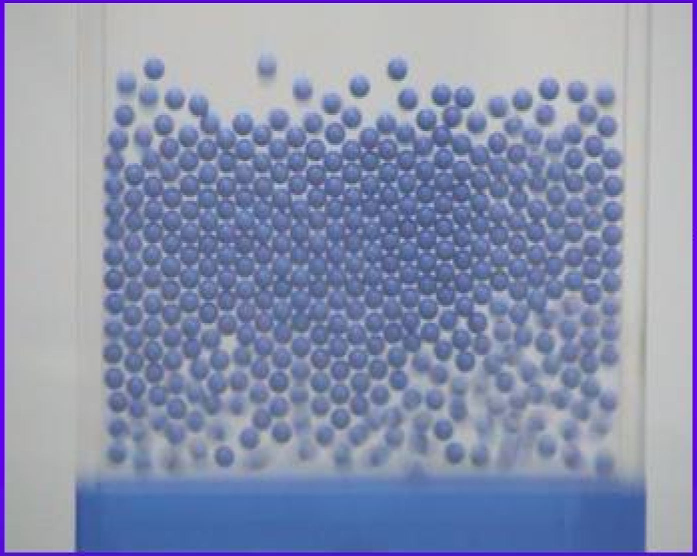
Granular Leidenfrost Effect

Peter Eshuis



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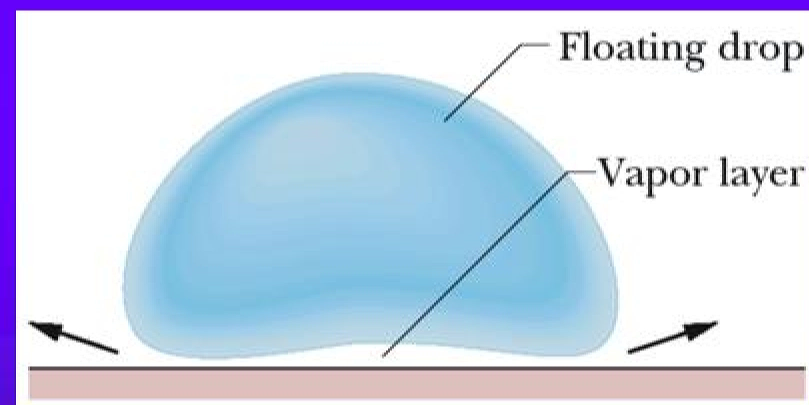
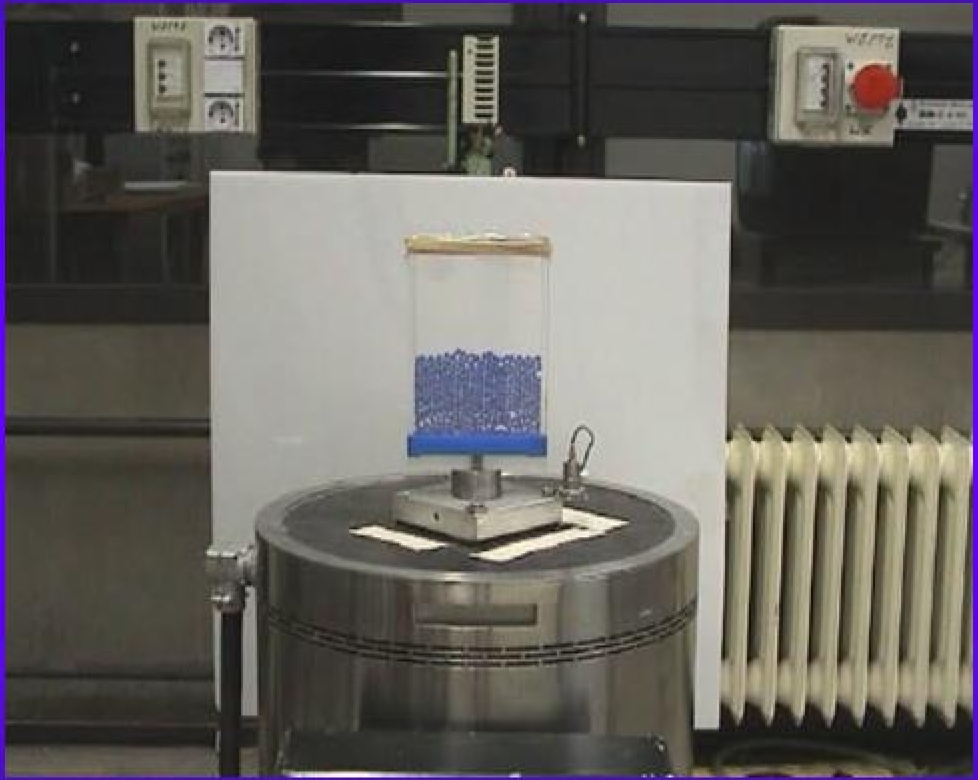
Original Leidenfrost effect

Johann Gottlob Leidenfrost, 1756



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

Granular Leidenfrost effect



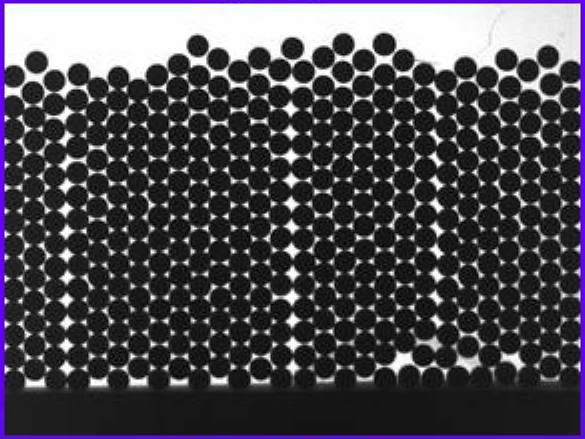
Quasi-2D container: 10x0.45x14cm

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

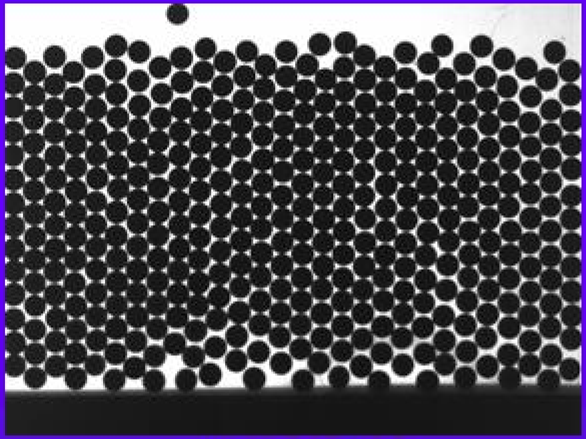
Experiments: shaking strength

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

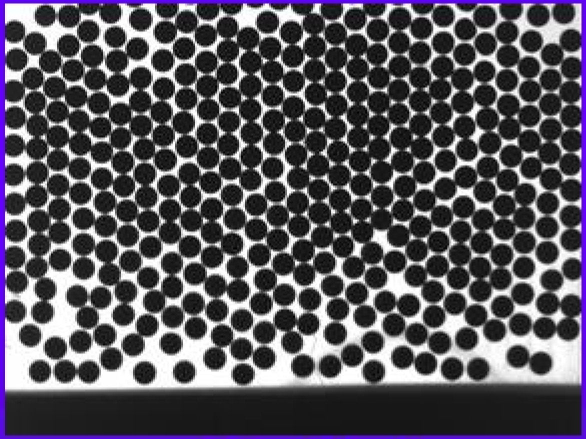
F=16 layers, f=80Hz



$\Gamma=7.7$



$\Gamma=25.8$

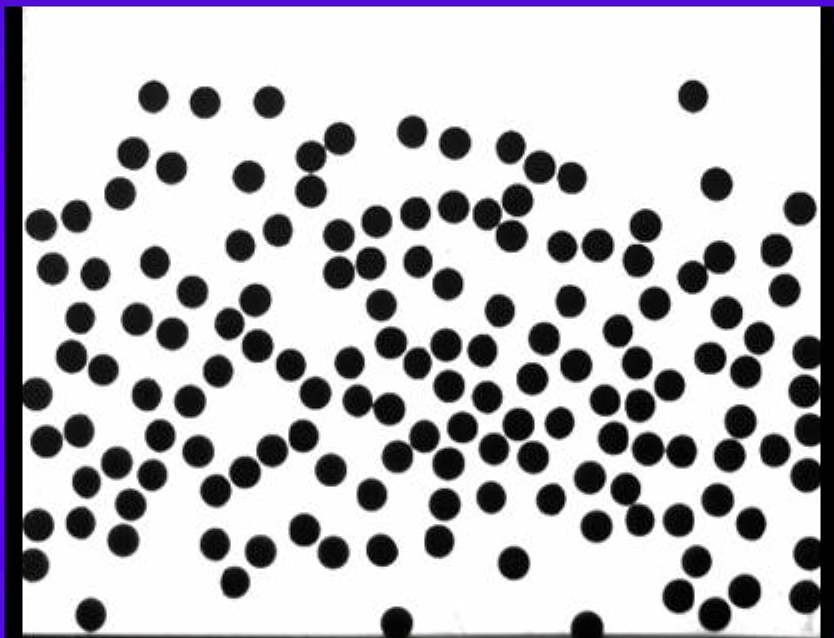


$\Gamma=51.5$

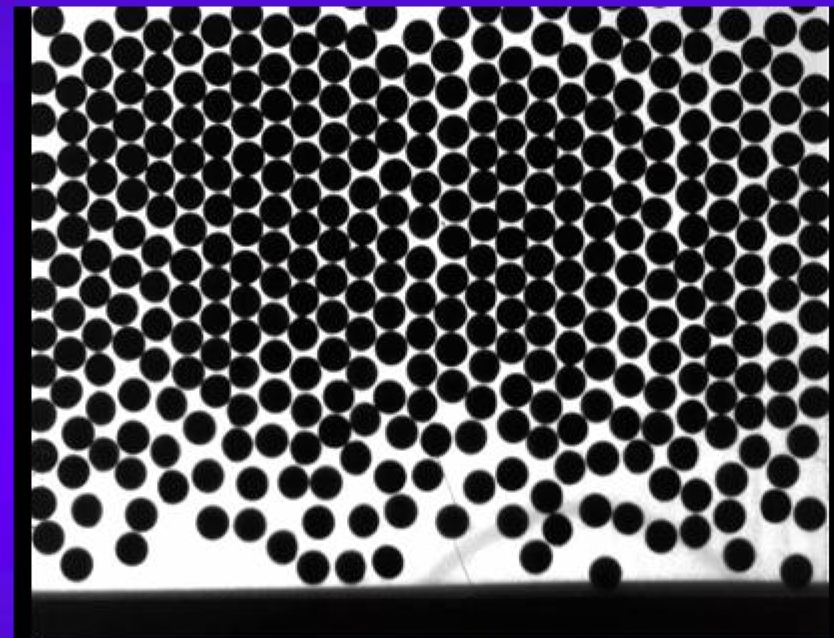
Density Inversion for $\Gamma_c > 25$ (for F=16)

Experiments: number of layers

$\Gamma=51.5$ @ 1000 fps



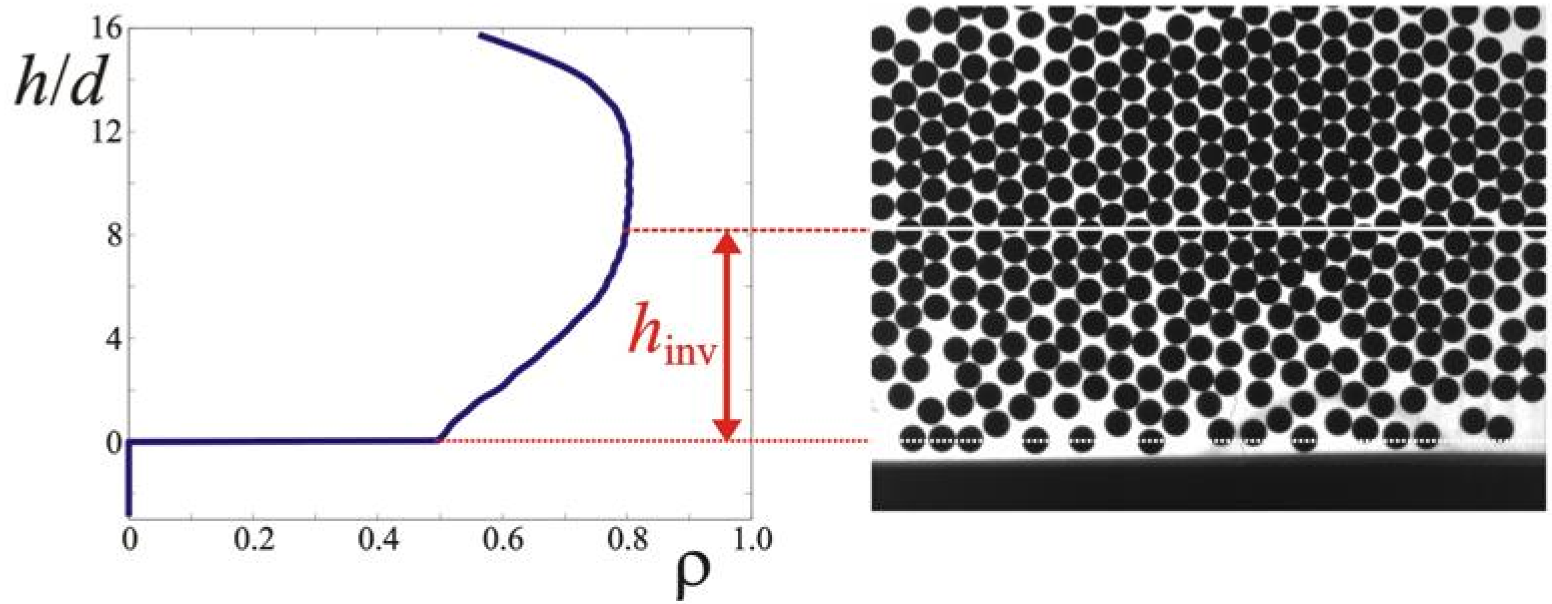
F=6 layers



F=16 layers

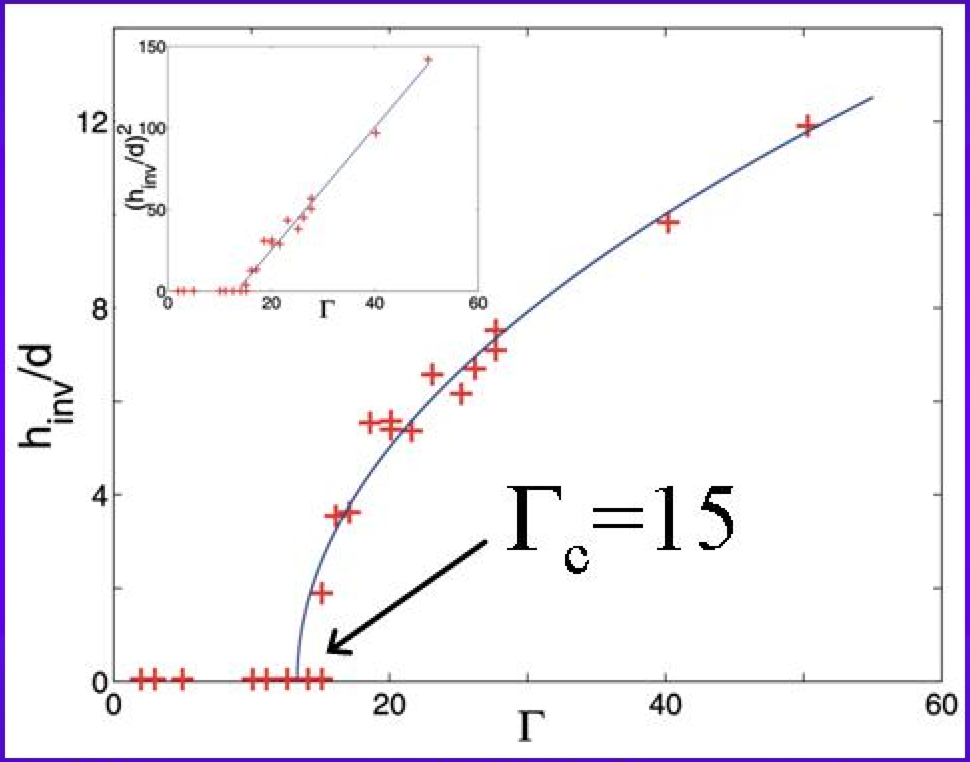
Density Inversion only for $F\geq10$

Experiments: inversion height



(F=16 layers, Γ=51.5)

Experiments: phase transition for h_{inv}



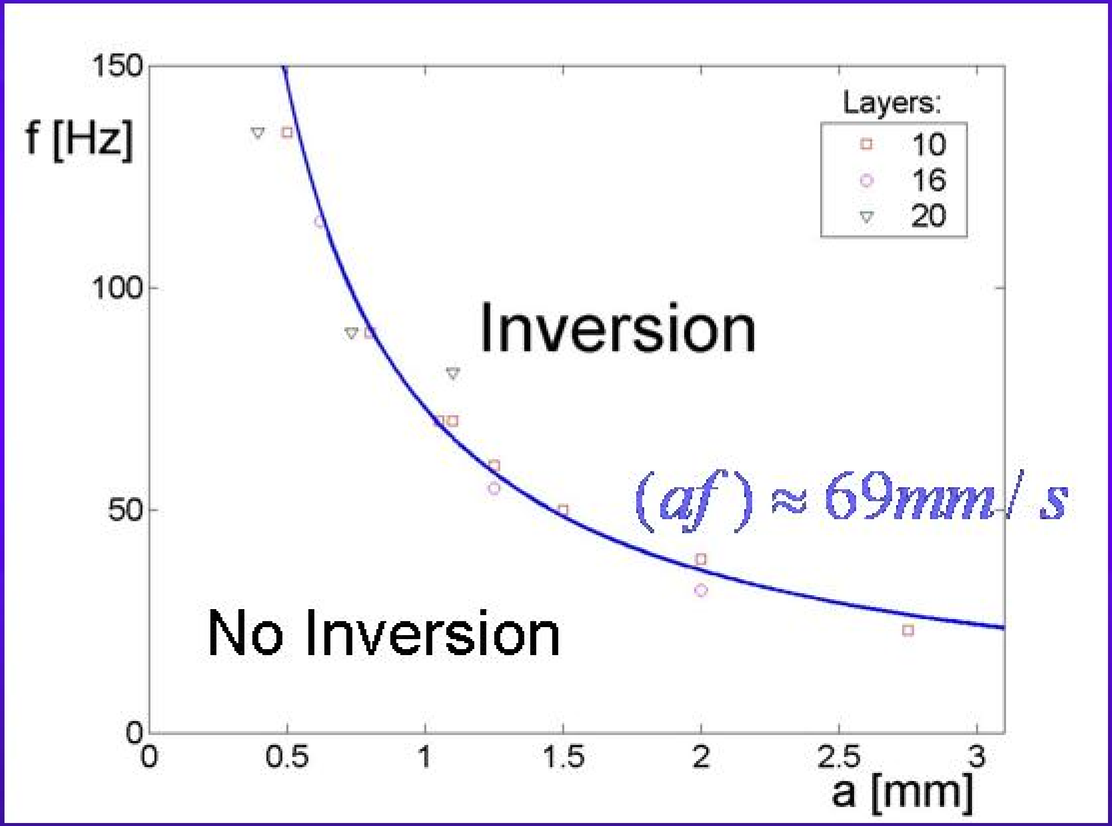
(F=10 layers constant, f=50Hz, a varied)

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

2nd order, continuous phase transition

Experiments: phase space

Critical values of *a* and *f* at phase transition:



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

Theory: hydrodynamic model

(see e.g. Jenkins and Richman 1986, Grossman et al. 1997, Eggers 1999, Meerson et al. 2003)

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

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:

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

Theory: boundary conditions

-Constant granular temperature at bottom:

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

-Zero heat flux at the top:

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

-Conservation of total number of particles:

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

Theory: dimensionless form

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

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

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

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

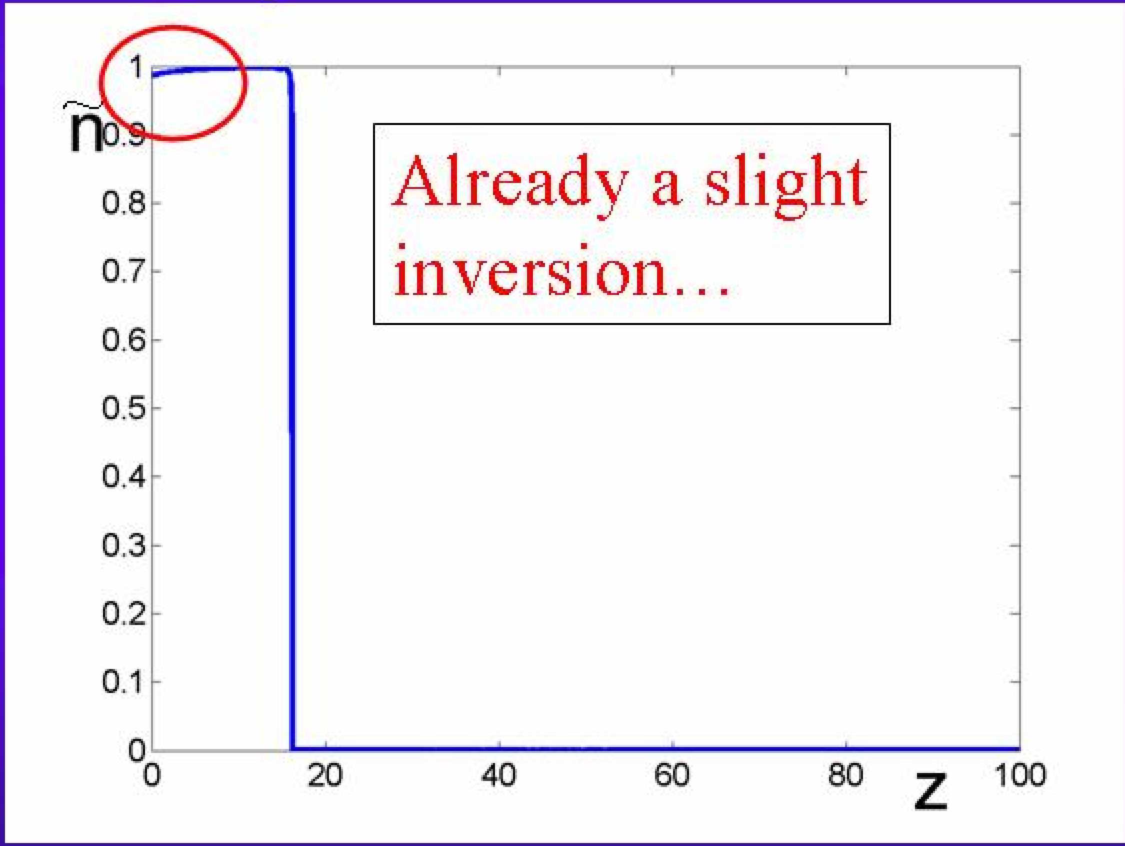
$\left.\right\} S = \Gamma A$

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

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

Theory: density profiles

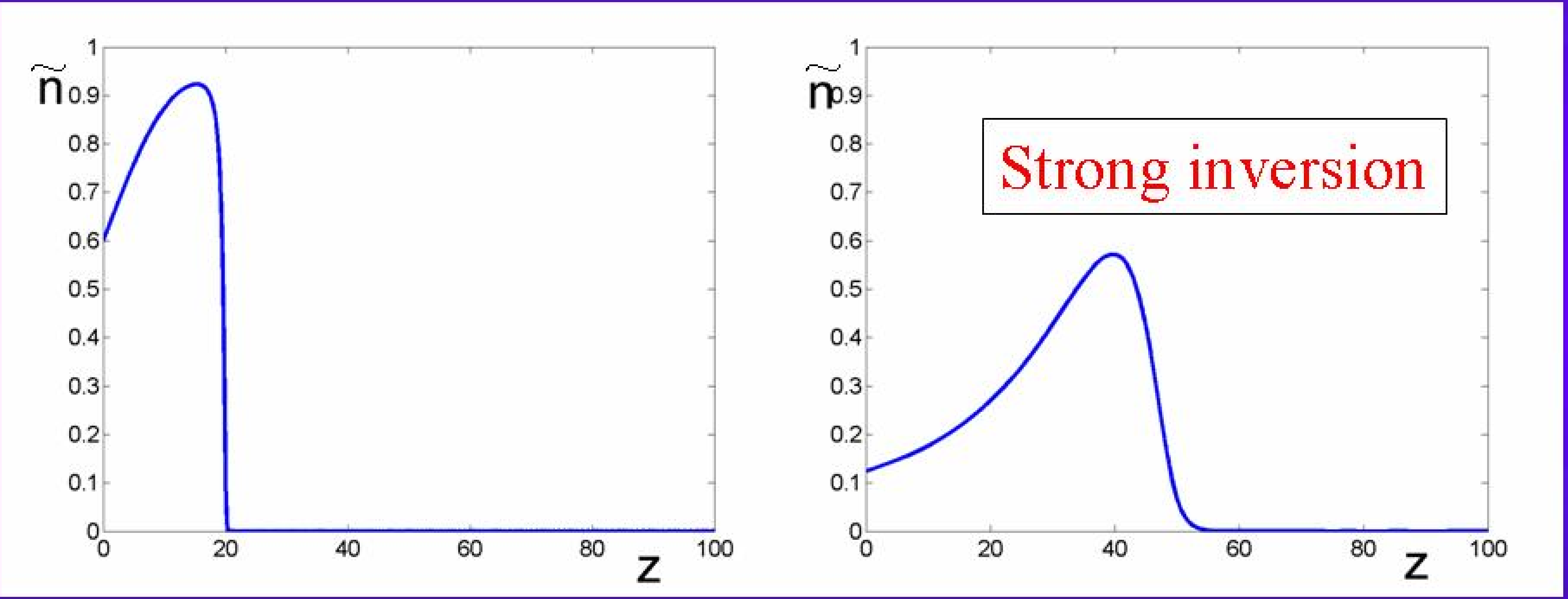
$(\tilde{n} = n / n_{cp})$



F=16 layers,
Mild shaking:
S=ΓA=0.11

Theory: density profiles

F=16 layers

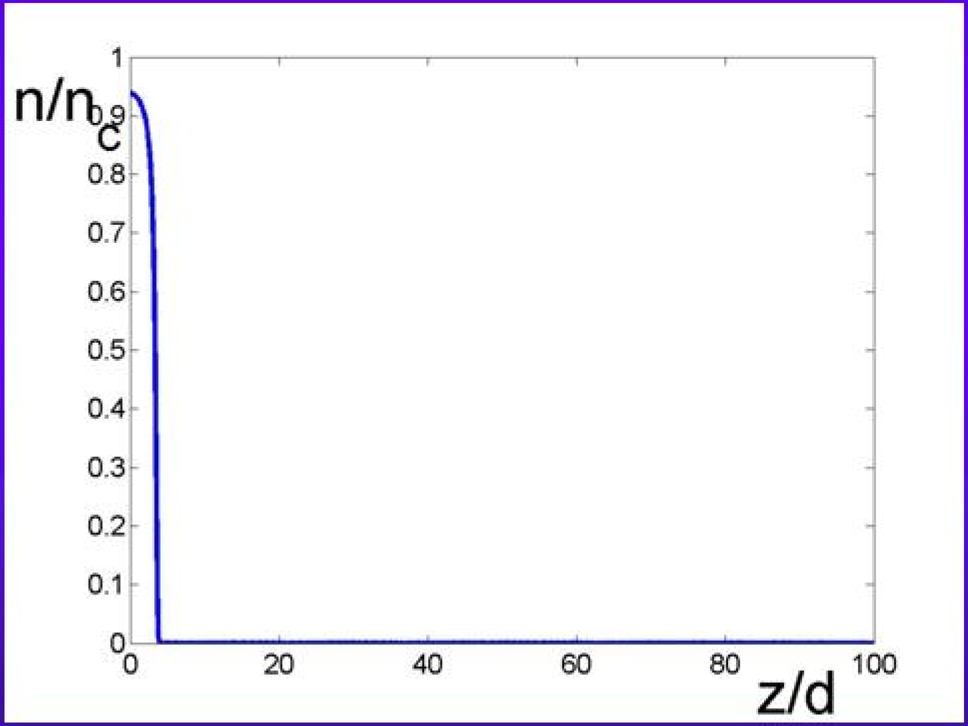


Moderate shaking:
S=ΓA=6.7

Vigorous shaking:
S=ΓA=100

Exp vs. Theory: phase transition

Theoretical model: *never* Inversion for F≤3

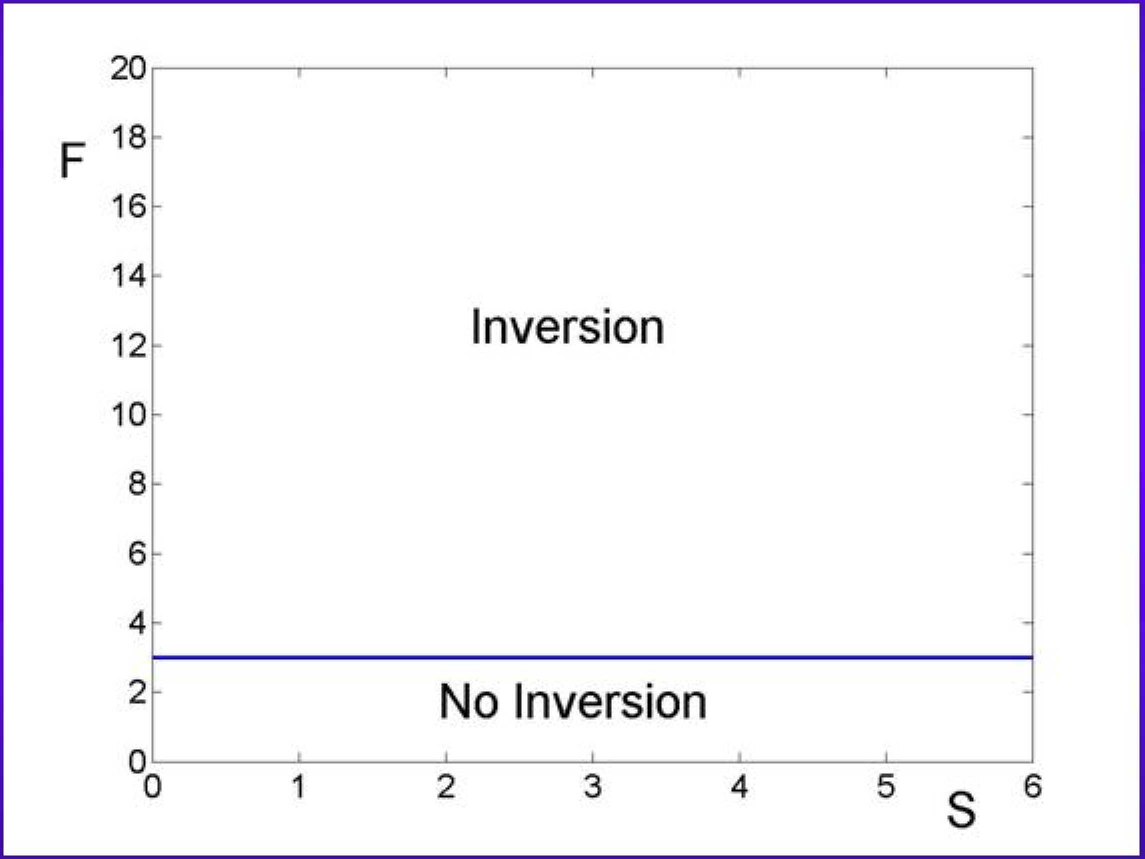


F=3 layers,
S= ΓA=0.1

Phase diagram

Phase transition for increasing F *as in experiment*

No phase transition with increasing S *in contrast to experiment*



Conclusions & Outlook

- Granular Leidenfrost Effect observed in experiment.
- Second order phase transition.
- Relevant control parameters: F and S=ΓA, both in experiment and theory.
- Current model *qualitatively* correct: phase transition for increasing F, but no phase transition with increasing S.
- Use different relations for κ and λ:

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

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

with $l = l(n)$ mean free path.