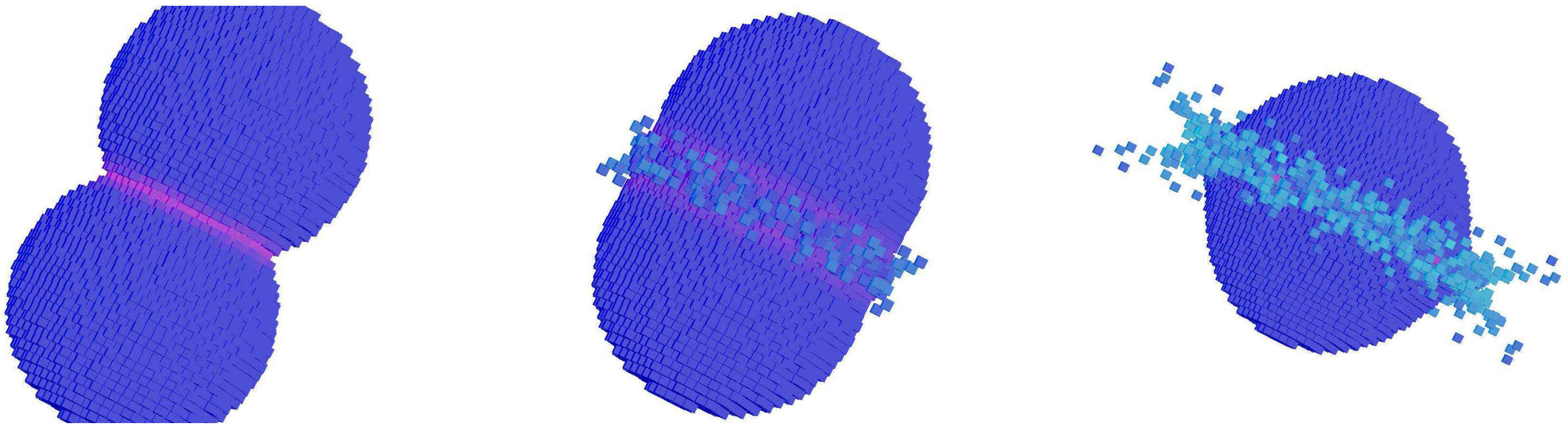
Simulations of Collisions Between Pre-Planetesimals



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Question for collisional coagulation from cm to km:

What is dominating in collisional outcome, accretion or erosion?

Answer depends on several parameters:

- Size and shape of target and projectile.
- Impact velocities (velocity dispersion due to gas drag in the disc and due to collisional history).
- Impact parameter / angle.
- Material composition and structure of target and projectile.

$\Rightarrow$ Model for 2-body collisions of pre-planetesimals needed (e.g. for global evolution simulations of the planetesimal disc).

Modelling collisions

Two regimes have to be distinguished:

- Large objects ($R \gtrsim 1\,\mathrm{km}$). Main influence: self-gravity.
  $\longrightarrow$ Gravity dominated regime
- Small objects ($R \lesssim$ few $100\,\mathrm{m}$). Main influence: material properties.
  $\longrightarrow$ Strength dominated regime

Objectives:

- What is the collisional outcome? Growth or erosion?
- Distribution of size and shape of possible fragments.
- Velocity distribution of possible fragments.

No laboratory experiments for sizes $R \gtrsim 1\,\mathrm{m}$ possible.
$\Rightarrow$ Numerical modelling necessary.

Currently favoured numerical method:

Smooth Particle Hydrodynamics (SPH)

- Originally developed to simulate hydrodynamic problems in astrophysics. Later extended to elasto-plasto-dyn.
- 3D mesh-free Lagrangian particle method

$\Rightarrow$ The continuum of the flow is represented by interacting "particles", which move like point masses according to the Lagrangian form of the equation of motion, but represent all physical properties of that fluid part.

- Due to mesh-free Lagrangian nature:

$\Rightarrow$ natural reference frame for representing deformations and fragmentation.

- Due to particle nature: Easy to include self-gravity.

Collisions of brittle solid bodies (I)

First astrophysical applications:

- Collisional evolution of asteroids and asteroid families.
  - Gravitationally dominated regime.
  - Impact velocities higher ($\sim \mathrm{km/s}$) than assumed for pre-planetesimal collisions.

$\Rightarrow$ Transition to strength regime at $R \sim 250 \pm 150\,\mathrm{m}$ (e.g. Love & Ahrens 1996).

$\Rightarrow$ More likely shattering impacts with gravitationally reaccumulated fragments than dispersing impacts.

Collisions of brittle solid bodies (II)

More general study: Benz & Asphaug 1999

- Collisions of basalt and of ice spheres,
  - $R \sim 1\,\mathrm{cm} \cdots 100\,\mathrm{km}$,
  - impact velocities of $\gtrsim 1\,\mathrm{km/s}$.

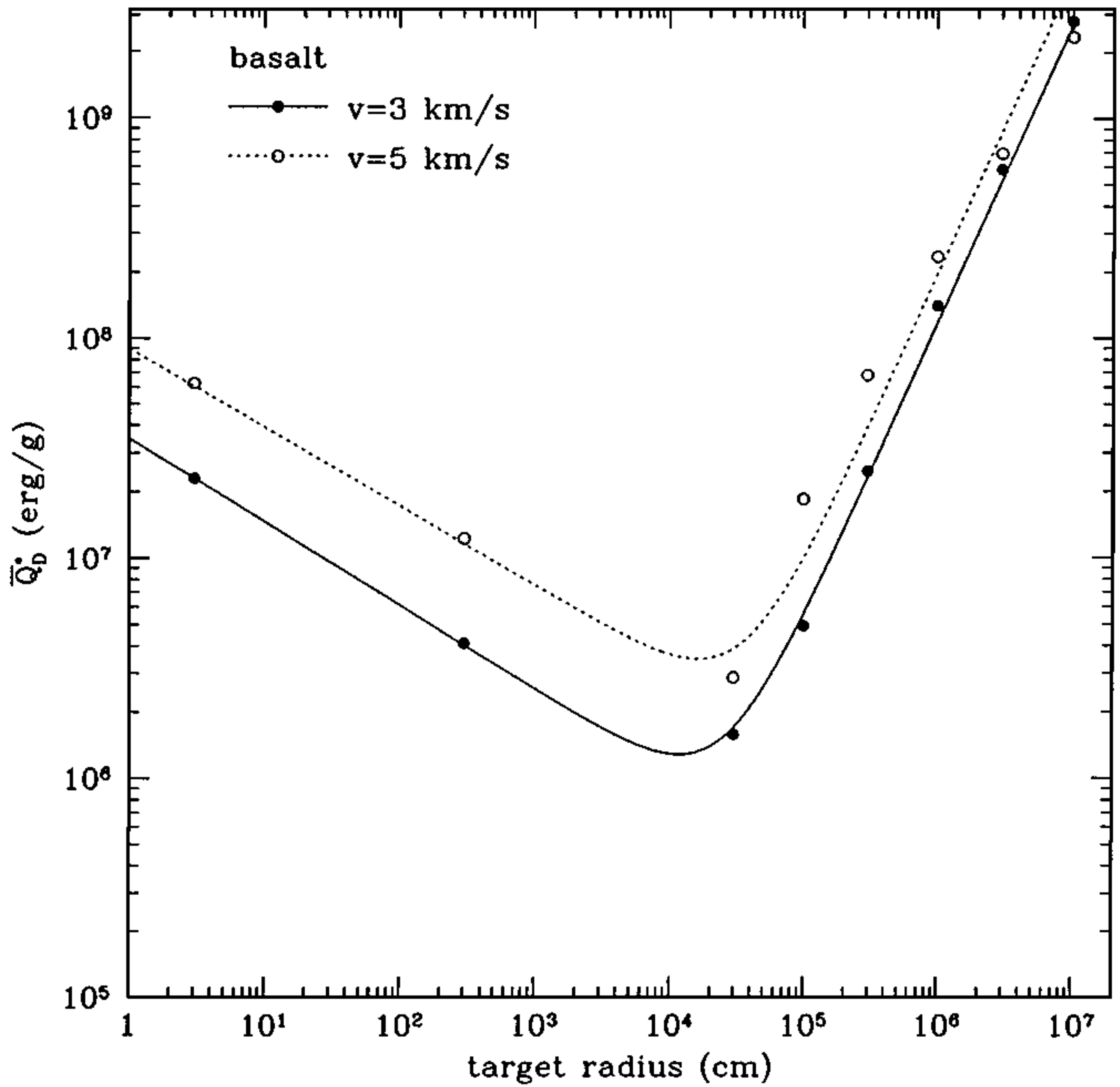
$\Rightarrow$ Similar conclusion: remnants of targets with $R \gtrsim 1\,\mathrm{km}$ consist essentially of shattered, gravitationally bound fragments $\Rightarrow$ "rubble piles".

Characteristic quantity for impacts:

- Catastrophic Disruption Threshold

Specific incoming kinetic energy (kinetic energy in the collision per target mass), for which largest remaining object is half in size of target. (Note: remnant may well be fragmented!).

Catastrophic Disruption Threshold



$\Rightarrow$ weakest bodies at $R \sim 200\,\mathrm{m}$

(Benz & Asphaug 99)

Low velocity collisions and rubble piles

Similar study but dedicated to the growth of planetesimals: Benz 2000

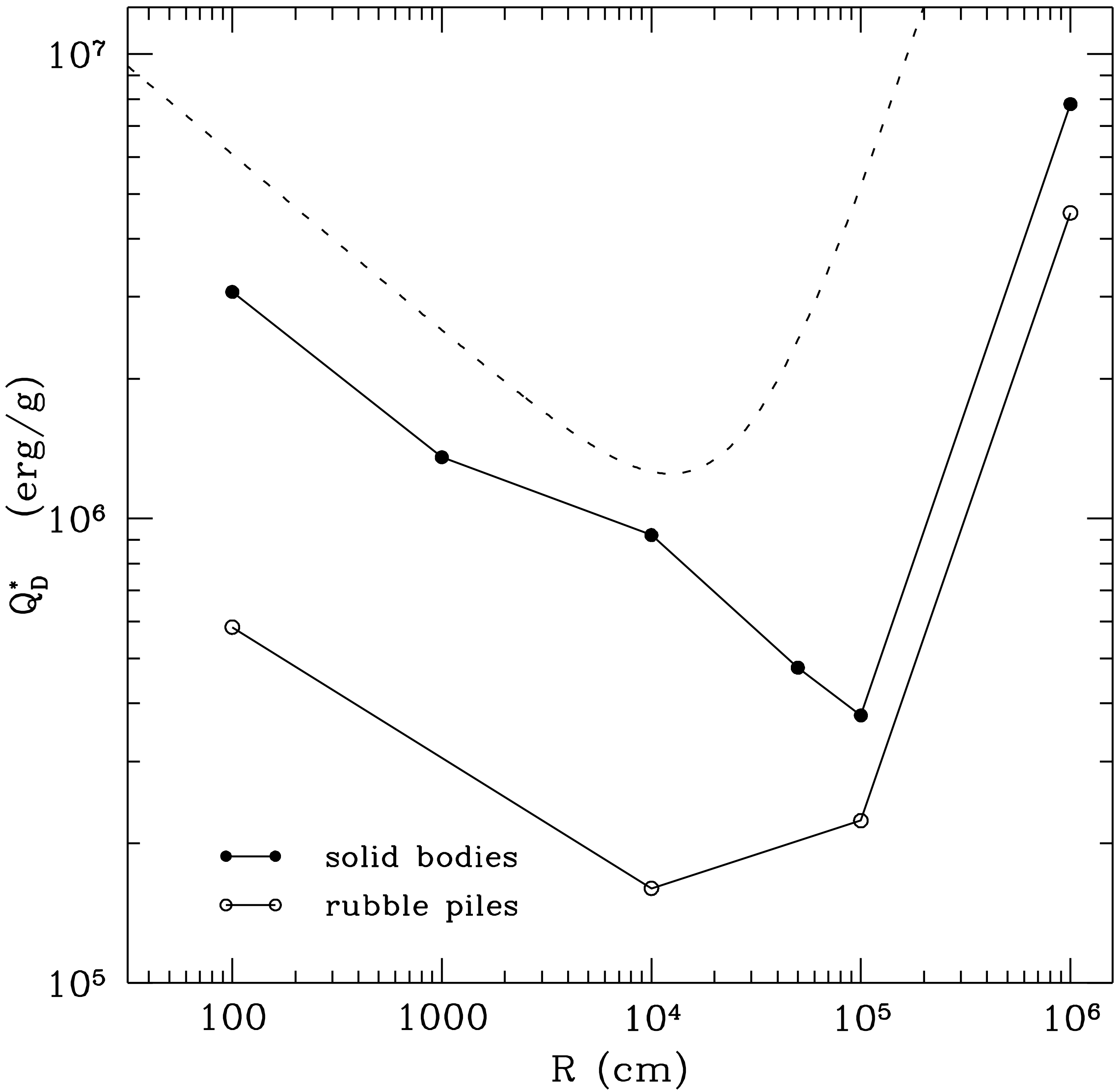
- Collisions of solid spheres and of rubble piles,
  - basaltic material,
  - $R \sim 1\,\mathrm{m} \cdots 10\,\mathrm{km}$,
  - collision velocities of $5 \cdots 40\,\mathrm{m/s}$.

$\Rightarrow$ Low velocity collisions more vulnerable to disruption.

$\Rightarrow$ Rubble piles considerably weaker than solid bodies.

- Reason: more efficient momentum transfer upon impact.

Catastrophic Disruption Threshold



dashed line:
collisions with
$v = 3\,\mathrm{km/s}$

(Benz 2000)

⇒ Weakest objects: in the $R \sim 100\,\mathrm{m}$ regime.

More problematic for pre-planetesimal growth:

Metre-sized bodies

- Fastest radial drift due to gas drag

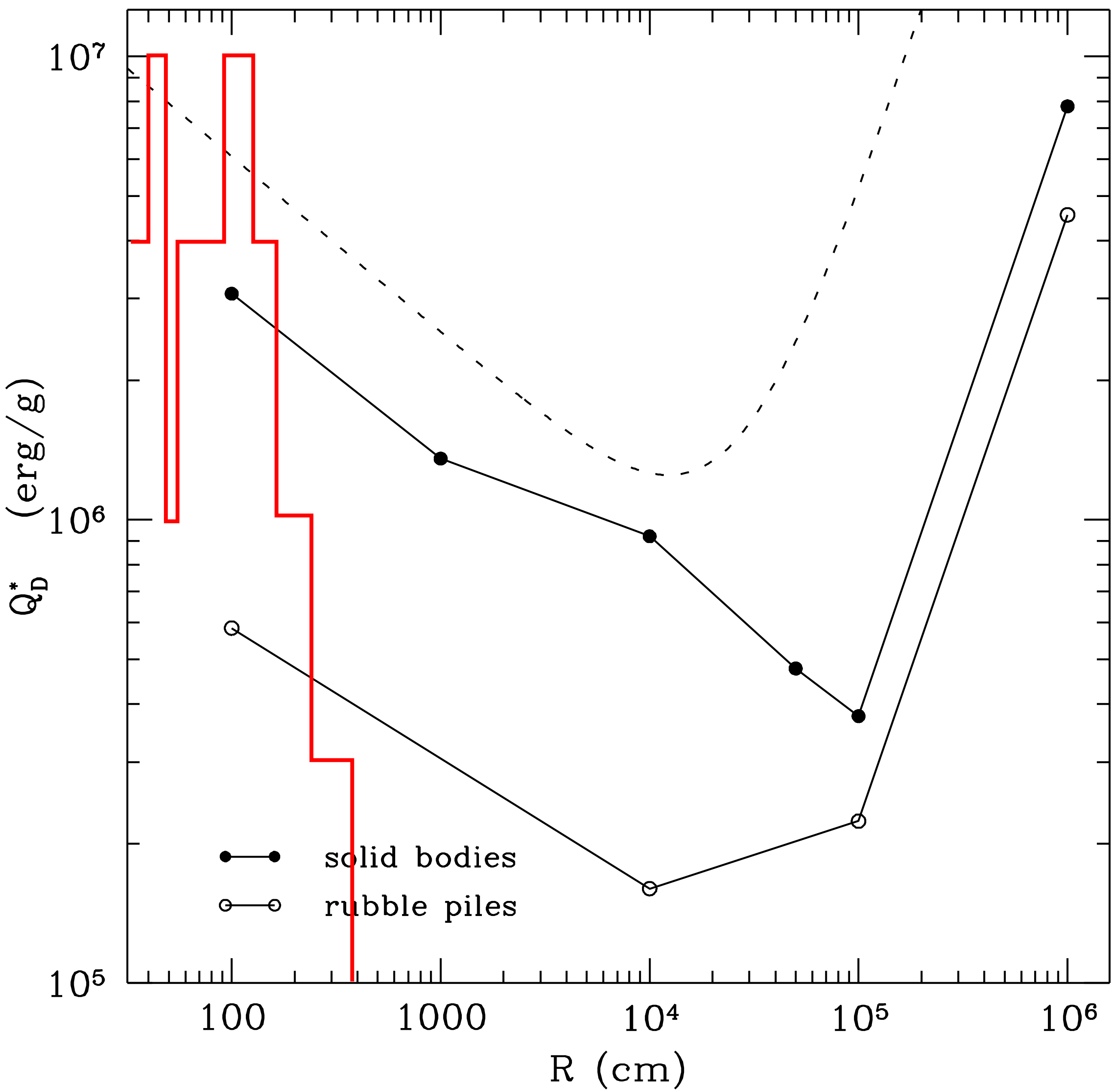
  ⇒ largest velocity dispersion and relative velocities (~ 10 – $\lesssim 100\,\mathrm{m/s}$, depending on shape)

  ⇒ well above critical disruption threshold

  ⇒ easy destruction and dispersion upon collisions

⇒ Bottleneck in growth of pre-planetesimals?

Specific kinetic collisional energy due to gas drag compared with Critical Disruption Threshold



(red line: estimated from Fig. 7 of Benz 2000 for equal sized targets)

Collisions of porous (m-sized) bodies

- So far: simulations of collisions of solid bodies
  - consisting of rocky materials,
  - consisting of rocky rubble piles.

⇒ Results: Erosion or fragmentation, no net growth.

- However, pre-planetesimals may consist of porous agglomerates with differing material properties

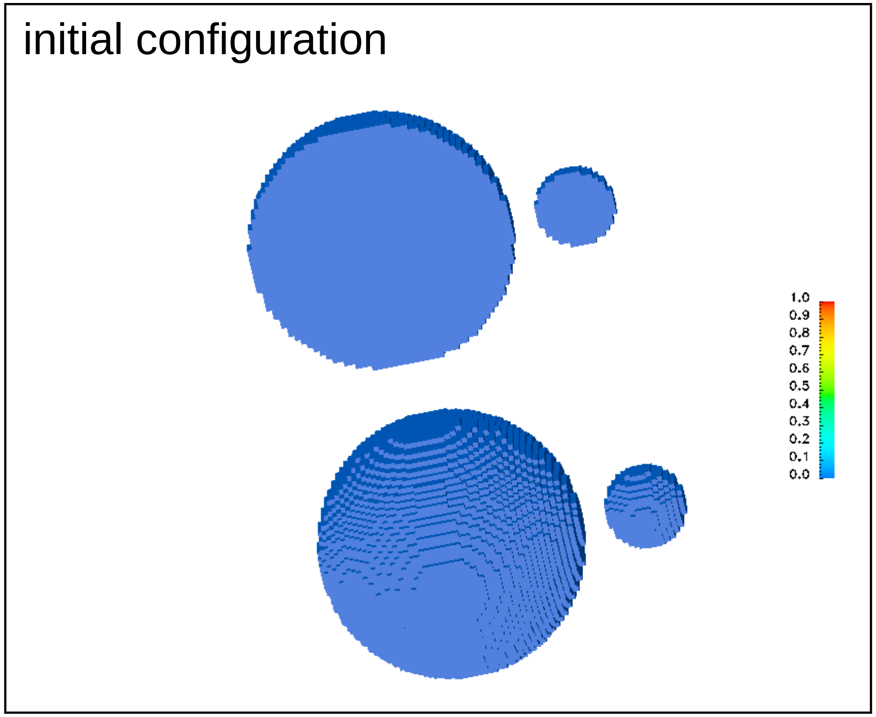
  (strongly indicated, e.g., by low density of asteroids and comets, by lab experiments of dust growth (Blum, Wurm), and theoretical simulations (Dominik, Tanaka)).

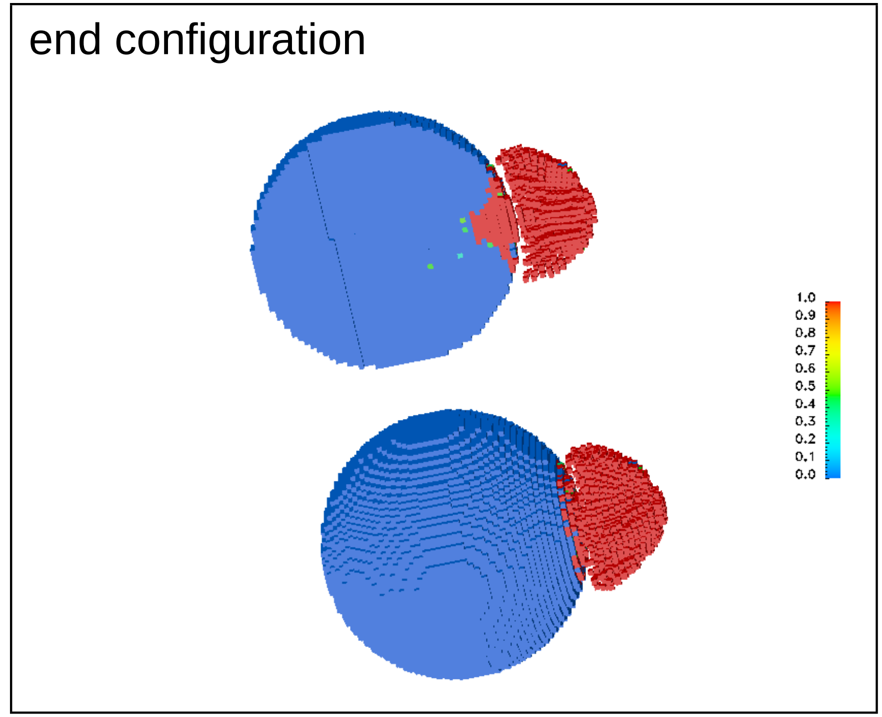
⇒ Next step: SPH simulations to study collisions of porous bodies.

⇒ Porosity model in SPH: material parameters depend on filling factor of density (Sirono 2004) (– see C. Dominik's talk).

- Problem: material parameters fitted from experimental data, but usually unknown.

Collision with small impactor – solid rocky material





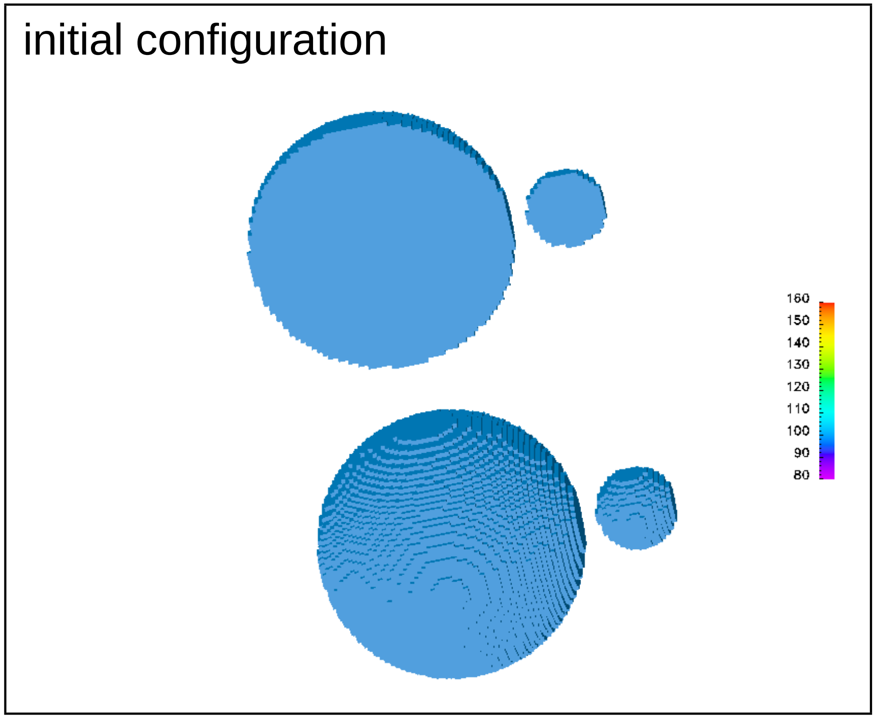
Colour-coded: damage

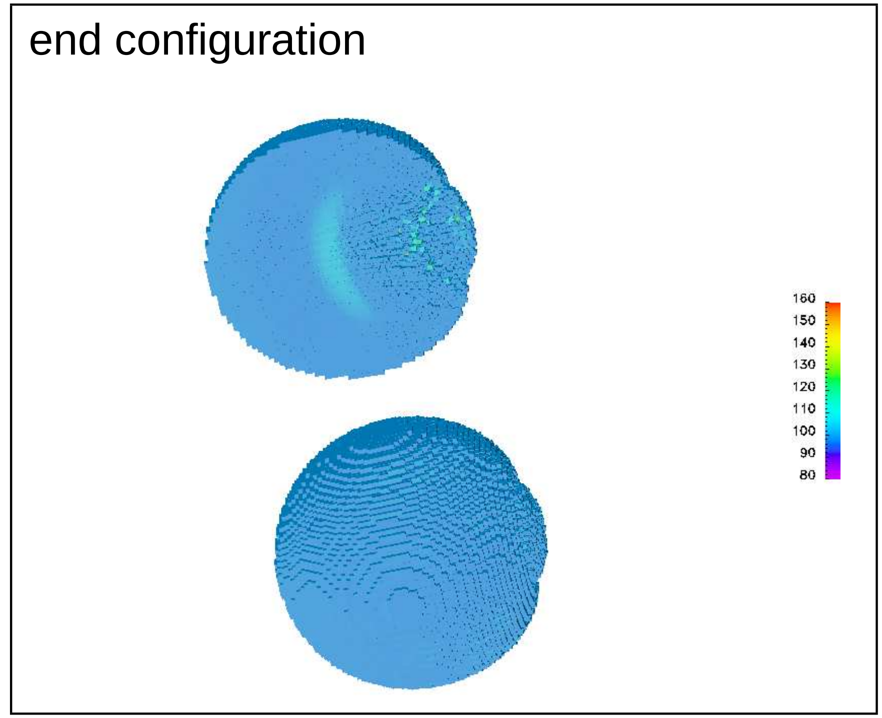
Target-radius: $1\,\mathrm{m}$, Impactor-radius: $1/3\,\mathrm{m}$, Initial density: $3\,\mathrm{g/cm^3}$,

Relative velocity: $20\,\mathrm{m/s}$

(Movie)

Collision with small impactor – porous material





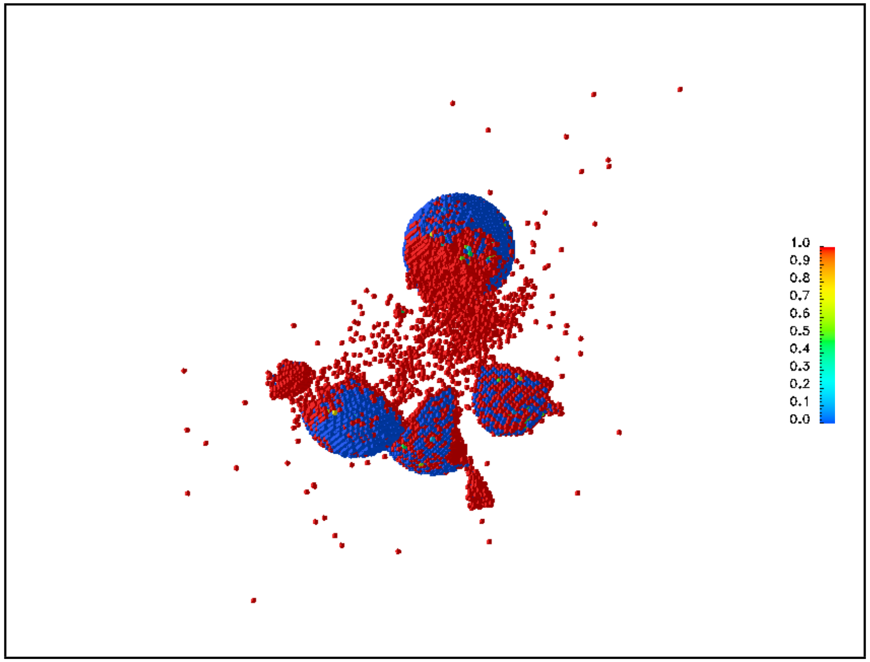
Colour-coded: density

Target-radius: $1\,\mathrm{m}$, Impactor-radius: $1/3\,\mathrm{m}$, Initial density: $0.1\,\mathrm{g/cm^3}$, Porous filling: 0.1,

Relative velocity: $20\,\mathrm{m/s}$

(Movie)

Collision with equal size targets – oblique impact



Brittle material,
Target and impactor radius: $1\,\mathrm{m}$,
Initial density: $3\,\mathrm{g/cm^3}$,
Impact velocity: $20\,\mathrm{m/s}$.

(Movie)

Porous material, filling factor: 0.1,
Target and impactor radius: $1\,\mathrm{m}$,
Initial density: $0.1\,\mathrm{g/cm^3}$,
Impact velocity: $20\,\mathrm{m/s}$.

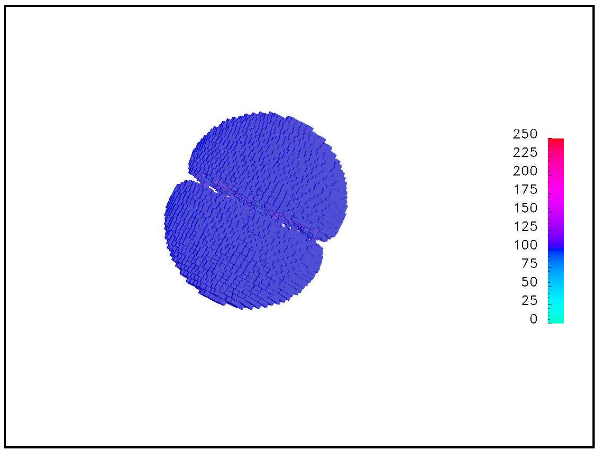
(Movie)

Influence of material parameters

Porous material, filling factor: 0.1, equal size targets (radius: $1\,\mathrm{m}$), direct impact with $10\,\mathrm{m/s}$.

Compressive strength: $\Sigma(\rho) = \Sigma_0(\rho/\rho_0)^6$ Tensile strength: $T(\rho) = T_0(\rho/\rho_0)^5$

$\Sigma_0 = 6{\cdot}10^2$, $T_0 = -6{\cdot}10^3$



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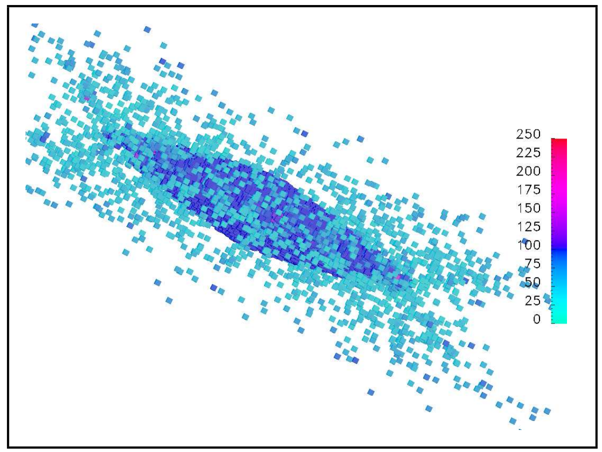

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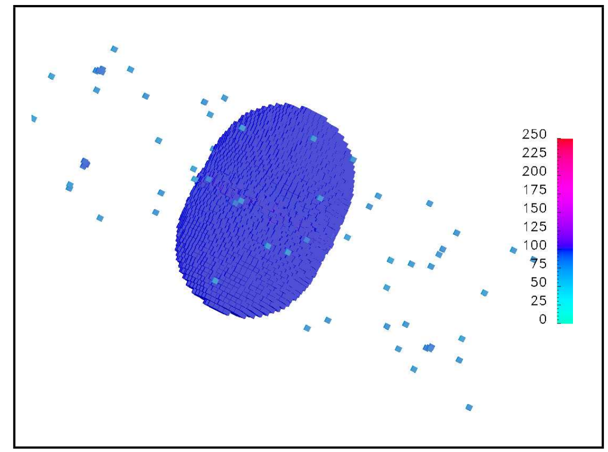
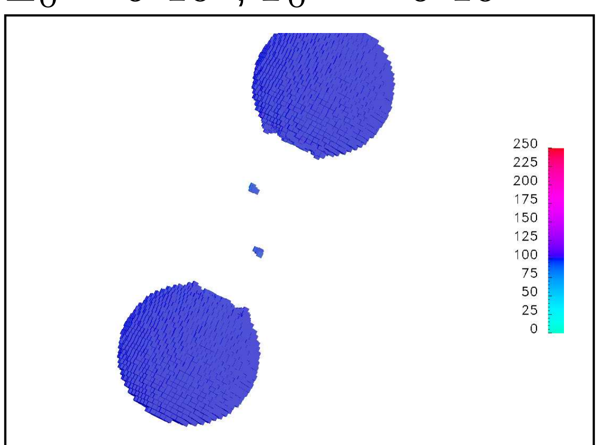
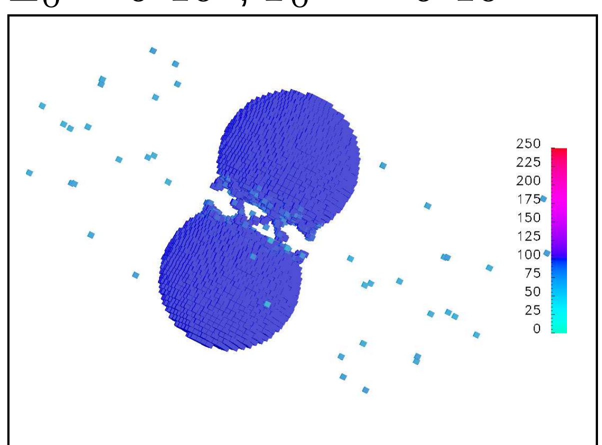


$\Sigma_0 = 6{\cdot}10^4$, $T_0 = -6{\cdot}10^4$



$\Sigma_0 = 6{\cdot}10^4$, $T_0 = -6{\cdot}10^3$



(All coefficients are in Pa)

Conclusion

1. For porous pre-planetesimals, growth is possible even by incorporating objects larger than grains.

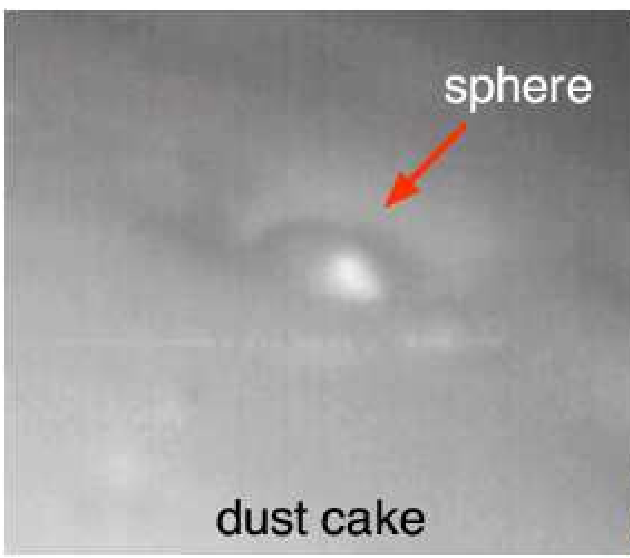
2. Distinctly different collisional outcome for porous and rocky material, though indications for a general effect of erosion and fragmentation upon equal size collisions.

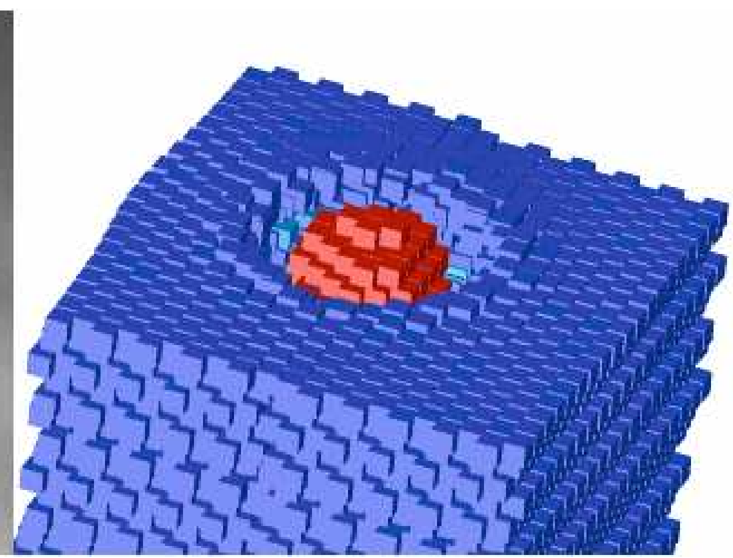
3. Collisions of metre-sized bodies still seem to be a barrier in growth of pre-planetesimals, however this is highly material dependent.

Outlook

- More quantitative evaluation of collisional outcome.
- Methodical parameter studies.
  (→ Catastrophic Disruption Threshold, etc.)
- More realistic material parameters.
- Improvements of damage model and porous model.

⇒ Calibration with laboratory experiments.





Blum et al.

Many Thanks

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