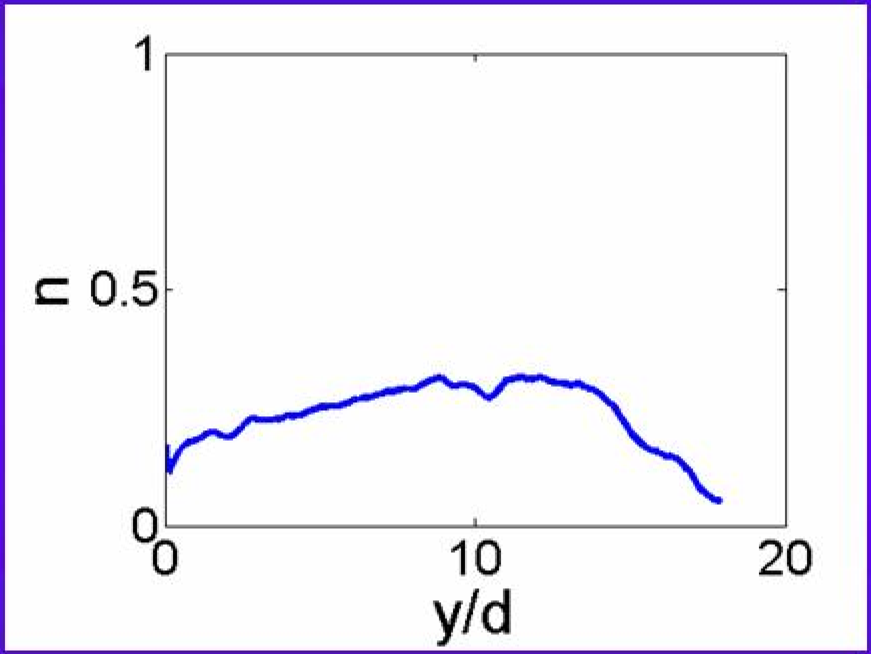
$\Gamma_c \approx 25$ (for F = 16 layers)

Critical number of layers

Γ=51.5 @ 1000 fps



F = 6 layers



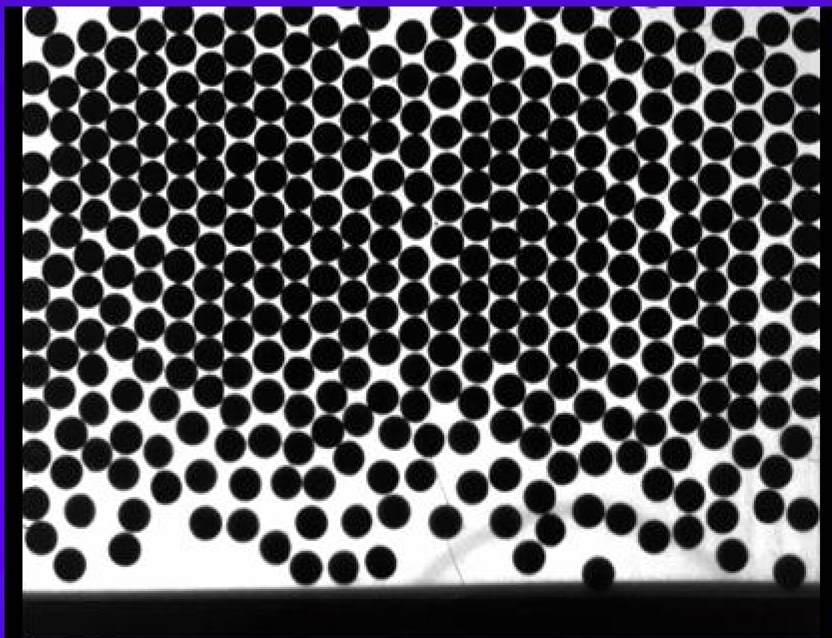
Gaseous state

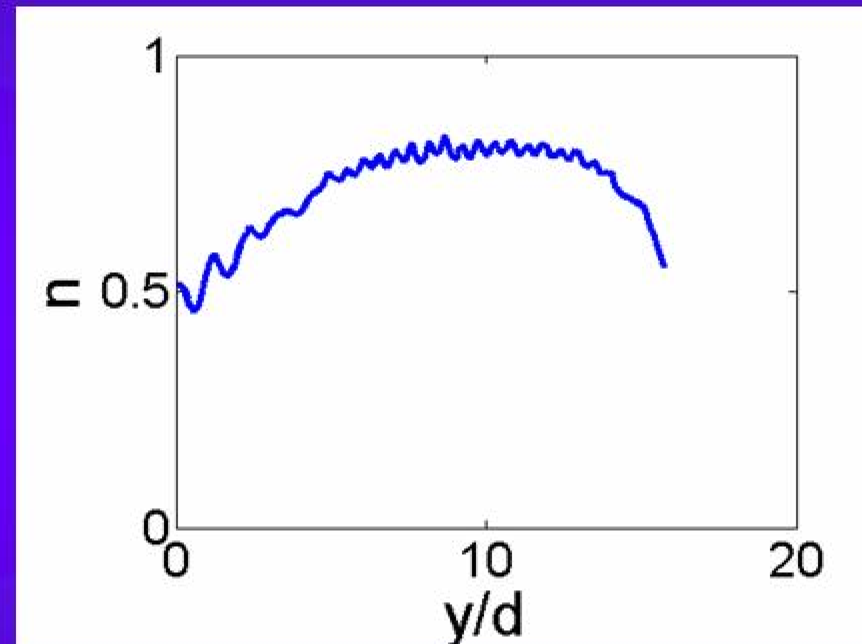
Experiment

Critical number of layers

Γ=51.5 @ 1000 fps

y





F = 16 layers

Leidenfrost state

Granular Leidenfrost effect only for F $\geq$10

Experiment

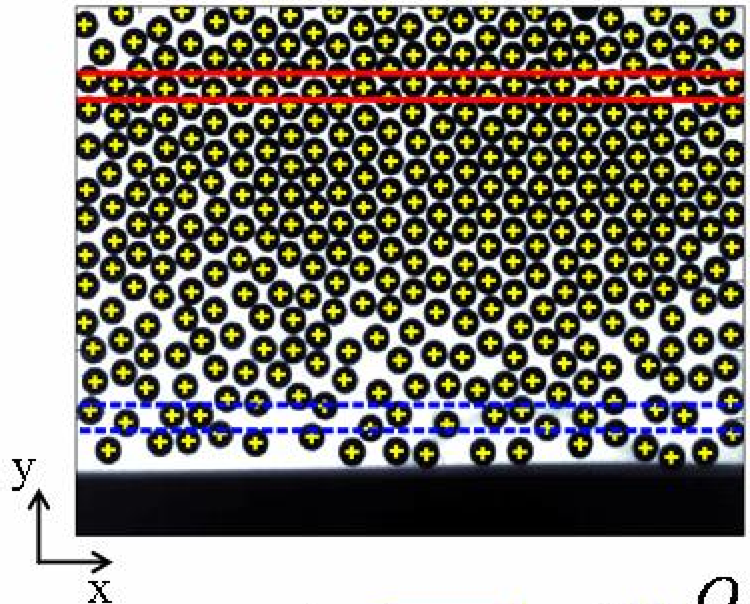
What's a suitable ***order parameter*** to distinguish between the different phases in the Leidenfrost state?

→ Employ the concept of *pair correlations*:

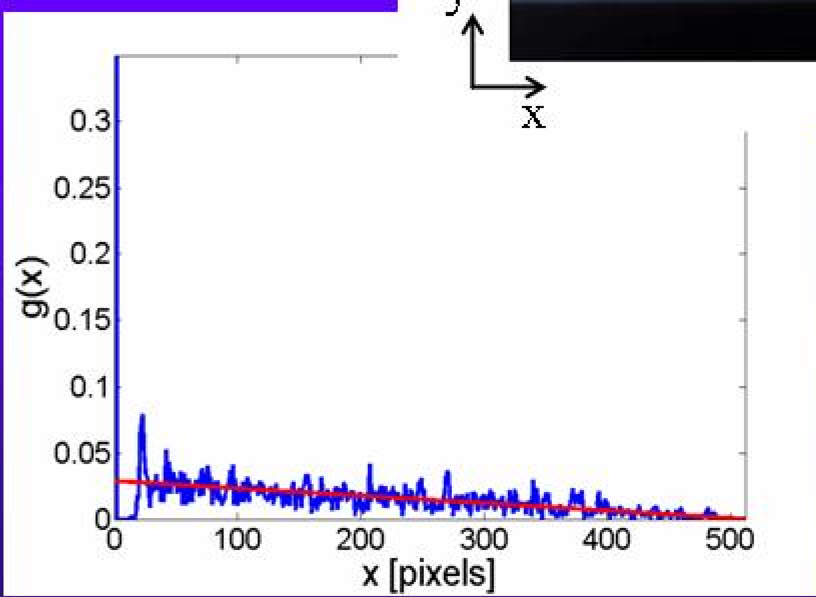
$$g(x;y) = \frac{1}{\#} \sum_{\substack{particles\ j\ in \\ strip\ (y,y+dy)}} \sum_{i \neq j} \delta\left(x - \left(x_i - x_j\right)\right)$$

Experiment

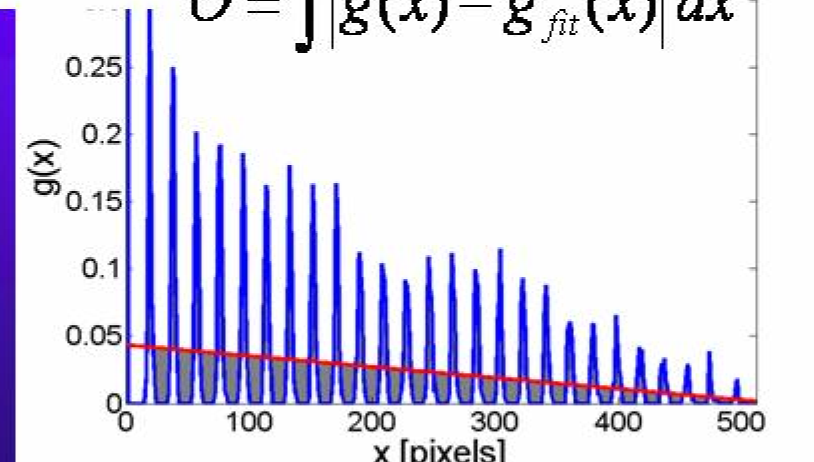
Identifying the order parameter



F=16 layers
Γ=64.4

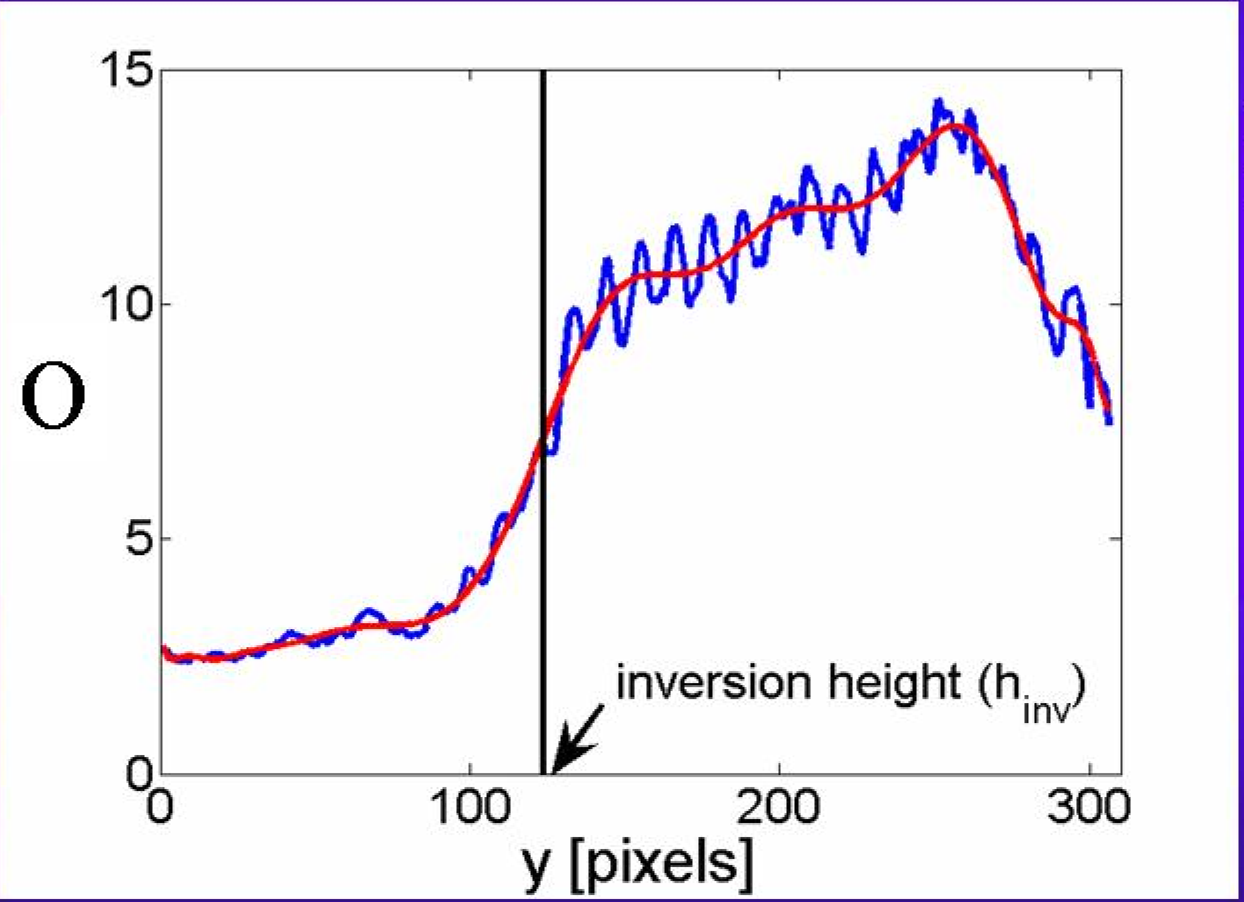


$$O = \int \left| g(x) - g_{fit}(x) \right| dx$$



Experiment

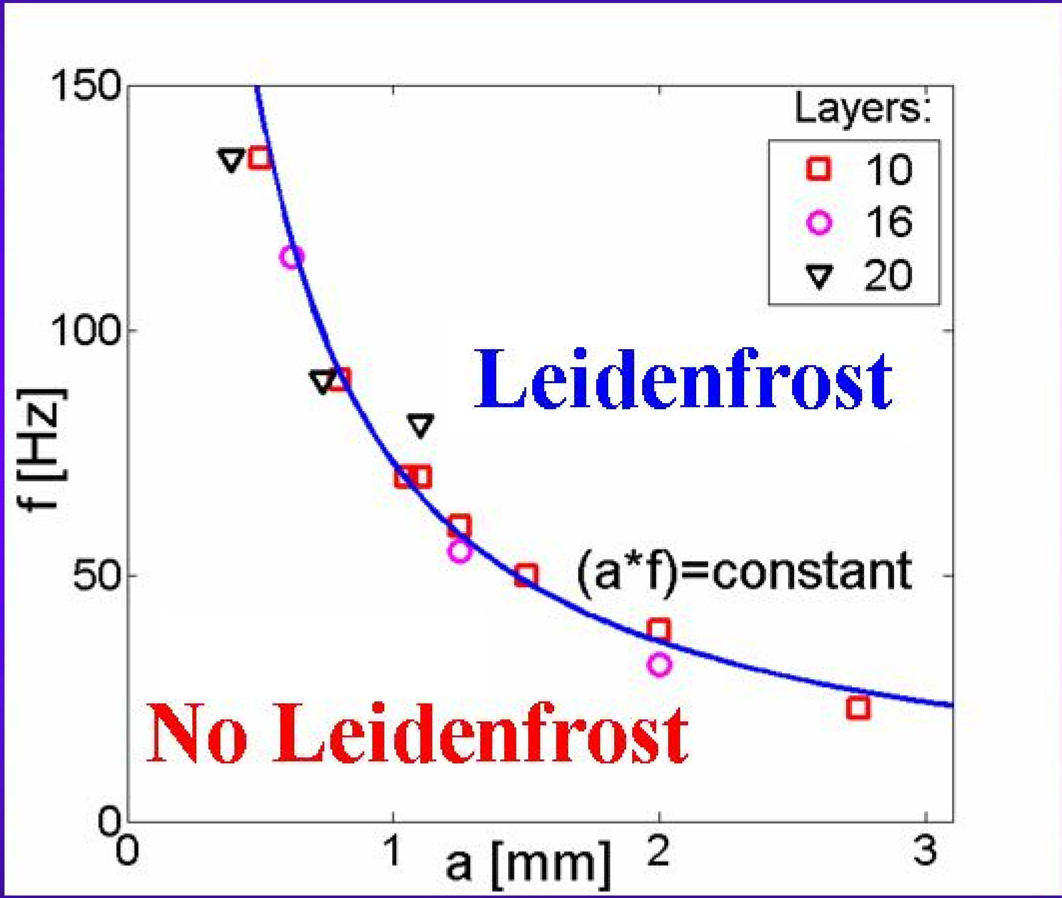
Order parameter *O* determines inversion height:



F=16 layers
Γ=64.4

Experiment

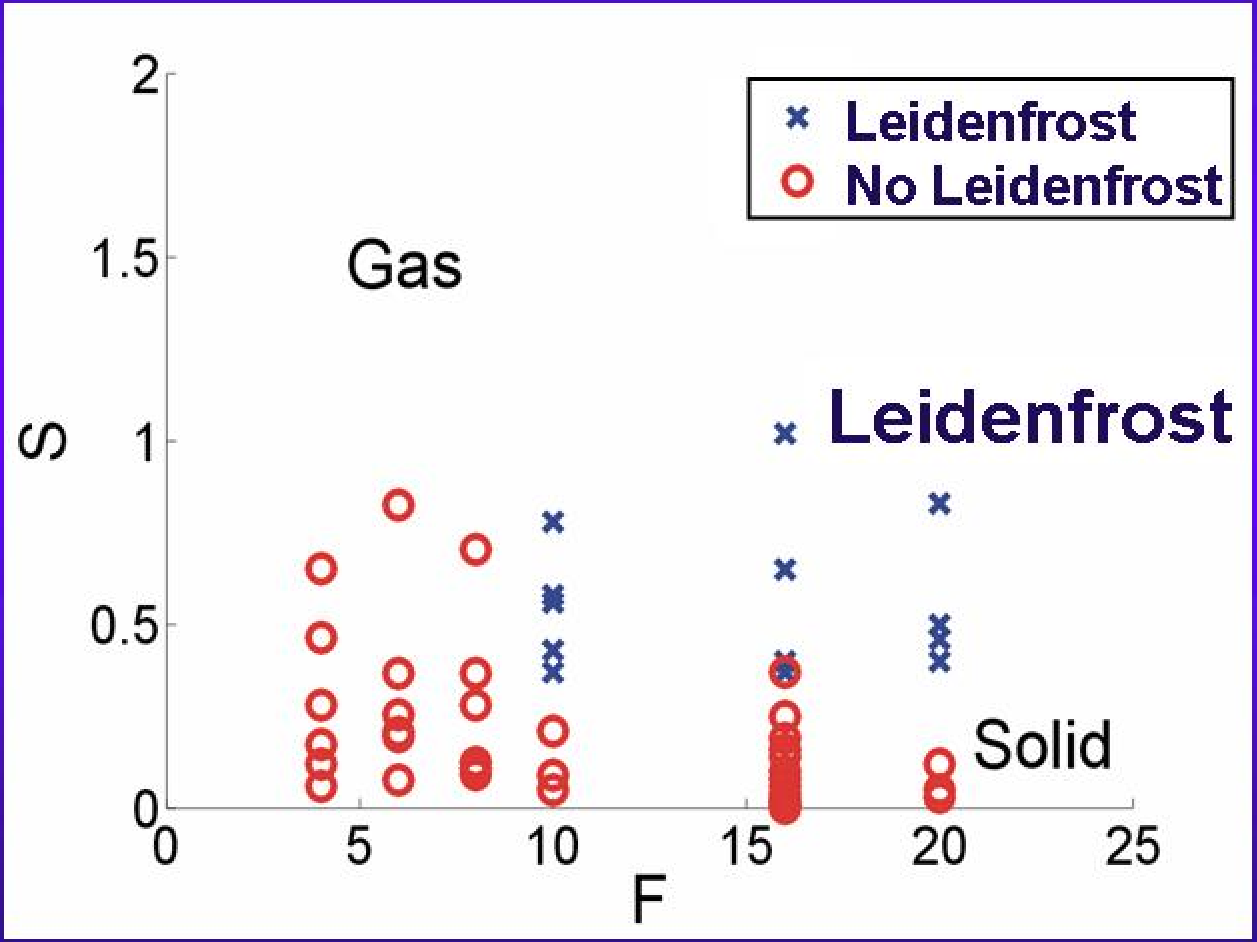
Leidenfrost threshold



Transition at constant $(a^*f)^2 \propto \Gamma A \equiv S$

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:

$$\left.\frac{dT}{dy}\right|_{y\to\infty} = 0$$

- Conservation of total number of particles:

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

Theory

Dimensionless control parameters

Energy input: $S = \frac{m(af)^2}{mgd}$

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

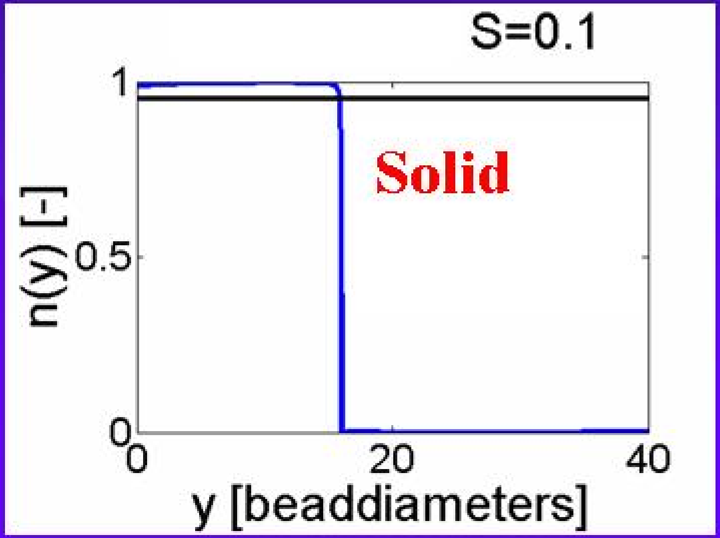
Number of layers: F

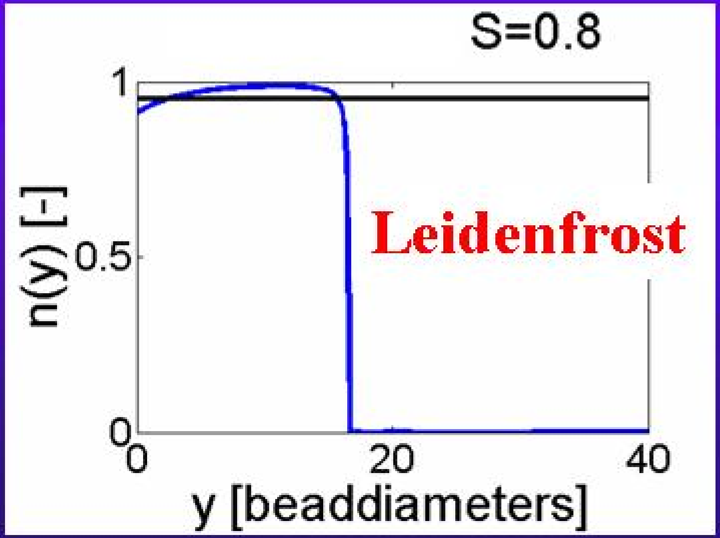
Note: Relevant shaking parameter is not Γ, but $S \equiv \Gamma A$

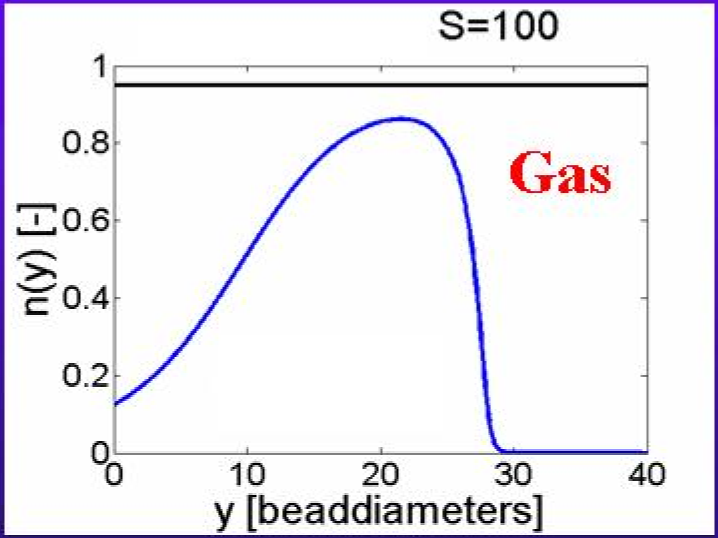
Density profiles from model:

F = 16 layers

$\varepsilon = 0.9$

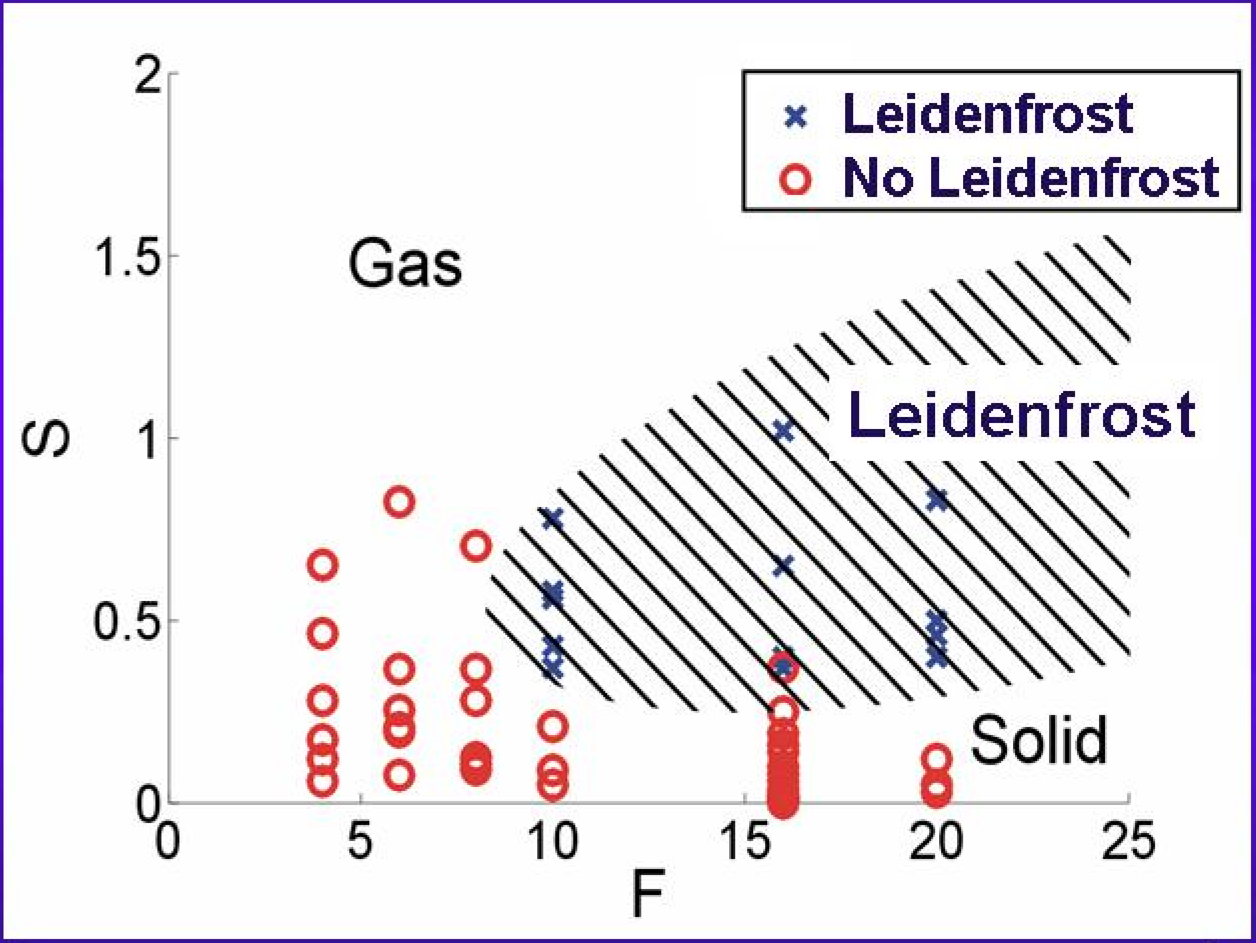






Experiment vs. Theory

Phase diagram in S-F plane



Experiment and theory agree!

Conclusions

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