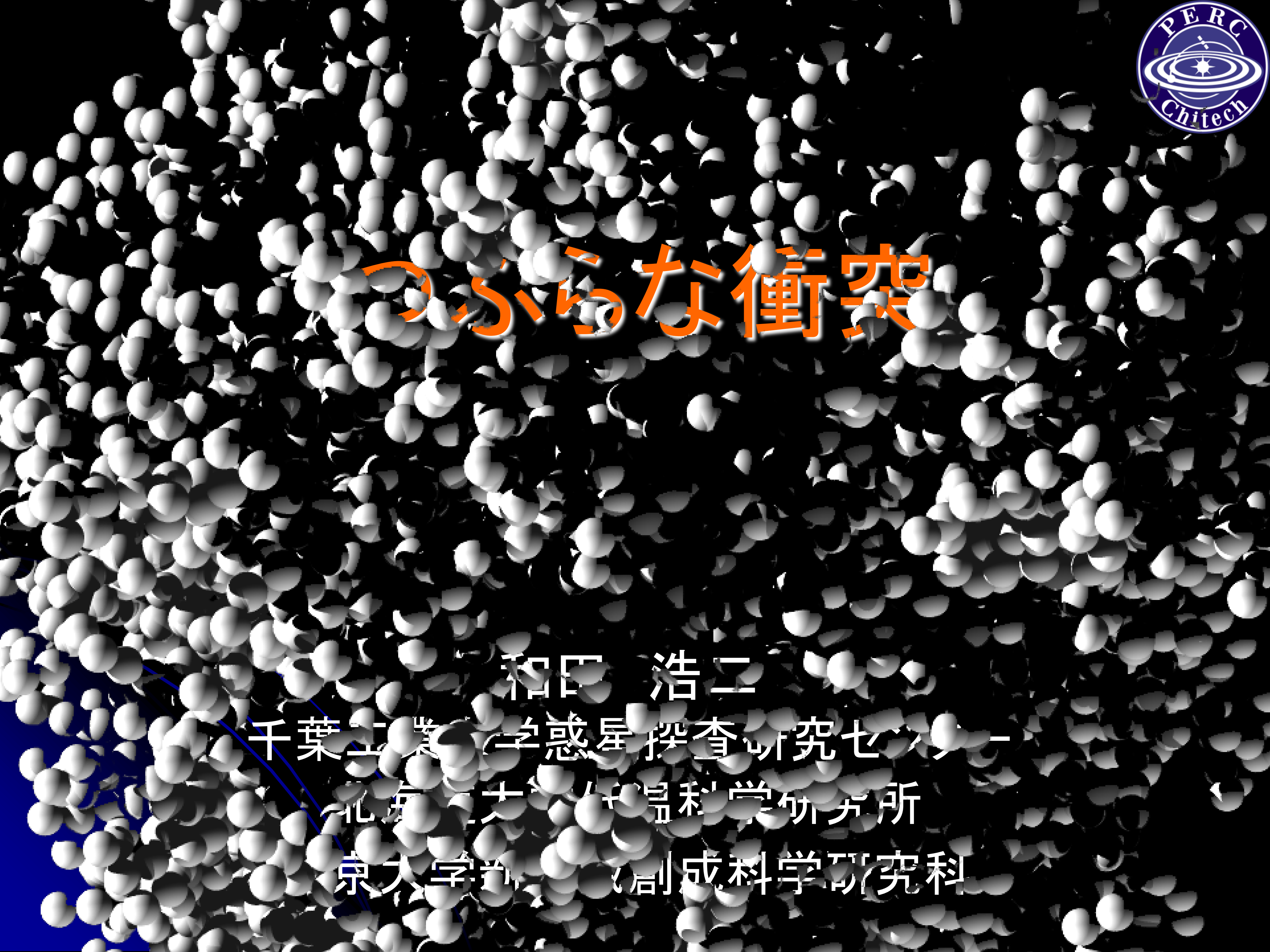
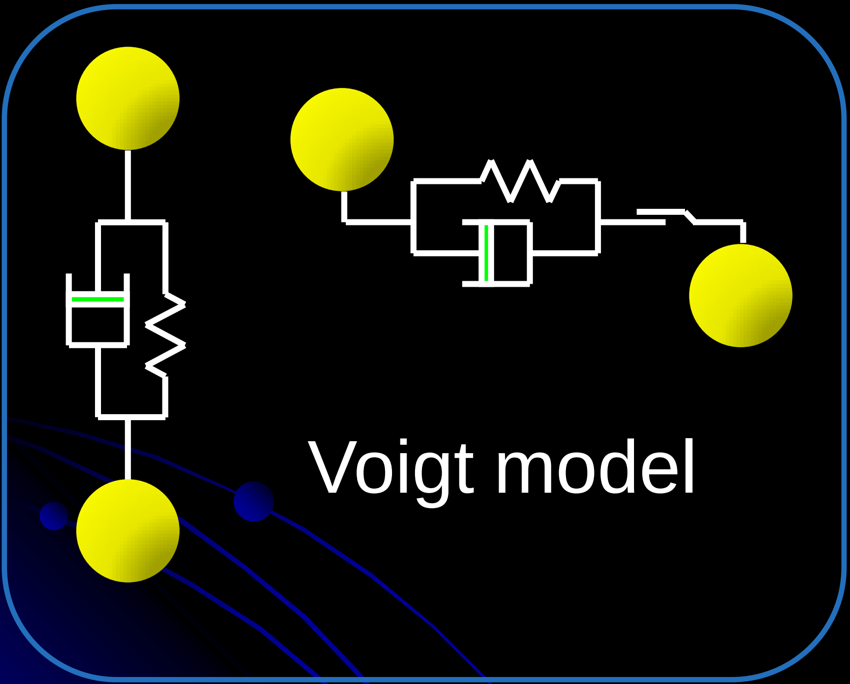
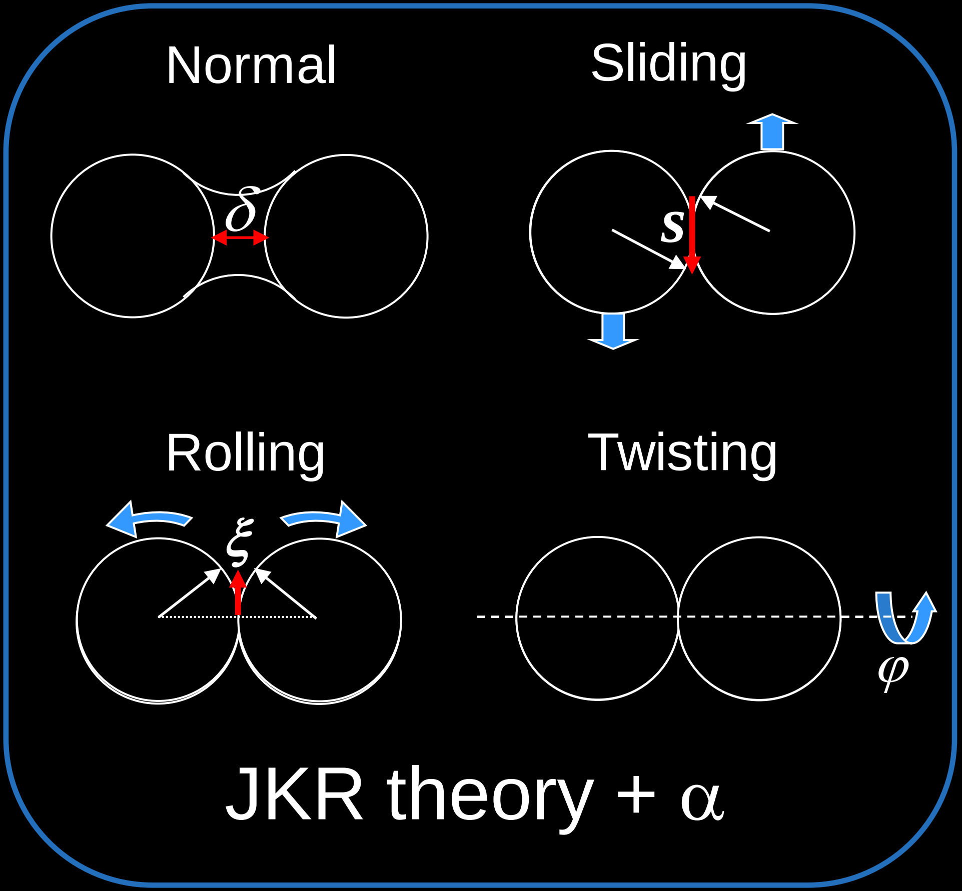

PERC
Chitech
つぶらな衝突
和田 浩二
千葉工業大学惑星探査研究センター
北海道大学低温科学研究所
東京大学新領域創成科学研究科

粒の衝突

接触粒子間相互作用　＋　個々の粒子の運動を計算





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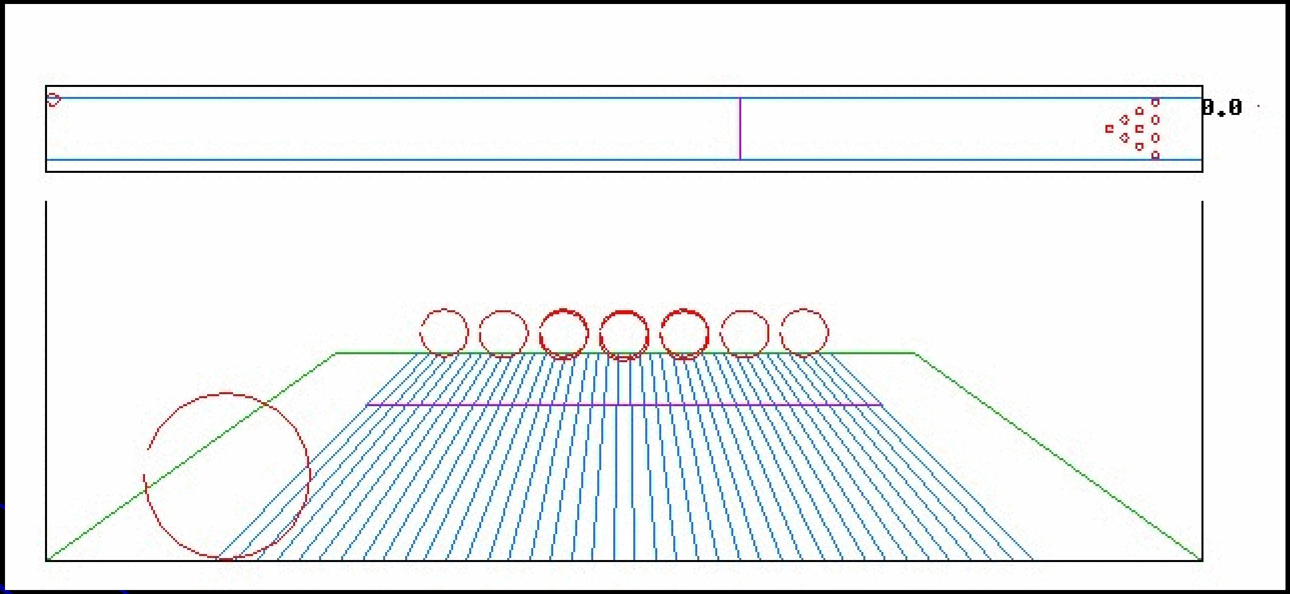
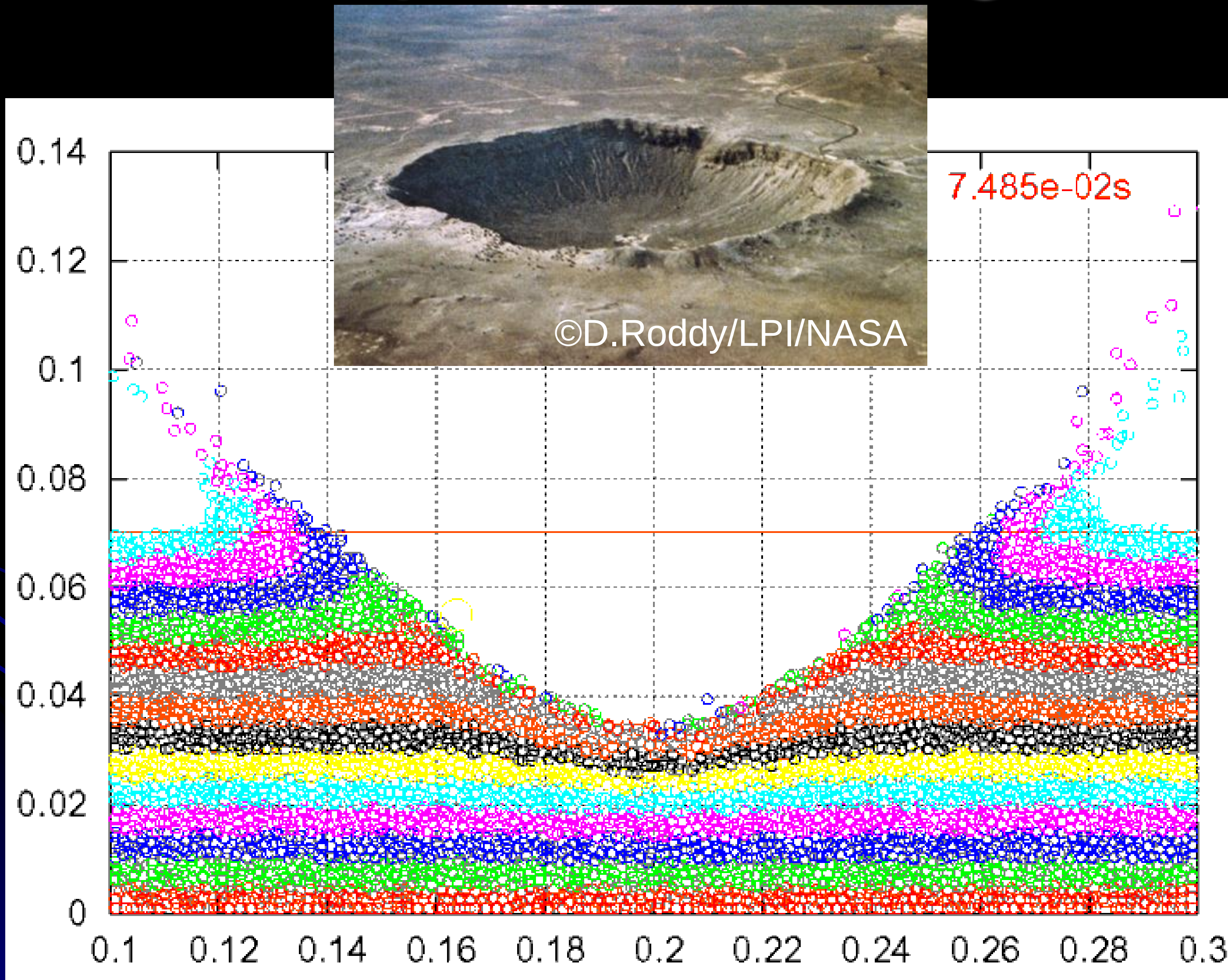
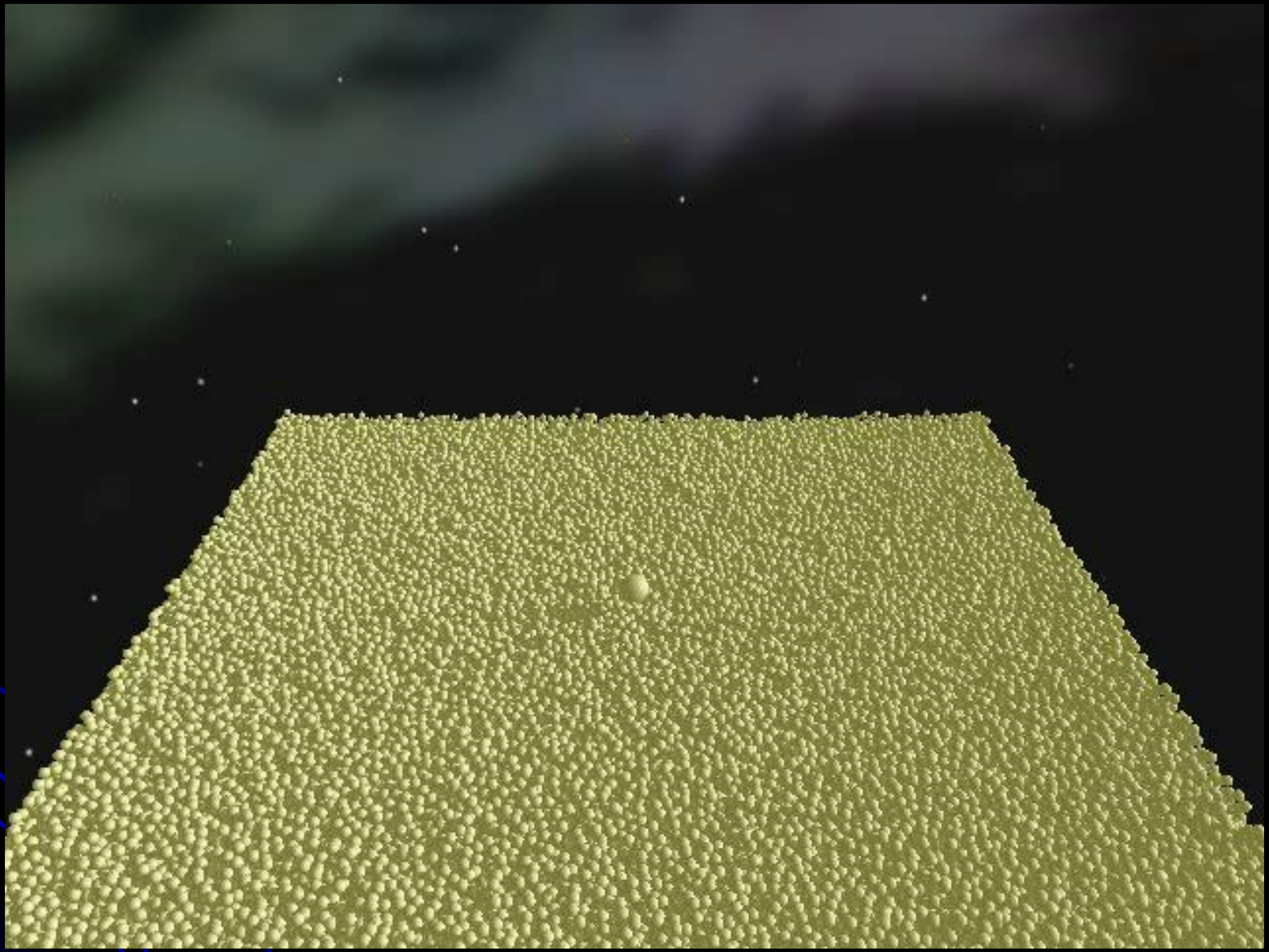


Impact cratering



Impact cratering



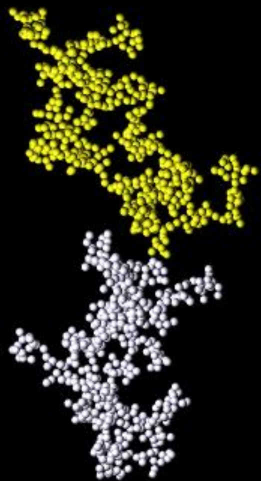
CG by Dr. T. Takeda, NAOJ

Impact cratering

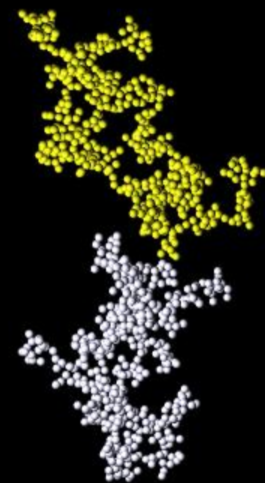
CG by Dr. T. Takeda, NAOJ

Dust aggregate collisions

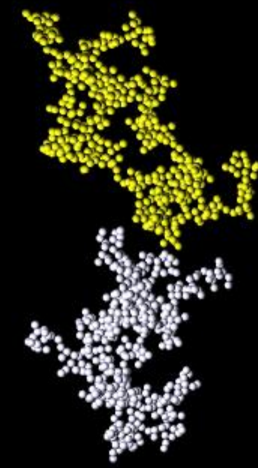
0.4 m/s

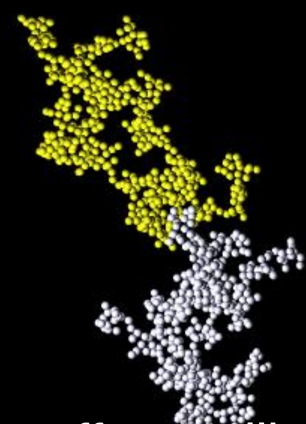


9 m/s



50 m/s





offset collision

Ice aggregates, N =1024

Background

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

Structure evolution of dust aggregates in protoplanetary disks

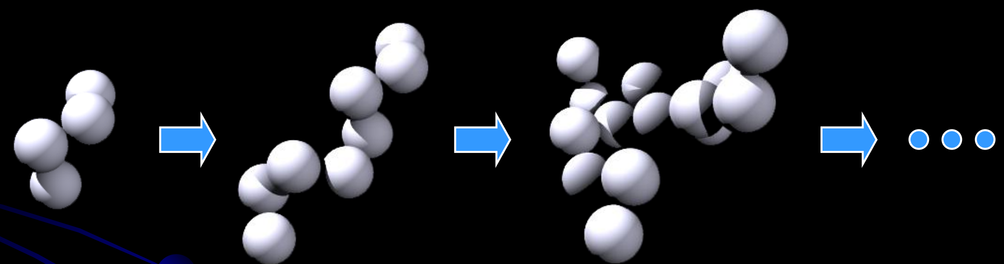
When and how are aggregates compressed and/or disrupted ?

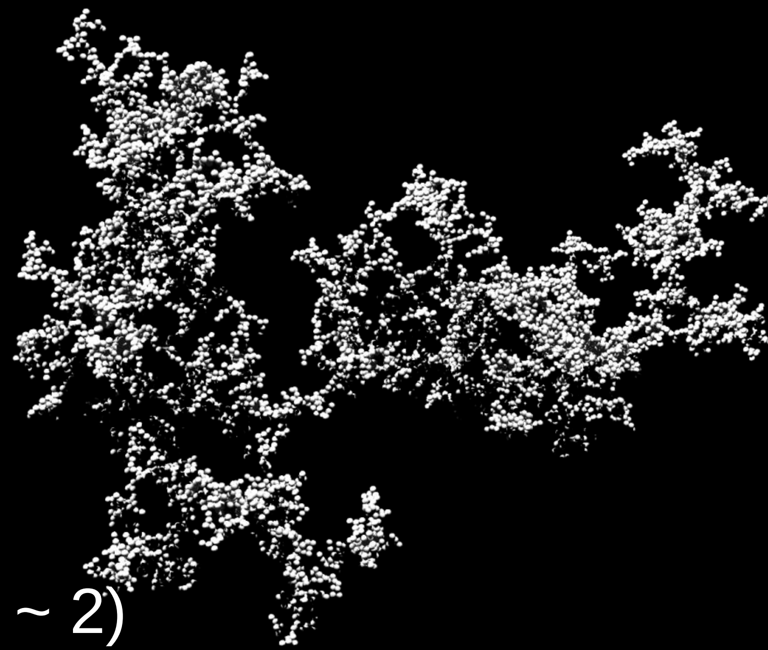
→ **Numerical simulation of dust aggregate collisions!**

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 < ~ 2)

How are the BCCA structures compressed ?

Dominik & Tielens 1997;
Wada et al. 2007, 2008; Suyama et al. 2008

Background

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 ?

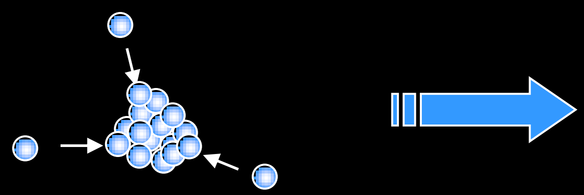
Maybe possible in head-on collisions

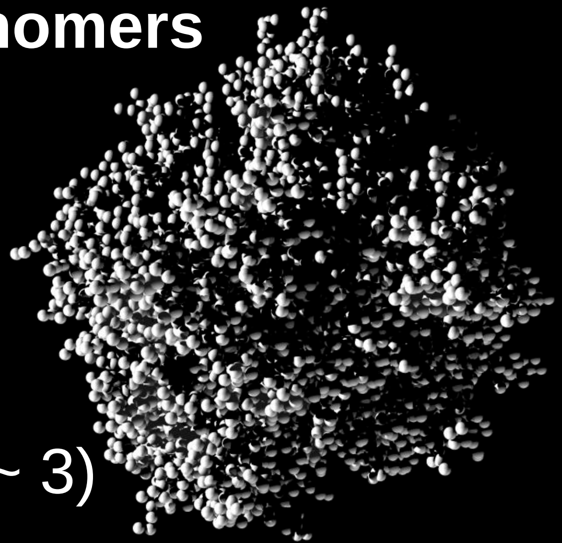
Experimental: Blum & Wurm 2000, Wurm et al. 2005
Numerical: Dominik & Tielens 1997, Wada et al. 2008

What if in offset collisions ?

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

Wada et al. 2009, Paszun & Dominik 2009

Objective

To construct a macroscopic model of aggregate structure evolution by numerical simulations of aggregate collisions

Collisions of BCCA & BPCA clusters

- Compression process （BCCAs）

  Gyration radius → scaling law

  圧縮アグリゲイトのフラクタル次元 ＝ ~ 2.5

- Growth and Disruption process （BPCAs）

  Number of particles in largest fragments

  → growth efficiency

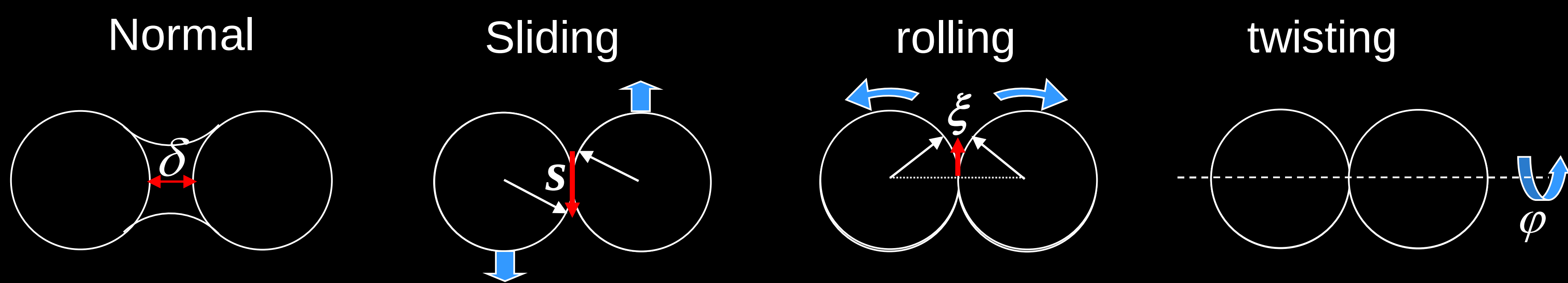
  氷アグリゲイトの破壊臨界速度 ＝ ~ 50 m/s

Simulation Method

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

E_{break}: Energy to break a contact

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

Previous study

Dominik and Tielens (1997)

Each grain motion is directly calculated,
taking into account particle interactions

```
DUST AGGREGATE COLLISIONS
        (c) 1996
C. DOMINIK and A. TIELENS

TYPE:      CLUSTER-CLUSTER
MATERIAL:  ICE
SIZES:     1E-5 .. 1E-5 CM
```

✓modeling grain interactions seriously

Limitations:

- 2-D, Head-on collision
- Small size（40＋40 grains）
- Initial structure: only 1 type

D&T "recipe"

$$E_{\mathrm{impact}} = \begin{cases} \sim n_{\mathrm{k}} E_{\mathrm{roll}} & \Rightarrow \text{Max. compression} \\ > 10\, n_{\mathrm{k}} E_{\mathrm{break}} & \Rightarrow \text{Catastrophic disruption} \end{cases}$$

E_{roll} : Energy to roll a grain by 90˚

E_{break} : Energy to break a contact

n_{k} : Number of contacts in initial aggregates

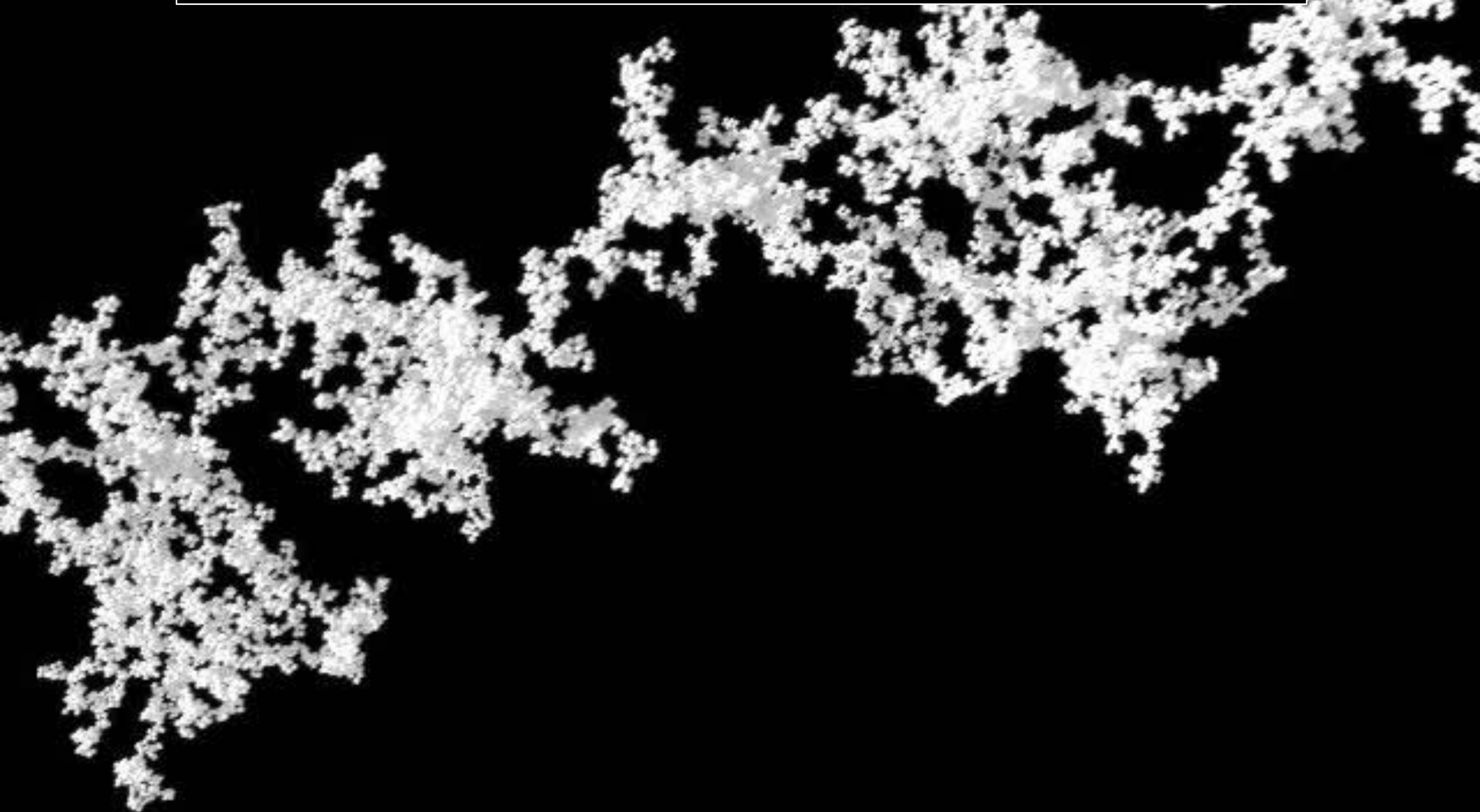
Collisions between BCCA clusters

: Compression process

A collision of BCCAs

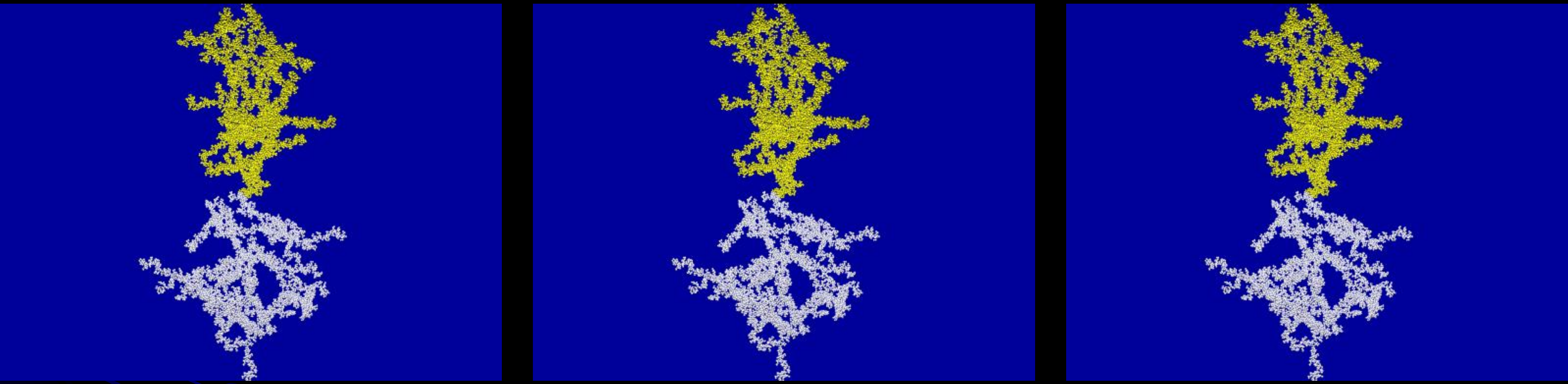
8192+8192 ice particles (r=0.1μm, ξ_c = 8Å)

Collision velocity = 22 m/s



Example of simulations

Ice, 8192 + 8192, $\xi_{crit} = 8$ Å



$E_{impact} \sim 0.7\, E_{roll}$

$V_{impact} = 0.2$ m/s

$E_{impact} \sim 0.3\, n_k\, E_{roll}$

$V_{impact} = 17$ m/s

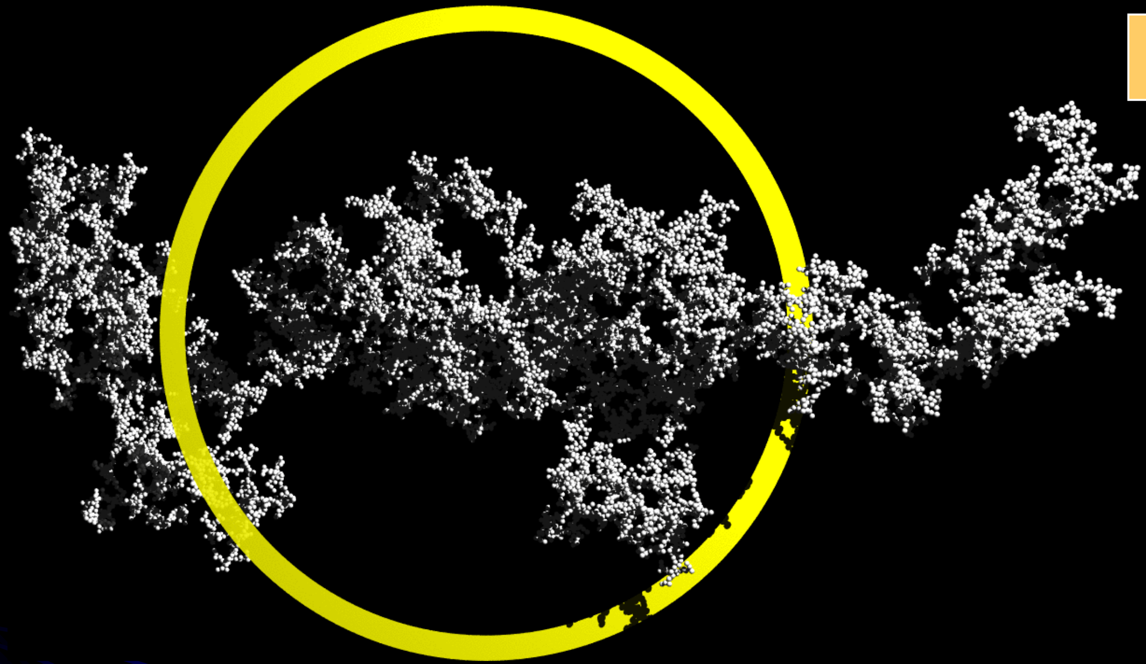
$E_{impact} \sim 13\, n_k\, E_{break}$

$V_{impact} = 39$ m/s

Numerical Results on

Gyration Radius

Gyration radius r_g : *compression process*

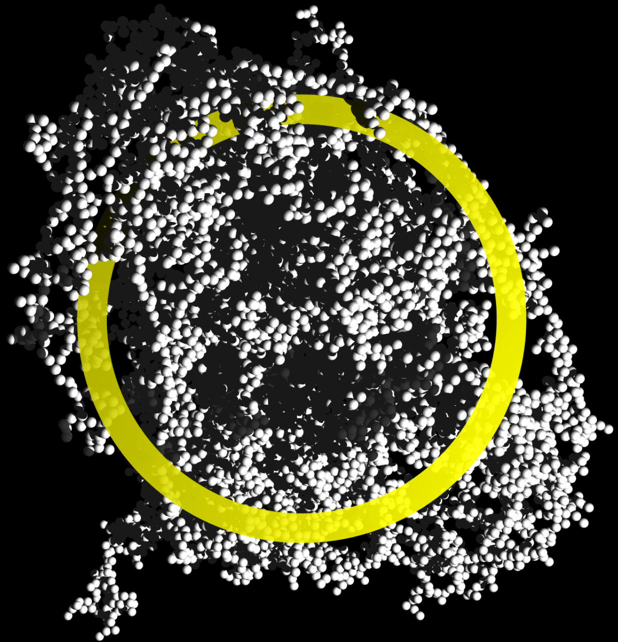


$E_{impact} \sim 0.01\ E_{roll}$

Impact velocity: 0.024 m/s

$E_{impact} \sim 0.19\ N\ E_{roll}$

Impact velocity: 13 m/s

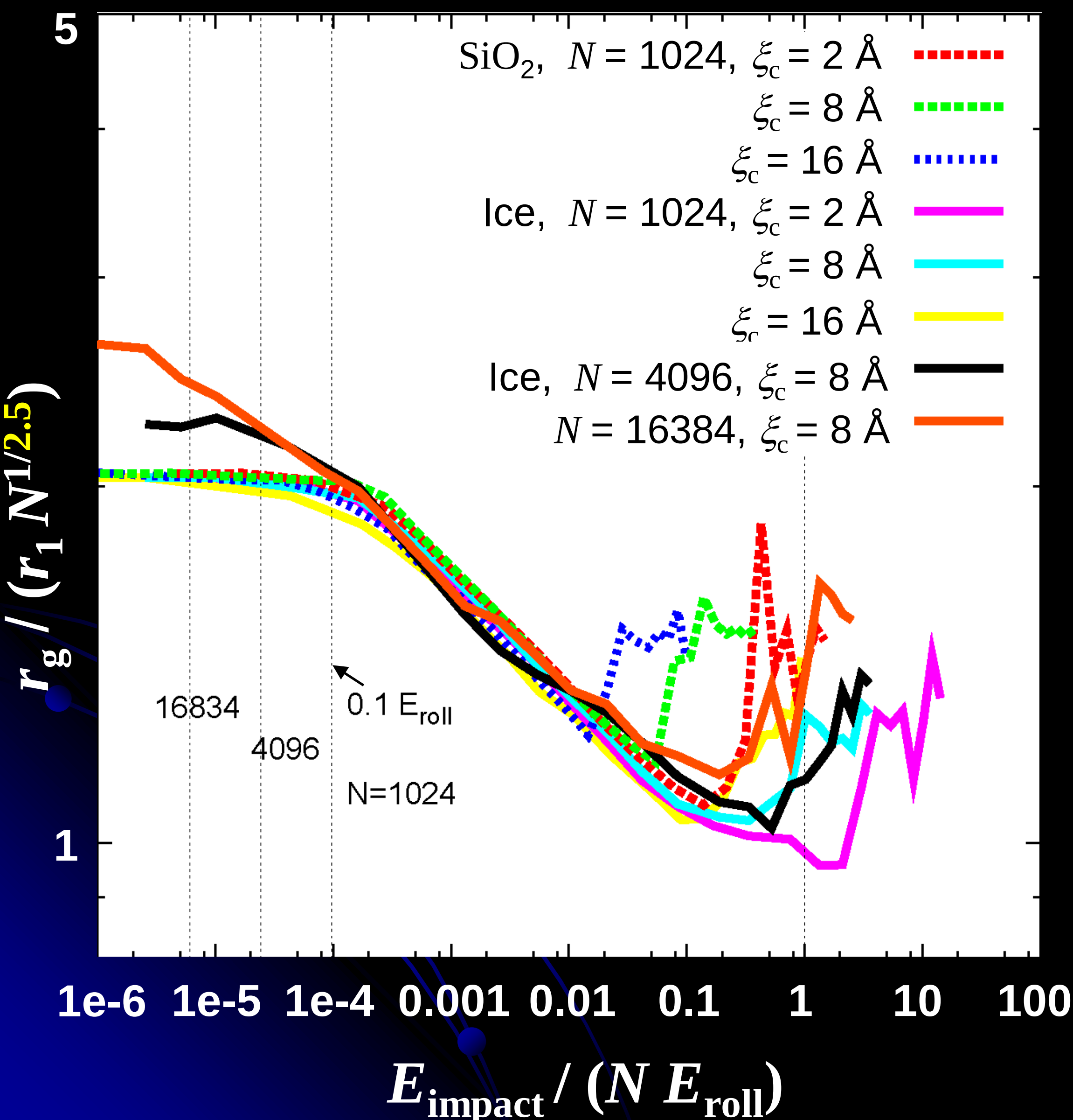


Ice, 8192 + 8192, ξ_{crit} = 8 Å

$$r_g = \sqrt{\frac{1}{N}\sum_i \left|x_i - x_g\right|^2}$$

x_g: center of mass

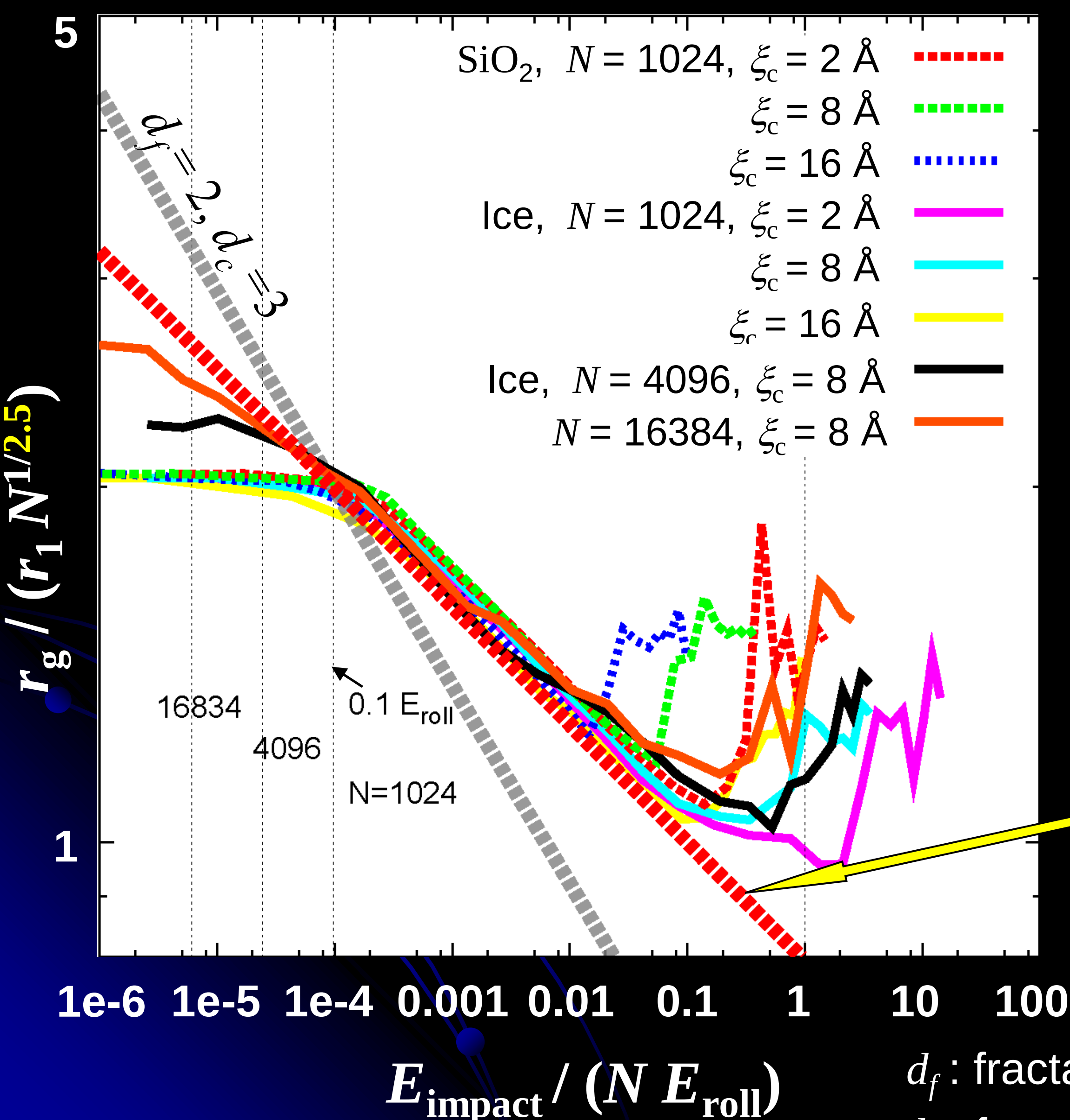
Gyration radius r_g : *compression process*



✓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

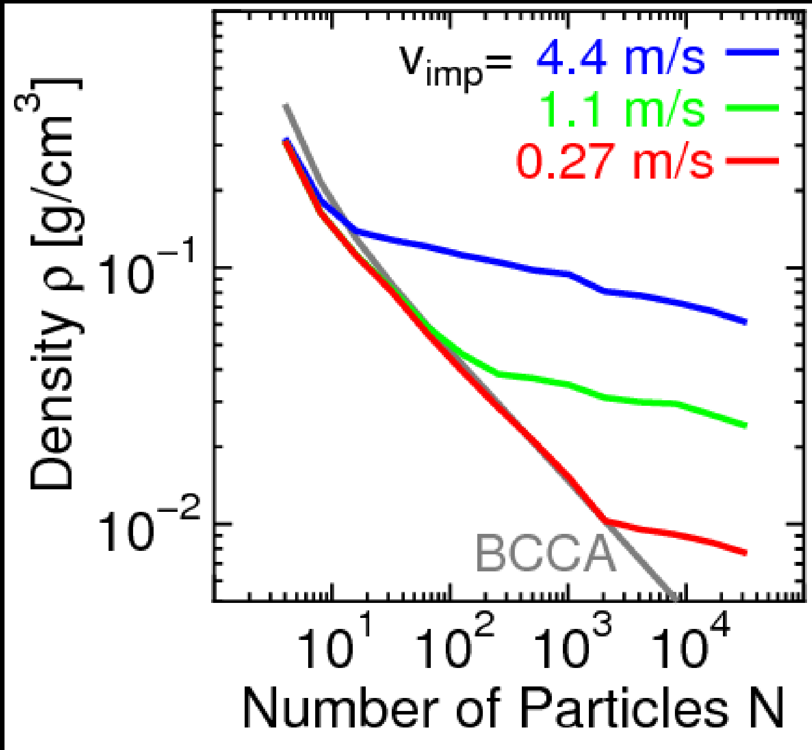
d_c : fractal dimension of max. compression

Successive collisions in a BCCA mode

Suyama et al. 2008

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

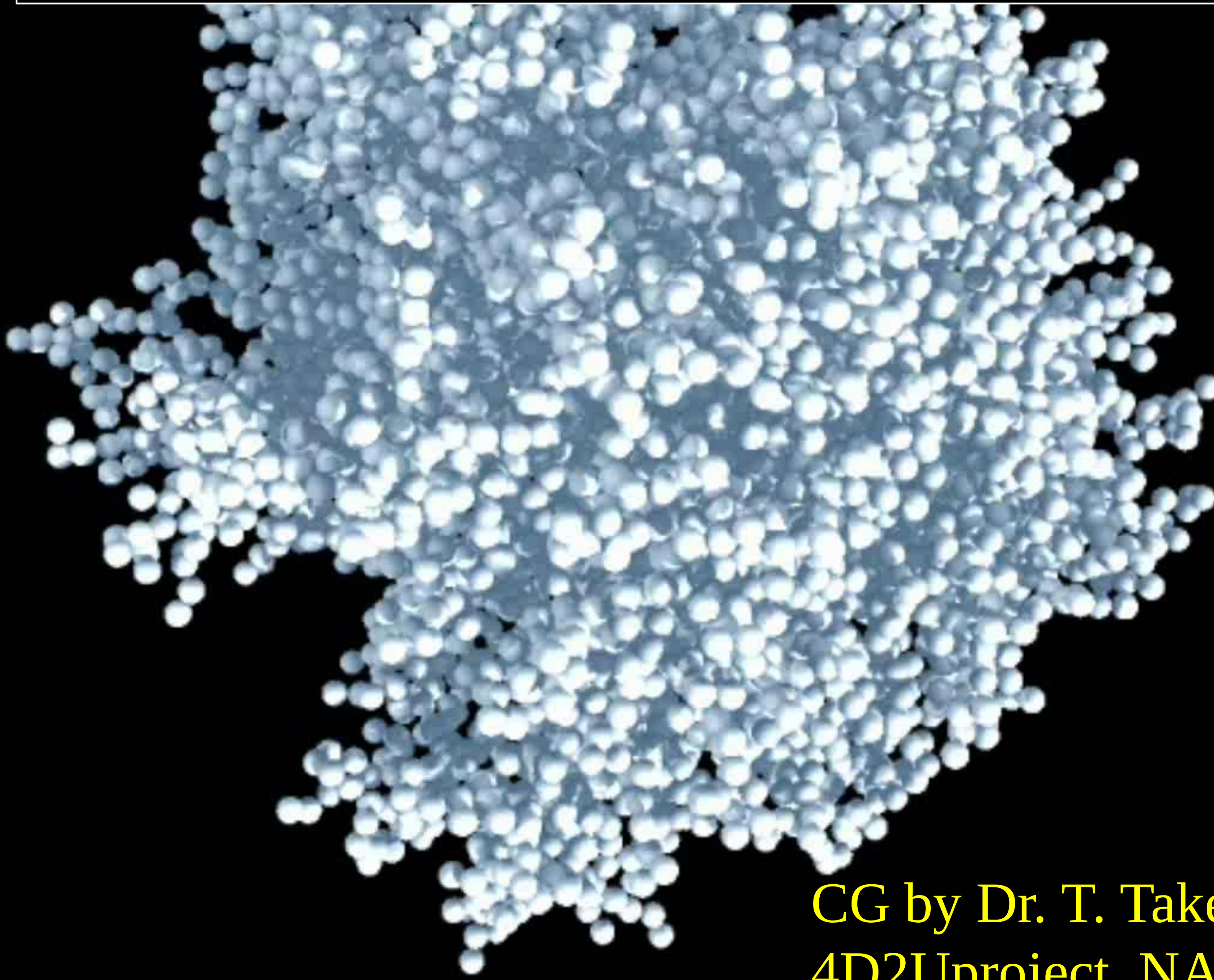
- Fractal dimension ~2.5
- Decrease in density



Collisions between BPCA clusters

: Growth and Disruption process

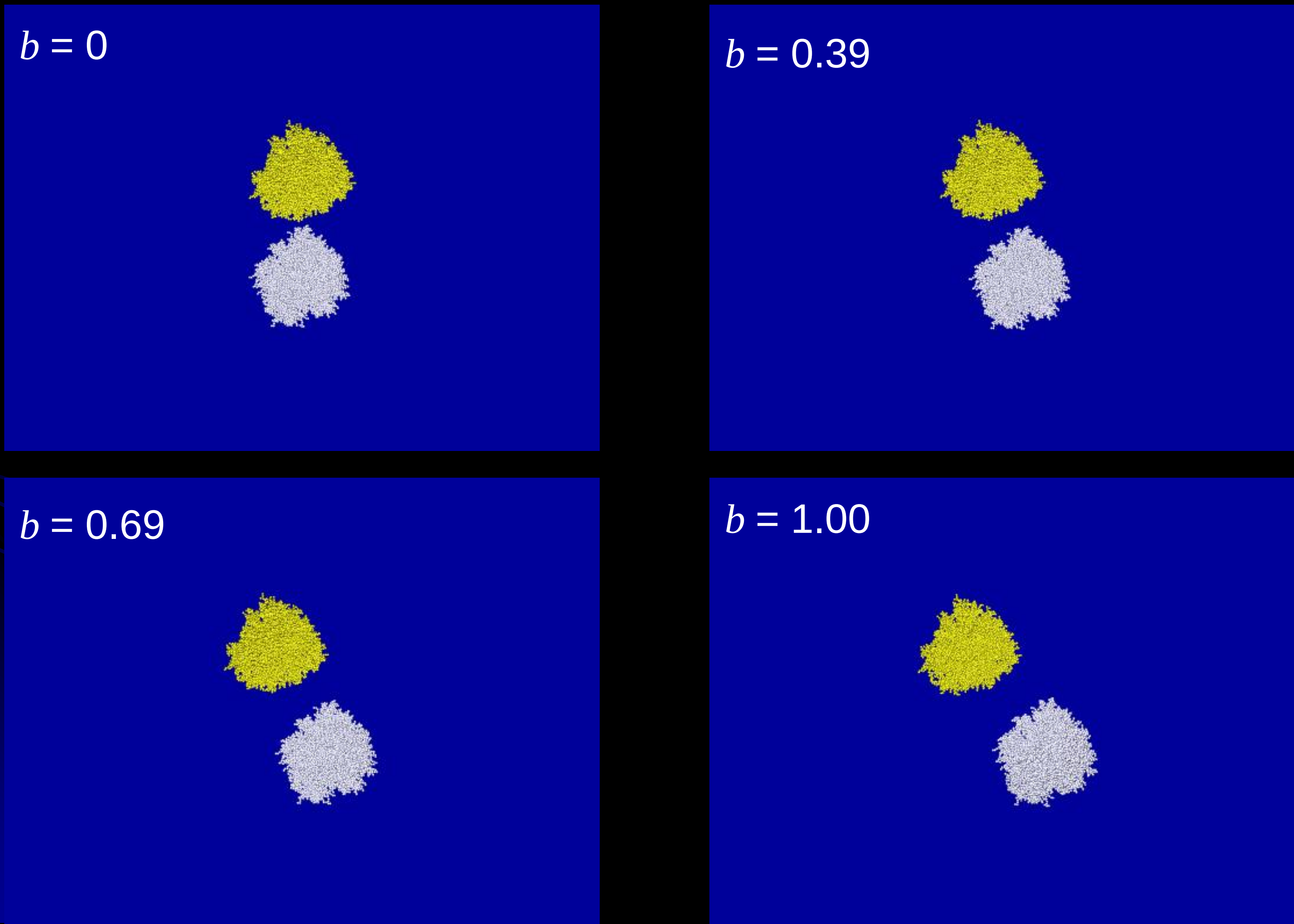
A collision of BPCAs
8000+8000 ice particles (r=0.1μm, ξ_c = 8Å)
Collision velocity = 57 m/s



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

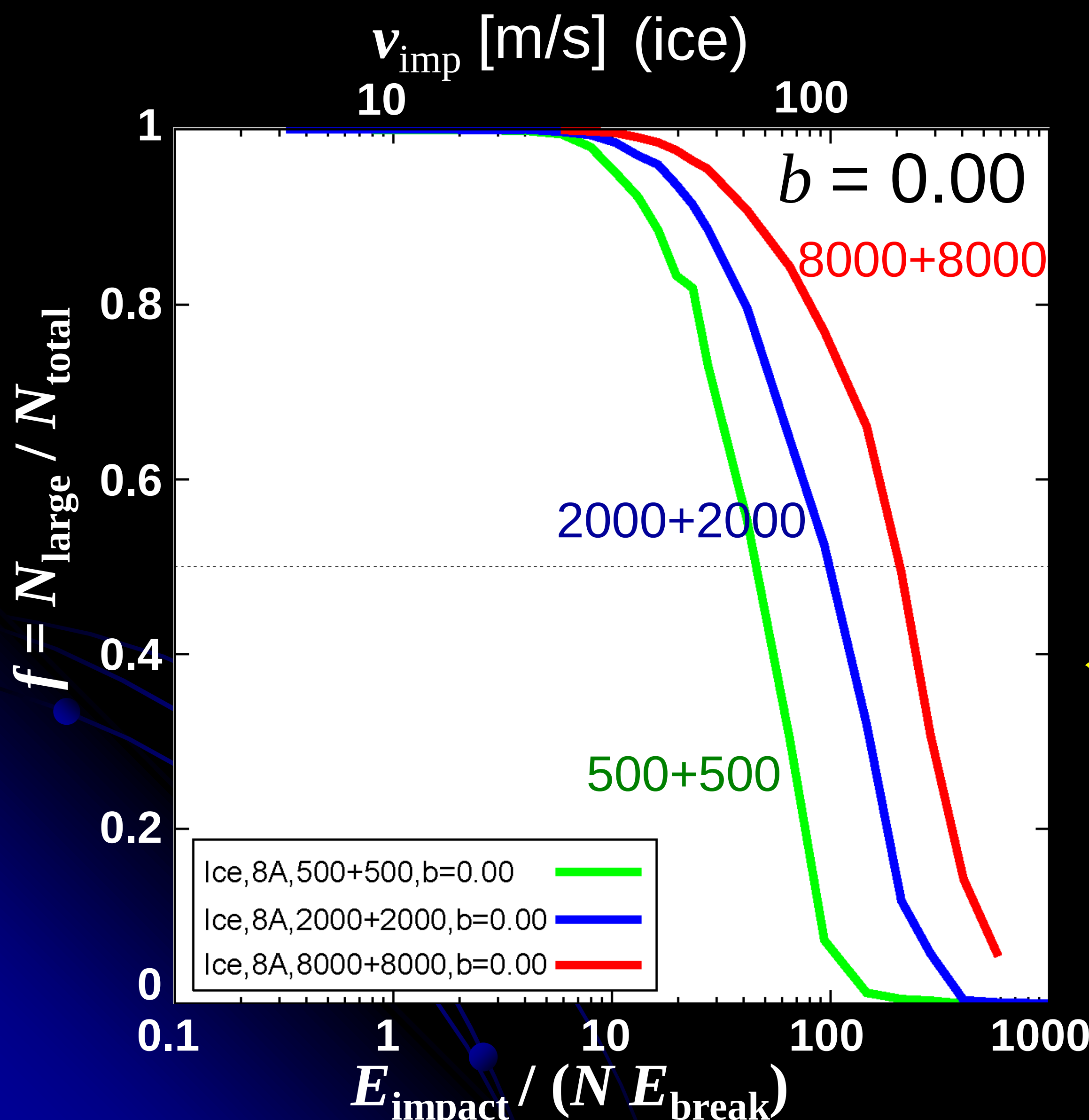
Collisions of BPCA clusters

N=8000+8000, ice, ξ_c = 8Å, v_{imp} = 70 m/s ($E_{imp} = 42\ NE_{break}$)



Growth Efficiency For Collisions of BPCAs

Largest fragment mass N_{large}: *growth efficiency*



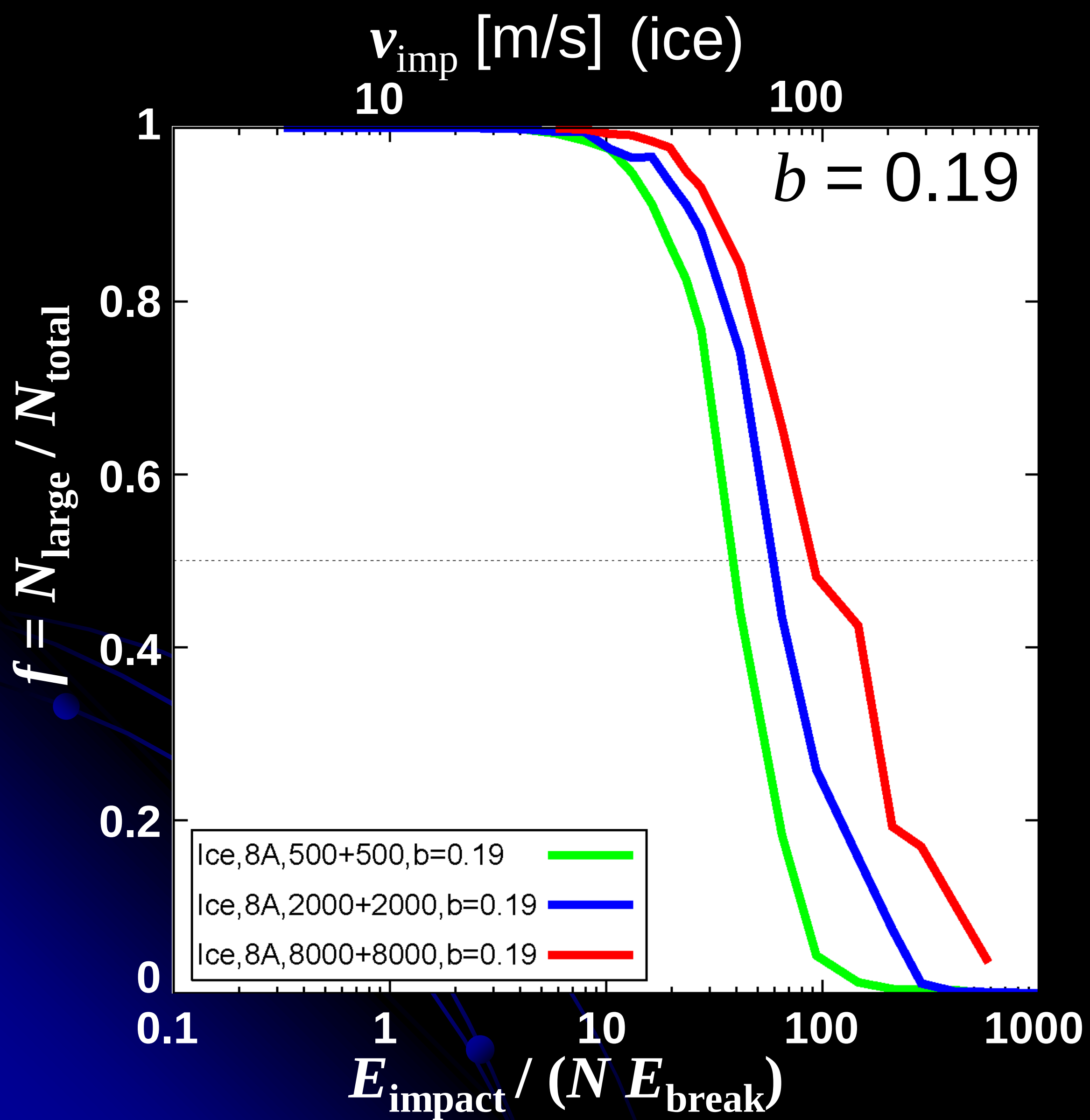
$f \equiv N_{large} / N_{total}$

: growth efficiency

- $f > 0.5$ → + growth
- $f < 0.5$ → - growth

✓dependent on N

Largest fragment mass N_{large}: *growth efficiency*

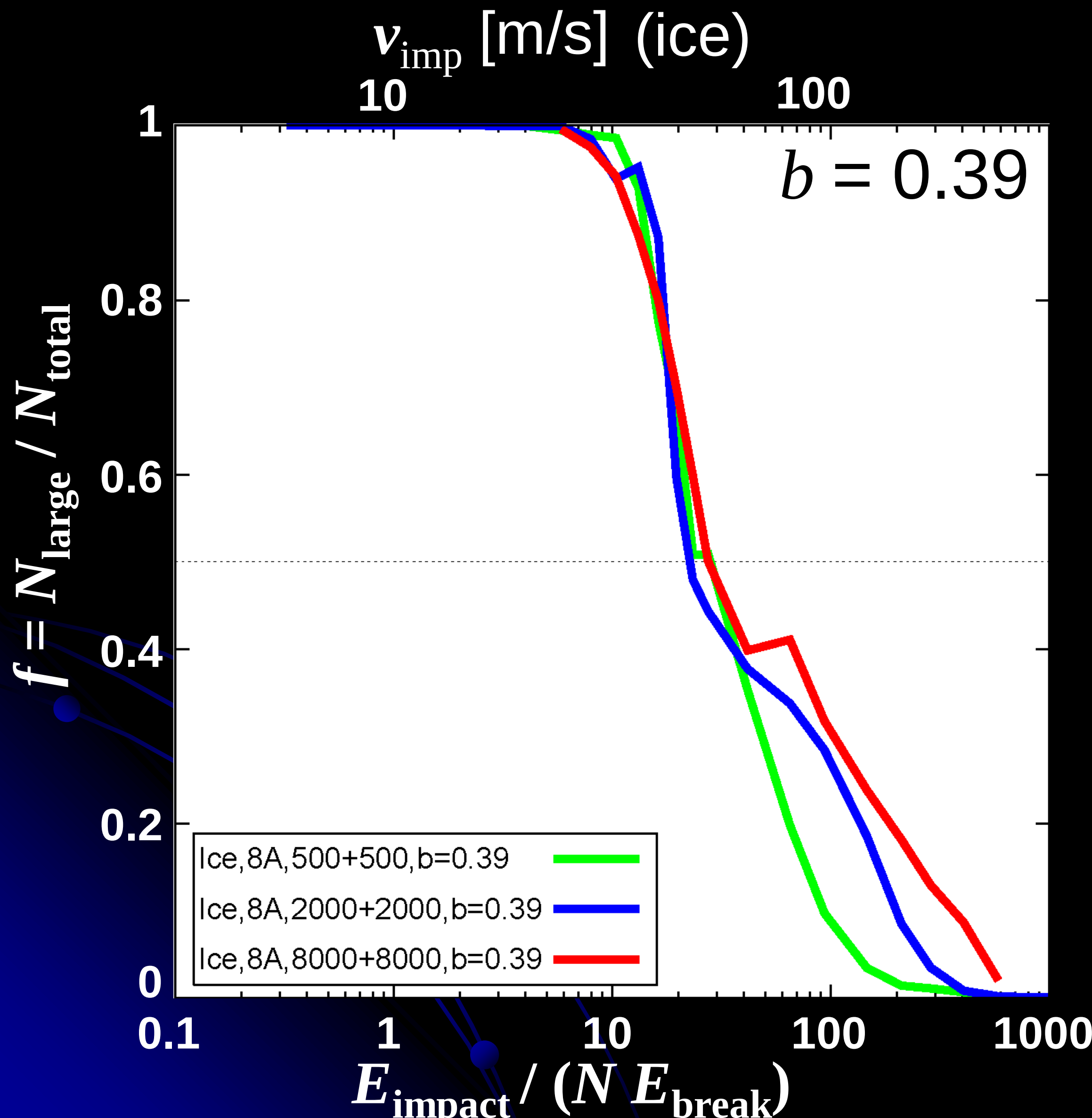


$f \equiv N_{\text{large}} / N_{\text{total}}$

: growth efficiency

- $f > 0.5 \rightarrow$ + growth
- $f < 0.5 \rightarrow$ - growth

Largest fragment mass N_{large}: *growth efficiency*



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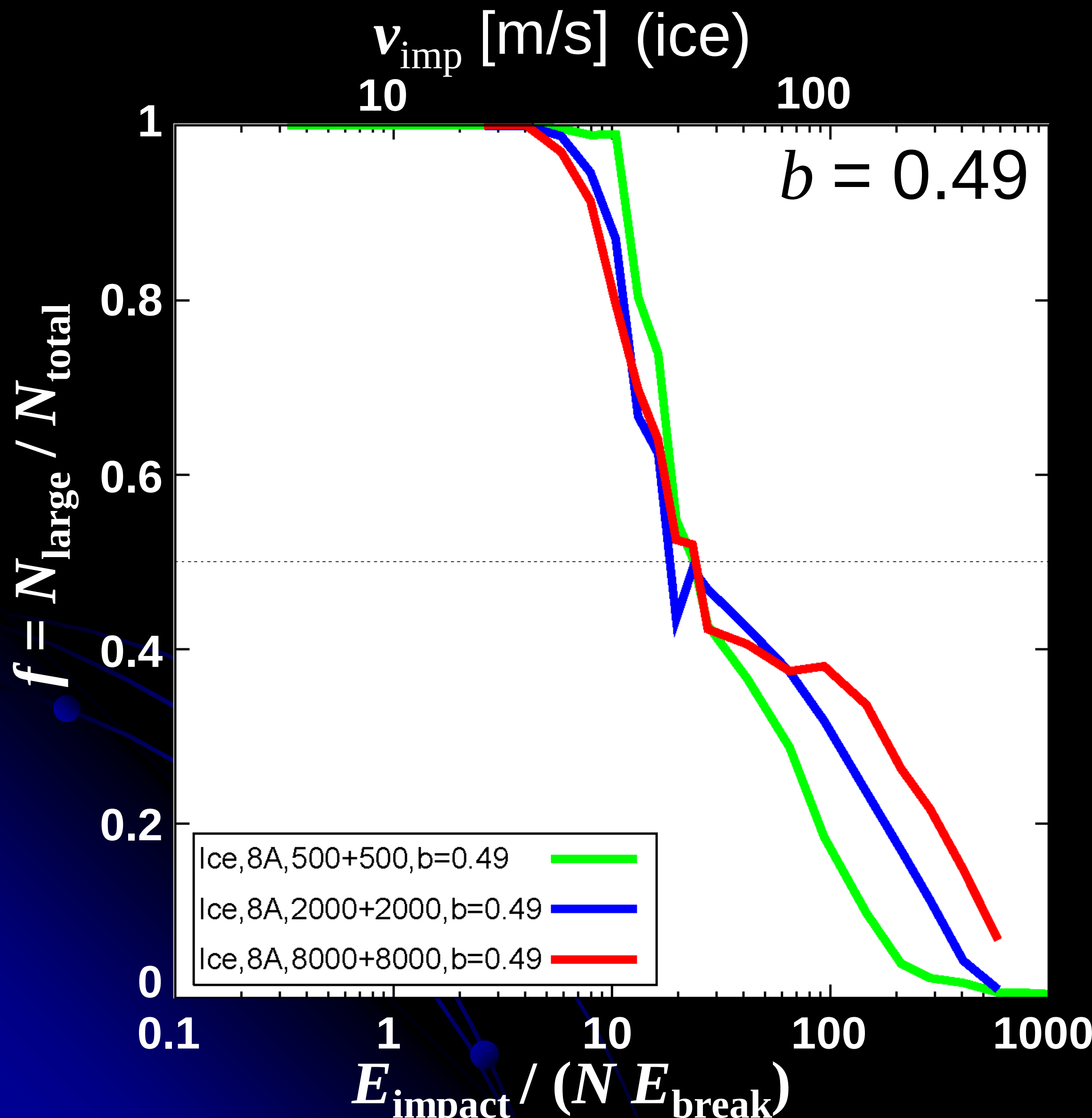

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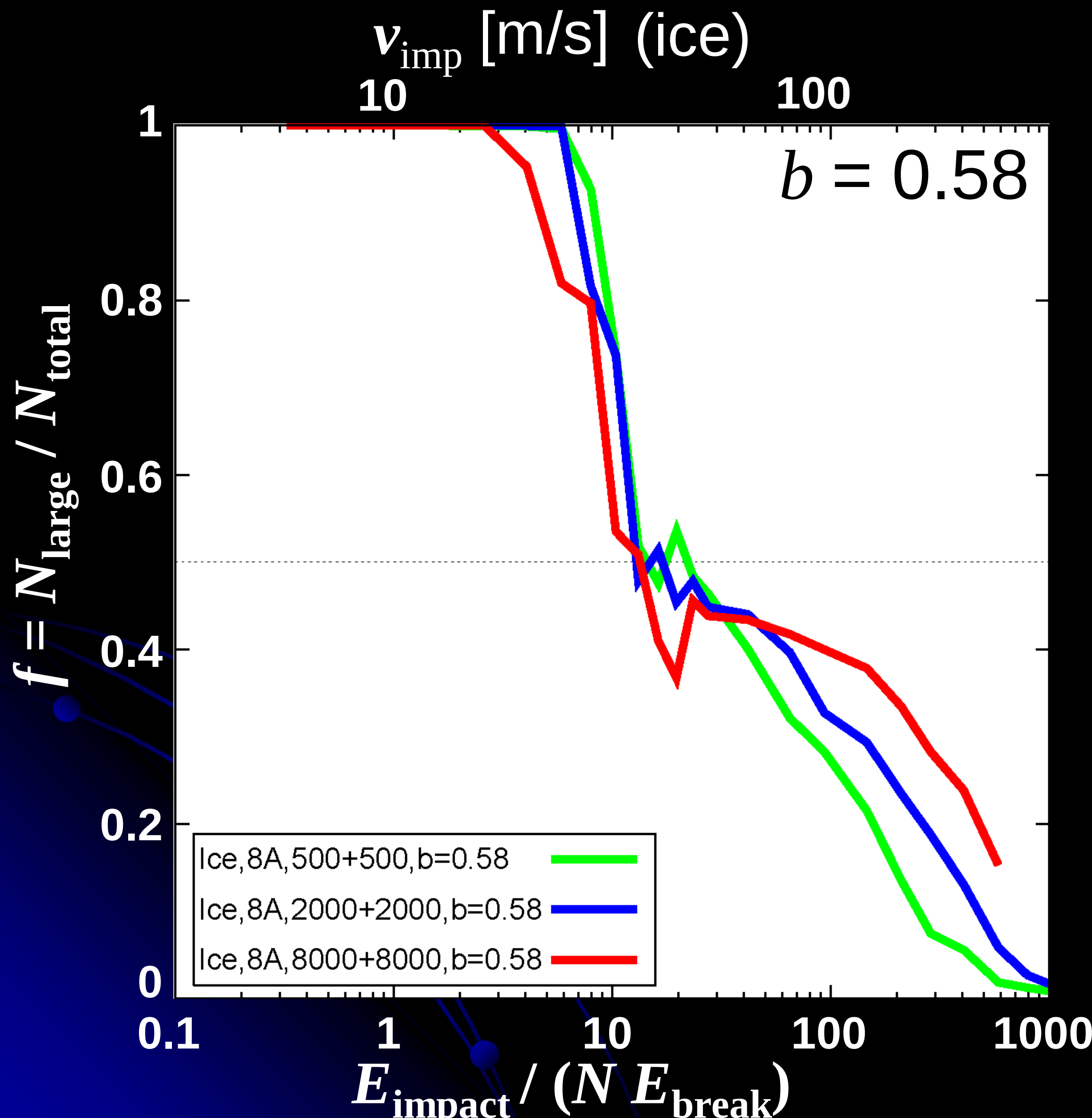

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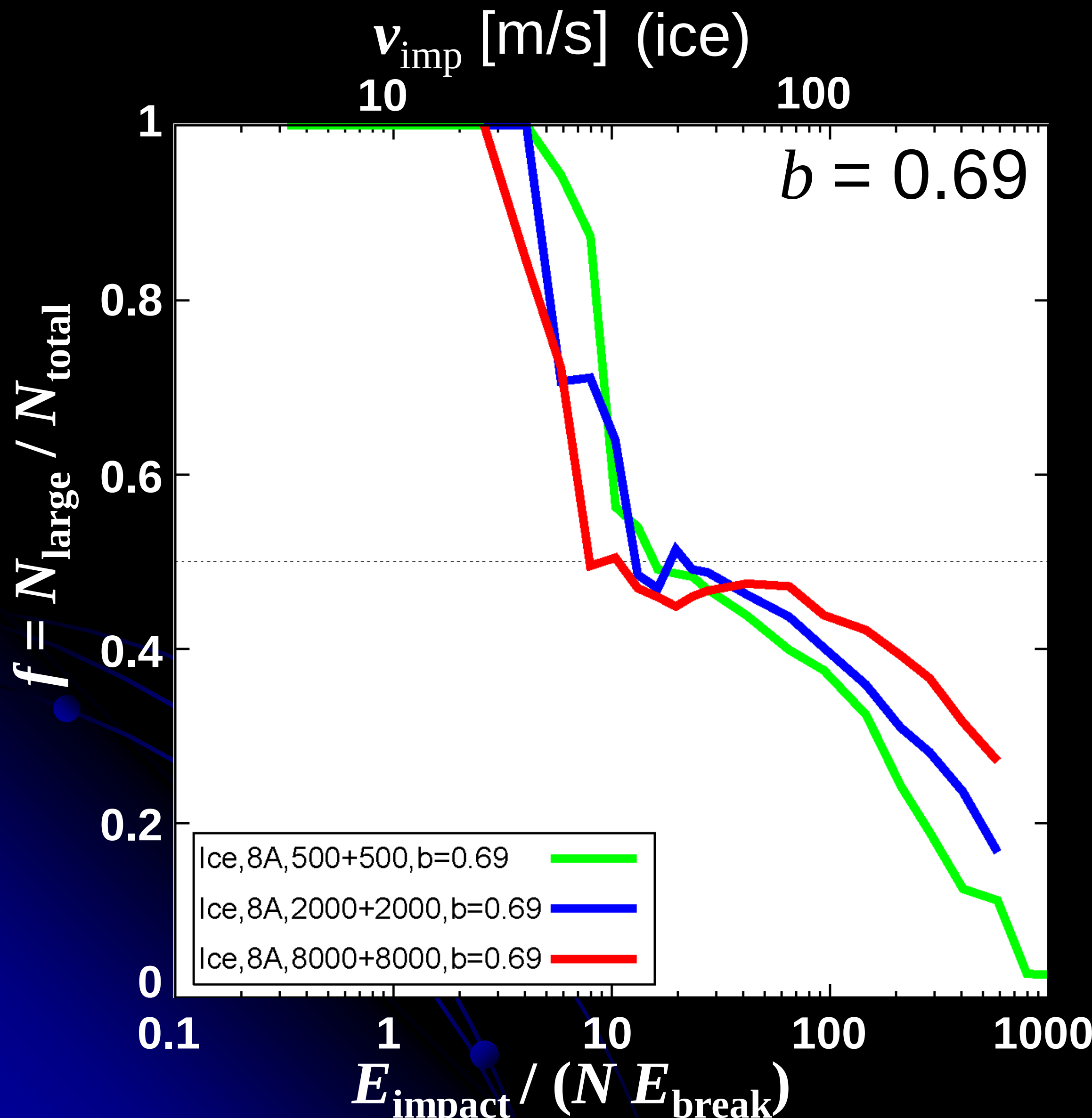

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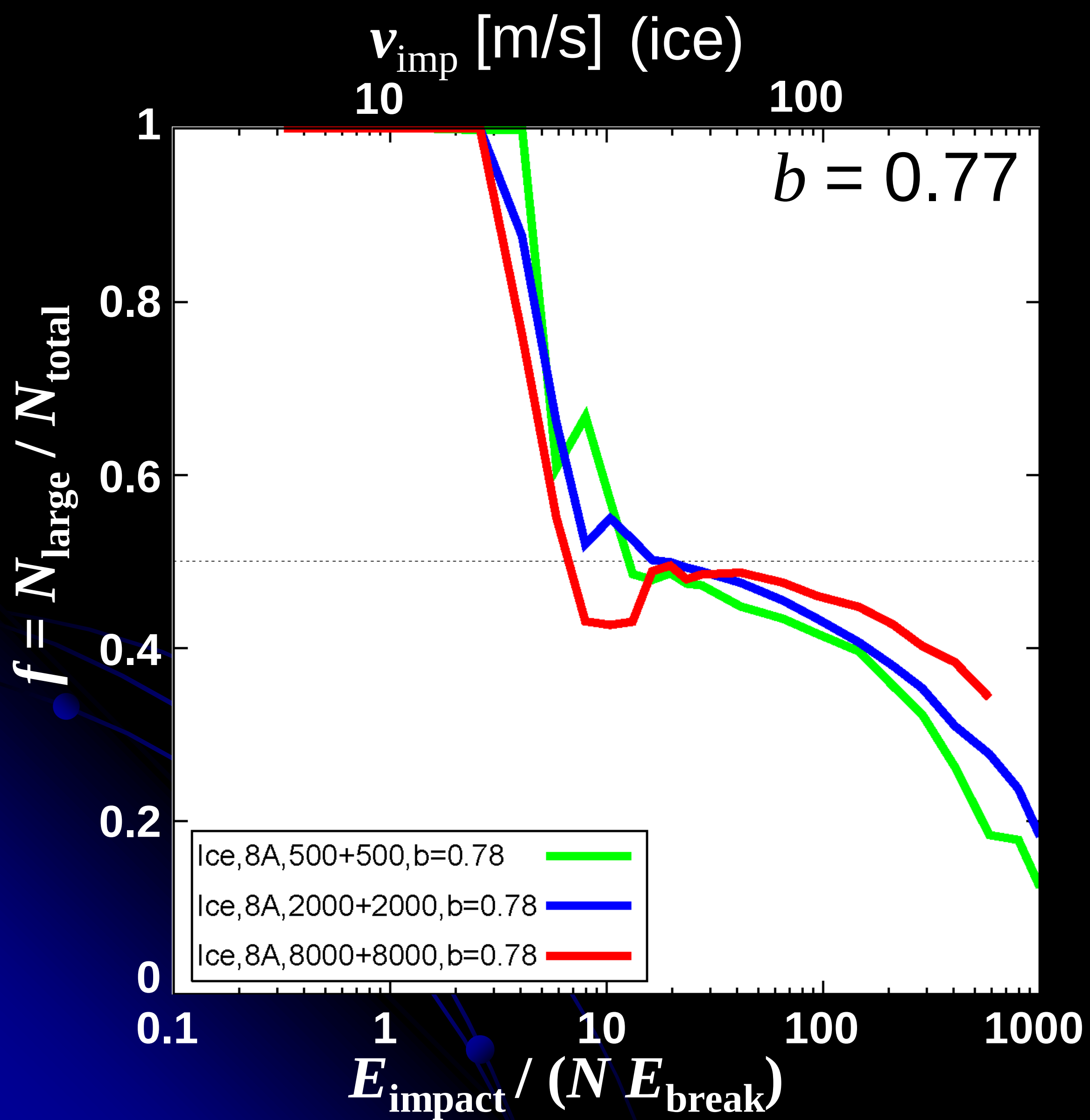
Largest fragment mass N_{large}: *growth efficiency*

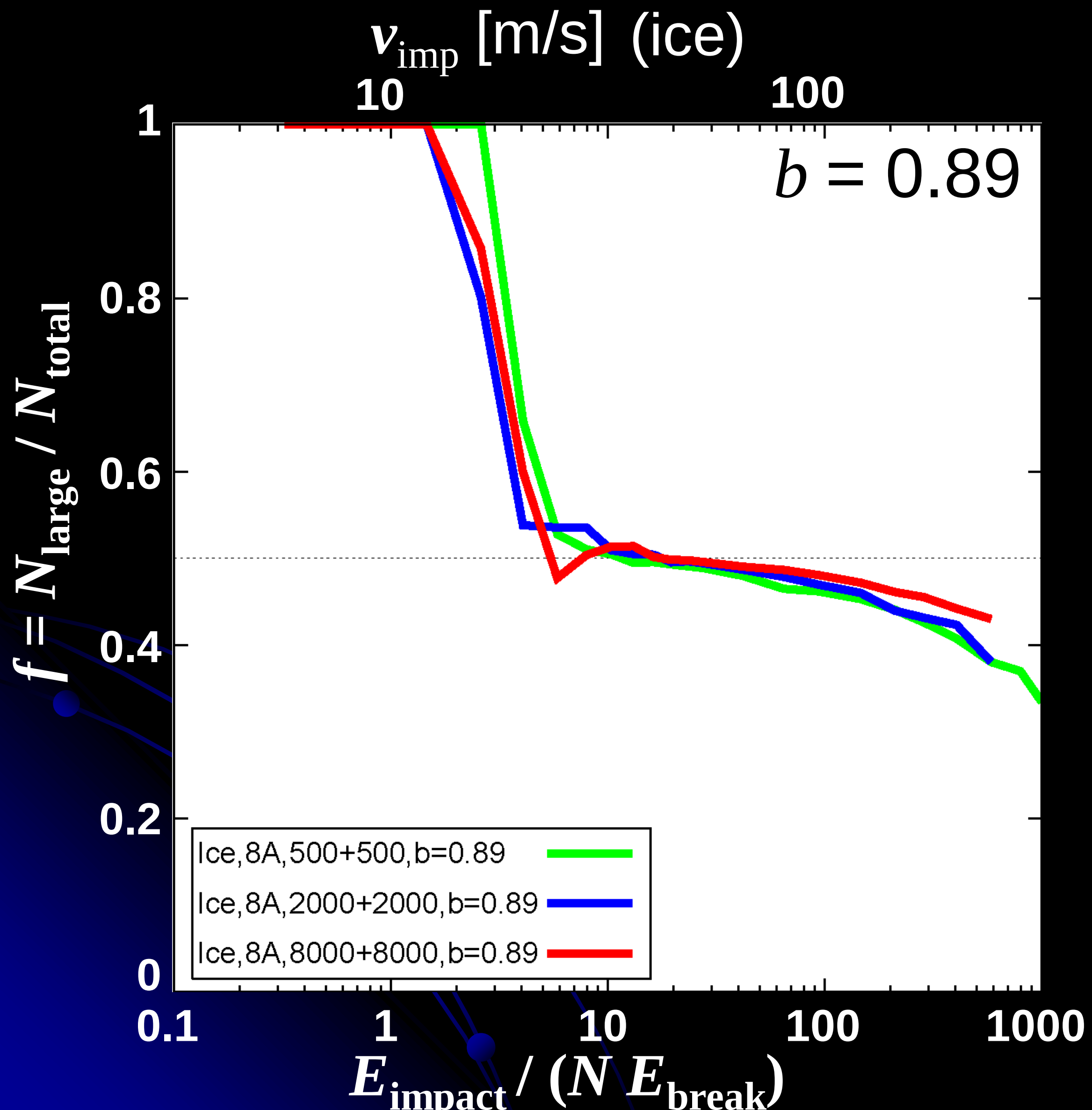


$f \equiv N_{\text{large}} / N_{\text{total}}$

: growth efficiency

- $f > 0.5$ → + growth
- $f < 0.5$ → - growth

Largest fragment mass N_{large}: *growth efficiency*

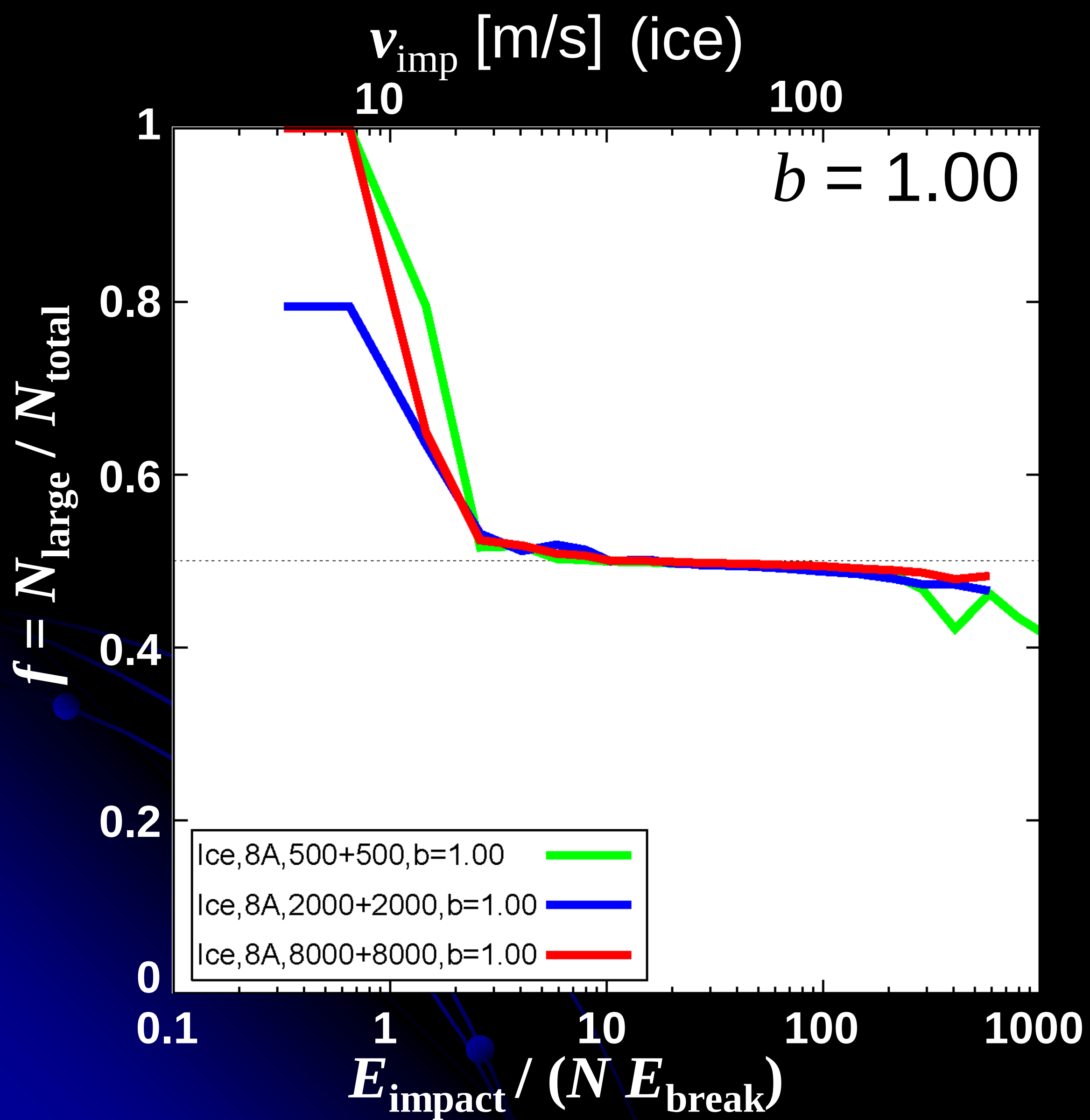


$f \equiv N_{\mathrm{large}} / N_{\mathrm{total}}$

: growth efficiency

- $f > 0.5 \rightarrow$ + growth
- $f < 0.5 \rightarrow$ - growth

Largest fragment mass N_{large}: *growth efficiency*



$f \equiv N_{\mathrm{large}} / N_{\mathrm{total}}$

: growth efficiency

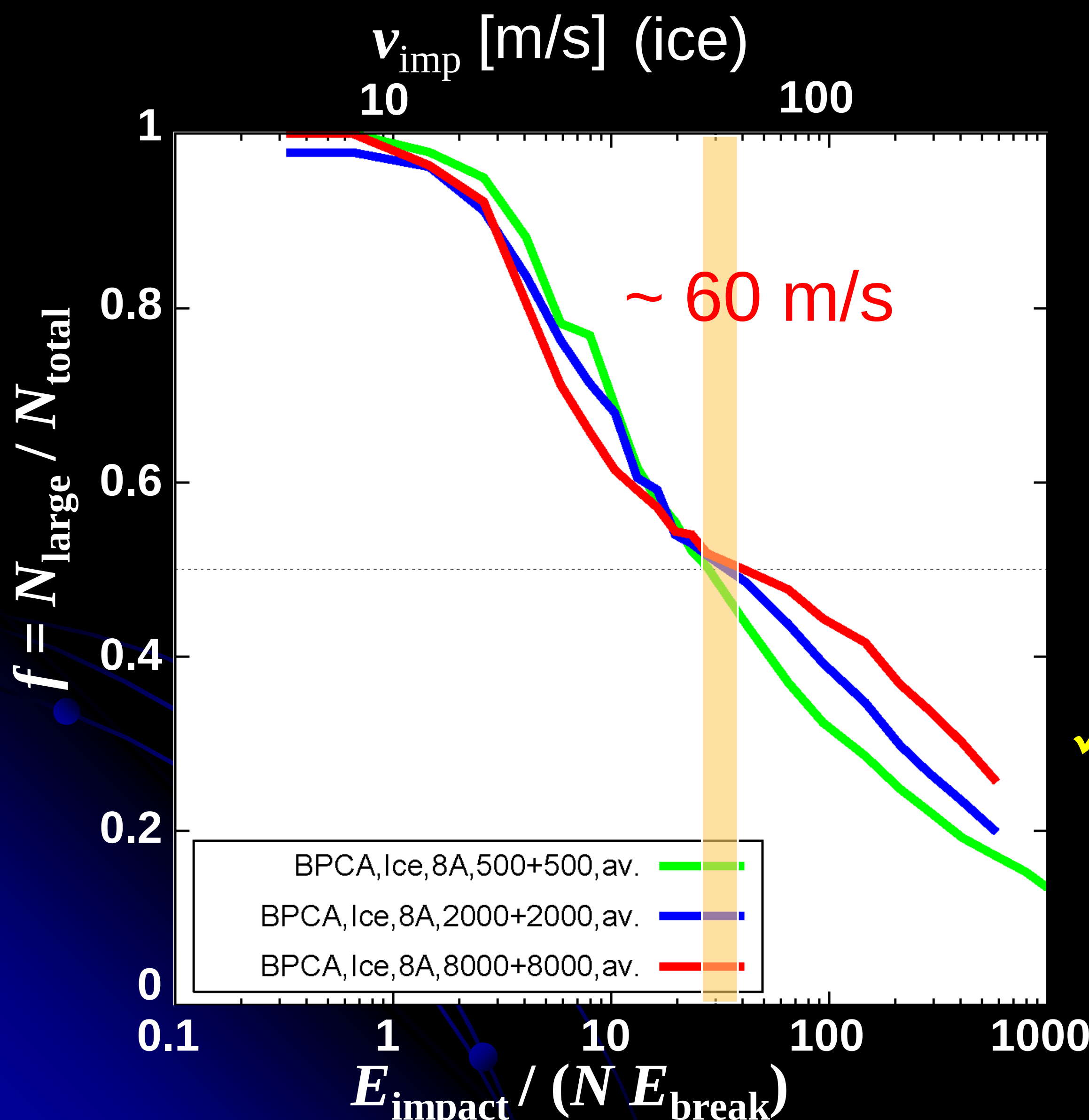
- $f > 0.5 \rightarrow$ + growth
- $f < 0.5 \rightarrow$ - growth

✓Offset collisions

⬇

independent of N

Growth efficiency averaged



Averaged for b^2

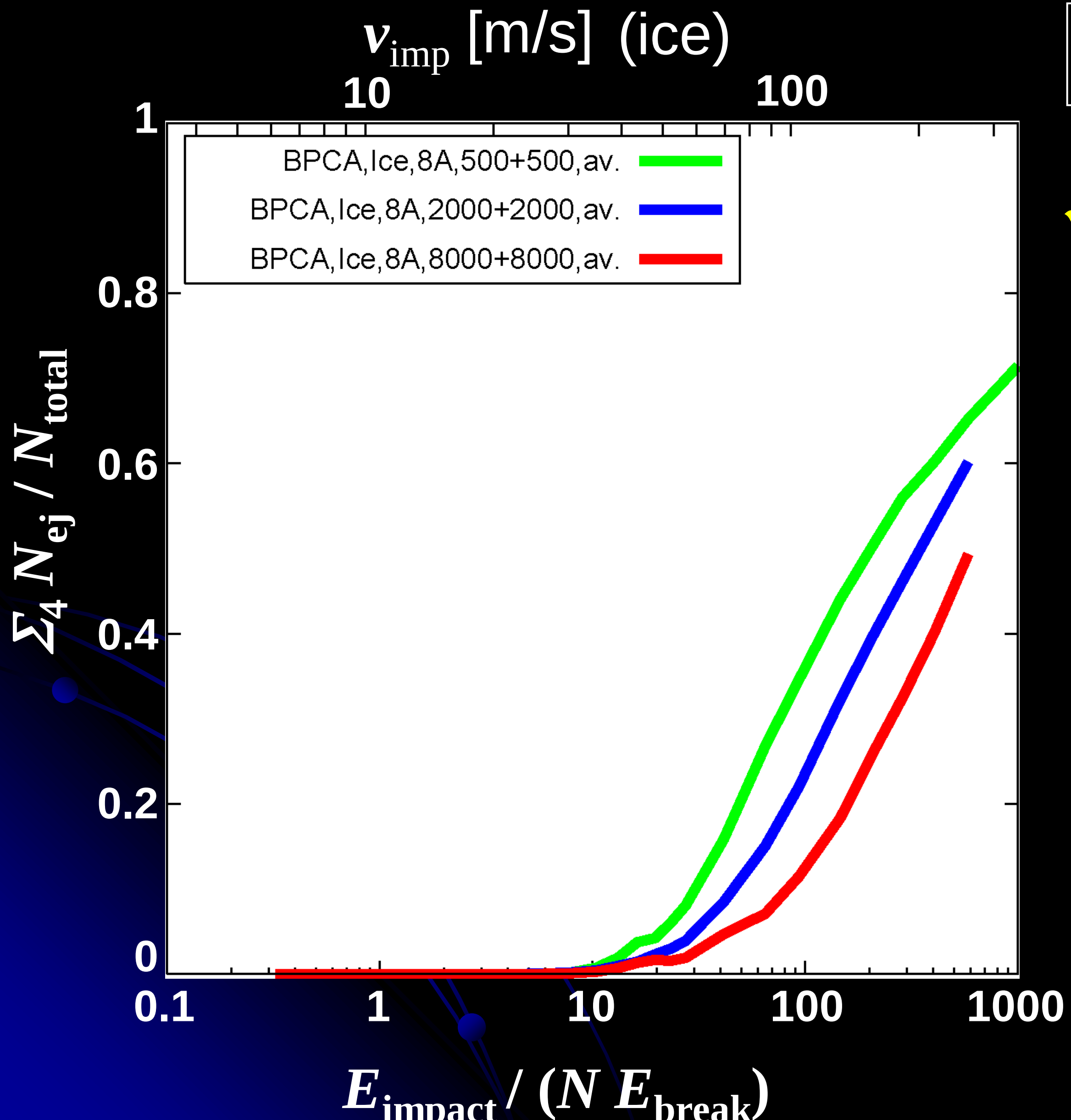
$f \equiv N_{large} / N_{total}$

: growth efficiency

- $f > 0.5 \rightarrow$ + growth
- $f < 0.5 \rightarrow$ - growth

✓small dependence on N

Amount of ejecta mass: $\Sigma_4 N_{ej}$, *averaged*



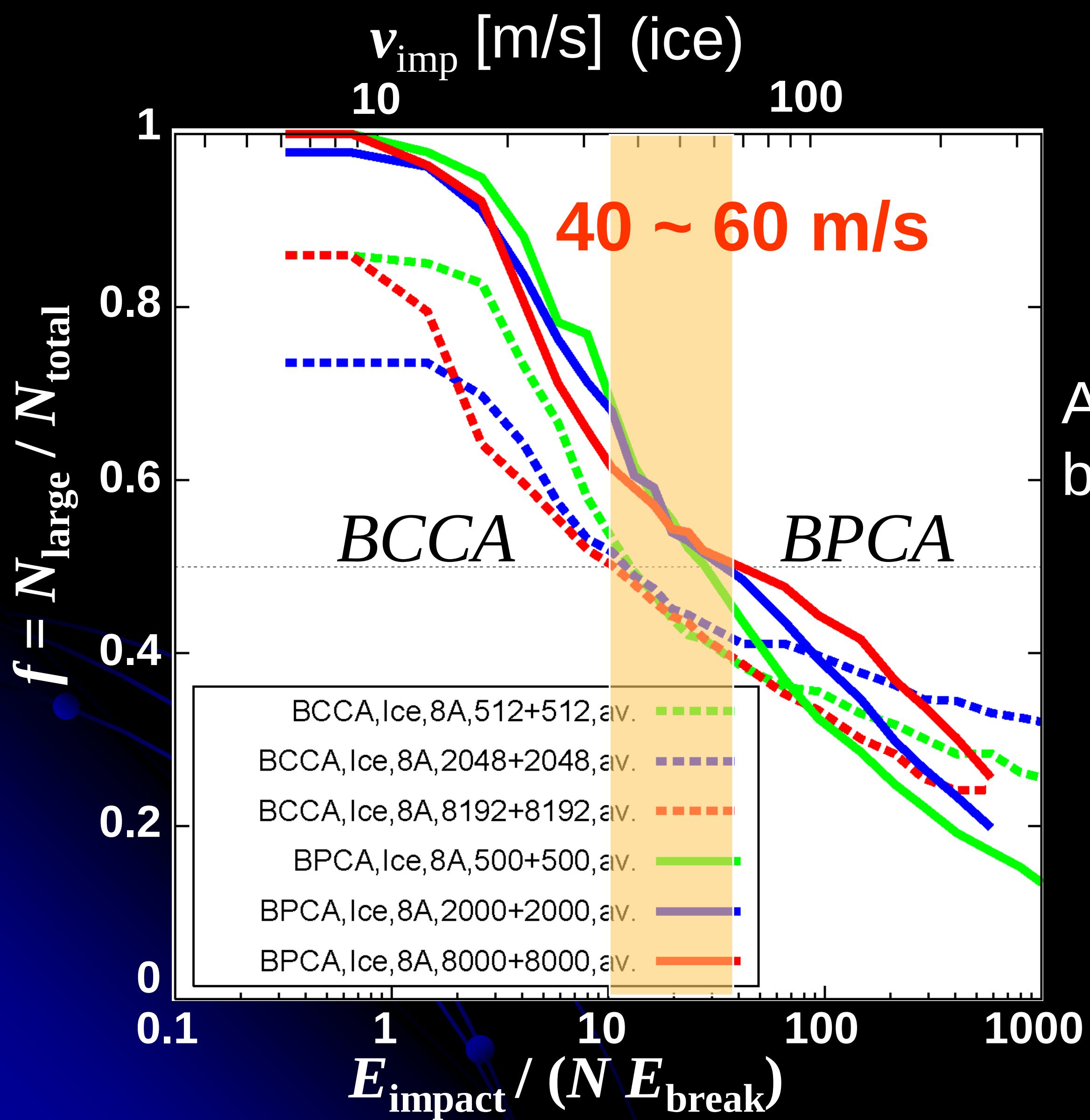
Averaged over b^2

✓dependent on N

The larger aggregates,
the smaller amount of ejecta.

Averaged *growth efficiency* : *BCCA & BPCA*

Averaged over b^2



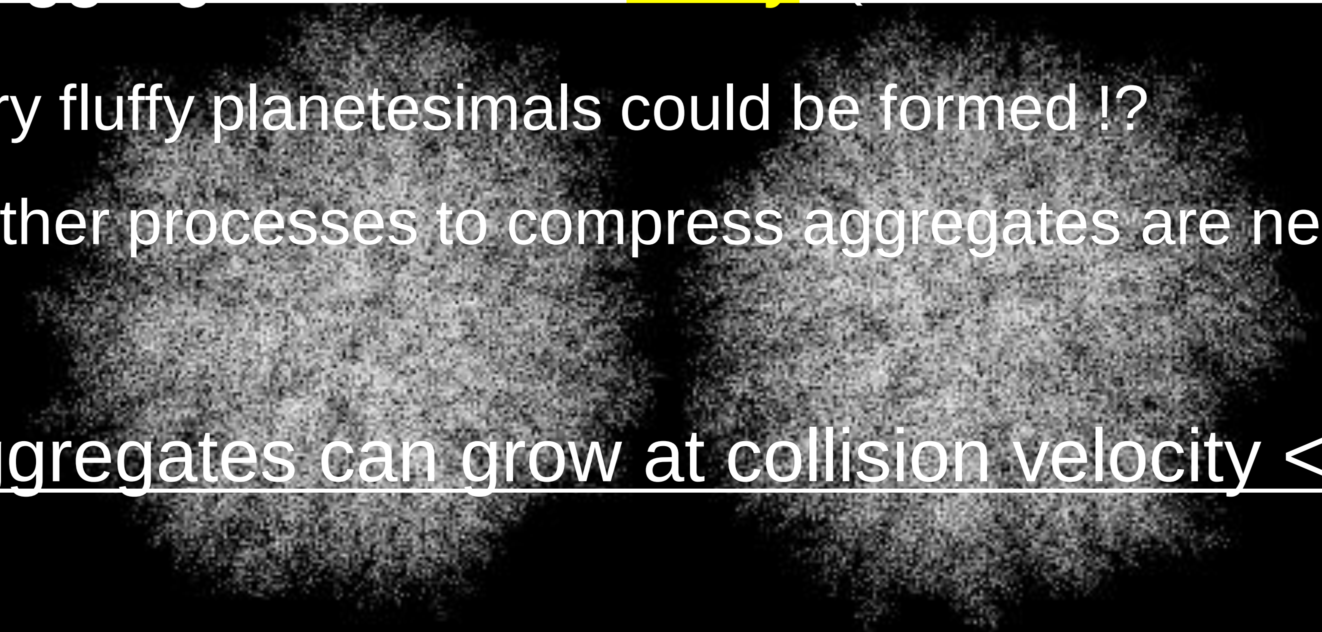
Actual dust structure:
between BCCA and BPCA

Summary and Implications

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

  Very fluffy planetesimals could be formed !?

  Other processes to compress aggregates are necessary.



- Icy aggregates can grow at collision velocity < 60 m/s.

  Planetesimals can be formed through collisions of dust.

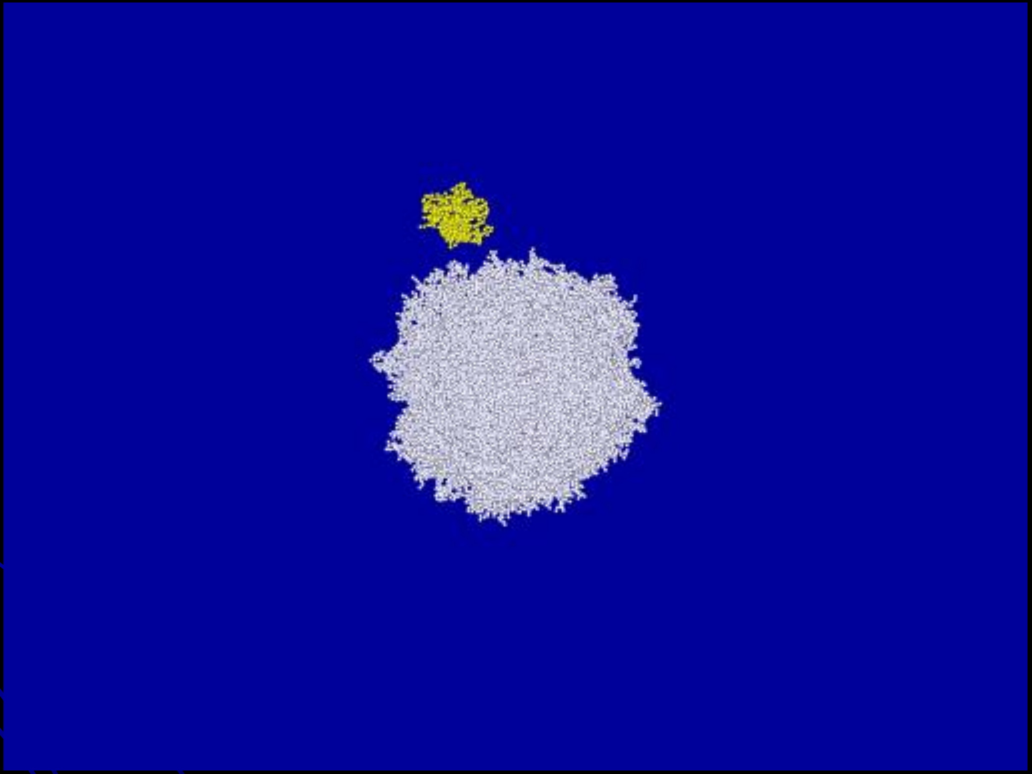
Animation by Prof. H. Tanaka

What’s next?

Collisions between different sized aggregates

BPCA, N = 32000 + 500, ice, ξ_c = 8Å, u_{col} = 70 m/s

b = 0.39



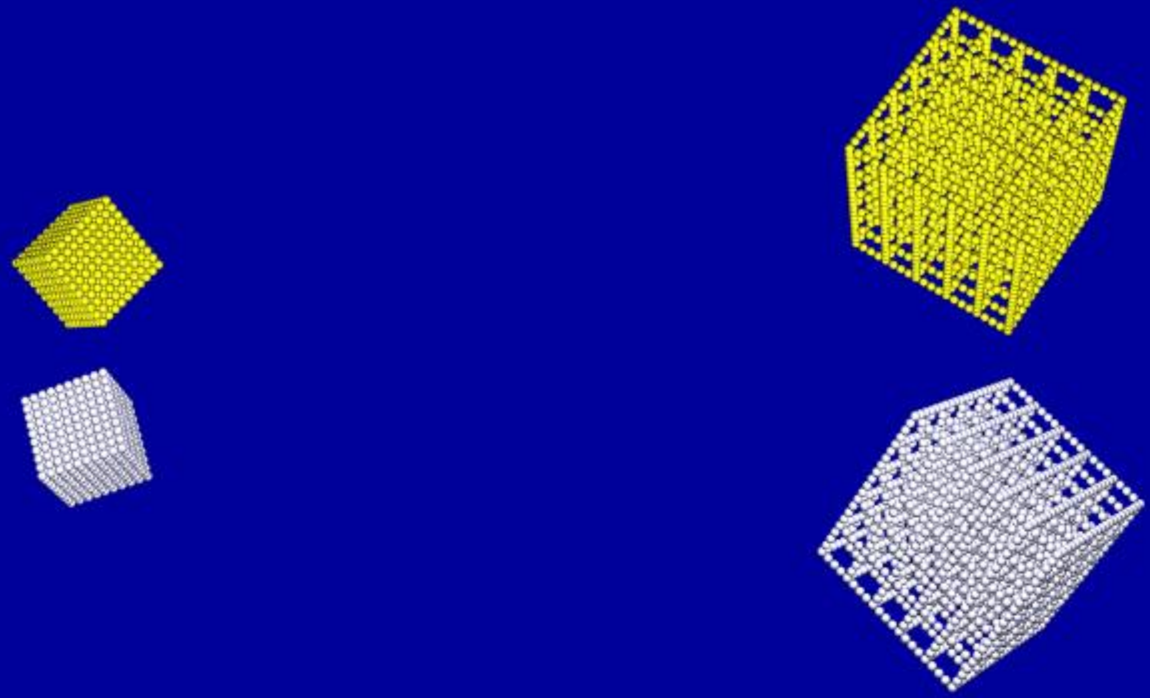
Bouncing problem

"Bouncing" prevents dust from growing

In experiments: Bouncing at $u_{\mathrm{col}} < \sim 1$ m/s

Blum & Münch 1993; Blum and Wurm 2008; Güttler et al. 2009

In our simulation: No bouncing for coordination number < 6



What's next?

焼結の影響
非球形粒子の影響
粒子のサイズ分布の影響
粒子間相互作用モデルの改良・検証

静的圧縮の効果
帯電の影響

破片のサイズ分布・構造
彗星・小惑星の表層進化

衝突クレーター

ありがとうございました

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