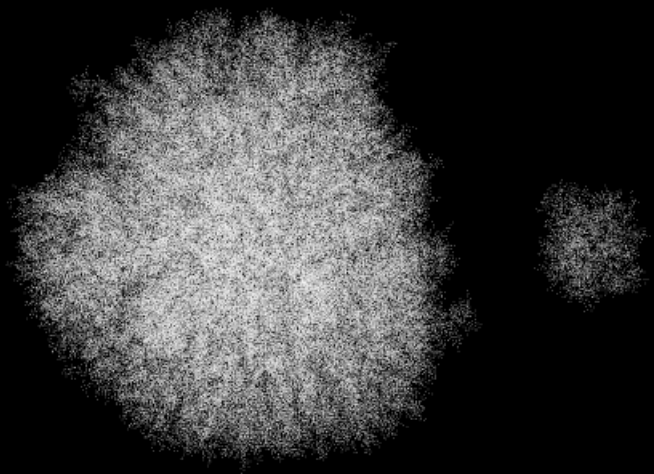
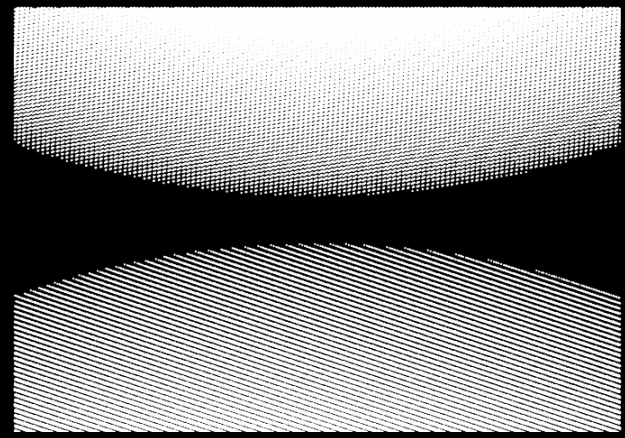
Dust Growth in Protoplanetary Disks



Collision of icy aggregates
with 90m/sec, N= 0.5 millions



Collision between two monomers
(MD simulation with N=6millions)

Are dust aggregates sticky enough? ***Yes.***

Is that true?

Problems in Planetesimal Formation

Two formation processes

- Gravitational Instability (or Stream Instability)

***Problem*: Turbulent diffusion decreases dust concentration.**
Gas drag force is too strong!
(Streaming instability requires dust particles > 10cm-size.)

- Direct Dust Growth

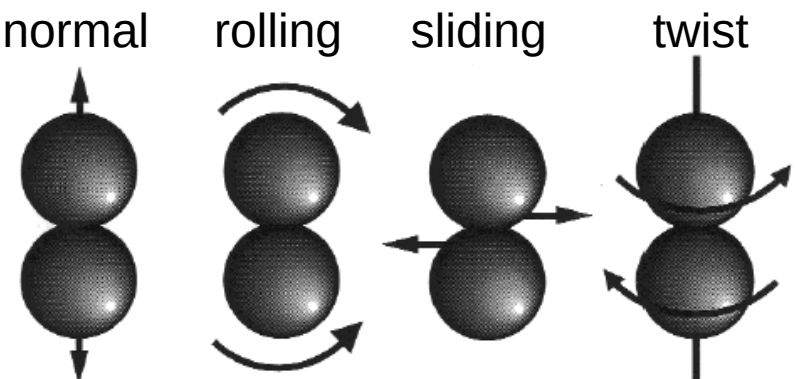
Problem: **Fragmentation Barrier**

"Can m-sized dust particles stick each other?"
(Collision speed is ~50m/sec [~200km/hr]!)

The answer is YES! (Wada's talk)

Why do the aggregates stick?

- Sticking force between two monomer particles in contact comes from van der Waals force for silicate particles (or hydrogen bond for icy particles).
- Particle interaction model
  - The binding energy between two particles is determined by their surface tension. (**J**ohnson, **K**endall & **R**oberts' theory, 1970's)
  - Drag force against sliding, rolling, & twisting motions (*Dominik & Tielens* 1995,1996, *Wada et al.* 2007)



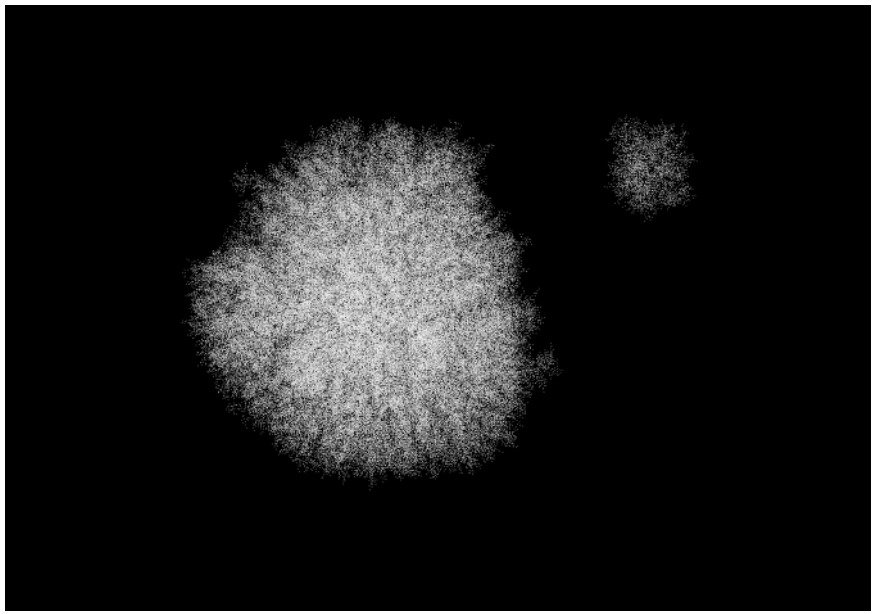
Wada et al. use this interaction model.

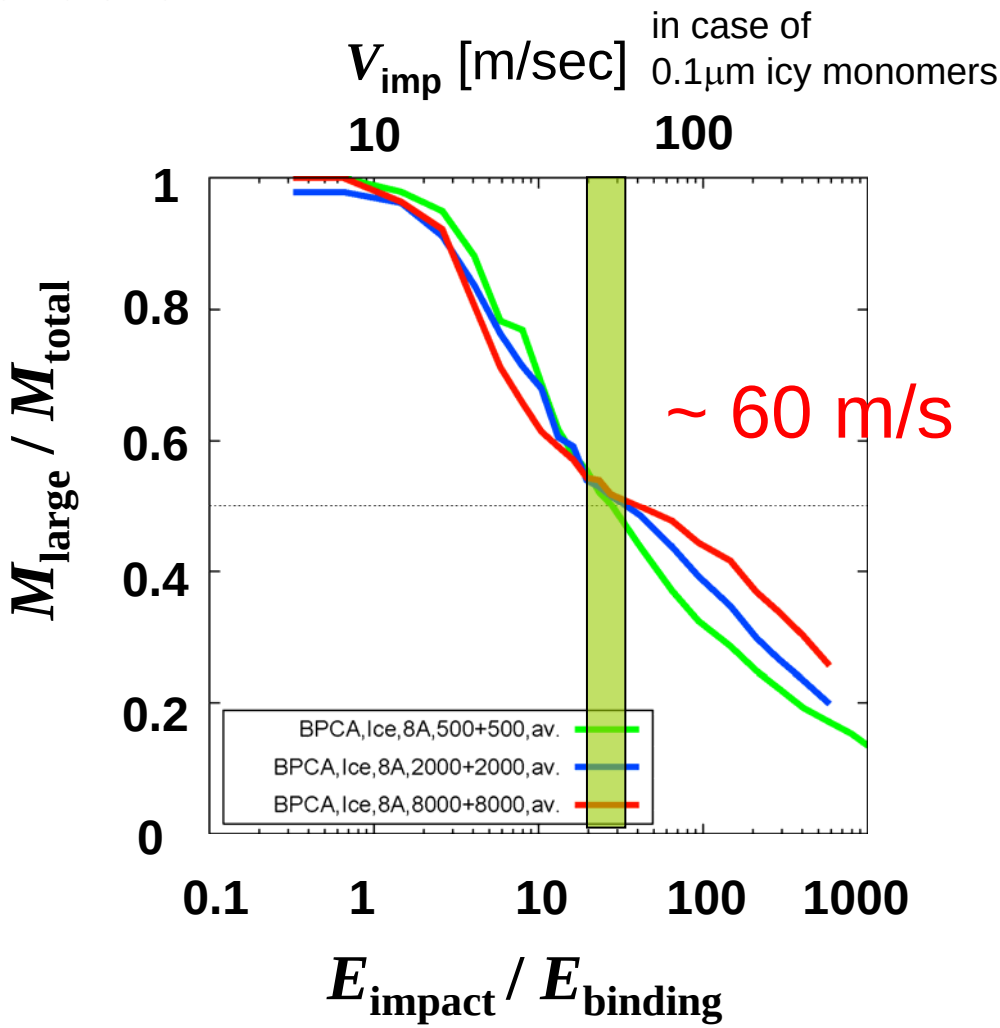
N-body Simulations of Aggregate Collisions

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

- compression of aggregates at collisions
- condition for fragmentation

Off-set Collision of Icy Aggregates

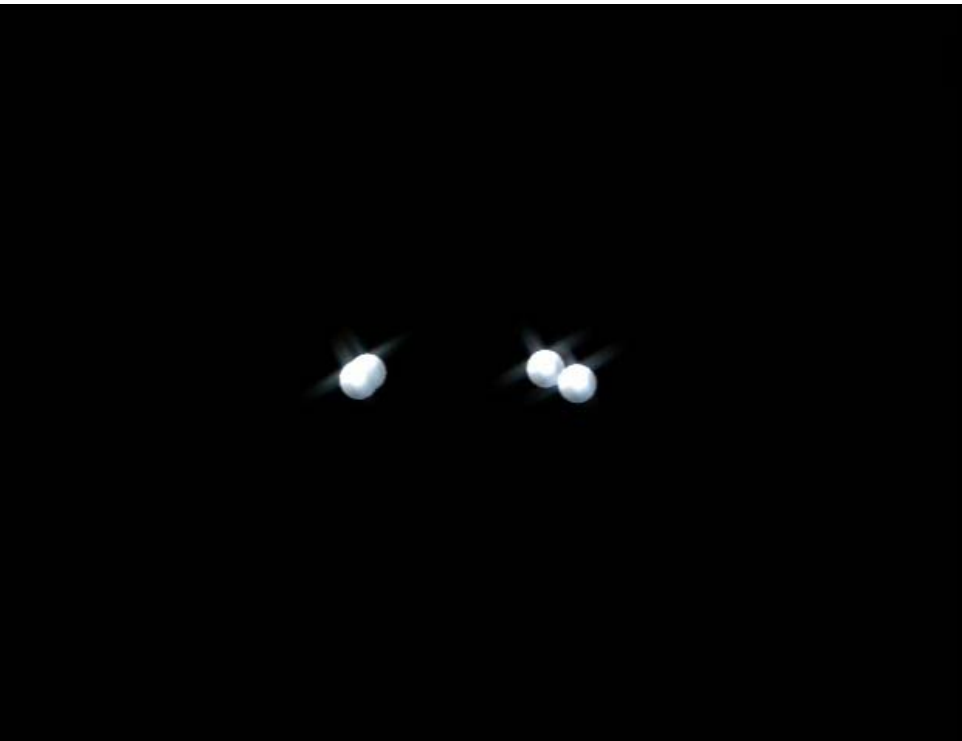


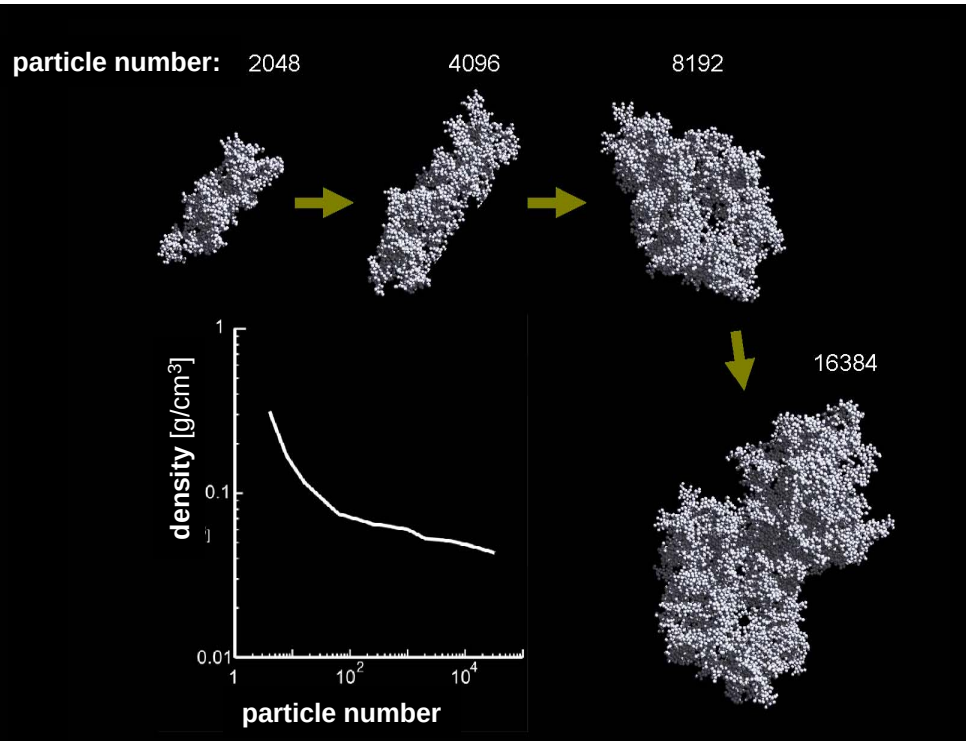


N-body Simulations of Aggregate Collisions

Density evolution in successive collisions (*Suyama et al.* 2008)

- formulation of density changes during growth
- formation of extremely low density aggregates
  ($\rho = 10^{-4}$ g/cm^3 for m-sized aggregates!)





Summary of Our N-body simulations

- Icy aggregates can grow if the impact velocity < 60m/sec. This overcomes the fragmentation barrier!
- Large aggregates have an extremely low bulk densities.

Planetesimal formation by "direct dust growth" is possible!

(for icy planetesimals in the outer disk region).

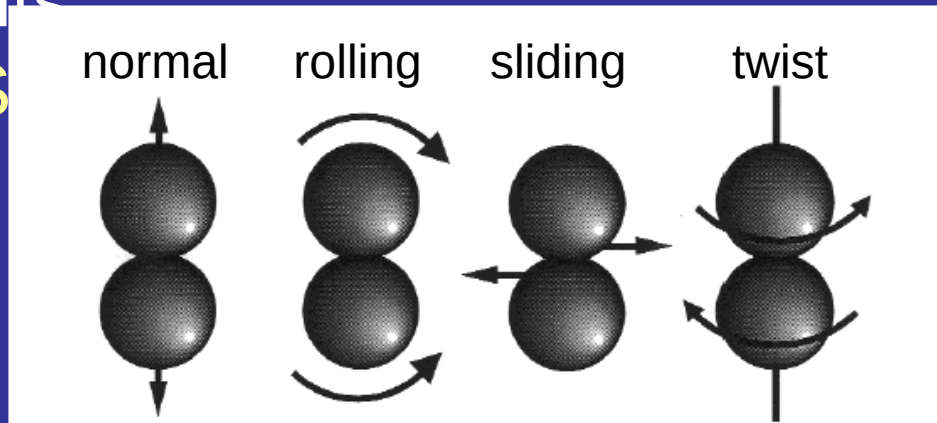
Are aggregates really sticky & fluffy?

Yes, as long as the particle interaction model of JKR theory (+Dominik & Tielens) is correct.

Next question: ***Is the interaction model correct?***

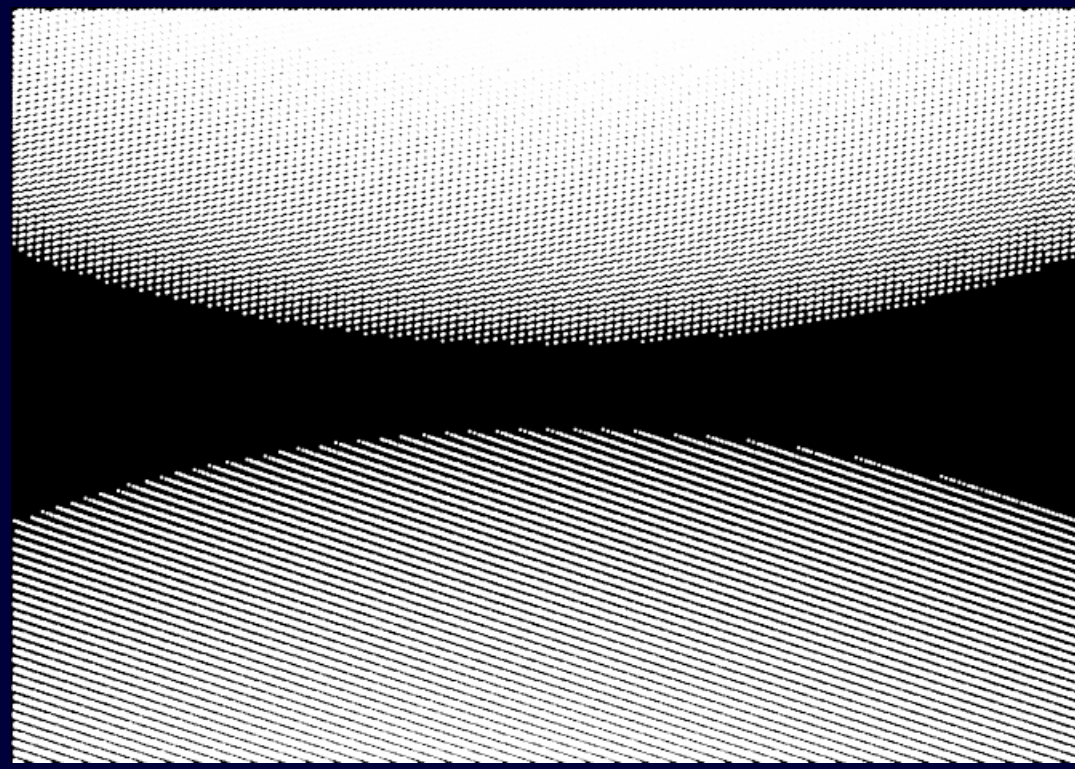
Answer is “We don’t know yet”.

We should re-examine the interaction
with Laboratory Experiments
and Molecular Dynamics S

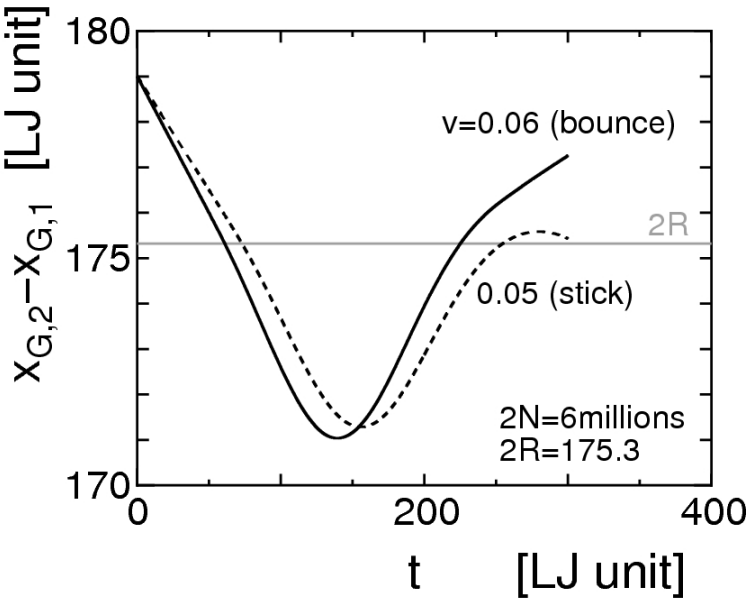


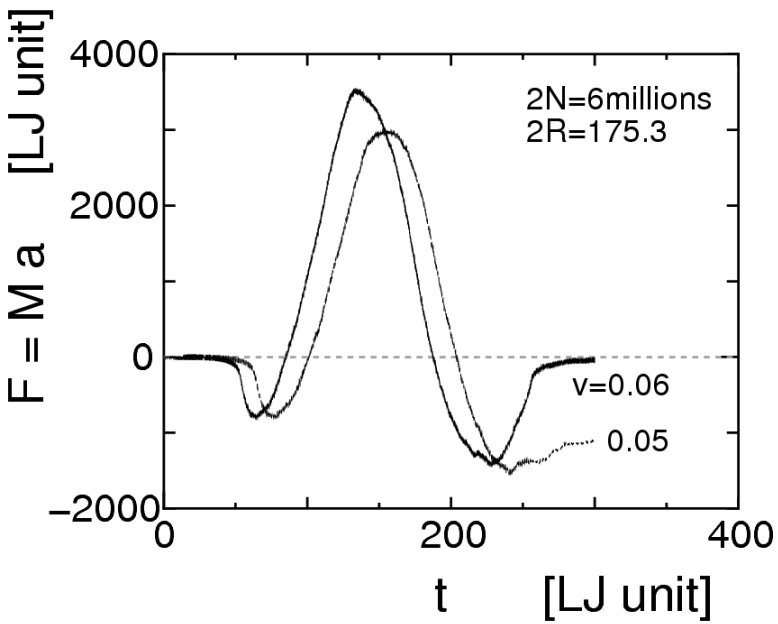
Molecular Dynamics Simulation of Monomer Particle Collisions

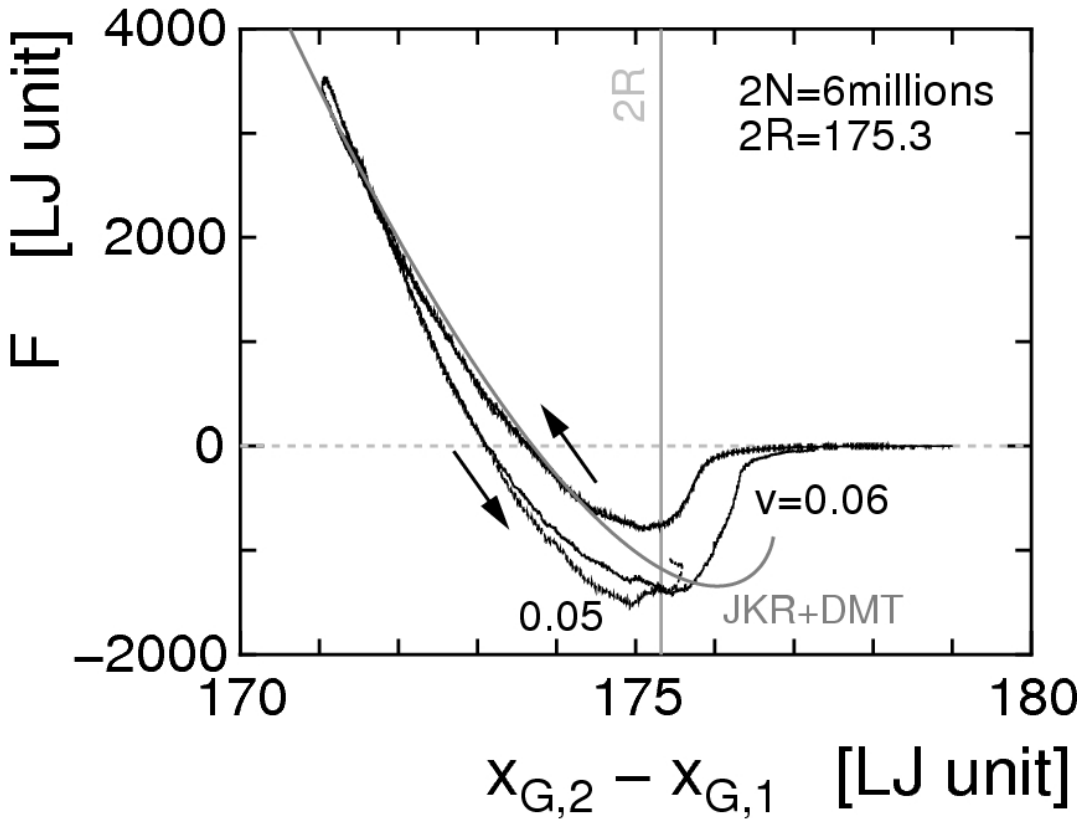
- Each monomer consists of 3millions of molecules. (FCC crystal)
- Lennard-Jones molecules (Surface tension & Young modulus are known.)
- Head-on collision
- In the case of Ar, monomer radius = 30nm impact velocity = 9m/sec



MD Simulation of Monomer Collisions







JKR theory is not bad!

Molecular Dynamics Simulation of Monomer Particle Collisions

Preliminary Results :

- JKR theory almost agrees with MD simulation.
- Extra energy dissipation exists, which comes from plastic deformation of the monomers.

Rolling (& sliding) dissipation can be also examined with this MD simulations.

Monomer Interaction can be examined with MD simulation.

More laboratory experiments on monomer interaction are also necessary.