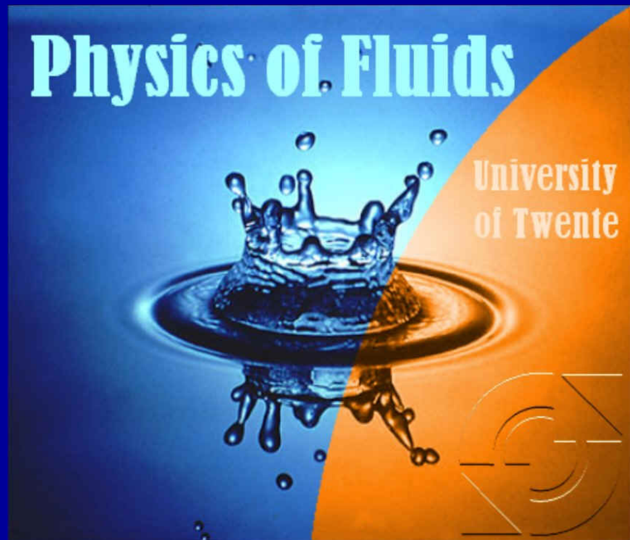
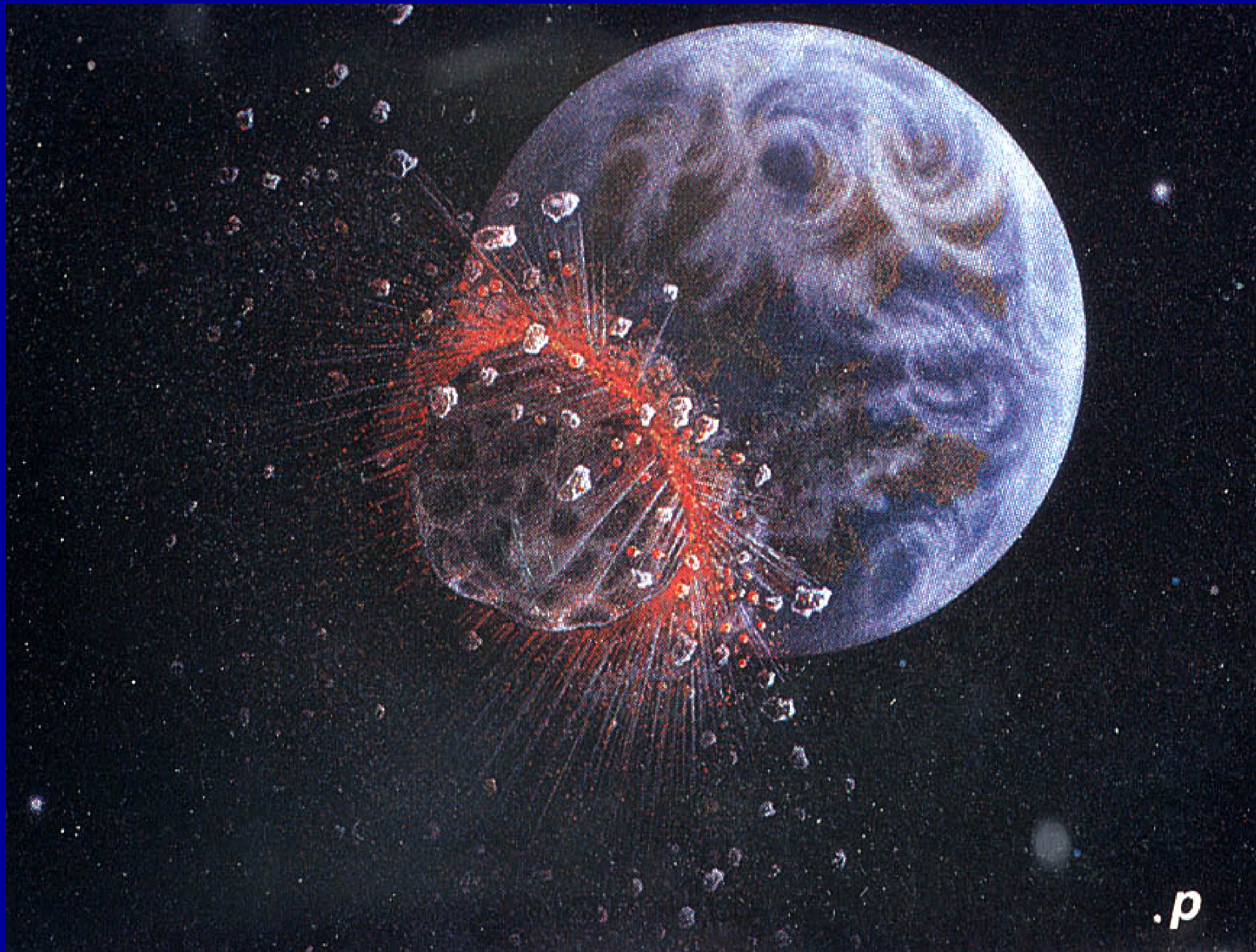
Impact on soft sand: The effect of the ambient air

Detlef Lohse
Department of Physics
University of Twente



- Phys. Rev. Lett. 93, 198003 (2004)
- Nature 432, 689 (2004)
- Phys. Rev. Lett. 99, 018001 (9th July 2007)

Astroid impact on earth



Craters

…on the moon

Moltke

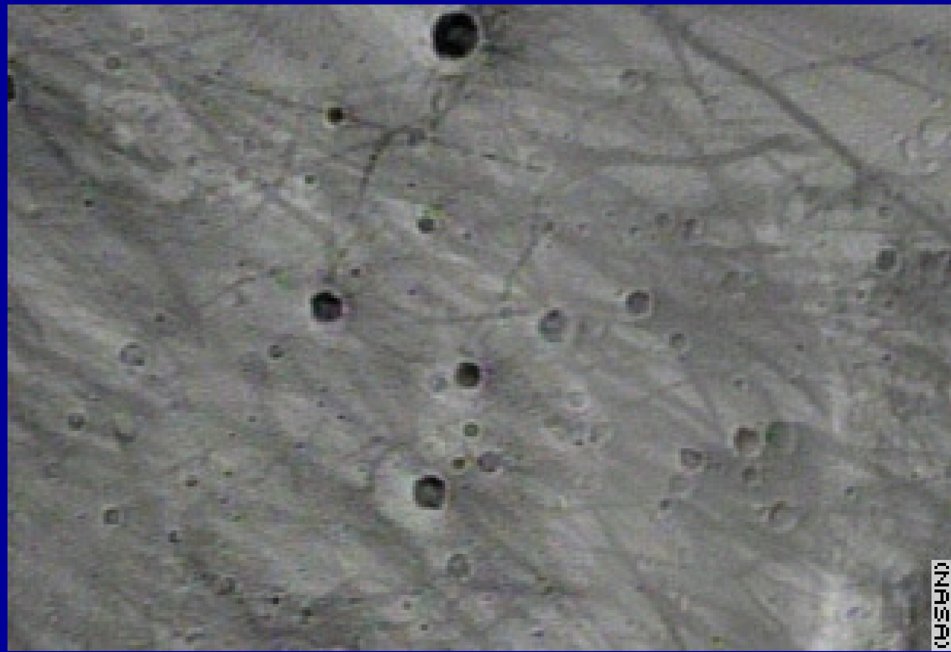
Tycho

central peak

Craters

…on Mars

Mars explorer,
January 2004



…on earth

Arizona

Speculation on crater formation

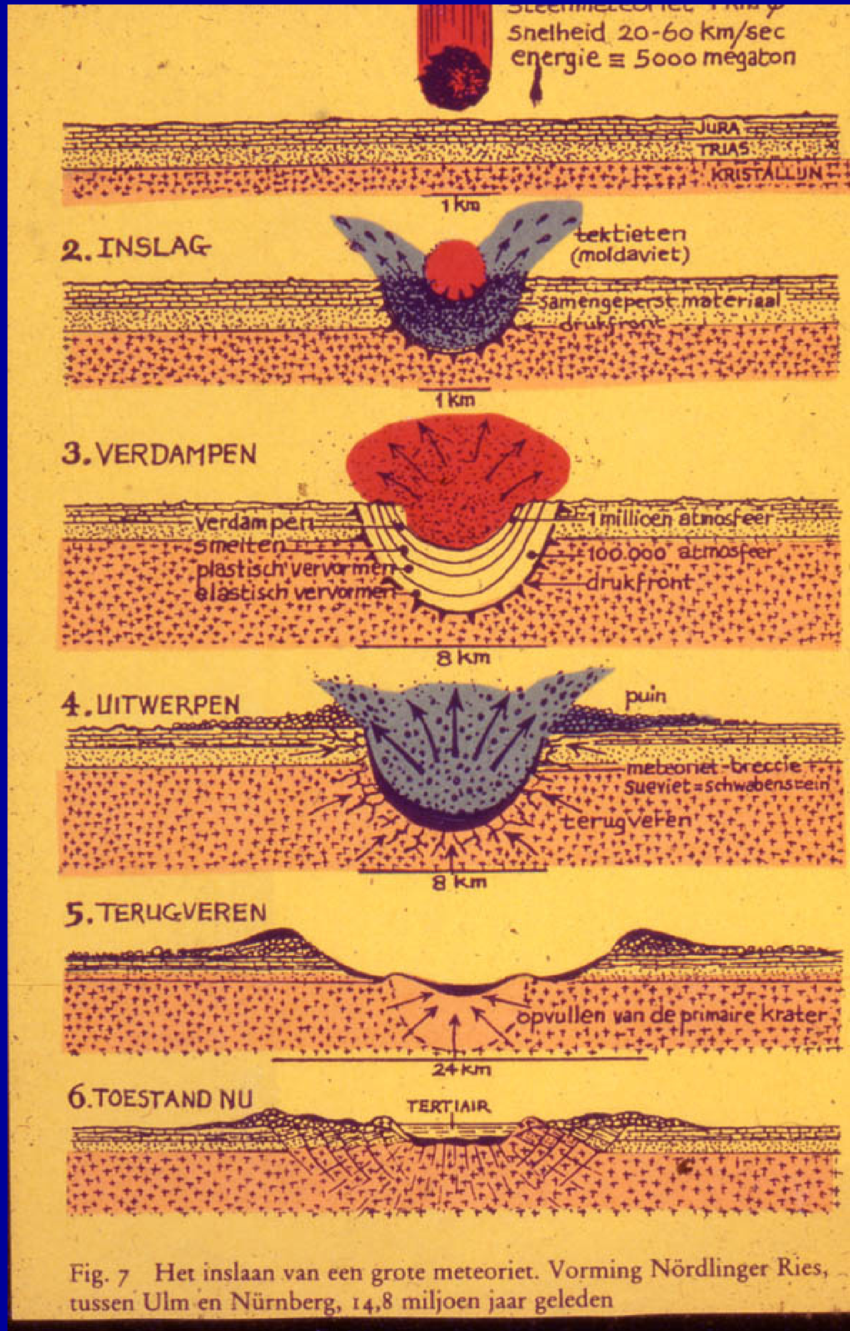
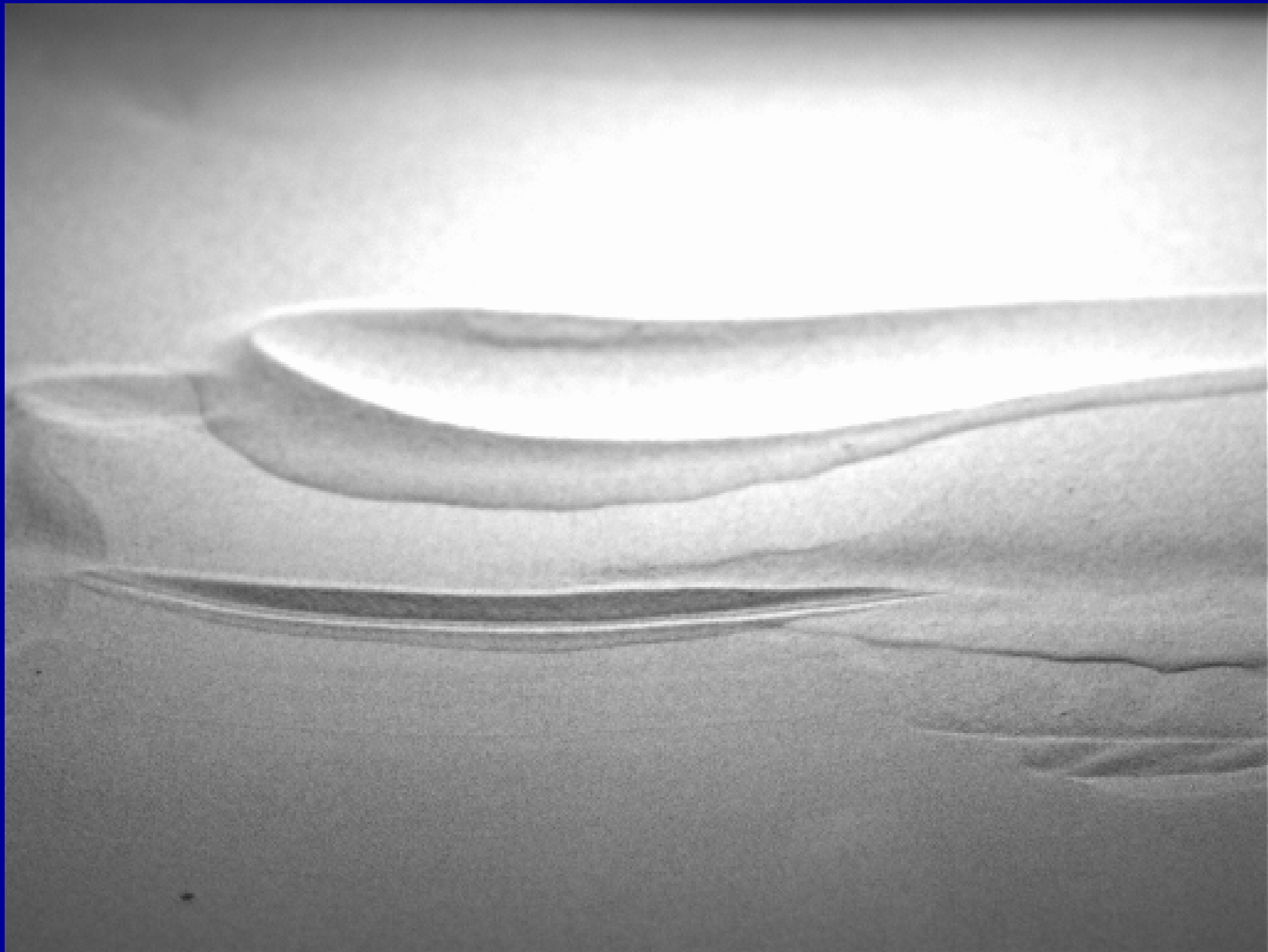


Fig. 7 Het inslaan van een grote meteoriet. Vorming Nördlinger Ries, tussen Ulm en Nürnberg, 14,8 miljoen jaar geleden

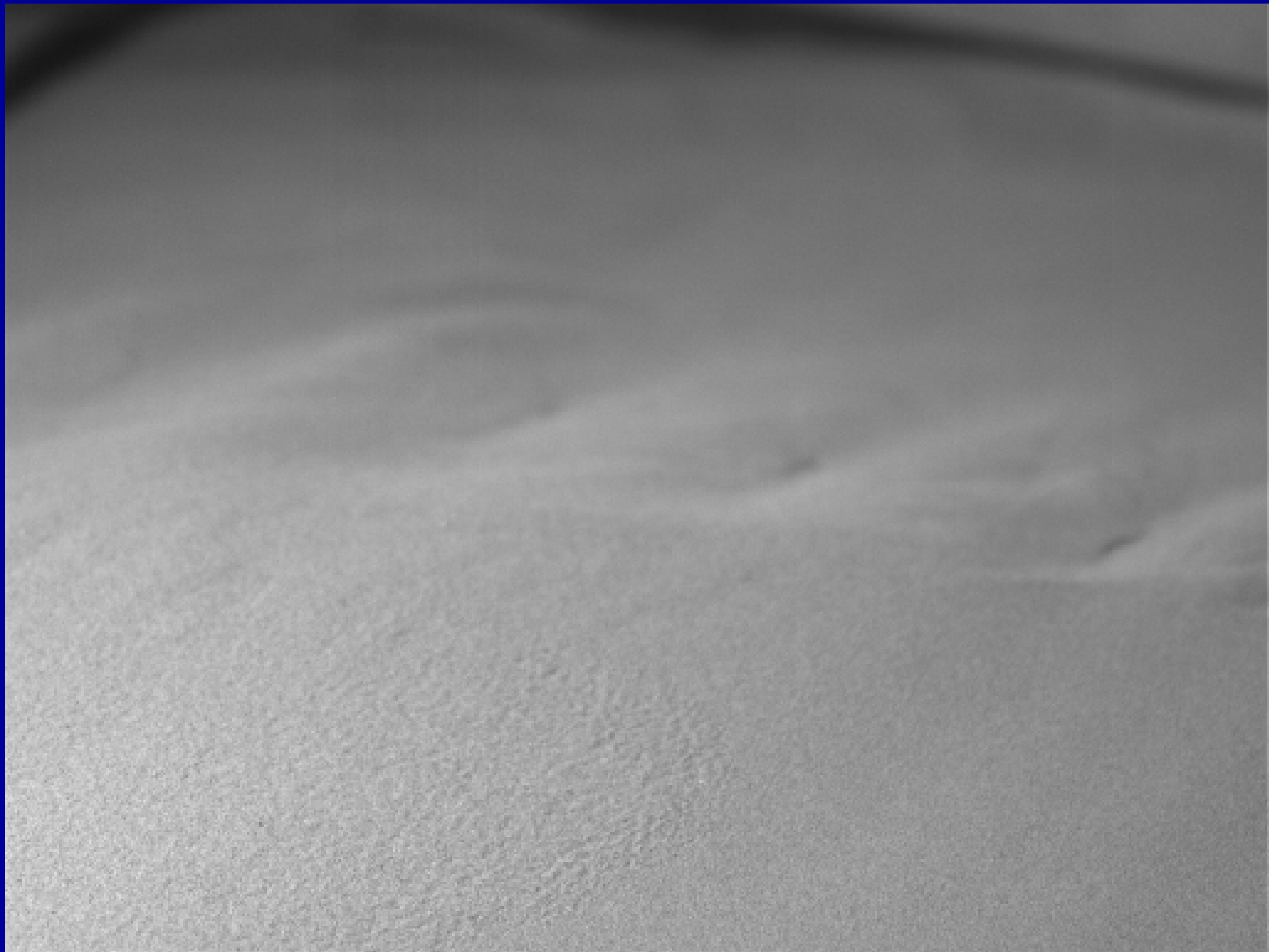
Source:
Jan Smit,
Amsterdam,
Dept. Geology

What’s really going on?

Downscaled experiments: Impact of steel ball on fine sand

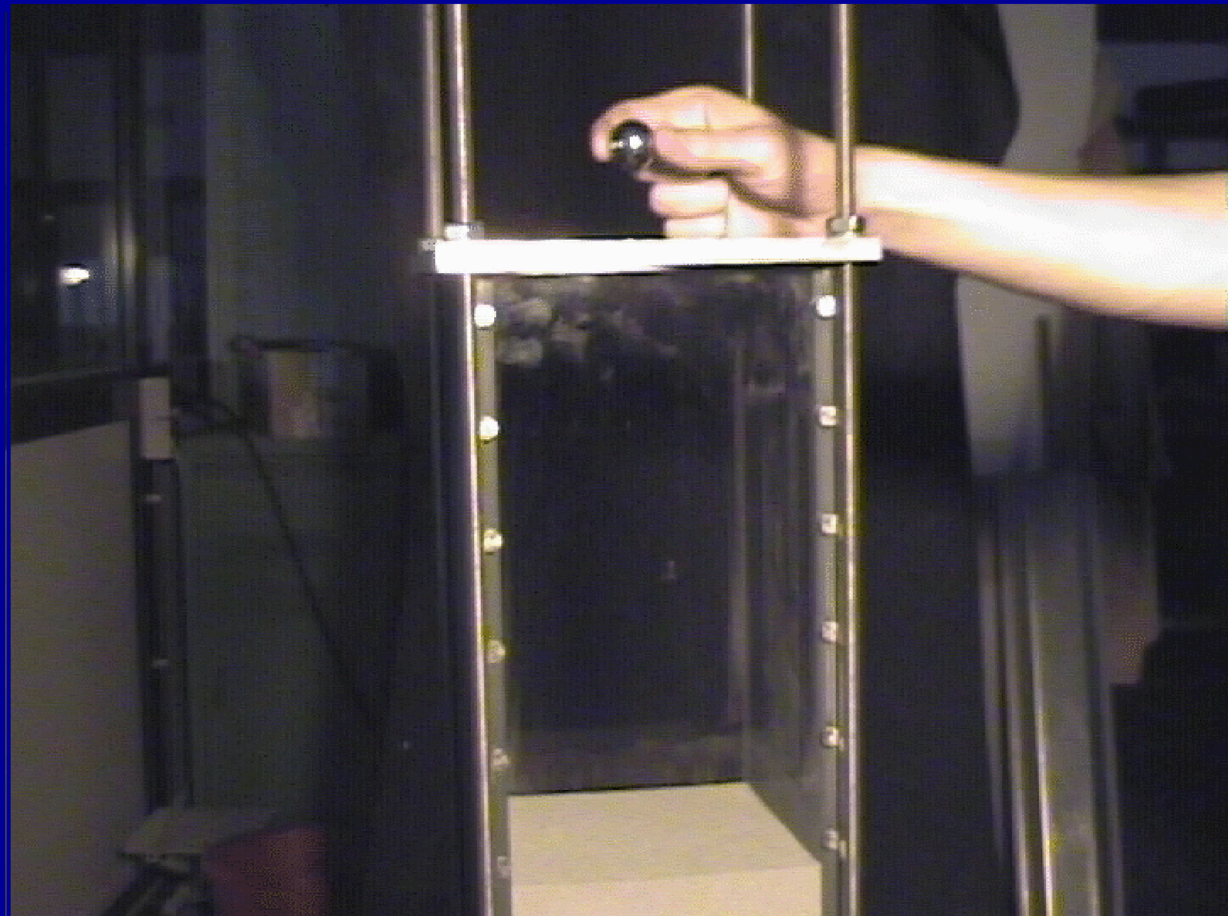


Problem: reproducibility



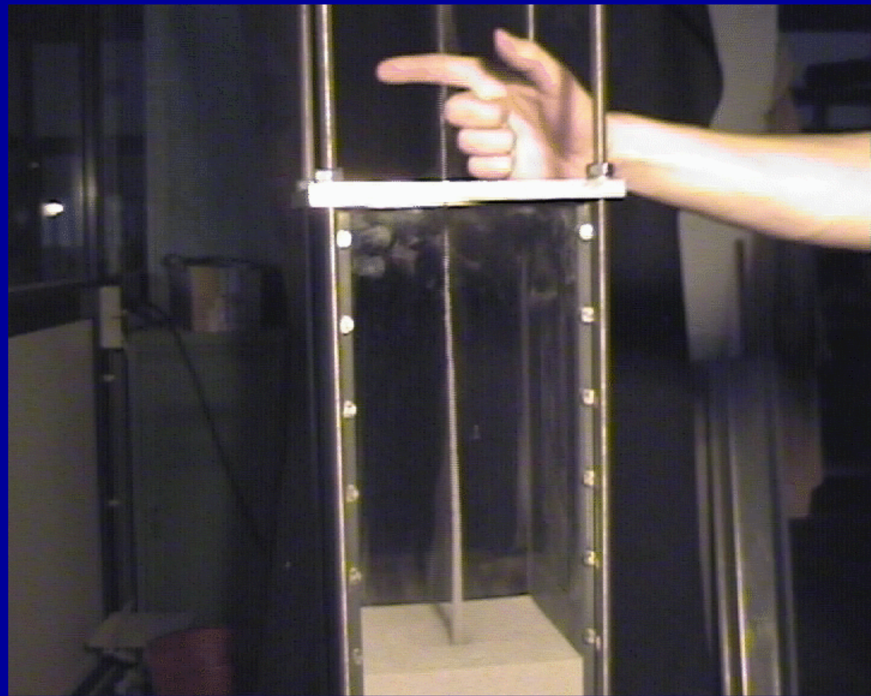
Controlled experiments

Ball dropped on **decompactified**, very fine sand



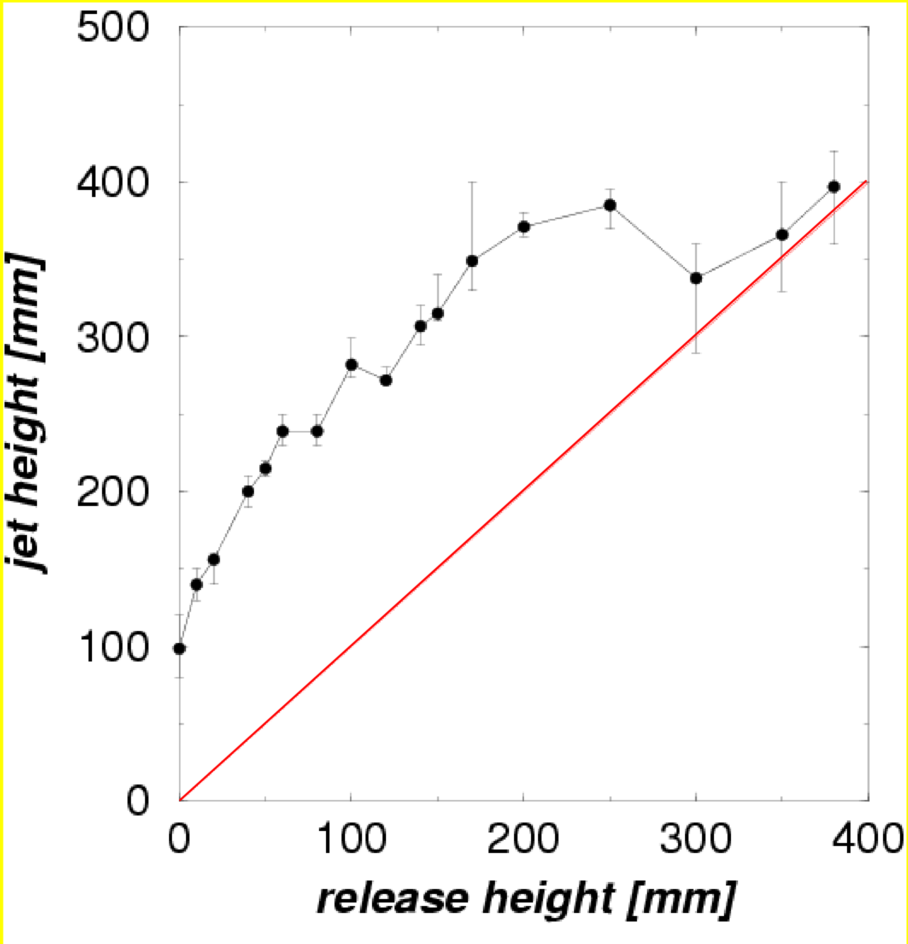
Ball at release point

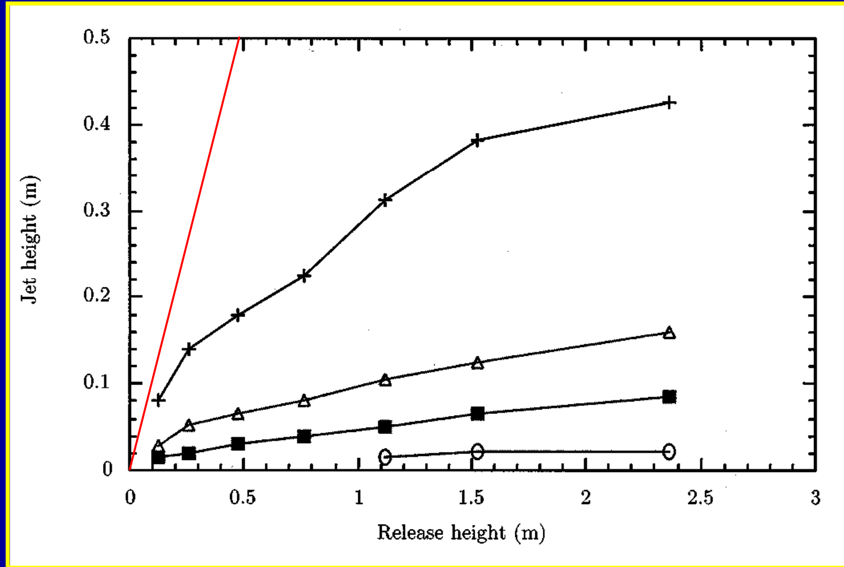
Maximum jet height



Jet height > Release height !

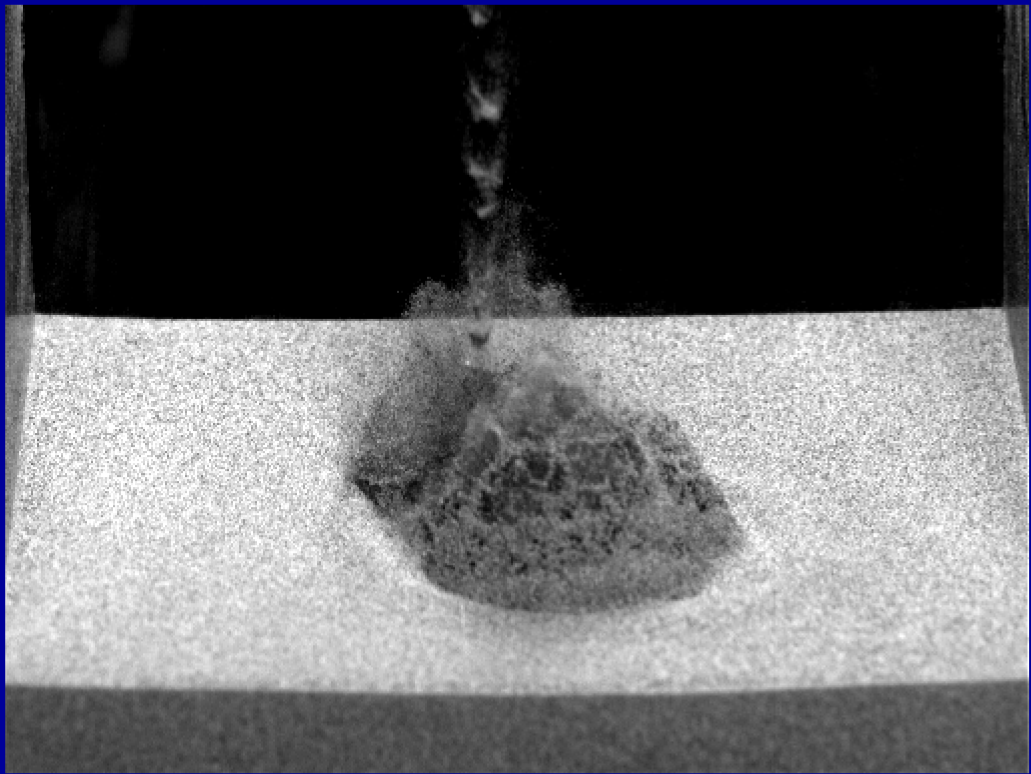
Jet height vs release height





Siggi Thoroddsen,
and Amy Shen,
Phys. Fluids **13**, 4 (2001):

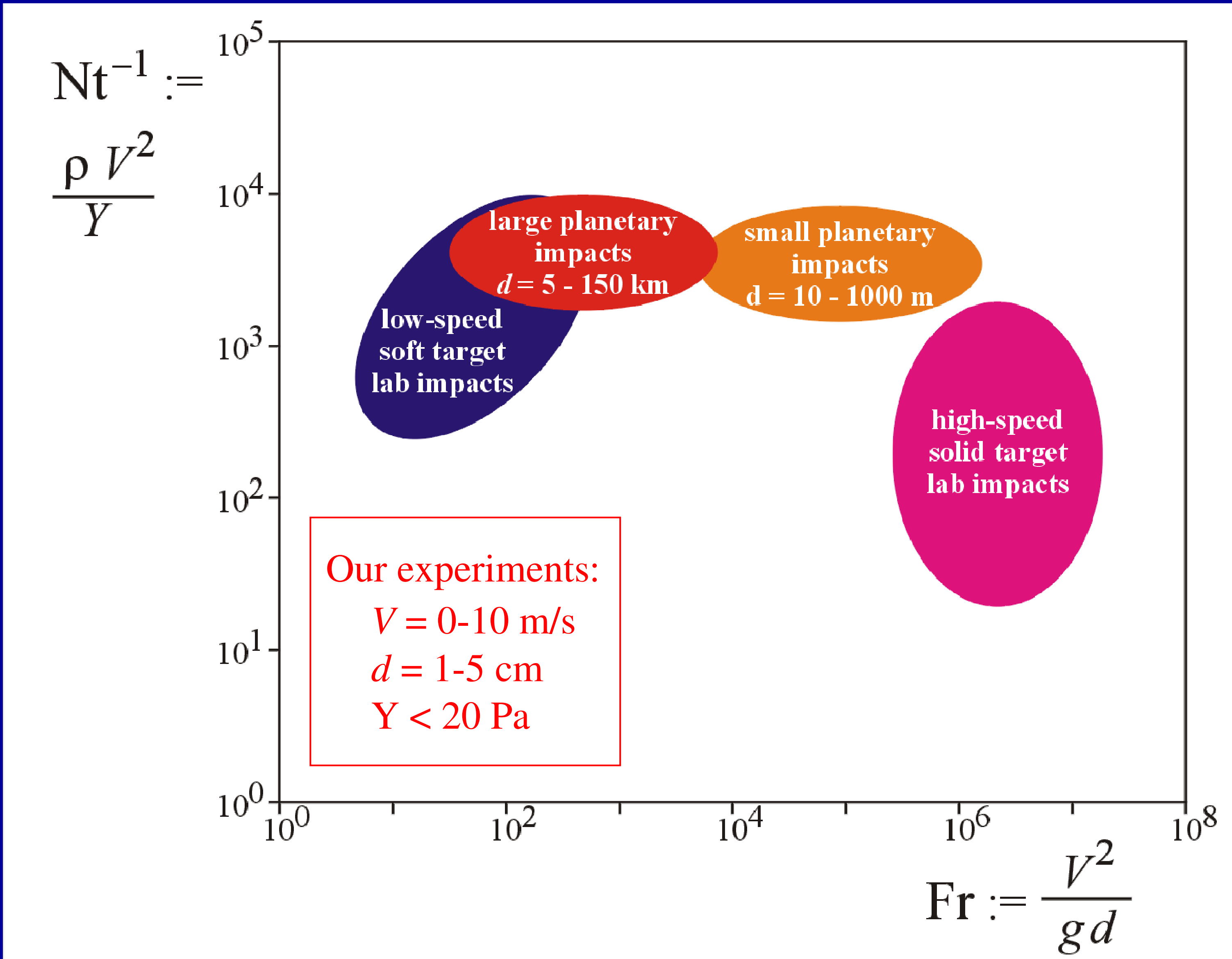
Impact of ball on decompactified sand



3 events:

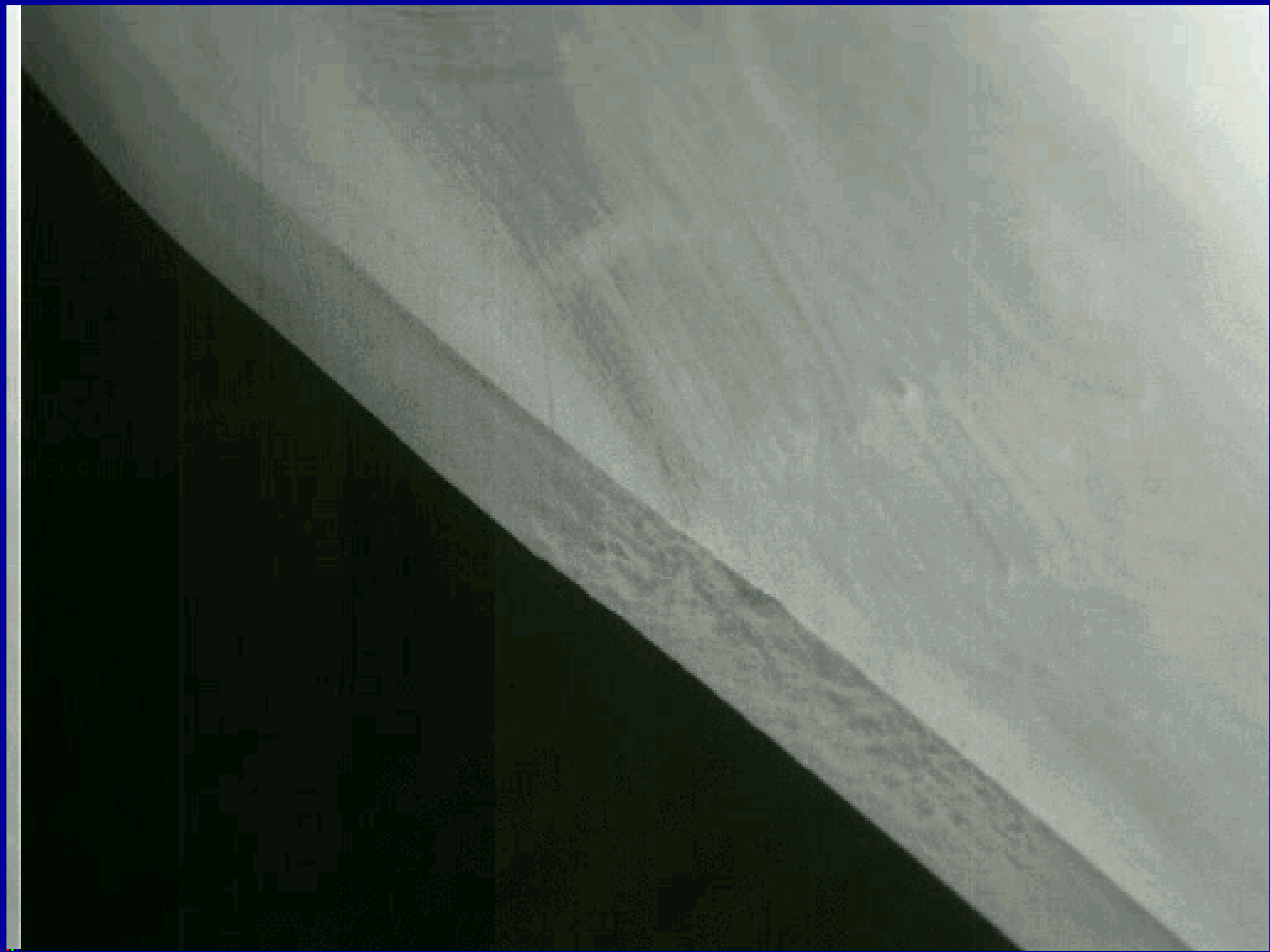
- Impact creates splash
- A jet is formed
- Granular eruption

Impact: planetary vs. lab



How to look into the sand?

2D experimental setup



2D experiment: high impact velocity

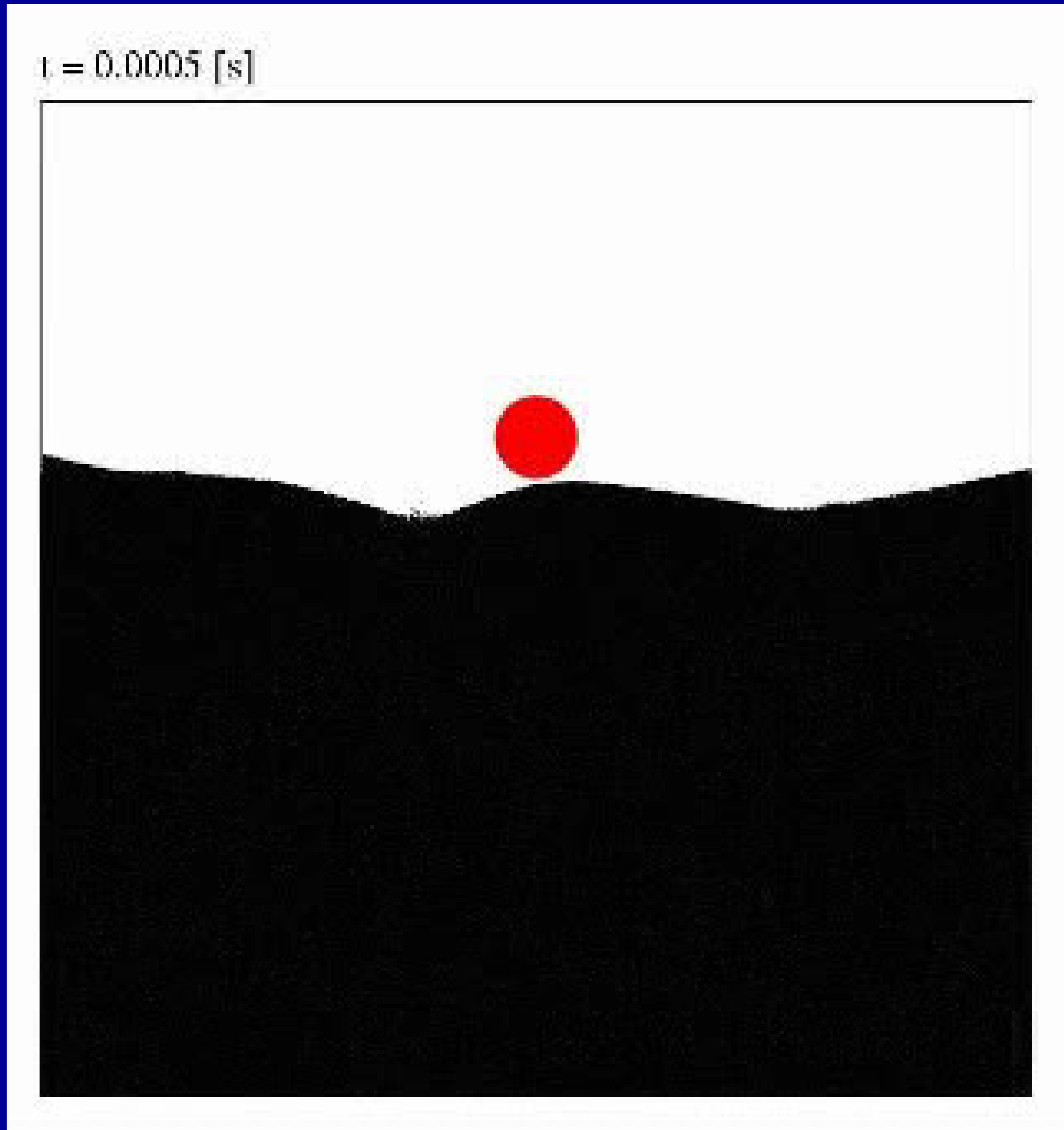
Just as in water:

1. void formation
2. void collapse
3. two jets (sheets in 2D)
4. bubble formation

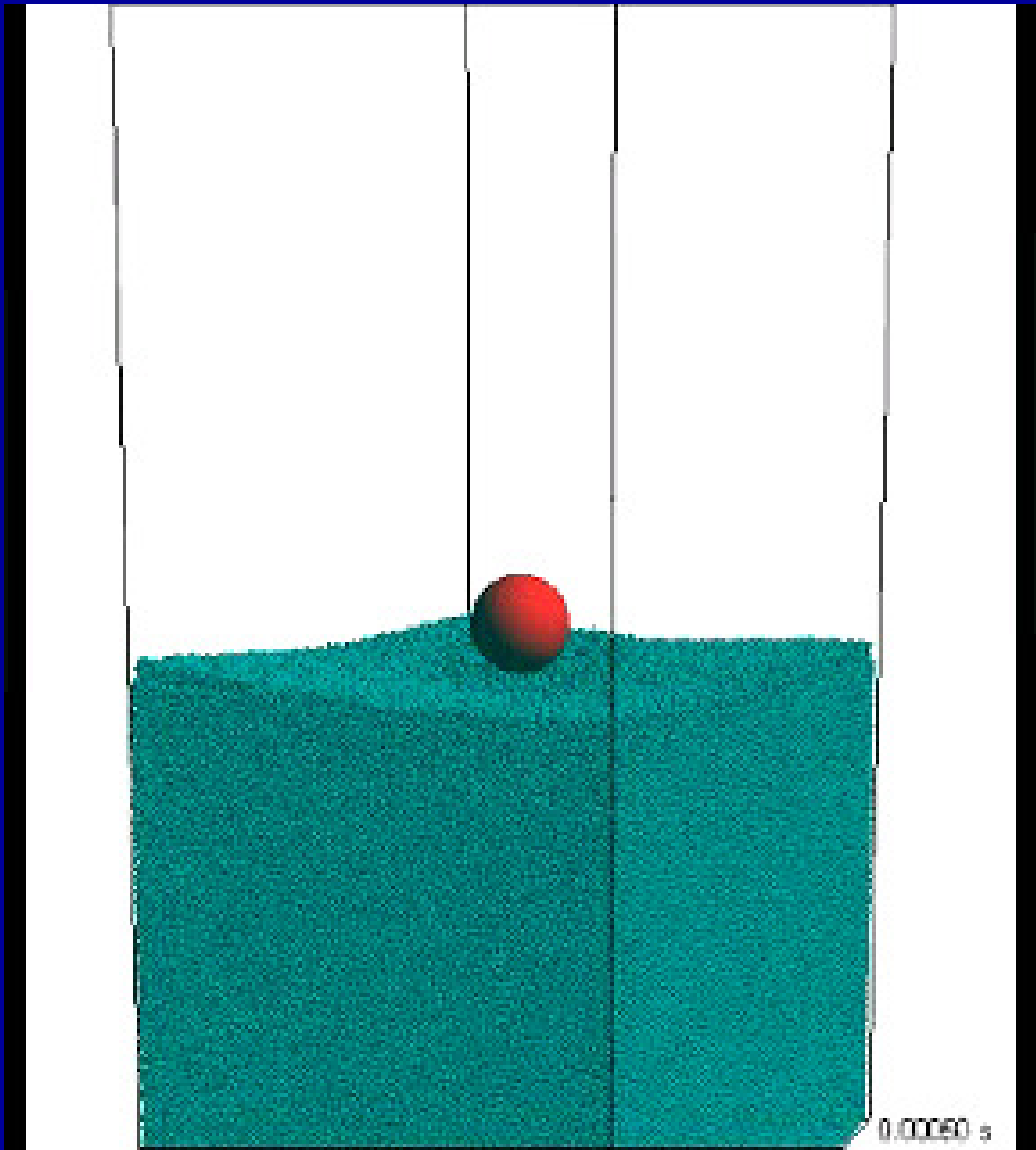
Discrete particle simulations

- soft sphere code
- N = 1000000
- $d_s = 0.5$ mm
- $d_b = 15$ mm
- quasi 2D (8 grains thick)
- pre-fluidized

Discrete particle simulation



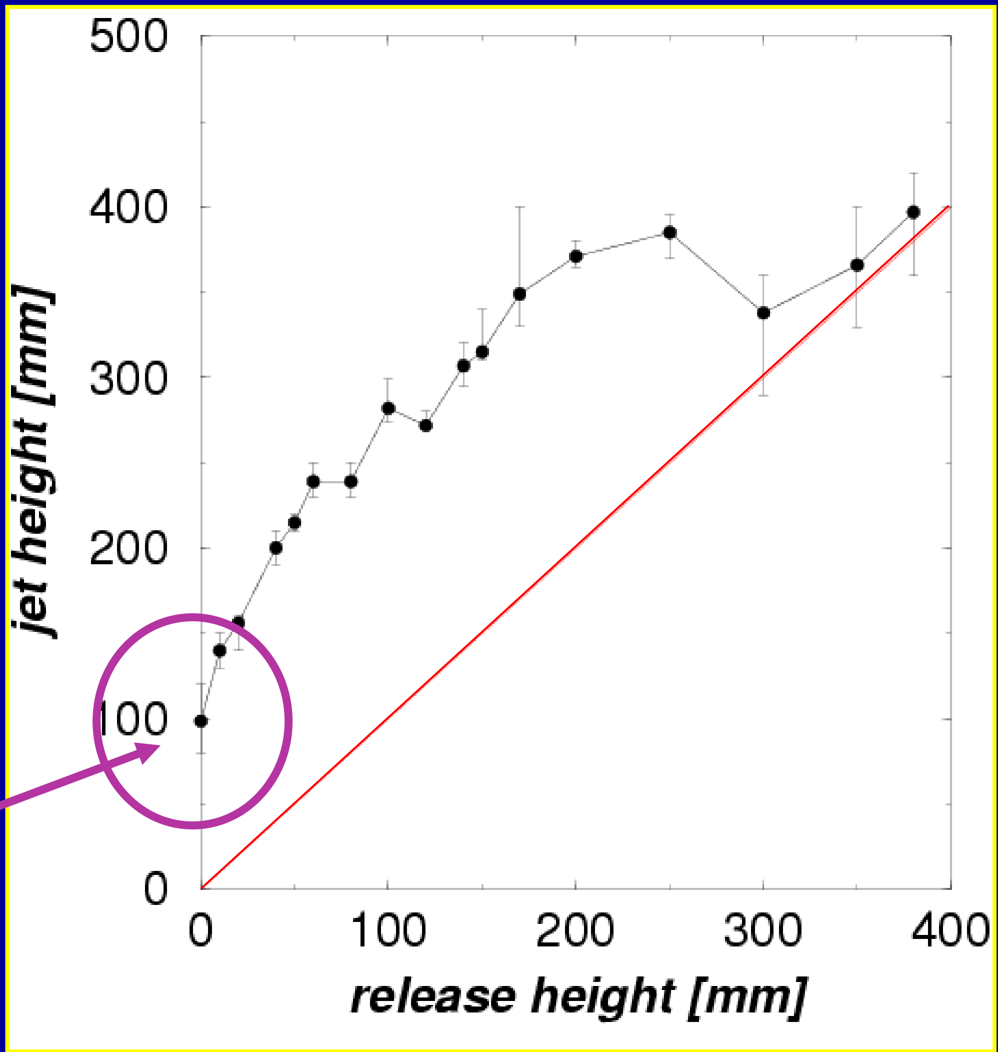
3D discrete particle simulation



Does sandbed support weight?

D. Lohse, R.Rauhe, D. van der Meer, R. Bergmann, Nature 432, 689 (2004)

“Dry quick sand”



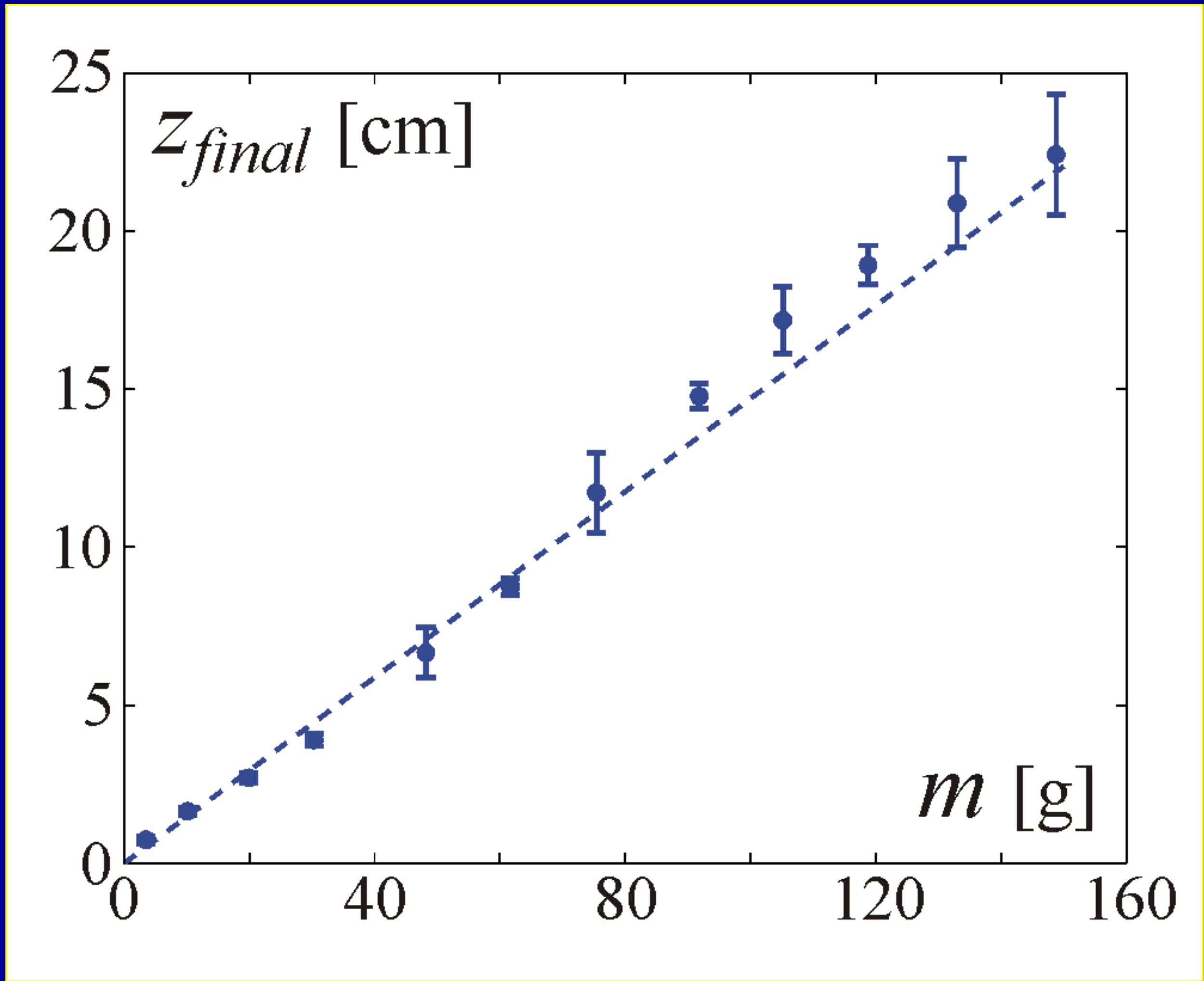
No!

Packing density only 41% !

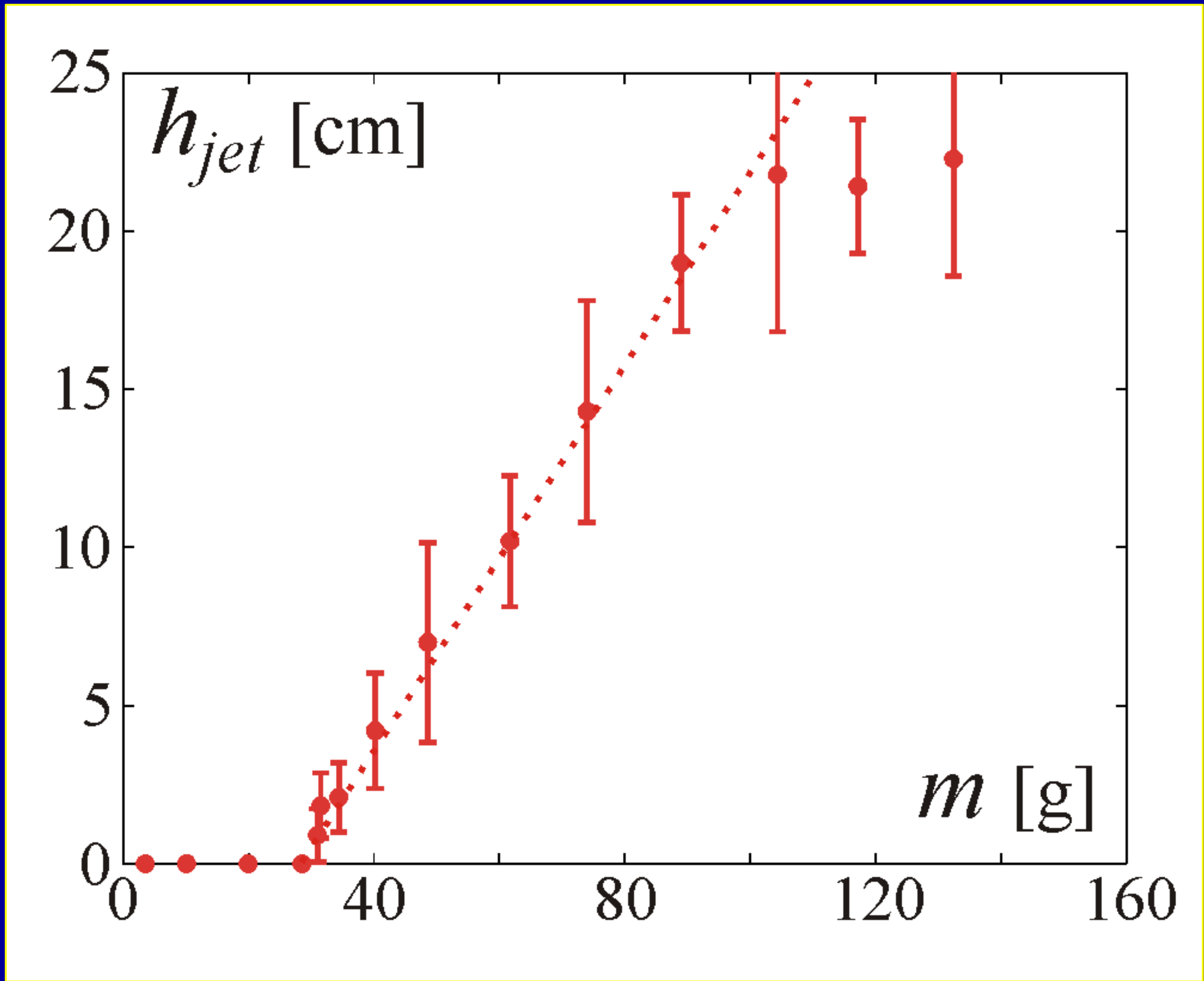
Myth from Lawrence of Arabia…

Sandbed does not support weight

final depth ~ mass



Jet height vs mass: threshold behavior



Model: Coulomb friction

Coulomb friction

$$F_{coulomb} = -\kappa z$$

Force balance

$$(m + m_A)\ddot{z} = mg - \kappa z$$

Solution

$$z(t) = \tfrac{1}{2} z_{final}(1 - \cos \omega t)$$?

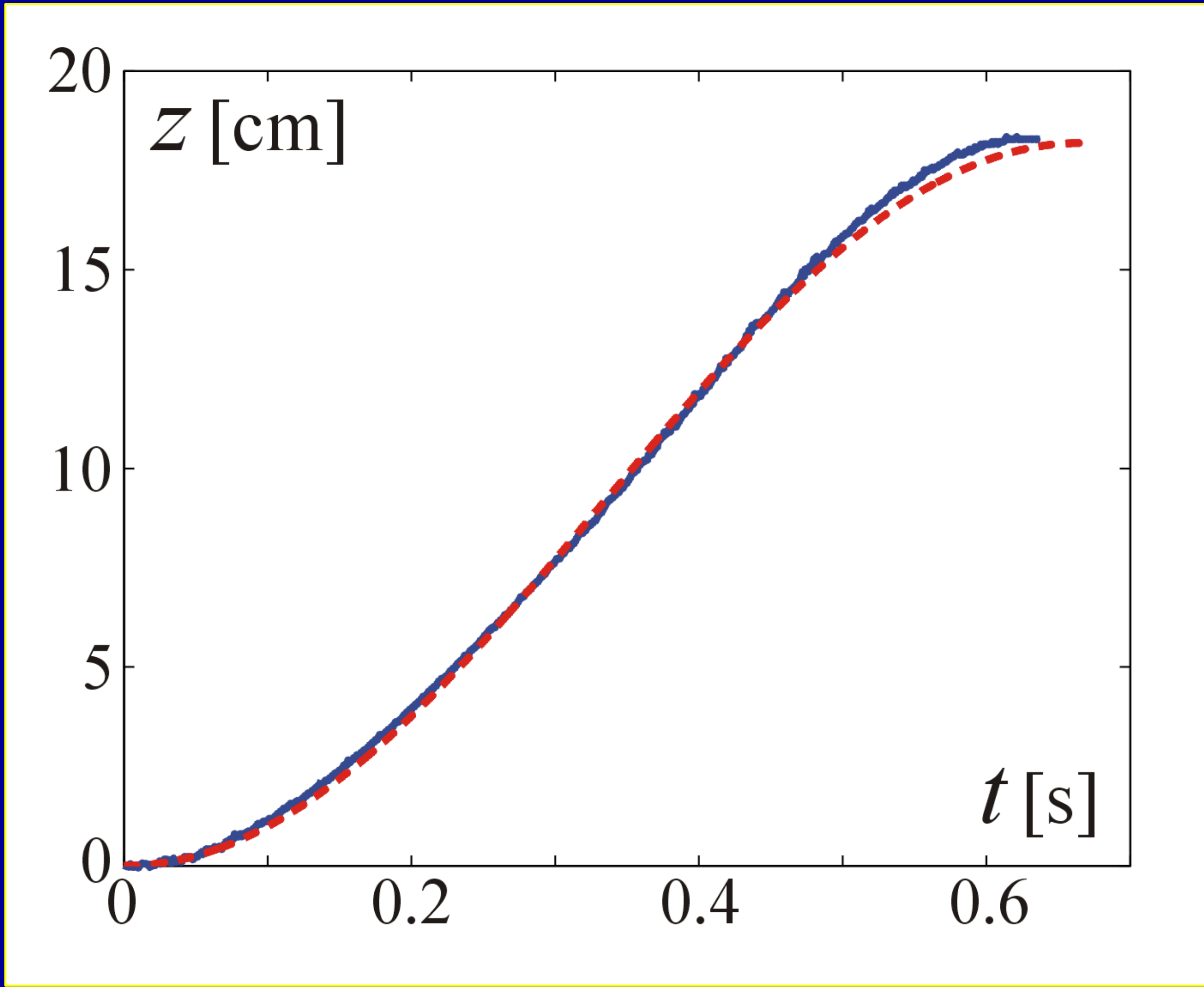
Final depth

$$z_{final} = \frac{2mg}{\kappa}$$ ✓

$$\omega = \sqrt{\frac{\kappa}{m + m_A}}$$

$$0 \le t \le \frac{\pi}{\omega}$$

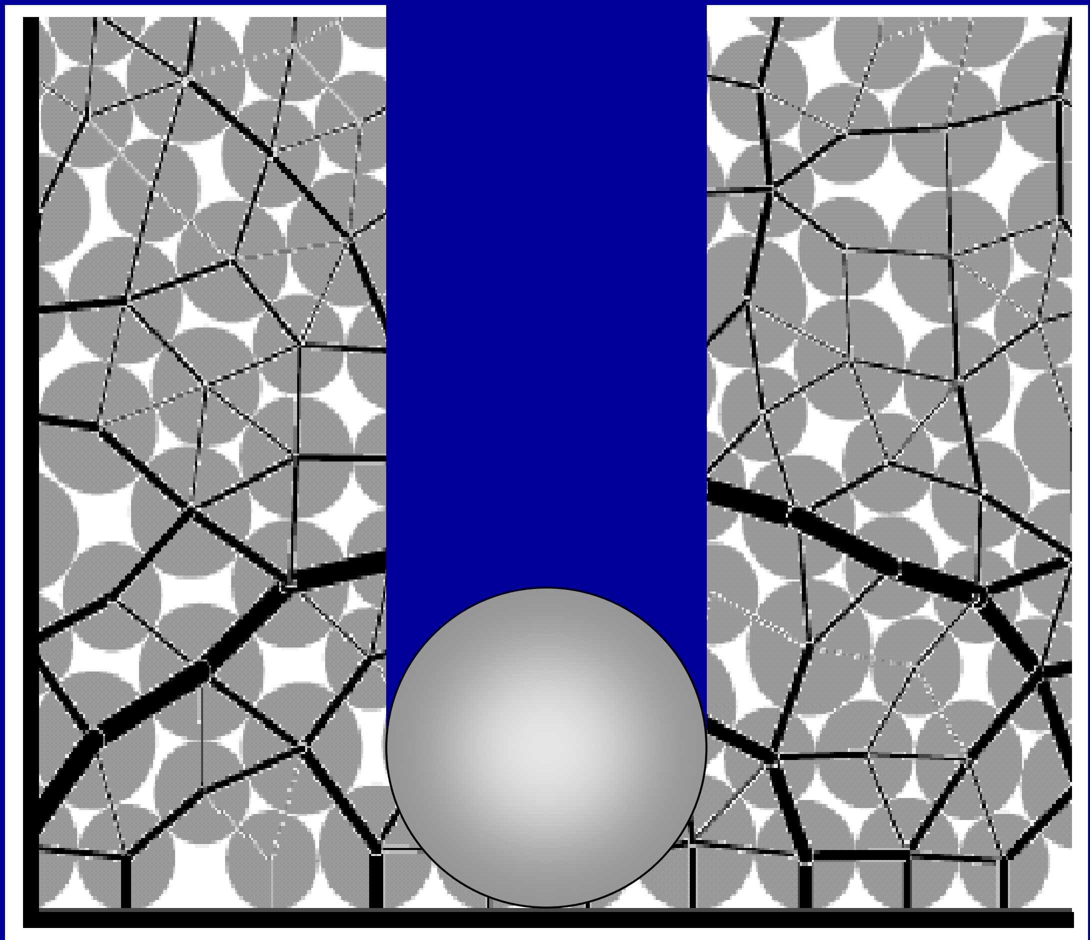
Depth vs time



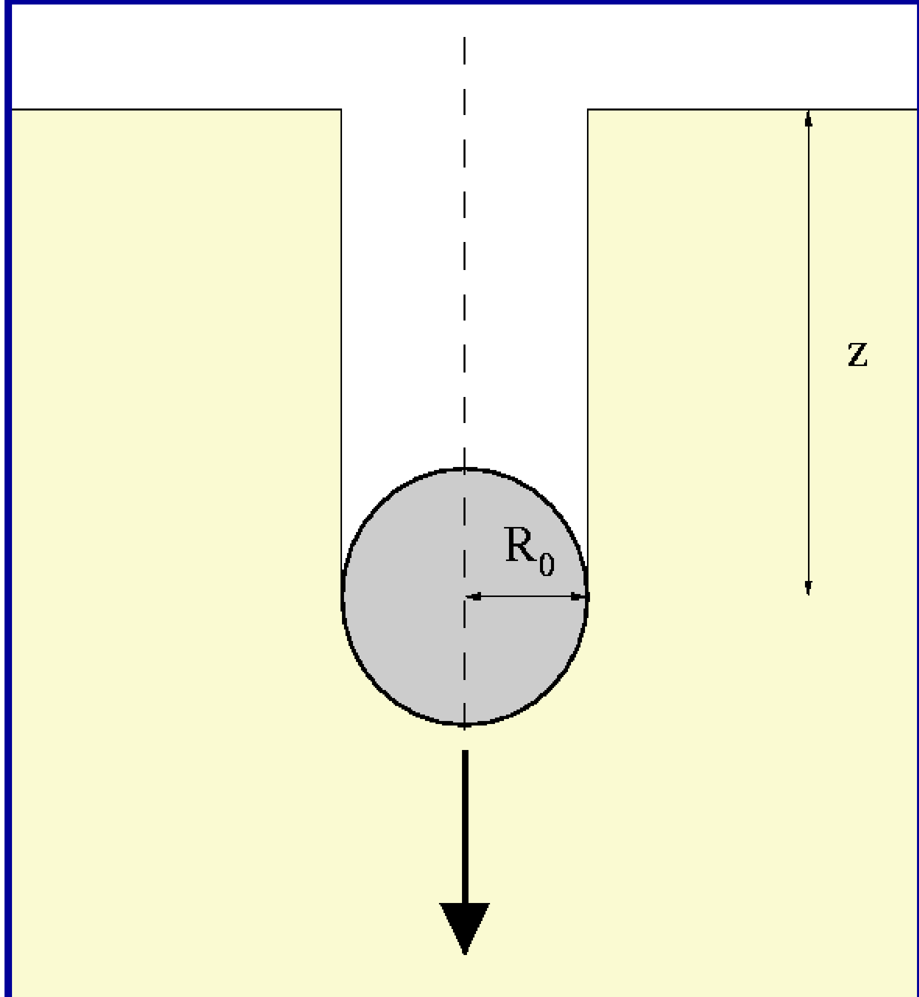
experiments + model

Continuum model for void collapse

Force chains do not seem to play a role



Cavity formation



Coulomb drag: $F_{coulomb} = -\kappa z$

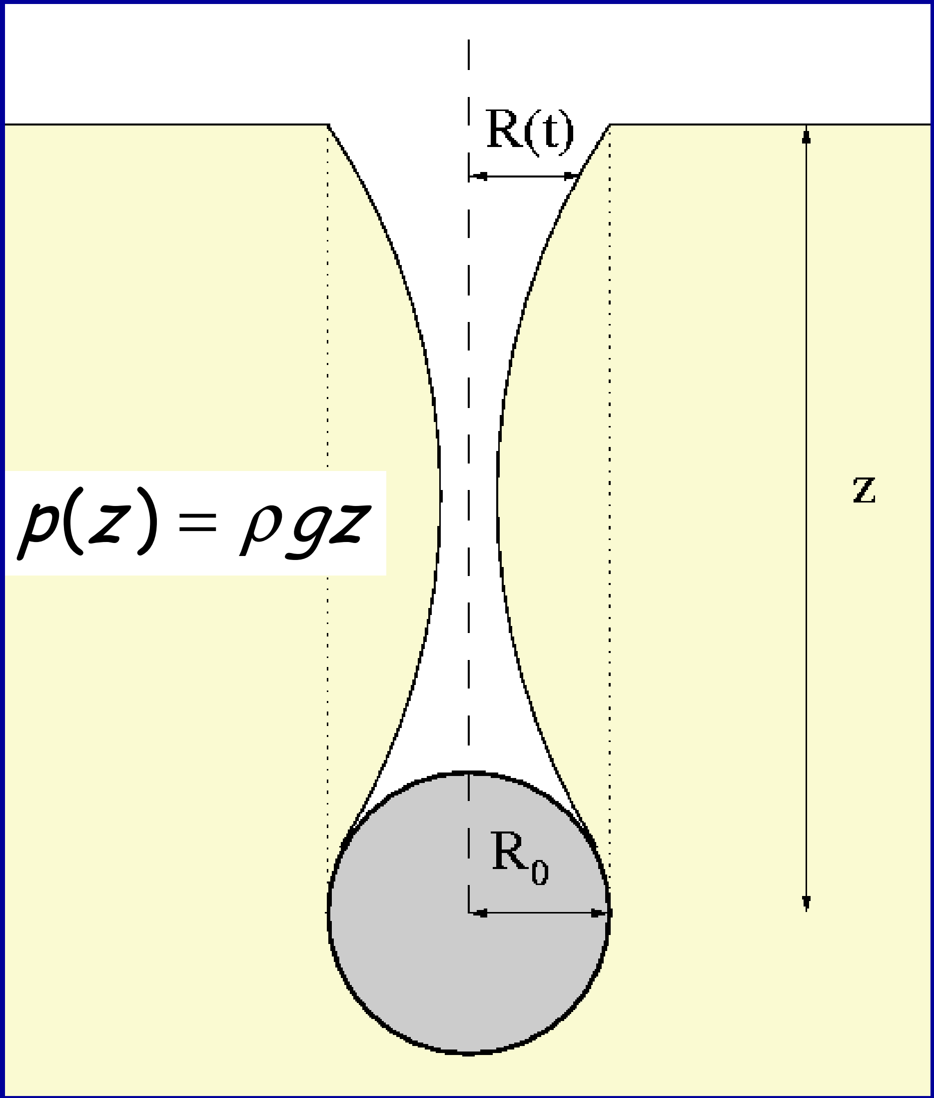
Solution:

$$z(t) = \tfrac{1}{2} z_{final} (1 - \cos \omega t)$$

Invert:

$$t_{pass}(z) = \omega^{-1} arcos\left(1 - \frac{2z}{z_{final}}\right)$$

Cavity collapse



Initial conditions

$$R(z, t_{pass}) = R_0$$

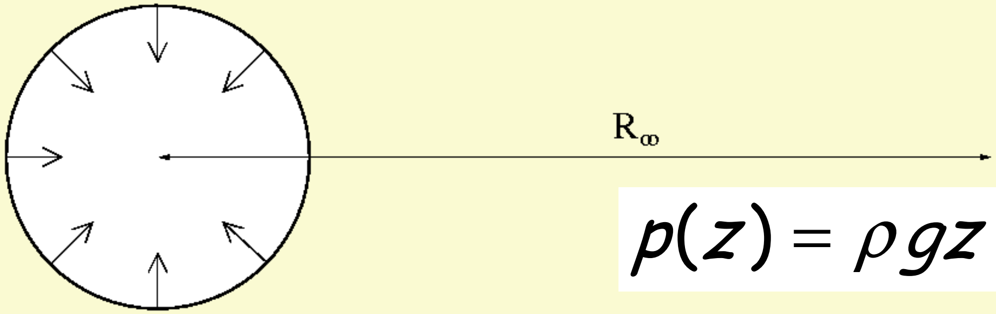
$$\dot{R}(z, t_{pass}) = 0$$

Sand pressure

$$p(z) = \rho g z$$

Rayleigh-type dynamics of cavity collapse

2D slice at depth z



$$p(z) = \rho g z$$

Euler equation in cylindrical coordinates

$$\partial_t v + v \partial_r v = -\frac{1}{\rho} \partial_r p$$

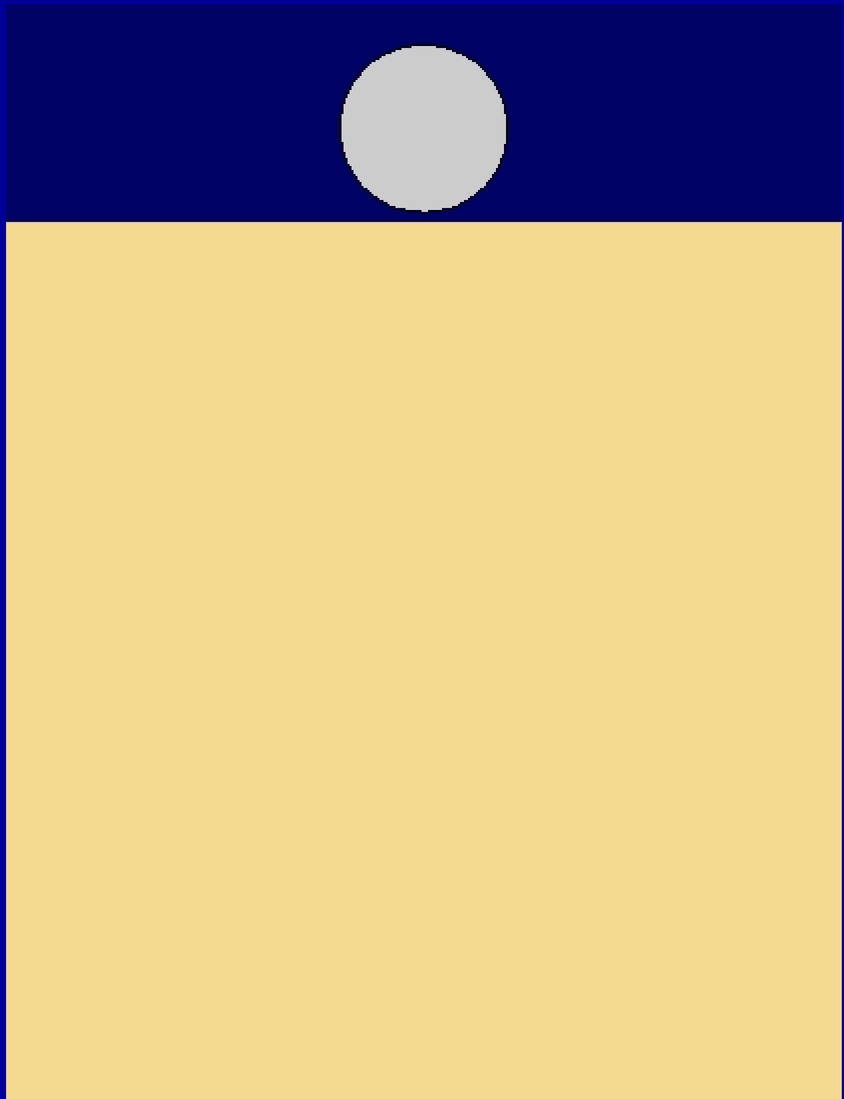
Continuity equation and boundary conditions

$$r\, v(r) = R(t)\, \dot{R}(t)$$

Equation for 2D collapsing void

$$(R\ddot{R} + \dot{R}^2)\ln\left(\frac{R}{R_\infty}\right) + \tfrac{1}{2}\dot{R}^2 = gz$$

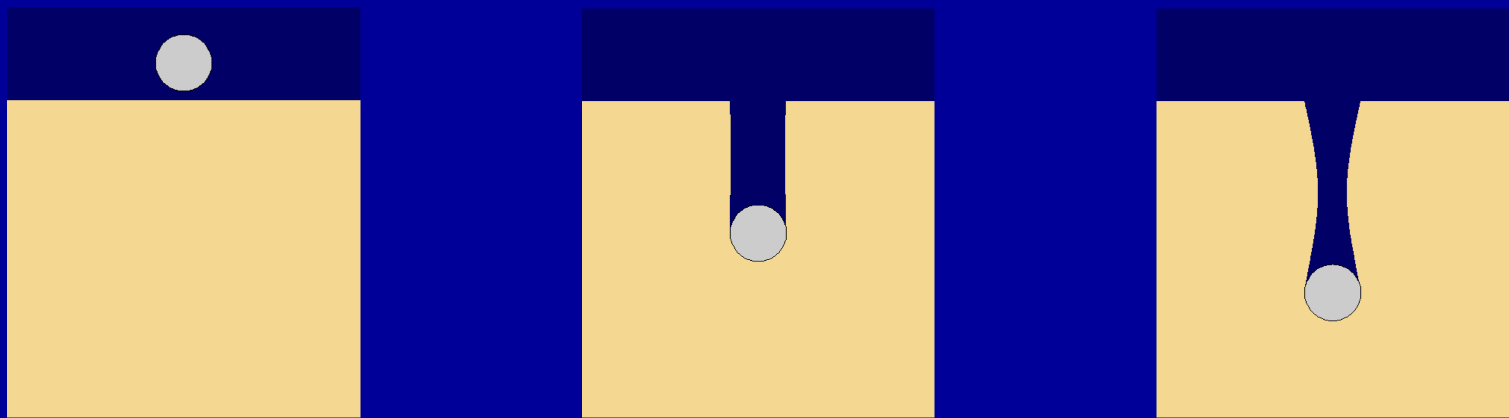
Rayleigh model at high impact velocity



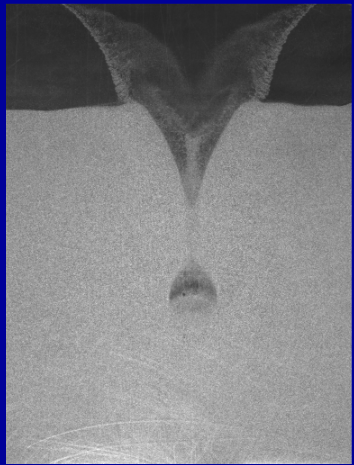
bubble formation !

Experiments vs. hydrodynamic theory

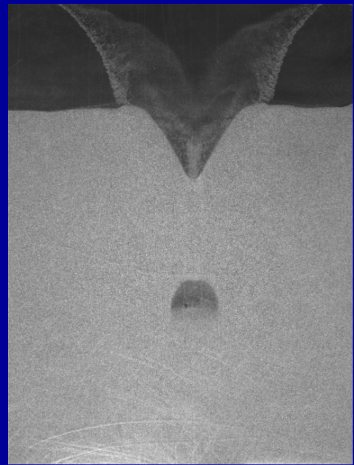
T = -21ms T = 37ms T = 78ms



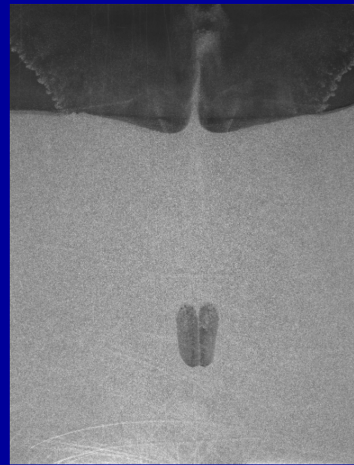
Experiments vs. hydrodynamic theory



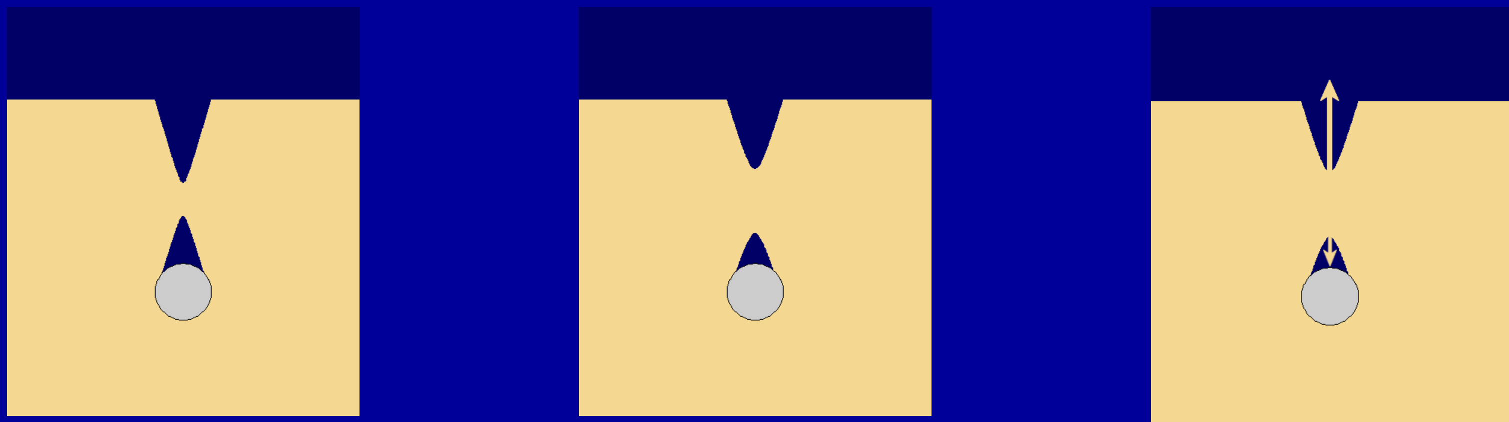
T = 100ms



T = 116ms



T = 191ms



Conclusions I

Series of events:

1. void formation
2. void collapse
3. two jets
4. bubble formation

Granular jet is formed by hydrostatic collapse of the impact cavity

Force balance model & hydrodynamic description work

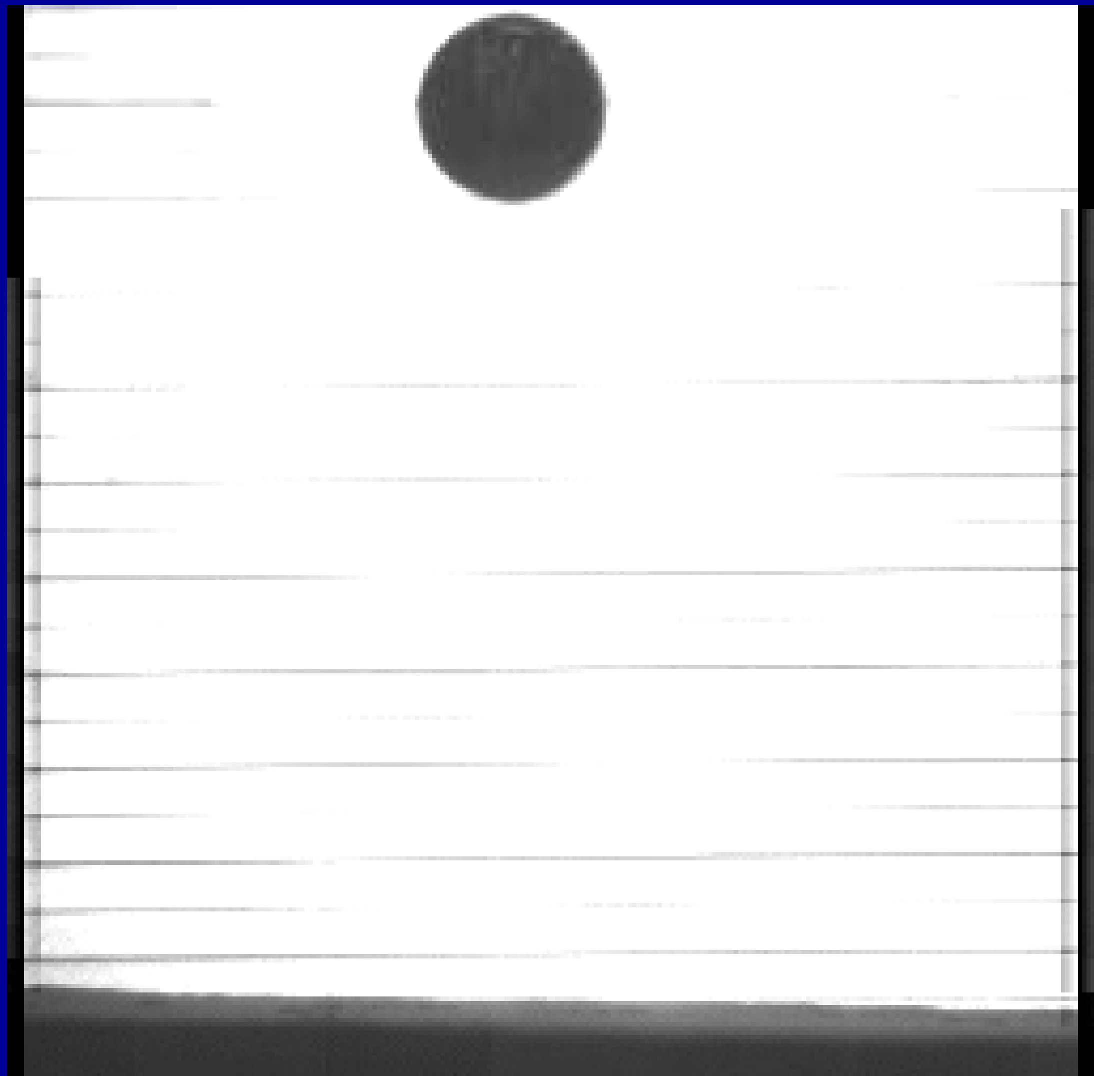
D. Lohse *et al.*, Phys. Rev. Lett. 93, 198003 (2004),
Nature 432, 689 (2004)

Is this the full story?

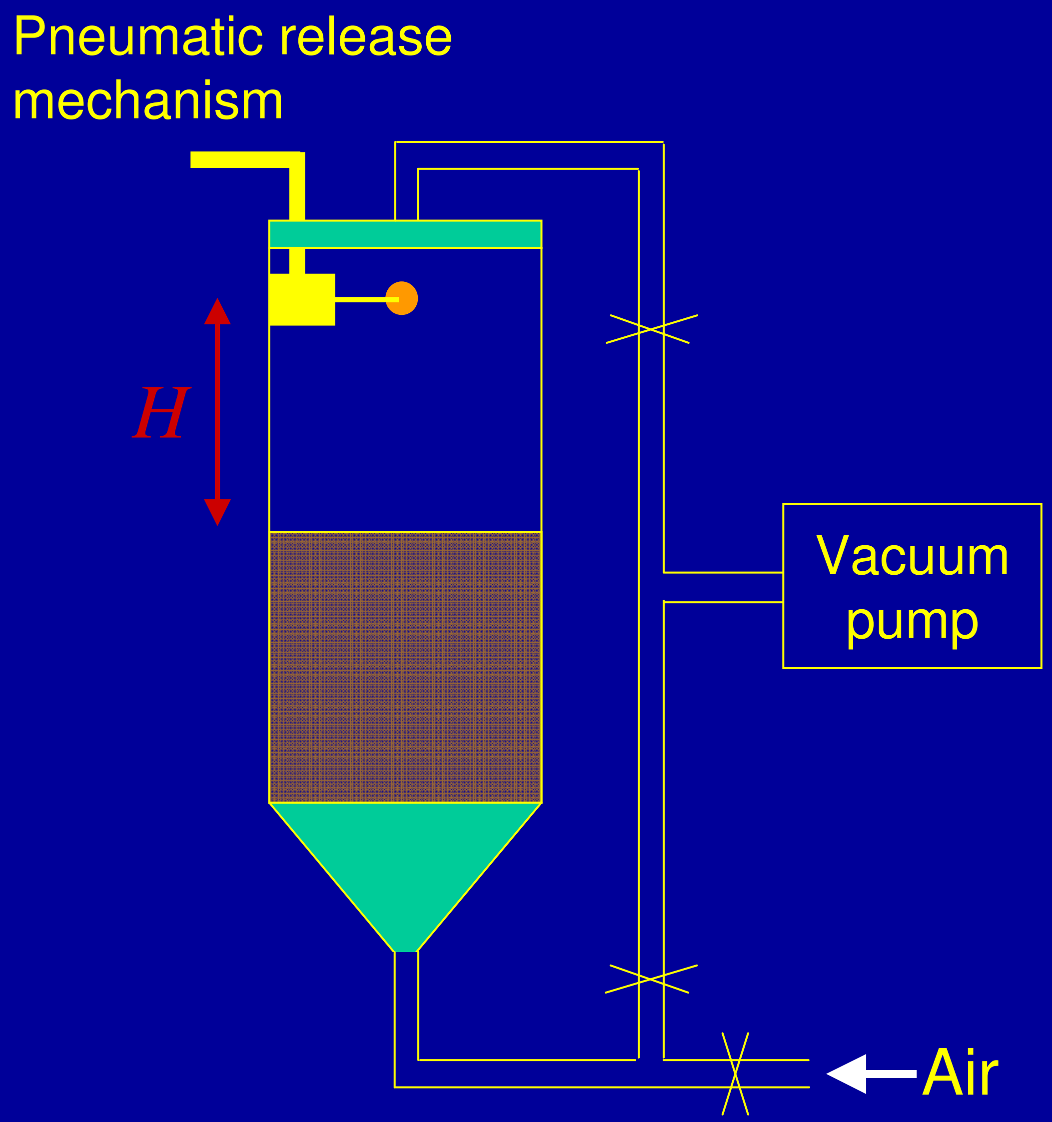
Large-Fr impact on sand

Surface seal

Fr=100



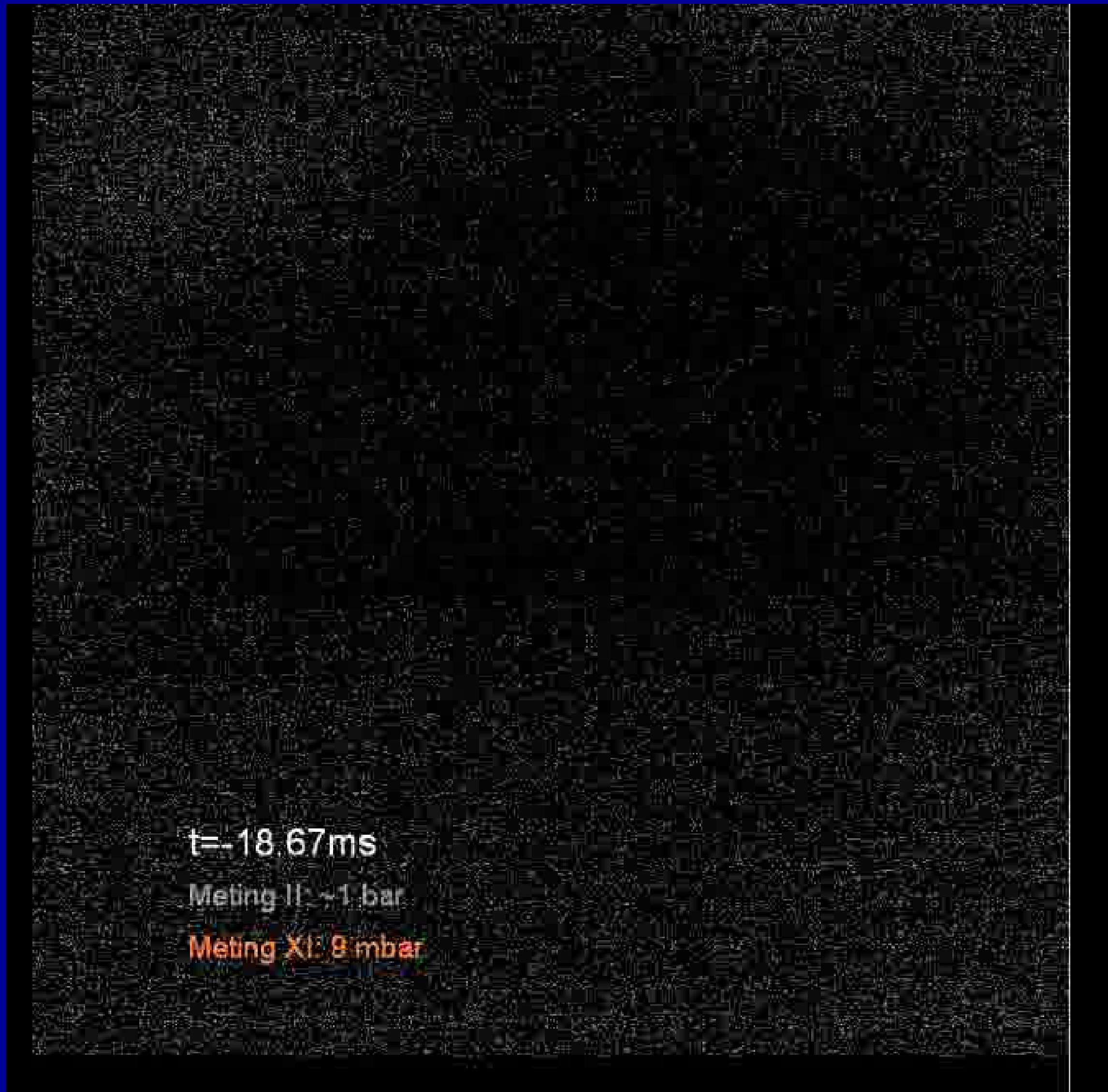
Analyse effect of ambient air

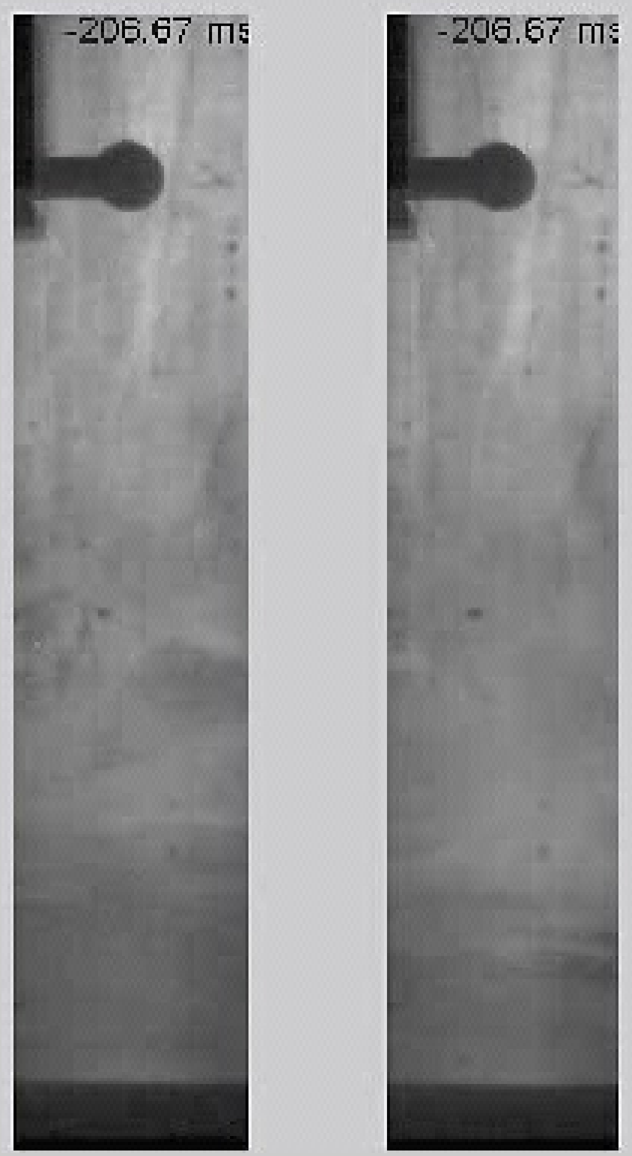


Effect of ambient pressure on…

- … splash
- … jet
- …penetration depth

Splash depends on ambient pressure



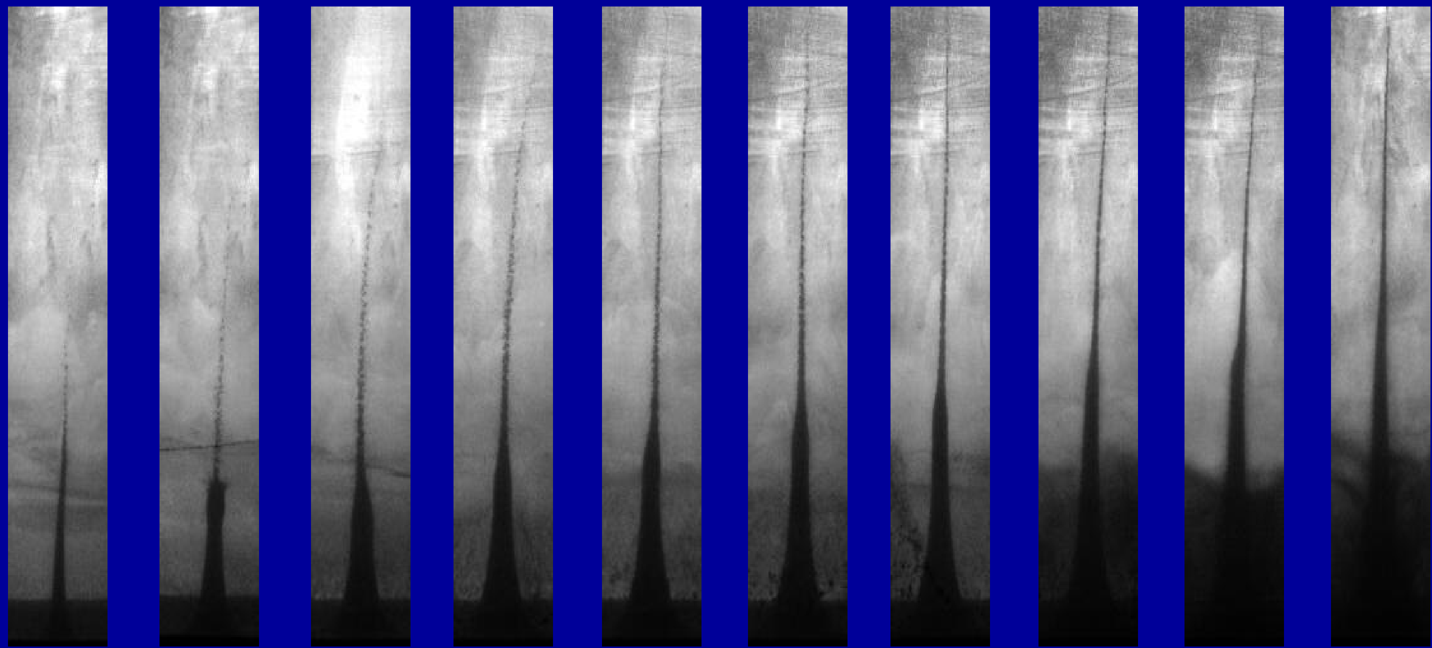


25 mbar **1000 mbar**

Jet much less pronounced under reduced pressure!

see also Royer et al.,
Nature Phys. 1, 164 (2005)

Effect of ambient air pressure

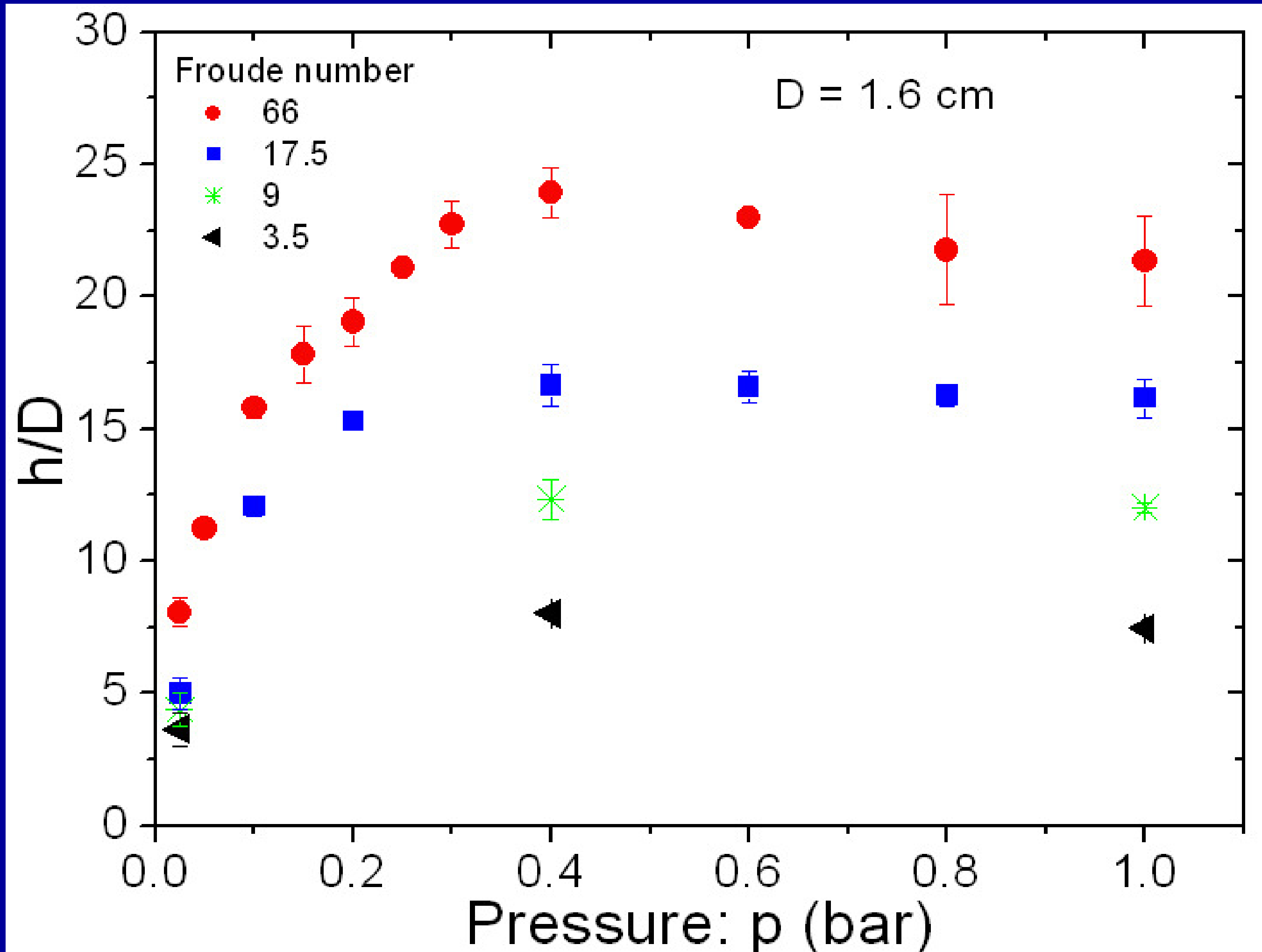


25 50 100 150 200 300 400 600 800 1000

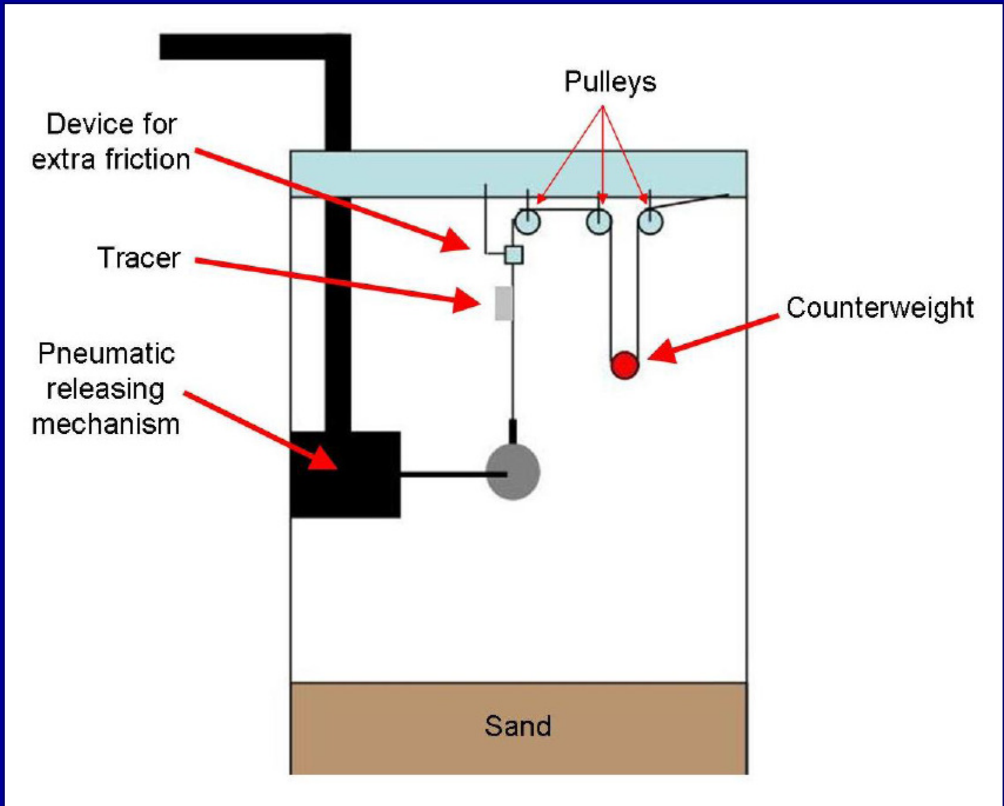
Pressure (mbar)

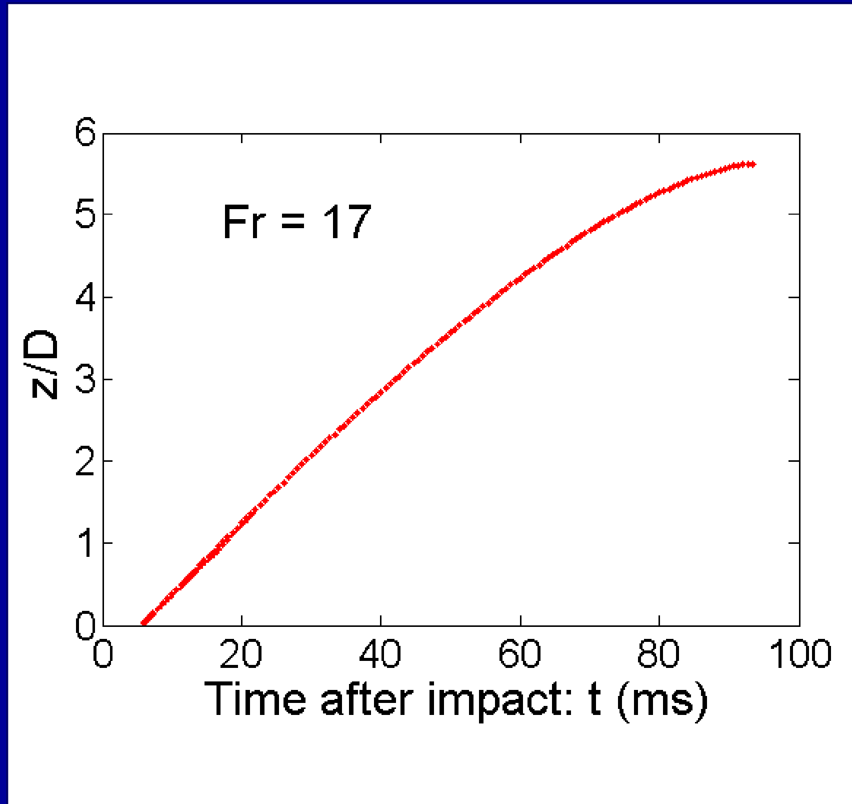
D = 2.5cm ; Fr = 32 ; t = 159ms

Jet height vs ambient pressure: saturation effects: two regimes

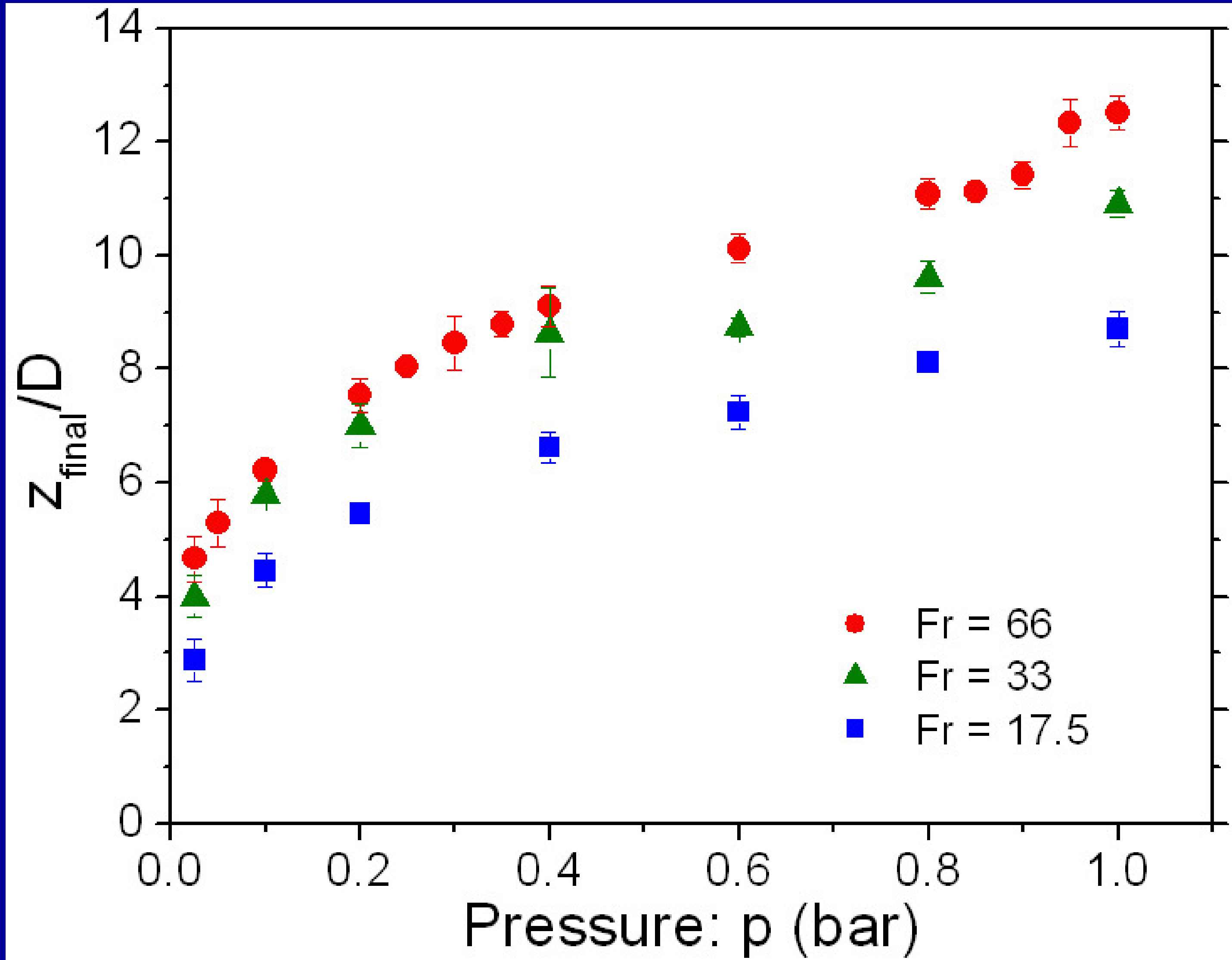


Ball trajectory in sand

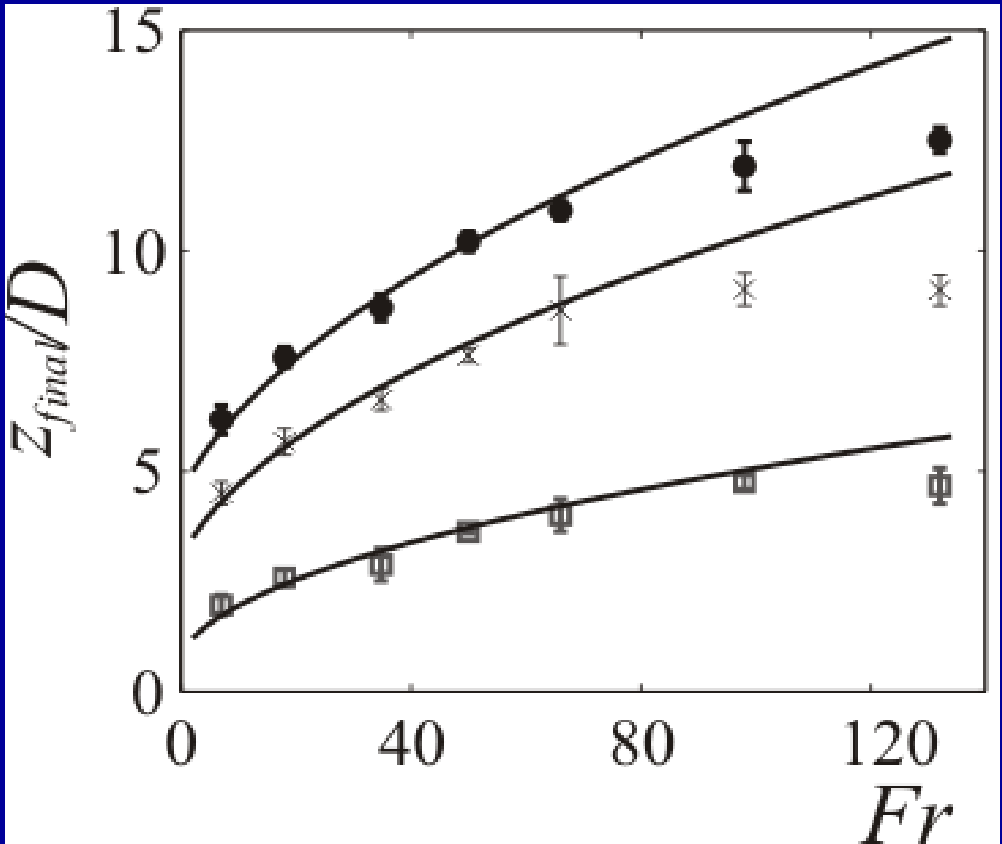




Final depth of intruder vs p



Final depth described by force balance model



1000 mbar

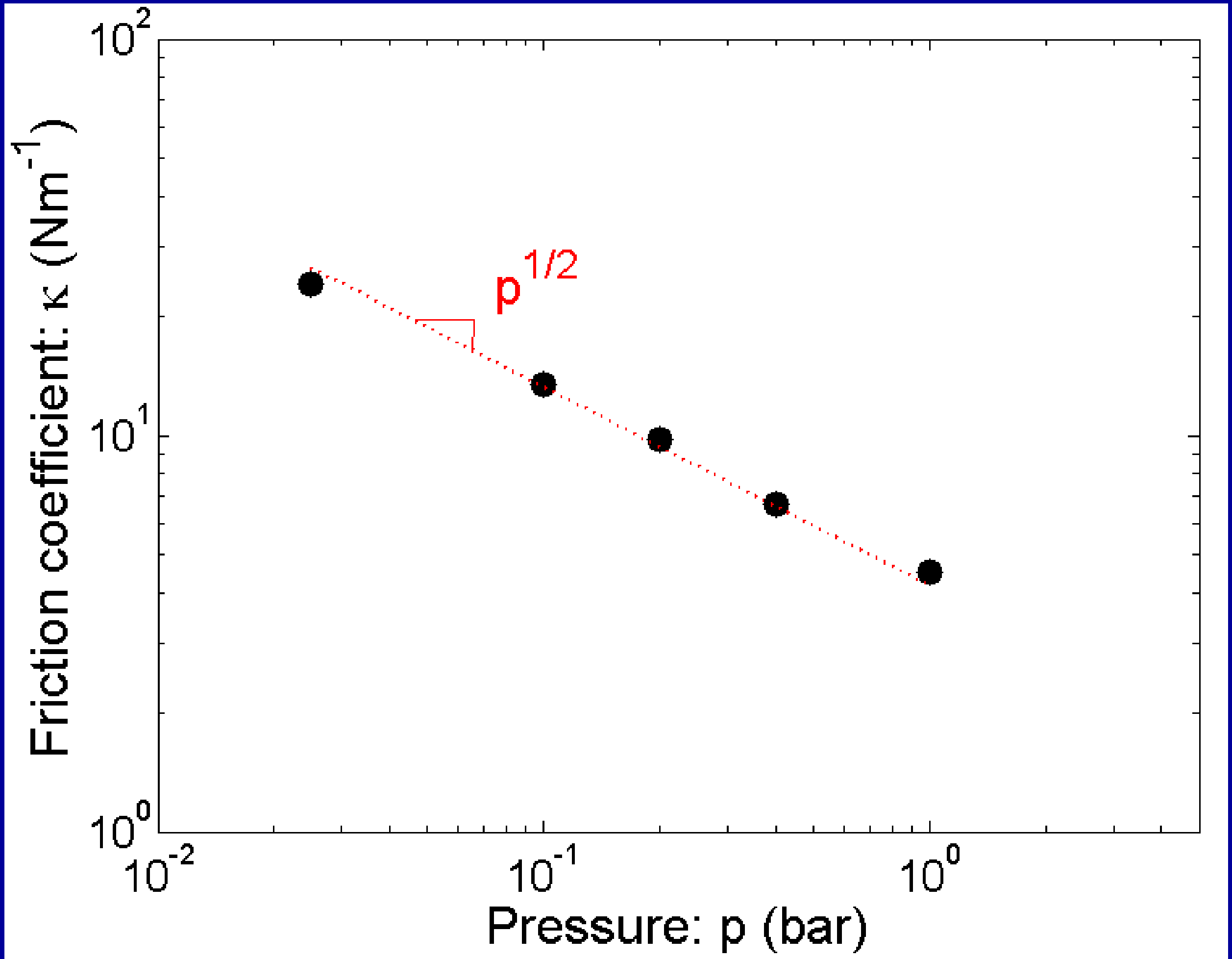
400 mbar

25 mbar

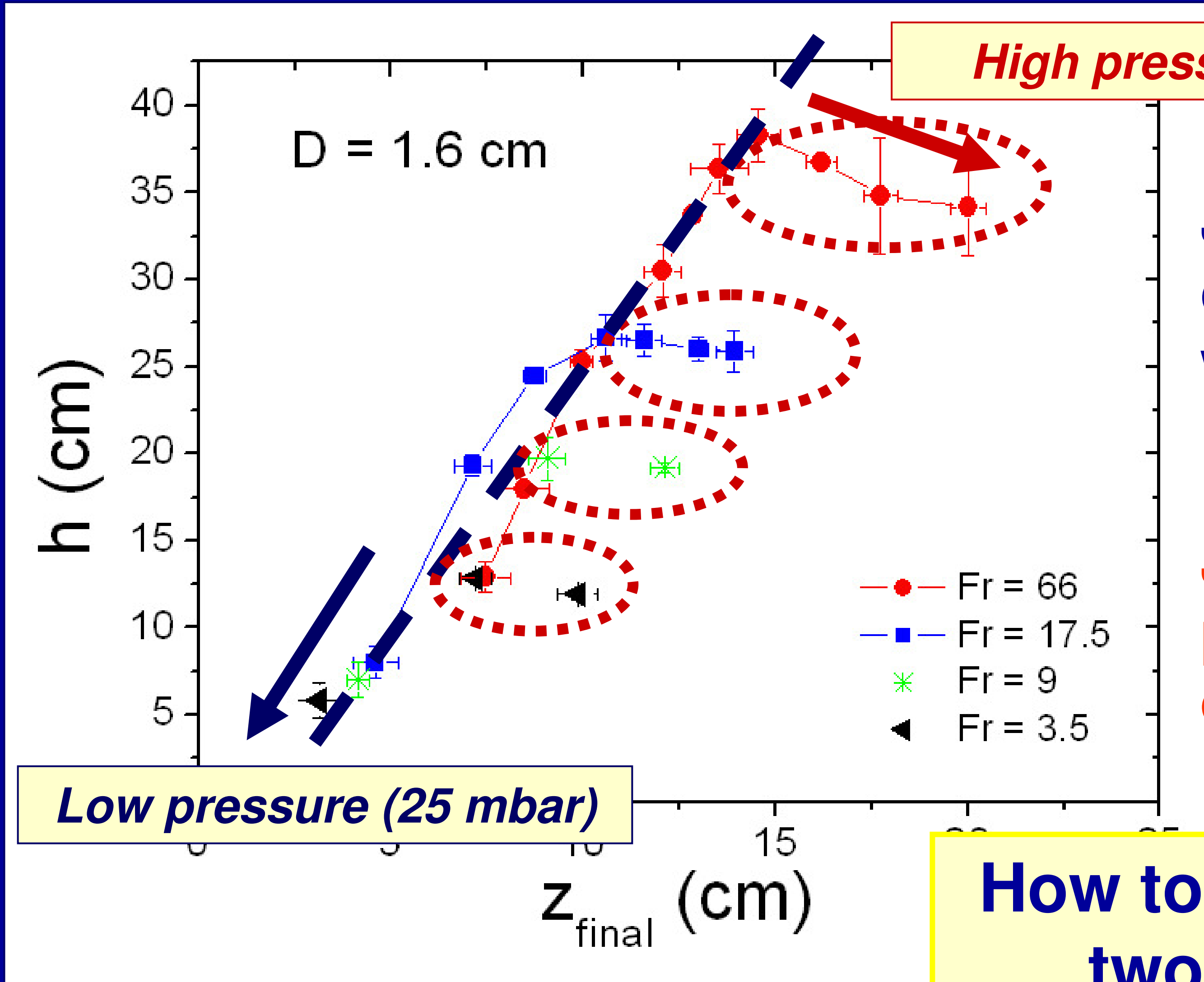
$$m\ddot{z} = mg - \kappa z,$$

$$z_{final} = \frac{gm}{\kappa}\left(1 + \sqrt{1 + \frac{\kappa D \mathrm{Fr}}{2\mathrm{gm}}}\right).$$

Coulomb friction coefficient depends on ambient pressure



Final depth correlated with jet height



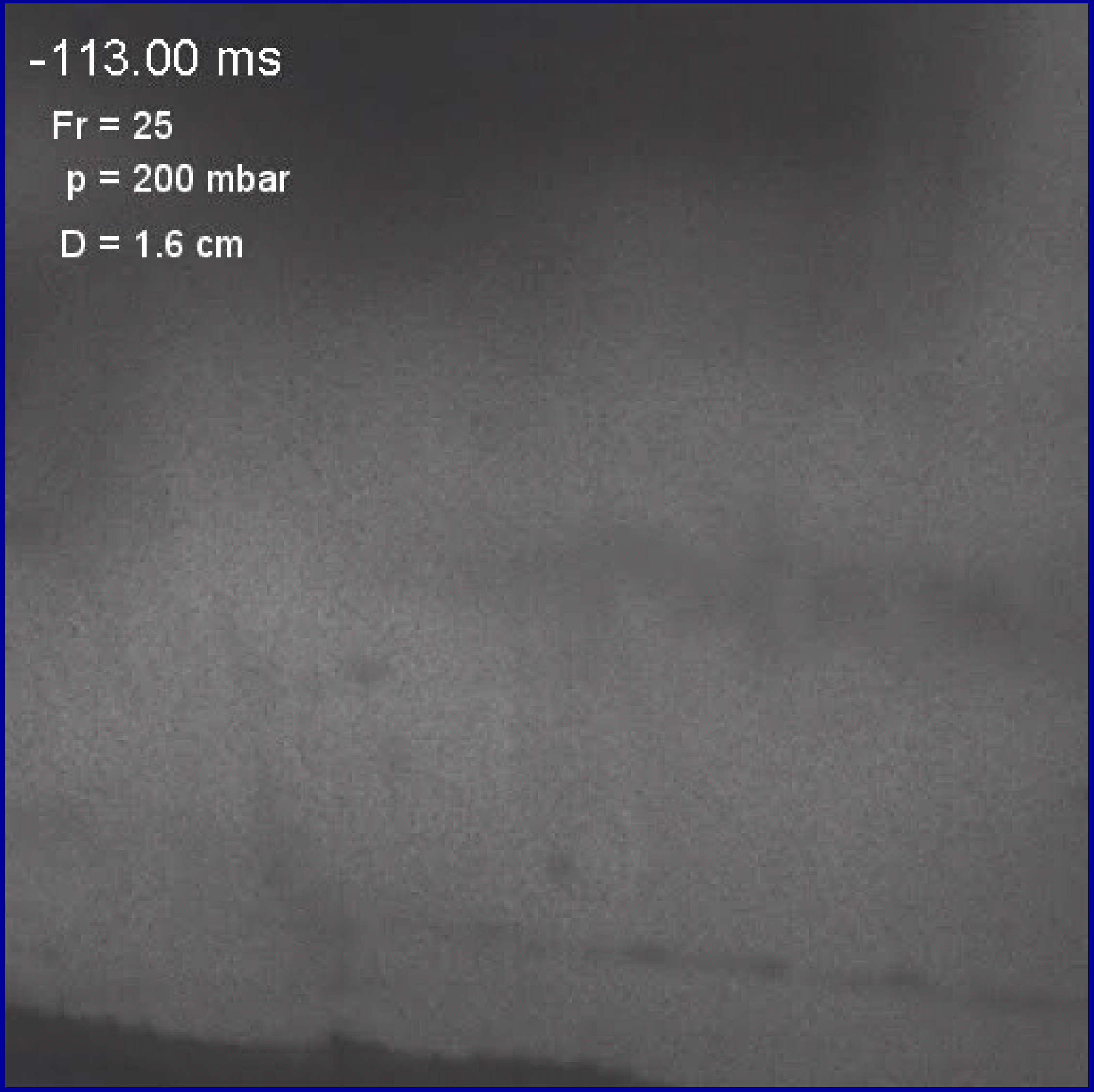
Two regimes:

Regime 1 (low p):
Jet height increases linearly with final depth

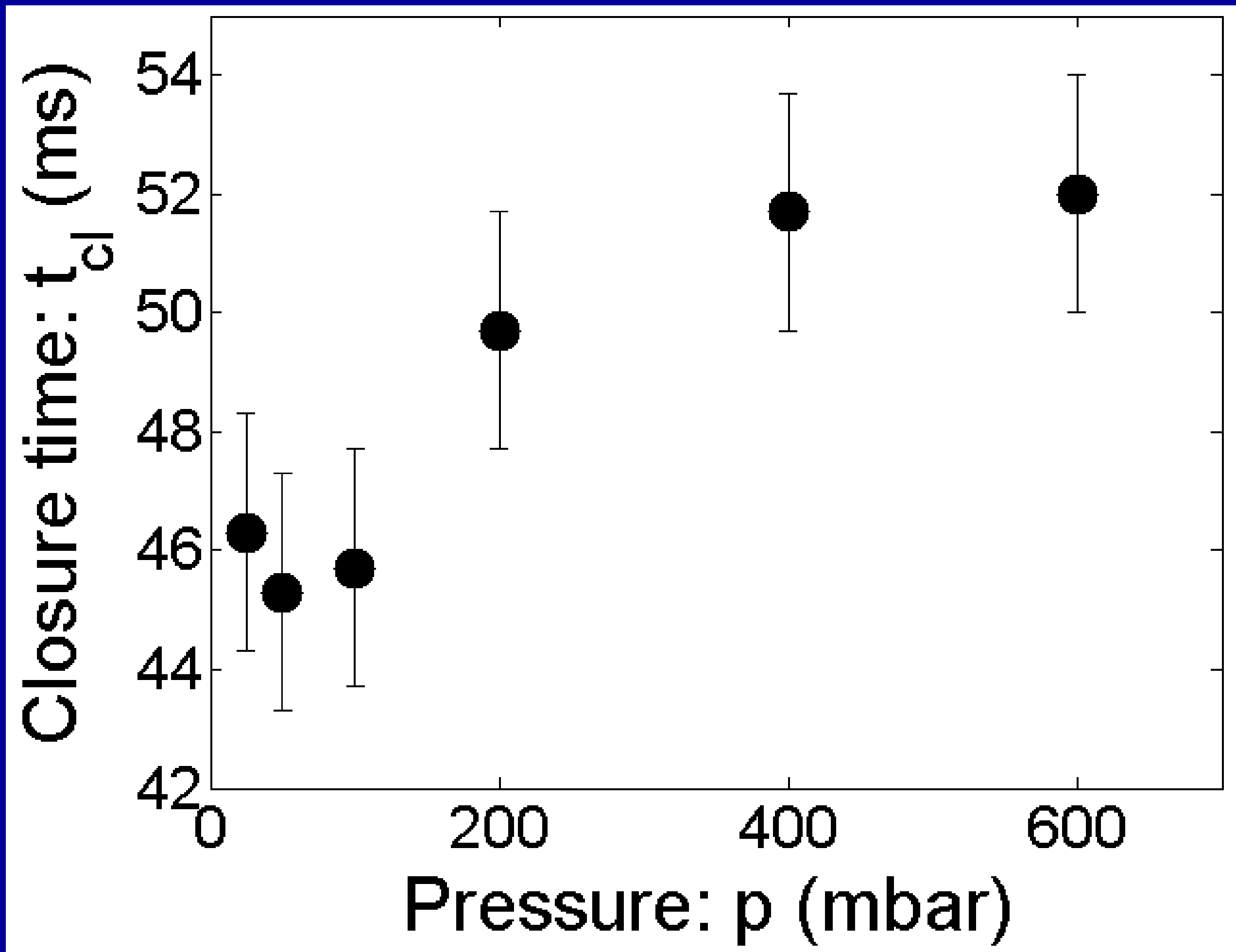
Regime 2 (high p):
Jet height independent of final depth

How to explain these two regimes ?

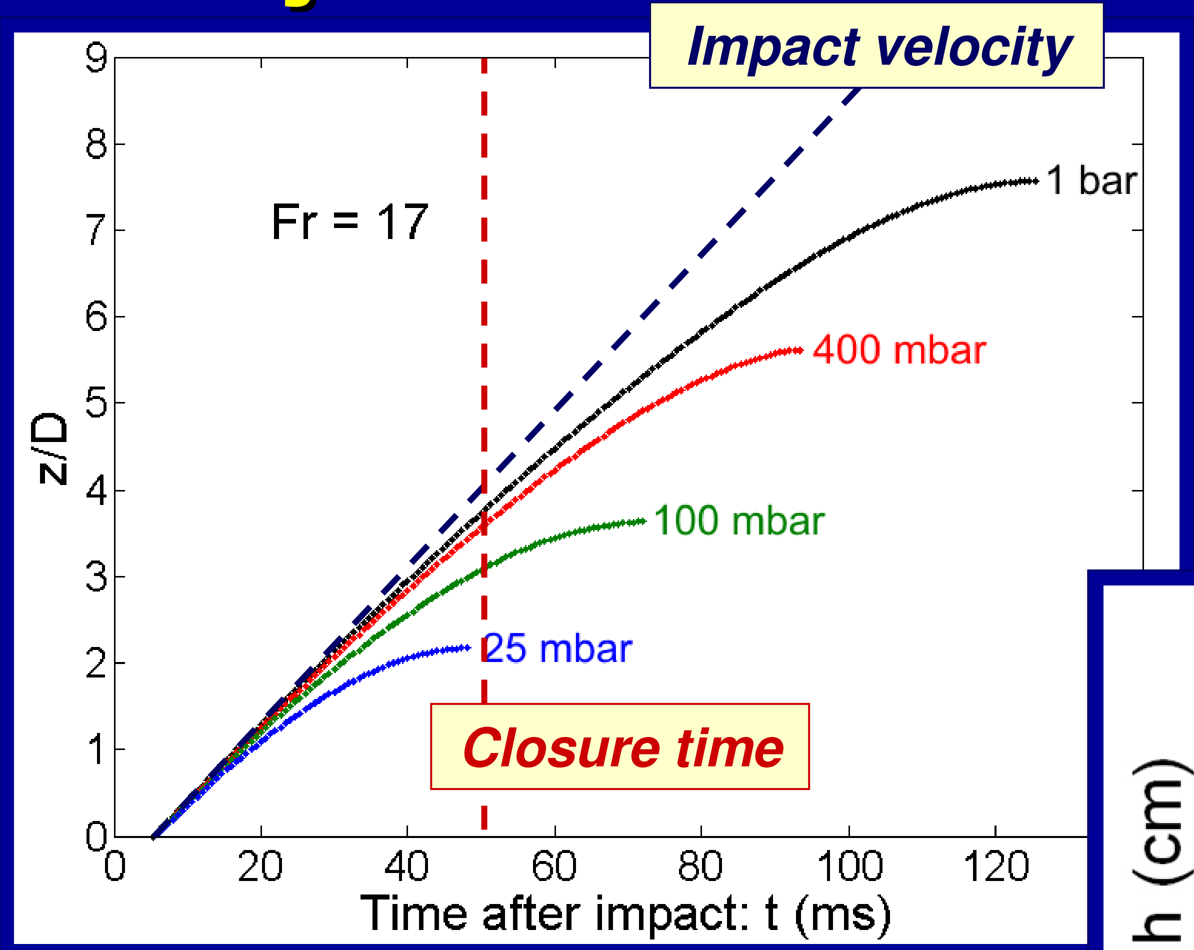
Closure time



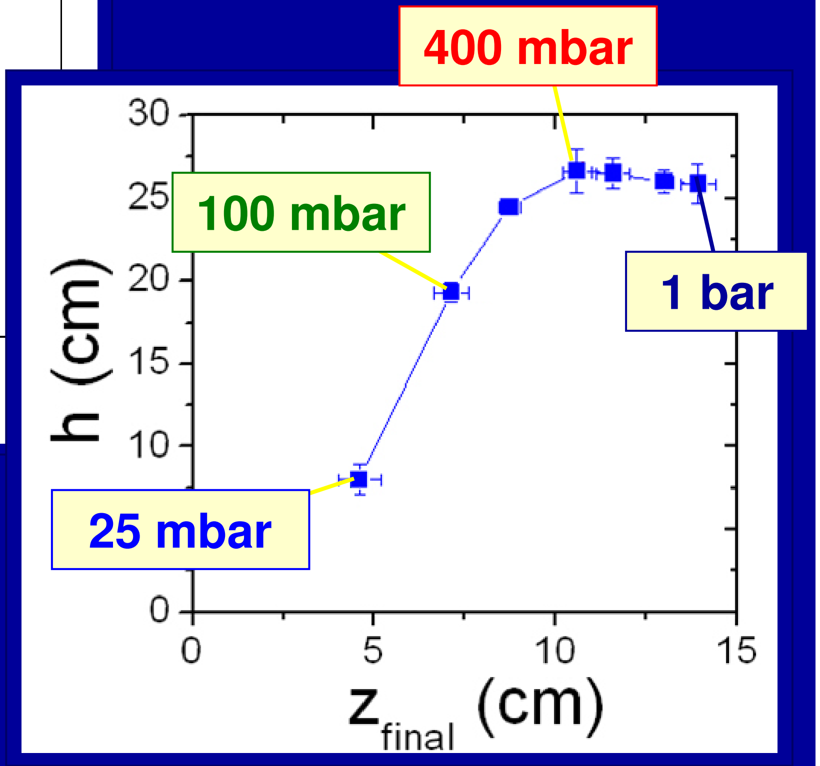
Closure time: nearly constant



Trajectories: when closure?



High pressures:
Identical trajectories until closure time
→ *same jet height (regime 2)*



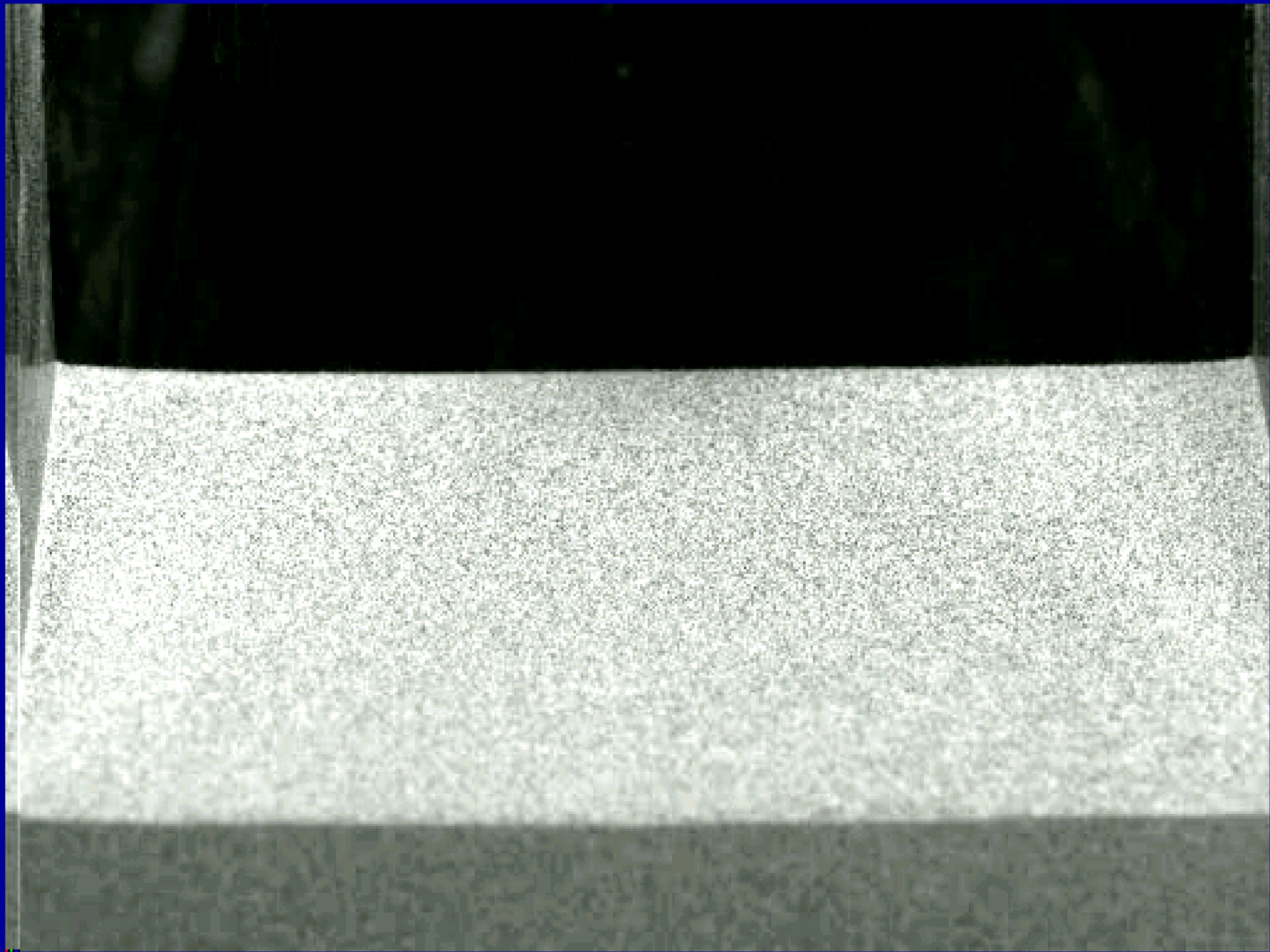
Low pressures:
Trajectories deviate substantially
→ *final depth determines jet height (regime 1)*

Final question:

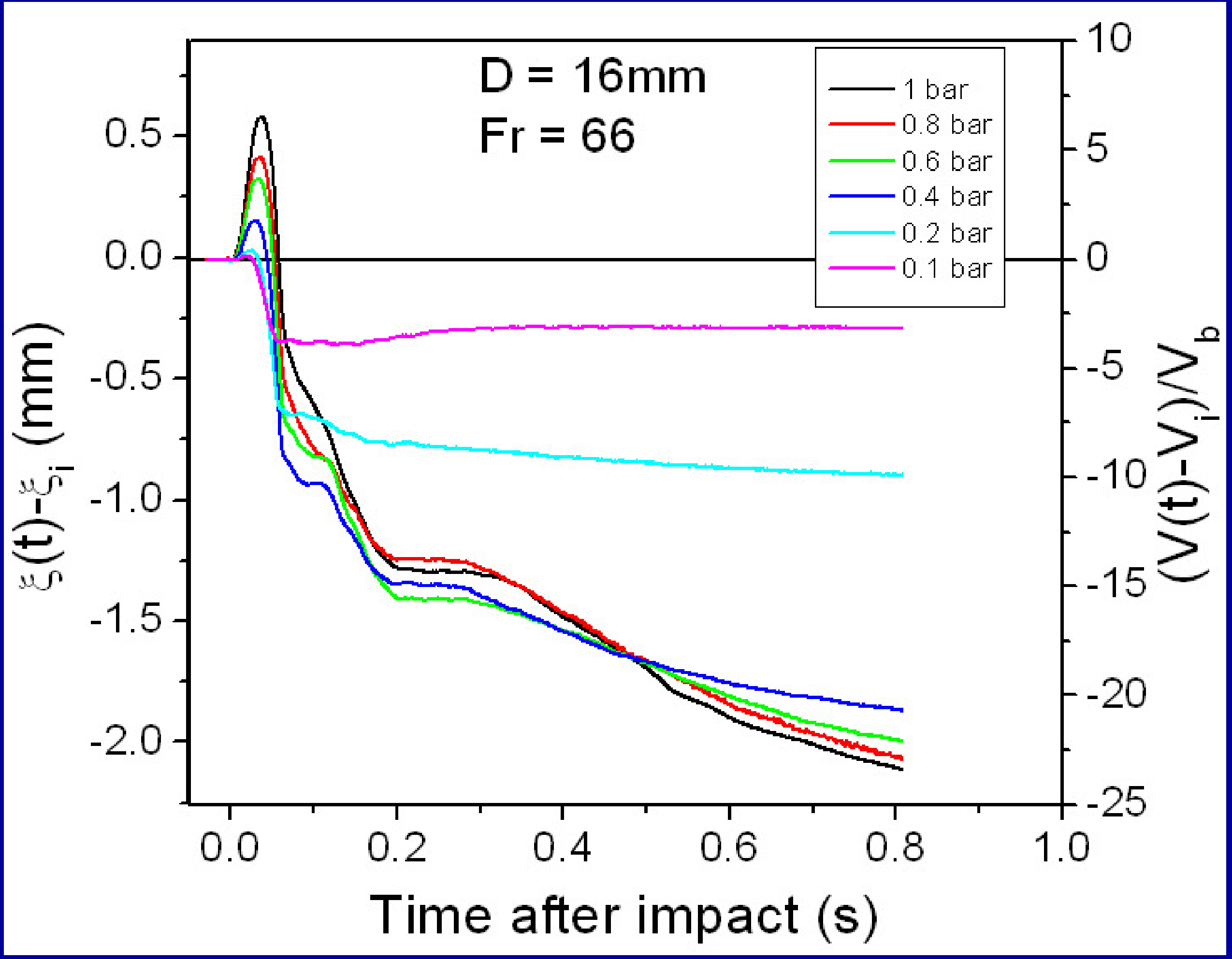
What causes the sphere to penetrate less at lower pressures (i.e., the friction reduction)?

The sand bed is fluidized by the air flow around the impacting ball ($Re_{sand\ grains} \approx 5$)!

Impact of ball on decompactified sand



Height of sand bed vs time at impact



Ambient air leads to expansion of granular bed at impact: **extra fluidization**

Conclusions II

- Ambient air pressure strongly influences the penetration depth of the ball and thus the jet height
- Ambient air pressure hardly affects the collapse of the cavity
- Two regimes: high p: trajectories unchanged up to closure
  low p: trajectories deviate: jet height <-> depth
- Autofluidization effect

Gabriel Caballero et al., Phys. Rev. Lett. 99, 018001 (2007)

Collaborators:

- **Raymond Bergmann**
- **Gabriel Caballero**
- Martin van der Hoef
- Kevin Kelly
- Hans Kuipers
- **Devaraj van der Meer**
- Andrea Prosperetti
- Remco Rauhe
- Christiaan Zeilstra

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