To Be Planetesimals, or Not to Be: That is the Question of Dust Aggregates.

Numerical Simulations of Dust Aggregate Collisions

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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 ?

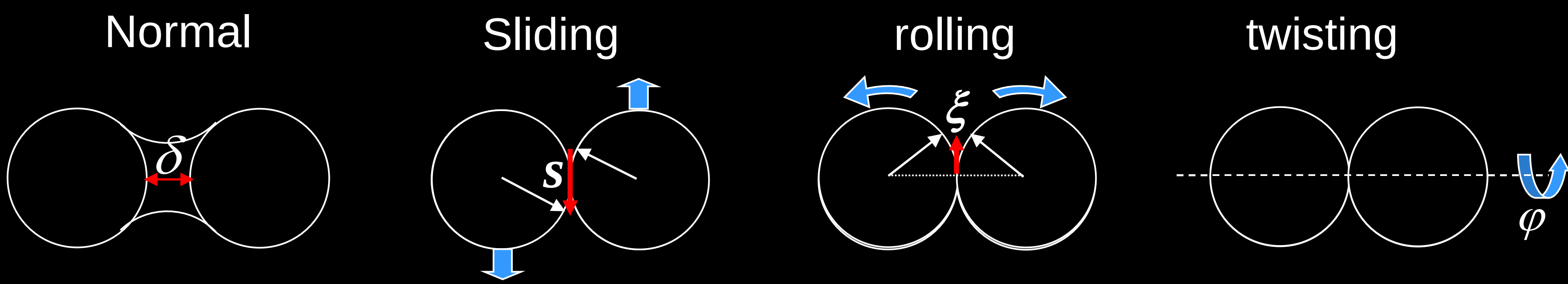
✓Can dust aggregates grow through collisions?

→ **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



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°

Today's topics

Can dust grow through collisions?

for Low-velocity collisions

- Does "bouncing barrier" for dust growth really exist?

  ⇒ No!

for high-velocity collisions

- Do collisions between different-sized aggregate encourage dust growth?

  ⇒ Partly Yes.

Bouncing Conditions

To bounce, or not to bounce?

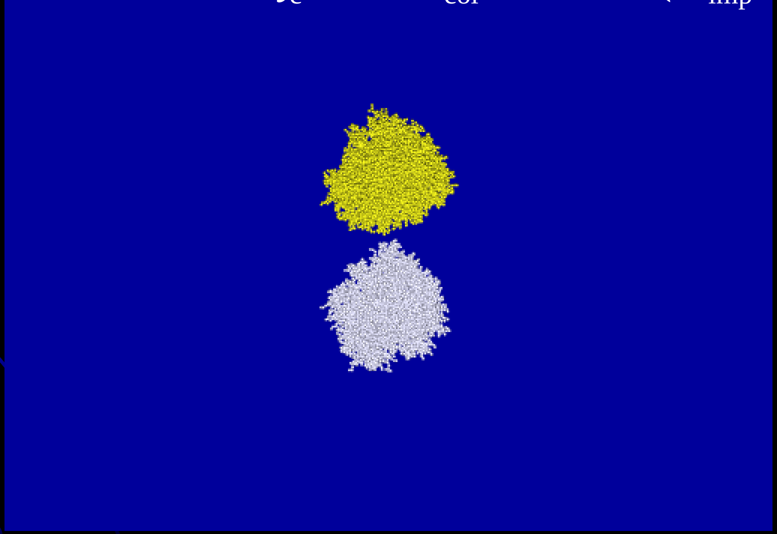
Bouncing Problem

"Bouncing" prevents dust from growing

Previous numerical simulaitons: Dominik & Tielens 1997; Wada et al. 2007, 2008, 2009; Suyama et al. 2008, etc…

No bouncing ➡ Collisional growth is feasible!

BPCA, N=8000+8000, ice, ξ_c = 8Å, u_{col} = 70 m/s (E_{imp} = 42 NE_{break})



Bouncing in experiments

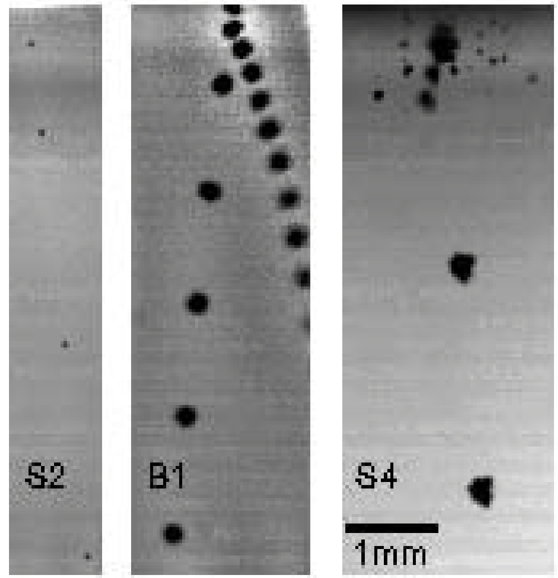


Fig. 5. Examples for the experimental outcomes in the collisions of small aggregates with a solid target. The collision can lead to sticking bouncing or fragmentation (from left to right). The time between two exposures is 2 ms.

Güttler et al. 2010

Stiking | Bouncing | Fragmentation and/or sticking

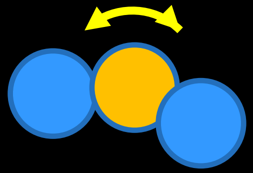
u_{col} → ~ 1 m/s

Bouncing condition

- Why bouncing in experiments？
- What’s the condition for bouncing？

Hypothesis：Number of contacts controls？

Bouncing would be caused by immobility of particles, inhibiting energy dissipation.



Aggregates in numerical simulations：

Number of particles in contact with a particle （Coordination number, C.N.）＝ 2～4, on average

More C.N. in experiments？

Objective

● To reveal the dependence on coordination number for aggregate bouncing

Simulation of aggregate collisions

parameter : Coordination Number (C.N.)

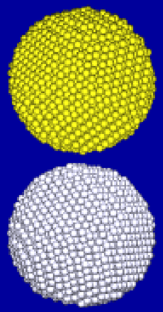
Idea for making required C.N. :

Extracting particles randomly from close-packed structure (C.N.=12)

↓

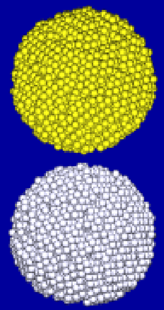
aggregates with C.N. = ~12 to ~3

Initial conditions and settings

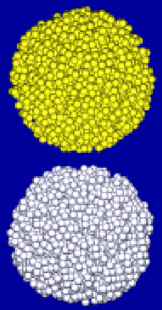


- ✓ (hexagonal) close-packed aggregates：
  mean C.N. ~ 11
  - Number of particles：4197 （3 types randomly produced）
- ✓ particle-extracted aggregates：
  extraction rate f = 0.05 - 0.75 C.N.~12 (1 – f)

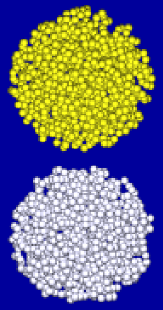
f = 0.2
mean C.N. = 8.8



f = 0.5
mean C.N. = 5.5



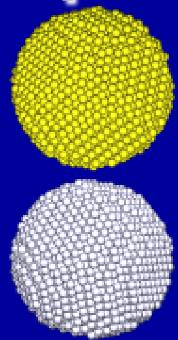
f = 0.75
mean C.N. = 2.8



- ✓ Ice (E = 7.0 GPa, ν = 0.25, γ = 100 mJ/m^2, R = 0.1μm) , critical rolling displace. ξ_{crit} = 8Å
- ✓ SiO_2 (E = 54 GPa, ν = 0.17, γ = 25 mJ/m^2, R = 0.1μm) , critical rolling displace. ξ_{crit} = 8Å
- ✓ u_{col} = 0.1 - 22 m/s (Ice), 0.01 - 2.2 m/s (SiO_2)

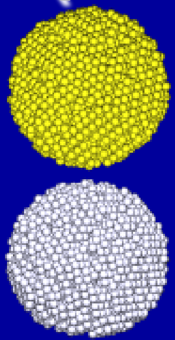
Examples of simulation (Ice)

C.N.= 11



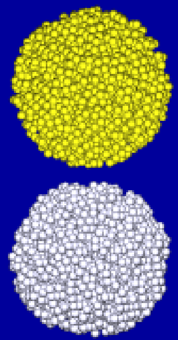
u_{col} = 0.096 m/s (E_{imp} = 0.66 E_{break})

C.N.= 8.8



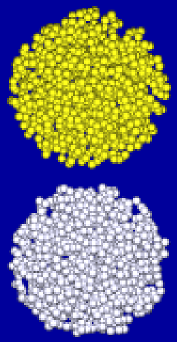
u_{col} = 0.096 m/s (E_{imp} = 0.53 E_{break})

C.N.= 5.5



u_{col} = 0.38 m/s (E_{imp} = 5.3 E_{break})

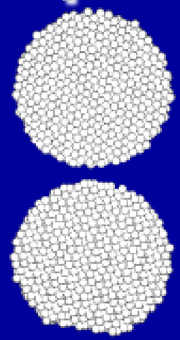
C.N.= 2.8



u_{col} = 0.38 m/s (E_{imp} = 2.7 E_{break})

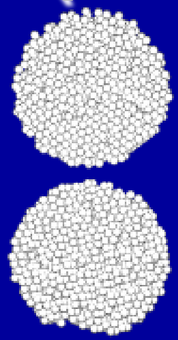
Examples of simulation (Ice)

C.N.= 11



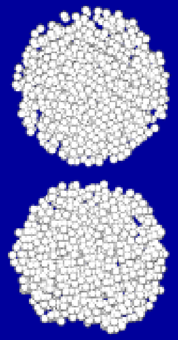
$u_{col} = 0.096$ m/s ($E_{imp} = 0.66\, E_{break}$)

C.N.= 8.8



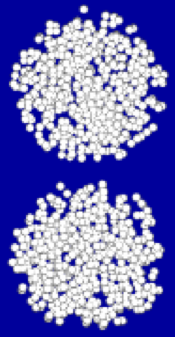
$u_{col} = 0.096$ m/s ($E_{imp} = 0.53\, E_{break}$)

C.N.= 5.5



$u_{col} = 0.38$ m/s ($E_{imp} = 5.3\, E_{break}$)

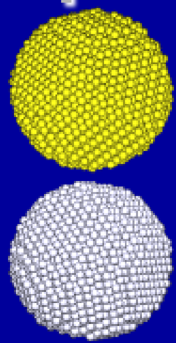
C.N.= 2.8



$u_{col} = 0.38$ m/s ($E_{imp} = 2.7\, E_{break}$)

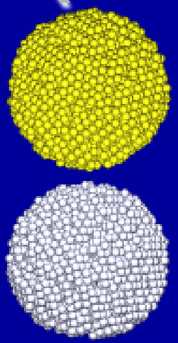
Examples of simulation (Ice)

C.N.= 11



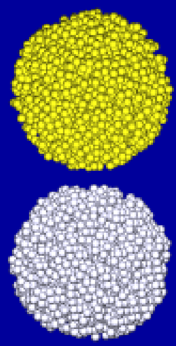
$u_{col} = 1.5$ m/s ($E_{imp} = 170\ E_{break}$)

C.N.= 8.8



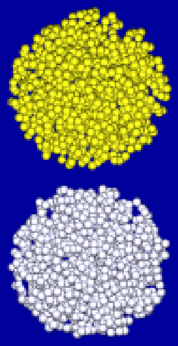
$u_{col} = 1.5$ m/s ($E_{imp} = 135\ E_{break}$)

C.N.= 5.5



$u_{col} = 1.5$ m/s ($E_{imp} = 85\ E_{break}$)

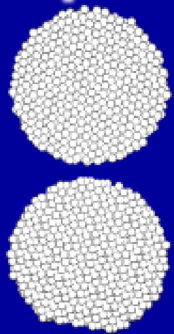
C.N.= 2.8



$u_{col} = 1.5$ m/s ($E_{imp} = 43\ E_{break}$)

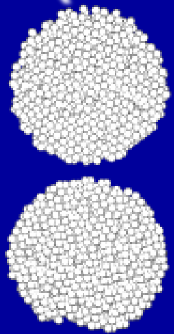
Examples of simulation (Ice)

C.N.= 11



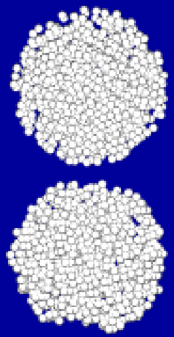
u_{col} = 1.5 m/s (E_{imp} = 170 E_{break})

C.N.= 8.8



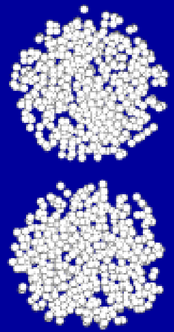
u_{col} = 1.5 m/s (E_{imp} = 135 E_{break})

C.N.= 5.5



u_{col} = 1.5 m/s (E_{imp} = 85 E_{break})

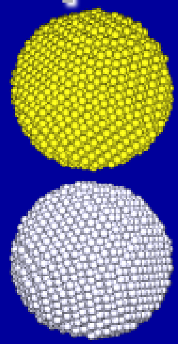
C.N.= 2.8



u_{col} = 1.5 m/s (E_{imp} = 43 E_{break})

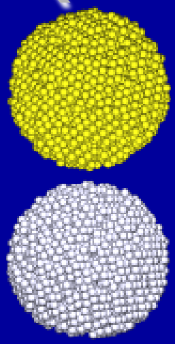
Examples of simulation (Ice)

C.N.= 11



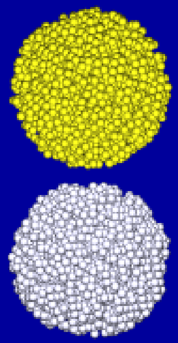
$u_{\mathrm{col}} = 22$ m/s ($E_{\mathrm{imp}} = 4.1\, N\, E_{\mathrm{break}}$)

C.N.= 8.8



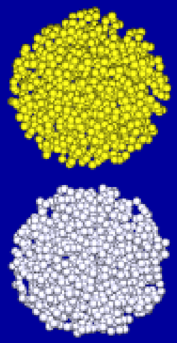
$u_{\mathrm{col}} = 22$ m/s ($E_{\mathrm{imp}} = 4.1\, N\, E_{\mathrm{break}}$)

C.N.= 5.5



$u_{\mathrm{col}} = 22$ m/s ($E_{\mathrm{imp}} = 4.1\, N\, E_{\mathrm{break}}$)

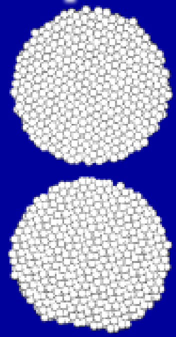
C.N.= 2.8



$u_{\mathrm{col}} = 22$ m/s ($E_{\mathrm{imp}} = 4.1\, N\, E_{\mathrm{break}}$)

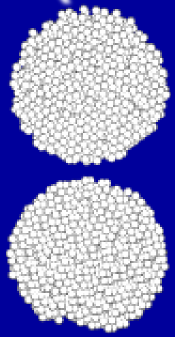
Examples of simulation (Ice)

C.N.= 11



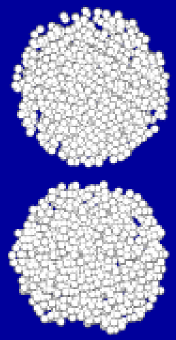
$u_{col} = 22$ m/s ($E_{imp} = 4.1\, N\, E_{break}$)

C.N.= 8.8



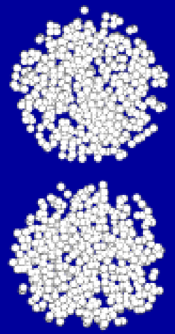
$u_{col} = 22$ m/s ($E_{imp} = 4.1\, N\, E_{break}$)

C.N.= 5.5



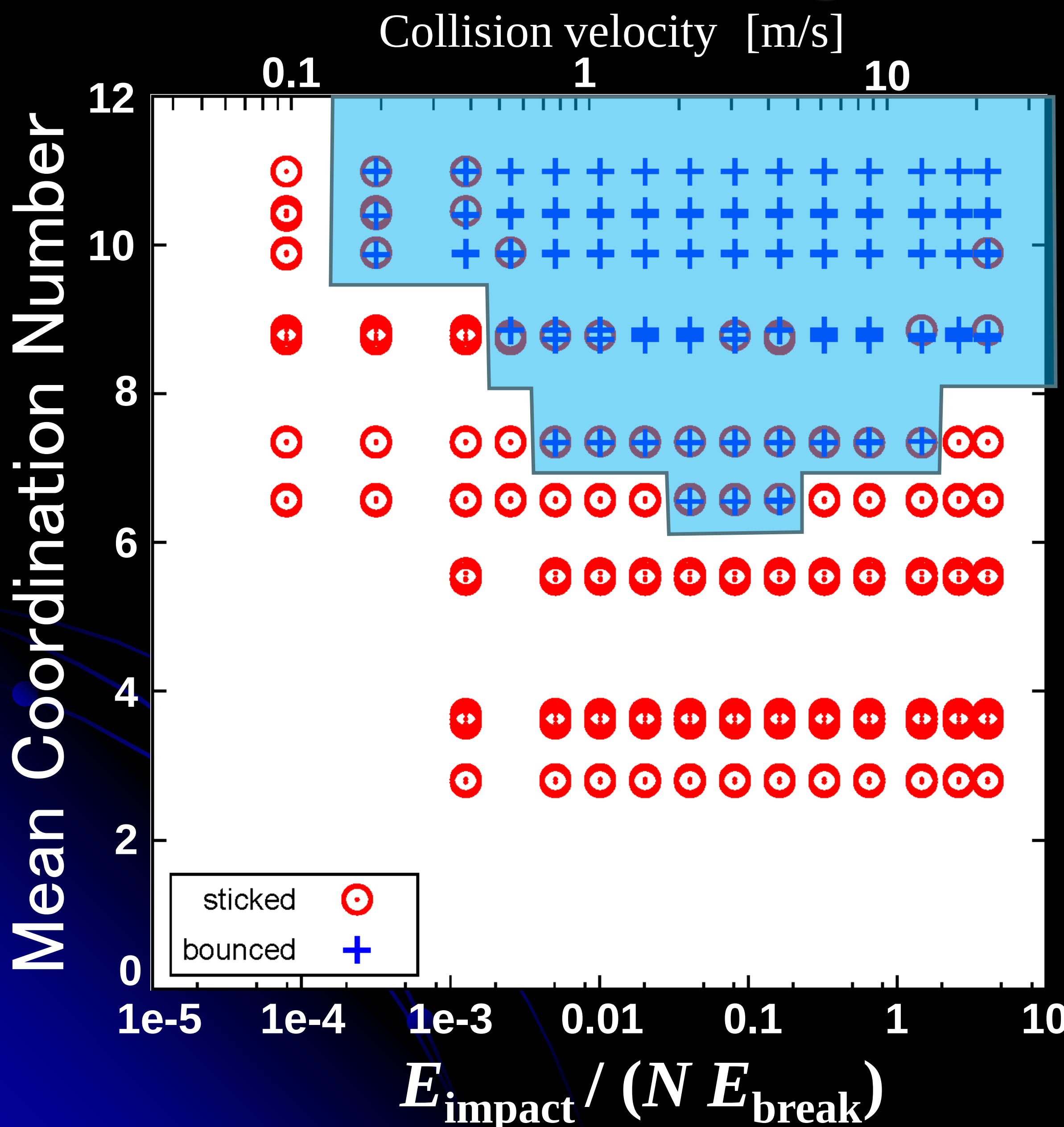
$u_{col} = 22$ m/s ($E_{imp} = 4.1\, N\, E_{break}$)

C.N.= 2.8



$u_{col} = 22$ m/s ($E_{imp} = 4.1\, N\, E_{break}$)

Result : Bouncing Condition (Ice)

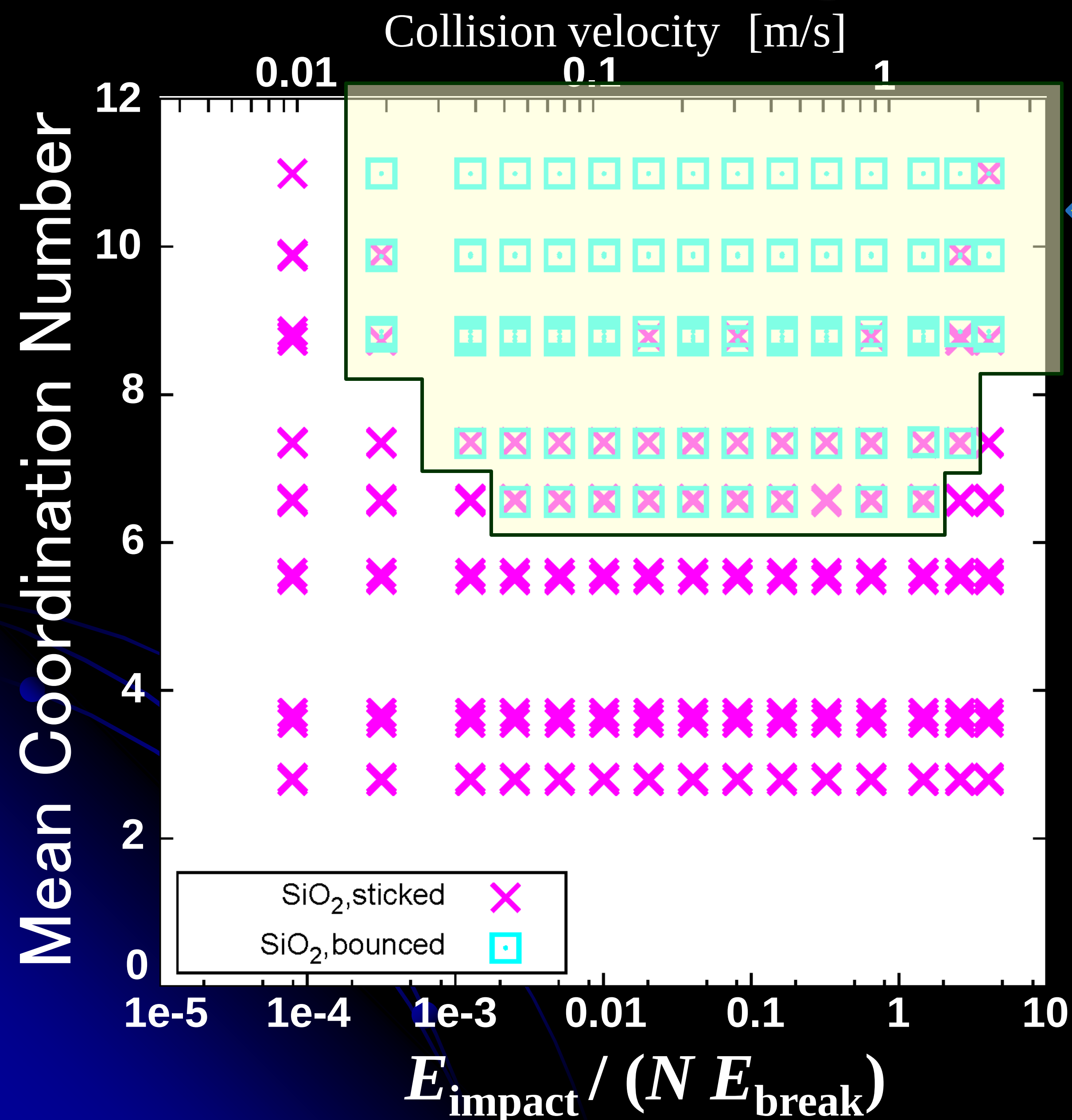


Bouncing

Mean C.N. < ~ 6

Sticking

Result: Bouncing Condition (SiO_2)

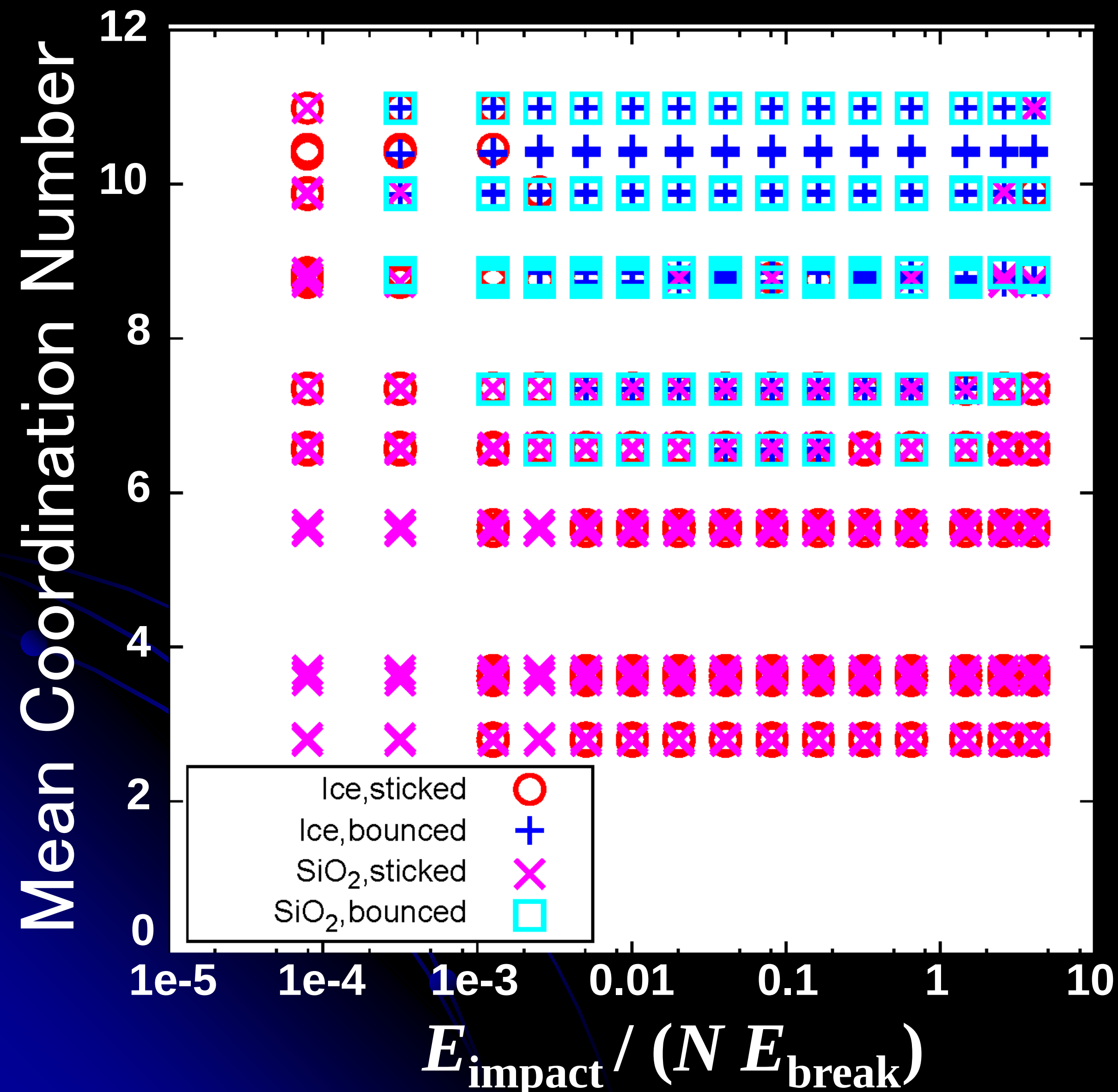


Bouncing

Mean C.N. < ~ 6

Sticking

Result: Bouncing Condition
(Ice, SiO_2)

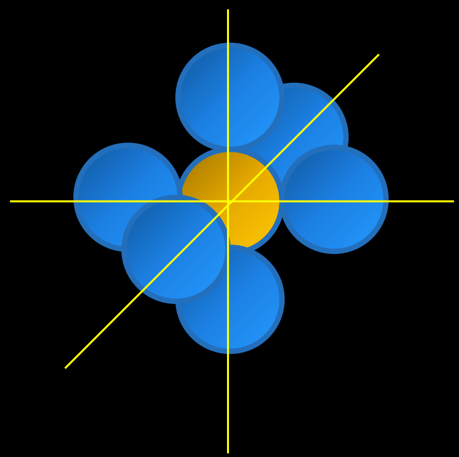


No difference between Ice and SiO_2

Scaled well by using E_{break}

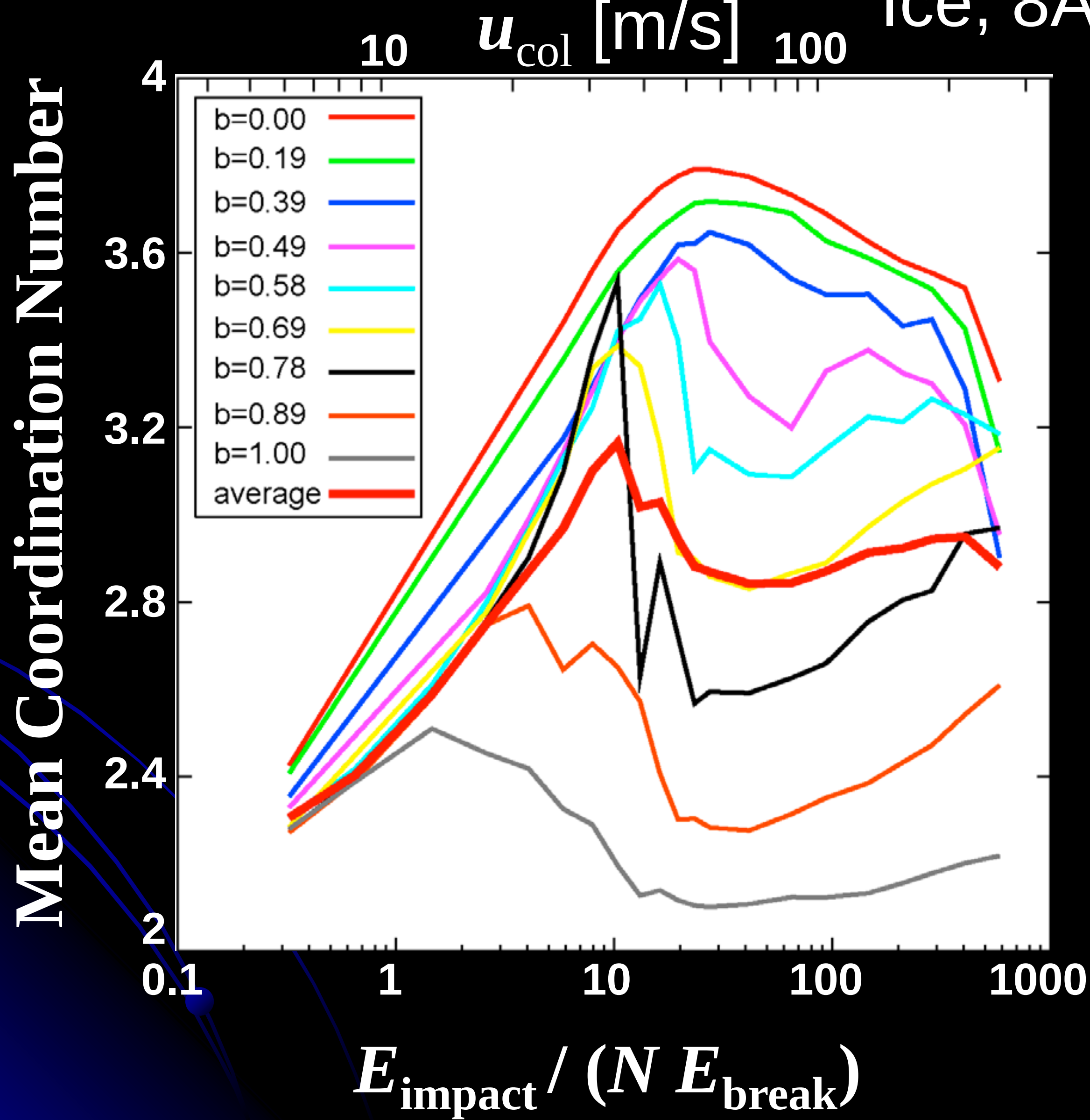
Why C.N. = 6 ?

A particle cannot move freely with C.N. = 6 in 3D:



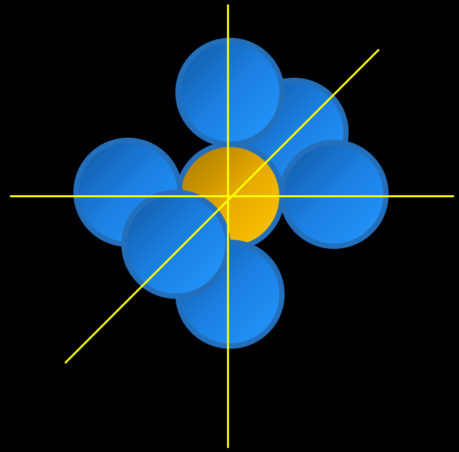
C.N.@BPCA collisions

Ice, 8Å, 8000+8000

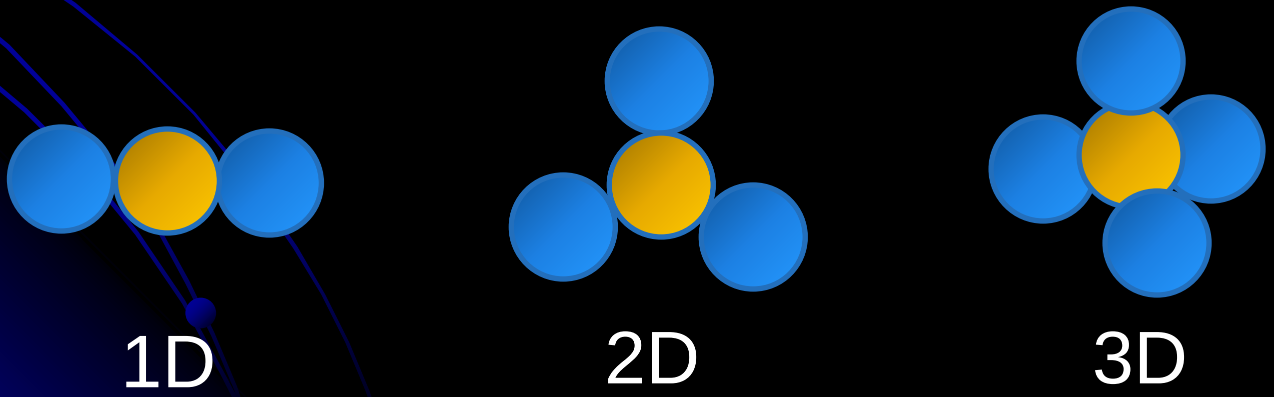


Why C.N. = 4 ?

A particle cannot move freely with C.N. = 6 in 3D:

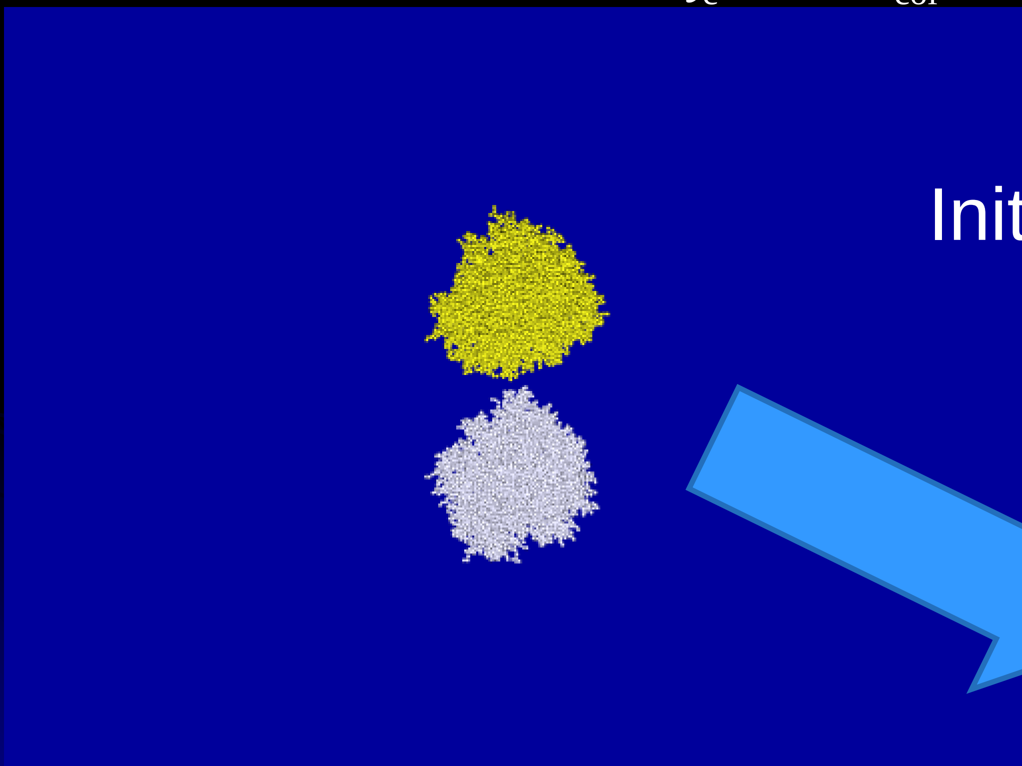


But, stable enough with at least C.N. = 4 in 3D:

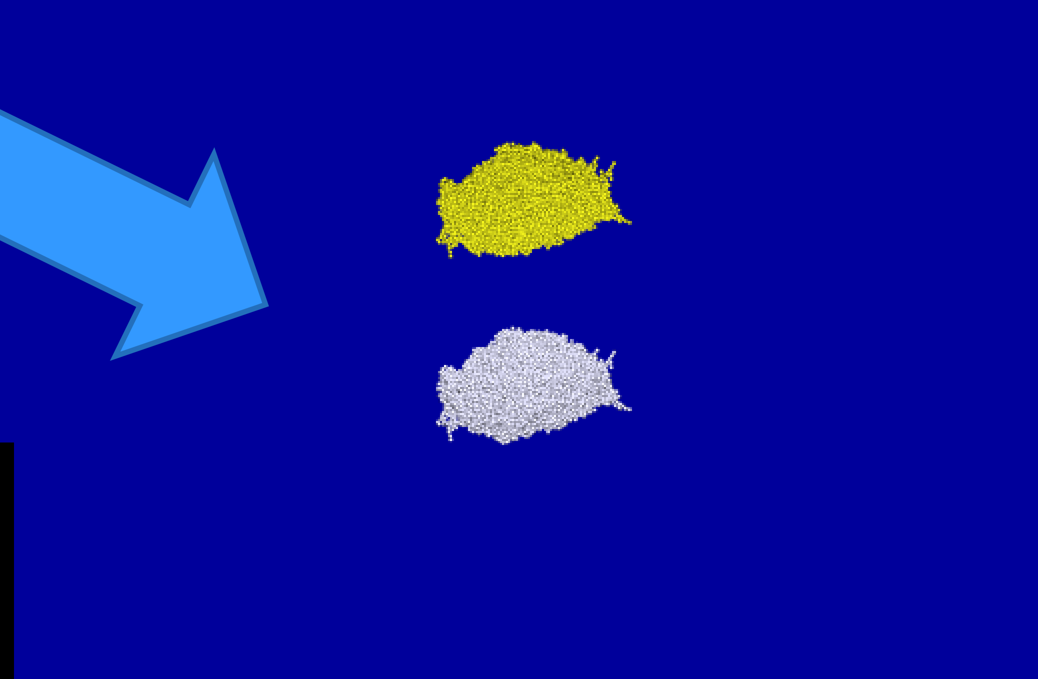


aggregates produced by collisions

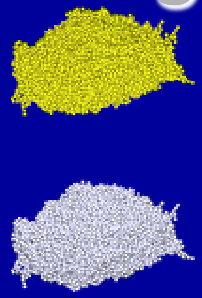
BPCA, N=8000+8000, ice, ξ_c = 8Å, u_{col} = 57 m/s (E_{imp} = 27 NE_{break})



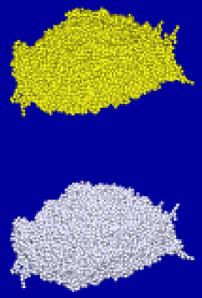
Initial condition(C.N. = 3.8)
15288+15288



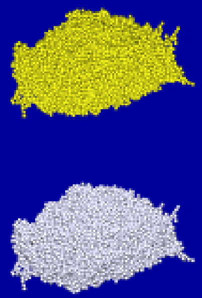
Collisions of collision-produced aggregates (C.N.=3.8)



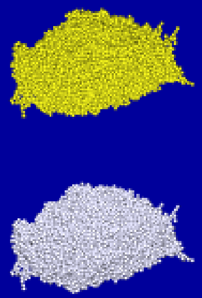
$u_{col} = 0.38$ m/s ($E_{imp} = 1.2 \times 10^{-3}\ NE_{break}$)



$u_{col} = 0.77$ m/s ($E_{imp} = 5.1 \times 10^{-3}\ NE_{break}$)

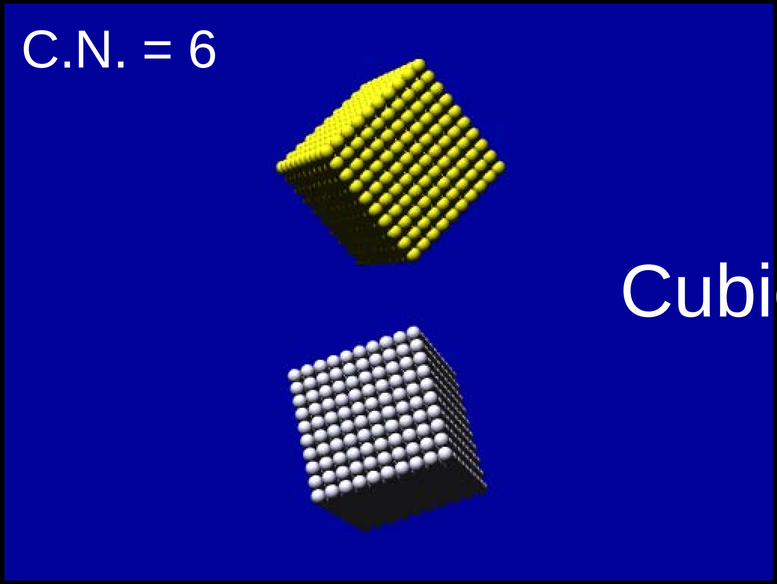


$u_{col} = 1.54$ m/s ($E_{imp} = 2.0 \times 10^{-2}\ NE_{break}$)

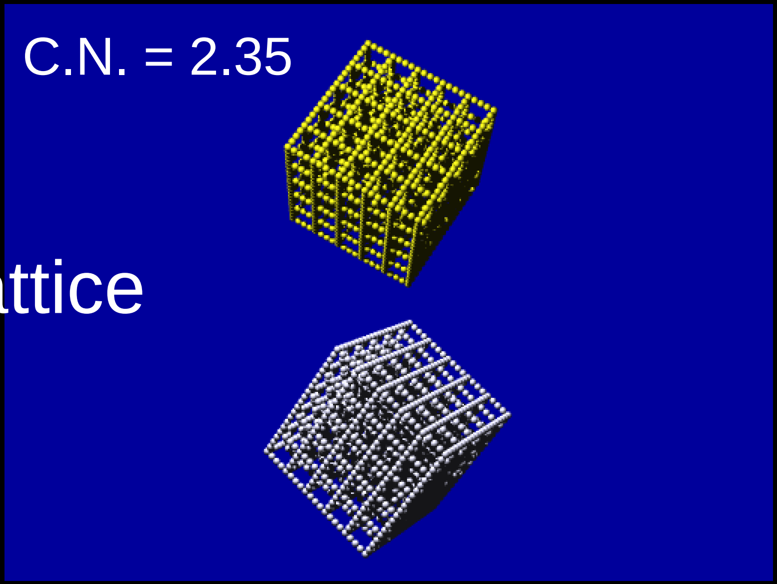


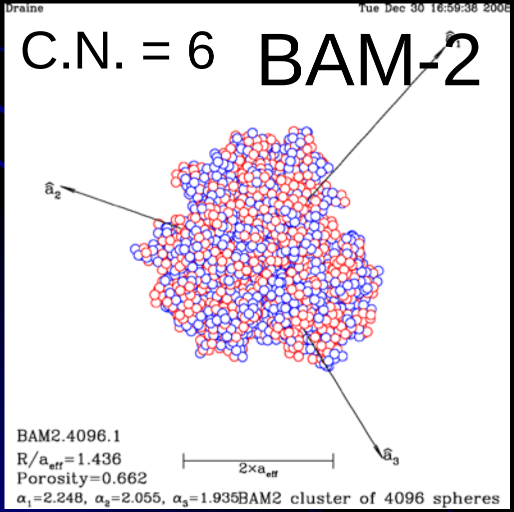
$u_{col} = 17.4$ m/s ($E_{imp} = 2.6\ NE_{break}$)

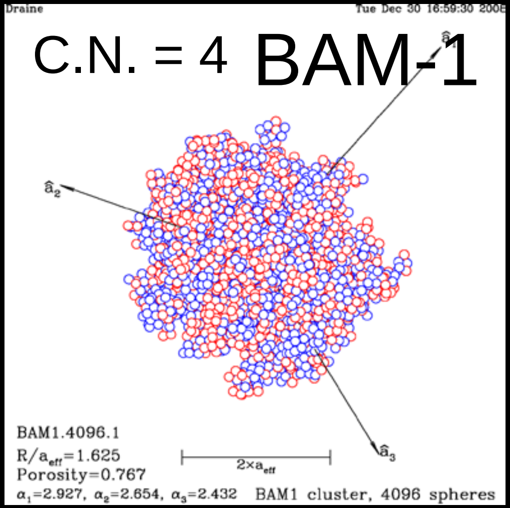
Structure is also important?



Cubic lattice



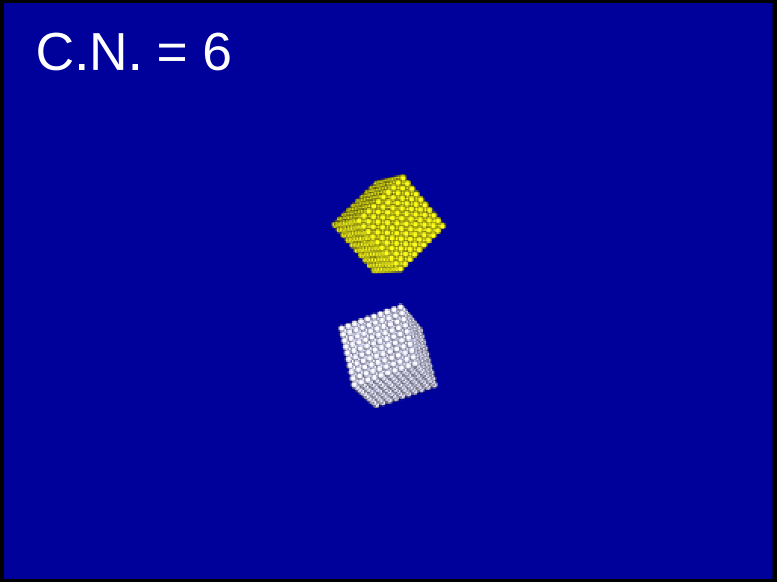


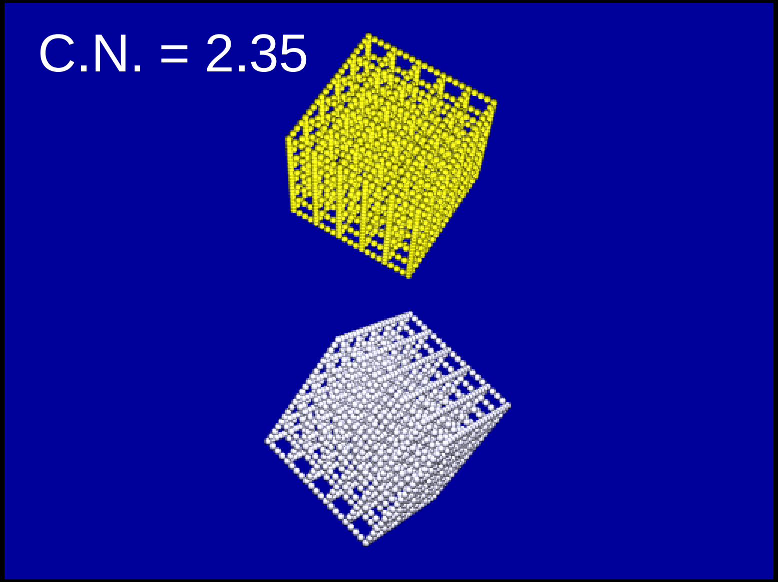


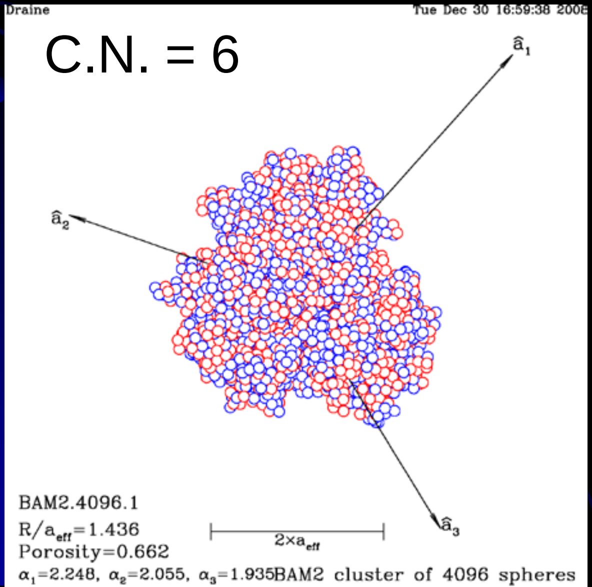
Ballistic Agglomeration with Migration (BAM)

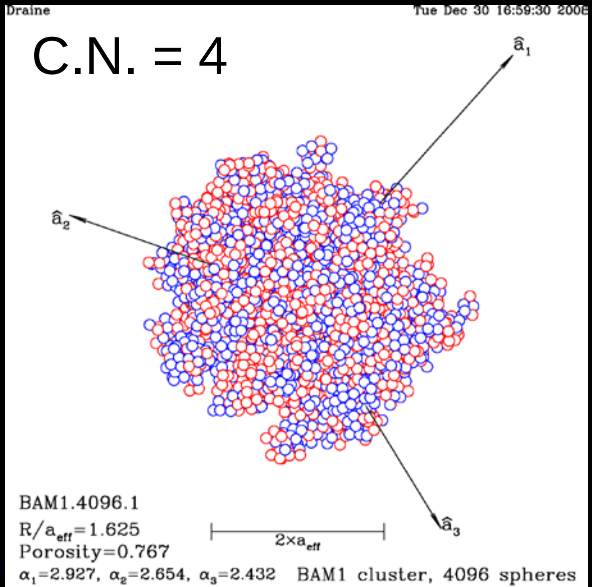
Shen, Draine, and Johnson (2008)

Structure is not important.









No!
Bouncing
only for C.N.$\simeq$6

Summary

We examine the bouncing condition, focusing on C.N. of aggregates.

- Always sticking if C.N. < 6.
- Collision velocity for transition from bouncing to sticking is consistent with experimental results.
- collision-produced aggregates have C.N. < 4

Not to bounce.

It is feasible to form planetesimals through direct collisions of dust aggregates.

C.N. ~ 2 for aggregates in experiments ?

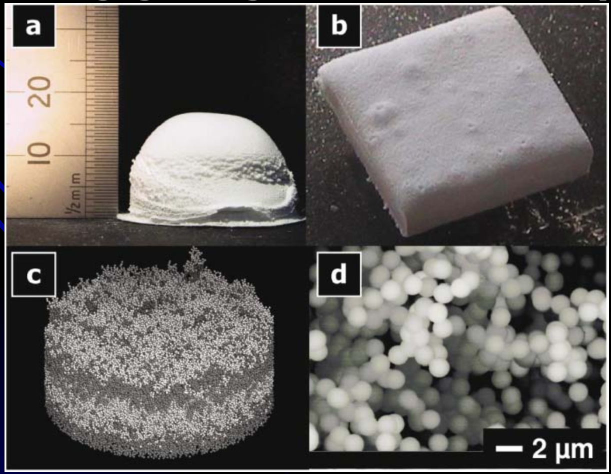
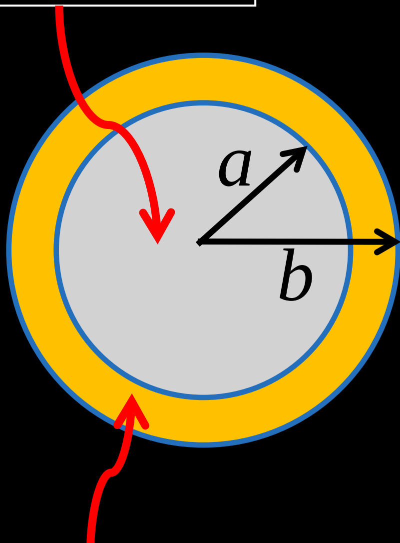


FIG. 2 (color online). (a) An example of an agglomerate with a volume filling factor of *0:15. (b) Specimen of an agglomerate* after manual cutting to 10 10 mm2. (c) Result of a Monte Carlo simulation of ballistic deposition. (d) High resolution scanning electron microscopy (SEM) image of the surface of an agglomerate consisting of SiO2 spheres with 1:*5 m diameter.*

(Blum & Schräpler 2004)

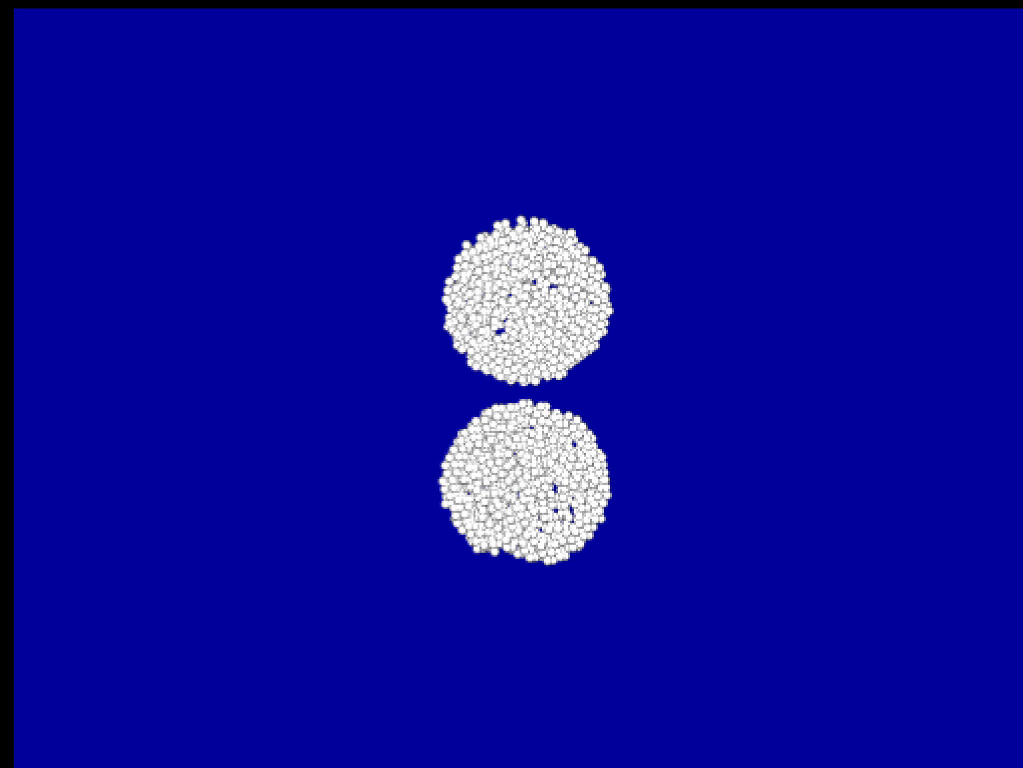
A Hard Shell ?

f = 0.75
mean C.N. = 2.8



f = 0.2
mean C.N. = 8.8

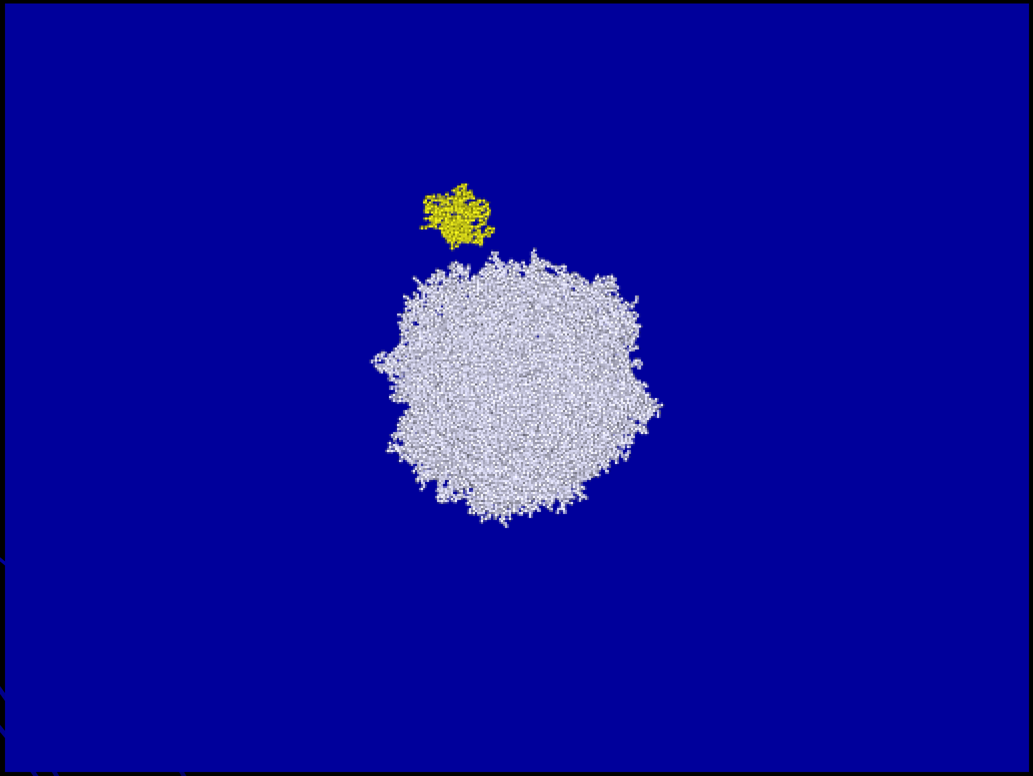
$a/b = 0.8$



Ice

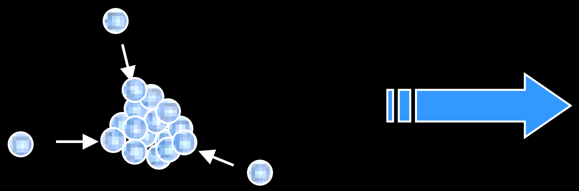
u_{col} = 1.1 m/s (vimp = 3)

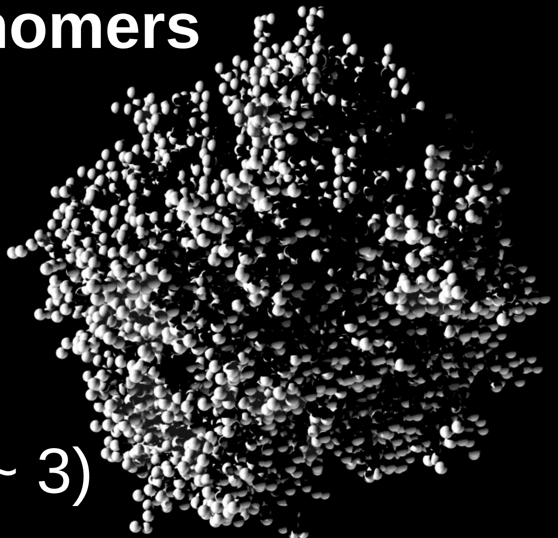
Collisions between different-sized dust aggregates



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

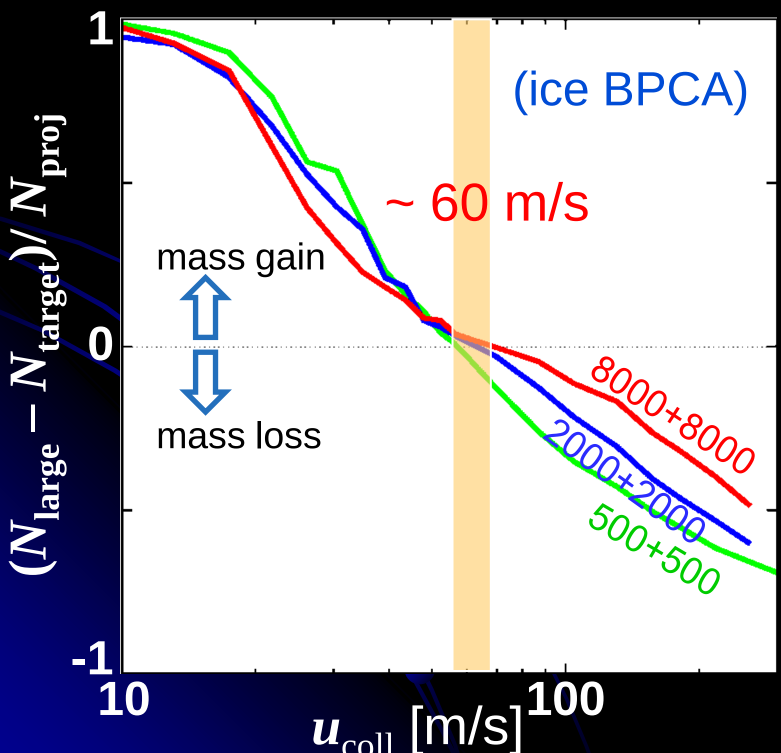
Collisions of BPCA clusters
→ implication for growth and disruption of dust

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 ?



Possible for ice dust of equal-sized aggregates

But, for silicate dust?

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

What if different-sized?

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

Objective

Do collisions of different-sized aggregates encourage dust growth?

Simulations of collisions between BPCAs of different sizes

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

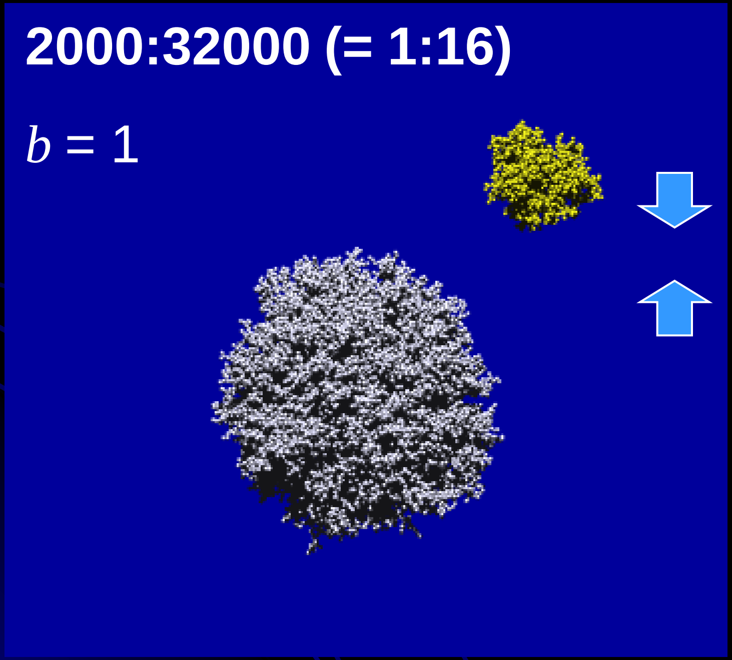
Size dependence

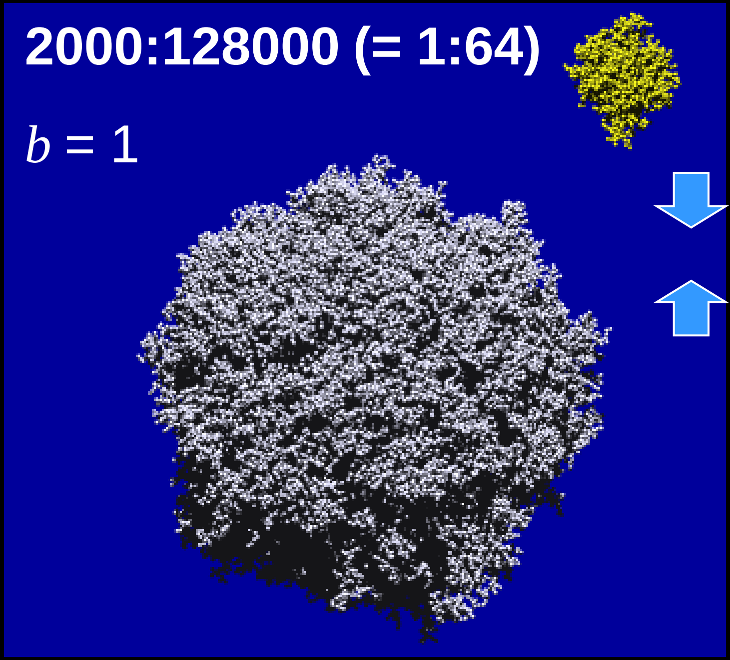
Size-ratio dependence

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)



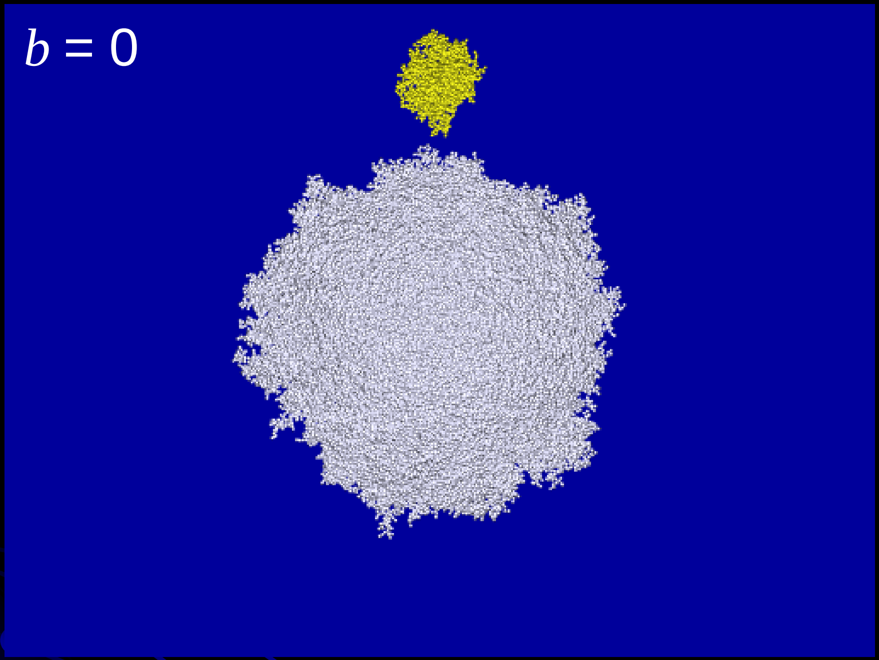


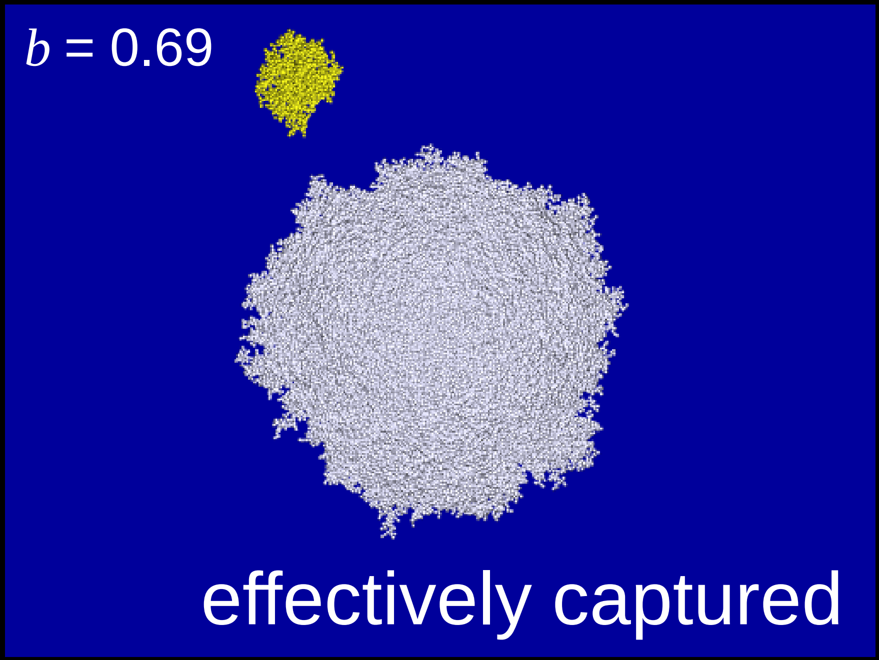
✓Ice (E = 7.0 × 10^{10} Pa, ν = 0.25, γ = 100 mJ/m^2, R = 0.1μm) , critical rolling displace. ξ_{crit} = 8Å

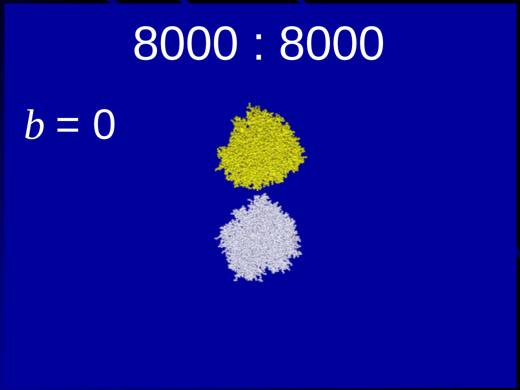
✓Collision velocity u_{coll} = 15 - 300 m/s

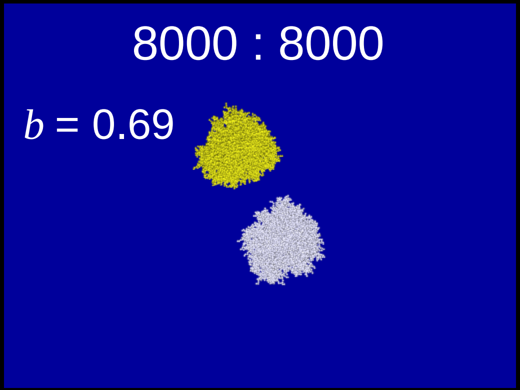
Examples of simulations

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

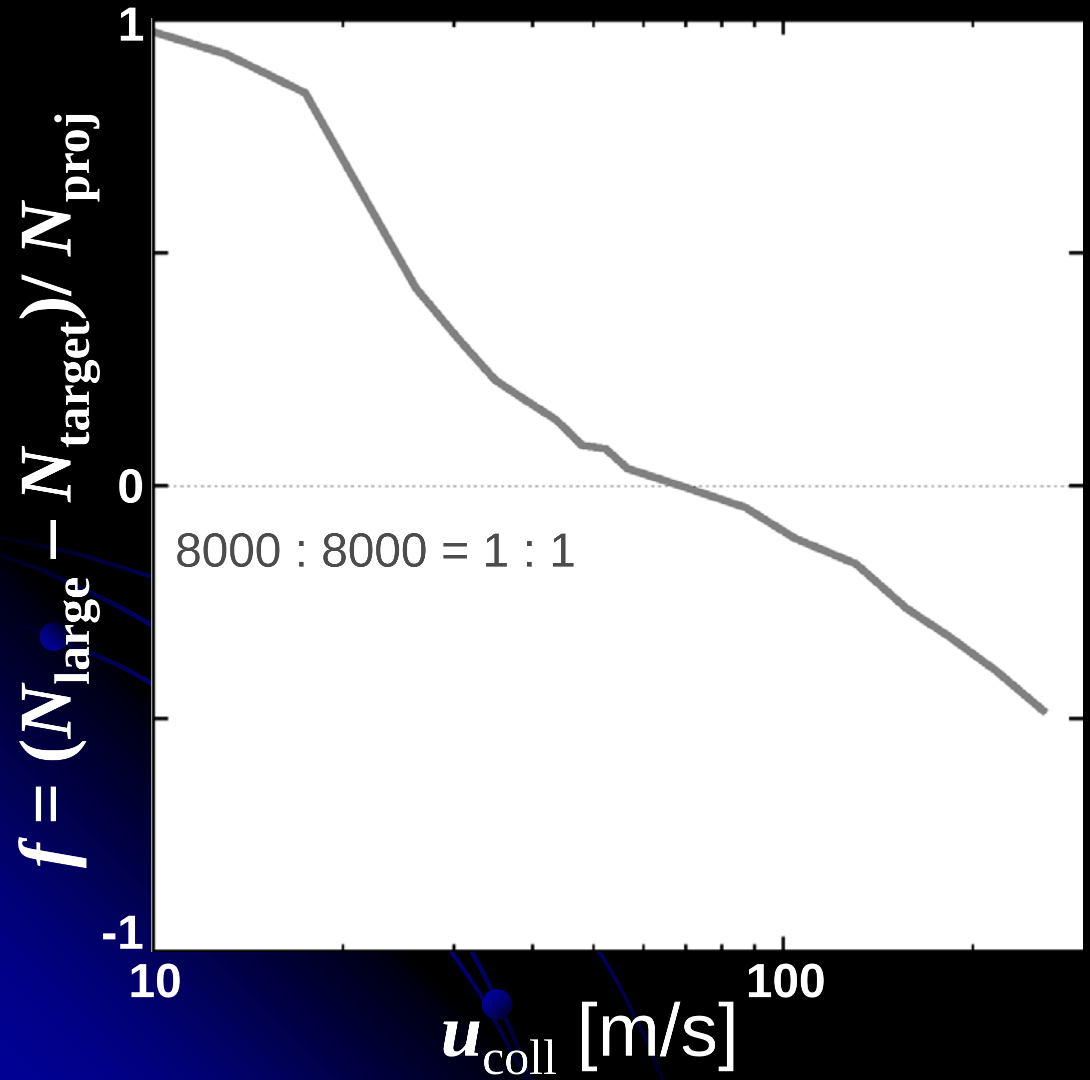








Growth efficiency (ice)



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

: growth efficiency

- $f > 0$ → mass gain
- $f < 0$ → mass loss

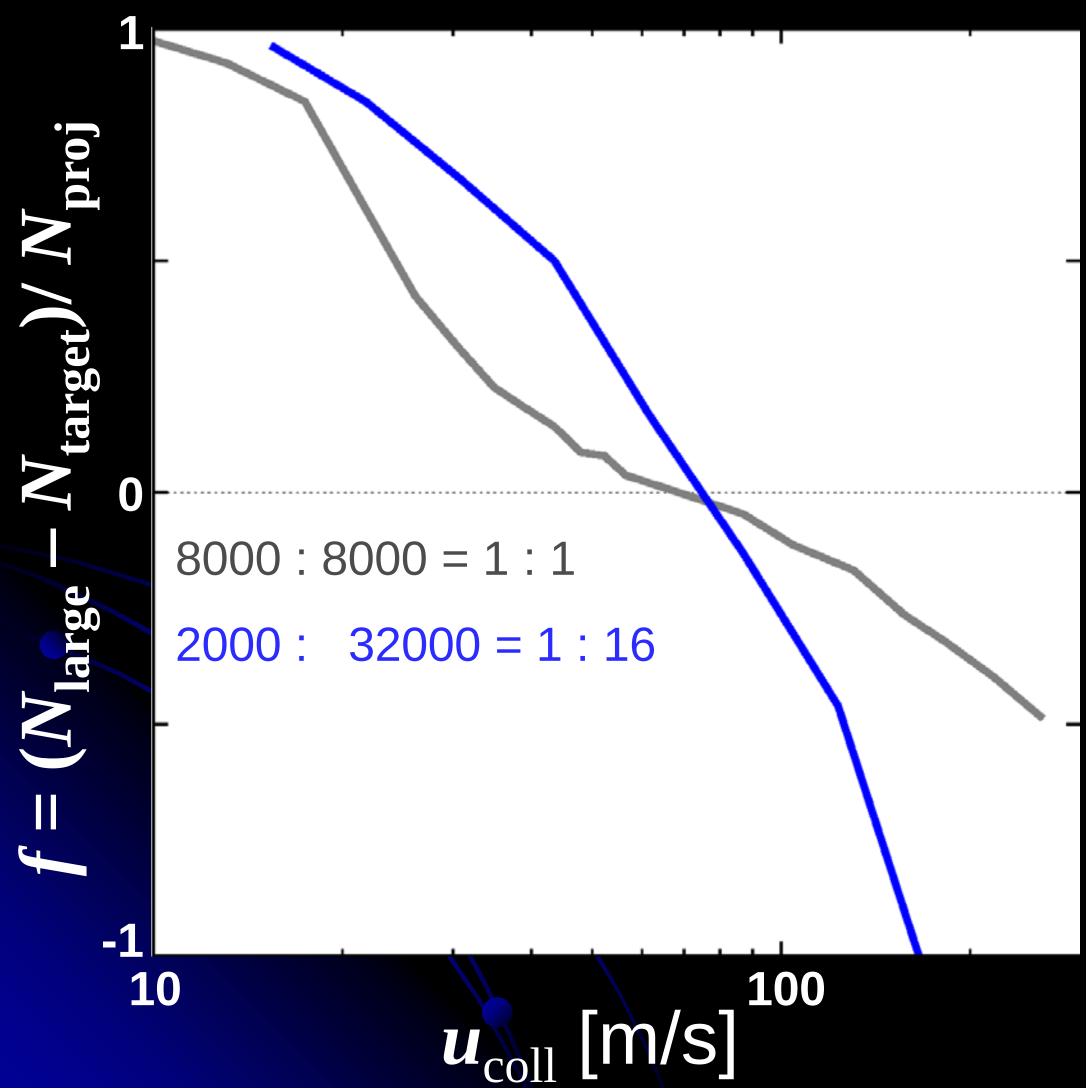
Growth efficiency (ice)

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

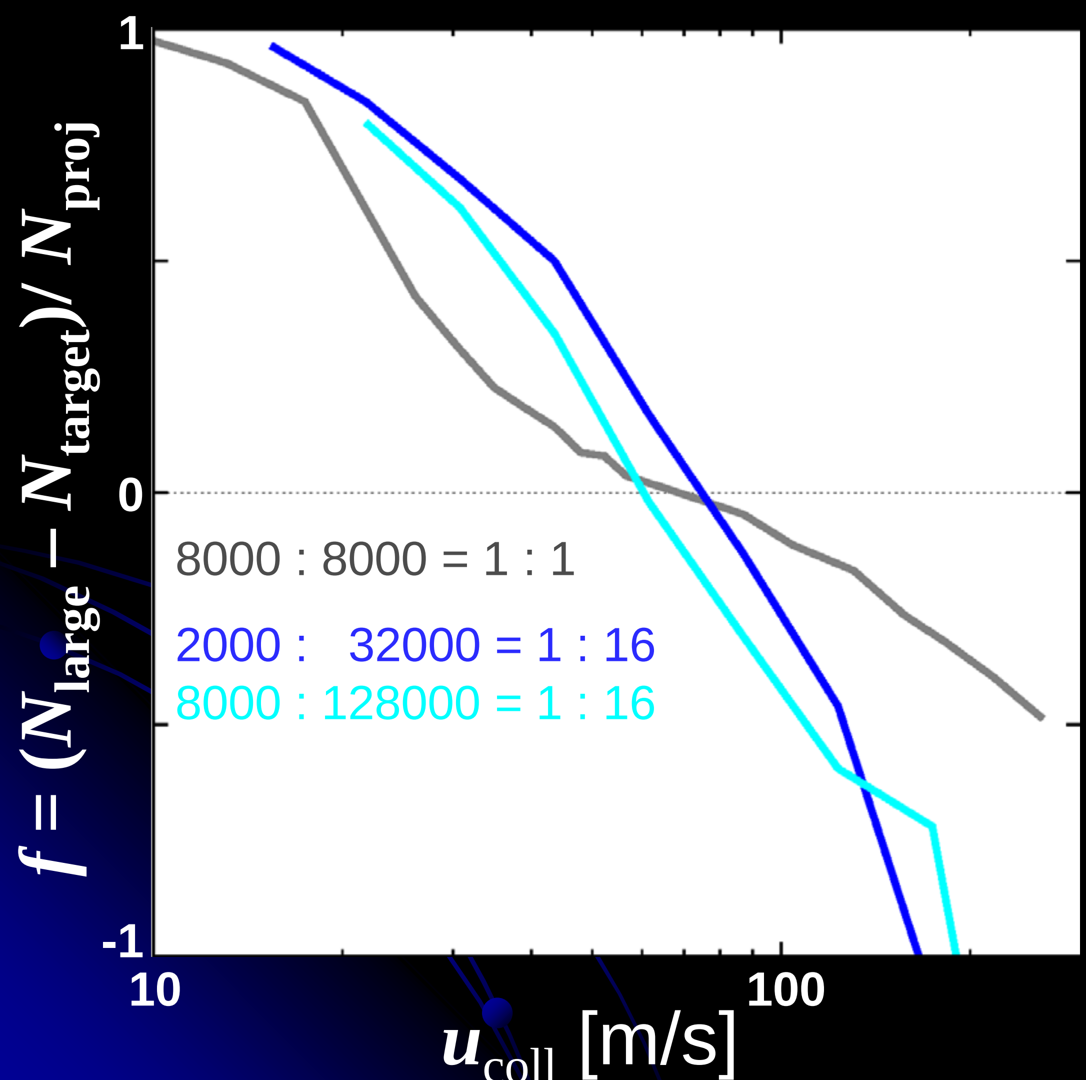
: growth efficiency

$f > 0$ → mass gain

$f < 0$ → mass loss



Growth efficiency (ice)



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

: growth efficiency

- $f > 0 \rightarrow$ mass gain
- $f < 0 \rightarrow$ mass loss

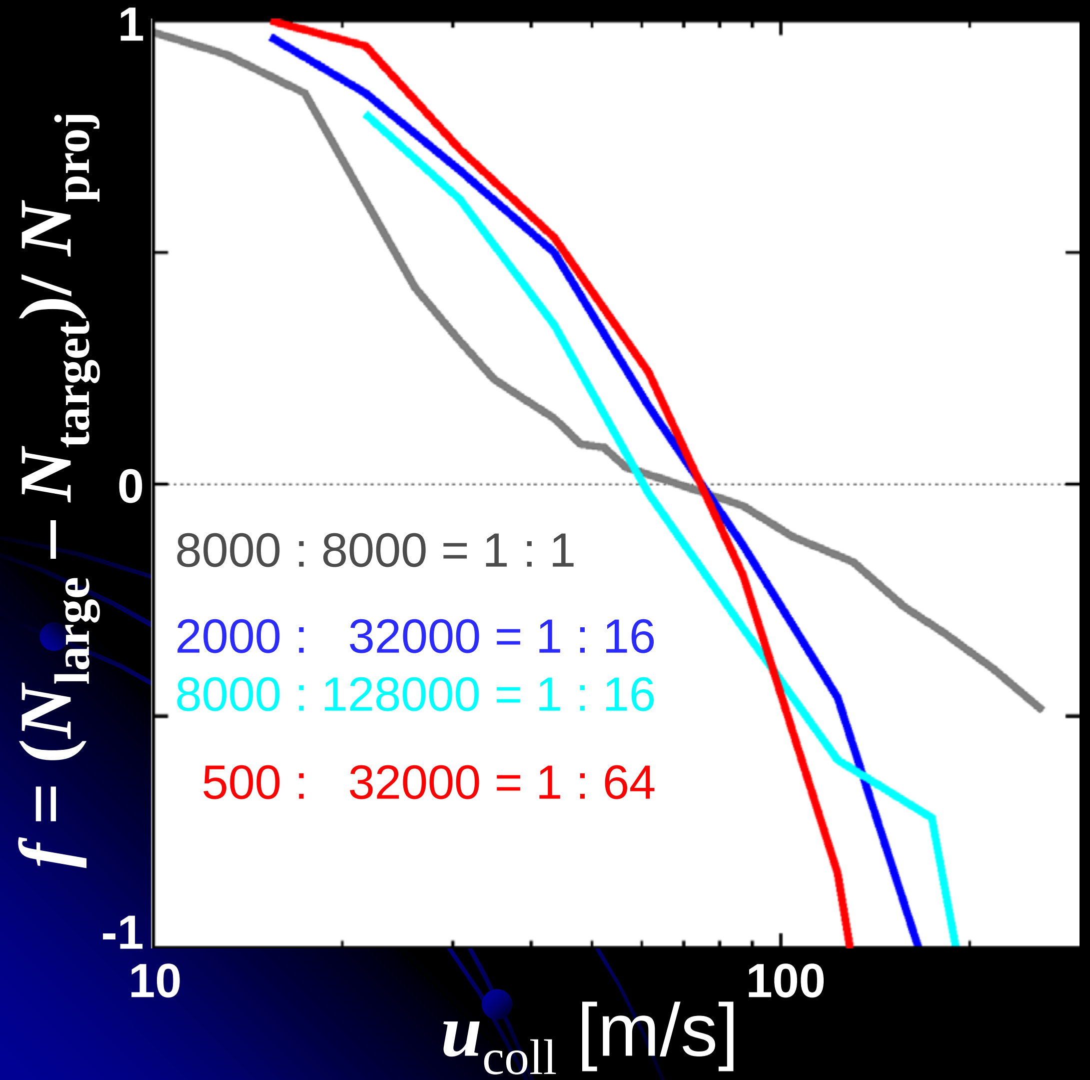
No size dependence

Growth efficiency (ice)

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

: growth efficiency

- $f > 0$ → mass gain
- $f < 0$ → mass loss



Growth efficiency (ice)

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

: growth efficiency

- $f > 0$ → mass gain
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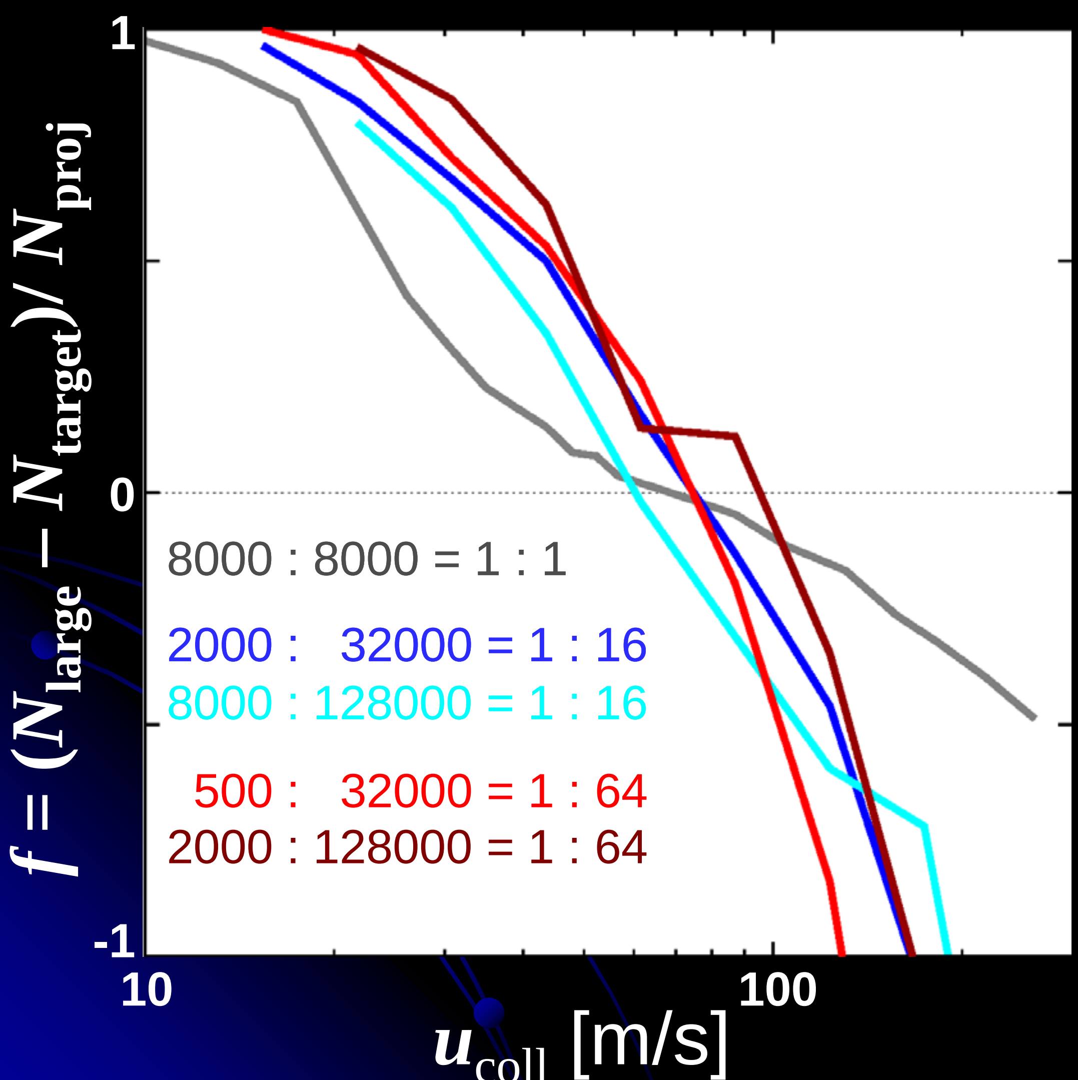
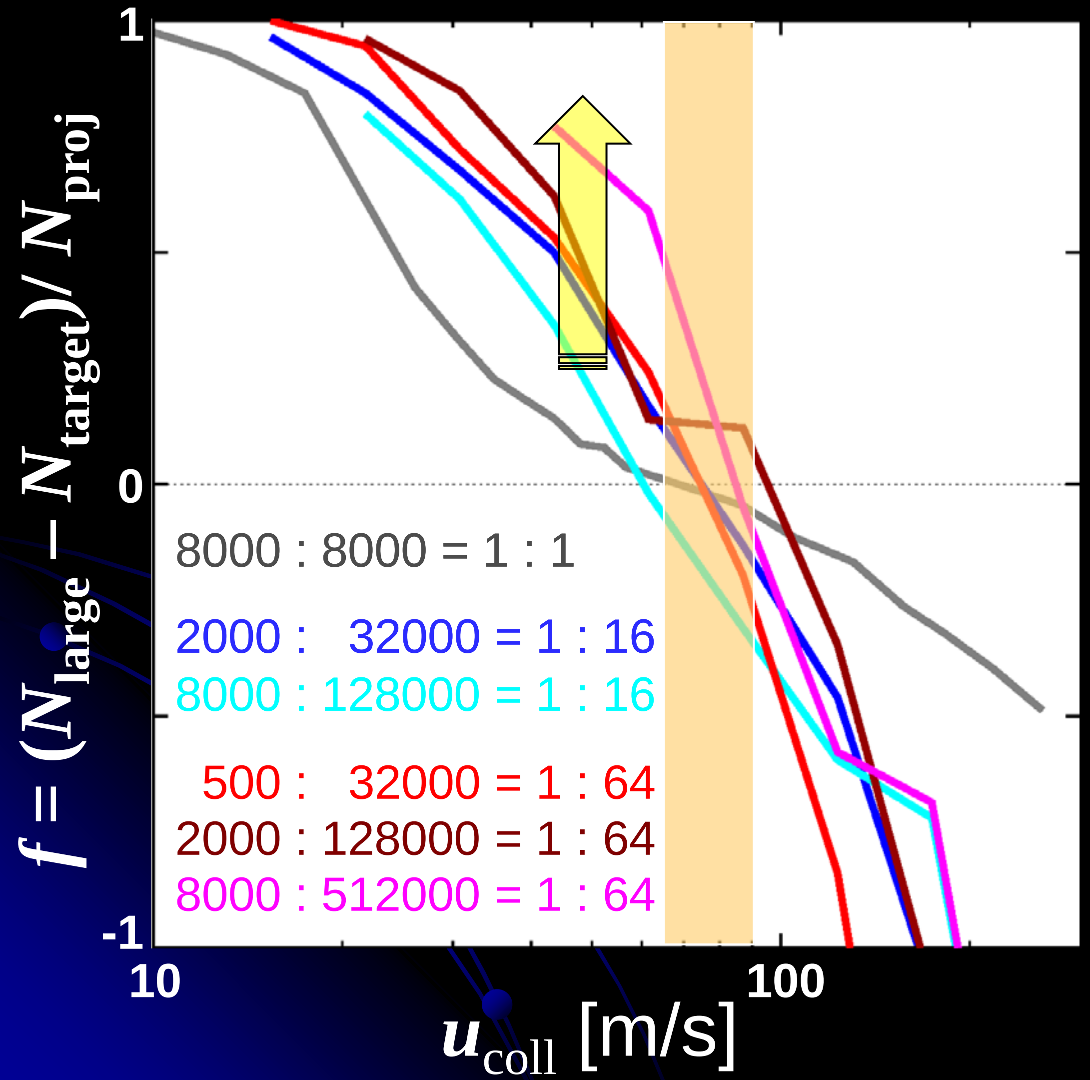


Growth efficiency (ice)



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

: growth efficiency

$f > 0$ → mass gain

$f < 0$ → mass loss

No size dependence

Dependent on size ratio

The larger ratio, the more gain.

No increase in the critical velocity (< 100 m/s)

Summary and Implication

Simulations of collisions of different-sized BPCAs

- Large size-ratio leads to large growth efficiency.

  ⇒ encouraging dust growth and planetesimal formation

- The critical collision velocity $u_{\mathrm{coll,crit}}$ is unchanged.

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

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

  ⇒ It is still difficult for silicate dust to grow?

Take-home messages

for Low-velocity collisions

- Does "bouncing barrier" for dust growth really exist?

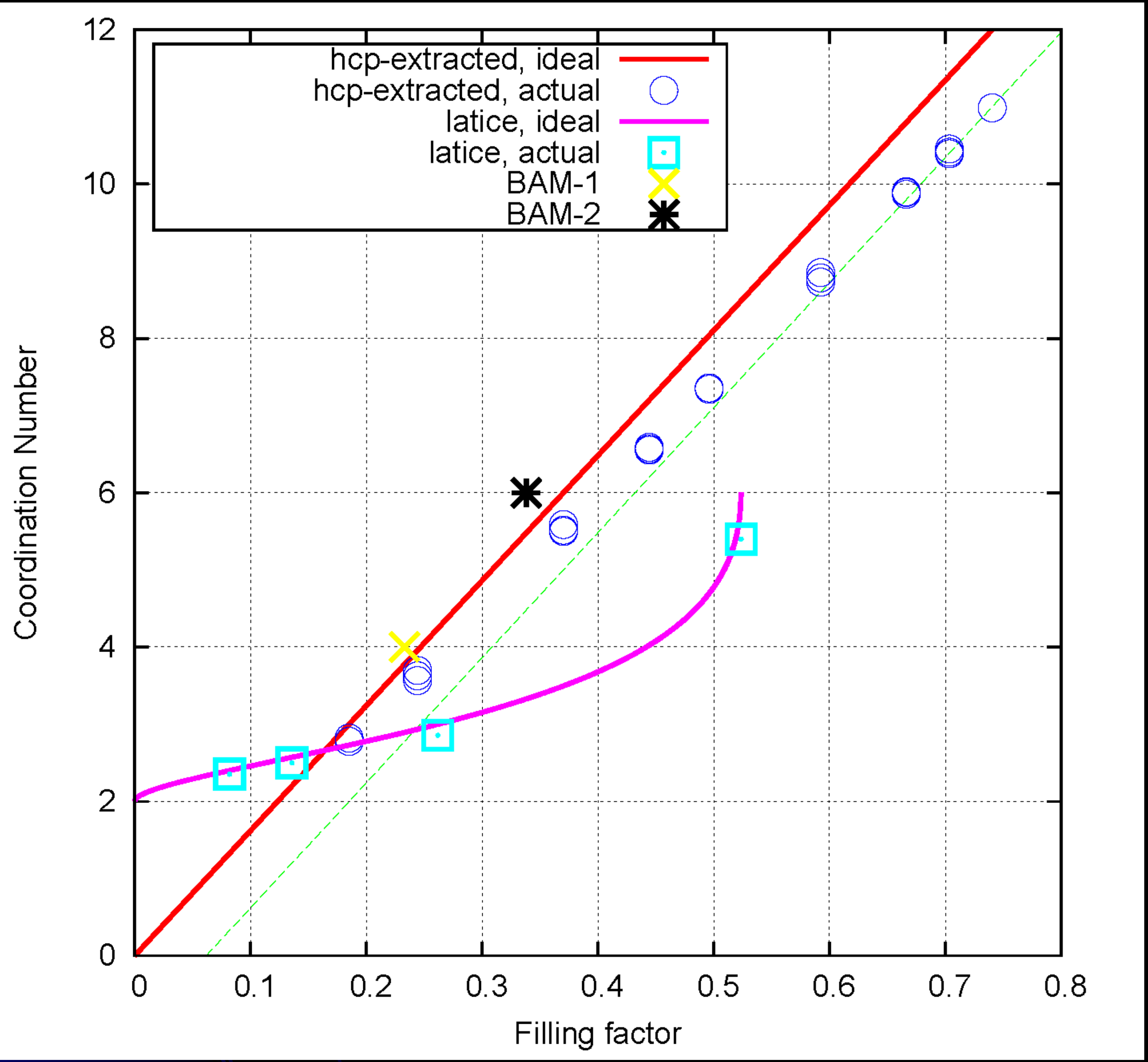
  → No!

for high-velocity collisions

- Do collisions between different-sized aggregate encourage dust growth?

  → Partly Yes,
  But, not enough for silicate dust.

Can dust grow through collisions?


hcp-extracted, ideal
hcp-extracted, actual
latice, ideal
latice, actual
BAM-1
BAM-2
Coordination Number
Filling factor
0
2
4
6
8
10
12
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8

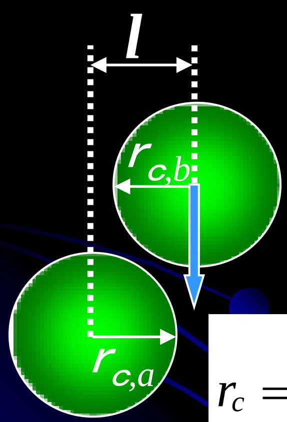
Initial Conditions and Parameters

Collisions of BPCA clusters

Results are averaged

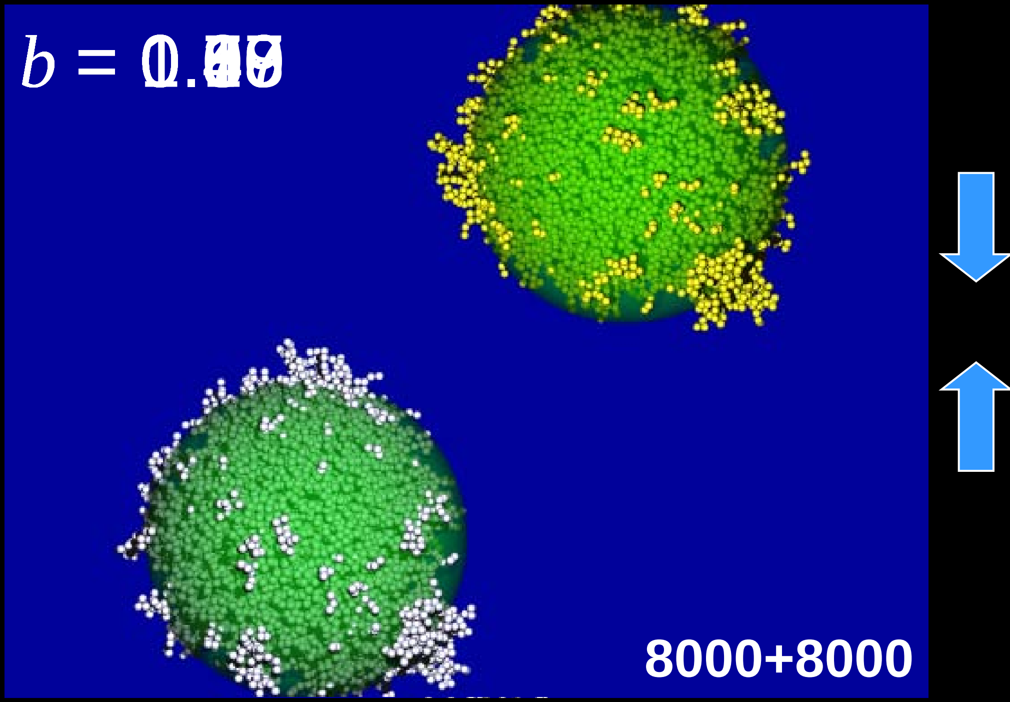
✓ BPCA clusters are:

- composed of 500, 2000, or 8000 particles (3 types randomly produced)
- Impact parameter : b (defined by using characteristic radius r_c)



$$b = \frac{l}{r_{c,a} + r_{c,b}}$$

$$r_c = \sqrt{\frac{5}{3}\frac{1}{N}\sum (x_i - x_G)^2}$$

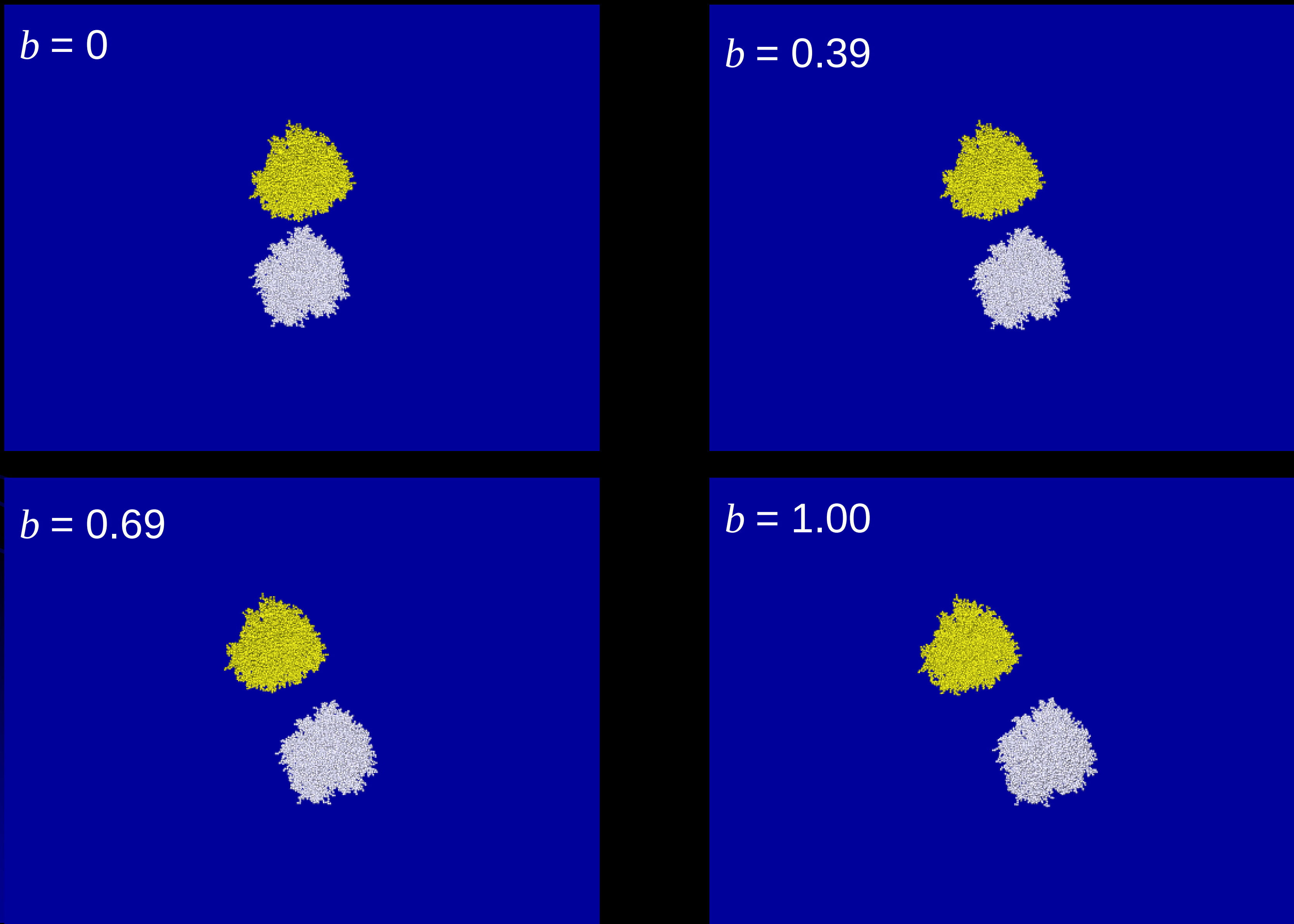


✓Ice (E = 7.0 × 10^{10} Pa, ν = 0.25, γ = 100 mJ/m², R = 0.1μm) , critical rolling displace. ξ_{crit} = 8Å

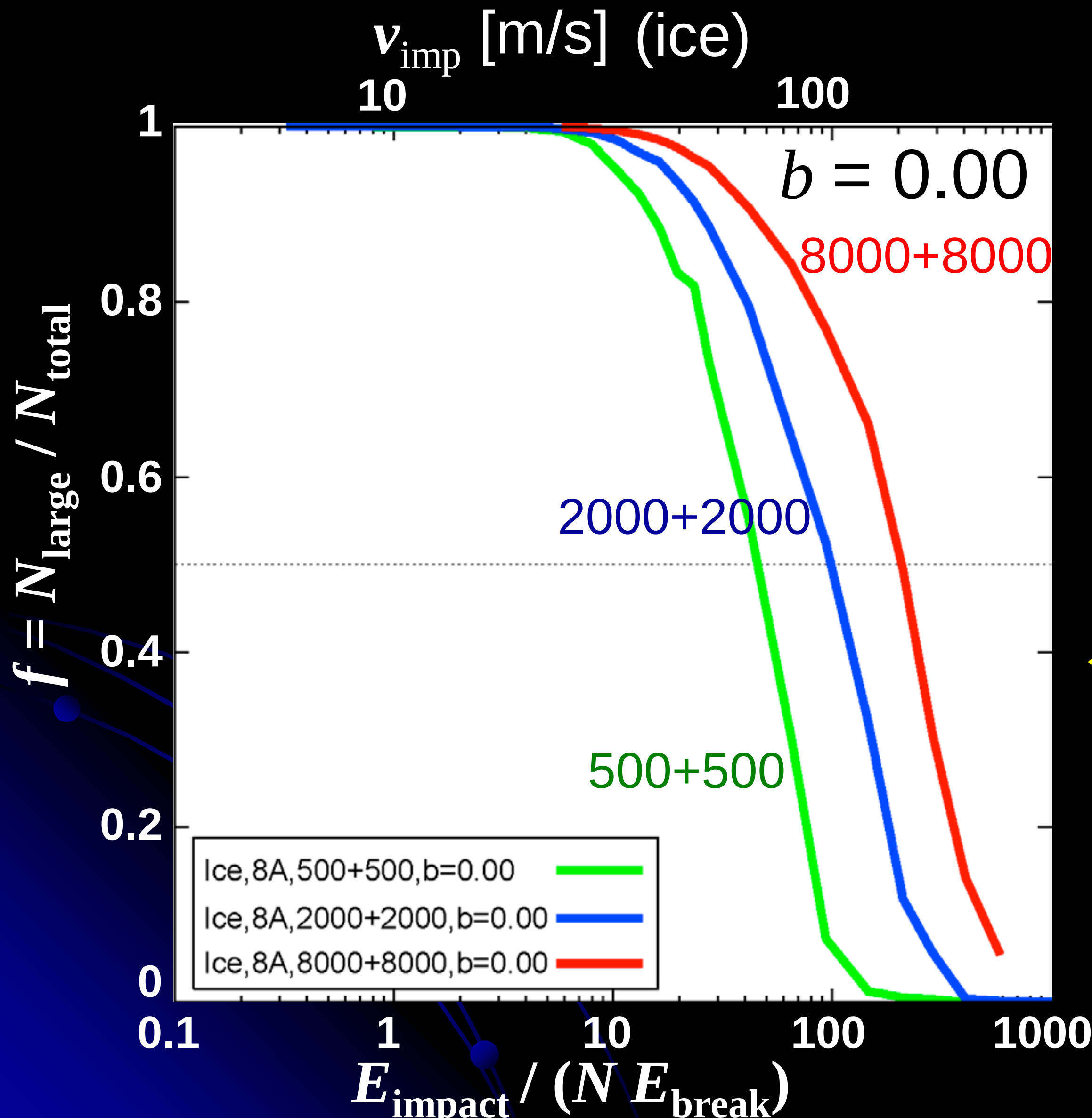
✓Impact velocity v_{imp} = 6 - 300 m/s

Collisions of BPCA clusters

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



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



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

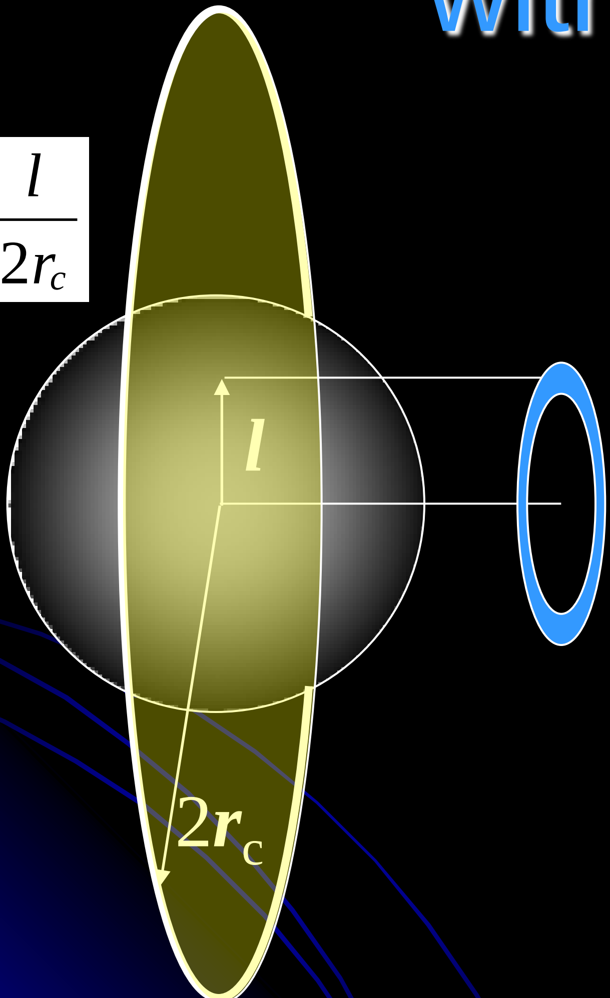
: growth efficiency

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

✓dependent on N

Probability of collisions within [b, b+db]

$$b = \frac{l}{2r_c}$$



$$P(b)db = \frac{2\pi\, l\, \mathrm{d}l}{\pi(2r_c)^2} = \frac{\pi(2r_c)^2\, 2b\mathrm{d}b}{\pi(2r_c)^2}$$

$$\therefore\ \ P(b)\,\mathrm{d}b = 2b\,\mathrm{d}b \quad (0 \le b \le 1)$$

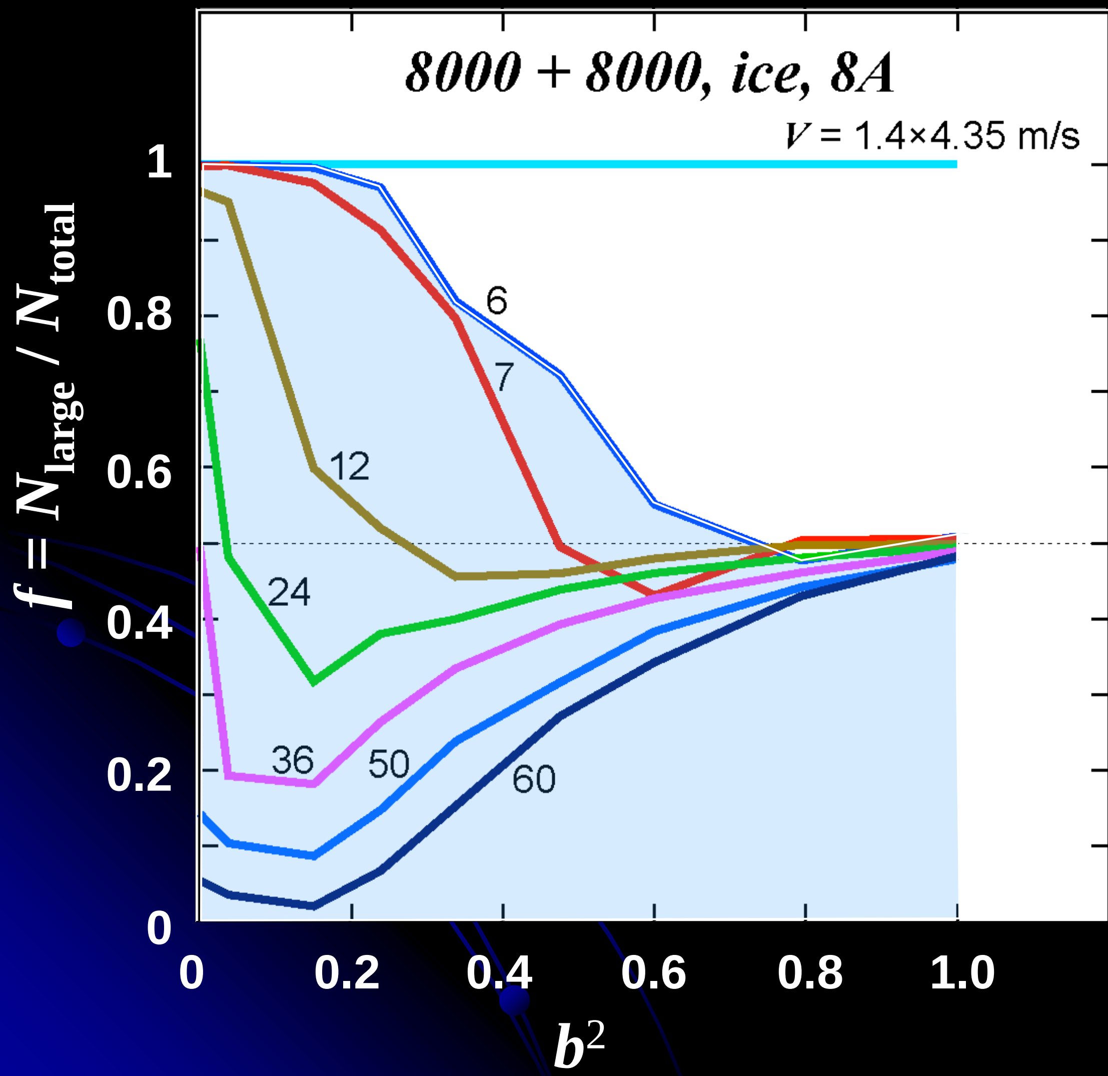
$$= \mathrm{d}b^2 \quad (0 \le b^2 \le 1)$$

Average value of f

$$\bar{f} = \frac{\int_0^1 f\,\mathrm{d}b^2}{\int_0^1 \mathrm{d}b^2} = \int_0^1 \underline{f(b^2)}\,\mathrm{d}b^2$$

Growth efficiency: $f\,(b^2)$

f as a function of b^2



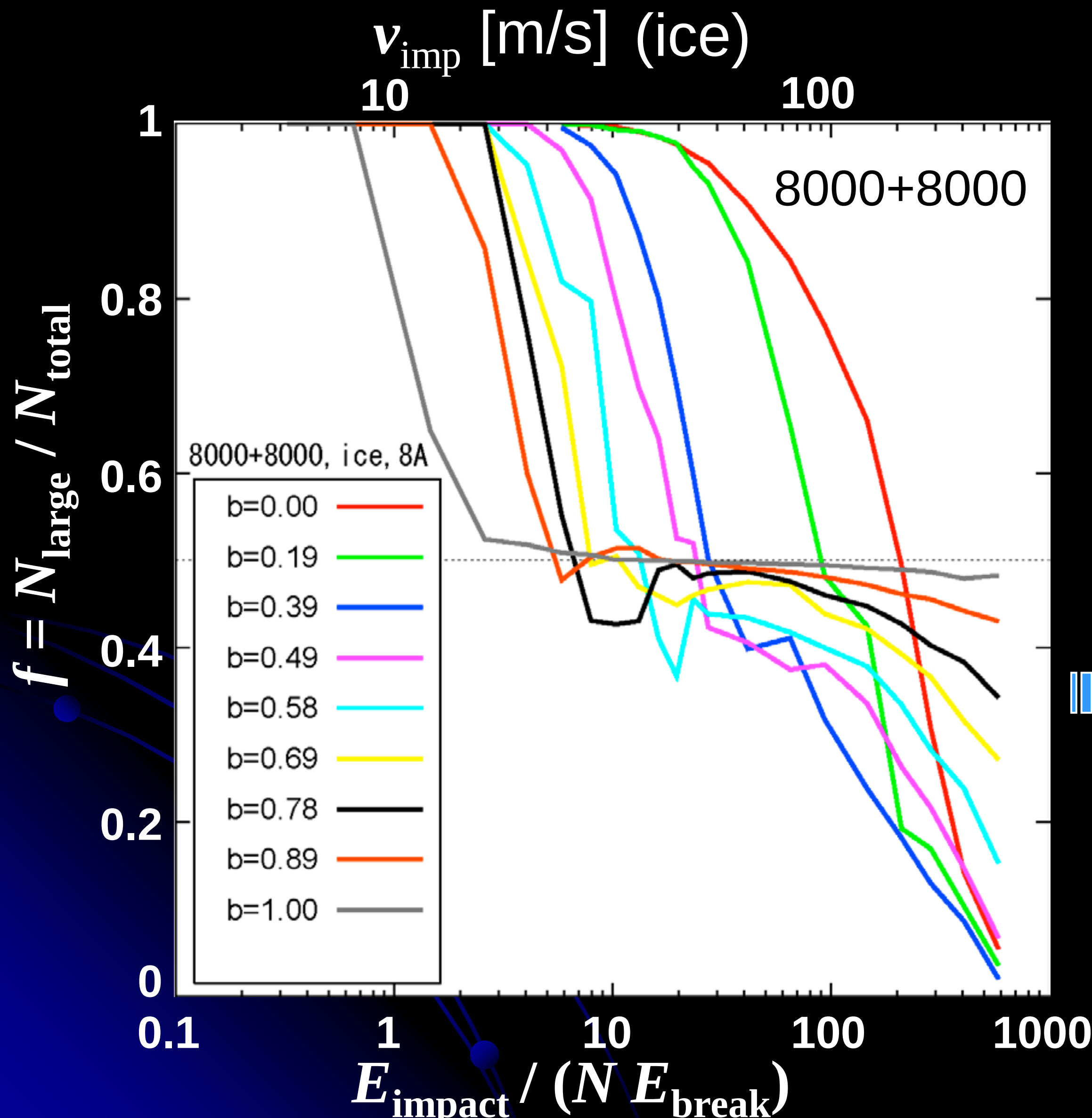
$f \equiv N_{large} \,/\, N_{total}$

: growth efficiency

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

$$\bar{f} = \int_0^1 f\,(b^2)\,\mathrm{d}b^2$$

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



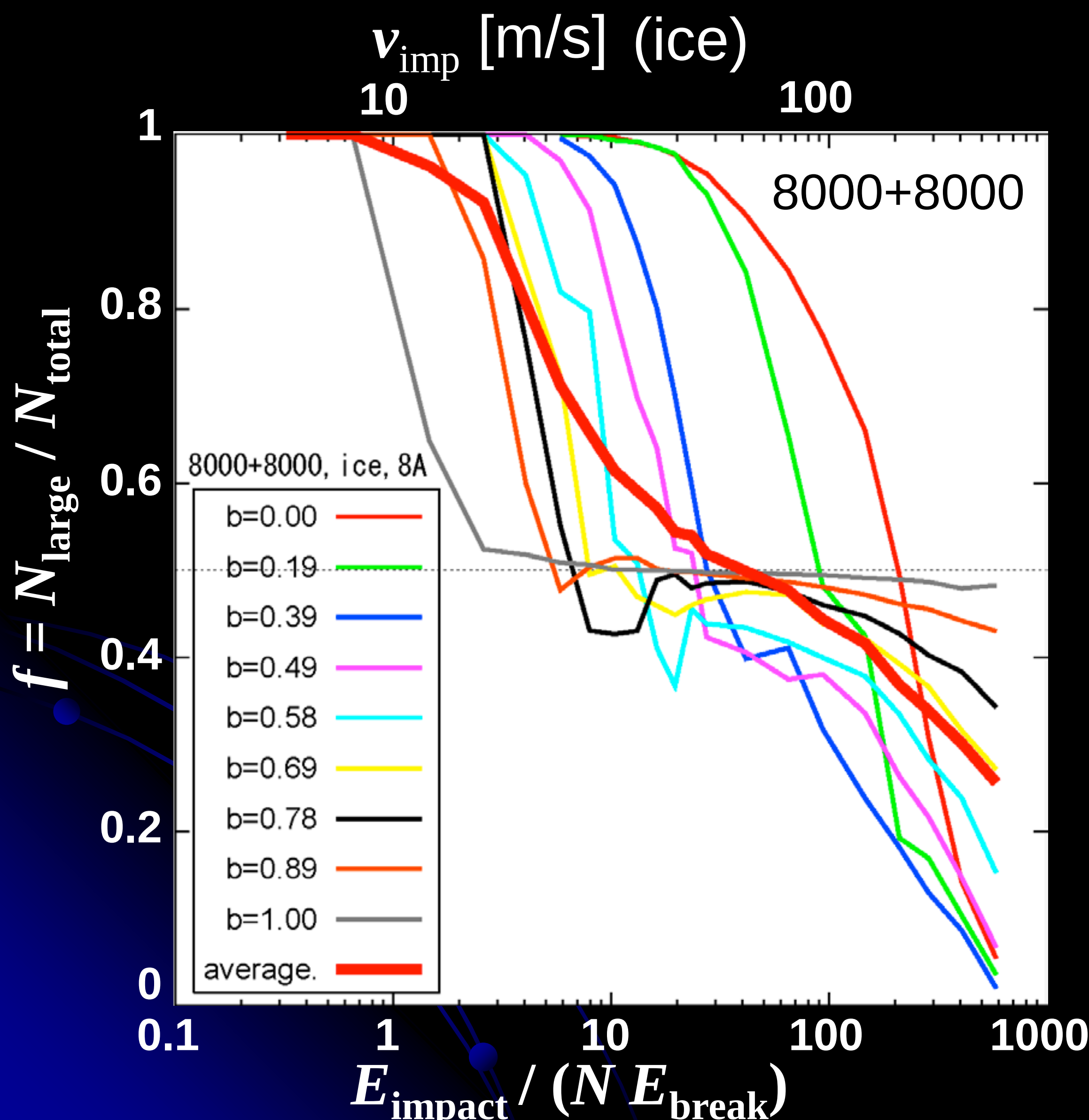
$f \equiv N_{large} / N_{total}$

: growth efficiency

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

⇒ Average weighted by b^2

Growth efficiency averaged



Averaged for b^2

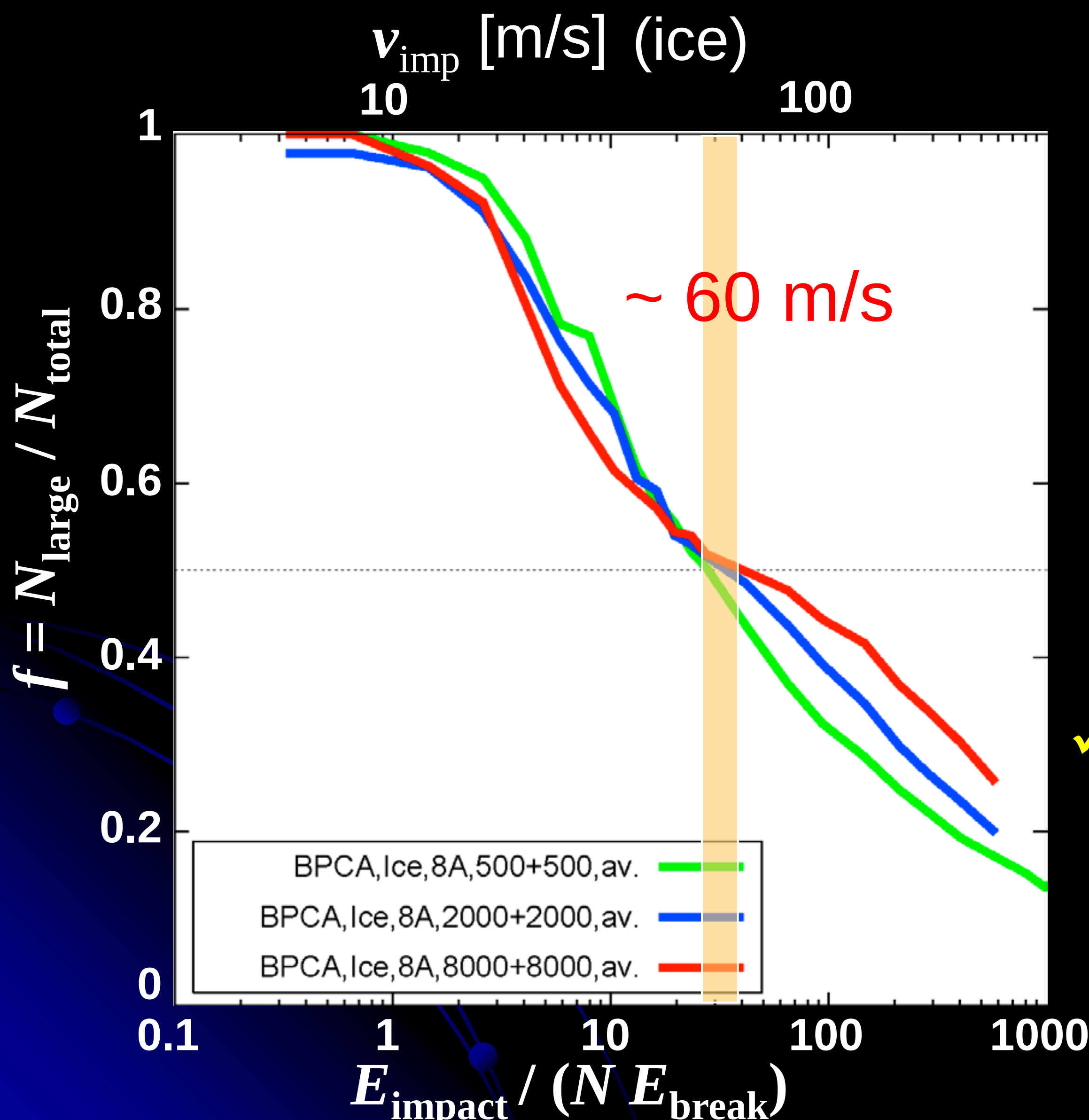
$f \equiv N_{large} / N_{total}$

: growth efficiency

$f > 0.5 \rightarrow$ + growth

$f < 0.5 \rightarrow$ - growth

Growth efficiency averaged



Averaged for b^2

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

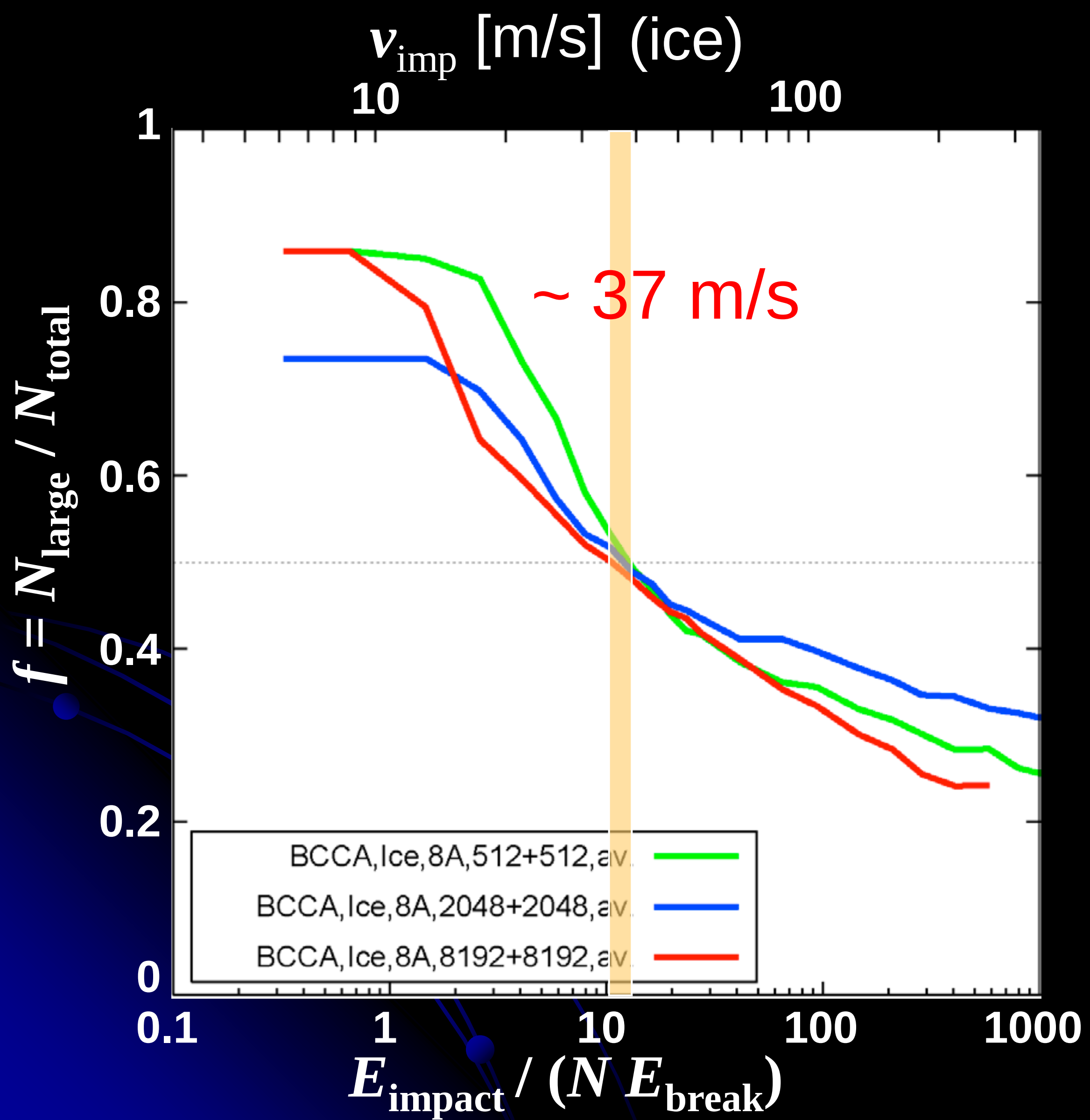
: growth efficiency

$f > 0.5 \rightarrow$ + growth

$f < 0.5 \rightarrow$ - growth

✓small dependence on N

Averaged *growth efficiency* for BCCA clusters

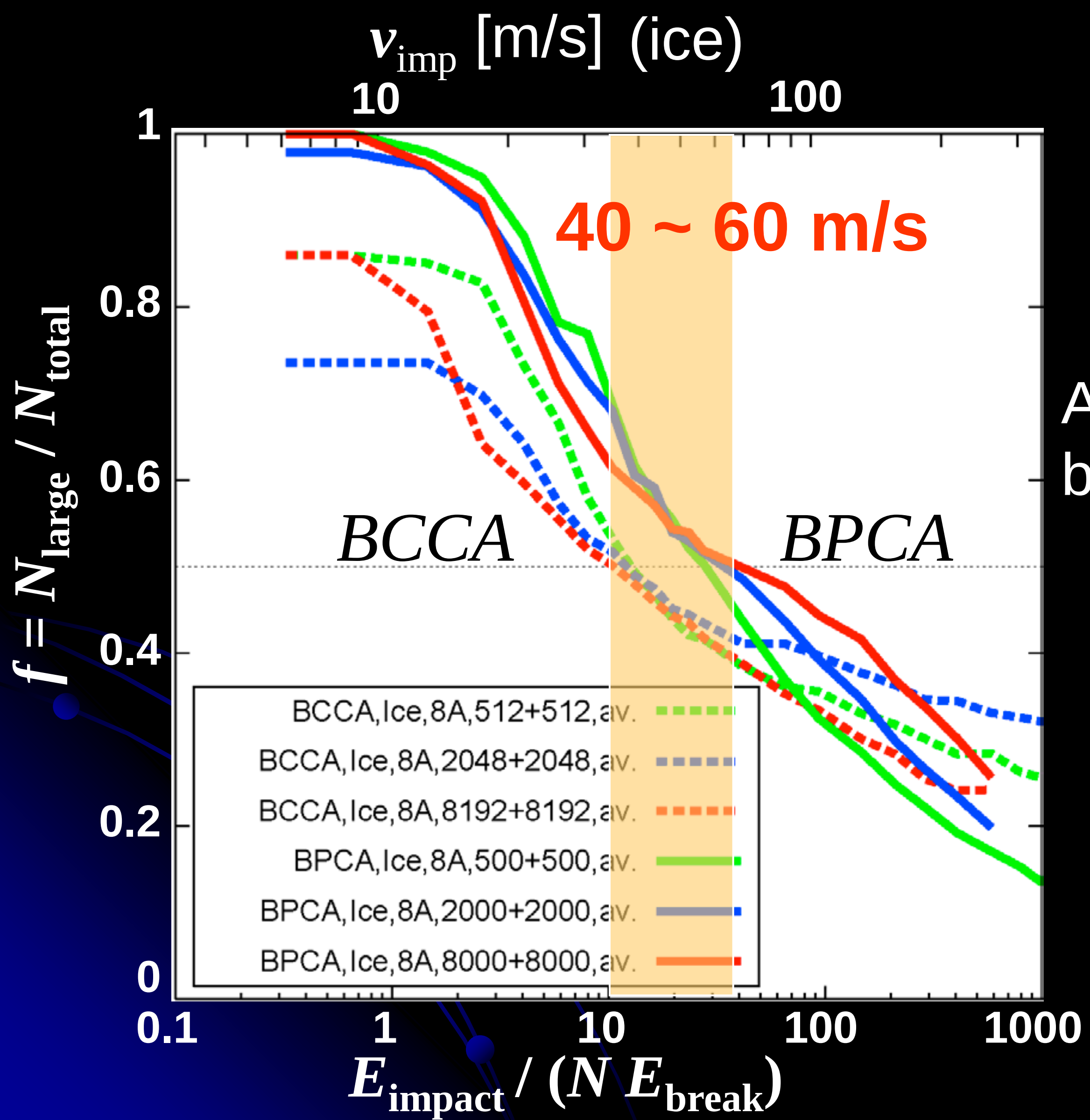


Averaged over b^2

✓independent of N

Averaged *growth efficiency* : *BCCA & BPCA*

Averaged over b^2



Actual dust structure:
between BCCA and BPCA