Dynamics of a solid projectile impact onto a porous dust aggregate

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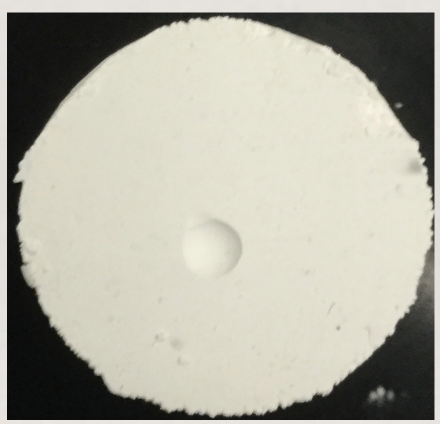
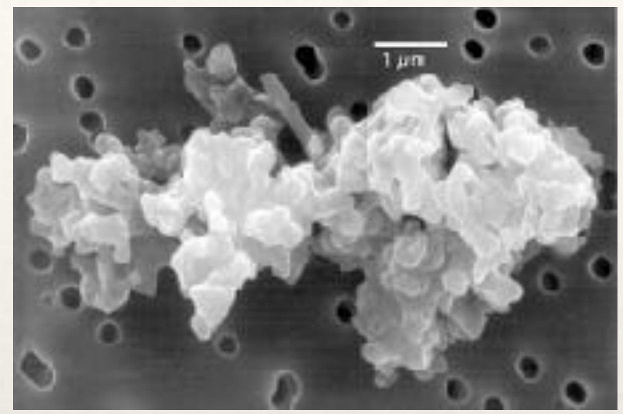


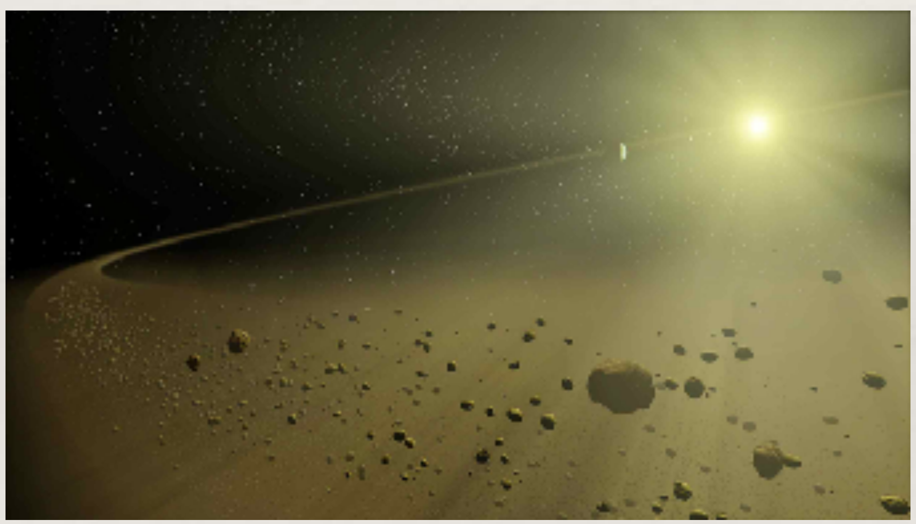
Planet formation & dust aggregate

Cosmic dust (Wikipedia)

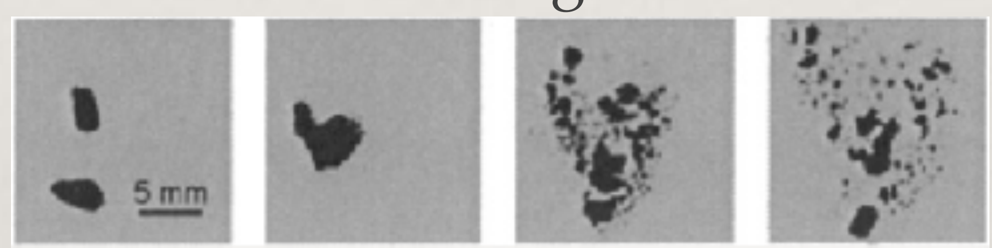


Growing to Planets?

Solar nebula (© NASA)



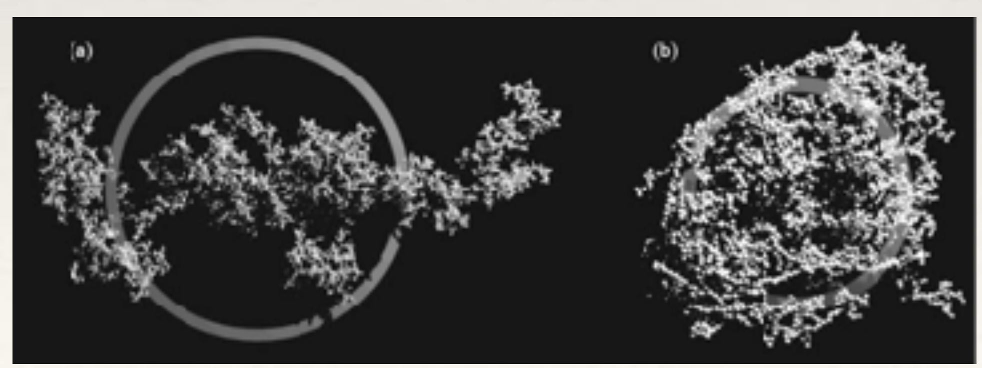
Collision & fragmentation



Blum, RAA (2010)

Mechanics
for
Dust Aggregate

Collision & deformation of DA

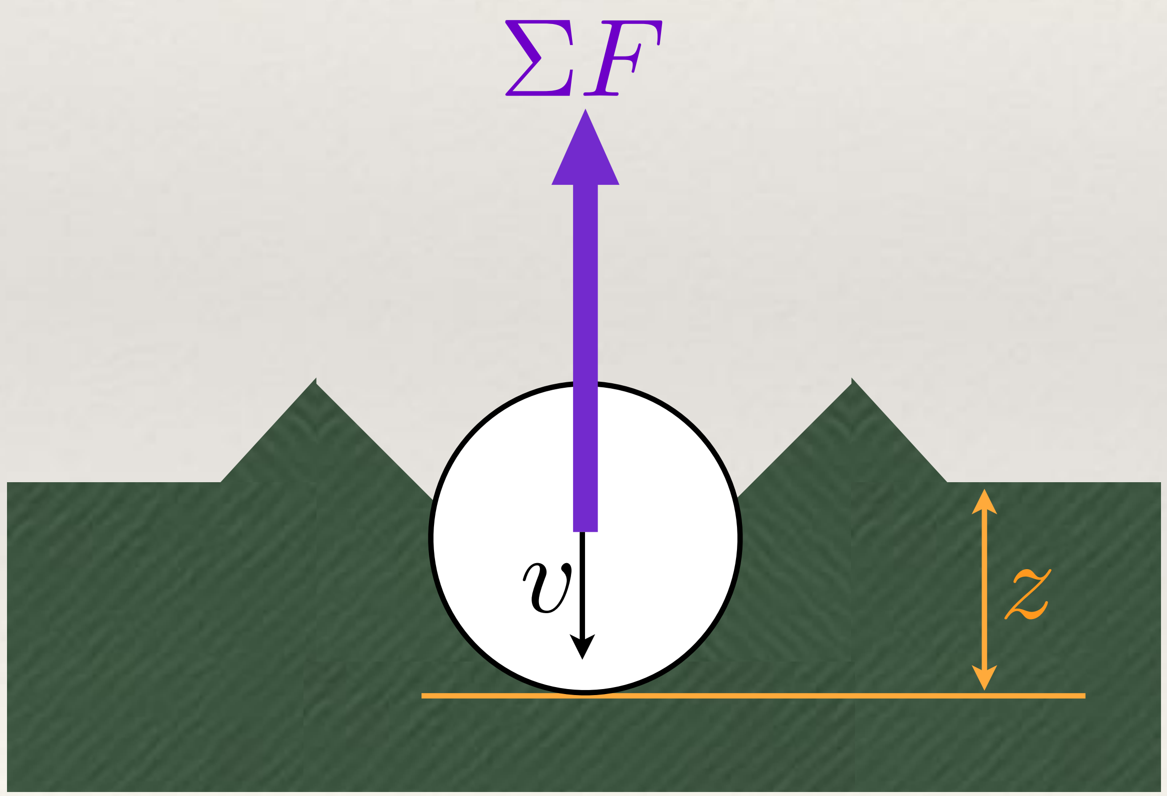


Wada et al., ApJ (2008)

Impact drag force

Solid projectile impact to loose granular matter:

Drag force



$$m\frac{d^2z}{dt^2} = mg - kz - m\frac{v^2}{d_1}$$

(drag force equation)

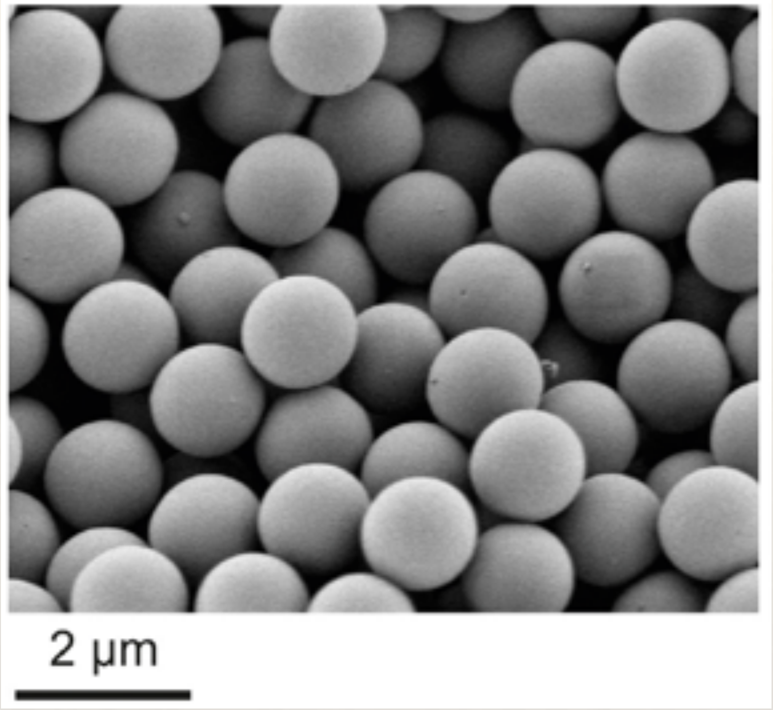
Katsuragi & Durian,
NP (2007)
PRE (2013)

Research objective

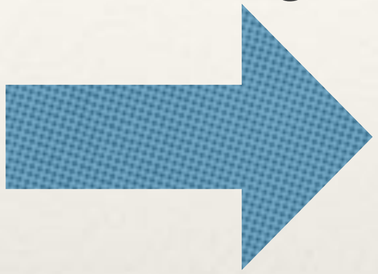
- Revealing the bulk mechanical properties of dust aggregate by low-speed impact test
- Impact drag-force law is compared between dust aggregate and granular matter

Dust aggregate

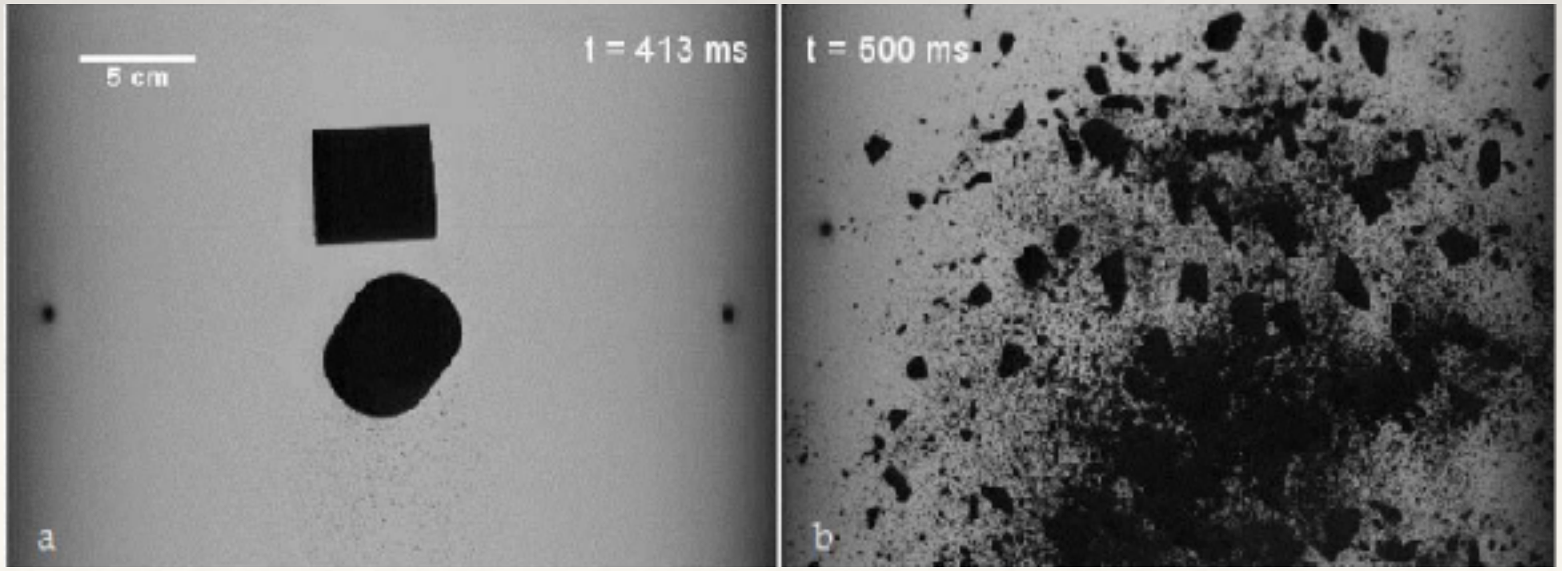
SiO_2 monomer 1.5 μm diam.



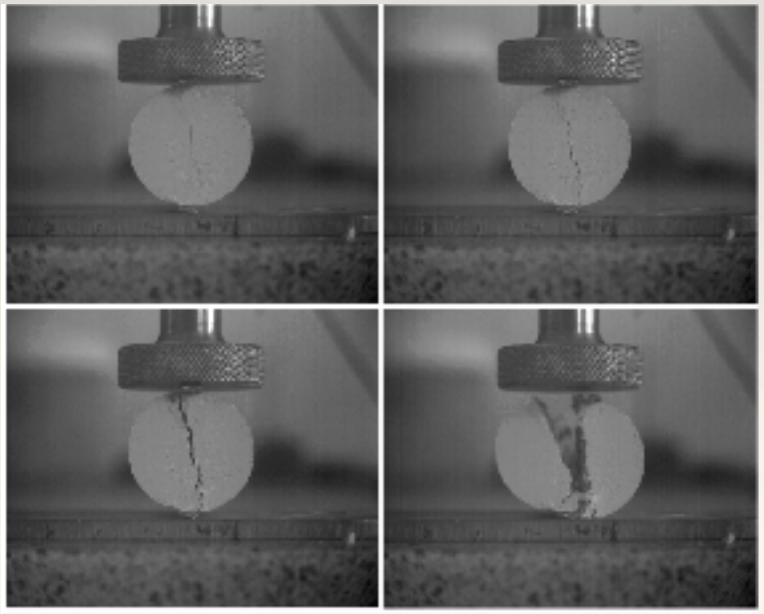
molding



Blum et al., JoVE (2014)

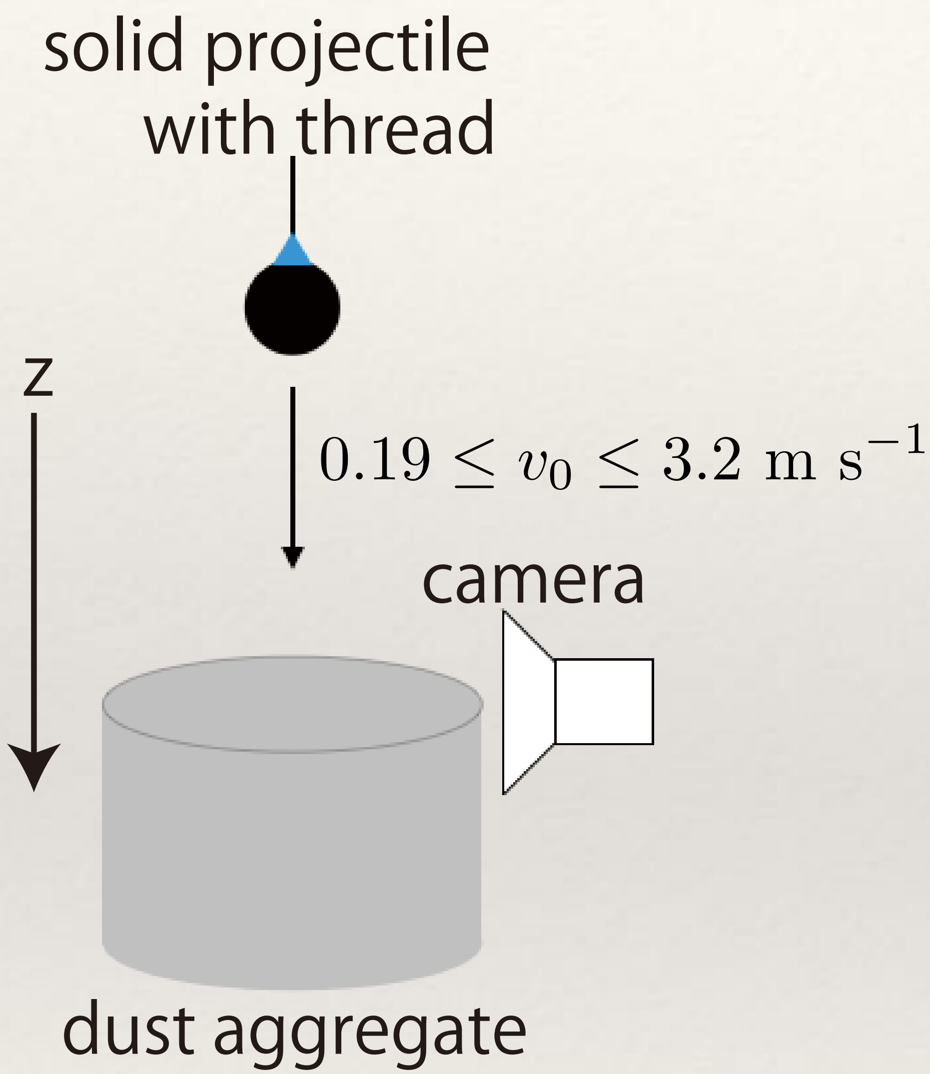


Collision: Bukhari Syed et al. ApJ (2017)



Brazilian test: Meisner et al. A&A (2012)

Experiment



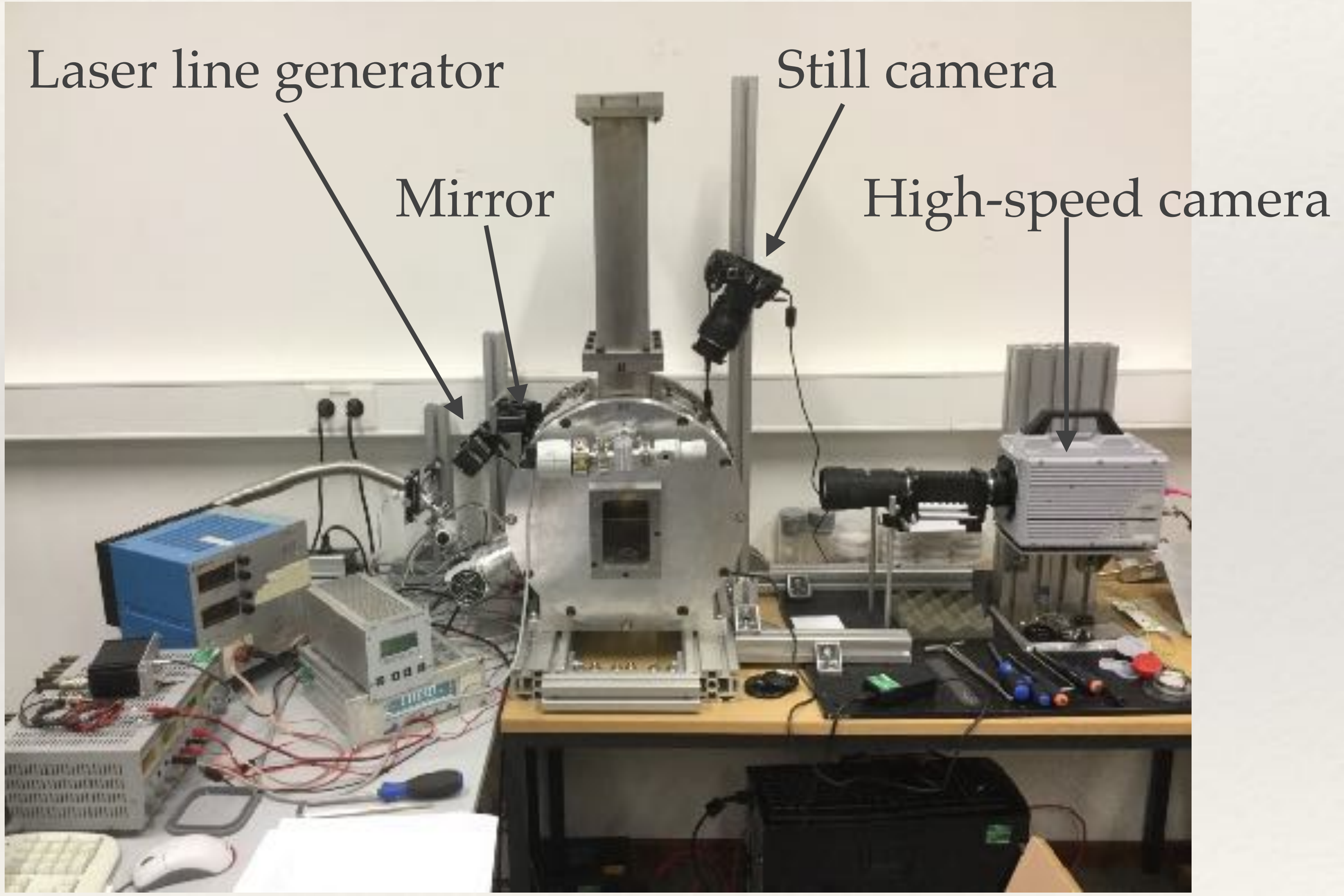
<Projectiles>

glass: D=4.0 mm, ρ_p=2.6×10^3 kg m^{-3}

steel: D=4.0 mm, ρ_p=4.0×10^3 kg m^{-3}

lead: D=4.5 mm, ρ_p=11×10^3 kg m^{-3}

High-speed imaging and laser profilometry

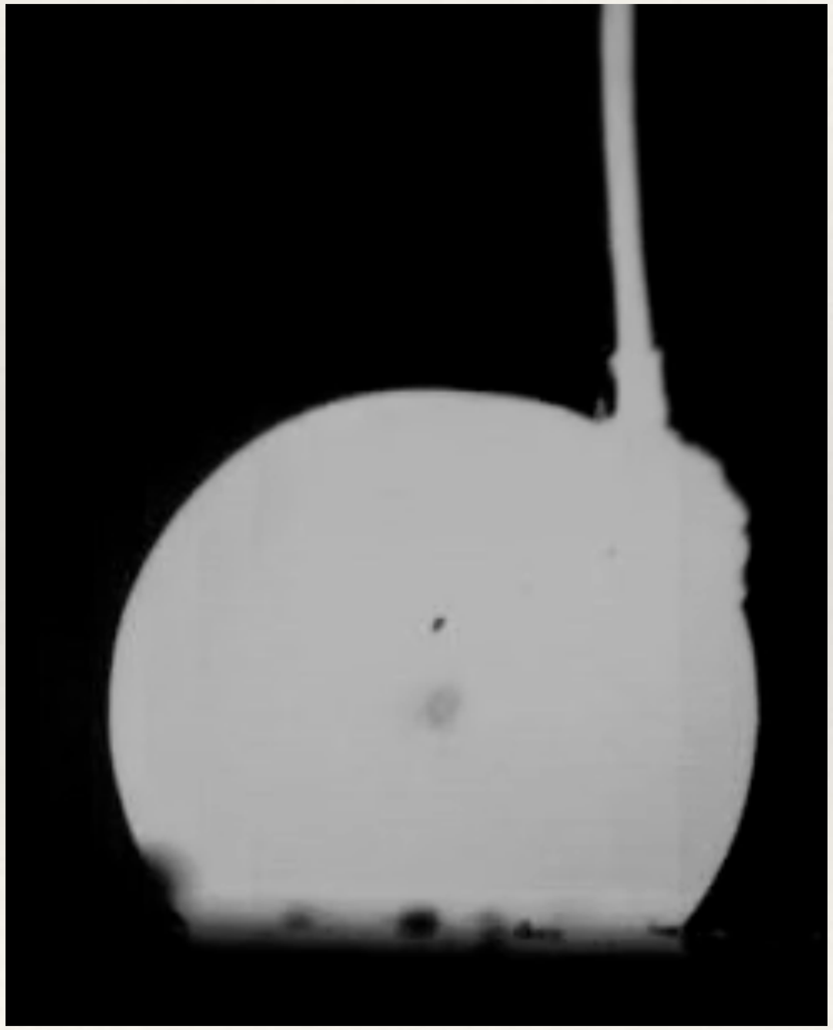


512×320 pixels, 20 μm / pixel resolution , 42,000 fps

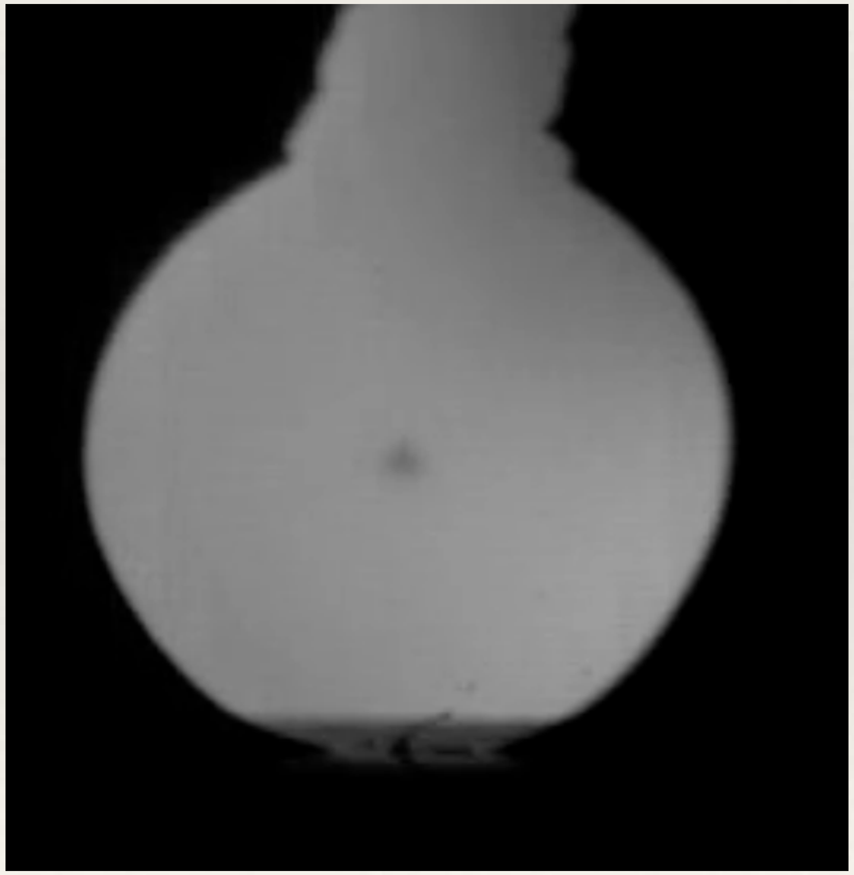
Raw data

Glass sphere projectile

$v_0 = 3.2\ \mathrm{m\ s^{-1}}$

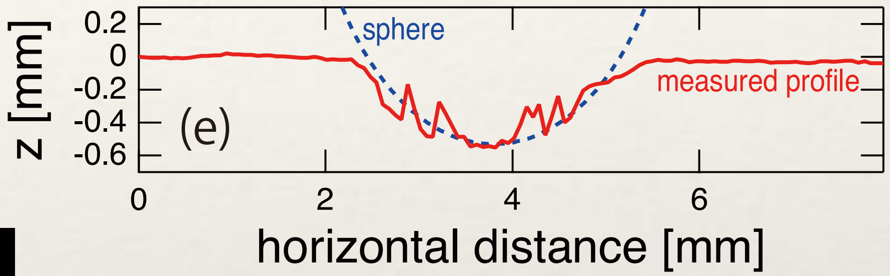


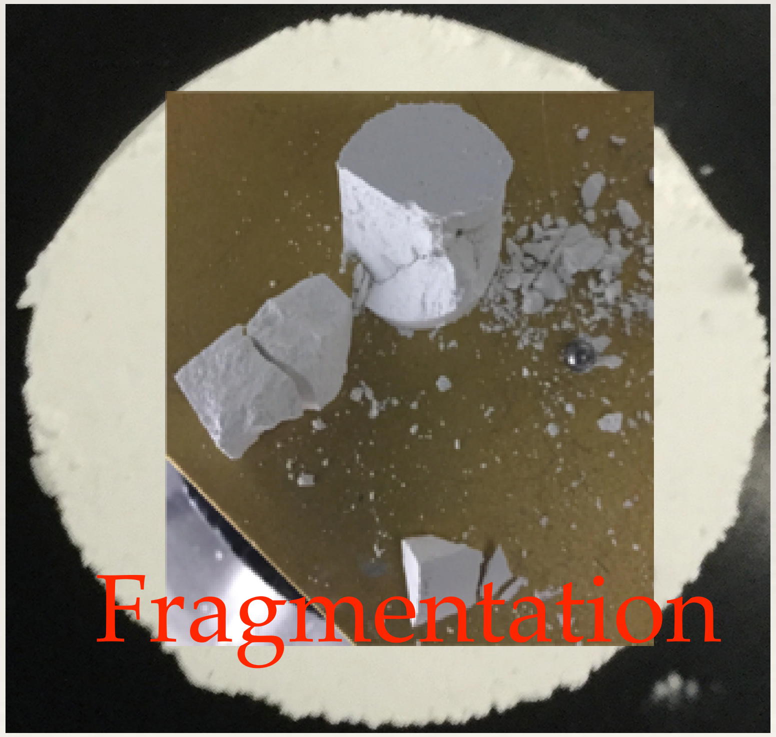
$v_0 = 0.29\ \mathrm{m\ s^{-1}}$



(Background is subtracted and FOV is trimmed.)

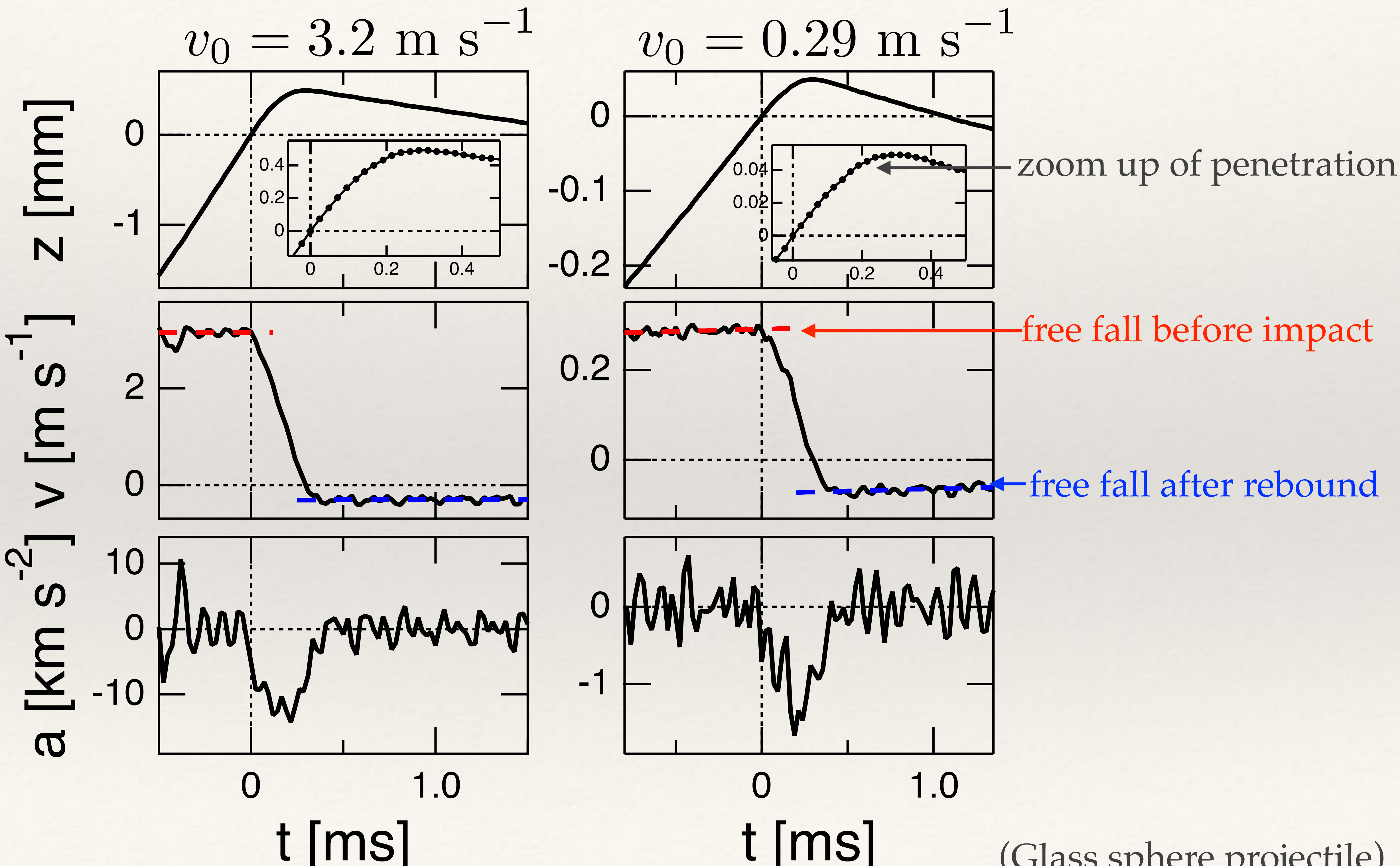
Crater





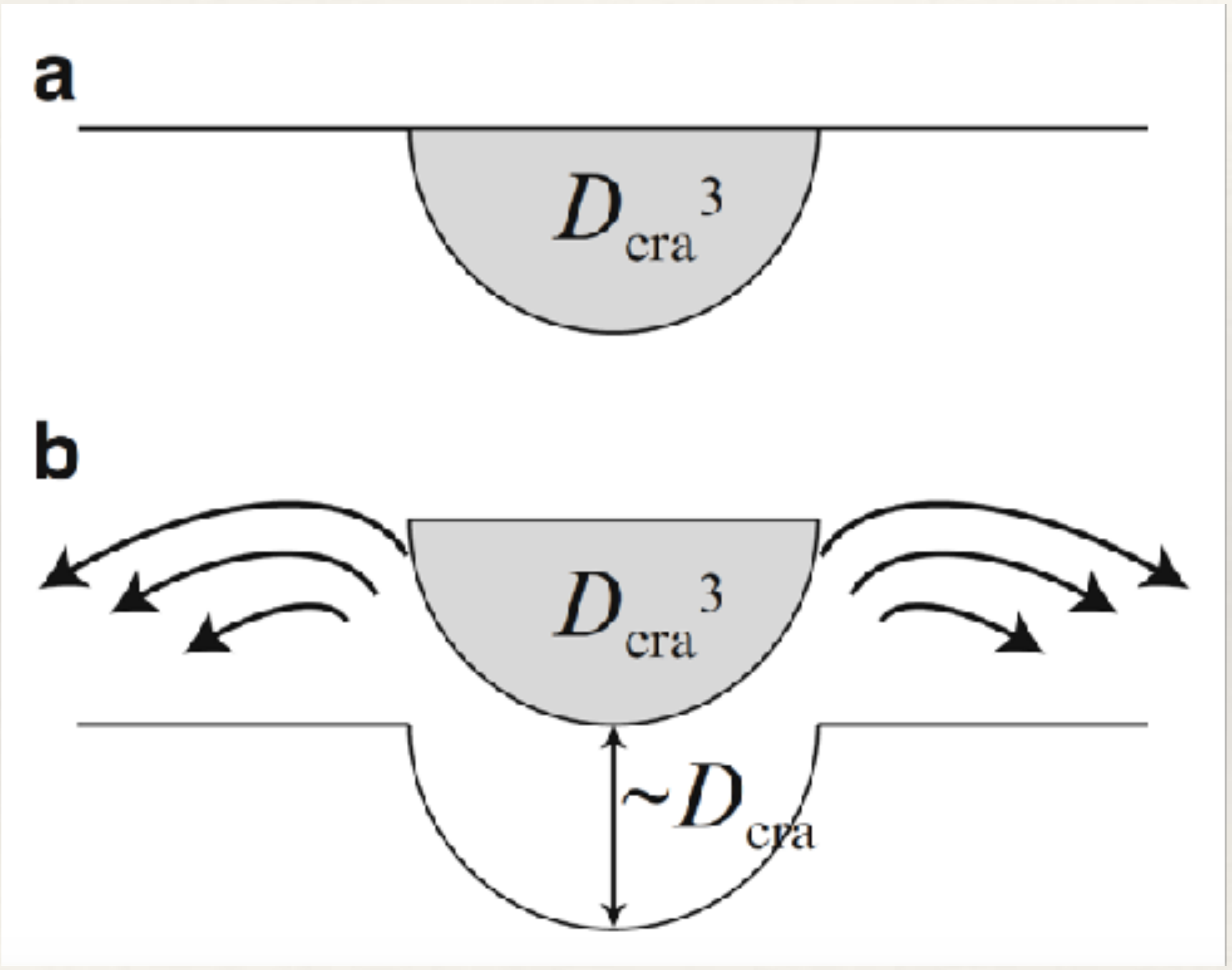
Spherical crater shape
-> only indentation

Kinematic data



(Glass sphere projectile)

Strength- or gravity-dominant cratering



Katsuragi (2016)

Impact energy is dissipated by:

(Crater volume) × (Strength)

Strength regime

$$(E \sim Y_{\mathrm{cra}} D^3_{\mathrm{cra}})$$

$$D_{\mathrm{cra}} \propto z_{\mathrm{max}} \propto E^{1/3}$$

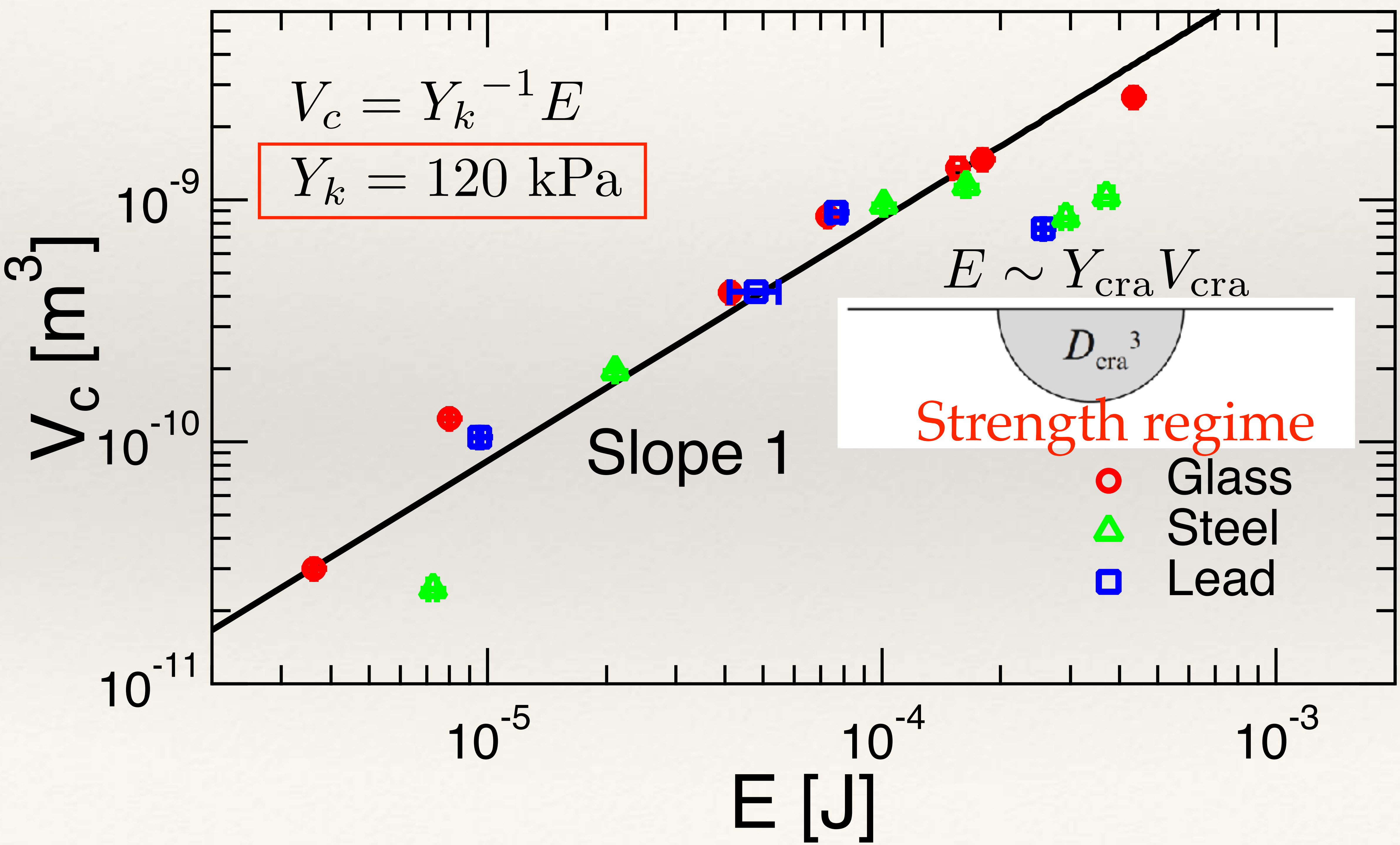
(Ejecta gravitational potential)

Gravity regime

$$(E \sim \rho g D^3_{\mathrm{cra}} D_{\mathrm{cra}})$$

$$D_{\mathrm{cra}} \propto z_{\mathrm{max}} \propto E^{1/4}$$

Strength-dominant cratering



Drag force law

Granular drag equation

$$m\frac{d^2z}{dt^2} = mg - kz - m\frac{v^2}{d_1}$$

$F_k = kz$ (deformation drag)

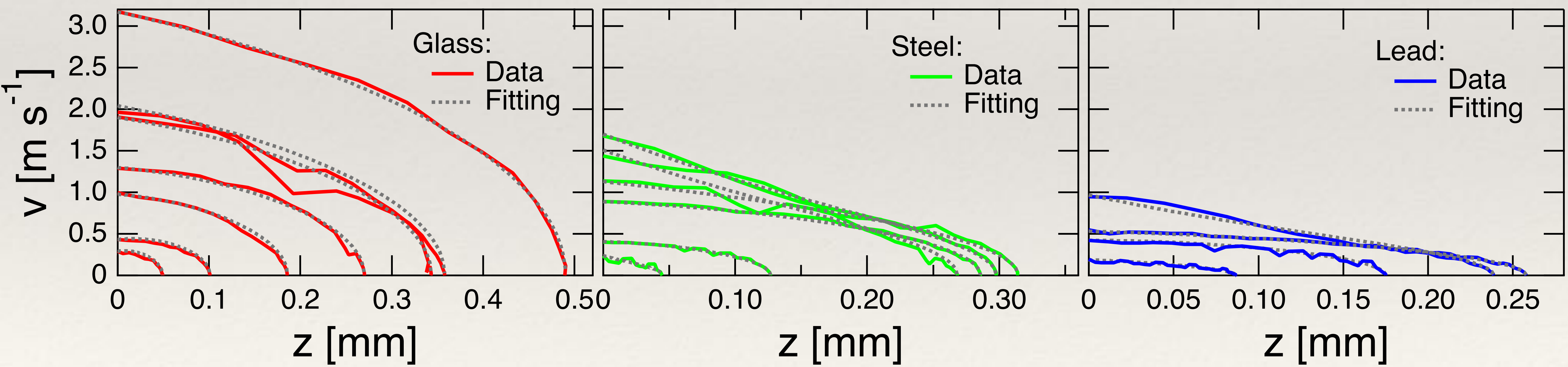
$F_{\rm in} = m\frac{v^2}{d_1}$ (inertial drag)

Analytic solution in v-z space

$$\frac{v^2}{v_0^2} = e^{-\frac{2z}{d_1}} - \frac{kd_1z}{mv_0^2} + \left(\frac{gd_1}{v_0^2} + \frac{kd_1^2}{2mv_0^2}\right)\left(1 - e^{-\frac{2z}{d_1}}\right)$$

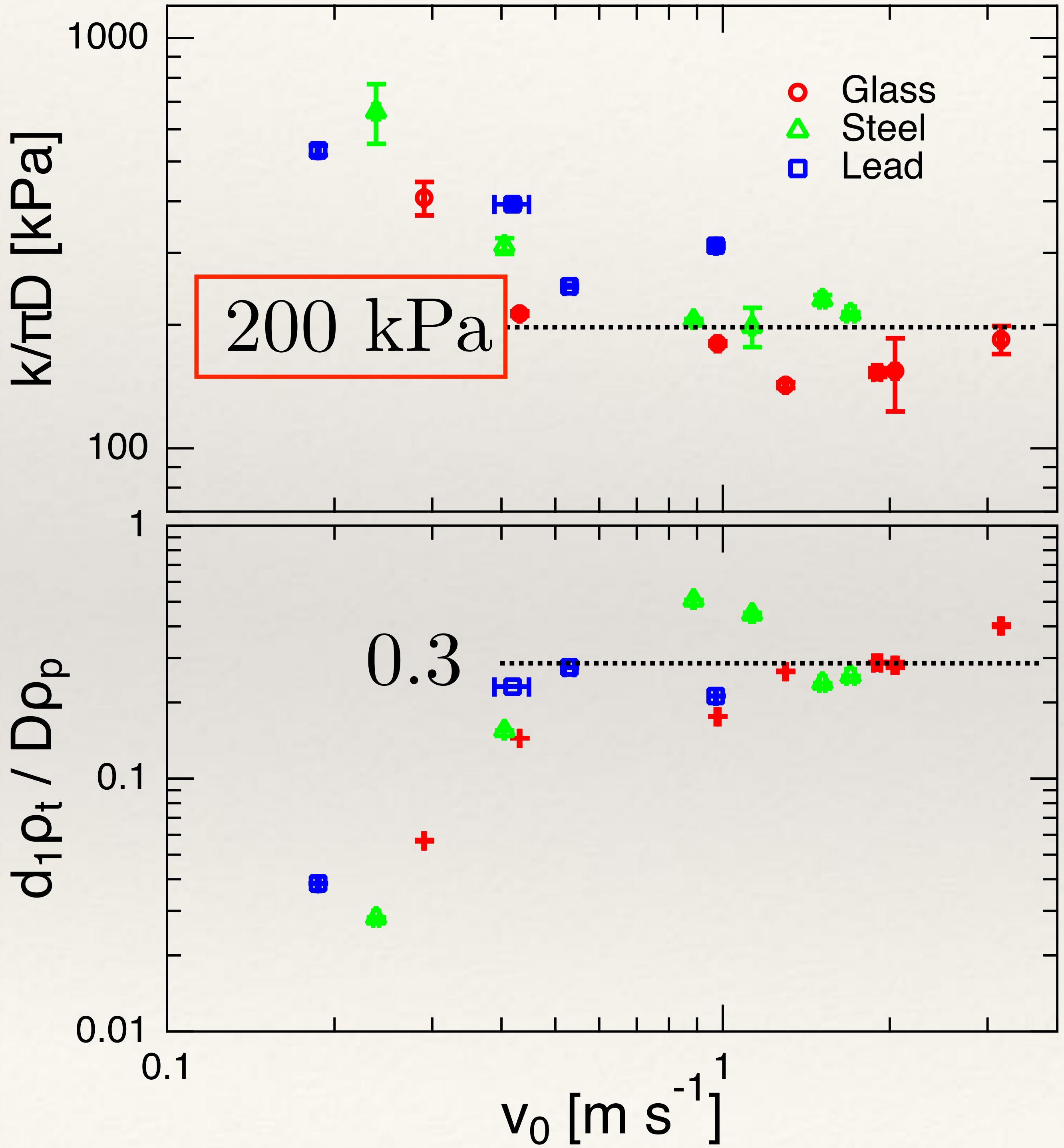
Katsuragi & Durian, PRE (2013)

Fitting parameters: k, d_1



The granular impact drag force model can explain the impact drag force by dust aggregate!

Fitting parameter values



k has a dimension of stiffness

kz should be divided by area $A \simeq \pi z D$

$k/\pi D$ corresponds to strength characterizing deformation-based drag

From the momentum transfer:

$$\rho_t v^2 D^2 dt \sim \rho_p D^3 dv$$

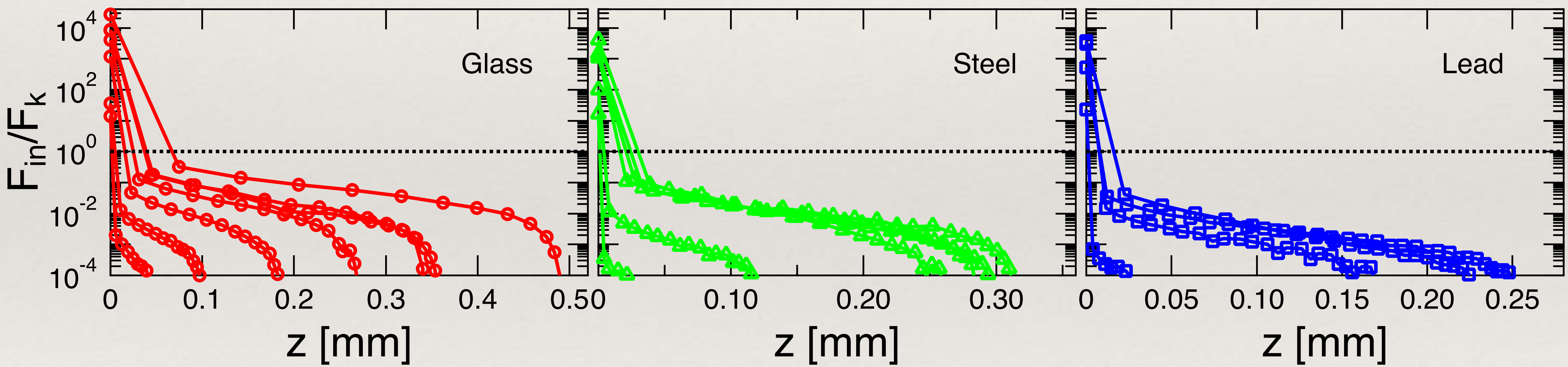
$$F_{\text{in}} = \frac{m}{d_1}\frac{dv}{dt} = \rho_p D^3 \frac{dv}{dt}$$

$$d_1 \sim (\rho_p/\rho_t) D$$

Inertial and deformation drag

Inertia-dominant: $\frac{F_{\mathrm{in}}}{F_k} \gg 1$ only at the very early stage of the impact $t < 24\ \mu\mathrm{s}$

Deformation-dominant: $\frac{F_{\mathrm{in}}}{F_k} \ll 1$ almost all the penetration



(Plastic) deformation governs the penetration dynamics

Strength regime

Dynamic pressure for shallow impact

Energy balance at the maximum penetration:

$$\rho_p V_p a_{\max} \left(\frac{V}{A}\right)_{\max} = \frac{1}{2}\rho_p V_p v_0^2$$

(Work by penetration) (Impact kinetic energy)

cross-sectional area

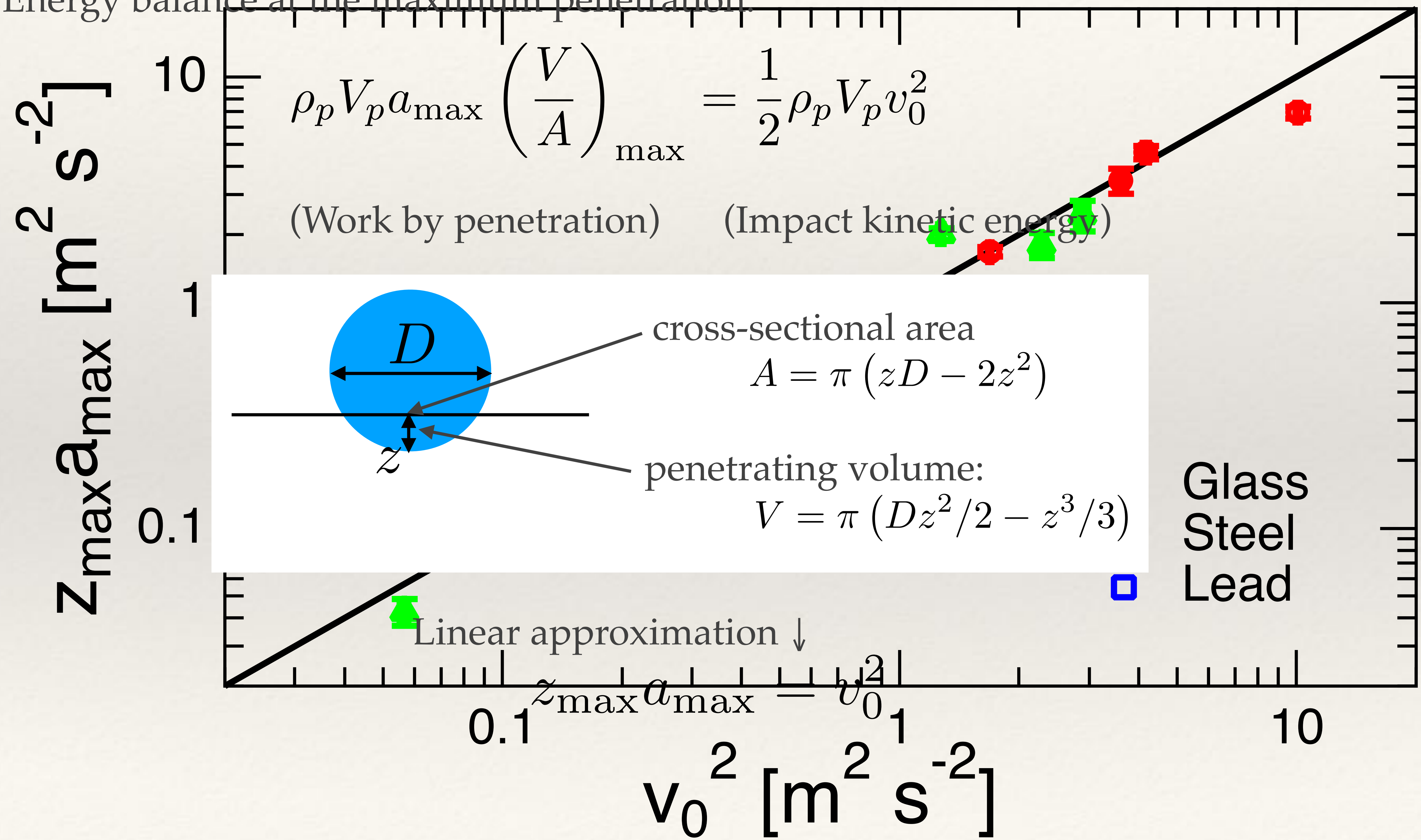
$$A = \pi \left(zD - 2z^2\right)$$

penetrating volume:

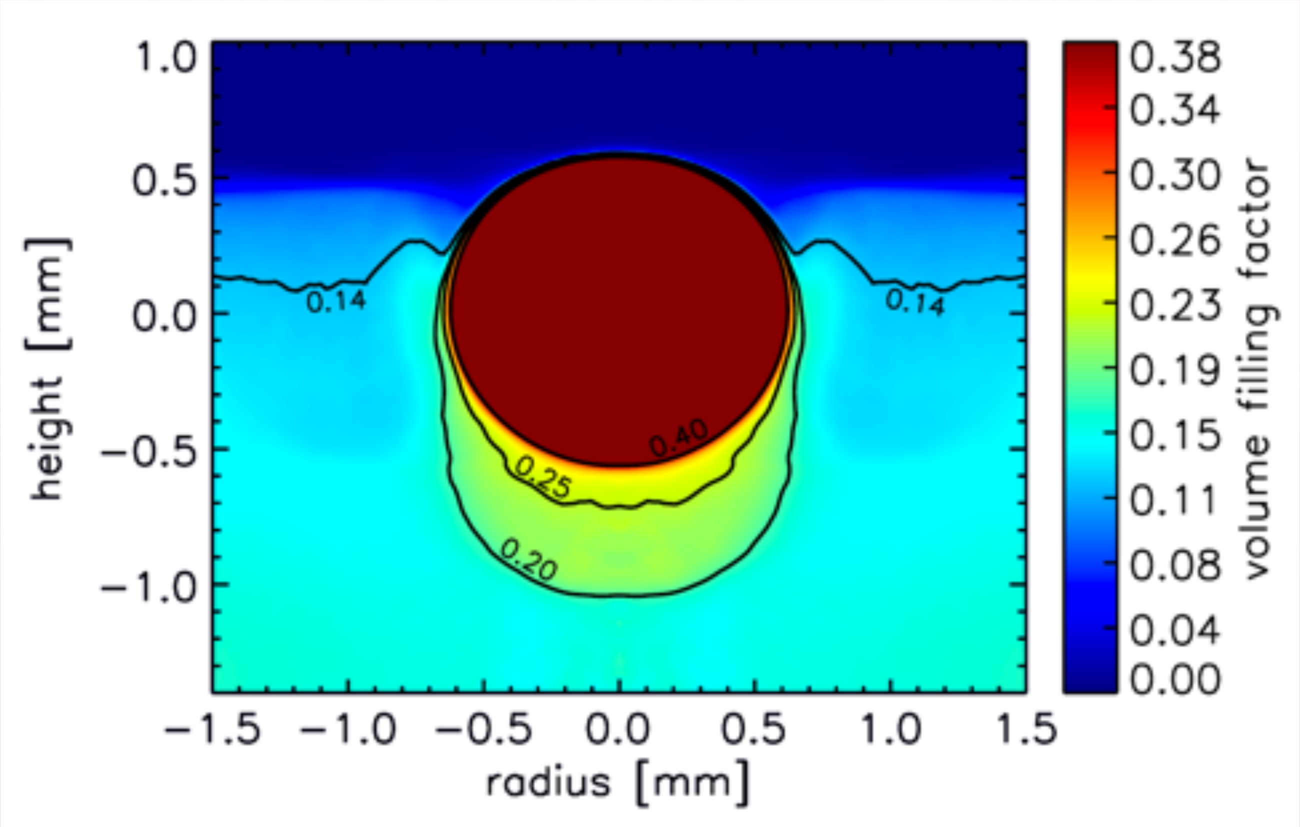
$$V = \pi \left(Dz^2/2 - z^3/3\right)$$

Linear approximation ↓

$$z_{\max} a_{\max} = v_0^2$$



Impact-affected volume



Güttler et al., ApJ (2009)

Glass sphere impact to dust aggregate of $\phi = 0.15$

Compressed volume is 0.8-1.2 of sphere's volume V_p

(measured by X-ray micro CT)

Dynamic pressure

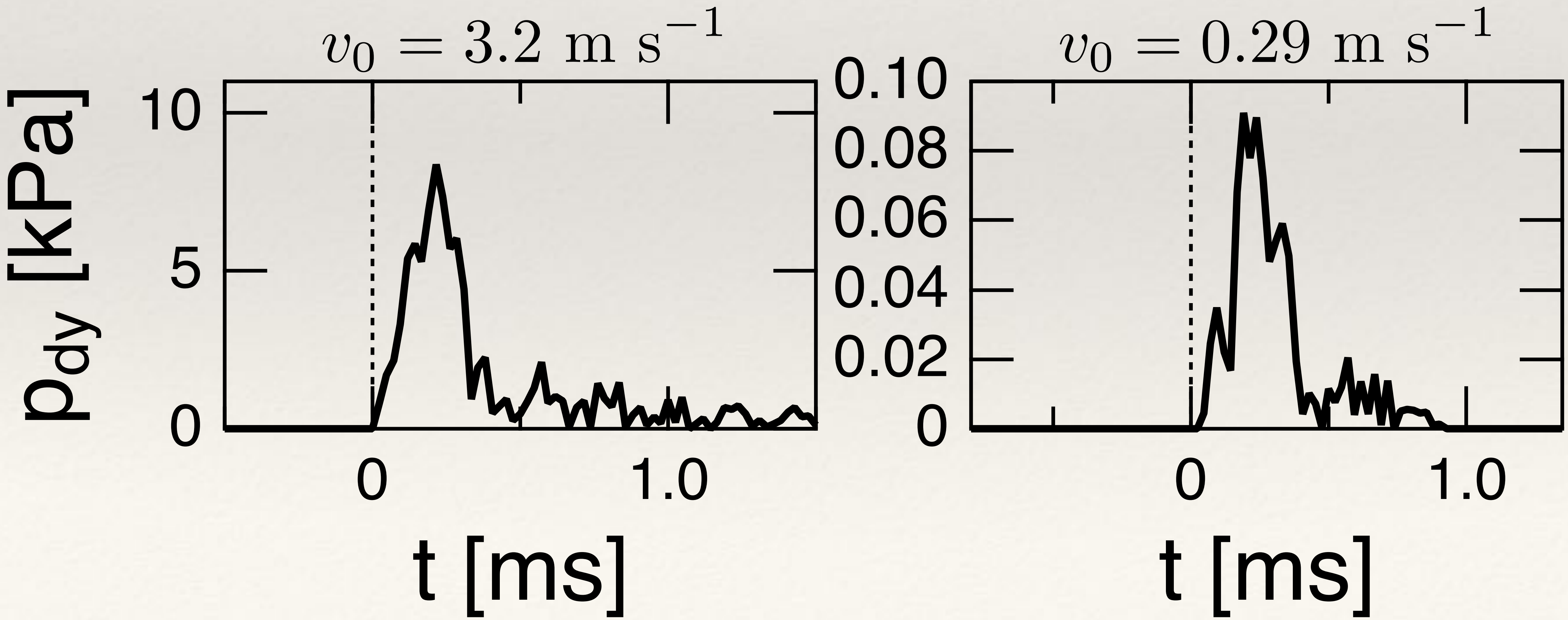
Energy balance:

$$\frac{1}{2}\rho_p V_p v_0^2 = V_p \max(p_{\rm py})$$

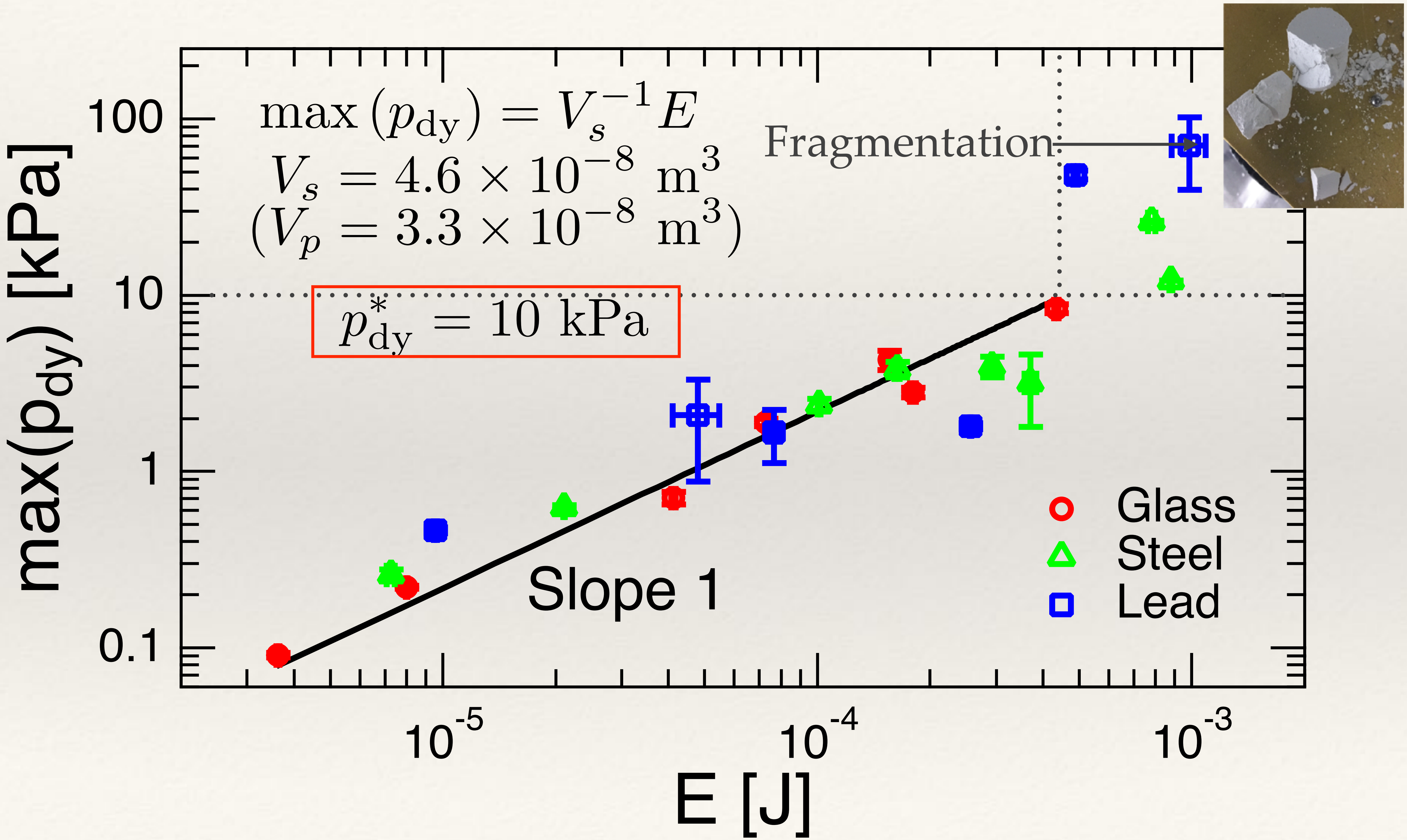
assumption: dynamic pressure is supported by V_p

$$\max(p_{\rm dy}) = \frac{1}{2}\rho_p z_{\max} a_{\max}$$
$$= \frac{1}{2}\rho_p v_0^2 \quad \leftarrow (v^2 \simeq |a|z)$$

$$p_{\rm dy} = \frac{1}{2}\rho_p |a| z$$



Fragmentation threshold



Fragmentation threshold

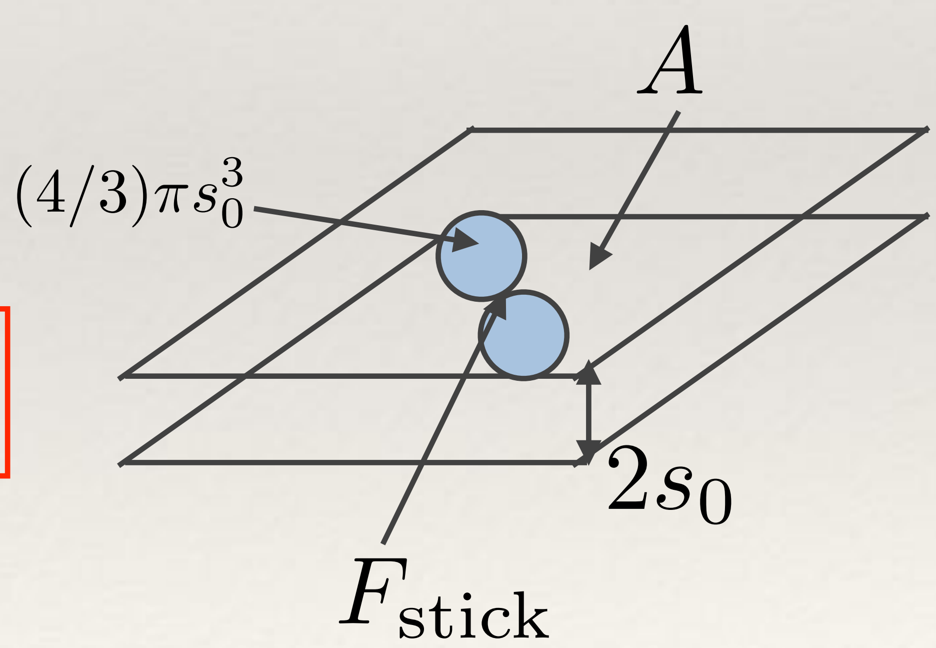
From the current experimental result : $p^*_{\rm dy} = 10\ {\rm kPa}$

Tensile strength model by Blum et al. 2006:

Number of monomers ≈ Number of contacts (each monomer has 2 contacts)

$$N \simeq \phi \frac{2As_0}{(4/3)\pi s_0^3} = \phi \frac{3A}{2\pi s_0^2}$$

$$Y = \frac{NF_{\rm stick}}{A} = \frac{3\phi F_{\rm stick}}{2\pi s_0^2} = 19\ {\rm kPa}$$



s_0 : monomer radius = 0.76 μm

$F_{\rm stick}$: sticking force among monomers = 67 nN

Blum et al., ApJ (2006)

Summary

- By solid projectile impact to dust aggregate, following mechanical properties are revealed:
  - Strength with local dynamic pressure ~ 10 kPa
  - Deformation-based strength ~ 120 kPa (or 200 kPa)
  - Volume supporting local dynamic pressure is identical to projectile volume
- Drag-force law of dust aggregate is similar to granular matter. But the physical meaning of kz term is different.

H. Katsuragi and J. Blum, ApJ, 851, 23 (2017); (arXiv:1709.03118)