つぶらな衝突

ダストアグリゲイト衝突シミュレーション

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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 ?

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

Today's Topics:

ダストは大きくなれるのか？

- Collisional growth conditions for dust aggregates
  - Can dust grow through high velocity collisions?

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

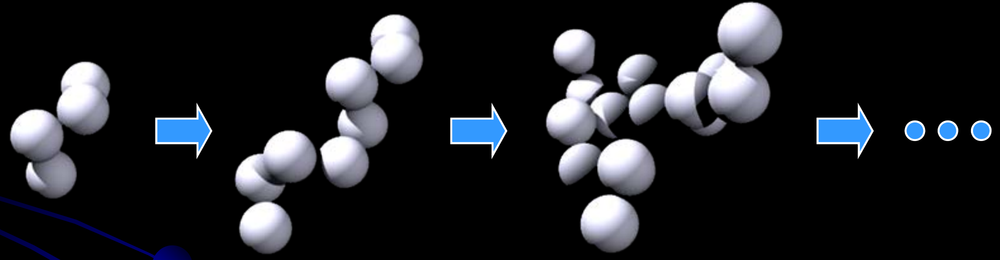
- Bouncing conditions for dust aggregates
  - What causes aggregates to bounce?

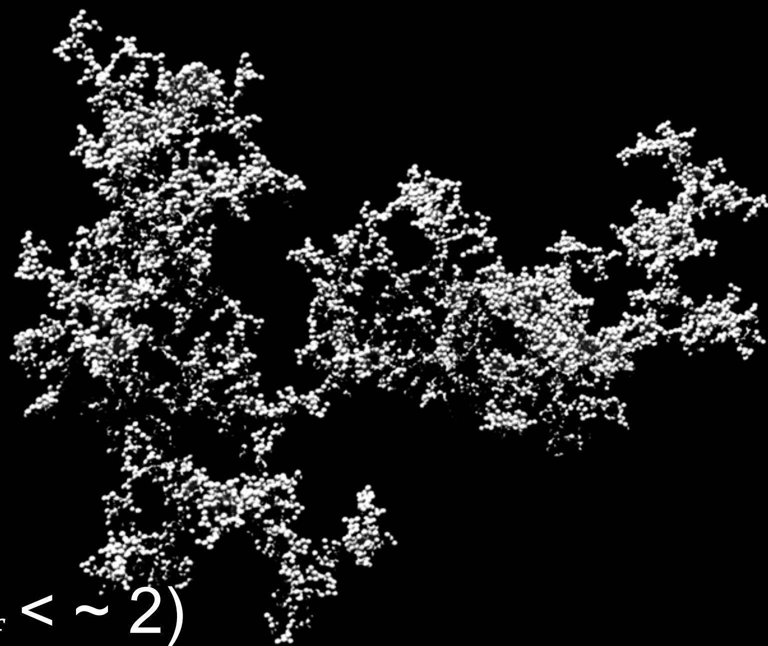
Collisional Growth Conditions

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)

BCCA structures are compressed (d_f ~ 2.5) by collisions

(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 ?

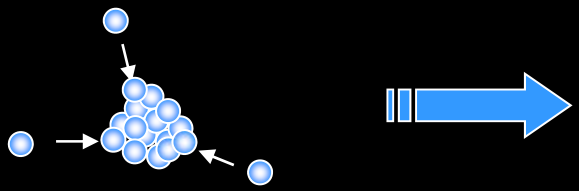
Maybe possible in head-on collisions

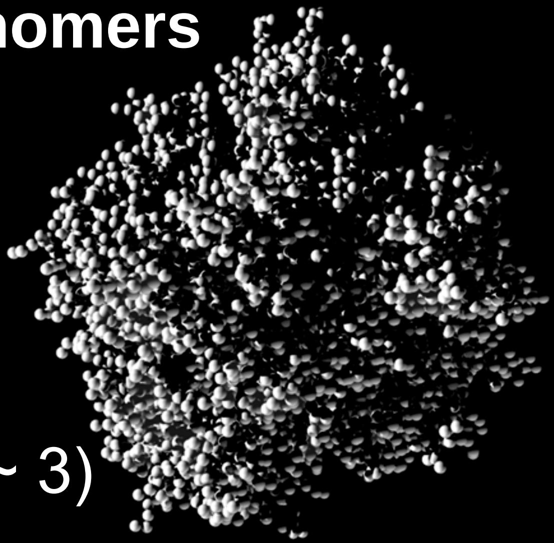
Experimental: Blum & Wurm 2000, Wurm et al. 2005
Numerical: Dominik & Tielens 1997, Wada et al. 2008

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

Objective

Wada et al. 2008, ApJ 677, 1296-1308
Wada et al. 2009, ApJ 702, 1490-1501

Can dust aggregates grow ?

（even in offset collisions）

Numerical simulation of

High velocity collisions of BPCAs（& BCCAs ）

✓Degree of disruption (Growth efficiency)

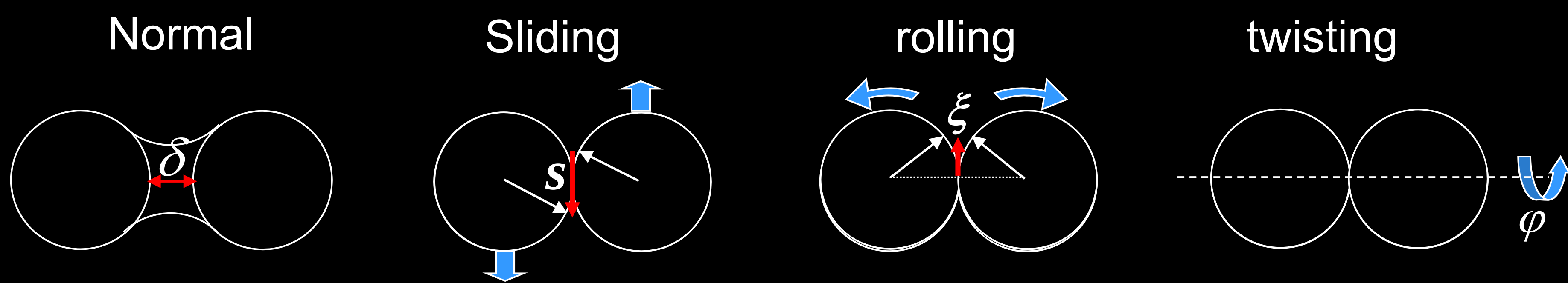
⬆

Number of particles in the largest fragment

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

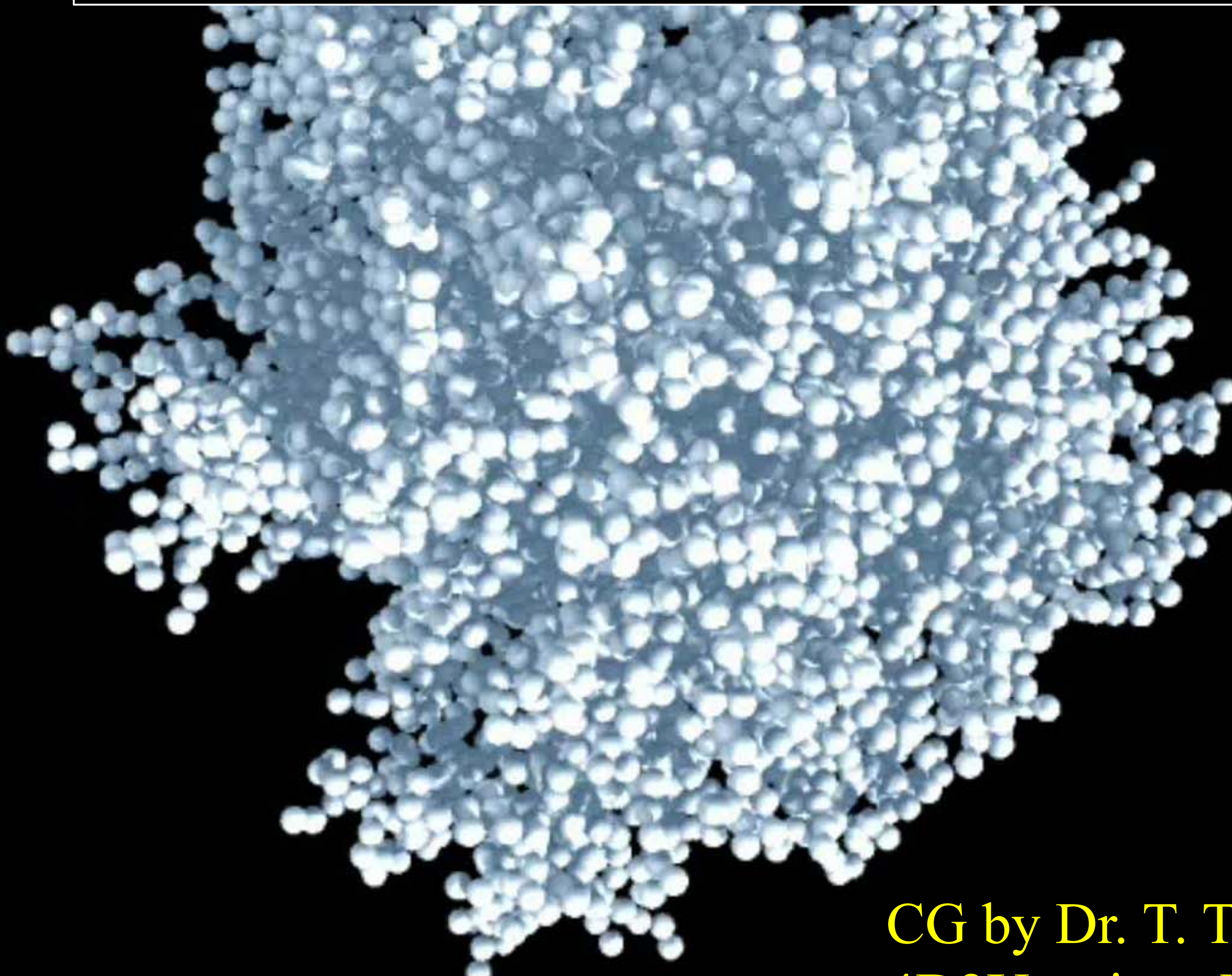


Contact & Separation
s, ξ, φ > critical displacements
→ Energy dissipation

E_{break}: Energy to break a contact

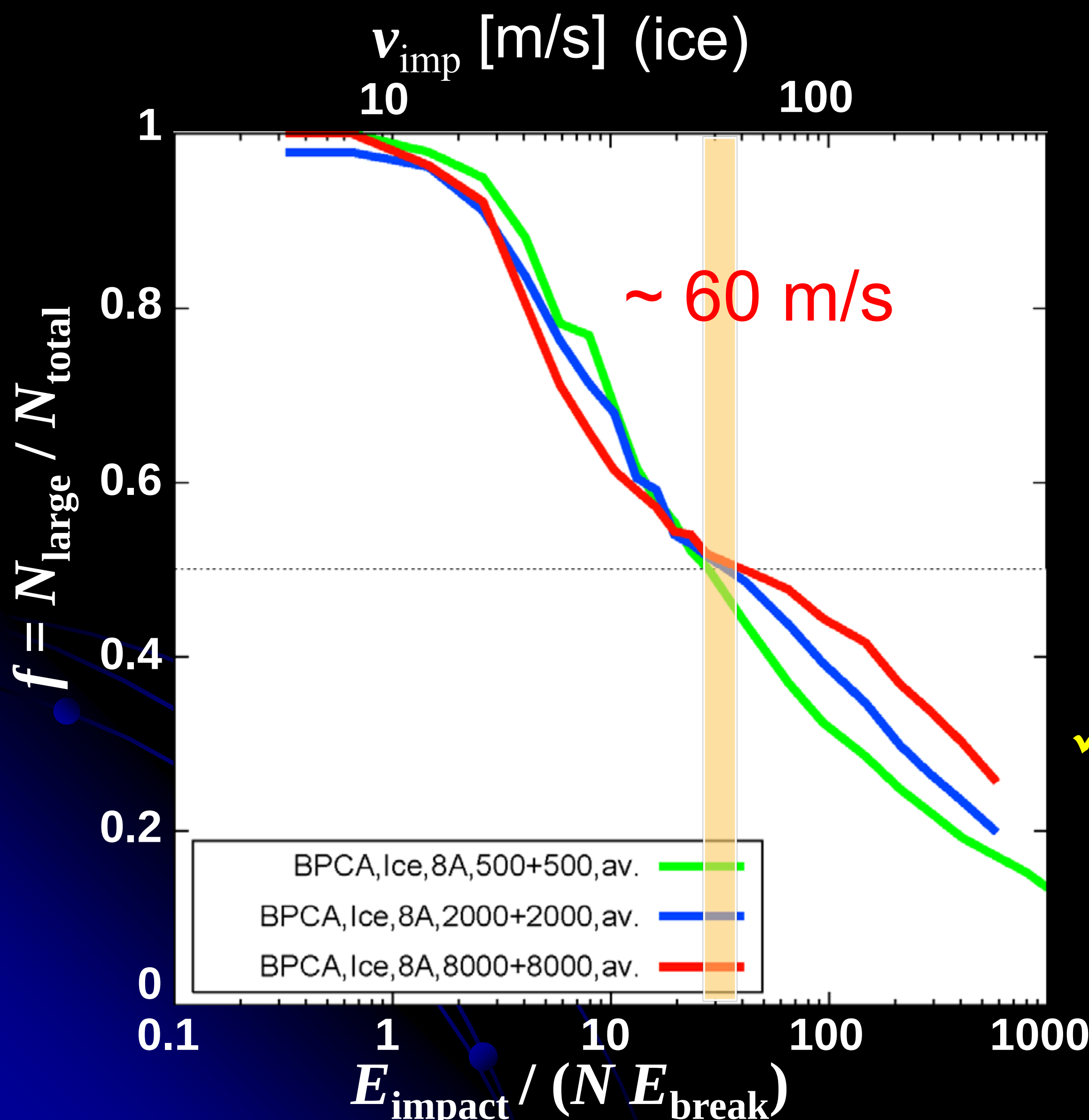
E_{roll} : Energy to roll a pair of gains by 90˚

A collision of BPCAs
8000+8000 ice particles ($r=0.1\mu m$, $\xi_c = 8Å$)
Collision velocity = 57 m/s



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

Growth efficiency averaged



Averaged for b^2

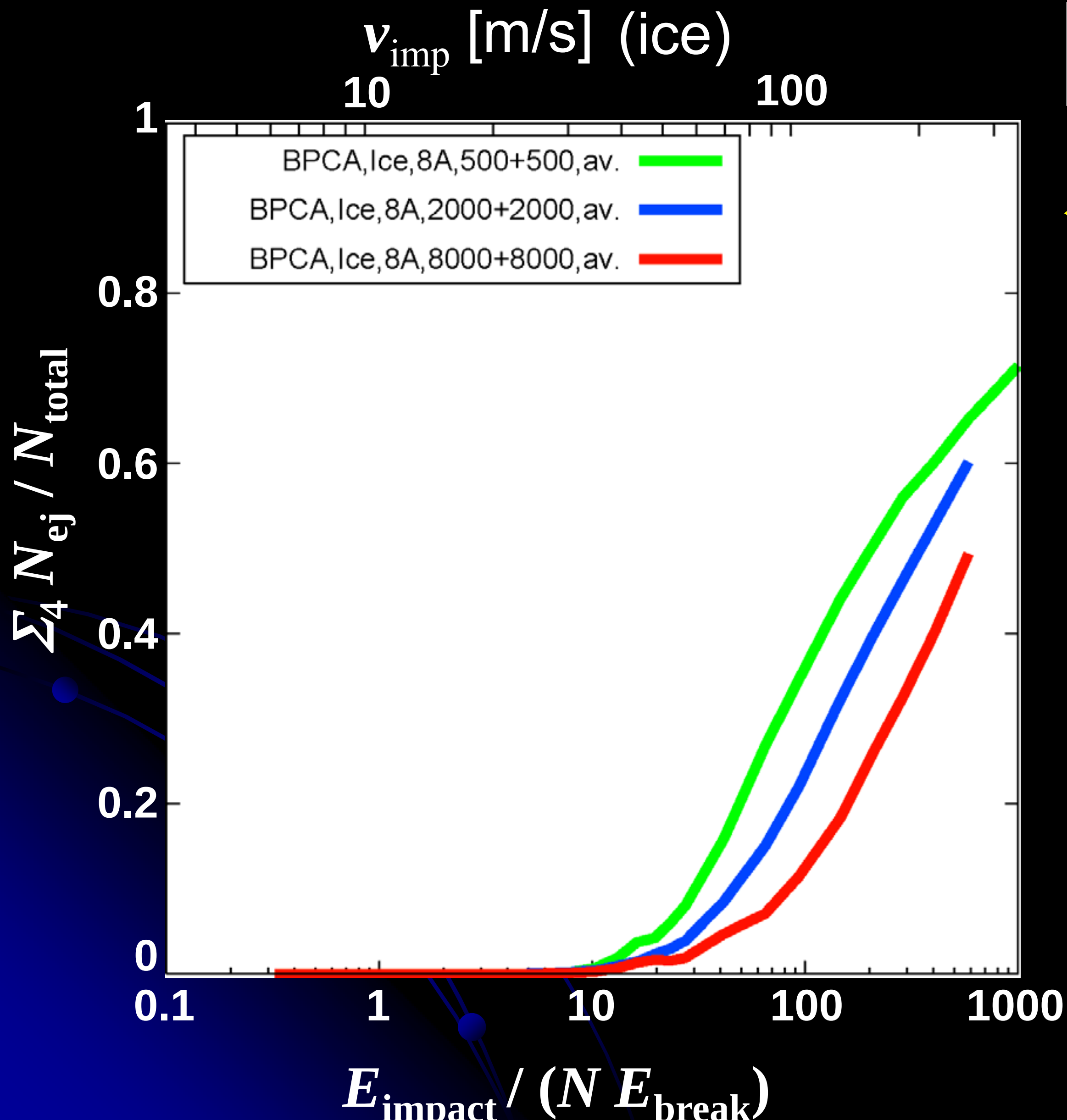
$f \equiv N_{large} / N_{total}$

: 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*



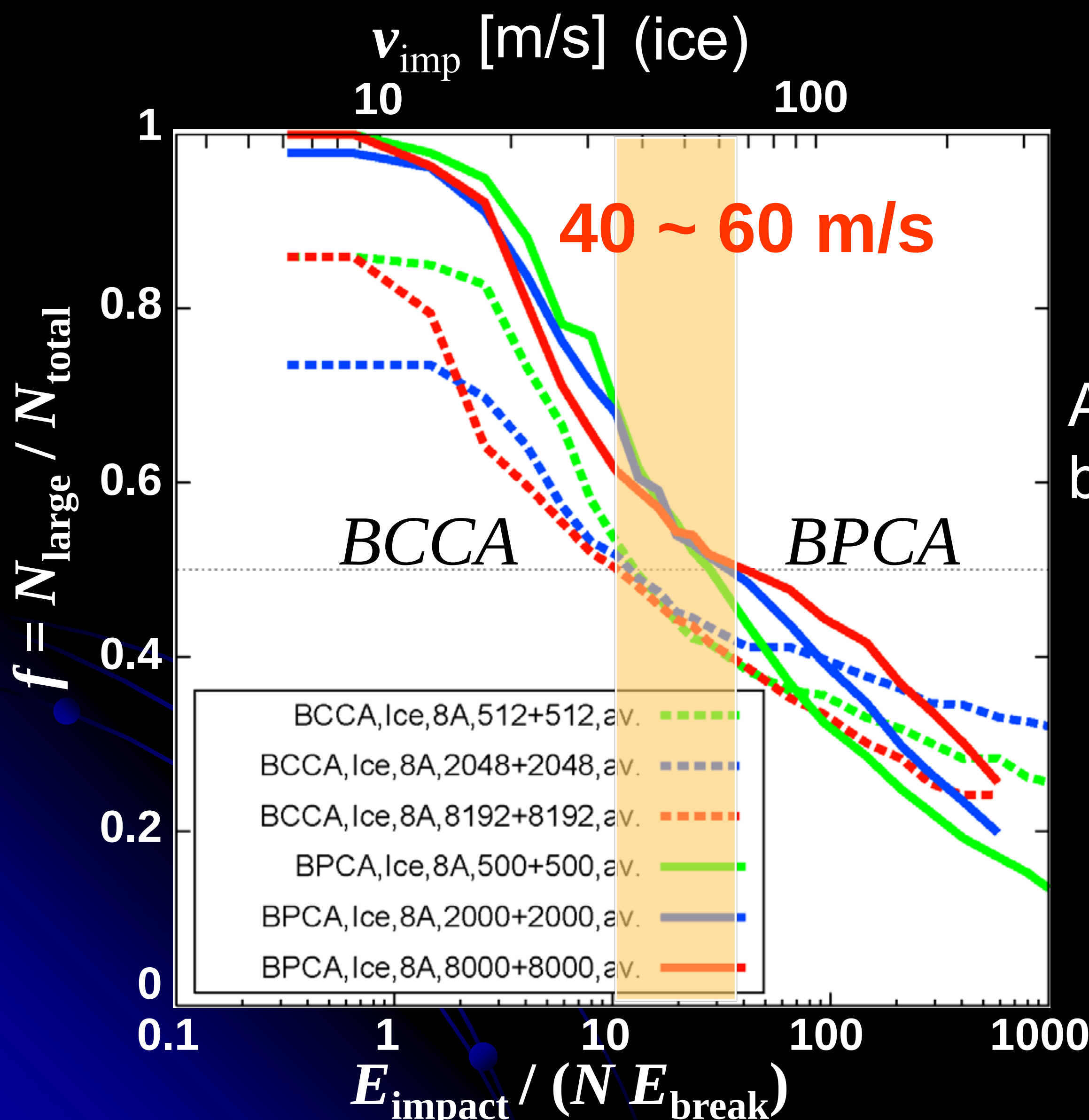
Averaged over b^2

✓dependent on *N*

The larger aggregates,
the smaller amount of ejecta.

Averaged *growth efficiency* : *BCCA & BPCA*

Averaged over b^2



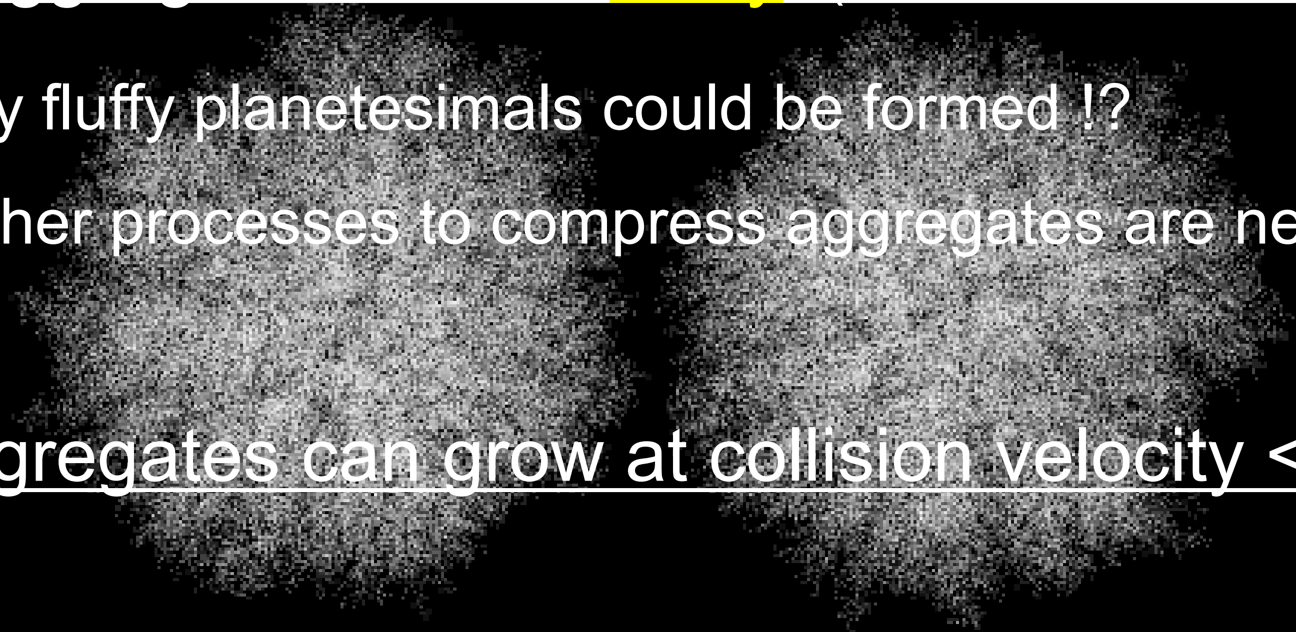
Actual dust structure:
between BCCA and BPCA

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.

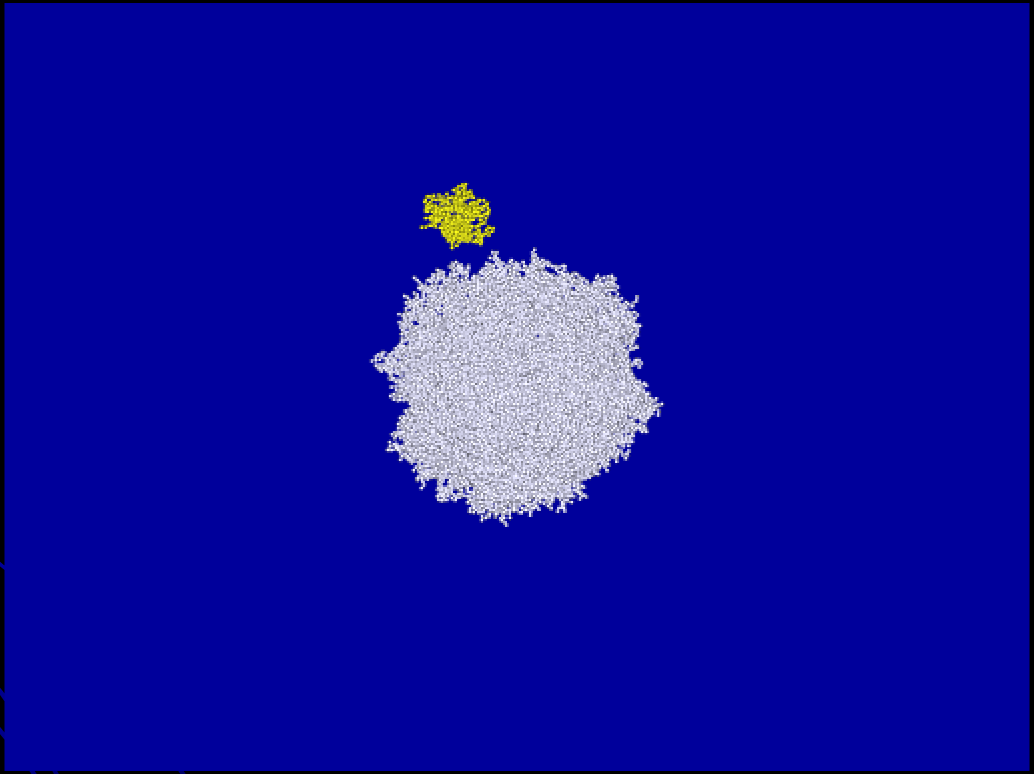
Planetesimals can be formed through collisions of dust.

Animation by Prof. H. Tanaka

Collisions of BPCA clusters of different sizes

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

b = 0.39



Bouncing Conditions

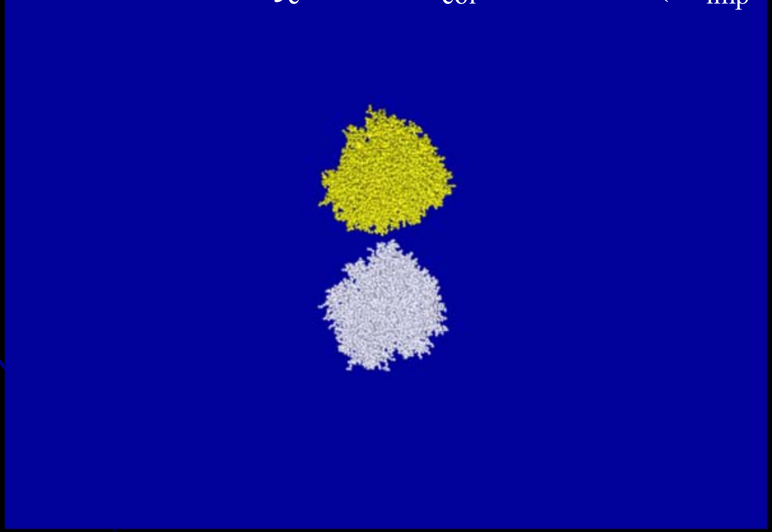
Bouncing Problem

"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})



Blum and Wurm 2008; Heißelmann et al. (in prep.)

SiO_2 grain : ~1.52 μm; porosity 85 %

SiO_2 grain (Aerosol 200) : ~12 nm; porosity 97%

Collision velocity: 0.15 – 4.5 m/s

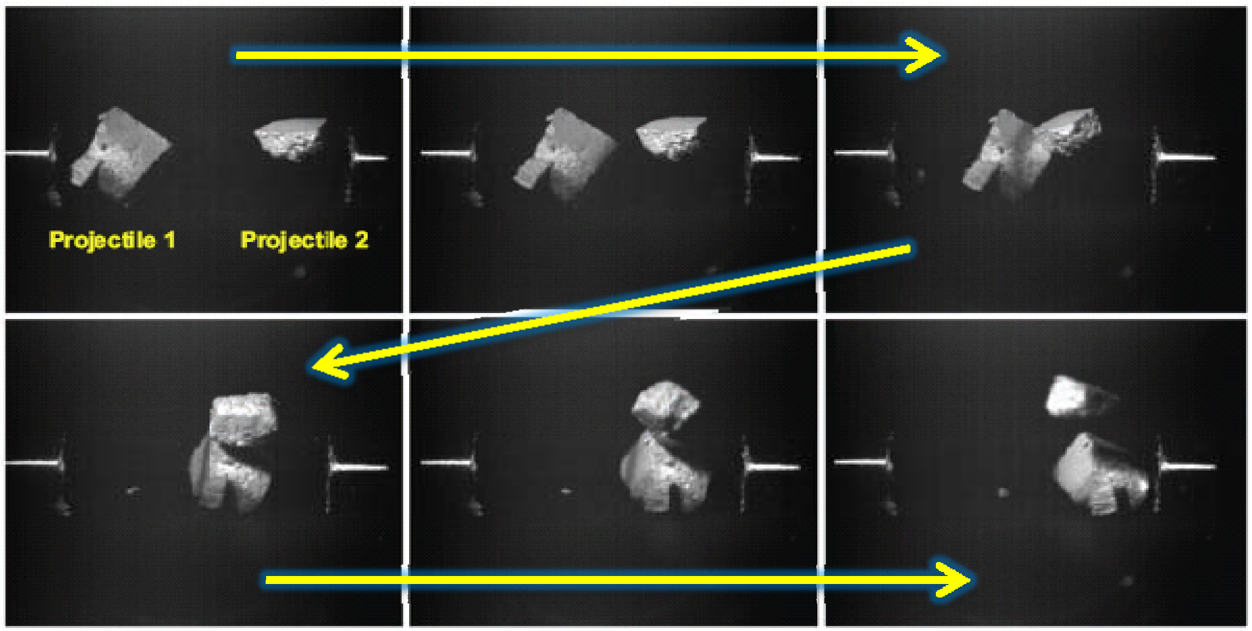


Figure 5

Bouncing of two irregular-shaped, nonfractal, but highly porous dust aggregates ($\phi = 0.15$) at a relative velocity of ~0.4 m s^{-1} (see Section 5.3). The images were taken with a high-speed camera in a microgravity experiment onboard a parabolic-flight aircraft. The field of view is 24 × 20 mm^2. Figure by D. Heißelmann, H. Fraser & J. Blum (unpublished data).

Güttler et al. 2009 (submitted to A&A)

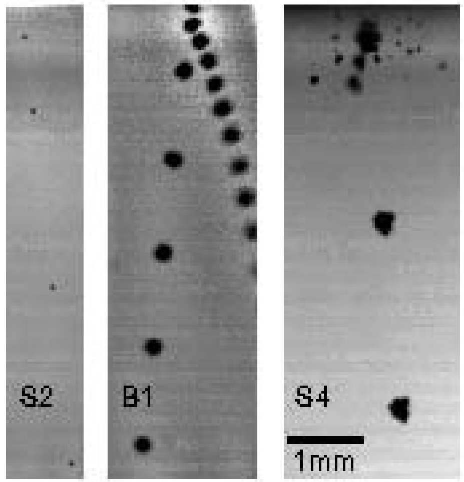


Fig. 5. Examples for the experimental outcomes in the collisions of small aggregates with a solid target. The collision can lead to sticking bouncing or fragmentation (from left to right). The time between two exposures is 2 ms.

u_{col}

Stiking

Bouncing

~ 1 m/s

Stiking
and/or fragmentation

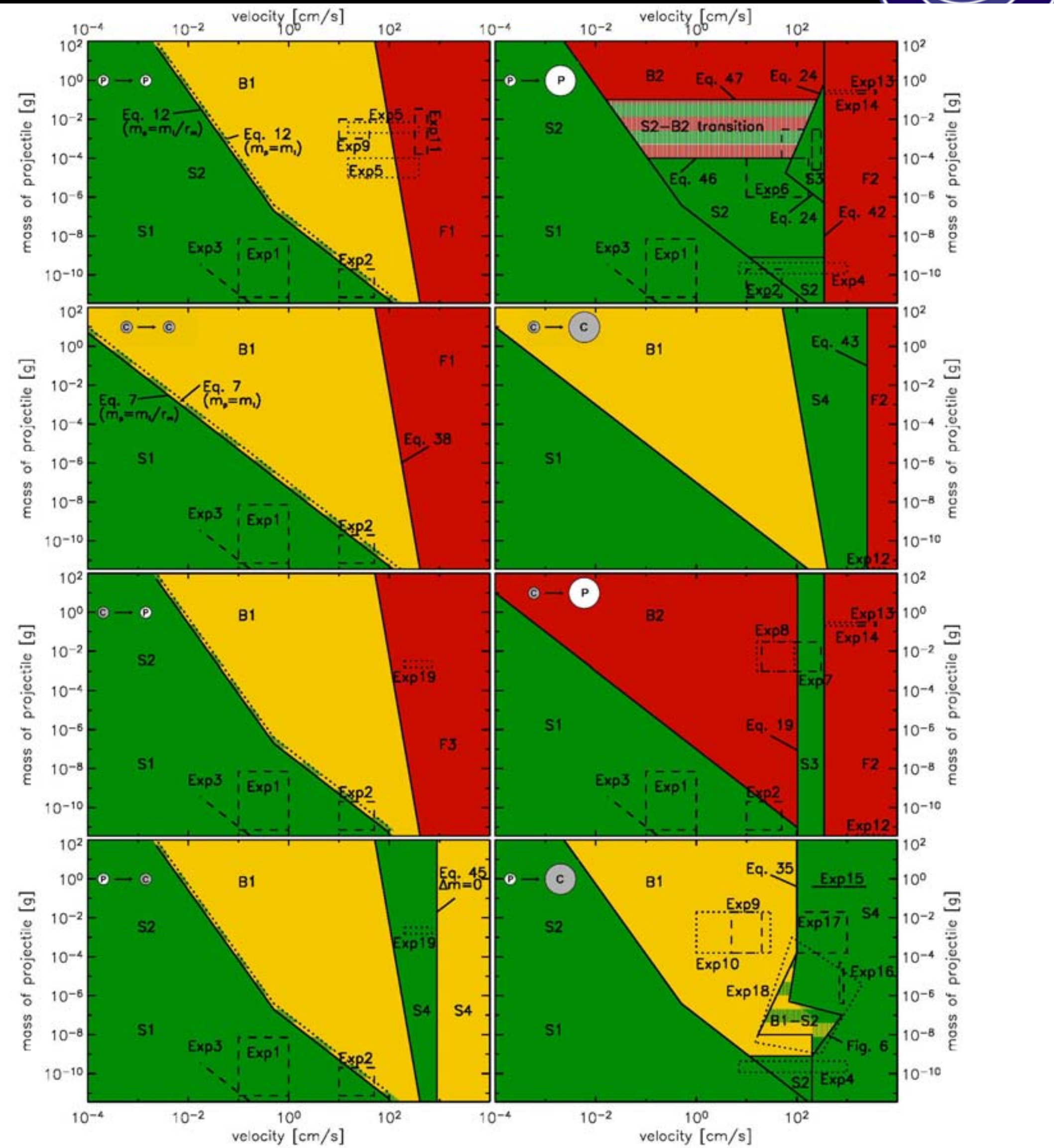


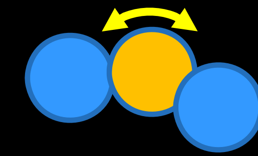
Fig. 11. The resulting collision model as described in this paper. We distinguish between similar-sized (left column) and different-sized (right column) collision partners, which are either porous or compact (also see Fig. 10). For each case, the important parameters to determine the collisional outcome are the projectile mass and the collision velocity. collisions within green regions can lead to the formation to larger bodies while red regions denote mass loss. Yellow regions are neutral in terms of growth. The dashed and dotted boxes show where experiments directly support this model.

Bouncing problem

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

Hypothesis：Number of contacts controls？

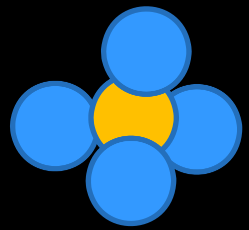
Aggregates in numerical simulations：



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

More C.N. in experiments？

→ Energy dissipation is difficult due to immobility of particles？



Objective

● To reveal the dependence on coordination number for aggregate bouncing

Collision simulation of aggregate collisions

parameter : Coordination Number (C.N.)

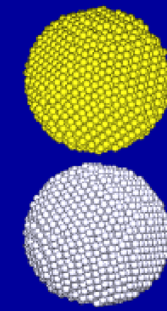
Idea for making required C.N. :

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

↓

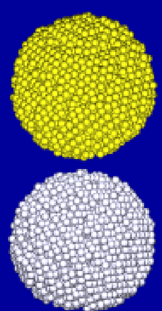
aggregates with C.N. = ~12 to ~3

Initial conditions and settings

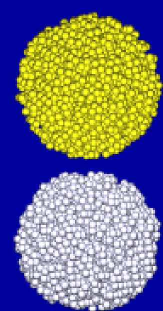


- ✓ (hexagonal) close-packed aggregates：
  mean C.N. ∼ 11
  - Number of particles：4197 （3 types randomly produced）
- ✓ particle-extracted aggregates：
  extraction rate f = 0.05 - 0.75 C.N.∼12 (1 − f)

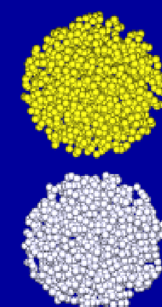
f = 0.2
mean C.N. = 8.8



f = 0.5
mean C.N. = 5.5



f = 0.75
mean C.N. = 2.8



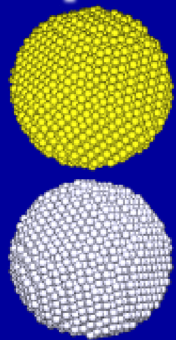
✓Ice (E = 7.0 GPa, ν = 0.25, γ = 100 mJ/m^2, R = 0.1μm) , critical rolling displace. ξ_{crit} = 8Å

✓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)

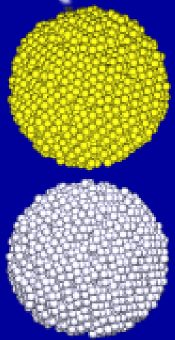
Examples of simulation (Ice)

C.N.= 11



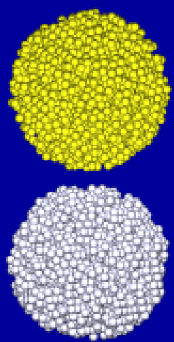
$u_{col} = 0.096$ m/s ($E_{imp} = 0.66\, E_{break}$)

C.N.= 8.8



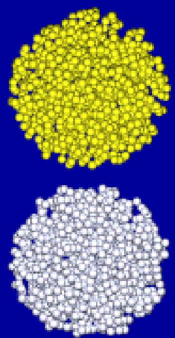
$u_{col} = 0.096$ m/s ($E_{imp} = 0.53\, E_{break}$)

C.N.= 5.5



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

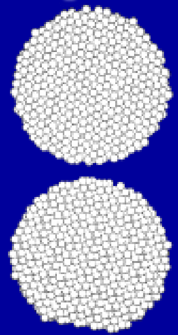
C.N.= 2.8



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

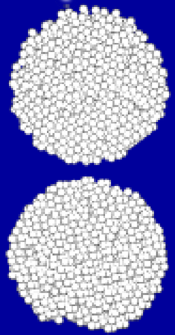
Examples of simulation (Ice)

C.N.= 11



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

C.N.= 8.8



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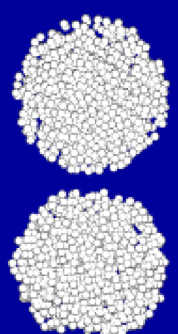

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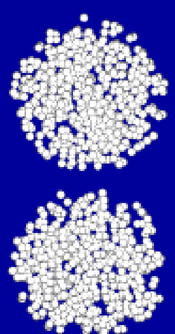
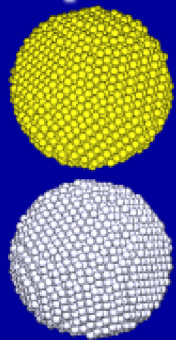
C.N.= 2.8



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

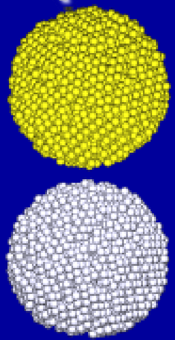
Examples of simulation (Ice)

C.N.= 11



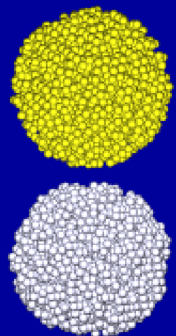
$u_{col} = 1.5$ m/s ($E_{imp} = 170\ E_{break}$)

C.N.= 8.8



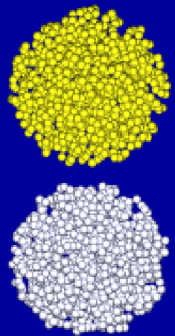
$u_{col} = 1.5$ m/s ($E_{imp} = 135\ E_{break}$)

C.N.= 5.5



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

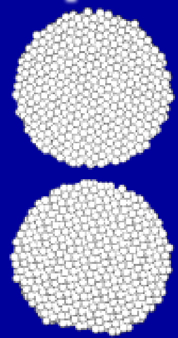
C.N.= 2.8



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

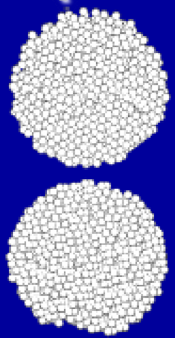
Examples of simulation (Ice)

C.N.= 11



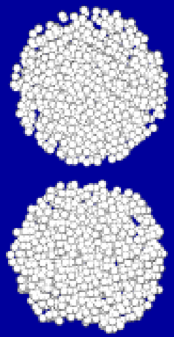
$u_{col} = 1.5$ m/s ($E_{imp} = 170\ E_{break}$)

C.N.= 8.8



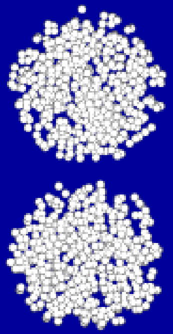
$u_{col} = 1.5$ m/s ($E_{imp} = 135\ E_{break}$)

C.N.= 5.5



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

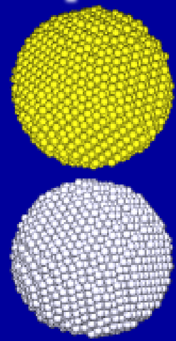
C.N.= 2.8



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

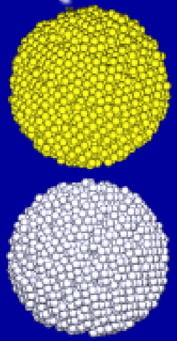
Examples of simulation (Ice)

C.N.= 11



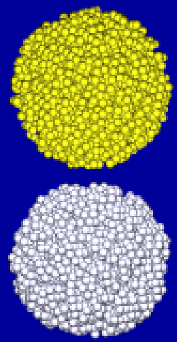
$u_{\mathrm{col}} = 22$ m/s ($E_{\mathrm{imp}} = 4.1\, N\, E_{\mathrm{break}}$)

C.N.= 8.8



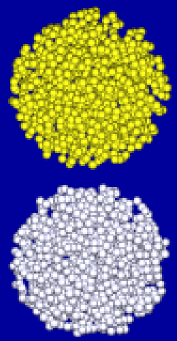
$u_{\mathrm{col}} = 22$ m/s ($E_{\mathrm{imp}} = 4.1\, N\, E_{\mathrm{break}}$)

C.N.= 5.5



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

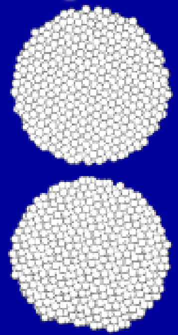
C.N.= 2.8



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

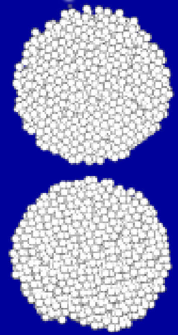
Examples of simulation (Ice)

C.N.= 11



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

C.N.= 8.8



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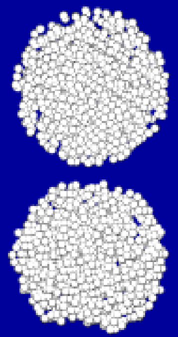
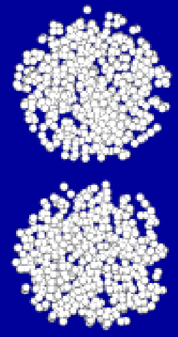
C.N.= 5.5



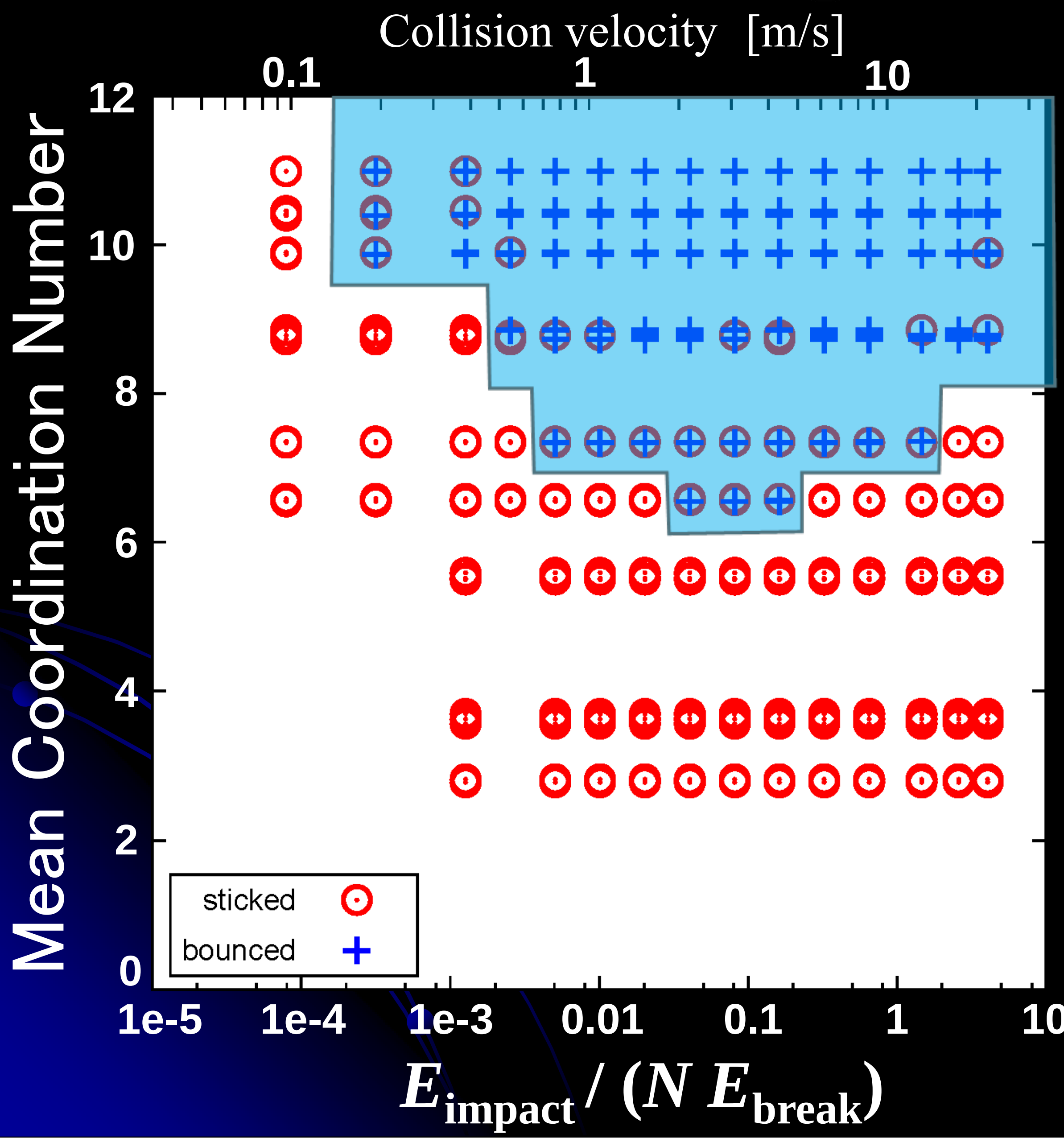
$u_{col} = 22$ m/s ($E_{imp} = 4.1\, N\, E_{break}$)

C.N.= 2.8



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

Result : Bouncing Condition (Ice)

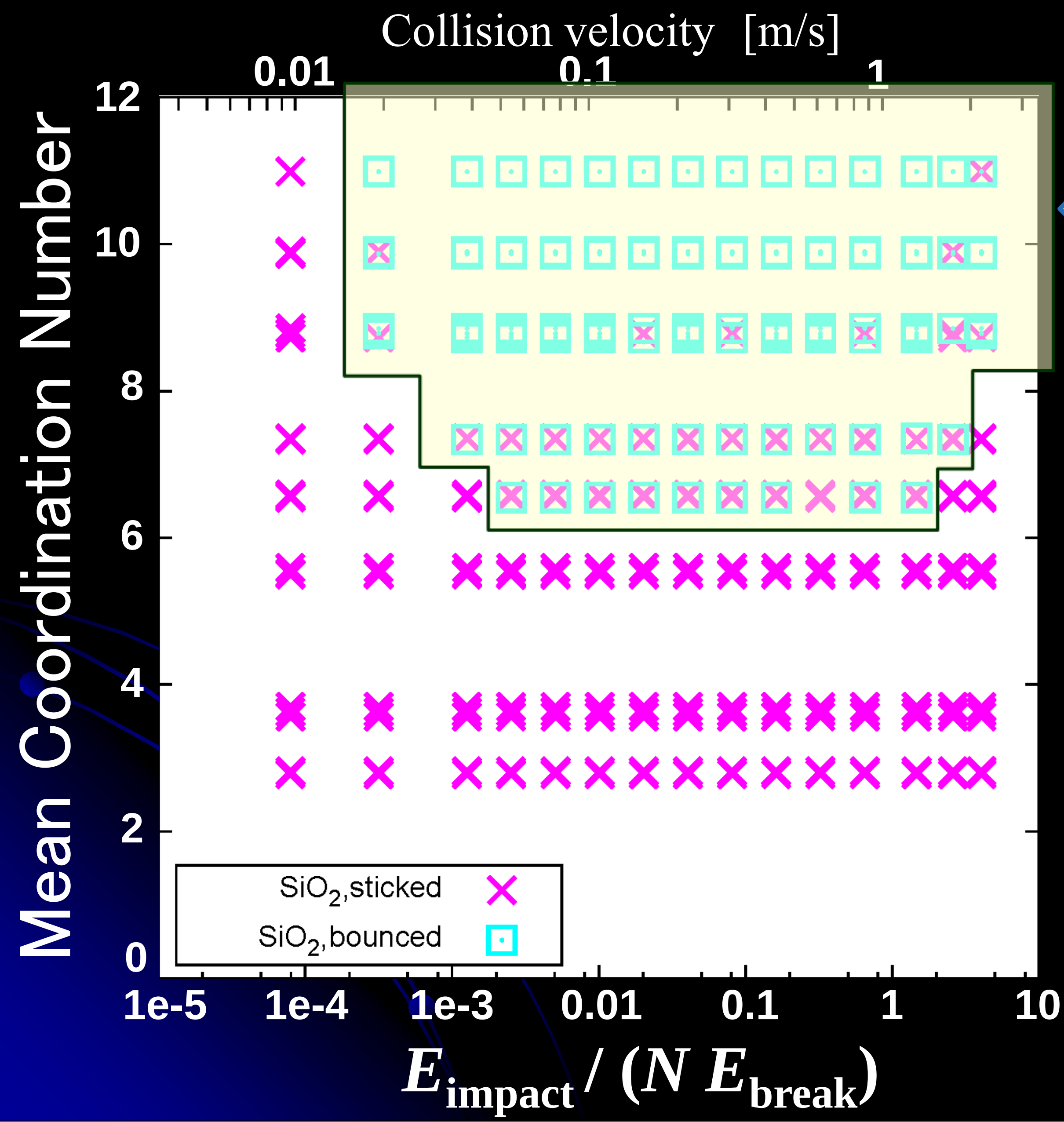


Bouncing

Mean C.N. < ~ 6

Sticking

Result: Bouncing Condition (SiO_2)

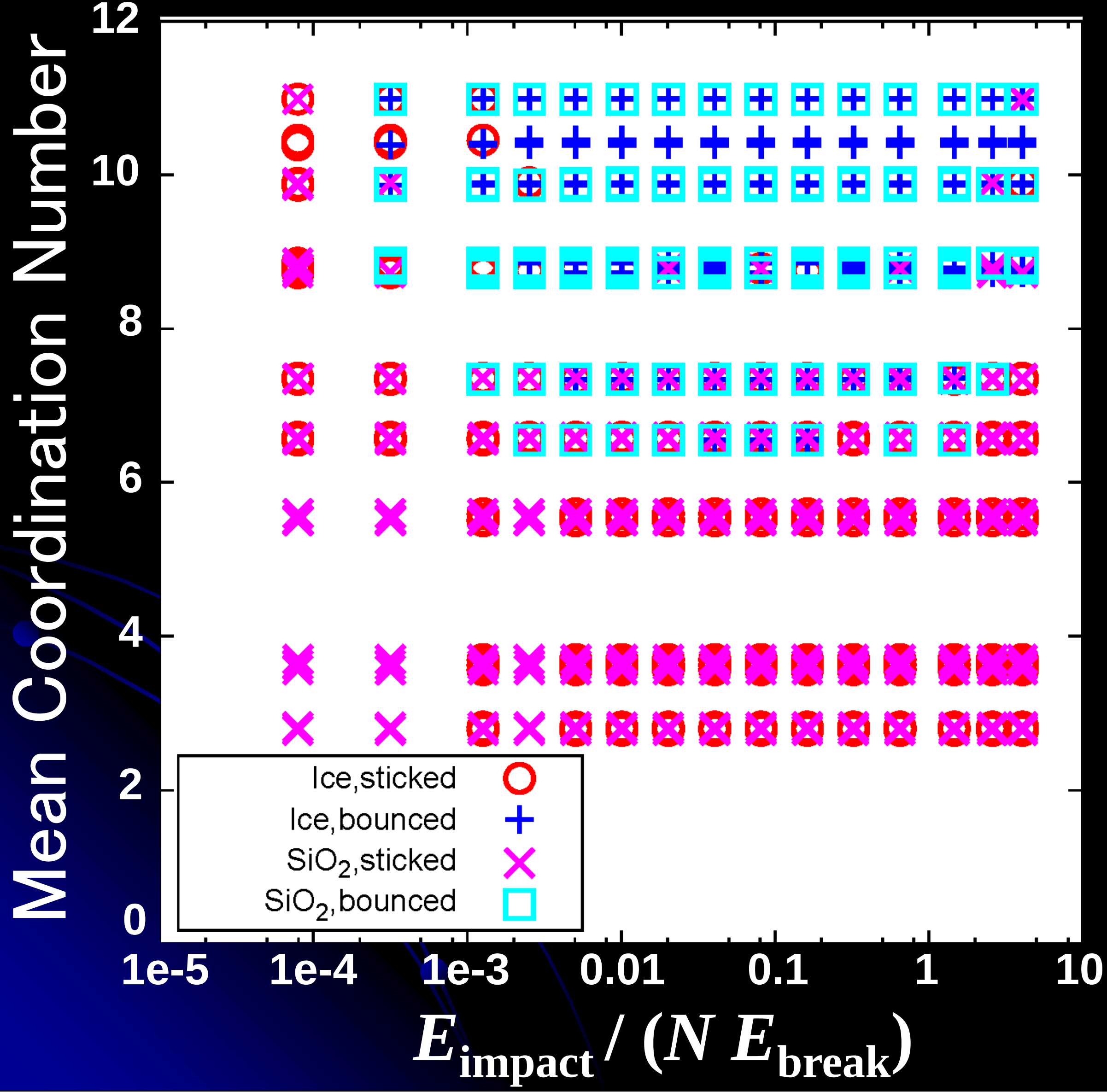


Bouncing

Mean C.N. < ~ 6

Sticking

Result: Bouncing Condition
(Ice, SiO_2)

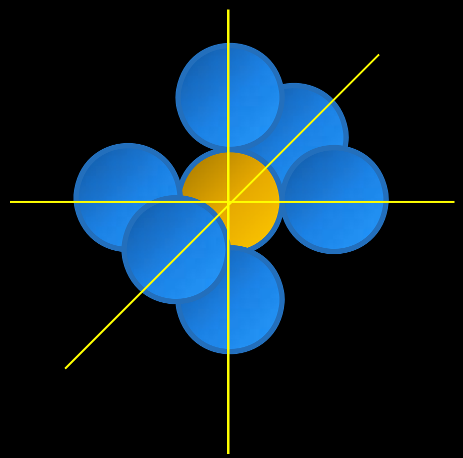


No difference between Ice and SiO_2

Scaled well by using E_{break}

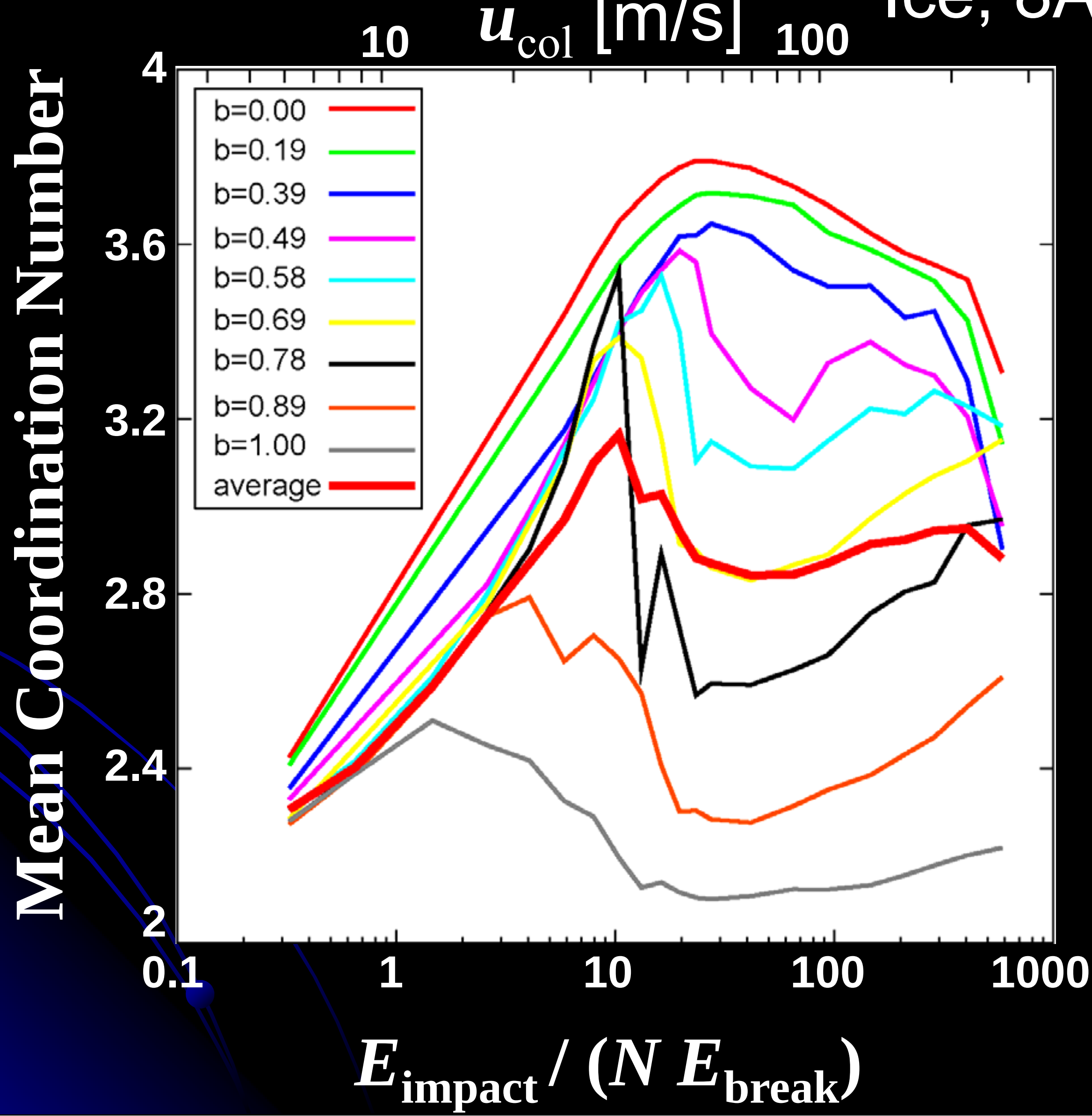
Why C.N. = 6 ?

A particle is stable enough with C.N. = 6 in 3D:



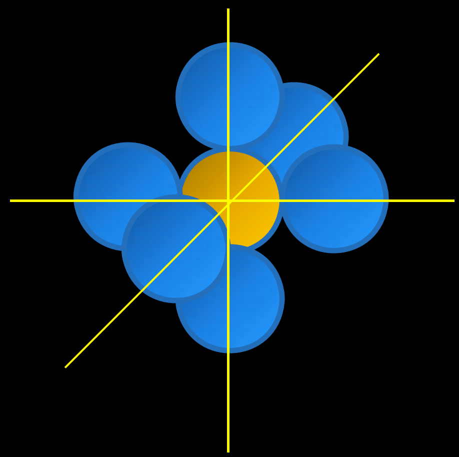
C.N.@BPCA collisions

Ice, 8Å, 8000+8000

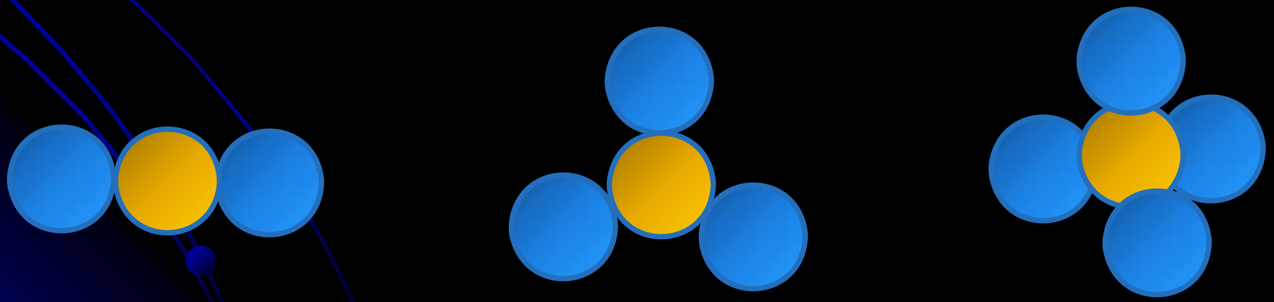


Why C.N. = 4 ?

A particle is stable enough with C.N. = 6 in 3D:



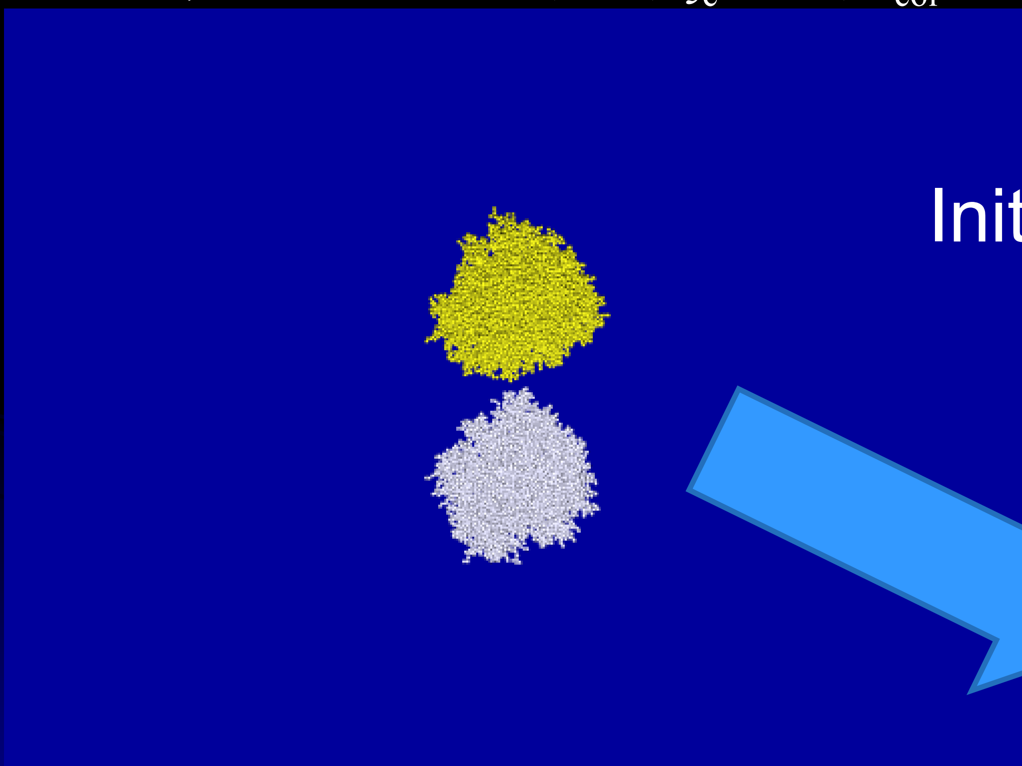
Stable with at least C.N. = 4 in 3D:



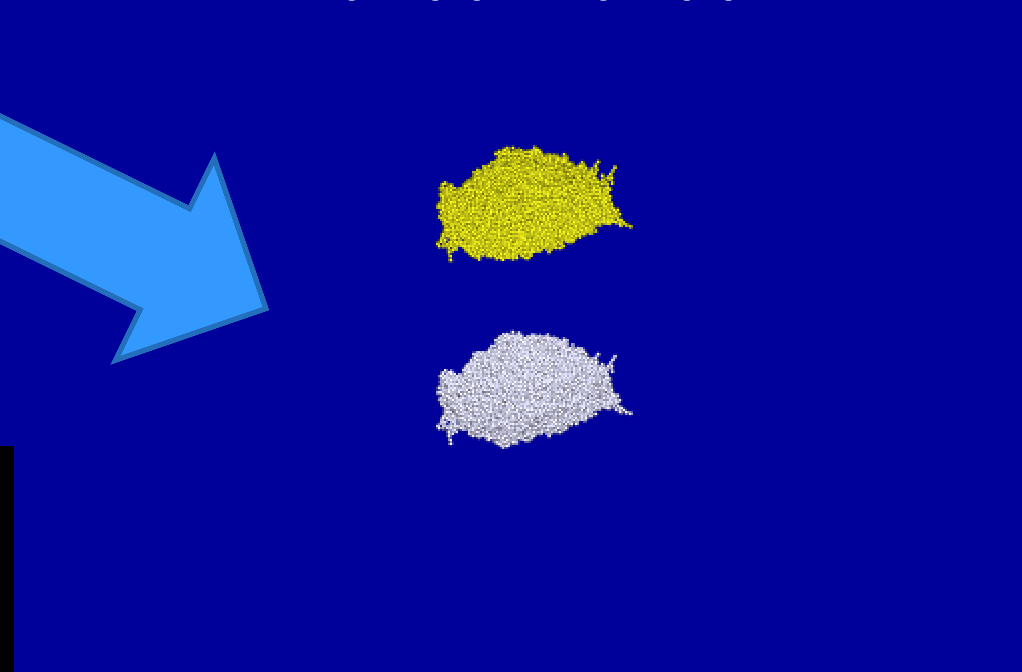
1D 2D 3D

aggregates produced by collisions

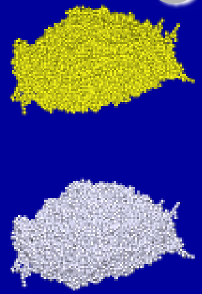
BPCA, N=8000+8000, ice, ξ_c = 8Å, $u_{col} = 57$ m/s ($E_{imp} = 27\ NE_{break}$)



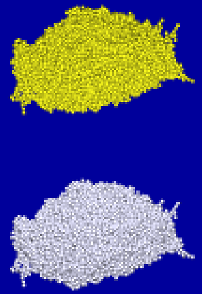
Initial condition(C.N. = 3.8)
15288+15288



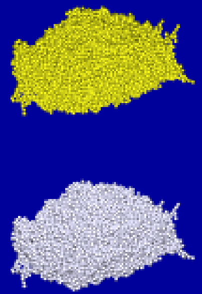
Collisions of collision-produced aggregates（C.N.=3.8）



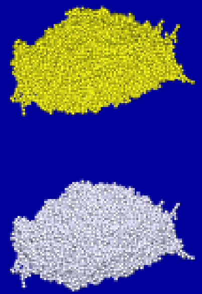
$u_{col} = 0.38$ m/s （$E_{imp} = 1.2 \times 10^{-3}\ NE_{break}$）



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

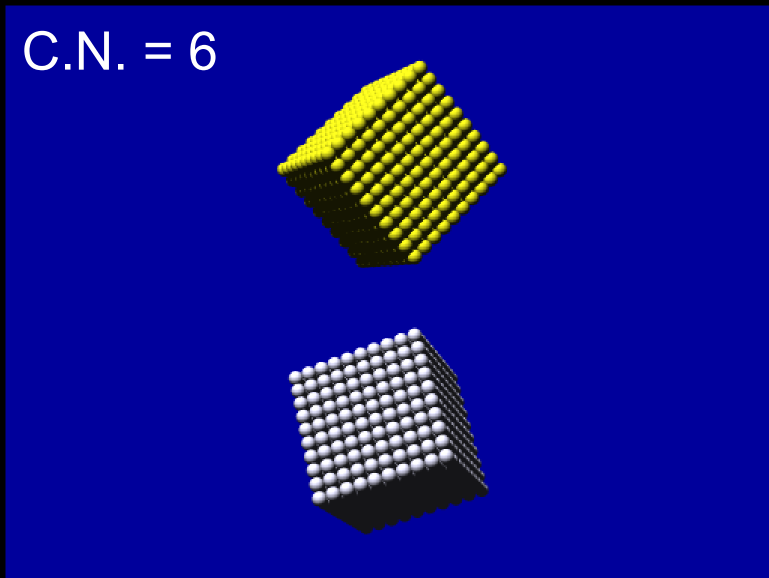


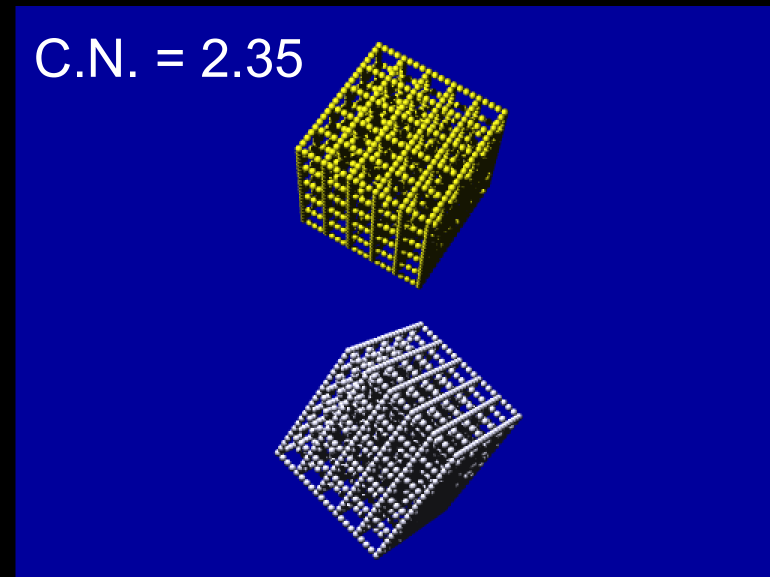
$u_{col} = 1.54$ m/s （$E_{imp} = 2.0 \times 10^{-2}\ NE_{break}$）

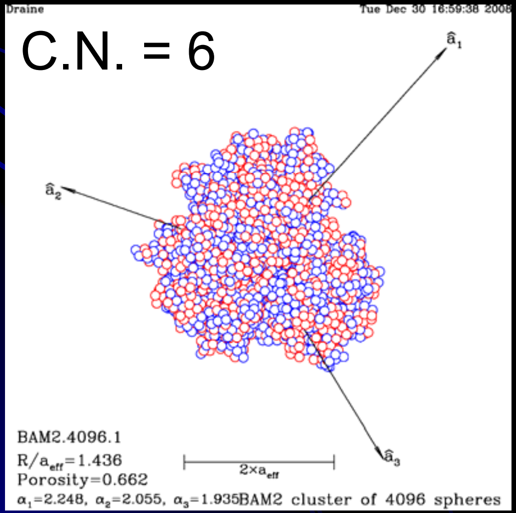


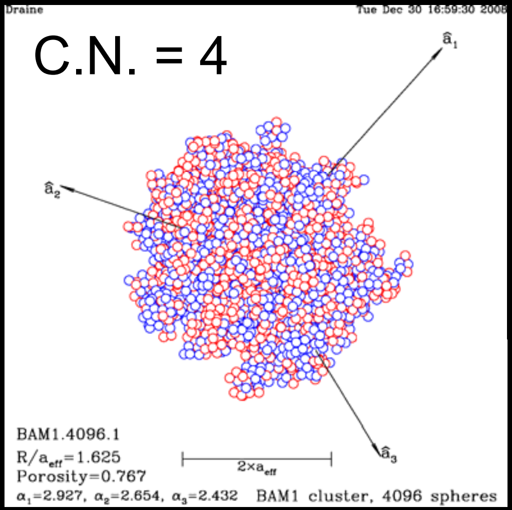
$u_{col} = 17.4$ m/s （$E_{imp} = 2.6\ NE_{break}$）

Structure is also important?





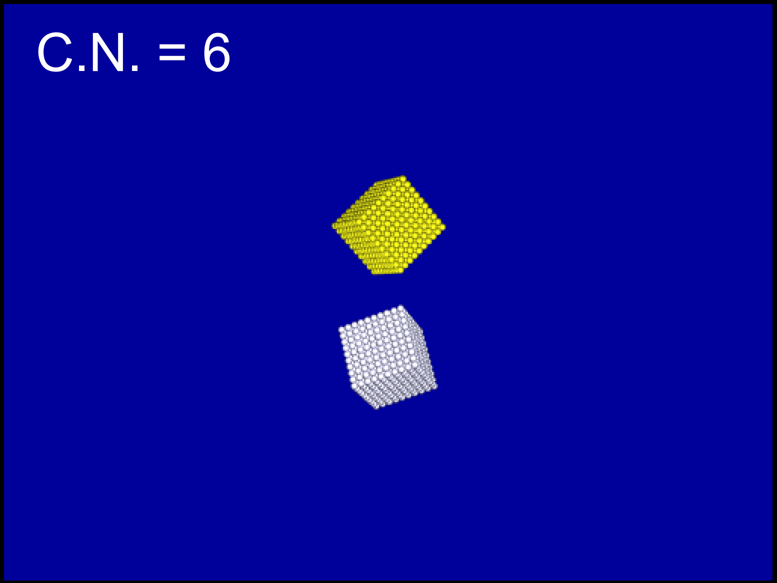


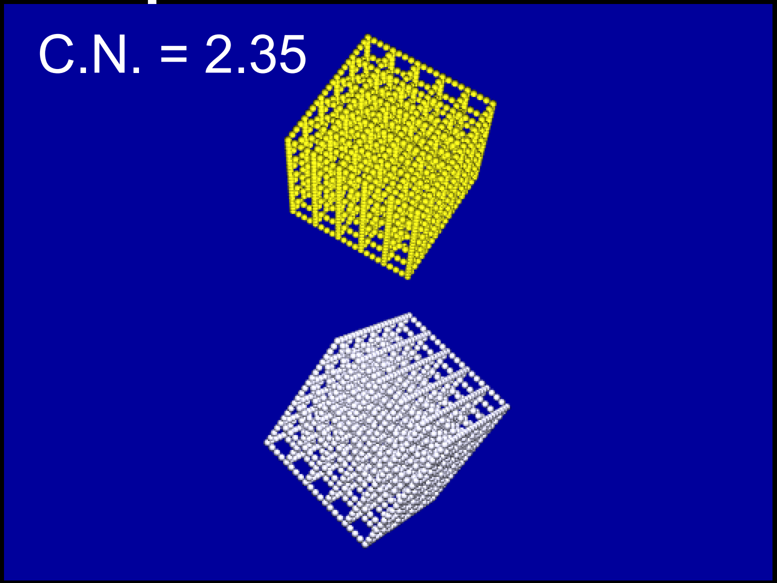


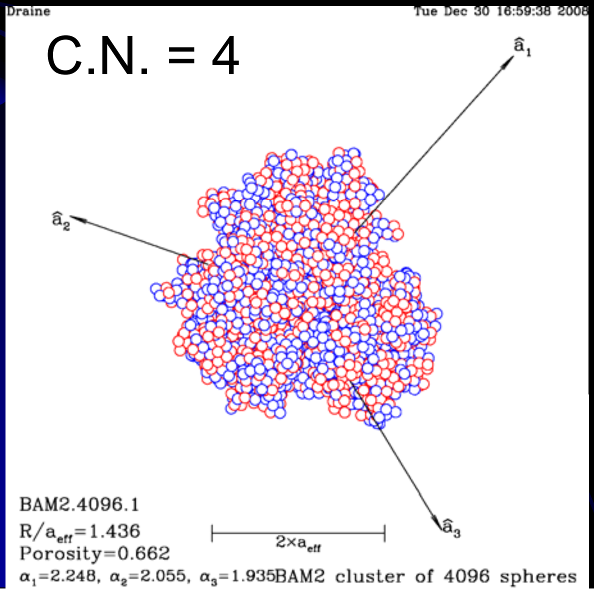
Shen, Draine, and Johnson (2008)

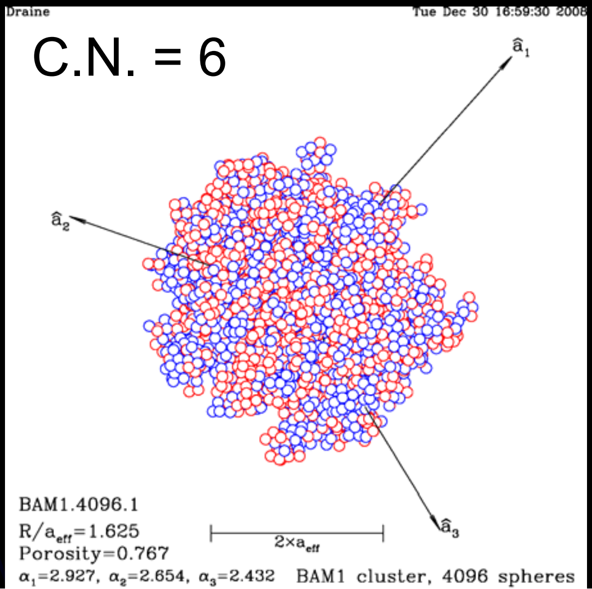
New Calculations at Braunschweig

Structure is also important?









No!
Bouncing
only for C.N.=6

Summary

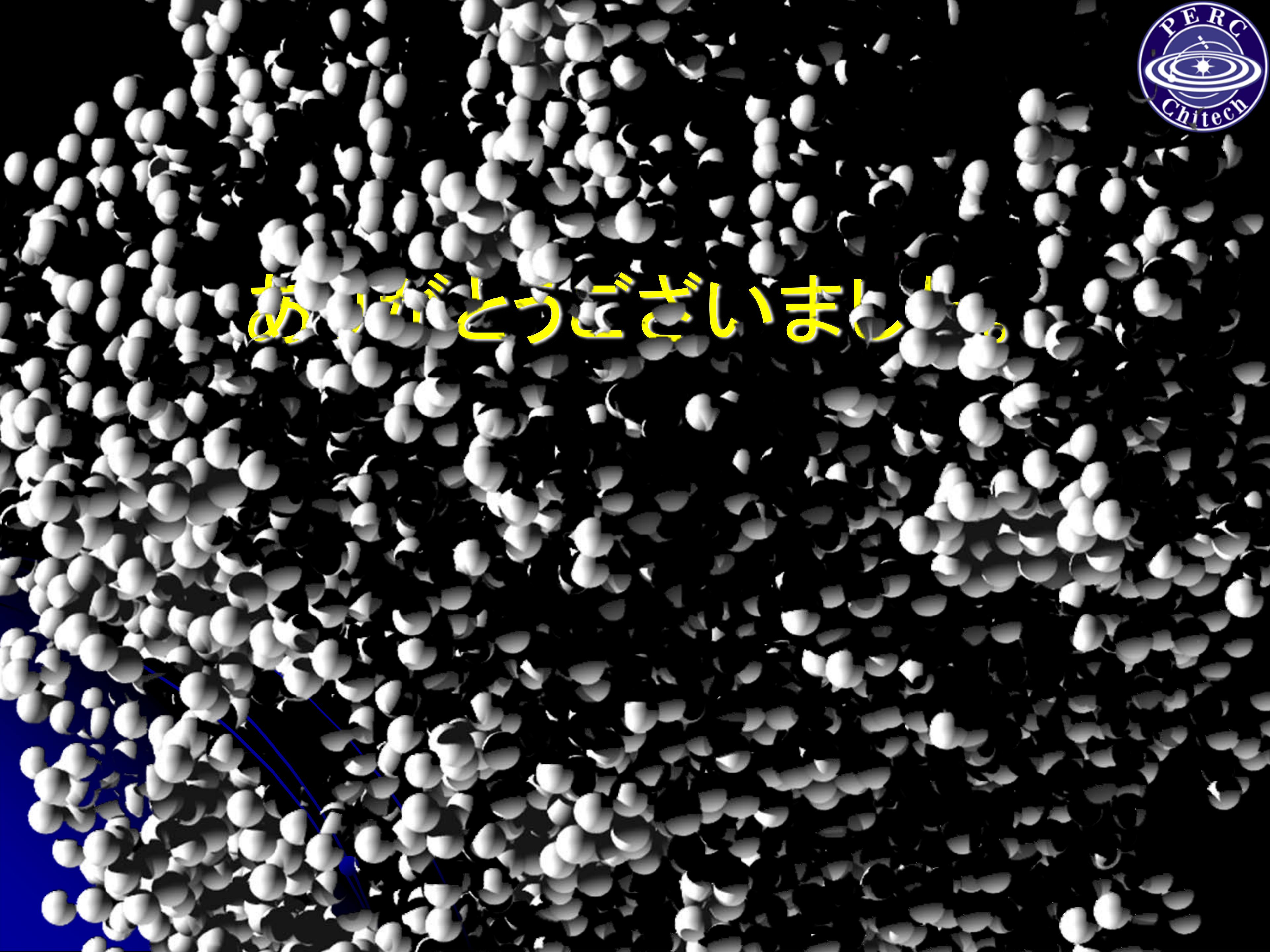
We examine the bouncing condition, focusing on C.N. of aggregates.

- 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

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

Future work

- dependence on size (and size ratio) of aggregates and offset collision


ありがとうございました。