# Growth of Dust Aggregates in Protoplanetary Disks and Reexamination of Particle Interaction Models

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Animation produced by Takeda(NAOJ)
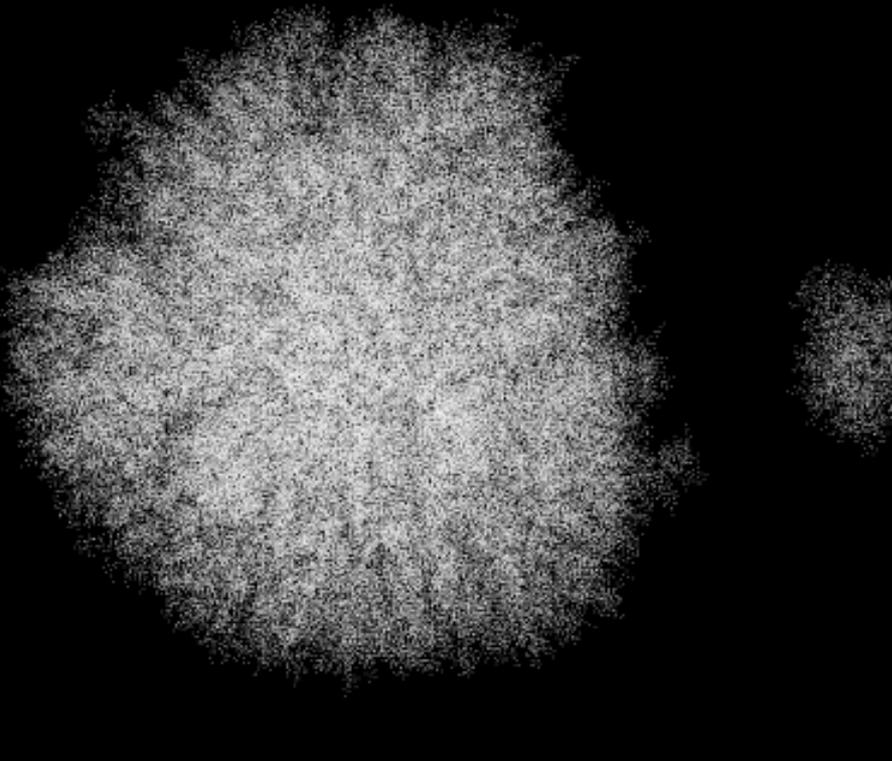
Numerical Simulation of Collision between Icy Aggregates
Impact speed 90m/sec, N=0.5million
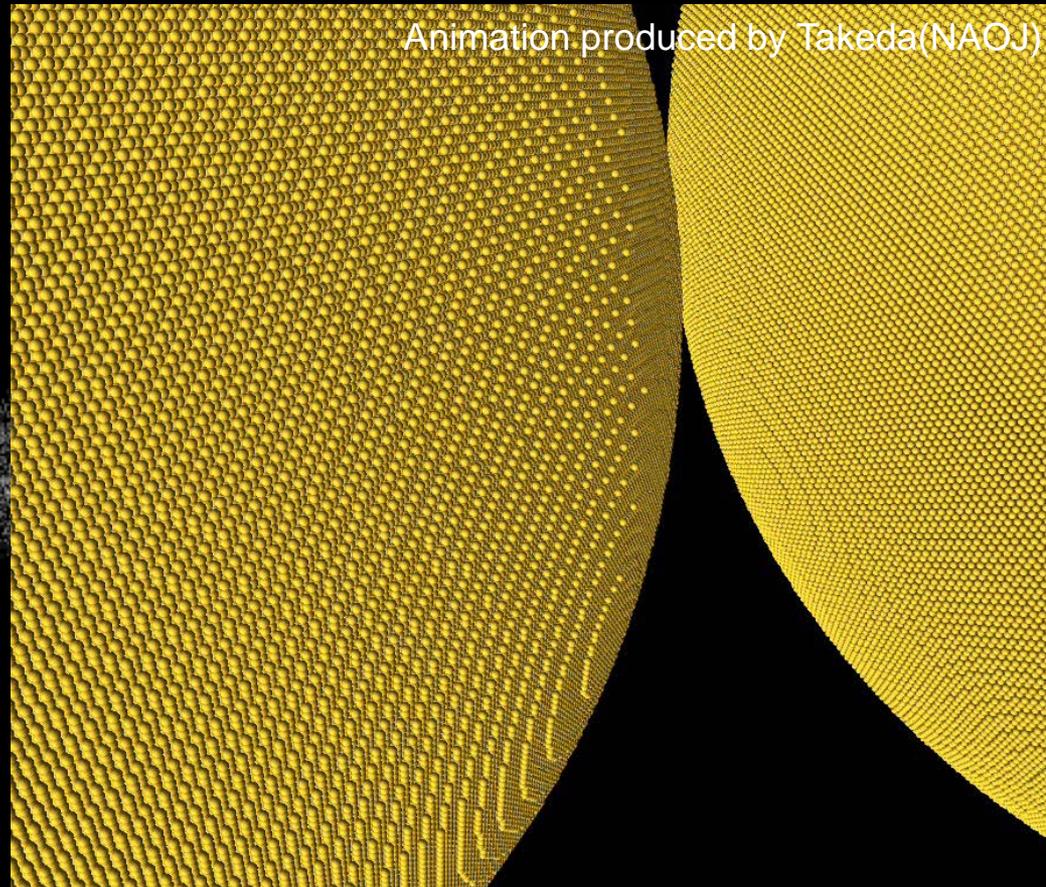
Collision of Sub-micron Particles
Molecular Dynamics Simulation, N= 20 millions

Numerical Simulation of Aggregate Collisions

Collision Outcomes (Wada et al.2007,2008,2009,2011; Suyama et al.2008)

- Maximum impact velocity for growth is ~ 60m/sec for icy dust.

- Fractal dimension of compressed aggregates is 2.5.

Koji Wada

Off-set Collision of Icy Aggregates v=90m/sec
Number of constituent particles is 0.5million.
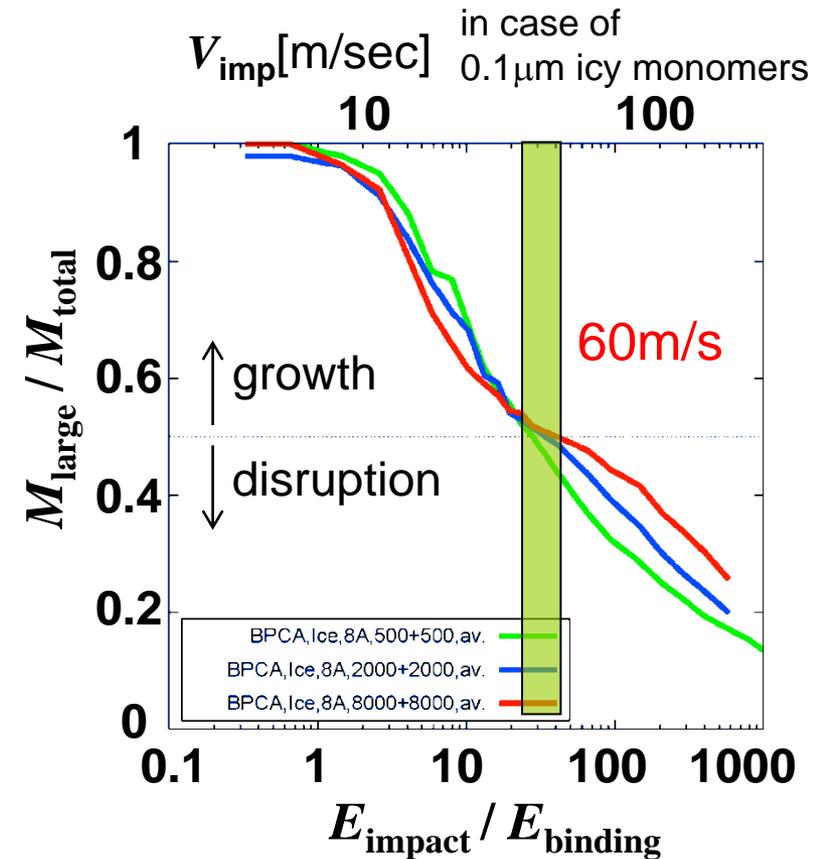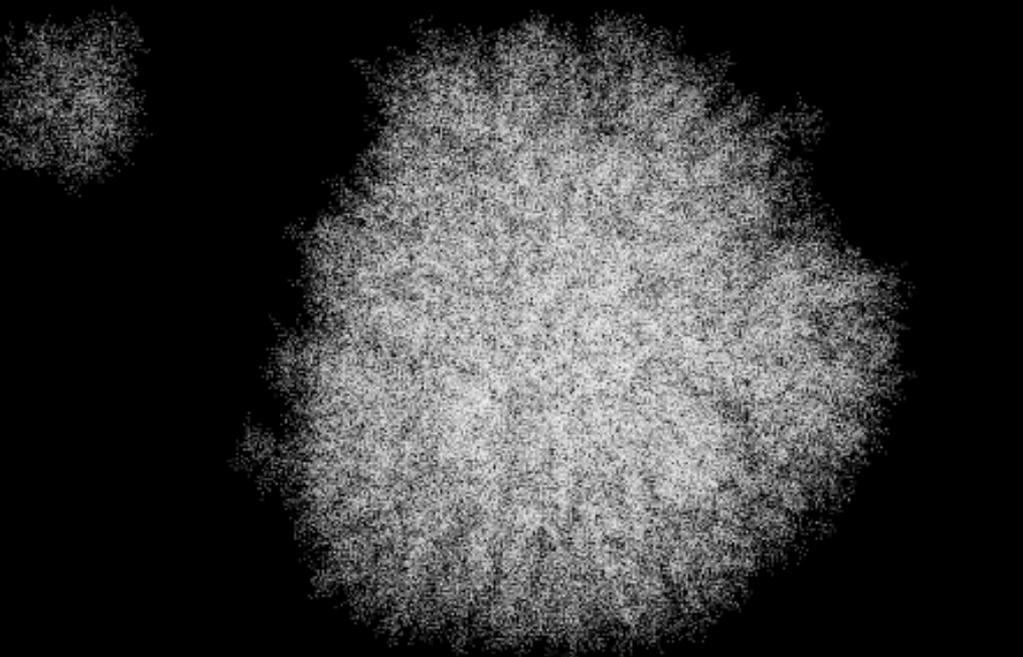
V_{imp}[m/sec] in case of 0.1μm icy monomers

10   100

M_{large} / M_{total}

↑ growth

60m/s

↓ disruption

BPCA,Ice,8A,500+500,av.
BPCA,Ice,8A,2000+2000,av.
BPCA,Ice,8A,8000+8000,av.

0.1   1   10   100   1000

$E_{impact} / E_{binding}$

# Numerical Simulation of Aggregate Collisions

Collision Outcomes (Wada et al.2007,2008,2009,2011; Suyama et al.2008)

- Maximum impact velocity for growth is ~ 60m/sec.

- Fractal dimension of compressed aggregates is 2.5.

Fluffy aggregates are not easy to compress!

Fractal dimension is 2.5
=
"Large aggregates are hard to compress"

Compression of fluffy aggregates at collisions

V_{impact} = 0.2 m/s

17 m/s

Wada et al. 2008, ApJ

no compression

compression

disruption

Ice,8Å,512+512
Ice,8Å,2048+2048
Ice,8Å,8192+8192
Eq. (40)

$E_{imp} = 0.1 E_{roll}$

(N=16384) (N=4096) (N=1024)

SIZE r_g/r_1

$E_{imp}/(N E_{roll})$
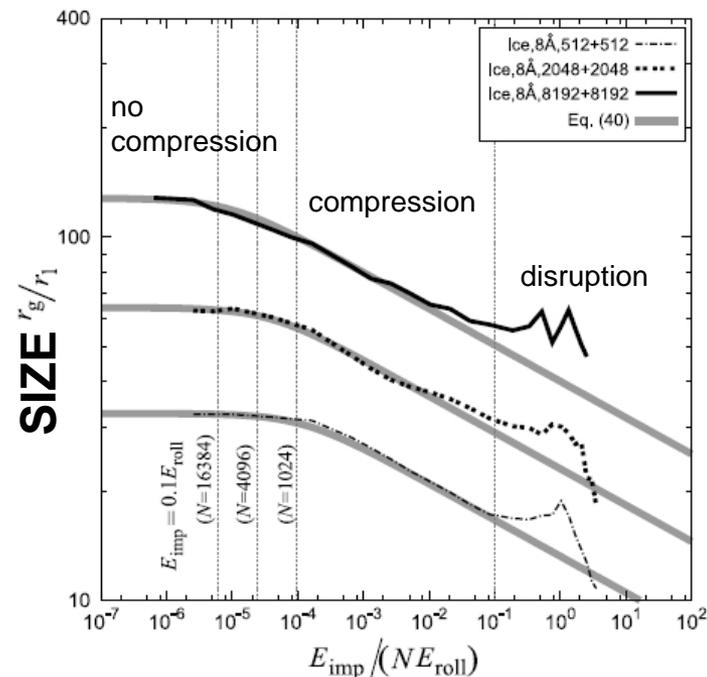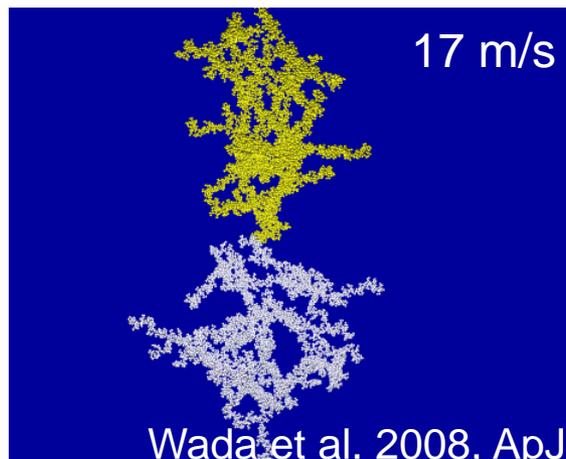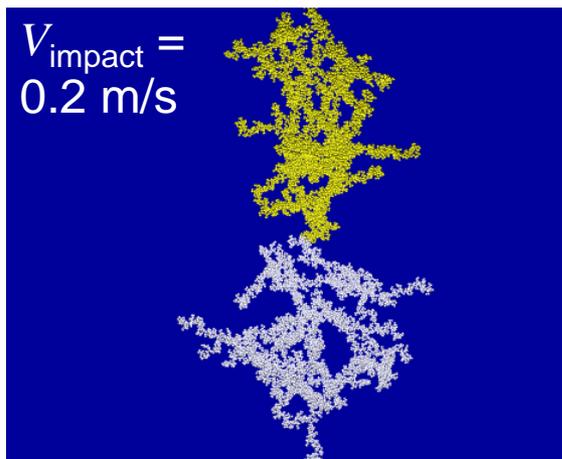
IMPACT ENERGY PER MASS

This compression model is applied to Planetesimal Formation (Okuzumi's talk).

Interaction Model of Dust Particles

· Adhesion force between two particles in contact comes from
van der Waals force for silicate particles
(or hydrogen bond for icy particles).

· Particle Interaction Model

- Adhesion force between two particles is determined by
their surface tension. (***Johnson, Kendall & Roberts' theory***, 1970's)

- Frictional forces against sliding, rolling, & twisting motions

(***Dominik & Tielens*** 1995,1996)

normal   rolling   sliding   twist
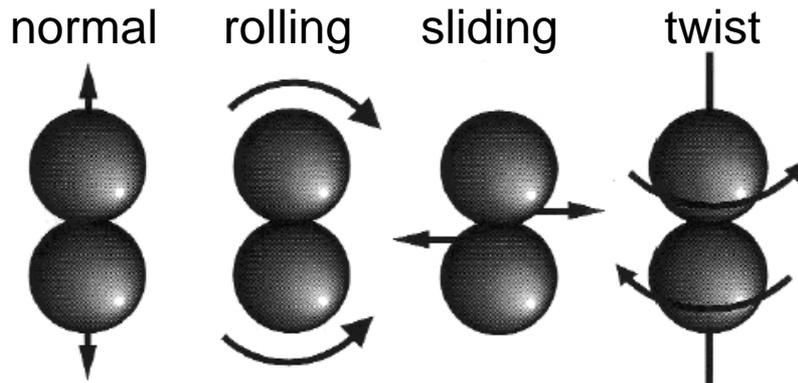
**Is this interaction model correct?**

Molecular Dynamics Simulation of Sub-micron Particle Collisions

- Each particle consists of *3 millions of molecules*. (FCC-crystal, no lattice defect)

- Lennard-Jones molecules (Surface tension & Young's modulus are known.)

- Head-on collision

- In the case of Ar, particle diameter = 60nm, impact velocity = 9m/sec
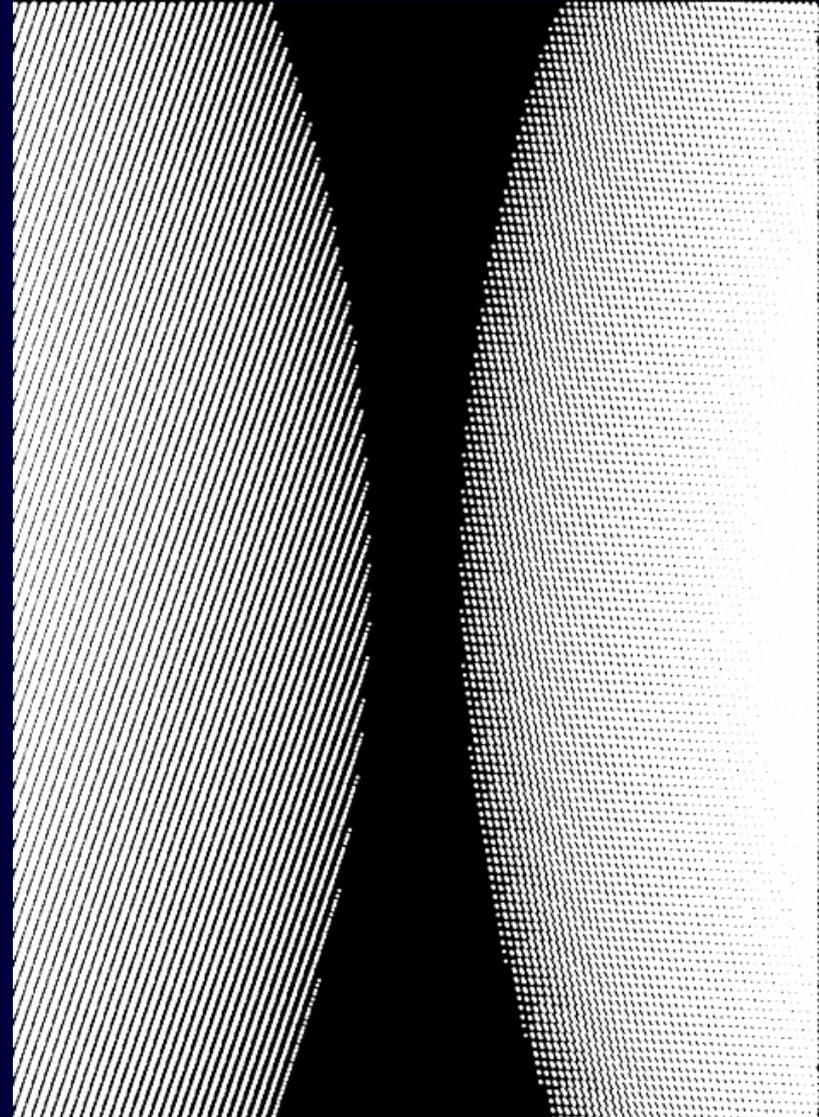
MD Simulation of Particle Collisions

Distance between two centers of mass
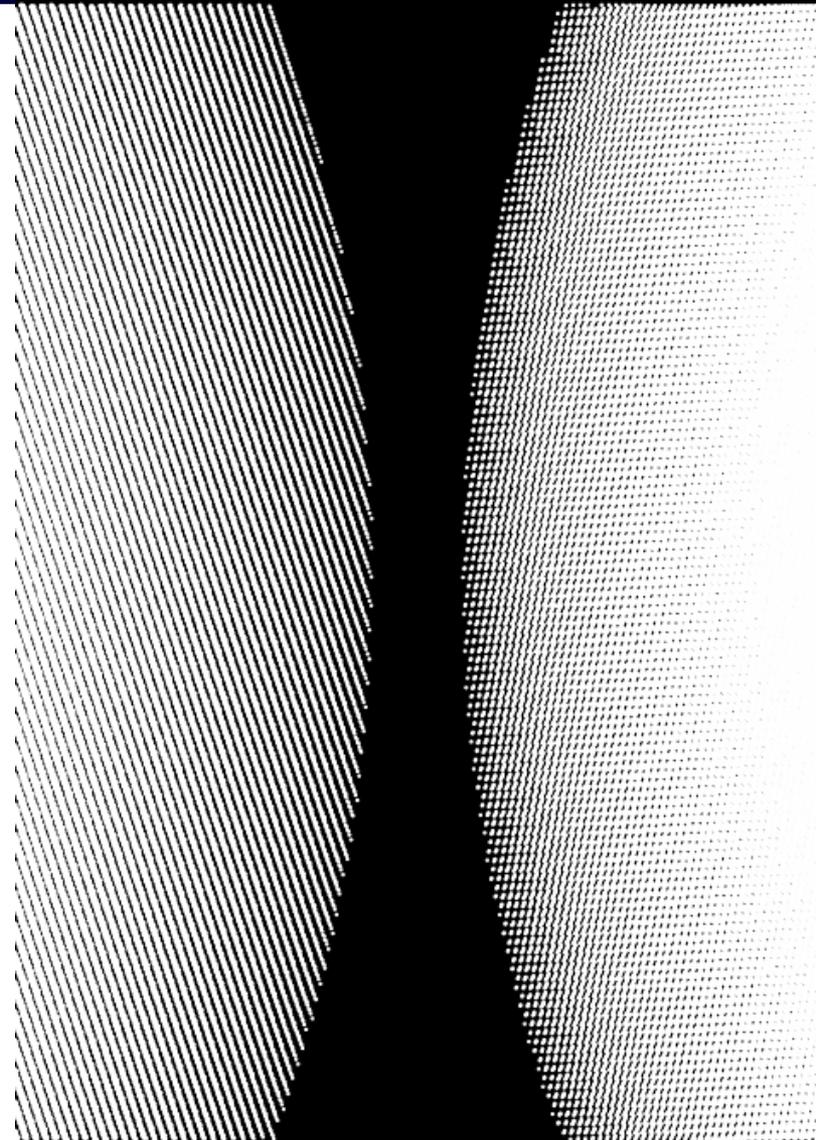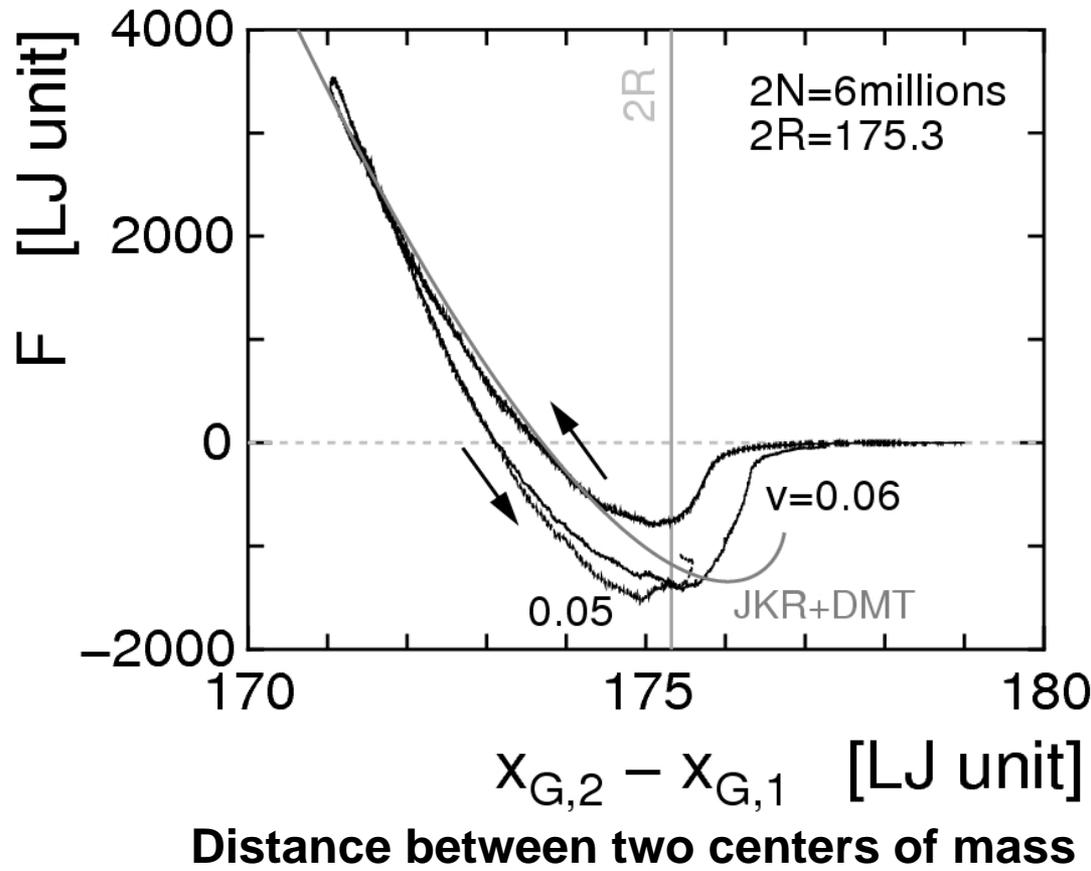
- *JKR theory is not bad!*

- *Some hysteresis exists.*
energy dissipation & friction

MD simulations of rolling & sliding frictions
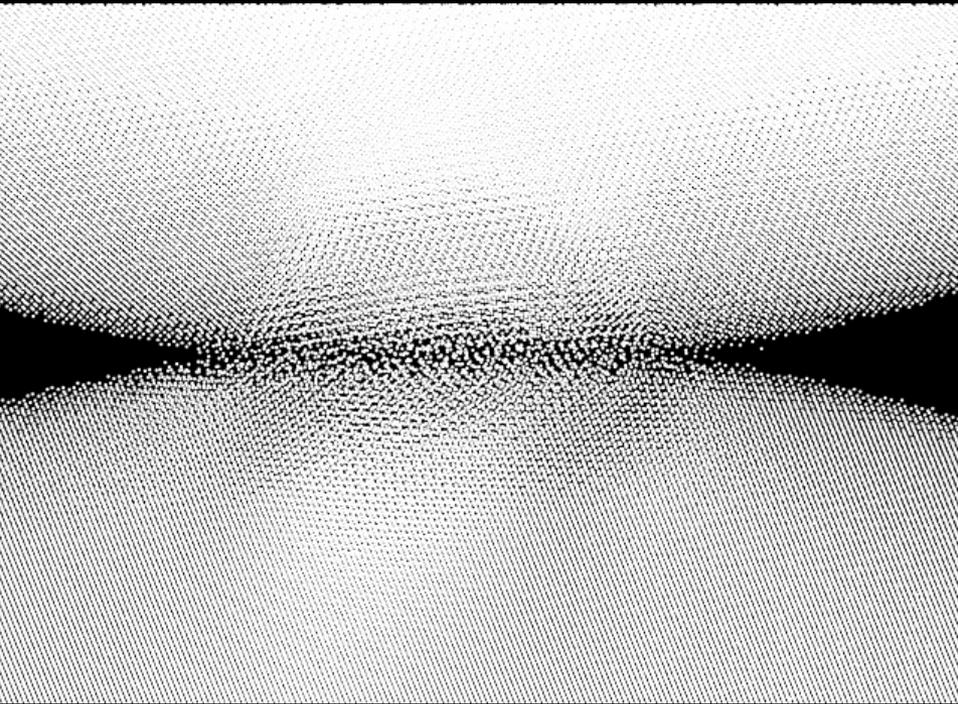
Rolling Motion   Sliding Motion
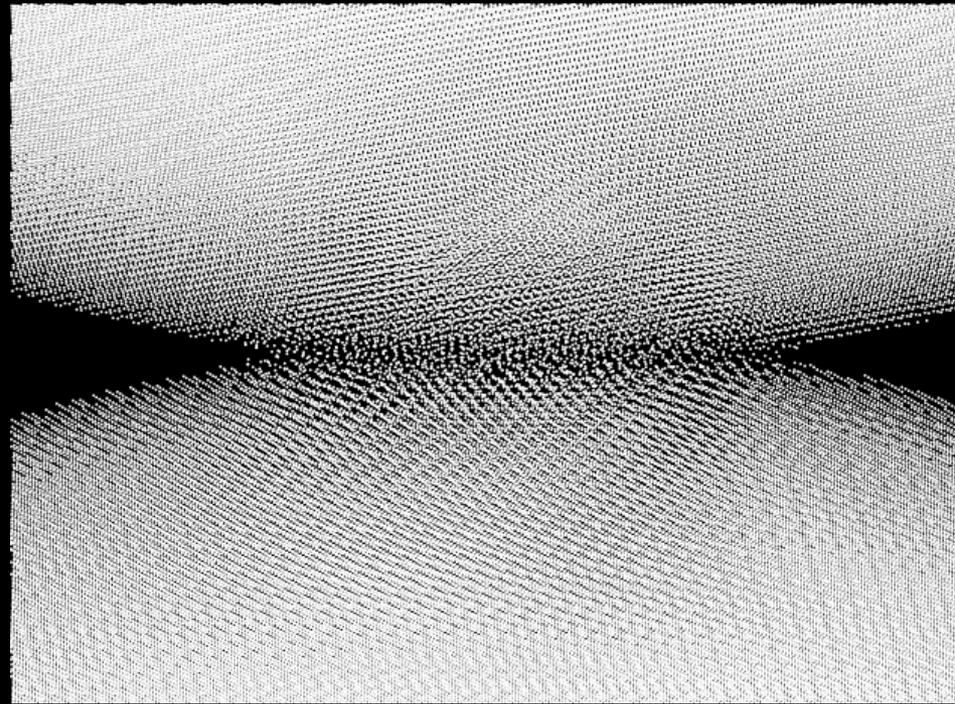
- Frictional torques against rolling & sliding are obtained.

- These results almost agree with Dominik & Tielens' prediction.

Summary

Collision Outcome in aggregate simulations

- Maximum impact velocity for icy dust growth is ~ 60m/sec.

- Fulffy aggregates are hard to compress with collisions because of their fractal dimension of 2.5.

MD Simulation of Particle Interaction

- MD simulation almost agree with JKR theory and Dominik & Tielens' model.

- Extra energy dissipation exists at the normal relative motion.