Planetesimal formation by sweep-up coagulation

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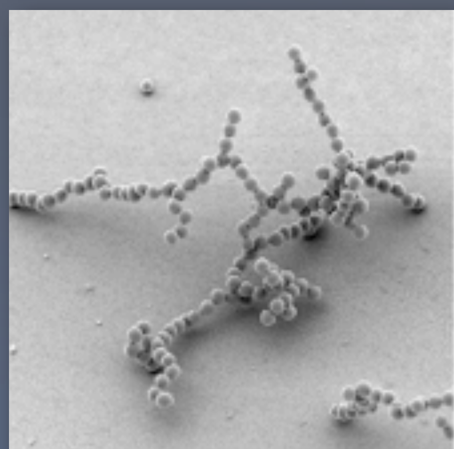
DFG
Research Group
Planet Formation

Outline

- Introduction
  - Dust motion in the protoplanetary disk
  - Laboratory studies of dust collisions
  - Tracking the dust-size evolution
- Dust coagulation by sweep-up
  - A new collision model
  - Planetesimal formation by sweep-up
  - The formation of the first seeds
- Summary & Outlook

How far can dust coagulation proceed?



Blum et al. (1998)

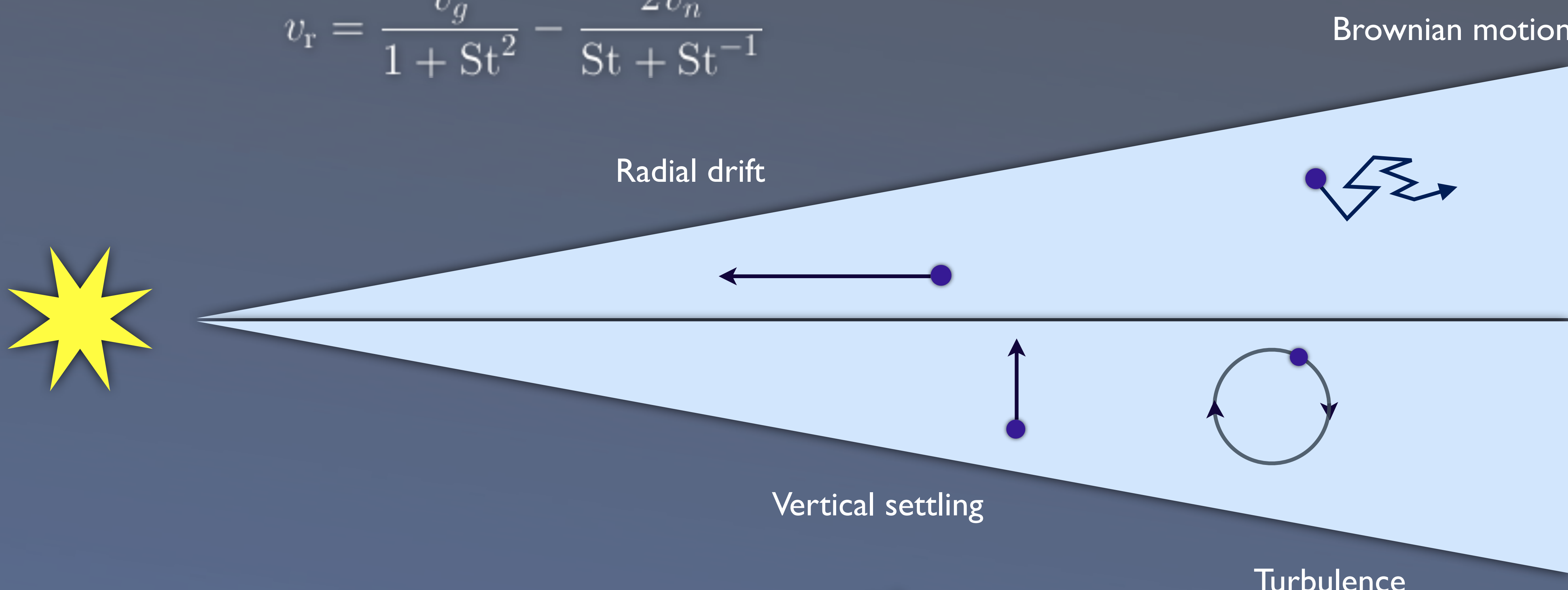
Asteroid 243 Ida

Relative velocities in the disk

$$\Delta v_{\rm r} = |v_{r,1} - v_{r,2}|$$

$$v_{\rm r} = \frac{v_g}{1 + {\rm St}^2} - \frac{2 v_n}{{\rm St} + {\rm St}^{-1}}$$

$$\Delta v_{\rm bm} = \sqrt{\frac{8 k_{\rm b} T (m_1 + m_2)}{\pi m_1 m_2}}$$



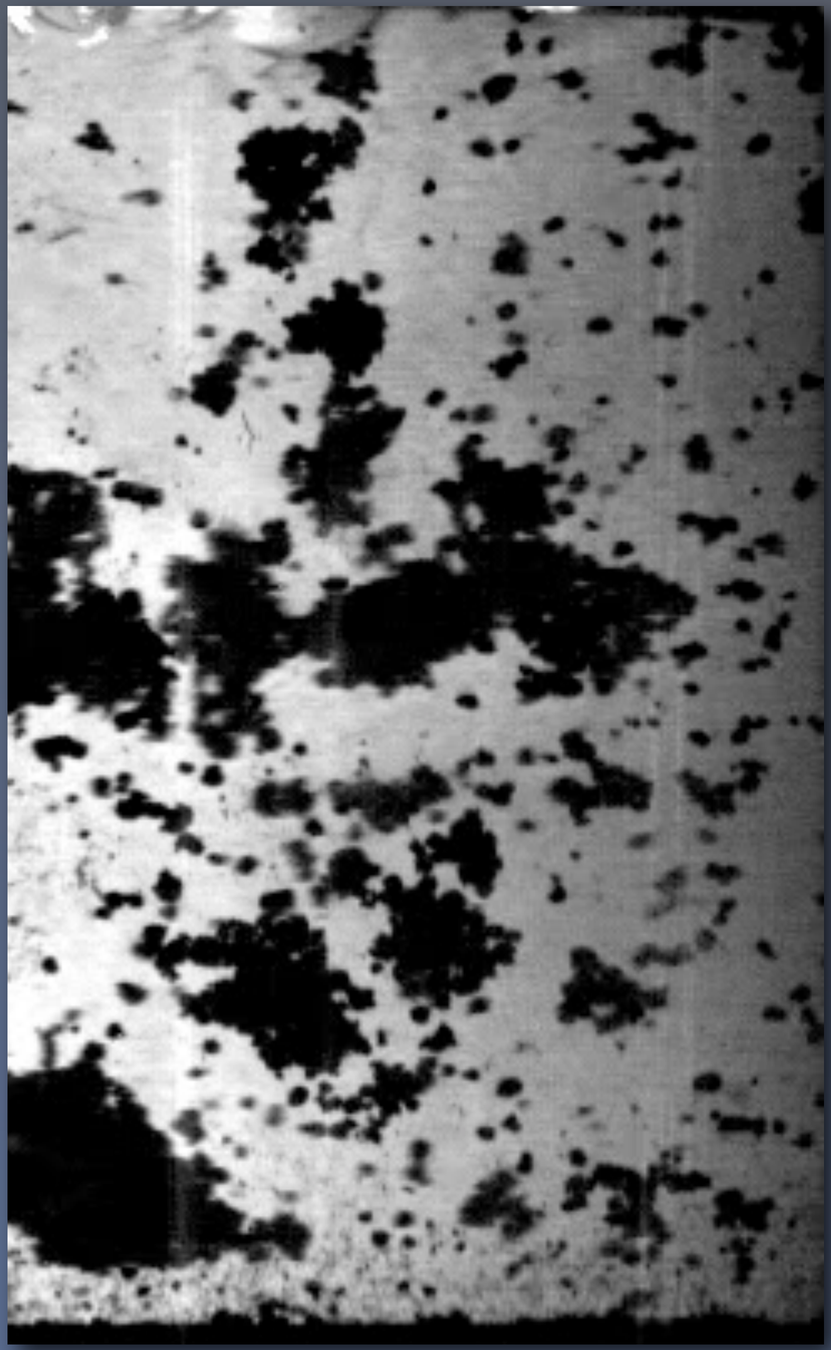
$$v_{\rm sett} = -\frac{3 \Omega_{\rm k}^2 z}{4 \rho c_{\rm s}} \frac{m}{\sigma_{\rm g}}$$

(See Ormel & Cuzzi 2007)

Stokes number:

$${\rm St} = \tau_{\rm s} / \tau_{ed} = \tau_{\rm s} \Omega_{\rm k}$$

Laboratory dust collision studies



a ~ 0.1-5 mm

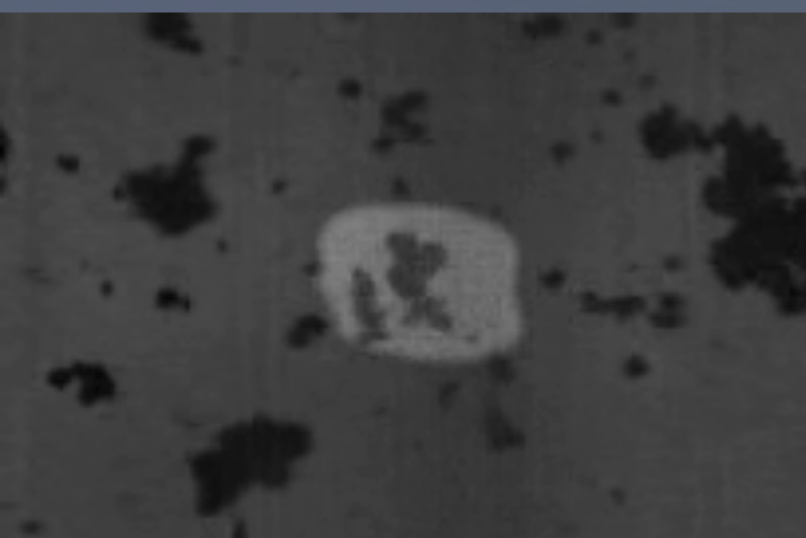
v ~ 0.1-1 cm/s

Weidling et al. (2011)

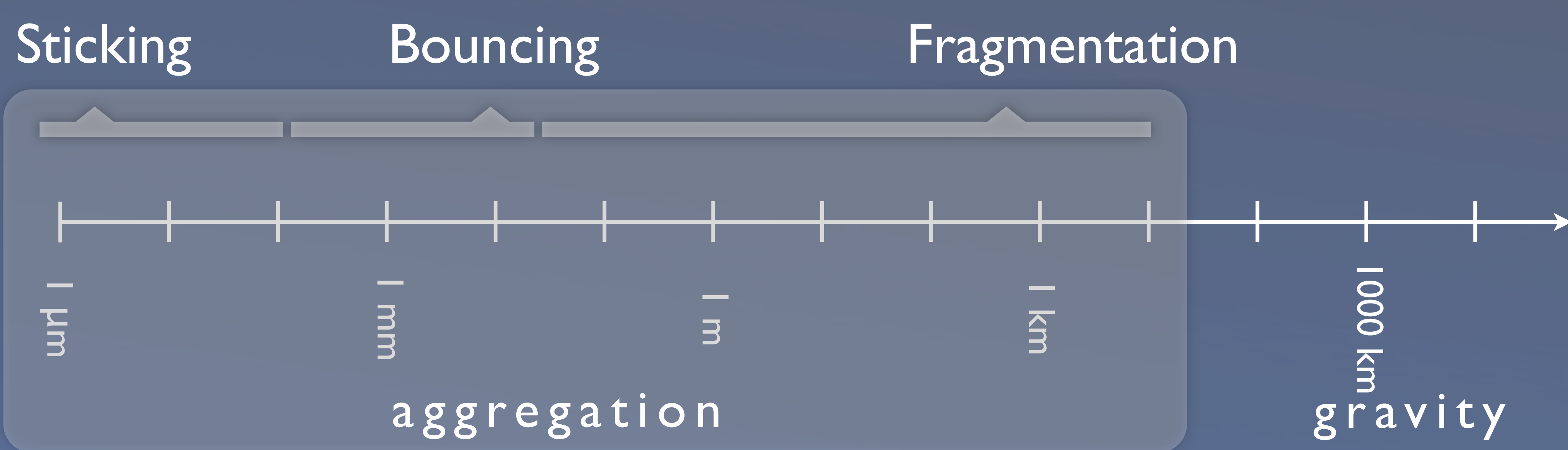
The barriers to growth

Weidling et al. (2011)

Kothe et al.

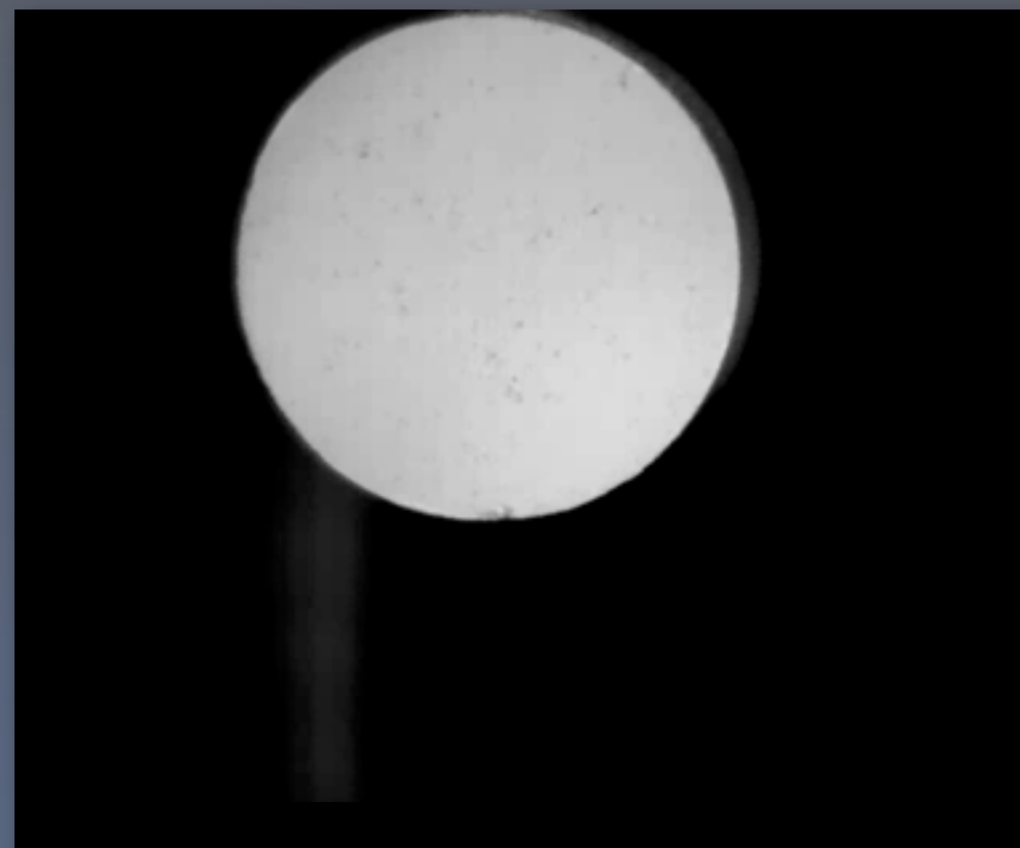


Lammel (2008)

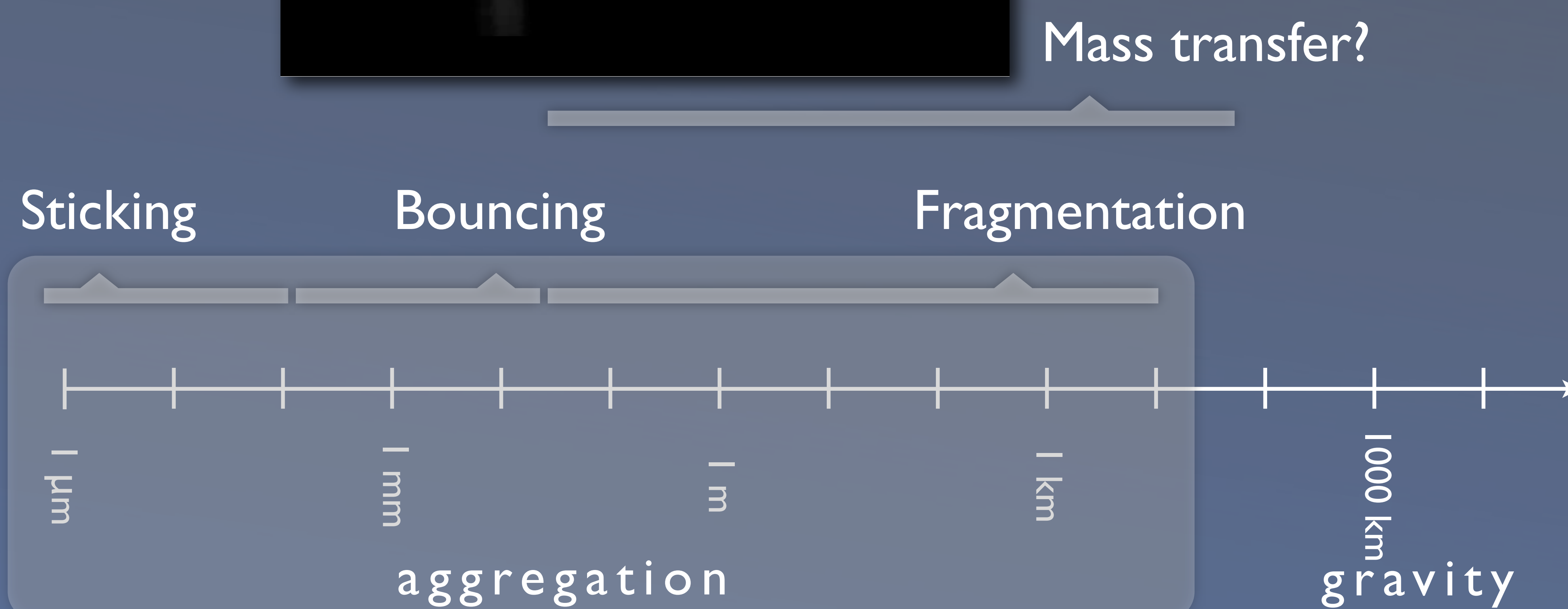


Dust collision studies in the laboratory

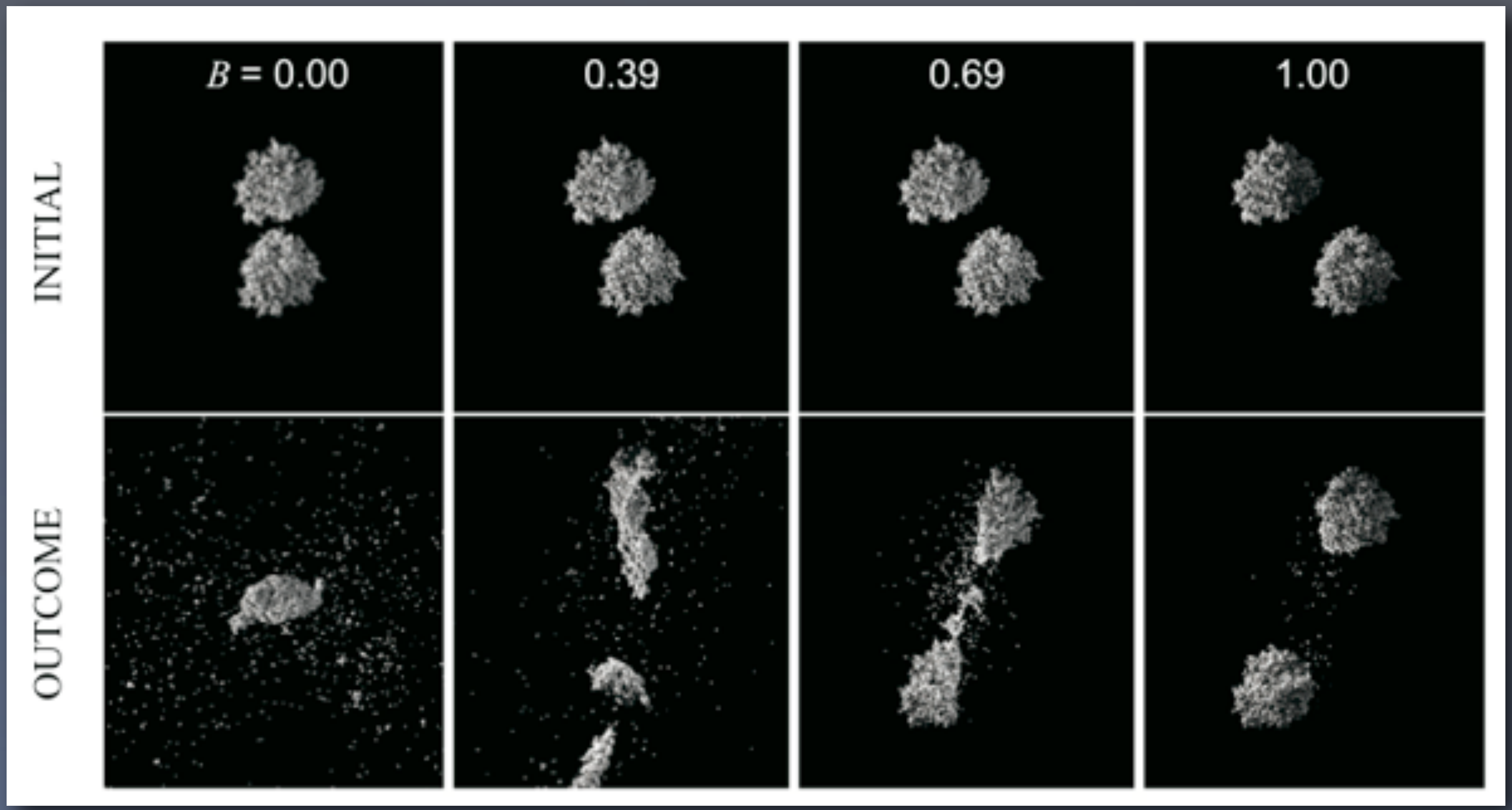
v = 100 cm/s
a = 1 cm



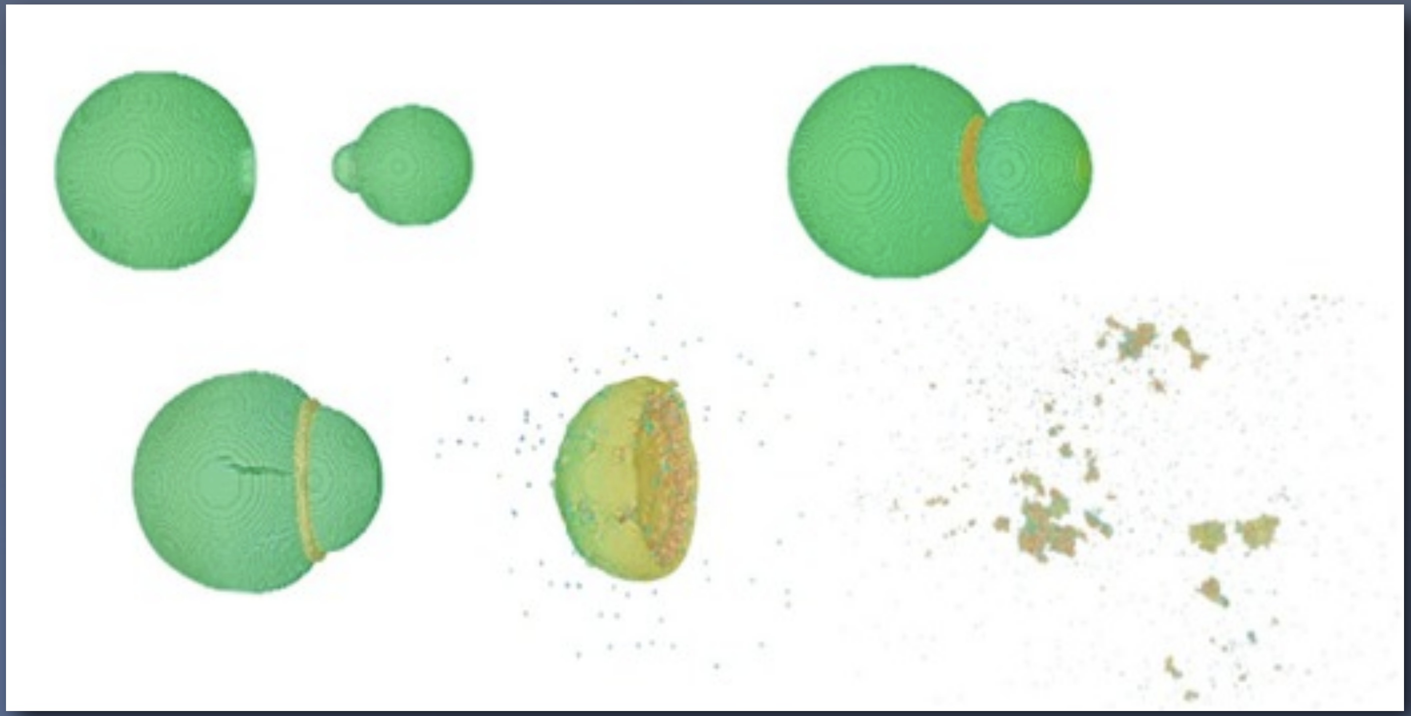
Beitz, Meisner et al. (2011)



Numerical dust collision studies

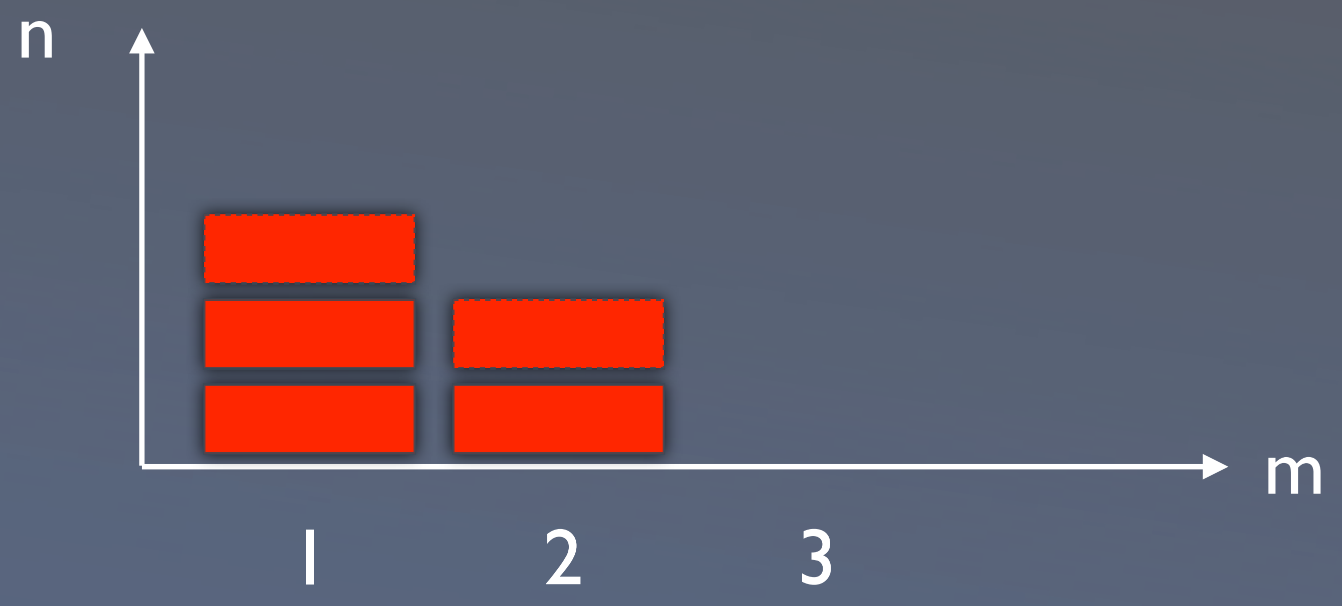


Molecular dynamics by Wada et al. (2008-2012)
Paszun & Dominik (2008, 2009)



SPH by Geretshauser et al. (2011a,b)

Tracking the dust-size evolution

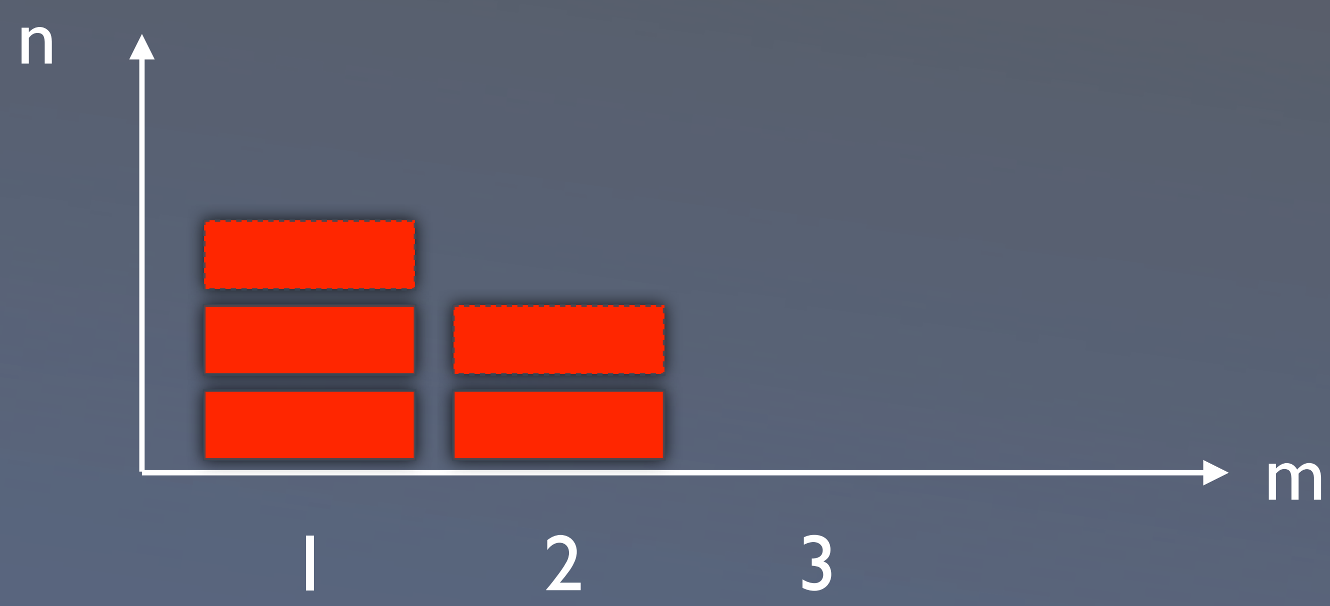


Dust size evolution followed statistically and macroscopically with the Smoluchowski equation:

$$\frac{\partial}{\partial t} n(m,r,z) = \int \int_0^\infty M(m,m',m'') \times$$
$$n(m',r,z) n(m'',r,z) dm' dm''$$

See Brauer et al. (2008), Birnstiel et al. (2010)

Tracking the dust-size evolution



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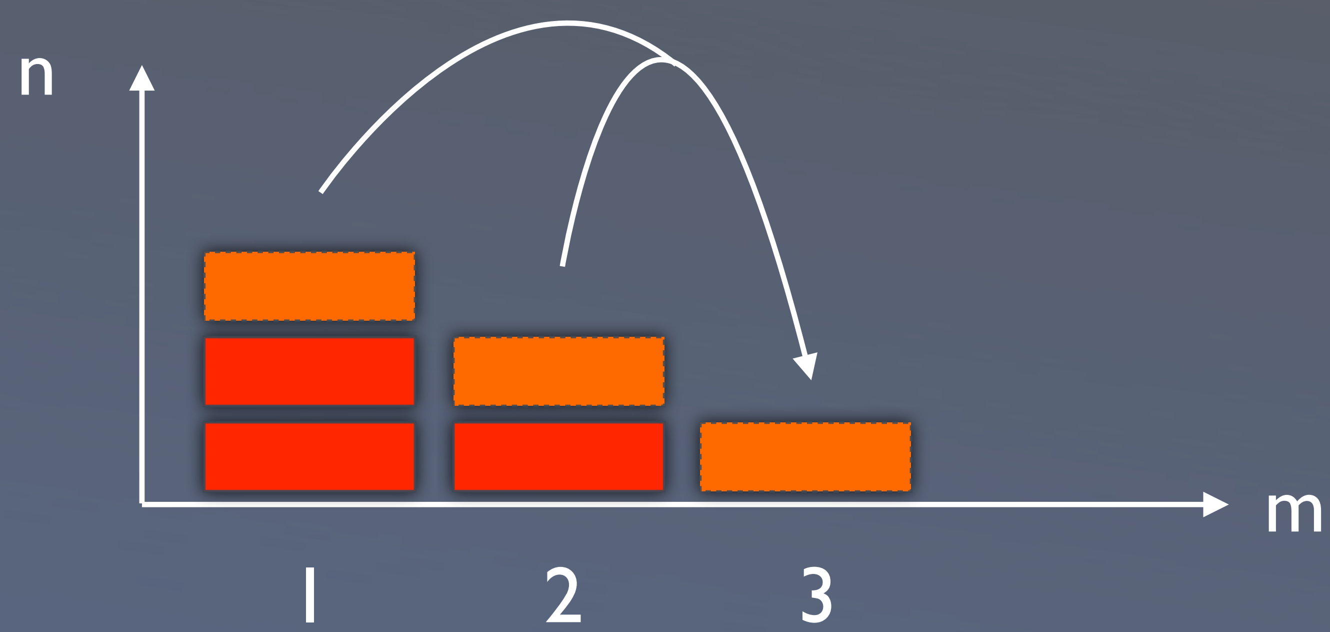
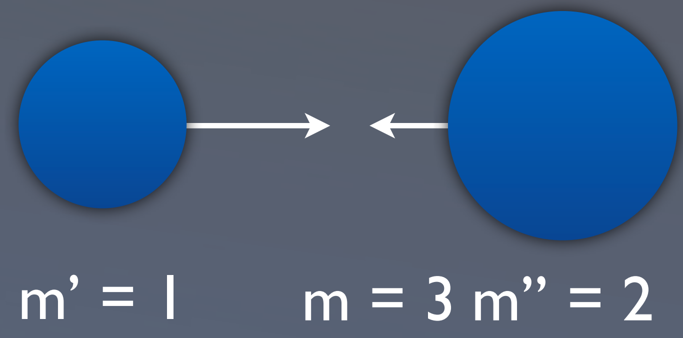
$$\frac{\partial}{\partial t}n(m,r,z) = \int\int_0^\infty M(m,m',m'')\times$$
$$n(m',r,z)n(m'',r,z)dm'dm''$$

See Brauer et al. (2008), Birnstiel et al. (2010)

Tracking the dust-size evolution





Dust size evolution followed statistically and macroscopically with the Smoluchowski equation:

$$\frac{\partial}{\partial t} n(m,r,z) = \int\int_0^\infty M(m,m',m'')\times n(m',r,z)n(m'',r,z)dm'dm''$$

See Brauer et al. (2008), Birnstiel et al. (2010)

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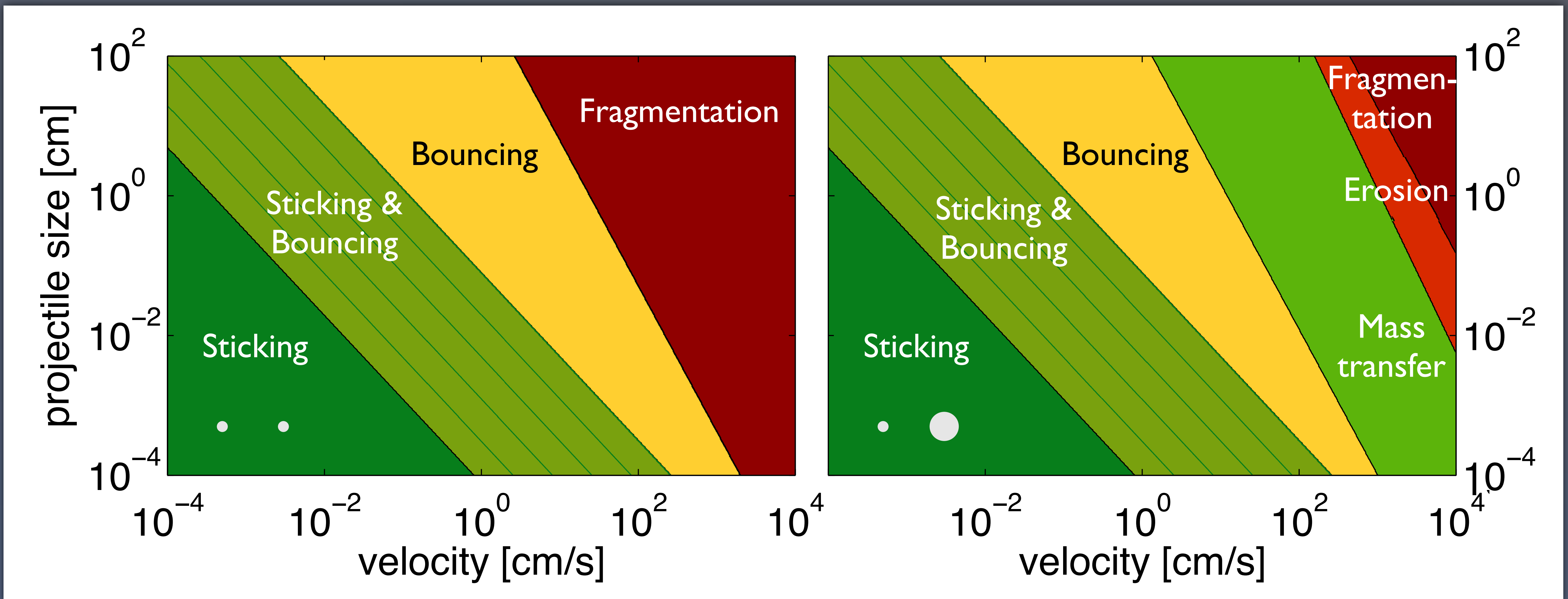
A new collision model - Collisional outcome

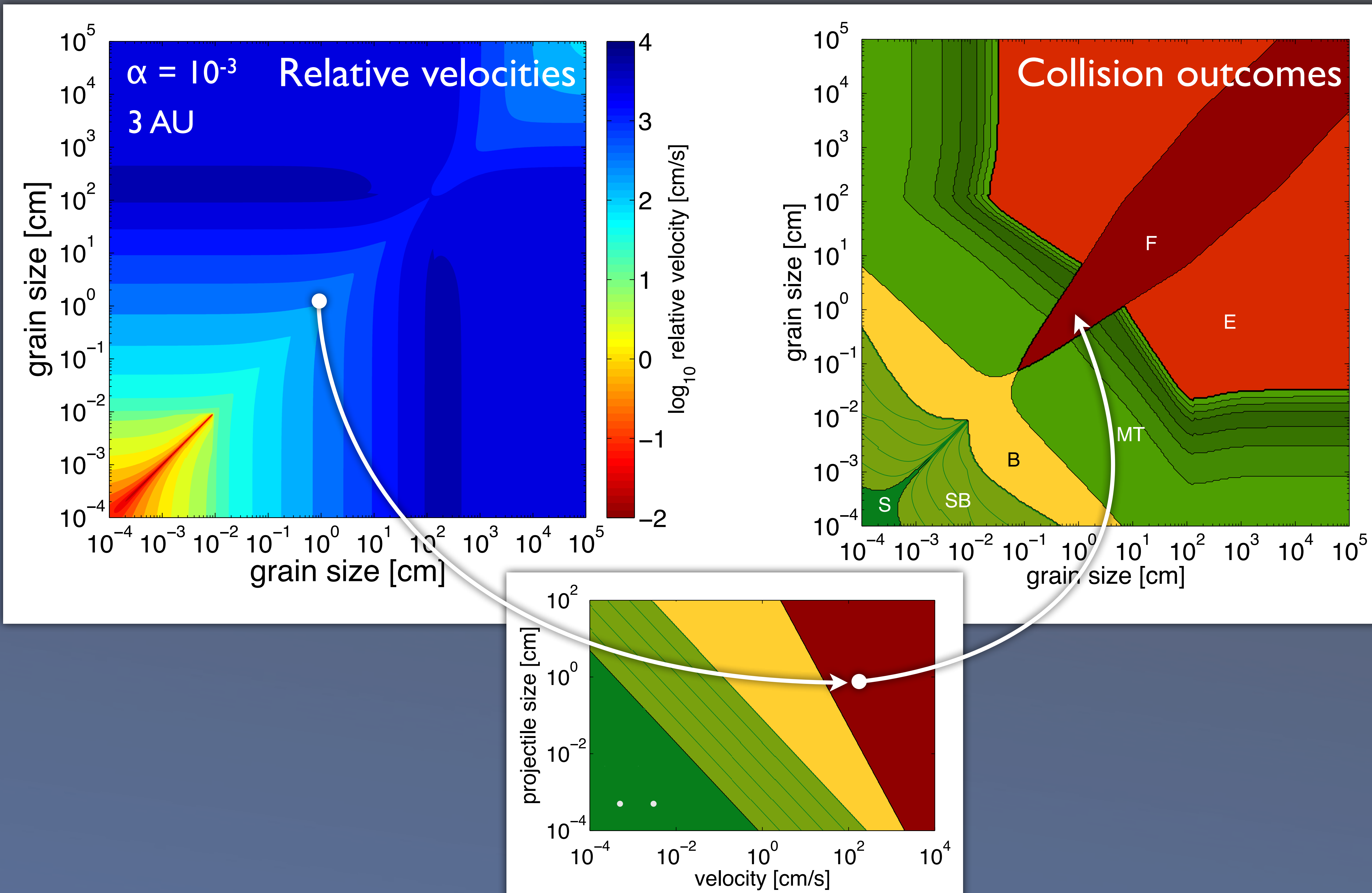
$m_t / m_p = 1$ $m_t / m_p = 1000$



Windmark et al. (2012)

Based on:
Blum & Wurm (2000), Wurm et al. (2005), Teiser & Wurm (2009a,b), Güttler et al. (2010), Kothe et al. (2011), Schräpler & Blum (2011), Beitz et al. (2011), Weidling et al. (2011)

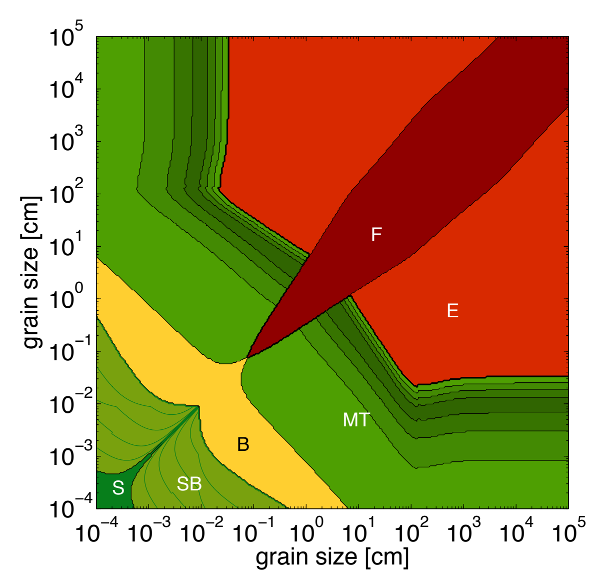
A new collision model - Collisional outcome

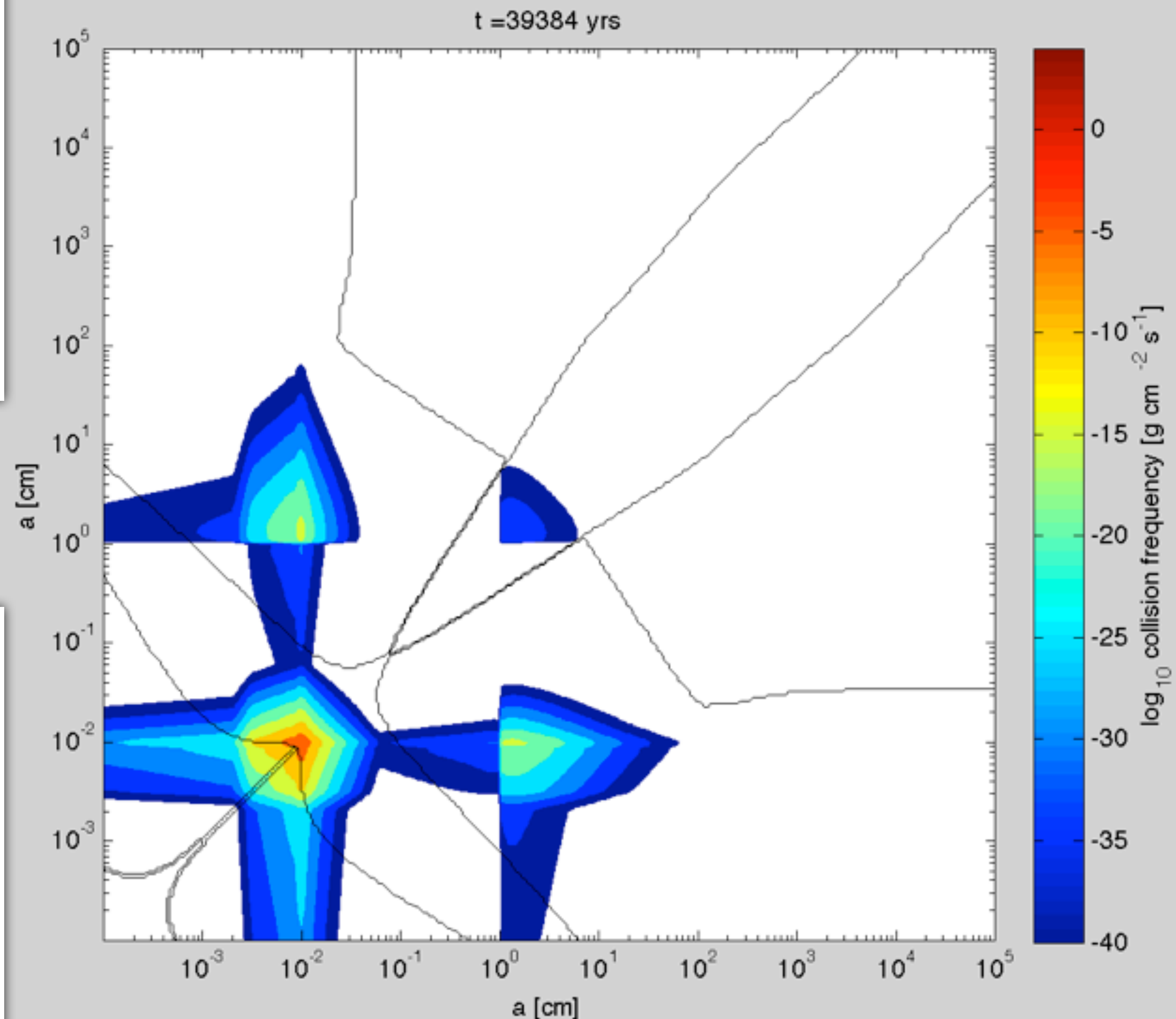


Local simulations at 3 AU
(full collision model)

Diagonal interactions - Equal-size collisions

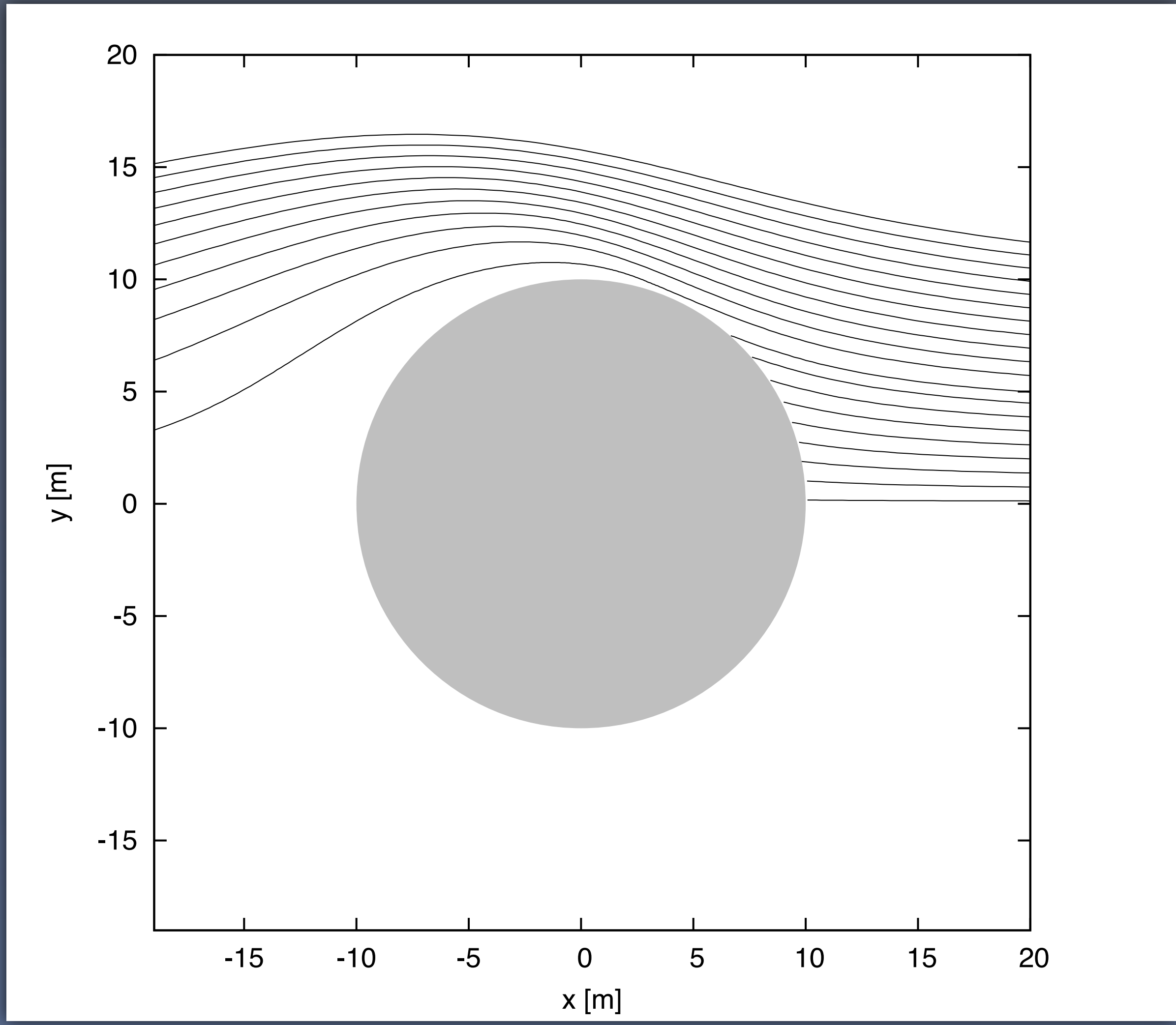
Horizontal interactions - Sweep-up growth



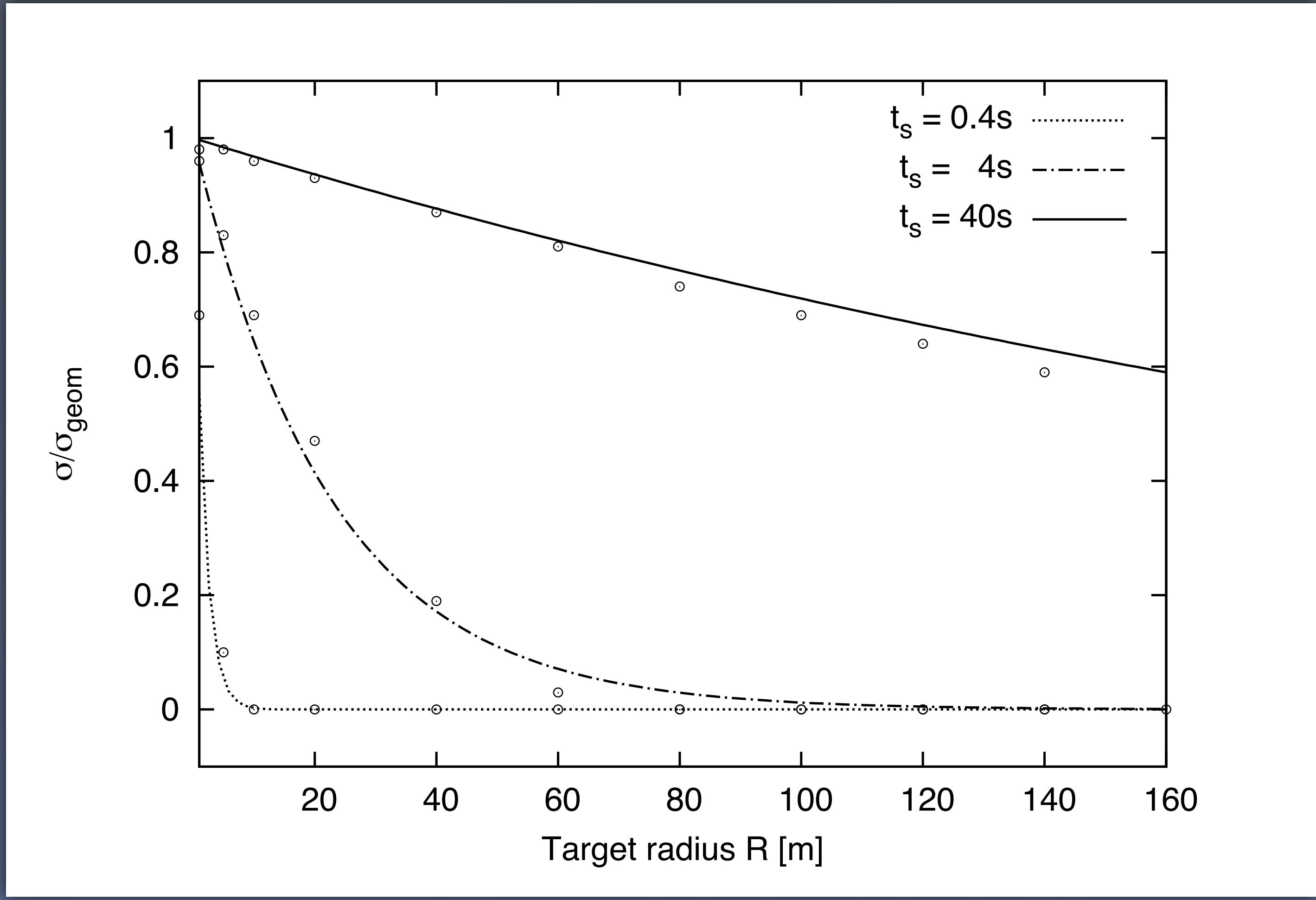


The gas-drag effect on coagulation

Gas flow can drag small particles around a large body...



... leading to a decrease in collisional cross-section



Selentin, Windmark, Ramsey, Dullemond (in prep)

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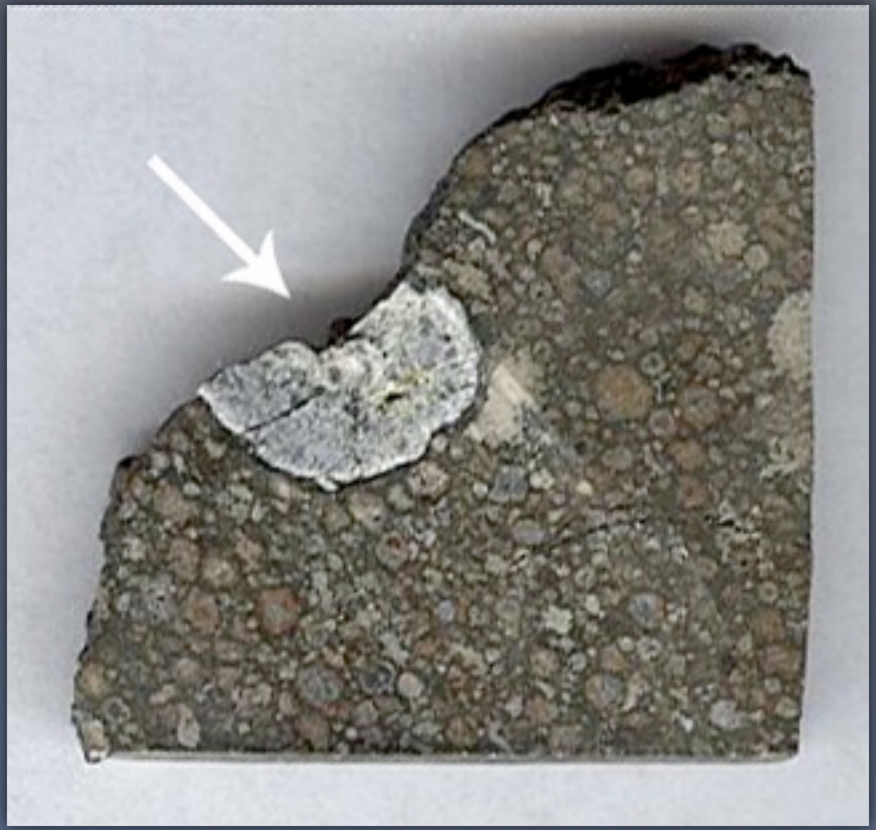
The first seeds

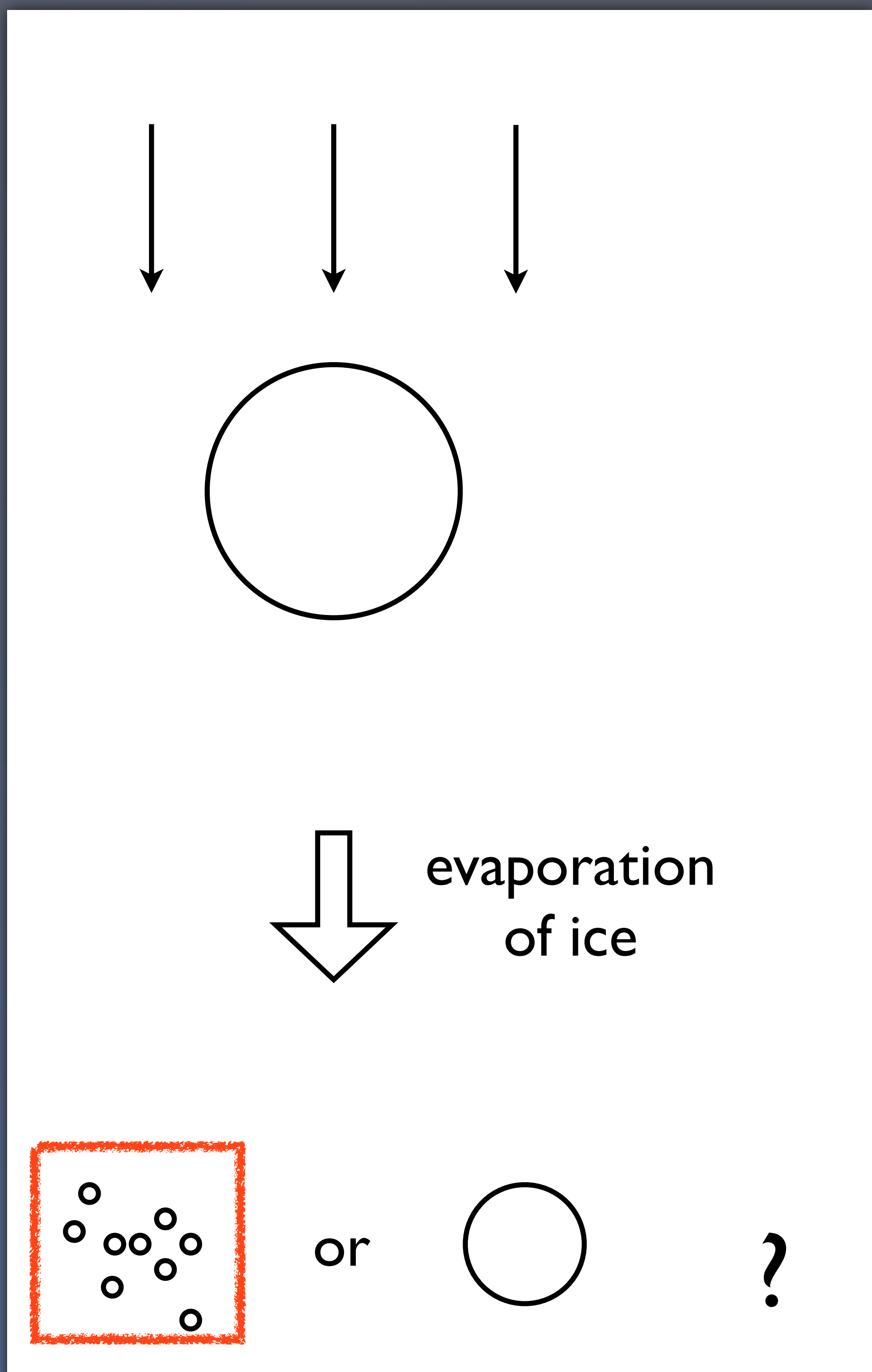
Only need a few "seeds" to initiate sweep-up, but how were they formed?

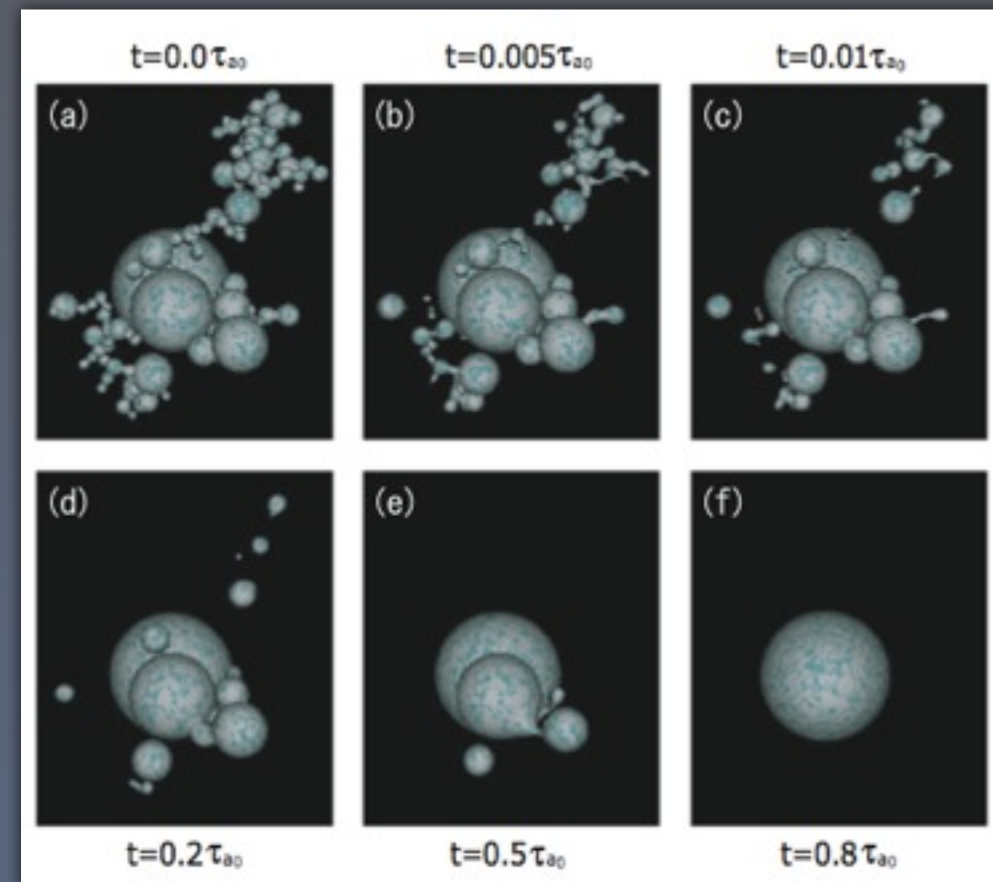
- Primordial CAIs?
- Drift from outer parts of disk?
- Lucky sticking particles?

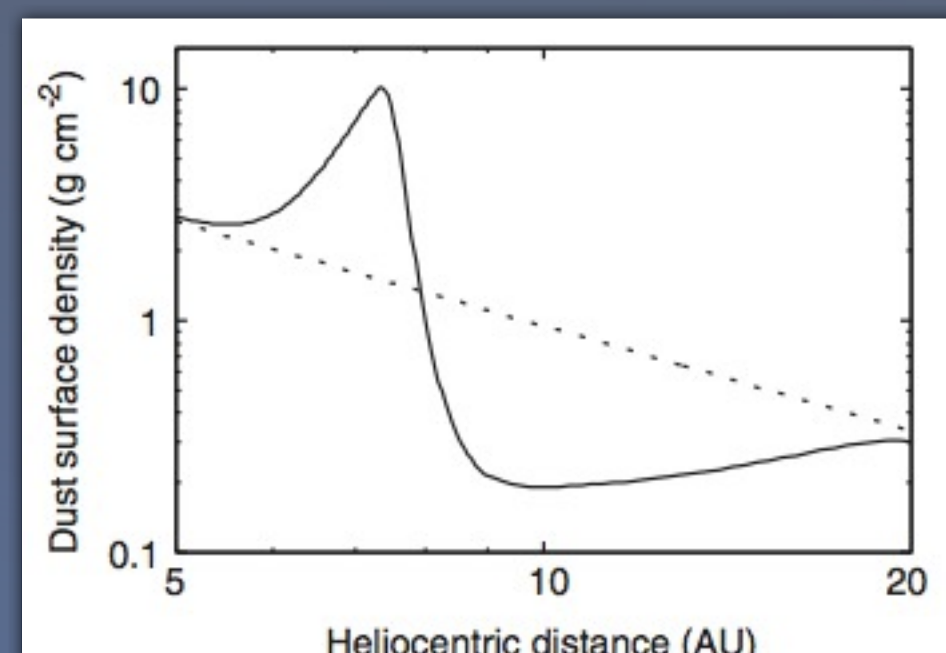


Meteorite containing a
Calcium-aluminium-rich inclusion

Drift through the snowline

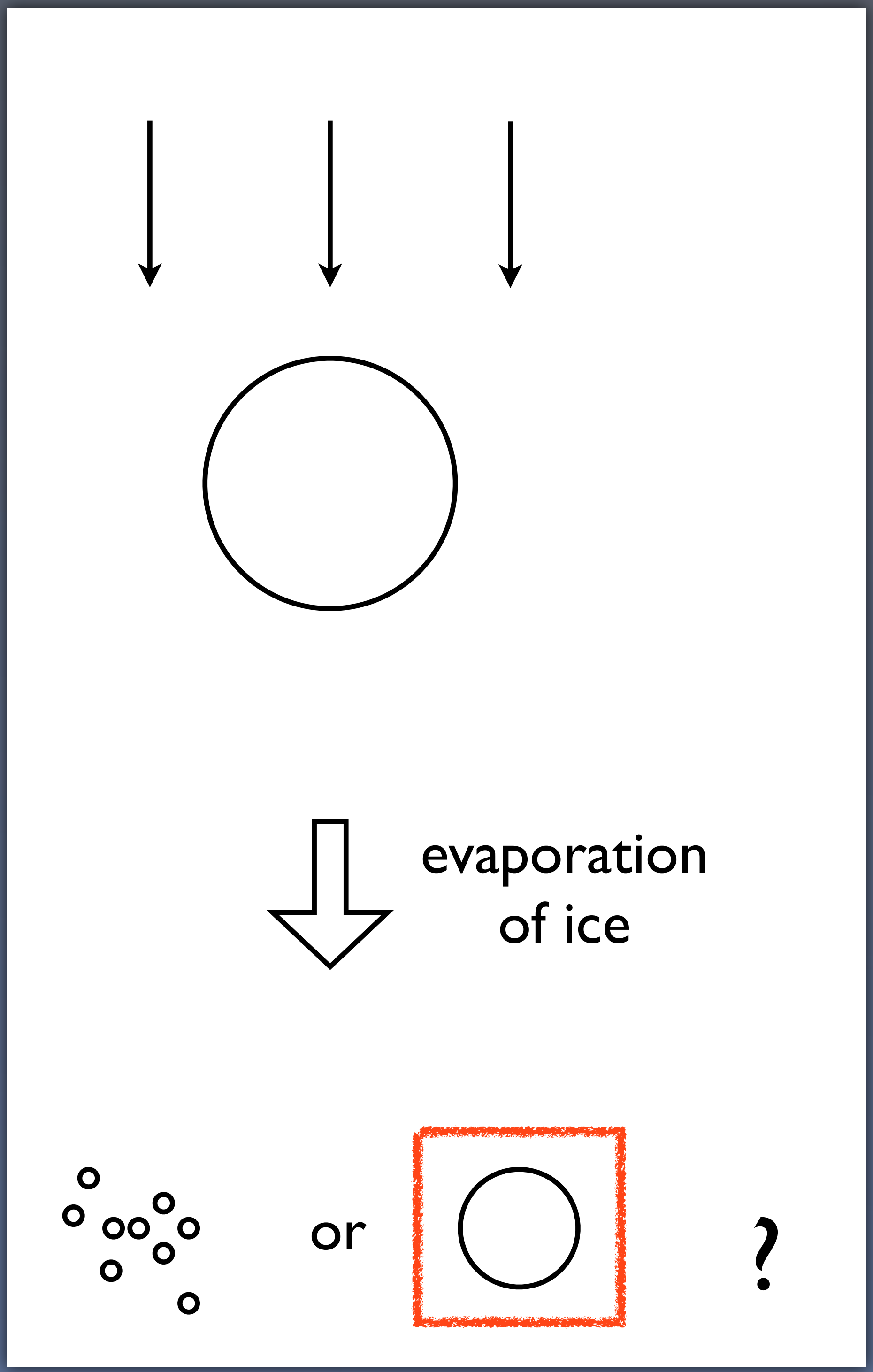




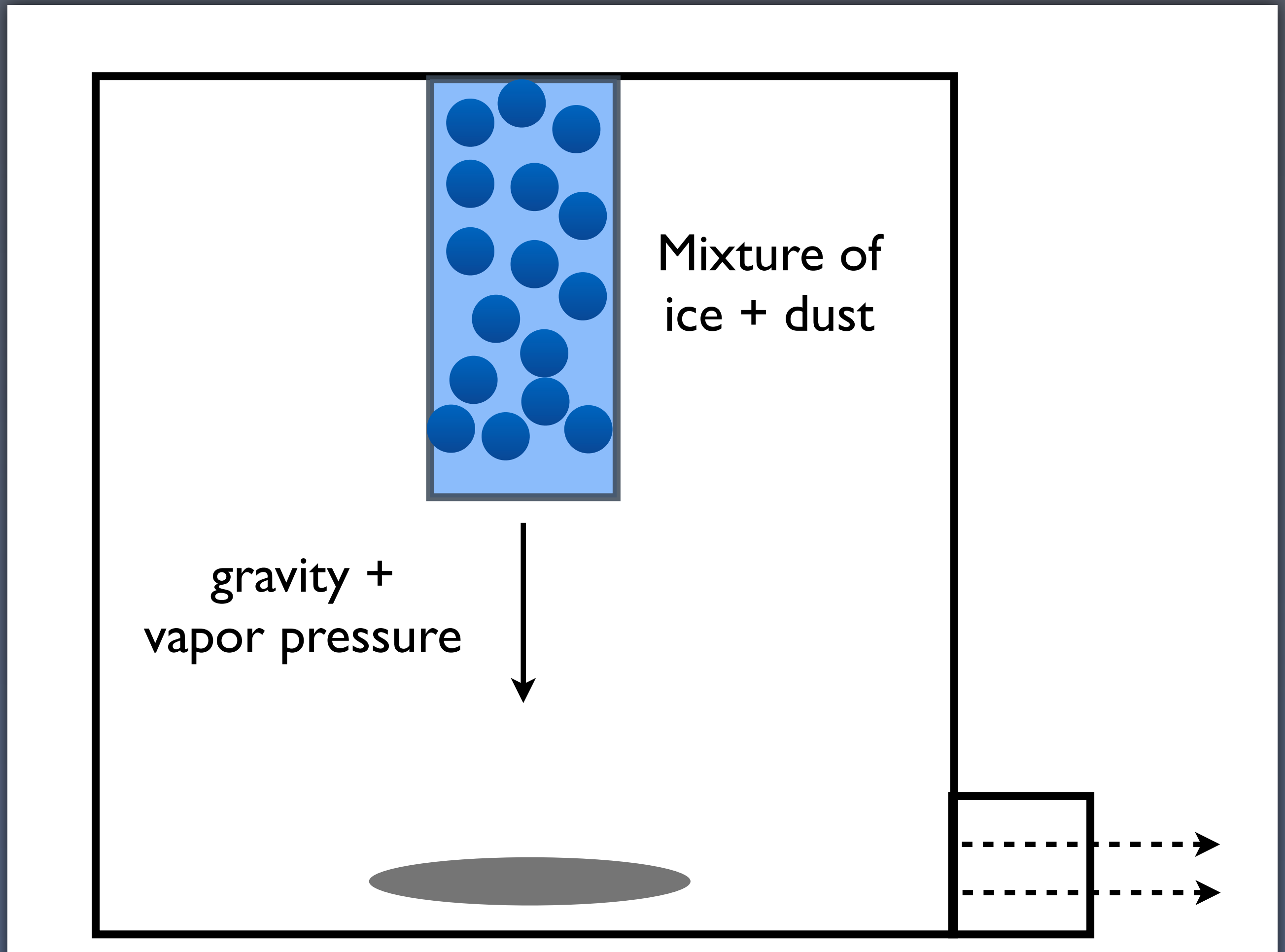


Sirono (2011)

Drift through the snowline



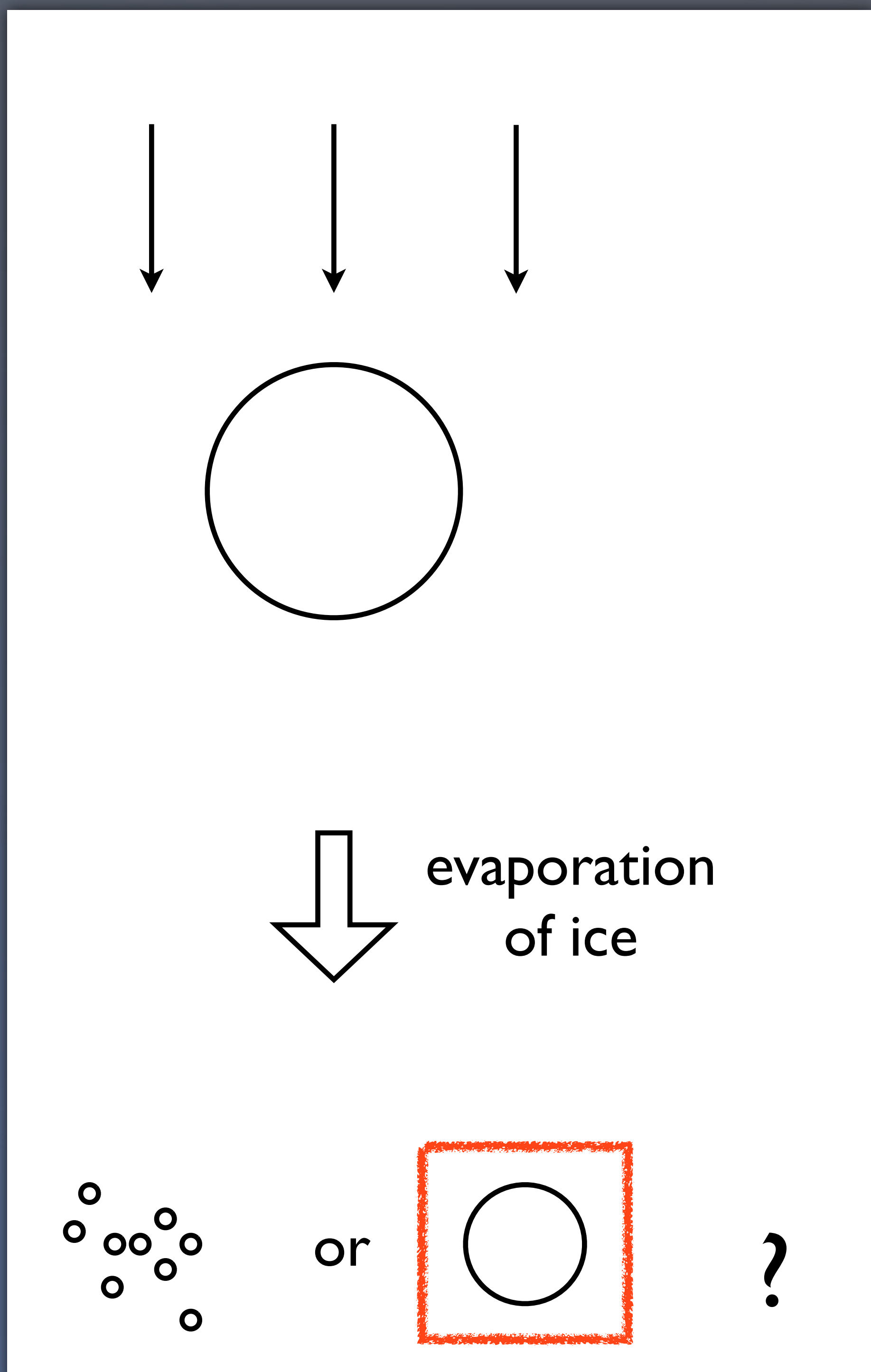
Experimental setup - Evaporation of dirty ice



Vacuum chamber in ambient temperature

Windmark, Okuzumi, Blum (work in progress)

Drift through the snowline



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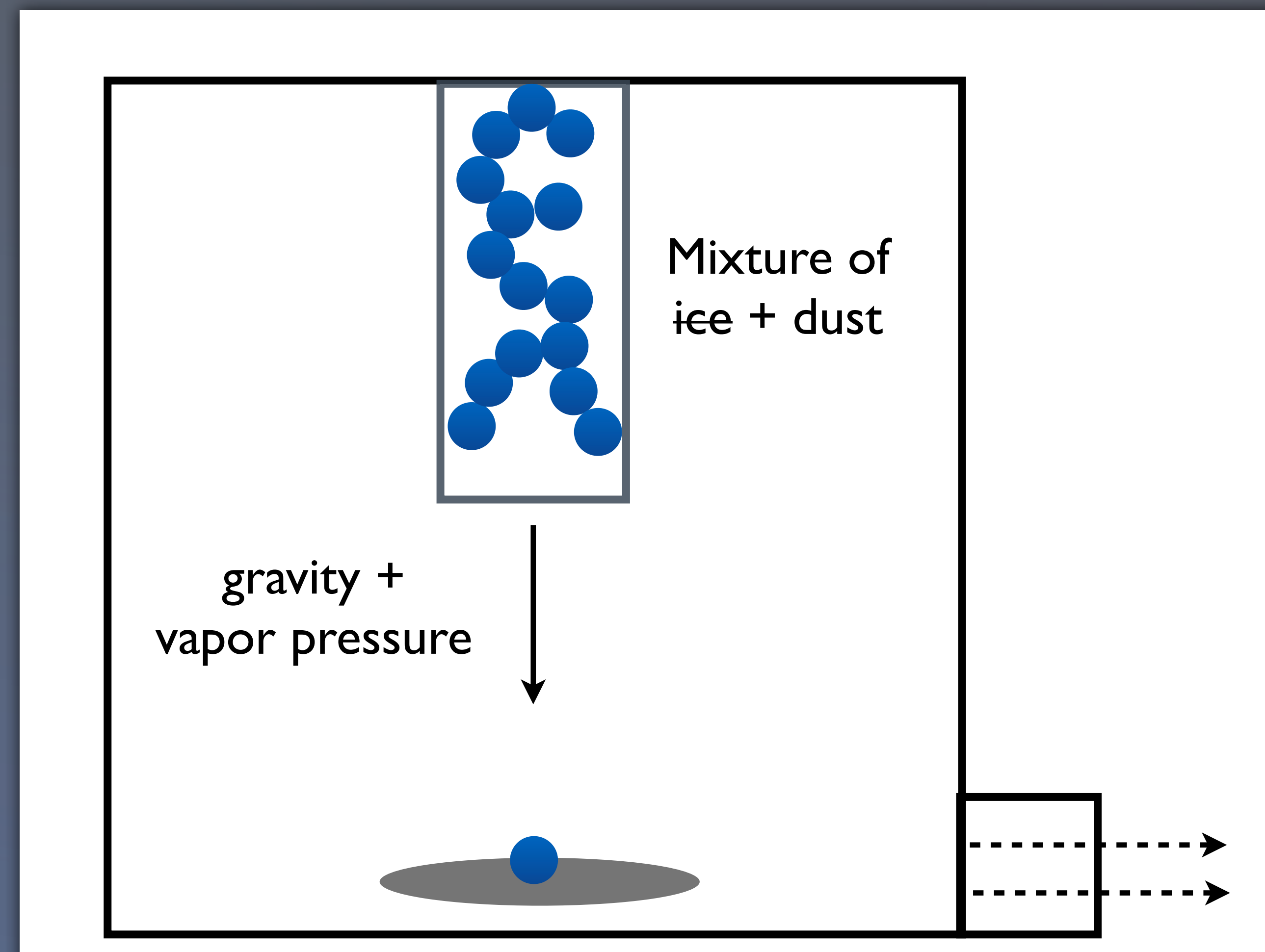

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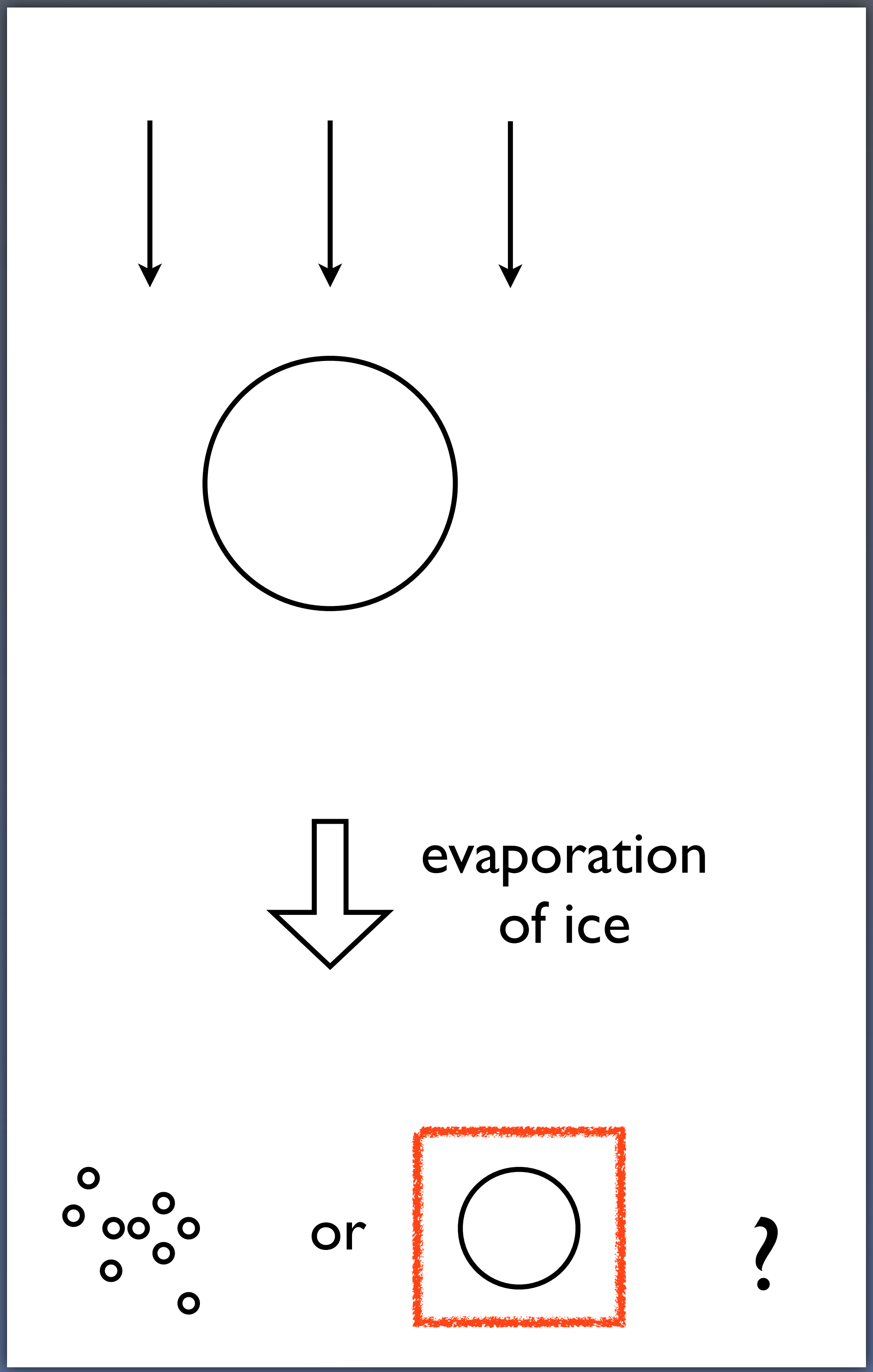
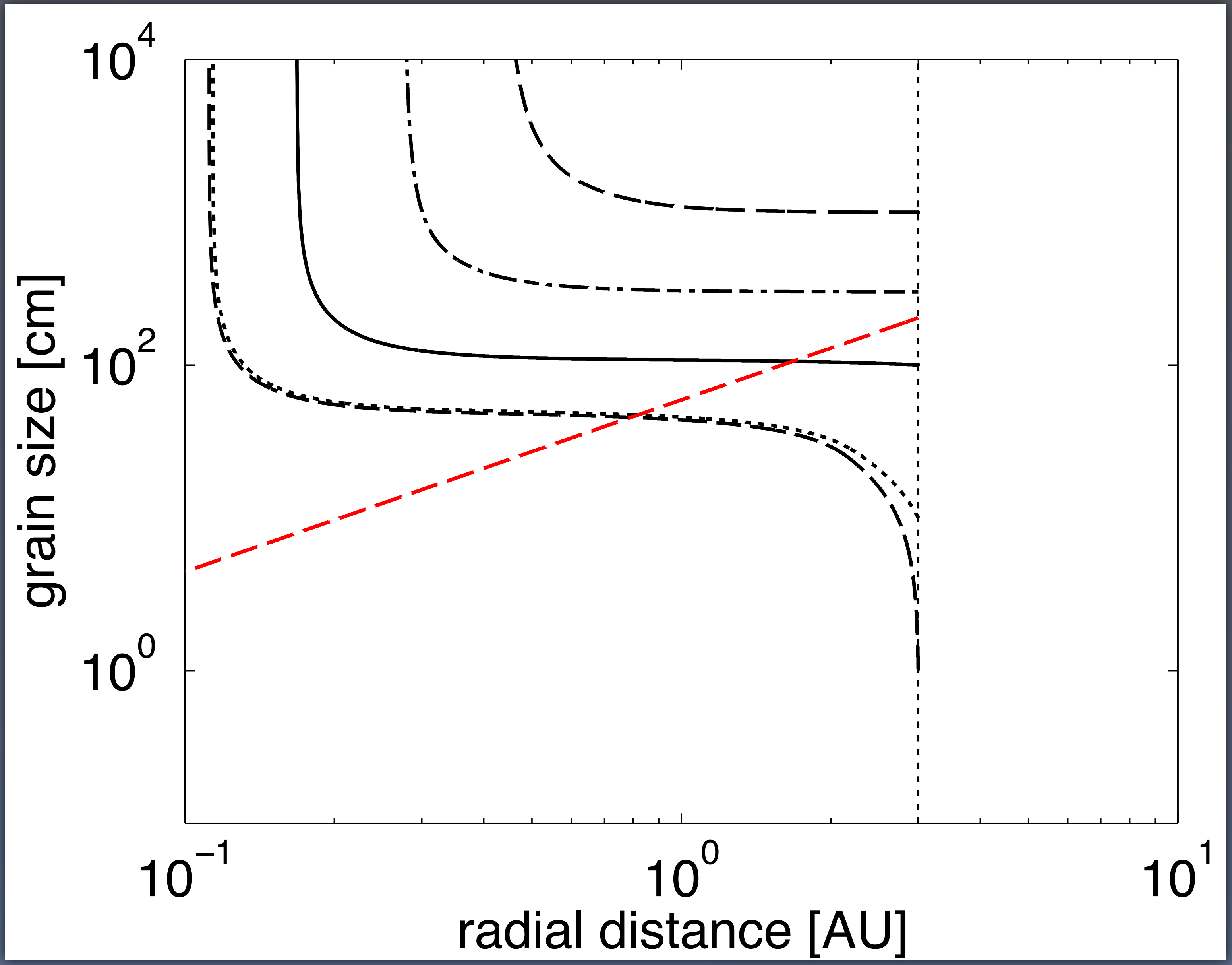


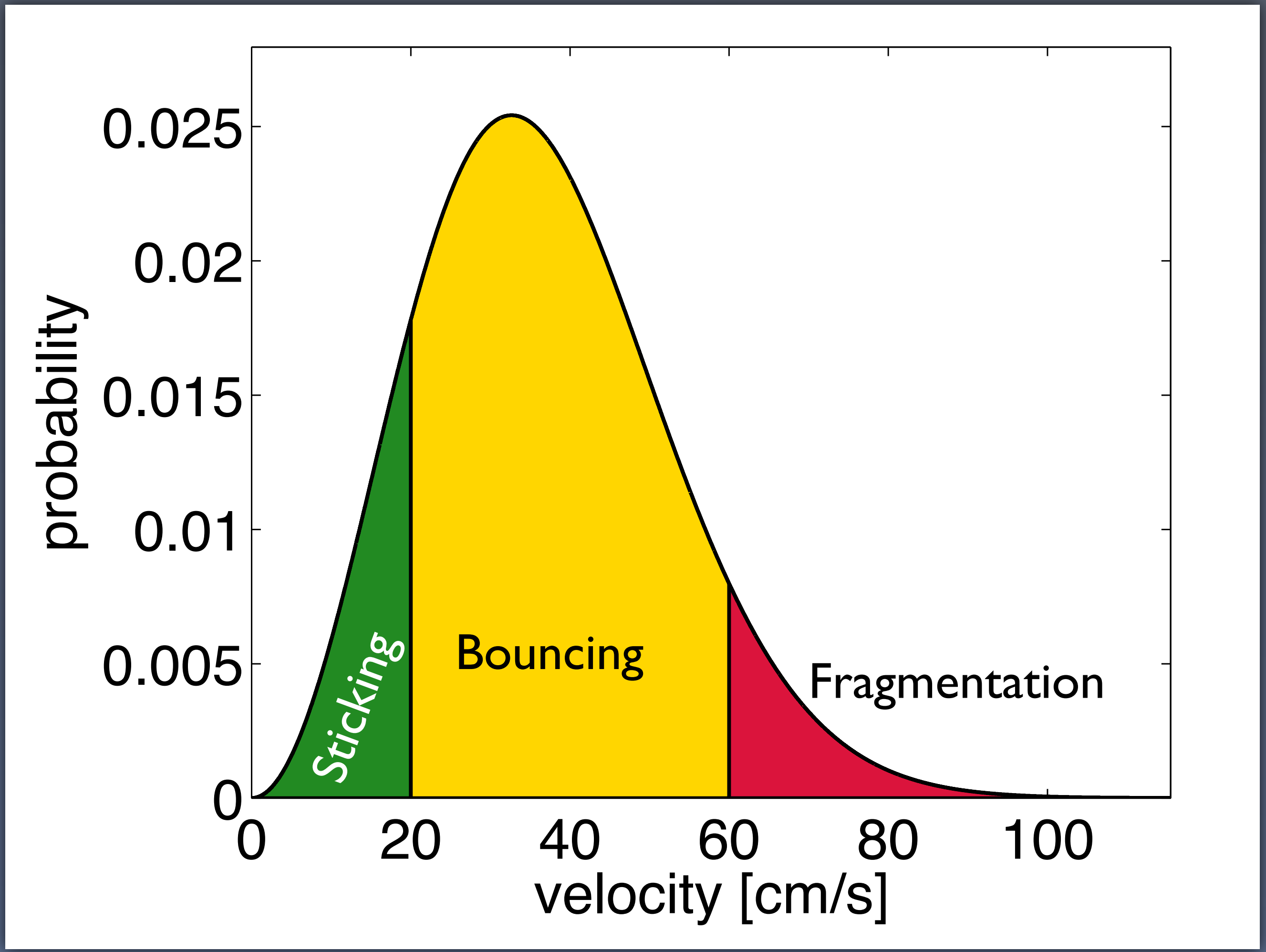


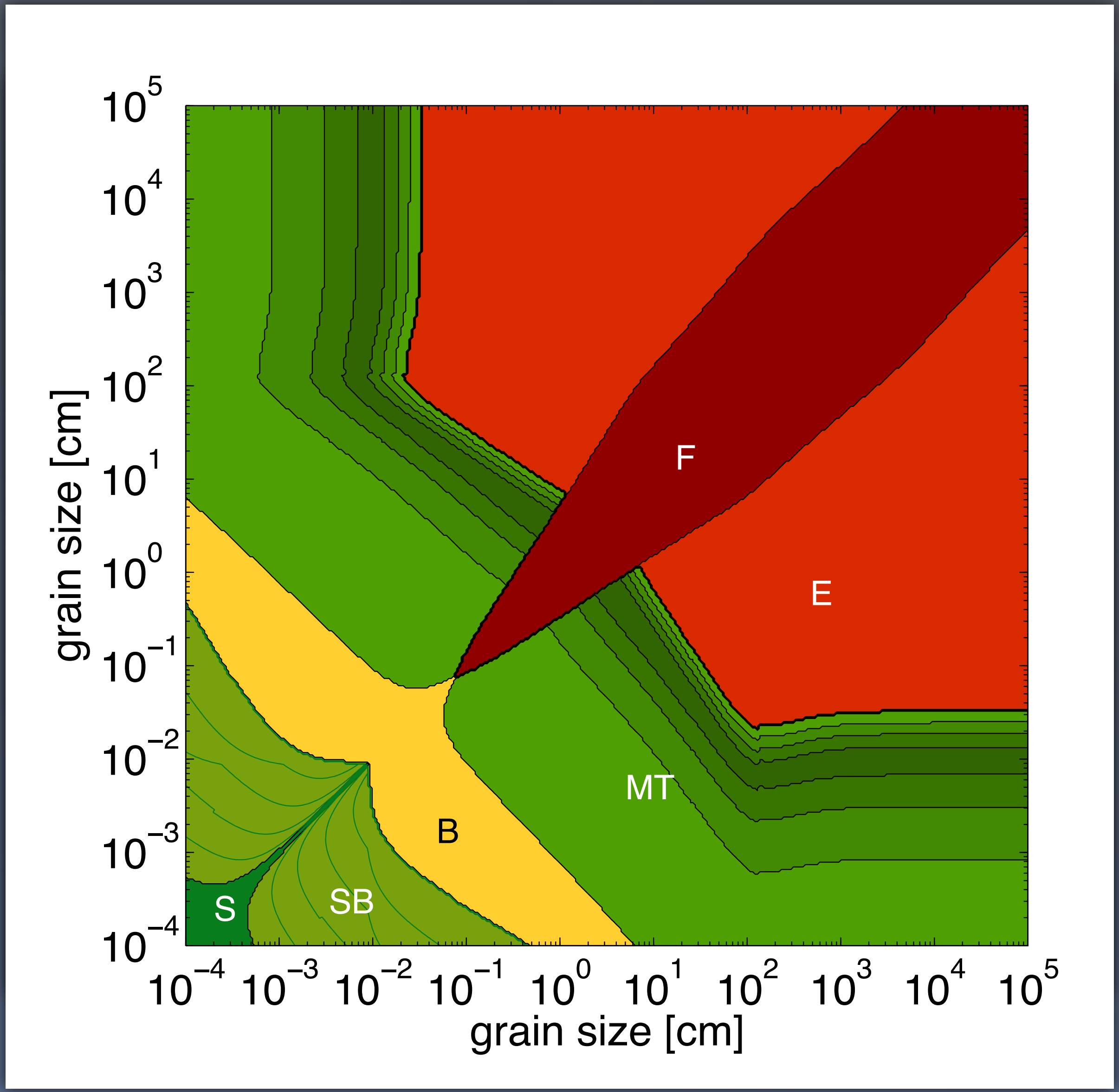
Toy model: Drift, sweep-up and decoupling

Windmark, Okuzumi, Blum (work in progress)

Including a particle velocity distribution

Maxwellian velocity distribution





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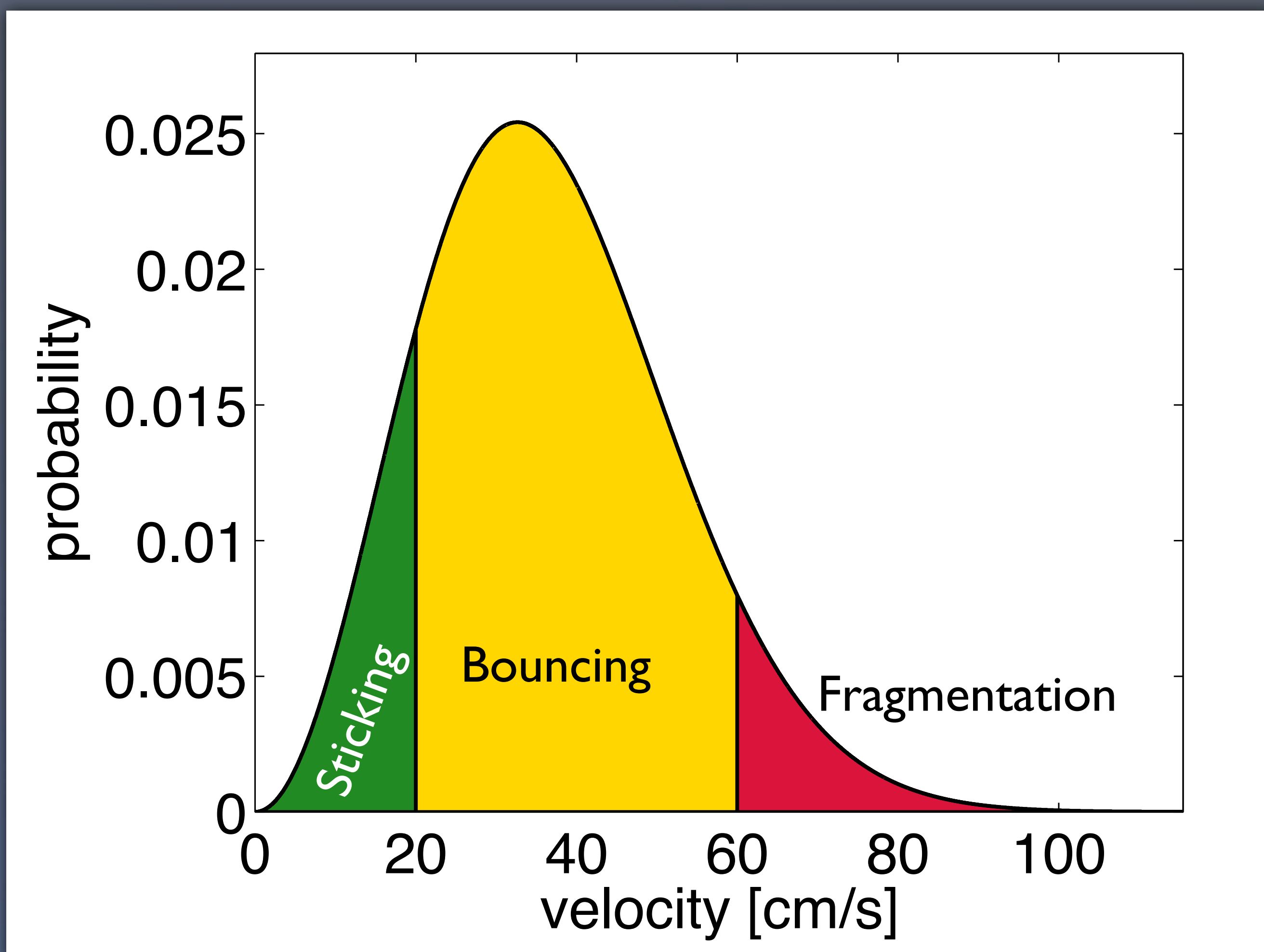

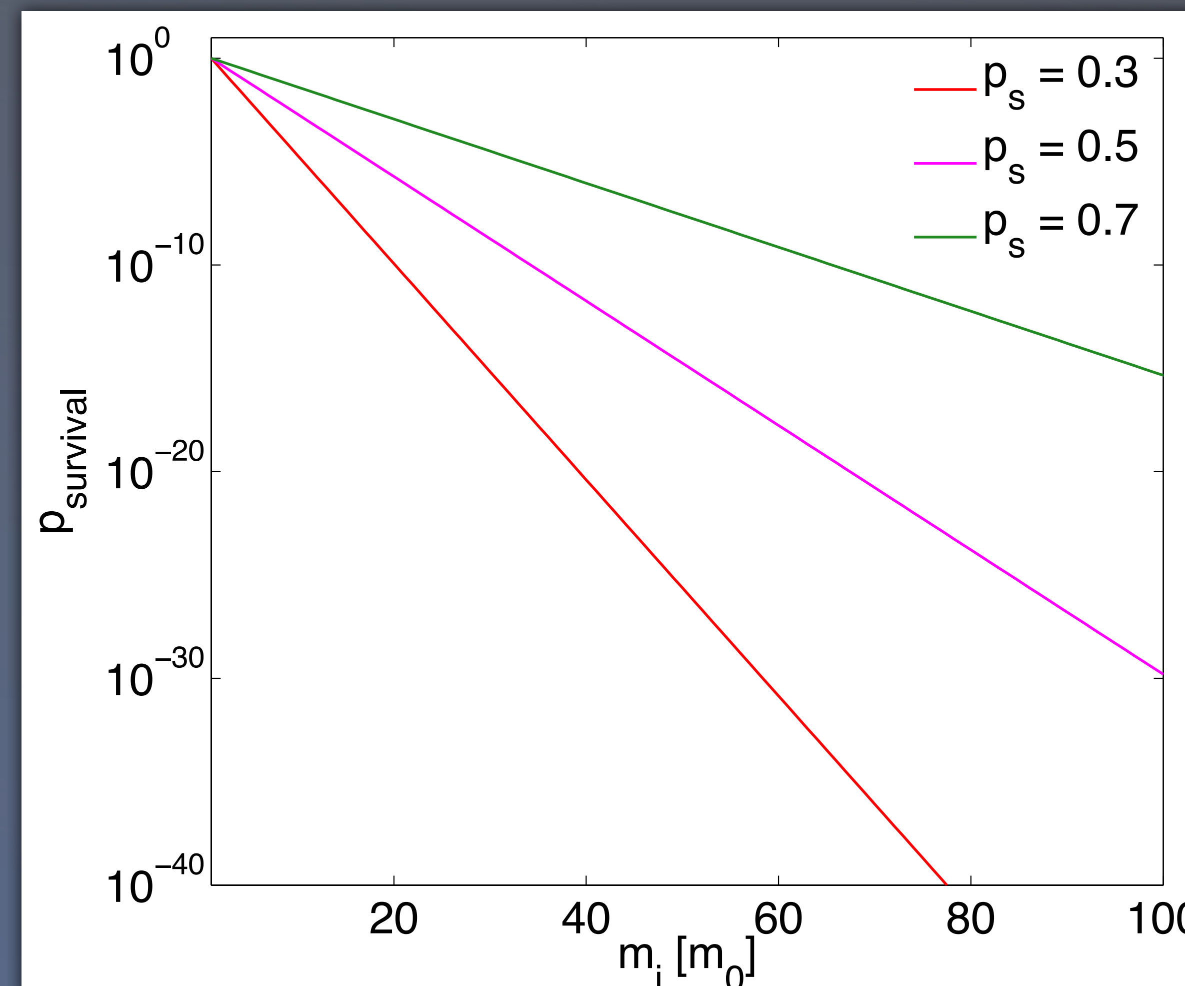

Summary & Outlook

Planetesimal formation is still uncertain, with many growth barriers to pass.

Collaboration between theory and laboratory can provide a better understanding of the processes involved.

Our work shows that:

* Bouncing prevents growth above mm-sizes
* Artificially introduced "seeds" can grow by sweeping up small grains

The sweep-up scenario explains growth above fragmentation barrier, but rather slow, so radial drift is still a problem.

How are the first seeds produced?

* Drift from outer parts of disk?
* Primordial CAIs?
* Lucky sticking particles?