Laboratory work on planet formation

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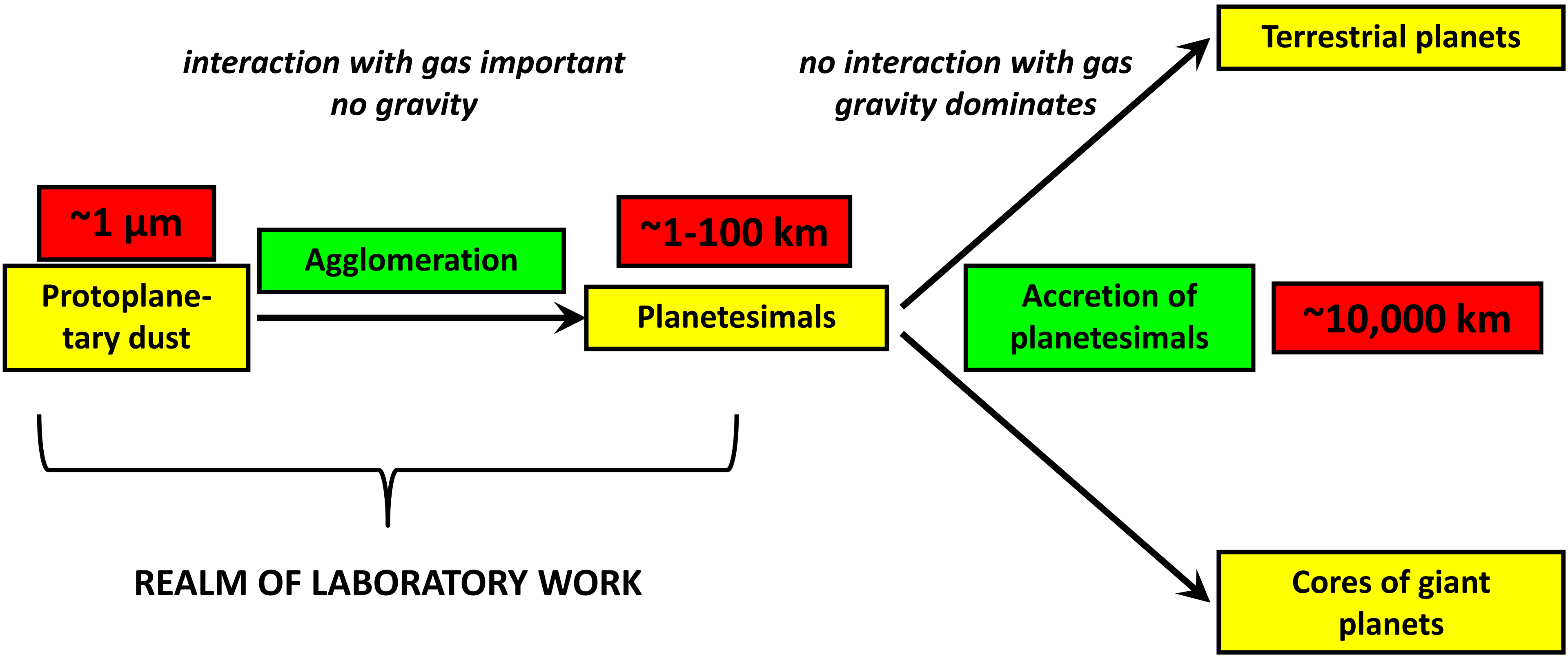
DFG Research Group Planet Formation

The “classical” two-stage model of planet formation

Safronov 1969:
Planets form in protoplanetary discs around young stars from dust and ice grains that stick together to form ever larger bodies



ULTIMATE GOAL: A LABORATORY-CALIBRATED MODEL OF PLANETESIMAL FORMATION

Input into the model

- Ingredient A: Accretion-disk model
  (→ e.g., the MMSN model)
- Ingredient B: Motion of gas and dust within the disk
- Ingredient C: Dust(-aggregate) collision model

Expected output of the model

- Growth timescale
- Maximum dust-aggregate size
- Size distribution of dust aggregates

Ingredient A: the minimum mass solar nebula (MMSN)

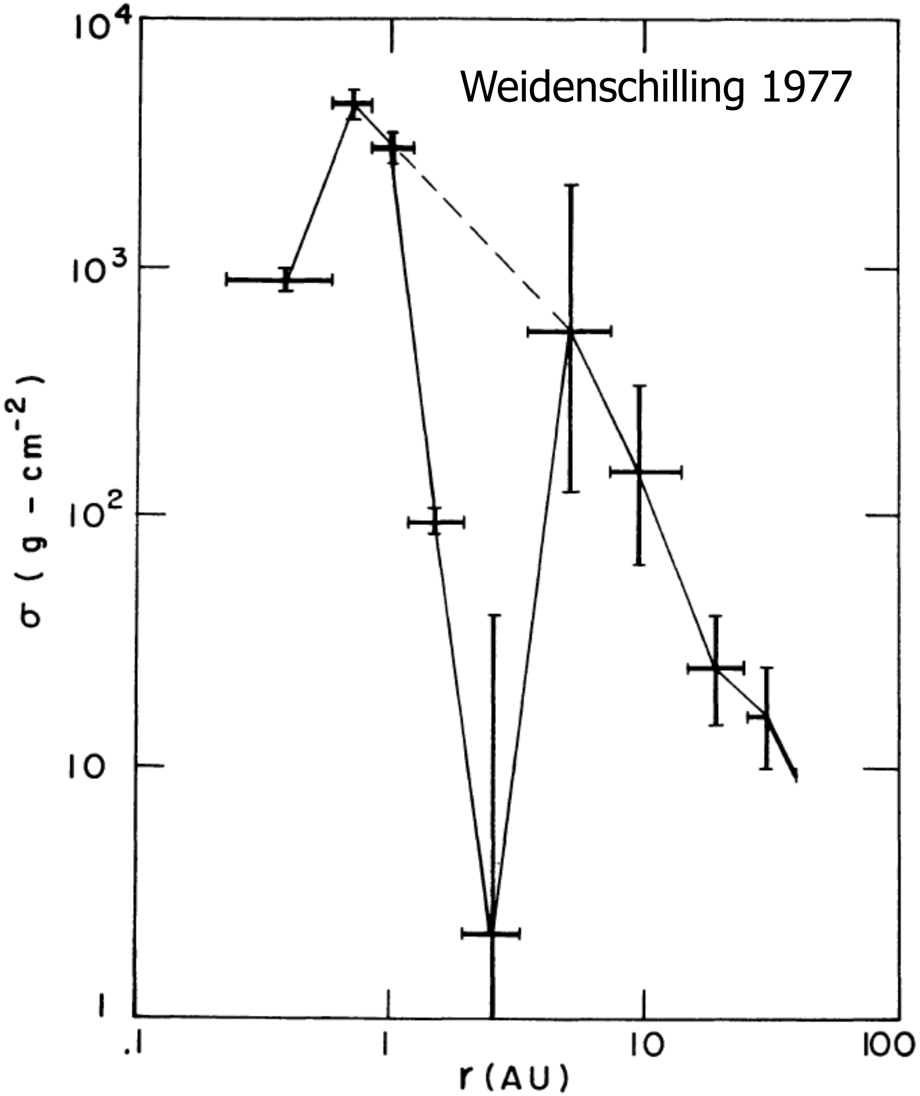
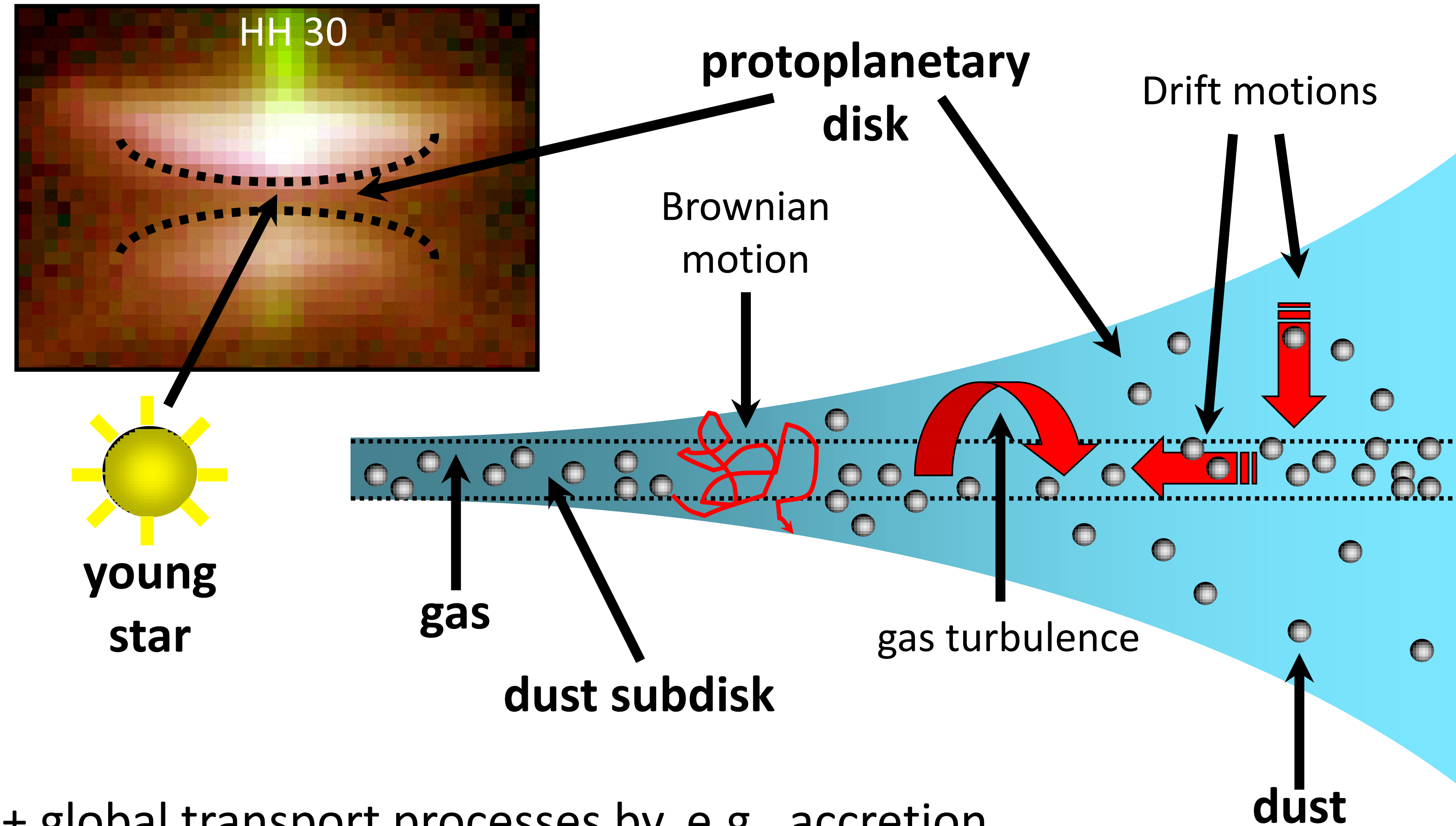


Fig. 1. Surface densities, σ, obtained by restoring the planets to solar composition and spreading the resulting masses through contiguous zones surrounding their orbits. The meaning of the 'error bars' is discussed in the text.

A power-law approximation:

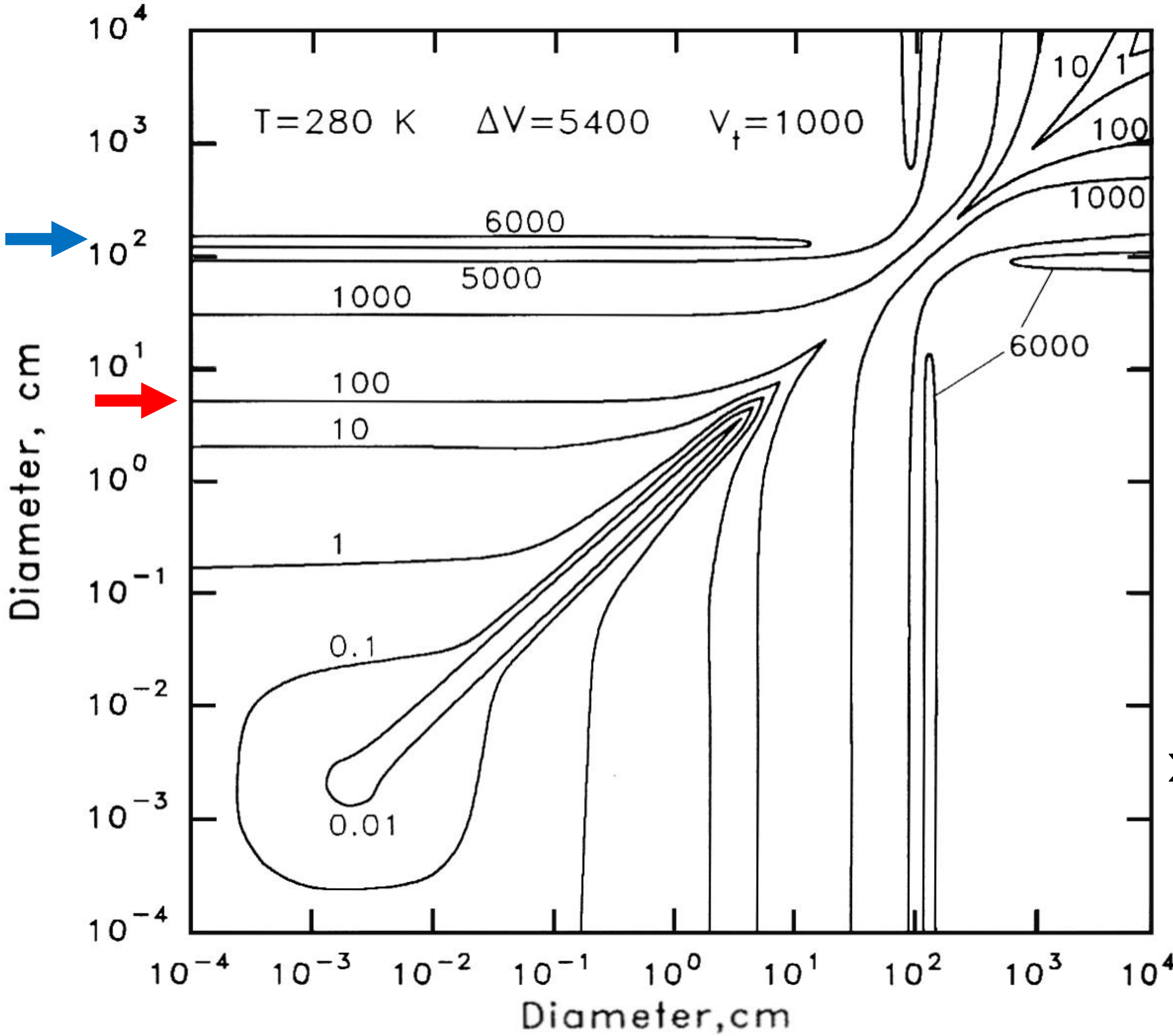
$$\Sigma_s(r) = 1700\,\mathrm{g/cm}^2 \cdot \left(\frac{r}{1\,\mathrm{AU}}\right)^{-3/2}$$

Ingredient B: motion of protoplanetary dust



+ global transport processes by, e.g., accretion, turbulence, X-wind, photophoresis, …

Ingredient B: motion of protoplanetary dust – The MMSN model



1 AU

Velocity contours in cm/s

Fragmentation velocity of 1 m/s reached for 5-cm particles

St=1 at 50-60 m/s reached for 1-m particles

$$\Sigma_s(r) = 1700\ \mathrm{g/cm}^2 \cdot \left(\frac{r}{1\,\mathrm{AU}}\right)^{-3/2}$$

Weidenschilling & Cuzzi 1993

Ingredient B: motion of protoplanetary dust – alternative PPD models

$$\Sigma_s(r) = 1700\ \mathrm{g/cm}^2 \cdot \left(\frac{r}{1\,\mathrm{AU}}\right)^{-3/2}$$

Fragmentation velocity of 1 m/s reached for 5-cm particles

Weidenschilling 1977

$$\Sigma_s(r) = 20\ \mathrm{g/cm}^2 \cdot \left(\frac{r}{1\,\mathrm{AU}}\right)^{-0.8}$$

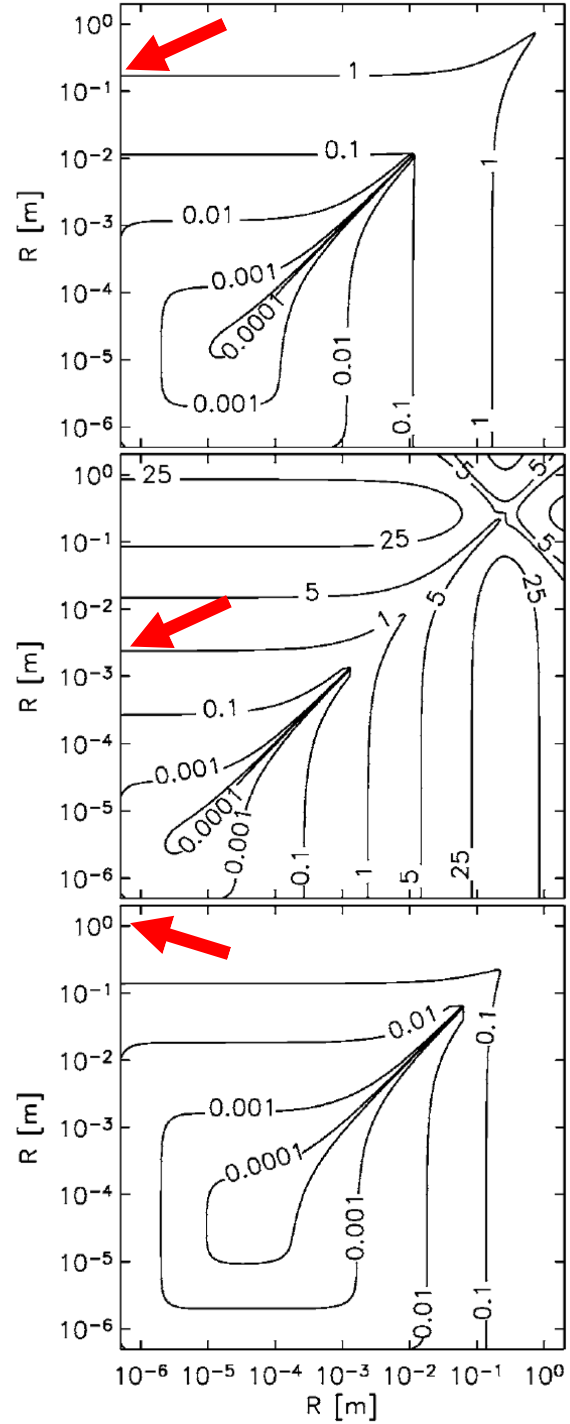
Fragmentation velocity of 1 m/s reached for 4-mm particles

Andrews & Williams 2007

$$\Sigma_s(r) = 50500\ \mathrm{g/cm}^2 \cdot \left(\frac{r}{1\,\mathrm{AU}}\right)^{-2.17}$$

Fragmentation velocity of 1 m/s reached for >1-m particles

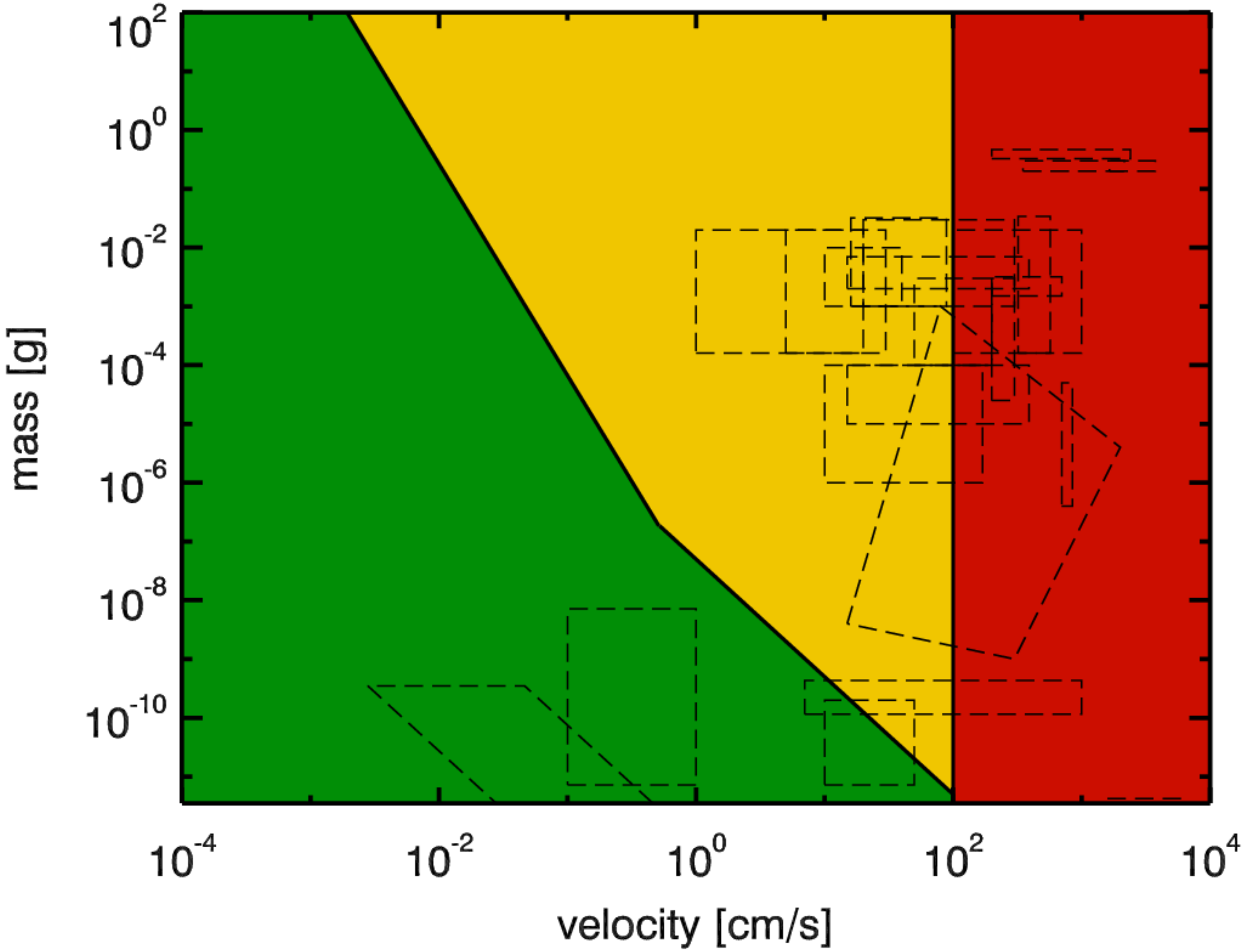
Desch 2007



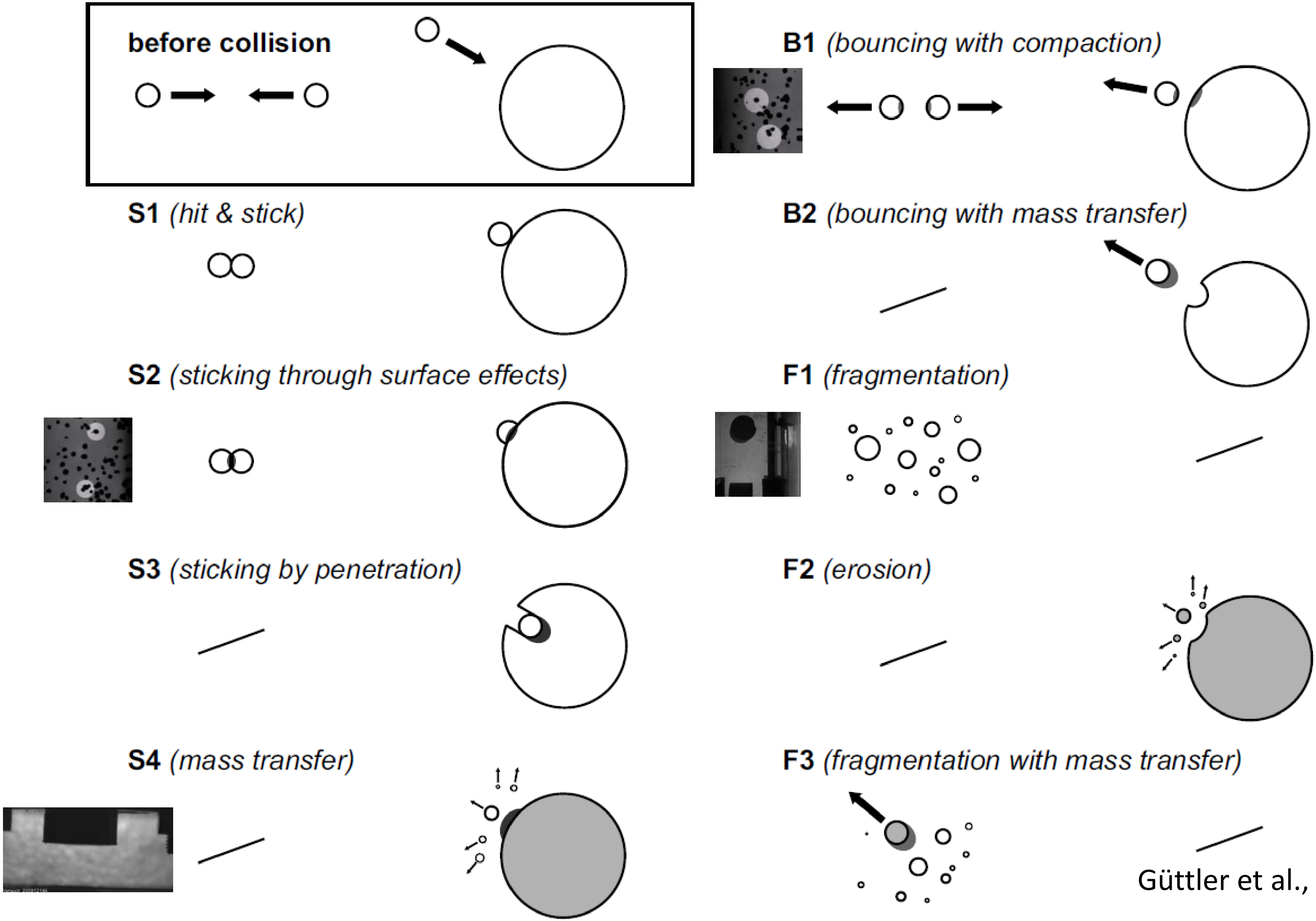
Ingredient C: systematic dust-aggregate collision experiments

- Good characterization of dust material (surface force/energy, size distribution)
- Various dust-aggregate production methods (fractal growth, random ballistic deposition, sifting, compression)
- Measured dust-aggregate properties: porosity, fractality, compressive and tensile strength
- Wide range of collision velocities (mm/s … 100 m/s) and aggregate sizes (~1 µm … 100 mm)
- Experiments performed under vacuum conditions
- Some experiments require microgravity conditions
- Restriction to (mostly) silicate (refractory) materials
  - Role of organics?
  - Role of (water) ice? → see below
- Uncharged dust aggregates → dead zones

Ingredient C: systematic dust-aggregate collision experiments – parameter-space coverage (as of 2010)



Ingredient C: a dust-aggregate collision model – overview

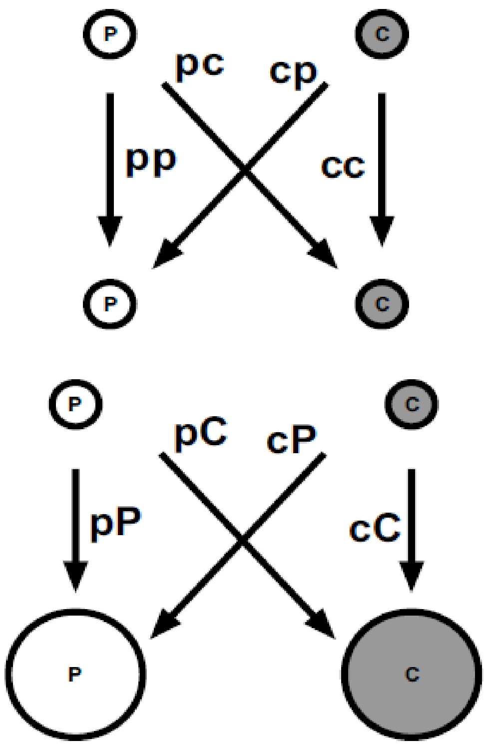


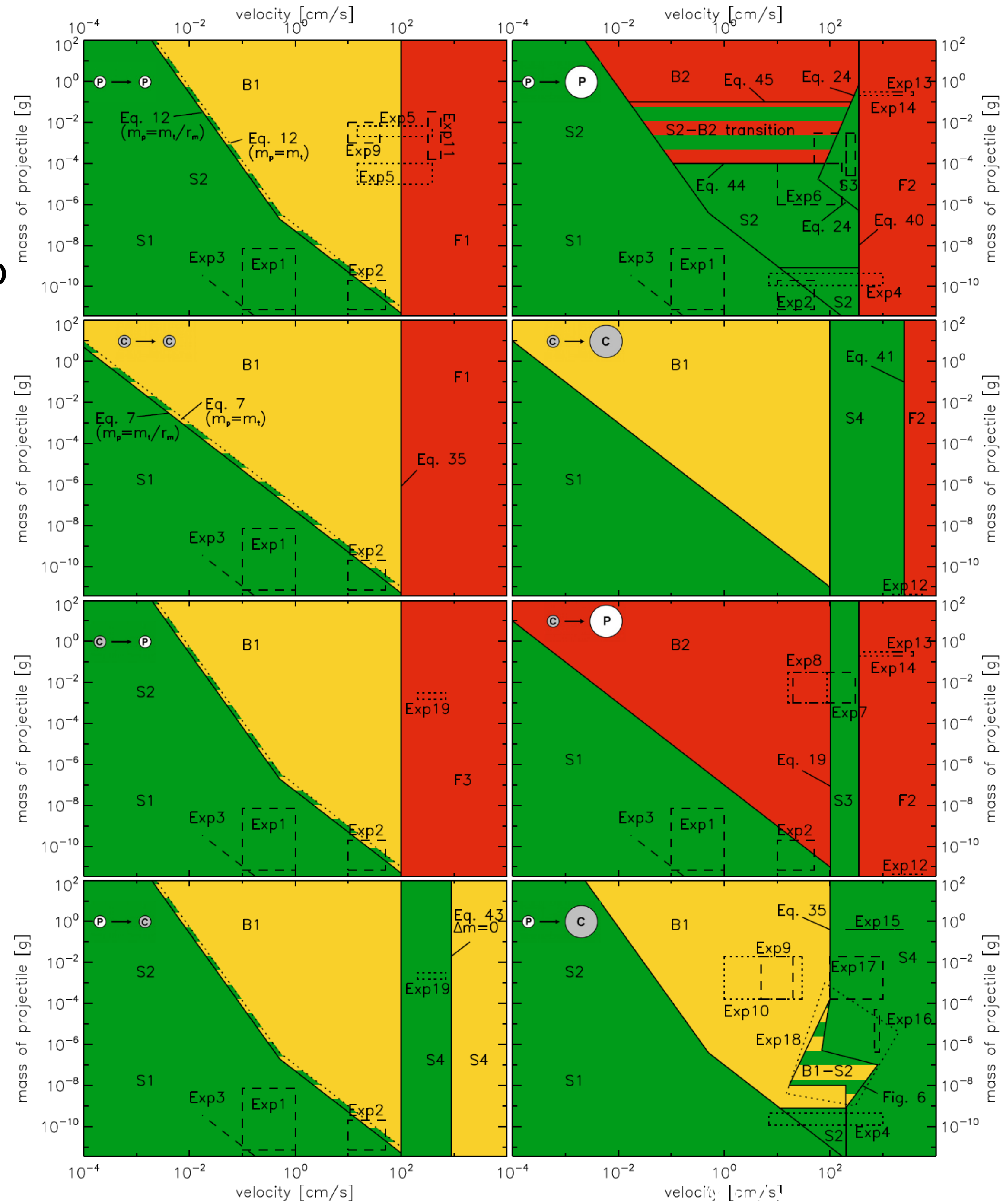
Güttler et al., 2010

→ See talks and posters by Brisset, Güttler, Kothe, Meisner, Schräpler, Weidling

Ingredient C: the complete collision model

- Valid for dust aggregates
- Binary model with respect to
  - mass ratio
  - porosity





Güttler et al., 2010

Ingredient C: a dust-aggregate collision model – material parameters

Table 2. Particle and aggregate material properties used for generating Fig. 11.

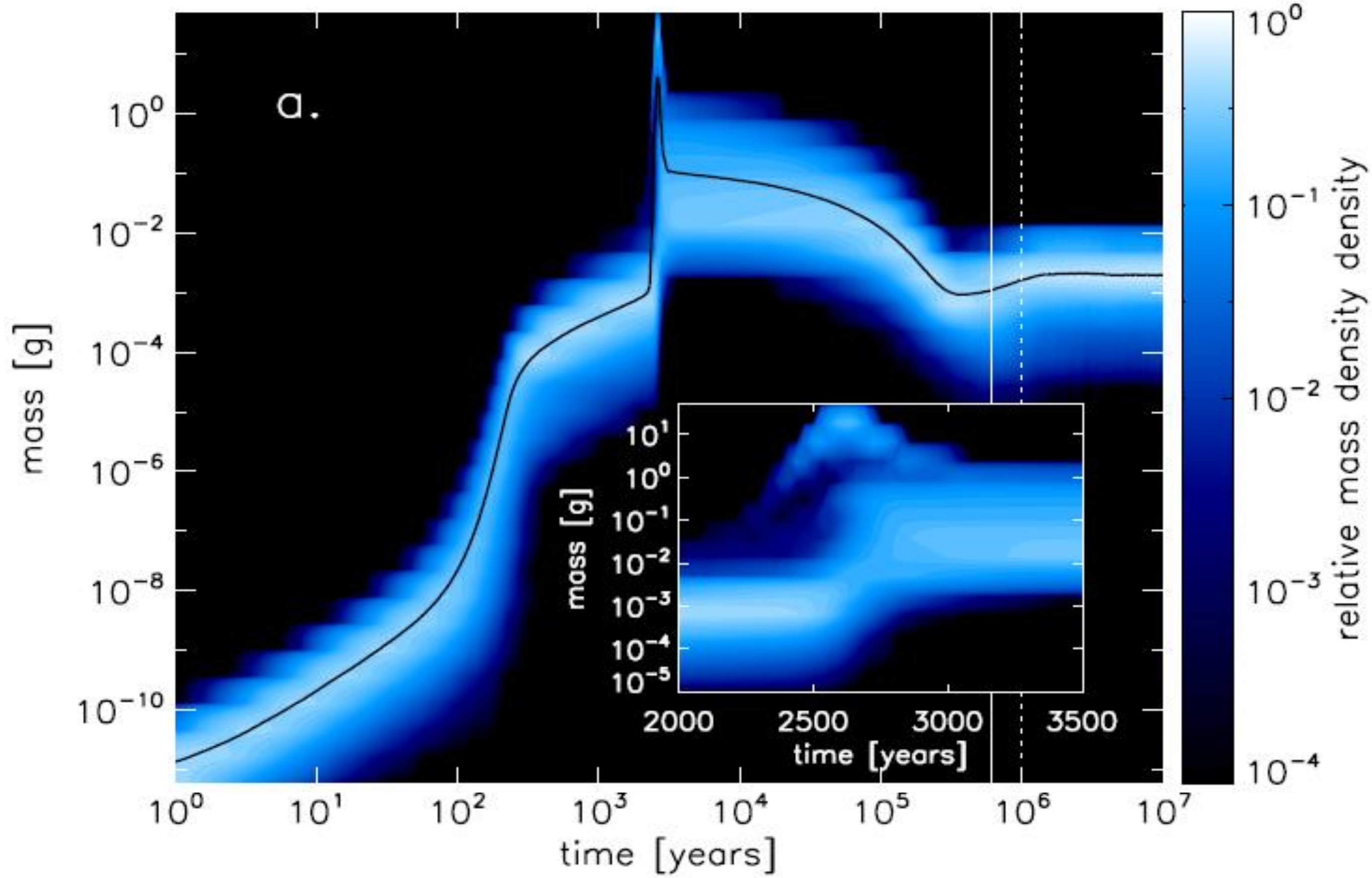
Symbol	Value	Reference
monomer-grain properties:		
a_0	$0.75\ \mu$m	
m_0	3.18×10^{-12} g	
ρ_0	2 g cm^{-3}	
E_0	2.2×10^{-8} erg	Blum & Wurm (2000), Poppe et al. (2000)
$F_{\rm roll}$	10^{-4} dyn	Heim et al. (1999)
aggregate properties:		
ε^2	0.05	Blum & Münch (1993), D. Heißelmann et al. (in prep.)
G	6320 dyn cm^{-2}	this work
T	10^4 dyn cm^{-2}	Blum & Schräpler (2004)
$\phi_{\rm c}$	0.40	this work
$r_{\rm m}$	10–1000	this work
γ	8.3×10^{-3} s cm^2 g^{-1}	Güttler et al. (2009)
$E_{\rm t}$	3.5×10^4 erg	Langkowski et al. (2008)
$E_{\rm min}$	3.1×10^{-2} erg	Langkowski et al. (2008)
ϕ_1	0.12	Güttler et al. (2009)
ϕ_2	0.58	Güttler et al. (2009)
Δ	0.58	Güttler et al. (2009)
$p_{\rm m}$	1.3×10^4 dyn cm^{-2}	Güttler et al. (2009)
$f_{\rm c}$	0.79	this work
ν_0	850	Weidling et al. (2009)
λ	–1.4	this work

Güttler et al., 2010

The first laboratory-based growth model for PPD dust

Result: temporal evolution of dust-aggregate masses for the minimum-mass solar nebula model

Zsom et al. 2010



The first laboratory-based growth model for PPD dust

Result: temporal evolution of dust-aggregate masses for the minimum-mass solar nebula model

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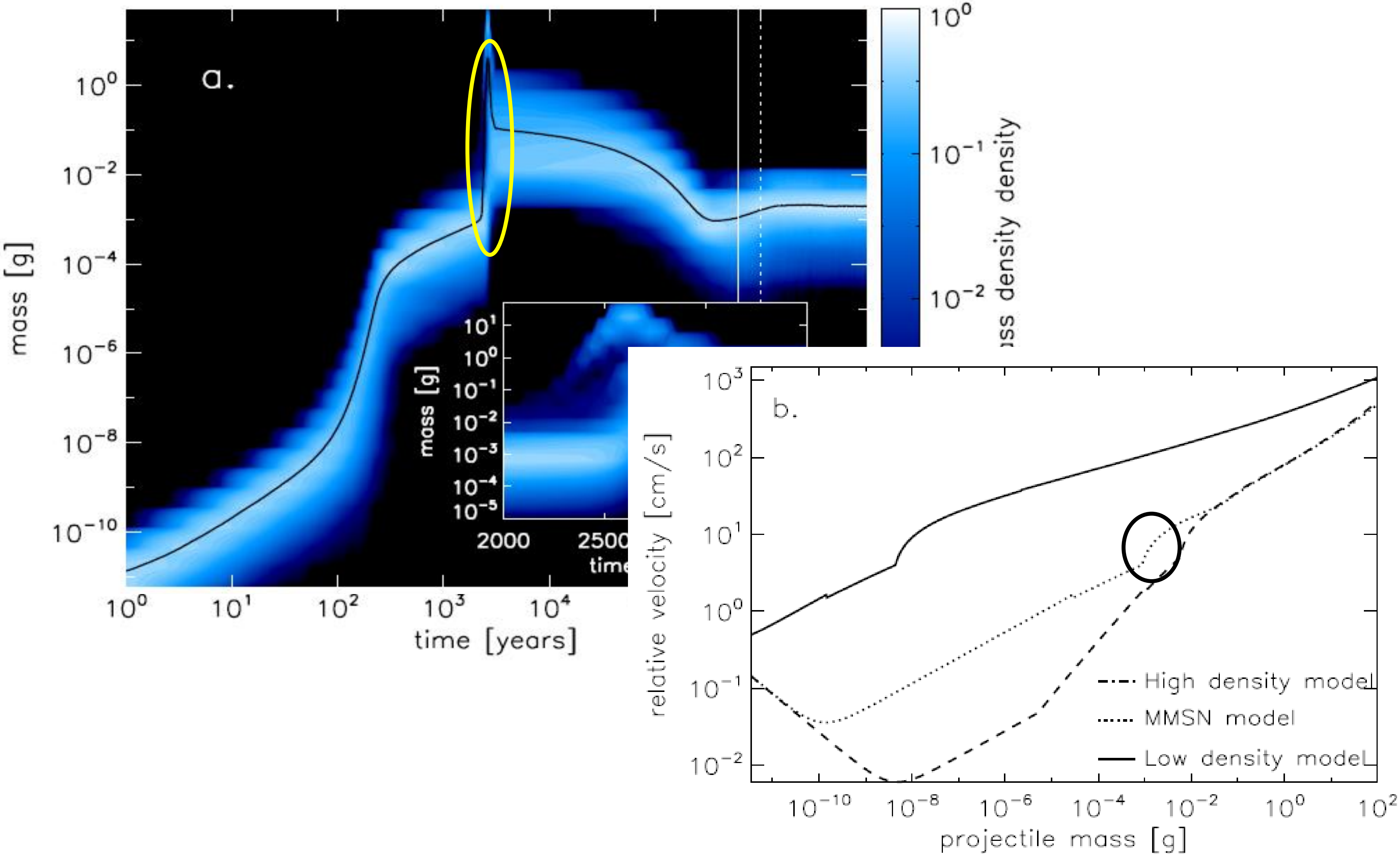
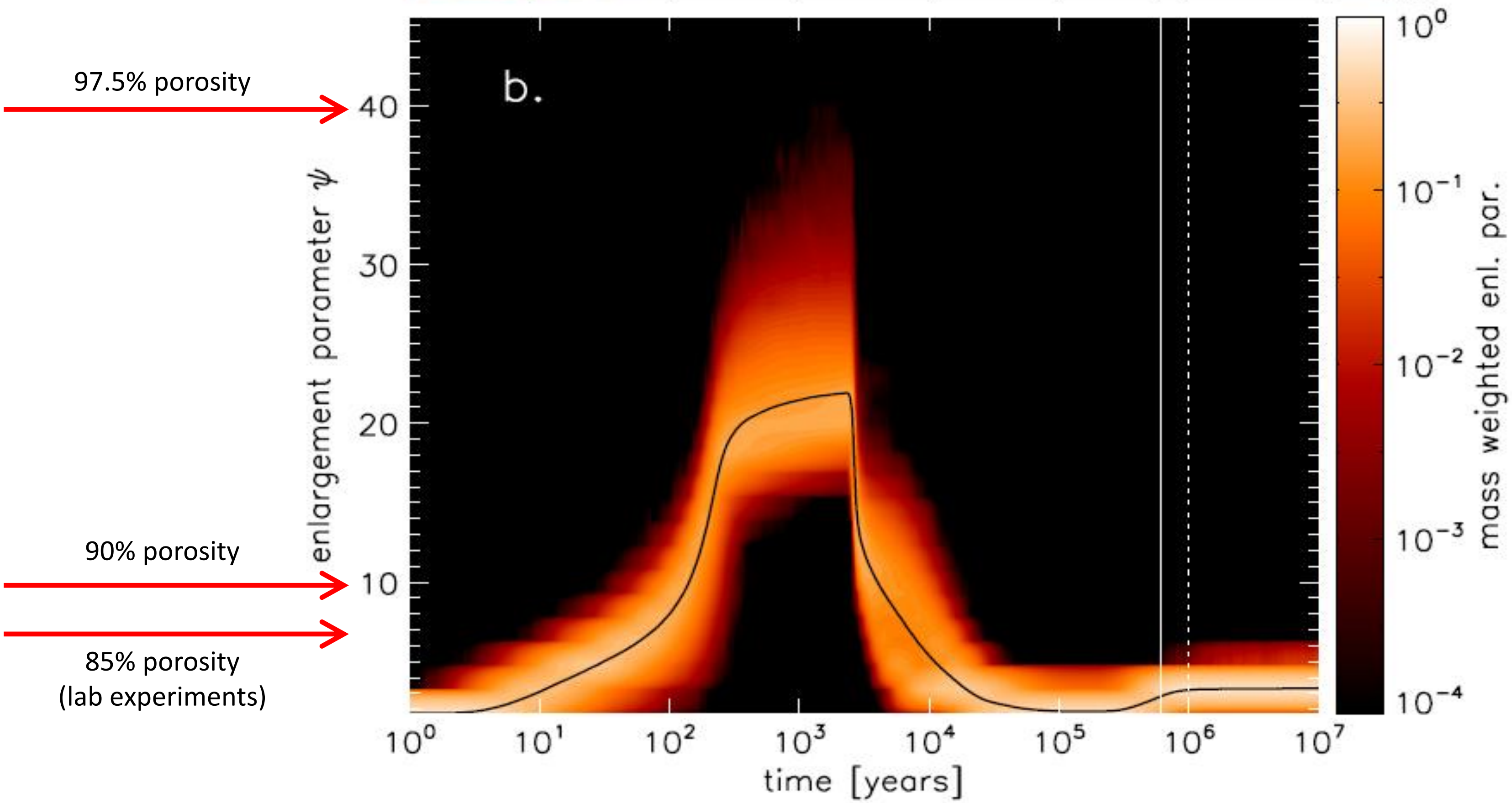


The first laboratory-based growth model for PPD dust

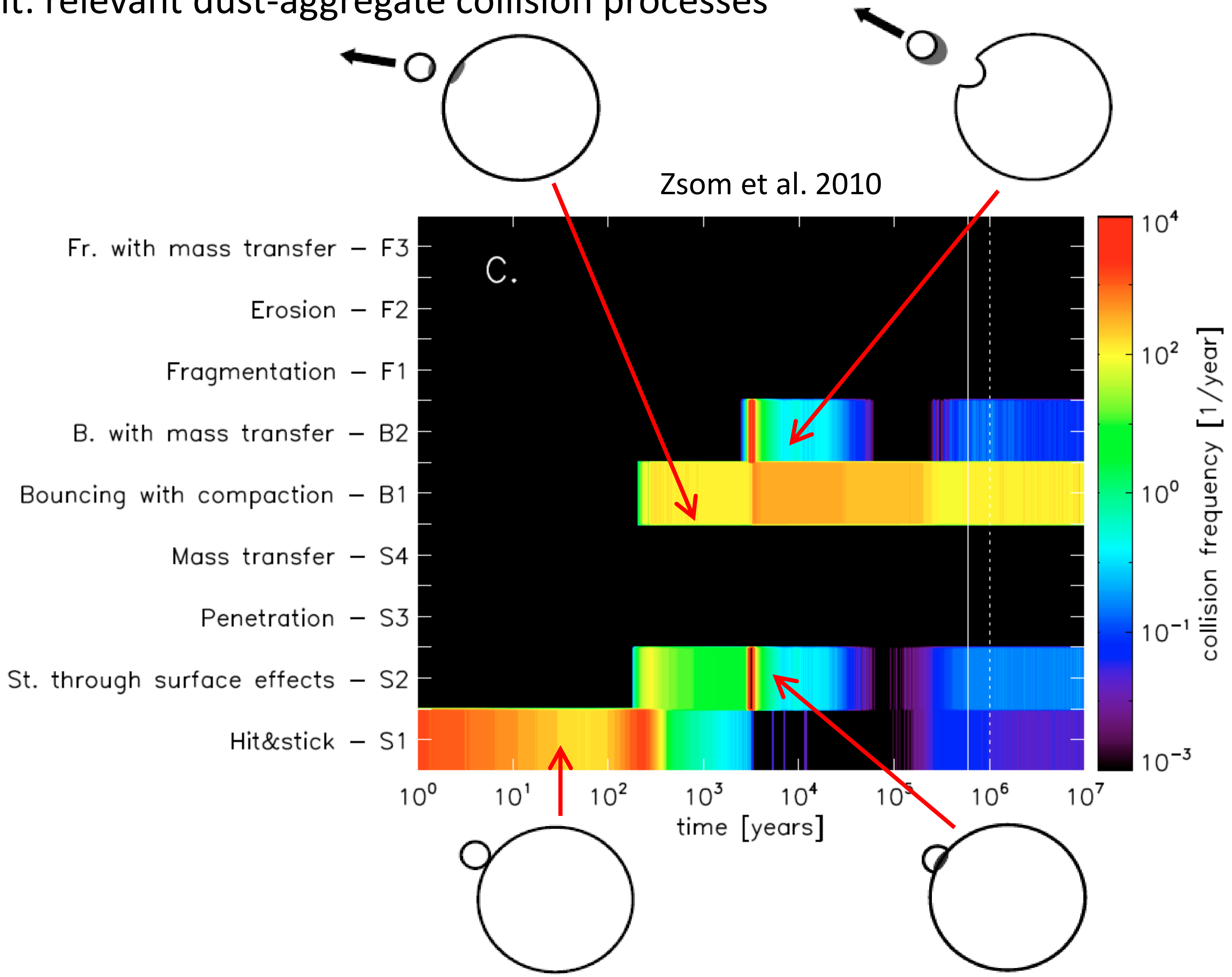
Result: temporal evolution of dust-aggregate enlargement factors for the minimum-mass solar nebula model

Zsom et al. 2010



The first laboratory-based growth model for PPD dust

Result: relevant dust-aggregate collision processes



The first laboratory-based growth model for PPD dust

Main results of the 0D (local)model of the dust evolution in protoplanetary disks:

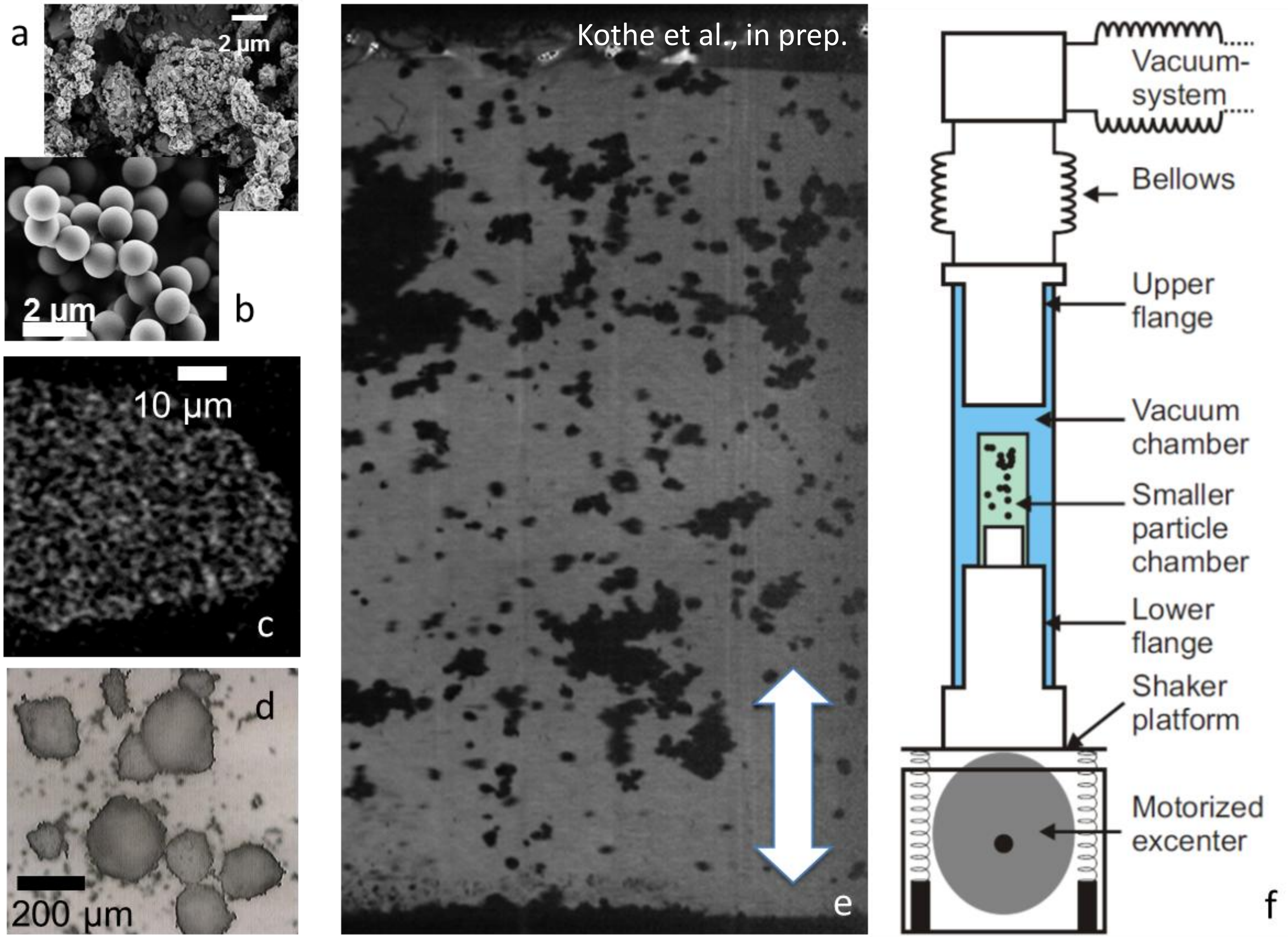
- Growth stops due to bouncing → "bouncing barrier"
- Maximum aggregate sizes ~cm
- Growth timescale to maximum size ~10^3 … 10^4 years
- Mass distribution stays narrow
- Compaction in bouncing collisions is of eminent importance; final porosity "only" ~60-70%
- Fragmentation regime is only reached for highest turbulence but does not invoke a new growth mode
- 1D model including sedimentation (Zsom et al. 2011):
  - For $\alpha=10^{-4}$ not much change
  - For $\alpha=10^{-2}$ maximum size: sub-mm

→ See talk by Andras Zsom

How to get from cm-size aggregates to planetesimals? A collection of ideas and preliminary assessments

1. The dust-aggregate collision model revisited (Kothe et al, subm.; Brisset et al., in prep.)
2. Chondrules (Beitz et al. 2011)
3. CAIs (Windmark et al. 2012a)
4. Velocity distribution (Windmark et al. 2012b)
5. Water ice and snow line
   - Higher surface energy (Gundlach et al. 2011) and “stickiness”
   - Due to local pressure maximum at snow line, higher dust concentration and no radial drift
   - But: growth of water-free planetesimals in the terrestrial-planet region needs also be explained
6. Collective effects and gravitational instability in dusty component (Johansen, Youdin, and collaborators)

1 The dust-aggregate collision model revisited

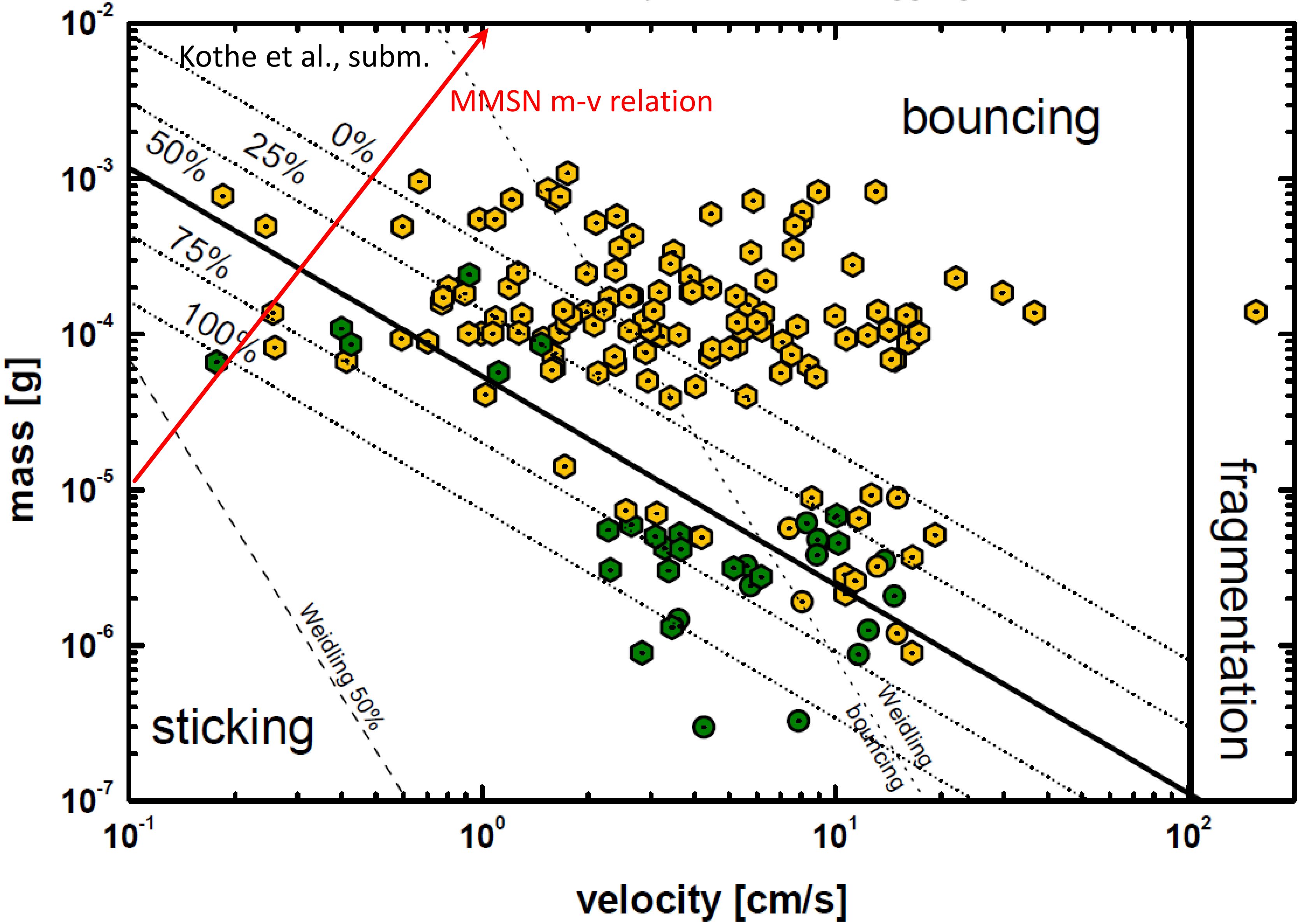


→ See poster by Stefan Kothe

Kothe et al., subm.

1 The dust-aggregate collision model revisited

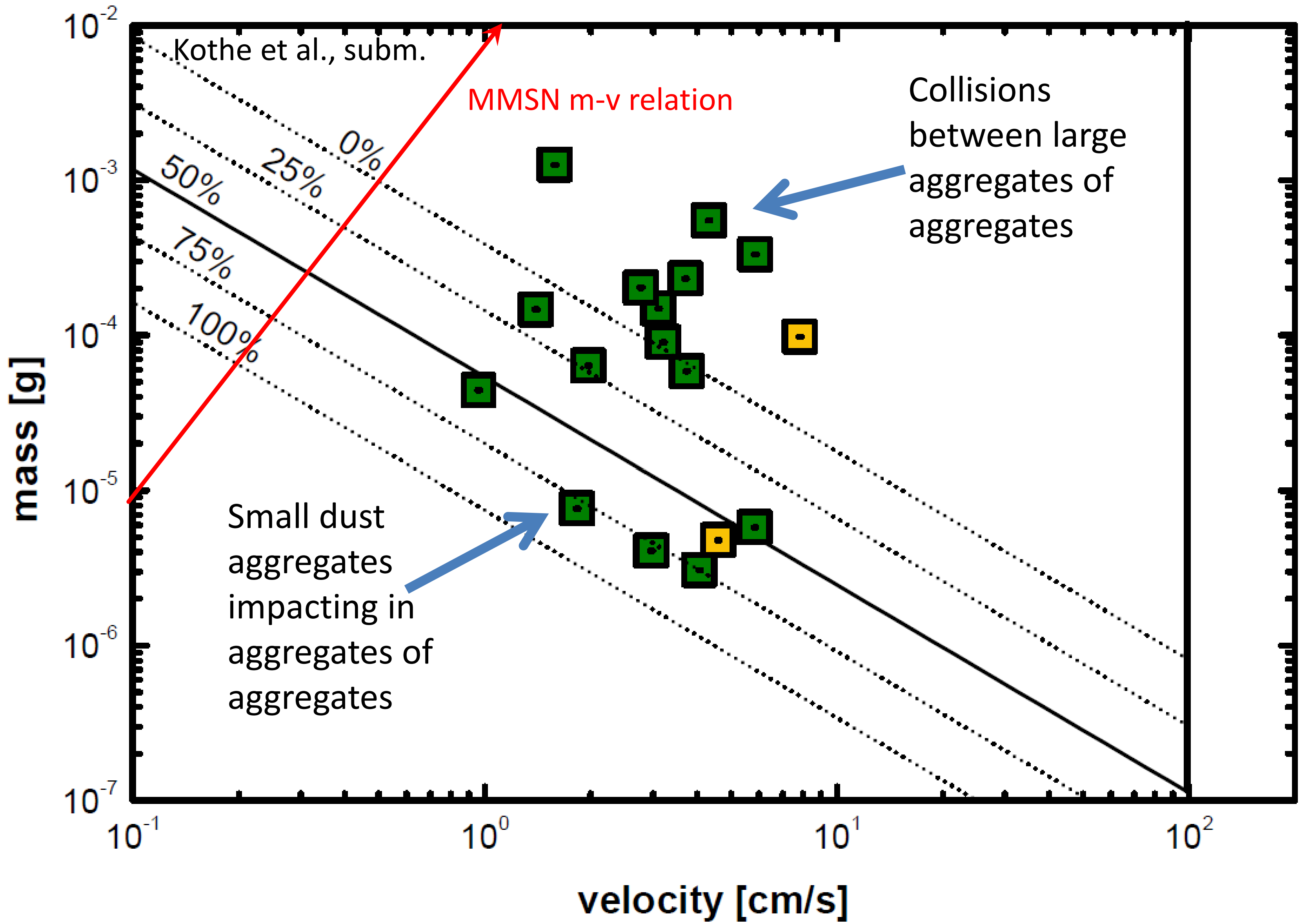
Collisions between spheroidal dust aggregates



→ See poster by Stefan Kothe

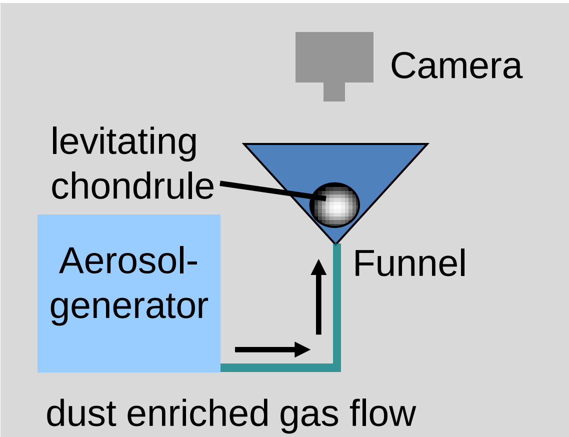
1 The dust-aggregate collision model revisited

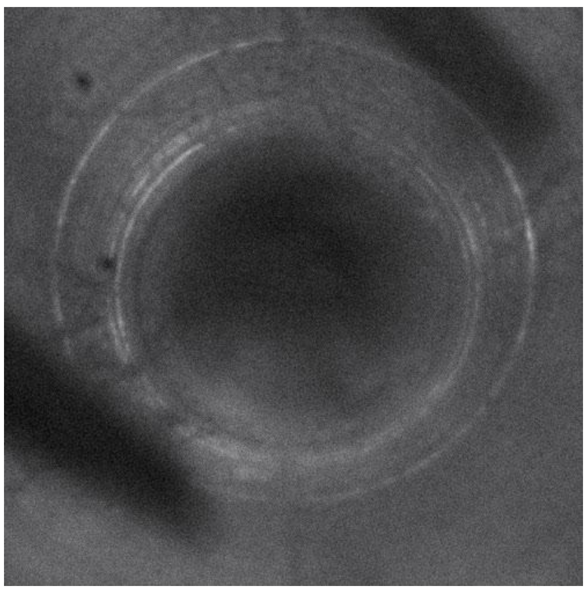
Collisions between aggregates of aggregates

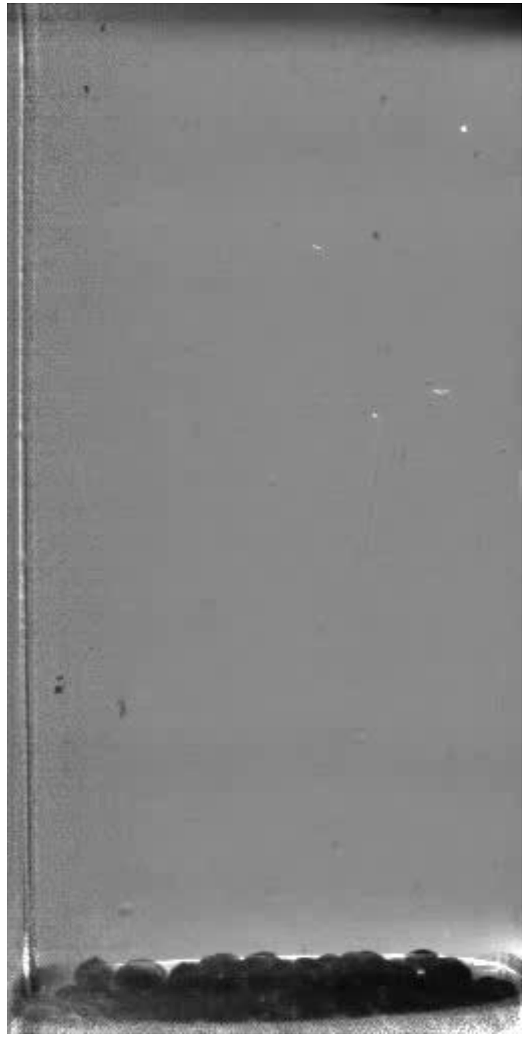


→ See poster by Stefan Kothe

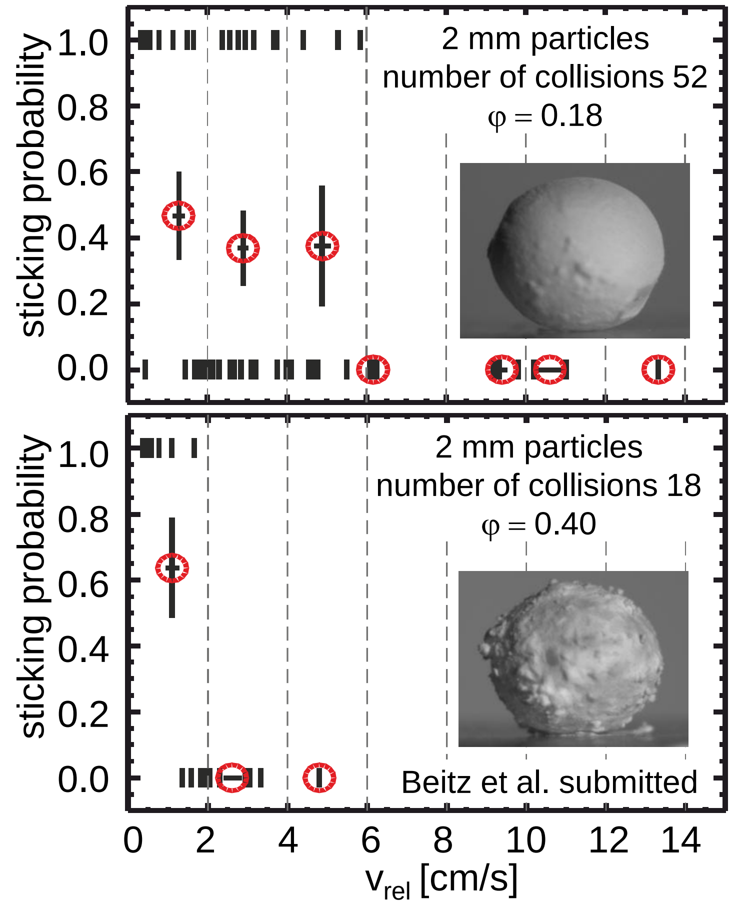
2 The impact of chondrules on the dust growth







Beitz et al. 2011

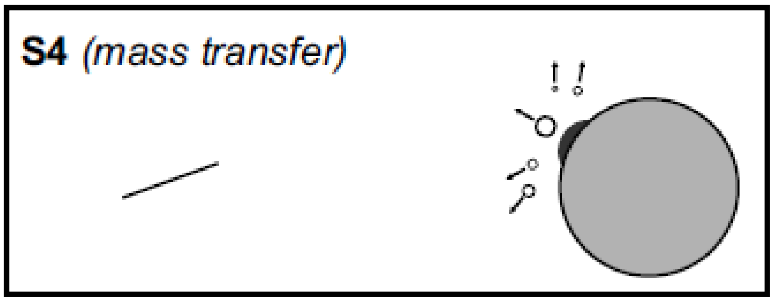


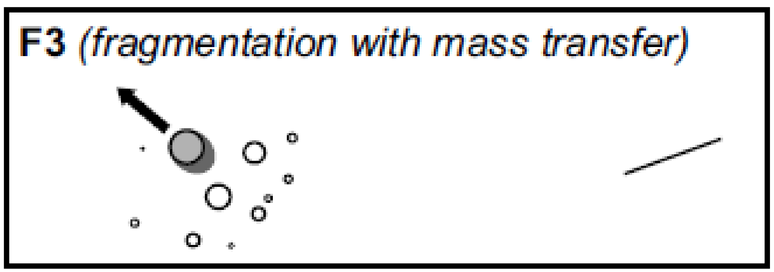
→ See talk by Eike Beitz

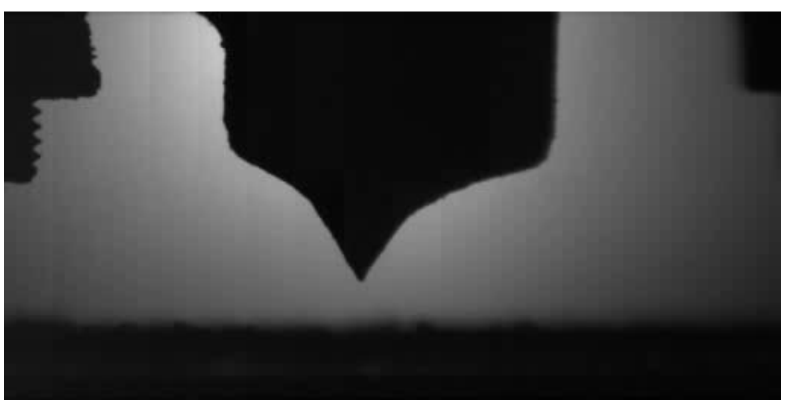
- Highly porous dust rims can be formed by "hit and stick" growth.
- Dust-coated chondrules are much more sticky compared to non-coated beads and dust aggregates of the same size or mass.
- Sticking probability depends on rim morphology and chondrule size.
- Rapid clustering of several tens of beads could be observed in the experiments.

3 The impact of CAIs on the dust growth

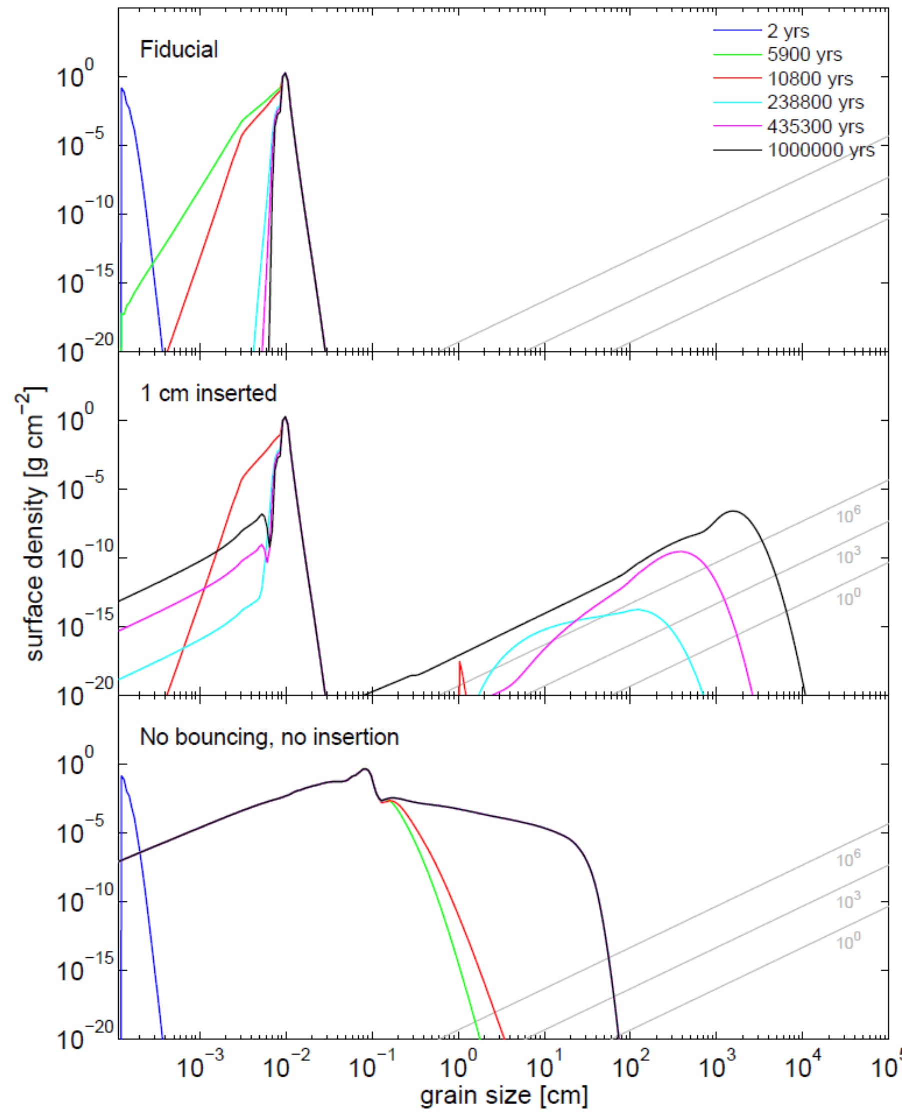
Formation of much larger (planetesimal-sized) objects can be triggered by a few indestructible 1-cm-sized particles (e.g., CAIs), due to the S4 (mass transfer) and F3 (fragmentation with mass transfer) processes (Windmark et al. 2012a)







Kothe et al. 2010



Windmark et al. 2012a

→ See talks by Carsten Güttler and Fredrik Windmark

4 Velocity distribution

Windmark et al. 2012b

Replace $v = v_{rms}$ by

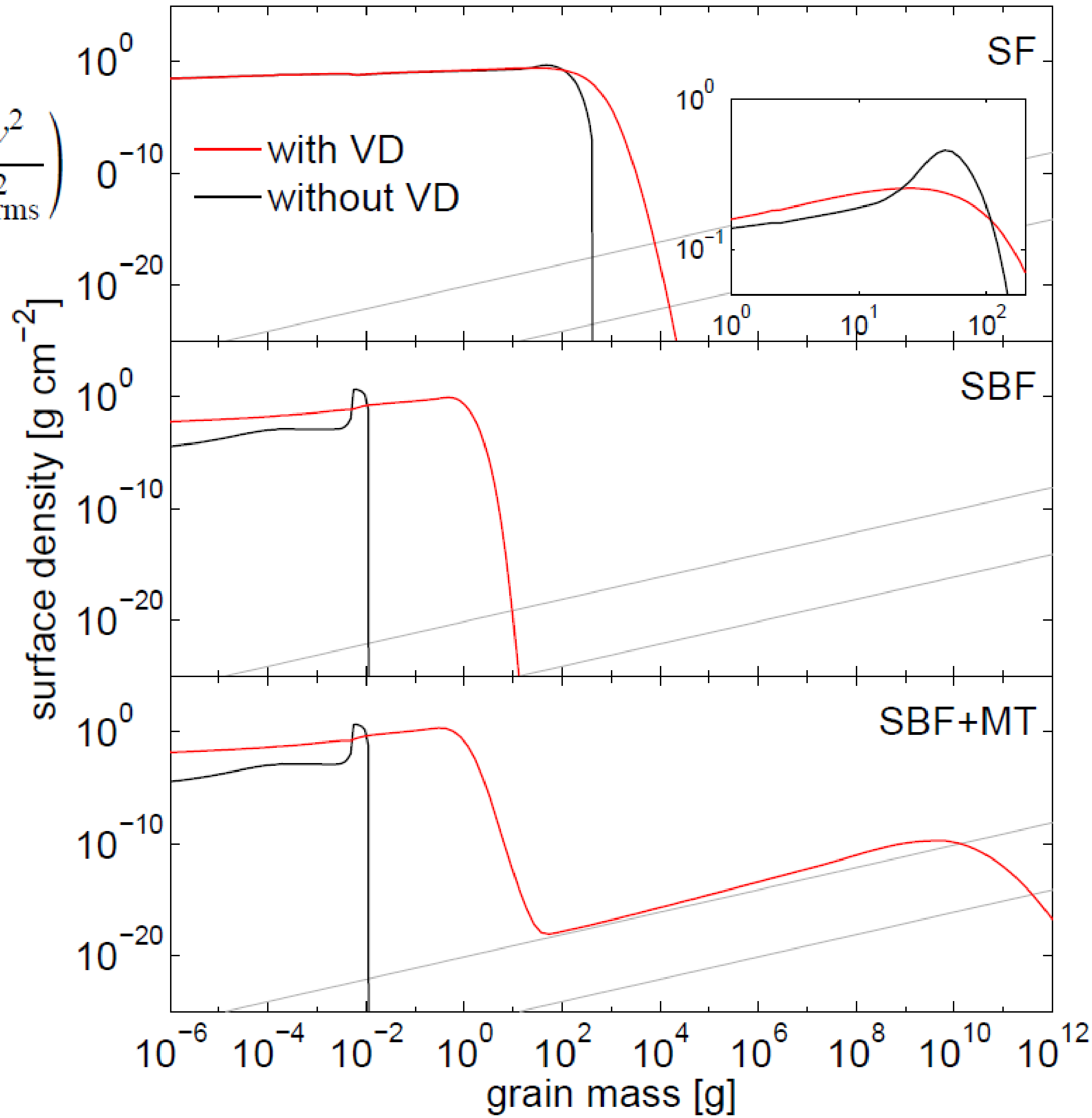
$$P(v \mid v_{\rm rms}) = \sqrt{\frac{54}{\pi}}\,\frac{v^2}{v_{\rm rms}^3}\exp\left(-\frac{3}{2}\frac{v^2}{v_{\rm rms}^2}\right)$$

(Windmark et al. 2012b)

SF = sticking + fragmentation

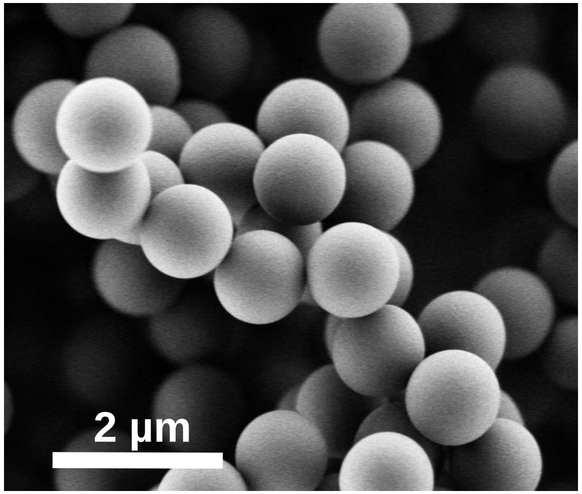
SBF = sticking + bouncing + fragmentation

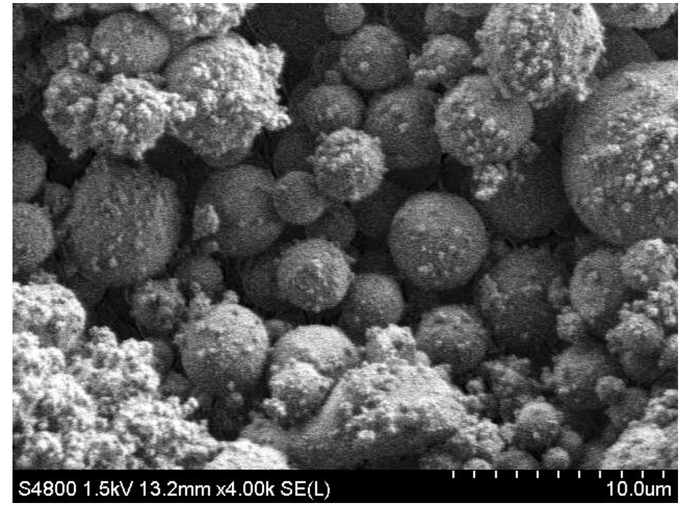
SBF+MT = sticking + bouncing + fragmentation + mass transfer

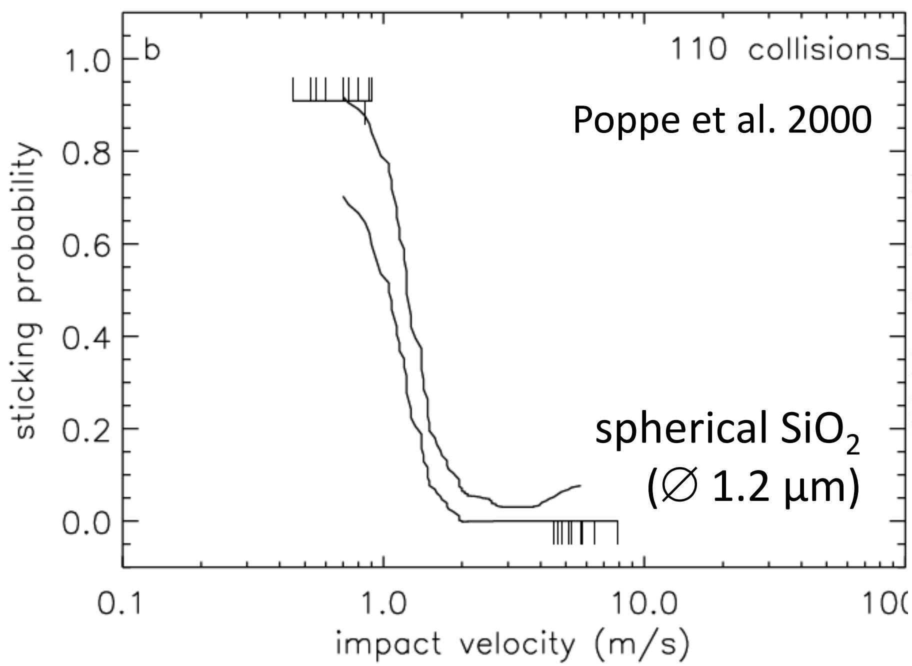


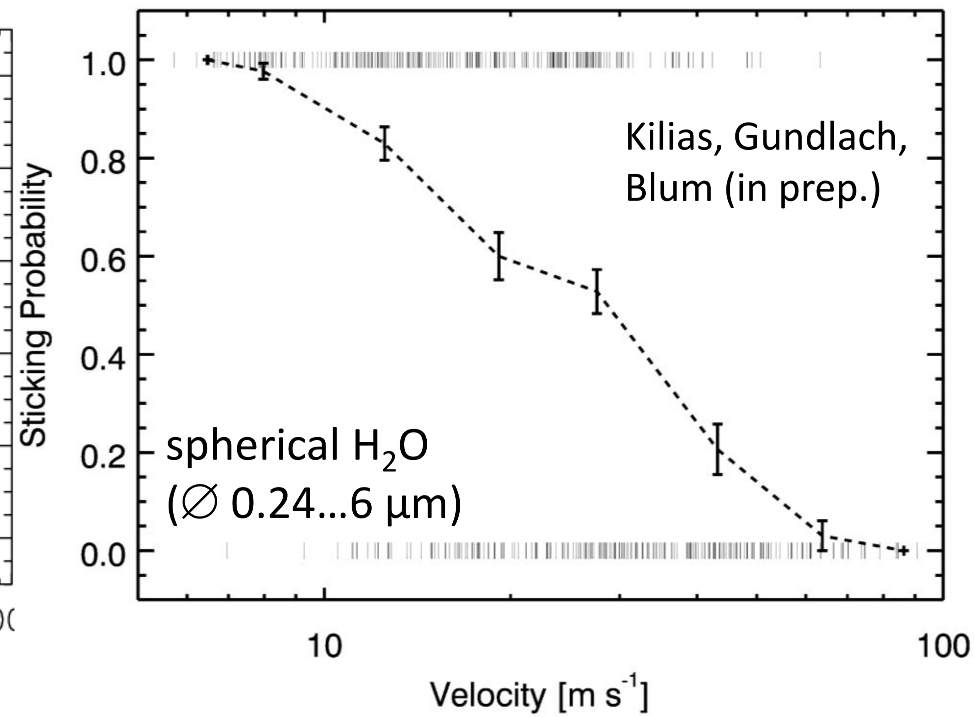
→ See talk by Fredrik Windmark

5 The "stickiness" of water ice



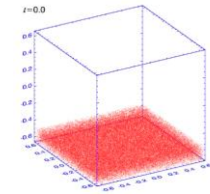




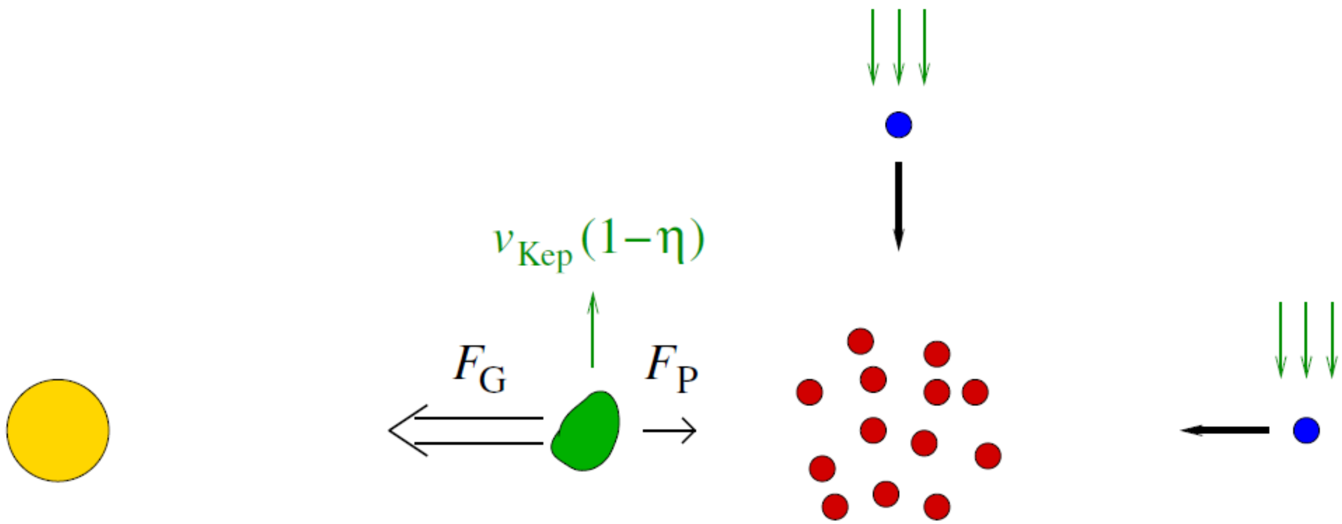


→ See talk by Satoshi Okuzumi

❻ Collective dust effects



- Particle concentration in MRI or KHI pressure bumps
  - Strong correlation between high gas density and high particle density (Johansen et al. 2006; Johansen et al. 2007)
  - Solid particles are trapped in gas overdensities (Whipple 1972)
- Streaming instability (Youdin & Goodman 2005)



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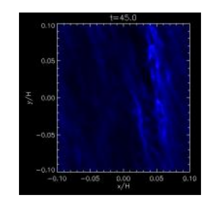
- Ceres-size planetesimals form by gravitational instability (Johansen et al. 2006-2012)



- Collision physics of dust aggregates not yet taken into account (→ importance of fragmentation and mass transfer?)

Future laboratory work on planetesimal formation

- Get input from the models in which parameter regime dust-aggregate collisions are predicted
- Check collision outcomes
- Give feedback to models
- Examples:
  - Duisburg – collision behavior of 10-cm particles

    → See talk by Johannes Deckers
  - Braunschweig – collisional evolution of trapped dust aggregates; collisional evolution of many-particle systems
  - Tübingen – SPH simulations of collisions of very large dust aggregates

    → See talk by Roland Speith

CONCLUSION

The formation of cm-size dust aggregates can be understood under solar-nebula conditions with the “stickiness” of dust aggregates.

The formation of planetesimals from such dust aggregates is still speculative. However, many ideas exist how the further dust growth can proceed:

- Refinements of the dust-aggregate collision model
- Chondrules
- CAIs
- Velocity distribution
- Water ice
- Collective dust effects

Stay tuned …


Thank you very much!
IGEP TU BS
Research group on Planet Formation
& Small Bodies in the Solar System
Questions?