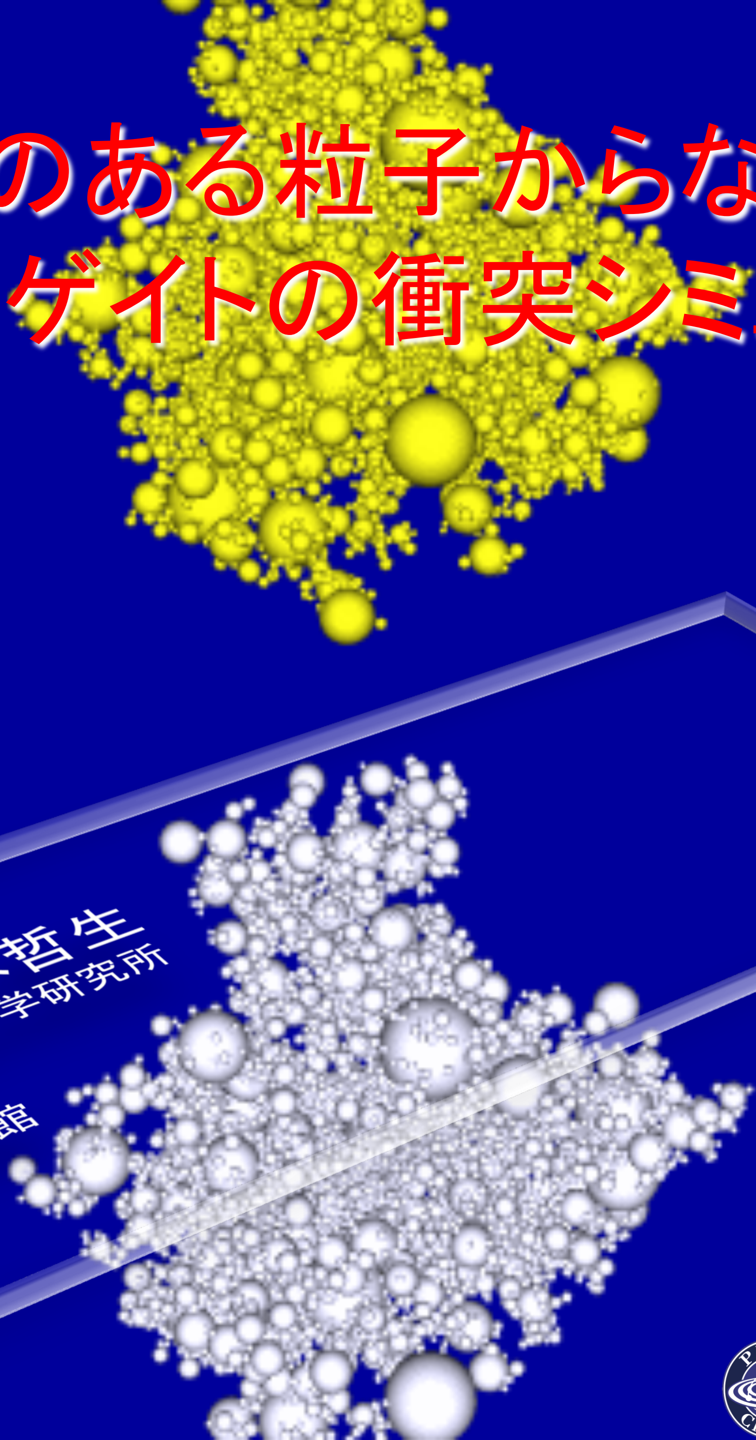
サイズ分布のある粒子からなるダストアグリゲイトの衝突シミュレーション



和田浩二
千葉工業大学PERC
田中秀和，山本哲生
北海道大学低温科学研究所
陶山徹
長野市立博物館
木村宏
CPS

惑星探査研究センター
Planetary Exploration Research Center

Background

Collisional growth of dust (< μm) → ? → Planetesimal formation (> km)

Structure evolution of dust aggregates in protoplanetary disks:

✓When and how are aggregates compressed and/or disrupted ?

✓Can dust aggregates grow through collisions?

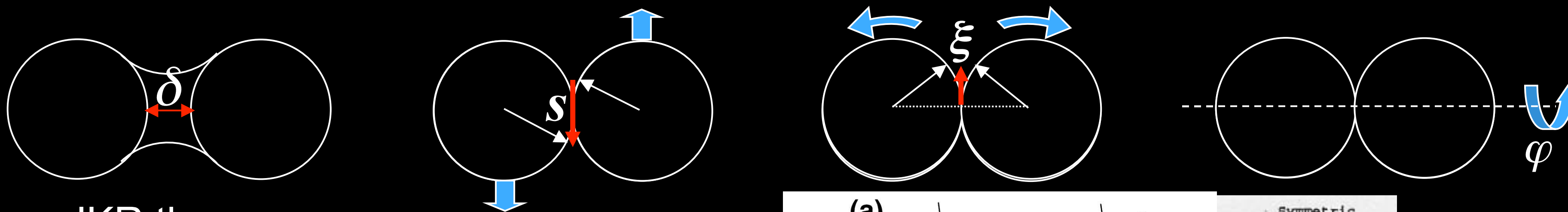
→ **Numerical simulation of dust aggregate collisions!**

Grain interaction model

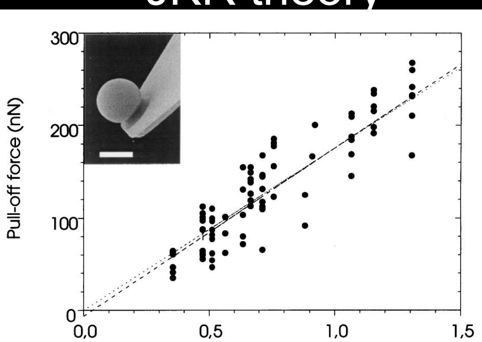
Johnson, Kendall and Roberts (1971)
Johnson (1987), Chokshi et al. (1993)
Dominik and Tielens (1995,96)
Wada et al. (2007)

Elastic spheres having surface energy

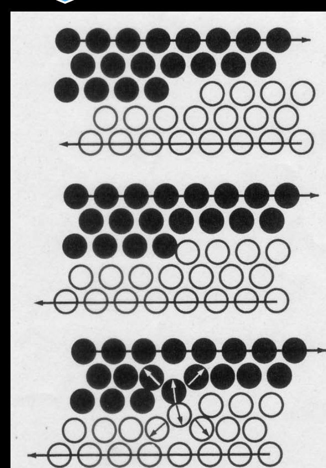
Normal Sliding rolling twisting



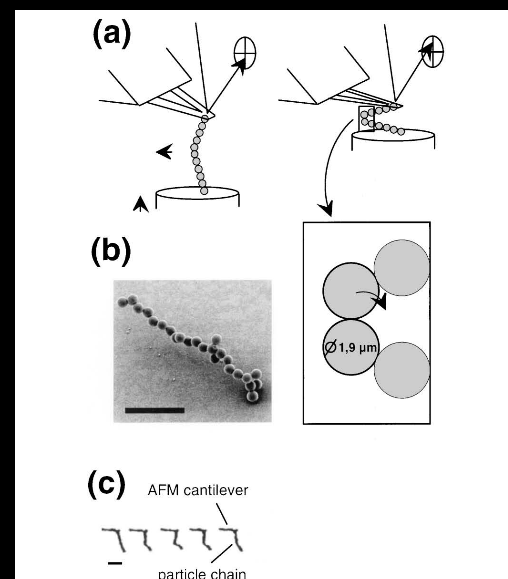
JKR theory



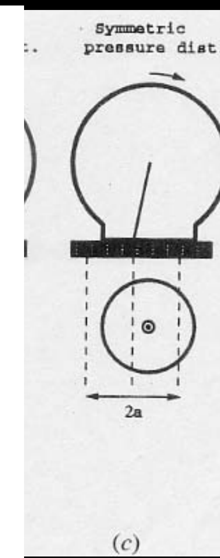
Critical sticking velocity:
exp.~10×theo.!?
(Poppe et al. 2000)



(Dominik & Tielens 1996)



(Heim et al. 1999)



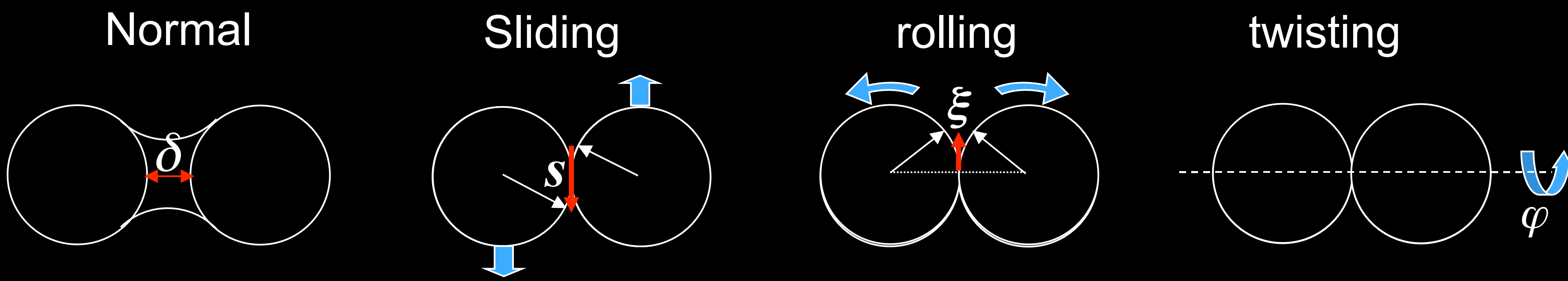
(Dominik & Tielens 1995)

JKR and rolling resistance have been tested with experiments using ~1μm SiO_2 particles. (Heim et al. 1999; Poppe et al. 2000; Blum & Wurm 2000)

Grain interaction model

Johnson, Kendall and Roberts (1971)
Johnson (1987), Chokshi et al. (1993)
Dominik and Tielens (1995,96)
Wada et al. (2007)

Elastic spheres having surface energy



Contact & Separation
s, ξ, φ > critical displacements → Energy dissipation

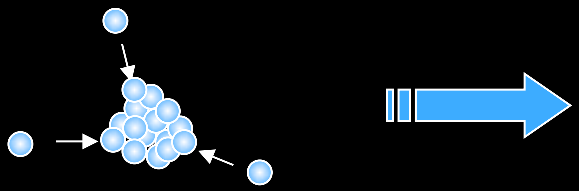
- Critical slide s_{crit} ~ 1.5 Å (for 0.2 μm quartz)
- Critical roll ξ_{crit} ~ 2 Å (or ~30 Å (Heim et al.,1999))
- Critical twist φ_{crit} ~ 1°

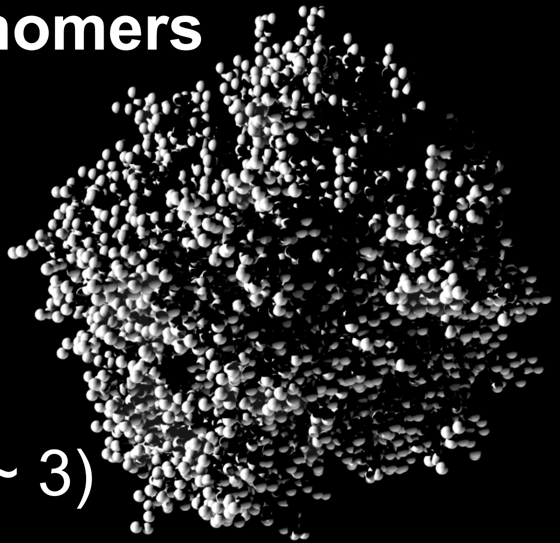
E_{break} : Energy to break a contact

E_{roll} : Energy to roll a pair of gains by 90˚

Ballistic Particle-Cluster Aggregation (BPCA)

- **Formed by one-by-one sticking of monomers**





- Compact structure (fractal dimension ~ 3)

Dust is expected to be compact

- at high velocity collisions causing their disruption

Collisions of BPCA clusters

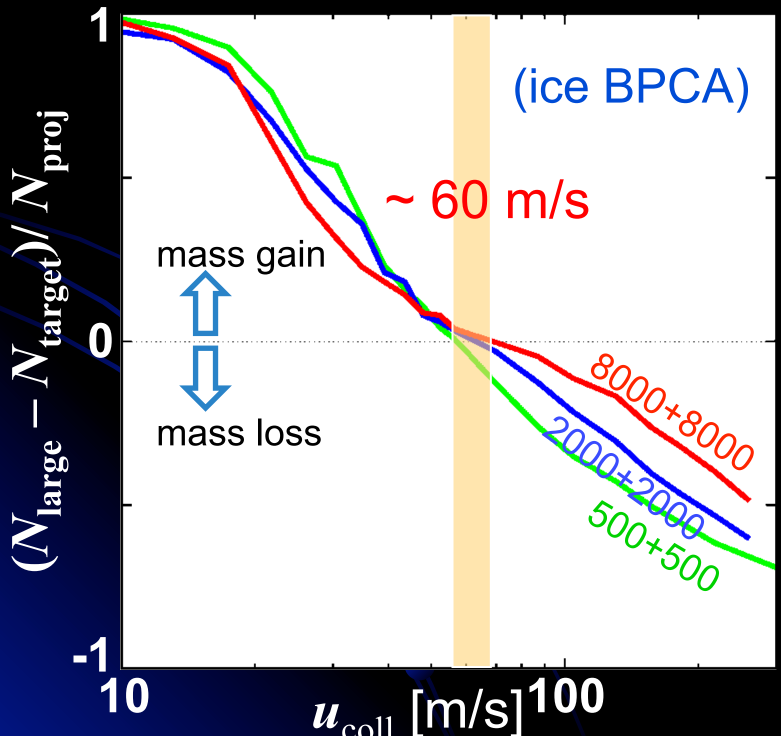
→ implication for growth and disruption of dust

Motivation

Collision velocity of dust in protoplanetary disks < several 10 m/s !

e.g., <~50 m/s (Hayashi model, without turbulence)

Is it possible for dust to grow through collisions ?



(Wada et al. 2009, ApJ 702, 1490-1501)

Possible for ice dust aggregates composed of particles with the same radius of 0.1μm

But for silicate dust?

u_{coll} for silicate = 0.1×u_{coll} for ice

What if size-distribution of constituent particles?

Particle size-distribution

Interstellar dust grains:

r = ~ 0.025 - 0.25 μm

Power-law with an exponent of -3.3 to -3.6

from interstellar extinction (Mathis, Rumpl, & Nordsieck 1977)

Interaction b/w different-sized particles

- <u>Connections become strong for small particles.</u>

Critical collision velocity for sticking of two monomers

$$\frac{1}{2}\mu v_c^2 = E_{break} = 1.5 F_c \delta_c \propto R^{\frac{4}{3}} \quad \Rightarrow \quad v_c \sim \sqrt{\frac{F_c \delta_c}{\mu}} \propto R^{-\frac{5}{6}}$$

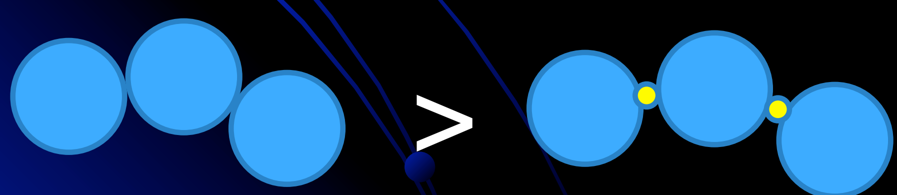
v_c increases with decreasing reduced radius R.

μ: Reduced mass, F_c: Separation force, δ_c: Compression (separation) length

- <u>But small particles make aggregates weak?</u>

Energy for catastrophic disruption $E_c \sim 10 n_k E_{break} \propto n_k R^{4/3}$

n_k:Number of contacts



$$\frac{E_{c,L}}{E_{c,S}} \sim \frac{2 \times R_L^{4/3}}{4 \times R_s^{4/3}} \approx 10 \left(\frac{R_L / R_S}{10} \right)^{4/3}$$

Objective

Do collisions of aggregates composed of particles with a size distribution encourage dust growth?

Simulations of collisions between BPCAs composed of particles with various size distributions.

✓Growth efficiency: $f = (M_{\mathrm{large}} - M_{\mathrm{target}}) / M_{\mathrm{proj}}$

Critical collision velocity for disruption of aggregates

u_{coll} at $f = 0$

Initial Conditions and Parameters

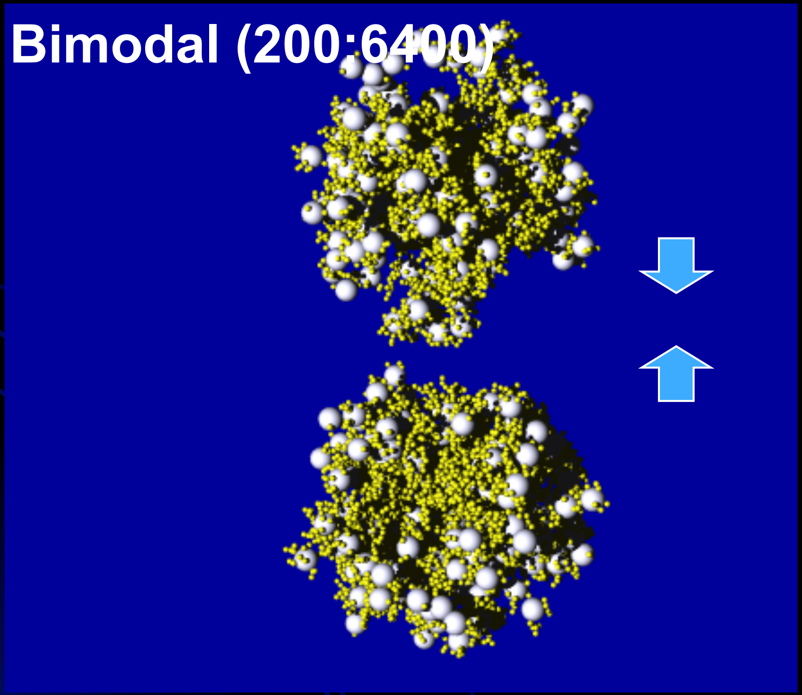
<u>Head-on</u> collisions of BPCA clusters with the same size

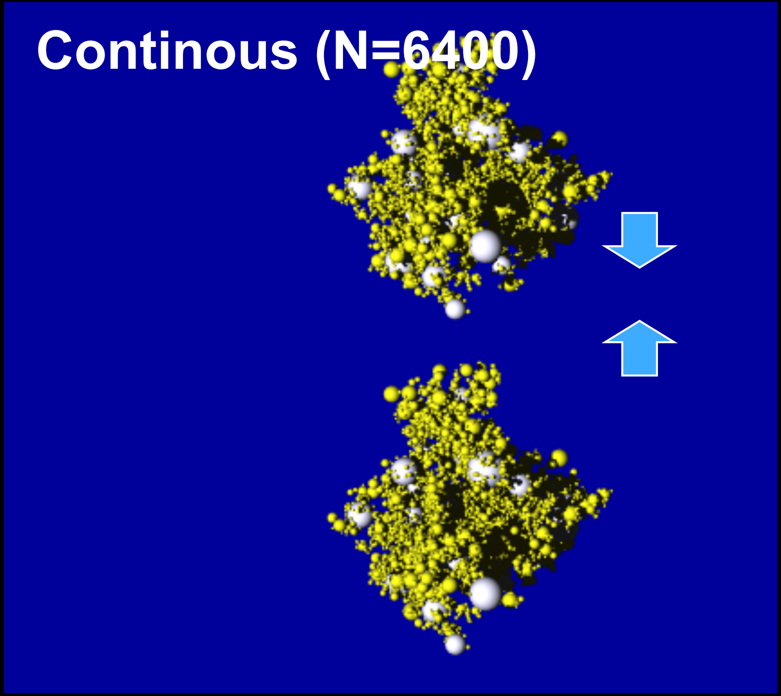
- Particle size distribution $n(r)dr \propto r^{-3.5}\,dr$

•r = 0.1μm×100, 0.025μm×3200 (binary: total mass=0.1×150)

•r = 0.1μm×200, 0.025μm×6400 (binary: total mass=0.1×300)

•r = 0.2 - 0.025μm, N=6600 (continuous: total mass=0.1×201.6)



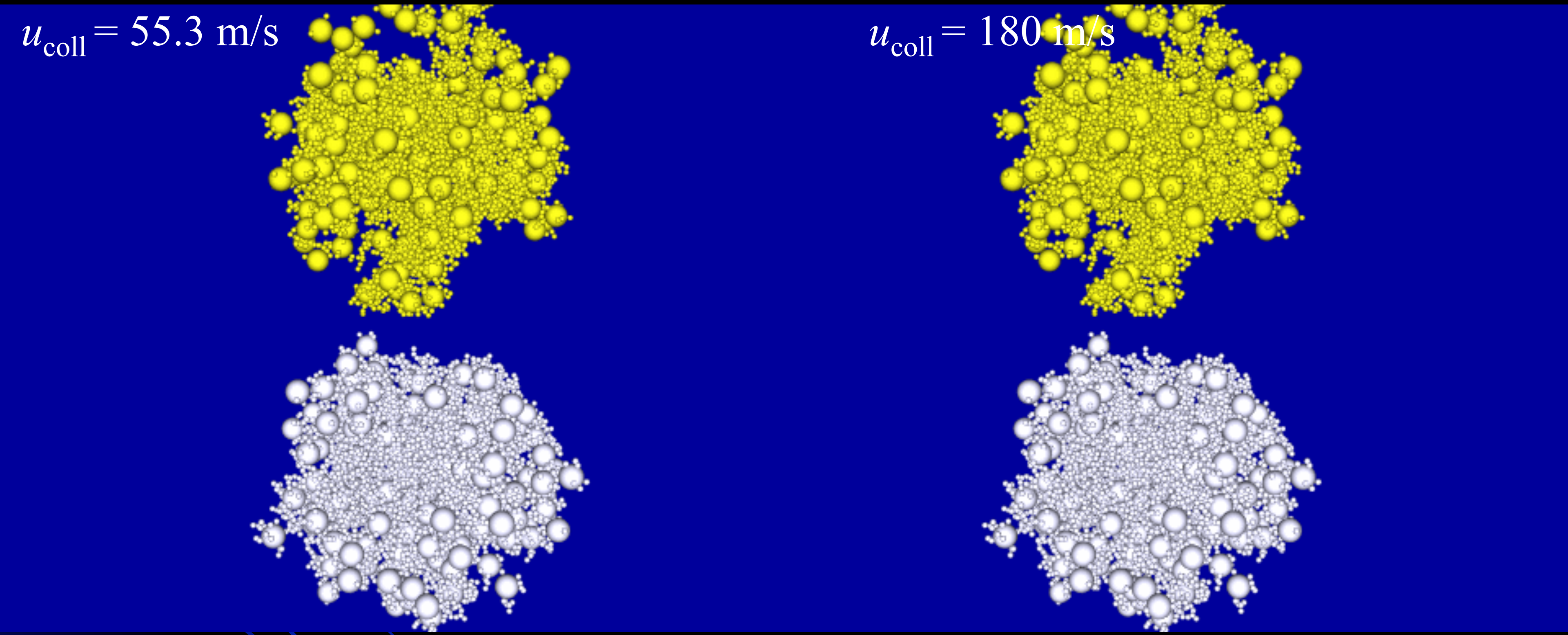


✓Ice (E = 7.0·10^{10} Pa, ν = 0.25, γ = 100 mJ/m^2) , critical rolling displace. ξ_{crit} = 8Å

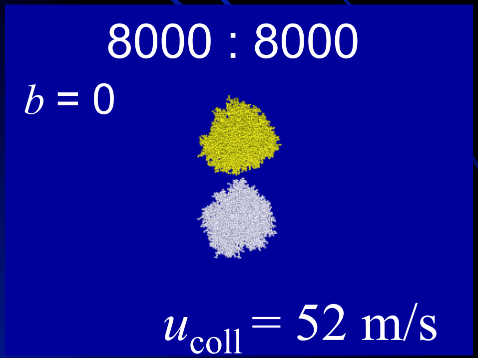
✓Collision velocity u_{coll} = 20 - 700 m/s

Examples of simulations

- r=0.1μm×200, 0.025μm×6400 (binary: total mass=0.1×300)



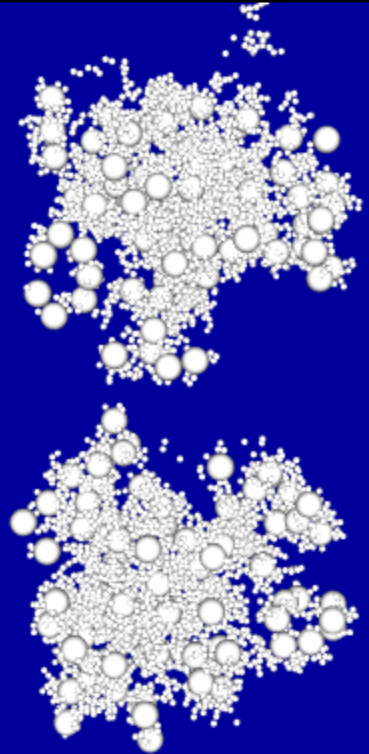
No.11

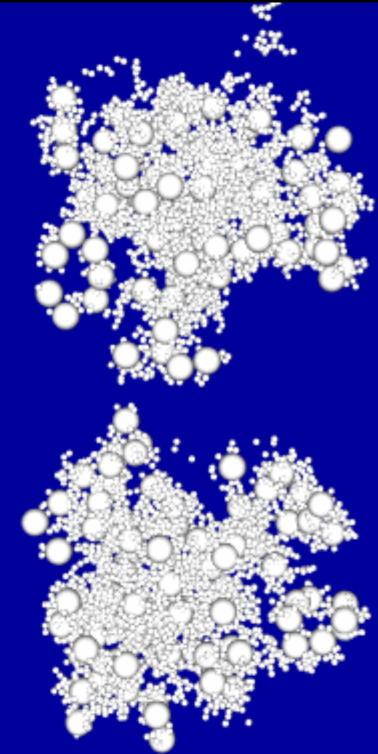


No.20

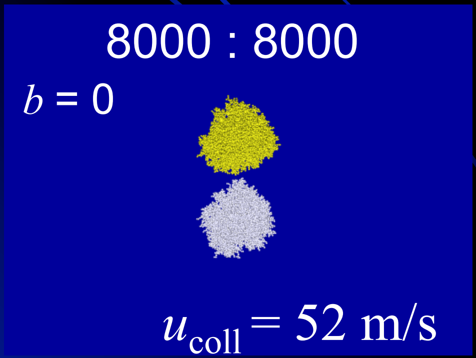
Examples of simulations

• r=0.1μm×200, 0.025μm×6400 (binary: total mass=0.1×300)





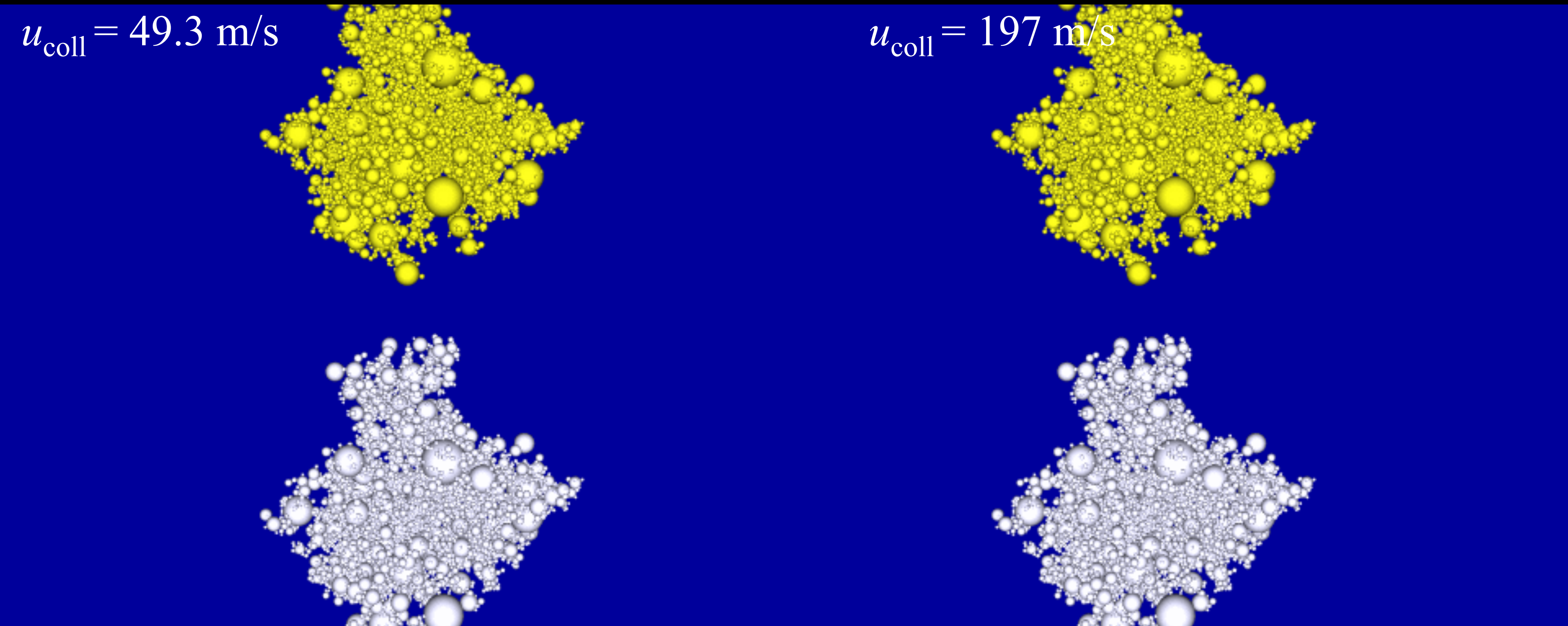
No.11



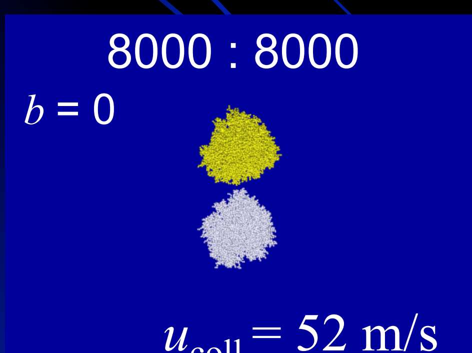
No.20

Examples of simulations

- r=0.2μm - 0.025μm N=6600 (continuous: total mass=0.1×201.6)



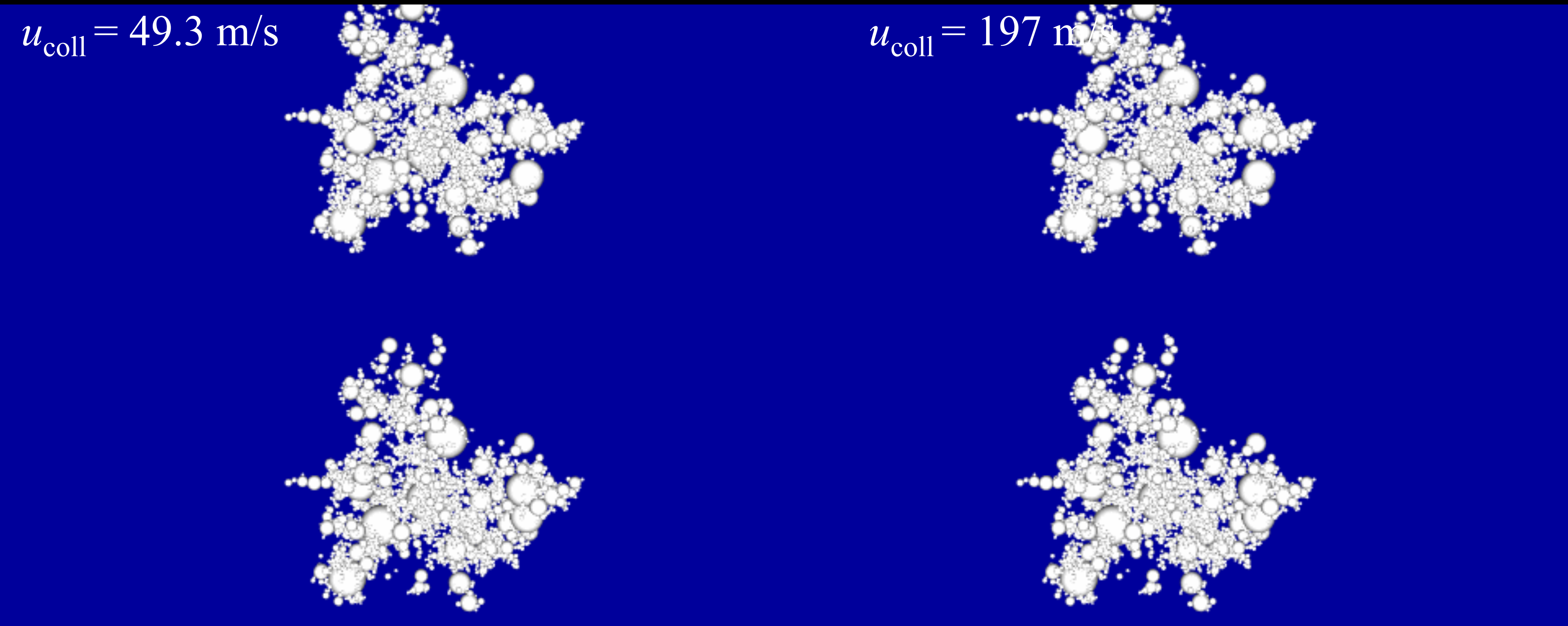
No.09



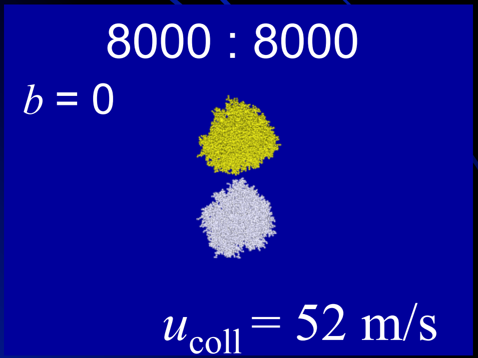
No.15

Examples of simulations

• r=0.2μm - 0.025μm N=6600 (continuous: total mass=0.1×201.6)

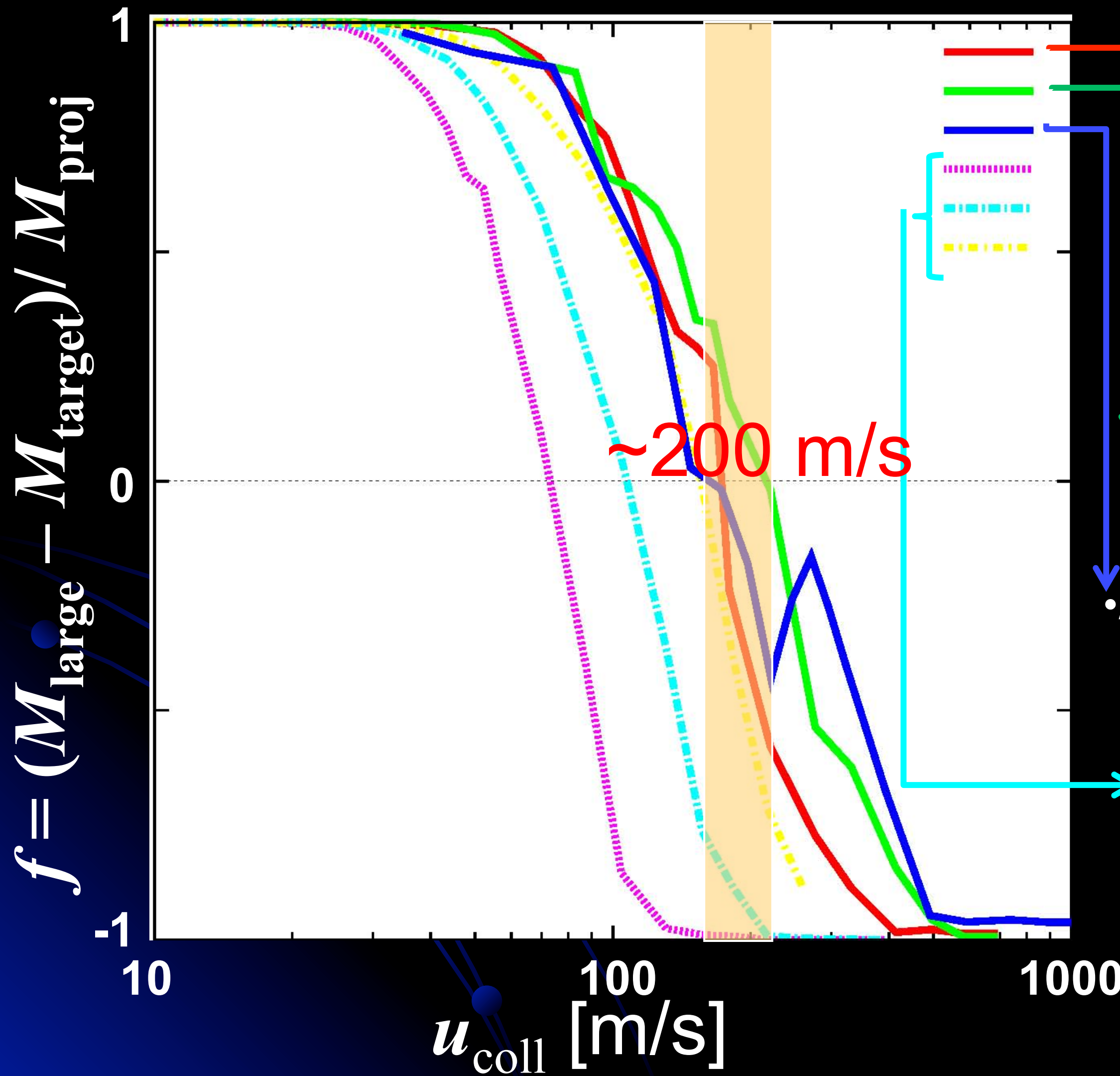


No.09



No.15

Growth efficiency (ice)



$f \equiv (M_{\rm large} - M_{\rm target}) / M_{\rm proj}$: growth efficiency

$f > 0$ → mass gain

$f < 0$ → mass loss

- r=0.1μm×100, 0.025μm×3200 (binary:150+150)
- r=0.1μm×200, 0.025μm×6400 (binary:300+300)
- r=0.2μm - 0.025μm, N=6600 (continuous:201.6+206.1)
- BPCA (500+500)
- BPCA(2000+2000)
- BPCA(8000+8000)

Summary and Implication

Simulations of collisions of aggregates composed of particles with a size distribution

- Particle size distribution leads to large growth efficiency.

  ⇒ encouraging dust growth and planetesimal formation

- The critical collision velocity $u_{\rm coll,crit}$ is unchanged?

$u_{\rm coll,crit}$ for ice ~ 200 m/s

$u_{\rm coll,crit}$ for silicate = 0.1×$u_{\rm coll,crit}$ for ice ~ 20 m/s

Caution! These $u_{\rm coll,crit}$ are for head-on collisions.

Offset collisions must be investigated.

Can dust grow through collisions?