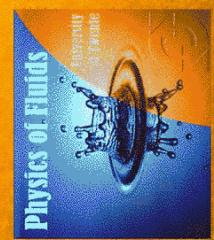


Impact Dynamics: Void Collapse and Jet Formation

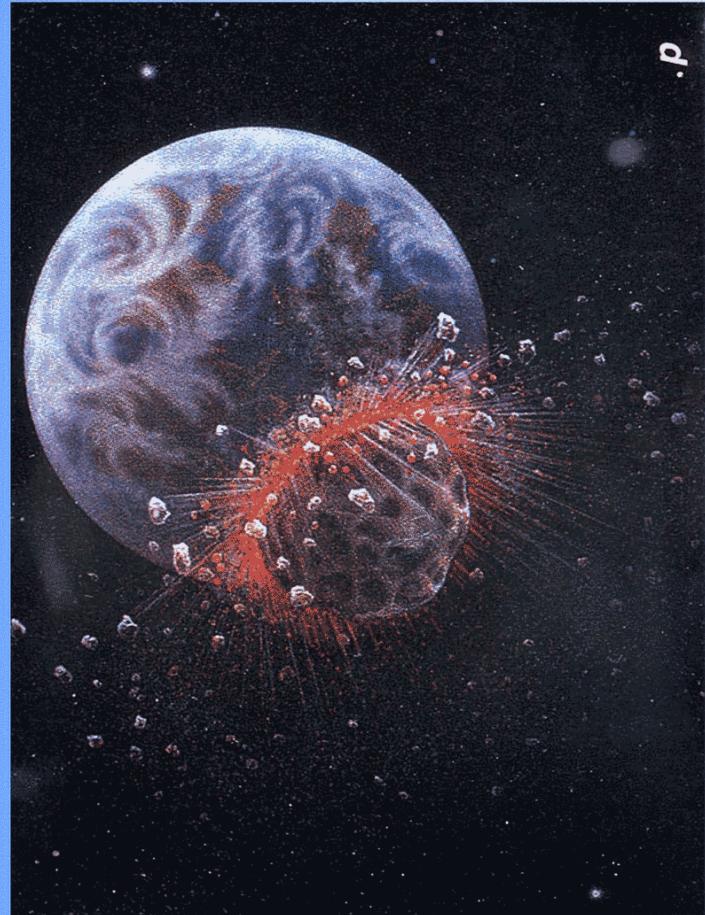
Devaraj van der Meer



Raymond Bergmann Christiaan Zeilstra
René Mikkelson Martin van der Hoef
Marijn Sandtke Hans Kuipers
Remco Rauh 
Michel Versluis
Ko van der Weele
Detlef Lohse
Mark Stijnman
Andrea Prosperetti
Physics of Fluids – University of Twente

J.M. Burgerscentrum

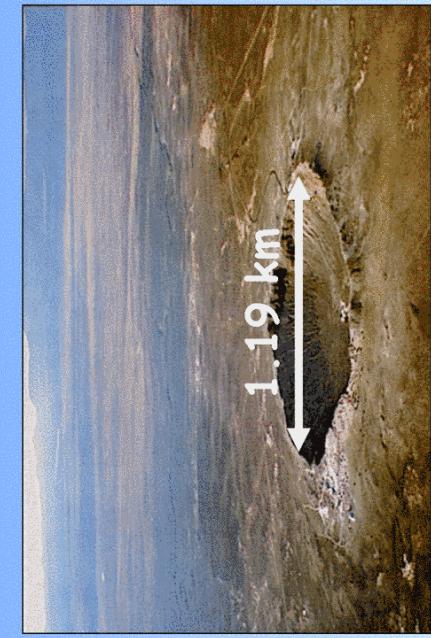
Asteroid impact on earth



.p

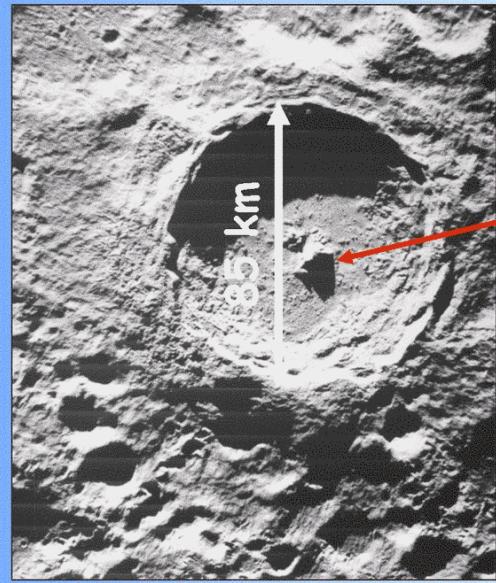
Craters

...on earth



Arizona

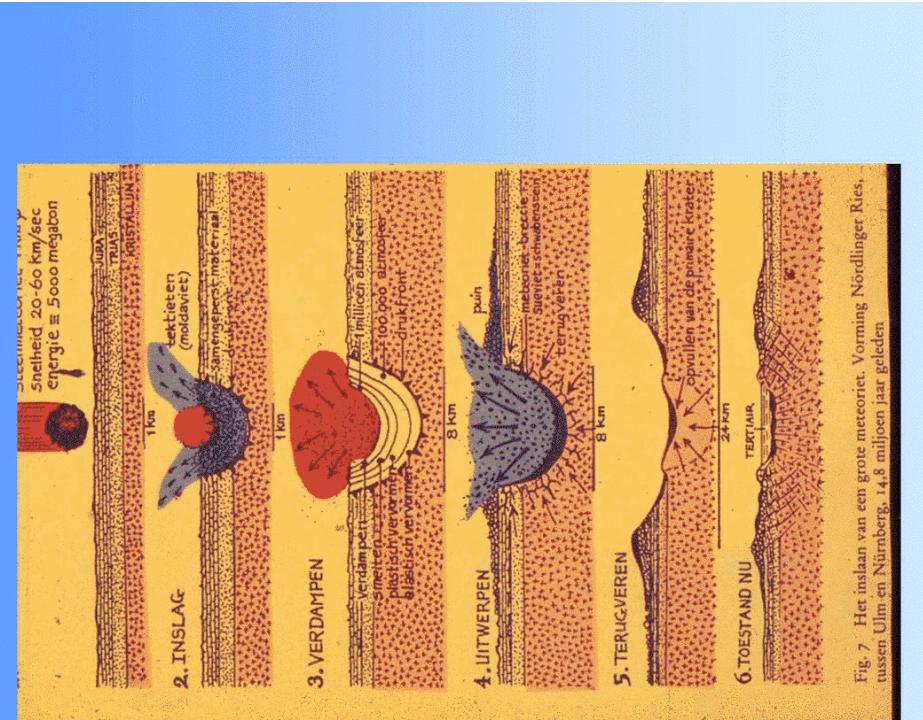
...on the moon



Tycho

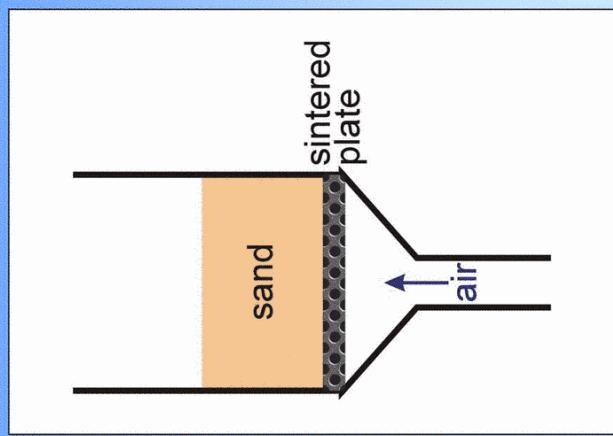
central peak

Speculation on crater formation

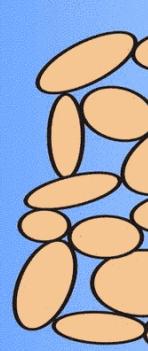
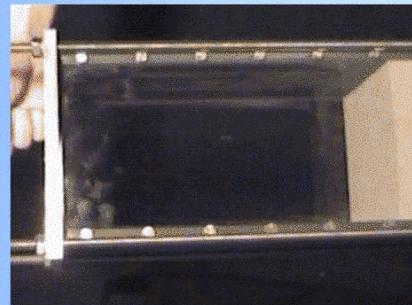


Source:
Jan Smit,
Amsterdam,
Dept. Geology

Preparing the sand



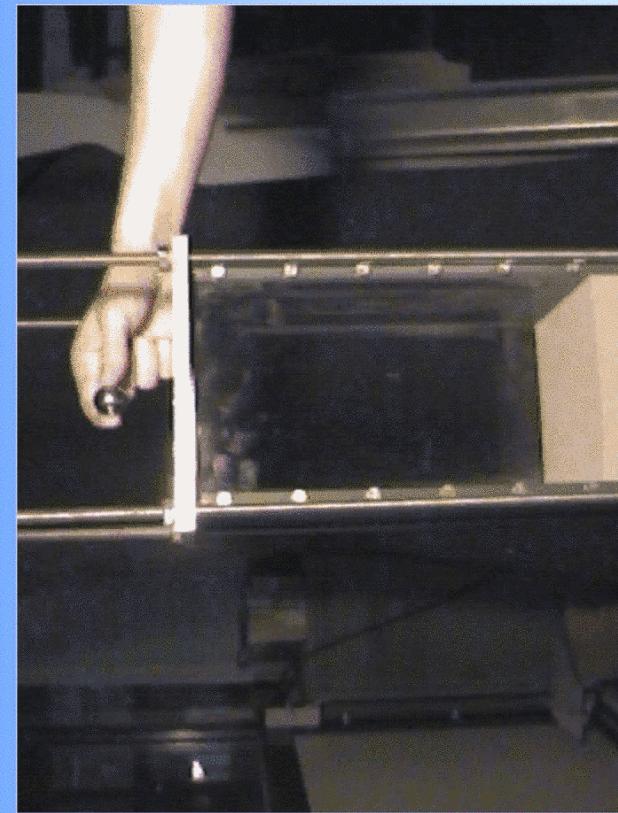
turn
off
air



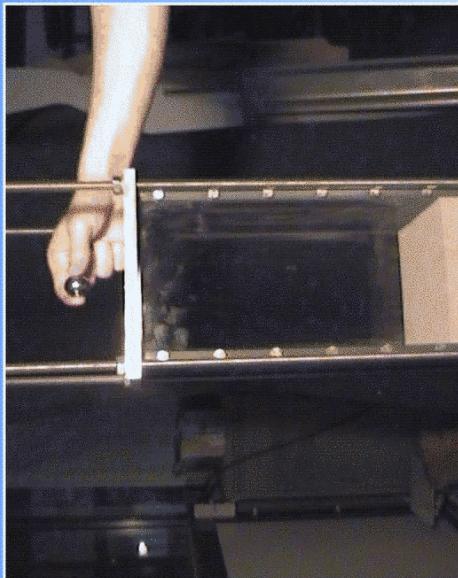
very loose
packing:
solid fraction
= 41 %

Controlled experiments

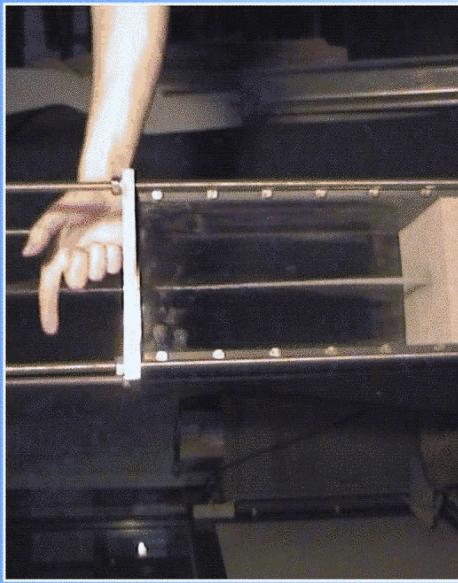
Ball dropped on decompactified, very fine sand



Ball at release point

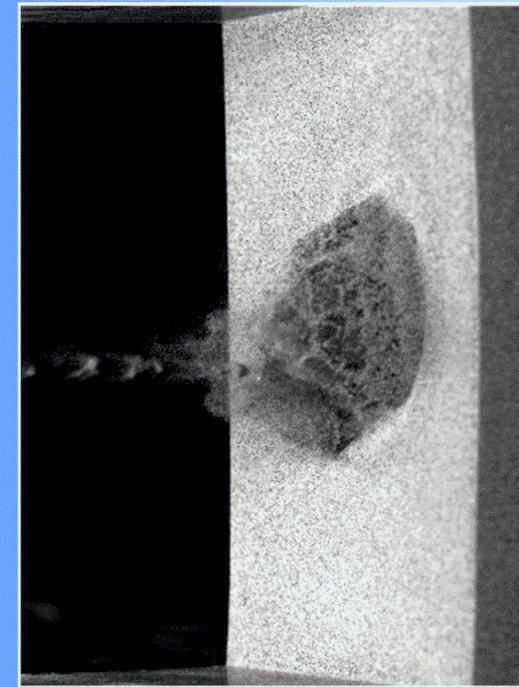


Maximum jet height



Jet height > Release height !

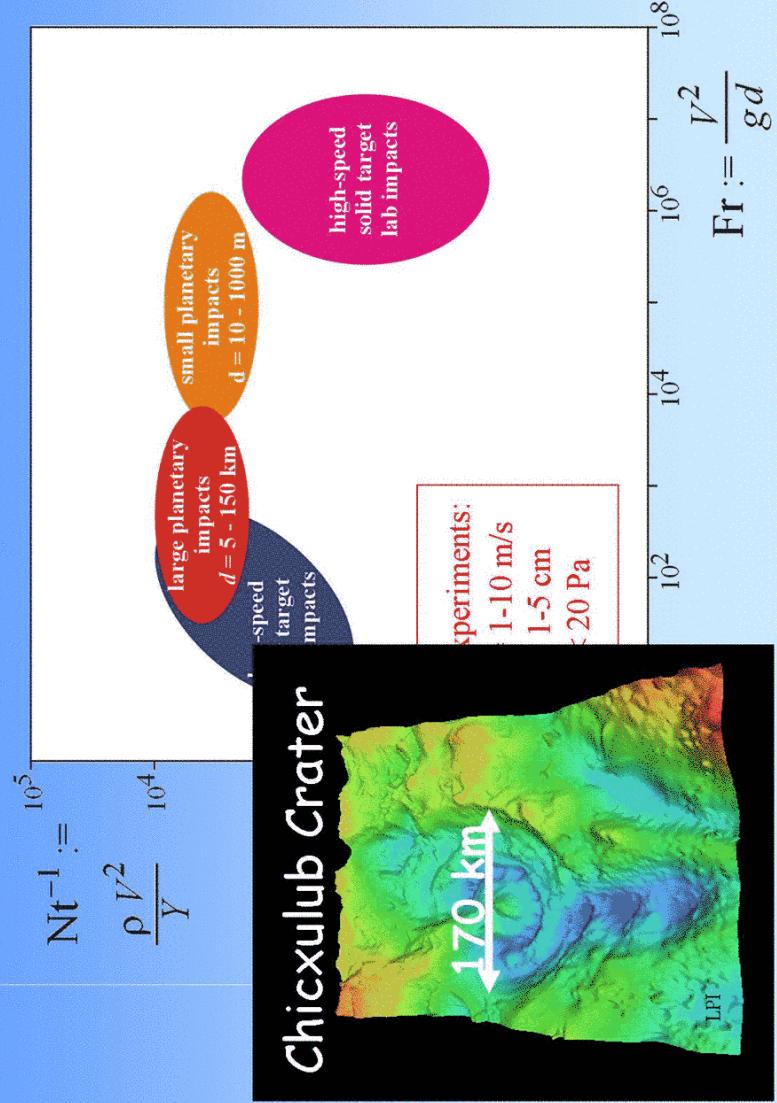
Ball impact on sand



3 events:

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

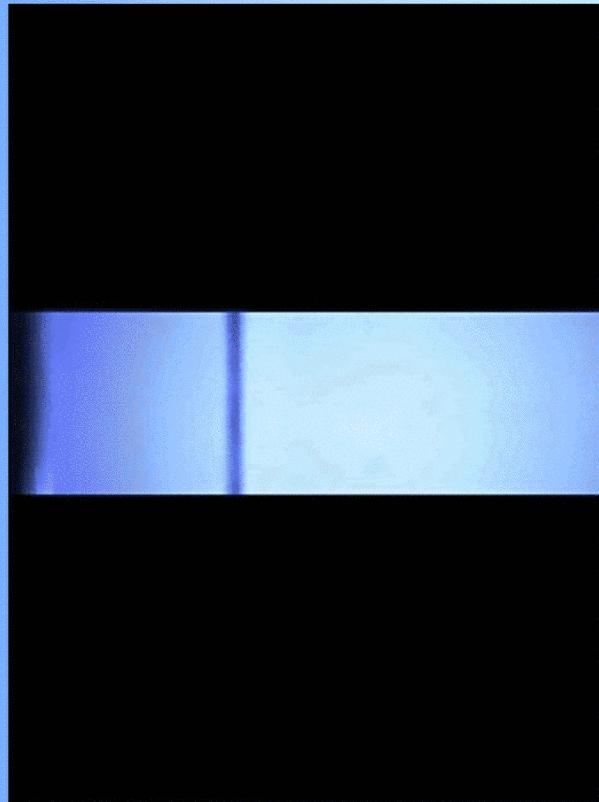
Impact: planetary vs. lab



What is the mechanism?

- A. Analogy to object falling on water
- B. "2D" sand experiments

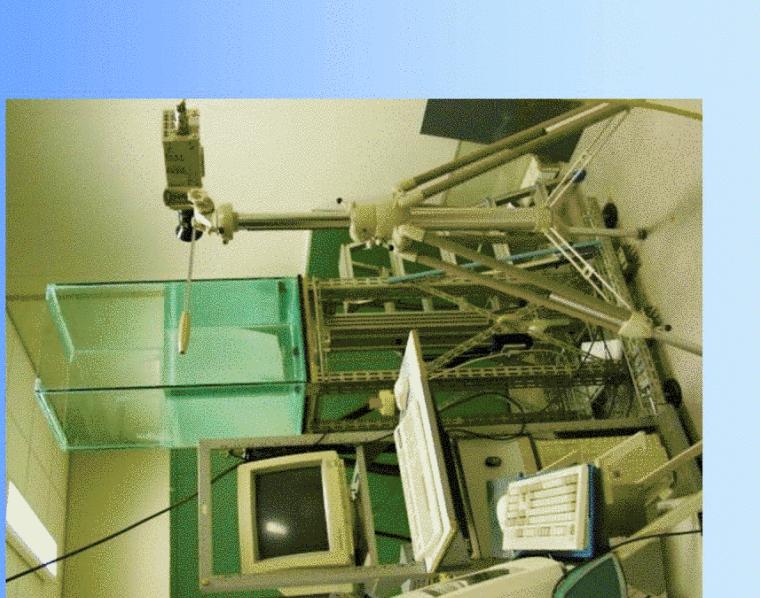
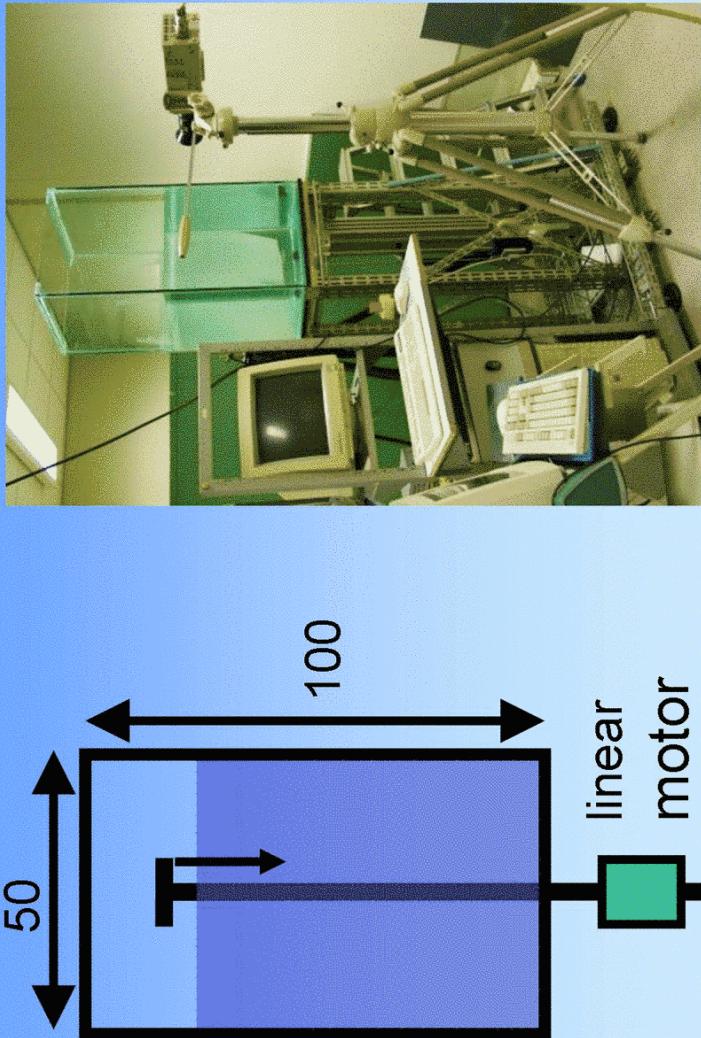
Impact on water



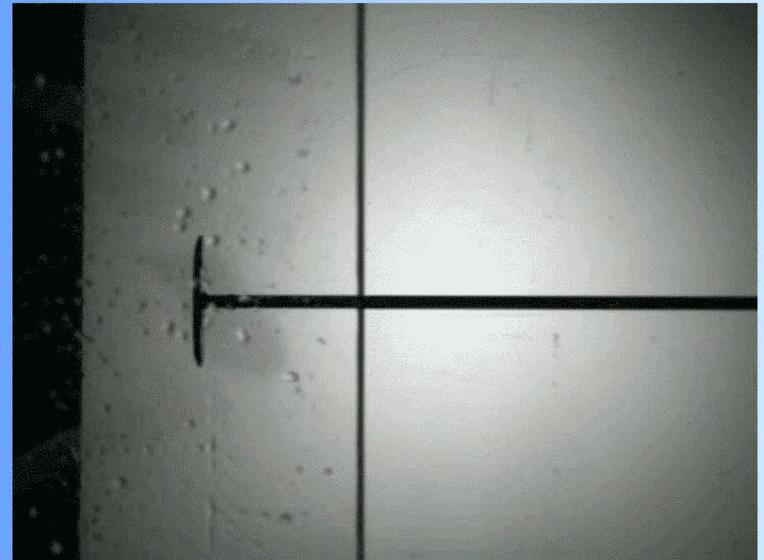
Mechanism

1. Void formation
2. Void collapse due to hydrostatic pressure
3. Jet formation at singularity point
4. Air entrainment (bubble formation)

Experimental setup



Disk pulled through a liquid



$$V_{\text{impact}} \approx 1.0 \text{ m/s}$$

$$R_{\text{disk}} = 0.03 \text{ m}$$

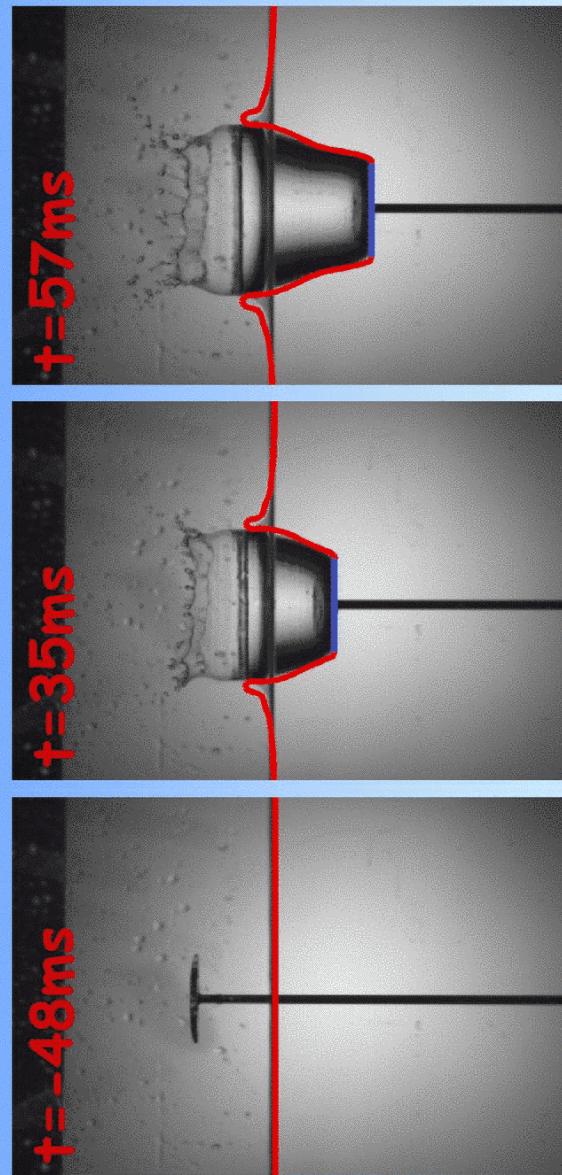
Boundary Integral simulation

Potential theory:

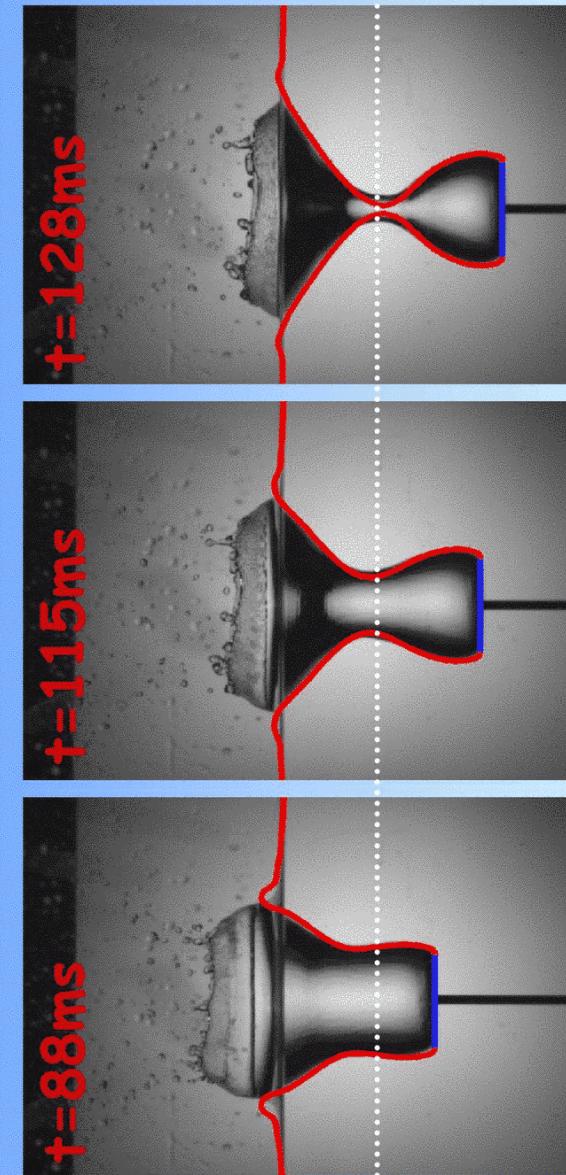
- inviscid
- irrotational

Mark Stijnman,
Twente, 2003,
ongoing PhD thesis

Comparison BI simulation with experiment

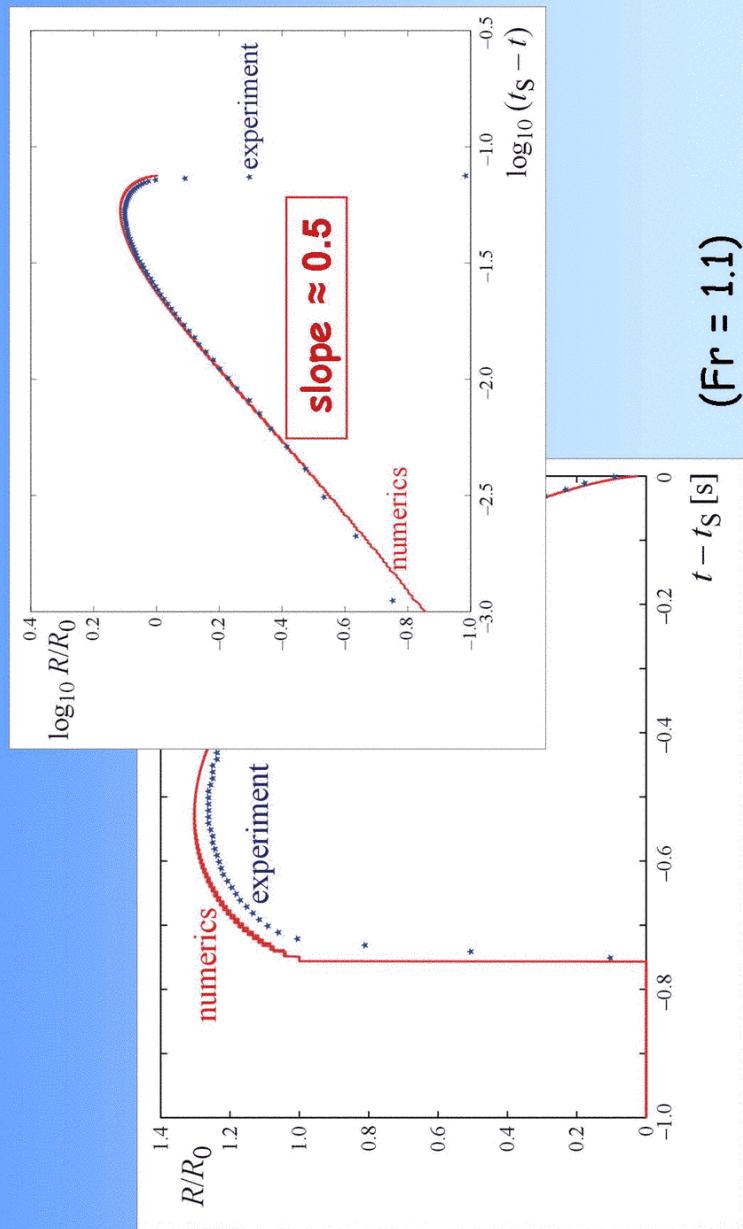


Comparison BI simulation with experiment

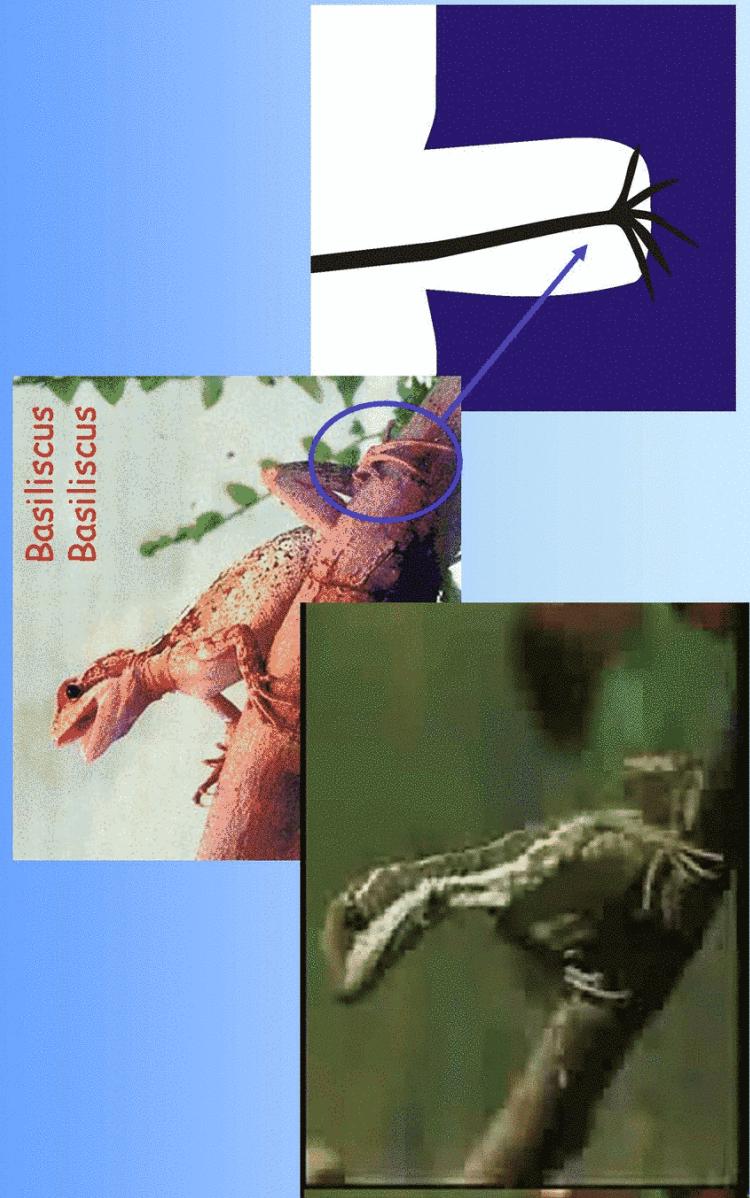


(No fit parameters)

Void radius vs. time



Jesus Christ lizard

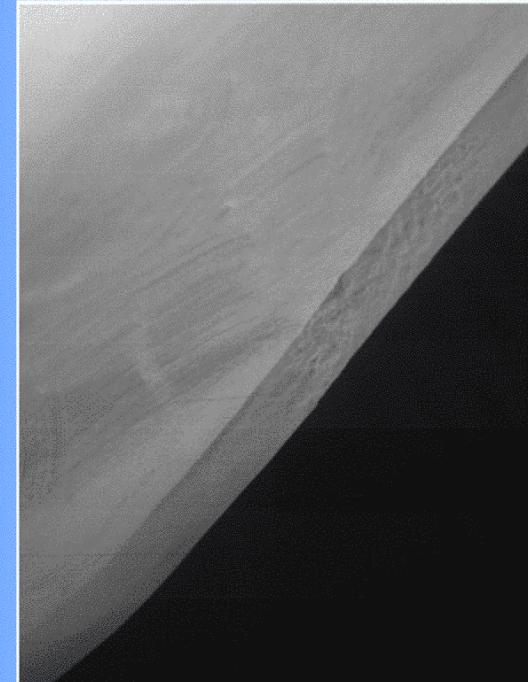
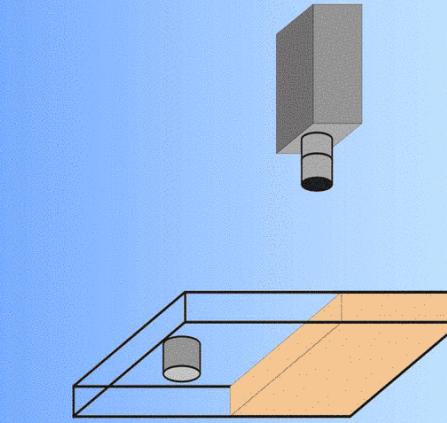


Back to granular

What is the mechanism?

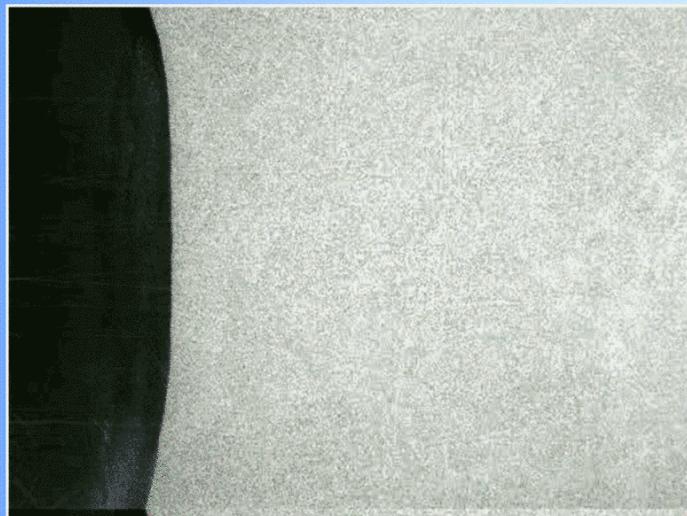
- A. Analogy to drop falling on water
- B. "2D" sand experiments

B. "2D" experimental setup



PRL 93, 198003 (2004)

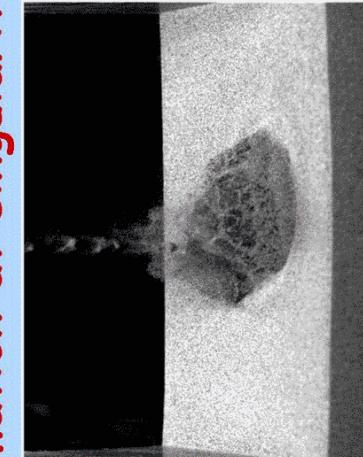
2D experiment: high impact velocity



2 jets + air
entrainment !

Same mechanism as in fluid

1. Void formation
2. Void collapse due to "hydrostatic" pressure
3. Jet (in 2D sheet) formation at singularity
4. Air entrainment (bubble formation)

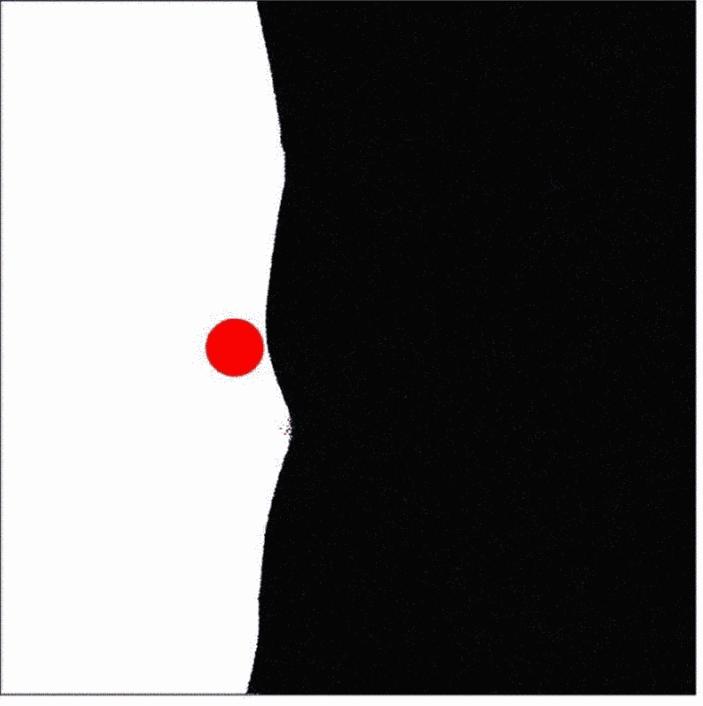


Discrete particle simulation

- soft sphere code
- $N = 400,000$
- $d_s = 0.5 \text{ mm}$
- $d_b = 15 \text{ mm}$
- quasi 2D (8 grains)
- pre-fluidized

Christiaan Zeilstra
Martin v.d. Hoeft
Hans Kuipers

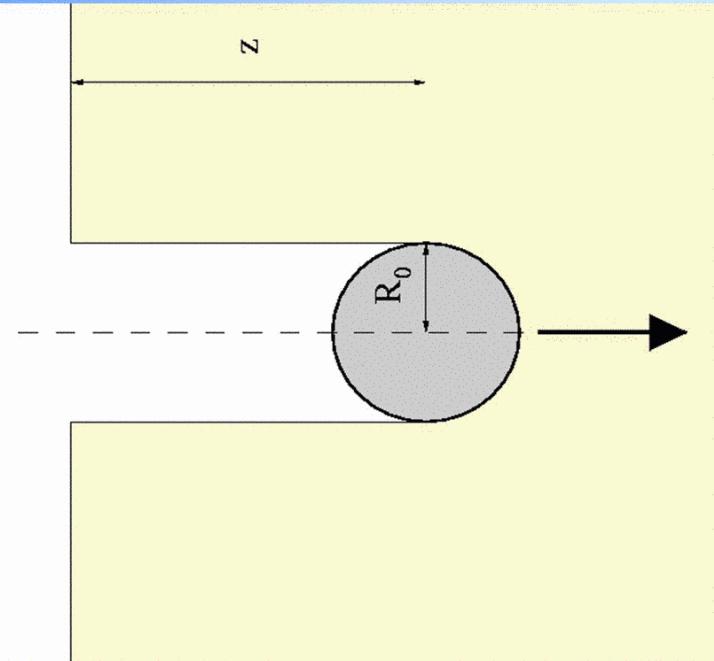
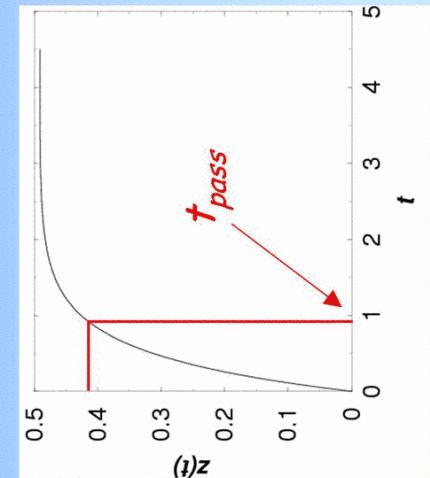
$t = 0.0005 \text{ [s]}$



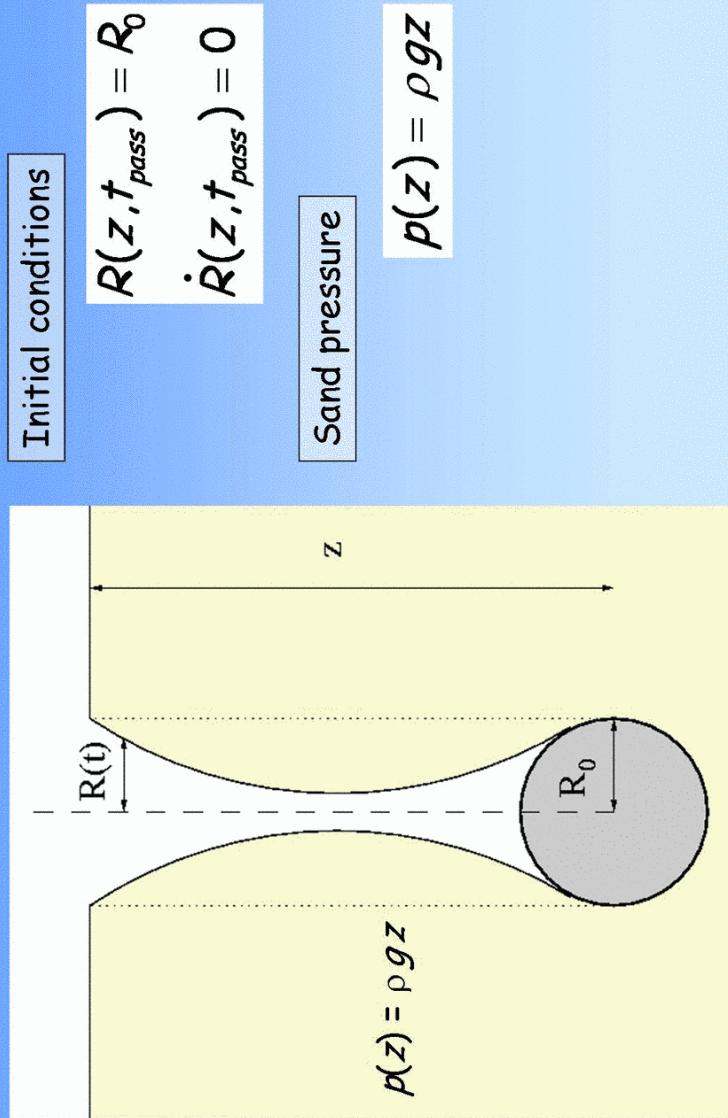
Cavity creation

$$F_d = F(z, \dot{z})$$

$$z(t) \Rightarrow t_{pass}(z)$$

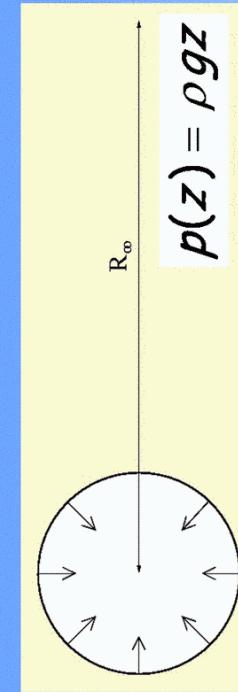


Cavity collapse



Rayleigh-type dynamics

2D slice at depth z



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

Euler equation in cylindrical coordinates

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

Continuity equation and boundary conditions

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

2D Rayleigh equation for collapsing void

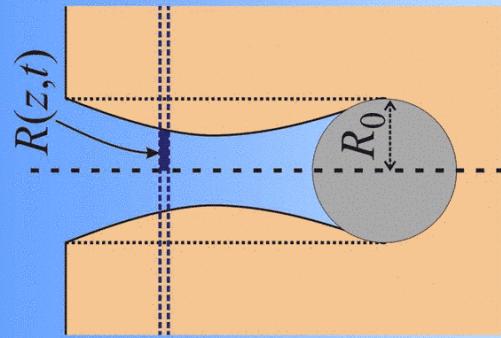
Rayleigh-type model

void creation (from drag law):

$$t_{pass}(z)$$

void collapse (simultaneous) in 2D layers:

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

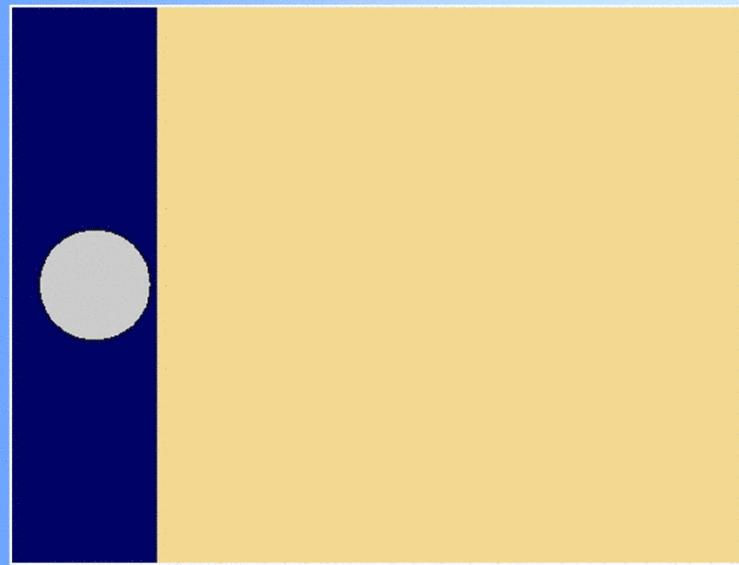


Time-evolution of cavity profile:
 $R(z,t)$



Linked by boundary conditions:
 $R(z, t_{pass}(z)) = R_0$
 $\dot{R}(z, t_{pass}(z)) = 0$

Rayleigh model: high impact velocity



Rayleigh: large τ limit

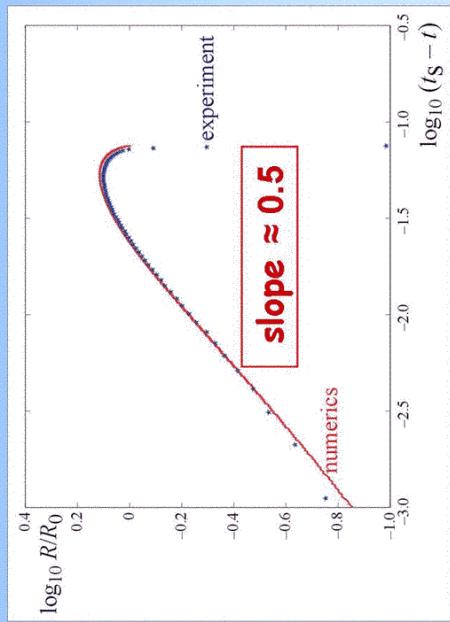
Limit $R \rightarrow 0$:

$$(R\ddot{R} + \dot{R}^2) \ln \frac{R}{R_\infty} + \frac{1}{2}\dot{R}^2 = \cancel{\rho\ddot{R}}$$

$$(R\ddot{R} + \dot{R}^2) = \frac{d^2}{dt^2} \left(\frac{1}{2} R^2 \right) = 0$$

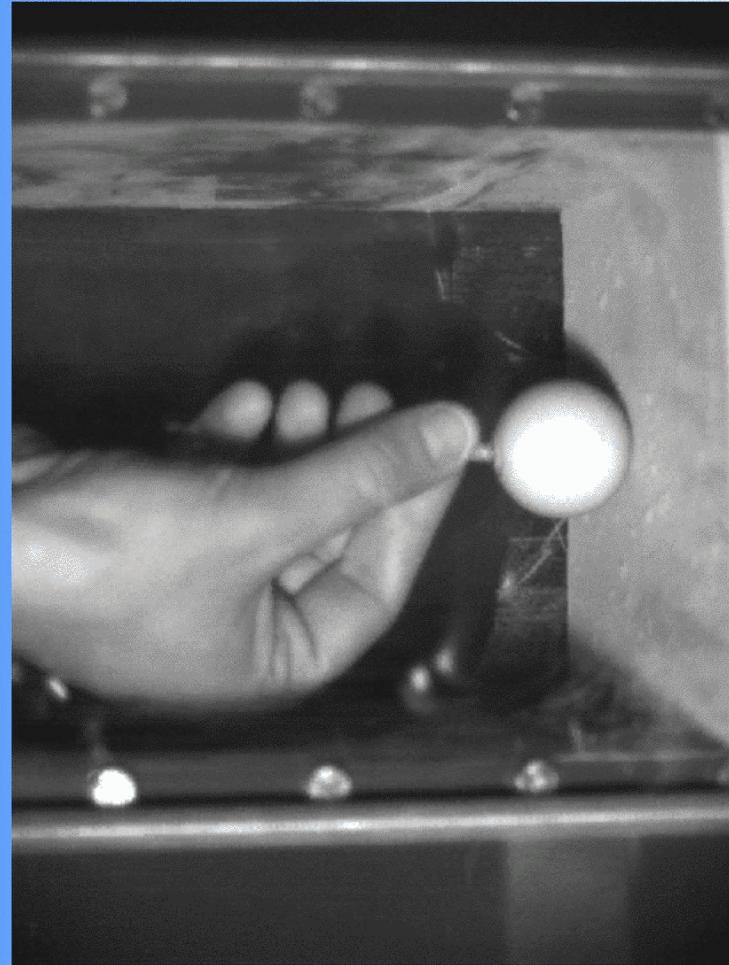
For $t \rightarrow t_s$:

$$R(t) \propto (t_s - t)^{1/2}$$



Characterization of the sandbed:

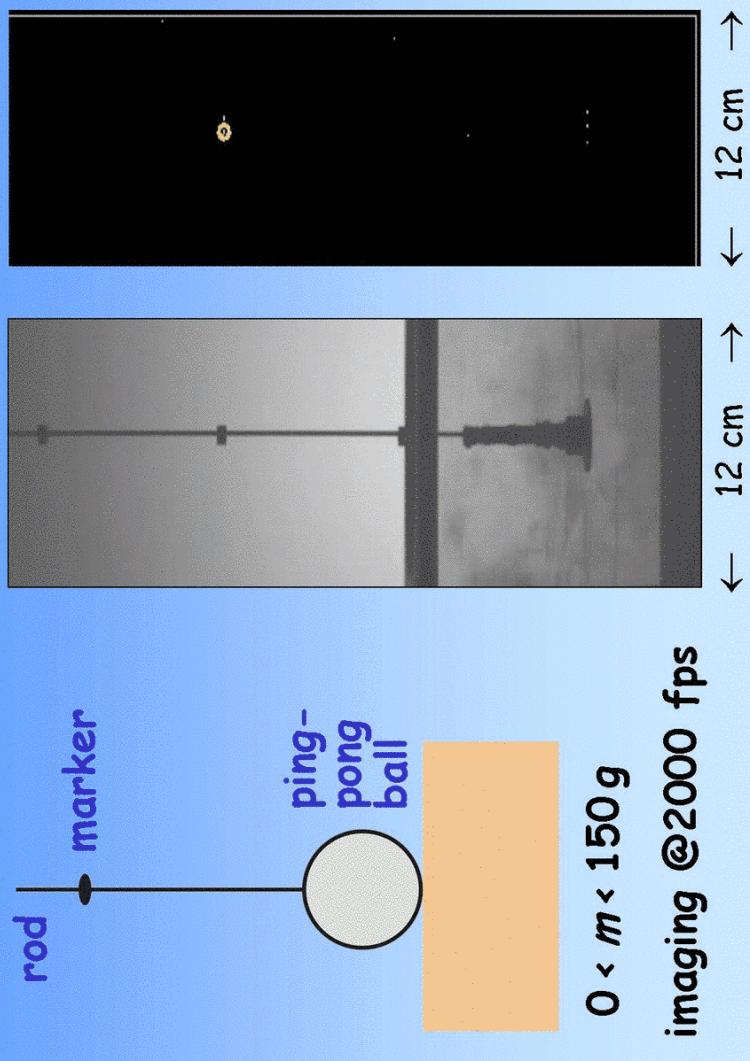
Does the sandbed support weight?



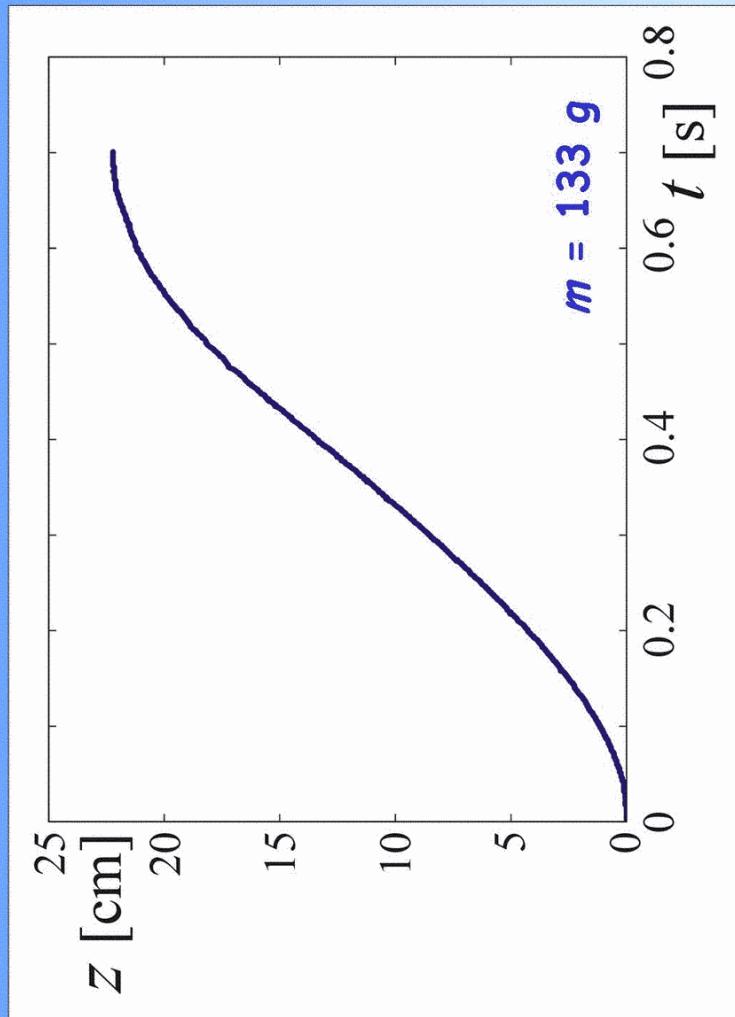
D Lohse, R Rauh  , R Bergmann, DvdM, Nature **432**, 689 (2004)



Measuring drag in sand



Drag in sand



Model: Coulomb friction

Coulomb friction

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

Force balance

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

Solution

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

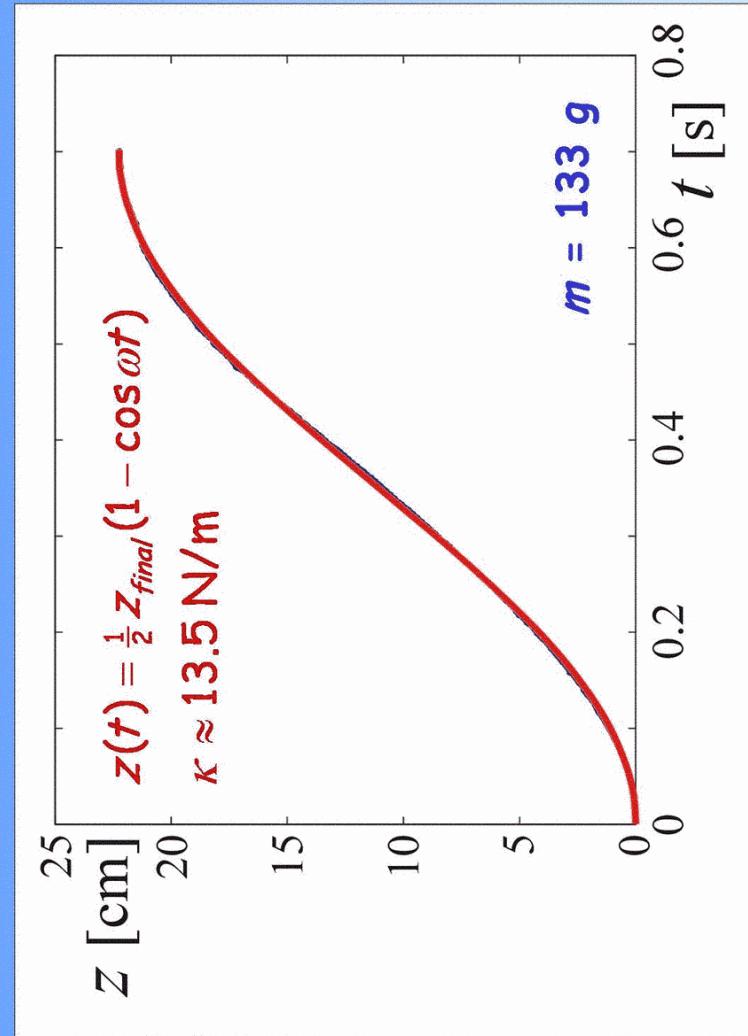
$$\omega = \sqrt{\frac{\kappa}{m}}$$

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

Final depth

$$z_{final} = \frac{2mg}{\kappa}$$

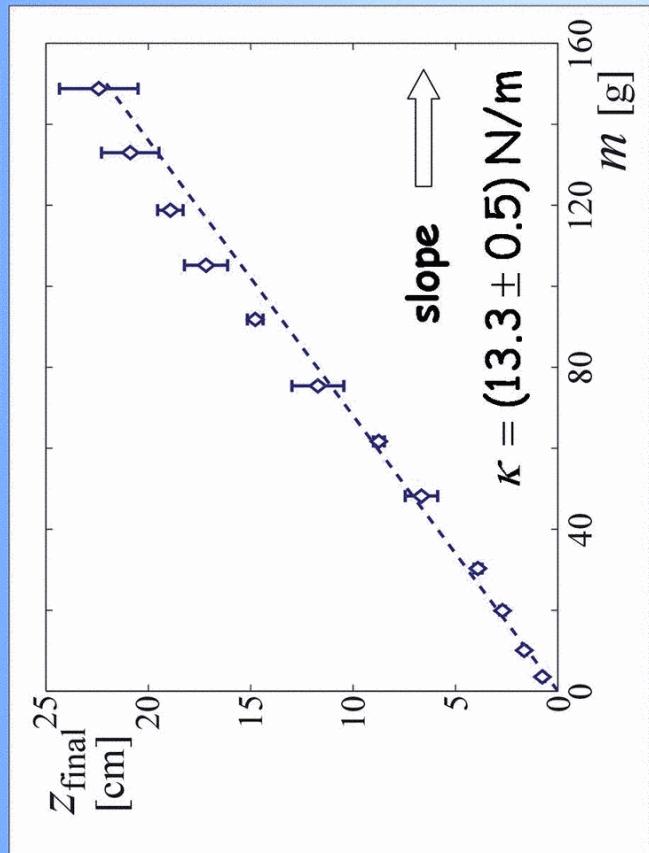
Drag: experiment and theory



Final depth vs. mass

Final depth

$$Z_{final} = \frac{2g}{K} m$$



Conclusions:

Jet formation process:

Series of events similar in liquid and sand:

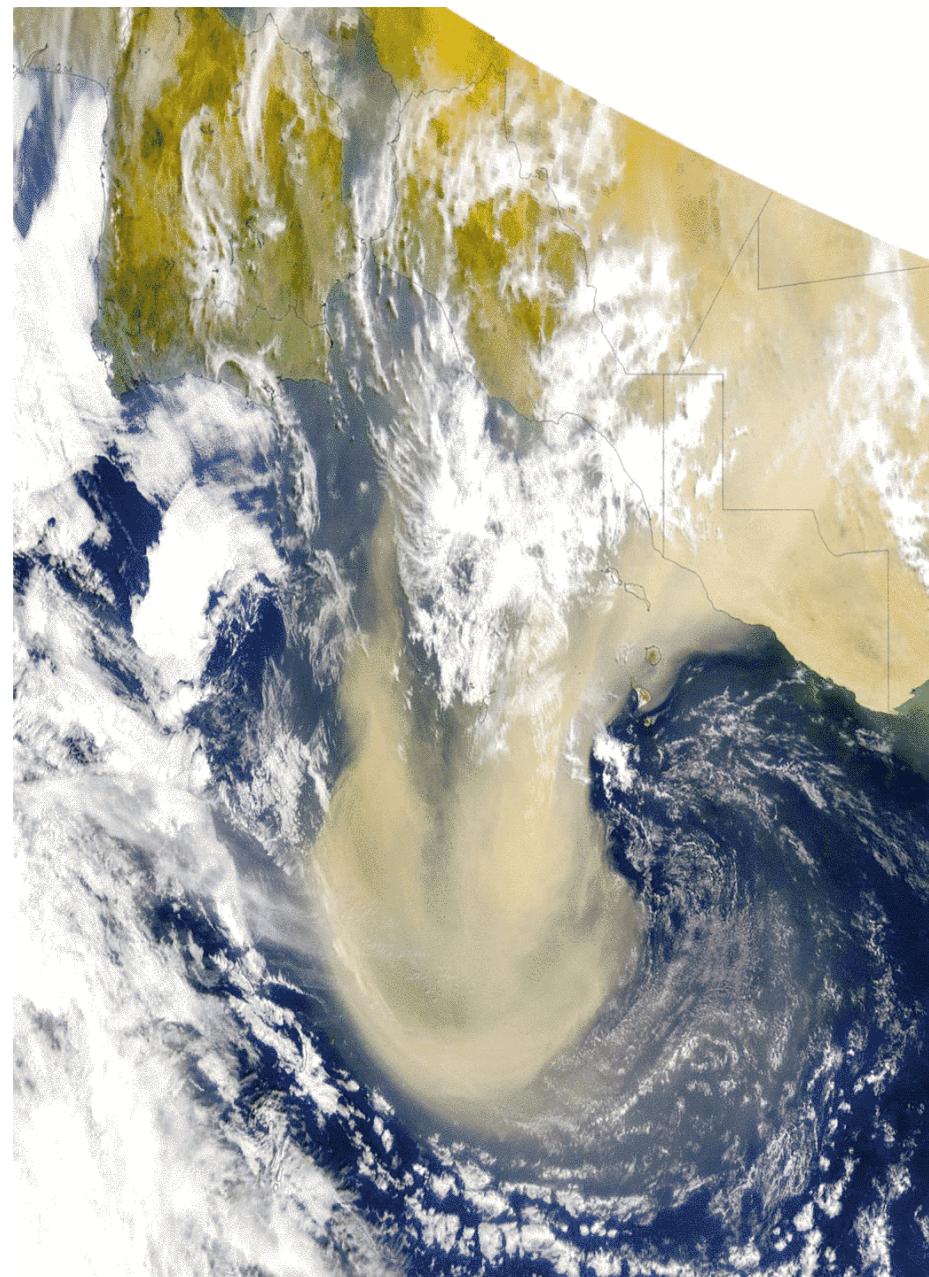
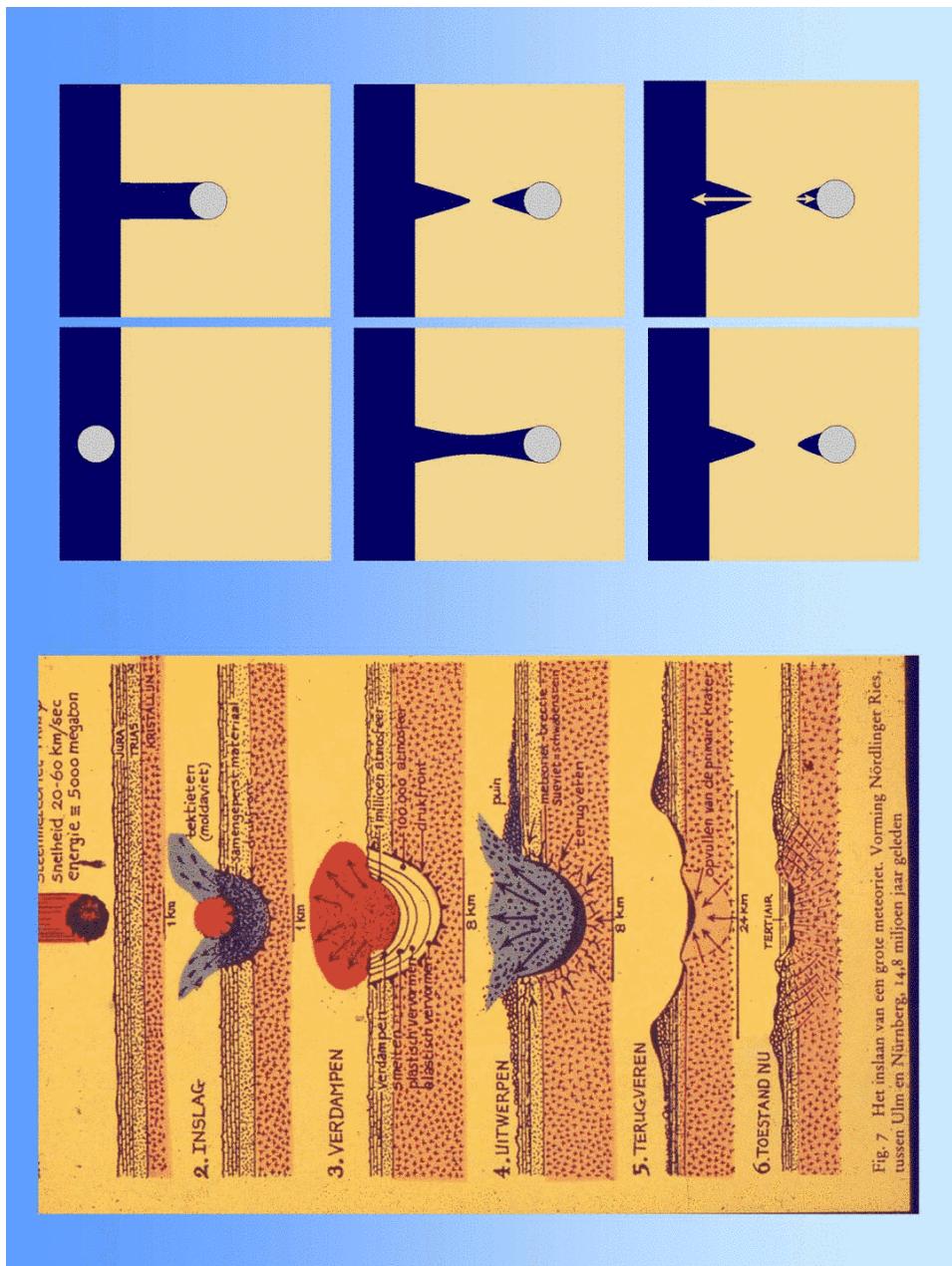
1. void formation
2. void collapse
3. two jets: one upward and one downward
4. bubble formation

Prepared sand bed:

In the "Dry Quicksand" state, sand cannot support weight; objects sink many diameters

Impact cratering:

Jets are likely to play a key role in large scale planetary impacts



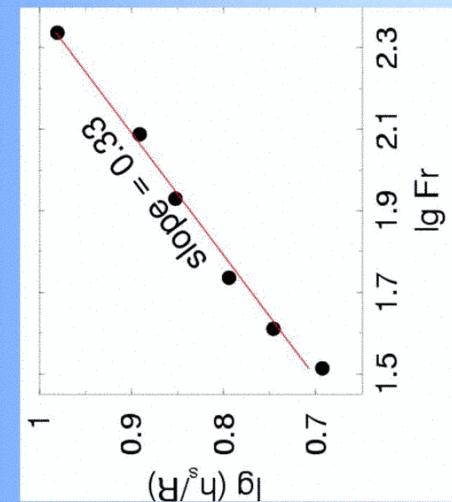
SeaWiFS Project/ORBIMAGE

February 26, 2000

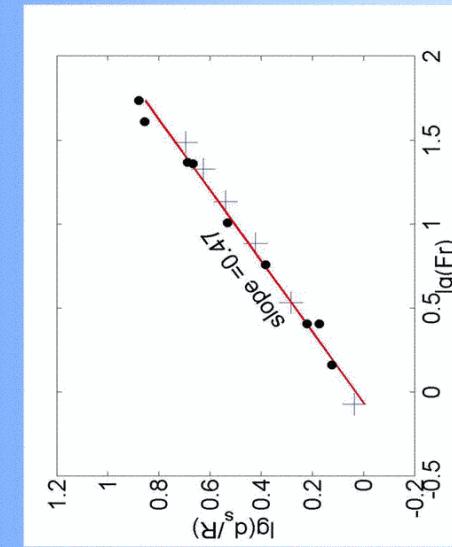
SeaWiFS Captures Massive Dust Storm

Different scaling laws !

sand



water

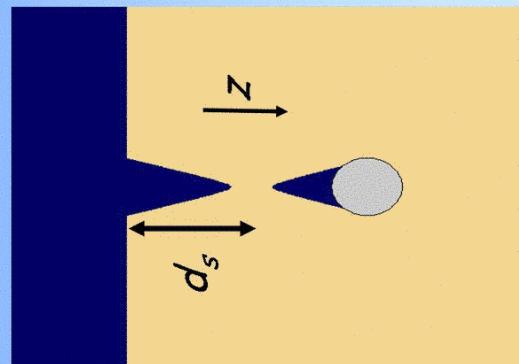


$$d_s/R = 1.0 \text{ Fr}^{1/2}$$

$$d_s/R = 0.69 \text{ Fr}^{1/3}$$

Why scaling with $\text{Fr}^{1/3}$ in sand?

$$t_s(z) = \frac{z}{V} + \tau \frac{R_0}{\sqrt{gz}} \quad (\text{time of closure along cavity})$$



t_s is minimum at closure point

sphere moving down to depth z

void closure (from Rayleigh eq.)

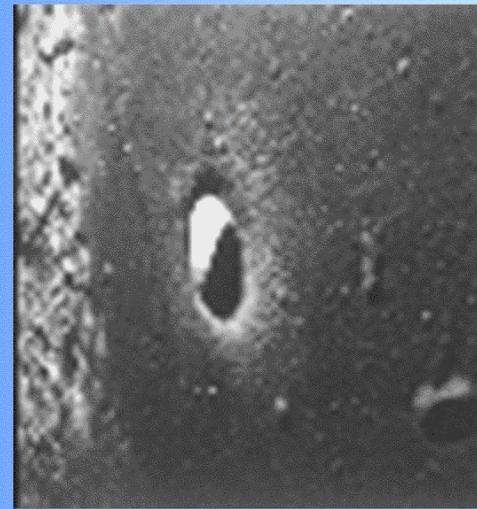
$$\frac{d_s}{R_0} \propto \text{Fr}^{1/3}$$

$$\frac{1}{V} = \frac{1}{2} \tau \frac{R_0}{\sqrt{g d_s^{3/2}}} \Rightarrow$$

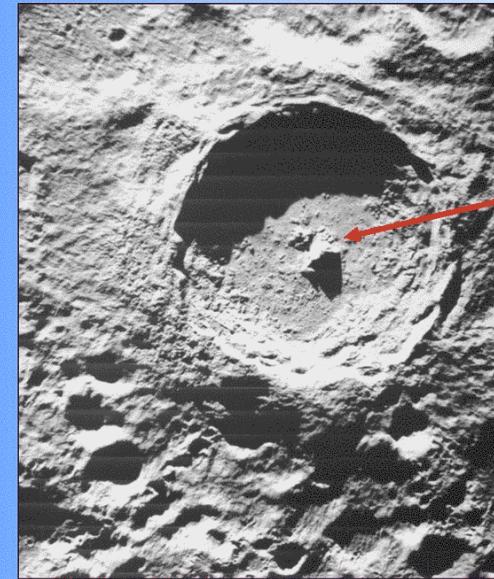
$$d_s \propto V^{2/3} \quad \text{or:} \quad \frac{d_s}{R_0} \propto \text{Fr}^{1/3}$$

Craters

...on the moon



Moltke

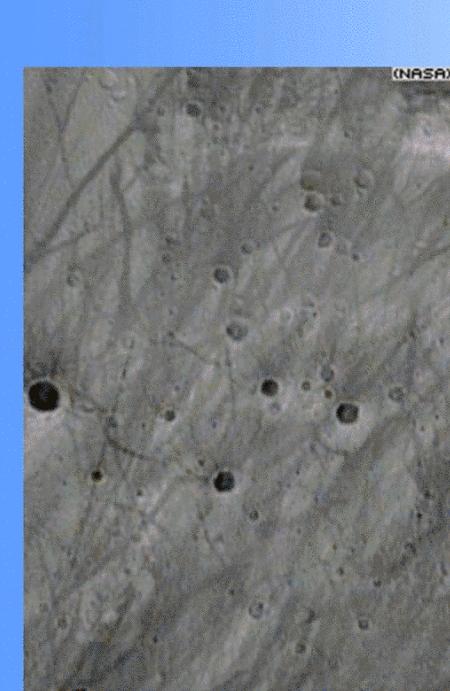


Tycho
central peak

Craters

...on Mars

Mars explorer,
January 2004

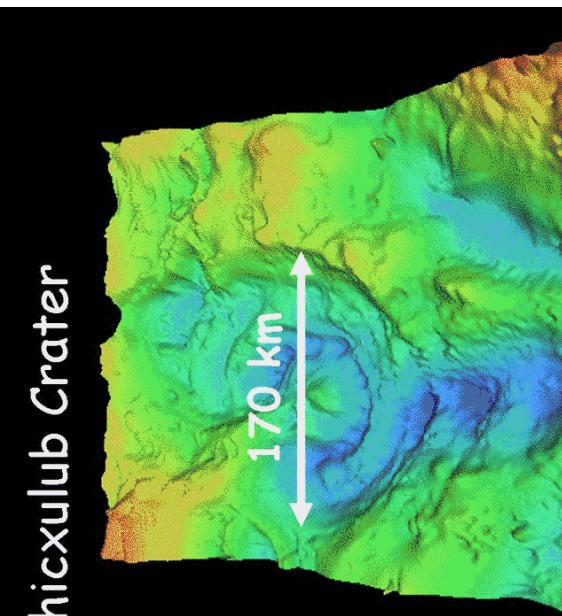


...on earth



Impact craters

Chicxulub Crater



Outlook

Coulomb friction model ceases to work for $v > 0$

Recent drag models:

$$m\ddot{z} = mg - F(z) - G(v)$$

$$F(z) = \text{const} ; \quad G(v) = \eta v$$

de Bruyn, Walsh (2004)

$$F(z) = \text{const} ; \quad G(v) = \alpha v^2$$

Forrestal, Luk (1992)

$$\text{non-const. } F(z) : \quad G(v) = \alpha v^2$$

Tsimring, Volfson
Ambroso, Kamien, Durian