To be, or not to be: that is the question of dust aggregates

衝突シミュレーションによるダストの合体成長過程の理解

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Now, I'm in PERC/Chitech.

Planetary Exploration Research Center:

- Founded in April, 2009 at Chiba Institute of Technology

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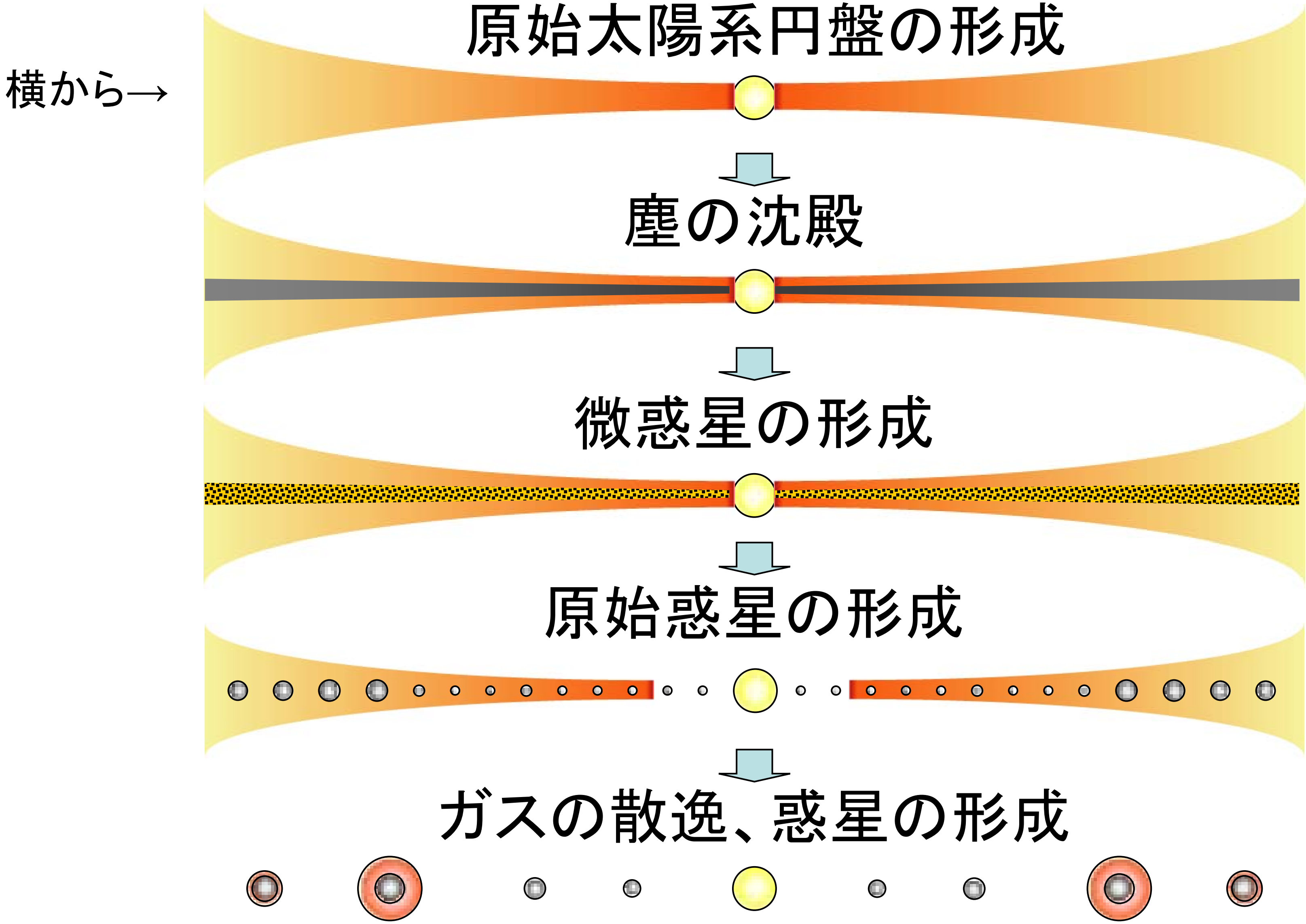
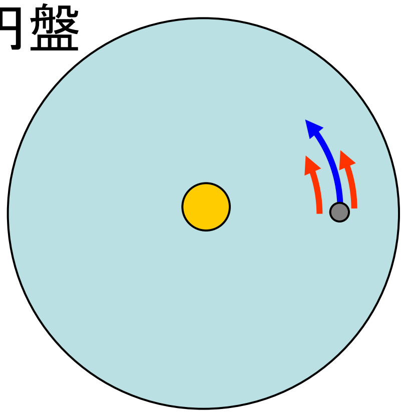
太陽系形成の標準モデル



微惑星をつくらなきゃ

上から見た円盤



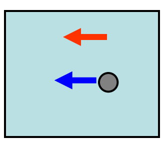
ガス：ゆっくり回る（圧力勾配力のため）

塵：速く回る　　速度差~$\eta\, v_k$ ~$10^{-3}\, v_k$

(v_k: ケプラー速度)

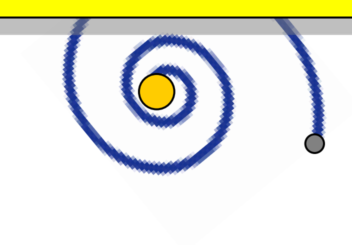
塵はガス抵抗（向かい風）を受ける

- 塵が十分小さい（<～mm）　→　ガスとともに回る

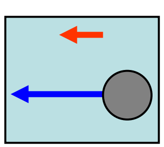


短時間（10^2~10^3年）で成長させる必要がある

- 塵が少々大きい（～1m）→ガス抵抗で失速
  →太陽へ落下



- 塵が十分成長（>100m）　→　ガスと関係なく回る
  （ガス抵抗効かなくなる）



微惑星をつくらなきゃ

上から見た円盤

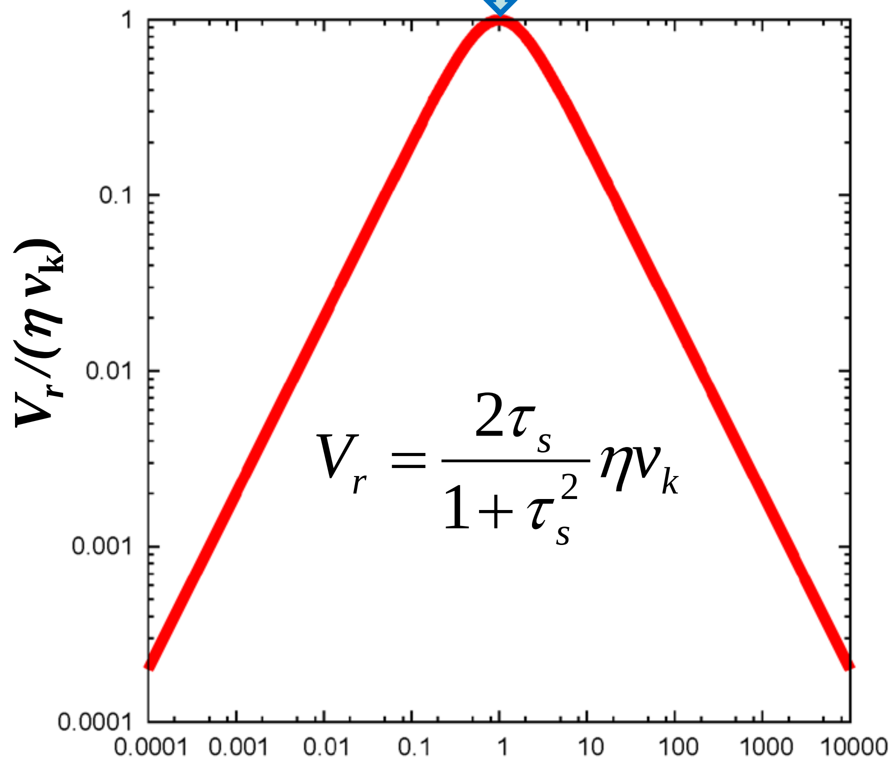
(圧力勾配力のため)

度差~$\eta\, v_k$ ~$10^{-3}\, v_k$

(v_k: ケプラー速度)

かい風)を受ける

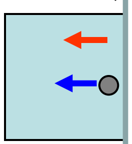
~50m/s@林モデル



$\tau_s = t_{stop}\Omega_k \propto D$ or D^2

$$\frac{\text{ガス抵抗緩和時間}}{\text{ケプラー時間}}$$

➤塵が十

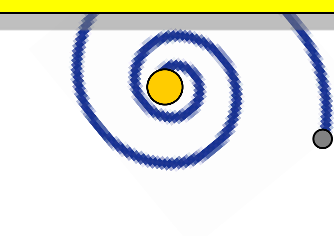


ともに回る

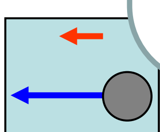
させる必要がある

➤塵が少

失速



➤塵が十



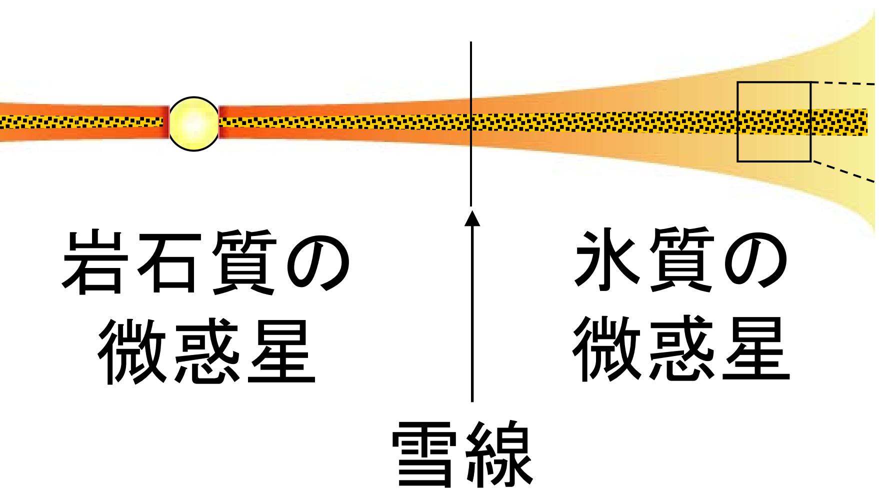
関係なく回る

ス抵抗効かなくなる)

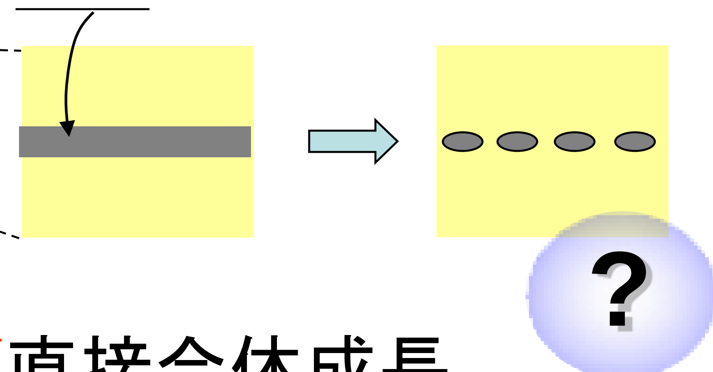
微惑星の形成

● 塵が集まる → 微惑星

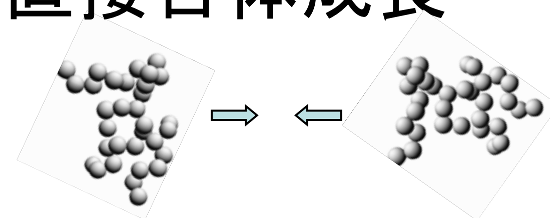
数百億個



✓塵層の自己重力不安定



✓直接合体成長



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？

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!**

Today's Topics:

- Collisional growth and compression of dust aggregates
  - How compact are dust aggregates compressed?

2.5

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

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

50 m/s

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

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

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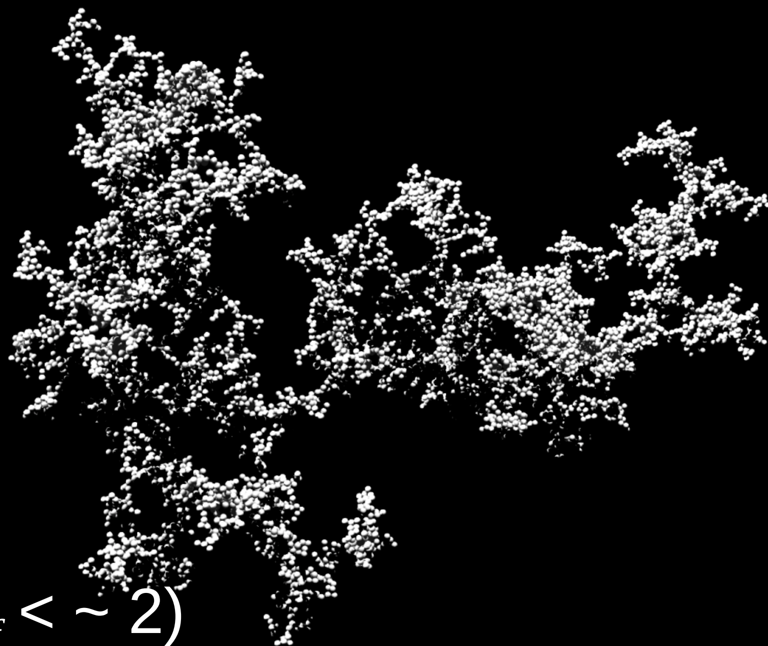
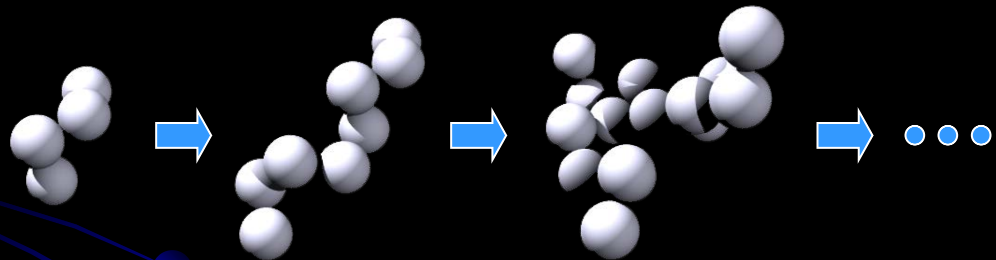
Wada et al. 2010, in preparation

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 $d_f < \sim 2$)

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

BCCA structures are compressed by collisions.

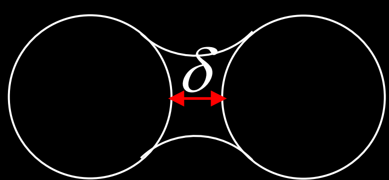
(Dominik & Tielens 1997; Wada et al. 2007, 2008; Suyama et al. 2008)

Grain interaction model

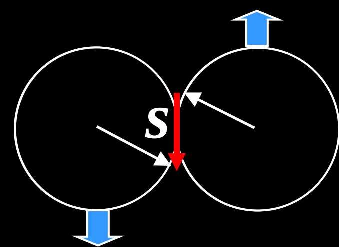
Johnson, Kendall and Roberts (1971)
Johnson (1987), Chokshi et al. (1993)
Dominik and Tielens (1995,96)
Wada et al. (2007)

Elastic spheres having surface energy

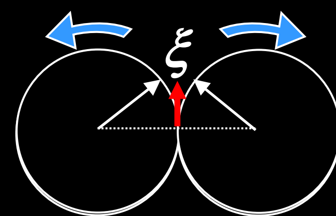
Normal



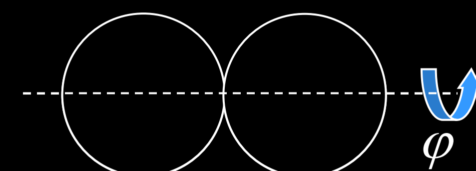
Sliding



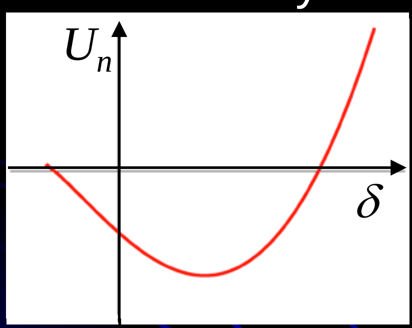
rolling



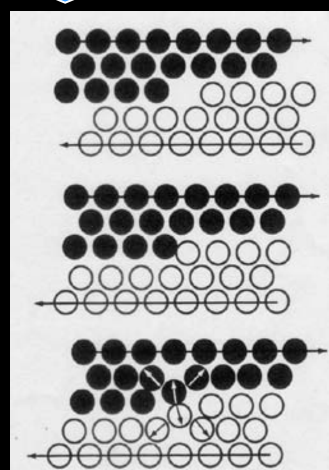
twisting



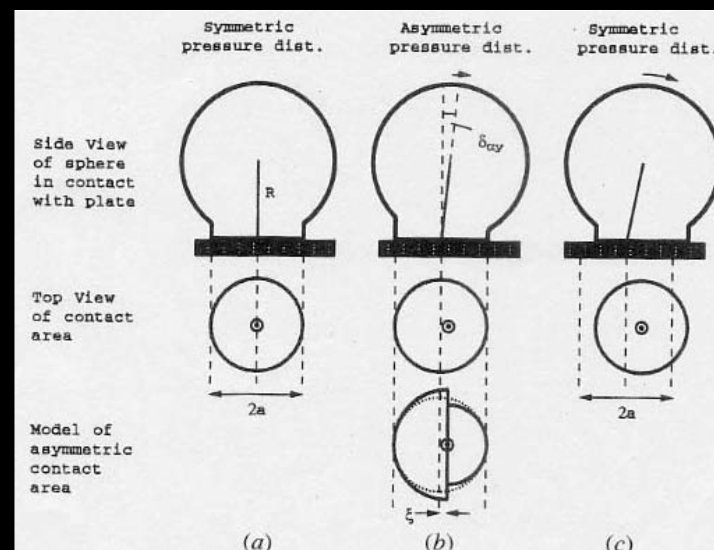
JKR theory



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



(Dominik & Tielens 1996)



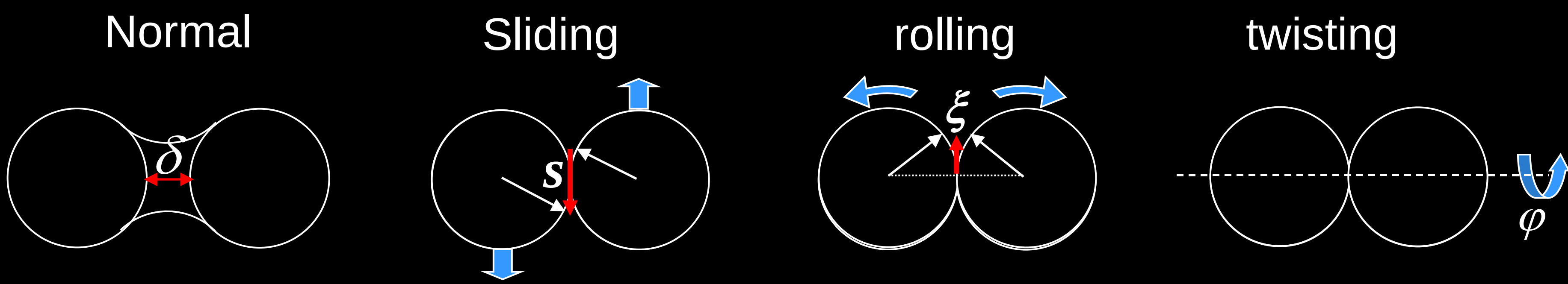
(Dominik & Tielens 1995)

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

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°

A classical 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
```

Confirmed by experiments
(Blum & Wurm 2000)

✓modeling grain interactions seriously

D&T "recipe"

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

Limitations:

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

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

To be compressed, or not to be?

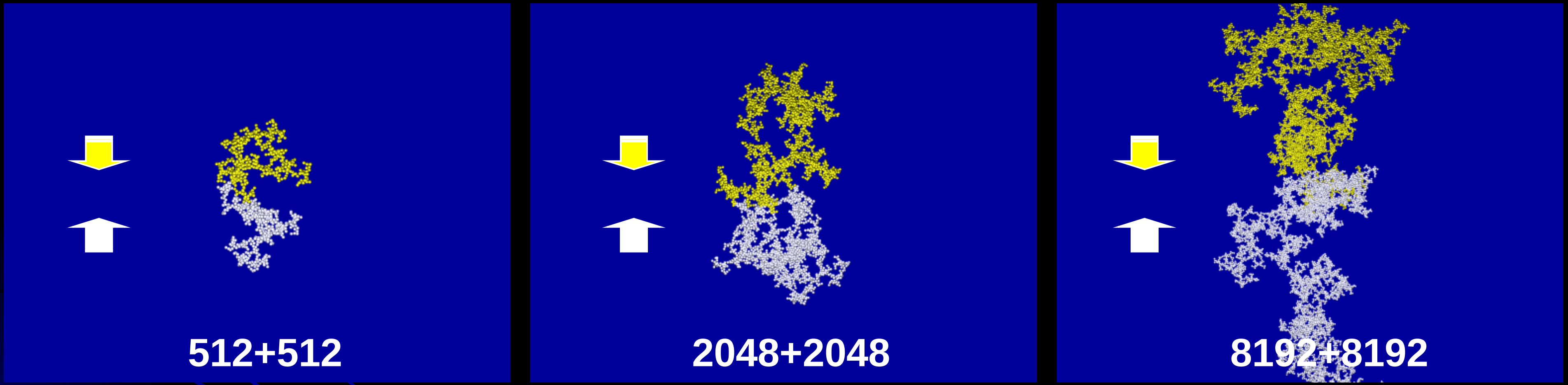
Initial Conditions and Parameters

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

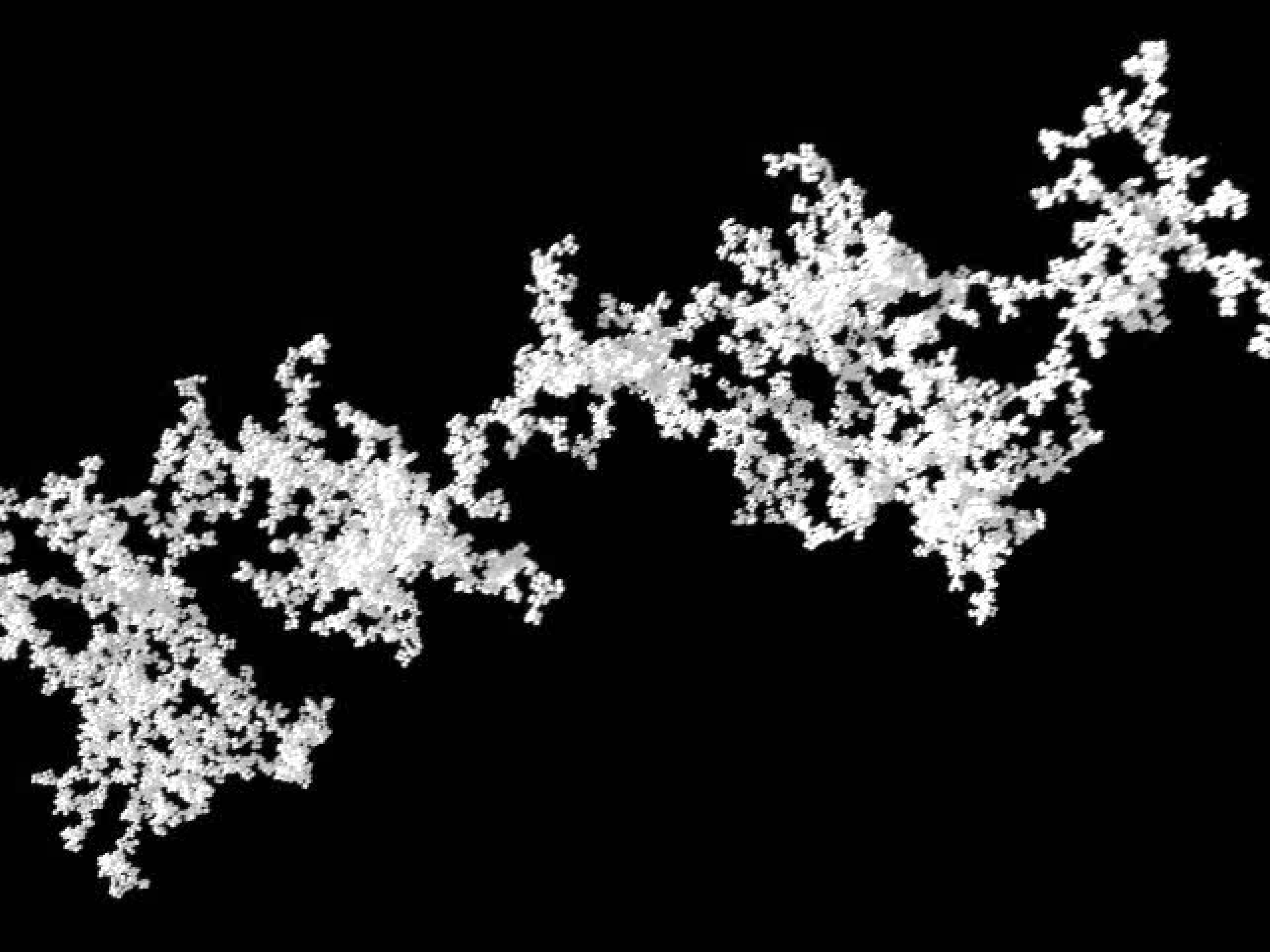


✓particle : radius = 0.1 μm,

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

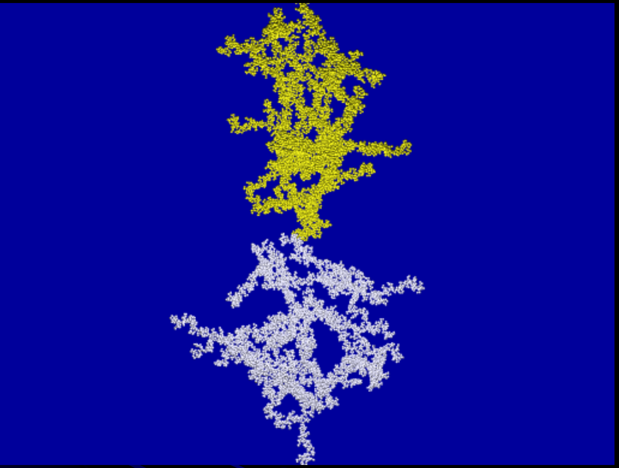
SiO_2 (*E* = 54 GPa, ν = 0.17, γ = 25 mJ/m^2)

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



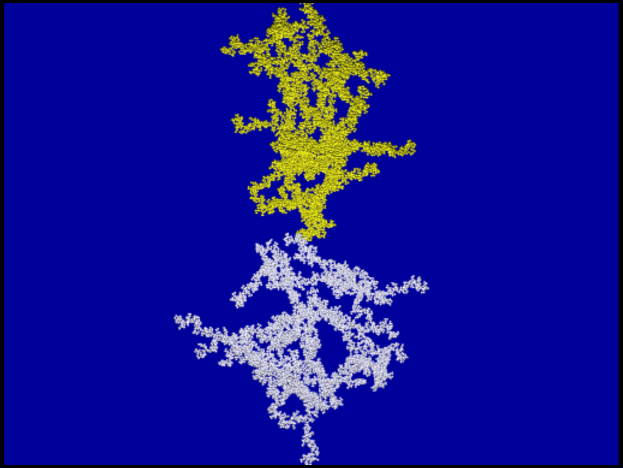
Example of simulations

Ice, 8192 + 8192, $\xi_{crit} = 8$ Å



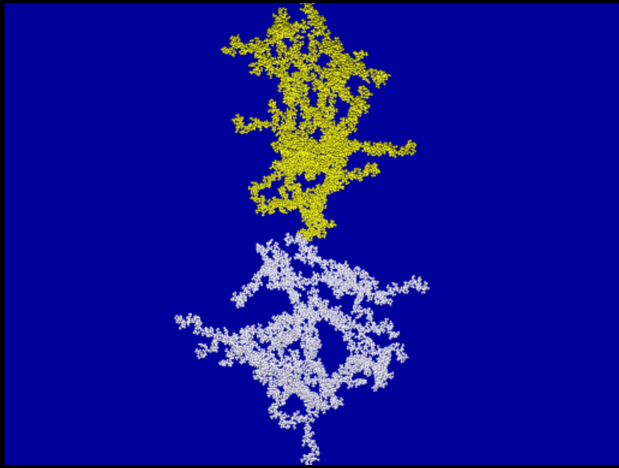
$E_{impact} \sim 0.7\, E_{roll}$

$V_{impact} = 0.2$ m/s



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

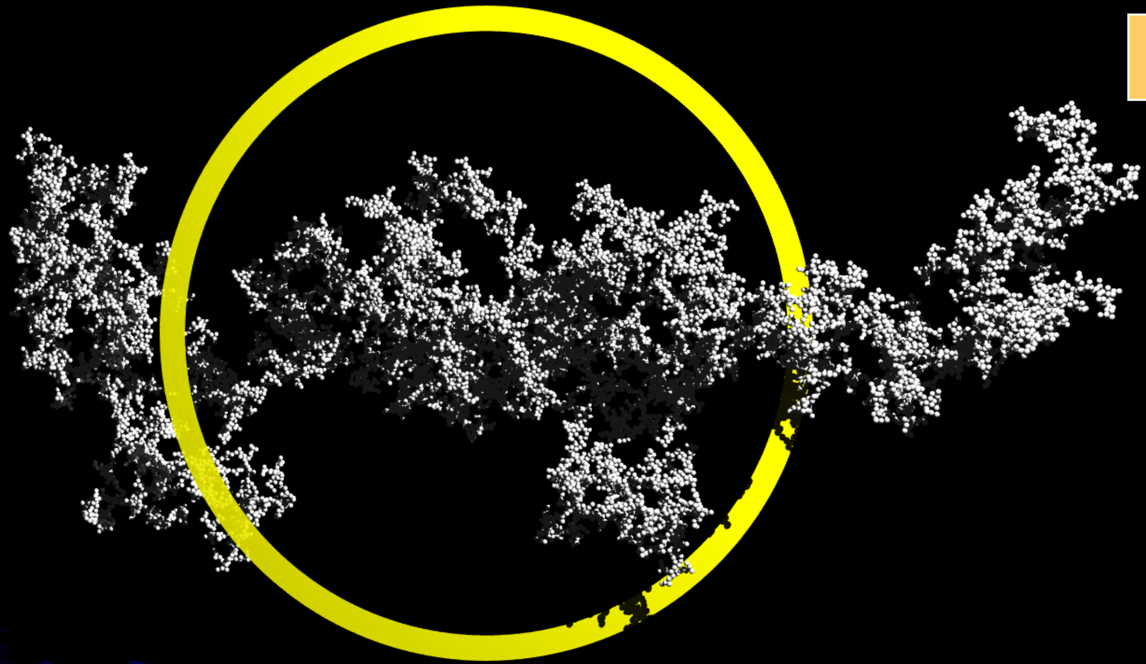
$V_{impact} = 17$ m/s



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

$V_{impact} = 39$ m/s

Gyration radius r_g : *compression process*

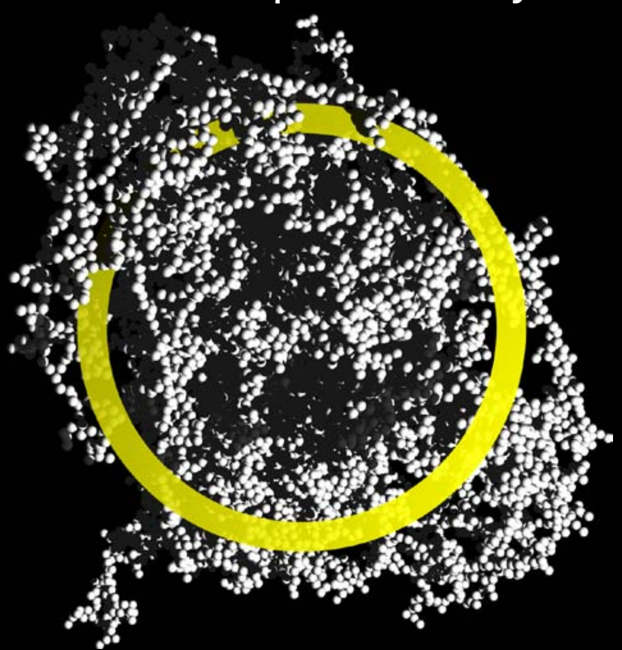


$E_{impact} \sim 0.01\, E_{roll}$

Impact velocity: 0.024 m/s

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

Impact velocity: 13 m/s

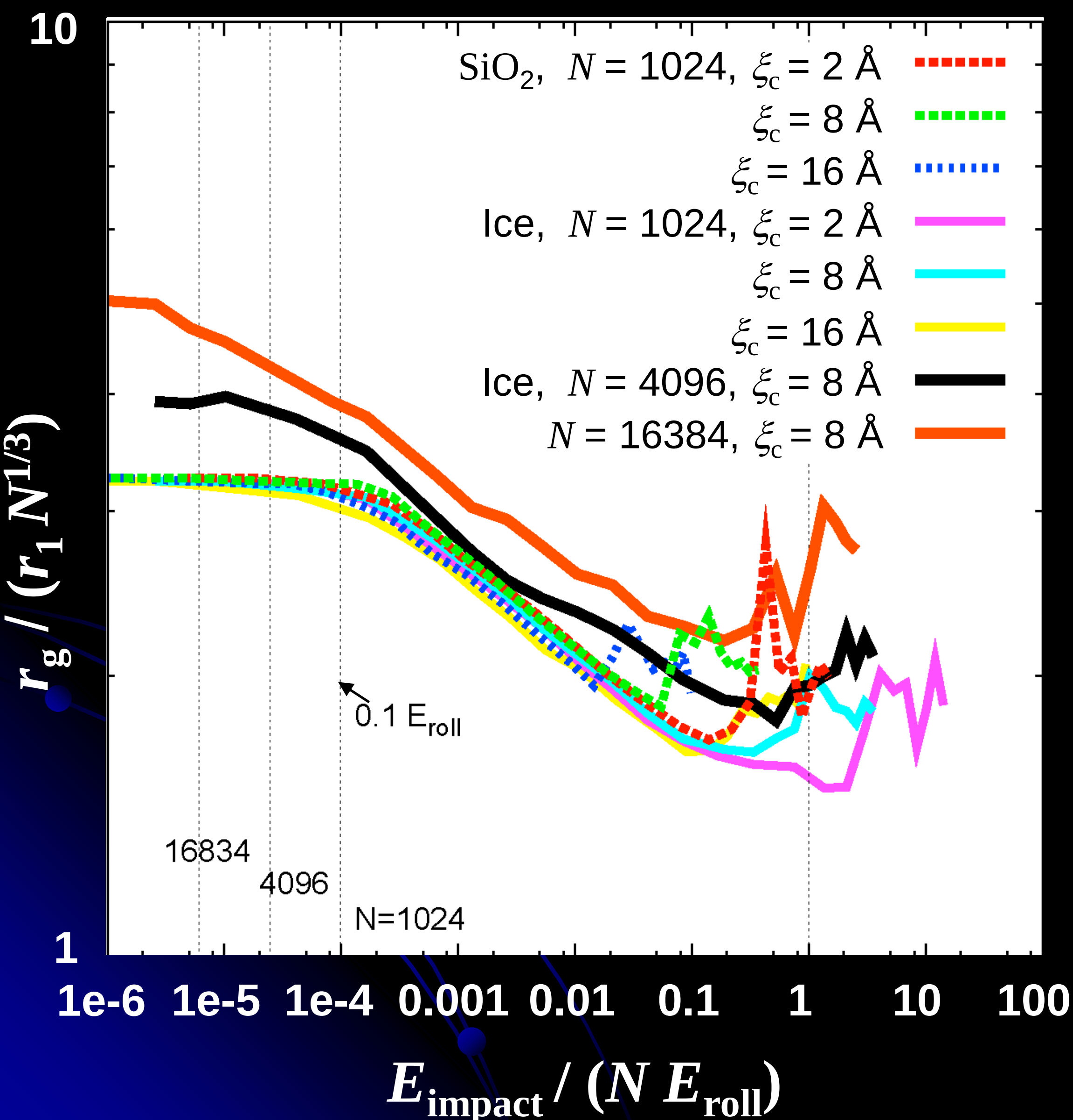


Ice, 8192 + 8192, ξ_{crit} = 8 Å

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

x_g: center of mass

Gyration radius r_g : *compression process*



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

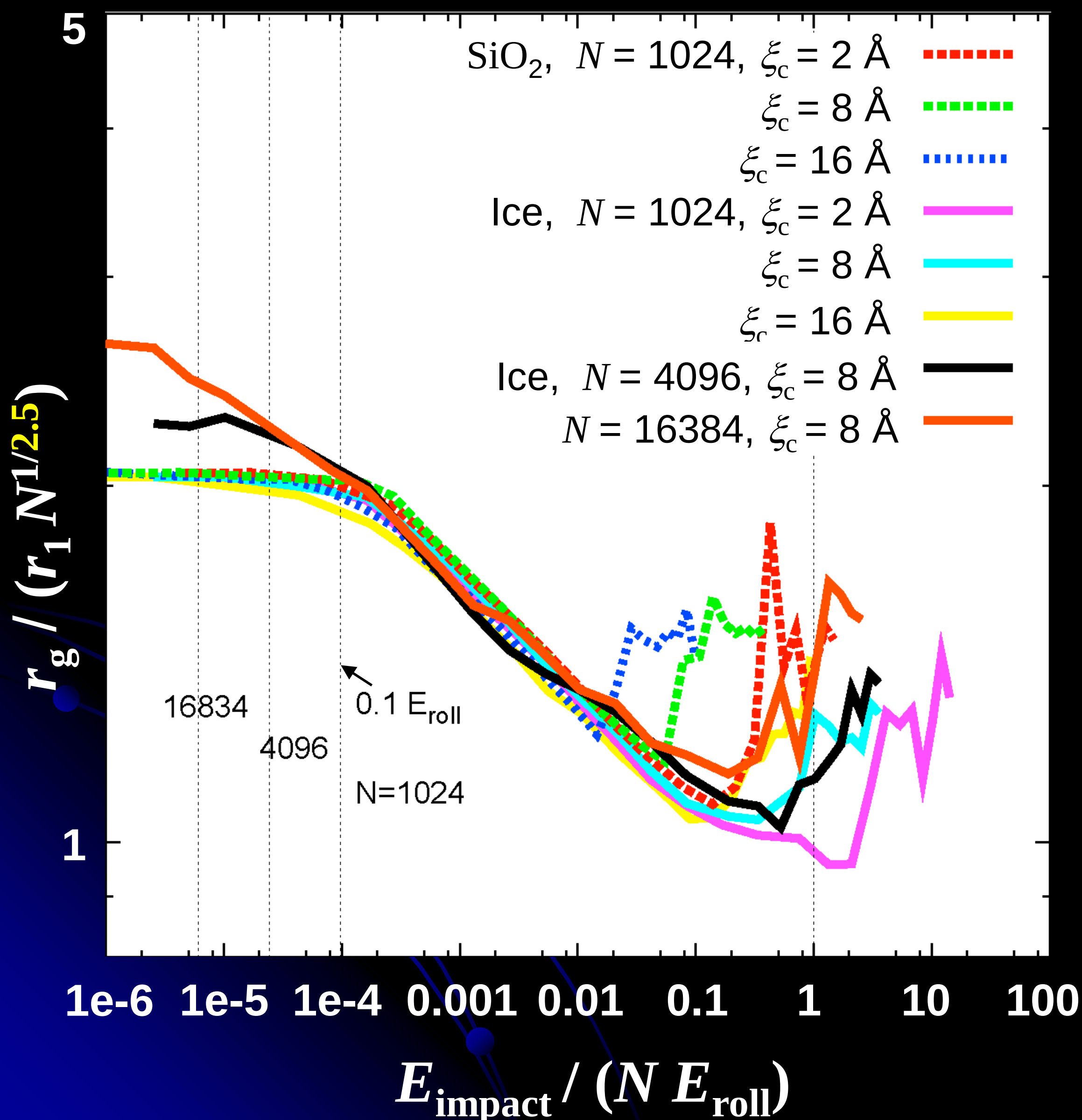
⇩

Max. compression

⇕

Consistent with Dominik & Tielens (1997)

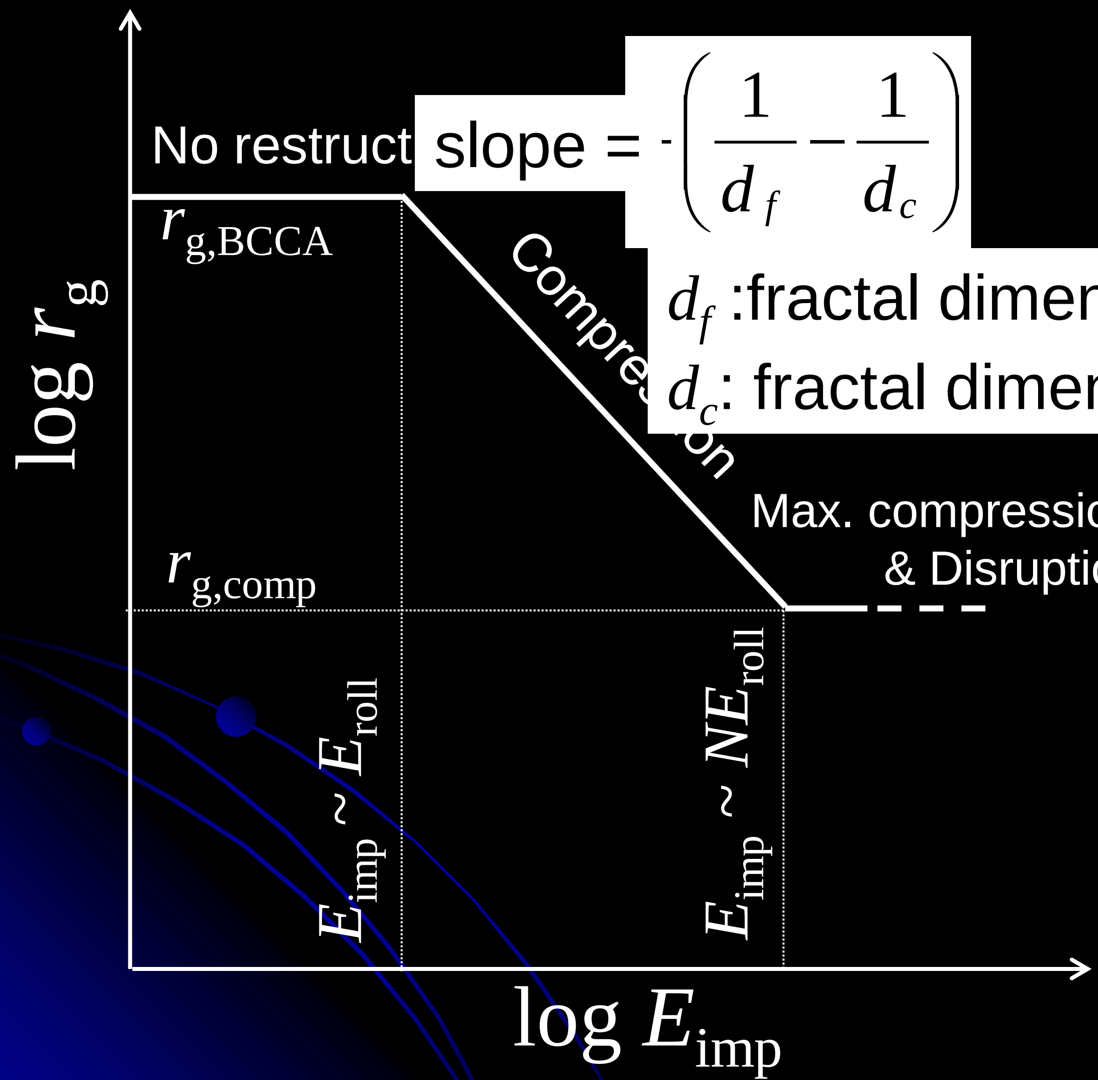
Gyration radius r_g : *compression process*



✓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

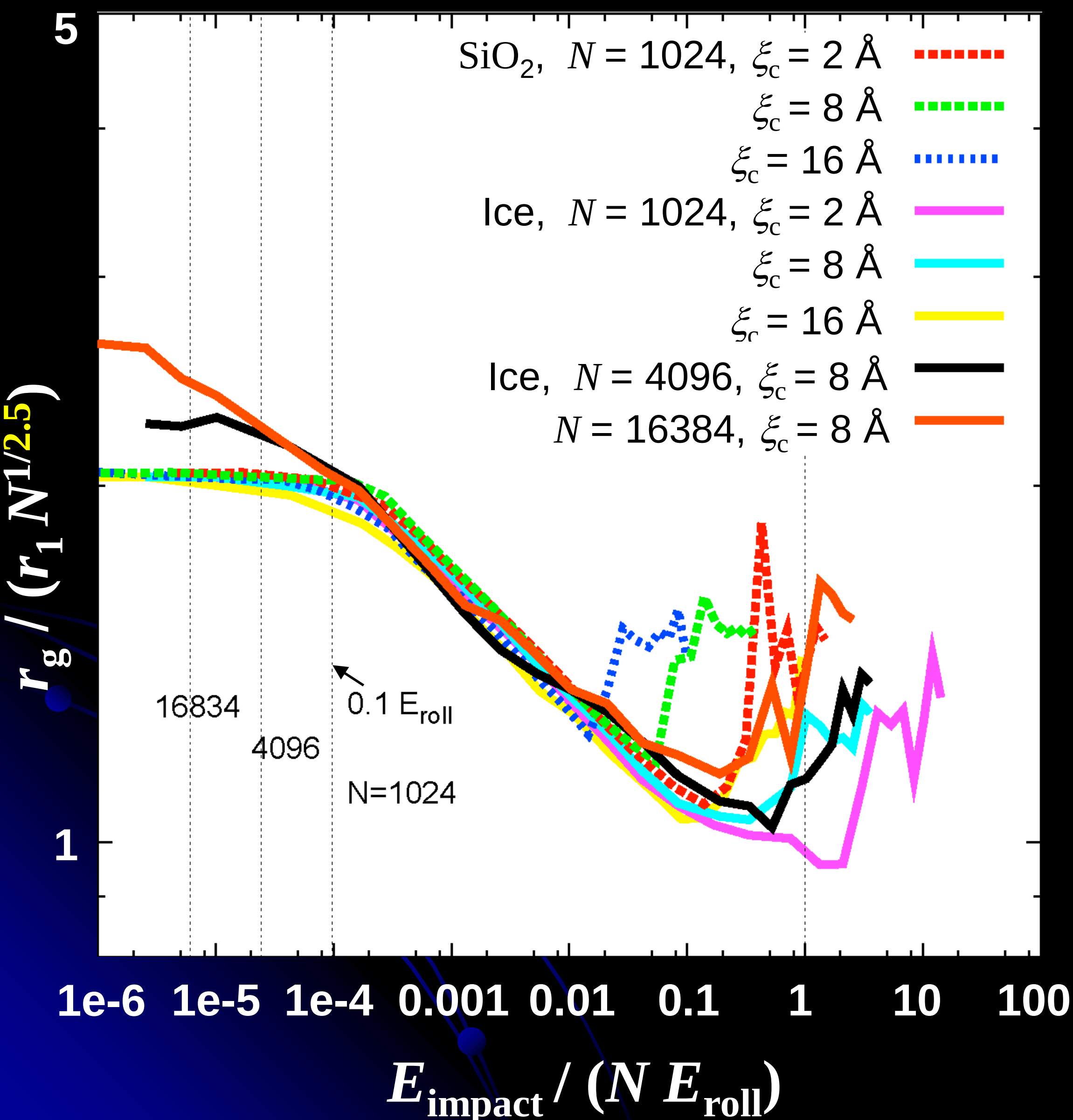
d_c: fractal dimension of max. compression

✓Scaled by

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

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

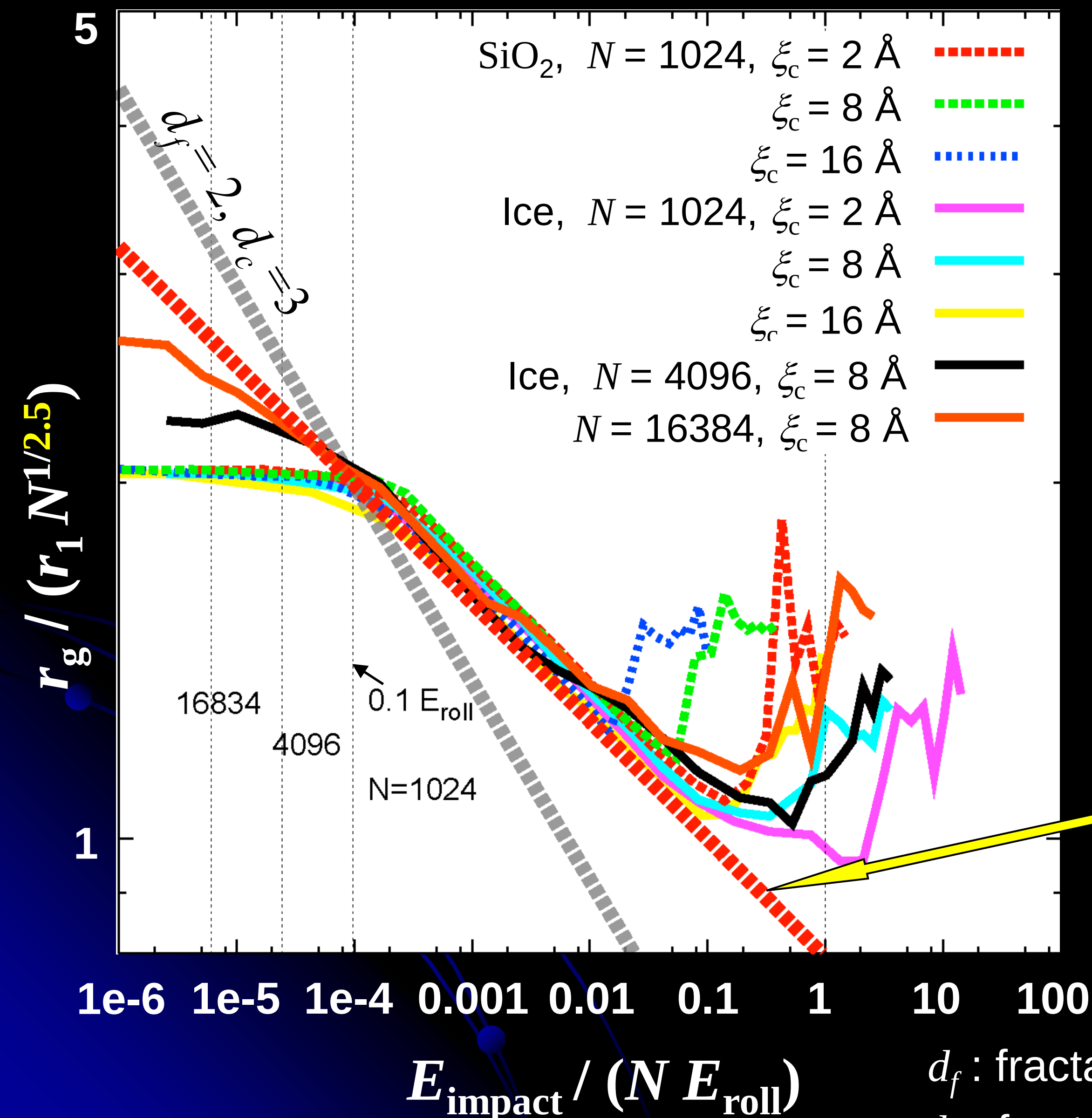
Gyration radius r_g : *compression process*



✓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

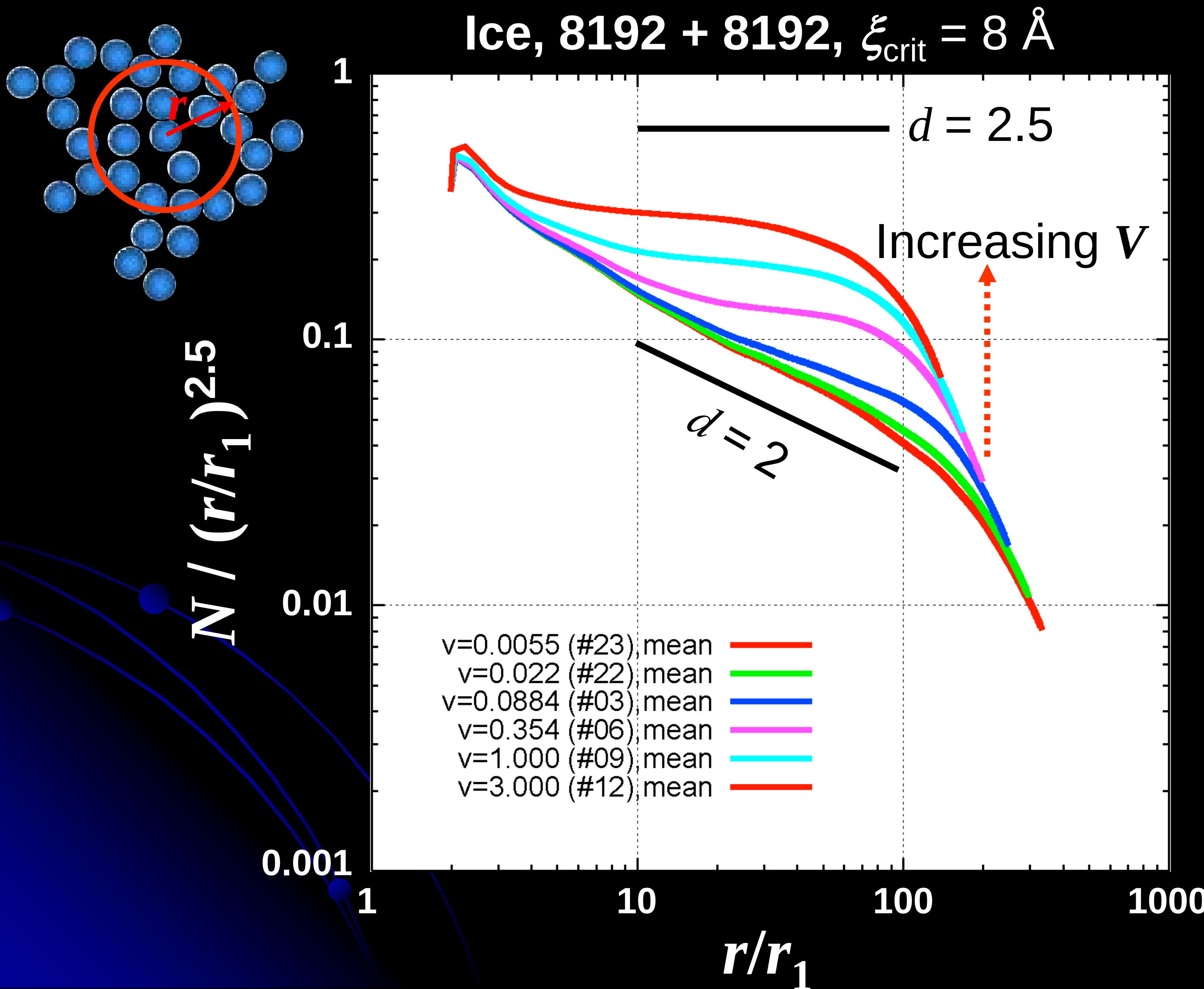
$$\frac{r_g}{r_1 N^{1/2.5}} \approx 0.8 \left(\frac{E_{impact}}{N E_{roll}} \right)^{-0.1}$$

(d_f = 2, d_c = 2.5)

d_f : fractal dimension of BCCA

d_c : fractal dimension of max. compression

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

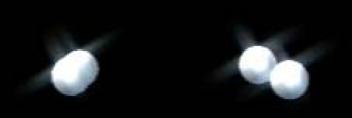


Successive collisions in a BCCA mode

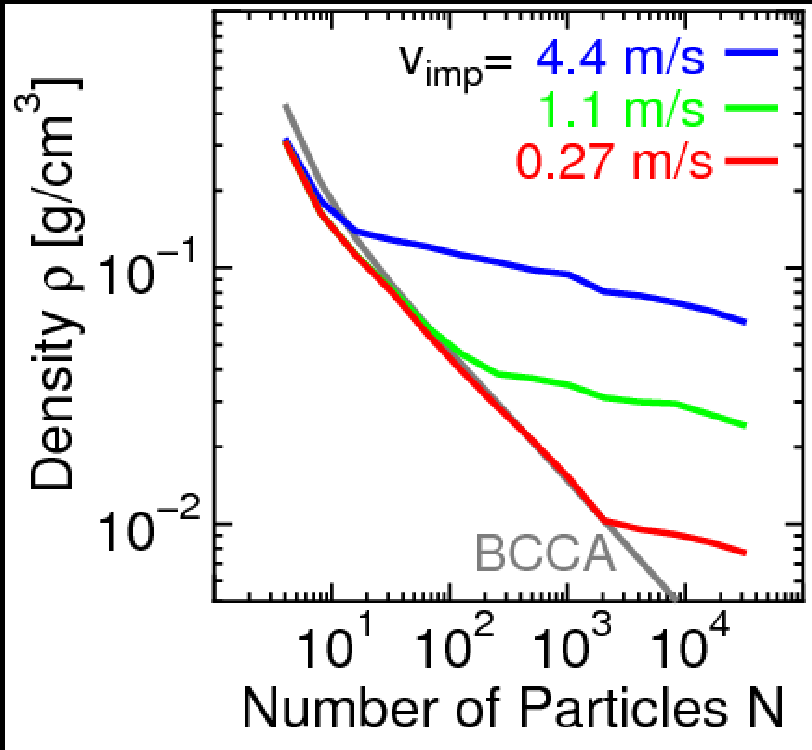
Suyama et al. 2008

✓Fractal dimension ~2.5

✓Decrease in density



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



Collisional Growth Conditions

To be disrupted, or not to be?

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 ?

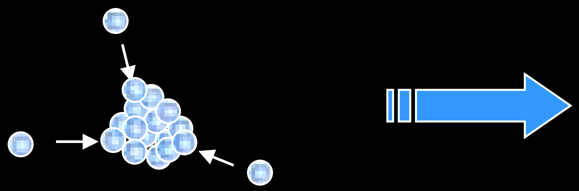
Maybe possible in head-on collisions

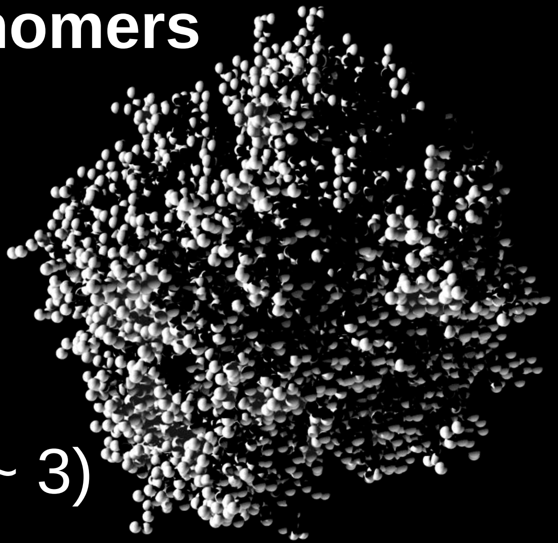
Experimental: Blum & Wurm 2000, Wurm et al. 2005
Numerical: Dominik & Tielens 1997, Wada et al. 2008

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

Growth Efficiency For Collisions of BPCAs

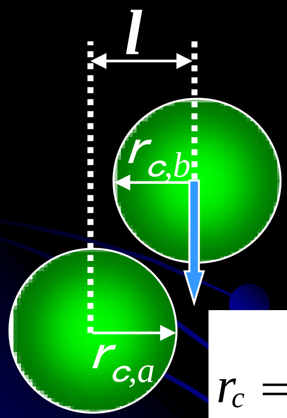
Initial Conditions and Parameters

Collisions of BPCA clusters

Results are averaged

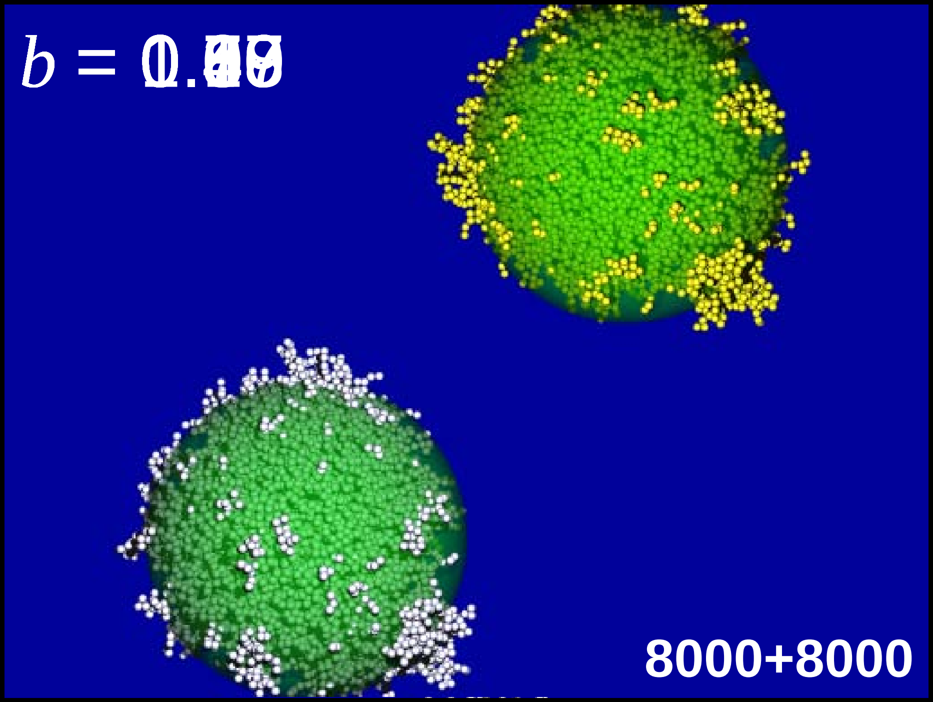
✓ BPCA clusters are:

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



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

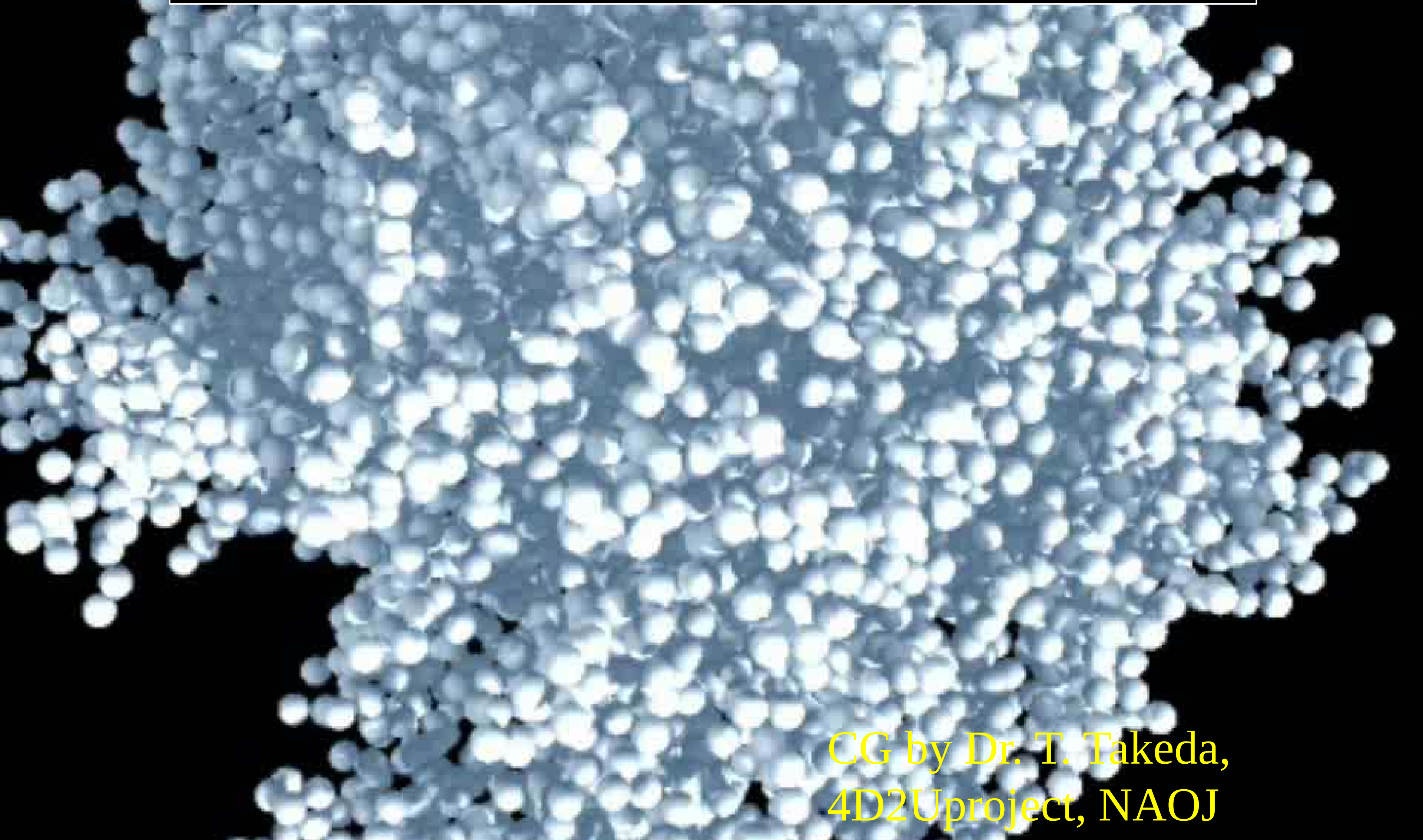
$$r_c = \sqrt{\frac{5}{3}\frac{1}{N}\sum (x_i - x_G)^2}$$



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

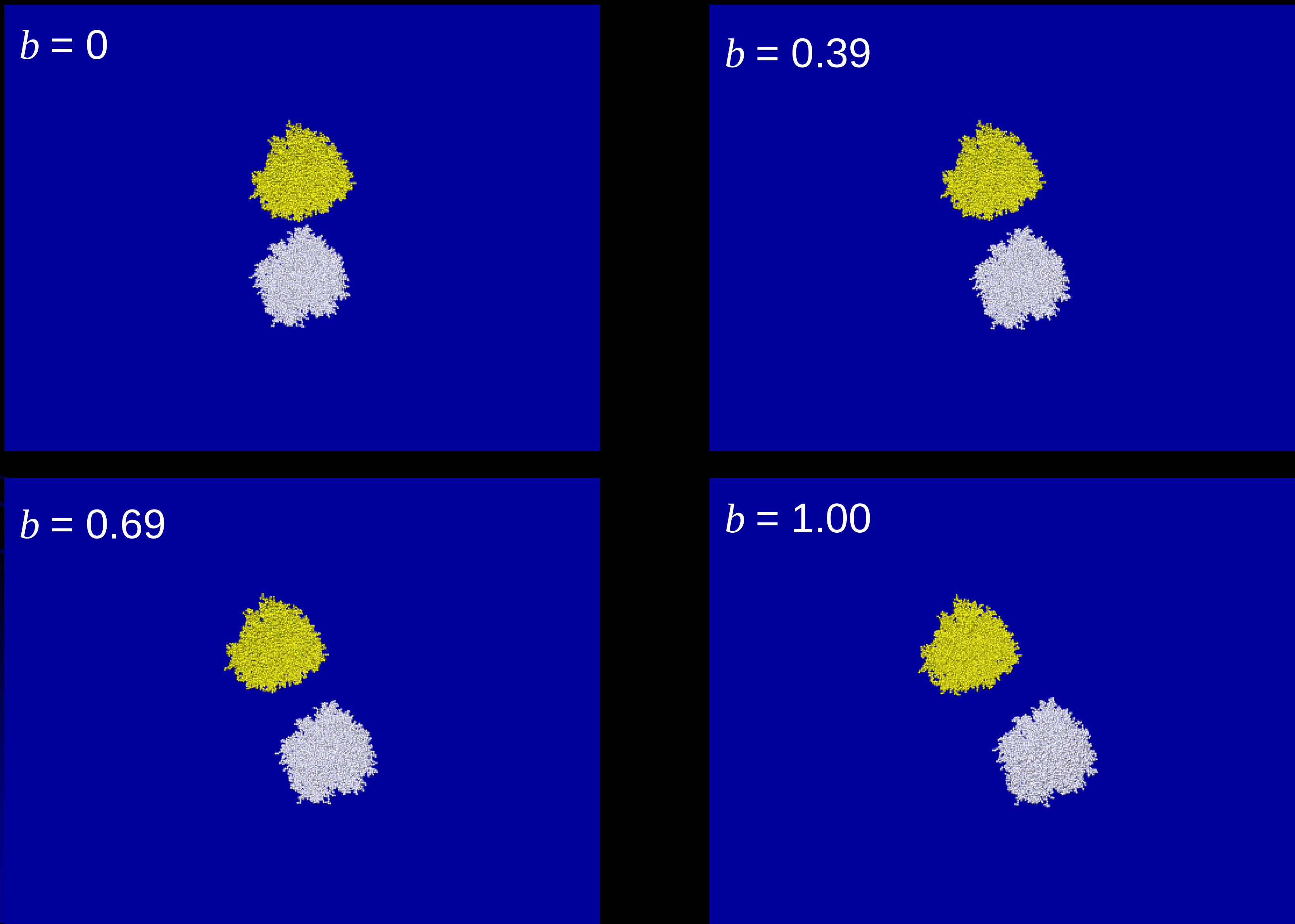
✓ Impact velocity v_{imp} = 6 - 300 m/s

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

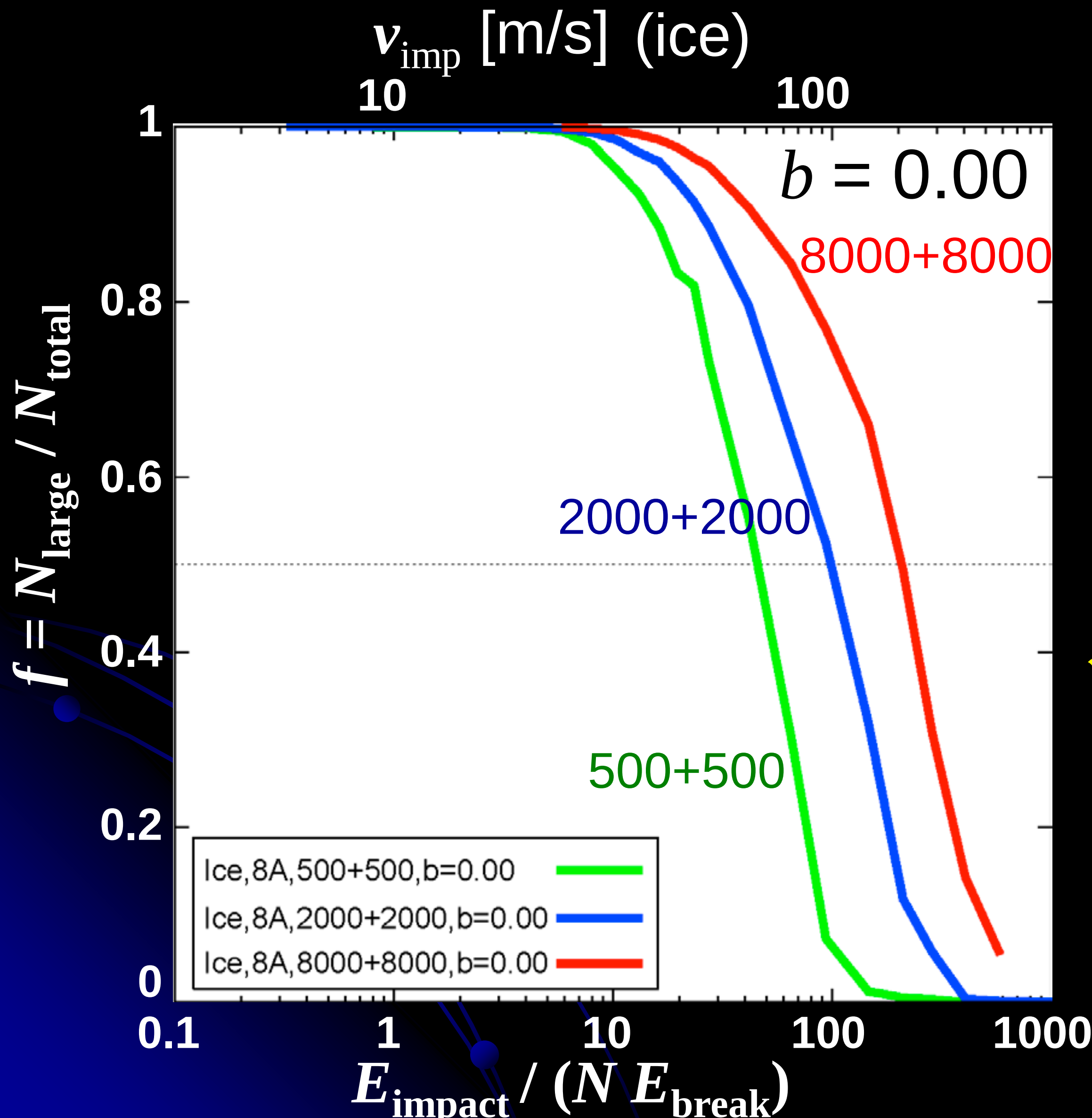


Collisions of BPCA clusters

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



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



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

: growth efficiency

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

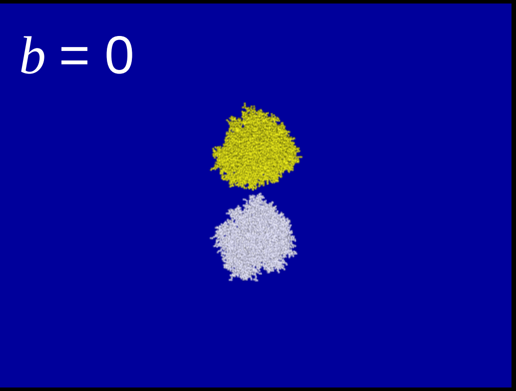
✓dependent on N

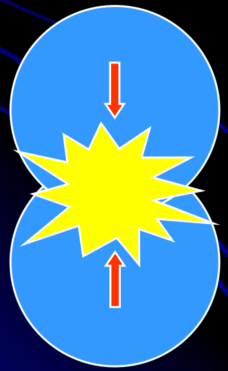
● Head-on

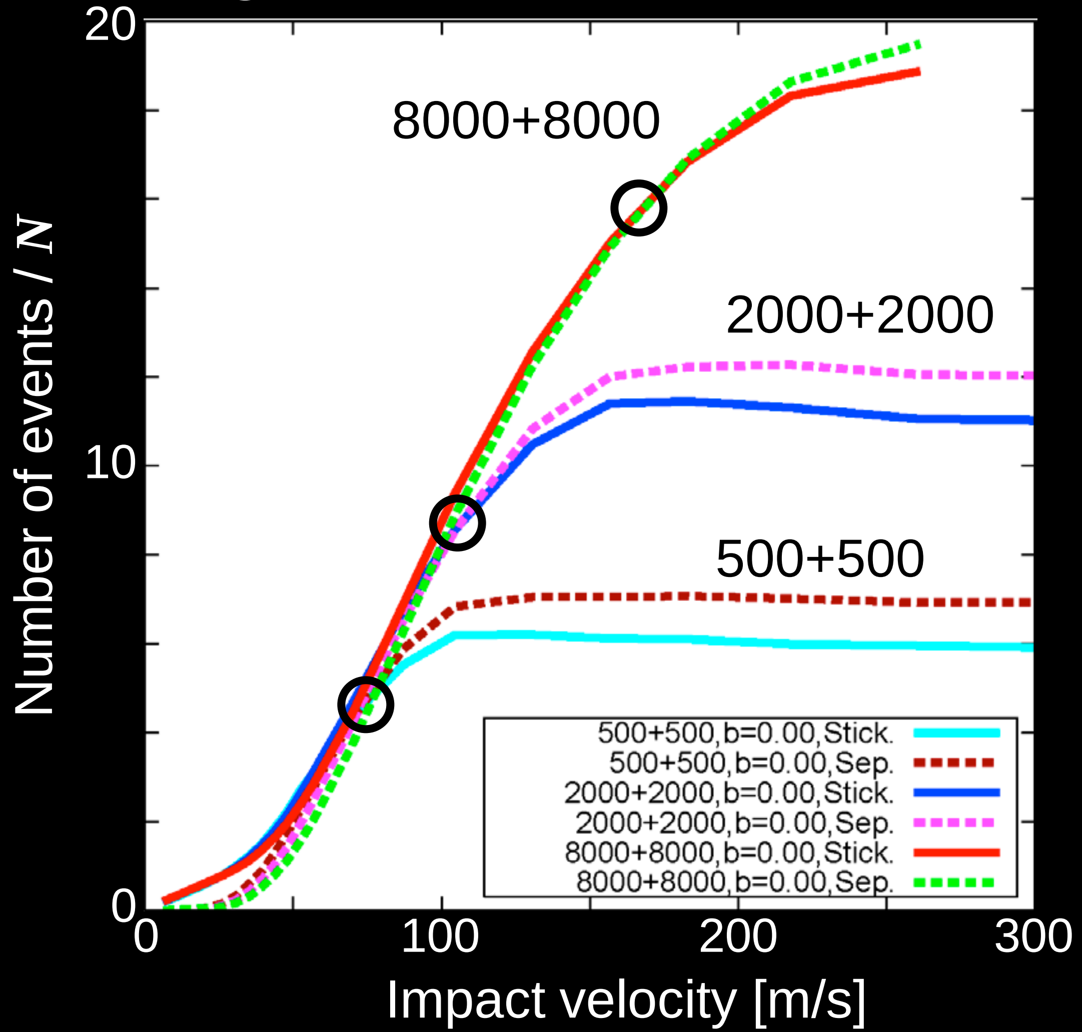
→ narrow escape space for fragments

→ many events of sticking and separating

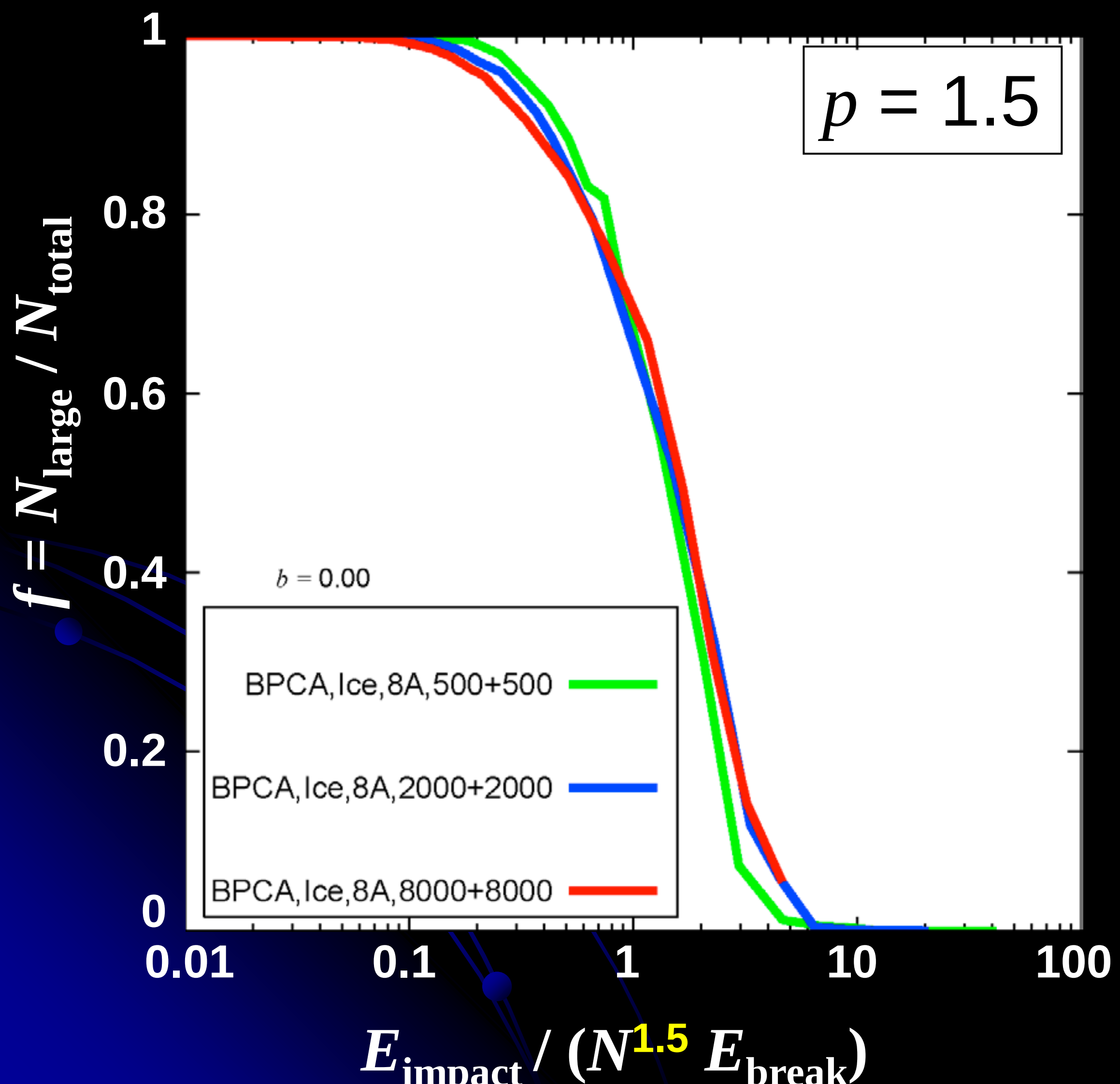
The larger N, the more grains remain inside.







Scaling for BPCAs' head-on collision



Paszun & Dominik (2008):

N^p instead of N,

$p = 2 - 2/d_f$

$p = 1$ for $d_f = 2$

$p = 1.33$ for $d_f = 3$

p =1.5 is best ?

Paszun & Dominik (2009):

●Largest fragments（Head-on）

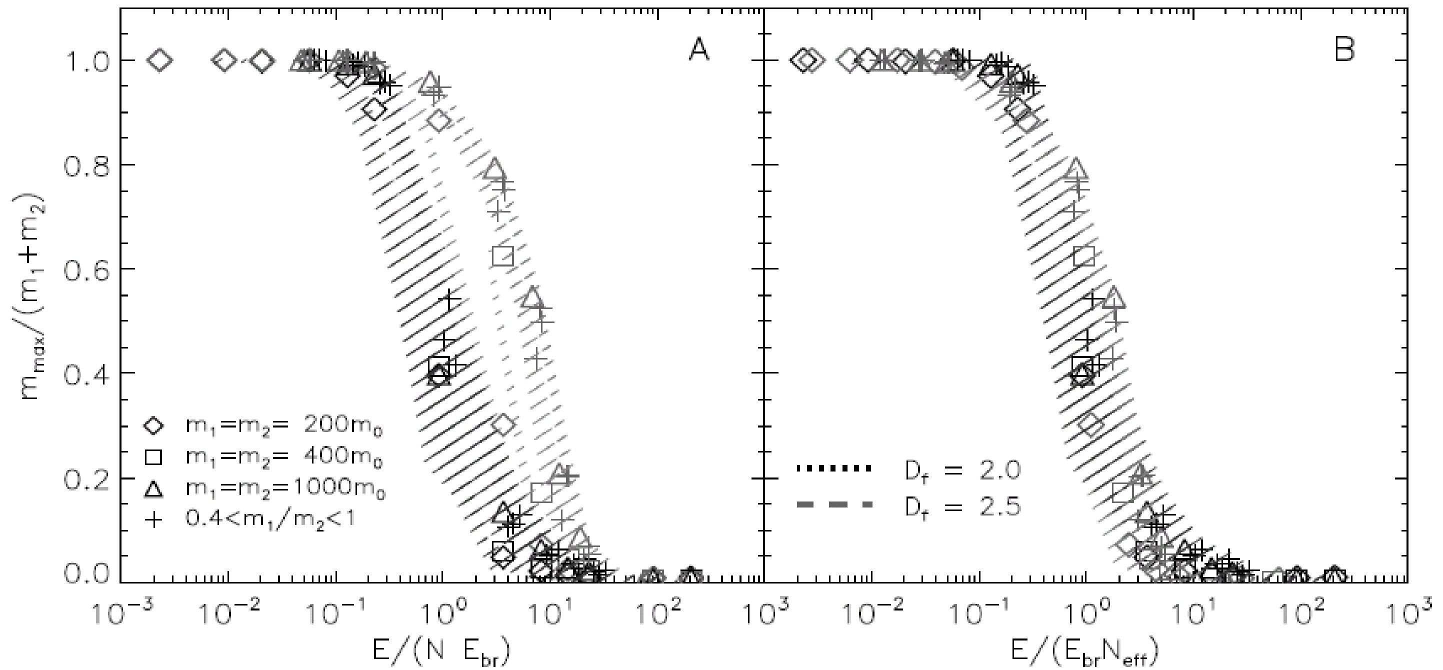
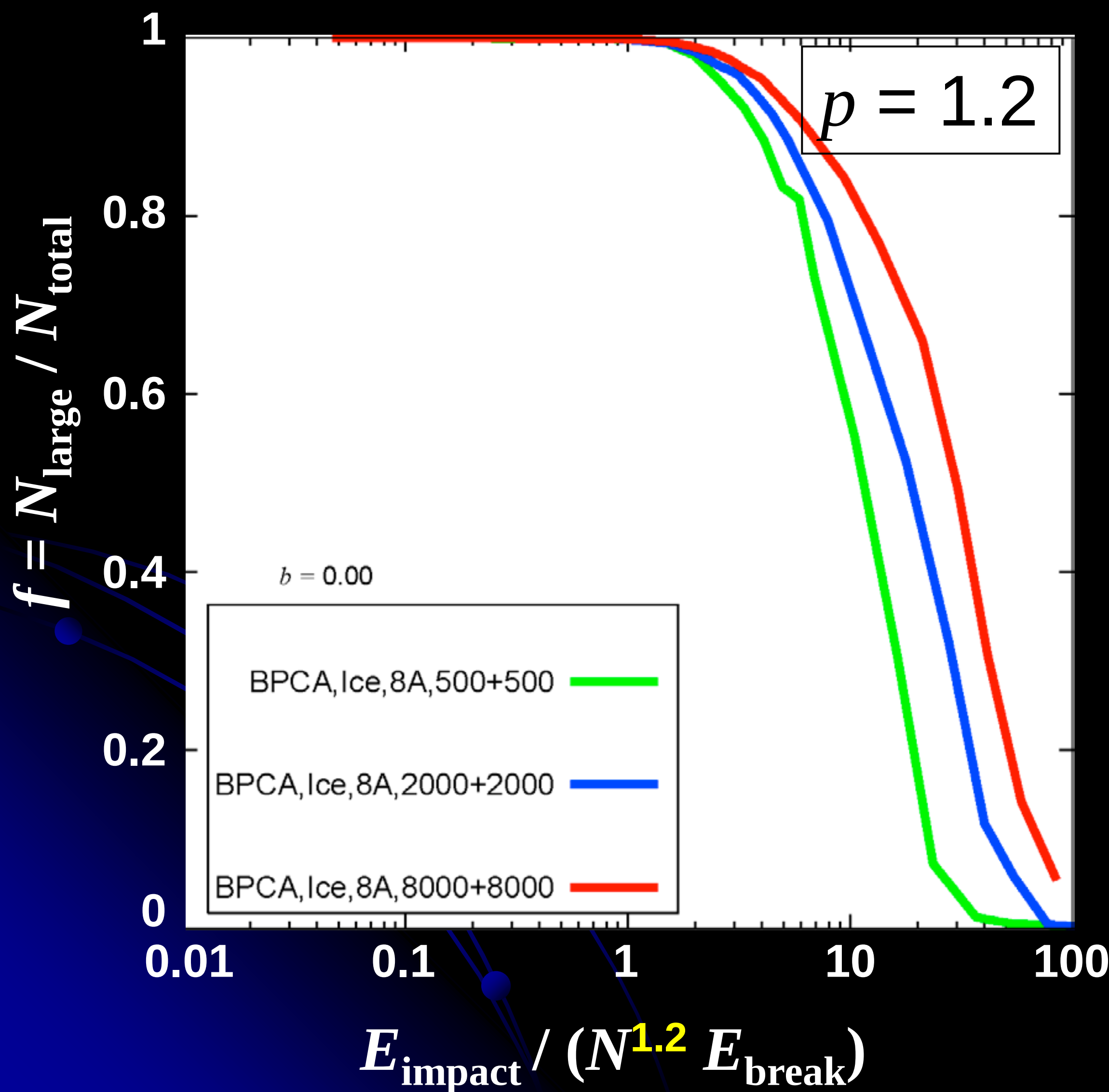


Fig. 26. The mass of the largest collision remnant as a function of the collision energy. The impact energy is normalized to the breaking energy times the total number of monomers (A) and to the breaking energy and the effective number of grains $N_{\rm eff}$ (B). Presented are only results of head-on collisions of aggregates of different mass and different porosity.

Using $N_{\rm eff}$, size of largest fragment is well scaled independent of mass and fractal dimensions of colliding aggregates

$$N_{eff} \propto \frac{N_{tot}}{S} \times N_{tot} \propto \frac{N_{tot}}{N_{tot}^{2/d_f}} \times N_{tot} = N_{tot}^{2-2/d_f}$$

Scaling for BPCAs' head-on collision



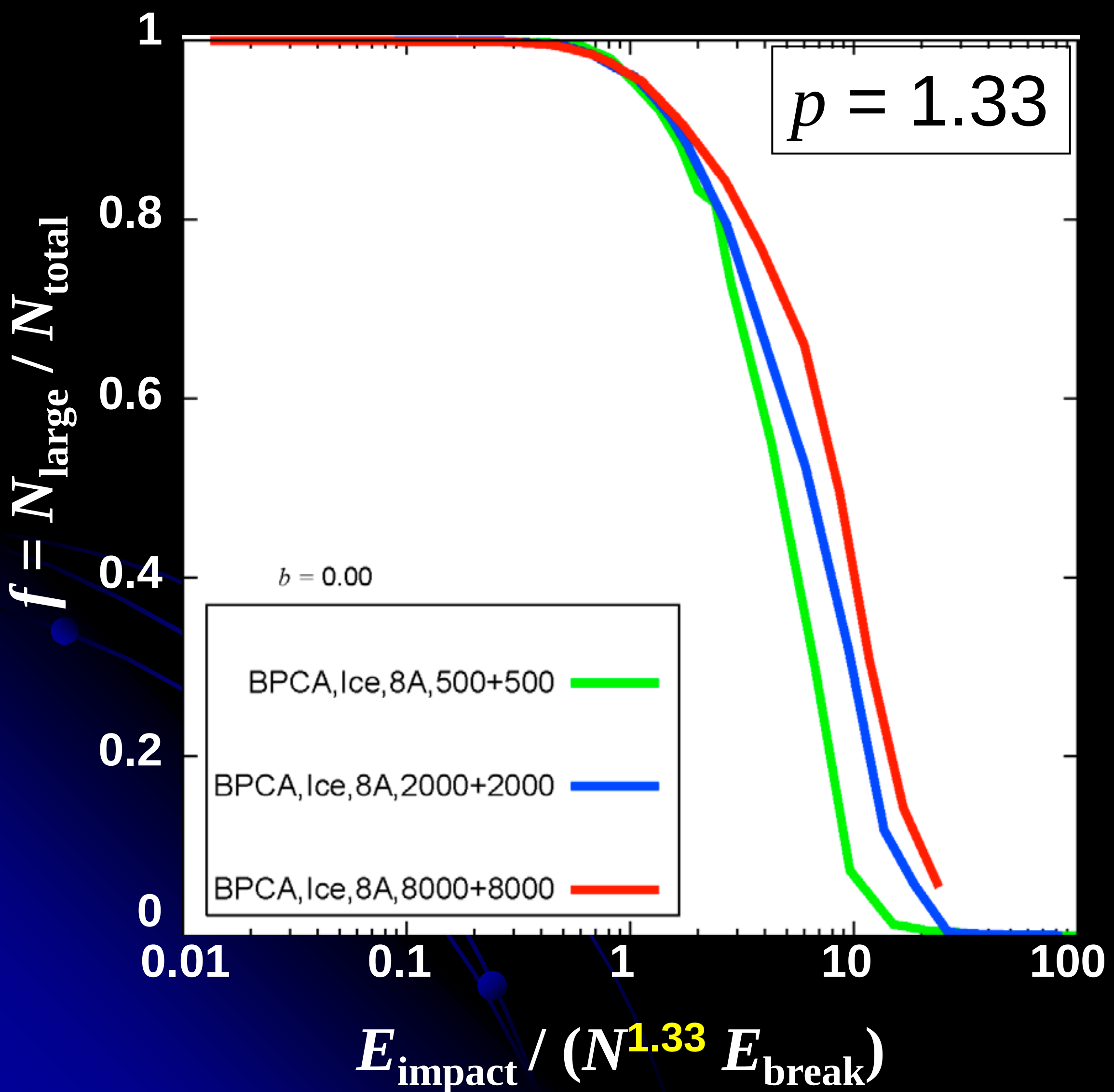
Paszun & Dominik (2008):

N^{p} instead of N,

$p = 2 - 2/d_f$

($p = 1$ for $d_f = 2$
$p = 1.33$ for $d_f = 3$)

Scaling for BPCAs' head-on collision



Paszun & Dominik (2008):

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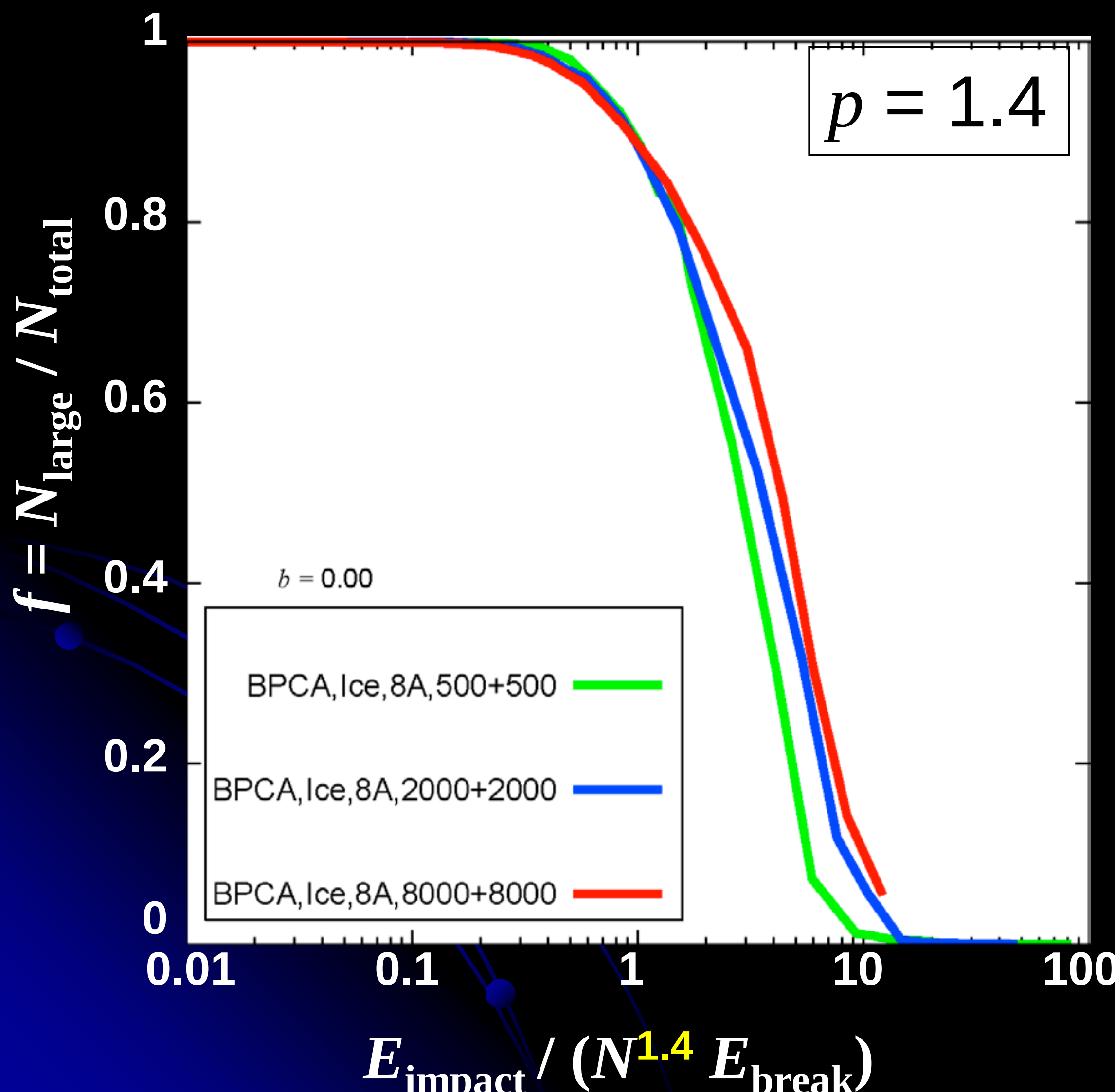
Scaling for BPCAs' head-on collision



Paszun & Dominik (2008):

N^{p} instead of N,

$p = 2 - 2/d_f$

$p = 1$ for $d_f = 2$

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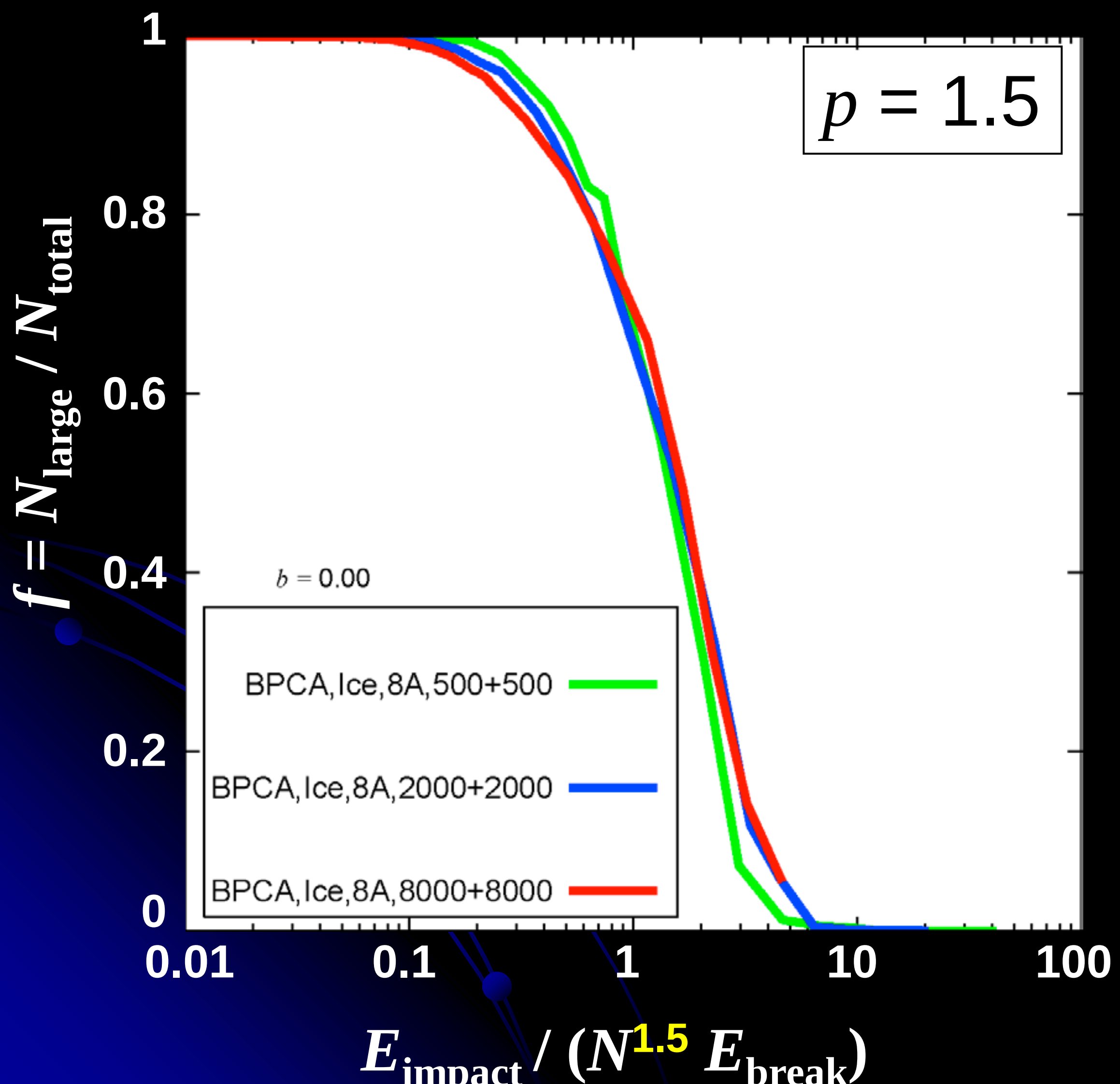
Scaling for BPCAs' head-on collision



Paszun & Dominik (2008):

N^{p} instead of N,

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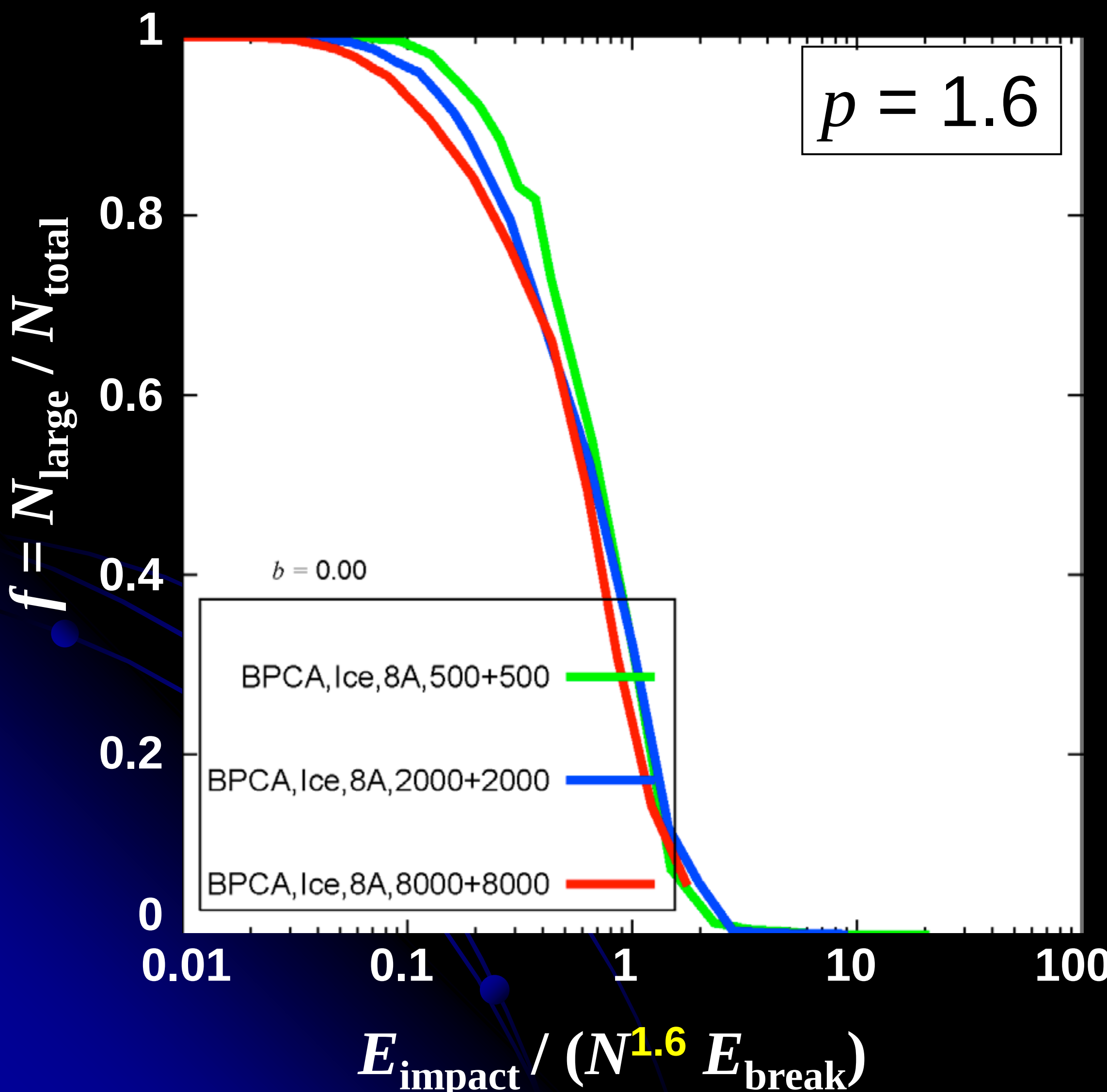
p =1.5 is best ?

Scaling for BPCAs' head-on collision



Paszun & Dominik (2008):

N^{p} instead of N,

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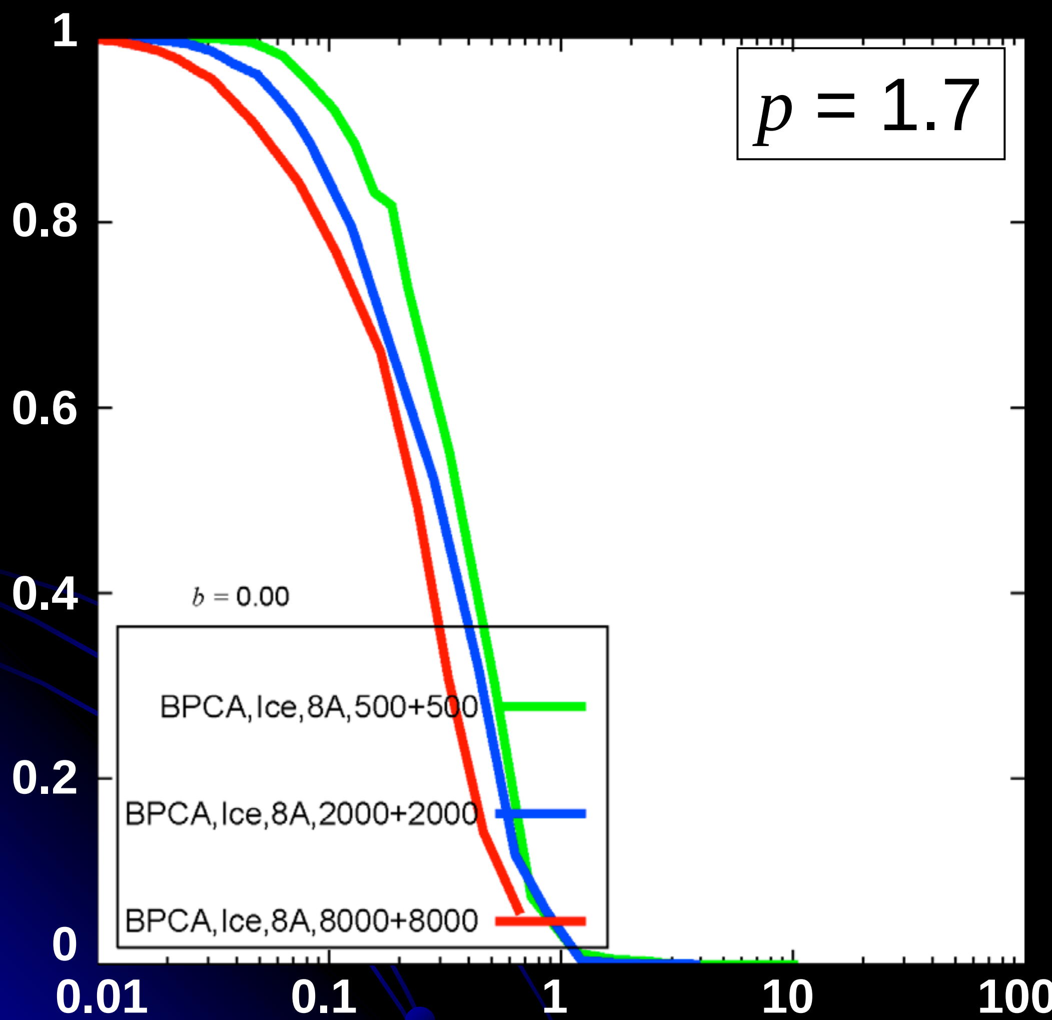
Scaling for BPCAs' head-on collision



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

$E_{\text{impact}} / (N^{1.7} E_{\text{break}})$

Paszun & Dominik (2008):

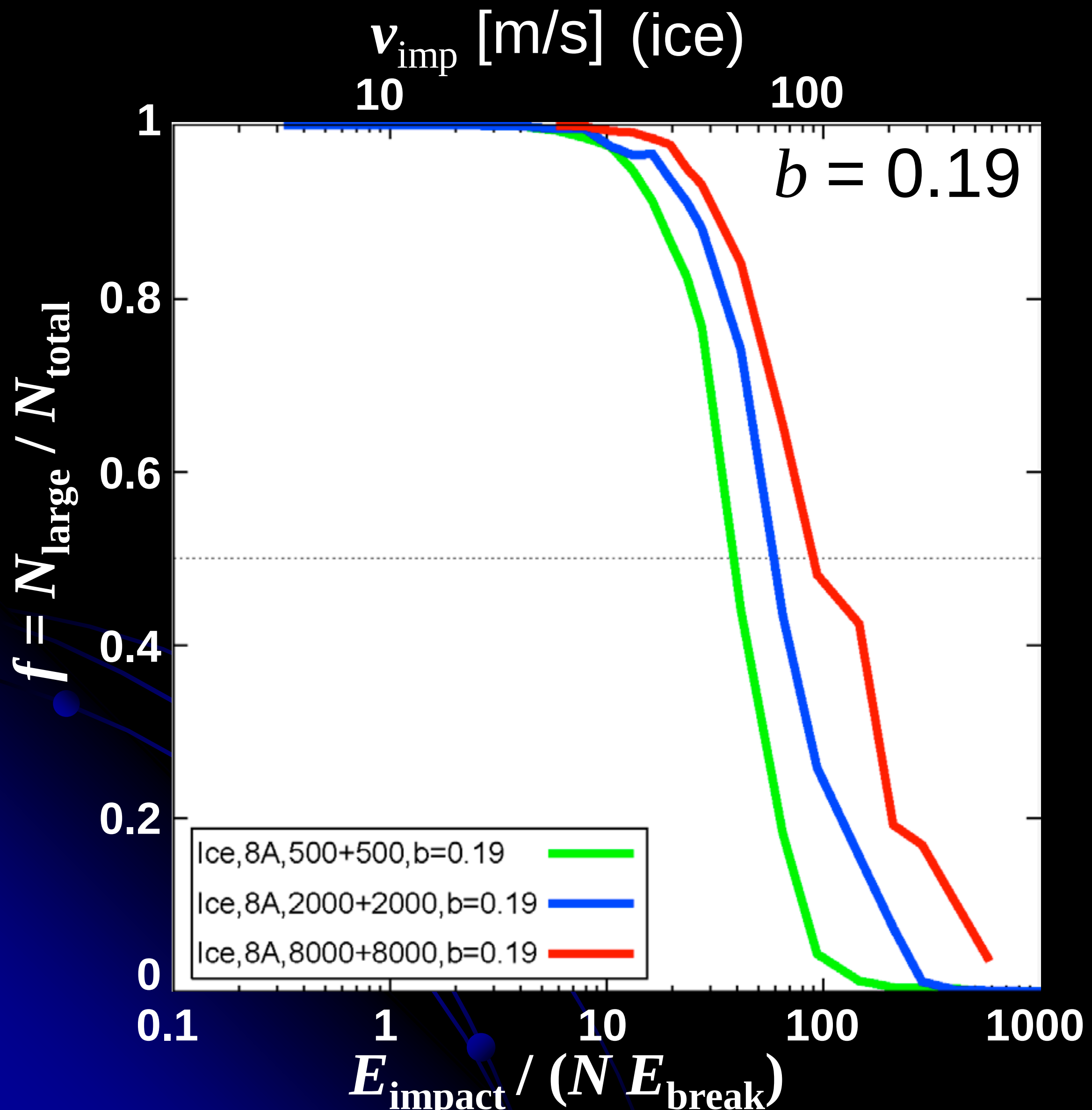
N^{p} instead of N,

$p = 2 - 2/d_f$

$p = 1$ for $d_f = 2$

$p = 1.33$ for $d_f = 3$

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

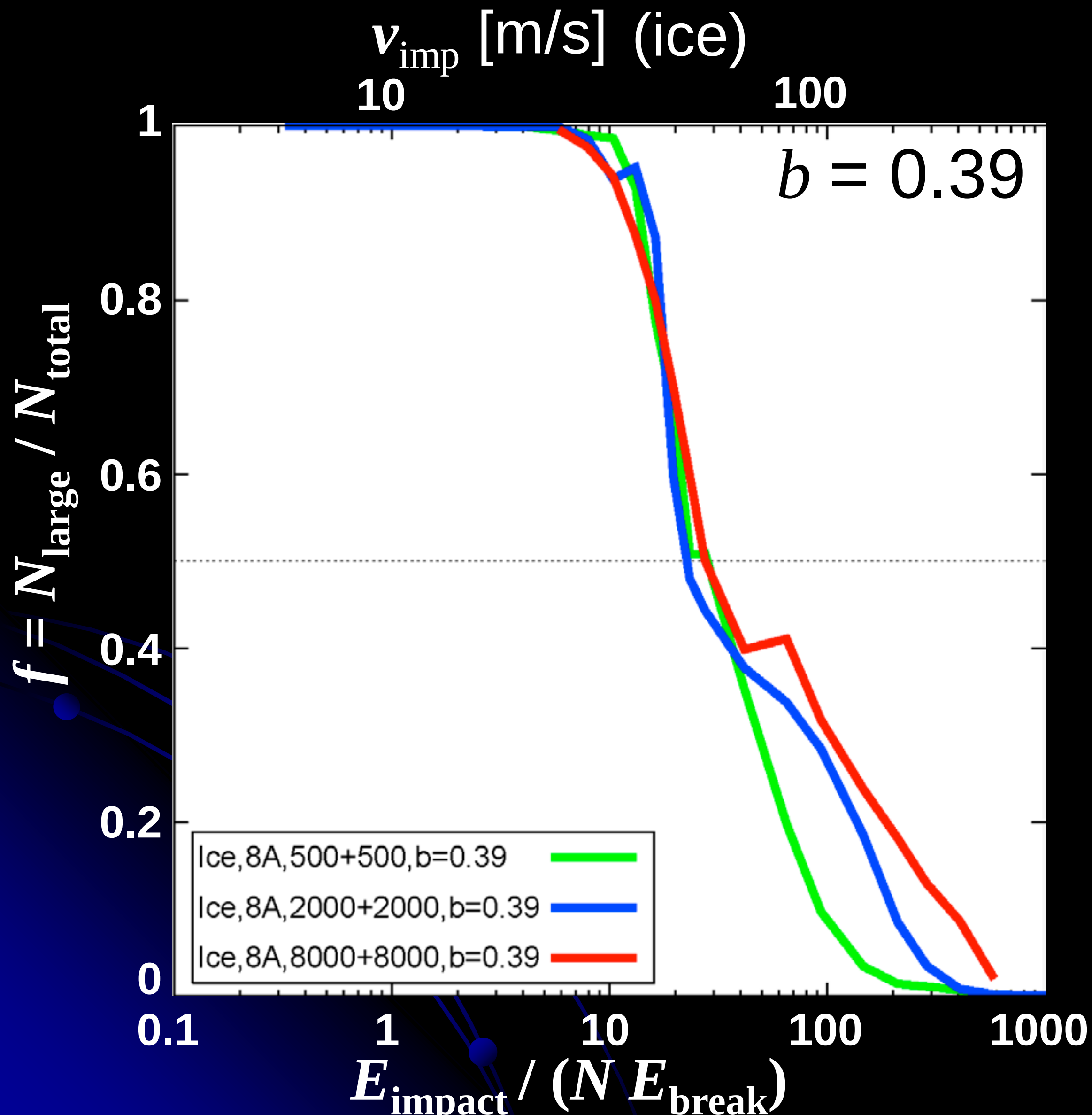


$f \equiv N_{\mathrm{large}} / N_{\mathrm{total}}$

: growth efficiency

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

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



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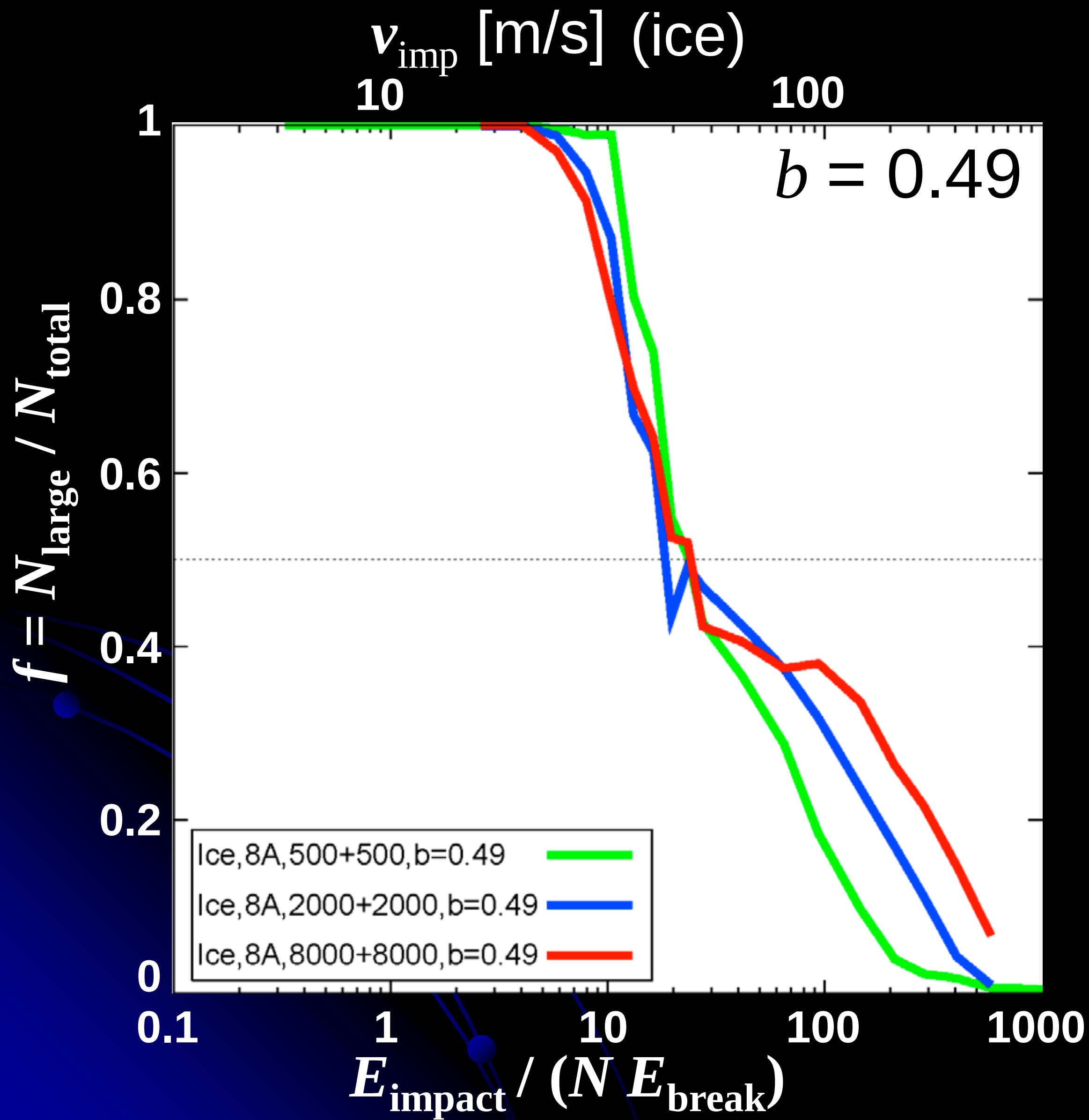
Largest fragment mass N_{large}: *growth efficiency*



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

: growth efficiency

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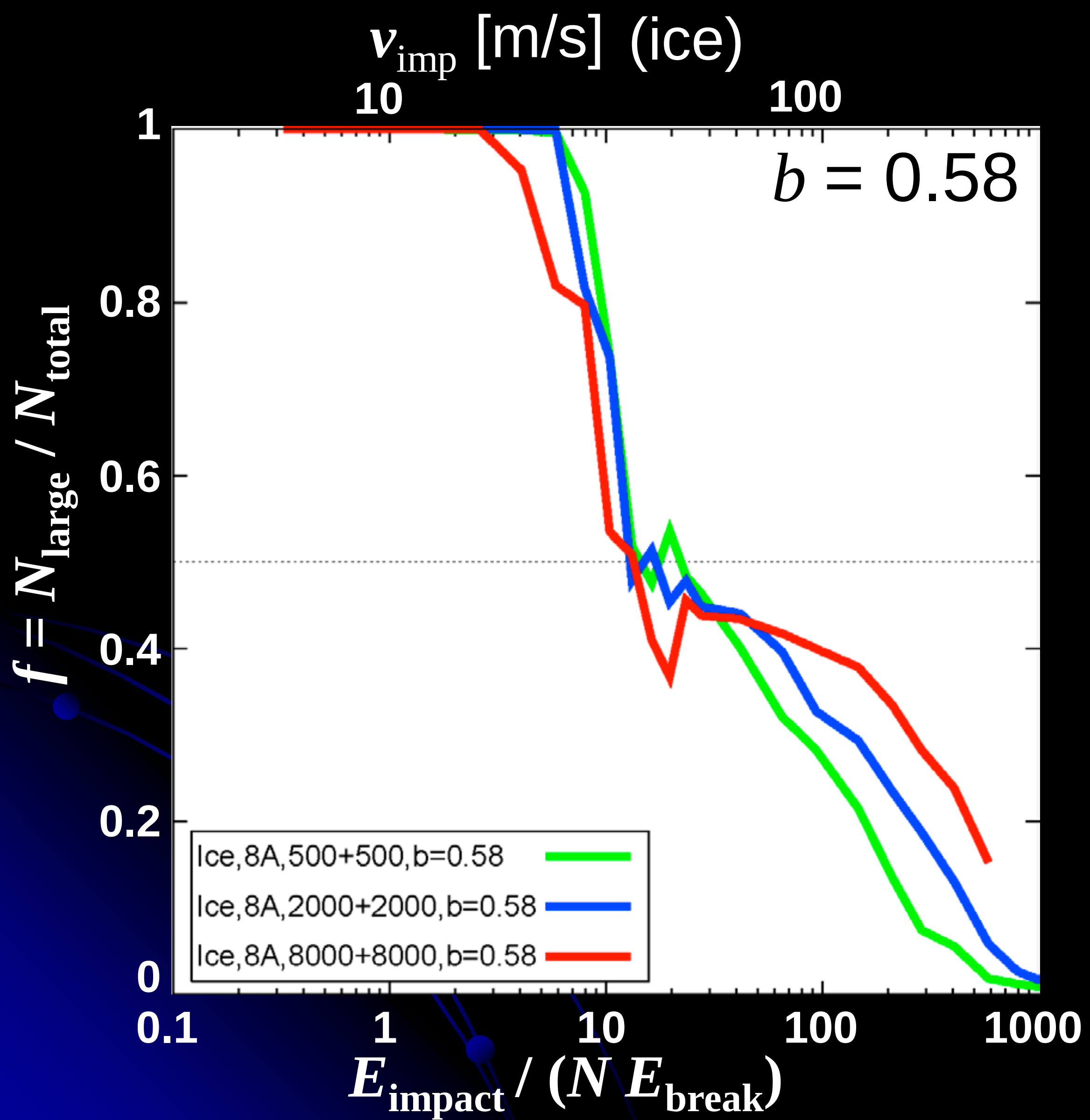
- $f < 0.5$ → - growth

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



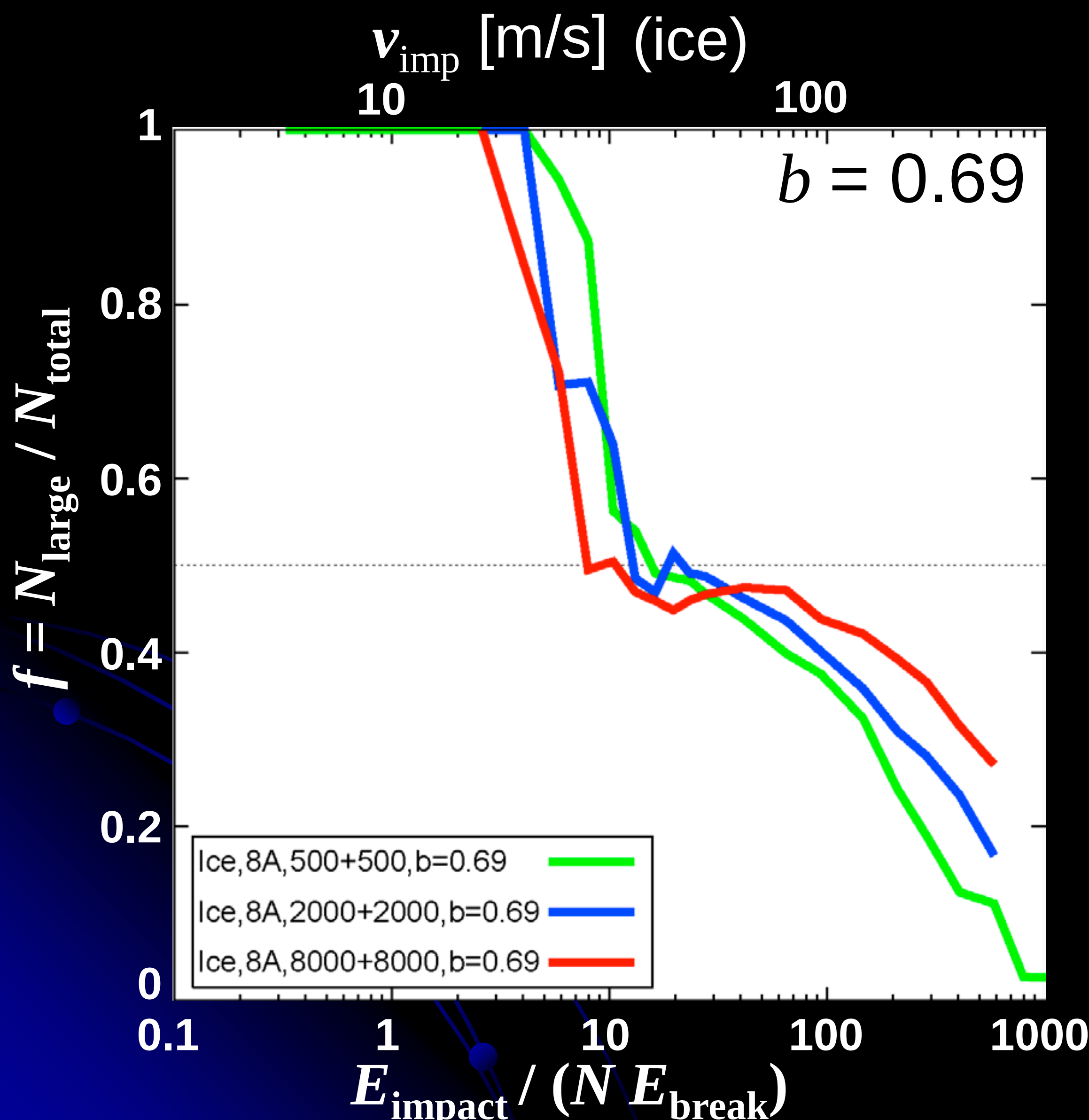
$f \equiv N_{\mathrm{large}} / N_{\mathrm{total}}$

: growth efficiency

$f > 0.5$ → + growth

$f < 0.5$ → - growth

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

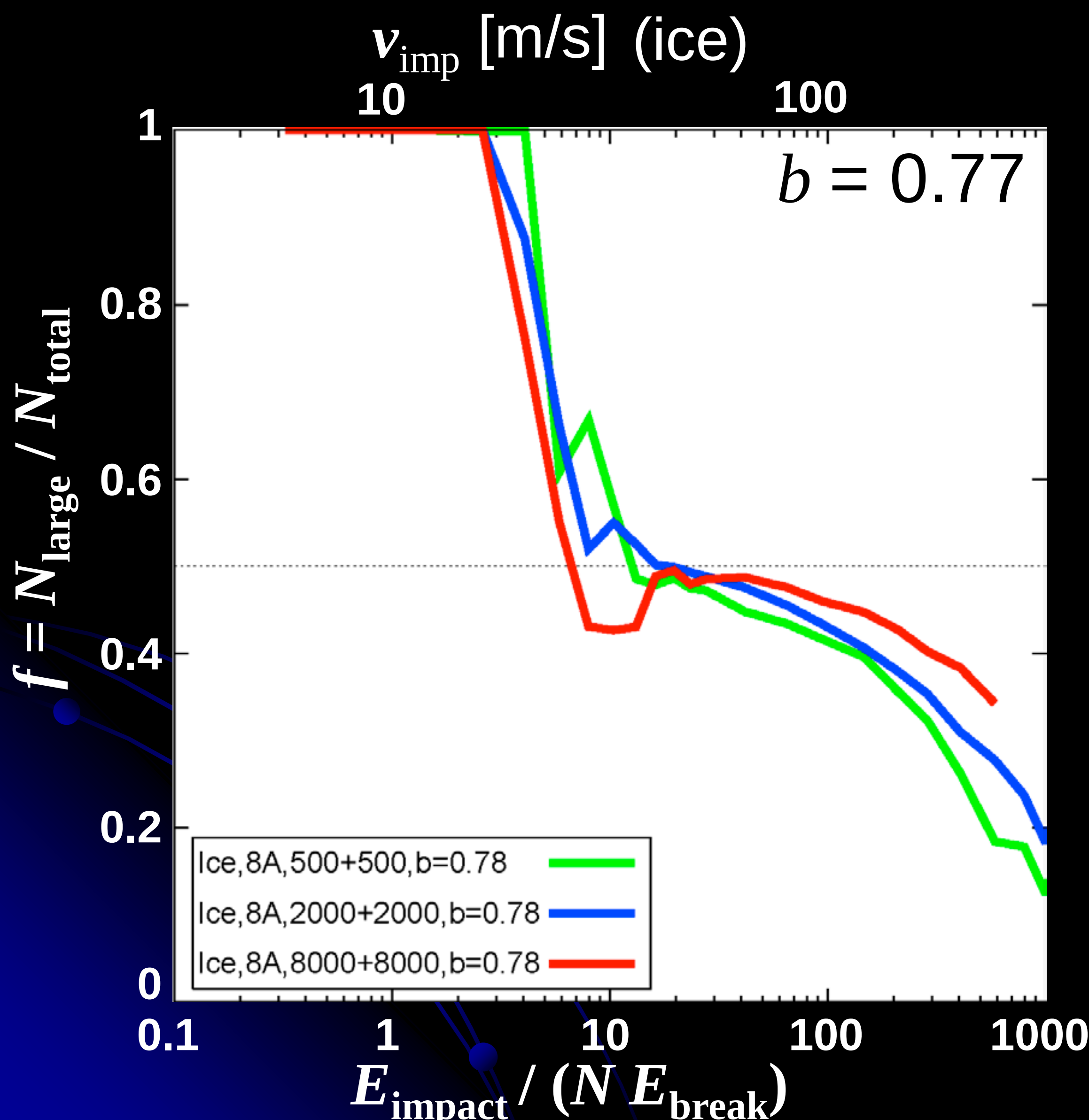


$f \equiv N_{\mathrm{large}} / N_{\mathrm{total}}$

: growth efficiency

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

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

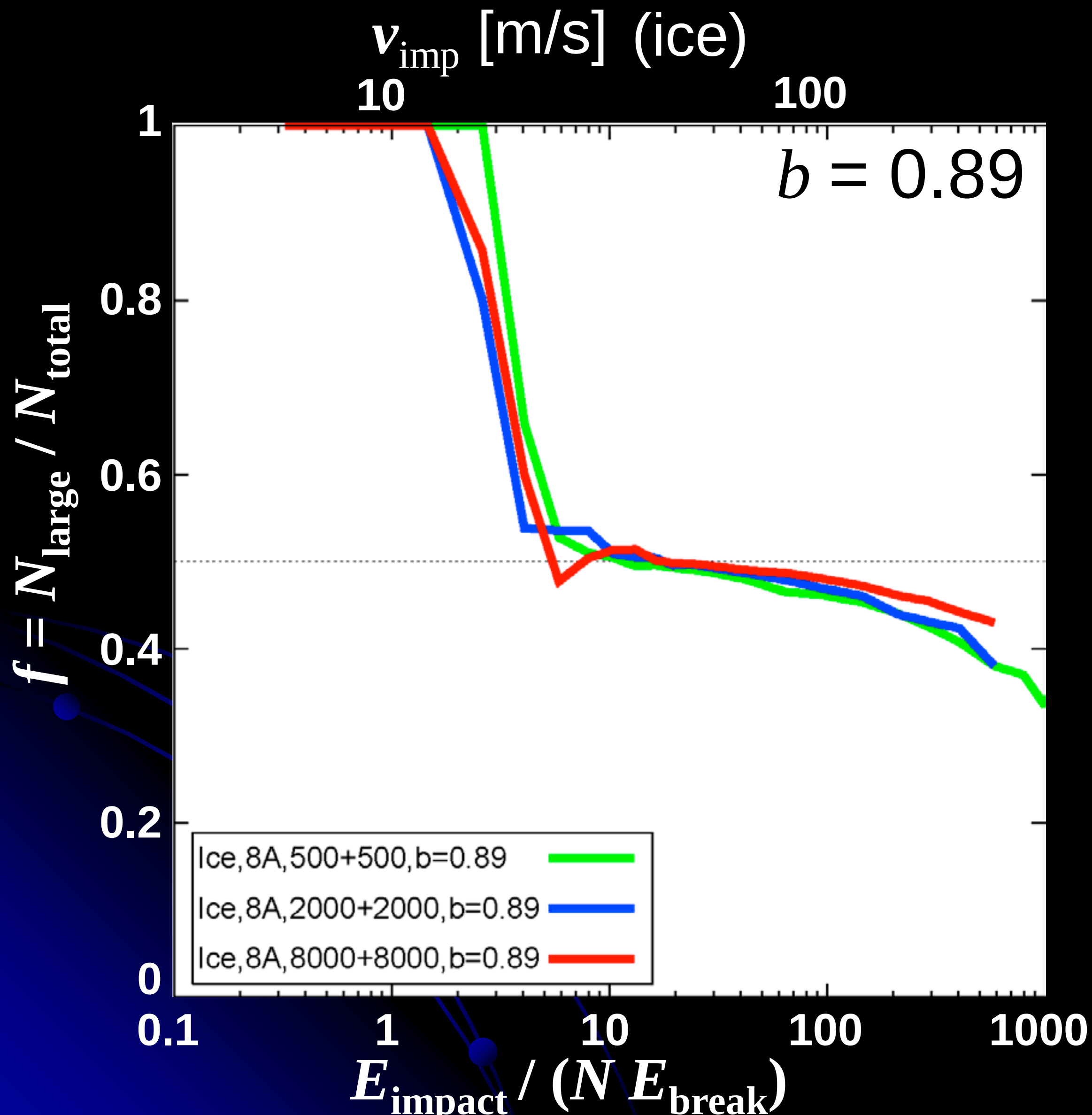


$f \equiv N_{large} / N_{total}$

: growth efficiency

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

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

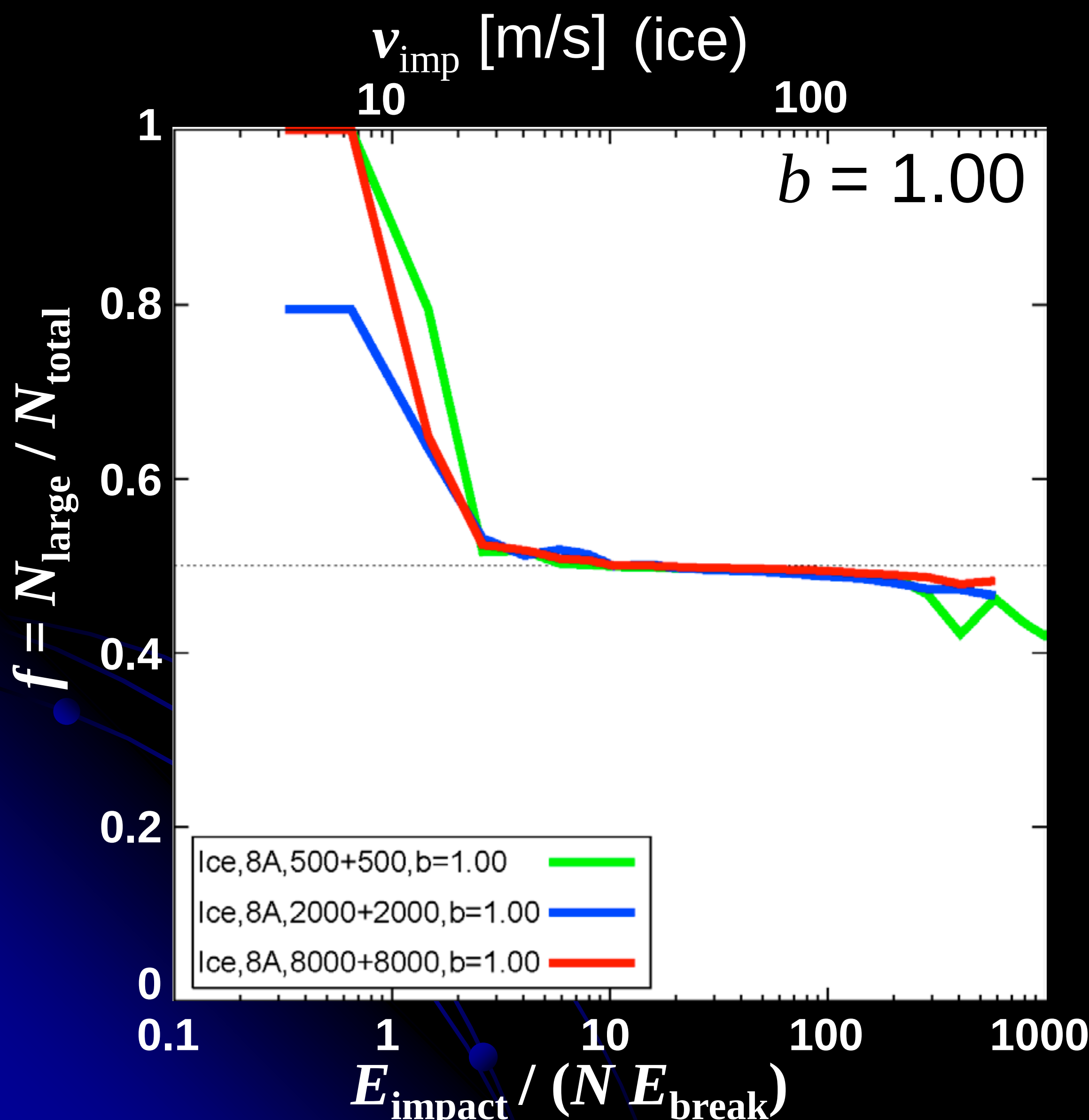


$f \equiv N_{\mathrm{large}} / N_{\mathrm{total}}$

: growth efficiency

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

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



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

: growth efficiency

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

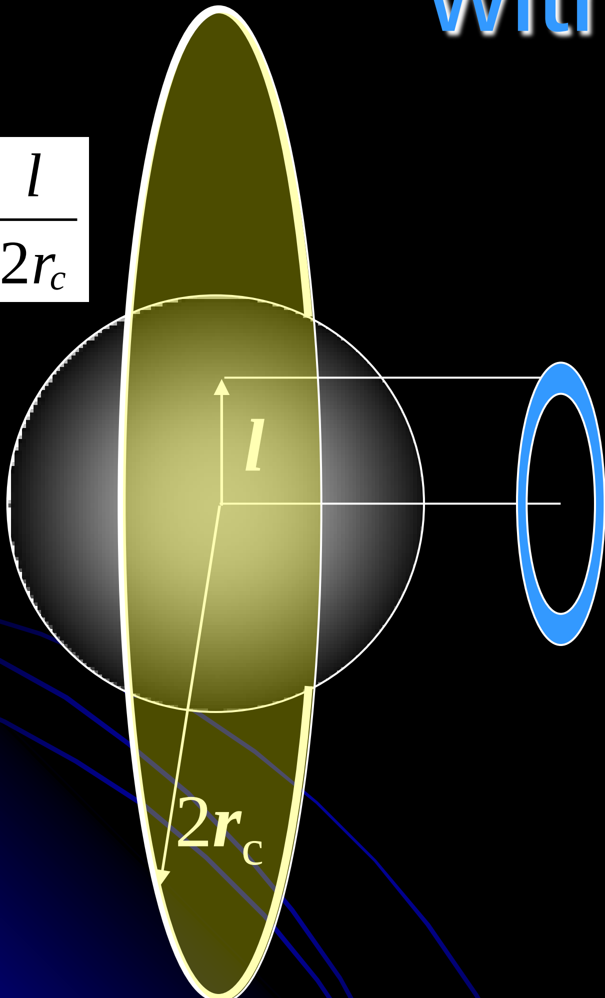
✓Offset collisions

⬇

independent of N

Probability of collisions within [b, b+db]

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



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

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

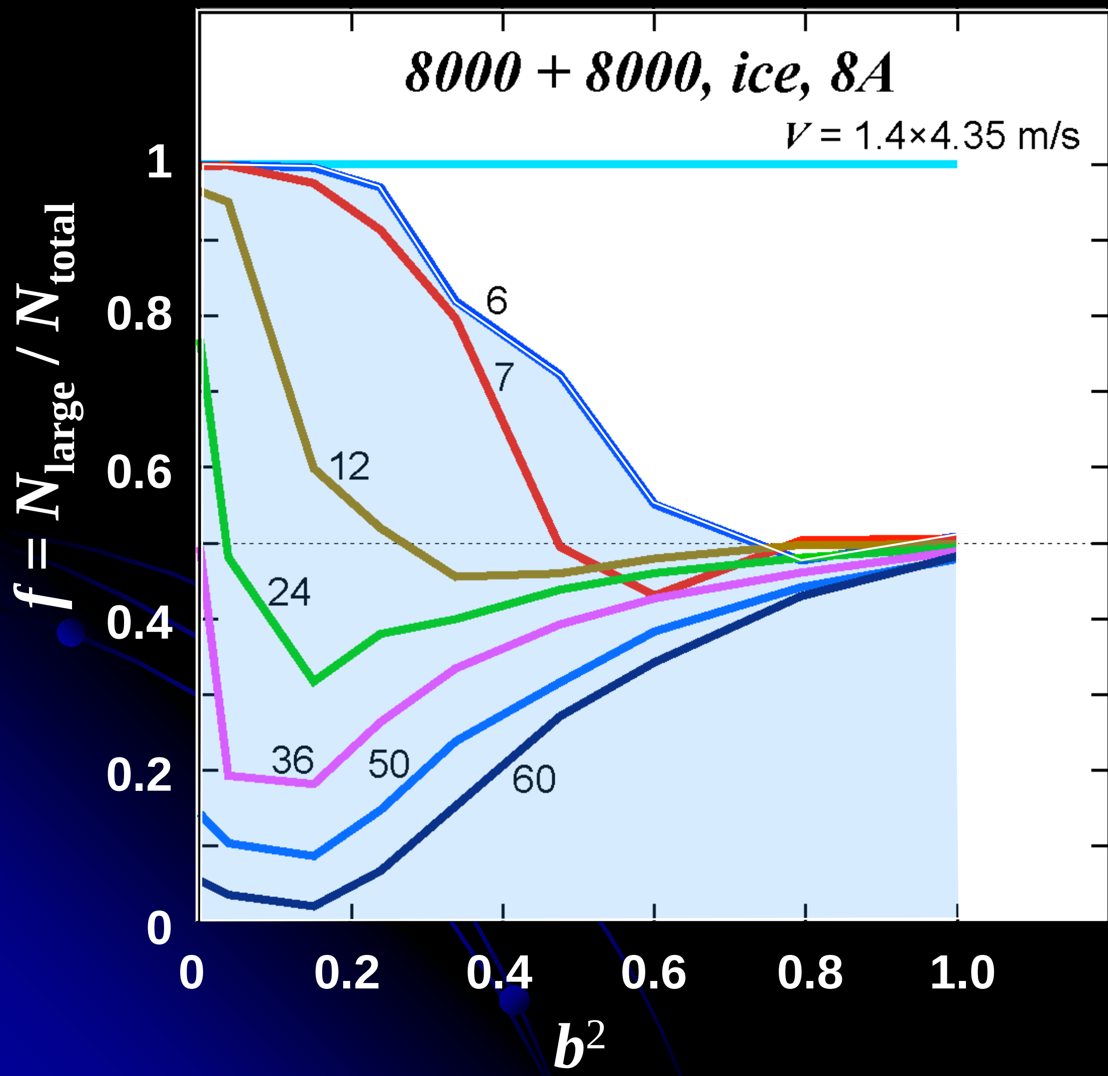
$$= \mathrm{d}b^2 \quad (0 \le b^2 \le 1)$$

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



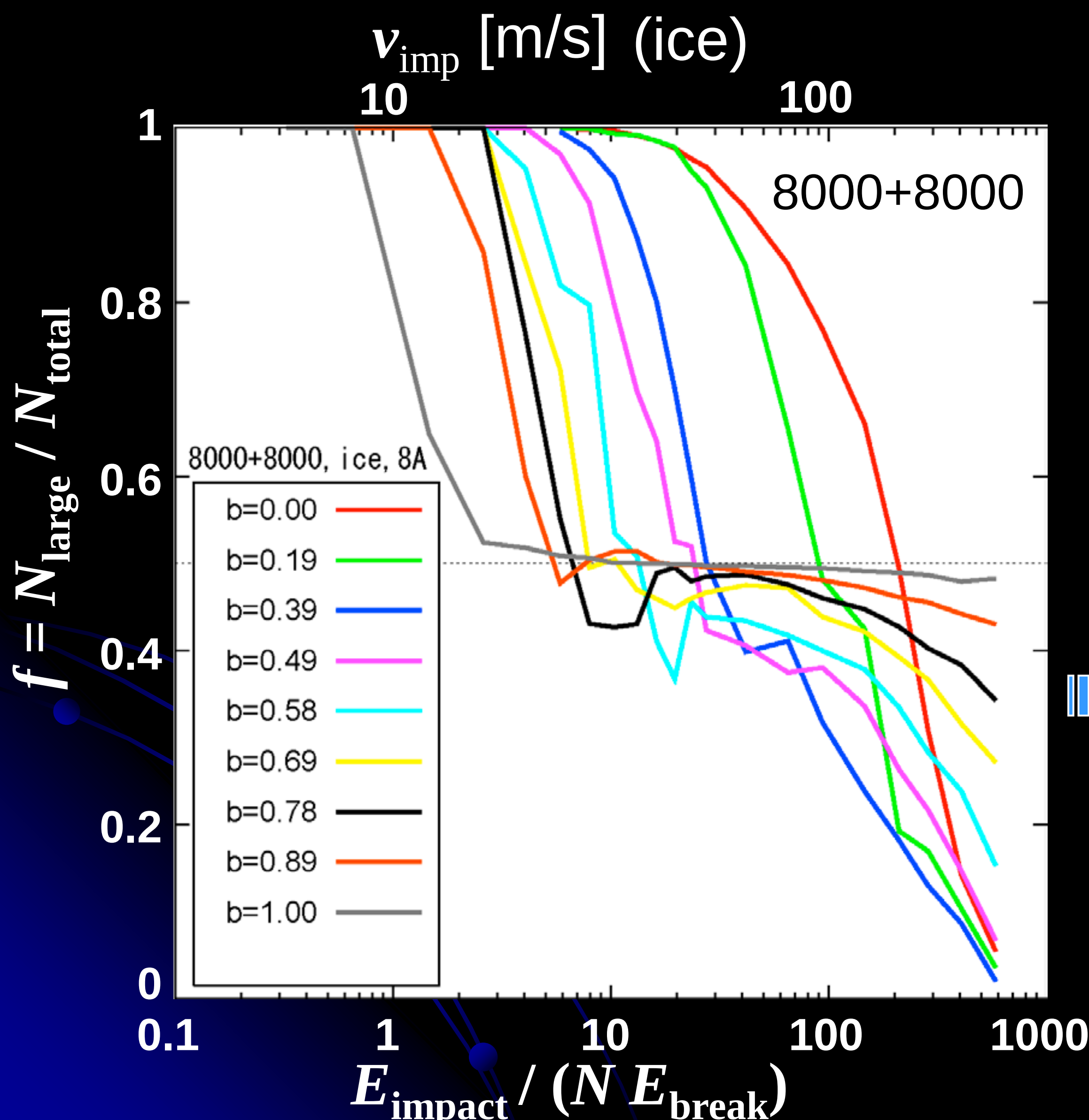
$f \equiv N_{large} / N_{total}$

: 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*



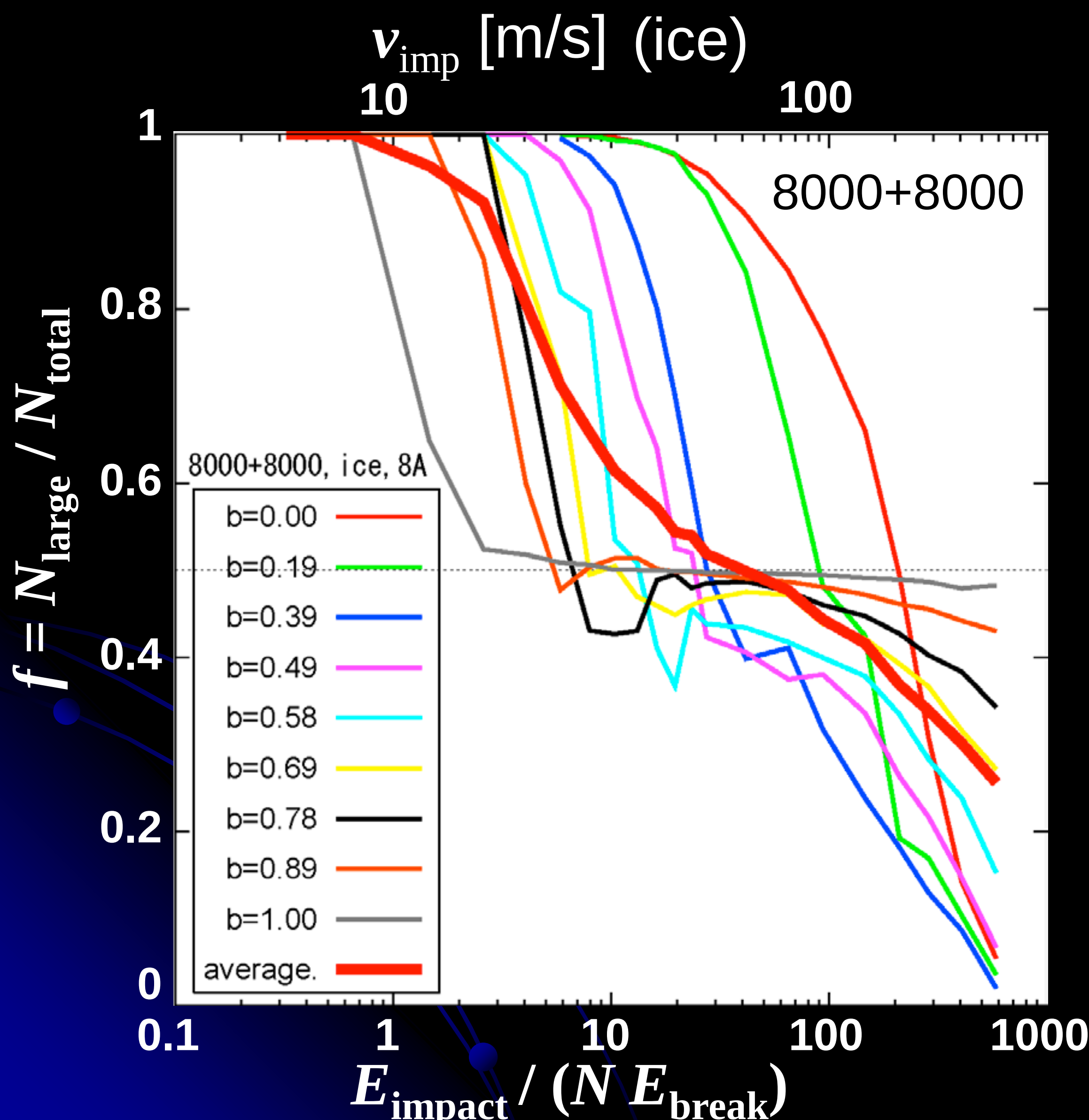
$f \equiv N_{\mathrm{large}} / N_{\mathrm{total}}$

: growth efficiency

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

⇒ Average weighted by b^2

Growth efficiency averaged



Averaged for b^2

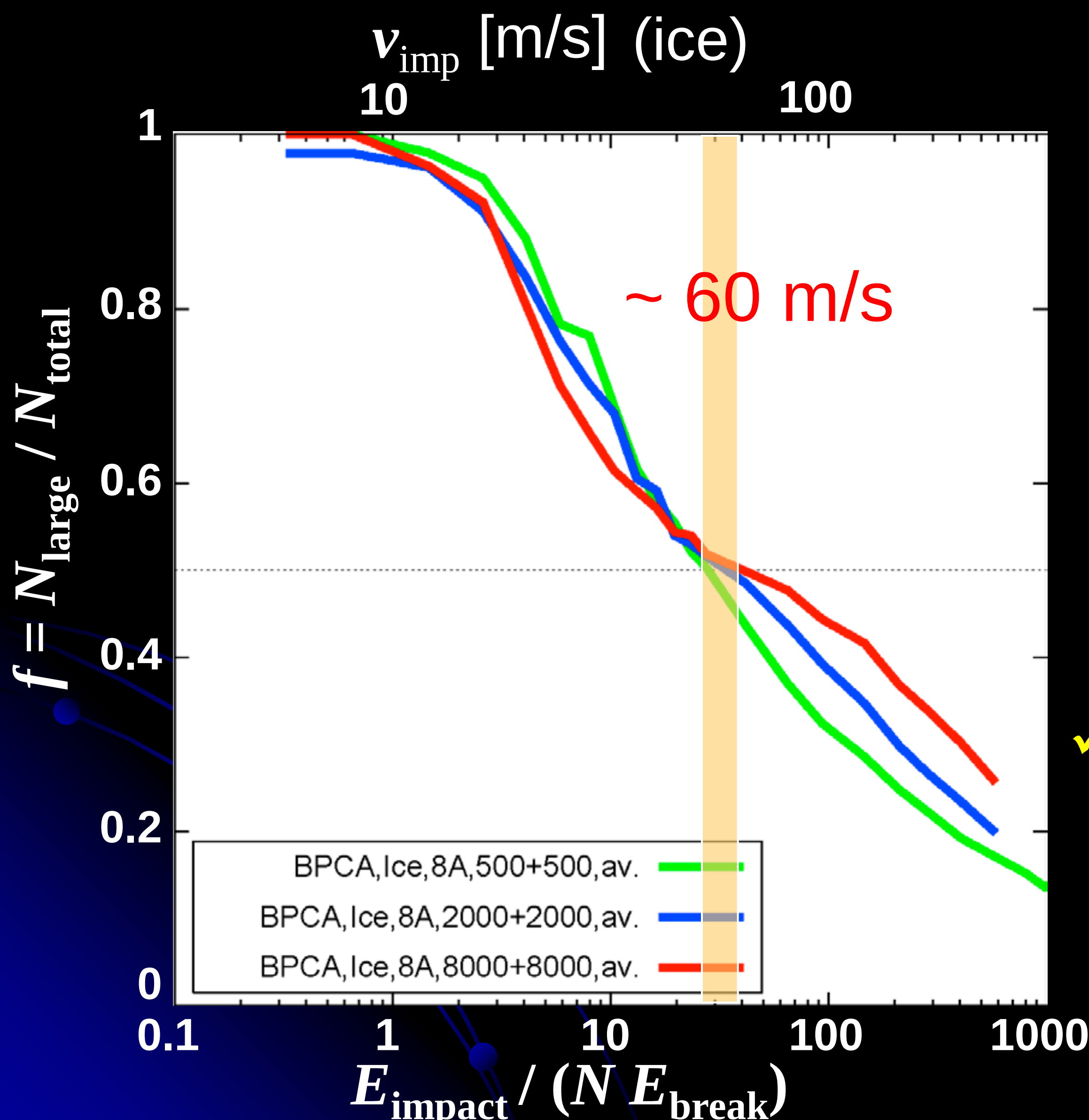
$f \equiv N_{large} / N_{total}$

: growth efficiency

$f > 0.5 \rightarrow$ + growth

$f < 0.5 \rightarrow$ - growth

Growth efficiency averaged



Averaged for b^2

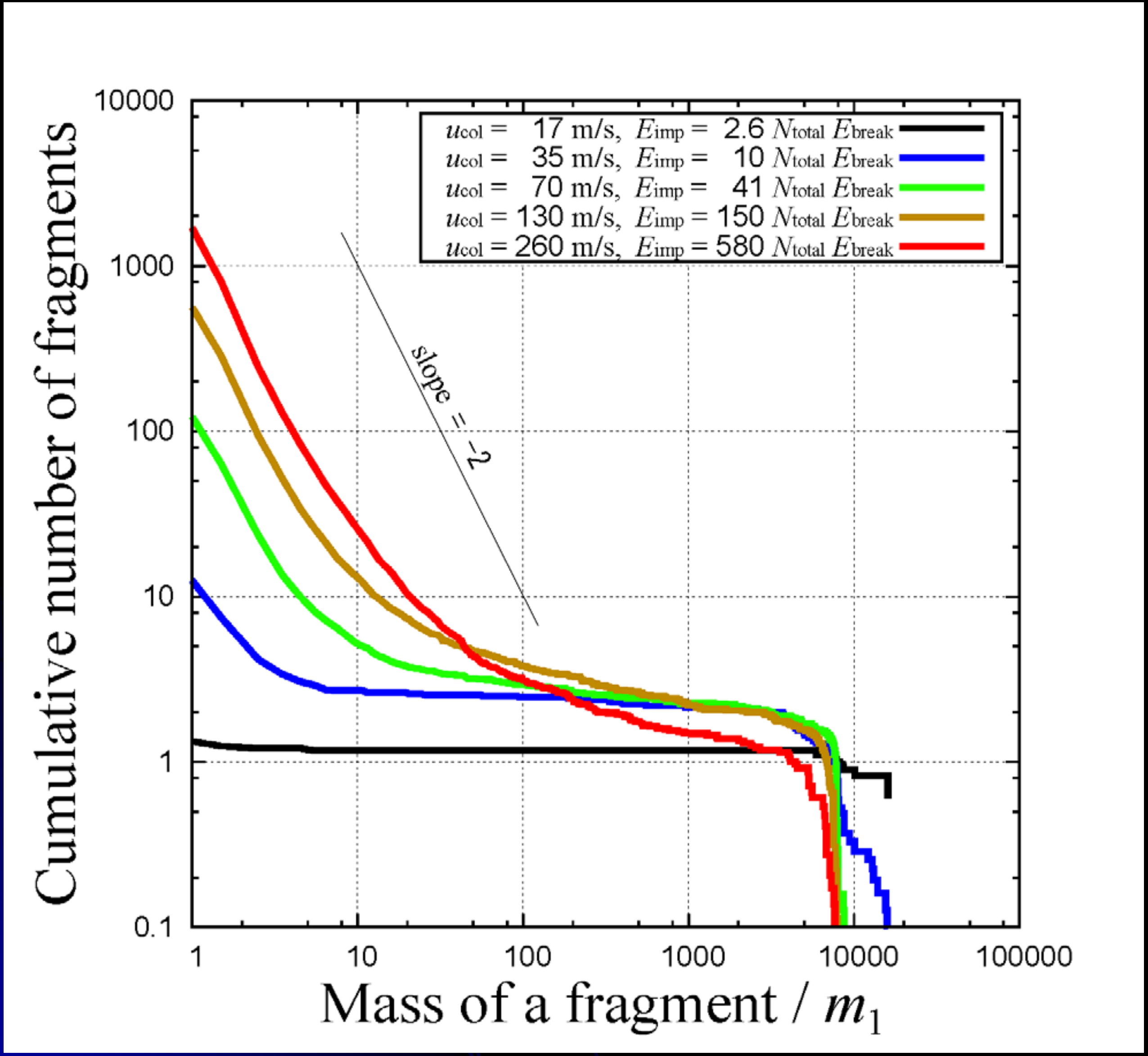
$f \equiv N_{large} / N_{total}$

: growth efficiency

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

✓small dependence on N

Cumulative number distribution : $N(>m)$



8000+8000

b^2 average

✓Small fragments：
slope < ~ -2

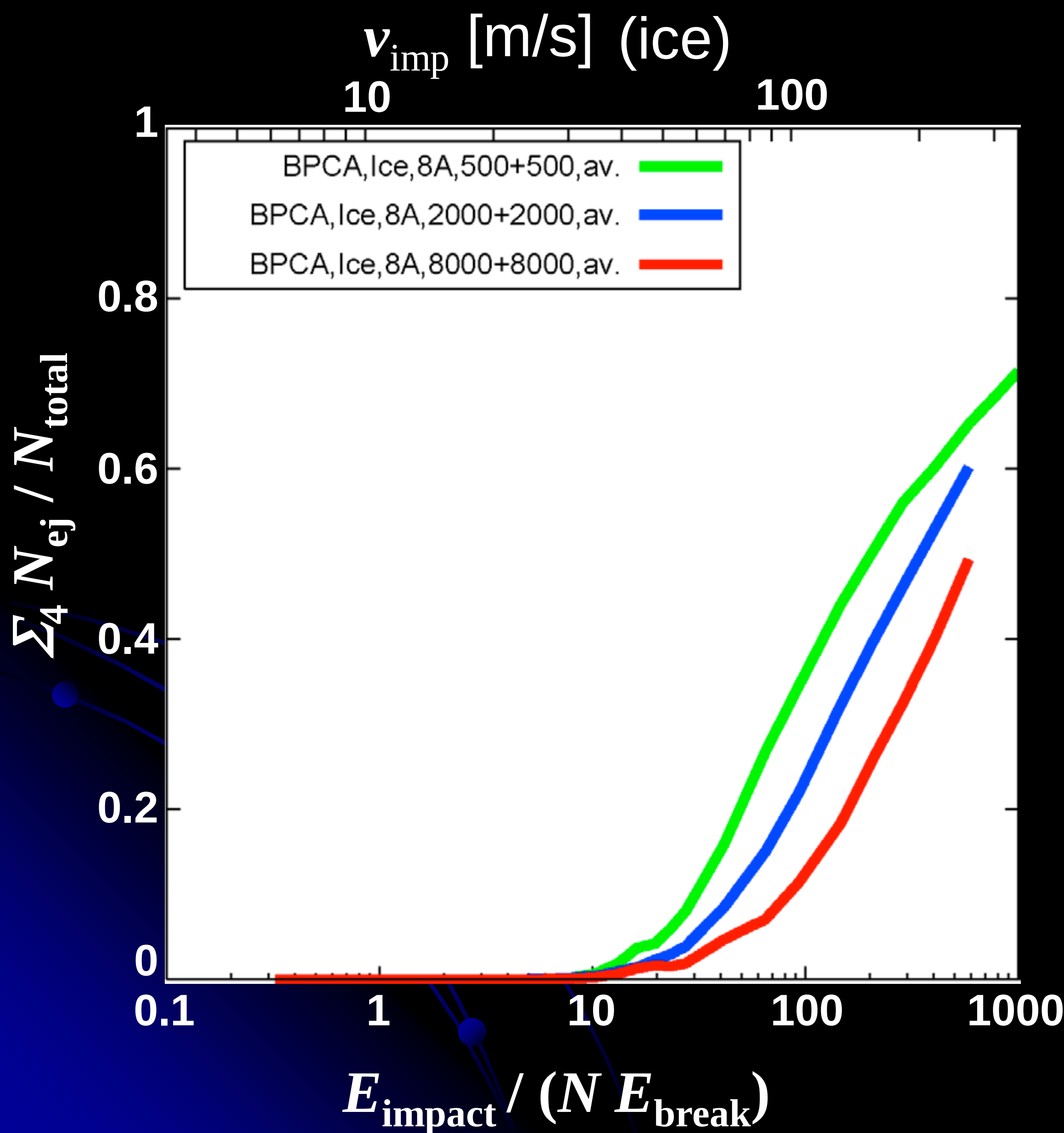
✓Large & small fragments

cf. slope:

S.C.C.→-5/6

Collisional disruption in experiments
→ -0.3 ~ -1

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



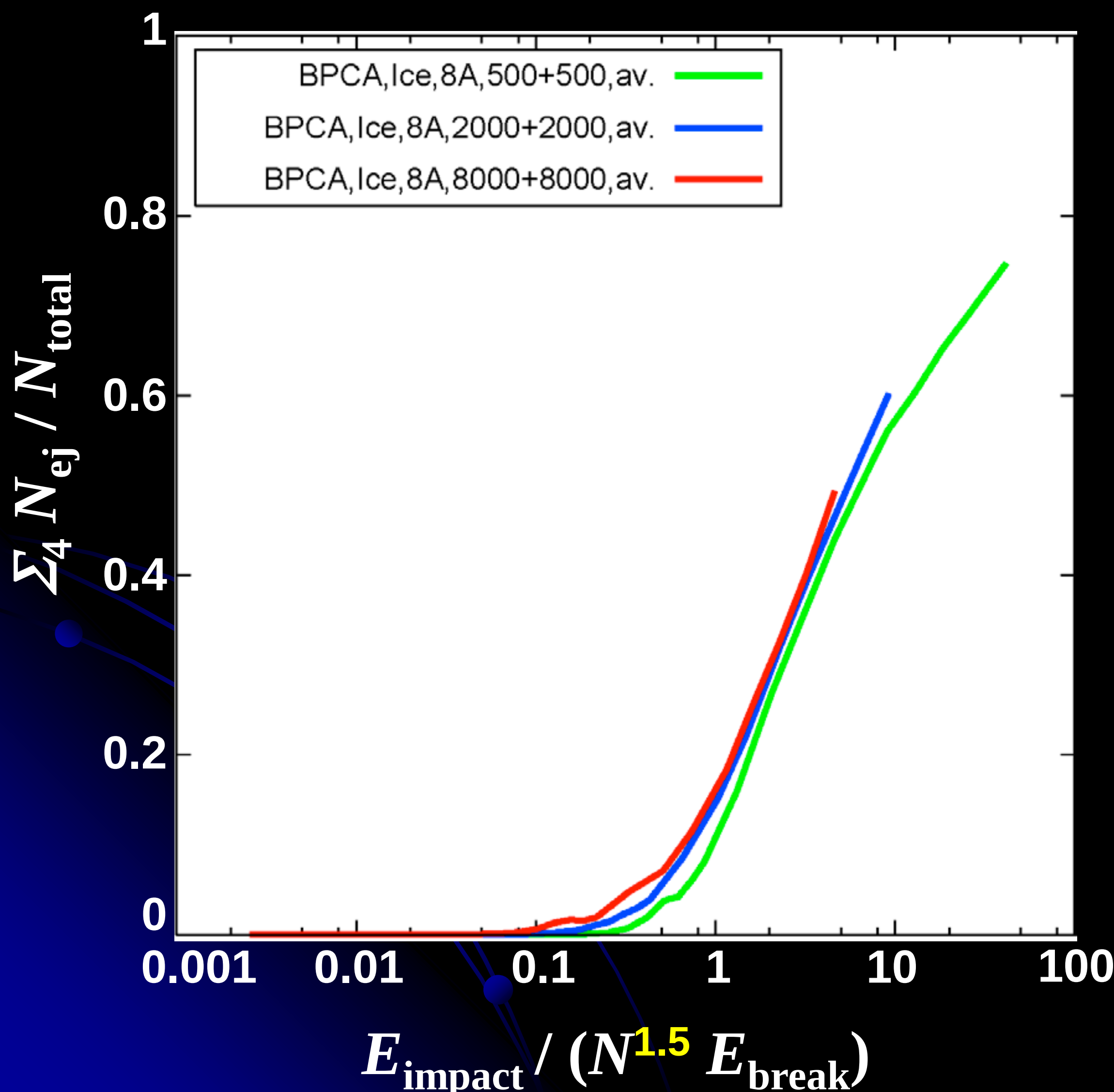
Averaged over b^2

✓dependent on N

The larger aggregates,
the smaller amount of ejecta.

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

Averaged over b^2



✓dependent on N

The larger aggregates,
the smaller amount of ejecta.

Normalized
by using $N^{1.5}$

Growth Efficiency For Collisions of BCCAs

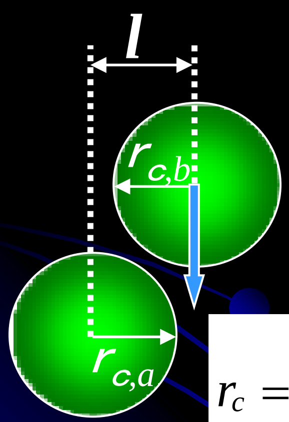
Initial Conditions and Parameters

Collisions of BCCA clusters

Results are averaged

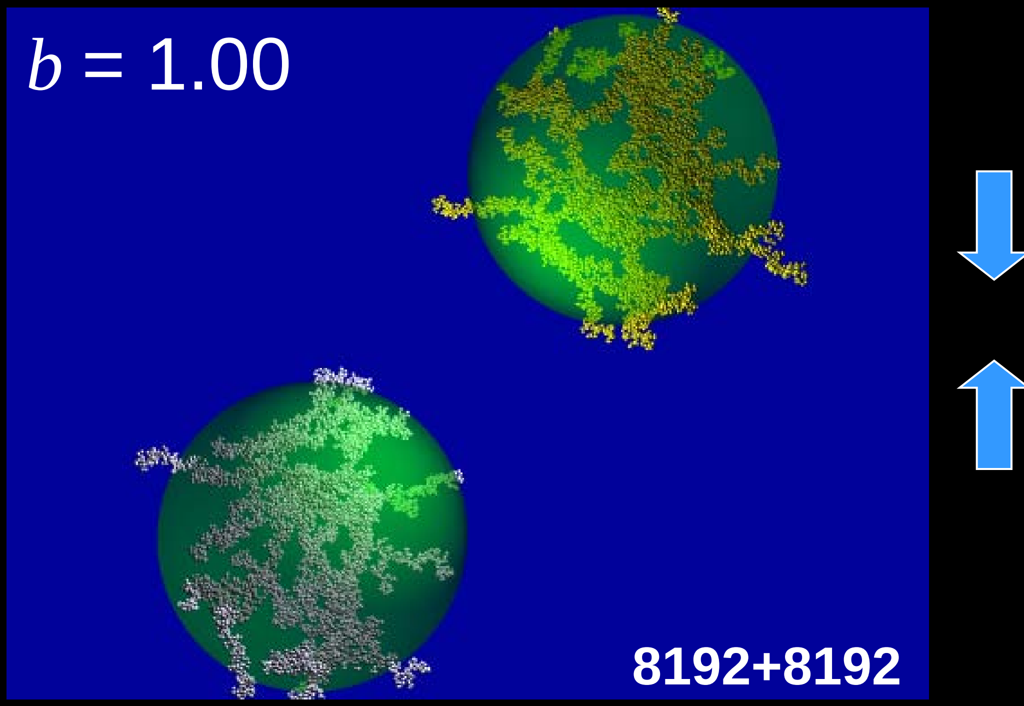
✓ BCCA clusters are:

- composed of 512, 2048, or 8192 particles (5 types randomly produced)
- Impact parameter : $\boldsymbol{b}$ (defined by using characteristic radius r_c)



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

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

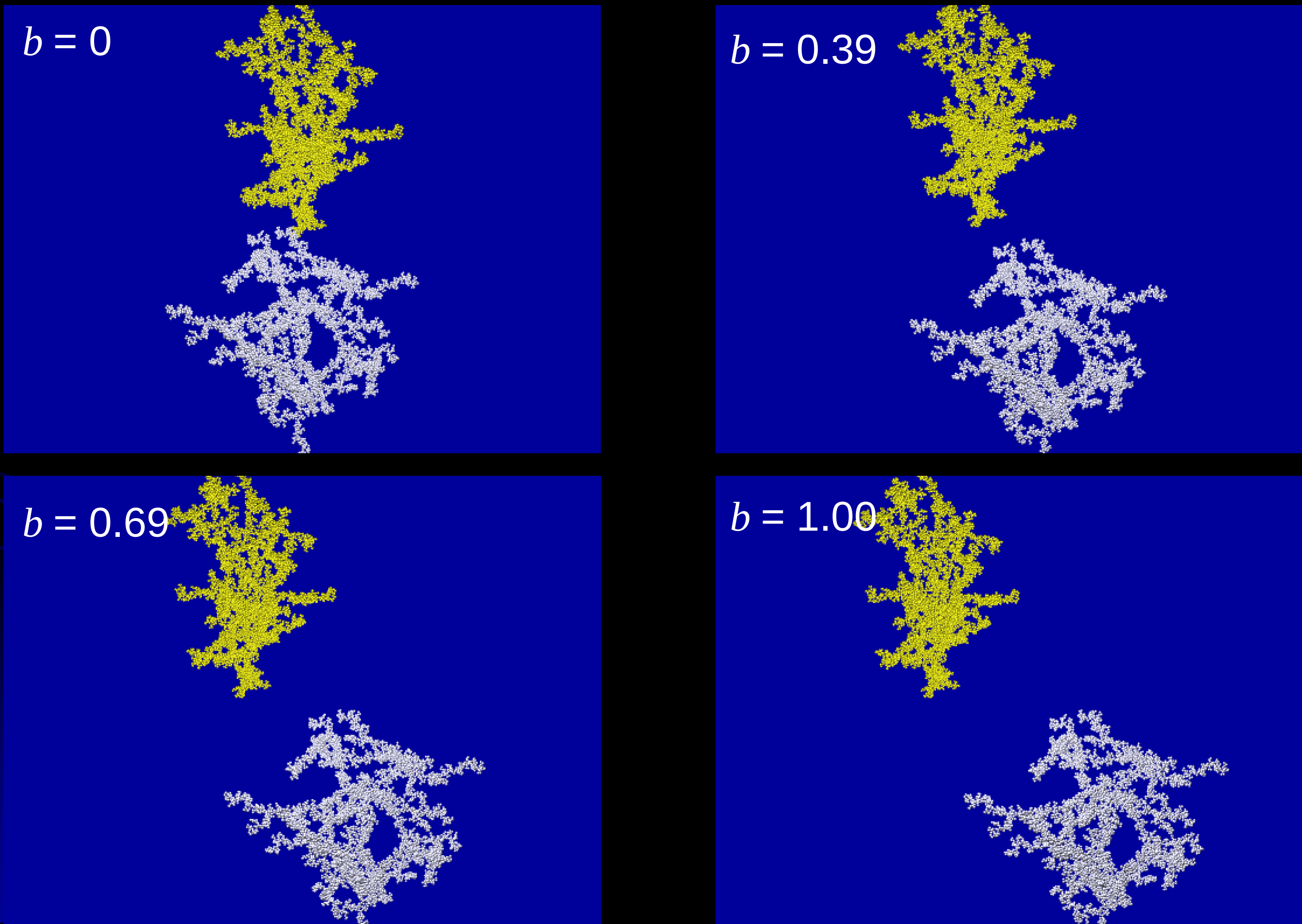


✓Ice (E = 7.0×10^{10} Pa, ν = 0.25, γ = 100 mJ/m^2, R = 0.1μm) , critical rolling displace. ξ_{crit} = 8Å

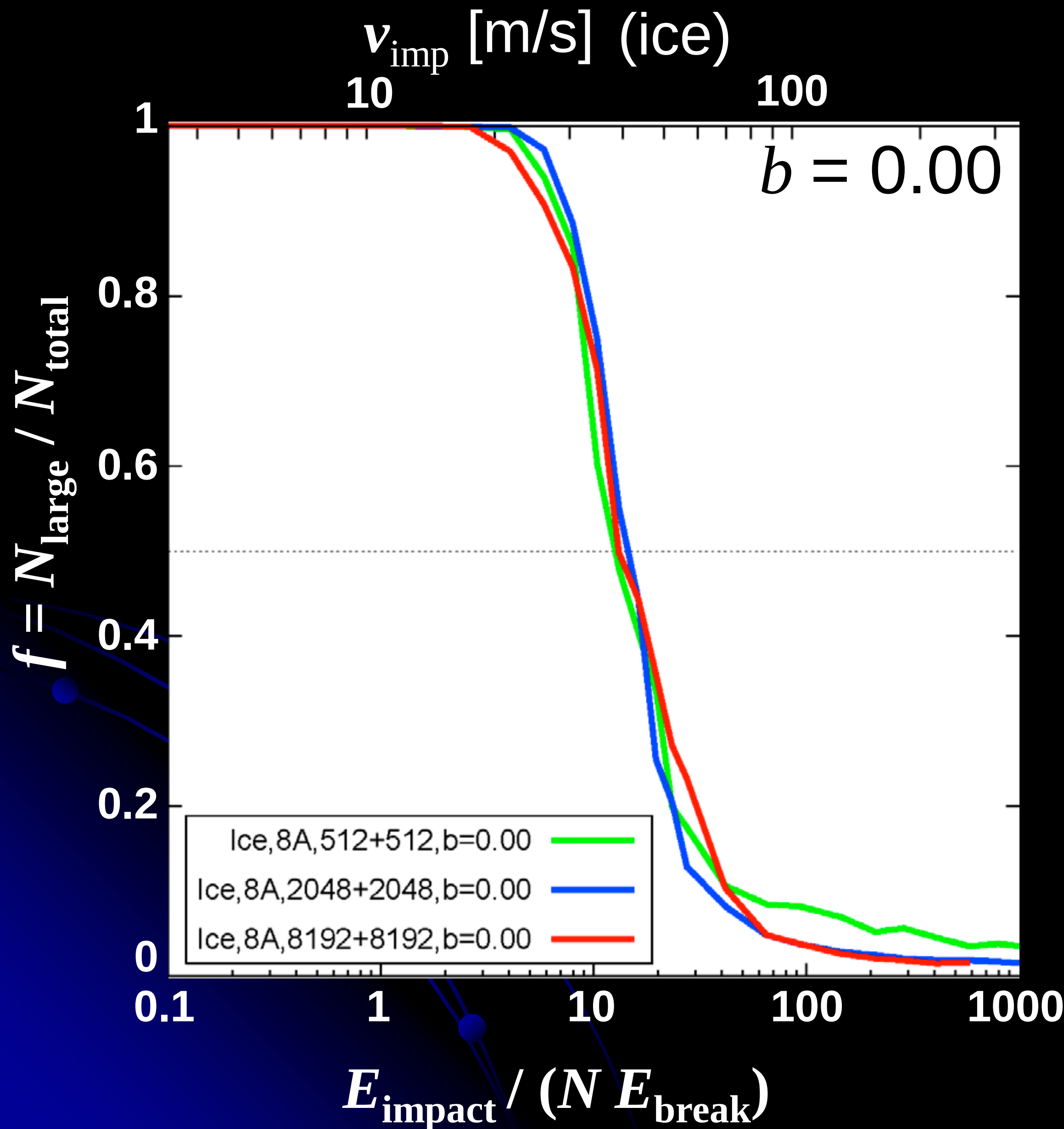
✓Impact velocity v_{imp} = 6 - 300 m/s

Collisions of BCCA clusters

N=8192+8192, ice, ξ_c = 8Å, v_{imp} = 70 m/s (E_{imp} = 41 NE_{break})

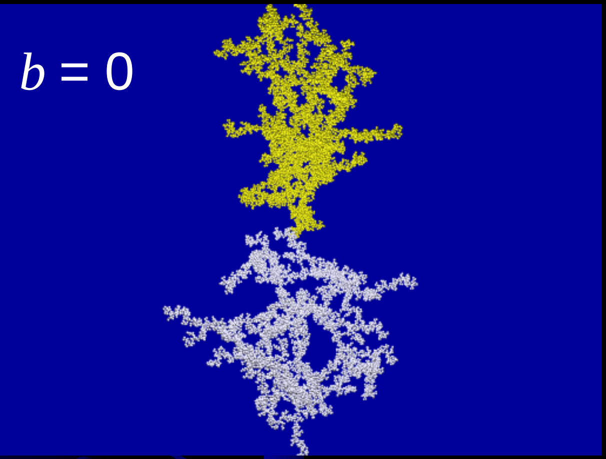


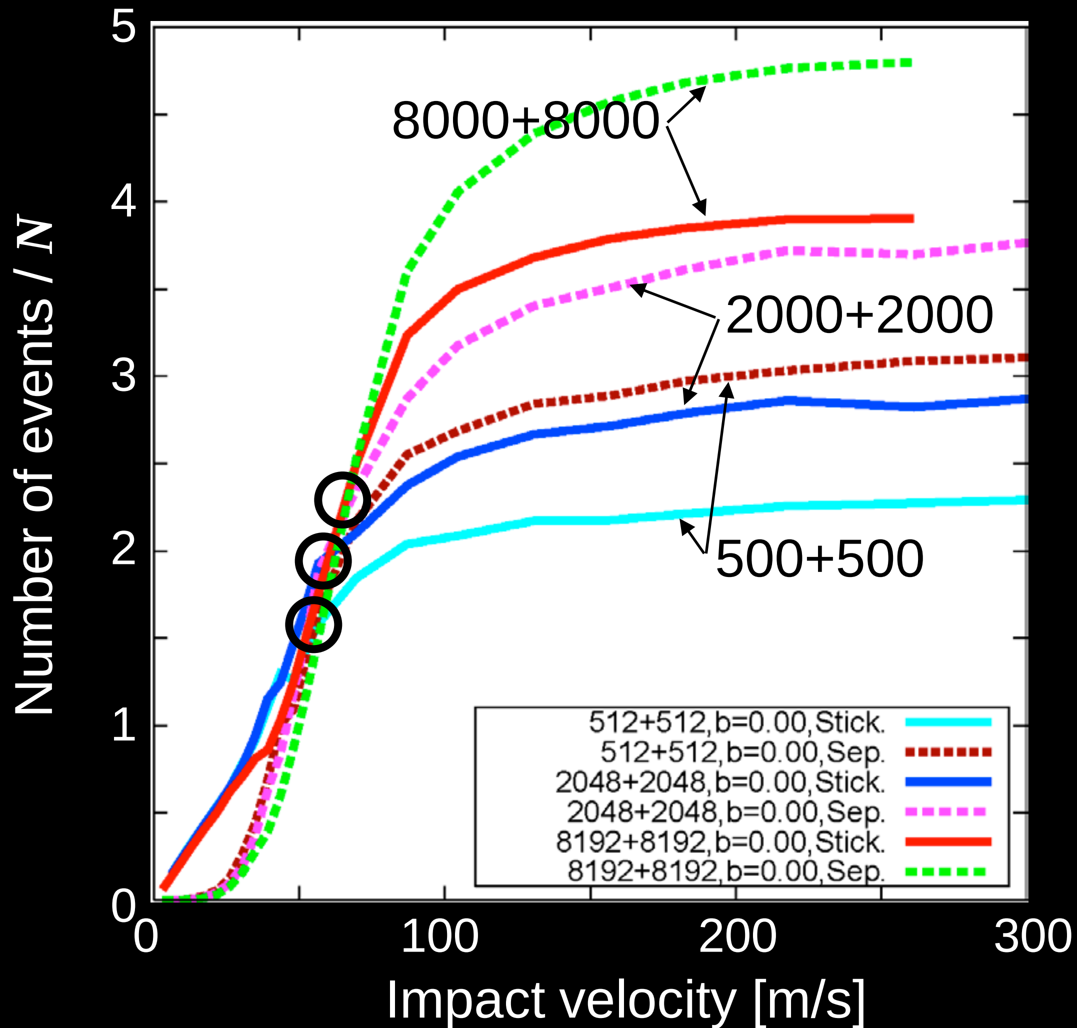
Largest fragment mass N_{large}: *growth efficiency*



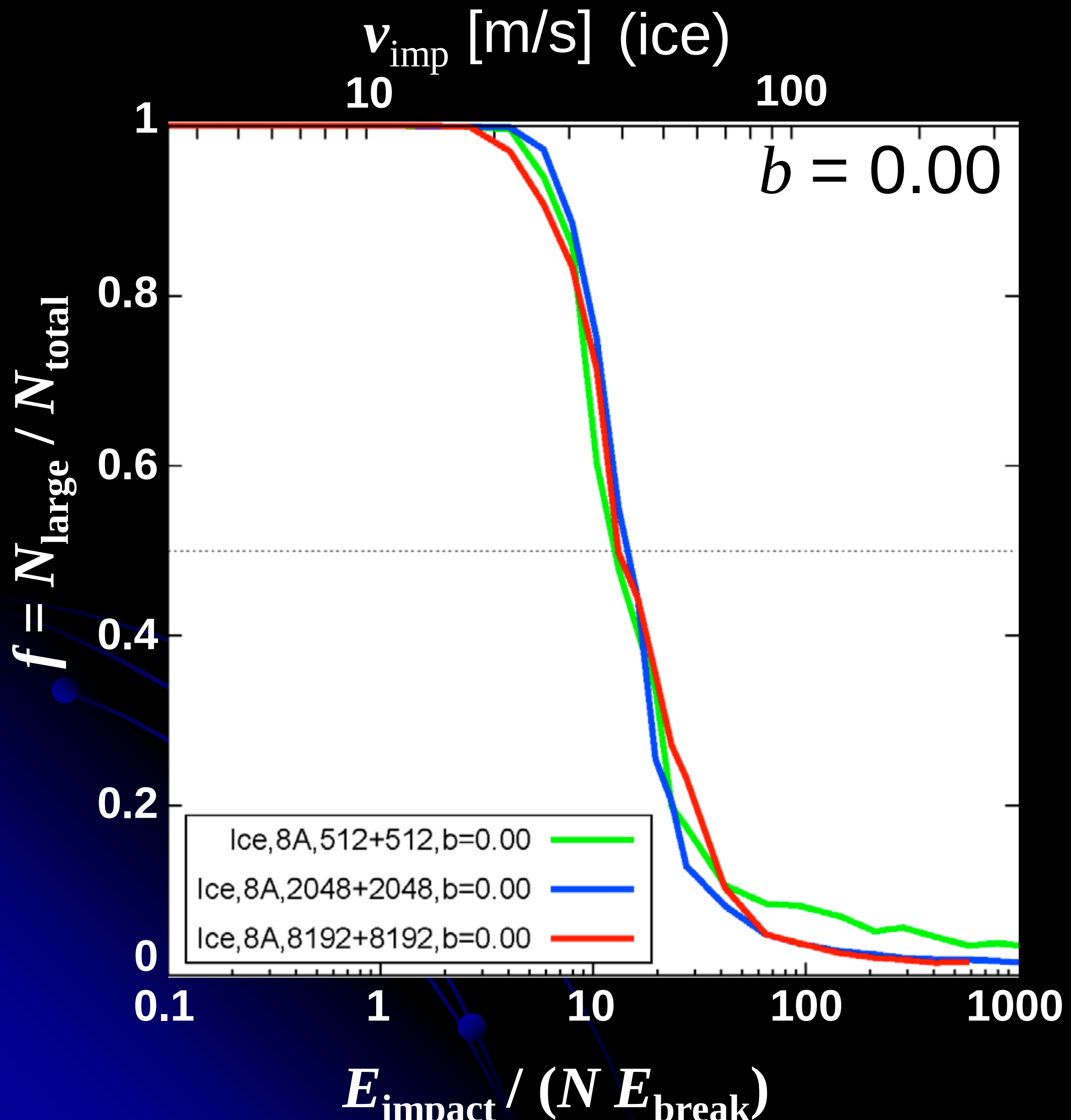
✓independent of N

- Head-on → large escape space for fragments
→ few events of sticking and separating



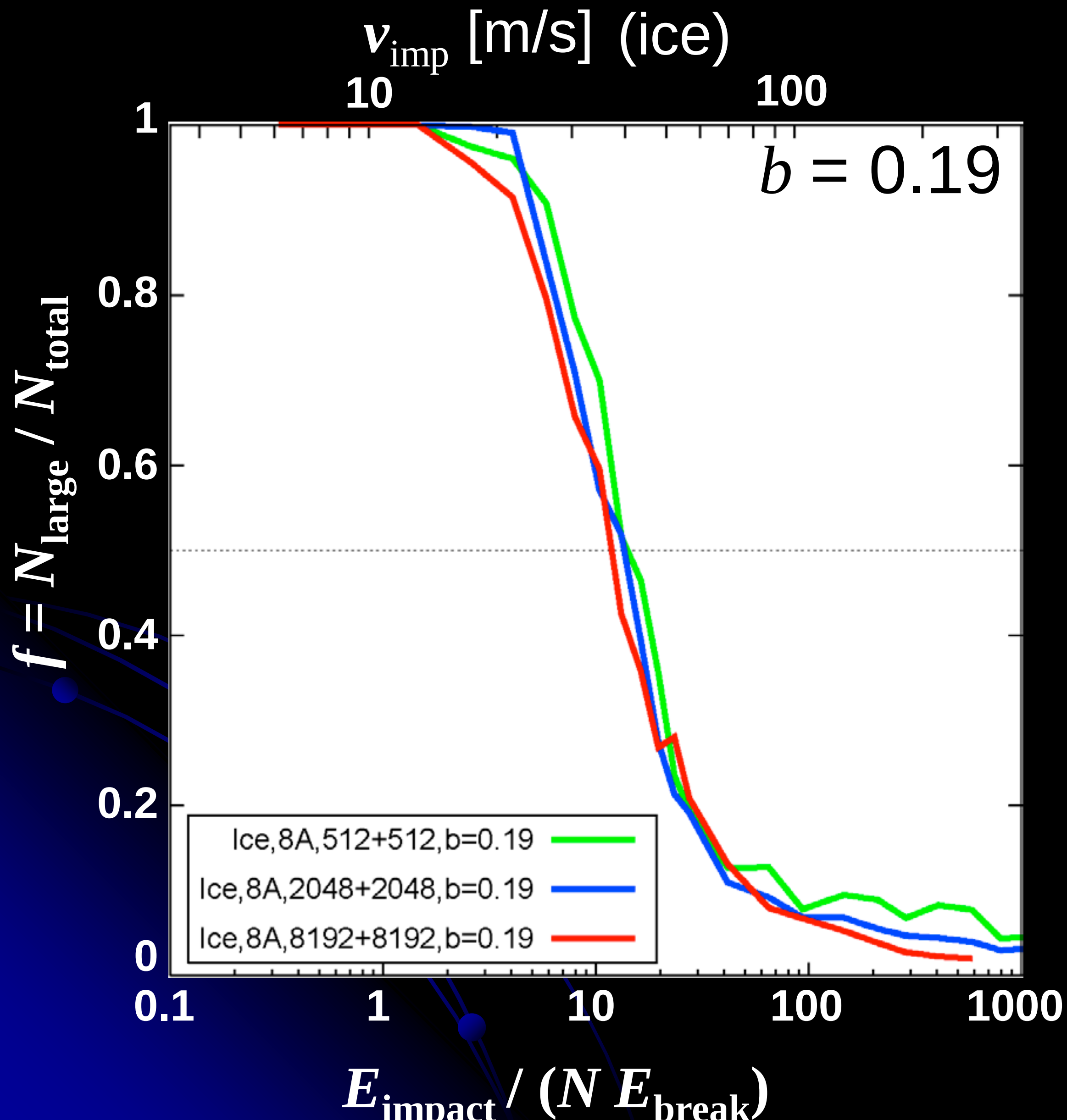


Largest fragment mass N_{large}: *growth efficiency*



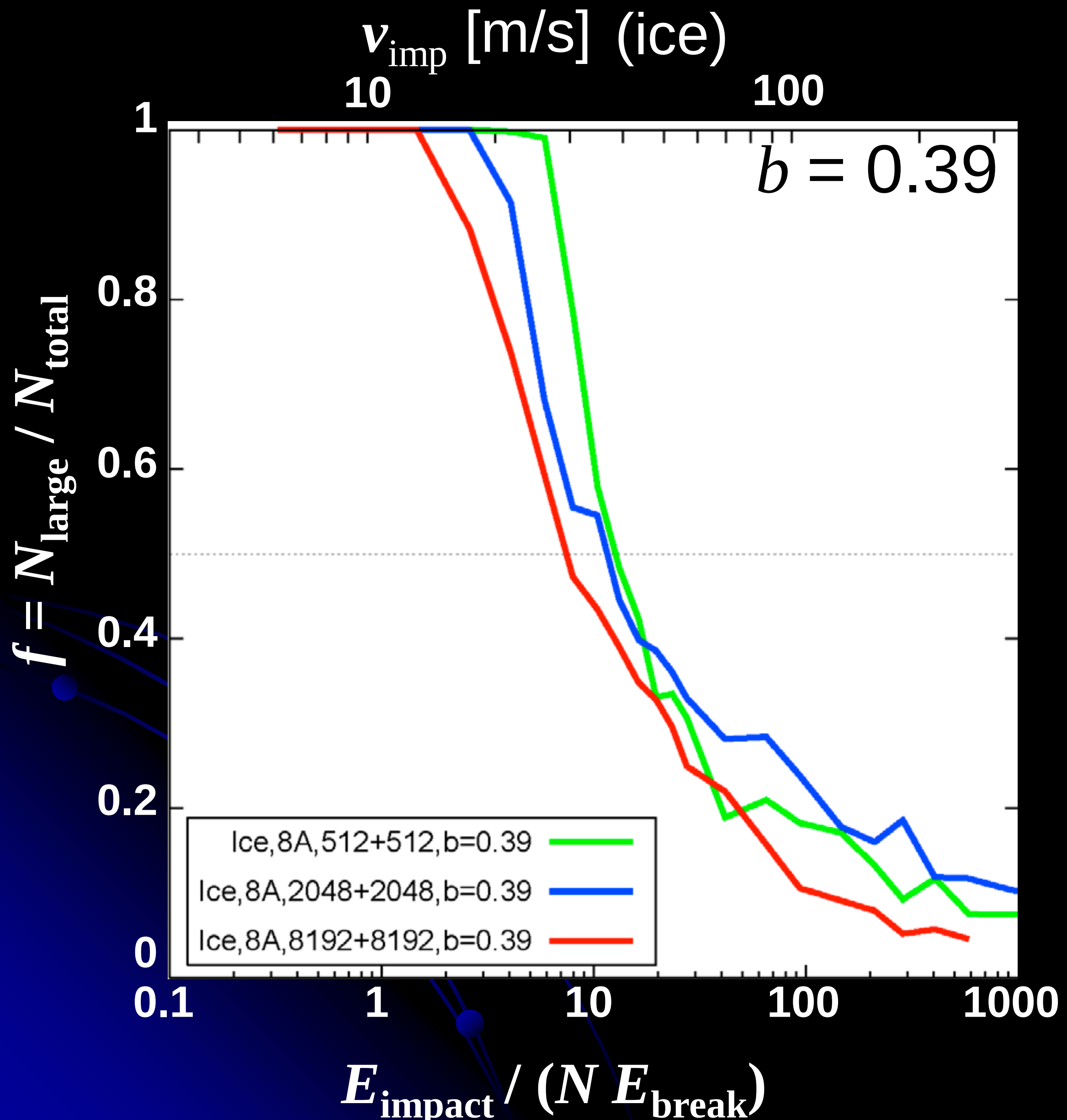
✓independent of N

Largest fragment mass $N_{\rm large}$: *growth efficiency*



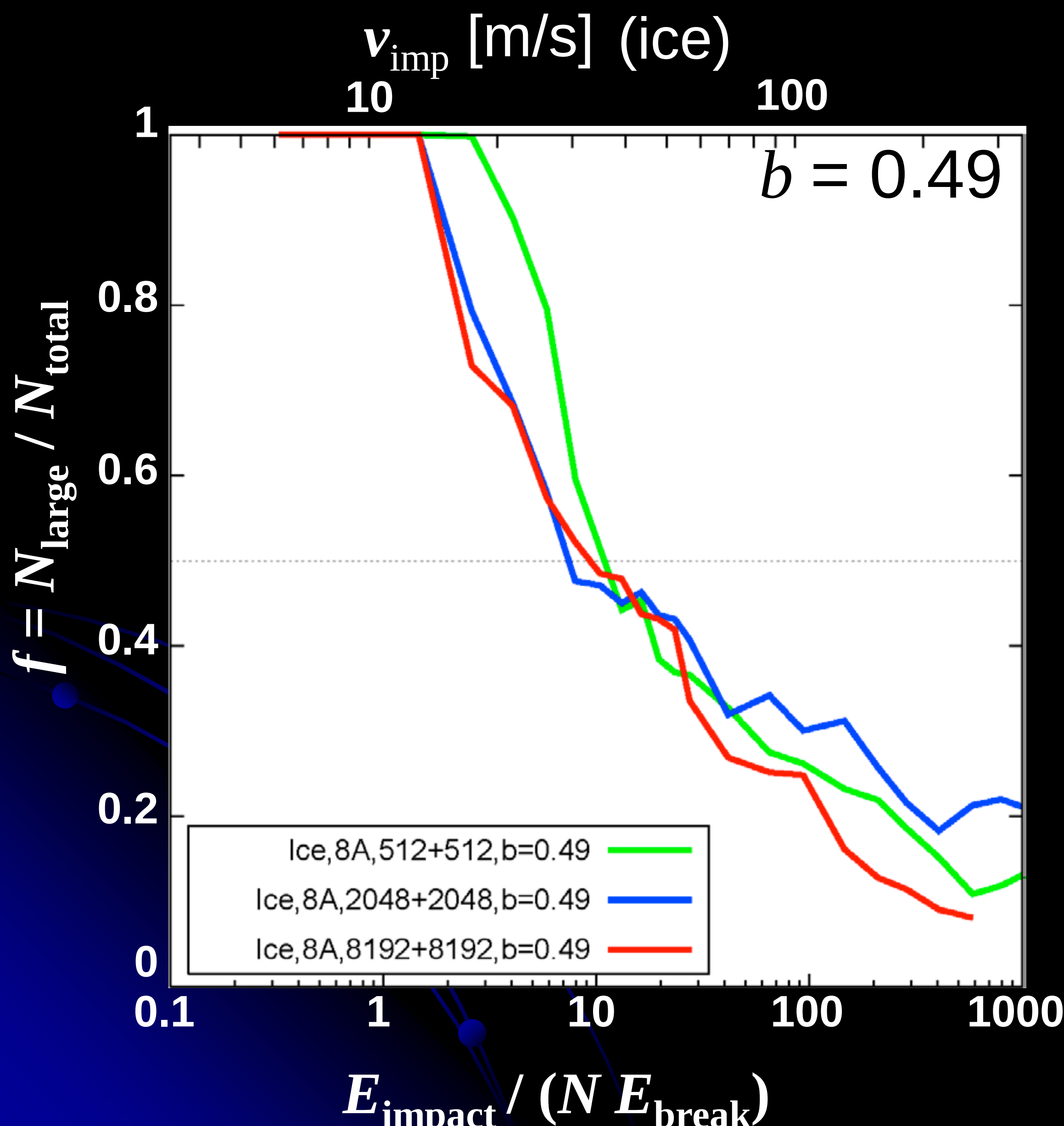
✓independent of N

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



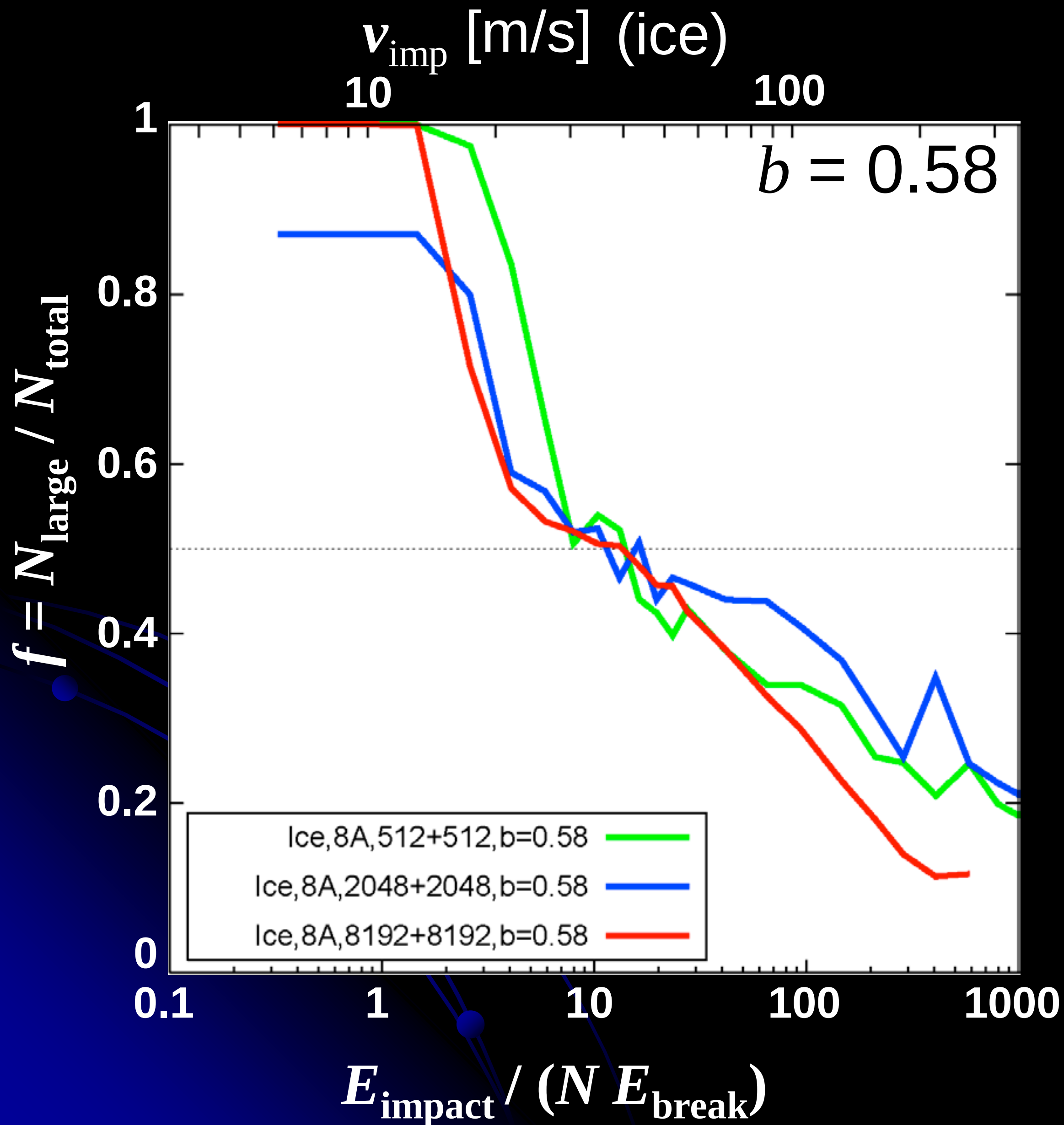
✓independent of N

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



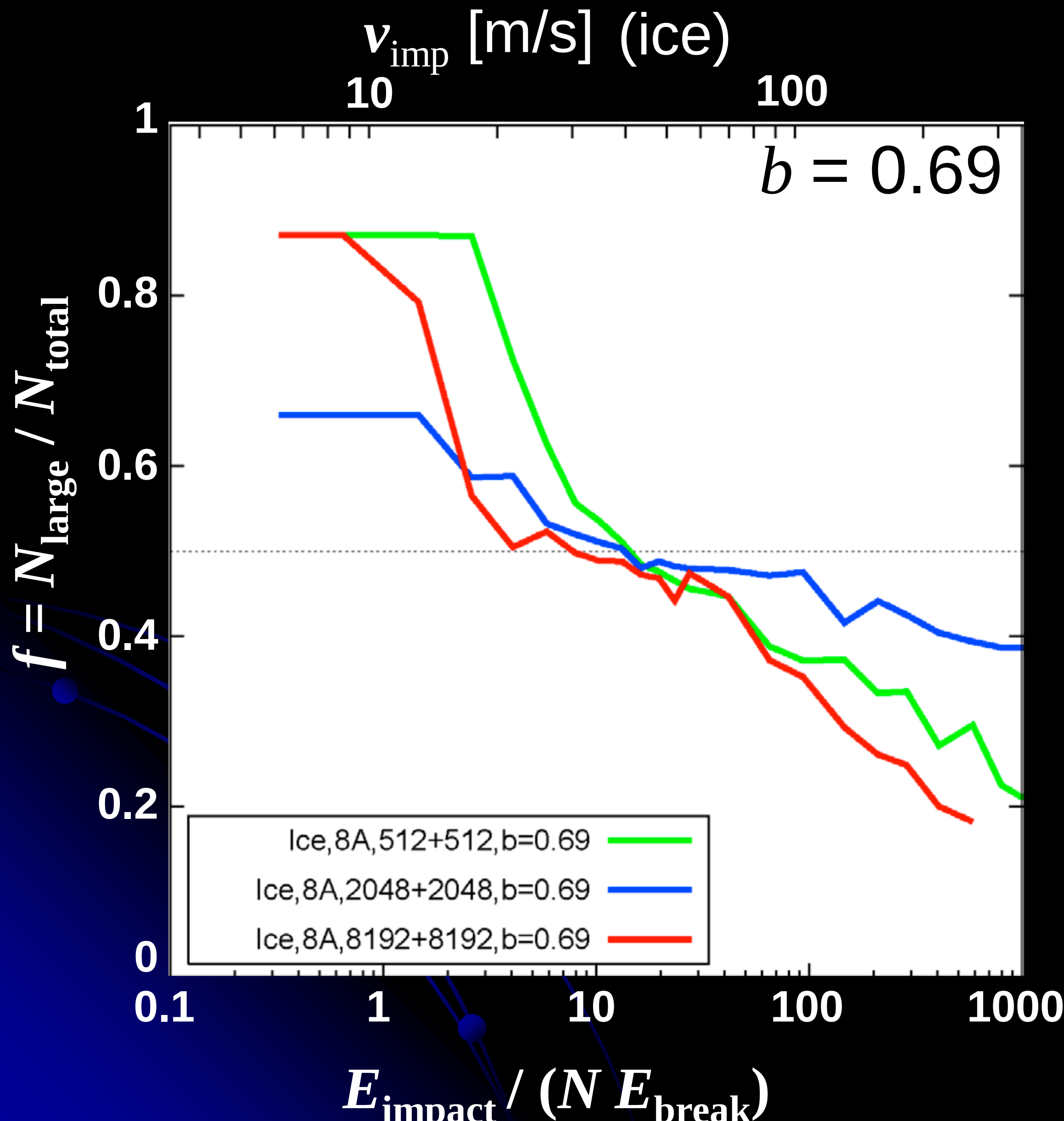
✓independent of N

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



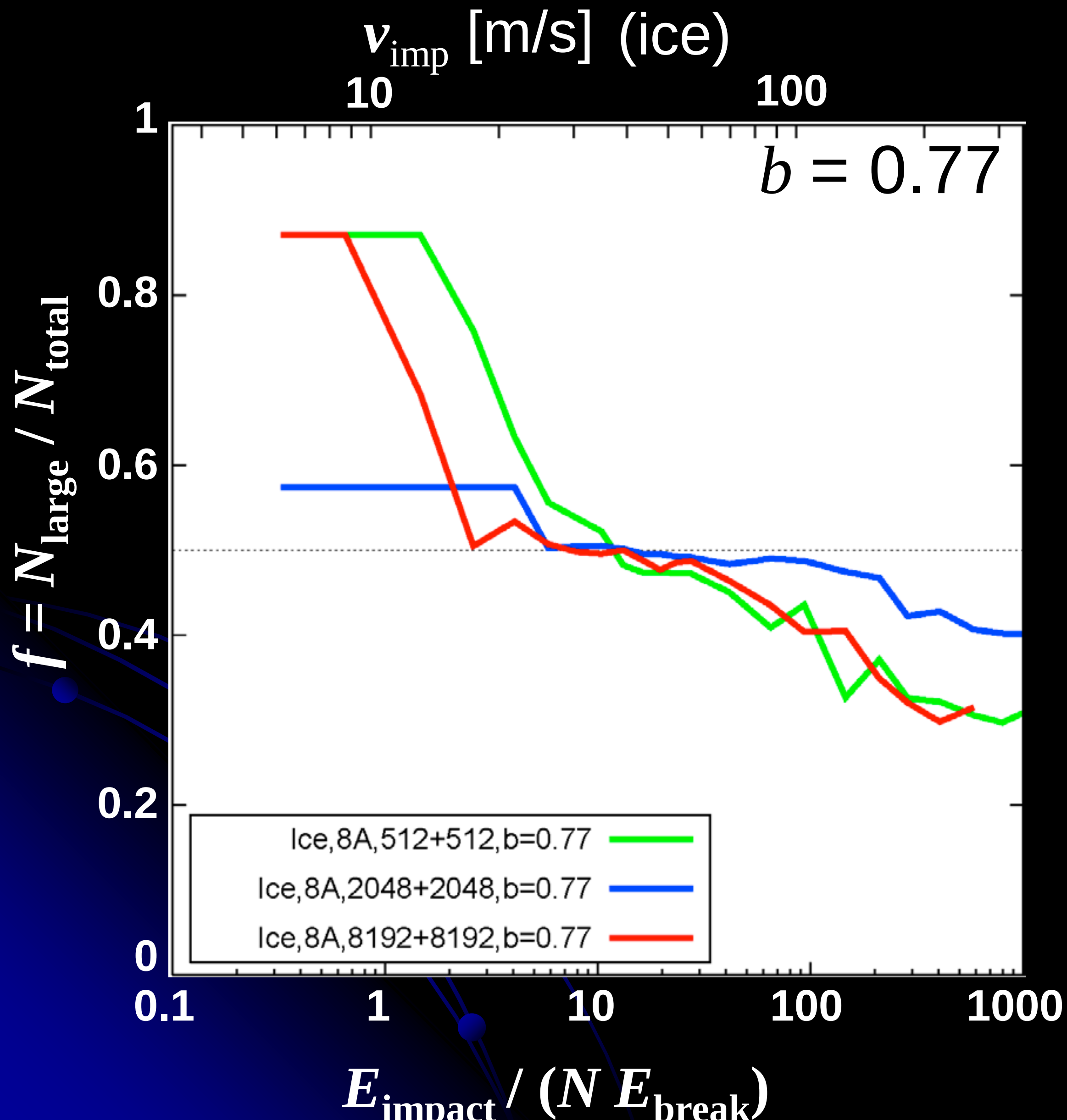
✓independent of N

Largest fragment mass $N_{\rm large}$: *growth efficiency*



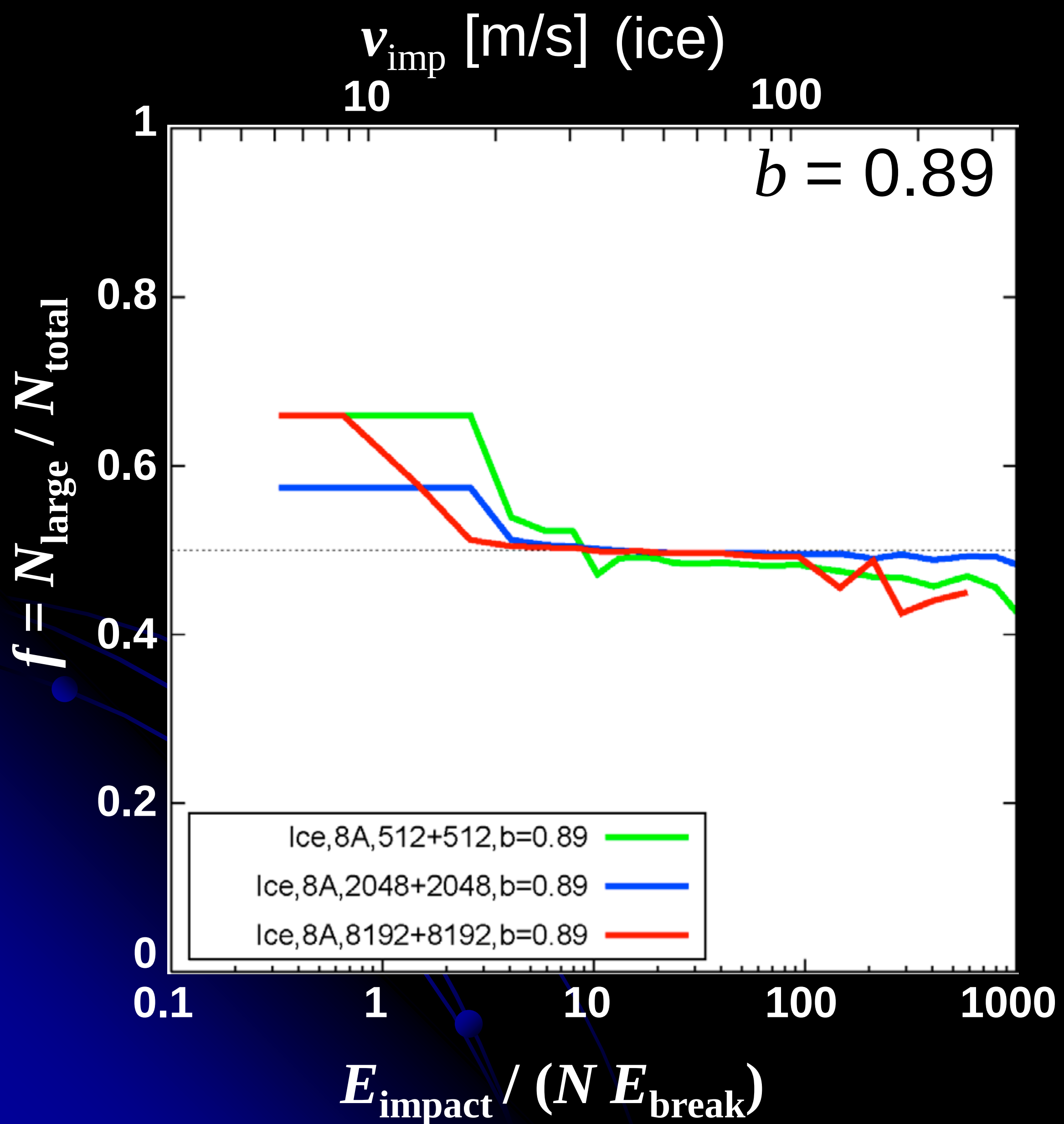
✓independent of N

Largest fragment mass $N_{\rm large}$: *growth efficiency*



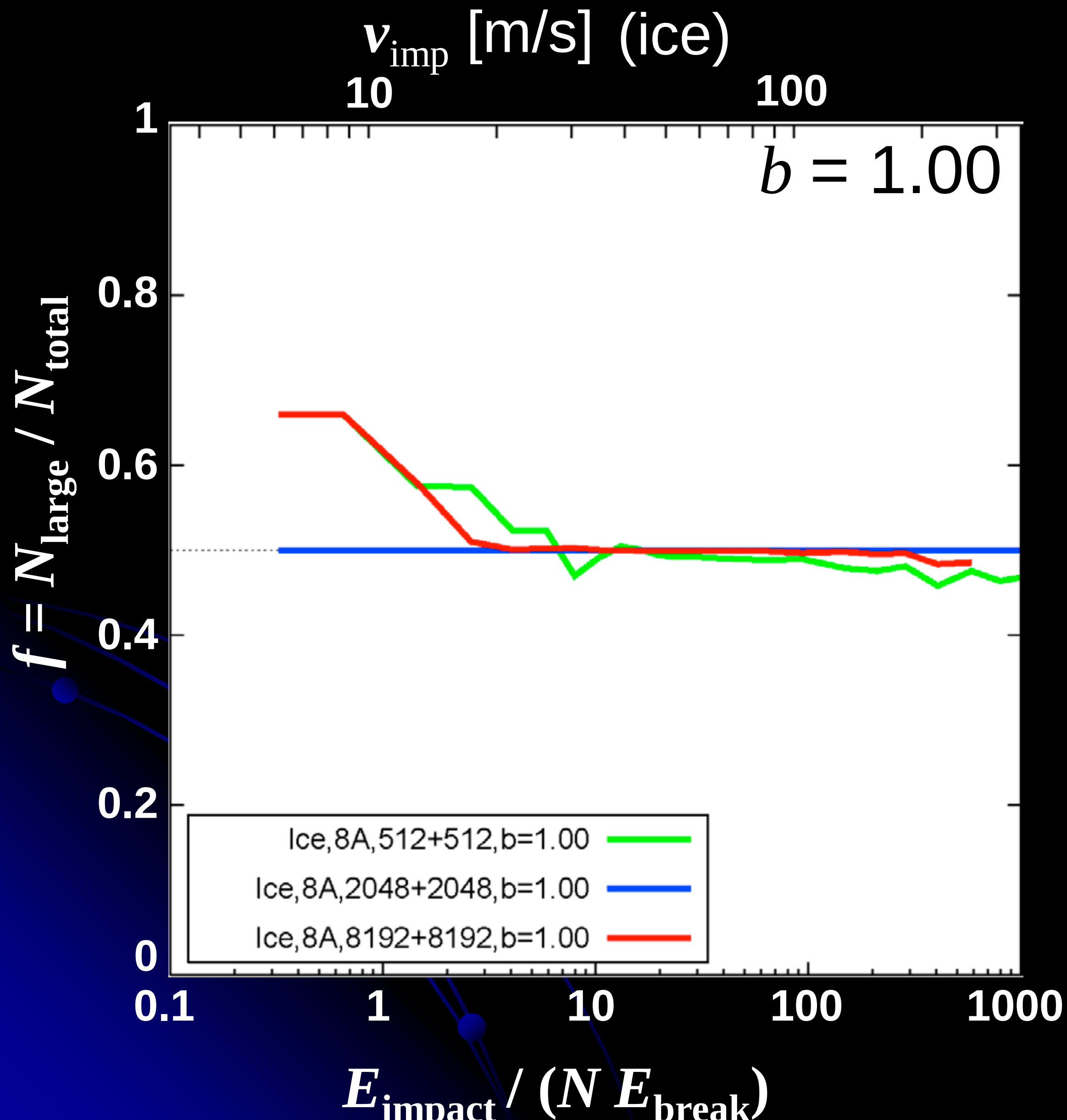
✓independent of N

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



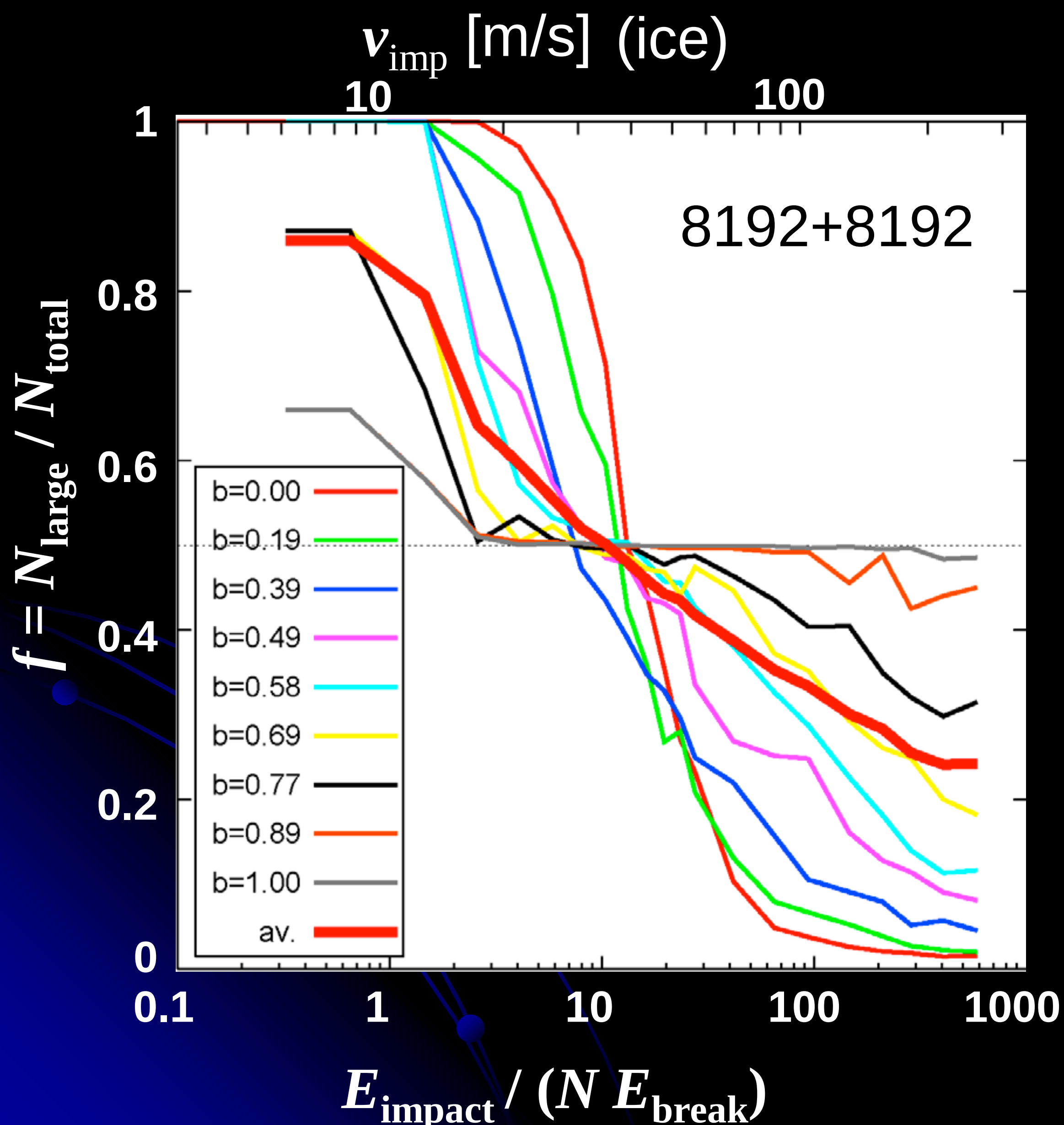
✓independent of N

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



✓independent of N

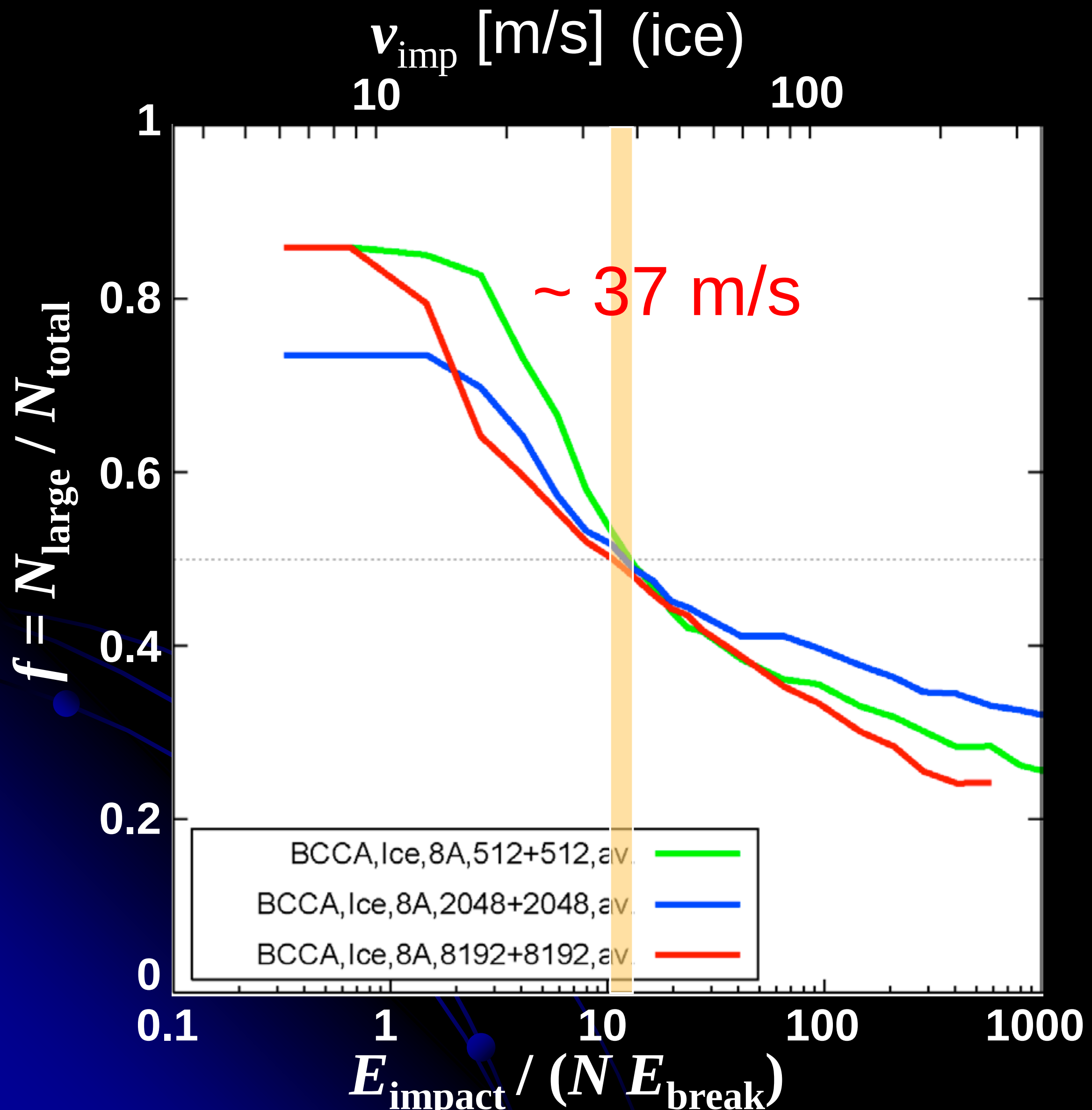
Largest fragment mass N_{large}: *growth efficiency*



Averaged over b^2

✓independent of N

Averaged *growth efficiency* for BCCA clusters

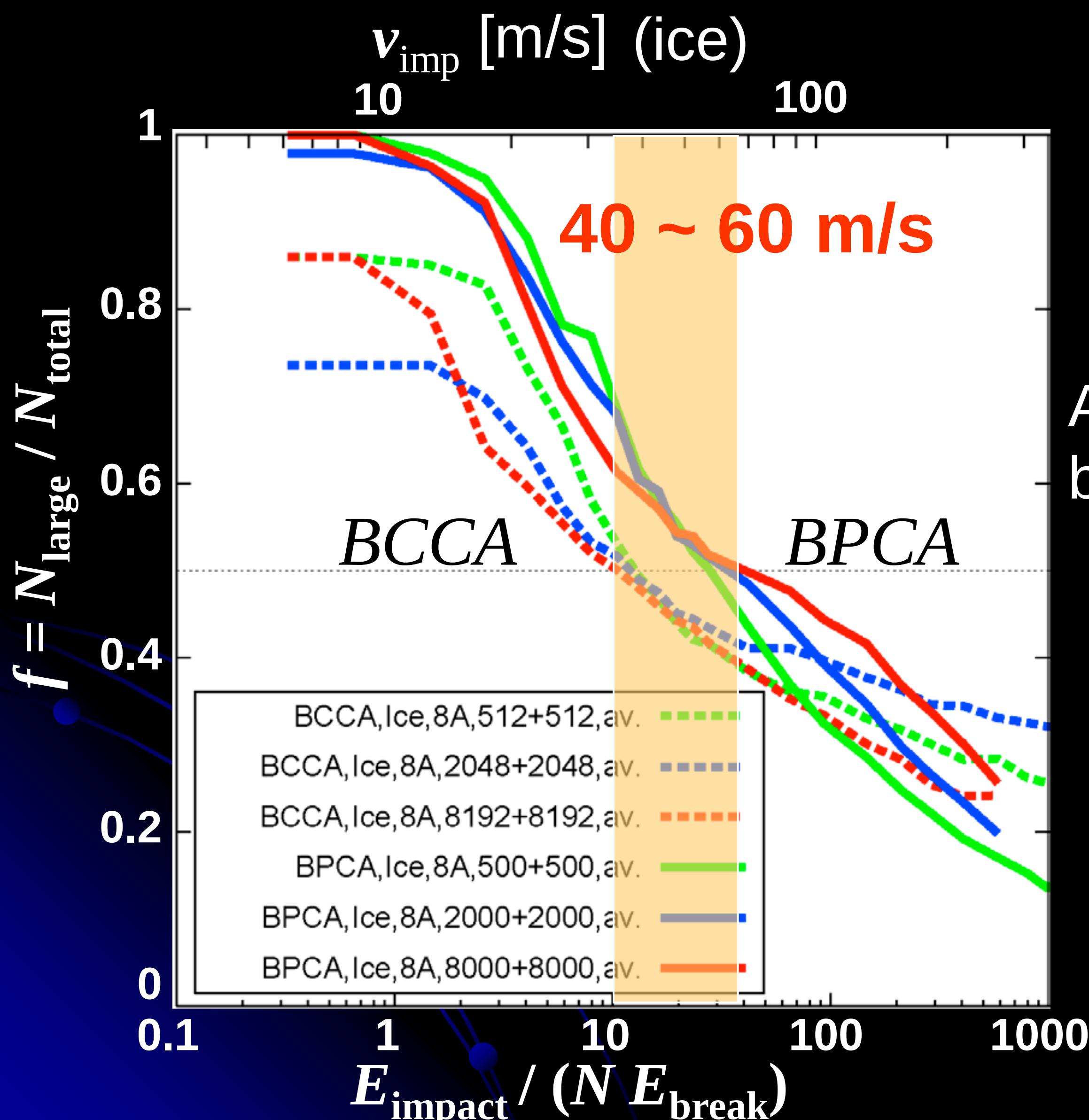


Averaged over b^2

✓independent of N

Averaged *growth efficiency* : *BCCA & BPCA*

Averaged over b^2



Actual dust structure: between BCCA and BPCA

Summary and Implications

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

To be compressed, but not so much.

Very fluffy planetesimals could be formed !?

Other processes to compress aggregates are necessary.

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

To be disrupted for silicate dust, not to be for icy dust.

Planetesimals can be formed through collisions of icy dust.

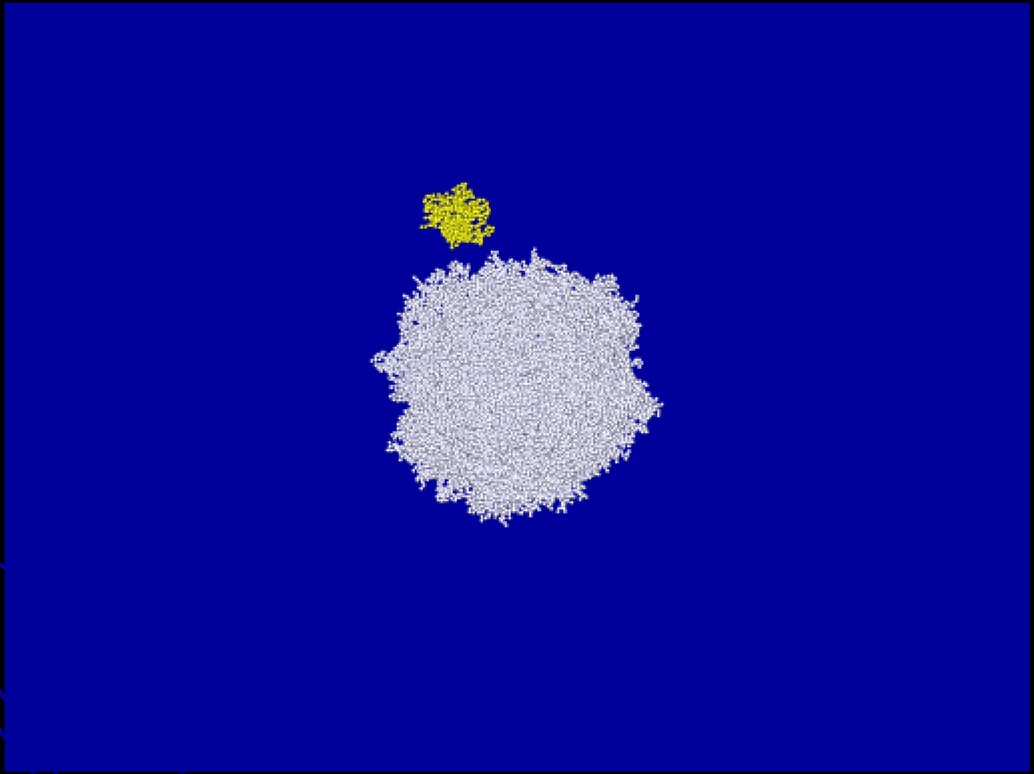
Can silicate dust grow?

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

To bounce, or not to bounce?

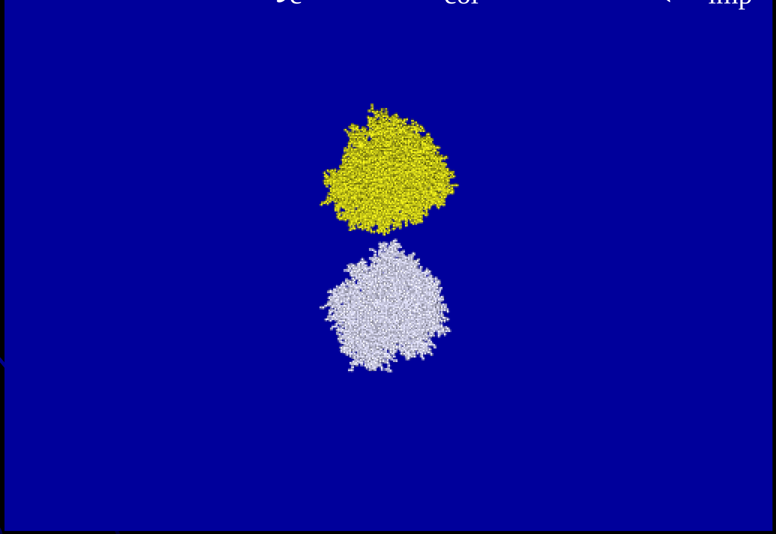
Bouncing Problem

"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})



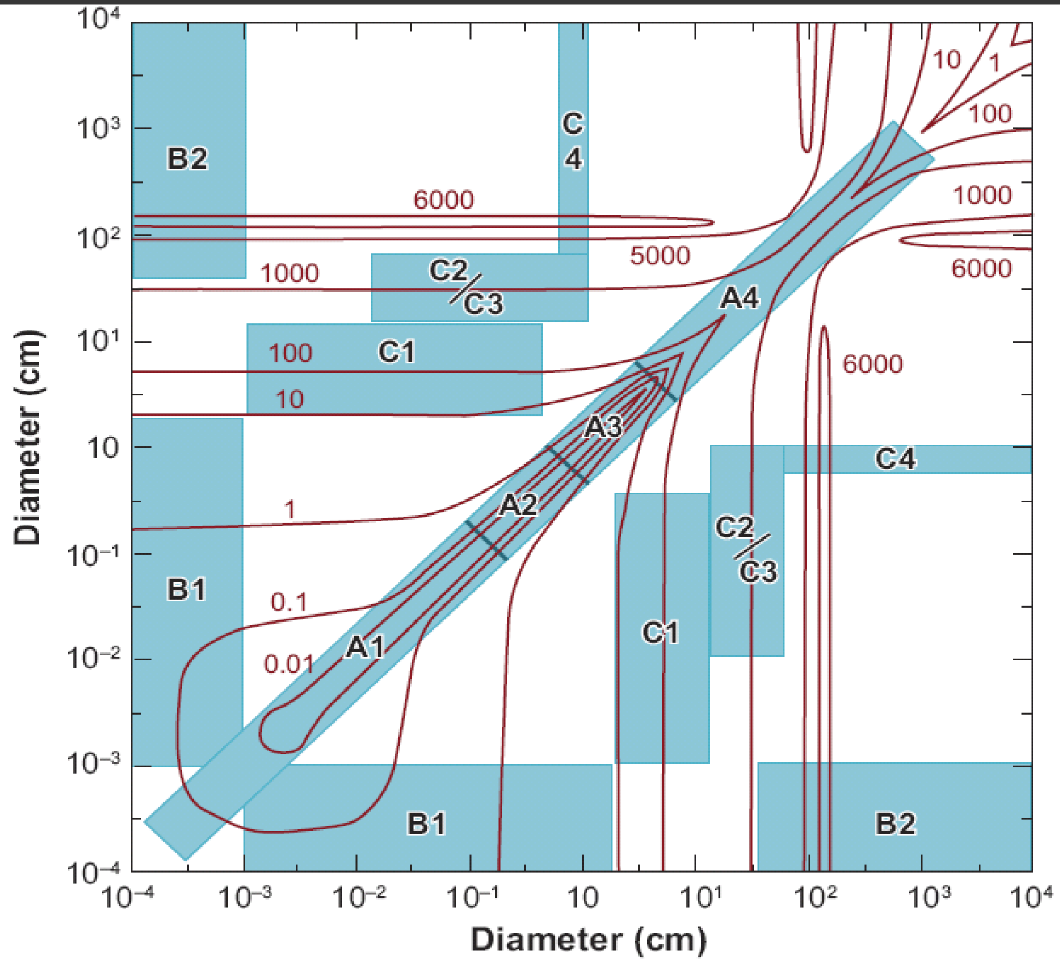


Figure 1

The parameter space of the experiments described in Section 5. The blue boxes indicate the applicability of the individual experiments to the collision scenario described by Weidenschilling & Cuzzi (1993) for a minimum-mass solar nebula. In the background, the original contour plot of the collision velocities (in cm s^{-1}) for all pair-collisions by Weidenschilling & Cuzzi (1993) is shown. The data from Weidenschilling & Cuzzi (1993) are valid for 1 AU and for a turbulent gas velocity of $\sim$10 m s^{-1}.

Blum and Wurm 2008

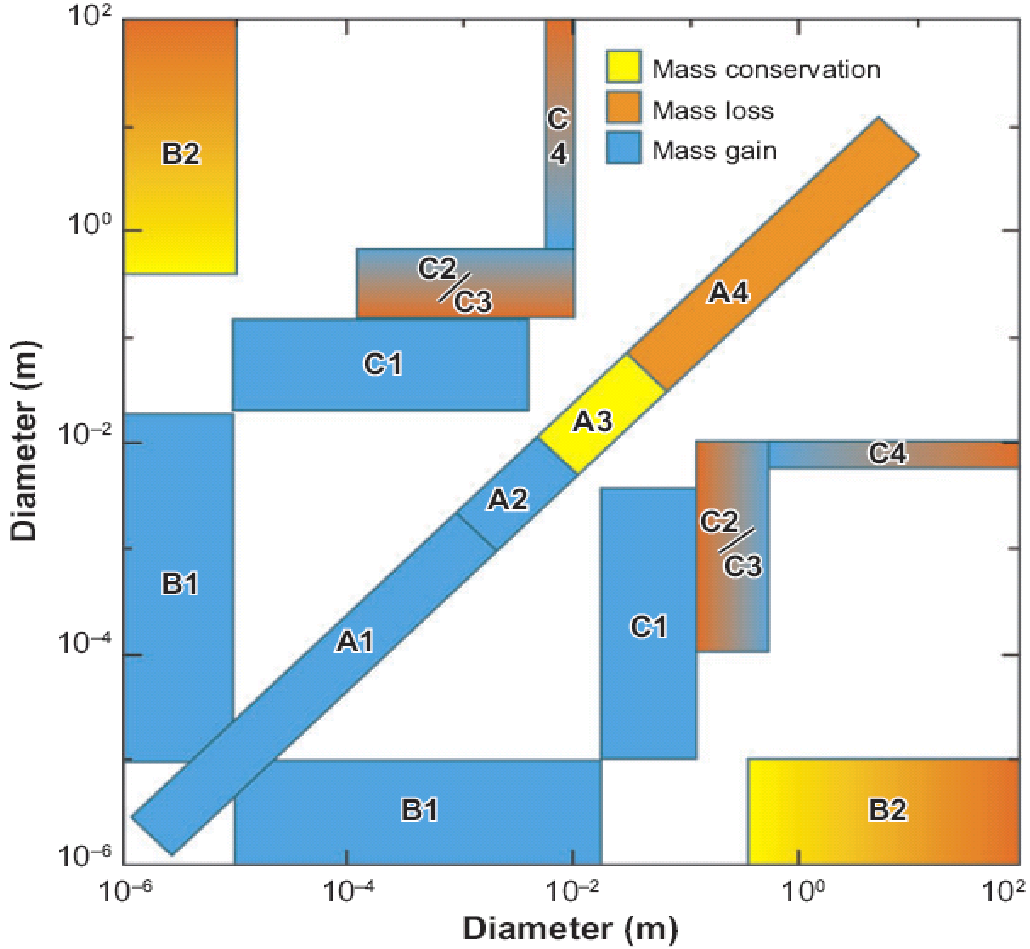


Figure 12

Overview of the results of the laboratory experiments described in Section 5. The blue, yellow, and orange boxes denote sticking, bouncing, and fragmentation for collisions between two protoplanetary dust aggregates of the sizes indicated at the axes of the diagram, respectively. Collision velocities were implicitly taken from Weidenschilling & Cuzzi (1993) (see **Figure 1**) for a minimum-mass solar nebula. It is clearly visible that direct growth of protoplanetary bodies $\gtrsim$10 cm is not possible.

Blum and Wurm 2008

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

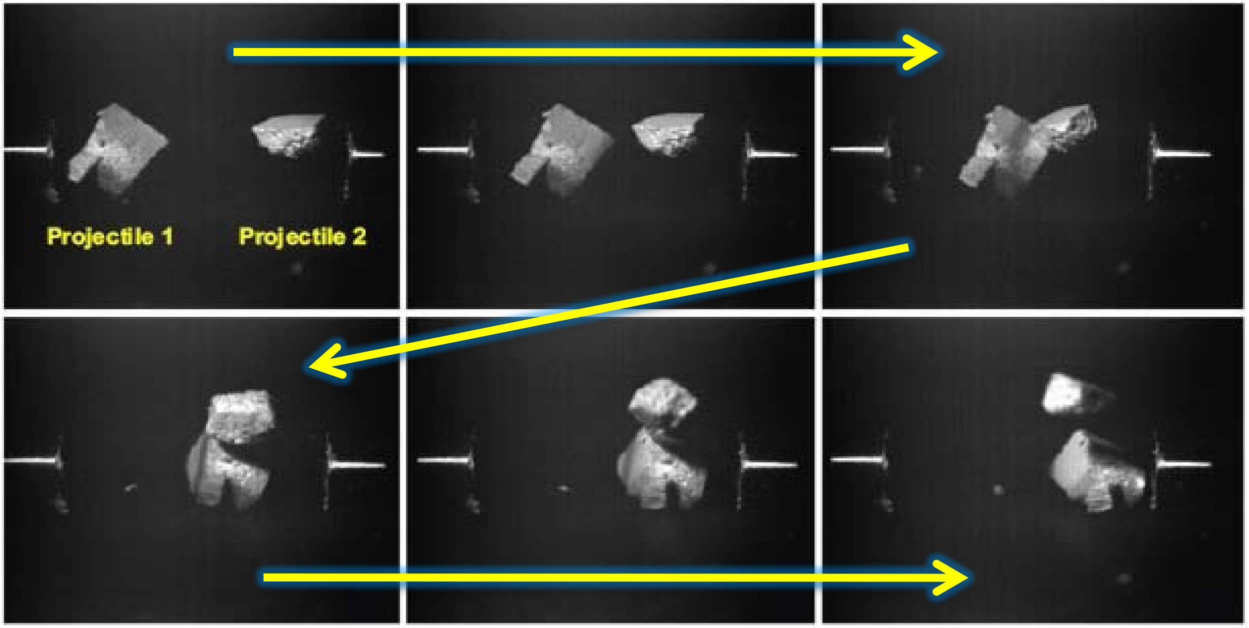


Figure 5

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)

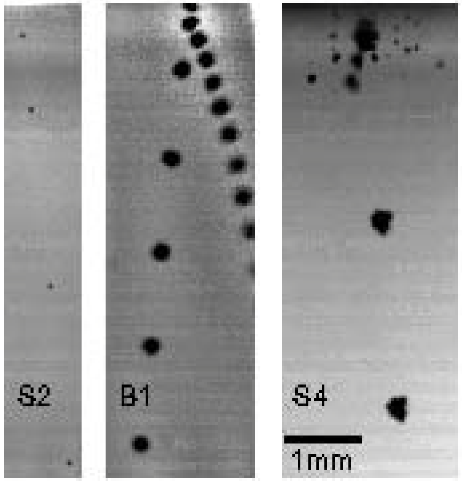


Fig. 5. Examples for the experimental outcomes in the collisions of small aggregates with a solid target. The collision can lead to sticking bouncing or fragmentation (from left to right). The time between two exposures is 2 ms.

u_{col}

Stiking

Bouncing

~ 1 m/s

Stiking
and/or fragmentation

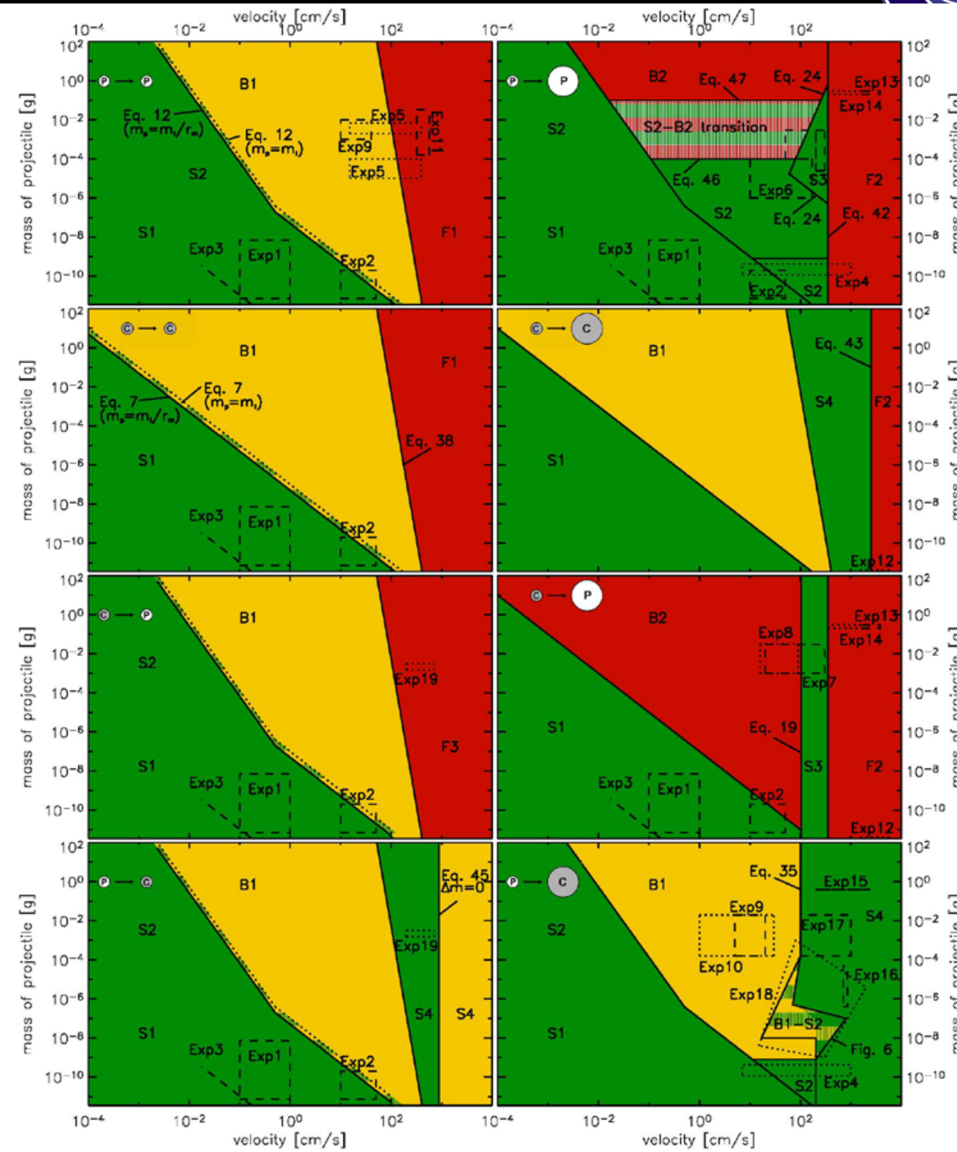


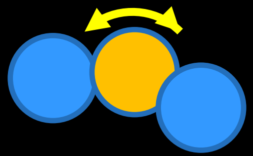
Fig. 11. The resulting collision model as described in this paper. We distinguish between similar-sized (left column) and different-sized (right column) collision partners, which are either porous or compact (also see Fig. 10). For each case, the important parameters to determine the collisional outcome 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？

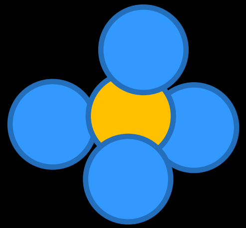
Hypothesis： Number of contacts controls？

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.)

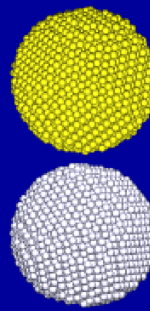
Idea for making required C.N. :

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

↓

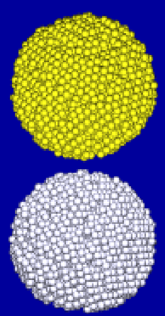
aggregates with C.N. = ~12 to ~3

Initial conditions and settings

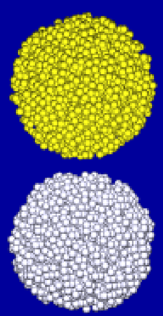


- ✓ (hexagonal) close-packed aggregates: mean C.N. ∼ 11
  - Number of particles: 4197 (3 types randomly produced)
- ✓ particle-extracted aggregates: extraction rate f = 0.05 - 0.75   C.N.∼12 $(1 - f)$

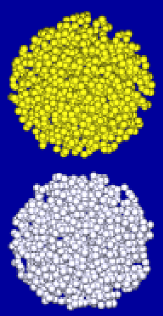
f = 0.2
mean C.N. = 8.8



f = 0.5
mean C.N. = 5.5



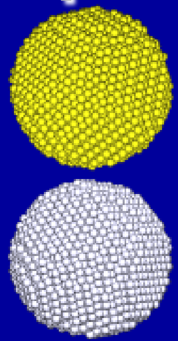
f = 0.75
mean C.N. = 2.8



- ✓ 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)

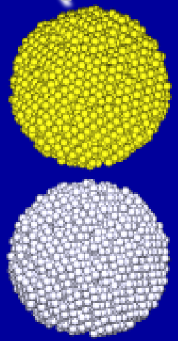
Examples of simulation (Ice)

C.N.= 11



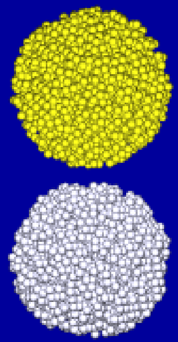
u_{col} = 0.096 m/s (E_{imp} = 0.66 E_{break})

C.N.= 8.8



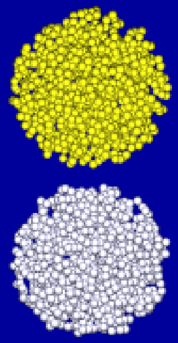
u_{col} = 0.096 m/s (E_{imp} = 0.53 E_{break})

C.N.= 5.5



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

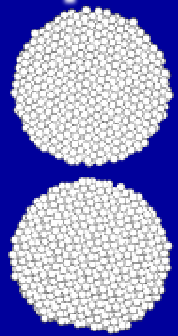
C.N.= 2.8



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

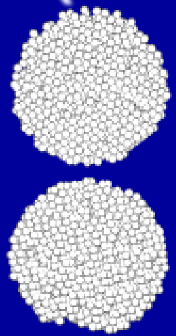
Examples of simulation (Ice)

C.N.= 11



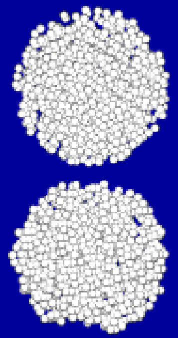
$u_{col} = 0.096$ m/s ($E_{imp} = 0.66\ E_{break}$)

C.N.= 8.8



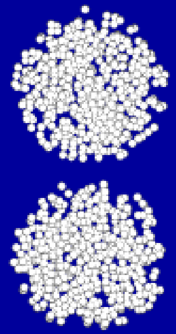
$u_{col} = 0.096$ m/s ($E_{imp} = 0.53\ E_{break}$)

C.N.= 5.5



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

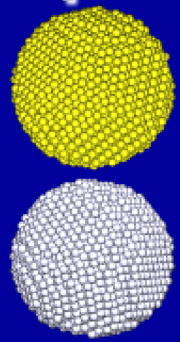
C.N.= 2.8



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

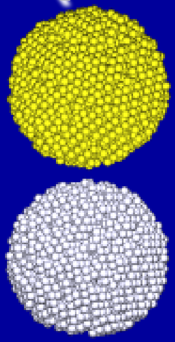
Examples of simulation (Ice)

C.N.= 11



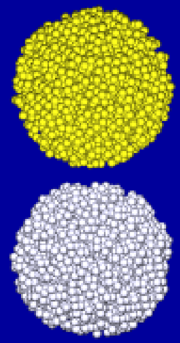
$u_{col} = 1.5$ m/s ($E_{imp} = 170\, E_{break}$)

C.N.= 8.8



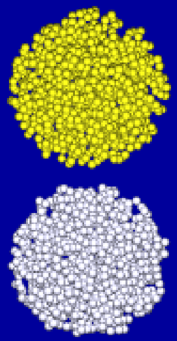
$u_{col} = 1.5$ m/s ($E_{imp} = 135\, E_{break}$)

C.N.= 5.5



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

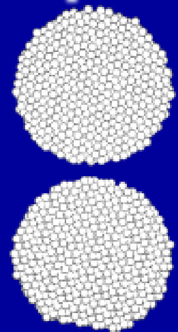
C.N.= 2.8



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

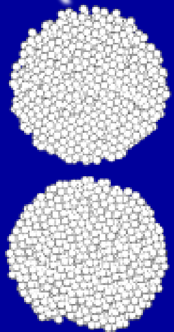
Examples of simulation (Ice)

C.N.= 11



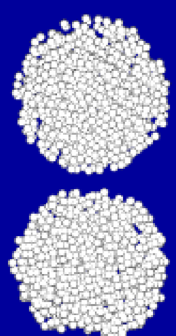
u_{col} = 1.5 m/s (E_{imp} = 170 E_{break})

C.N.= 8.8



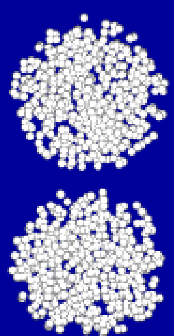
u_{col} = 1.5 m/s (E_{imp} = 135 E_{break})

C.N.= 5.5



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

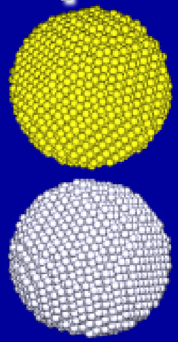
C.N.= 2.8



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

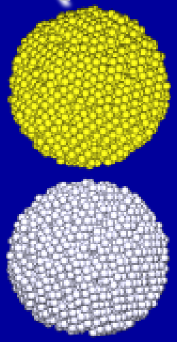
Examples of simulation (Ice)

C.N.= 11



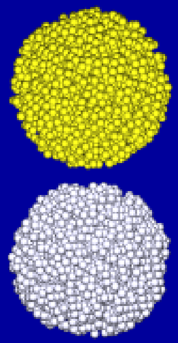
$u_{col} = 22$ m/s ($E_{imp} = 4.1\, N\, E_{break}$)

C.N.= 8.8



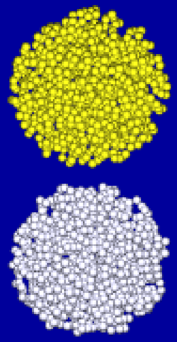
$u_{col} = 22$ m/s ($E_{imp} = 4.1\, N\, E_{break}$)

C.N.= 5.5



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

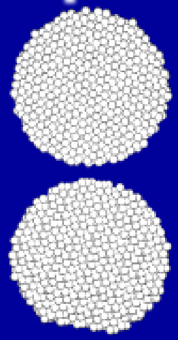
C.N.= 2.8



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

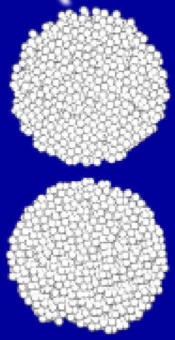
Examples of simulation (Ice)

C.N.= 11



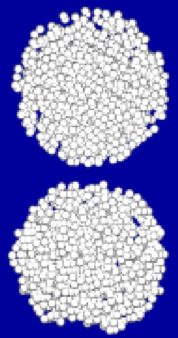
$u_{\mathrm{col}} = 22$ m/s ($E_{\mathrm{imp}} = 4.1\, N\, E_{\mathrm{break}}$)

C.N.= 8.8



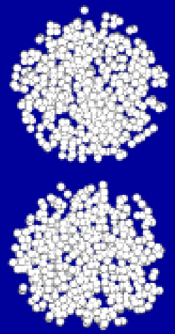
$u_{\mathrm{col}} = 22$ m/s ($E_{\mathrm{imp}} = 4.1\, N\, E_{\mathrm{break}}$)

C.N.= 5.5



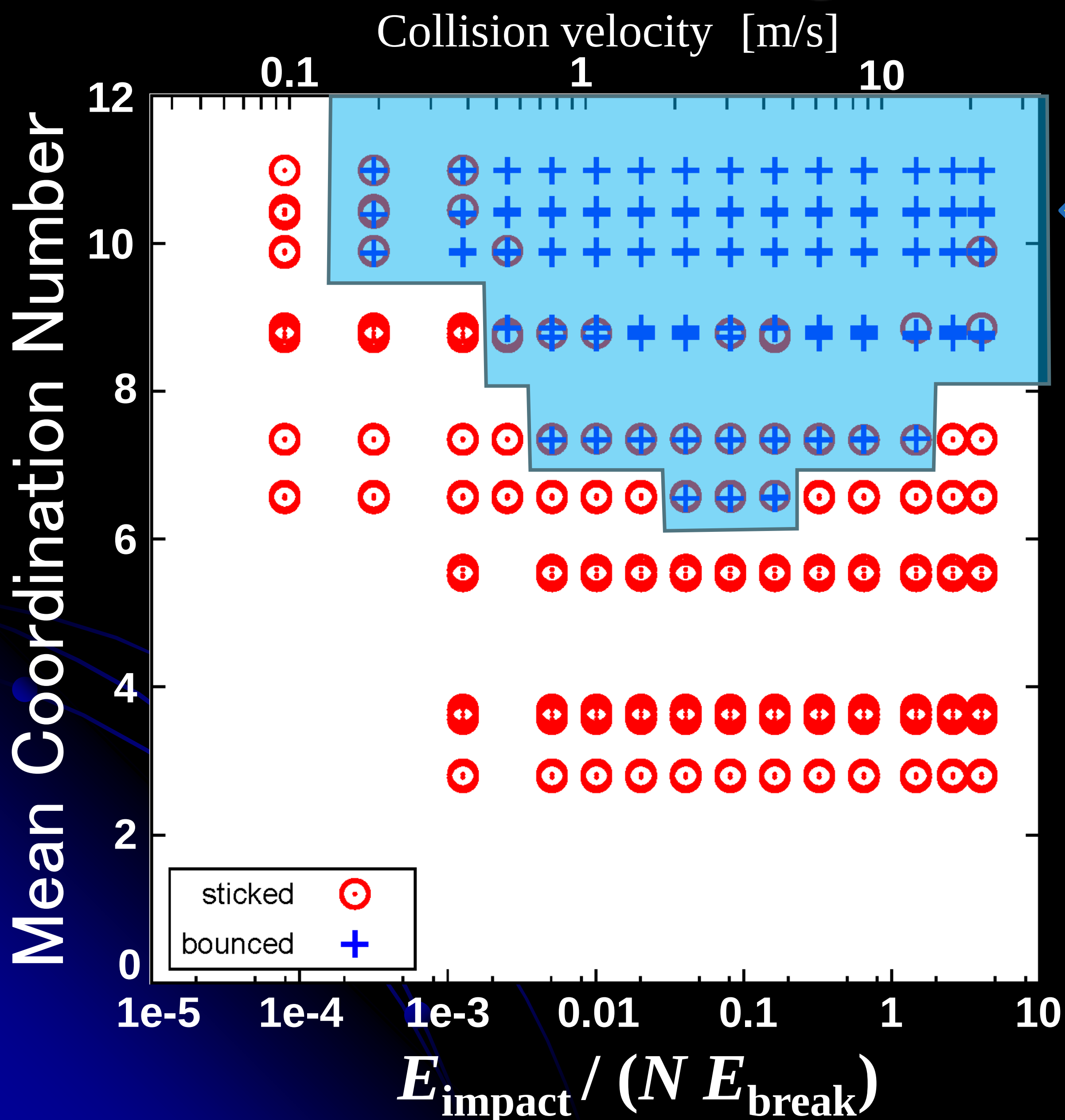
$u_{\mathrm{col}} = 22$ m/s ($E_{\mathrm{imp}} = 4.1\, N\, E_{\mathrm{break}}$)

C.N.= 2.8



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

Result：Bouncing Condition (Ice)

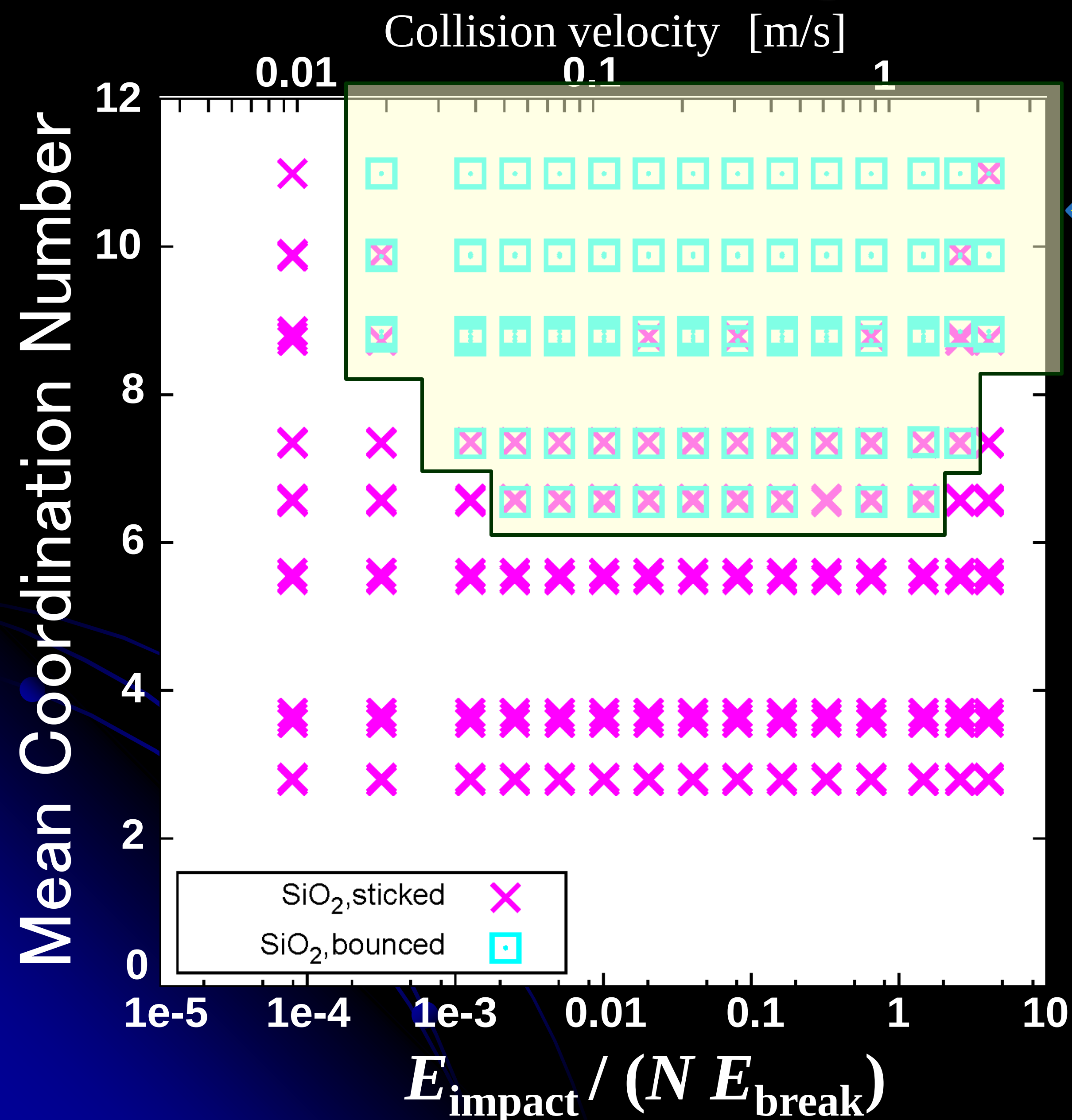


Bouncing

Mean C.N. < ~ 6

Sticking

Result: Bouncing Condition (SiO_2)

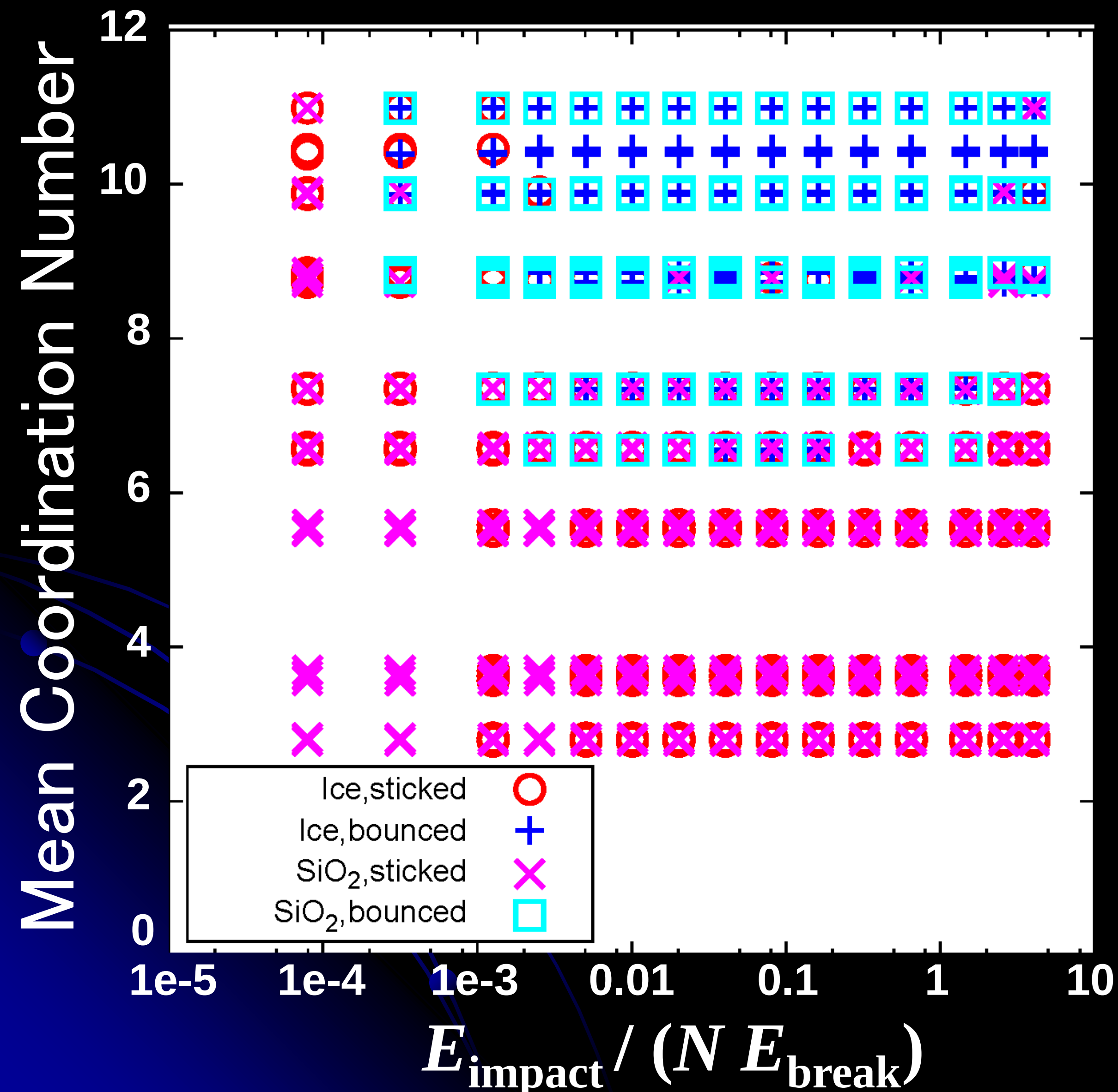


Bouncing

Mean C.N. < ~ 6

Sticking

Result: Bouncing Condition (Ice, SiO_2)



No difference between Ice and SiO_2

Scaled well by using E_{break}

Comparison with experiments

- Transition velocity from bouncing to fragmentation(sticking)

In experiments: u_{col} ~ 1 m/s

for r=0.75μm SiO_2 particles

Scaled with $E_{\mathrm{imp}}/NE_{\mathrm{break}}$ → $u_{\mathrm{col}} \propto r^{-5/6}$

$$u_{\mathrm{col}} \sim 1\ \mathrm{m/s}\ (r/0.75\mu\mathrm{m})^{-5/6}$$

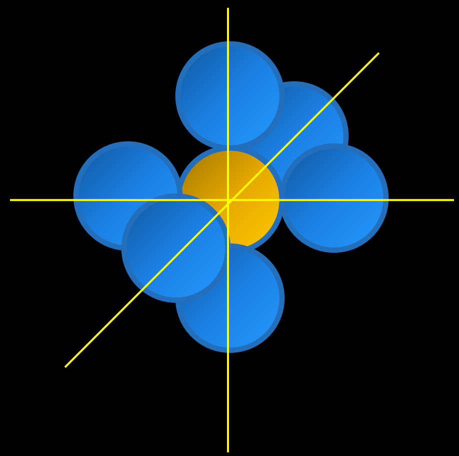
For r=0.1μm SiO_2 particles:

$$u_{\mathrm{col}} \sim 1\mathrm{m/s}\ (0.1\mu\mathrm{m} / 0.75\mu\mathrm{m})^{-5/6} = 5.4\ \mathrm{m/s}$$

Consistent with our numerical results!

Why C.N. = 6 ?

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



N_f: Number of degrees of freedom of motion of an aggregate

$$N_f = 6N_d - xN_d\, z/2$$ (Sirono & Greenberg 2000)

N_d: Number of particles in the aggregate

z: Coordination number

x: Number of freedom inhibited

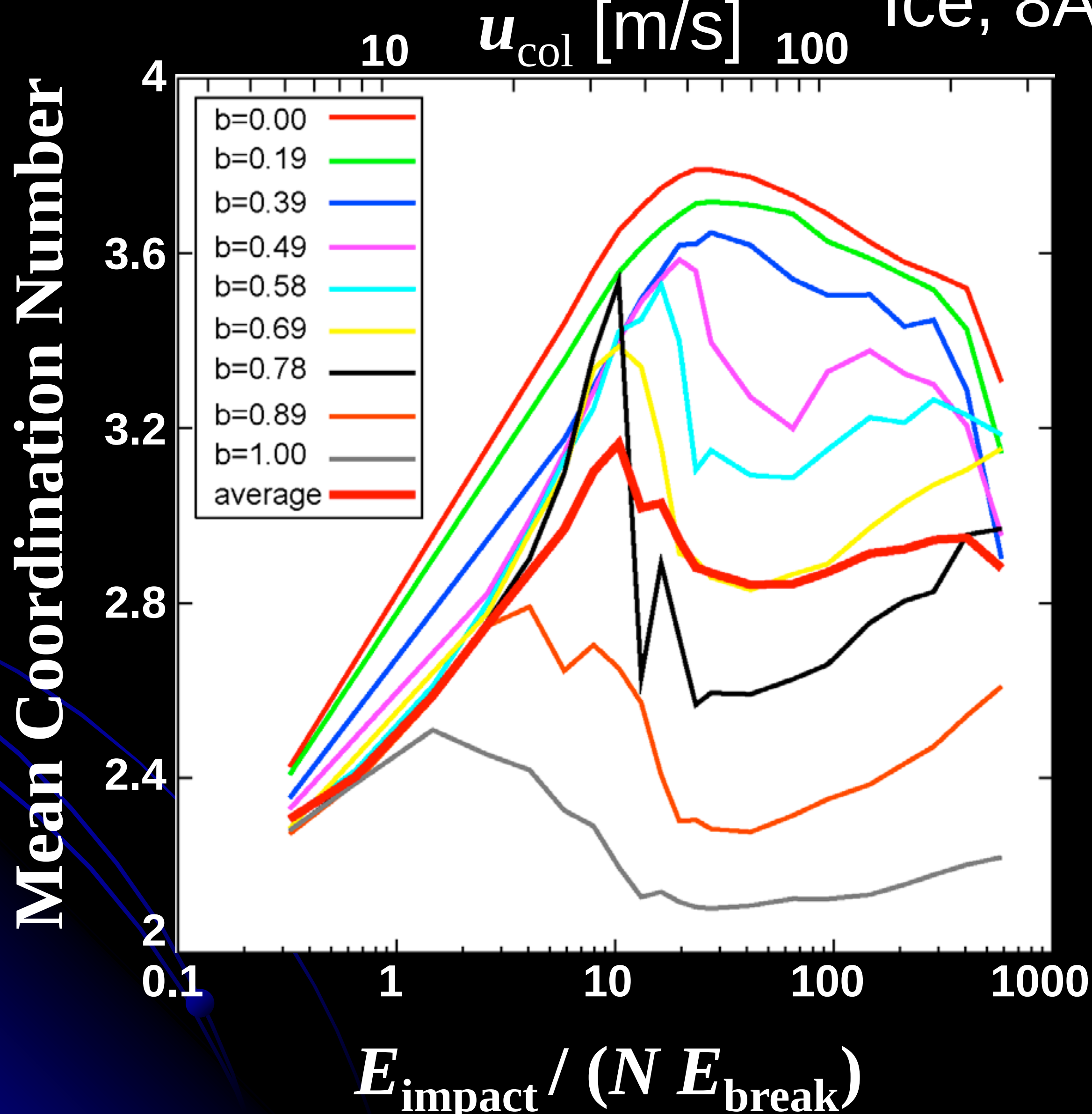
$N_f > 0$

C.N. < 3 (x=4)⟶ energy is dissipated by rolling.

C.N. < 6 (x=2)⟶ energy is dissipated by rolling and sliding.

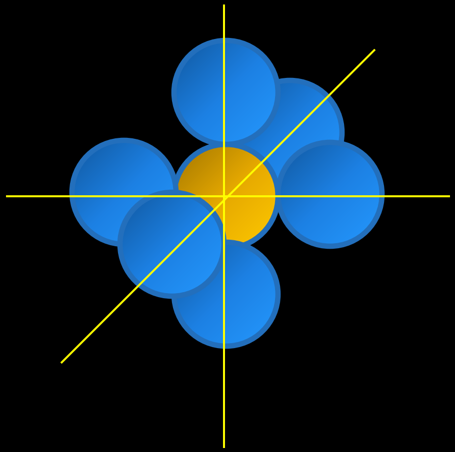
C.N.@BPCA collisions

Ice, 8Å, 8000+8000

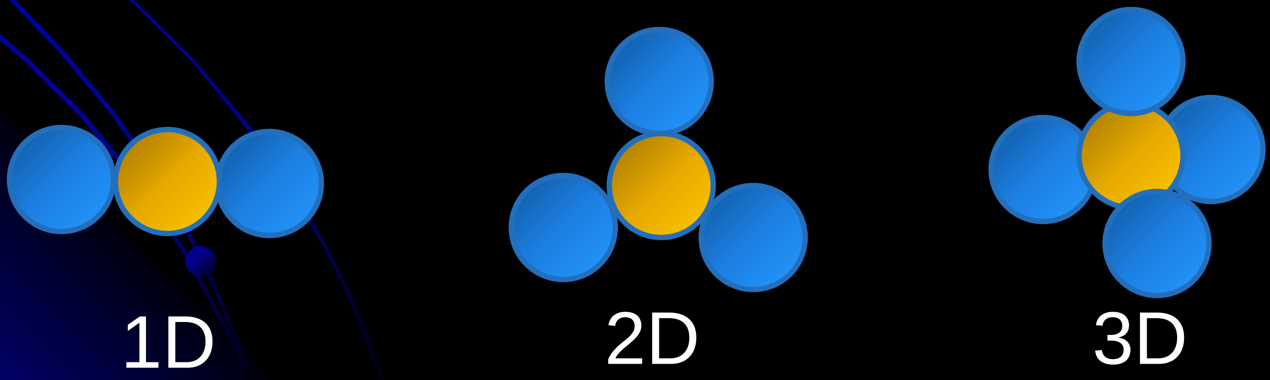


Why C.N. = 4 ?

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

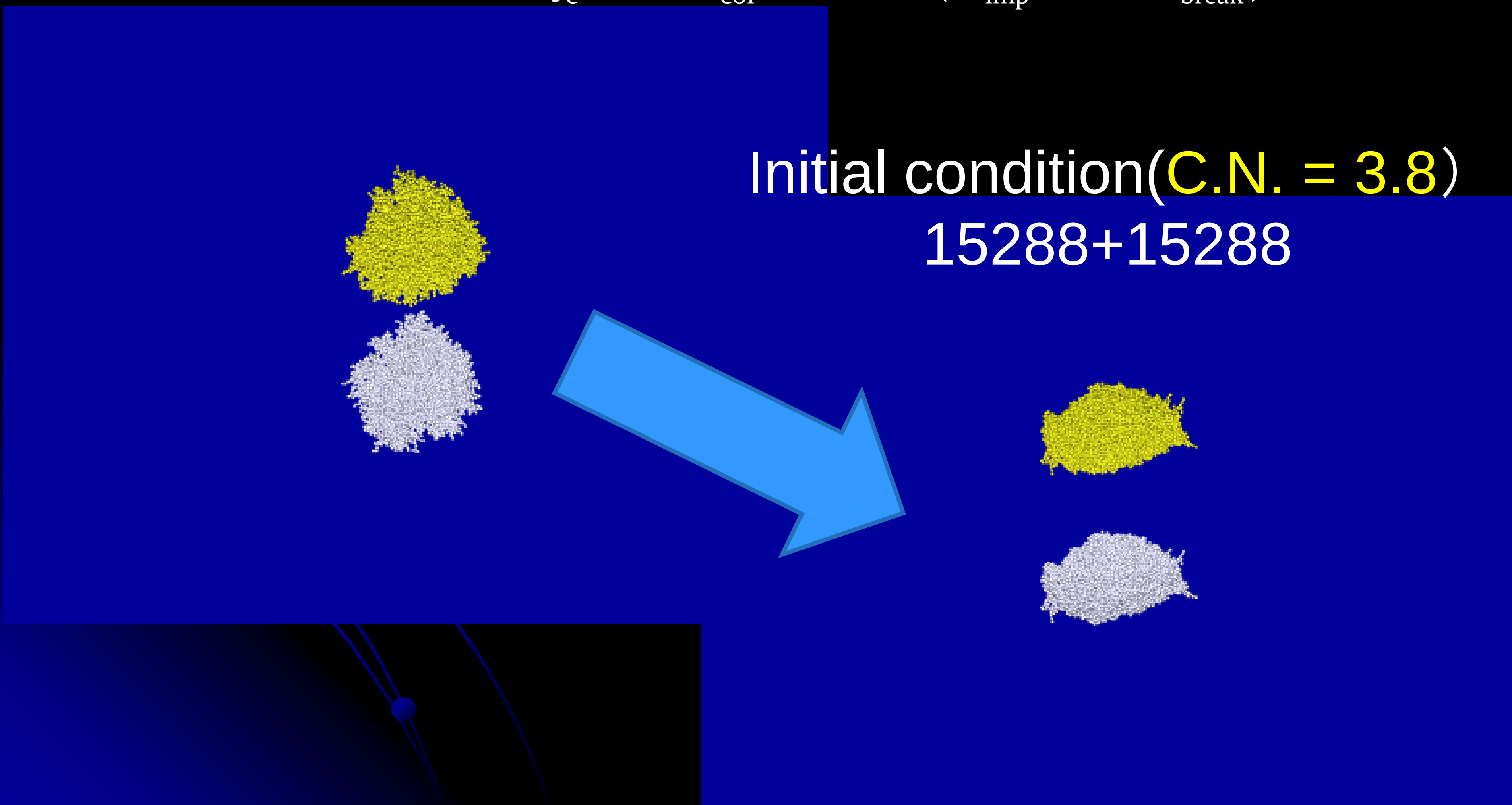


Stable with at least C.N. = 4 in 3D:

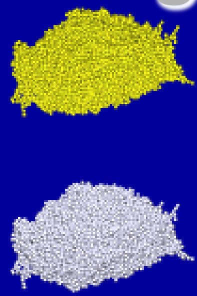


aggregates produced by collisions

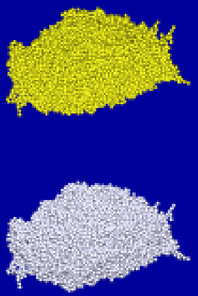
BPCA, N=8000+8000, ice, ξ_c = 8Å, u_{col} = 57 m/s (E_{imp} = 27 NE_{break})



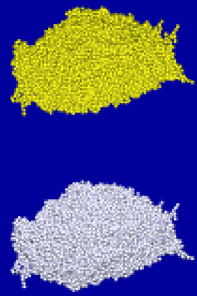
Collisions of collision-produced aggregates (C.N.=3.8)



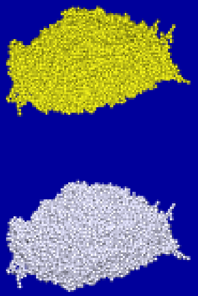
$u_{col} = 0.38$ m/s ($E_{imp} = 1.2 \times 10^{-3}\, NE_{break}$)



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

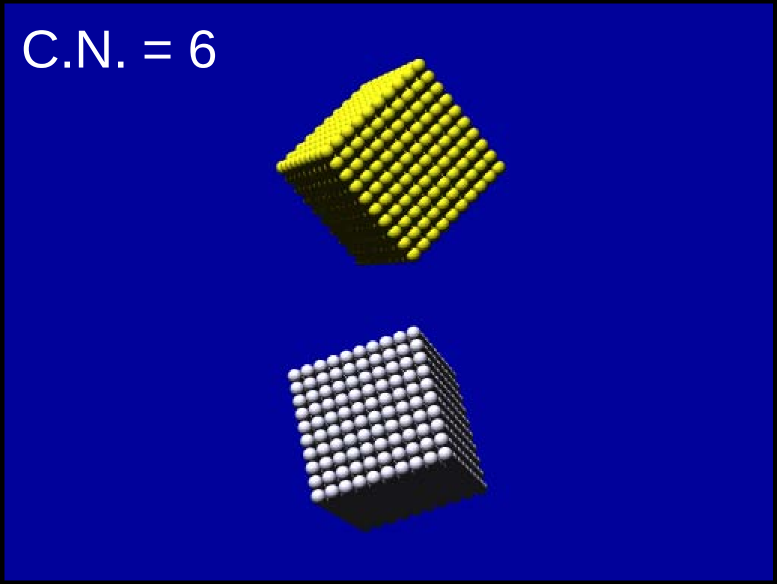


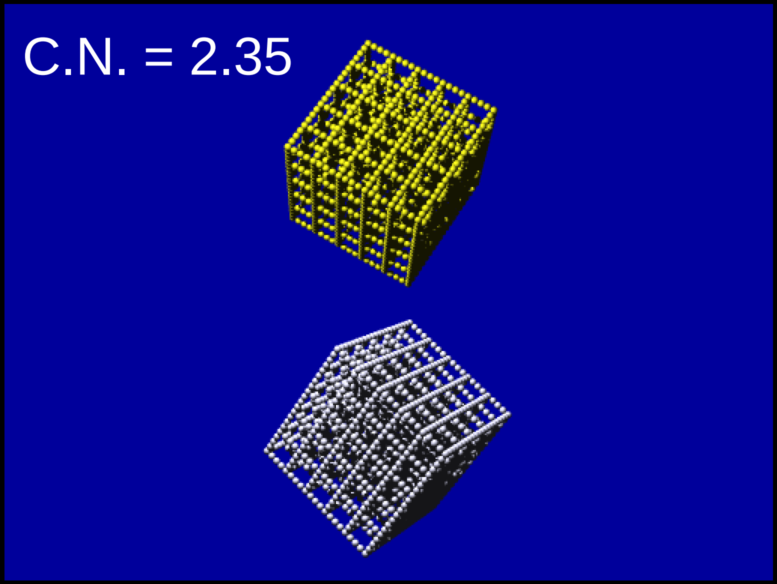
$u_{col} = 1.54$ m/s ($E_{imp} = 2.0 \times 10^{-2}\, NE_{break}$)

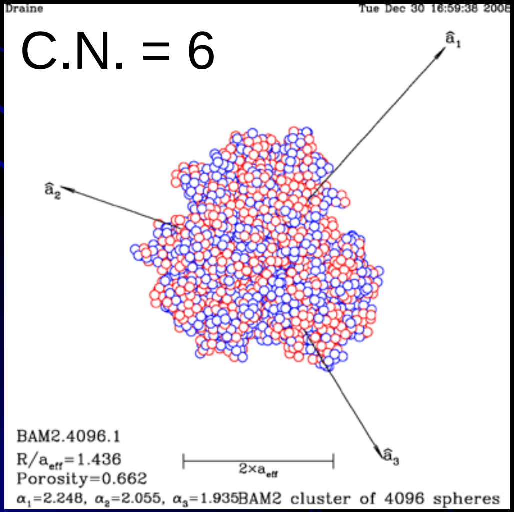


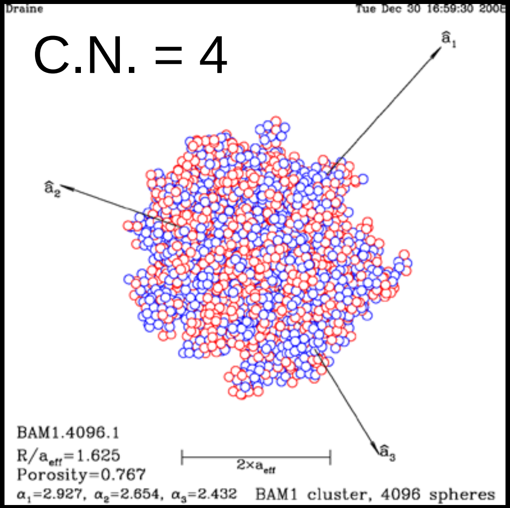
$u_{col} = 17.4$ m/s ($E_{imp} = 2.6\, NE_{break}$)

Structure is also important?





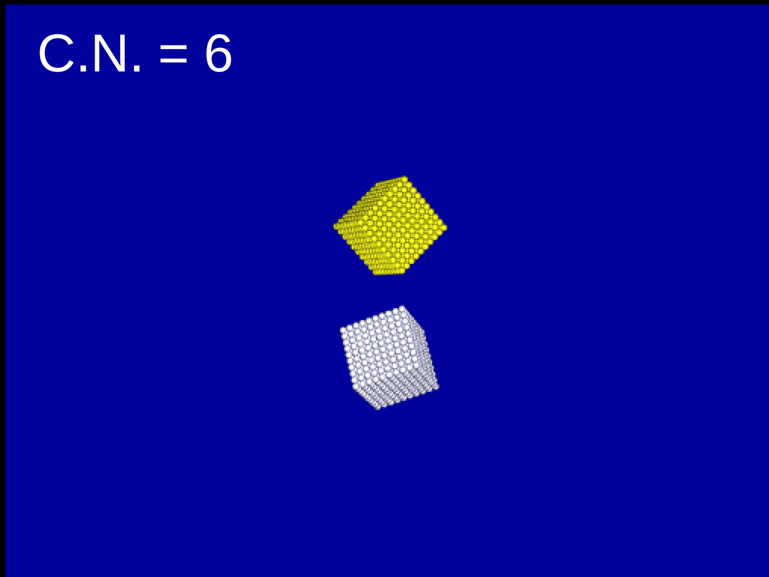


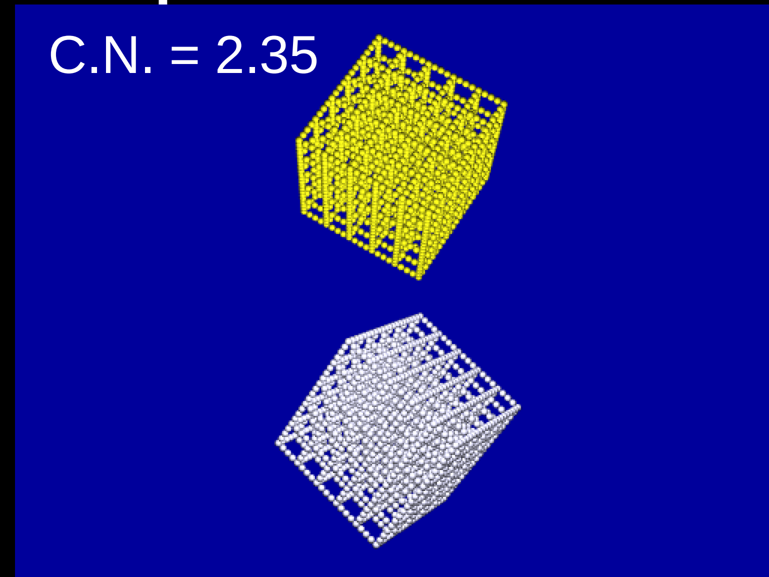


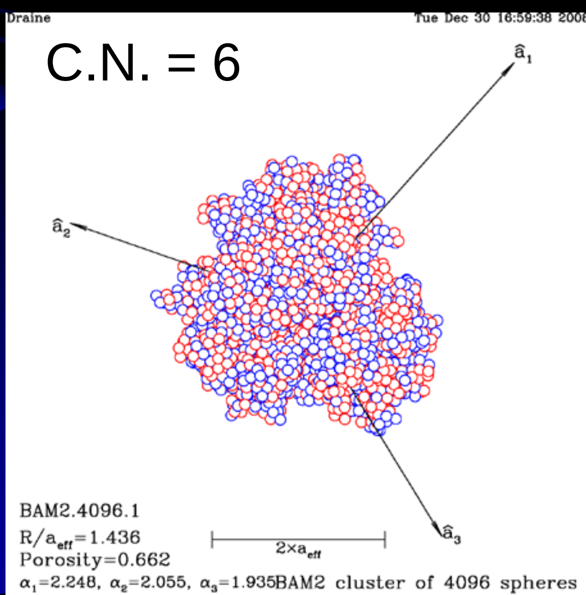
Shen, Draine, and Johnson (2008)

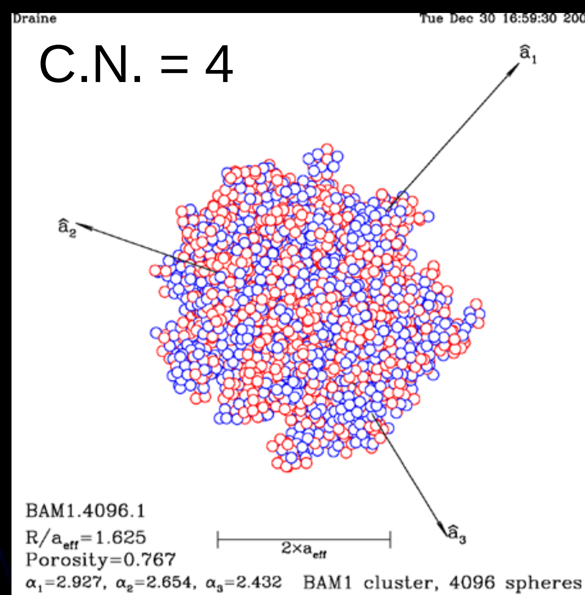
New Calculations at Braunschweig

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

Not to bounce.

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

C.N. ~ 2 for aggregates in experiments ?

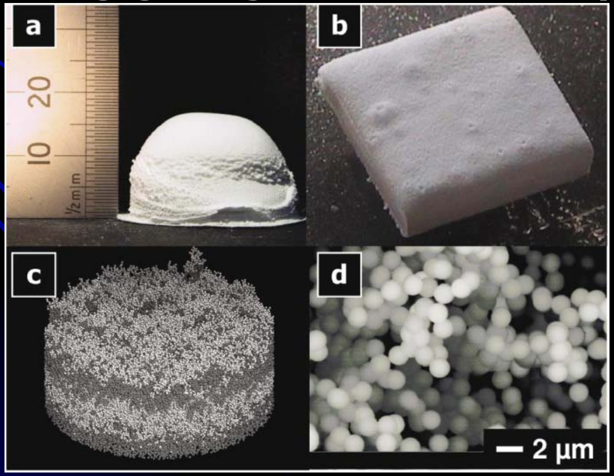
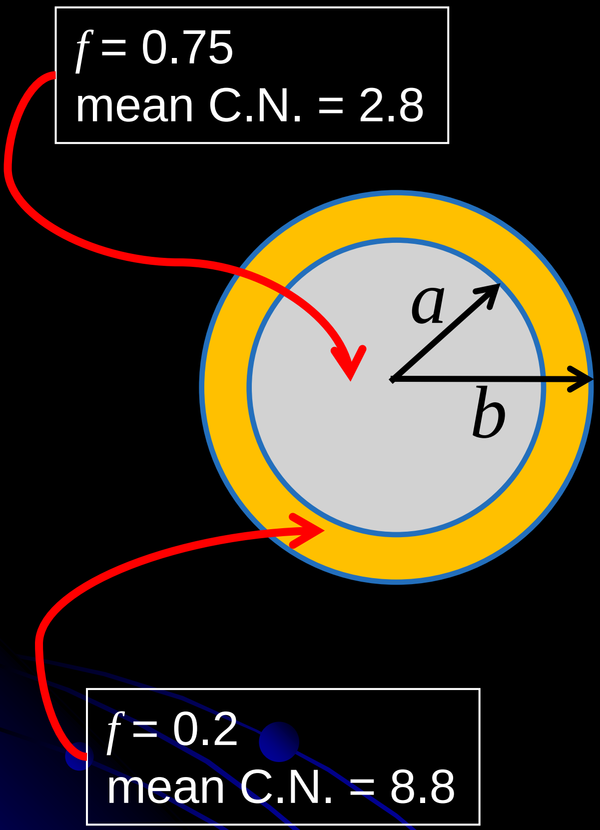


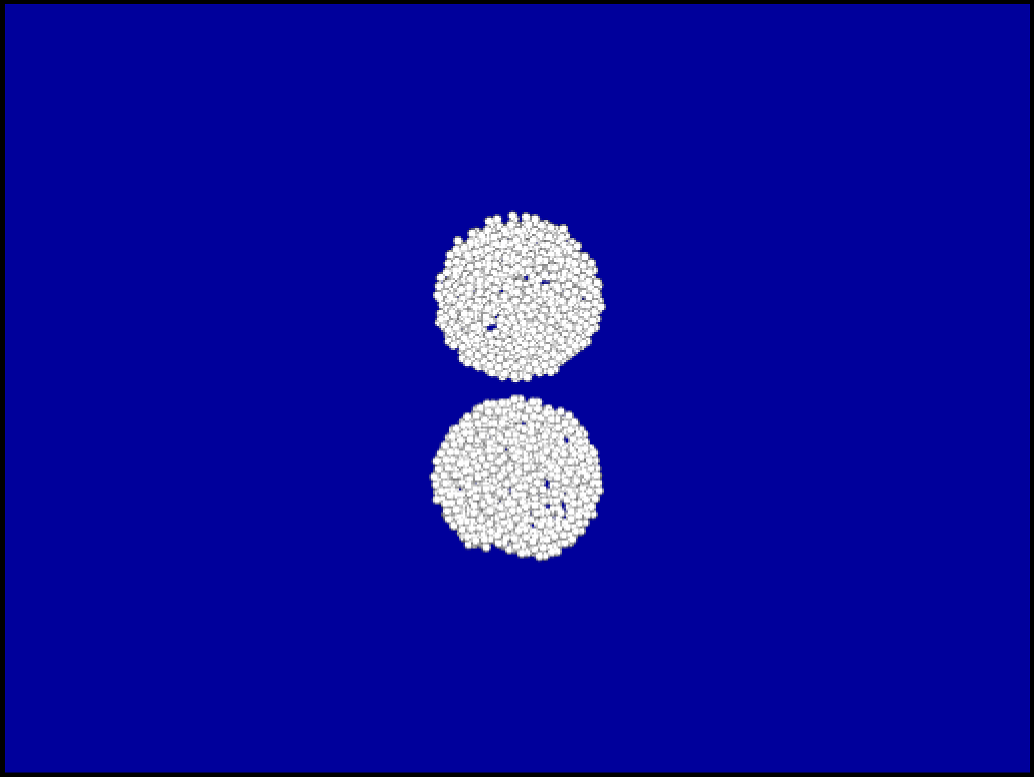
FIG. 2 (color online). (a) An example of an agglomerate with a volume filling factor of *0:15. (b) Specimen of an agglomerate* after manual cutting to 10 10 mm2. (c) Result of a Monte Carlo simulation of ballistic deposition. (d) High resolution scanning electron microscopy (SEM) image of the surface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

(Blum & Schräpler 2004)

A Hard Shell ?



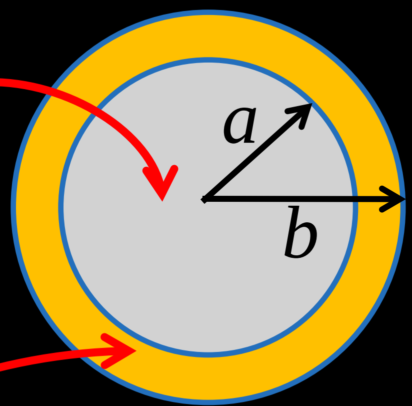
$a/b = 0.8$



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

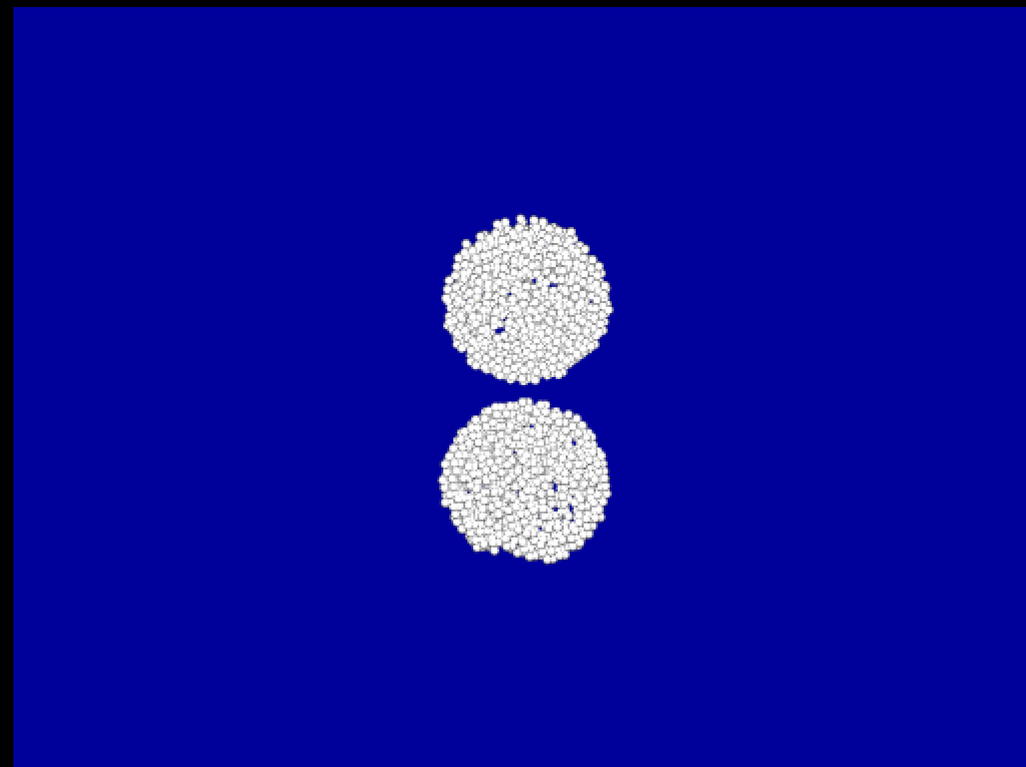
A Hard Shell ?

$f = 0.75$
mean C.N. = 2.8



$f = 0.2$
mean C.N. = 8.8

$a/b = 0.8$



u_{col} = 6.2 m/s (vimp = 8)

To be planetesimals…

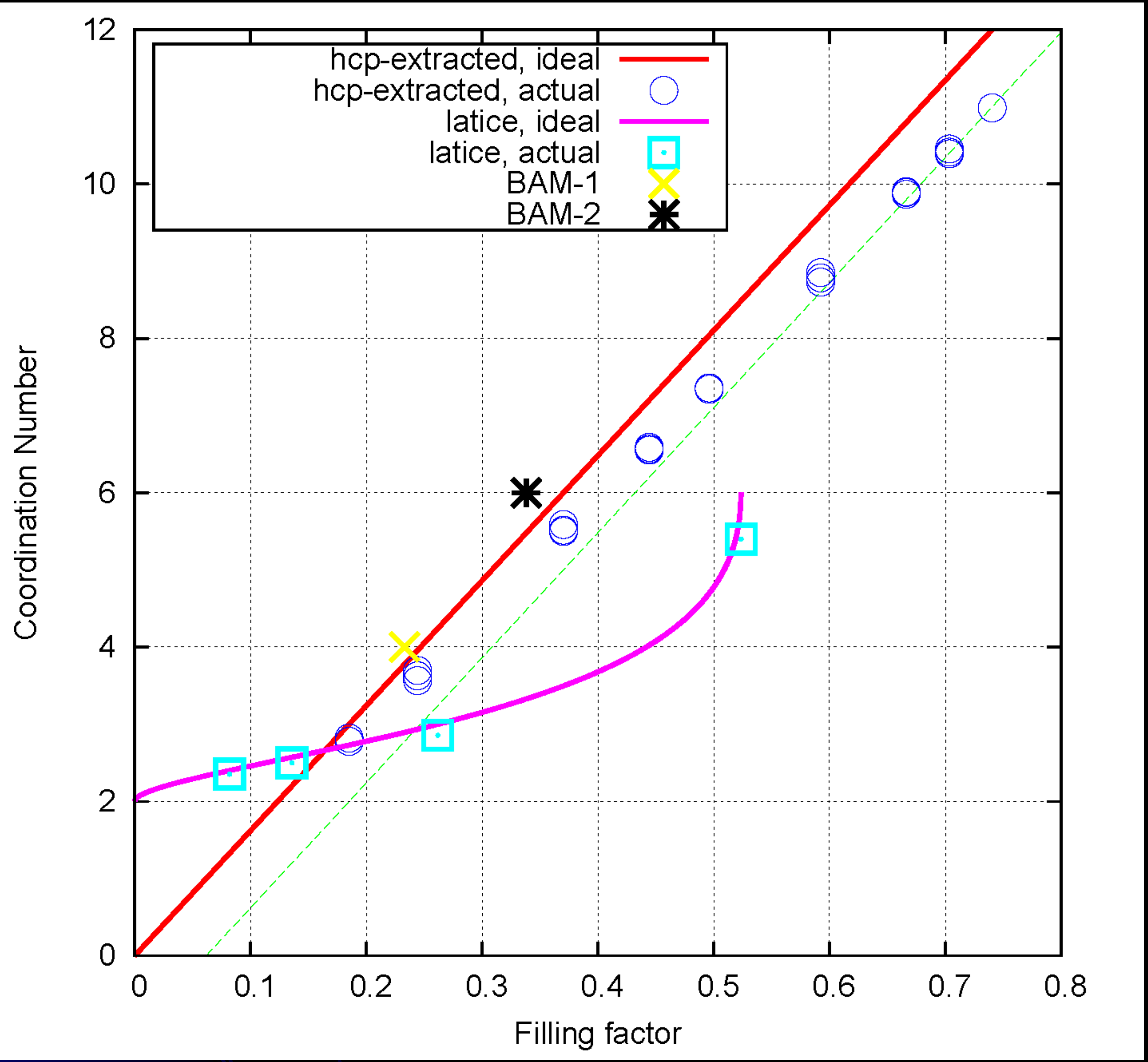
What's next?

サイズ比のついた衝突
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

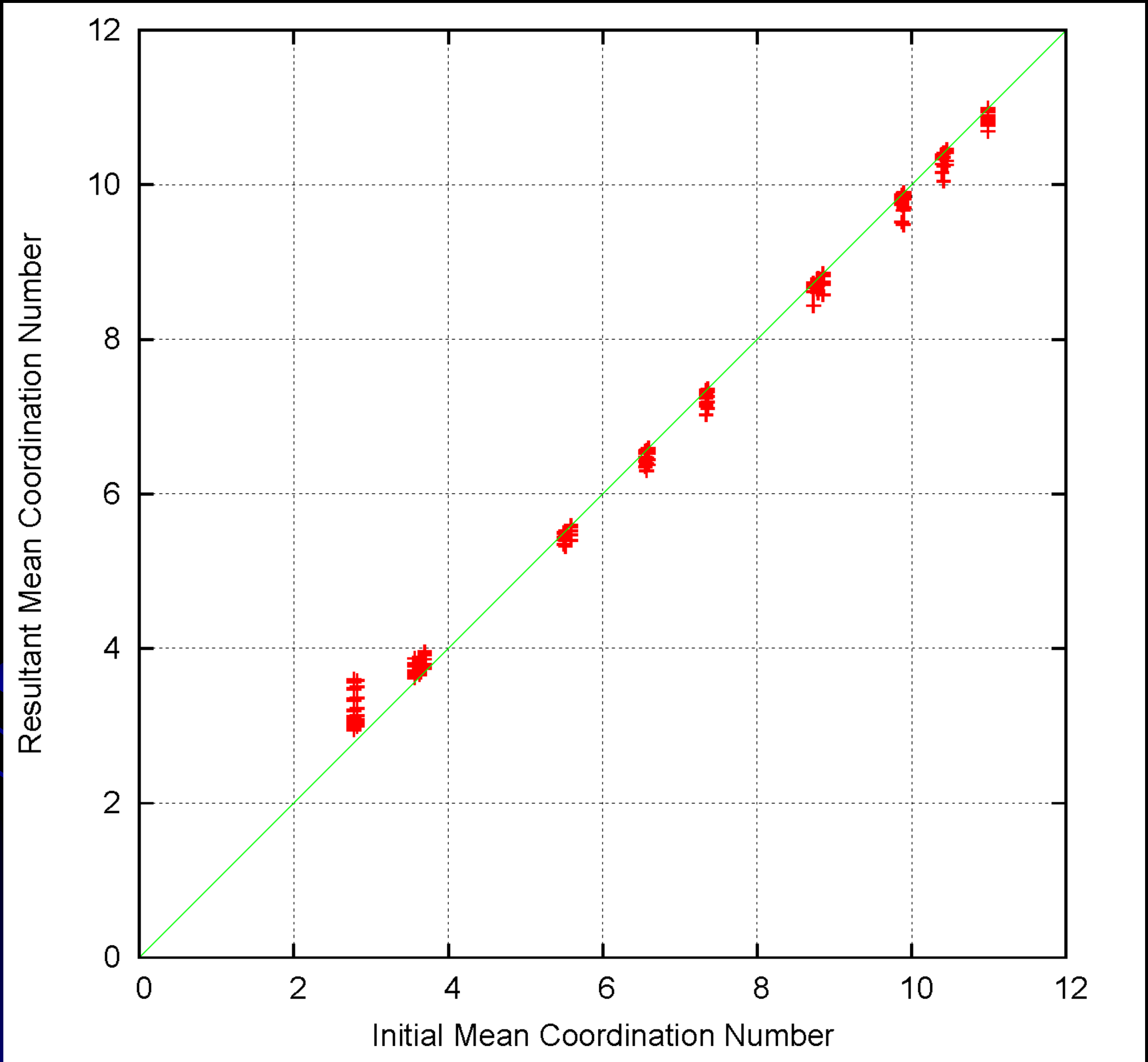
静的圧縮の効果
帯電の影響

破片のサイズ分布・構造
彗星・小惑星の表層進化

To be, or not to be?



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


Resultant Mean Coordination Number
Initial Mean Coordination Number
0
2
4
6
8
10
12