A Dust Aggregate Model Based on Numerical Simulations of Aggregate Collisions

ダストアグリゲイト同士のDEM(?)衝突シミュレーション

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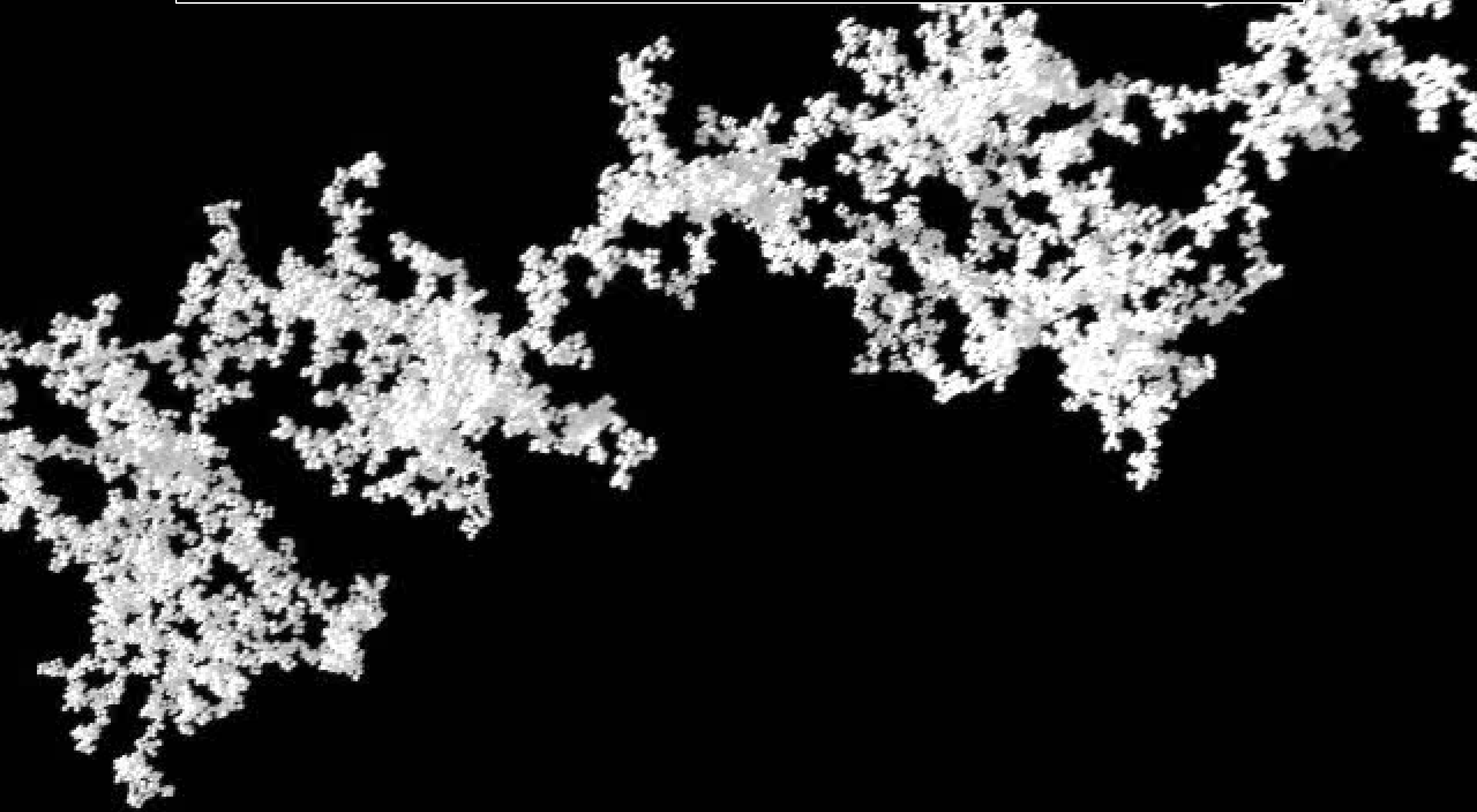
A collision of BCCAs

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

Collision velocity = 22 m/s



Background

Collisional growth of dust ($< \mu m$) → ? → Planetesimal formation ($> km$)

Structure evolution of dust aggregates in protoplanetary disks

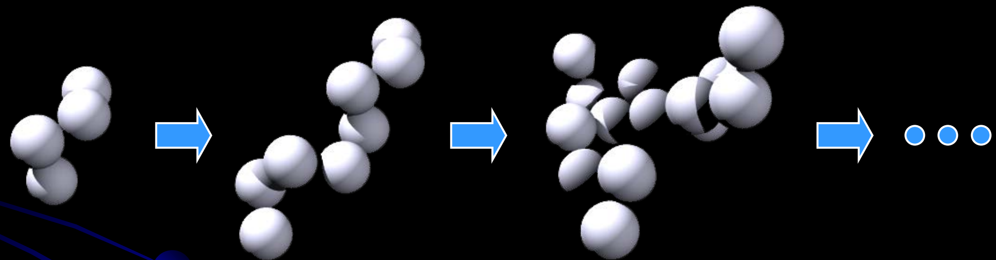
When and how are aggregates compressed and/or disrupted ?

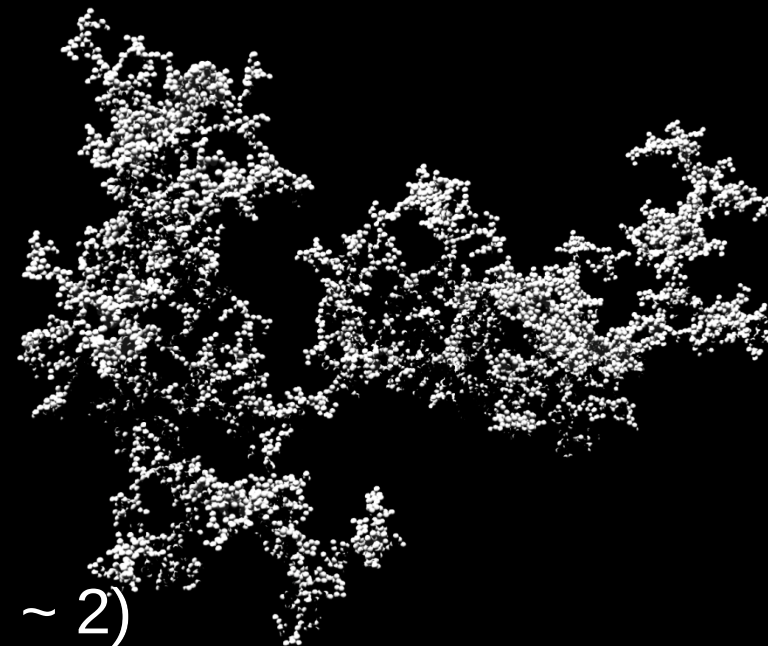
→ **Numerical simulation of dust aggregate collisions!**

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)

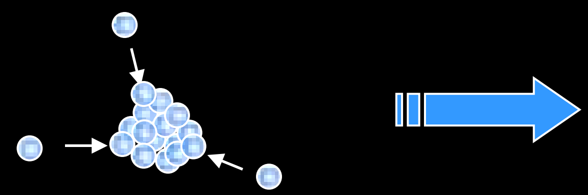
⬇

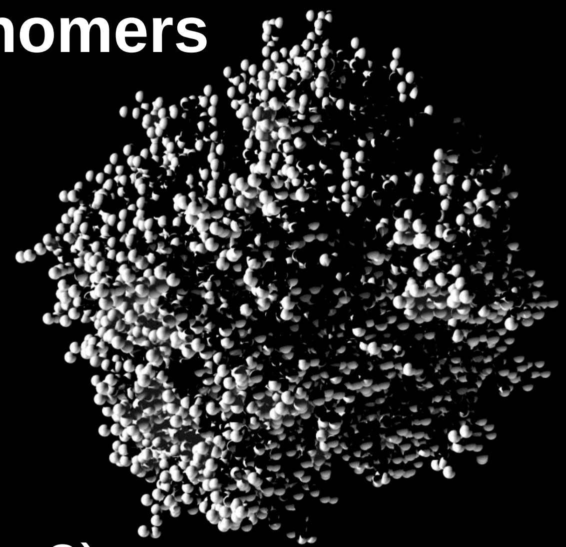
Is it possible for dust to grow through collisions?
To what extent is dust compressed?

Experimental: Blum & Wurm 2000, Wurm et al. 2005
Numerical: Dominik & Tielens 1997, Wada et al. 2008; 2009

Ballistic Particle-Cluster Aggregation (BPCA)

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





- Compact structure (fractal dimension ~ 3)

Dust should be compact
in high velocity collisions causing their disruption

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

Objective

To construct a structural evolution model of dust aggregates by numerical simulations of aggregate collisions

Collisions of BCCA & BPCA clusters

- Compression process (BCCAs)

  Gyration radius → Degree of compression

- High-velocity collisions (BPCAs)

  Number of particles in the largest remnant → Growth efficiency

  Coordination numbers in the largest remnant → Degree of compression

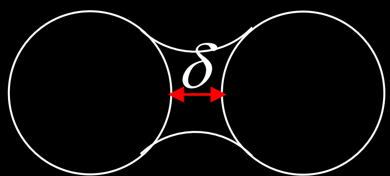
Simulation Method

Grain interaction model

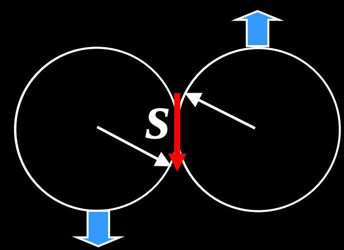
Johnson, Kendall and Roberts (1971)
Johnson (1987), Chokshi et al. (1993)
Dominik and Tielens (1995,96)
Wada et al. (2007)

Elastic spheres having surface energy

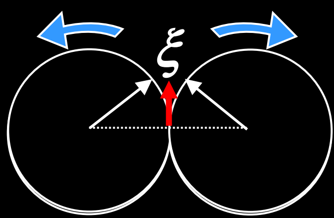
Normal



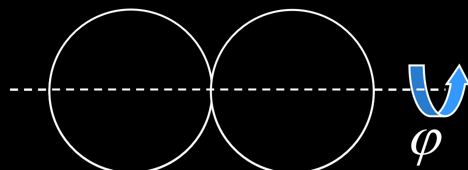
Sliding



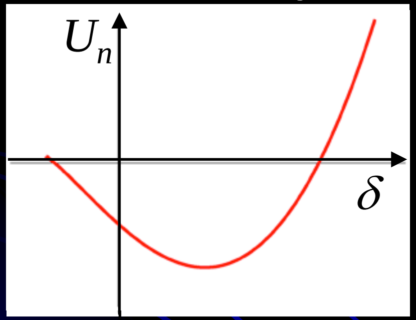
rolling



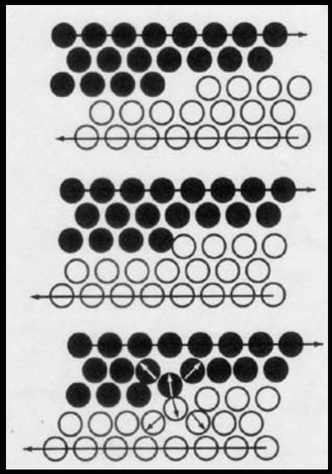
twisting



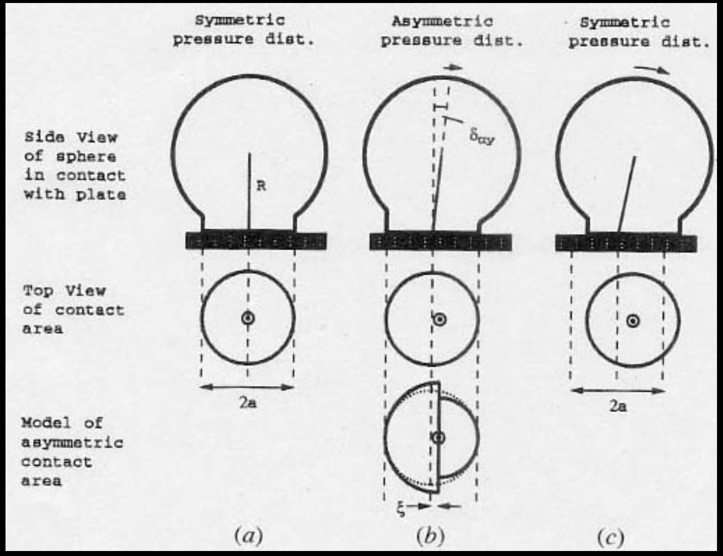
JKR theory



Critical sticking velocity:
exp.~10 × theo.!?



(Dominik & Tielens 1996)



(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

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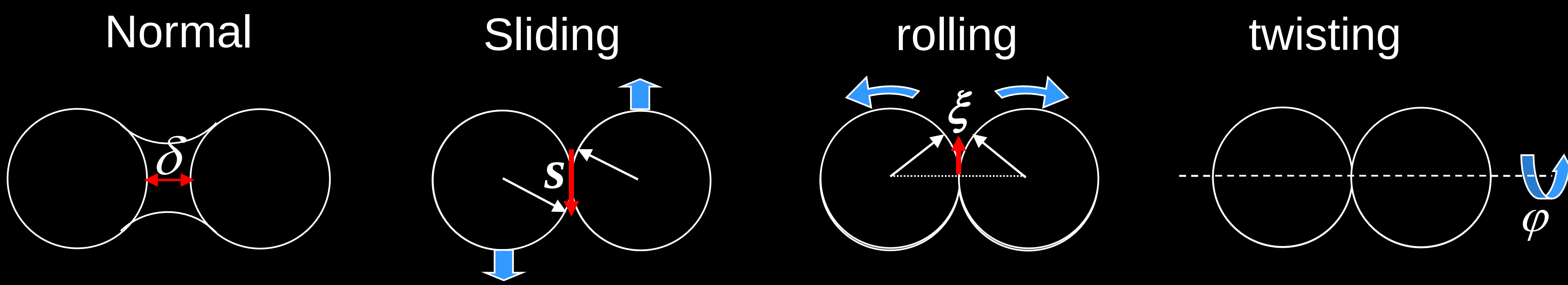
Elastic spheres having surface energy



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°

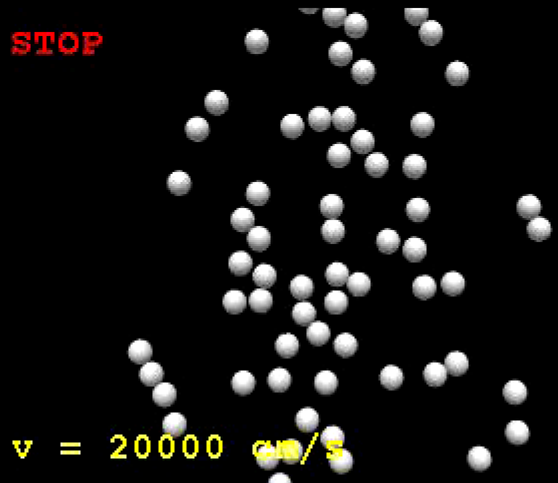
E_{break}: Energy to break a contact

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

A classical study

Dominik and Tielens (1997)

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



Confirmed by experiments (Blum & Wurm 2000)

✓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

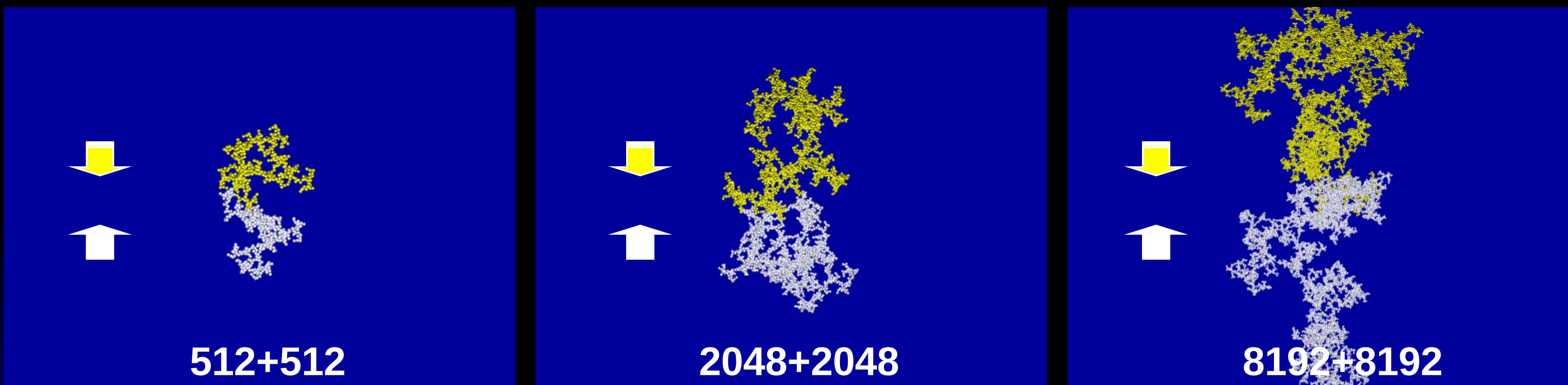
: Compression process

Initial Conditions and Parameters

Collisions of BCCA clusters

Results are averaged

- ✓ BCCA clusters are
  - composed of 512, 2048, or 8192 particles (10 types randomly produced)
  - impacted by head-on collision



✓ particle : radius = 0.1 μm,

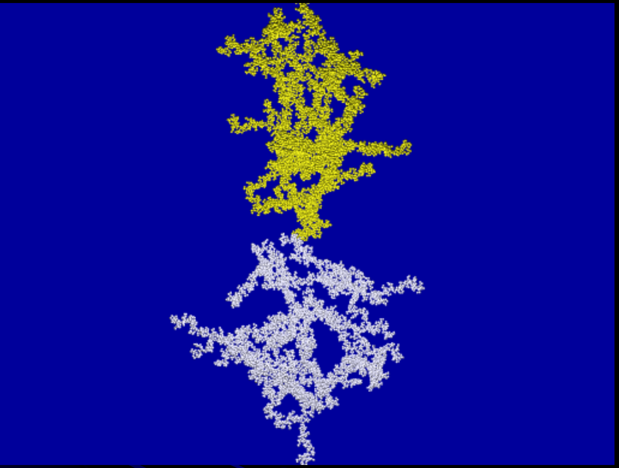
Ice (E = 7 GPa, ν = 0.25, γ = 100 mJ/m^2)

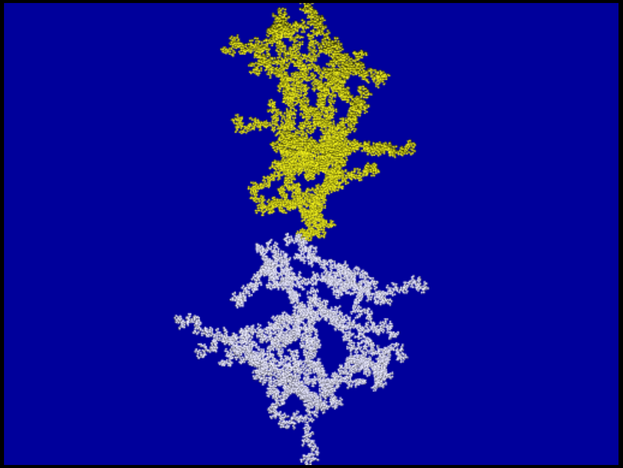
SiO_2 (E = 54 GPa, ν = 0.17, γ = 25 mJ/m^2)

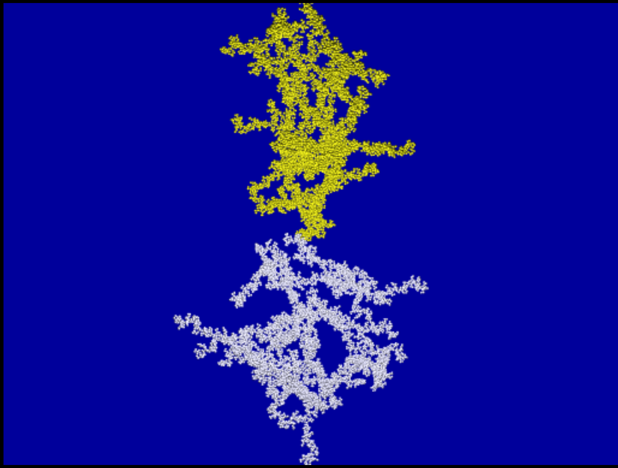
✓ Critical rolling displacement : ξ_{crit} = 2, 8, 30 Å

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

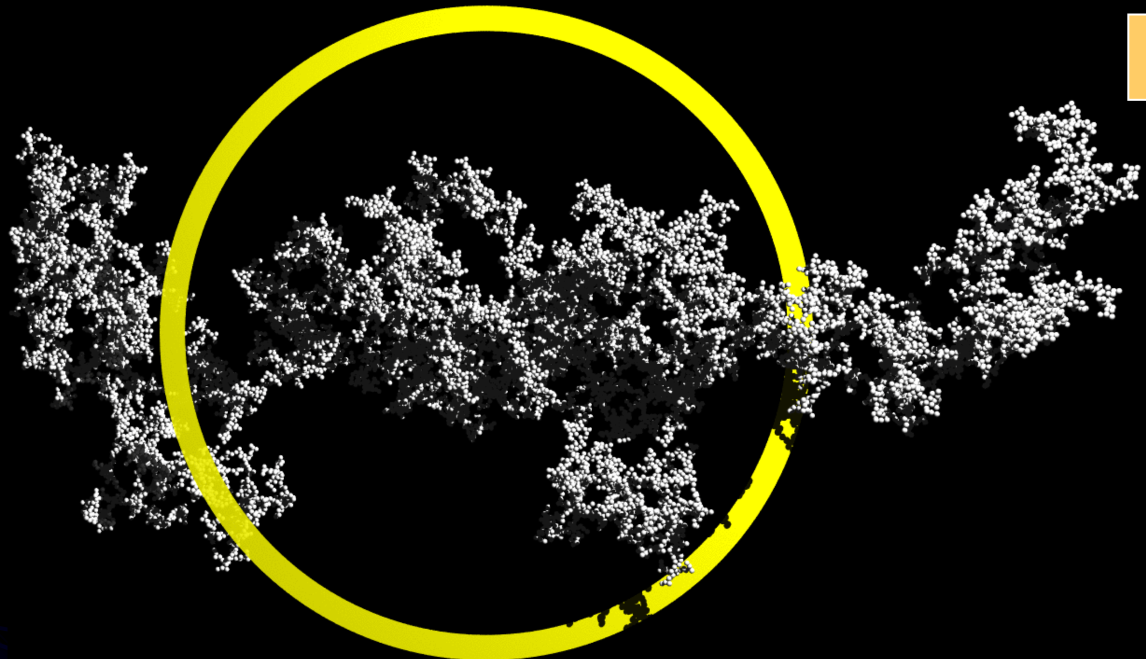
$E_{impact} \sim 13\, n_k\, E_{break}$

$V_{impact} = 39$ m/s

Numerical Results on

Gyration Radius

Gyration radius r_g : *compression process*

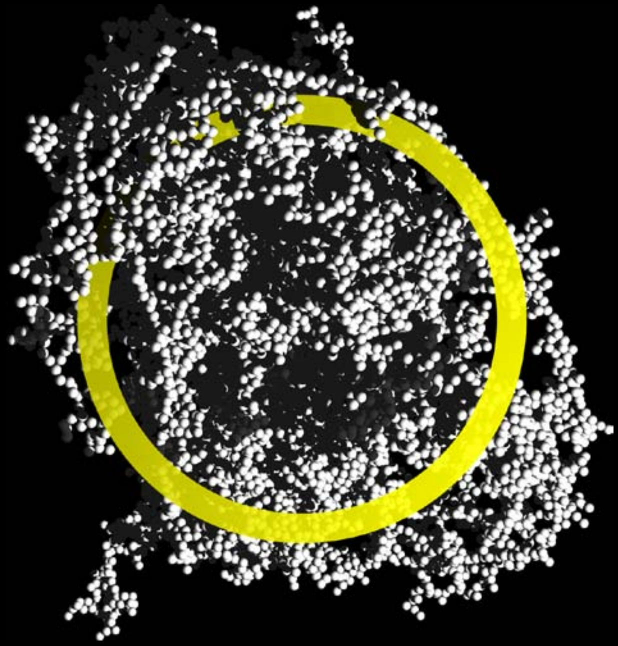


$E_{impact} \sim 0.01\, E_{roll}$

Impact velocity: 0.024 m/s

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

Impact velocity: 13 m/s

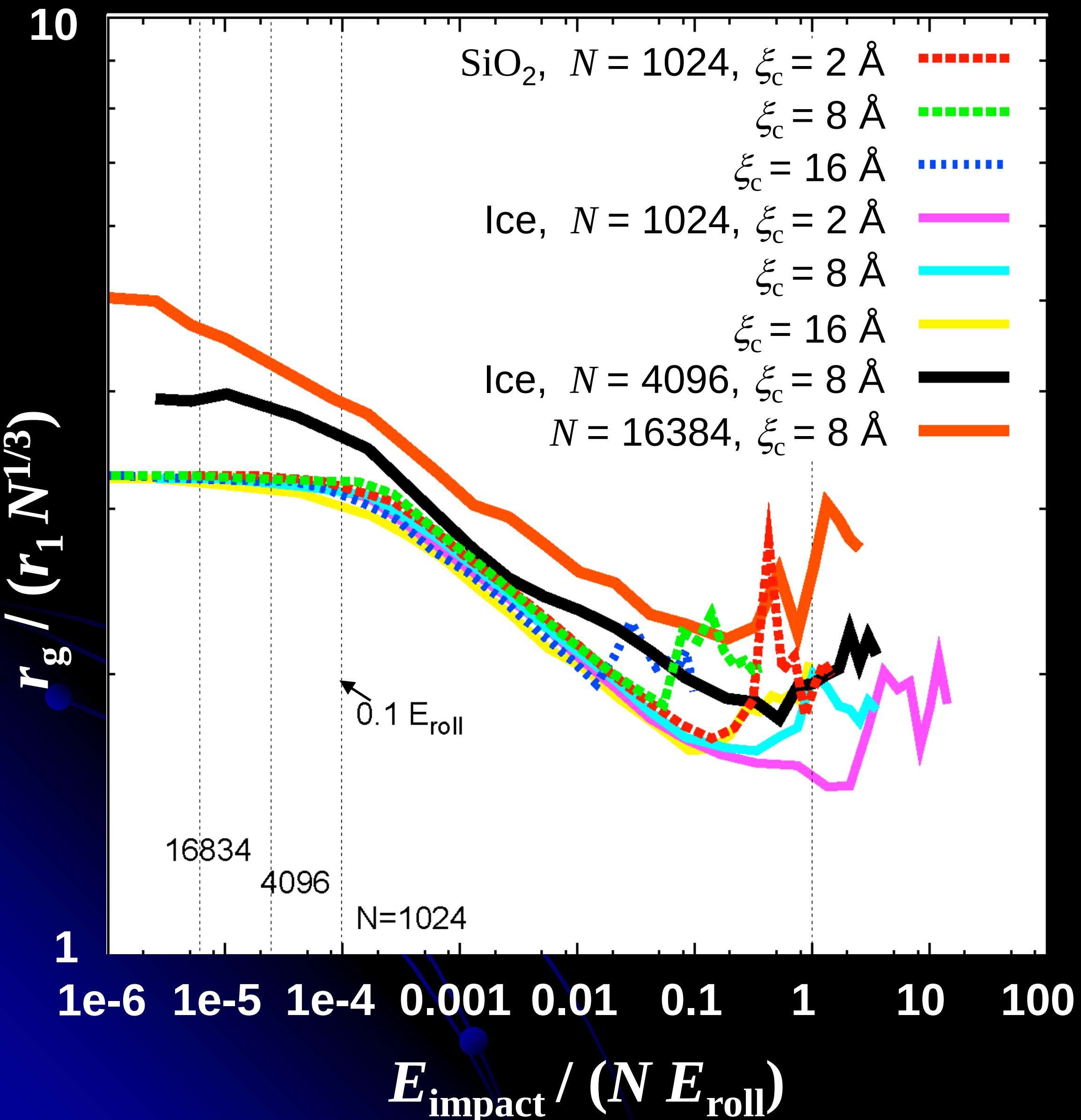


Ice, 8192 + 8192, ξ_{crit} = 8 Å

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

x_g: center of mass

Gyration radius r_g : *compression process*



✓ $E_{impact} \sim (0.1 - 1)\, N E_{roll}$

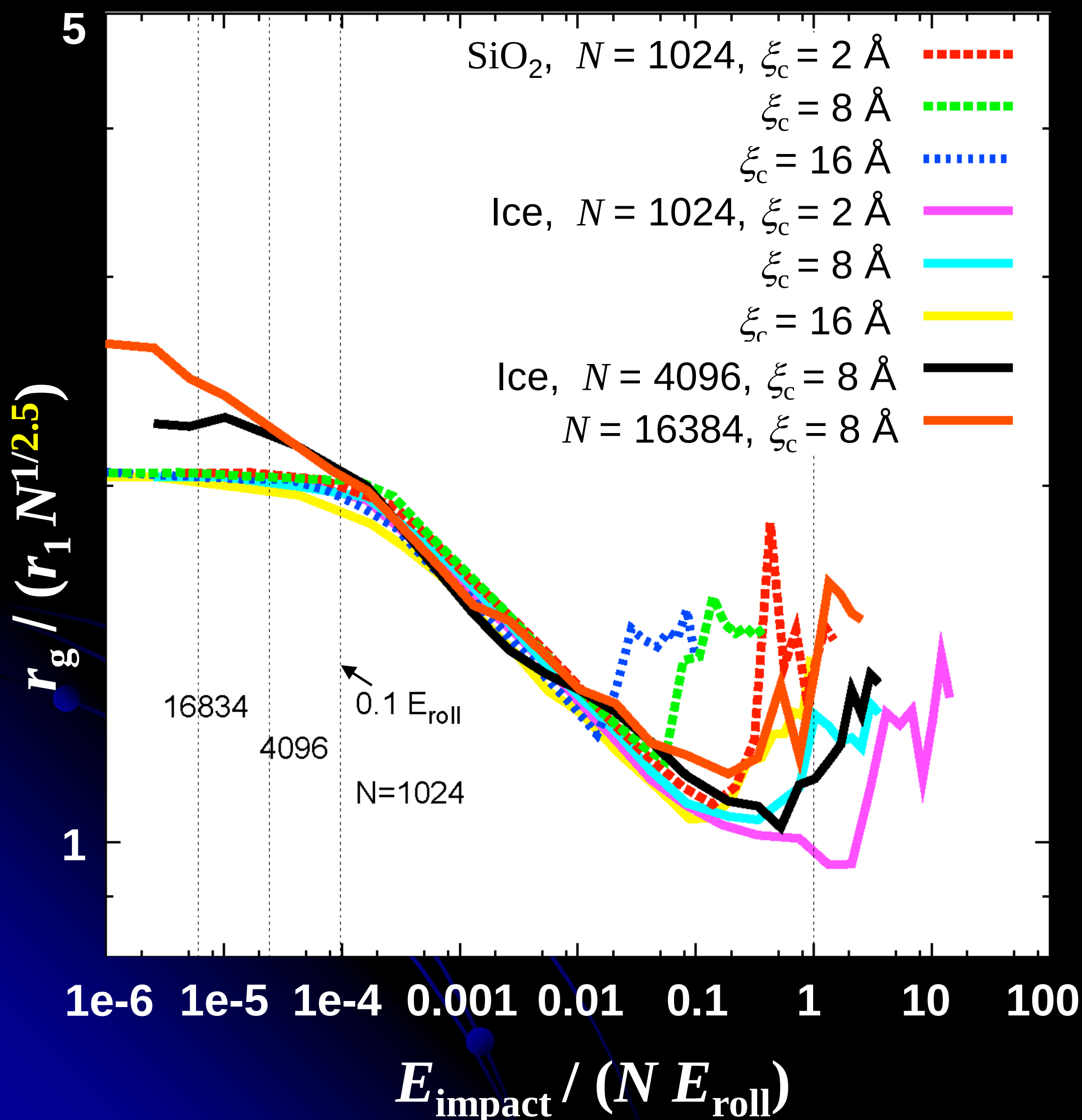
⇓

Max. compression

⇕

Consistent with Dominik & Tielens (1997)

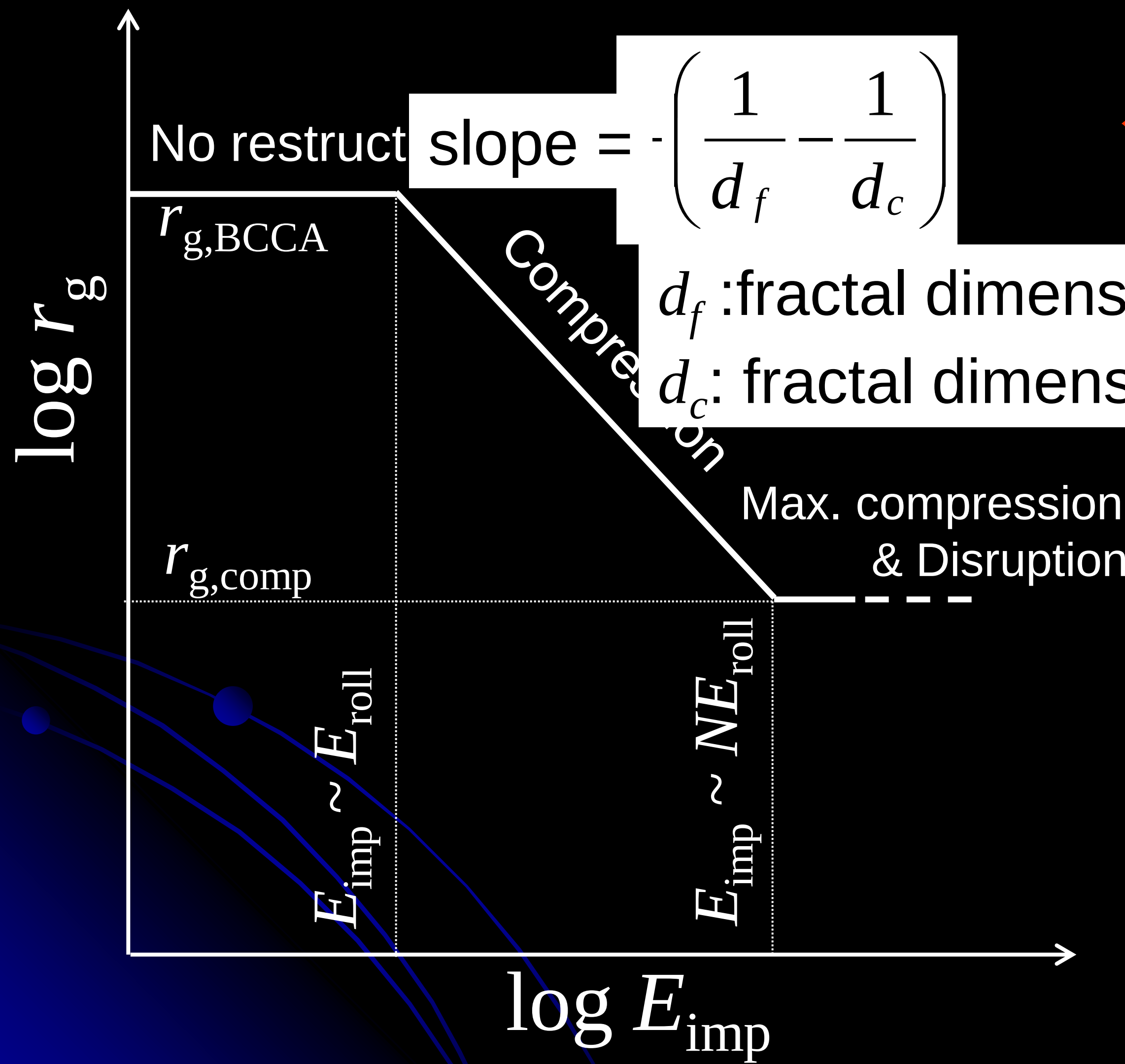
Gyration radius r_g : *compression process*



✓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*



$$\text{slope} = -\left(\frac{1}{d_f} - \frac{1}{d_c}\right)$$

d_f :fractal dimension of BCCA

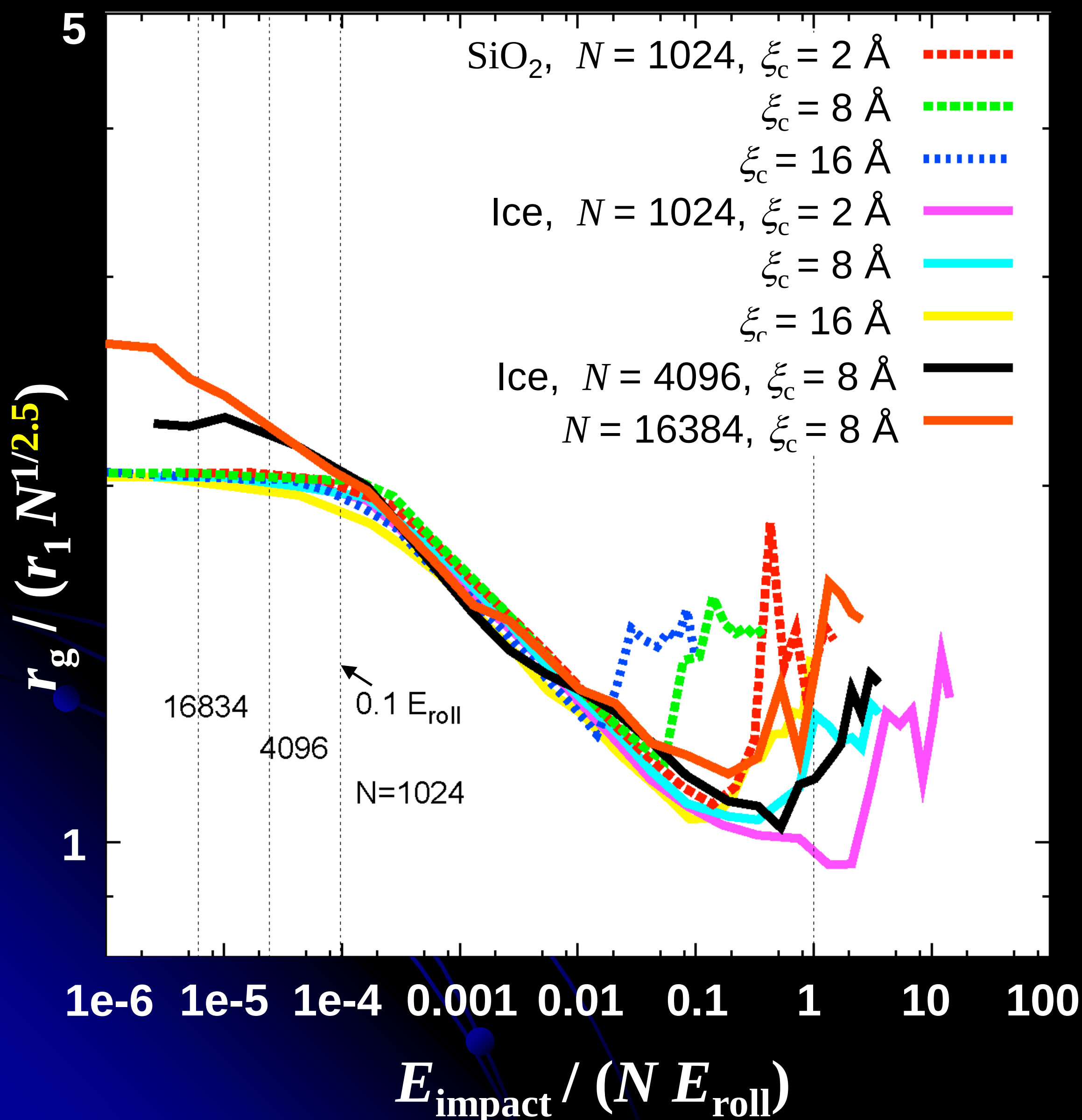
d_c: fractal dimension of max. compression

✓Scaled by

$E_{impact} / (N\, E_{roll})$

$$r_1 N^{\frac{1}{2.5}}$$

Gyration radius r_g : *compression process*



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$E_{impact} / (N E_{roll})$

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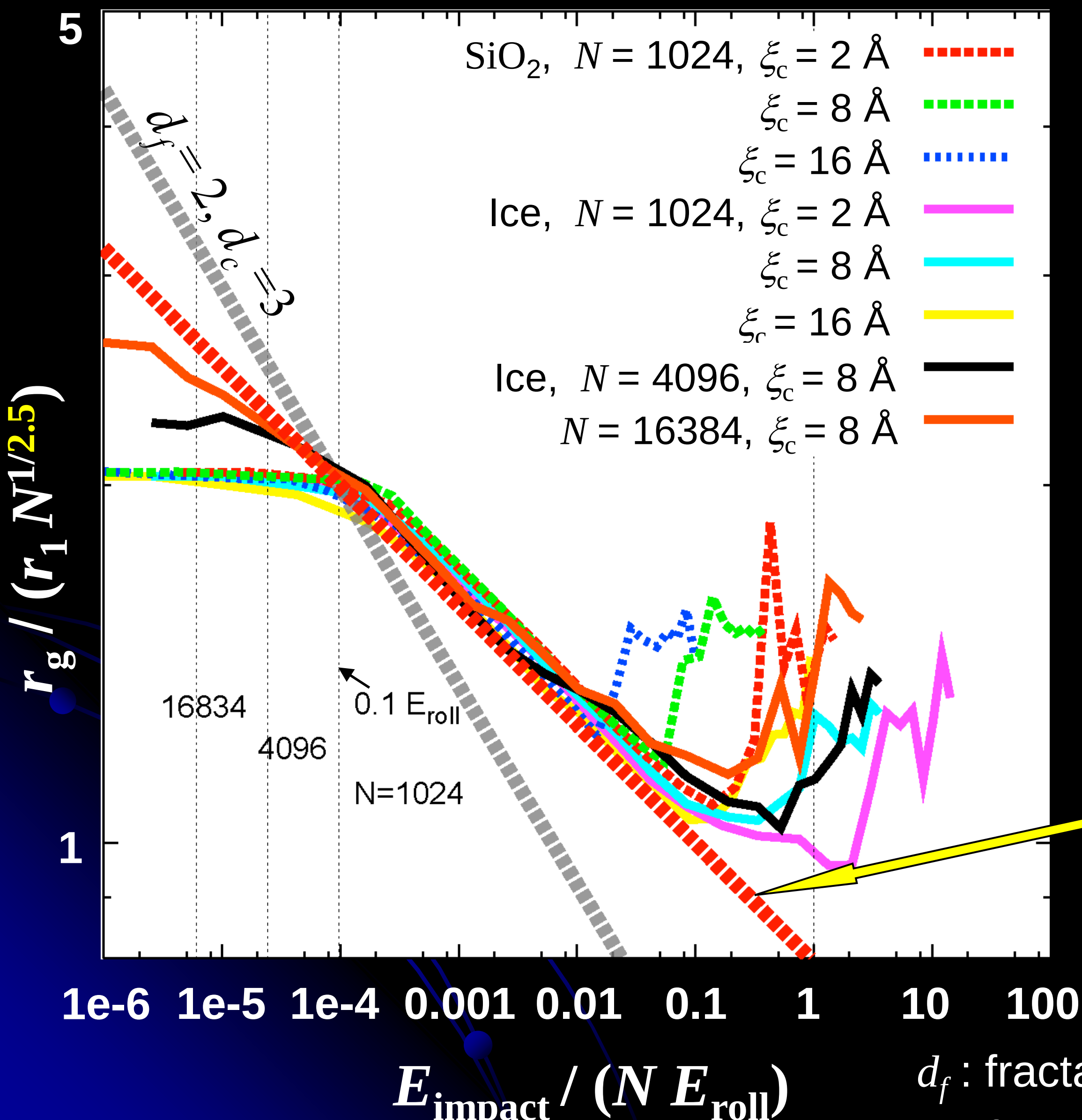
Gyration radius r_g : *compression process*



✓Scaled by

$E_{impact} / (N E_{roll})$

✓r_g is normalized by

$$r_1 N^{\frac{1}{2.5}}$$

✓Not fully compressed

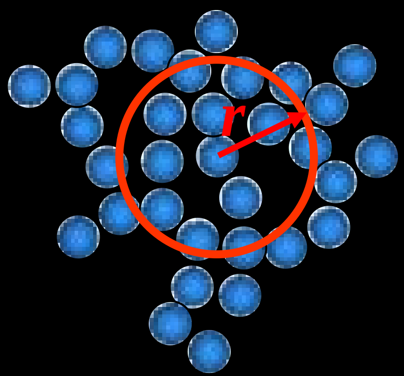
$$\frac{r_g}{r_1 N^{1/2.5}} \approx 0.8\left(\frac{E_{impact}}{N E_{roll}}\right)^{-0.1}$$

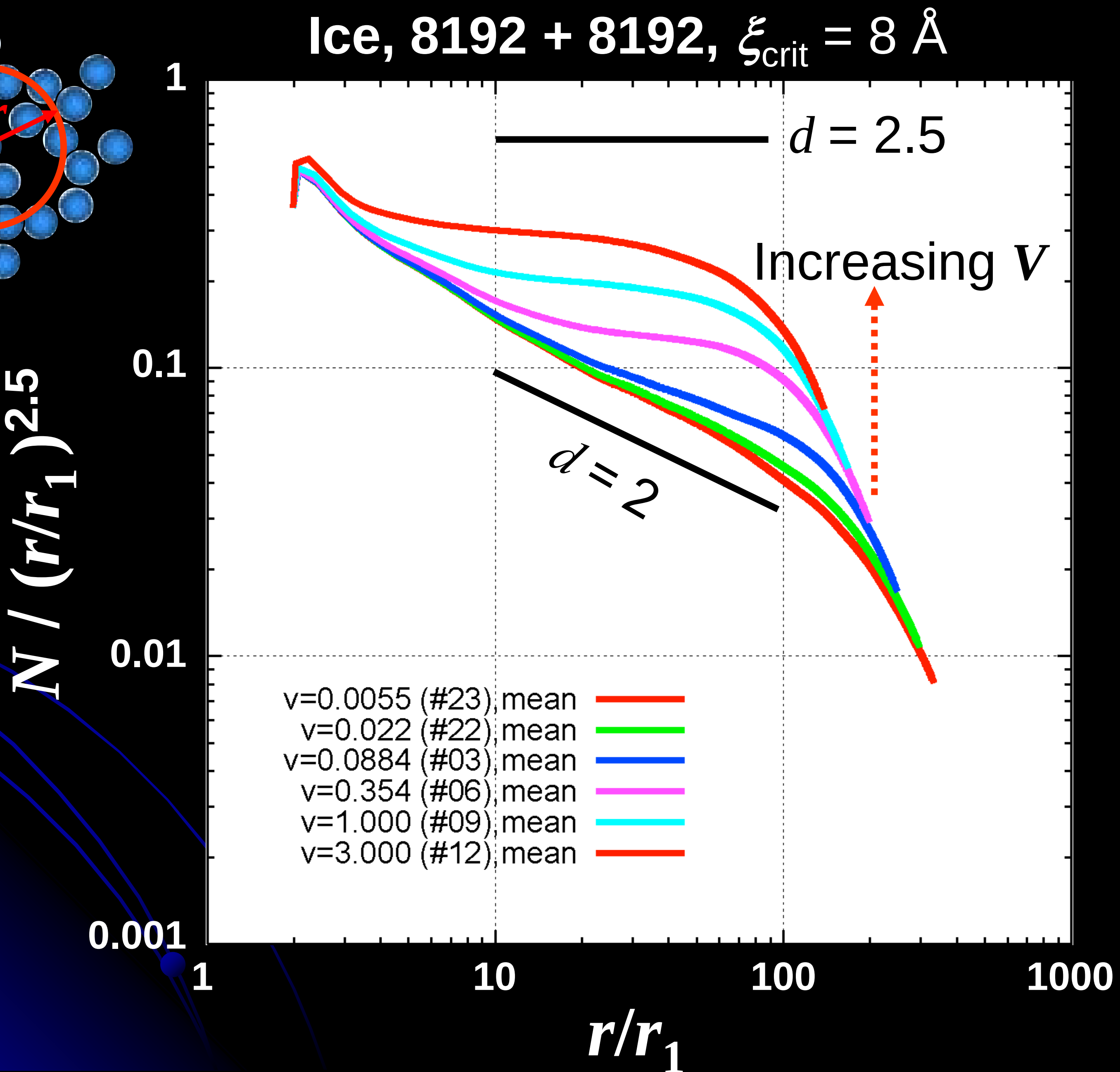
($d_f = 2$, $d_c = 2.5$)

d_f : fractal dimension of BCCA

d_c : fractal dimension of max. compression

The number of particles $N(<r)$ within r in an aggregate



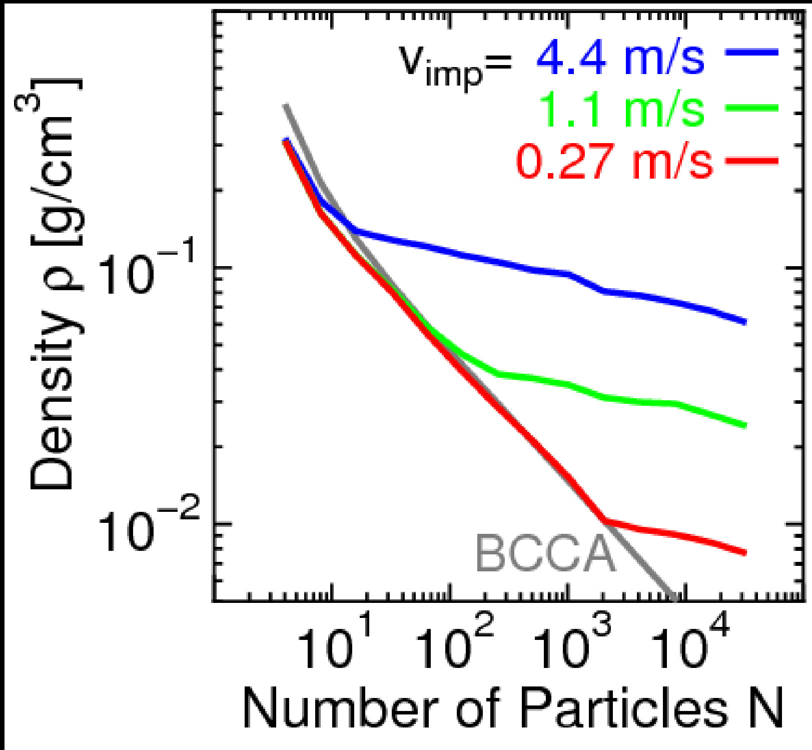


Successive collisions in a BCCA mode

Suyama et al. 2008

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

- ✓Fractal dimension ~2.5
- ✓Decrease in density



Summary of Compression Process

- 3D BCCA clusters ($d_f \sim 2$) are not fully compressed
  - Fractal dimension for max. compression : $\boldsymbol{d_c \sim 2.5}$
  - Gyration radius : $r_g \sim r_1 N^{\frac{1}{2.5}} [\, E_{\rm impact} / (n_k E_{\rm roll}) \,]^{-0.1}$

$$\left(r_g \sim r_1 N^{1/d_c} [\, E_{\rm impact} / (N E_{\rm roll}) \,]^{-(1/d_f - 1/d_c)} \right)$$

- Successive collisions also lead to $\boldsymbol{d_c \sim 2.5}$

  The results for single collisions are applicable.

Collisions between BPCA clusters

: High-velocity collisions

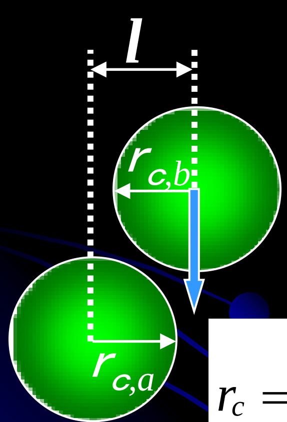
Initial Conditions and Parameters

Collisions of BPCA clusters

Results are averaged

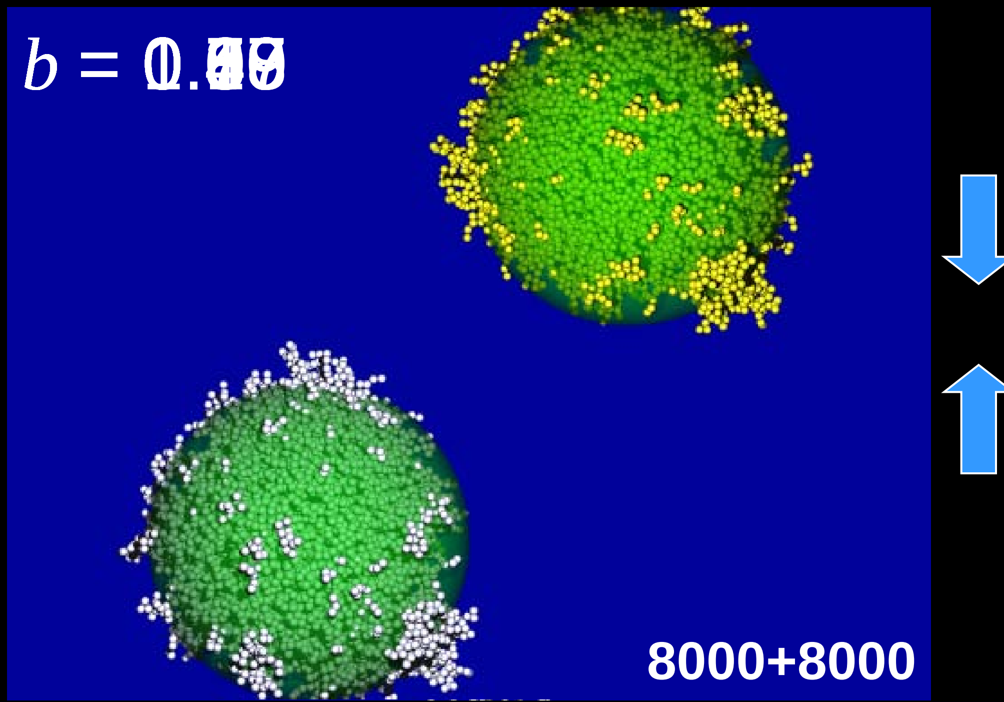
✓ BPCA clusters are:

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



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

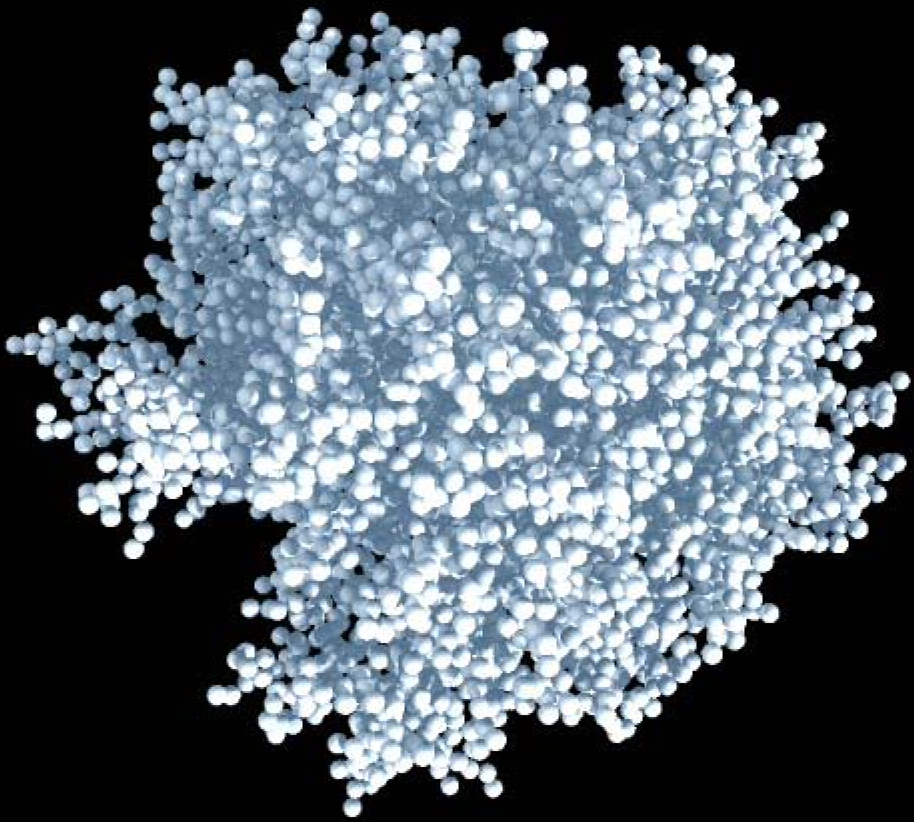
$$r_c = \sqrt{\frac{5}{3}\frac{1}{N}\sum (x_i - x_G)^2}$$



✓ Ice ($E = 7.0 \times 10^{10}$ Pa, $\nu = 0.25$, $\gamma = 100$ mJ/m^2, $R = 0.1\mu$m) , critical rolling displace. $\xi_{crit} = 8$Å

✓ Impact velocity $v_{imp} = 6 - 260$ m/s

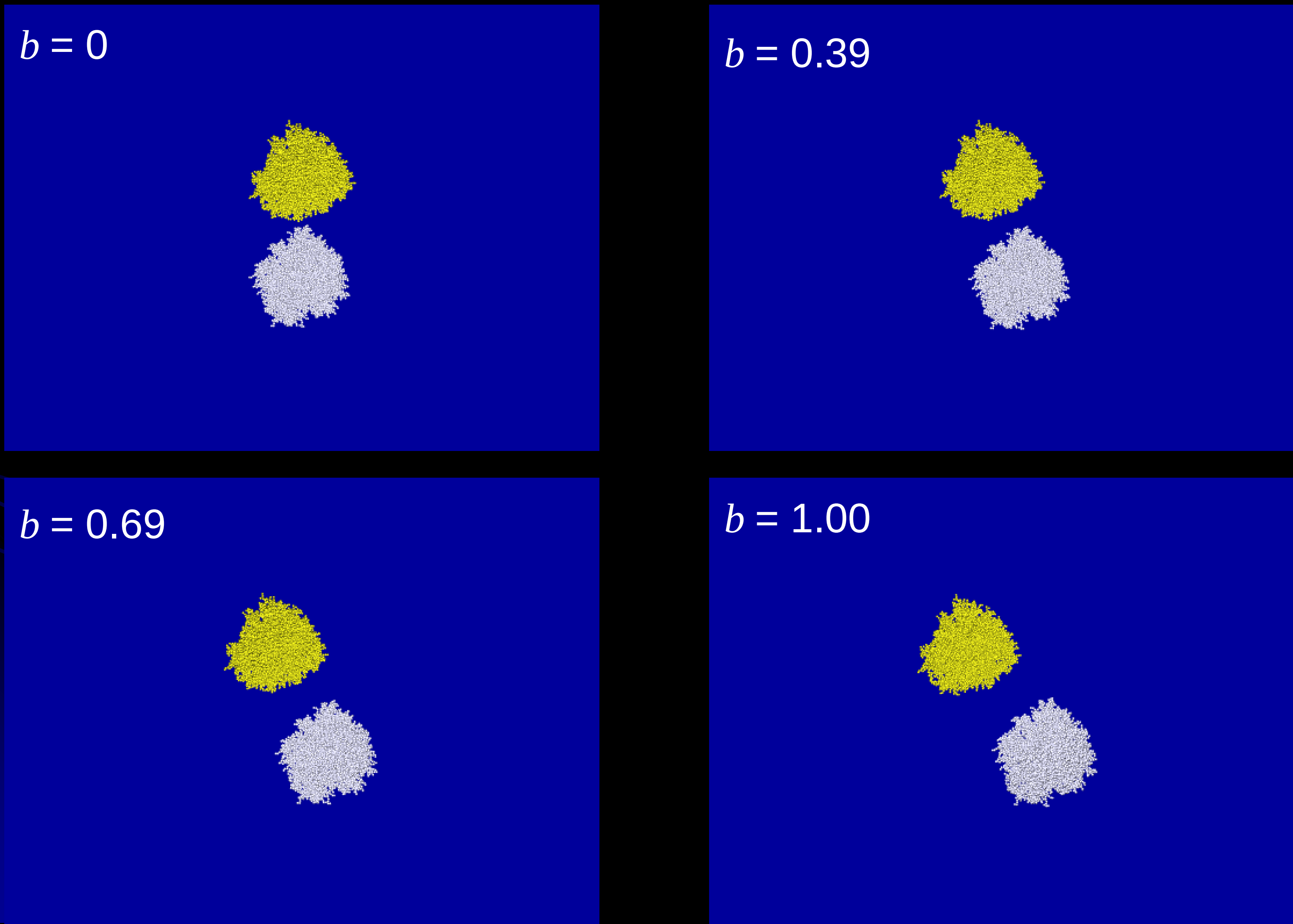
A collision of BPCAs
8000+8000 ice particles ($r=0.1\mu m$, $\xi_c = 8Å$)
Collision velocity = 57 m/s



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

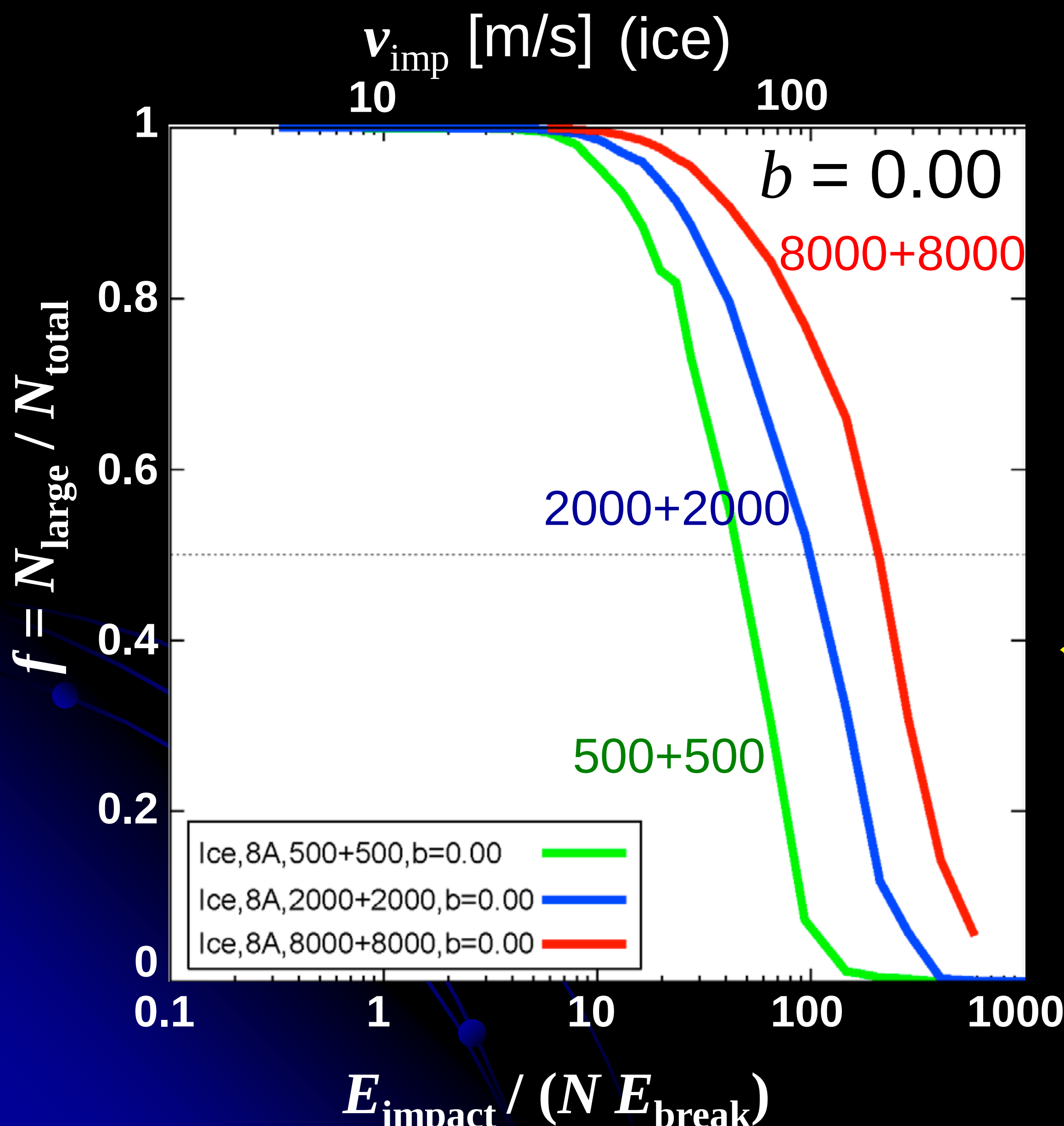
Collisions of BPCA clusters

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



Degree of Disruption: Growth Efficiency

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



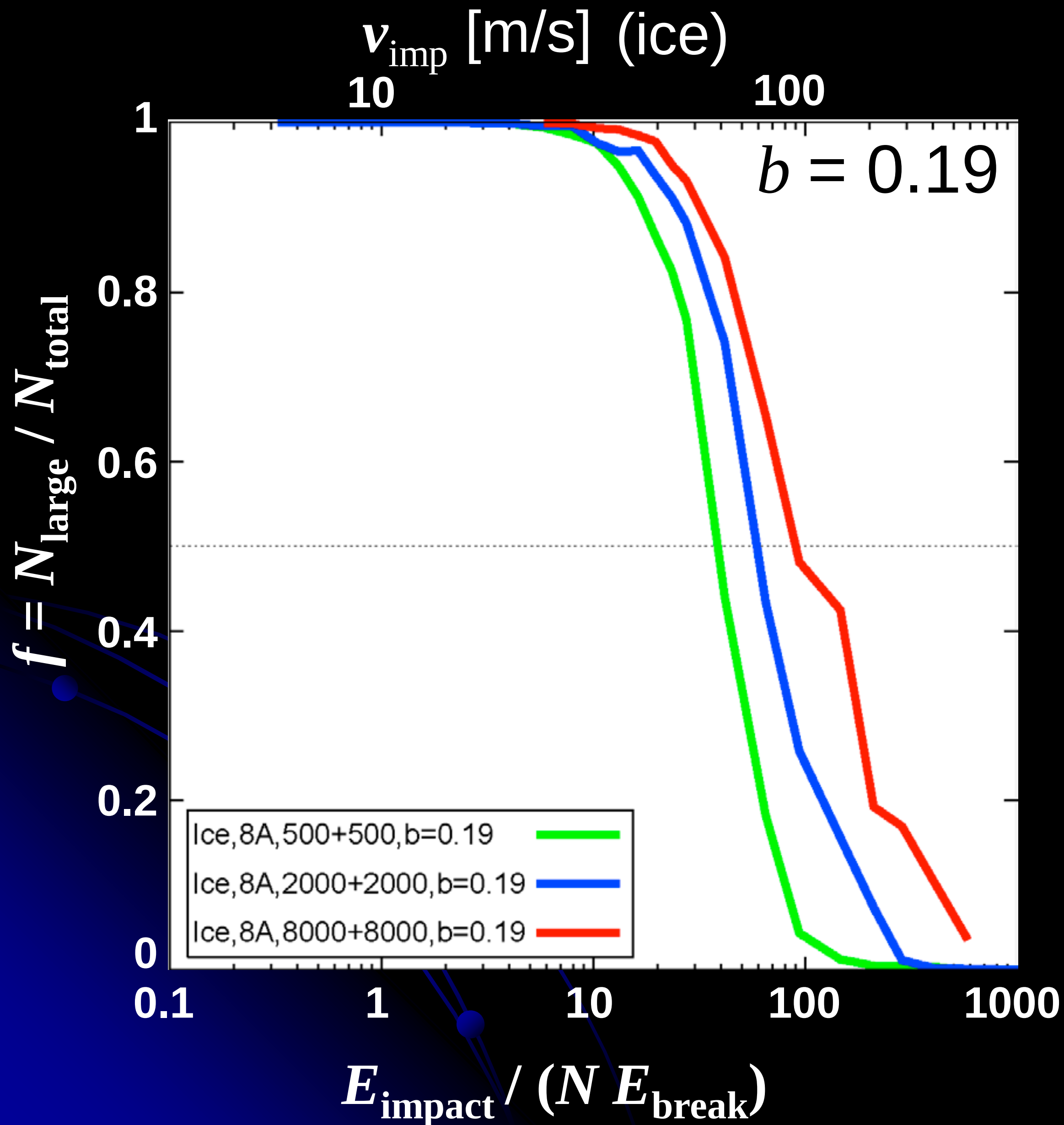
$f \equiv N_{large} / N_{total}$

: growth efficiency

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

✓dependent on N

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



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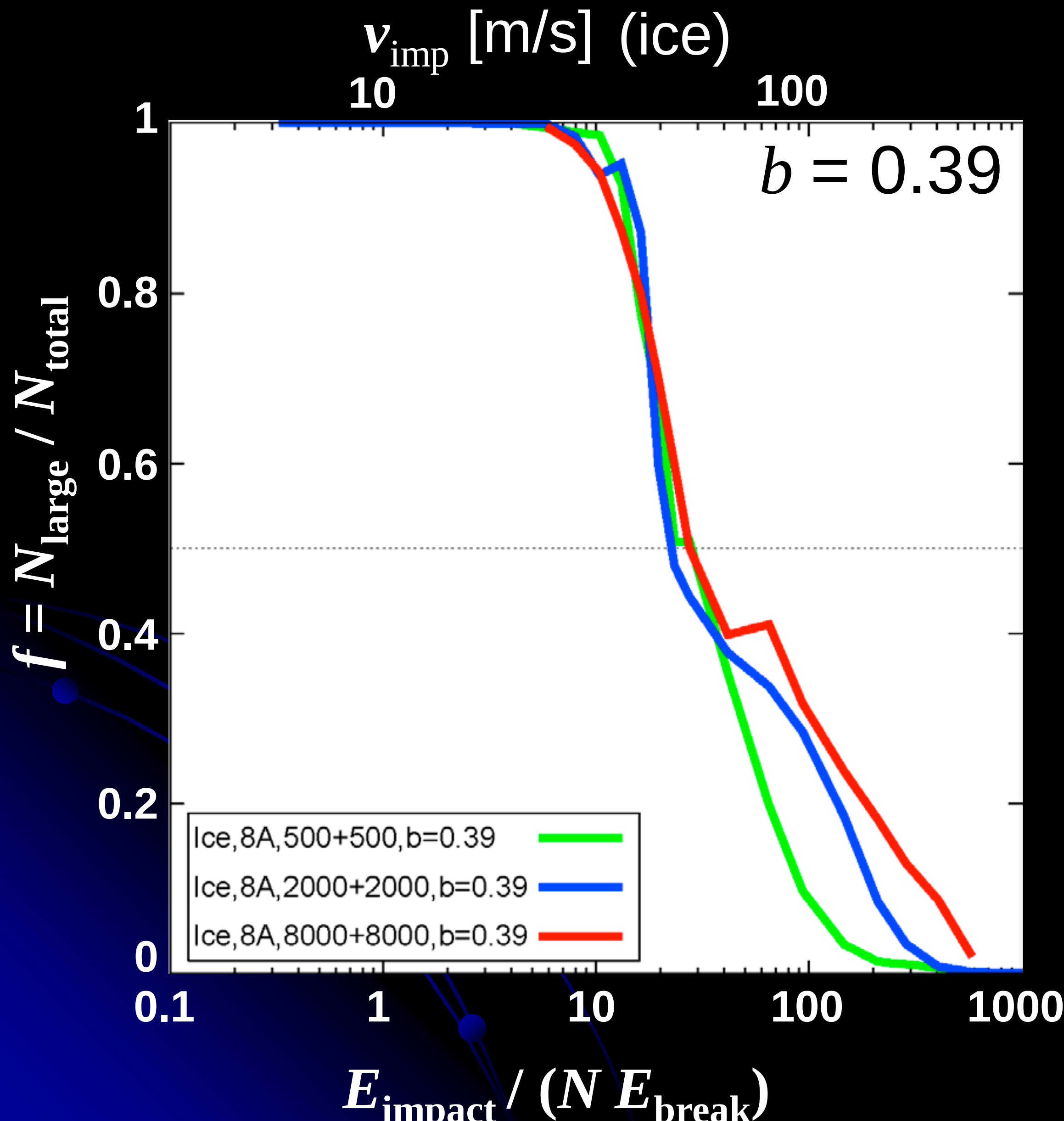

$f \equiv N_{\mathrm{large}} / N_{\mathrm{total}}$

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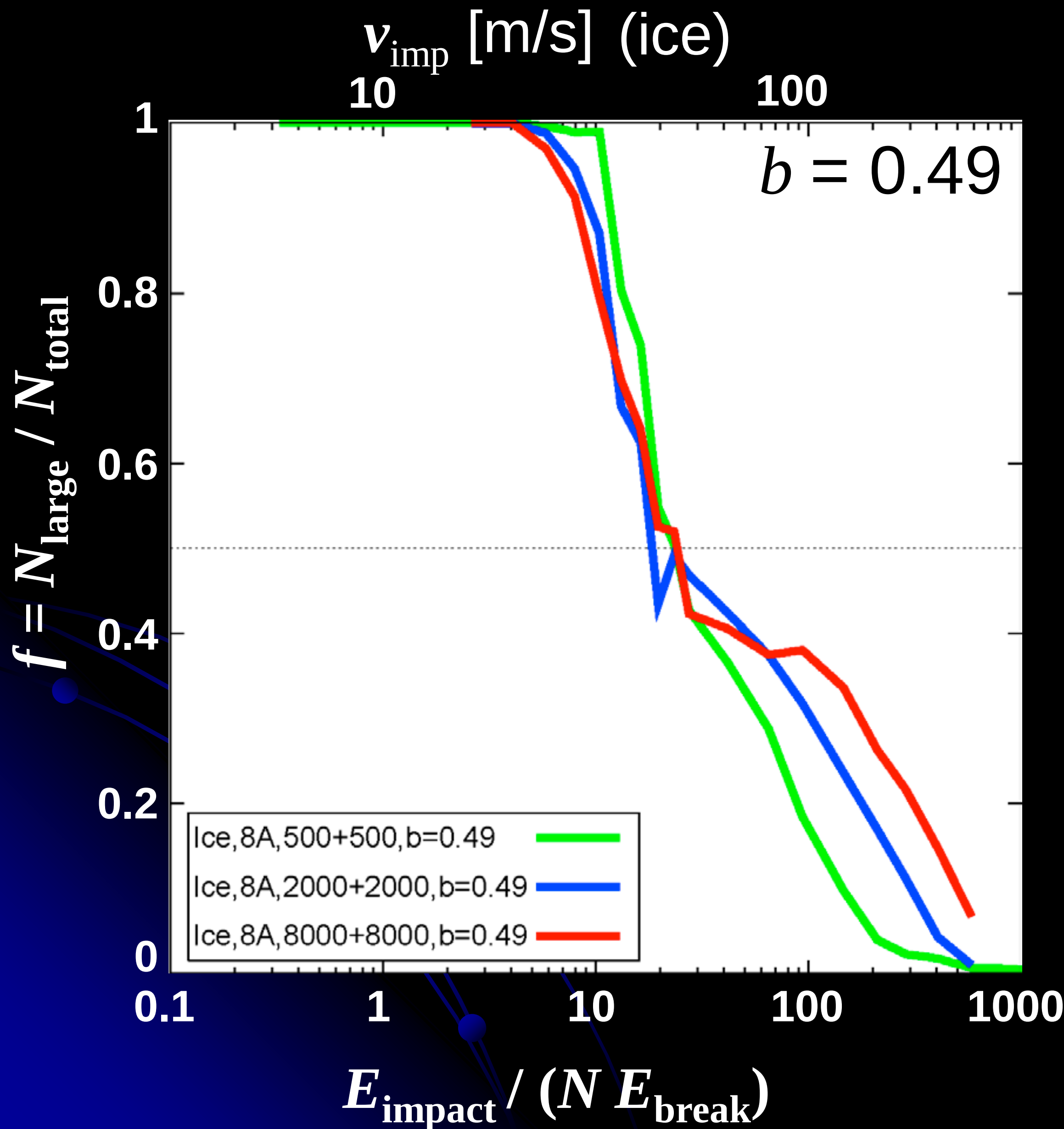

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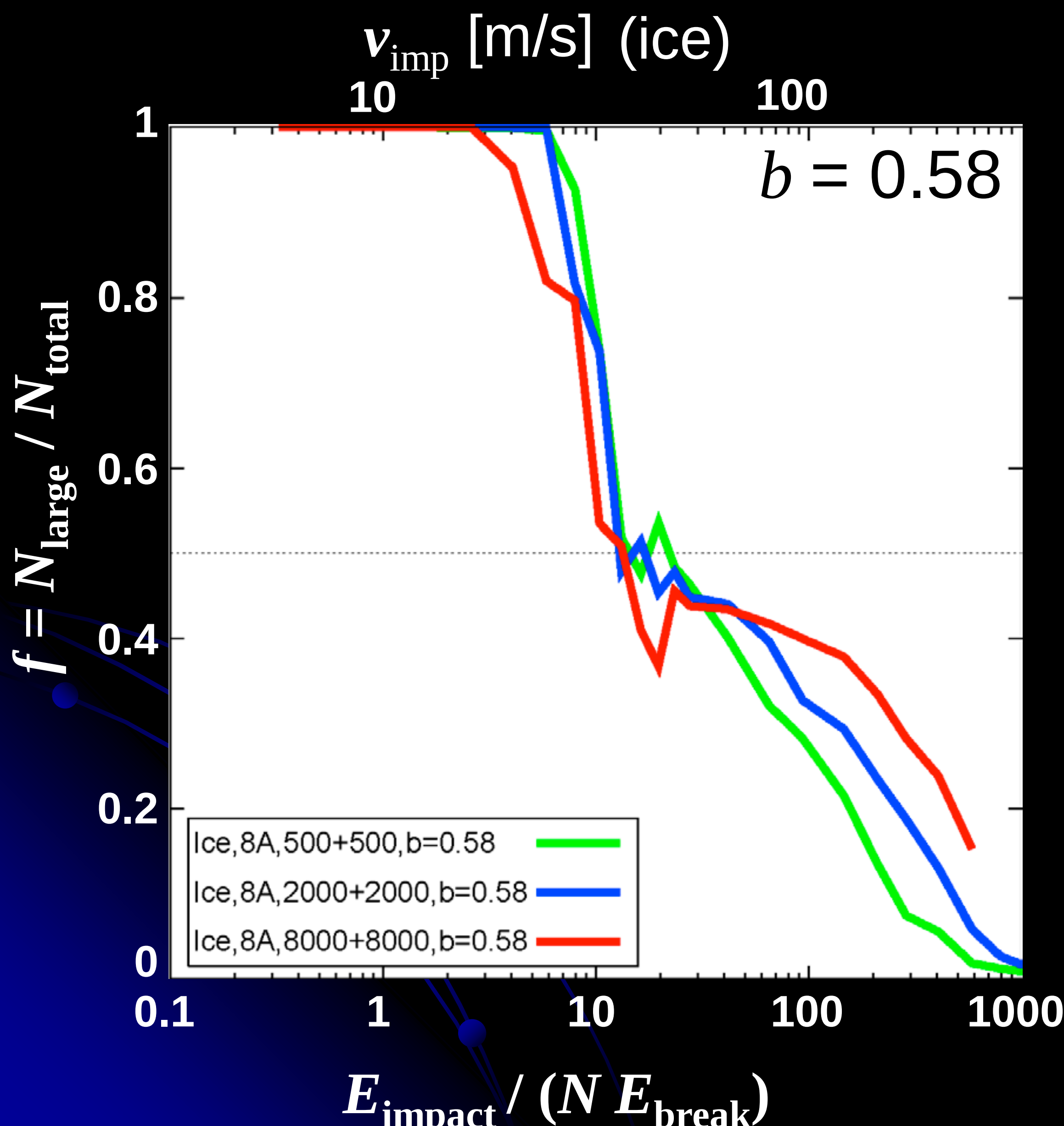

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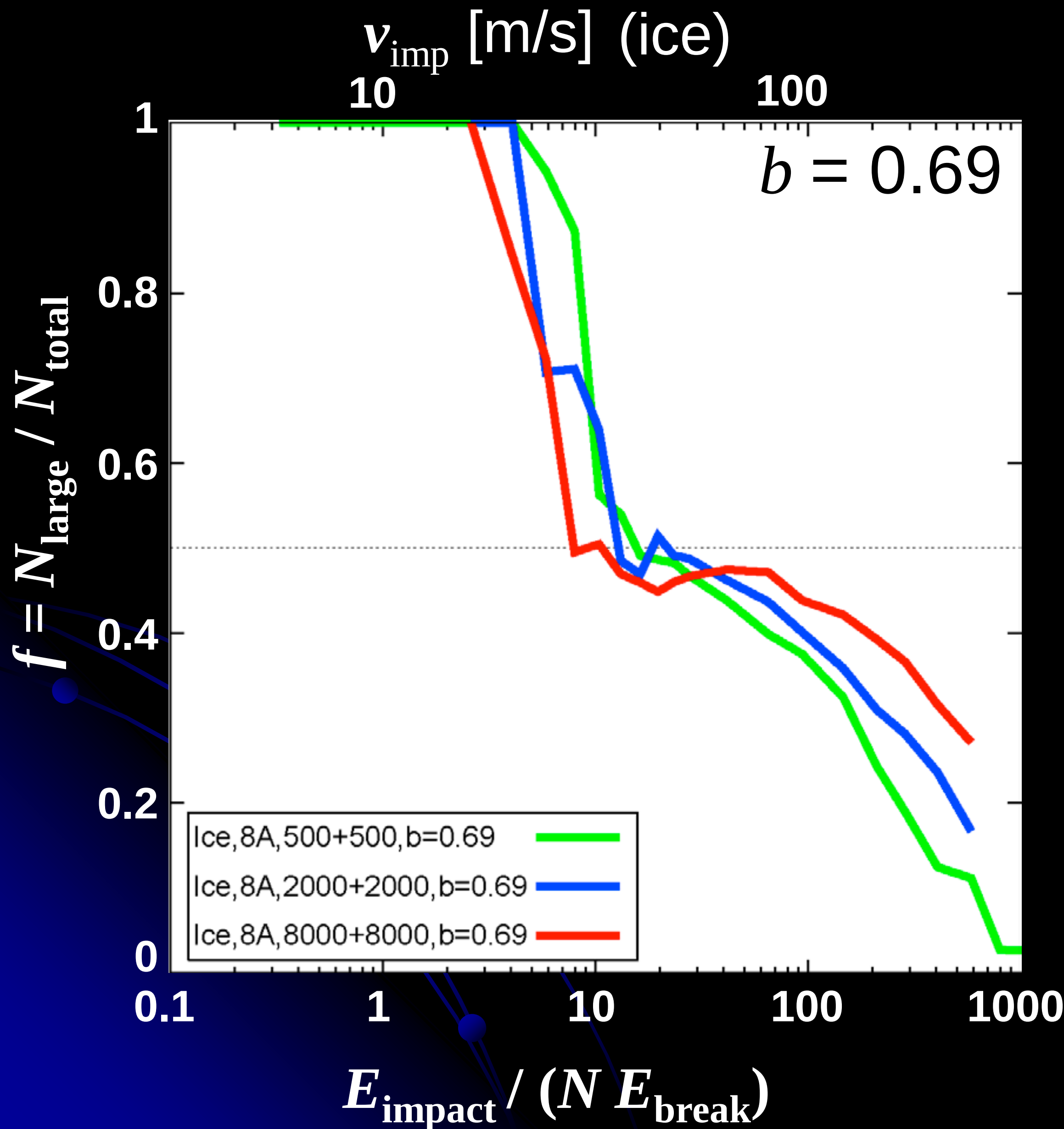

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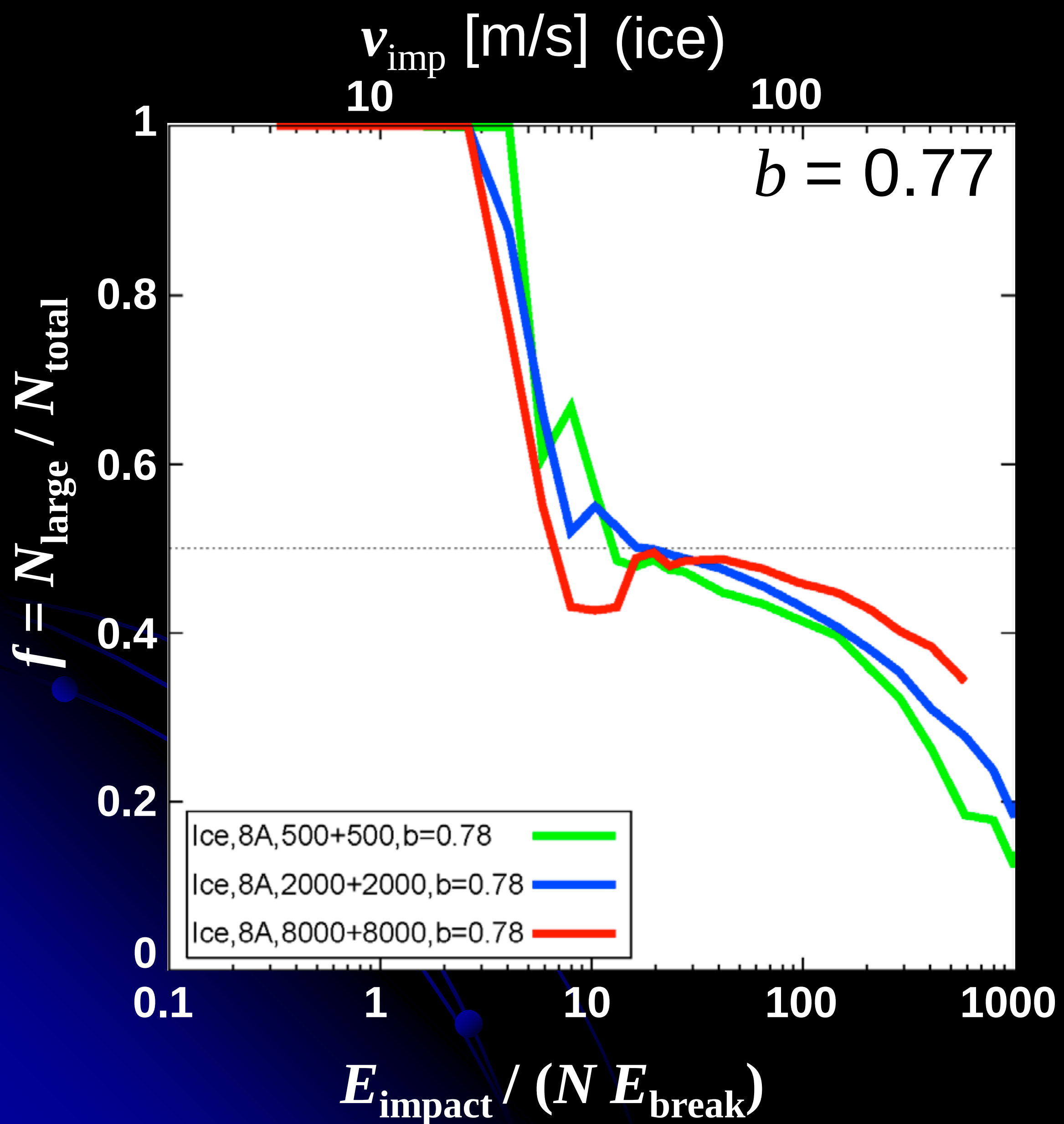

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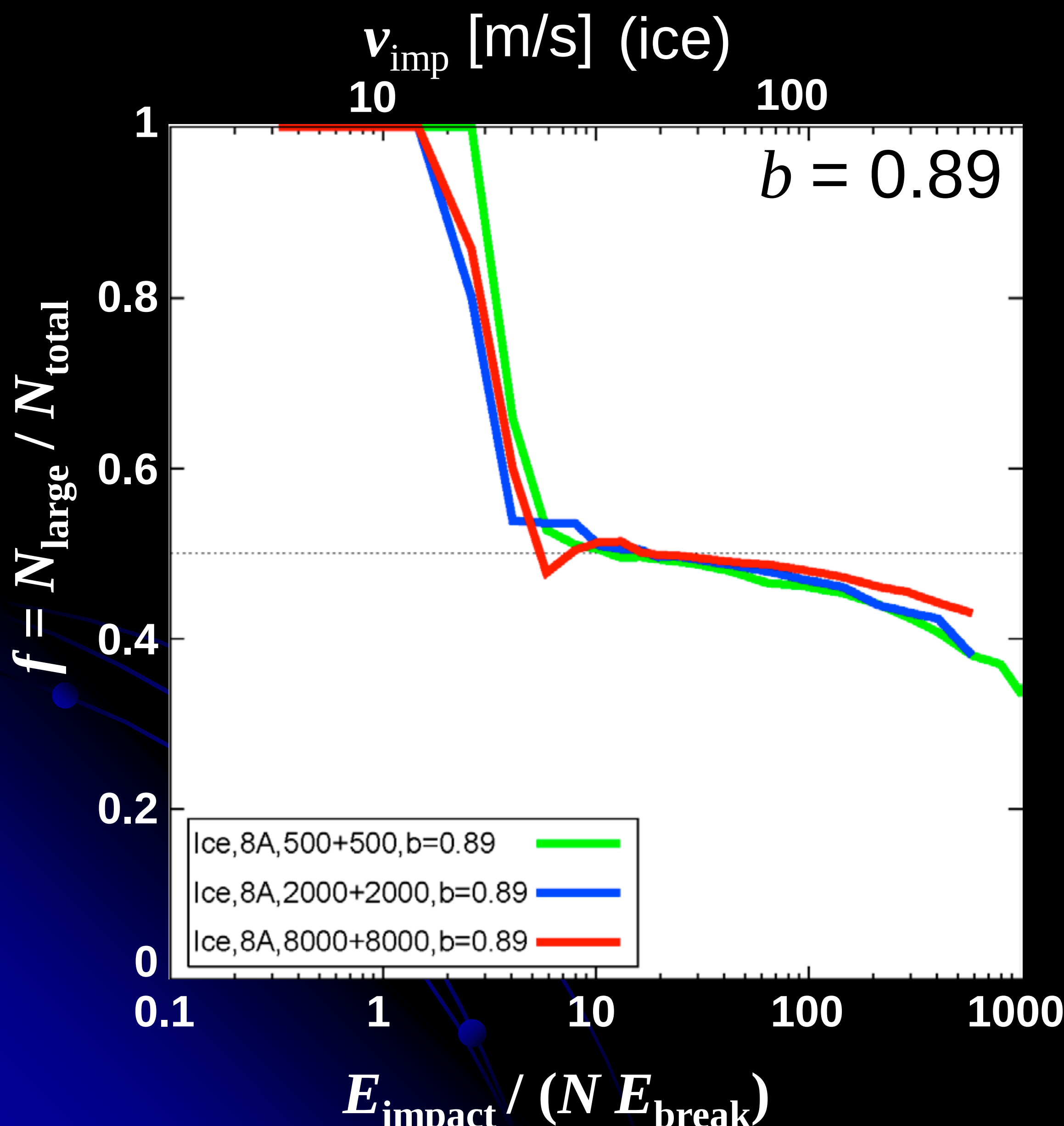

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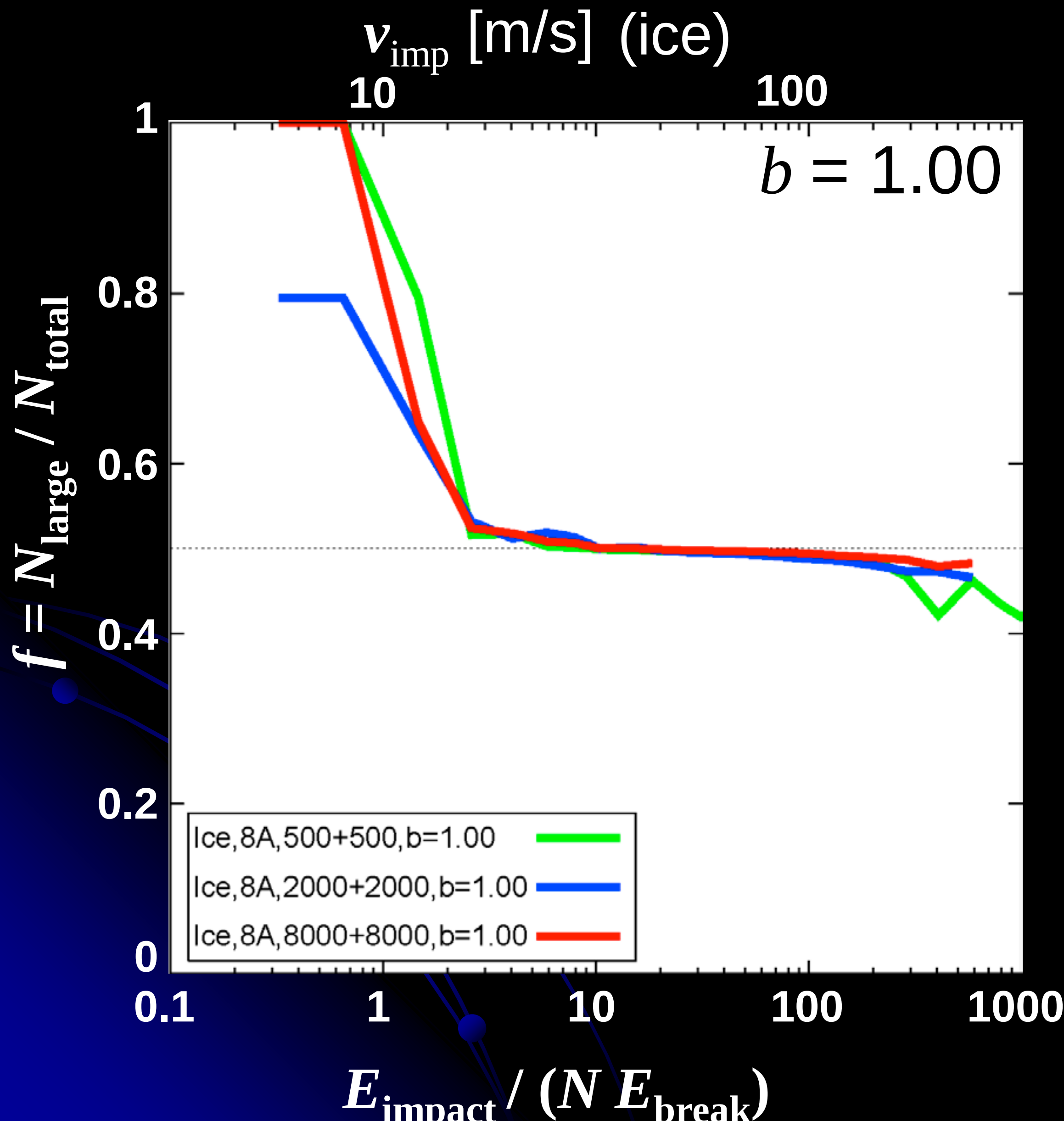
Largest fragment mass N_{large}: *growth efficiency*



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

: growth efficiency

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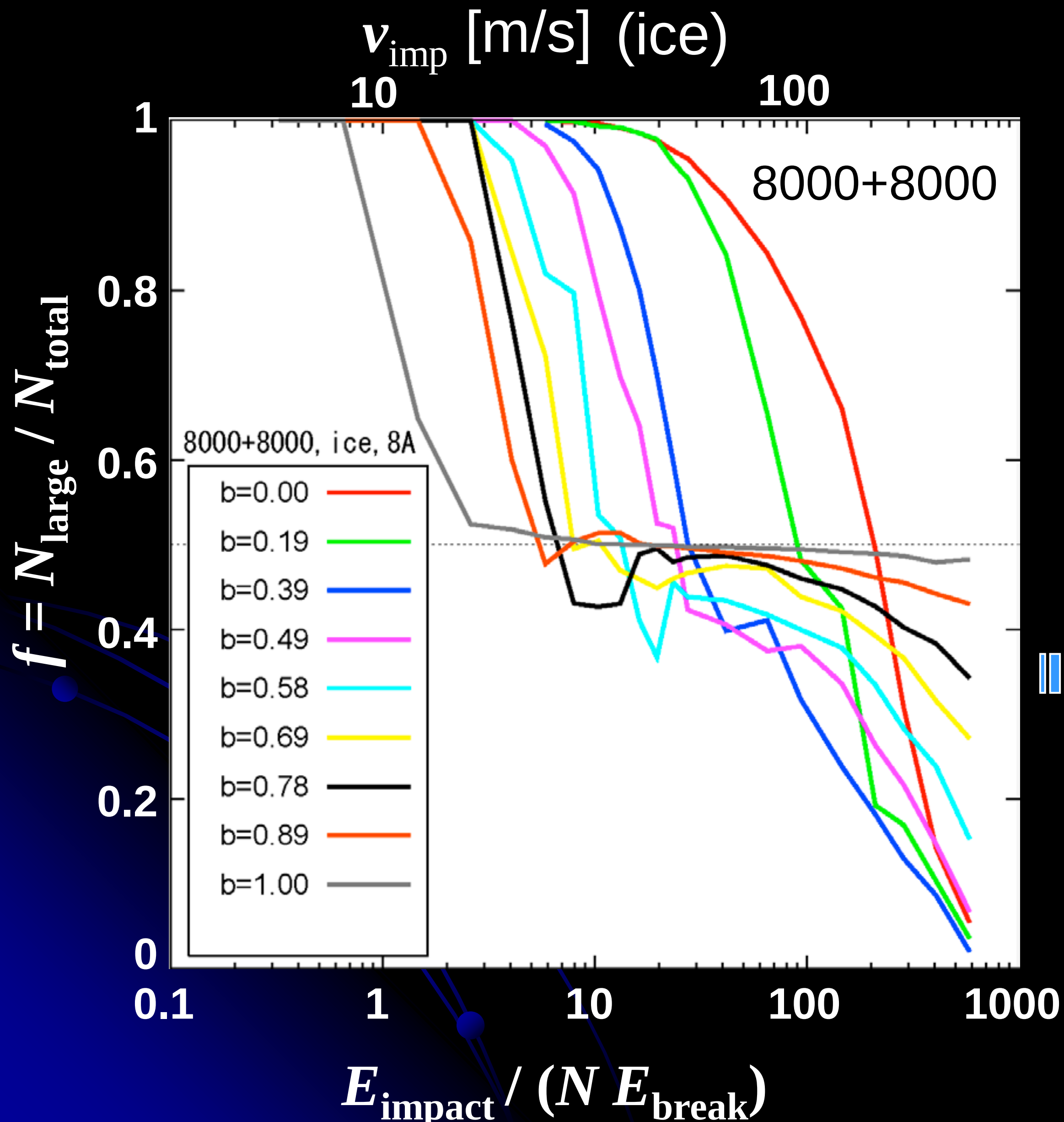
- $f < 0.5$ → - growth

✓Offset collisions

⬇

independent of N

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



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

: growth efficiency

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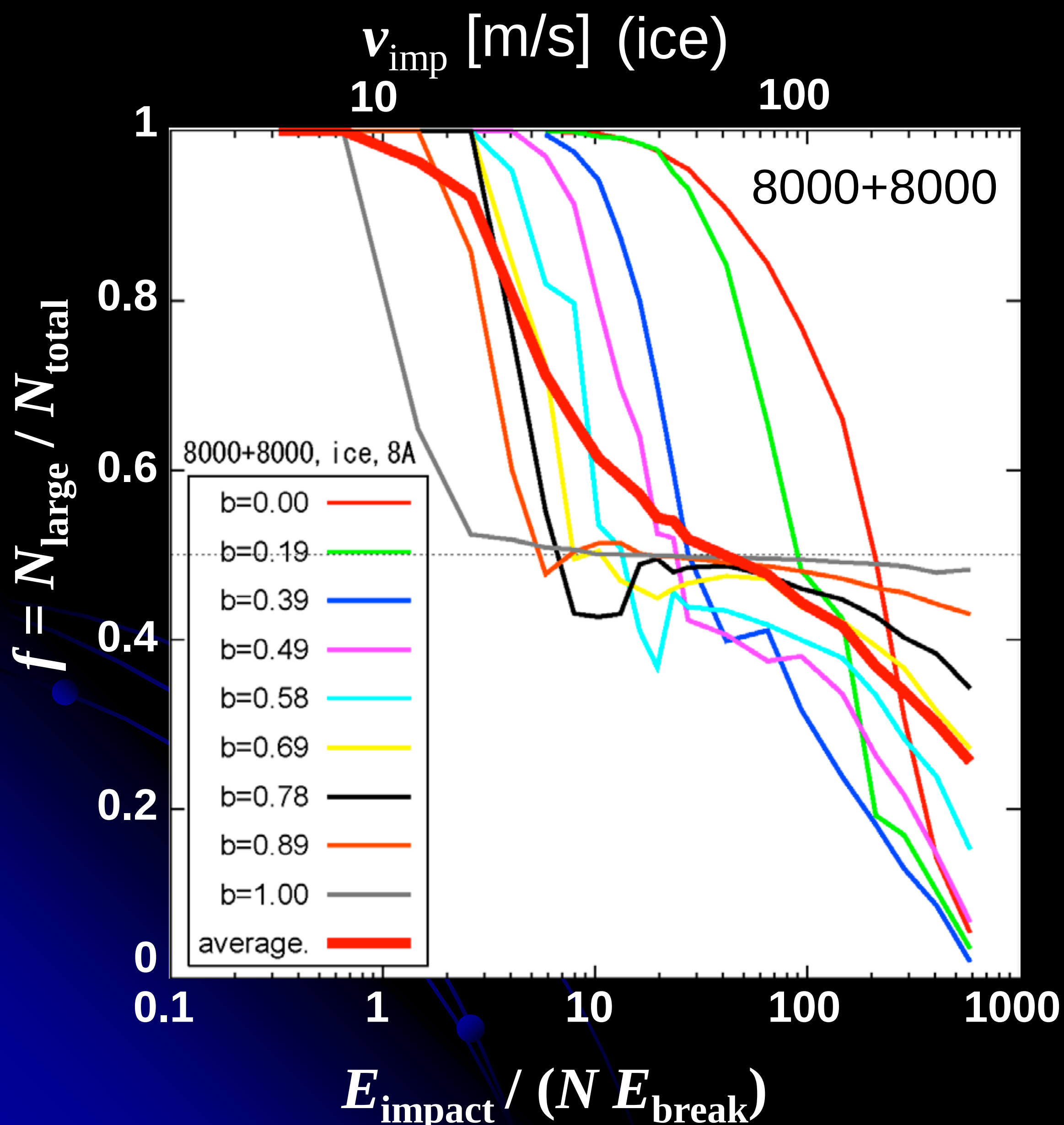
- $f < 0.5 \rightarrow$ - growth

⇒ Average weighted by b^2

Growth efficiency averaged



Averaged for b^2

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: growth efficiency

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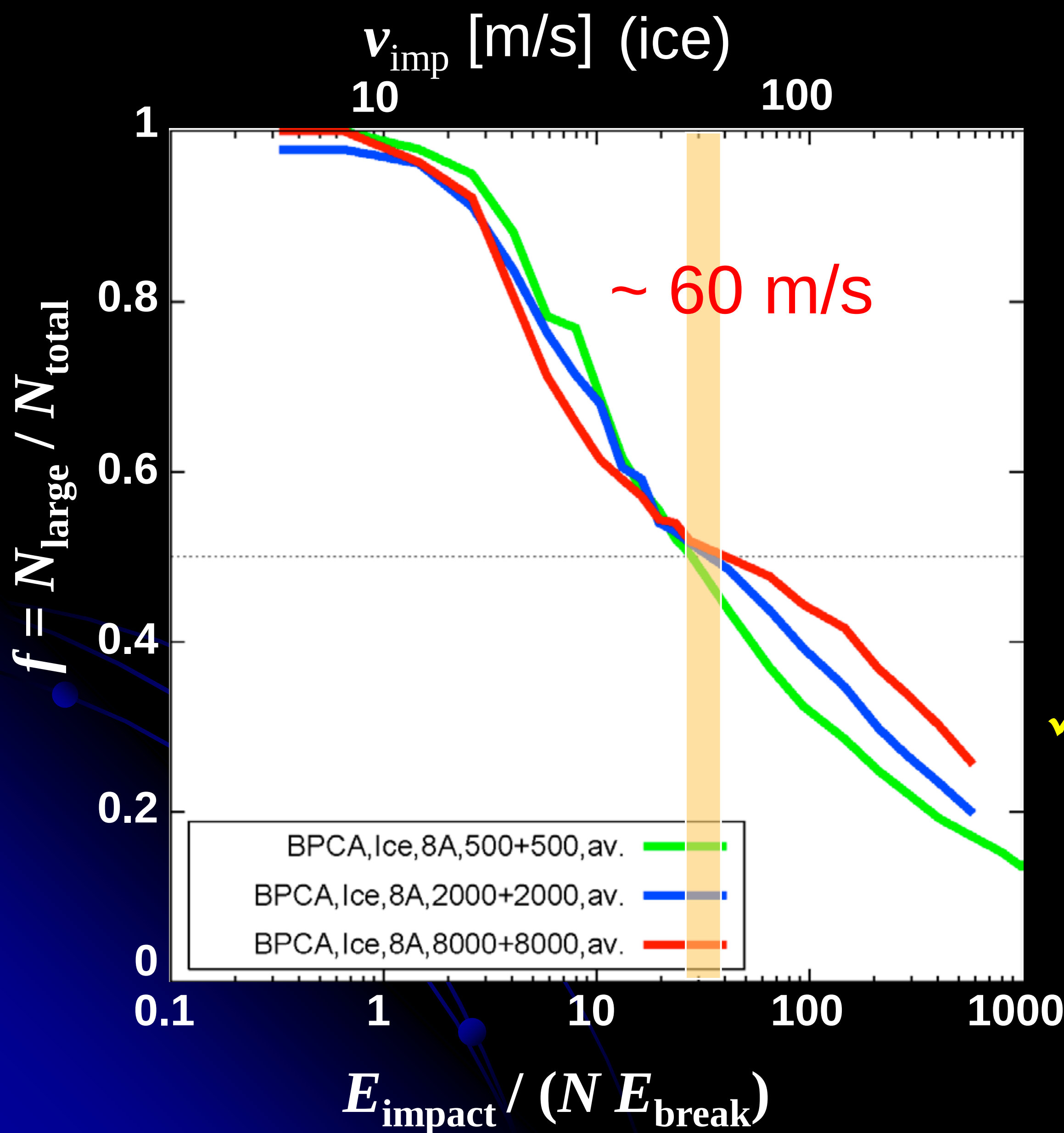
$f < 0.5 \rightarrow$ - growth

Growth efficiency averaged



Averaged for b^2

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

: growth efficiency

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

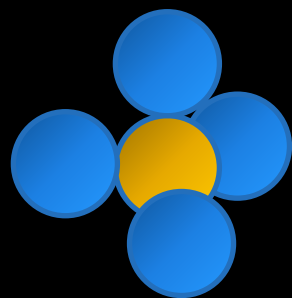
✓small dependence on N

Degree of compression: Coordination number

Coordination number N_c

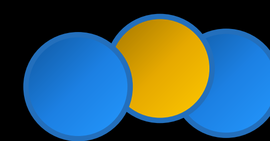
Number of particles in contact with a particle

e.g.,



$N_c = 4$

$N_c = 2$ *for BCCA and BPCA*



Max. $N_c = 12$ *for close-packing*

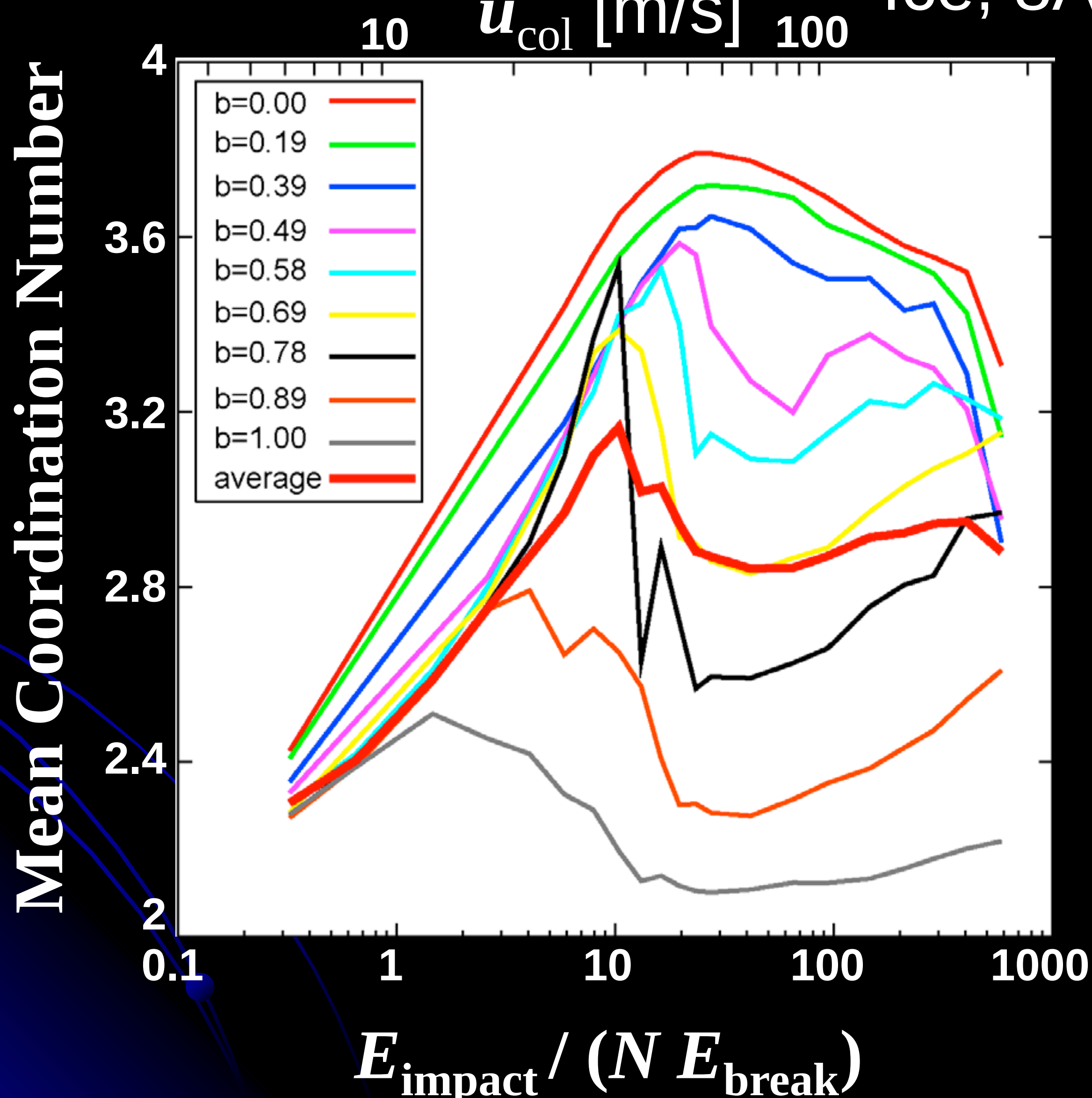
An index of compression:

The more compact are aggregates, the larger N_c is.

What value of N_c is achieved at BPCA collisions?

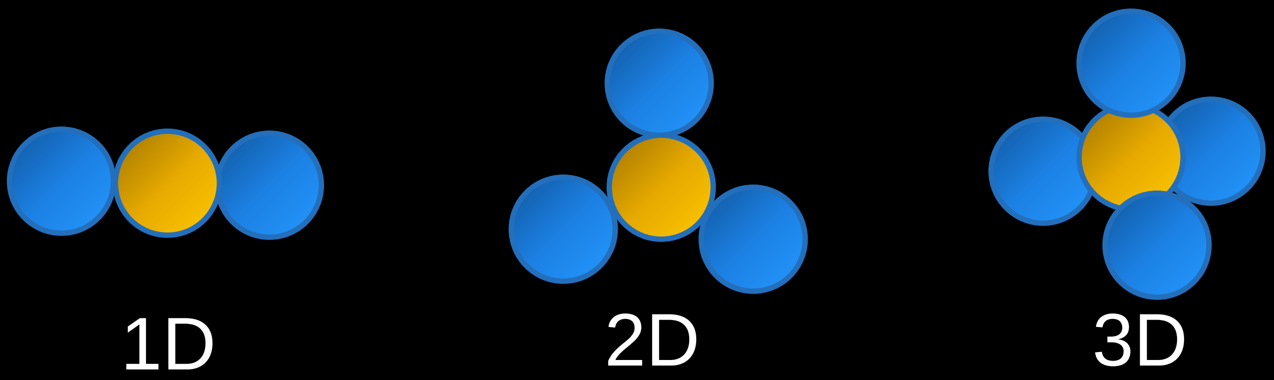
Coordination number N_c @ BPCA collisions

Ice, 8Å, 8000+8000



Why $N_c = 4$?

Particles are stable enough with $N_c = 4$ in 3D:



Summary

- Dust aggregates remain fluffly only through collisions.

  Fractal dimension ~ 2.5

  Coordination number < 4

  Very fluffy planetesimals could be formed !?

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

  Other compression processes are required.

- Icy aggregates can grow at collision velocity ~ 50 m/s.

  Planetesimals can be formed through collisions of dust.