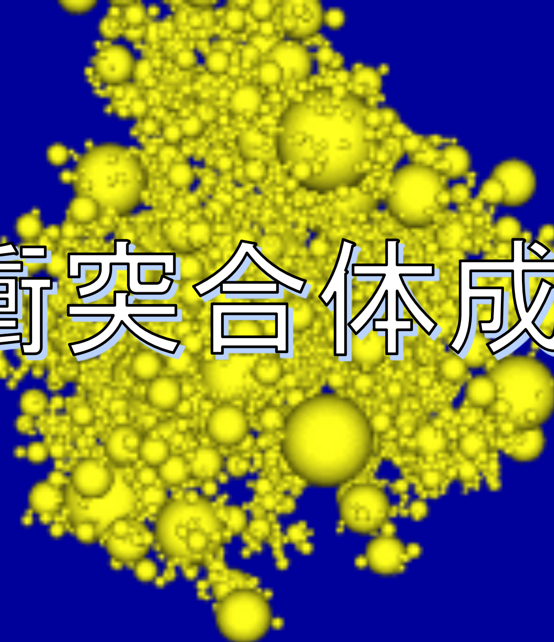
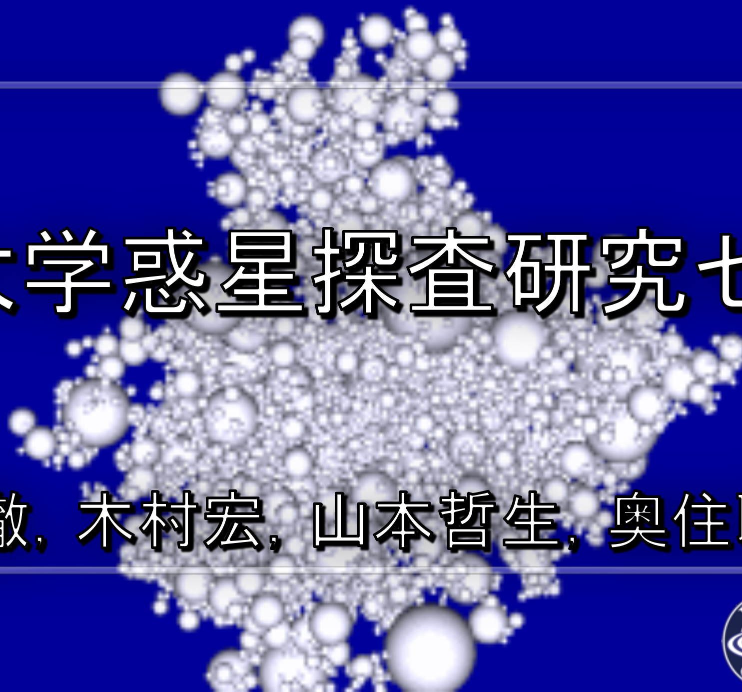
ダストの衝突合体成長と破壊





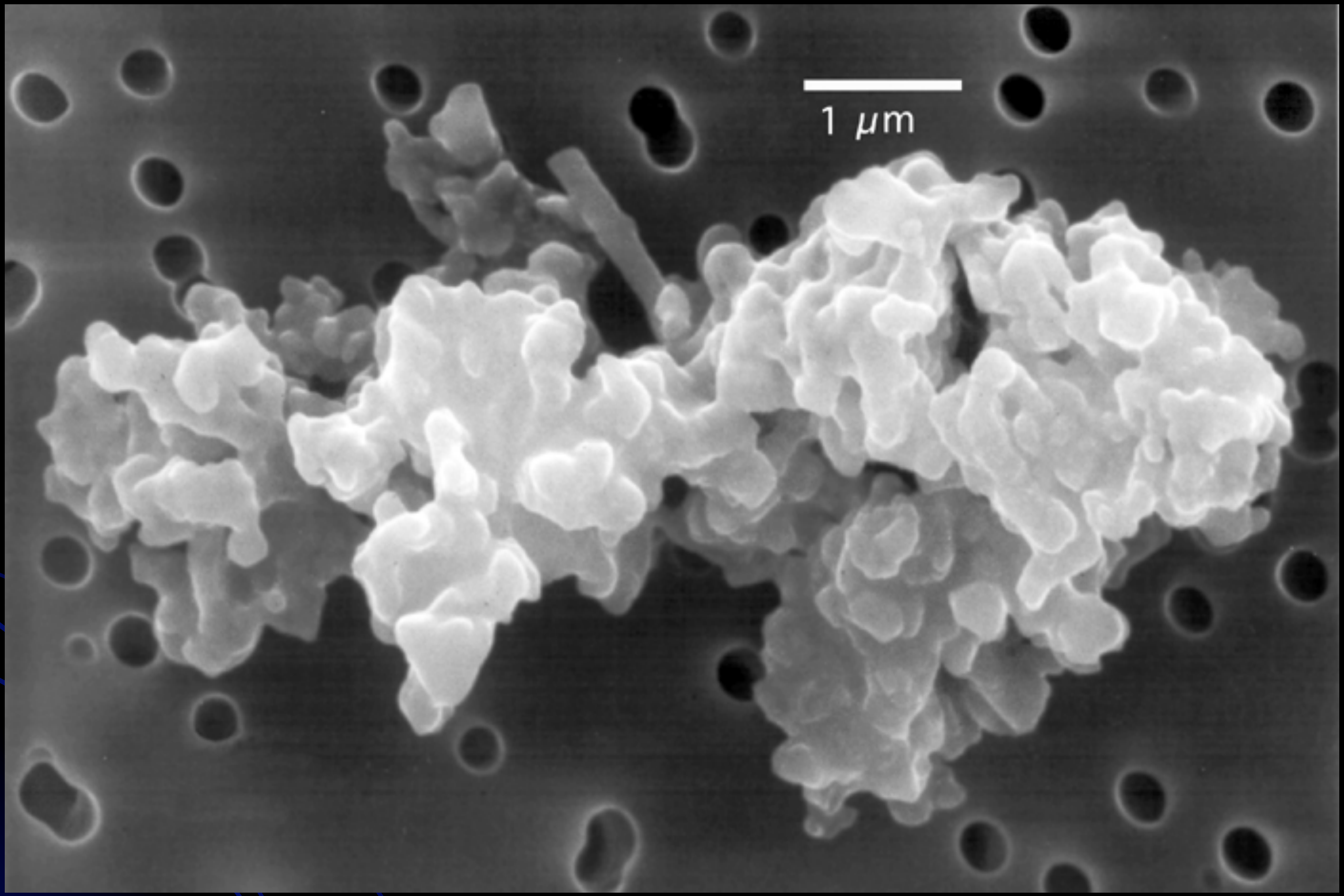
和田浩二
千葉工業大学惑星探査研究センター

共同研究者:
田中秀和, 陶山徹, 木村宏, 山本哲生, 奥住聡, 小林浩

本日の目的

- 原始惑星系円盤のダストの具体的なイメージを共有する.
- シミュレーション計算結果を堪能する.

ダストとは？



Interplanetary Dust Particle

ダストとは

- 星間ダスト　from interstellar extinction (Mathis, Rumpl, & Nordsieck 1977)
  - r = ~ 0.025 - 0.25 μm
  - Power-law with an exponent of -3.3 to -3.6
- 原始惑星系円盤では…
  - ～0.1 μm のモノマーから構成されるアグリゲイト
  - 衝突合体によって成長していく
  - 微惑星になる前を「ダスト」と呼ぶ…→>kmのダスト!

微惑星形成の問題点

- ダスト層の重力不安定
  - 乱流によってダスト層は薄く(高密度)になれない
    - 円盤の厚さ(スケールハイト)の~10^{-4}まで薄くなる必要
- ダストの直接合体成長
  - 中心星へ落下してしまう?
  - 数十m/s の衝突速度で合体できるのか?
  - 合体せずに反発する?

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 ?

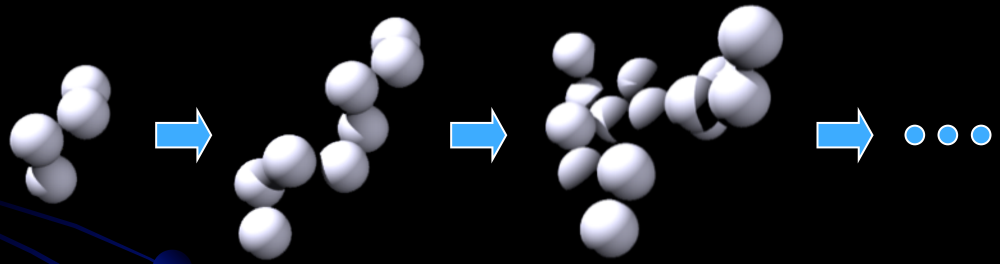
✓Can dust aggregates grow through collisions?

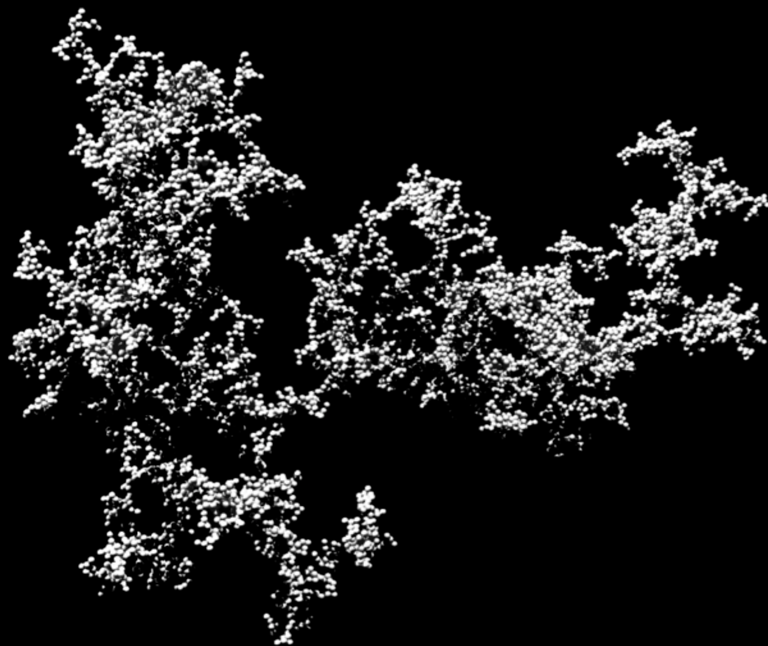
→ **Numerical simulation of dust aggregate collisions!**

Ballistic Cluster-Cluster Aggregation (BCCA)

✓In the early growth stage, undeformed BCCAs are formed because of their low collision velocity (< mm/s)

- A series of hit-and-sticks of comparable aggregates





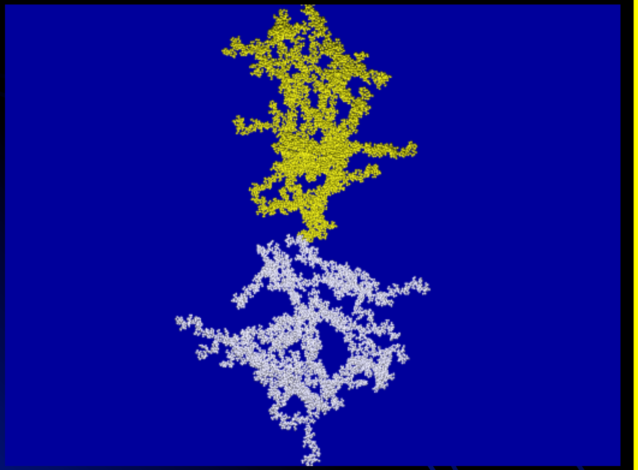
- Fluffy structure (fractal dimension d_f < ~ 2)

(Smirnov 1990; Meakin 1991; Mukai et al. 1992; Kempf et al. 1999; Blum & Wurm 2000; Krause & Blum 2004; Paszun & Dominik 2006)

Three(?) stages of collisional growth

Compression

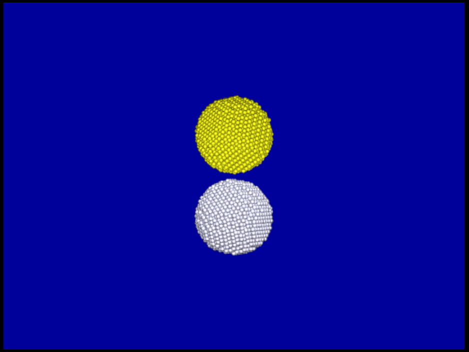
Low velociy

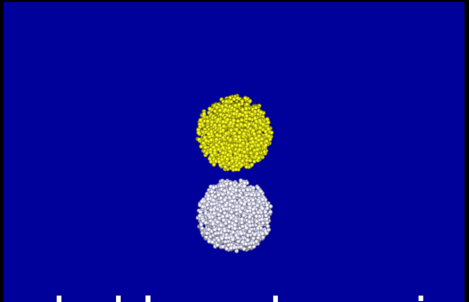


Not fully compressed

Wada et al. 2008, ApJ 677, 1296-1308;
Suyama et al. 2008, ApJ 684, 1310-1322

Bouncing?



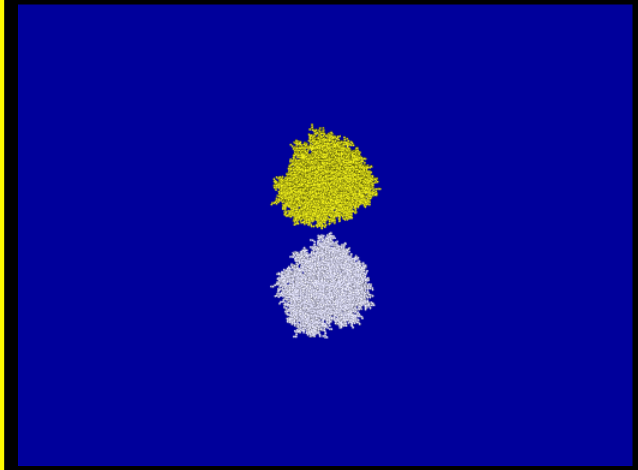


probably no bouncing

Wada et al. 2011, ApJ 737, 36 (12pp)

Disruption

High velocity



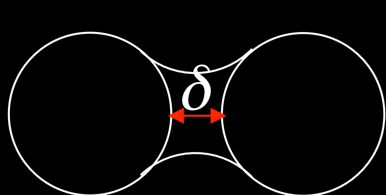
Wada et al. 2009, ApJ 702, 1490-1501
Wada et al. 2013, A&A 559, A62

Grain interaction model

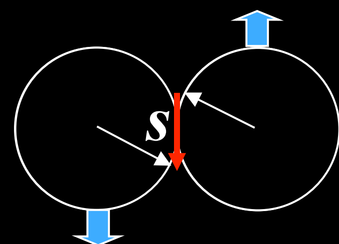
Johnson, Kendall and Roberts (1971)
Johnson (1987), Chokshi et al. (1993)
Dominik and Tielens (1995,96)
Wada et al. (2007)

Elastic spheres having surface energy

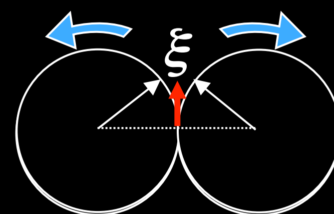
Normal



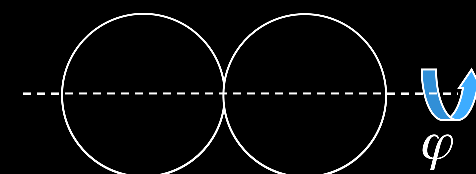
Sliding



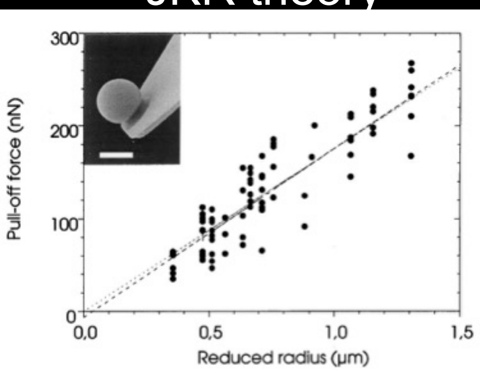
rolling



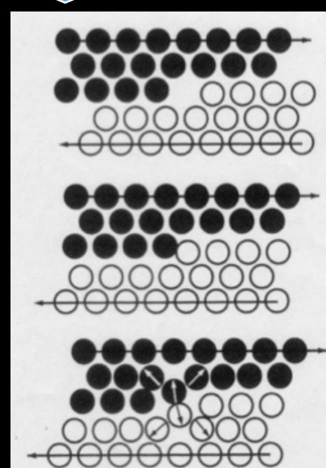
twisting



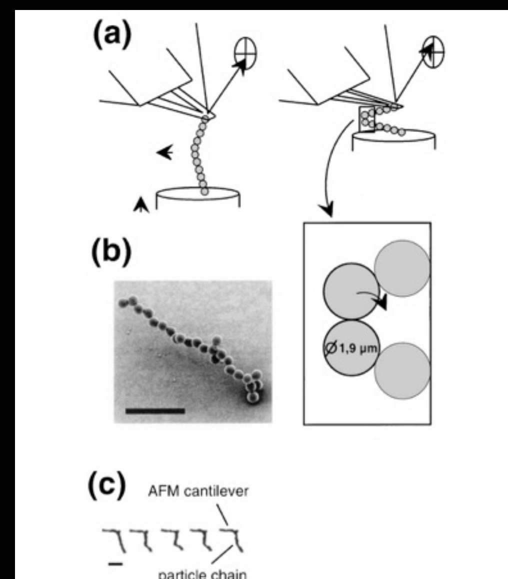
JKR theory



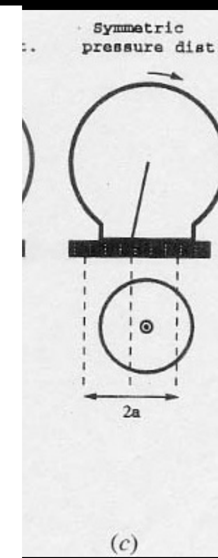
(Heim et al. 1999)



(Dominik & Tielens 1996)



(Heim et al. 1999)



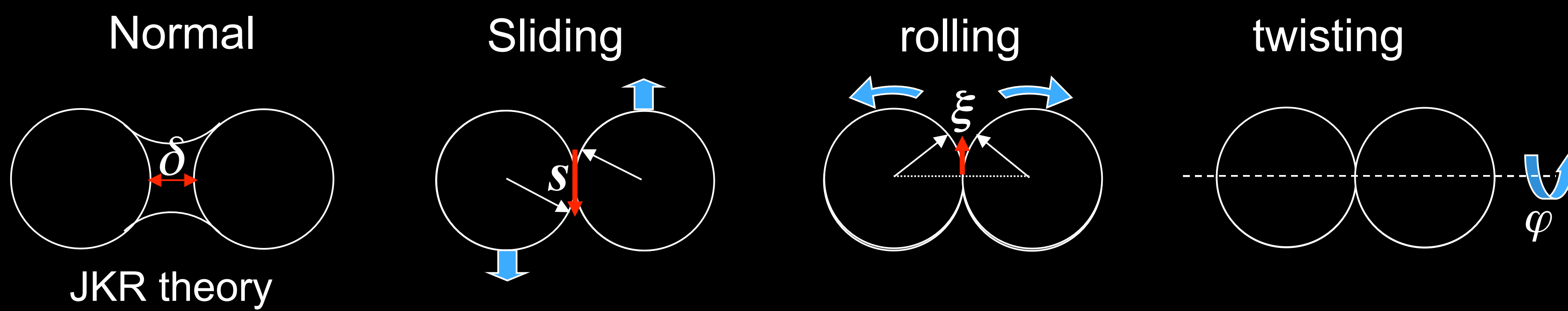
(Dominik & Tielens 1995)

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

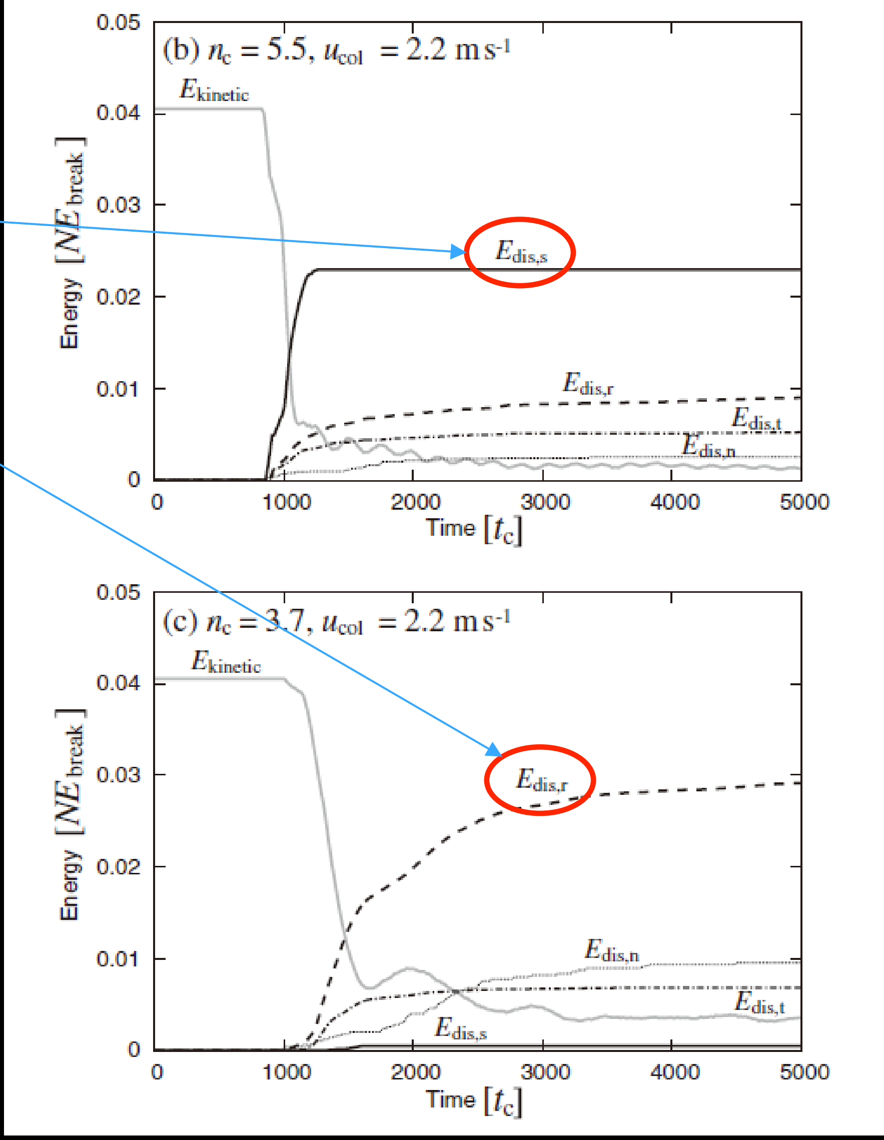
- Critical slide s_{crit} ~ **1.5 Å** (for 0.2 μm quartz)
- Critical roll ξ_{crit} ~ **2 Å** (or ~**30 Å** (Heim et al.,1999))
- Critical twist φ_{crit} ~ **1°**

E_{break} : Energy to break a contact

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

アグリゲイトの衝突時のエネルギー散逸の仕方

- 変形困難(破壊的):
  - すべりでエネルギー散逸
- 変形可能:
  - 転がりでエネルギー散逸



(Wada et al. 2011)

Collisions between BCCA clusters

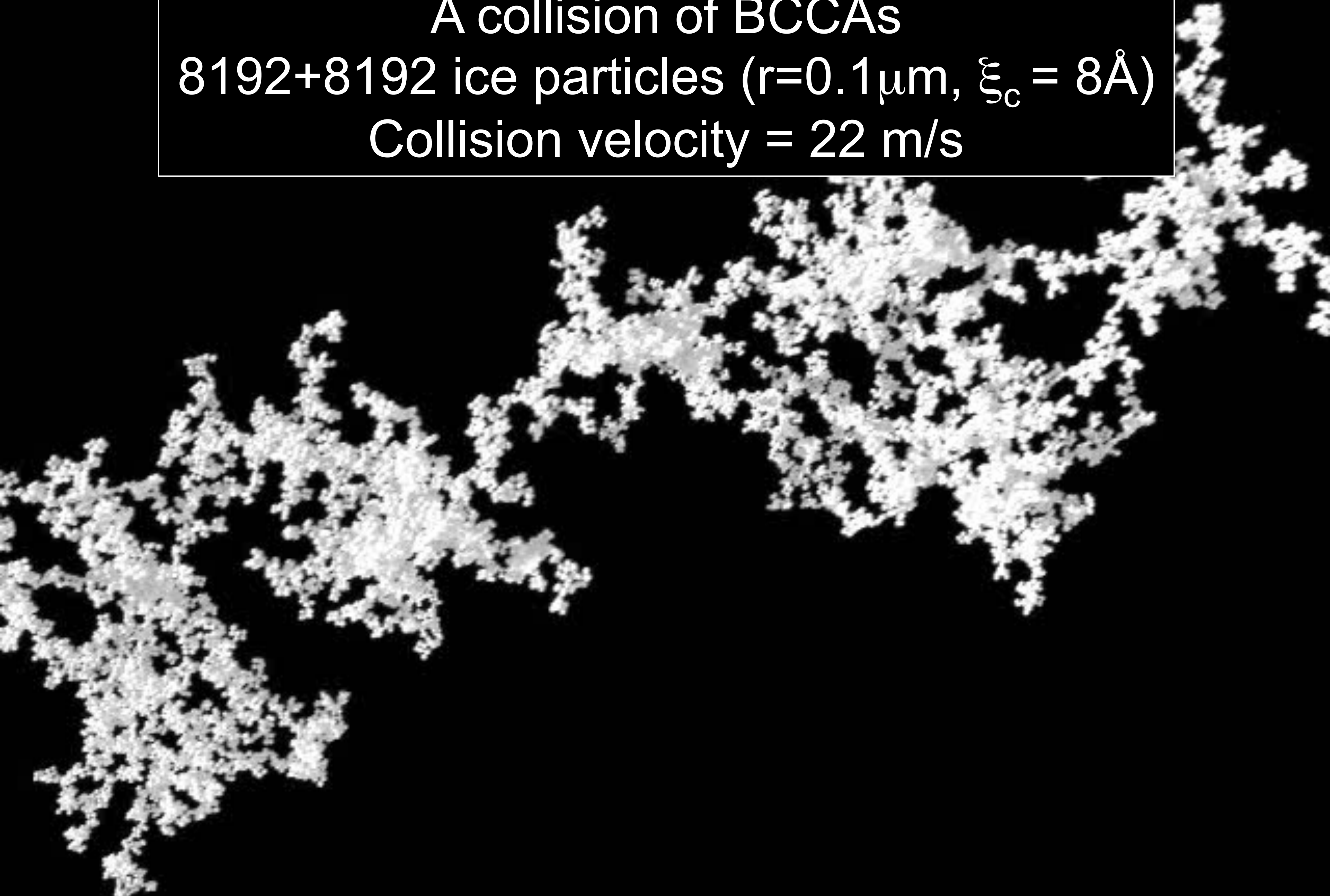
: Compression process

To be compressed, or not to be?

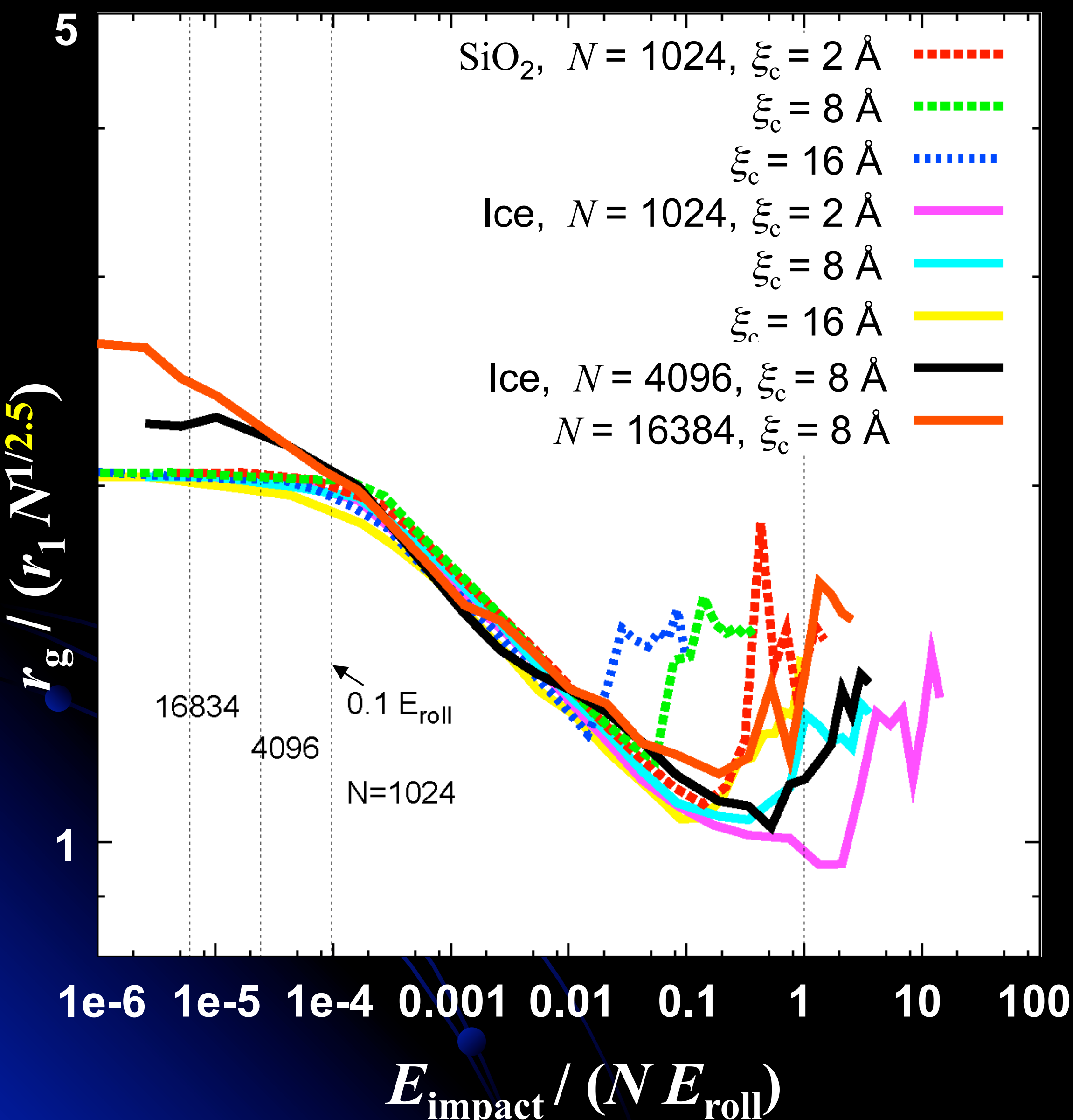
A collision of BCCAs

8192+8192 ice particles ($r=0.1\mu m$, $\xi_c = 8$Å)

Collision velocity = 22 m/s



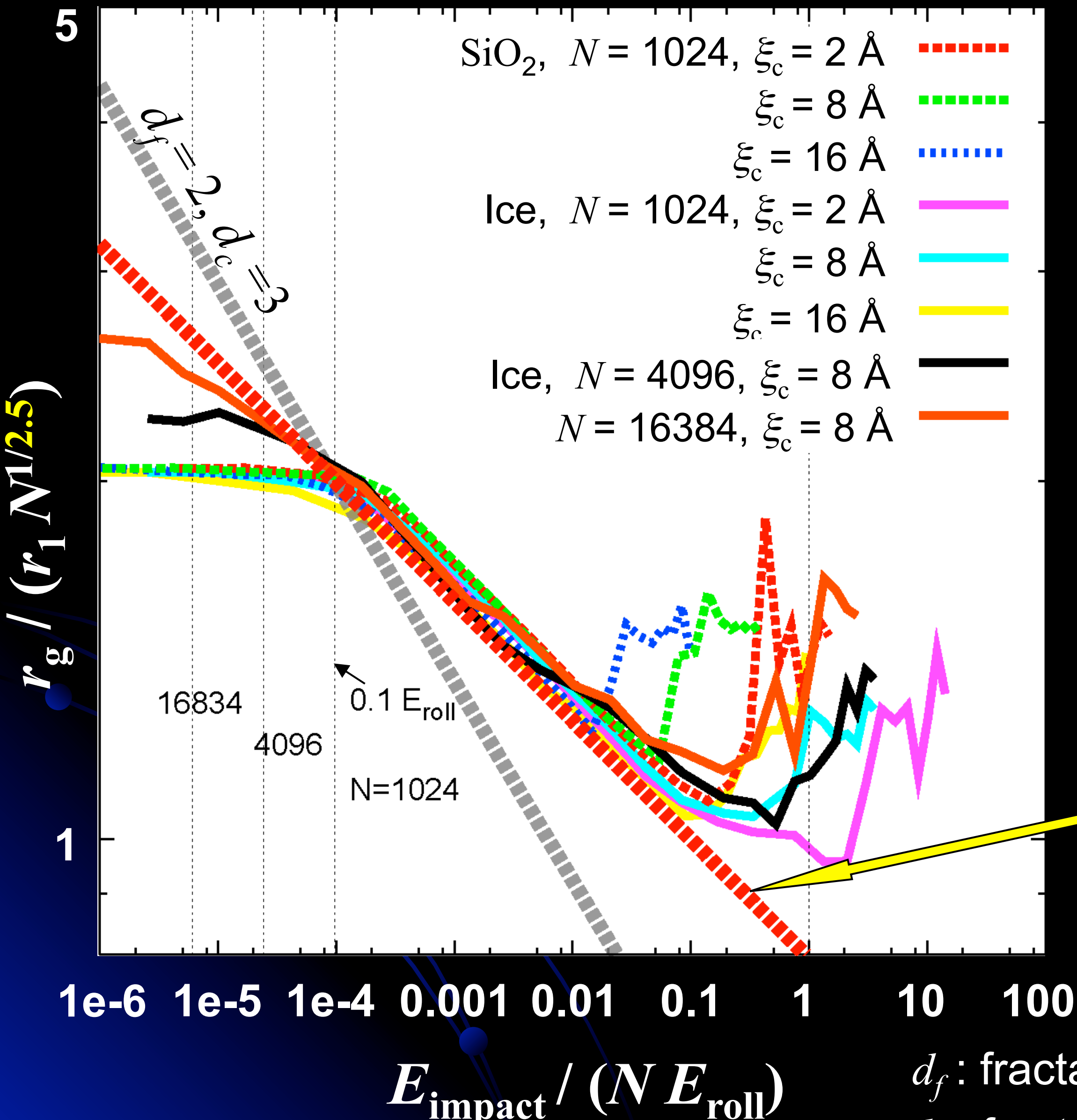
Gyration radius r_g : *compression process*



✓Scaled by $E_{impact} / (N E_{roll})$

✓r_g is normalized by $r_1 N^{\frac{1}{2.5}}$

Gyration radius r_g : *compression process*



✓Scaled by $E_{impact} / (N E_{roll})$

✓r_g is normalized by $r_1 N^{\frac{1}{2.5}}$

✓Not fully compressed

$$\frac{r_g}{r_1 N^{1/2.5}} \approx 0.8 \left(\frac{E_{impact}}{N E_{roll}} \right)^{-0.1}$$

($d_f = 2$, $d_c = 2.5$)

d_f : fractal dimension of BCCA

d_c : fractal dimension of max. compression

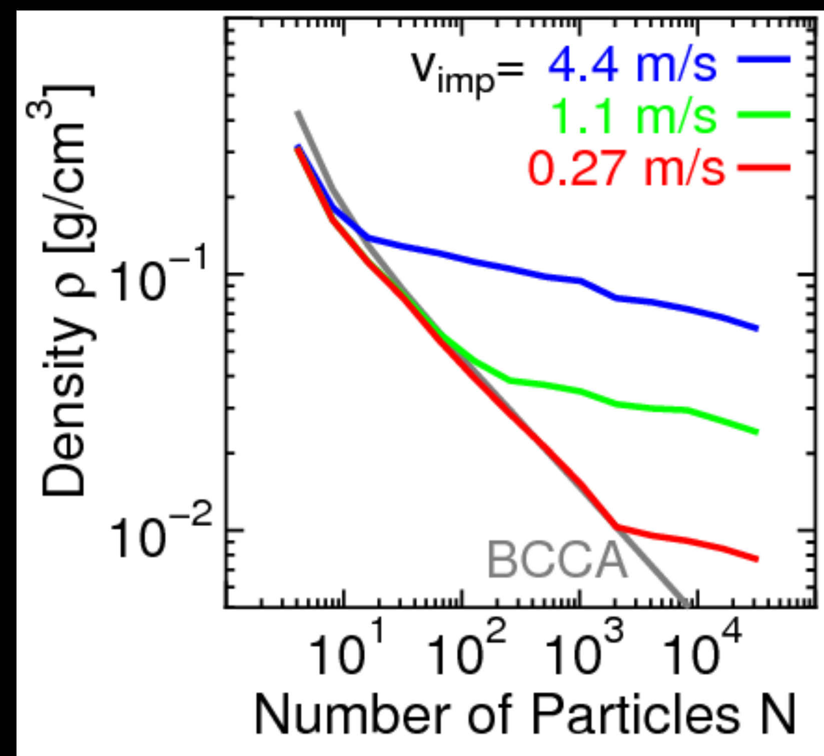
Successive collisions in a BCCA mode

Suyama et al. 2008

✓Fractal dimension ~2.5

✓Decrease in density

CG by Dr. T. Takeda, 4D2Uproject, NAOJ



Lesson 1

- Dust aggregates remain fluffly (fractal dimension ~ 2.5) .

  Very fluffy planetesimals could be formed !?

  ~10^{-4} g/cc (Suyama et al. 2008)

What processes compress aggregates more?

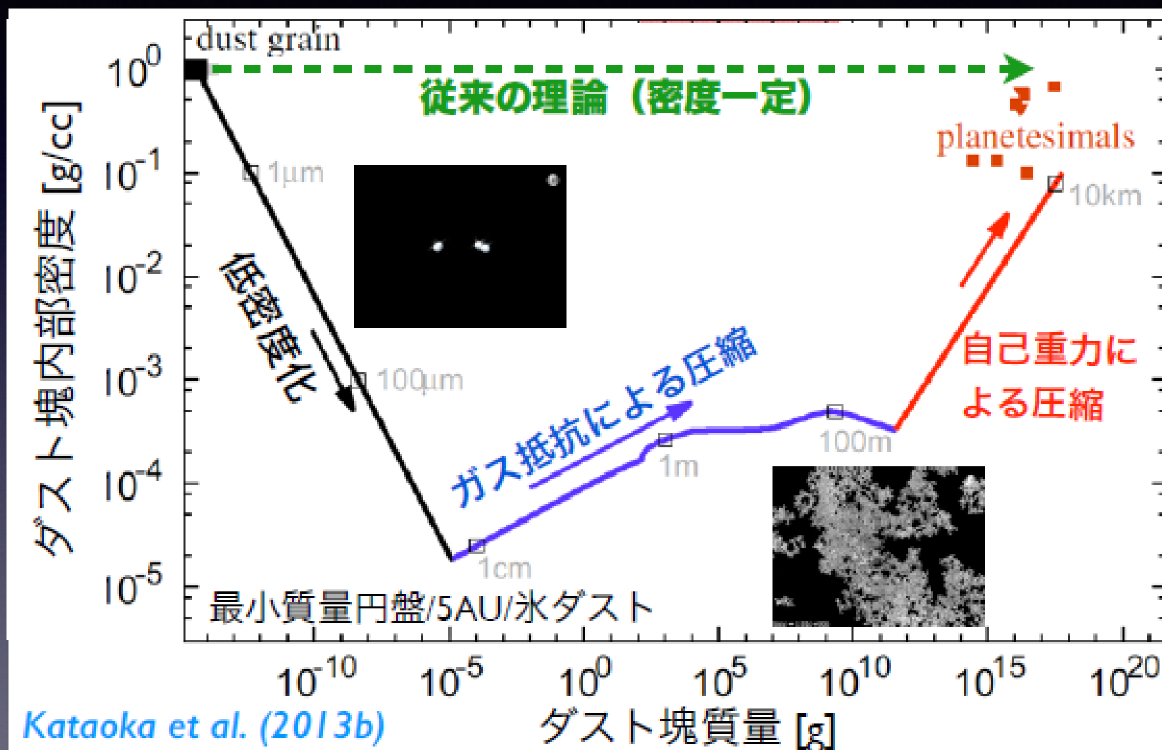
Gas pressure & self gravity could compress aggregates (Kataoka et al. 2013a, b)

その後の圧縮過程：ガス圧と自己重力

ダスト内部密度進化曲線

（奥住スライド）

衝突密度進化公式： *SO+(2009); Suyama, Wada, Tanaka, & SO (2012)*
静的密度進化公式： *Kataoka, Tanaka, SO, & Wada (2013a)*



初期の低速衝突 + 弱いガス圧 ➡ 極低密度ダストの形成

Collisional Growth Conditions

To be disrupted, or not to be?

Background

Collision velocity of dust in protoplanetary disks — up to several 10 m/s

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

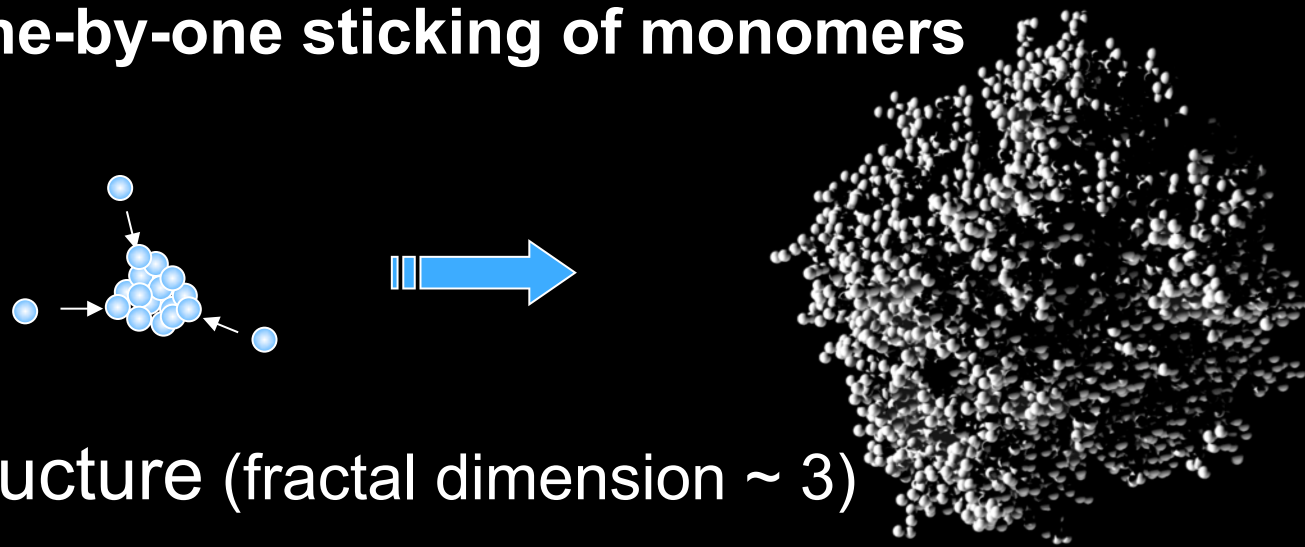
↓

Is it possible for dust to grow through collisions ?

Mass gain at head-on collisions of > 10 m/s in experiments (Wurm et al. 2005, 2011; Teiser & Wurm 2009)

Ballistic Particle-Cluster Aggregation (BPCA)

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



- Compact structure (fractal dimension ~ 3)

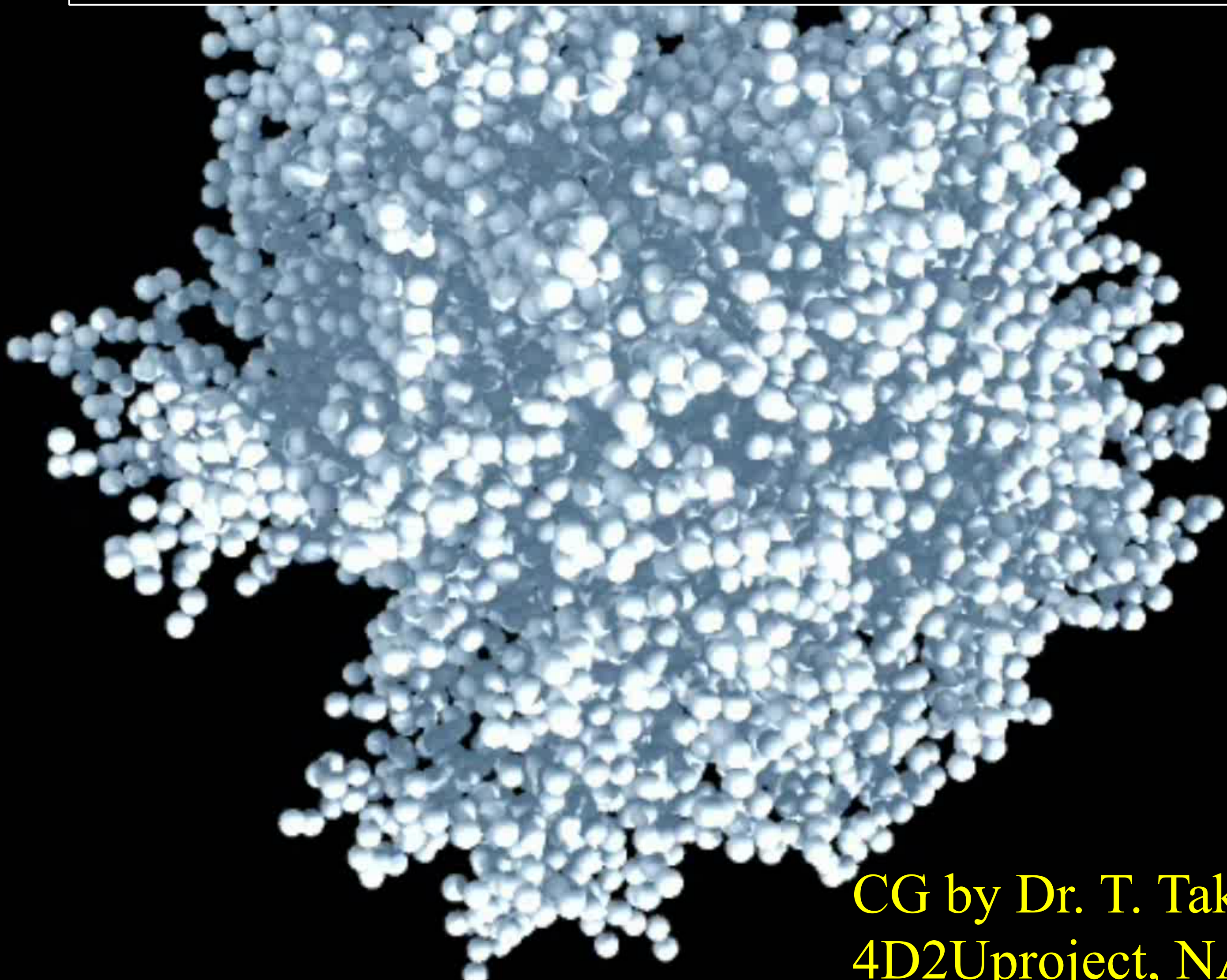
Dust is expected to be compact

at high velocity collisions causing their disruption

Collisions of BPCA clusters

→ implication for growth and disruption of dust

A collision of BPCAs
8000+8000 ice particles (r=0.1μm, ξ_c = 8Å)
Collision velocity = 57 m/s



CG by Dr. T. Takeda,
4D2Uproject, NAOJ

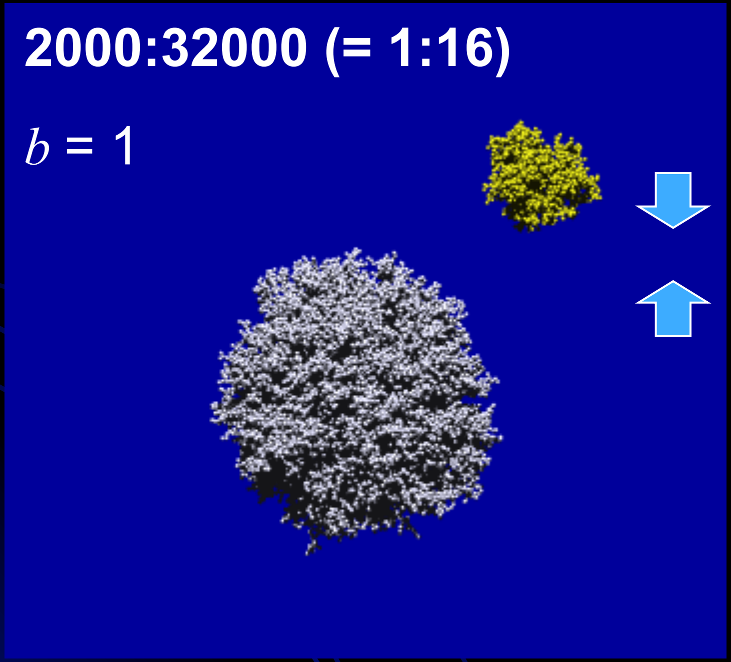
Collisions of BPCAs with relatively high mass ratios

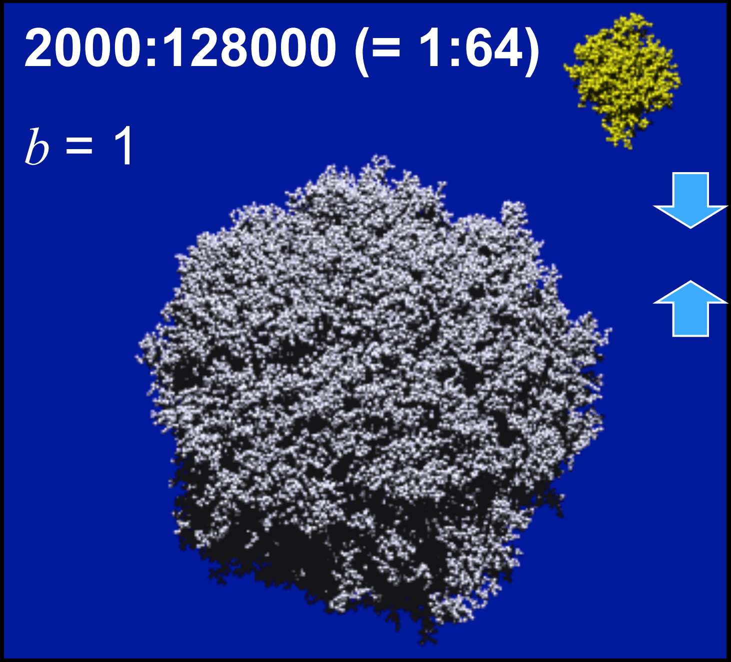
Initial Conditions and Parameters

Collisions of BPCA clusters: projectile vs. target

- Size ratio = 1 : 16 (2000:32000, 8000:128000)
  1 : 64 (500:32000, 2000:128000, 8000:512000)

- Impact parameter : b (defined by using characteristic radius)



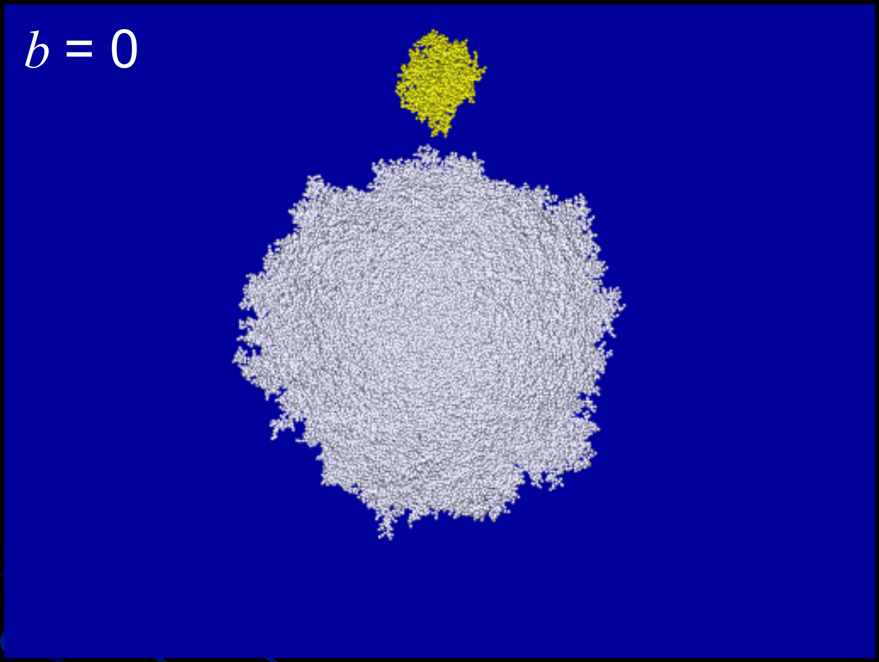


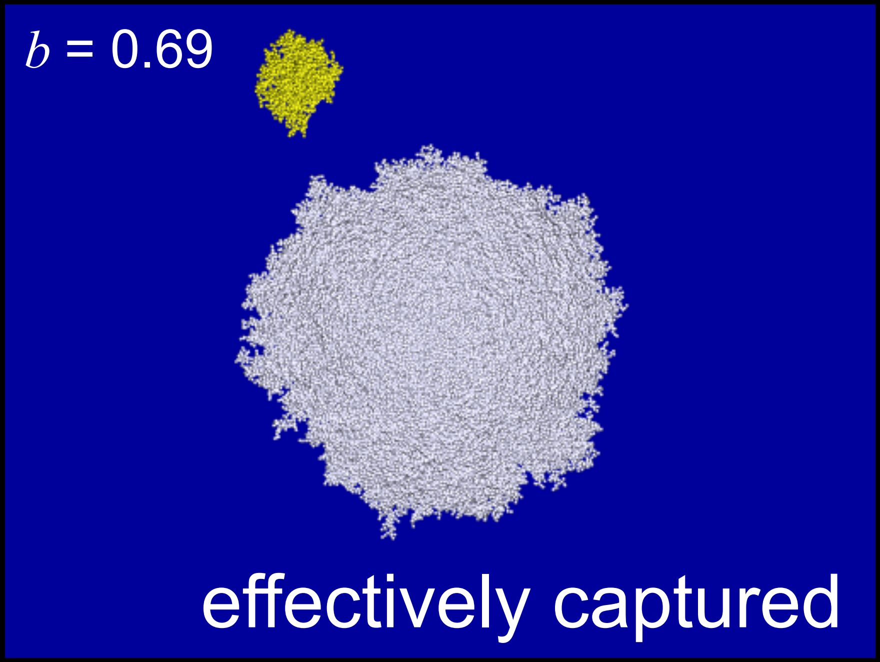
✓Ice (E = 7.0·10^{10} Pa, ν = 0.25, γ = 100 mJ/m^2, R = 0.1μm) , critical rolling displace. $\xi_{\rm crit}$ = 8

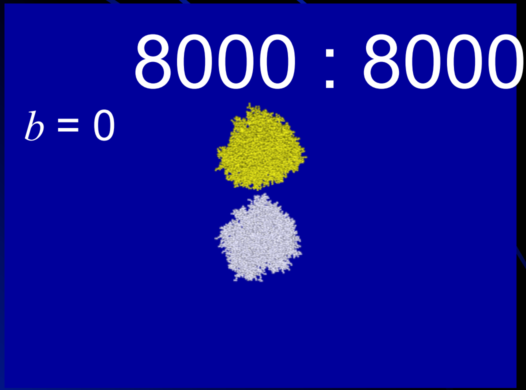
✓Collision velocity $u_{\rm coll}$ = 15 - 300 m/s

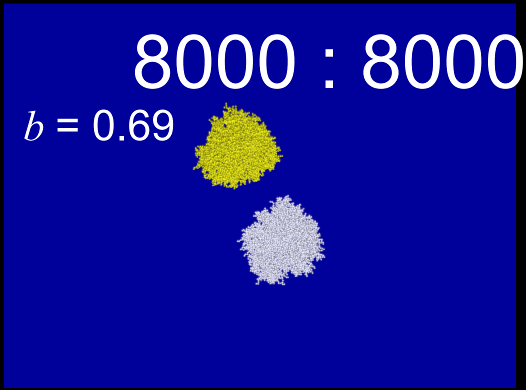
Examples of simulations

2000 : 128000 (= 1 : 64) ice, $u_{\mathrm{coll}} = 52$ m/s



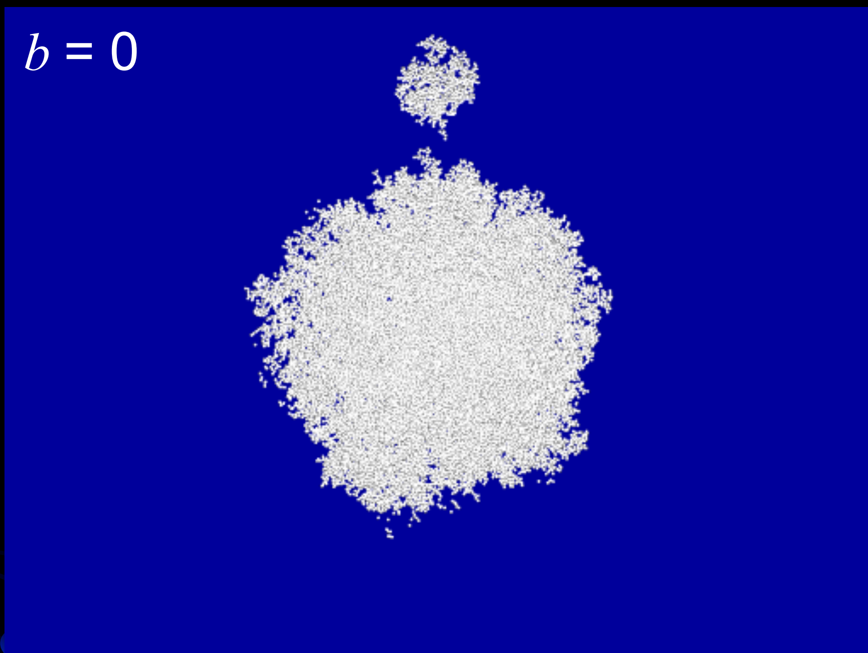


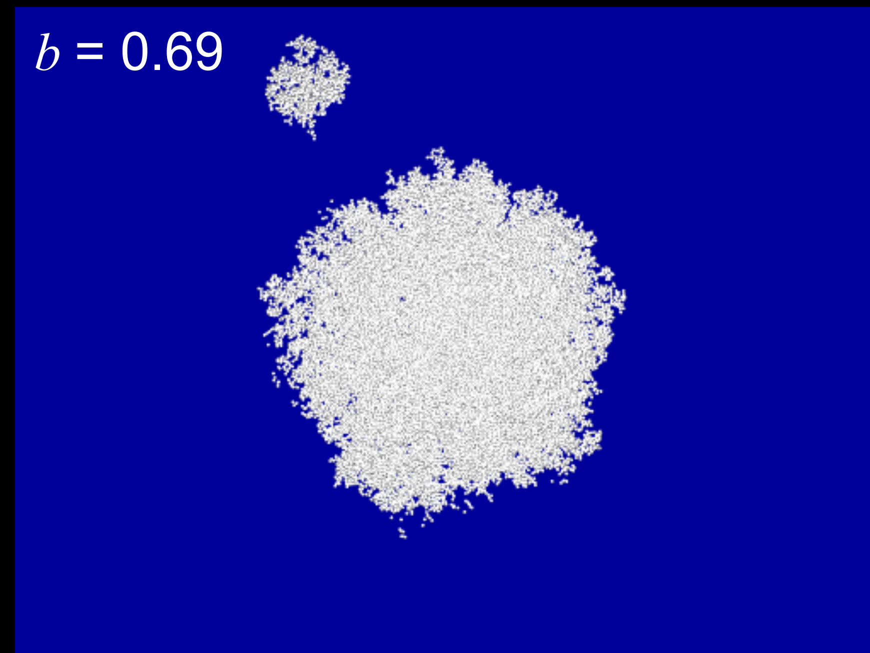




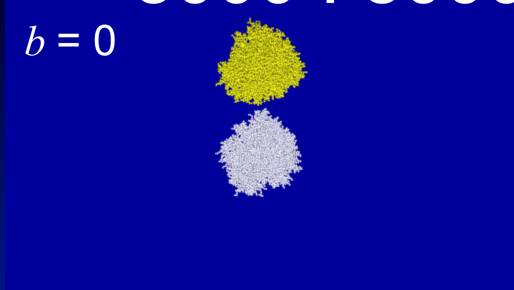
Examples of simulations

2000 : 128000 (= 1 : 64) ice, $u_{\mathrm{coll}} = 52$ m/s

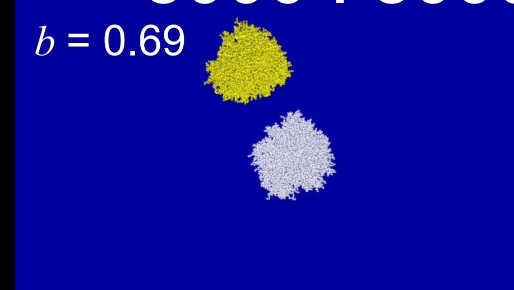




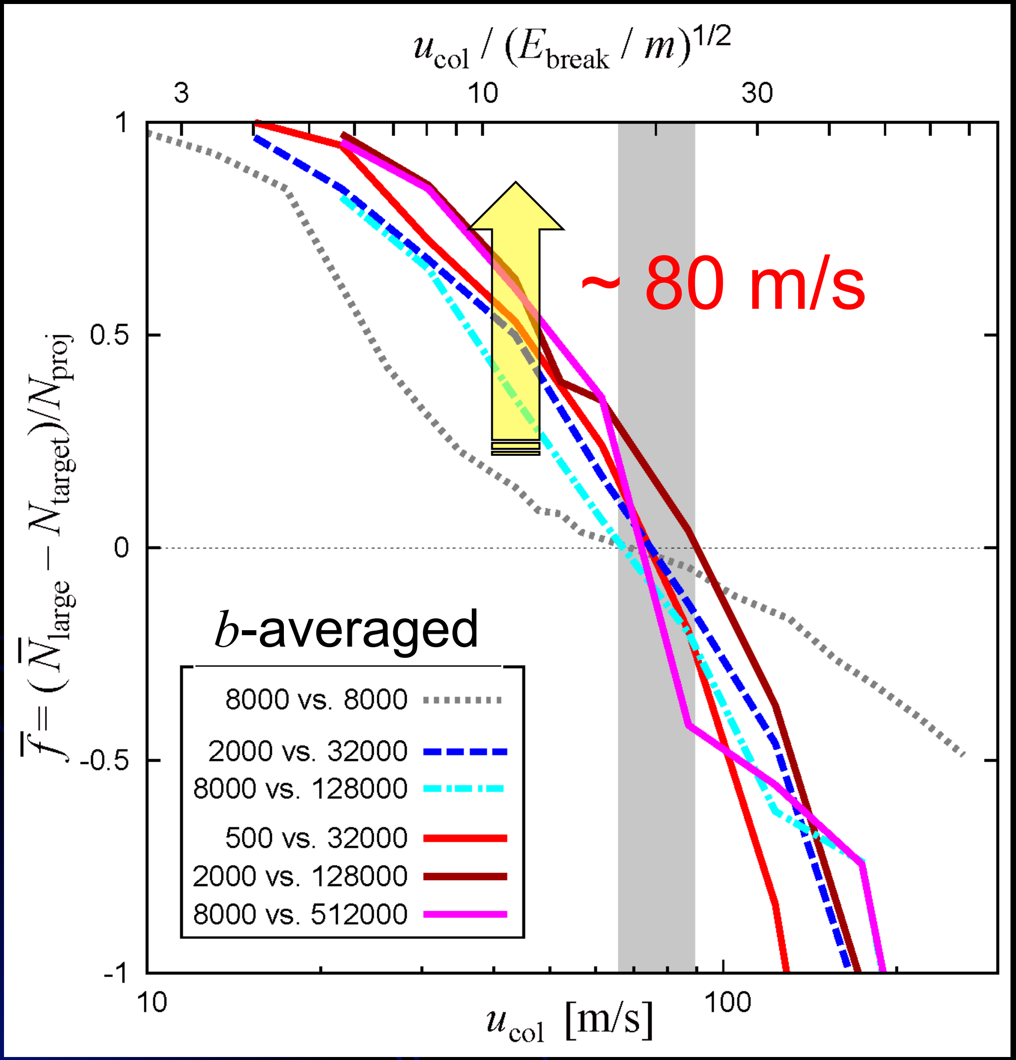
8000 : 8000



8000 : 8000



Growth efficiency (ice)



$f \equiv (N_{large} - N_{target}) / N_{proj}$

: growth efficiency

$f > 0 \rightarrow$ mass gain

$f < 0 \rightarrow$ mass loss

No size dependence

Dependent on size ratio?

The larger ratio, the more gain.

The critical velocity

~ 80 m/s

Lesson 2

- Icy aggregates can grow at collision velocity < 80 m/s.

Icy planetesimals can be formed through collisions of icy dust.

- Large size-ratio leads to large growth efficiency.

  ⇒ encouraging dust growth and planetesimal formation

Can silicate dust grow?

Critical velocity for silicate is 10 times smaller than that for ice.

⇒ 8 m/s is too small!

Do collisions of aggregates having monomer size distributions encourage dust growth?

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

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

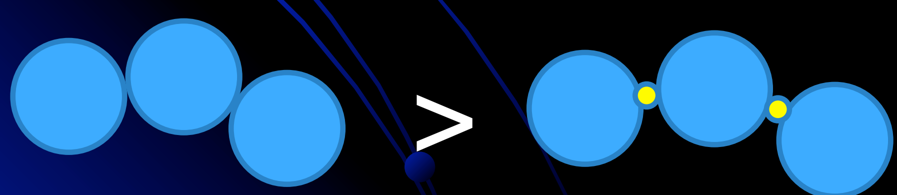
v_c increases with decreasing reduced radius R.

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



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

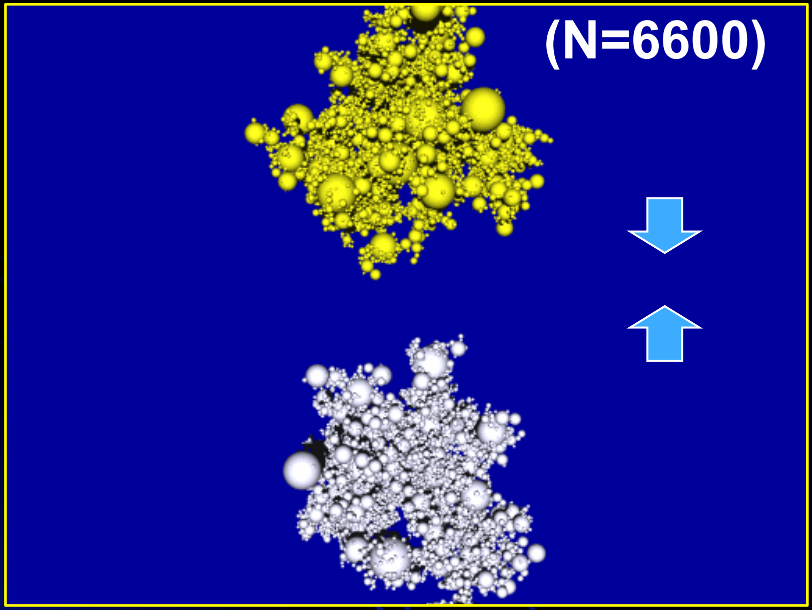
Initial Conditions and Parameters

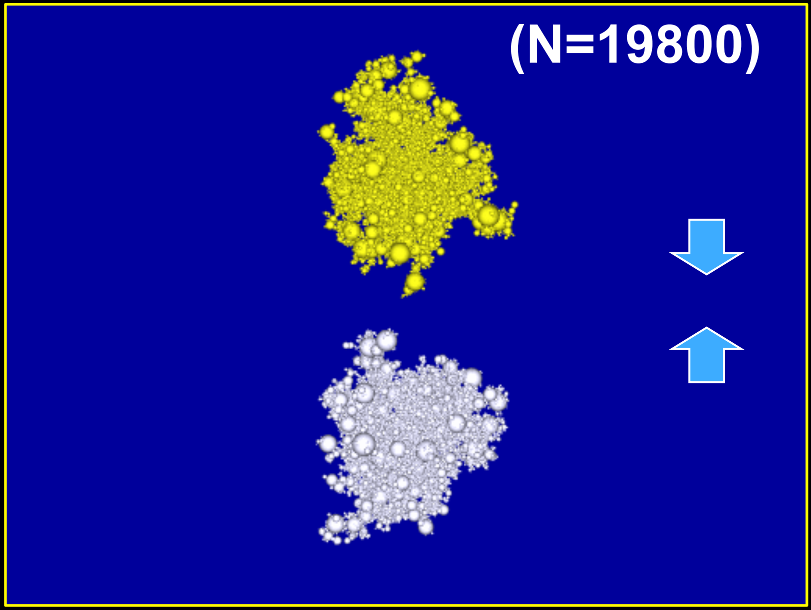
- Monomer size distribution $n(r)dr \propto r^{-3.5}\,dr$

•r = 0.2 - 0.0125μm, N=6600 (continuous: total mass=209.1mu)

•r = 0.2 - 0.0125μm, N=19800 (continuous: total mass=634.4mu)

mu: mass unit defined by the mass of 0.1μm-radius particle



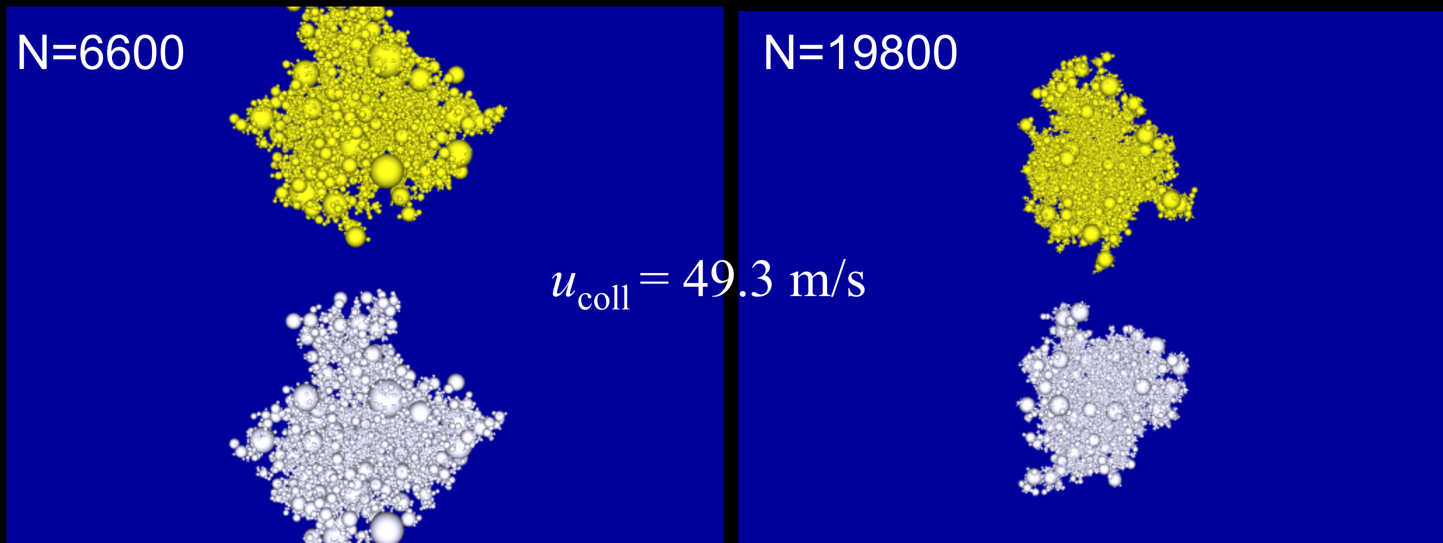


✓Ice (E = 7.0·10^{10} Pa, ν = 0.25, γ = 100 mJ/m^2) , critical rolling displace. ξ_{crit} = 8Å

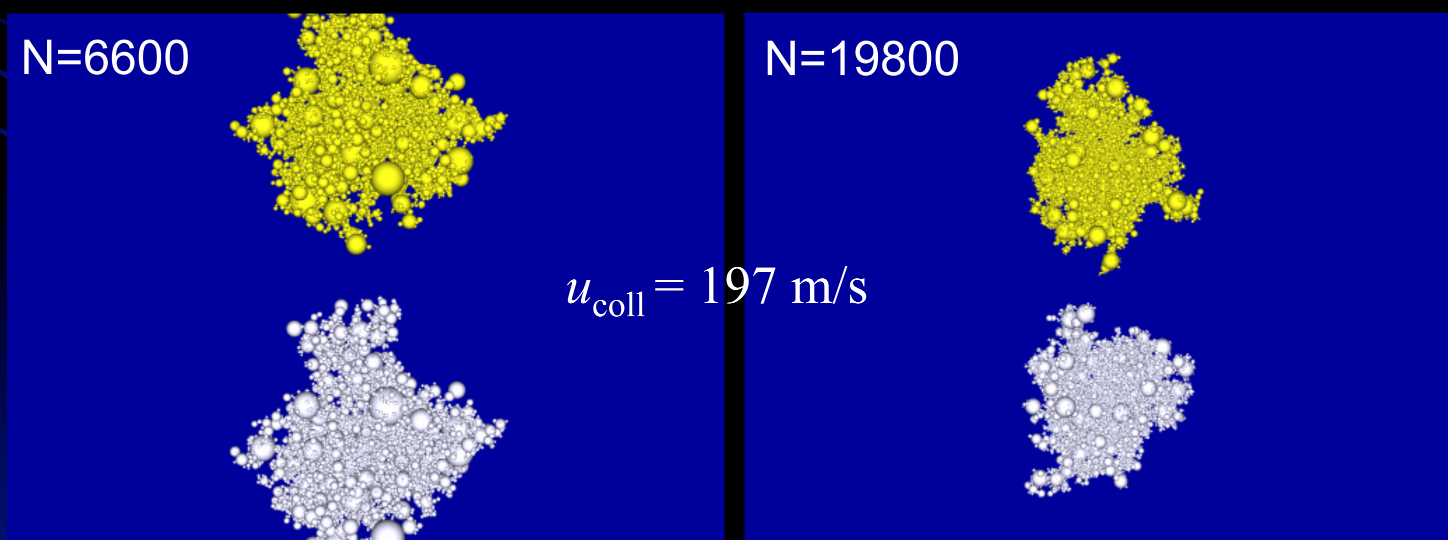
✓Collision velocity $u_{coll} =$ 20 - 700 m/s ✓Impact parameter $b = 0 - 1$

Examples of simulations

$b = 0$



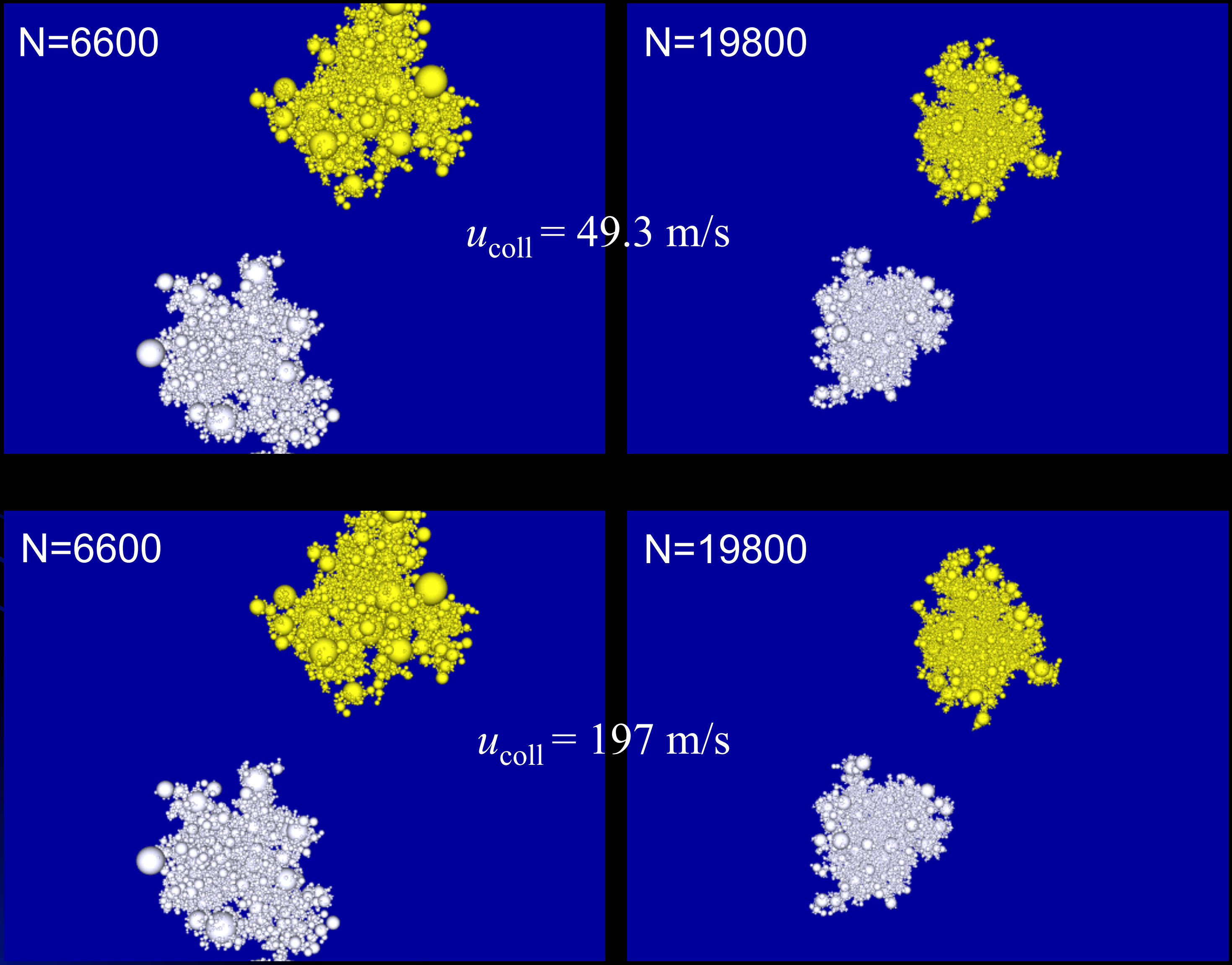
$u_{\mathrm{coll}} = 49.3$ m/s



$u_{\mathrm{coll}} = 197$ m/s

Examples of simulations

b = 0.707



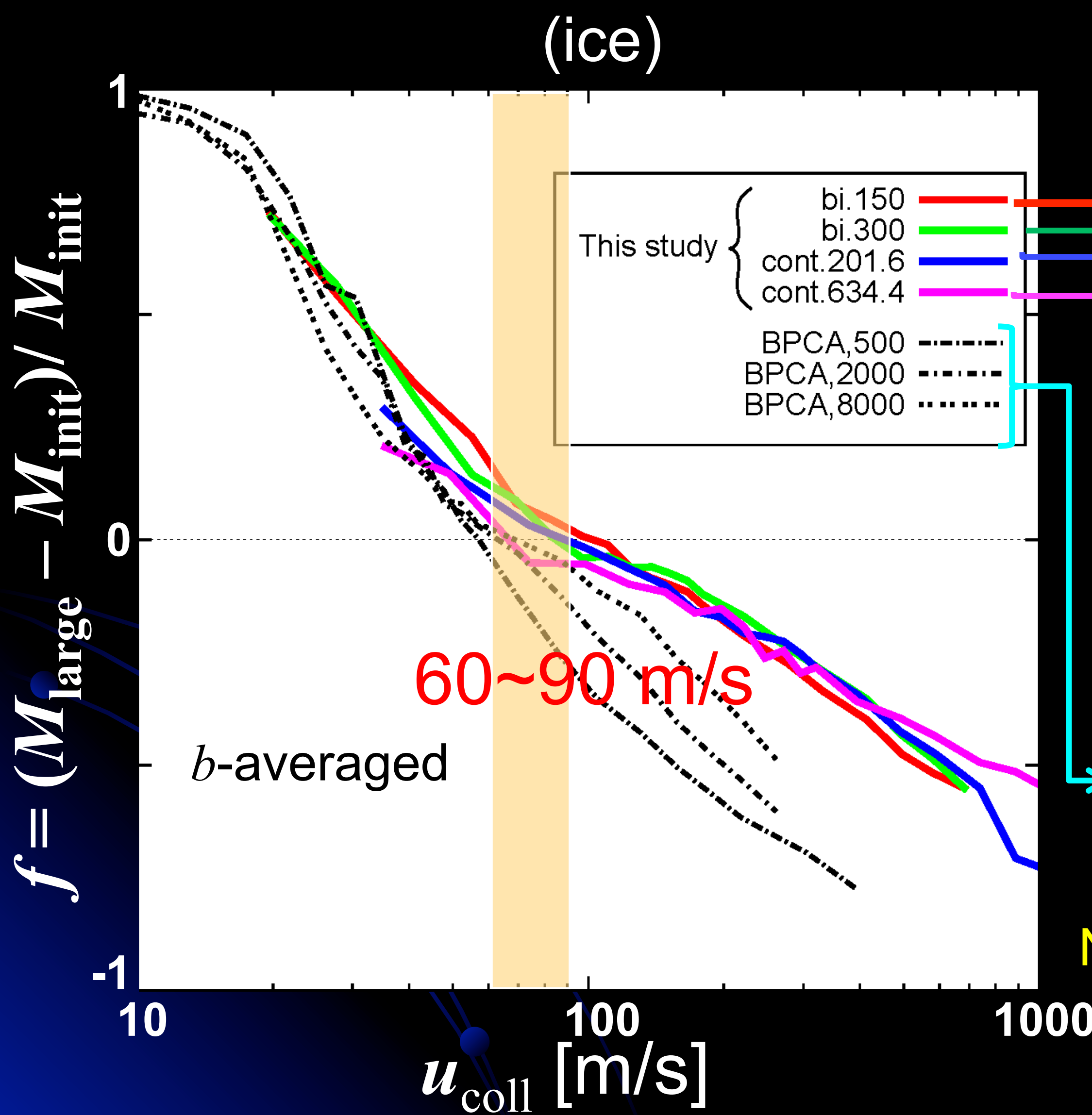
Growth efficiency

$f \equiv (M_{large} - M_{init}) / M_{init}$

: growth efficiency

$f > 0 \rightarrow$ mass gain

$f < 0 \rightarrow$ mass loss



• r=0.1μm×100, 0.025μm×3200 (bimodal:150+150)

• r=0.1μm×200, 0.025μm×6400 (bimodal:300+300)

• r=0.2μm - 0.025μm, N=6600 (continuous:209.1+209.1)

• r=0.2μm - 0.025μm, N=19800 (continuous:634.4+634.4)

• BPCA (500+500)
• BPCA(2000+2000)
• BPCA(8000+8000)

No increase in critical velocity

No size dependence

Lesson 3

Simulations of collisions of aggregates having
a monomer size distribution

- The critical collision velocity $u_{\mathrm{coll,crit}}$ is not significantly increased.

$u_{\mathrm{coll,crit}}$ for ice ~ <100 m/s

$u_{\mathrm{coll,crit}}$ for silicate = 0.1×$u_{\mathrm{coll,crit}}$ for ice ~ <10 m/s

Can silicate dust grow through collisions?

We will simulate with various types of size distribution.

Conclusion:

Icy dust aggregates are

FLUFFY and STICKY,

but need more study for silicate dust...

今後の課題例:

- モノマーサイズ分布の影響詳細
- モノマー形状の影響
- 粒子間焼結の影響
- ・・・