Dynamics of Dust Aggregates

Wilhelm Kley & Alexander Seizinger

Institut für Astronomie & Astrophysik
& Kepler Center for Astro and Particle Physics Tübingen

EBERHARD KARLS
UNIVERSITÄT
TÜBINGEN

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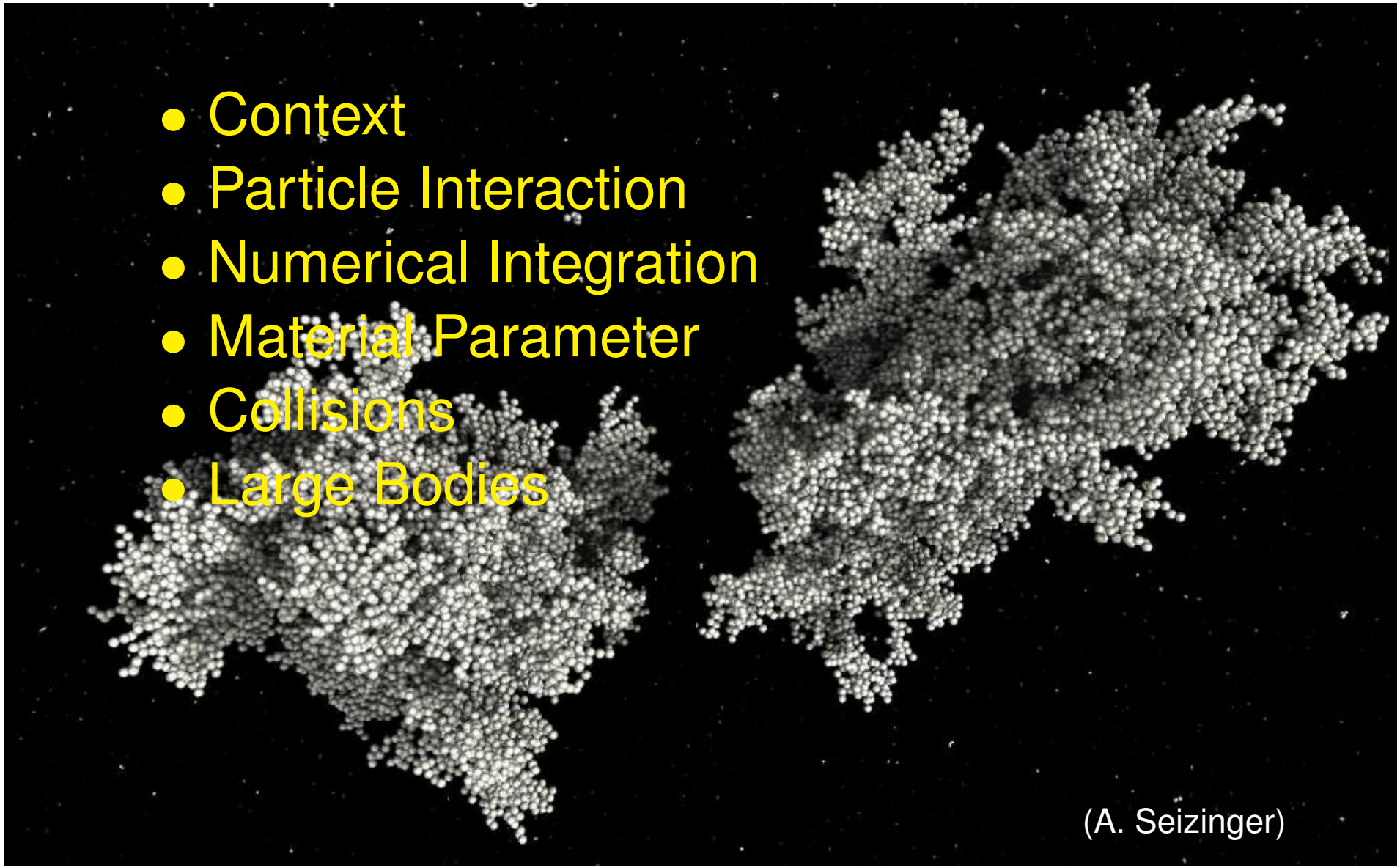
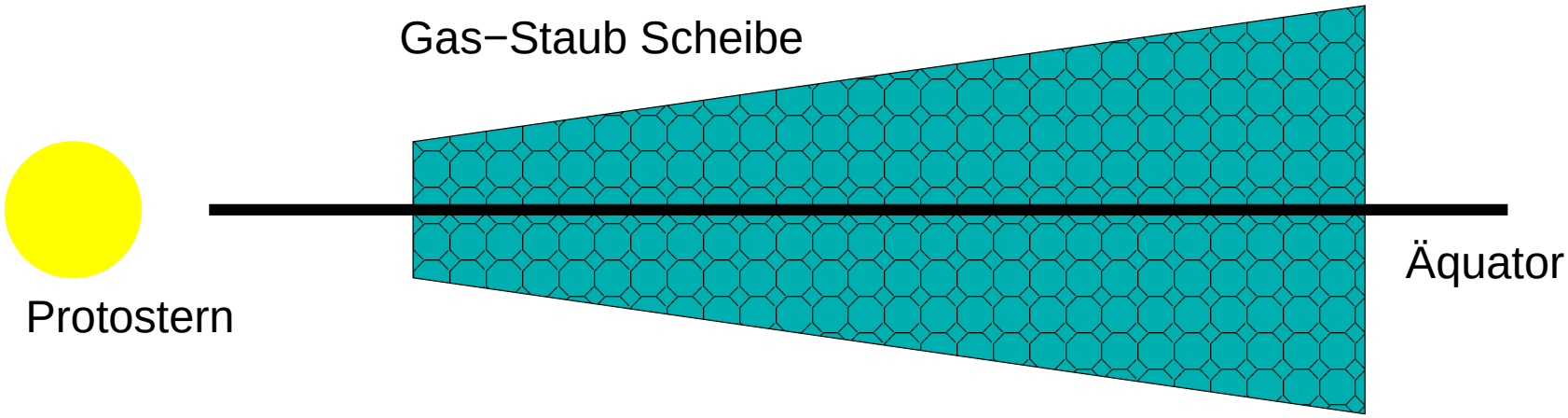
Organisation



Growth to Planets: Overview

Coagulation of Dust & Accretion of Gas (99% Gas, 1% Dust)



Growth: Dust $\Rightarrow$ Planets (μm $\Rightarrow$ 1000km)

(Mass Growth of 35 orders of Magnitude)

Original Matter:

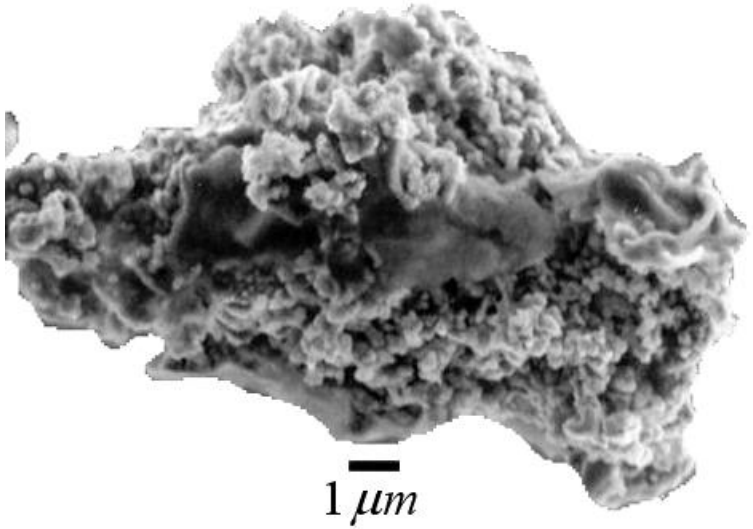
- Oxides, silicates, organic material, ice

Size: μm

Dust Particles condense in Disk

Growth by :

- Sequence of Collisions & coagulations



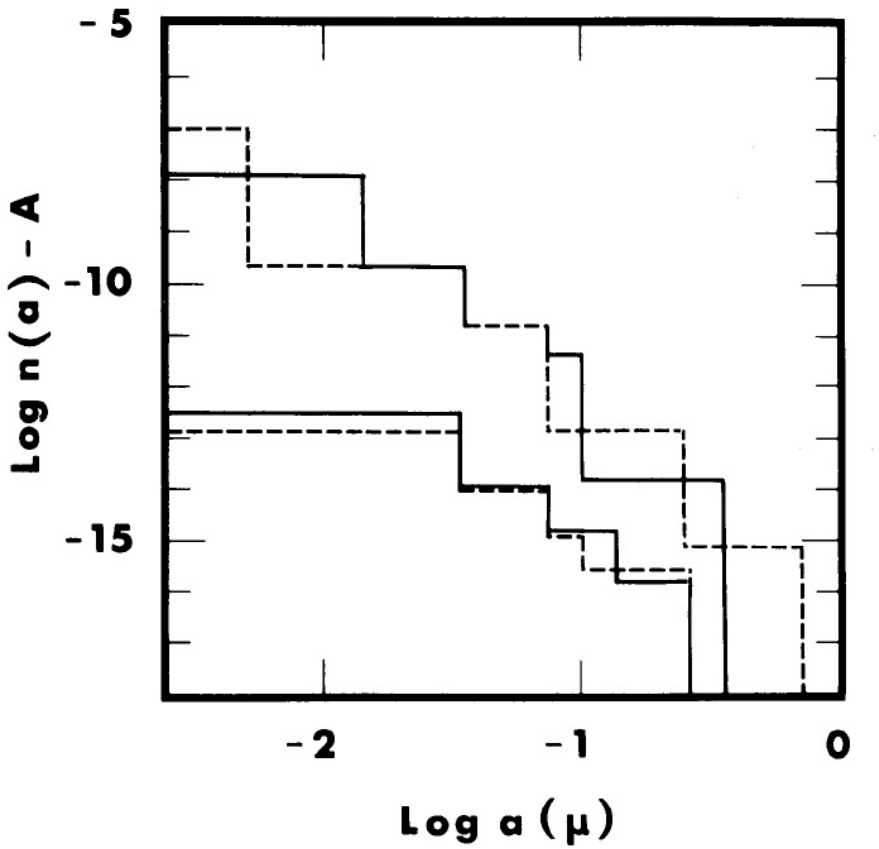
Ingredients I

1) Interstellar Dust

Measure interstellare Extinction

Size distribution (MRN)

$n(a) \propto a^{-3.5}$



(Mathis, Rumpl, Nordsieck, 1977)

Ingredients II

2) Protoplanetary Disk

MMSN: Minimum Mass Solar Nebula

- Augment planet mass with Gas to solar abundance
- split into rings
- spread material therein

$$\Sigma(r) \approx 1700 \left(\frac{r}{1AE}\right)^{-3/2} \text{ g/cm}^2 \quad (1)$$

(Hayashi, 1981)

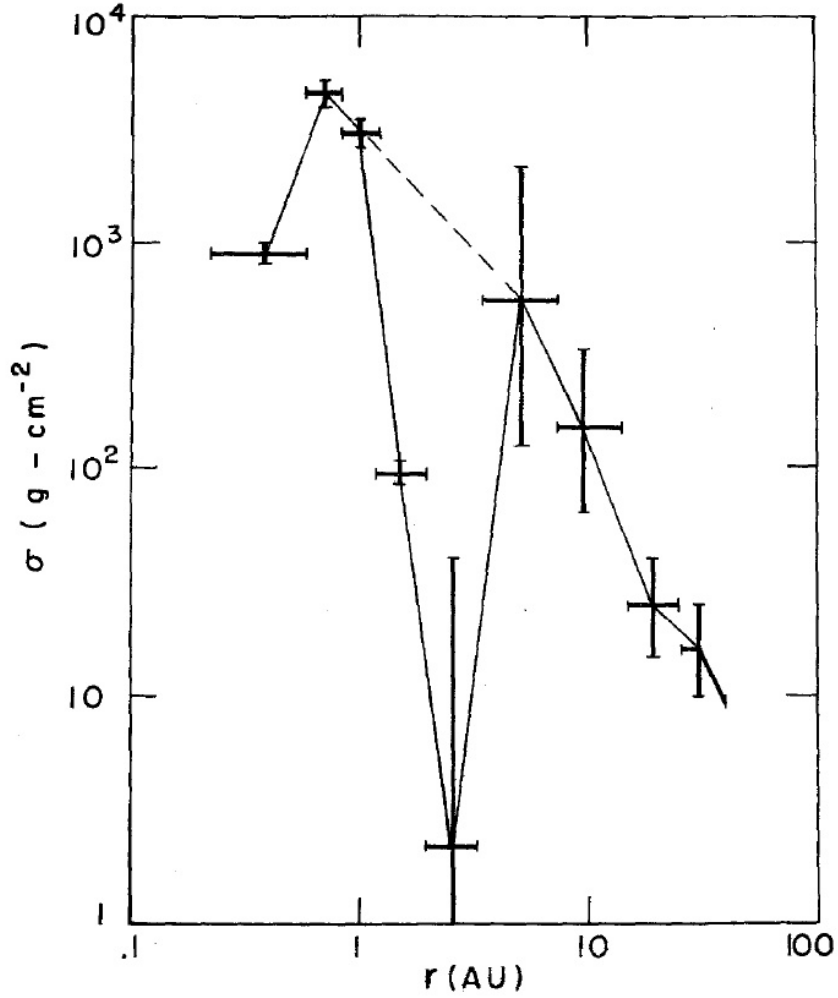
Total Mass:

$\approx 0.01 - 0.07 M_\odot$

total angular momentum:

$\approx 3 \cdot 10^{51} - 2 \cdot 10^{52}$ g cm^2 s^{-1}

typical model for protoplanetary disks



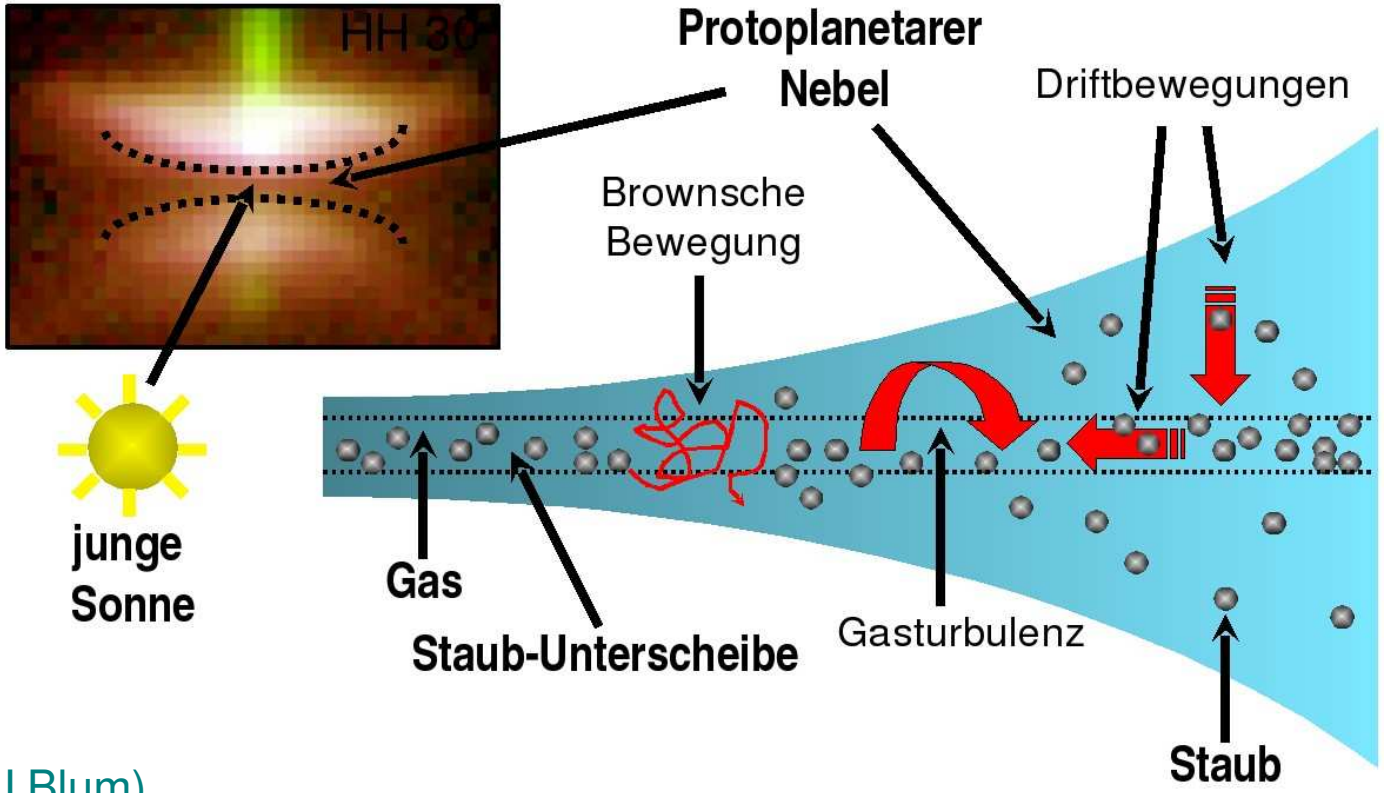
(Weidenschilling, 1977)

Particle Dynamics in Disk

Particles need relative Velocity for mutual collisions

Causes:

- Brownian Motion
- Vertical Sedimentation (Settling), radial Drift
- Turbulence in the Disk



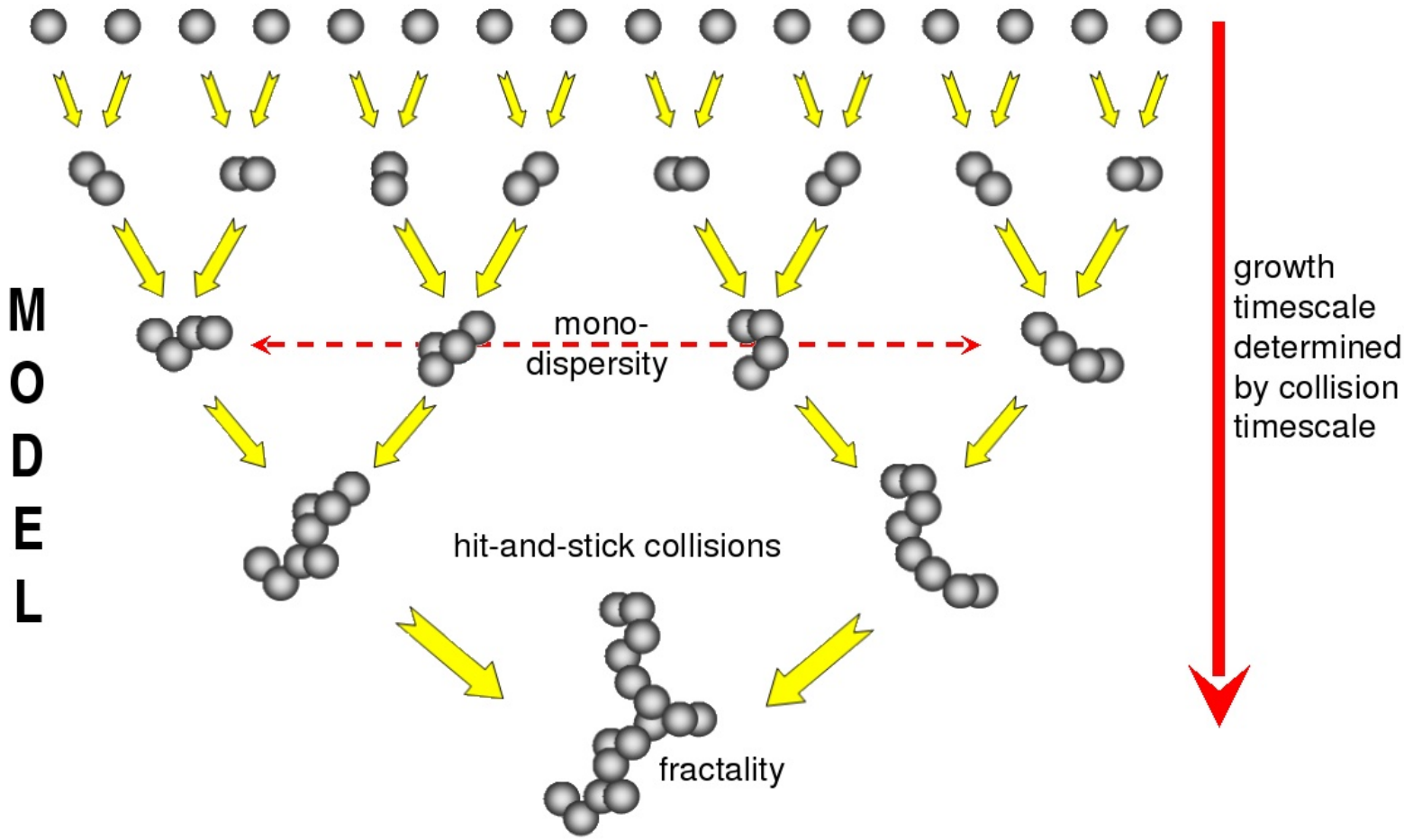
(J.Blum)

Particles have relative velocity with gas $\Rightarrow$ Drag forces

Problems: 1) Destructive collisions, 2) Bouncing collisions, 3) fast Drift

so called meter-sized barrier

Growth Principle I



(J. Blum, Braunschweig)

Need: Adhesive forces

- Van der Waals
- Sticking enhancement with ice
- Organic compounds

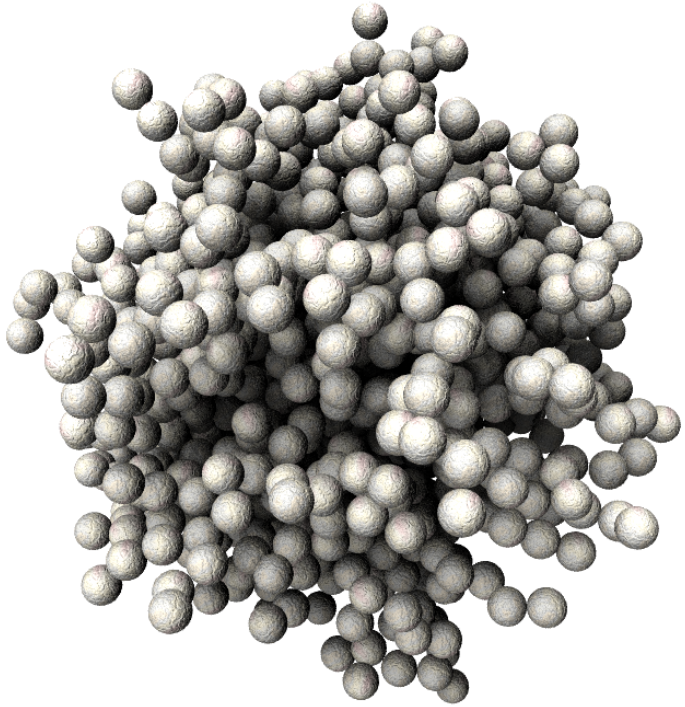
Growth Principle II

Two basic growth modes:

BPCA

Ballistic Particle-Cluster Agglomeration:

Connect individual particles

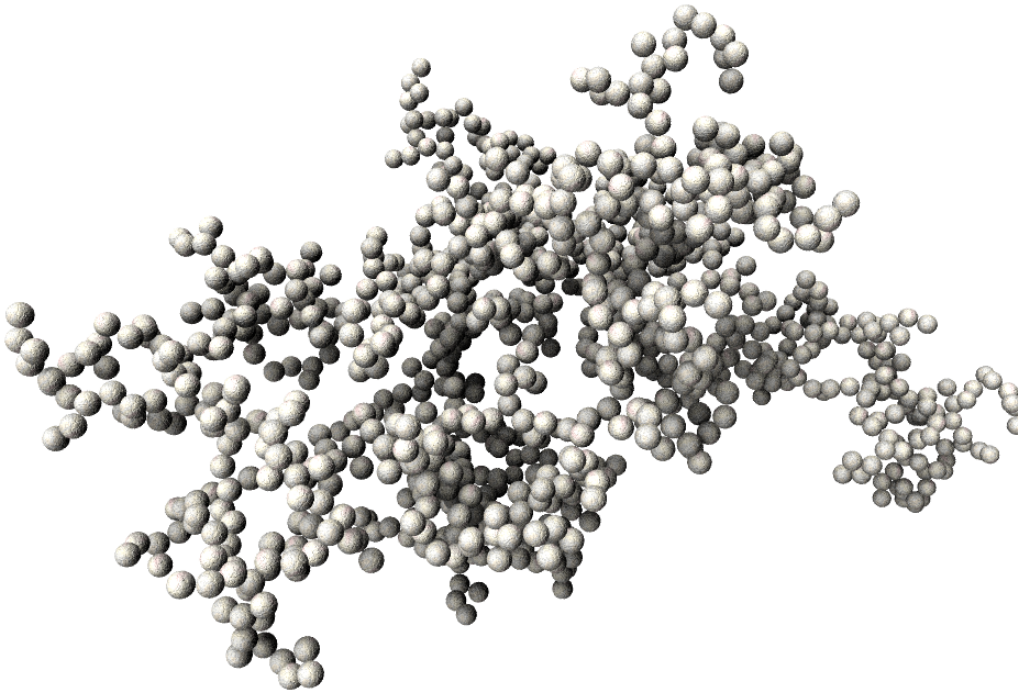


(A. Seizinger)

BCCA

Ballistic Cluster-Cluster Agglomeration:

Connect whole clusters



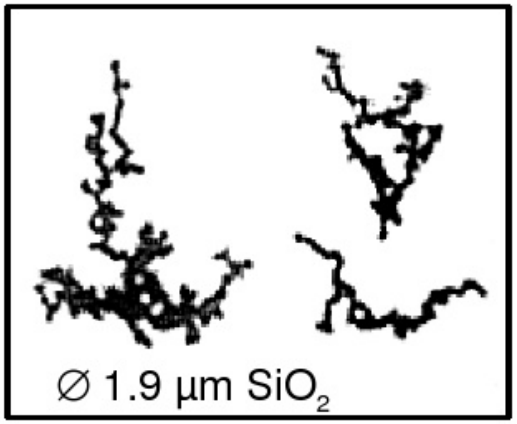
Example with $N = 1024$ Particles (here 100% Sticking)

Problems: Sticking probability, velocity dependence, rolling friction,
Destruction in collisions, compactification, etc ...

Initial Growth: Experimentally

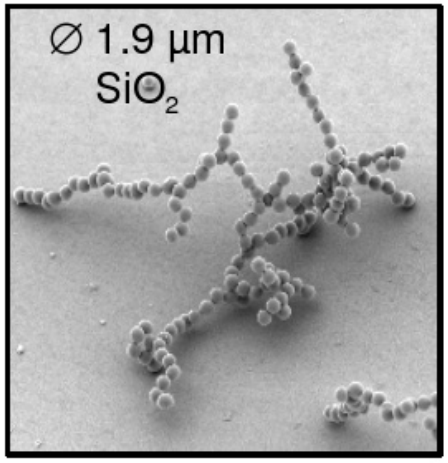
Test of different experimental conditions (mit $v_{\rm rel} \approx 10^{-4} - 10^{-2}$ m/s)

Gas turbulence



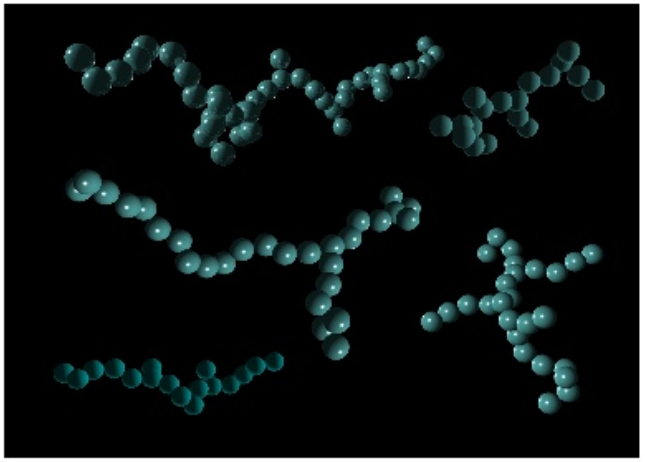
Wurm & Blum 1998

Differential sedimentation



Blum et al. 1998

Brownian motion



Blum et al. 2000

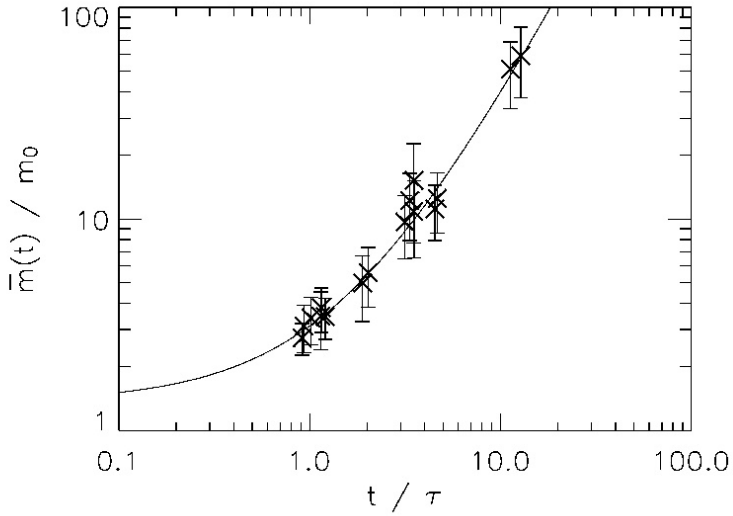
Fractal Growth

Mass (m)-Size (s) Relation:

$m \propto s^{D_f}$ mit $D_f \leq 2$

Typical here: $1.4 \leq D_f \leq 1.8$

Approximative: $m(t) \propto t^{1.7}$

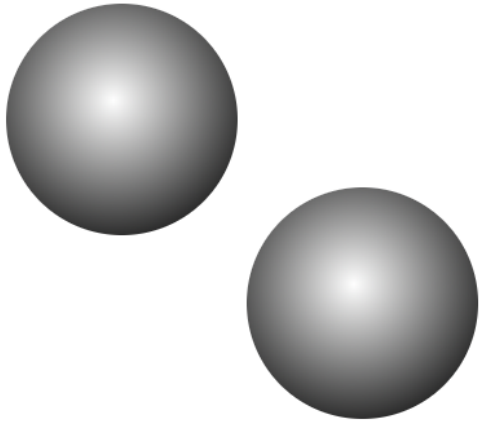


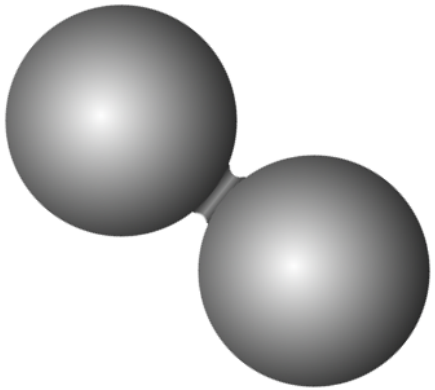
Growth Model

- Assume Dust Aggregates consist of individual monomers
- Take equal sized, spherical monomers
- Need interaction model
- Not simple non-interaction billard balls
- local attractive force
- force depends on history
- use specific physical model
- Integration: Discrete Element Method
- Molecular dynamics type

Molecular Dynamics I

Model the motion of N Particles with Newtonian Dynamics



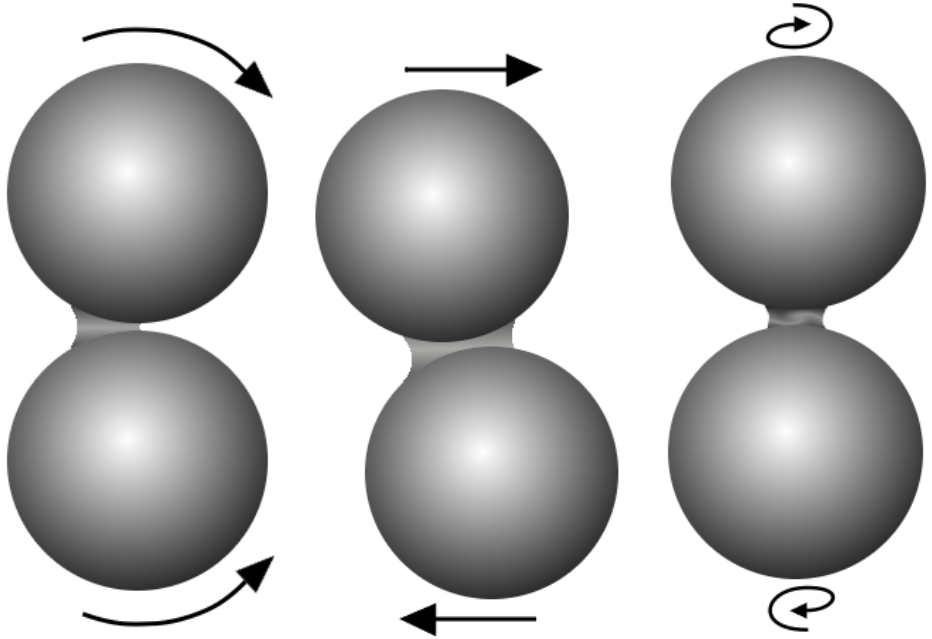


and suitable
interaction forces

- Adhesion
- van-der Waals
- Rolling friction

etc

based on experiments
and theory



Grain Properties

Each spherical grain is described by the following properties

m	mass
I	moment of inertia
r	radius
$\vec{x}$	position
$\vec{v}$	velocity
$\vec{\omega}$	angular velocity
$\vec{F}$	force acting on particle
$\vec{M}$	torque acting on particle

Plus additional **material** parameter

Young's modulus (E): tensile stress divided by strain

Poisson's ratio (ν): ratio transverse to axial strain

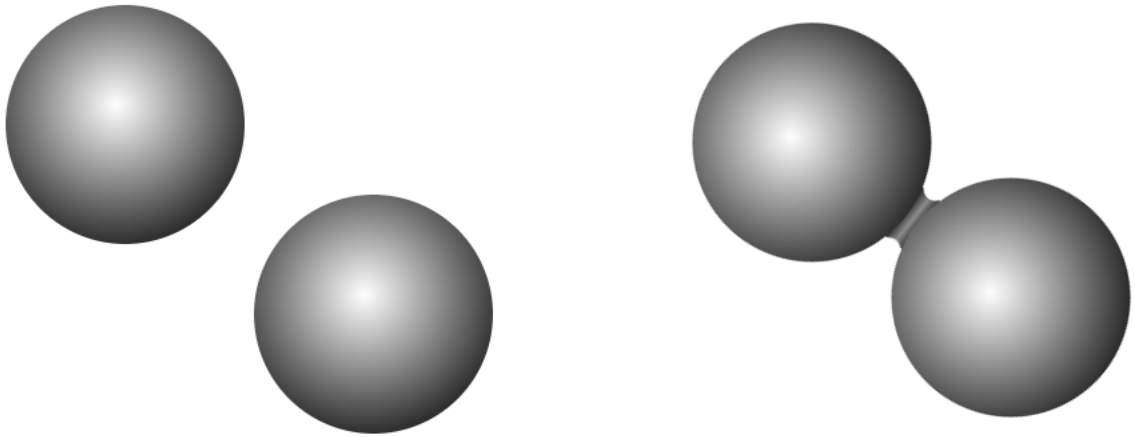
Shear modulus (G): shear stress divided by strain

Surface energy (γ): per unit contact area

Contacts I

Two *freely moving* particles **form a contact** if

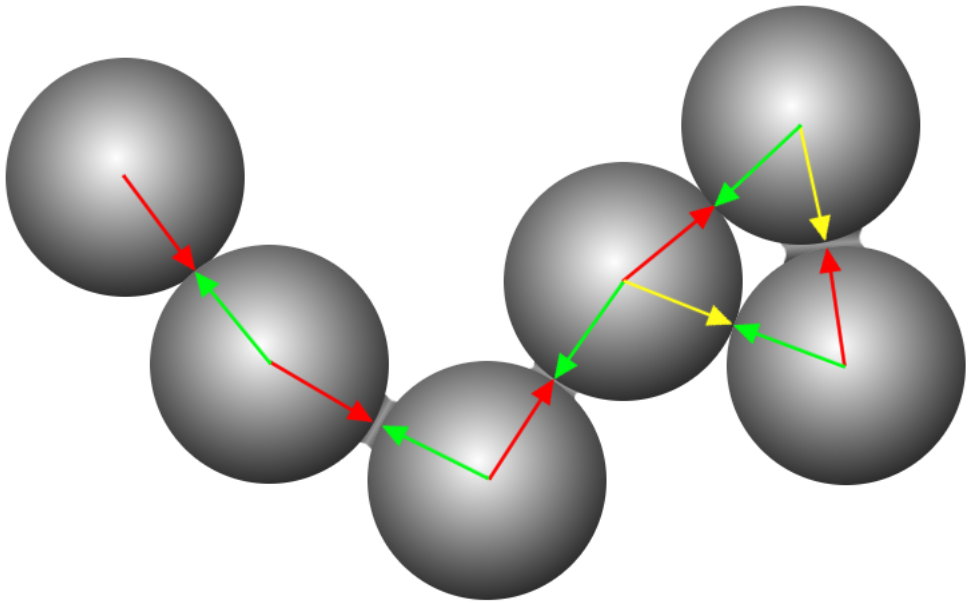
$$\|\vec{x}_i - \vec{x}_j\| \leq r_i + r_j$$



On impact, some of the material the particles are made of forms a circular **contact area**.
Some of the kinetic energy is dissipated (Chokshi et al. 1993).
No longrange force: Particles must be in contact to interact with each other.

Contacts II

Each particle can be part of several contacts.



Use **contact pointers** to describe the geometry (Dominik & Nübold, 2002).
In stress free equilibrium they are the normal vectors of the contact area.

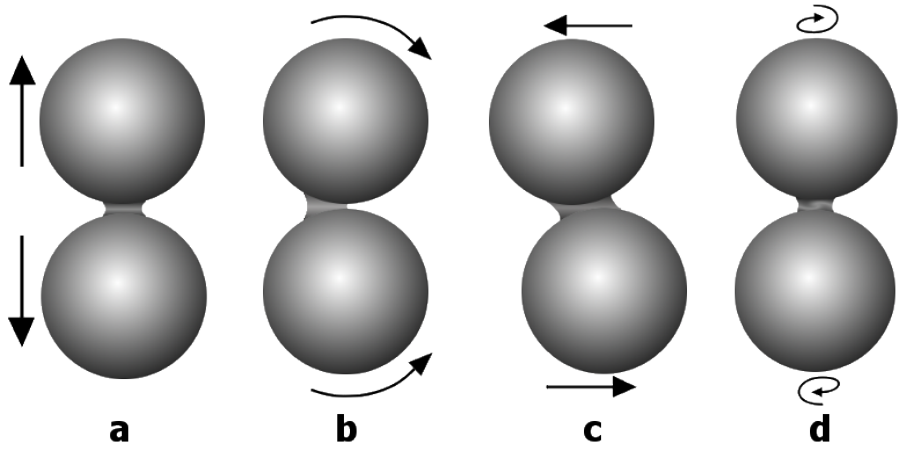
Type of Interactions

The interaction may be divided into the following types:

a) Compression/Adhesion
(Johnson *et al.*, 1971)

b) Rolling
(Dominik & Tielens, 1995)

c) Sliding
(Dominik & Tielens, 1996)

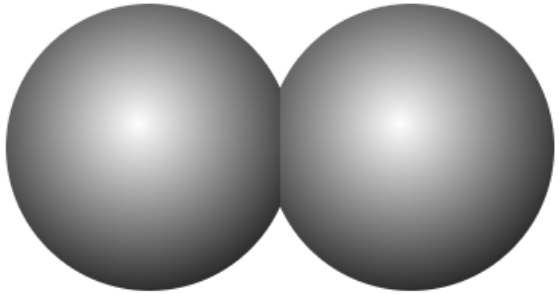


d) Twisting
(Dominik & Tielens, 1996)

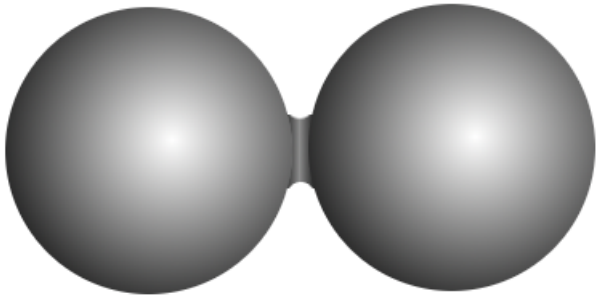
Forces and torques of those types of interaction can be derived from *corresponding potentials* (Wada *et al.*, 2007)
Advantage: Can track in detail the energy evolution.

Compression/Adhesion

We define the compression length $\delta := r_i + r_j - \|\vec{x}_i - \vec{x}_j\|$



$\delta > 0$



$\delta < 0$

An established contact will break if $-\delta$ exceeds the critical compression length δ_c.

Note the sign convention of δ.

Contact Geometry

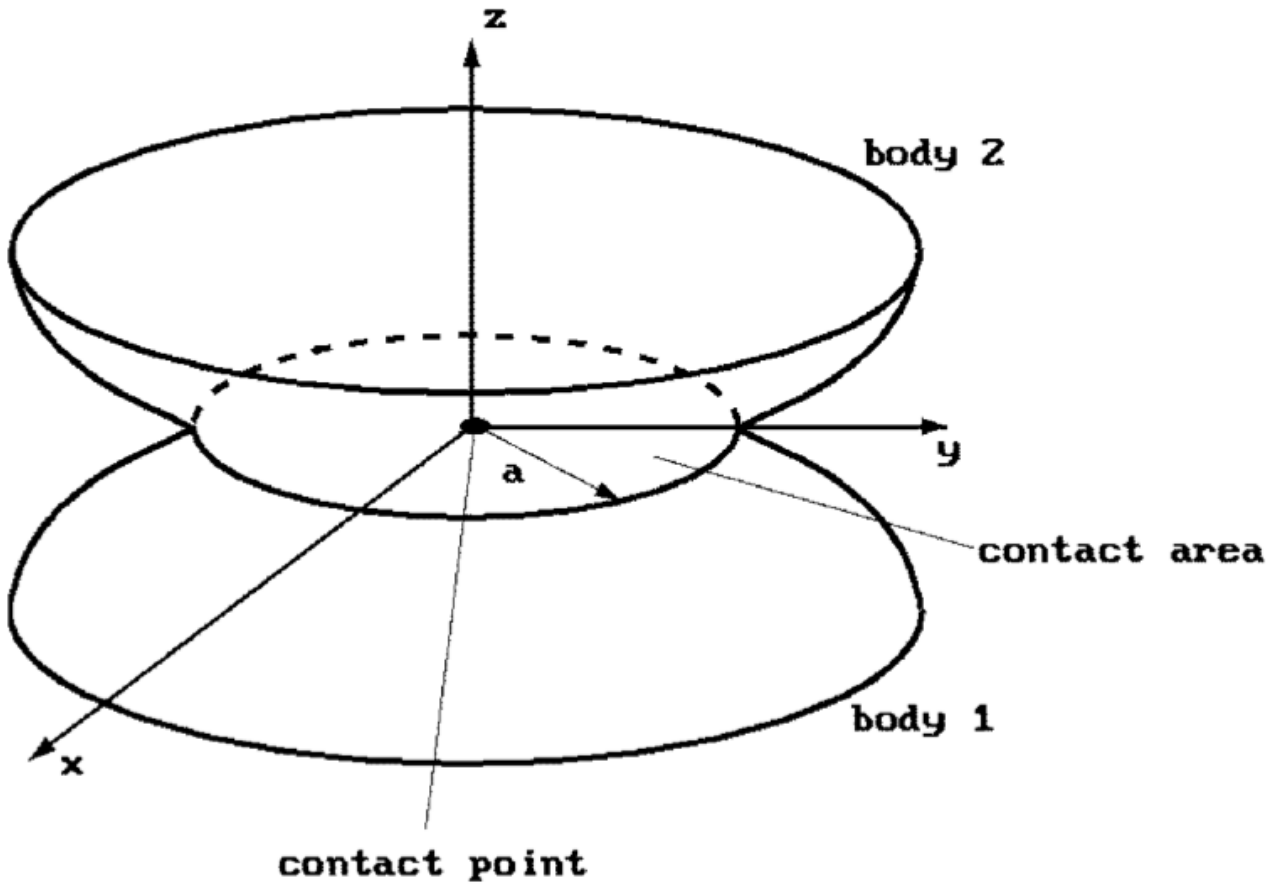
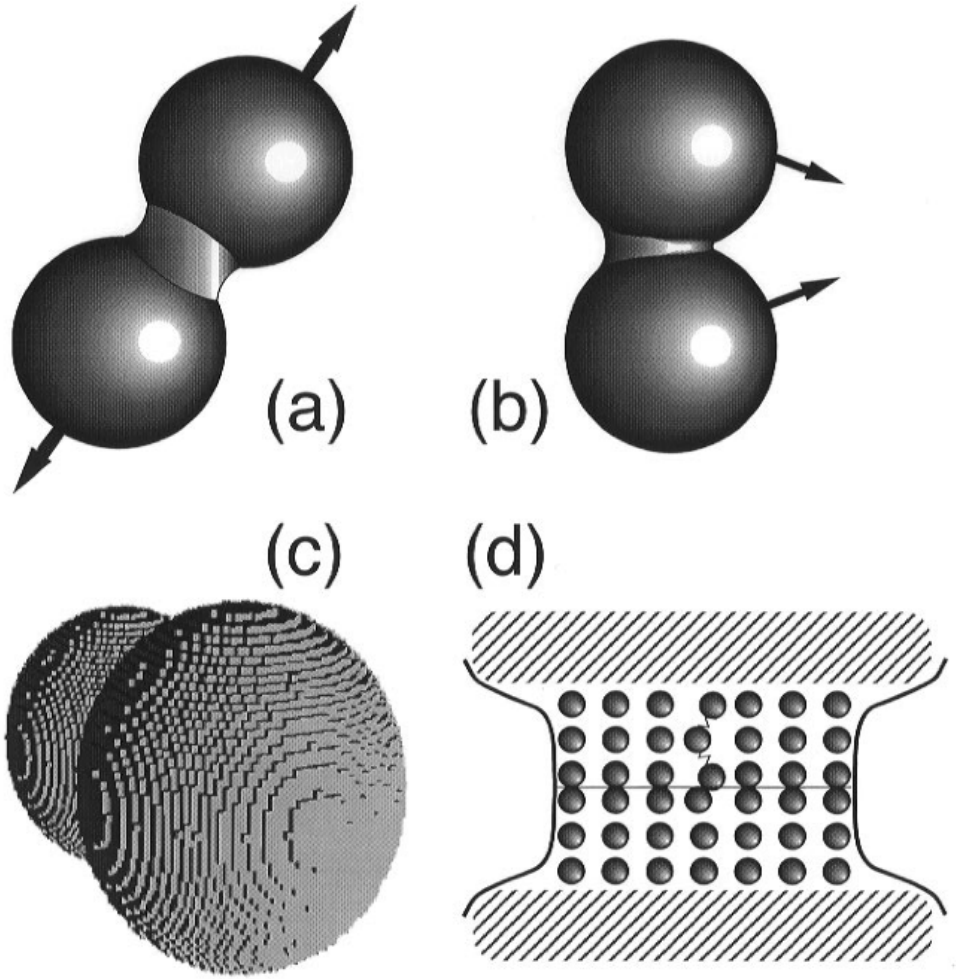


FIG. 1.—Contact geometry: Two grains make contact over a finite circular area with radius a. The size of the area is controlled by the competition between attractive (van der Waals, dipole, etc.) forces and repulsive elastic forces.

The contact area is given by: $\pi\, a^2$, where a is the contact radius.

Dissipation

4 dissipation Channels in contact dynamics of micron-sized particles
(from: Dominik & Tielens, 1997)



a) neck formation during pull-off

b) lagging of contact area during rolling

c) surface roughness

d) jump-wise sliding of individual atoms

Contact Evolution

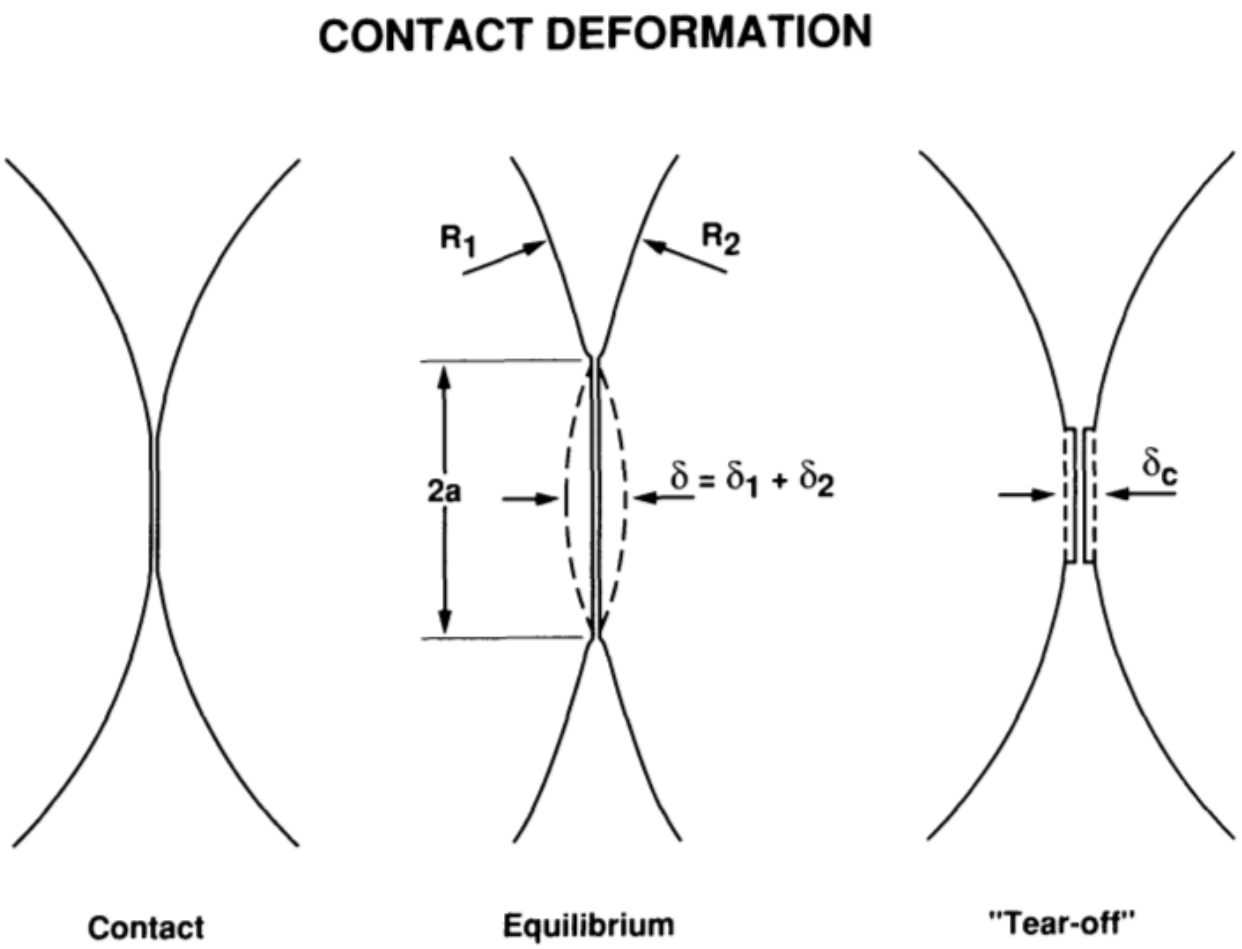
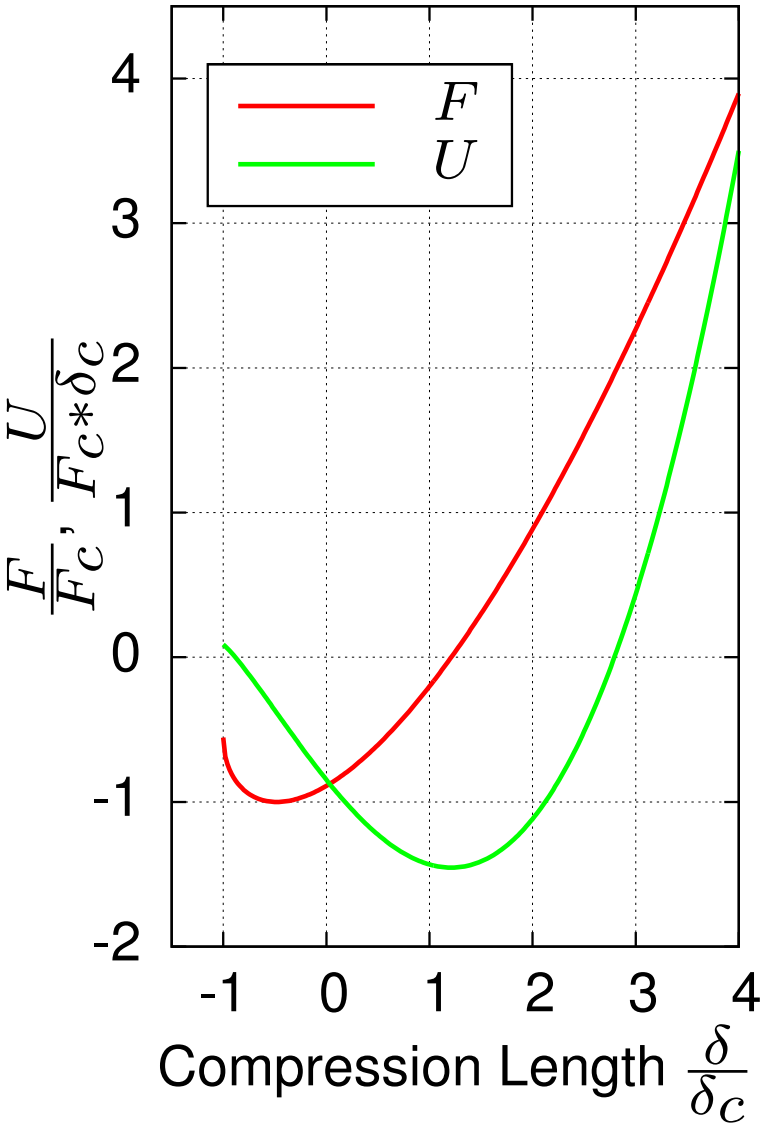


FIG. 2.—Schematic of the deformation during the collision process. At contact, a finite contact area is rapidly formed. This contact area grows in size during the compression and slowing down of the collision partners. Upon reversal of the collision process, the two grains will pull out a neck area, until they separate at a critical displacement, δ_c. See text for details.

Compression/Adhesion

- Based on JKR-Theory (Johnson, Kendall, Roberts, 1971)
- Establishing or breaking contacts dissipates kinetic energy (Chokshi *et al.* 1993)
- Additional damping of normal oscillations (Paszun & Dominik 2008)



Normal Forces

According to JKR-Theory (Johnson et al. 1971), the force acting on two particles that are in contact is given by

$$\frac{F}{F_c} = 4\left(\frac{a}{a_0}\right)^3 - 4\left(\frac{a}{a_0}\right)^{\frac{3}{2}}$$

where a denotes the radius of the contact area. We can obtain a via

$$\frac{\delta}{\delta_0} = 3\left(\frac{a}{a_0}\right)^2 - 2\left(\frac{a}{a_0}\right)^{\frac{1}{2}}$$

The potential energy linked with this force is given by

$$\frac{U_{normal}}{F_c\delta_c} = 6^{\frac{1}{3}}\left[\frac{16}{5}\left(\frac{a}{a_0}\right)^5 - \frac{16}{3}\left(\frac{a}{a_0}\right)^{\frac{7}{2}} + \frac{4}{3}\left(\frac{a}{a_0}\right)^2\right]$$

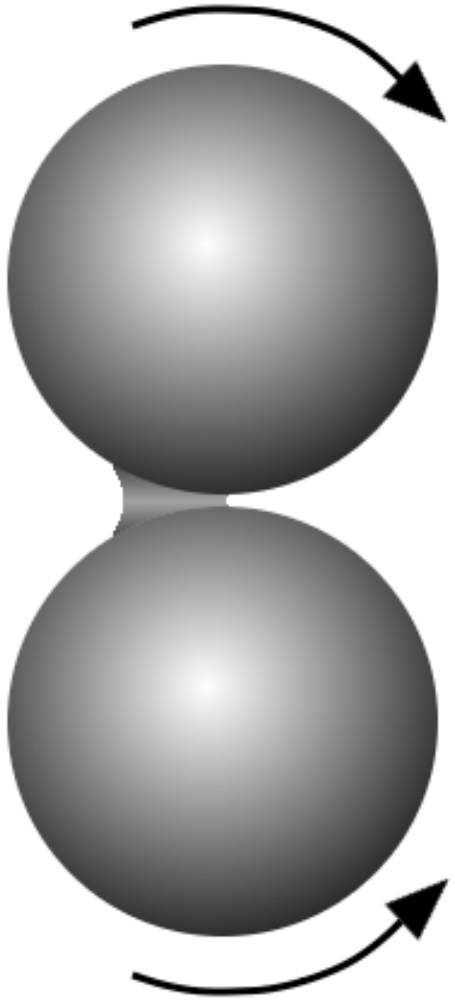
(F_c=Pulloff-Force, δ_0, a_0 equilibrium values)

Rolling I

Two particles that are rolling over each other satisfy

$$\|x_i - x_j\| = const$$

However the contact area has to follow, which causes a torque that counteracts the rolling motion.



Rolling II

The **rolling displacement** $\vec{\xi}$ is defined as

$$\vec{\xi} := R(\vec{n}_1 + \vec{n}_2)$$

From the rolling potential U_r (Wada *et al.* 2007)

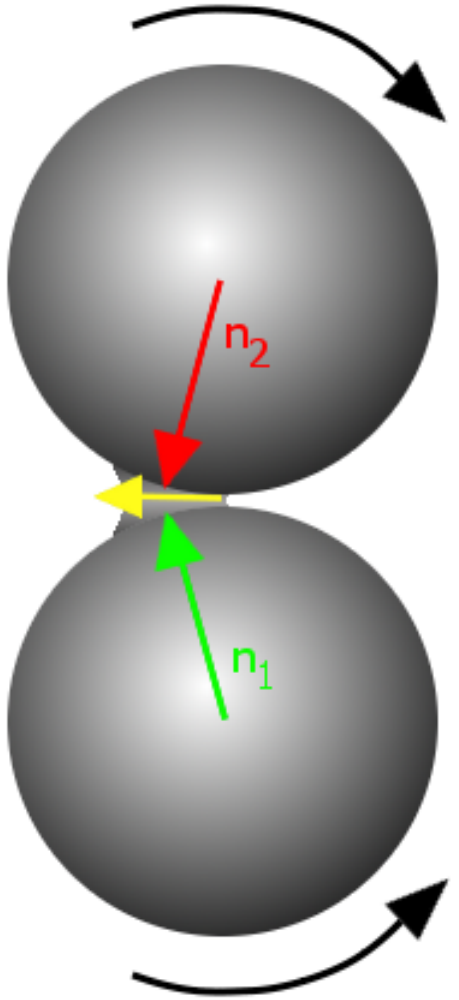
$$U_r = \frac{1}{2} k_r \|\vec{\xi}\|^2$$

we obtain the torques

$$\vec{M}_{r,12} = -\vec{n}_1 \times \nabla_{n_2} U_r = k_r R^2 \vec{n}_2 \times \vec{n}_1$$

which satisfy $\vec{M}_{r,12} + \vec{M}_{r,21} = 0$

$1/R = 1/r_1 + 1/r_2$ (R: reduced radius)



Sliding

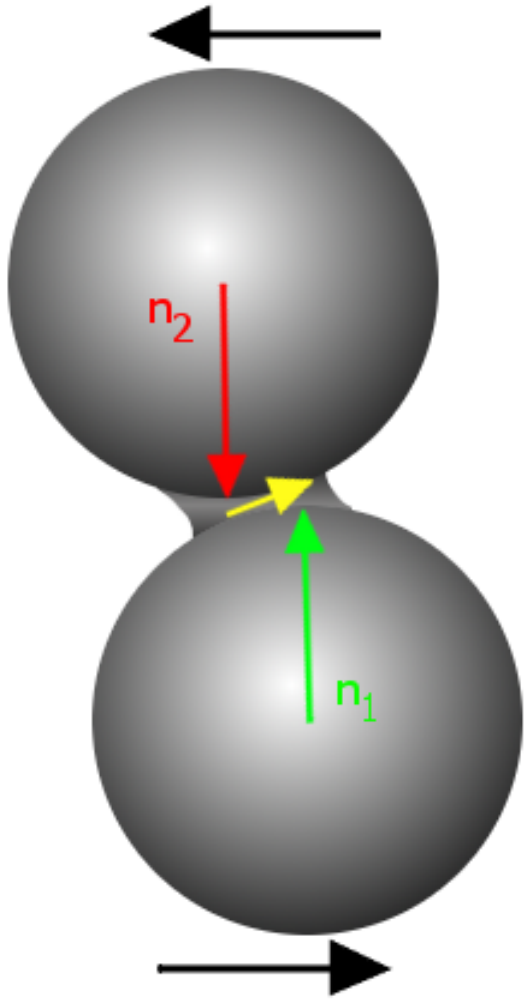
The sliding displacement is defined

$$\vec{\zeta} := r\left(\vec{n}_1 - \vec{n}_2 - \langle \vec{n}_1 - \vec{n}_2, \vec{n}_c \rangle \cdot \vec{n}_c\right)$$

Again, the sliding potential is given by

$$U_s = \frac{1}{2} k_s \|\vec{\zeta}\|^2$$

The result is both a force and a torque counteracting the sliding motion.



Twisting

Twisting describes the rotation of particles around the axis normal to the contact area.

$$\vec{\Phi} := \vec{n}_c \int_{t_0}^{t} (\vec{\omega}_i - \vec{\omega}_j) \cdot \vec{n}_c \, dt$$

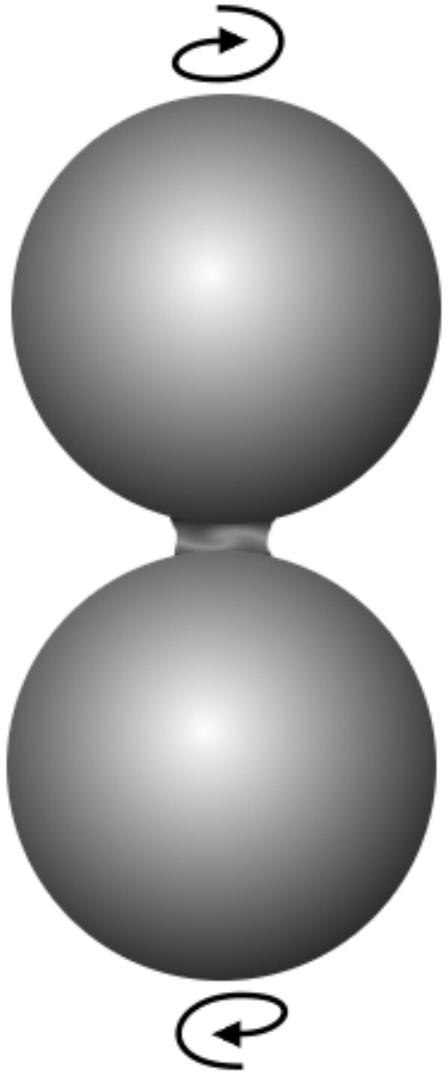
From the twisting potential

$$U_t := \frac{1}{2} k_t \|\vec{\Phi}\|^2$$

we derive the torques caused by twisting

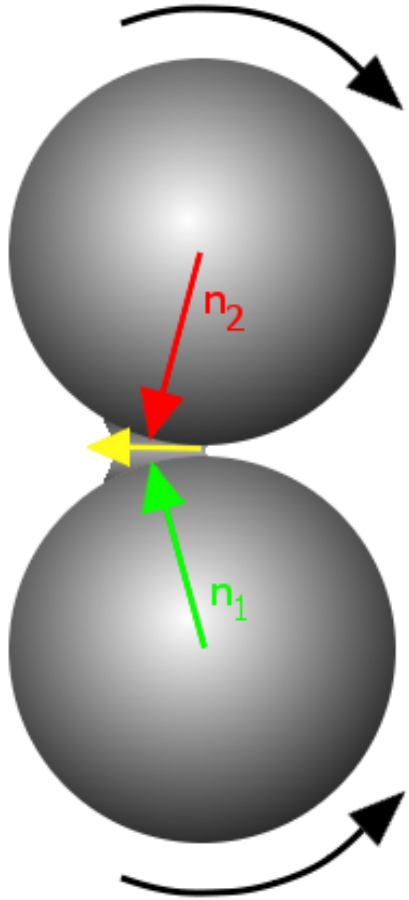
$$\vec{M}_{i,t} = -k_t \vec{\Phi}$$

$$\vec{M}_{j,t} = k_t \vec{\Phi}$$



Inelastic Movement I

- We use *contact pointers* (Dominik & Nübold, 2002) to track the time evolution of the contact area
- If certain limits are exceeded, the particle motion enters the inelastic regime
- This is reflected by modifications of the contact pointers
- The change of the potential energy due to these modifications can be tracked



Inelastic Movement II

Elastic motion only for small displacements.
If displacement exceeds a critical value

$$\|\xi\| > \xi_{crit}$$

modify contact pointers

$$\vec{n}_i \longrightarrow \vec{n}_i^c$$
$$\vec{n}_j \longrightarrow \vec{n}_j^c$$

in such a way that

$$\|\xi^c\| = \xi_{crit}$$

Energy dissipation due to this modification can be written as

$$\Delta E = k_r \xi_{crit}(\xi - \xi_{crit})$$

Particle Wall Interaction

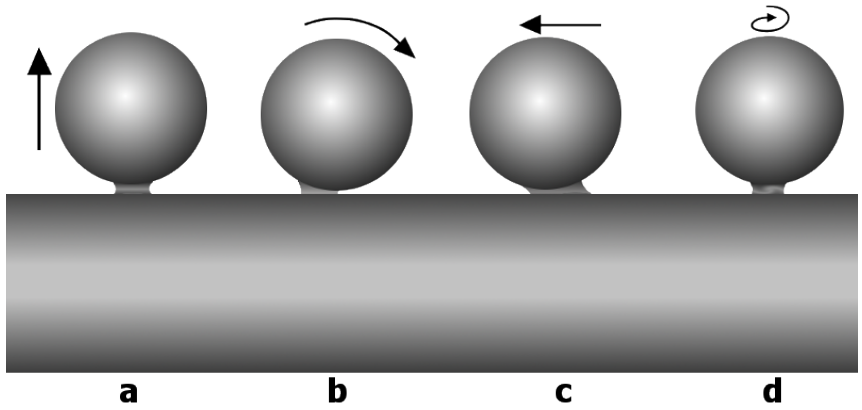
- Boundary conditions have been implemented via walls, that restrict the motion of the particles.

- Forces exerted on a wall by the particles are ignored ($\Rightarrow$ *fixed wall*)

Particle-Wall Interaction:

$\Rightarrow$ derive forces/torques in the limit of $r_1 = r_{\text{particle}}, r_2 \to \infty$

$\Rightarrow$ elastic and inelastic interaction has been implemented



Overview

- The positions and velocities of the monomers have to be followed
- The rotation angle and rotational velocity have to be followed
- The orientation of the rotation axis has to be followed
- The number of contacts have to followed
- Check for exceeding critical amplitudes (normal, rolling, twisting)

The equations of motions are integrated using a second order (symplectic) method.
This Velocity-Verlet or Leapfrog scheme requires one force evaluation per time step
It can be written as a predictor-corrector scheme.

Evolution of the contact pointers

The 3D vector $\vec{n} = (n_x, n_y, n_z)$ can be rotated using the 3 Euler angles. These are not useful due to possible singularities.
In numerical simulatins it is better to use the so called Euler parameter $e_0, \vec{e}$. Given a rotation of an angle φ around an axis $\vec{u}$ with $\|\vec{u}\| = 1$ we define

$$e_0 = \cos\left(\frac{\varphi}{2}\right) \quad , \tag{2}$$

$$\vec{e} = \hat{u} \sin\left(\frac{\varphi}{2}\right) \tag{3}$$

These parameters satisfy

$$e_0^2 + e_1^2 + e_2^2 + e_3^2 = 1 \quad . \tag{4}$$

Evolution of the contact pointers

The motion of a contact pointer is then described by

$$\vec{n}(t) = A(t)\vec{n}_i \tag{5}$$

where the matrix A is calculated from (Goldstein, 1950)

$$A = \begin{pmatrix} e_0^2 + e_1^2 - \frac{1}{2} & e_1e_2 - e_3e_0 & e_1e_3 + e_2e_0 \\ e_1e_2 + e_3e_0 & e_0^2 + e_2^2 - \frac{1}{2} & e_2e_3 - e_1e_0 \\ e_1e_3 - e_2e_0 & e_2e_3 + e_1e_0 & e_0^2 + e_3^2 - \frac{1}{2} \end{pmatrix} \tag{6}$$

and the equations of motion are

$$\dot{e_0}(\vec{\omega}, \vec{e}) = -\frac{1}{2}\,\vec{e} \cdot \vec{\omega} \tag{7}$$

$$\dot{\vec{e}}(\vec{\omega}, \vec{e}) = \frac{1}{2}\,(e_0\,\vec{\omega} - \vec{e} \times \vec{\omega}) \tag{8}$$

(see Dominik & Nübold, 2002 or Wada ea. 2007)

Overview

We must solve the following equations for each particle i:

$$\ddot{\vec{x}}_i = \frac{\vec{F}_i}{m} \qquad \dot{e}_{0,i} = -\frac{1}{2}\vec{\omega}_i \cdot \vec{e}_i$$

$$\dot{\vec{\omega}}_i = \frac{\vec{M}_i}{I} \qquad \dot{\vec{e}}_i = \frac{1}{2}\left(e_{0,i}\vec{\omega}_i - \vec{e}_i \times \vec{\omega}_i\right)$$

for the dynamics

for each contact

where $(e_0, \vec{e})$ denotes the quaternion used to represent the rotation of the particle

Prediction

In the prediction step the new positions $\vec{x}^{n+1}$ and the new rotational states e^{n+1} of the particles are calculated based on the current velocity, forces and torques.

$$\vec{x}_i^{n+1} = \vec{x}_i^n + \Delta t\ \vec{v}_i^n + \frac{\Delta t^2}{2m}\ \vec{F}_i^n$$

$$e^{n+1} = e^n + \Delta t \dot{e}^n + \frac{\Delta t^2}{2} \ddot{e}^n$$

with $e = (e_0, \vec{e})$.

Evaluation

At first, the new positions $\vec{x}^{n+1}$ are used to check for newly established or broken contacts. If contacts have changed, keep track of the energy dissipated by discontinuities in the various potentials.

Afterwards we go through the list of contacts to calculate the new forces and torques.

$$\vec{F}_i^{n+1} = \sum_j \vec{F}_{ij}(\vec{x}^{n+1}, e^{n+1})$$

$$\vec{M}_i^{n+1} = \sum_j \vec{M}_{ij}(\vec{x}^{n+1}, e^{n+1})$$

Correction

Finally both the velocity v and angular velocity ω are updated using the old and new forces/torques.

$$\vec{v}_i^{n+1} = \vec{v}_i^n + \frac{\Delta t}{2m}\left(\vec{F}_i^n + \vec{F}_i^{n+1}\right)$$

$$\vec{\omega}_i^{n+1} = \vec{\omega}_i^n + \frac{\Delta t}{2I}\left(\vec{M}_i^n + \vec{M}_i^{n+1}\right)$$

Updating Particle Interactions

Updating the particle interaction is the most expensive part:

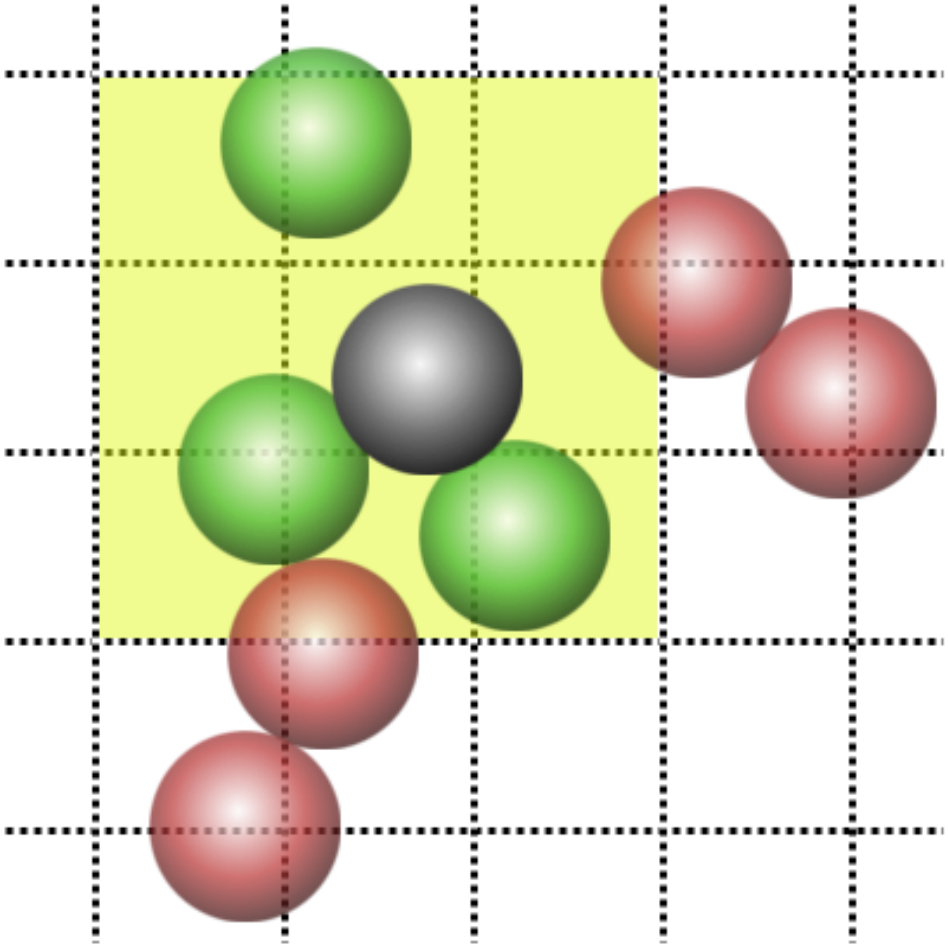
- Search for next neighbours
- Check for breaking or formation of contacts
- For each contact: Calculate current displacements and apply possible inelastic corrections
- For every particle: Calculate current force/torque

Difficult to implement on GPUs due to irregular memory access patterns and possible data hazards.

Next Neighbour Search

Spatial Subdivision:
Search for next neighbours in
$O\left(N \log(N)\right)$

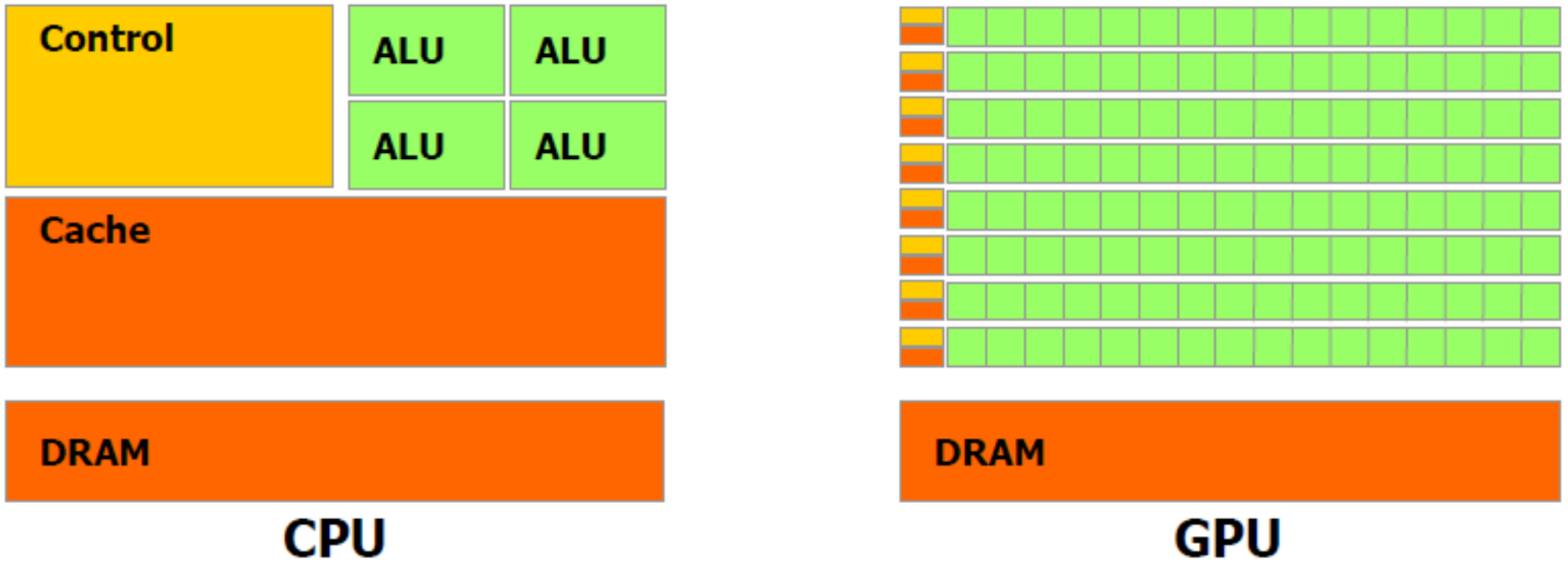
GPU Version:
Efficient implementation
described by Green (2008)



Challenges

- Normal vibrations (steep JKR-potential) severely limit timestep Δt, for $1.2\mu m$ SiO_2 particles $\Delta t \approx 0.2 - 0.4\mathrm{ns}$
- Due to the short timesteps the range of values is high $\Rightarrow$ double-precision floating point arithmetics are mandatory
- Discontinuities in forces when contacts are made or breaking up

GPU Computing



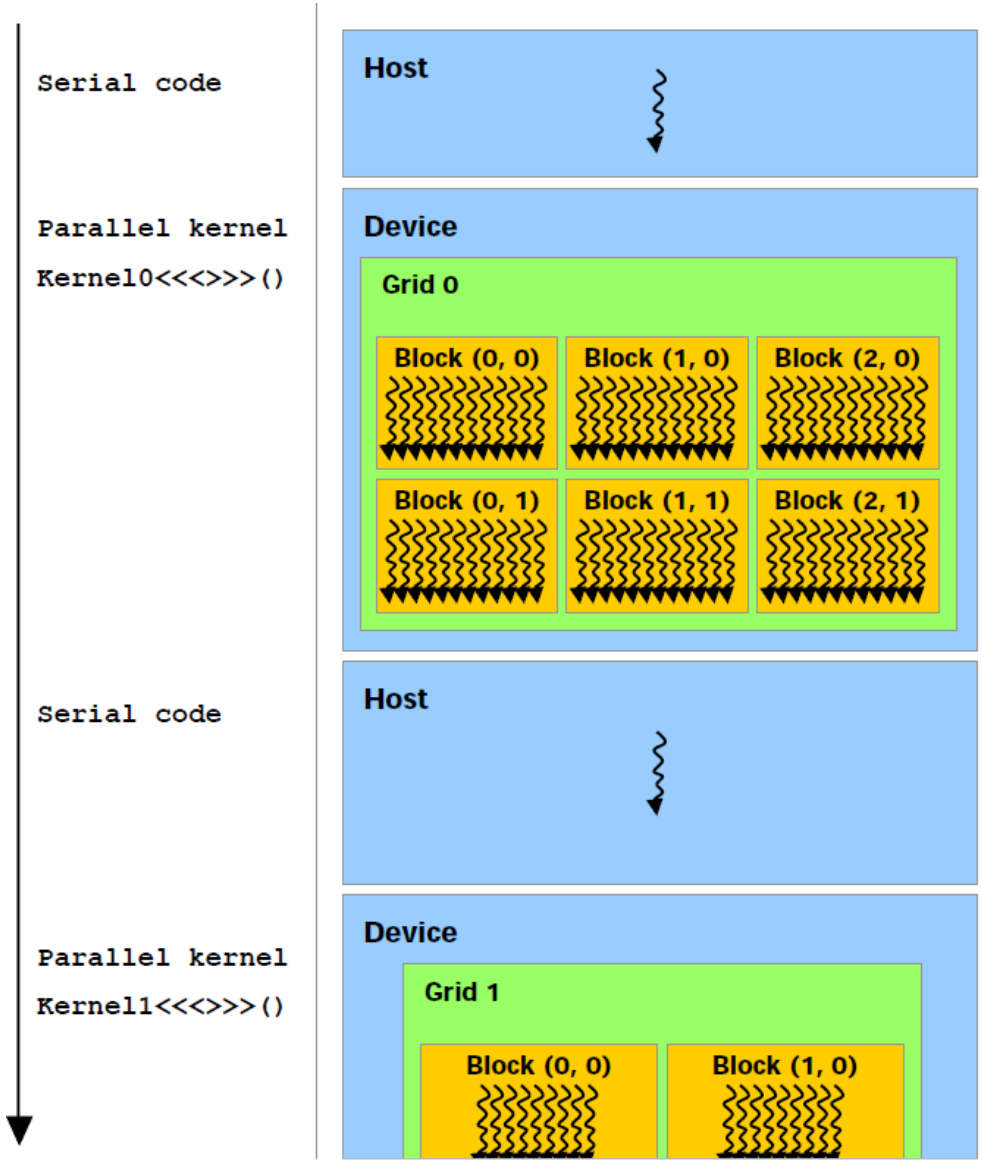
Main differences between CPU and GPU (taken from NVIDIA CUDA programming guide 2.2.1)

ALU: Arithmetic and Logical Unit

CUDA

Compute Unified Device Architecture:

- Parallel computing architecture developed by NVIDIA
- SIMD (single instruction - multiple data)
- Code targeting the GPU is written in a C-like language (CUDA C) and later linked with the serial code running on the CPU



Alternative Theory

JKR:

(Johnson, Kendall and Roberts)

- Short-range surface forces within contact area
- $F_c = 3\pi\gamma R$
- $\delta_c > 0 \Rightarrow$ Adhesive necks
- Suitable to model larger, soft grains

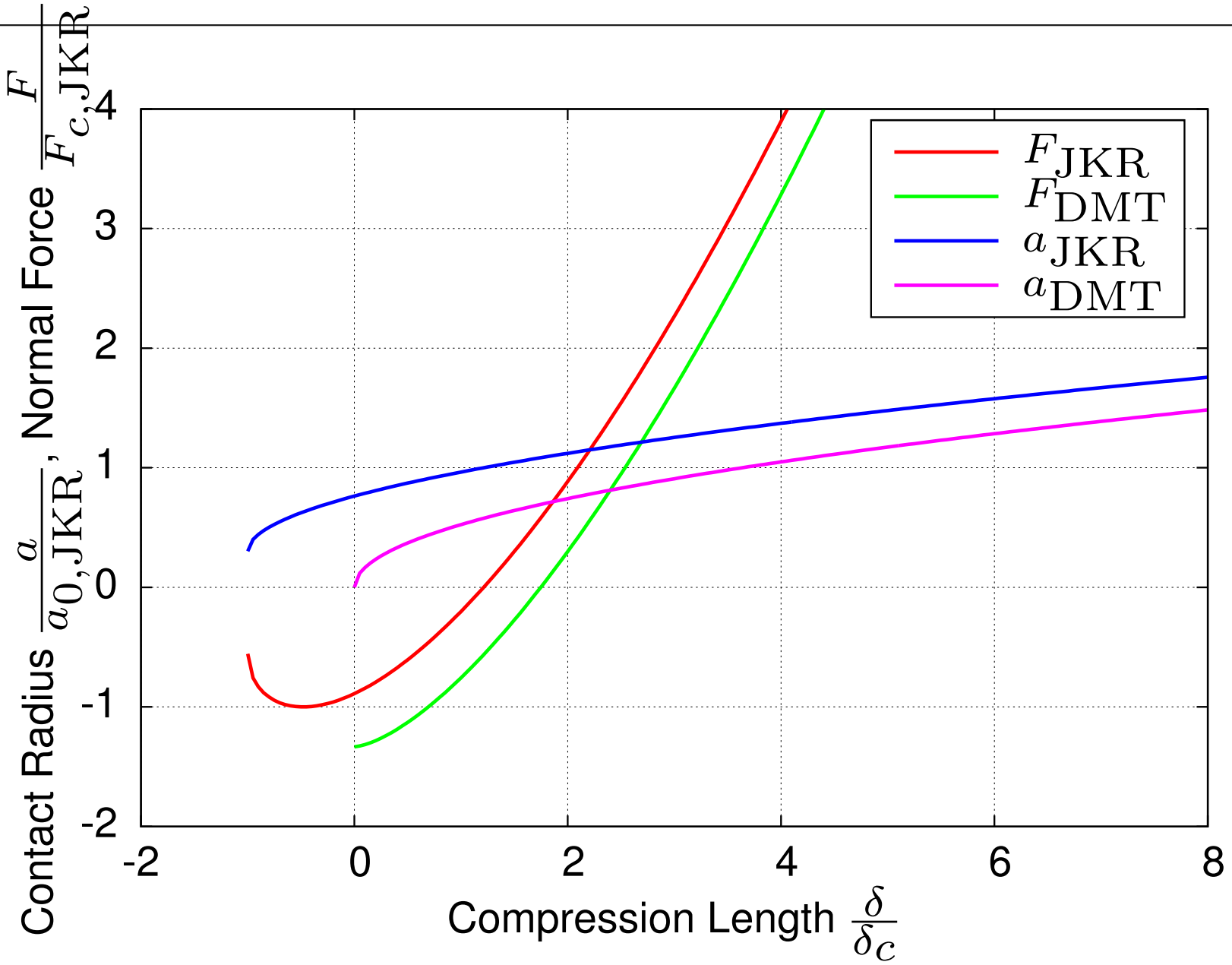
DMT:

(Derjaguin, Muller and Toporov)

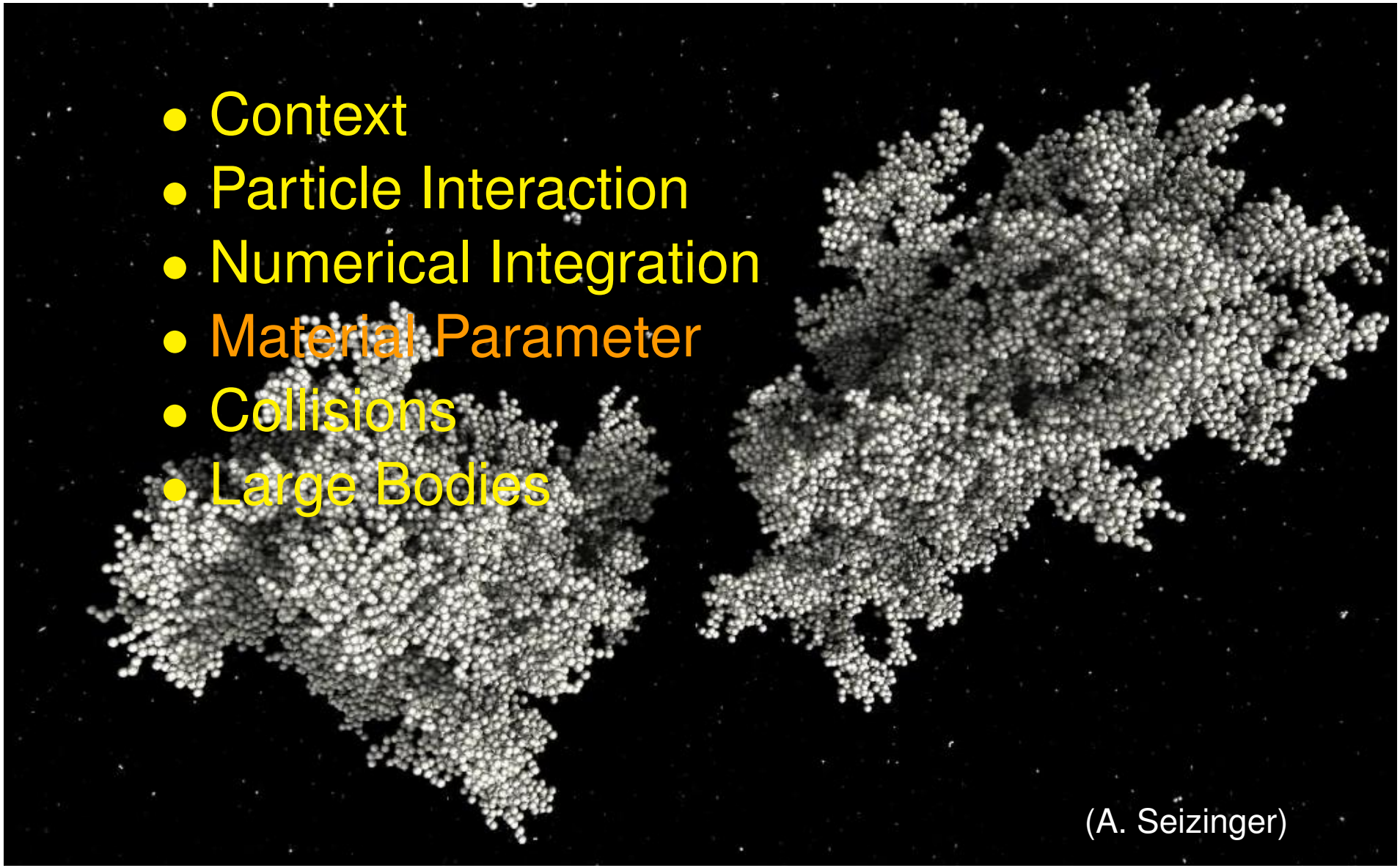
- Long-range surface forces outside contact area
- $F_c = 4\pi\gamma R$
- $\delta_c = 0 \Rightarrow$ No necks
- Suitable to model small, hard grains

JKR and DMT model are limits of a single theory (Tabor, 1977)

JKR vs. DMT

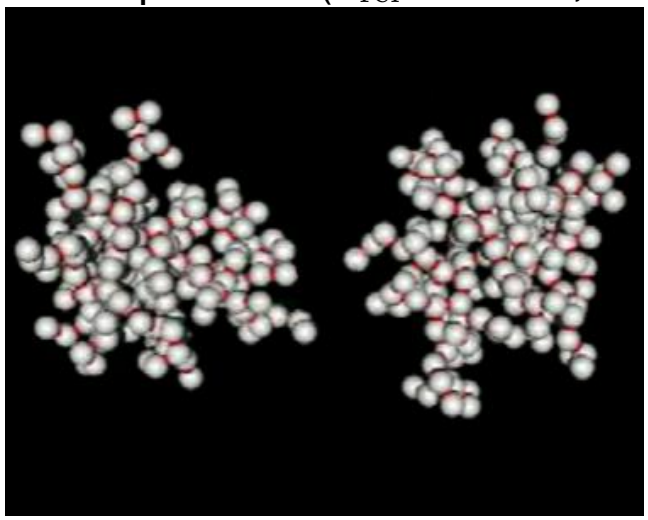

$\frac{F}{F_{c,\mathrm{JKR}}}$, Normal Force
$\frac{a}{a_{0,\mathrm{JKR}}}$ Contact Radius
Compression Length $\frac{\delta}{\delta_c}$
F_{JKR}
F_{DMT}
a_{JKR}
a_{DMT}
-2
-1
0
1
2
3
4
-2
0
2
4
6
8

Organisation

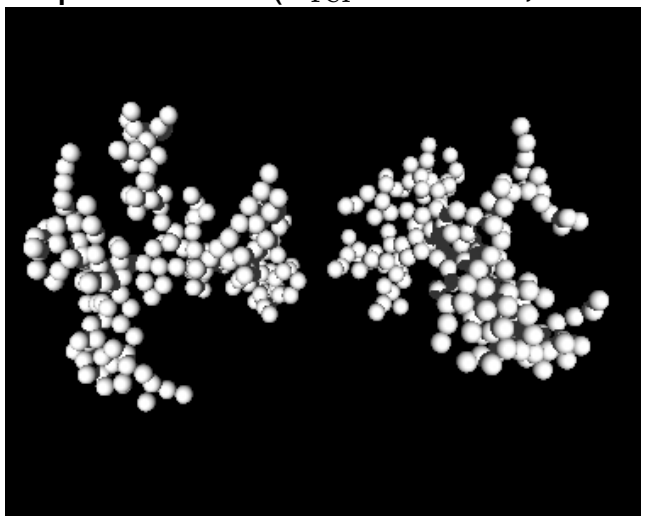


Sample Simulations

Silicia spheres ($v_{\rm rel} = 2$m/s, $N = 200$)

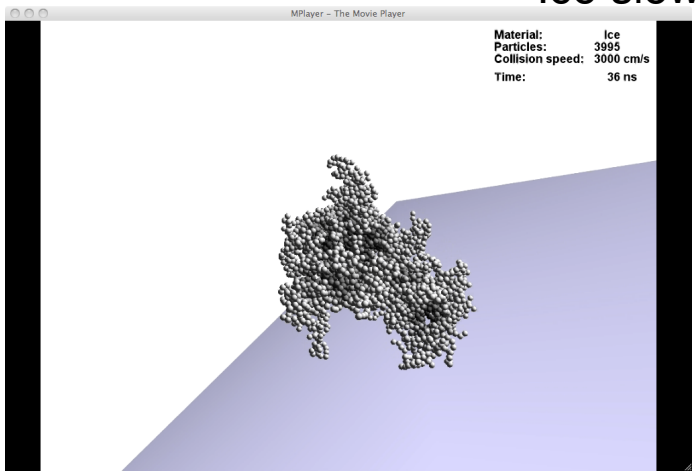


Ice particles ($v_{\rm rel} = 8$m/s, $N = 200$)

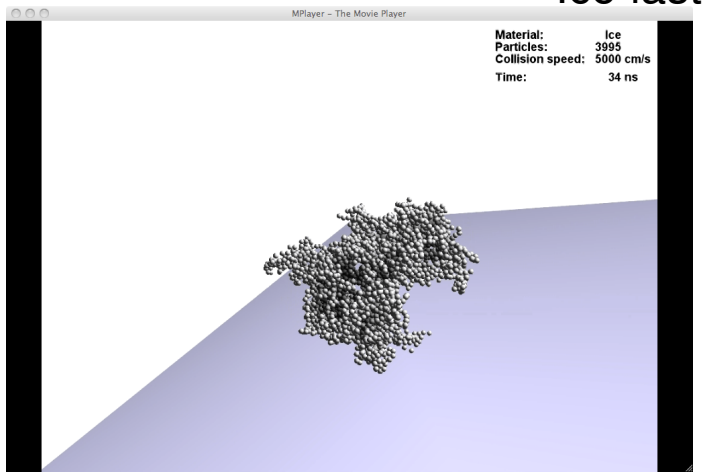


(D. Paszun, 2008)

Ice slow



Ice fast

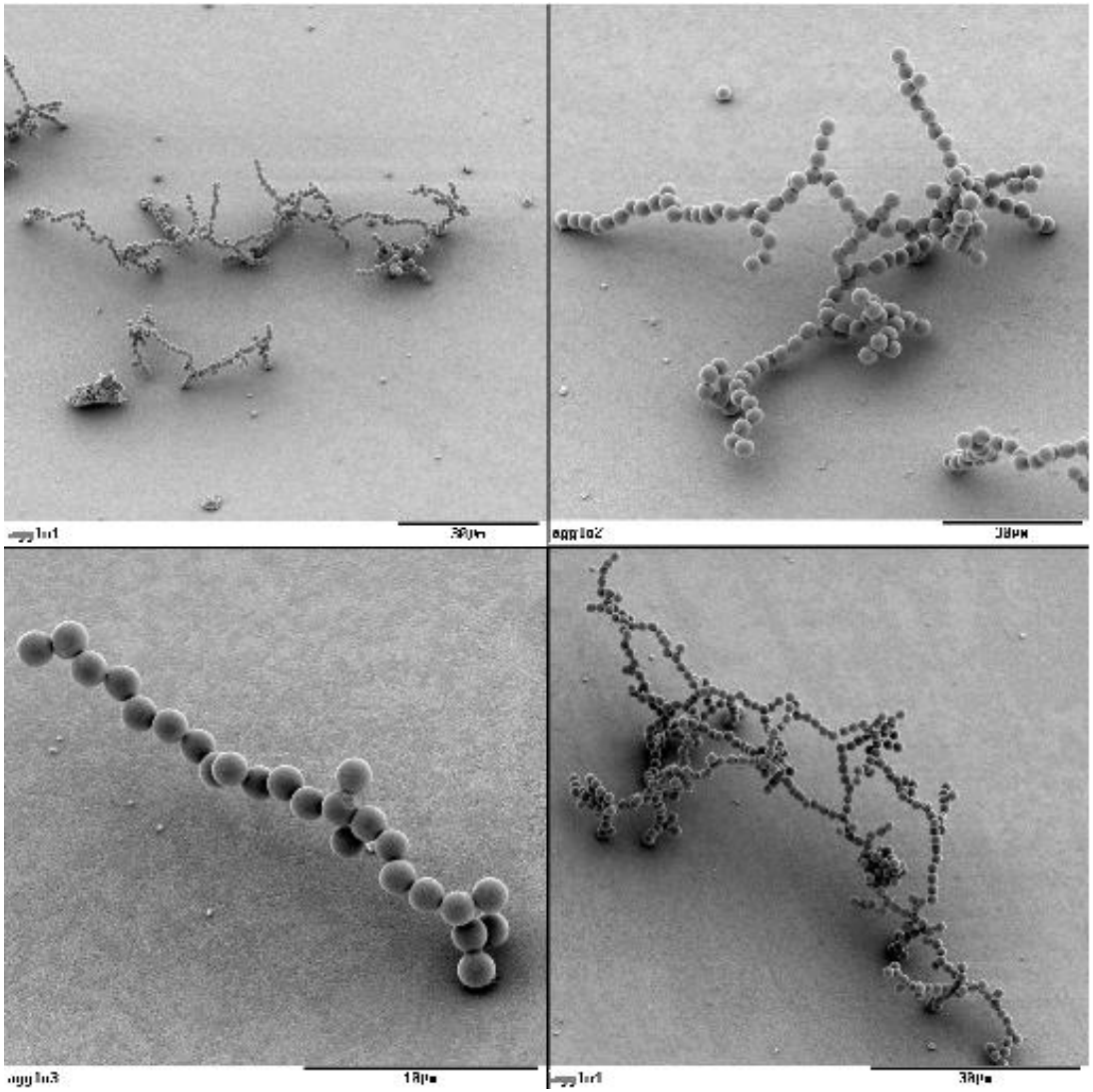


(Alex Seizinger, Tübingen, 2010)

Material properties play very important role: - Calibration with experiments required

Experimental Dust Growth

Laboratory-Experiments: μm-sized particles



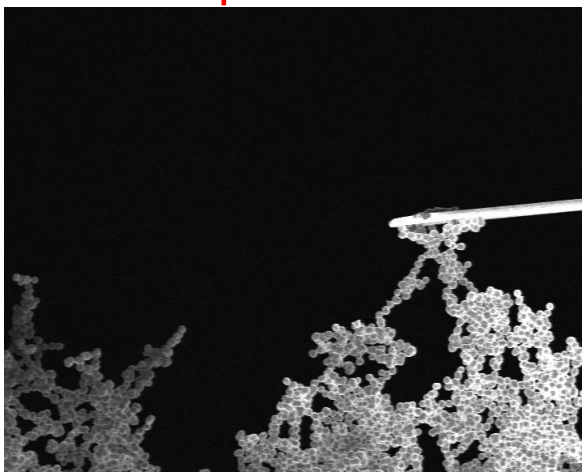
(J. Blum, Braunschweig)

in Vacuum, zero gravity
- in lab
- fall Tower (Bremen)
- parabolic flights
- space station

initial Fractal Growth

works up to cm-sizes

Measure pull off force



Some Definitions

- Filling factor ϕ:
  Mean density ρ of the aggregate devided by the matrix density (of each monomer), $\phi = \rho/\rho_{\mathrm{matrix}}$

- Porosity Φ:
  The complement of the filling factor, $\Phi = 1 - \phi$

- Coordination number n_c:
  Mean number of contacts each monomer has

Expectation: The material properties scale with the porosity

Quasi-static Compression I

Dustcake between two Plates $\Rightarrow$ Move them slowly towards each other
measure force/pressure (here: Simulation by Dominik Paszun, Amsterdam)

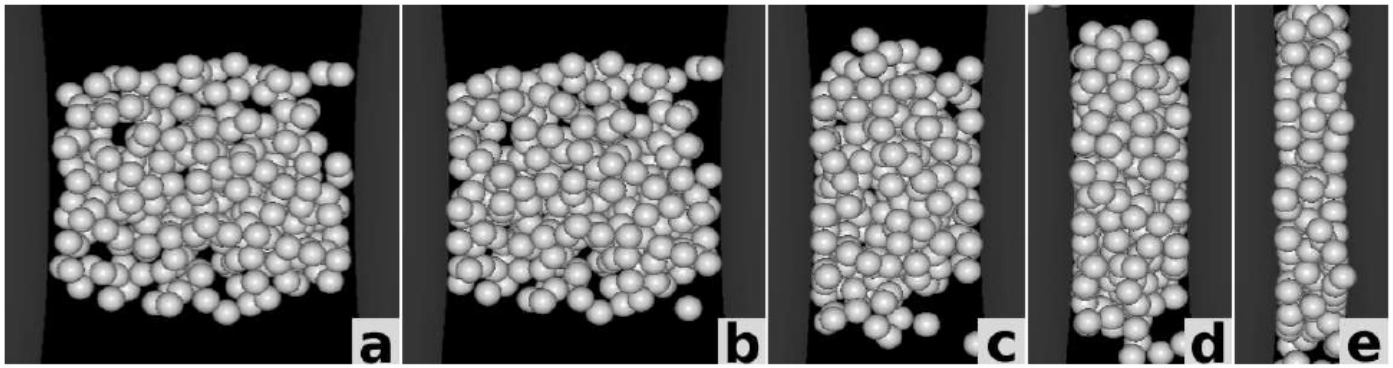
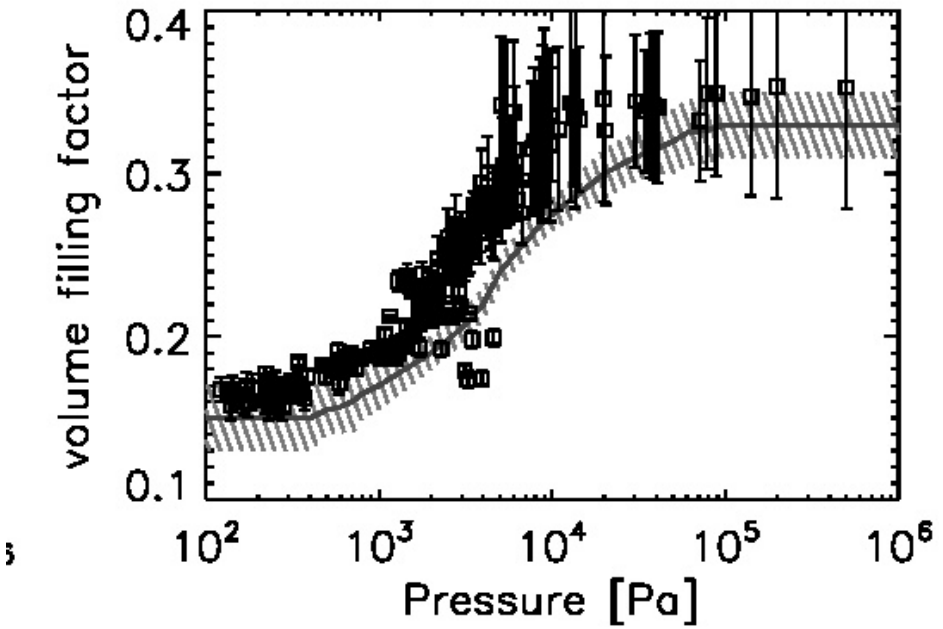


Fig. 3. The setup of the experiment. The dust cake in the center is compressed with different pressure. Initial arrangement (a), results of compression at $2 \cdot 10^2$ Pa (b),$2 \cdot 10^3$ Pa (c), $5 \cdot 10^3$ Pa (d), $1 \cdot 10^4$ Pa (e).

Experiments in Braunschweig,
Simulations Amsterdam/Tübingen

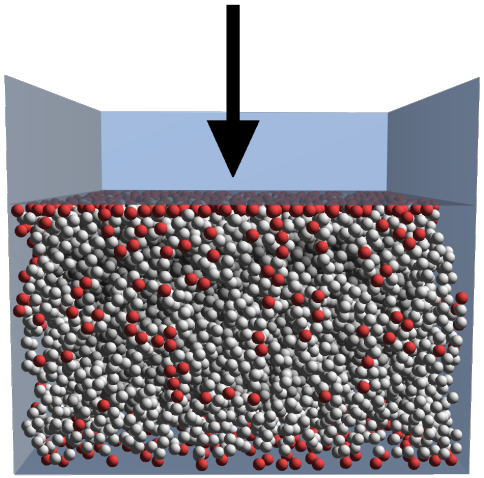
- initial filling factor: $\phi_0 = 0.15$
- radius of sphere: 0.75μm
- Particle number: $N = 291$

Right:
Comparison with expt.
(Blum&Schräpler, 2004)
(Paszun&Dominik, 2008)

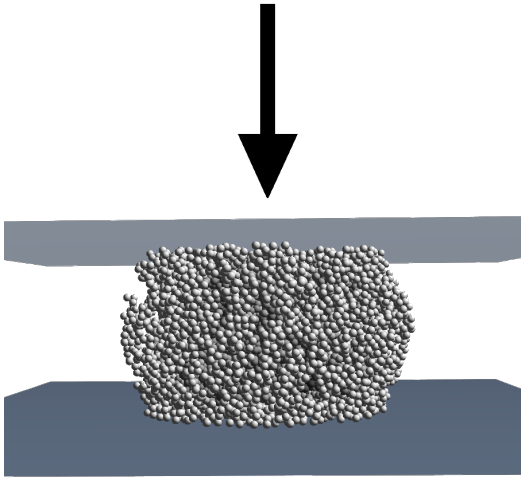


Quasi-static Compression II

a) Multi-directional compression

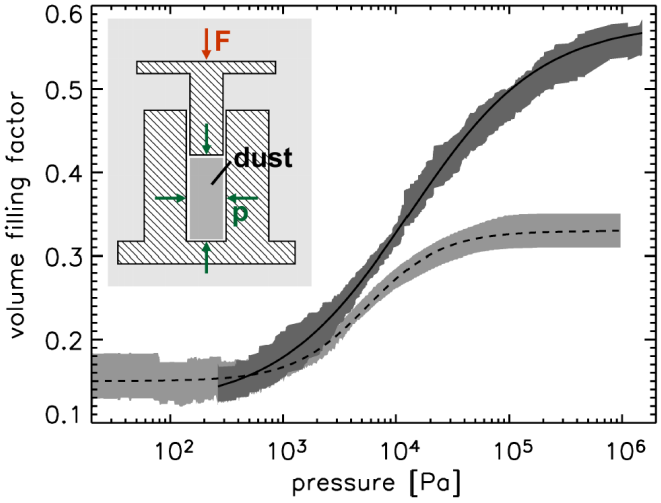


b) Uni-directional compression



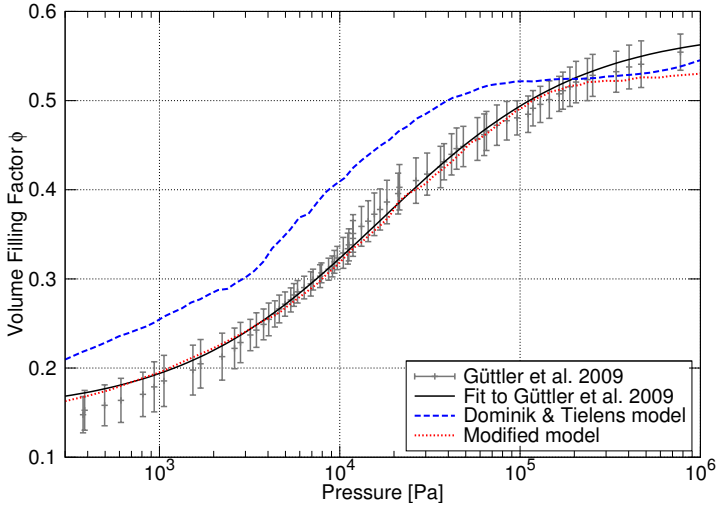
Experimental Setup & Results

(Güttler ea. 2009)



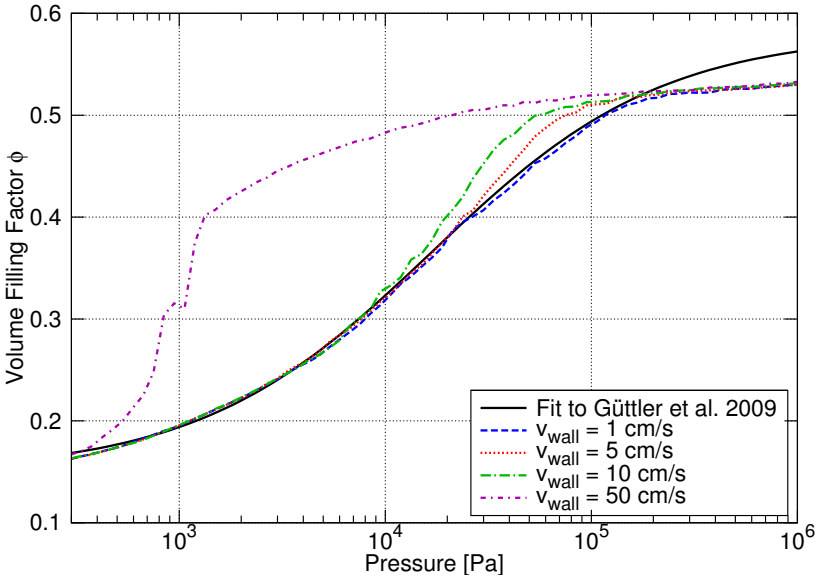
Numerical Results (case a)

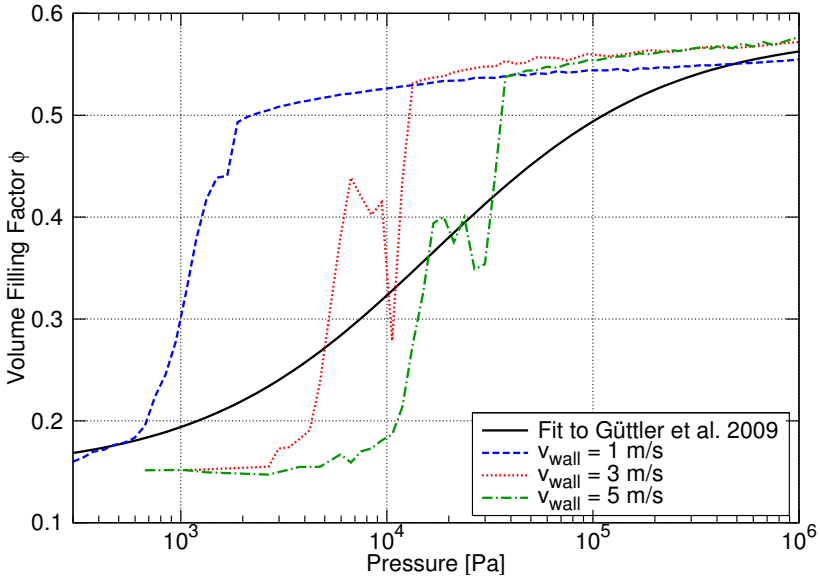
(Seizinger ea. 2012)



Dynamic Compression

Velocity Dependence

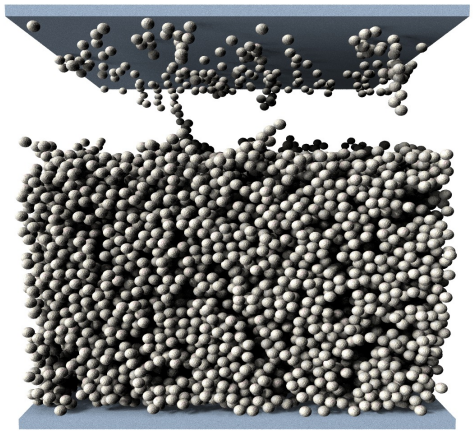




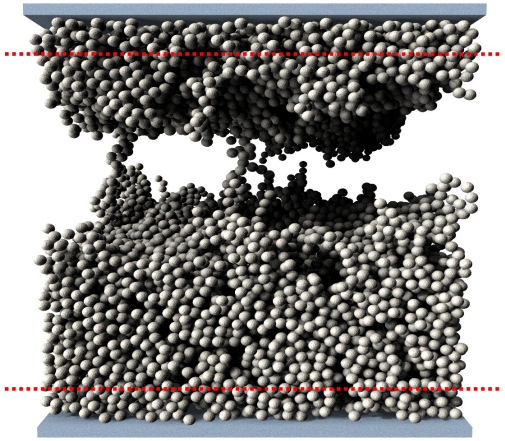
Tensile and Shear-strength

Setups for measuring tensile and shear strength as a function of the filling factor (Seizinger ea. 2013) (Difficult to measure experimentally)

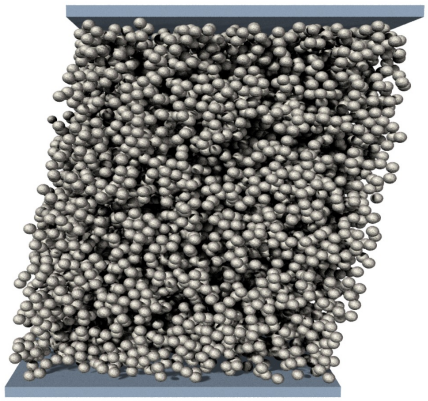
No wall glue



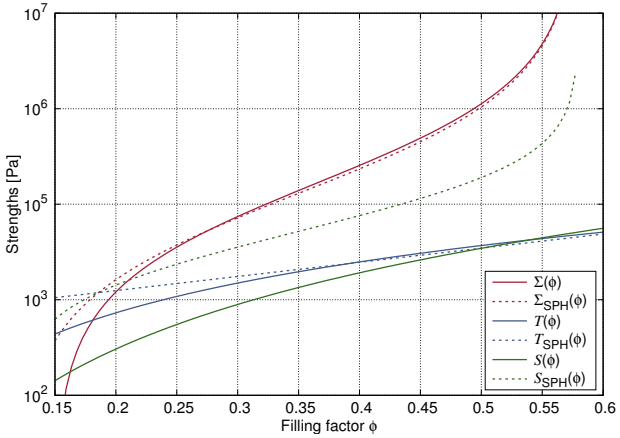
With wall glue



Measure shear strength



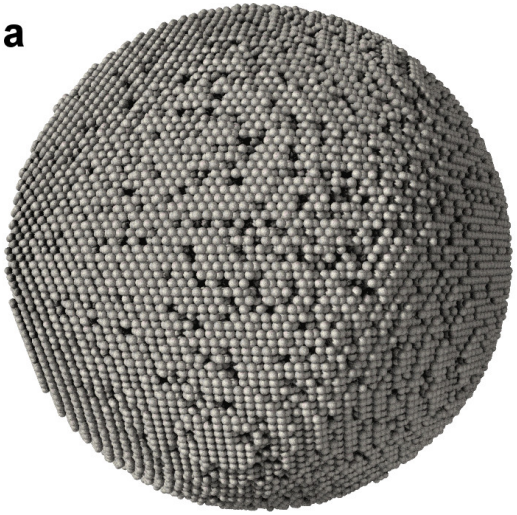
Comparison with SPH values



Sample Generation Methods I

Hexagonal Lattice

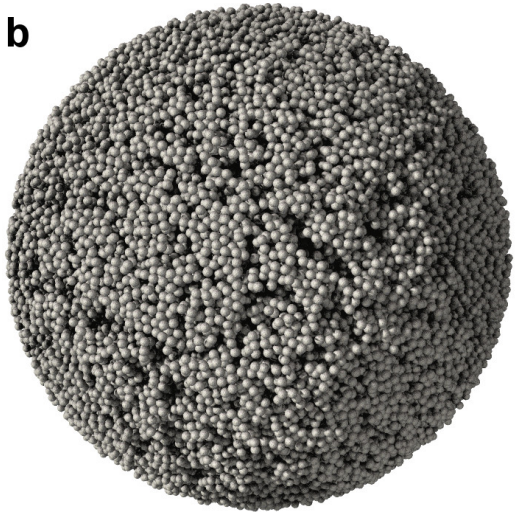
$\phi = 0.59,\ n_c = 9.93$



close packing with extraction (CPE)
Build hexagonal close packing
which has:
$\phi = 0.74,\ n_c = 12$
Then extract monomers until desired ϕ is reached

Ballistic Aggregation

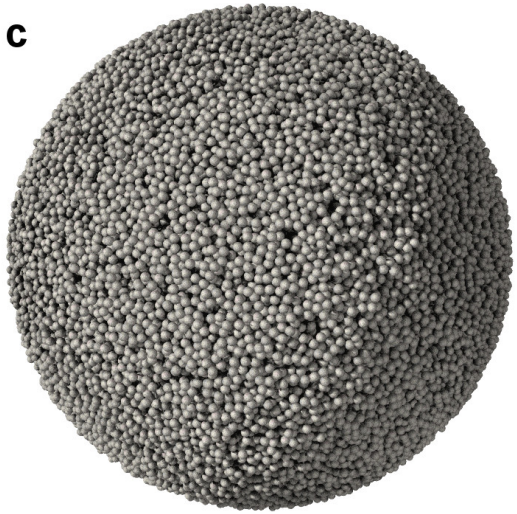
$\phi = 0.40,\ n_c = 3.98$



add particles from random direction
3 methods:
1) shortest migration
2) randon migration
3) center migration
Details:
Seizinger&Kley (2012)

Static Compaction

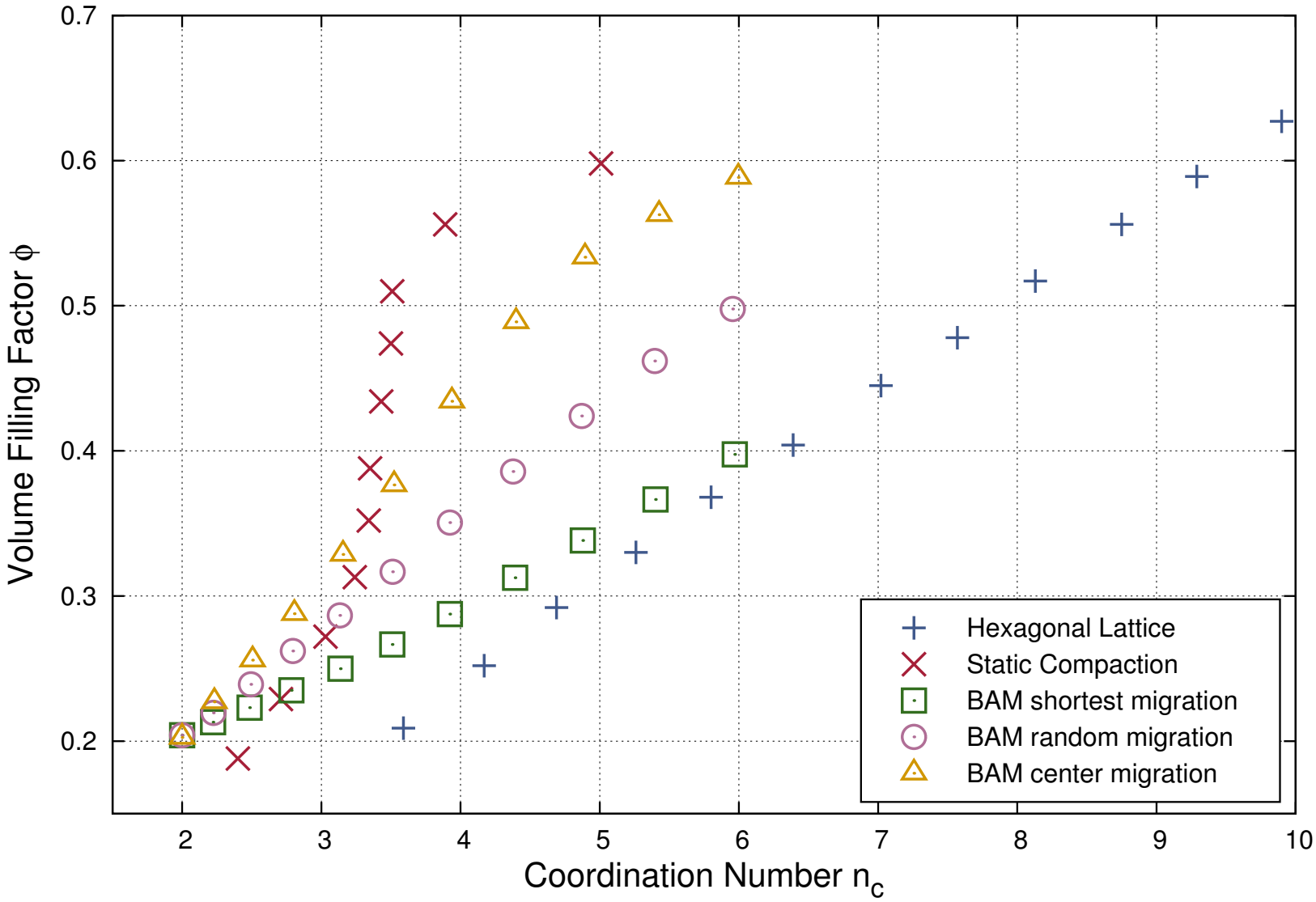
$\phi = 0.49,\ n_c = 3.50$



Use multi-directional compression
(as in calibration)
Until desired ϕ
Cut out spherical sample

Particle Generation Methods II

Relation between filling factor ϕ and the coordination number n_c



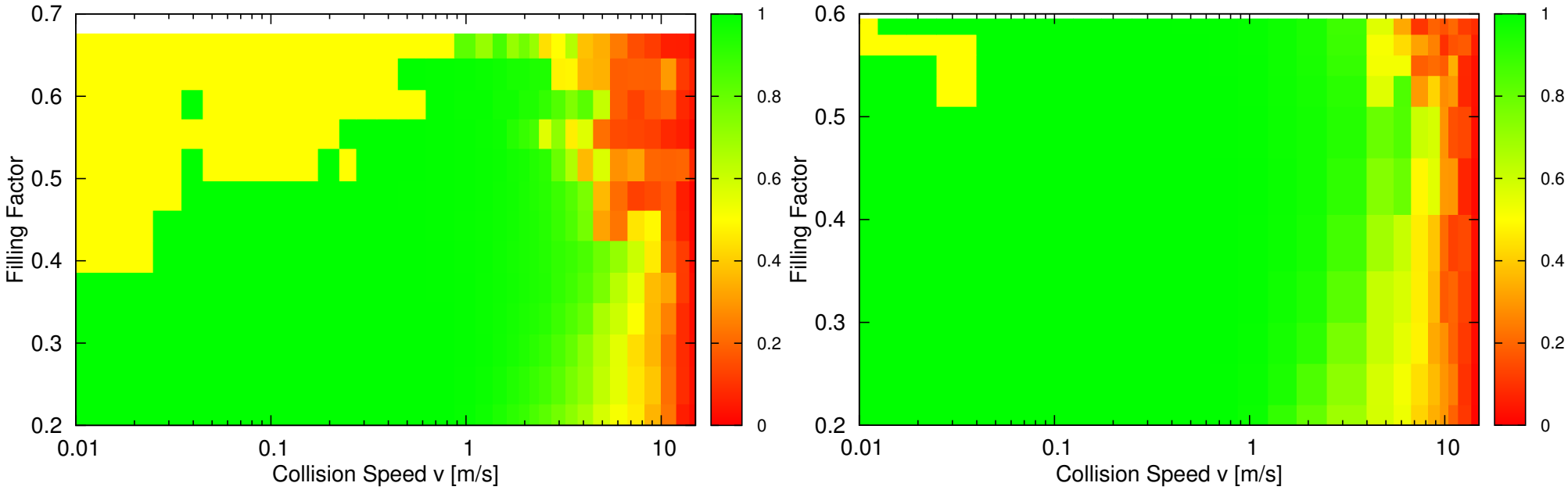
Bouncing Behaviour I

Collisions between particles with 60 μm diameter
Shown is the growthfactor

$$\gamma = \frac{m_{\mathrm{largest}}}{m_{\mathrm{tot}}} \tag{9}$$

CPE aggregate

BAM (center migration)

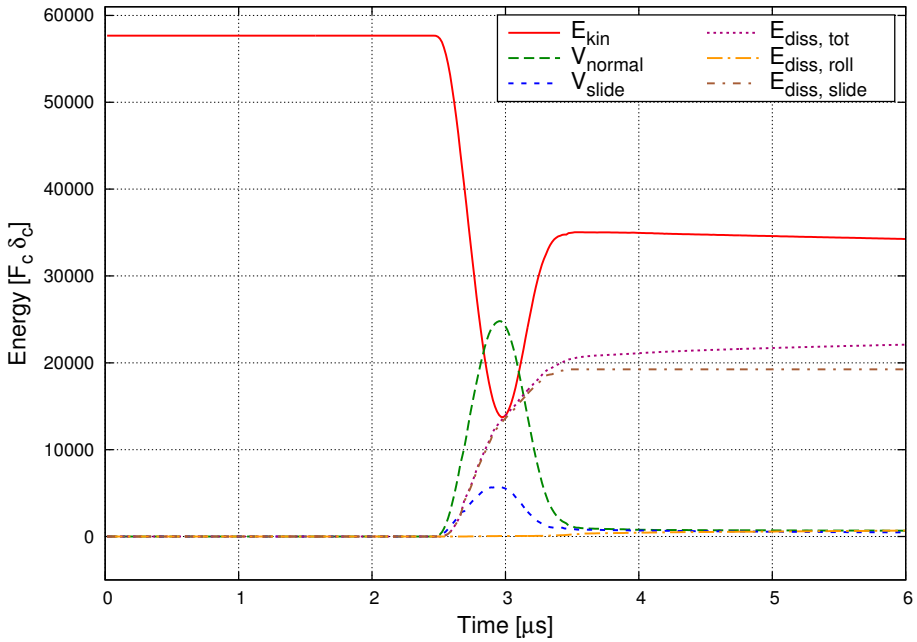


Green: Sticking
Yellow: Bouncing (or onset to fragmentation)
Red: Fragmentation (above $\approx$ 10 m/s)

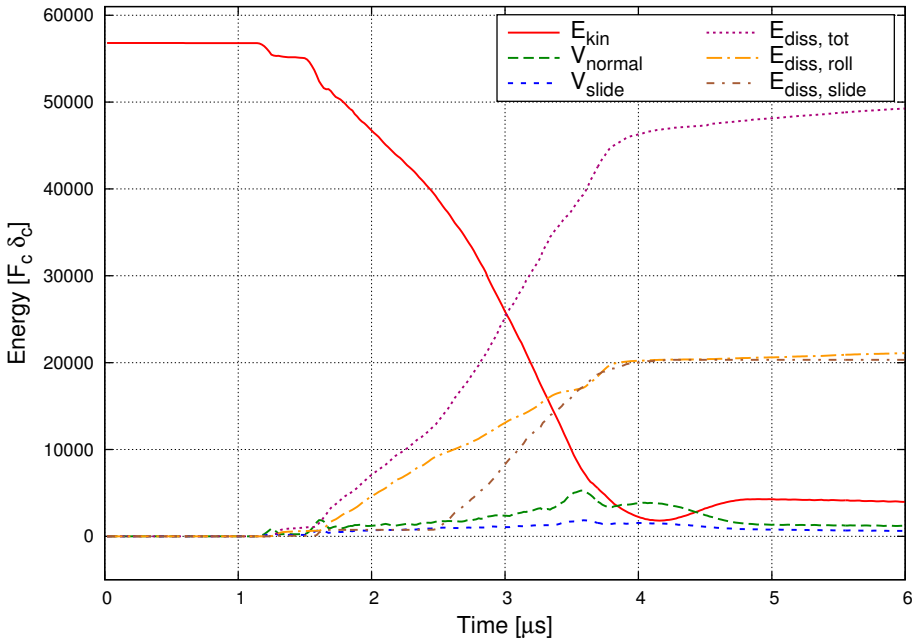
Bouncing Behaviour II

Monitor energies during the collisions (advantage of potential formulation)
use here two particles (CPE and BAM)
both with $d = 60\mu$m, and $\phi = 0.59$

CPE aggregate
(Bouncing)



BAM (center migration)
(Sticking)



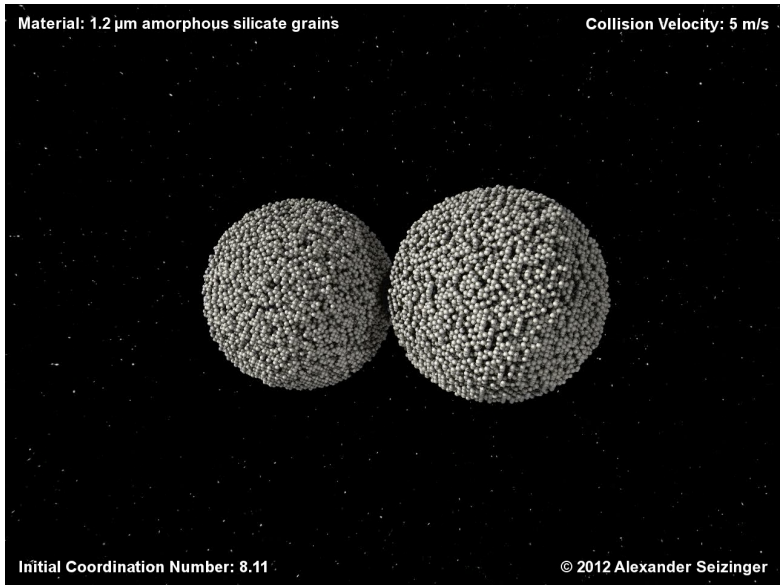
Sticking properties depend on preparation method, i.e. not only ϕ but also n_c
But: Experimentally n_c not known, only ϕ
Red: Fragmentation (above $\approx$ 10 m/s)

Bouncing/Fragmentation

Collide two CPE (Close Packing with Extraction) aggregates with coordination number $n_c = 8.11$ and filling factor $\phi = 0.52$ Two collision velocities

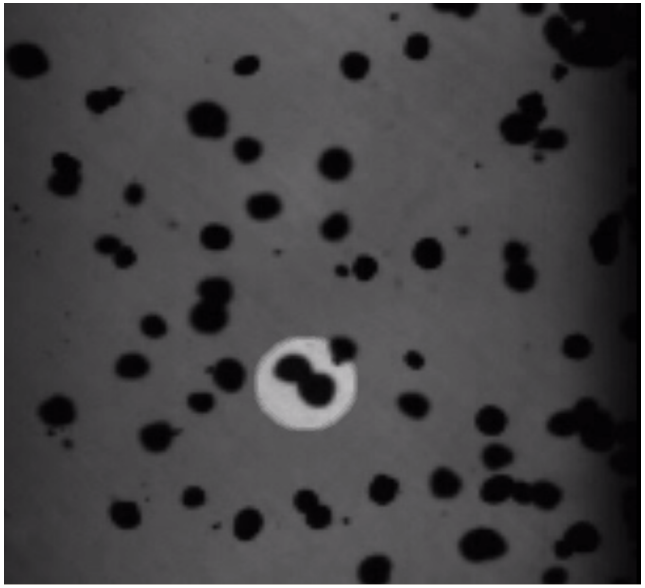
$v_{\rm rel} = 2$ m/s

$v_{\rm rel} = 5$ m/s

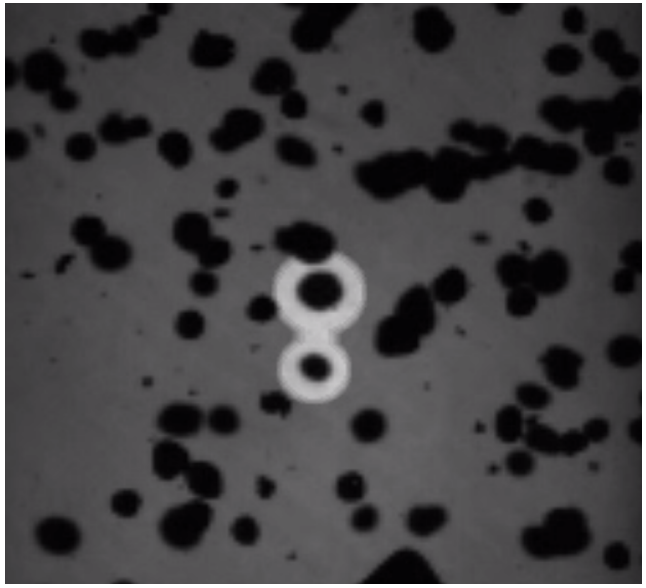


Expt.: Cluster-Cluster Collisions

Sticking



Bouncing



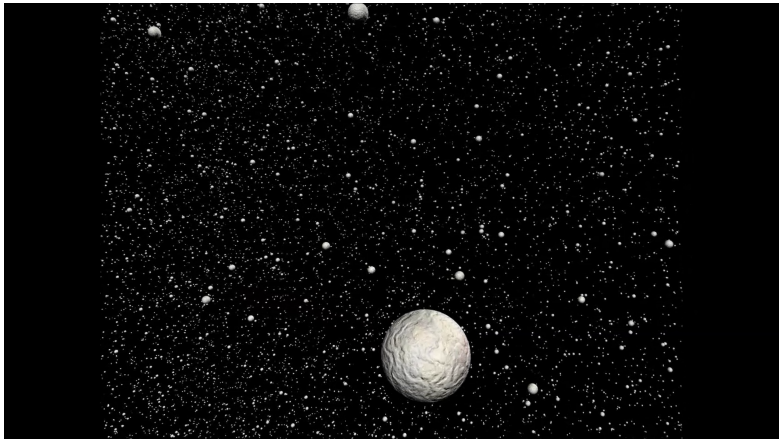
Material:	Silicate (mono- / polydispers)
Size:	$\approx \mathrm{mm} - \mathrm{cm}$
$v_{\mathrm{Kollision}}$	$\approx 0.1 - 100\,\mathrm{cm/s}$

in multiple collisions: Compactification $D_f \to 3$

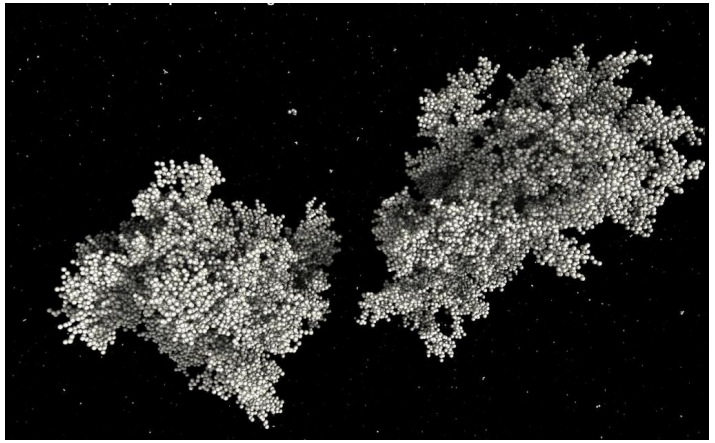
(S. Kothe, R. Weidling, D. Heißelmann & J. Blum, TU Braunschweig)

Numerical: Cluster-Cluster Collisions

Initial Growth Phase



Collision with different speeds



Animations by Alexander Seizinger (Tübingen)

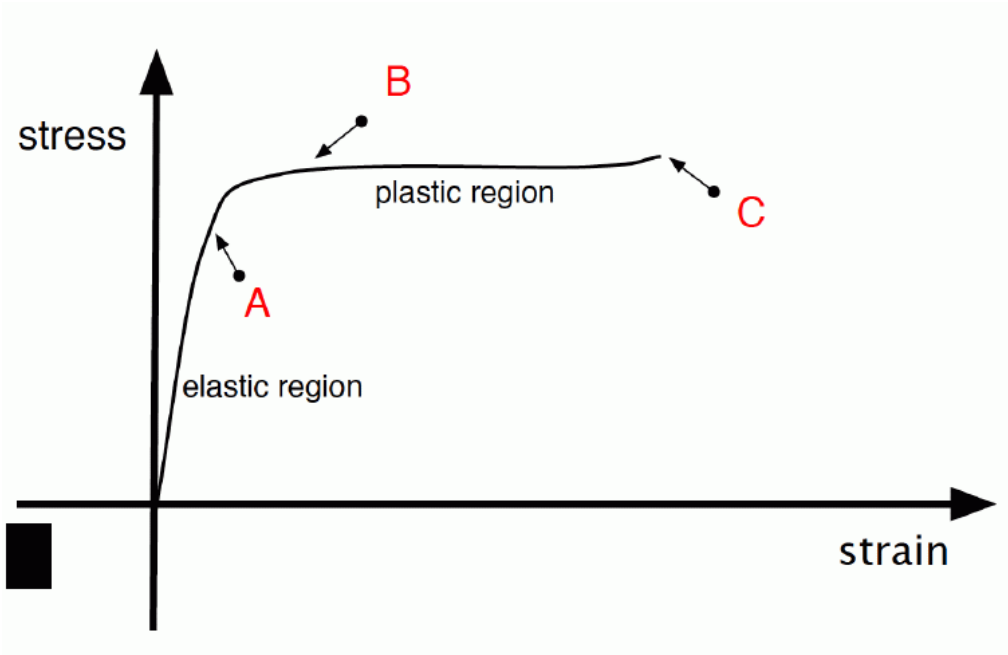
Continuum Approach

- For larger bodies the ab initio approach is not feasible
- Perform continuum simulations
- need again material parameter

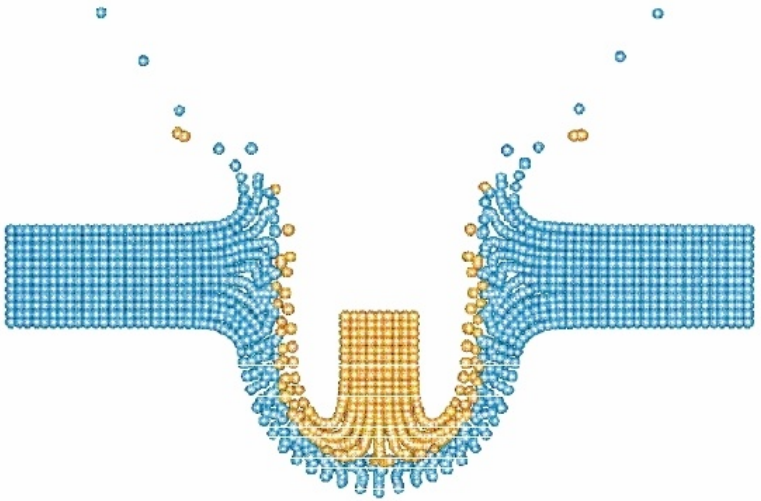
Contimuum Approach

For larger particles:
Our Method: SPH
(Smoothed-Particle-Hydrodynamics)
Hydrodynamical-Equations
augmented with:
Elasto-plastic Model (A-B)
Including:
Fractures (C)

Example: Impact into Al-Plate
(Rabczuk, 2002)



SPH Simulation:

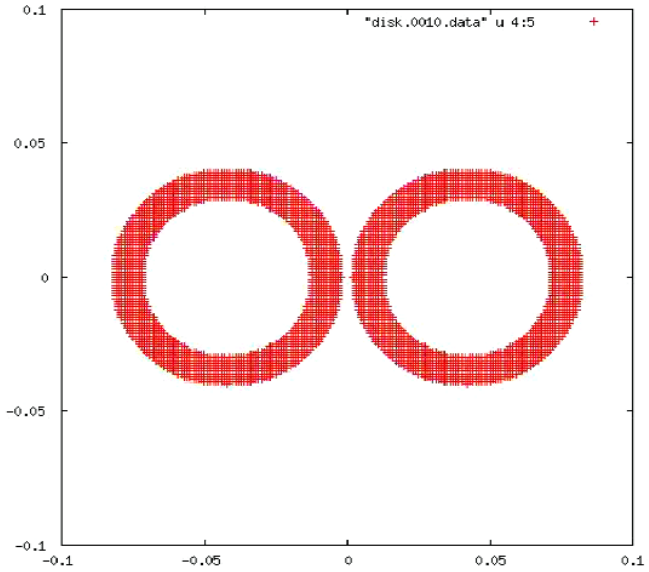


Finite Element Simulation:

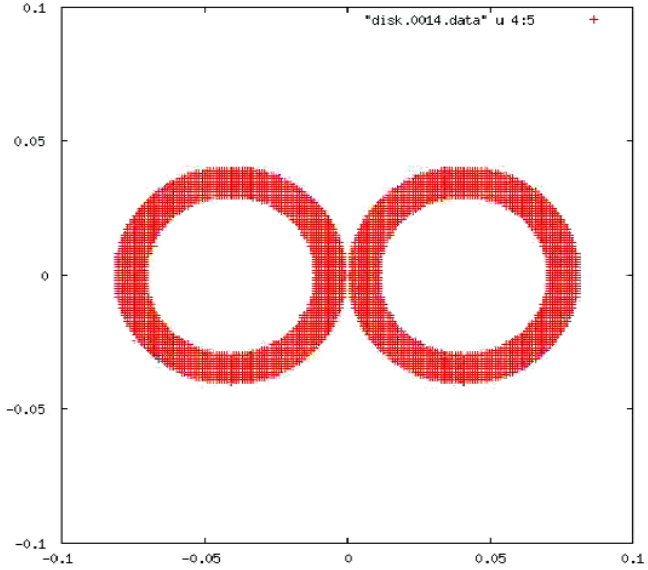
SPH-Testsimulations

Two colliding rubber rings

elastic Material



plastic Material

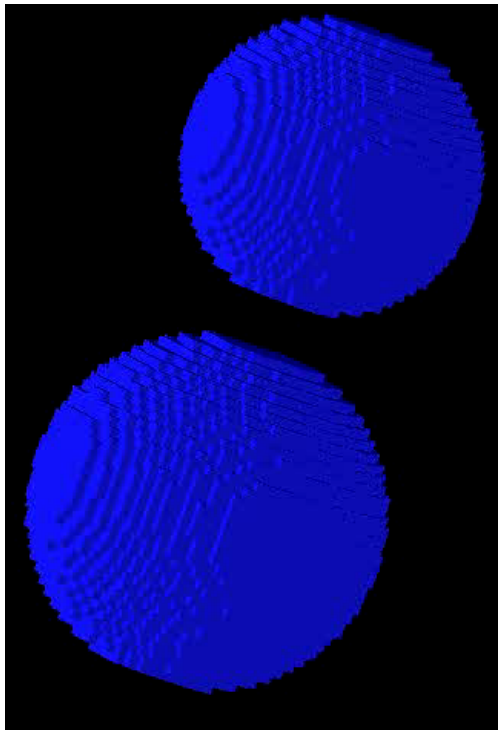


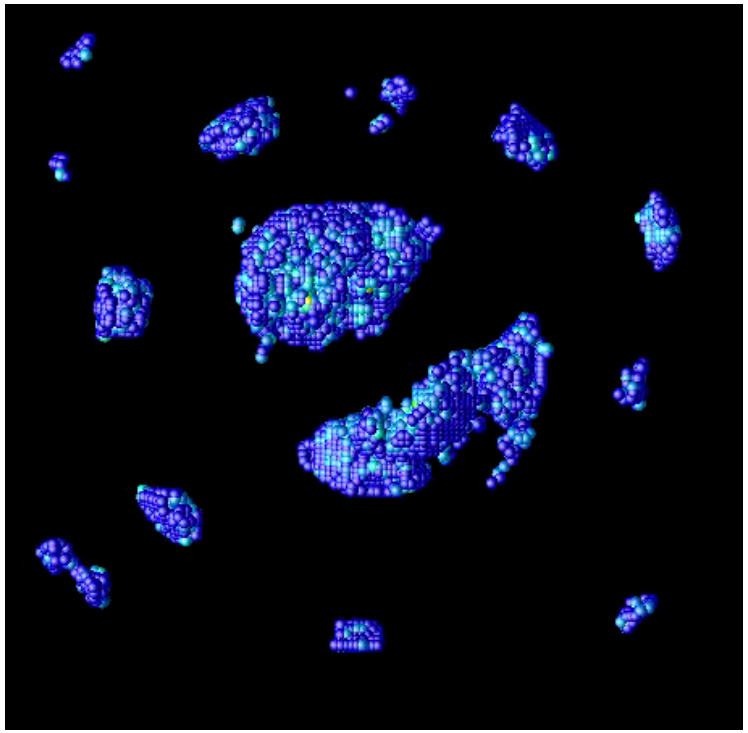
(Christoph Schäfer, Univ. Tübingen, 2005)

Particle Collisions: Stones

Investigate the growth of particles through Collisions/Accretion

2 Basalt spheres: ρ = 3g/cm^3, R_1=9m, R_2=7.5m, V_{rel}=25m/s , t_{max} = 4.5 sec





(Christoph Schäfer, PhD-Thesis, Univ. Tübingen 2005)

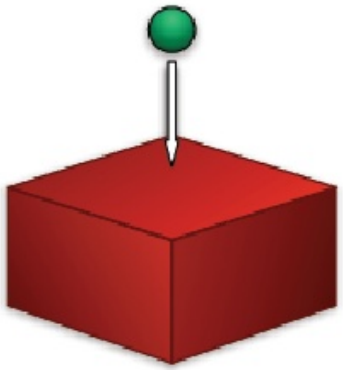
Problem : Destructive Collisions

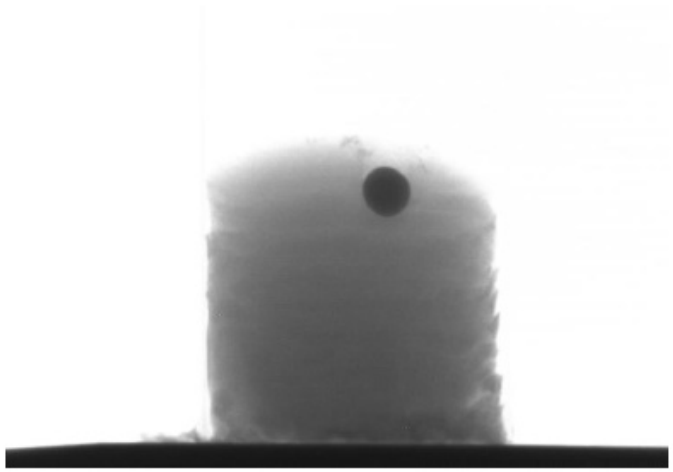
so called *meter-sized barrier*

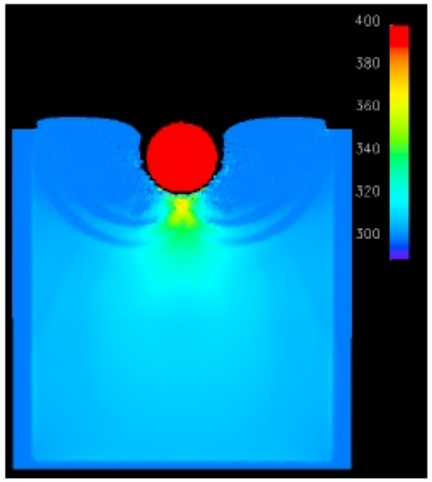
Possible Solution: Porous material, need Calibration simulation

Test: Dynamical Impact

Glass sphere 1 mm-diameter $\Rightarrow$ onto dust cake

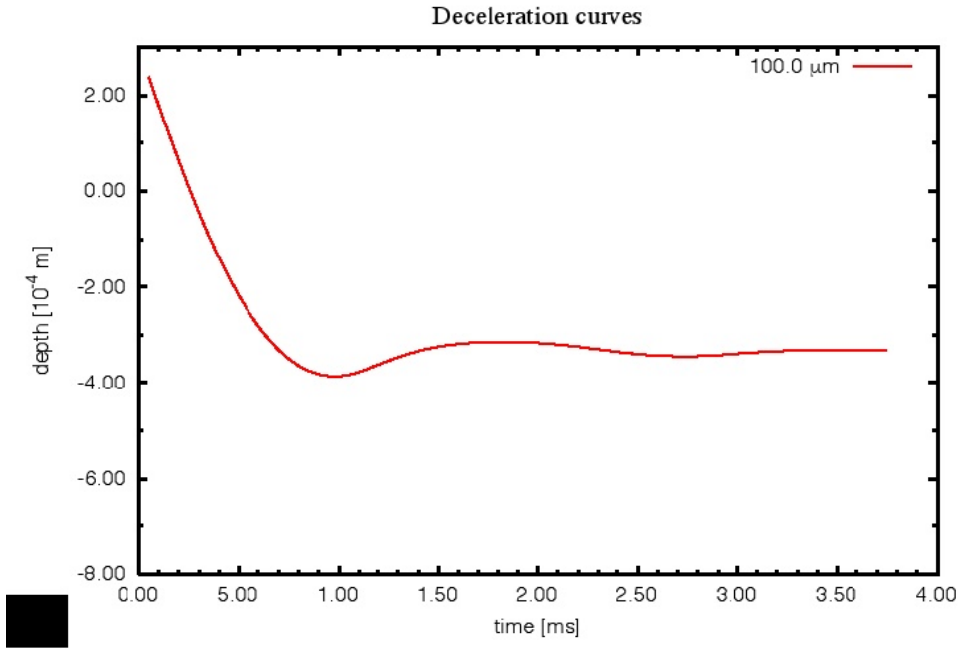






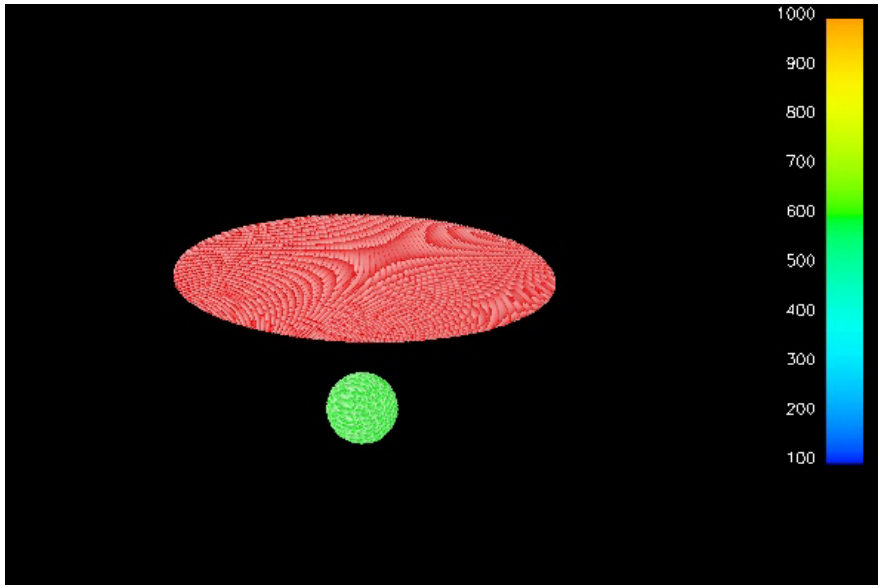
Expts.: in Braunschweig
Simulations: in Tübingen

Determine:
- Braking Curve (see right plot)
- Intrusion depth
- density distribution
- Porosity
- ...

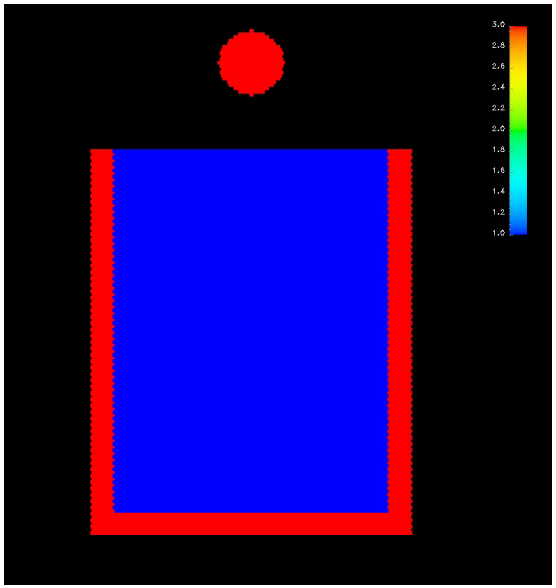


SPH-Testsimulatons

Dust-Particle against Wall



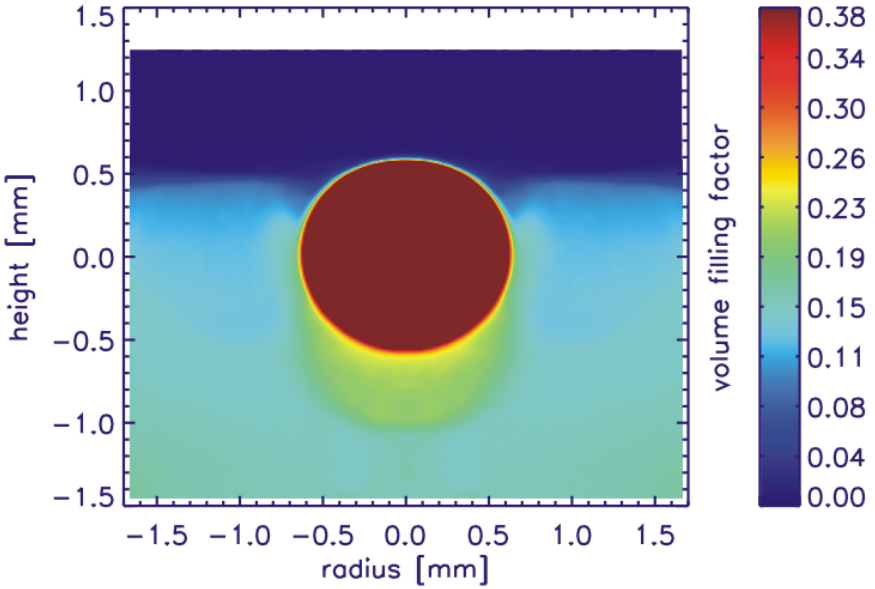
Glass sphere into Dust Cake



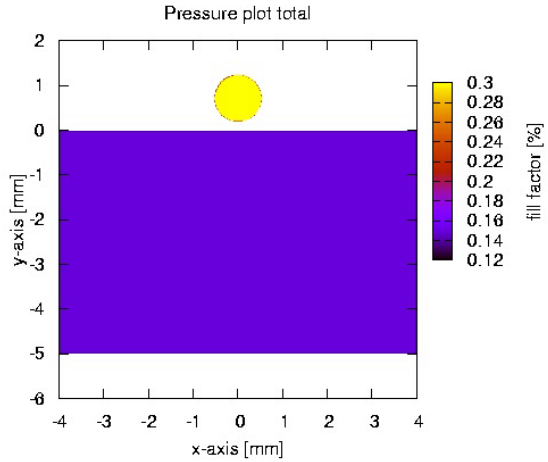
(Ralf Geretshauser, Univ. Tübingen, 2007/08)

SPH-Simulations

Experiment (color coded: filling factor)
(M. Krause, Braunschweig)



SPH-Simulations (density)
(Ralf Geretshauser
& Roland Speith, Tü)

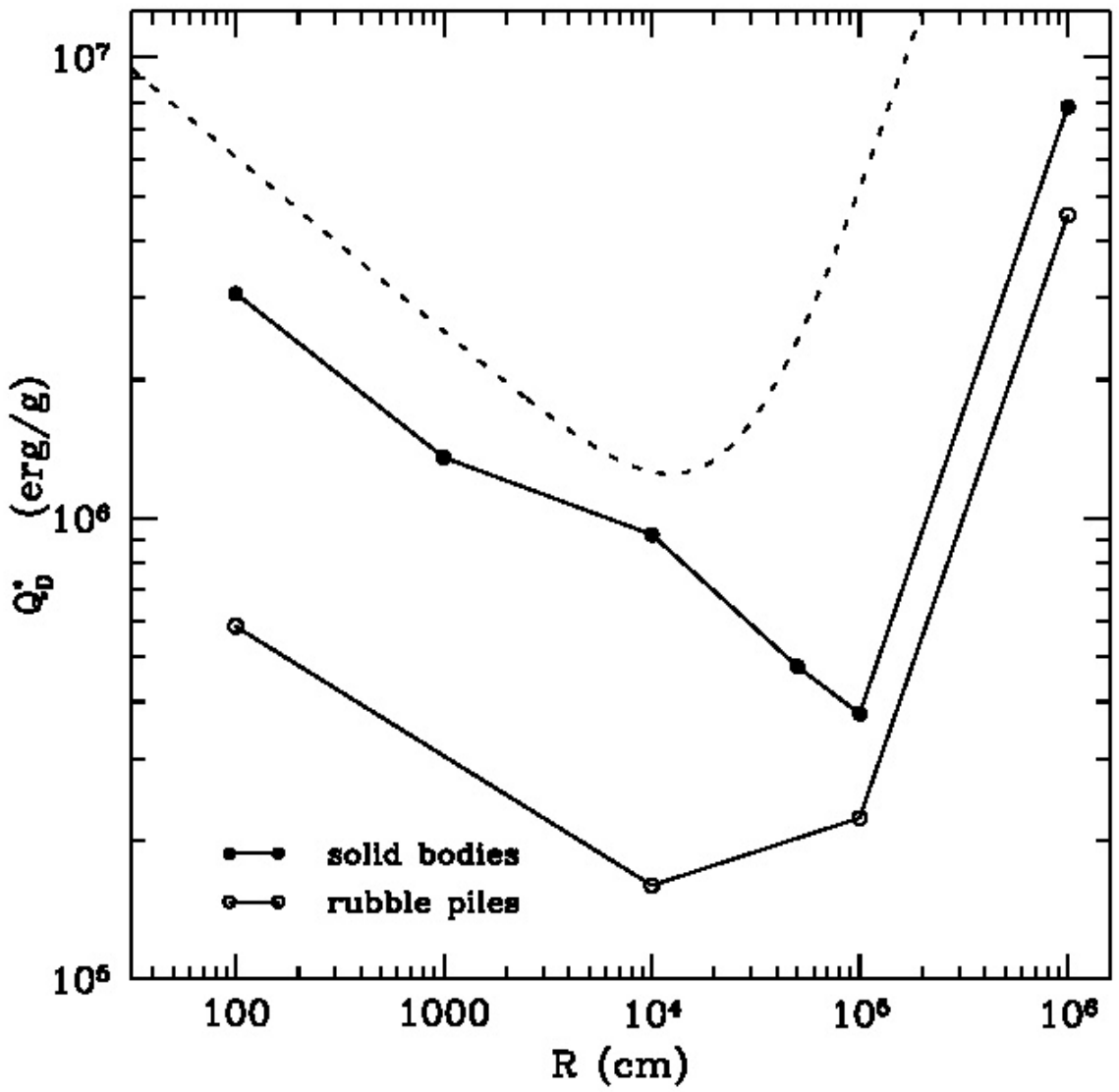


(DFG-Research Group: “First Phase of Planet Formation”, 2007-2013)
Joint Project: Braunschweig, Duisburg, Heidelberg & Tübingen

Idea:
Continuum Simulations of Particle Collisions
determine boundary: Sticking, Bouncing, Fragmentation, catalogue
as a function of relative velocity and particle size

Destruction Threshold

Catastrophic Disruption Threshold: (that specific energy Q, at which the largest intact particle has = 1/2 Targetmass)



Collisions of Basalt spheres with $v_{\rm rel} = 20$m/s
(dashed: 3km/s)

$$Q_D = \frac{1}{2} m_{\rm proj} v_{\rm proj}^2 / M_{\rm target}$$

Weakest Bodies:
$R \approx 100$m

●: Stones
○: Rubble Pile

(Benz, 2000)

(In protoplanetary Disk:
$v_{\rm rel} \approx 10 - 100$m/s,
depending on mass, size, location ..)

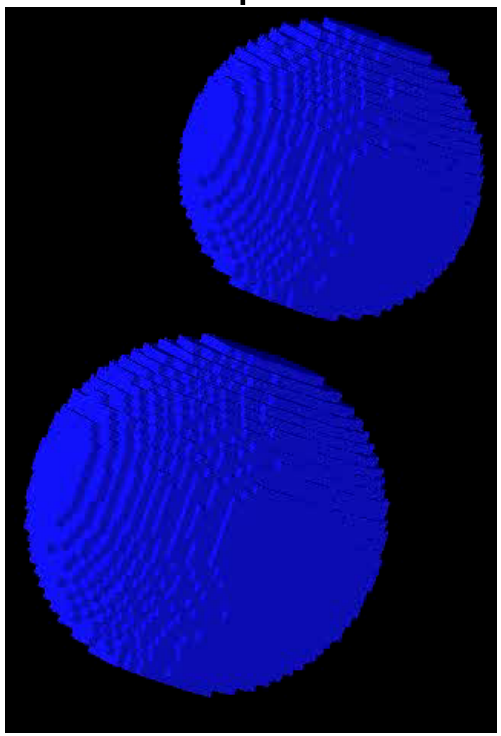
Porosity

Check growth of planetesimals by collisions/accretion

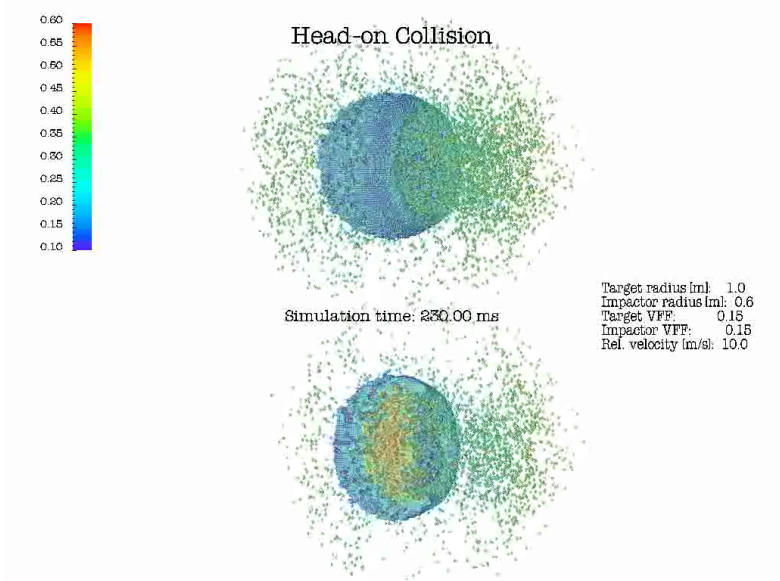
SPH (Smoothed-Particle-Hydrodynamics) using 250,000-500,000 particles

Here: Elastic-plastic strength model, formation and evolution of cracks

2 Basalt Spheres:



Porous Objects: $r = 6, 10$m, $v_{\rm ref} = 10$m/s



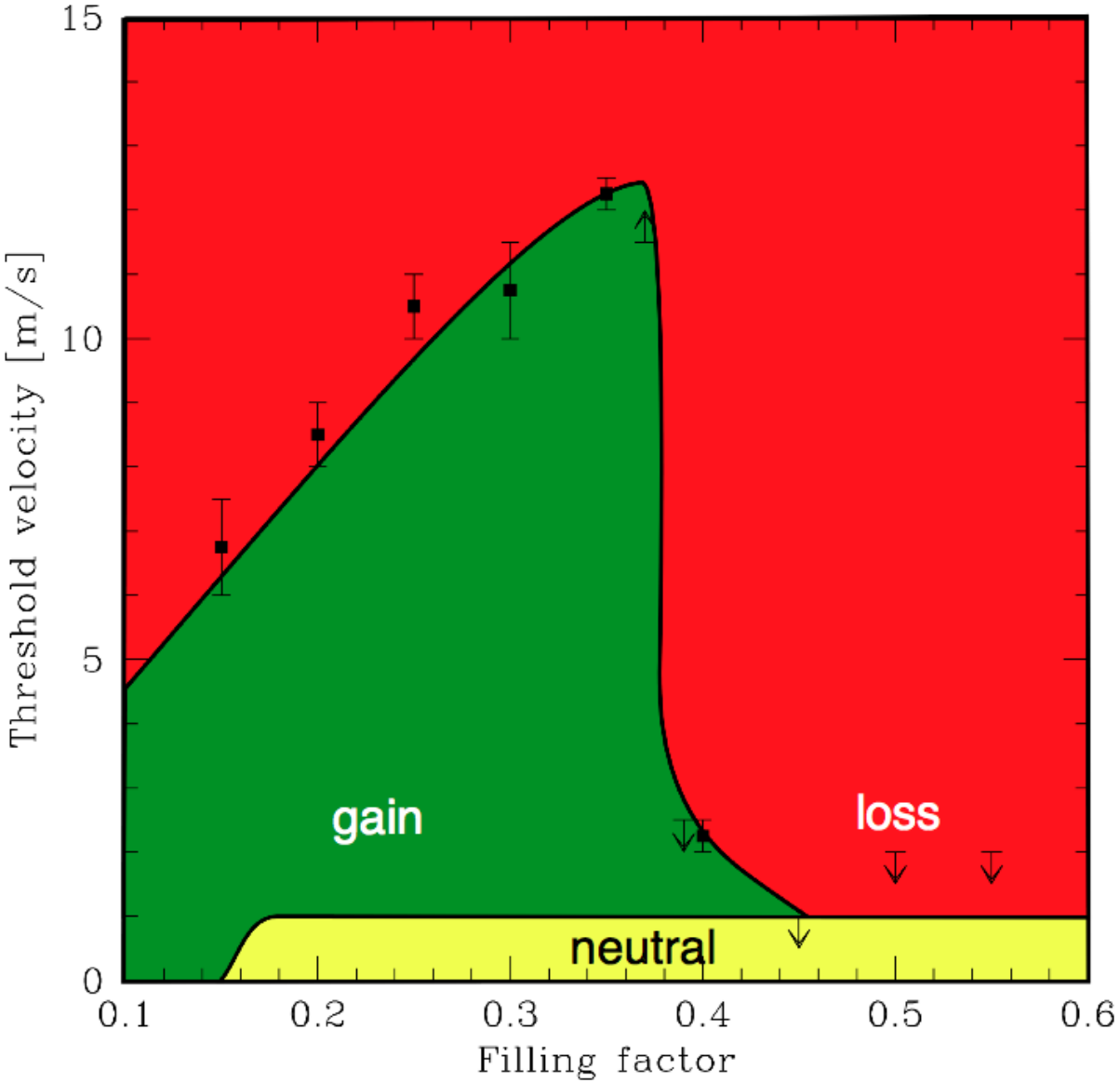
(cp. small objects in Solar System)

(Schäfer, Geretshauser, Speith, Meru; Tübingen) (Geretshauser ea., 2010, 2011a,b)

$\Rightarrow$ Need porous bodies !

Growth Regime

Collide two objects with $R_t = 10$ cm and $R_p = 6$ cm



Symbols:
Numerical Results
(Fragmentation velocity)

Red: Fragmentation
Green: Sticking (Growth)
Yellow: Bouncing

(Meru ea. 2013)

Summary/Outlook

Initial planetary growth through collisions of dust agregates

- Modelling by molecular dynamics
- 4 types of motion (normal, rolling, sliding, twisting)
- Non-elastic energy dissipation
- Computing on GPUs
- Determine continuum parameter

For larger particles

- Continuum SPH simulations
- Determine Fragmentation Threshold

The End